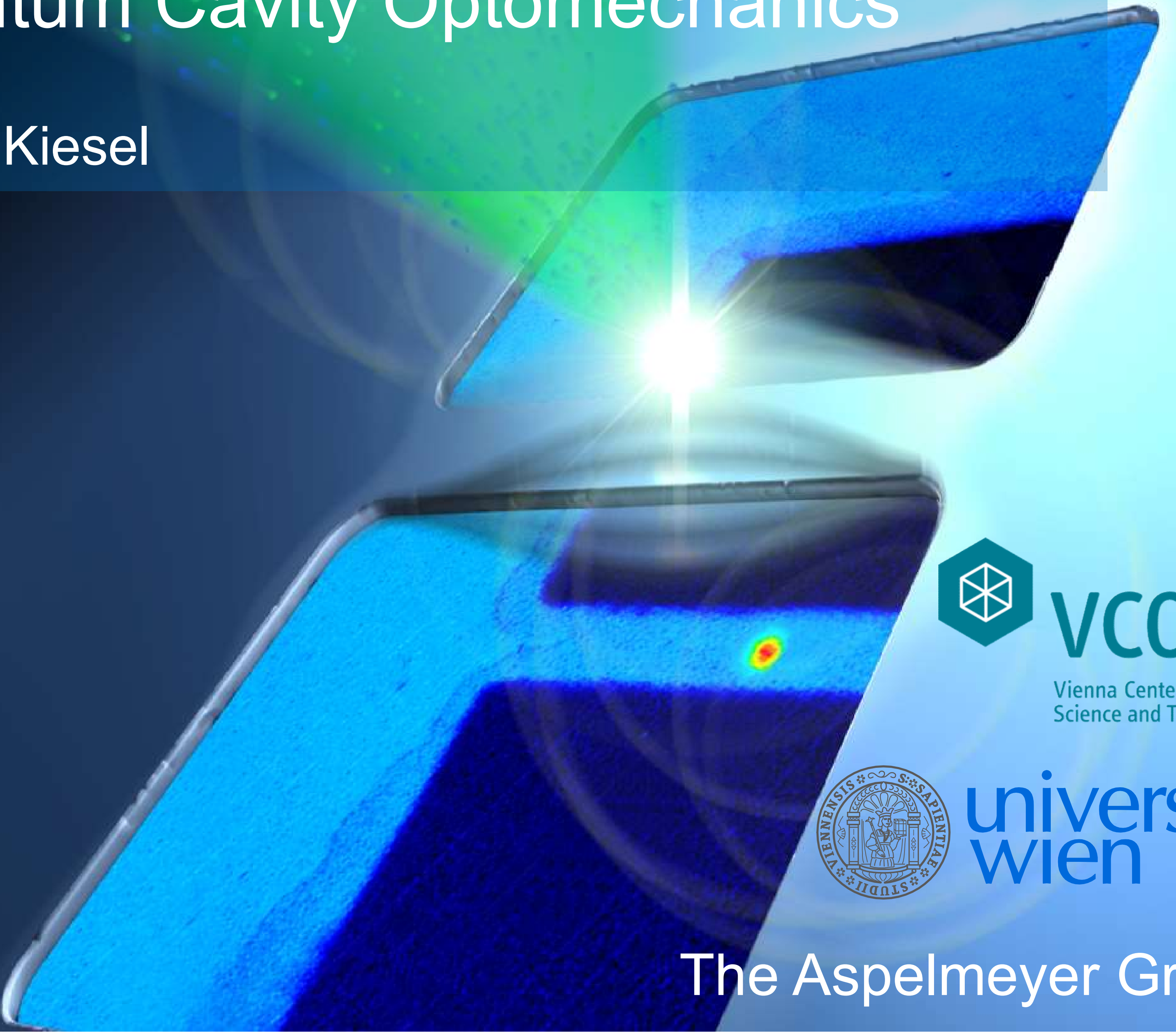
Quantum Cavity Optomechanics

Nikolai Kiesel



VCQ
Vienna Center for Quantum Science and Technology

universität wien

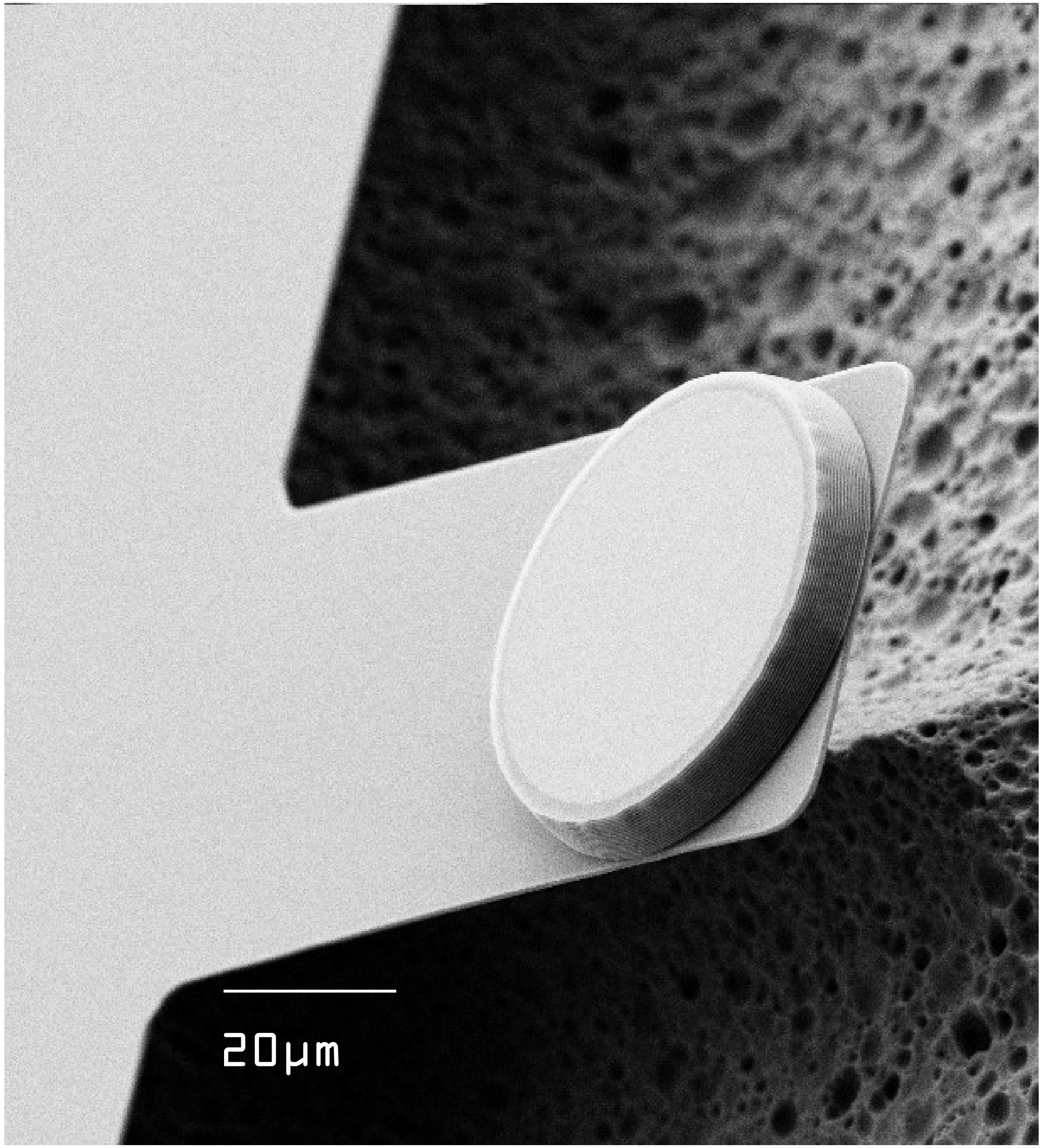
The Aspelmeyer Group

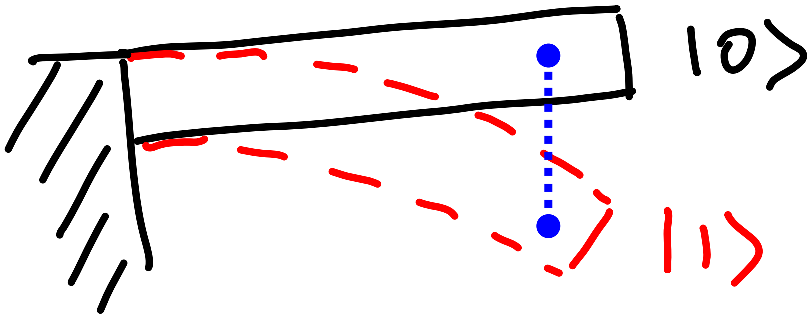
Optomechanics using Optical Levitation

Uros Delic, David Grass, Martin Siegle, Rainer Kaltenbaek, Nikolai Kiesel, Markus Aspelmeyer
VCQ, Faculty of Physics, University of Vienna

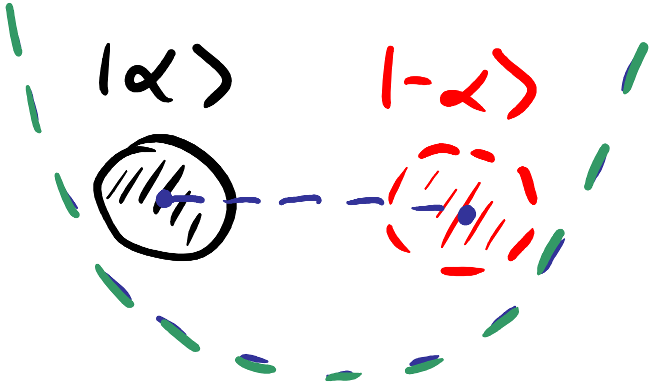
Magnetic and optical levitation teams

Mechanical Cats?





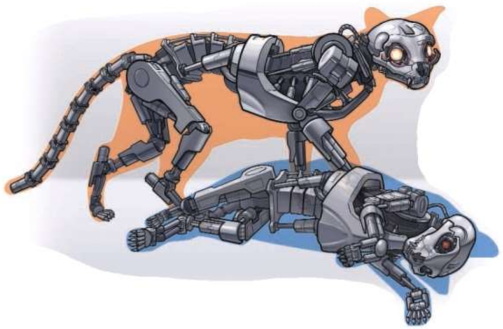
Cantilever



Trapped Particle

Quantum regime of massive resonators

Cho , *Science 327, 516 (2010)*

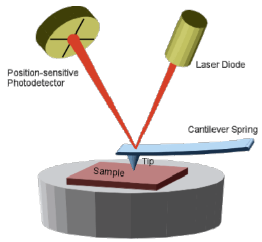


Access a new realm of experimental physics

Quantum Foundations

macroscopic quantum superposition involving up to 10^{20} atoms

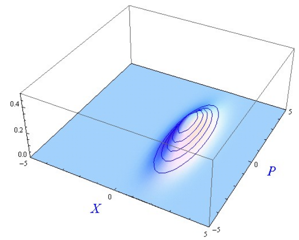
→ *Is there a limit to the size/mass of Schrödinger cats?*



Mechanical Sensing

present performance: zeptogram, zeptonewton, attometer, etc.

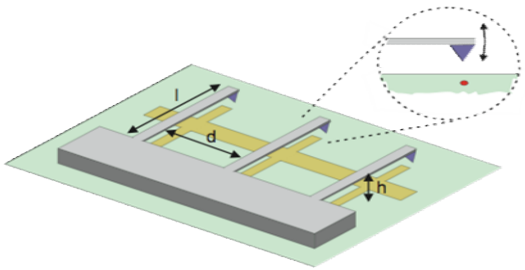
→ *What are the quantum limits to mechanical sensing?*



Quantum Information

e.g. potential for hybrid quantum information architectures on a chip

→ *Can mechanical systems serve as universal quantum bus?*



Rabl et al.,
Nature Physics 6, 602 (2010).

Mechanical Systems
IN the quantum regime

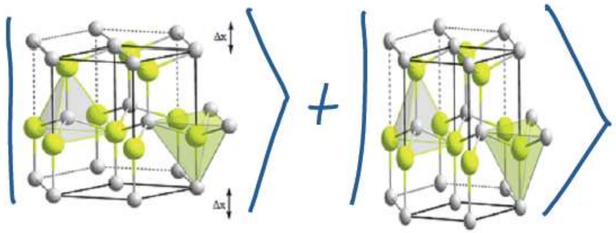
6 GHz piezo vibration
→ n ~ 0.07 @ 20 mK

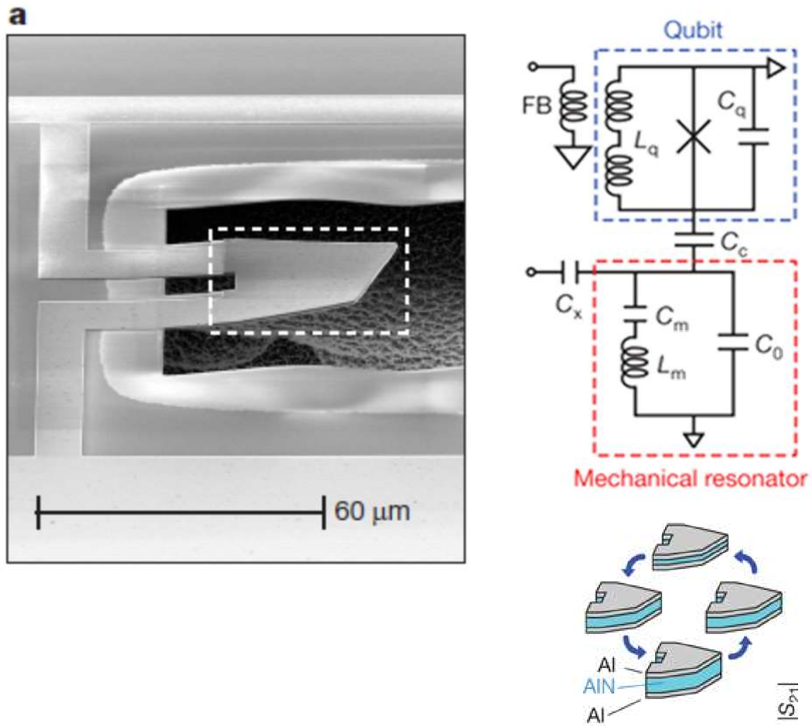
Cleland/Martinis groups (UCSB); April 2010

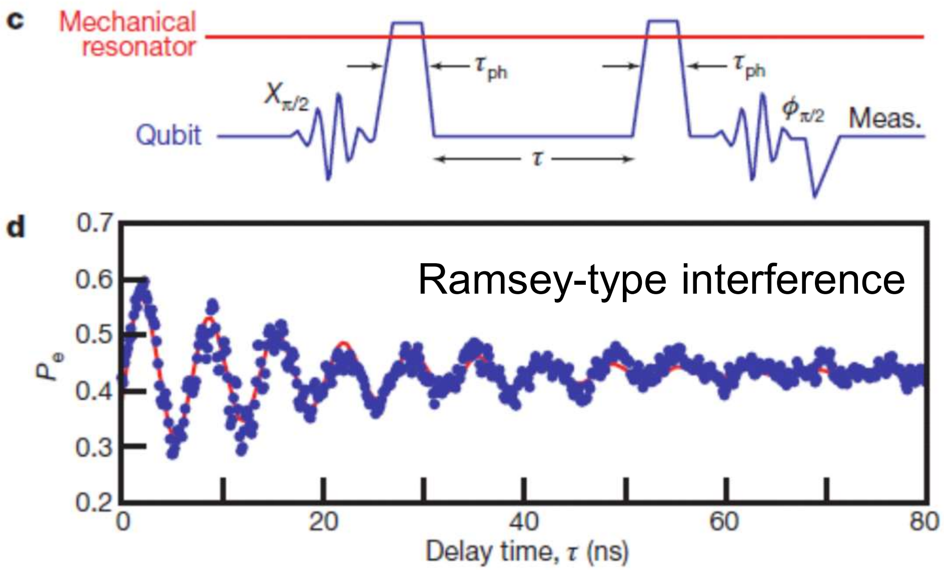
Micromechanics, 2×10^{13} atoms
m ~ 10^{-12} kg = 7×10^{14} AMU
Δx ~ 10^{-16} m (~10^{-10}x its diameter)

Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]



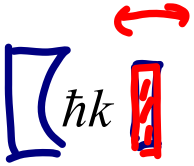


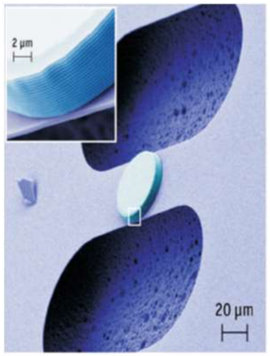


O'Connell, et al. *Nature*.464, 697 (2010)

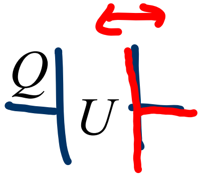
Versatility of mechanical resonators

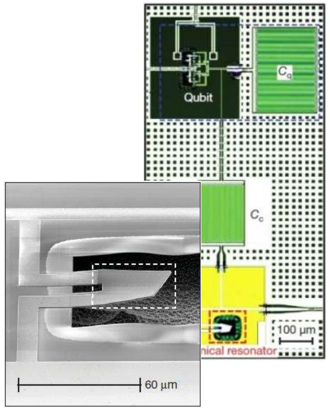
photon momentum



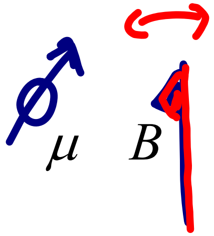


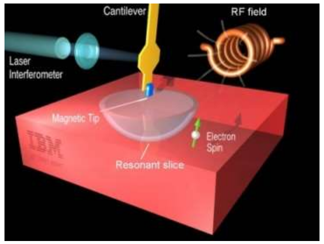
charge



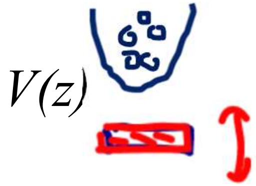


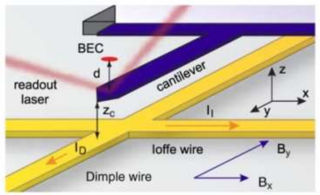
spin





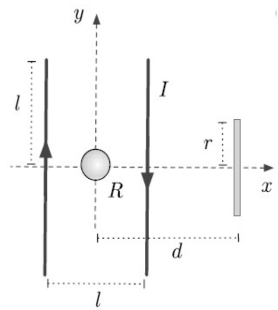
atoms





magnetic flux

Φ



Images from

S. Gröblacher et al., Nature Physics 5 (09)

A. O'Connell et al., Nature 464 (10)

D. Rugar et al., Nature 430 (04)

D. Hunger et al., PRL 104 (10)

O. Romero-Isart et al., PRL 109 (12)

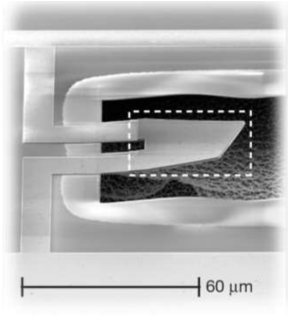
Minimizing Decoherence

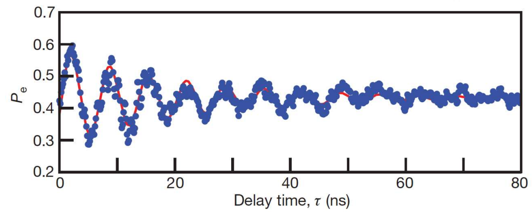
Q: How to achieve large mass **AND** long coherence time in a quantum experiment?

Solid-state mechanical quantum devices (clamped):

10^{10} – 10^{16} atoms

Coherence time τ_c 10^{-12} – 10^{-8} sec



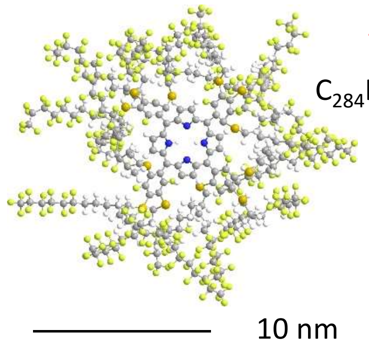


O'Connell et al., Nature 464, 697 (2010)

Matter-wave interferometry (free-fall):

10^{0} – 10^{4} atoms

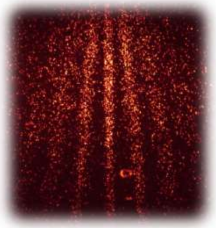
Coherence time τ_c 10^{-3} – 10^{0} sec



10 nm

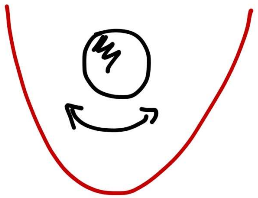
TPPF320

$C_{284}H_{190}F_{320}N_4S_{12}$



Juffmann et al., Nature Nanotech. 7, 297 (2012)

A: Quantum control of levitated mechanical systems!



- Quantum control of a trapped massive object >> 10^{10} atoms
- Long coherence times (up to seconds) through free fall dynamics
- Exceptional force sensitivity

1619 Johannes Kepler, *De cometis*

"solar repulsion of comet tails because of mechanical light force (radiation pressure)"

picture: Nature 444, 823 (2006)

Radiation pressure as propulsion

LightSail-A (32 m^2)

Radiation pressure in the lab

1901 Lebedev, Ann. Phys. 6, 433
Nichols & Hull, Phys. Rev. 13,307
experimental demonstration of radiation pressure

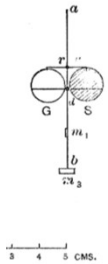


Fig. 1.

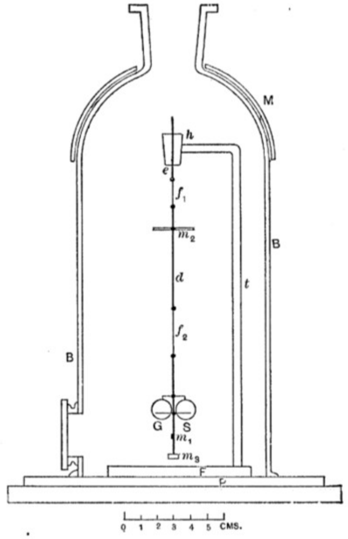


Fig. 2.

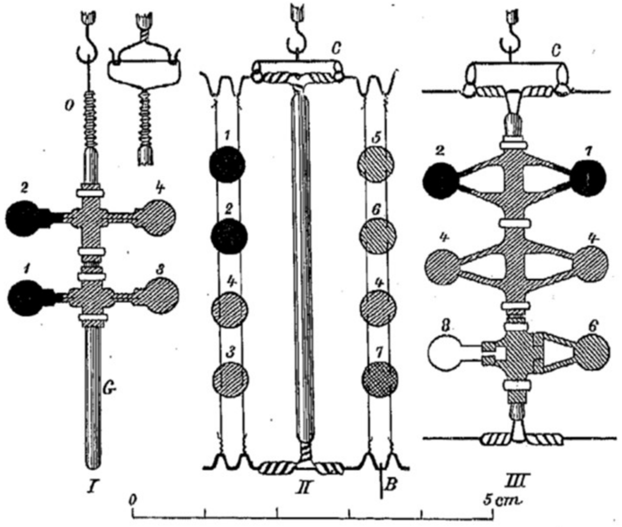
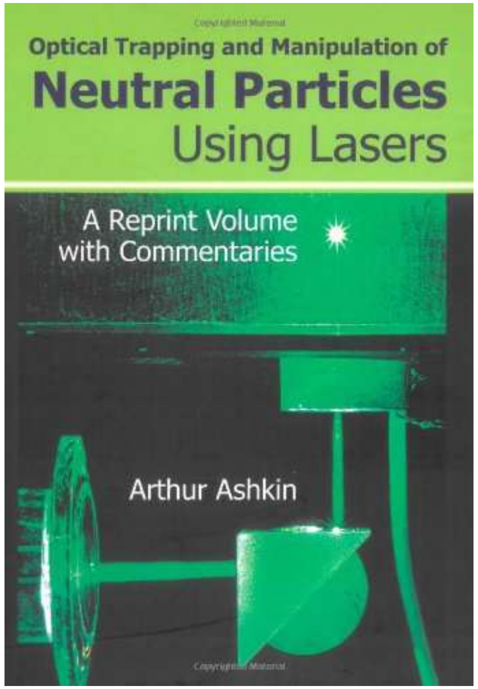


Fig. 3 (natürl. Grösse).

Trapping and Cooling Particles by Optical Forces

1970 Arthur Ashkin et al. „Acceleration and Trapping of Particles by Radiation Pressure“ *Phys. Rev. Lett.* 24, 156 (1970)

1986 Chu, S. et al. “Experimental observation of optically trapped atoms,” Phys. Rev. Lett. 57, 314



10-20 μm-sized Silica Spheres and Silicon Oil drops of @ 10^{-6} mbar, Calc. Energy Decay: days

Ashkin and J. M. Dziedzic, Appl. Phys. Lett. 28, 333 (1976)

Experimental Observation of Optically Trapped Atoms (1986)

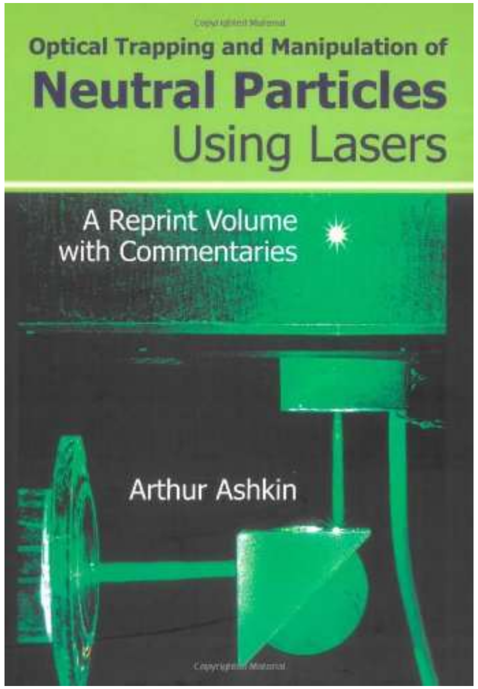
~ 500 Na Atoms
~ 10 mm diameter

Steven Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable Phys. Rev. Lett. 57, 314 (1986).

Trapping and Cooling Particles by Optical Forces

1970 Arthur Ashkin et al. „Acceleration and Trapping of Particles by Radiation Pressure“ *Phys. Rev. Lett.* 24, 156 (1970)

1986 Chu, S. et al. “Experimental observation of optically trapped atoms,” Phys. Rev. Lett. 57, 314



10-20 μm-sized Silica Spheres and Silicon Oil drops of @ 10^{-6} mbar, Calc. Energy Decay: days

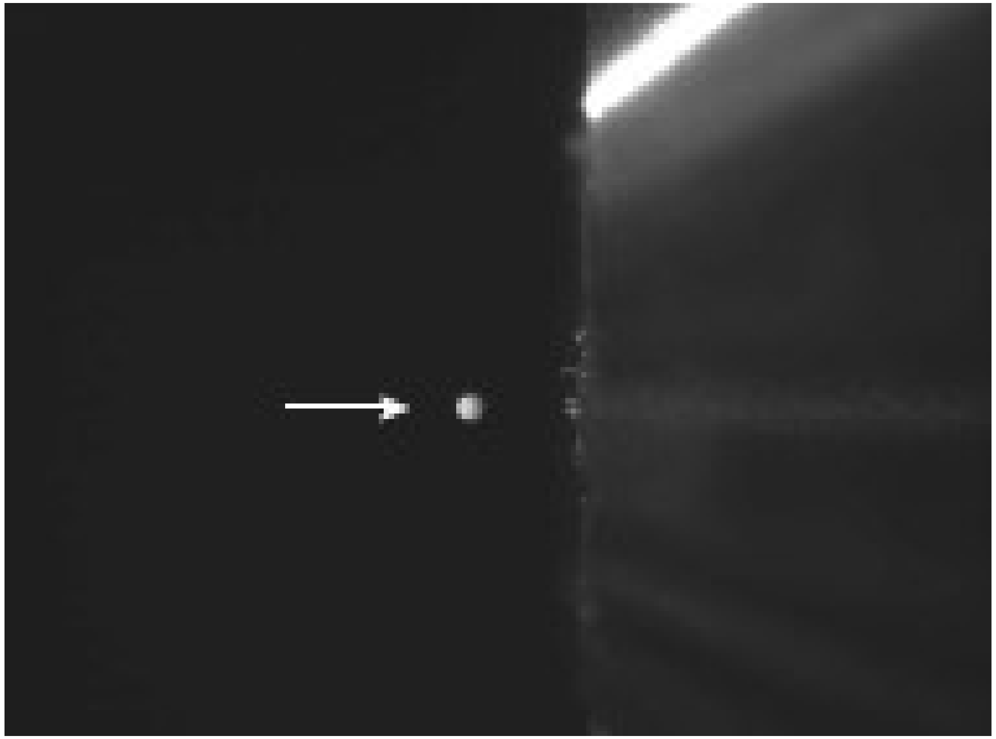
Ashkin and J. M. Dziedzic, Appl. Phys. Lett. 28, 333 (1976)

Experimental Observation of Optically Trapped Atoms (1986)

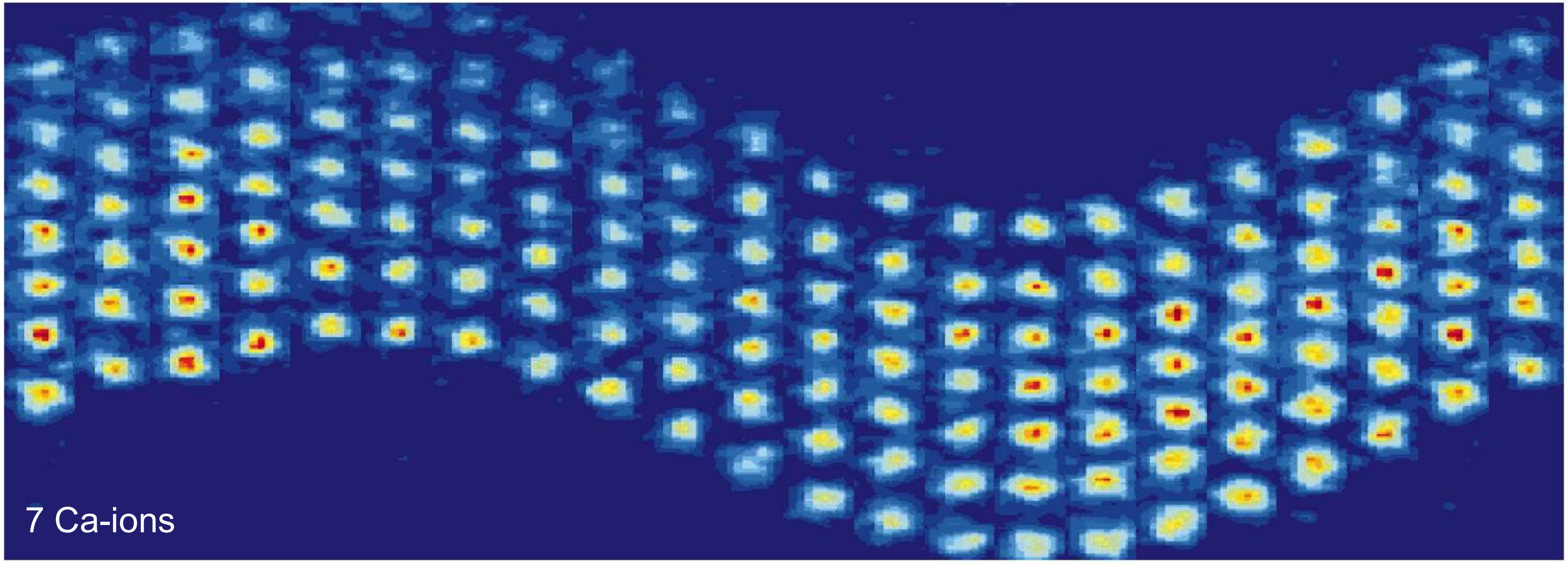
~ 500 Na Atoms
~ 10 mm diameter

Steven Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable Phys. Rev. Lett. 57, 314 (1986).

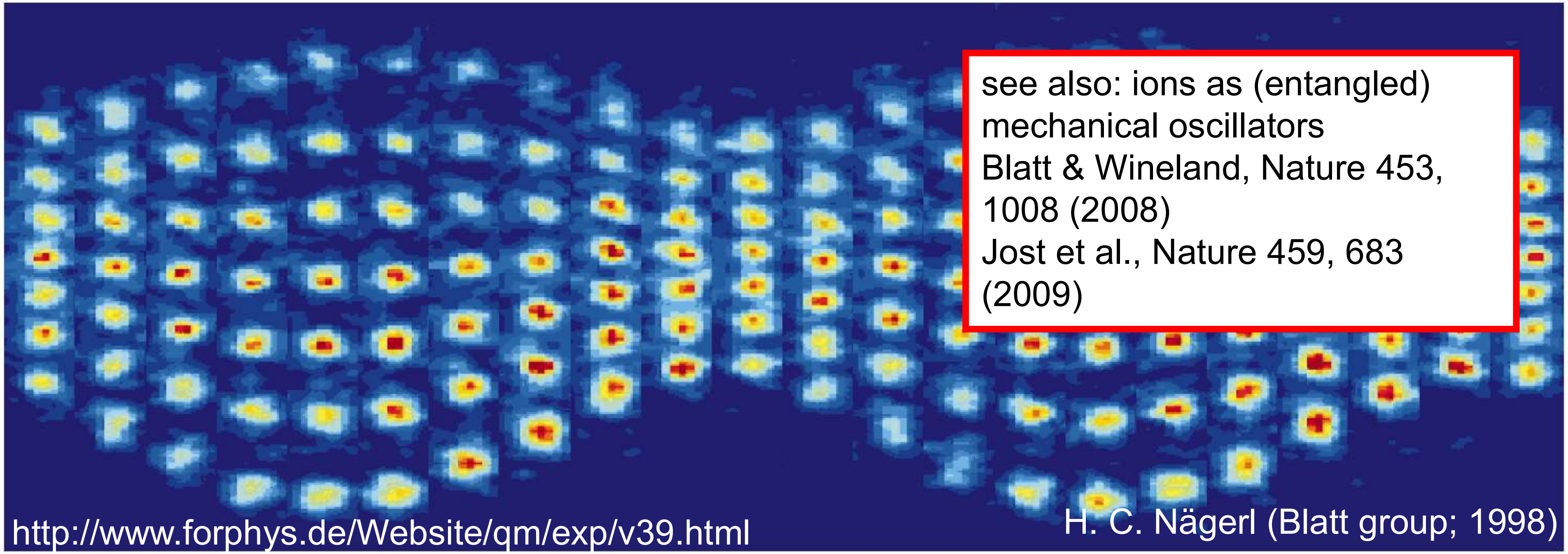
Optical Tweezers

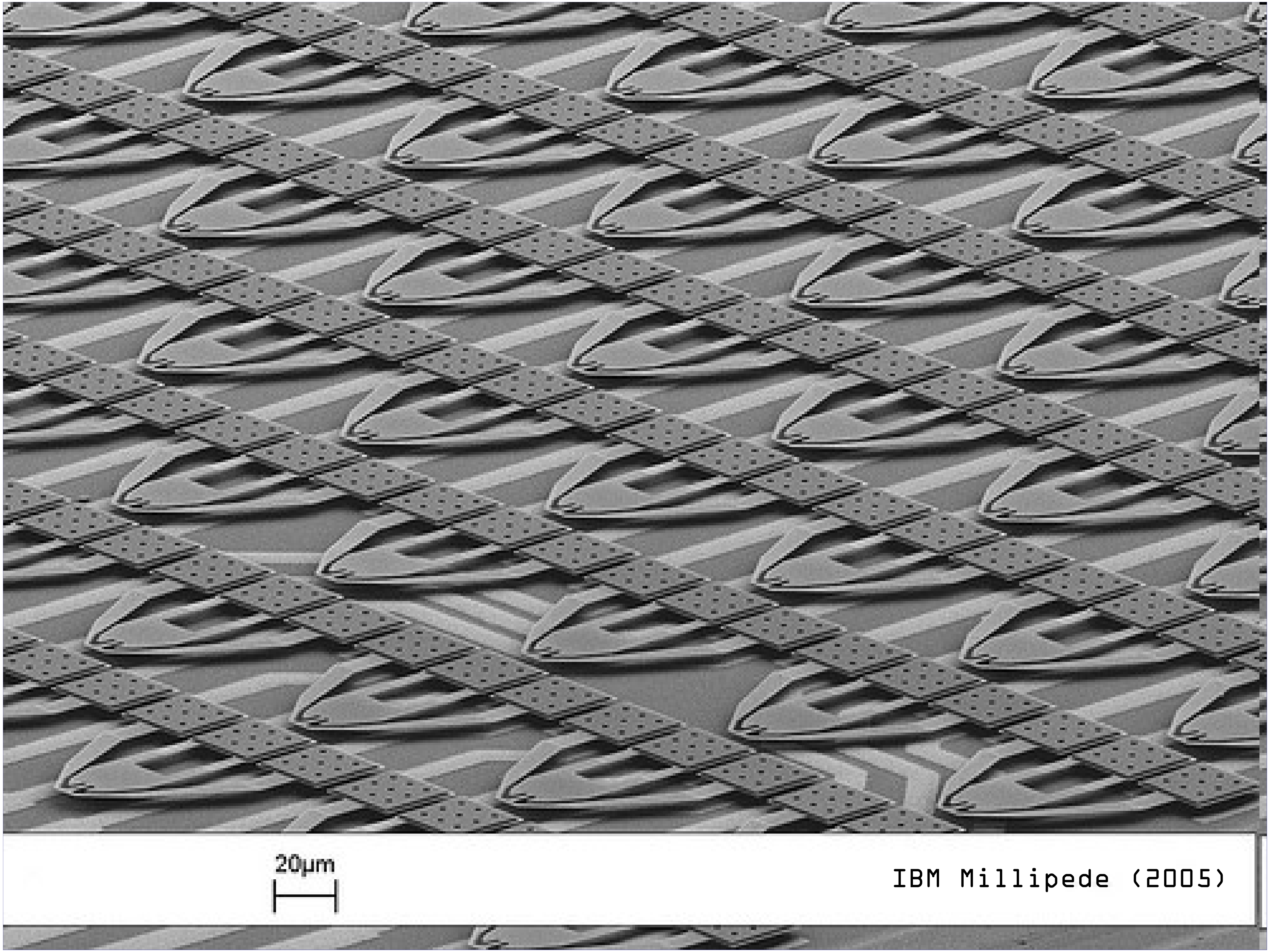


70nm silica sphere in optical trap,
Gieseler et al., PRL 109, 103603 (2012)



Trapped ions: **quantum physics with phonons** (Cirac & Zoller, PRL 74, 4091 (1995))

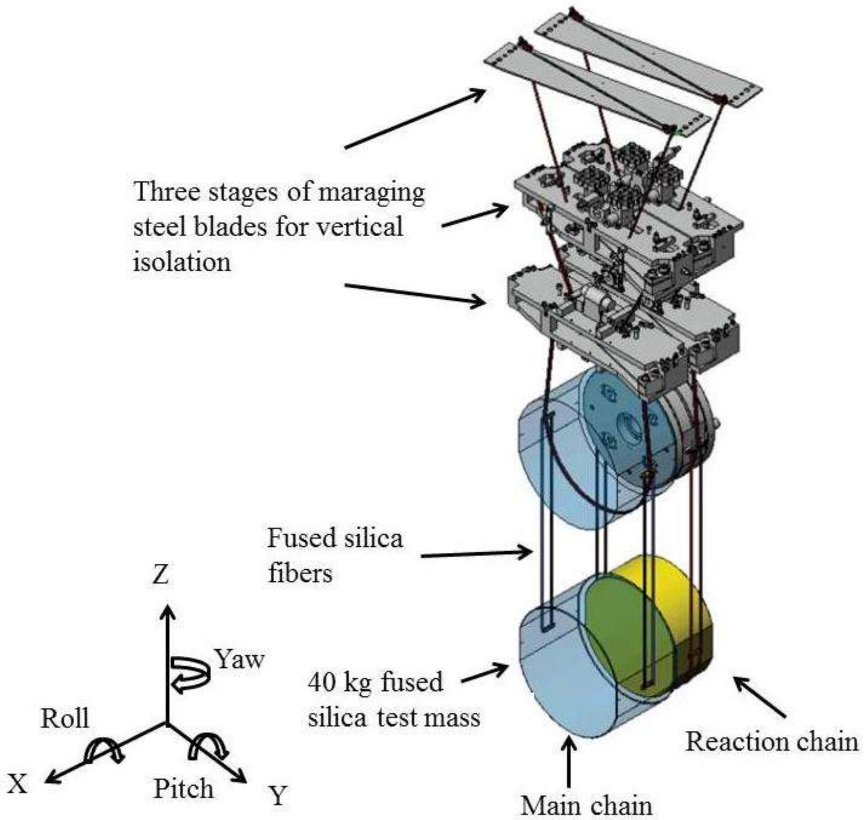




IBM Millipede (2005)

Quantum Noise in Massive Systems

Gravitational wave detectors

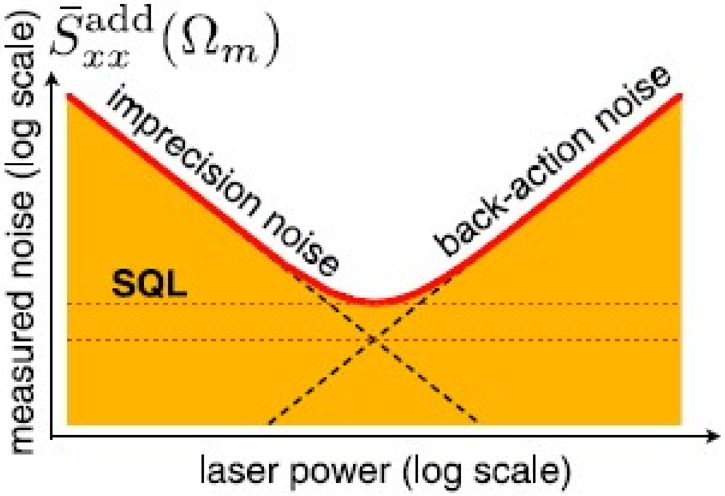


https://www.ligo.caltech.edu/LA/page/research-development

Quantum Noise in Massive Systems

Position Sensitivity: Standard Quantum Limit

Braginsky, Manukin: *Measurement of Weak Forces in Physics Experiments* (1977)



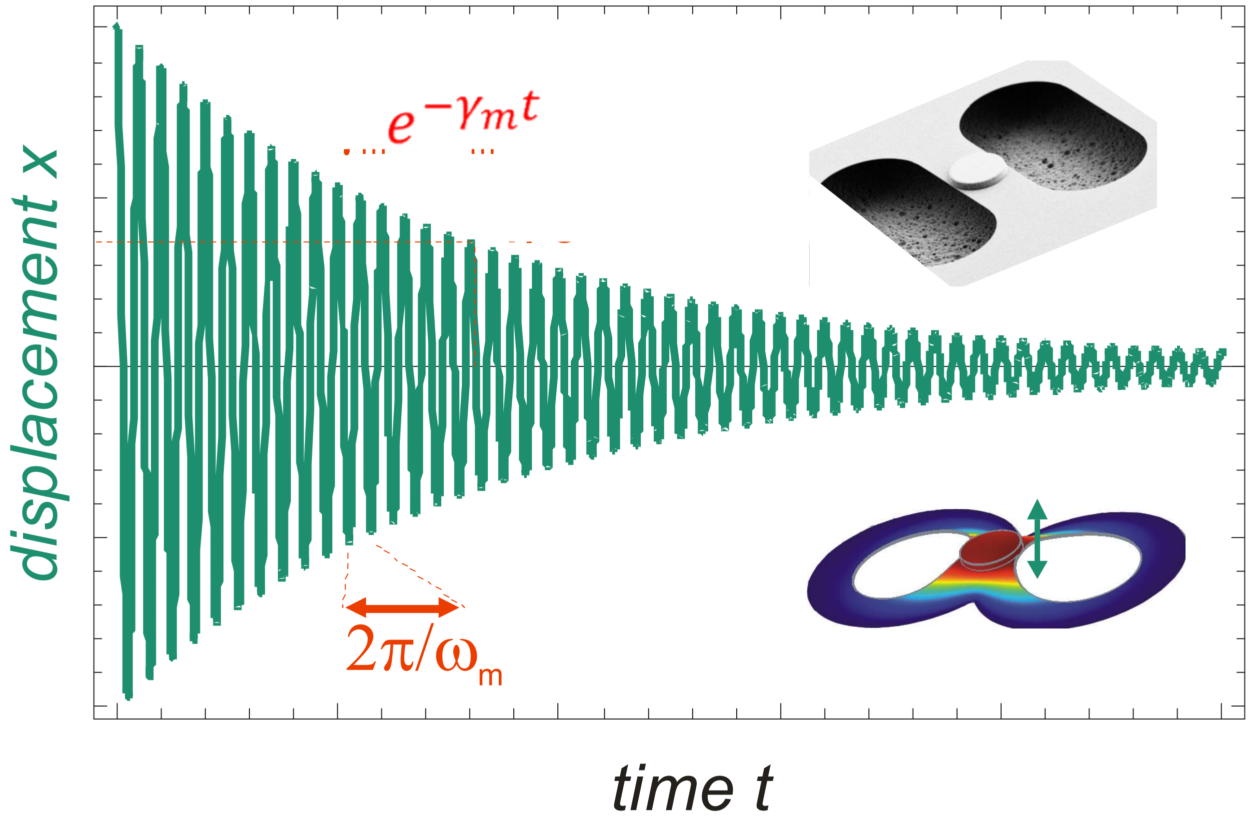
Phys. Rev. Lett. 45, 75 (1980)

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

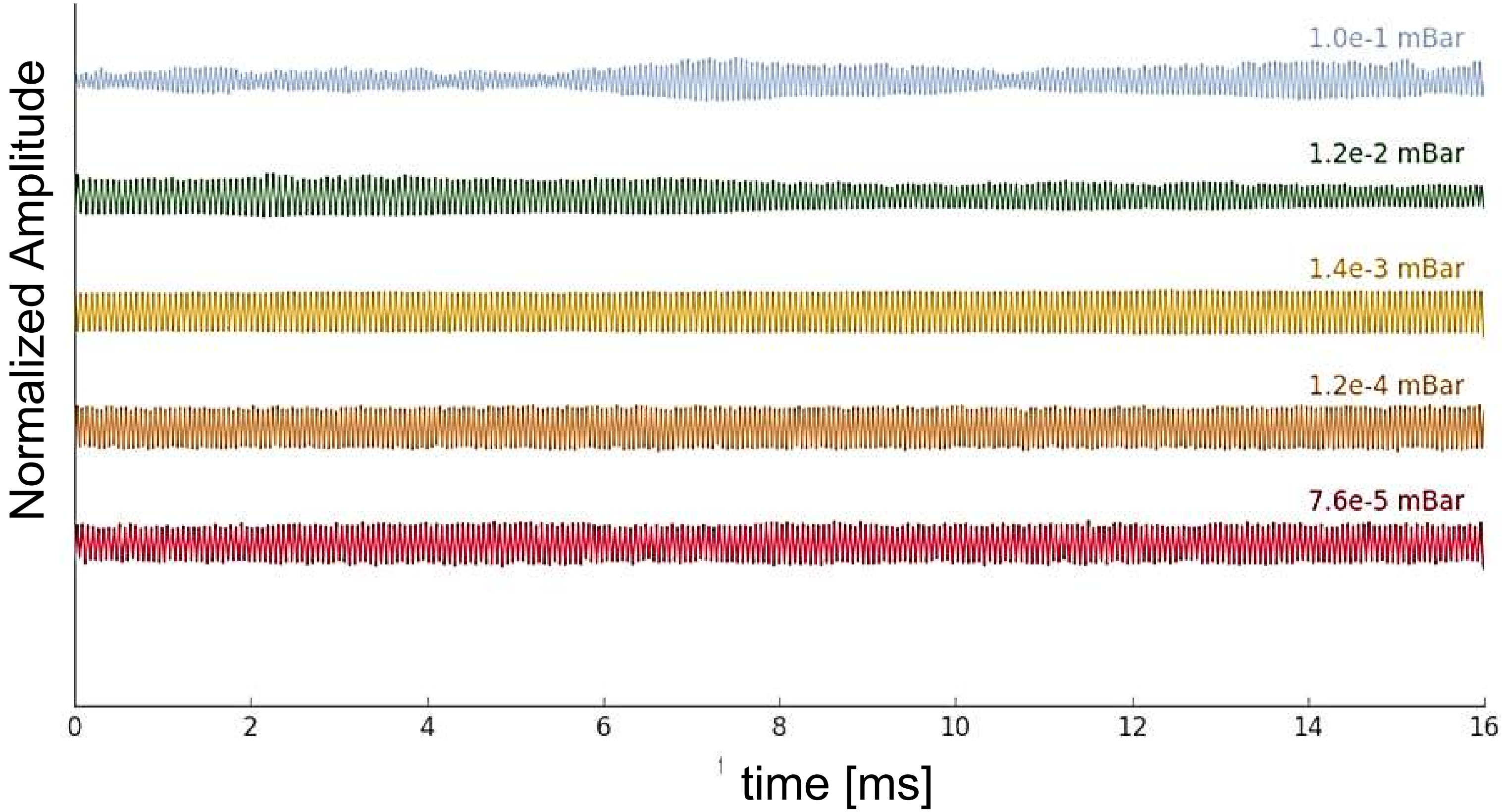
Mechanical Resonator



$$\frac{d^2x}{dt^2} + \gamma_m \frac{dx}{dt} + \omega_m^2 x = F_{th}$$

$$Q = \frac{\omega_m}{\gamma_0}$$

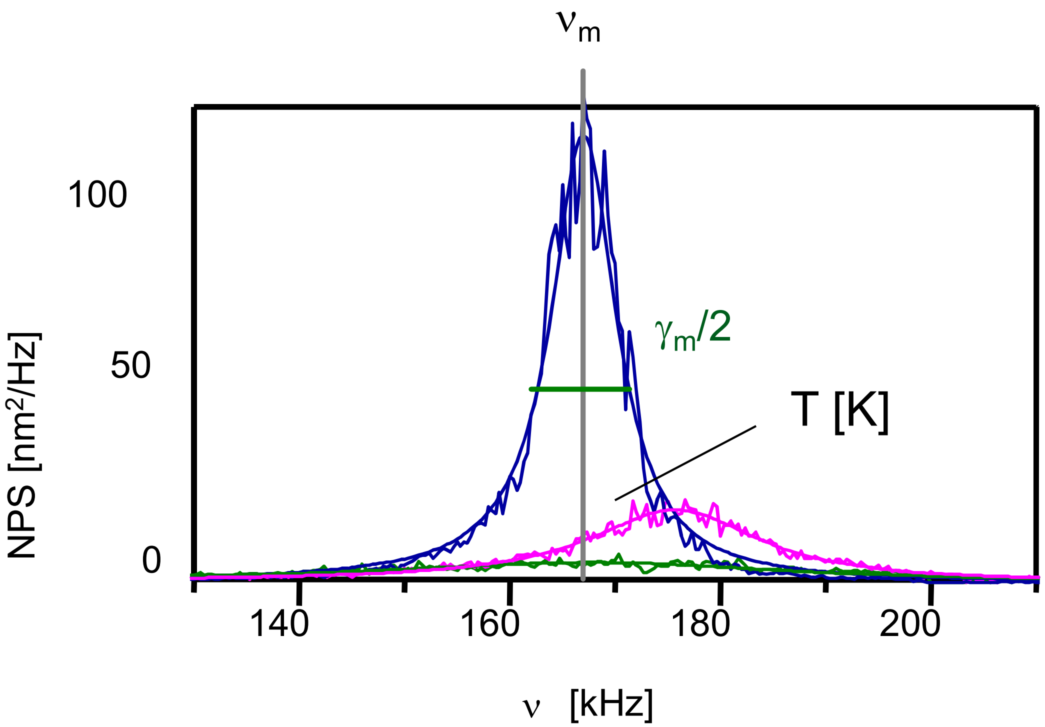
Mechanical Resonator



$$\frac{d^2x}{dt^2} + \gamma_m \frac{dx}{dt} + \omega_m^2 x = F_{th}$$

$$Q = \frac{\omega_m}{\gamma_0}$$

Brownian Force Noise

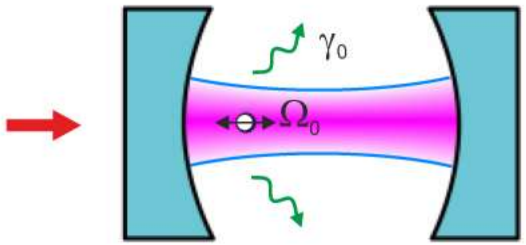


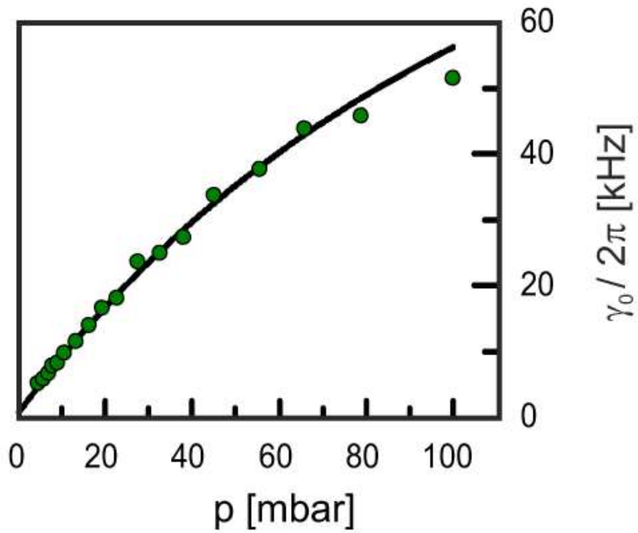
$$\frac{d^2x}{dt^2} + \gamma_m \frac{dx}{dt} + \omega_m^2 x = F_{th}$$

Characterizing an optical trap

Kiesel, N. et al., *PNAS 110*, 14180 (2013)

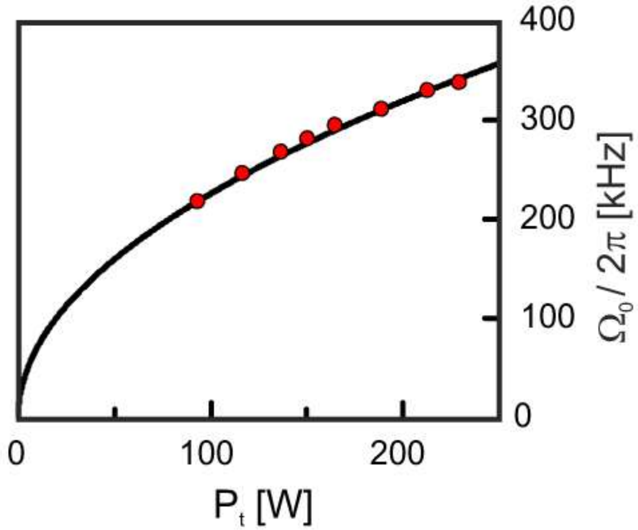
$$\frac{d^2x}{dt^2} + \gamma_0 \frac{dx}{dt} + \Omega_0^2 x = F_{th}$$



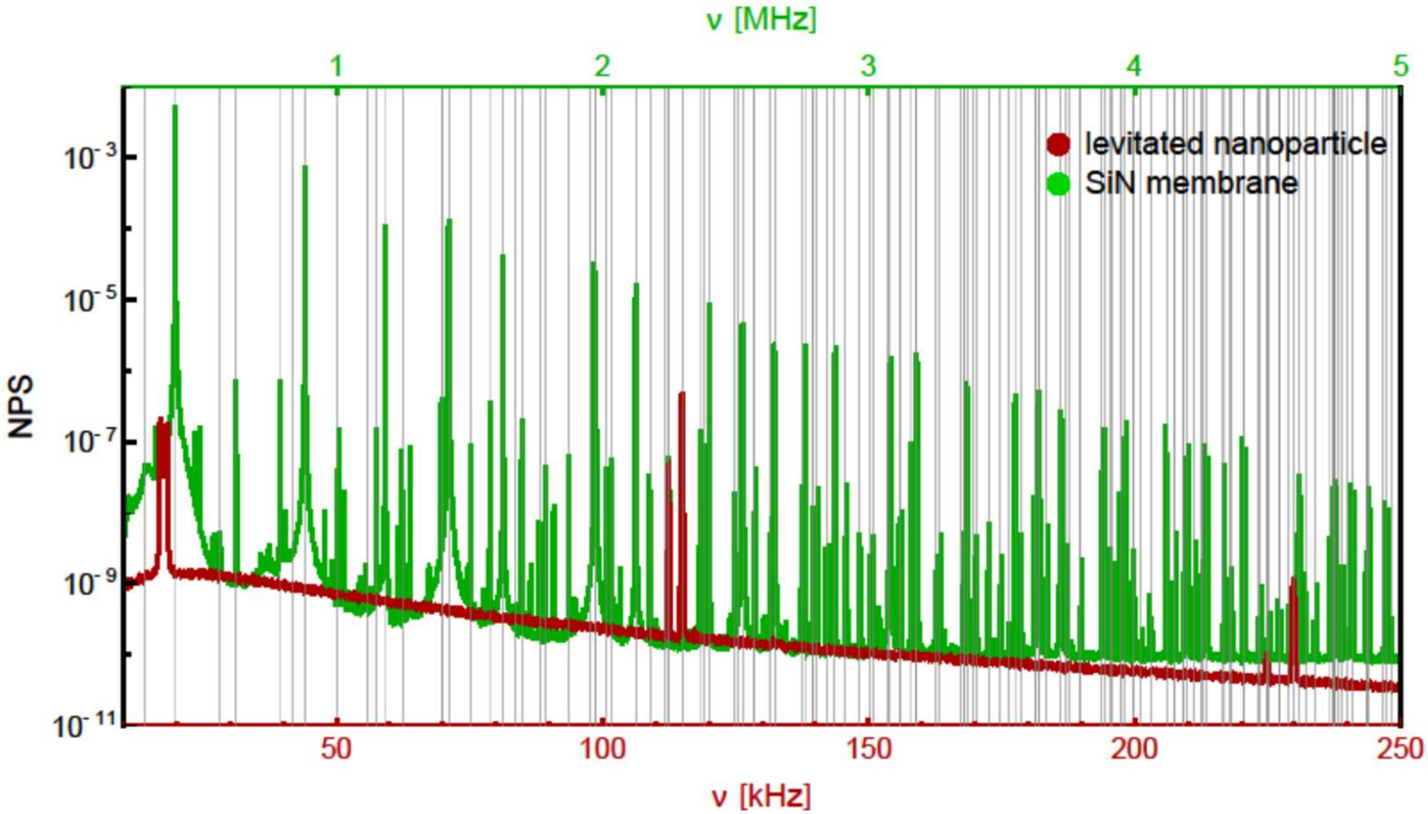


Mechanical
Trap Frequency

$$\Omega_0 \propto \sqrt{\frac{Power}{Waist(x)^2}}$$



Modes of mechanical resonators

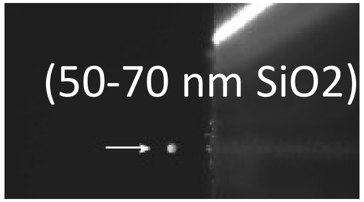


Aspelmeyer labs

Towards room-temperature QOM

3D Feedback (10^{-8}mbar)

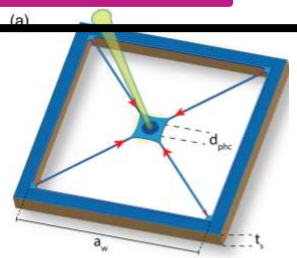
Direct Measurement of Photon Recoil
Vijay Jain et al.
PRL 116, 243601 (2016)



3D Feedback (10^{-6} mbar)

Vovrosh, J., M. Rashid, D. Hempston, J. Bateman, and H. Ulbricht
arXiv:1603.02917 (2016)

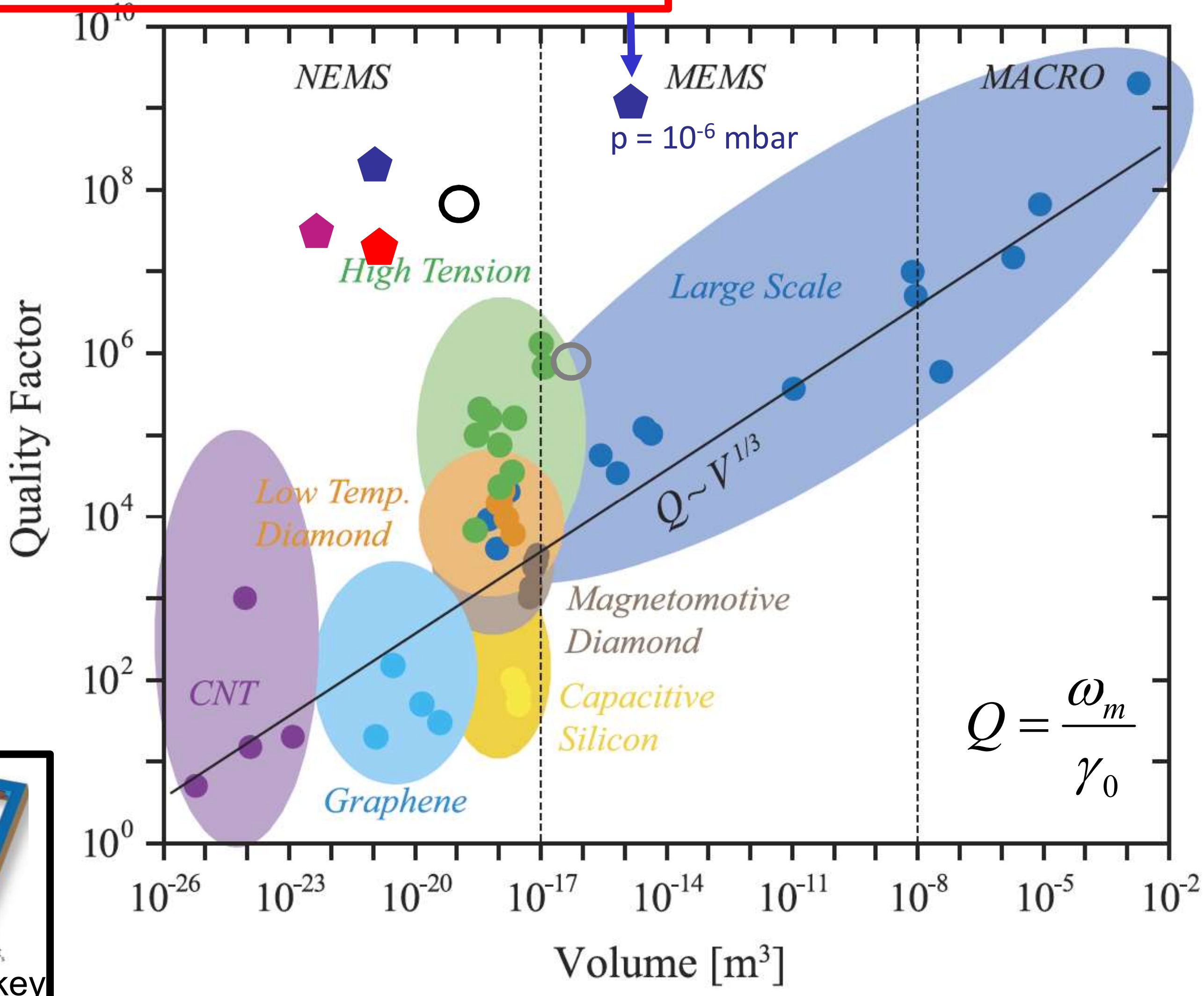
Norte, Moura, Gröblacher, PRL 116, 147202 (2016)



Reinhardt, Müller, Bourassa, Sankey Phys. Rev. X 6, 021001

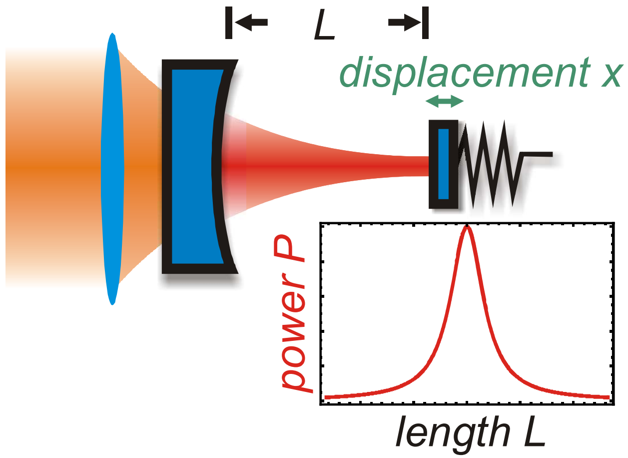
Direct — Magrini, Aspelmeyer et al. (2016)

Ashkin & Dziedzic, APL 28, 333 (1976)(20um Si oil - projected)



M. Imboden, P. Mohanty, Phys. Rep. 534, 89 (2014)

Cavity Optomechanics



Change in cavity length
leads to a
change in resonance frequency and
therefore in intra-cavitypower

Intracavity power responsible for force acting on the mirrors

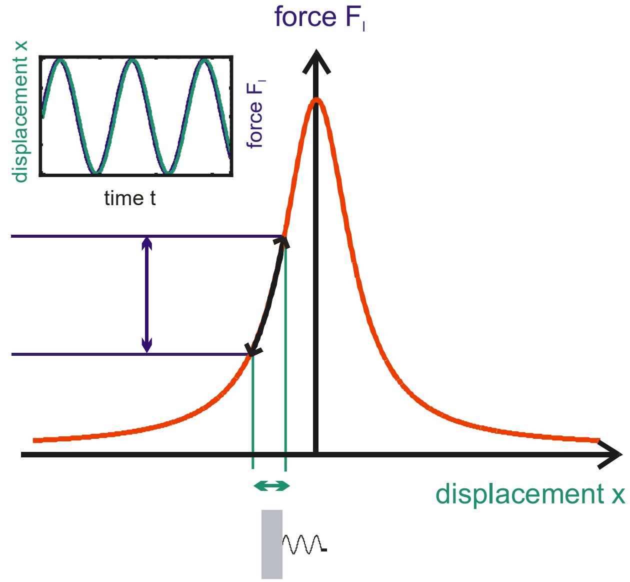
$$F_1(x) = \frac{2P(x)}{c} \approx \frac{2}{c}\frac{\mathrm{d}P(x)}{\mathrm{d}x}x.$$

→ Position Dependent Force
creates an additional harmonic potential

$$\ddot{x} + \gamma_{\mathrm{m}}\dot{x} + \left(\omega_{\mathrm{m}}^2 - \frac{2}{c \cdot m}\frac{\mathrm{d}P(x)}{\mathrm{d}x}\right)x = \frac{F_{\mathrm{B}}}{m}.$$

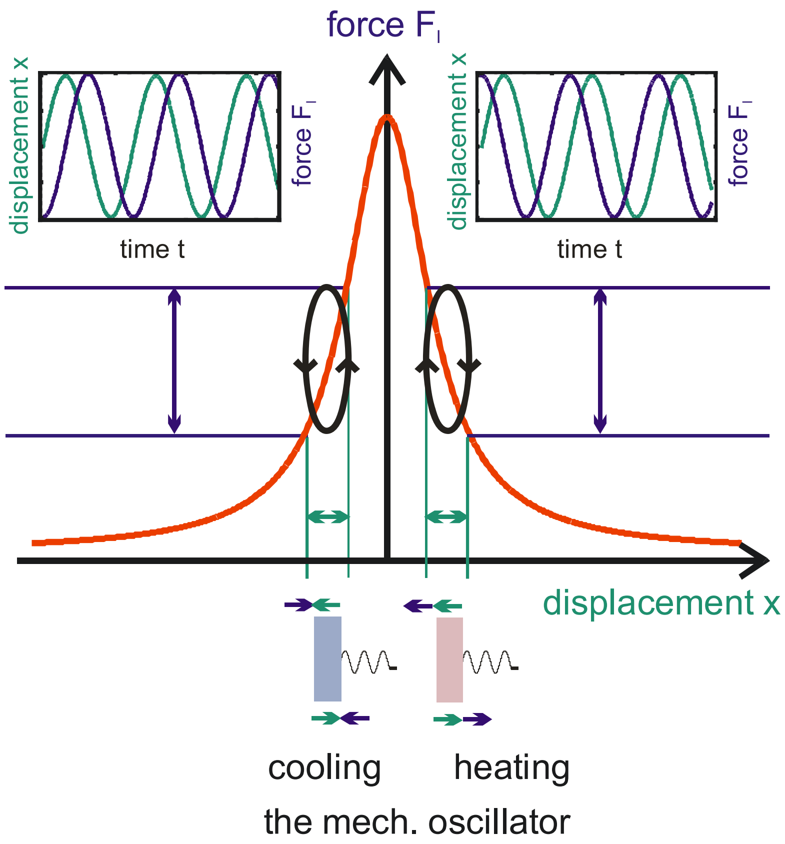
OPTICAL SPRING

Mechanical motion much slower
than cavity lifetime



Cavity Optomechanics

Mechanical Period comparable to
cavity lifetime



Phase delay in intracavity power relative to mechanical position:

Light field acts with/against motion of mirror

Work is done by the light field / mechanics

Heating / Cooling

$$\oint F_1(x)\mathrm{d}x > 0. \quad / \quad \oint F_1(x)\mathrm{d}x < 0.$$

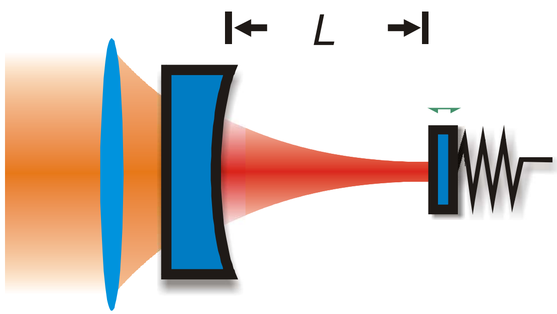
Cavity Optomechanics

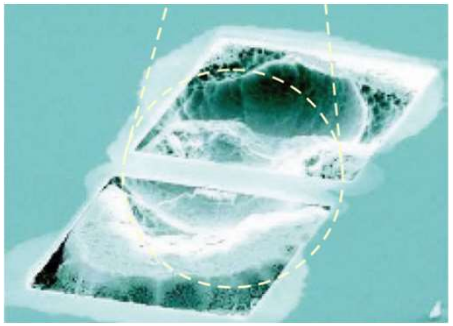
1983 Walther group: "Optical bistability and mirror confinement induced by radiation pressure" , Dorsel et al. PRL 51, 1550 (1983)

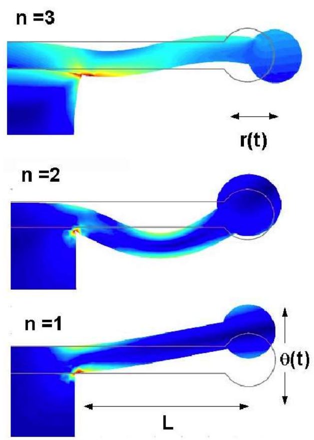
2003 Karrai group: „Optically tunable mechanics of microlevers"
Favero et al.,APL 83,1337 (2003)

2005 Vahala group: "Kerr-Nonlinearity Optical Parametric Oscillation in an Ultrahigh-Q Toroid Microcavity" Kippenberg et al.,PRL 93, 83904 (2004)

2006 Aspelmeyer and Kippenberg group, Selfcooling by Radiation Pressure
S. Gigan et al. Nature 444, 67–70 (2006), O. Arcizet et al. Nature 444, 71–74 (2006).







Cavity Optomechanics

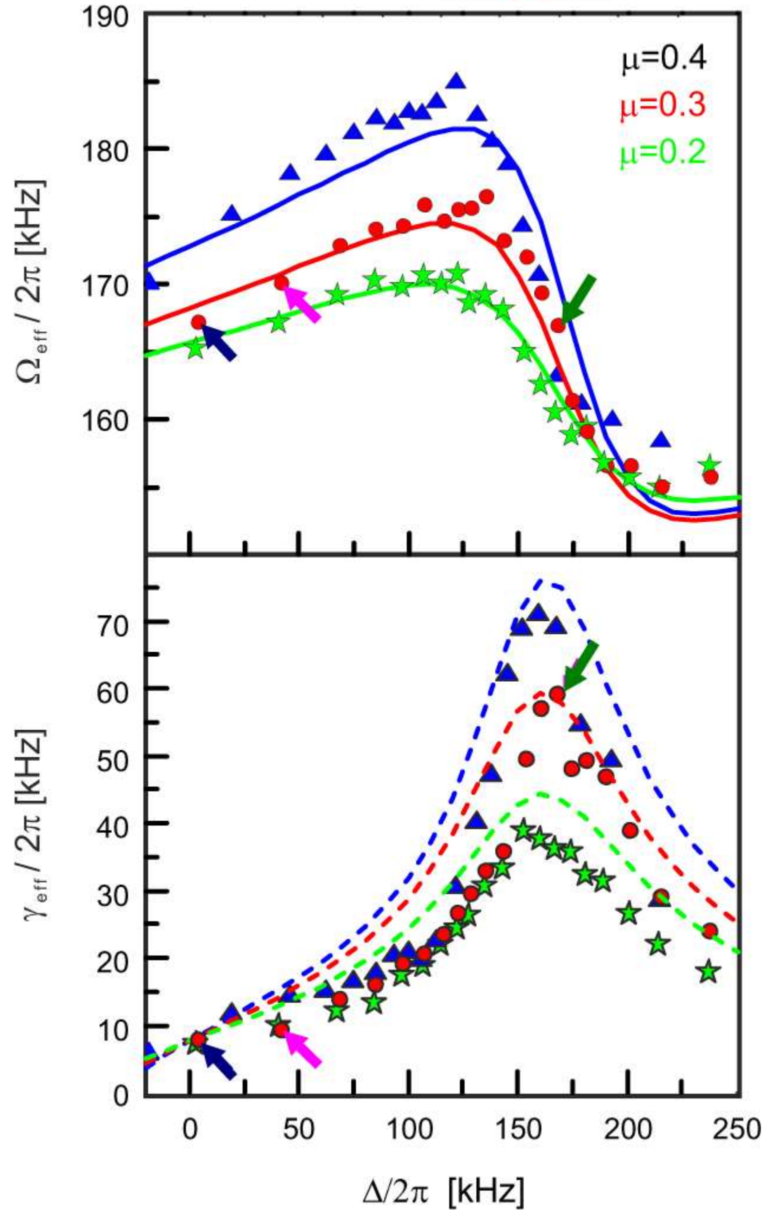
Radiation pressure induced:

- modification of frequency

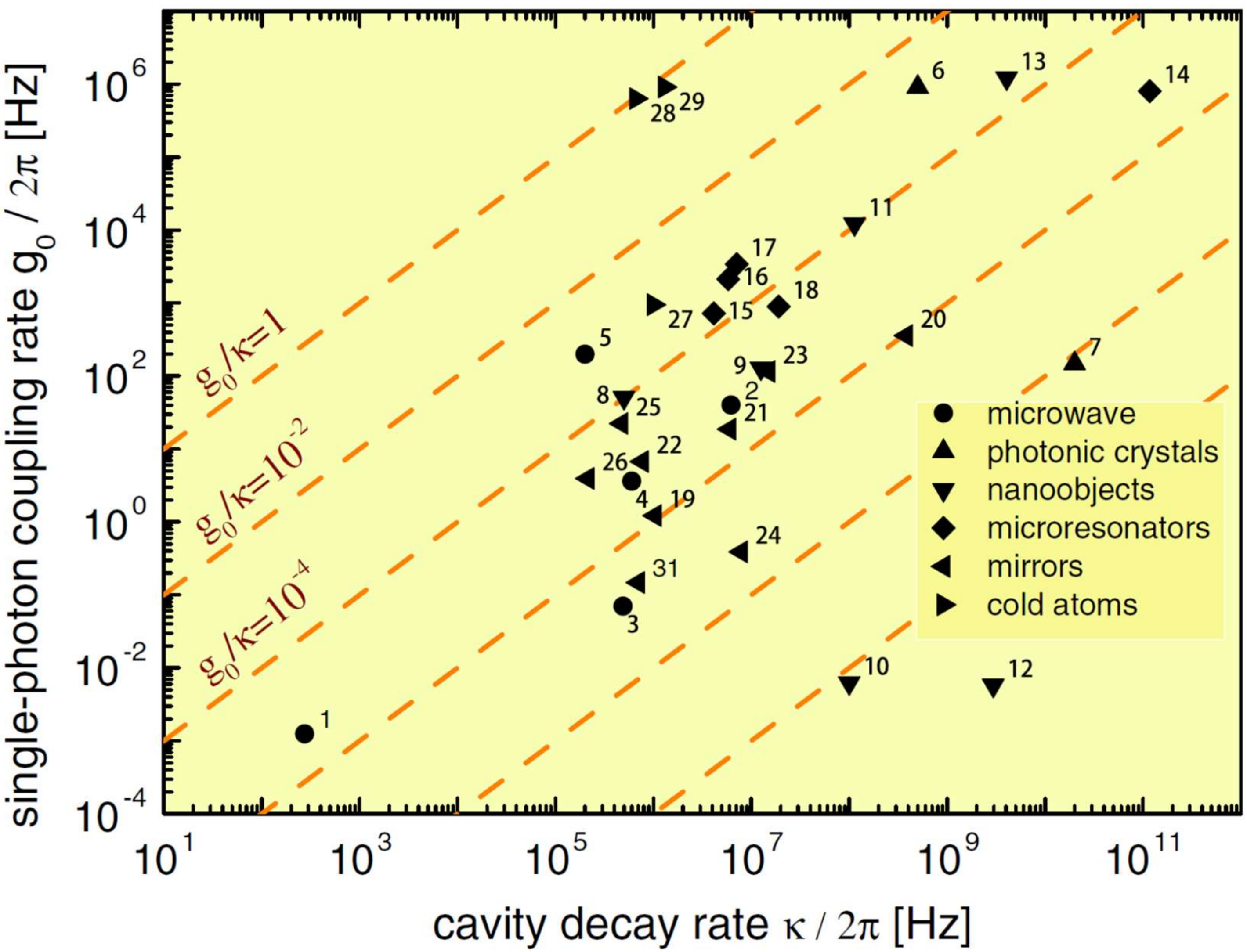
Optical spring

- modification of damping

Optical damping

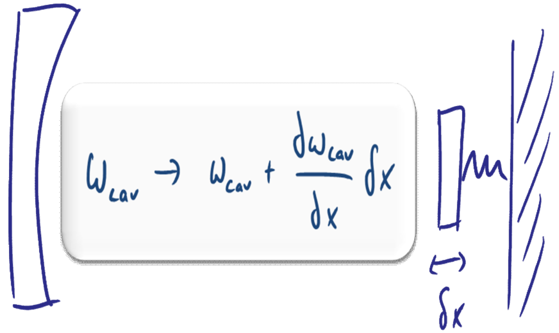


Theoretical dependencies:
Genes et al., *Phys. Rev. A* **77**, 033804

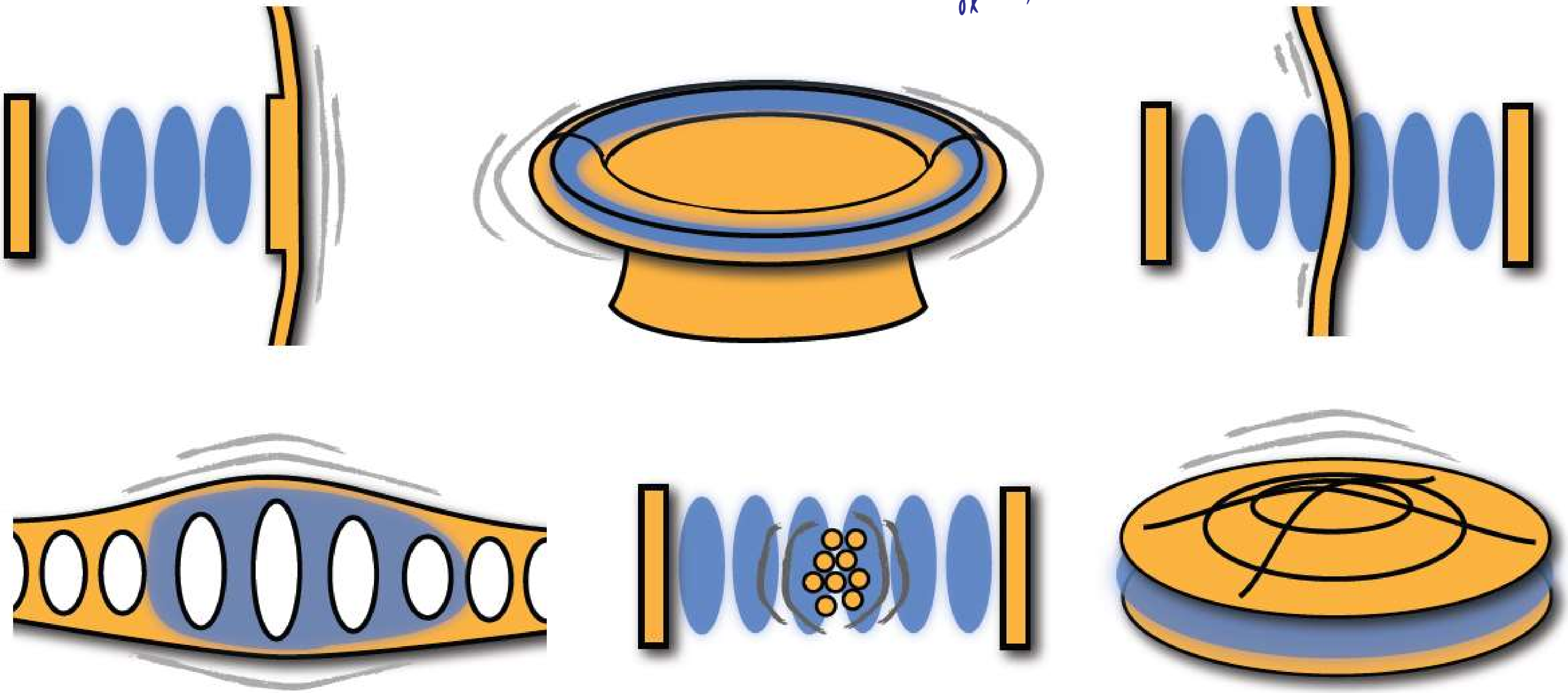


Rev. Mod. Phys. **86**, 1391 (2014)

Optomechanical Systems

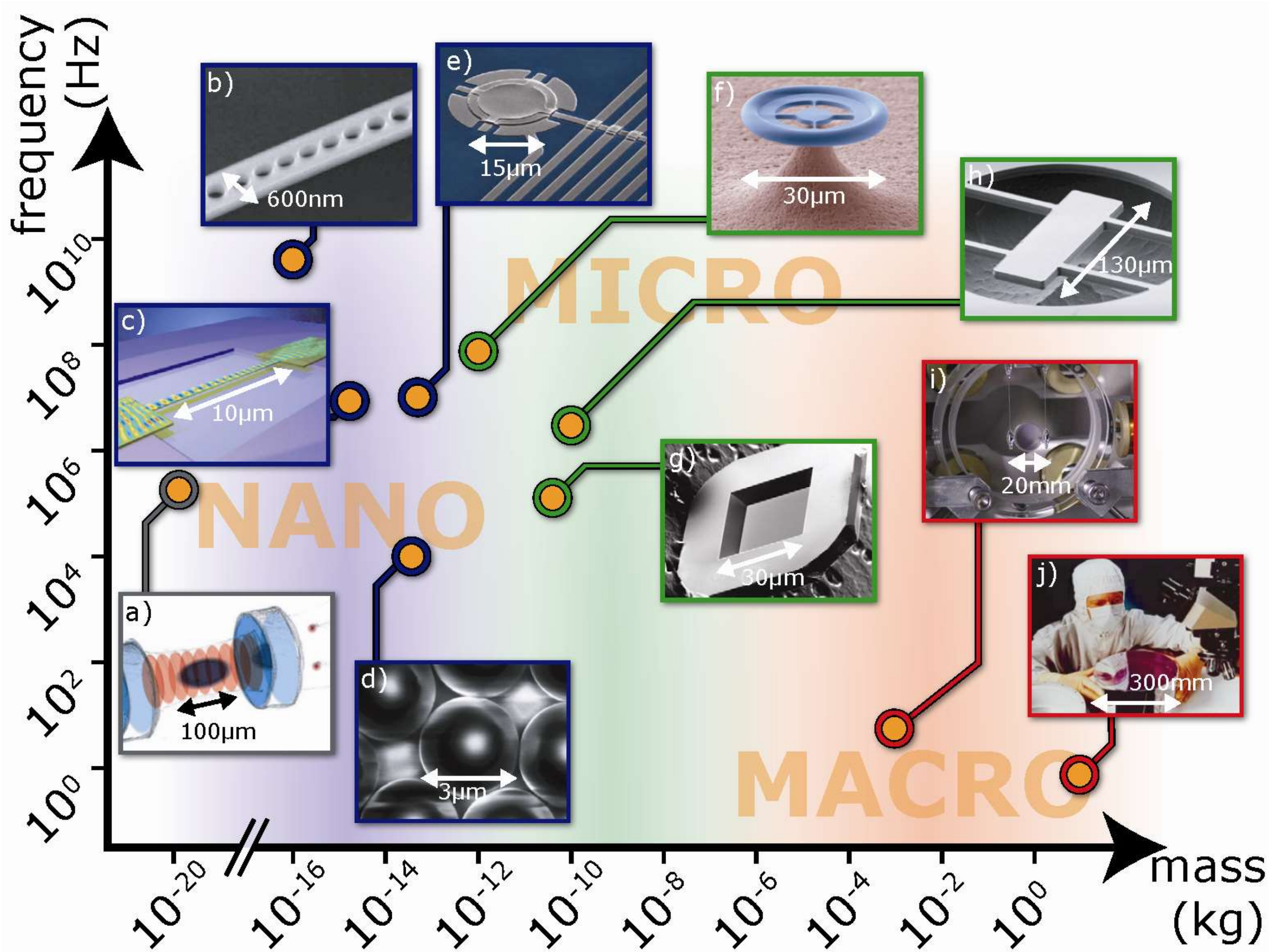


$$\omega_{cav} \rightarrow \omega_{cav} + \frac{d\omega_{cav}}{dx}\delta x$$



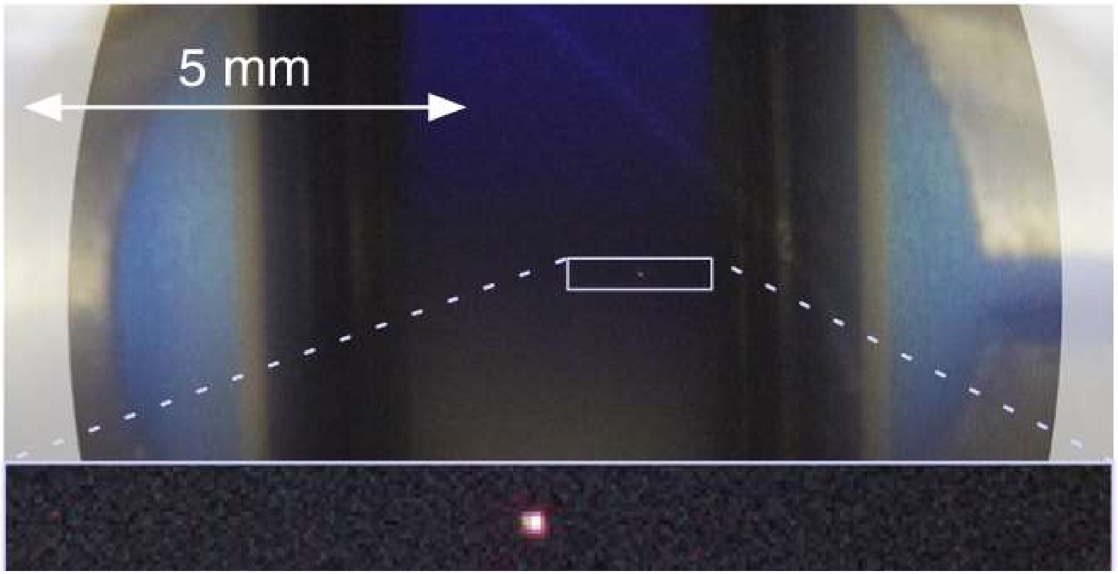
Rev. Mod. Phys. **86**, 1391 (2014)

Optomechanical Systems



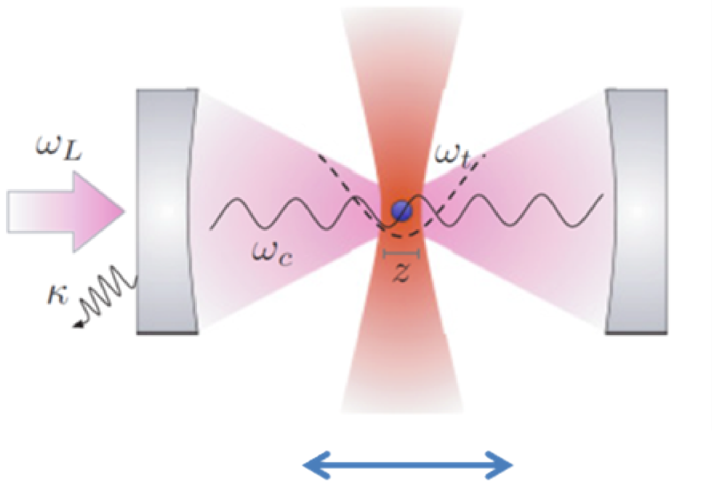
Quantum Optomechanics - M. Aspelmeyer. P. Meystre, K.Schwab - Physics Today 65 (7), 29 (2012)

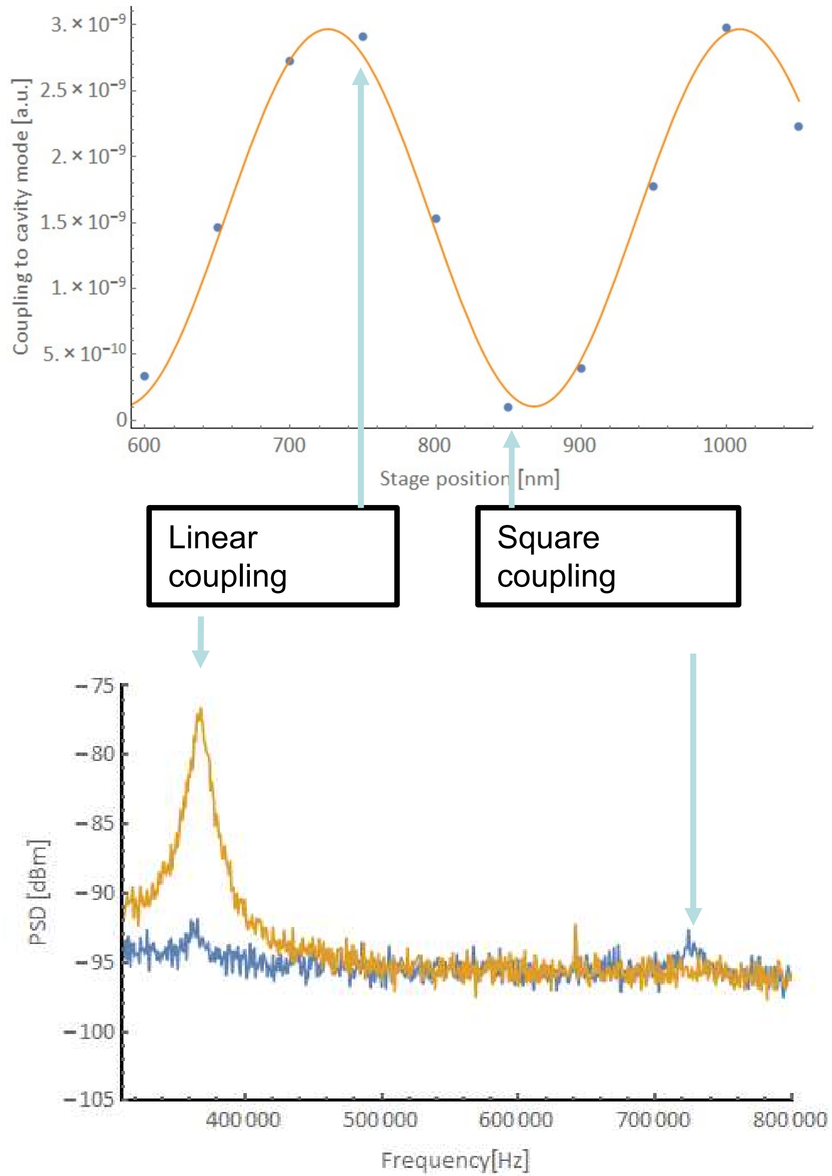
Particle in a cavity



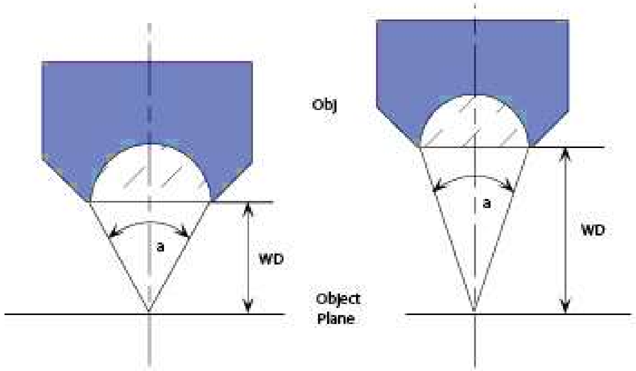
Particle in a cavity

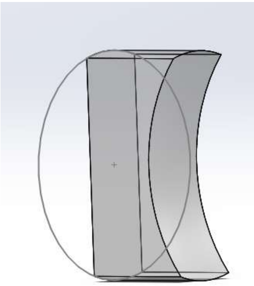
- Nanosphere moved in steps of 50 nm



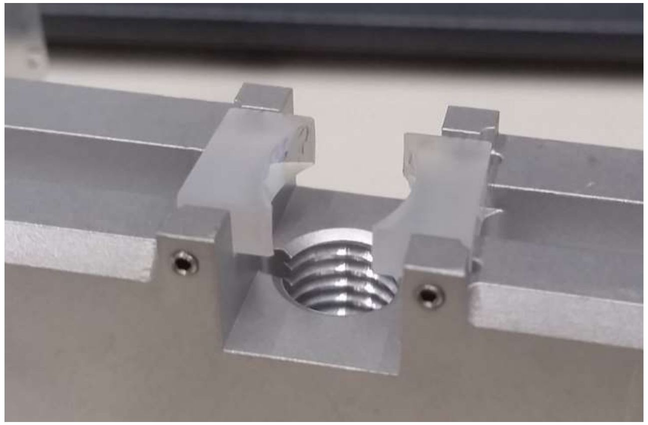


Particle in a cavity

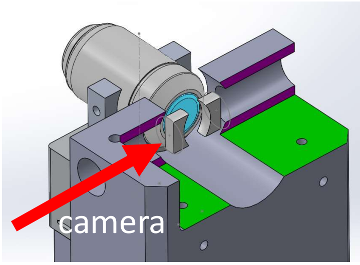




Original mirror:
diameter d=12.7mm
Cut mirror:
width=4mm

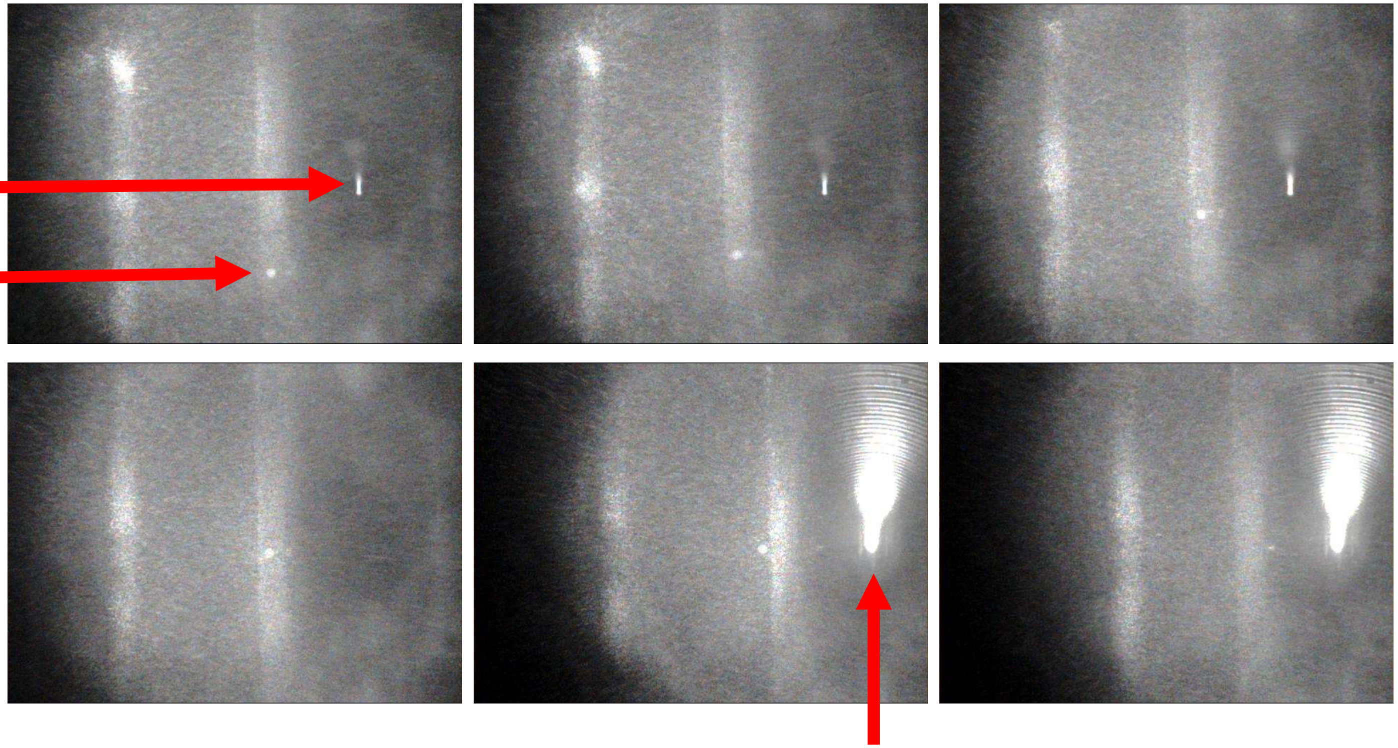


Particle in a cavity



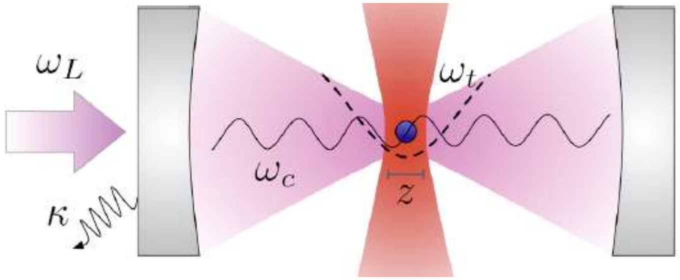
TEM00 mode
(cavity scanned)

nanosphere

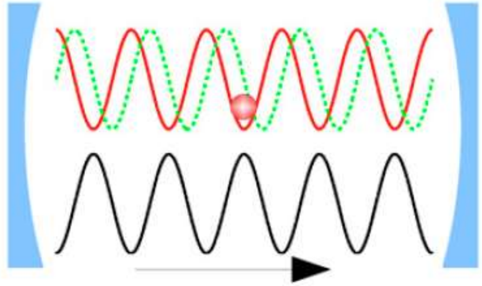


Levitated Cavity Optomechanics

Romero-Isart et al. NJP 12, 33015, (2010)

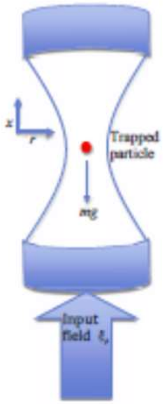


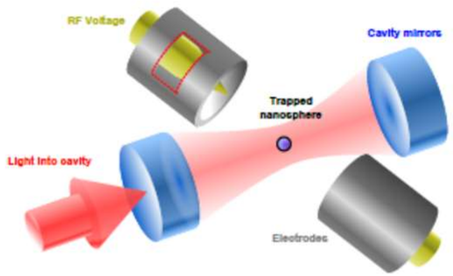
Chang et al., PNAS 107, 1005 (2010)



P. F. Barker et al., PRA 81, 023826 (2010)

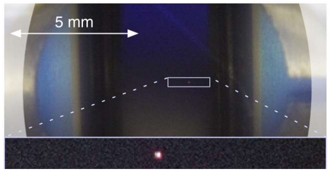
Millen et al., Phys. Rev. Lett. 114, 123602 (2015)

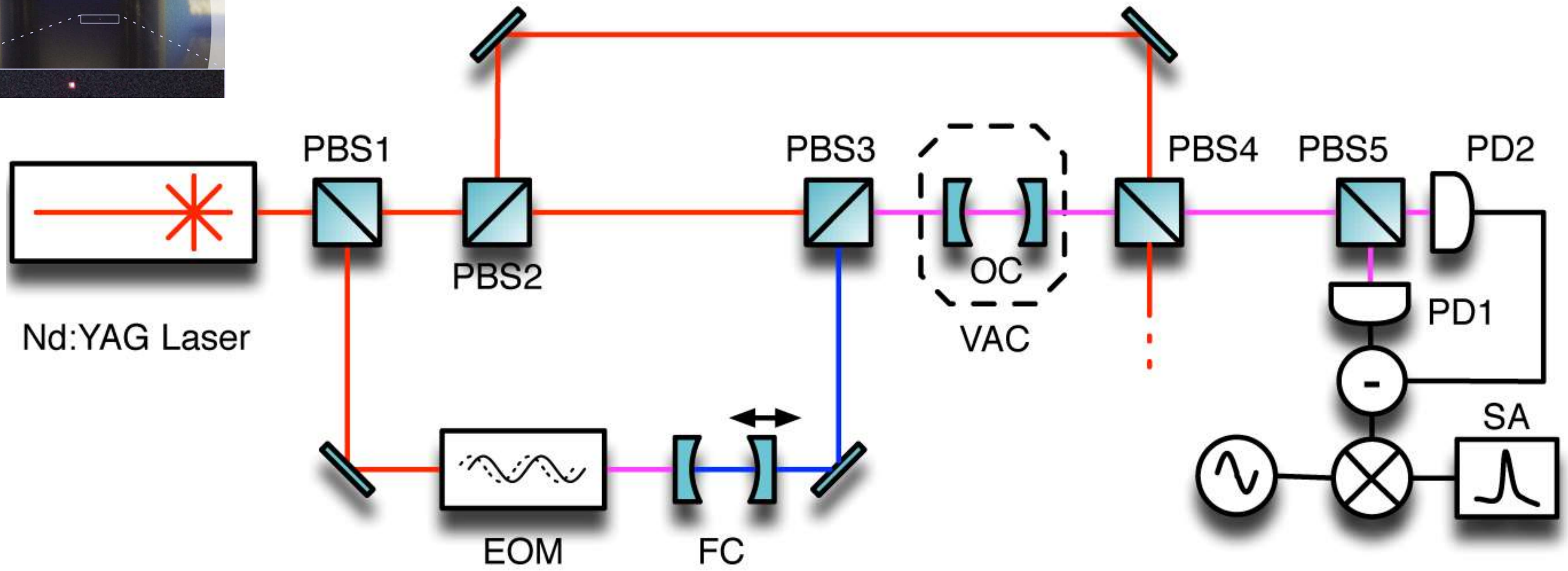




Cavity cooling of levitating mesoscopic particle proposed since
Horak et al. PRL 79, 4974 (1997),
Vuletic et al PRL 84,3787 (2000)

Our Experimental Setup





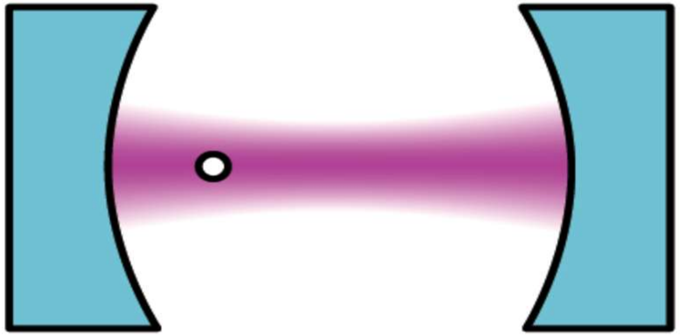
trap

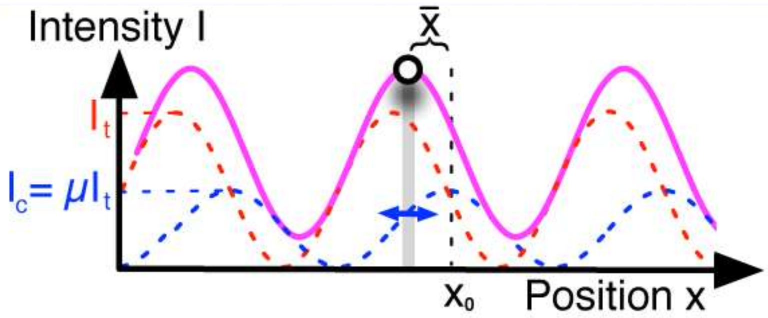
ω_c

$\omega_c + \Delta$

$+FSR$

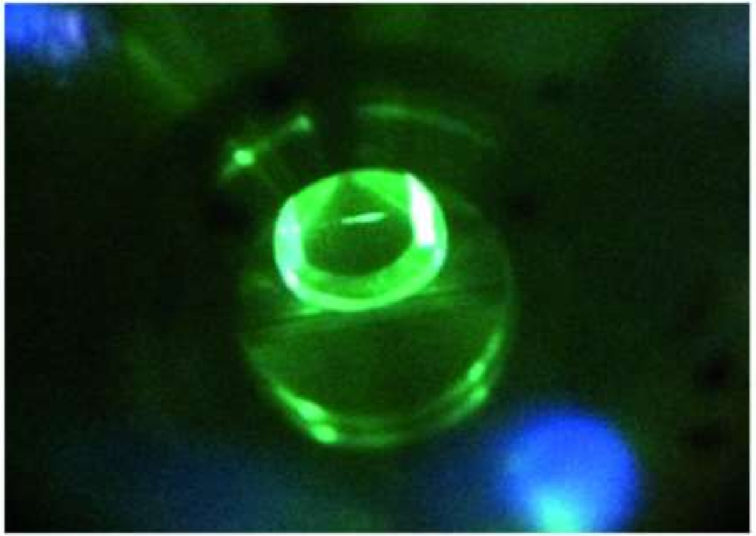
cooling



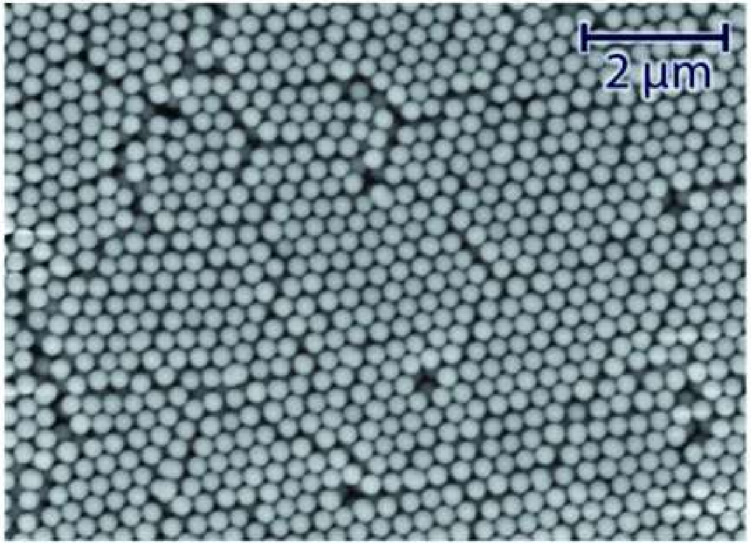


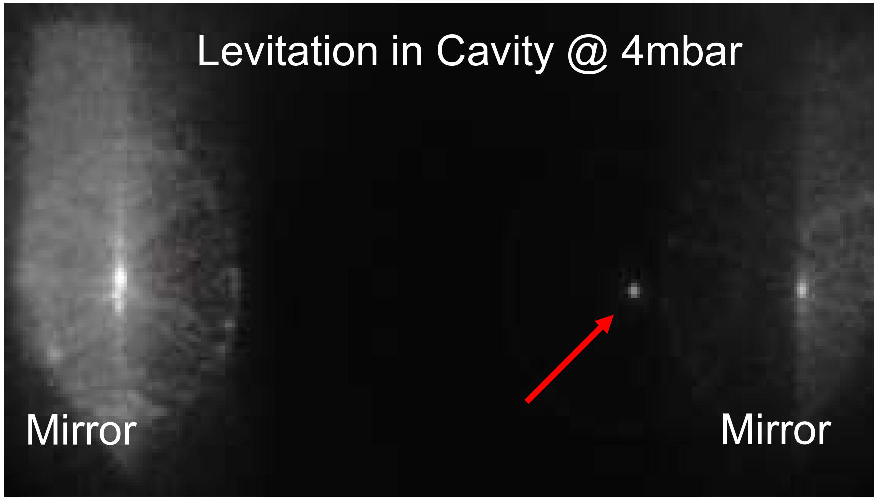
Kiesel, Blaser, Delic, Grass, Kaltenbaek,
Aspelmeyer, PNAS 110, 14180 (2013)

Experimental Setup II



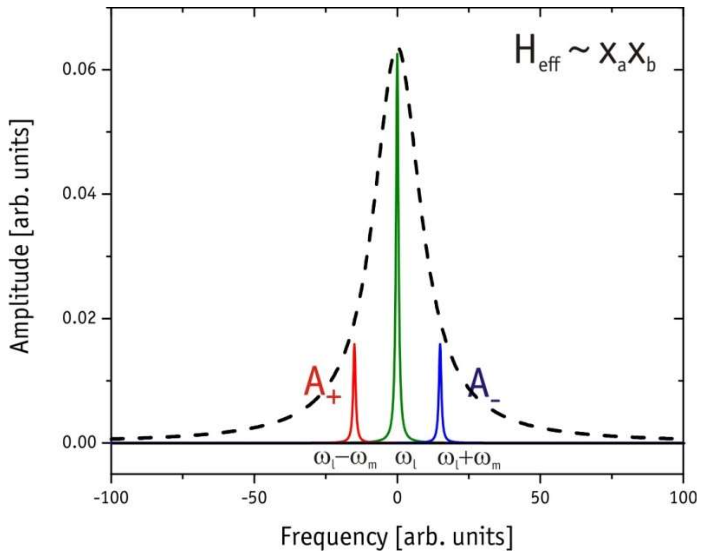
Silica : r=127 nm +/- 10%



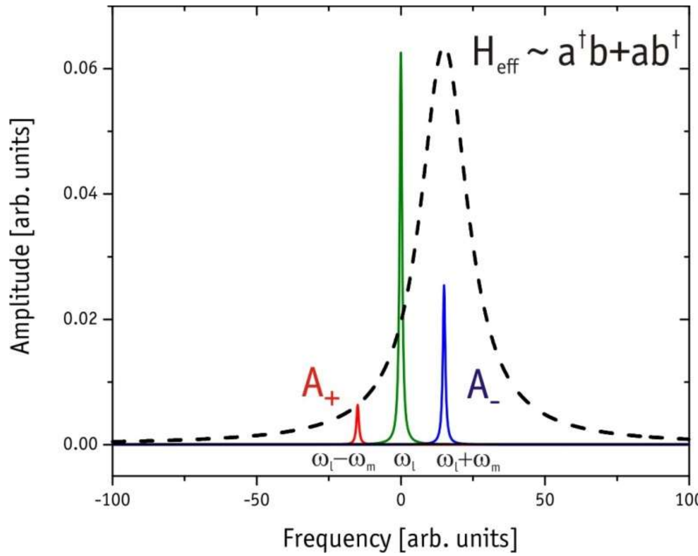


Particle Source: Nebulizer

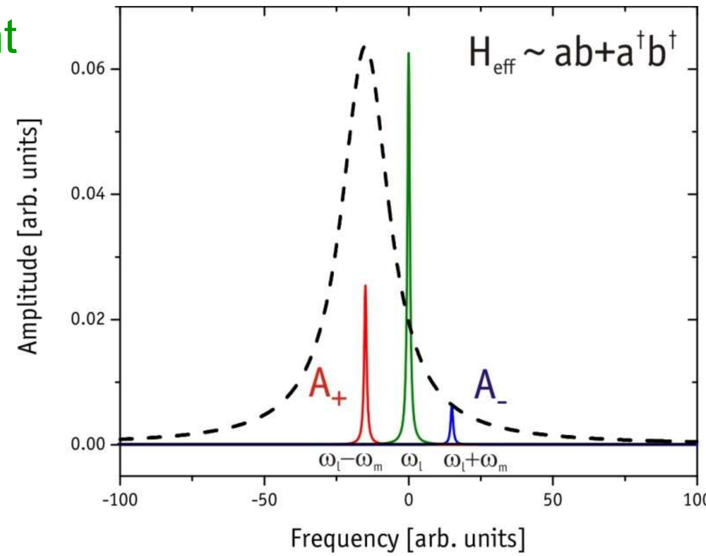
Choose your interaction



QND Measurement



Beamsplitter Interaction

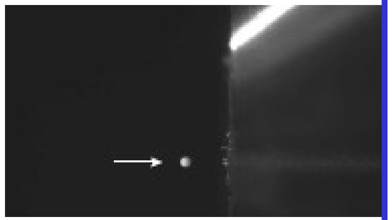


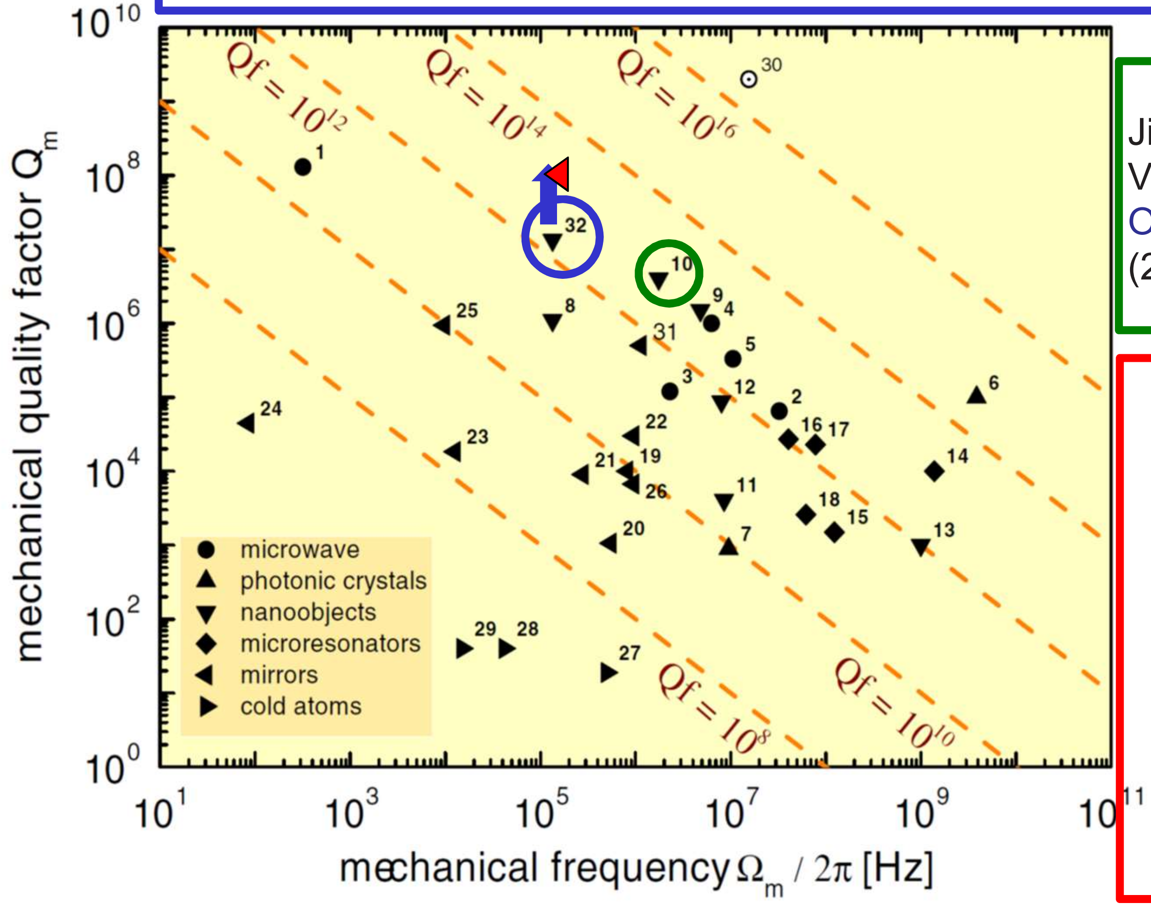
Squeezing Interaction

High Q / Qf

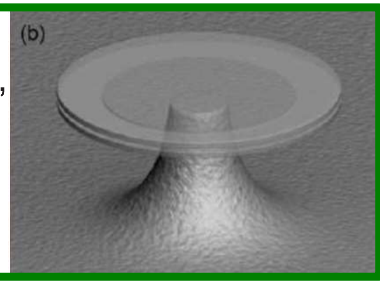
Subkelvin Parametric Feedback Cooling of a Laser-Trapped Nanoparticle
Gieseler et al. Phys. Rev. Lett. 109, 103603.

Direct Measurement of Photon Recoil
Vijay Jain et al.
PRL 116, 243601 (2016)

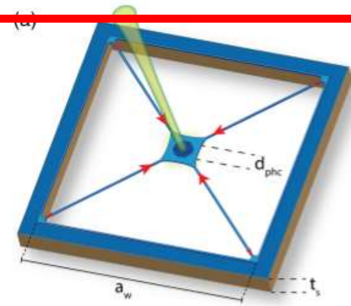




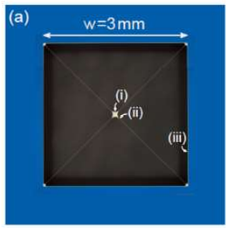
Jiang, Lin, Rosenberg, Vahala, Painter,,
Opt. Exp. 17, 20 911. (2009)



Norte, Moura, Gröblacher, PRL 116, 147202 (2016)



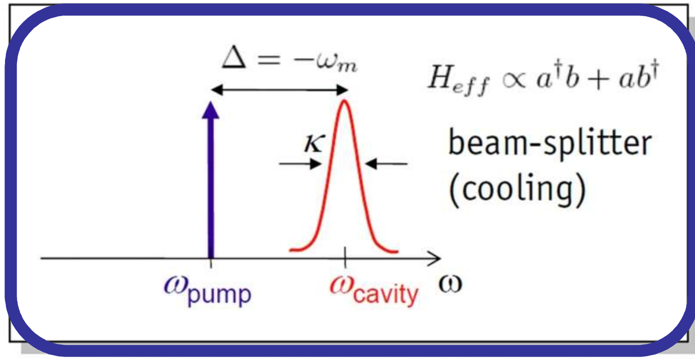
Reinhardt, Müller, Bourassa, Sankey
Phys. Rev. X 6, 021001

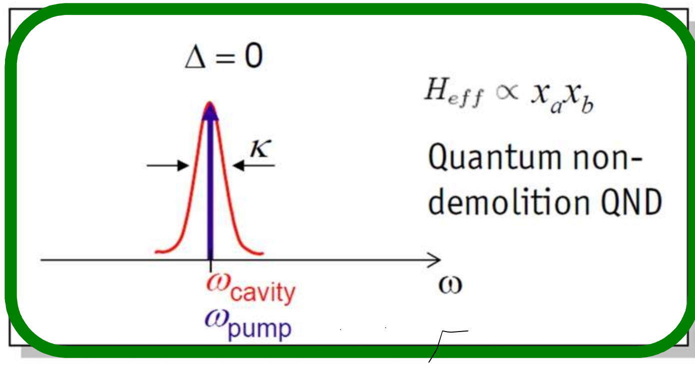


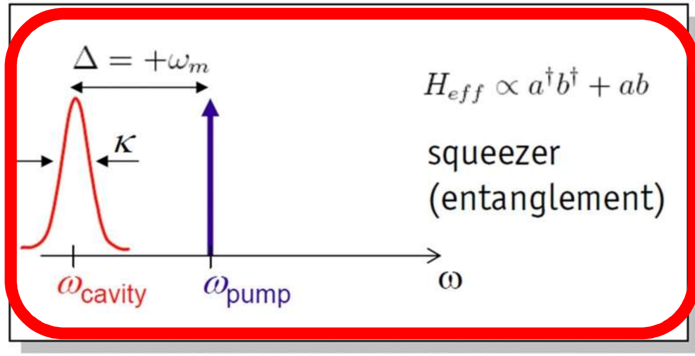
Aspelmeyer, Kippenberg, Marquardt, Rev. Mod. Phys. 86, (2014)

Quantum Optomechanics

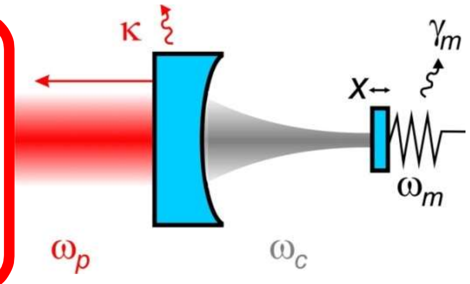
Ideal case:
resolved sideband regime, RWA







full **quantum optics toolbox**
to prepare and control
states
states



Teufel et al., Nature 2011
*Chan et al., Nature 2011**

Gröblacher et al., Nature 2009
Teufel et al., Nature 2011
Verhagen et al., Nature 2012

es:
echanical states
(e.g. ground state)
+
Strong cooperativity
g: OM coupling
decay
damping
on number

Brooks et al., Nature 2012
*Safavi-Naeini et al., Nature 2013**
Purdy et al., PRX 2013

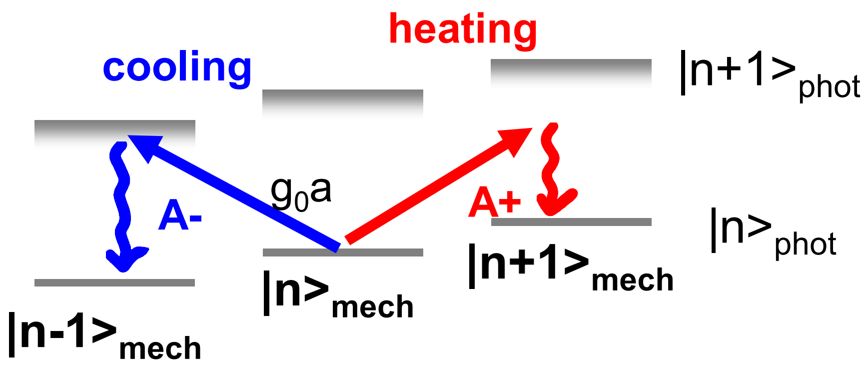
Palomaki et al., Science 2013
Riedinger et al., Nature 2016

013808 (2003)

Aspelmeyer, Kippenberg, Marquardt, RMP **86**, 1391 (2014)

Optomechanical Sideband Cooling

Analogue: sideband-resolved cooling of ions



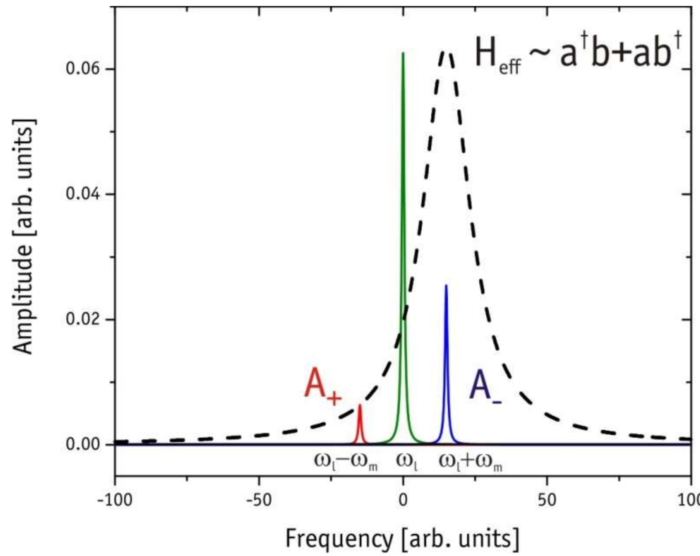
F. Marquardt et al. PPRL 99, 093902 (2007)
I. Wilson-Rae et al., PRL 99, 093901 (2007)
C. Genes et al., PRA 77, 033804 (2008)

Cooling rate $\Gamma = A_- - A_+ \approx \frac{(g_0\alpha)^2}{\kappa}$

Thermal coupling / decoherence) rate $\Gamma_{thermal} = \frac{k_B T}{\hbar Q}$

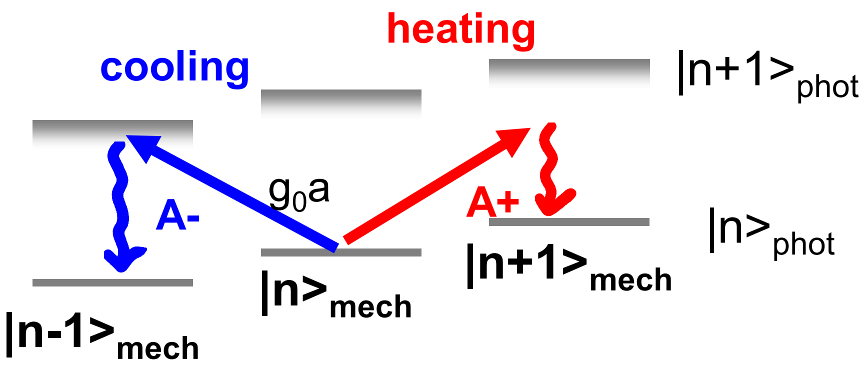
Effective mode occupation $\langle n \rangle_{mech} = \frac{\Gamma_{thermal} + A_+}{\Gamma}$

$\langle n \rangle_{mech}^{min} \approx \left(\frac{\kappa}{4\omega_m}\right)^2$ <<1 for sideband-resolved regime



Optomechanical Sideband Cooling

Analogue: sideband-resolved cooling of ions

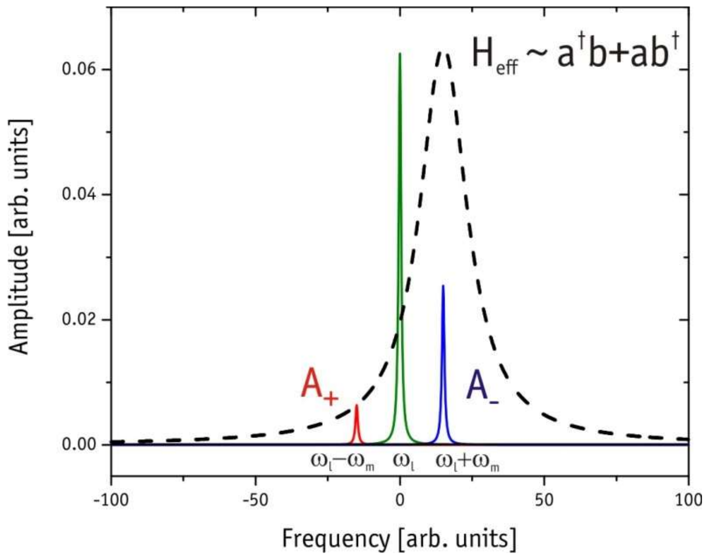


First proof-of-concept via photothermal forces

Karrai (LMU) 2004: Höhberger et al., Nature 432, 1002 (2004)

First demonstrations of Laser-cooling via radiation pressure...

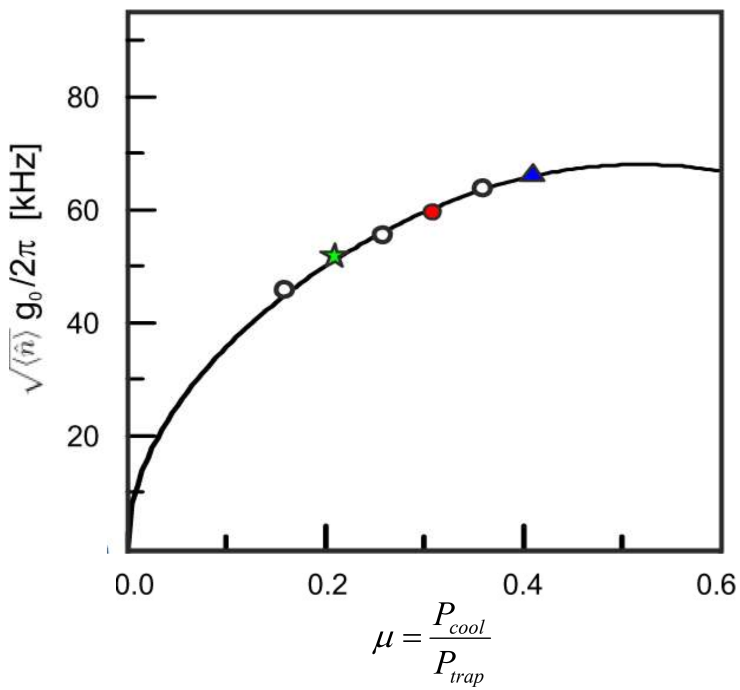
Vienna (Aspelmeyer): S. Gigan et al., Nature 444, 67 (2006)
Paris (Heidmann): O. Arcizet et al., Nature 444, 71 (2006)
Munich (Kippenberg): Schliesser et al, PRL 97, 243905 (2007)
MIT (Mavalvala): Corbitt et al., PRL 98, 150892 (2007)
Yale (Harris): Thompson et al., Nature 452, 72 (2008)



Cooling to approx. 50 K

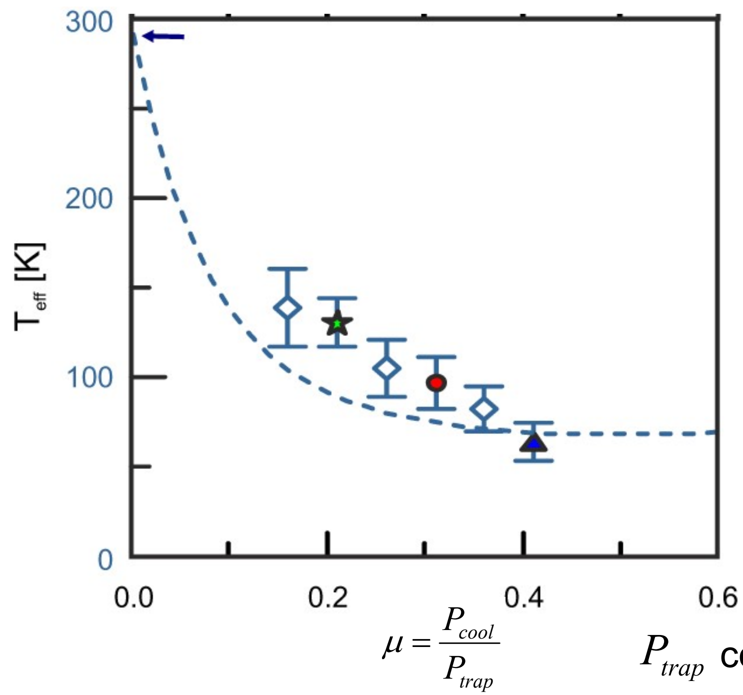
Kiesel, N. et al., *PNAS 110*, 14180 (2013)

Optomechanical Coupling



Cooling rate effectively up to approx. 40 kHz

Optomechanical Cooling



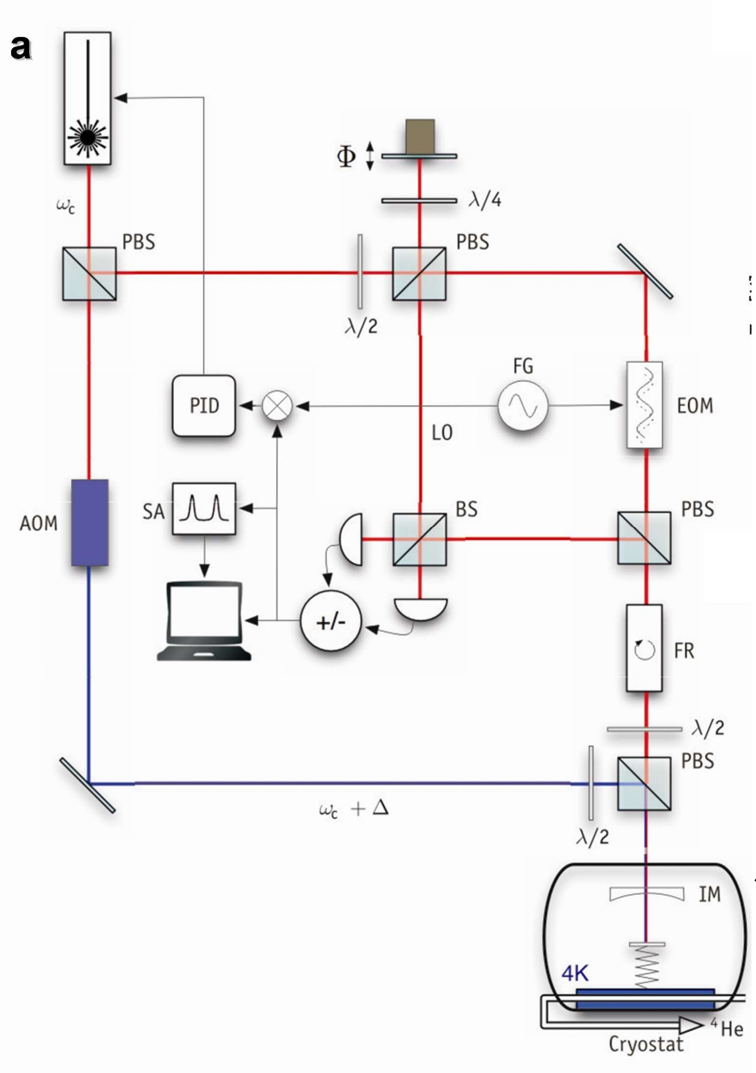
P_{trap} constant

Pressure range for ground state cooling $p<10^{-7}$ mbar

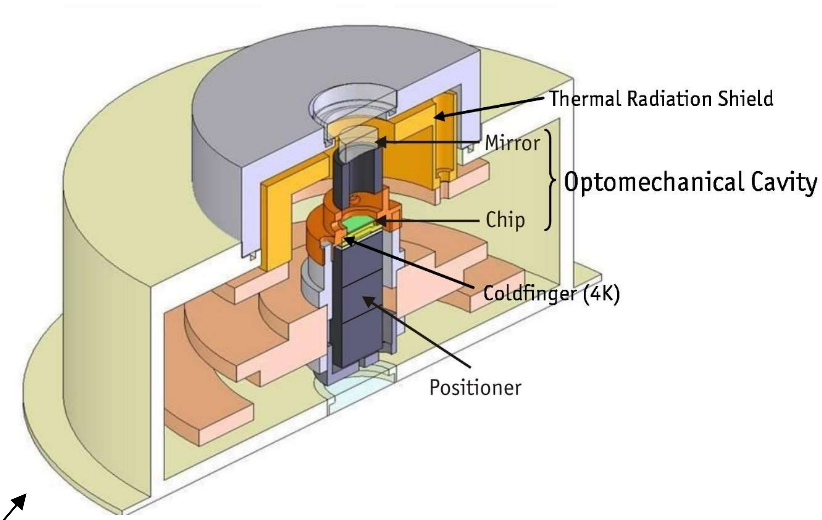
Rates were already comparable typical MHz- Cavity Optomechanics

Pressure Limited – Cooperativity ~ 10^{-7}

Vienna Cooling Experiment



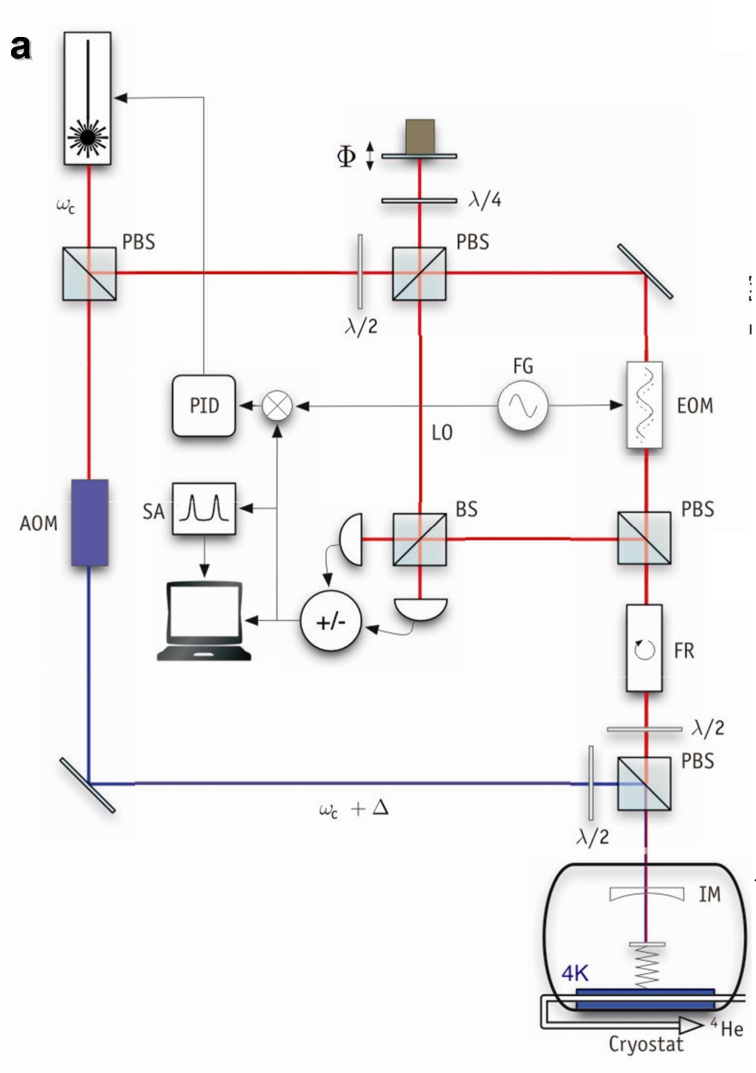
Kryostat holding the cavity with the sample

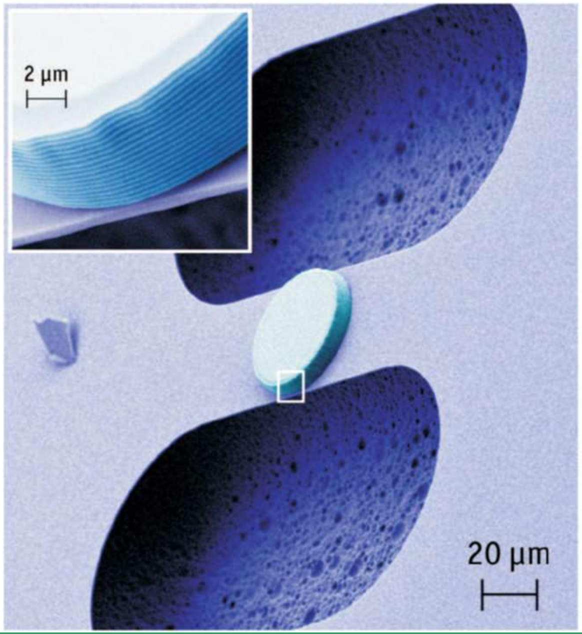


F=3800
κ= 2p × 793 kHz
w_m=2p × 945 kHz

Gröblacher et. al, Nature Physics, 5, 2009

Vienna Cooling Experiment

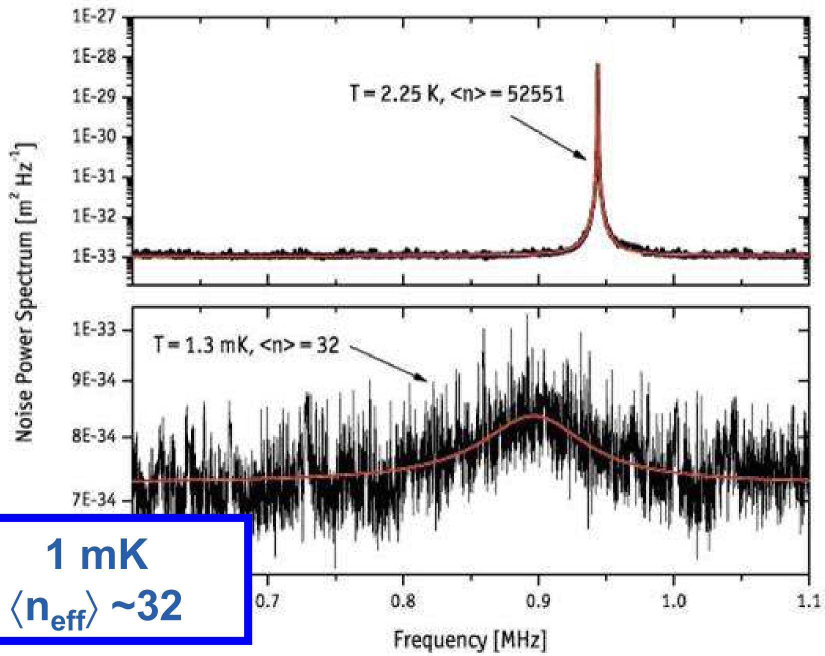




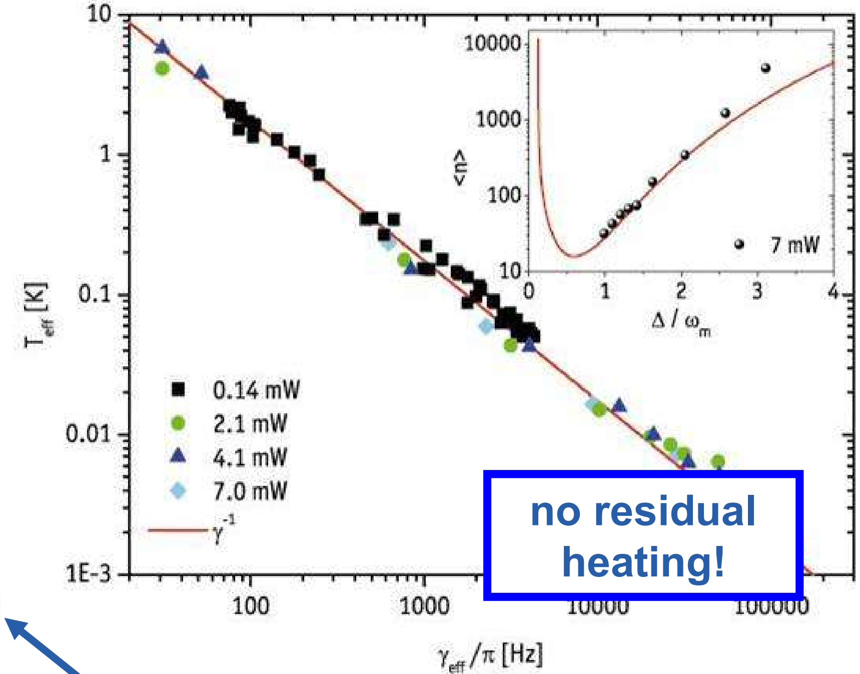
dielectric mirror pad (Ta_2O_5/ SiO_2) on SiN_x
dimensions: 100s x 50 x 6 mm^3
Quality factor: Q=30000 @ 5.3 K
Reflectivity > 0.9999

Gröblacher et. al, Nature Physics, 5, 2009

Ultracold optomechanical systems

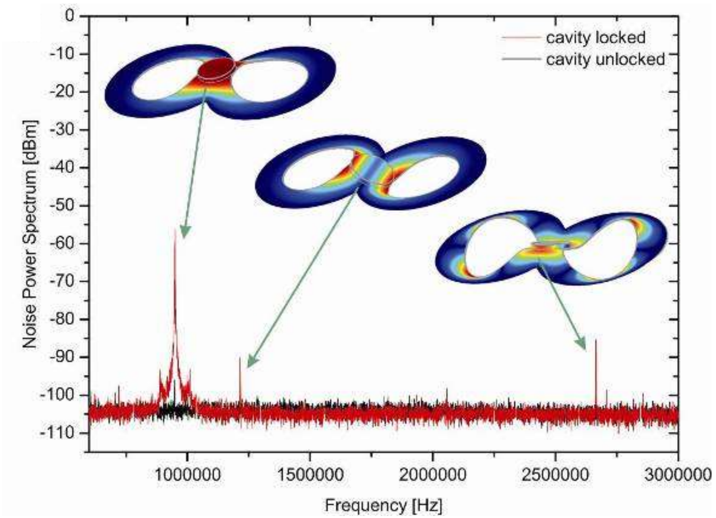


1 mK
⟨n_{eff}⟩ ~32



no residual heating!

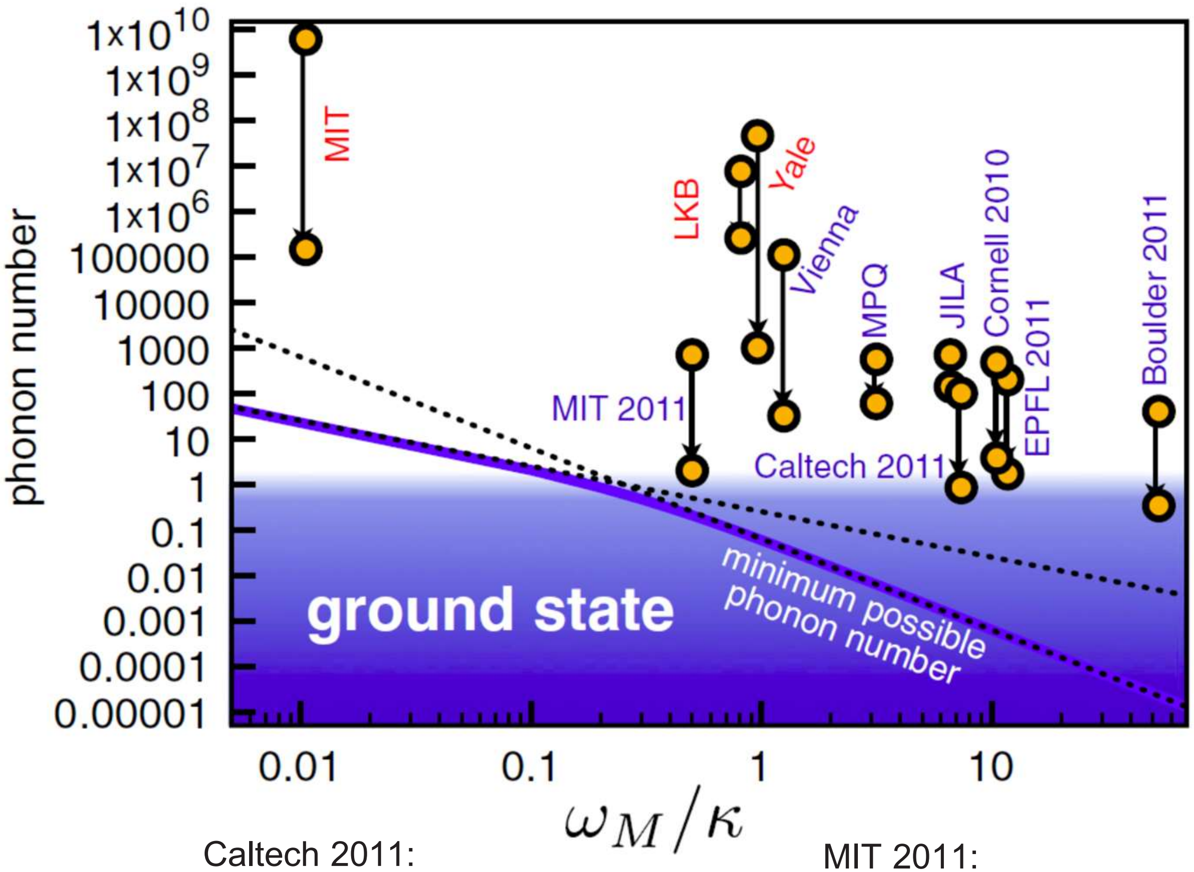
noise floor ~ 2.6×10^{-17} $mHz^{-1/2}$
4x above the shot noise limit



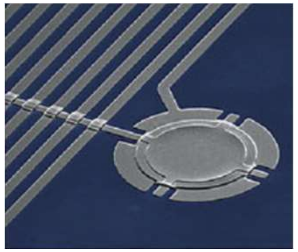
relevant modes identified via FEM

Gröblacher et. al, Nature Physics, 5, 2009

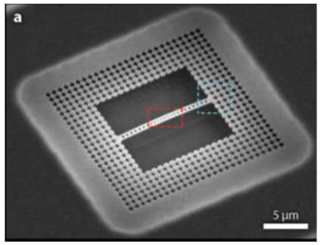
Ground State Cooling achieved



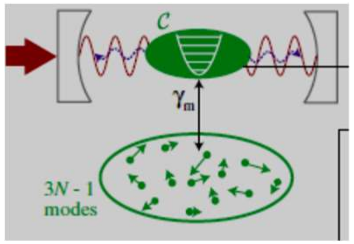
Boulder 2011:
Teufel, Donner et al. Nature 475, 379(2011);



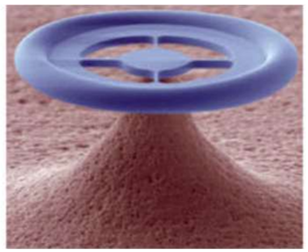
Caltech 2011:
Chan et al., Nature 478, 89, (2011)



MIT 2011:
Schleier-Smith et al., PRL 107, 143005 (2011).

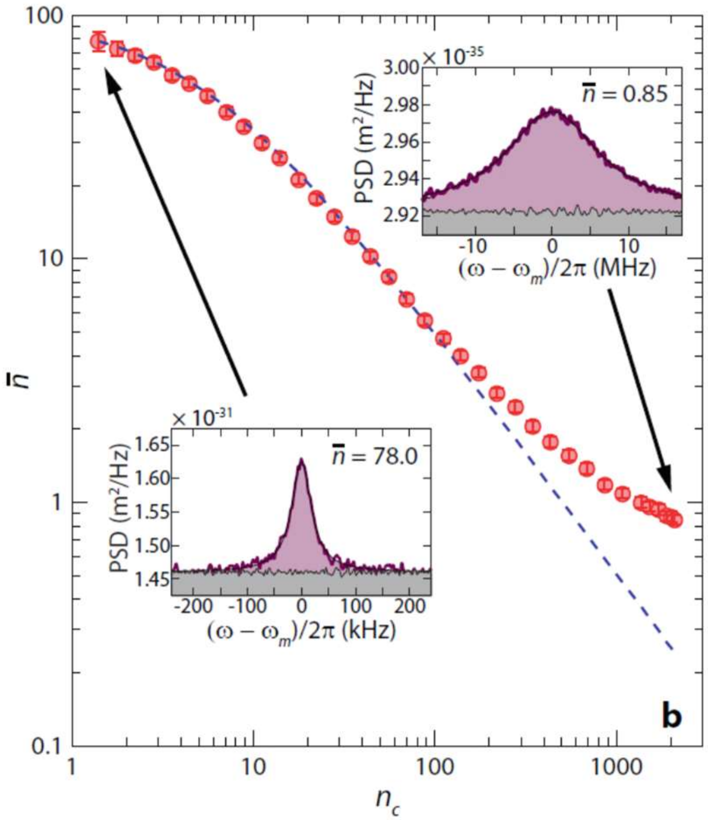


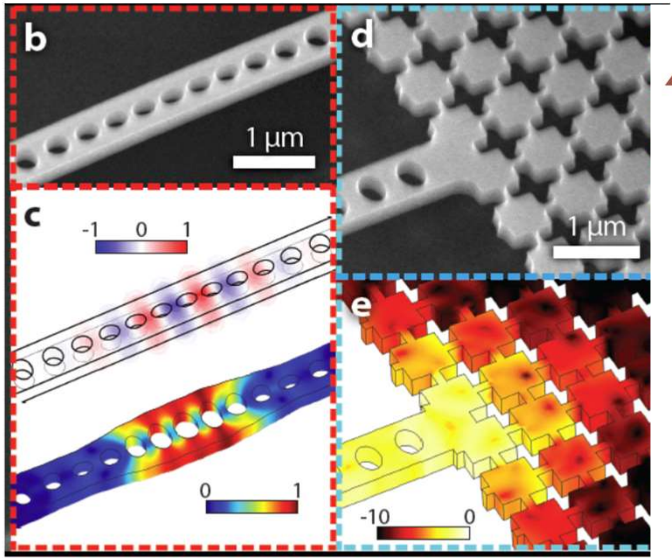
EPFL 2011:
Riviere et al., PRA 83, 063835 (2011)

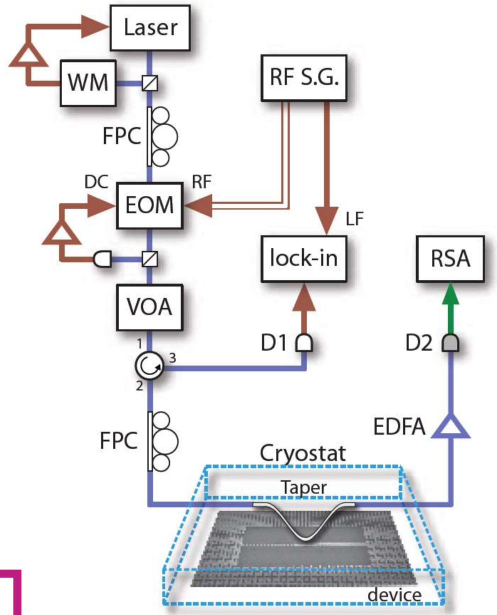


Ground-state laser cooling of a nanomechanical resonator

- **Optomechanical crystal** (photonic & phononic bandgap structure)
  - **3.5 GHz mechanical mode** at 20 K (<n> ~ 100)
    - m ~ O(pg), N ~ O(10^{10} atoms)
    - main limitation: absorption effects







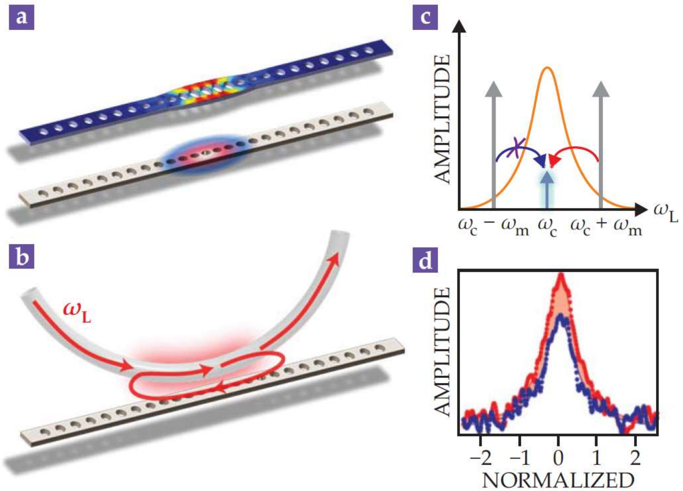
<n> ~ 0.8

Caltech/Vienna May 2011

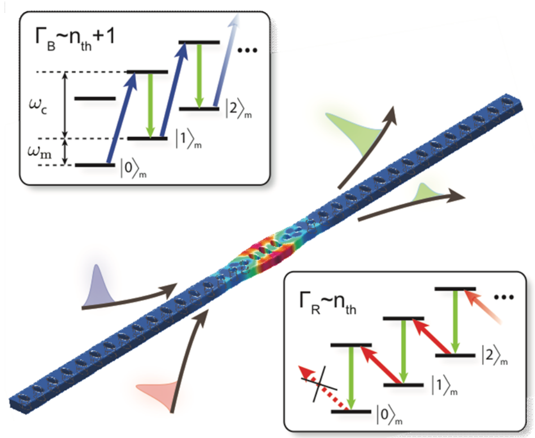
J. Chan, T. P. M. Alegre, A. H. Safavi-Naeini, J. T. Hill,A. Krause, S. Gröblacher, M. Aspelmeyer, O. J. Painter, *Nature, 478, 1* (2011)

Cryogenic Ground State Preparation

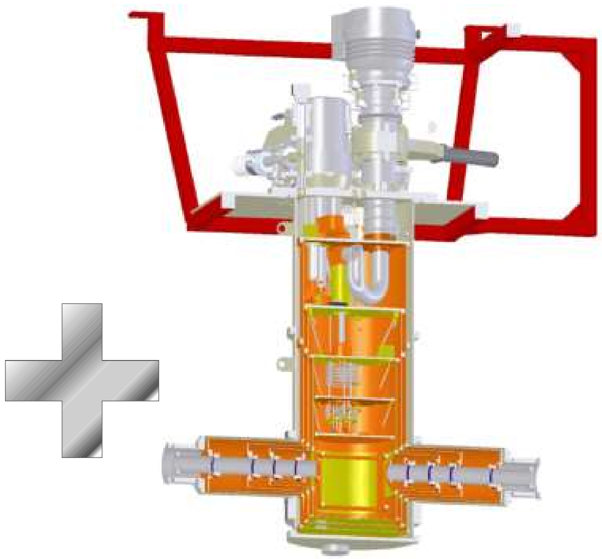
First: Meenehan et al., PHYSICAL REVIEW X 5, 041002 (2015)
Data: R. Riedinger*, Sungkun Hong*, .., M. Aspelmeyer, S. Gröblacher, Nature 530, 313–316 (2016)



$\omega_m/2\pi$ = 5.3 GHz



$\langle n_m \rangle \sim 2 \times 10^{-5}$ @ 25 mK
$\langle n_m \rangle_{exp} \lesssim 2.5 \times 10^{-2}$



T=25mK