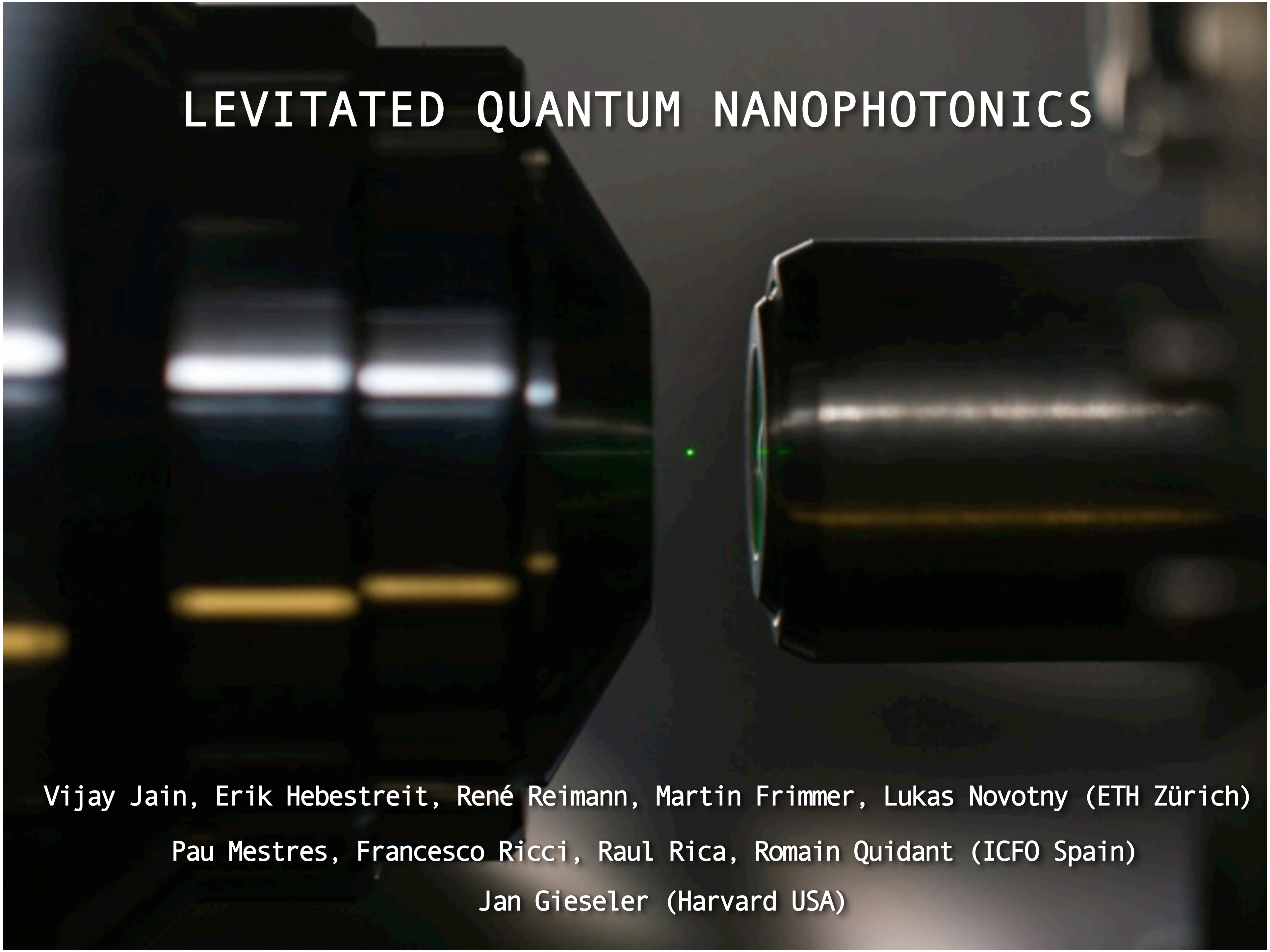


LEVITATED QUANTUM NANOPHOTONICS

Vijay Jain, Erik Hebestreit, René Reimann, Martin Frimmer, Lukas Novotny (ETH Zürich)

Pau Mestres, Francesco Ricci, Raul Rica, Romain Quidant (ICFO Spain)

Jan Gieseler (Harvard USA)

ETH zürich

OUTLINE

1: INTRODUCTION

2: PHOTON RECOIL

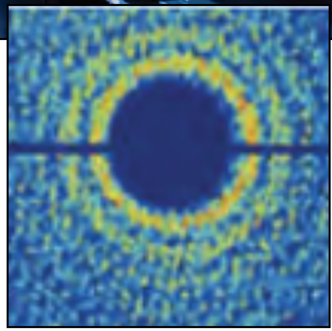
3: CLASSICAL QUANTUM SIMULATION

4: NONRECIPROCITY

5: CONCLUSIONS

SLAC NATIONAL ACCELERATOR LABORATORY

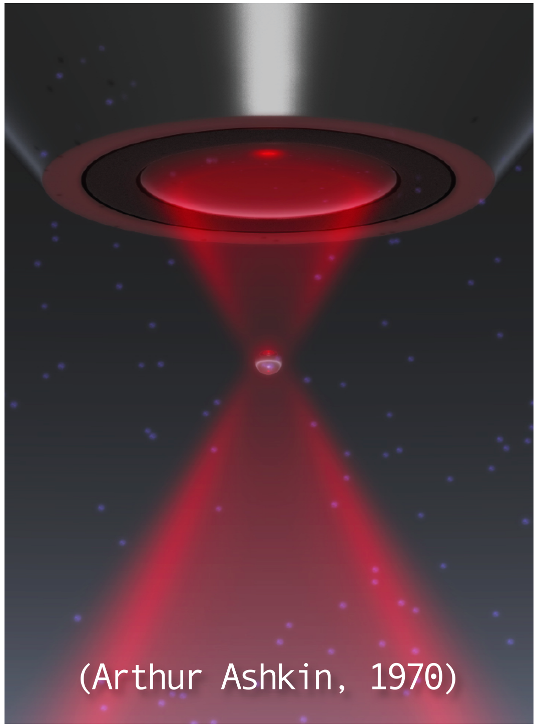
LINAC Coherent Light Source (LCLS)



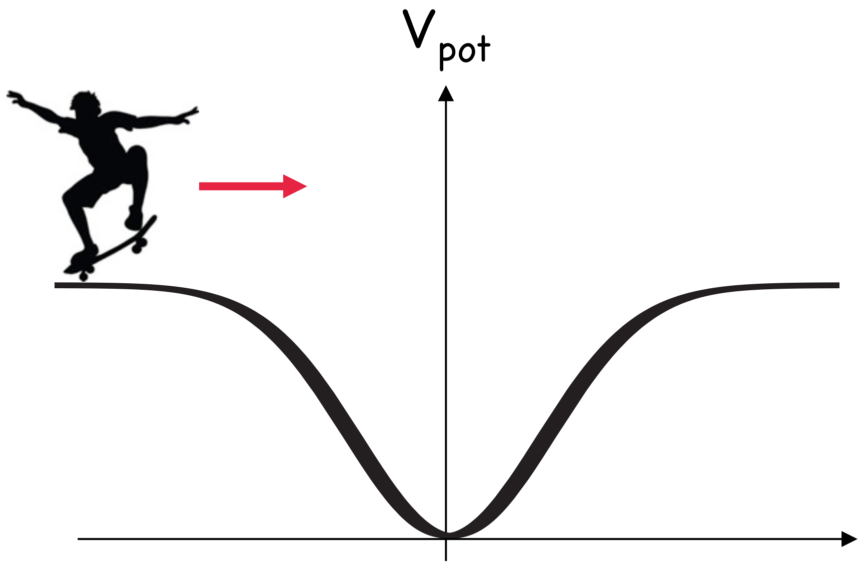
www.slac.stanford.edu

with Henry Chapman, Matthias Frank @ LLNL (2004)

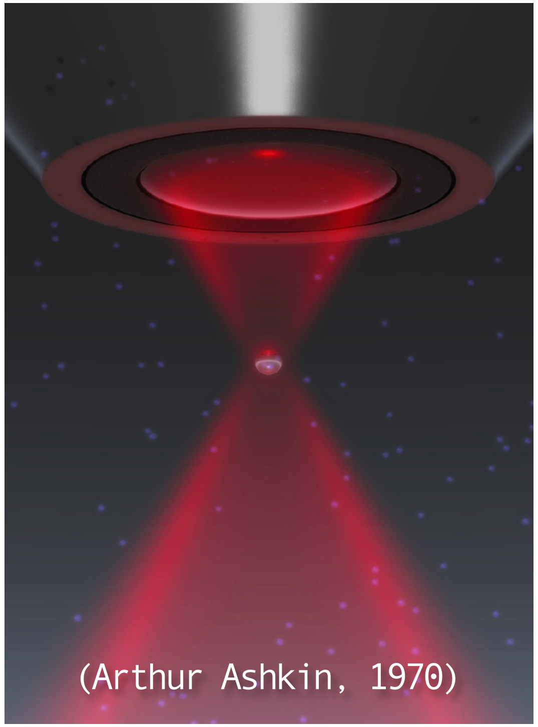
OPTICAL TRAPPING



$$\langle \mathbf{F} \rangle = -\frac{\alpha}{2} \nabla E^2(\mathbf{r})$$

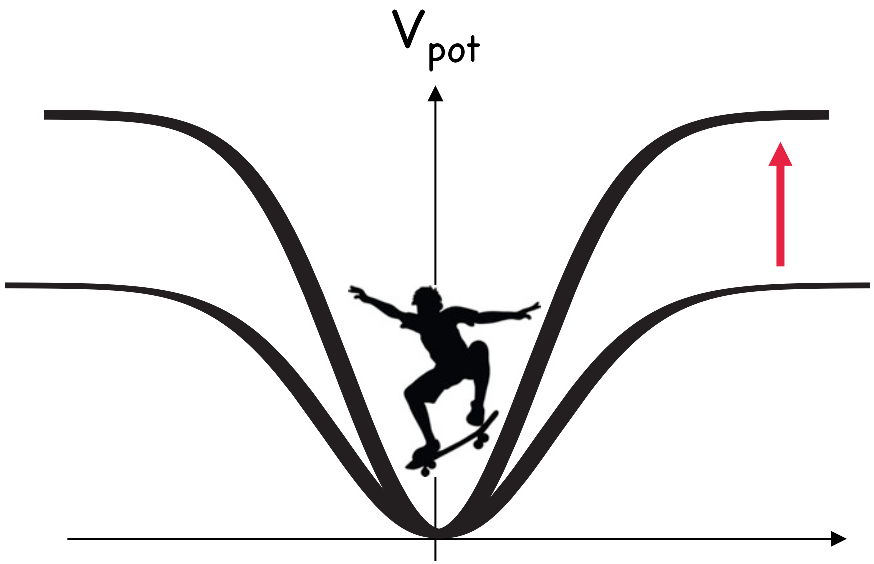


OPTICAL TRAPPING



(Arthur Ashkin, 1970)

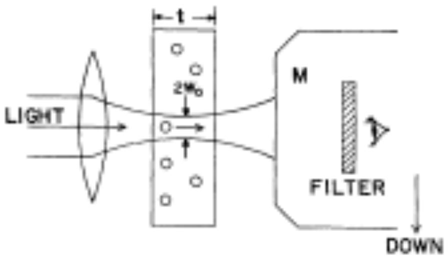
$$\langle \mathbf{F} \rangle = -\frac{\alpha}{2} \nabla E^2(\mathbf{r})$$



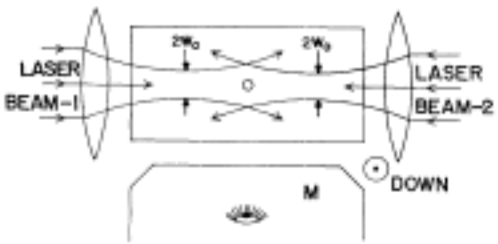
VOLUME 24, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1970

ACCELERATION AND TRAPPING OF PARTICLES BY RADIATION PRESSURE

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



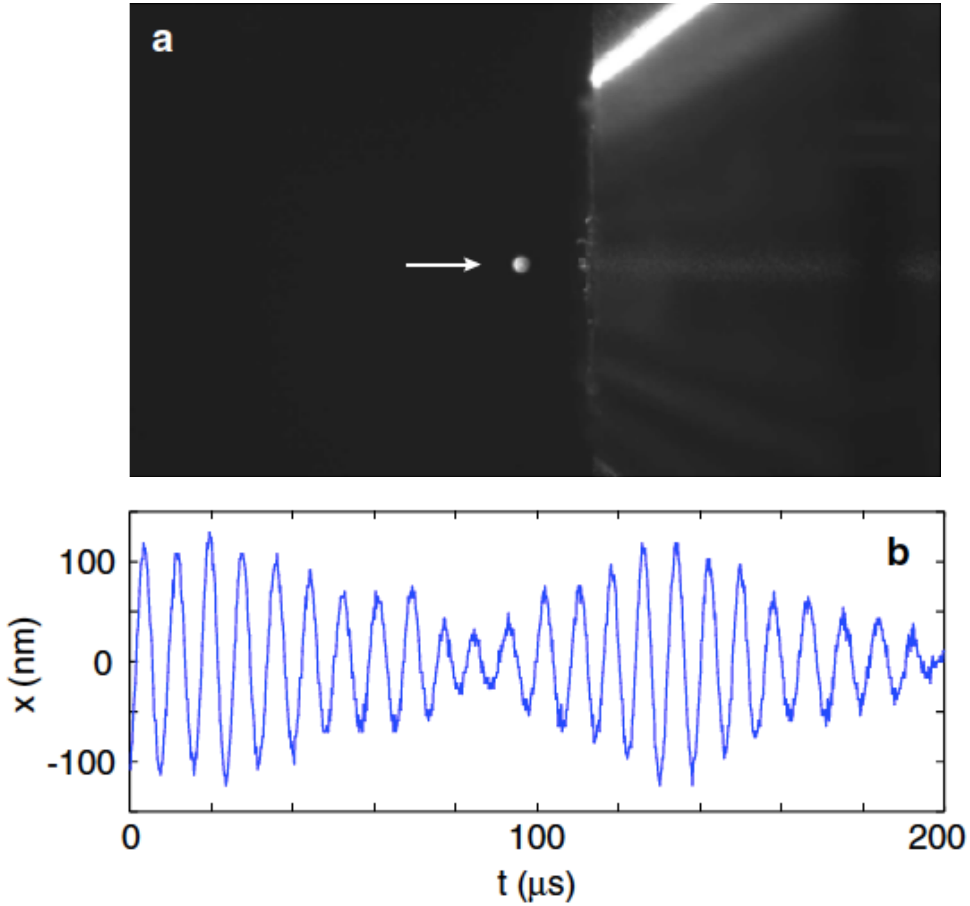
(a)



(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-

TIME DOMAIN



$$\Omega_0 = \sqrt{k_{\text{trap}}/m}.$$

$$\downarrow$$

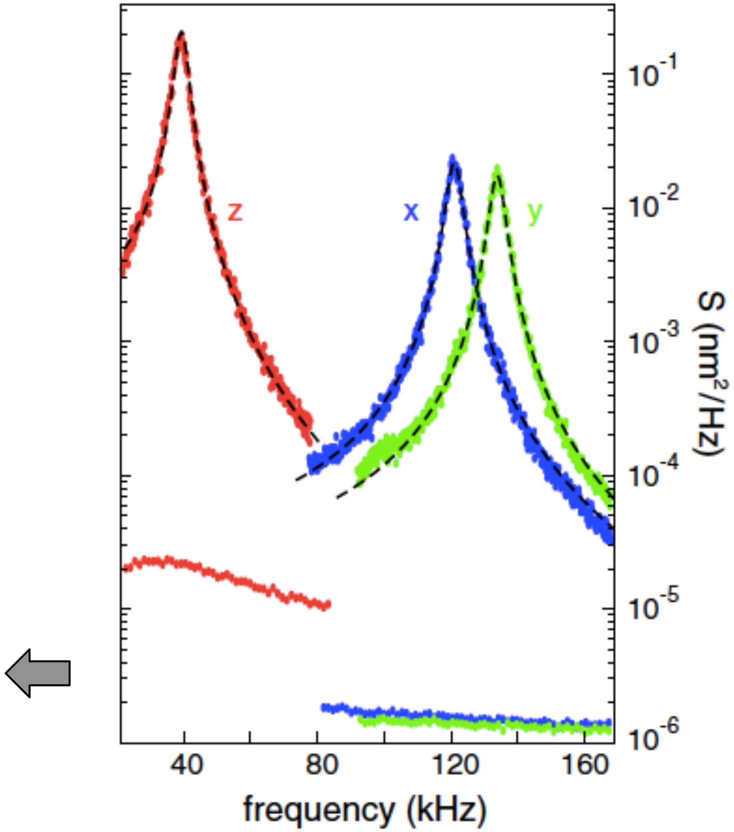
$$4\pi^3 \frac{\alpha P}{c\varepsilon_0} \frac{(\text{NA})^4}{\lambda^4}$$

PRL **109**, 103603 (2012)

ETH zürich

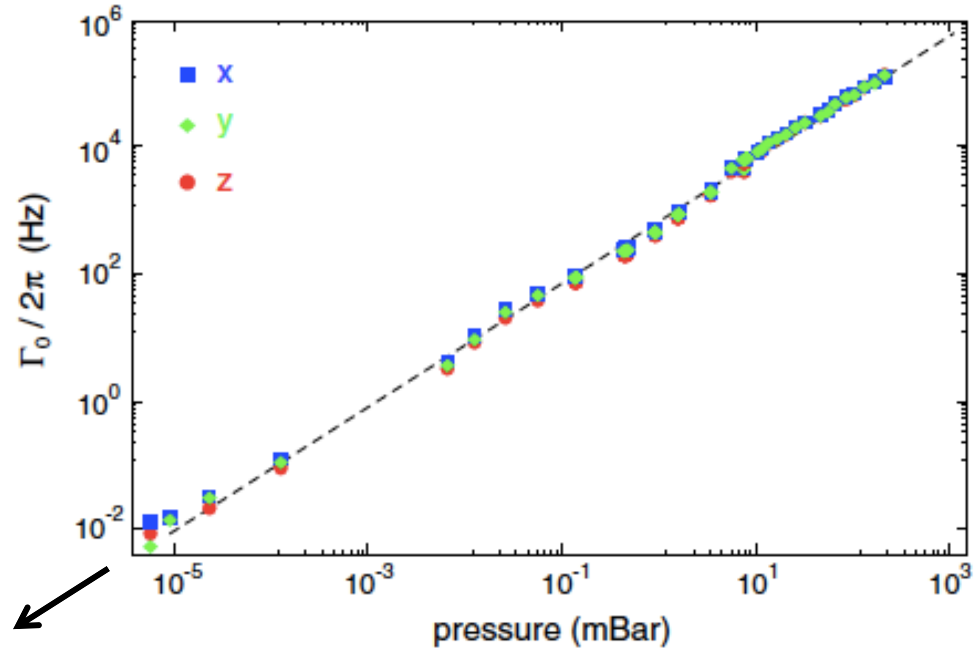
FREQUENCY DOMAIN

$$S_x(\Omega) = \int_{-\infty}^{\infty} \langle x(t)x(t-t')\rangle e^{-i\Omega t'} dt' = \frac{k_B T}{\pi m} \frac{\Gamma_0}{(\Omega_0^2 - \Omega^2)^2 + \Omega^2 \Gamma_0^2}$$



$\sim 1.2\ \mathrm{pm}/\sqrt{\mathrm{Hz}}$

QUALITY FACTOR



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

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

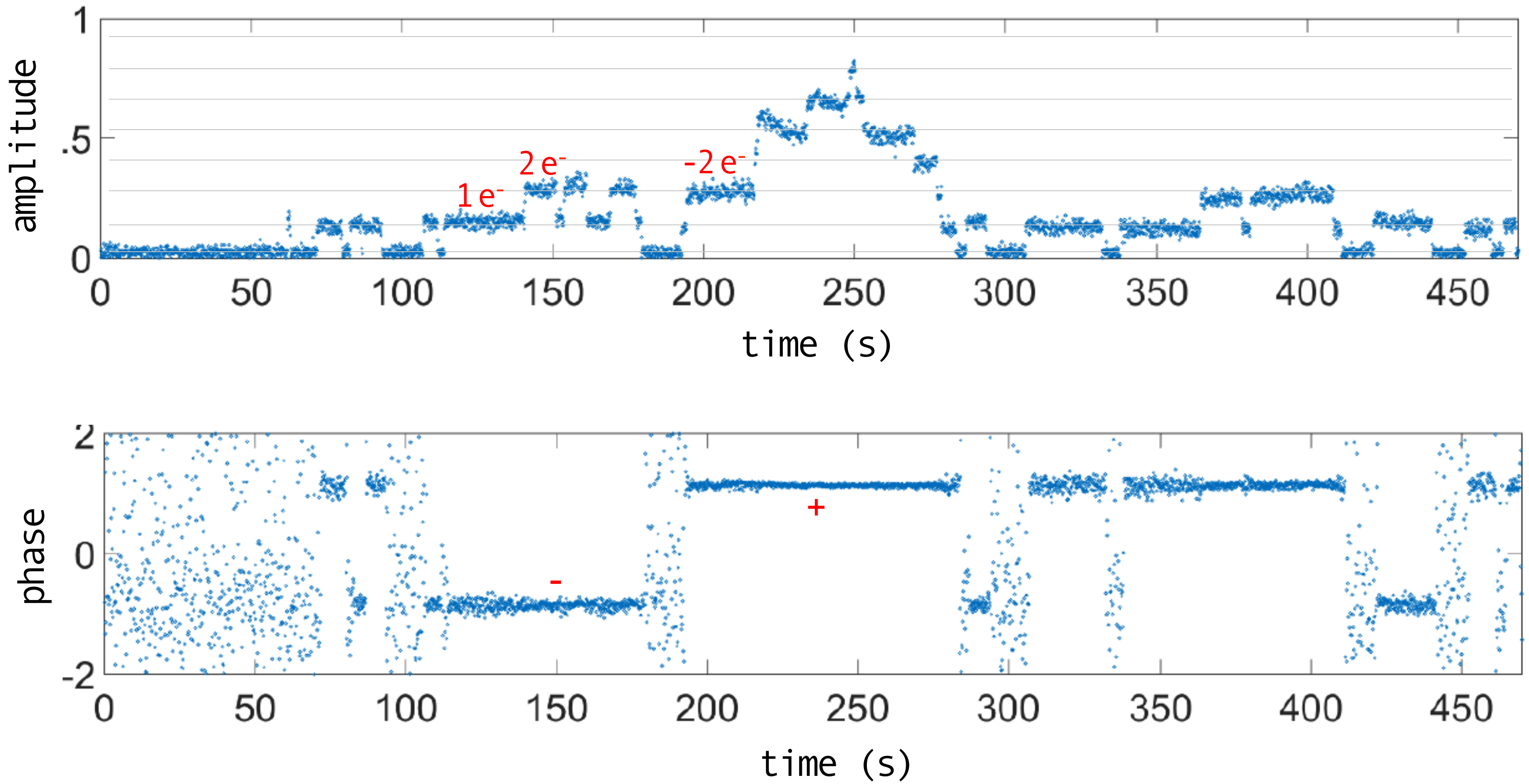
FORCE SENSITIVITY

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

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



PRA **95**, 061801 (2017)

SENSITIVITY

$q_{min} = e^- / 8$

↑

$$F_{min} = \sqrt{4 k_B T m \gamma \Delta f} = qE$$

→ 2720 V/m

(300 K → 3 K)

$\propto P_{gas}$ (1 mBar → 10^{-9} mBar)

→ $q_{min} = 10^{-7}\ e^-$

2 oders of magnitude better than current bounds !

CONSTRAINTS ON DARK MATTER

PHYSICAL REVIEW D **83,** 063509 (2011)

Turning off the lights: How dark is dark matter?

Samuel D. McDermott, Hai-Bo Yu, and Kathryn M. Zurek
Michigan Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA
(Received 24 November 2010; published 9 March 2011)

We consider current observational constraints on the electromagnetic charge of dark matter. The velocity dependence of the scattering cross section through the photon gives rise to qualitatively different constraints than standard dark matter scattering through massive force carriers. In particular, recombination epoch observations of dark matter density perturbations require that ϵ, the ratio of the dark matter to electronic charge, is less than 10^{-6} for $m_X = 1$ GeV, rising to $\epsilon < 10^{-4}$ for $m_X = 10$ TeV.

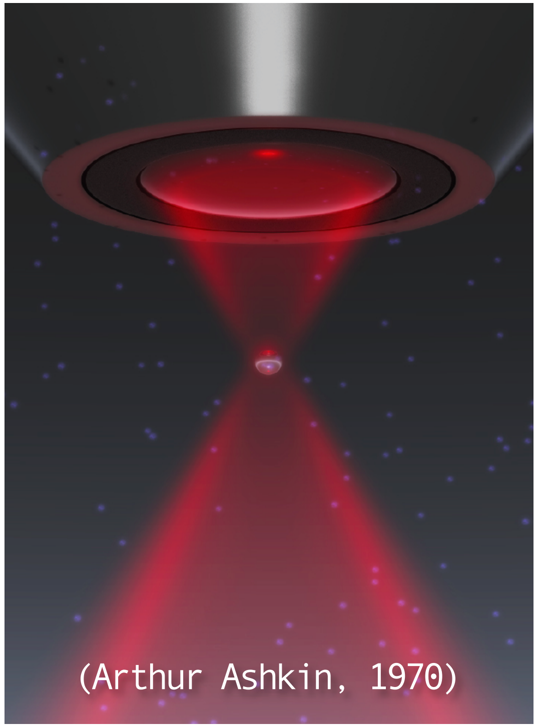
PRL **113,** 251801 (2014) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2014

Search for Millicharged Particles Using Optically Levitated Microspheres

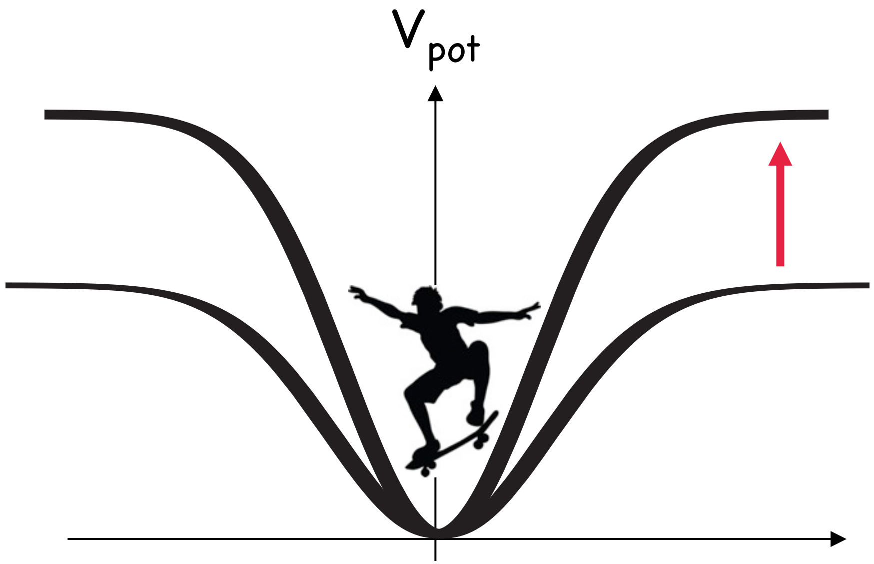
David C. Moore,* Alexander D. Rider, and Giorgio Gratta
Physics Department, Stanford University, Stanford, California 94305, USA

Millicharged particles, i.e., particles with charge $|q| = \epsilon e$ for $\epsilon \ll 1$, have been proposed in extensions to the standard model that include new, weakly coupled gauge sectors (e.g., [1]). It is possible that millicharged particles are a component of the Universe's dark matter [2,3]. If millicharged particles exist, they could have been produced in the early universe [4] and may have formed stable bound states that can be searched for in terrestrial matter today [5,6].

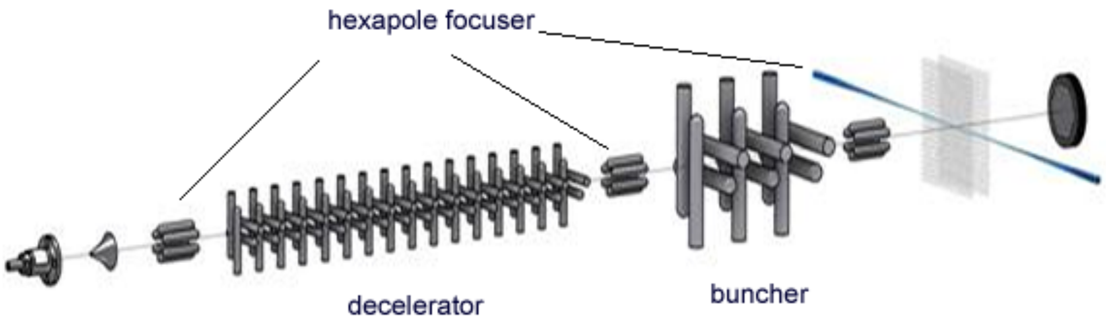
CONTROL OF MOTION ?



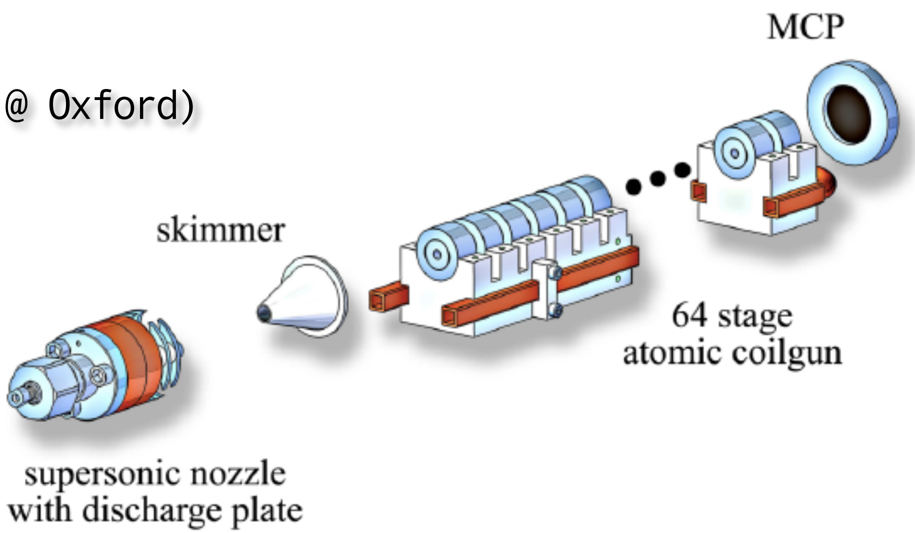
$$\langle \mathbf{F} \rangle = -\frac{\alpha}{2} \nabla E^2(\mathbf{r})$$



DECELERATION / COOLING

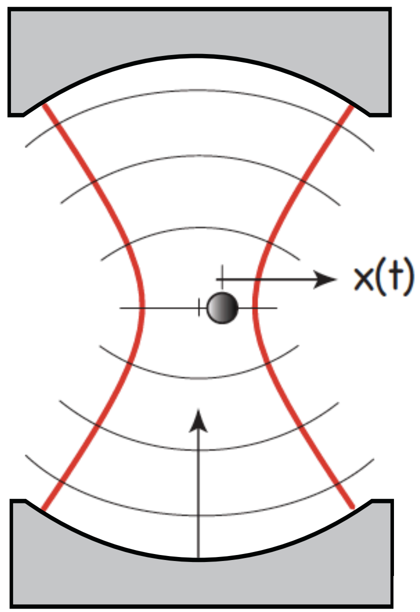


Stark decelerator (Tim Softley @ Oxford)



Atomic coilgun (Mark Raizen @ UT Austin,
Frédéric Merkt @ ETH)

PASSIVE BACKACTION

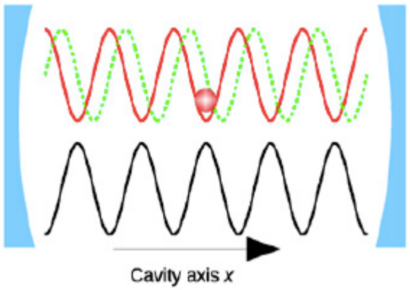


ETH zürich

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]

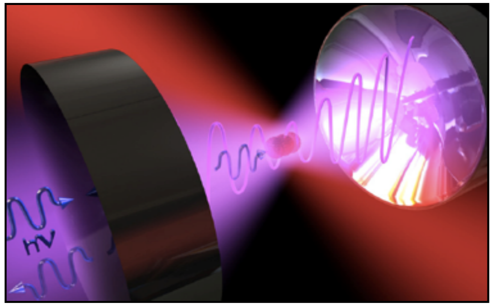
PNAS | January 19, 2010 | vol. 107 | no. 3 | 1005–1010



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

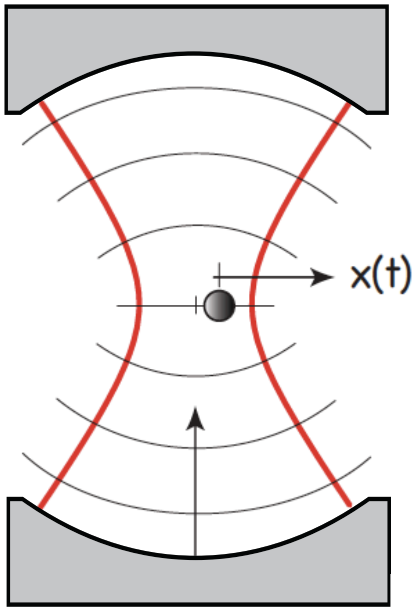
Cavity Cooling a Single Charged Levitated Nanosphere

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



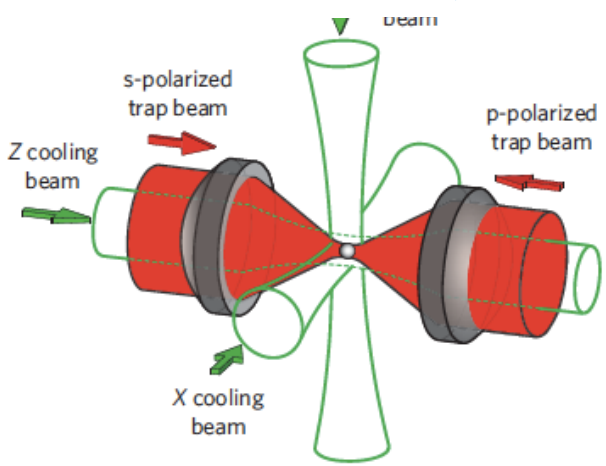
nature physics

LETTERS

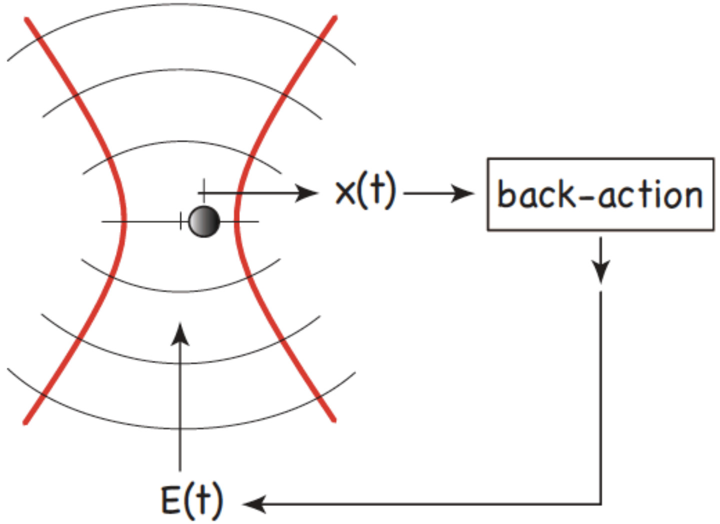
PUBLISHED ONLINE: 20 MARCH 2011 | DOI: 10.1038/NPHYS1952

Millikelvin cooling of an optically trapped microsphere in vacuum

Tongcang Li, Simon Kheifets and Mark G. Raizen*



PROBLEM STATEMENT



$$\langle \mathbf{F}_{\text{fluct}}(t)\,\mathbf{F}_{\text{fluct}}(t')\rangle = 2m\Gamma_0\,k_B T\,\overleftrightarrow{\mathrm{I}}\,\delta(t-t')$$

$$\ddot{\mathbf{r}}(t) + \Gamma_0\,\dot{\mathbf{r}}(t) - \frac{\alpha}{2}\nabla E^2(\mathbf{r}) = \frac{1}{m}\left[\mathbf{F}_{\text{fluct}}(t) + \mathbf{F}_{\text{opt}}(t)\right]$$

$$\Gamma_0 = 4\pi R^2\,P_{\text{gas}}\,/\,(m\,v_{\text{gas}})$$

focal field

$$\oint F_{\text{opt}}(x)\,dx \neq 0$$

$$\alpha = 4\pi\varepsilon_0 R^3[\varepsilon-1]/[\varepsilon+2]$$

letters to nature

Cavity cooling of a microlever

Constanze Höhberger Metzger & Khaled Karrai

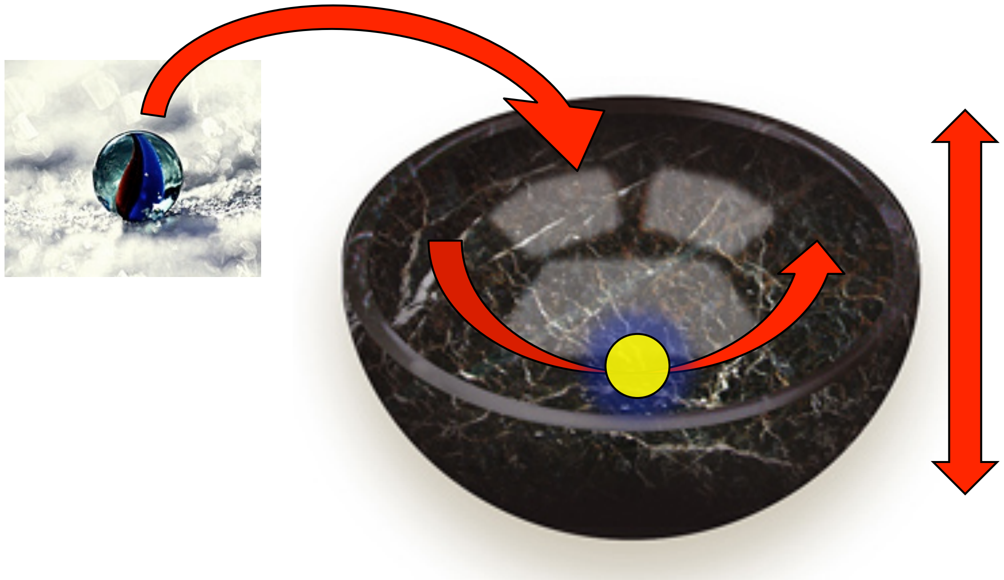
Center for NanoScience and Sektion Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, 80539 München, Germany

1002 NATURE | VOL 432 | 23/30 DECEMBER 2004 | www.nature.com/nature

$$m\frac{d^2z}{dt^2} + m\Gamma\frac{dz}{dt} + Kz = F_{th} + \sum_n \int_0^t \frac{dF_n[z(t')]}{dt} h_n(t-t')dt'$$

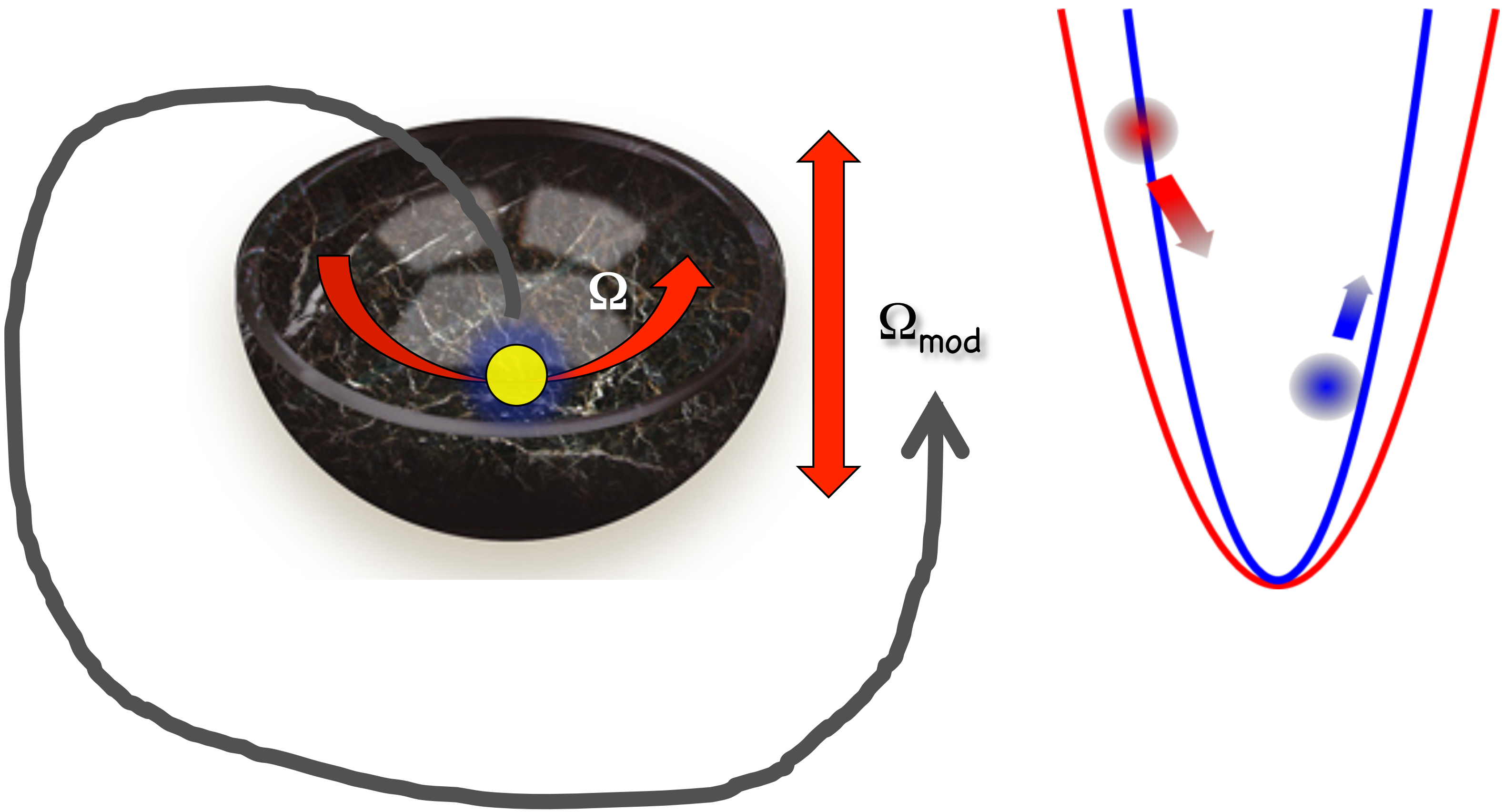
As we will see below, the essence of cooling is based on the fact that the optically induced forces acting on the lever are delayed with respect to a sudden change in the lever position.

CONTROL OF MOTION



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

PARAMETRIC COOLING

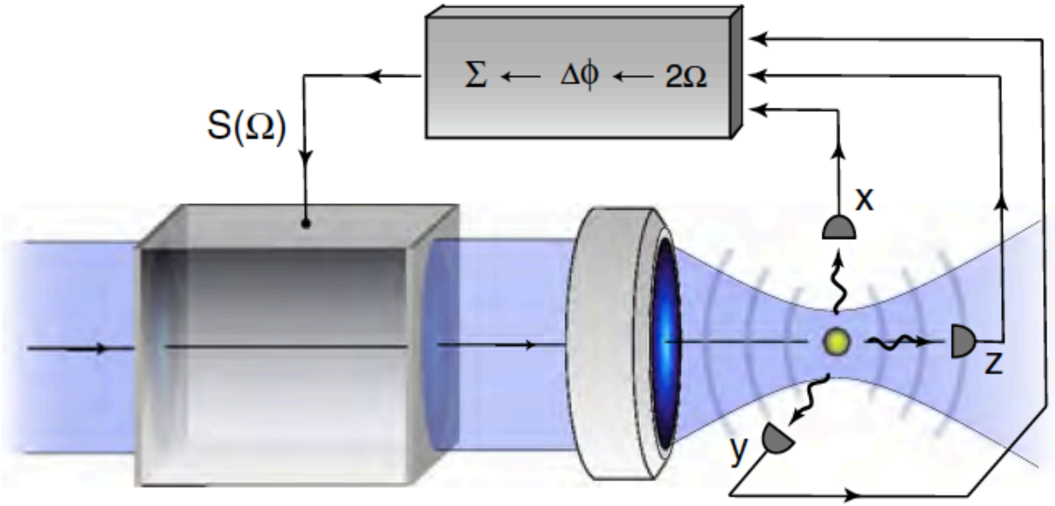


PARAMETRIC FEEDBACK

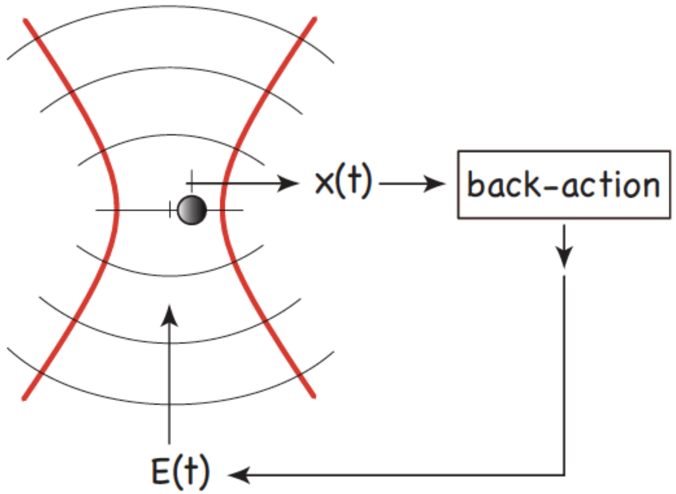
$$\ddot{x}(t) + \gamma\,\dot{x}(t) + \Omega_0^2\,x(t) = (1/m)\left[F_{\mathrm{fluct}}(t) + F_{\mathrm{opt}}(t)\right]$$

$$F_{\mathrm{opt}}(t) = \Delta k_{\mathrm{trap}}(t)\,x(t)$$

$$x(t)\dot{x}(t)$$



FEEDBACK LINEARIZED

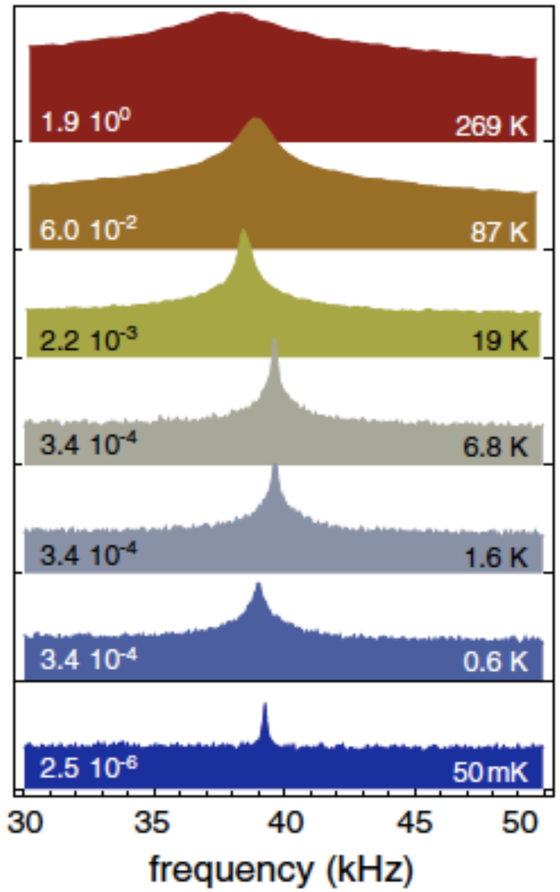


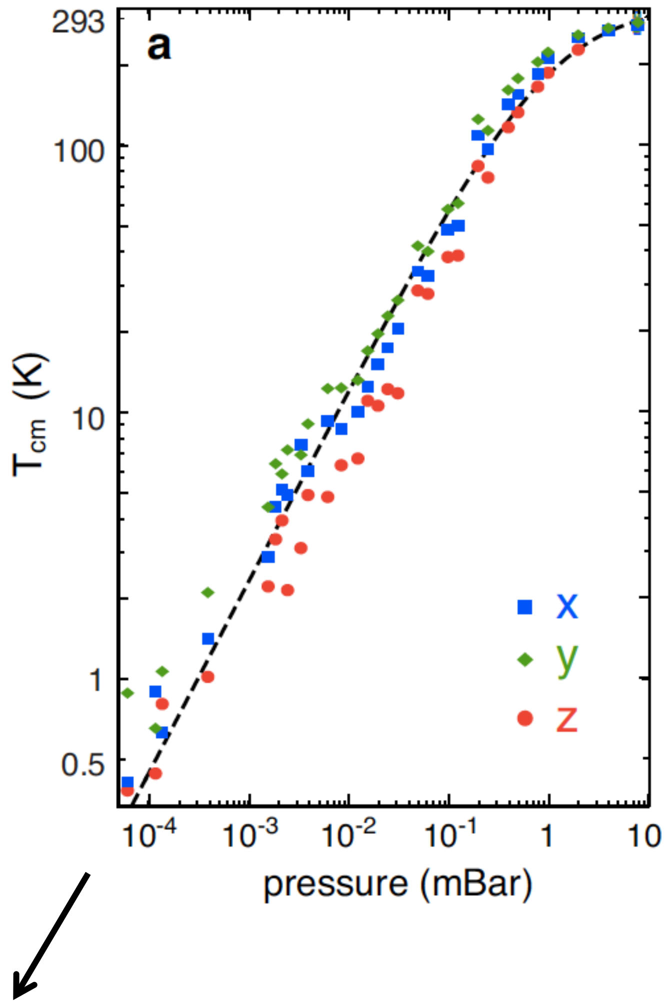
$$\ddot{x}(t) + \gamma\,\dot{x}(t) + \Omega_0^2\,x(t) = (1/m)\,[F_{\text{fluct}}(t) + F_{\text{opt}}(t)]$$

$$\ddot{x}(t) + [\gamma + \delta\Gamma]\,\dot{x}(t) + [\Omega_0 + \delta\Omega]^2\,x(t) = F_{\text{fluct}}(t)\,/\,m$$

ETH zürich

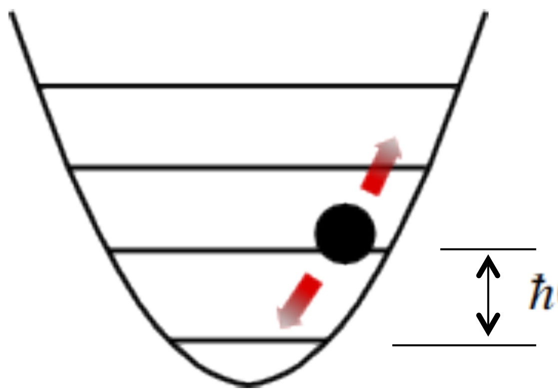
CENTER-OFF-MASS TEMPERATURE





PRL **109**, 103603 (2012)

QUANTUM GROUNDSTATE



$$\hbar(\Omega_0 + \delta\Omega) \sim \hbar\Omega_0$$

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

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

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OUTLINE

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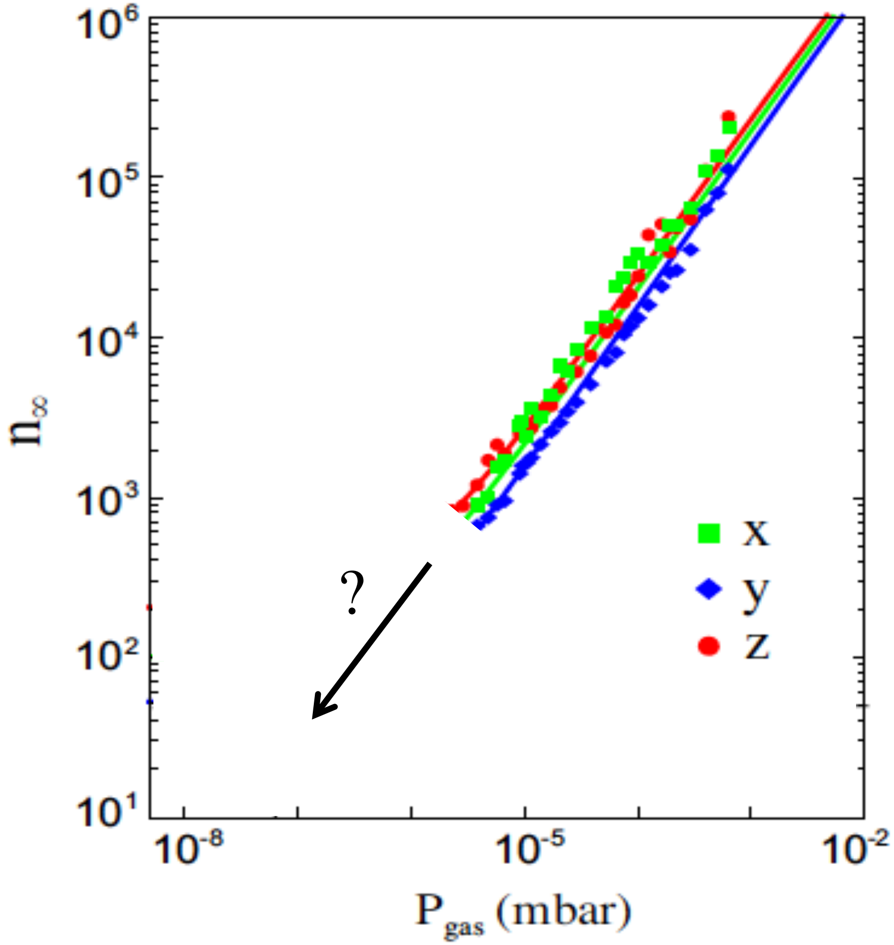
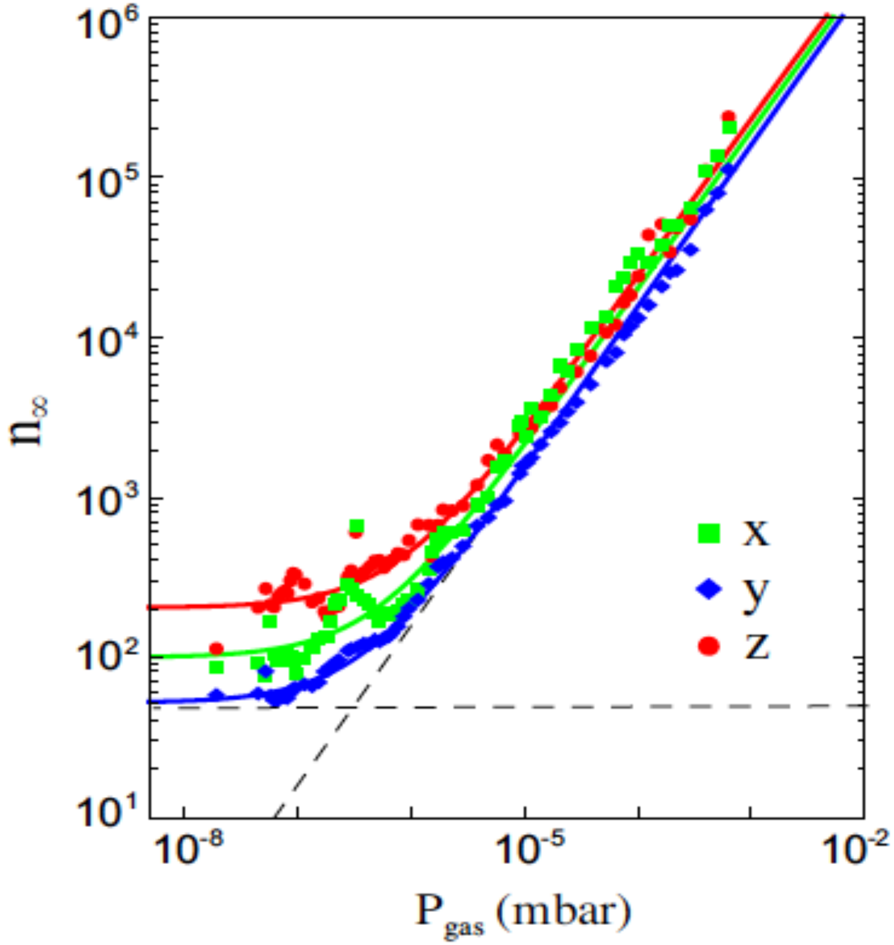
ENTERING NEW HEATING REGIME



PRL **116**, 243601 (2016)

ENTERING NEW HEATING REGIME



PRL **116**, 243601 (2016)

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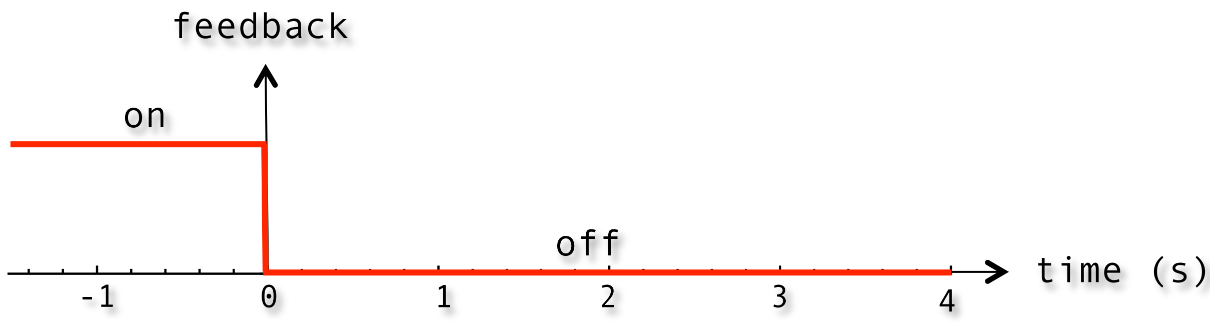
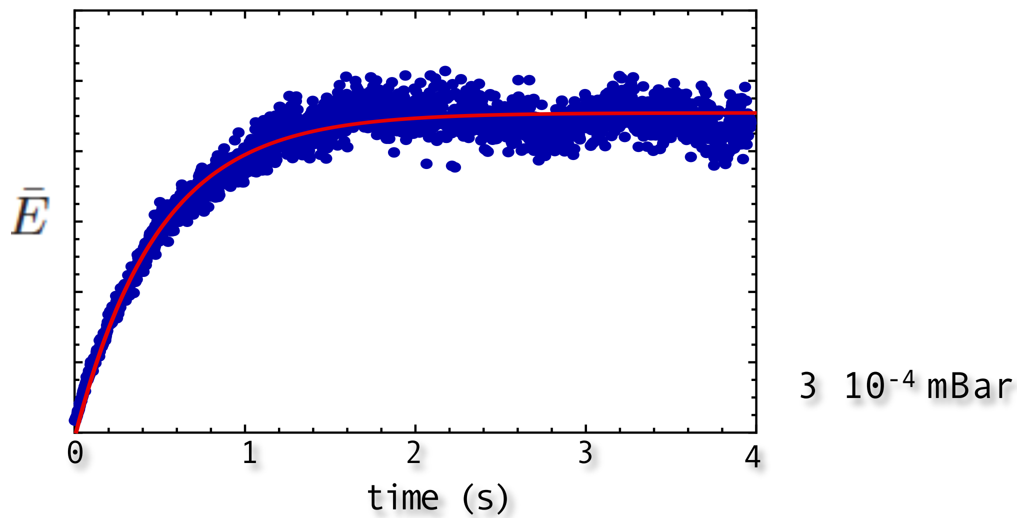
REHEATING DYNAMICS



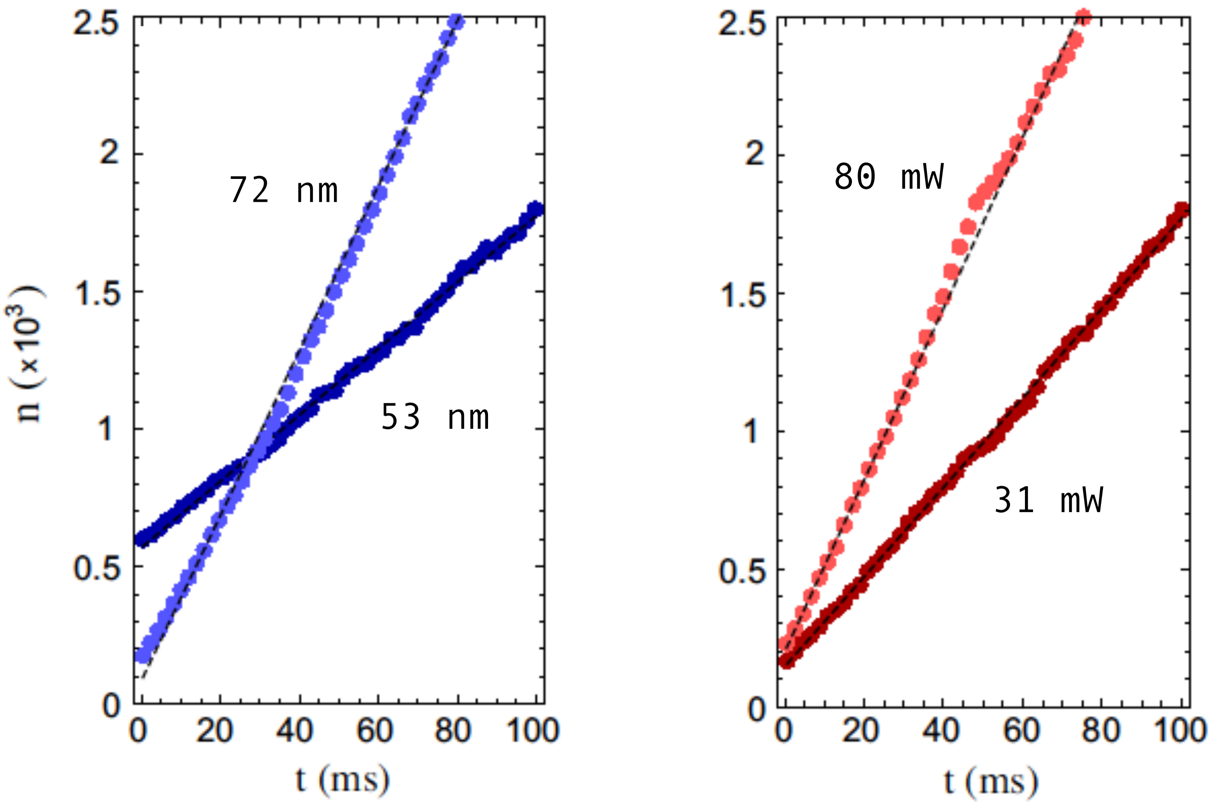


Fokker-Planck: $$\frac{d}{dt}\bar{E}(t) = -\gamma\left[\bar{E}(t) - E_\infty\right]$$

Nature Nanotech. 9, 358 (2014)

MEASURING PHOTON RECOIL

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



10-40 kHz

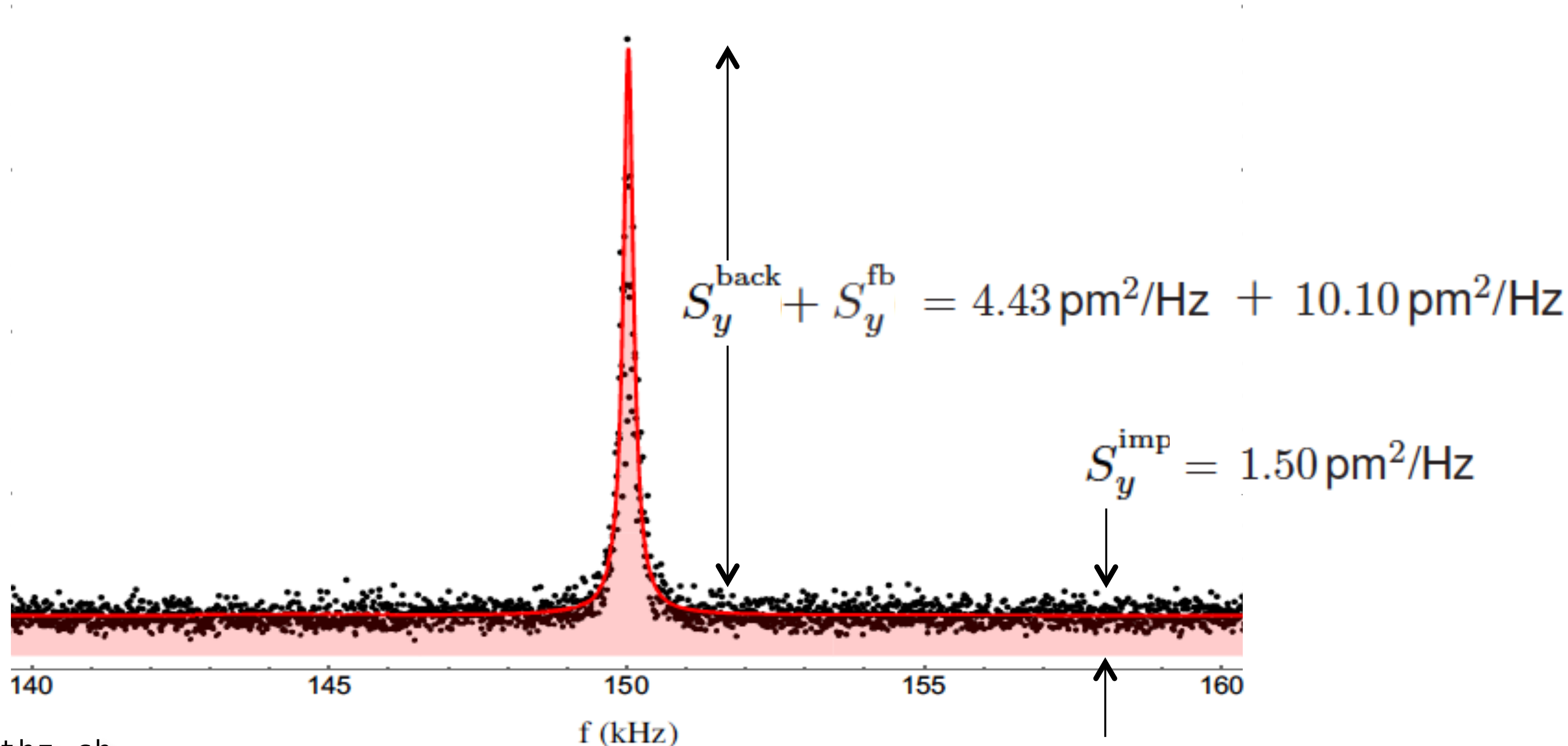
$$\Gamma_{recoil} = \frac{1}{5}\,\frac{P_{scatt}}{mc^2}\,\frac{\omega_0}{\Omega_0}$$

PRL **116**, 243601 (2016)

MEASUREMENT BACKACTION

$$S_y(\Omega_0) = S_y^{\text{imp}}(\Omega_0) + S_y^{\text{back}}(\Omega_0) + S_y^{\text{fb}}(\Omega_0)$$

$$\sim \frac{1}{P_{\text{scatt}}} \qquad \sim P_{\text{scatt}}$$

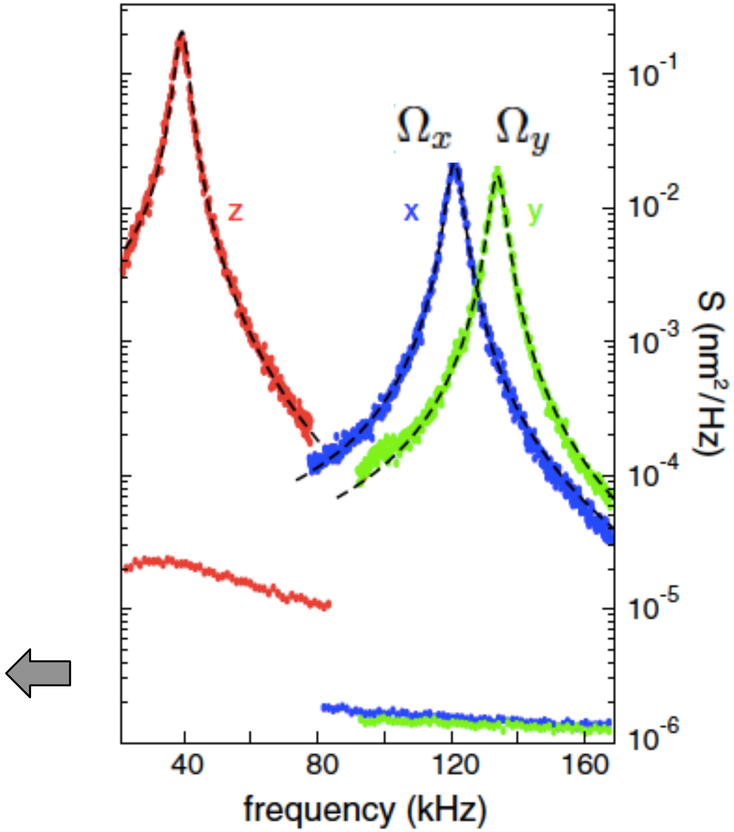


OUTLINE

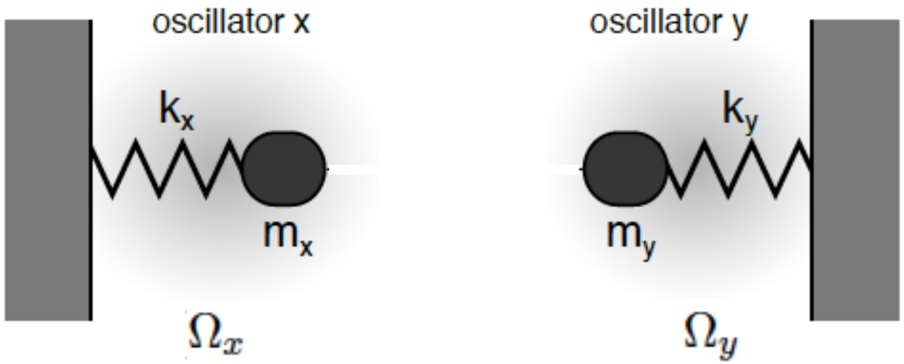
FREQUENCY DOMAIN

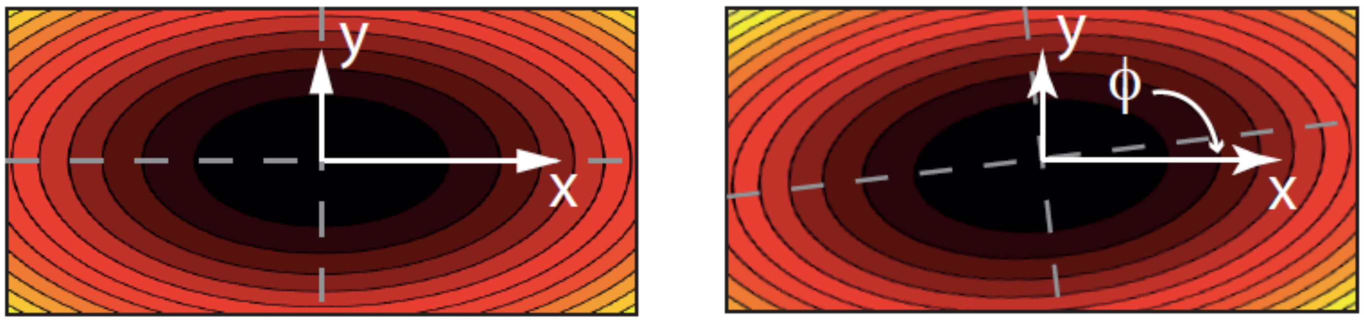
$$S_x(\Omega) = \int_{-\infty}^{\infty} \langle x(t)x(t-t')\rangle e^{-i\Omega t'} dt' \;= \frac{k_B T}{\pi m} \frac{\Gamma_0}{(\Omega_0^2 - \Omega^2)^2 + \Omega^2 \Gamma_0^2}$$

$\sim 1.2 \text{ pm}/\sqrt{\text{Hz}}$

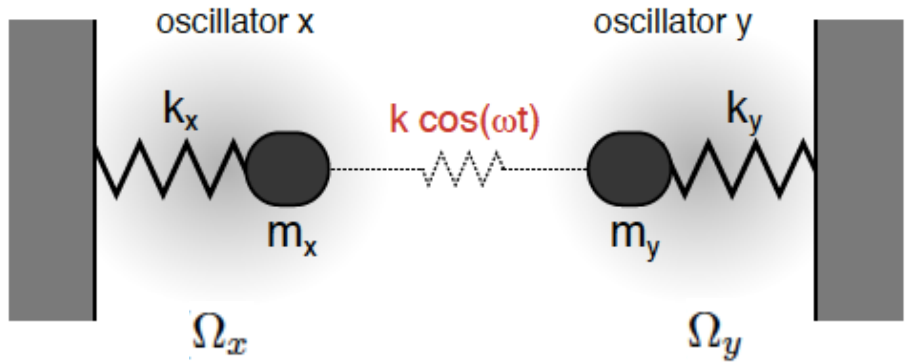


PARAMETRICALLY COUPLED OSCILLATORS

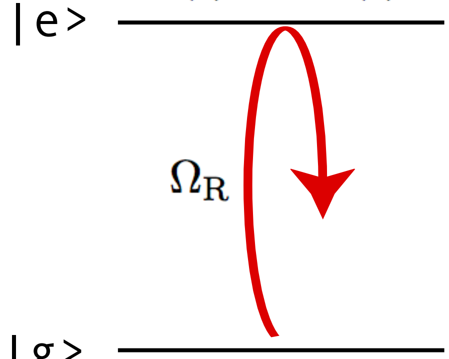




CLASSICAL QUANTUM MECHANICS



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



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

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

$$\Omega_\mathrm{R} = \sqrt{\delta^2 \omega_0^2 + \Delta^2}$$

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

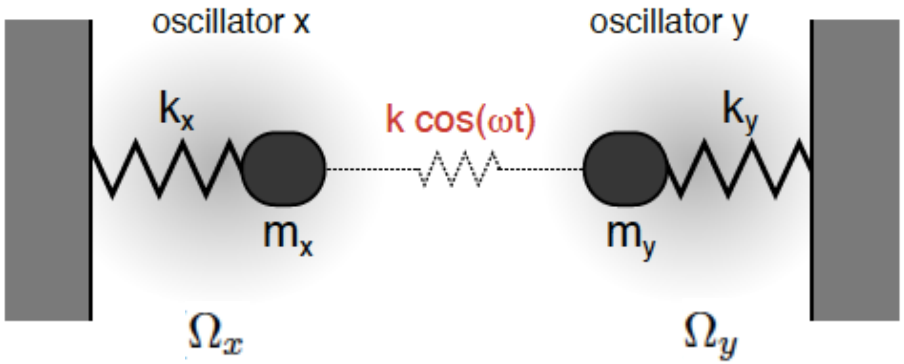
CLASSICAL QUANTUM MECHANICS

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

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

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

MAPPING ON BLOCH SPHERE



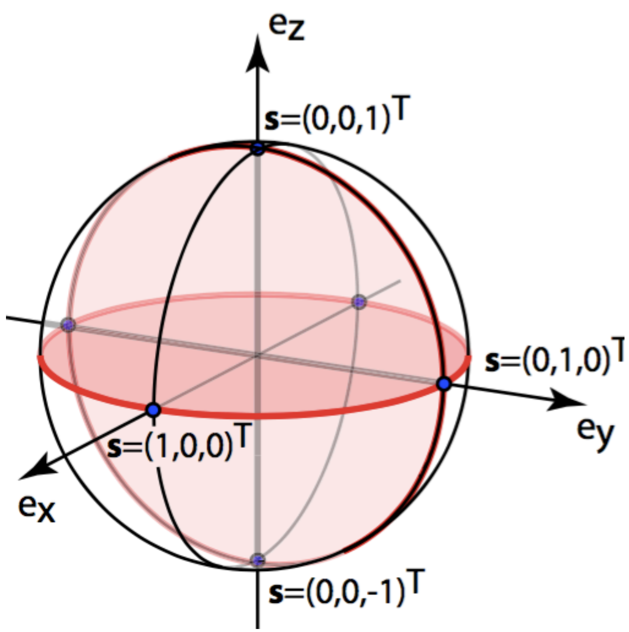
$$x(t) \;=\; \bar{a}(t)\,\exp[i(\Omega_0 - \omega/2)t]$$

|e>

Ω_R

|g>

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



PRL **117**, 163601 (2016)

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Am. J. Phys. 82 (10), October 2014 http://aapt.org/ajp 947

The classical Bloch equations

Martin Frimmer and Lukas Novotny
ETH Zürich, Photonics Laboratory, 8093 Zürich, Switzerland (www.photonics.ethz.ch)

PHYSICAL REVIEW A **VOLUME 33, NUMBER 6** **JUNE 1986**

SU(2) and SU(1,1) interferometers

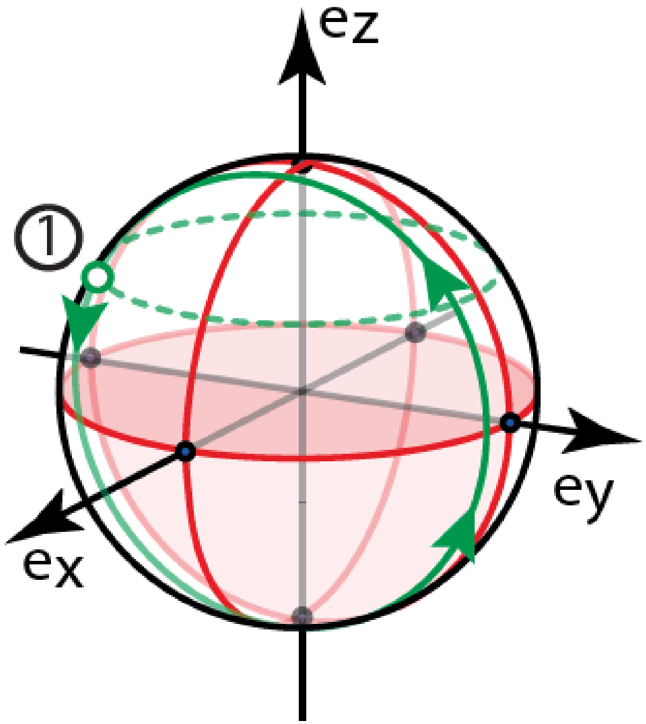
Bernard Yurke, Samuel L. McCall, and John R. Klauder
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 30 October 1985)

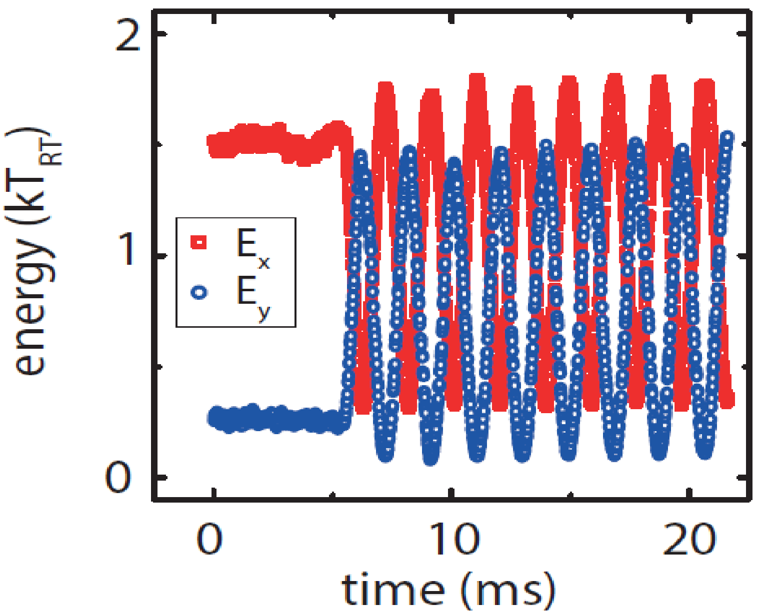
IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-22, NO. 11, NOVEMBER 1986 2131

A Generalized Geometrical Representation of Coupled Mode Theory

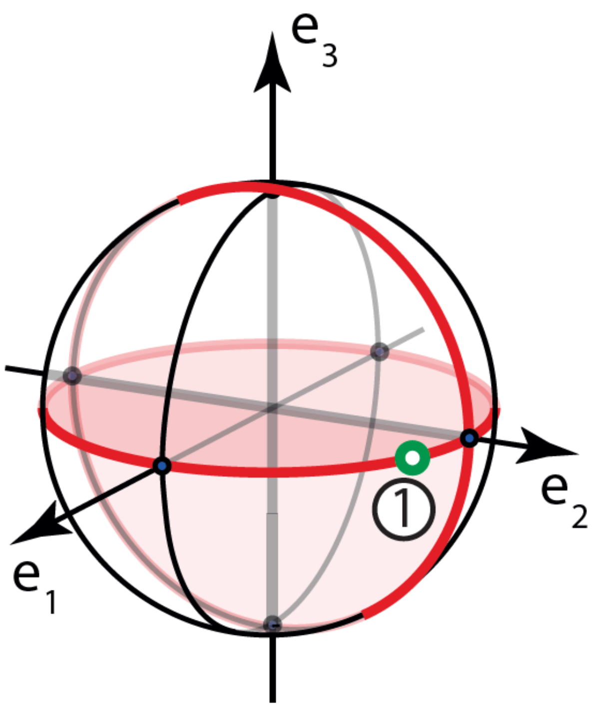
NICHOLAS J. FRIGO

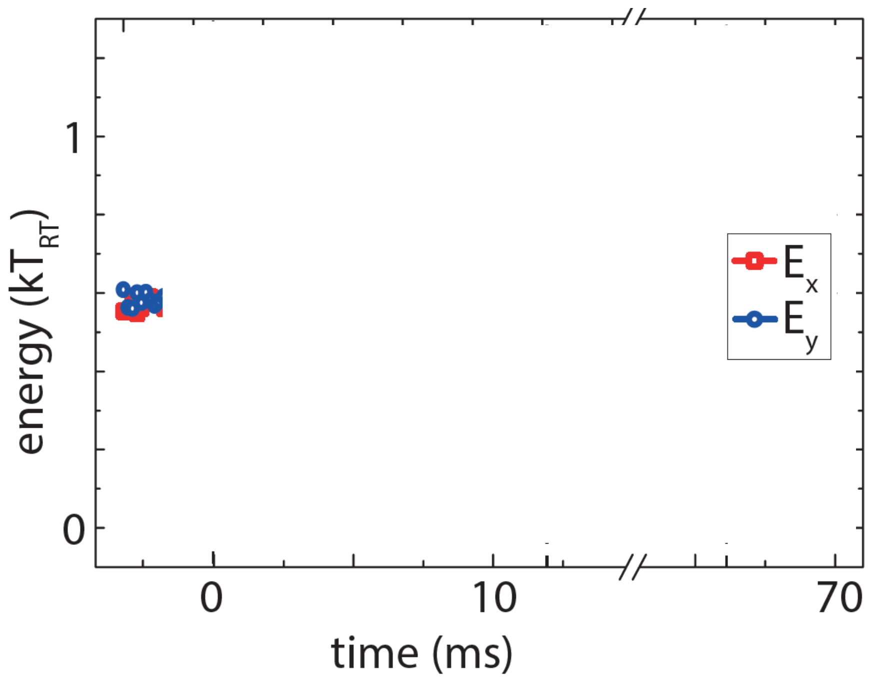
RABI OSCILLATIONS





COOLING PROTOCOL





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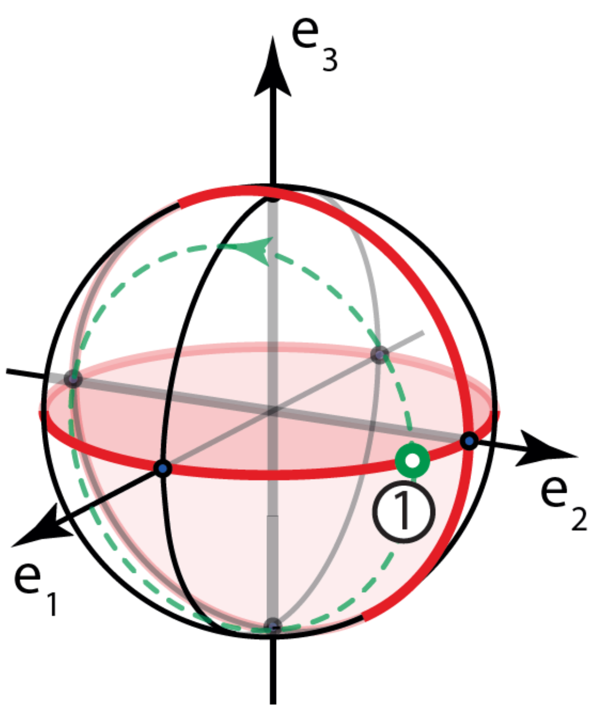

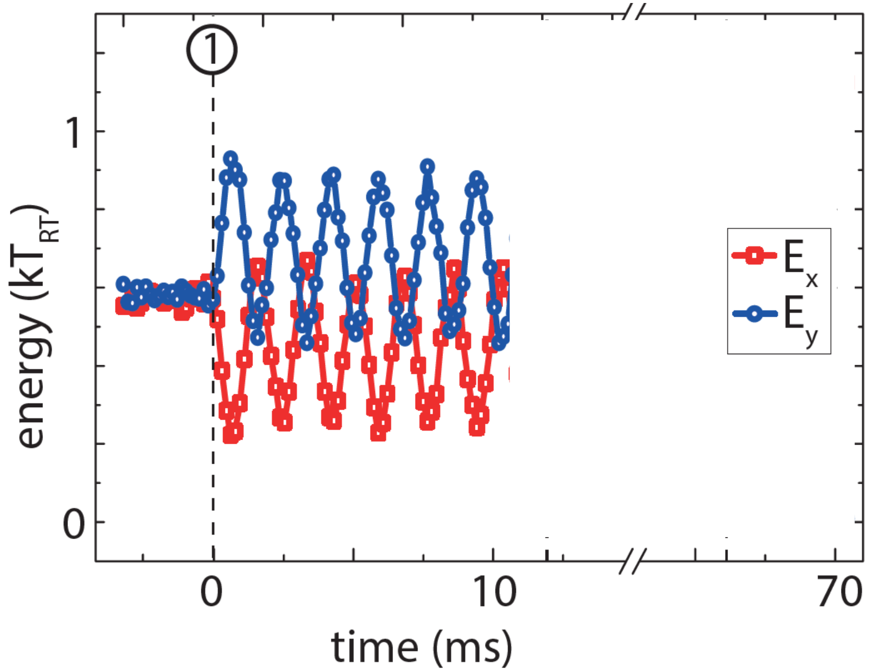

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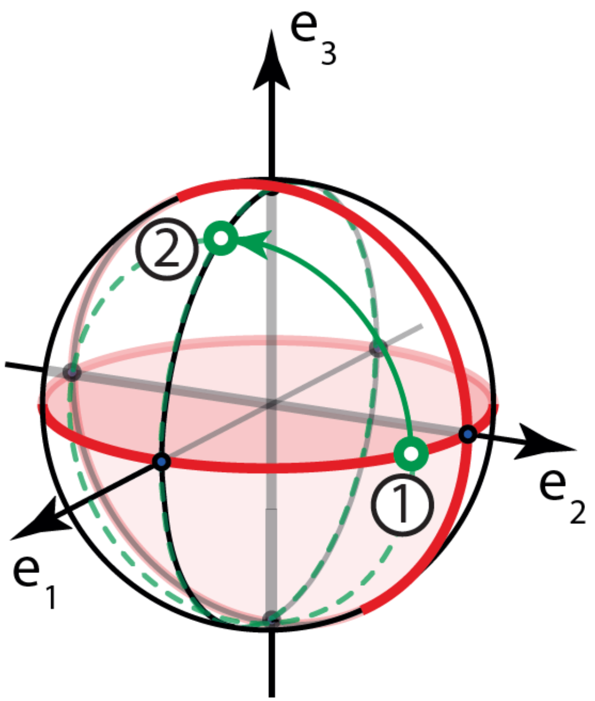

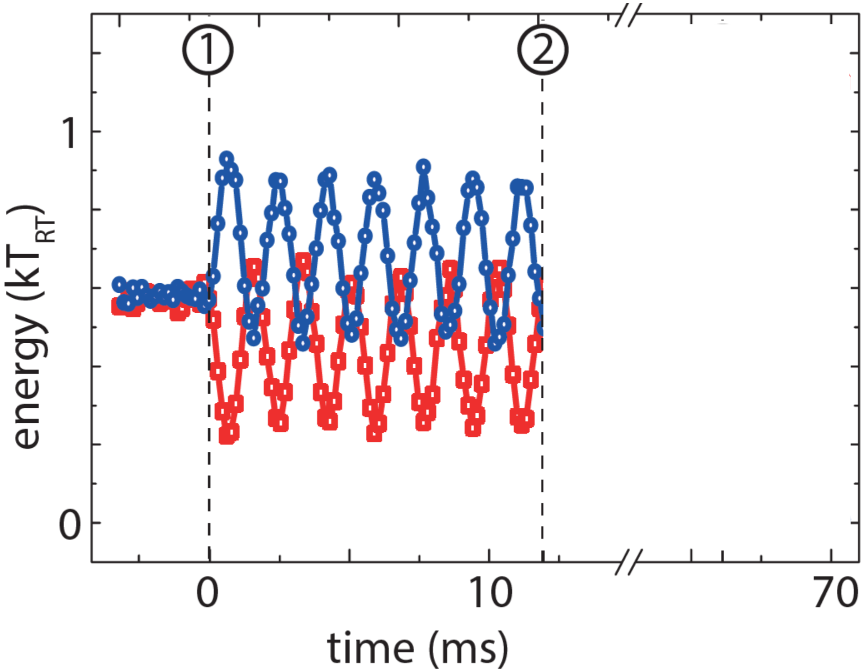

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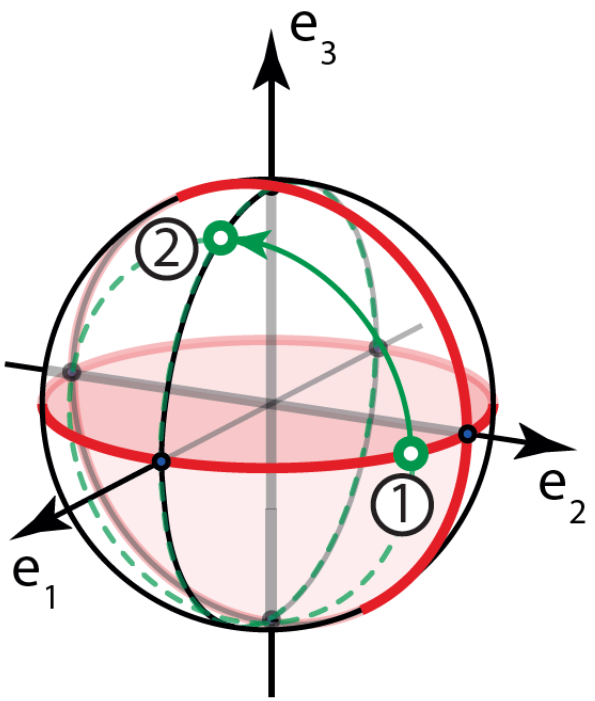

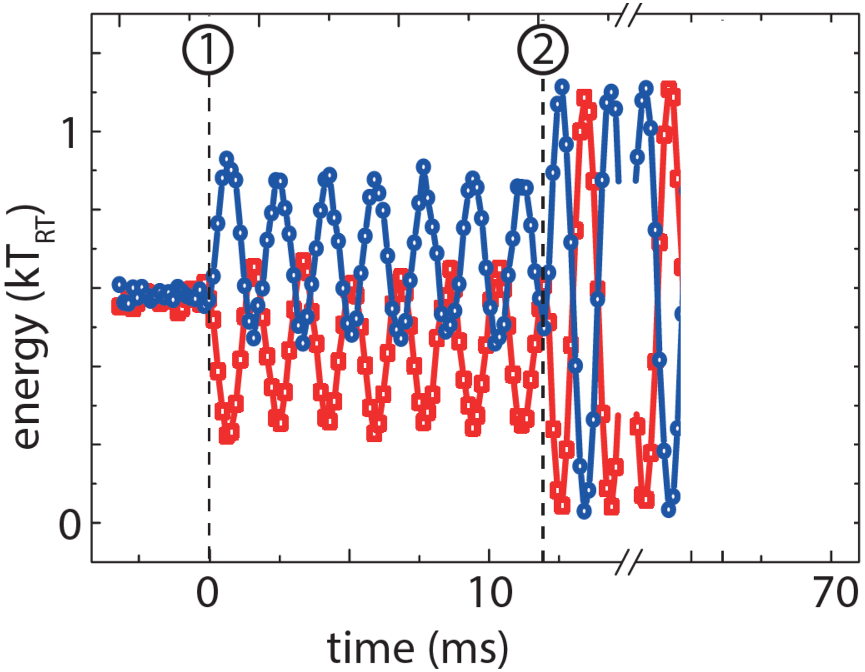

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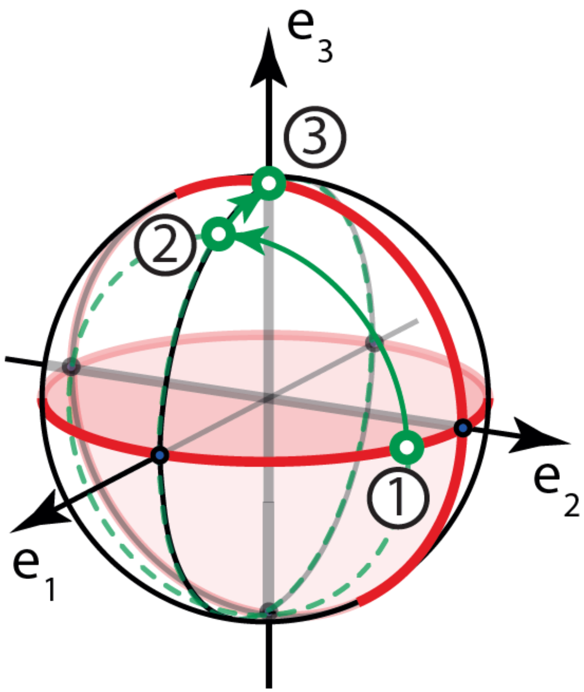

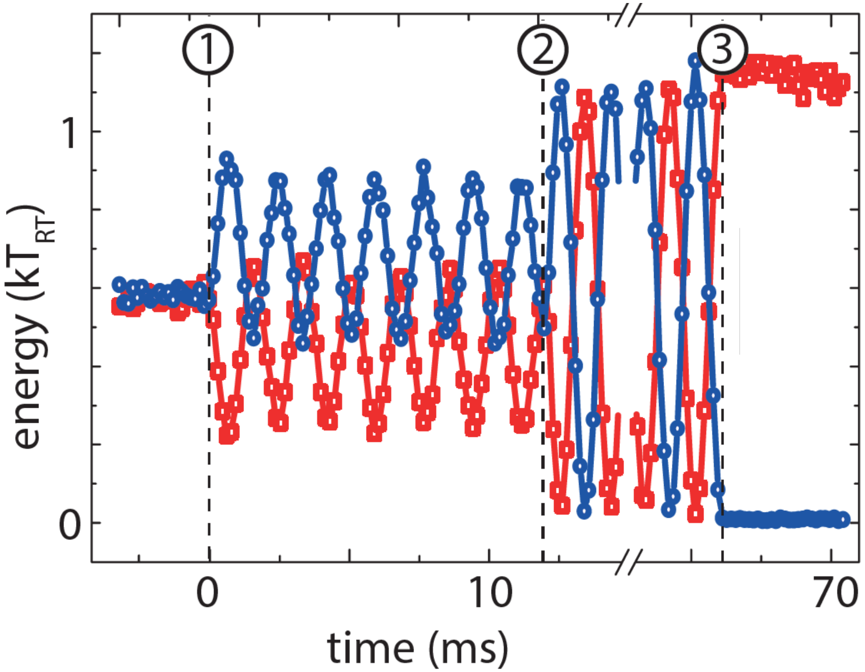

Cooling limit : $\langle E_{\min} \rangle = \frac{1}{2} m \Omega^2_{\mathrm{mech}} S^{\mathrm{noise}}_{xx} \gamma$

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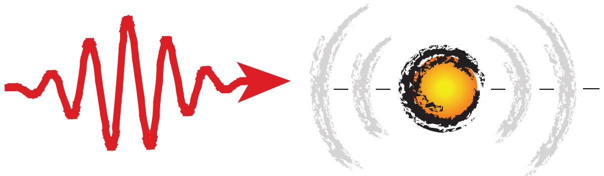
OUTLINE

QUANTUM COLLAPSE



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

Number of scattered photons before recoil : 10^9

???

CONTINUOUS WEAK MEASUREMENTS

Stochastic Schrödinger Equation (with measurement) :

$$d|\psi\rangle = \left[-\frac{i}{\hbar}\hat{H}\,dt + \sqrt{2k}(\hat{x} - \langle\hat{x}\rangle)\,dW - k(\hat{x} - \langle\hat{x}\rangle)^2\,dt\right]|\psi\rangle$$

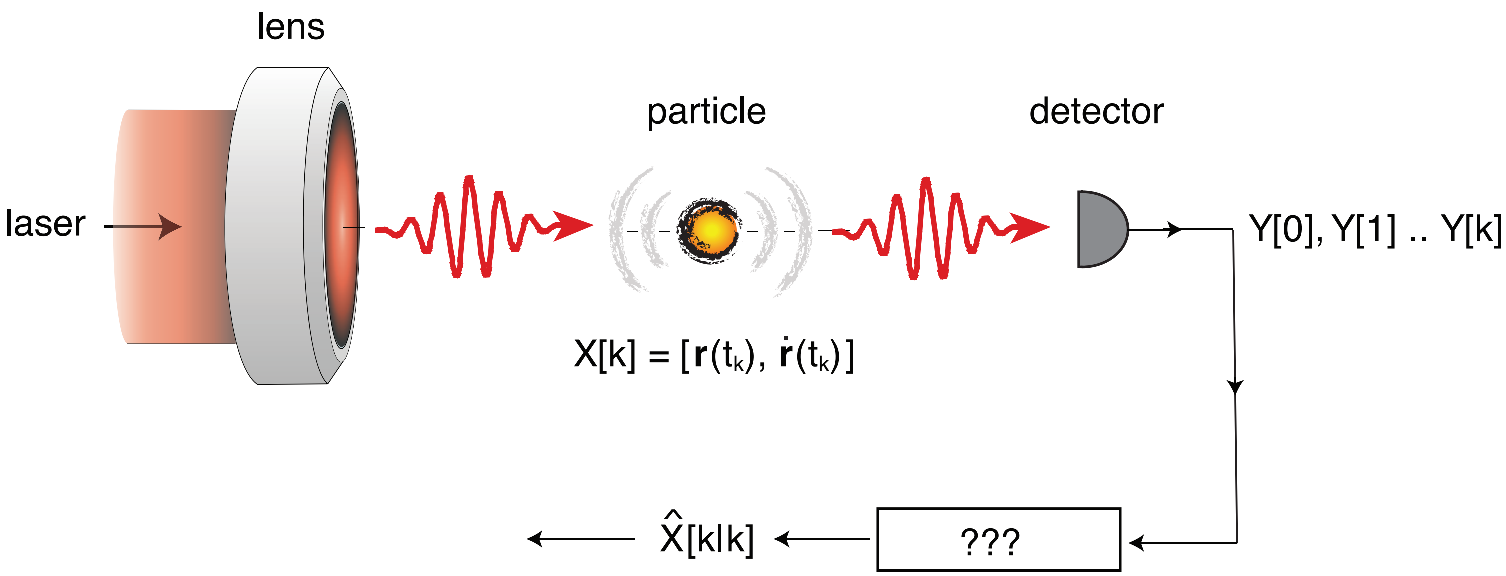
measurement rate ($\sqrt{2k}$)

Wiener process (dW)

diffusion ($k(\hat{x} - \langle\hat{x}\rangle)^2\,dt$)

Jacobs & Steck, arXiv: 0611067v1 (2006)

FEEDBACK ON STATE ESTIMATE



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

SUMMARY

- Trapping and cooling with a single laser beam
- Parametric feedback (amplification and cooling)
- Compression ratio of 10^6 (300 μK)
- Ultrahigh force sensitivity
- Nonequilibrium dynamics, coherent control, free fall, multiple traps, ..