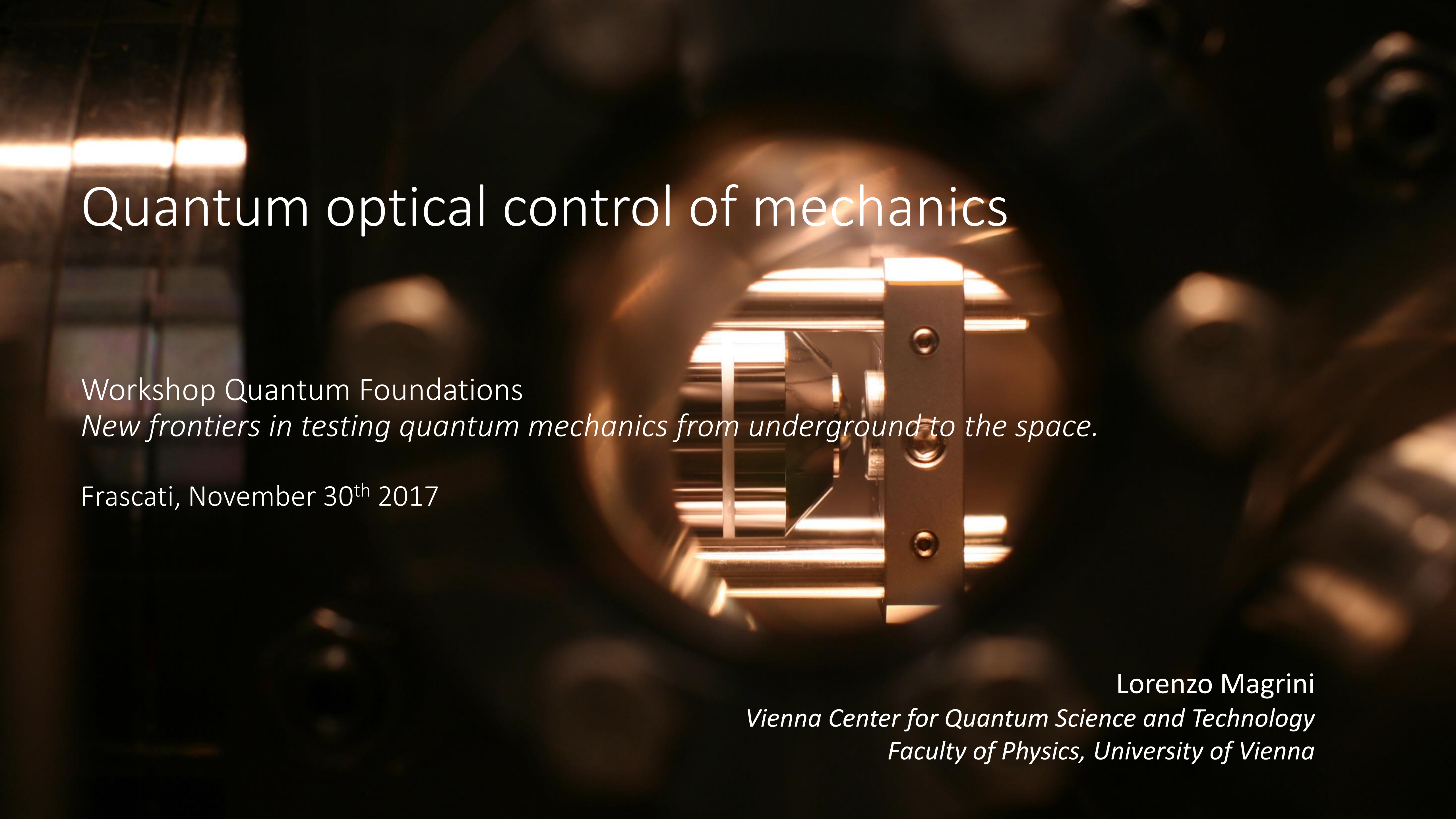


Quantum optical control of mechanics

Workshop Quantum Foundations
New frontiers in testing quantum mechanics from underground to the space.

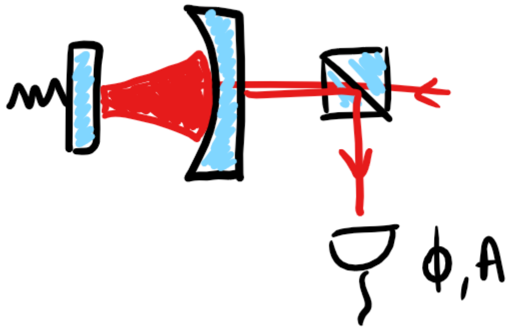
Frascati, November 30th 2017

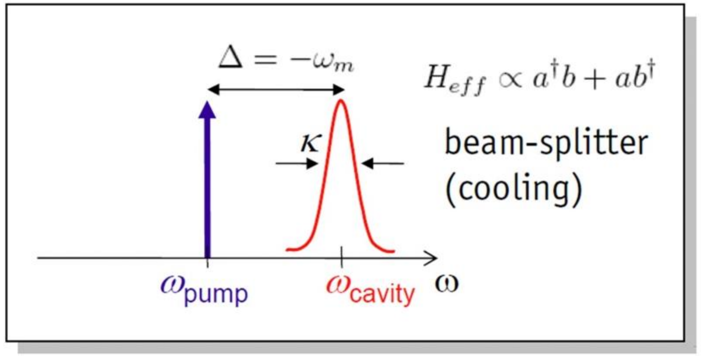
Lorenzo Magrini
Vienna Center for Quantum Science and Technology
Faculty of Physics, University of Vienna

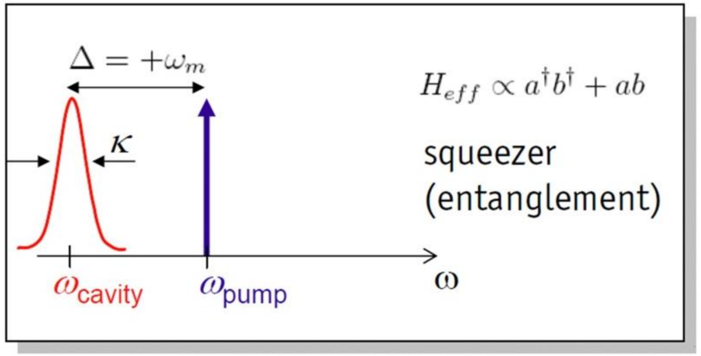
why optomechanics?

$$F = \hbar k \frac{\langle \hat{a}^\dagger \hat{a} \rangle}{\tau_c} = \hbar \overbrace{\frac{\omega_{cav}}{L}}^{G} \langle \hat{a}^\dagger \hat{a} \rangle$$

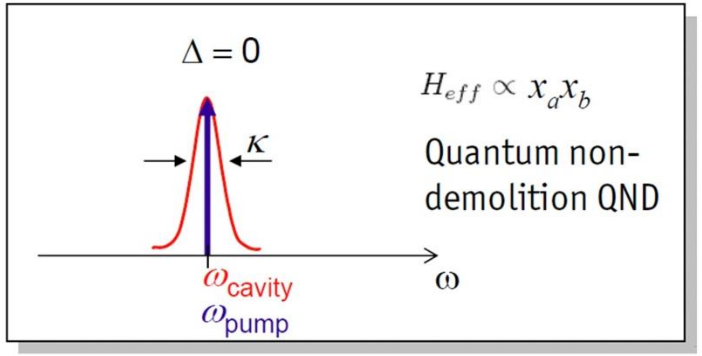
$$H = \hbar\omega_{cav}\hat{a}^\dagger\hat{a} + \hbar\omega_M \hat{b}^\dagger\hat{b} + \overbrace{\hbar G x_{ZPF}(\hat{a}+\hat{a}^\dagger)(\hat{b}+b^\dagger)}^{H_I}$$







$$\omega_{cav} = \omega_0 + \overbrace{\frac{d\omega}{dx}}^{G} x$$

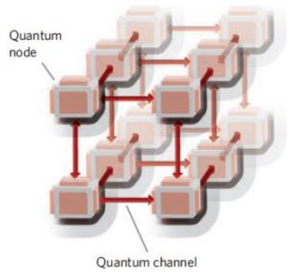


M. Aspelmeyer *et al.*, Rev. Mod. Phys., 2014

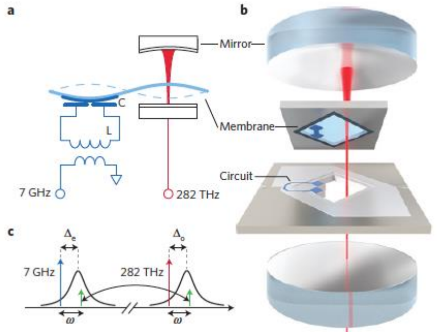
why optomechanics?

QUANTUM INFORMATION

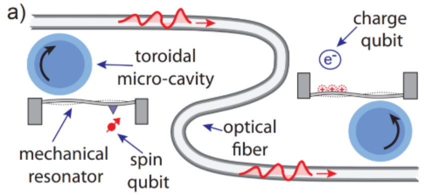
Q. MEMORY
Q. TRANSDUCERS



*H. J. Kimble, Nature **453**, 2008.*



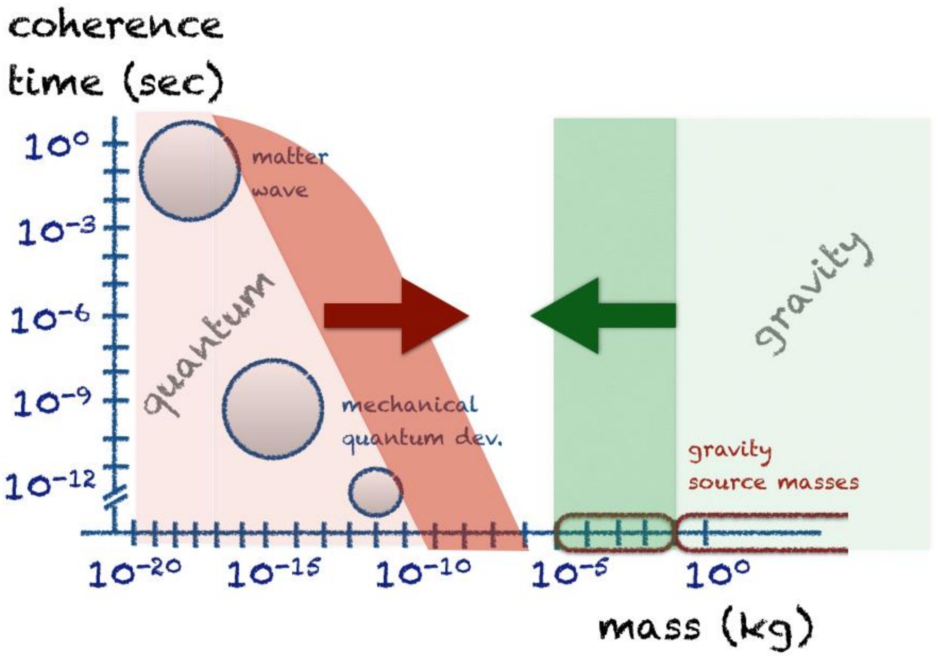
R.W. Andrews et al, Nature, 2014



K. Stanniger et al., PRL 105, 2010

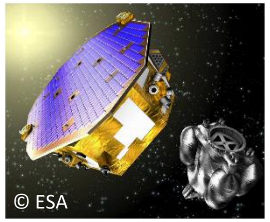
FUNDAMENTAL PHISICS AND METROLOGY

Juffmann et al., Nature Nanotech. 7, 297

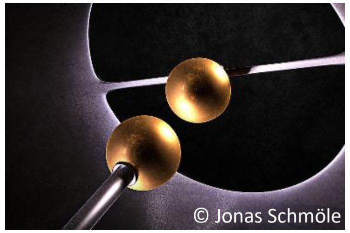


experiments in the Aspelmeyer group

MAQRO
Rainer Kaltenbaek

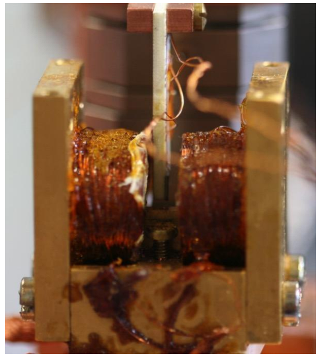


Milli-G



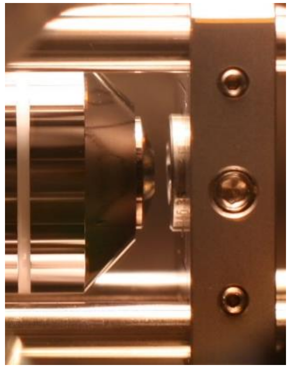
$\Omega_m \sim 60\ Hz$
$m \sim mg$
$T \sim 300K$

Magnetic levitation



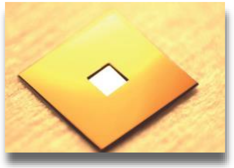
$\Omega_m \sim 100\ Hz$
$m \sim \mu g$
$T \sim 4\ K$

Optical levitation



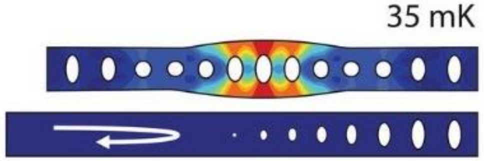
$\Omega_m \sim 0.01 - 1\ MHz$
$m \sim fg$
$T \sim 300\ K$

Membrane cavity optomechanics



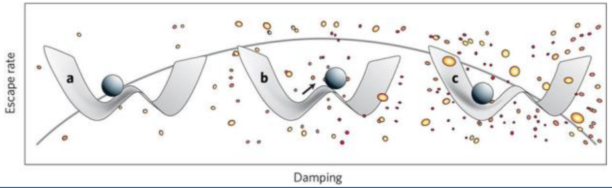
$\Omega_m \sim 1 - 10\ MHz$
$m \sim ng$
$T \sim 5\ K$

Photonic-phononic crystals

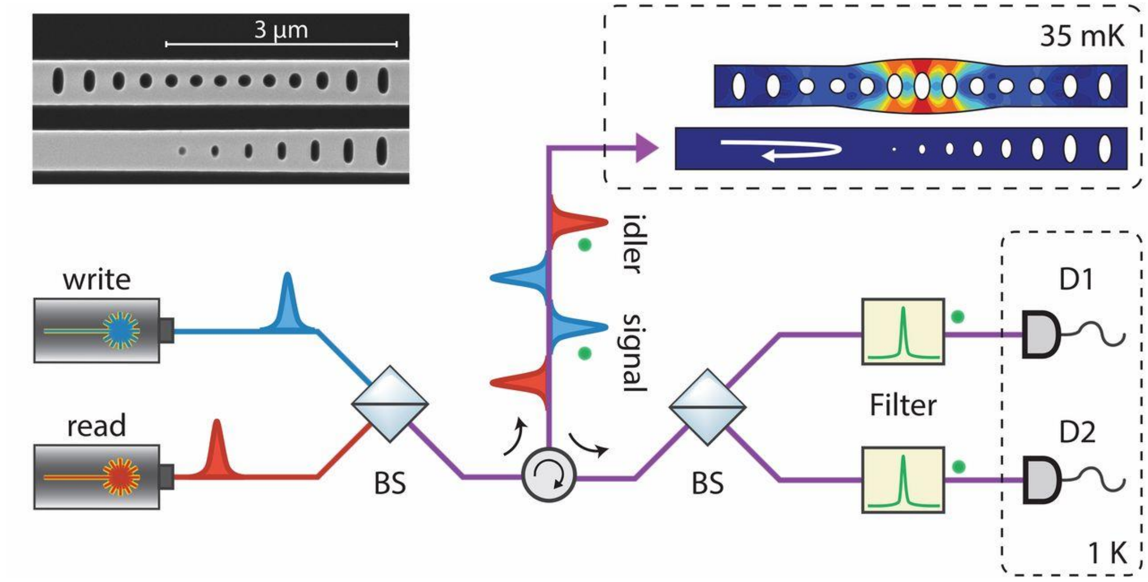


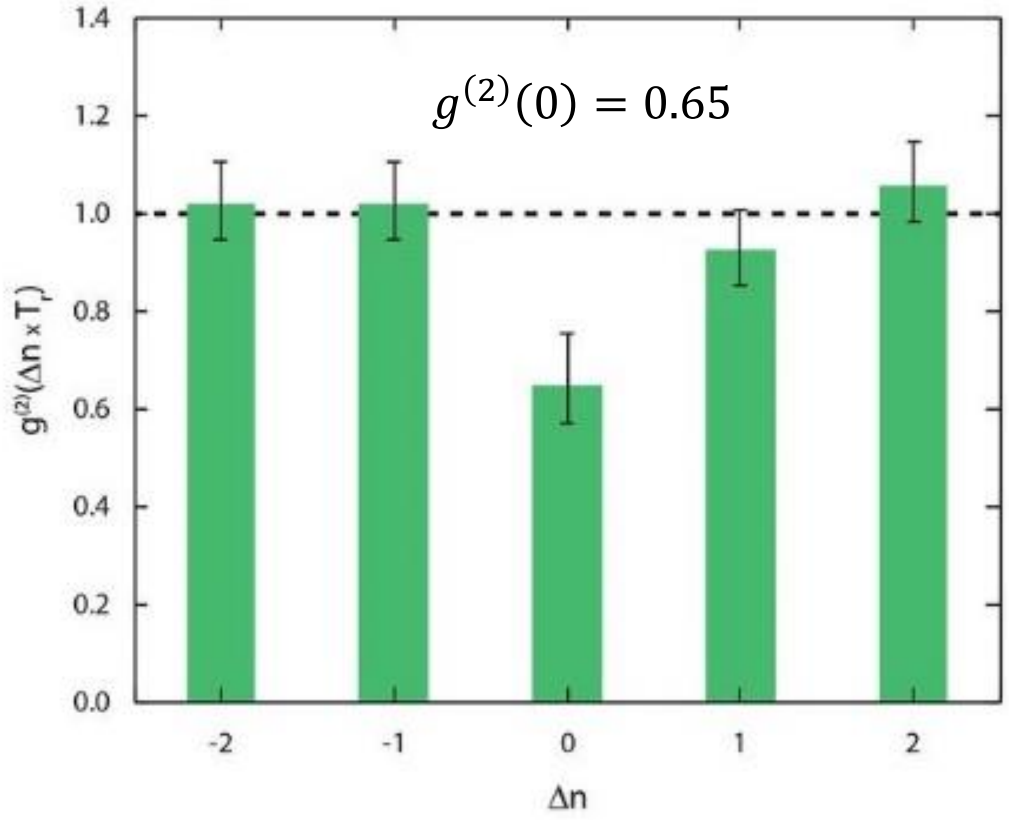
$\Omega_m \sim 5\ GHz$
$m \sim 100\ fg$
$T \sim 35\ mK$

Quantum Thermodynamics
Nikolai Kiesel



photonic-phononic crystals: control of mechanical Fock states



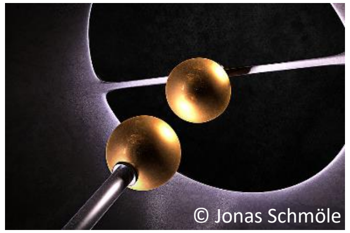


R. Riedinger, …, M. Aspelmeyer, Nature 2016.
S. Hong, …, M. Aspelmeyer, Science 2017.
R. Riedinger, …, S. Gröblacher, ArXiv 2016.

R. Riedinger, S. Hong, A. Wallucks, R. Norte, I. Marinković, S. Gröblacher

experiments in the Aspelmeyer group

Milli-G



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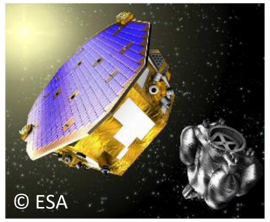
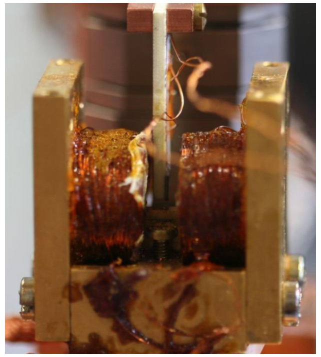
MAQRO
Rainer Kaltenbaek



Magnetic levitation



$\Omega_m \sim 100\ Hz$
$m \sim \mu g$
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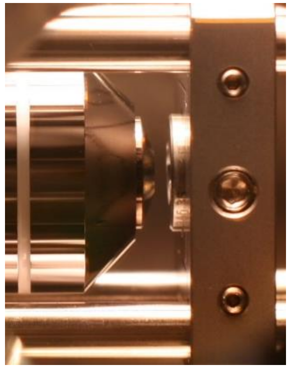
Optical levitation



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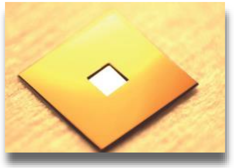
Membrane cavity optomechanics



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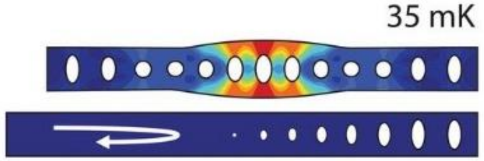
Photonic-phononic crystals



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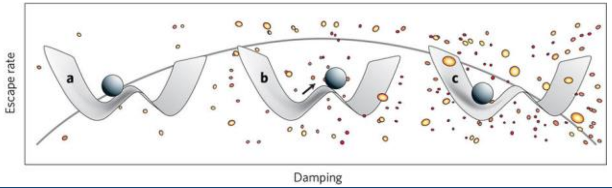
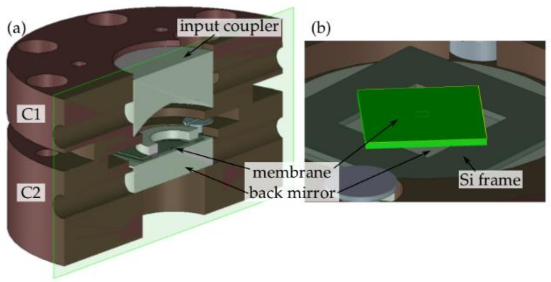
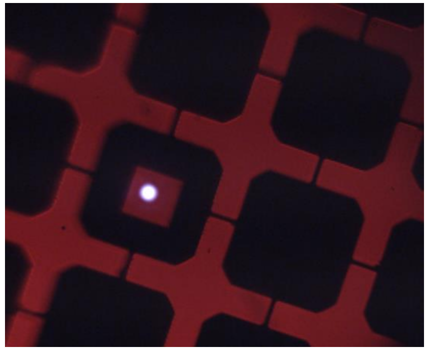
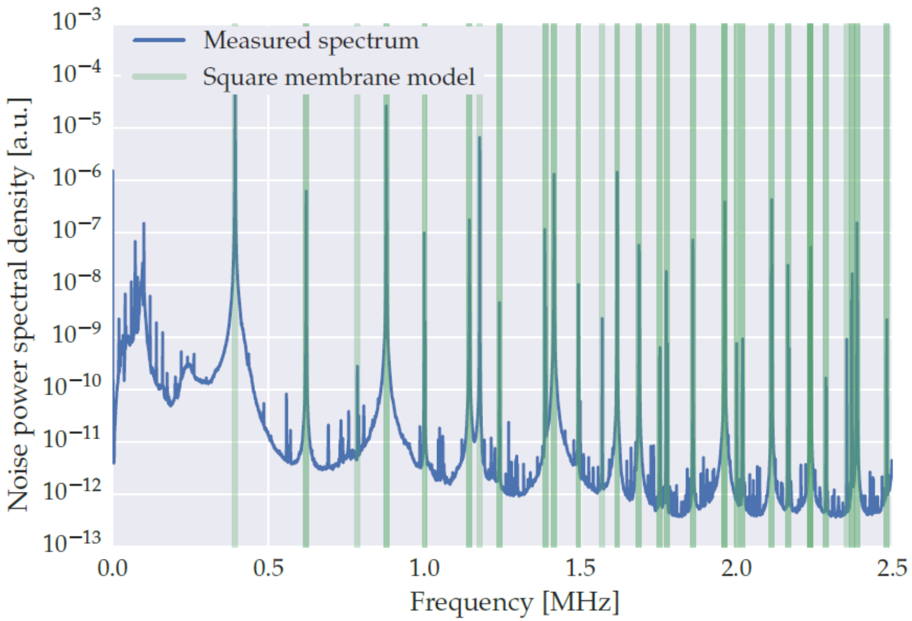
Quantum Thermodynamics
Nikolai Kiesel



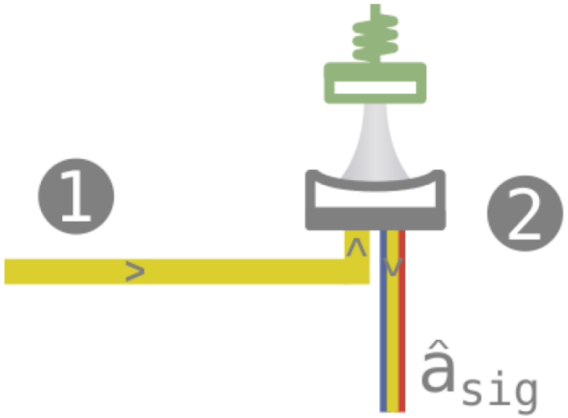
membrane optomechanics: chasing entanglement in CW



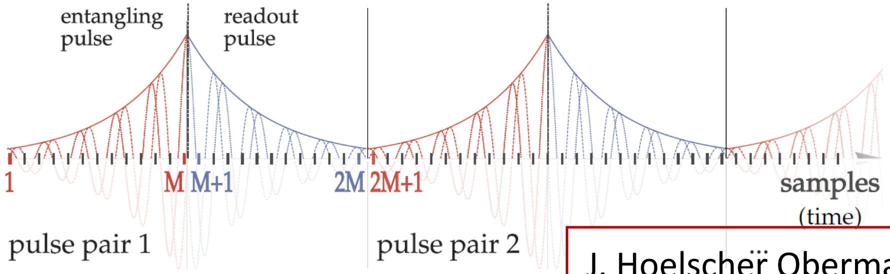




J. D. Thompson *et al.*, Nature 452, 2008



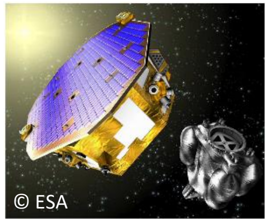
$$H_I = g_0\alpha(a^\dagger b^\dagger + ab) + g_0\alpha(a^\dagger b + ab^\dagger)$$



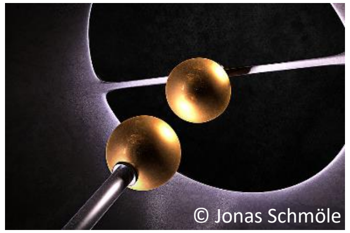
J. Hoelscher Obermaier
R. Moghadas Nia
W. Wieczorek
C. Gaertner
S. Hofer
C. Gut
C. Hammerer

experiments in the Aspelmeyer group

MAQRO
Rainer Kaltenbaek

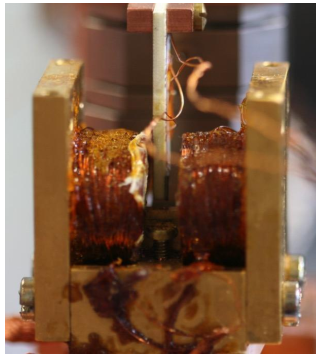


Milli-G



$\Omega_m \sim 60\ Hz$
$m \sim mg$
$T \sim 300K$

Magnetic levitation



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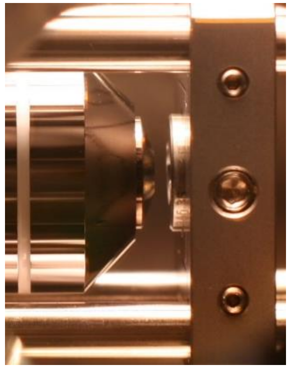
Optical levitation



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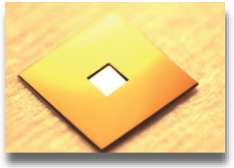

$\Omega_m \sim 1 - 10\ MHz$
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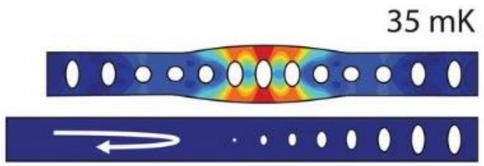
Photonic-phononic crystals



$\Omega_m \sim 5\ GHz$
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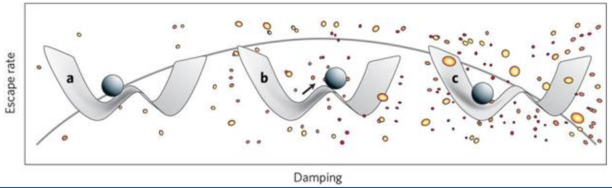
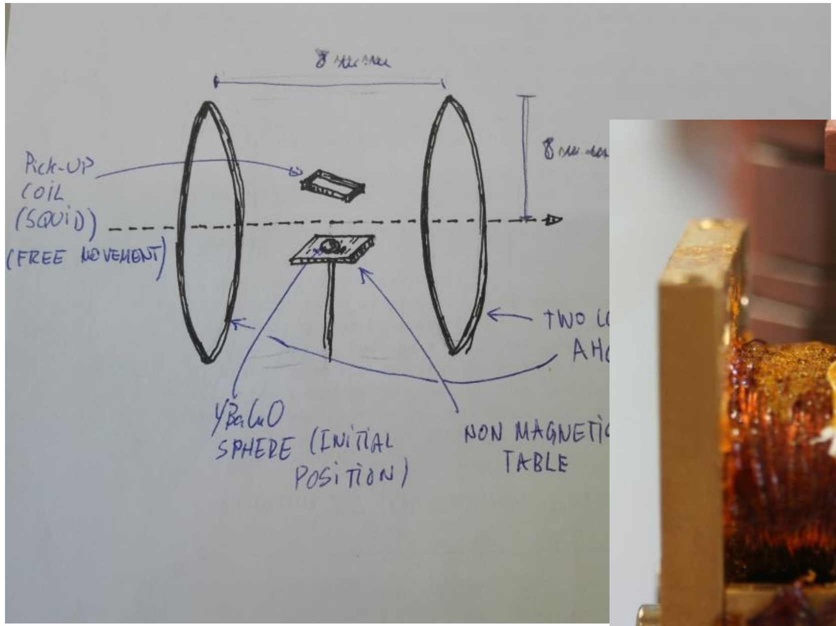
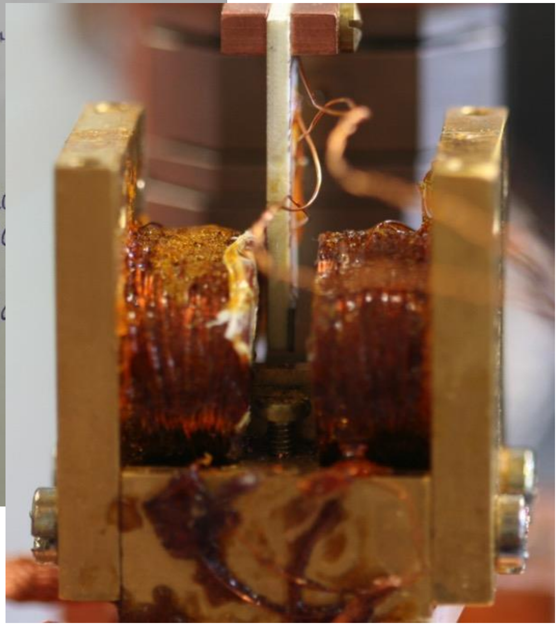
Quantum Thermodynamics
Nikolai Kiesel



measuring gravity of a small mass (the ***top down*** approach)

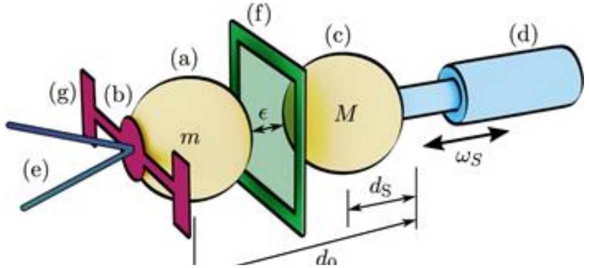
magnetic levitation

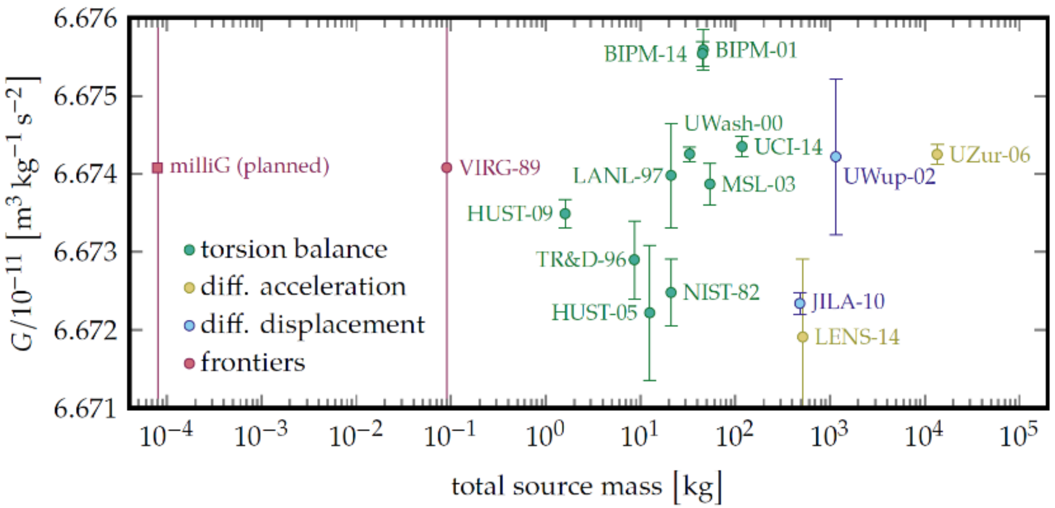




J. Hofer
J. Slater
F. Wulschner

milli-G project



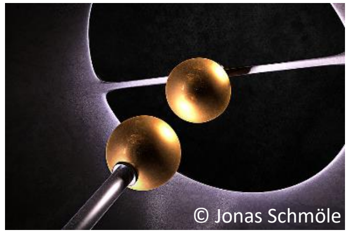


J. Schmöle H. Hepach J. Pfaff
T. Westphal M. Draghositis

J. Schmöle,..., and M. Aspelmeyer, Class. Quantum Grav. 33 125031, 2016

experiments in the Aspelmeyer group

Milli-G



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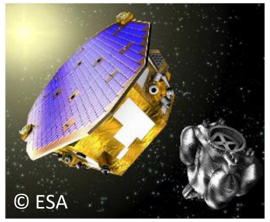
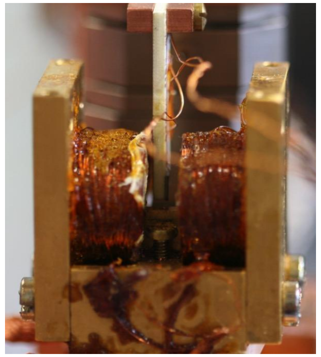
Rainer Kaltenbaek



Magnetic levitation



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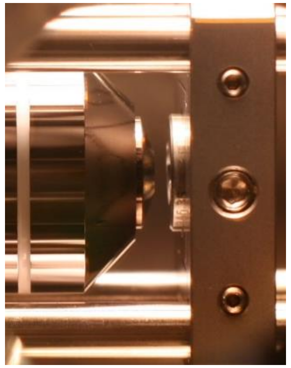

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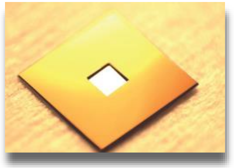
Membrane cavity optomechanics



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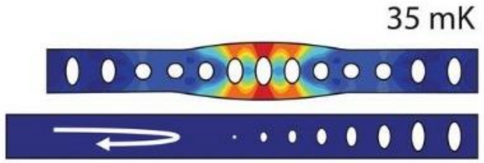

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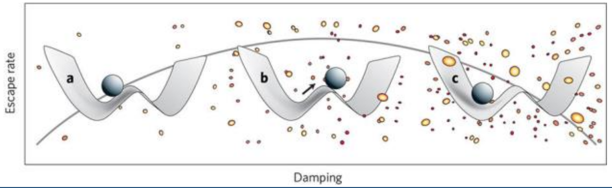


quantum mechanics with optically levitated nanoscale objects (*bottom up*)

PHYSICAL REVIEW A **81**, 023826 (2010)

Cavity cooling of an optically trapped nanoparticle

P. F. Barker
Department of Physics and Astronomy, University College London, WC1E 6BT, United Kingdom

M. N. Shneider
Applied Physics Group, Department of Mechanical and Aerospace Engineering, Princeton University,

Cavity opto-mechanics using an optically levitated nanosphere

D. E. Chang[a], C. A. Regal[b], S. B. Papp[b], D. J. Wilson[b], J. Ye[b,c], O. Painter[d], H. J. Kimble[b,1], and P. Zoller[b,e]

[a]Institute for Quantum Information and Center for the Physics of Information, California Institute of Technology, Pasadena, CA 91125; [b]Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, CA 91125; [c]JILA, National Institute of Standards and Technology, and Department of Physics, University of Colorado, Boulder, CO 80309; [d]Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125; and [e]Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria

Contributed by H. Jeffrey Kimble, November 10, 2009 (sent for review October 17, 2009)

New Journal of Physics
The open-access journal for physics

Toward quantum superposition of living organisms

Oriol Romero-Isart[1,4], Mathieu L Juan[2], Romain Quidant[2,3] and J Ignacio Cirac[1]
[1] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1

nature COMMUNICATIONS

ARTICLE
Received 18 Mar 2014 | Accepted 24 Jul 2014 | Published 2 Sep 2014
DOI: 10.1038/ncomms5788

Near-field interferometry of a free-falling nanoparticle from a point-like source

Experimental Astronomy
October 2012, Volume 34, Issue 2, pp 123–164 | Cite as

Macroscopic quantum resonators (MAQRO)

Testing quantum and gravitational physics with massive mechanical resonators

Authors Authors and affiliations

Rainer Kaltenbaek, Gerald Hechenblaikner, Nikolai Kiesel, Oriol Romero-Isart, Keith C. Schwab, Ulrich Johann, Markus Aspelmeyer

PHYSICAL REVIEW A **84**, 052121 (2011)

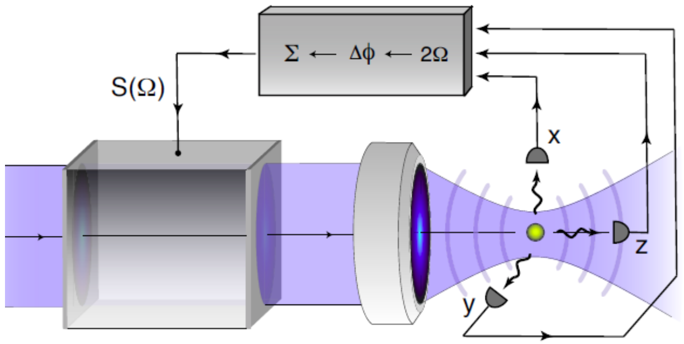
Quantum superposition of massive objects and collapse models

Oriol Romero-Isart
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
(Received 19 October 2011; published 28 November 2011)

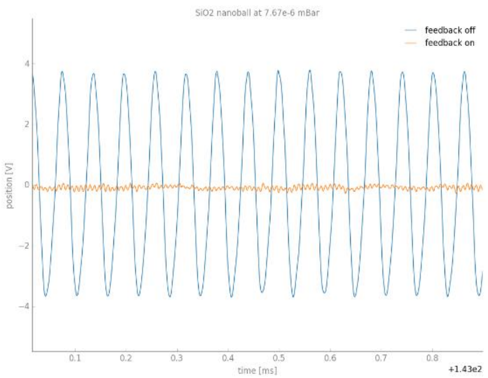
We analyze the requirements to test some of the most paradigmatic collapse models with a protocol that prepares quantum superpositions of massive objects. This consists of coherently expanding the wave function of a ground-state-cooled mechanical resonator, performing a squared position measurement that acts as a double slit, and observing interference after further evolution. The analysis is performed in a general framework and

An alternative point of view: resolution

GOAL
Quantum control of mechanical massive objects at room temperature.

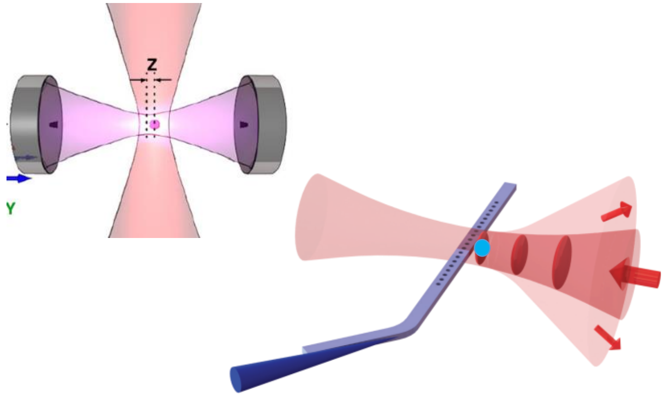


LIMIT
Detection efficiency and back action



How does it move when its not moving much?

SOLUTION?
Boost information with a cavity!



GOAL: $$C = \frac{4\, g_0^2\, n_{cav}}{\kappa\, \Gamma_{th}} > 1$$

J. Gieseler *et al.*, PRL **109**, 103603, (2012)

cavity optomechanics with levitated nanoparticles

Cavity cooling of an optically levitated submicron particle

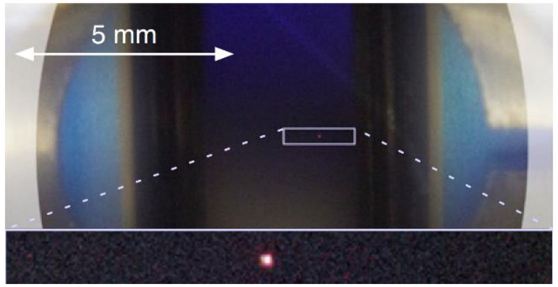
Nikolai Kiesel[1,2], Florian Blaser[1], Uroš Delić, David Grass, Rainer Kaltenbaek, and Markus Aspelmeyer[2]

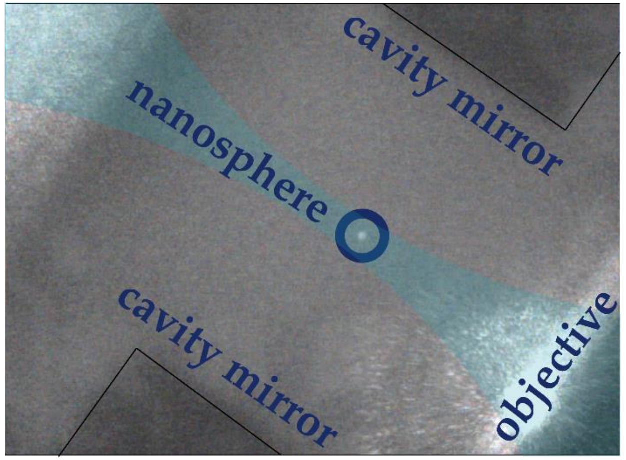
Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna, A-1090 Vienna, Austria

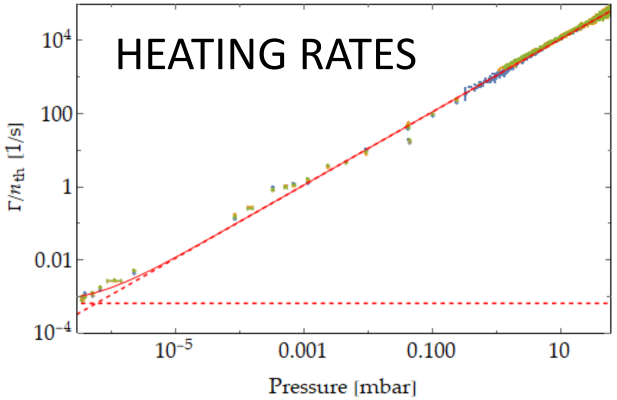
Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved July 16, 2013 (received for review May 14, 2013)

The coupling of a levitated submicron particle and an optical cavity field promises access to a unique parameter regime both for macroscopic quantum experiments and for high-precision force

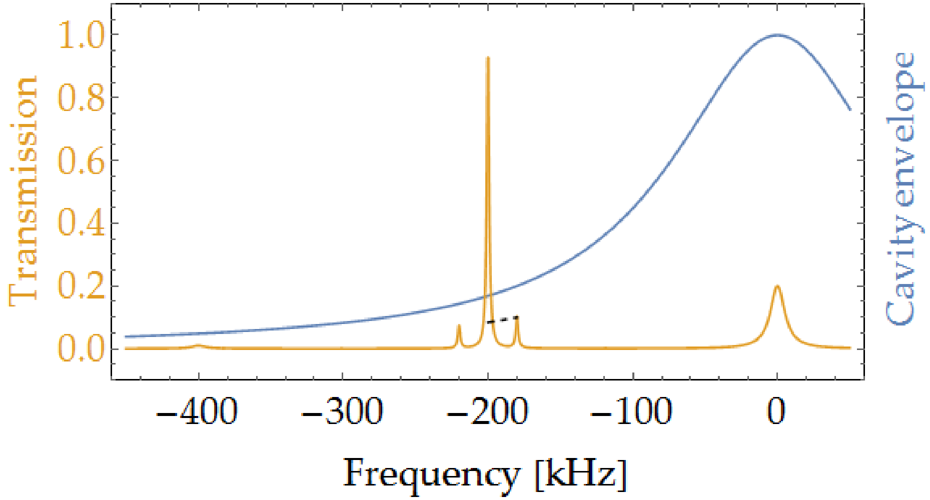
optically trapped single atoms (22, 23) and for clouds of up to 10^5 ultracold atoms (34–36). In comparison to such clouds, massive solid objects provide access to a different parameter regime: on

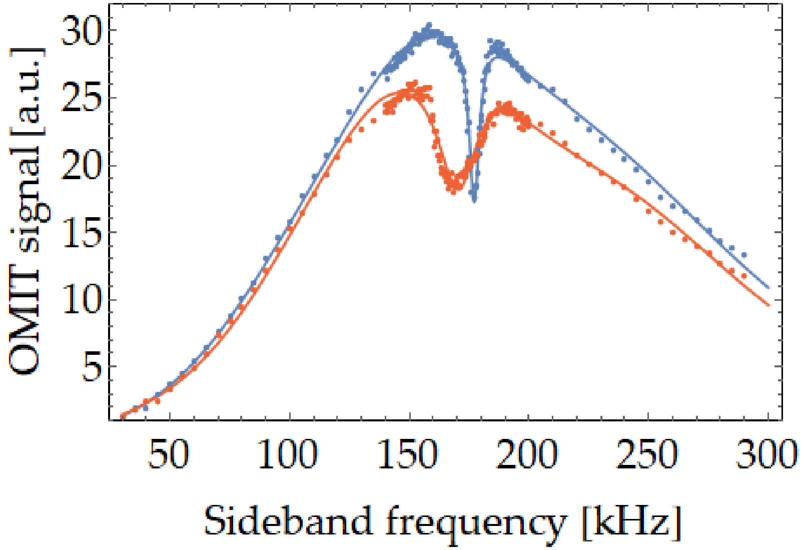






OPTOMECHANICAL INDUCED TRANSPARENCY





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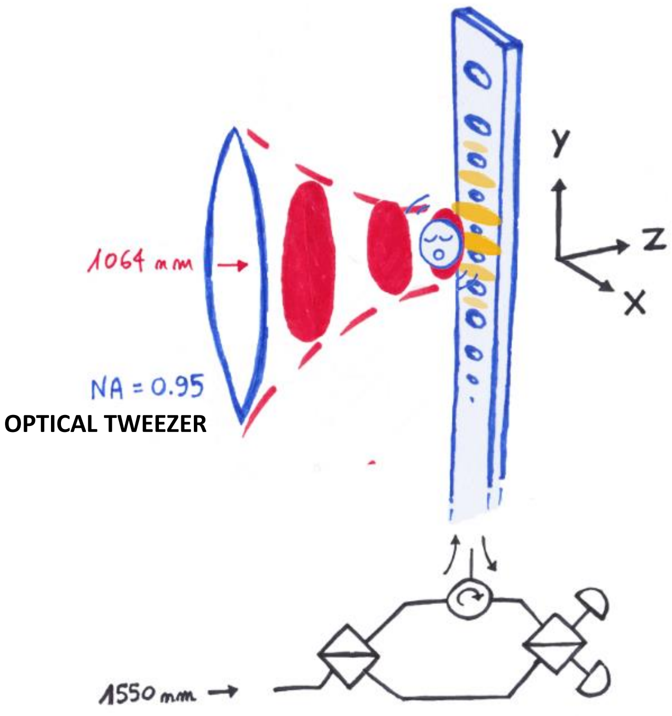
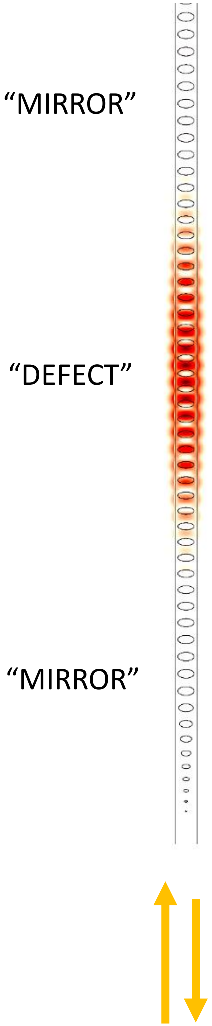
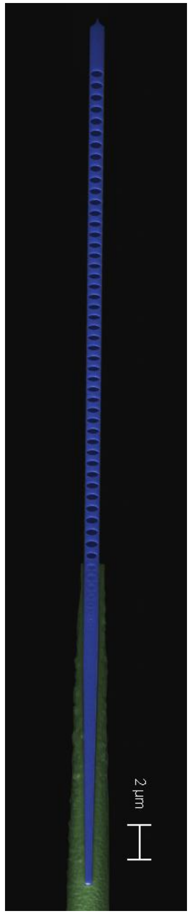
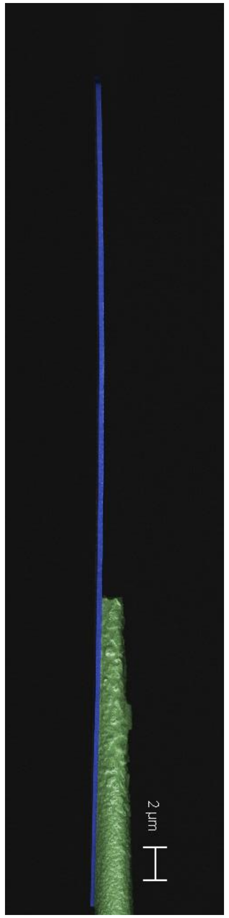
D. Grass	F. Blaser
N. Kiesel	

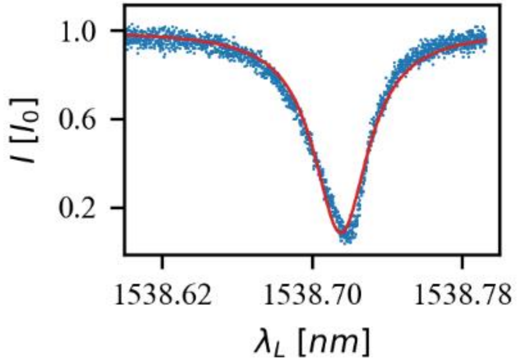
near field coupling of a levitated nanoparticle to a photonic crystal cavity











J. Thompshon *et al.*, Science, 2013

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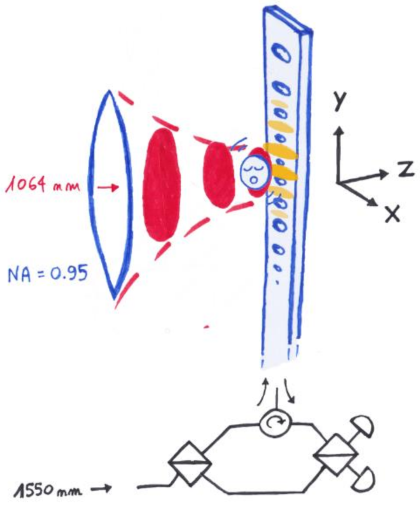
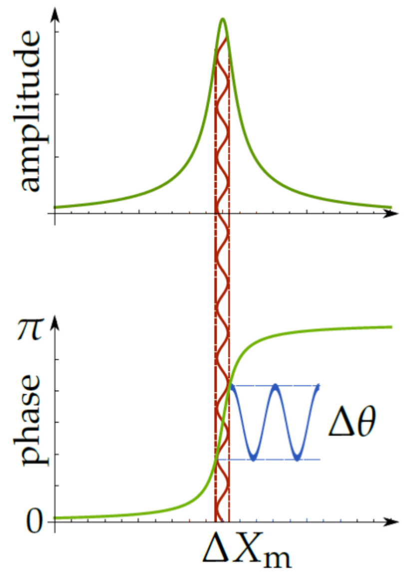
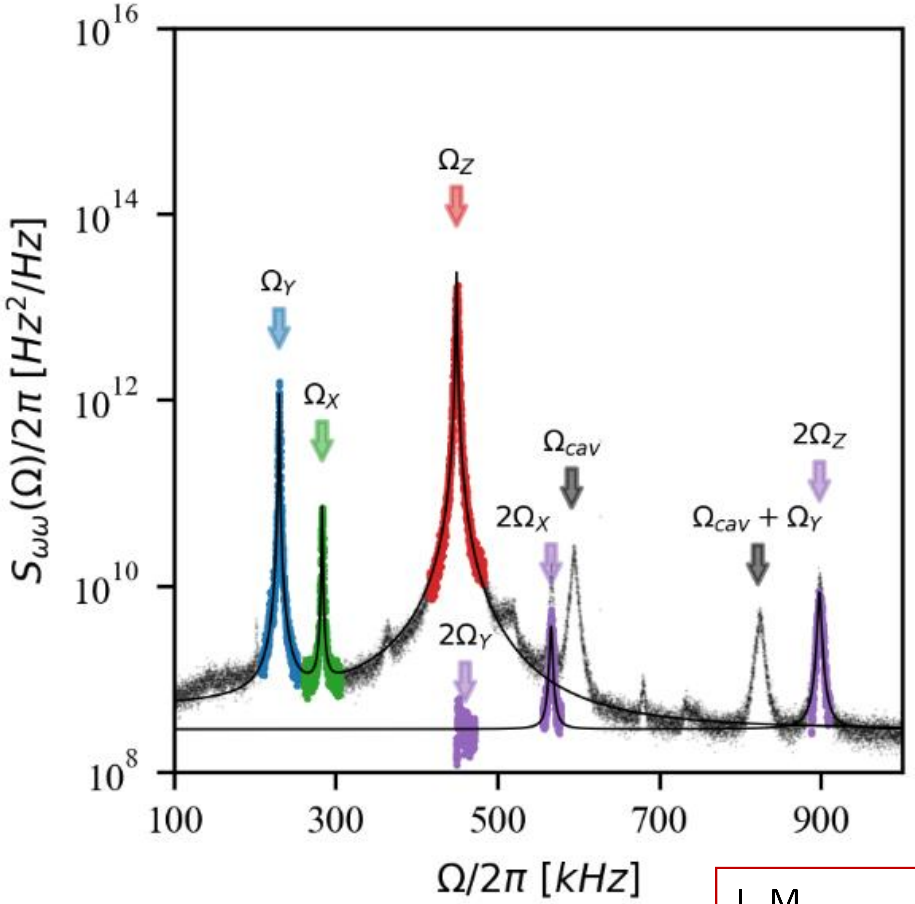
modulation of the cavity resonance

$$S_{\varphi\varphi}(\Omega) = \frac{4}{\kappa^2} S_{\omega\omega}(\Omega) = \frac{4G^2}{\kappa^2} S_{xx}(\Omega)$$







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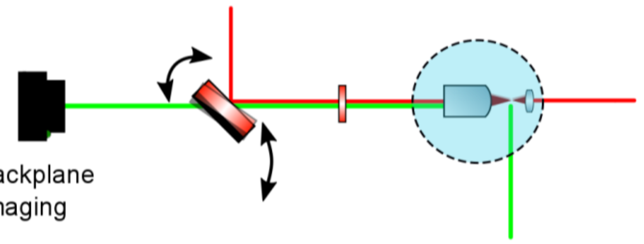
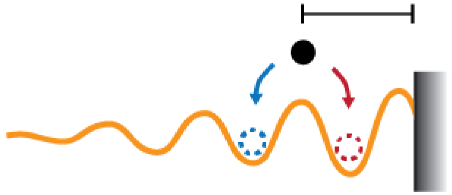
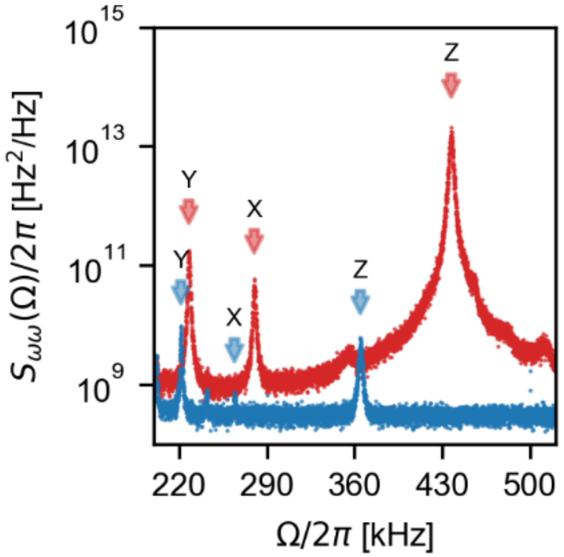
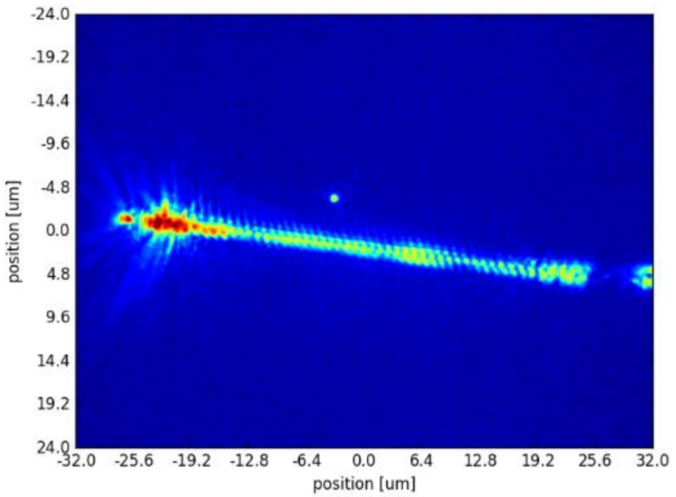
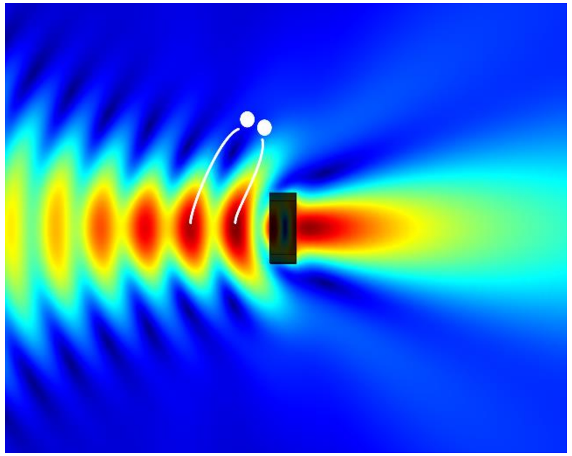
how is the particle loaded close to the cavity

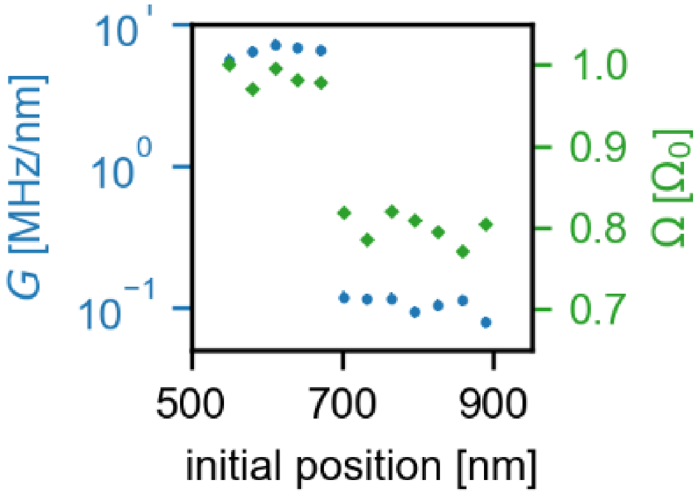












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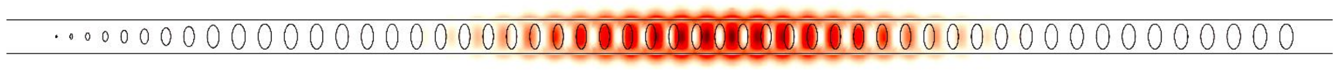
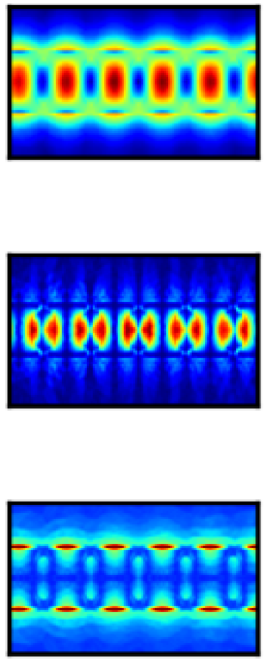
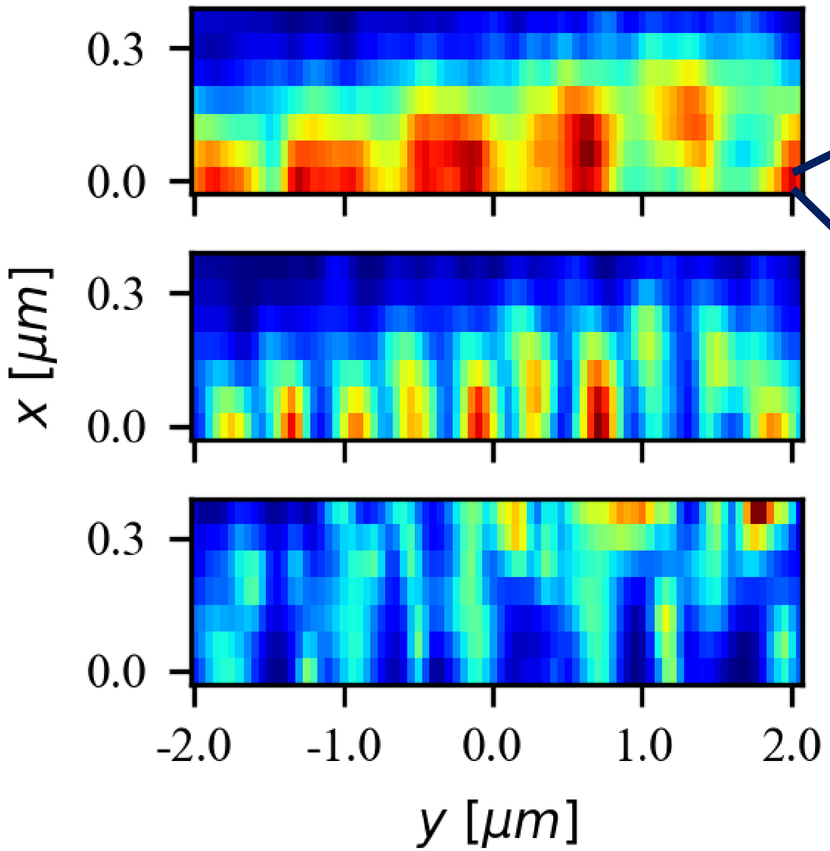
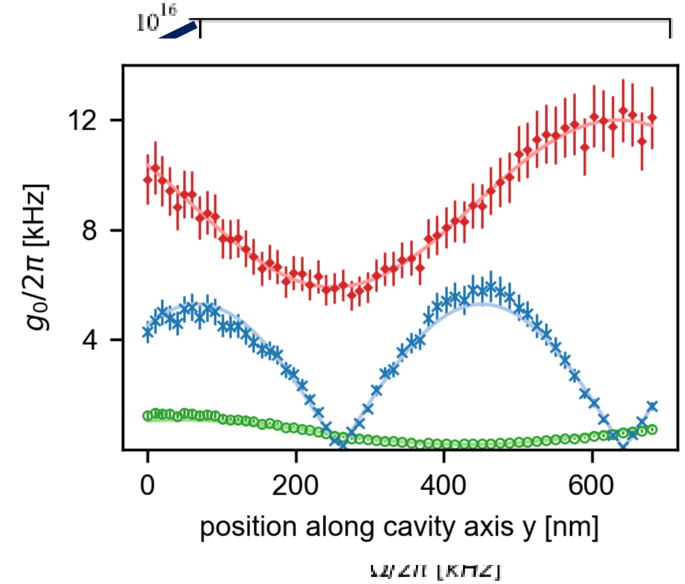
tuning the coupling (mapping the field gradient)

$$g_0^i(x,y,z) \propto \nabla_i E^* E$$









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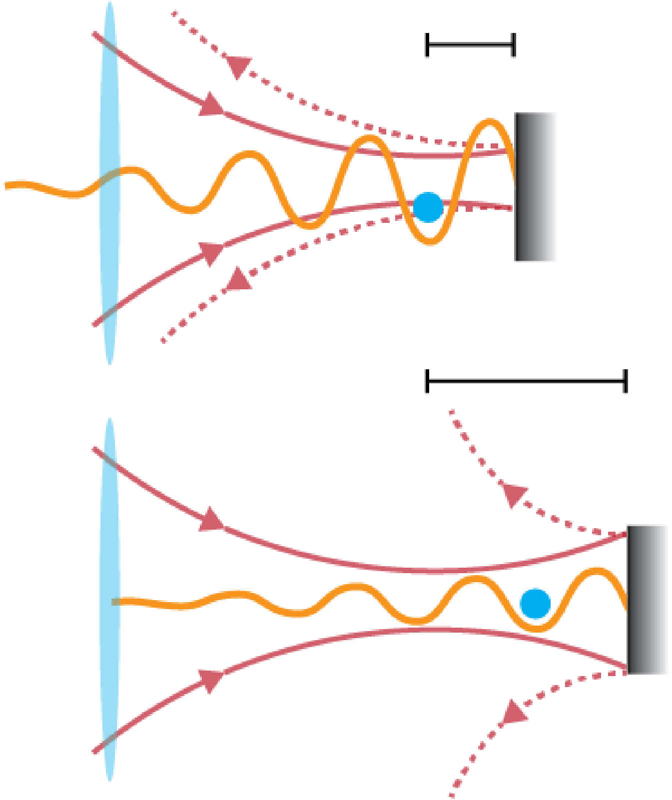
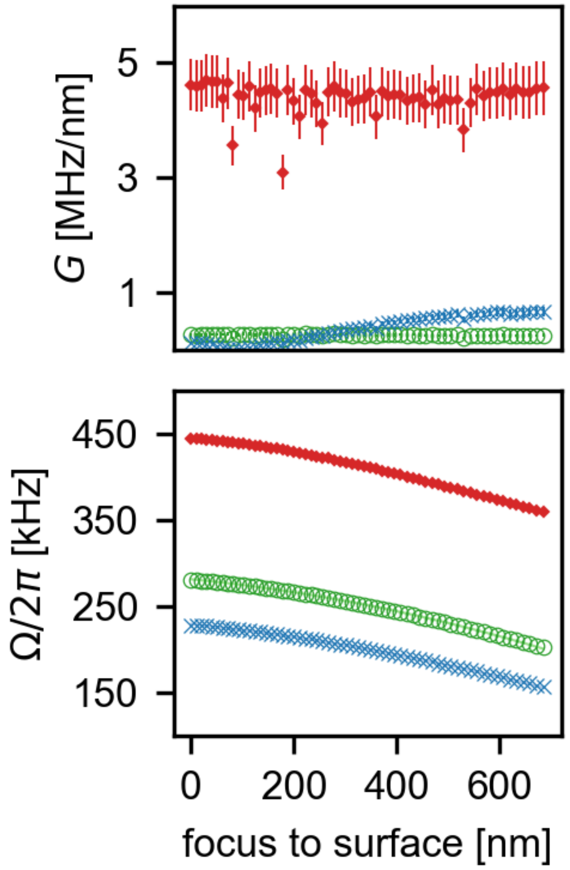
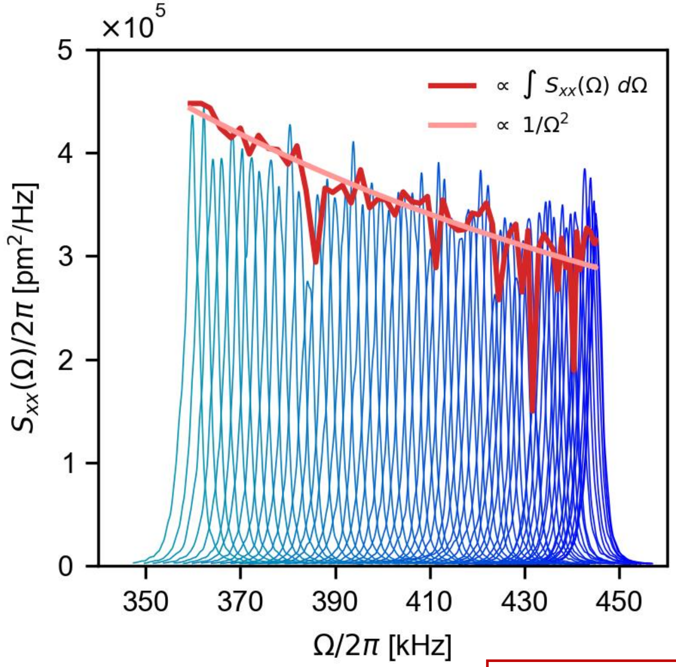
mechanical frequency control





$$\frac{1}{2}k_B T = \frac{1}{2}m\Omega_m^2\langle x^2\rangle$$



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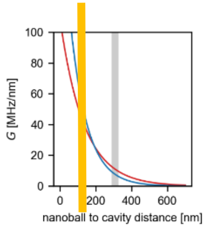
outlook

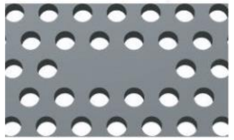
$$C = \frac{4\, g_0^2\, n_{cav}}{\kappa\, \Gamma_{th}} > 1$$

$$\chi = \frac{g_0}{\kappa}\sqrt{n_p} > 1$$

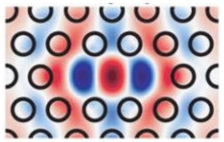
PULSED EXPERIMENTS FOR MECHANICAL SQUEEZING, OPTICAL SQUEEZING, QUANTUM ENHANCED METROLOGY, THERMODYNAMICS…



TRAPPING CLOSER → change cavity thickness



MORE PHOTONS → reduce heating (2D cavity)



IMPROVE CAVITY Q → state of the art is 10^7 (now $3 \cdot 10^4$)

T. Asano *et al.*, Optics Express 3, 2017

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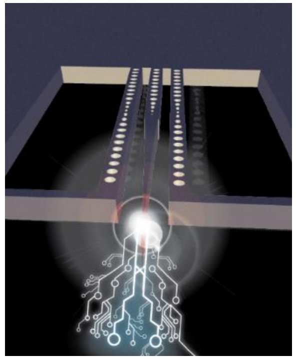
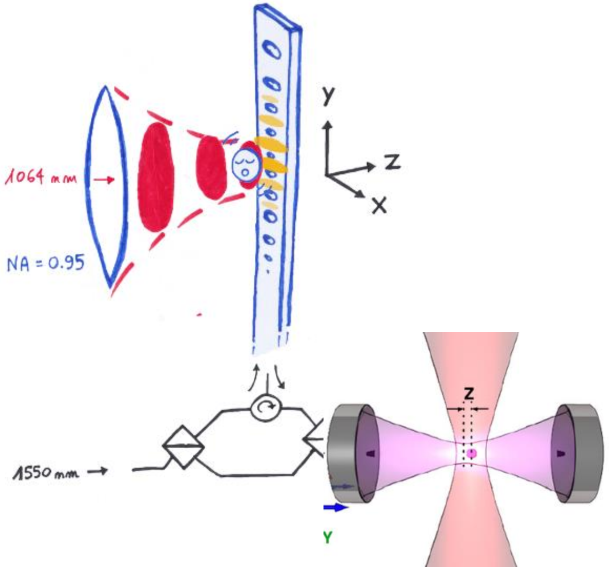
conclusions

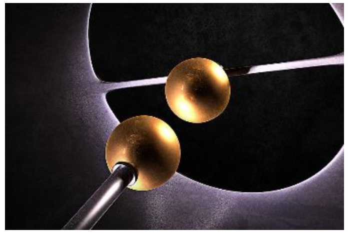


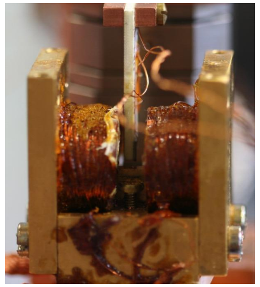
quantum optical control of optomechanical devices with silicon photonics architecture and InGaAs membranes for quantum transducers.

„bottom up“
optical levitation for quantum measurements and manipulation of massive objects



“top down”
how small can one make a gravitational source mass and still detect its gravitational coupling to a nearby test mass?





thank you!

erc

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