Quantum Physics with Massive Objects

Nikolai Kiesel

The Aspelmeyer Group

VCQ
Vienna Center for Quantum Science and Technology

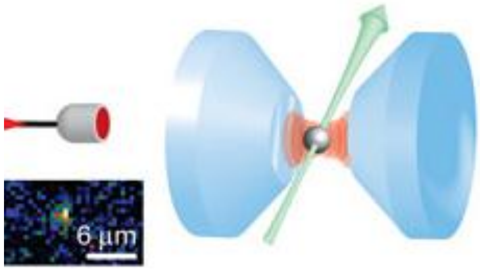
universität wien

ICFP

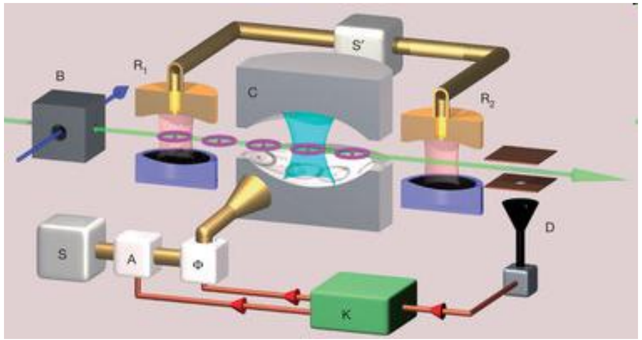
14.06.2012

Well-controlled quantum systems

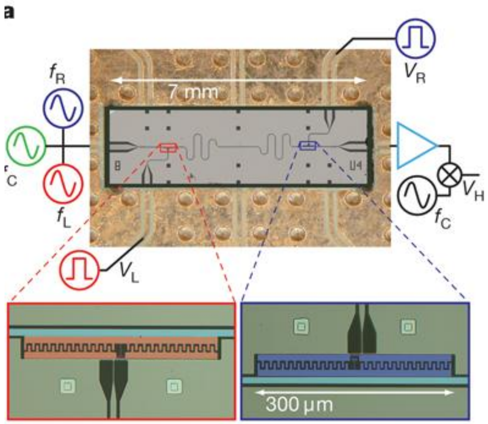
an incomplete selection



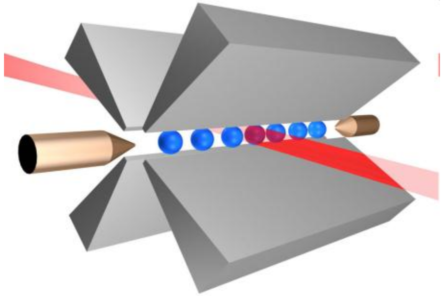
Nature 484, 195 (2012)



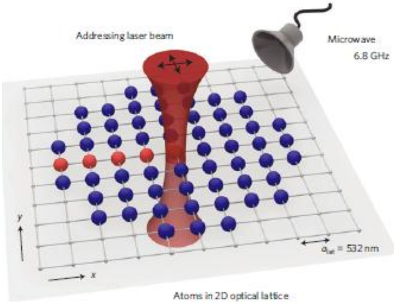
Nature 477, 73 (2011)



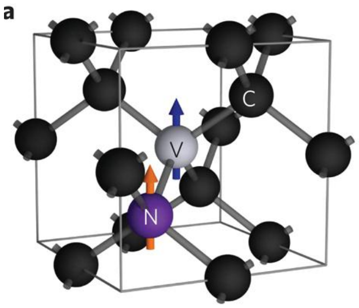
Nature 460, 240 (2009)



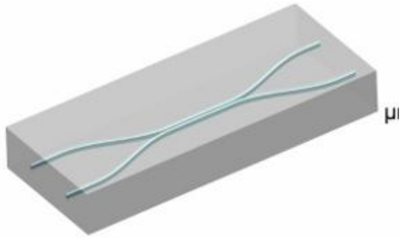
Science 334, 57 (2011),



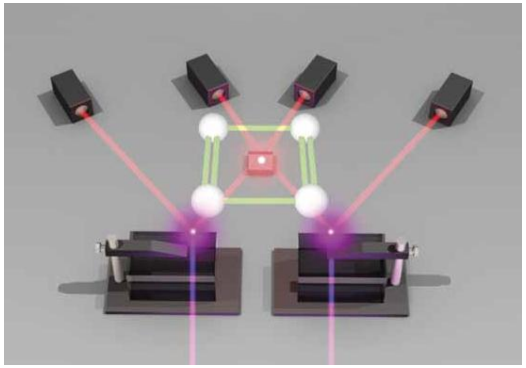
Nat Phys 8, 267 (2012)



. Nanotec. 7, 105-108 (2012)

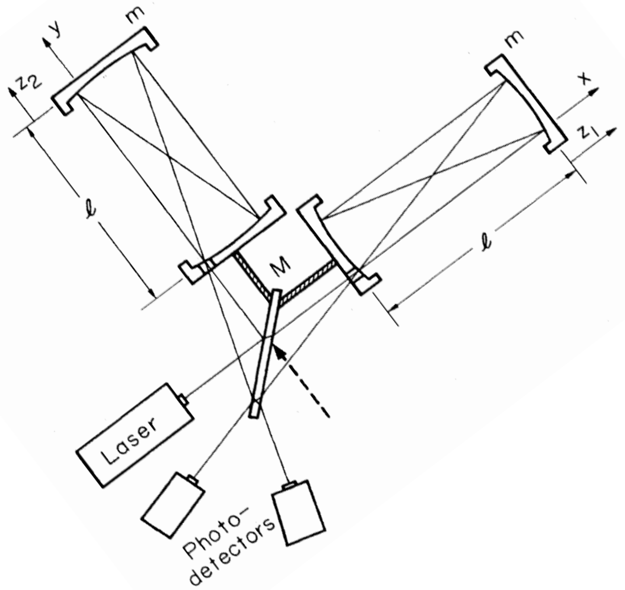


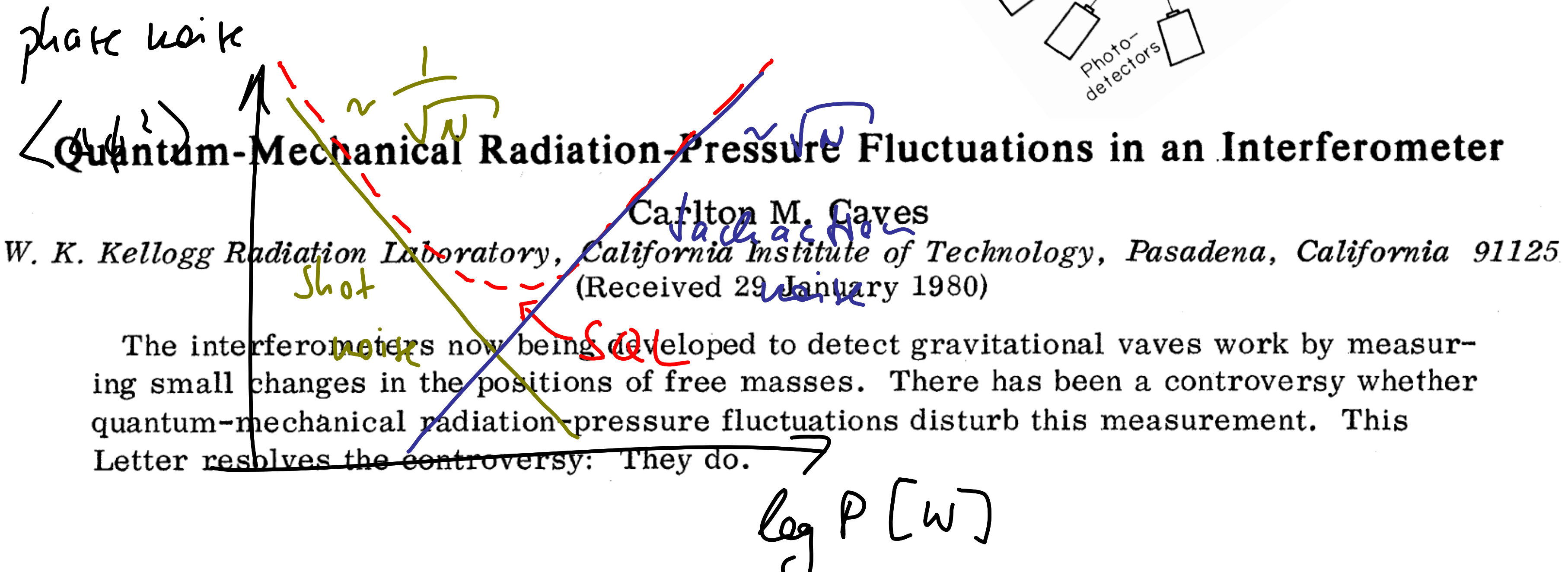
Science 320, 646



Nat. Phys. 8, 285 (2012)

Quantum physics with massive objects?





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.

Controlling mechanical systems in the quantum regime

See also Teufel et al., arxiv 1103.2144 (2011)

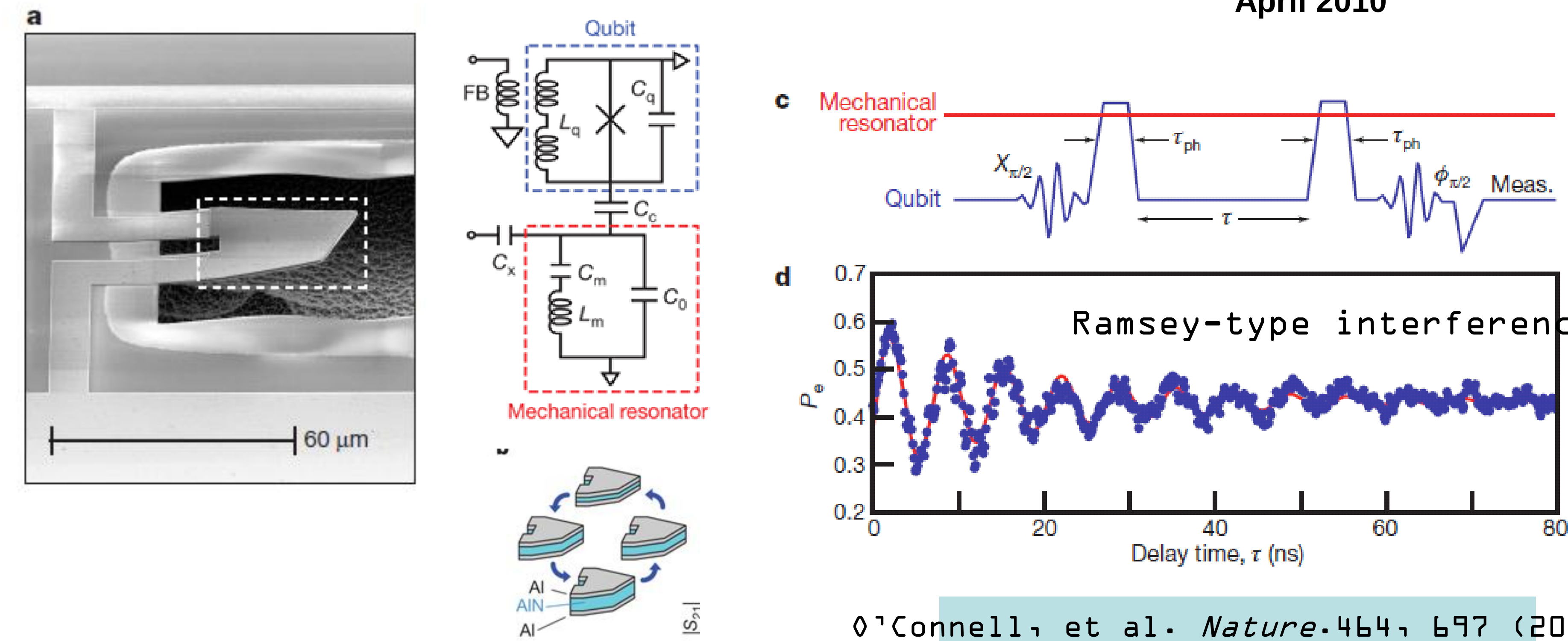
ARTICLES

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]

6 GHz piezo vibration → n ~ 0.07 @ 20 mK

Cleland/Martinis groups (UCSB); April 2010



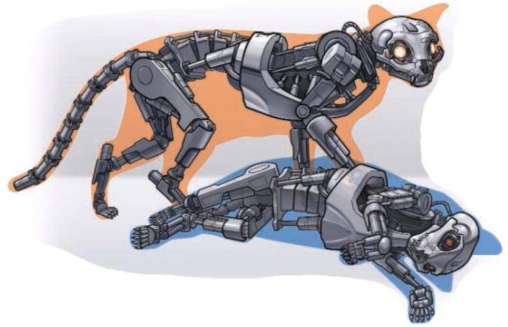
Ramsey-type interference

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

Quantum regime of massive resonators

Cho , Science 327, 516 (201

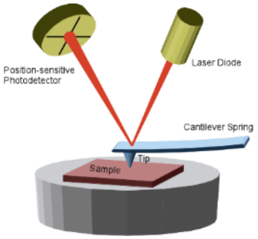
Access a new realm of experimental physi



Quantum Foundations

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

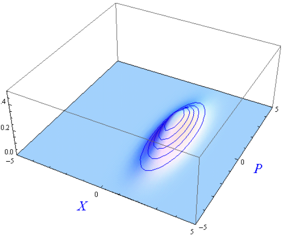
→ *Is there a limit to the size/mass of Schrödinger cats?*



Mechanical Sensing

present performance: zeptogram, zeptonewton, attom

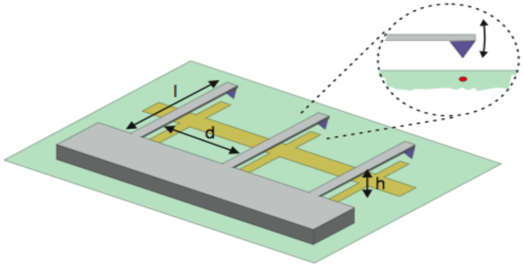
→ *What are the quantum limits to mechanical sensi*



Quantum Information

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

→ *Can mechanical systems serve as universal quantu*



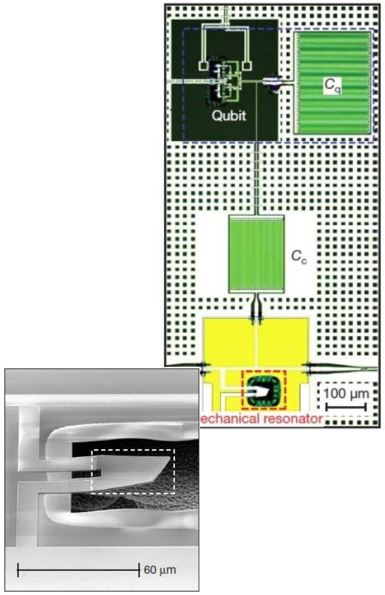
Rabl et al.,
ature Physics 6, 602 (2010).

Coupling to mechanics

charge

Q

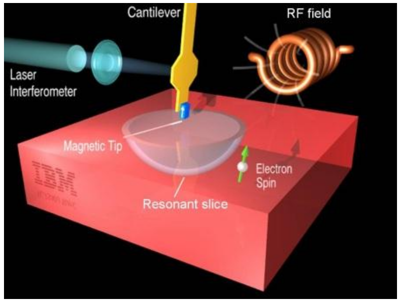
U



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

spin

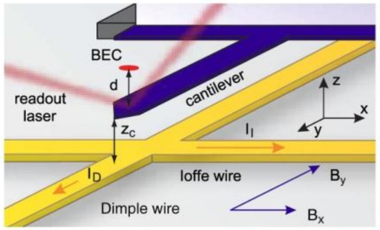
$\mu \quad B$



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

atoms

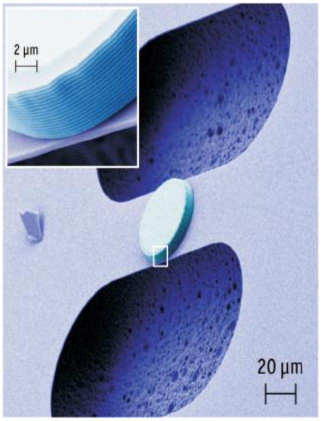
$V(z)$



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

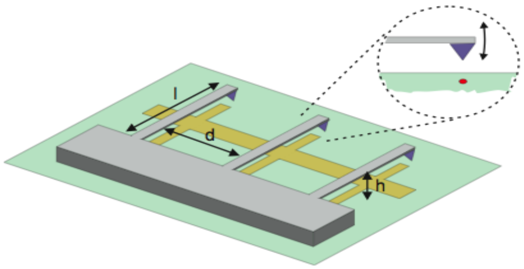
photon momentum

$\hbar k$

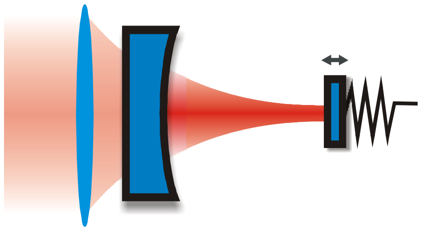


S. Gröblacher et al.,
Nature Phys. 5 (09)

Cavity Optomechanics

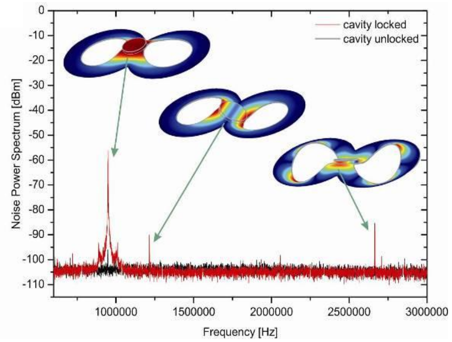


Massive mechanical quantum systems?



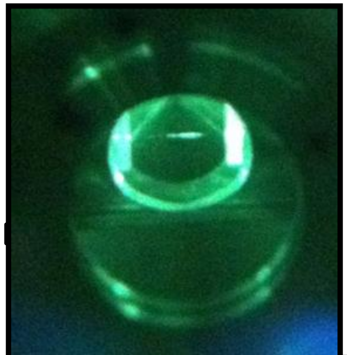
ics and Light - a short history and basic princi

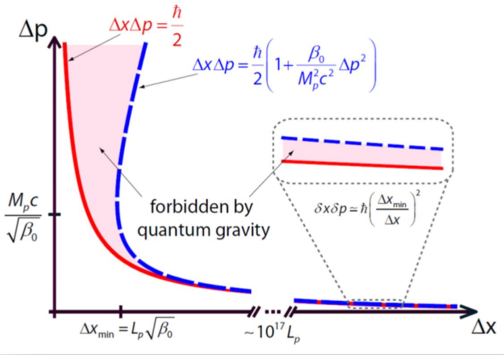
http://vcq.quantum.at/fet11.5397.html



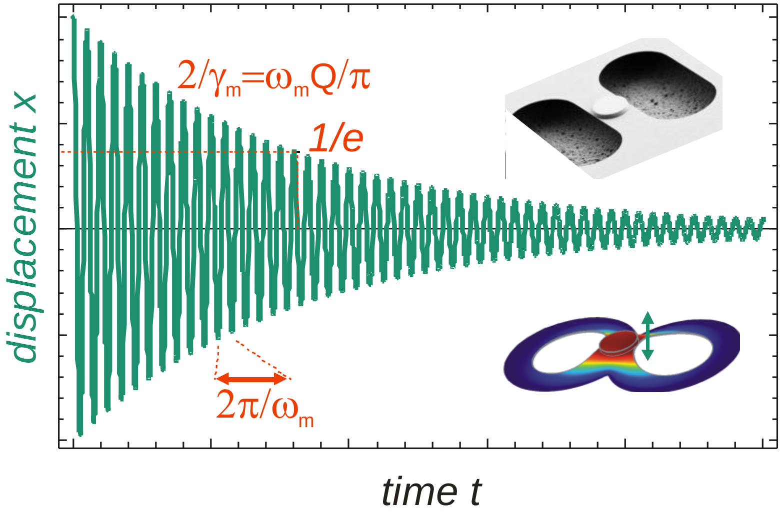
Towards Quantum Optomechanics - Experiments

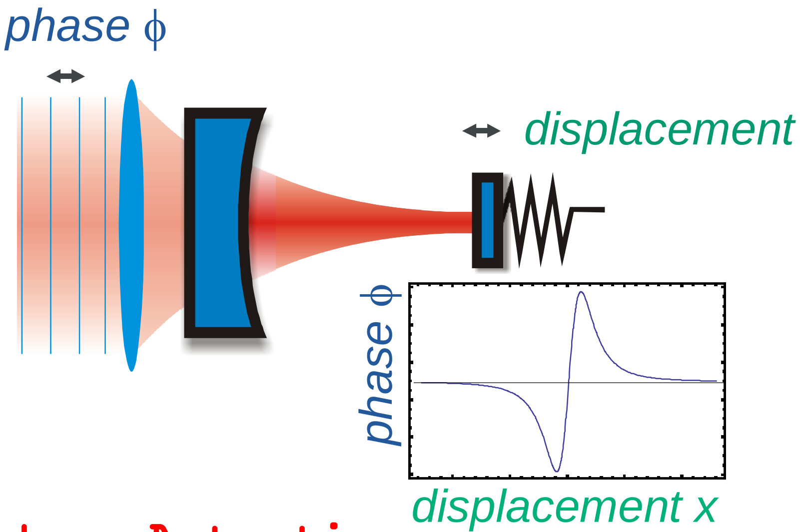
New ideas and future pla



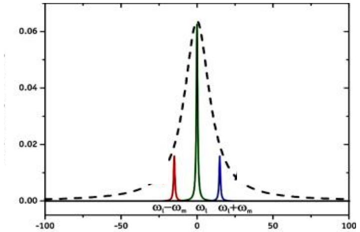


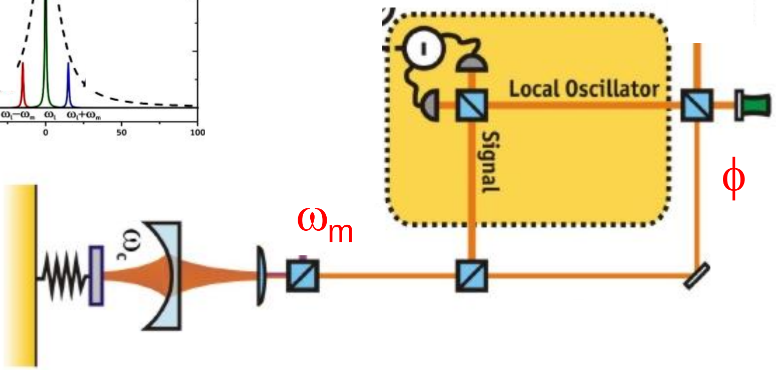
Cavity Optomechanics - Readout

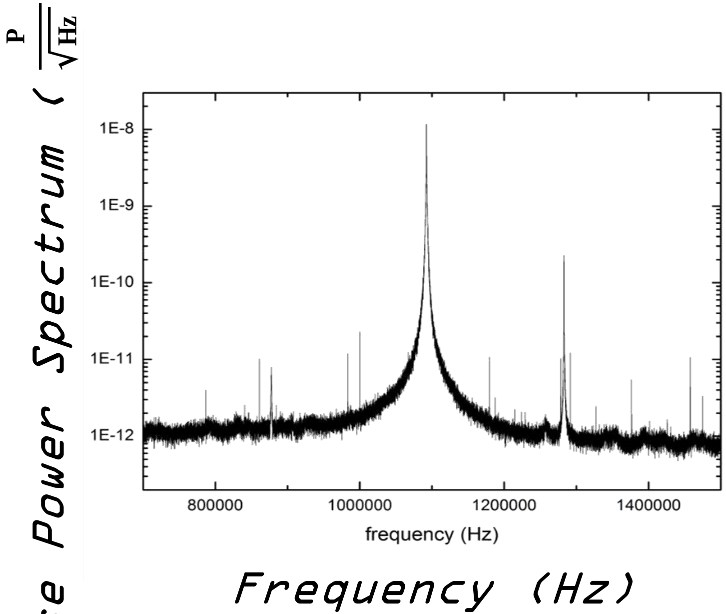




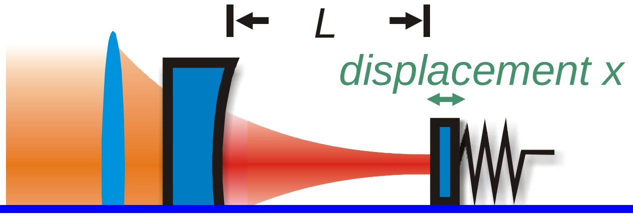
Readout by Homodyne Detection







Cavity Optomechanics



Idea: Added optical cavity allows to **manipulate**

A bit of history…

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

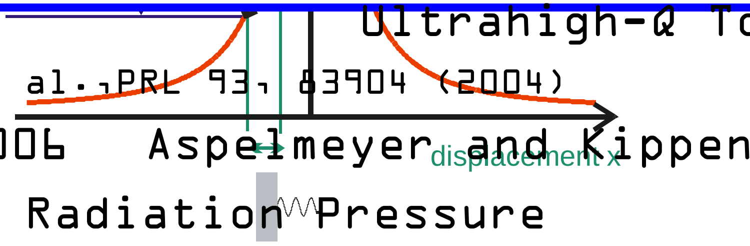
2003 Karrai group: „Optically tunable mechanics of microlevers"

Favero et al.,APL 83,1337 (2003)

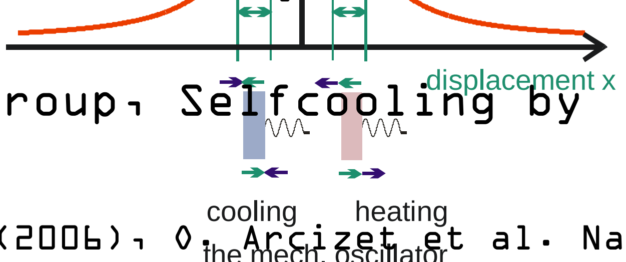
2005 Vahala group: "Kerr-Nonlinearity Optical Parametric Oscillation in an Ultrahigh-Q Toroid Microcavity" Kippenberg et al.,PRL 93, 83904 (2004)

2006 Aspelmeyer and Kippenberg group, Selfcooling by Radiation Pressure

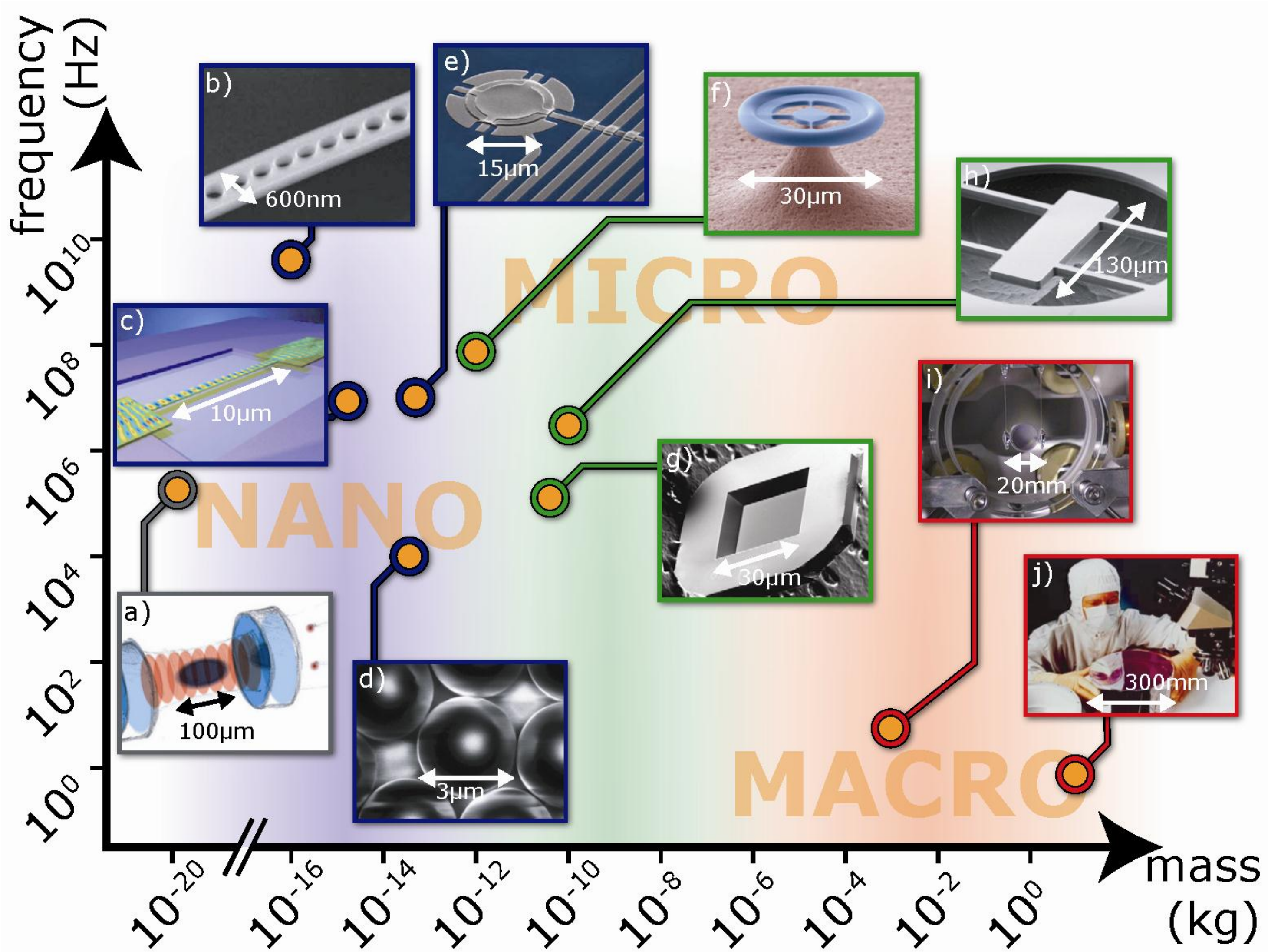
S. Gigan et al. Nature 444, 67970 (2006), O. Arcizet et al. Nature



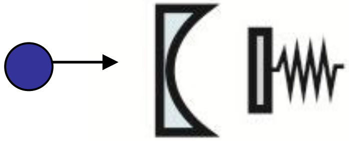
nge in spring constant : optical spring



Optomechanical Systems



Cavity Optomechanics – The quantum version



$$H_{\text{int}} = -\hbar g_0 n_c X_m$$

single-phonon cavity frequency shift

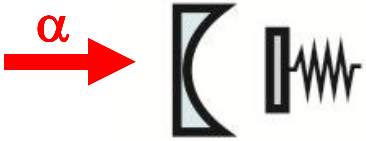
$$g_0 = \frac{\omega_c}{L}\sqrt{\frac{\hbar}{m\omega_m}}$$

0.1...100 Hz

with most current systems (exception later)

(too small!!)

Solution: strongly driven optomechanics



$$H_{\text{int}} = \hbar g_0 \alpha X_c X_m$$

enhancement by α

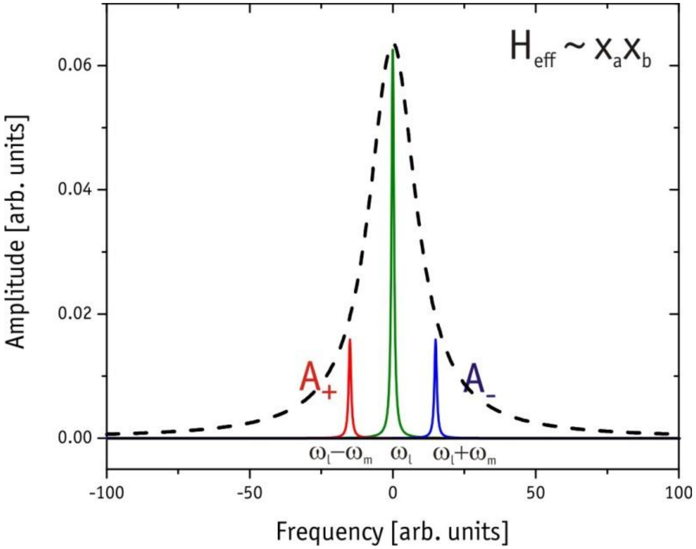
$$a \to \alpha + \bar{a}$$

$$\alpha = \sqrt{n_c} \approx \theta(10^5)$$

→ strong coupling

rade-off: only linear coupling... BUT...

Linear coupling is sufficient



QND Measurement

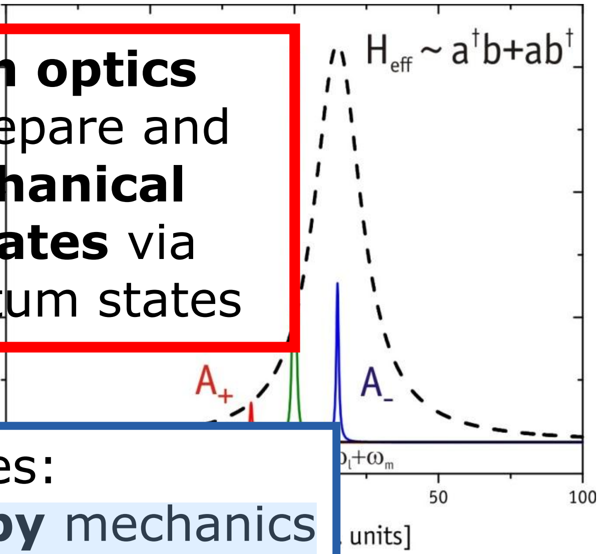
full **quantum optics toolbox** to prepare and control **mechanical quantum states** via photonic quantum states

Requires:

Minimum entropy mechanics (e.g. ground state)

+

Strong optomechanical coupling (coupling rate > decoherence rate)



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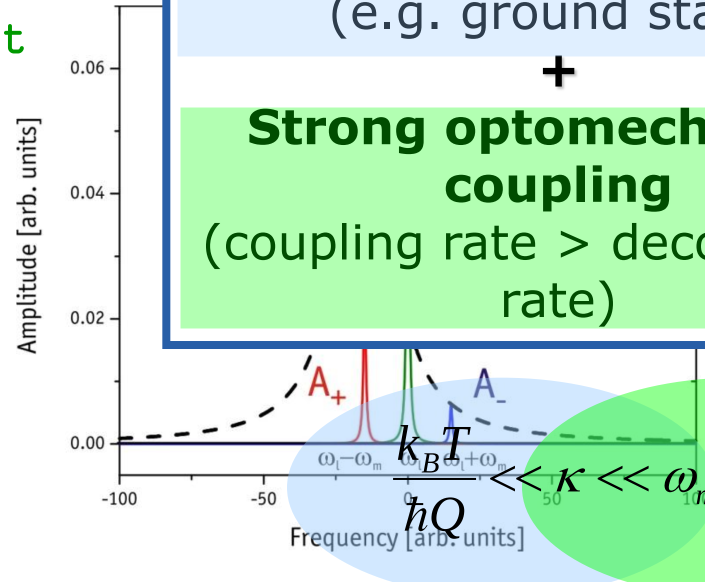


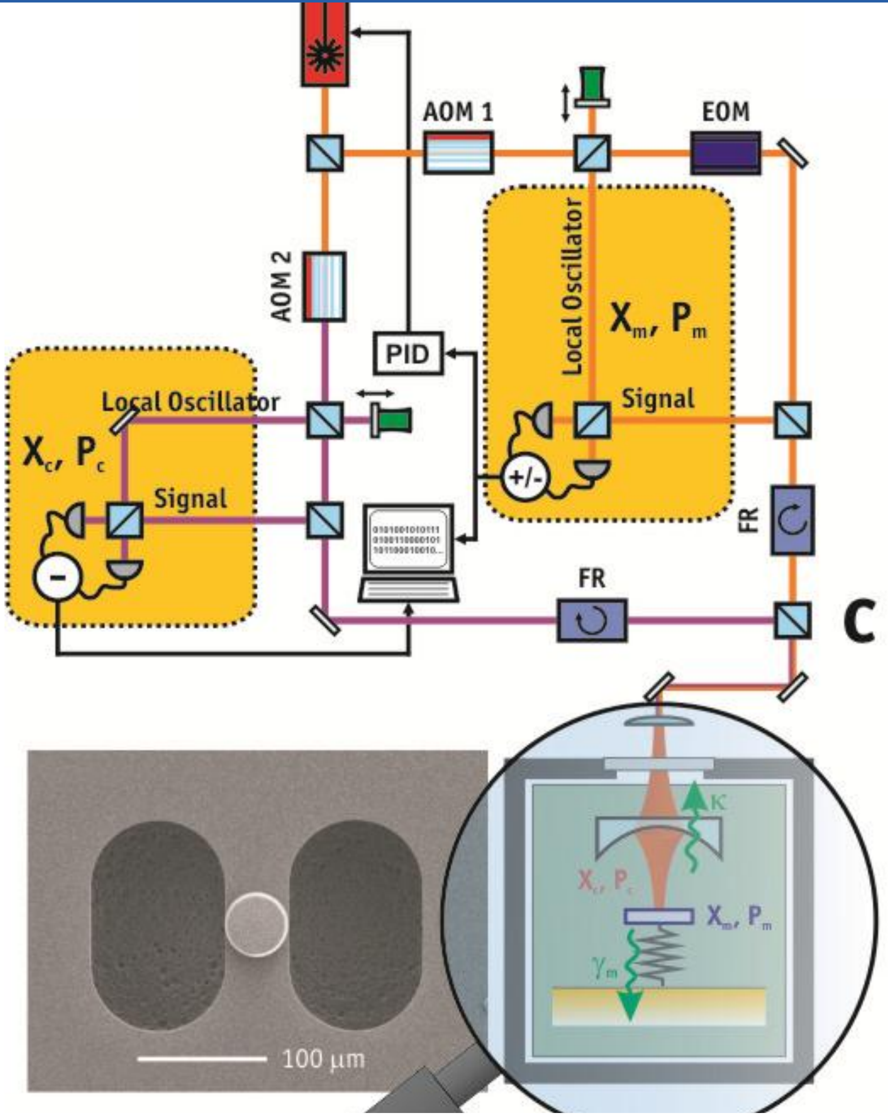
$$\frac{k_B T}{\hbar Q} << \kappa << \omega_m, g$$

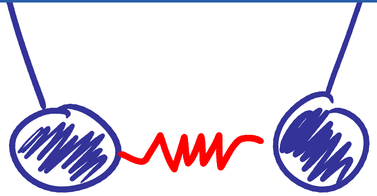
ng et al., PRA 68, 13808 (2003)

Squeezing Interaction

RWA approximation: $g \ll \omega_m$

Strong optomechanical coupling





„strong coupling“: hybrid „optomechanical“ system → new energy spectrum

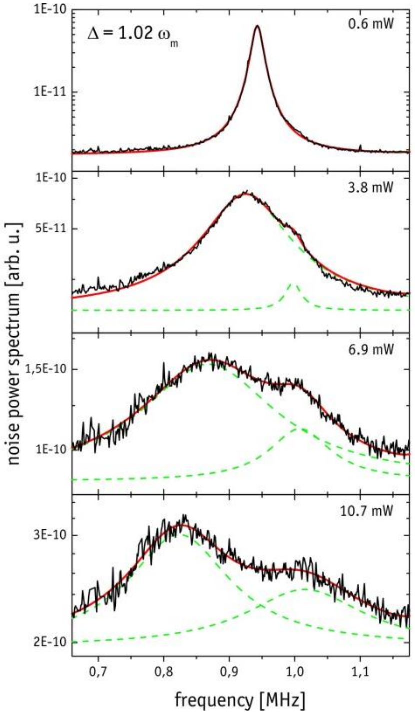
$$X_{\pm} = \sqrt{\frac{\omega_\mathrm{m} \pm g}{2\omega_\mathrm{m}}}(X_\mathrm{c} \pm X_\mathrm{m}) \quad P_{\pm} = \sqrt{\frac{\omega_\mathrm{m}}{2(\omega_\mathrm{m} \pm g)}}(P_c \pm P_\mathrm{m})$$

$g \approx 2\pi \times 325$ kHz
$\kappa = 2\pi \times 215$ kHz
$\gamma_m = 2\pi \times 140$ Hz

$$g > \kappa, \gamma_m$$

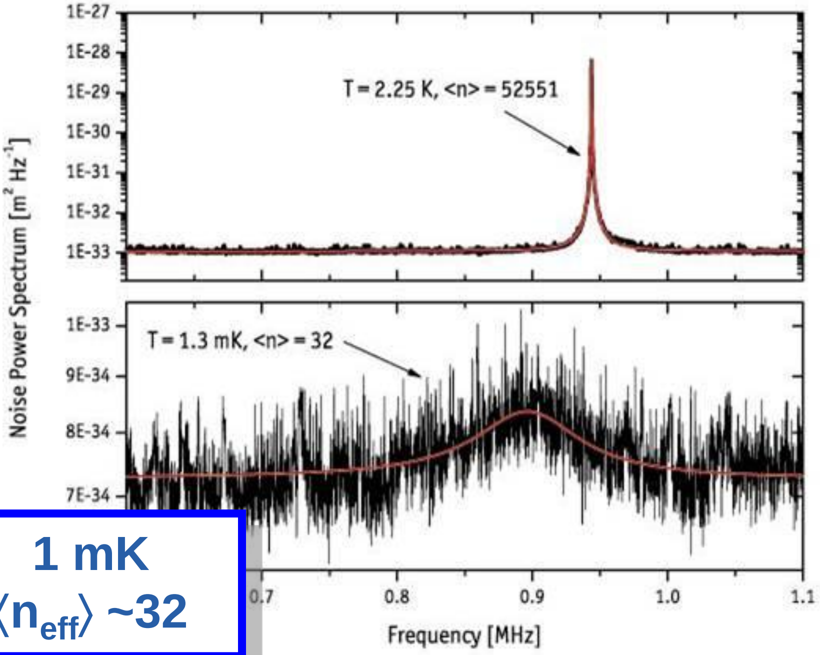
↑

Important coupling condition for coherent quantum control!

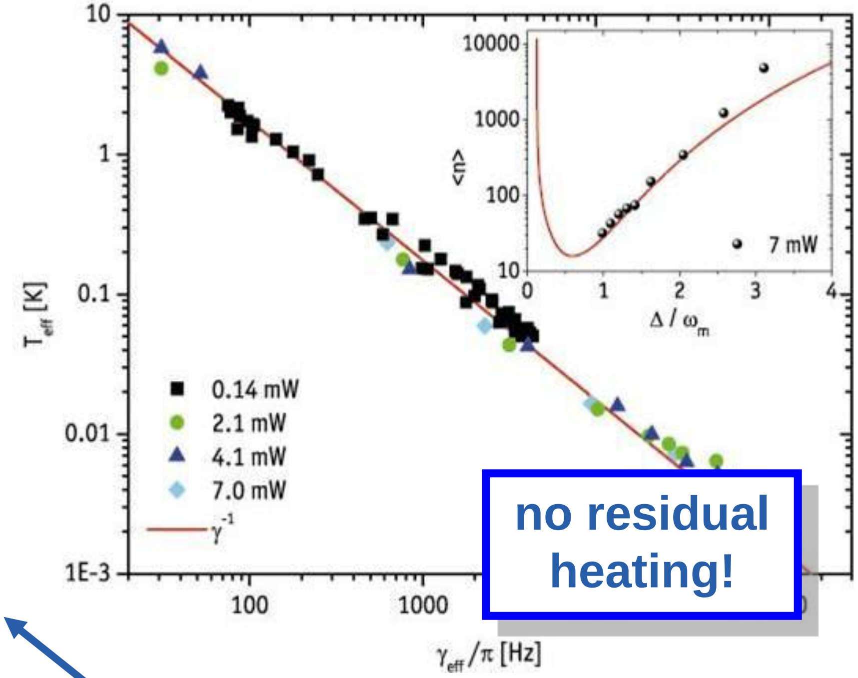


Gröblacher, Hammerer, Vanner, Aspelmeyer, **Nature 460, 724 (2009)**
See also Teufel et al., Nature 471, 204 (2011); Verhagen et al., Nature 482, 63 (2012)

Optomechanical Cooling



1 mK
⟨n_{eff}⟩ ~32

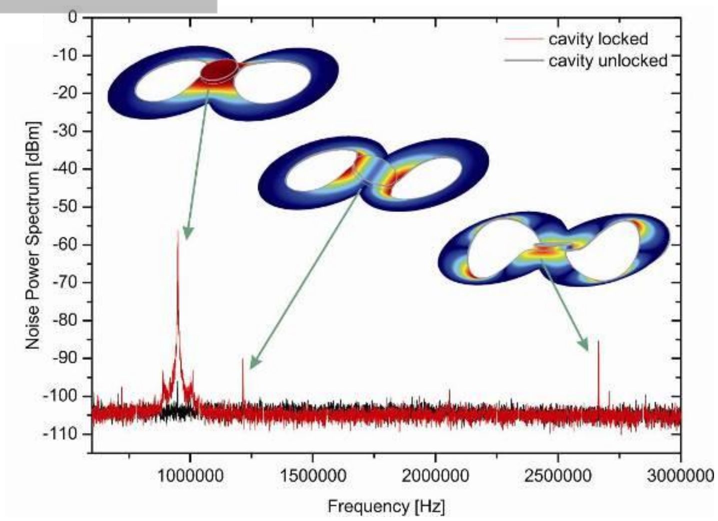


no residual heating!

noise floor ~ 2.6×10^{-17} mHz$^{-1/2}$

4x above the shot noise

4x above the shot noise



relevant modes identified via

via

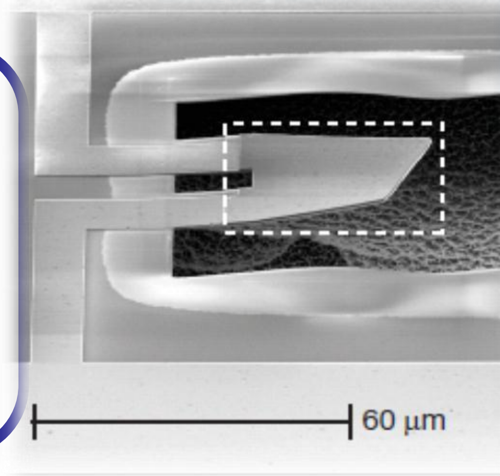
Gröblacher et. al, Nature Physics, 5, 2009

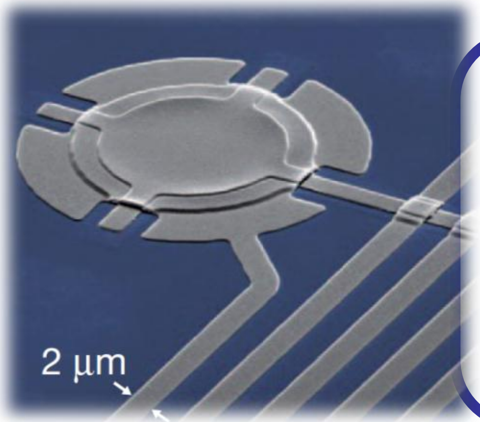
Mechanical Systems IN the quantum regime

Nature **464**, 697-703 (2010)

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]





Nature **475**, 359-363 (2011)

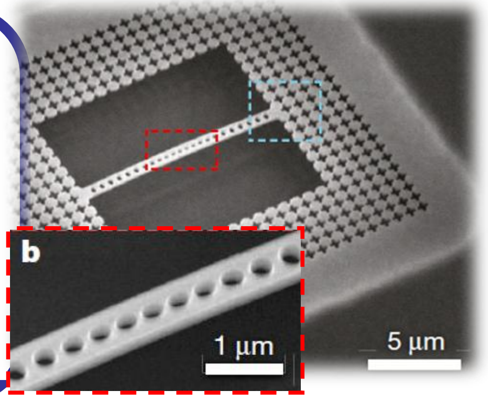
Sideband cooling of micromechanical motion to the quantum ground state

J. D. Teufel[1], T. Donner[2,3], Dale Li[1], J. W. Harlow[2,3], M. S. Allman[1,3], K. Cicak[1], A. J. Sirois[1,3], J. D. Whittaker[1,3], K. W. Lehnert[2,3] & R. W. Simmonds[1]

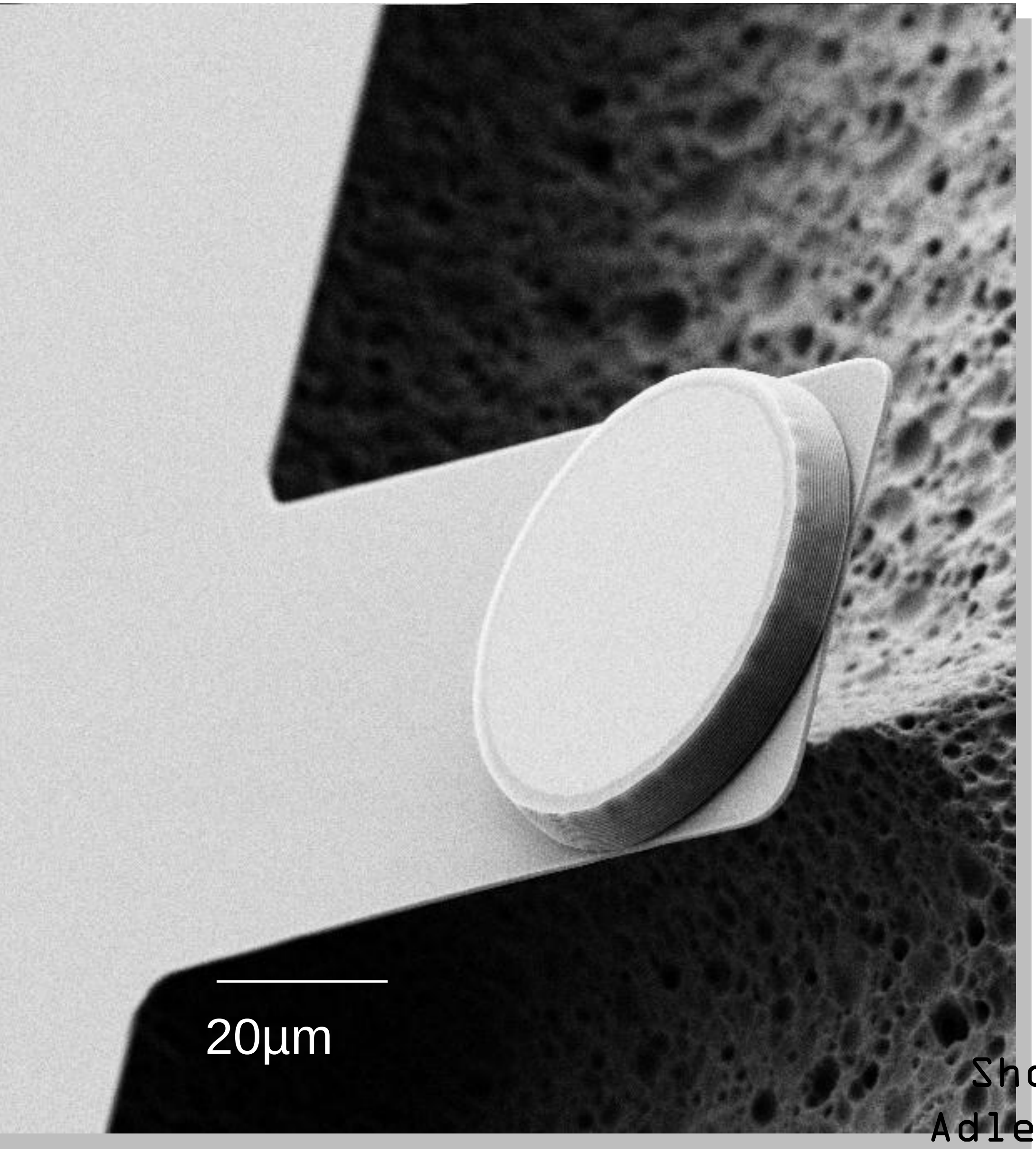
Nature **478**, 89-92 (2011)

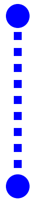
Laser cooling of a nanomechanical oscillator into its quantum ground state

Jasper Chan[1], T. P. Mayer Alegre[1]†, Amir H. Safavi-Naeini[1], Jeff T. Hill[1], Alex Krause[1], Simon Gröblacher[1,2], Markus Aspelmeyer[2] & Oskar Painter[1]



A mechanical cat? Schrödinger's mirrors?





Superposition of macroscopically distinct states?

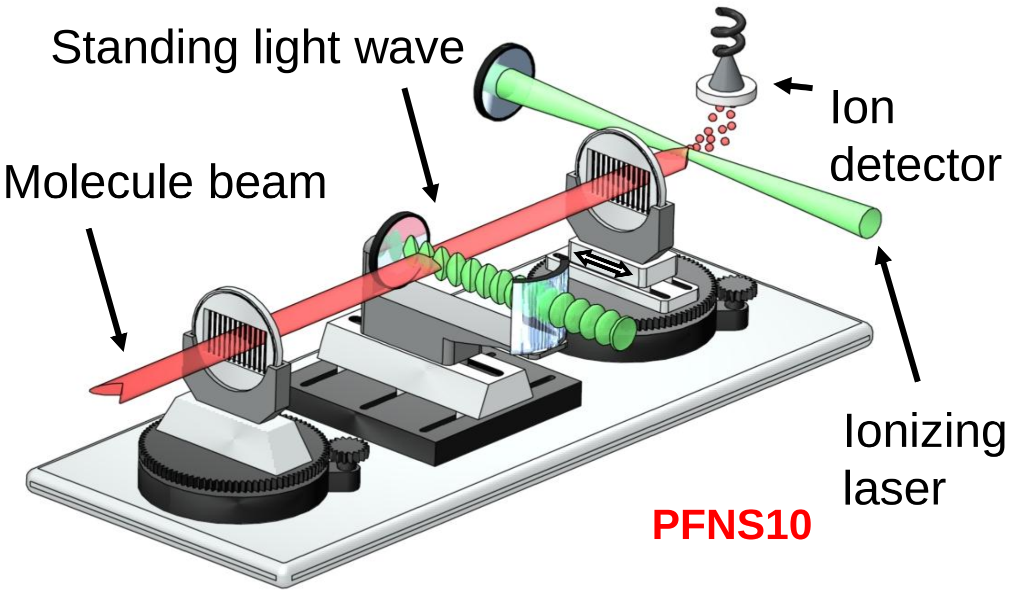
Tests of macrorealistic theories? (Collapse models, Leggett-Garg, …)

Tests of predictions of quantum gravity?

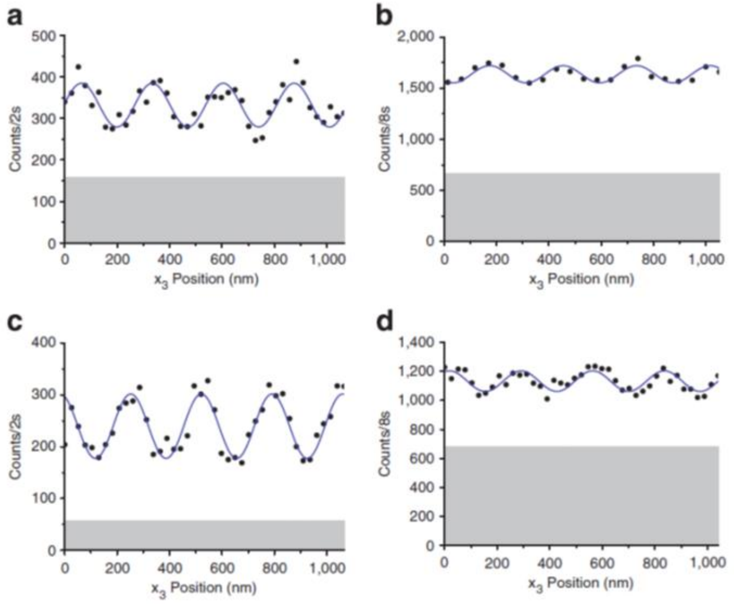
Short introduction to the subje

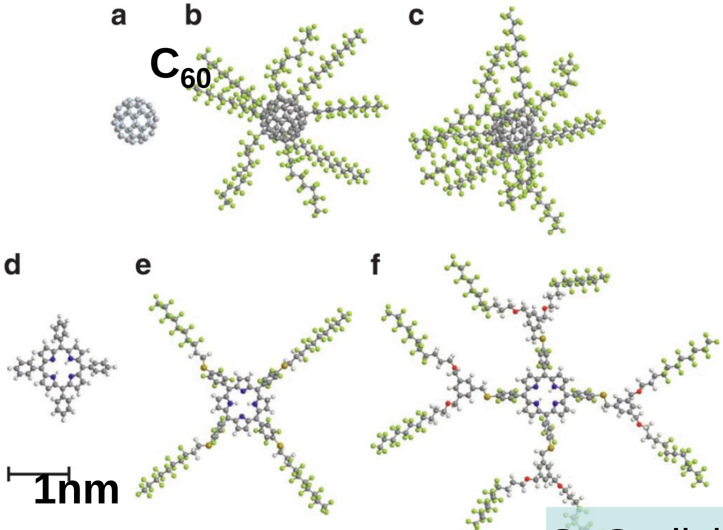
Adler, Bassi, Science 325, 275 (2

Talbot-Lau Interferometry with Macromolecules (Arndt group)



PFNS10





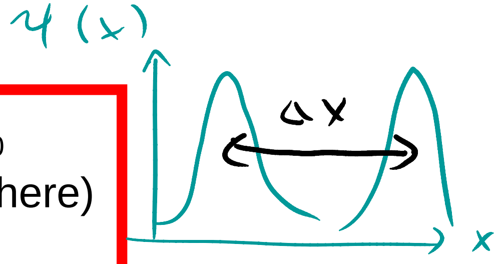
PFNS10: $C_{60}[C_{12}F_{25}]_{10}$

(perfluoroalkylated nanosphere)

430 atoms

m ~ 10^{-23} kg = 6910 AMU

Δx ~ 100 nm (~50x its diameter)



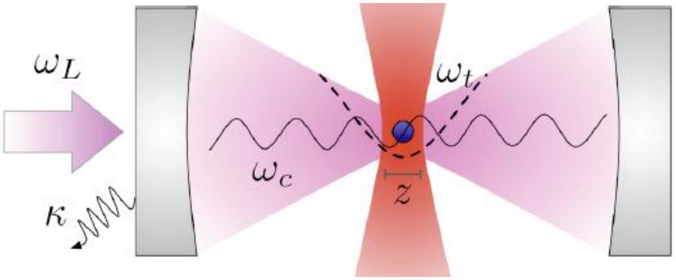
S. Gerlich, S. Eibenberger et al., Nature Communications **2**, 263 (2011)

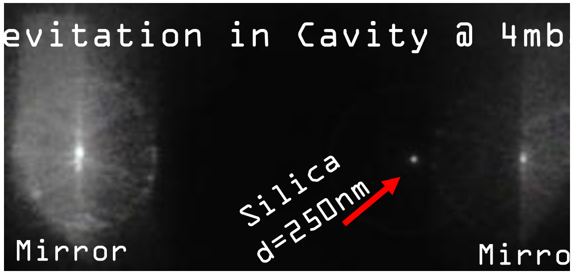
Towards state preparation of a free particle

Magnetically levitated spheres Romero-Isart et al., 1112.5609, Cirio et al., 1112.5208

Optically levitated nanospheres

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)

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

→ **Full Control of Spring Constant**
(parametric contol, thermodynamic cycles, removing potential)

Generation of quantum superposition states of CM position/ momentum

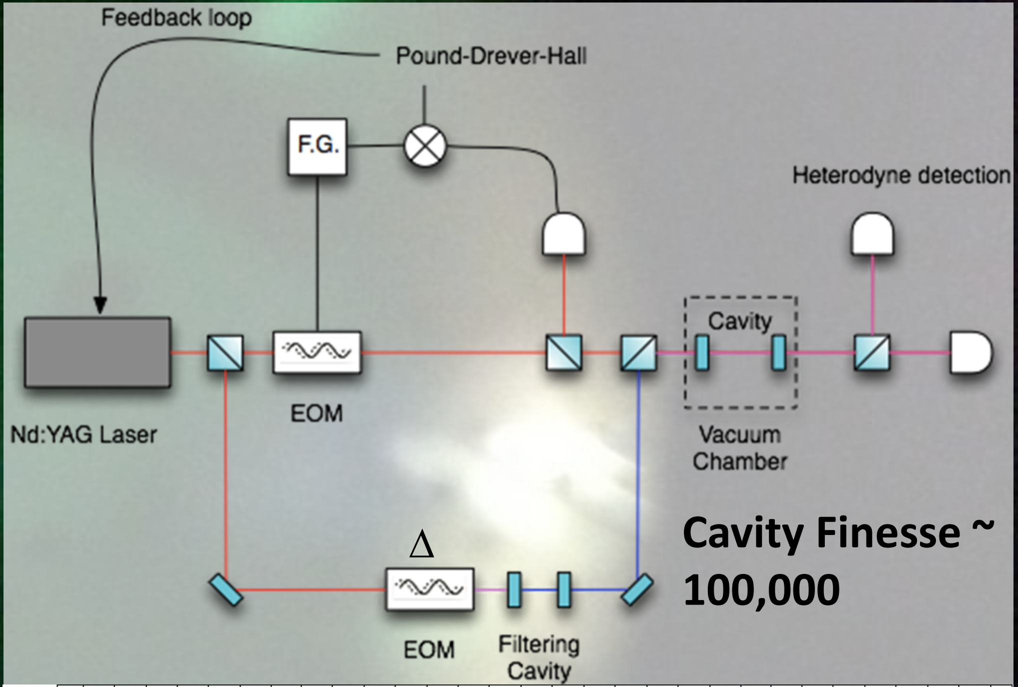
- single-photon quantum state transfer
- quantum state teleportation
- …

Akram, et al., NJP 12, 083030 (2010)
Khalili, Phys. Rev. Lett. 105, 070403 (2010)
Romero-Isart et al., PRA 83, 013803 (2011)

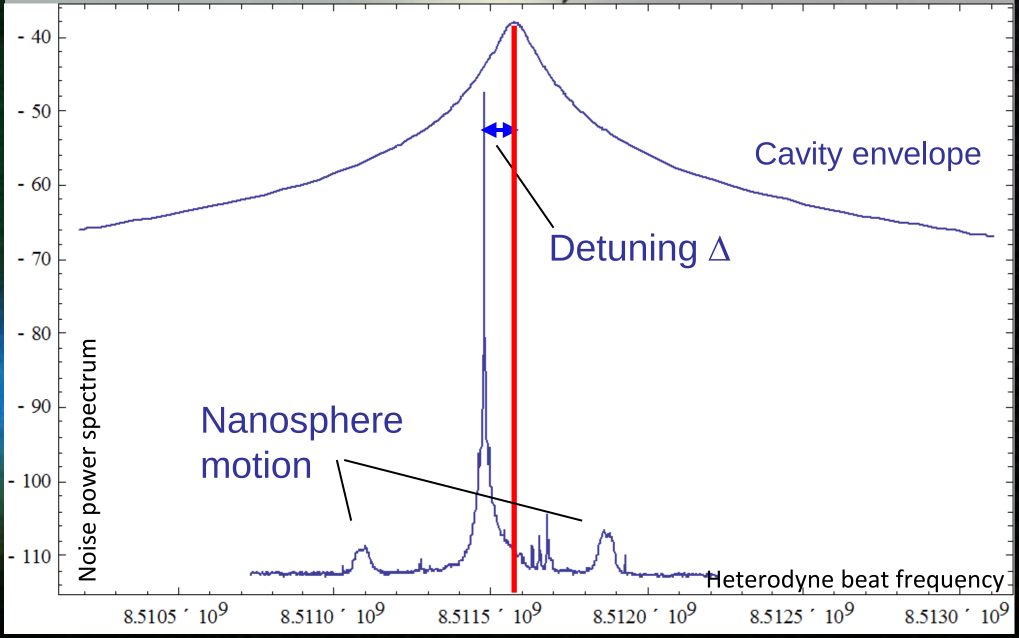
- ***free fall experiments - interferometry :*** *is there intrinsic additional decoherence for massive objects (here 10^10 amu)?*

Optically trapped nanospheres as mechanical resonators

Ashkin since 1967
Raizen group, Science 2010
Novotny 2012



Cavity Finesse ~ 100,000



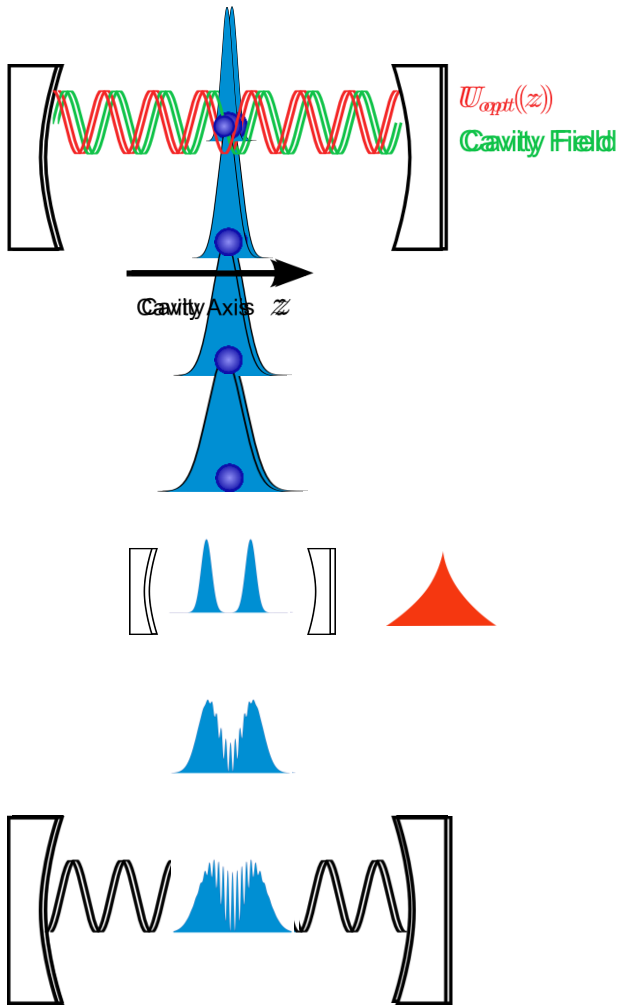
Cavity envelope

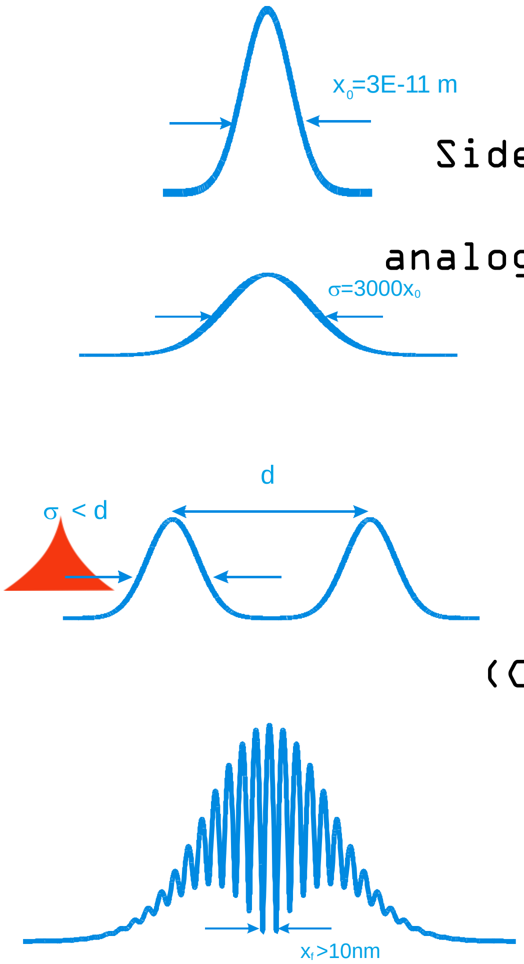
Detuning Δ

Nanosphere motion

Optical trapping inside a cavity… (R~20nm – 2µm)
Kiesel et al., work in progress

Potential Parameter Set





Object: D=40nm
Silica Sphere

Sideband Cooling of Nanospher
to 0.1 phonons
analogous to cooling of micromi

3.3 ms

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

125 ms

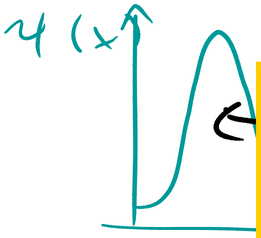
Position Detection
Precision: 10nm

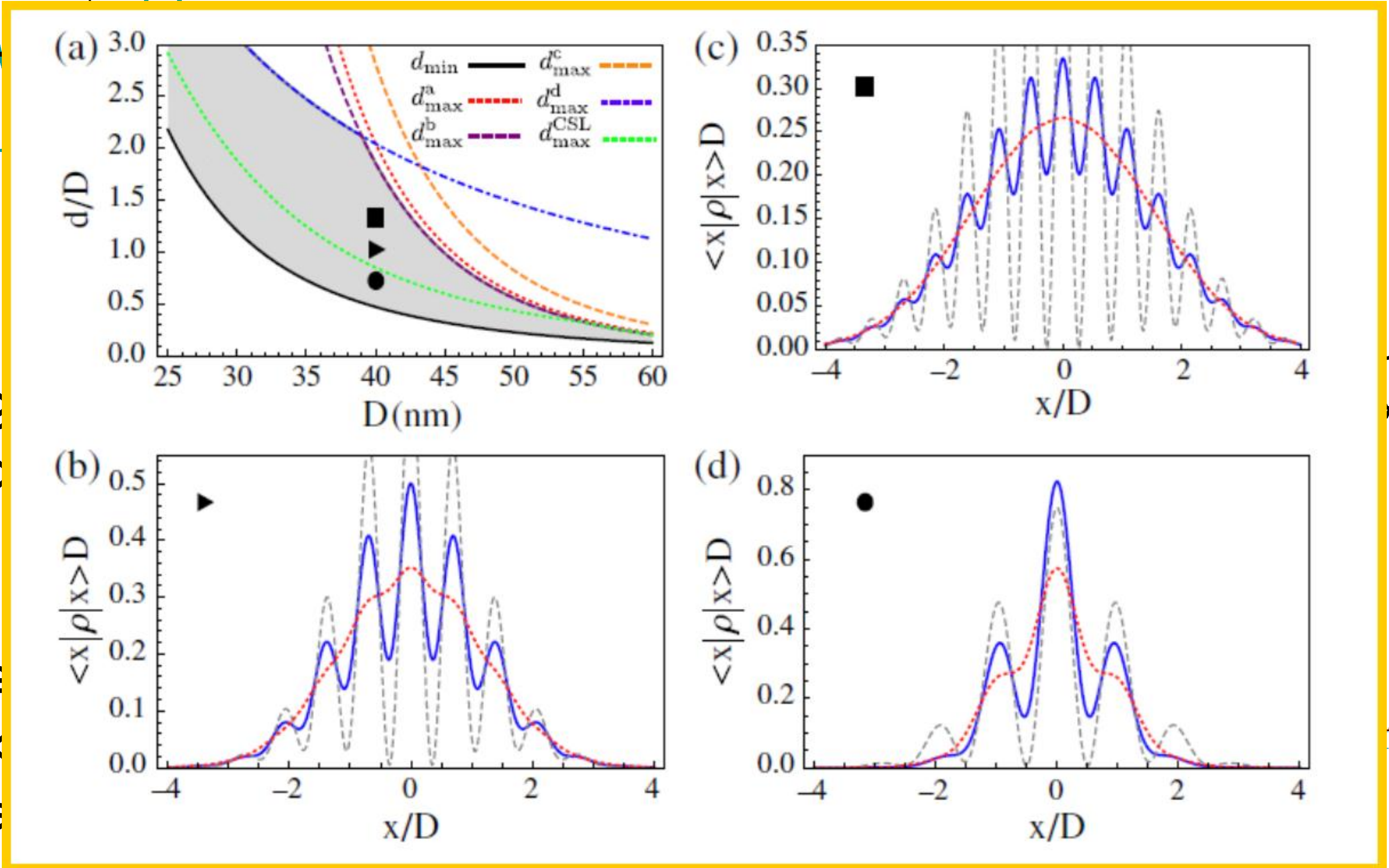
O. Romero-Isart et al., PRL 107, 020405
(2011)
sart , arXiv:1110.4495

See also YouTube-talk by O.R.I. at
ITAMP

One possible application: test of alternative decoherence models

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





Δx ~

Backg

gas p

mbar

(here

black

radi

um

y

nm)

Karolyh

Diosi (

Penrose (1980s), e.g. Gen. Rel. Grav. 34, 1141 (2002)

mbar , T ~

In collaboration with O. Romero-Isart, A. Pf

see also Romero-Isart, Phys. Rev. A 84, 0521

MAQRO: Macroscopic Quantum Resonators for Space

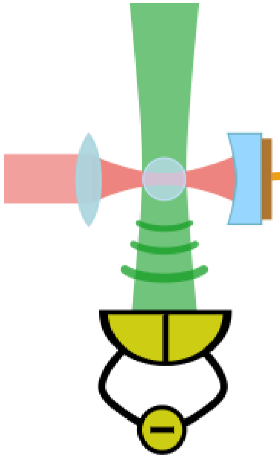
A possible space experiment under extreme conditions (vacuum, temperature)

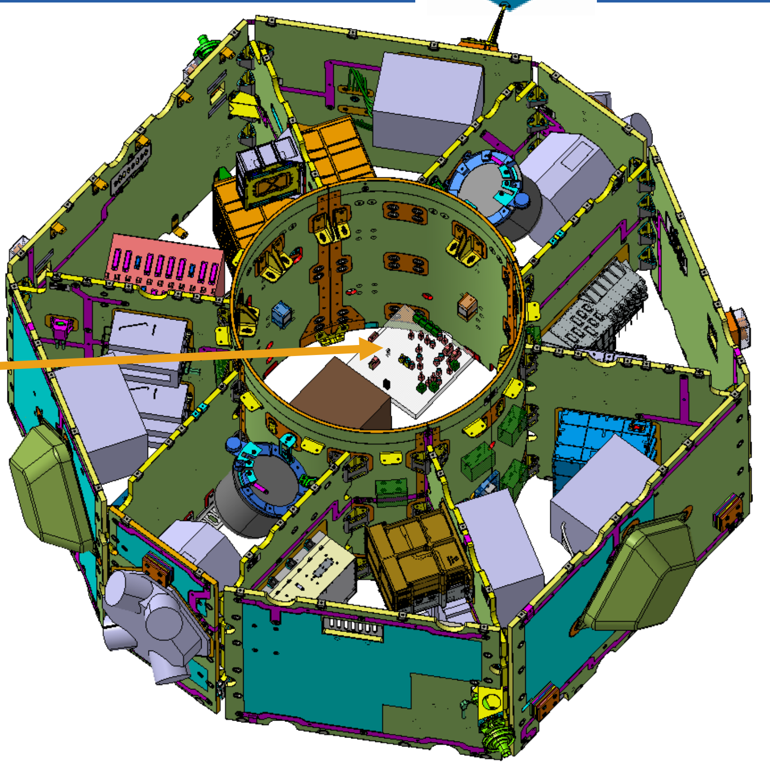
T_{env} ~ 10 K

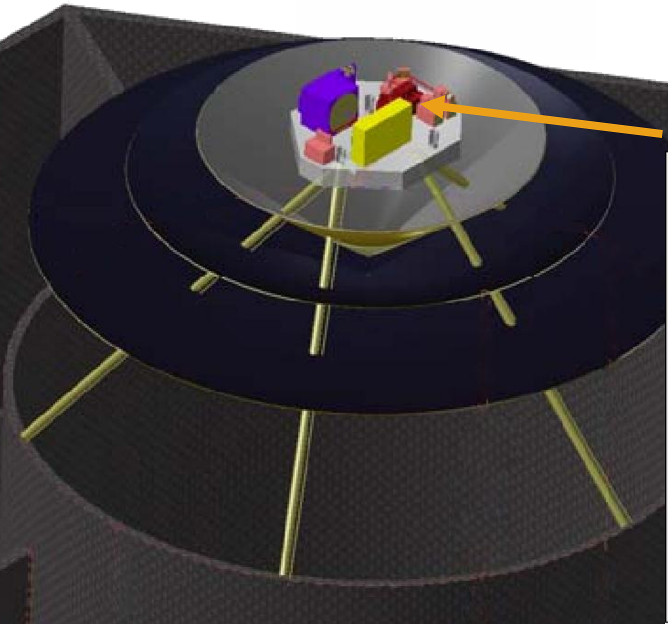
Background pressure << 10^{-15}mbar

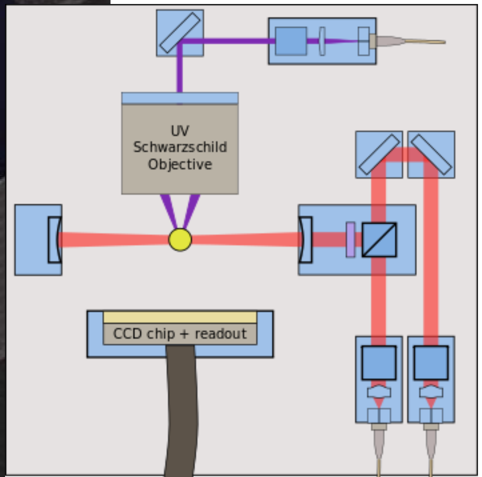
Miro-gravity environment

R. Kaltenbaek et al., arXiv:1201.4756
in collaboration with EADS ASTRIUM Friedrichshafen







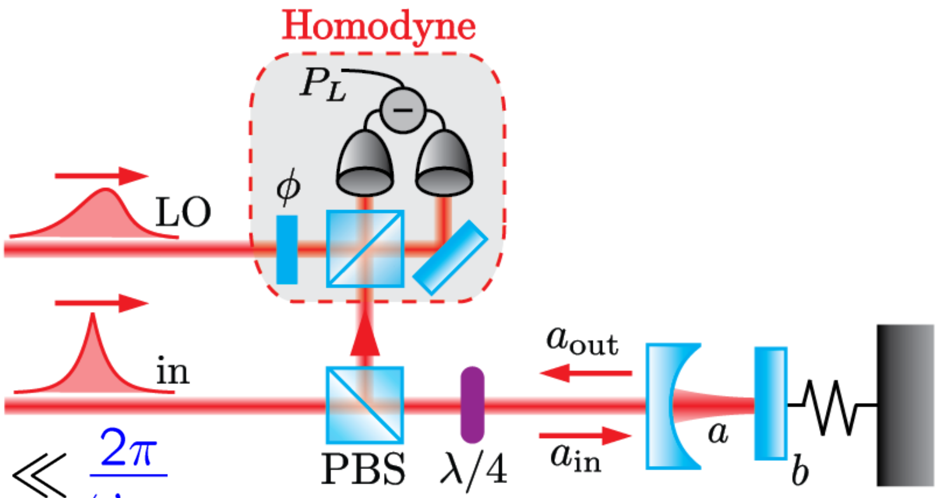


DECIDE

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

R. Kaltenbaek et al.,
(MAQRO, Experimental
Astronomy (2012),

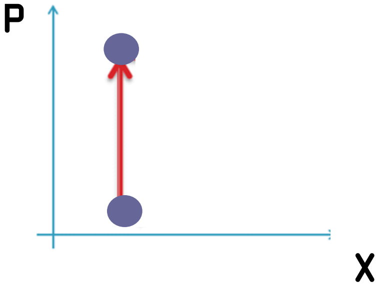
Pulsed Optomechanics



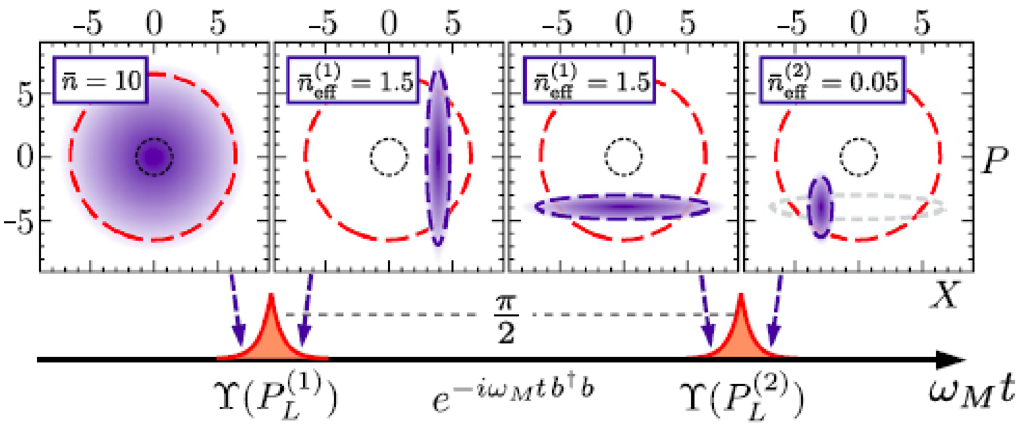
$\tau \ll \frac{2\pi}{\omega_M}$

Short optical pulse „kicks“ mechanical resonator (displacement)
Homodyne Phasereadout allows mechanical position measurement below mechanical shot noise (squeezing)

Displacement



Squeezing



→ Squeezing and displacement of mechanical resonator

Vanner, Pikovski et al., PNAS 108, 16182 (2011)

→ Hamiltonian engineering by quantum interference

Machnes et al., arxiv 1104.5448; PRL (in press)

Towards tests of quantum gravity predictions?

Idea: **Closed loop** in (mechanical) phase space generates an (optical) **phase** related to the (mechanical) **commutator**

$$\hat{\xi} = e^{i\lambda\hat{n}_a\hat{P}}\, e^{-i\lambda\hat{n}_a\hat{X}}\, e^{-i\lambda\hat{n}_a\hat{P}}\, e^{i\lambda\hat{n}_a\hat{X}} = e^{-\lambda^2\hat{n}_a^2[\hat{X},\hat{P}]}$$

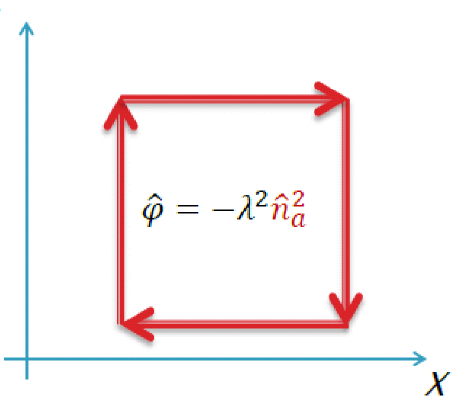
$$\langle\hat{a}_a\rangle = \langle\alpha|\hat{\xi}^{+}\hat{a}_a\hat{\xi}|\alpha\rangle \approx \alpha e^{-2|\alpha|^2\lambda^2[\hat{X},\hat{P}]}$$

Test of uncertainty principle!

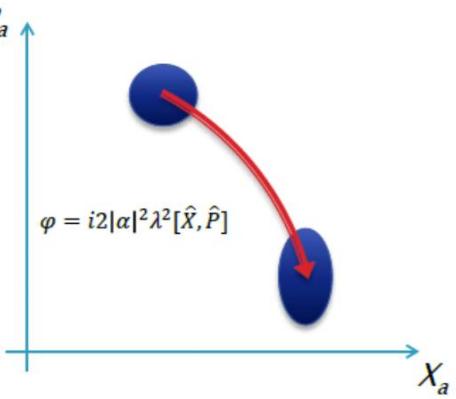
Revision due to minimal length scale?

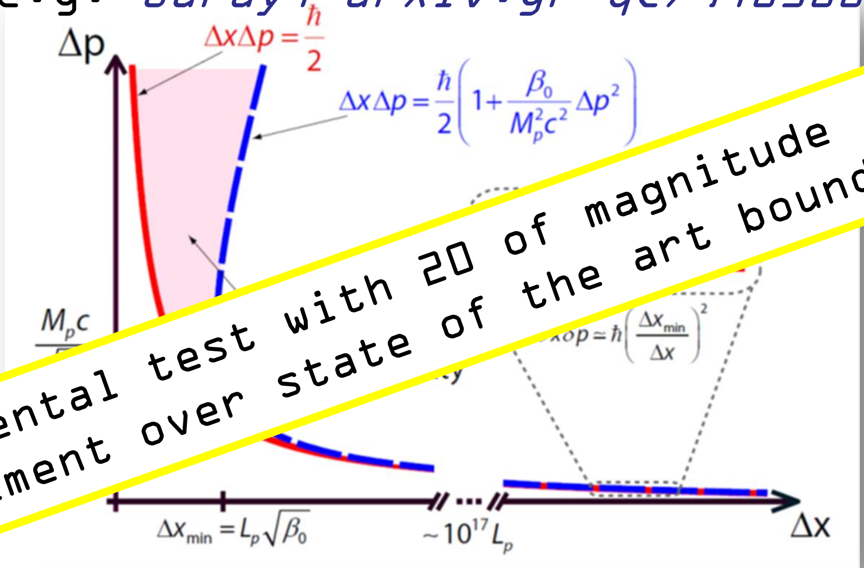
(e.g. *Garay, arXiv:gr-qc/9403008*)

mechanics



Optical ancilla





mental test with 20 of magnitude orders or more

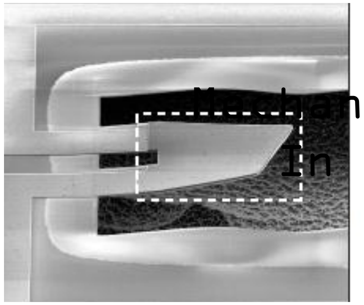
vement over state of the art bounds seems feasible

Without ancilla: see e.g. ion

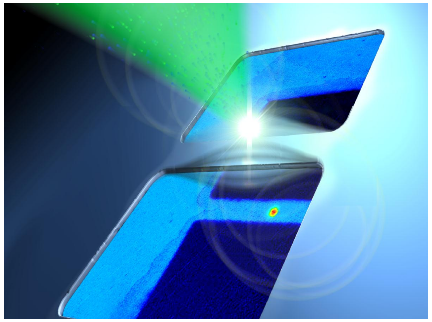
Leibfried et al., Nature 422,

Pikovski et al. Nature Physics (2012); doi:10.1038/nphys2262

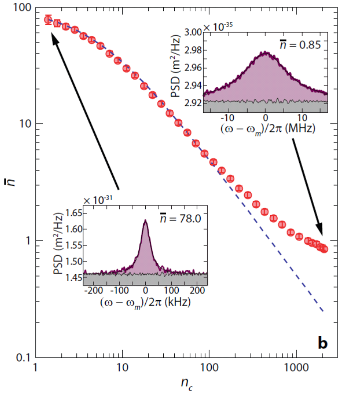
Summary



Mechanical Oscillators can serve as taylored quantum devic
in a completely new parameter regime in mass and size

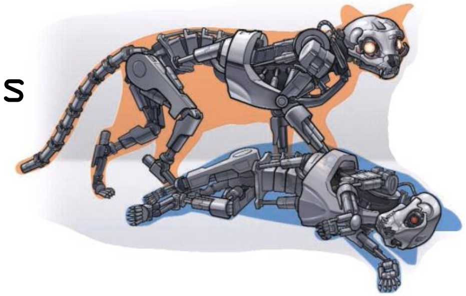


Light allows control of mechanic
resonators at the quantum level
This requires careful design of
optics and mechanics



Experiments already demonstrate
cooling into the quantum ground state

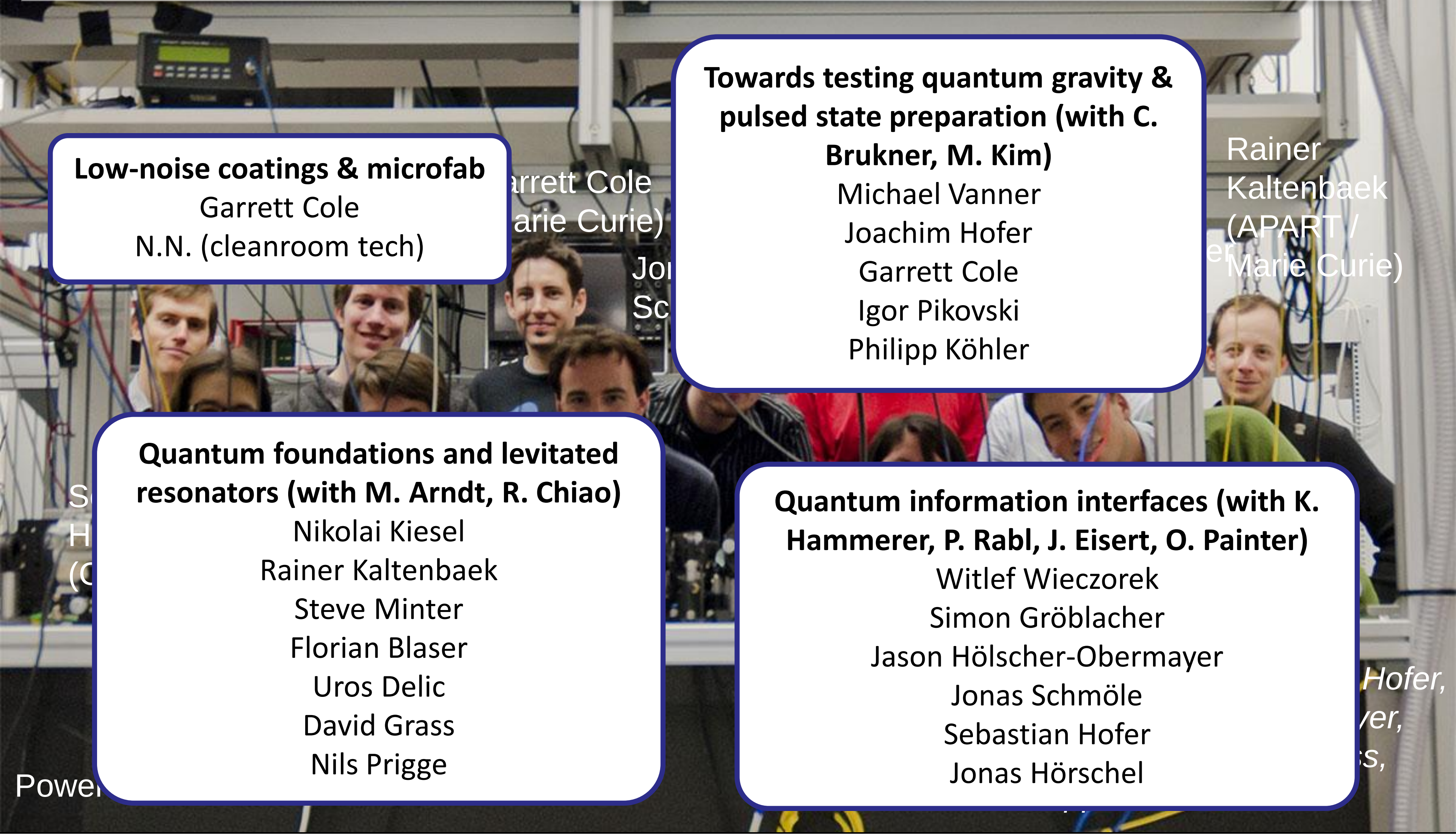
Studies of
(de)coherence and tests
of altenative quantum
theory with extremely
massive systems can be



General Overview Articles on OM

Kippenberg et al., Science 321, 1172 (2008).
Favero, Nat. Photonics 3, 201 (2009).
Marquardt, Phys. 2, 40 (2009).

Quantum-“Mechanics“ in Vienna: The Mirror Team 2012



Low-noise coatings & microfab
Garrett Cole
N.N. (cleanroom tech)

Towards testing quantum gravity & pulsed state preparation (with C. Brukner, M. Kim)
Michael Vanner
Joachim Hofer
Garrett Cole
Igor Pikovski
Philipp Köhler

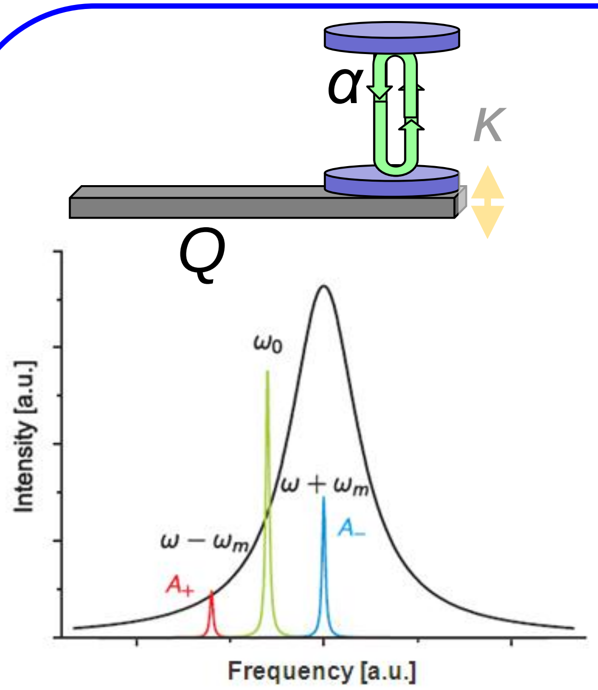
Quantum foundations and levitated resonators (with M. Arndt, R. Chiao)
Nikolai Kiesel
Rainer Kaltenbaek
Steve Minter
Florian Blaser
Uros Delic
David Grass
Nils Prigge

Quantum information interfaces (with K. Hammerer, P. Rabl, J. Eisert, O. Painter)
Witlef Wieczorek
Simon Gröblacher
Jason Hölscher-Obermayer
Jonas Schmöle
Sebastian Hofer
Jonas Hörschel

FWF Der Wissenschaftsfonds.
SEVENTH FRAMEWORK PROGRAMME
erc European Research Council
fq(x) Foundational Questions Institute
ÖAW Österreichische Akade
der Wissenschaften
Alexander von Humboldt Stiftung/Foundation
esa

Mechanical laser cooling by radiation pressure

Karrai (LMU) 2004: first proof-of-concept via photothermal forces
Nature 432, 1002 (2004)



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

$$\boxed{\langle n\rangle_{mech}^{min} \approx \left(\frac{\kappa}{4\omega_m}\right)^2}$$

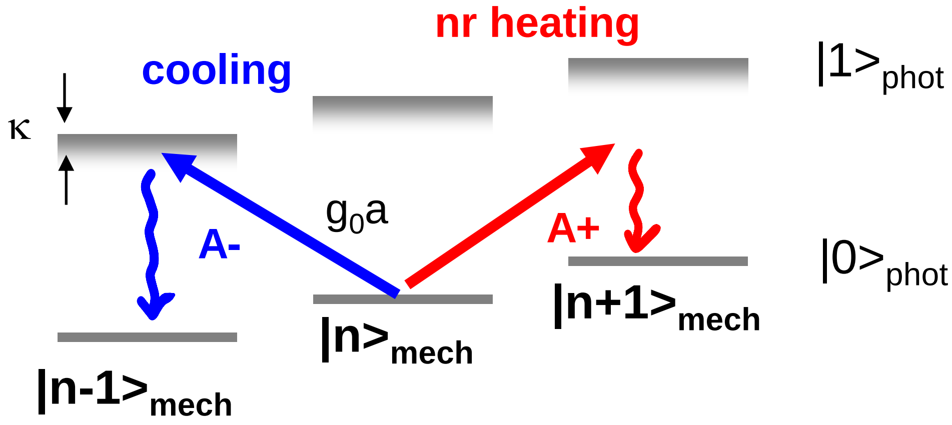
$$H_{\mathrm{BS}} \propto a_{\mathrm{m}}^\dagger a_{\mathrm{c}} + a_{\mathrm{m}} a_{\mathrm{c}}^\dagger$$

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 (2006)
MIT (Mavalvala): Corbitt et al., PRL 98, 150892 (2007)
Yale (Harris): Thompson et al., Nature 452, 72 (2008)
JILA (Lehnert): Regal et al., Nature Physics 4, 555 (2008)

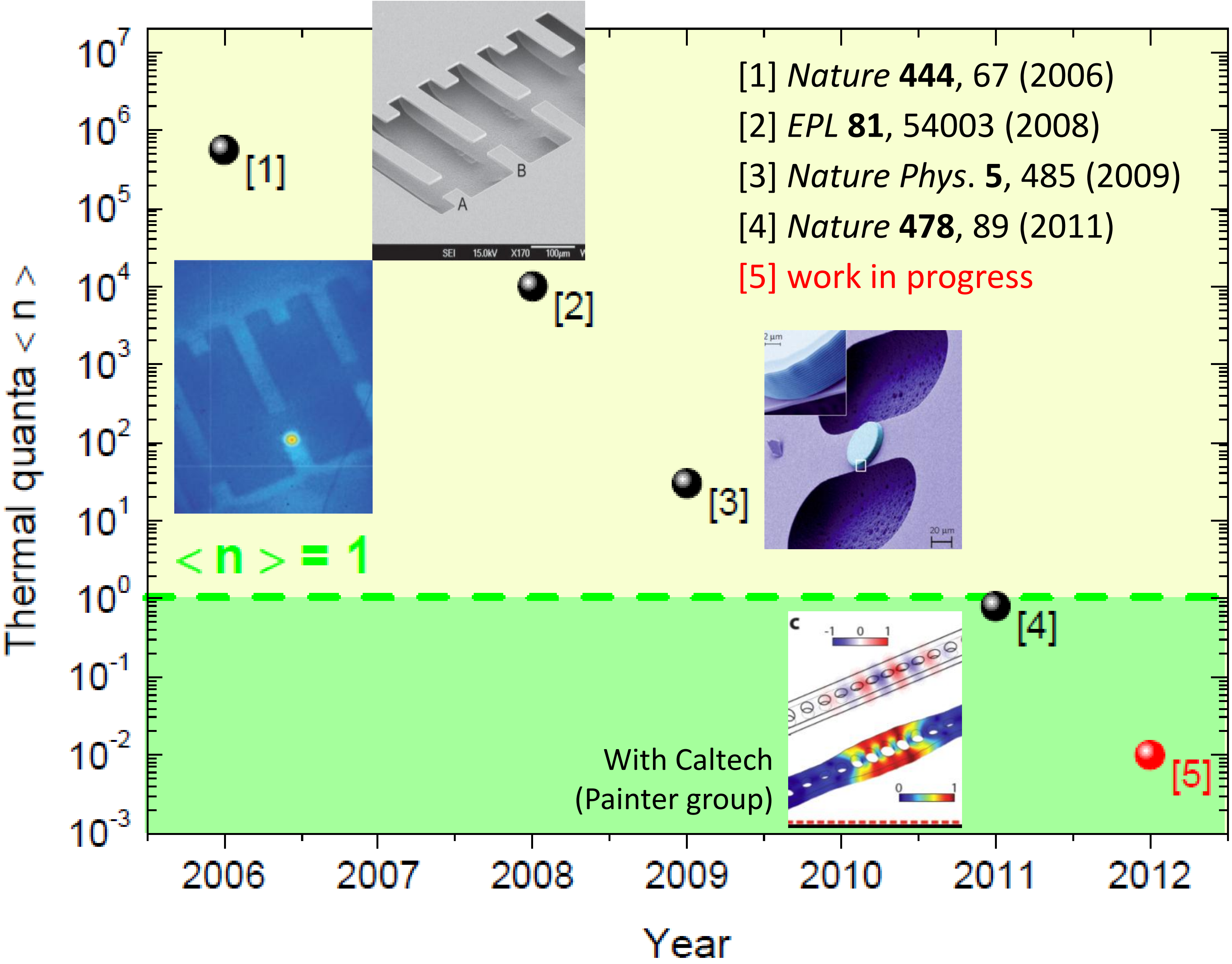
...allows cooling into the quantum ground state

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



Analogue: sideband-resolved cooling of ions

Vienna cooling…



[1] *Nature* **444**, 67 (2006)

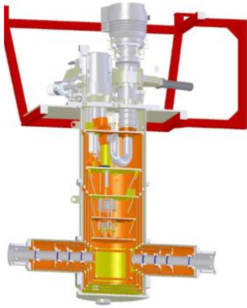
[2] *EPL* **81**, 54003 (2008)

[3] *Nature Phys*. **5**, 485 (2009)

[4] *Nature* **478**, 89 (2011)

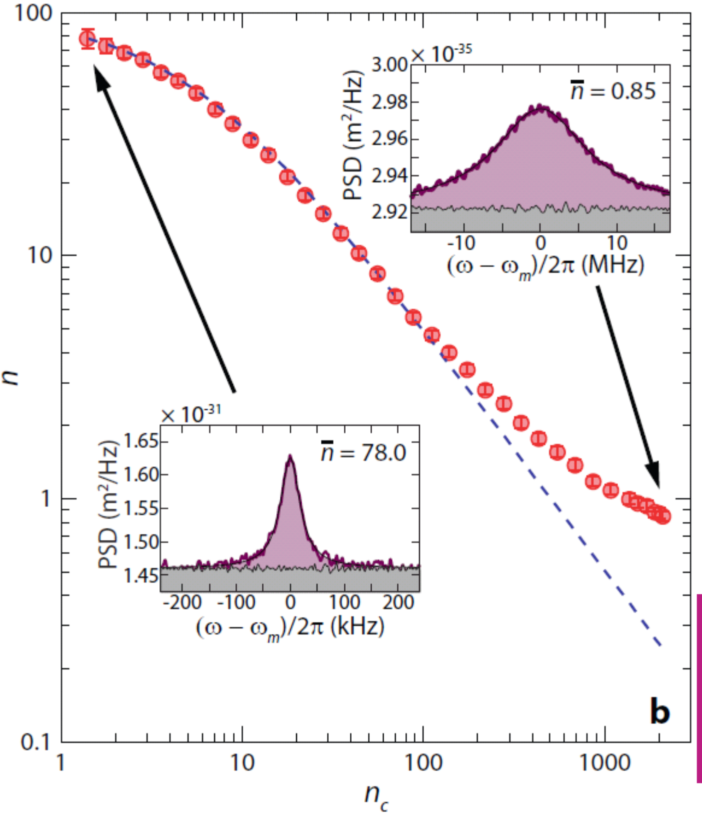
[5] work in progress

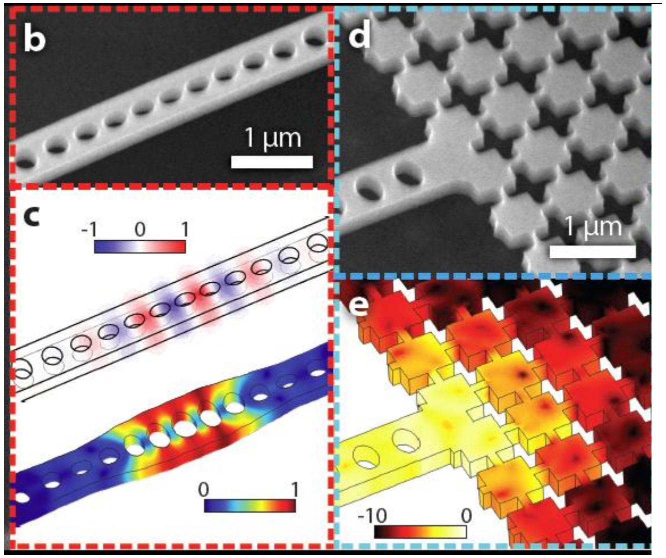
With Caltech
(Painter group)

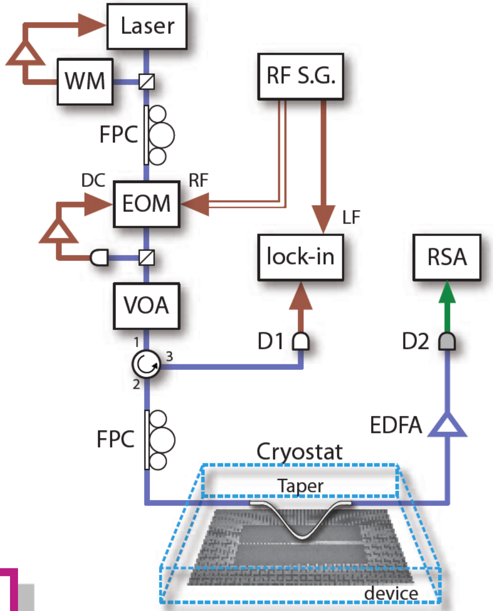


Ground-state laser cooling of a nanomechanical resonator

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







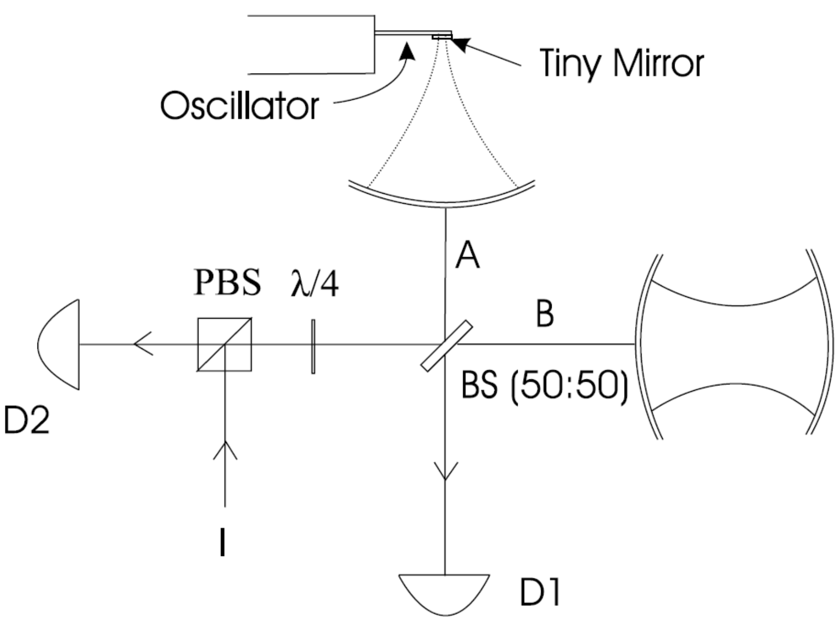
<n> ~ 0.8

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*

A mechanical cat? Schrödinger's mirrors?

Marshall, Simon, Penrose, Bouwmeester, PRL 91, 130401 (2003)



also: A.D. Armour, M.P. Blencowe, and K. Schwab, PRL 88, 148301 (2002.)

A single photon - 2 path

1. Path energy exchange
with mechanical de
2. Path no interaction

Interference and project
Photon: ½ excitation of

Challenging:

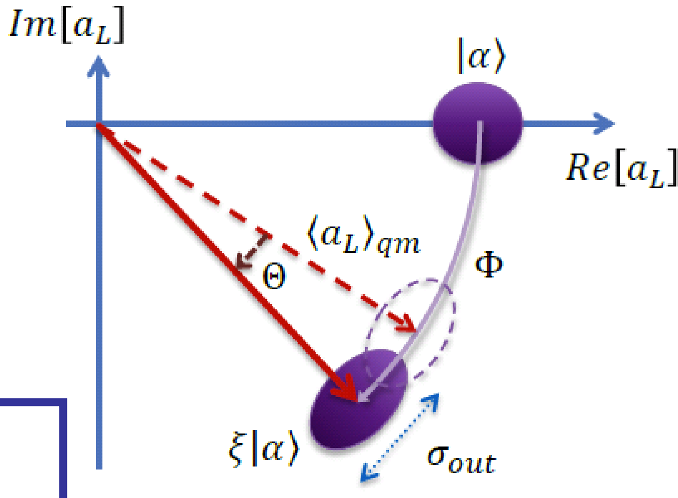
Single Photon Coupling
and
Low Frequencies
(for large displacement)

(high mechanical Q/T required

Towards tests of quantum gravity predictions?

Current state of the art:

system/ experiment	$\beta_{0,max}$	$\gamma_{0,max}$
Position measurements	10^{24}	10^{24}
Lamb shift in Hydrogen	10^{36}	10^{10}
Electron tunneling	10^{33}	10^{11}



Estimates for optomechanics scheme:

$[X_m, P_m]$ $\lvert\Theta\rvert$	Eq. 2 $\mu_0 \frac{32\hbar\mathcal{F}^2 m N_P}{M_P^2\lambda_L^2\omega_m}$	Eq. 3 $\gamma_0 \frac{96\hbar^2\mathcal{F}^3 N_P^2}{M_P c\lambda_L^3 m\omega_m}$	Eq. 1 $\beta_0 \frac{1024\hbar^3\mathcal{F}^4 N_P^3}{3M_P^2 c^2\lambda_L^4 m\omega_m}$
$\mathcal{F}$	10^5	2×10^5	5×10^5
m	10^{-11} kg	10^{-11} kg	10^{-6} kg
$\omega_m/2\pi$	10^5 Hz	10^5 Hz	10^5 Hz
λ_L	1064 nm	1064 nm	532 nm
N_p	10^8	5×10^{10}	10^{14}
N_r	1	10^2	10^4
$\delta\langle\Phi\rangle$	10^{-4}	5×10^{-7}	10^{-8}

$$\boxed{\langle a_L\rangle \simeq \langle a_L\rangle_{qm}\, e^{-i\Theta}}$$

→ Improvement by more than 20 orders of magnitude compared to existing bounds !

$\delta\mu_0 \sim 1,\ \delta\gamma_0 \sim 1$ and $\delta\beta_0 \sim 1$ → measuring **Planck-scale deformations**

Pikovski et al.
Nature Physics (2012);
doi:10.1038/nphys2262