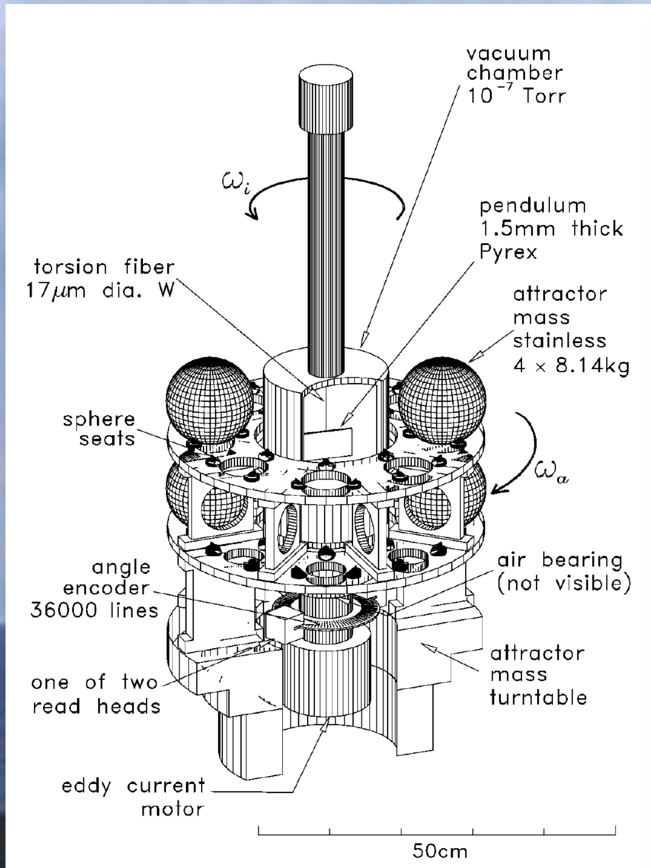
LNF, Frascati, November 2019

Quantum tests of gravity.
State of the Play, Prospects, and Experimental Challenges

Markus Aspelmeyer

Vienna Center for Quantum Science and Technology (VCQ)
Faculty of Physics , University of Vienna, Austria
IQOQI, Austrian Academy of Sciences

Mechanical Sensing – early attempts



Mt Schehallien (Scotland)

Gundlach et al., PRL 2000

ΔG/G = 15ppm

Earth: a solid body or a hollow sphere with a core?

1774 (Maskelyne): **gravitational force of a mountain** via pendulum

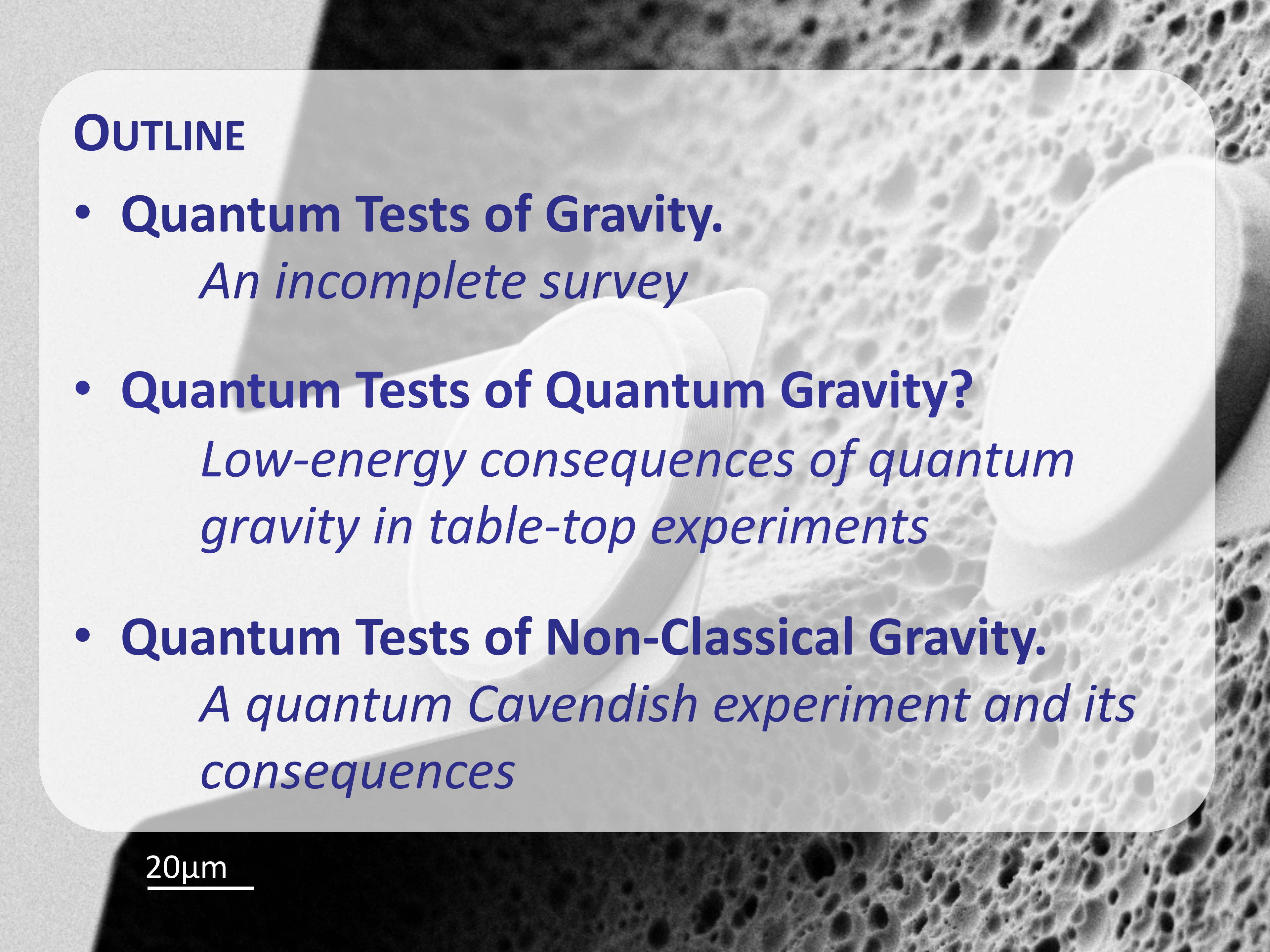
1798 (Cavendish): gravitational force of spheres via torsional pendulum

OUTLINE

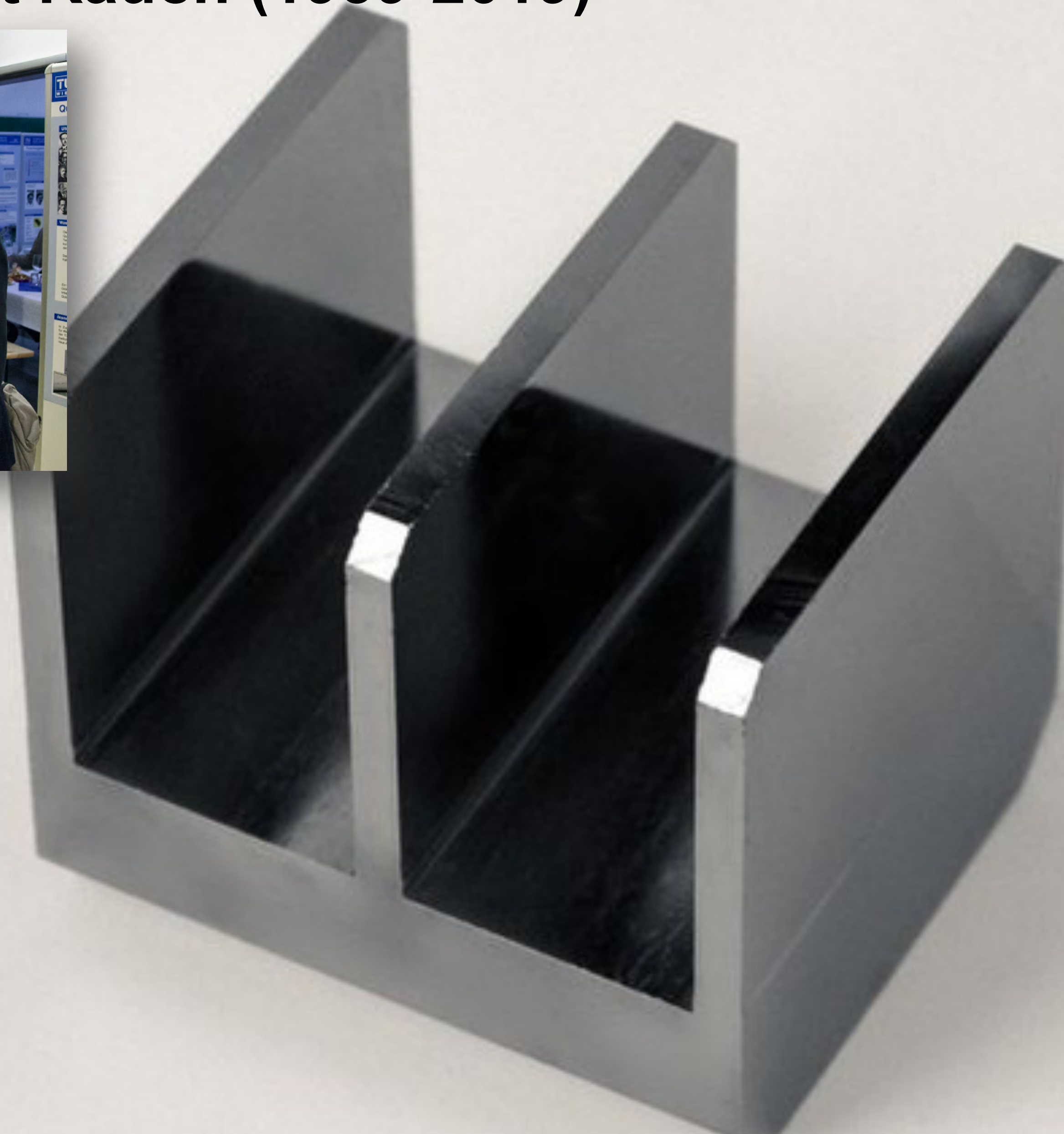
- **Quantum Tests of Gravity.**
  An incomplete survey

- **Quantum Tests of Quantum Gravity?**
  Low-energy consequences of quantum gravity in table-top experiments

- **Quantum Tests of Non-Classical Gravity.**
  A quantum Cavendish experiment and its consequences



In memory of Helmut Rauch (1939-2019)



The neutron interferometer

Rauch, Treimer, Bonse,
Physics Letters A 47, 369 (1974)

Quantum systems as sensitive probes of gravity

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

and

S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121
(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

$$\Delta\varphi = \frac{1}{\hbar}\int m\,\Delta\phi\,dt$$

gravitational potential
(on Earth: $\phi = g \cdot h$)

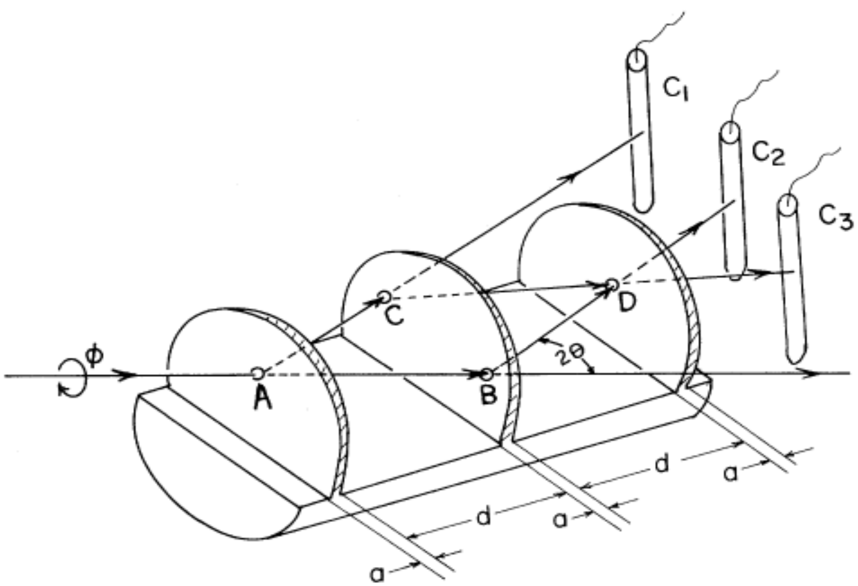
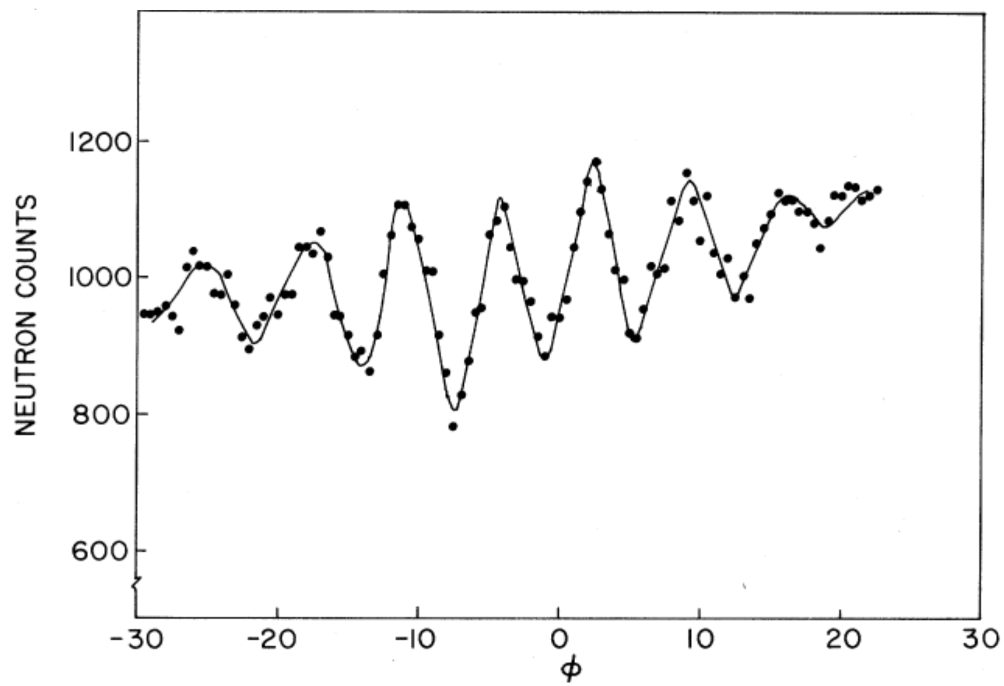


FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.



Quantum systems as sensitive probes of gravity

universität wien

VCQ
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(on Earth: $\phi = g \cdot h$)

Nature 1999

Measurement of gravitational acceleration by dropping atoms

Achim Peters, Keng Yeow Chung & Steven Chu
Physics Department, Stanford University, Stanford, California 94305-4060, USA

Laser-cooling of atoms and atom-trapping are finding increasing application in many areas of science[1]. One important use of laser-cooled atoms is in atom interferometers[2]. In these devices, an atom is placed into a superposition of two or more spatially separated atomic states; these states are each described by a quantum-mechanical phase term, which will interfere with one another if they are brought back together at a later time. Atom

Nature 2002

Quantum states of neutrons in the Earth's gravitational field

Valery V. Nesvizhevsky*, Hans G. Börner*, Alexander K. Petukhov*, Hartmut Abele†, Stefan Baeßler†, Frank J. Rueß†, Thilo Stöferle†, Alexander Westphal†, Alexei M. Gagarski‡, Guennady A. Petrov‡ & Alexander V. Strelkov§

* *Institute Laue-Langevin, 6 rue Jules Horowitz, Grenoble F-38042, France*
† *University of Heidelberg, 12 Philosophenweg, Heidelberg D-69120, Germany*
‡ *Petersburg Nuclear Physics Institute, Orlova Roscha, Gatchina, Leningrad reg. R-188350, Russia*
§ *Joint Institute for Nuclear Research, Dubna, Moscow reg. R-141980, Russia*

The discrete quantum properties of matter are manifest in a variety of phenomena. Any particle that is trapped in a sufficiently deep and wide potential well is settled in quantum bound states. For example, the existence of quantum states of electrons in an electromagnetic field is responsible for the structure of atoms[16], and quantum states of nucleons in a strong nuclear field give rise to the structure of atomic nuclei[17]. In an analogous way, the gravitational field should lead to the formation of quantum states.

• • •

Quantum systems as sensitive probes of gravity

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$\Delta\varphi = \frac{1}{\hbar}\int m\,\Delta\phi\, dt$

gravitational potential
(on Earth: $\phi = g \cdot h$)

(Kasevich group)

1991 $\Delta g/g = 1\times10^{-6}$

1998 $\Delta g/g = 3\times10^{-8}$

2014 $\Delta g/g = 5\times10^{-13}$

Nature 1999

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Nature 2002

...neutrons

(Kasevich/Tino groups)

2007 $\Delta G/G = 3\times10^{-3}$

2014 $\Delta G/G = 1\times10^{-4}$

mainly limited by position of atoms

...

The discrete quantum properties of matter are manifest... variety of phenomena. Any particle that is trapped in a sufficiently deep and wide potential well is settled in quantum bound states. For example, the existence of quantum states of electrons in an electromagnetic field is responsible for the structure of atoms[16], and quantum states of nucleons in a strong nuclear field give rise to the structure of atomic nuclei[17]. In an analogous way, the gravitational field should lead to the formation of quantum states.

Newtonian Gravity in Quantum Experiments

Nature 2002

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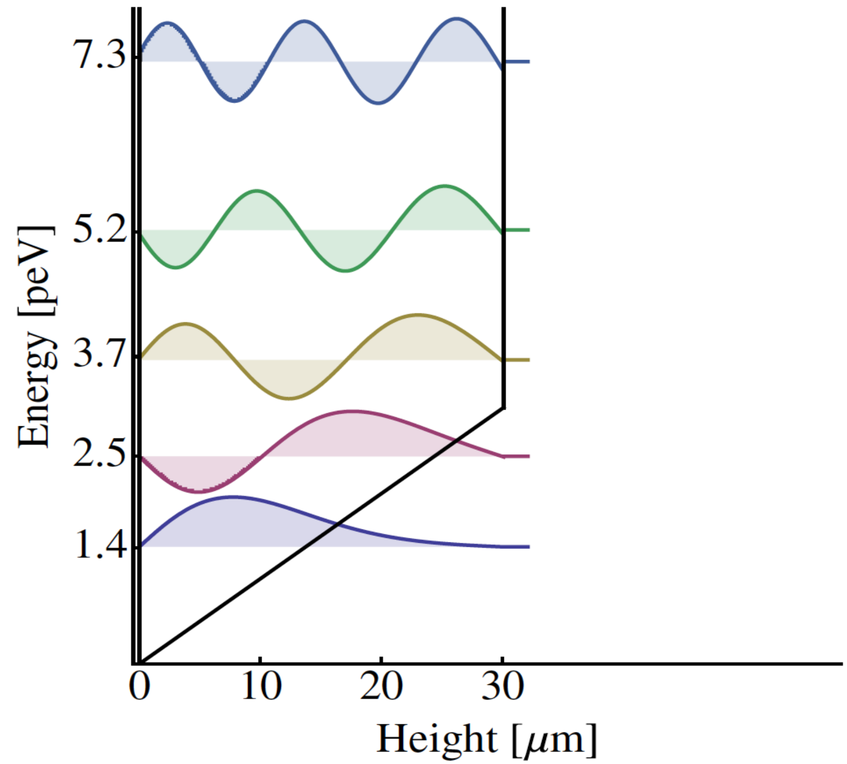


LETTERS
PUBLISHED ONLINE: 17 APRIL 2011 | DOI: 10.1038/NPHYS1970
nature physics

Realization of a gravity-resonance-spectroscopy technique

Tobias Jenke[1], Peter Geltenbort[2], Hartmut Lemmel[1,2] and Hartmut Abele[1,3,4]*

Sensitivity **δE = 1e-14 eV**

→ test short-range modifications of V(r) on (sub-) μm scale

→ Most stringent bound on pseudoscalar axions

Abele2014: PRL **112**, 151105

Quantum tests of the gravitational time dilation

PHYSICAL REVIEW LETTERS

VOLUME 4 APRIL 1, 1960 NUM

APPARENT WEIGHT OF PHOTONS*

R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received March 9, 1960)

As we proposed a few months ago,[1] we have now measured the effect, originally hypothesized by Einstein,[2] of gravitational potential on the apparent frequency of electromagnetic radiation by using the sharply defined energy of recoil-free γ rays emitted and absorbed in solids, as discovered by Mössbauer.[3] We have already re-

solutely necessary to measure a chang relative frequency that is produced by the perturbation being studied. Observation of a frequency difference between a given source and absorber cannot be uniquely attributed to this perturbation. More recently, we have discovered and explained a variation of frequency with tem-

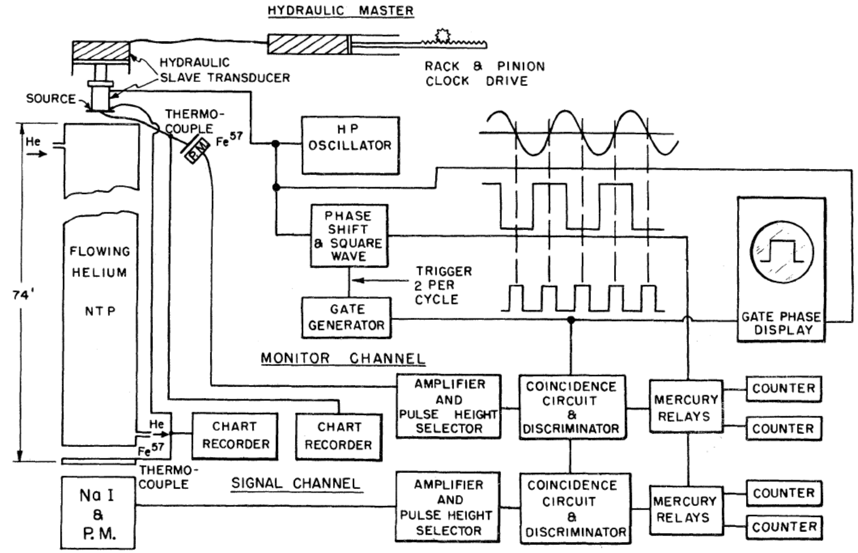
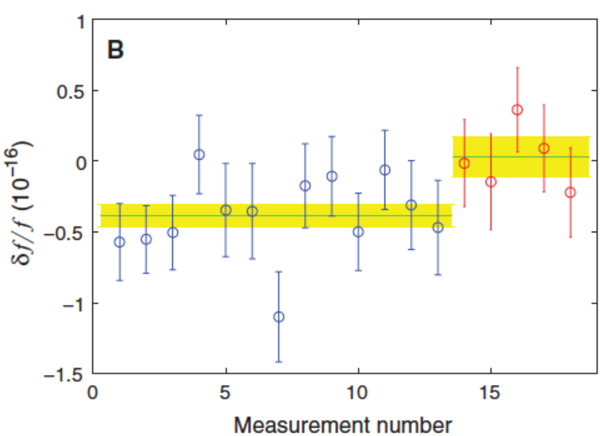


FIG. 1. A block diagram of the over-all experimental arrangement. The source and absorber-detector units were frequently interchanged. Sometimes a ferroelectric and sometimes a moving-coil magnetic transducer was used with frequencies ranging from 10 to 50 cps.

$$\Delta\nu/\nu = gh/c^2 = 10^{-16} \times h$$



Frequency shift due to 33 cm lift in Earth's gravitational field

Science AAAS

Optical Clocks and Relativity
C. W. Chou, *et al.*
Science **329**, 1630 (2010);
DOI: 10.1126/science.1192720

Optical Clocks and Relativity

C. W. Chou,* D. B. Hume, T. Rosenband, D. J. Wineland

Observers in relative motion or at different gravitational potentials measure disparate clock rates. These predictions of relativity have previously been observed with atomic clocks at high velocities and with large changes in elevation. We observed time dilation from relative speeds of less than 10 meters per second by comparing two optical atomic clocks connected by a 75-meter length of optical fiber. We can now also detect time dilation due to a change in height near Earth's surface of less than 1 meter. This technique may be extended to the field of geodesy, with applications in geophysics and hydrology as well as in space-based tests of fundamental physics.

(microwave atomic clocks: e.g. Hafele & Keating, Science 177, 166 (1972), Vessot et al., PRL 45, 2081 (1980): h=10^7m)

What is time? Quantum superpositions of clocks

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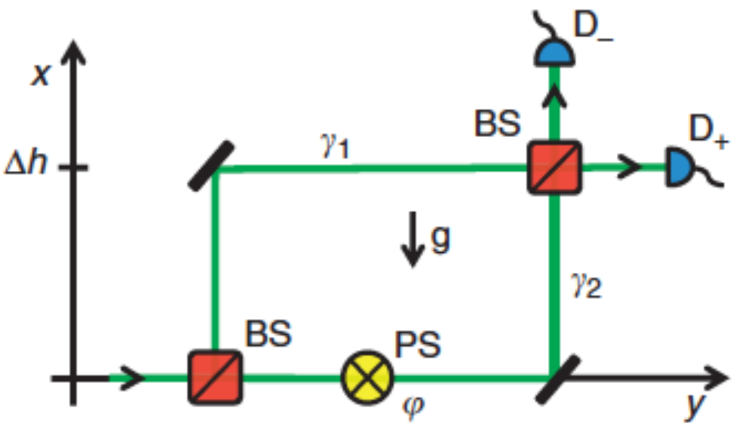
qubit in a gravitational field

$$|g\rangle + |e\rangle \rightarrow |g\rangle + exp\left\{-\frac{i}{\hbar}\frac{(E_g - E_e)}{c^2}ght\right\}|e\rangle$$

i.e. the qubit rotates on the Bloch sphere at a frequency $\omega_g = \frac{\Delta E}{\hbar c^2} gh$



If the qubit is placed in a spatial superposition of two vertical heights (in Earth's gravitational field) separated by Δh the qubits will evolve differently:

Dephasing will occur at a frequency $\Delta\omega_g = \frac{\Delta E}{\hbar c^2} g \Delta h$

Complete dephasing (orthogonal qubit states) will occur after a time $T_\pi = \frac{\pi}{\Delta\omega_g} = \frac{\pi \hbar c^2}{\Delta E g \Delta h}$

Complete re-phasing will occur after a time $2T_\pi$

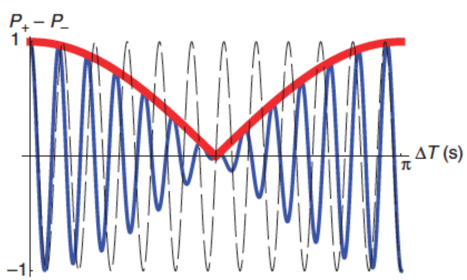


Figure 2 | Visibility of the interference pattern and the phase shift in the cases with and without the 'clock.' The plot of the difference between

Received 13 Jun 2011 | Accepted 5 Sep 2011 | Published 18 Oct 2011 DOI: 10.1038/ncomms1498

Quantum interferometric visibility as a witness of general relativistic proper time

Magdalena Zych[1], Fabio Costa[1], Igor Pikovski[1] & Časlav Brukner[1,2]

Example:
Δh=20m (Kasevich drop tower, Stanford), ΔE=2eV (optical qubit, e.g. 4S-3D transition in Ca-2+)
→ T_π = 500 ms (compatible with achievable coherence times)

What is time? Quantum superpositions of clocks

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VCQ Vienna Center for Quantum Science and Technology

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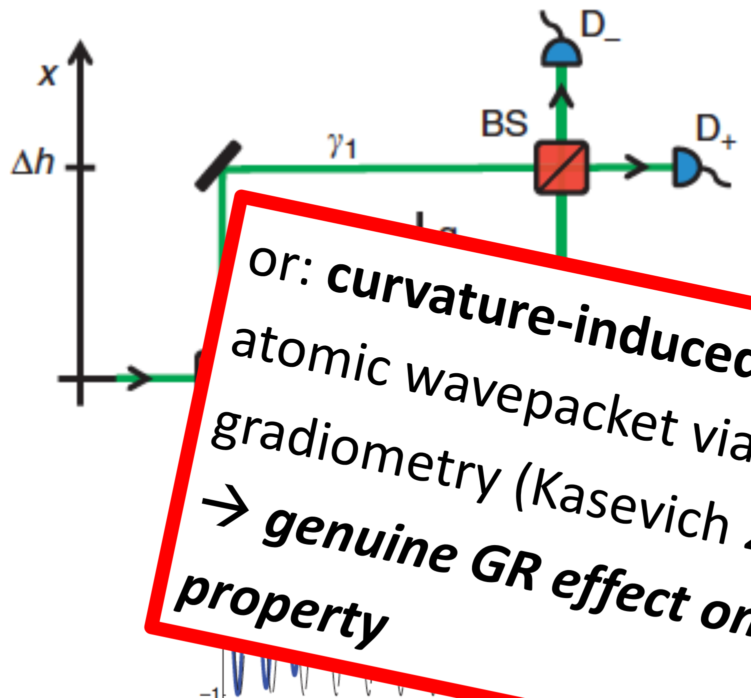

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Dephasing will occur at a frequency $\Delta\omega_g = \frac{\Delta E}{\hbar c^2} g\Delta h$

… (orthogonal qubit states) will occur

$$\ldots \frac{\pi}{\Delta\omega_g} = \frac{\pi\hbar c^2}{\Delta E g \Delta h}$$

…ing will occur after a time $2T_\pi$

or: **curvature-induced phase shift** of atomic wavepacket via gravity-gradiometry (Kasevich 2019; PITP talk)
→ **genuine GR effect on a quantum property**

Figure 2 | Visibility of the interference pattern and the phase shift in the … cases with and without the 'clock.' The plot of the difference between

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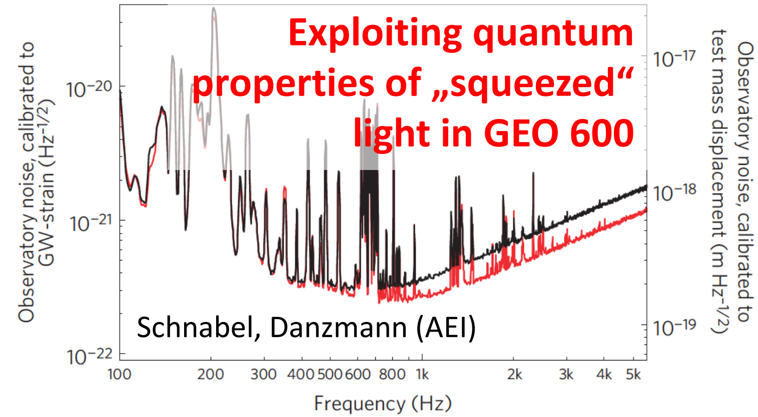
Quantum-enhancing GWD

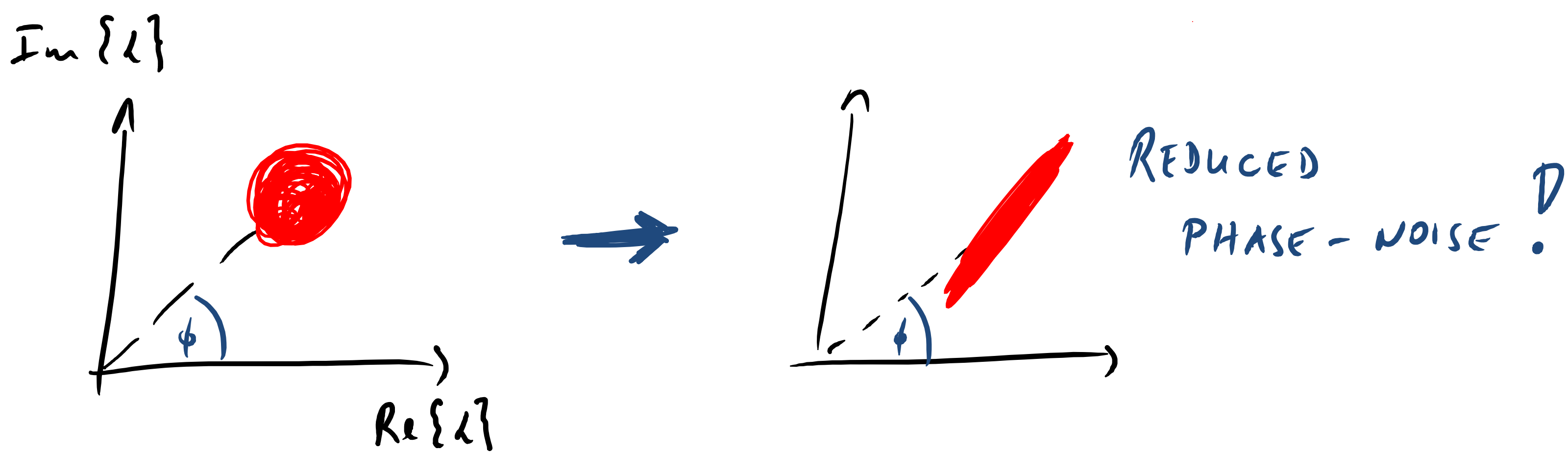
LETTERS
PUBLISHED ONLINE: 11 SEPTEMBER 2011 | DOI: 10.1038/NPHYS2083
nature physics

A gravitational wave observatory operating beyond the quantum shot-noise limit

The LIGO Scientific Collaboration †*



→ f-dependent squeezing: Oelker 2016: PRL 116, 041102



Quantum squeezed light

(Caves 1981): PRD 23, 1693
GEO 600: Nature Physics 7, 962 (2011)
LIGO: Nature Photonics 7, 613 (2013)

Quantum-enhancing GWD

LETTERS
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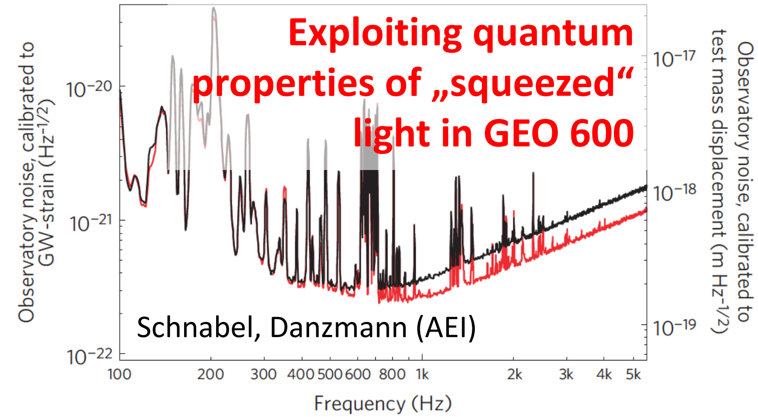
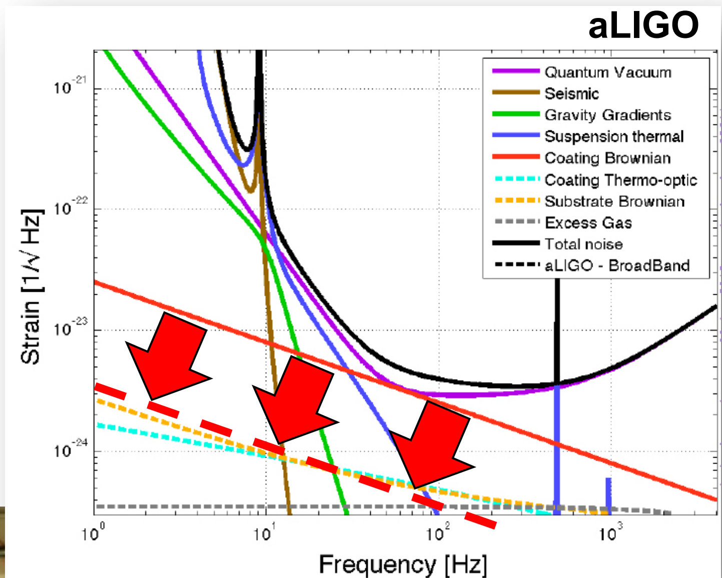


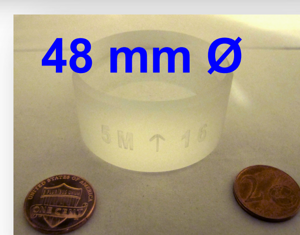
Towards the ultimate quantum limits of measurement



ARTICLES
PUBLISHED ONLINE: 21 JULY 2013 | DOI: 10.1038/NPHOTON.2013.174
nature photonics

Tenfold reduction of Brownian noise in high-reflectivity optical coatings

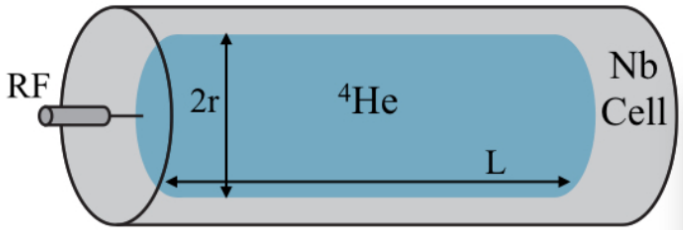
Garrett D. Cole[1,2†]*, Wei Zhang[3†], Michael J. Martin[3], Jun Ye[3]* and Markus Aspelmeyer[1]*

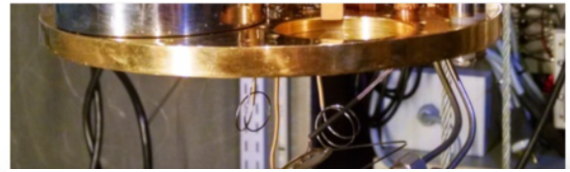


with H. Lück (AEI), K. Danzmann (AEI)

... and many more gravitational wave detectors

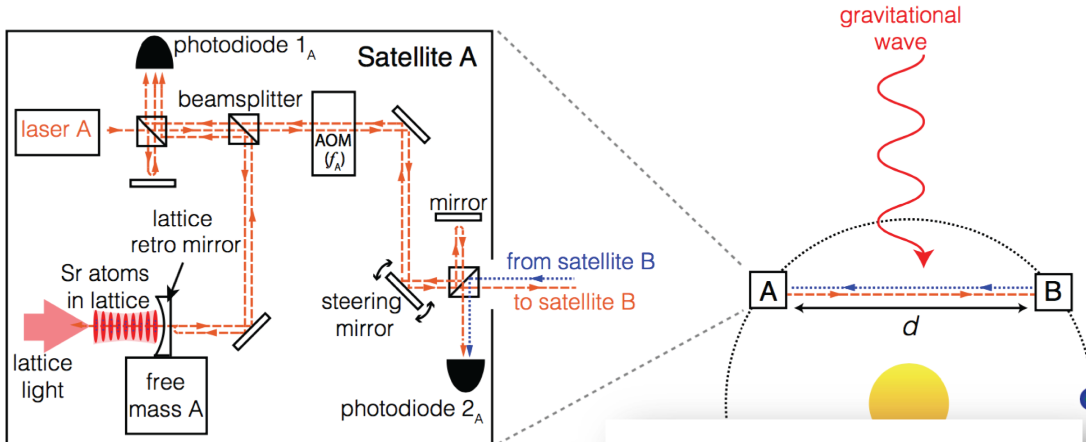
Detecting continuous gravitational waves with **superfluid He4**





Schwab 2017: NJP 19, 091001

Gravitational wave detection with **optical lattice atomic clocks**

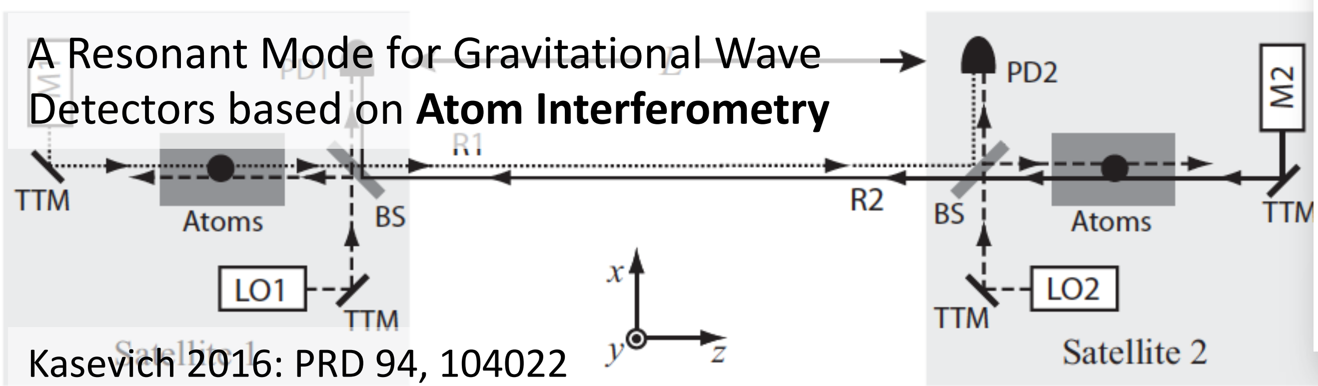


Ye 2016: PRD 94, 124043

Detecting gravitational waves with **highly nonclassical states of Bose-condensed atoms?**

Fuentes 2014: NJP 16, 085003

A Resonant Mode for Gravitational Wave Detectors based on **Atom Interferometry**



Kasevich 2016: PRD 94, 104022

... and many more opportunities

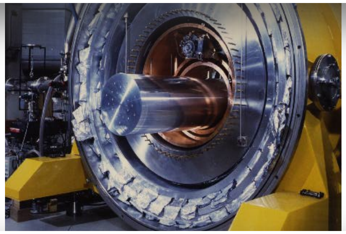
Science **349**, 849 (2015)

Atom-interferometry constraints on dark energy

nature physics

PUBLISHED ON

Gravitational bar detectors set limits to Planck-scale physics on macroscopic variables



assimo Cerdonio[7], Livia Conti[7],
i A. Prodi[6,9], Luca Taffarello[7],

IOP PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **29** (2012) 224011 (44pp) doi:10.1088/0264-9381/29/22/224011

Fundamental quantum optics experiments conceivable with satellites—reaching relativistic distances and velocities

David Rideout[1,2,3], Thomas Jennewein[2,4], Giovanni Amelino-Camelia[6], Tommaso F Demarie[7], Brendon L Higgins[2,4], Achim Kempf[2,3,4,5], Adrian Kent[3,8], Raymond Laflamme[2,3,4], Xian Ma[2,4], Robert B Mann[2,4], Eduardo Martín-Martínez[2,4,5], Nicolas C Menicucci[3,9], John Moffat[3], Christoph Simon[10], Rafael Sorkin[3], Lee Smolin[3] and Daniel R Terno[7]

Science **341**, 1213 (2013)

From Cosmology to Cold Atoms: Observation of Sakharov Oscillations in a Quenched Atomic Superfluid

Chen-Lung Hung,[1]* Victor Gurarie,[2] Cheng Chin[1]†

Predicting the dynamics of many-body systems far from equilibrium is a challenging theoretical problem. A long-predicted phenomenon in hydrodynamic nonequilibrium systems is the occurrence

, 563–573 (2006)

0340-006-2375-y

Applied Physics B
Lasers and Optics

The search for quantum gravity effects II: Specific predictions

(ZARM), University of Bremen,

PRL **98,** 111102 (2007) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2007

Testing General Relativity with Atom Interferometry

Savas Dimopoulos, Peter W. Graham, Jason M. Hogan, and Mark A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305, USA

(Received 10 October 2006; published 15 March 2007)

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  An incomplete survey

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  Low-energy consequences of quantum gravity in table-top experiments

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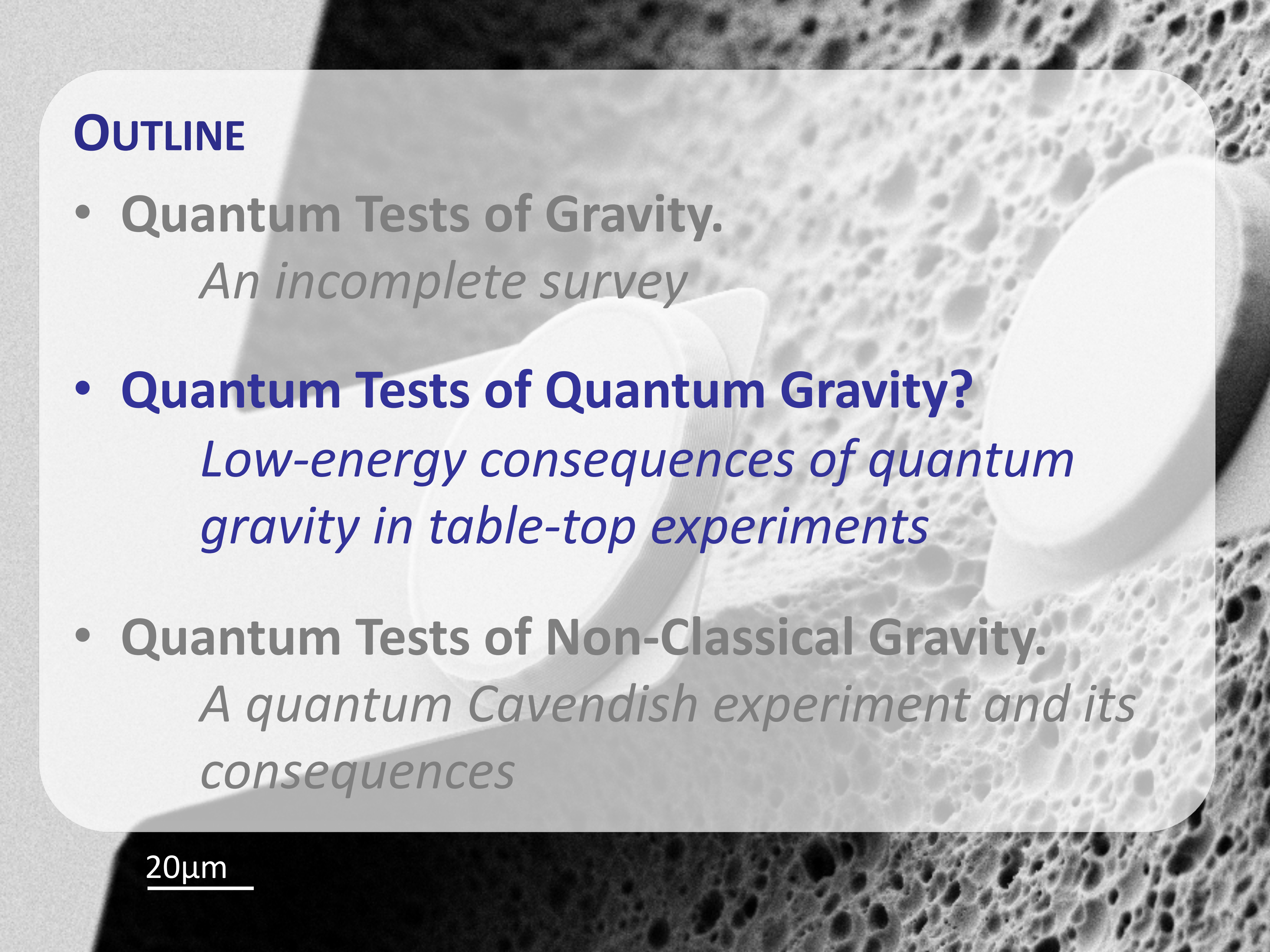


Testing High-Energy Physics in Table-Top Experiments: The example of Supersymmetry

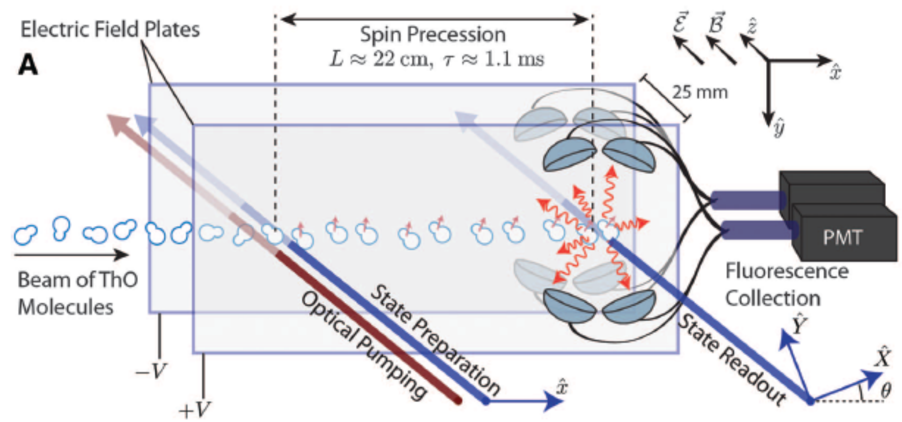
What about quantum gravity?

See also: Regan et al., Phys. Rev. Lett. **88**, 071805 (2002); Hudson et al., Nature **473**, 493 (2011).

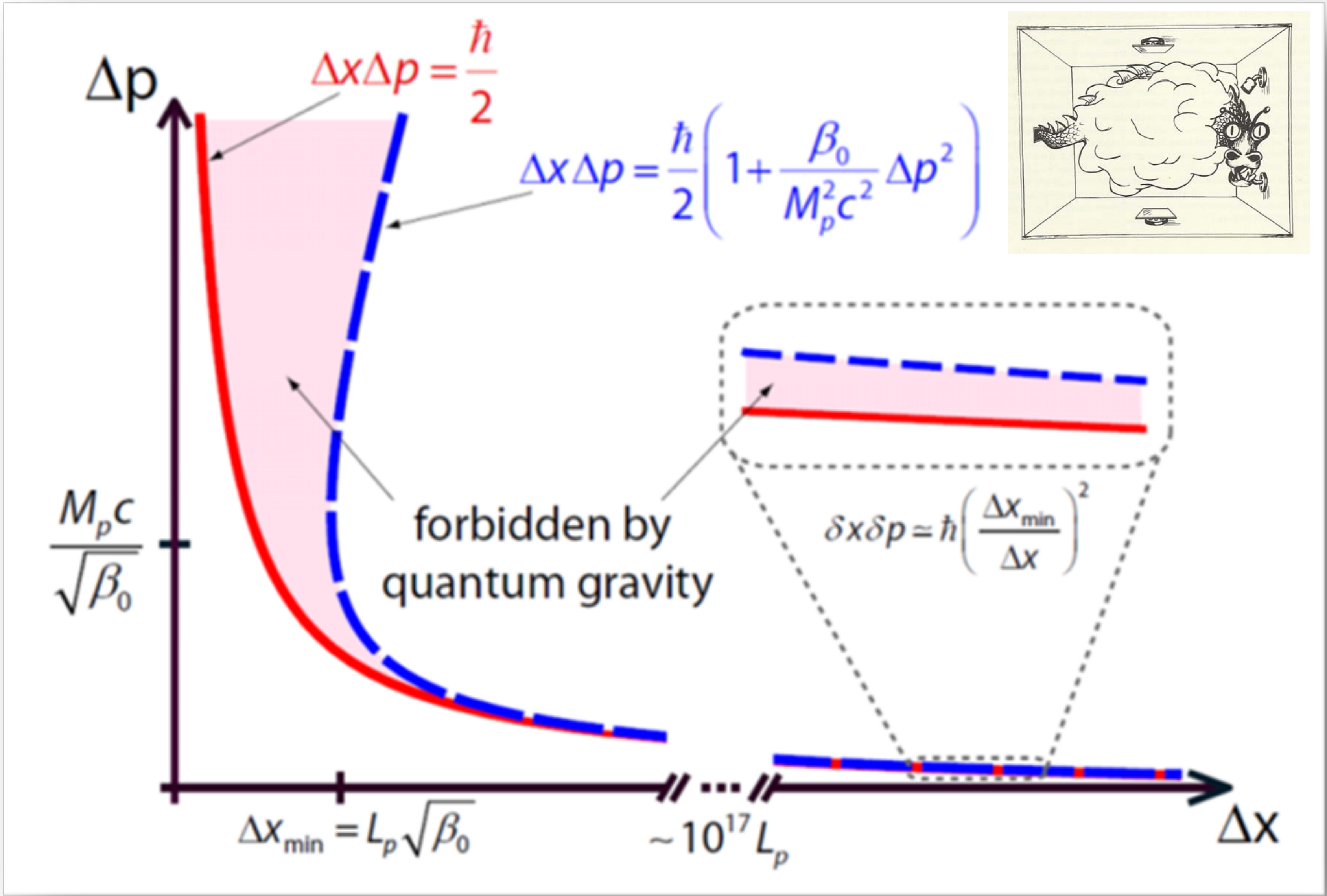
Electric Dipole Moment of the Electron

The ACME Collaboration,* J. Baron,[1] W. C. Campbell,[2] D. DeMille,[3]† J. M. Doyle,[1]† G. Gabrielse,[1]† Y. V. Gurevich,[1]‡ P. W. Hess,[1] N. R. Hutzler,[1] E. Kirilov,[3]§ I. Kozyryev,[3]|| B. R. O'Leary,[3] C. D. Panda,[1] M. F. Parsons,[1] E. S. Petrik,[1] B. Spaun,[1] A. C. Vutha,[4] A. D. West[3]

The Standard Model of particle physics is known to be incomplete. Extensions to the Standard Model, such as weak-scale supersymmetry, posit the existence of new particles and interactions that are asymmetric under time reversal (T) and nearly always predict a small yet potentially measurable electron electric dipole moment (EDM), d_e, in the range of 10^{-27} to 10^{-30} $e\cdot$cm. The EDM is an asymmetric charge distribution along the electron spin ($\vec{S}$) that is also asymmetric under T. Using the polar molecule thorium monoxide, we measured $d_e = (-2.1 \pm 3.7_{stat} \pm 2.5_{syst}) \times 10^{-29}$ $e\cdot$cm. This corresponds to an upper limit of $|d_e| < 8.7 \times 10^{-29}$ $e\cdot$cm with 90% confidence, an order of magnitude improvement in sensitivity relative to the previous best limit. Our result constrains T-violating physics at the TeV energy scale.



„Hence, within the context of many models, our EDM limit constrains CP violation up to energy scales similar to, or higher than, those explored directly at the Large Hadron Collider."



e.g. L. Garay, arXiv:gr-qc/9403008

Measuring the canonical commutator of a massive system

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

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

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

By measuring the ancilla one can obtain a measure of the commutator.

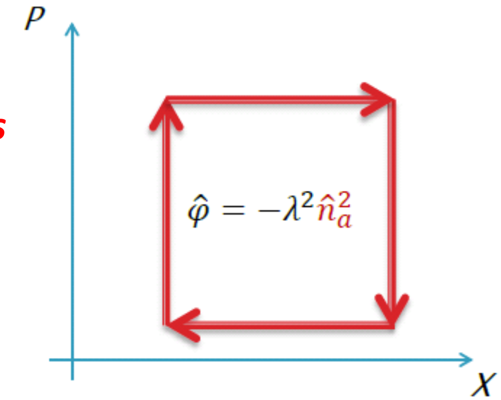
For an initial coherent state:

$$\langle\hat{a}_a\rangle = \langle\alpha|\hat{\xi}^+\hat{a}_a\hat{\xi}|\alpha\rangle$$

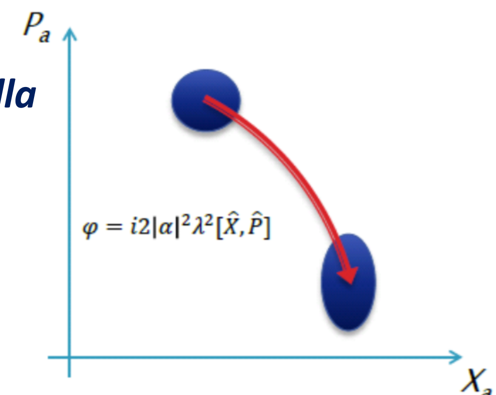
$$= \alpha e^{-\lambda^2[\hat{X},\hat{P}]} e^{-|\alpha|^2\left(1-e^{-2\lambda^2[\hat{X},\hat{P}]}\right)}$$

$$\approx \alpha e^{-2|\alpha|^2\lambda^2[\hat{X},\hat{P}]} \qquad (\text{for } \lambda^2\,[\hat{X},\hat{P}] \ll 1)$$

mechanics



optical ancilla



Phase shift scales with the intensity of the input state.
⇒ Can measure the commutator even for small coupling λ!

Pikovski, Vanner, Aspelmeyer, Kim, Brukner
Nature Physics 8, 393 (2012)

Without ancilla: see e.g. ion experiments
Leibfried et al., Nature 422, 427 (2003)

Towards tests of quantum gravity predictions?

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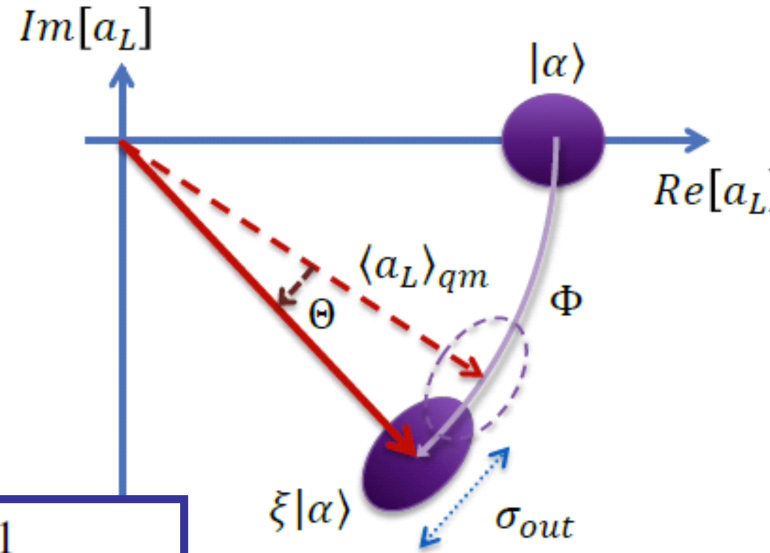
Current state of the art:

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}

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

→ 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 8, 393 (2012)

Restricting Modified Commutators via Thermometry

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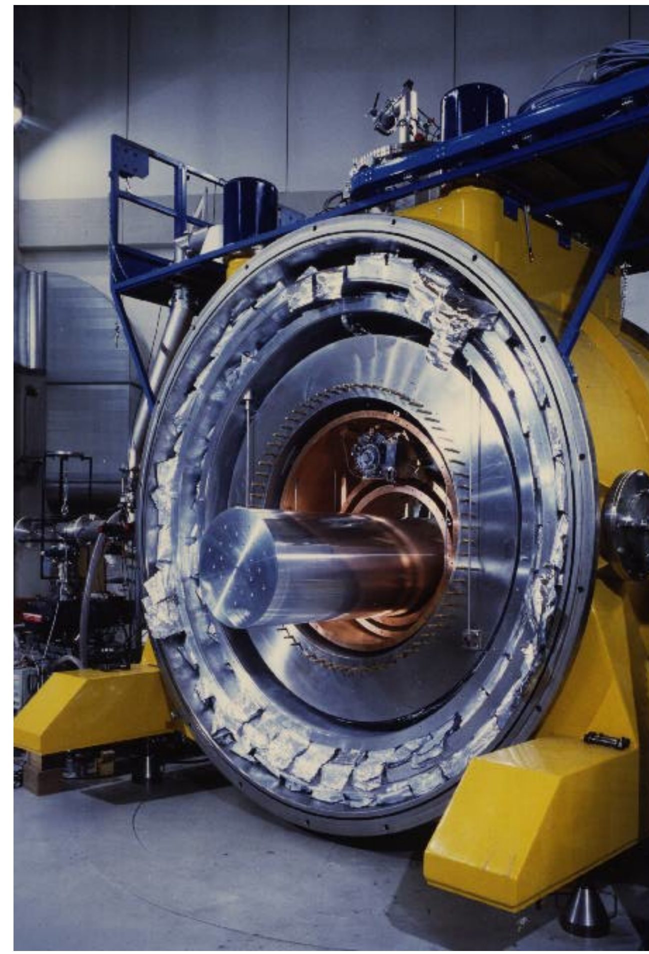
nature physics | LETTERS
PUBLISHED ONLINE: 16 DECEMBER 2012 | DOI: 10.1038/NPHYS2503

Gravitational bar detectors set limits to Planck-scale physics on macroscopic variables

Francesco Marin[1,2,3]★, Francesco Marino[3,4], Michele Bonaldi[5,6], Massimo Cerdonio[7], Livia Conti[7], Paolo Falferi[6,8], Renato Mezzena[6,9], Antonello Ortolan[10], Giovanni A. Prodi[6,9], Luca Taffarello[7], Gabriele Vedovato[7], Andrea Vinante[8,11] and Jean-Pierre Zendri[7]

Different approaches to quantum gravity, such as string theory[1,2] and loop quantum gravity, as well as doubly special relativity[3] and gedanken experiments in black-hole physics[4–6], all indicate the existence of a minimal measurable length[7,8] of the order of the Planck length, $L_p = \sqrt{\hbar G/c^3} = 1.6 \times 10^{-35}$ m. This observation has motivated the proposal of generalized uncertainty relations, which imply changes in the energy spectrum of quantum systems. As a consequence, quantum gravitational effects could be revealed by experiments able to test deviations from standard quantum mechanics[9–11], such as those recently proposed on macroscopic mechanical oscillators[12]. Here we exploit the sub-millikelvin cooling of the normal modes of the ton-scale gravitational wave detector AURIGA, to place an upper limit for possible Planck-scale modifications on the ground-state energy of an oscillator. Our analysis calls for the development of a satisfactory treatment of multi-particle states in the framework of quantum gravity models.



AURIGA (Webber bar detector)

Deformation of the commutator can be cast into a (modified) effective Hamiltonian picture
→ modified ground state energy can be tested by thermometry

nature COMMUNICATIONS

ARTICLE

Received 25 Nov 2014 | Accepted 12 May 2015 | Published 19 Jun 2015

DOI: 1

Probing deformed commutators harmonic oscillators

Mateusz Bawaj[1,2], Ciro Biancofiore[1,2], Michele Bonaldi[3,4], Federica Bon
Giovanni Di Giuseppe[1,2], Lorenzo Marconi[5], Francesco Marino[6,7], Ricca
Giovanni A. Prodi[4,8], Enrico Serra[4,8,9,10], David Vitali[1,2] & Francesco M

A minimal observable length is a common feature of theories that aim to merge physics and gravity. Quantum mechanically, this concept is associated with minimal uncertainty in position measurements, which is encoded in deformed cor relations. In spite of increasing theoretical interest, the subject suffers from the lack of dedicated experiments and bounds to the deformation parameters have extrapolated from indirect measurements. As recently proposed, low-energy n oscillators could allow to reveal the effect of a modified commutator. Here we analy evolution of high-quality factor micro- and nano-oscillators, spanning a wide range around the Planck mass m_P ($\approx$22 µg). The direct check against a model of dynamics substantially lowers the previous limits on the parameters quant commutator deformation.

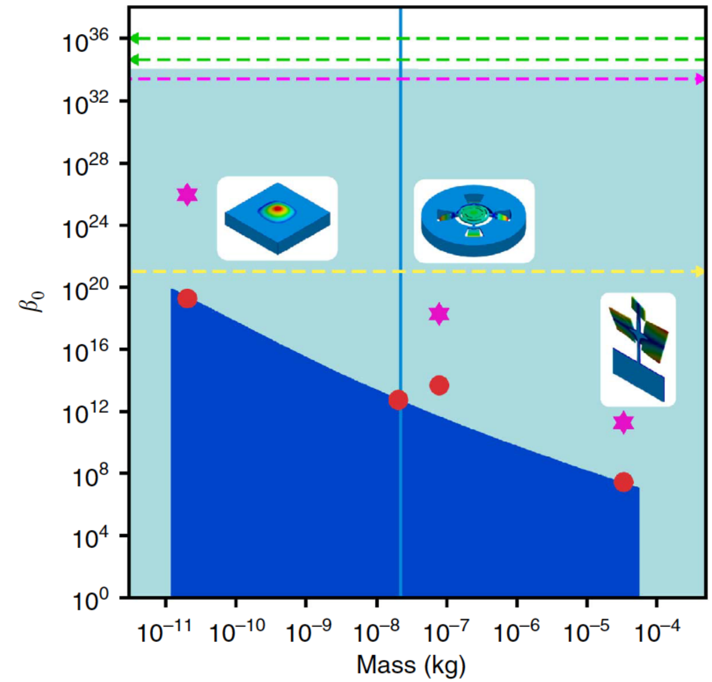


Figure 3 | Upper limits to the deformed commutator. The parameter β_0 quantifies the deformation to the standard commutator between position and momentum, or the scale $\sqrt{\beta_0}L_P$ below which new physics could come into play. Full symbols reports its upper limits obtained in this work, as a function of the mass. Red dots: from the dependence of the oscillation frequency from its amplitude; magenta stars: from the third harmonic distortion. In the former data set, for the intermediate mass range (10–100 µg), we report the results obtained with two different oscillators. Light blue shows the area below the electroweak scale, dark blue the area that remains unexplored. Dashed lines report some previously estimated upper limits, obtained in mass ranges outside this graph (as indicated by the arrows). Green: from high-resolution spectroscopy on the hydrogen atom, considering the ground state Lamb shift (upper line)[21] and the 1S–2S level difference (lower line)[22]. Magenta: from the AURIGA detector[10,11]. Yellow: from the lack of violation of the equivalence principle[39]. The vertical line corresponds to the Planck mass (22 µg).

Quantum Optical Tests of Nonlocal Effective Field Theories

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PRL 116, 161303 (2016) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2016

Testing Quantum Gravity Induced Nonlocality via Optomechanical Quantum Oscillators

Alessio Belenchia,[1,*] Dionigi M. T. Benincasa,[1,†] Stefano Liberati,[1,‡] Francesco Marin,[2,3,§] Francesco Marino,[4,‖] and Antonello Ortolan[5,¶]

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[2]Dipartimento di Fisica e Astronomia, University of Florence and INFN, Sezione di Firenze, Via Sansone, 1, I-50019 Sesto Fiorentino, Firenze, Italy

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[4]CNR-Istituto Nazionale di Ottica, Largo E. Fermi 6, I-50125 Firenze, Italy and INFN, Sez. di Firenze

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(Received 18 December 2015; revised manuscript received 22 February 2016; published 21 April 2016)

Several quantum gravity scenarios lead to physics below the Planck sca
Lorentz invariant equations of motion. We show that such nonlocal effe
modified Schrödinger evolution in the nonrelativistic limit. In particula
optomechanical quantum oscillators is characterized by a spontaneous peri
generated by environmental effects. We discuss constraints on the nonloca
ments, and show how future experiments (already under construction) w
otherwise cast severe bounds on the nonlocality scale (well beyond the cu
Hadron Collider). This paves the way for table top, high precision experiment
as a promising new avenue for testing some quantum gravity phenomenol

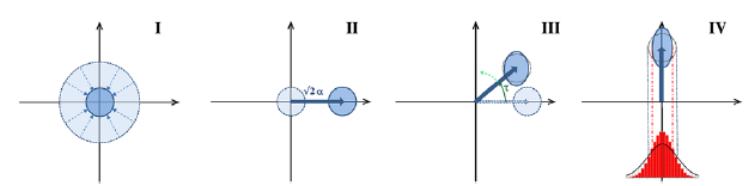


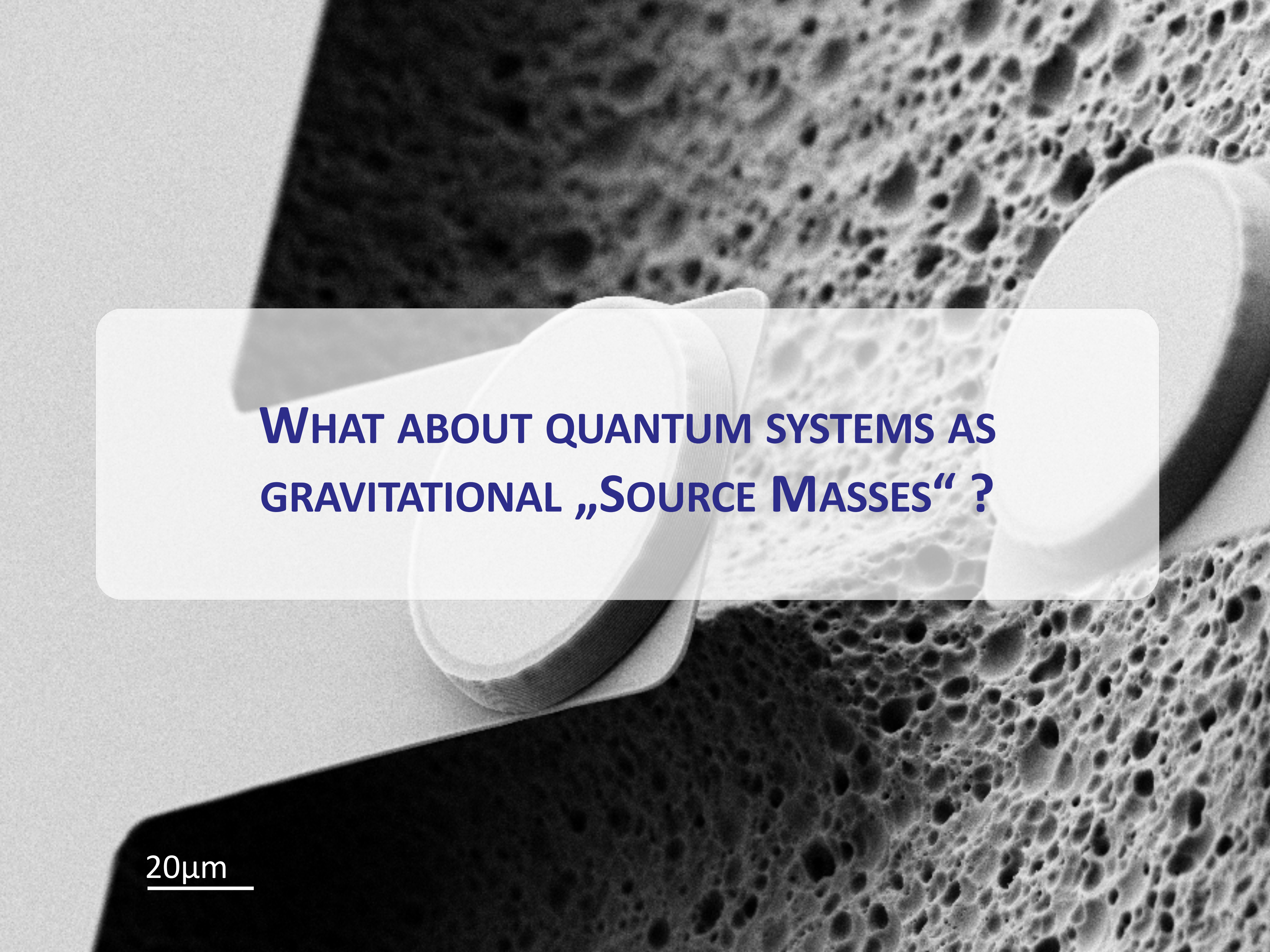
FIG. 1. Time dependence of the variances of a coherent state for $\alpha = 1$ and $b_2\epsilon = 10^{-2}$. The continuous (blue) and dashed (red) lines represent the position and momentum variances, respectively. The black dot-dashed line is the standard value $1/2$ of both variances in the local theory. Below the plot we sketch in x-p phase diagrams the proposed experimental procedure for measuring the variance of x, involving (I) cooling the oscillator down to $\langle n \rangle \ll 1$, (II) a pulsed excitation in a well-defined coherent state, (III) free evolution for a time τ, and (IV) the measurement of x in a time interval shorter than the oscillation period. Steps (II) and (III) should last much less than the thermal decoherence time. The cycle is iterated several times, the variance of the measurements of x is calculated, and then τ is changed and the whole measurement procedure is repeated.

Background: Combining fundamental discreteness and local Lorentz invariance (LLI) may require some form of nonlocality

Idea: Nonlocal effective field theories can be solved perturbatively

Result: Modified dynamics results in observable time-dependent squeezing of (opto-)mechanical systems

What about quantum systems as gravitational „Source Masses“ ?



OUTLINE

- **Quantum Tests of Gravity.**

  An incomplete survey

- **Quantum Tests of Quantum Gravity?**

  Low-energy consequences of quantum gravity in table-top experiments

- **Quantum Tests of Non-Classical Gravity.**

  A quantum Cavendish experiment and its consequences

$$G_{\mu\nu} \overset{?}{=} 8\pi \langle T_{\mu\nu} \rangle.$$

20µm

An ultimate experiment? Entanglement by gravity…

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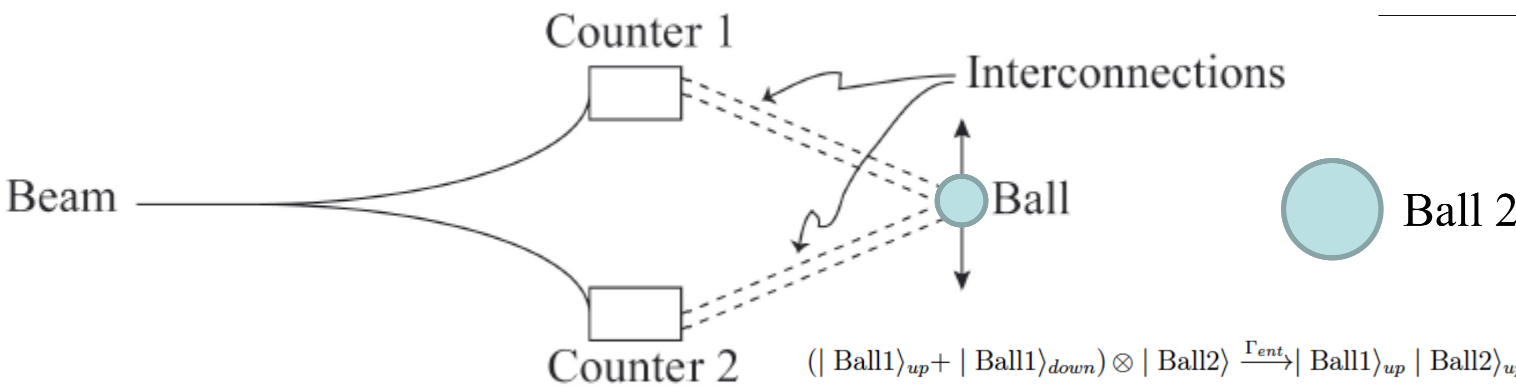

$$(|\text{Ball1}\rangle_{up} + |\text{Ball1}\rangle_{down}) \otimes |\text{Ball2}\rangle \xrightarrow{\Gamma_{ent}} |\text{Ball1}\rangle_{up}\,|\text{Ball2}\rangle_{up} + |\text{Ball1}\rangle_{down}\,|\text{Ball2}\rangle_{down}$$

FEYNMAN: "Therefore, there must be an amplitude for the gravitational field, *provided* that the amplification necessary to reach a mass which can produce a gravitational field big enough to serve as a link in the chain does not destroy the possibility of keeping quantum mechanics all the way. There is a *bare* possibility (which I shouldn't mention!) that quantum mechanics fails and becomes classical again when the amplification gets far enough, because of some minimum amplification which you can get across such a chain. But aside from that possibility, if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."

Chapel Hill Conference 1957 (29)

WITTEN: "What prevents this from becoming a practical experiment?"

see also Belenchia, Wald, et al., *Phys. Rev. D* **98**, 126009 (2018)

An ultimate experiment? Entanglement by gravity…

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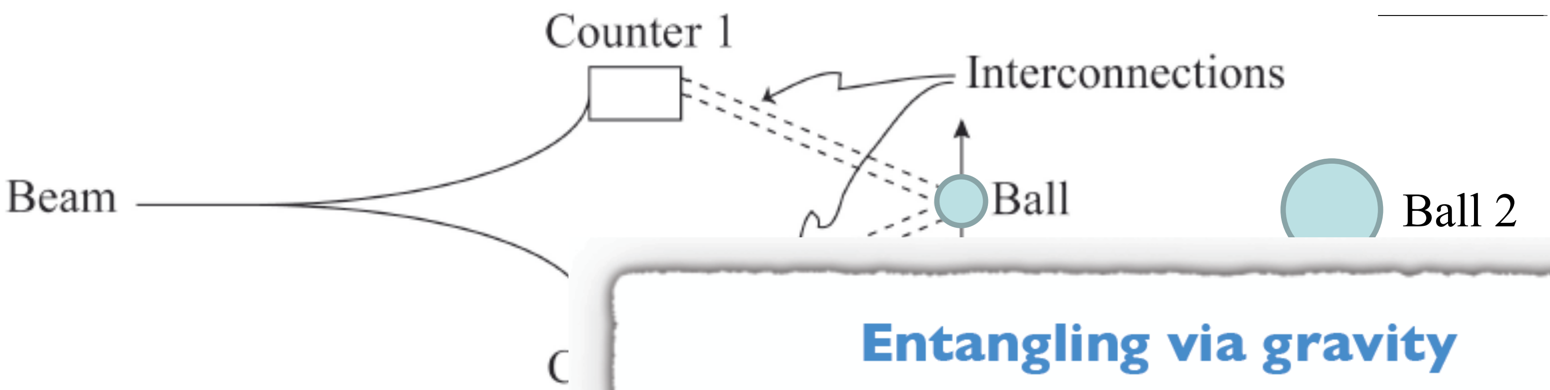
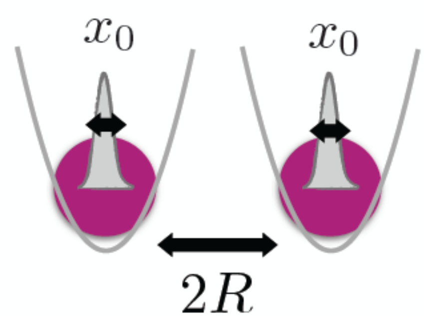


FEYNMAN: "Therefore, …
provided that the…
duce a gravitation…
destroy the possi…
is a *bare* possibilit…
fails and become…
because of some …
chain. But aside …
ics up to any level then you have to believe in gravitational quantization
in order to describe this experiment."

Entangling via gravity



Entangling time:

$$t_{ent} = \frac{2\hbar}{GM^2} R^3 \left(\frac{1}{x_0}\right)^2$$

Pino et al., arXiv:1603.01553

Chapel Hill Conference 1957 (29)

WITTEN: "What prevents this from becoming a practical experiment?"

see also Belenchia, Wald, et al., *Phys. Rev. D* **98**, 126009 (2018)

An ultimate experiment? Entanglement by gravity…

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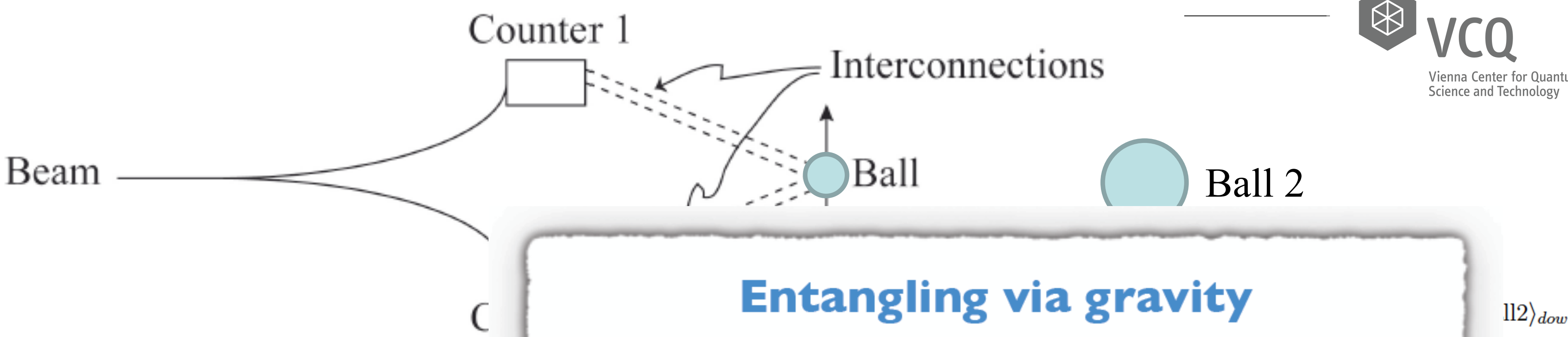

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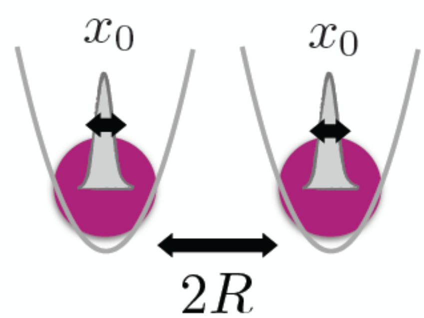
Entangling via gravity



Entangling time:

$$t_{ent} = \frac{2\hbar}{GM^2} R^3 \left(\frac{1}{x_0}\right)^2$$

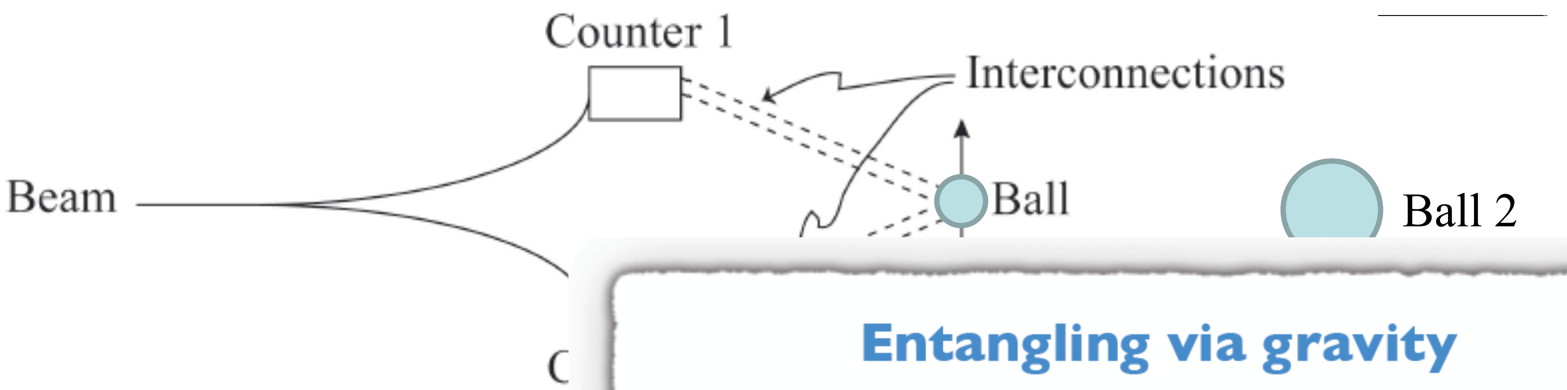
Pino et al., arXiv:1603.01553

Chapel Hill Conference 1957 (29)

Example: For 2 **lead spheres** of **diameter 500 µm**, an initial **superposition size for sphere 1** of **$\Delta r = 5\times10^{-7}$ m** and preparation of **sphere 2** in a **motional ground state** (100 Hz trap frequency) with **$\Delta x_0 = 10^{-15}$ m**, we obtain **$\Gamma_{ent} = 1.5$ Hz**, i.e. **gravitational entanglement** is established on a **second time scale**.

$$\Gamma_{ent} = \left(\frac{GM}{\hbar}\right) \Delta r \rho \Delta x_0$$

An ultimate experiment? Entanglement by gravity…



FEYNMAN: "Therefore, …
provided that the …
duce a gravitatio…
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chain. But aside …
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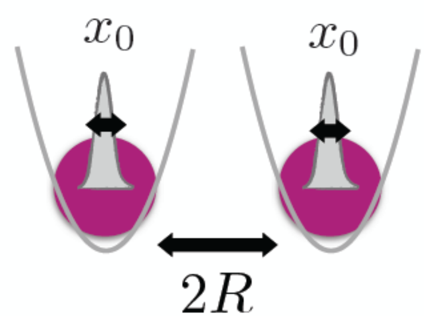
…el Hill Conference 1957 (29)

Entangling via gravity



Entangling time:

$$t_{ent} = \frac{2\hbar}{GM^2} R^3 \left(\frac{1}{x_0}\right)^2$$

Pino et al., arXiv:1603.01553

Note: **dynamical potential landscape** allows for significantly smaller masses (Pino 2016: **2 μm**)

Example: For 2 **lead spheres** of **diame**… **superposition size for sphere 1** of **Δr = 5×10^{-7} m** and p… of **sphere 2** in a **motional ground state** (100 Hz trap frequency) with **Δx$_0$=10^{-15} m**, we obtain **Γ$_{ent}$=1.5 Hz**, i.e. **gravitational entanglement** is established on a **second time scale**.

$$\Gamma_{ent} = \left(\frac{GM}{\hbar}\right) \Delta r \rho \Delta x_0$$

An ultimate experiment? Entanglement by gravity…

Beam

FEYNMAN: "Therefo
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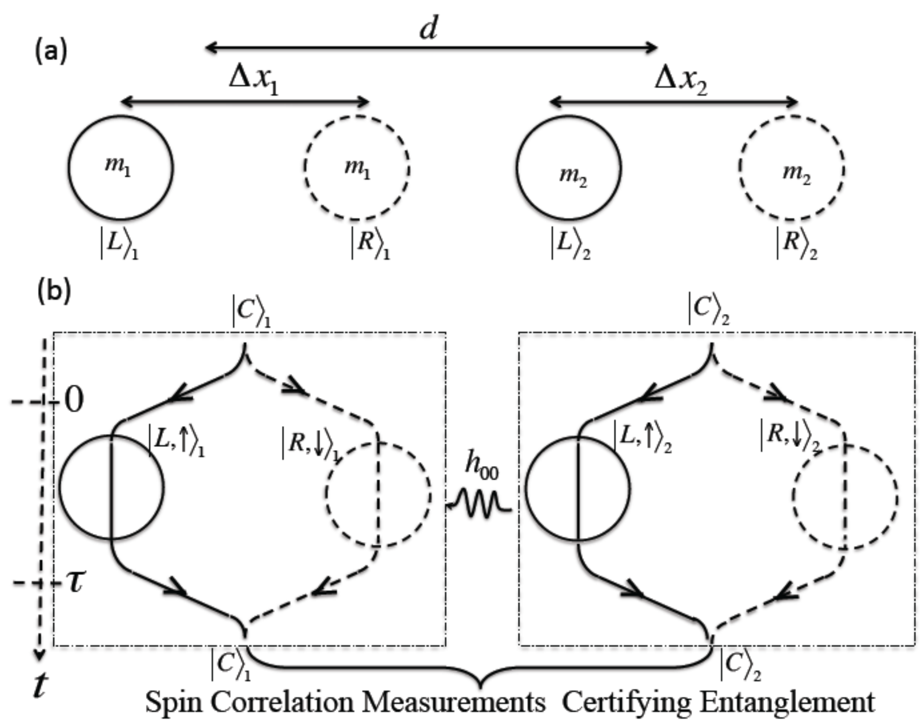
ics up to any level then you have to believe in gravitational quantization
in order to describe this …"

…el Hill Conference 1957 (29)

Refined proposal by *Bose, Kim, Milburn et al. 2017*:
Entanglement by gravitational phase shift (COW) and CSIGN gate

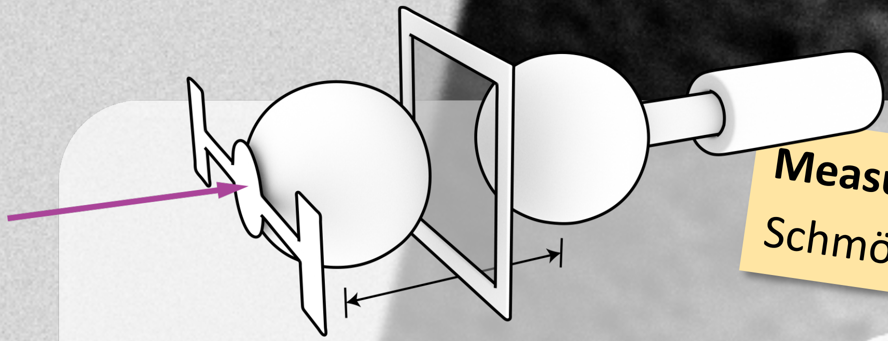


Bose et al., PRL 119, 240401 (2017)

Note: **dynamical potential landscape** allows for significantly smaller masses (*Pino 2016*: **2 μm**)

Example: For 2 **lead spheres** of diame… **superposition size for sphere 1** of **Δr = 5×10⁻⁷ m** and … of **sphere 2** in a **motional ground state** (100 Hz trap frequency) with **Δx_0=10^{-15} m**, we obtain **Γ_{ent}=1.5 Hz**, i.e. **gravitational entanglement** is established on a **second time scale**.

$$\Gamma_{ent} = \left(\frac{GM}{\hbar}\right) \Delta r \rho \Delta x_0$$

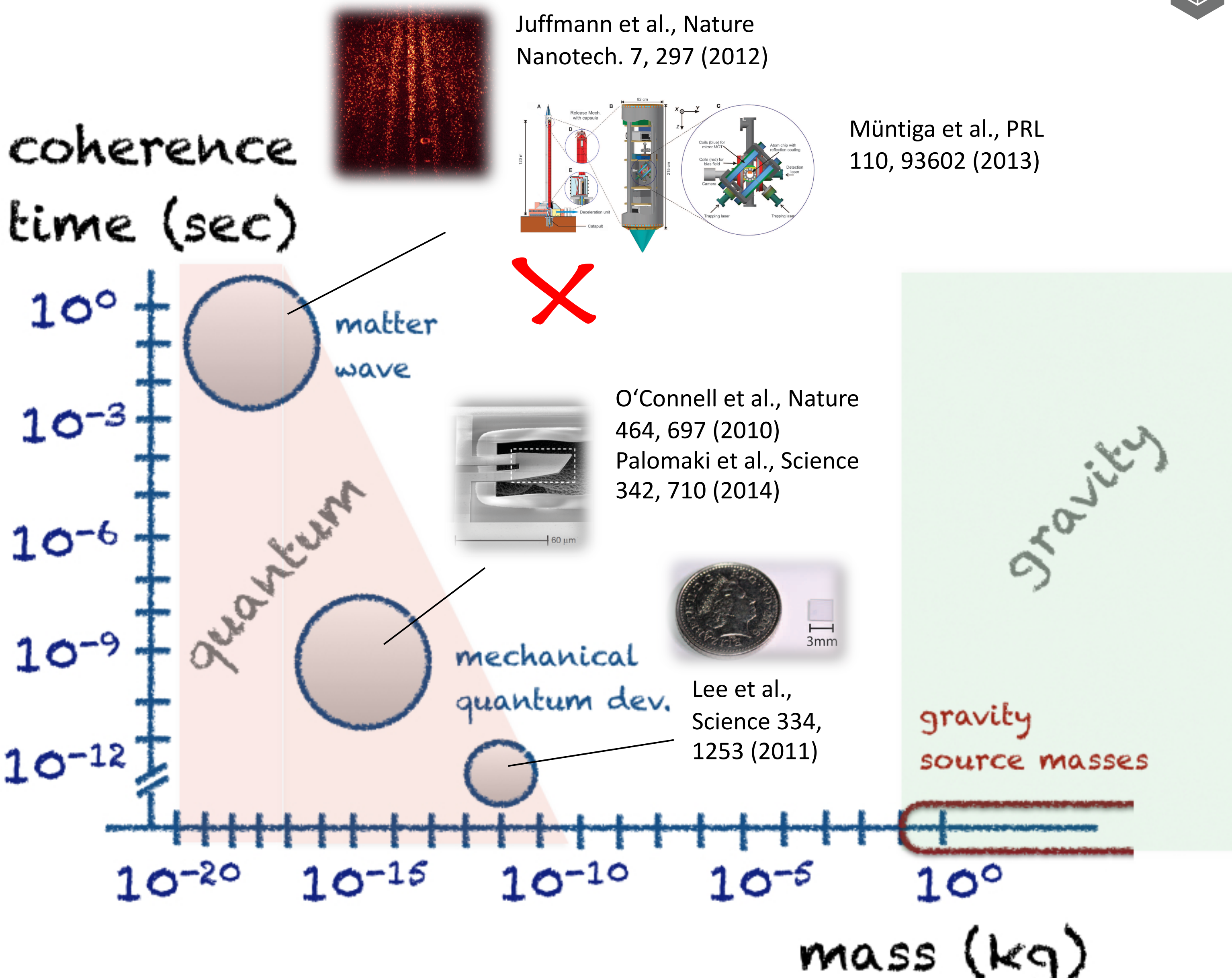


Measuring the gravitational force of milligram masses
Schmöle et al., *Class. Quant. Grav.* **33**, 125031 (2016)

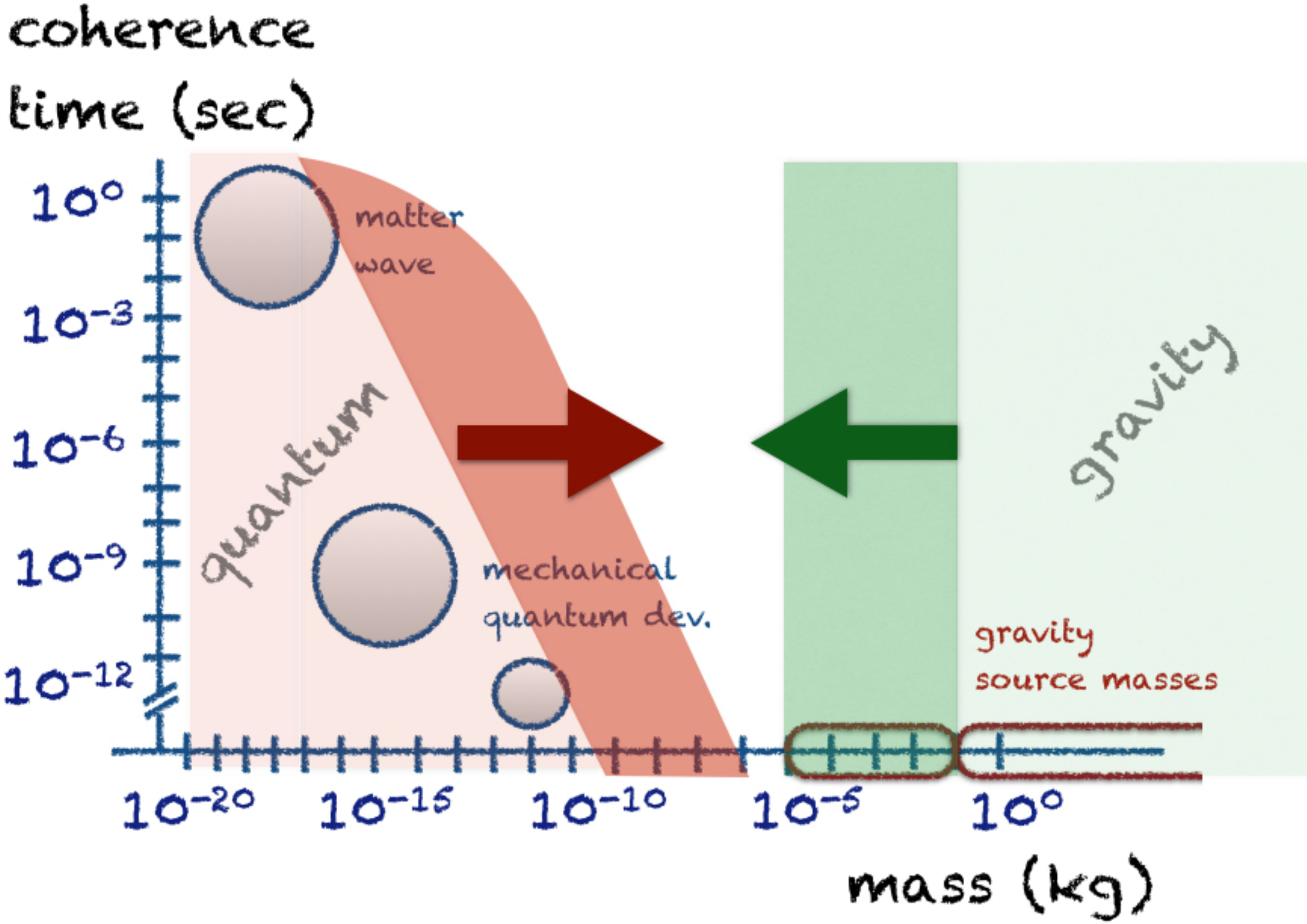
- **How small can a source mass be?**
- **How massive can a quantum system be?**

20µm

How massive/small can we go?



How massive/small can we go?



COM superposition states of massive systems: where do we stand?

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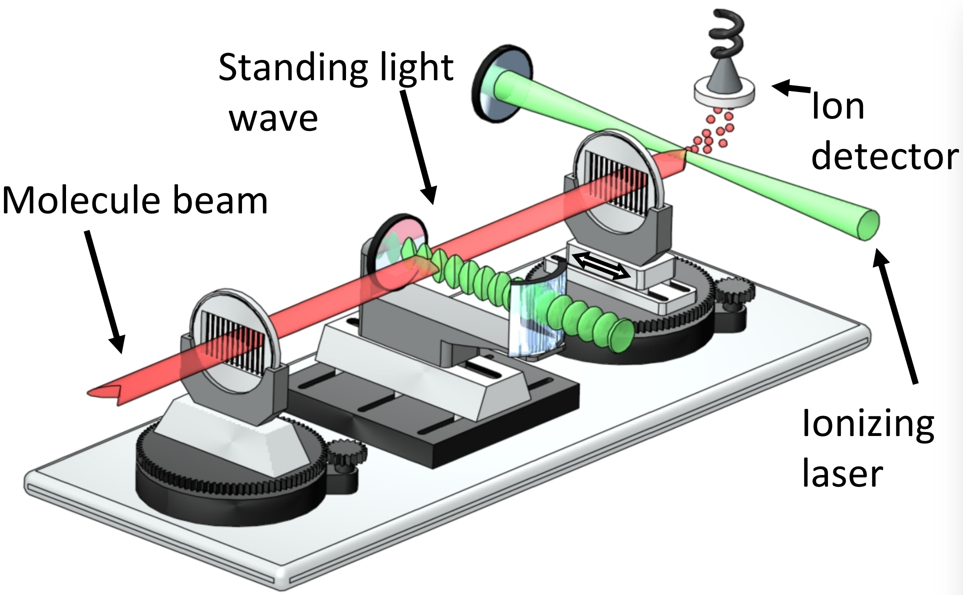
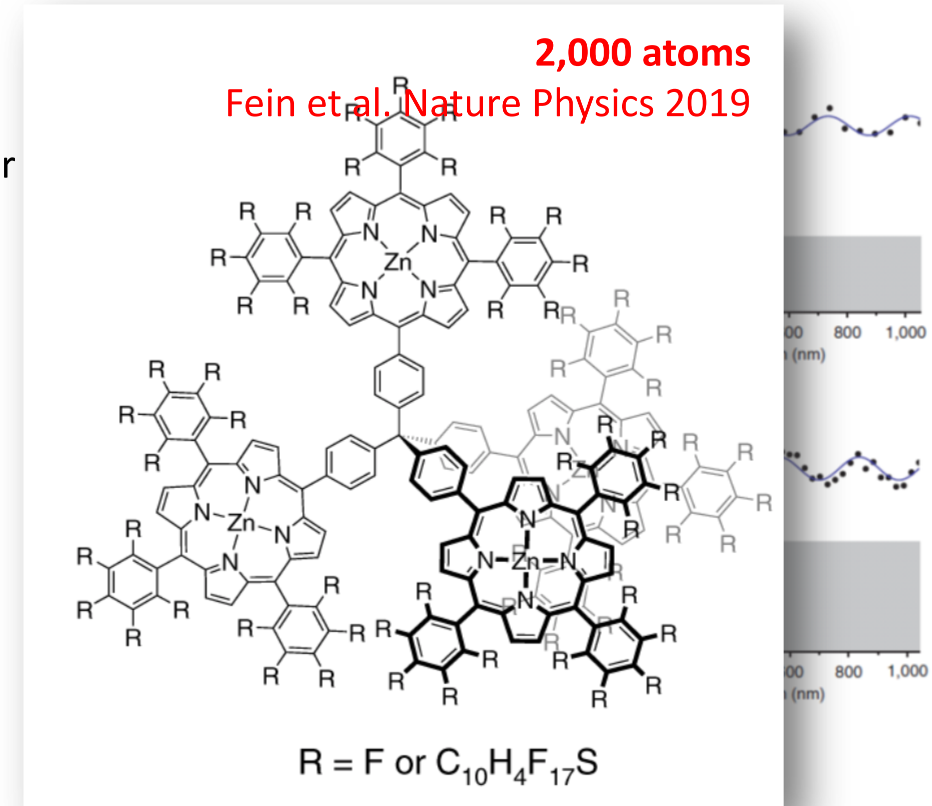
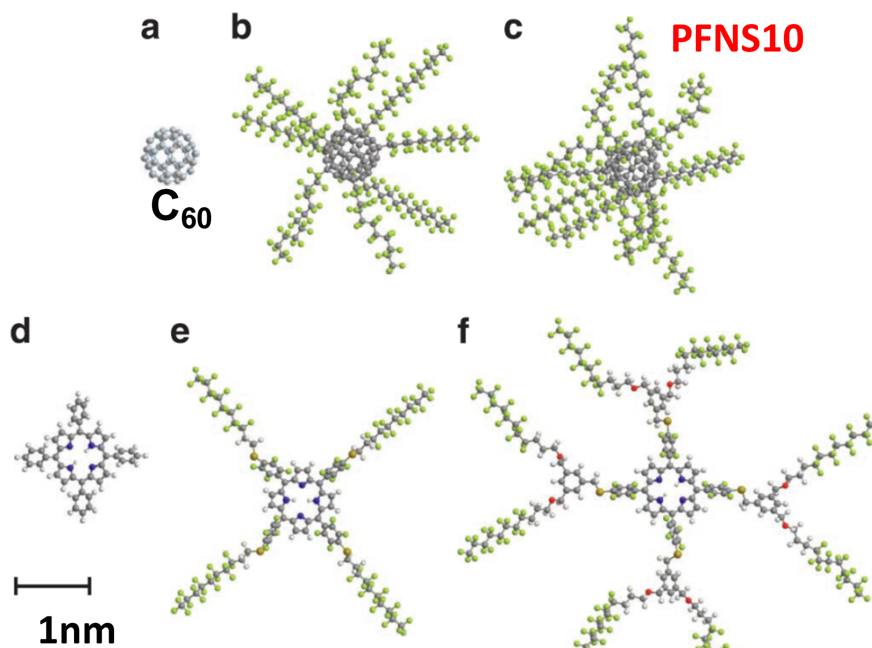
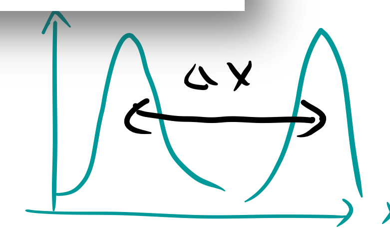






PFNS10: $C_{60}[C_{12}F_{25}]_{10}$
(perfluoroalkylated nanosphere)
430 atoms
m ~ 10^{-23} kg = 6910 AMU
Δx ~ 100 nm (~50x its diameter)



Arndt group (Vienna): S. Gerlich, S. Eibenberger et al., Nature Communications **2**, 263 (2011)

COM superposition states of massive systems: where do we stand?

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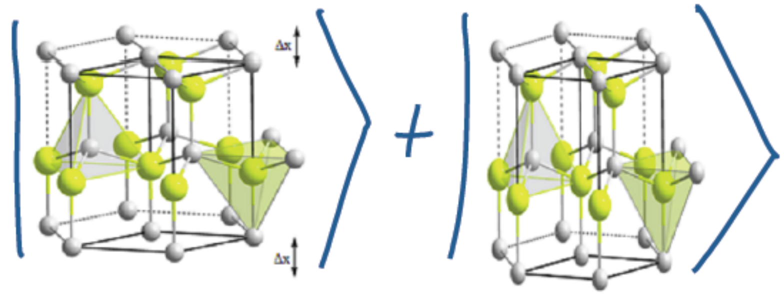
Micromechanics, 2×10^{13} atoms

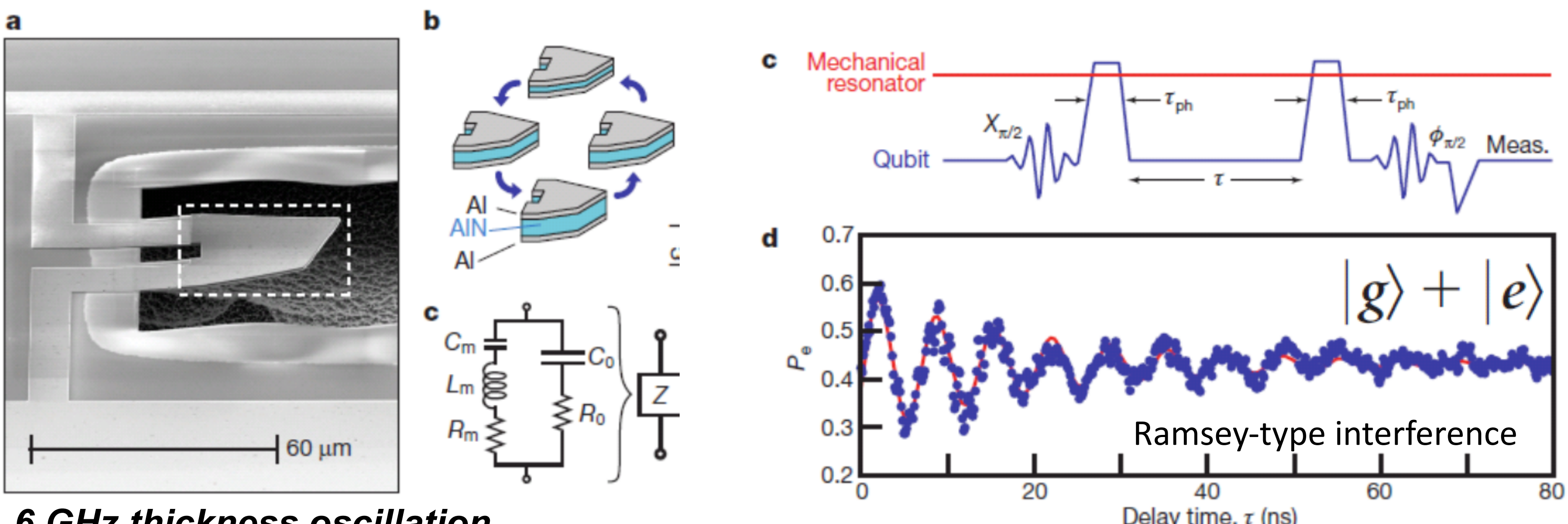
m ~ 10^{-12} kg = 7×10^{14} AMU

Δx ~ 10^{-16} m (~10^{-10}x its diameter)



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]

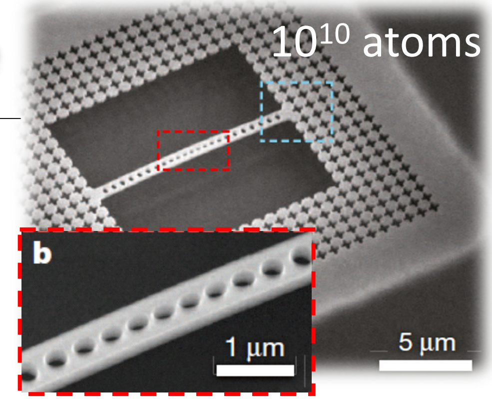


6 GHz thickness oscillation

→ n ~ 0.07 @ 20 mK

Note: E_g-E_e = $h*f_m$ ≈ 20µeV

Mechanical Systems IN the quantum regime



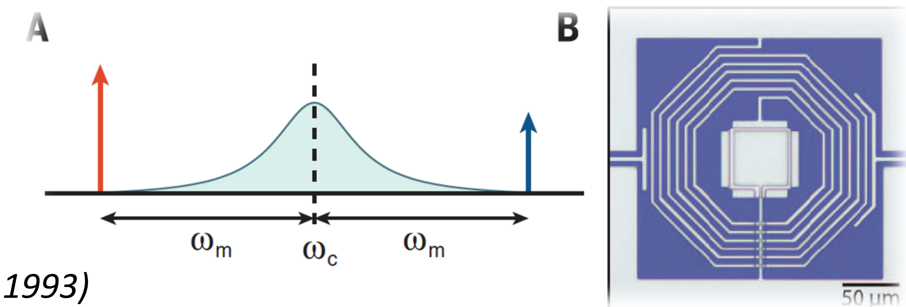
Quantum ground state of motion

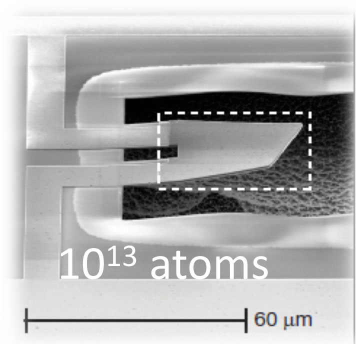
Microwave cavity cooling: Teufel et al., Nature 475, 359 (2011)
Laser cooling: Chan et al., Nature 478, 89 (2011)
... and many more around the world...

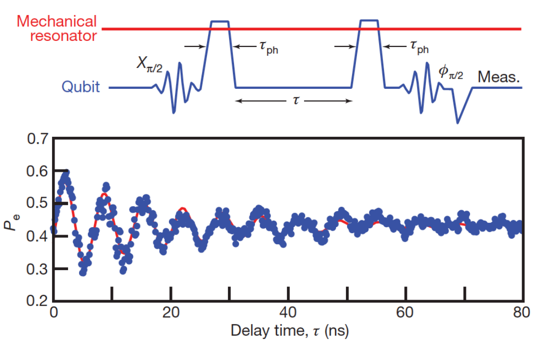
Quantum squeezed states of motion

Wollman et al., Science 349, 952 (2015)
J.-M. Pirkkalainen et al., PRL 115, 243601 (2015)
F. Lecocq et al., PRX 5, 041037 (2015)

„reservoir engineering“
(see also Cirac et al. PRL 70, 556 1993)

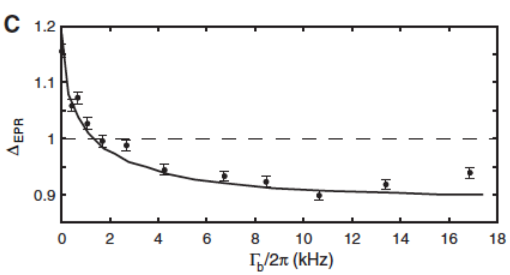


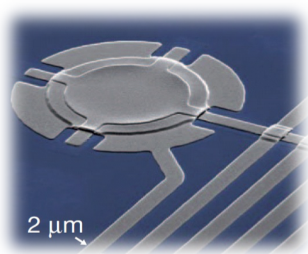




Non-Gaussian quantum states of motion

Phonon control through superconducting qubit:
O'Connell et al., Nature 464, 697 (2010)
Photon-phonon correlations:
Riedinger, Hong et al., Nature 530, 313 (2016)





Quantum entanglement

EPR-type entanglement (MW):
Palomaki et al., Science 342, 710 (2013)
Bell-type entanglement (optical):
Lee et al., Science 334, 1253 (2011)
Riedinger et al., Nature 556, 473 (2018)

Pushing mechanical quantum control to the next level

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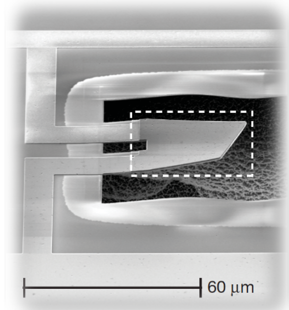
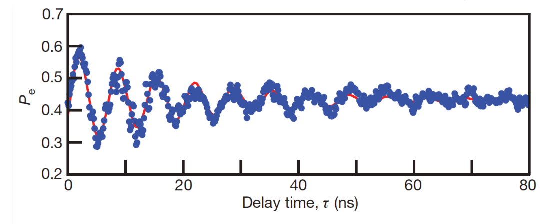
Q: How to achieve large mass **AND** long coherence time in a quantum experiment?

Solid-state mechanical quantum devices (clamped):

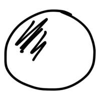
10^{10} – 10^{16} atoms

Coherence time τ_c 10^{-12} – 10^{-8} sec





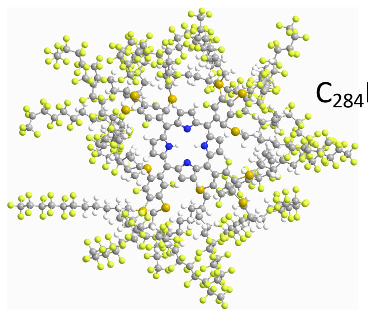
O'Connell et al., Nature 464, 697 (2010)



Matter-wave interferometry (free-fall):

10^0 – 10^4 atoms

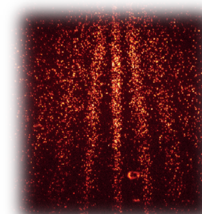
Coherence time τ_c 10^{-3} – 10^0 sec



10 nm

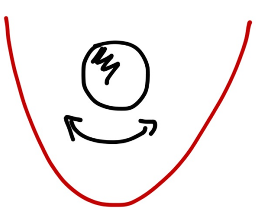
TPPF320

$C_{284}H_{190}F_{320}N_4S_{12}$



Juffmann et al., Nature Nanotech. 7, 297 (2012)

A: Quantum control of levitated mechanical systems!



- Quantum control of a trapped massive object >> 10^{10} atoms
- Long coherence times (up to seconds)
- Exceptional force sensitivity
- Externally **engineerable (and controllable) arbitrary potential landscape**

Optically levitating nanoparticles

OPTICAL LEVITATION:

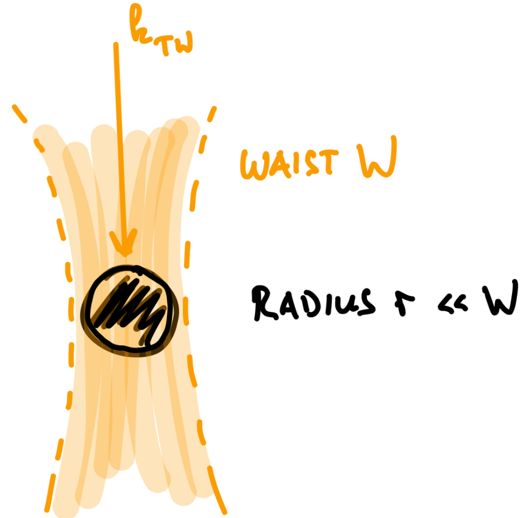
$$\hat{H} \propto \underline{d} \cdot \underline{E} = \alpha \cdot E^2$$

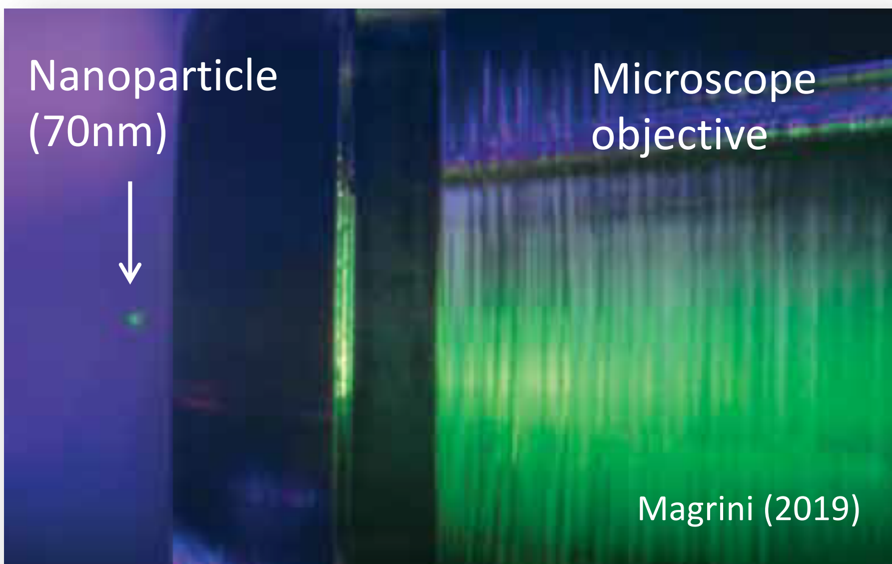
α: Re{Polarizability}

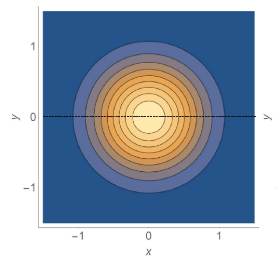
E: optical trapping field

↳ beam intensity

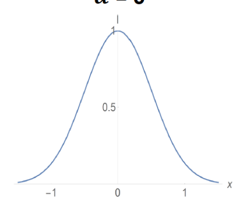
→ GRADIENT FORCE $F \propto (\nabla E^2) \cdot \alpha$



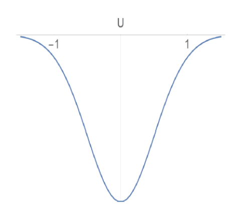




$\alpha = 0$



intensity



potential

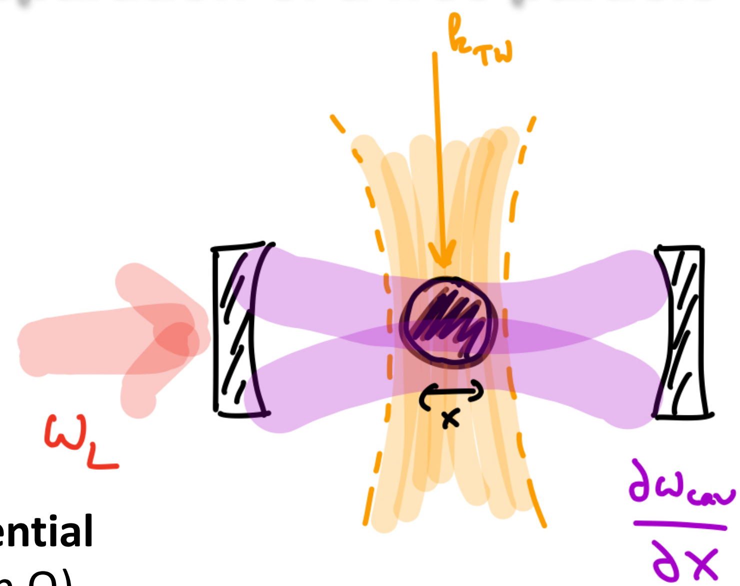
Pioneering work by Ashkin:

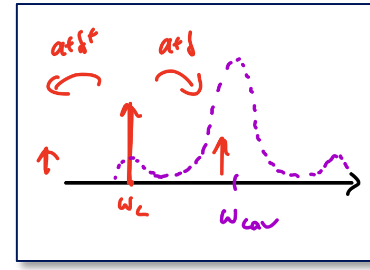
A. Ashkin, PRL 24, 156 (1970).

A. Ashkin, J. M. Dziedzic, APL 28, 333 (1976).

Towards quantum state preparation of a free particle

Chang et al., PNAS 2010
Romero-Isart et al., NJP 2010
P. F. Barker et al., PRA 2010
early work:
Hechenblaikner, Ritsch et al., PRA 58, 3030 (1998)
Vuletic & Chu, PRL 84, 3787 (2000)





→ **Harmonic oscillator in optical potential**
(negligible support loss, high Q)

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

OPTOMECHANICS:

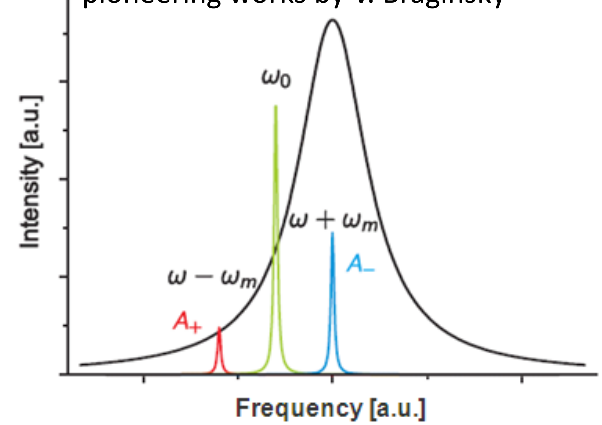
$$\hat{H}_{int} \propto \alpha \cdot E_{cav}^2 = \hbar g_0 \hat{a}^\dagger \hat{a} (b + b^\dagger)$$

cavity, mechanics

with $g_0 = \frac{\partial \omega_c}{\partial x} = \frac{\alpha}{V_c} \frac{\omega_c^2}{c \varepsilon_0} x_{zp}$

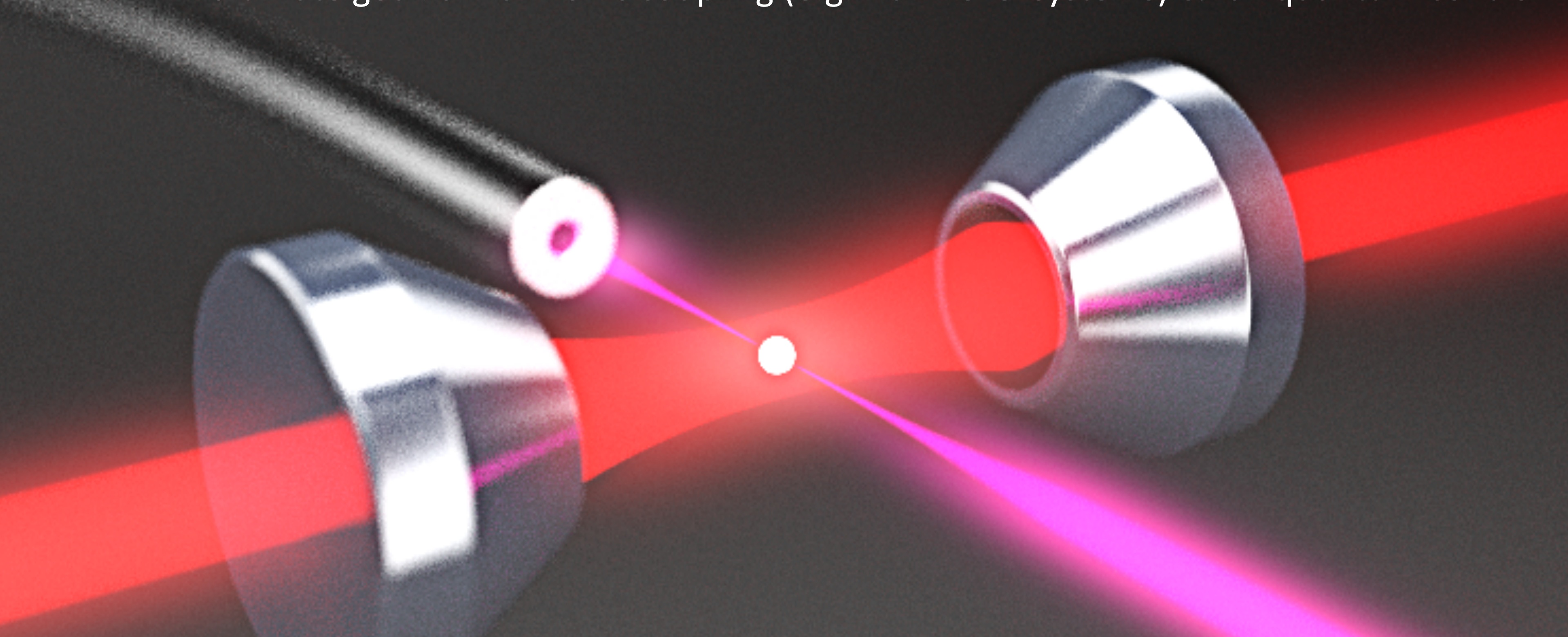
α: Re{polarizability}
V_c: cavity mode volume
x_{zp}: zero-point motion

Cavity-Optomechanics
Rev.Mod.Phys. 86, 1391 (2014)
pioneering works by V. Braginsky



Cavity control of levitated particles

- dielectrics and superconductors (100nm – 10um)
- ultimate goal: anharmonic coupling (e.g. via 2-level systems) & full quantum control



Grass et al., Appl. Phys. Lett. 108, 221103 (2016): optical control in hollow-core fibres
Kiesel et al., PNAS 110, 14180 (2013): cavity cooling of levitated particles
Magrini et al., Optica 5, 1597 (2018): near-field coupling to photonic crystal cavity
Delic et al., PRL 122, 123602 (2019): cavity cooling via coherent scattering

Cavity control of levitated particles

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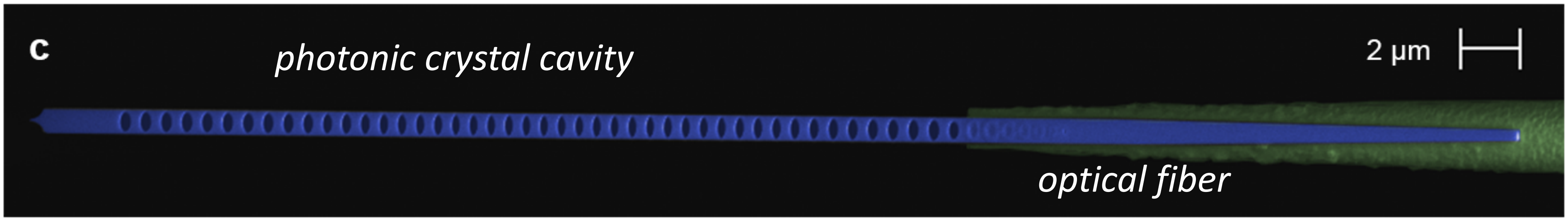

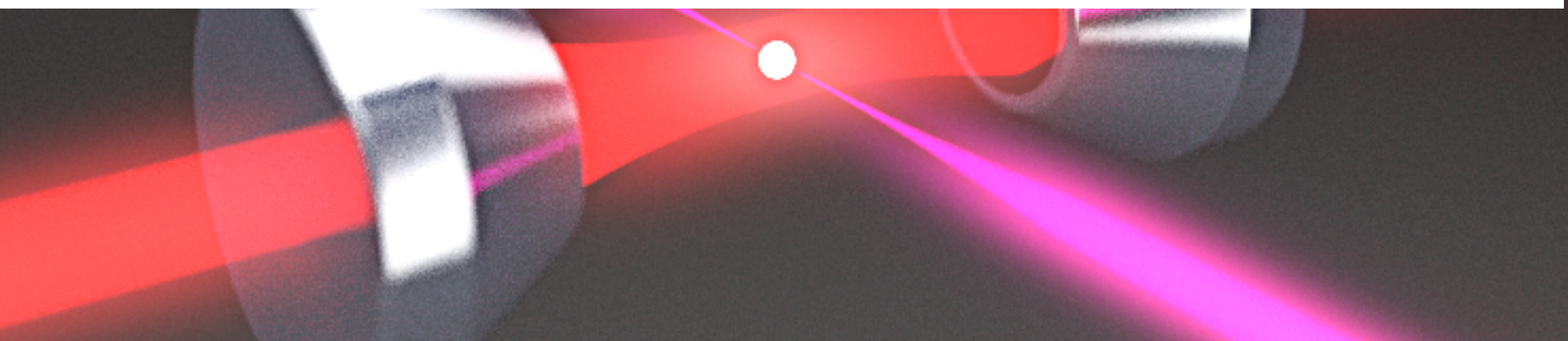

Grass et al., Appl. Phys. Lett. 108, 221103 (2016): optical control in hollow-core fibres
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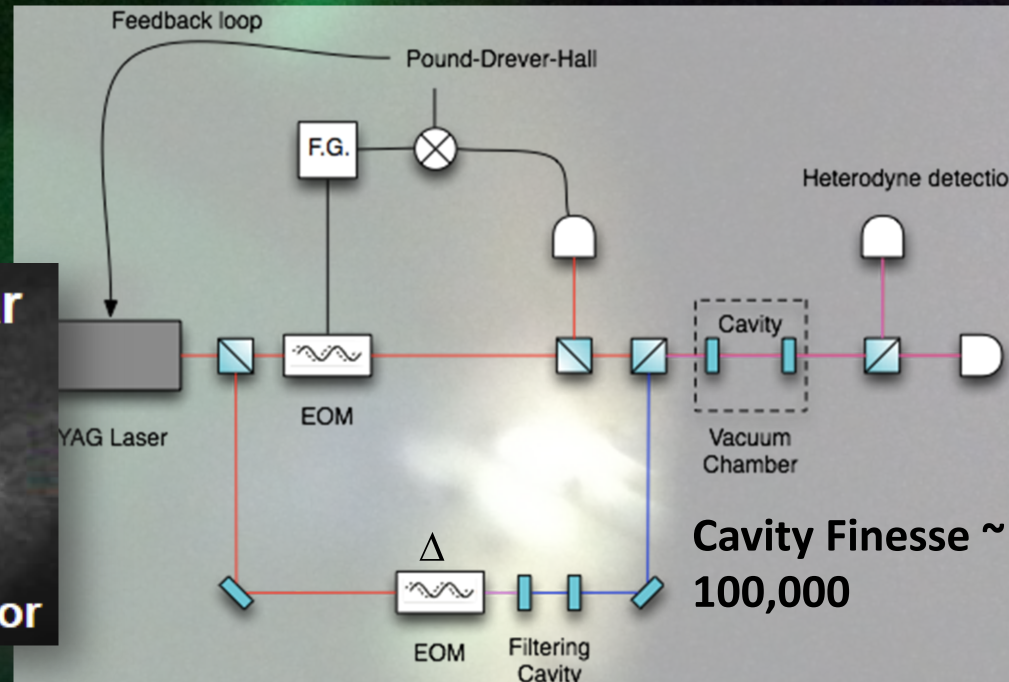
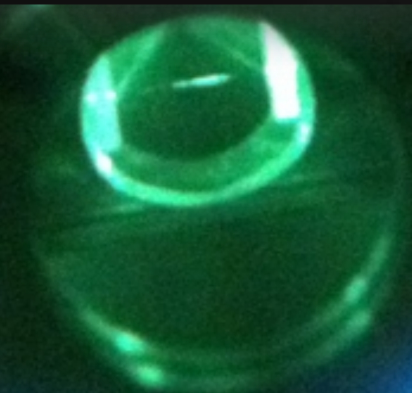
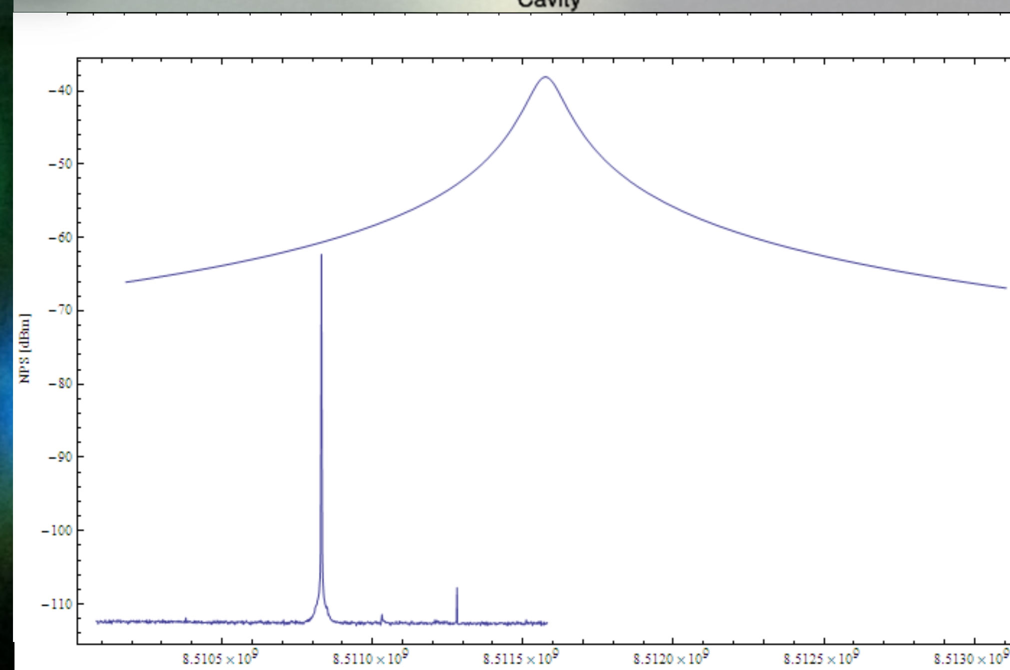
Cavity Optomechanics with levitated nanoparticles

Ashkin since 1967
Raizen group, Science 2010
Novotny, Quidan 2012
Barker group 2014
Geraci group 2015







Optical trapping and cavity cooling (R~200nm)
Kiesel, Delic, Grass et al., PNAS USA 110, 14180 (2013)

Cavity Optomechanics with levitated nanoparticles

Delić et al., arXiv:1911.04406

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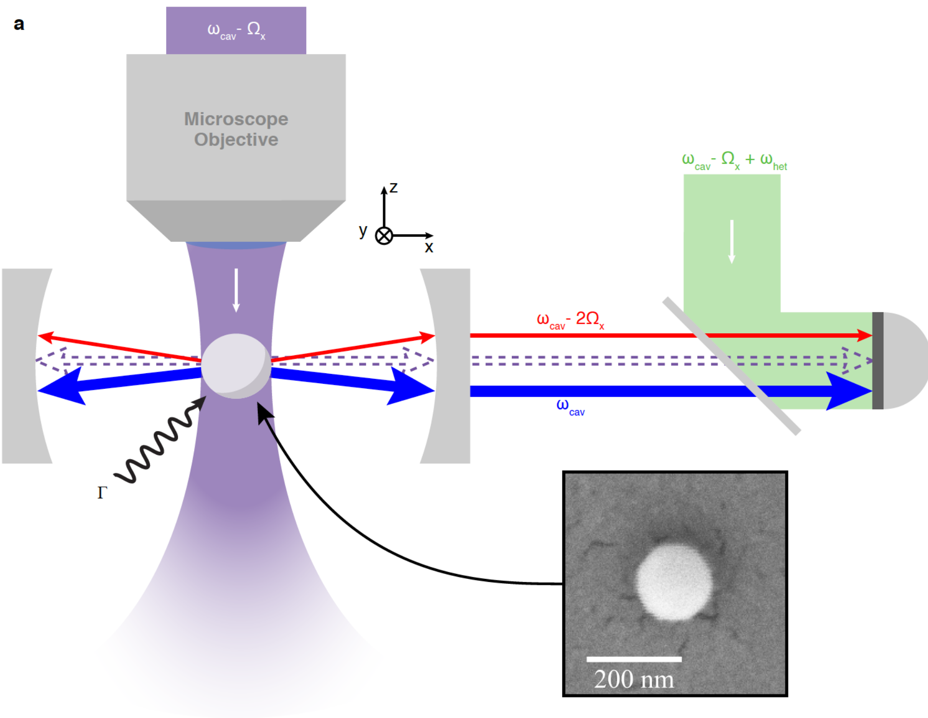
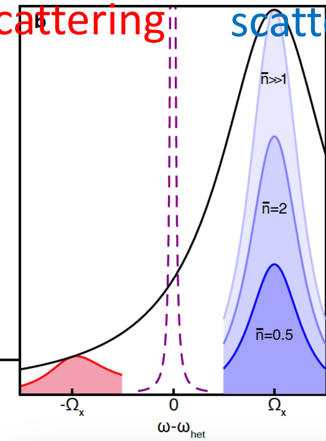
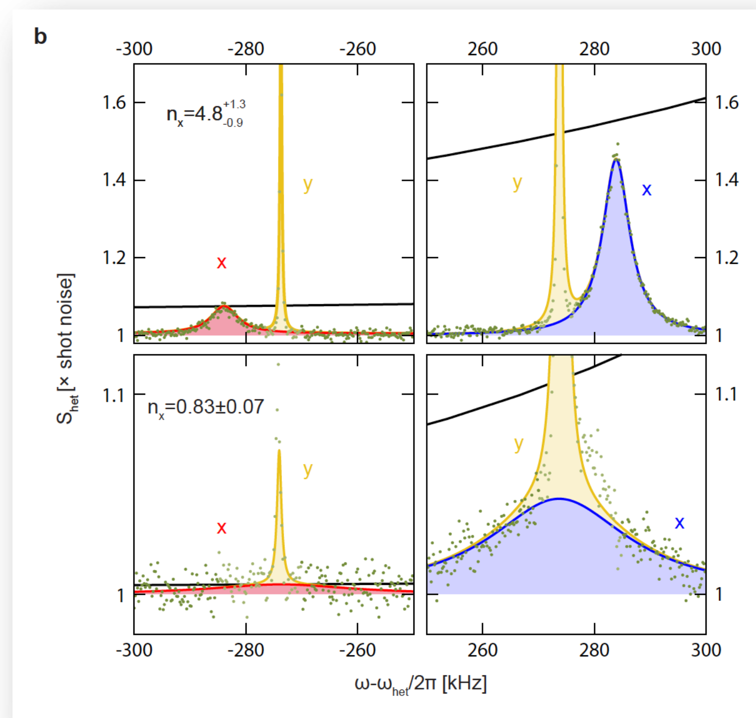
VCQ Vienna Center for Quantum Science and Technology



Stokes scattering **anti-Stokes scattering**





$$\omega_x \approx 2\pi\times 305\ \text{kHz}$$

$$\omega_z \approx 2\pi\times 80\ \text{kHz}$$

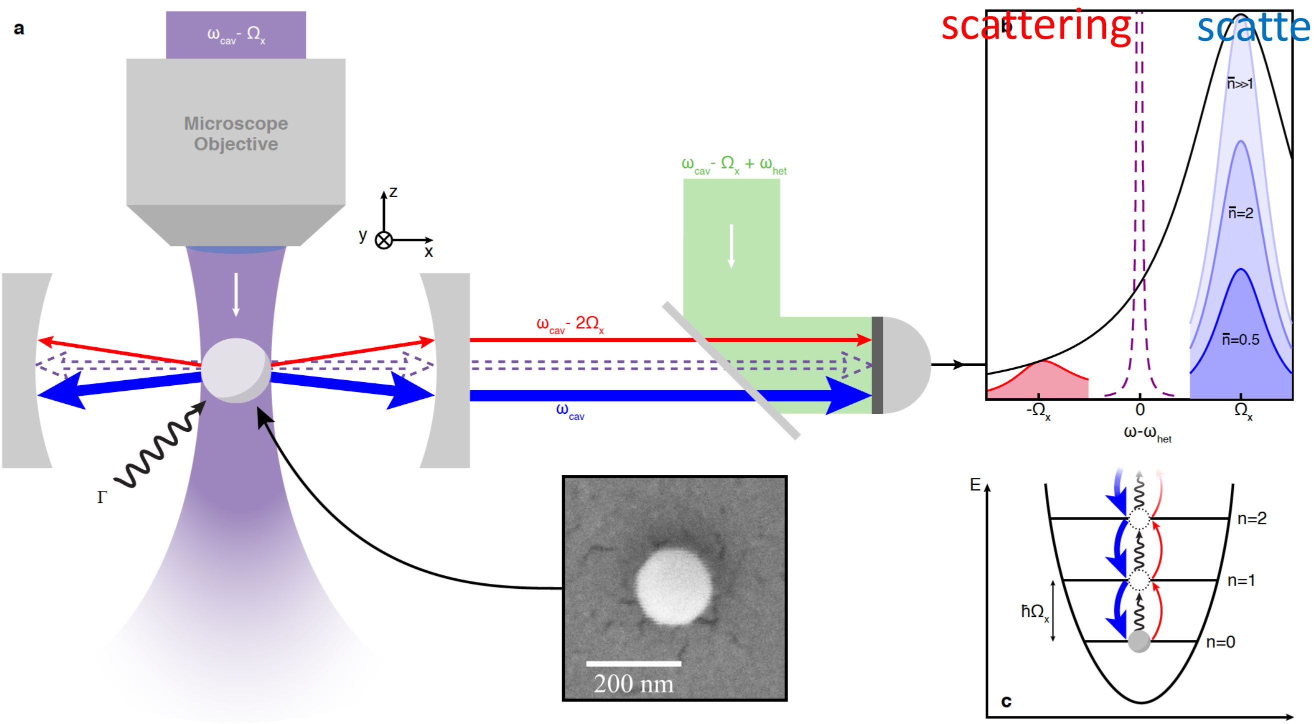
$$\omega_y \approx 2\pi\times 275\ \text{kHz}$$

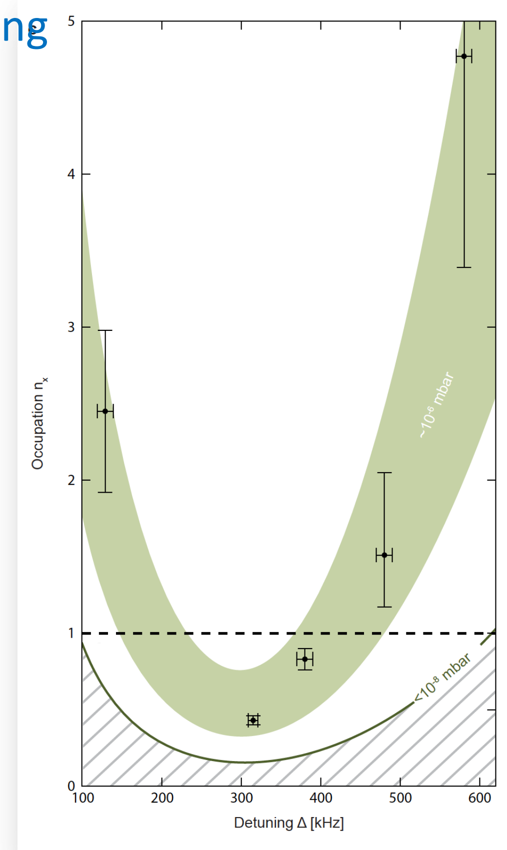
$$\kappa = 2\pi\times 193\ \text{kHz}$$

$$p = 1\text{e-}6\ \text{mbar},\ T = 300\text{K}$$

Cavity Optomechanics with levitated nanoparticles

Delić et al., arXiv:1911.04406





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n_x **< 0.5** (ground state probability **> 2/3**)

Center-of-mass Tc = 12uK; environment Te > 300K

$g_x = 2\pi$ x 71 kHz, Cooperativity C = 5

Cavity Optomechanics with levitated nanoparticles

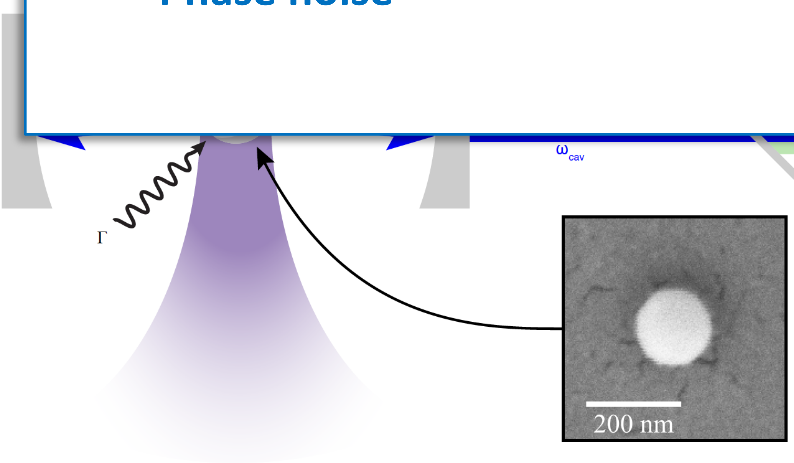
Delić et al., arXiv:1911.04406

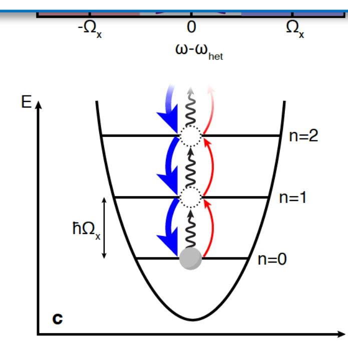
Limitations:

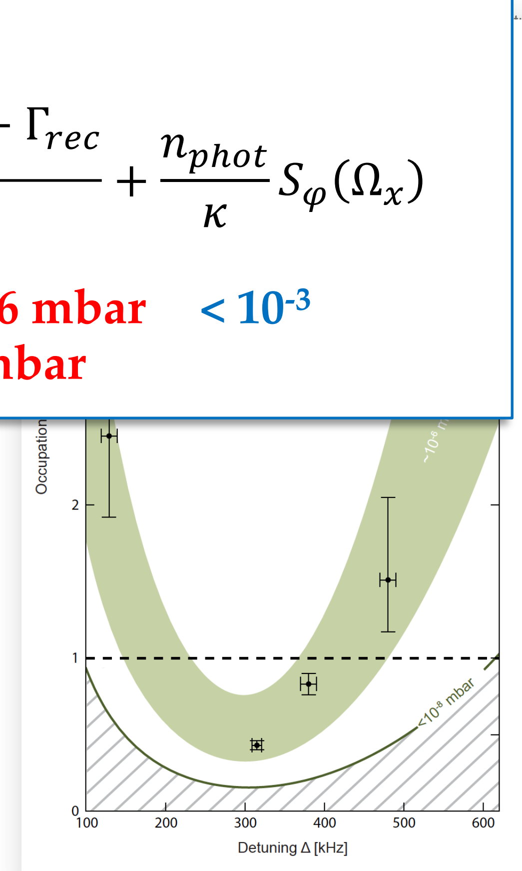
- Sideband resolution
- Gas and recoil scattering
- Phase noise

$$\bar{n} = \left(\frac{\kappa}{4\Omega_x}\right)^2 + \frac{\gamma_g \frac{k_B T_{bath}}{\hbar\Omega_x} + \Gamma_{rec}}{\Gamma_- - \Gamma_+} + \frac{n_{phot}}{\kappa} S_\varphi(\Omega_x)$$

0.026 | $2\text{x}10^5$ @ 0.06 mbar, 0.5 @ 1e-6mbar | $< 10^{-3}$







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Decoherence

Joos & Zeh, Caldeira & Leggett, Unruh & Zurek
Paz & Zurek, Hu & Paz & Zhang, Milburn, …

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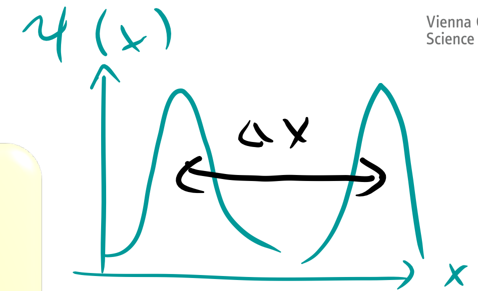
$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + \mathcal{L}[\rho]$$

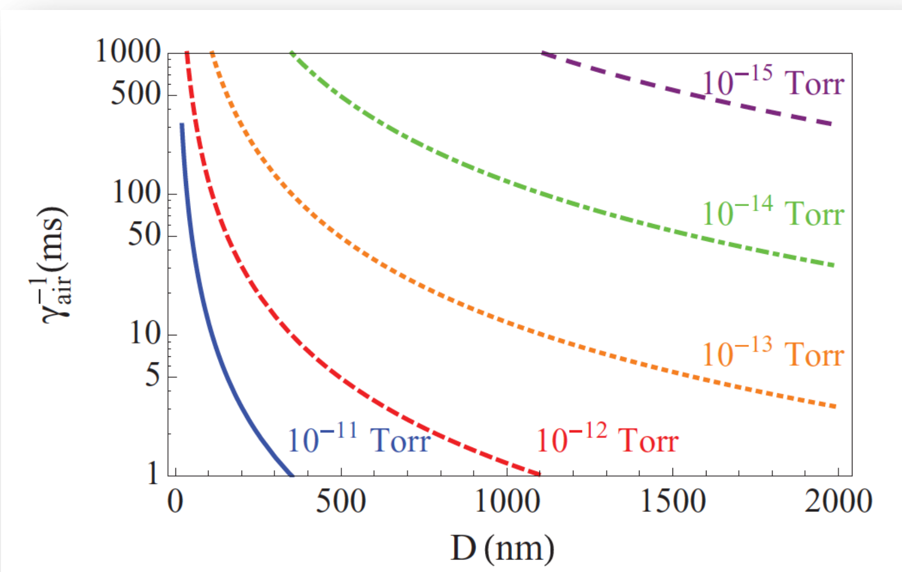
Master equation approach



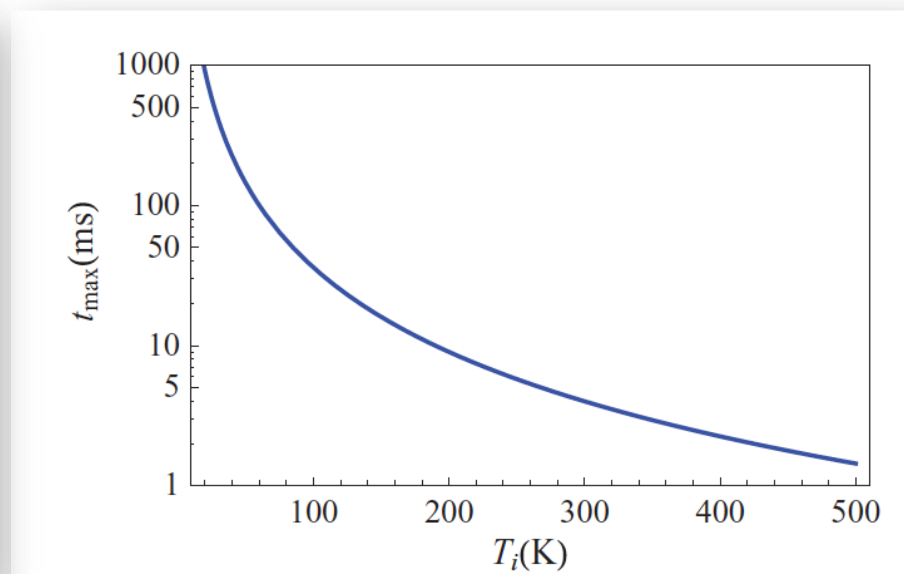
See also
O. Romero-Isart et al., PRL 107, 020405 (2011)
O. Romero-Isart, PRA 84, 052121 (2011)

Example: a free nanoparticle

*Decoherence due to **gas scattering** on a glass sphere (Romero-Isart 2011)*



*Decoherence due to **blackbody absorption** (50 nm sphere)*



Decoherence

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho]$$

In our case (p=1e-6 mbar; Te > 300K): $\Gamma gas/2\pi$ = 15kHz, $\Gamma rec/2\pi$ = 6kHz

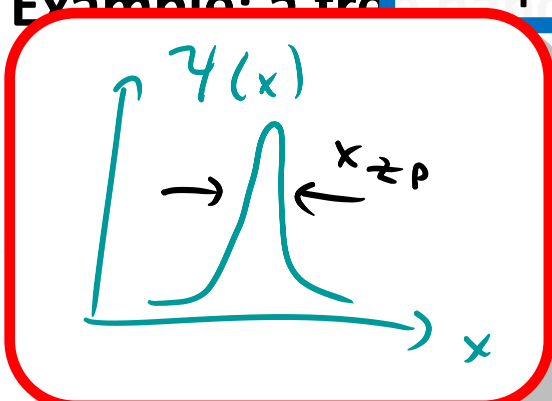
Photon Recoil & Gas Scattering limit **in-trap coherence time** to < 8us
(**15 coherent oscillations**)

Gas Scattering limits **free-fall coherence** time to < 2us
(**wavepacket expansion by factor of 3**: 3pm → 10pm)

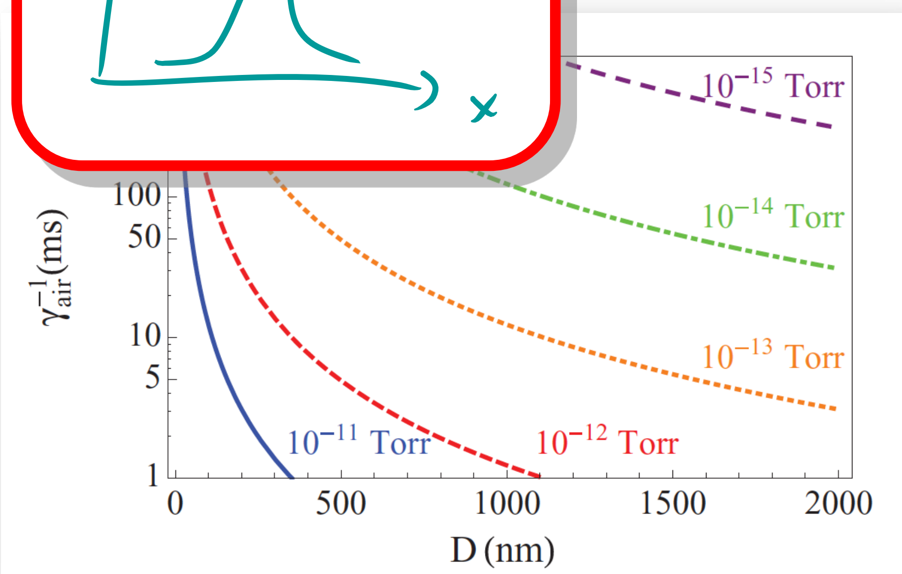
Wavepacket size > particle size will require **p < 1e-11mbar** and **Te < 130K**

84, 052121 (2011)

Example: a fr



...ttering on a ...2011)



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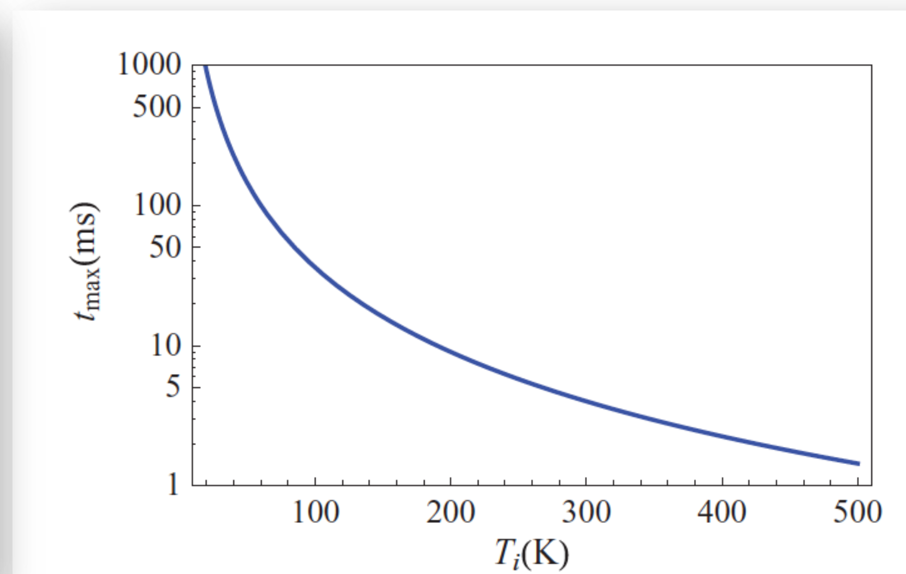
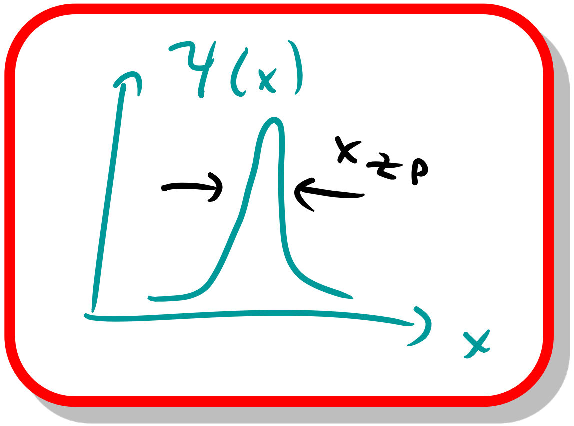
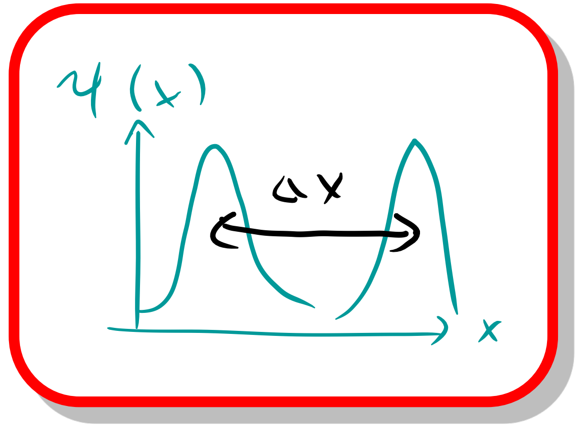
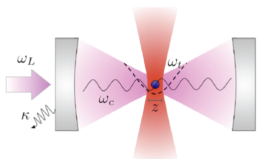


Towards „large“ quantum superposition states



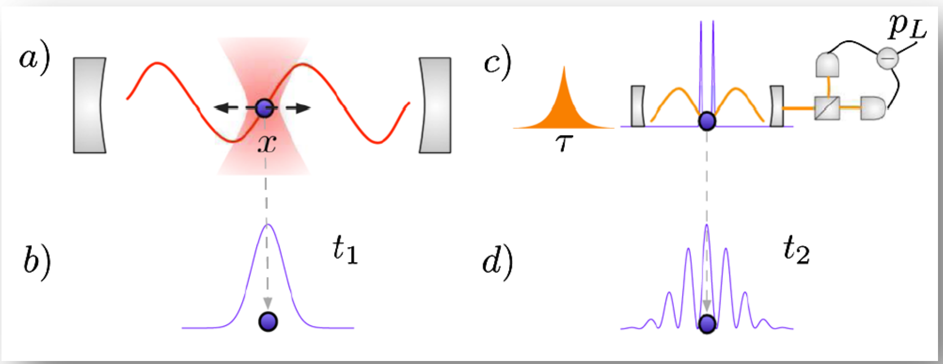


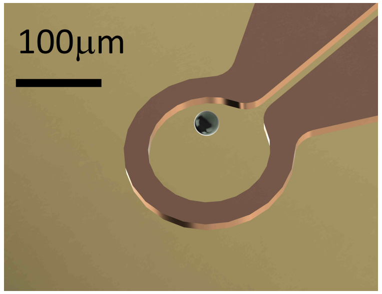
Free-fall + quantum measurement



Optical levitation

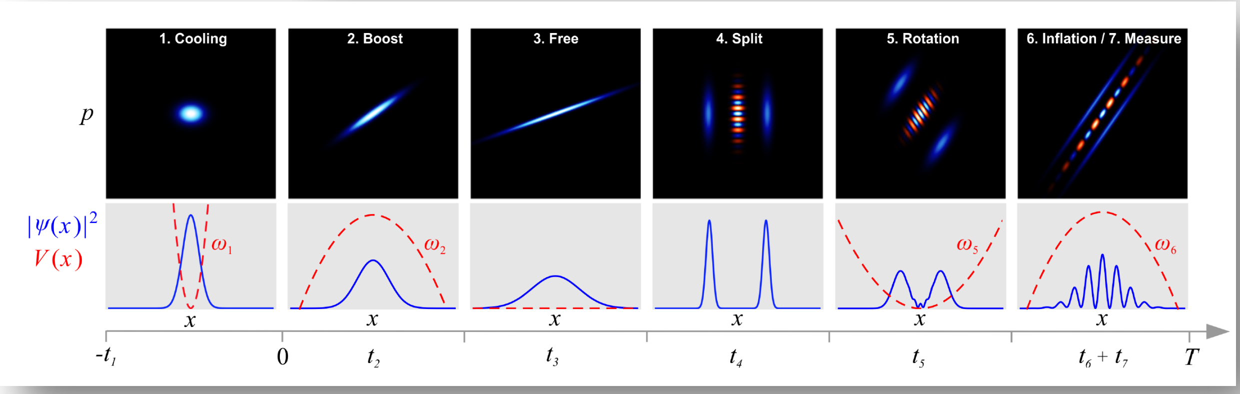
(Romero-Isart 2011)
PRL107, 020405





Superconducting levitation

(Pino 2016) arxiv: 1603.01553



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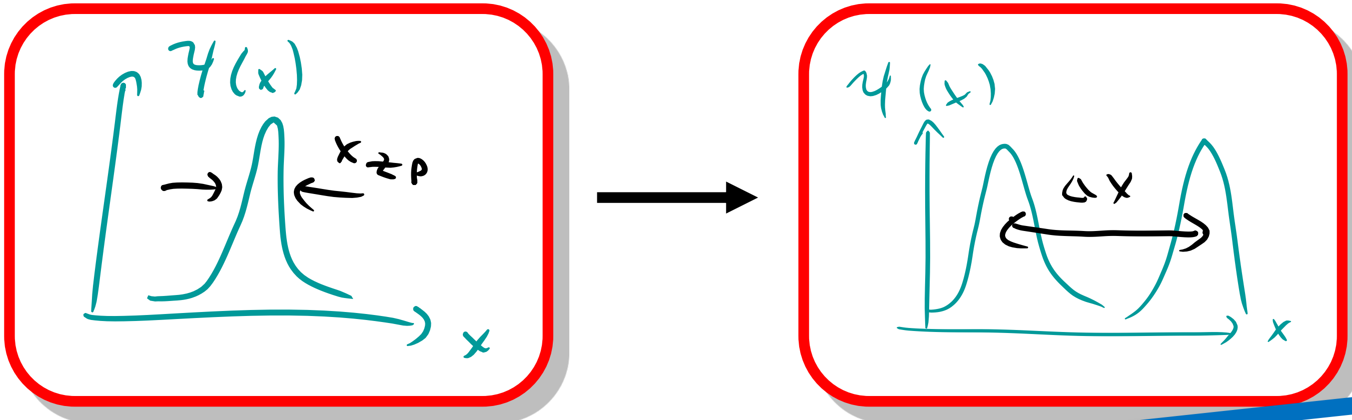

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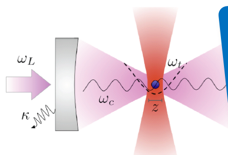
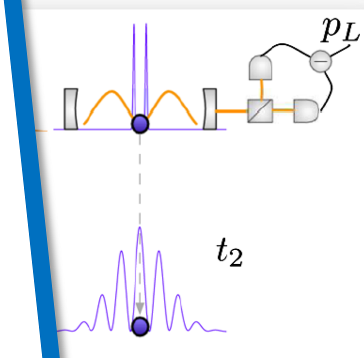
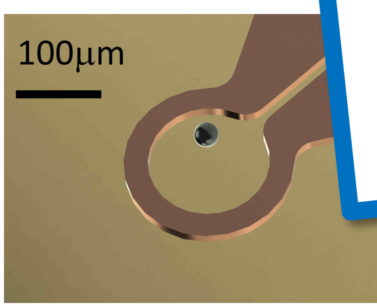
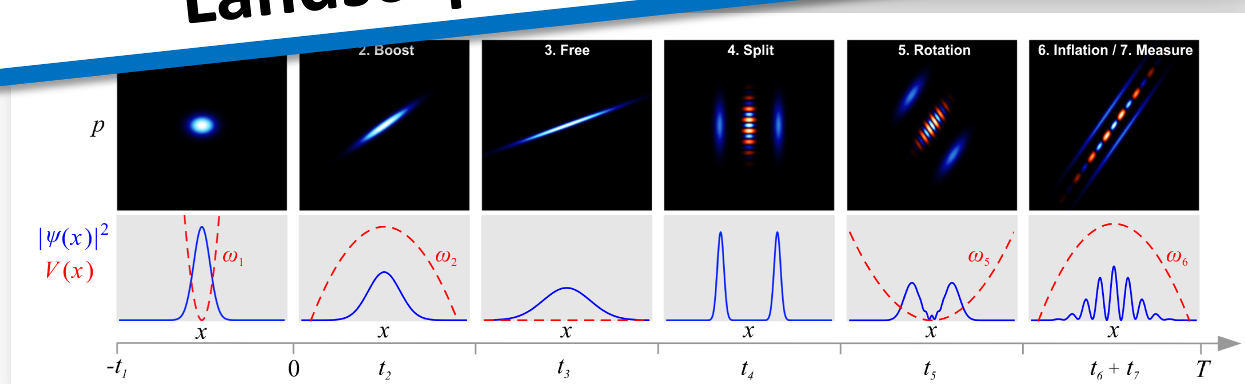




Next Step: Controlling the Potential Landscape



Superconducting levitation



(Pino 2016) arxiv: 1603.01553

Shaping the potential landscape of optical tweezers

OPTICAL LEVITATION:

$\hat{H} \propto \underline{d} \cdot \underline{E} = \alpha \cdot E^2$

α: Re{Polarizability}

E: optical trapping field

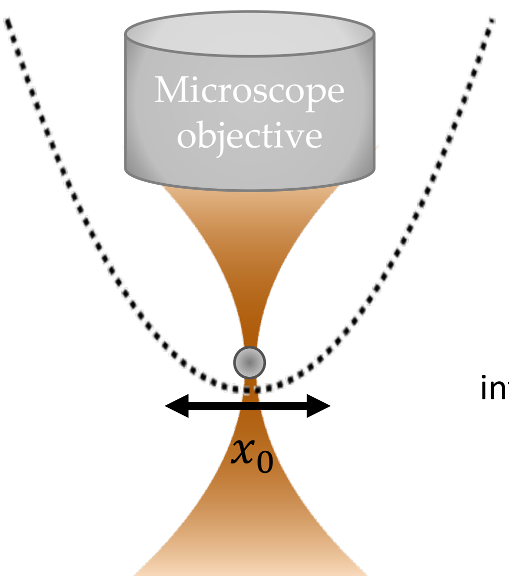
↳ beam intensity

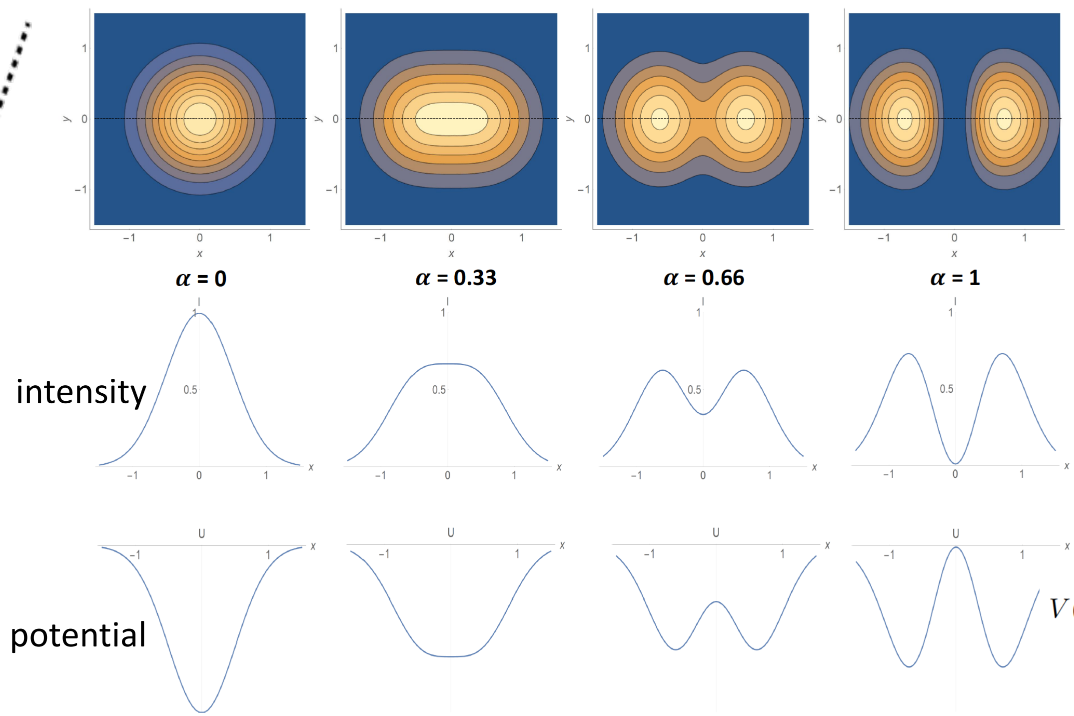
→ GRADIENT FORCE $F \propto (\nabla E^2) \cdot \alpha$

Gaussian TEM00 provides 3D harmonic trap (to first order)

Superposition of TEM00 with TEM01 provides control over potential landscape, e.g. from harmonic to repulsive

Mario Ciampini (Kiesel group)



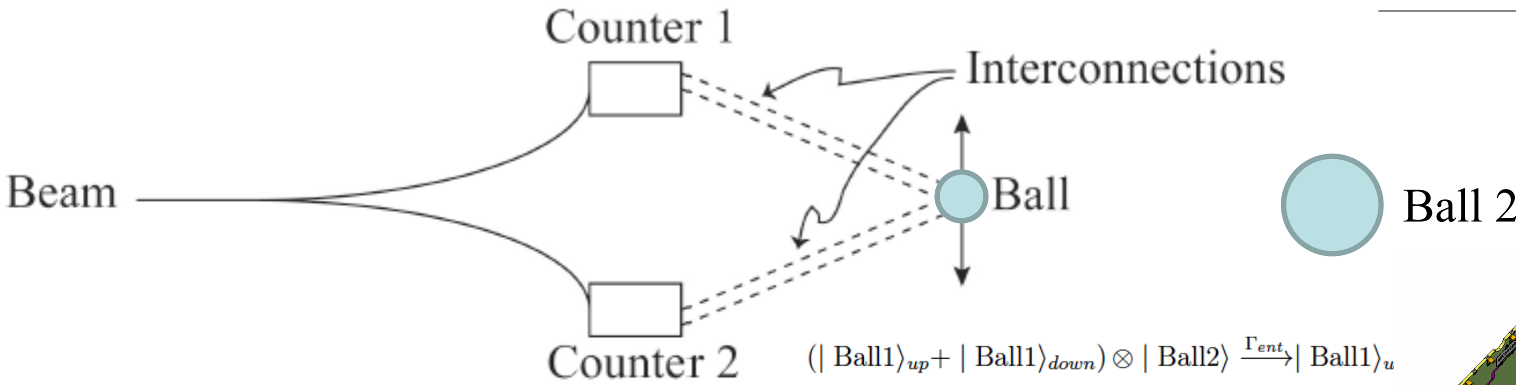


$\alpha TEM_{00}(H) + \beta TEM_{01}(V)$

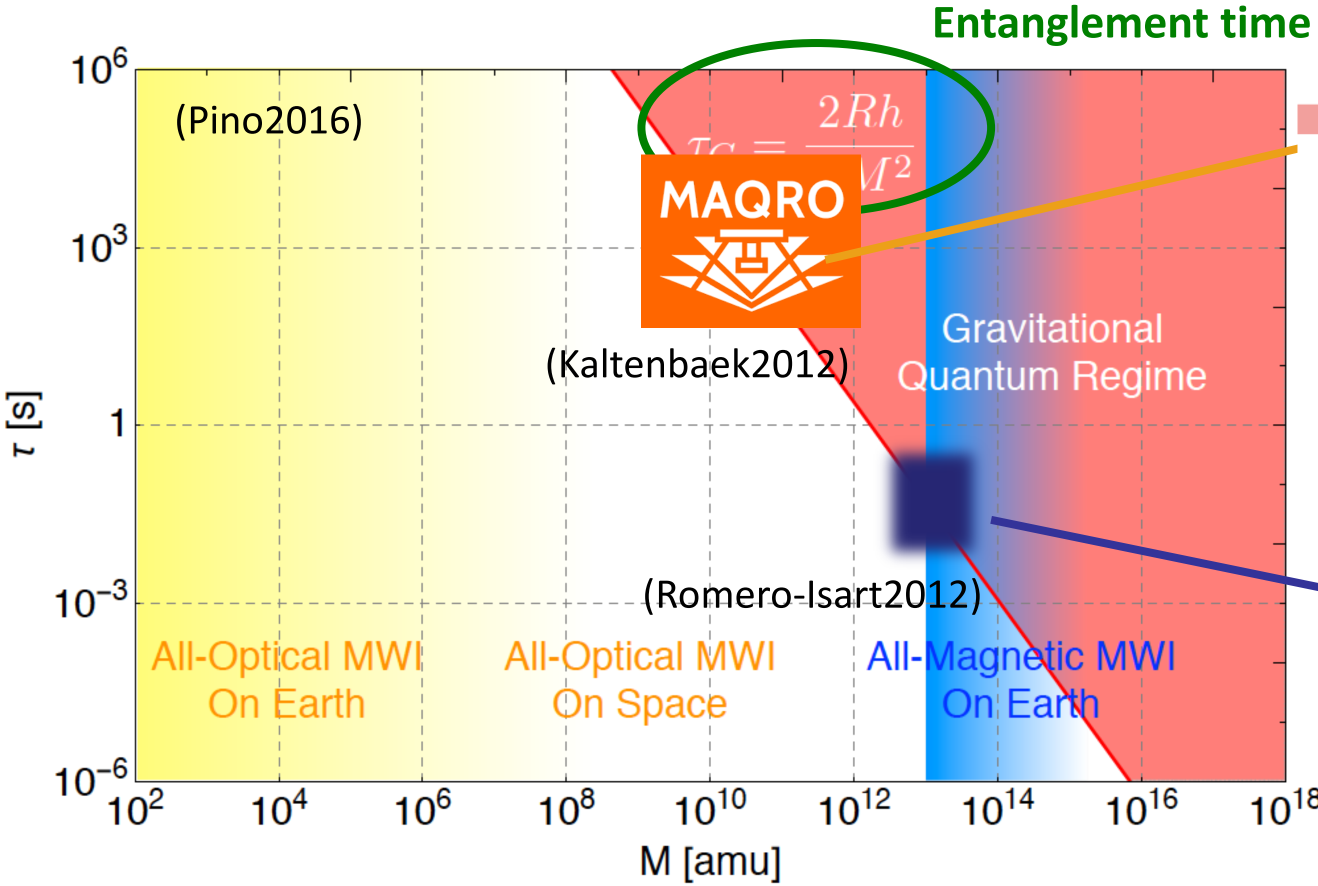
↓

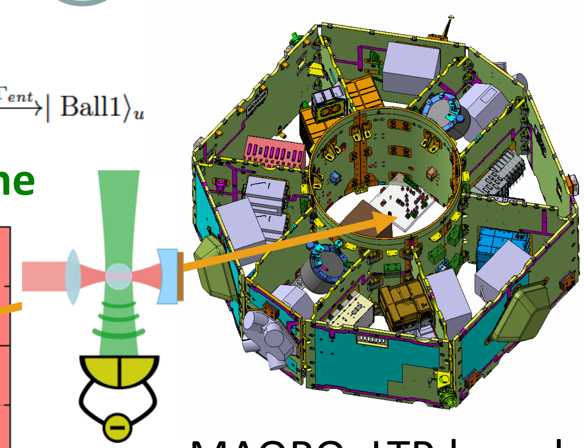
$$V(x,t) = -\left[\alpha + \frac{\beta}{2}x^2\right]\exp\left(\frac{-x^2}{2\omega_0^2}\right)$$

An ultimate experiment? Entanglement by gravity…



$(|\,\mathrm{Ball1}\rangle_{up} + |\,\mathrm{Ball1}\rangle_{down}) \otimes |\,\mathrm{Ball2}\rangle \xrightarrow{\Gamma_{ent}} |\,\mathrm{Ball1}\rangle_{u}$

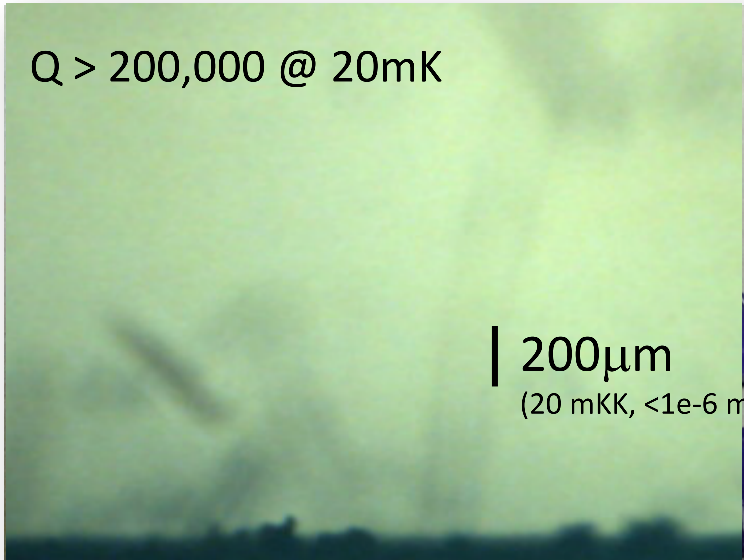


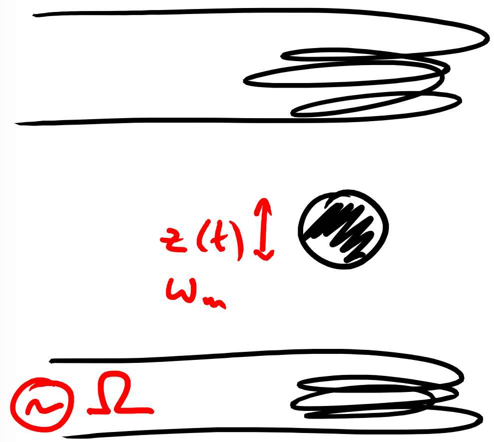


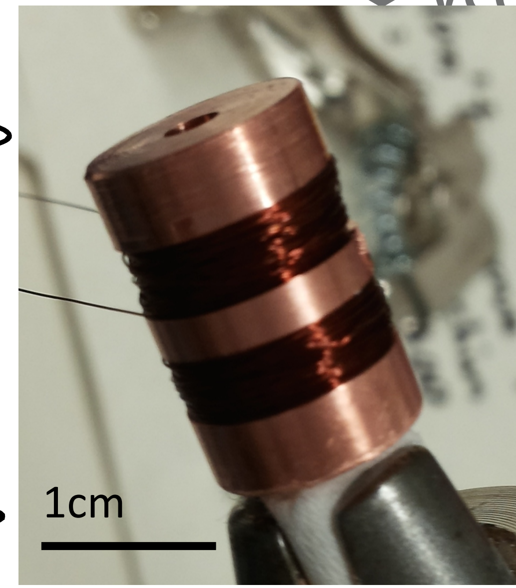
MAQRO: LTP-based satellite mission

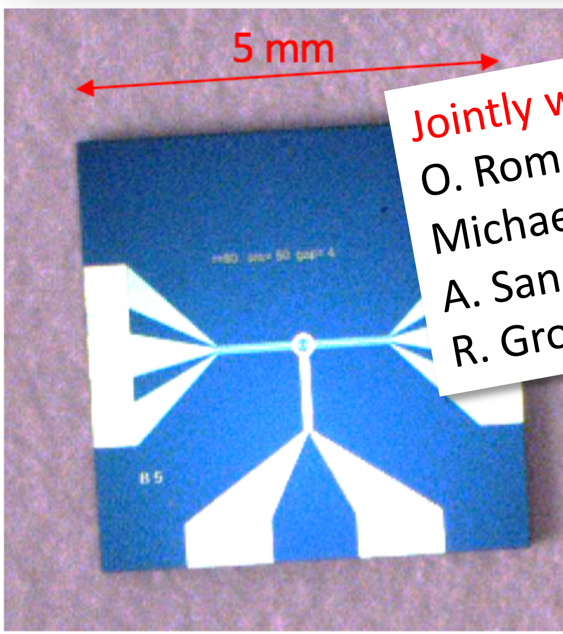
Superconducting levitation

Magnetically trapped superconductors as mechanical resonators







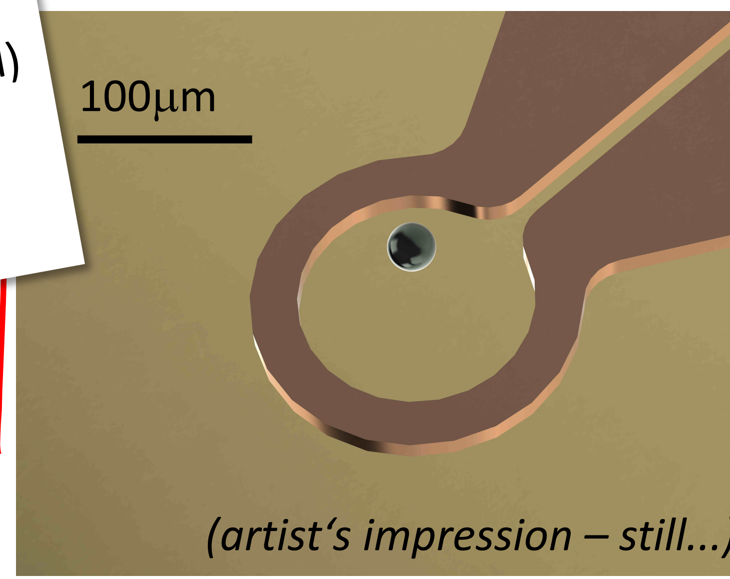


Jointly with:
O. Romero-Isart, G. Kirchmair (IQOQI)
Michael Trupke (U Vienna)
A. Sanchez (UA Barcelona)
R. Gross, H. Huebel (WMI Munich)

Magnetic levitation in anti-Helmholtz coil configuration

Trap frequencies ~ 1 kHz

T= 20 mK, p = 1e-8 mbar



J. Hofer, S. Miniberger, M. Trupke

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VCQ

Piling up momentum...

time, precision, mass, ...

1960-1975 | 1980-2010 | > 2010 | ?

photons
neutron interferometry
microwave atomic clocks

Gravitational coupling to quantum systems

atom interferometry
ultracold neutrons
ultrastable optical clocks

Precision measure-ments of Newtonian gravity & GR

„extreme“ matter waves
optical lattice clocks

Experimental constraints for Dark Energy, Dark Matter

„CLASSICAL“ GRAVITY

Analogue (Quantum) Gravity

Testing gravitational decoherence (incl. Schrödinger-Newton dynamics)

Low-Energy constraints for Quantum Gravity theories

Gravitationally induced entanglement

„QUANTUM“ GRAVITY

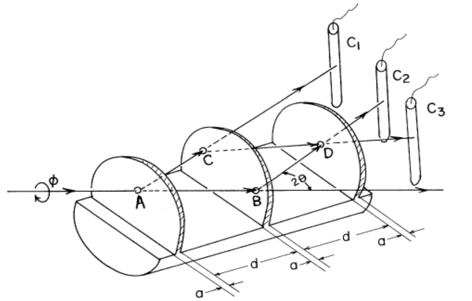

FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.

Quantum Controlling Levitated Massive Mechanical Systems

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VCQ
Vienna Center for Quantum Science and Technology

GOAL

Establish **quantum control of levitated massive mechanical systems**

MOTIVATION

Enable a new class of experiments at the **interface between quantum physics and gravity**

METHOD

- **Optical levitation** coupled to cavities
- **Magnetic levitation** coupled to superconducting circuits

EXPECTED RESULTS

Bottom-up: Demonstrate **long-lived quantum coherence** of increasingly massive systems

Top-down: Measure **gravity** between **sub-mm source masses**

Long-term: establish experiments that exploit the **source mass character of the quantum system**

Optical levitation in cavities (with Kiesel Group, V. Vuletic)

Uros Delic
David Grass (@Duke)
Constanze Bach
Yuriy Coroli
Jelena Cvijan
Kahan Dare
Lorenzo Magrini
Manuel Reisenbauer

Potential landscape shaping & optimal control (with Kiesel Group, A. Kugi, M. Ritsch-Marte)

Mario Ciampini
Maxime Debiossac
Stefan Lindner
Tobias Wenzl
Qianze Zhu

Precision measurements of gravity

Tobias Westphal
Mathias Dragosits
Hans Hepach
Jeremias Pfaff

Superconducting levitation (with R. Gross, O. Romero-Isart, M. Trupke)

Josh Slater (@ Delft)
Stefan Minniberger
Milan Gemaljevic
Joachim Hofer

Quantum foundations and the gravity-quantum interface (with C. Brukner, B. Dakic, R. Wald, A. Zeilinger)

Alessio Belenchia (@ Belfast)
Lukas Neumeier
Fatemeh Bibek
Philipp Köhler

Quantum information interfaces (with K. Hammerer, S. Gröblacher, O. Painter, R. Schnabel, J. Eisert)

Sungkun Hong (@ KAIST)
Ralf Riedinger (@ Harvard)
Witlef Wieczorek (@ Chalmers)
Claus Gärtner
Corentin Gut
Klemens Winkler

Low-noise coatings & microfab

Garrett Cole @ CMS

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VCQ Vienna Center for Quantum Science and Technology
FWF Der Wissenschaftsfonds.
WWTF Science and Technology Fund
SEVENTH FRAMEWORK PROGRAMME
European Research Council
DARPA
Humboldt Stiftung/Foundation
esa
EURAMET European Association of National Metrology Institutes
EMRP European Metrology Research Programme

Quantum Optomechanics at ultra-low temperatures

HBT of single phonons

Hong, Riedinger et al., *Science* **358**, 203 (2017)

Entangled mechanical oscillators

Riedinger, Wallucks, et al. *Nature* **556**, 473 (2018)

Marinković et al., *Phys. Rev. Lett.* **121**, 220404 (2018)

The gravity-quantum interface

Quantum Superposition of Massive Objects and the Quantization of Gravity

Belenchia et al., *Phys. Rev. D* **98**, 126009 (2018)

Levitating dielectrics and superconductors

Near-field coupling to a photonic crystal cavity

Magrini et al., *Optica* **5**, 1597 (2018)

Ground-state cooling from room temperature

Delic et al., arXiv:1911.04406 (2019)

Cavity cooling via coherent scattering

Delic et al., *Phys. Rev. Lett.* **122**, 123602 (2019)