The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2445-11

Advanced Workshop on Nanomechanics

9 - 13 September 2013

Cavity Optomechanics with Levitated Nanospheres

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Cavity Optomechanics with Levitated Nanospheres

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David Grass

Rainer Kaltenbaek

Marzieh Bathaee

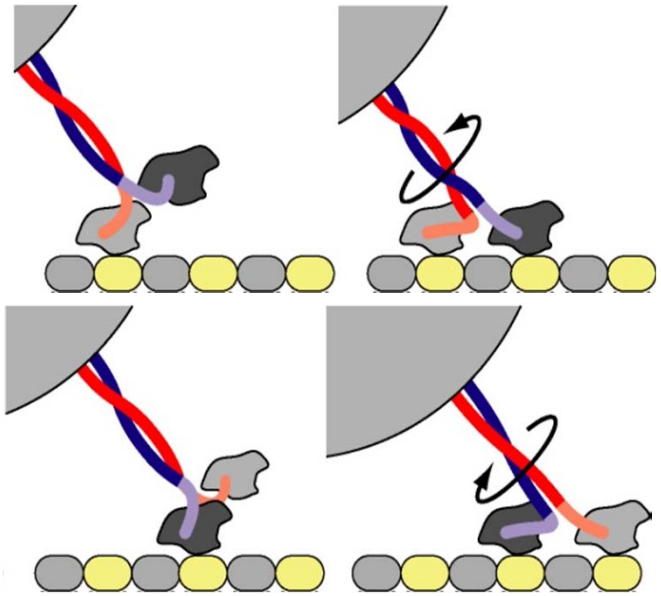
Markus Aspelmeyer

Optical Trapping in liquid
A great level of control

Real-life μ-Tetris was created by Theodoor Pielage, Bram van den Broek and Joost van Mameren. Please send an e-mail to Joost van Mameren for more information.

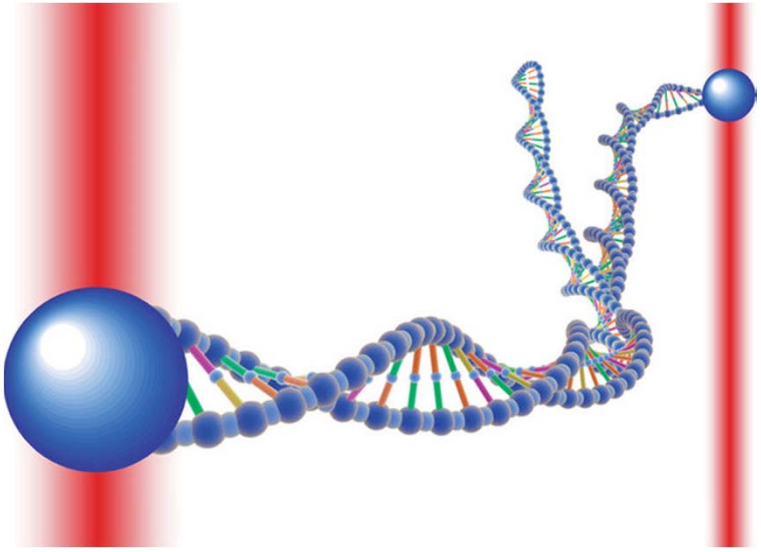
Optical Trapping in liquid
Applications

Kinesin Moves by an Asymmetric Hand-Over-Hand Mechanism
C.L. Asbury, A.N. Fehr, and S.M. Block (2003)
Science *Dec 19 2003: 2130-2134.*
www.stanford.edu/group/blocklab/ScienceLimping/

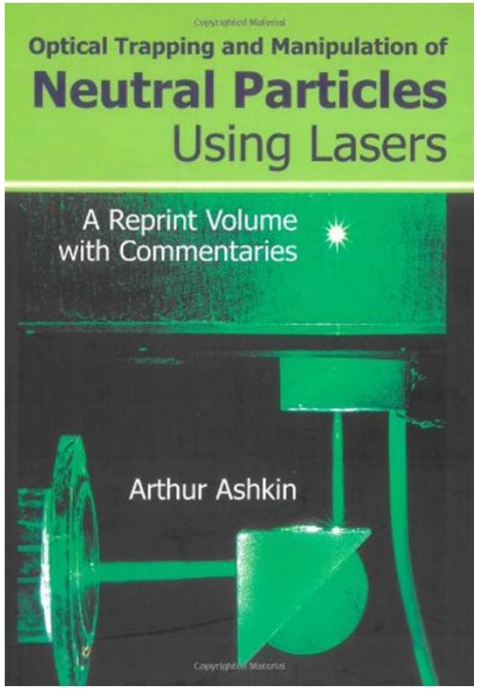


Gupta, A. N. et al.
Nature Phys. 7, 631–634 (2011)

Christopher Jarzynski
Single-molecule experiments: Out of equilibrium
Nature Physics 7, 591 (2011)



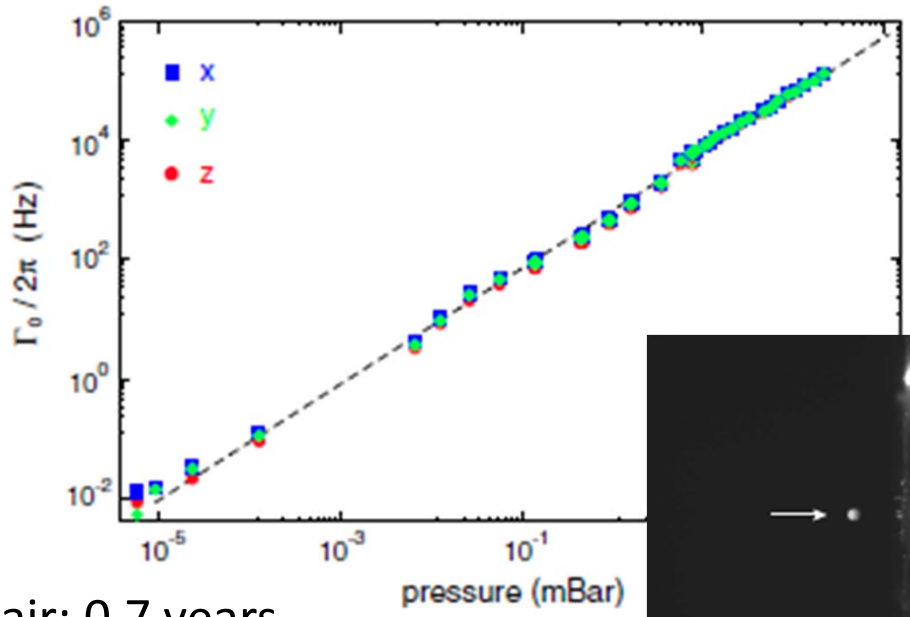
Optical trapping in Vacuum – High Q



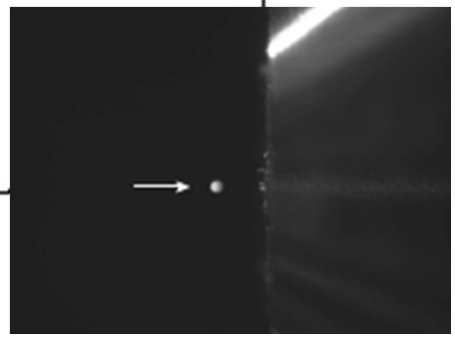
Gieseler, J., et al.
Subkelvin Parametric Feedback Cooling of a Laser-Trapped Nanoparticle.
PRL, 109, 103603 (2012)

Silica nanosphere, 70nm @ 10^{-5} mbar
approx. 100kHz, decay time 100s, Q~10^7

Optical levitation in high vacuum,
A. Ashkin and J. M. Dziedzic
Appl. Phys. Lett. 28, 333 (1976);



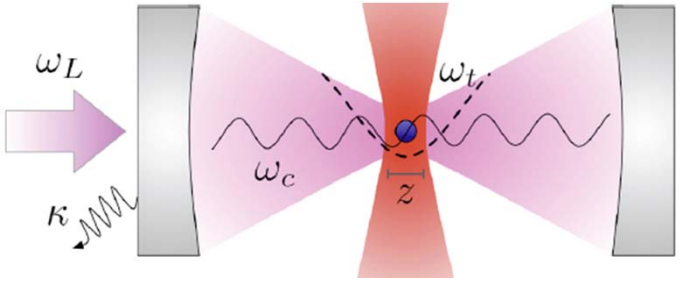
Silica and Silicon Oil drops
Several micrometer @ 10^{-6} mbar:
20 Hz, 4.5h decay time, Q~10^5 , no air: 0.7 years

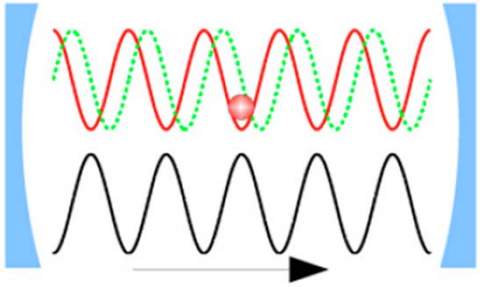


High Q and Big Mass?

Optically levitated nanospheres & 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)





→ **Harmonic oscillator in optical potential**
(no support loss, high Q, excellent force sensitvity)

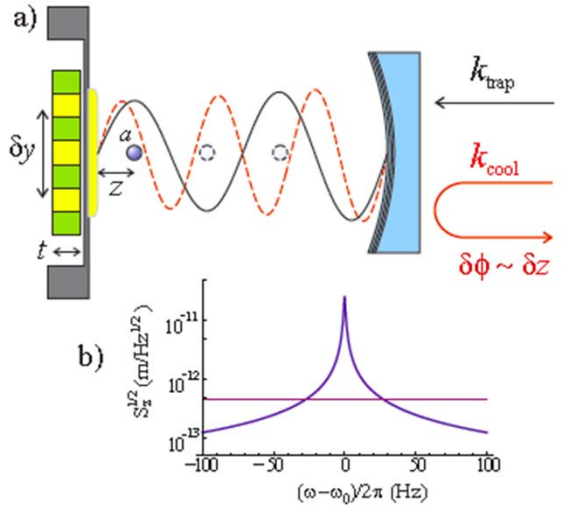
→ **Full Control of mechanical frequency**
(parametric contol, thermodynamic cycles, removing potential)

→ **Quantum control via cavity optomechanics**
(laser cooling, state transfer, etc.)

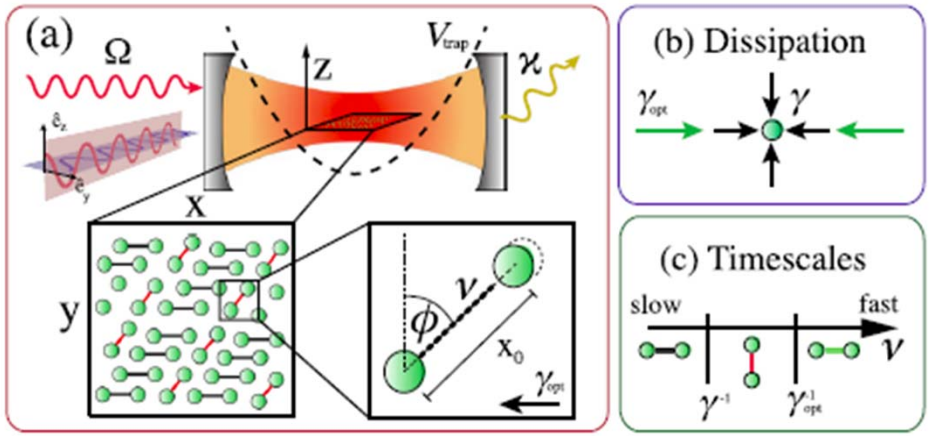
Cavity cooling levitating mesoscopic particle proposed since
Horak et al. PRL 79, 4974 (1997),
Vuletic et al PRL 84,3787 (2000)

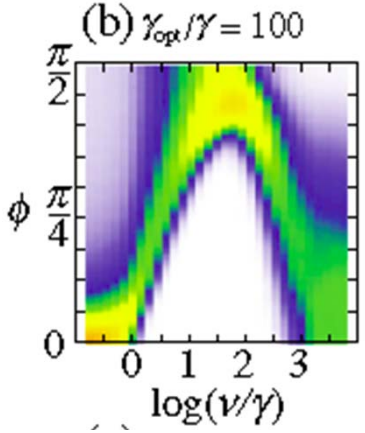
Further Ideas - Examples

Geraci, A., Papp, S., & Kitching, J. (2010).
Short-Range Force Detection Using Optically Cooled Levitated Microspheres.
Phys. Rev. Lett., *105*(10), 101101.



Lechner, W., Habraken, S. J. M., Kiesel, N., Aspelmeyer, M., & Zoller, P. (2013). Cavity **Optomechanics of Levitated Nanodumbbells: Nonequilibrium Phases and Self-Assembly.** Physical Review Letters, 110(14), 143604.

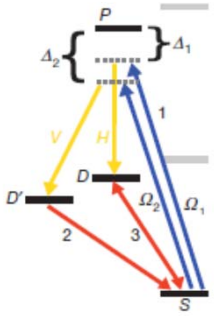


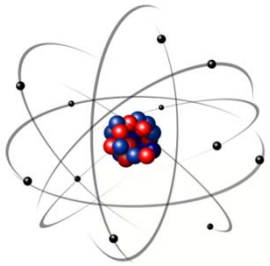


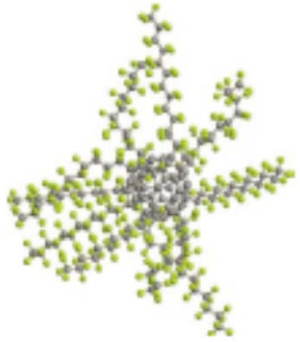
Recent Overview:
Zhang-qi Yin, Andrew A. Geraci and Tongcang Li
Optomechanics of Levitated Dielectric Particles
arXiv: 1308.4503

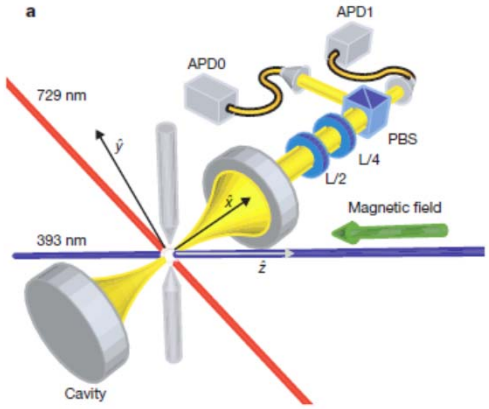
Quantum Optics – Quantum Optomechanics

Number of atoms in entity

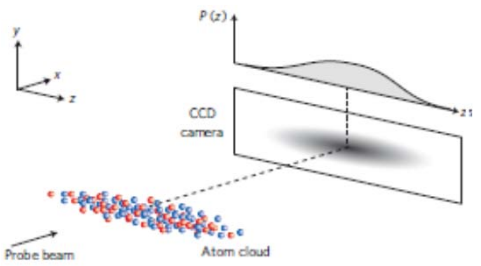


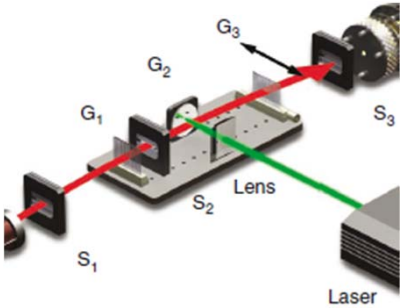


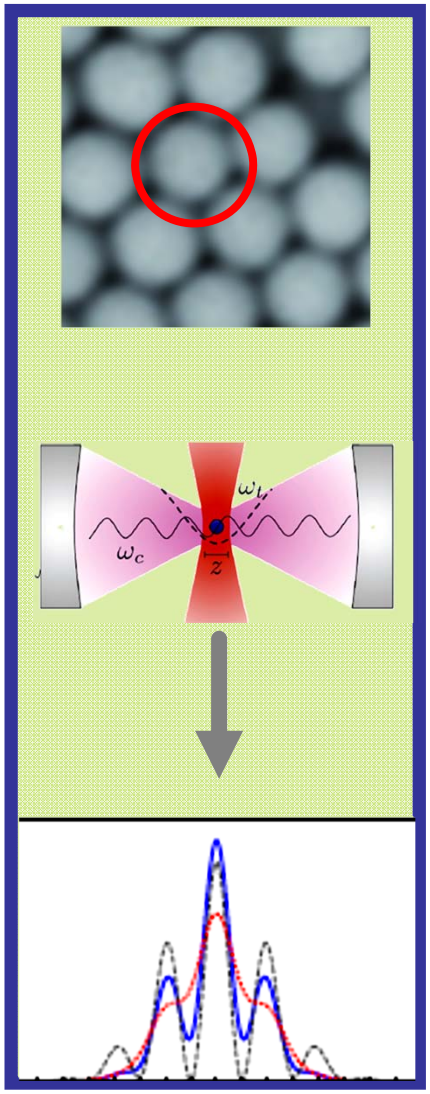


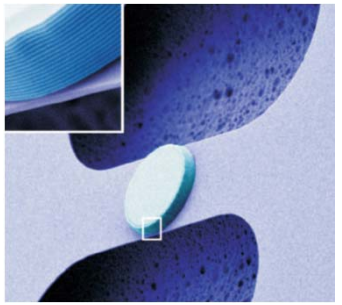


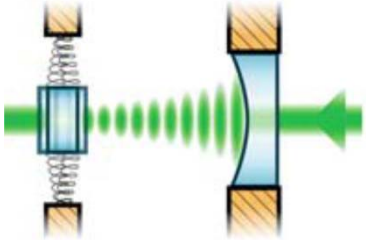
Polarizability





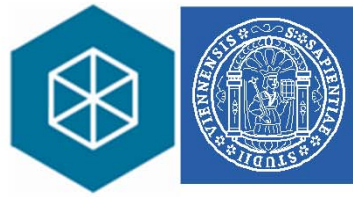






Clamping

Outline



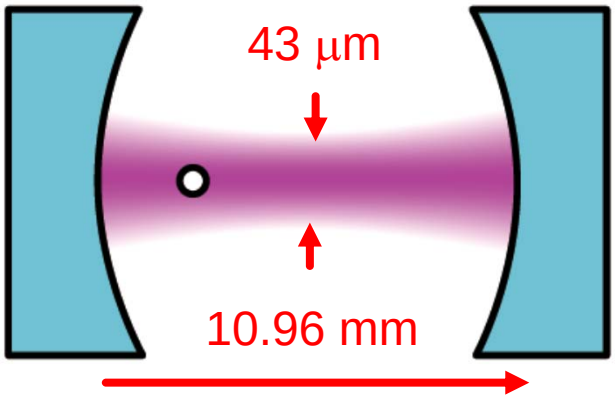
- Intro: Levitating Optomechanics and Related Systems

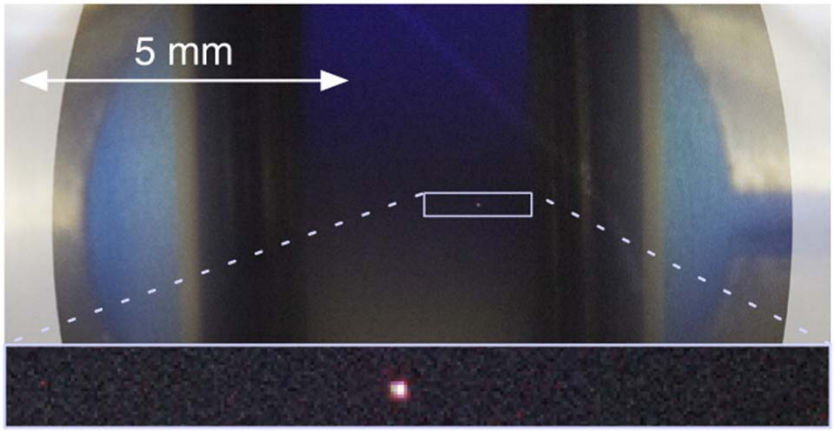
- **Vienna Experiment on Levitating Optomechanics**
  - Scheme and Setup
  - Optomechanical Effects and Cooling

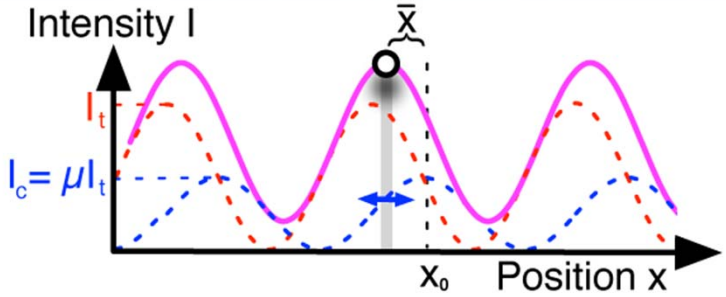
- The Future
  - Next Steps on the Experiments
  - Matter Wave interferometry with huge objects
    * Excursion: Pulsed Optomechanics

Our Experiment

Nearly confocal cavity







Cavity Linewidth

k = 180 kHz

Free Spectral Range

FSR = 13.667 GHz

Finesse

F = 78000

2nd field shifted by FSR for coupling

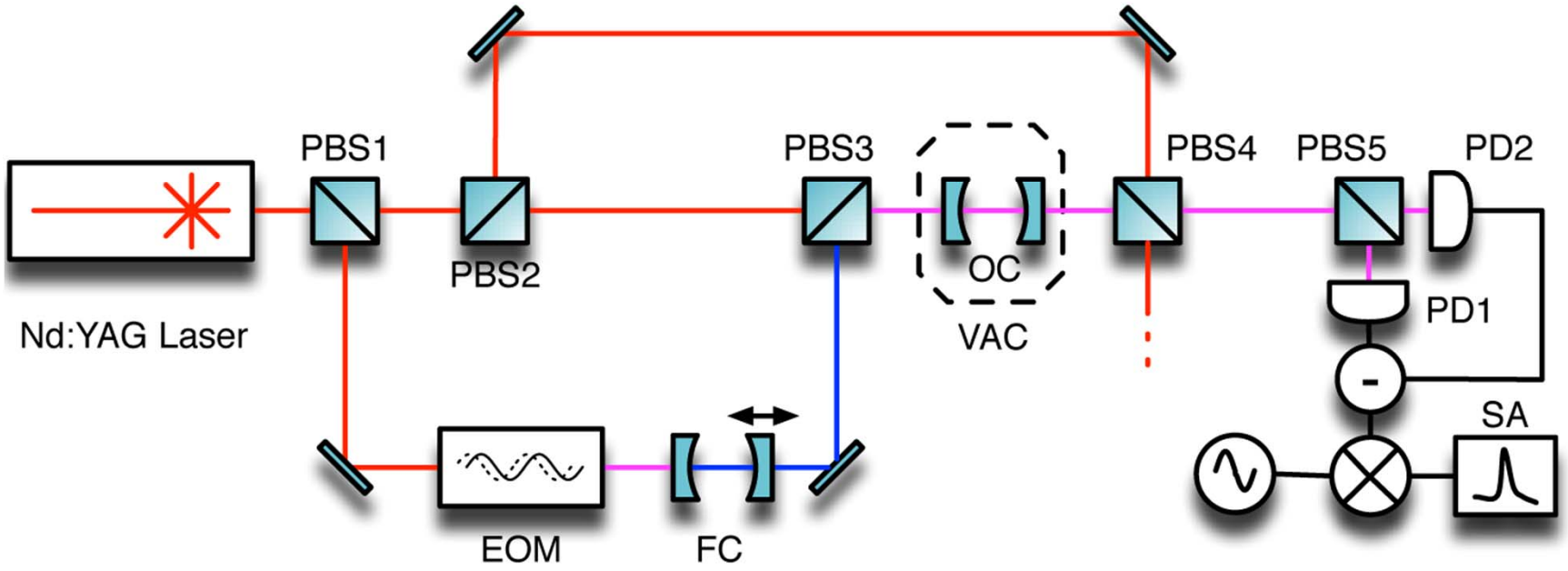
$$\frac{\partial \omega_c}{\partial x} \propto \frac{\partial I_c}{\partial x}$$

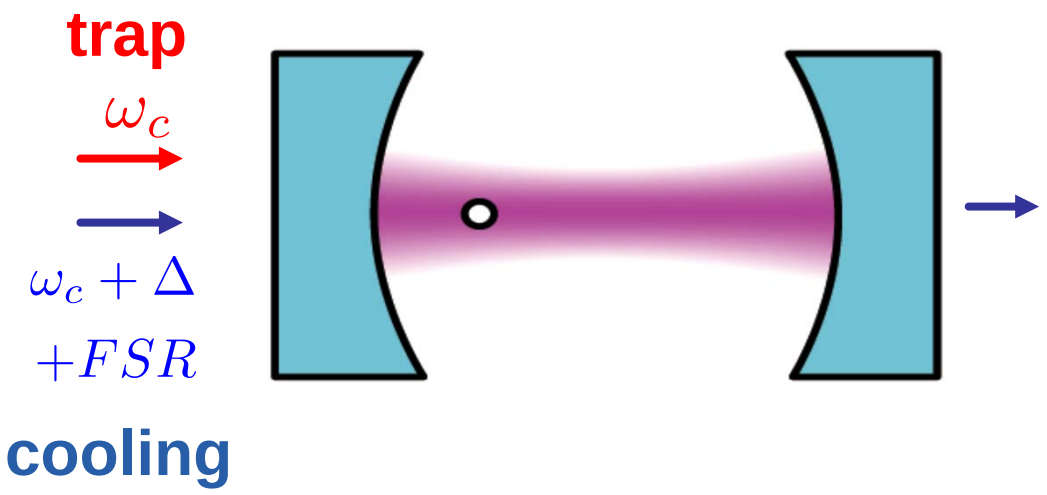
Power and Position dependence:
Control Beam part of optical trap

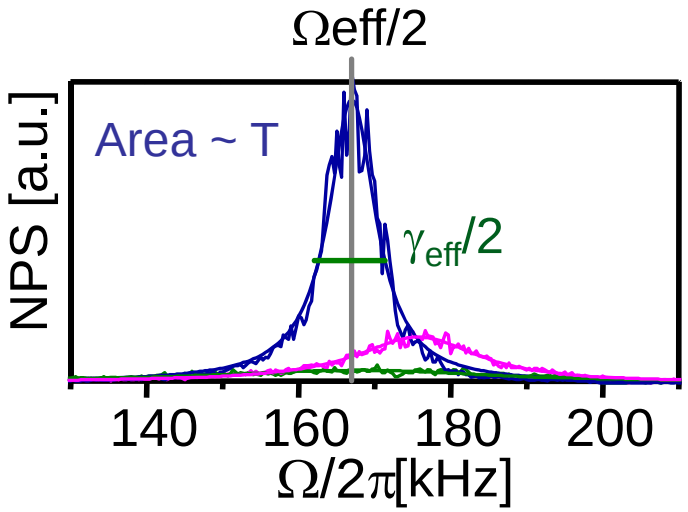
$\mu = I_{cool}/I_{trap} = P_{cool}/P_{trap}$

μ >.1 theory, Pender et al., PRA 85, 021802 (2012)

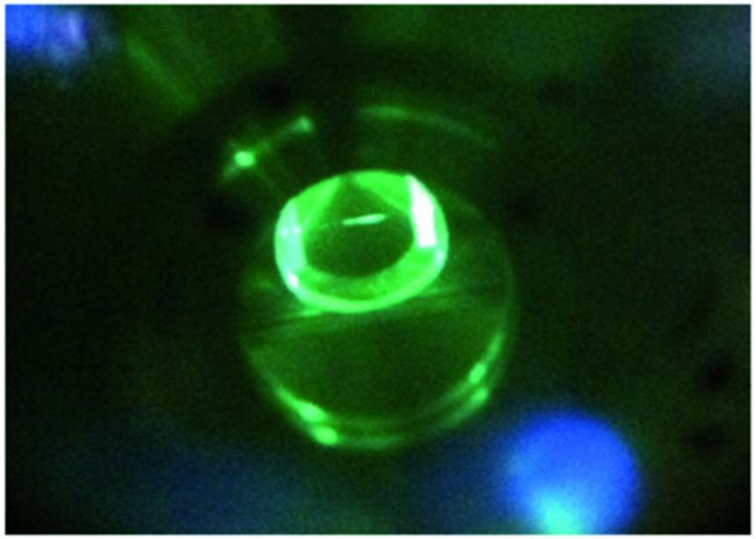
Experimental Setup



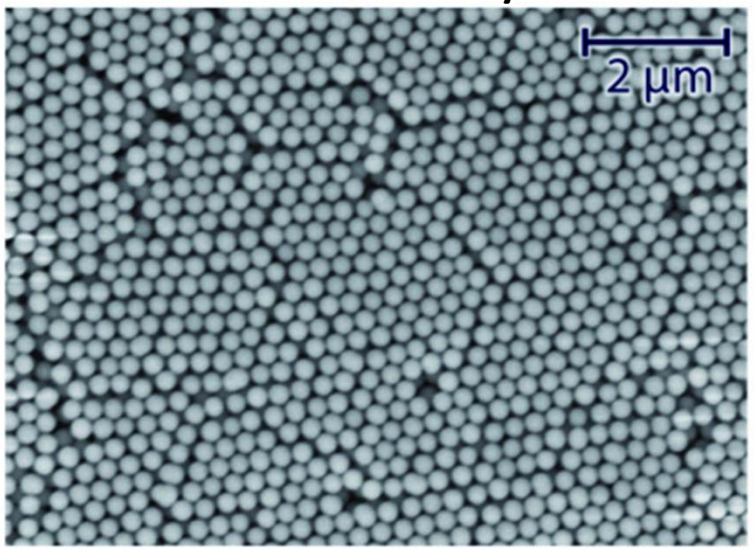




Experimental Setup II



Silica : r=127 nm +/- 10%



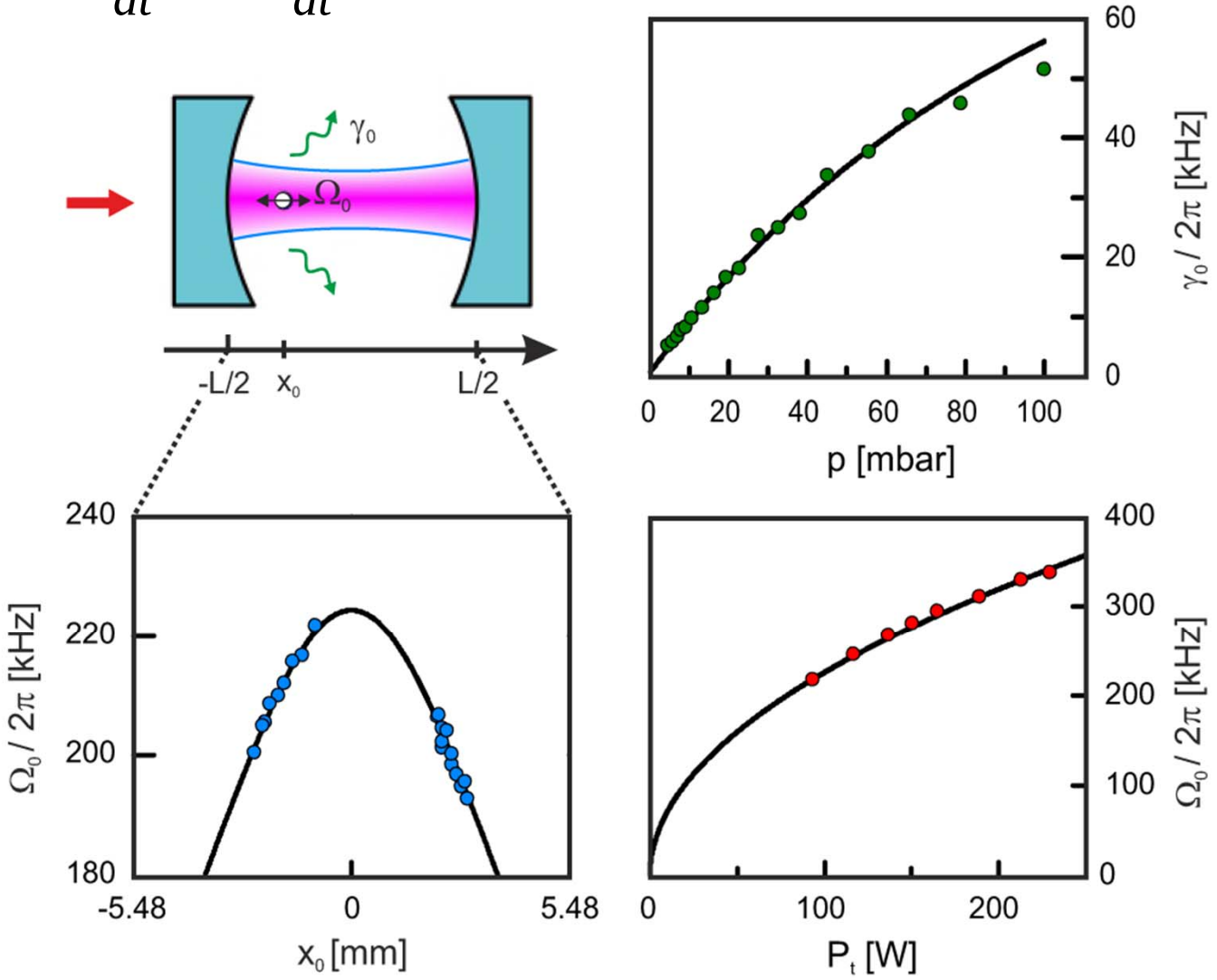
Particle Source: Nebulizer

Characterizing the optical trap

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

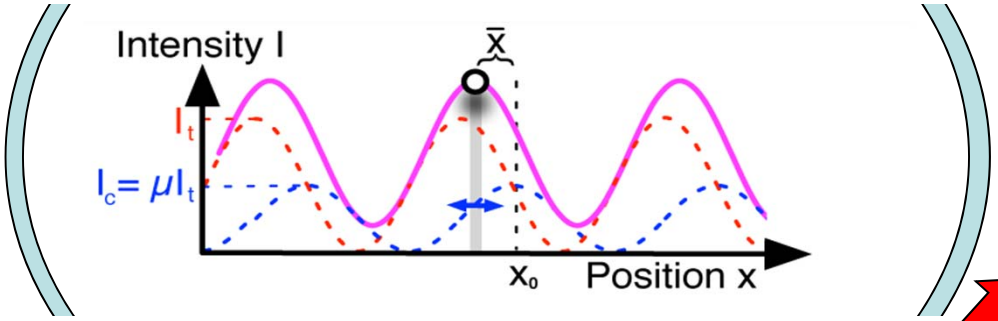
Mechanical
Trap Frequency

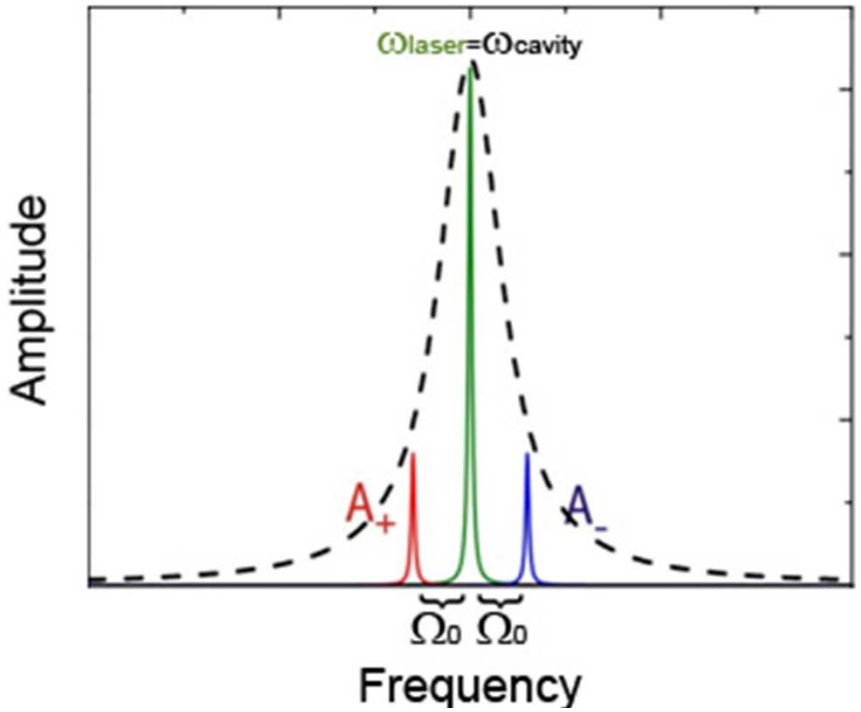
$$\Omega_0 \propto \sqrt{\frac{Power}{Waist(x)^2}}$$

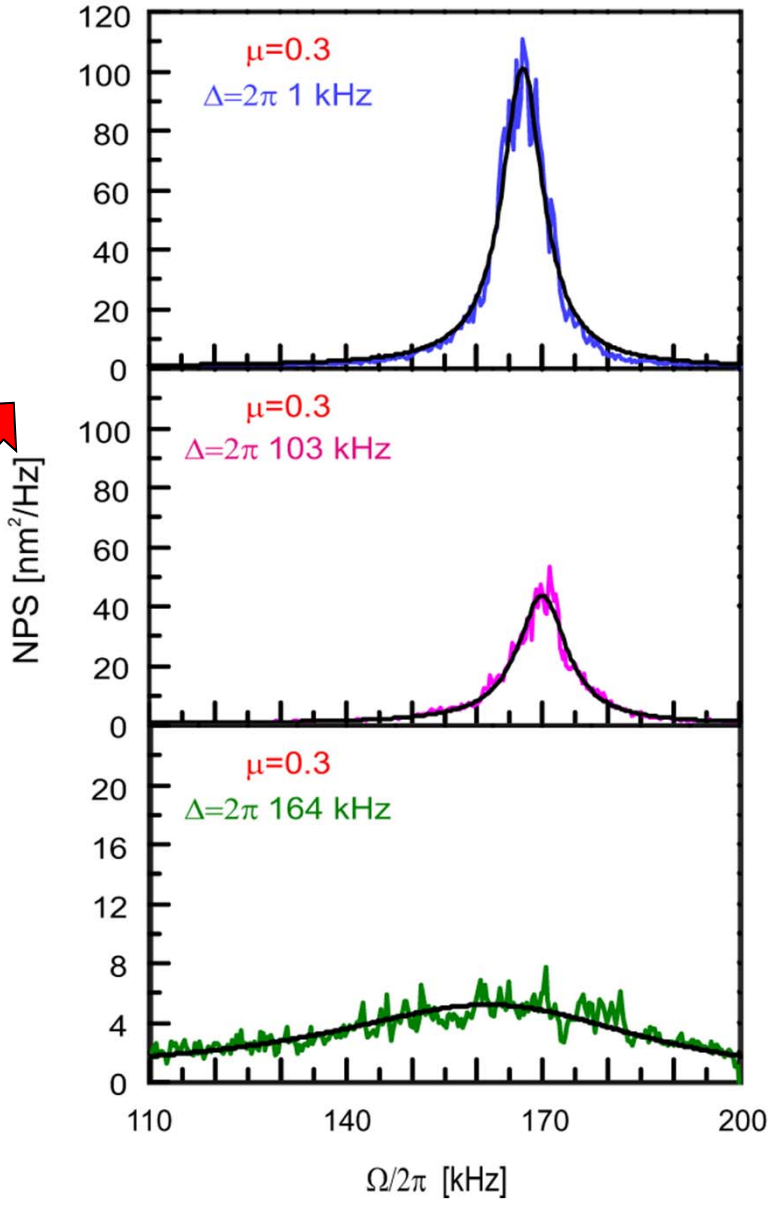


Cavity Optomechanics

$$g_0 = \frac{\partial \omega}{\partial x}\sqrt{\frac{\hbar}{m\Omega_0}}$$







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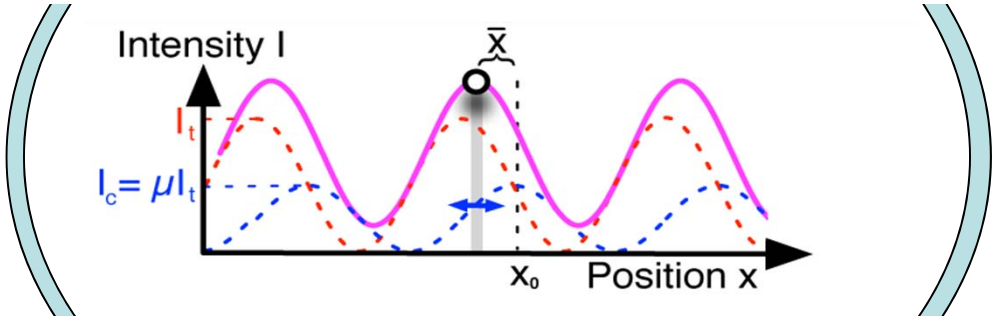
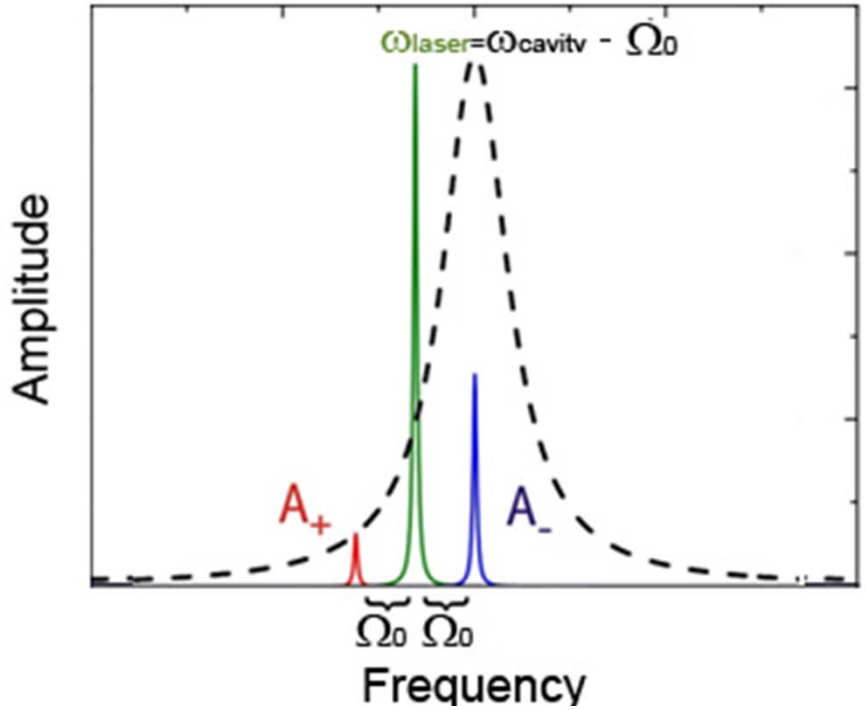
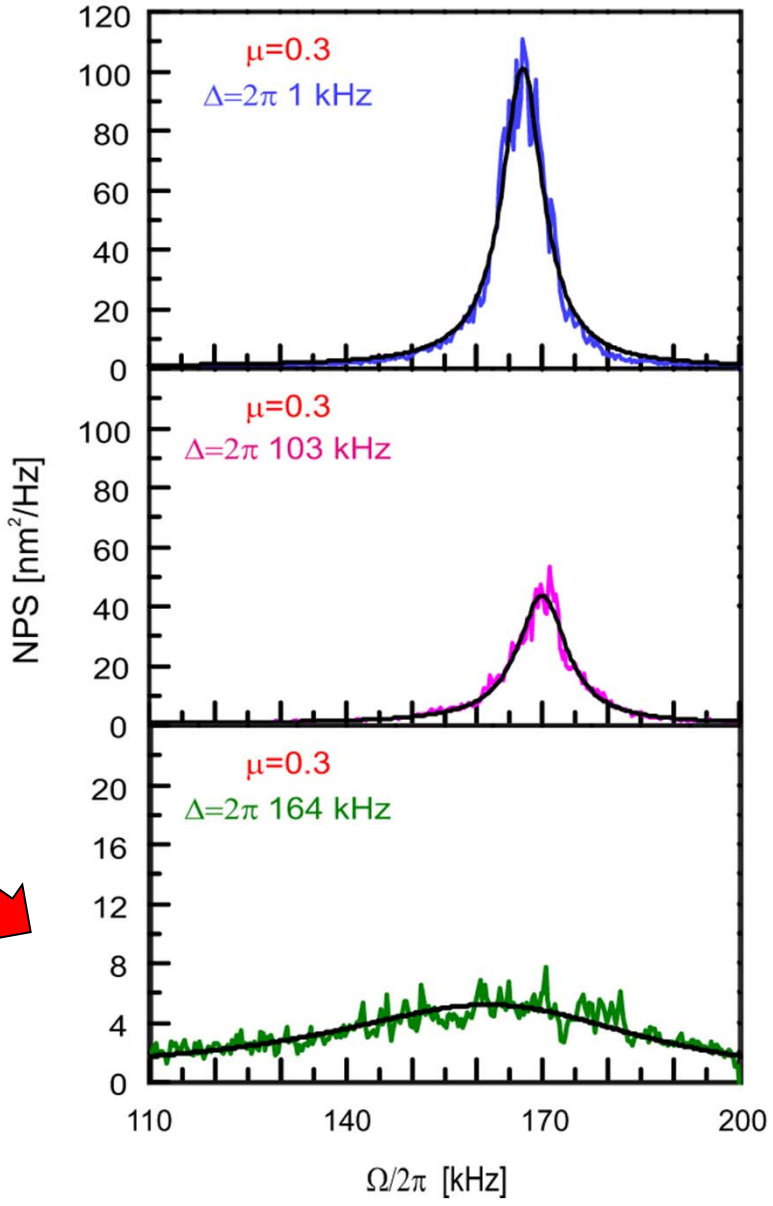






Cavity Optomechanics

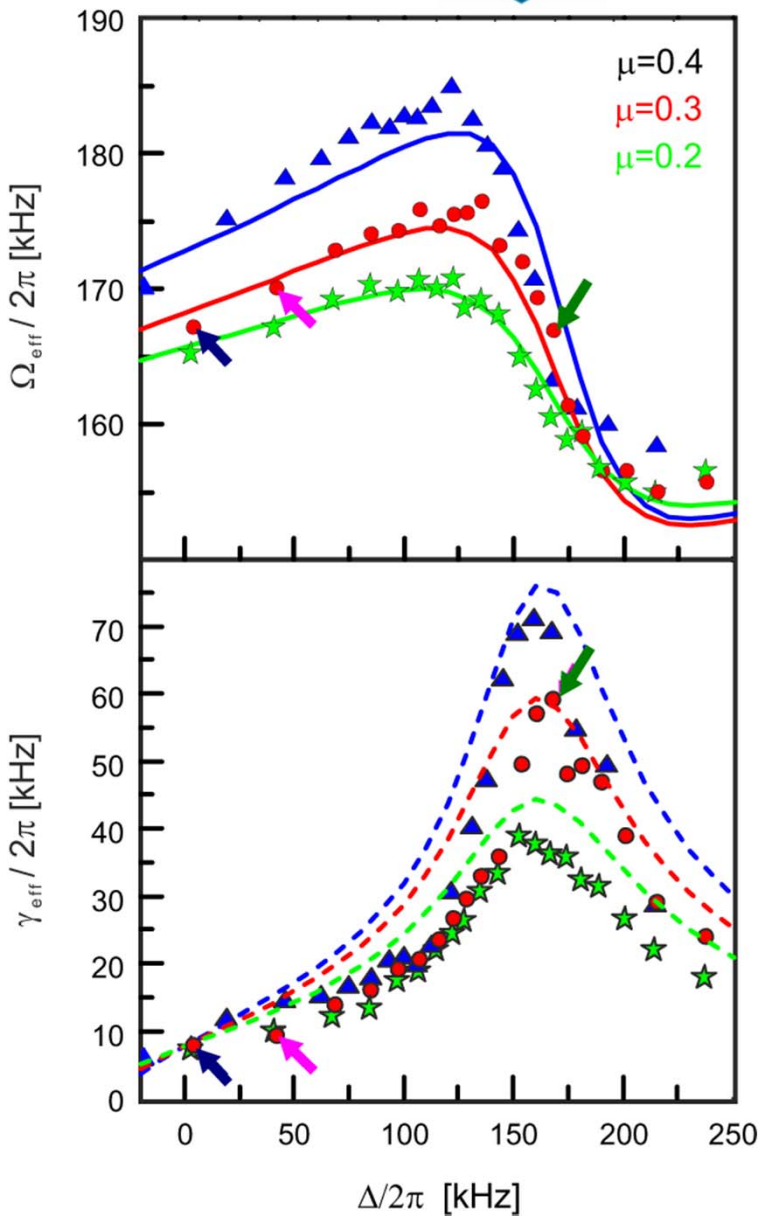
Radiation pressure induced:

- modification of frequency

Optical spring

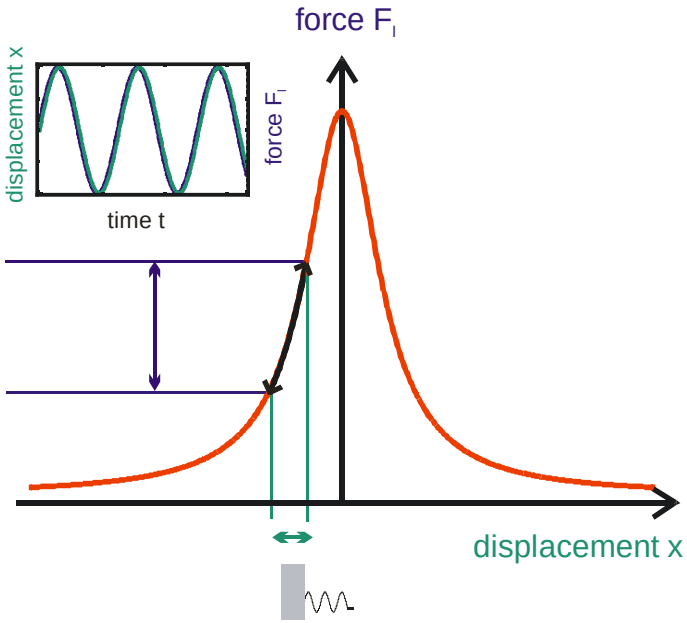
- modification of damping

Optical damping



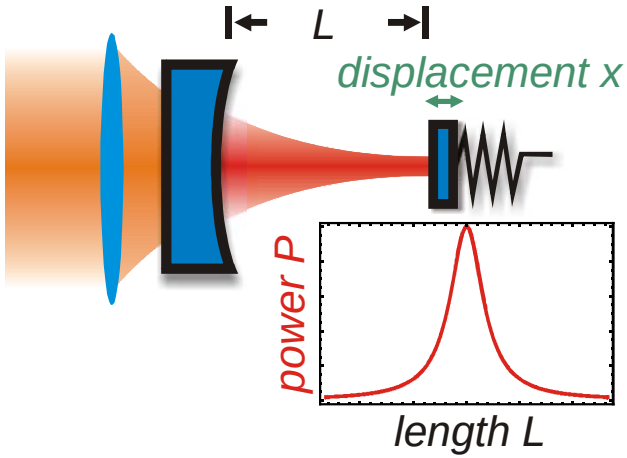
Theoretical dependencies:
Genes et al., *Phys. Rev. A* **77**, 033804

Cavity Optomechanics

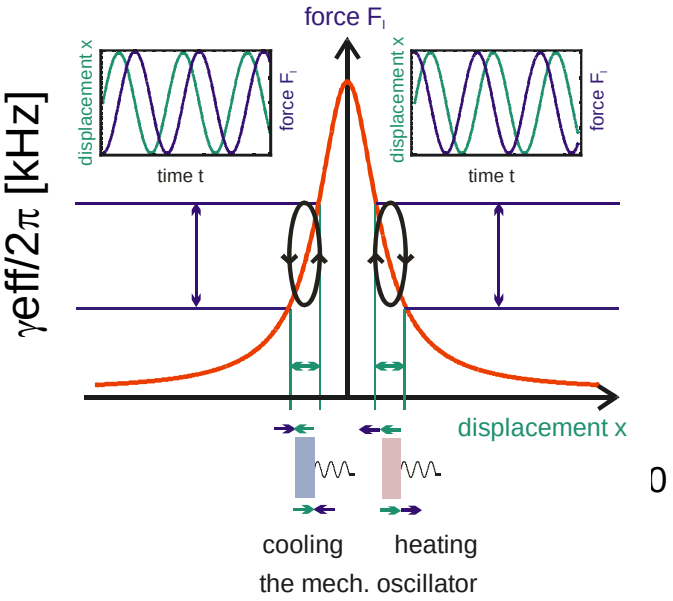


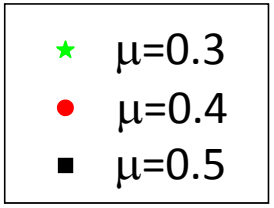
Optical spring

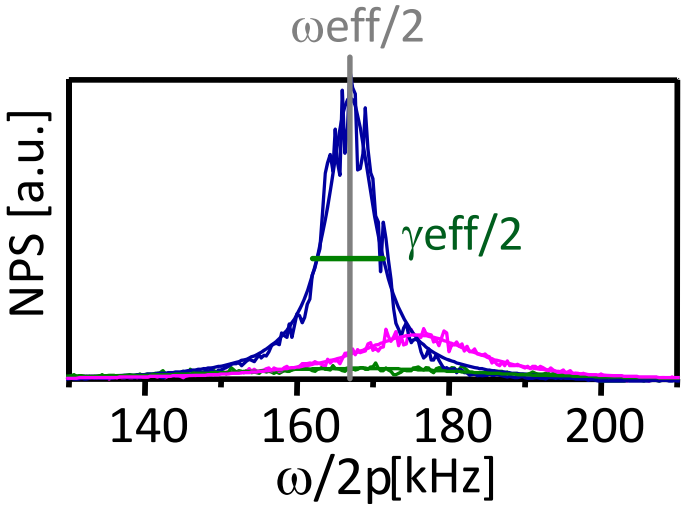
Theory curve, e.g. Genes C et al., PR*A 77, 033804 (*2008)



Optical damping

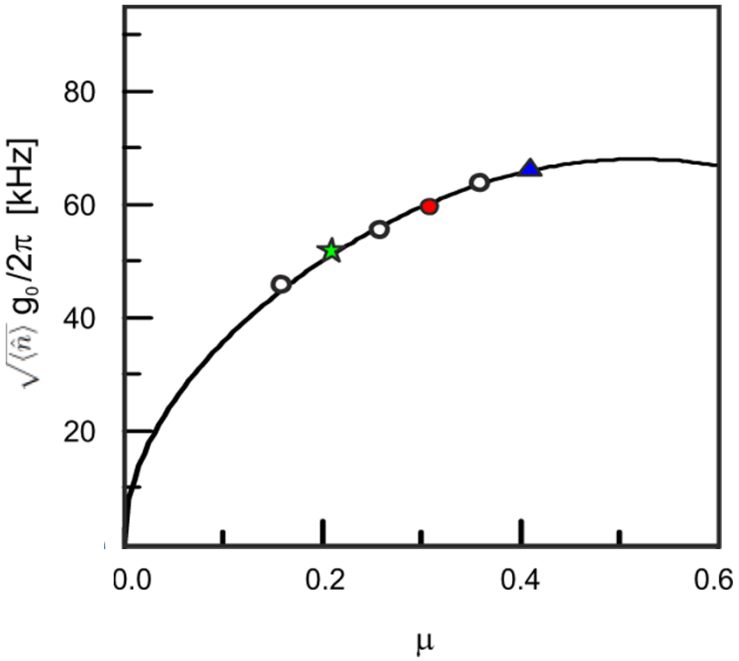




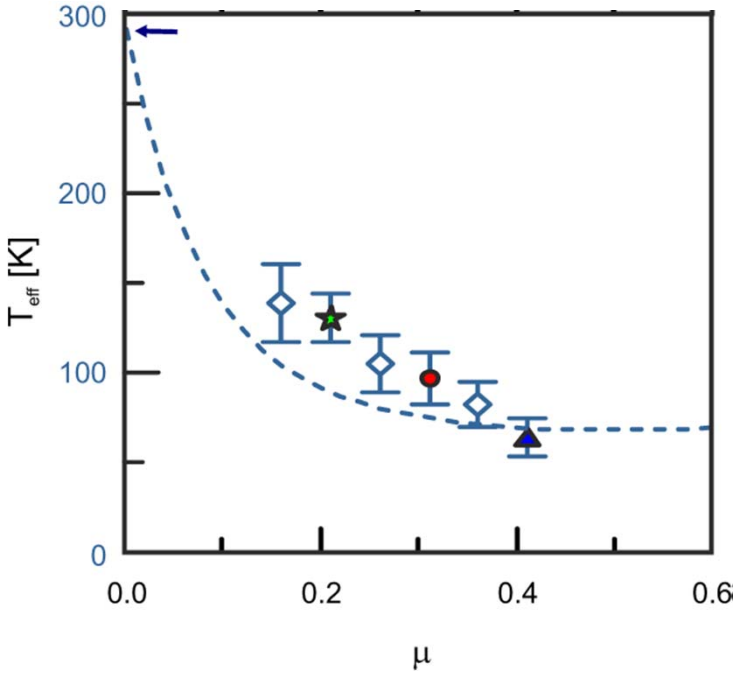


Cavity-Optomechanics

Optomechanical Coupling



Optomechanical Cooling



Cooling rate effectively up to approx. 40 kHz → Pressure range for Ground state cooling $p<10^{-7}$ mbar

N. Kiesel, F. Blaser et al., PNAS 110, 14180-14185; arXiv: 1304.6679

Rates are already comparable to typical MHz- Cavity Optomechanics

Limitation currently – particle loss when reducing pressure

Outline

- Intro: Levitating Optomechanics and Related Systems

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- **The Future**
    - Next Steps on the Experiments
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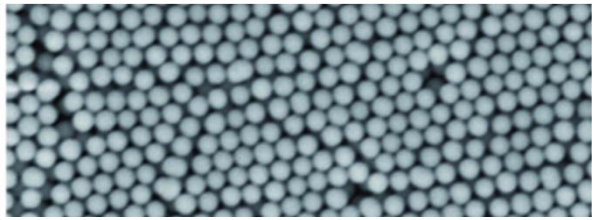
Next: Low pressures and high Q

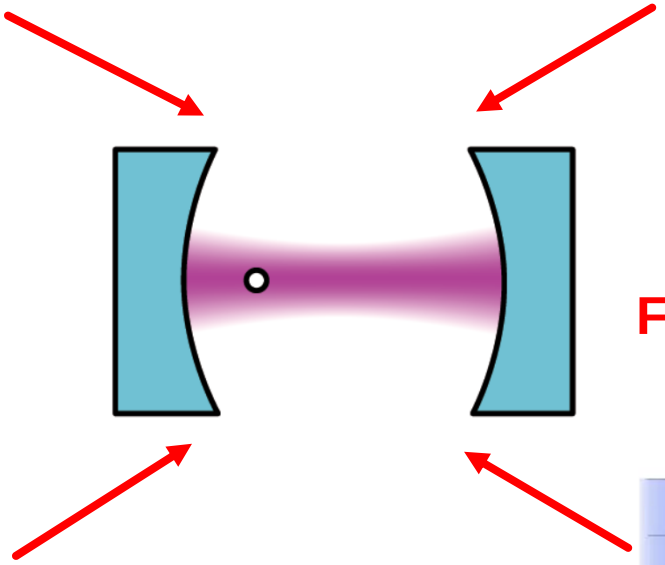
Noise reduction

Laser, Vibrations, Thermal

Nanoparticle Design

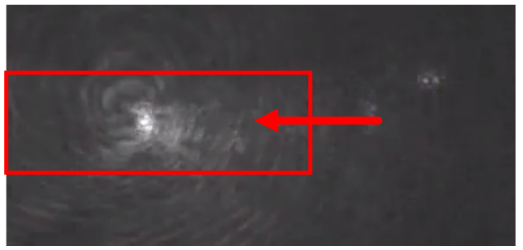
Defined Sizes, Materials



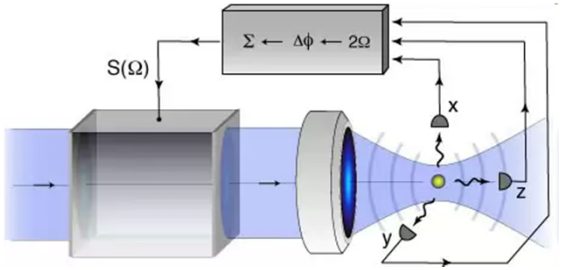


Loading mechanisms

Dry loading in UHV



Feedback Cooling in 3D

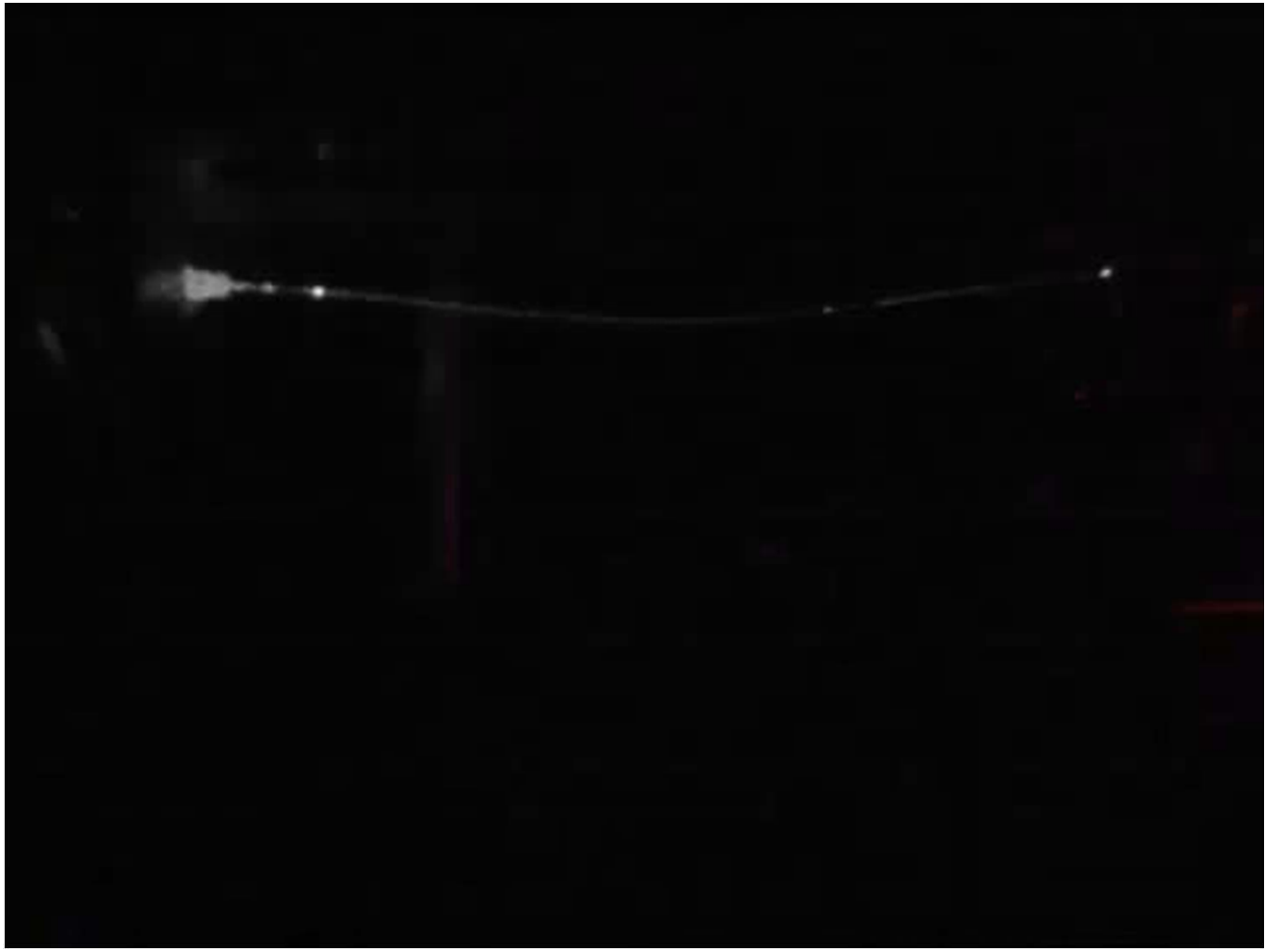


<u>Pressures of 10^{-6} mbar achieved by 3D cooling</u>

Gieseler, J, PRL **109** (2012).

Li et al, Nat Phys 7, 527 (2011),

Particle Transport in HCPCF



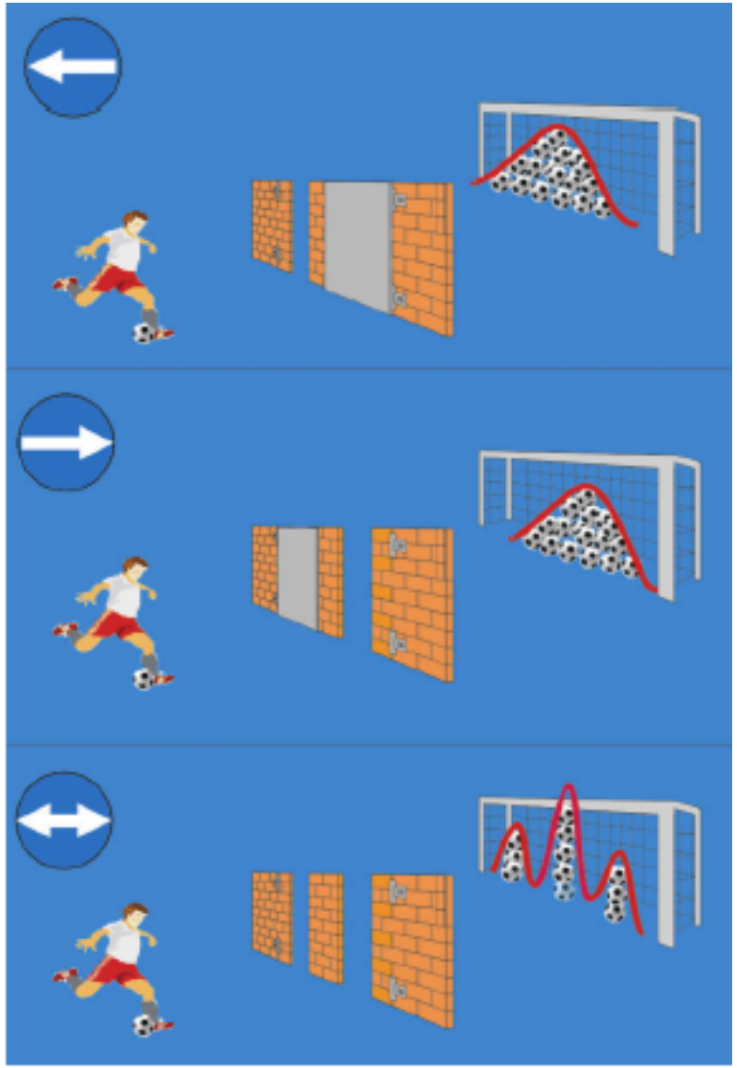
Some previous work
Renn et. al., PRL 82, 1574 (1999)
Benabid et. al., Op. Exp. 10, 1195 (2002)
Schmidt et. al., Op. Lett. 37, 91(2012)

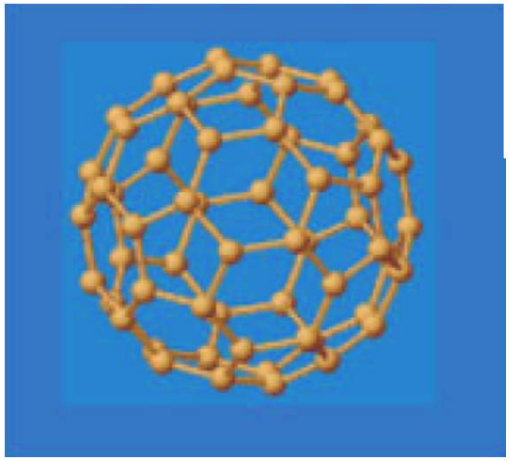
Master Thesis, David Grass, 2013

Matter-Wave Interferometry

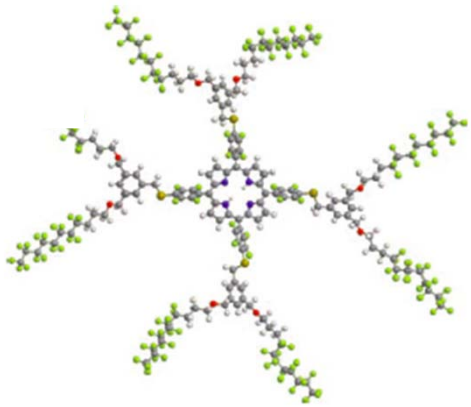
Arndt M, Hackermüller L, Hornberger K.
Physik in unserer Zeit. 2006;37(1):24-29.

Review: Juffmann, T., Ulbricht, H., & Arndt, M. (2013).
In Reports on progress in physics. 76(8), 086402.





Arndt M, et al.
Nature. 1999;401:680-682.



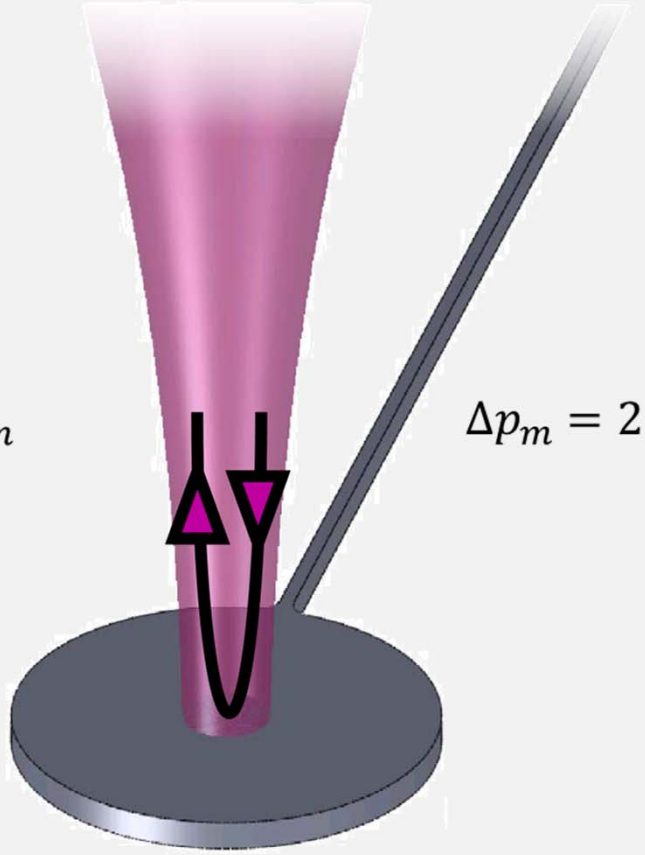
Gerlich, S., et al.
Nat. com., *2*, 263.

Some Infotainment:
Youtube channel, QuantumnanoVienna

Note also, experiment on cavity cooling by Asenbaum et al., arXiv.: 1306.4617

Excursion: Pulsed Optomechanics

$$\Delta\varphi = 2\frac{2\pi}{\lambda}\, x_m$$



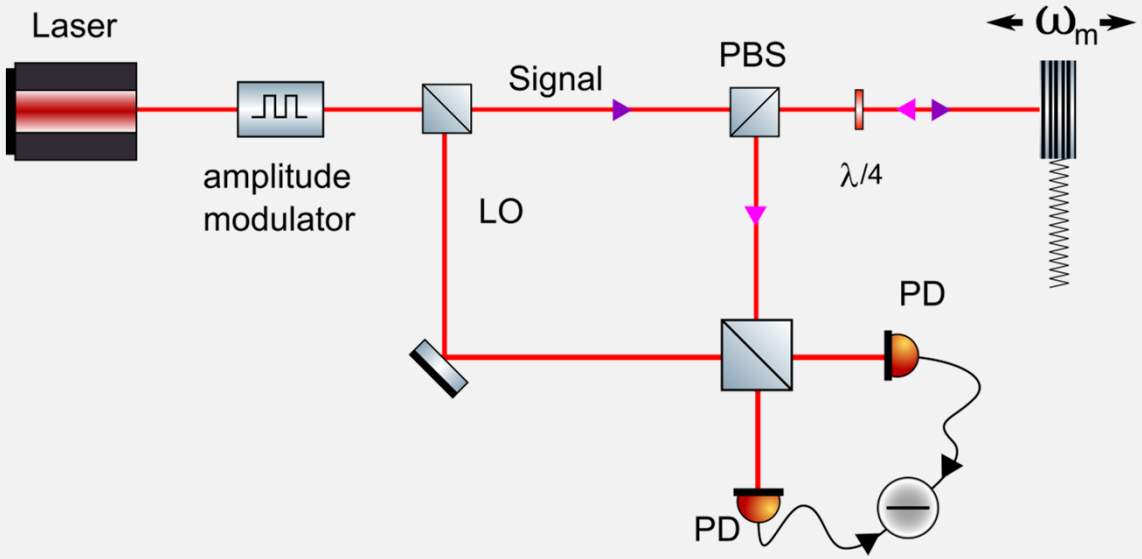
$$\Delta p_m = 2\frac{\hbar\omega}{c}\, N_{ph}$$

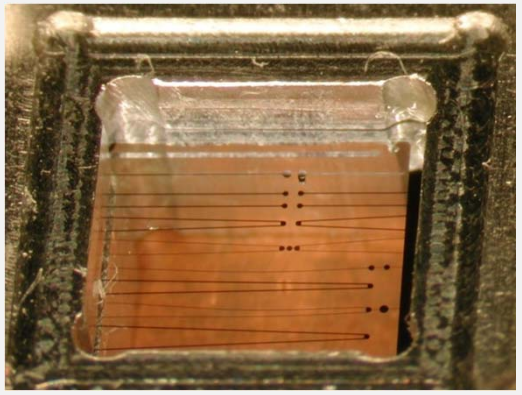
QND Measurement of Position

for short interaction

Setup

Homodyne setup to read out the phase shift





$m_{eff} \approx 260\,ng$

$$\langle P_L \rangle = \chi \langle X_m \rangle$$

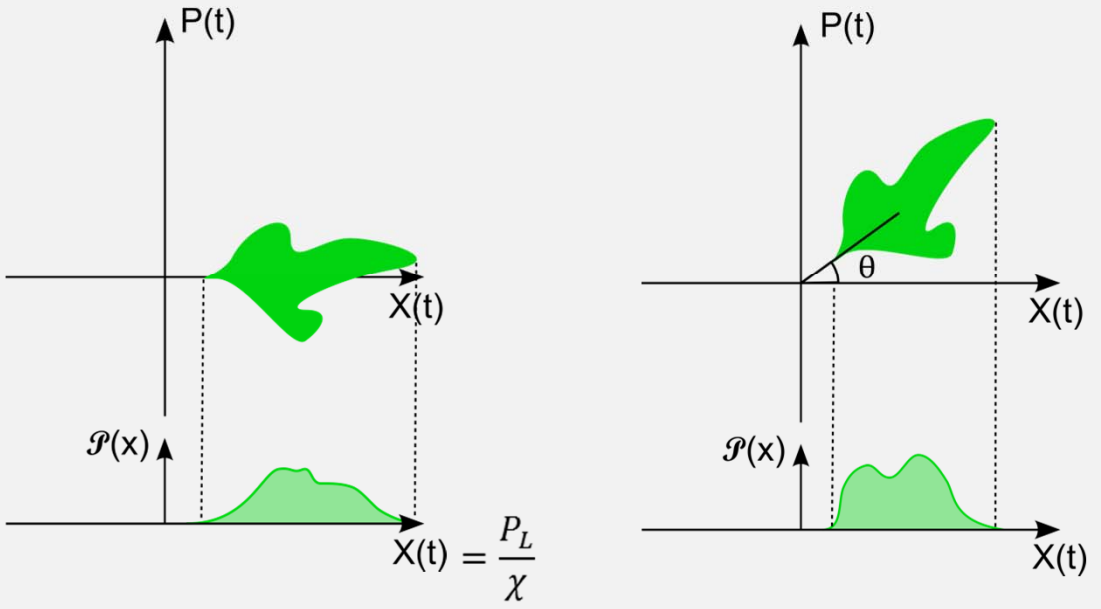
$$\chi \propto \sqrt{N_{ph}}$$

Vanner, M. R., et al. (2013).
Nature communications, *4*, 2295.

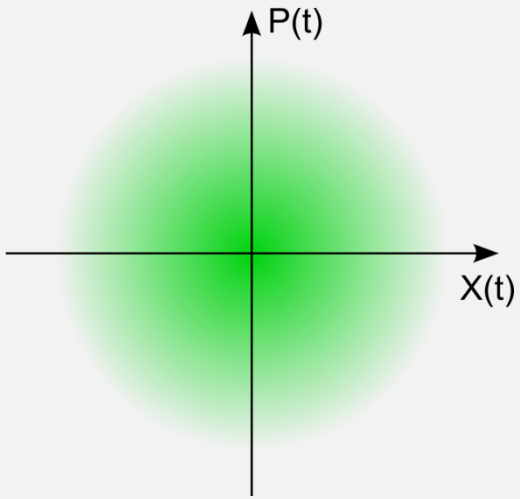
Tomography

Dynamics: harmonic oscillator

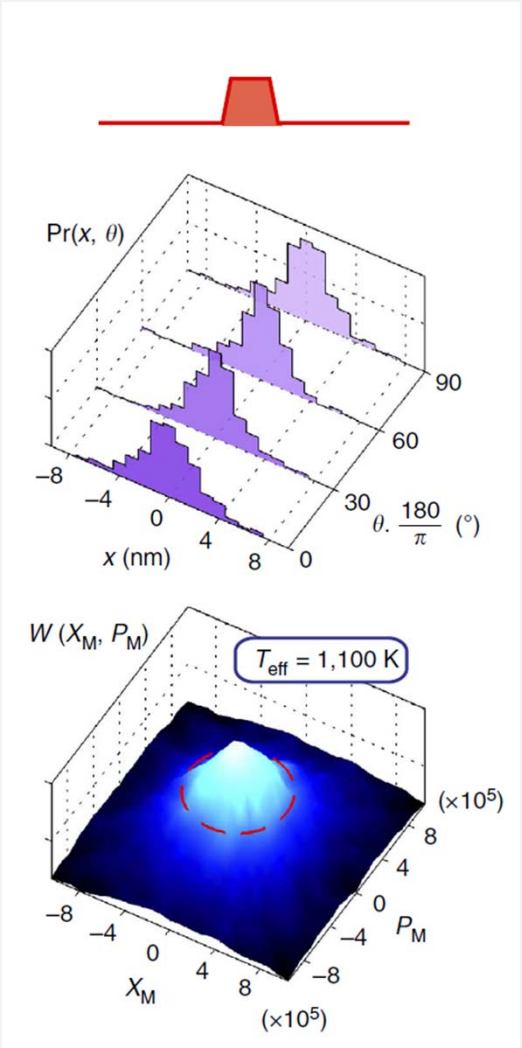
$$X(t) = X_0 \cos(\omega_m t) + P_0 \sin(\omega_m t)$$



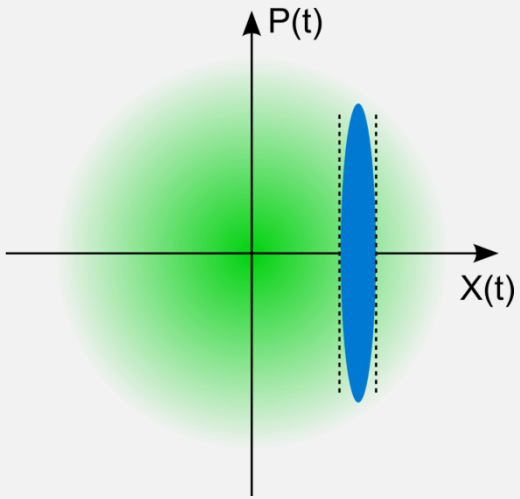
Thermal State

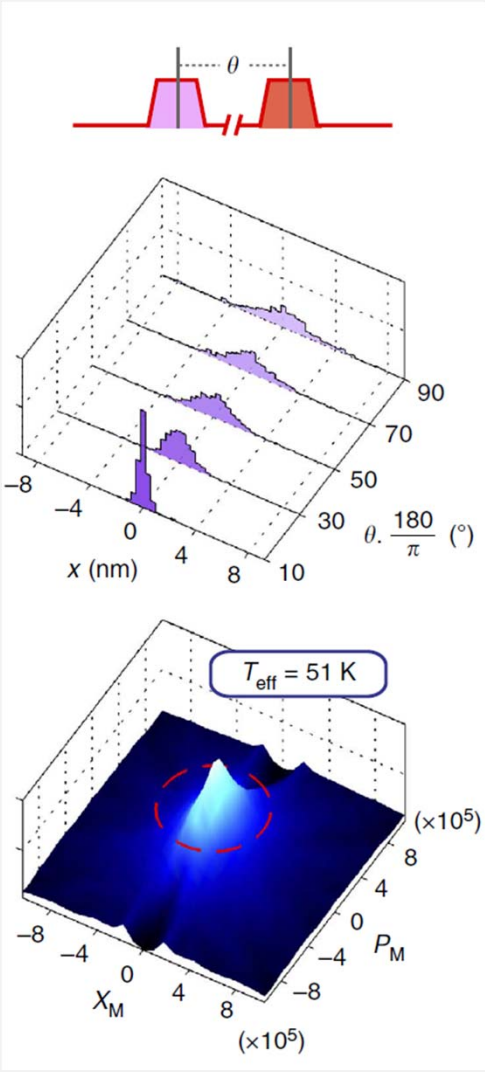


$$k_B T_{eff} = m_{eff} \omega_m^2 \, (\sigma_x{}^2)$$

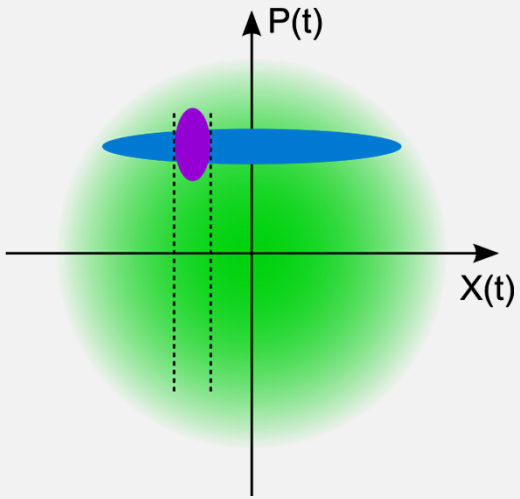


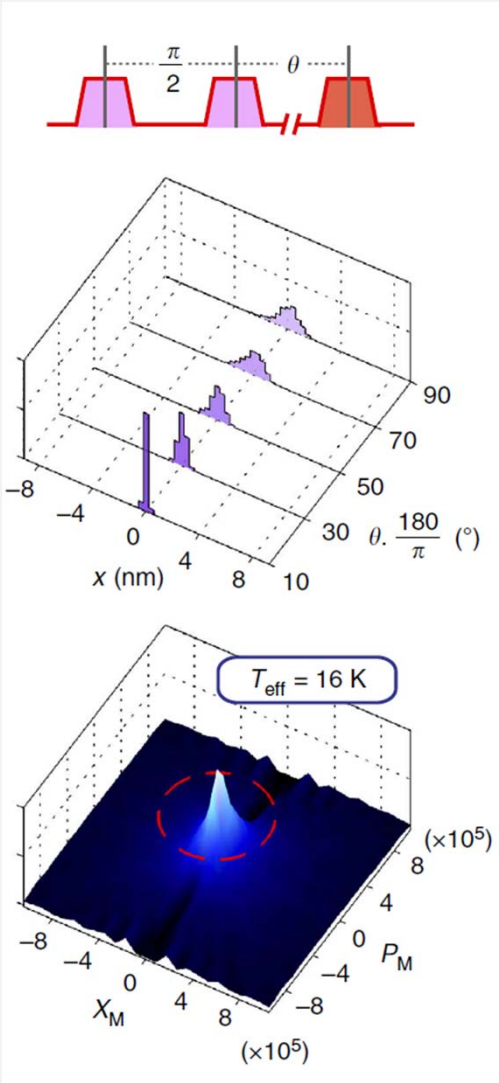
"Squashed" State



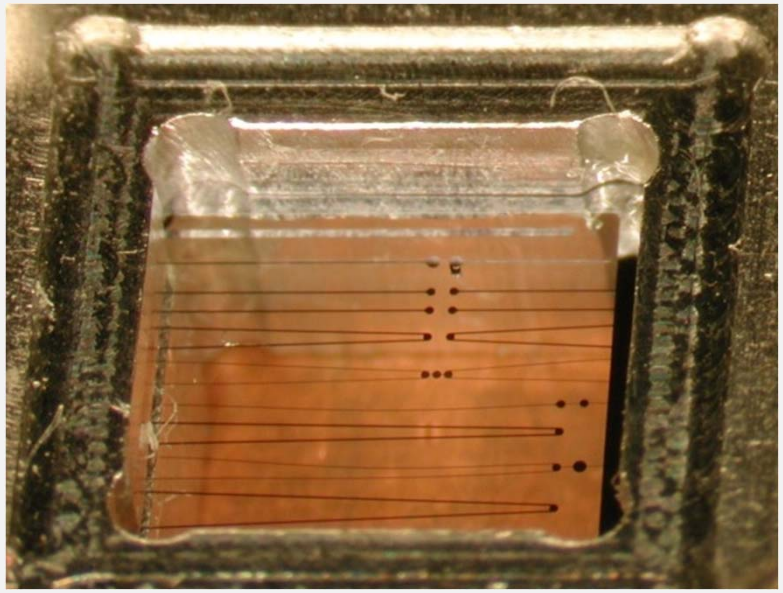


Cooled State

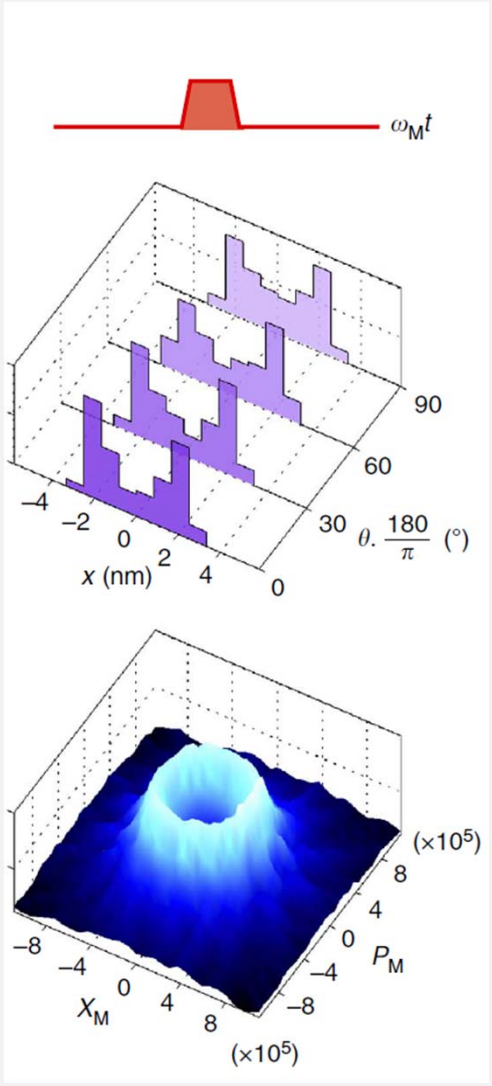




Driven State



ω_M



Matter-Wave Interferometry

Arndt M, Hackermüller L, Hornberger K.
Physik in unserer Zeit. 2006;37(1):24-29.

Review: Juffmann, T., Ulbricht, H., & Arndt, M. (2013).
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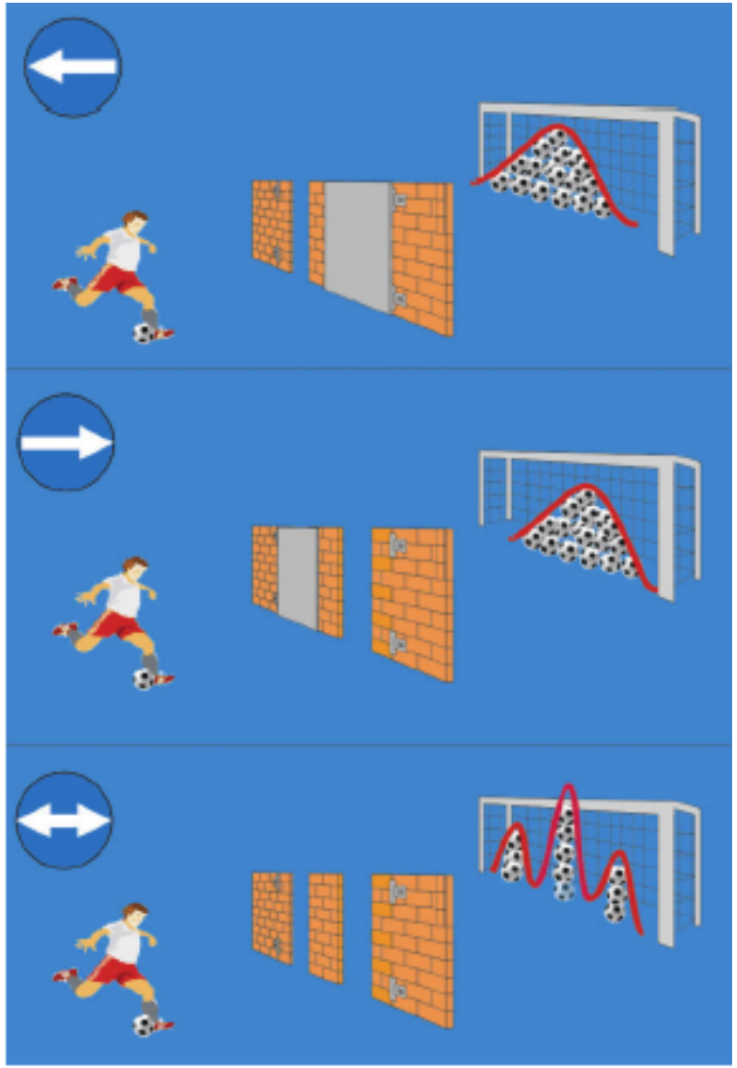

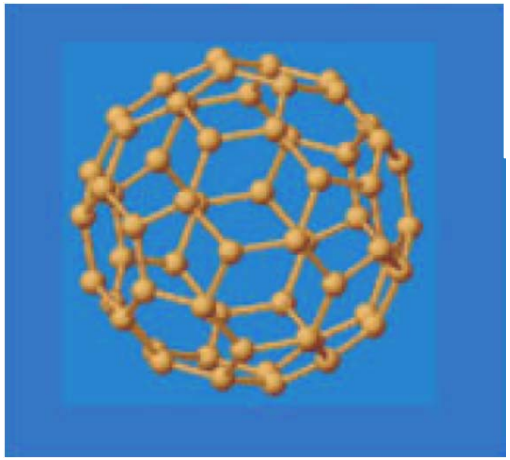

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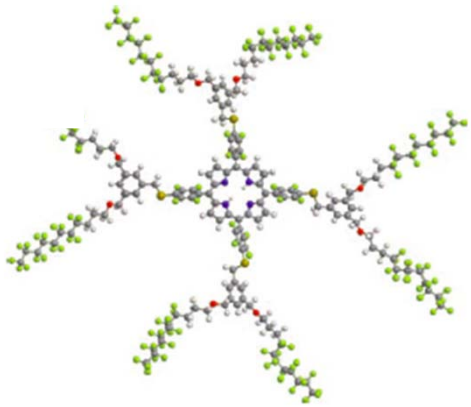

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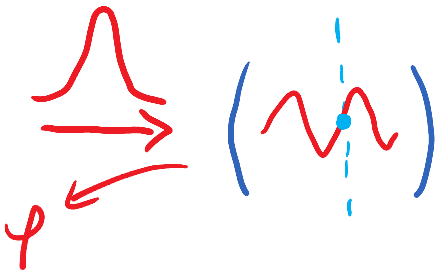
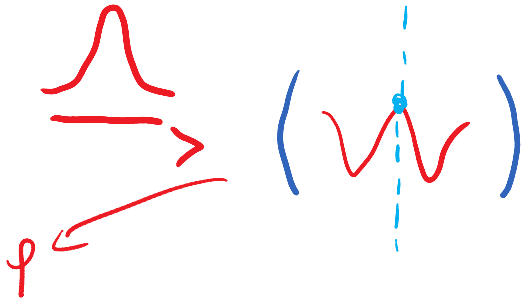
Pulsed Optomechanics - Spheres





$$\Delta\varphi \propto \frac{\Delta x}{\lambda} F$$

$$\propto g_0 \frac{\Delta x}{x_{ZPF}} F$$

$$\Delta\varphi \propto \frac{1}{2}\left(\frac{\Delta x}{\lambda}\right)^2 F$$

$$\propto \frac{1}{2}\left(g_0 \frac{\Delta x}{x_{ZPF}}\right)^2 F$$

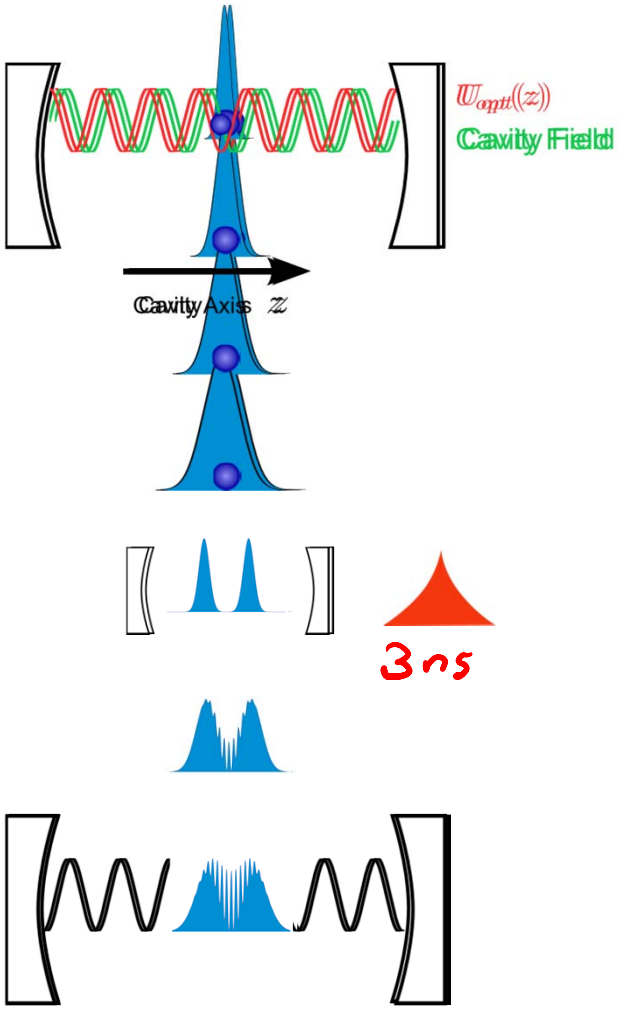
Result of Measurement

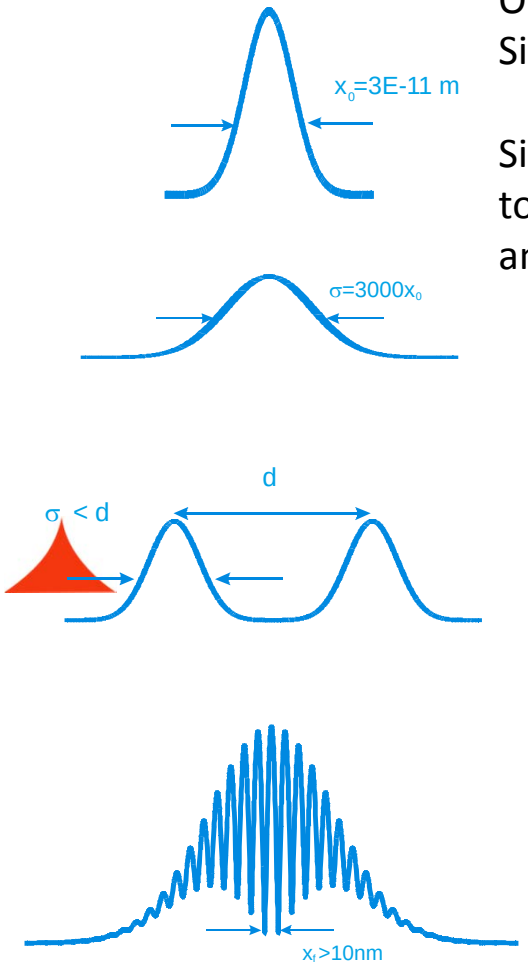
$\varphi \rightarrow x$

$\varphi \rightarrow x^2 \rightarrow \pm x$

Conditional Double Slit

Potential Parameter Set





Object: D=40nm
Silica Sphere

Sideband Cooling of Nanosphere
to 0.1 phonons
analogous to cooling of micromirror

↓ 3.3 ms

Short Pulse
x^2–readout Projection
on Cat-State $|x\rangle + |-x\rangle$
(Cavity: L=2mm, F=130000)

↓ 125 ms

Position Detection
Precision: 10nm

O. Romero-Isart et al., PRL 107, 020405 (2011)

O. Romero-Isart , Phys. Rev. A, 84 e052121 (2011)

See also Kaltenbaek et al. Experimental Astronomy 34, 123-164.
(MAQRO) arXiv:1201.4756

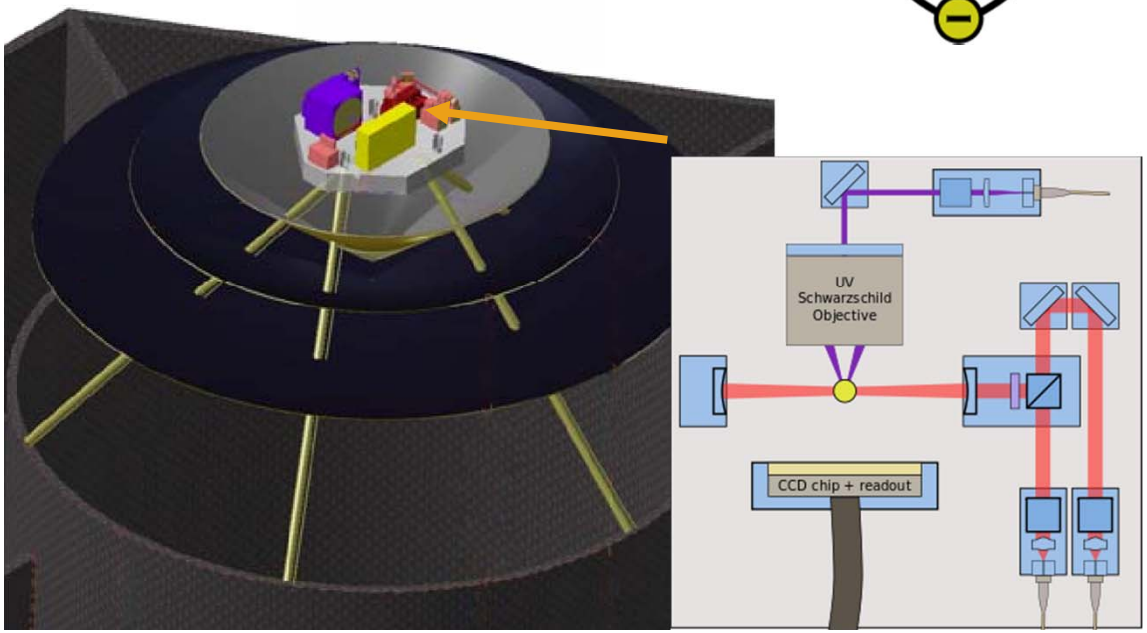
MAQRO: Macroscopic Quantum Resonators for Space

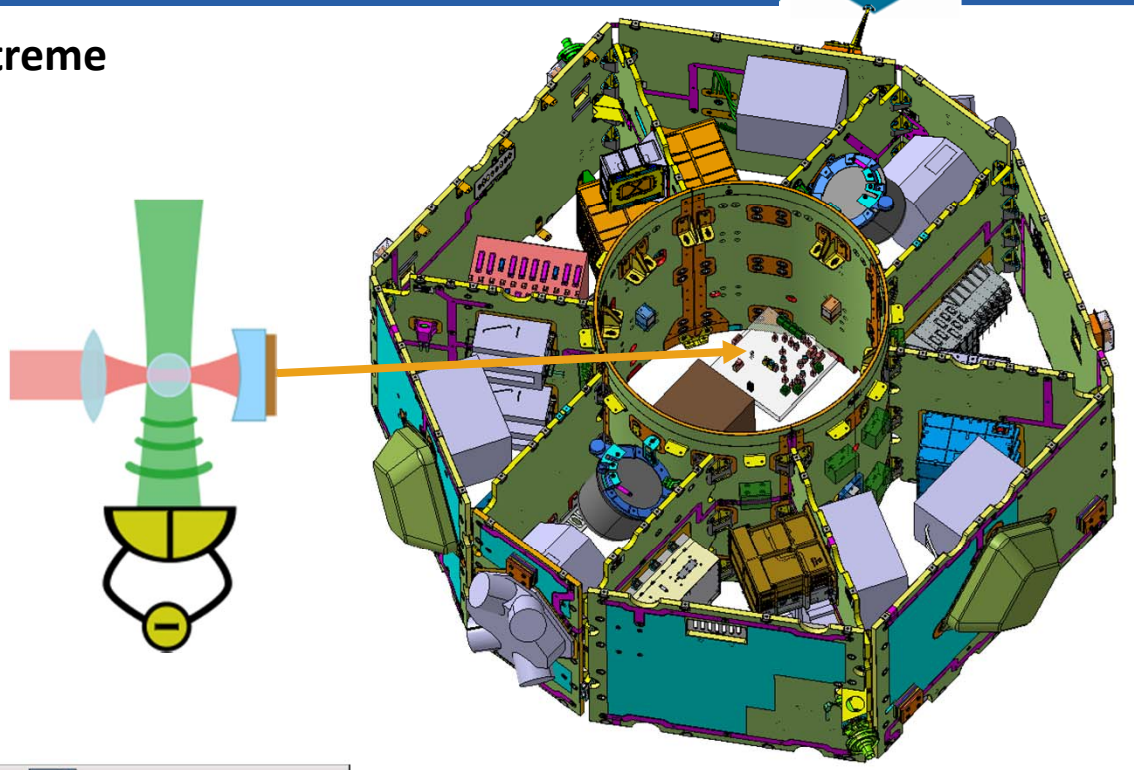
A possible space experiment under extreme conditions (vacuum, temperature)

R. Kaltenbaek et al., in collaboration with ASTRIUM Friedrichshafen

CASE

novel **high-precision inertial sensor**





LTP Modul

DECIDE

- **macroscopic quantum state** („Schrödinger Cat“)
- test quantum theory against macrorealistic models

See also: Kaltenbaek et al. Experimental Astronomy 34, 123-164. (MAQRO) arXiv:1201.4756