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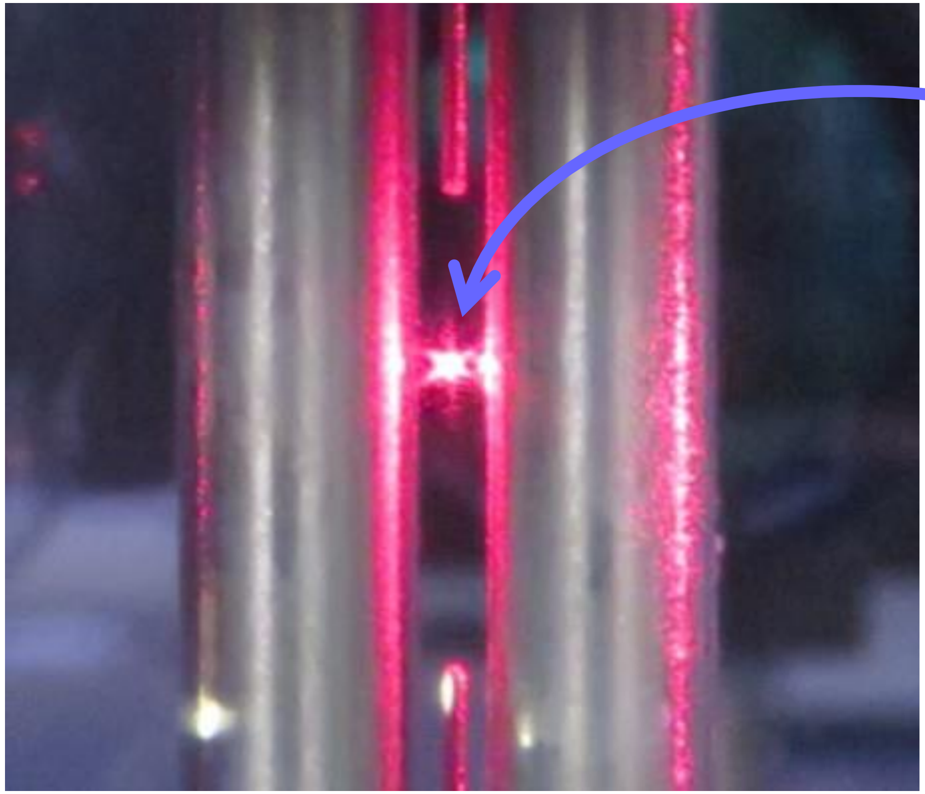
Levitated mechanical systems for experiments at the quantum level

Tracy Northup, Institute for Experimental Physics, University of Innsbruck

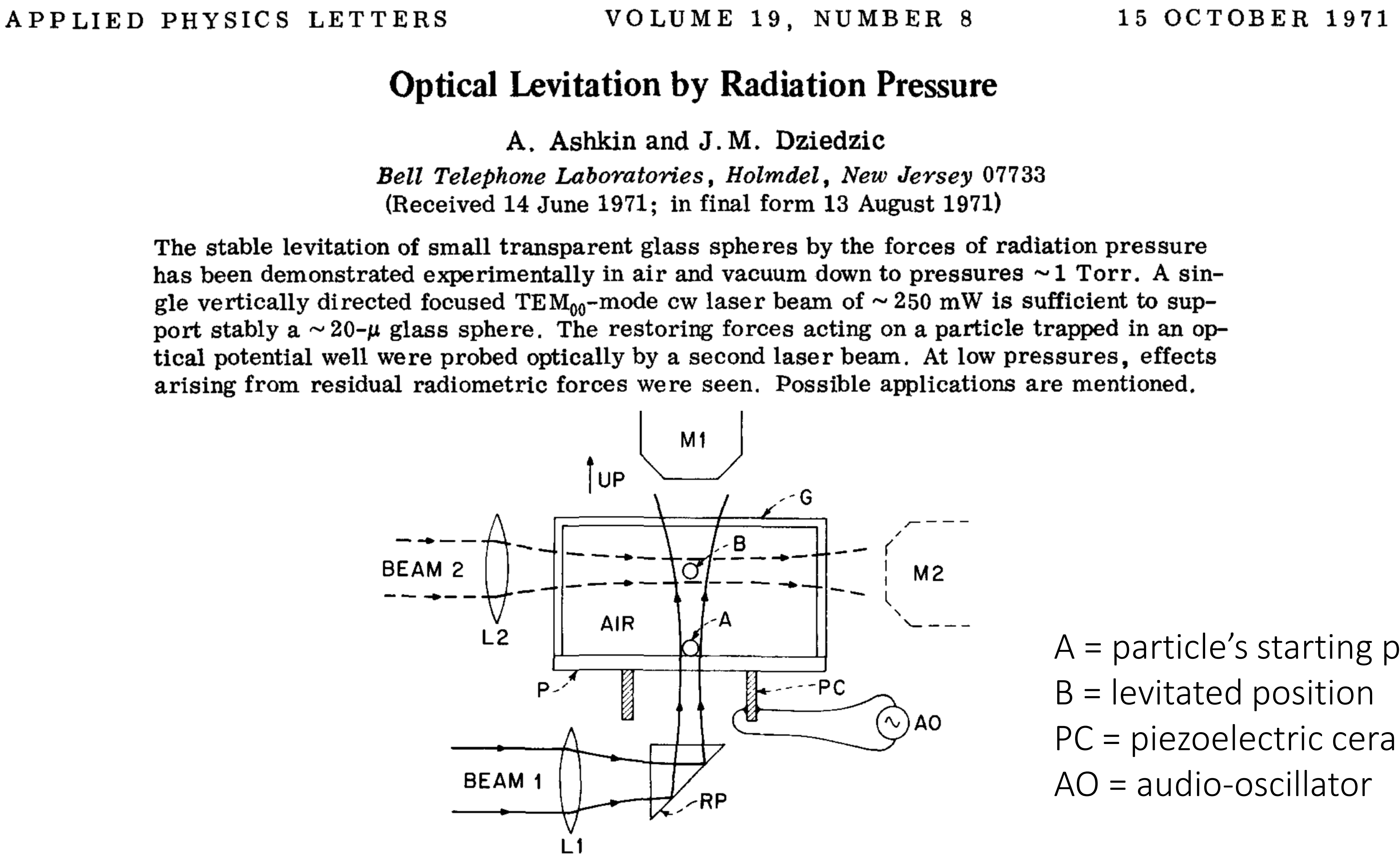
QUANTUM
INTERFACES
GROUP



a silica nanoparticle in an ion trap
(linear Paul trap)

a nanomechanical oscillator in a harmonic potential,
interacting with light

Can we bring the center-of-mass motion
of such oscillators into the quantum regime?



APPLIED PHYSICS LETTERS VOLUME 19, NUMBER 8 15 OCTOBER 1971

Optical Levitation by Radiation Pressure

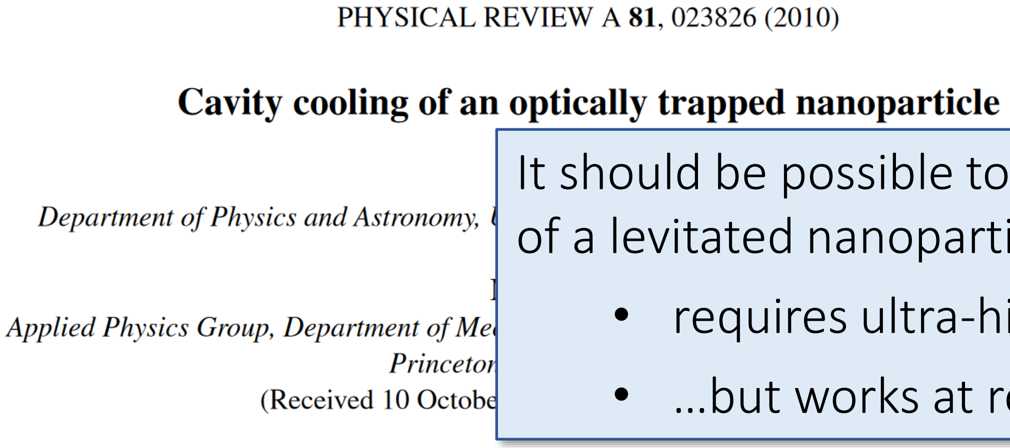
A. Ashkin and J. M. Dziedzic
Bell Telephone Laboratories, Holmdel, New Jersey 07733

(Received 14 June 1971; in final form 13 August 1971)

The stable levitation of small transparent glass spheres by the forces of radiation pressure has been demonstrated experimentally in air and vacuum down to pressures ~1 Torr. A single vertically directed focused TEM_{00}-mode cw laser beam of ~250 mW is sufficient to support stably a ~20-μ glass sphere. The restoring forces acting on a particle trapped in an optical potential well were probed optically by a second laser beam. At low pressures, effects arising from residual radiometric forces were seen. Possible applications are mentioned.

A = particle's starting position
B = levitated position
PC = piezoelectric ceramic
AO = audio-oscillator

Levitated optomechanics: the quantum vision (2010)



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

Cavity cooling of an optically trapped nanoparticle

Department of Physics and Astronomy,

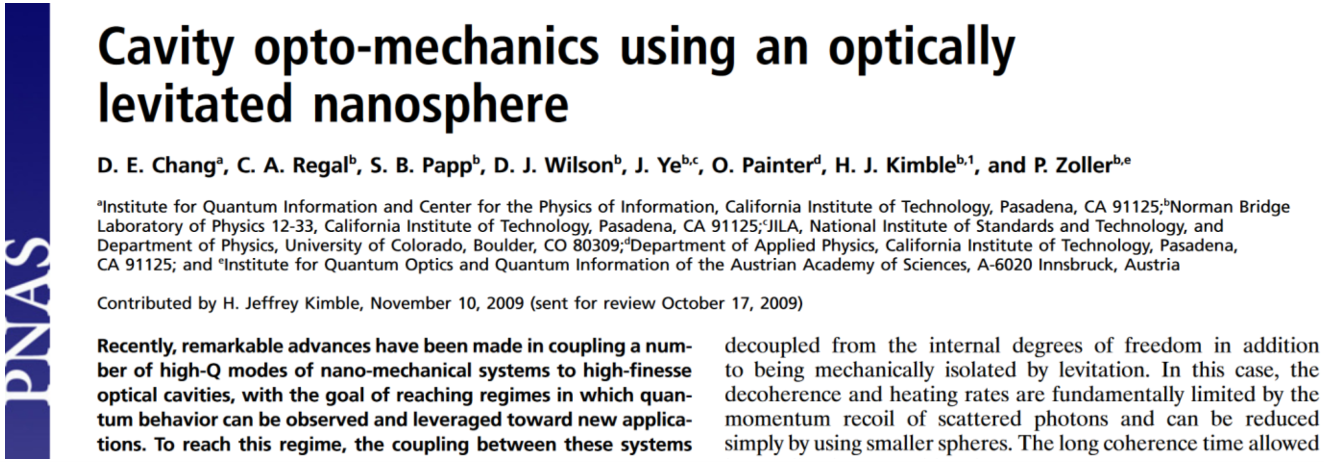
Applied Physics Group, Department of Me

Princeton

(Received 10 Octobe

It should be possible to prepare quantum states of motion of a levitated nanoparticle coupled to an optical cavity.

- requires ultra-high vacuum
- …but works at room temperature



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)

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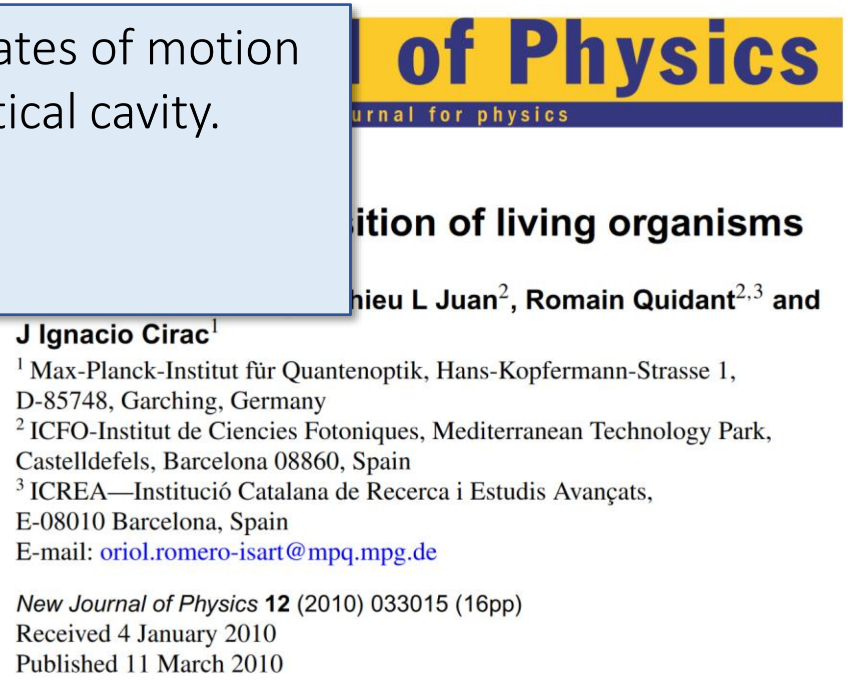

of Physics

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ition of living organisms

hieu L Juan[2], Romain Quidant[2,3] and J Ignacio Cirac[1]

[1] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748, Garching, Germany
[2] ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, Castelldefels, Barcelona 08860, Spain
[3] ICREA—Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona, Spain
E-mail: oriol.romero-isart@mpq.mpg.de

New Journal of Physics **12** (2010) 033015 (16pp)
Received 4 January 2010
Published 11 March 2010

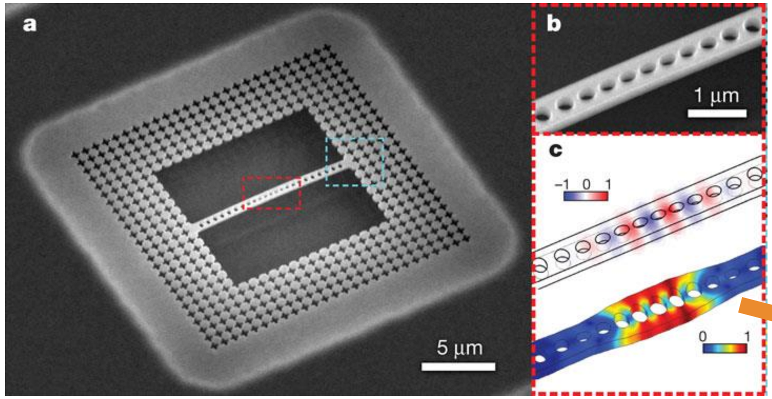
Topics: Lecture 1

1. Quantum optomechanics:
   interactions between light and motion in the quantum regime
2. Why *levitated* optomechanics?
3. What objects should we levitate? And how can we levitate them?
4. Cooling mechanical motion to the quantum ground state
5. Outlook: into the quantum regime

Let's bring optomechanical systems into the quantum realm.

Let's extend quantum control of atoms and photons to mesoscopic systems.

Quantum optomechanics experiments span a wide range of experimental platforms



Nanoscale: Laser cooling to the motional ground state

J. Chan et al., *Nature* **478**, 89 (2011)

interactions of light & motion in the quantum regime

Kilometer scale: Enhanced LIGO sensitivity using squeezed vacuum states

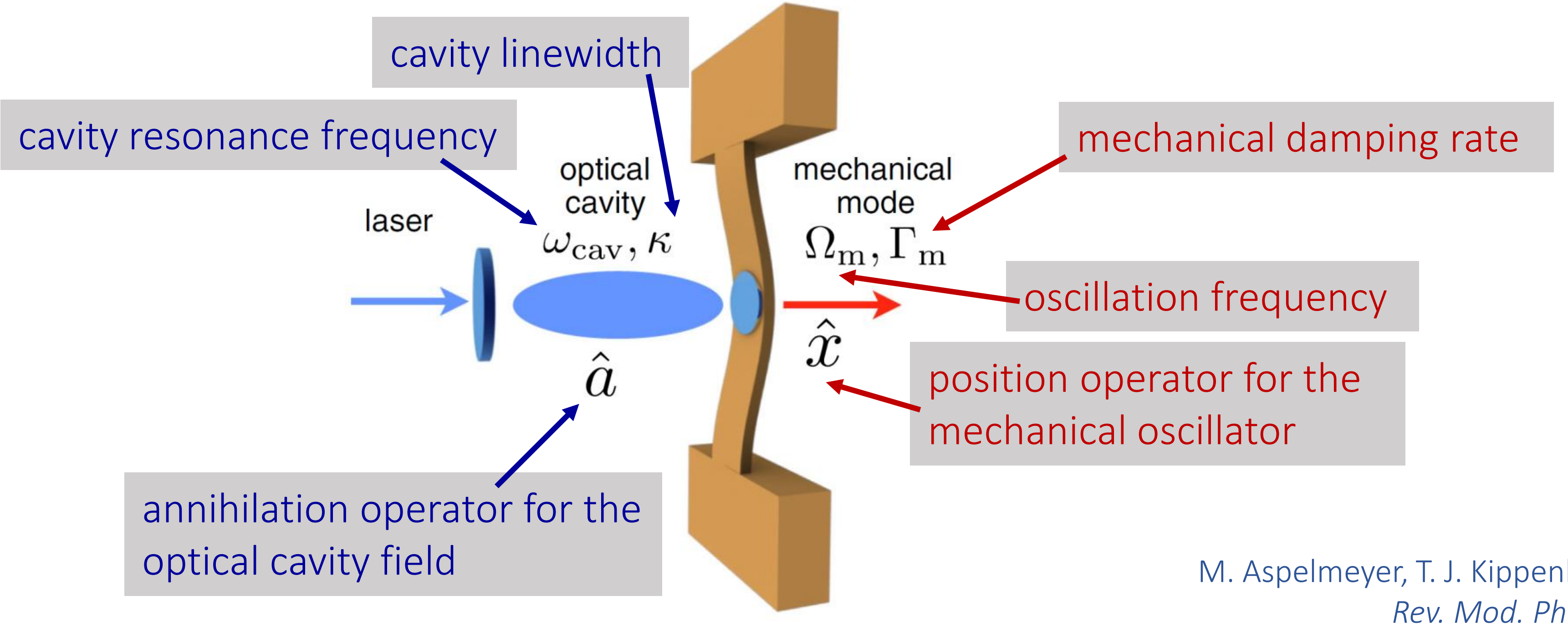
J. Aasi et al., *Nat. Photon.* **7**, 613 (2013)

Courtesy Caltech/MIT/LIGO Laboratory

Theoretical foundations of quantum optomechanics

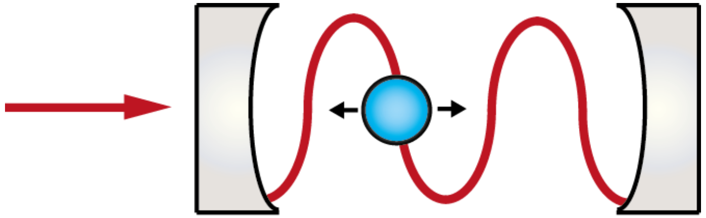
Early work by Braginsky and others:

- Radiation pressure can damp or amplify mechanical motion.
- Quantum fluctuations of radiation pressure limit position measurement.



M. Aspelmeyer, T. J. Kippenberg, F. Marquardt, *Rev. Mod. Phys.* **86**, 1391 (2014)

Light-motion interaction:
mechanical motion shifts the cavity resonance



cavity frequency

photon

mechanical frequency

phonon

$$\hat{H} = \hbar\omega_{\mathrm{cav}}\hat{a}^\dagger\hat{a} + \hbar\Omega_{\mathrm{m}}\hat{b}^\dagger\hat{b} - \hbar g_0\hat{a}^\dagger\hat{a}(\hat{b}+\hat{b}^\dagger)$$

number of photons

oscillator position

Problem: g_0 is small!
Solution: use a strong field;
only fluctuations are quantized
Cost: a linearized interaction

$$\Rightarrow -\hbar g_0\sqrt{\bar{n}}(\delta\hat{a}^\dagger + \delta\hat{a})(\hat{b}+\hat{b}^\dagger)$$

mean photon number

fluctuations of photon field

M. Aspelmeyer, T. J. Kippenberg, F. Marquardt,
Rev. Mod. Phys. **86**, 1391 (2014)

What’s wrong with a linearized interaction?

$$\Rightarrow -\hbar g_0 \sqrt{\bar{n}}(\delta\hat{a}^\dagger + \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$

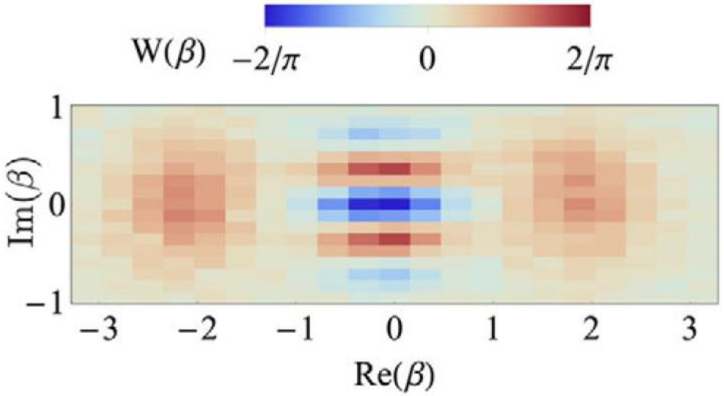
This Hamiltonian maps Gaussian states to Gaussian states.

One way to draw a line between the classical and quantum world:
states with a negative Wigner function (quasiprobability distribution).

To make these non-Gaussian states, we need to introduce a nonlinearity.

non-Gaussian states are the basis for:

- quantum transducers
- superposition states for sensing
- testing foundations of quantum mechanics

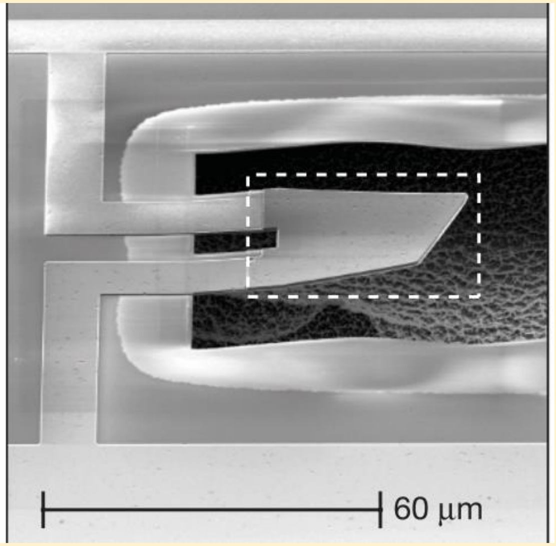


trapped-ion cat state

D. Kienzler et al., *Phys. Rev. Lett.* **116**, 140402 (2016)

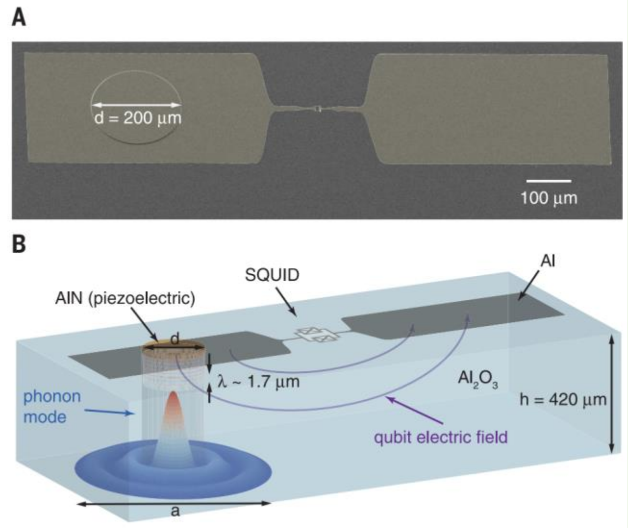
A qubit can act as a nonlinear element

“Quantum ground-state and single-phonon control of a mechanical resonator,” A. D. O’Connell et al., *Nature* **464**, 697 (2010)



mechanical oscillator
+
superconducting qubit

“Creation and control of multi-phonon Fock states in a bulk acoustic-wave resonator,”
Y. Chu et al., *Nature* **563**, 666 (2018)



bulk acoustic mode
+
superconducting qubit

Y. Chu et al, *Science* 358, 199 (2017)

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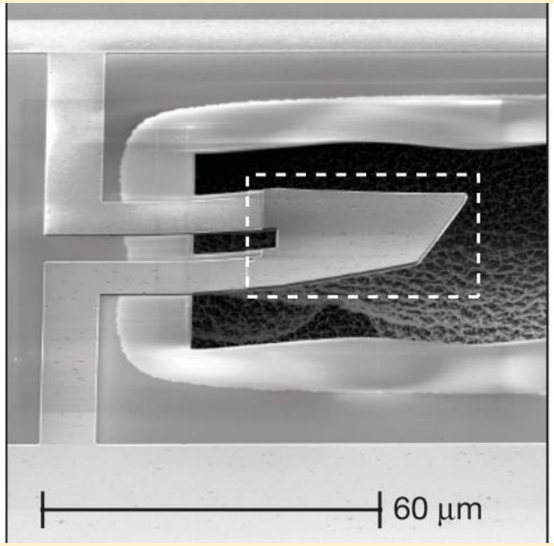


mechanical oscillator
+
superconducting qubit

entanglement of the motion of two micromechanical oscillators (10^{12} atoms each!)

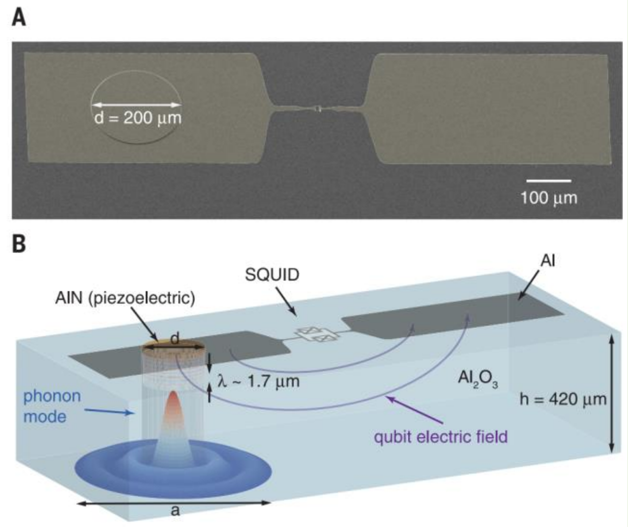
C. F. Ockeloen-Korppi et al., *Nature* **556**, 478 (2018)

S. Kotler et al., *Science* **372**, 622 (2021)

A qubit can act as a nonlinear element

“Schrödinger cat” states: superposition states of a 16-microgram mechanical oscillator
M. Bild et al., *Science* **380**, 274 (2023)

“Creation and control of multi-phonon Fock states in a bulk acoustic-wave resonator,”
Y. Chu et al., *Nature* ***563***, 666 (2018)



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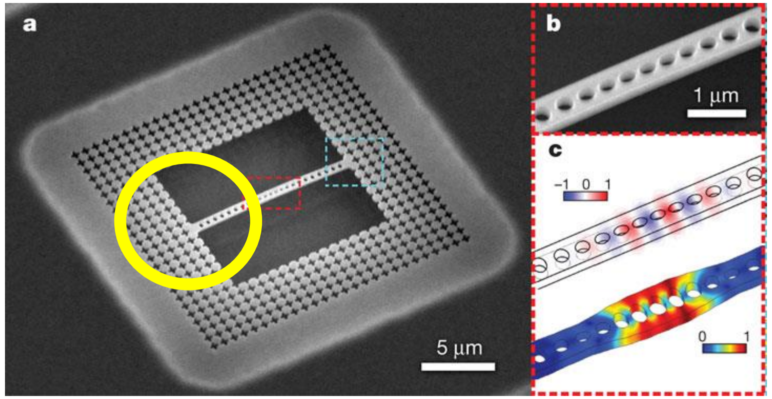
A challenge for quantum optomechanics: reducing the mechanical coupling to the environment



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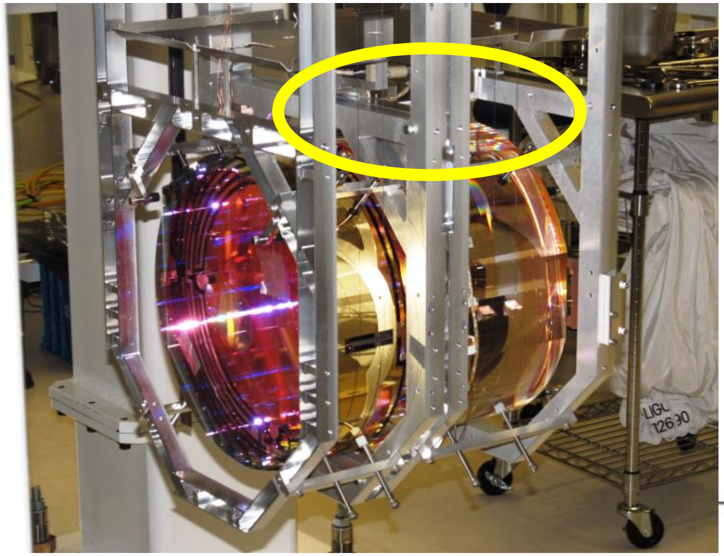
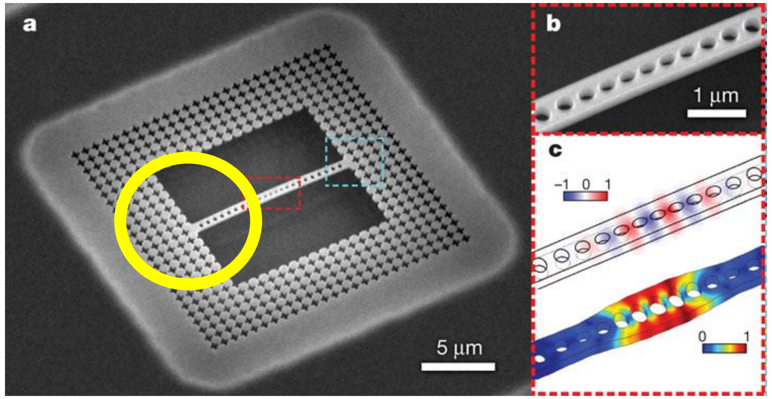


Courtesy Caltech/MIT/LIGO Laboratory

A challenge for quantum optomechanics: reducing the mechanical coupling to the environment



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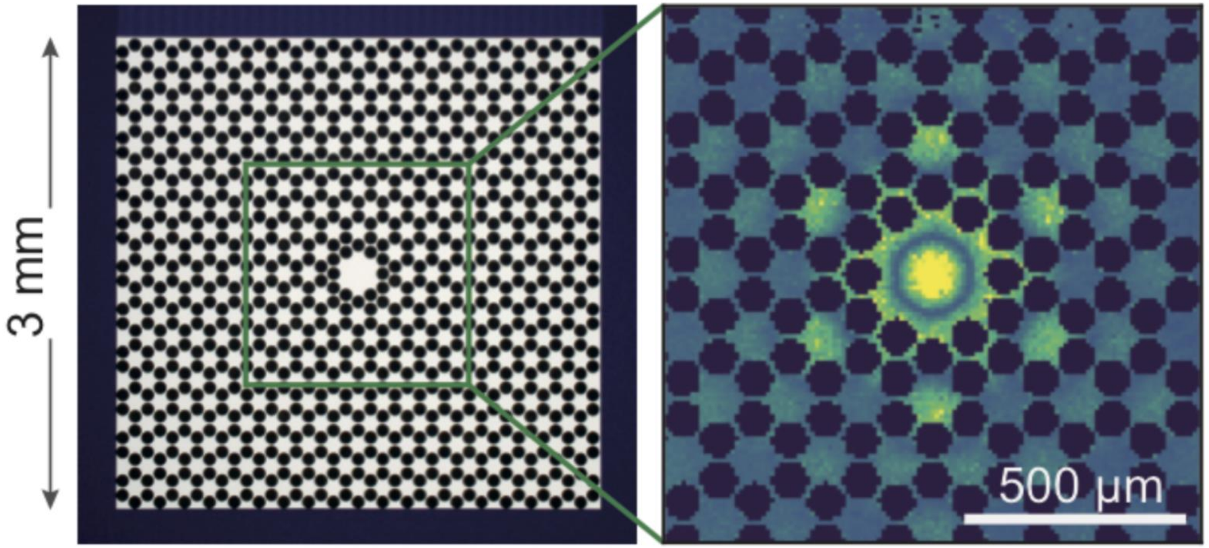
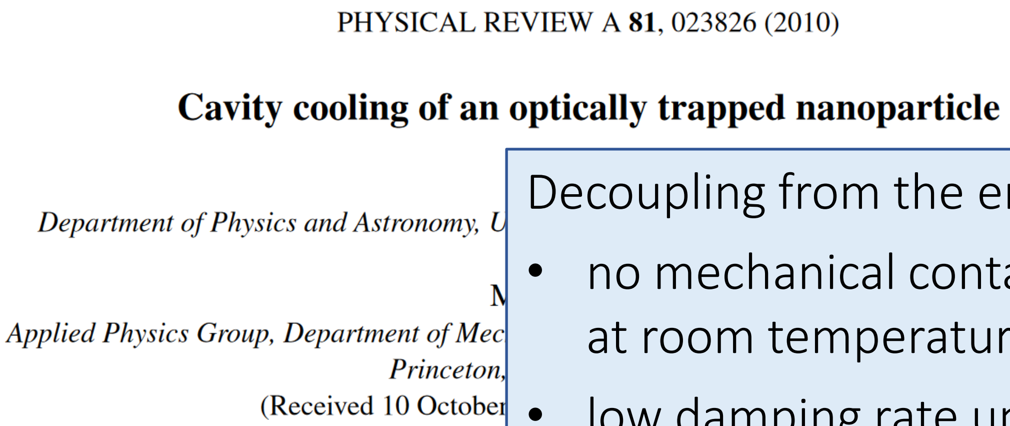
J. Chan et al., *Nature* **478**, 89 (2011)

Approach for clamped structures:
nanostructure engineering, careful choices of materials, operation at cryogenic temperatures.



Y. Tsaturyan, A. Barg, E. S. Polzik, and A. Schliesser, *Nat. Nanotechnol.* **12**, 776 (2017) particle is suspended stably against gravity

Levitated optomechanics: the quantum vision (2010)



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Department of Physics and Astronomy, U

M

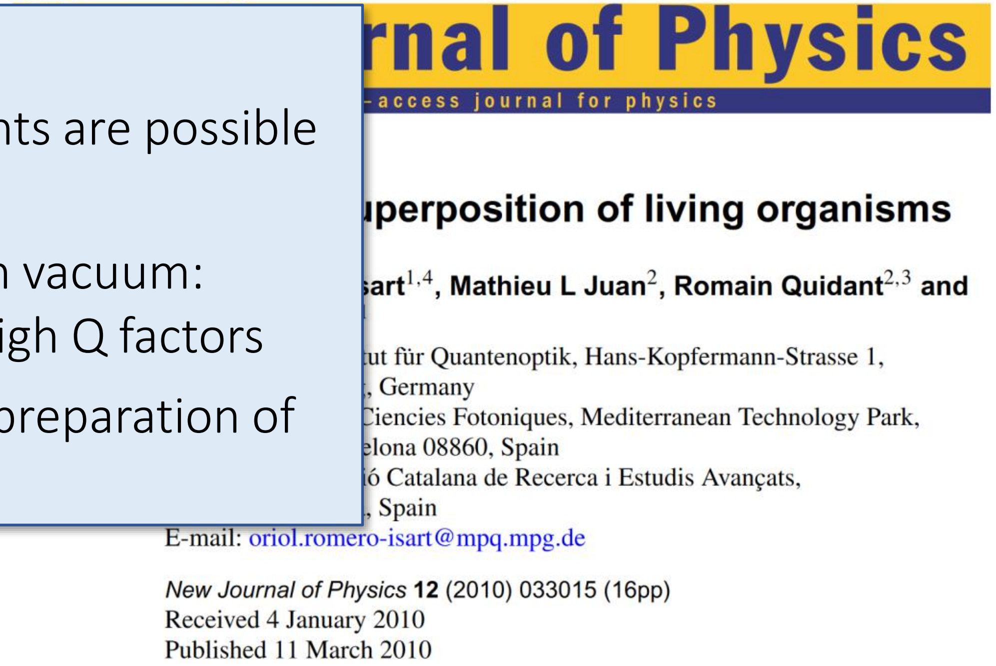
Applied Physics Group, Department of Mec

Princeton,

(Received 10 October

Decoupling from the environment:

- no mechanical contact: experiments are possible at room temperature
- low damping rate under ultra-high vacuum: mechanical oscillators with very high Q factors
- long coherence times enable the preparation of exotic states



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-access journal for physics

uperposition of living organisms

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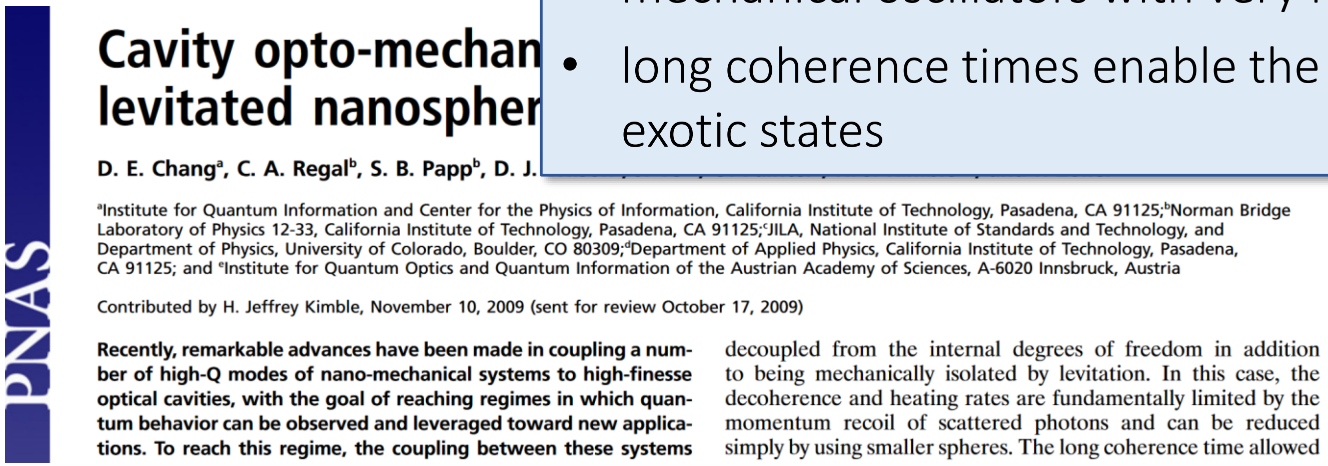

PNAS

Cavity opto-mechan

levitated nanospher

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Levitated optomechanics: applications in force sensing

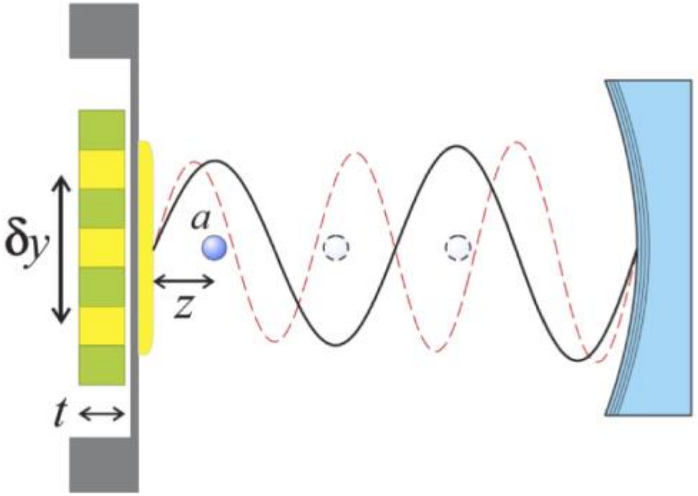
Advantages for force sensing:

- high Q factor
- high mass density improves acceleration sensitivity over atoms/ions

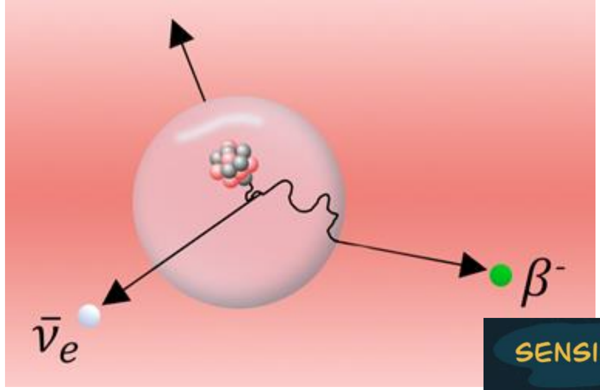
…and more exotic proposals:

- scattered dark-matter particles
- gravitational waves
- sterile neutrinos…

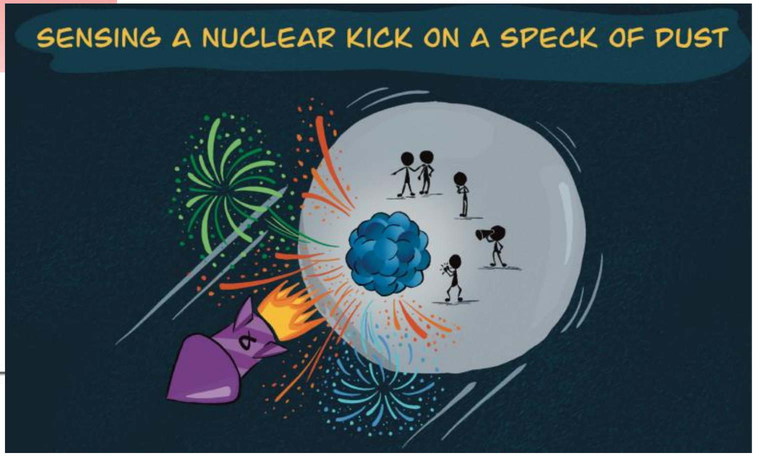
Example: measurement of short-range gravity



"Searching for new physics using optically levitated sensors," D. C. Moore and A. Geraci, *Quantum Sci. Technol.* **6**, 014008 (2021)



K. McCormick, *Physics* **16**, s23 (2023);
D. Carney et al., *PRX Quantum* **4** 020315 (2023)



L. Canil, M. Schirber, *Physics* **17**, 108 (2024);
J. Wang et al., *Phys. Rev. Lett.* **133**, 023602 (2024)

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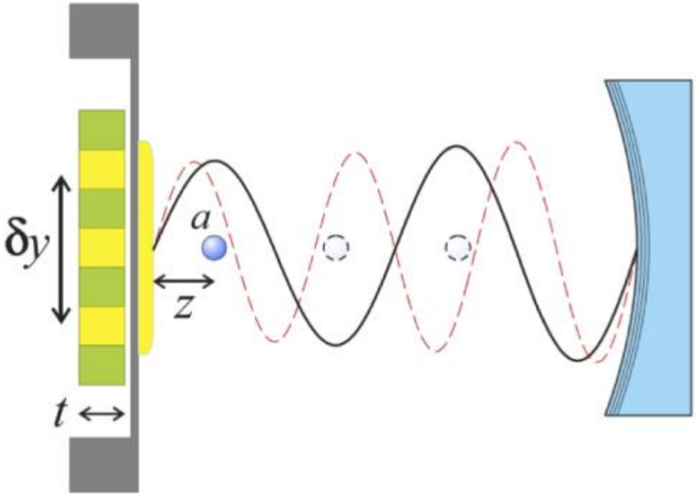
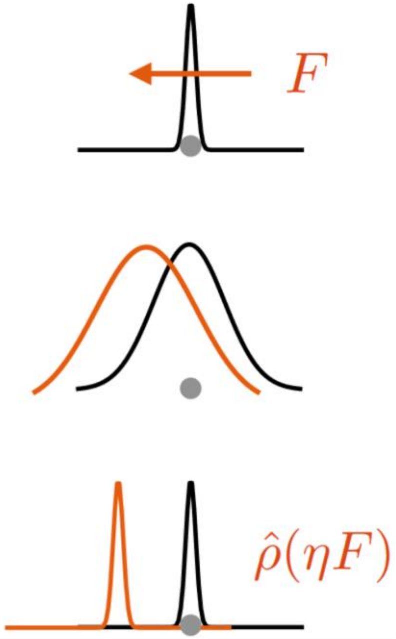
Example: measurement of short-range gravity



“Searching for new physics using optically levitated sensors,” D. C. Moore and A. Geraci, *Quantum Sci. Technol.* **6**, 014008 (2021)

Other proposals exploit delocalization & superposition for enhanced sensitivity.

Example: expansion and contracting the particle wavefunction by dynamically changing the potential.



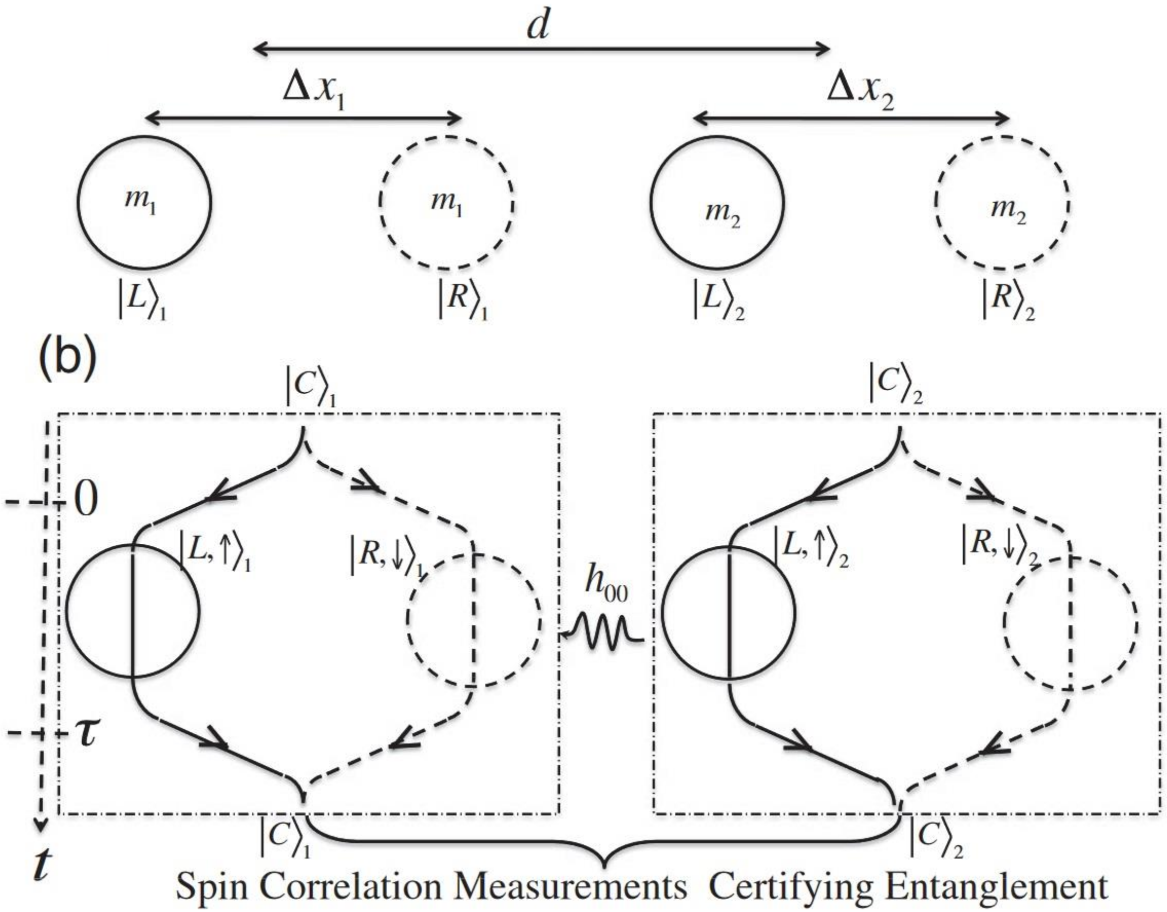
T. Weiss, M. Roda-Llordes, E. Torrontegui, M. Aspelmeyer, O. Romero-Isart, *Phys. Rev. Lett.* **127**, 023601 (2021)

Levitated optomechanics: testing quantum physics

Quantum superpositions of increasingly massive, dense objects would allow us to test proposed extensions to quantum mechanics.

Proposed test of quantum gravity:

- requires a superposition of internal spin and spatial position (e.g., via an inhomogeneous external field)
- relies on the extreme isolation of levitated systems



"Spin-entanglement witness for quantum gravity," S. Bose et al., *Phys. Rev. Lett.* **119**, 240401 (2017)

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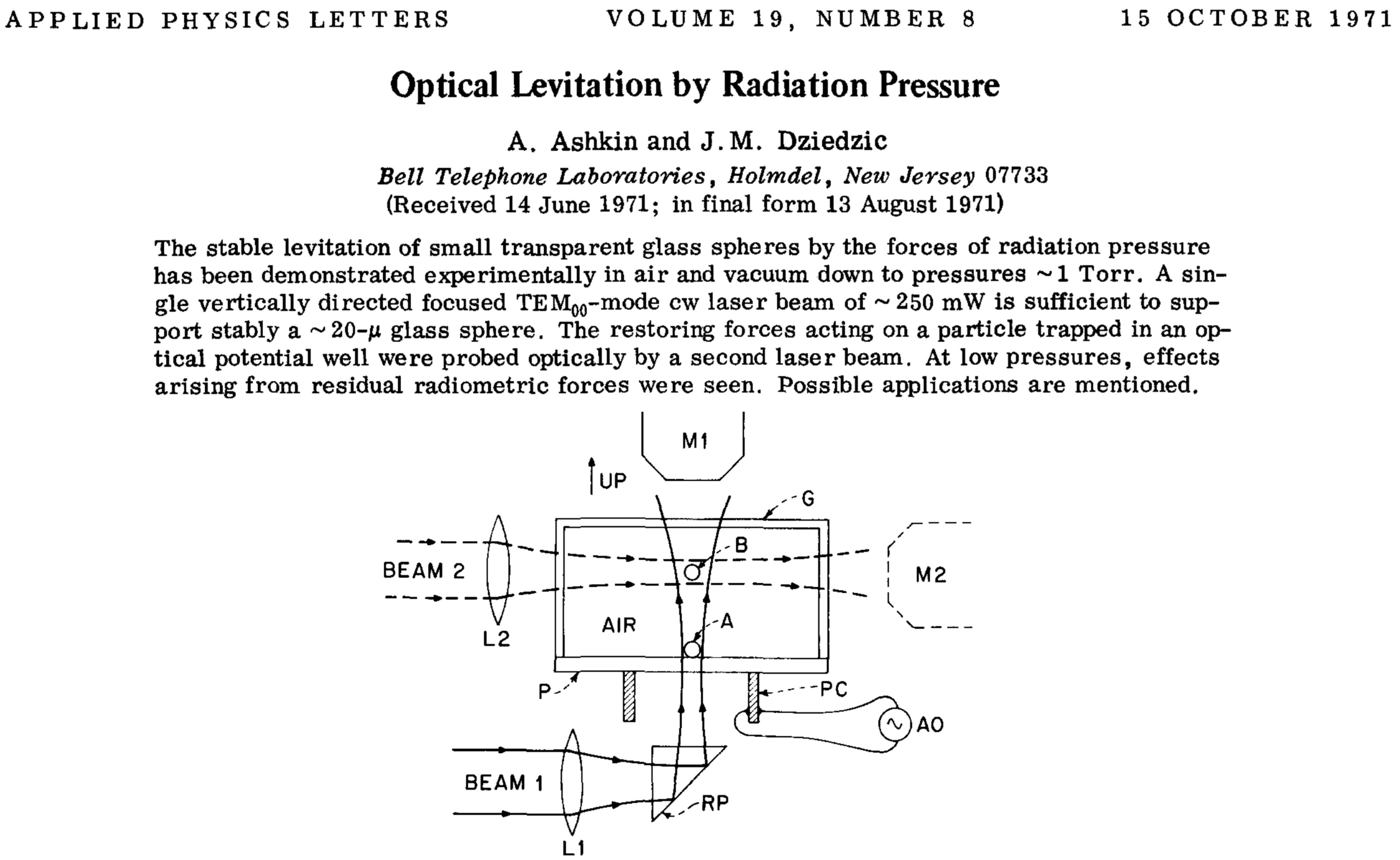

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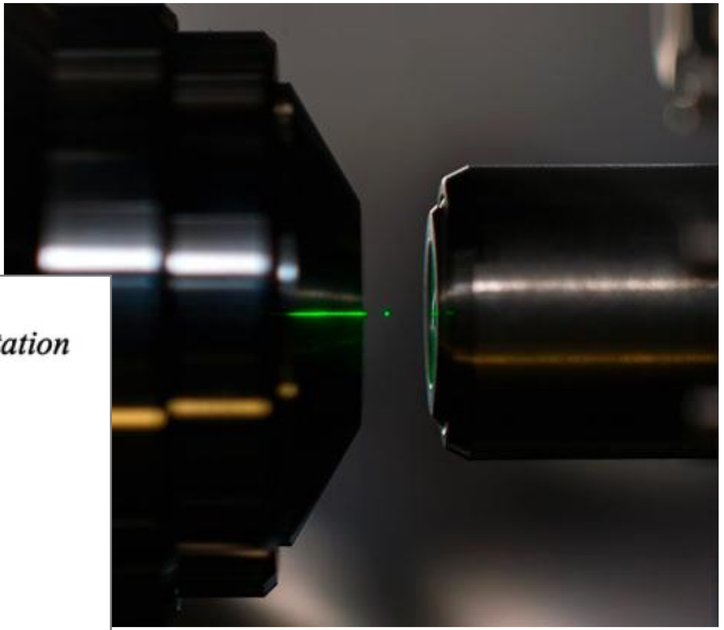
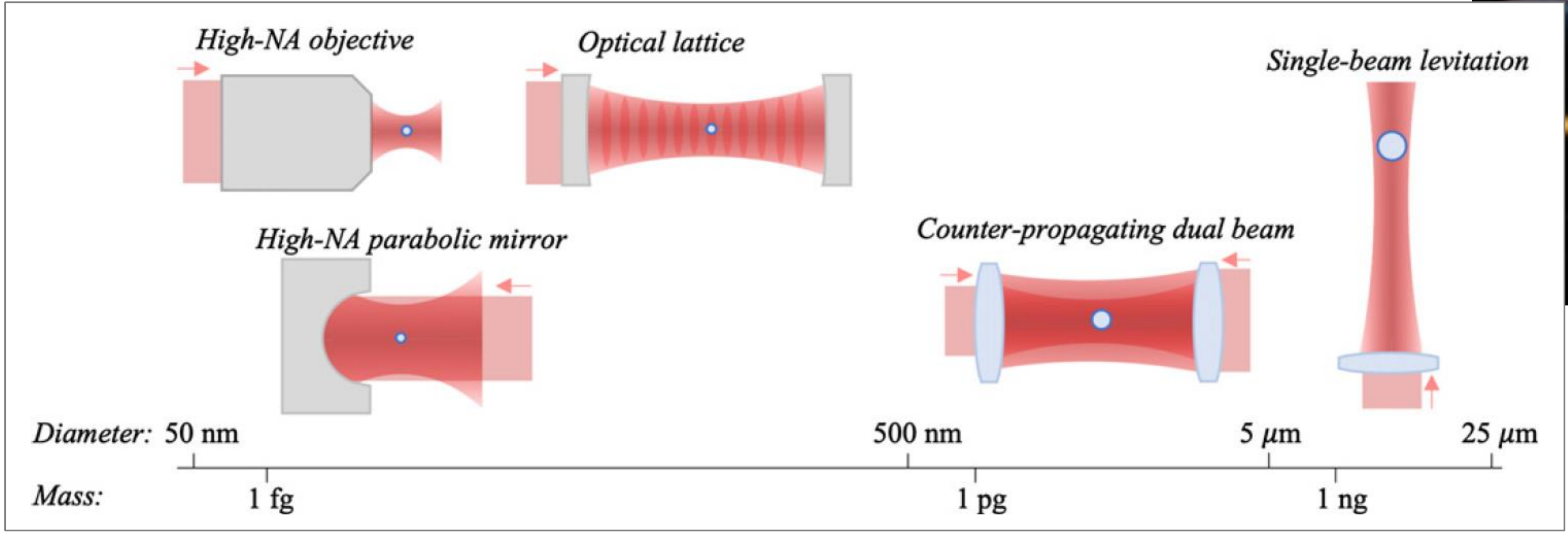
L. P. Neukirch and A. N. Vamivakas, *Contemp. Phys.* **56**, 48 (2015)

(a) Optical levitation



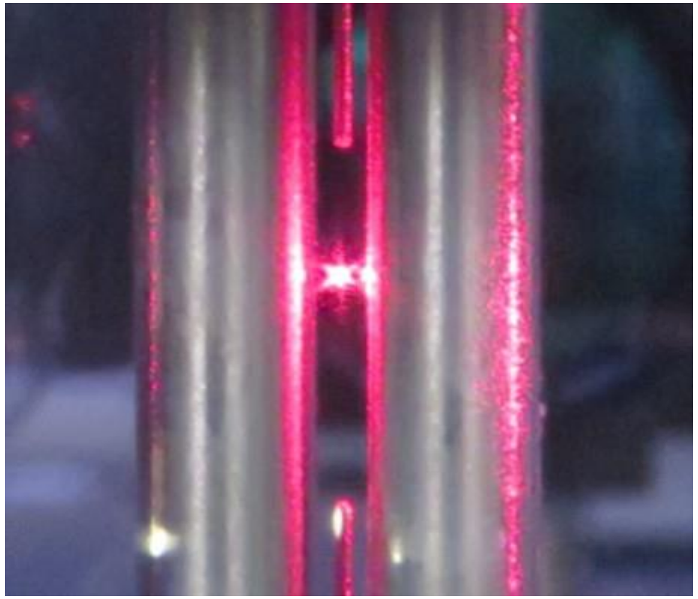


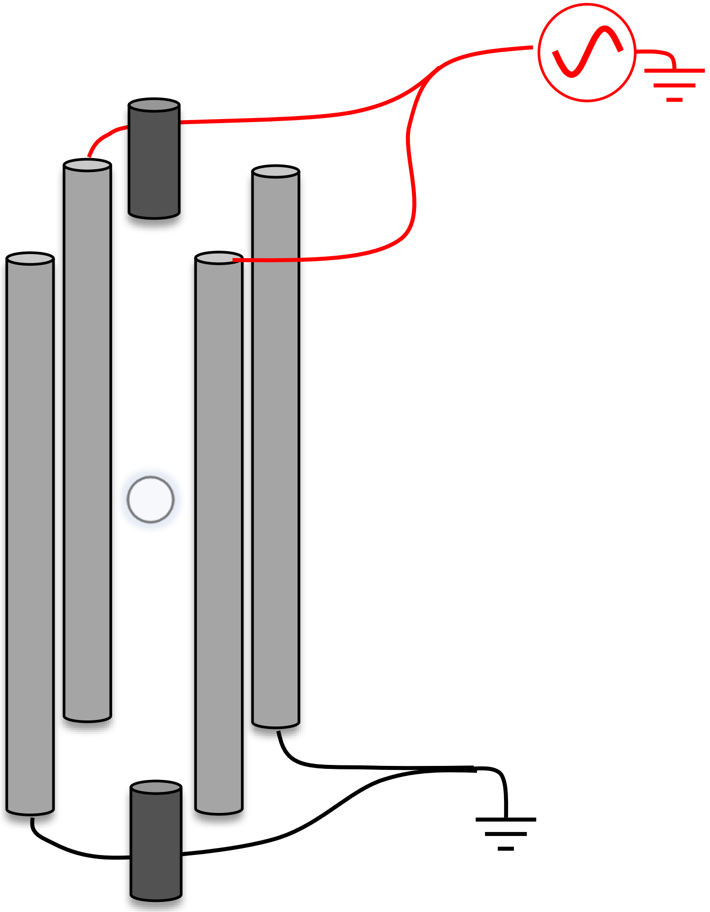
D. C. Moore and A. A. Geraci, *Quant. Sci. Technol.* **6**, 014008 (2021)

Mechanism:

- Gradient & radiation-pressure forces acting on a dielectric particle
- Rayleigh regime: electric field gradient acting on an induced point dipole

(b) Electrical levitation

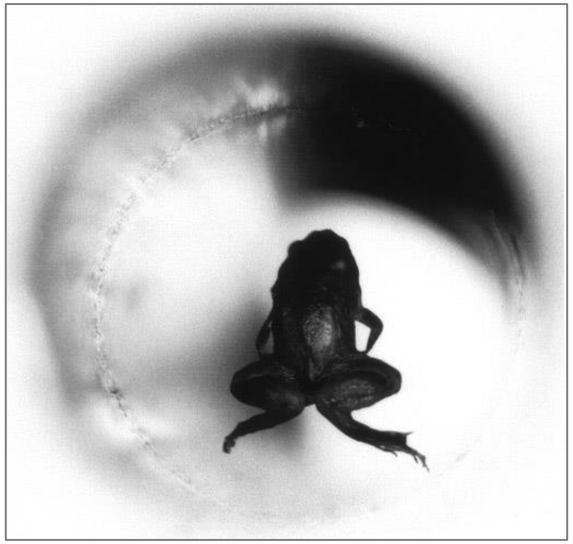




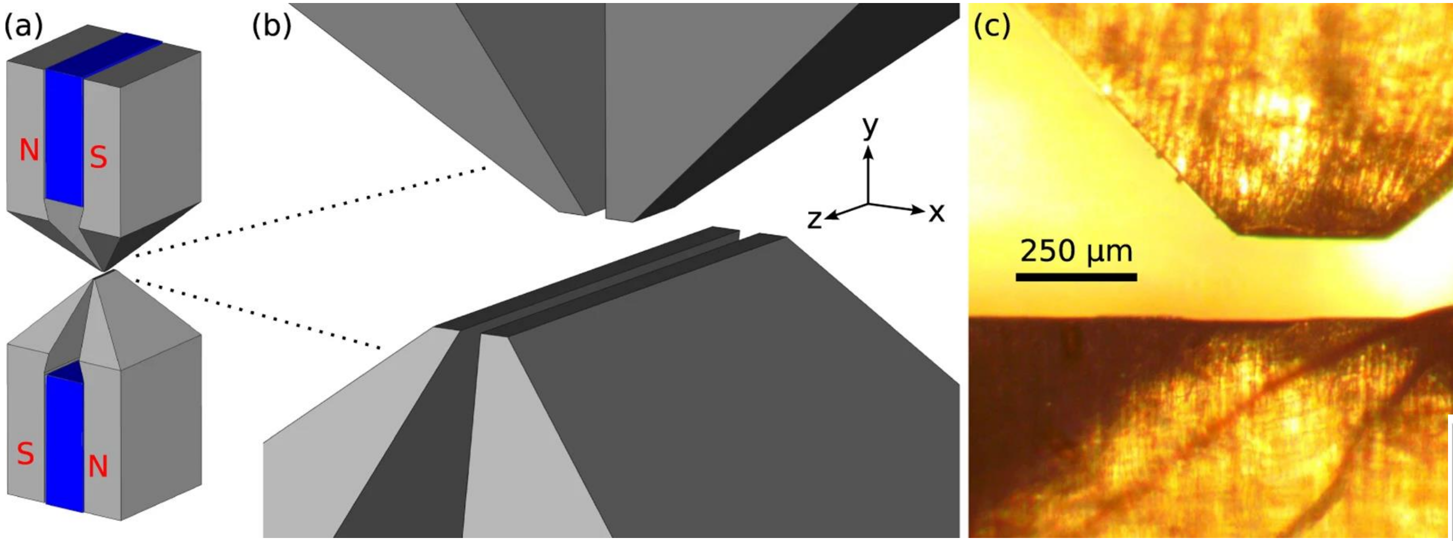
Mechanism:

- Paul trap: inhomogeneous AC potential confines a charged particle
- Trap frequencies depend on the charge-to-mass ratio (typically: kilohertz)

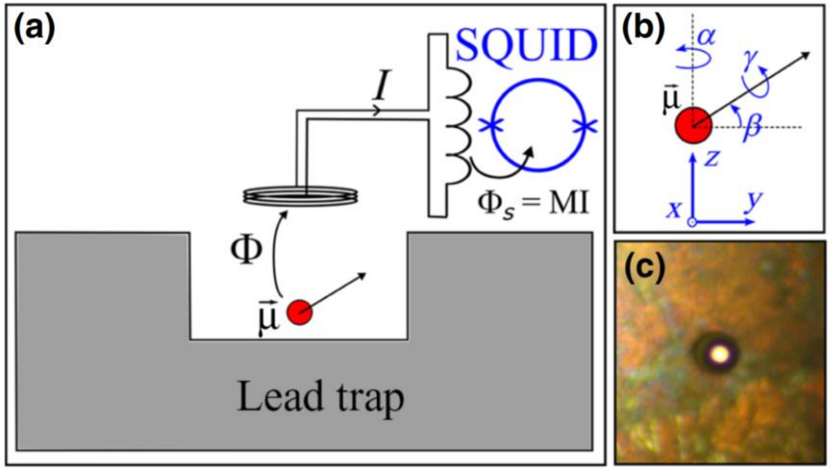
M. V. Berry and A. K. Geim, *Eur. J. Phys.* **18**, 307 (1997)



(c) Magnetic levitation



J. F. Hsu, P. Ji, C. W. Lewandowski, and B. D’Urso, *Sci. Rep.* **6**, 30125 (2016)



A. Vinante et al., *Phys. Rev. Appl.* 13, 064027 (2020)

Mechanism:

- Diamagnetic objects in magnetogravitational traps
- Ferromagnets levitated above superconductors

Some good candidates for levitated (quantum) optomechanics

- silica
- silicon

dielectric, ultralow optical absorption; can be charged

- NV centers (or other color centers) in nanodiamonds

internal spin degree of freedom

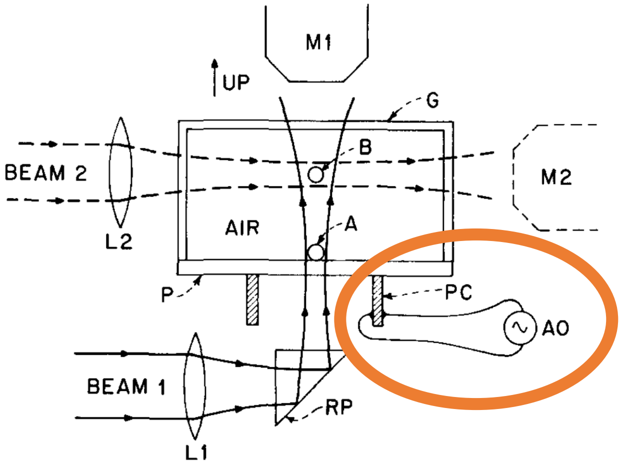
- Yb^{3+}-doped $YLiF_4$

cooling of internal temperature demonstrated

- magnetically levitated superconductors

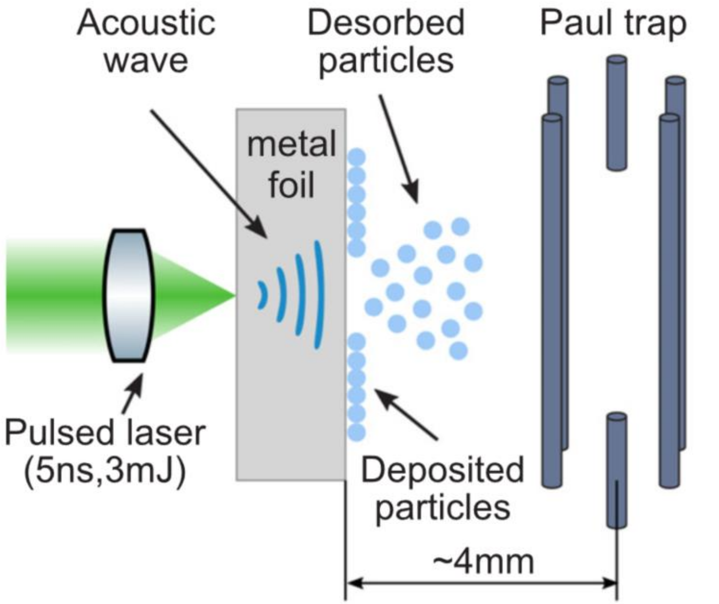
proposed for high-mass quantum superpositions

How can these particles be (cleanly) trapped?



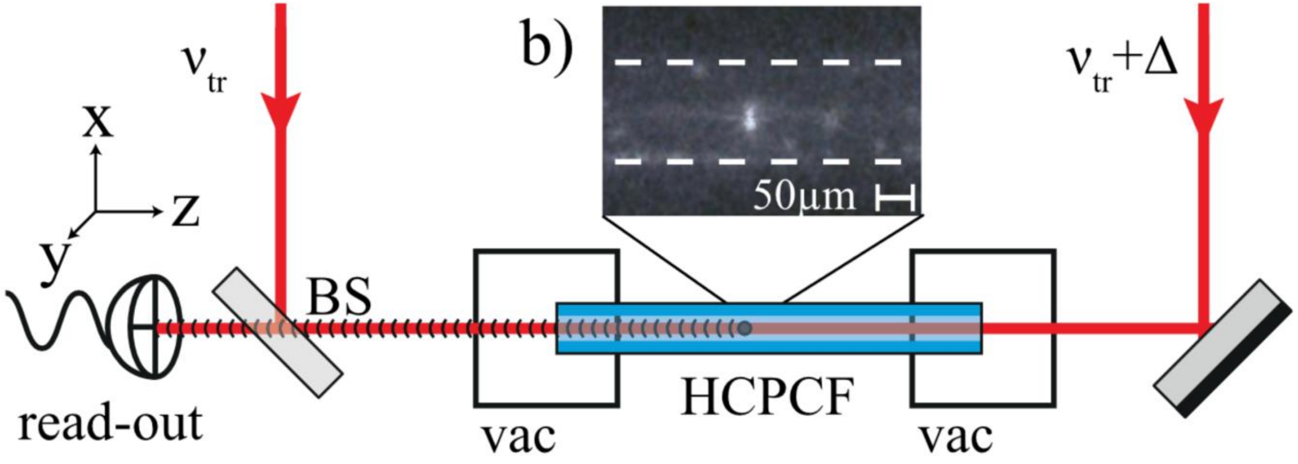
- laser-induced acoustic desorption

D. S. Bykov, P. Mestres, L. Dania, L. Schmöger, T. E. Northup, *Appl. Phys. Lett.* **115**, 034101 (2019)



- hollow-core photonic-crystal fiber transport

D. Grass, J. Fesel, S. G. Hofer, N. Kiesel, M. Aspelmeyer, *Appl. Phys. Lett.* **109**, 221103 (2016)



- piezoelectric vibration

(challenging for small particles due to van der Waals forces)

- commercial nebulizer
- electrospray

…but solvents are not ultra-high-vacuum friendly!

Is it still optomechanics without optical trapping?

It can be!

Light can interact with a nanoparticle’s motion for

- trapping, *but also for*
- cooling or heating,
- engineering nonclassical states,
- measurement.

Topics: Lecture 1

1. Quantum optomechanics:
   interactions between light and motion in the quantum regime
2. Why *levitated* optomechanics?
3. What objects should we levitate? And how can we levitate them?
4. Cooling mechanical motion to the quantum ground state
5. Outlook: into the quantum regime

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