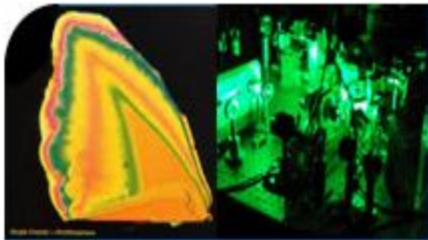


**MATÉRIAUX ET PHÉNOMÈNES QUANTIQUES**

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

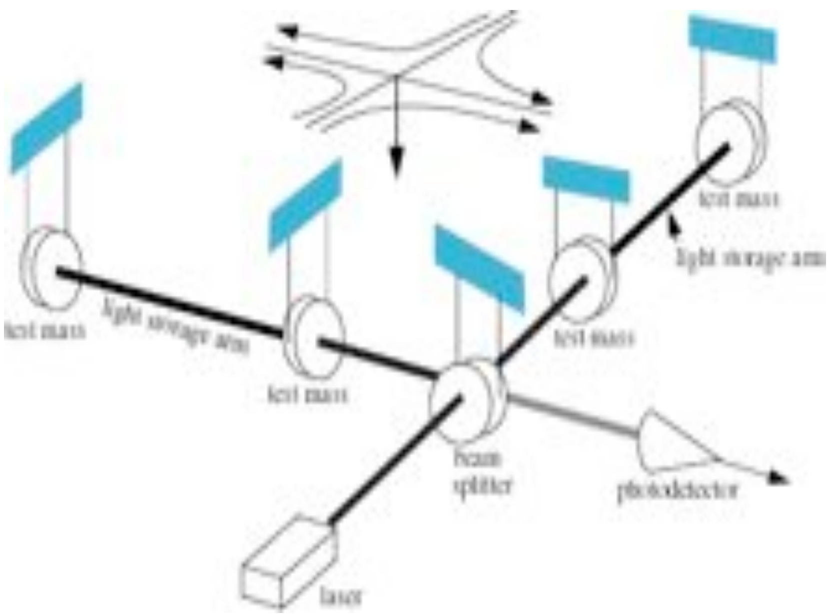

***Ivan Favero***

*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/√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 »*

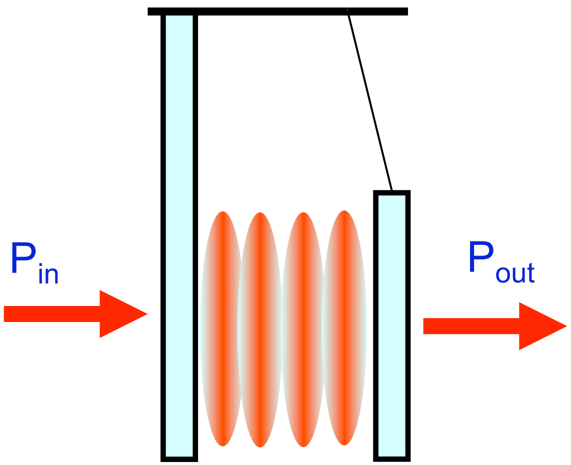
V. B. Braginsky, F. Khalili, « *Quantum measurement* »,Cambridge University Press (1995)

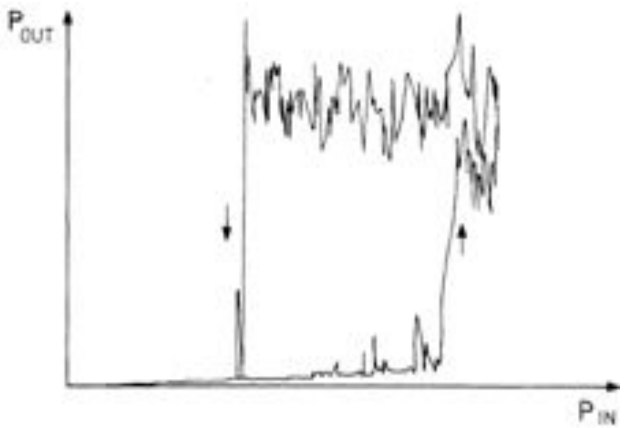
## Photons dynamical back-action

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**

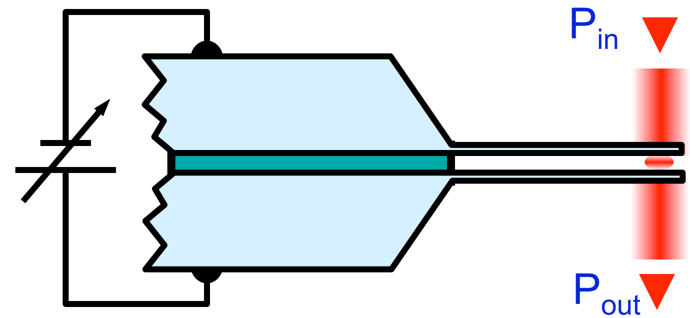
# Coupling light to the mechanical motion of a mirror



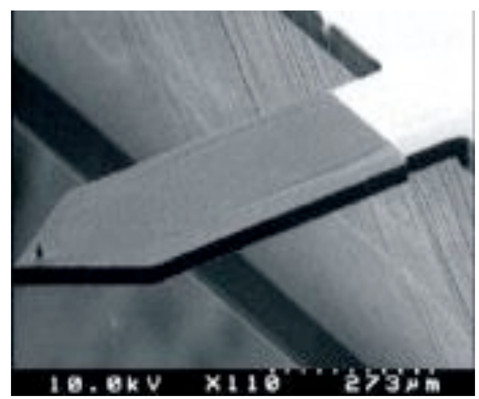



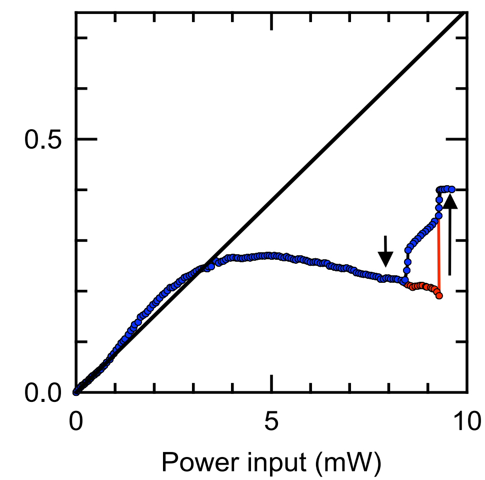

A. Dorsel et al., *PRL 51, 1550 (1983)*

**Optical bi-stability and mirror trapping**




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



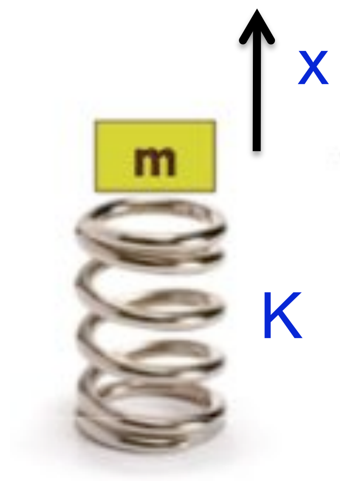

Back-action on a micro-mirror (2003)

# Quantum regime of a mechanical oscillator

- Classical harmonic oscillator $md^2x(t)/dt^2+Kx(t)=0$

$x(t)=x_0\cos(\omega_m t+\varphi)$

$\langle E\rangle = \frac{1}{2}.m\omega_m^2 x_0^2$

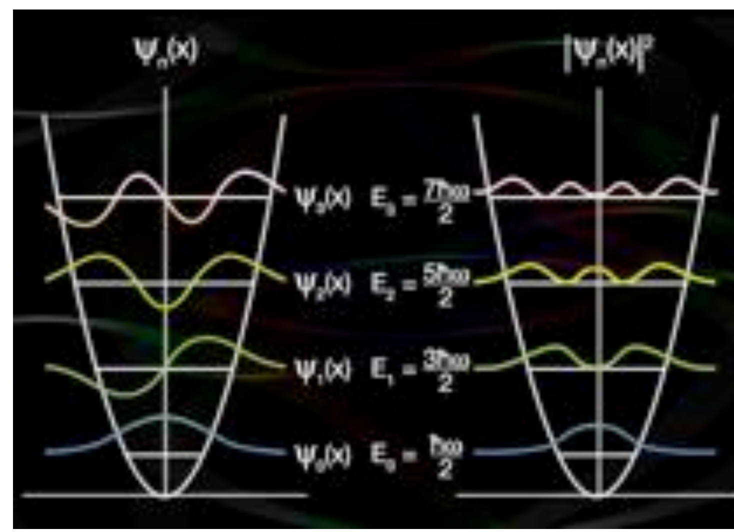



- Quantum harmonic oscillator

$E_n=(n+1/2)\hbar\omega_m$ n phonon number

n=0 is the quantum ground-state

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

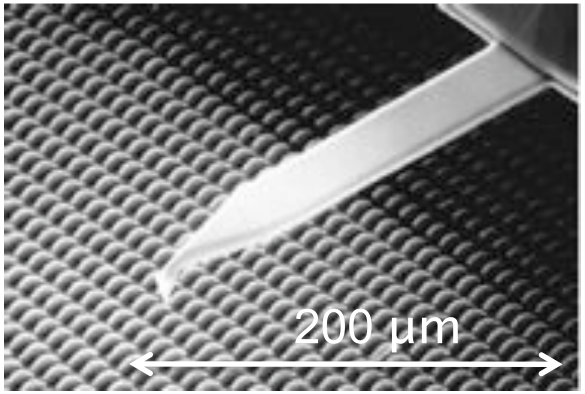


Difficulties

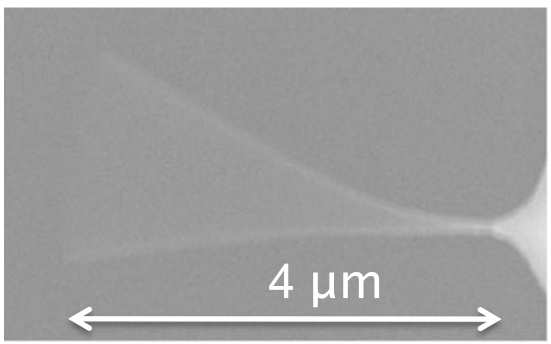
- Detect the « quantum » motion
- Reach the regime $k_B T \leq \hbar\omega_m$

# Quantum temperature $k_BT \le \hbar\omega_m$ ?

Micro

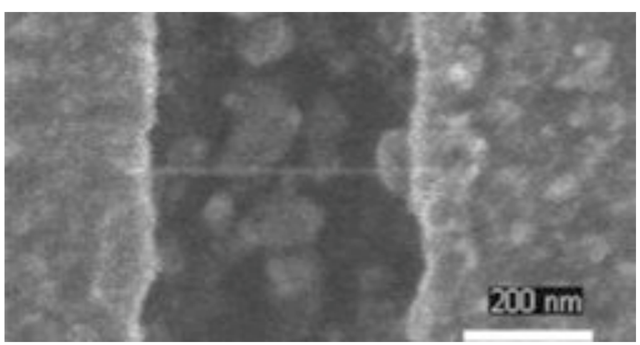



- 10 KHz corresponds to 500 nK




- 1MHz corresponsd to 50 µK

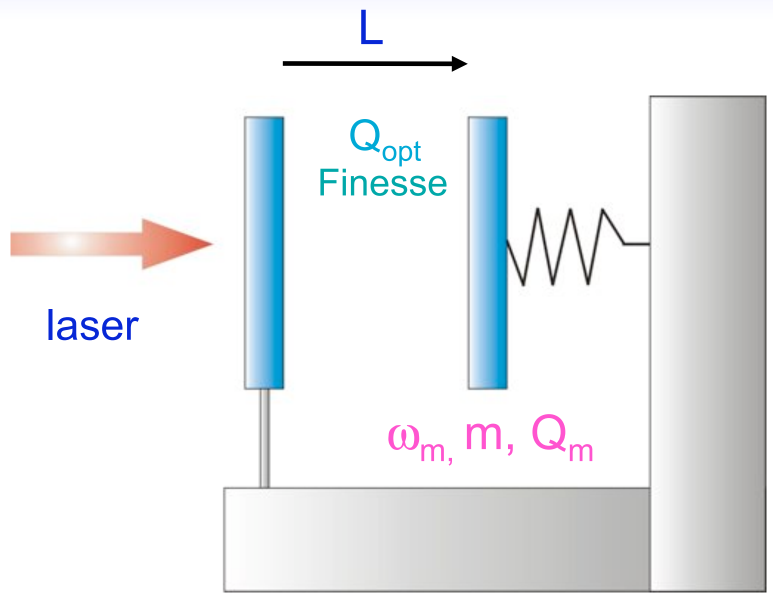
Nano

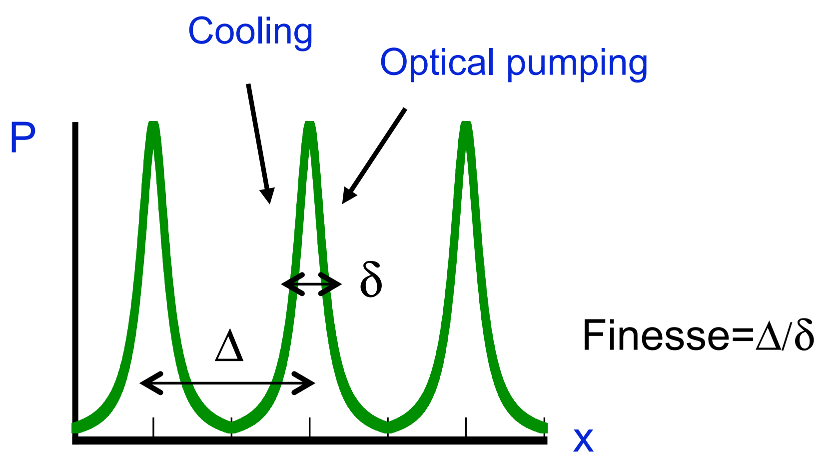



- 1GHz corresponds to 50 mK

# Principles of optical cooling

# Optical cavity cooling of a mirror motion




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

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

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

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

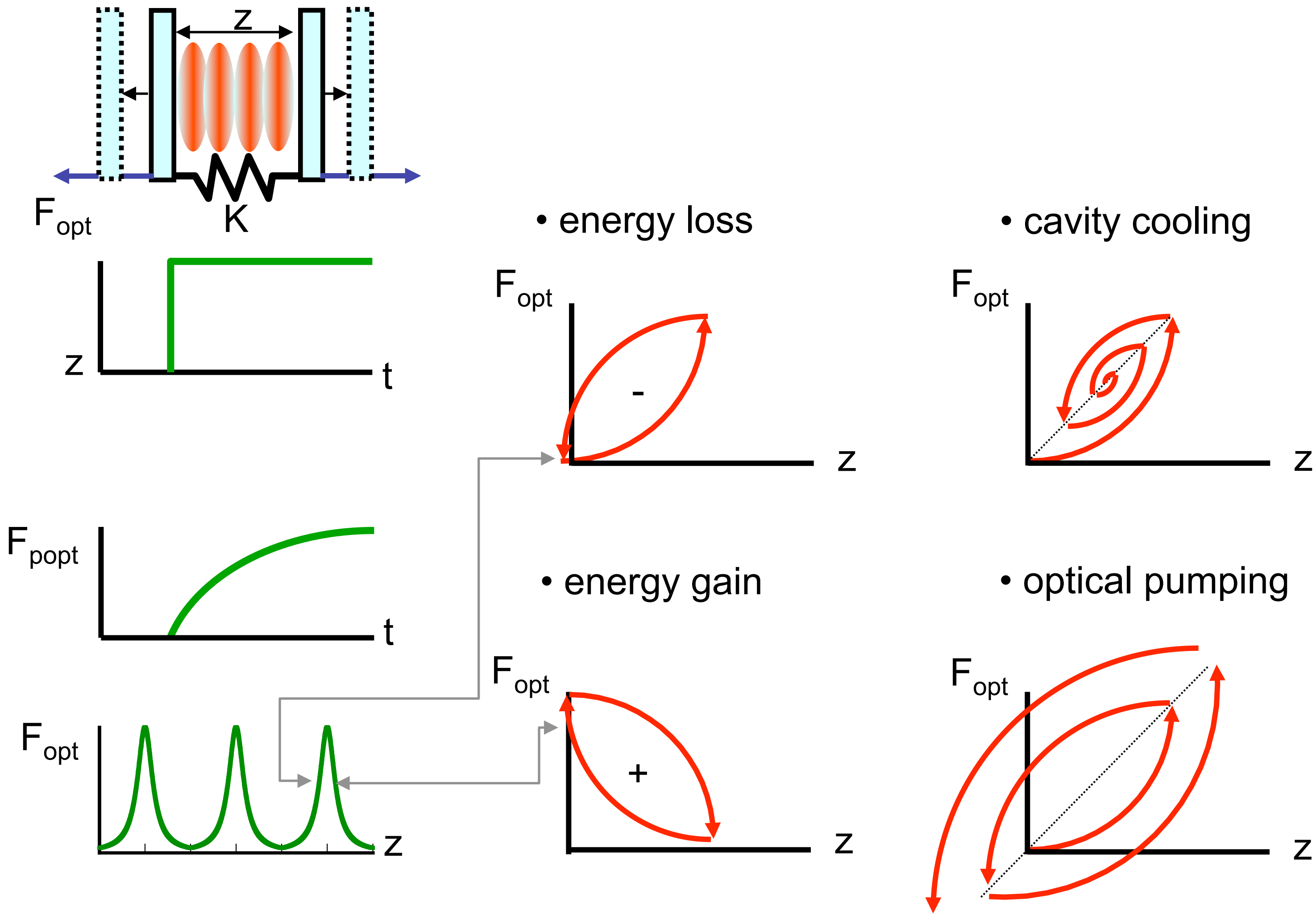
Optical Pressure $\alpha P_{opt}$ /c (delay $\tau$ )

- Photothermal pressure
- Radiation pressure
- Opto-electronic pressure

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

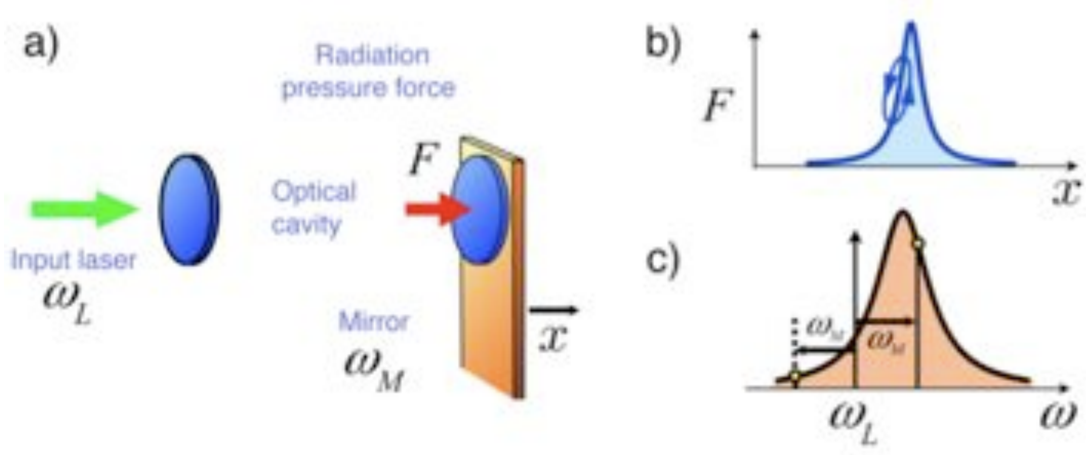
$(\Delta x_{zpf})^2 = \hbar / 2m\omega_m$ small mass

# Thermodynamic picture of optomechanical cooling



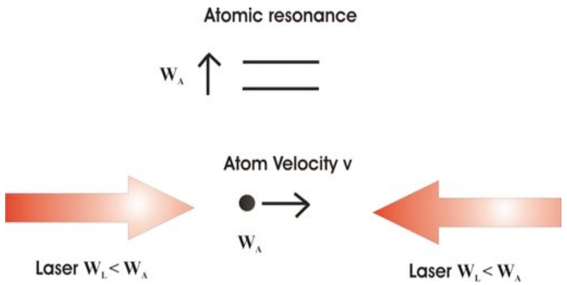

Brownian motion modified by the mechanical action of light

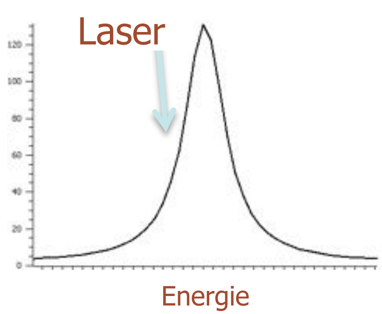
# Sideband picture of optomechanical cooling




*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

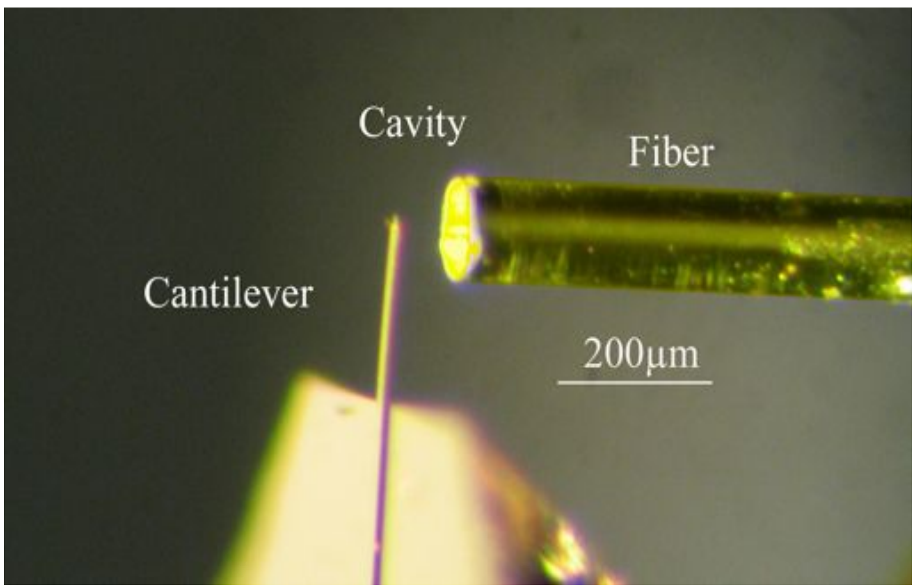
## Cavity cooling of a microlever

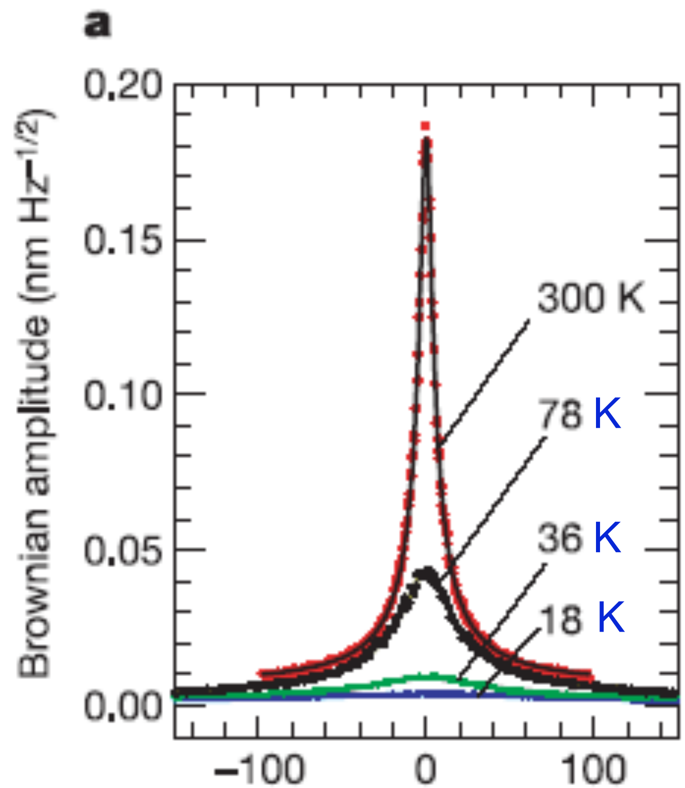
**Constanze Höhberger Metzger & Khaled Karrai**

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

*December 2004*

**18 K !**




*Frequency $f$-$f_0$ (Hz)*

*Frequency =10 KHz*

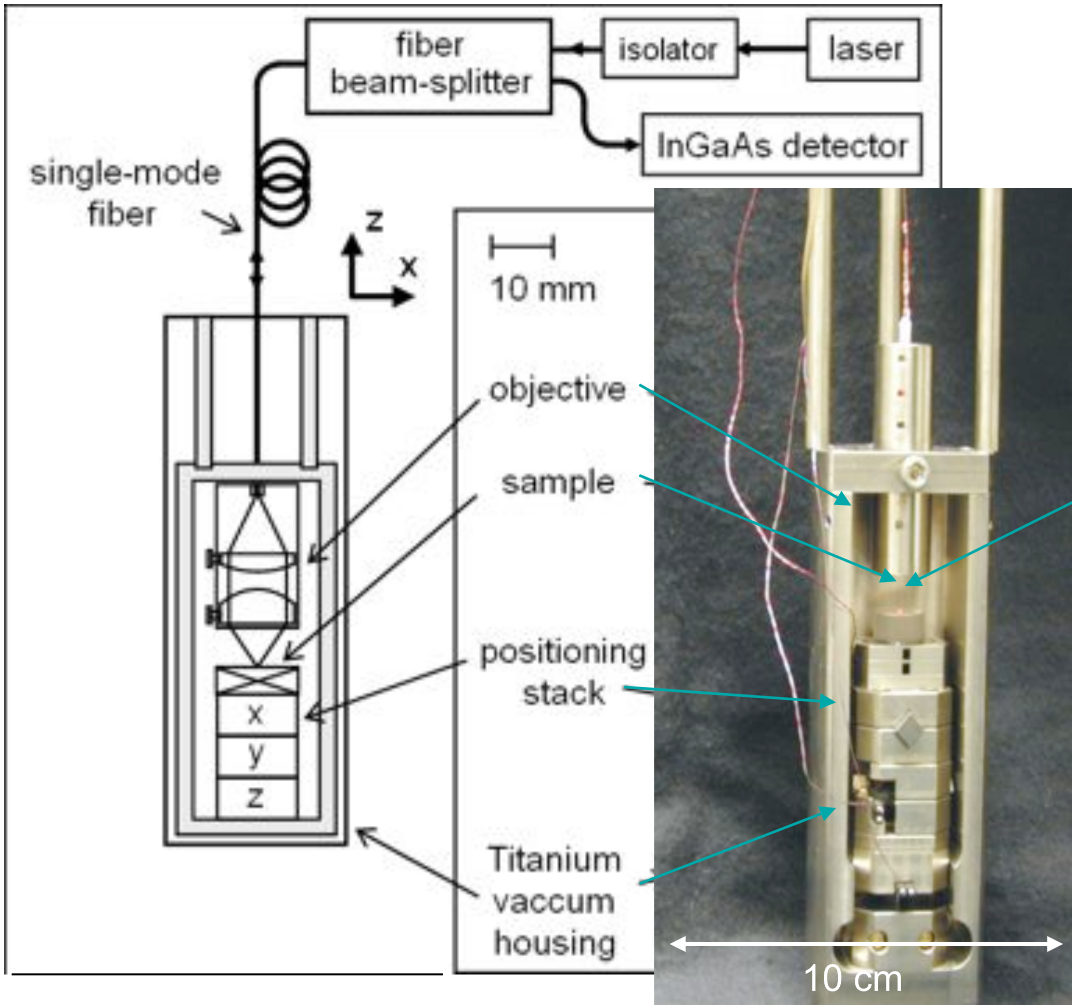
See also external feed-back cooling: PRL 83, 3174 (1999)

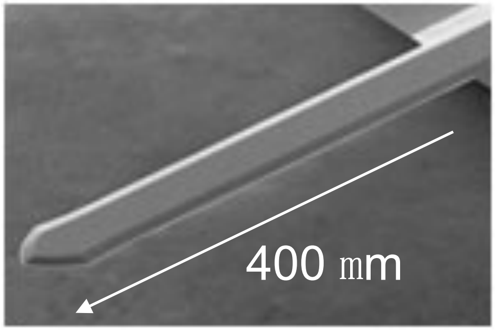
# Limits of the system

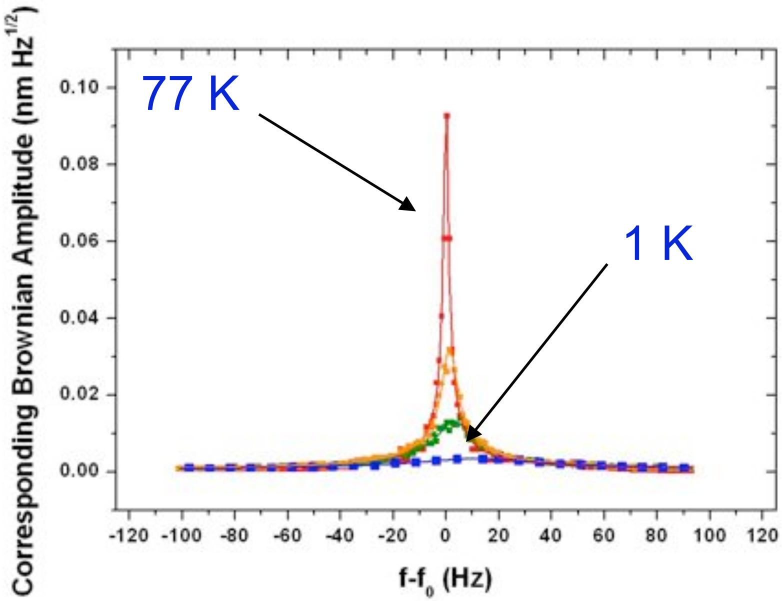
Mass = $10^{-7}$ g, Finesse = 10

$Q_m$ = 3000,

$g_{om} \approx 100$MHz/nm

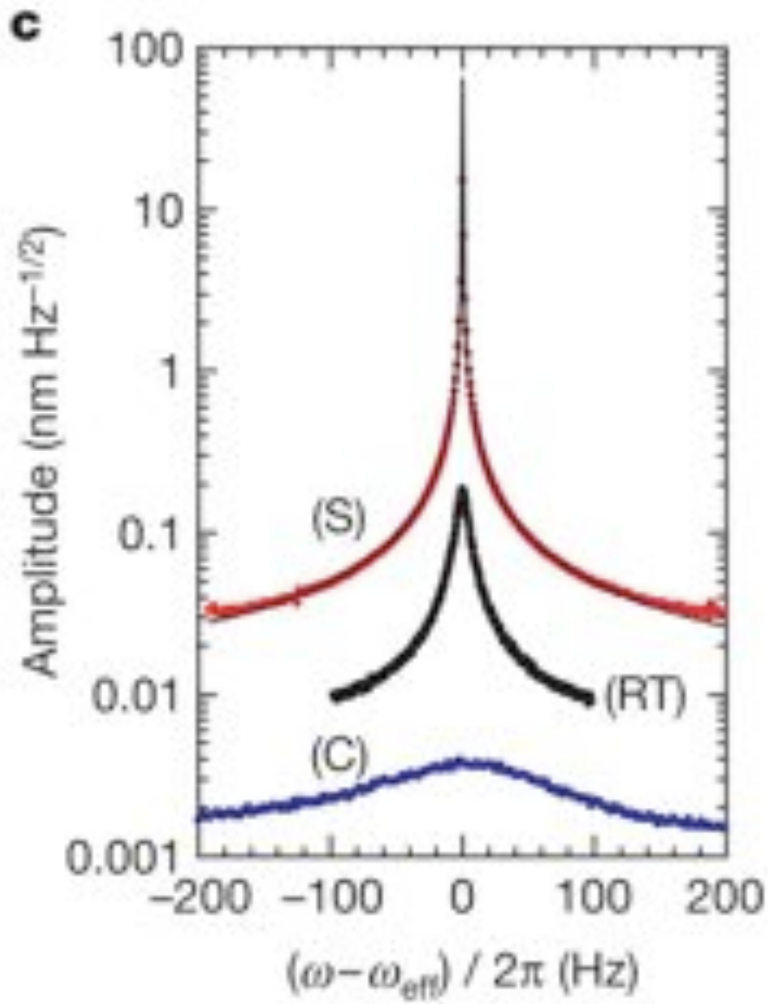


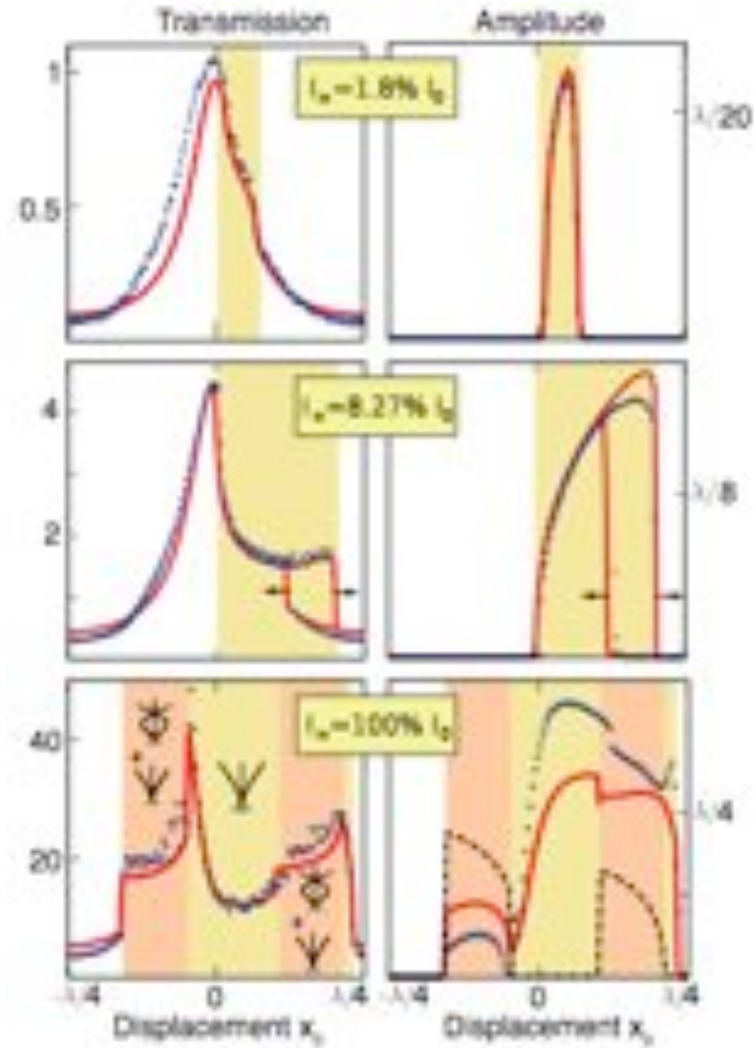




Metzger, Favero, Ortlieb, Karrai Phys. Rev. B 78, 035309 (2008)

# Linear and non-linear optomechanical self-oscillation



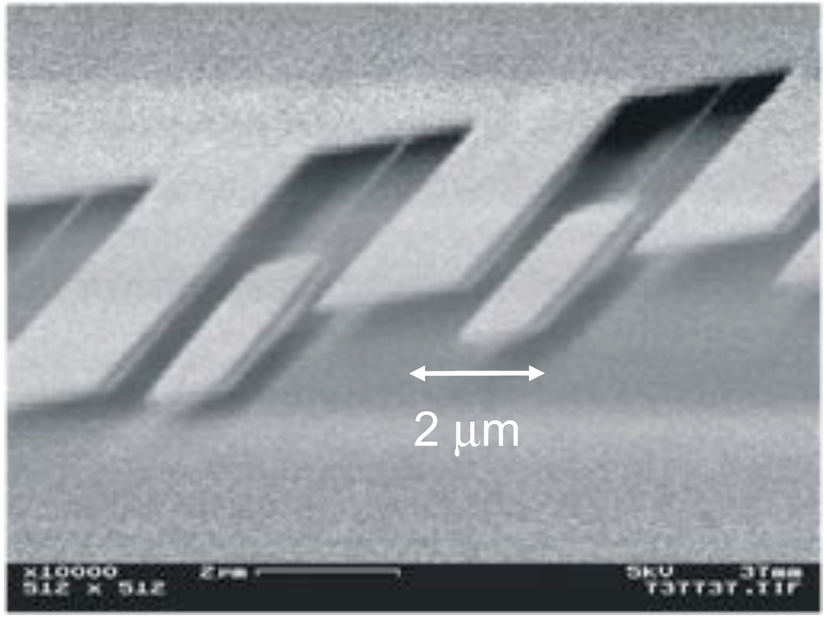

F.Marquardt et al. Phys. Rev. Lett. 96, 103901 (2006)
Ludwig, Neuenhahn, Metzger, Favero, Karrai, Marquardt. PRL 101, 133903 (2008)

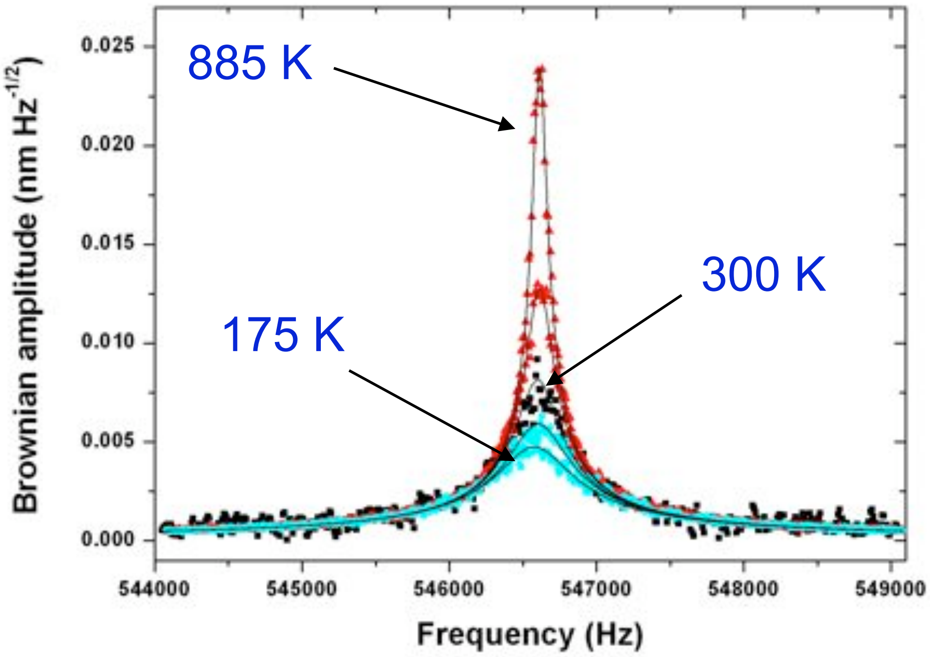
# Scale down dimensions to boost optomechanical effects

# Dwarf micro-mirror at the diffraction limit

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

$g_{om}$≈100MHz/nm



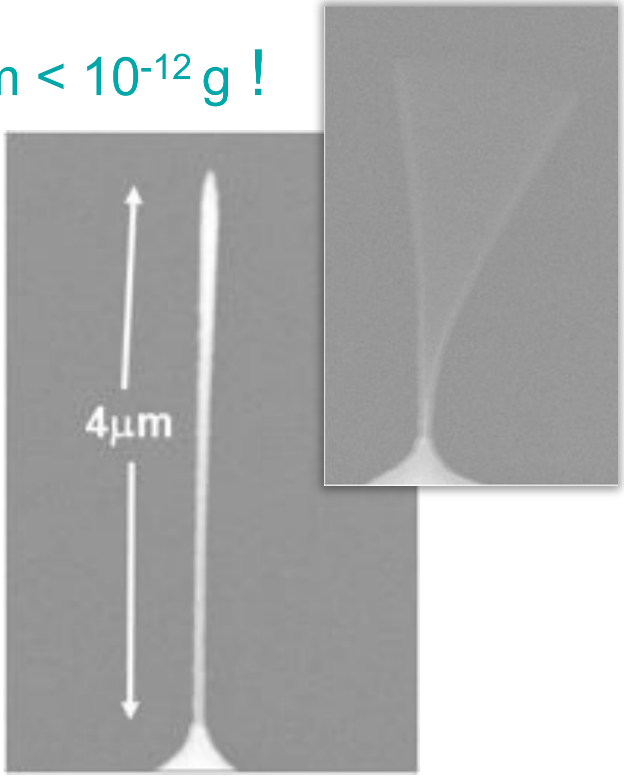

$Q_m$=1000

Finesse=10

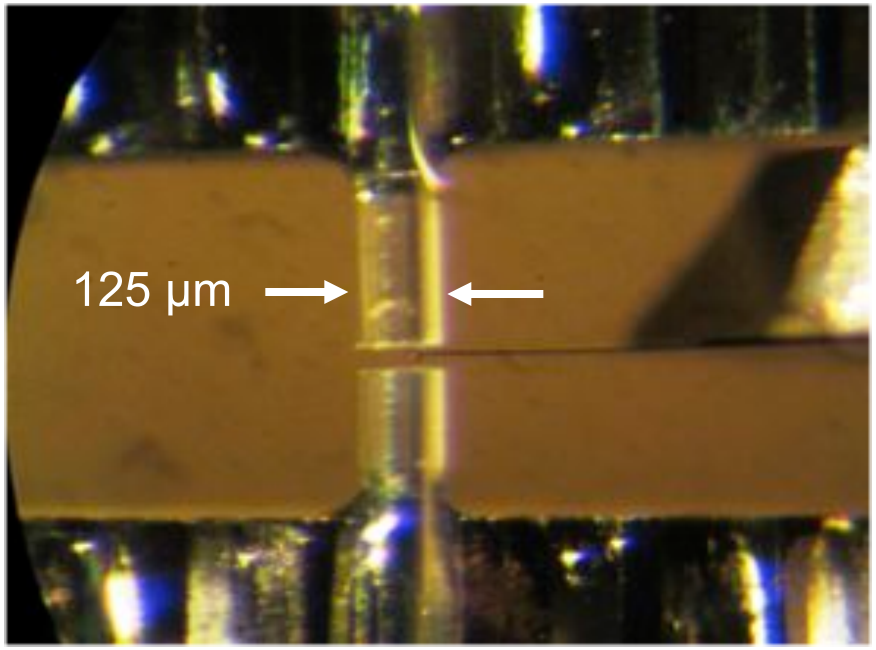
*[Optical cooling of a micro-mirror with wavelength size](#)*
*Applied Physics Letters, 90, 104101 ( january2007)*

# Nanomechanical system in a fibered Fabry-Pérot cavity

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




Finesse=5000




$Q_m$=1000

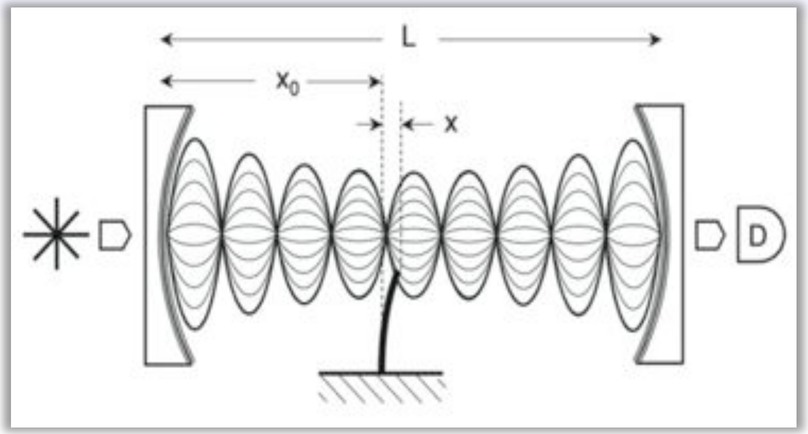
*Collaboration: Sebastian Stapfner, Eva Weig group, Jakob Reichel*

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*

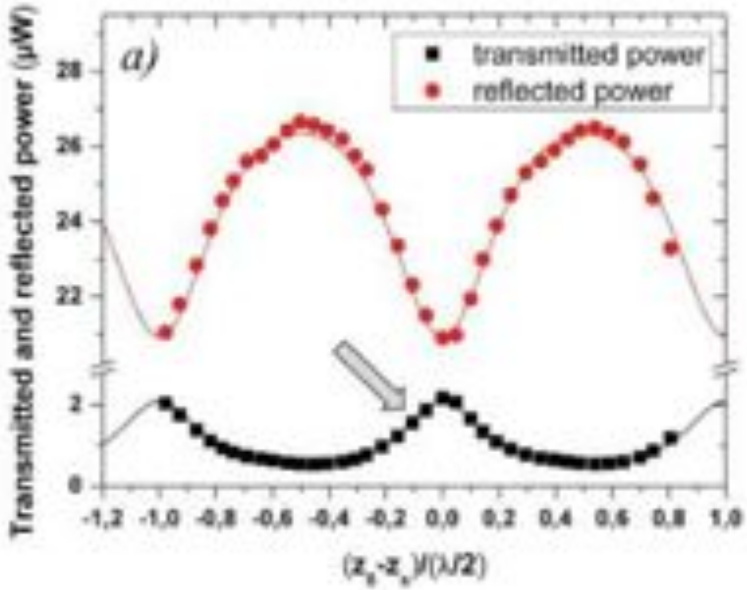
$m < 10^{-12}$ g !

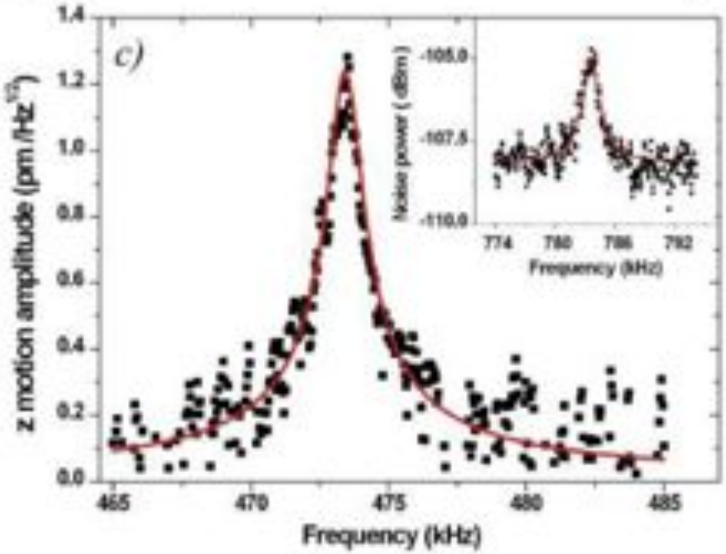
$Q_m$=1000




Finesse=5000

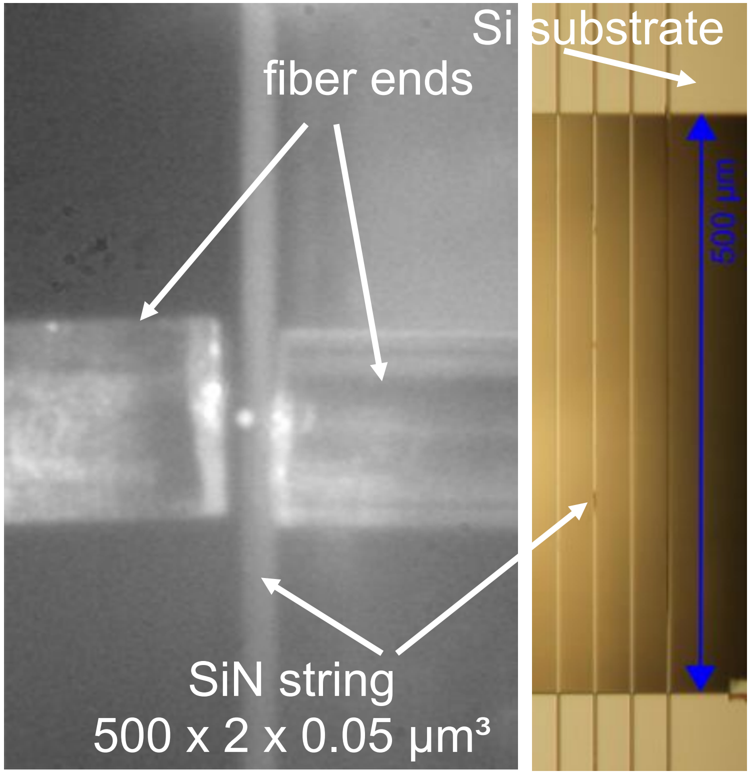
$g_{om}$≈50MHz/nm

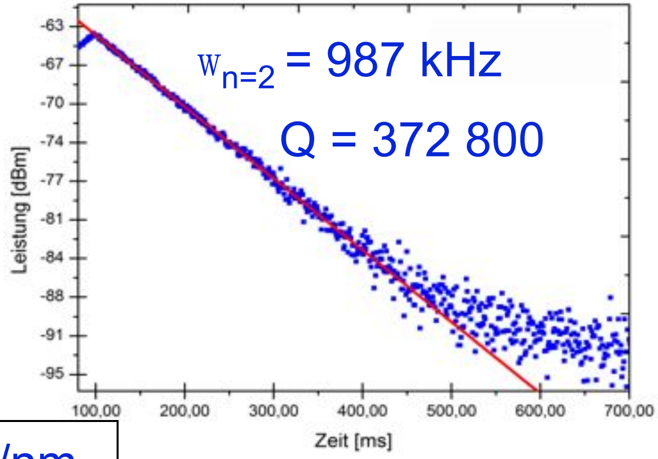


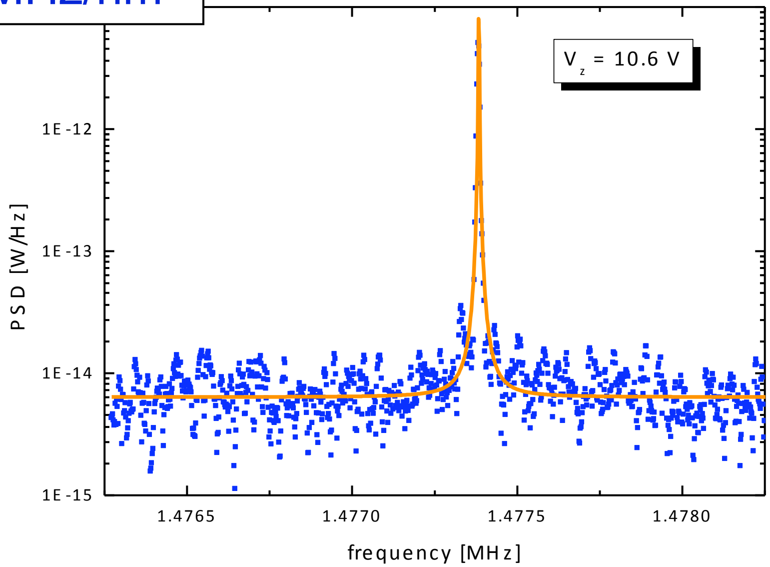

I. Favero, S. Stapfner et al. Fluctuating nanomechanical system in a high finesse optical microcavity. Optics Express, 17, 12813 (2009)

# Nanomechanical SiN beam in a Fabry-Pérot cavity



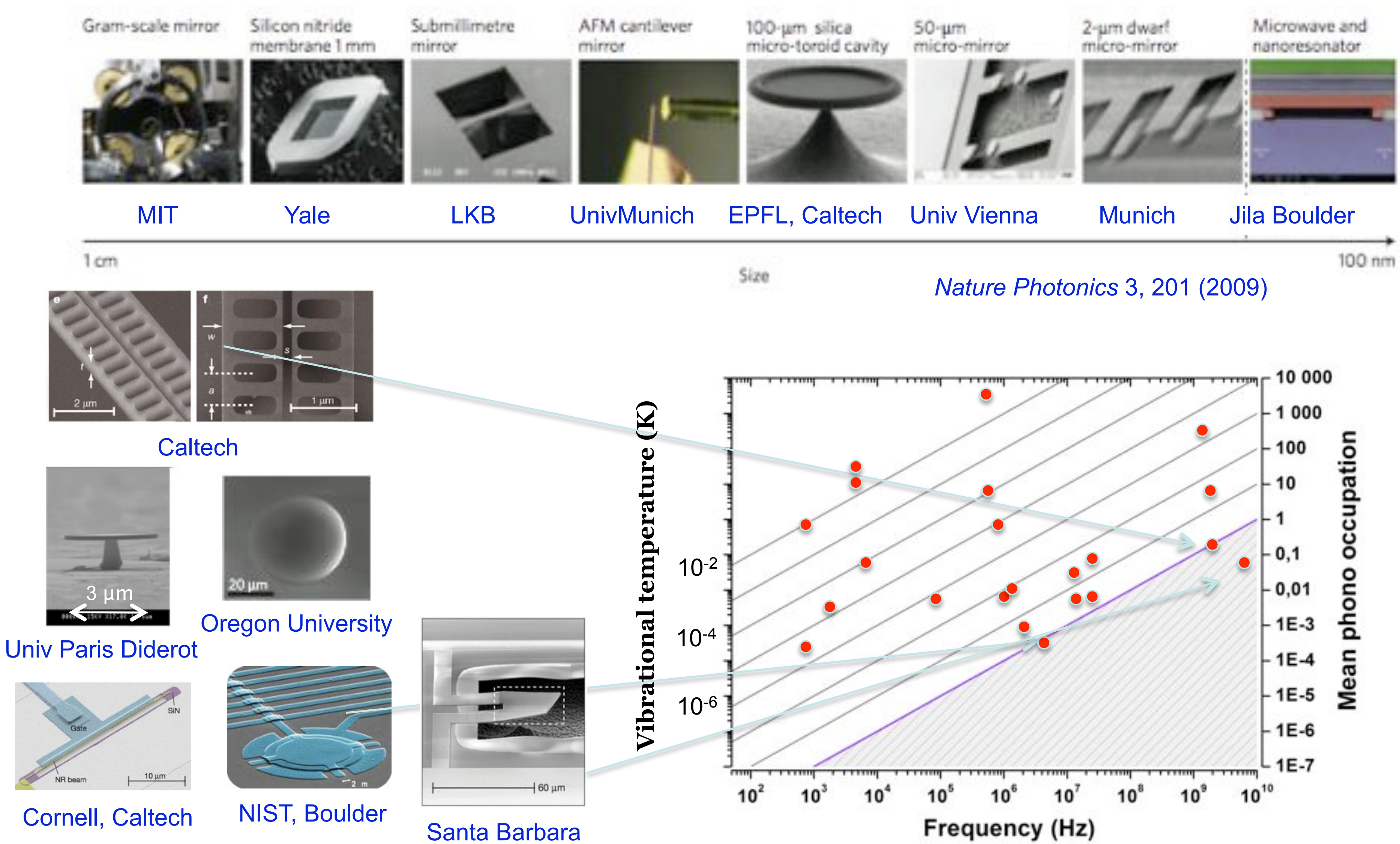

$g_{om}$≈100MHz/nm




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

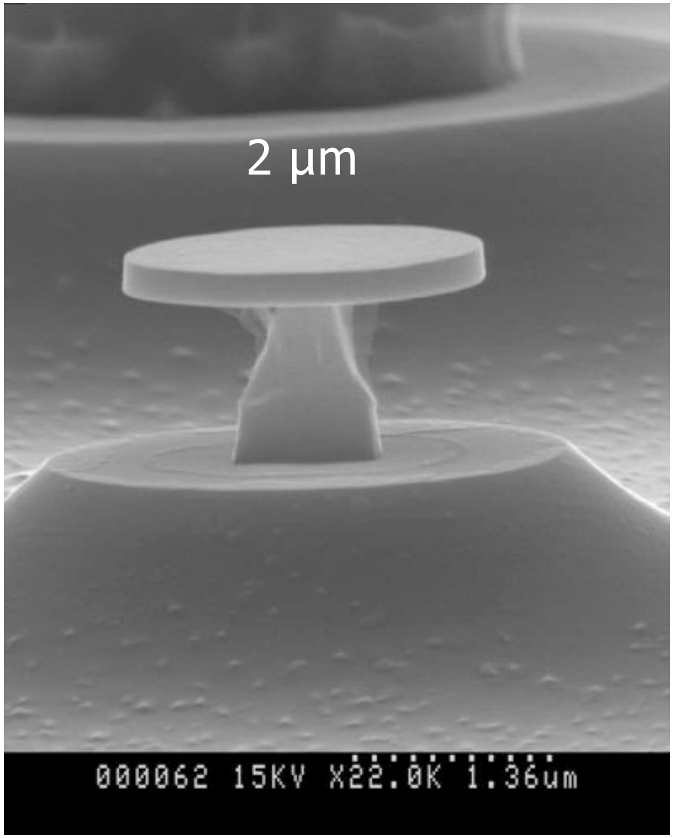
*Collaboration: Eva Weig group, Sebastian Stapfner, Jakob Reichel*

# Optomechanical systems today N=0.5



# Nanoscale GaAs optomechanics

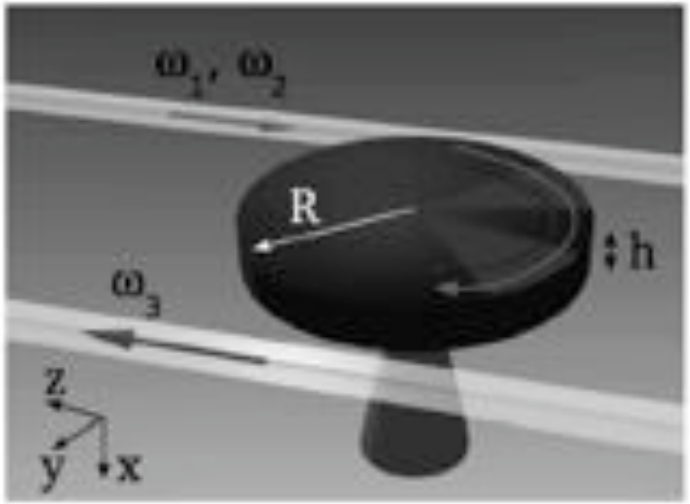
# Nano-Optomechanics with GaAs disks



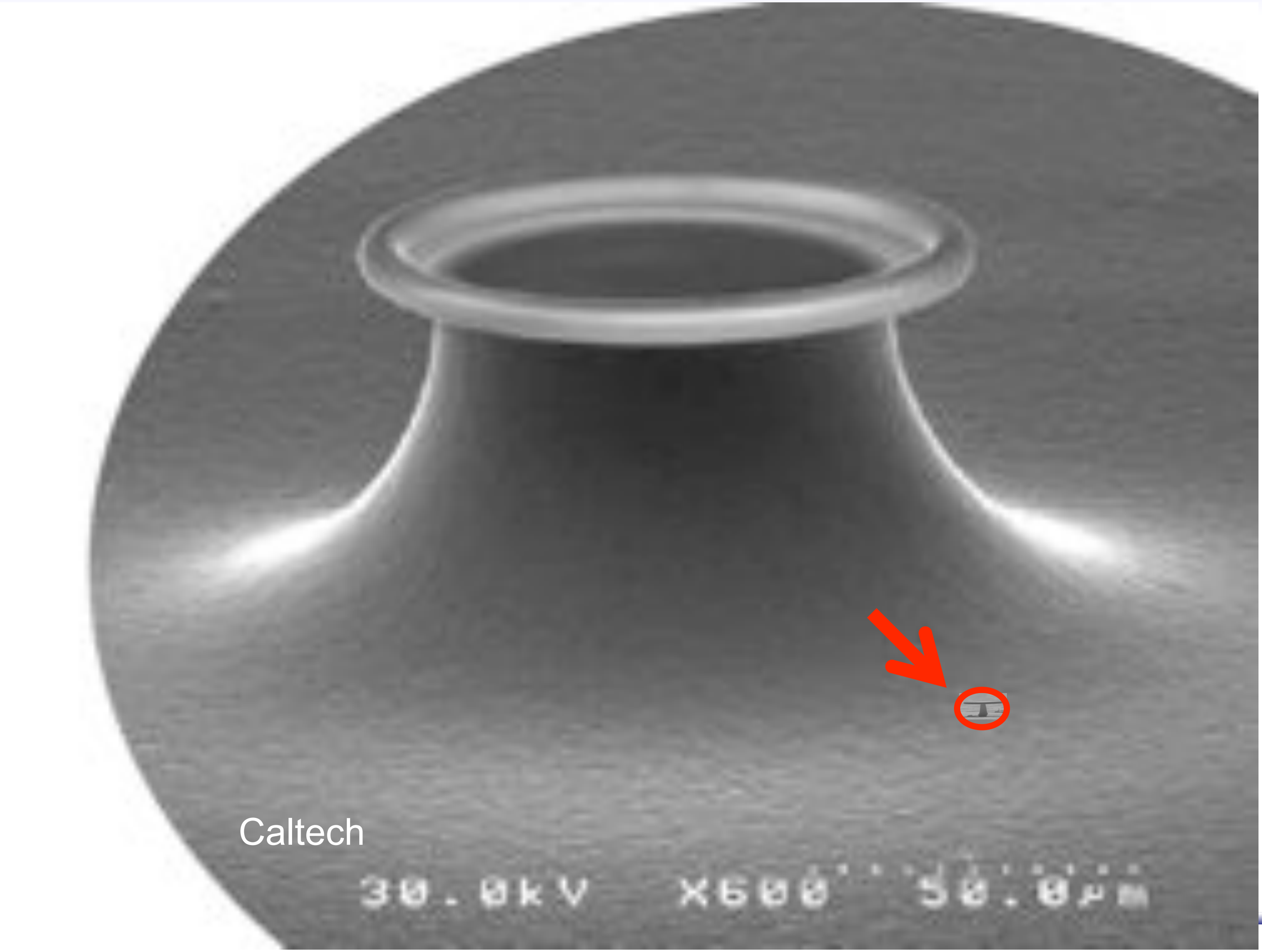

E. Peter et al. Phys. Rev. Lett. 95, 067401 (2005)

- Small mode volume (sub-$\lambda^3$)
- High optical Q (high finesse)

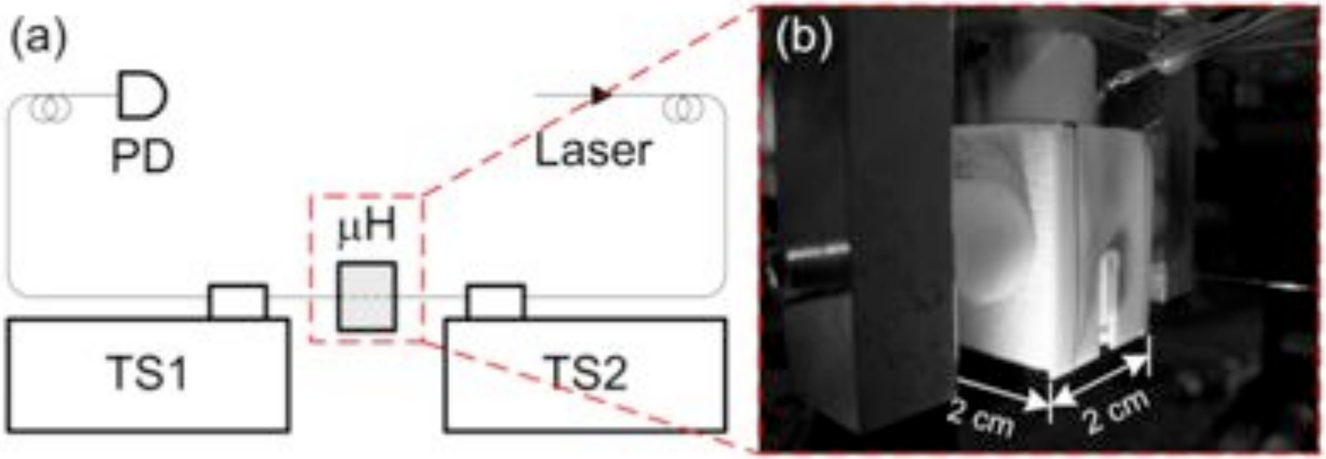
- High frequency
- Small mass (pg)
- Low mechanical dissipation

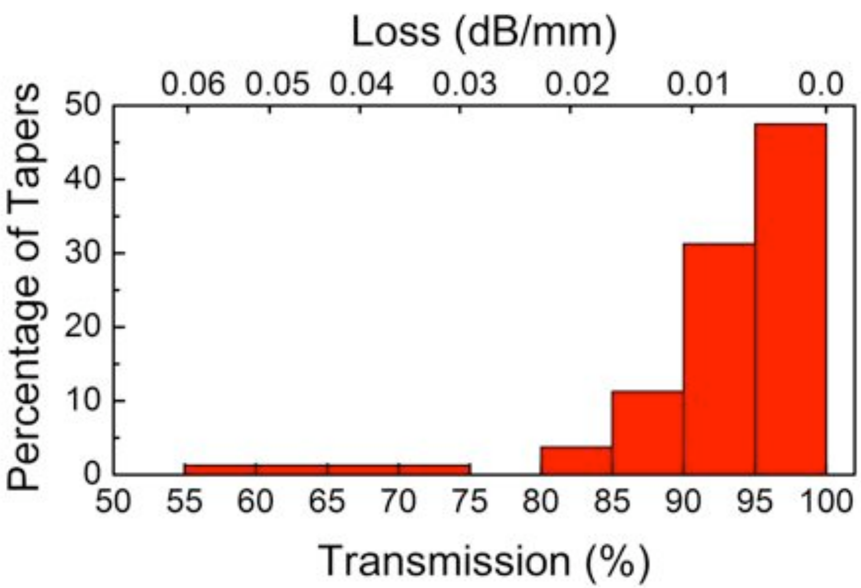


# Comparing the scales: size matters !



# Ultra low-loss sub-micron optical fiber taper



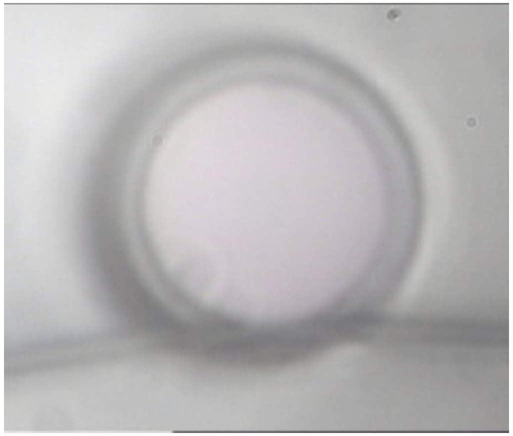



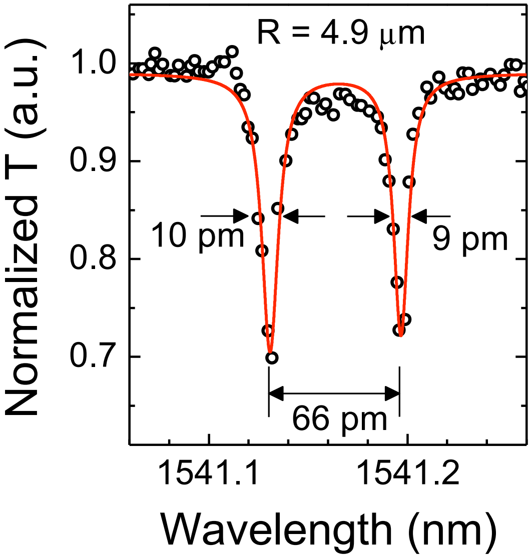

Ave. T = 94 %

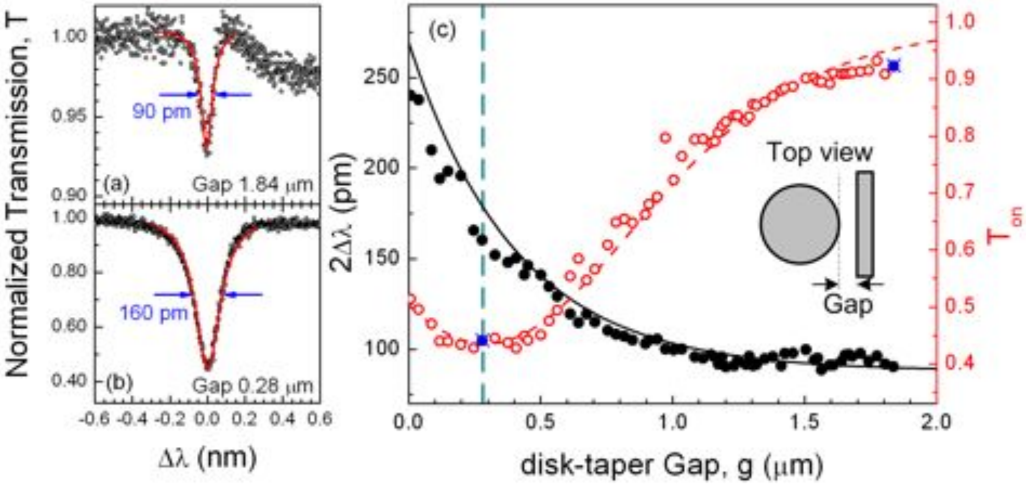
Best T > 99%

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

# Whispering gallery modes with optical Q above $10^5$

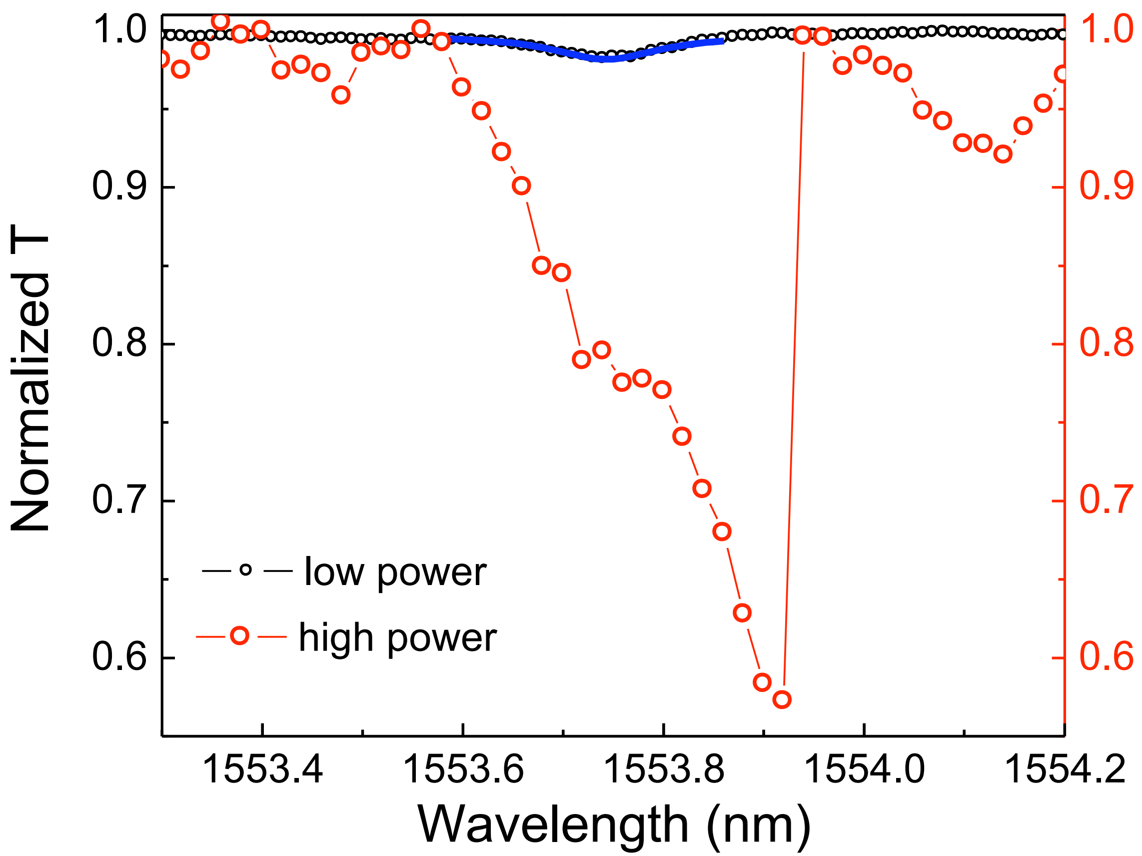





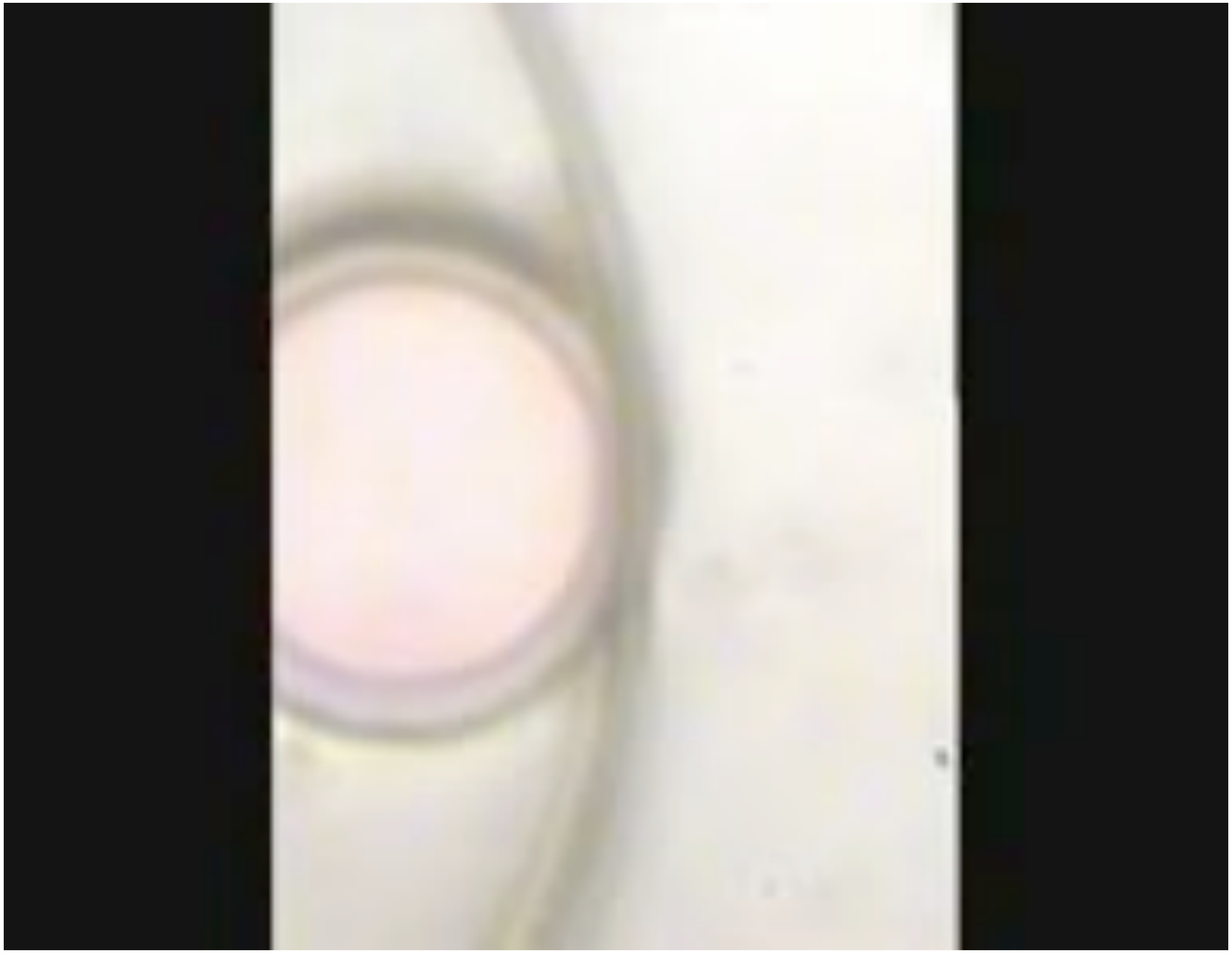

L. Ding et al. Proc. SPIE 7712, 771211 (2010).

# Optically actuated micron-scale fiber motion

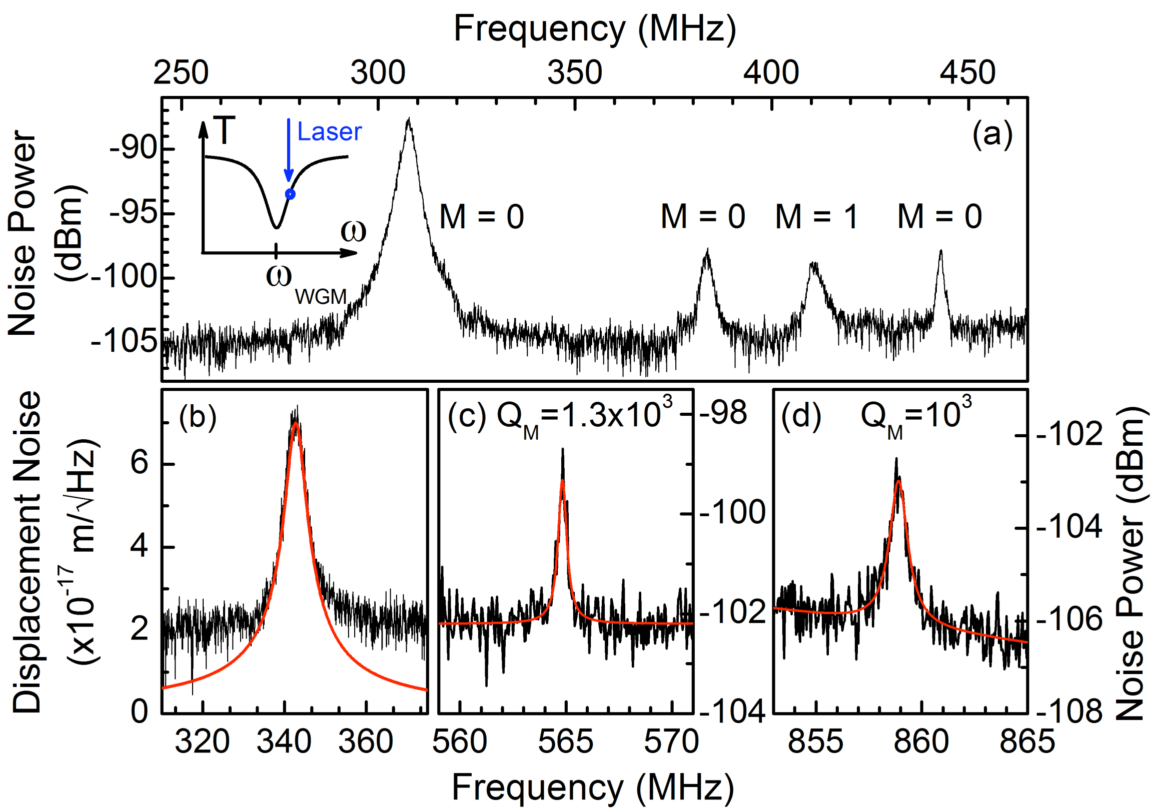



L. Ding et al. Proc. SPIE 7712, 771211 (2010).

# Optically actuated micron-scale displacement



# Ultra-sensitive optical measurement of disk motion



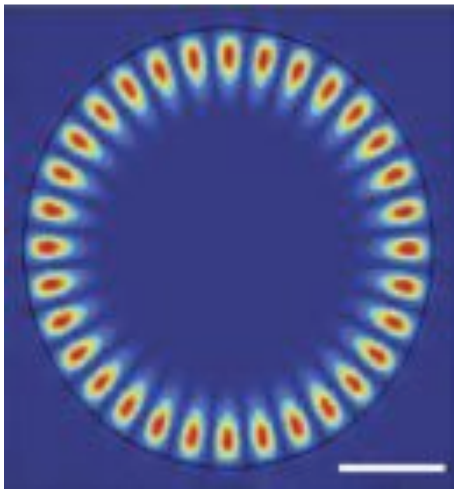

- Frequency of mechanical modes up to GHz
- In air, mechanical Q factor $10^2$ to $10^3$ with Qf up to $10^{12}$
- Sensitivity $10^{-17}$ m/√Hz (approaching the quantum limit)
- Giant optomechanical coupling 100 - 600 GHz/nm

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

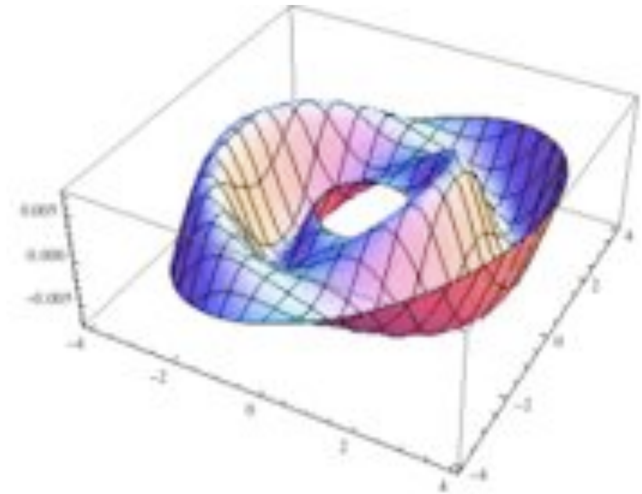
$F = \Psi(\rho)\Theta(\theta)G(z)$ with $\Theta(\theta) = e^{im\theta}$



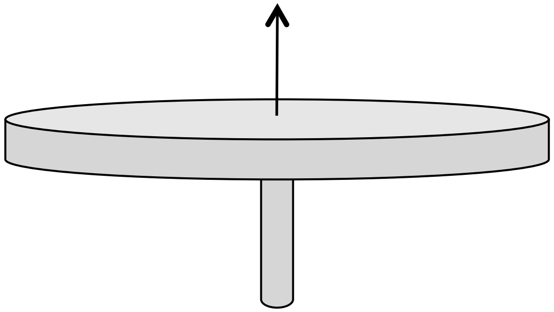
m optical azimuthal number

## Mechanical modes

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



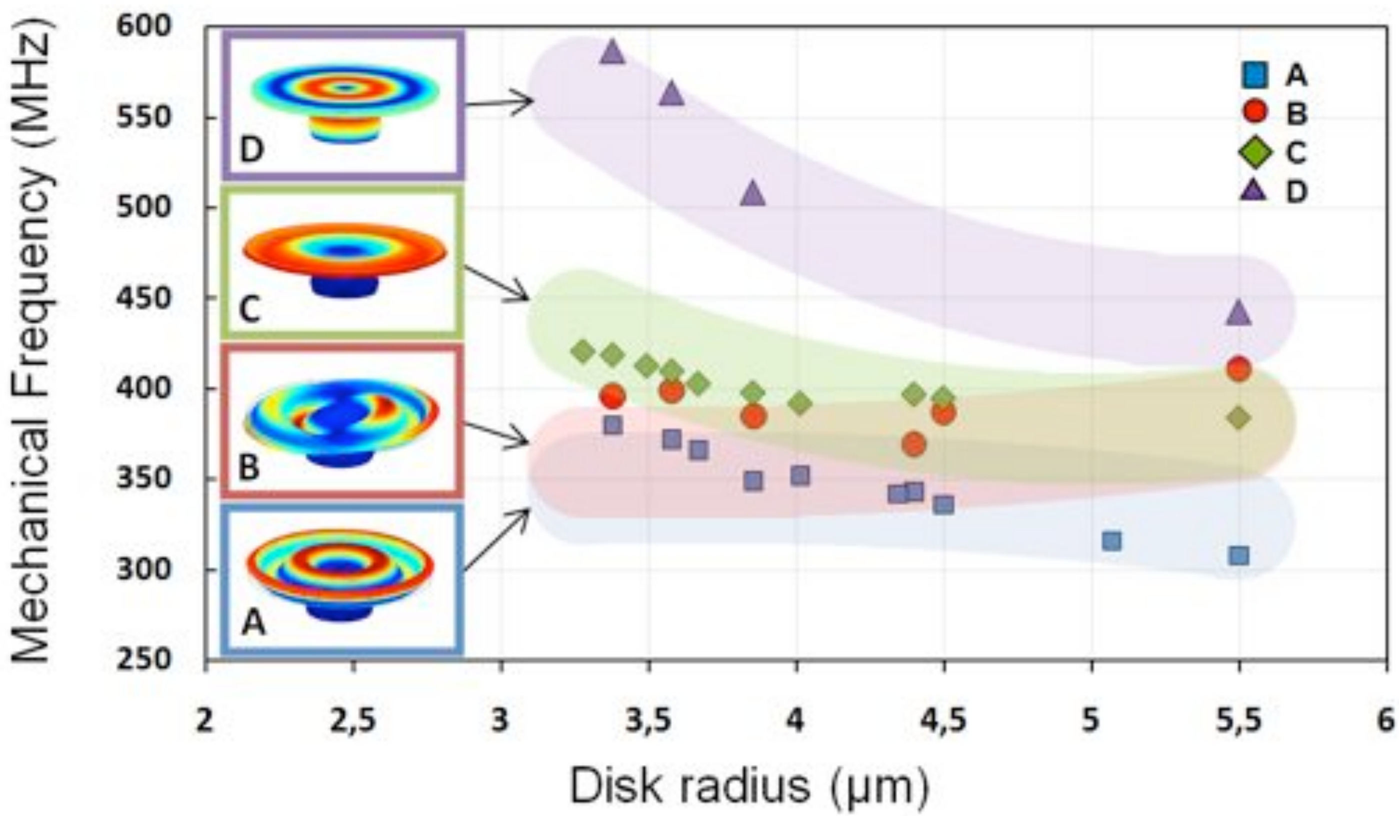
M mechanical azimuthal number



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

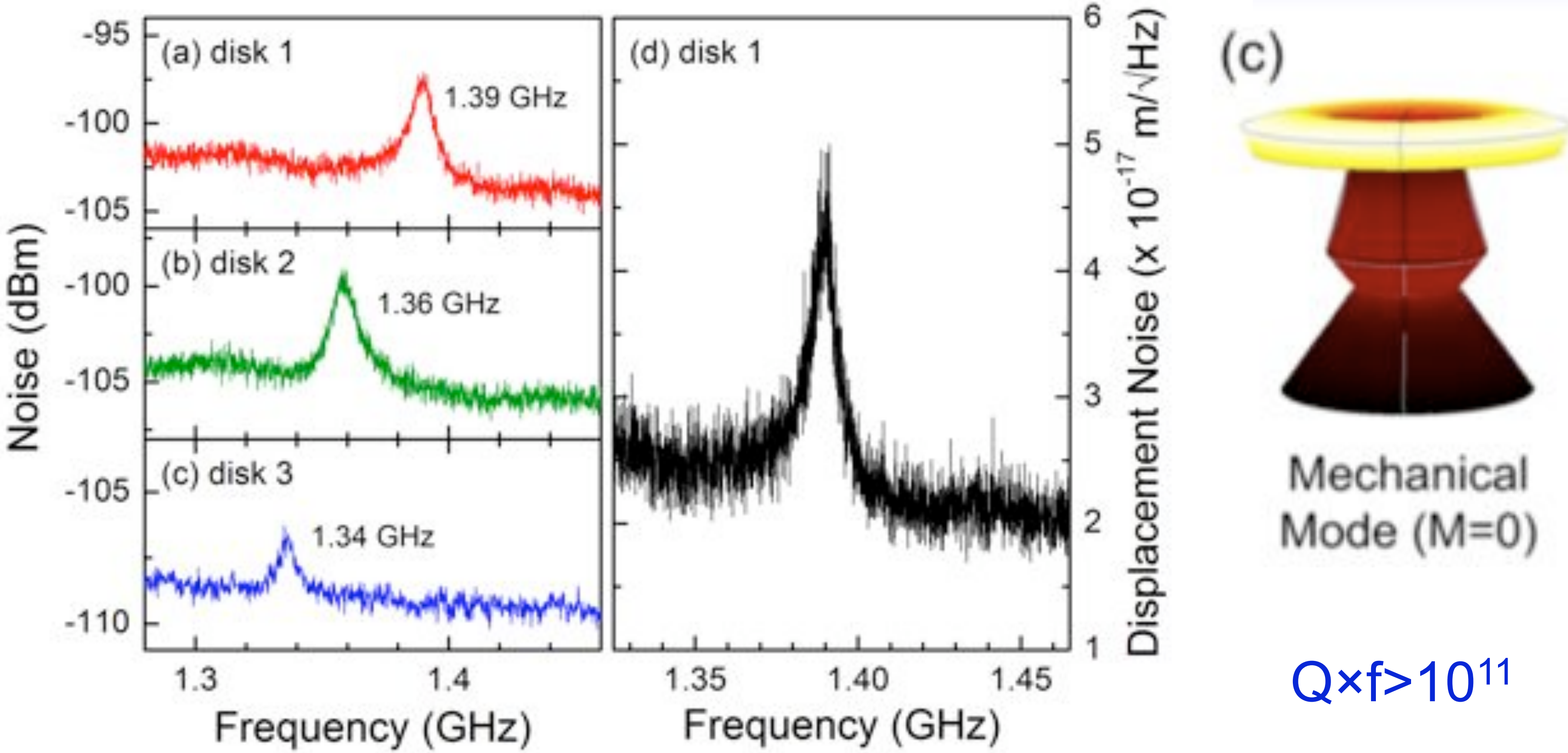
S. G. Johnson et al., Phys. Rev. E 65, 066611 (2002)

# 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

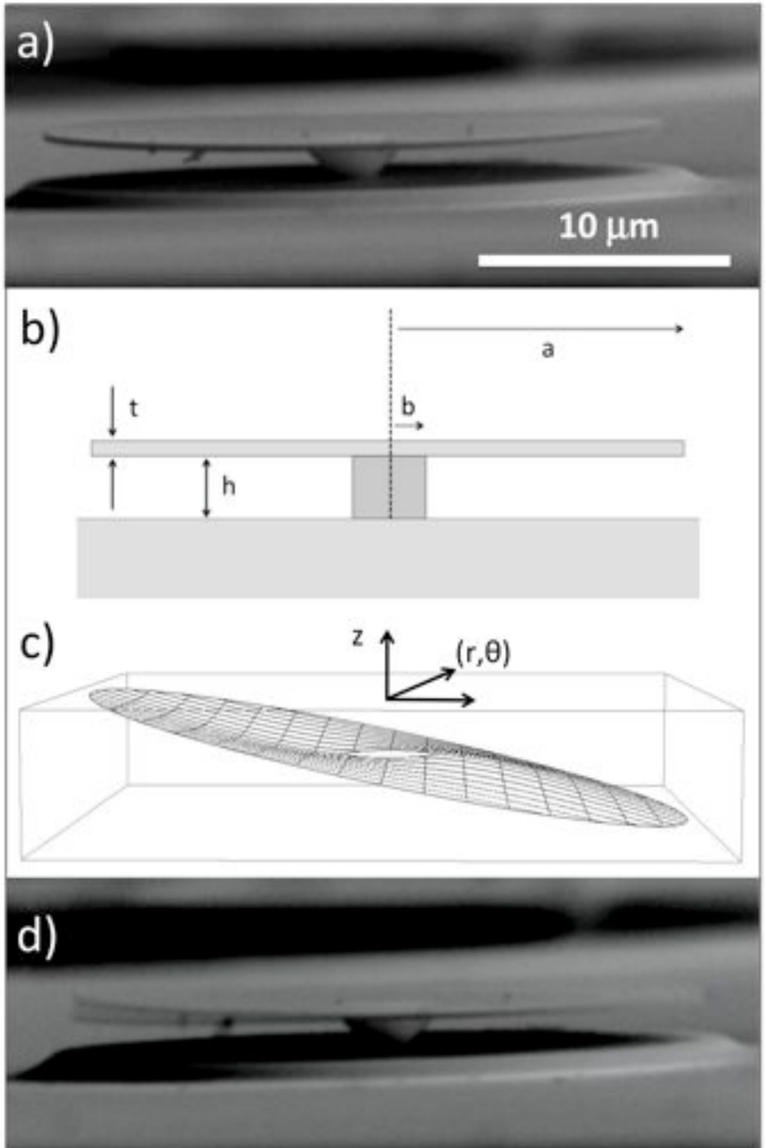
$g_o = g_{om}\, \Delta x_{zpf}$ vacuum coupling

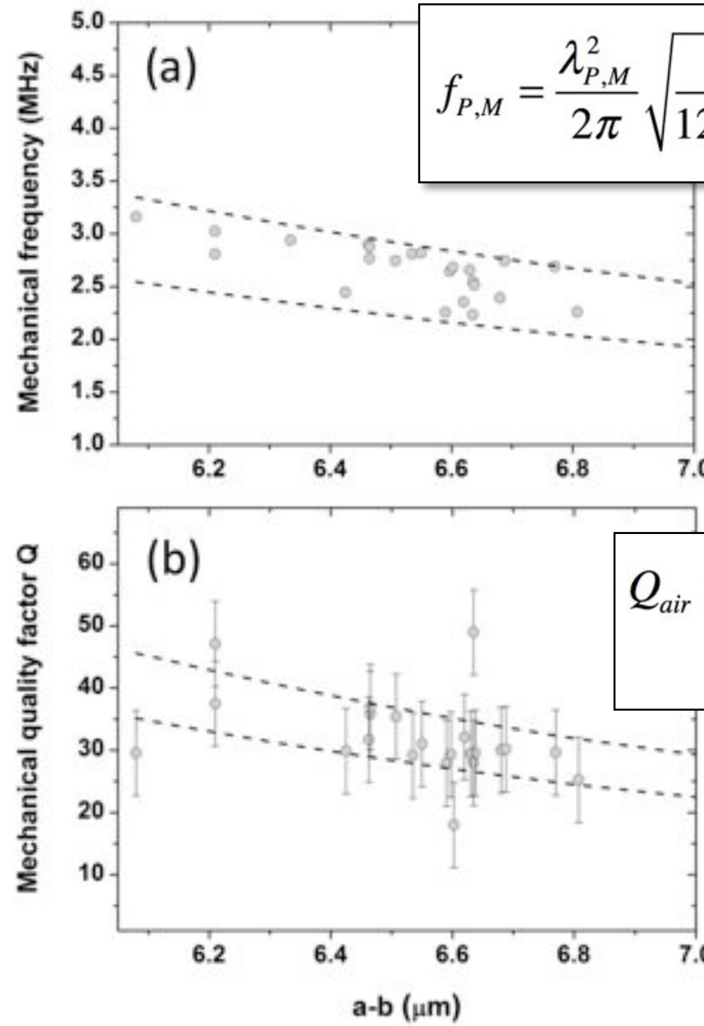
L. Ding, C. Baker, et al.
« Wavelength-sized GaAs optomechanical resonators with GHz frequency »
Applied Physics Letters 98, 113108 (2011).

M. Eichenfield et al. Nature 462, 78 (2009).
Young-Geun Roh et al, PRB 81, 121101(R) (2010).
E. Gavartin et al. PRL 106, 203902 (2011).

# Mechanical dissipation in GaAs disk resonators

# Mechanical dissipation of GaAs disk resonators in air



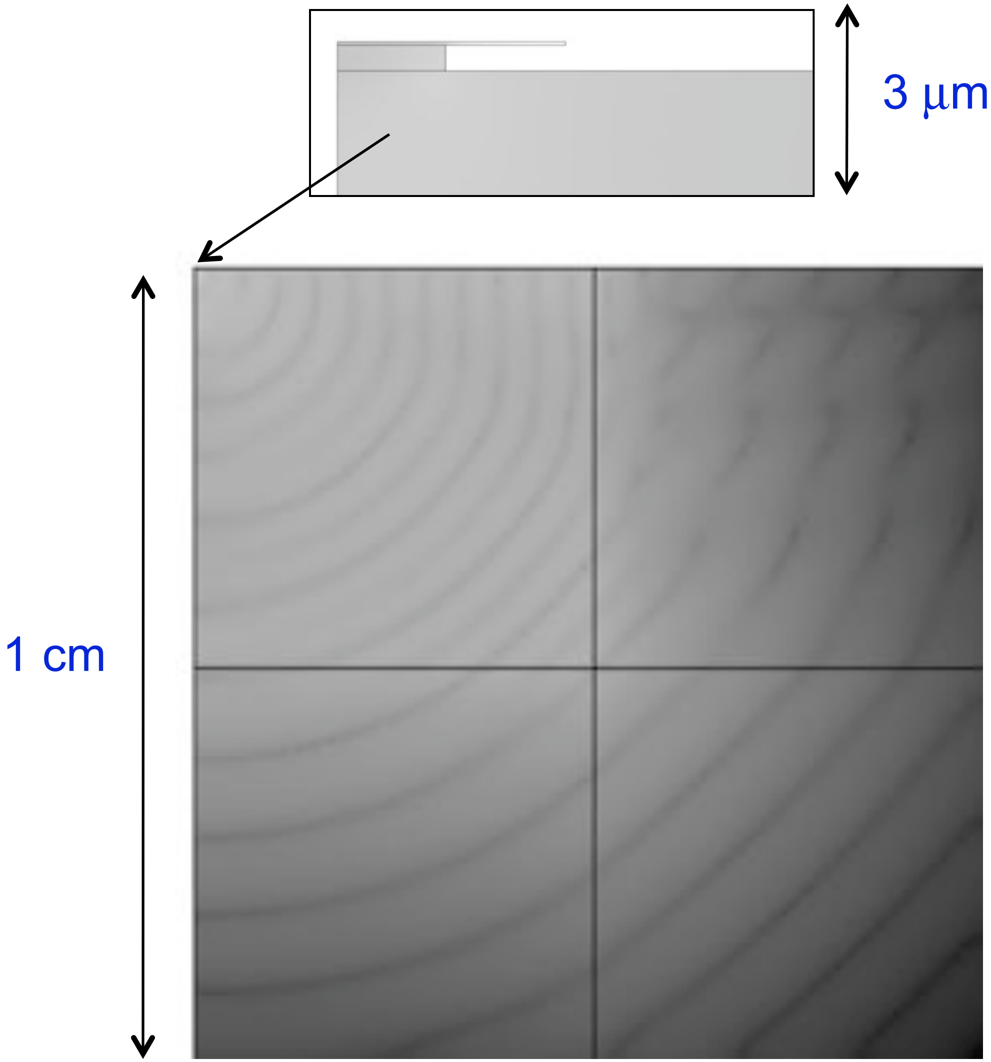




$$f_{P,M} = \frac{\lambda_{P,M}^2}{2\pi} \sqrt{\frac{E}{12\rho(1-\nu^2)}} \frac{t}{a^2}$$

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

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

# Clamping losses of GaAs disk resonators



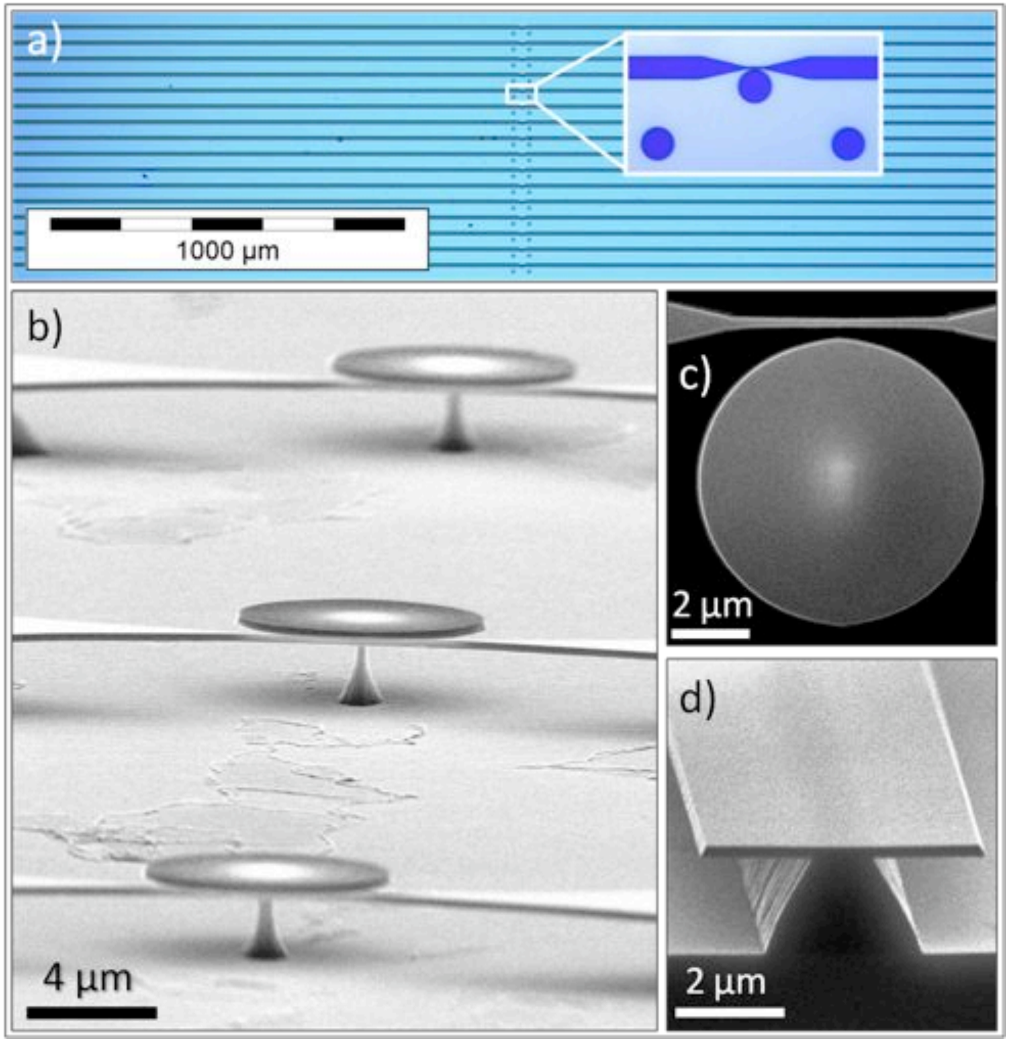

For a GHz disk mode,
Q clamping of the order $10^4$ to $10^5$

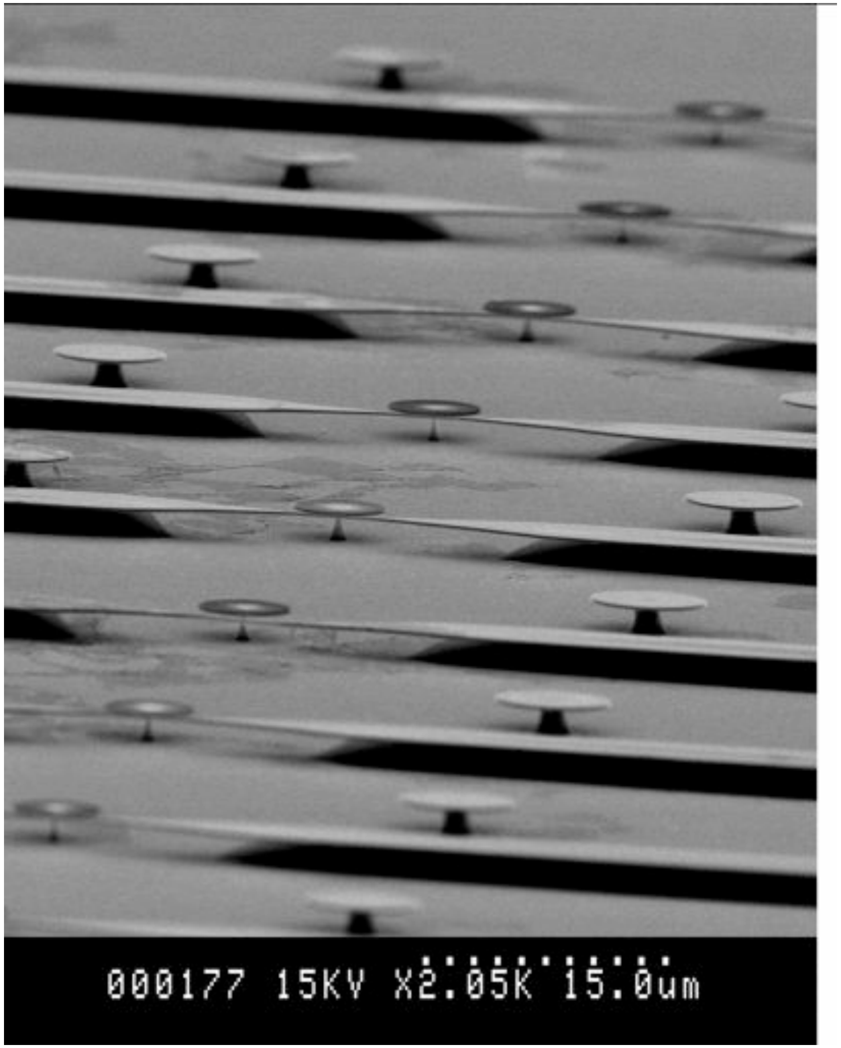
Q×f between $10^{13}$ and $10^{14}$

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

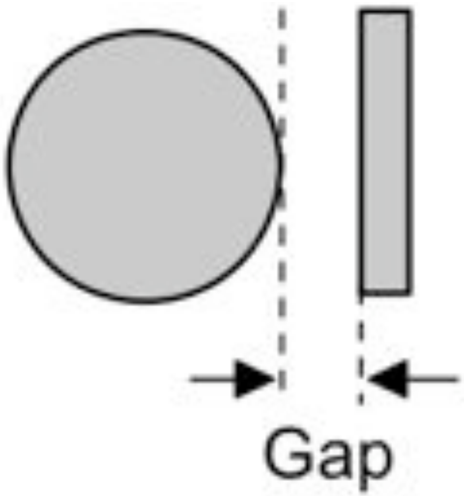
# Integrated GaAs nano-optomechanics

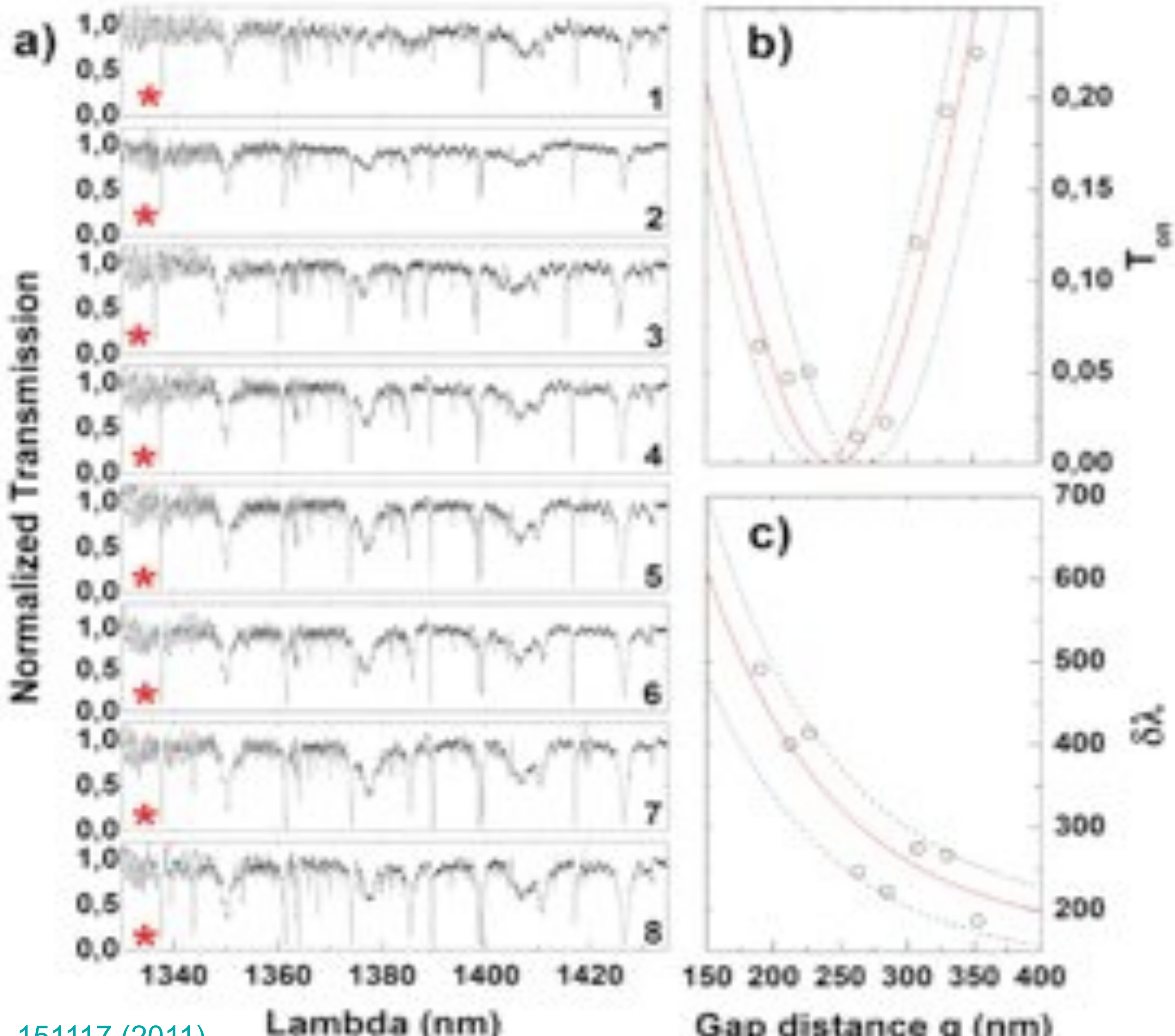
# Integrated GaAs optomechanical resonators



# On-chip critical evanescent coupling

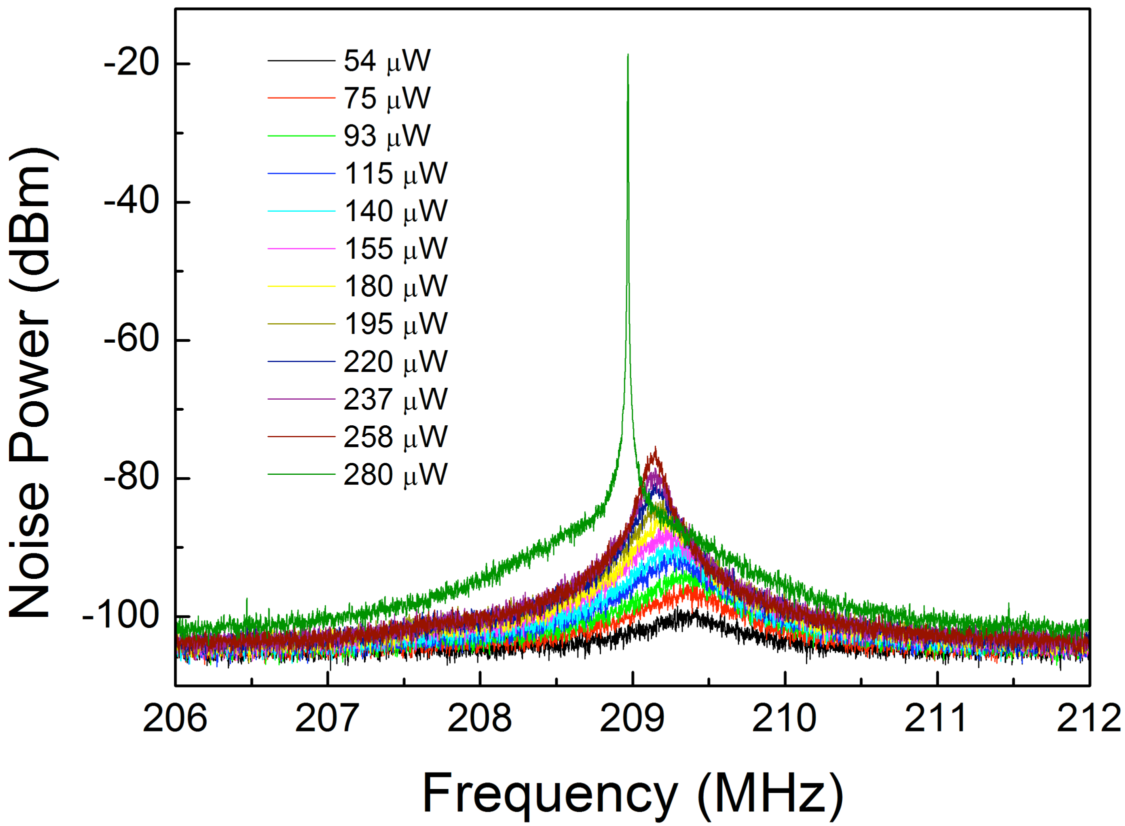



C. Baker et al. [Applied Physics Letters 99, 151117 (2011)]

# Dynamical back-action in GaAs disk resonators

# Optomechanical self-oscillation of a GaAs disk





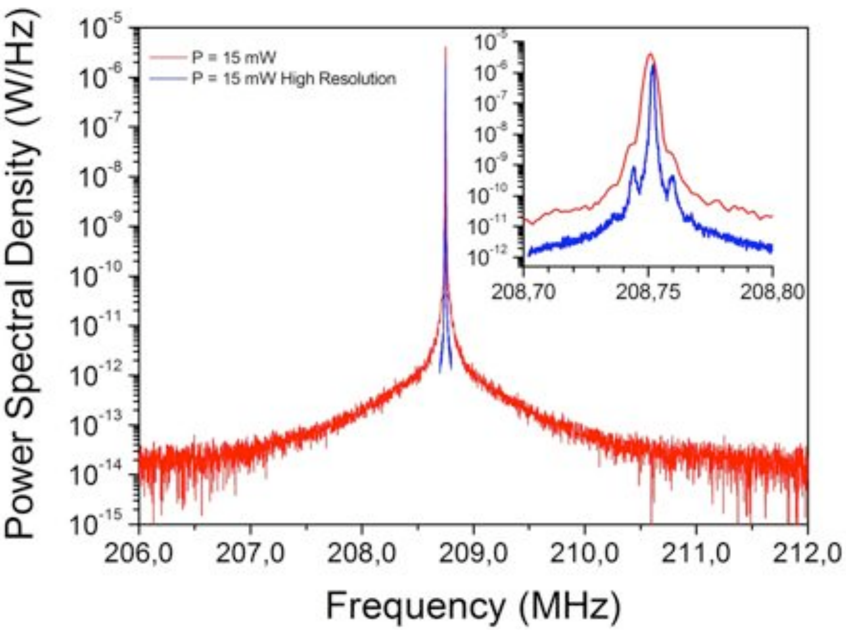
C. Metzger and K. Karrai, *Cavity cooling of a microlever,* Nature 432, 1002 (2004).

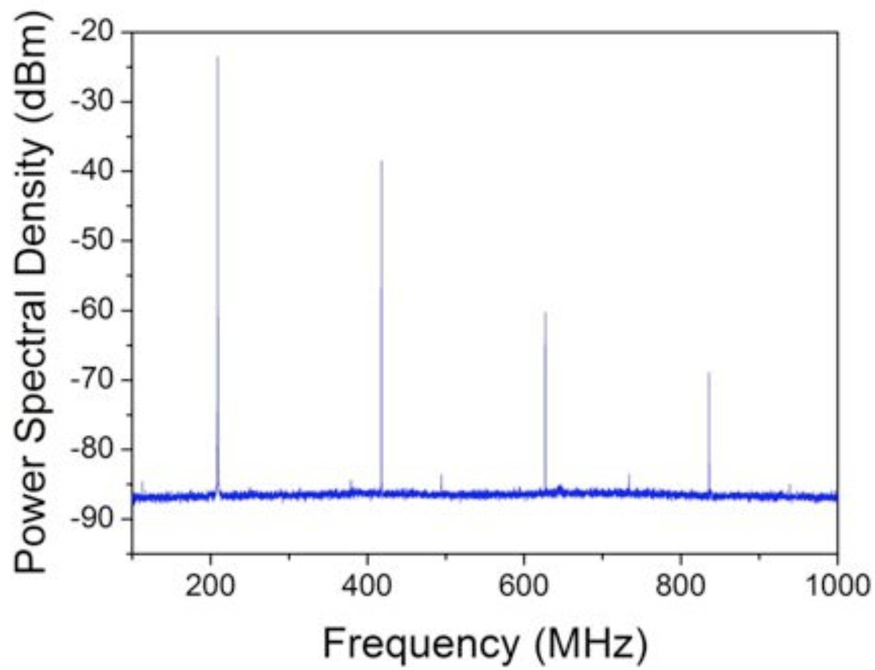
C. Höhberger Metzger and K. *Karrai* 2004 4th *IEEE* Conf. on *Nanotechnology,* pp 419–21 (2004).

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

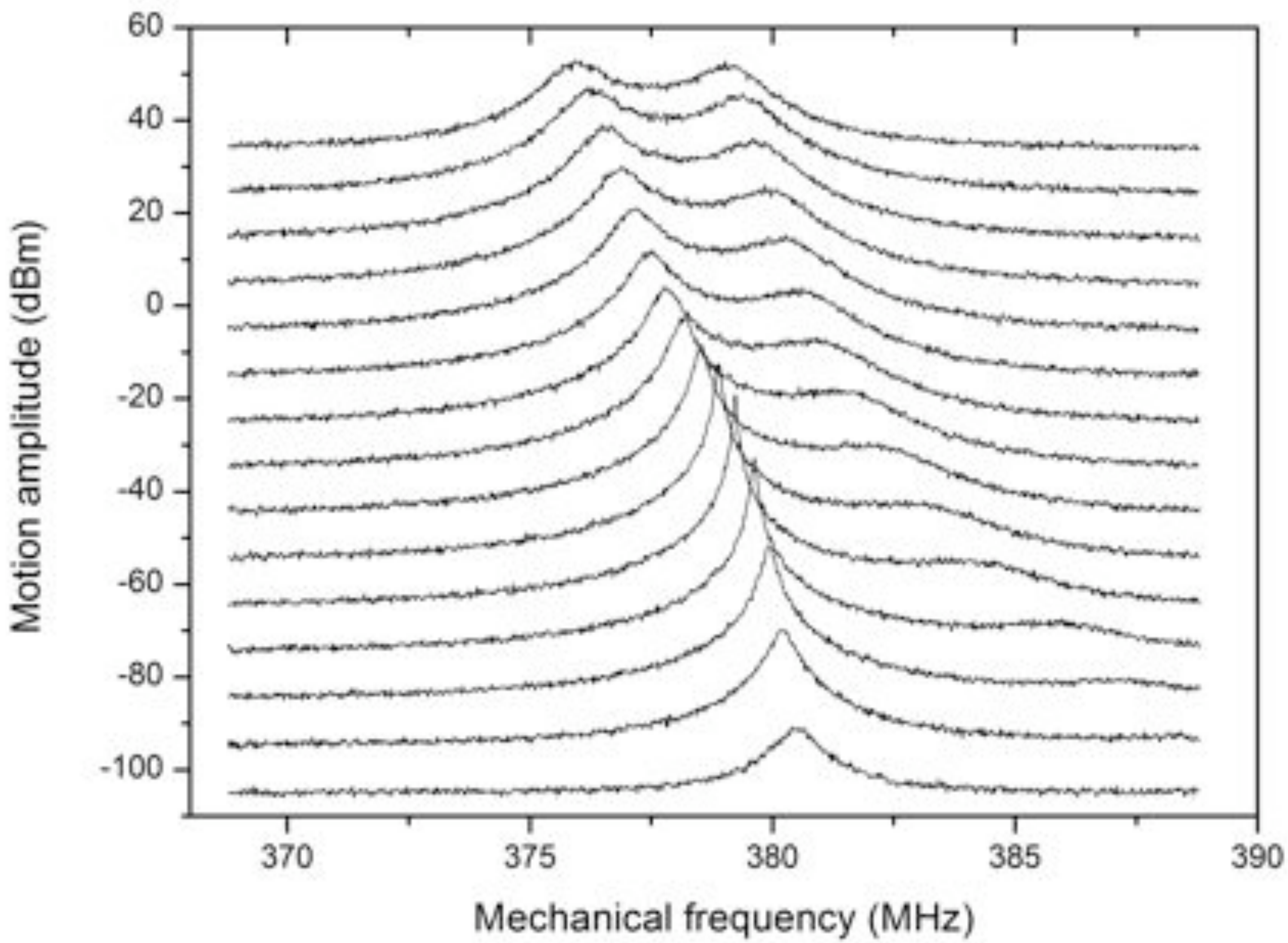
Rokhsari, H., Kippenberg, T.J., Carmon, T. and Vahala, K.J. Optics Express 13, 5293 (2005).

# Optomechanical self-oscillation of a GaAs disk



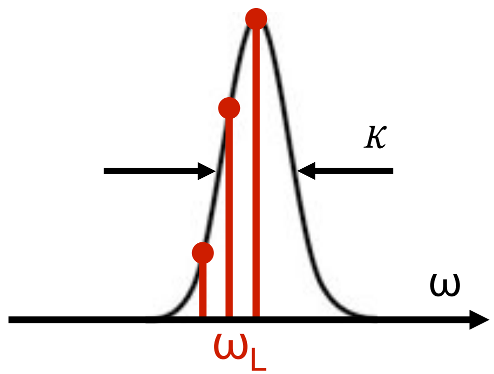
# Strong coupling versus self-oscillation in a GaAs disk

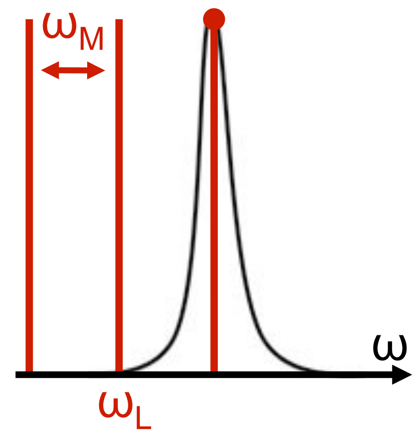



Gröblacher et al. Nature 460, 724–727 (2009). Teufel, J. D. et al. Nature 475, 359–363 (2011). E. Verhagen et al, Nature 482, 63 (2012).

# 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).
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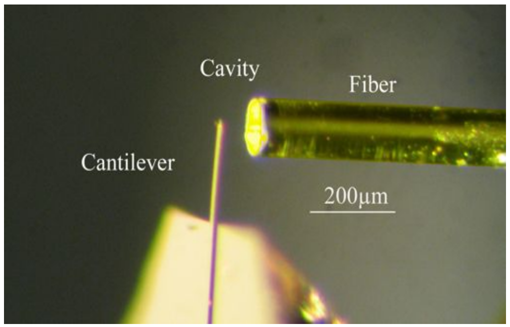
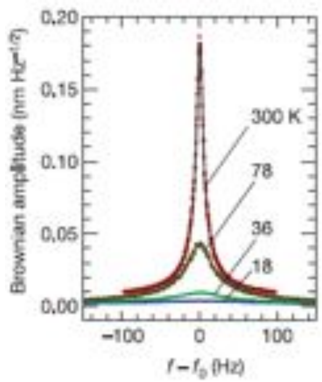
# Cooling by other « dissipative » forces in GaAs ?

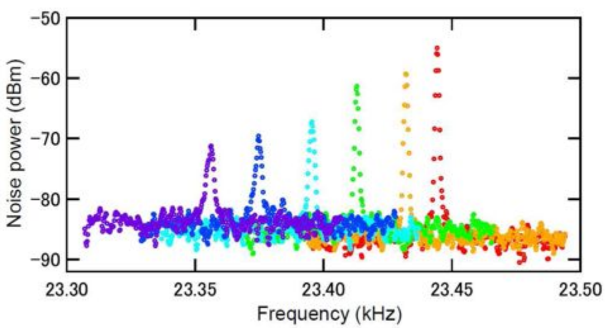
## Photothermal forces




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

## Opto-electronic forces

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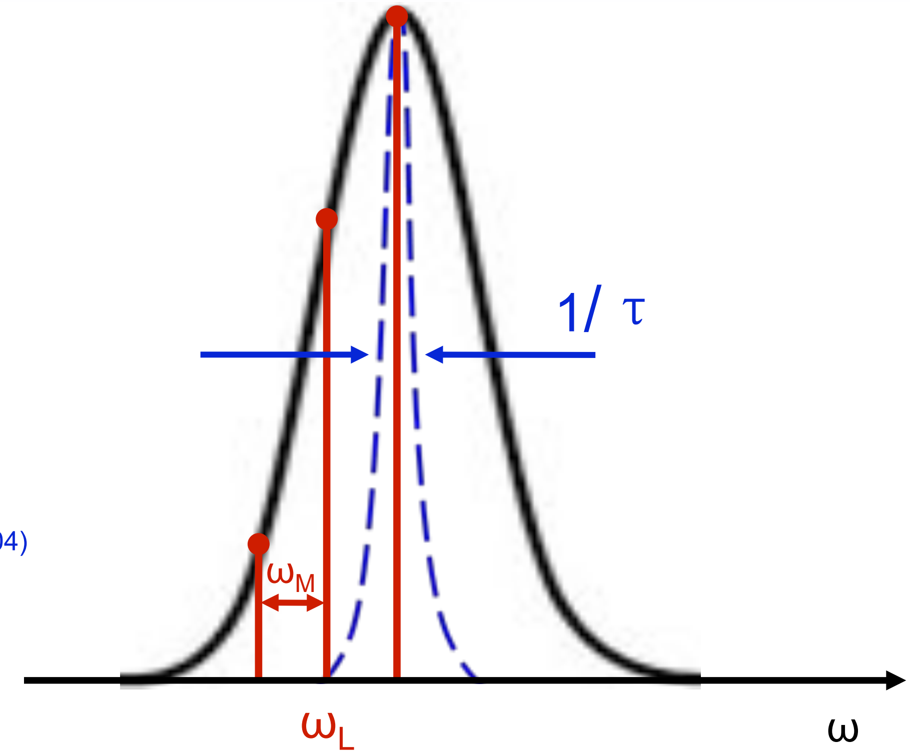
H. Okamoto et al. Phys. Rev. Lett. 106, 036801 (2011).

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*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)
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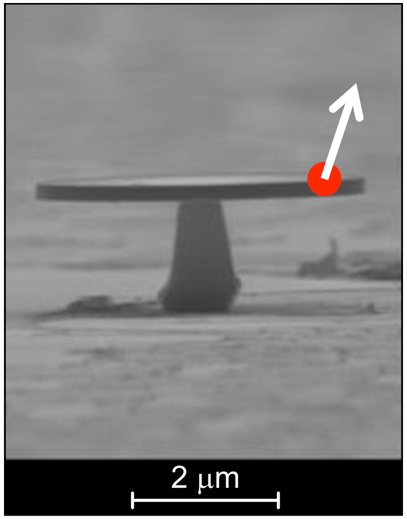
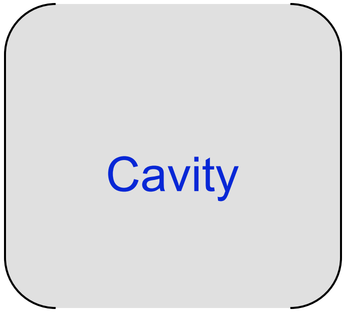
# Conclusions/Perspectives

## •GaAs optomechanical resonators

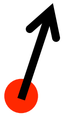
- ➢Motional Sensitivity of $10^{-17}$ m/√Hz
- ➢Mechanical modes in the GHz range
- ➢Strong coupling of optics and mechanics
- ➢Optomechanical resonator with a single quantum dot



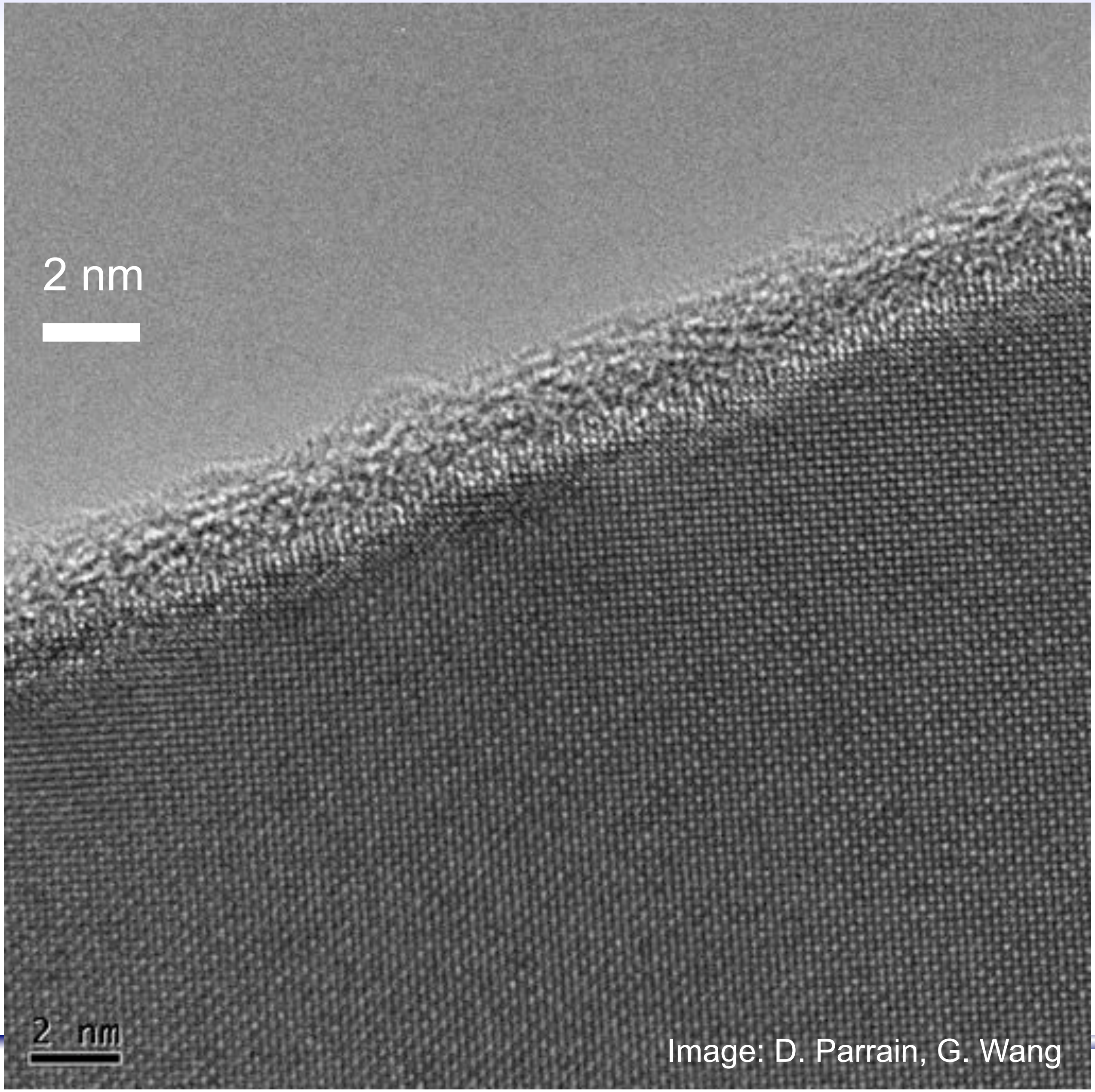





Atom



# Optical dissipation: TEM analysis




$\sigma$=0.15 nm (RMS)
$L_c$= 0.91 nm

Optical Q of $10^7$-$10^9$

↓

Surface Absorption

↓

Surface Passivation

Thank you