Seven Pines 2014

The Gravity-Quantum Interface

An experimental outlook

Markus Aspelmeyer

Vienna Center for Quantum Science and Technology (VCQ)

Faculty of Physics

University of Vienna, Austria

- The predictions of **quantum theory** and of **general relativity**, our current theory of gravity, are **extremely well confirmed by experiment**.
- There are **few table-top experiments to date** that probe the **interface between quantum physics and gravity**. In all these experiments, Earth's gravity acts as a **constant classical background field**. Loosely speaking, the quantum system is used as a **„test particle"** in an external gravitational field.
- The current accuracy of optical atomic clocks in combination with techniques from atom interferometry should already allow to perform experiments on **„superposition of clocks"**. I am confident that this will happen soon.
- On the other hand, the last decade has seen large progress in controlling the **quantum regime of massive micro-mechanical oscillators**. These systems may lead the way to a **new class of gravitational quantum physics experiments**, in which the quantum system itself, e.g. the center of mass degree of freedom of a massive sphere, serves as a **gravitational source mass**.
- These developments will lead to:
  - Tests of semiclassical gravity models
  - Observation of dephasing through superposition of clocks
  - Generation of quantum entanglement through gravity
  - Observation of decoherence through quantum gravity

„The predictions of quantum theory and of general relativity, our current theory of gravity, are extremely well confirmed by experiment.“

universität wien

VCQ
Vienna Center for Quantum Science and Technology

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)
- acoustic vibrational degrees of freedoms of mechanical resonators (up to 10^{11} amu) (7,8)

Examples from GR:

- dynamics of binary pulsars (9), CMB analysis (BICEP2) (10) **→ 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

„The predictions of quantum theory and of general relativity, our current theory of gravity, are extremely well confirmed by experiment.“

Nature **406**, 43 (2000)

Quantum superposition of distinct macroscopic states

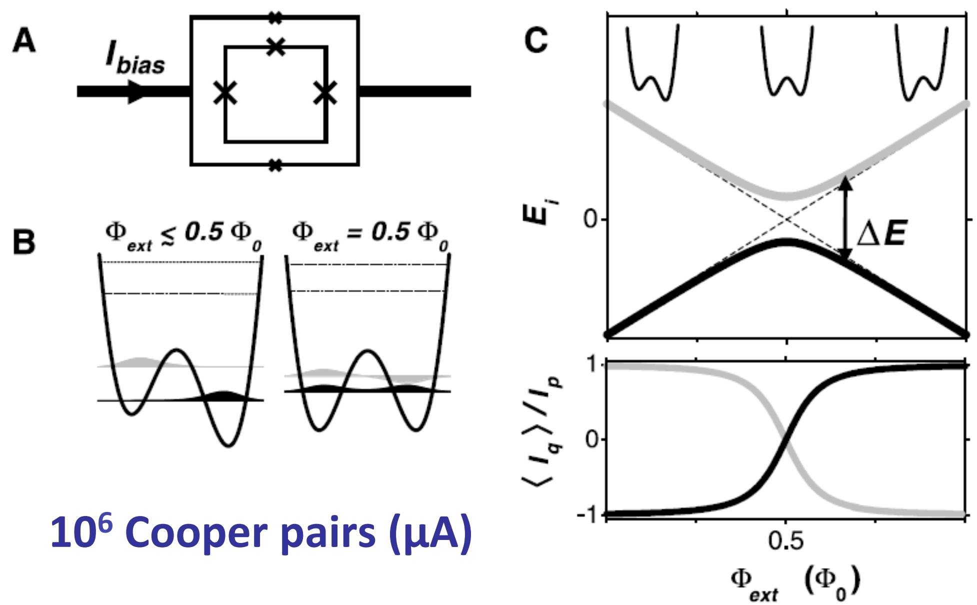
Jonathan R. Friedman, Vijay Patel, W. Chen, S. K. Tolpygo & J. E. Lukens

Department of Physics and Astronomy, The State University of New York, Stony Brook, New York 11794-3800, USA

Science **290**, 773 (2000)

Quantum Superposition of Macroscopic Persistent-Current States

Caspar H. van der Wal,[1*] A. C. J. ter Haar,[1] F. K. Wilhelm,[1] R. N. Schouten,[1] C. J. P. M. Harmans,[1] T. P. Orlando,[2] Seth Lloyd,[3] J. E. Mooij[1,2]



10^6 Cooper pairs (μA)

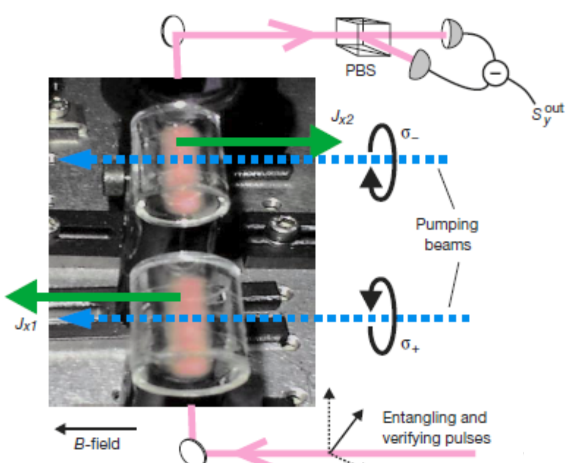
Nature **413**, 400 (2001)

Experimental long-lived entanglement of two macroscopic objects

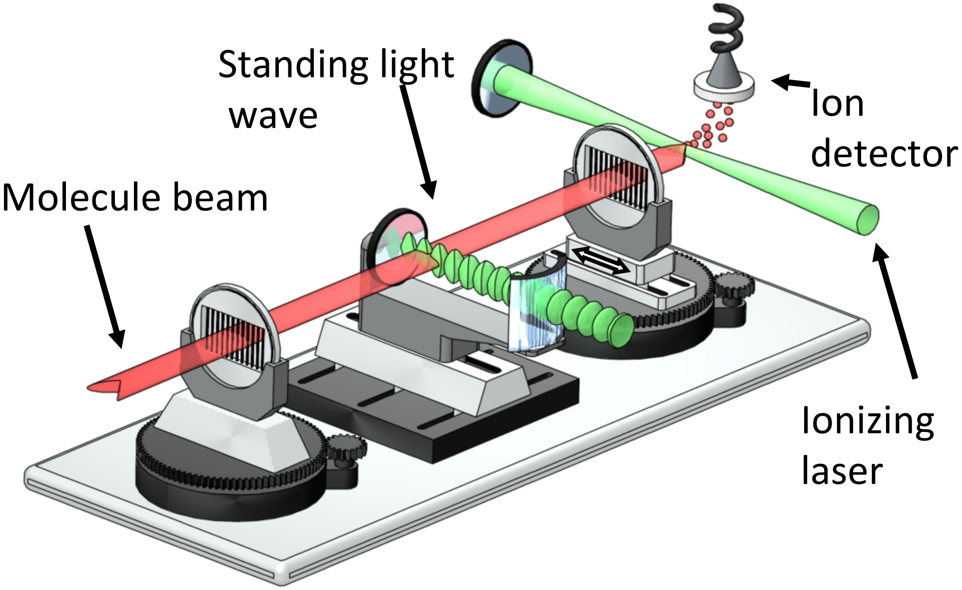
Brian Julsgaard, Alexander Kozhekin & Eugene S. Polzik

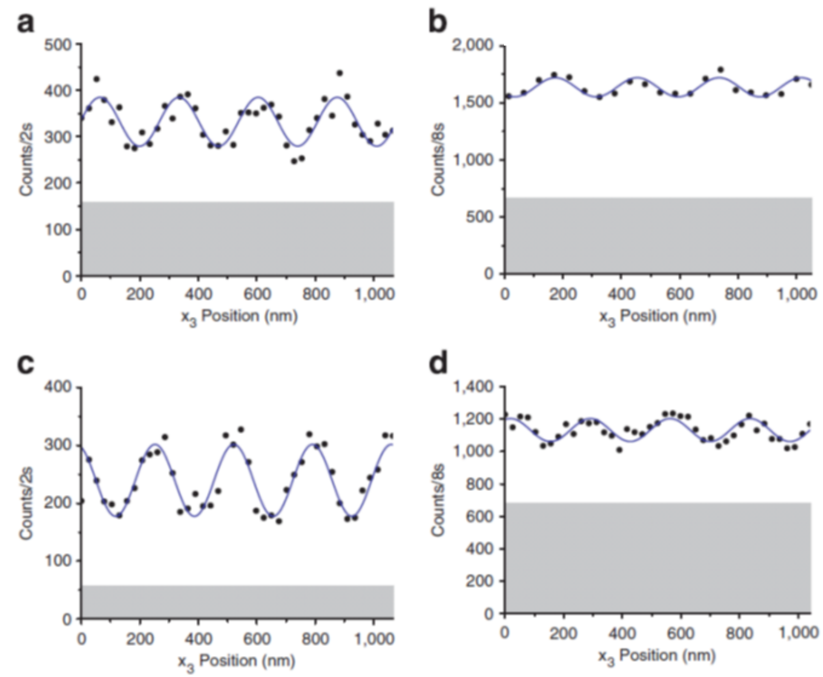
Institute of Physics and Astronomy, University of Aarhus, 8000 Aarhus, Denmark

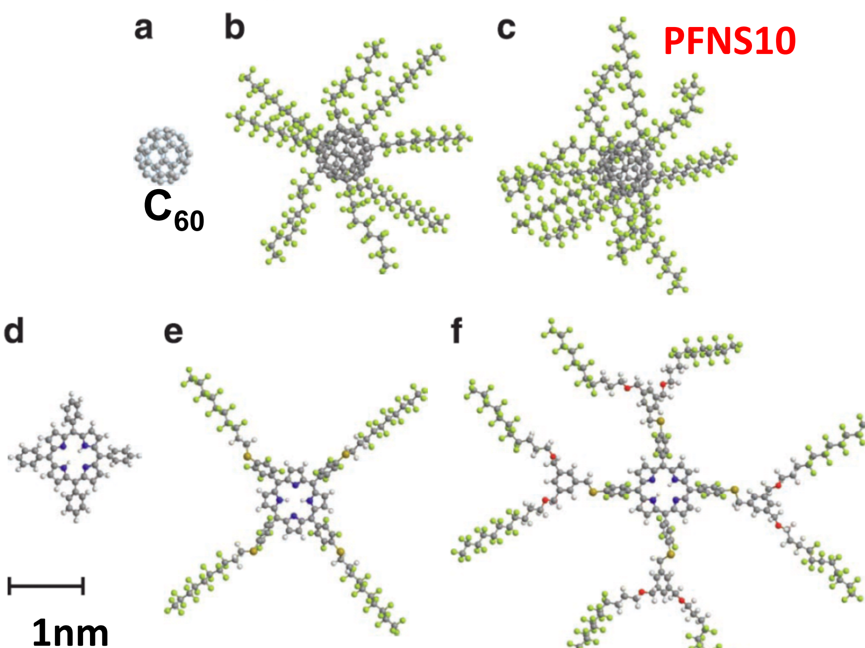
2-mode spin squeezing of 10^{12} Rb atoms



„The predictions of quantum theory and of general relativity, our current theory of gravity, are extremely well confirmed by experiment."







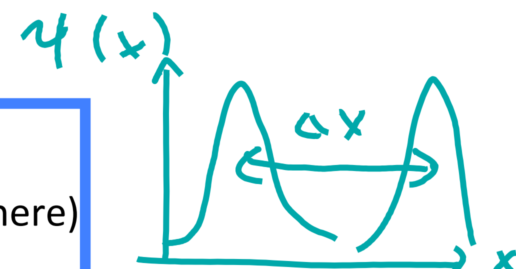
PFNS10: $C_{60}[C_{12}F_{25}]_{10}$

(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

„The predictions of quantum theory and of general relativity, our current theory of gravity, are extremely well confirmed by experiment.“

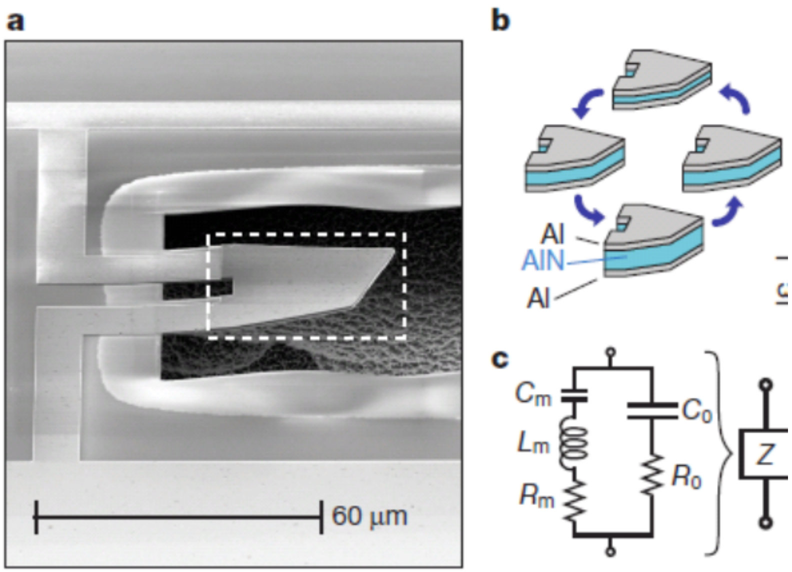
Micromechanics, 2×10^{13} atoms

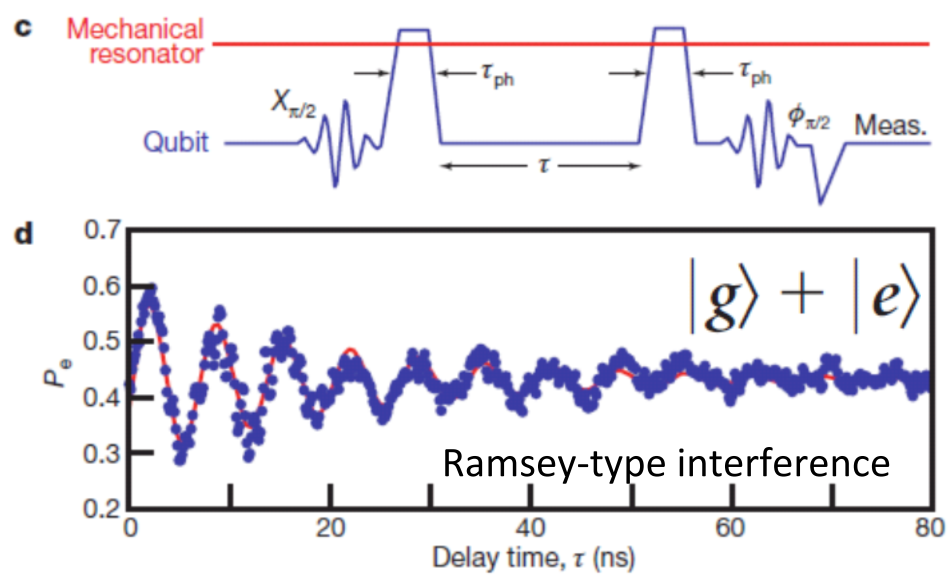
m ~ 10^{-12} kg = 7×10^{14} AMU

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

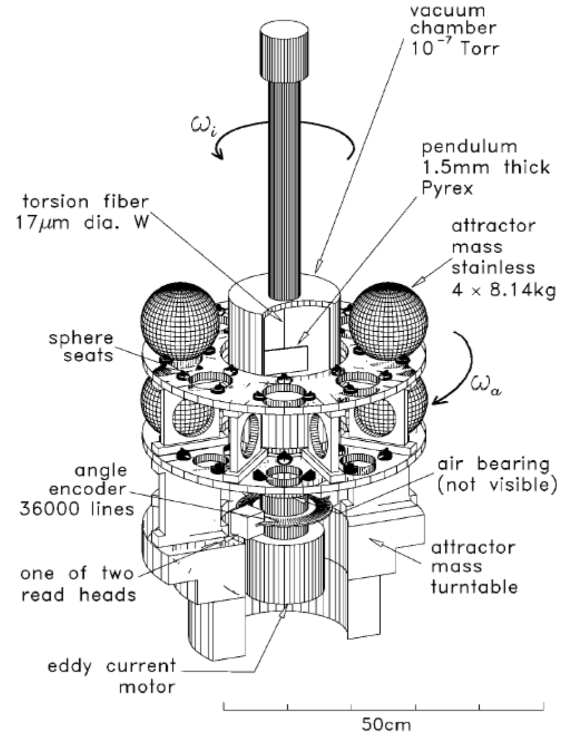
„The predictions of quantum theory and of general relativity, our current theory of gravity, are extremely well confirmed by experiment.“

VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

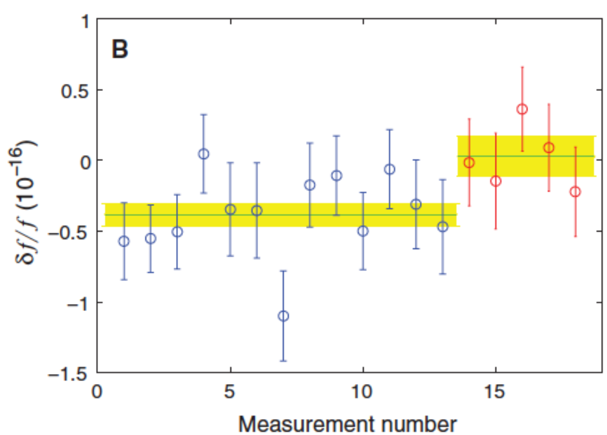
Measurement of Newton's Constant Using a Torsion Balance with Angular Acceleration Feedback

Jens H. Gundlach and Stephen M. Merkowitz
Department of Physics, Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195
(Received 5 June 2000)

We measured Newton's gravitational constant G using a new torsion balance method. Our technique greatly reduces several sources of uncertainty compared to previous measurements: (1) It is insensitive to anelastic torsion fiber properties; (2) a flat plate pendulum minimizes the sensitivity due to the pendulum density distribution; (3) continuous attractor rotation reduces background noise. We obtain $G = (6.674215 \pm 0.000092) \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$; the Earth's mass is, therefore, $M_\oplus = (5.972245 \pm 0.000082) \times 10^{24}$ kg and the Sun's mass is $M_\odot = (1.988435 \pm 0.000027) \times 10^{30}$ kg.



Source mass: 8kg spheres



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.

„There are few table-top experiments to date that probe the interface between quantum physics and gravity*. In all these experiments, Earth's gravity acts as a constant classical background field. Loosely speaking, the quantum system is used as a „test particle" in an external gravitational field."

universität wien

VCQ
Vienna Center for Quantum Science and Technology

The most prominent examples are

- the wonderful **"COW" experiment** of Colella, Overhauser and Werner (Aharonov-Bohm type relative phase shift between two spatially separated arms of a neutron interferometer) (16)
- the **atomic fountain experiments** pioneered by Kasevich and Chu (17) (phase shift is generated by interaction between light and atoms accelerated in Earth's gravitational field); allows to measure gravitational gradients with an accuracy better than $\Delta g/g = 10^{-9}$
- experiments with **quantum states of ultra-cold neutrons** that are bound in the gravitational field of the Earth (18); their energy spectrum can be probed experimentally and is for example sensitive to deviations of Newton's $1/r^2$ law at very short distances (19).
- **matter waves in free fall** as has been shown recently with 10^4 atoms (20) and macromolecules (21).

* I am explicitly neglecting all GR tests that are „motivated" by quantum gravity such as searches for the fifth force, 1/r2 deviations, violations of UFF, EEP, etc. They fall in the category of „indirect" tests.

„There are few table-top experiments to date that probe the interface between quantum physics and gravity. In all these experiments, Earth's gravity acts as a constant classical background field. Loosely speaking, the quantum system is used as a „test particle" in an external gravitational field."

universität wien

VCQ
Vienna Center for Quantum Science and Technology

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.

Aharonov-Bohm type phase shift

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

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

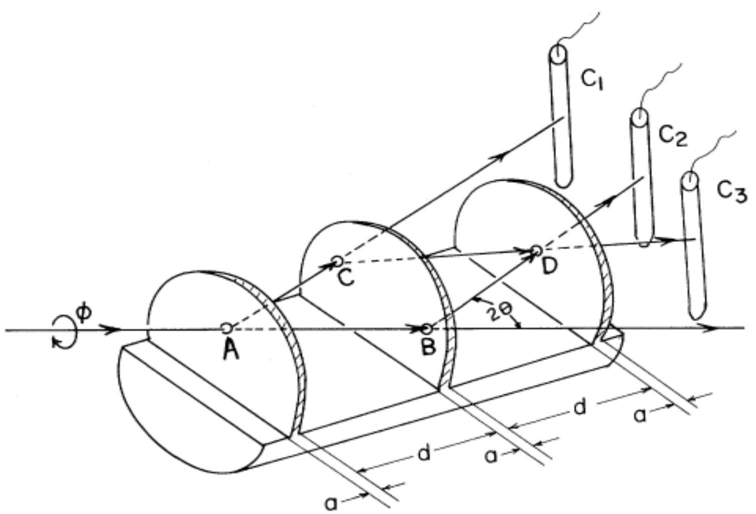
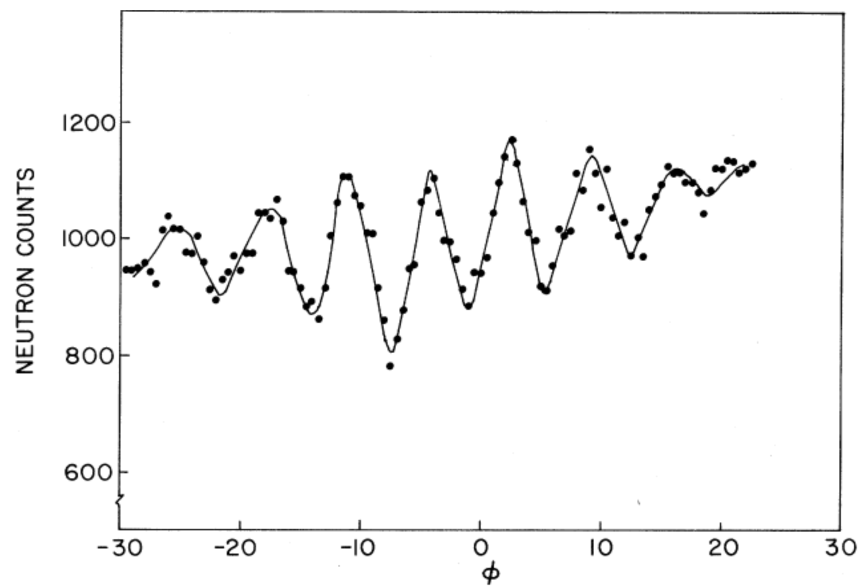


FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.



„There are few table-top experiments to date that probe the interface between quantum physics and gravity. In all these experiments, Earth's gravity acts as a constant classical background field. Loosely speaking, the quantum system is used as a „test particle" in an external gravitational field."

universität wien

VCQ
Vienna Center for Quantum Science and Technology

NATURE | VOL 400 | 26 AUGUST 1999 |

Measurement of gravitational acceleration by dropping atoms

Achim Peters, Keng Yeow Chung & Steven Chu

Physics Department, Stanford University, Stanford, California 94305-4060, USA

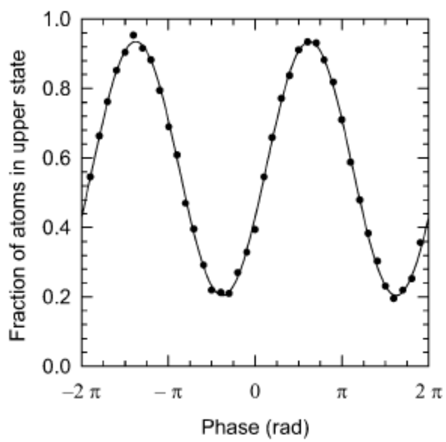
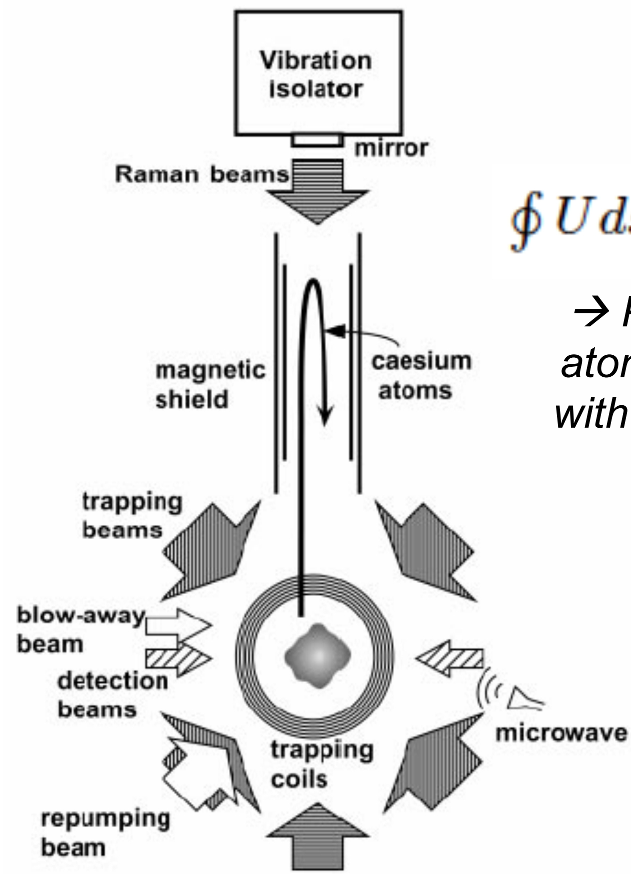


Figure 2 Typical Doppler-sensitive interferometer fringe for $T = 160$ ms. Shown are the 588,638th and 588,639th fringes. Each of the 40 data points represents a single launch of the atoms, spaced 1.3 s apart and taken over a period of 1 min. One full fringe corresponds to $\sim 2 \times 10^{6} g$. Performing a least-squares fit determines local gravity to approximately $3 \times 10^{-9} g$.



$$\oint U ds = 0$$

→ Phase shift due to atom-laser interaction with accelerated atoms

„There are few table-top experiments to date that probe the interface between quantum physics and gravity. In all these experiments, Earth's gravity acts as a constant classical background field. Loosely speaking, the quantum system is used as a „test particle" in an external gravitational field."

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,*]

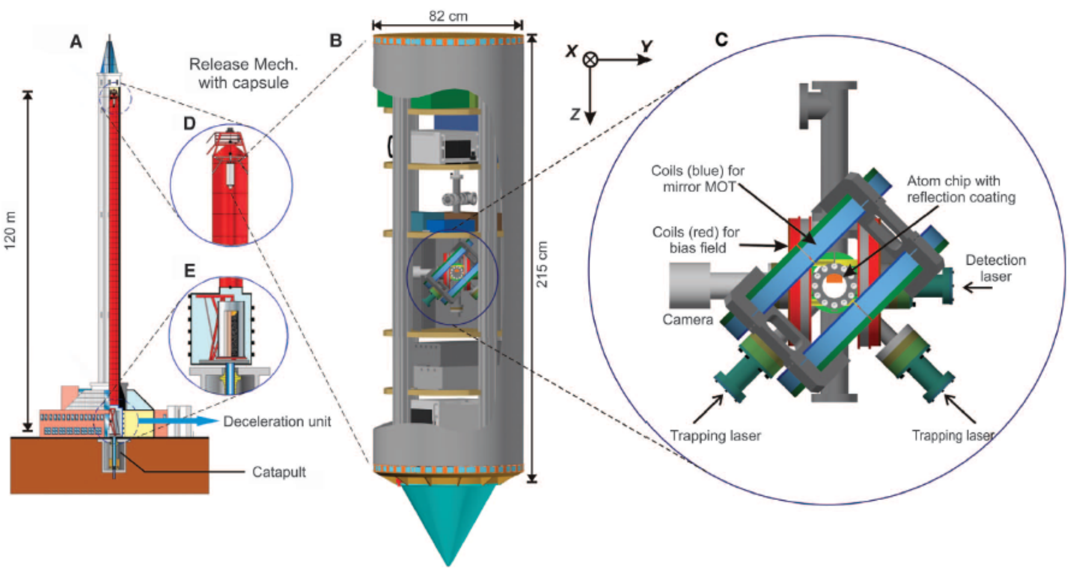


Fig. 1. Cuts through the ZARM drop tower facility in Bremen (**A**) and the capsule (**B**) containing the heart of the BEC experiment (**C**). The capsule is released from the top of the tower (**D**) and is recaptured after a free fall of 4.7 s through an evacuated stainless steel tube at the bottom 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.

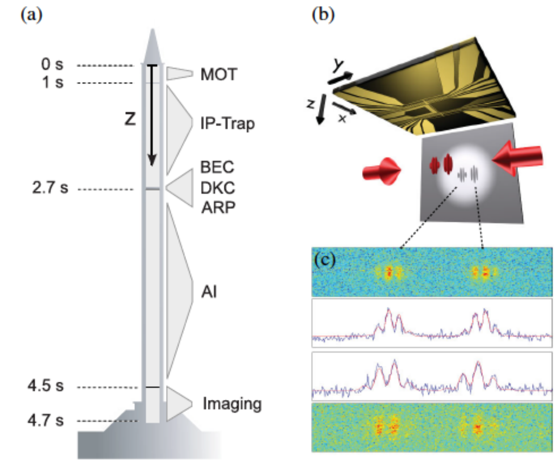


FIG. 2 (color). Mach-Zehnder interferometry of a BEC in microgravity as realized in the ZARM drop tower in Bremen (a) where absorption imaging (b) brings out the interference fringes (c). The preparatory experimental sequence (a) includes capturing cold atoms in a magneto-optical trap (MOT), loading 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), resulting in two pairs of interfering BECs. A resonant laser beam propagating along the x axis projects the shadow of the BEC onto a CCD camera. Typical interference patterns and the corresponding column densities (c) are shown for T_{ex} of 180 and 260 ms with corresponding fringe spacing of 75 and 107 μm.

„The current accuracy of optical atomic clocks in combination with techniques from atom interferometry should already allow to perform experiments on „superposition of clocks“. I am confident that this will happen soon.“

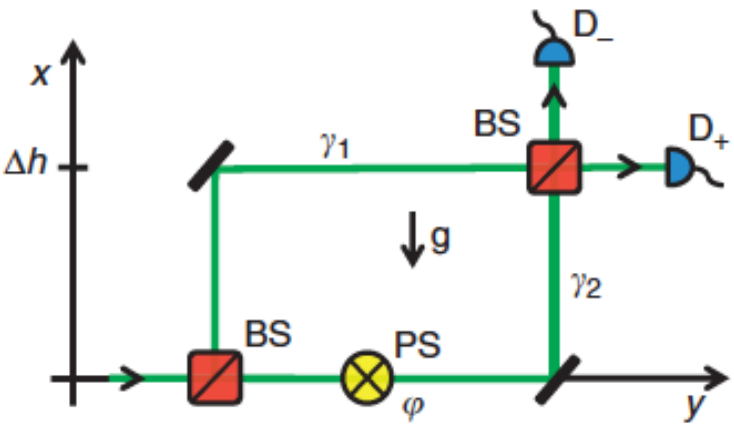
universität wien

VCQ Vienna Center for Quantum Science and Technology

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 $\omega_g = \frac{\Delta E}{\hbar c^2} gh$



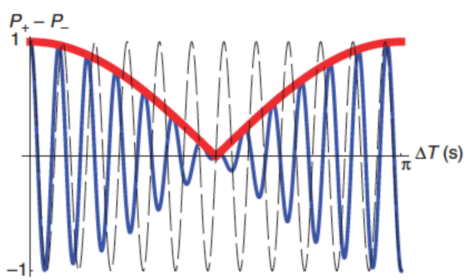


Figure 2 | Visibility of the interference pattern and the phase shift in the cases with and without the 'clock.' The plot of the difference between

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]

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 $2T_\pi$

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)

„The current accuracy of optical atomic clocks in combination with techniques from atom interferometry should already allow to perform experiments on „superposition of clocks". I am confident that this will happen soon."

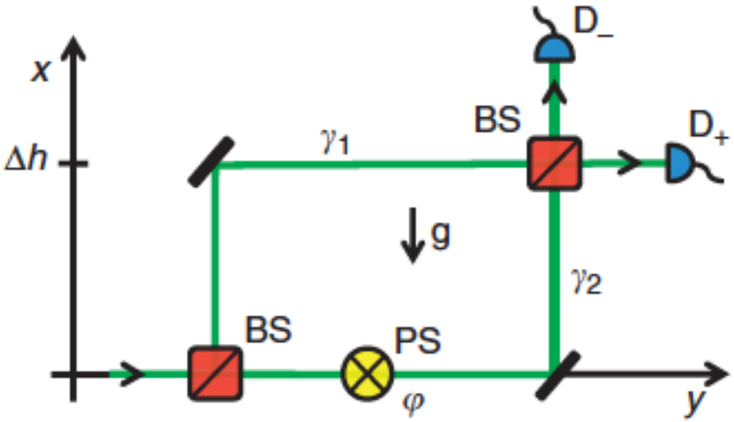
universität wien

VCQ Vienna Center for Quantum Science and Technology

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 $\omega_g = \frac{\Delta E}{\hbar c^2} gh$



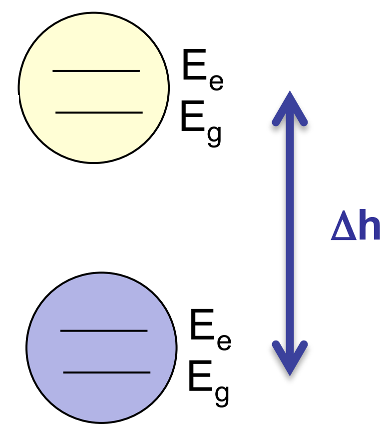
If the qubit is placed in a spatial superposition of two vertical heights (in Earth's gravitational field) separated by Δh the qubits will evolve differently:

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

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:

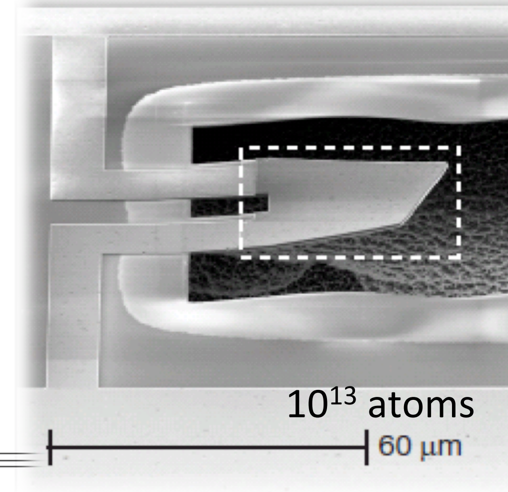
- Entanglement between states of separated atoms has been demonstrated (e.g. Weinfurter group (22))
- Large Δh through optical fibers

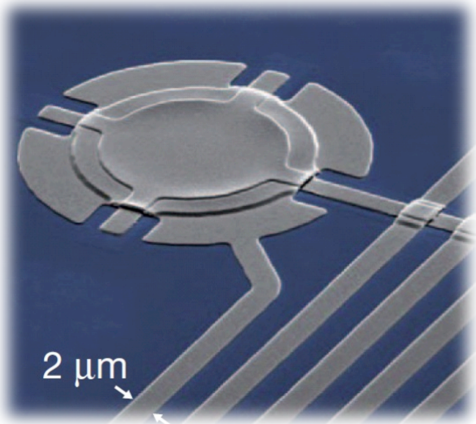
„On the other hand, the last decade has seen large progress in controlling the quantum regime of massive micro-mechanical oscillators. These systems may lead the way to a new class of gravitational quantum physics experiments, in which the quantum system itself, e.g. the center of mass degree of freedom of a massive sphere, serves as a gravitational source mass.“

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 **475**, 359-363 (2011)

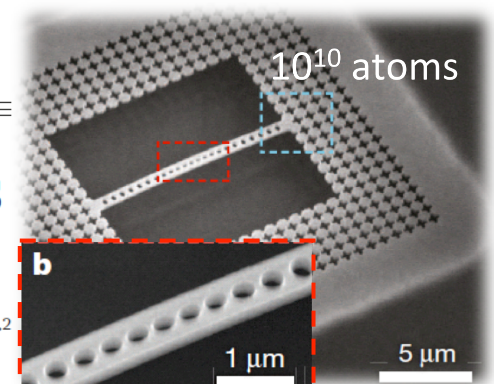
Sideband cooling of micromechanical motion to the quantum ground state

J. D. Teufel[1], T. Donner[2,3], Dale Li[1], J. W. Harlow[2,3], M. S. Allman[1,3], K. Cicak[1], A. J. Sirois[1,3], J. D. Whittaker[1,3], K. W. Lehnert[2,3] & R. W. Simmonds[1]

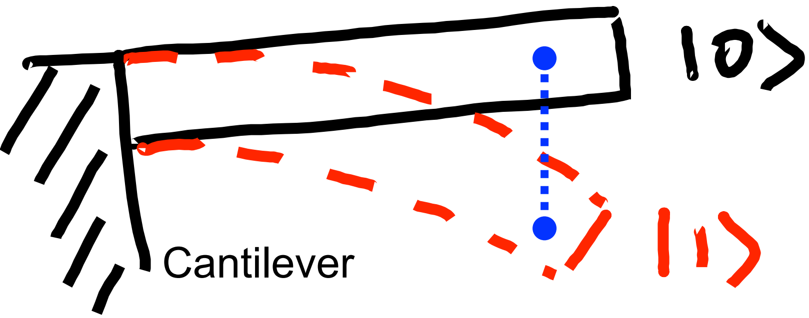
Nature **478**, 89-92 (2011)

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]



„On the other hand, the last decade has seen large progress in controlling the quantum regime of massive micro-mechanical oscillators. These systems may lead the way to a new class of gravitational quantum physics experiments, in which the quantum system itself, e.g. the center of mass degree of freedom of a massive sphere, serves as a gravitational source mass.“



Advantage: large mass (>> 10^{10} atoms)

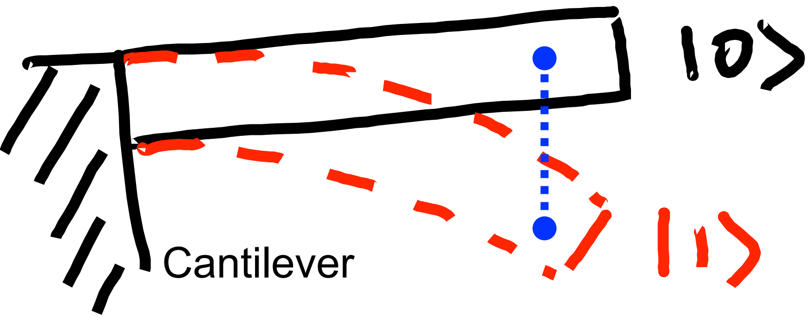
Disadvantage of current approaches: small coherence time (mainly limited by mechanical losses*)

For example, if we prepare the center of mass state of a micron-scale mechanical oscillator of 1 MHz resonance frequency and comprising 10^{13} atoms in a coherent spatial superposition of 1 nm separation, a quality factor of $Q=10^7$ at an environment temperature of 20 mK will decohere the superposition on a timescale of one picosecond.

$$\gamma_m \left(\frac{\Delta x}{\lambda_{dB}(T)}\right)^2 = \frac{2 m \gamma_m k_B T (\Delta x)^2}{\hbar^2} = \frac{k_B T}{\hbar Q}\left(\frac{\Delta x}{x_{zp}}\right)^2 = \Gamma_{dec}$$

* Note to Philip: in current approaches, mechanical losses are modelled by x-x coupling to a bosonic (non-Markovian) heat bath, hence there is loss-induced decoherence.

„On the other hand, the last decade has seen large progress in controlling the quantum regime of massive micro-mechanical oscillators. These systems may lead the way to a new class of gravitational quantum physics experiments, in which the quantum system itself, e.g. the center of mass degree of freedom of a massive sphere, serves as a gravitational source mass.“



Advantage: large mass (>> 10^{10} atoms); quantum control is achievable through optical cavities, superconducting circuits, etc.

Disadvantage of current approaches: small coherence time (mainly limited by internal mechanical losses)

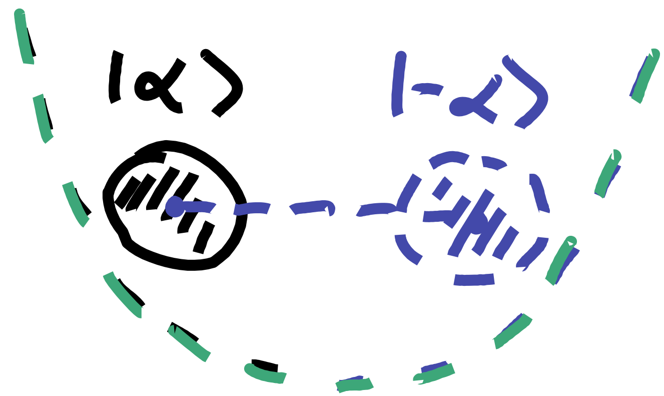
Solution: **Levitation** of masses

→ Optical or magnetic traps are essentially **loss-free → long coherence times**

→ **Quantum state control** through coupling to optical cavities or superconducting circuits

→ **Free-fall** dynamics

Theory see e.g. (23-26)



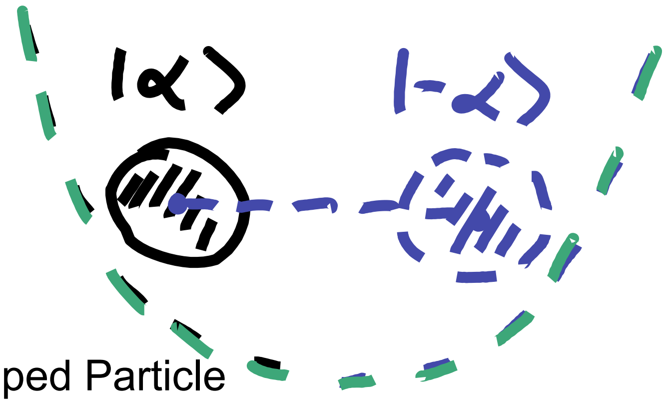
Trapped Particle

For example, a sphere with 10^{11} atoms that is prepared in its quantum ground state of motion in a 100kHz frequency optical trap can achieve coherent wavepacket expansion times of **seconds** at an environment temperature of 20 K and a background pressure of 10^{-11} mbar (26).

„On the other hand, the last decade has seen large progress in controlling the quantum regime of massive micro-mechanical oscillators. These systems may lead the way to a new class of gravitational quantum physics experiments, in which the quantum system itself, e.g. the center of mass degree of freedom of a massive sphere, serves as a gravitational source mass."

Solution: **Levitation** of masses

→ Optical or magnetic traps are essentially **loss-free**
→ **Quantum state control** through coupling to optical cavities or superconducting circuits
→ **Free-fall** dynamics

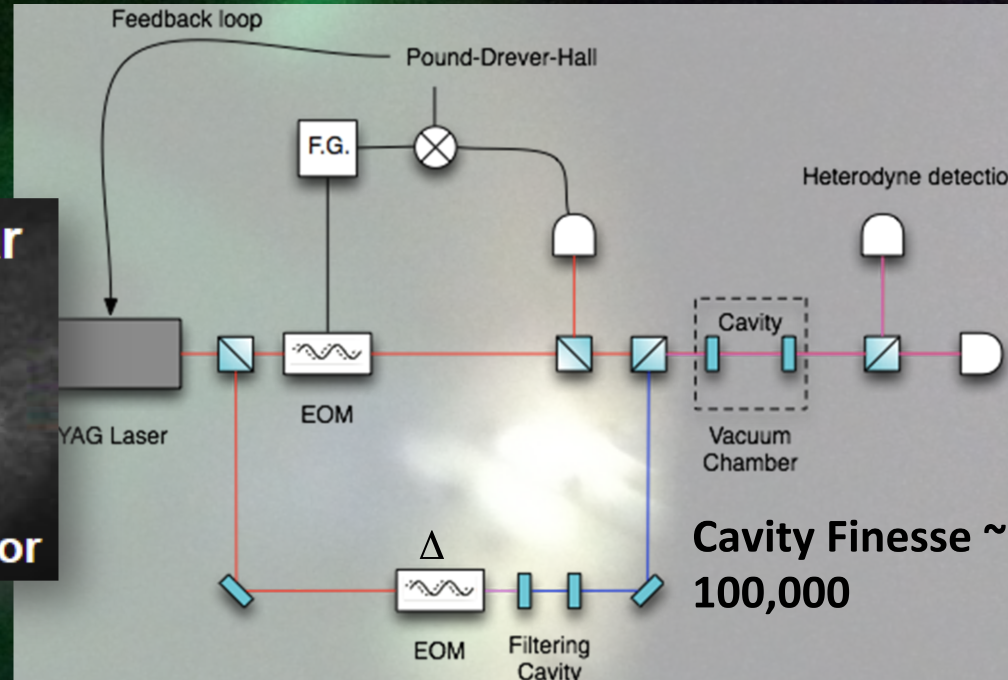


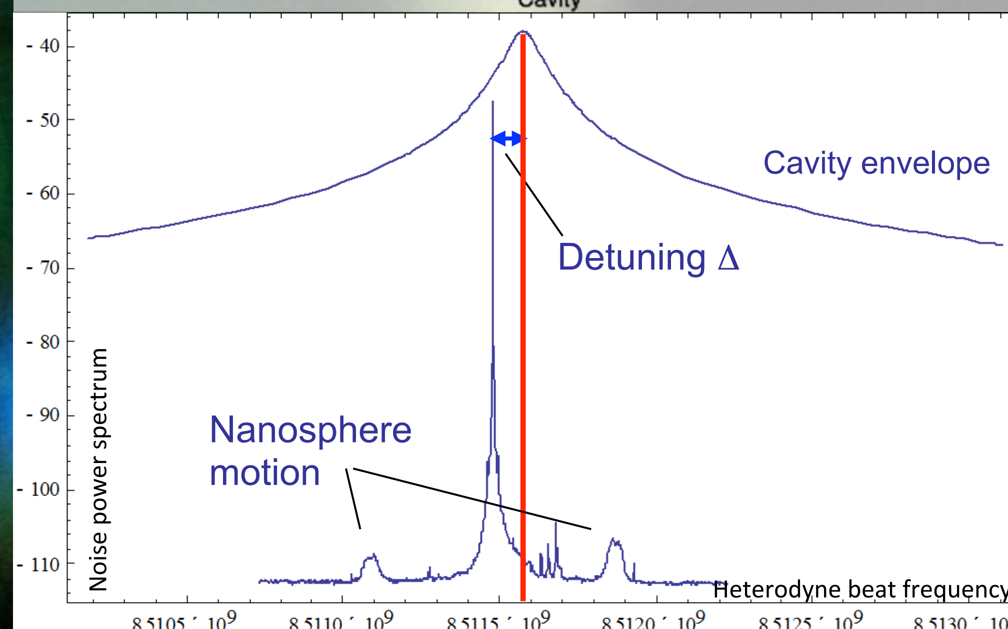
Trapped Particle

- Mechanical resonators can be used as **measurement devices of external driving forces**, with sensitivity limited by the **oscillator thermal noise** (essentially the product of temperature, mass, ω/Q and detection bandwidth).
- Levitated masses can achieve Q-factors well beyond 10^{10} → for a sphere of 500 µm trapped at a frequency of 100 Hz the force noise can be **suppressed below 5×10^{-19} N for integration times shorter than 100 seconds.**
- This corresponds to the gravitational force due to a sphere of same size at a distance of 1.5 mm. In other words, it becomes possible to detect **gravitational forces between sub-mm masses**.
- Such experiments provide **a top-down approach** for future experiments at the interface between quantum physics and gravity: the lowest masses above which gravitational coupling can be observed will be a benchmark for future quantum experiments. In the most optimistic scenario, the combination of force sensitivity and coherence time will eventually enable the **quantum regime of gravitational source masses**.

Optically trapped nanospheres as mechanical resonators

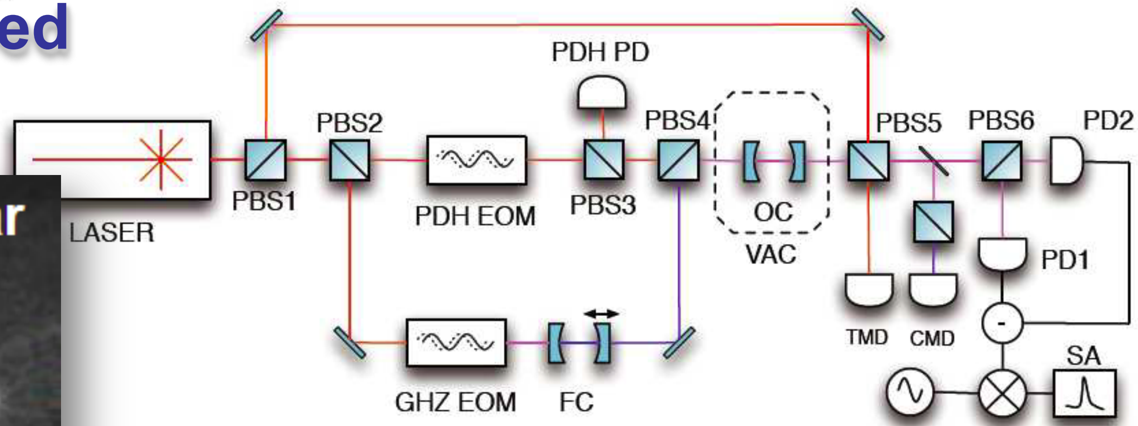
Ashkin since 1967
Raizen group, Science 2010
Novotny 2012



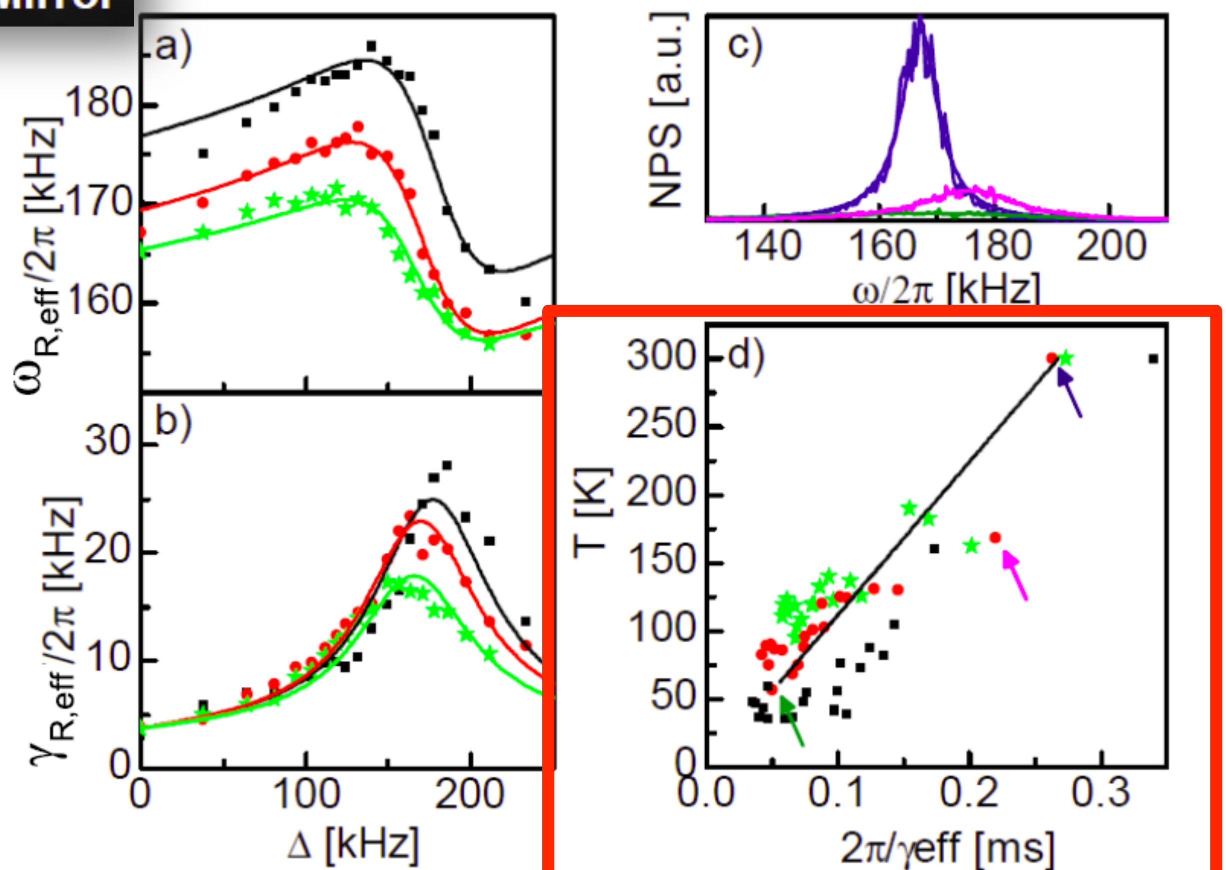


Optical trapping inside a cavity… (R~20nm – 2µm)
Kiesel et al., work in progress

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)

„These developments will lead to:

- Tests of semiclassical gravity models
- Observation of dephasing through superposition of clocks
- Generation of quantum entanglement through gravity
- Observation of decoherence through quantum gravity?“

Classical gravity: localization of macro-objects

universität wien

VCQ
Vienna Center for Quantum Science and Technology

How to incorporate a Newtonian gravity field into quantum framework?

e.g. add **gravitational self-interaction** (Diosi, Penrose)

$$i\hbar\partial_t\Psi(t,\vec{x}) = \left(-\frac{\hbar^2}{2m}\Delta - Gm^2\int\frac{|\Psi(t,\vec{y})|^2}{\|\vec{x}-\vec{y}\|}\,d^3y\right)\Psi(t,\vec{x})$$

Schrödinger-Newton equation (Diosi 1984)

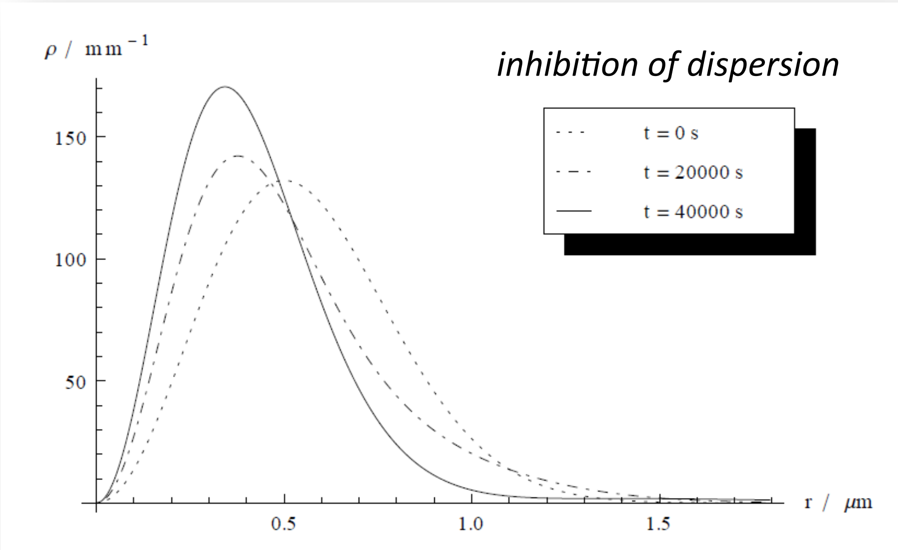


Figure 4: Collapsing wave packet for $m = 7\times10^9$ u. Plotted is the radial probability density $\rho = 4\pi r^2\,|\psi|^2$ against r at three different times.

Giulini & Großardt (27), Colin, Durt & Willox (28) and references therein

→ **gravitational inhibition of dispersion**
→ gravitationally bound states
→ modified ground state (Gross-Pitaevskii)

m = 10^{10} amu, $\sigma(0)$ = 500 nm
→ collapse time t~30,000 sec

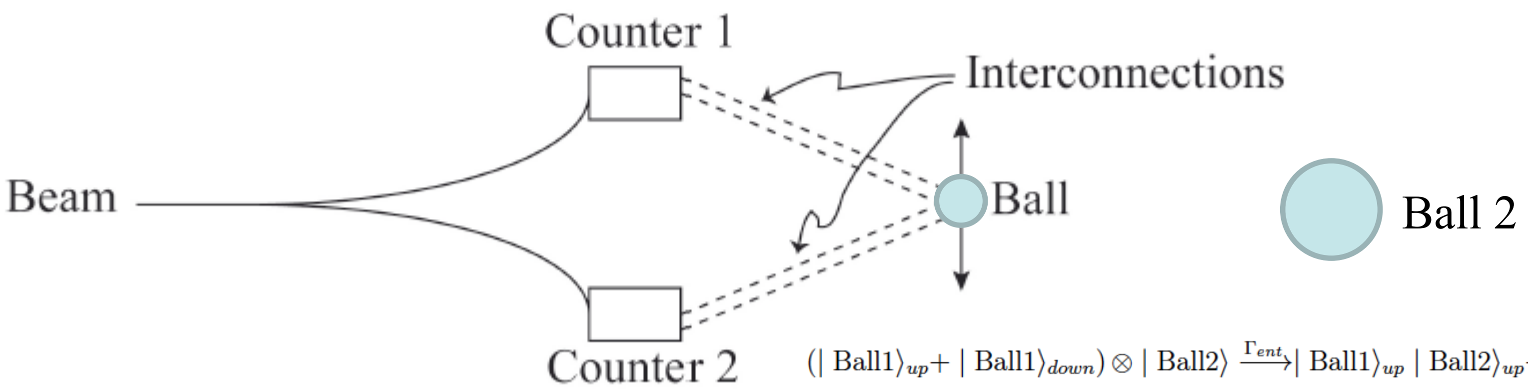
m = **10^{12} amu**, $\sigma(0)$ = **500 fm**
→ collapse time t~**3×10^{-6} sec**

↳ $R\sim400\,nm$, $\omega_m\sim10^6\,Hz$!

An ultimate experiment? Entanglement by gravity…

universität wien

VCQ Vienna Center for Quantum Science and Technology



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

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."

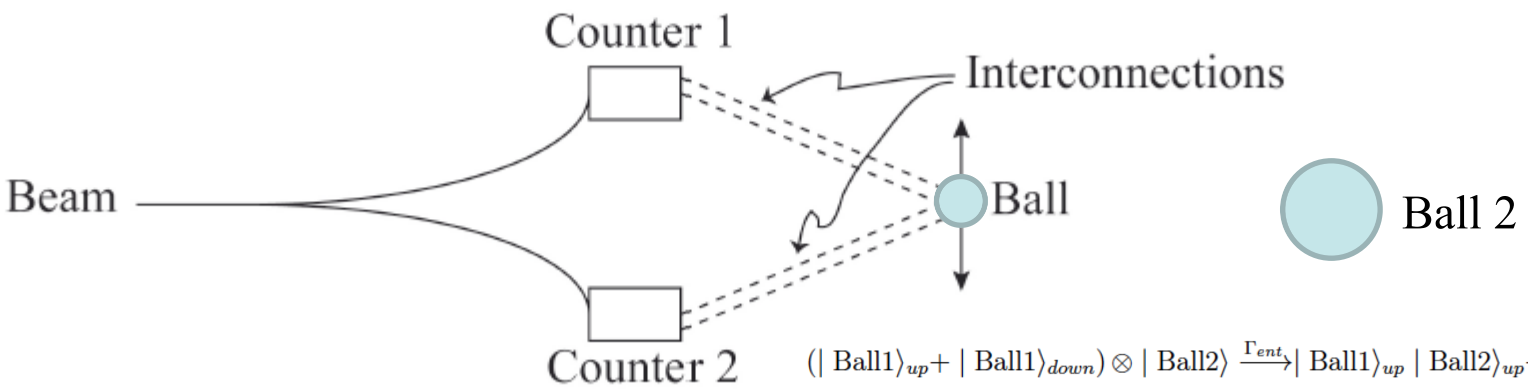
Chapel Hill Conference 1957 (29)

For an initial superposition (Ball 1) of size Δr (distance between center of mass states), separation between the two balls on the order of their diameter and preparation of Ball 2 in a wavepacket of size Δx_0, the "entanglement rate" (decoherence rate) is
(M: mass, ρ: density)

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

An ultimate experiment? Entanglement by gravity…

universität wien
VCQ Vienna Center for Quantum Science and Technology



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

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)

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**.

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

„Will we be able to observe decoherence as a consequence of gravity?“

PRL 111, 021302 (2013) PHYSICAL REVIEW LETTERS week ending 12 JULY 2013

Effective Field Theory Approach to Gravitationally Induced Decoherence

M. P. Blencowe*

Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire 03755, USA

(Received 27 November 2012; revised manuscript received 10 April 2013; published 12 July 2013)

Adopting the viewpoint that the standard perturbative quantization of general relativity provides an effective description of quantum gravity that is valid at ordinary energies, we show that gravity as an environment induces the rapid decoherence of stationary matter superposition states when the energy differences in the superposition exceed the Planck energy scale.

See also current (different) approaches by Philip Stamp, Bill Unruh, ...

$$\Gamma_{\text{decohere}} = \frac{k_B T}{\hbar}\left(\frac{E - \tilde{E}}{E_P}\right)^2$$

for superposition of different energy eigenstates

For a matter system comprising an Avogadro's number of atoms ~1 gram in a quantum superposition where all of the atoms are either in their ground state or all in their excited state, then we have $\Gamma_{\text{decohere}} \sim 10^2\ \text{sec}^{-1}$. For a system with mass ~1 kg in such a superposition state, the gravitationally induced decoherence rate is $\Gamma_{\text{decohere}} \sim 10^8\ \text{sec}^{-1}$.

→ This is „really, really hard“. I do not have an obvious idea how to achieve this. Maybe magnetic particles are a way to go... Levitation would certainly help to significantly suppress other decoherence sources (blackbody localization)

Summary and Outlook

- **Levitated massive oscillators** coupled to optical cavities or superconducting circuits open a new avenue to quantum experiments with a **unique combination of large mass and long coherence times**
- Such experiments will enable a new class of **gravitational quantum physics experiments**, in which **quantum systems** will eventually serve as a **source mass**
- In **20 years from now** we (as in „we as scientific community“) will have
  - **eliminated** the idea of **semiclassical gravity models** through unambiguous experiments;
  - **eliminated** (in passing) the idea of ad-hoc **„collapse“ models** (GRWP, Penrose), essentially through the same experiments;
  - found a **new key experiment** whose outcome has led the way to a almost working quantum theory of gravity .
- **Table-top experiments** will have played a vital role in this development.

Acknowledgements:

I want to thank all my coworkers and collaborators for making this area of research so exciting and worth while pusrsuing.

I want to thank Philip Stamp for giving this presentation for me. Not being able to make it to this Seven Pines Symposium is already a great punishment by itself. But now Philip is given all the opportunity of making fun of me without me being there to enjoy it

I want to thank Lee for his constant support of fundamental questions through these wonderful Seven Pines Symposia.

Picture on the right:
Almost like Seven Pines - Aspelmeyer group retreat in Dienten, Austria

universität wien

VCQ

Vienna Center for Quantum Science and Technology

(1) Fickler et al., Science **338**, 640 (2012).
(2) Friedman et al., Nature **406**, 43 (2000).
(3) van der Wal et al., Science **290**, 773 (2000).
(4) Julsgaard et al., Nature **413**, 400 (2001).
(5) Arndt et al., Nature **401**, 680 (1999).
(6) Gerlich et al., Nat. Commun. **2**, 263 (2011).
(7) O'Connell et al., Nature **464**, 697 (2010).
(8) Palomaki et al., Science **342**, 710 (2013).
(9) Taylor and McCulloch, Ann. N. Y. Acad. Sci. **336**, 442 (1980).
(10) BICEP2 collaboration, arXiv:1403.3985v2 (2014).
(11) I. Ciufolini and E. C. Pavlis, Nature **431**, 958 (2004).
(12) Everitt et al., Phys. Rev. Lett. **106**, 221101 (2011).
(13) E. Adelberger, Class. Quantum Gravity **2397**, (2001).
(14) J. Gundlach and S. Merkowitz, Phys. Rev. Lett. **85**, 2869 (2000).
(15) Chou et al., Science **329**, 1630 (2010).
(16) R. Colella, A. Overhauser, and S. Werner, Phys. Rev. Lett. **34**, 1472 (1975).
(17) M. Kasevich and S. Chu, Phys. Rev. Lett. **67**, 181 (1991).
(18) Nesvizhevsky et al., Nature **415**, 297 (2002).
(19) Jenke et al., Phys. Rev. Lett. **112**, 151105 (2014).
(20) Müntinga et al., Phys. Rev. Lett. **110**, 093602 (2013).
(21) Juffmann et al., Nat. Nanotechnol. **7**, 297 (2012).
(22) Hofmann et al. Science **337**, 72 (2012)
(23) O. Romero-Isart et al., New J. Phys. **12**, 033015 (2010).
(24) D. E. Chang et al., Proc. Natl. Acad. Sci. U. S. A. **107**, 1005 (2010).
(25) O. Romero-Isart et al., Phys. Rev. Lett. **109**, 1 (2012).
(26) Romero-Isart et al., Phys. Rev. Lett. **107**, 1 (2011).
(27) D. Giulini and A. Großardt, Class. Quantum Gravity **28**, 195026 (2011).
(28) S. Colin, T. Durt, and R. Willox, arXiv Prepr. arXiv1402.5653 3 (2014).
(29) *Role Gravit. Physics. Rep. from 1957 Chapel Hill Conf.*, edited by C. M. DeWitt and D. Rickles (Max Planck Research Library for the History and Development of Knowledge, 2011).