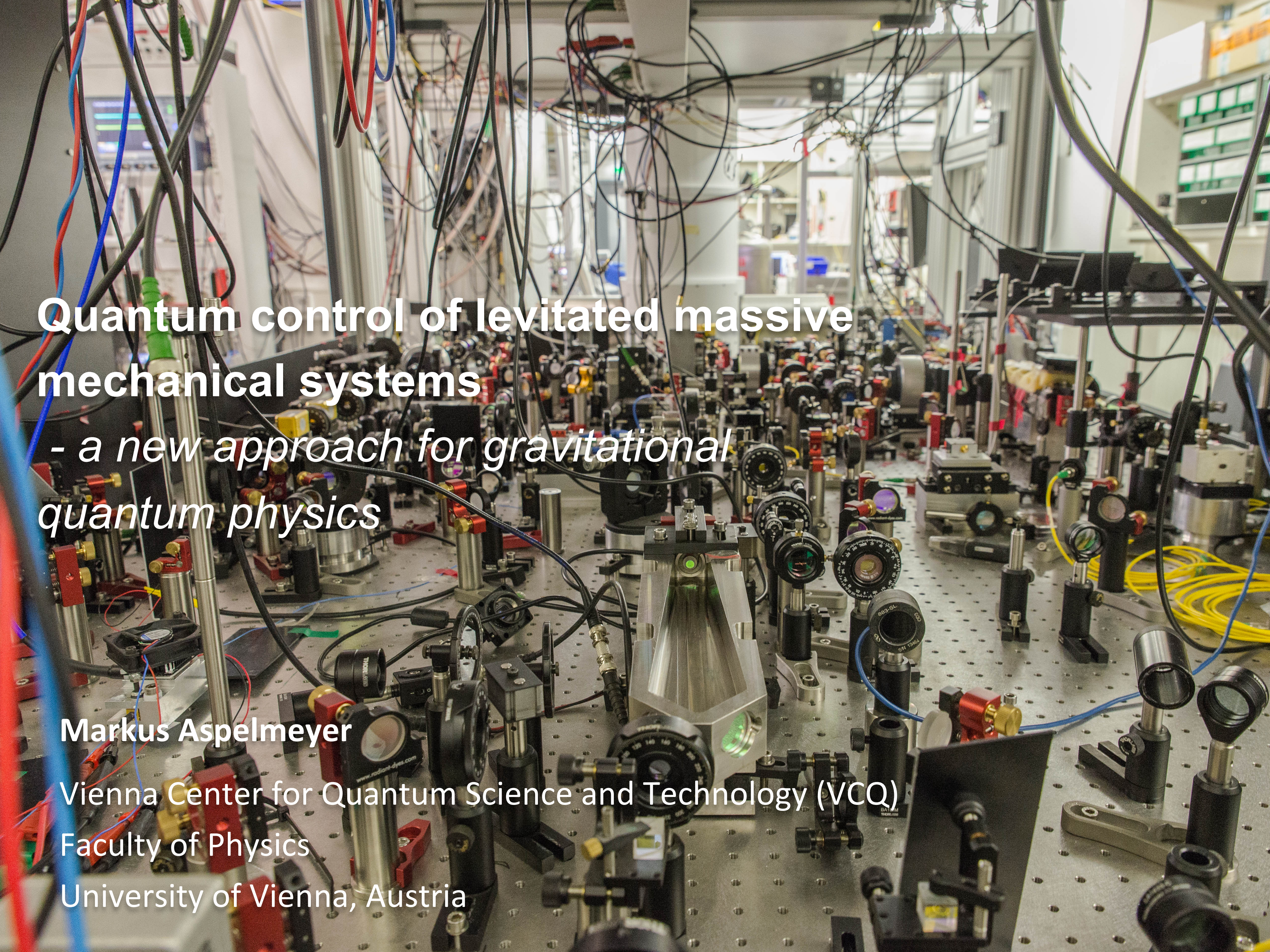


Quantum control of levitated massive mechanical systems

- a new approach for gravitational quantum physics

Markus Aspelmeyer

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

Summary

- 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.

- 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**.

Quantum theory works, as does GR...

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)

Examples from GR:

- dynamics of binary pulsars (9)

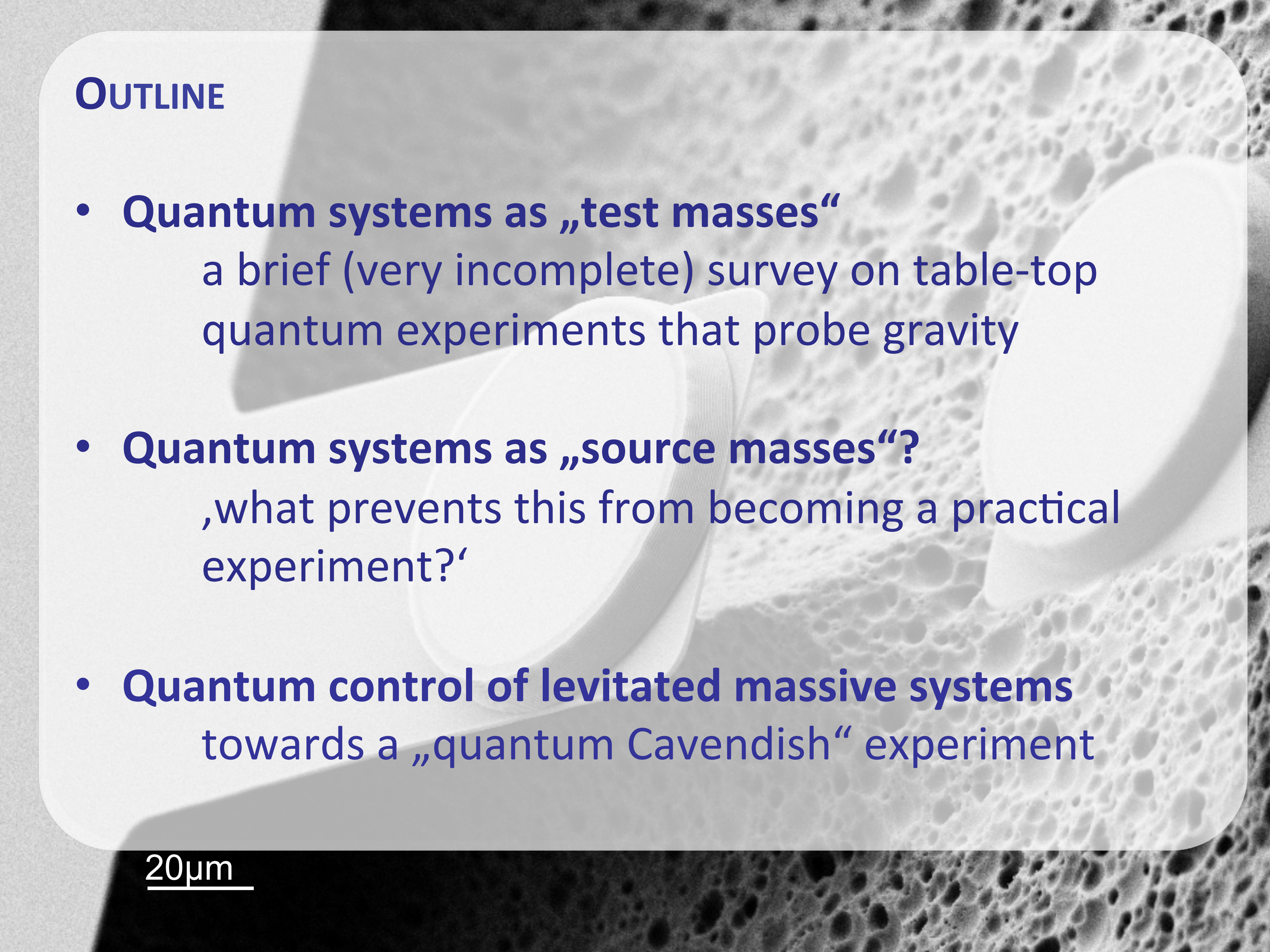
→ strong relativistic fields and gravitational radiation

- 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

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.

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

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

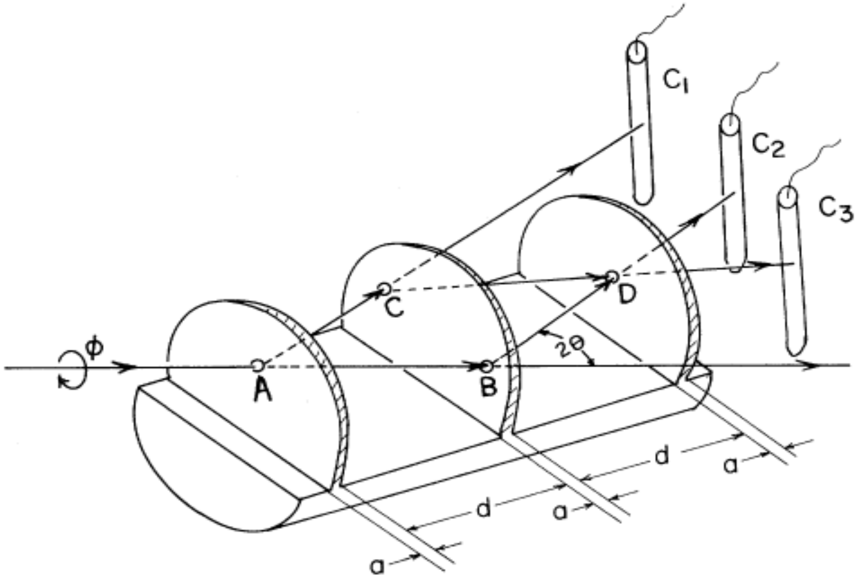
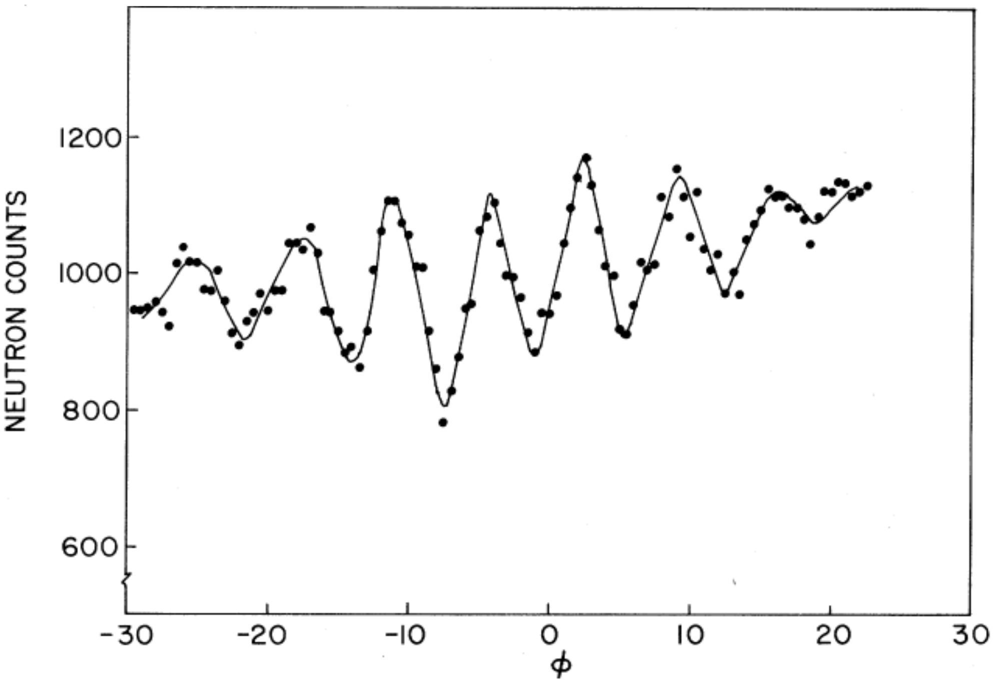
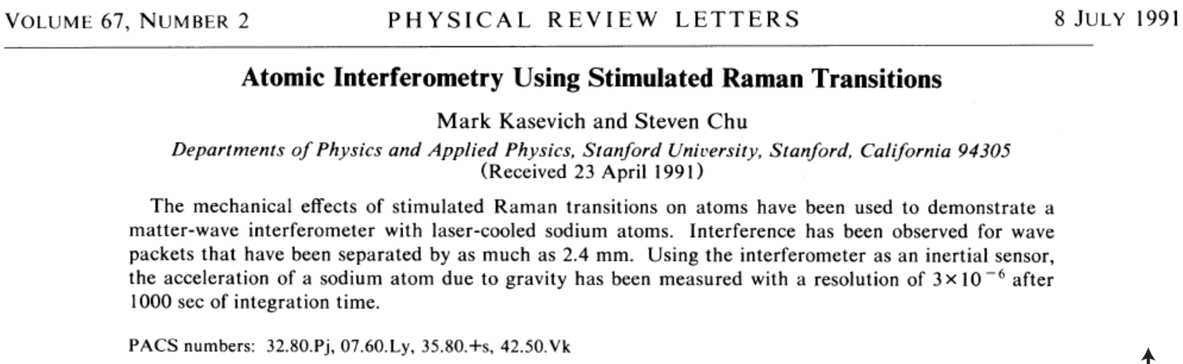


FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.



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)

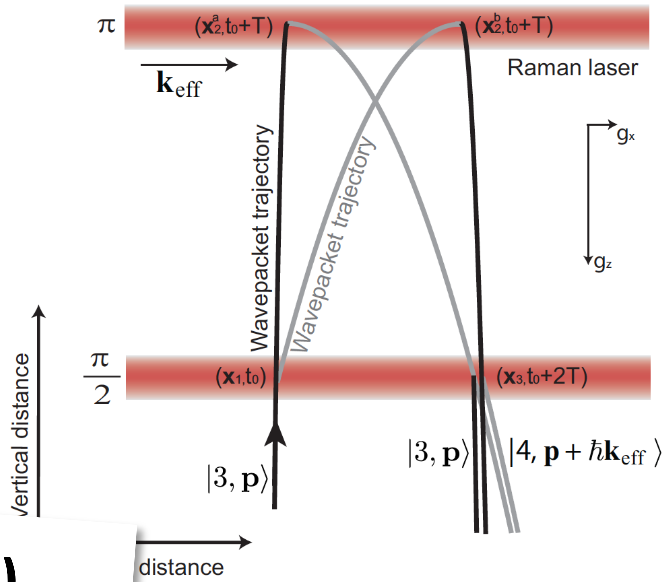
The mechanical effects of stimulated Raman transitions on atoms have been used to demonstrate a matter-wave interferometer with laser-cooled sodium atoms. Interference has been observed for wave packets that have been separated by as much as 2.4 mm. Using the interferometer as an inertial sensor, the 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

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

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

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



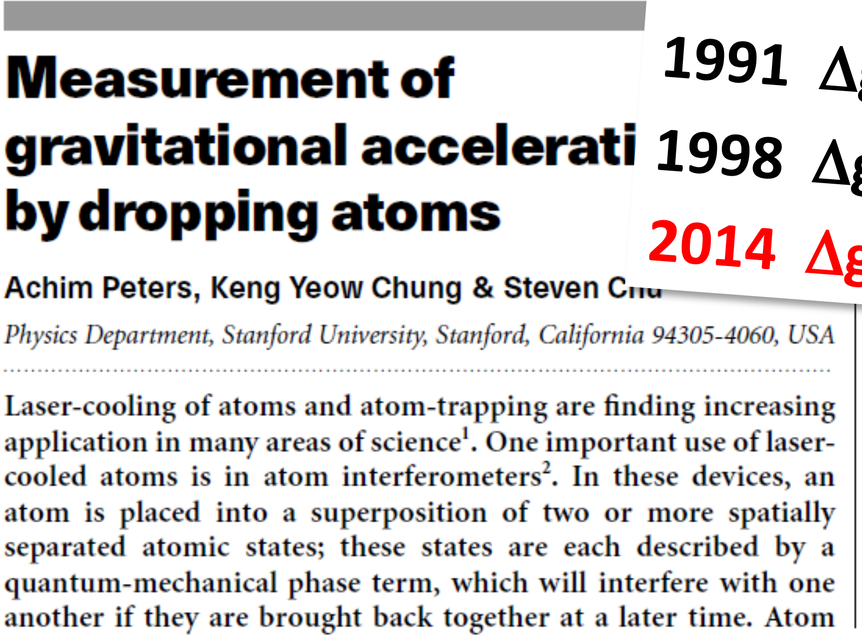
(Kasevich group)

1991 Δg/g = 1×10^{-6}

1998 Δg/g = 3×10^{-8}

2014 Δg/g = 5×10^{-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

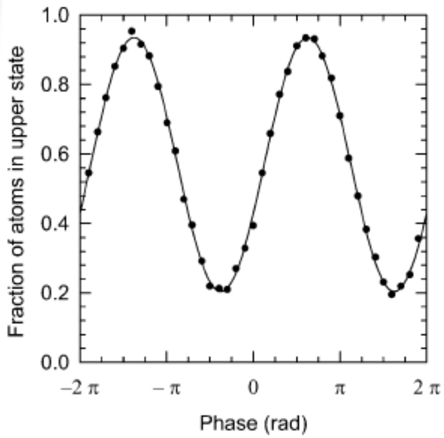


Figure 2 Typical Doppler-sensitive interferometer fringe for $T = 160$ ms. Shown are the 588,638th and 588,639th fringes. Each of the 40 data points represents a single launch of the atoms, spaced 1.3 s apart and taken over a period of 1 min. One full fringe corresponds to $\sim 2\times10^{-8}g$. Performing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

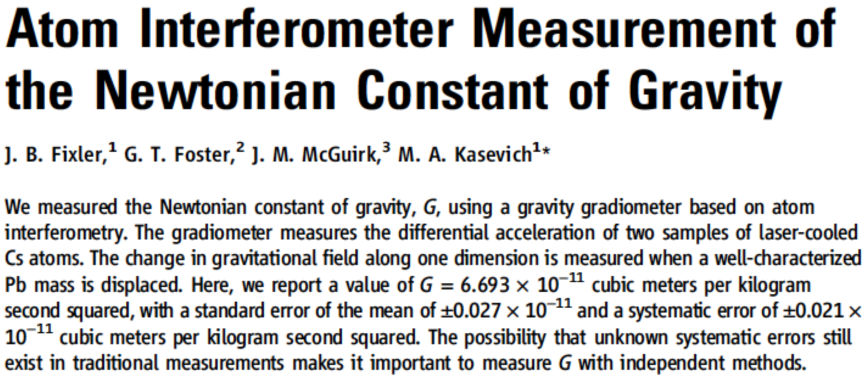
Newtonian Gravity in Quantum Experiments

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

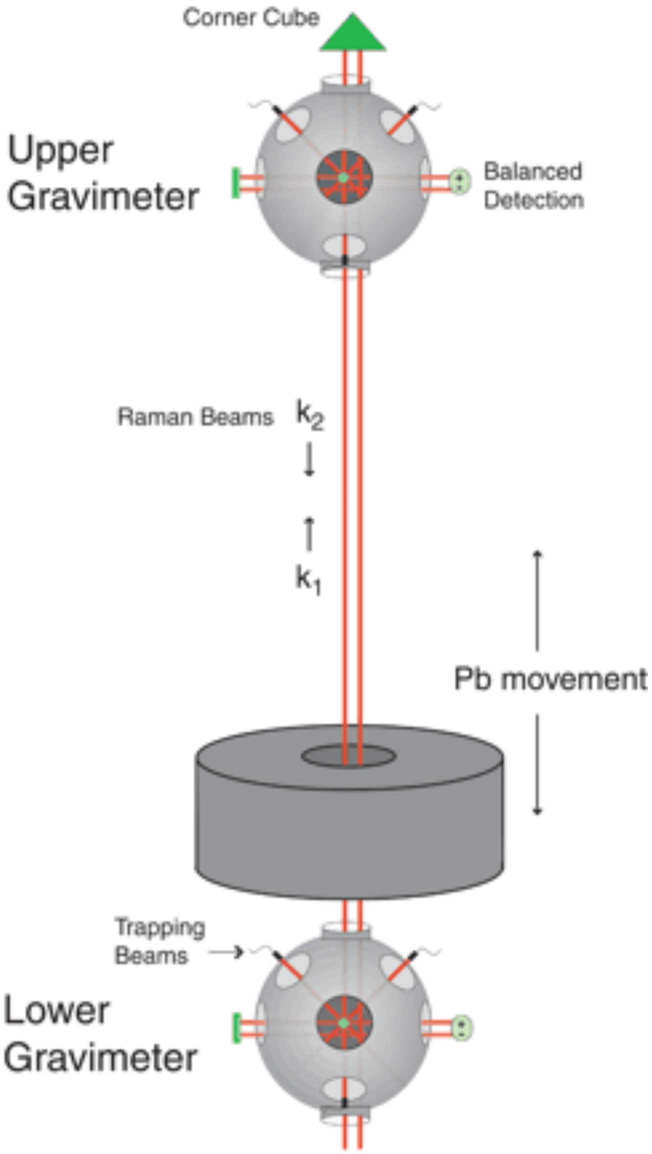
J. B. Fixler,[1] G. T. Foster,[2] J. M. McGuirk,[3] M. A. Kasevich[1]*

We measured the Newtonian constant of gravity, *G*, using a gravity gradiometer based on atom interferometry. The gradiometer measures the differential acceleration of two samples of laser-cooled Cs atoms. The change in gravitational field along one dimension is measured when a well-characterized Pb mass is displaced. Here, we report a value of $G = 6.693 \times 10^{-11}$ cubic meters per kilogram second squared, with a standard error of the mean of $\pm 0.027 \times 10^{-11}$ and a systematic error of $\pm 0.021 \times 10^{-11}$ cubic meters per kilogram second squared. The possibility that unknown systematic errors still exist in traditional measurements makes it important to measure *G* with independent methods.

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]



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→ differential acceleration measurement
→ **Measure G** through additional test mass

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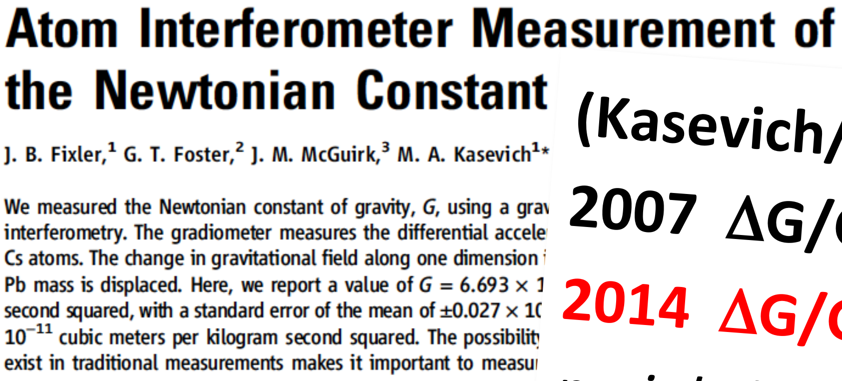

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Pb mass is displaced. Here, we report a value of G = 6.693 × 1
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(Kasevich/Tino groups)

2007 ΔG/G = 3×10^{-3}

2014 ΔG/G = 1×10^{-4}

mainly limited by position of atoms

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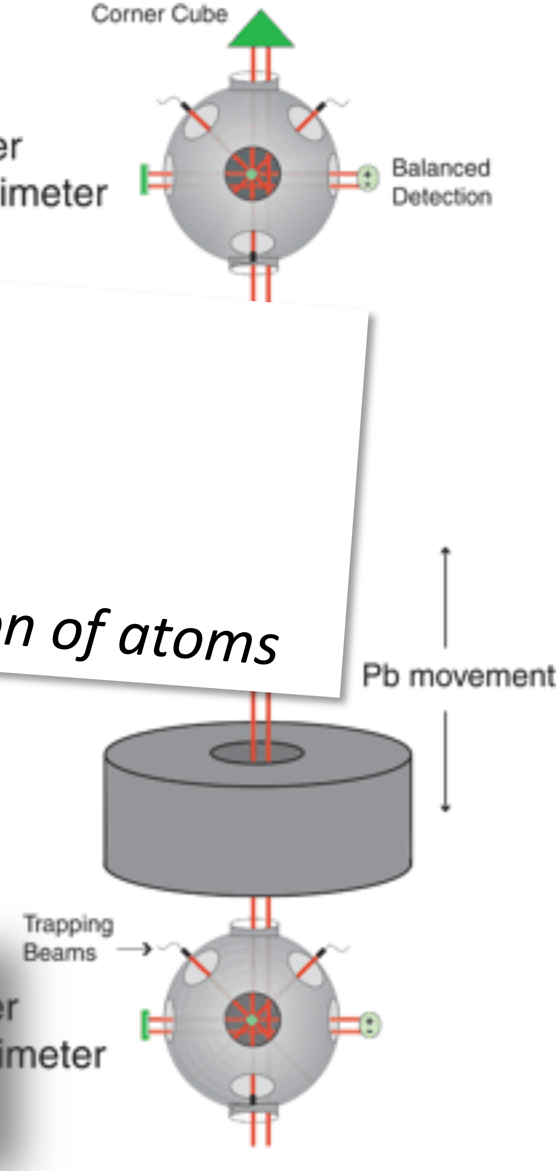
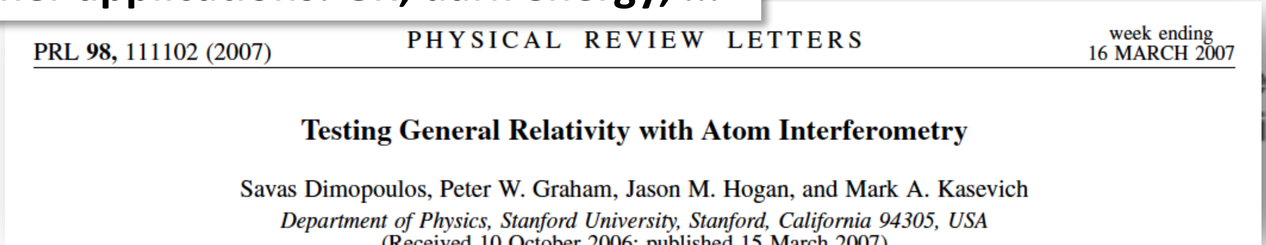


Other applications: GR, dark energy, ...



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

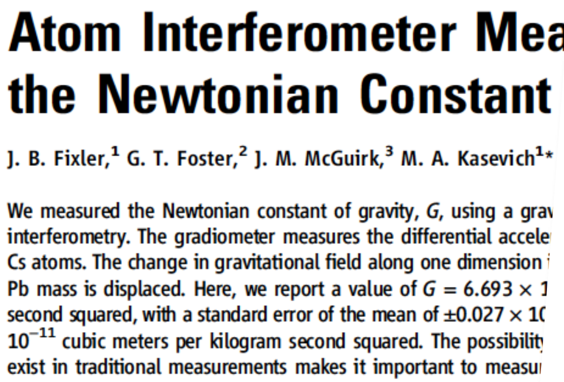
Testing General Relativity with Atom Interferometry

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)

Newtonian Gravity in Quantum Experiments

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

Science 2007



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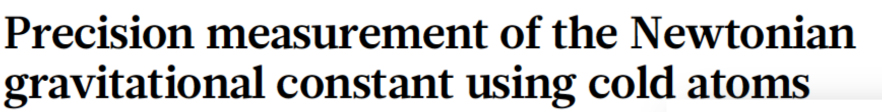
Nature 2014



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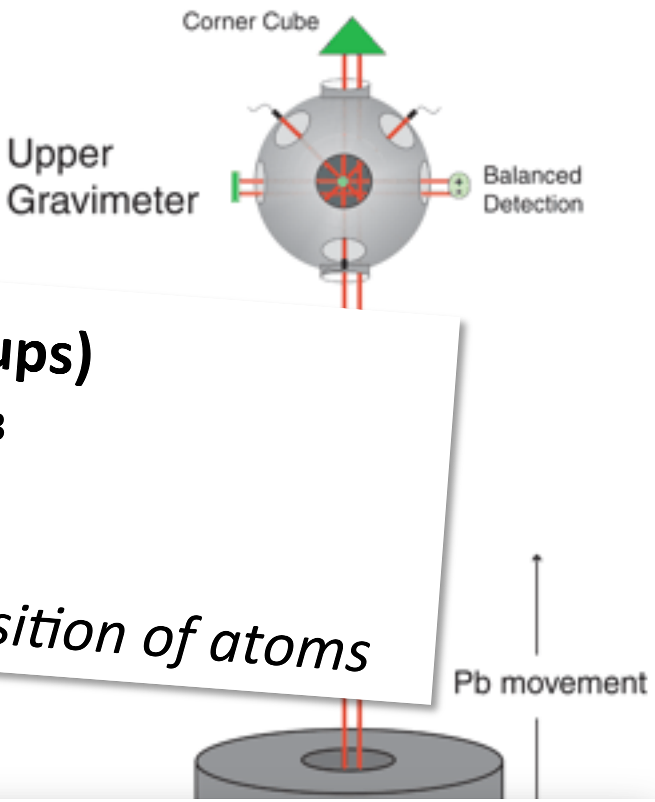
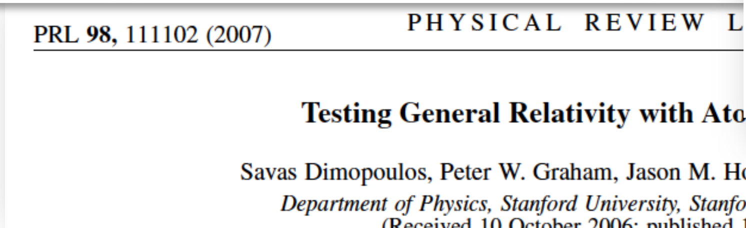


Other applications: GR, dark energy, ...



PRL **98,** 111102 (2007) PHYSICAL REVIEW L

Testing General Relativity with Ato

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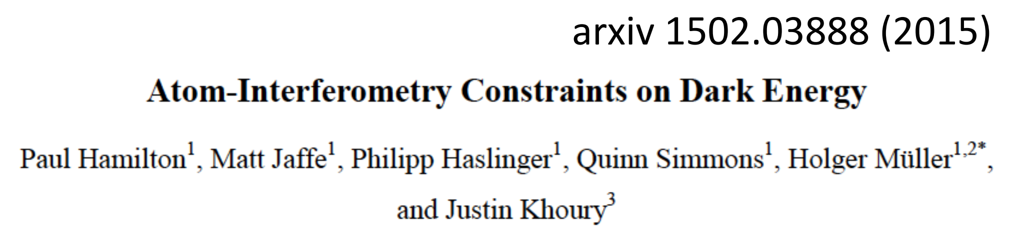


arxiv 1502.03888 (2015)

Atom-Interferometry Constraints on Dark Energy

Paul Hamilton[1], Matt Jaffe[1], Philipp Haslinger[1], Quinn Simmons[1], Holger Müller[1,2*],
and Justin Khoury[3]

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,*]

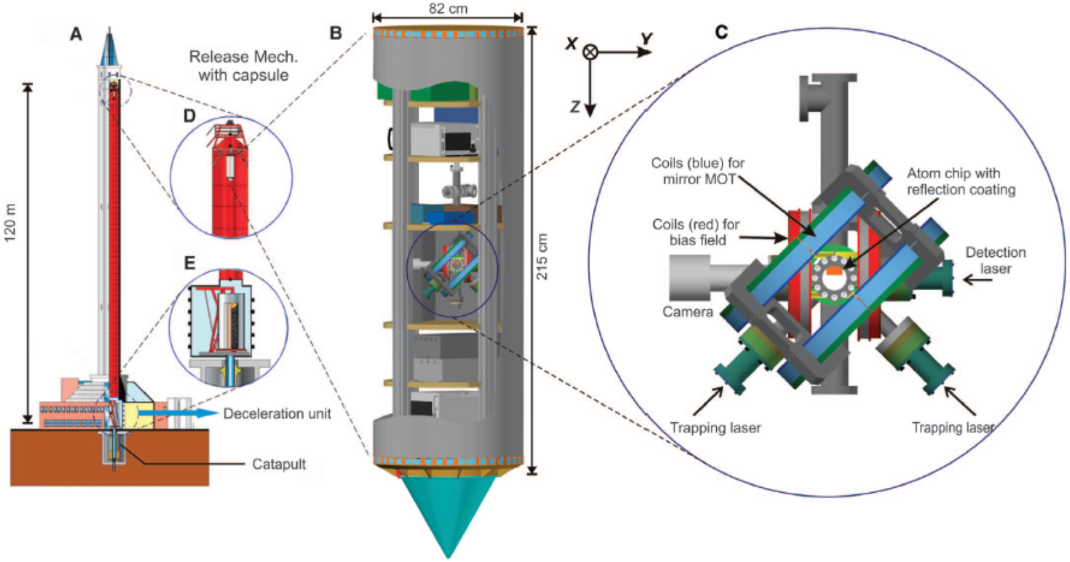


Fig. 1. Cuts through the ZARM drop tower facility in Bremen (**A**) and the capsule (**B**) containing the heart of the BEC experiment (**C**). The capsule is released from the top of the tower (**D**) and is recaptured after a free fall of 4.7 s through an evacuated stainless steel tube at the bottom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

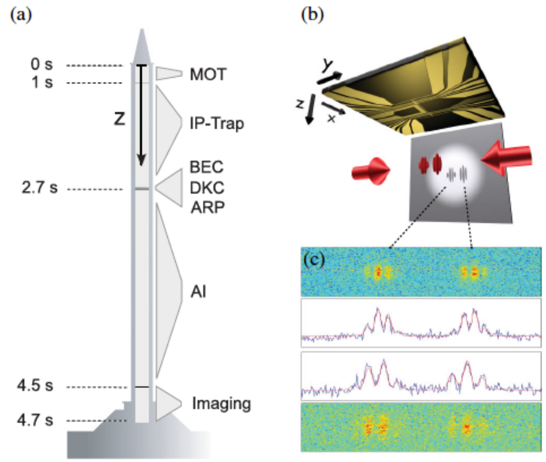
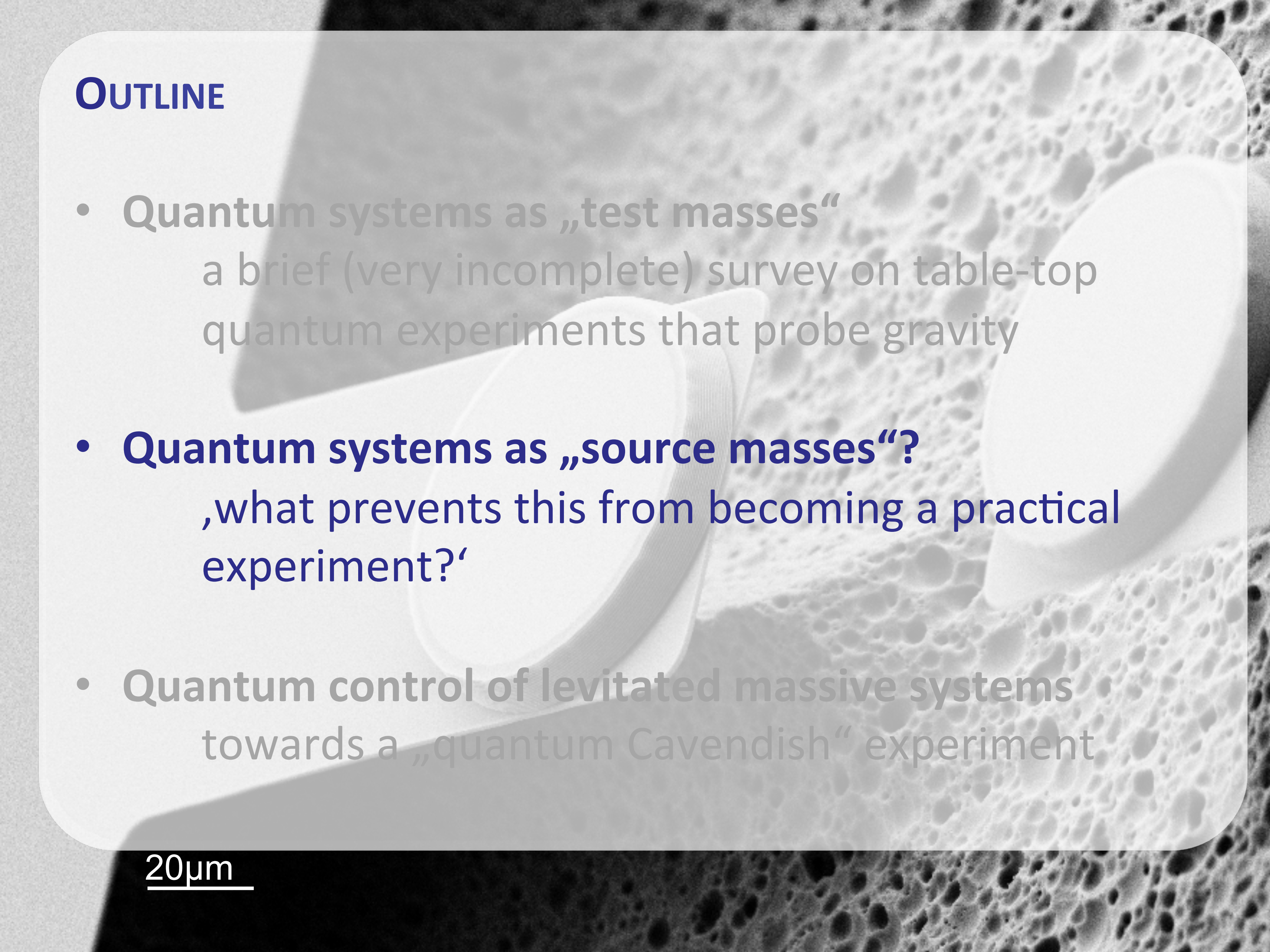


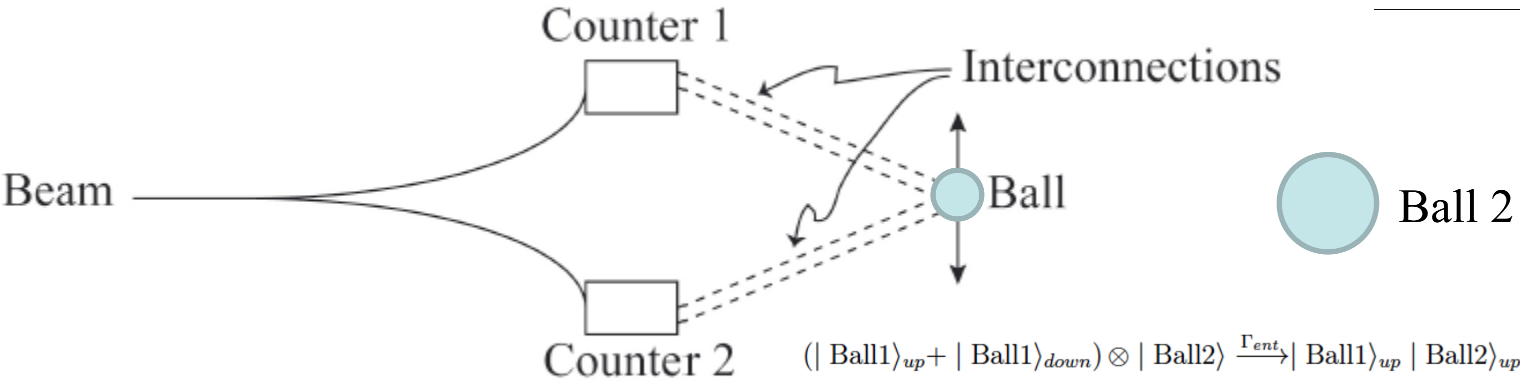
FIG. 2 (color). Mach-Zehnder interferometry of a BEC in microgravity as realized in the ZARM drop tower in Bremen (a) where absorption imaging (b) brings out the interference fringes (c). The preparatory experimental sequence (a) includes capturing cold atoms in a magneto-optical trap (MOT), loading 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),



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

An ultimate experiment? Entanglement by gravity…



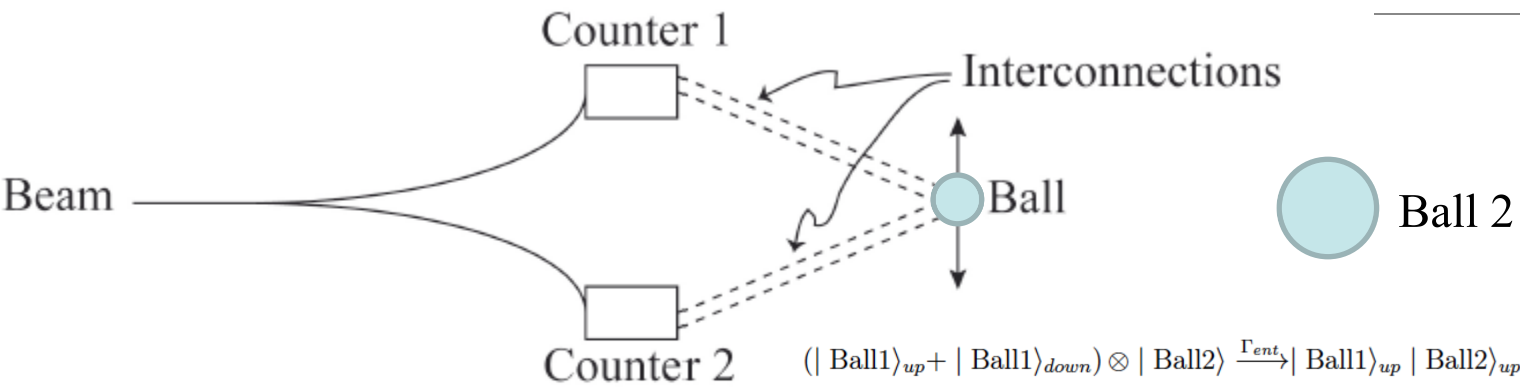
$$(|\,\text{Ball1}\rangle_{up} + |\,\text{Ball1}\rangle_{down}) \otimes |\,\text{Ball2}\rangle \xrightarrow{\Gamma_{ent}} |\,\text{Ball1}\rangle_{up}\,|\,\text{Ball2}\rangle_{up} + |\,\text{Ball1}\rangle_{down}\,|\,\text{Ball2}\rangle_{down}$$

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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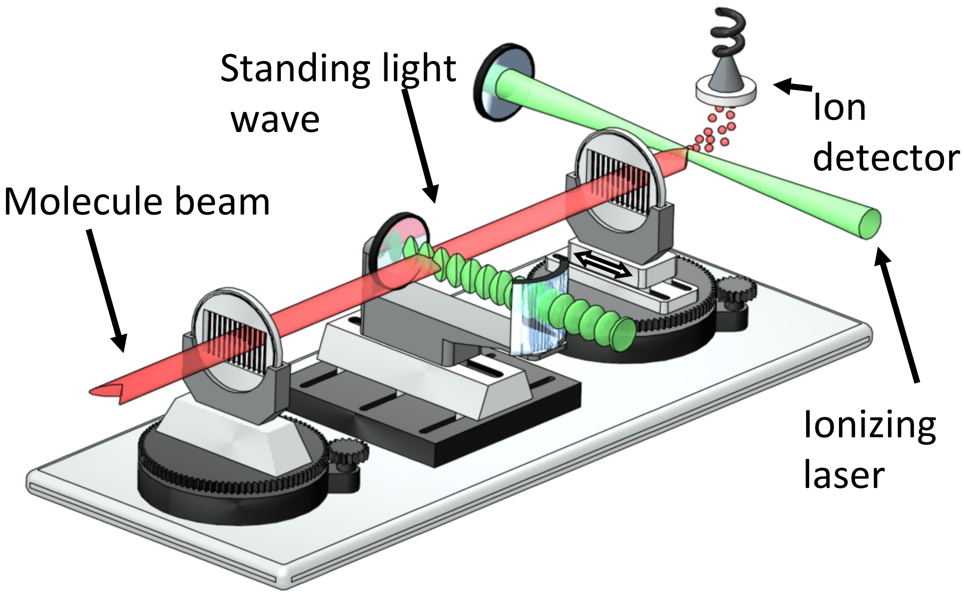
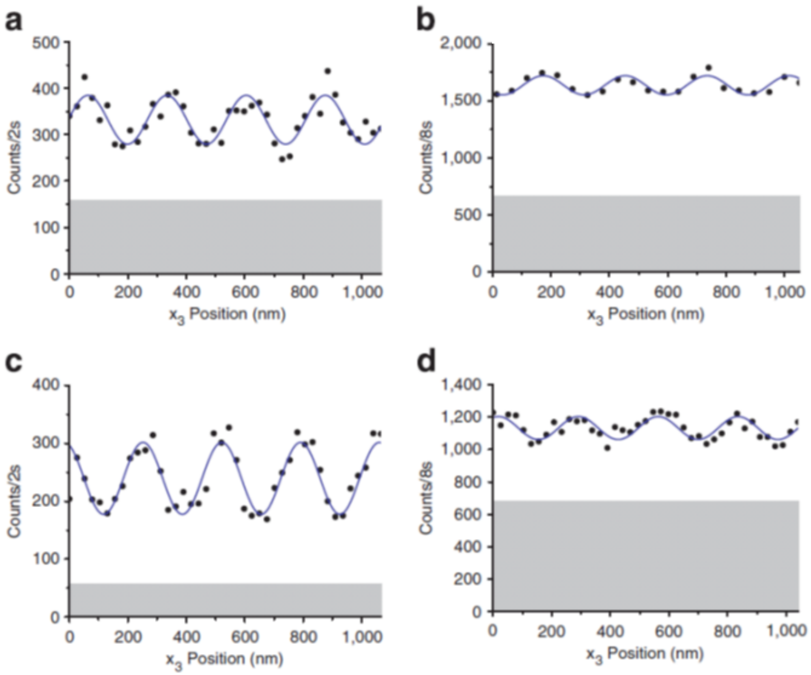
Chapel Hill Conference 1957 (29)

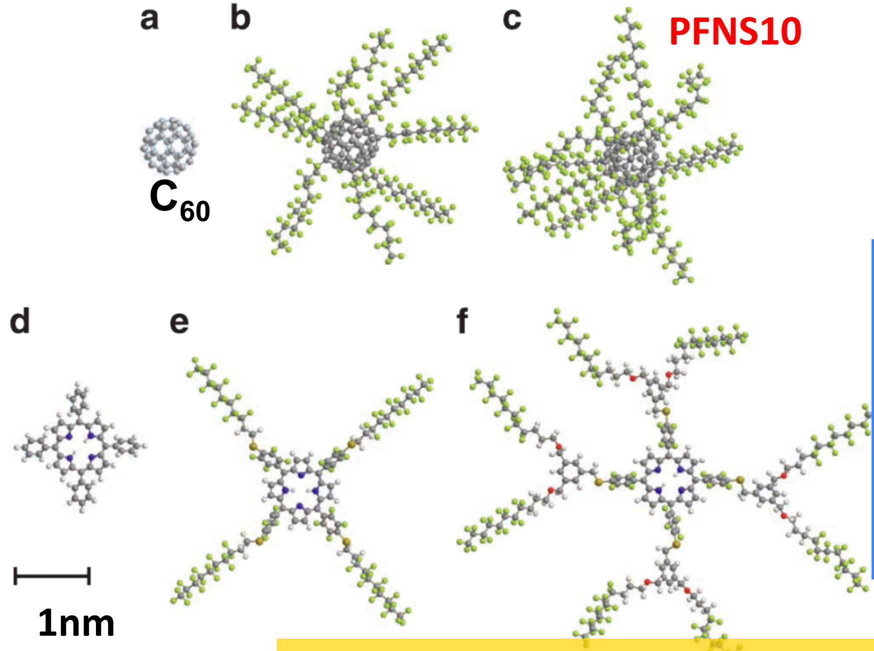
Example: For 2 **lead spheres** of **diameter 500 μm**, an initial **superposition size for sphere 1** of **$\Delta r = 5\times10^{-7}$ m** and preparation of **sphere 2** in a **motional ground state** (100 Hz trap frequency) with **$\Delta x_0 = 10^{-15}$ m**, we obtain **$\Gamma_{ent} = 1.5$ Hz**,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

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

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







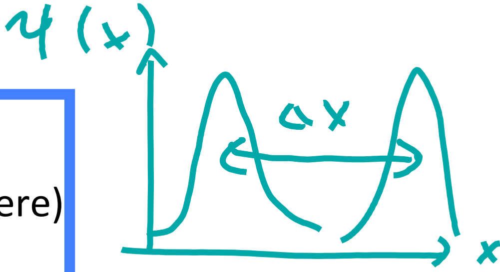
PFNS10: $C_{60}[C_{12}F_{25}]_{10}$

(perfluoroalkylated nanosphere)

430 atoms

m ~ 10^{-23} kg = 6910 AMU

Δx ~ 100 nm (~50x its diameter)



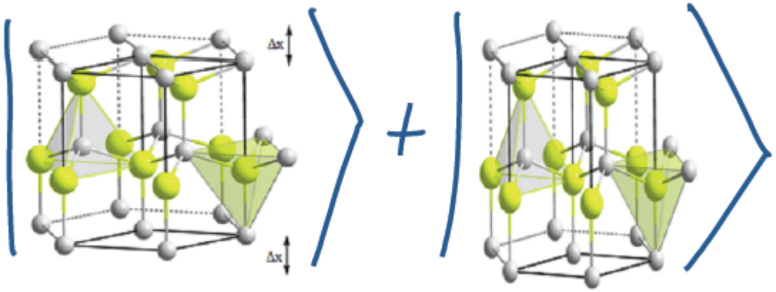
Arndt group (Vienna): S. Gerlich, S. Eibenberger et al., Nature Communications **2**, 263 (2011)

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

Micromechanics, 2×10^{13} atoms

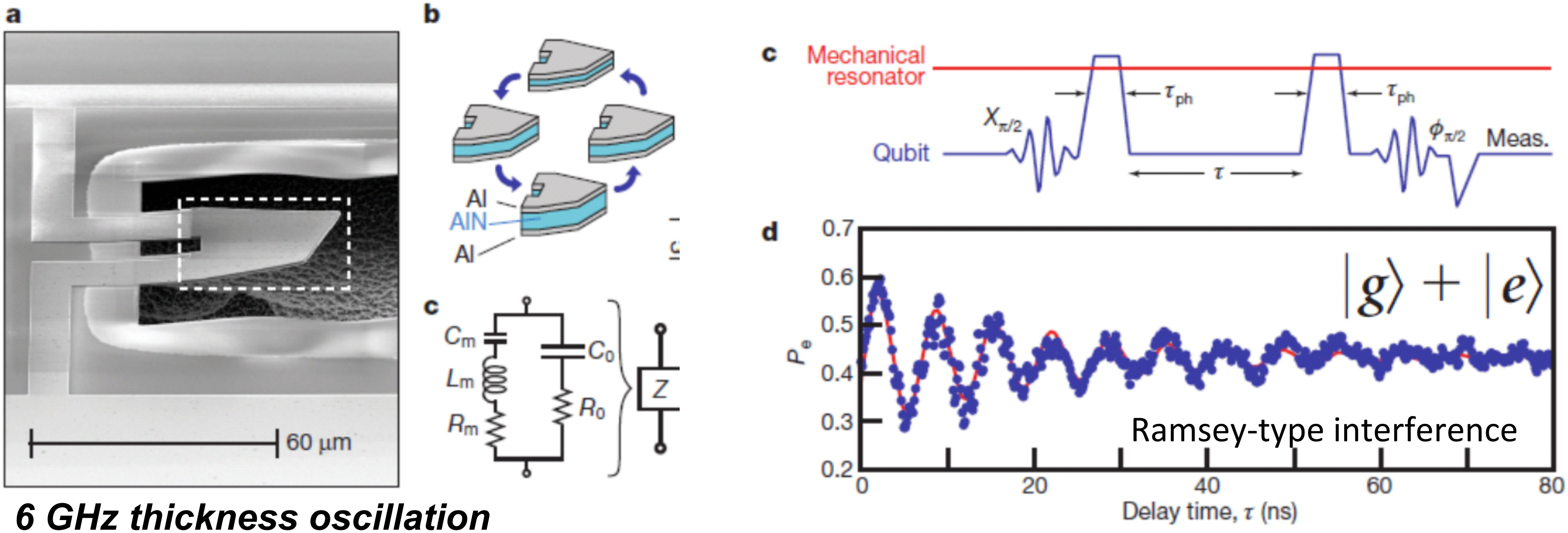
$m \sim 10^{-12}$ kg = 7×10^{14} AMU

$\Delta x \sim 10^{-16}$ 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]



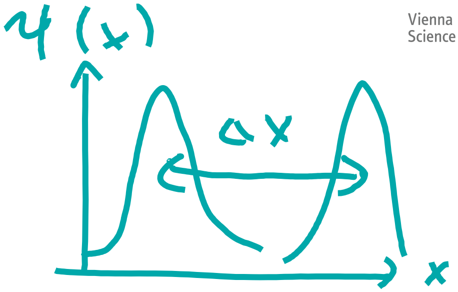
Ramsey-type interference

6 GHz thickness oscillation
→ n ~ 0.07 @ 20 mK

Note: $E_g - E_e = h^* f_m \approx 20\mu\text{eV}$

Decoherence

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



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

Master equation approach

$$\langle x|\mathcal{L}_g[\rho]|x'\rangle = \begin{cases} -[\Delta x]^2\Lambda_g\langle x|\rho|x'\rangle, & \Delta x < \frac{h}{m\bar{v}} \\ -\Gamma_g'\langle x|\rho|x'\rangle, & \Delta x > \frac{h}{m\bar{v}}. \end{cases}$$

where

$$\Lambda_g = \frac{3m\bar{v}P\pi R^2}{\hbar^2}$$
$$\Gamma_g' = \frac{\pi R^2 P}{m\bar{v}}$$

Gas scattering

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

$$\langle x|\mathcal{L}_g[\rho]|x'\rangle = \begin{cases} -\Lambda_P\Delta x^2\langle x|\rho|x'\rangle, & \Delta x \ll R \\ \Lambda_P\langle x|\rho|x'\rangle, & \Delta x > R. \end{cases}$$

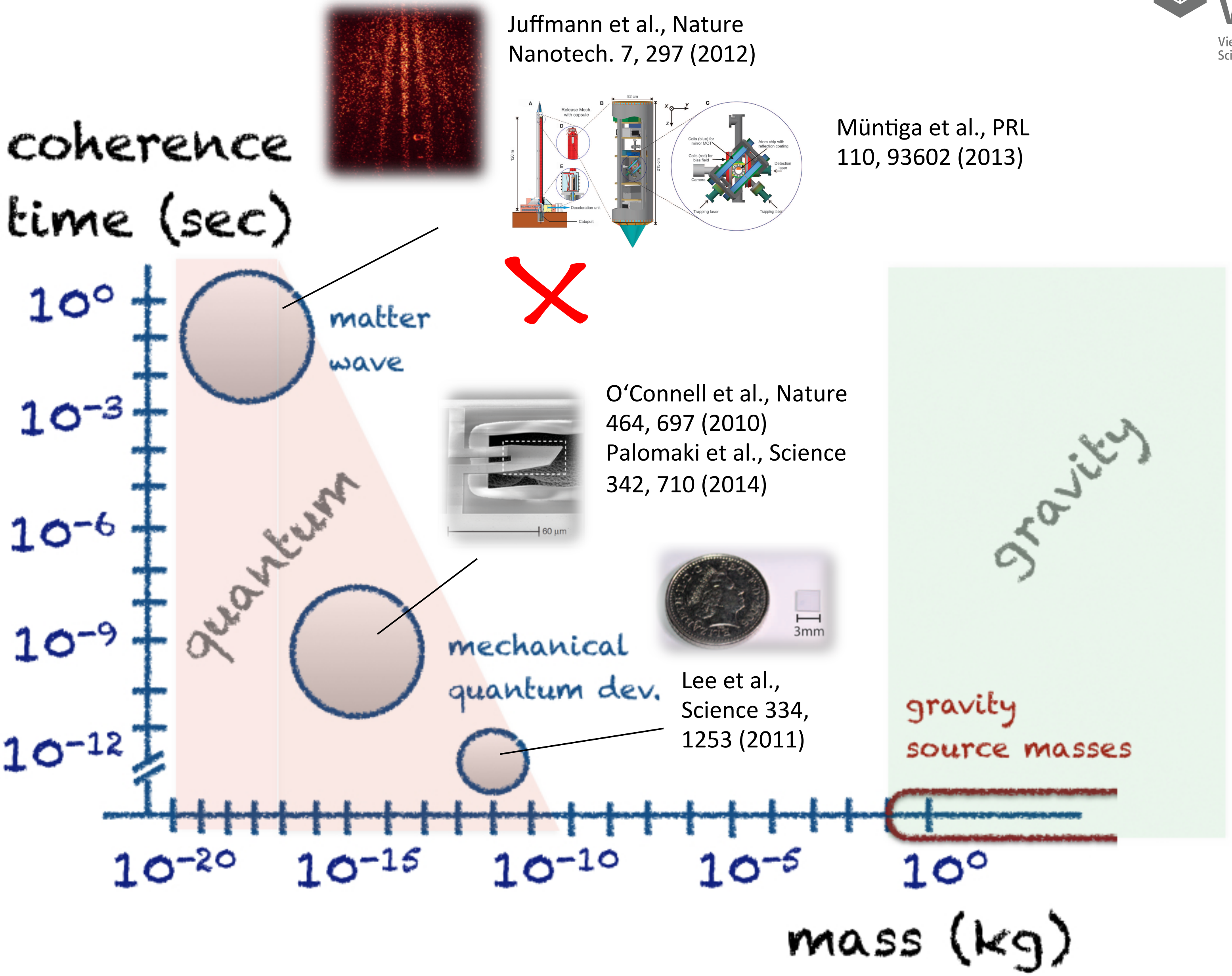
$$\Lambda_P = \Lambda_D = \frac{20\rho^2 R^3}{\hbar}, \quad \Delta x \ll R$$
$$\Lambda_P' = \frac{20\rho^2 R^5}{\hbar}, \quad \Delta x \geq R.$$

Penrose model

$$\Lambda_{\mathrm{CSL}} = m^2\lambda_0\alpha f(\sqrt{\alpha}R)/(2m_0^2)$$
$$\alpha^{-1/2} \approx 10^{-7}\ \mathrm{m}$$
$$\lambda_0 \approx 2.2\times 10^{-17}\ \mathrm{s}^{-1}$$

GRWP

How massive 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)

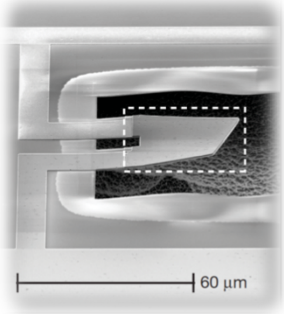
Pushing mechanical quantum control to the next level

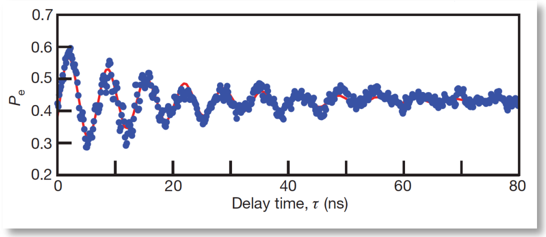
Q: How to achieve large mass **AND** long coherence time in a quantum experiment?

Solid-state mechanical quantum devices (clamped):

10^{10} – 10^{16} atoms

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



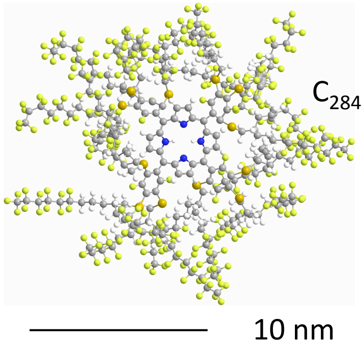


O'Connell et al., Nature 464, 697 (2010)

Matter-wave interferometry (free-fall):

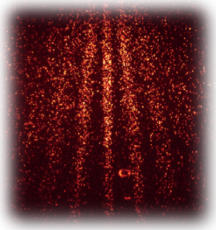
10^0 – 10^4 atoms

Coherence time τ_c 10^{-3} – 10^0 sec



TPPF320

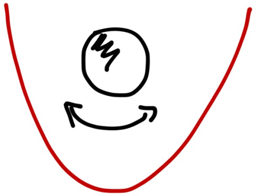
$C_{284}H_{190}F_{320}N_4S_{12}$



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

A: Quantum control of levitated mechanical systems!

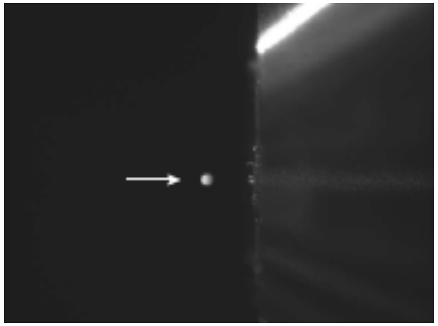
Coupling to gravity



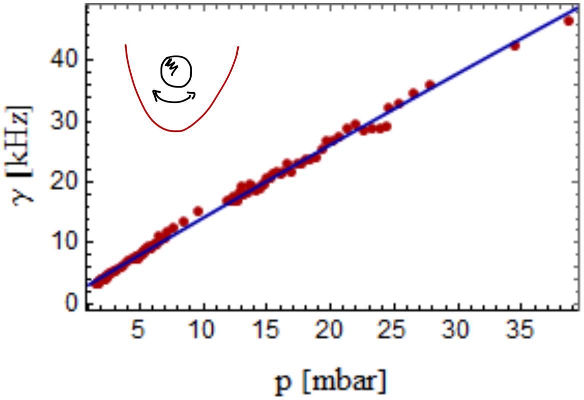
- Quantum control of a trapped massive object >> 10^{10} atoms
- Long coherence times (up to seconds) through free fall dynamics
- Exceptional force sensitivity

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

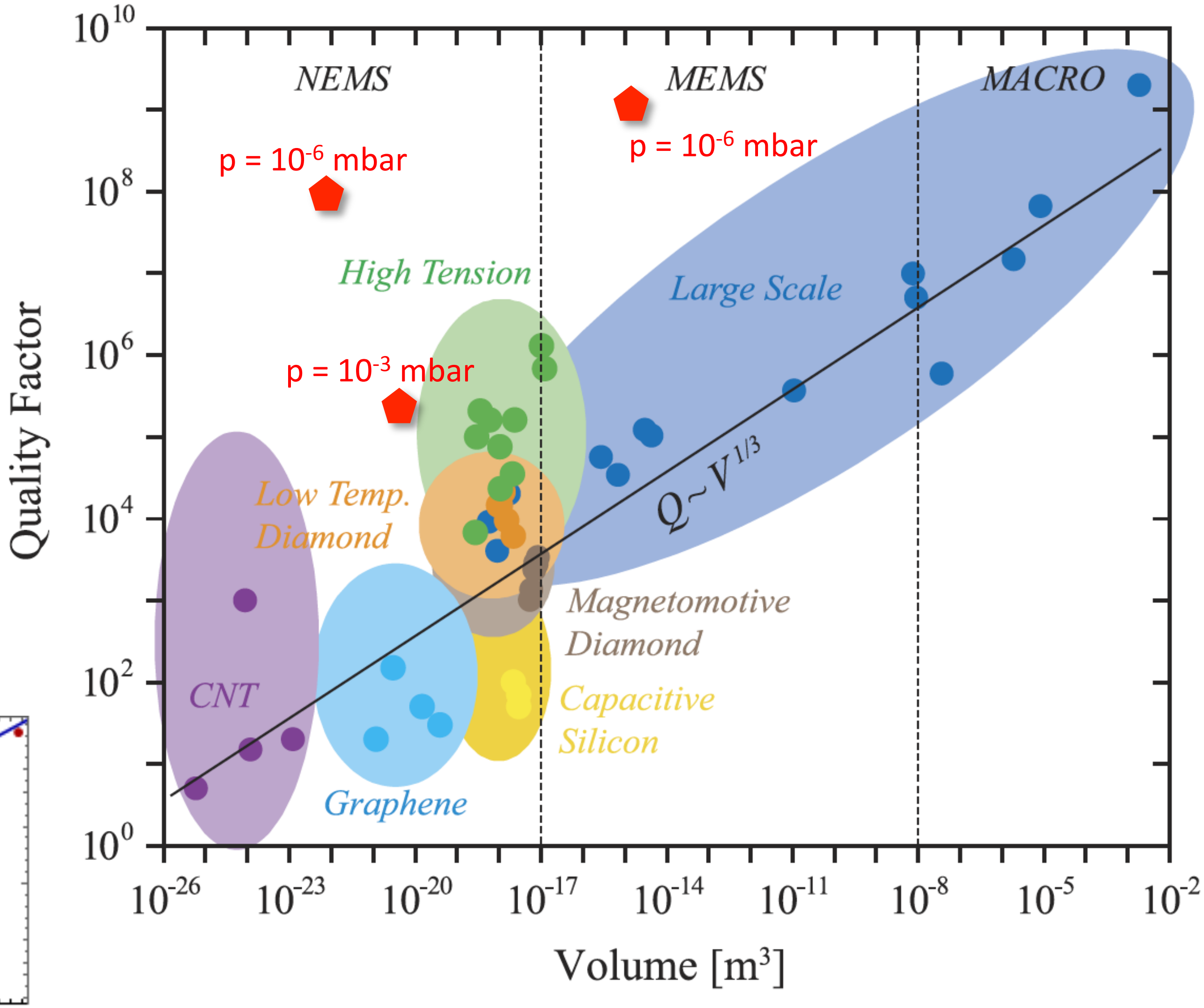
J. Gieseler, R. Quidant, C. Dellago, L. Novotny, Nature Nanotechnology 9, 358 (2014)
(70 nm SiO2)



D. Grass (Vienna)
(350 nm SiO2
inside hollow core fibre)

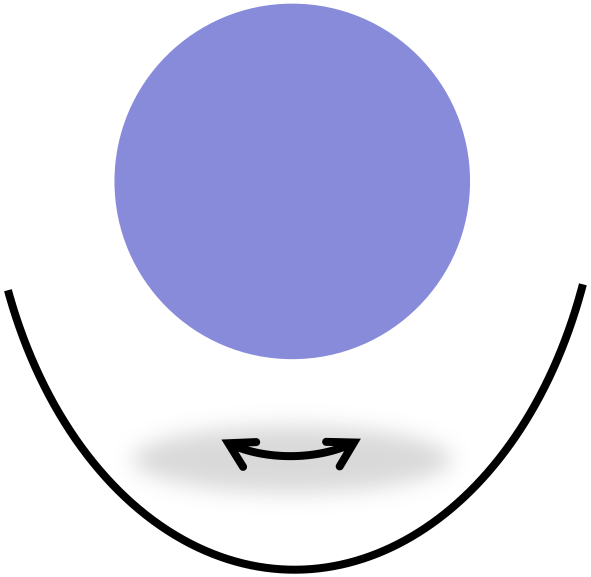


Ashkin & Dziedzic, APL 28, 333 (1976)
(20um Si oil)



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

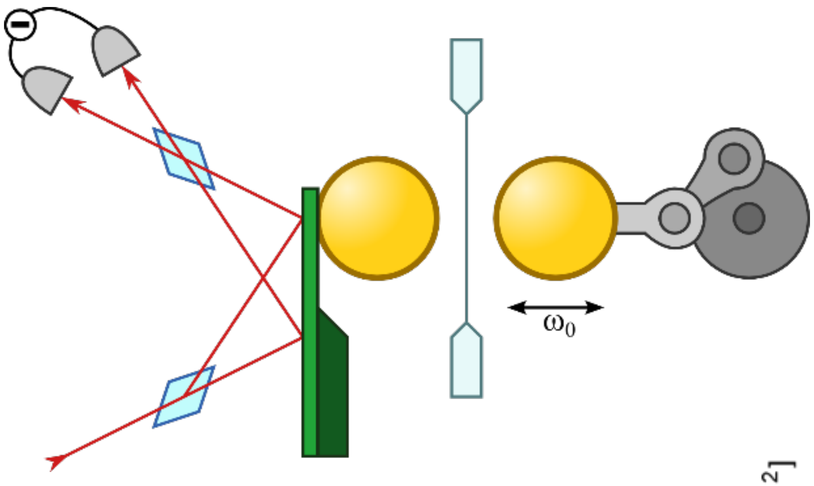
Sensitivity to gravitational forces?



{T, Q , ω, m}

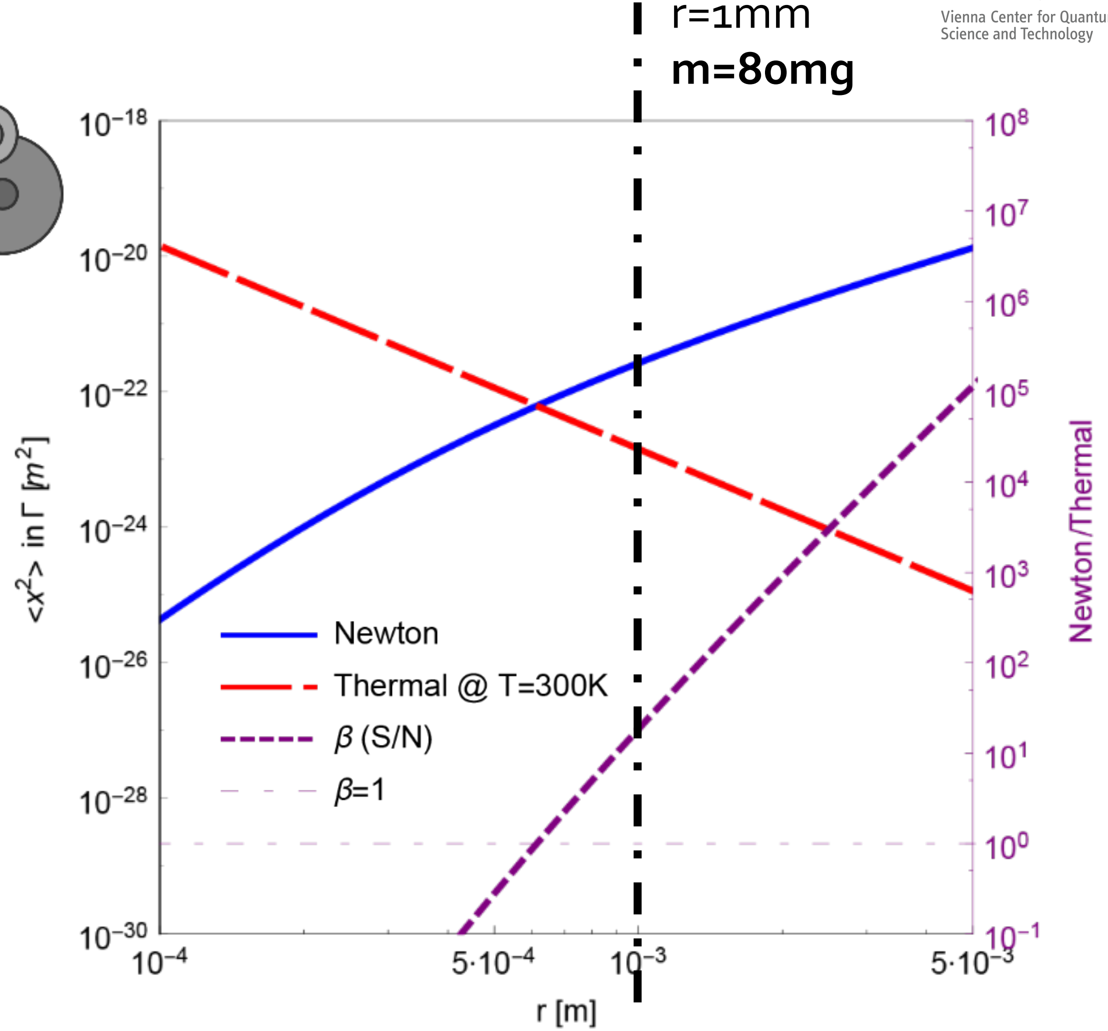
Thermal force noise $F_{th} = \sqrt{k_B T m \left({}^{\omega}\!/_{Q}\right) \left({}^{1}\!/_{\tau}\right)}$

Measuring gravity between microscopic source masses ?



Example

- f_0 = 100 Hz
- Q = 20,000
- T = 300 K
- ρ = 20,000 kg/m³ (gold)
- Γ = 1/(60 min)

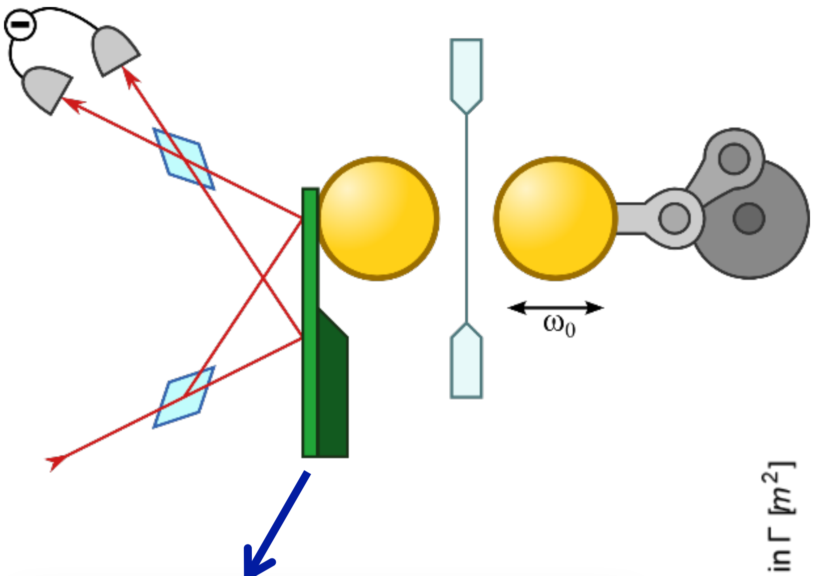


Smallest source mass to date: **120 g**

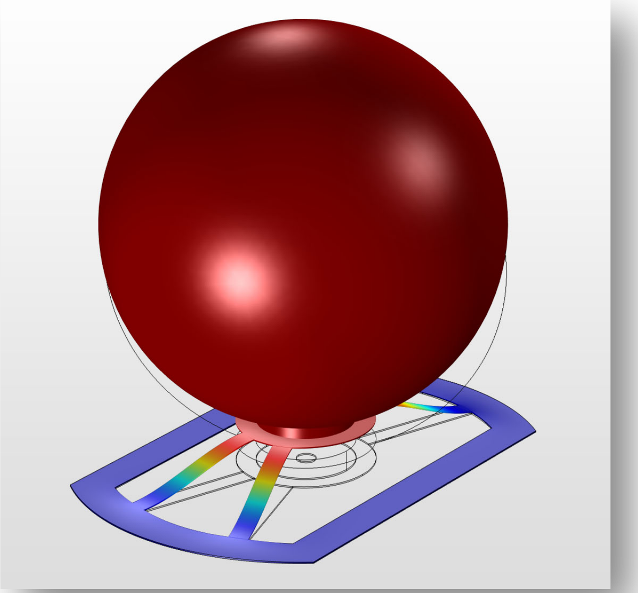
W. Michaelis et al., Meterologia 32, 267–276 (1995)

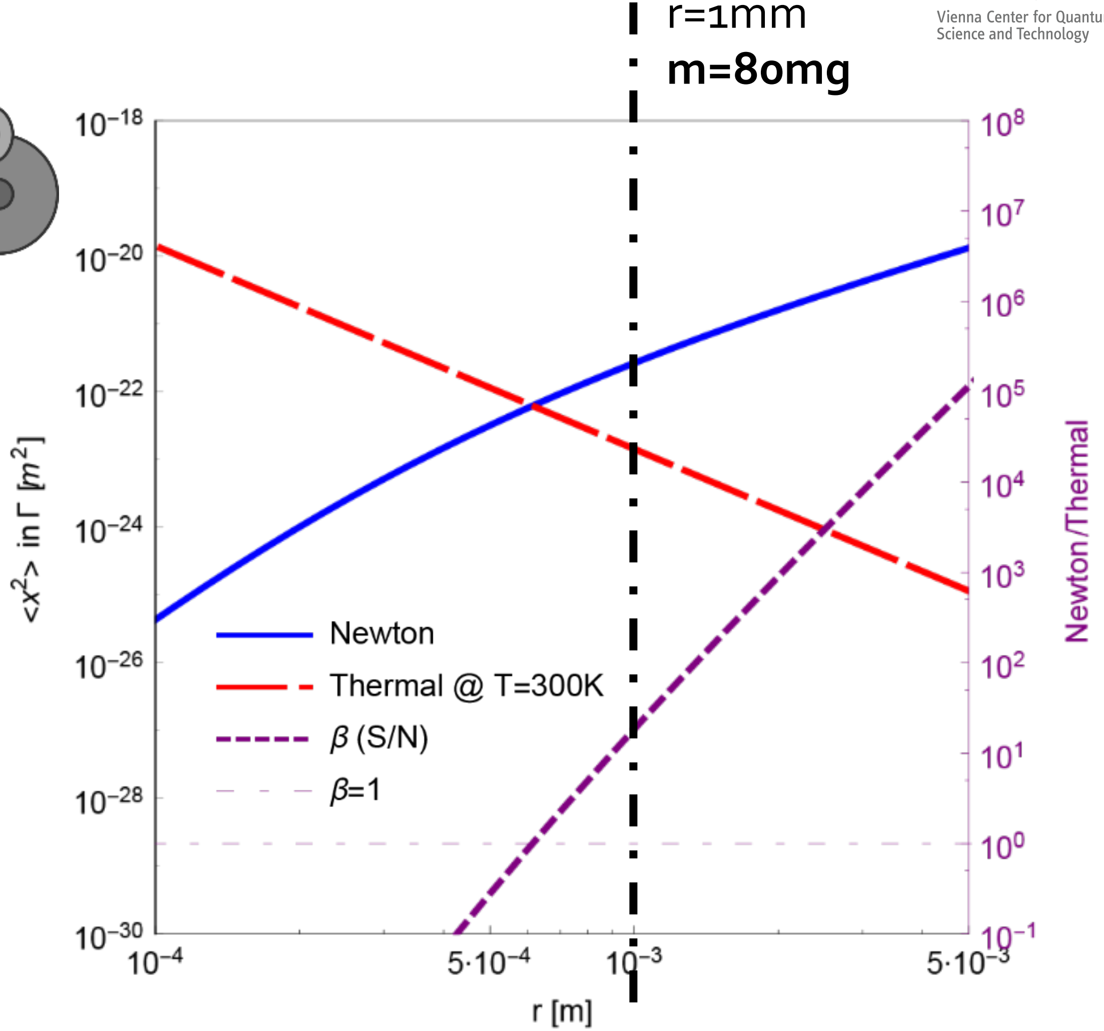
Jonas Schmöle, Mathias Dragosits, Hans Hepach

Measuring gravity between microscopic source masses ?



Example





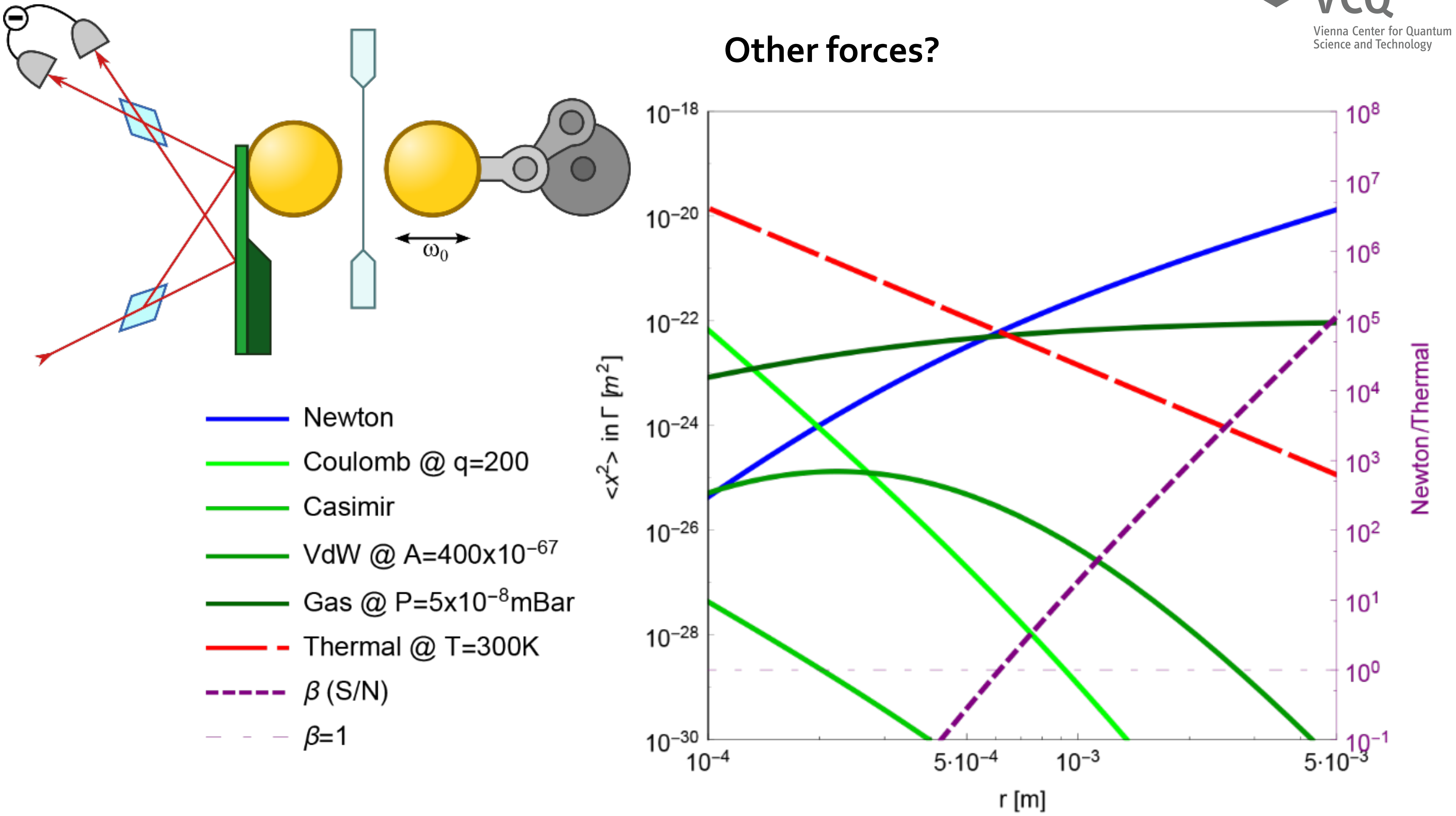
SiN cantilever with micromirror + 1mm gold sphere (in progress)

Jonas Schmöle, Mathias Dragosits, Hans Hepach

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

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

Measuring gravity between microscopic source masses ?



Other forces?

Jonas Schmöle, Mathias Dragosits, Hans Hepach

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

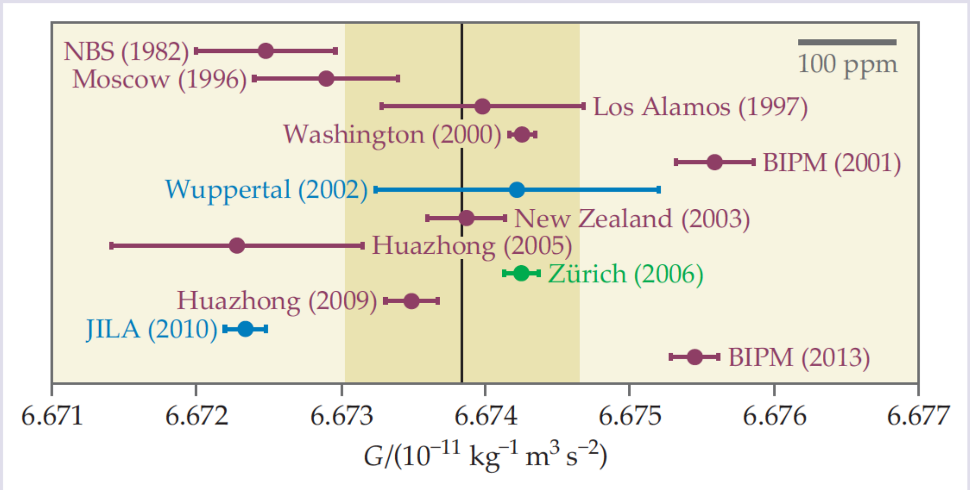


Figure 1. Measurements of Newton's gravitational constant *G* have yielded conflicting results. Here, the results of torsion-balance (maroon), pendulum (blue), and beam-balance (green) experiments discussed in the text are shown, along with the location and year in which they were measured. Error bars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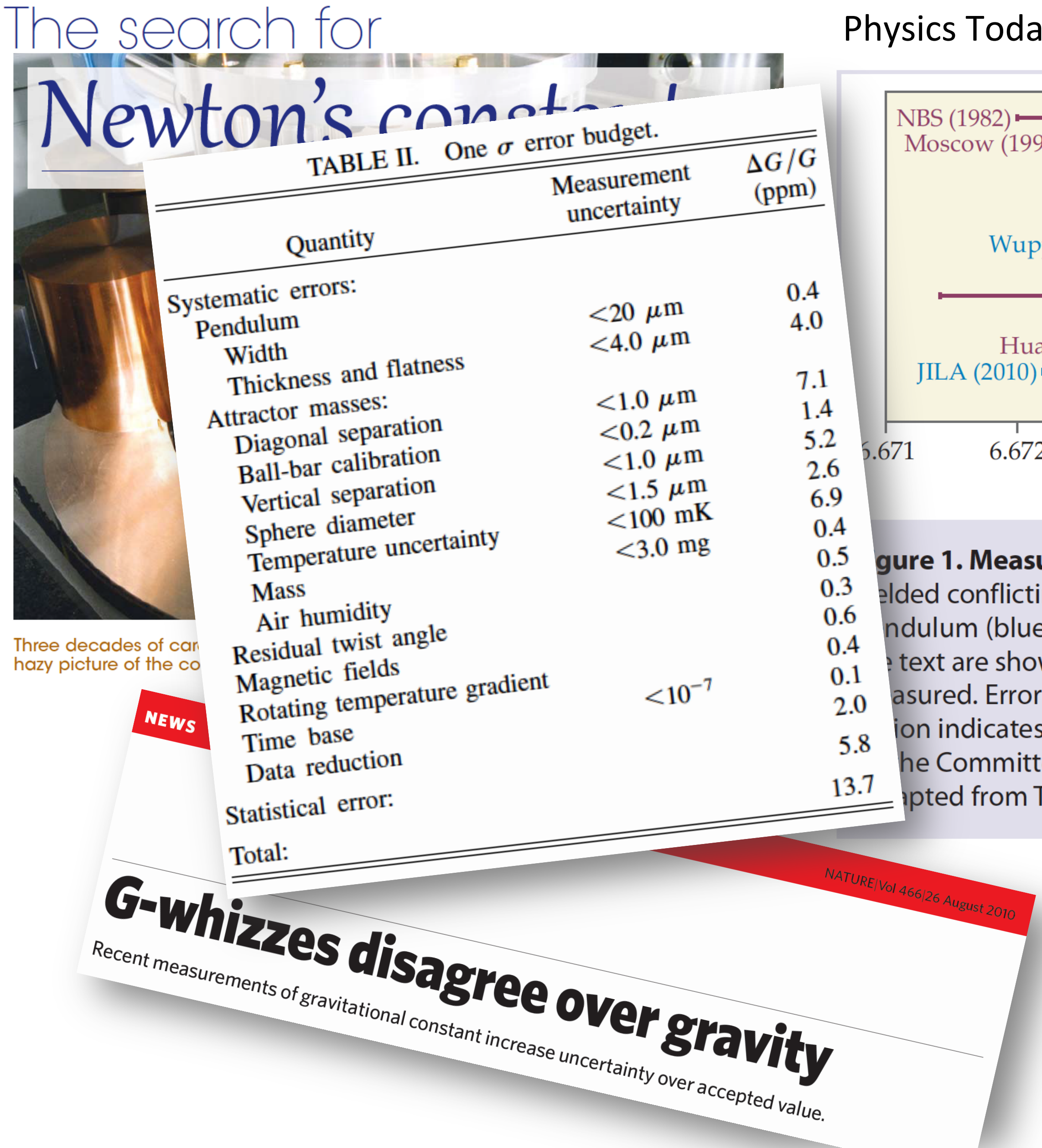
Science and Technology



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	$<20\ \mu$m	0.4
Thickness and flatness	$<4.0\ \mu$m	4.0
Attractor masses:		
Diagonal separation	$<1.0\ \mu$m	7.1
Ball-bar calibration	$<0.2\ \mu$m	1.4
Vertical separation	$<1.0\ \mu$m	5.2
Sphere diameter	$<1.5\ \mu$m	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

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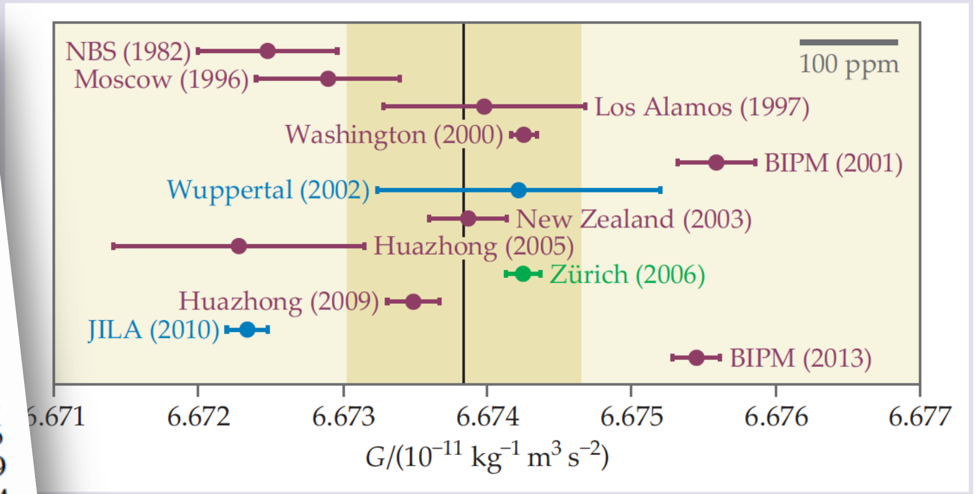
Physics Today July 2014



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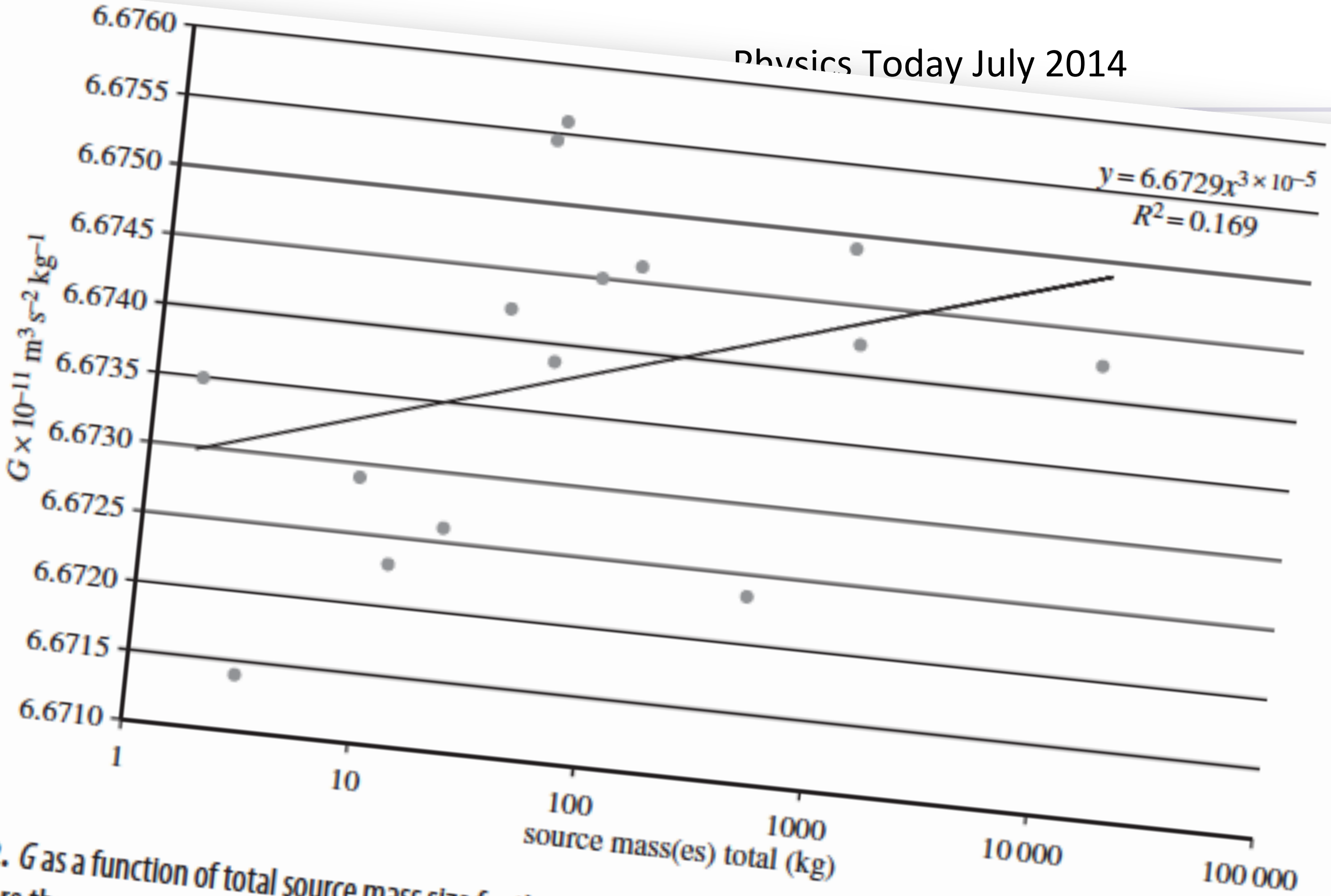

Figure 2. G as a function of total source mass size for the measurements with $\Delta G/G < 250$ ppm. The 15 data points from left to right are the results from Tu *et al.* [12], Pontikis [13], Karagioz *et al.* [15], Hu *et al.* [18], Luther *et al.* [23], Gundlach *et al.* [25], Quinn *et al.* [27], 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].

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

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-balance (maroon),
ments discussed in
in which they were
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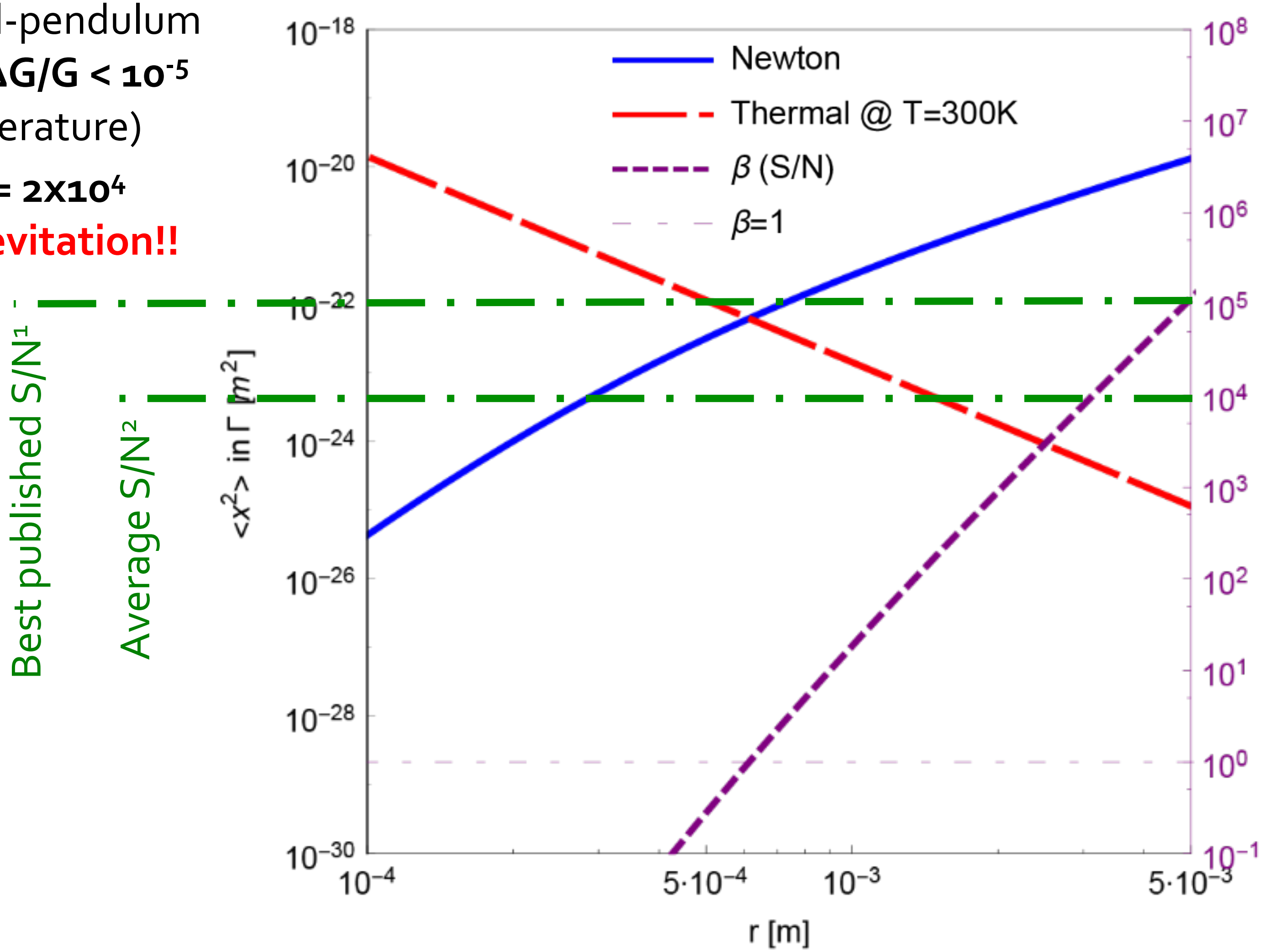
Potential Application for "Big G" measurement

- >**10mm** diameter spheres
- reach torsional-pendulum like precision **$\Delta G/G < 10^{-5}$** (at room temperature)
- This is for a **Q = 2x10^4** oscillator! → **levitation!!**



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[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)

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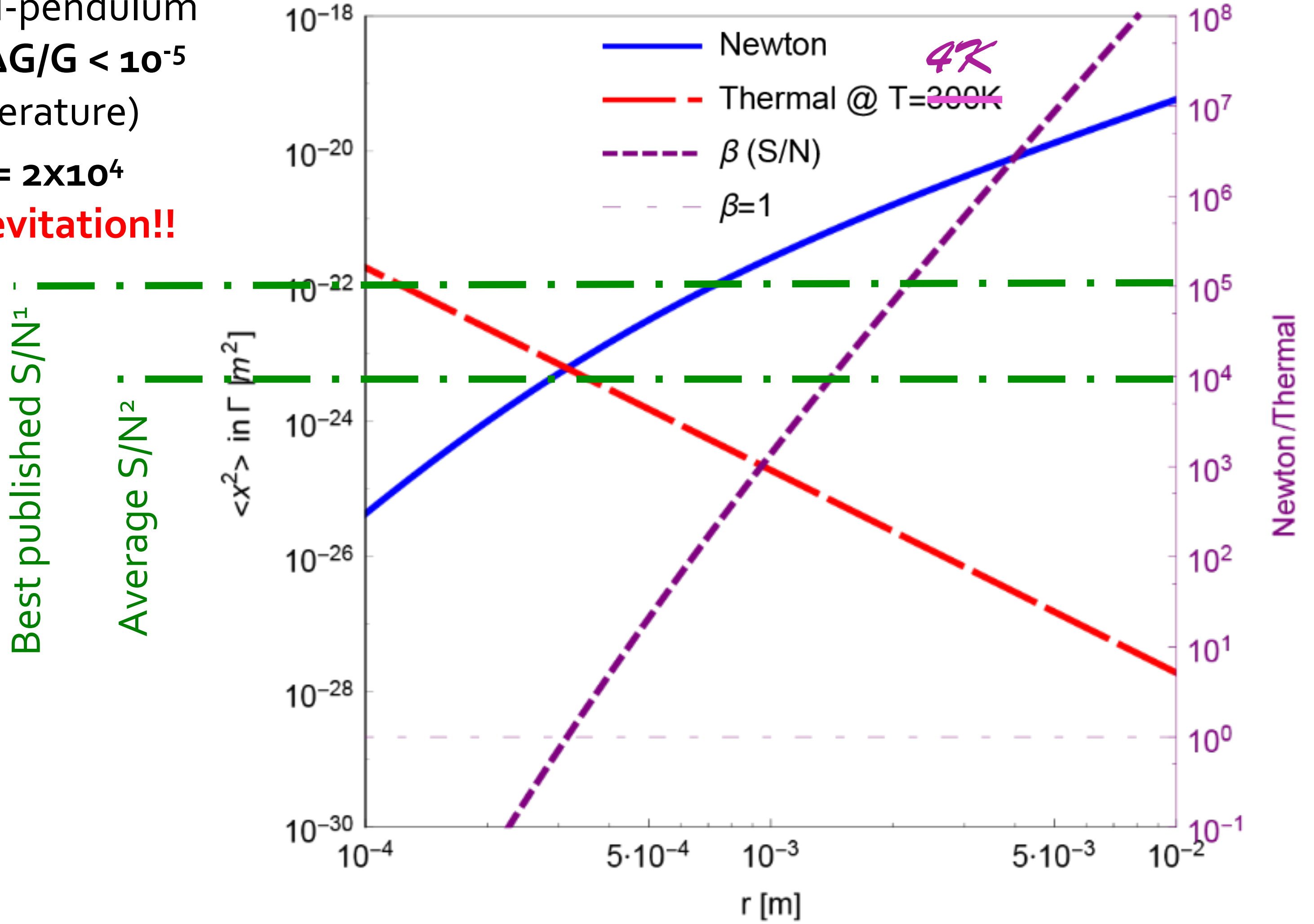

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[2] G. T. Gillies and C. S. Unnikrishnan, Phil. Trans. R. Soc. A 2014 372 (2014)

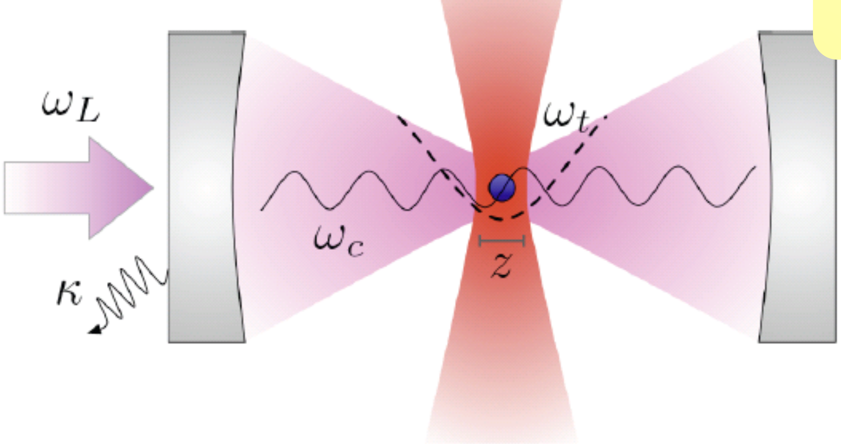
Towards quantum state preparation of a free particle

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)

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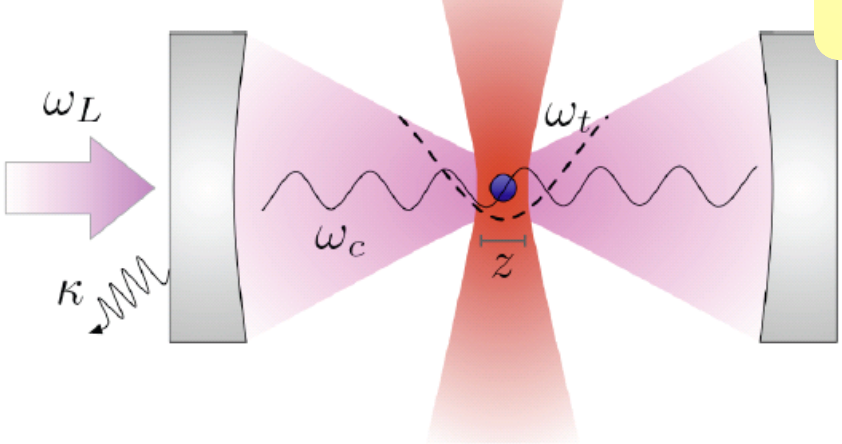
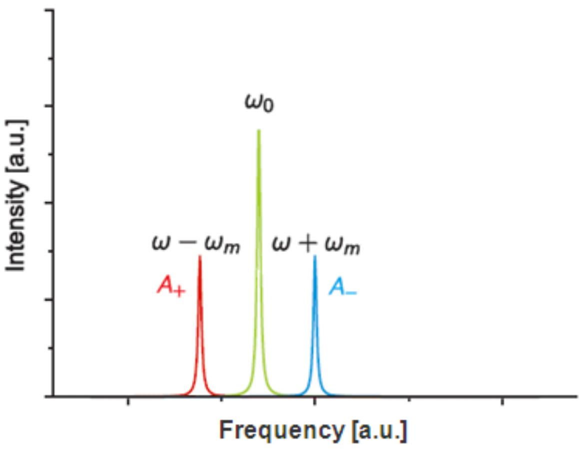


Chang et al., qu
Romero-Isart e 2010
P. F. Barker et
early work: Hec 1998)
Vule

→ **Harm**

→ **Quant ics**

Cavity Optomechanics



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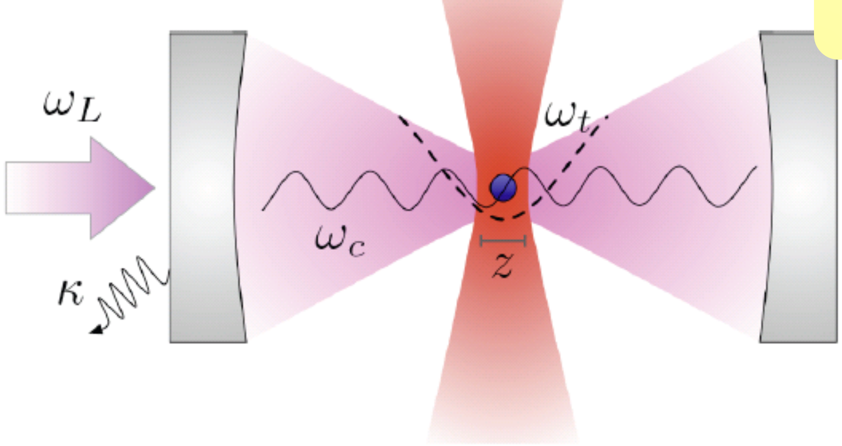

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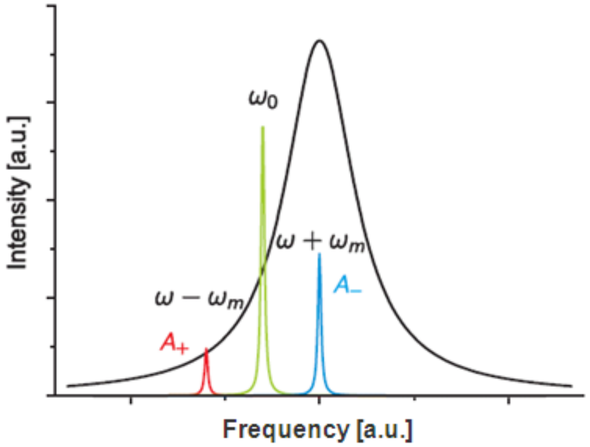
Cavity Optomechanics



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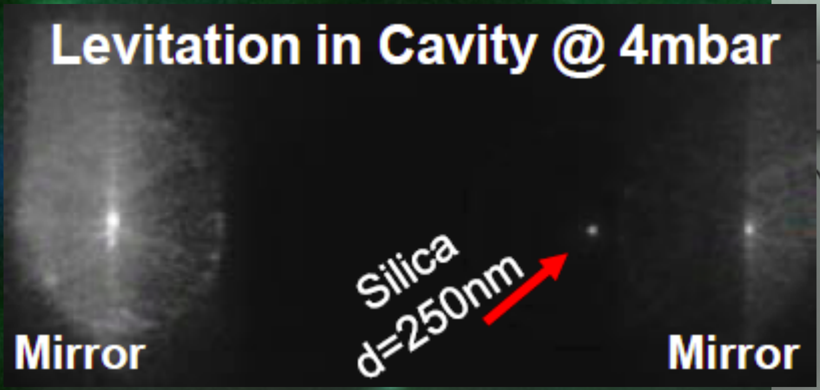
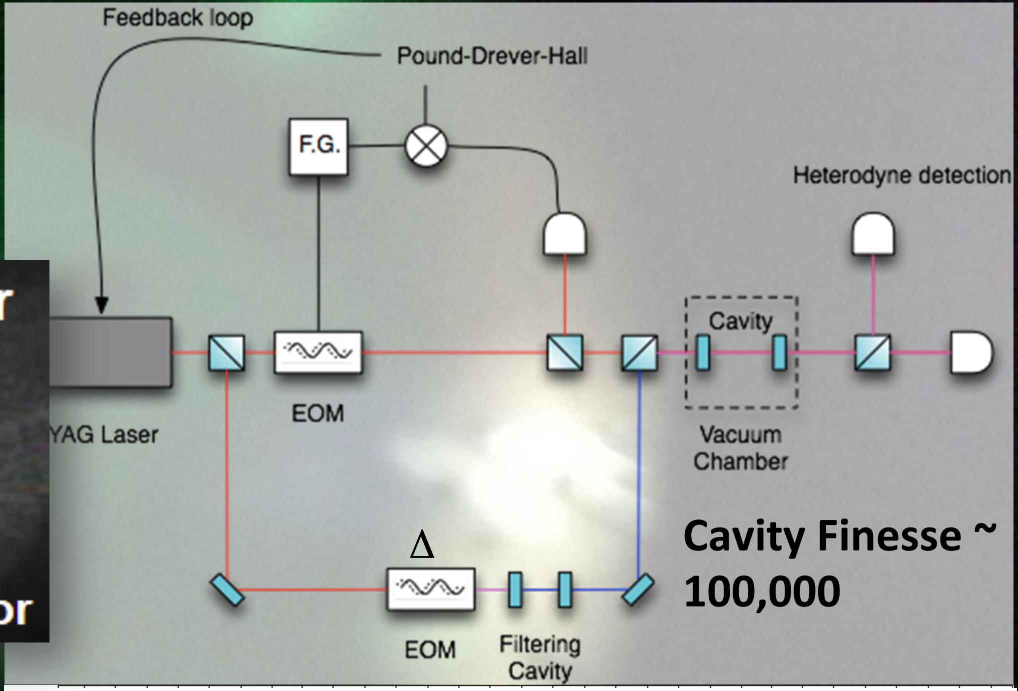
Optically trapped nanospheres as mechanical resonators

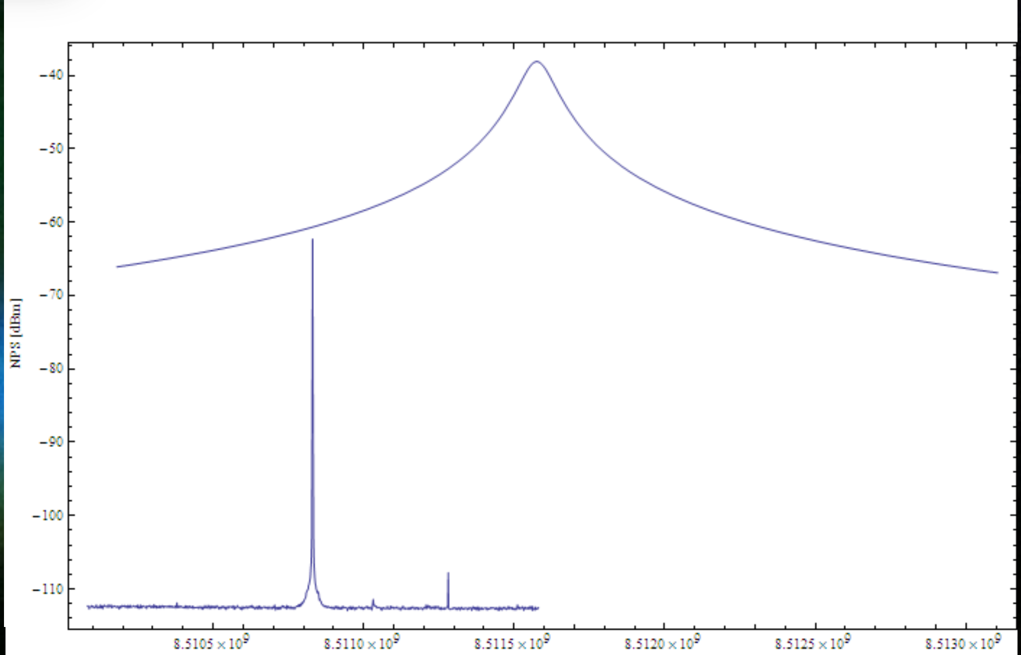
Ashkin since 1967
Raizen group, Science 2010
Novotny, Quidan 2012
Barker group 2014
Geraci group 2015



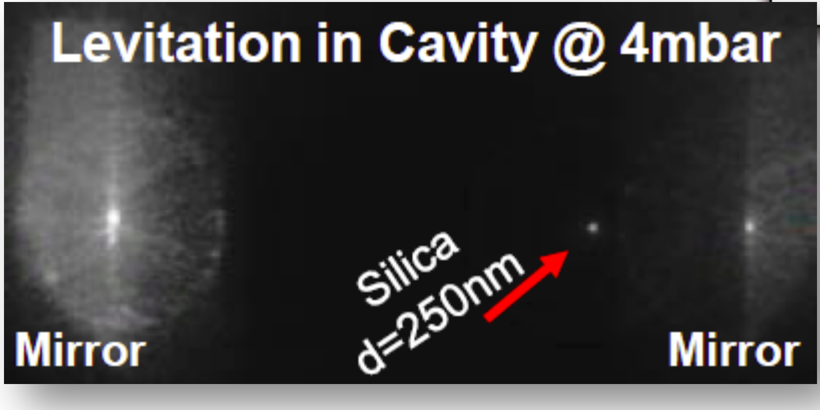


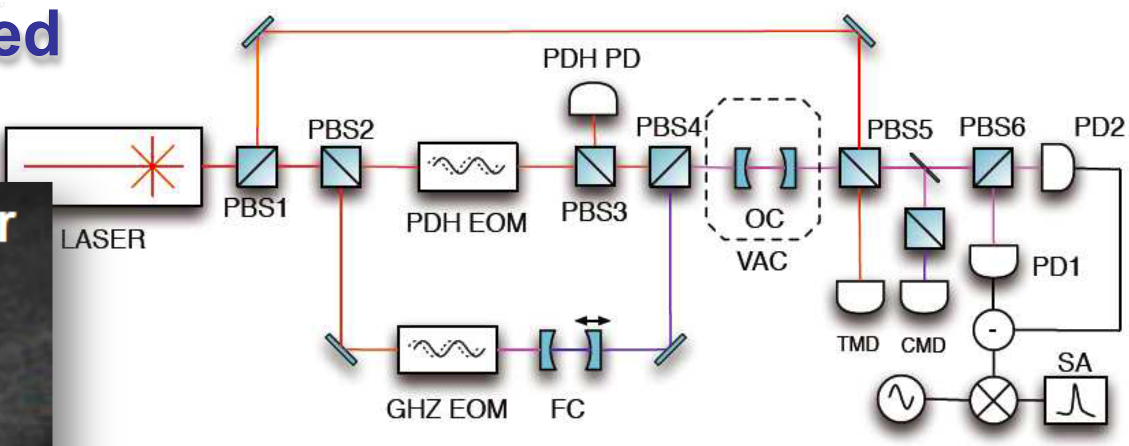
Cavity Finesse ~ 100,000

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

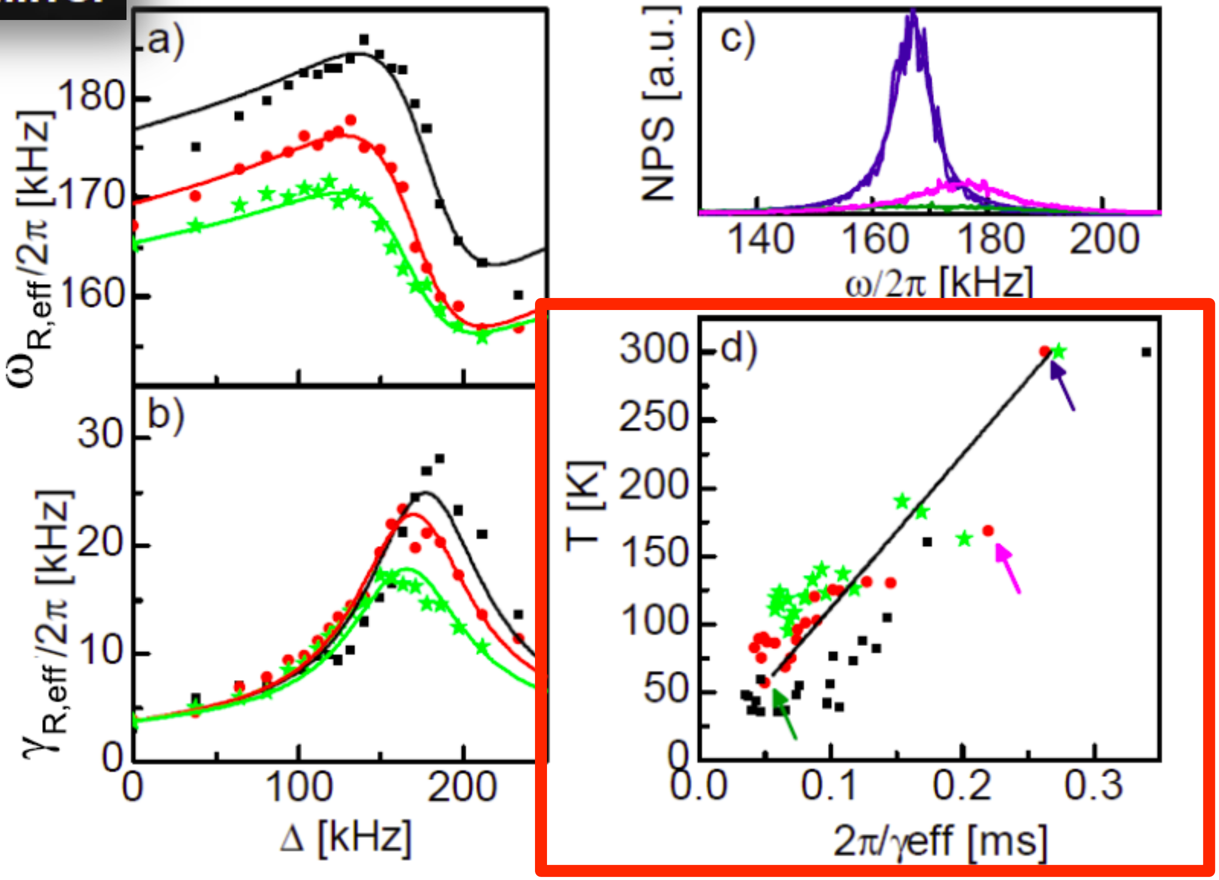


Cavity cooling of a trapped nanosphere





$\kappa \approx 180$ kHz, FSR ≈ 13.6 GHz, F ≈ 78,000



Q ~ 25 @ 4 mbar

Q ~ 10^9 @ 10^{-7} mbar

⇒ 10^{-21} N/$\sqrt{Hz}$

$F_c \sim 10^{-19}$ 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

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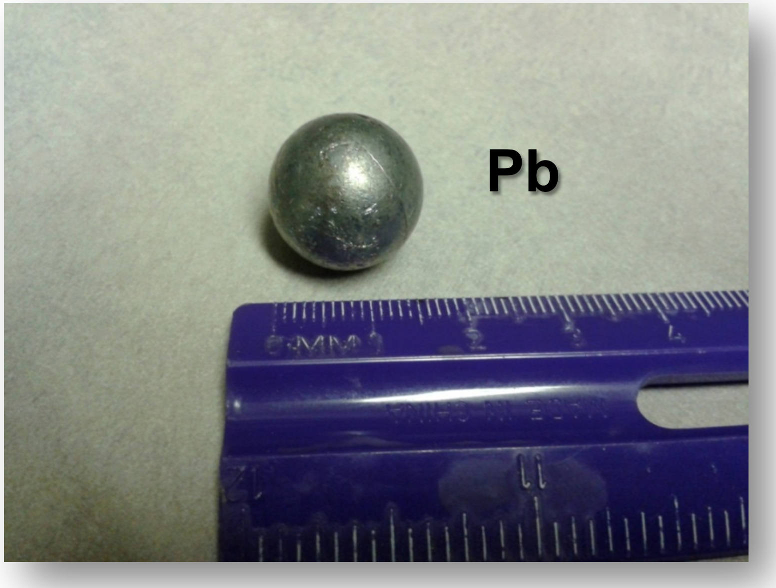
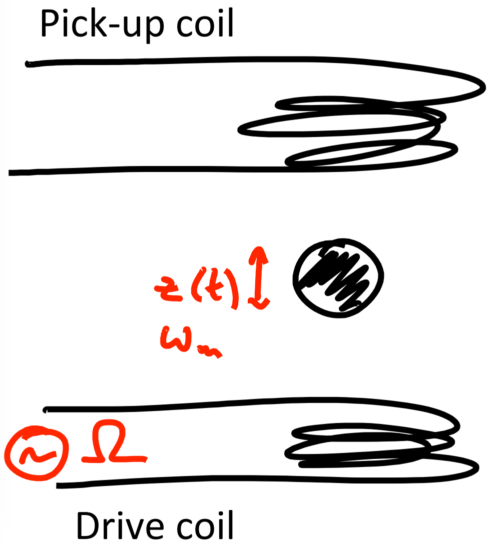
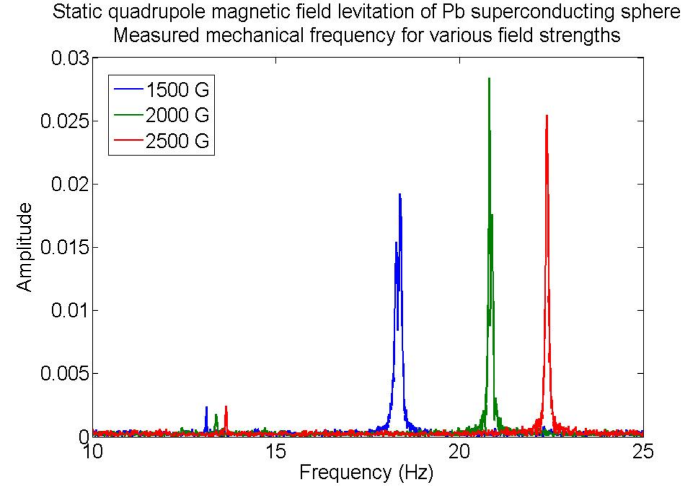
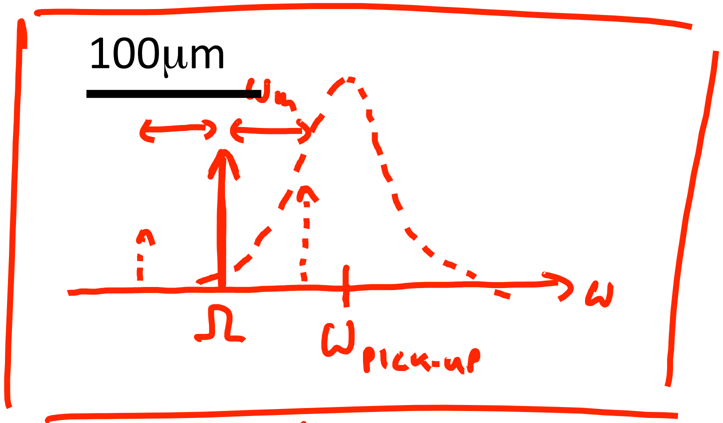




$$H_{int} \propto -\frac{\phi_1 \phi_2}{L_1 L_2} M_{12}(z)$$

M_{12} : mutual inductance





"CAVITY OPTO-MECHANICS"

(artist's impression – still...)

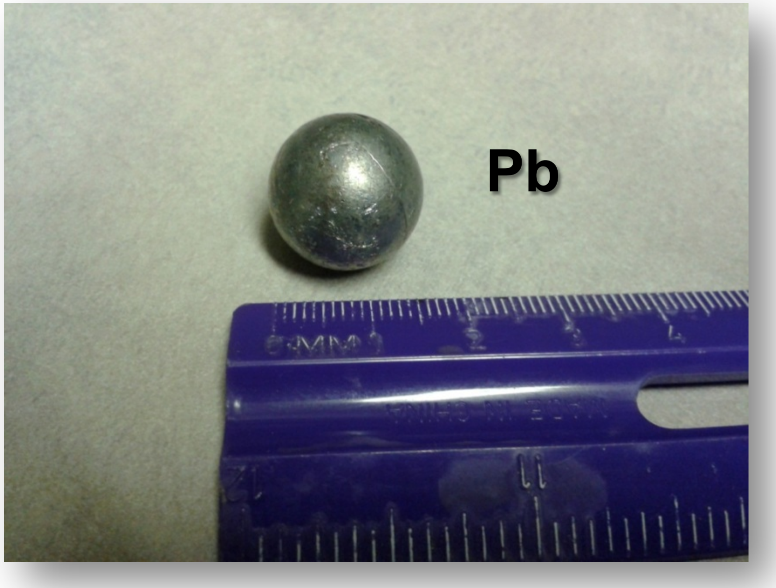
Magnetic levitation in anti-Helmholtz coil configuration

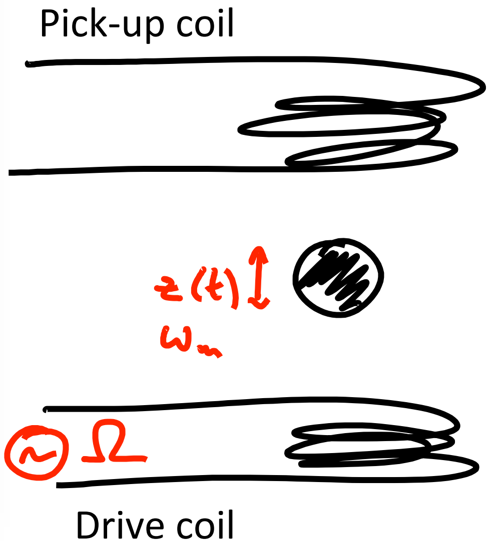
Trap frequencies ~ 20 Hz

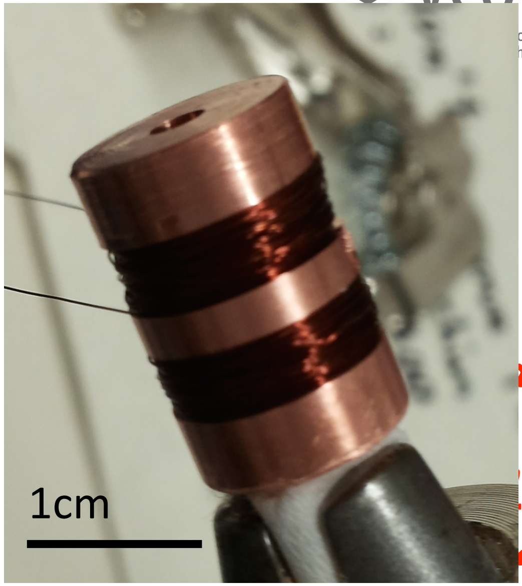
T= 20 mK, p = 1e-6 mbar

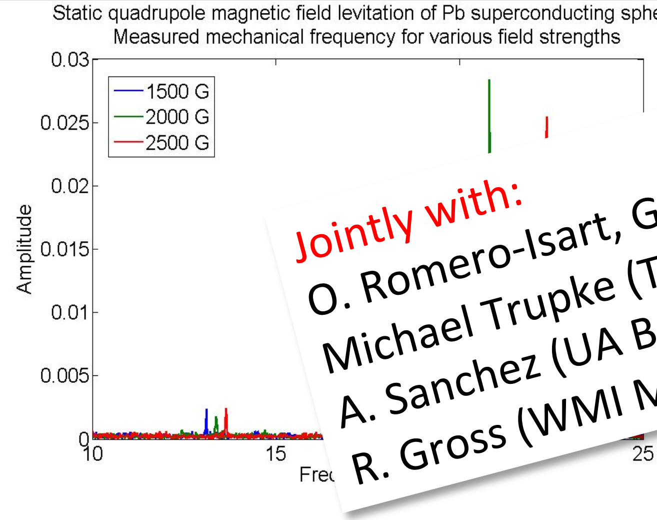
S. Minter, R. Chiao, N. Prigge, M. Aspelmeyer

Magnetically trapped superconductors as mechanical resonators

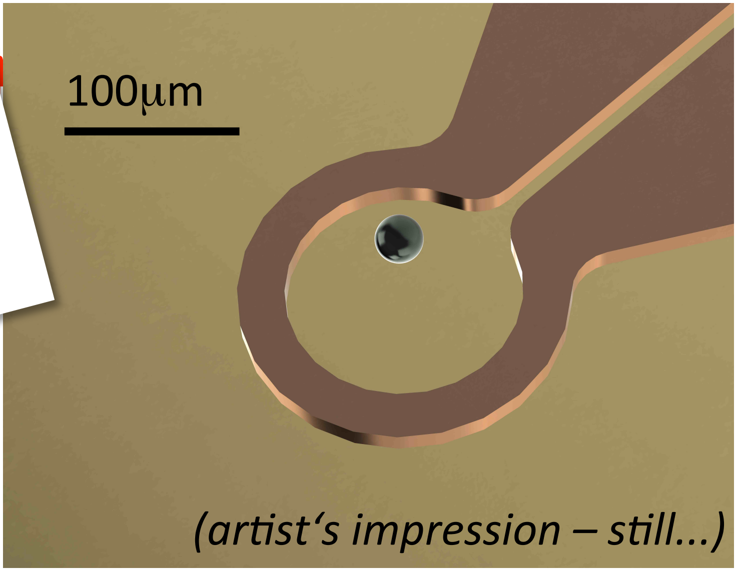








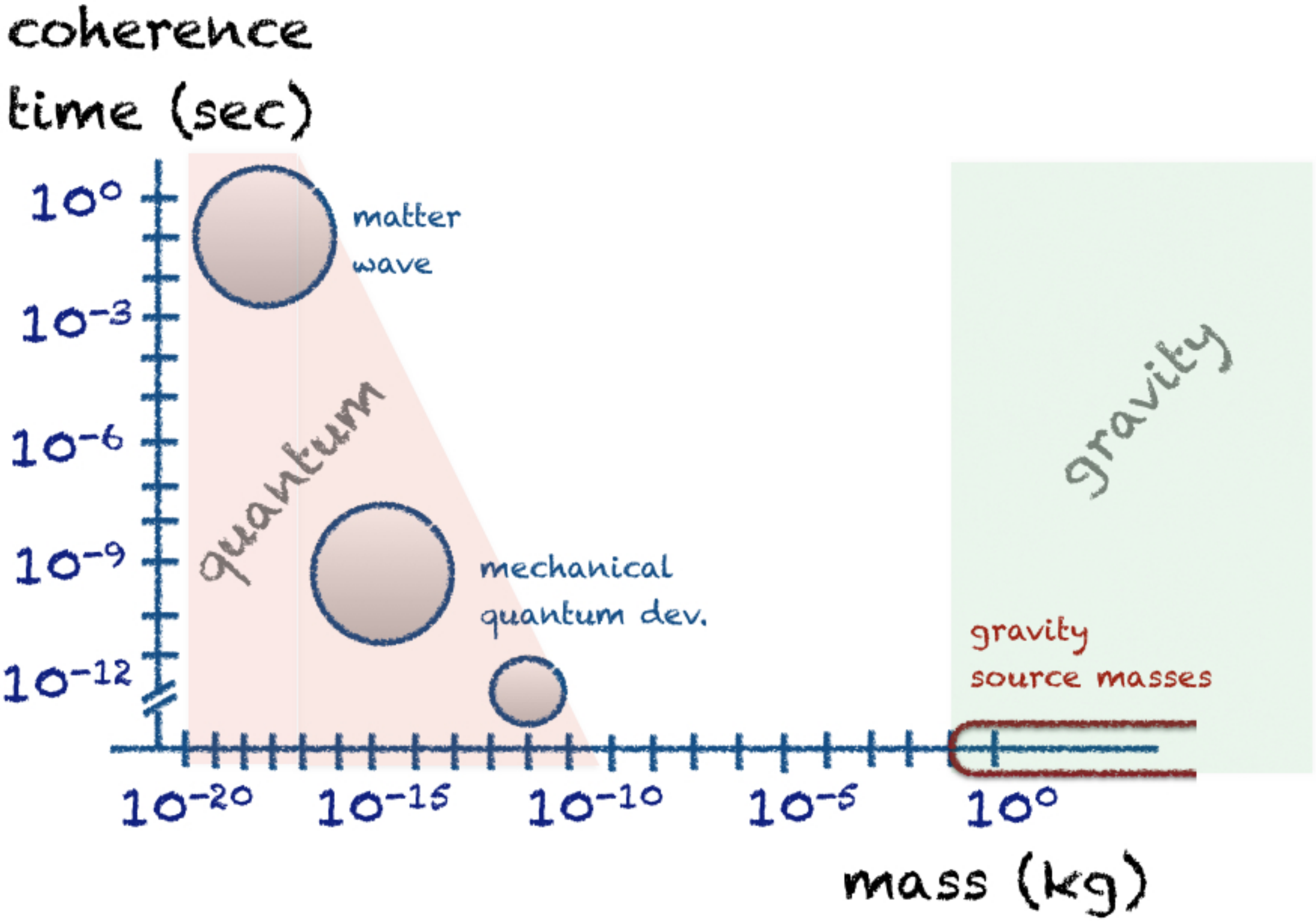
Jointly with:
O. Romero-Isart, G. Kirchmair (IQOQI)
Michael Trupke (TU Vienna)
A. Sanchez (UA Barcelona)
R. Gross (WMI Munich)



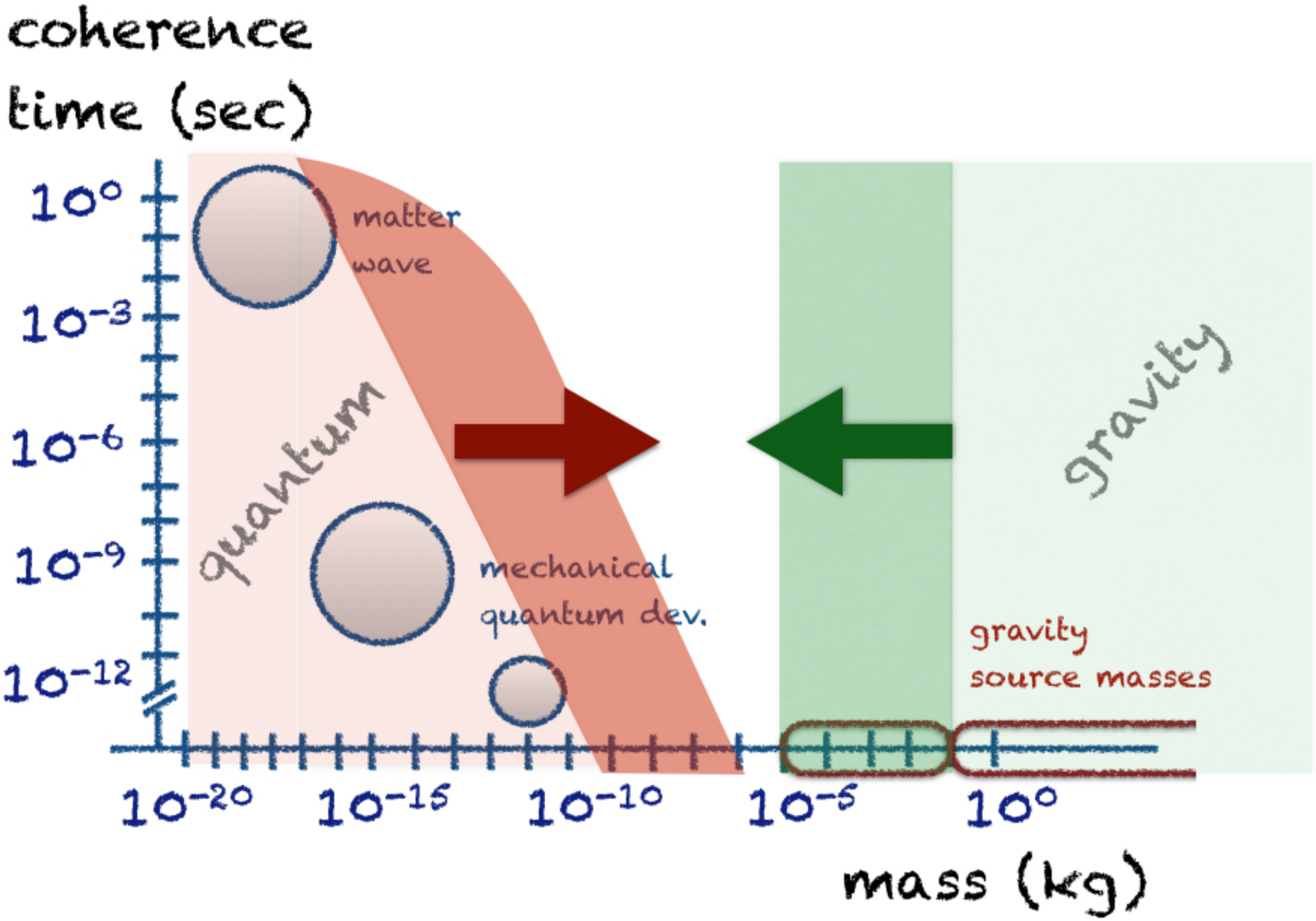
(artist's impression – still...)

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

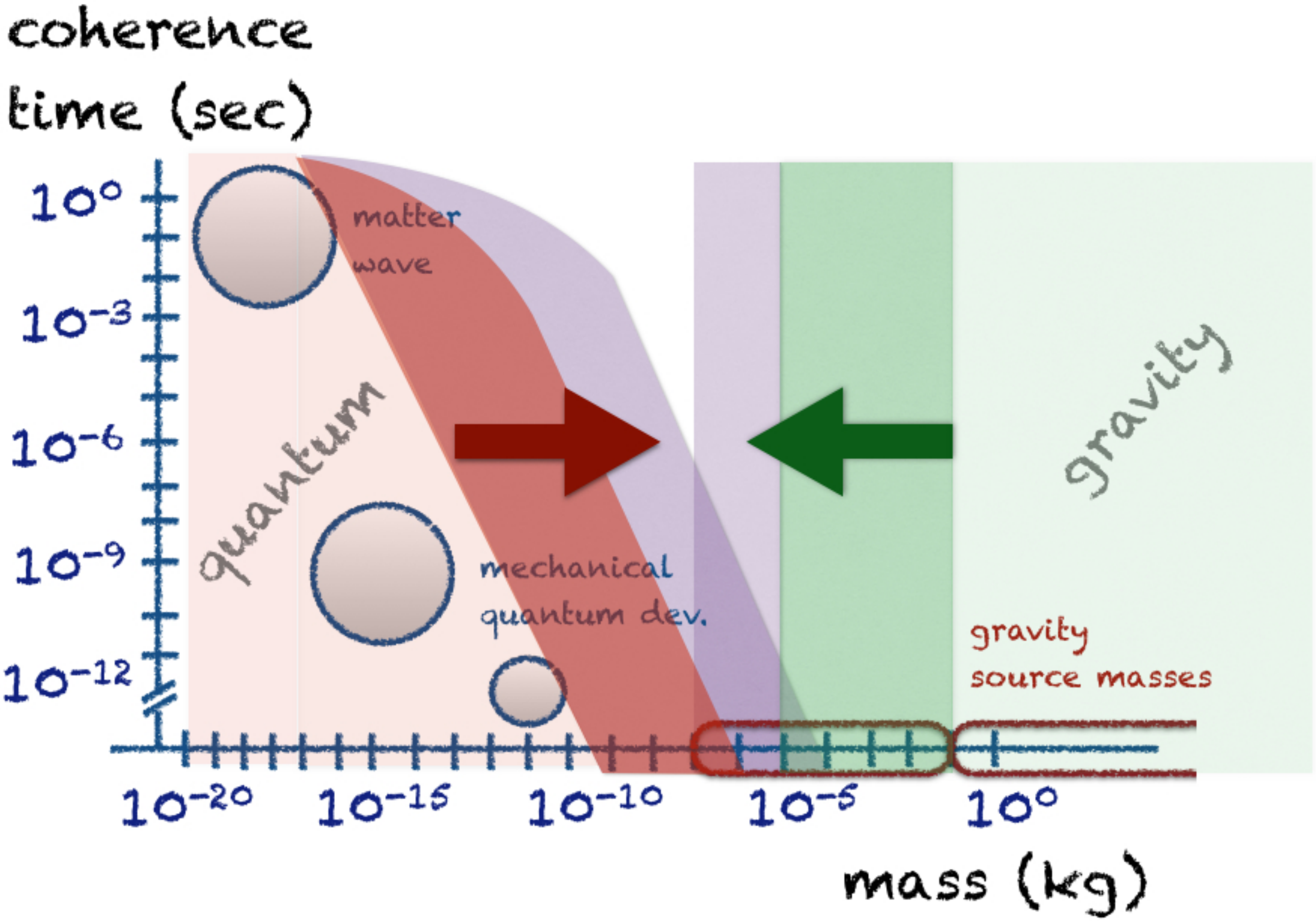
How massive can we go?

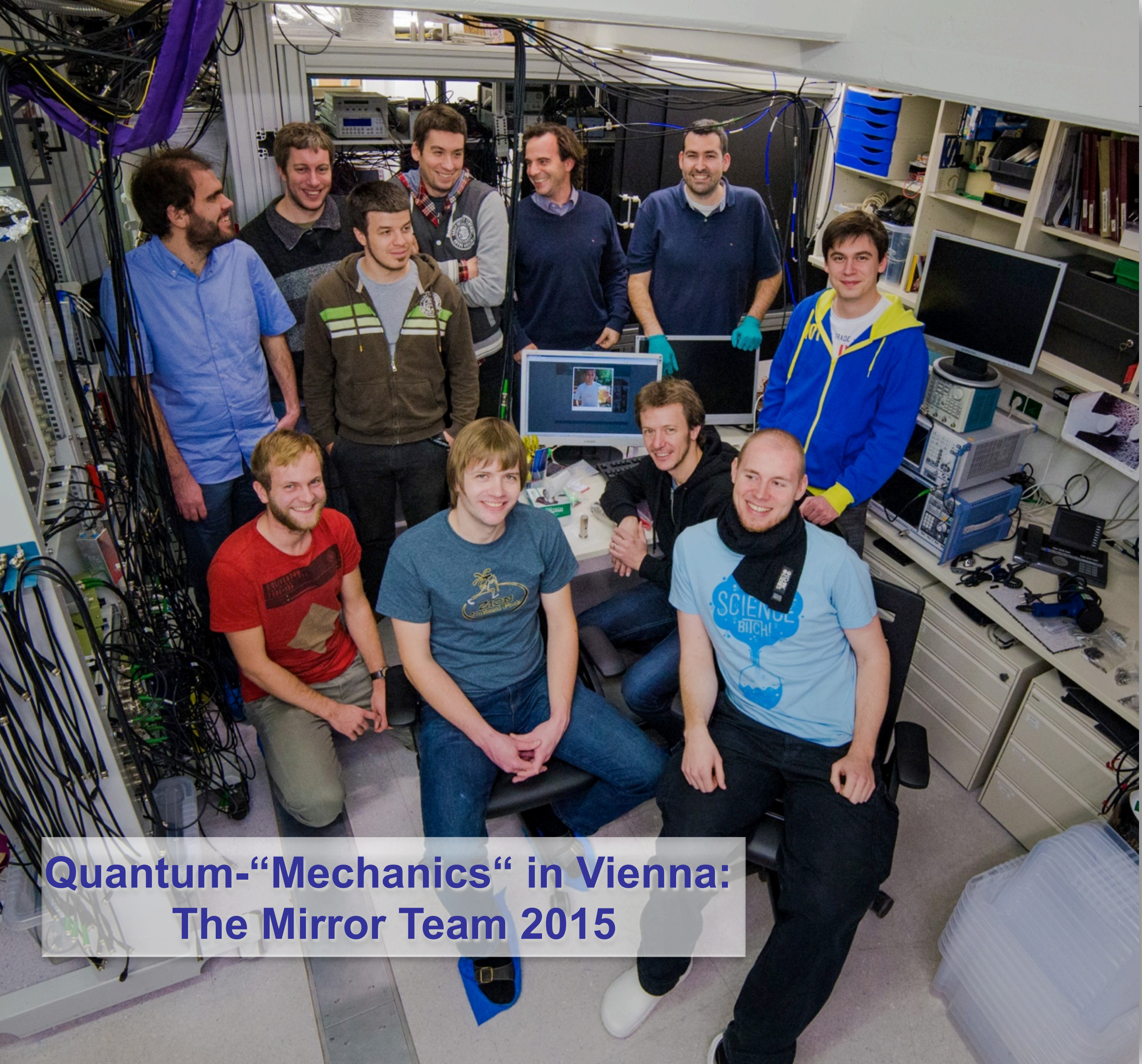


How massive can we go?



How massive can we go?





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

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

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

N.N. (cleanroom tech)

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 M. Arndt, 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 Hepbach

Christian Siegele

enna:

Quantum information interfaces (with K. Hammerer, J. Eisert, O. Painter)

Witlef Wieczorek

Jason Hölscher-Obermayer

Sebastian Hofer

Ramon Moghadas Nia

Claus Gärtner

Thomas Zauner

Quantum Controlling Levitated Massive Mechanical Systems

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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**

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