PITP, UBC, Vancouver 2019

Quantum Controlling Levitated Solids: *a novel probe for the gravity-quantum interface*

Markus Aspelmeyer

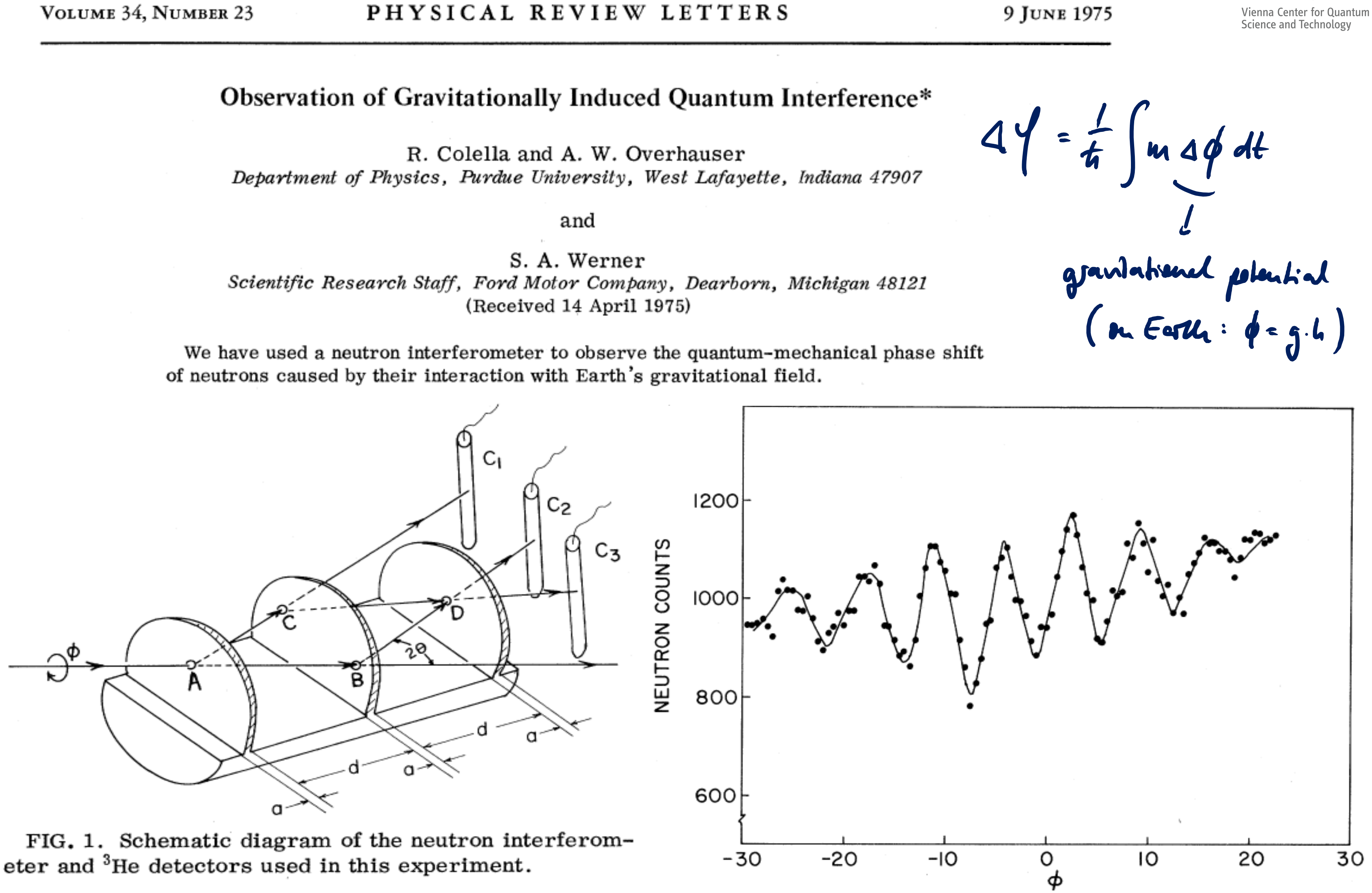
Vienna Center for Quantum Science and Technology (VCQ)
Faculty of Physics , University of Vienna, Austria
IQOQI, Austrian Academy of Sciences

In memory of Helmut Rauch (1939-2019)

The neutron interferometer

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

Quantum systems as sensitive probes of gravity



VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

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

and

S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121

(Received 14 April 1975)

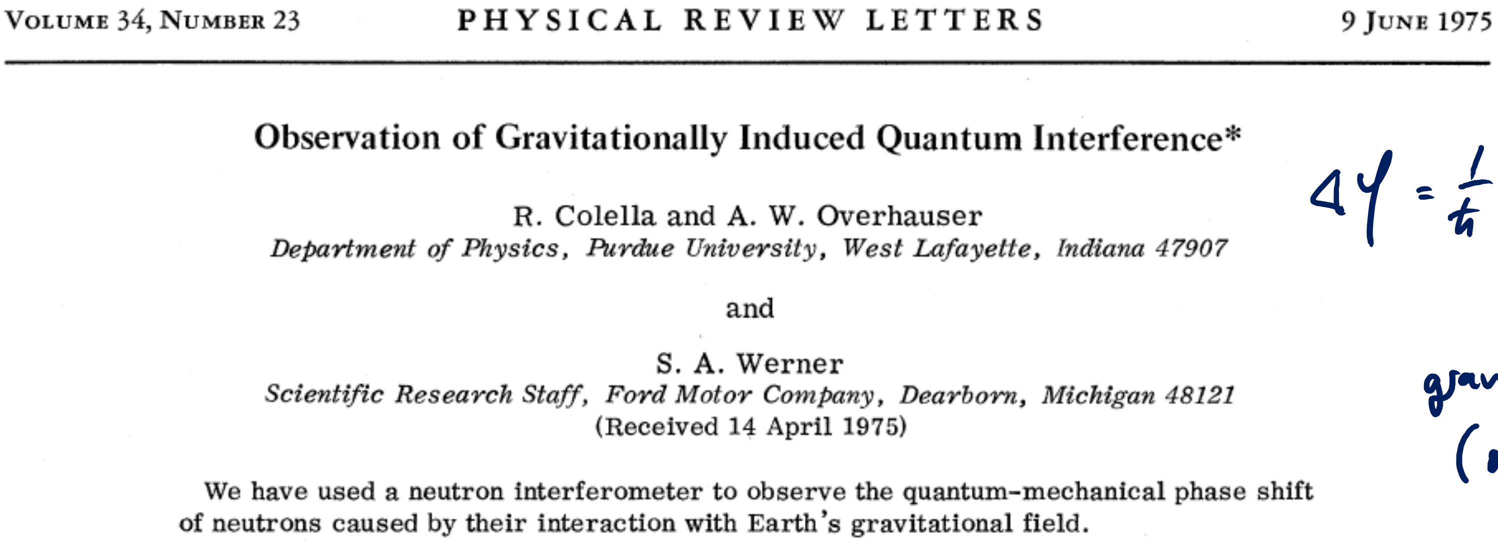
We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

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

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

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

Quantum systems as sensitive probes of gravity



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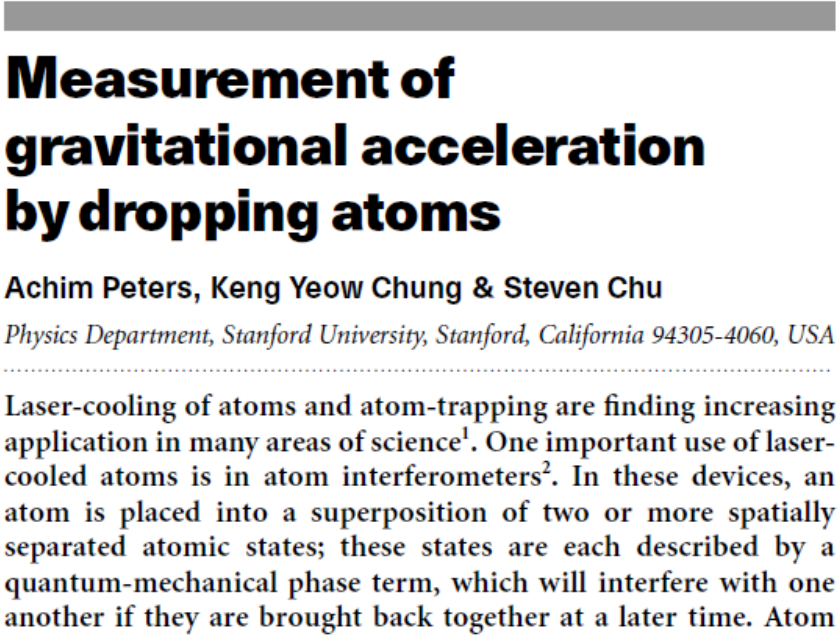
Nature 1999

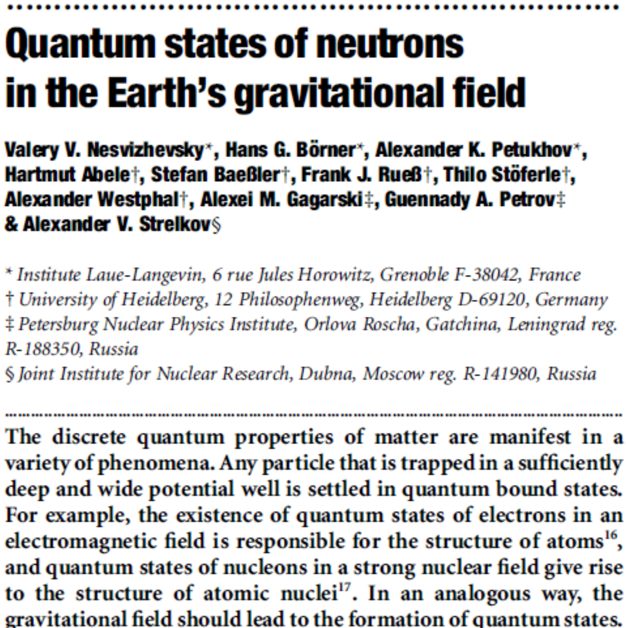


Measurement of gravitational acceleration by dropping atoms

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

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

Nature 2002



Quantum states of neutrons in the Earth's gravitational field

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

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

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

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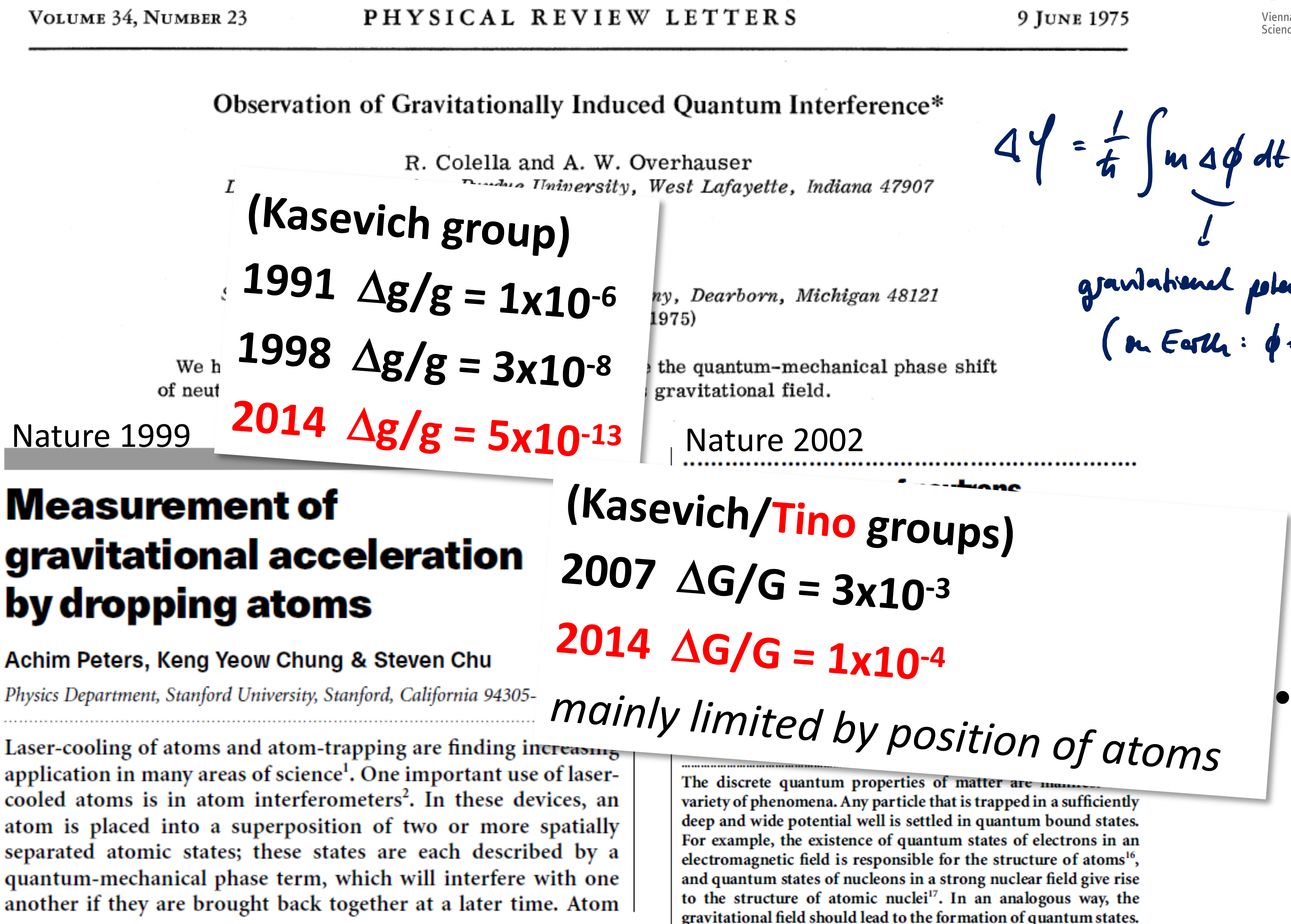
Quantum systems as sensitive probes of gravity



Volume 34, Number 23 PHYSICAL REVIEW LETTERS 9 June 1975

Observation of Gravitationally Induced Quantum Interference*

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ny, Dearborn, Michigan 48121

1975)

We h … the quantum-mechanical phase shift of neut … gravitational field.

(Kasevich group)

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

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

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

Nature 1999

Measurement of gravitational acceleration by dropping atoms

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Nature 2002

(Kasevich/Tino groups)

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

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

mainly limited by position of atoms

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Quantum systems as sensitive probes of gravity

universität wien

VCQ
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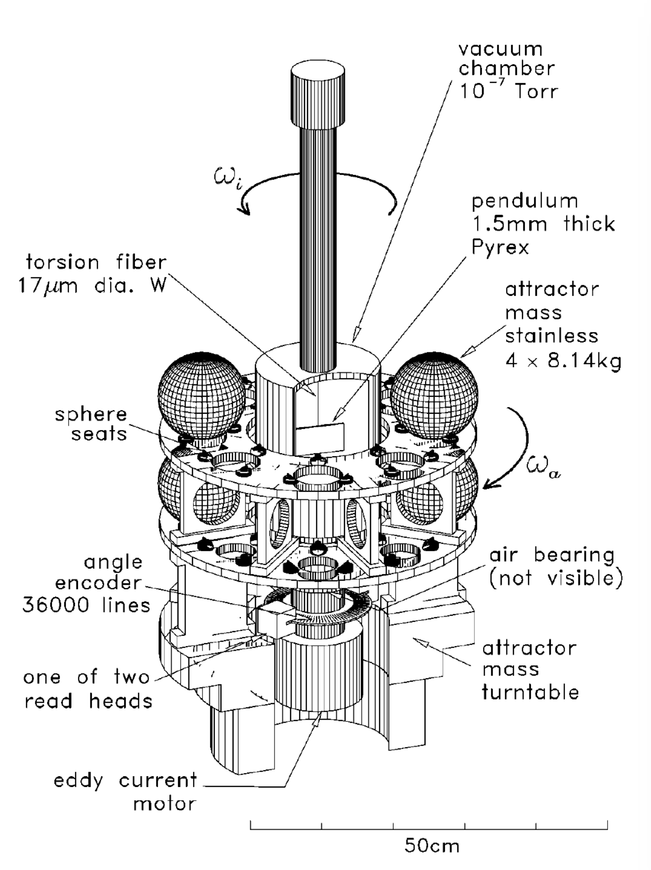
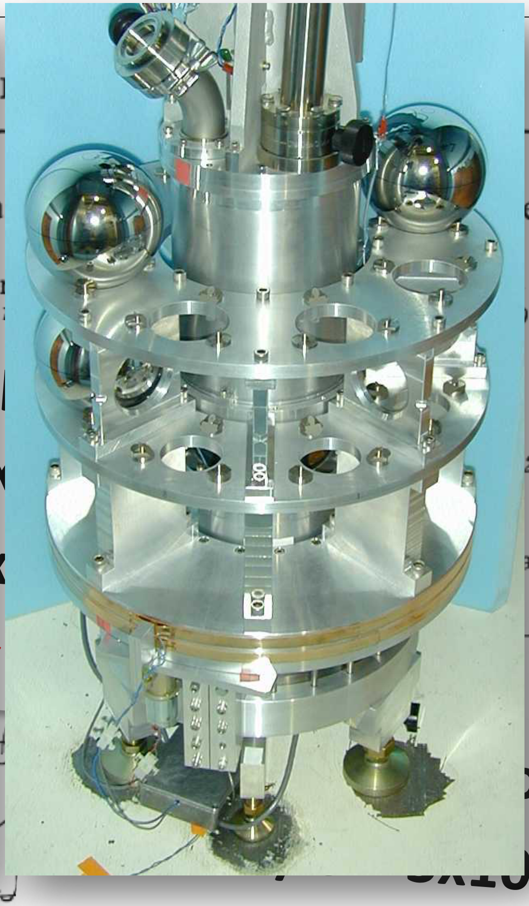




9 JUNE 1975

e*

ase shift

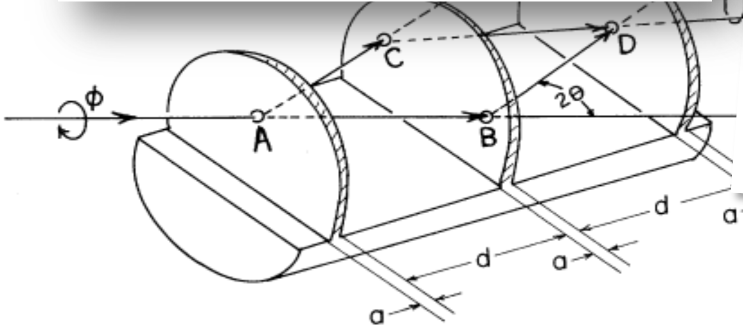
$$\Delta\Psi = \frac{1}{\hbar}\int m \underbrace{\Delta\phi}_{\downarrow} \, dt$$

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

Gundlach et al.,
PRL 2000
ΔG/G = 15ppm

2014 ΔG/G = 1x10^{-4}

mainly limited by position of atoms



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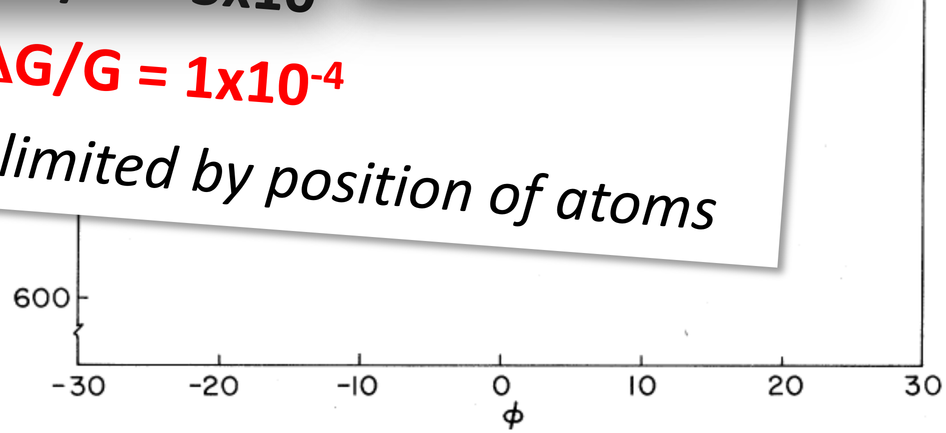
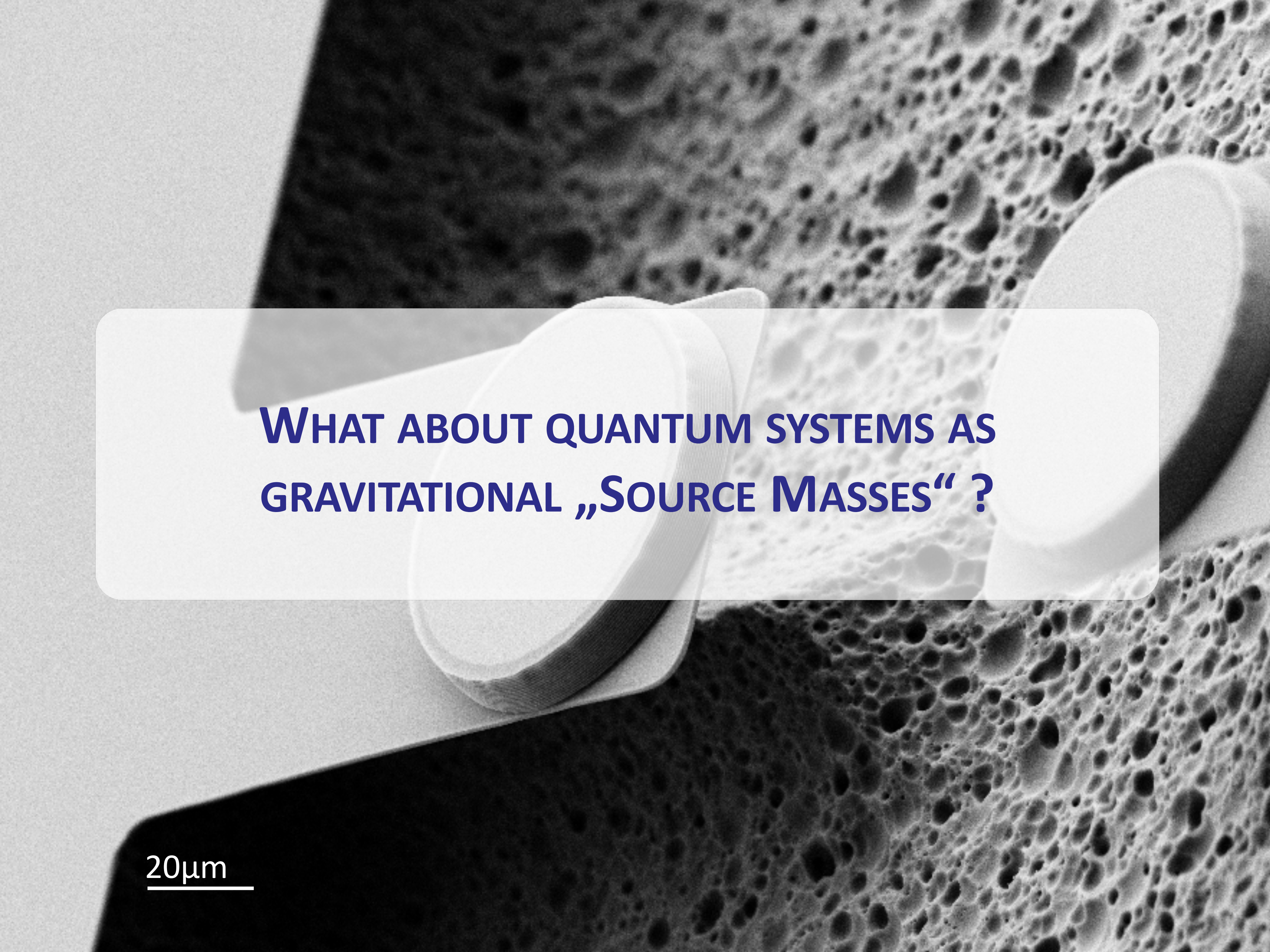
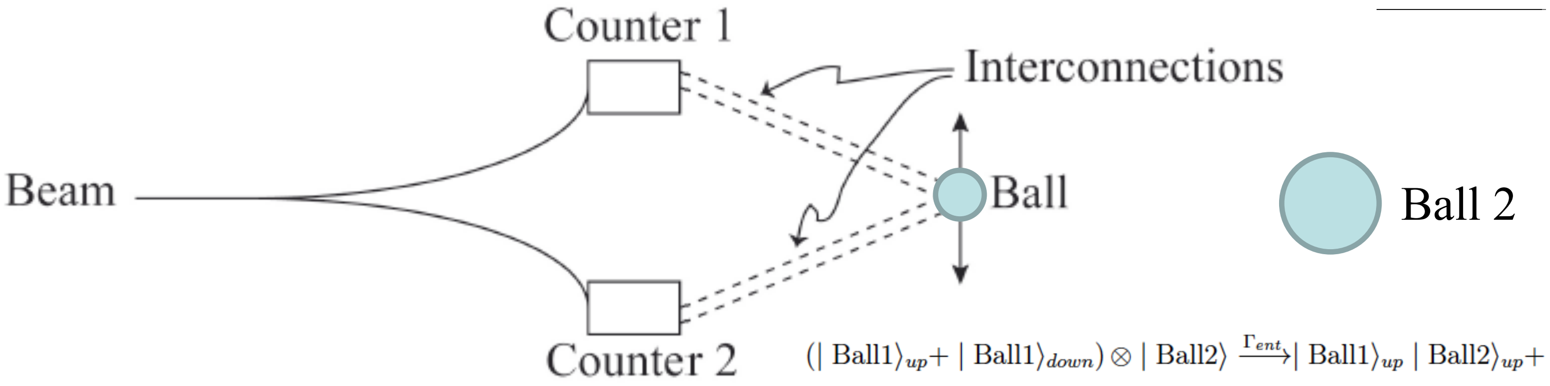




WHAT ABOUT QUANTUM SYSTEMS AS GRAVITATIONAL „SOURCE MASSES“ ?

An ultimate experiment? Entanglement by gravity…



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

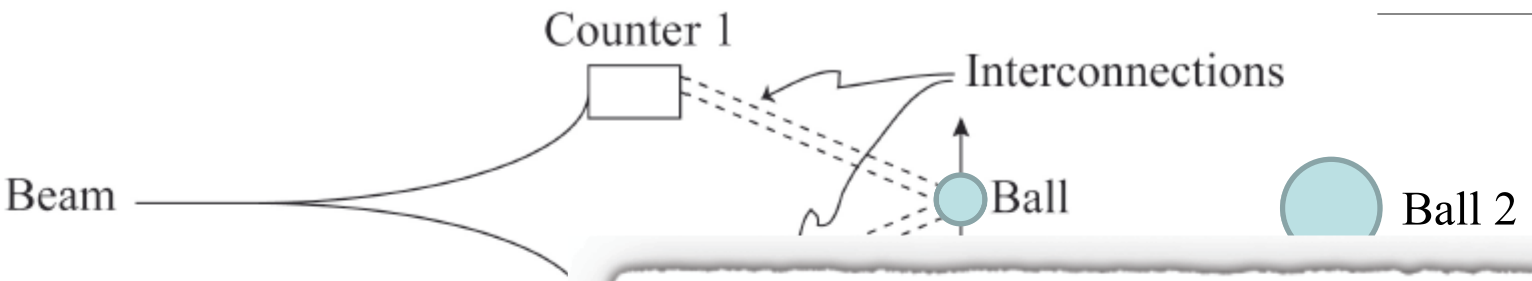
FEYNMAN: “Therefore, there must be an amplitude for the gravitational field, *provided* that the amplification necessary to reach a mass which can produce a gravitational field big enough to serve as a link in the chain does not destroy the possibility of keeping quantum mechanics all the way. There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

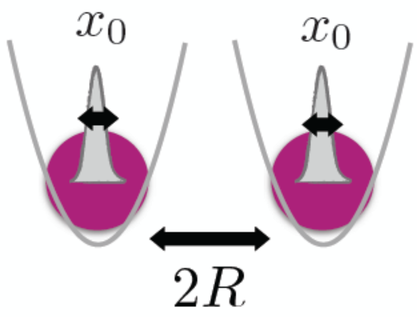
WITTEN: “What prevents this from becoming a practical experiment?”

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

An ultimate experiment? Entanglement by gravity…



Entangling via gravity



Entangling time:

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

Pino et al., arXiv:1603.01553

FEYNMAN: "Therefore,
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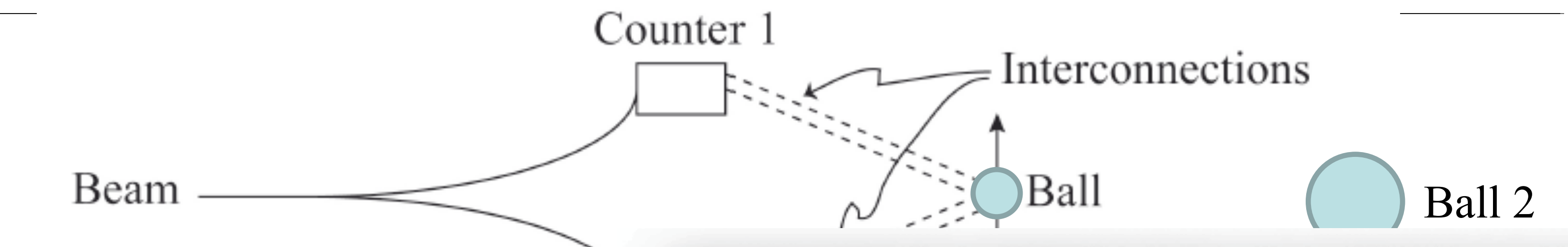
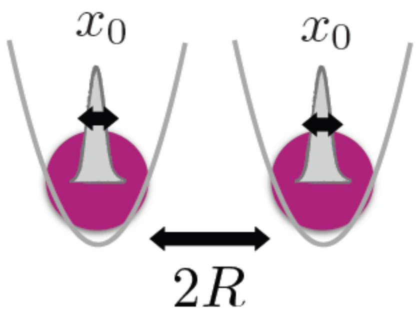


C

$\mathrm{ll2}\rangle_{down}$

Entangling via gravity



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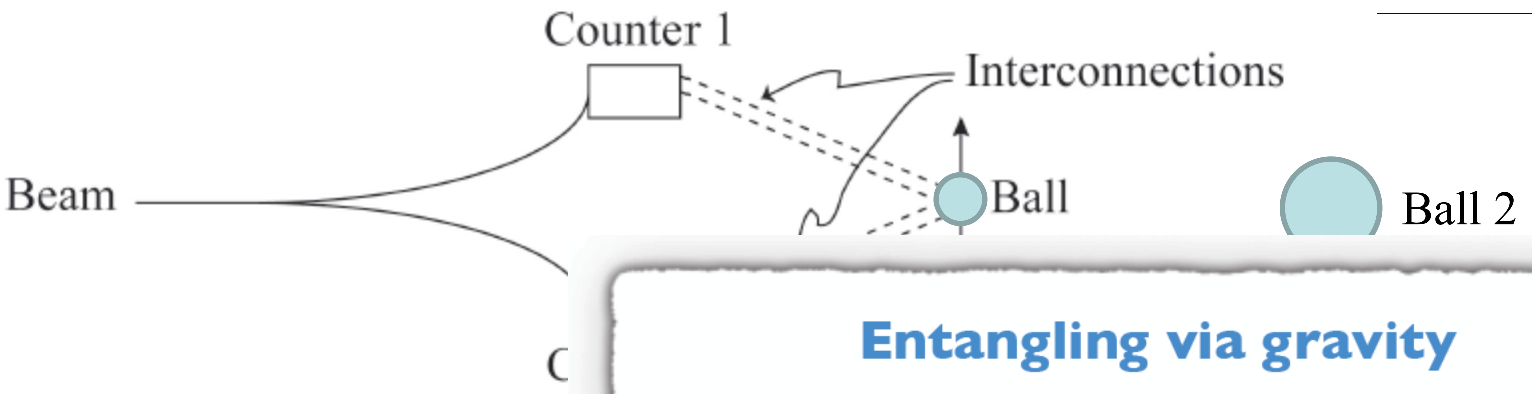
Chapel Hill Conference 1957 (29)

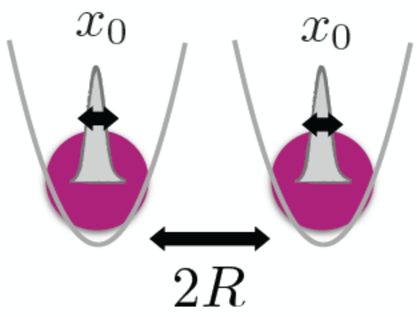
Example: For 2 **lead spheres** of **diameter 500 μm**, an initial **superposition size for sphere 1** of **$\Delta r = 5\times10^{-7}$ m** and preparation of **sphere 2** in a **motional ground state** (100 Hz trap frequency) with **$\Delta x_0 = 10^{-15}$ m**, we obtain **$\Gamma_{ent} = 1.5$ Hz**,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

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

An ultimate experiment? Entanglement by gravity…



Entangling via gravity



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Pino et al., arXiv:1603.01553

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

Example: For 2 **lead spheres** of **diame**
superposition size for sphere 1 of $\Delta r = 5\times10^{-7}$ **m** and p
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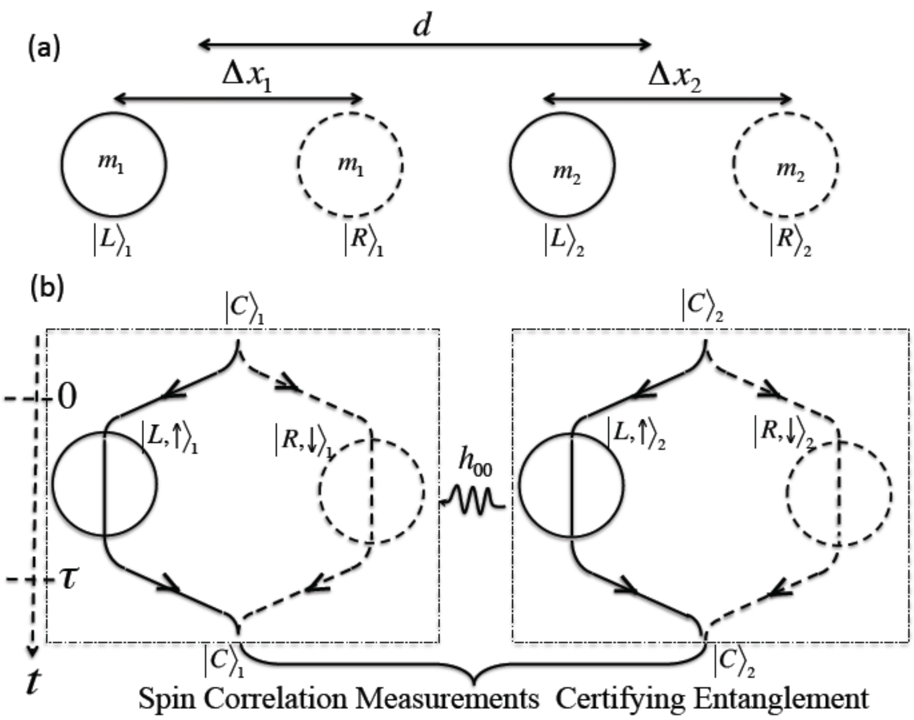
Refined proposal by *Bose, Kim, Milburn et al. 2017*:
Entanglement by gravitational phase shift (COW) and CSIGN gate



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

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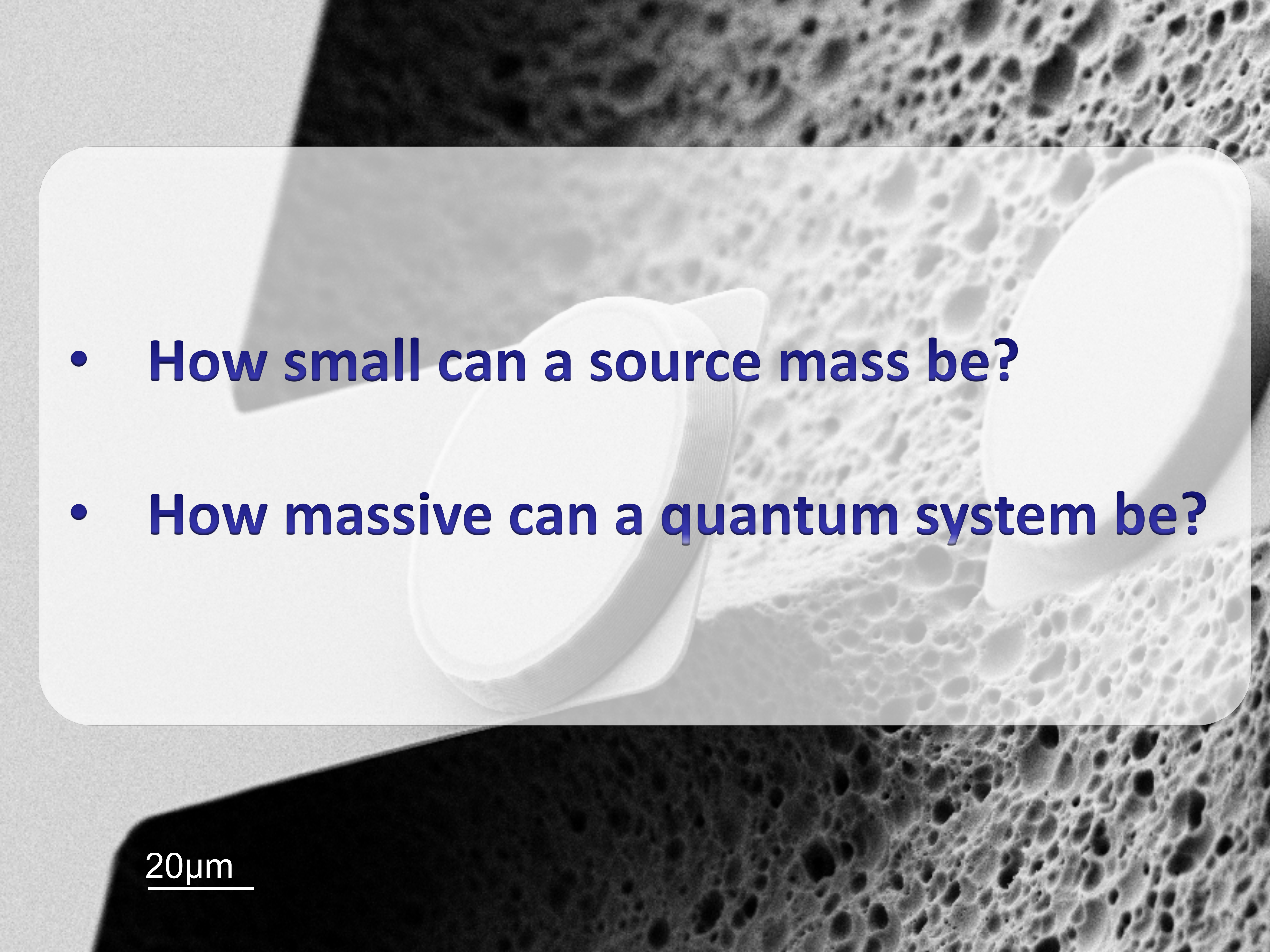
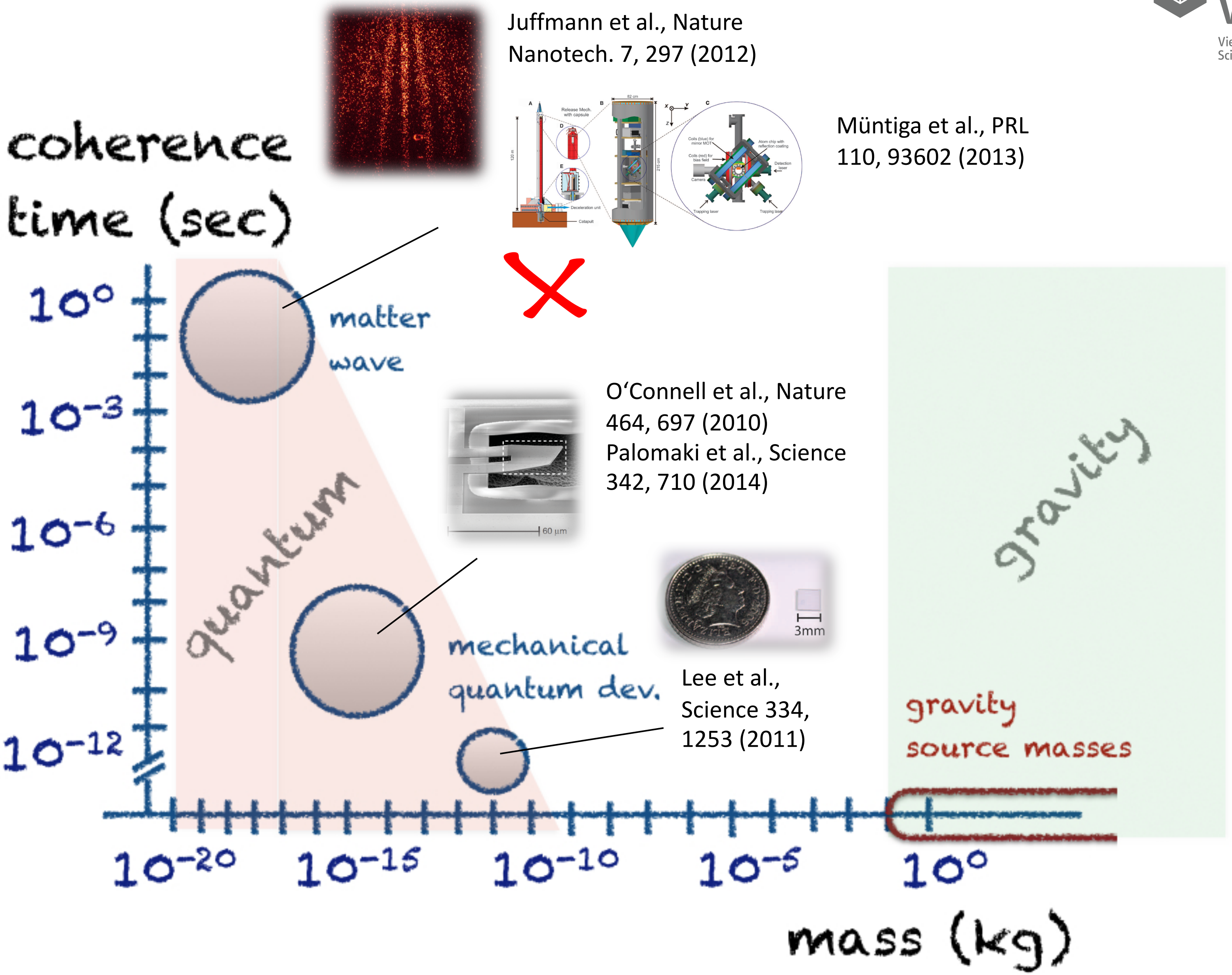


- How small can a source mass be?
- How massive can a quantum system be?

How massive/small can we go?



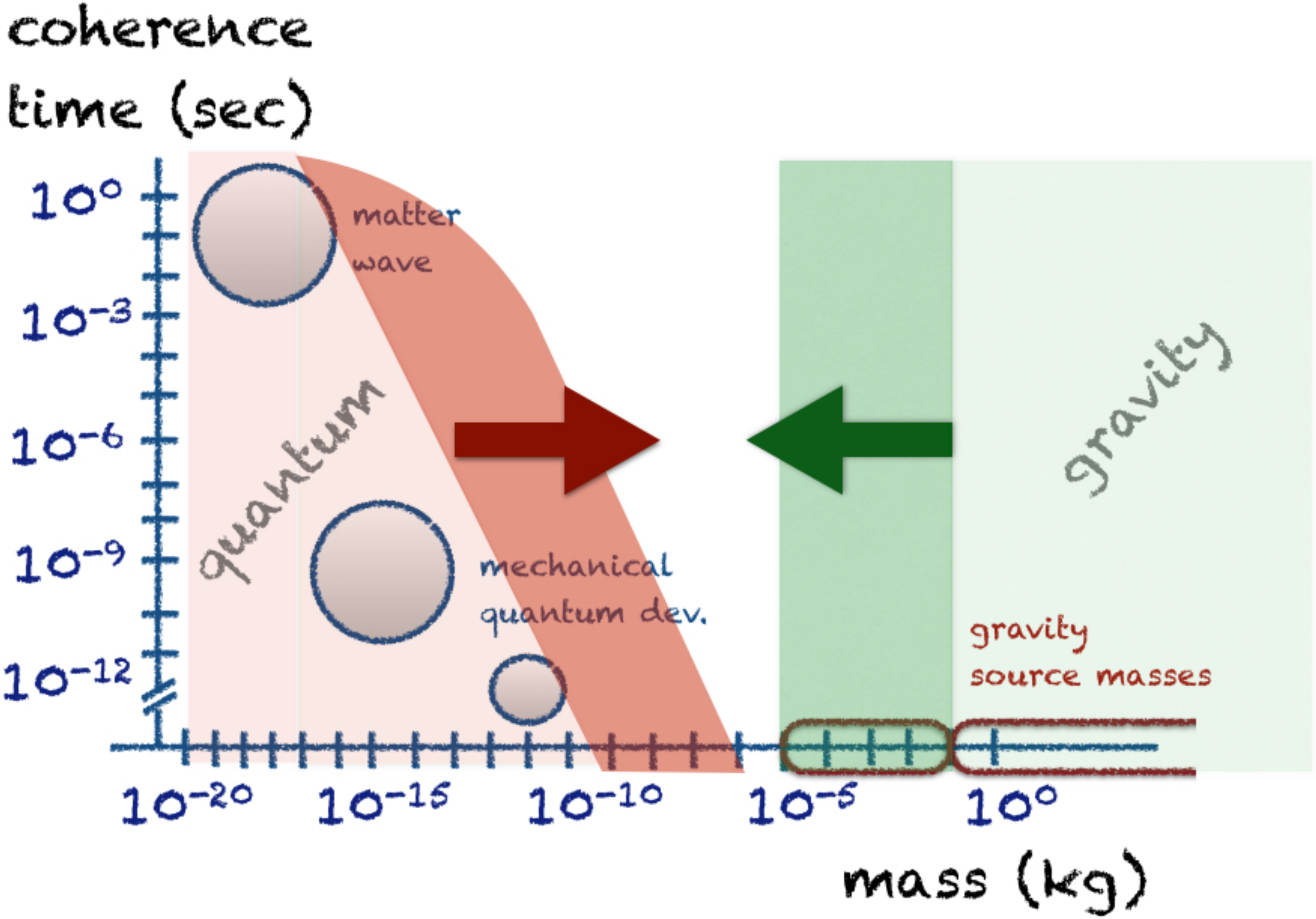
Juffmann et al., Nature Nanotech. 7, 297 (2012)

Müntiga et al., PRL 110, 93602 (2013)

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

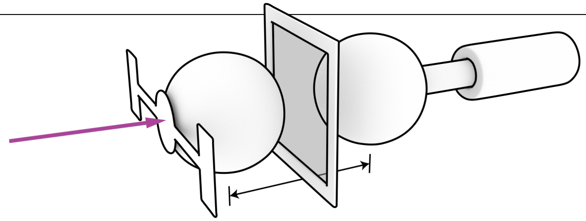
Lee et al., Science 334, 1253 (2011)

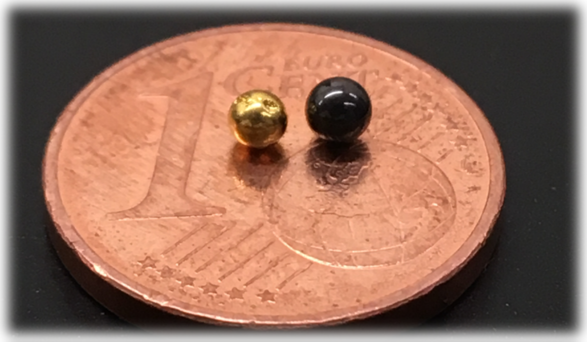
How massive/small can we go?



Measuring gravity between microscopic source masses ?

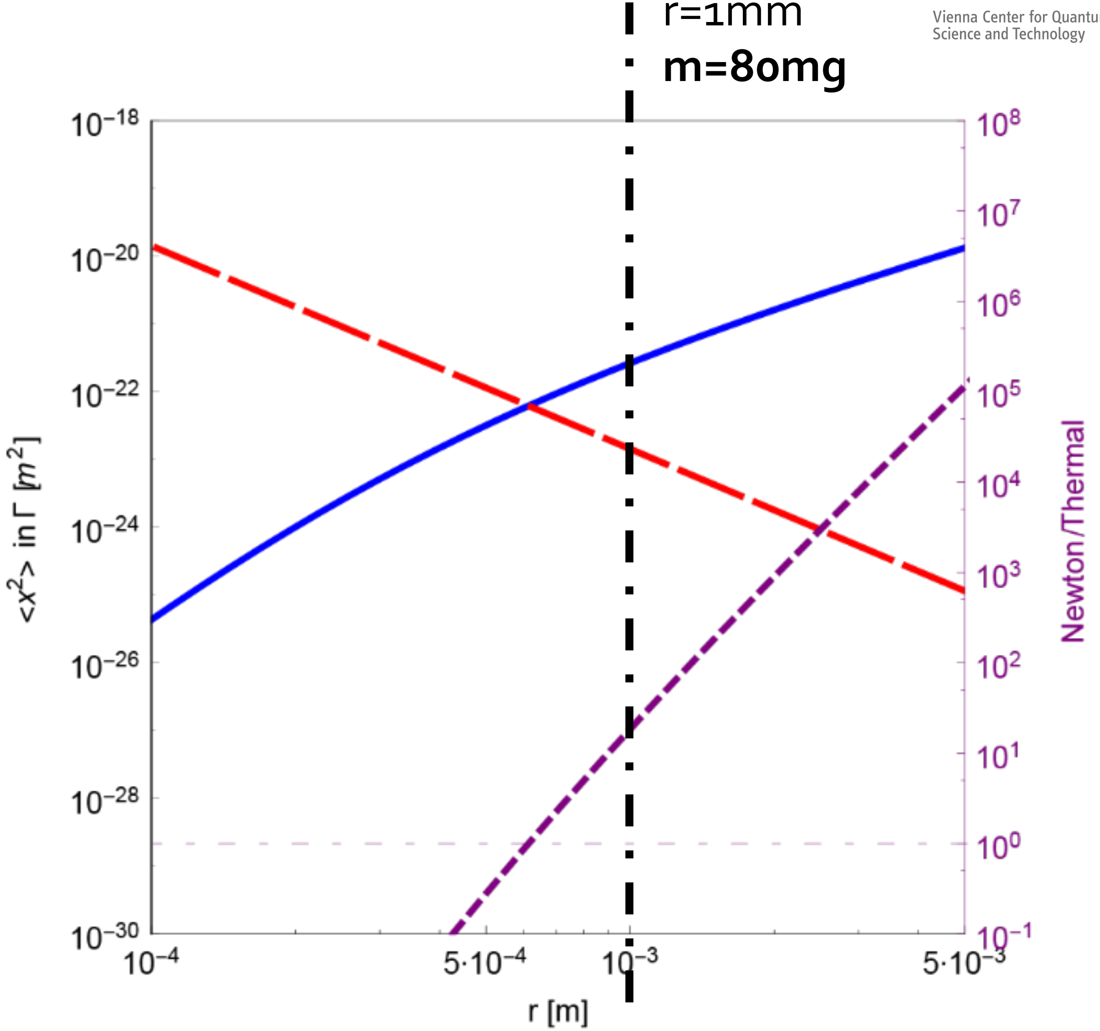
Schmöle et al., Class. Quant. Grav. 33, 125031 (2016)





In collaboration with Gröblacher group (TU Delft)

© Scientific American

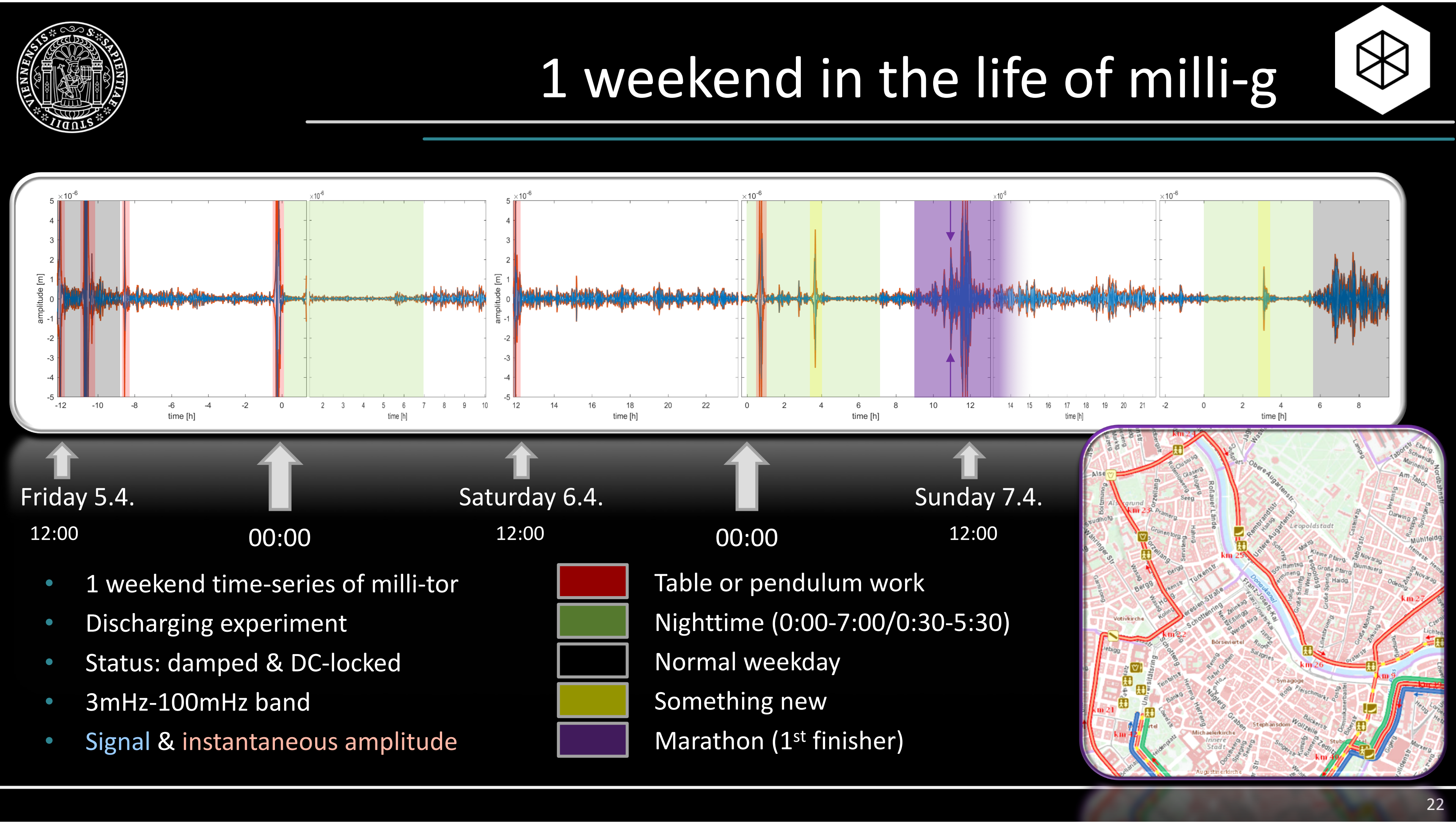


Smallest source mass to date: **0.7 g**

Mitrofanov & Ponomareva, Zh. Eksp. Teor. Fiz. 94,16-22 (1988)

J. Pfaff, H. Hepach, M. Dragosits, T. Westphal

The vibration isolation challenge...



1 weekend in the life of milli-g

Friday 5.4.
12:00
00:00
Saturday 6.4.
12:00
00:00
Sunday 7.4.
12:00

- 1 weekend time-series of milli-tor
- Discharging experiment
- Status: damped & DC-locked
- 3mHz-100mHz band
- Signal & instantaneous amplitude

🟥	Table or pendulum work
🟩	Nighttime (0:00-7:00/0:30-5:30)
⬛	Normal weekday
🟨	Something new
🟪	Marathon (1st finisher)

J. Pfaff, H. Hepach, M. Dragosits, T. Westphal

Big G: the open problem

Vienna Center for Quantum Science and Technology

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

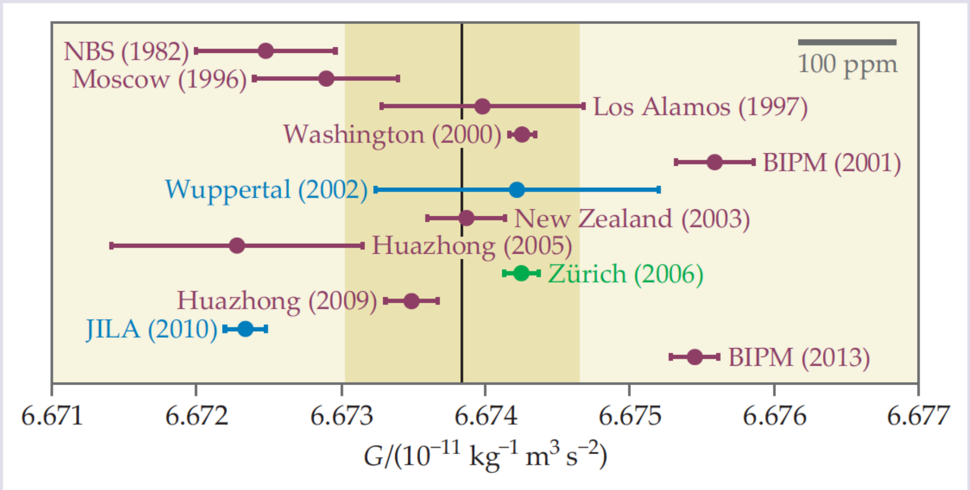


Figure 1. Measurements of Newton's gravitational constant *G* have yielded conflicting results. Here, the results of torsion-balance (maroon), pendulum (blue), and beam-balance (green) experiments discussed in the text are shown, along with the location and year in which they were measured. Error bars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

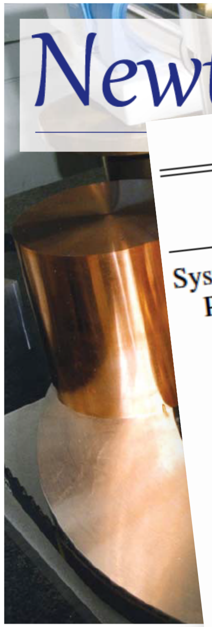
NATURE|Vol 466|26 August 2010

G-whizzes disagree over gravity

Recent measurements of gravitational constant increase uncertainty over accepted value.

Big G: the open problem

The search for Newton's cons



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

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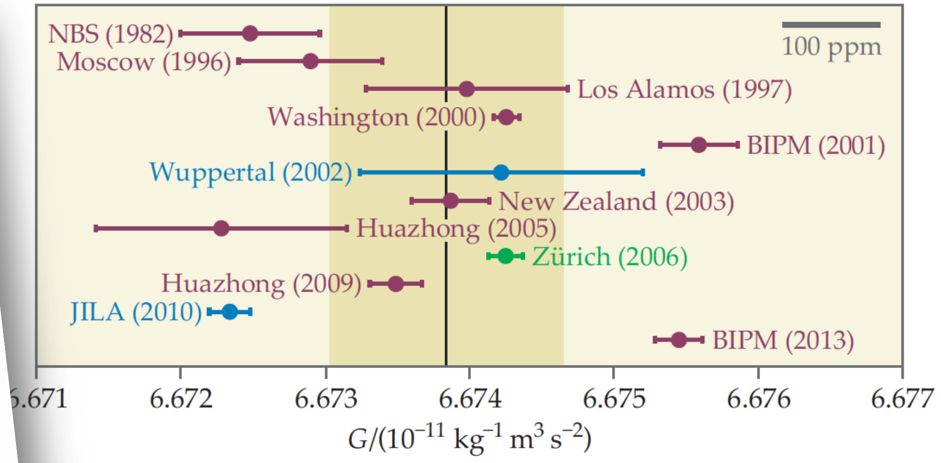

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Big G: the open problem

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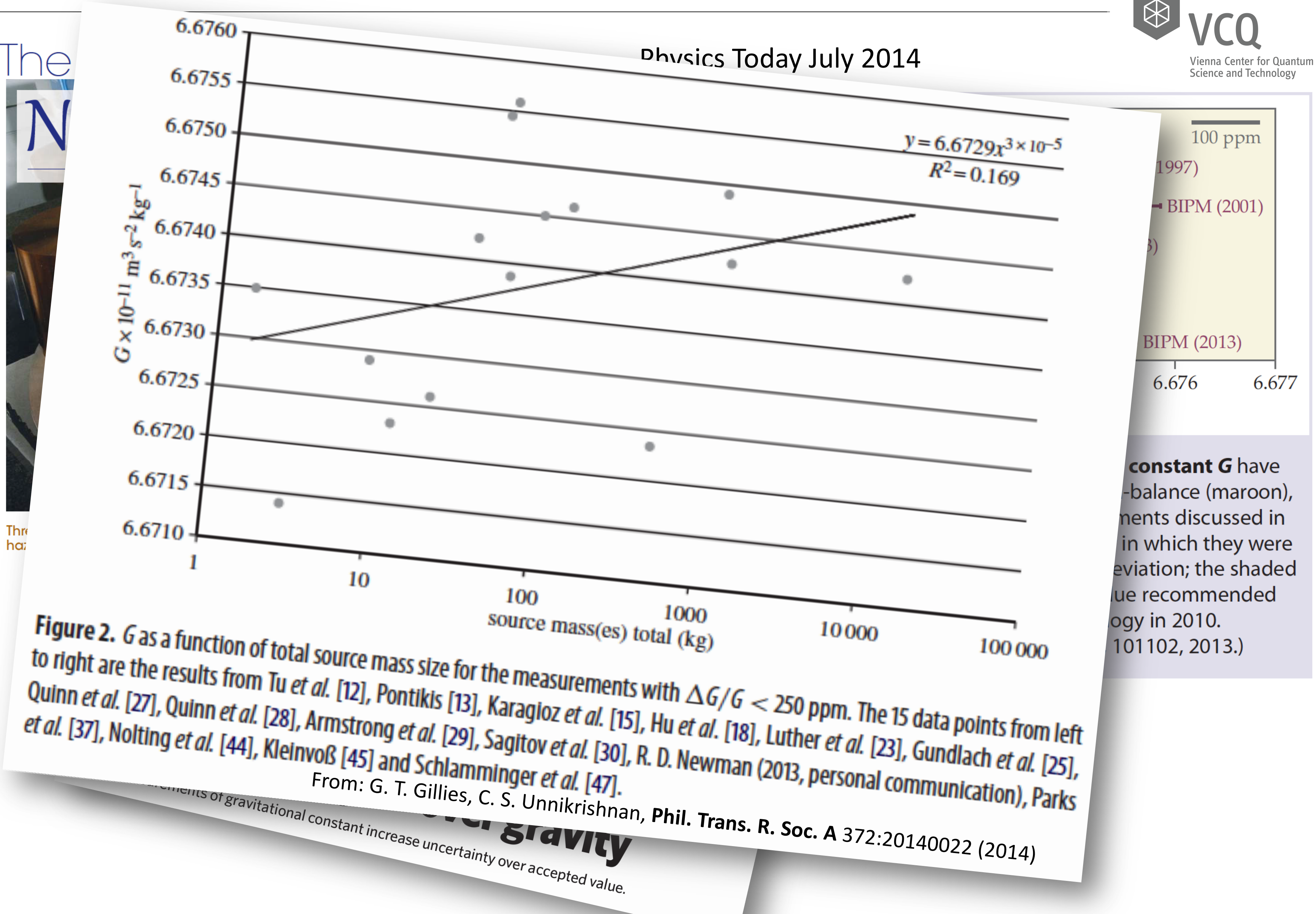
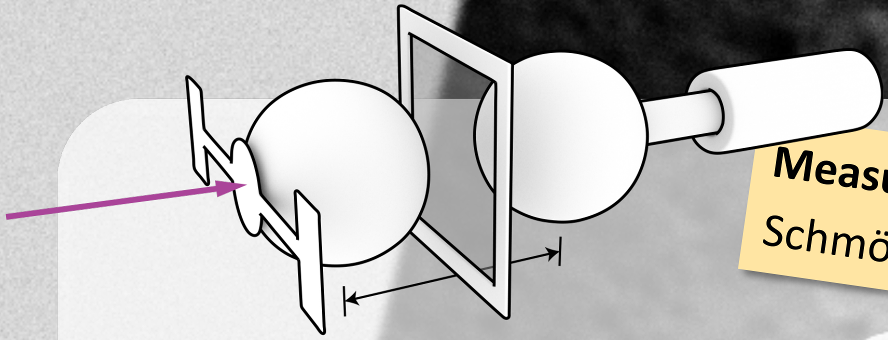


Figure 2. *G* as a function of total source mass size for the measurements with $\Delta G/G < 250$ ppm. The 15 data points from left to right are the results from Tu *et al.* [12], Pontikis [13], Karagioz *et al.* [15], Hu *et al.* [18], Luther *et al.* [23], Gundlach *et al.* [25], Quinn *et al.* [27],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



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

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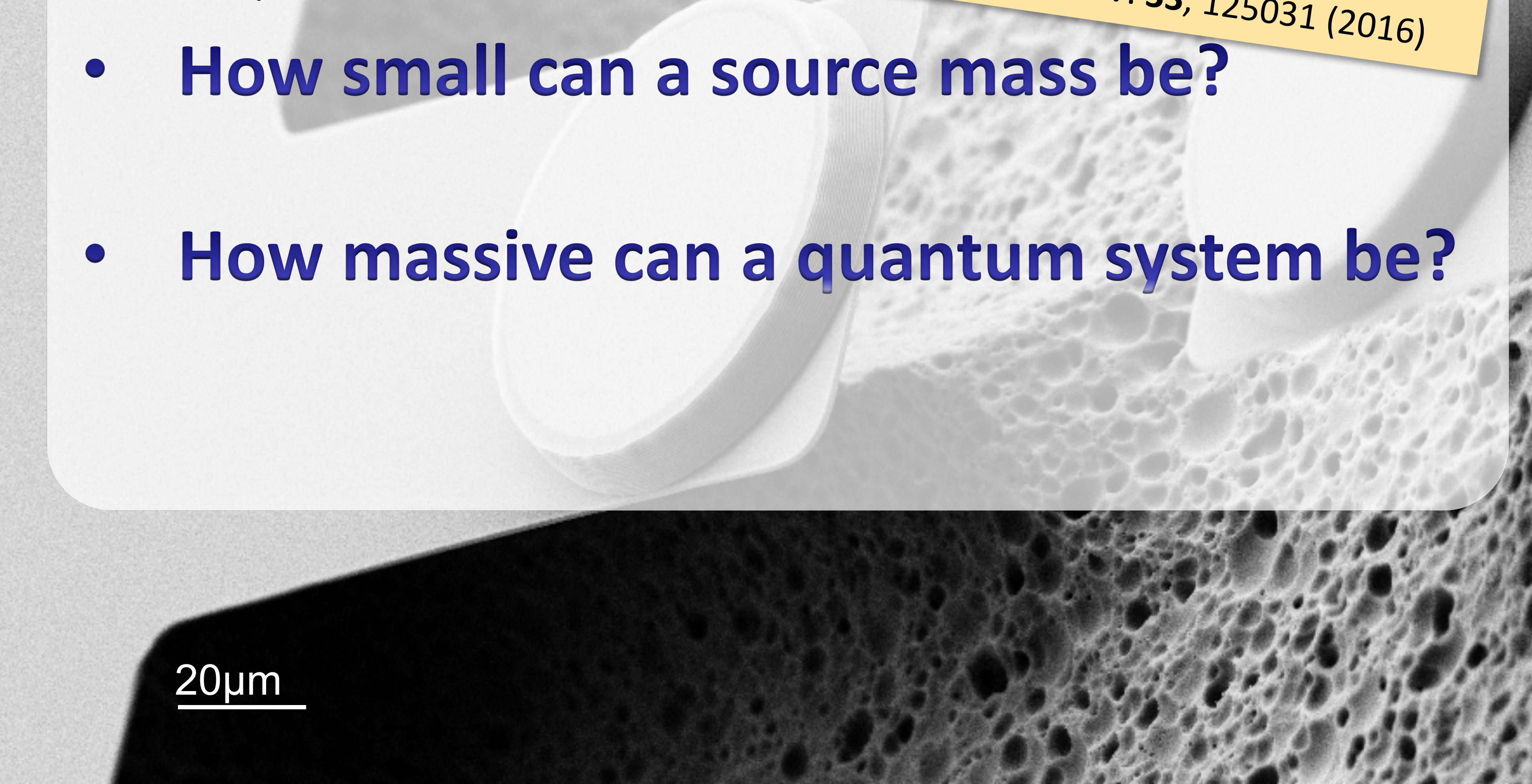
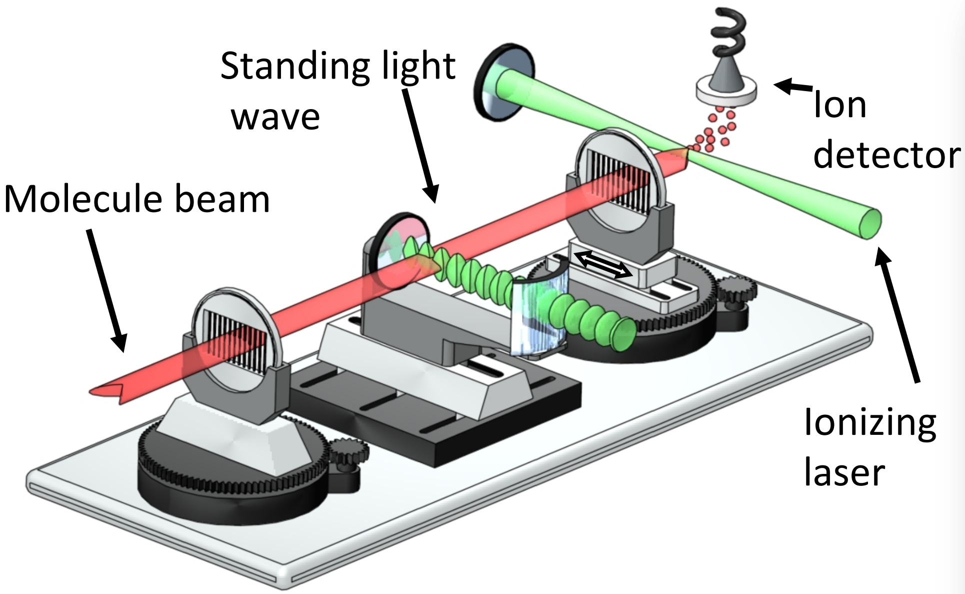
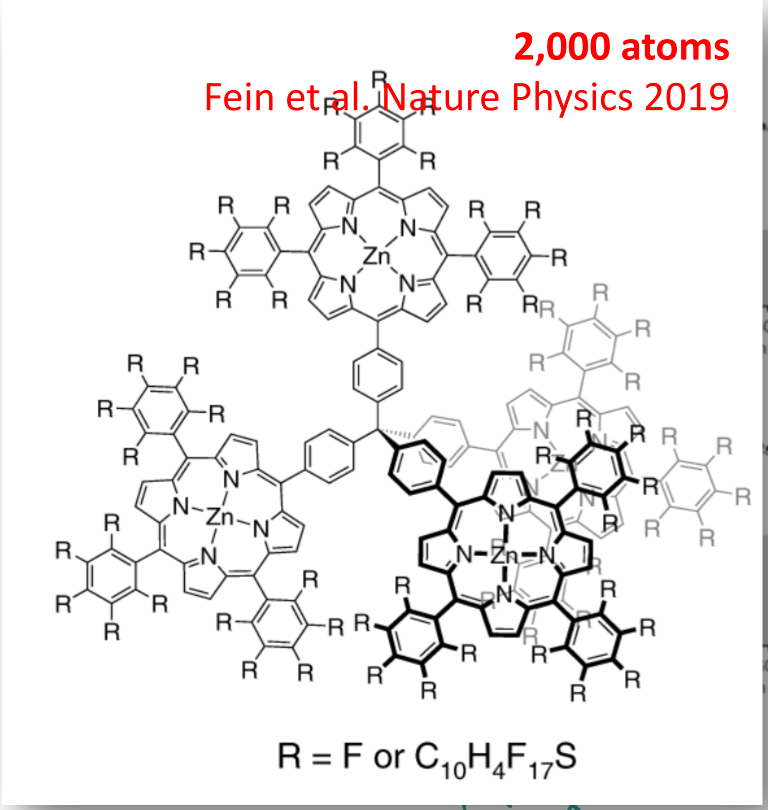
- How massive can a quantum system be?



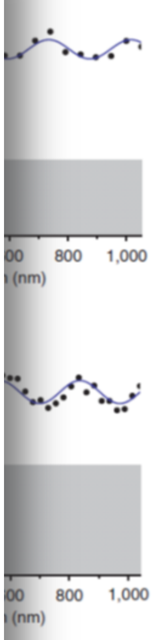
COM superposition states of massive systems: where do we stand?

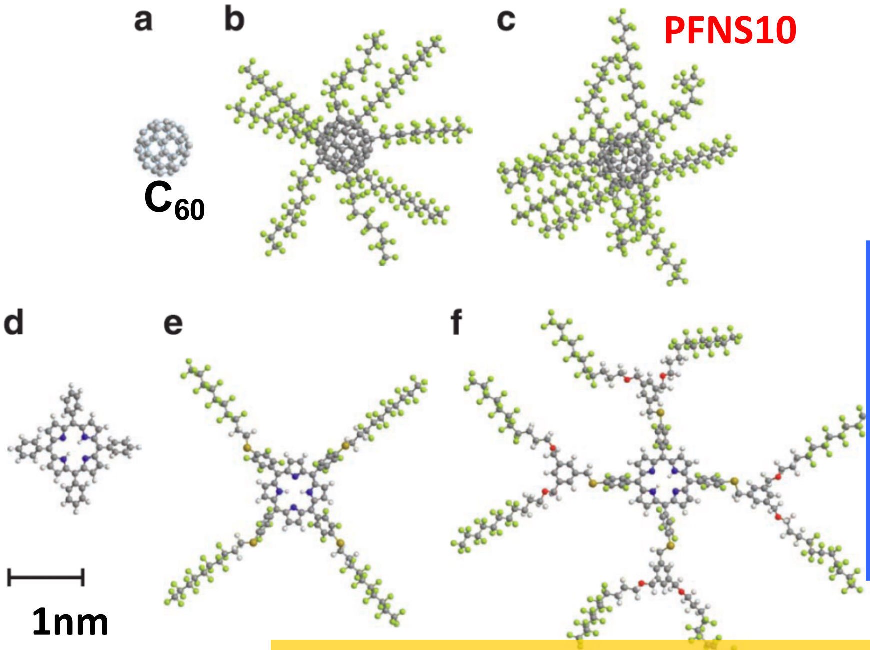




2,000 atoms

Fein et al. Nature Physics 2019





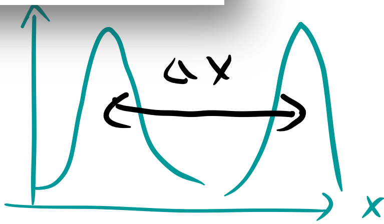
PFNS10: $C_{60}[C_{12}F_{25}]_{10}$

(perfluoroalkylated nanosphere)

430 atoms

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

Δx ~ 100 nm (~50x its diameter)



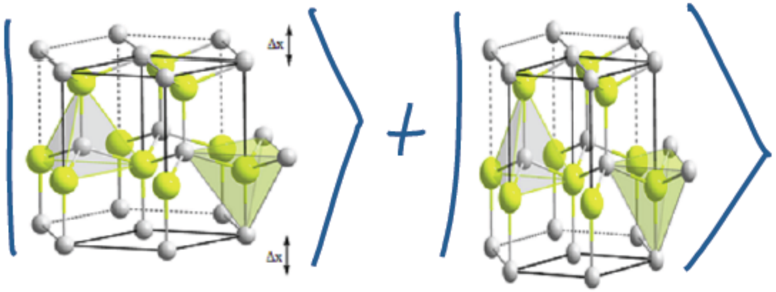
Arndt group (Vienna): S. Gerlich, S. Eibenberger et al., Nature Communications **2**, 263 (2011)

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

Micromechanics, 2×10^{13} atoms

m ~ 10^{-12} kg = 7×10^{14} AMU

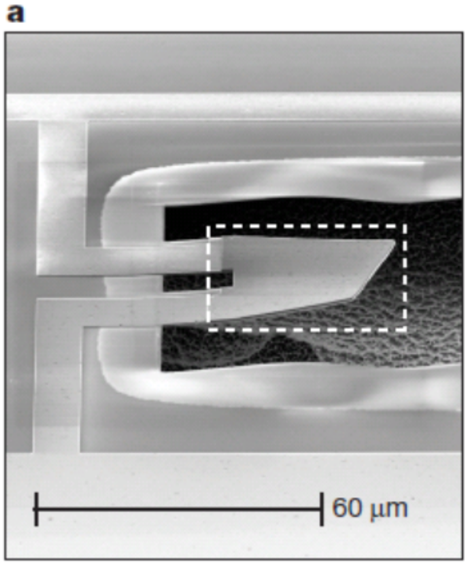
Δx ~ 10^{-16} m (~10^{-10}x its diameter)

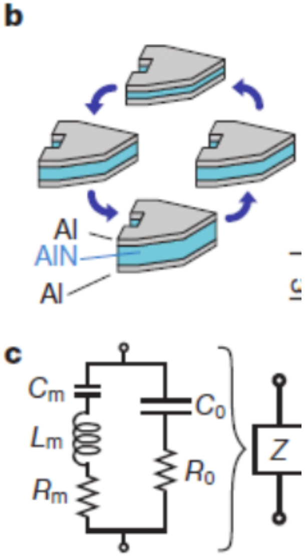


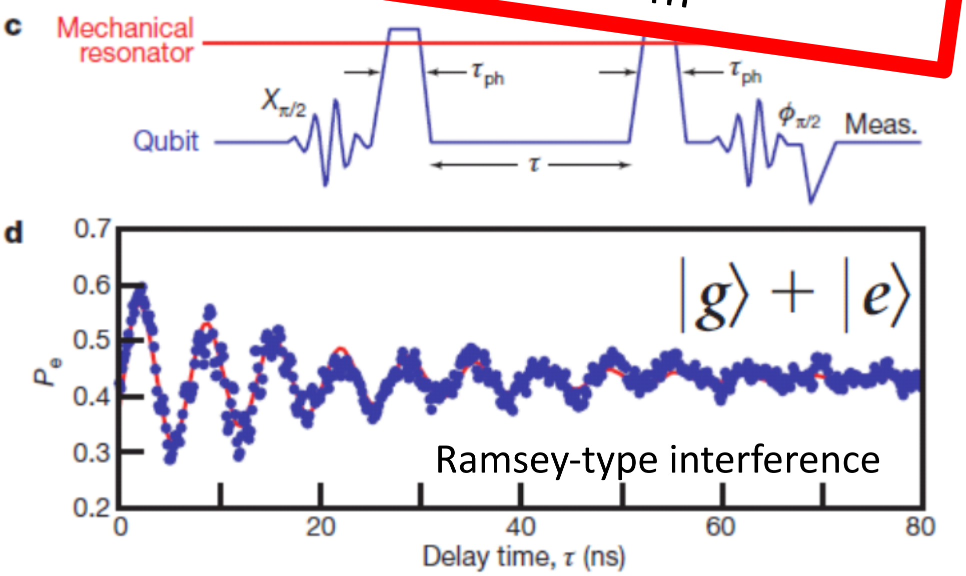
Quantum ground state and sing phonon control of a mechanical resonat

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

Observed coherence time (>20ns) bounds **Penrose's "mass distribution localization"** to R > 10^{-21}m







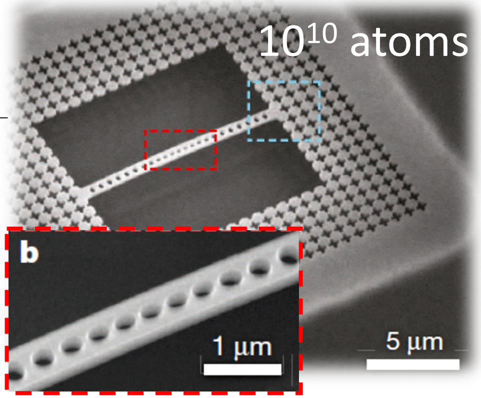
6 GHz thickness oscillation
→ n ~ 0.07 @ 20 mK

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

Mechanical Systems IN the quantum regime

Quantum ground state of motion

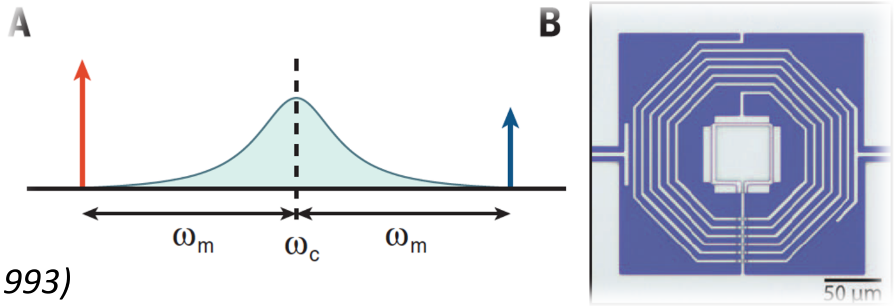
Microwave cavity cooling: Teufel et al., Nature 475, 359 (2011)
Laser cooling: Chan et al., Nature 478, 89 (2011)
... and many more around the world...

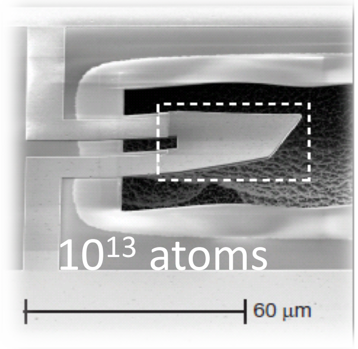


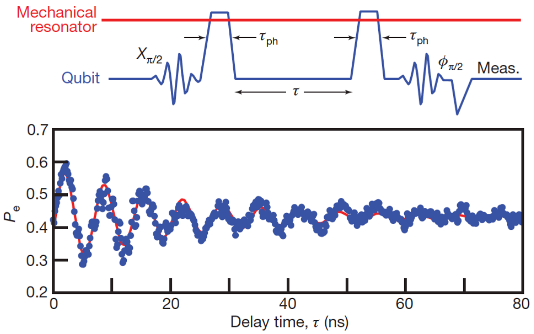
Quantum squeezed states of motion

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

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

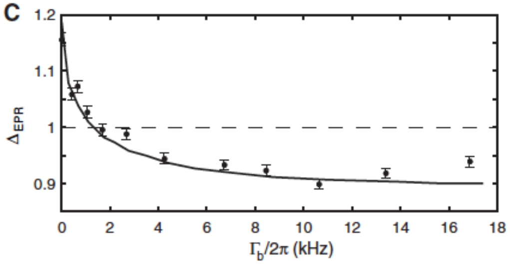


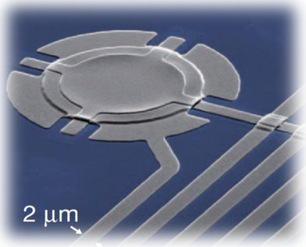




Non-Gaussian quantum states of motion

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





Quantum entanglement

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

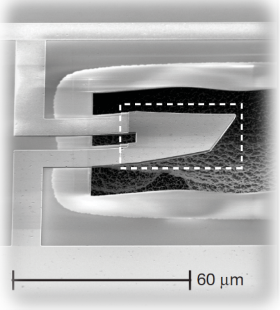
Pushing mechanical quantum control to the next level

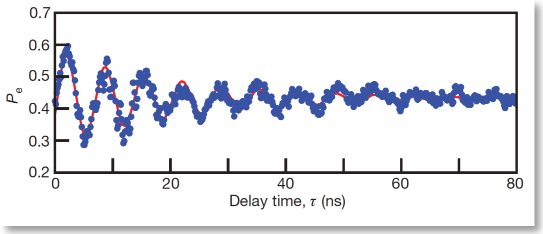
Q: How to achieve large mass **AND** long coherence time in a quantum experiment?

Solid-state mechanical quantum devices (clamped):

$10^{10} – 10^{16}$ atoms

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



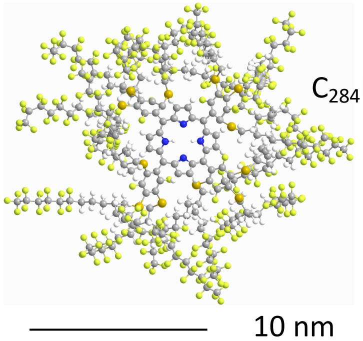


O‘Connell et al., Nature 464, 697 (2010)

Matter-wave interferometry (free-fall):

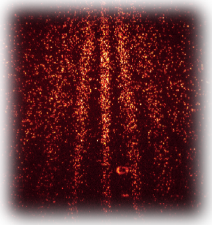
$10^{0} – 10^{4}$ atoms

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



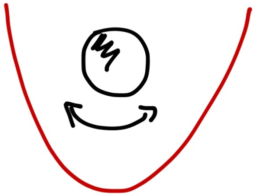
TPPF320

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



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

A: Quantum control of levitated mechanical systems!



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

Optically levitating nanoparticles

OPTICAL LEVITATION:

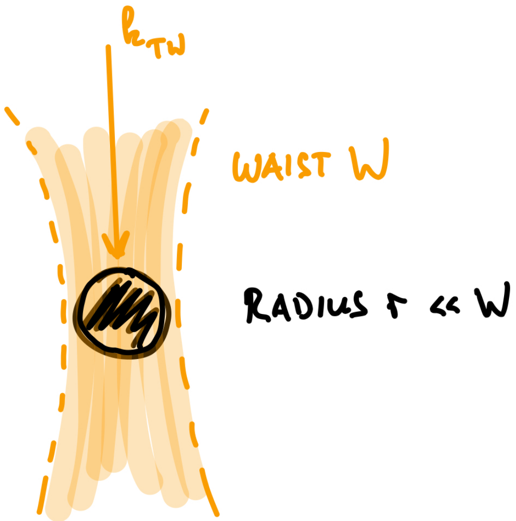
$$\hat{H} \propto \underline{d} \cdot \underline{E} = \alpha \cdot E^2$$

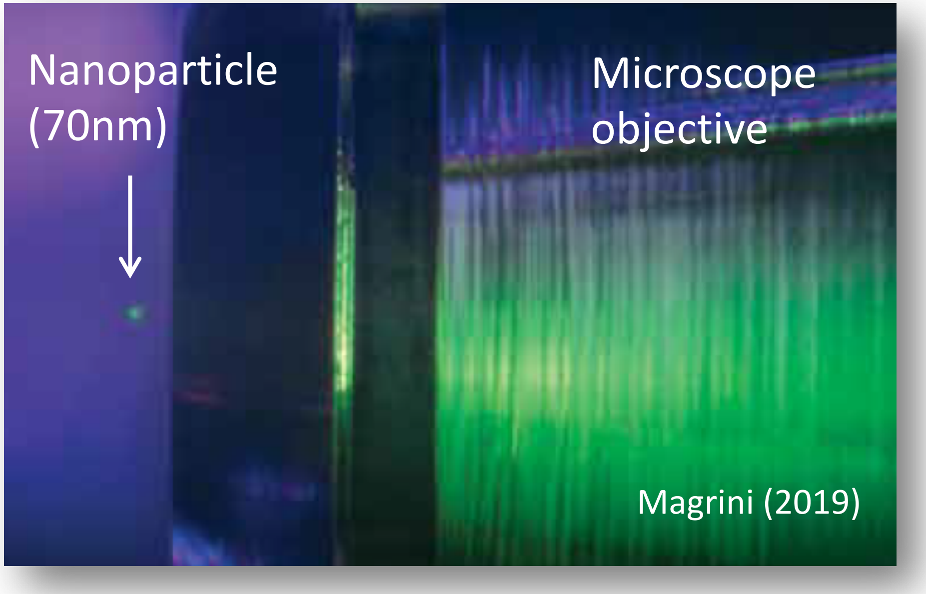
α: Re{Polarizability}

E: optical trapping field

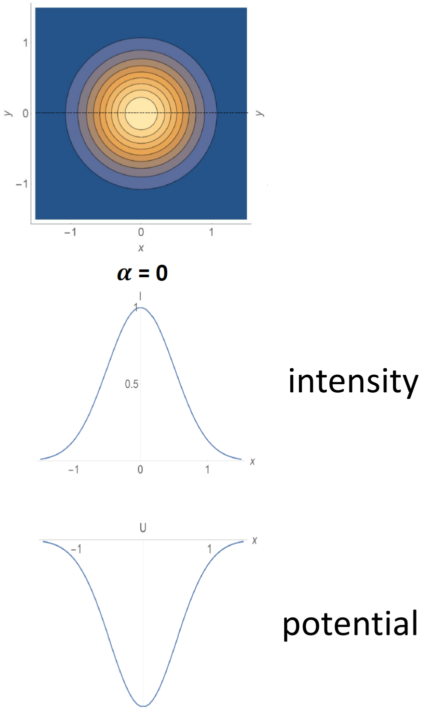
↳ beam intensity

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





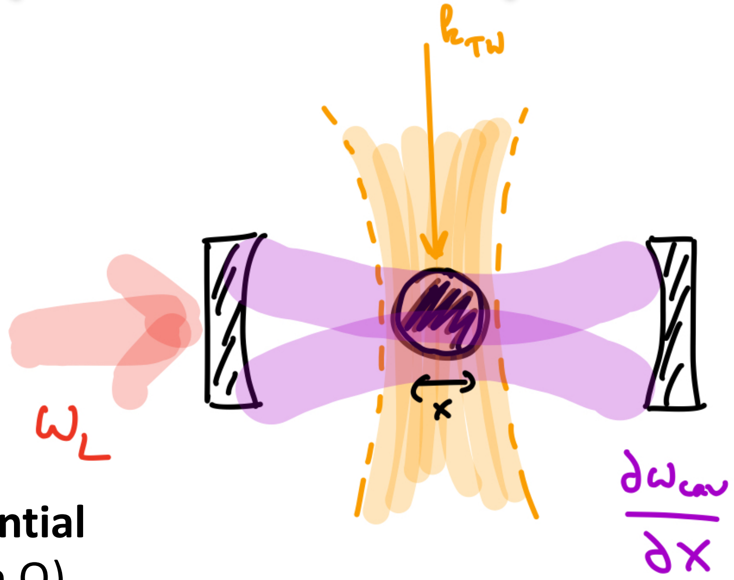
Magrini (2019)



Pioneering work by Ashkin:
A. Ashkin, PRL 24, 156 (1970).
A. Ashkin, J. M. Dziedzic, APL 28, 333 (1976).

Towards quantum state preparation of a free particle

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



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

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

OPTOMECHANICS:

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

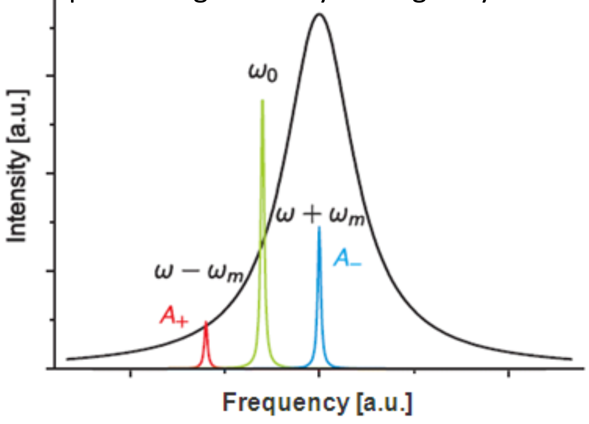
$$\text{with } g_0 = \frac{\partial \omega_c}{\partial x} = \boxed{\frac{\alpha}{V_c}} \frac{\omega_c^2}{c \varepsilon_0} x_{zp}$$

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

Cavity-Optomechanics

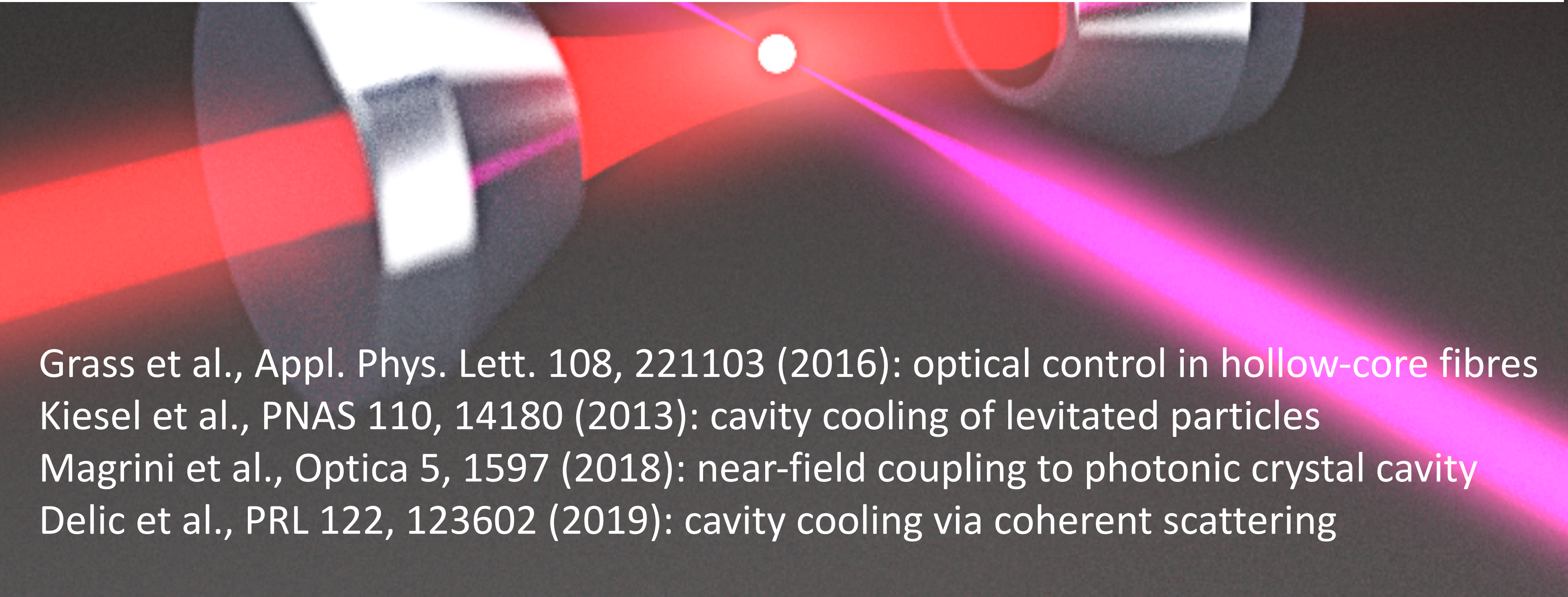
Rev.Mod.Phys. 86, 1391 (2014)

pioneering works by V. Braginsky



Cavity control of levitated particles

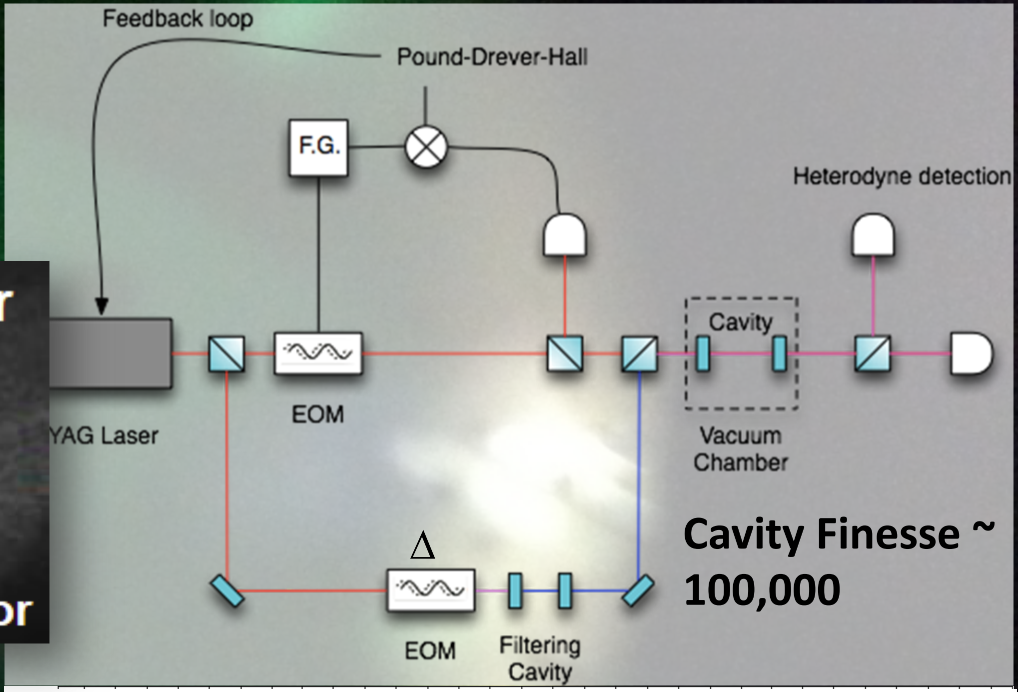
- dielectrics and superconductors (100nm – 10um)
- ultimate goal: anharmonic coupling (e.g. via 2-level systems) & full quantum control



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

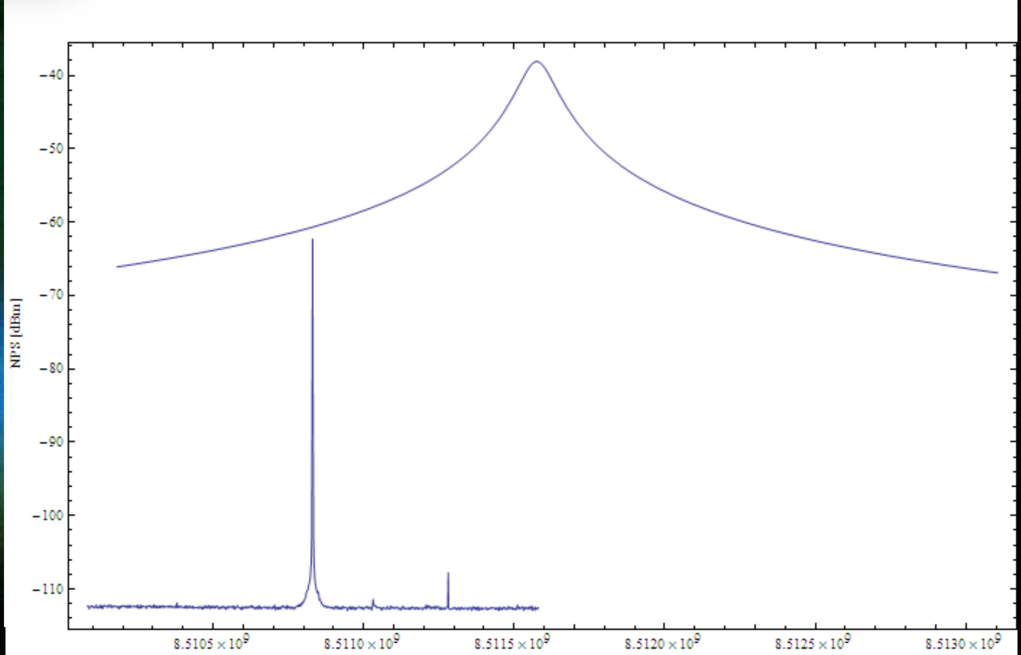
Cavity Optomechanics with levitated nanoparticles

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



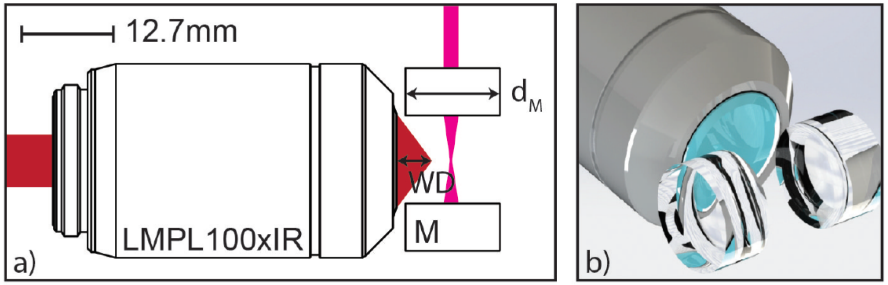
Cavity Finesse ~ 100,000

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

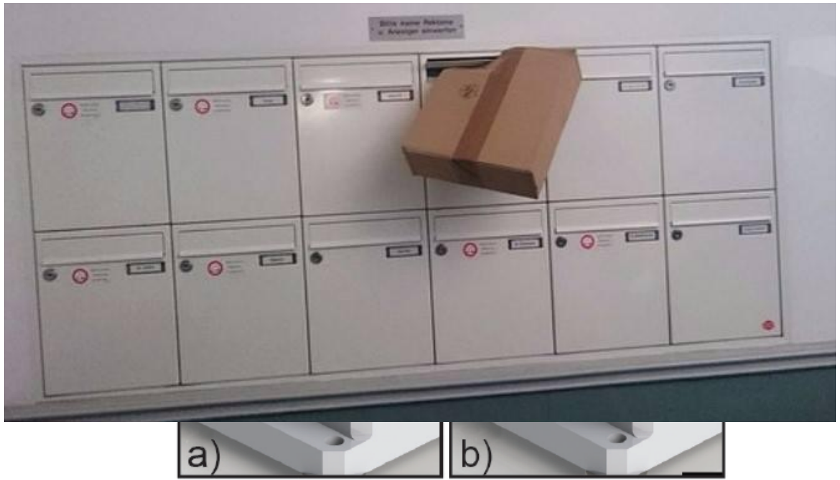


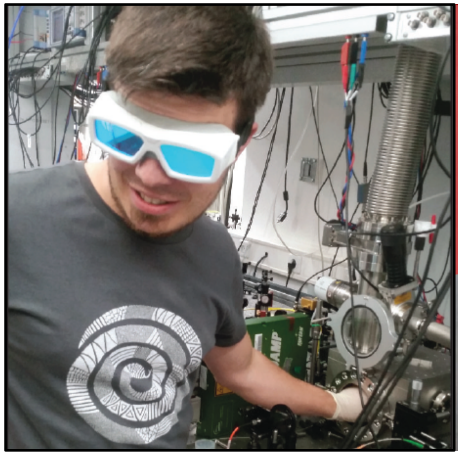
Cavity Optomechanics with levitated nanoparticles

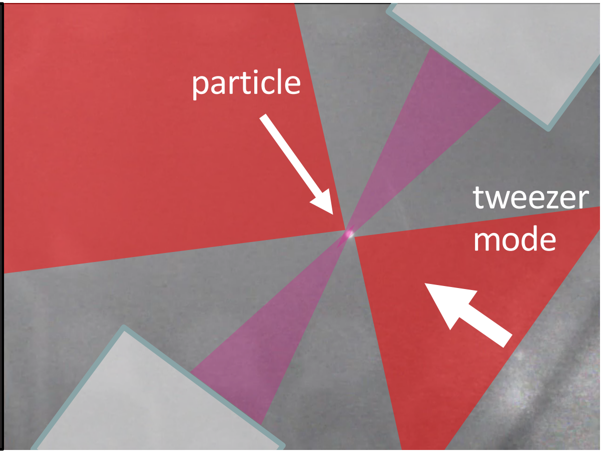
Delić, Grass et al., arXiv:1902.06605

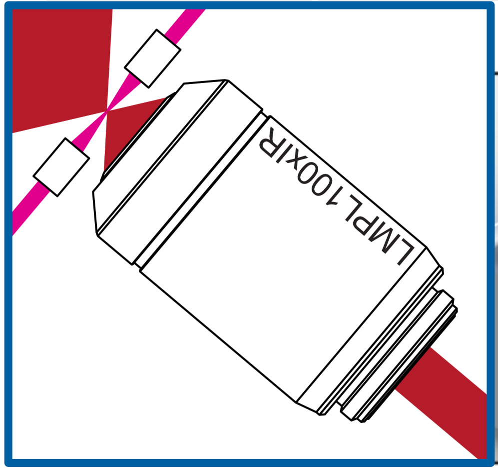


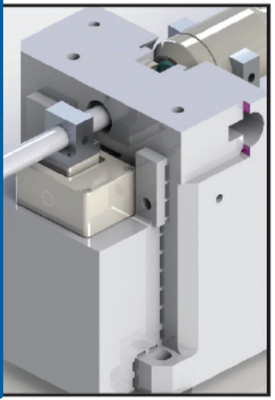
Working distance of tweezer < Radius of cavity mirrors
→ mirror cutting (@Weitz group, U Bonn)





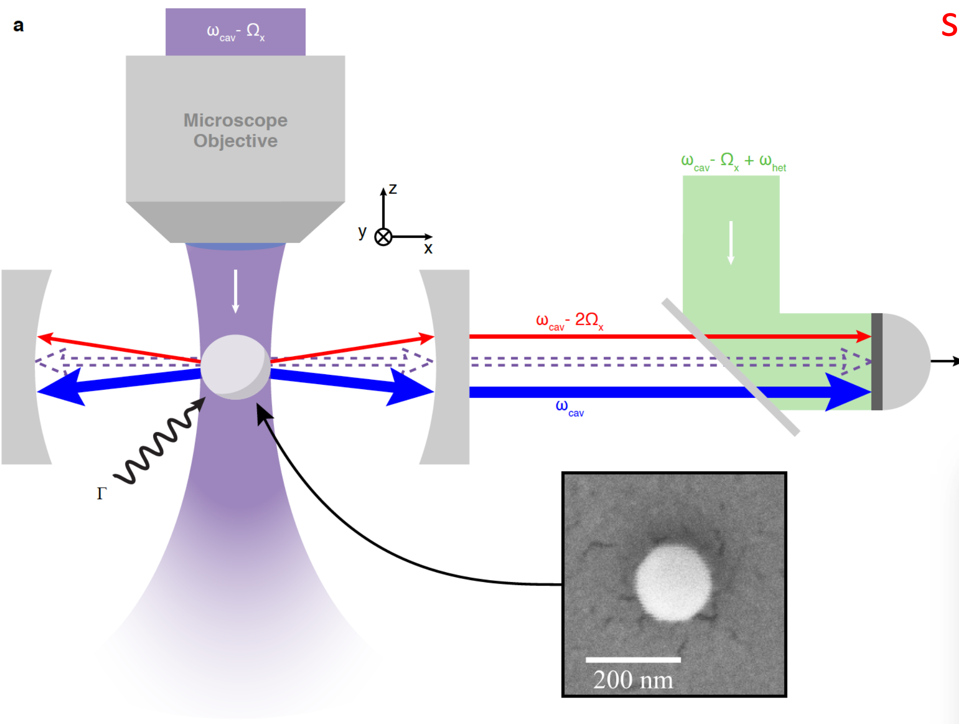






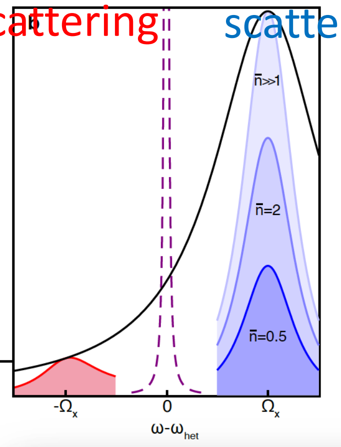
Cavity Optomechanics with levitated nanoparticles

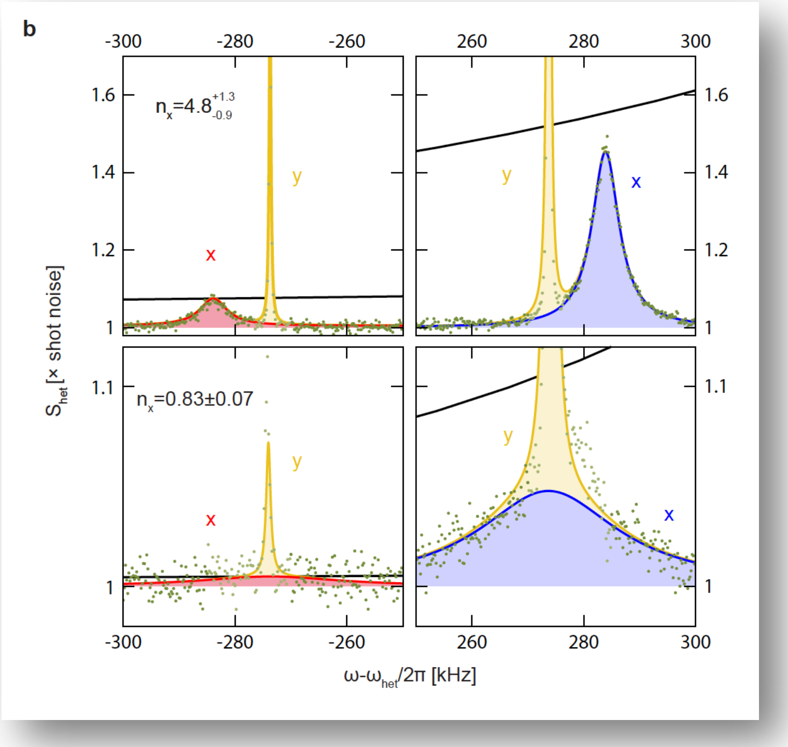
Delić et al., arXiv:1911.04406



Stokes scattering

anti-Stokes scattering





$$\omega_x \approx 2\pi\times305\ \text{kHz}$$

$$\omega_z \approx 2\pi\times80\ \text{kHz}$$

$$\omega_y \approx 2\pi\times275\ \text{kHz}$$

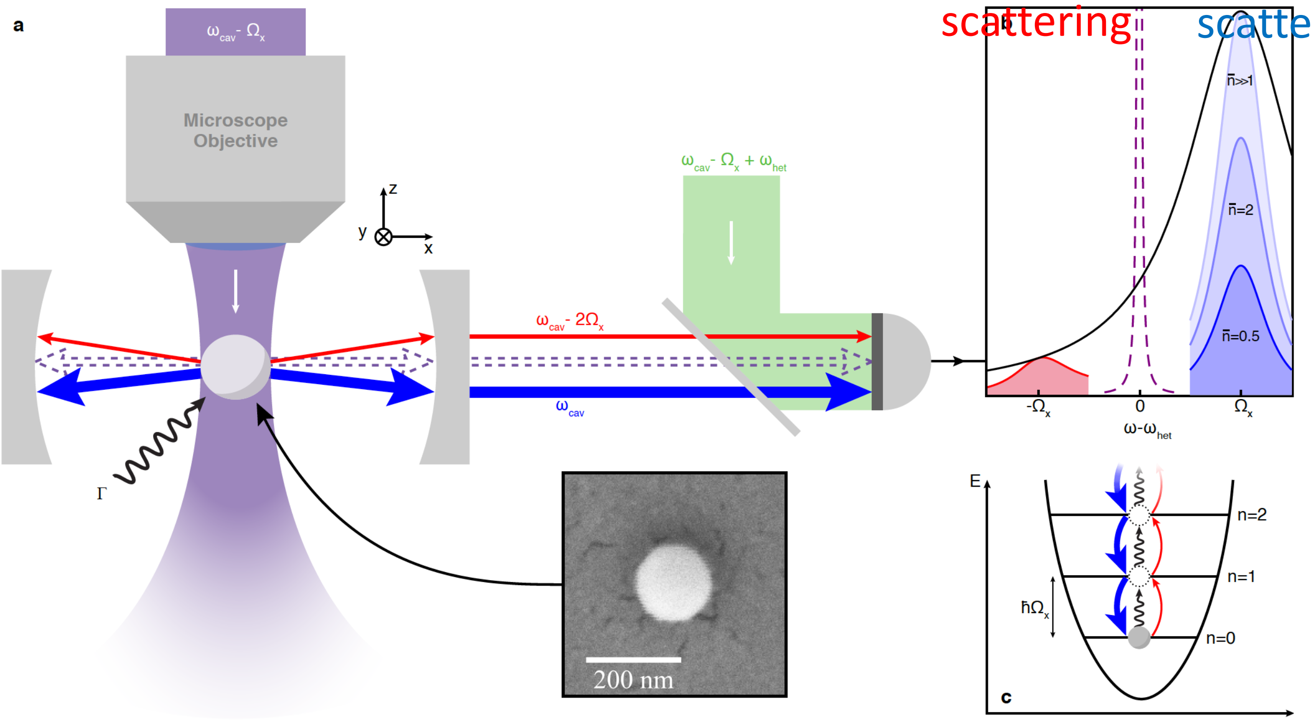
$$\kappa = 2\pi\times193\ \text{kHz}$$

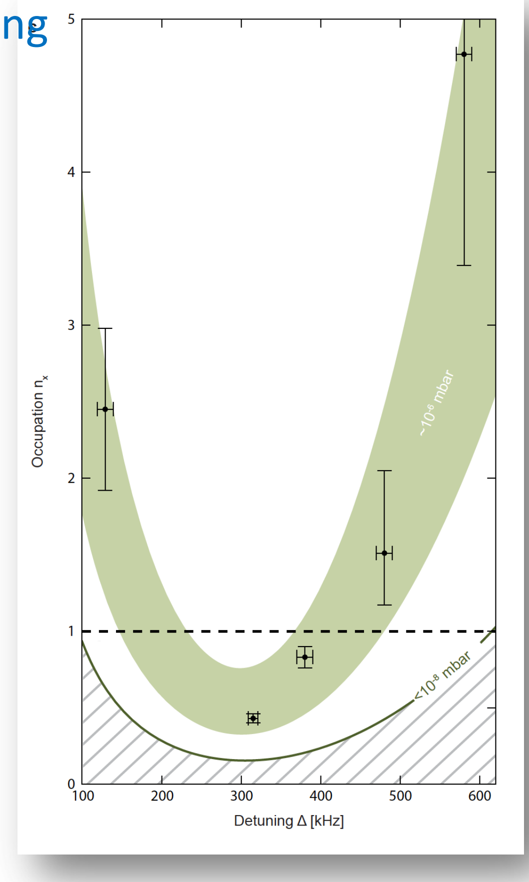
p = 1e-6 mbar, T = 300K

Cavity Optomechanics with levitated nanoparticles

Delić et al., arXiv:1911.04406

Stokes scattering **anti-Stokes scattering**





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$\kappa = 2\pi\times193$ kHz

p = 1e-6 mbar, T = 300K

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

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

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

Cavity Optomechanics with levitated nanoparticles

Delić et al., arXiv:1911.04406

Limitations:

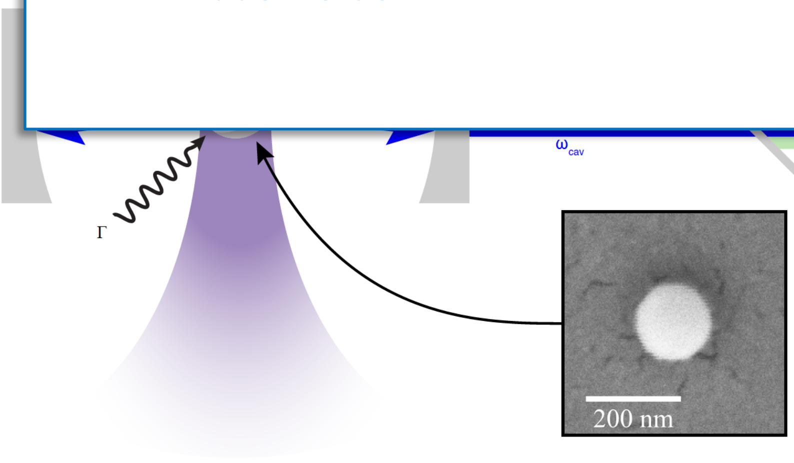
- **Sideband resolution**
- **Gas and recoil scattering**
- **Phase noise**

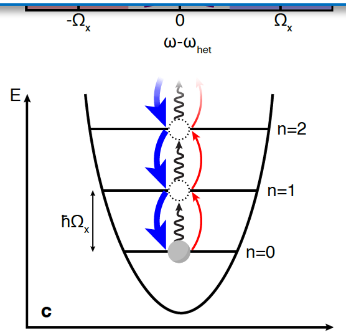
$$\bar{n} = \left(\frac{\kappa}{4\Omega_x}\right)^2 + \frac{\gamma_g \frac{k_B T_{bath}}{\hbar\Omega_x} + \Gamma_{rec}}{\Gamma_- - \Gamma_+} + \frac{n_{phot}}{\kappa} S_\varphi(\Omega_x)$$

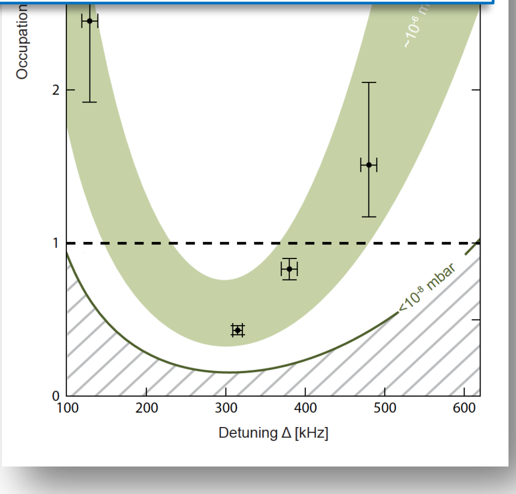
0.026

2×10^5 @ 0.06 mbar
0.5 @ 1e-6mbar

$< 10^{-3}$







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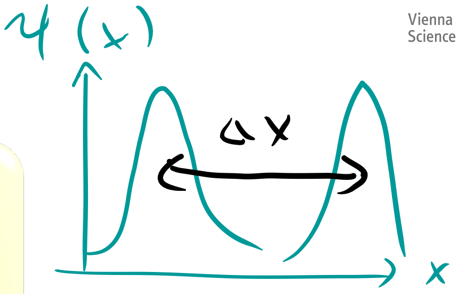
Decoherence

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

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

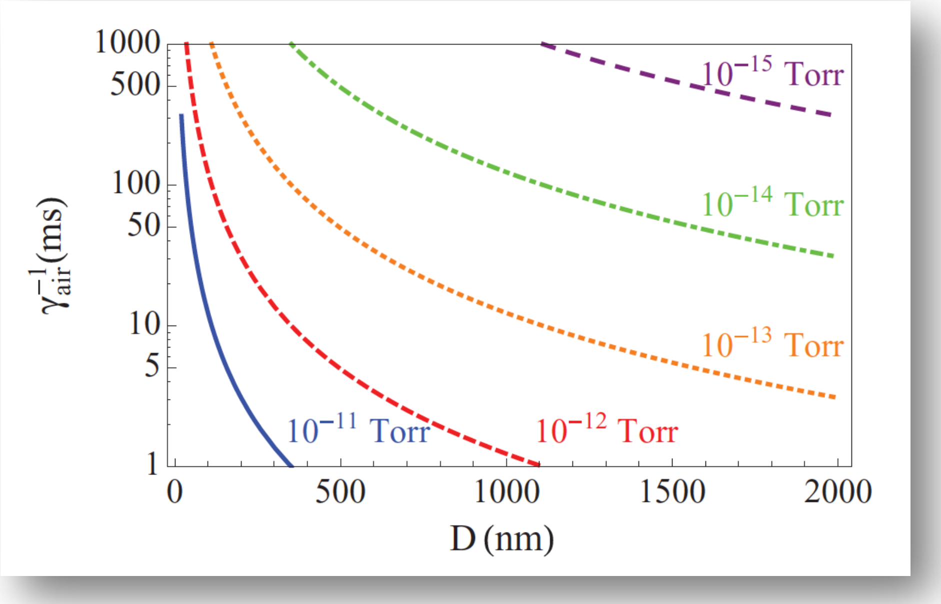
Master equation approach



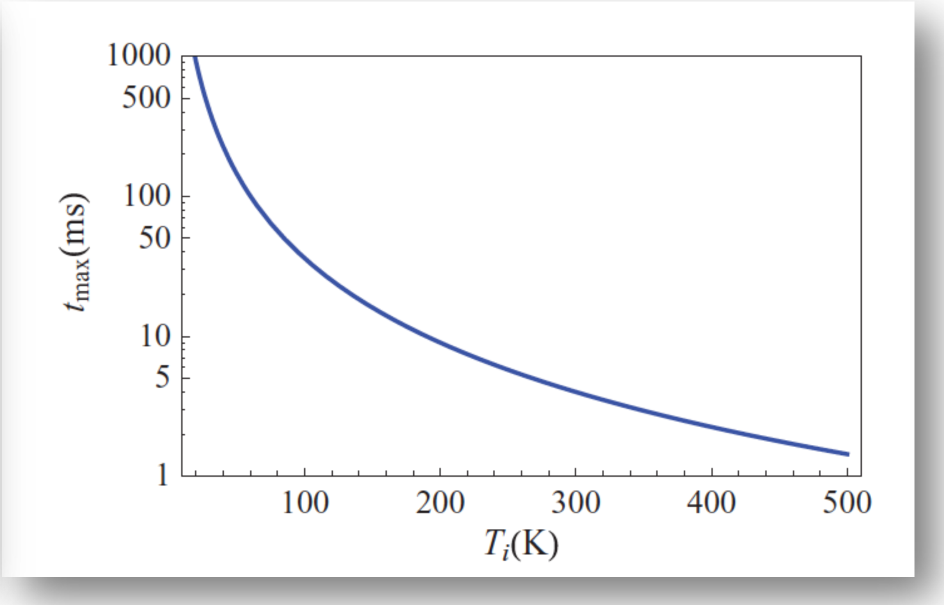
See also
O. Romero-Isart et al., PRL 107, 020405 (2011)
O. Romero-Isart, PRA 84, 052121 (2011)

Example: a free nanoparticle

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



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



Decoherence

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

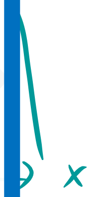
In our case (p=1e-6 mbar; Te > 300K): Γgas/2π = 15kHz, Γrec/2π = 6kHz

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

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

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

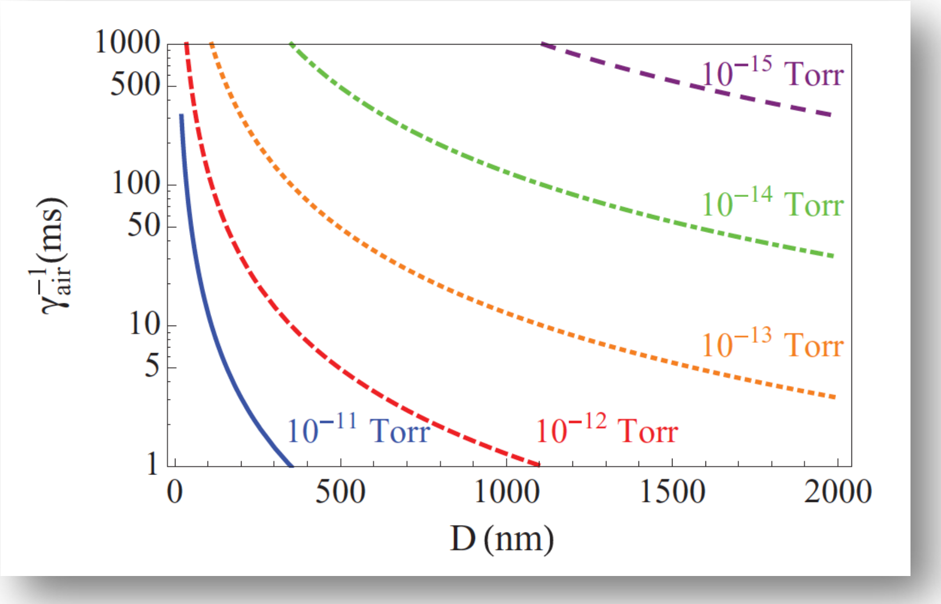
$\dot{\rho} = -$

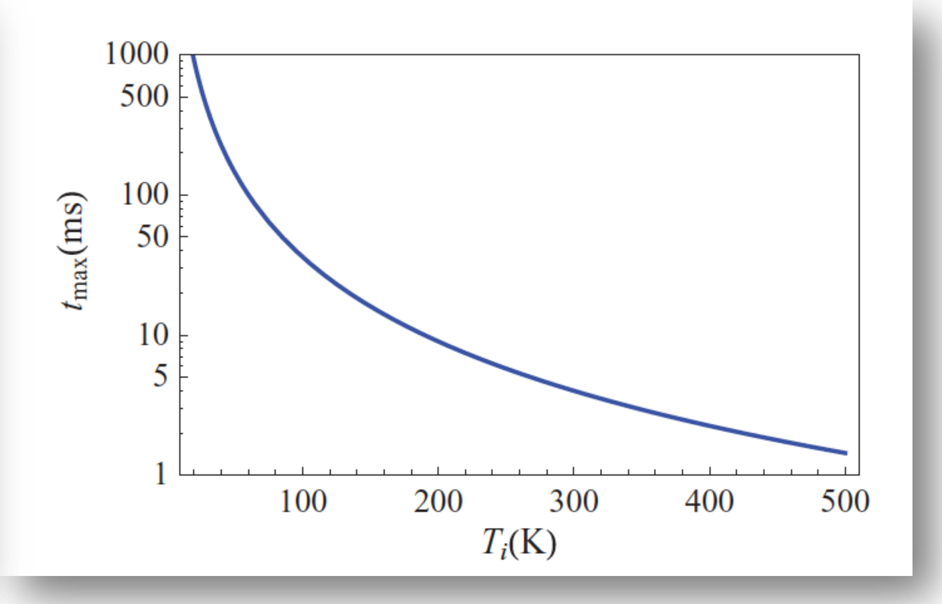


Examp

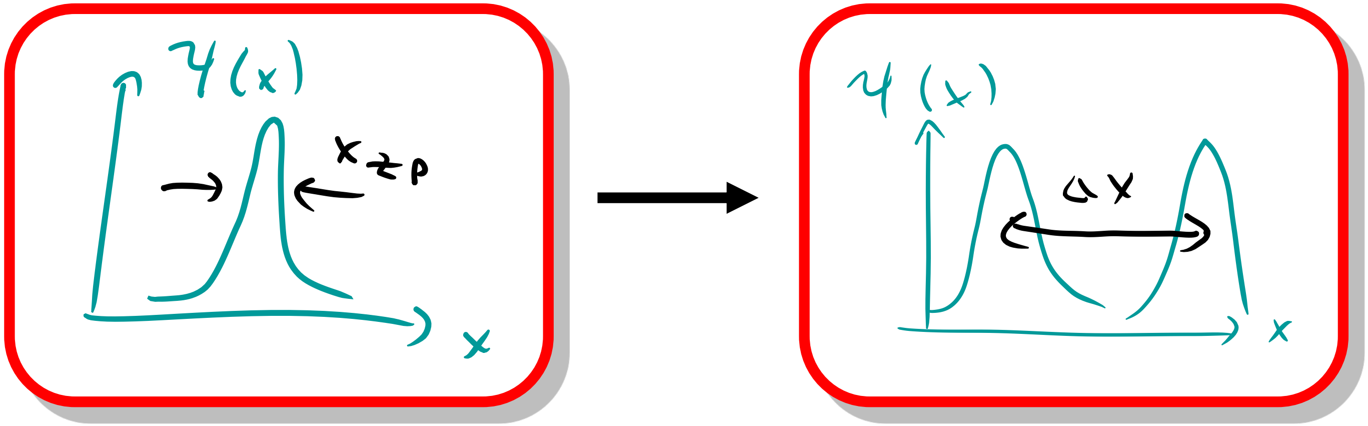
Decohere
glass sph

rption

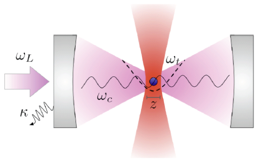




Towards „large“ quantum superposition states

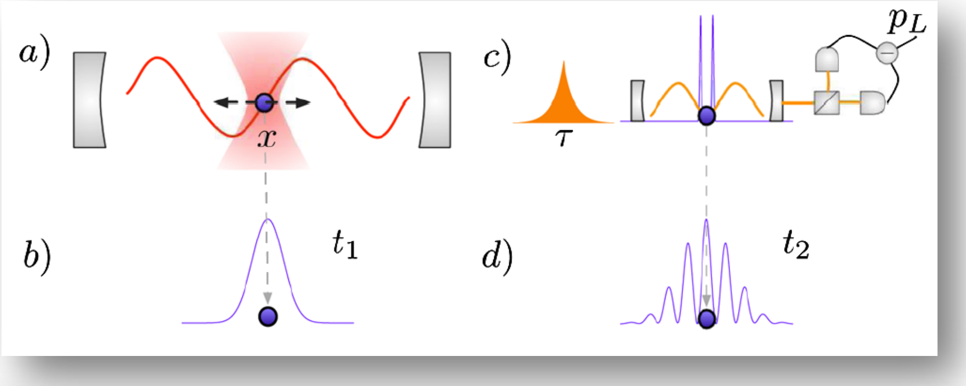


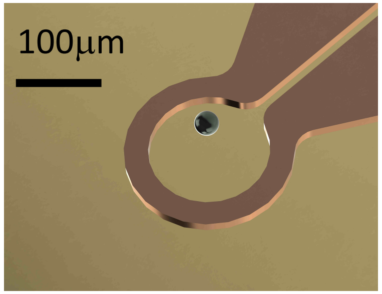
Free-fall + quantum measurement



Optical levitation

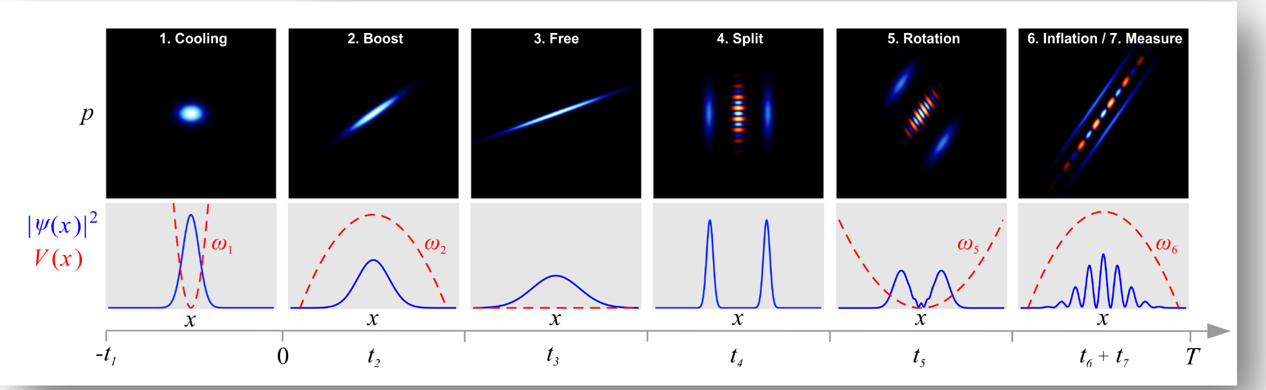
(Romero-Isart 2011)
PRL107, 020405



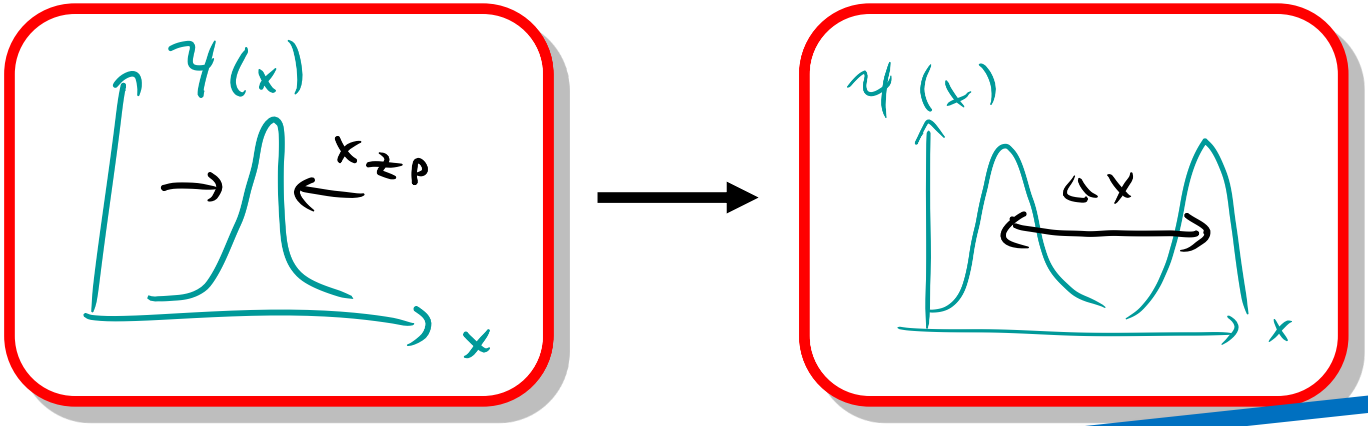


Superconducting levitation

(Pino 2016) arxiv: 1603.01553



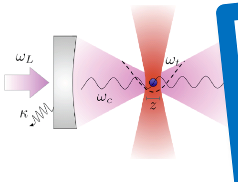
Towards „large“ quantum superposition states

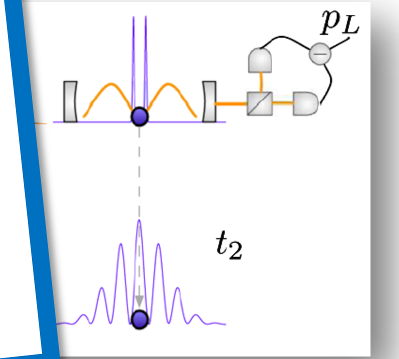


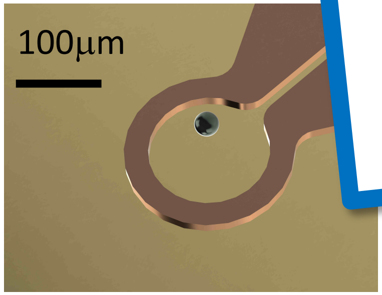
Free-fall + quantum measurement

Next Step:

Controlling the Potential Landscape

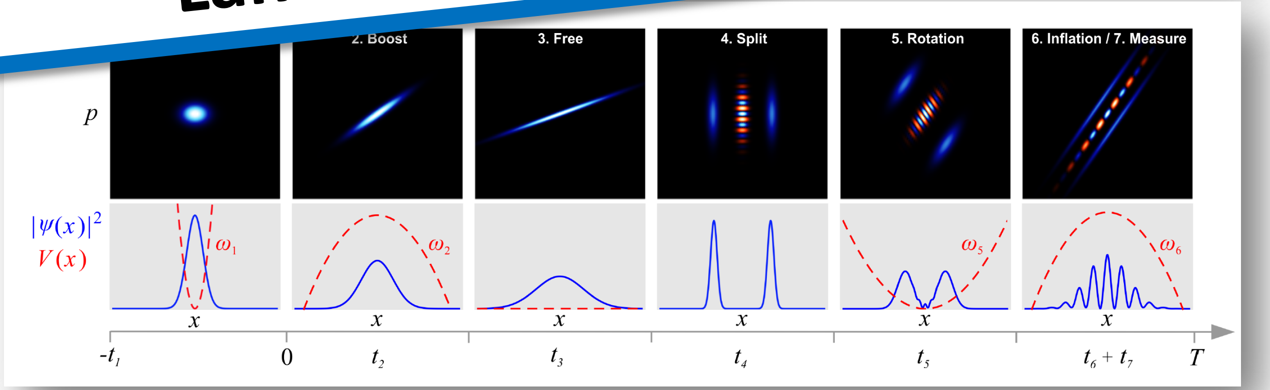






Superconducting levitation

(Pino 2016) arxiv: 1603.01553



Shaping the potential landscape of optical tweezers

OPTICAL LEVITATION:

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

α: Re{Polarizability}

E: optical trapping field

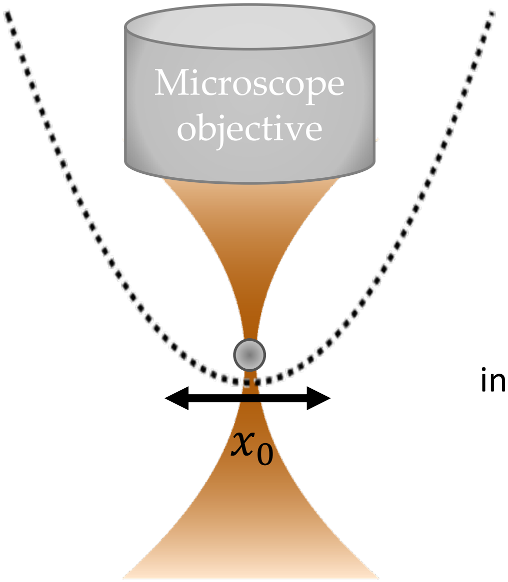
↳ beam intensity

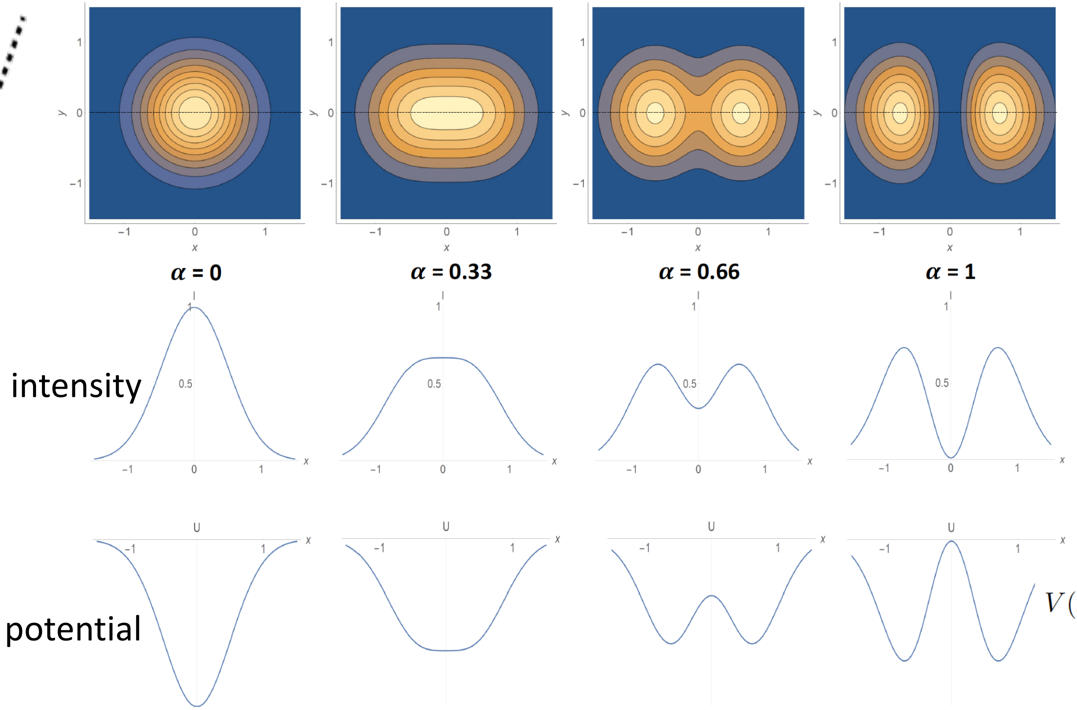
→ GRADIENT FORCE $F \propto (\nabla E^2) \cdot \alpha$

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

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

Mario Ciampini (Kiesel group)



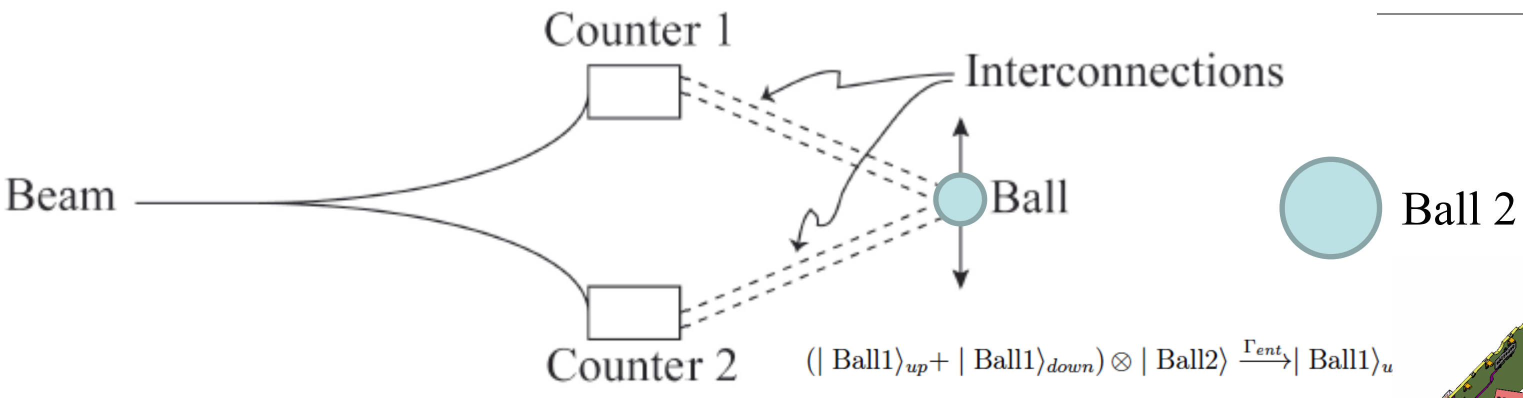


$$\alpha TEM_{00}(H) + \beta TEM_{01}(V)$$

↓

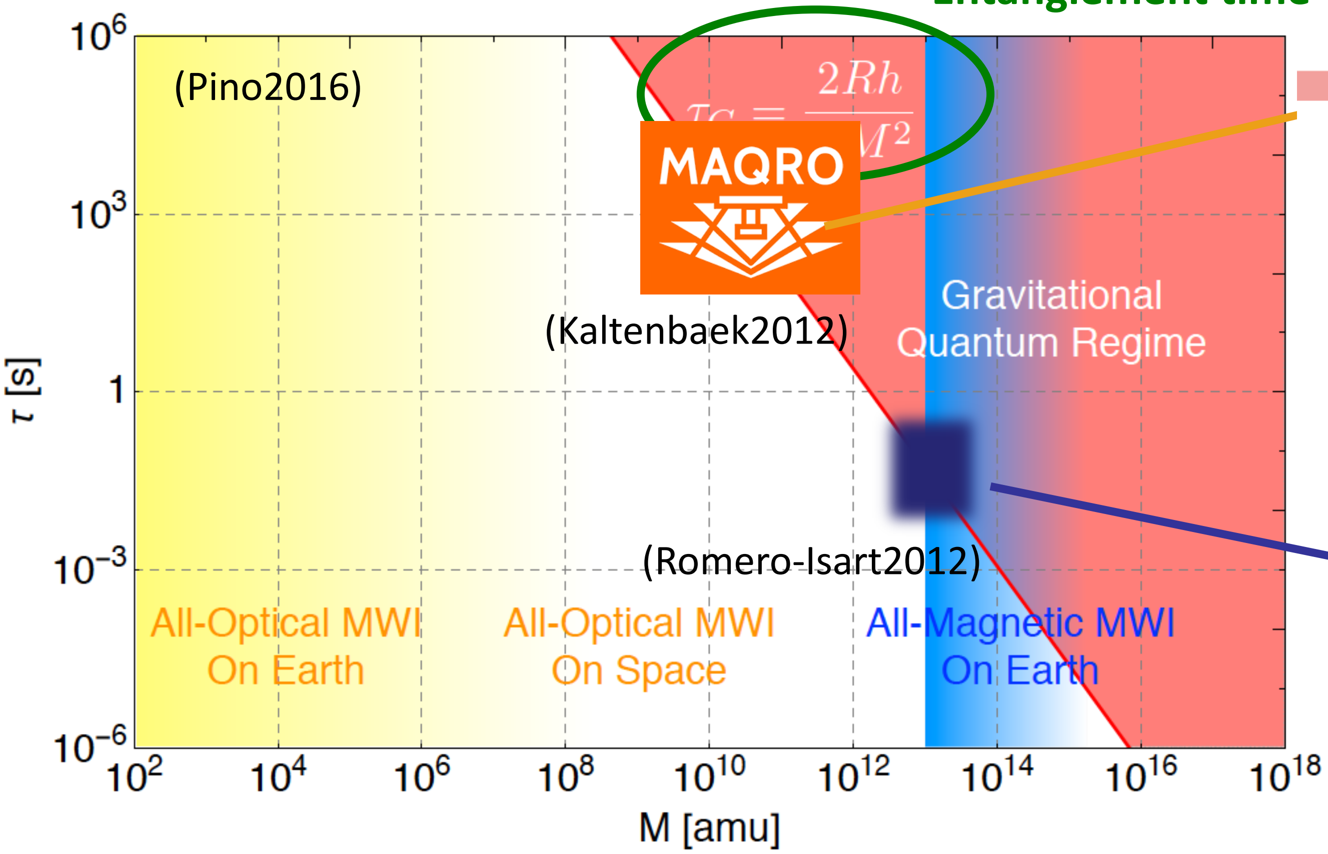
$$V(x,t) = -\left[\alpha + \frac{\beta}{2}x^2\right]\exp\left(\frac{-x^2}{2\omega_0^2}\right)$$

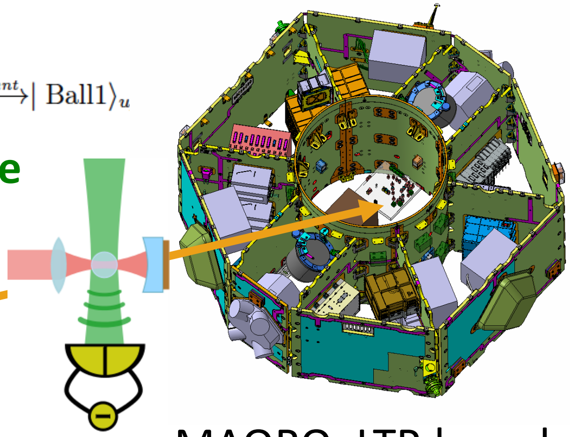
An ultimate experiment? Entanglement by gravity…



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

Entanglement time

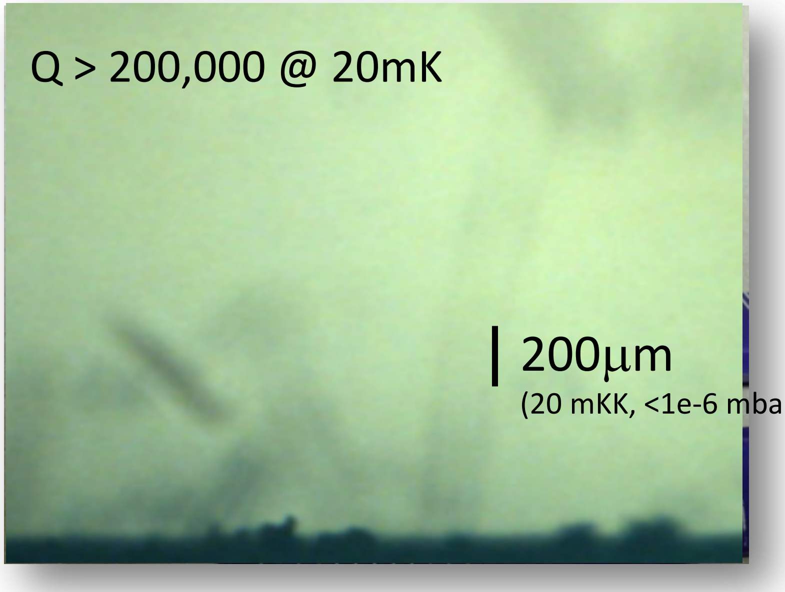


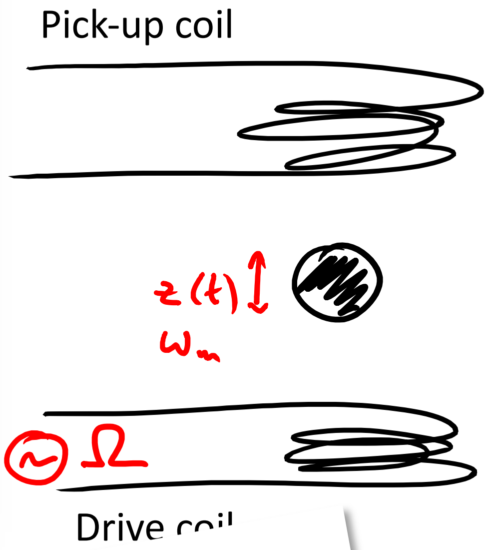


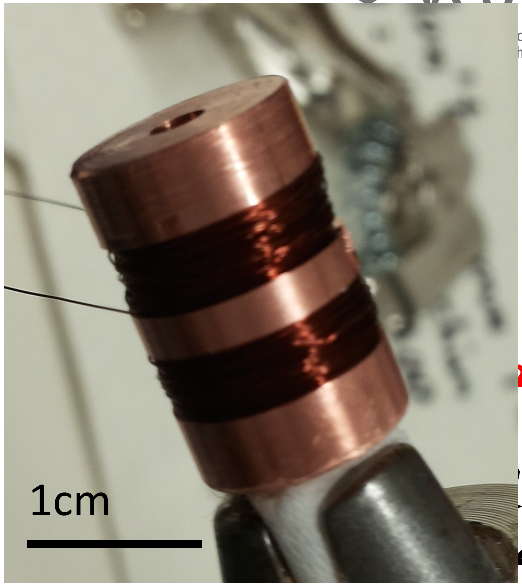
MAQRO: LTP-based satellite mission

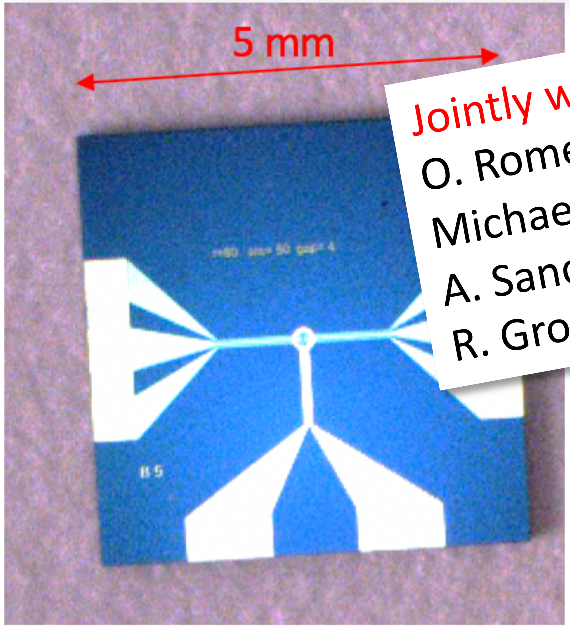
Superconducting levitation

Magnetically trapped superconductors as mechanical resonators







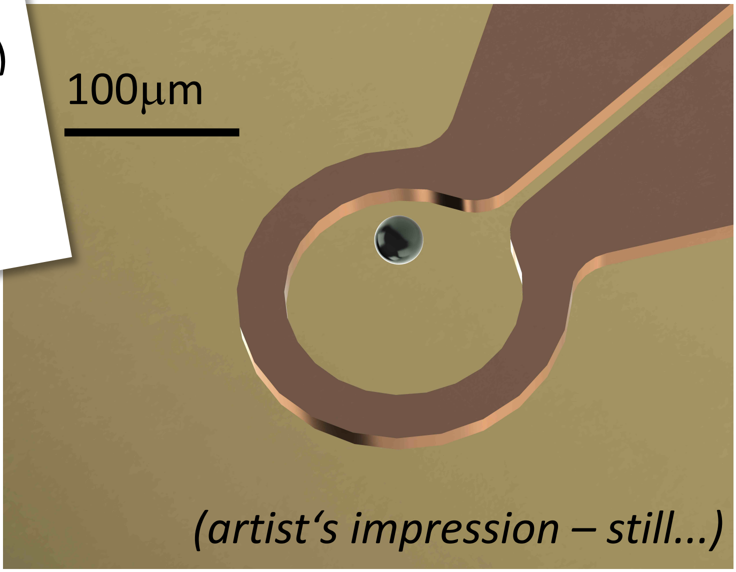


Jointly with:
O. Romero-Isart, G. Kirchmair (IQOQI)
Michael Trupke (U Vienna)
A. Sanchez (UA Barcelona)
R. Gross, H. Huebel (WMI Munich)

Magnetic levitation in anti-Helmholtz coil configuration

Trap frequencies ~ 1 kHz

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



(artist's impression – still...)

J. Hofer, S. Miniberger, M. Trupke

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

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

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

Mario Ciampini
Maxime Debiossac
Stefan Lindner
Tobias Wenzl
Qianze Zhu

Precision measurements of gravity

Tobias Westphal
Mathias Dragosits
Hans Hepach
Jeremias Pfaff

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

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

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

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

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

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

Low-noise coatings & microfab

Garrett Cole @ CMS

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

Quantum Optomechanics at ultra-low temperatures

HBT of single phonons

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

Entangled mechanical oscillators

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

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

The gravity-quantum interface

Quantum Superposition of Massive Objects and the Quantization of Gravity

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

Levitating dielectrics and superconductors

Near-field coupling to a photonic crystal cavity

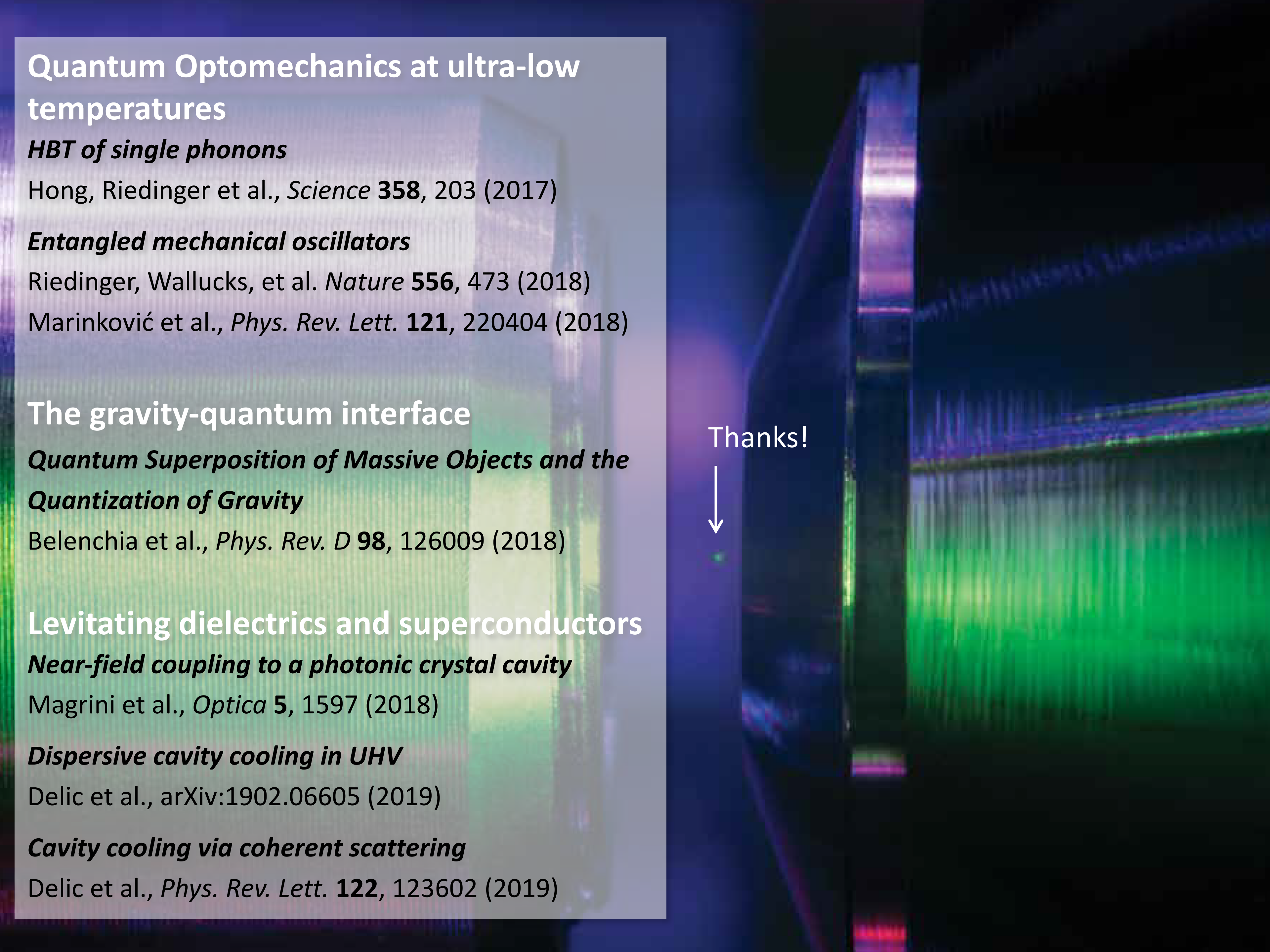
Magrini et al., *Optica* **5**, 1597 (2018)

Dispersive cavity cooling in UHV

Delic et al., arXiv:1902.06605 (2019)

Cavity cooling via coherent scattering

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



Thanks!
↓