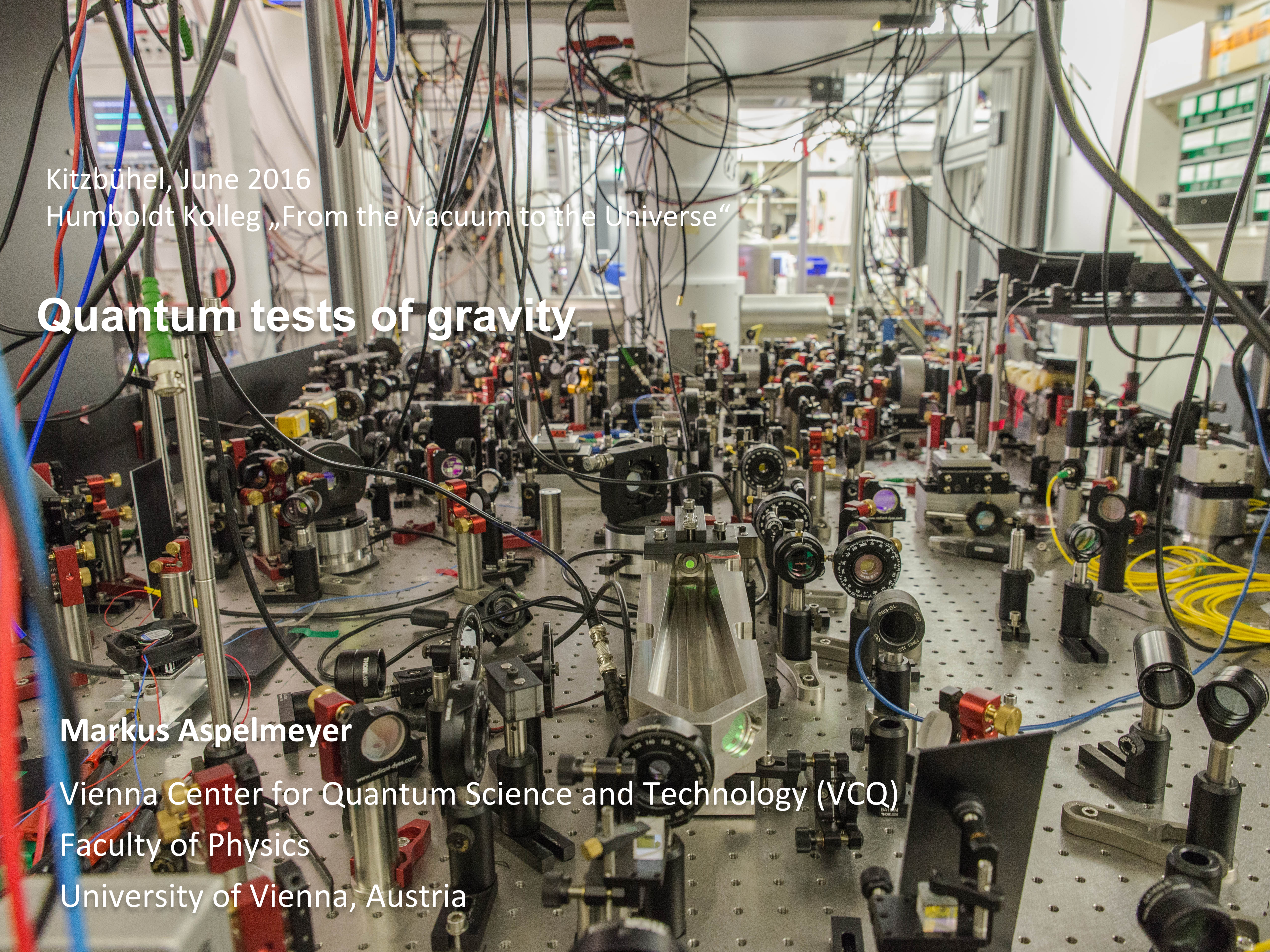


Kitzbühel, June 2016
Humboldt Kolleg „From the Vacuum to the Universe“

Quantum tests of gravity

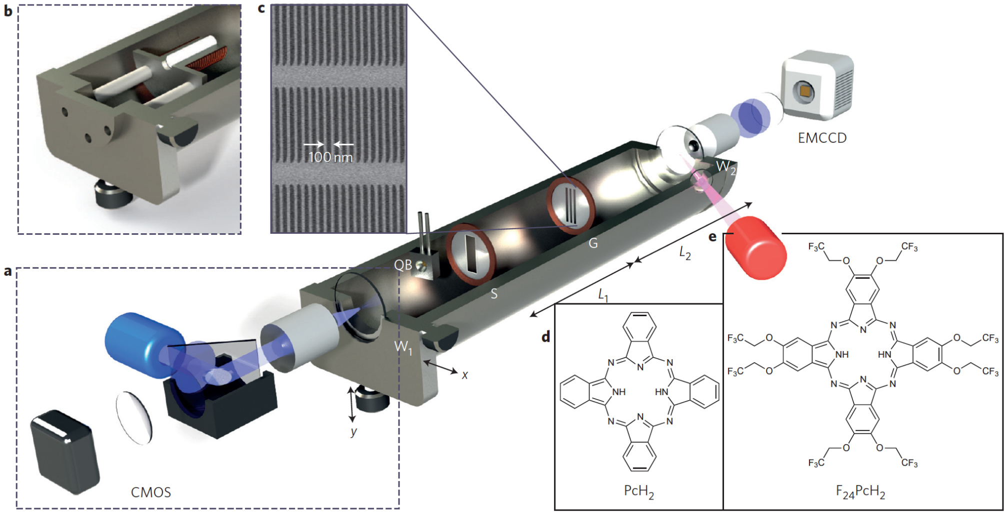
Markus Aspelmeyer

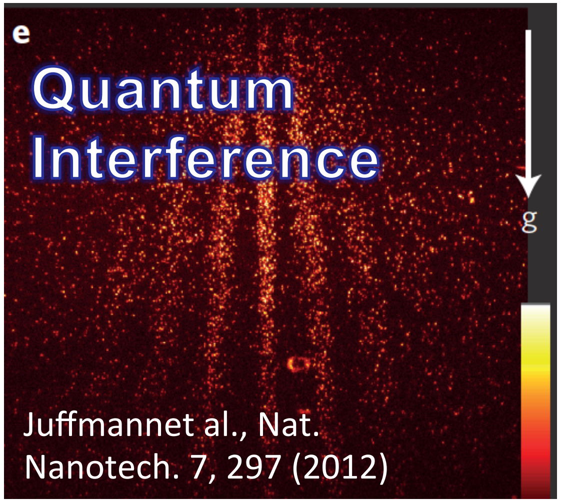
Vienna Center for Quantum Science and Technology (VCQ)
Faculty of Physics
University of Vienna, Austria

Quantum theory works, as does GR...

universität wien

VCQ
Vienna Center for Quantum
Science and Technology





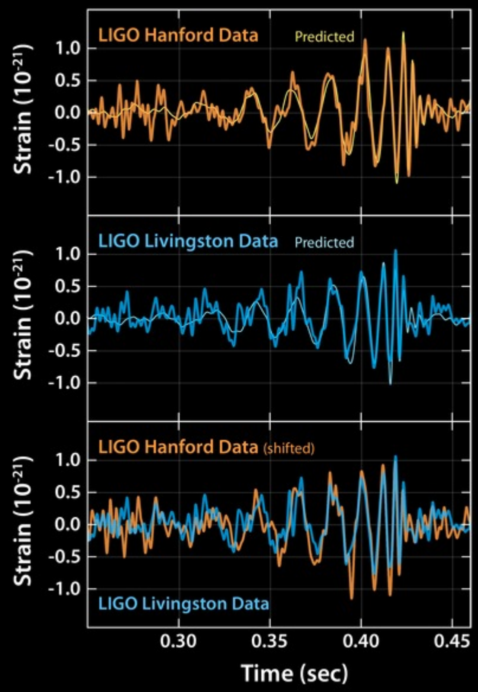
Quantum Interference

Juffmannet al., Nat. Nanotech. 7, 297 (2012)

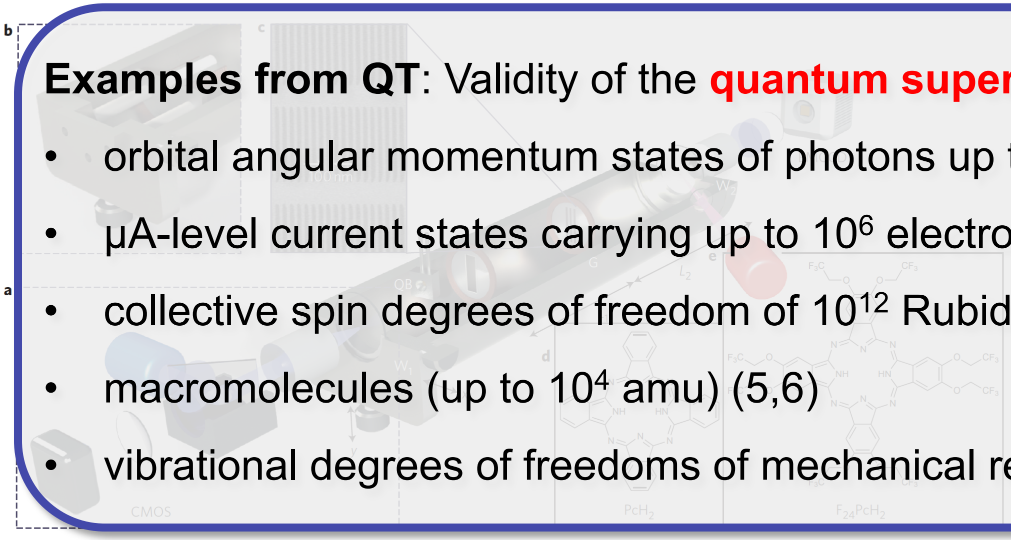
Gravitational Waves

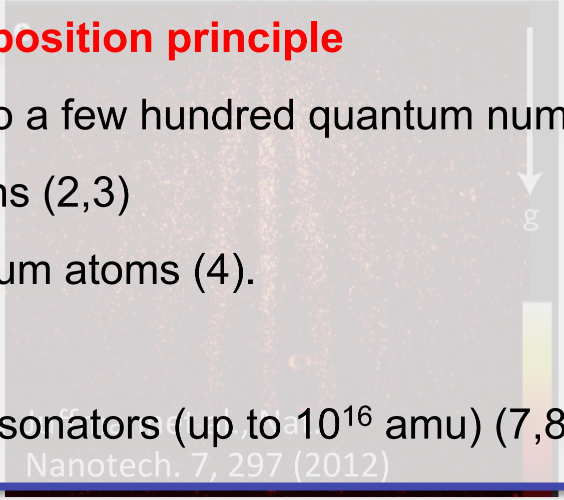
LIGO – Laser Interferometer Gravitational Wave Observatory

Abbott et al., PRL 116, 061102 (2016)



Quantum theory works, as does GR...

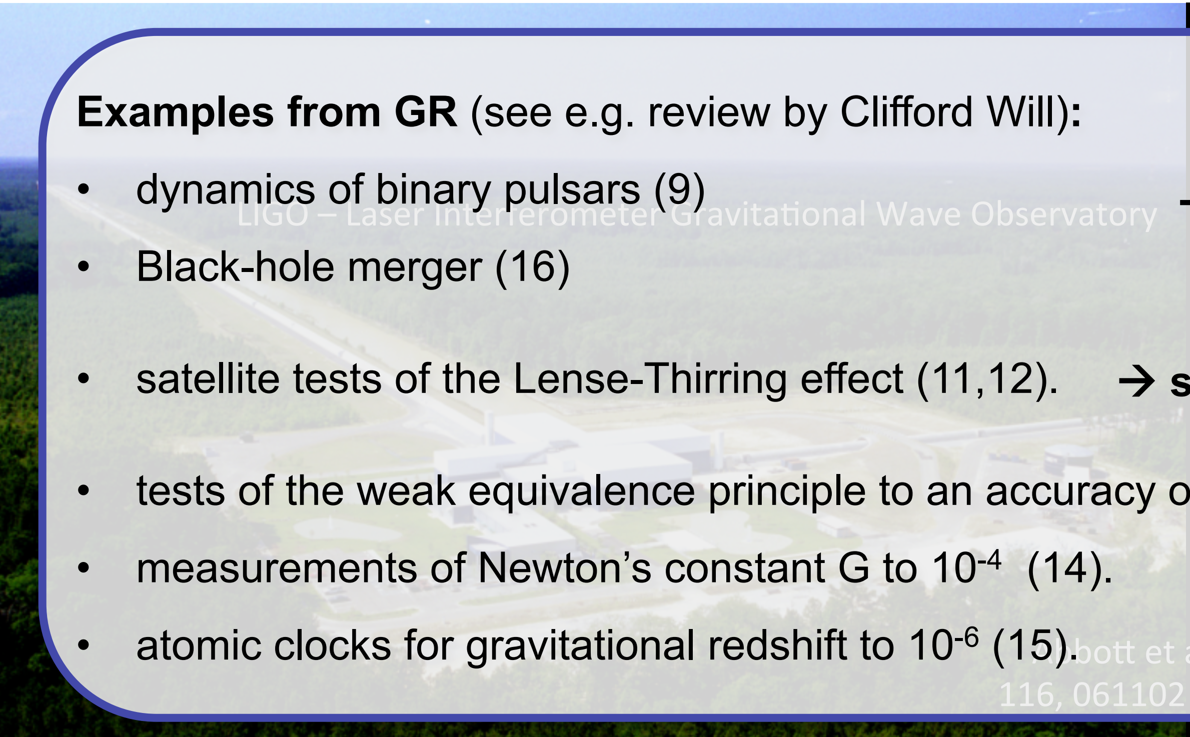




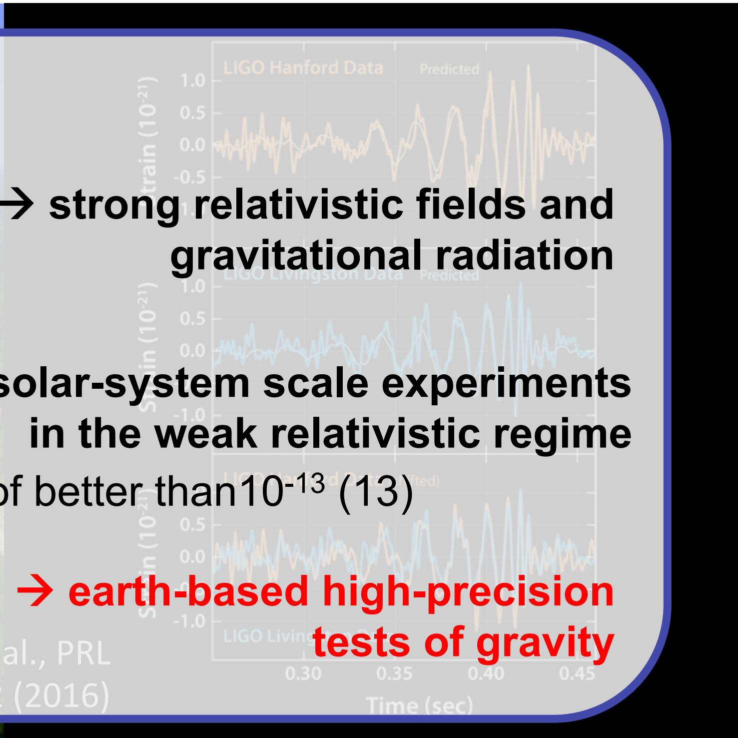
Nanotech. 7, 297 (2012)

Examples from QT: Validity of the **quantum superposition principle**

- 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)



LIGO – Laser Interferometer Gravitational Wave Observatory



Abbott et al., PRL 116, 061102 (2016)

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

- dynamics of binary pulsars (9)
- Black-hole merger (16)

→ 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“**

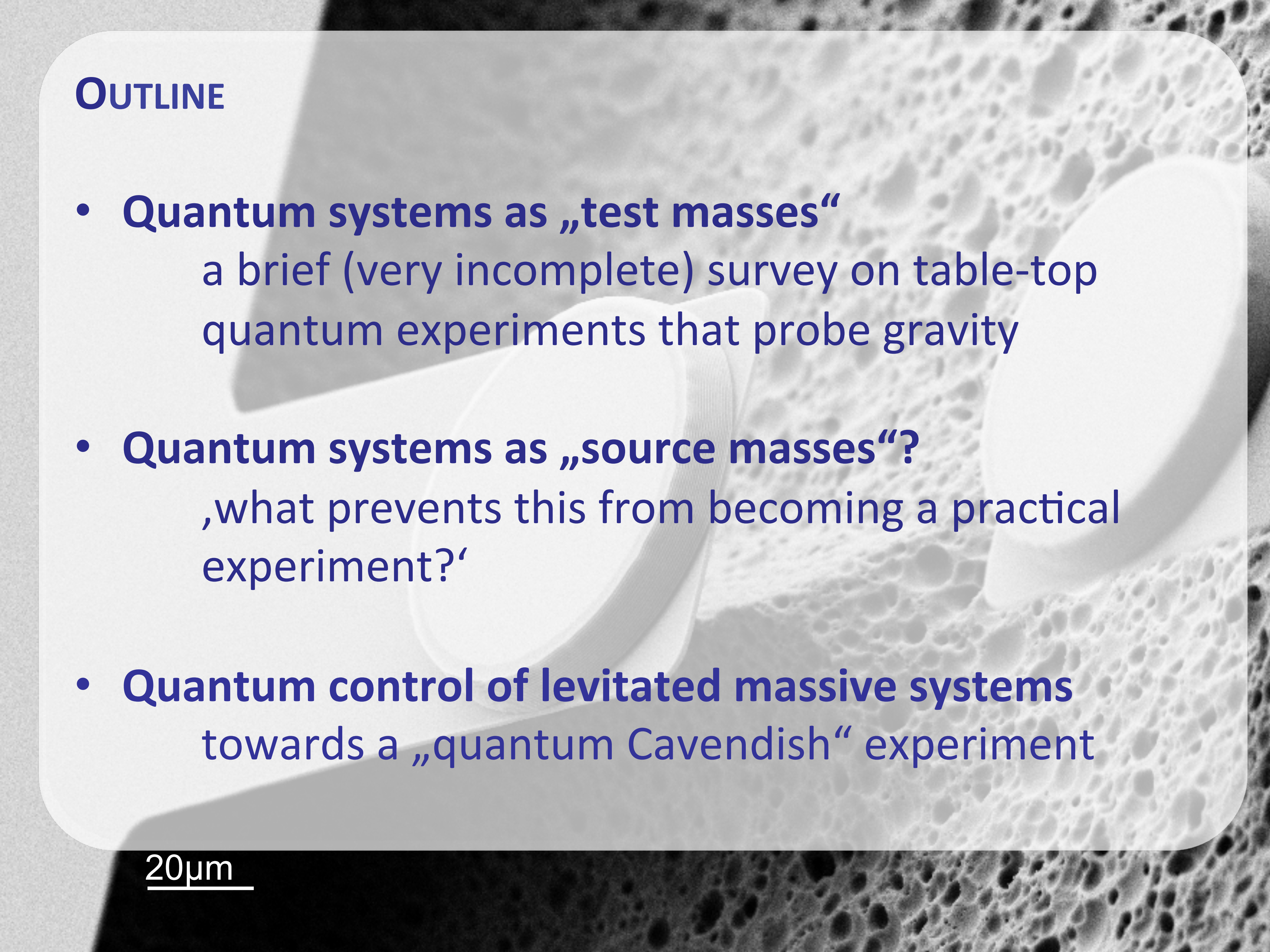
  a brief (very incomplete) survey on table-top quantum experiments that probe gravity

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

  ‚what prevents this from becoming a practical experiment?‘

- **Quantum control of levitated massive systems**

  towards a „quantum Cavendish“ experiment



Newtonian Gravity in Quantum Experiments

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.

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

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

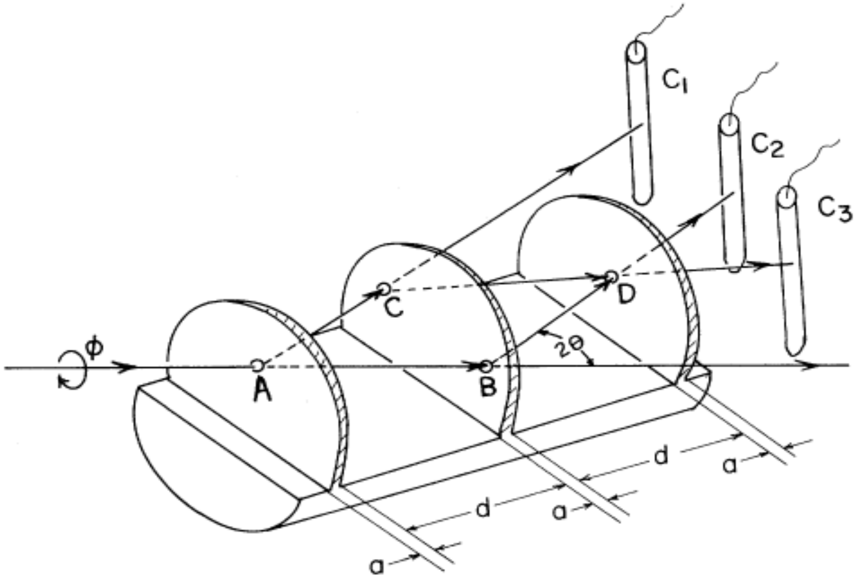
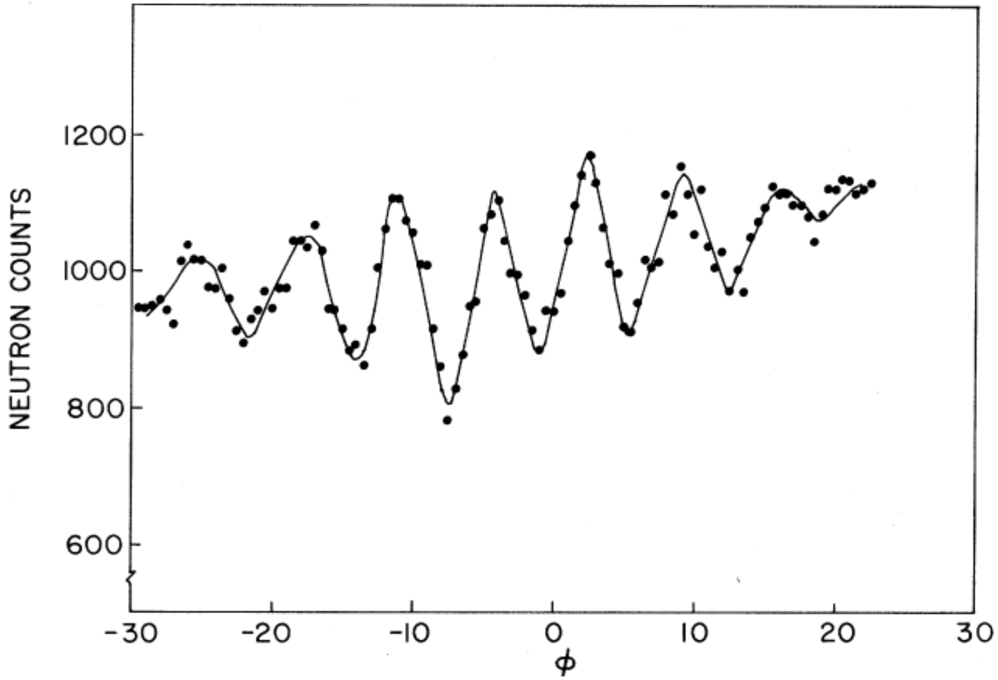
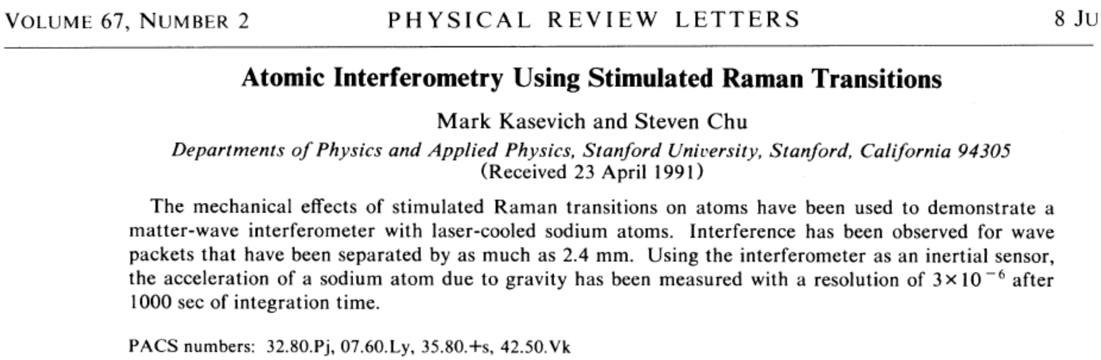


FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.



Newtonian Gravity in Quantum Experiments



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

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

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

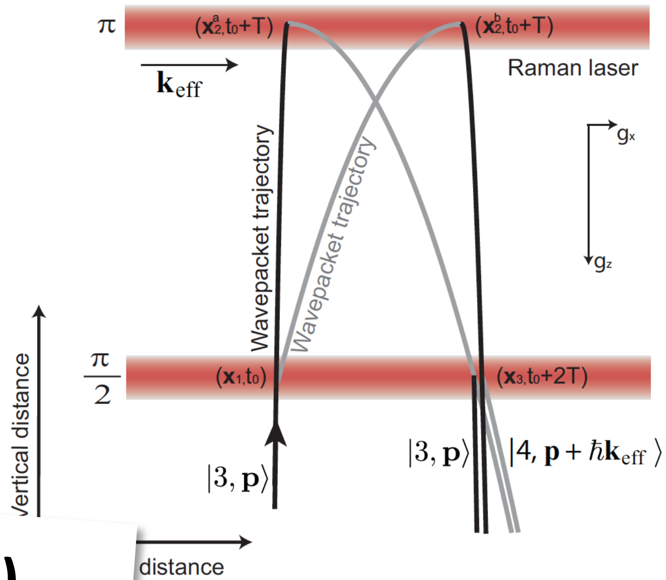
$$\Delta\Phi = -k_{eff}\, g\, T^2$$

(Kasevich group)

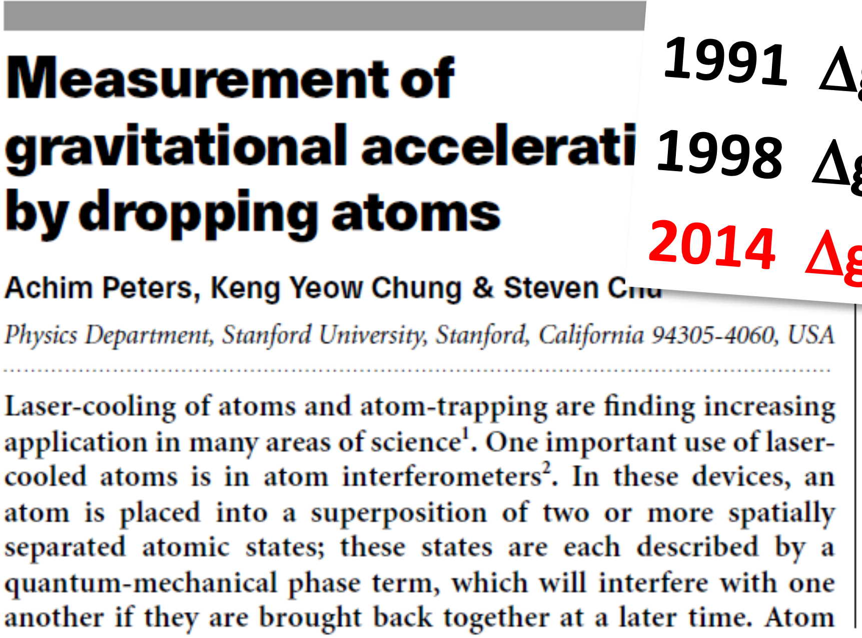
1991 $\Delta g/g = 1\text{x}10^{-6}$

1998 $\Delta g/g = 3\text{x}10^{-8}$

2014 $\Delta g/g = 5\text{x}10^{-13}$



Nature 1999



Measurement of gravitational accelerati 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

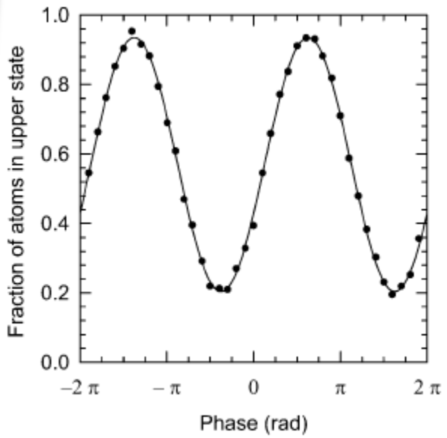
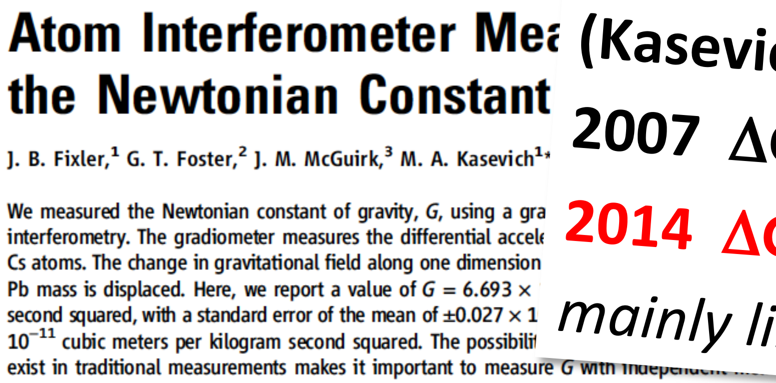


Figure 2 Typical Doppler-sensitive interferometer fringe for $T = 160$ ms. Shown are the 588,638th and 588,639th fringes. Each of the 40 data points represents a single launch of the atoms, spaced 1.3 s apart and taken over a period of 1 min. One full fringe corresponds to $\sim 2\times10^{6}g$. Performing 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 Mea
the Newtonian Constant

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 gra
interferometry. The gradiometer measures the differential accele
Cs atoms. The change in gravitational field along one dimension
Pb mass is displaced. Here, we report a value of $G = 6.693 \times$
second squared, with a standard error of the mean of $\pm 0.027 \times 1$
10^{-11} cubic meters per kilogram second squared. The possibilit
exist in traditional measurements makes it important to measure G with independent

(Kasevich/Tino groups)

2007 $\Delta G/G = 3 \times 10^{-3}$

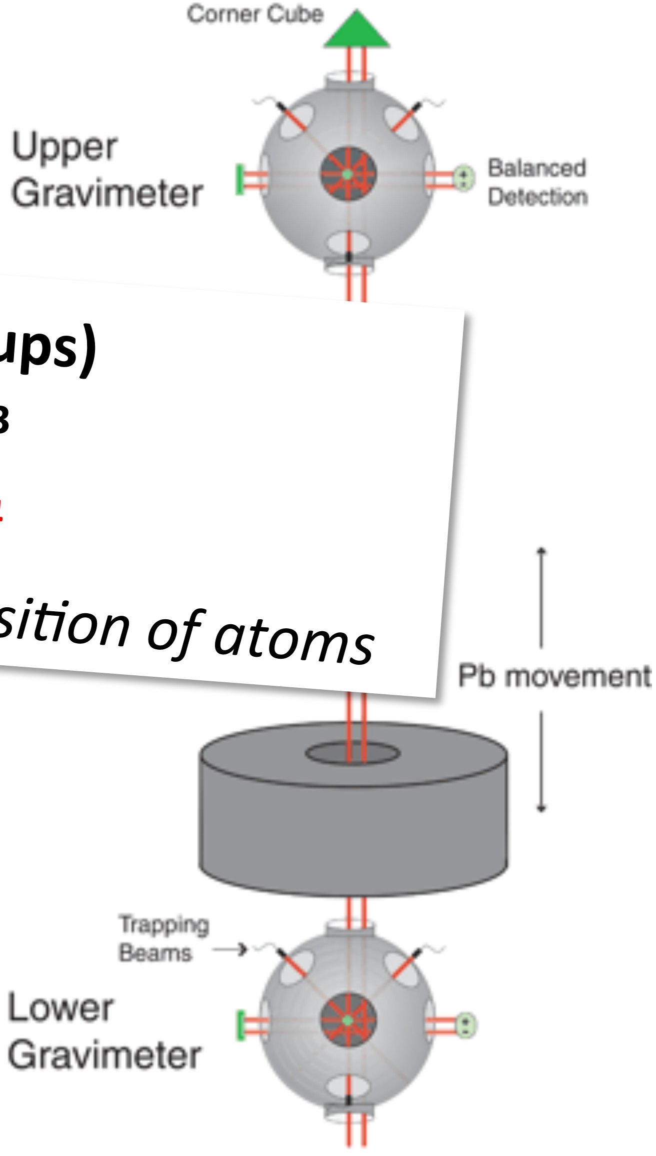
2014 $\Delta G/G = 1 \times 10^{-4}$

mainly limited by position of atoms

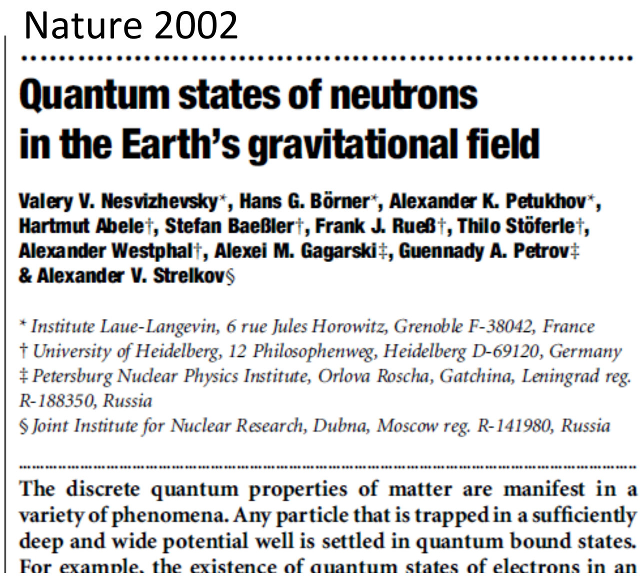
Nature 2014

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



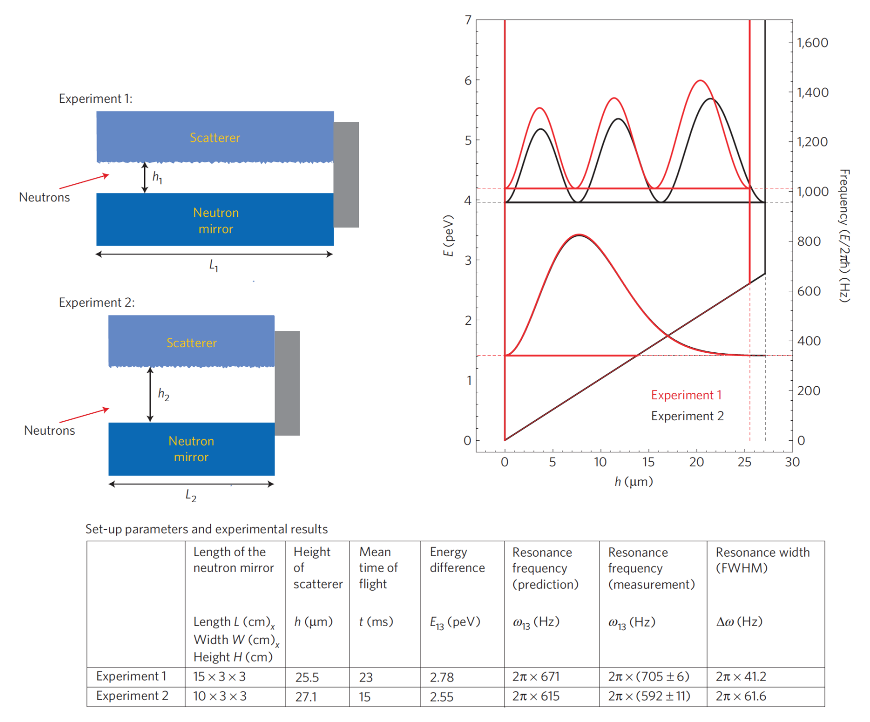
Nature 2002

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§

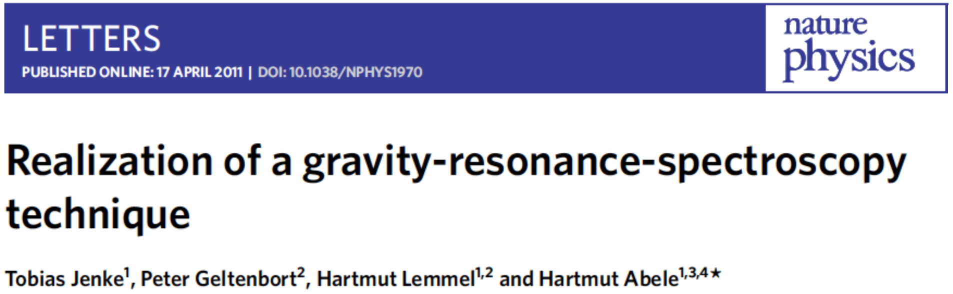
* *Institute Laue-Langevin, 6 rue Jules Horowitz, Grenoble F-38042, France*
† *University of Heidelberg, 12 Philosophenweg, Heidelberg D-69120, Germany*
‡ *Petersburg Nuclear Physics Institute, Orlova Roscha, Gatchina, Leningrad reg. R-188350, Russia*
§ *Joint Institute for Nuclear Research, Dubna, Moscow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

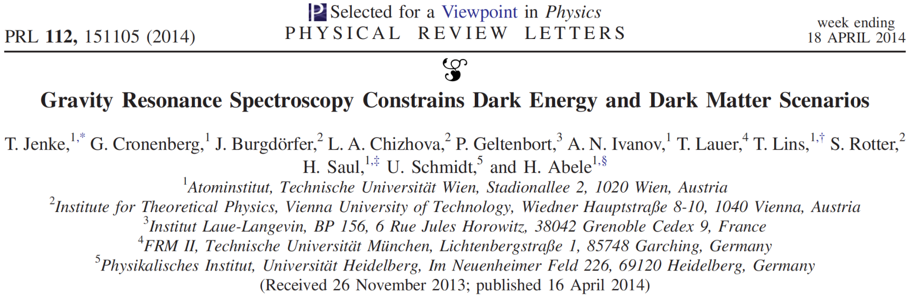
	Length of the neutron mirror Length *L* (cm)$_x$ Width *W* (cm)$_x$ Height *H* (cm)	Height of scatterer *h* (µm)	Mean time of flight *t* (ms)	Energy difference E_{13} (peV)	Resonance frequency (prediction) ω_{13} (Hz)	Resonance frequency (measurement) ω_{13} (Hz)	Resonance width (FWHM) $\Delta\omega$ (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]*



Selected for a Viewpoint in *Physics*
PRL **112**, 151105 (2014) PHYSICAL REVIEW LETTERS week ending 18 APRIL 2014

Gravity Resonance Spectroscopy Constrains Dark Energy and Dark Matter Scenarios

T. Jenke,[1,*] G. Cronenberg,[1] J. Burgdörfer,[2] L. A. Chizhova,[2] P. Geltenbort,[3] A. N. Ivanov,[1] T. Lauer,[4] T. Lins,[1,†] S. Rotter,[2] H. Saul,[1,‡] U. Schmidt,[5] and H. Abele[1,§]
[1]*Atominstitut, Technische Universität Wien, Stadionallee 2, 1020 Wien, Austria*
[2]*Institute for Theoretical Physics, Vienna University of Technology, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria*
[3]*Institut Laue-Langevin, BP 156, 6 Rue Jules Horowitz, 38042 Grenoble Cedex 9, France*
[4]*FRM II, Technische Universität München, Lichtenbergstraße 1, 85748 Garching, Germany*
[5]*Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany*
(Received 26 November 2013; published 16 April 2014)

... and many more...

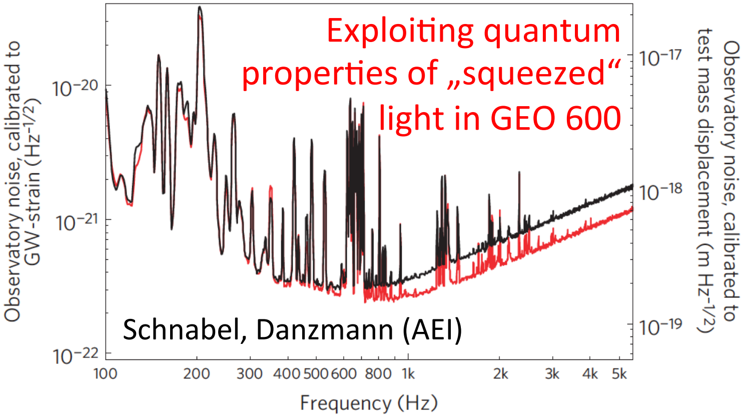
LETTERS

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 †*



Exploiting quantum properties of „squeezed“ light in GEO 600

Schnabel, Danzmann (AEI)

Towards the ultimate quantum limits of measurement

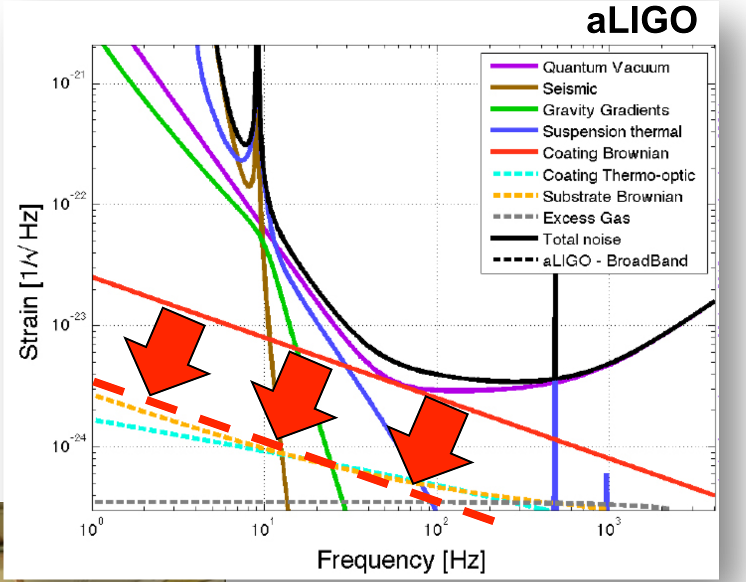
ARTICLES

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

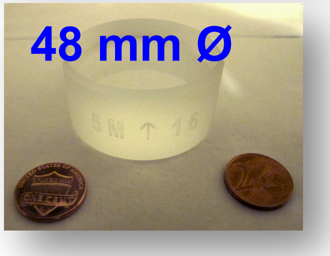
nature photonics

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]*



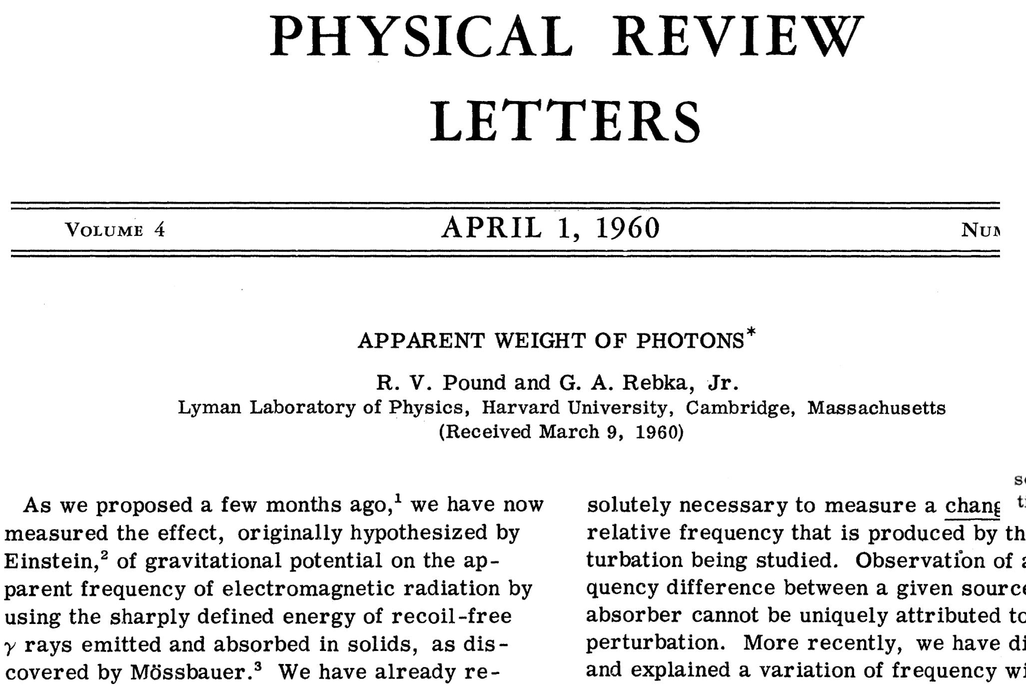
10m Prototype for Gravitational-Wave Detector Research
(Albert-Einstein Institut, Hannover)



48 mm Ø

with H. Lück (AEI),
K. Danzmann (AEI)

Quantum tests of the gravitational time dilation



PHYSICAL REVIEW
LETTERS

Volume 4 APRIL 1, 1960 Nu

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-

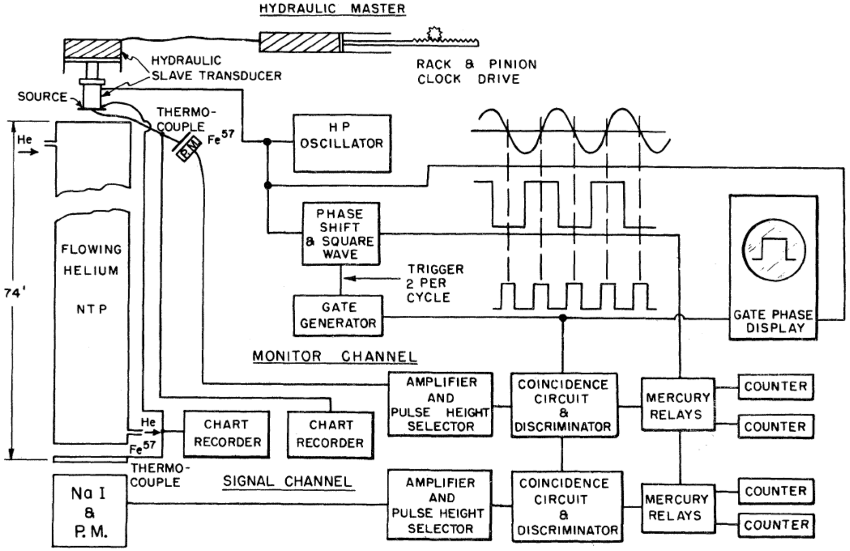
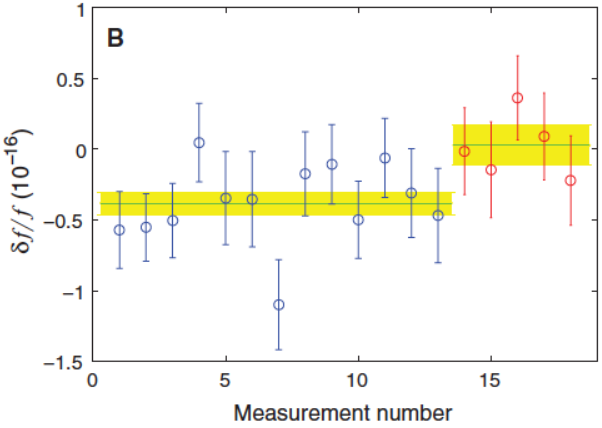
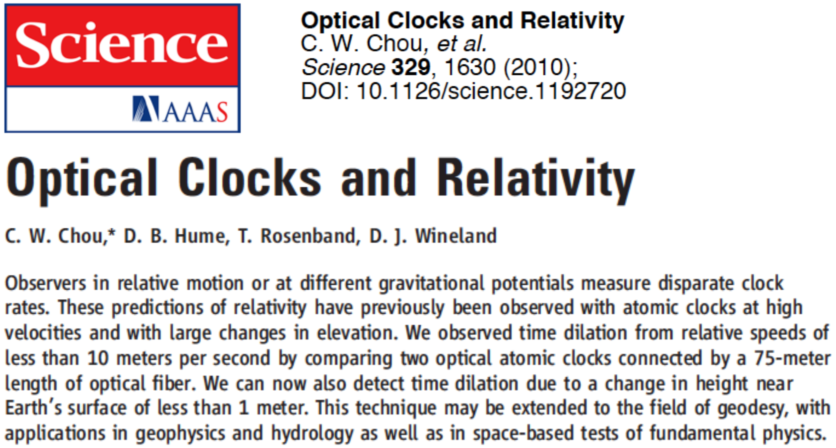


FIG. 1. A block diagram of the over-all experimental arrangement. The source and absorber-detector units were frequently interchanged. Sometimes a ferroelectric and sometimes a moving-coil magnetic transducer was used with frequencies ranging from 10 to 50 cps.

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



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)

Quantum tests of the gravitational time dilation

PHYSICAL REVIEW LETTERS

VOLUME 4 APRIL 1, 1960 NUı

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-

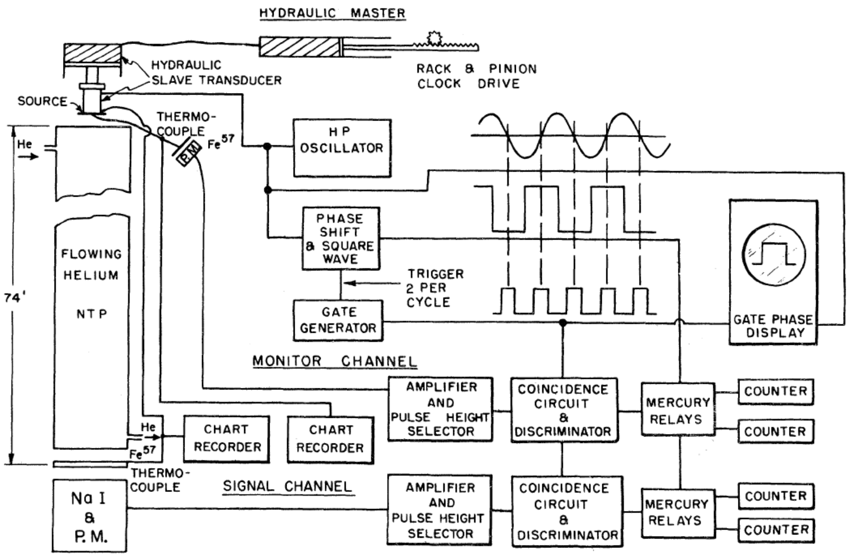


FIG. 1. A block diagram of the over-all experimental arrangement. The source and absorber-detector units were frequently interchanged. Sometimes a ferroelectric and sometimes a moving-coil magnetic transducer was used with frequencies ranging from 10 to 50 cps.

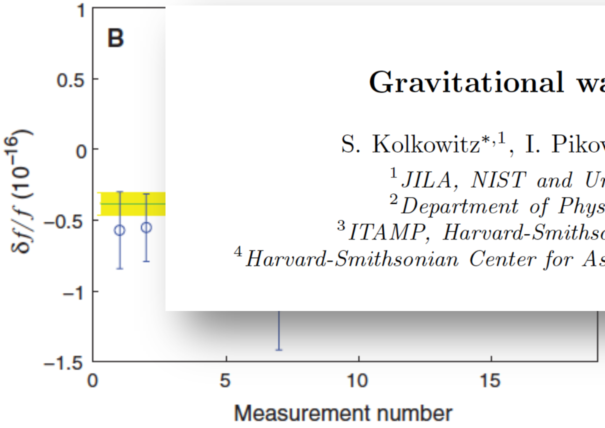
$$\Delta\nu/\nu = gh/c^2 = 10^{-16} \text{ x } h$$

arxiv.org/abs/1606.01859 (2016)

Gravitational wave detection with optical lattice atomic clocks

S. Kolkowitz*[,1], I. Pikovski[2,3], N. Langellier[2], M.D. Lukin[2], R.L. Walsworth[2,4], J. Ye[†,1]

[1] *JILA, NIST and University of Colorado, 440 UCB, Boulder, Colorado 80309, USA,*
[2] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA,*
[3] *ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA*
[4] *Harvard-Smithsonian Center for Astrophysics and Center for Brain Science, Cambridge, Massachusetts 02138, USA*
(Dated: June 7, 2016)

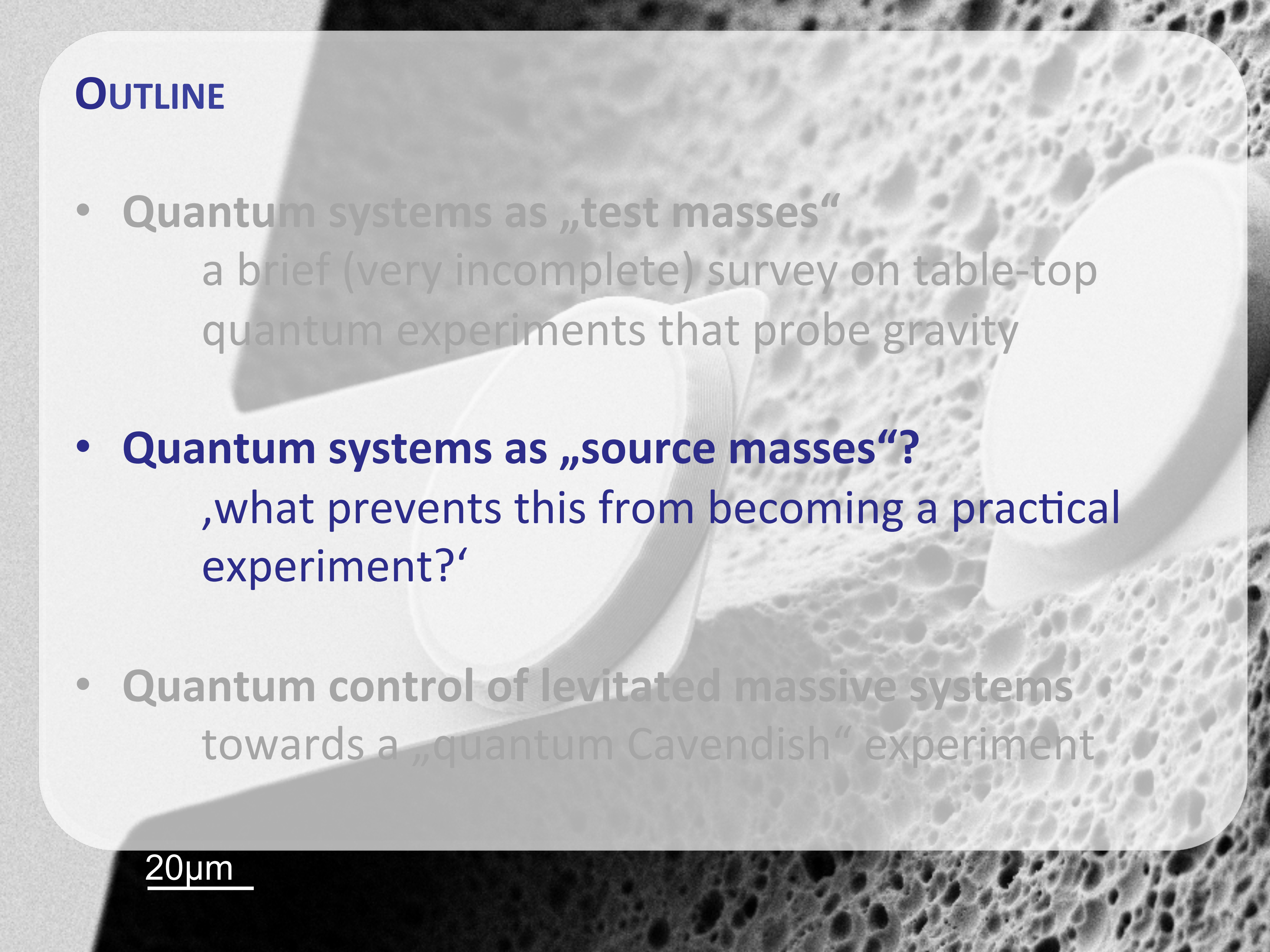


Frequency shift due to 33 cm lift in Earth's gravitational field

isparate 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.

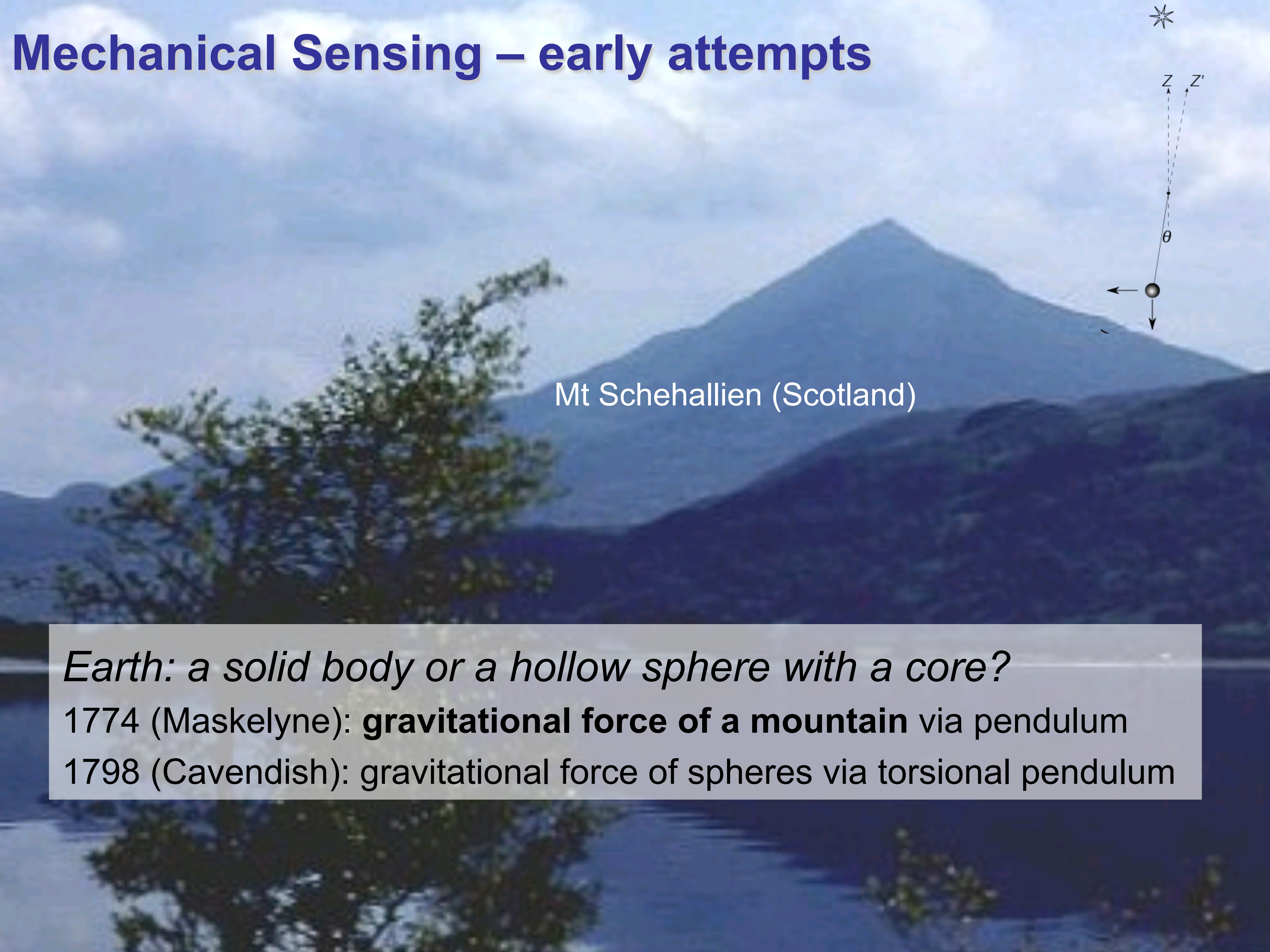
(microwave atomic clocks: e.g. Hafele & Keating, Science 177, 166 (1972), Vessot et al., PRL 45, 2081 (1980): $h=10^7$m)

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

Mechanical Sensing – early attempts



Mt Schehallien (Scotland)

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

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

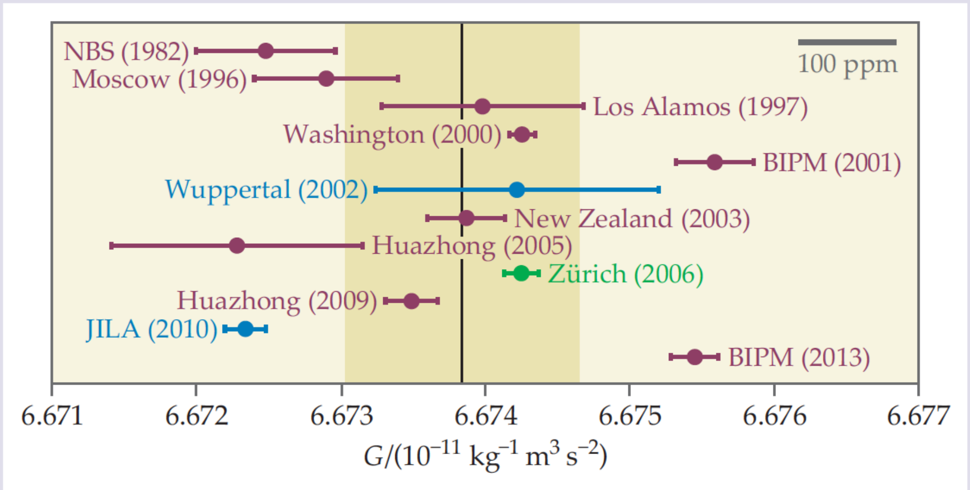


Figure 1. Measurements of Newton's gravitational constant *G* have yielded conflicting results. Here, the results of torsion-balance (maroon), pendulum (blue), and beam-balance (green) experiments discussed in the text are shown, along with the location and year in which they were measured. Error bars 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

universität wien

VCQ
Vienna Center for Quantum Science and Technology

The search for Newton's consta

Three decades of car
hazy picture of the co

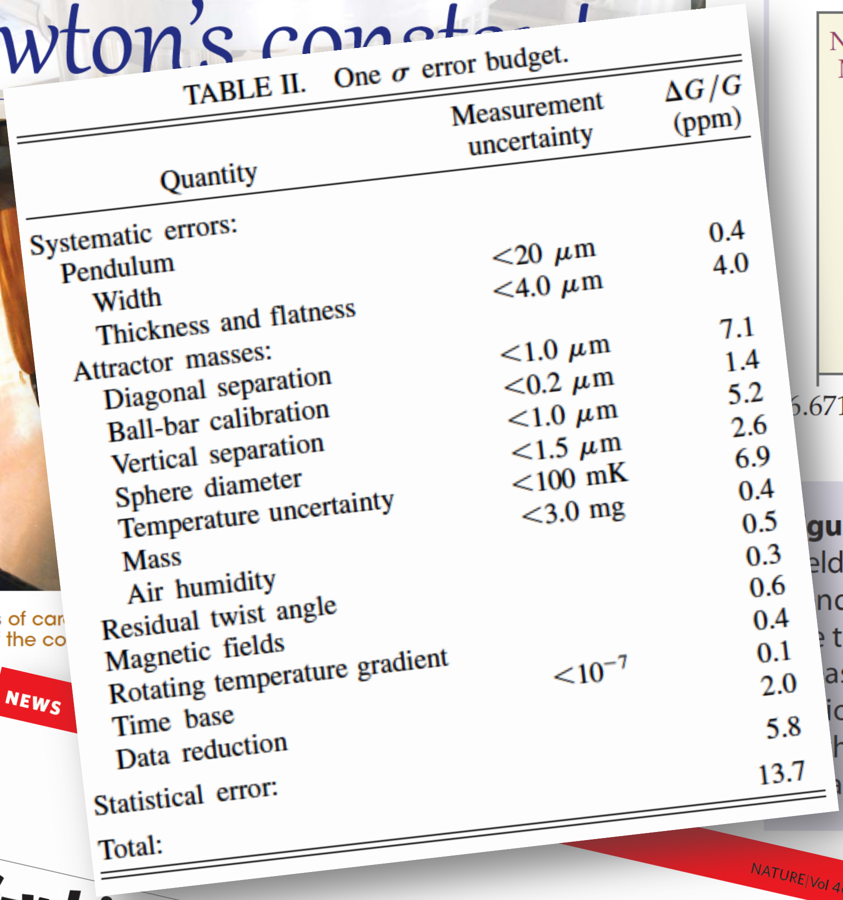


TABLE II. One σ error budget.

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

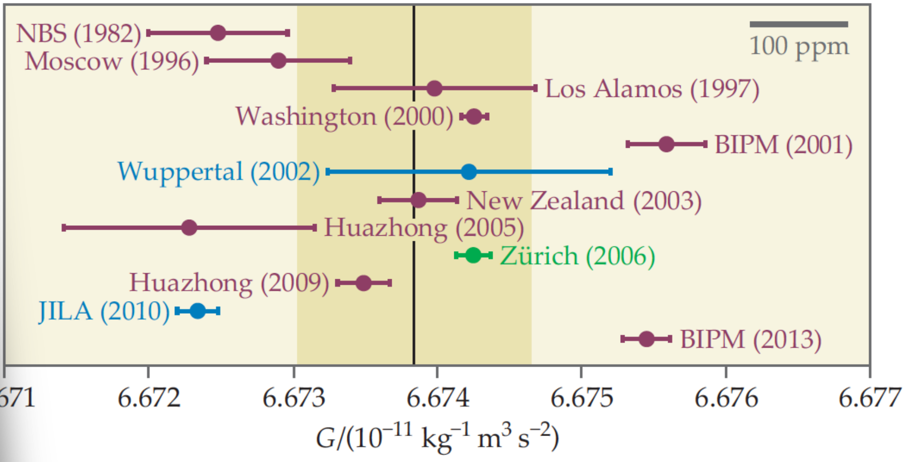
NEWS

NATURE|Vol 466|26 August 2010

G-whizzes disagree over gravity

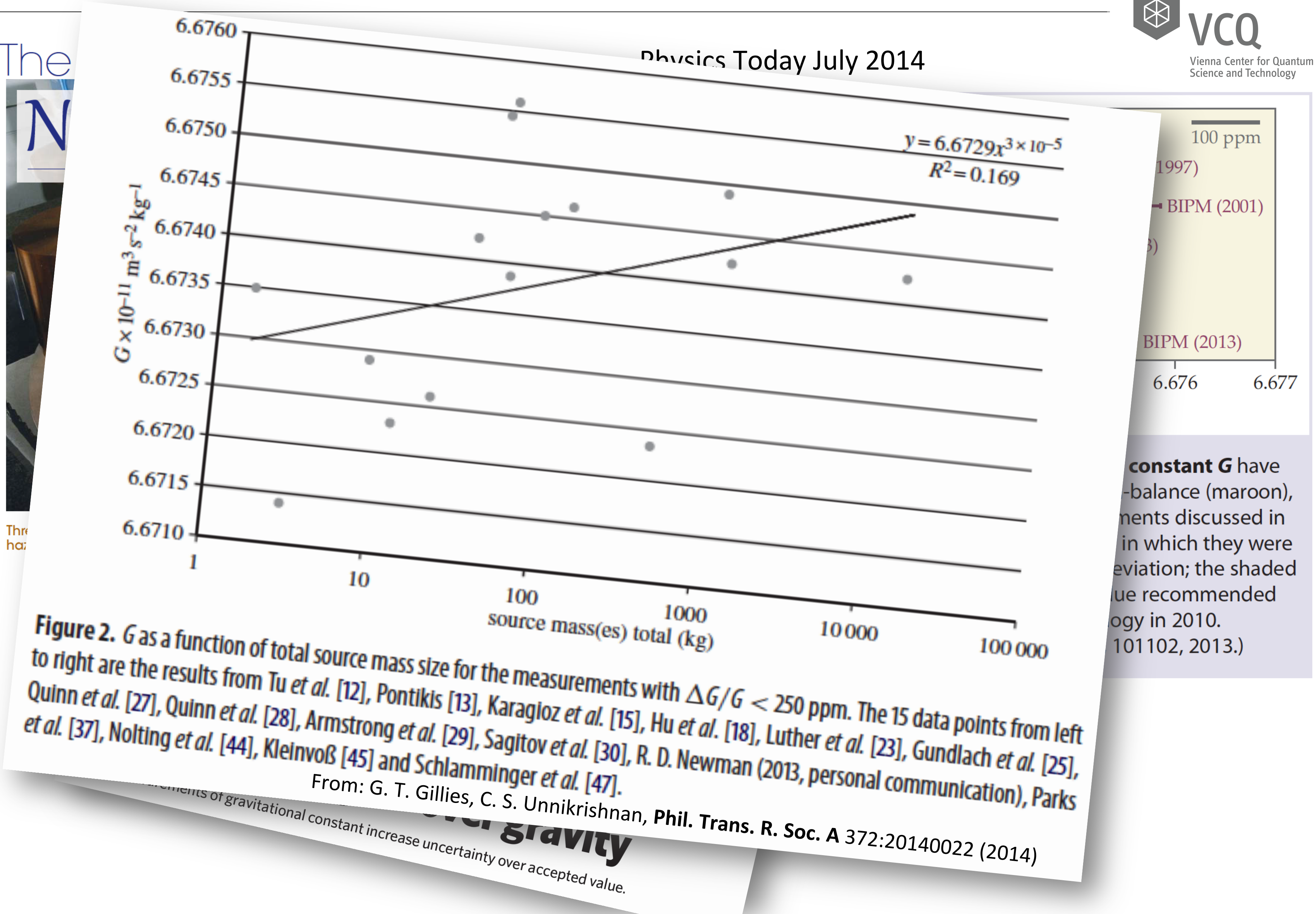
Recent measurements of gravitational constant increase uncertainty over accepted value.

Physics Today July 2014



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

Big G: the open problem



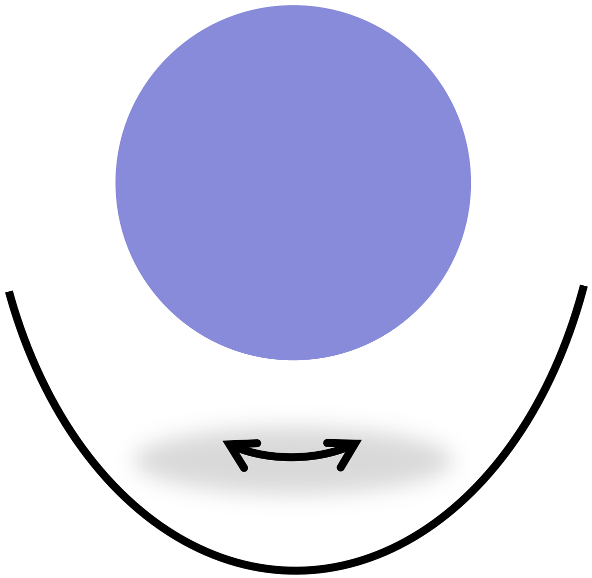
Physics Today July 2014

Figure 2. G as a function of total source mass size for the measurements with $\Delta G/G < 250$ ppm. The 15 data points from left to right are the results from Tu *et al.* [12], Pontikis [13], Karagioz *et al.* [15], Hu *et al.* [18], Luther *et al.* [23], Gundlach *et al.* [25], Quinn *et al.* [27], Quinn *et al.* [28], Armstrong *et al.* [29], Sagitov *et al.* [30], R. D. Newman (2013, personal communication), Parks *et al.* [37], Nolting *et al.* [44], Kleinvoß [45] and Schlamminger *et al.* [47].

constant *G* have
-balance (maroon),
ments discussed in
in which they were
eviation; the shaded
ue recommended
ogy in 2010.
101102, 2013.)

rements of gravitational constant increase uncertainty over accepted value.

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

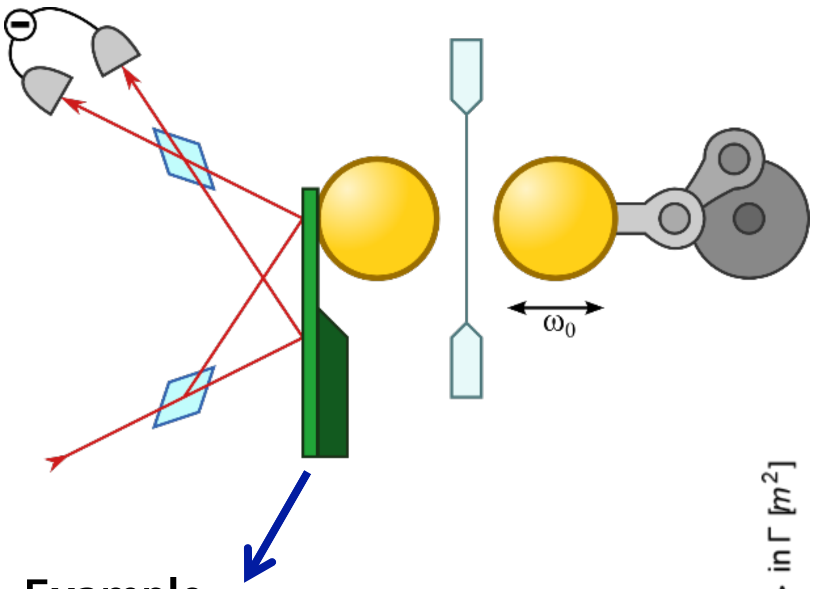


{T, Q , ω, m}

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

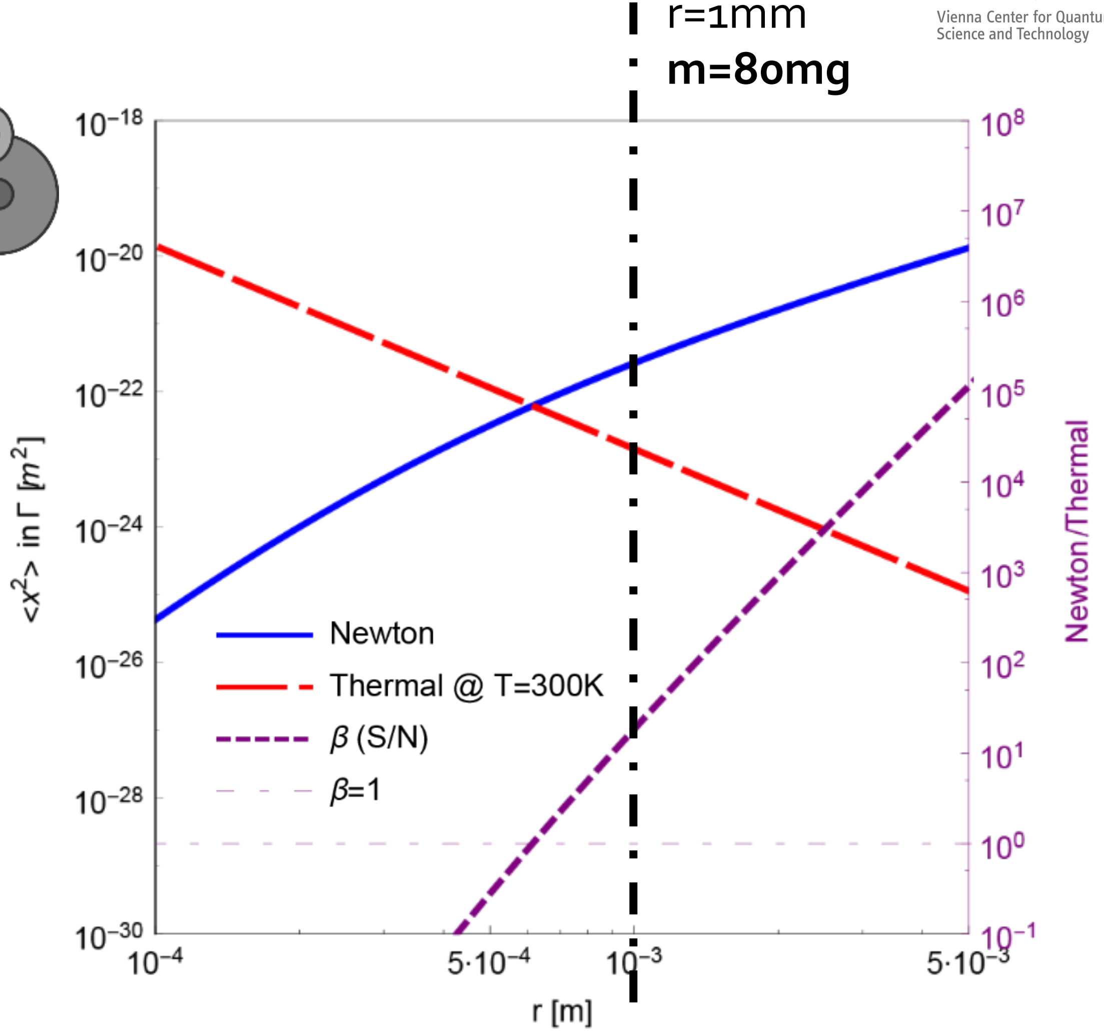
Measuring gravity between microscopic source masses ?

Schmöle et al., Class. Quant. Grav. 33, 125031 (2016)



Example

- f_o = 100 Hz
- Q = 20,000
- T = 300 K
- ρ = 20,000 kg/m^3 (gold)
- Γ = 1/(60 min)

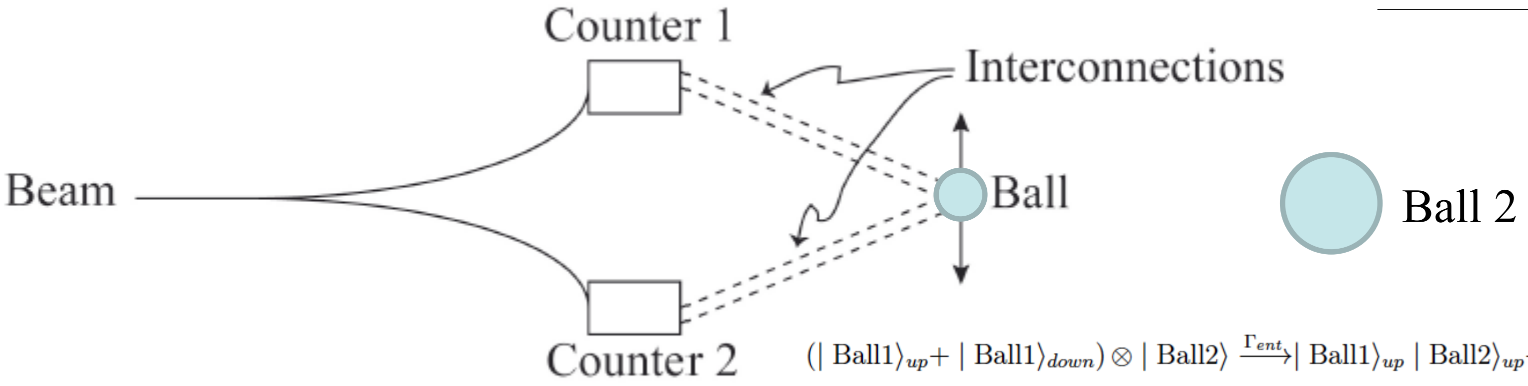


Smallest source mass to date: **120 g**

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

Jonas Schmöle, Mathias Dragosits, Hans Hepach

An ultimate experiment? Entanglement by gravity…



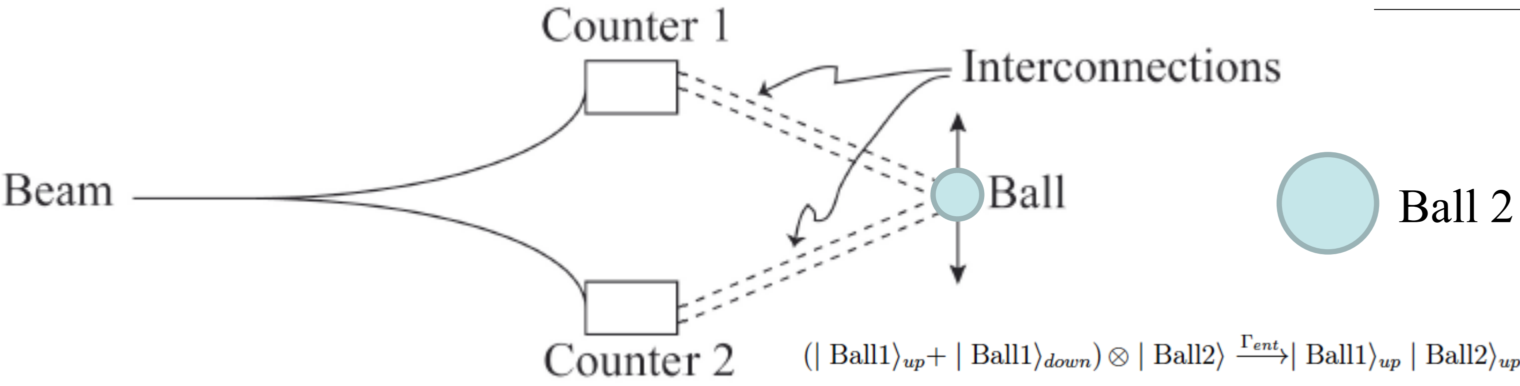
$$(|\mathrm{Ball1}\rangle_{up} + |\mathrm{Ball1}\rangle_{down}) \otimes |\mathrm{Ball2}\rangle \xrightarrow{\Gamma_{ent}} |\mathrm{Ball1}\rangle_{up}\,|\mathrm{Ball2}\rangle_{up} + |\mathrm{Ball1}\rangle_{down}\,|\mathrm{Ball2}\rangle_{down}$$

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.”

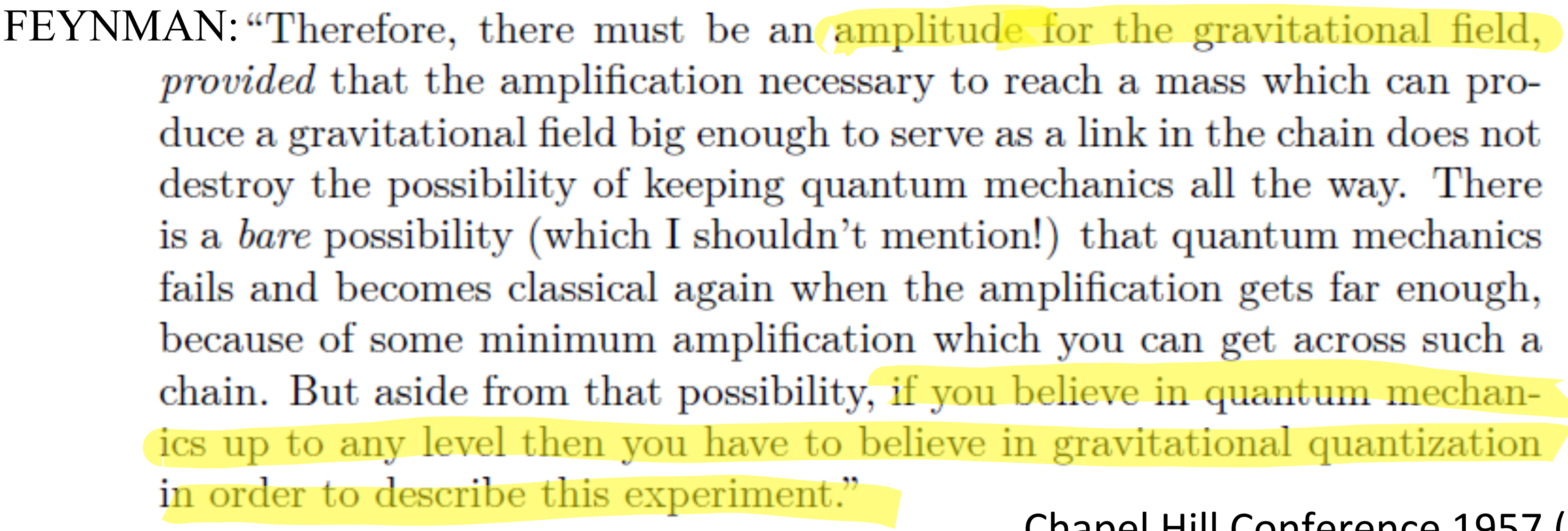
Chapel Hill Conference 1957 (29)

WITTEN: “What prevents this from becoming a practical experiment?”

An ultimate experiment? Entanglement by gravity…



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

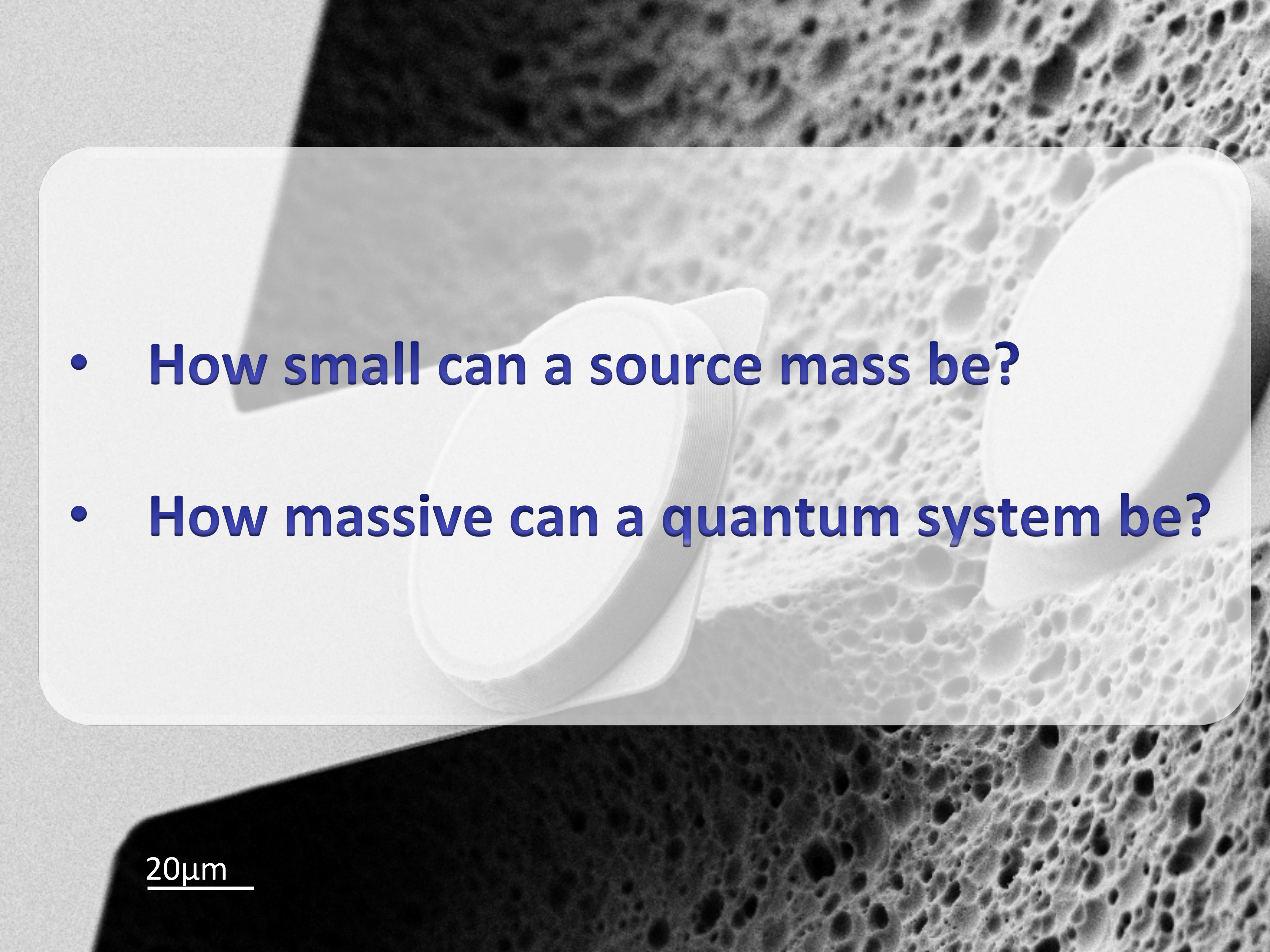


FEYNMAN: "Therefore, there must be an amplitude for the gravitational field, *provided* that the amplification necessary to reach a mass which can produce a gravitational field big enough to serve as a link in the chain does not destroy the possibility of keeping quantum mechanics all the way. There 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)

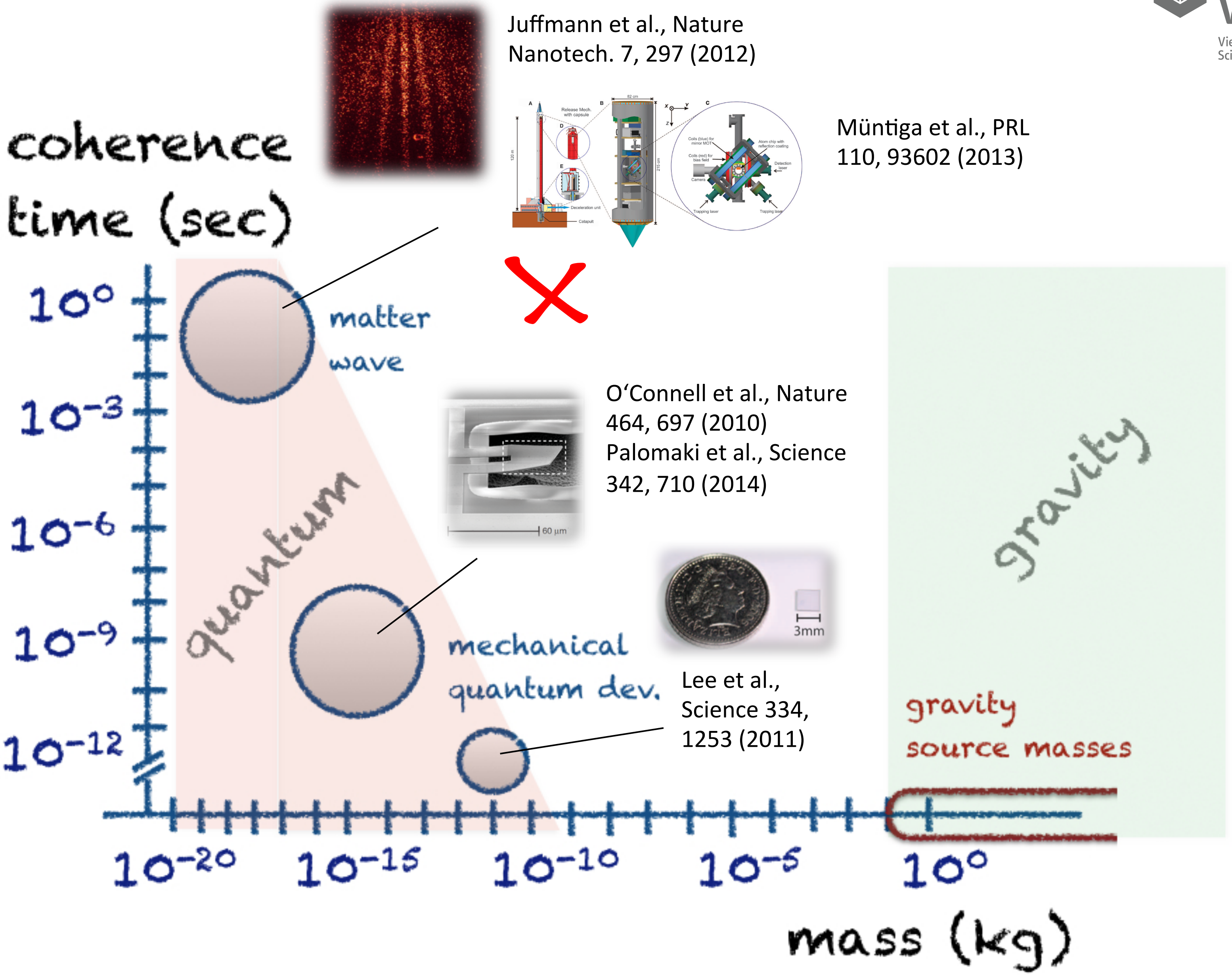
Example: For 2 **lead spheres** of **diameter 500 μm**, an initial **superposition size for sphere 1** of **Δr = 5×10^{-7} m** and preparation of **sphere 2** in a **motional ground state** (100 Hz trap frequency) with **Δx$_0$=10^{-15} m**, we obtain **Γ$_{ent}$=1.5 Hz**, i.e. **gravitational entanglement** is established on a **second time scale**.

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



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

How massive/small can we go?



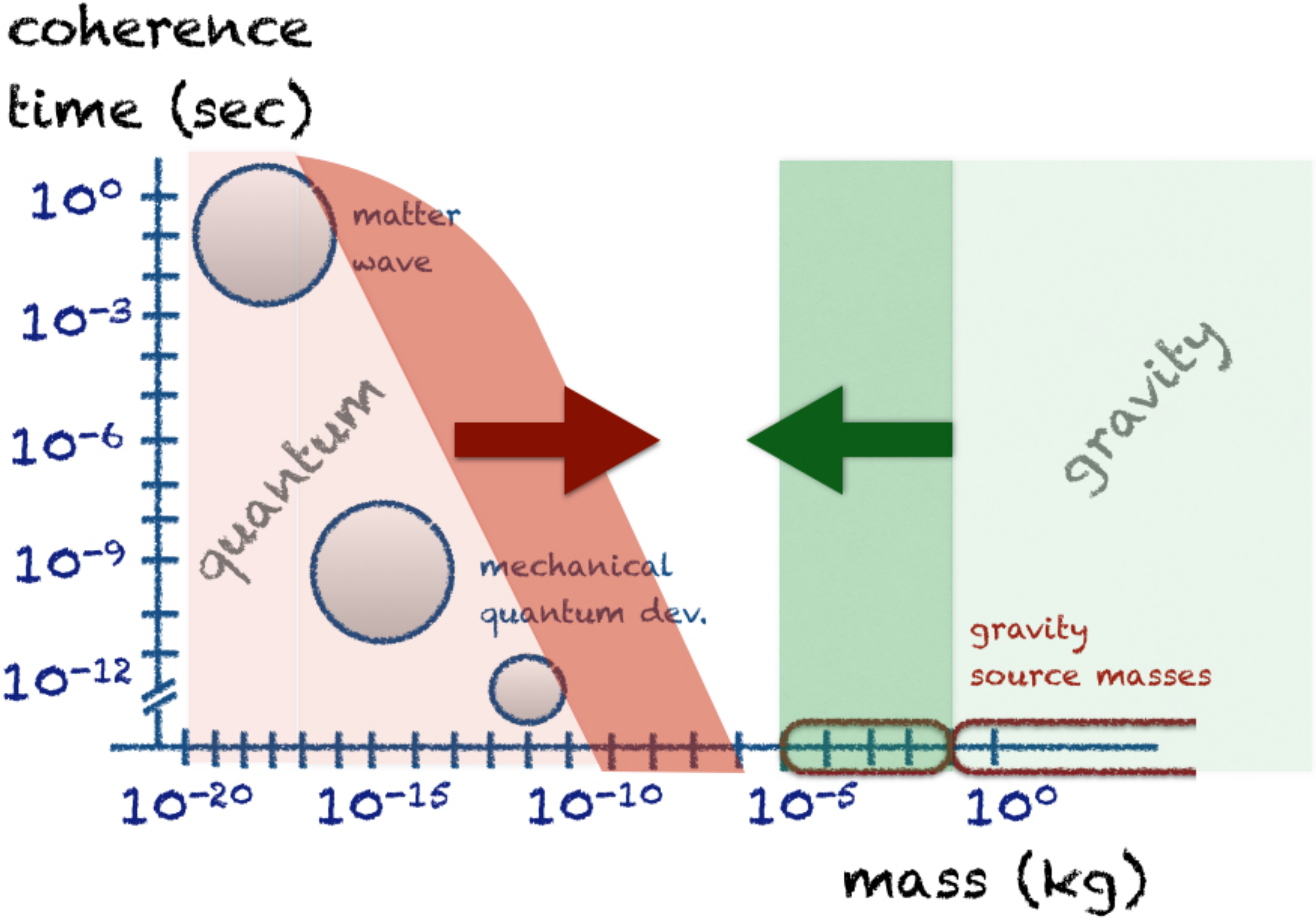
Juffmann et al., Nature Nanotech. 7, 297 (2012)

Müntiga et al., PRL 110, 93602 (2013)

O‘Connell et al., Nature 464, 697 (2010)
Palomaki et al., Science 342, 710 (2014)

Lee et al., Science 334, 1253 (2011)

How massive/small can we go?



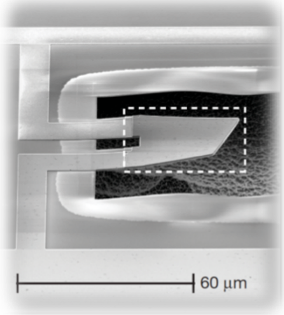
Pushing mechanical quantum control to the next level

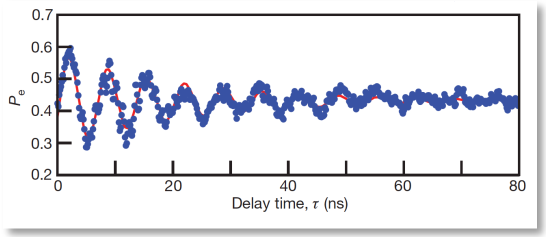
Q: How to achieve large mass **AND** long coherence time in a quantum experiment?

Solid-state mechanical quantum devices (clamped):

10^{10} – 10^{16} atoms

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



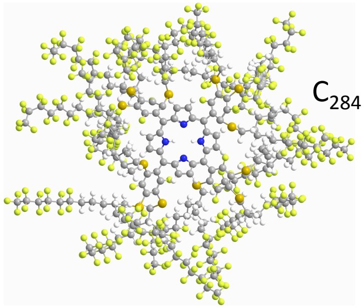


O‘Connell et al., Nature 464, 697 (2010)

Matter-wave interferometry (free-fall):

10^0 – 10^4 atoms

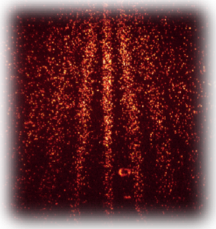
Coherence time τ_c 10^{-3} – 10^0 sec



10 nm

TPPF320

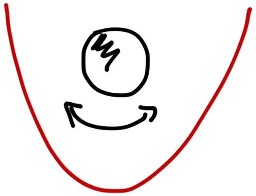
$C_{284}H_{190}F_{320}N_4S_{12}$



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

A: Quantum control of levitated mechanical systems!

Coupling to gravity



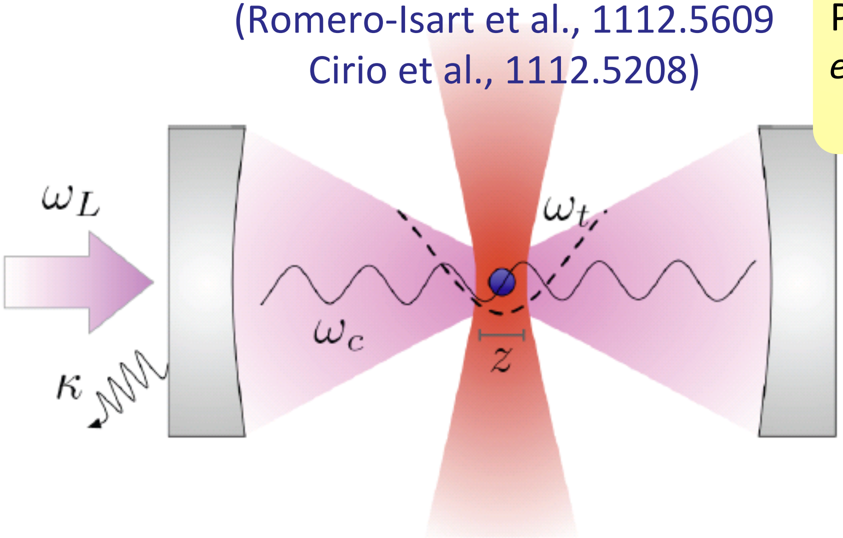
- Quantum control of a trapped massive object >> 10^{10} atoms
- Long coherence times (up to seconds) through free fall dynamics
- Exceptional force sensitivity

Towards quantum state preparation of a free particle

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 . . .***

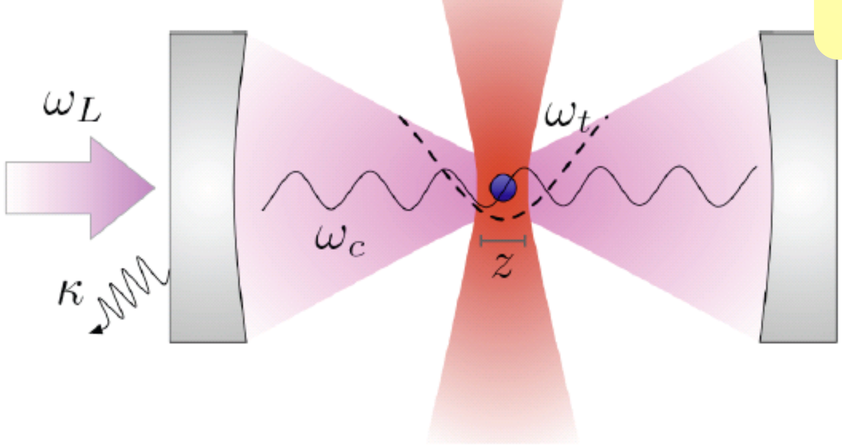
- Akram, Kiesel, Aspelmeyer, Milburn, NJP 12, 083030 (2010)
- Khalili, Danilishin, Miao, Müller-Ebhardt, Yang, Chen, quant-ph 1001.3738 (2010)
- Romero-Isart, Pflanzer, Juan, Quidant, Kiesel, Aspelmeyer, Cirac, Phys. Rev. A 83, 013803 (2011)

Towards quantum state preparation of a free particle

Optically levitated nanospheres

Magnetically levitated spheres

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



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

→ **Harm**

→ **Quant**

nics

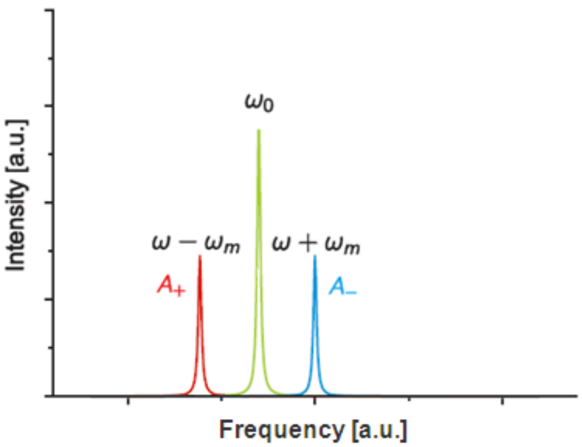
2010

1998)

enter for Quantum
nd Technology

Cavity Optomechanics

Rev.Mod.Phys. 86, 1391 (2014)



Generation of quantum superposition states

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

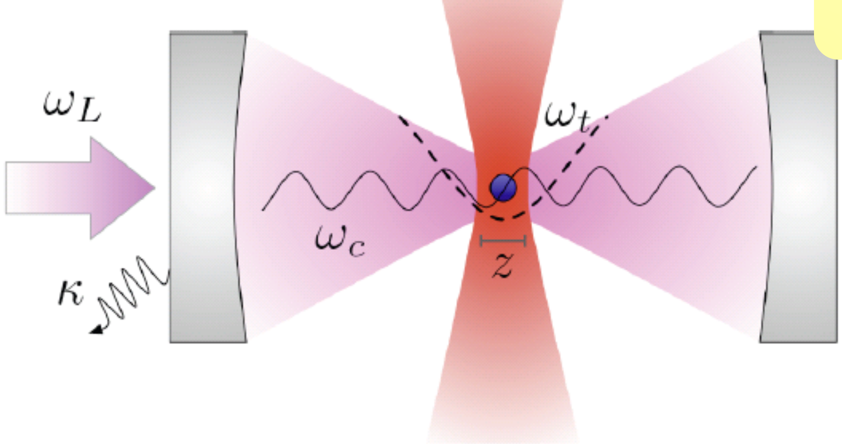
- Akram, Kiesel, Aspelmeyer, Milburn, NJP 12, 083030 (2010)
- Khalili, Danilishin, Miao, Müller-Ebhardt, Yang, Chen, quant-ph 1001.3738 (2010)
- Romero-Isart, Pflanzer, Juan, Quidant, Kiesel, Aspelmeyer, Cirac, Phys. Rev. A 83, 013803 (2011)

Towards quantum state preparation of a free particle

Optically levitated nanospheres

Magnetically levitated spheres

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



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

2010

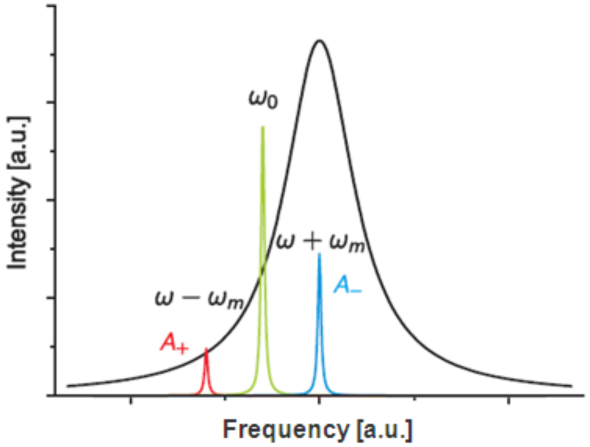
998)

→ **Harm**

→ **Quant** **nics**

Cavity Optomechanics

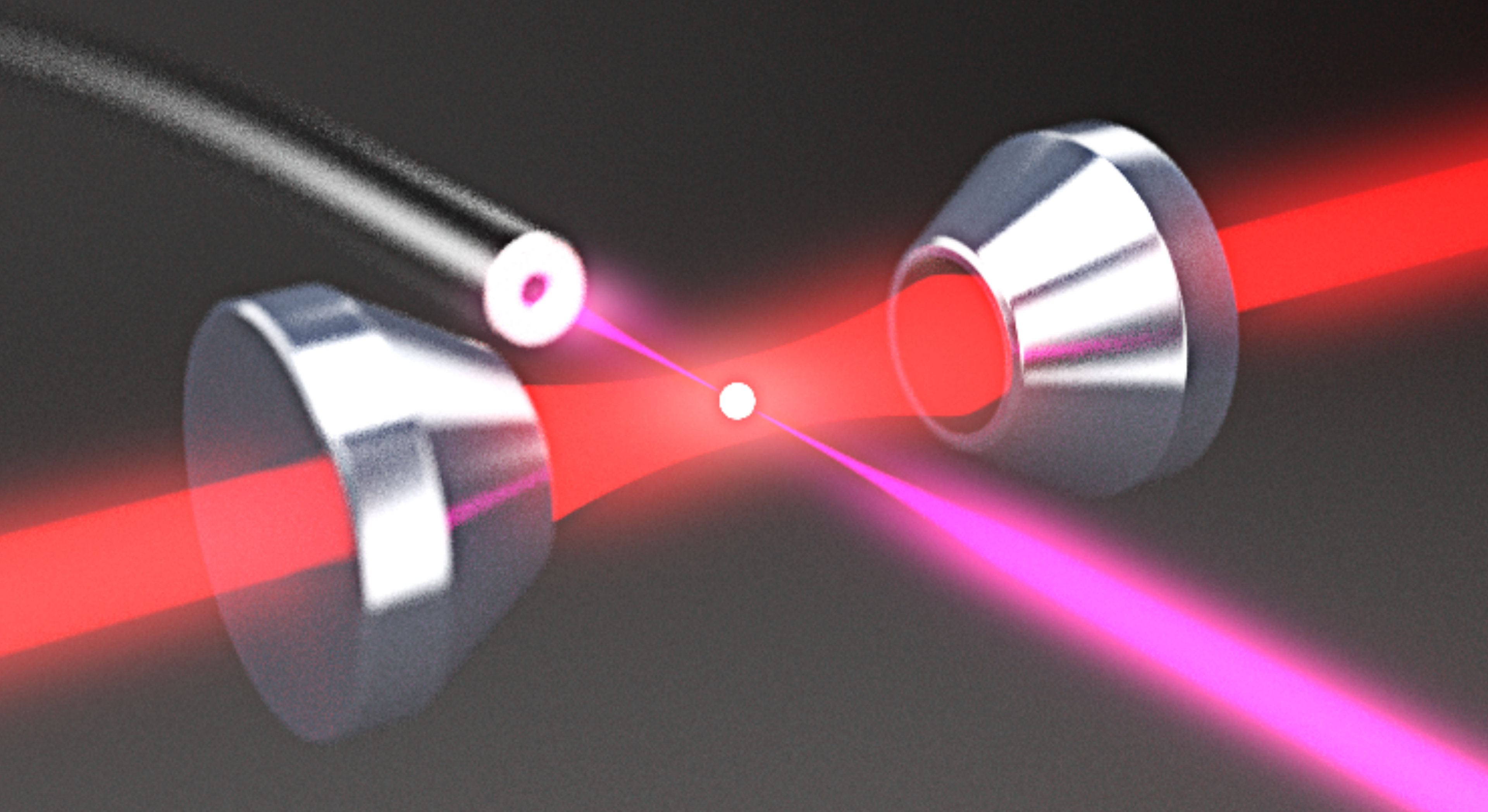
Rev.Mod.Phys. 86, 1391 (2014)



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)

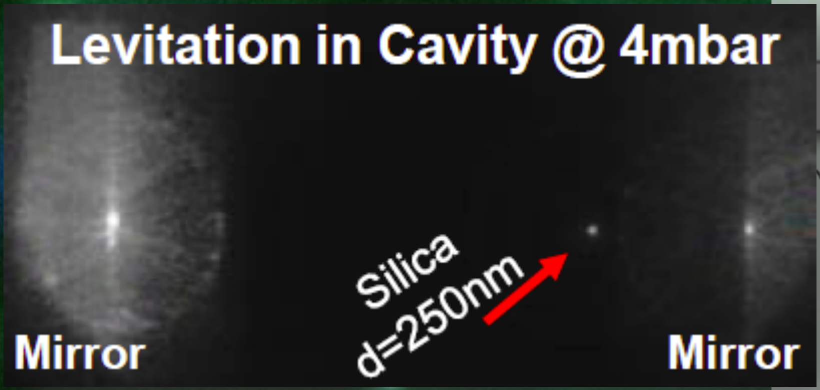


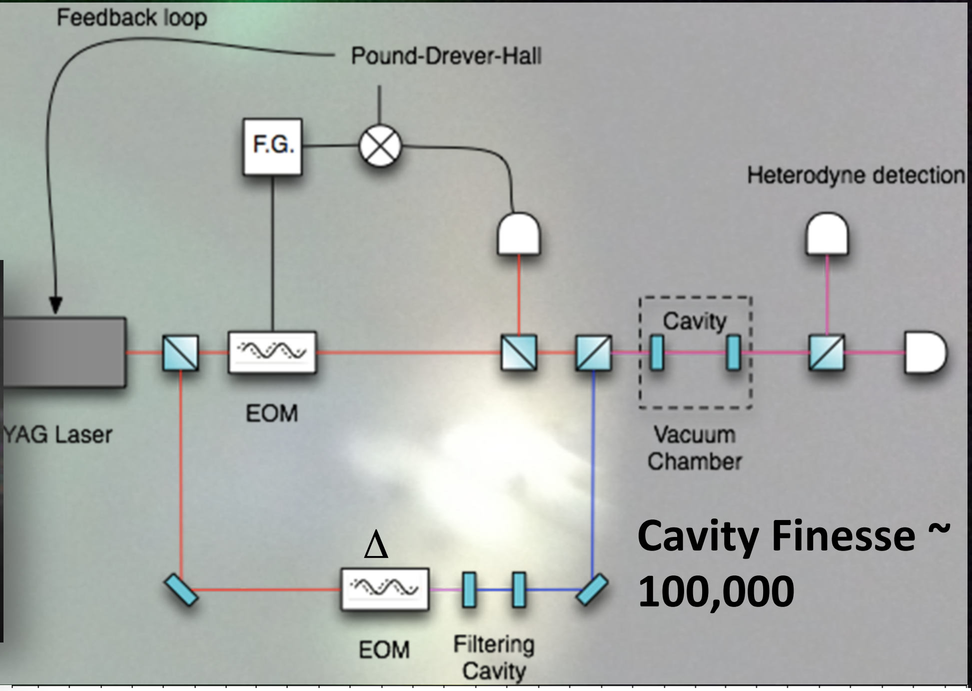
A cavity-fiber interface

D. Grass, U. Delic, M.&C. Siegele, N. Kiesel

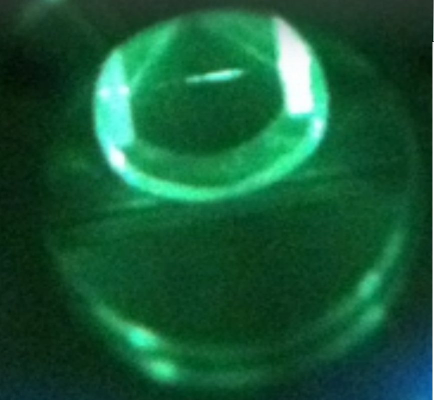
Optically trapped nanospheres as mechanical resonators

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

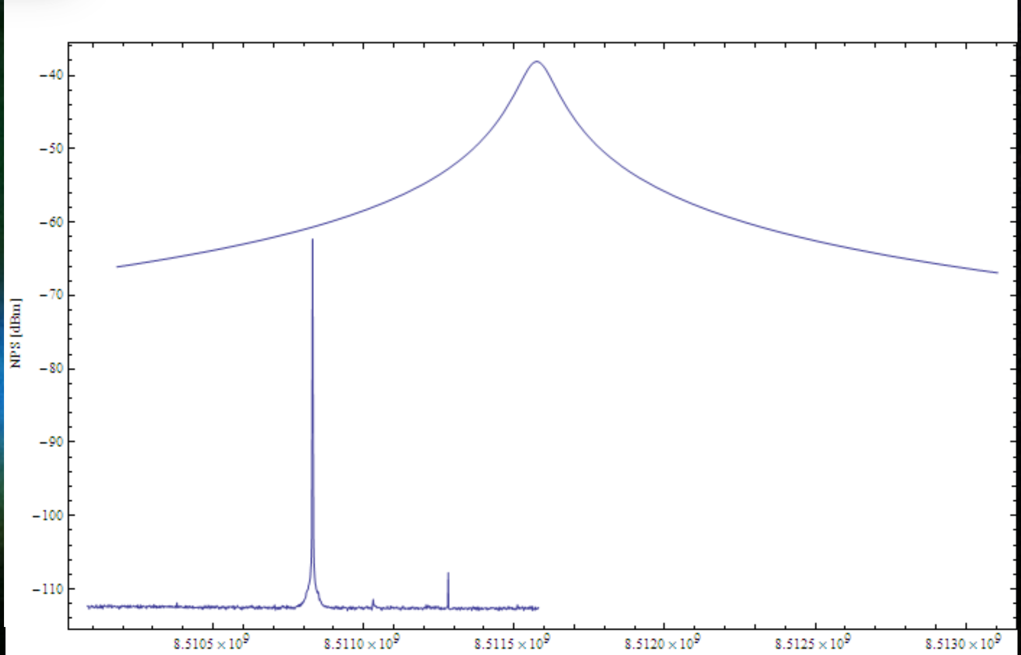




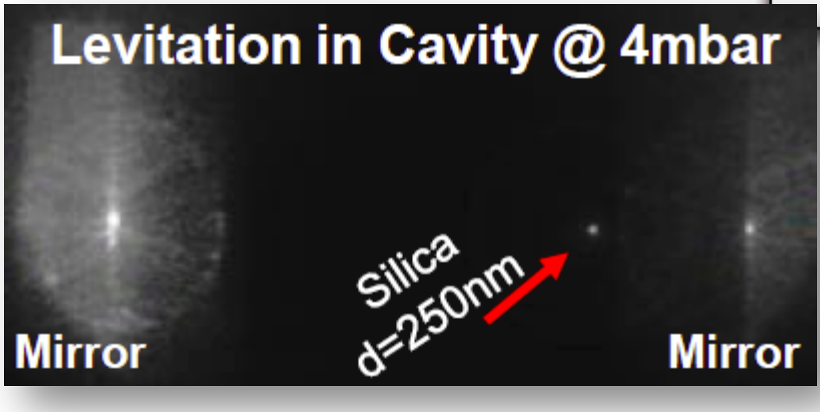
Cavity Finesse ~ 100,000

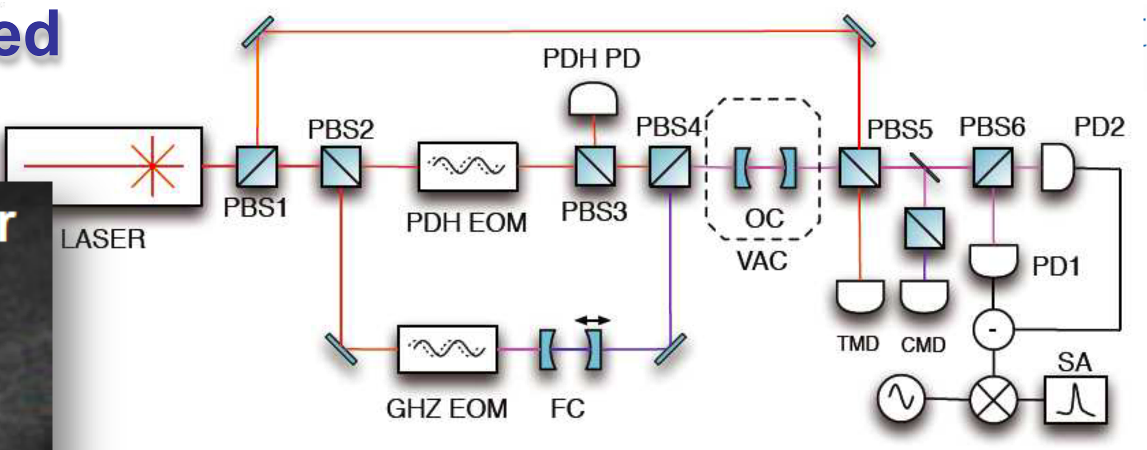


Optical trapping inside a cavity… (R~20nm – 2µm)
Kiesel, Kaltenbaek, Blaser, Delic et al., work in progress



Cavity cooling of a trapped nanosphere





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

$Q \sim 25$ @ 4 mbar

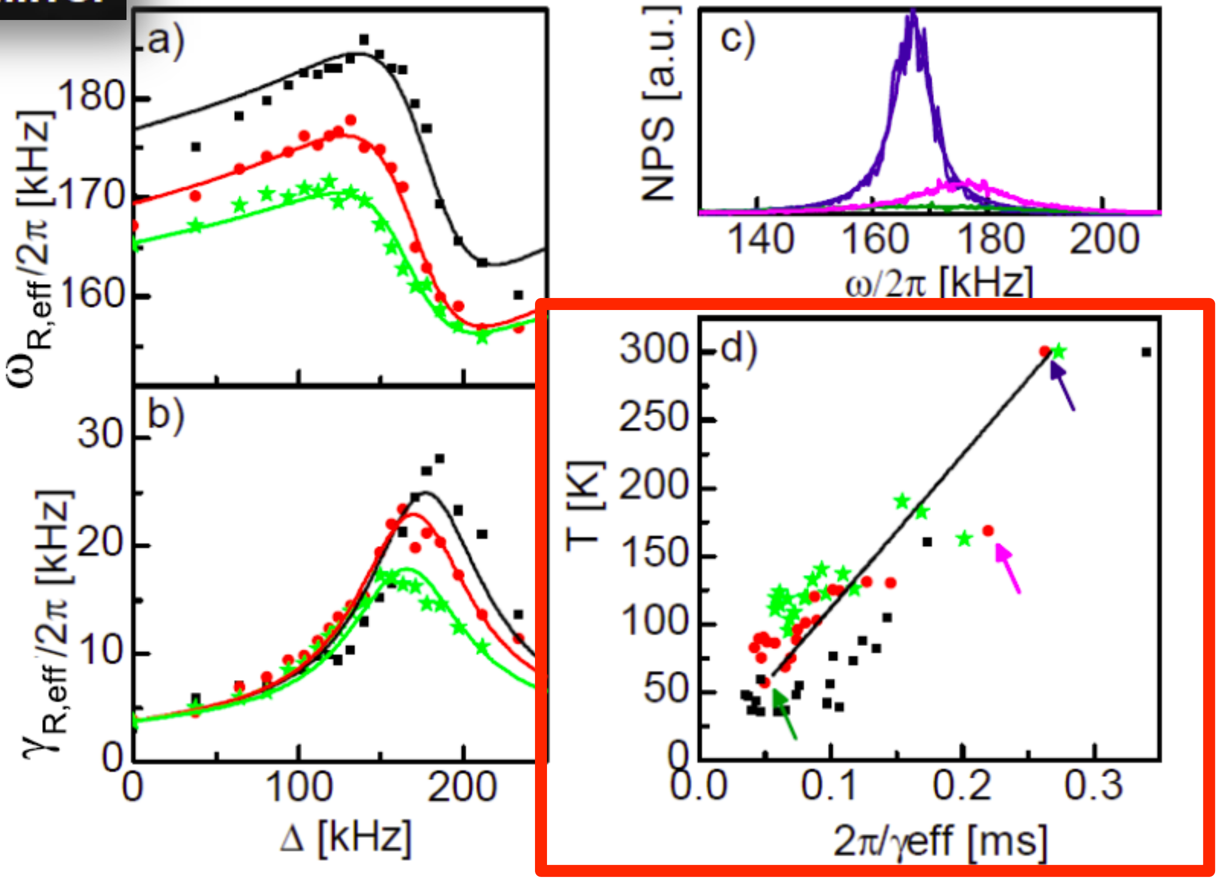
$Q \sim 10^9$ @ 10^{-7} mbar

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

100 μm

100 μm

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

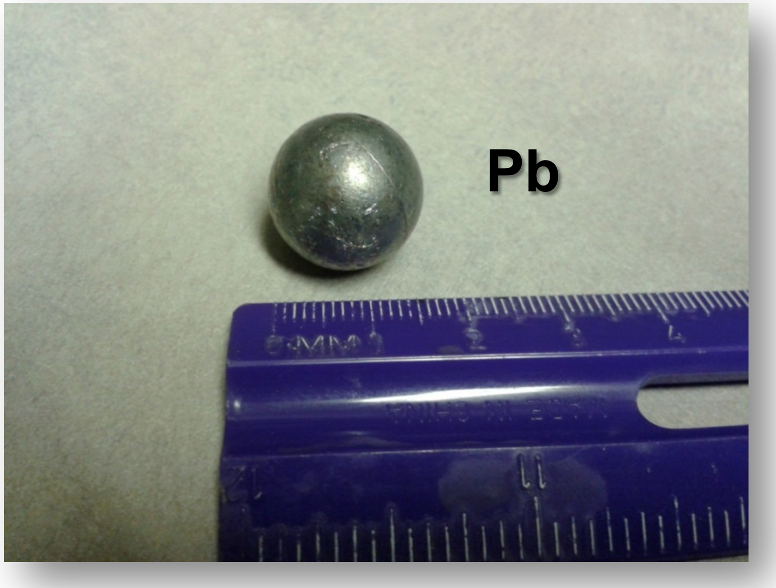


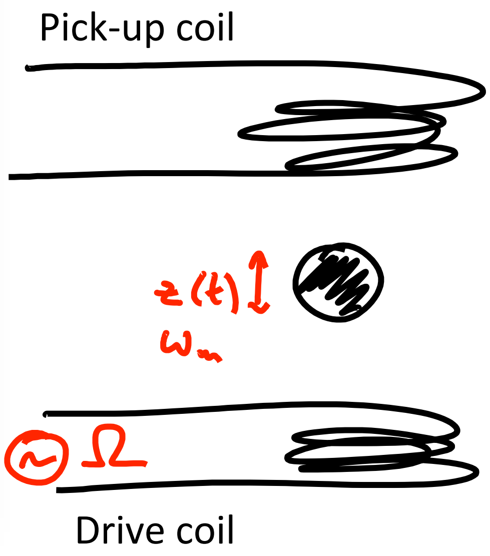
N. Kiesel, F. Blaser, U. Delic, D. Grass, R. Kaltenbaek, M. Aspelmeyer, *PNAS USA* **110**, 14180 (2013)
See also: P. Asenbaum et al., *Nat. Comm.* **4**, 2743 (2013)

Magnetically trapped superconductors as mechanical resonators

universität wien

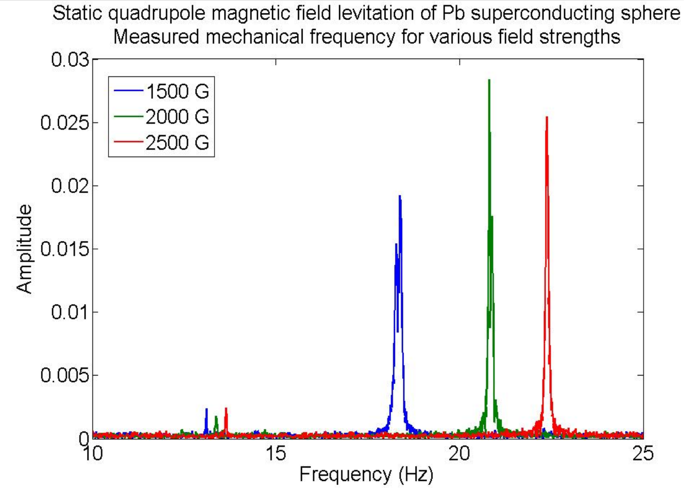
VCQ Vienna Center for Quantum Science and Technology

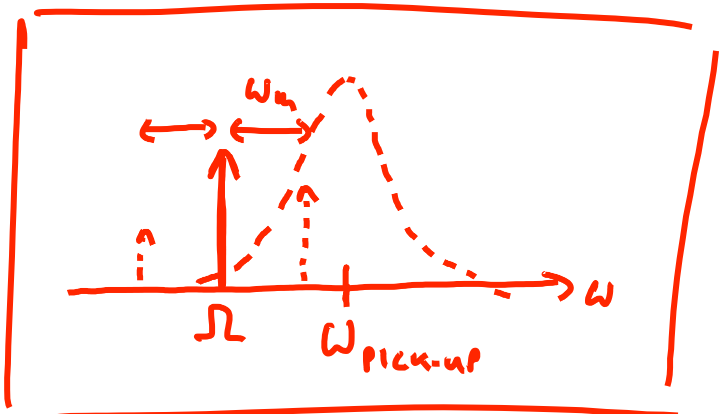




$$H_{int} \propto -\frac{\Phi_1 \Phi_2}{L_1 L_2} M_{12}(z)$$

M_{12} : mutual inductance





"CAVITY OPTO-MECHANICS"

(artist's impression – still...)

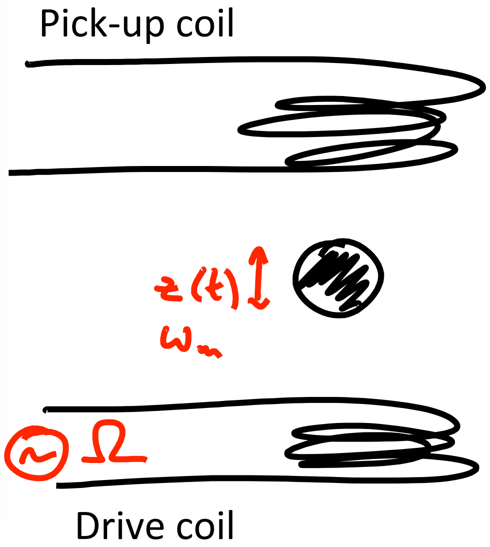
Magnetic levitation in anti-Helmholtz coil configuration

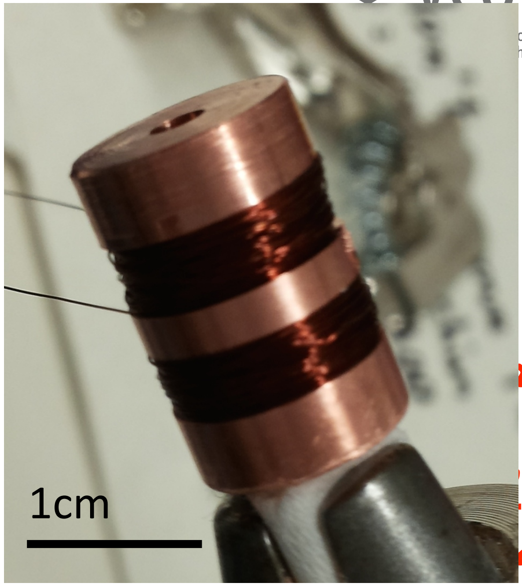
Trap frequencies ~ 20 Hz

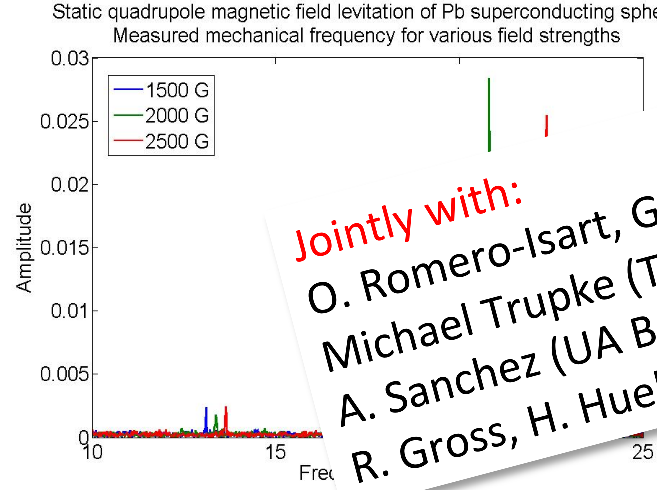
T= 20 mK, p = 1e-6 mbar

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

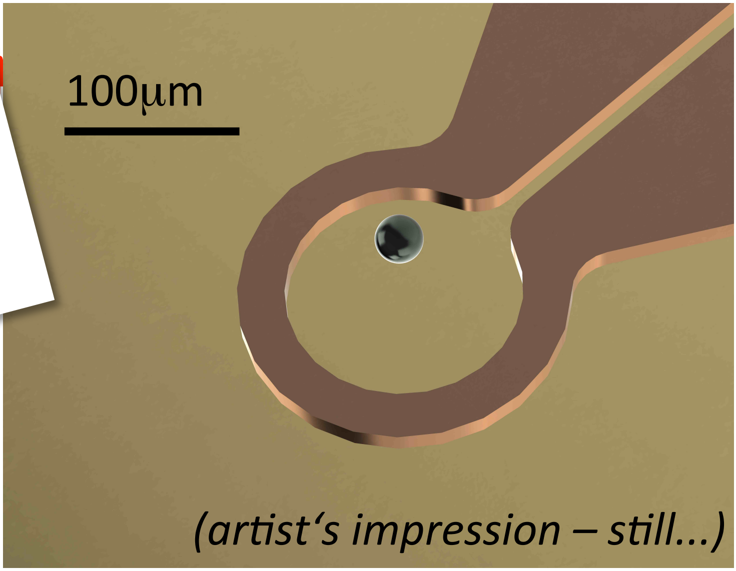
Magnetically trapped superconductors as mechanical resonators







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



(artist's impression – still...)

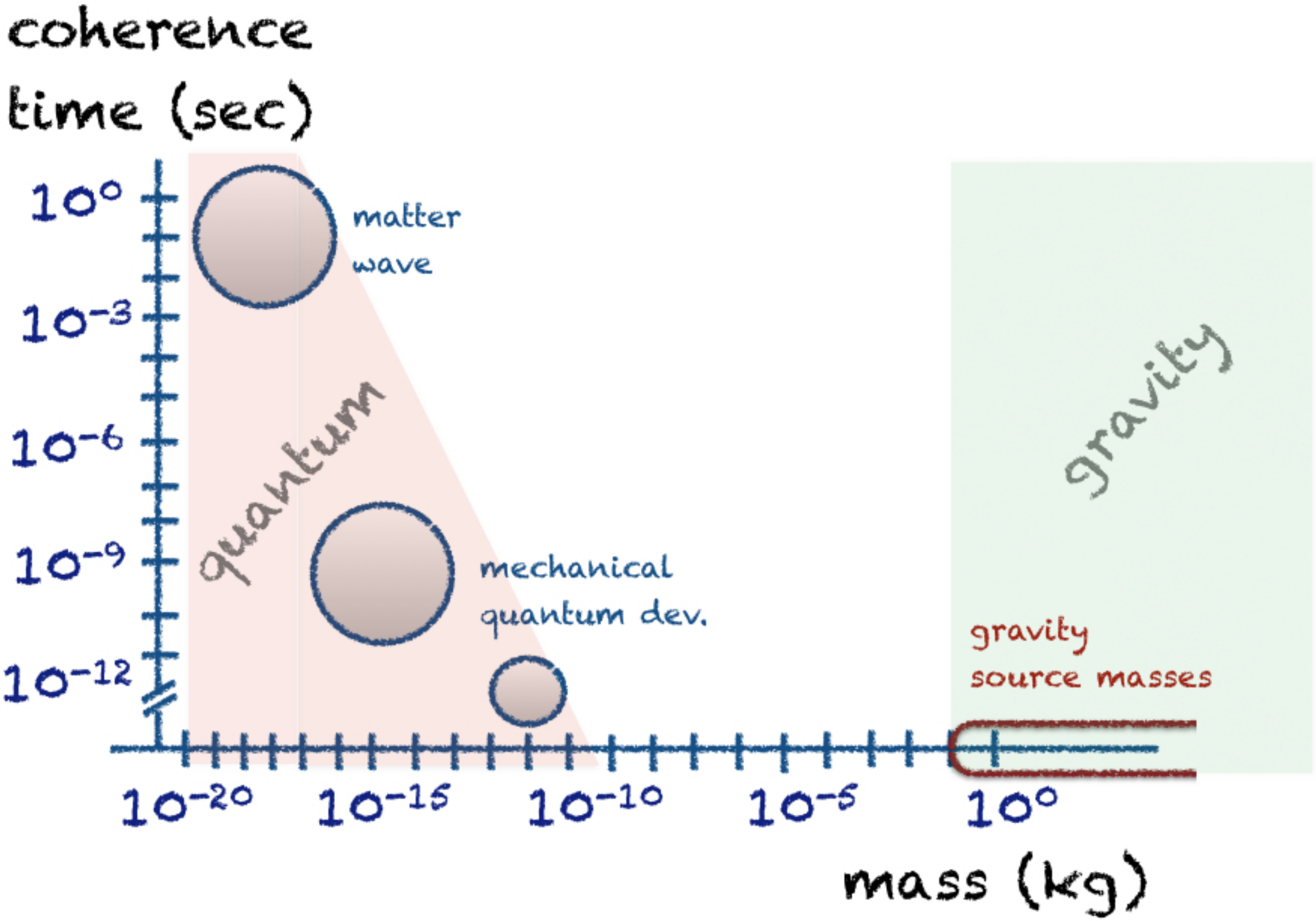
Magnetic levitation in anti-Helmholtz coil configuration

Trap frequencies ~ 10 kHz

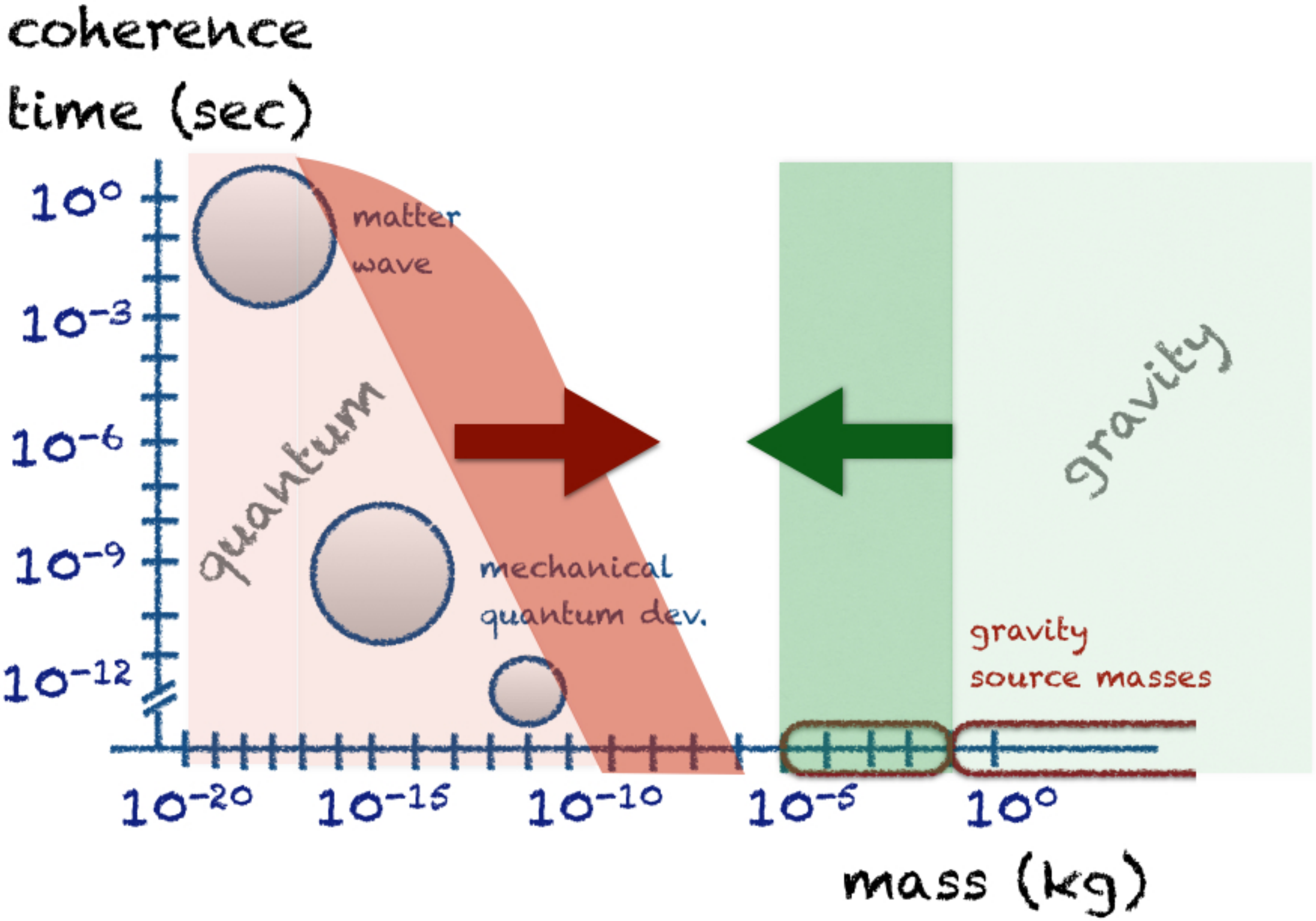
T= 20 mK, p = 1e-8 mbar

J. Slater, J. Hofer, F. Wulschner, W. Wieczorek, M. Aspelmeyer

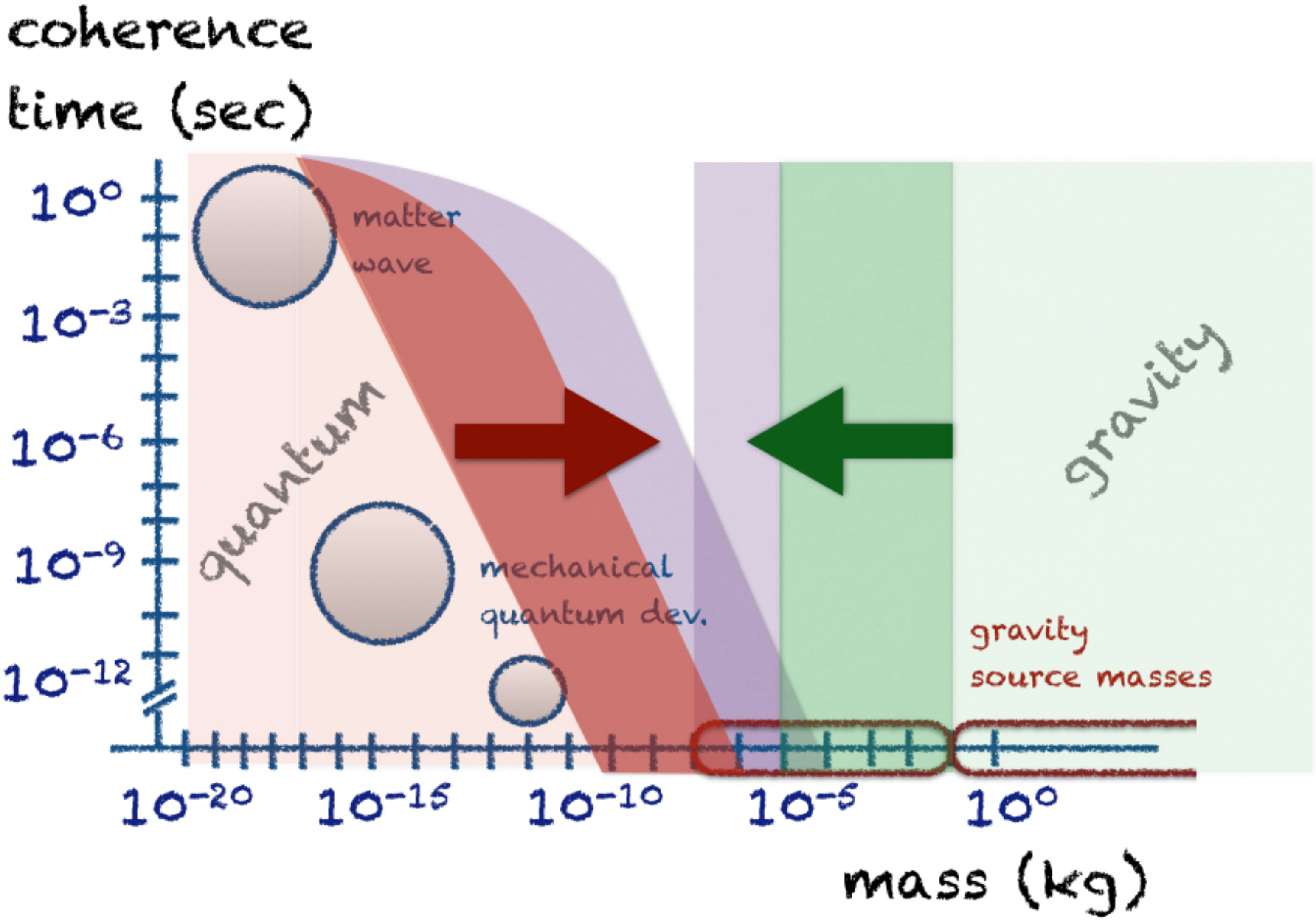
How massive can we go?

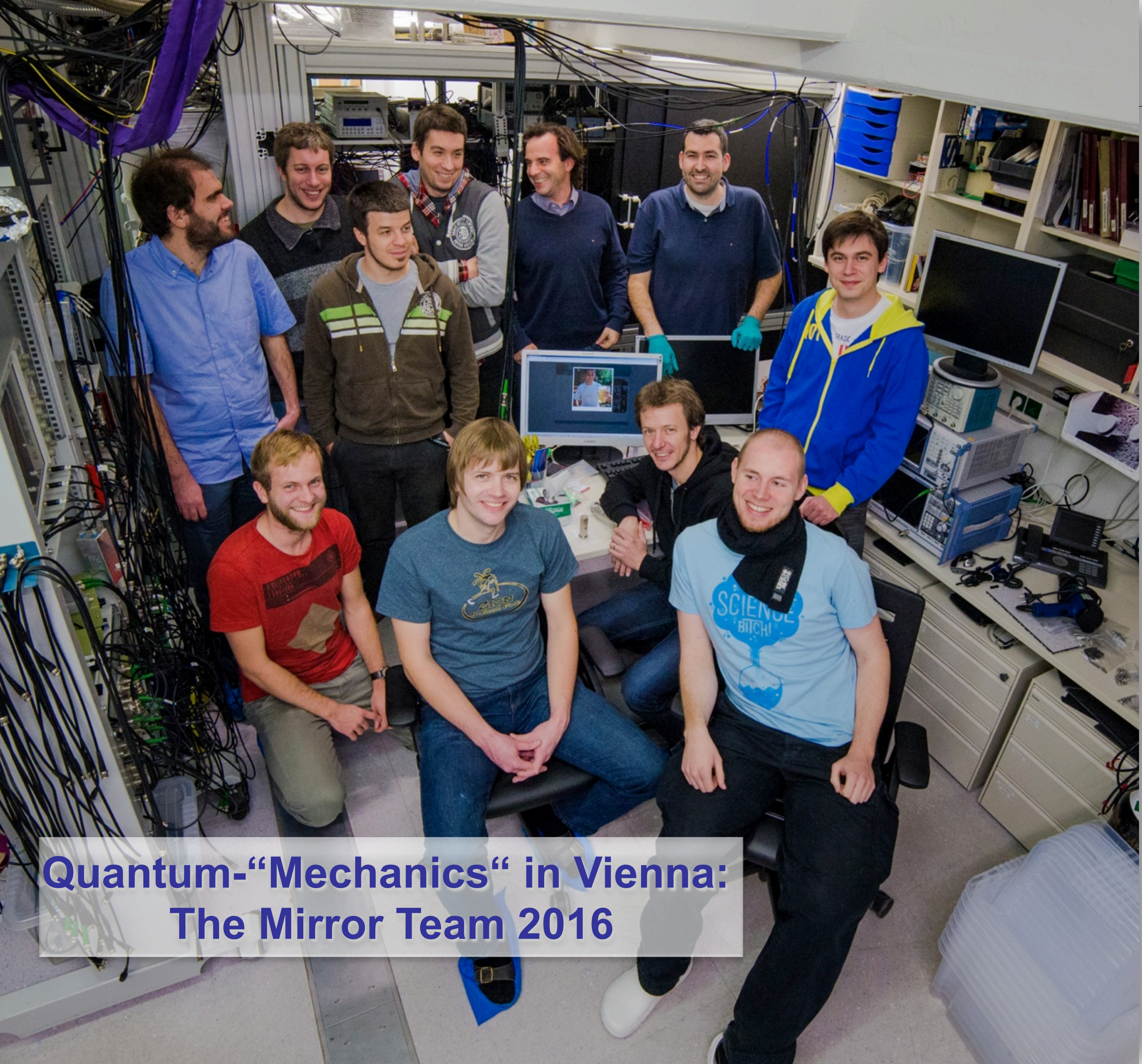


How massive can we go?



How massive can we go?





Quantum-“Mechanics“ in Vienna: The Mirror Team 2016

universität wien

VCQ
Vienna Center for Quantum Science and Technology

FWF
Der Wissenschaftsfonds.

WWTF
Vienna Science and Technology Fund

SEVENTH FRAMEWORK PROGRAMME

erc
European Research Council

cQOM

DARPA

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

Clemens Löschnauer

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

Friedrich Wulschner

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, R. Schnabel, J. Eisert)

Witlef Wieczorek

Jason Hölscher-Obermayer

Sebastian Hofer

Ramon Moghadas Nia

Claus Gärtner

Thomas Zauner

universität wien

VCQ
Vienna Center for Quantum Science and Technology

Wissenschaftsfonds.

W T F
nce and Technology Fund

SEVENTH FRAMEWORK PROGRAMME

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

Quantum Controlling Levitated Massive Mechanical Systems

universität wien

VCQ
Vienna Center for Quantum
Science and Technology

GOAL

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

METHOD

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

MOTIVATION

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

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**