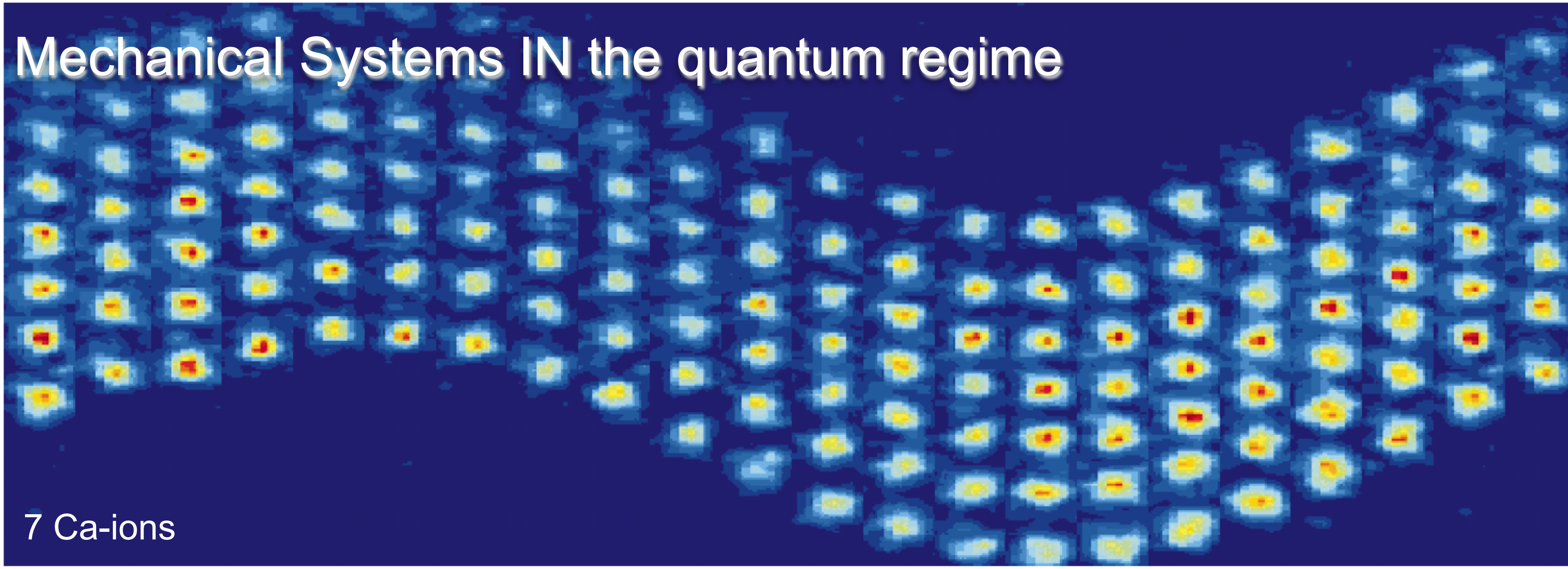
Centenary Conference on the History of General Relativity,
December 2015, Berlin

The Past, Present and Future of Quantum Tests of (Quantum) Gravity

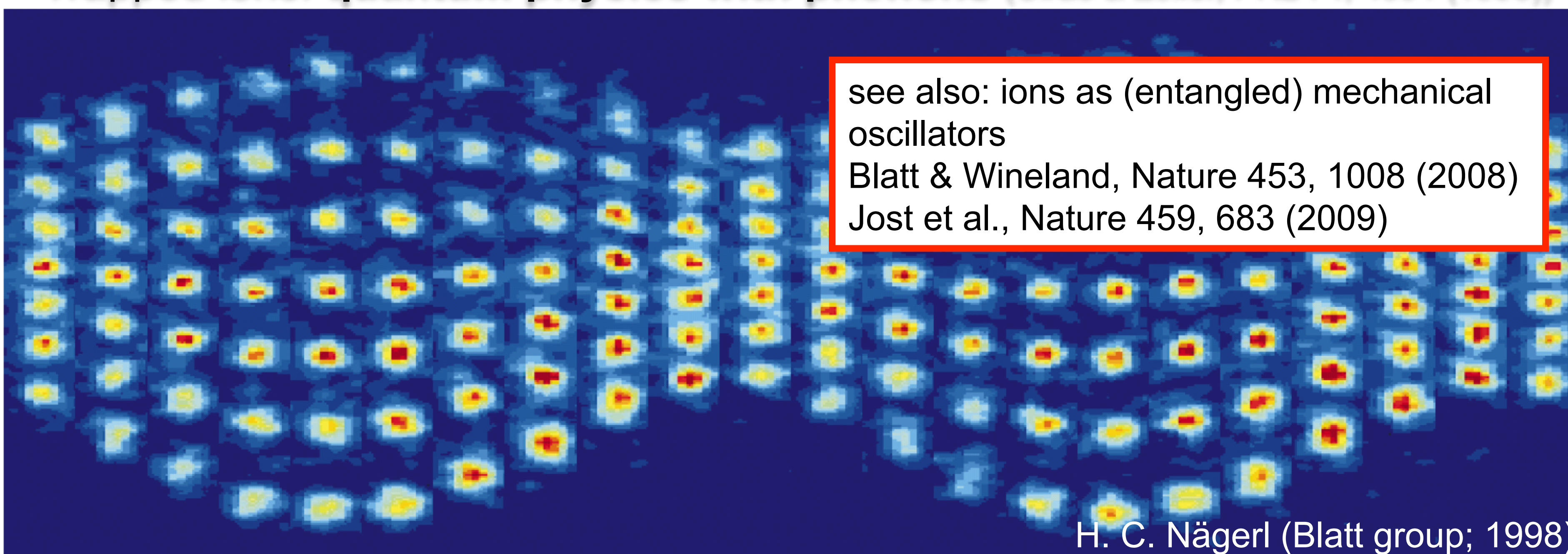
Markus Aspelmeyer

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

Mechanical Systems IN the quantum regime

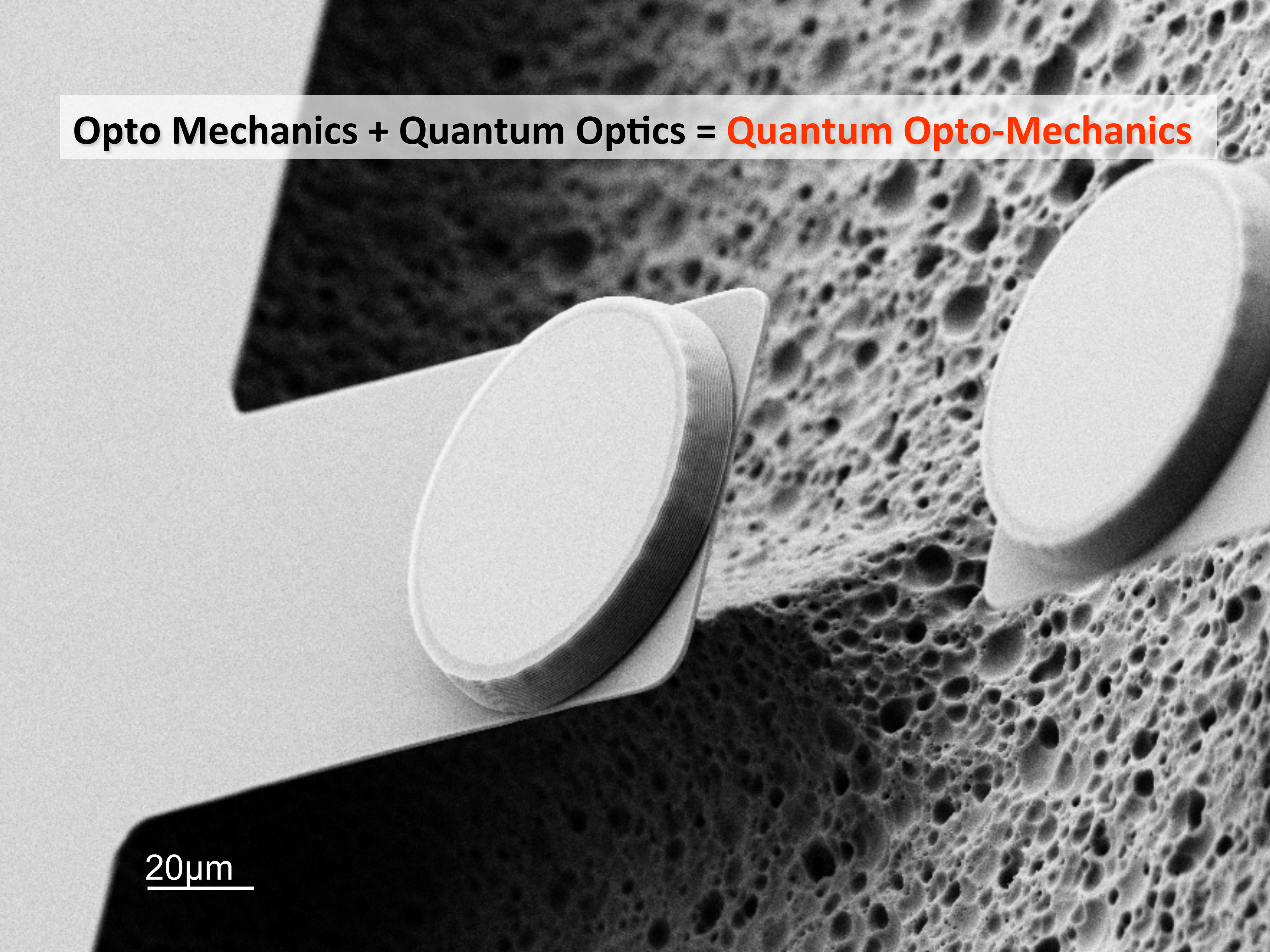


Trapped ions: **quantum physics with phonons** (Cirac & Zoller, PRL 74, 4091 (1995))

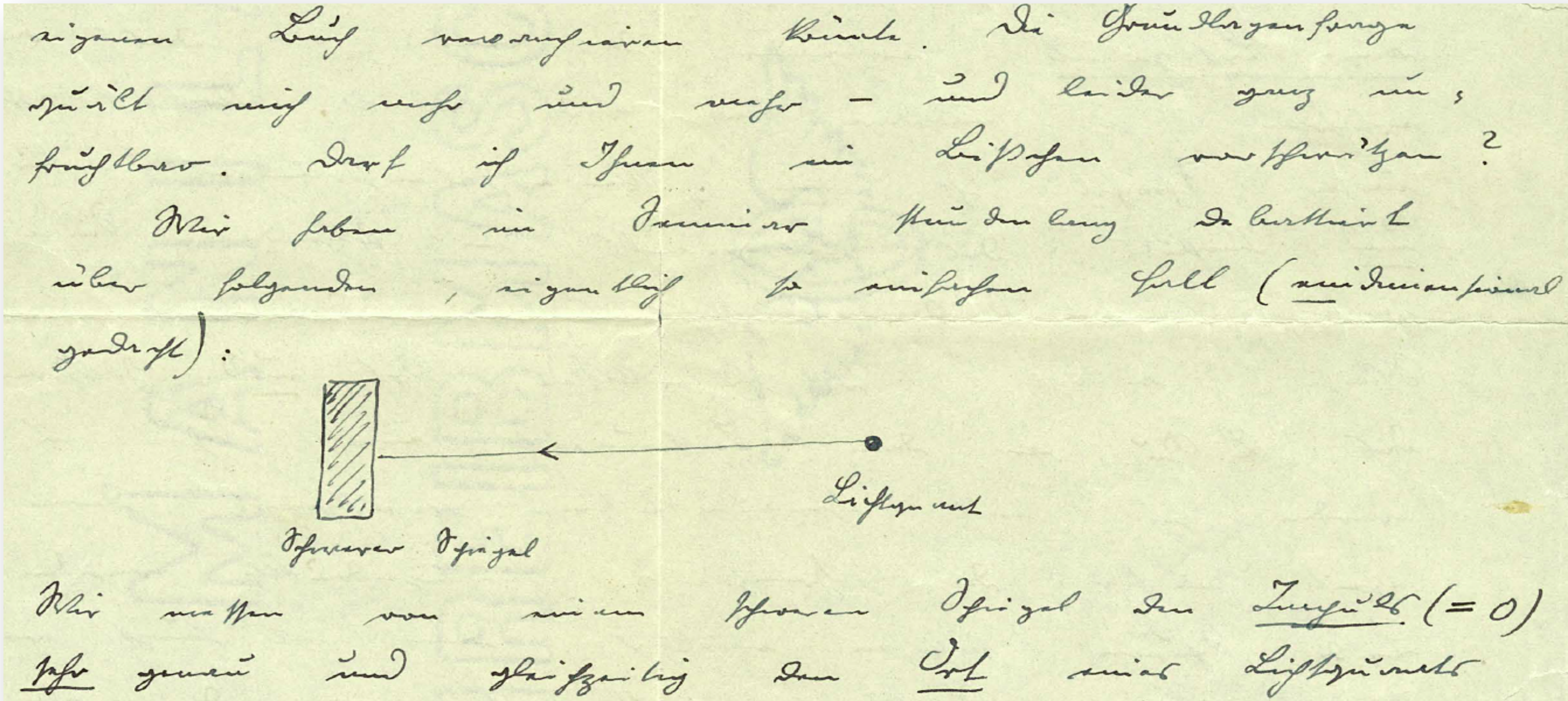


see also: ions as (entangled) mechanical oscillators
Blatt & Wineland, Nature 453, 1008 (2008)
Jost et al., Nature 459, 683 (2009)

Opto Mechanics + Quantum Optics = Quantum Opto-Mechanics



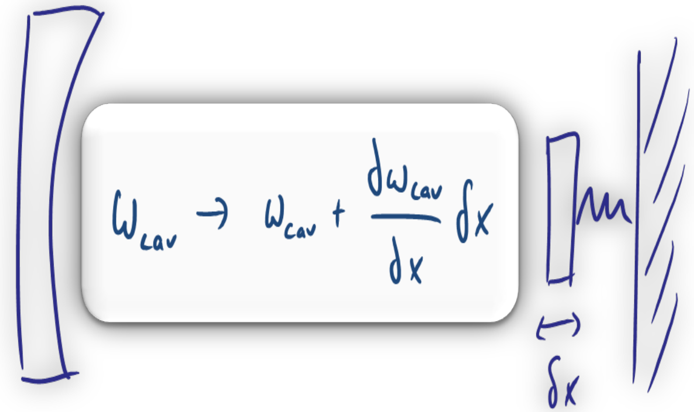
Schrödinger to Sommerfeld (11.12.1931)

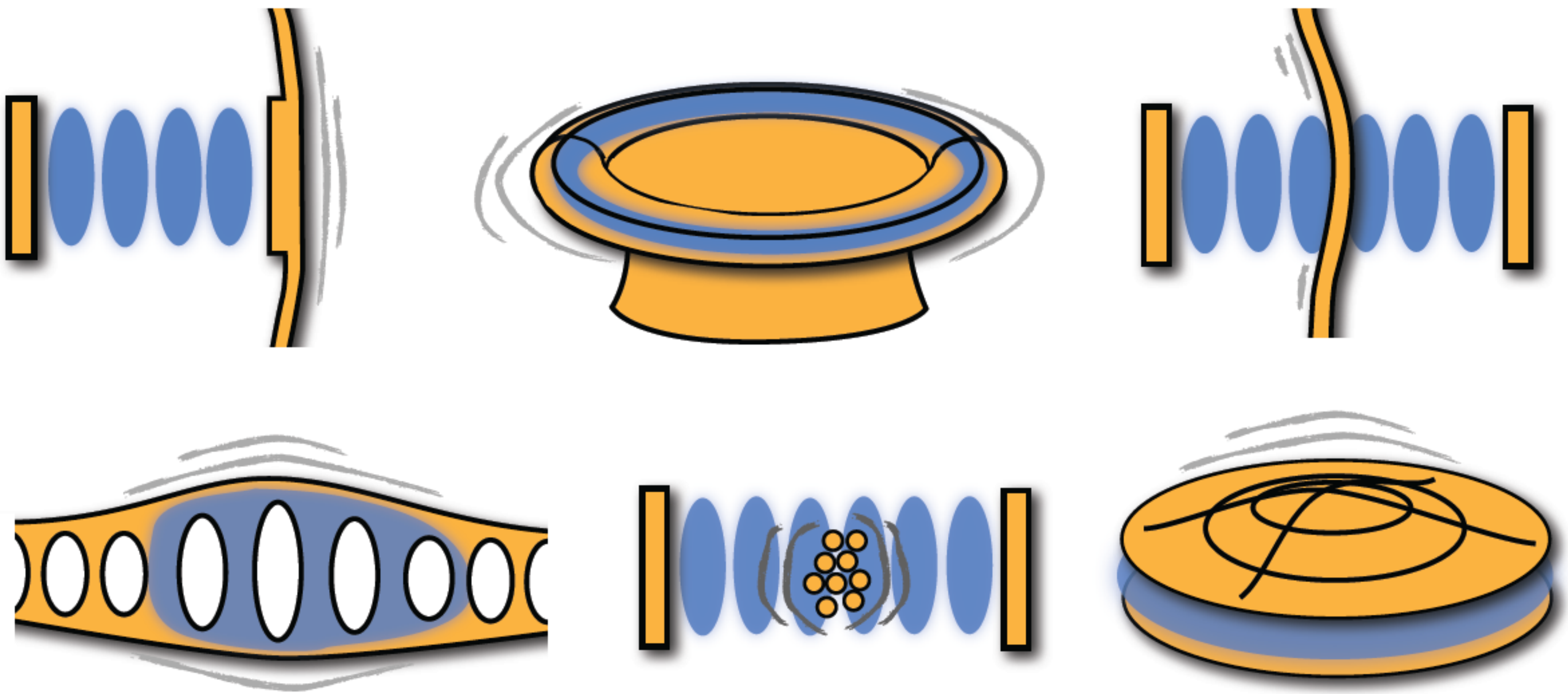


„[…] Our mirror is a universal measurement tool : […] momentum and position of the photon are imprinted on the mirror, namely both are registered with accuracies, the product of which can be pushed way below the limit of h […]“

= Entanglement!

Quantum Optomechanics





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

Quantum Optomechanics

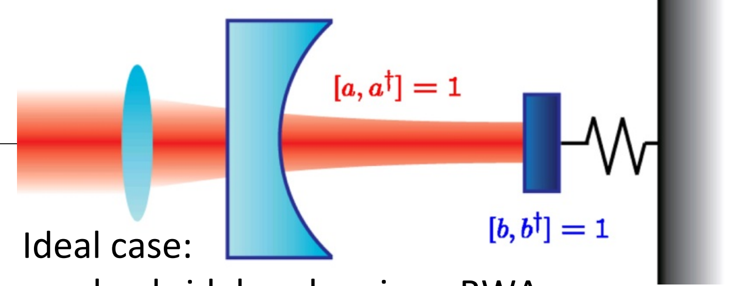
full **quantum optics toolbox** to prepare and control **mechanical quantum states** via photonic quantum states

Requires:
Minmum entropy mechanical states (e.g. ground state)
+
Strong cooperativity $\frac{g^2}{\kappa\gamma} \gg \langle n \rangle_{bath}$

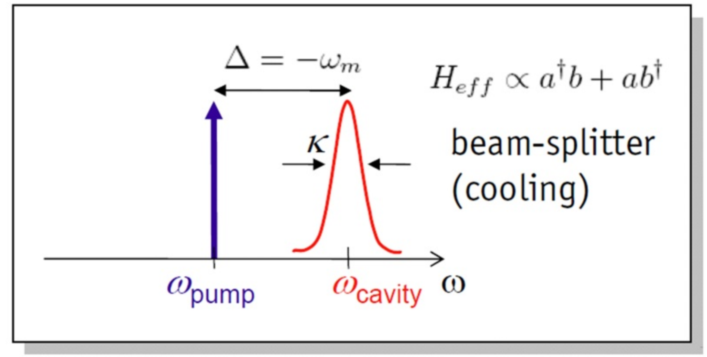
- g: OM coupling
- κ: cavity decay
- γ: mechanical damping
- n_{bath}: bath phonon number

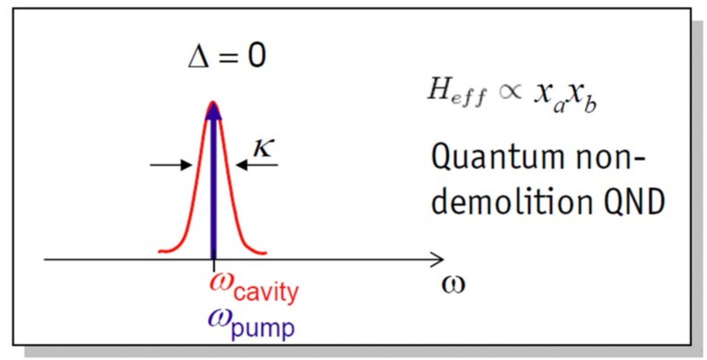
**** joint work with group of Oskar Painter (Caltech)***

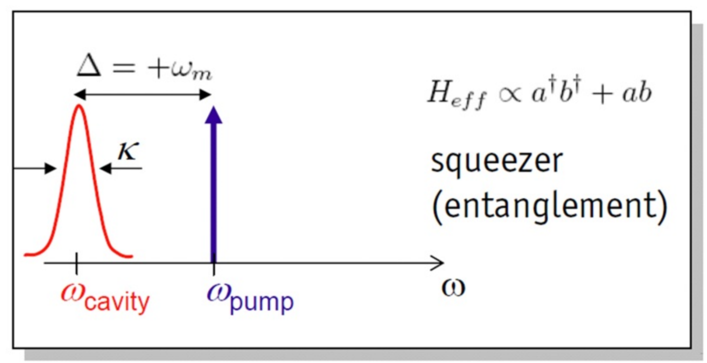
Early ideas:
Zhang, Peng, Braunstein, PRA **68**, 013808 (2003)
Recent review:
Aspelmeyer, Kippenberg, Marquardt, RMP **86**, 1391 (2014)



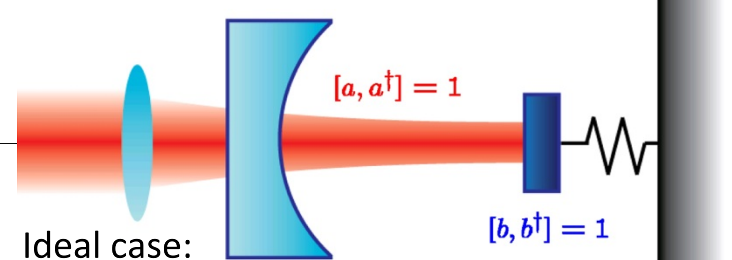
Ideal case:
resolved sideband regime, RWA







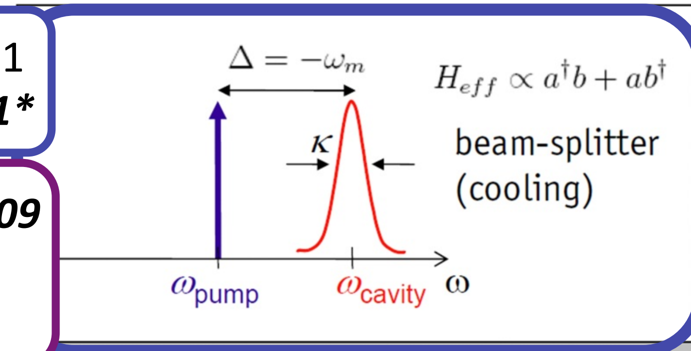
Quantum Optomechanics



Ideal case:
resolved sideband regime, RWA

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

Teufel et al., Nature 2011
Chan et al., Nature 2011*

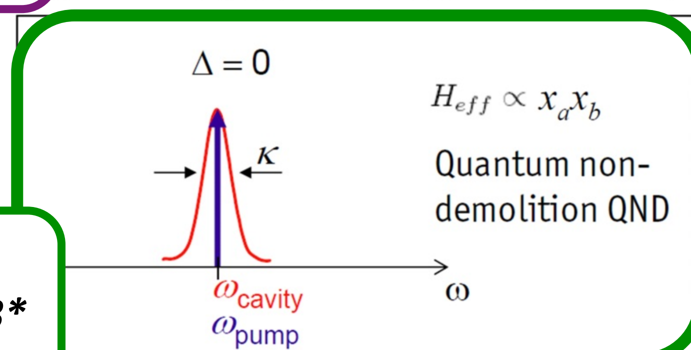


Requires:
Minmum entropy mec
(e.g. ground state)
+
Strong cooperativity

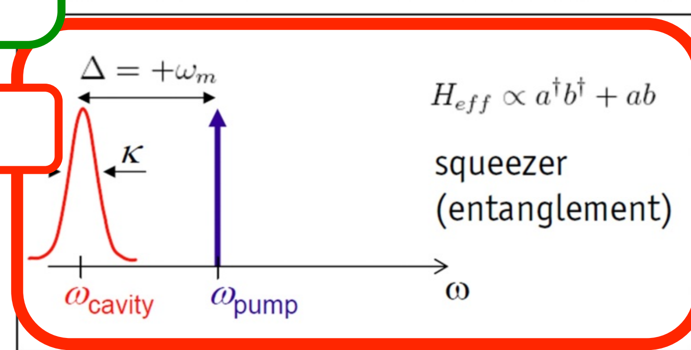
$$\frac{g^2}{\kappa\gamma} \gg \langle n \rangle_{bath}$$

g: OM coupling
κ: cavity decay
γ: mechanical d
n_{bath}: bath phor

Gröblacher et al., Nature 2009
Teufel et al., Nature 2011
Verhagen et al., Nature 2012



Brooks et al., Nature 2012
Safavi-Naeini et al., Nature 2013*
Purdy et al., PRX 2013



Palomaki et al., Science 2013

***** joint work with group of Oskar Painter (Caltech)***

Early ideas:
Zhang, Peng, Braunstein, PRA **68**, 013808 (2003)
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Mechanical Quantum Ground State

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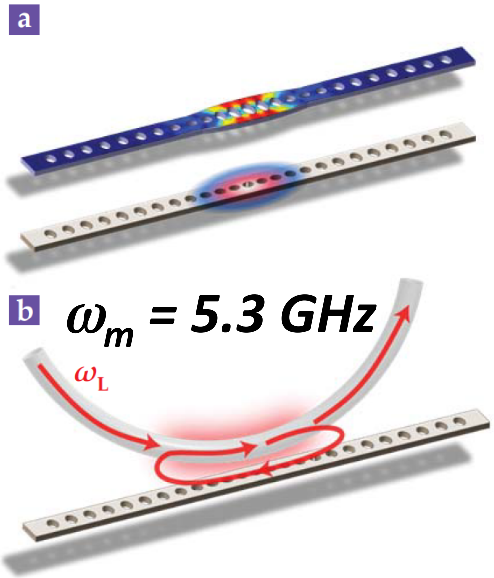
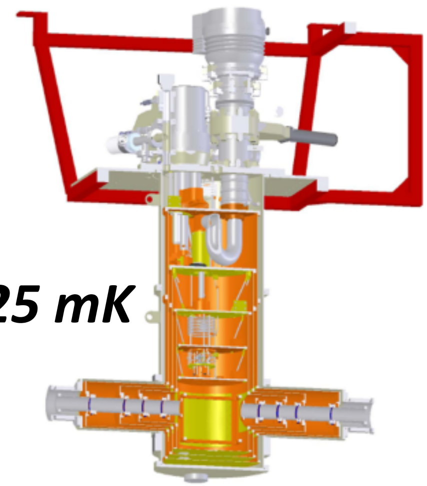


+

T=25 mK

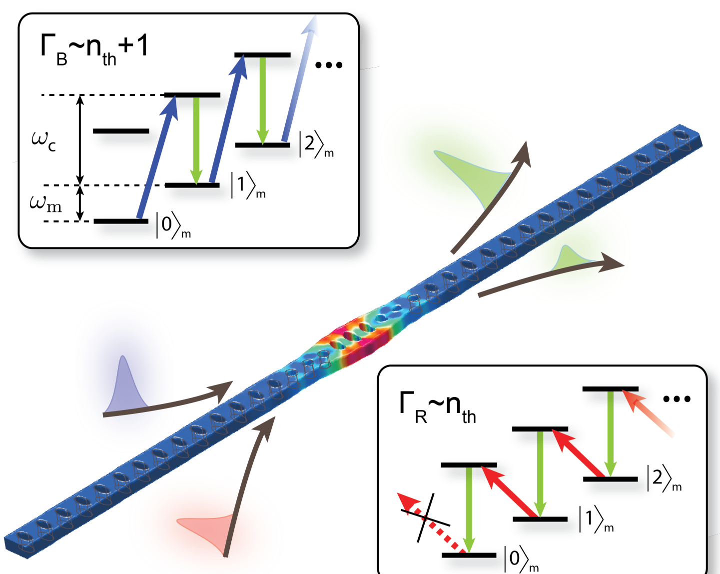


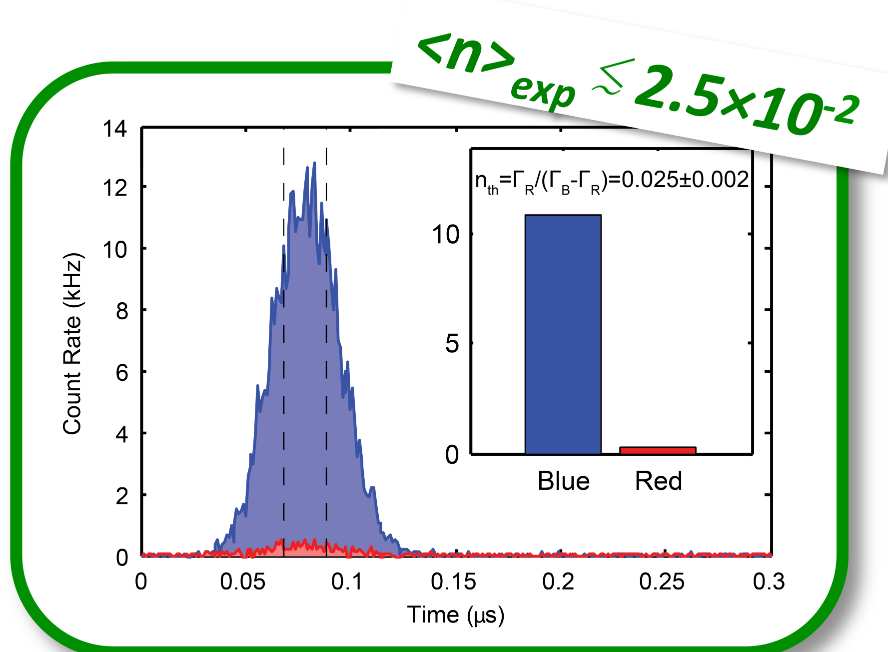
=

$\langle n \rangle = 2\times10^{-5}$

(Ground State!)

Photon-counting Sideband Thermometry





Ralf Riedinger, Sungkun Hong, Simon Gröblacher

Mechanical Systems IN the quantum regime

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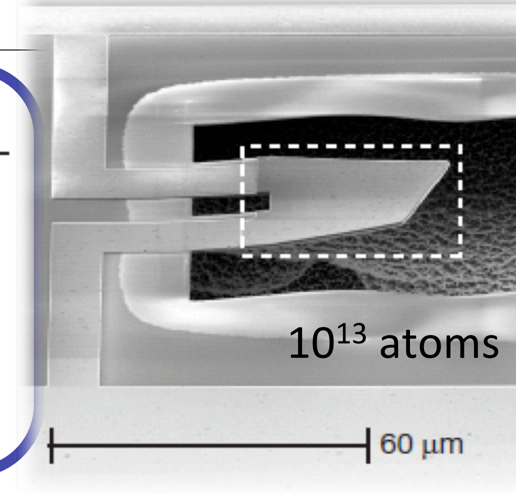
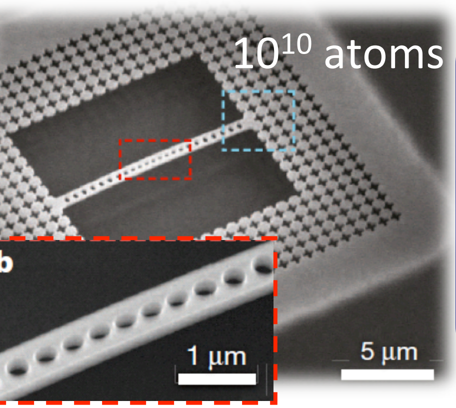
Nature **464**, 697-703 (2010)

Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]





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

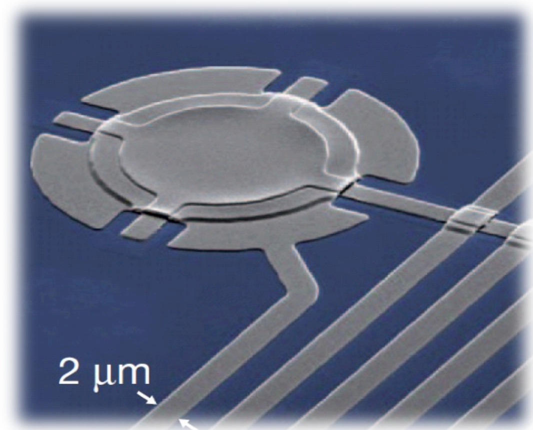
Laser cooling of a nanomechanical oscillator into its quantum ground state

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

Science **342**, 710-713 (2013)

Entangling Mechanical Motion with Microwave Fields

T. A. Palomaki,[1,2]* J. D. Teufel,[3] R. W. Simmonds,[3] K. W. Lehnert[1,2]



Quantum theory works, as does GR...

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Example from quantum theory: validity of the **quantum superposition principle** for

- orbital angular momentum states of photons up to a few hundred quantum numbers (1)
- µA-level current states carrying up to 10^6 electrons (2,3)
- collective spin degrees of freedom of 10^{12} Rubidium atoms (4).
- macromolecules (up to 10^4 amu) (5,6)
- vibrational degrees of freedoms of mechanical resonators (up to 10^{16} amu) (7,8)

→ 10^{25} particles?

PRL **100,** 013601 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

Entanglement of Macroscopic Test Masses and the Standard Quantum Limit in Laser Interferometry

Helge Müller-Ebhardt,[1] Henning Rehbein,[1] Roman Schnabel,[1] Karsten Danzmann,[1] and Yanbei Chen[2]

[1]*Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Institut für Gravitationsphysik, Leibniz Universität Hannover, Callinstr. 38, 30167 Hannover, Germany*

[2]*Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Am Mühlenberg 1, 14476 Potsdam, Germany*

(Received 27 February 2007; published 7 January 2008)

We show that the generation of entanglement of two heavily macroscopic mirrors is feasible with state of the art techniques of high-precision laser interferometry. The basis of such a demonstration would be a Michelson interferometer with suspended mirrors and simultaneous homodyne detections at both interferometer output ports. We present the connection between the generation of entanglement and the standard quantum limit (SQL) for a free mass. The SQL is a well-known reference limit in operating interferometers for gravitational-wave detection and provides a measure of when macroscopic entanglement can be observed in the presence of realistic decoherence processes.

DOI: 10.1103/PhysRevLett.100.013601 PACS numbers: 42.50.Xa, 03.65.Ta, 03.67.Mn, 42.50.Lc

Quantum theory works, as does GR...

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- macromolecules (up to 10^4 amu) (5,6)
- vibrational degrees of freedoms of mechanical resonators (up to 10^{16} amu) (7,8)

Examples from GR (see e.g. review by Clifford Will):

- dynamics of binary pulsars (9)

→ strong relativistic fields and gravitational radiation

- satellite tests of the Lense-Thirring effect (11,12).

→ solar-system scale experiments in the weak relativistic regime

- tests of the weak equivalence principle to an accuracy of better than10^{-13} (13)
- measurements of Newton's constant G to 10^{-4} (14).
- atomic clocks for gravitational redshift to 10^{-6} (15).

→ earth-based high-precision tests of gravity

Outline

- **Quantum systems as „test masses“**
  a brief (very incomplete) survey on table-top quantum experiments that probe gravity
- **Quantum systems as „source masses“?**
  ‚what prevents this from becoming a practical experiment?‘
- **Quantum control of levitated massive systems**
  towards a „quantum Cavendish“ experiment

20µm

Newtonian Gravity in Quantum Experiments

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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.

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

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

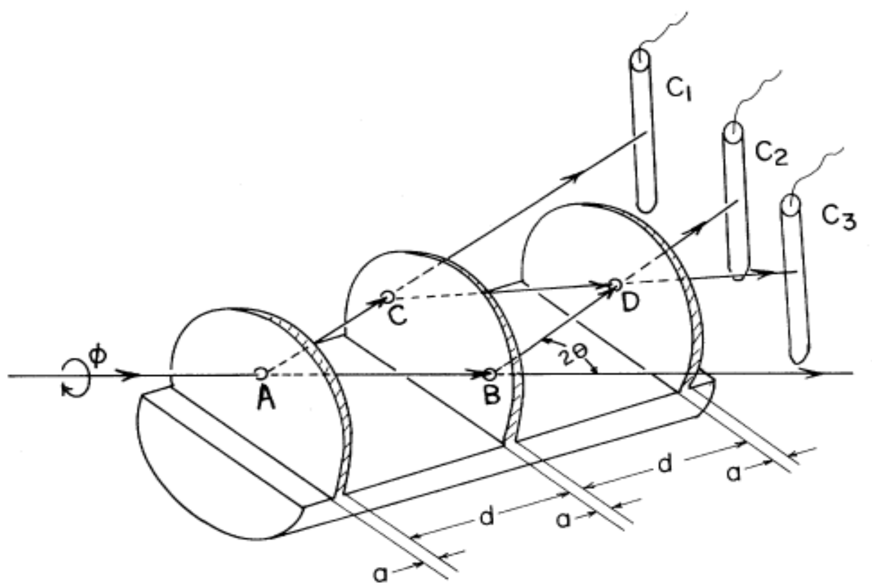
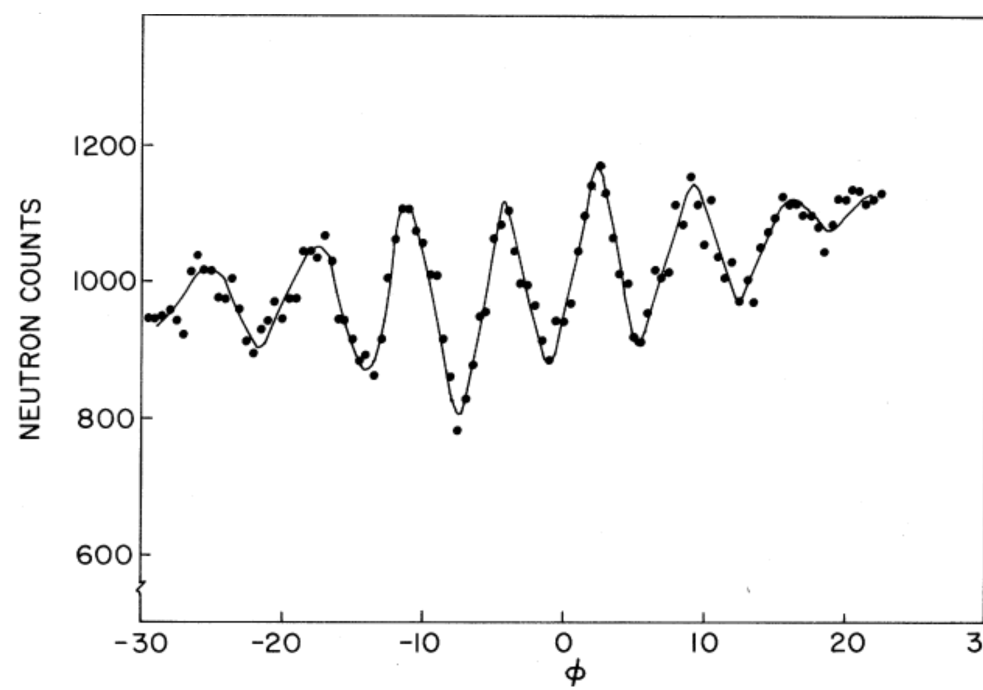


FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.



Newtonian Gravity in Quantum Experiments

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VOLUME 67, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JULY 1991

Atomic Interferometry Using Stimulated Raman Transitions

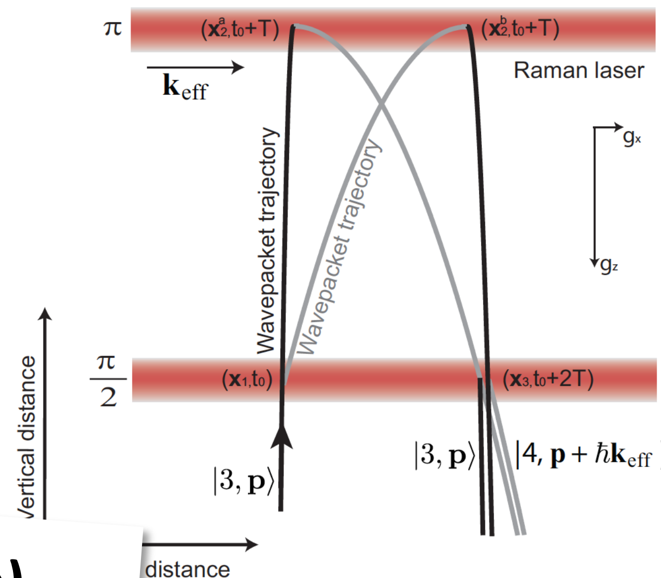
Mark Kasevich and Steven Chu
Departments of Physics and Applied Physics, Stanford University, Stanford, California 94305
(Received 23 April 1991)

The mechanical effects of stimulated Raman transitions on atoms have been used to demonstrate a matter-wave interferometer with laser-cooled sodium atoms. Interference has been observed for wave packets that have been separated by as much as 2.4 mm. Using the interferometer as an inertial sensor, the acceleration of a sodium atom due to gravity has been measured with a resolution of 3×10^{-6} after 1000 sec of integration time.

PACS numbers: 32.80.Pj, 07.60.Ly, 35.80.+s, 42.50.Vk

$$|3,\mathbf{p}\rangle \rightarrow e^{i\phi(t)}\,|4,\mathbf{p}+\hbar\mathbf{k}_{\text{eff}}\rangle$$
$$|4,\mathbf{p}+\hbar\mathbf{k}_{\text{eff}}\rangle \rightarrow e^{-i\phi(t)}\,|3,\mathbf{p}\rangle$$

$$\Delta\Phi = -k_{eff}\, g\, T^2$$



(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

Measurement of gravitational accelerati[on] 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

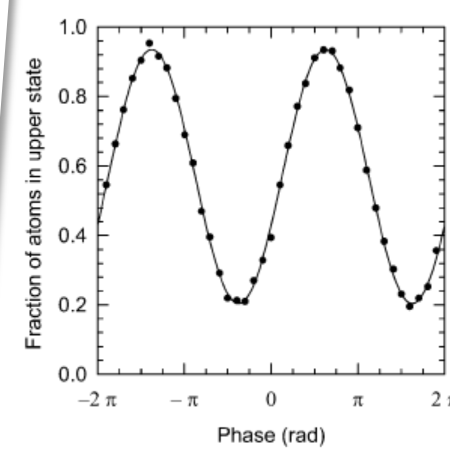


Figure 2 Typical Doppler-sensitive interferometer fringe for $T = 160$ ms. Shown are the 588,638th and 588,639th fringes. Each of the 40 data points represents a single launch of the atoms, spaced 1.3 s apart and taken over a period of 1 min. One full fringe corresponds to $\sim2\times10^{-8}g$. Performing a least-squares fit determines local gravity to approximately $3\times10^{-9}g$.

Newtonian Gravity in Quantum Experiments

2 atomic fountains at different locations
→ differential acceleration measurement
→ **Measure G** through additional test mass

Science 2007

Atom Interferometer Measurement of the Newtonian Constant of Gravity

J. B. Fixler,[1] G. T. Foster,[2] J. M. McGuirk,[3] M. A. Kasevich[1]*

We measured the Newtonian constant of gravity, *G*, using a gravi
interferometry. The gradiometer measures the differential acceler
Cs atoms. The change in gravitational field along one dimension i
Pb mass is displaced. Here, we report a value of $G = 6.693 \times 1$
second squared, with a standard error of the mean of $\pm 0.027 \times 10$
10^{-11} cubic meters per kilogram second squared. The possibility
exist in traditional measurements makes it important to measur

(Kasevich/Tino groups)

2007 ΔG/G = 3×10^{-3}

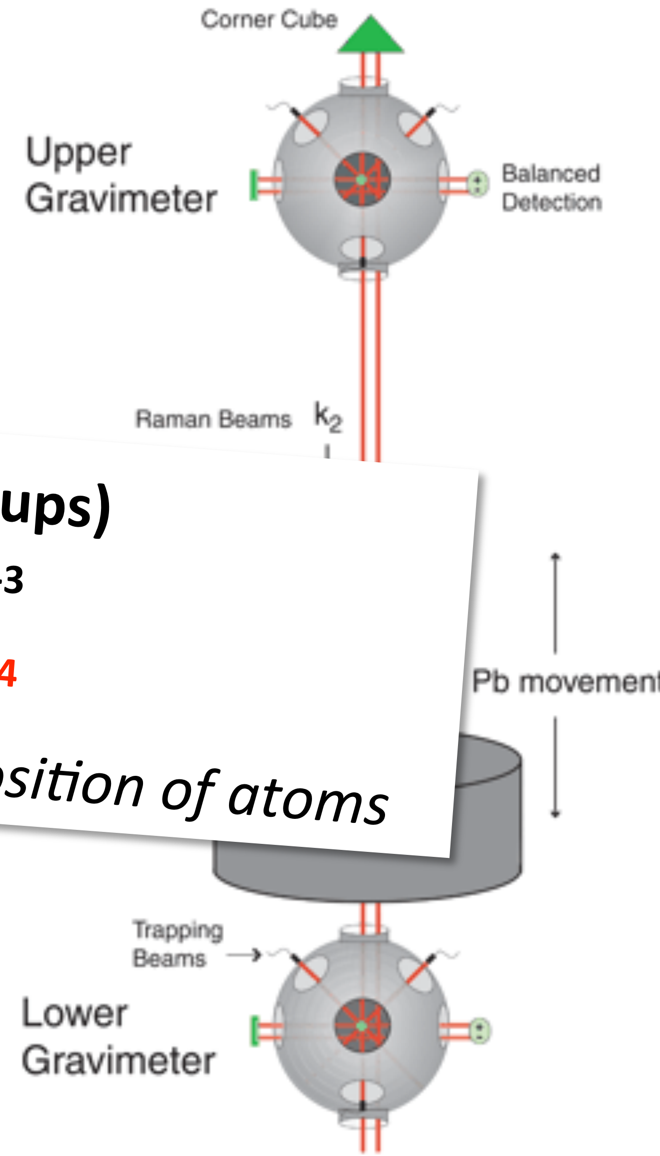
2014 ΔG/G = 1×10^{-4}

mainly limited by position of atoms

Nature 2014

Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi[1], F. Sorrentino[1], L. Cacciapuoti[2], M. Prevedelli[3] & G. M. Tino[1]



Newtonian Gravity in Quantum Experiments

QUANTUS

Selected for a Viewpoint in *Physics*
PRL **110,** 093602 (2013) PHYSICAL REVIEW LETTERS week ending 1 MARCH 2013

Interferometry with Bose-Einstein Condensates in Microgravity

H. Müntinga,[1] H. Ahlers,[2] M. Krutzik,[3] A. Wenzlawski,[4] S. Arnold,[5] D. Becker,[2] K. Bongs,[6] H. Dittus,[7] H. Duncker,[4] N. Gaaloul,[2] C. Gherasim,[8] E. Giese,[5] C. Grzeschik,[3] T. W. Hänsch,[9] O. Hellmig,[4] W. Herr,[2] S. Herrmann,[1] E. Kajari,[5,10] S. Kleinert,[5] C. Lämmerzahl,[1] W. Lewoczko-Adamczyk,[3] J. Malcolm,[6] N. Meyer,[6] R. Nolte,[8] A. Peters,[3,11] M. Popp,[2] J. Reichel,[12] A. Roura,[5] J. Rudolph,[2] M. Schiemangk,[3,11] M. Schneider,[8] S. T. Seidel,[2] K. Sengstock,[4] V. Tamma,[5] T. Valenzuela,[6] A. Vogel,[4] R. Walser,[8] T. Wendrich,[2] P. Windpassinger,[4] W. Zeller,[5] T. van Zoest,[7] W. Ertmer,[2] W. P. Schleich,[5] and E. M. Rasel[2,*]

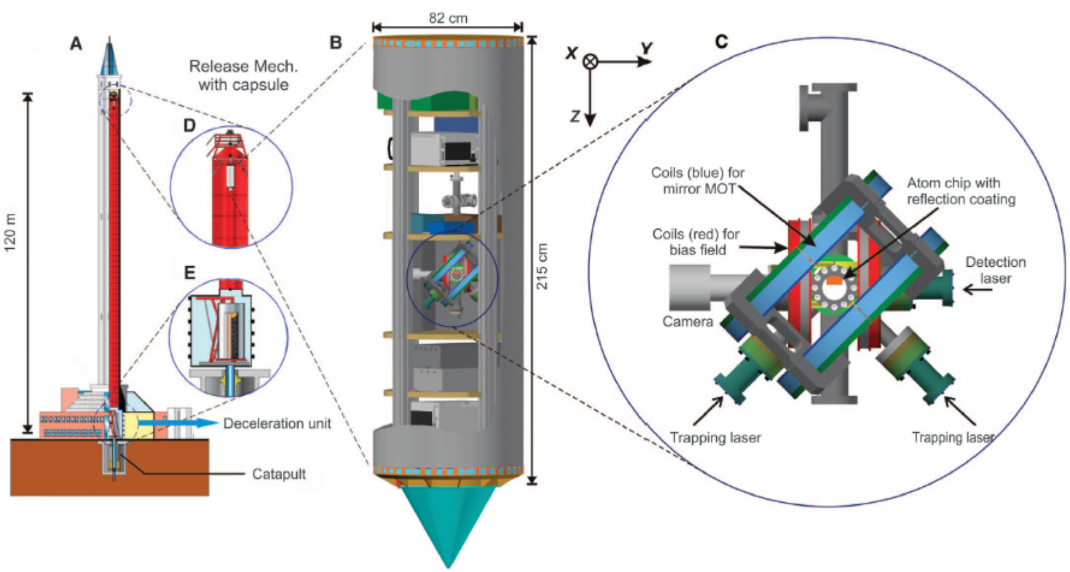


Fig. 1. Cuts through the ZARM drop tower facility in Bremen (**A**) and the capsule (**B**) containing the heart of the BEC experiment (**C**). The capsule is released from the top of the tower (**D**) and is recaptured after a free fall of 4.7 s through an evacuated stainless steel tube at the bottom of the tower by a 8-m-deep pool of polystyrene balls (**E**). In the process of recapturing the capsule, the experiment has to survive decelerations up to 500 m/s^2 (about 50 times the local gravitational acceleration). The facility permits up to three drops per day. The capsule contains all of the components necessary to prepare and observe a BEC, such as the laser systems for cooling the atoms, the ultrahigh-vacuum chamber with the atom chip, the current drivers and power supplies, a charge-coupled device (CCD) camera, and a control computer. The vacuum chamber is surrounded by two magnetic shields and allows us to include an atom interferometer in future experiments. Moreover, the catapult underneath the movable polystyrene pool offers the possibility of extending the time of free fall to 9 s.

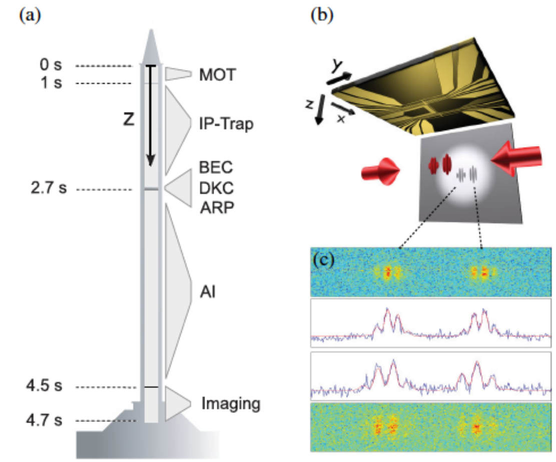


FIG. 2 (color). Mach-Zehnder interferometry of a BEC in microgravity as realized in the ZARM drop tower in Bremen (a) where absorption imaging (b) brings out the interference fringes (c). The preparatory experimental sequence (a) includes capturing cold atoms in a magneto-optical trap (MOT), loading an Ioffe-Pritchard trap, creating a BEC, and applying the DKC followed by the adiabatic rapid passage (ARP). The remaining time before the capture of the capsule at the bottom of the tower is used for AI and imaging of the atoms. The AMZI below the atom chip [top plane of (b)] is formed by scattering the BEC off moving Bragg gratings generated by two counter-propagating laser beams (red arrows directed along the *y* axis),

Newtonian Gravity in Quantum Experiments

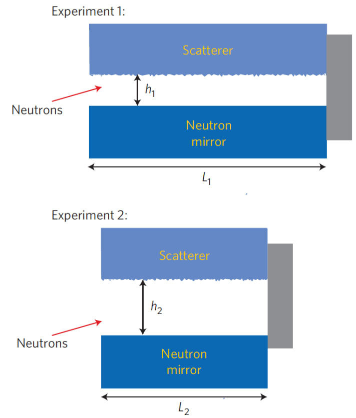
Nature 2002

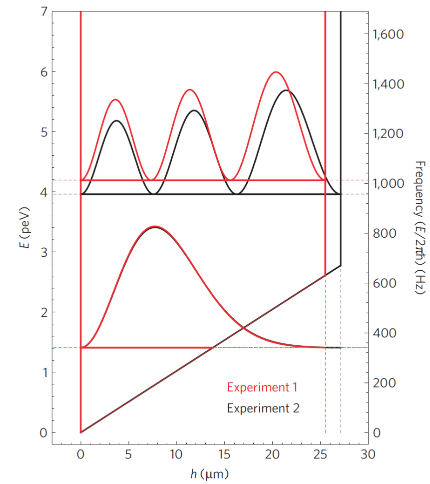
Quantum states of neutrons in the Earth's gravitational field

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





Set-up parameters and experimental results

	Length of the neutron mirror Length L (cm)$_x$ Width W (cm)$_x$ Height H (cm)	Height of scatterer h (µm)	Mean time of flight t (ms)	Energy difference E_{13} (peV)	Resonance frequency (prediction) ω_{13} (Hz)	Resonance frequency (measurement) ω_{13} (Hz)	Resonance width (FWHM) $\Delta\omega$ (Hz)
Experiment 1	15 × 3 × 3	25.5	23	2.78	$2\pi \times 671$	$2\pi \times (705 \pm 6)$	$2\pi \times 41.2$
Experiment 2	10 × 3 × 3	27.1	15	2.55	$2\pi \times 615$	$2\pi \times (592 \pm 11)$	$2\pi \times 61.6$

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]*

... and many more...

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)

The unprecedented precision of atom interferometry will soon lead to laboratory tests of general relativity to levels that will rival or exceed those reached by astrophysical observations. We propose such an experiment that will initially test the equivalence principle to 1 part in 10^{15} (300 times better than the current limit), and 1 part in 10^{17} in the future. It will also probe general relativistic effects—such as the nonlinear three-graviton coupling, the gravity of an atom's kinetic energy, and the falling of light—to several decimals. In contrast with astrophysical observations, laboratory tests can isolate these effects via their different functional dependence on experimental variables.

DOI: 10.1103/PhysRevLett.98.111102 PACS numbers: 04.80.Cc, 03.75.Dg

Phonon creation by gravitational waves

Carlos Sabín[1], David Edward Bruschi[2], Mehdi Ahmadi[1] and Ivette Fuentes[1]
[1] School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[2] Racah Institute of Physics and Quantum Information Science, The Hebrew University of Jerusalem, 91904 Givat Ram, Jerusalem, Israel
E-mail: c.sabin.les@gmail.com

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New Journal of Physics **16** (2014) 085003
doi:10.1088/1367-2630/16/8/085003

ASTROPHYSICS

Atom-interferometry constraints on dark energy

P. Hamilton,[1*] M. Jaffe,[1] P. Haslinger,[1] Q. Simmons,[1] H. Müller,[1,2†] J. Khoury[3]

If dark energy, which drives the accelerated expansion of the universe, consists of a light scalar field, it might be detectable as a "fifth force" between normal-matter objects, in potential conflict with precision tests of gravity. Chameleon fields and other theories with screening mechanisms, however, can evade these tests by suppressing the forces in regions of high density, such as the laboratory. Using a cesium matter-wave interferometer near a spherical mass in an ultrahigh-vacuum chamber, we reduced the screening mechanism by probing the field with individual atoms rather than with bulk matter. We thereby constrained a wide class of dark energy theories, including a range of chameleon and other theories that reproduce the observed cosmic acceleration.

Science 349, 849 (2015)

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-

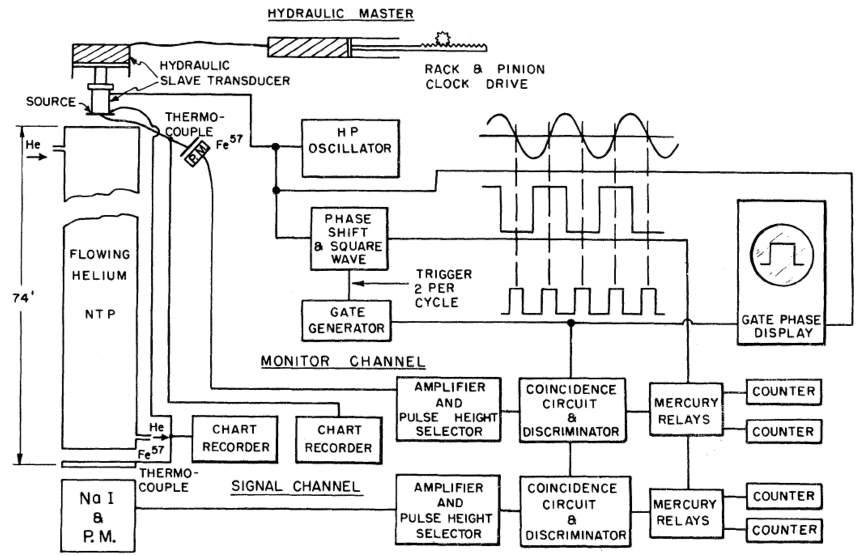
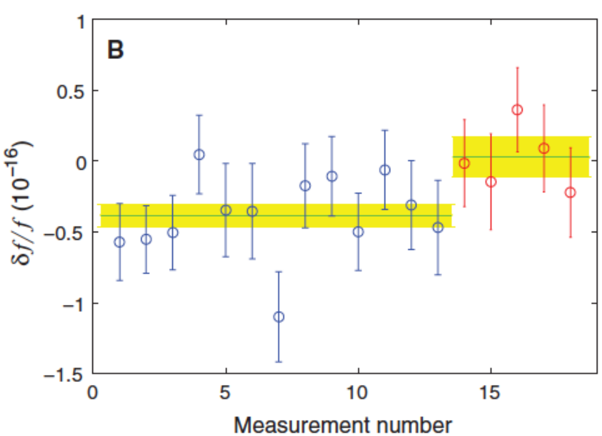


FIG. 1. A block diagram of the over-all experimental arrangement. The source and absorber-detector units were frequently interchanged. Sometimes a ferroelectric and sometimes a moving-coil magnetic transducer was used with frequencies ranging from 10 to 50 cps.

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



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 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): $h=10^7$m)

What is time? Quantum superpositions of clocks

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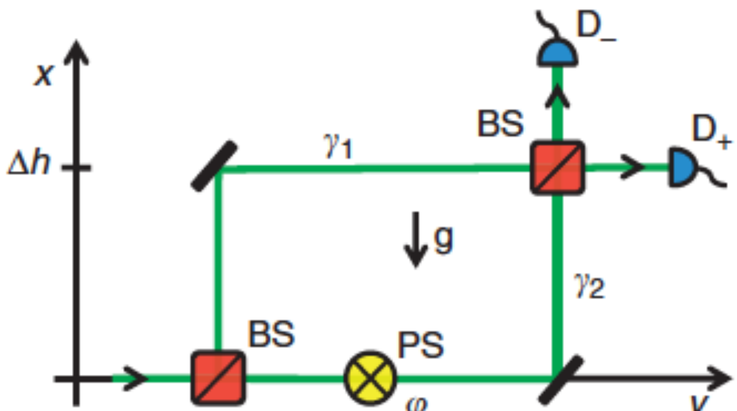
qubit in a gravitational field

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

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 $2T_\pi$

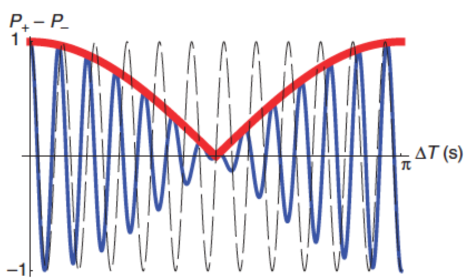


Figure 2 | Visibility of the interference pattern and the phase shift in the cases with and without the 'clock.' The plot of the difference between

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+)
→ Tπ = 500 ms (compatible with achievable coherence times)

What is time? Quantum superpositions of clocks

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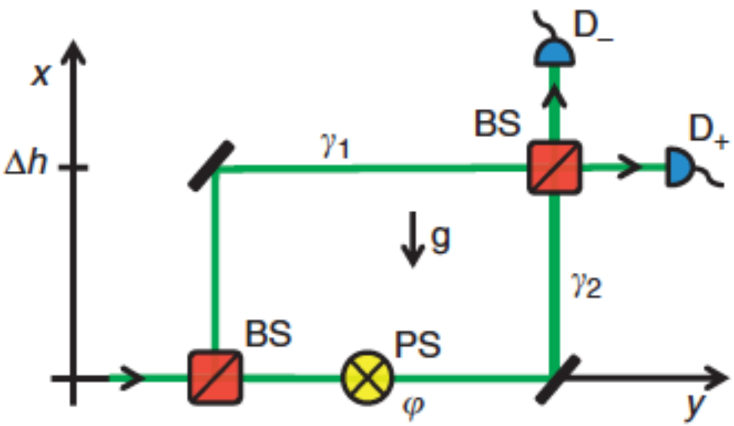
$$|g\rangle + |e\rangle \rightarrow |g\rangle + exp\left\{-\frac{i}{\hbar}\frac{(E_g - E_e)}{c^2}ght\right\}|e\rangle$$

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

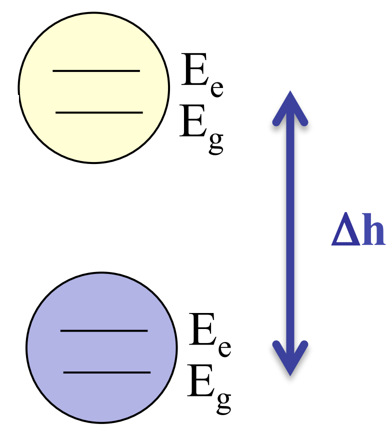


If the qubit is placed in a spatial superposition of two vertical heights (in Earth's gravitational field) separated by Δh the qubits will evolve differently:

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

Alternative: Entangle 2 qubits that are spatially separated by Δh

$$|g\rangle_{h1}|e\rangle_{h2} + |e\rangle_{h1}|g\rangle_{h2} \longrightarrow |g\rangle_{h1}|e\rangle_{h2} + exp\left\{-\frac{i}{\hbar}\frac{(E_g - E_e)}{c^2}g\Delta ht\right\}|e\rangle_{h1}|g\rangle_{h2}$$



→ singlet-triplet oscillation at frequency $\Delta\omega_g$

Feasible with present day technology:

- Entanglement between states of separated atoms has been demonstrated (e.g. Weinfurter group (22))
- Large Δh through optical fibers

Outline

- **Quantum systems as „test masses"**

  a brief (very incomplete) survey on table-top quantum experiments that probe gravity

- **Quantum systems as „source masses"?**

  ‚what prevents this from becoming a practical experiment?'

- **Quantum control of levitated massive systems**

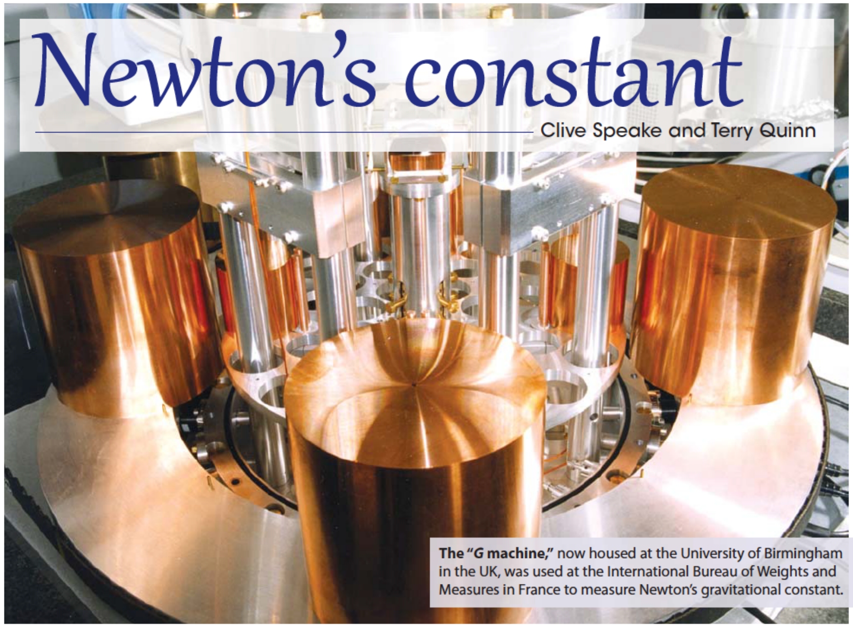
  towards a „quantum Cavendish" experiment

20µm

Big G: the open problem

The search for Newton's constant

Clive Speake and Terry Quinn



The "G machine," now housed at the University of Birmingham in the UK, was used at the International Bureau of Weights and Measures in France to measure Newton's gravitational constant.

Three decades of careful experimentation have painted a surprisingly hazy picture of the constant governing the most familiar force on Earth.

Physics Today July 2014

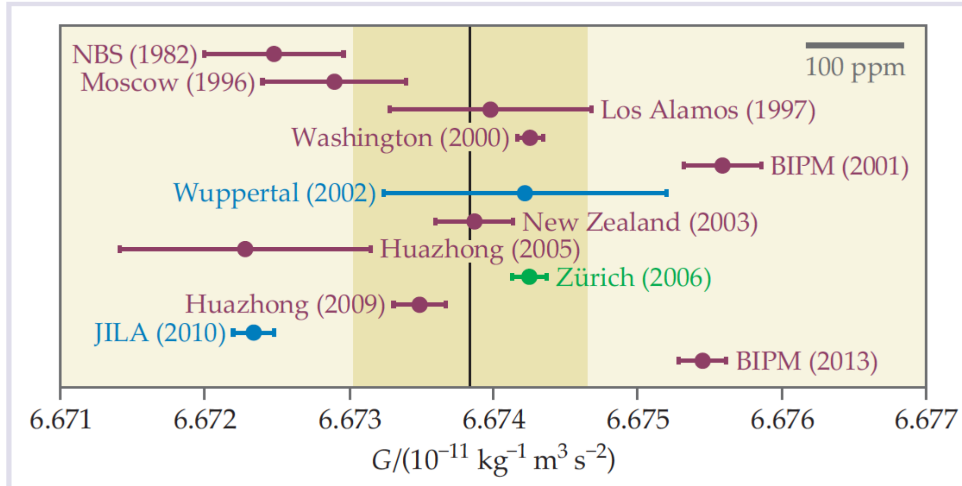


Figure 1. Measurements of Newton's gravitational constant *G* have yielded conflicting results. Here, the results of torsion-balance (maroon), pendulum (blue), and beam-balance (green) experiments discussed in the text are shown, along with the location and year in which they were measured. Error bars correspond to one standard deviation; the shaded region indicates the assigned uncertainty of the value recommended by the Committee on Data for Science and Technology in 2010. (Adapted from T. J. Quinn et al., *Phys. Rev. Lett.* **111**, 101102, 2013.)

NEWS

NATURE|Vol 466|26 August 2010

G-whizzes disagree over gravity

Recent measurements of gravitational constant increase uncertainty over accepted value.

Big G: the open problem

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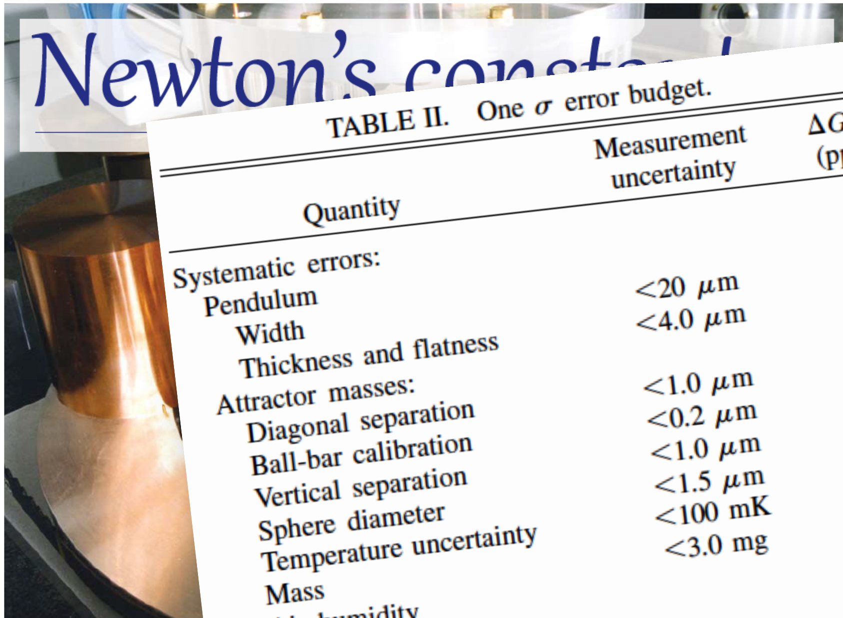
The search for Newton's constant

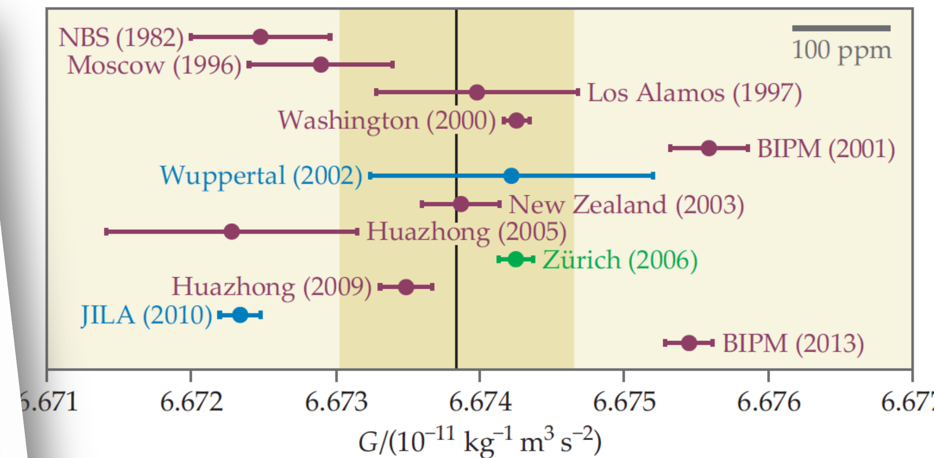


Three decades of car
hazy picture of the co

TABLE II. One σ error budget.

Quantity	Measurement uncertainty	$\Delta G/G$ (ppm)
Systematic errors:		
Pendulum		
Width	<20 μm	0.4
Thickness and flatness	<4.0 μm	4.0
Attractor masses:		
Diagonal separation	<1.0 μm	7.1
Ball-bar calibration	<0.2 μm	1.4
Vertical separation	<1.0 μm	5.2
Sphere diameter	<1.5 μm	2.6
Temperature uncertainty	<100 mK	6.9
Mass	<3.0 mg	0.4
Air humidity		0.5
Residual twist angle		0.3
Magnetic fields		0.6
Rotating temperature gradient		0.4
Time base	$<10^{-7}$	0.1
Data reduction		2.0
Statistical error:		5.8
Total:		13.7

Physics Today July 2014



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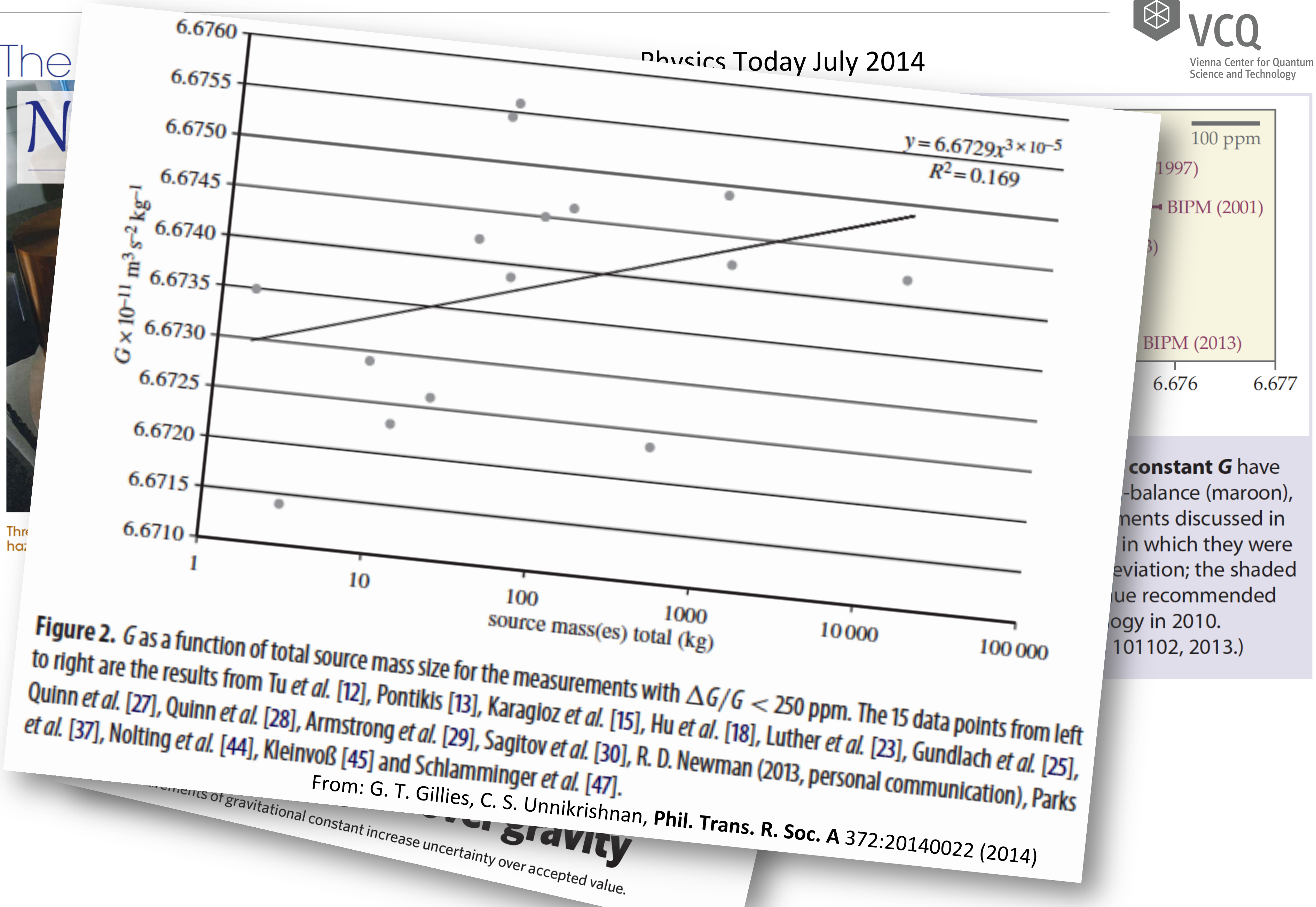
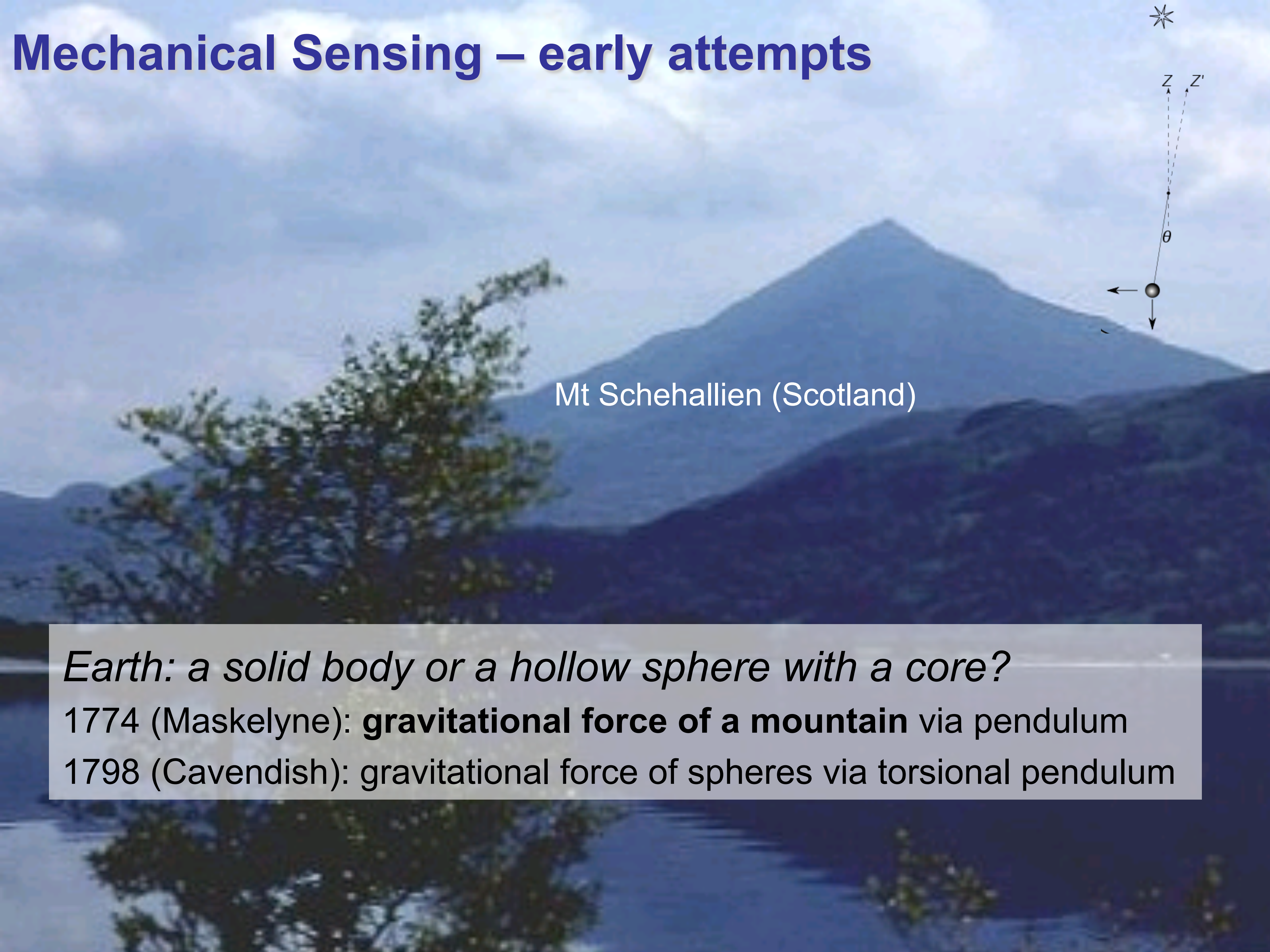


From: G. T. Gillies, C. S. Unnikrishnan, **Phil. Trans. R. Soc. A** 372:20140022 (2014)

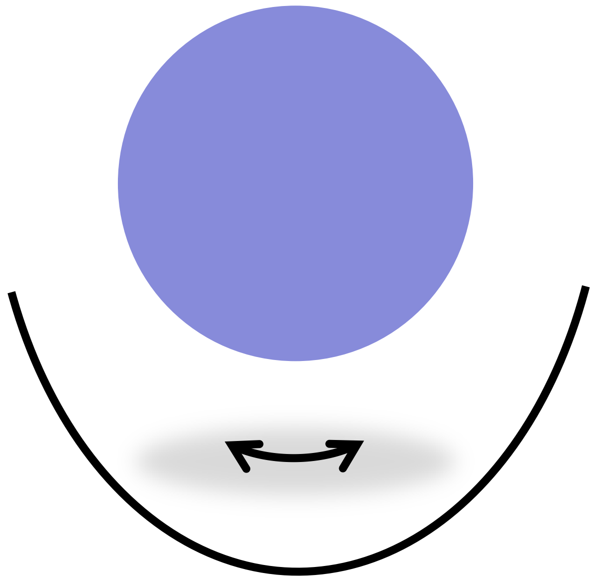
Mechanical Sensing – early attempts



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

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

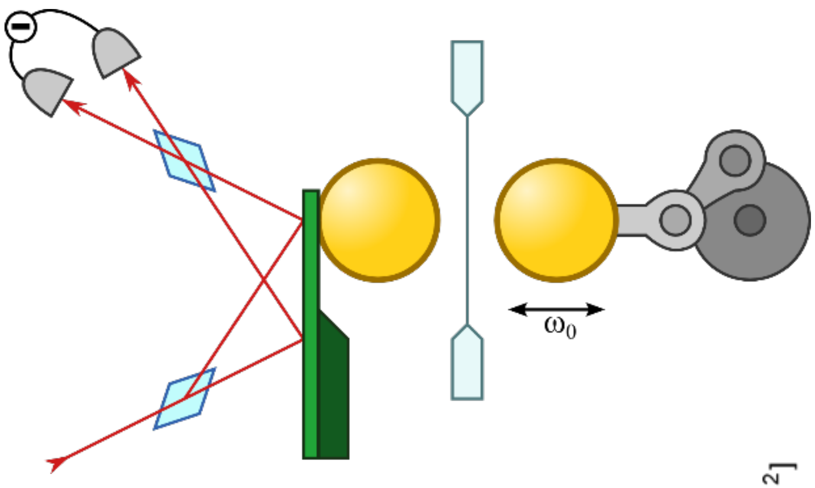
1798 (Cavendish): gravitational force of spheres via torsional pendulum

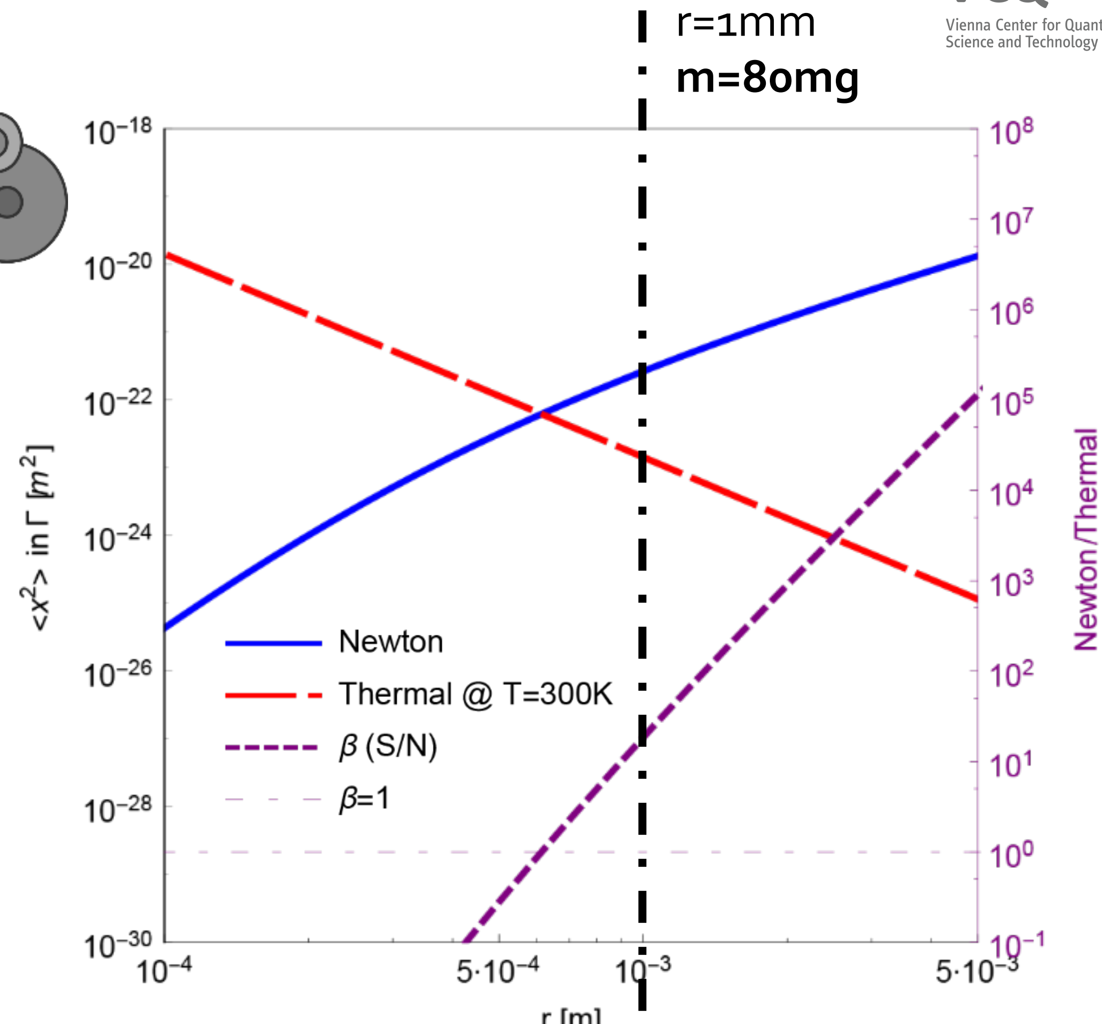


{T, Q , ω, m}

Thermal force noise $$F_{th} = \sqrt{k_B T m \left({}^{\omega}\!/\!{}_{Q} \right) \left({}^{1}\!/\!{}_{\tau} \right)}$$

Measuring gravity between microscopic source masses ?





Example

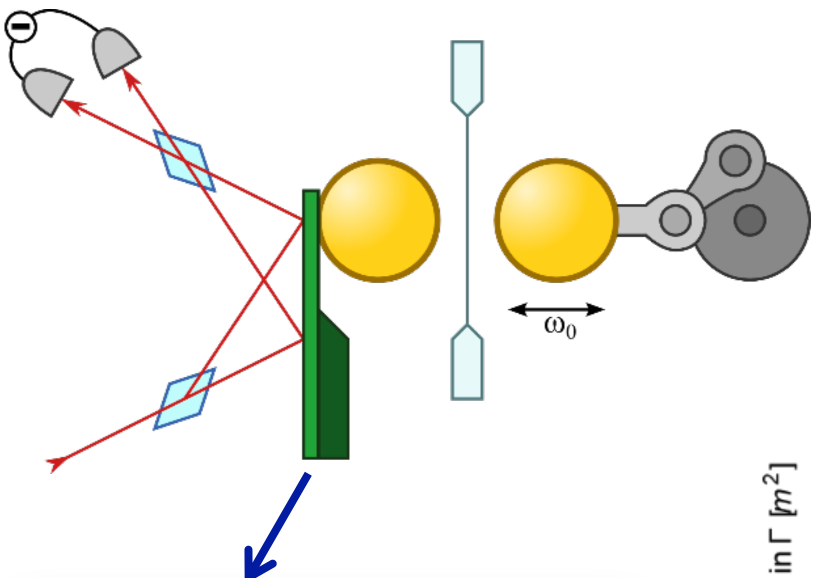
- f_o = 100 Hz
- Q = 20,000
- T = 300 K
- ρ = 20,000 kg/m³ (gold)
- Γ = 1/(60 min)

Smallest source mass to date: **100 g**

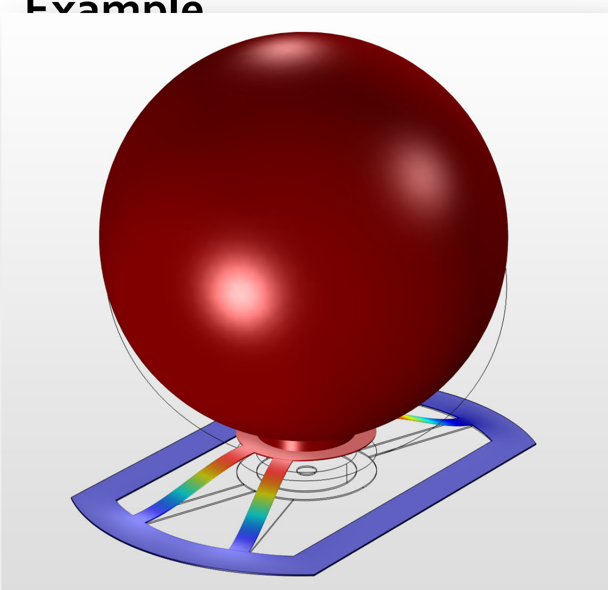
W. Michaelis et al., Meterologia 32, 267–276 (1995)

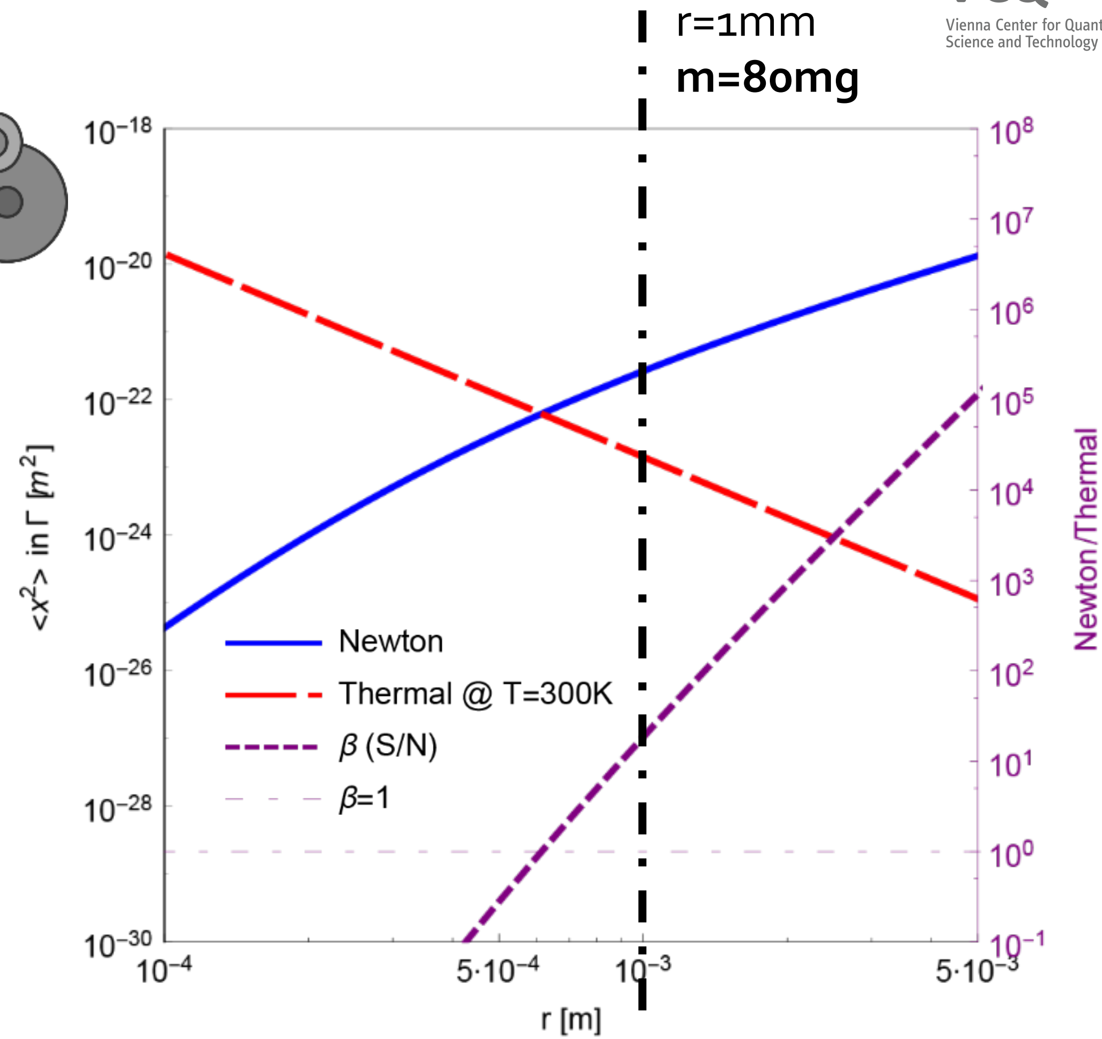
Jonas Schmöle, Mathias Dragosits, Hans Hepach

Measuring gravity between microscopic source masses ?



Example





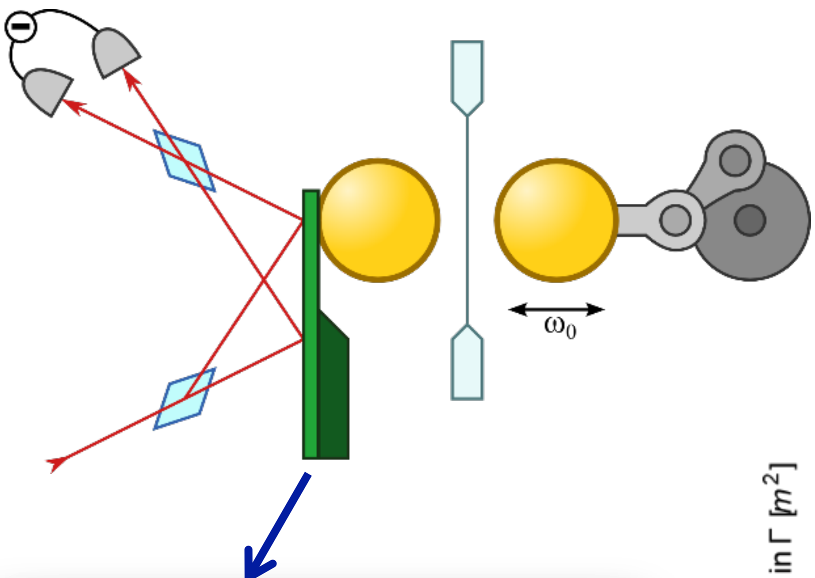
SiN cantilever with micromirror + 1mm gold sphere (in progress)

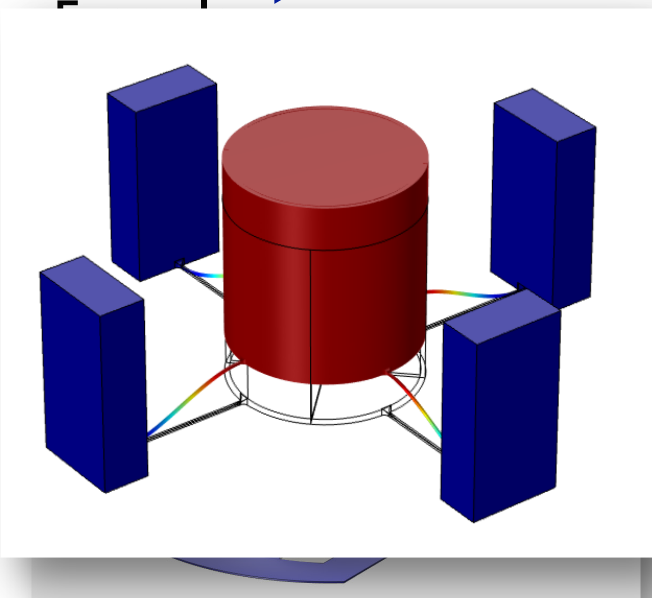
Smallest source mass to date: **100 g**

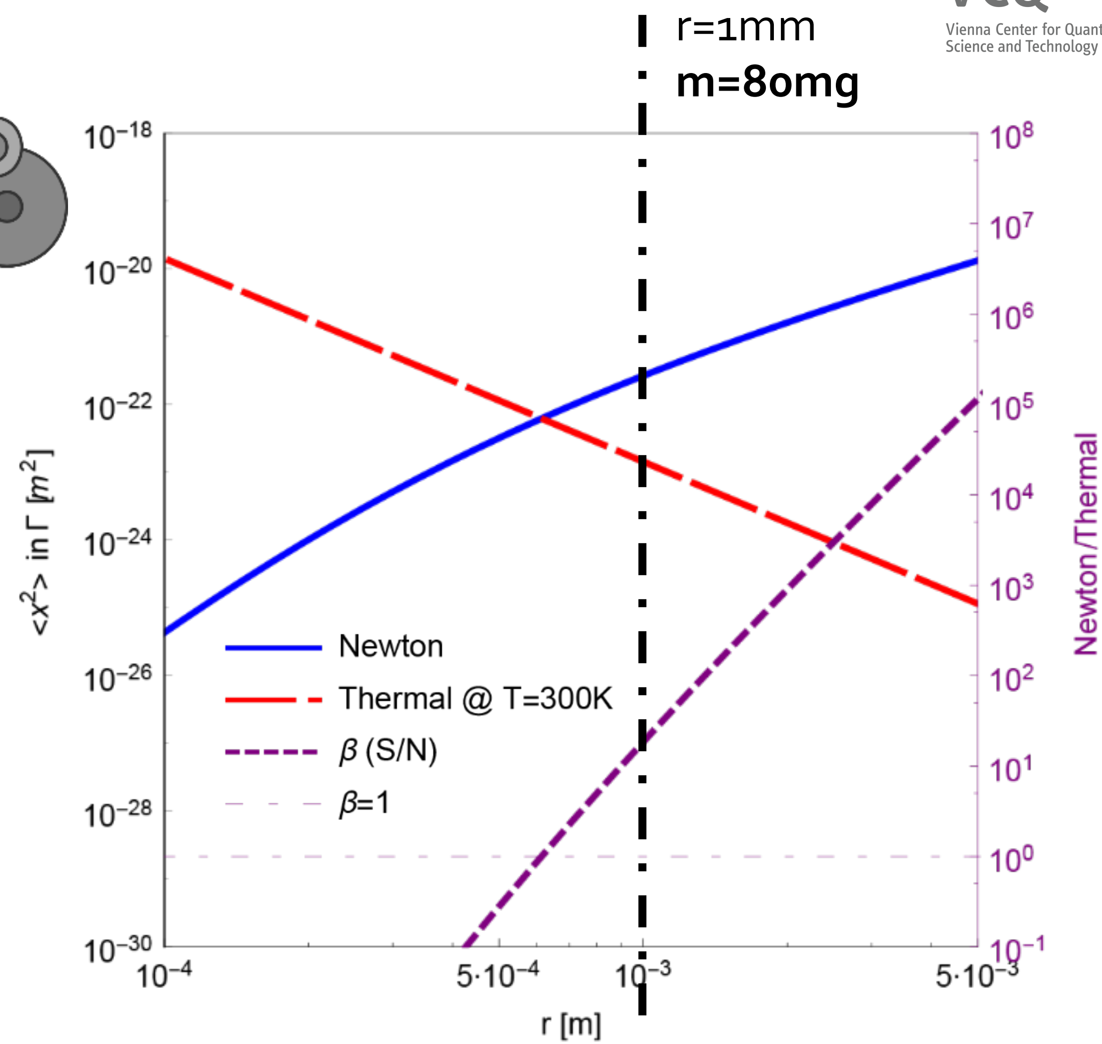
W. Michaelis et al., Meterologia 32, 267–276 (1995)

Jonas Schmöle, Mathias Dragosits, Hans Hepach

Measuring gravity between microscopic source masses ?







Si on SiN membrane (in progress)

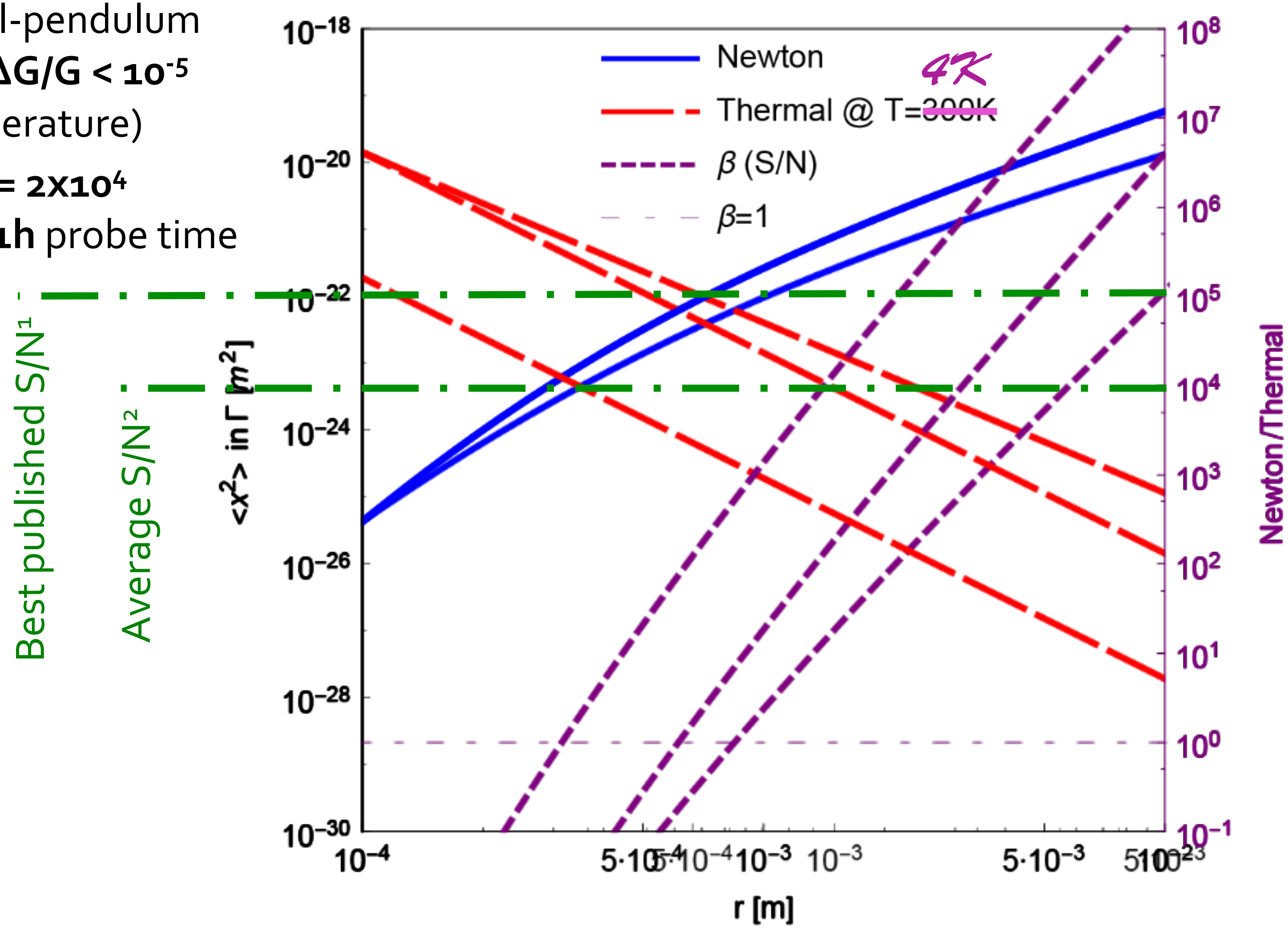
Smallest source mass to date: **100 g**

W. Michaelis et al., Meterologia 32, 267–276 (1995)

Jonas Schmöle, Mathias Dragosits, Hans Hepach

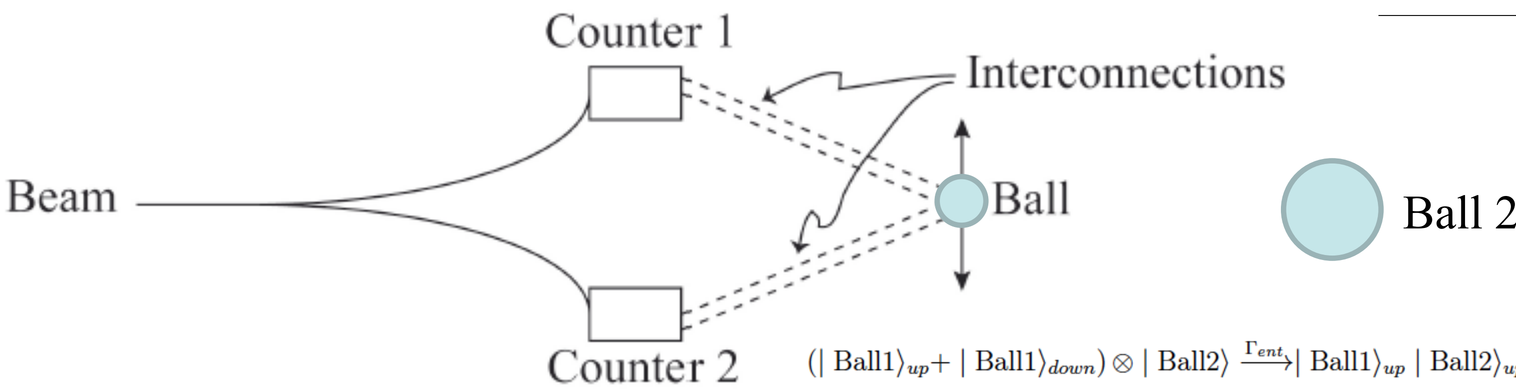
Potential Application for "Big G" measurement

- >**10mm** diameter spheres
- reach torsional-pendulum like precision **ΔG/G < 10^{-5}** (at room temperature)
- This is for a **Q = 2×10^4** oscillator and **1h** probe time



[1] J.H. Gundlach and S.M. Merkowitz, Phys. Rev. Lett. 85 2869 (2000)
[2] G. T. Gillies and C. S. Unnikrishnan, Phil. Trans. R. Soc. A 2014 372 (2014)

An ultimate experiment? Entanglement by gravity…



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

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?"

An ultimate experiment? Entanglement by gravity…

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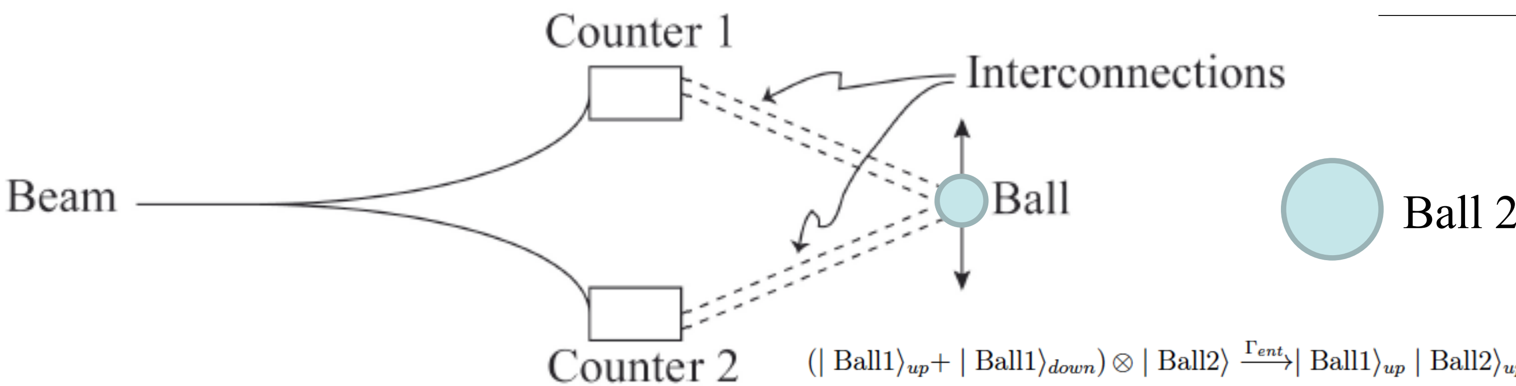

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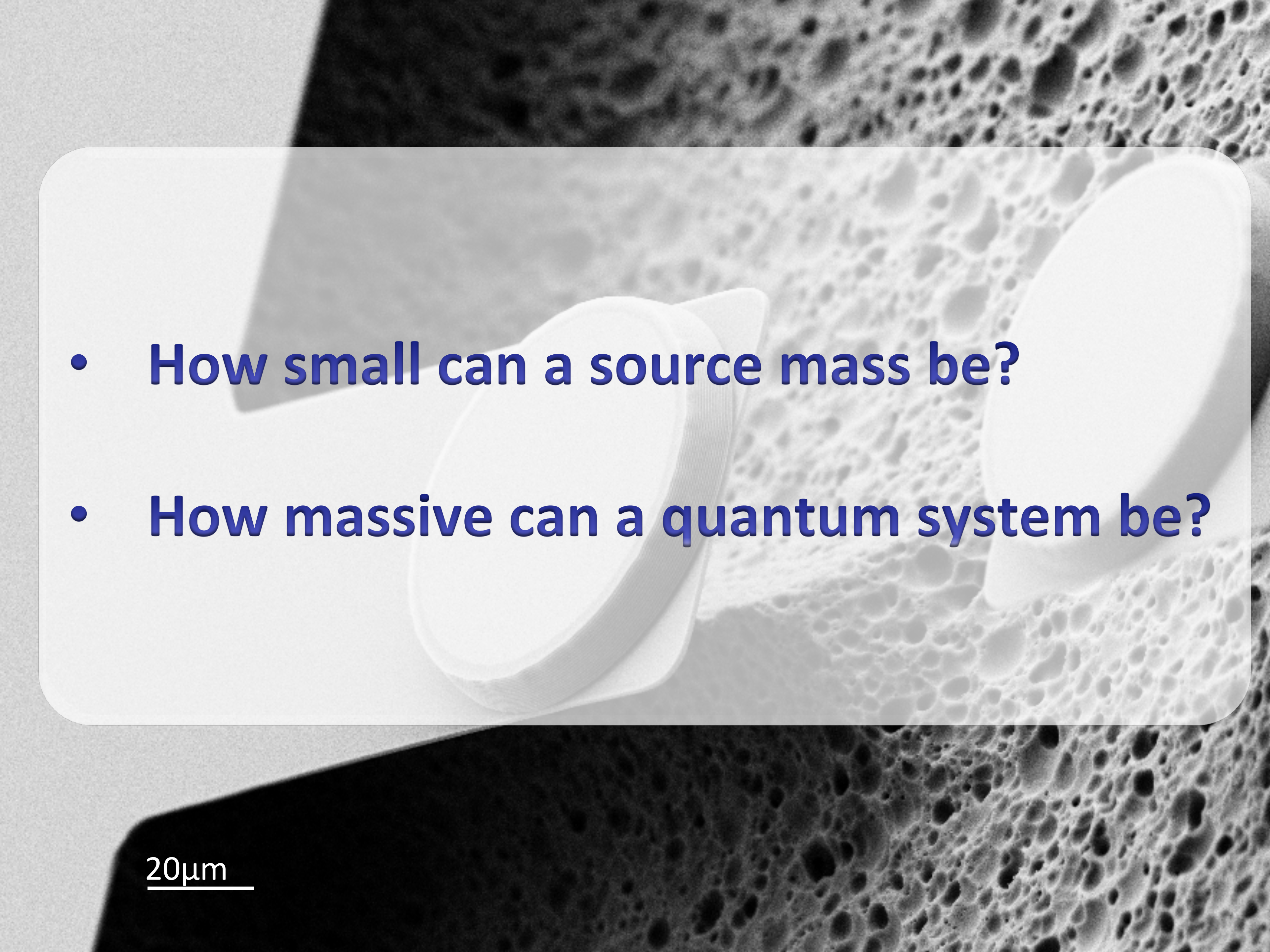
Chapel Hill Conference 1957 (29)

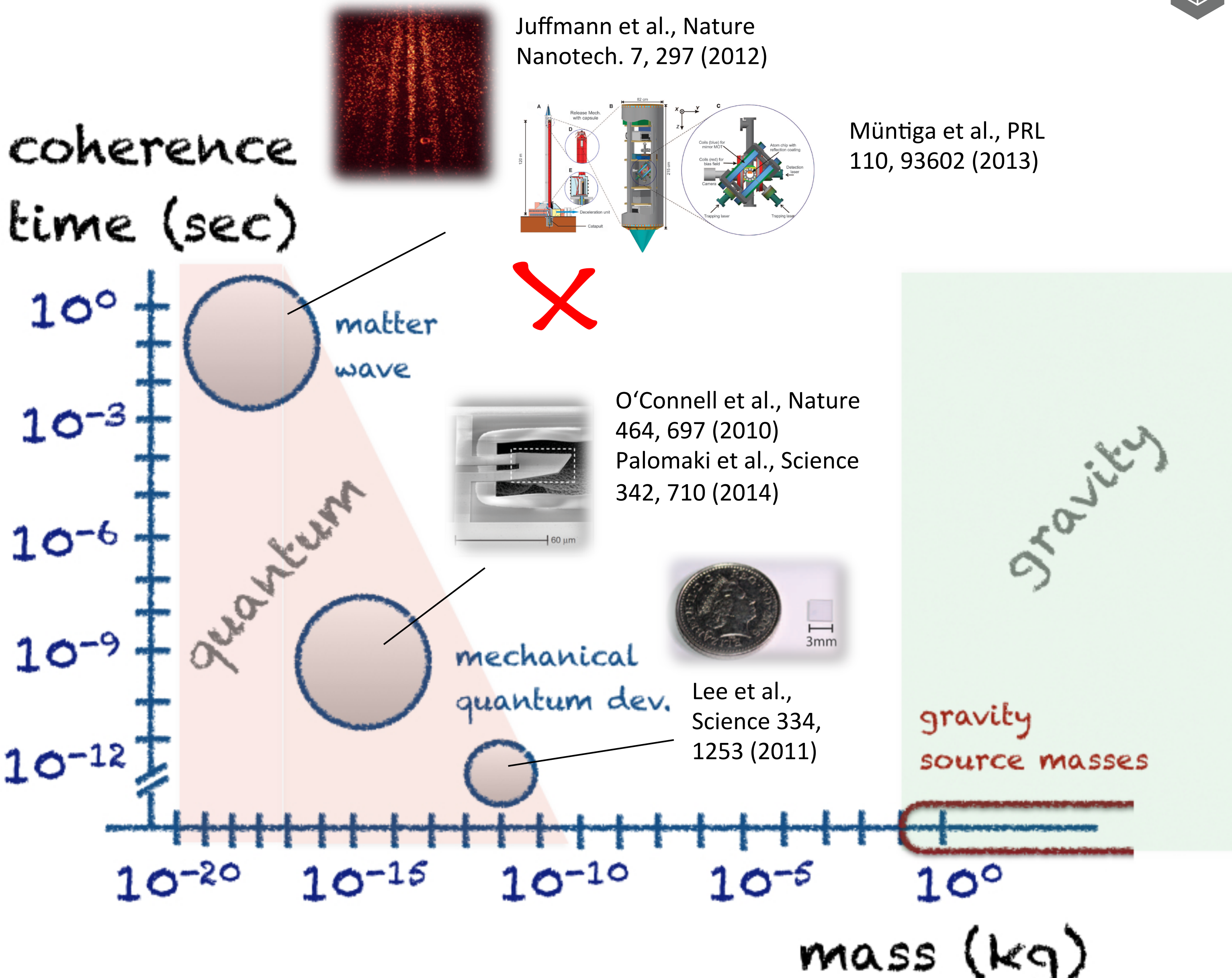
Example: For 2 **lead spheres** of **diameter 500 µm**, an initial **superposition size for sphere 1** of **$\Delta r = 5\times10^{-7}$ m** and preparation of **sphere 2** in a **motional ground state** (100 Hz trap frequency) with **$\Delta x_0 = 10^{-15}$ m**, we obtain **Γ_{ent}=1.5 Hz**, i.e. **gravitational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

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

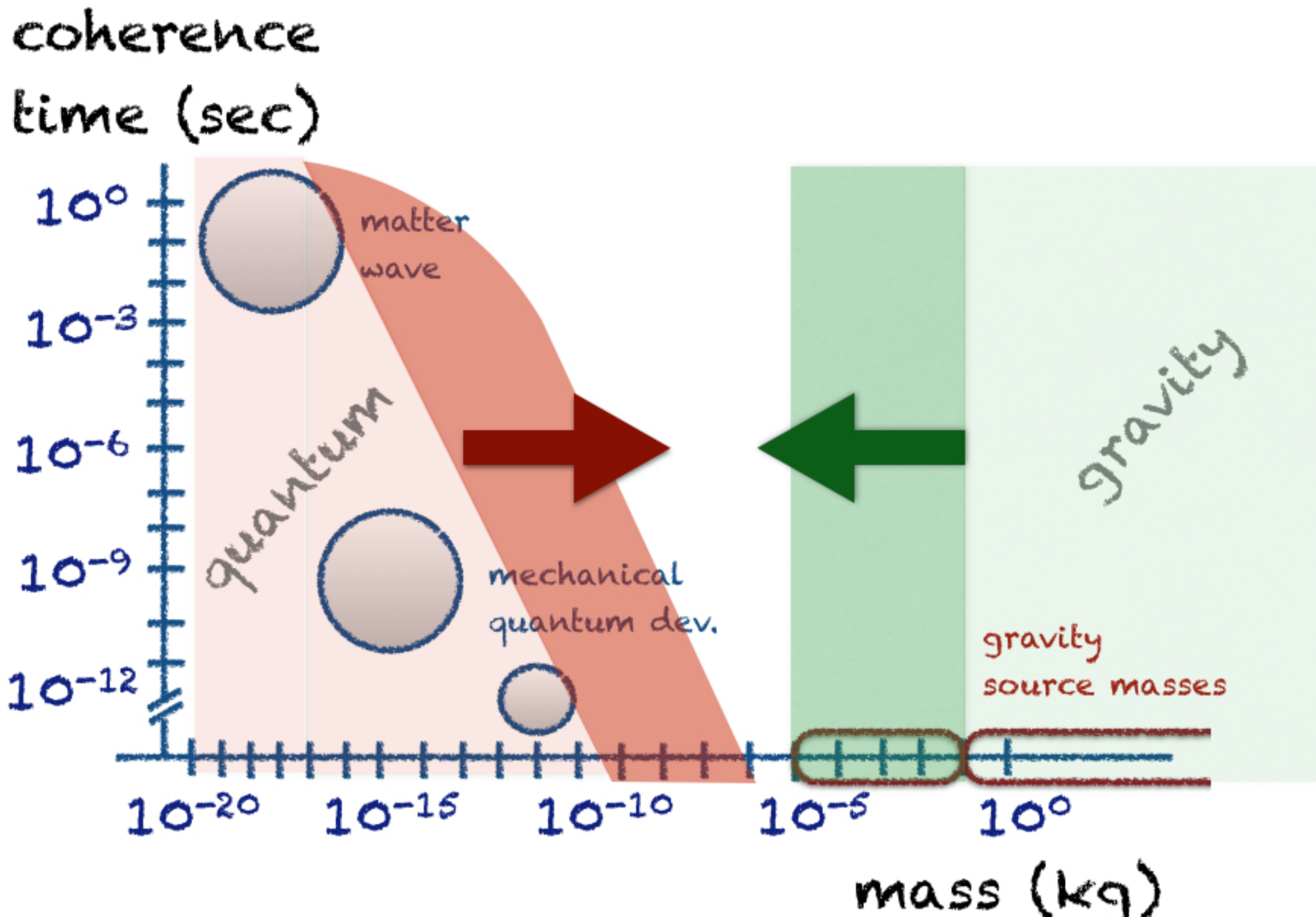
- **How small can a source mass be?**
- **How massive can a quantum system be?**



How massive/small can we go?



How massive/small can we go?



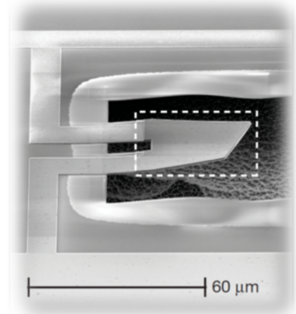
Pushing mechanical quantum control to the next level

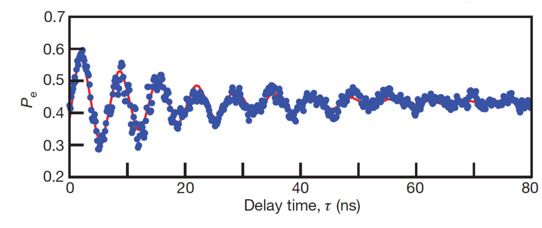
Q: How to achieve large mass **AND** long coherence time in a quantum experiment?

Solid-state mechanical quantum devices (clamped):

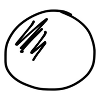
10^{10} – 10^{16} atoms

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





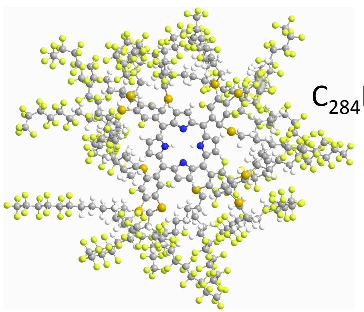
O'Connell et al., Nature 464, 697 (2010)



Matter-wave interferometry (free-fall):

10^{0} – 10^{4} atoms

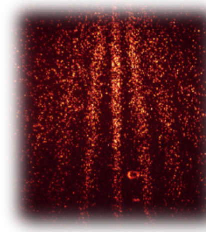
Coherence time τ_c 10^{-3} – 10^{0} sec



10 nm

TPPF320

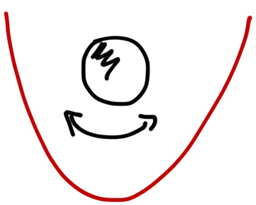
$C_{284}H_{190}F_{320}N_4S_{12}$



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

A: Quantum control of levitated mechanical systems!

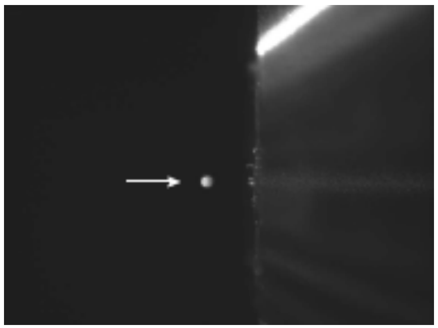
Coupling to gravity



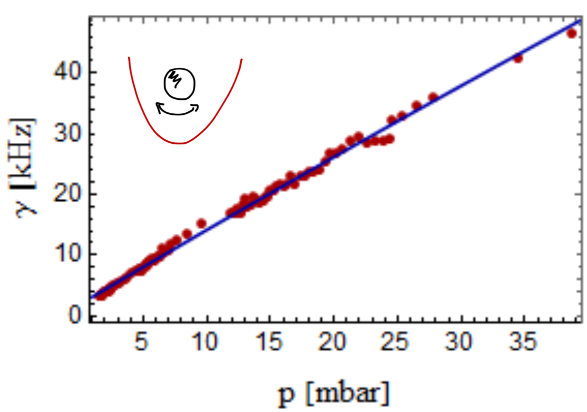
- Quantum control of a trapped massive object >> 10^{10} atoms
- Long coherence times (up to seconds) through free fall dynamics
- Exceptional force sensitivity

Isolation of COM motion from the environment: Levitated nanospheres as high-Q mechanical oscillators

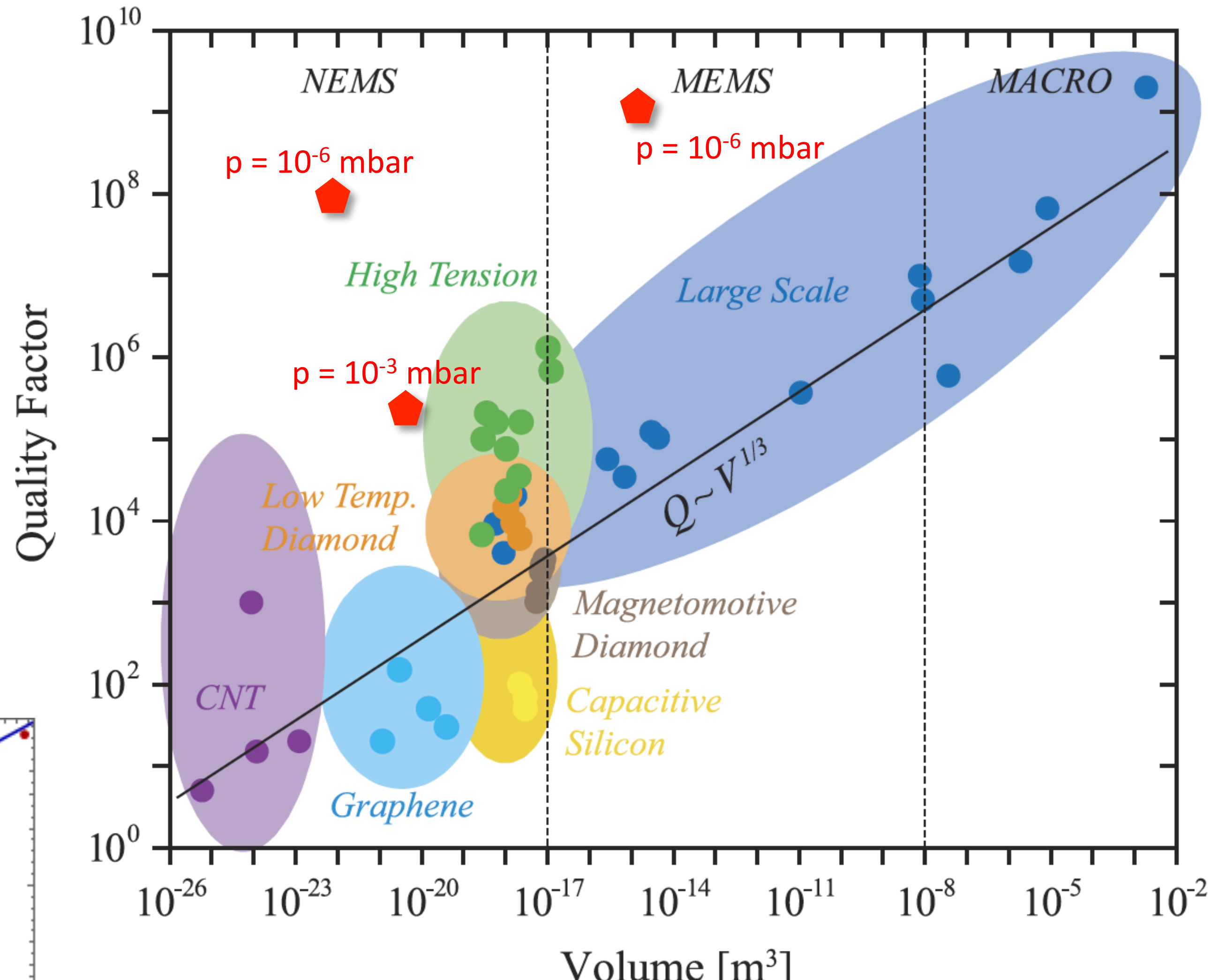
J. Gieseler, R. Quidant, C. Dellago, L. Novotny, Nature Nanotechnology 9, 358 (2014)
(70 nm SiO_2)



D. Grass (Vienna)
(350 nm SiO_2
inside hollow core fibre)



Ashkin & Dziedzic, APL 28, 333 (1976)
(20um Si oil)



M. Imboden, P. Mohanty, Phys. Rep. 534, 89 (2014)

Towards quantum state preparation of a free particle

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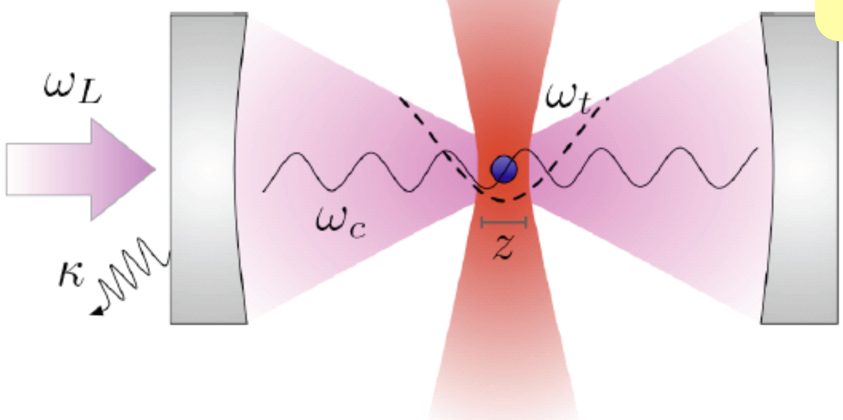
Optically levitated nanospheres

Magnetically levitated spheres

(Romero-Isart et al., 1112.5609
Cirio et al., 1112.5208)



Chang et al., quant-ph 0909.1548 (2009), PNAS 2010
Romero-Isart et al., quant-ph 0909.1469 (2009), 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.)

Generation of quantum superposition states

- single-photon quantum state transfer
- quantum state teleportation
- …
- ***free fall . . .***

- Akram, Kiesel, Aspelmeyer, Milburn, NJP 12, 083030 (2010)
- Khalili, Danilishin, Miao, Müller-Ebhardt, Yang, Chen, quant-ph 1001.3738 (2010)
- Romero-Isart, Pflanzer, Juan, Quidant, Kiesel, Aspelmeyer, Cirac, Phys. Rev. A 83, 013803 (2011)

Towards quantum state preparation of a free particle

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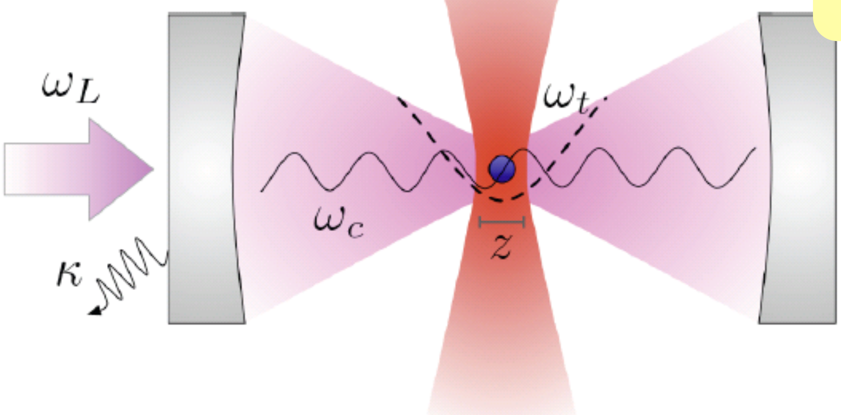
Optically levitated nanospheres

Magnetically levitated spheres

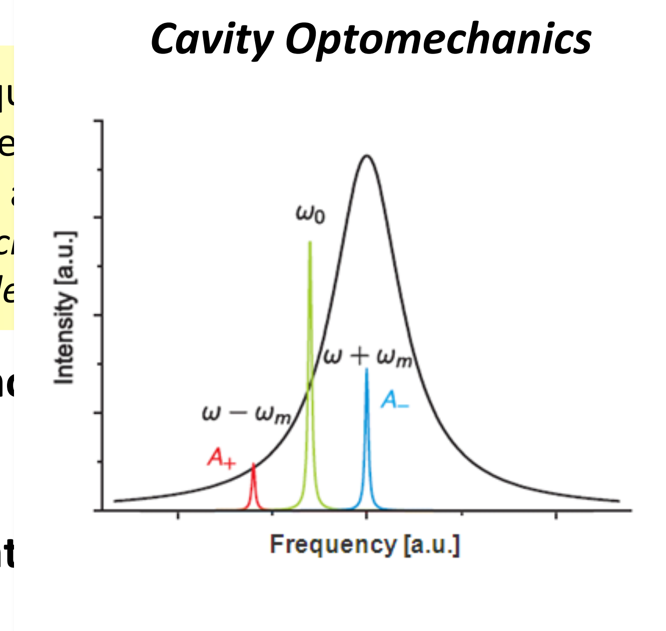
(Romero-Isart et al., 1112.5609
Cirio et al., 1112.5208)



Chang et al., qu … 2010
Romero-Isart e
P. F. Barker et a
early work: Hec … 1998)
Vule

→ **Harm**

→ **Quant … ics**



Generation of quantum superposition states

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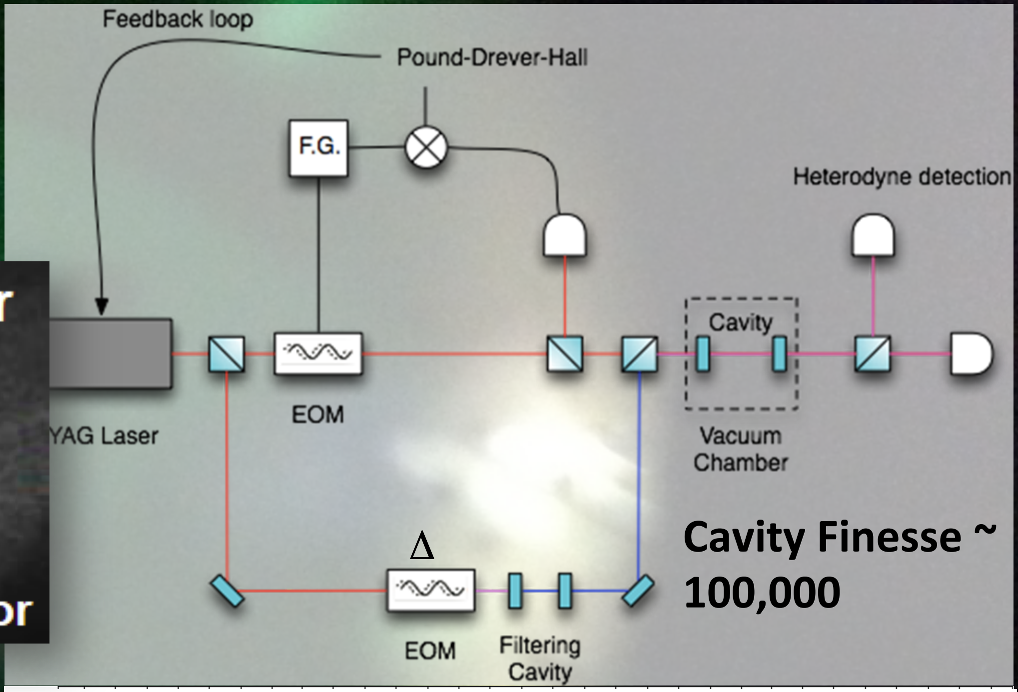
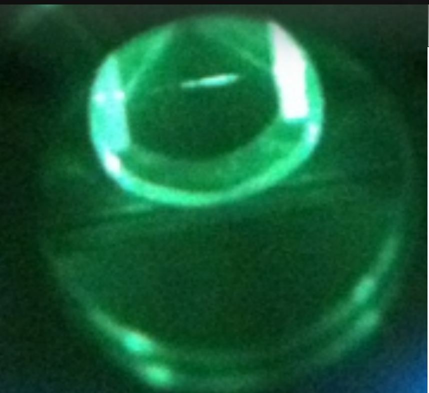
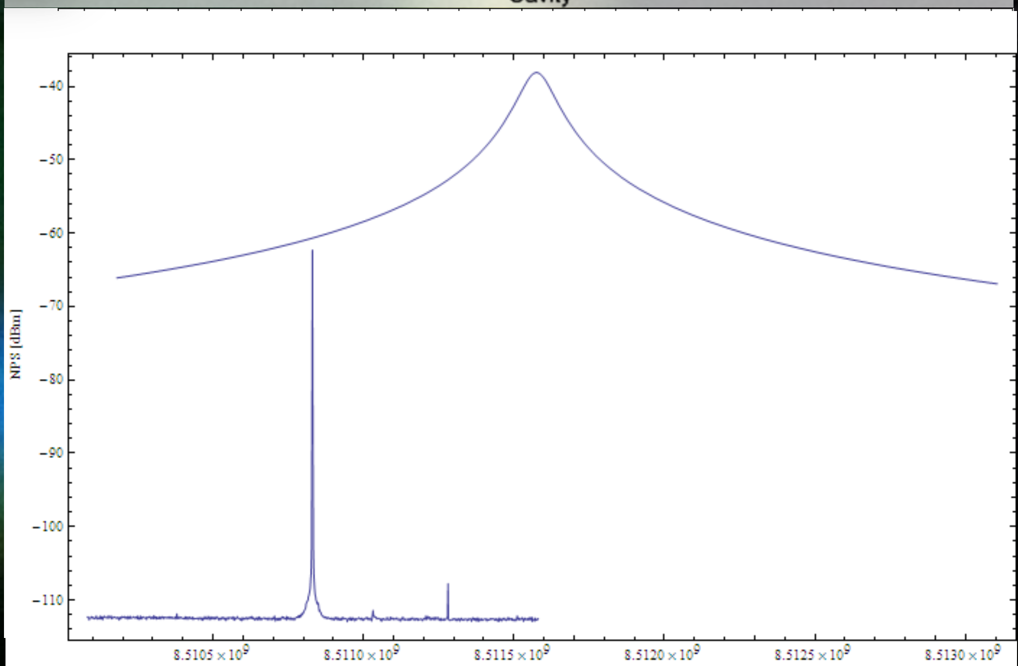
- Romero-Isart, Pflanzer, Juan, Quidant, Kiesel, Aspelmeyer, Cirac, Phys. Rev. A 83, 013803 (2011)

Optically trapped nanospheres as mechanical resonators

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

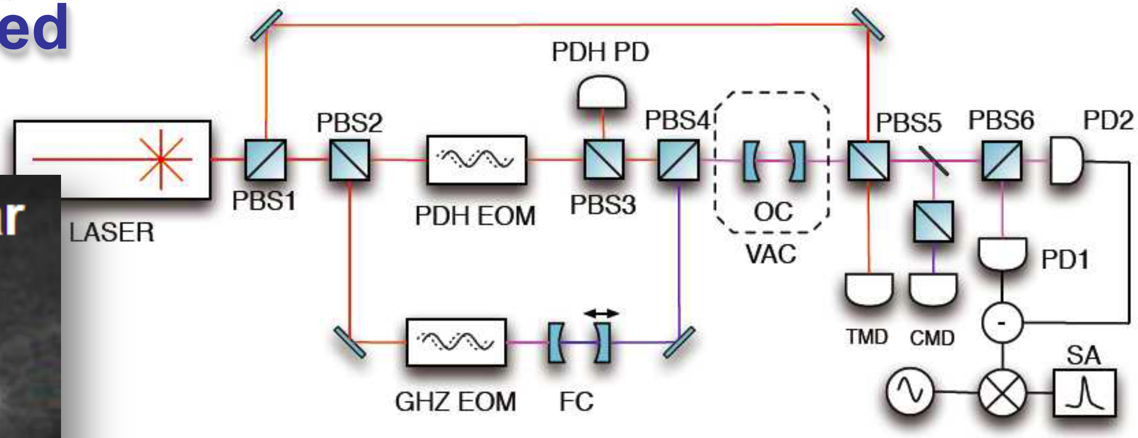






Optical trapping inside a cavity… (R~20nm – 2µm)
Kiesel, Kaltenbaek, Blaser, Delic et al., work in progress

Cavity cooling of a trapped nanosphere



κ ≈ 180 kHz, FSR ≈ 13.6 GHz, F ≈ 78,000

$Q \sim 25$ @ 4 mbar

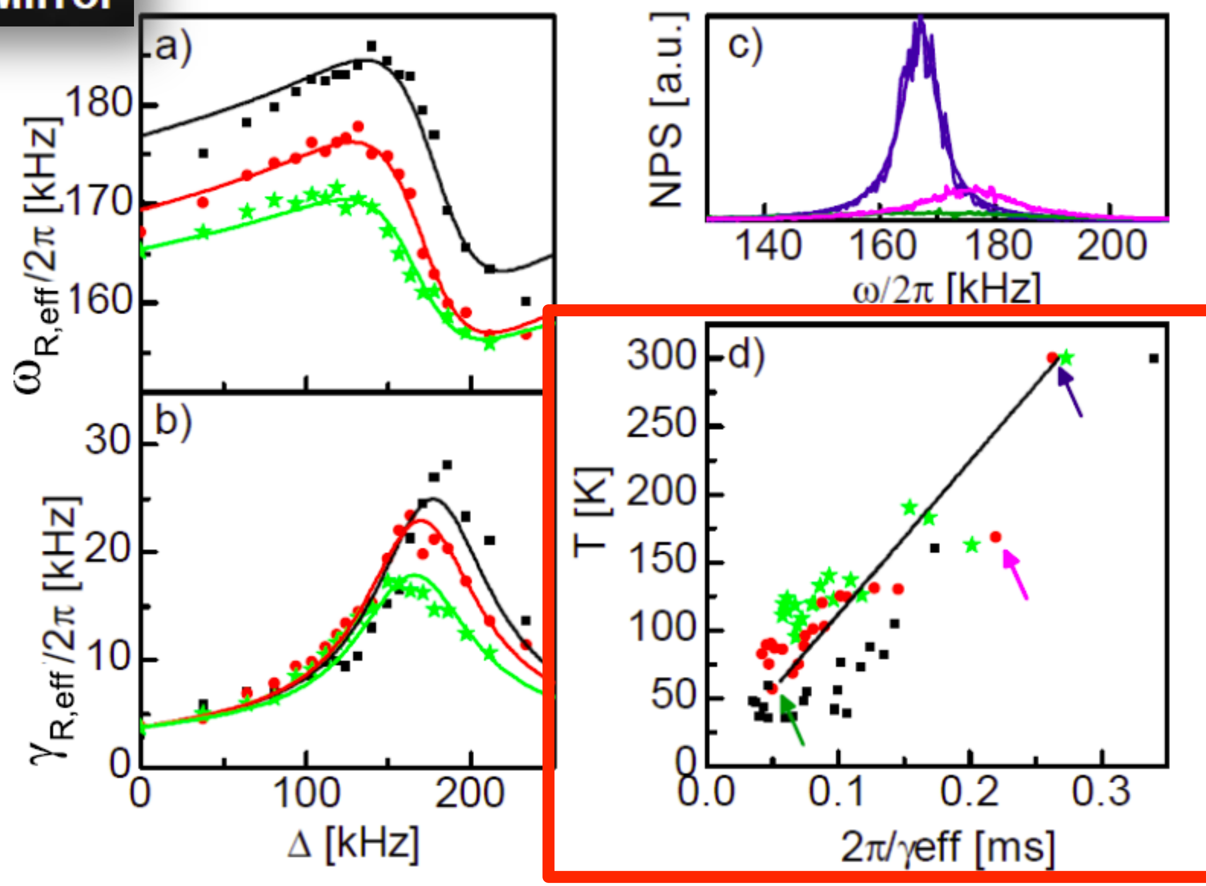
$Q \sim 10^9$ @ 10^{-7} mbar

$\Rightarrow 10^{-21}\ N/\sqrt{Hz}$

100 μm

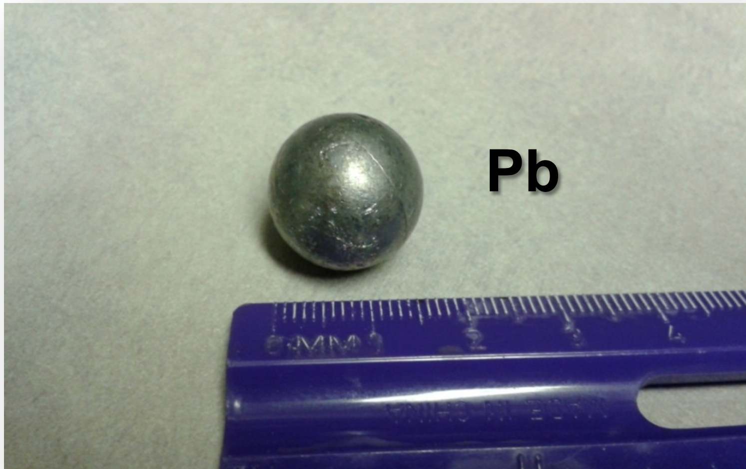
100 μm

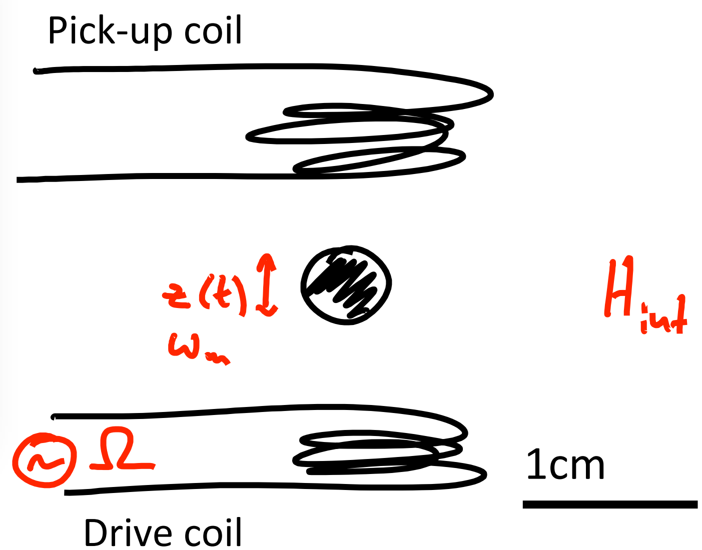
$F_c \sim 10^{-19}\ N$



N. Kiesel, F. Blaser, U. Delic, D. Grass, R. Kaltenbaek, M. Aspelmeyer, *PNAS USA* **110**, 14180 (2013)
See also: P. Asenbaum et al., *Nat. Comm.* **4**, 2743 (2013)

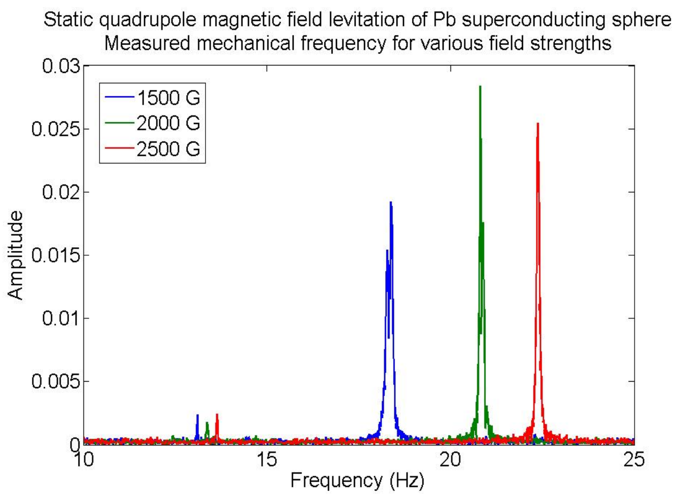
Magnetically trapped superconductors as mechanical resonators

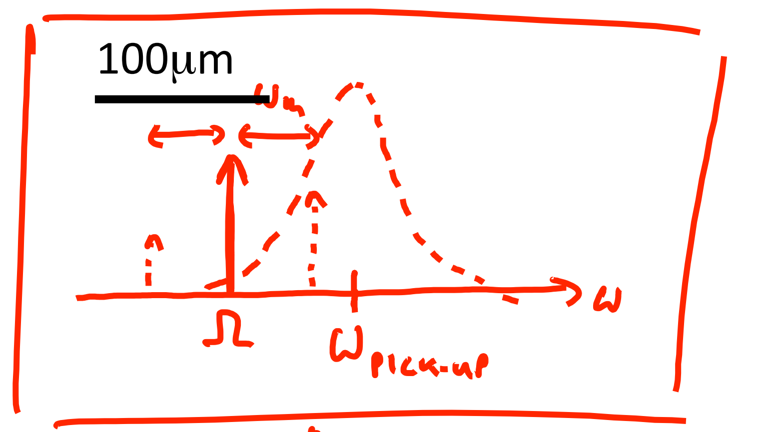




$$H_{int} \propto -\frac{\Phi_1 \Phi_2}{L_1 L_2} M_{12}(z)$$

M_{12} : mutual inductance





"CAVITY OPTO-MECHANICS"

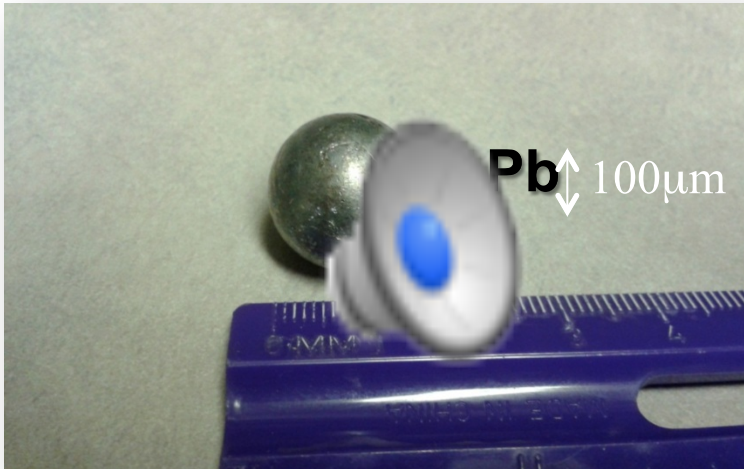
Magnetic levitation in anti-Helmholtz coil configuration

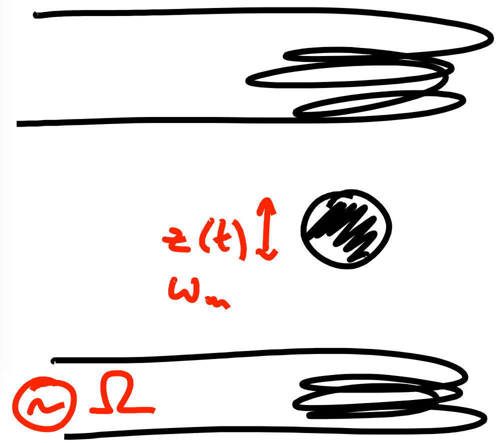
Trap frequencies ~ 20 Hz

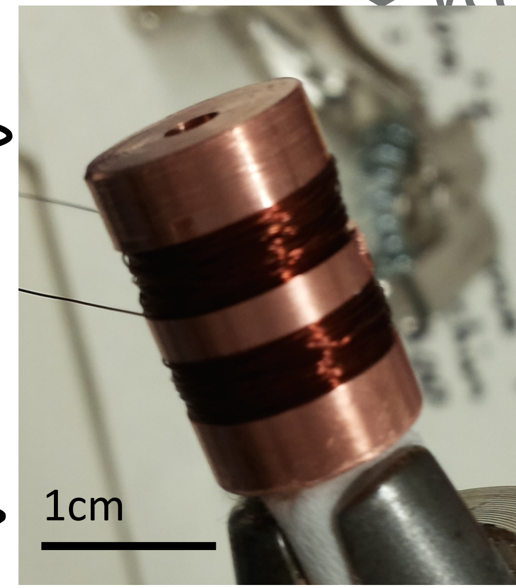
T= 20 mK, p = 1e-6 mbar

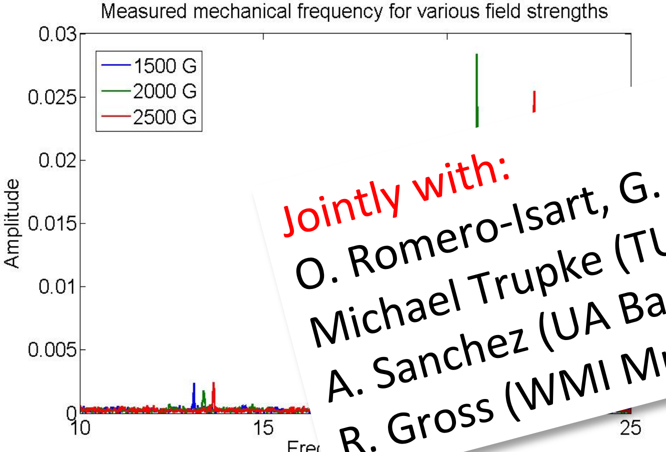
S. Minter, R. Chiao, N. Prigge, M. Aspelmeyer

Magnetically trapped superconductors as mechanical resonators

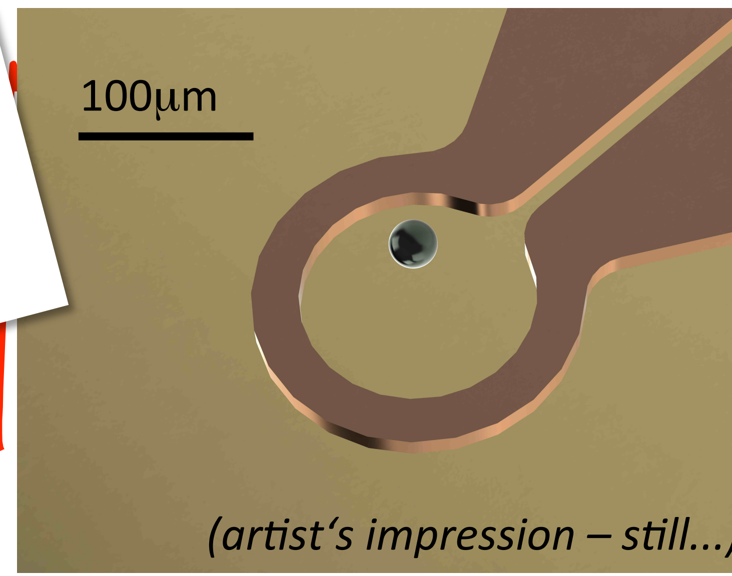








Jointly with:
O. Romero-Isart, G. Kirchmair (IQOQI)
Michael Trupke (TU Vienna)
A. Sanchez (UA Barcelona)
R. Gross (WMI Munich)



(artist's impression – still...)

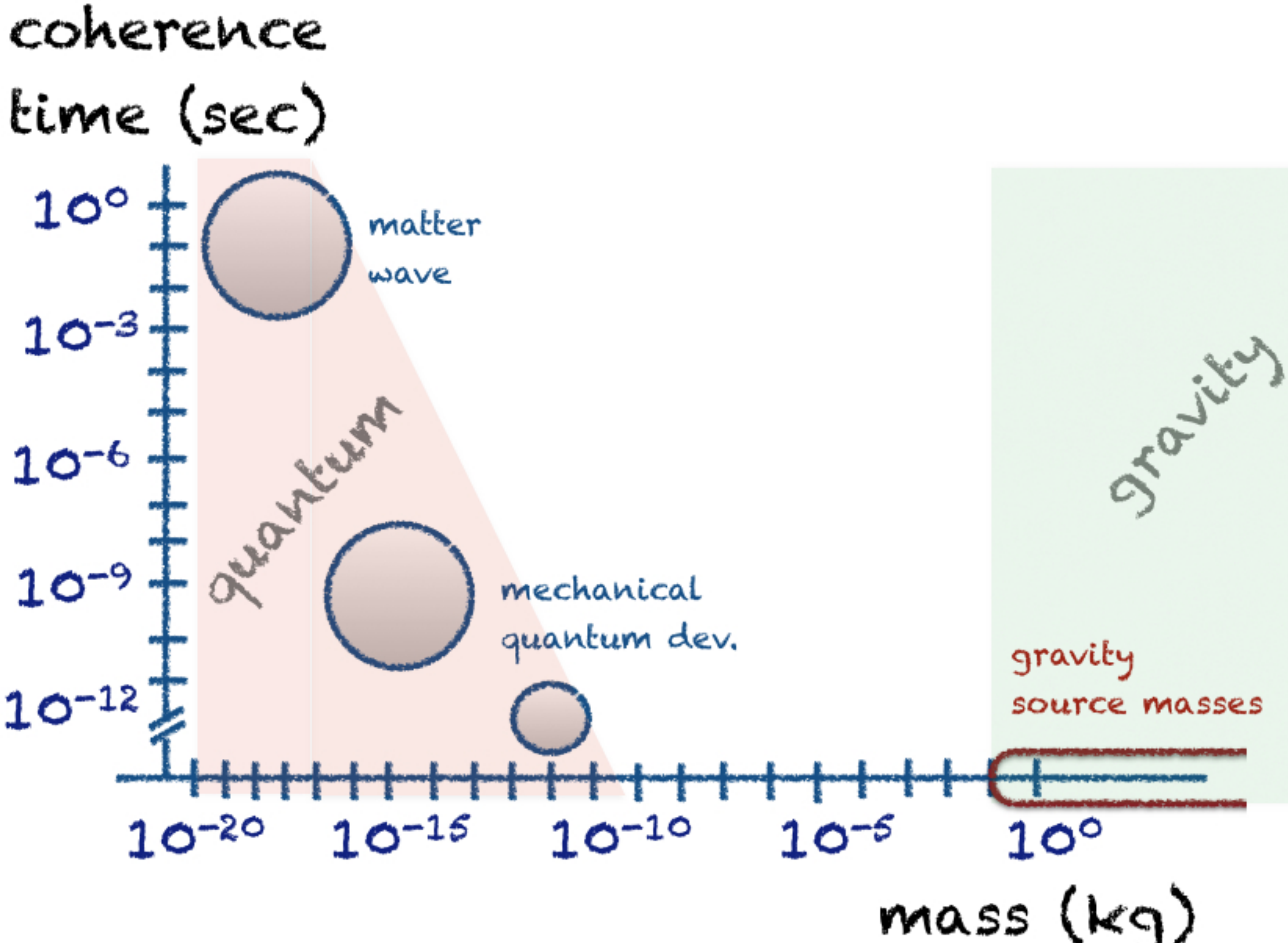
Magnetic levitation in anti-Helmholtz coil configuration

Trap frequencies ~ 10 kHz

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

J. Slater, J. Hofer, C. Wieczorek, **M. Aspelmeyer**

How massive can we go?



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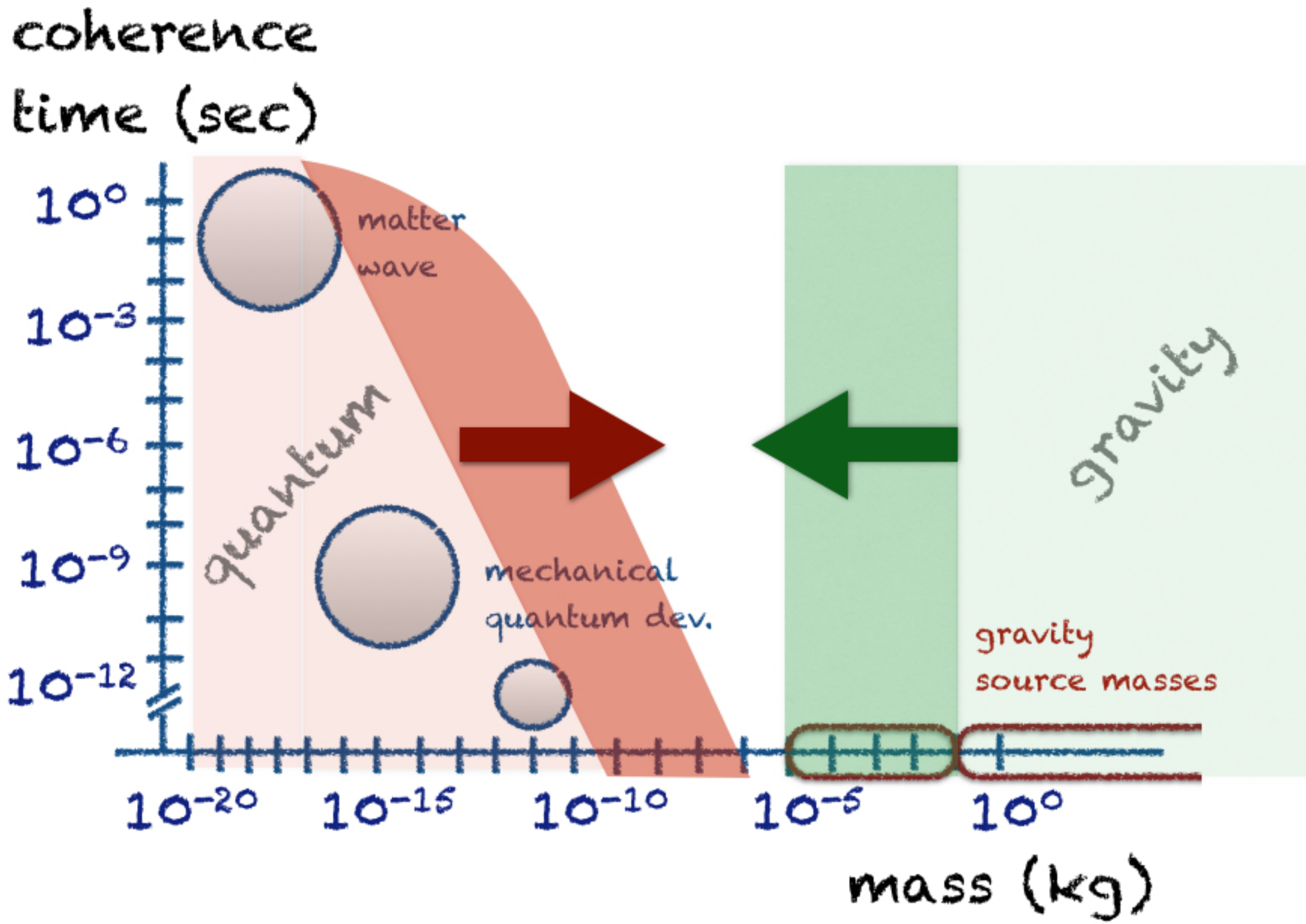

How massive can we go?

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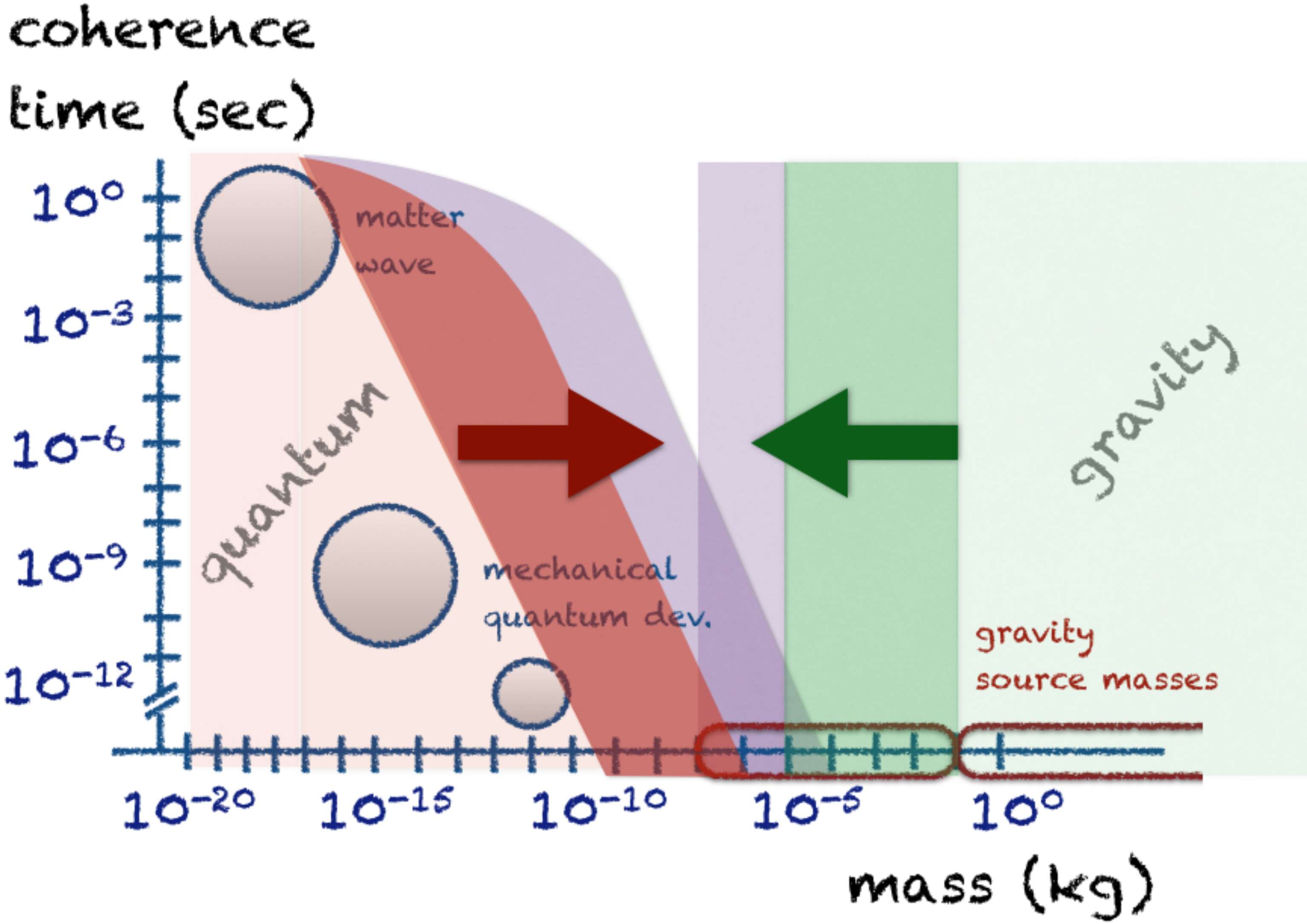
VCQ
Vienna Center for Quantum Science and Technology



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

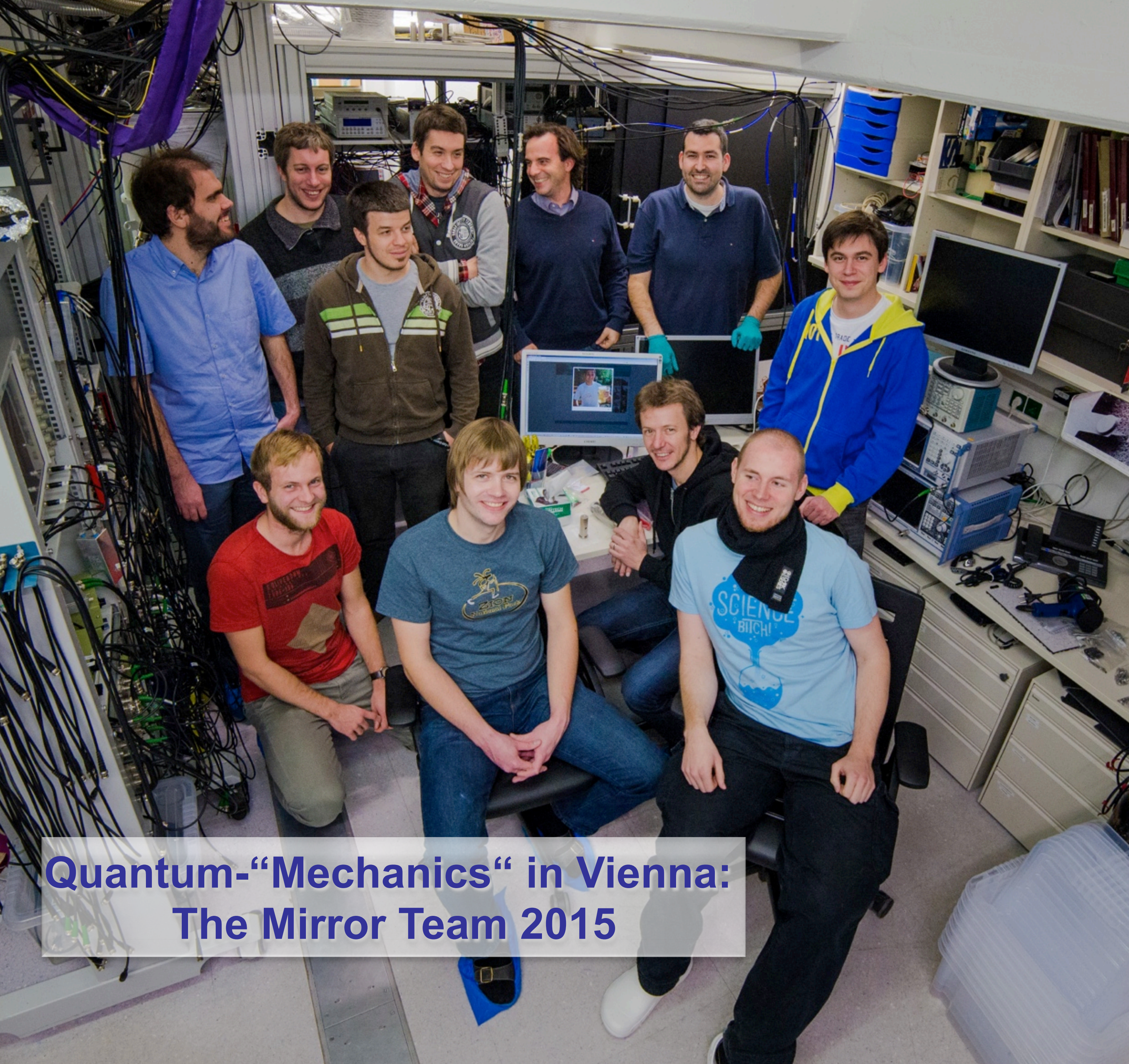
- **Optical levitation** coupled to cavities
- **Magnetic levitation** coupled to superconducting circuits

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**



Quantum-“Mechanics“ in Vienna: The Mirror Team 2015

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VCQ
Vienna Center for Quantum Science and Technology

FWF
Der Wissenschaftsfonds.

WWTF
Vienna Science and Technology Fund

SEVENTH FRAMEWORK PROGRAMME

erc European Research Council

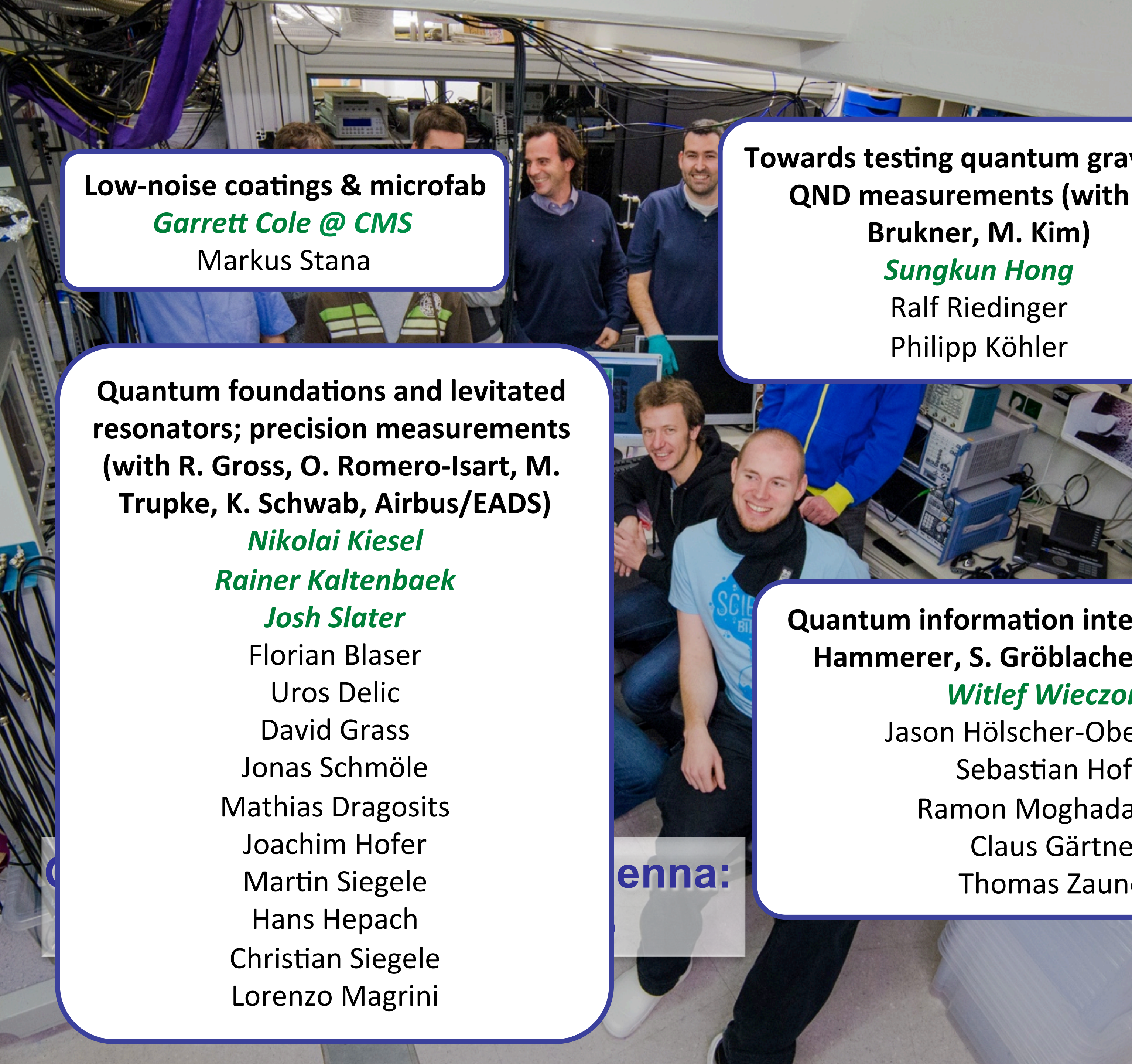
DARPA

cQOM

Alexander von Humboldt
Stiftung/Foundation

esa

EURAMET
European Association of National Metrology Institutes
EMRP
European Metrology Research Programme



Low-noise coatings & microfab

Garrett Cole @ CMS

Markus Stana

Towards testing quantum gravity & QND measurements (with C. Brukner, M. Kim)

Sungkun Hong

Ralf Riedinger

Philipp Köhler

Quantum foundations and levitated resonators; precision measurements (with R. Gross, O. Romero-Isart, M. Trupke, K. Schwab, Airbus/EADS)

Nikolai Kiesel

Rainer Kaltenbaek

Josh Slater

Florian Blaser

Uros Delic

David Grass

Jonas Schmöle

Mathias Dragosits

Joachim Hofer

Martin Siegele

Hans Hepach

Christian Siegele

Lorenzo Magrini

Quantum information interfaces (with K. Hammerer, S. Gröblacher, O. Painter)

Witlef Wieczorek

Jason Hölscher-Obermayer

Sebastian Hofer

Ramon Moghadas Nia

Claus Gärtner

Thomas Zauner