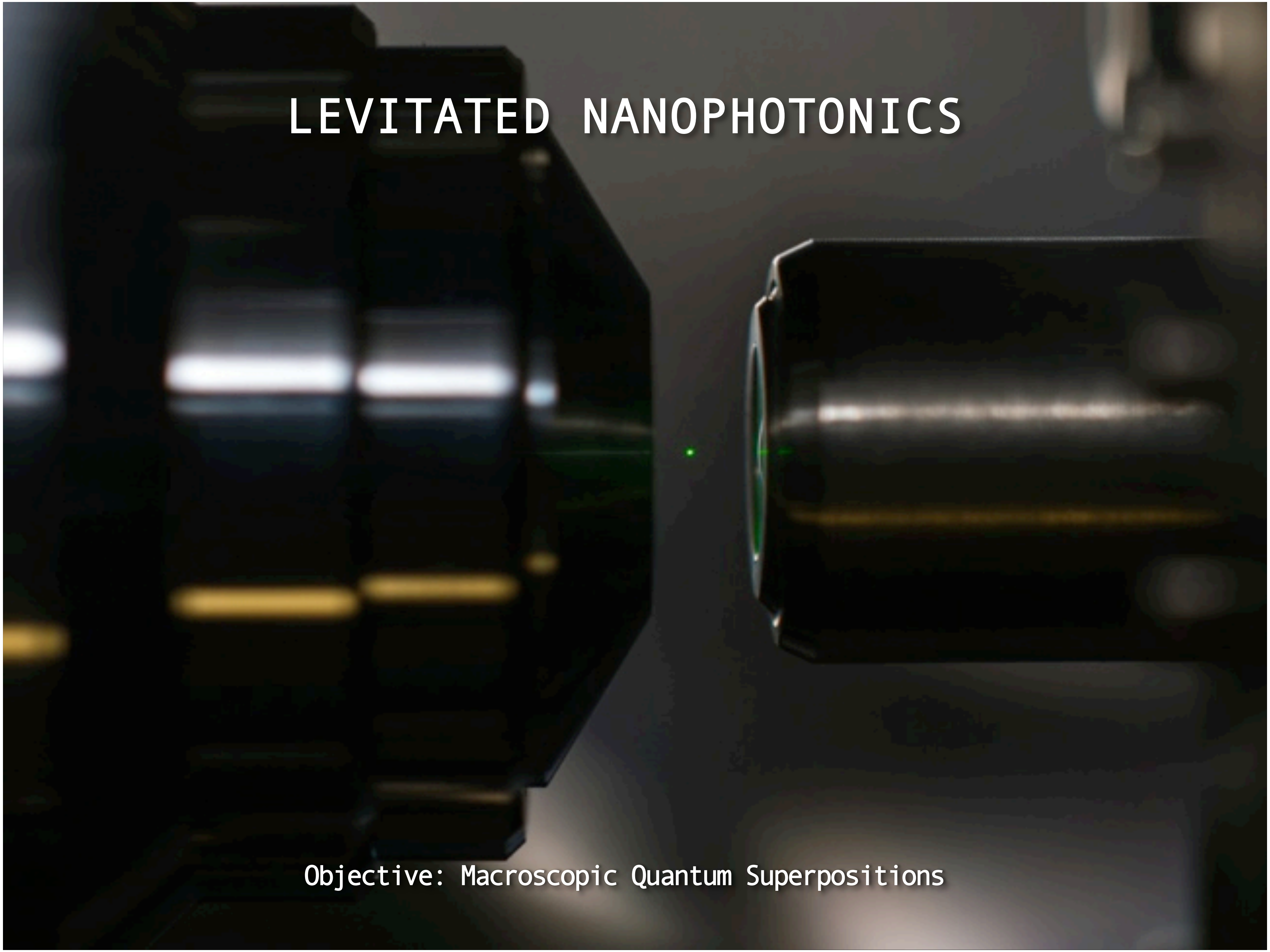
LEVITATED NANOPHOTONICS

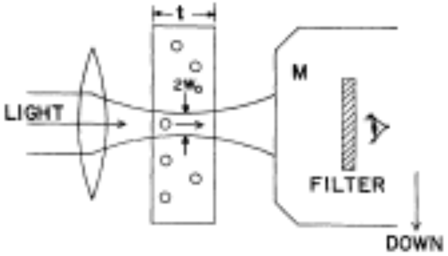


Objective: Macroscopic Quantum Superpositions

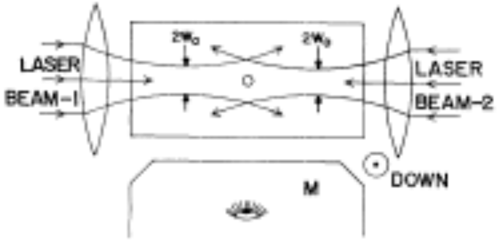
VOLUME 24, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1970

ACCELERATION AND TRAPPING OF PARTICLES BY RADIATION PRESSURE

A. Ashkin
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 3 December 1969)



(a)



(b)

The extension to vacuum of the present experiments on particle trapping in potential wells would be of interest since then any motions are frictionless. Uniform angular acceleration of trapped particles based on optical absorption of circular polarized light or use of birefringent particles is possible. Only destruction by mechanical failure should limit the rotational speed. In vacuum, particles will heat until they are cooled by thermal radiation or vaporize. With the minimum power needed for levitation, micron spheres will assume temperatures of hundreds to thousands of degrees depending on the loss. The ability to heat in vacuum without contaminating containing vessels is of interest. Acceleration of neutral spheres to velocities ~10^6-10^7 cm/sec is readily possible using powers that avoid vaporization. In this regard one could at-

ACKNOWLEDGMENTS

ETH:


Martin
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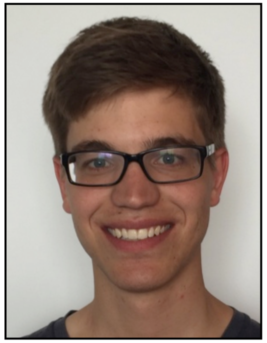
Jain


Erik
Hebestreit


René
Reimann


Dominik
Windey


Felix
Tebbenjohanns


Rozenn
Diehl

Harvard:


Jan
Gieseler

U. Paris-Sud:


Loïc
Rondin

ICFO:


Romain
Quidant

IQOQI:


Oriol
Romero-Isart

U. Vienna :


Christoph
Dellago

OUTLINE

1: INTRODUCTION

2: PHOTON RECOIL

3: RABI COOLING

4: SENSING

5: NONEQUILIBRIUM DYNAMICS

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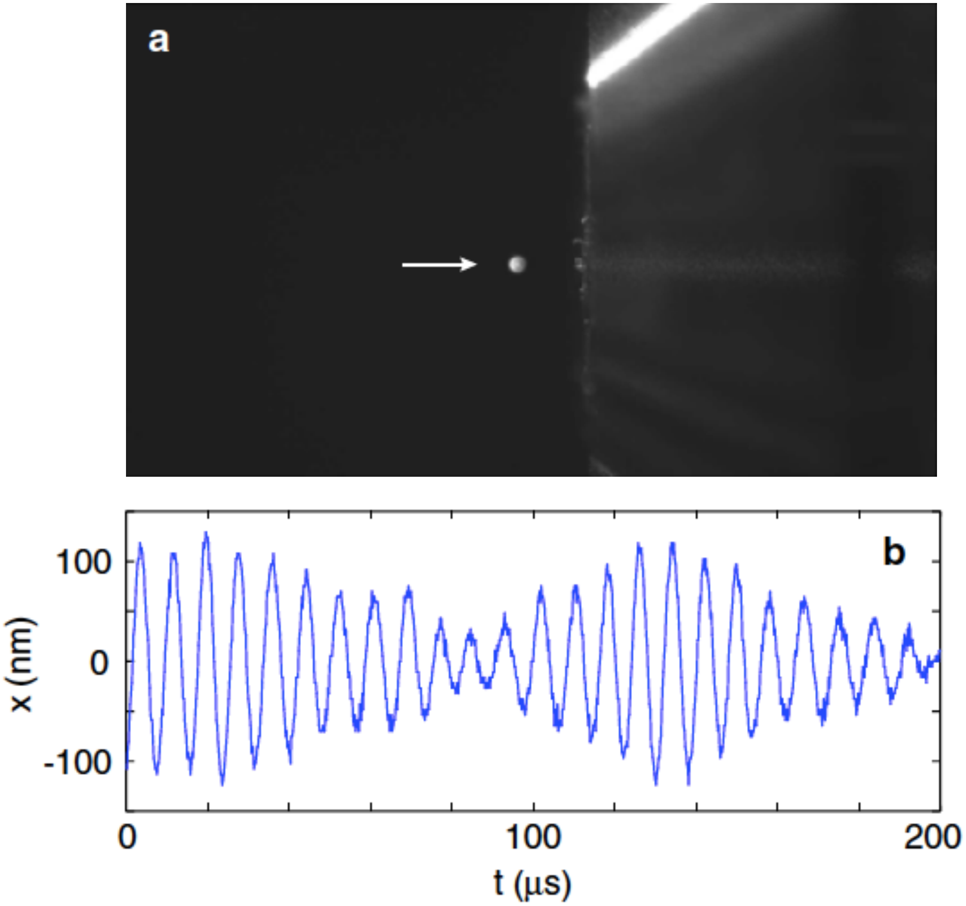
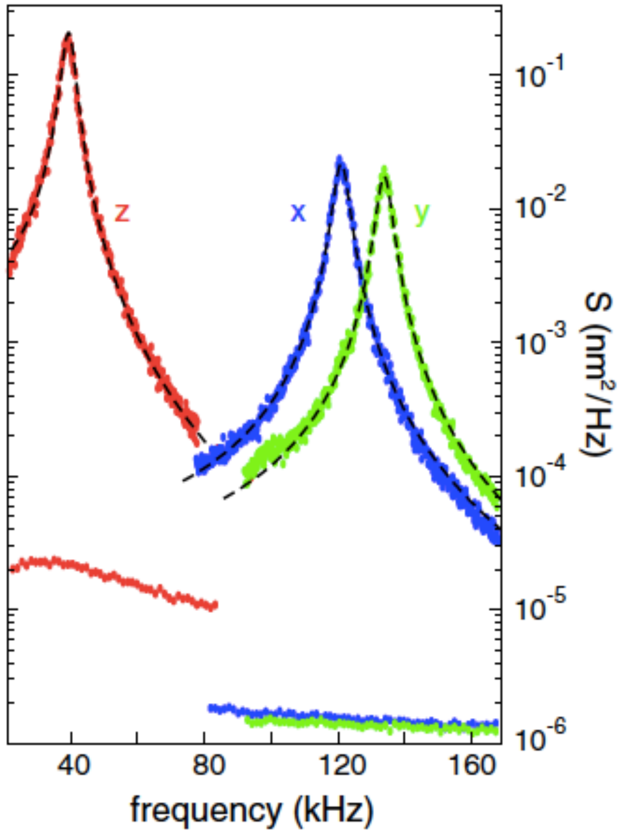
7: CONCLUSIONS

TIME DOMAIN

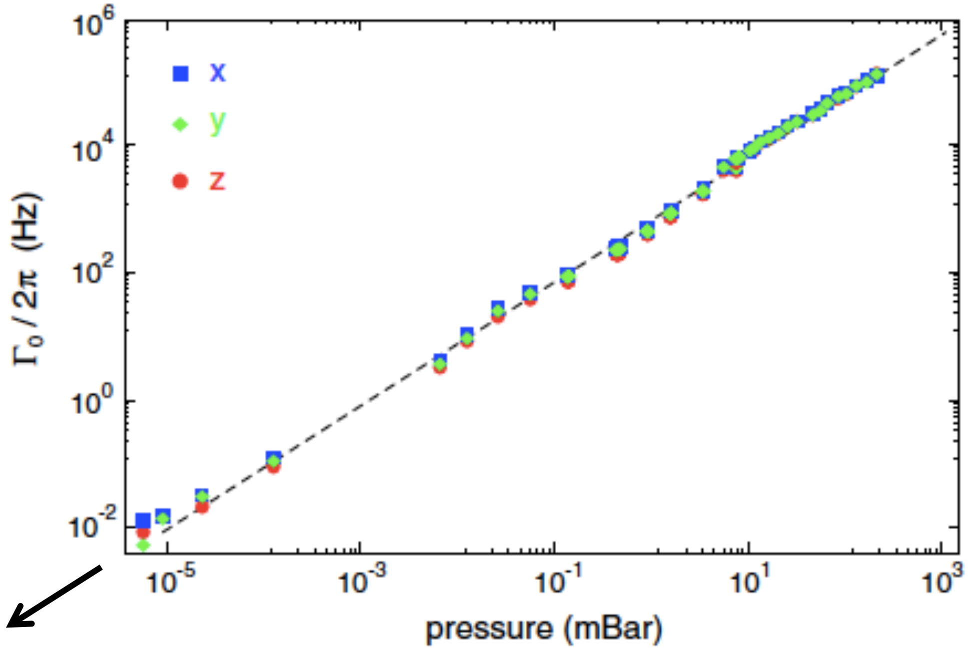


PRL **109**, 103603 (2012)

FREQUENCY DOMAIN



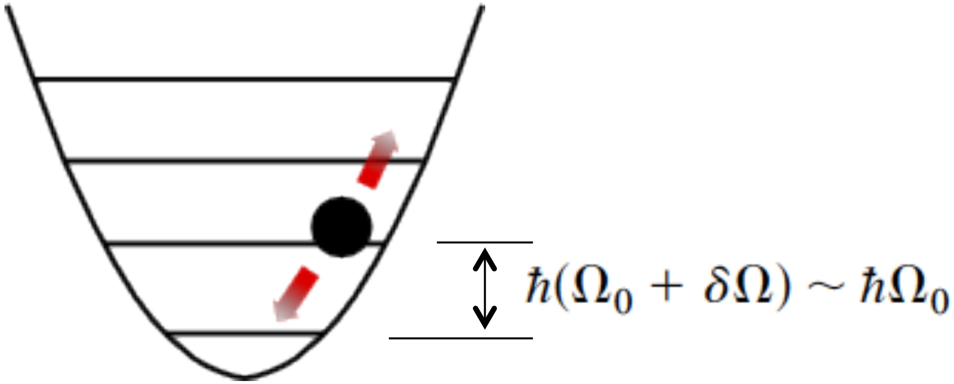
QUALITY FACTOR



$$P_{\mathrm{gas}} = 10^{-5}\,\mathrm{mbar} \;\longrightarrow\; \Gamma_0/2\pi = 10\ \mathrm{mHz} \;\longrightarrow\; Q = 10^7$$

$$P_{\mathrm{gas}} = 10^{-9}\,\mathrm{mbar} \;\longrightarrow\; \boxed{Q \sim 10^{11}}$$

QUANTUM GROUNDSTATE

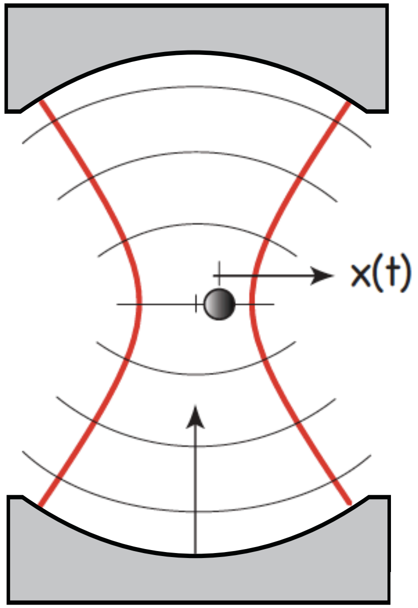


Mean thermal occupancy : $n = \dfrac{k_B T_{\text{c.m.}}}{\hbar\Omega_0}$

Quantum groundstate : $n < 1 \quad \longrightarrow \quad T_{\text{c.m.}} \sim 6\ \mu\text{K}$

$\longrightarrow$ compression ratio of 10^8 !

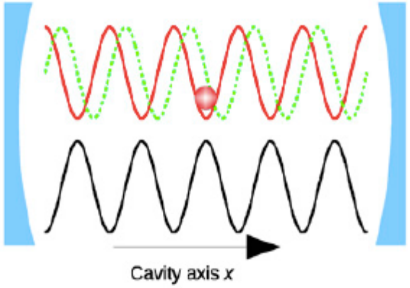
PASSIVE BACKACTION



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]

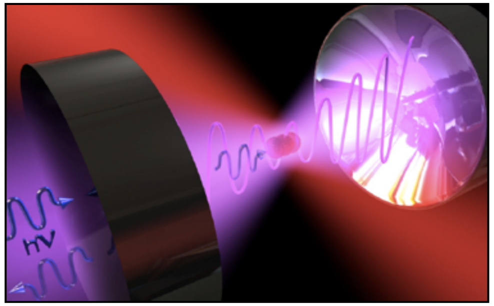
PNAS | January 19, 2010 | vol. 107 | no. 3 | 1005–1010

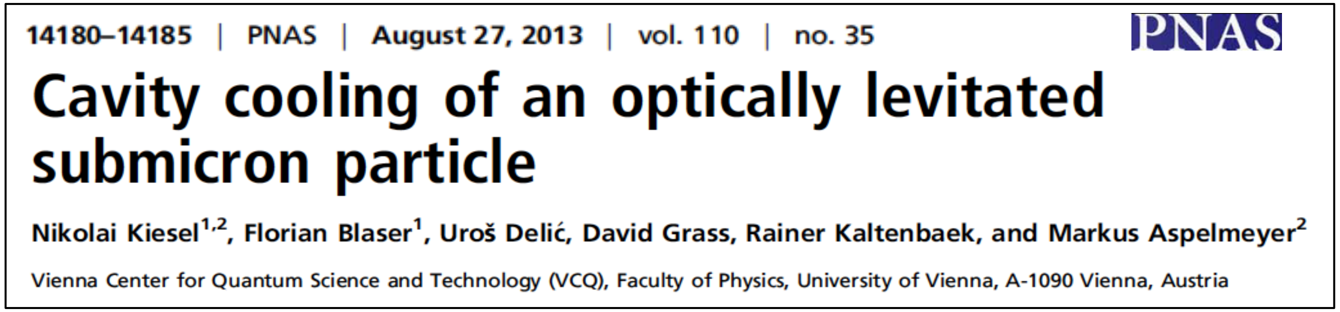


Toward quantum superposition of living organisms

Oriol Romero-Isart[1,4], Mathieu L Juan[2], Romain Quidant[2,3] and J Ignacio Cirac[1]

New Journal of Physics **12** (2010) 033015



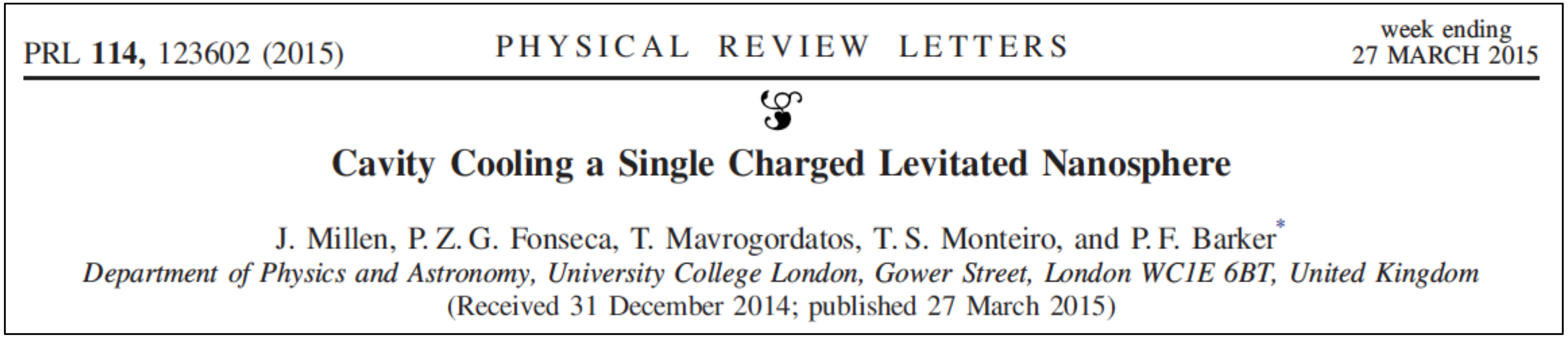


14180–14185 | PNAS | August 27, 2013 | vol. 110 | no. 35 PNAS

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



PRL **114,** 123602 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

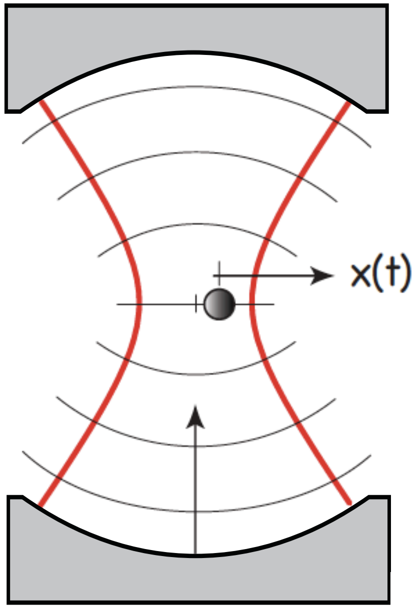
Cavity Cooling a Single Charged Levitated Nanosphere

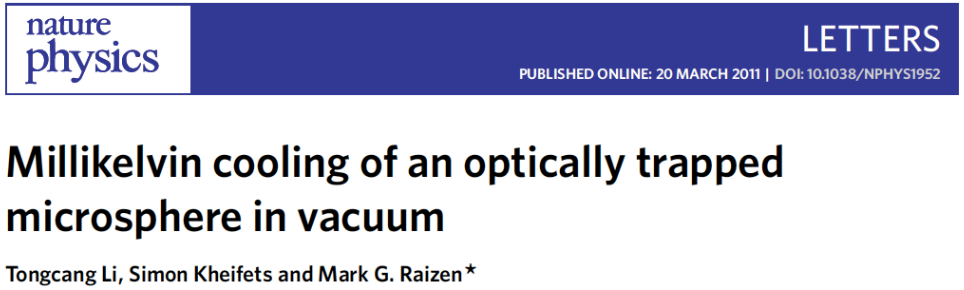
J. Millen, P. Z. G. Fonseca, T. Mavrogordatos, T. S. Monteiro, and P. F. Barker*

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

(Received 31 December 2014; published 27 March 2015)

ACTIVE BACKACTION



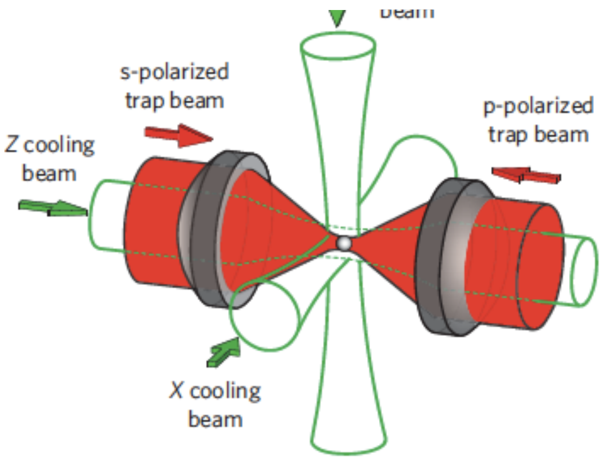

nature physics

LETTERS

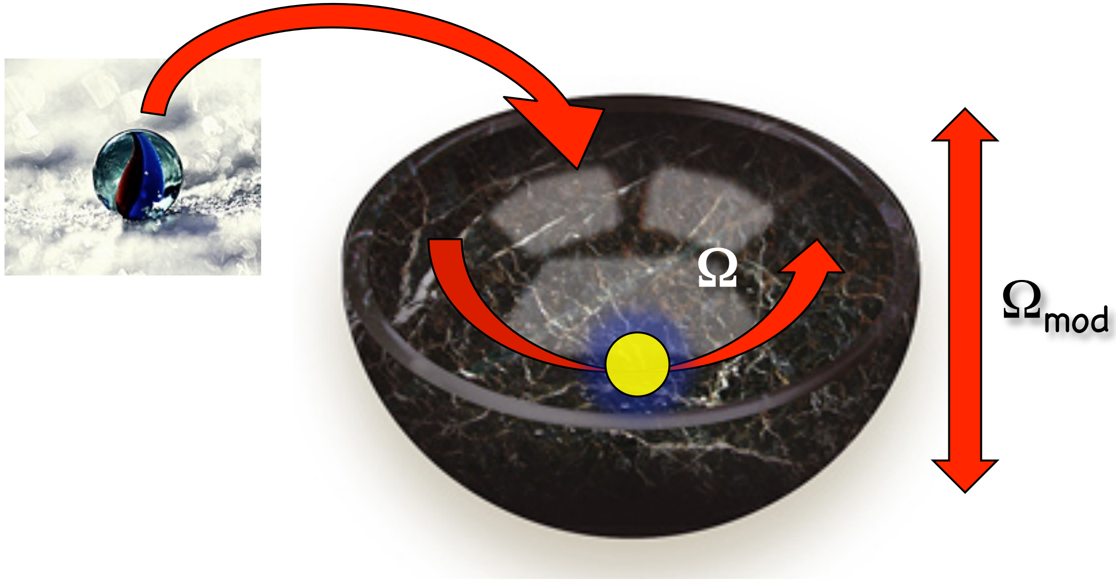
PUBLISHED ONLINE: 20 MARCH 2011 | DOI: 10.1038/NPHYS1952

Millikelvin cooling of an optically trapped microsphere in vacuum

Tongcang Li, Simon Kheifets and Mark G. Raizen*

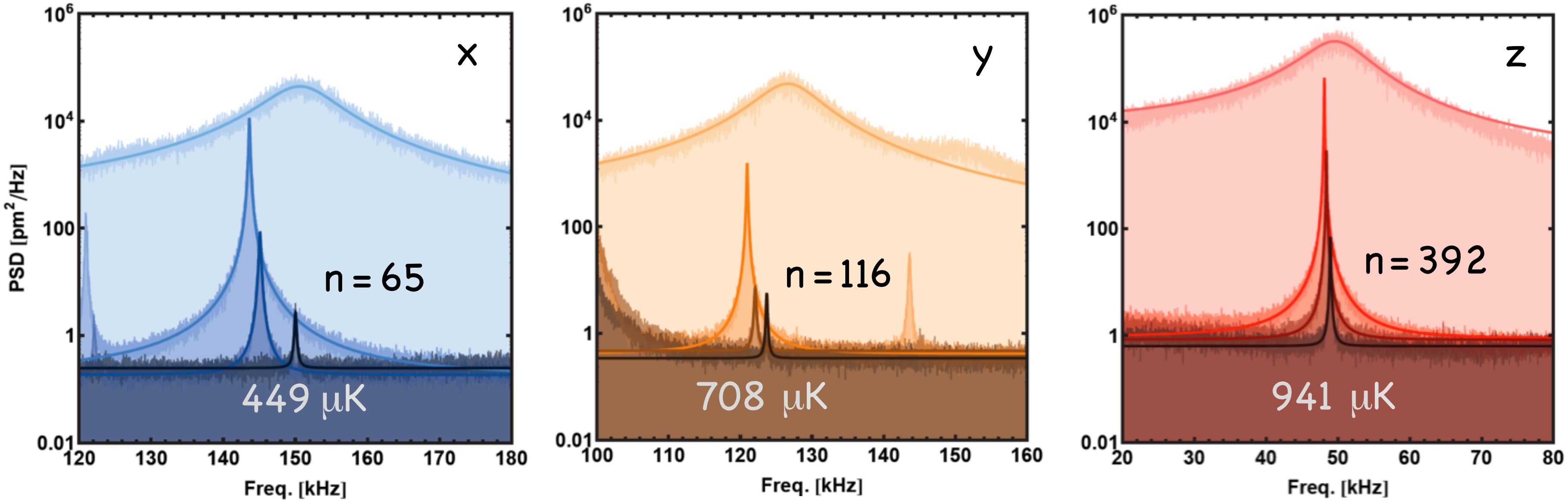


PARAMETRIC CONTROL OF MOTION



$$\langle E\rangle = \frac{1}{2}\,m\,\Omega_0^2\,\langle x^2\rangle = \frac{1}{2}\,k_B T_{cm} = n\,\hbar\Omega_0$$

FEEDBACK COOLING TO μK



pressures (mbar): 8.8, 6.6 10^{-4}, 1.1 10^{-5}, 2 10^{-8}

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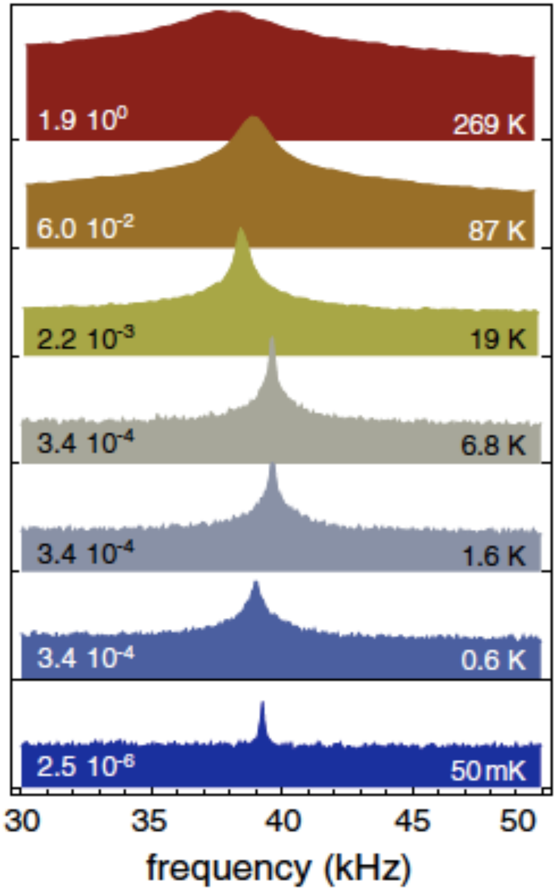
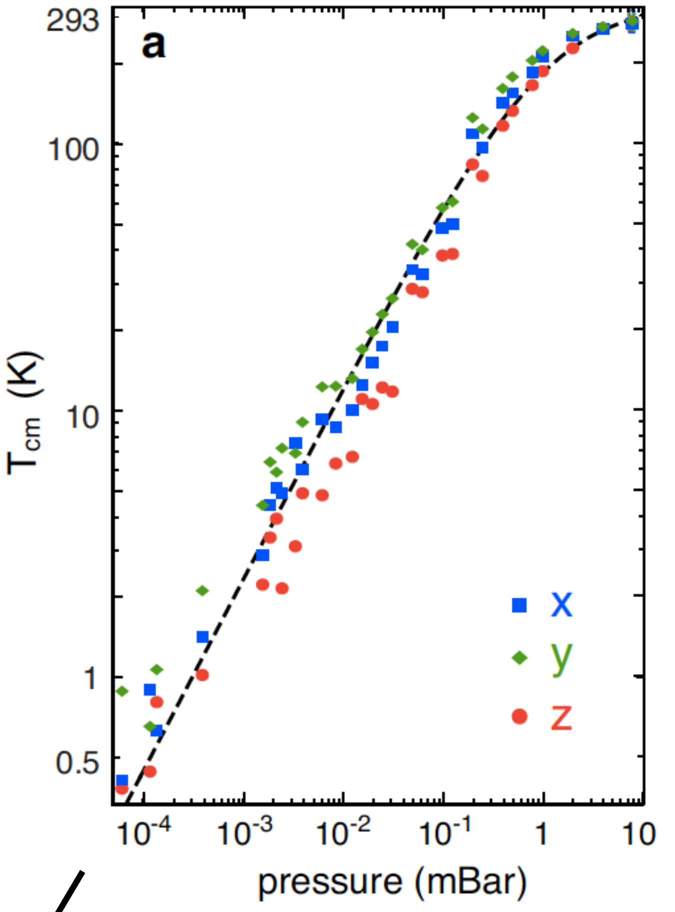
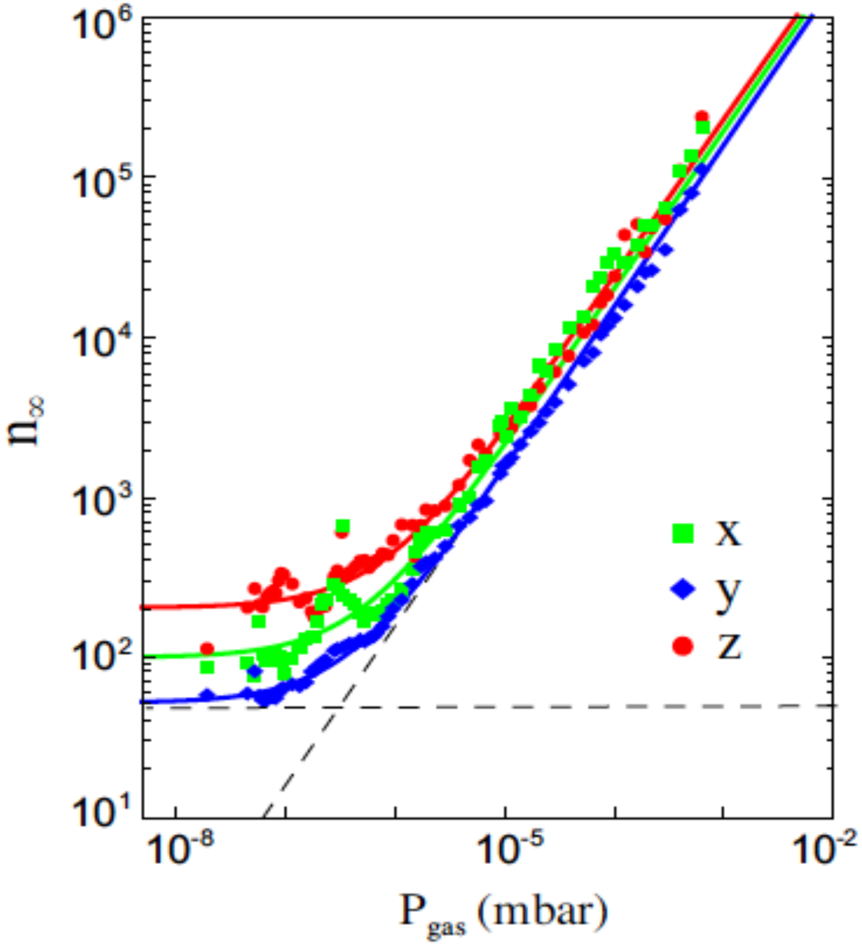
PARAMETRIC FEEDBACK COOLING





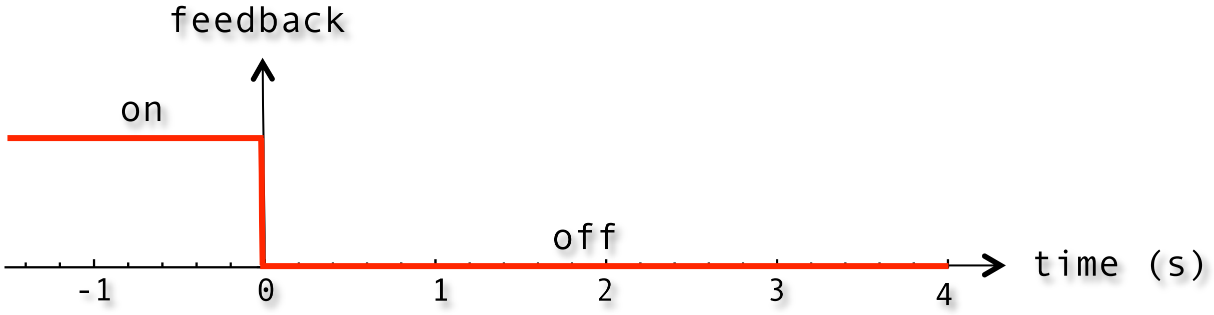
PRL **109**, 103603 (2012)

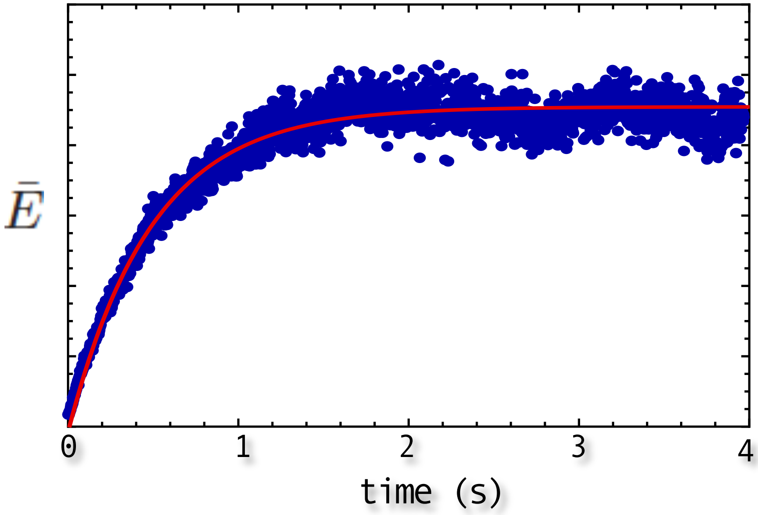
ENTERING NEW HEATING REGIME



PRL **116**, 243601 (2016)

REHEATING DYNAMICS



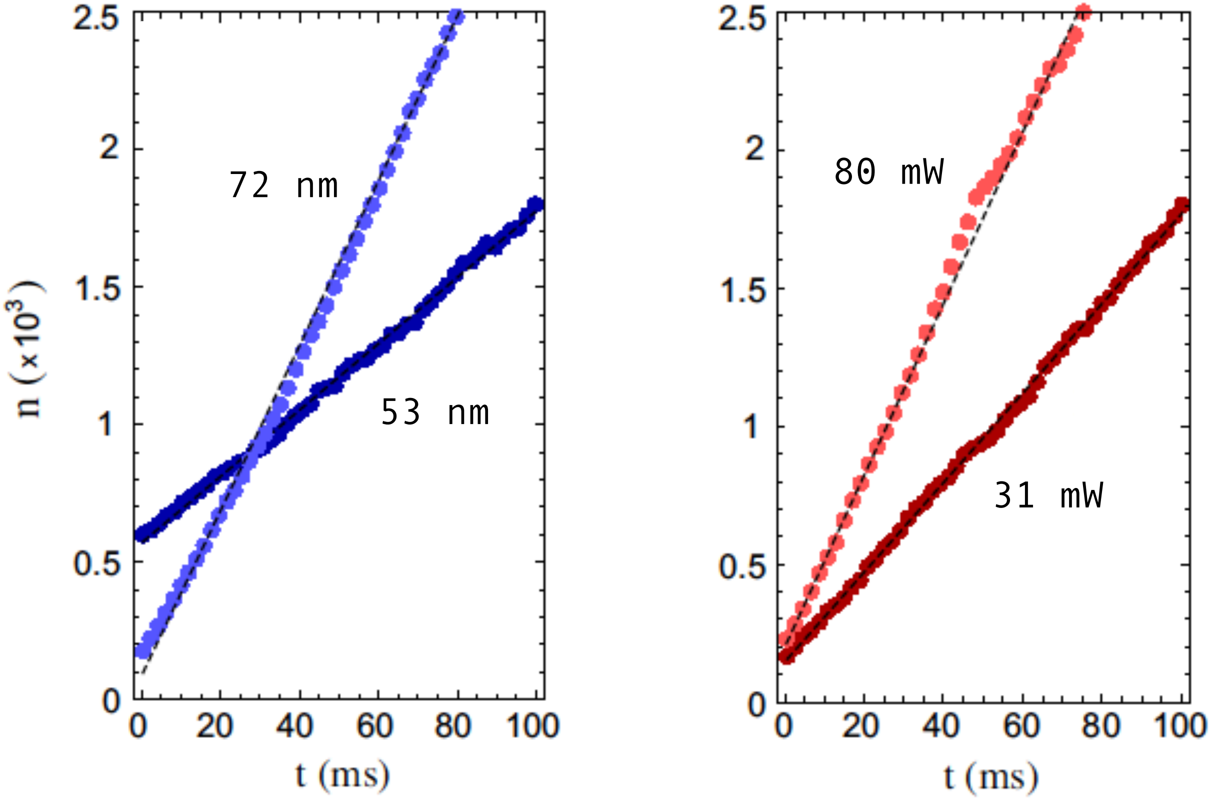


$3\ 10^{-4}$ mBar

$$\frac{d}{dt}\bar{E}(t) = -\gamma\left[\bar{E}(t) - E_\infty\right]$$

PHOTON RECOIL HEATING

$$n(t) = n_0 + \Gamma_{\mathrm{recoil}}\, t$$

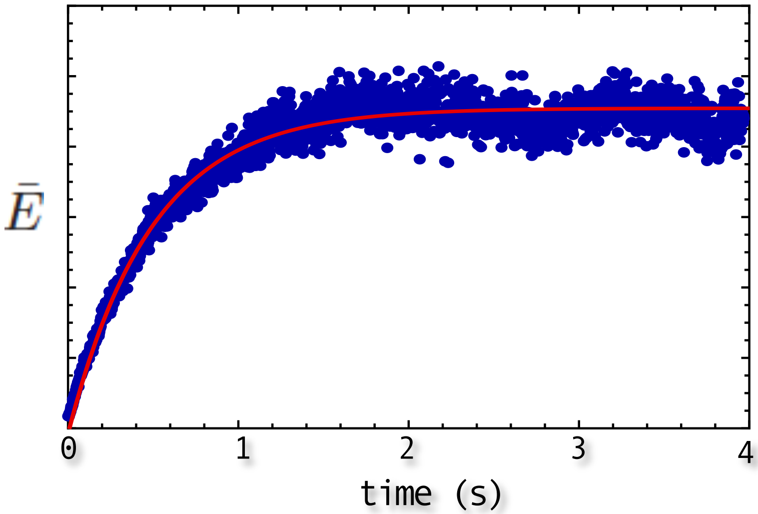


10-40 kHz

$$\Gamma_{\mathrm{recoil}} = \frac{1}{5}\,\frac{P_{\mathrm{scatt}}}{mc^2}\,\frac{\omega_0}{\Omega_0}$$

PRL **116**, 243601 (2016)

EQUILIBRIUM



→ radiation damping

PRA **96**, 032108 (2017)

3 10^{-4} mBar

$$\frac{d}{dt}\bar{E}(t) = \underbrace{-\gamma\bar{E}(t)}_{\text{cooling}} + \underbrace{\gamma E_\infty}_{\text{heating}} \longrightarrow \bar{E}(t) \approx \bar{E}(0) + \underbrace{\gamma E_\infty}_{\Gamma_{\text{recoil}}\,\hbar\Omega_0} t$$

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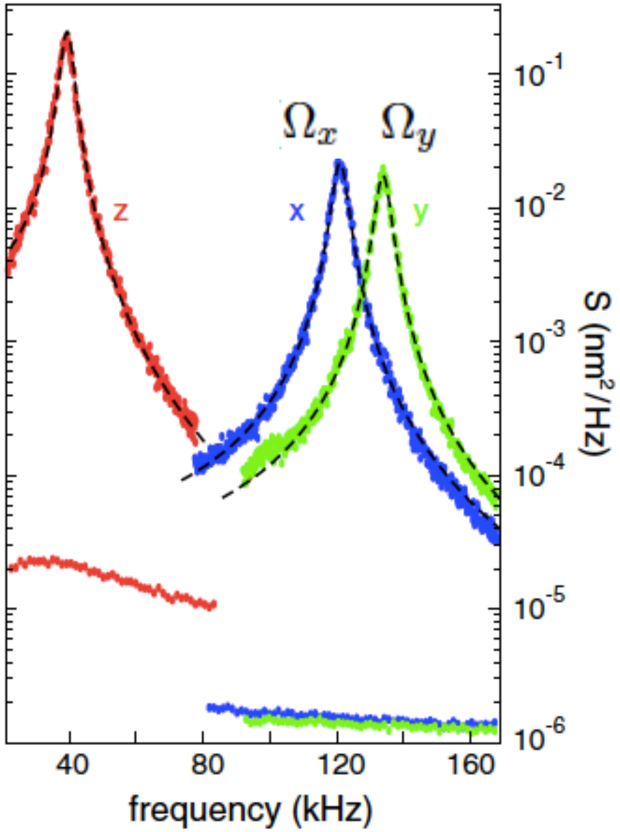
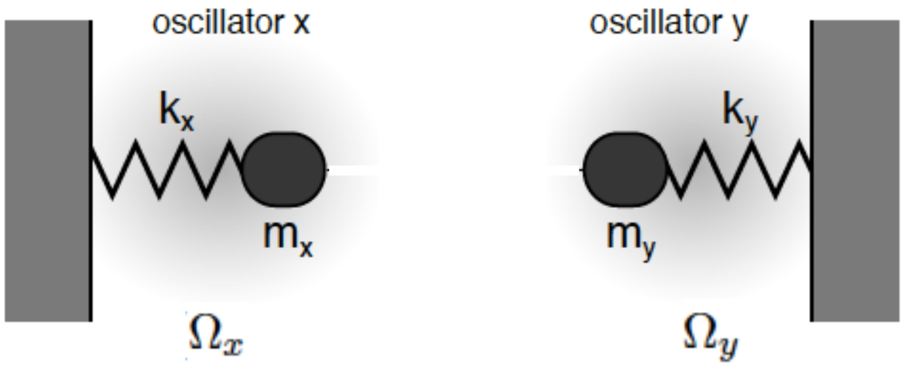
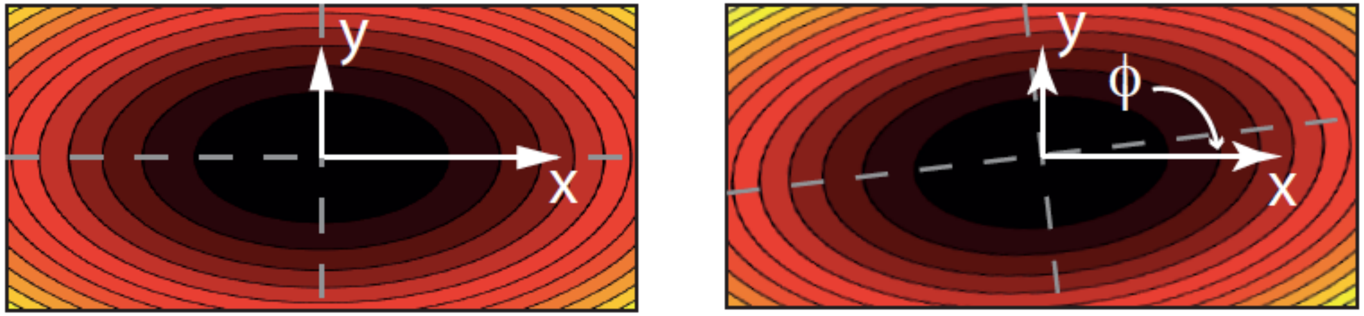
FREQUENCY DOMAIN

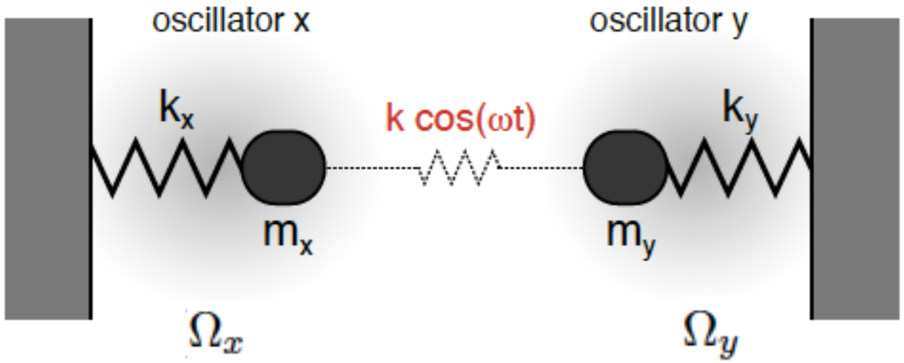


PARAMETRICALLY COUPLED OSCILLATORS

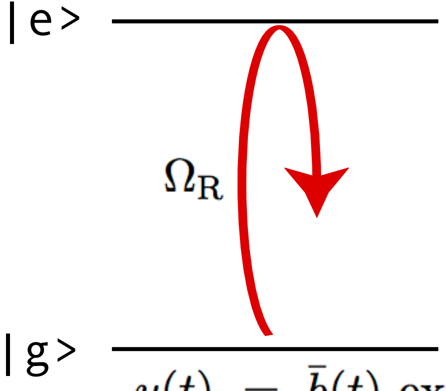




COUPLED MODE THEORY



$$x(t) = \bar{a}(t)\,\exp[i(\Omega_0 - \omega/2)t]$$



$$i\begin{bmatrix} \dot{\bar{a}} \\ \dot{\bar{b}} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} (\Delta - i\gamma) & \omega_x - i\omega_y \\ \omega_x + i\omega_y & -(\Delta - i\gamma) \end{bmatrix}\begin{bmatrix} \bar{a} \\ \bar{b} \end{bmatrix}$$

$$y(t) = \bar{b}(t)\,\exp[i(\Omega_0 + \omega/2)t]$$

$\longrightarrow$ SU(2)

JOSA B **34**, C52-C57(2017)

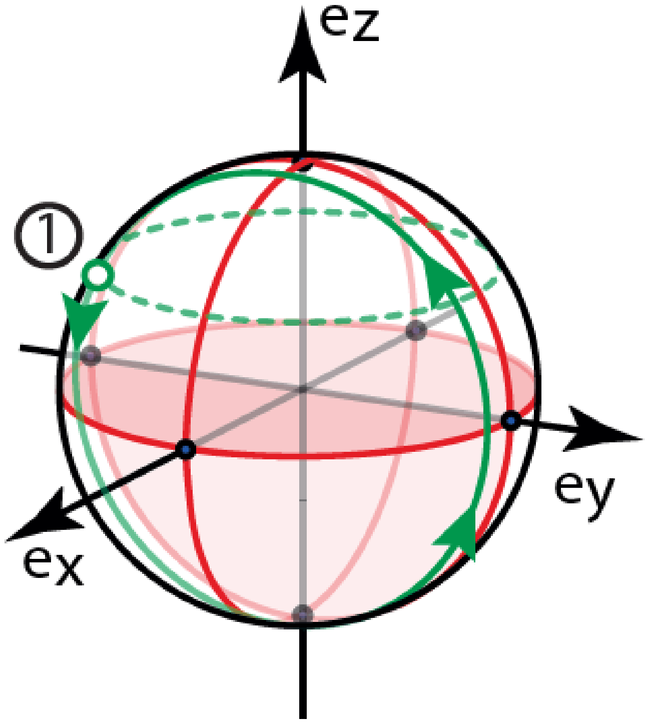
CLASSICAL SCHRÖDINGER EQUATION

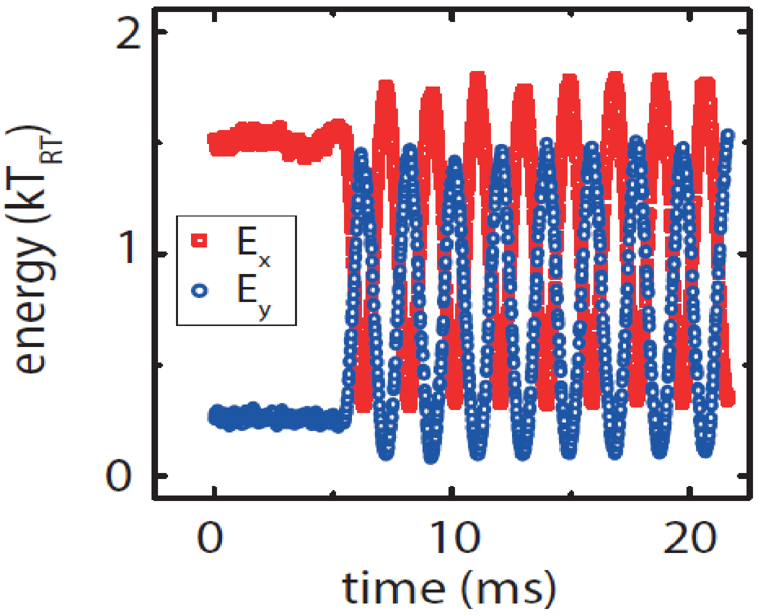
$$\underbrace{\hbar i \begin{bmatrix} \dot{\bar{a}} \\ \dot{\bar{b}} \end{bmatrix}}_{\frac{\partial}{\partial t}|\psi\rangle} = \underbrace{\frac{\hbar}{2}\begin{bmatrix} (\Delta - i\gamma) & \omega_x - i\omega_y \\ \omega_x + i\omega_y & -(\Delta - i\gamma) \end{bmatrix}}_{\hat{H}} \underbrace{\begin{bmatrix} \bar{a} \\ \bar{b} \end{bmatrix}}_{|\psi\rangle}$$

$$\hat{H} = \frac{\hbar}{2}(\Delta - i\gamma)\hat{\sigma}_z + \frac{\hbar\omega_x}{2}\hat{\sigma}_x + \frac{\hbar\omega_y}{2}\hat{\sigma}_y$$

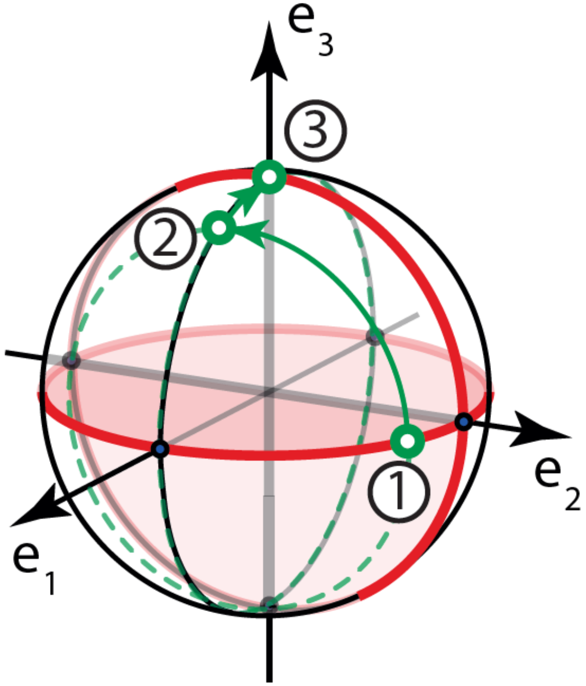
JOSA B **34**, C52-C57(2017)

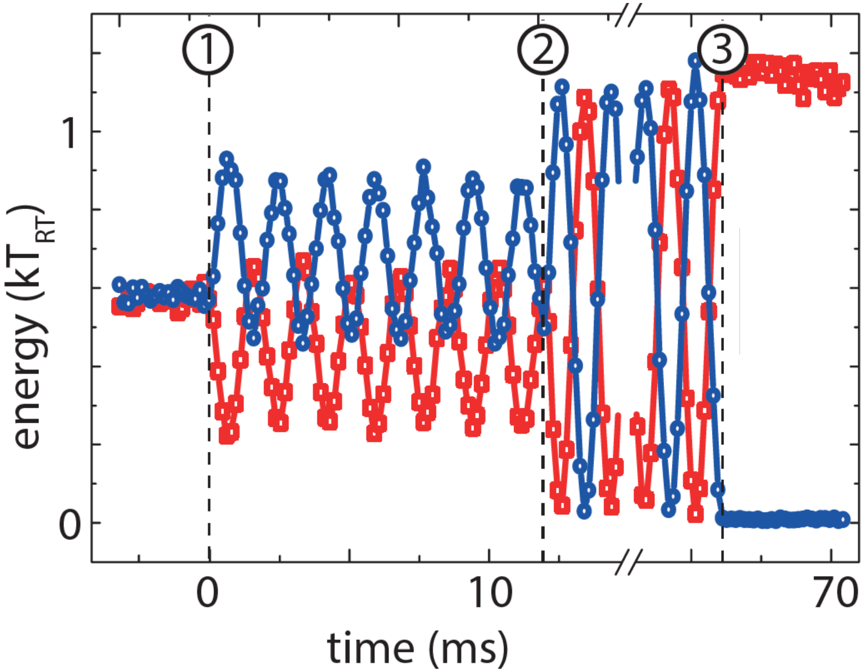
RABI OSCILLATIONS





COOLING PROTOCOL





Cooling limit : $\langle E_{\min} \rangle = \frac{1}{2} m \Omega_{\mathrm{mech}}^2 S_{xx}^{\mathrm{noise}} \gamma$

PRL **117**, 163601 (2016)

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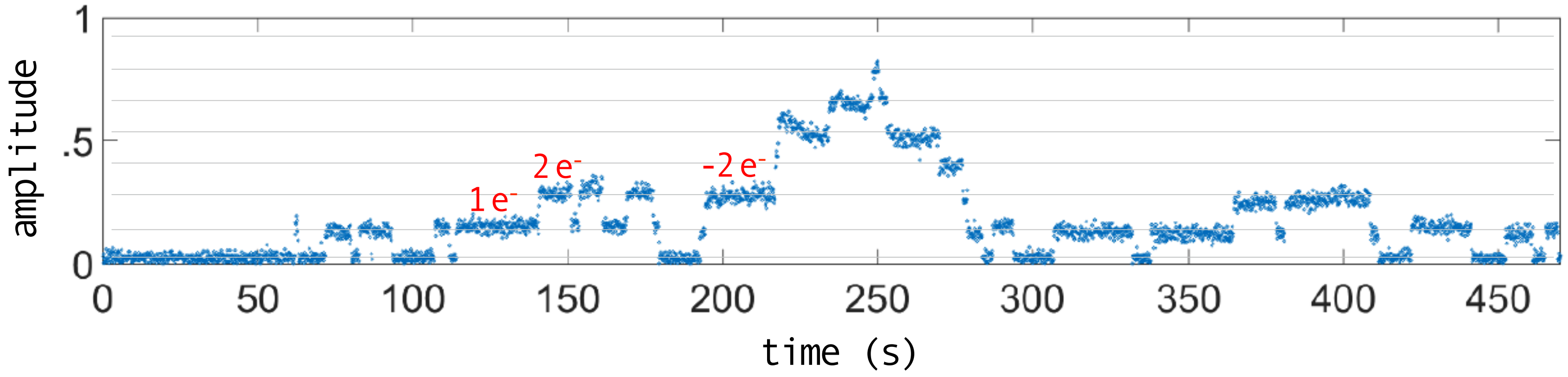
FORCE SENSITIVITY

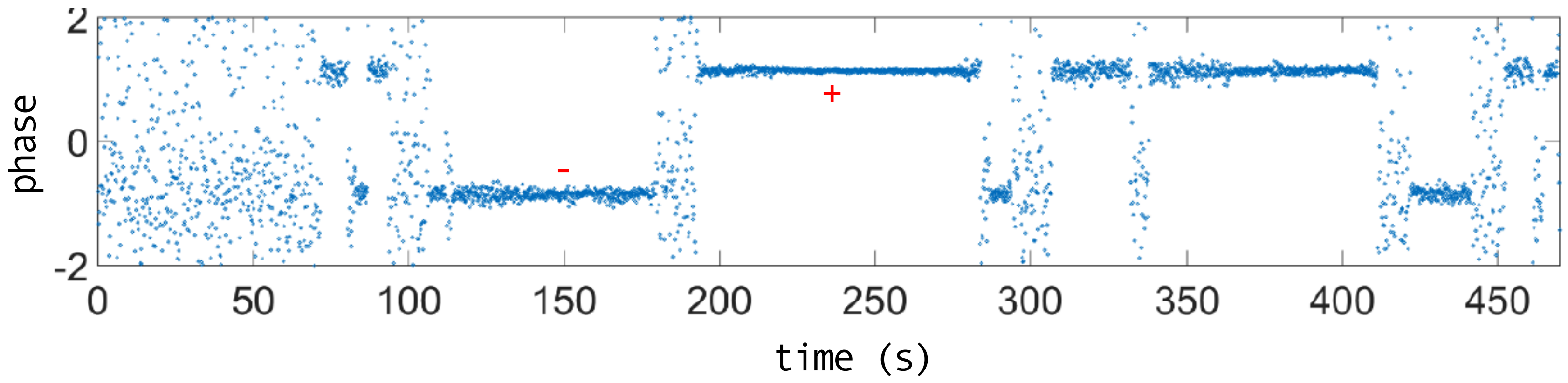
Minimum detectable force in bandwidth *B* : $F = \sqrt{\dfrac{4k_BT\, m\Omega_0\, B}{Q}}$

For $P_{\rm gas} = 10^{-9}\,{\rm mbar}:$ $\boxed{F \approx 10^{-20}\,{\rm N}}$ in 1 sec

a. Casimir / van der Waals forces
b. Vacuum friction
c. Nuclear spin detection
d. Phase transitions
e. Non-Newtonian gravitylike forces
f. Dark matter
g. …

CHARGING/DECHARGING OF PARTICLE

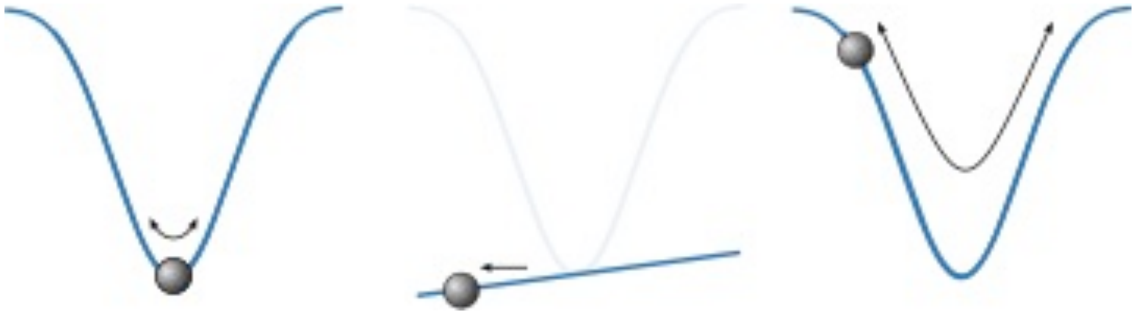


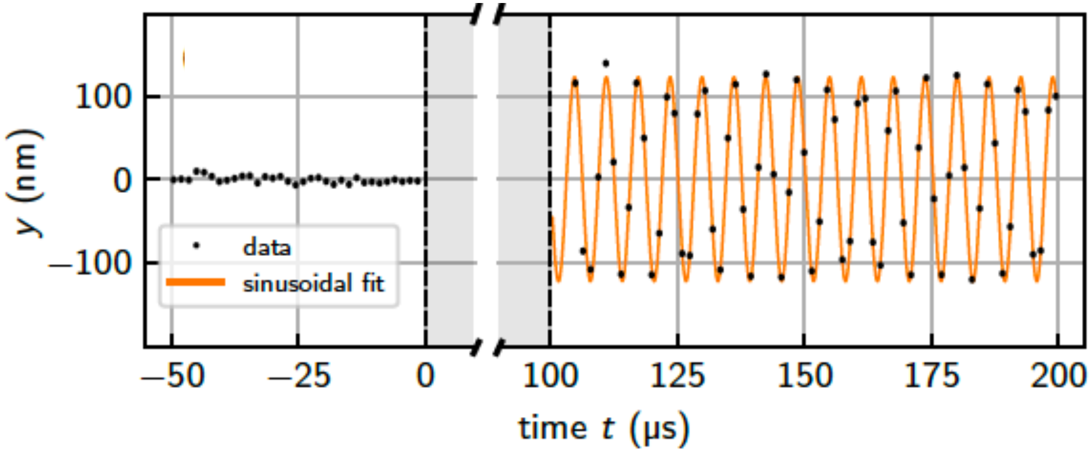


(300K / 1 mBar)

PRA **95**, 061801 (2017)

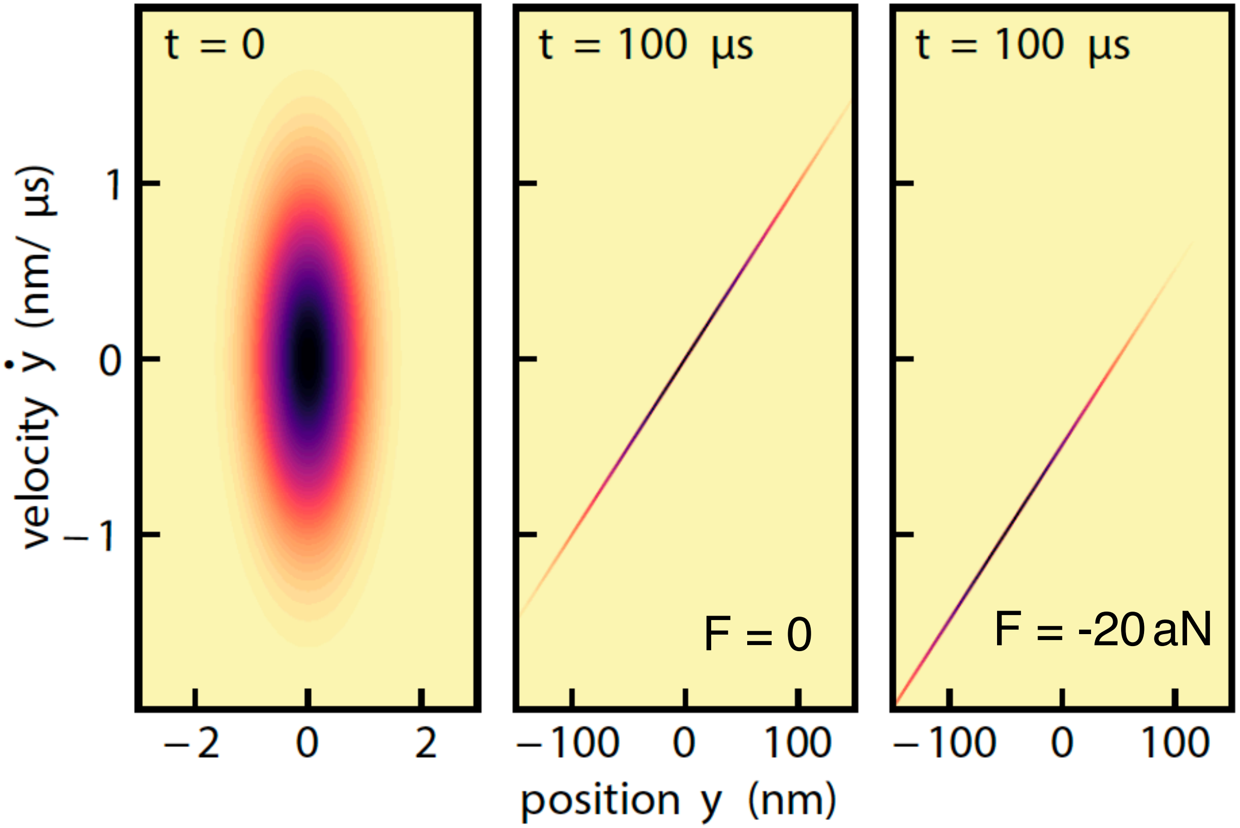
SENSING OF STATIC FORCES





arXiv:1801.01169

SENSING OF STATIC FORCES



arXiv:1801.01169

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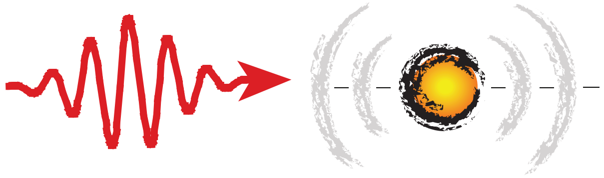
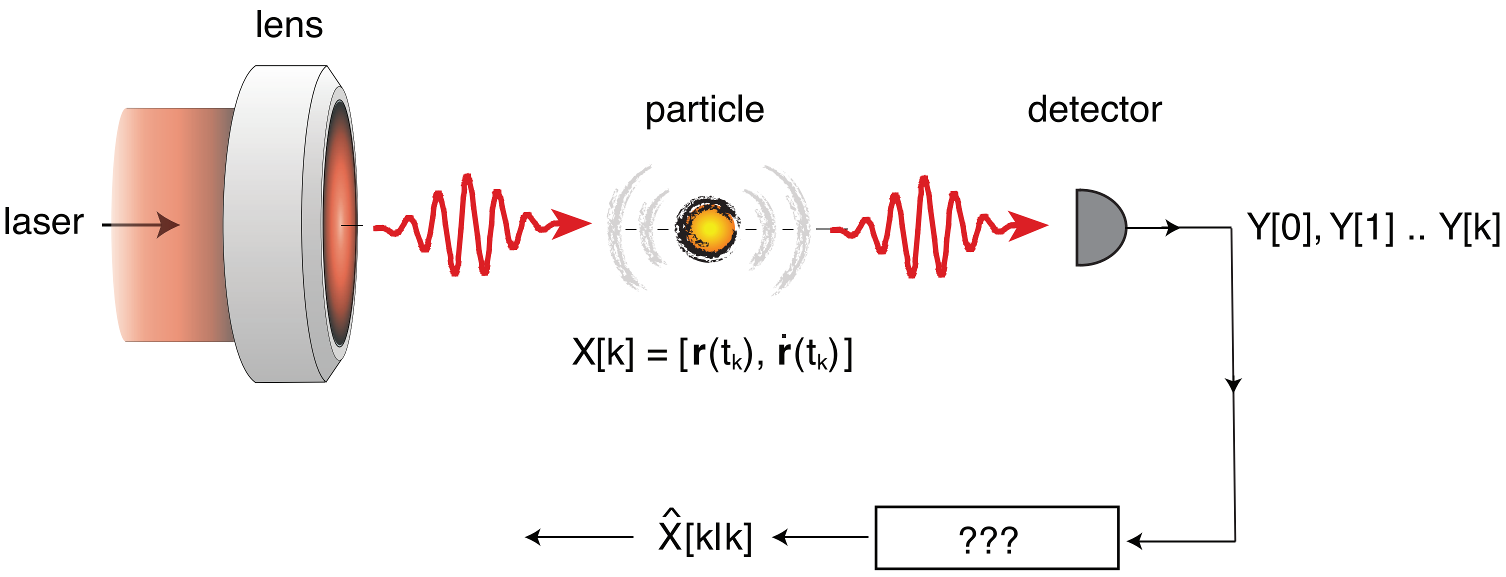
QUANTUM COLLAPSE



Number of coherent oscillations before recoil : $\Omega_0 / \Gamma_{\mathrm{recoil}} = 10$

Number of scattered photons before recoil : 10^9

FEEDBACK ON STATE ESTIMATE



$X[k] = [\mathbf{r}(t_k), \dot{\mathbf{r}}(t_k)]$

$\hat{X}[k|k]$

c.f. Aspelmeyer & co. (*PRL* **114**, 223601, 2015)

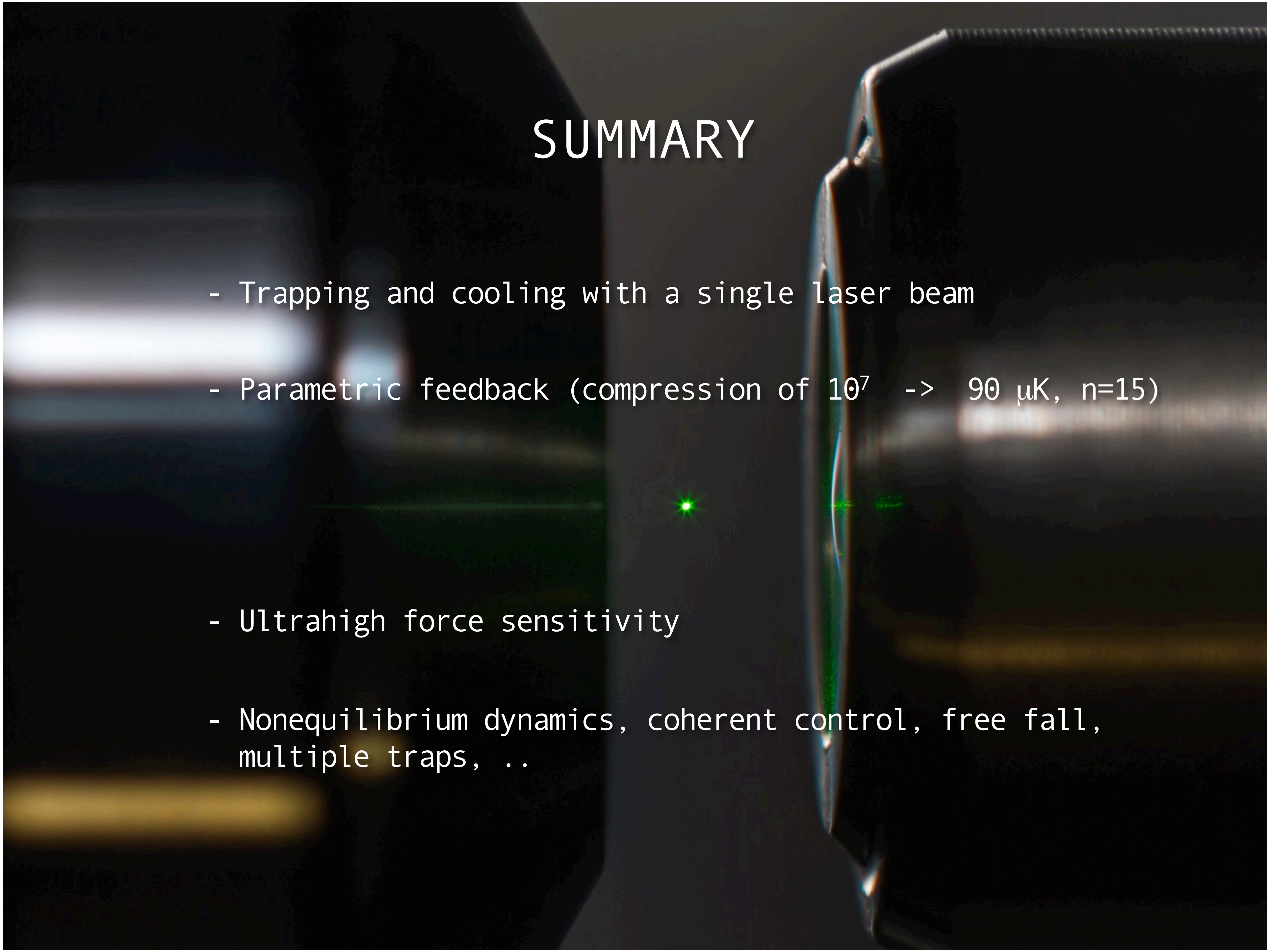
CONTINUOUS WEAK MEASUREMENTS

Stochastic Schrödinger Equation (with measurement) :

$$d|\psi\rangle \;=\; \left[-\frac{i}{\hbar}\,\hat{H}\,dt \;+\; \underset{\text{measurement rate}\;\leftarrow}{\sqrt{2k}}\,(\hat{x}-\langle\hat{x}\rangle)\,\underset{\substack{\downarrow\\ \text{Wiener process}}}{dW} \;-\; k\,\underbrace{(\hat{x}-\langle\hat{x}\rangle)^2\,dt}_{\text{diffusion}}\right]|\psi\rangle$$

Jacobs & Steck, arXiv: 0611067v1 (2006)

SUMMARY



- Trapping and cooling with a single laser beam
- Parametric feedback (compression of 10^7 -> 90 μK, n=15)
- Ultrahigh force sensitivity
- Nonequilibrium dynamics, coherent control, free fall, multiple traps, ..