Gravity and Entanglement Workshop, DESY, October 2024

Towards Quantum Sources of Gravity: *superposition of massive systems in experiments*

Markus Aspelmeyer

Vienna Center for Quantum Science and Technology (VCQ)

Faculty of Physics , University of Vienna, Austria

IQOQI, Austrian Academy of Sciences

All experiments to date can be explained by assuming the joint validity of quantum theory and general relativity

see also Overstreet, Asenbaum et al., Science 375, 6577 (2022)

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)

$\Delta\varphi = \frac{1}{\hbar}\int m\,\Delta\phi\,dt$
↓ gravitational potential (on Earth: $\phi = g\cdot h$)

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

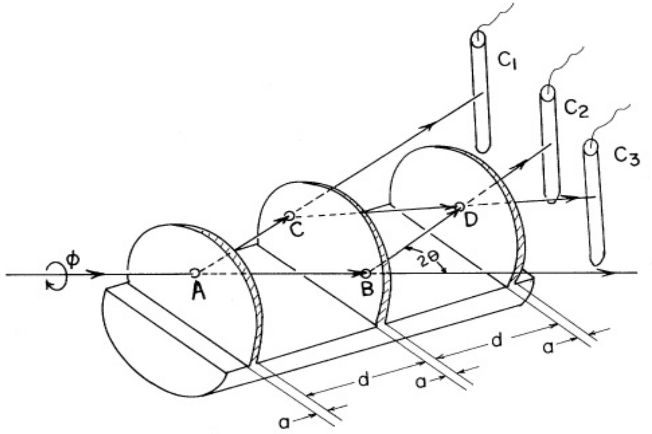
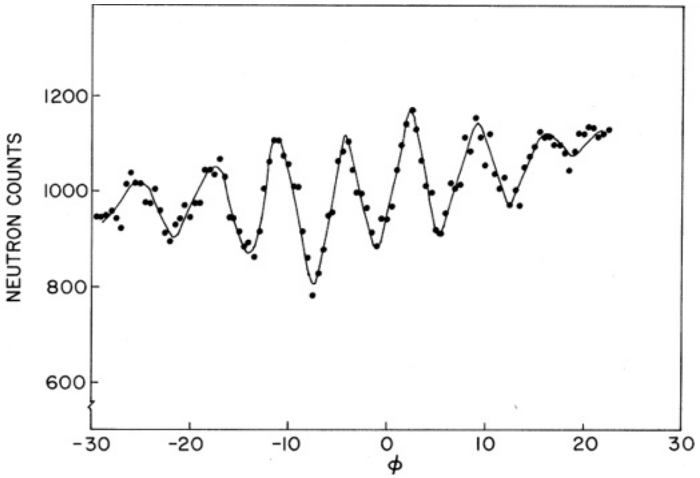
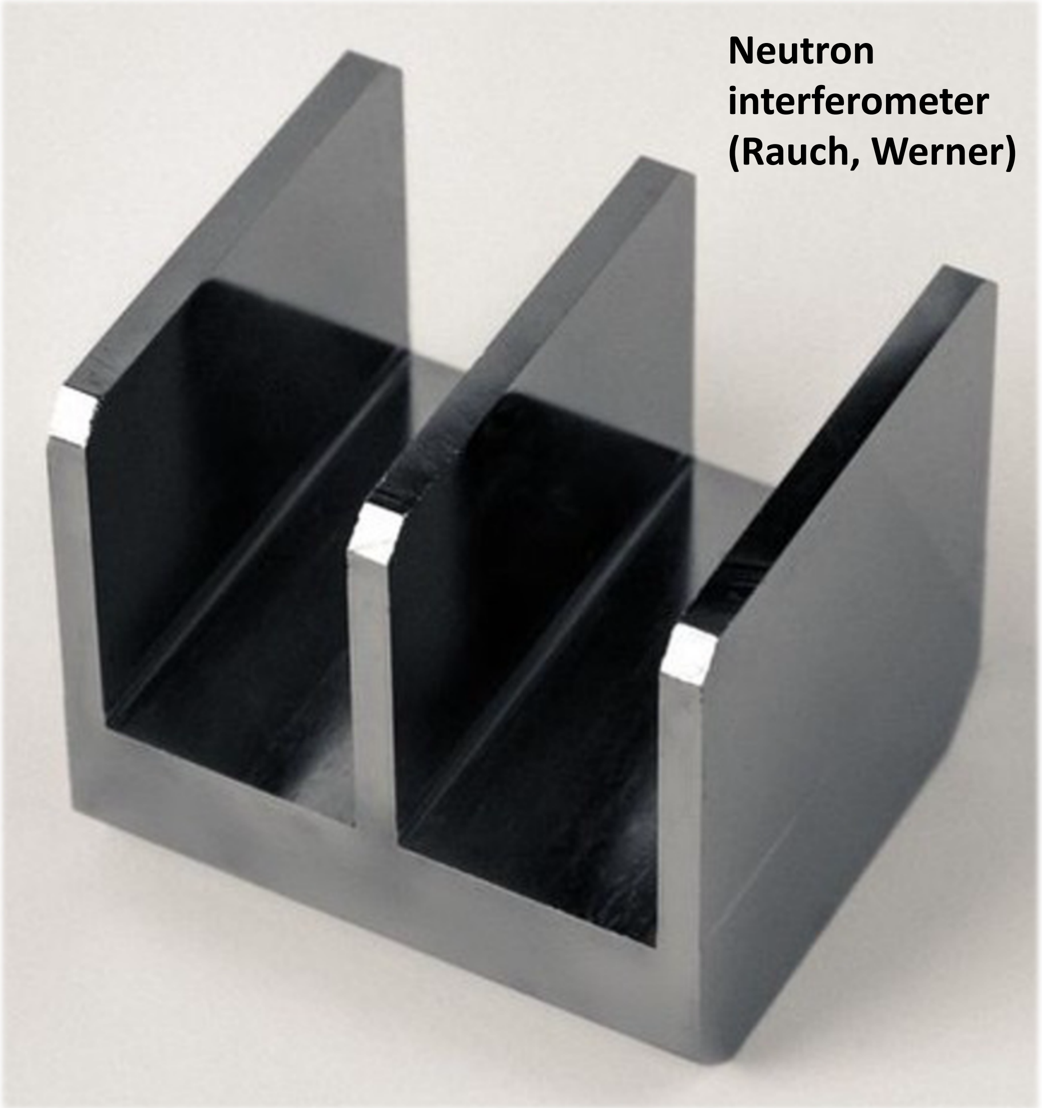


FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.





***Neutrons*: Earth's gravity impacts the wavefunction of a quantum particle**

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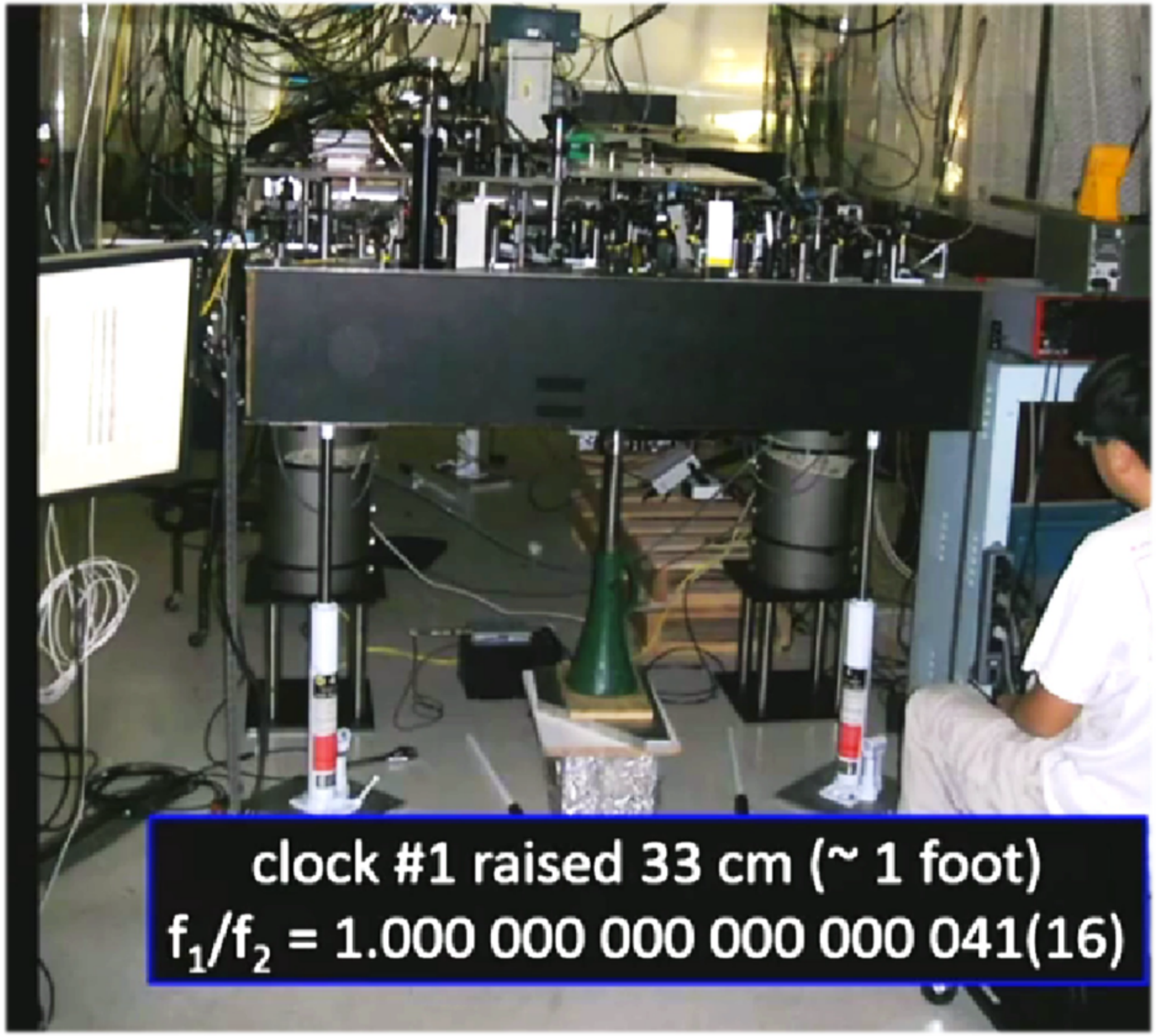
see also
Bothwell et al., Nature 602, 420 (2022)
Zheng et al., Nature 602, 425 (2022)

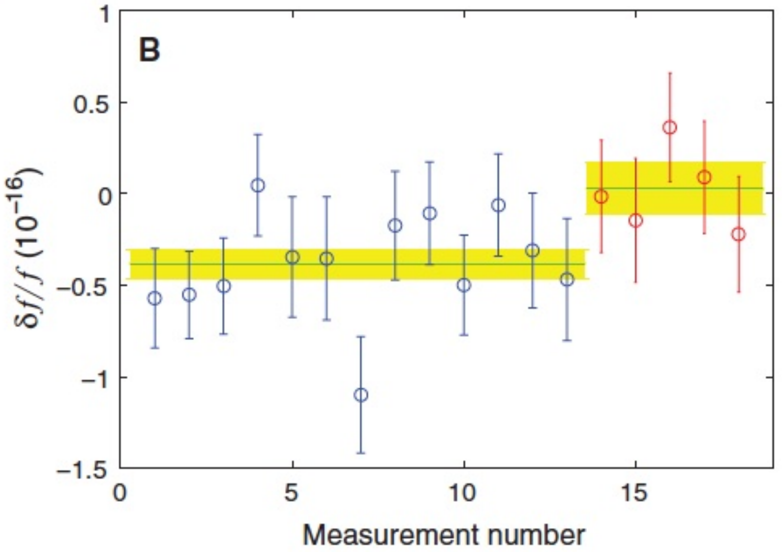


Science AAAS
Optical Clocks and Relativity
C. W. Chou, *et al.*
Science **329**, 1630 (2010);
DOI: 10.1126/science.1192720

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.



Atomic clocks: **Frequency shift due to 33 cm lift in Earth's gravitational field**

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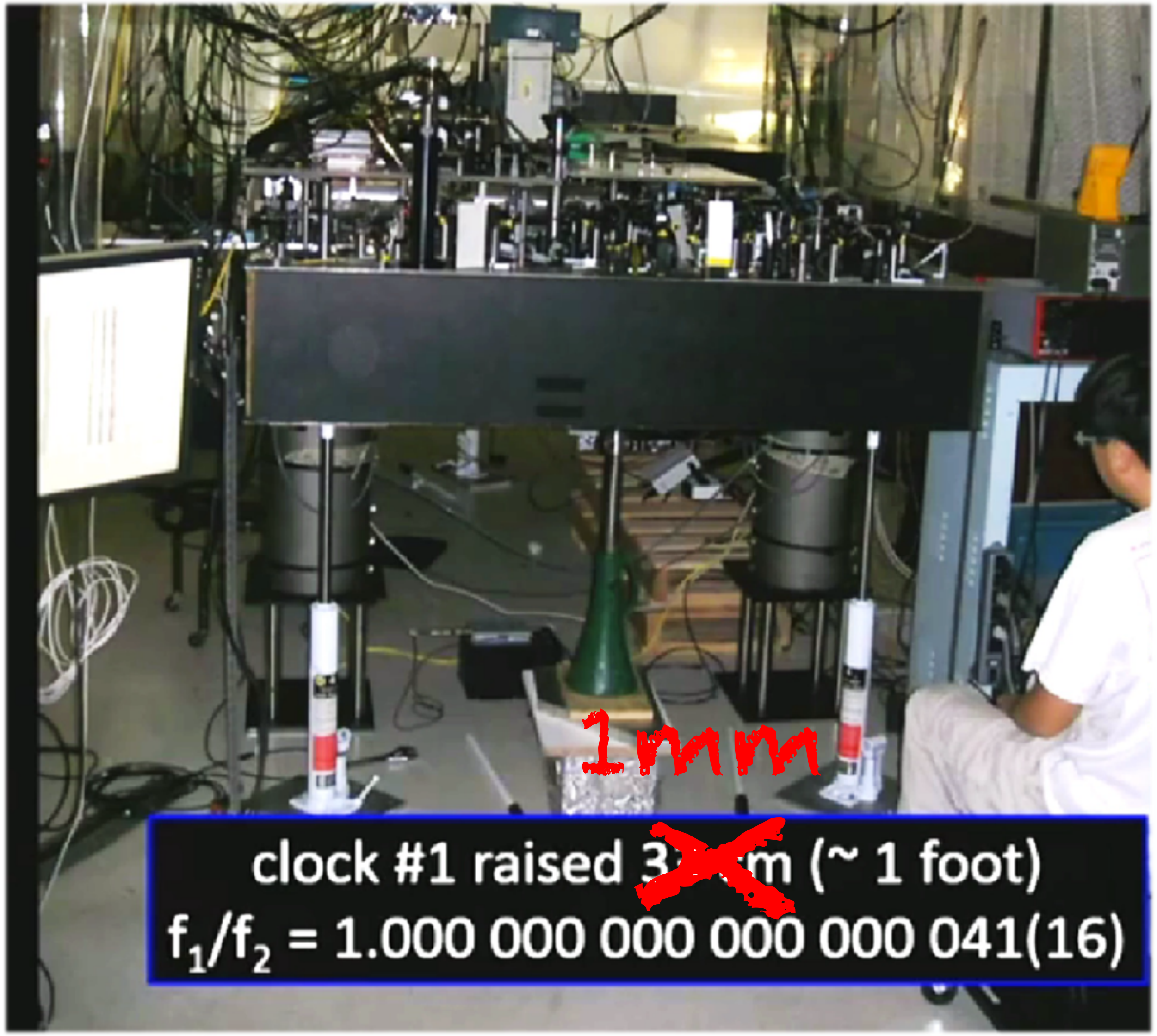

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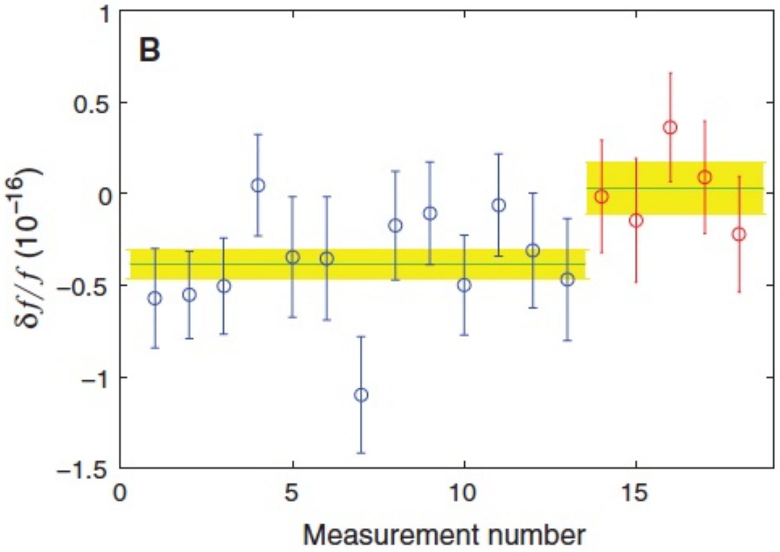


Atomic clocks: **Frequency shift due to 33 cm lift in Earth's gravitational field**

All experiments to date can be explained by assuming the joint validity of quantum theory and general relativity

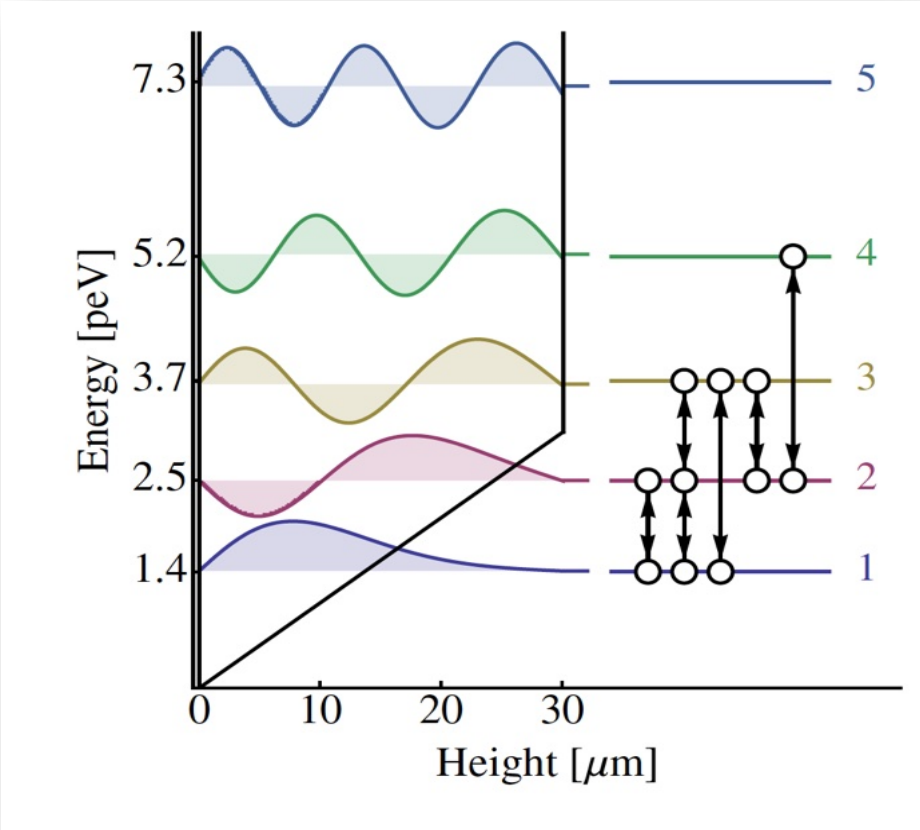
Nature 2002

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



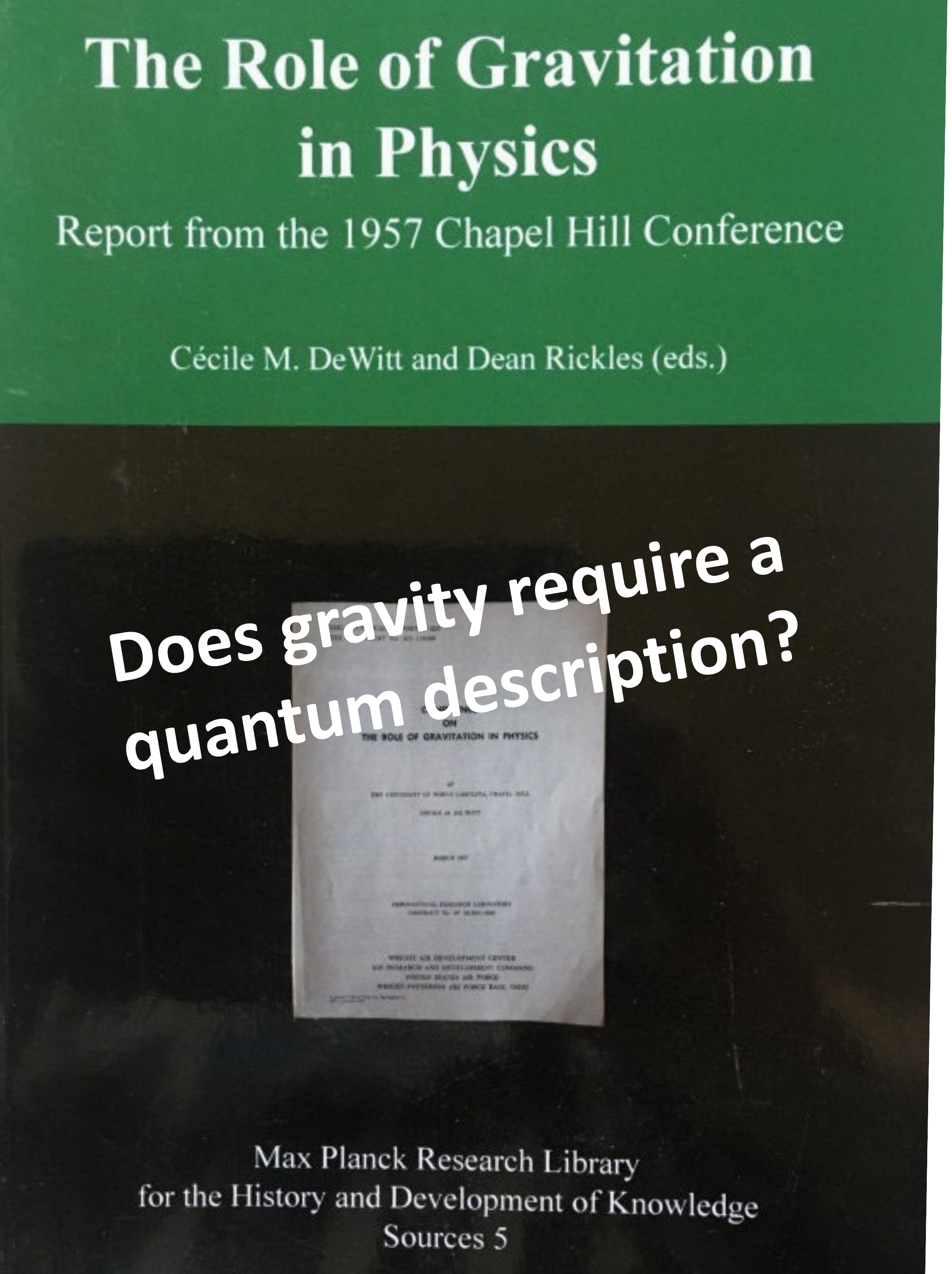
$$E_0 = \left(\frac{\hbar^2 m_n g^2}{2}\right)^{1/3}$$

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]*

Dropping Neutrons: quantum „particle in a box" with Earth's gravity as „box"



Does gravity require a quantum description?

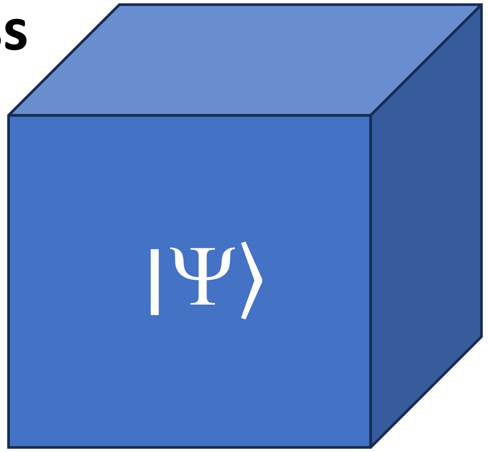
GOLD: „Can we have phenomena which the classical theory of gravity (without quantization) is unable to explain?“

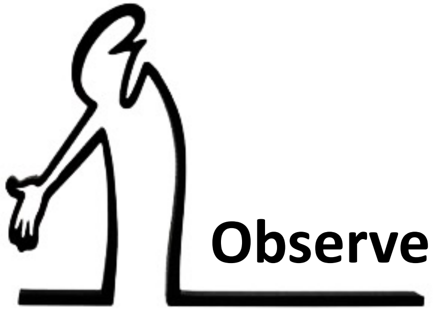
FEYNMAN: **„YES!“**

1957 Chapel Hill Conference

What if... we could have quantum sources of gravity in the laboratory

Mass





Observer

superposition of states that are **gravitationally distinct**, i.e. can be distinguished in gravity experiments

$$(|L\rangle_M + |R\rangle_M) \otimes |\tau\rangle_C$$

↓ Gravity

$$|L\rangle_M |\tau_L\rangle_C + |R\rangle_M |\tau_R\rangle_C$$

ENTANGLED IFF $\langle \tau_L | \tau_R \rangle \ll 1$

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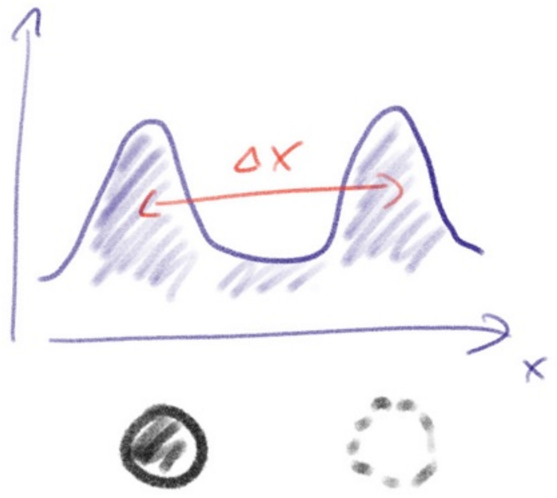
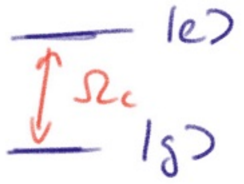




$$(|L\rangle_M + |R\rangle_M) \otimes |\tau\rangle_c$$

$$\phi_{L,R} = G \frac{M}{|x_{L,R} - x_0|}$$

$$\Delta\phi = \frac{G M \Delta x}{d^2}$$

$$|L\rangle_M |\tau_L\rangle_c + |R\rangle_M |\tau_R\rangle_c$$

ENTANGLED IFF $\langle \tau_L | \tau_R \rangle \ll 1$

Bothwell et al., Nature 602, 420 (2022)
Zheng et al., Nature 602, 425 (2022)

current experiments

$\Delta\nu/\nu = 7 \times 10^{-21}$

$$\frac{\Delta\phi}{c^2} = \frac{\Delta\nu}{\nu} \sim 10^{-32}$$

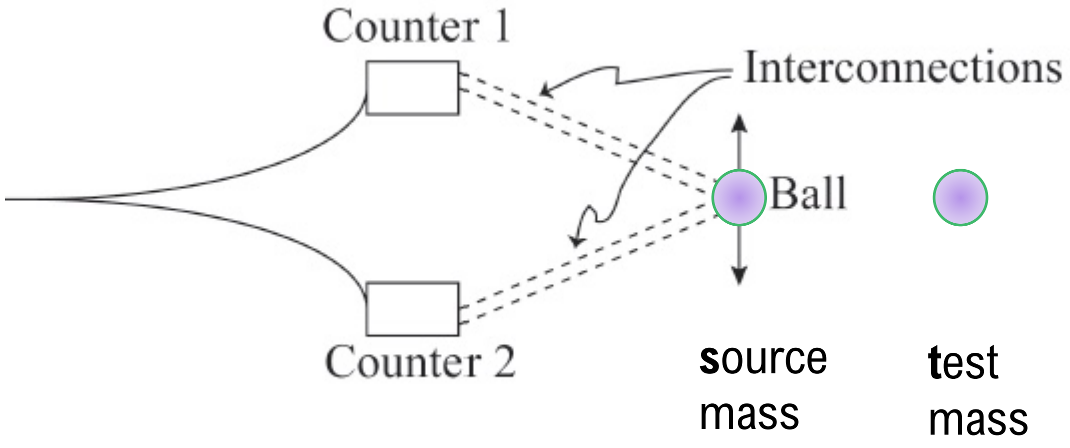
Can GR describe ALL gravitational phenomena? A YES/NO Experiment

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

R P Feynman

Quantum entanglement via gravity

” Since the ball is big enough to produce a real gravitational field we could **use that gravitational field to move another ball** (…) We would then have to analyze [this experiment] through the channel provided by the gravitational field itself via the quantum mechanical amplitudes.”



$$\left(|x_d\rangle_s + |x_{\bar{n}}\rangle_s\right) \otimes |x_0\rangle_t$$

$$\downarrow \quad a_G^{\bar{n},d} = G \cdot \frac{m_s}{|x_{\bar{n},d} - x_0|^2}$$

$$\left(|x_d \; G_{\mu\nu} \overset{?}{=} 8\pi \langle T_{\mu\nu}\rangle_s \, |\tilde{x}_d\rangle_t\right)$$

ENTANGLED $\Leftrightarrow \langle \tilde{x}_{\bar{n}} | \tilde{x}_d \rangle \ll 1$

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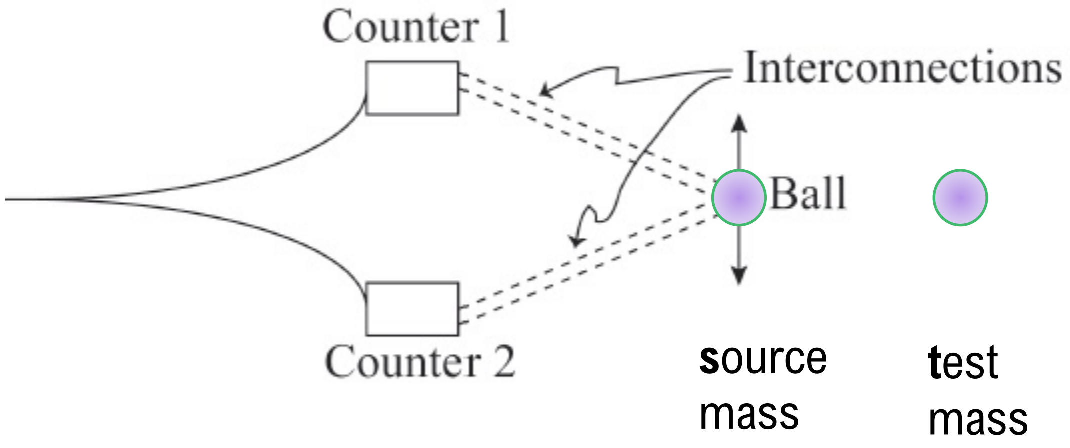


NOTE! Generation of **entanglement via gravity**

from a **quantum perspective**: *obvious*

from a **GR perspective**: *inconsistent with a fixed space-time geometry,*

e.g. Christodoulou and Rovelli, arxiv 1808.05842

$$G_{\mu\nu} \overset{?}{=} 8\pi \langle T_{\mu\nu} \rangle$$

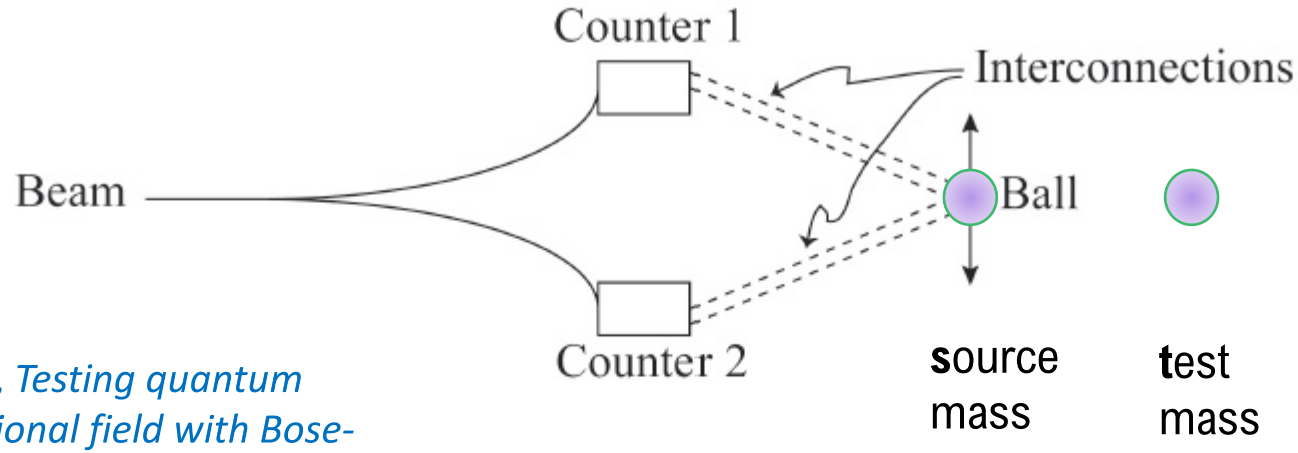
$\langle \tilde{x}_5 | \tilde{x}_d \rangle \ll 1$

Can GR describe ALL gravitational phenomena? A YES/NO Experiment

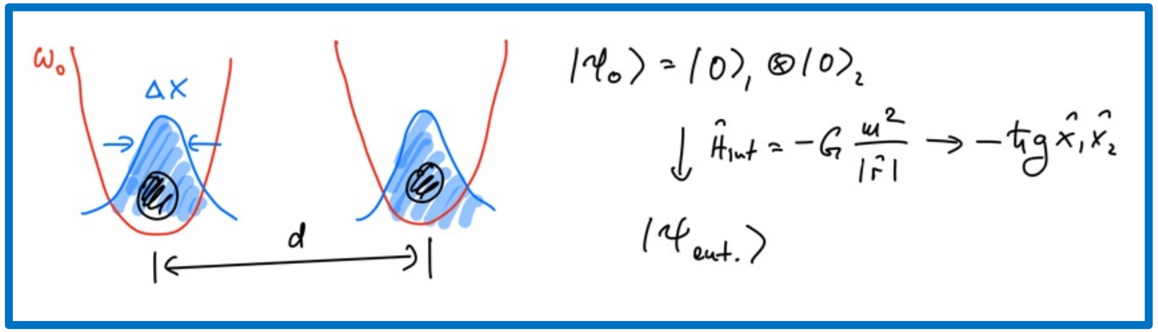
Louis Witten

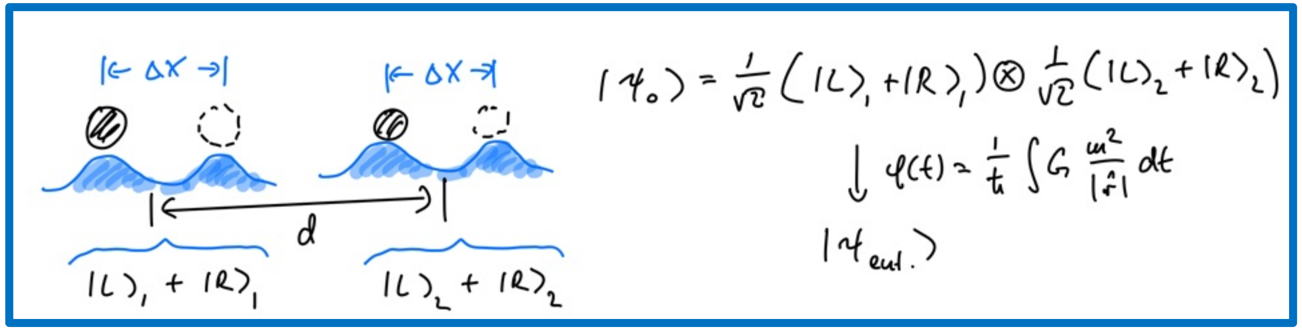
”What prevents this from becoming a practical experiment?”

Chapel Hill Conference 1957



Early works: Lindner & Peres, *Testing quantum superpositions of the gravitational field with Bose-Einstein condensates*, PRA 71, 024101 (2005)





Al Balushi et al., PRA 98, 043811(2018),
Krisnanda et al., npj Quantum Information 6, 12 (2020),
Cosco et al., PRA 103, L061501 (2021)
Weiss et al., PRL 127, 023601 (2021)

ENTANGLEMENT RATE $g = \frac{G}{\hbar}\frac{m^2}{d}\left(\frac{\Delta x}{d}\right)^2 \overset{!}{>} \Gamma_{decoherence}$

Bose et al., PRL 119, 240401 (2017),
Marletto et al., PRL 119, 240402 (2017)

Can GR describe ALL gravitational phenomena? A YES/NO Experiment

How long to generate entanglement?

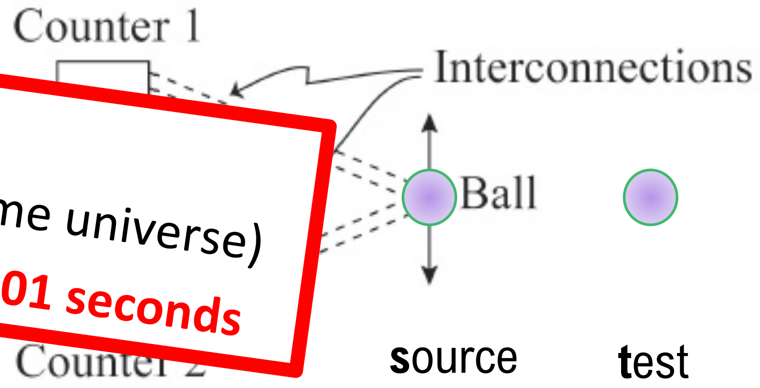
2 atoms separated by **1μm**: **10^24 seconds** (> lifetime universe)

2 Pb-spheres (50μm size) separated by **100μm**: **0.01 seconds**

Louis Witten

”What pre
from beco
practical experiment

Chapel Hill Conference 1957



source mass

test mass

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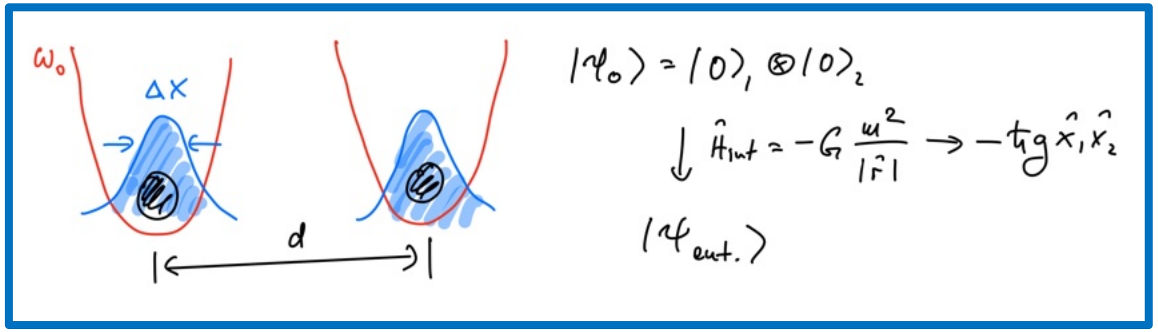

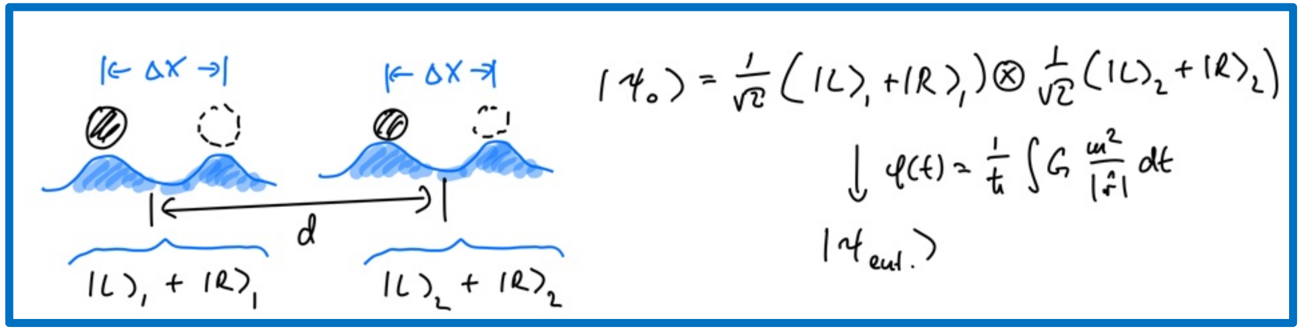

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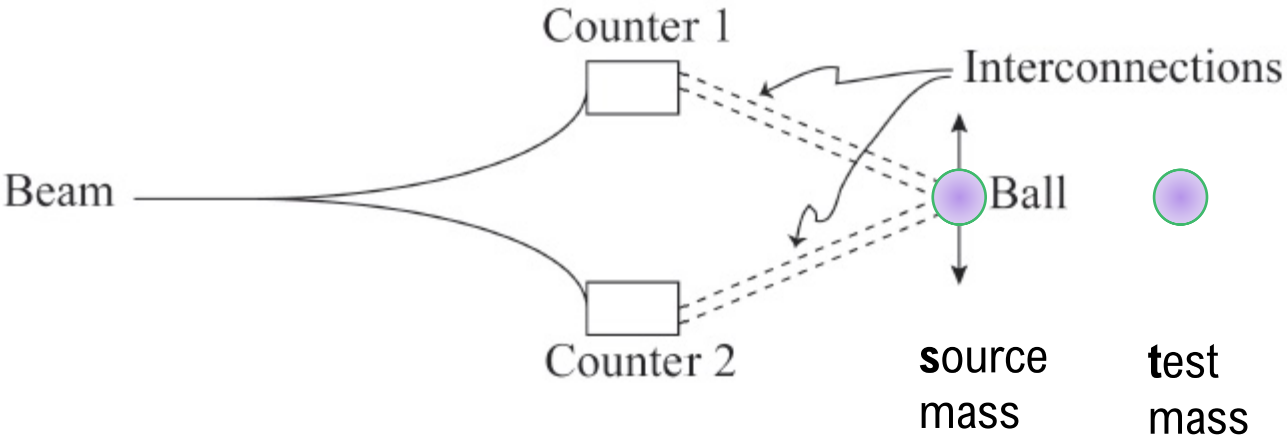
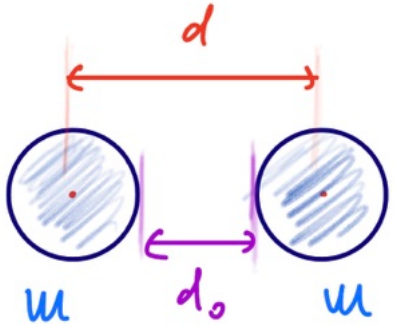


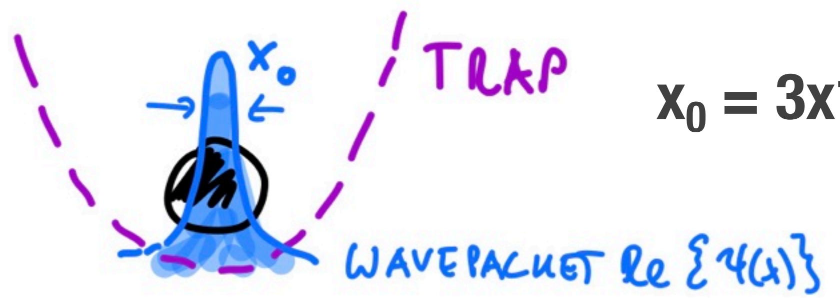
$$m^2 \, \Delta x^2 \, \tau_{coherence} \, d^{-3} \overset{!}{>} \hbar / G$$



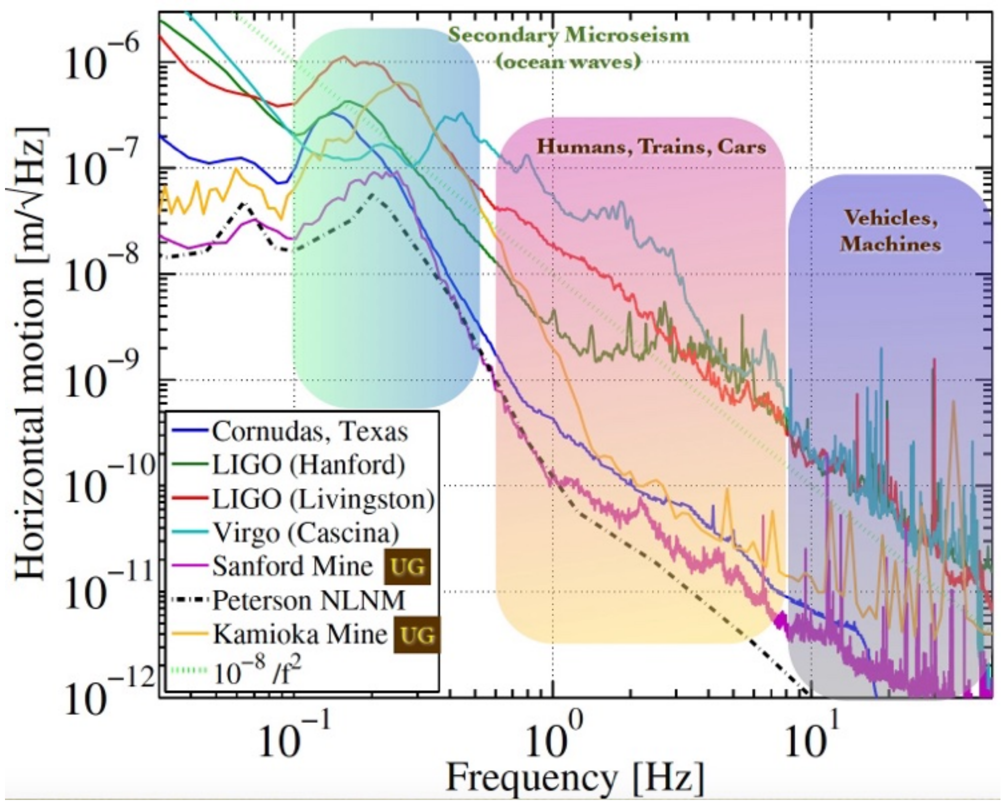
Quantum Experiments — $m^2 \, \Delta x^2 \, \tau_{coherence}$

Gravity Experiments — d^{-3}

The decoherence challenge: *displacement noise*



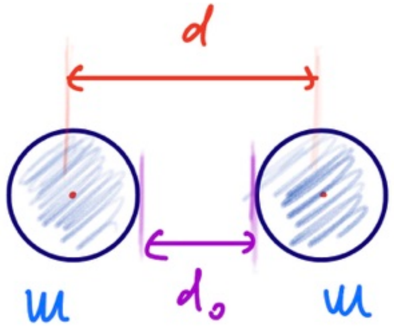
$x_0 = 3x10^{-12}$m (for 10^9 atoms)



Working Assumption 1: avoid displacement noise!

→ Duration of experiment < 0.01 sec (< $\tau_{coherence}$)

$$m^2 \Delta x^2 \tau_{coherence} d^{-3} \overset{!}{>} \hbar / G$$



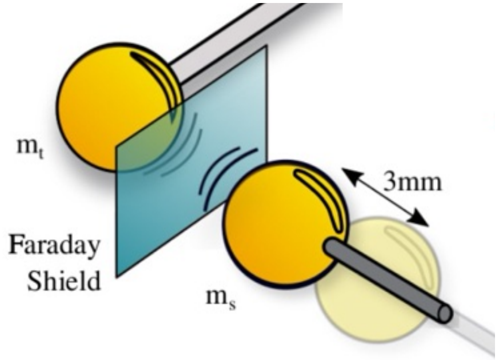
Quantum Experiments **Gravity Experiments**

The decoherence challenge: *electromagnetic shielding*

Gravity experiments require electromagnetic shielding between masses:

today: $d_0 > 50\ \mu m$ [Eöt-Wash group, Lee et al., PRL 124, 101101 (2020)]

10um thick Au-coated BeCu membrane

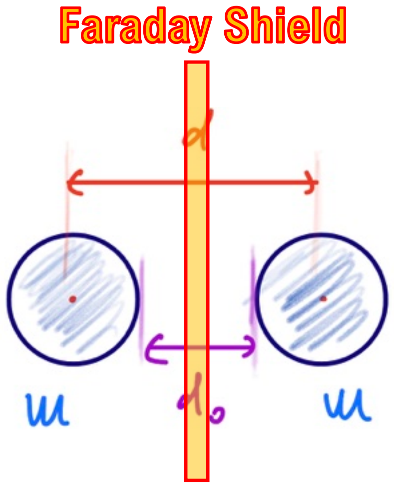


Westphal et al., Nature 591, 225 (2021)

planned: $d_0 > 10\ \mu m$ [Vienna; in collaboration with Eric Adelberger]

Working Assumption 2: need a Faraday shield!

→ Surface distance $d_0 > 10\ \mu m$ (> d)



Related to **tests of large extra dimensions**, e.g.
ADD: Arkani-Hamed, Dimopolous, Dvali, PLB 429, 263 (1998)
Swampland: Montero, Vafa, Valenzuela, arxiv 2205.12293 (2022)

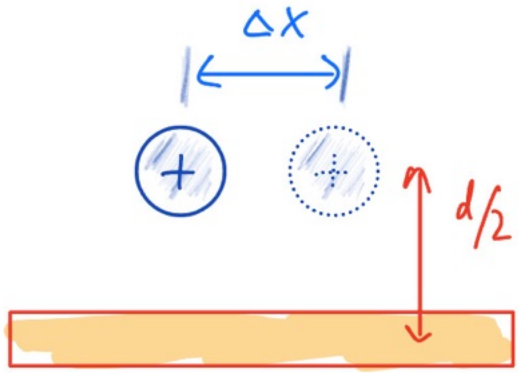
$$m^2 \Delta x^2 \tau_{coherence}\, d^{-3} \overset{!}{>} \hbar / G$$

Quantum Experiments **Gravity Experiments**

The decoherence challenge: *mirror charges*

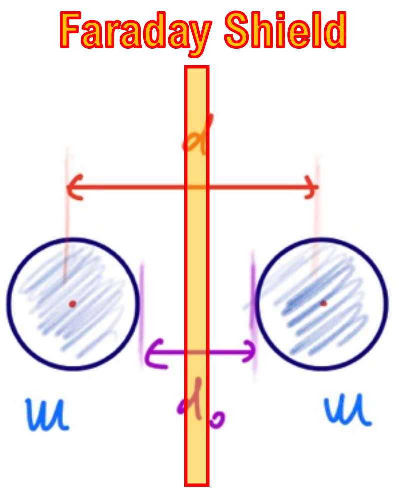
Decoherence by Coulomb interaction with Faraday shield

[Kerker et al., NJP 22, 063039 (2020)]
[Martinetz et al., PRX Quantum 3, 030327 (2022)]



Working Assumption 3: decoherence scales with some order of Δx/d!

→ Δx/d << 1



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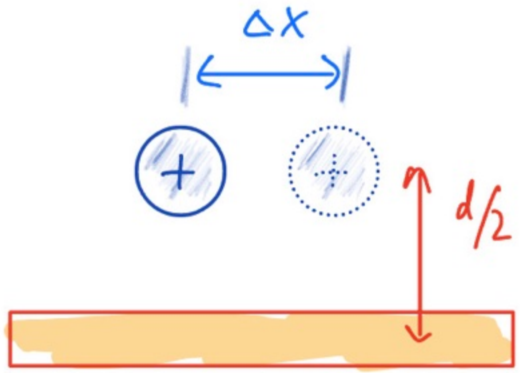
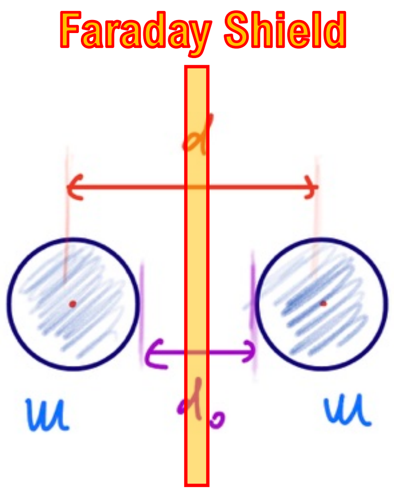


Working Assumption 3: decoherence scales with some order of Δx/d!

→ Δx/d << 1

$$m \gg m_p \sqrt{\frac{d}{c\,\tau_{coh}}} \approx 10^{-6}\, m_p$$



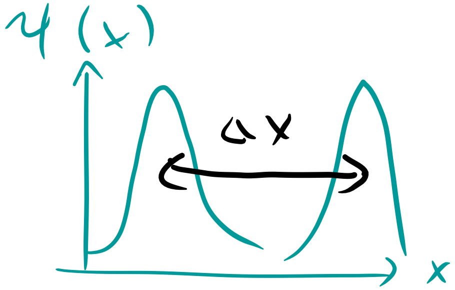
m_p: Planck Mass (10^{18} atoms, 2×10^{-8} kg)

The decoherence challenge: *gas, blackbody, etc...*

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

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

Master equation approach



see also
O. Romero-Isart et al., PRL 107, 020405 (2011)
O. Romero-Isart, PRA 84, 052121 (2011)
T. Weiss et al., arxiv: 2012.12260 (2021)

Decoherence from gas collisions

$\lambda_{th} = 2\pi\hbar\left(\sqrt{2\pi m_g k_B T}\right)^{-1} \sim 1\,\mathrm{nm}$ @ 1K << Δx (short wavelength regime)

$$\Gamma_{gas} = \frac{\lambda_{th}}{\hbar}\frac{16\pi}{3} p R^2$$

Decoherence from blackbody radiation

$\lambda_{th} = \frac{\pi^{2/3}\hbar c}{k_B T_c} \sim \mathcal{O}(\mathrm{mm})$ @ 1K >> Δx (long-wavelength regime)

$$\Gamma = \Lambda \Delta x^2$$

BB scattering $\Lambda_{sc} = \frac{8!\, 8\, \zeta(9)\, c R^6}{9\pi}\left(\frac{k_B T_e}{\hbar c}\right)^9 \mathrm{Re}\left\{\frac{\varepsilon-1}{\varepsilon+2}\right\}^2$

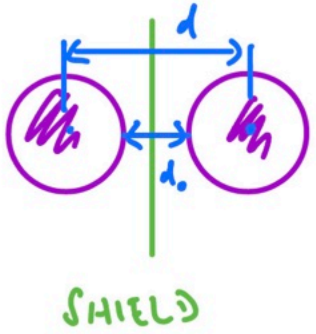
BB emission absorption $\Lambda_{e(a)} = \frac{16\pi^5 c R^3}{189}\left(\frac{k_B T_{i(e)}}{\hbar c}\right)^6 \mathrm{Im}\left\{\frac{\varepsilon-1}{\varepsilon+2}\right\}$

…

The decoherence challenge: *background gas, blackbody, etc. ...*

arxiv:2203.05587

see also
O. Romero-Isart et al., PRL 107, 020405 (2011)
O. Romero-Isart, PRA 84, 052121 (2011)
S. Rijavec et al., New J. Phys. 23, 043040 (2021)
T. Weiss et al., PRL 127, 023601 (2021)



$\tau_m = 10\,ms = 10^{-2}$

$d_0 = 10\,\mu m = 10^{-5}$

$\rho = 10^4\,kg/m^3$

MASS	GEOMETRY		DELOCALIZATION	SIZE	TEMPERATURE	
$\beta\,[M_0]$	$\gamma = (1+16\beta^{1/3})$	$\gamma^{3/2}$	Δx	r	T_a	$T_{e,i}$ [K]
1	17	70	$1.4\ 10^{-9}$	80 μm	7	11
10^{-1}	8.43	25	$4.9\cdot10^{-9}$	40 μm	9	11
10^{-2}	4.45	9.4	$19\cdot10^{-9}$	17 μm	11	10
10^{-3}	2.6	4.2	$84\cdot10^{-9}$	8 μm	13	9
10^{-4}	1.74	2.3	$460\cdot10^{-9}$	4 μm	15	8
10^{-5}	1.3	1.6	$3.1\cdot10^{-6}$	2 μm	16	6
	⋮	⋮	⋮	⋮	⋮	
10^{-9}	1.02	1.02	$2\cdot10^{-2}$	80 nm	18	1.5

for $\bar{n} \sim 0.1$, $p < 10^{-17}$ mbar

assuming GAS SCATTERING & BLACKBODY radiation

ÖAW

universität wien

Quantum Controlling LARGE MASSES...

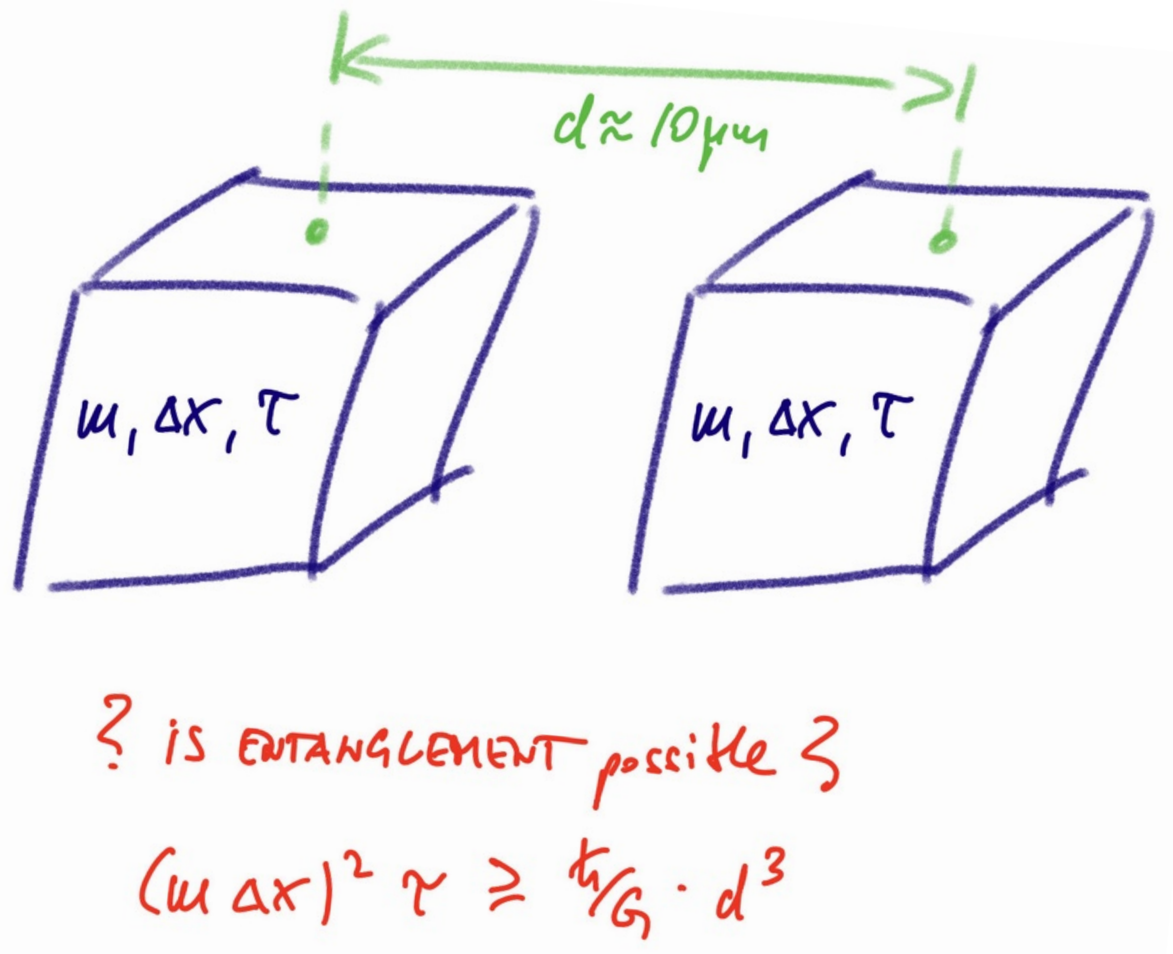
quantum optomechanics (solid-state densities)

Mass (#atoms)	10^0	10^3	10^9	10^{13}	10^{17}
	single atoms	**macromolecules**	**levitated nanoparticles**	**micro-mechanical devices**	**bulk solids**
	Schrödinger cat	Schrödinger cat	squeezed	squeezed non-Gaussian entangled	squeezed non-Gaussian Schrödinger cat
	Stanford 2015	Vienna 2019	Tokyo 2023 ETH/Vienna 2024	UCSB/Caltech/ Aalto/JILA/Vienna/ Delft/EPFL/Yale/ Copenhagen 2010+	Oxford 2011/ ETH 2024
Delocalization (m)	10^0	10^{-7}	10^{-11}	10^{-15}	10^{-18}

Current experiments involving delocalization of massive objects

We quantify the degree of "usability" as quantum source masses by assuming that we can prepare two systems in the same way and place them at a center of mass distance d = 10μm. Note that this is merely a hypothetical construct…

We express $(m\,\Delta x)^2\,\tau$ in units of $(h/G\,d^3)$, which means we require $(m\,\Delta x)^2\,\tau > 1$ for the system to be a useful quantum source mass



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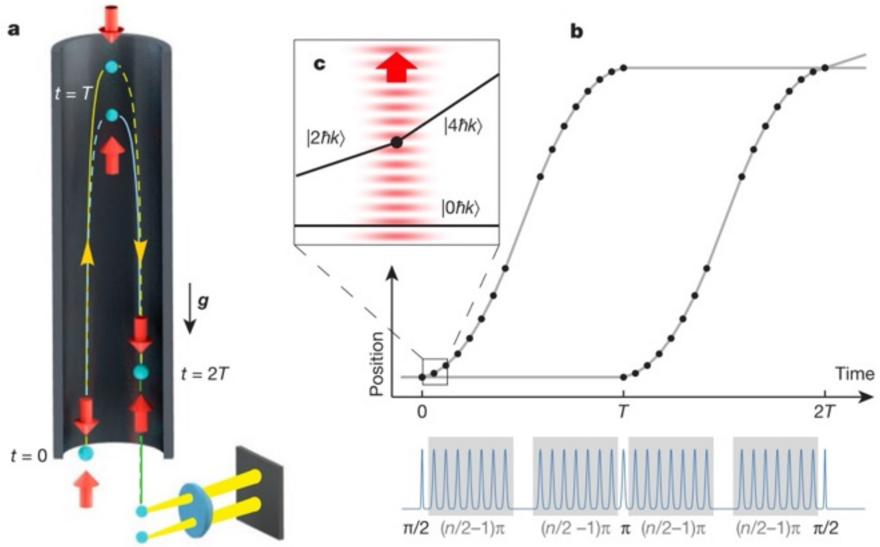
Current experiments involving delocalization of massive objects

Atoms

Atom interferometer; 1 atom; M = 87 a.m.u. = 8.7e-26 kg; superposition size $\Delta x > 0.5$m

T. Kovachy, P. Asenbaum et al., *Nature* **528**, 530-533 (2015)

$$(m\Delta x)^2 \tau \approx 10^{-12} \; [\hbar/G \;@\; d = 10\mu m]$$

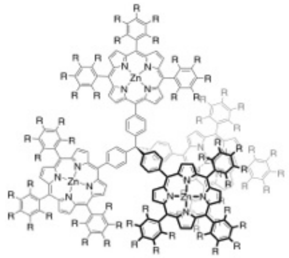


Macro-molecules

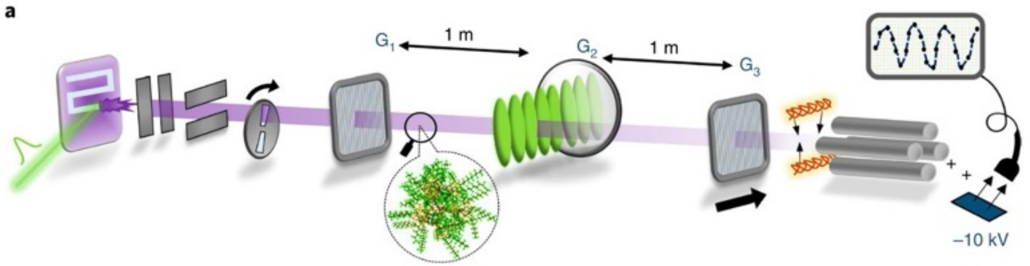
matter-wave interference; 2,000 atoms; M = 25,000 a.m.u. = 4e-23 kg; particle size D=5nm; superposition size $\Delta x > 500$ nm

Y. Y. Fein *et al.*, *Nat. Phys.* **15**, 1242–1245 (2019)

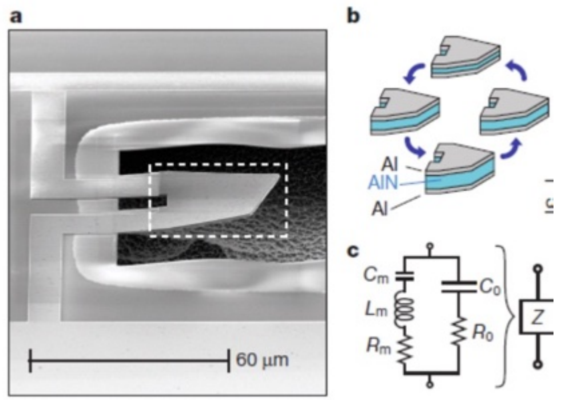
$$(m\Delta x)^2 \tau \approx 10^{-19} \; [\hbar/G \;@\; d = 10\mu m]$$



R = F or $C_{10}H_4F_{17}S$



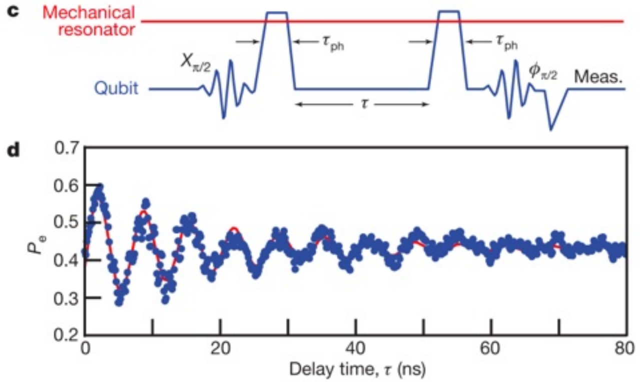
Current experiments involving delocalization of massive objects



Solid-state mechanical oscillators I

Ramsey interference 0+1 between ground state (0) and single-phonon (1) Fock state (6 GHz acoustic mode); 1e13 atoms, M = 8e-13 kg, SiO2/AlN slab (60umx10umx700nm); superposition size Δx = 2e-16 m (thickness oscillation); coherence time 40ns

A. D. O'Connell et al., *Nature* **464**, 697–703 (2010)

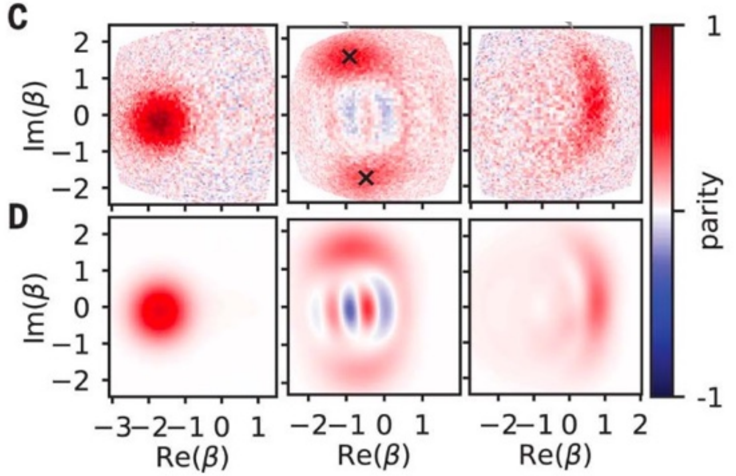


$$(m\Delta x)^2\tau \approx 10^{-24} \ [\hbar/G \ @ \ d = 10\mu m]$$

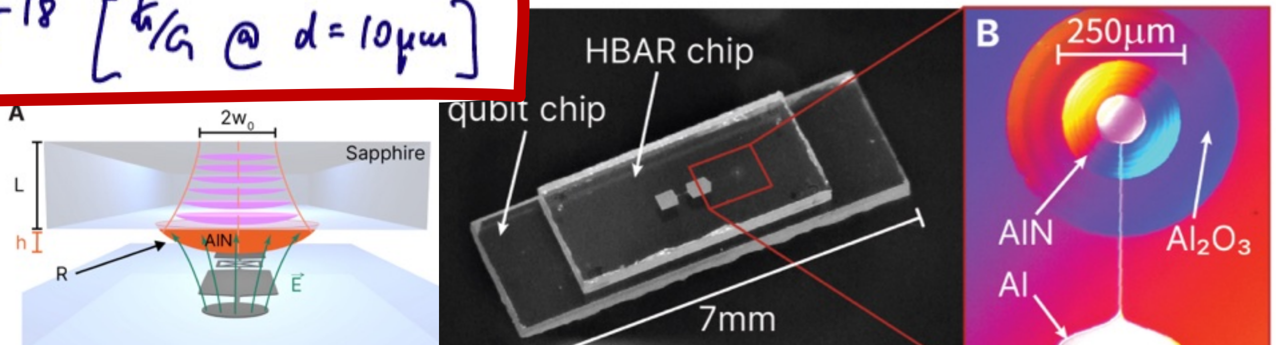
Solid-state mechanical oscillators II

Schrödinger cat state Iα> + I-α> between coherent phonon states I+/-α> with IαI=1.6 of a 6 GHz acoustic mode; 5e17 atoms, M = 2e-8 kg, saphire bulk acoustic resonator ((30um)^2x400um), superposition size Δx = 1e-18 m; coherence time 10μs

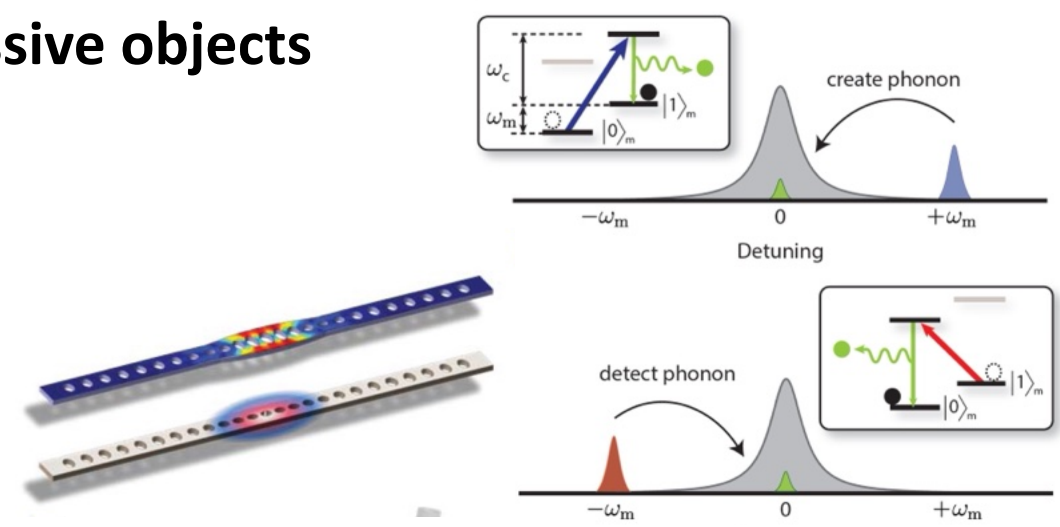
M. Bild, M. Fadel, Y. Yang et al., *Science* **380**, 274-278 (2023)



$$(m\Delta x)^2\tau \approx 10^{-18} \ [\hbar/G \ @ \ d = 10\mu m]$$



Current experiments involving delocalization of massive objects



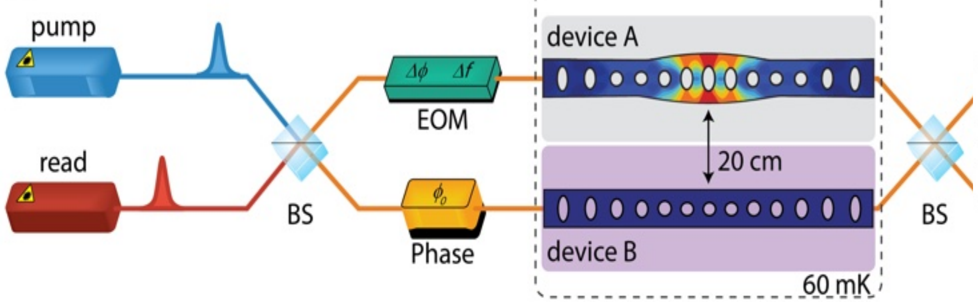
Motional entanglement of solids I

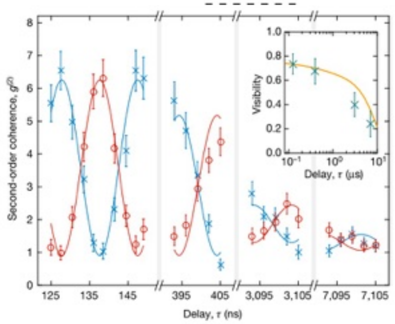
Optomechanical crystals; distributed single-phonon (5GHz acoustic phonon) entanglement 01+10 between 2 optomechanical crystals (DLCZ scheme); 1e11 atoms; M = 4e-15 kg; superposition size Δx = 1e-15m; coherence time 4 μs

R. Riedinger, A. Wallucks, I. Marinkovic et al., *Nature* **556**, 473-477 (2018)

$$(m\Delta x)^2\tau \approx 10^{-26}\ [\hbar/G\ @\ d = 10\mu m]$$

(c)





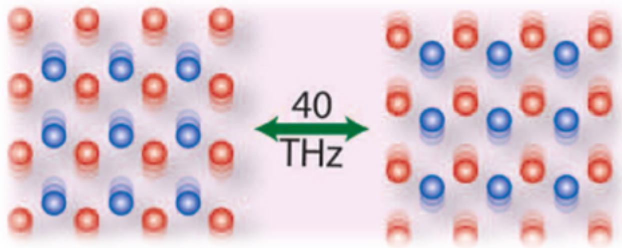
Motional entanglement of solids II

Bulk diamond; distributed single-phonon (40THz optical phonon) entanglement 01+10 between 2 bulk diamonds (DLCZ scheme); 1e16 atoms; M = 2e-9 kg; superposition size Δx = 1e-18m; coherence time order picoseconds

K. C. Lee et al., *Science* **334**, 1253-1256 (2011)

$|0_A 1_B\rangle + |1_A 0_B\rangle$

$$(m\Delta x)^2\tau \approx 10^{-29}\ [\hbar/G\ @\ d = 10\mu m]$$



Current experiments involving delocalization of massive objects

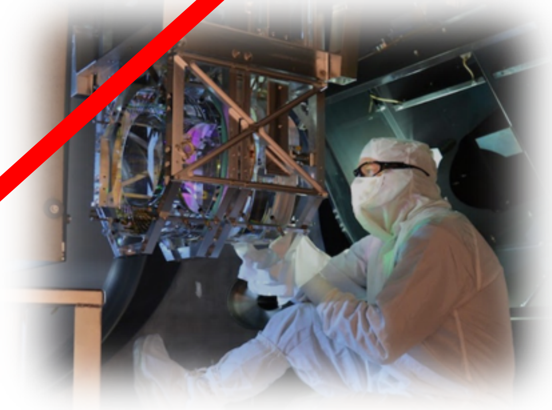
Motional quantum ground state I

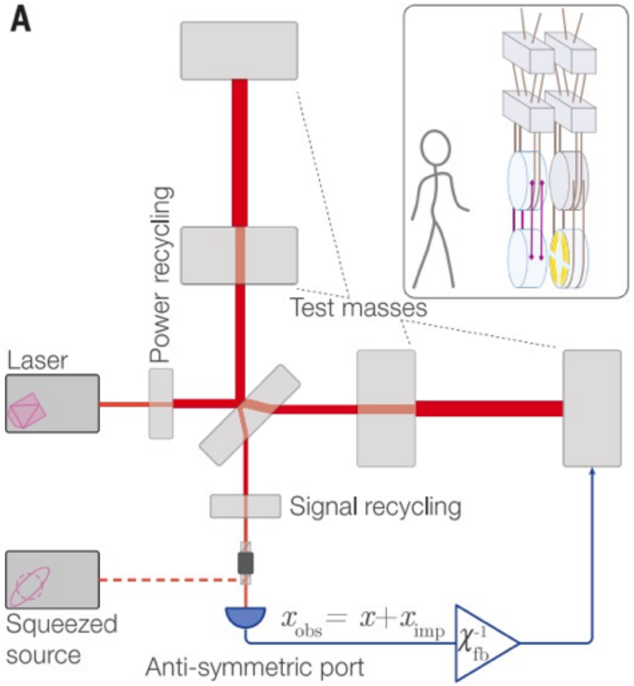
LIGO mirrors; differential motion of differential motion of cavity arms form effective mechanical oscillator with M = 10kg; 3e26 atoms; mirror size (35cm)^2 x **5cm**; ground state size Δx = 1e-19m (not yet fully achieved); coherence time ms (without blackbody radiation localization; requires T < 0.3K)

C. Whittle *et al.*, *Science* **372**, 1333–1336 (2021)

$$(m\Delta x)^2 \tau \approx 10^{+1} \;\; [\hbar/G \;@\; d = 10\mu m]$$

$$\rightarrow 10^{-11} \;\; @\; d = 10cm$$



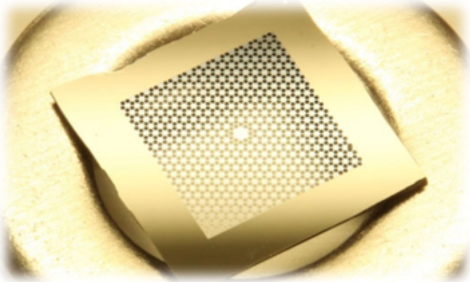


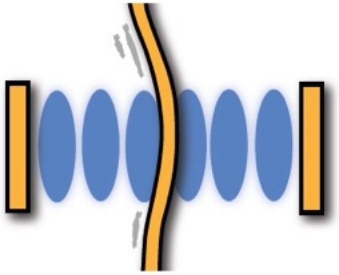
Motional quantum ground state II

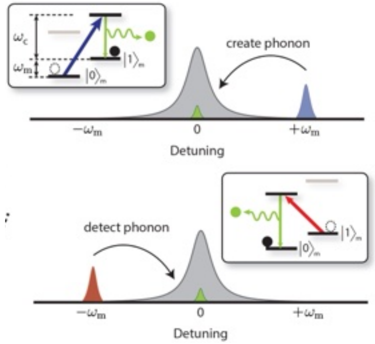
Micromechanical membranes; cavity cooling of fundamental COM mode of a membrane ((200υm)^2 x 100nm); 1e14 atoms; M = 6e15 a.m.u. = 1e-11 kg; ground state size Δx = 1e-15m; coherence time ms

I. Galinskyi *et al.*, arXiv:2312.05641 [quant.ph] (2023)

$$(m\Delta x)^2 \tau \approx 10^{-16} \;\; [\hbar/G \;@\; d = 10\mu m]$$





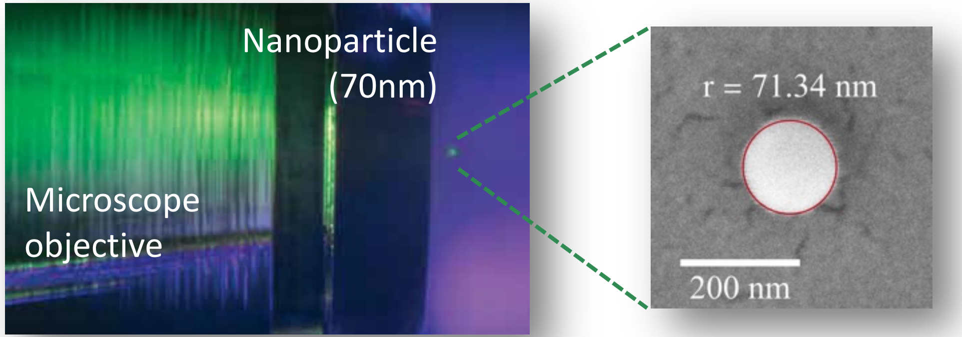


Current experiments involving delocalization of massive objects

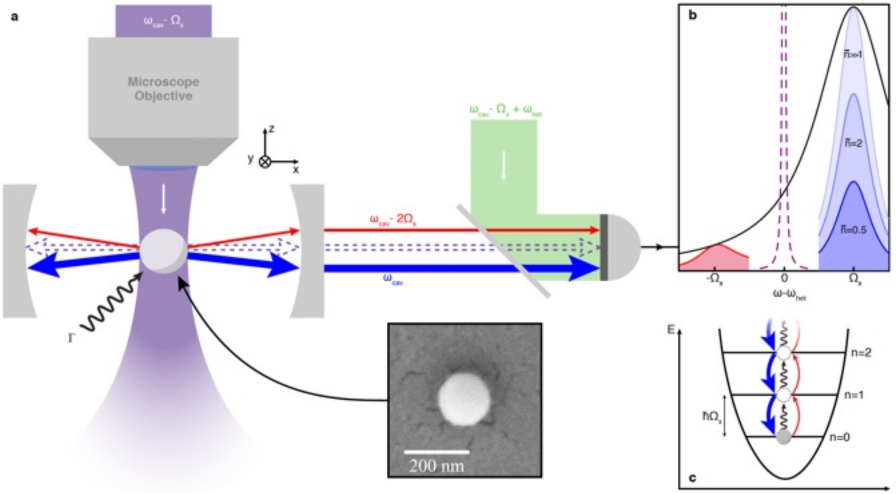
Motional quantum ground state III

Levitated nanoparticles; 1e9 particles; M = 2e10 a.m.u. = 3e-17 kg; ground state size Δx = 2e-12m; coherence time ms (in the trap; limited by photon recoil)

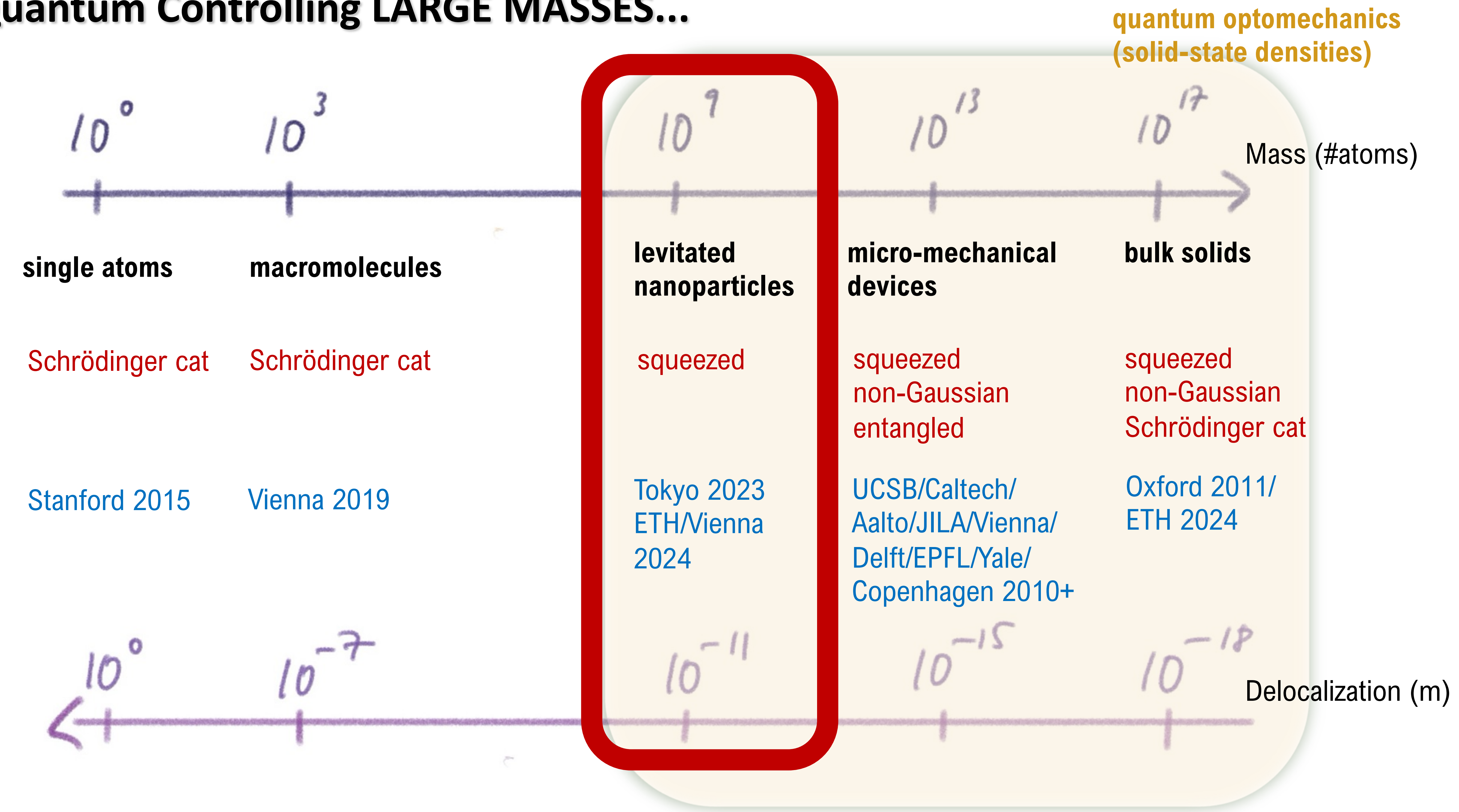
U. Delic *et al.*, *Science* **367**, 892–895 (2020)



$$(m\Delta x)^2 \tau \approx 10^{-20} \left[\hbar/G \text{ @ } d = 10\mu m\right]$$



Quantum Controlling LARGE MASSES...



Quantum controlling levitated solid-state objects

Combining LARGE MASSES with LONG COHERENCE TIMES and FULL MANIPULATION

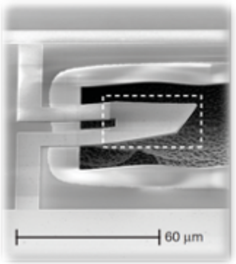
+

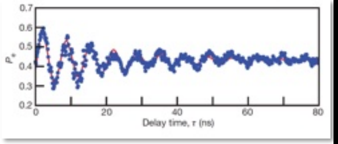
=

Solid-state mechanical quantum devices (clamped):

$10^{10} – 10^{16}$ atoms

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



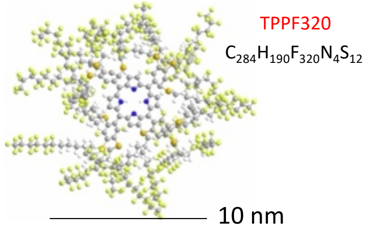


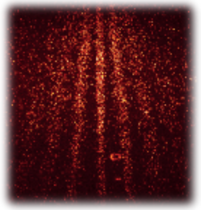
Nature 464, 697 (2010)

Matter-wave interferometry (free-fall):

$10^{0} – 10^{4}$ atoms

Coherence time
$10^{-3} – 10^{0}$ sec





Nature Nanotech. 7, 297 (2012)

Levitated (opto-)mechanics

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

recent review:
Gonzalez-Ballestero et al., Science **374**, 168 (2021)

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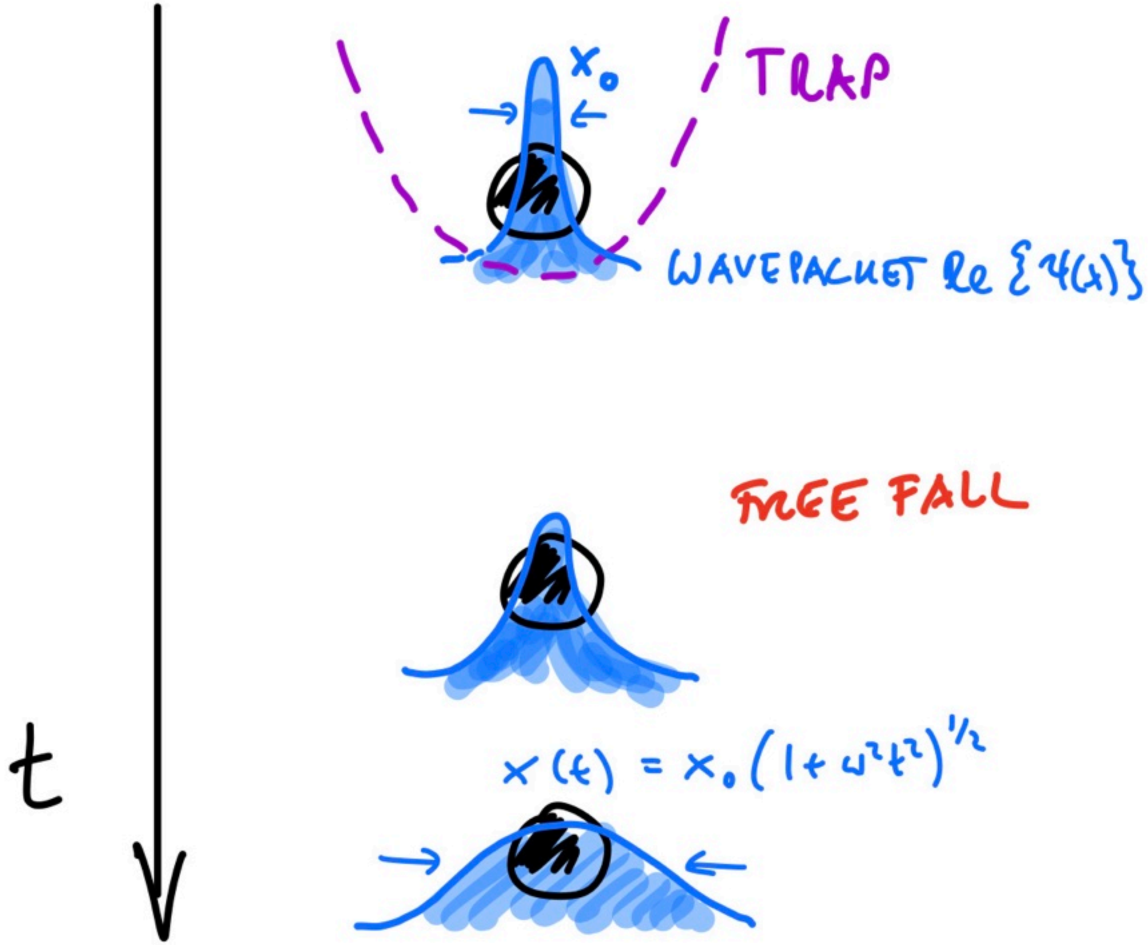
Towards „large“ quantum states?



x_0 = 3pm

x(12ms) = 80nm

= particle radius

Additional speedup by coherent inflation (inverted potential):

Romero-Isart, NJP 19, 123029 (2017)
Weiss et al., PRL 127, 023601 (2021)

Optically levitating nanoparticles

OPTICAL LEVITATION:

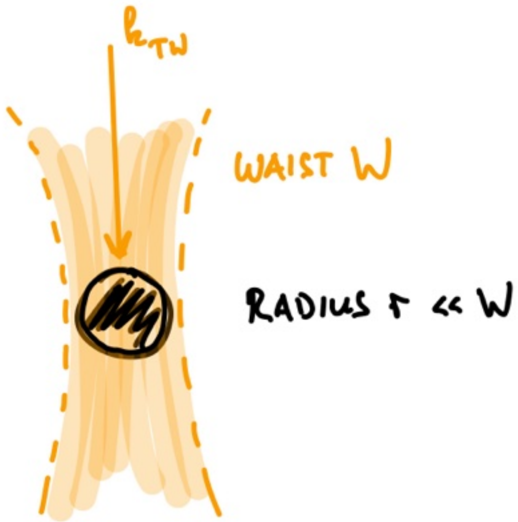
$\hat{H} \propto \underline{d} \cdot \underline{E} = \alpha \cdot E^2$

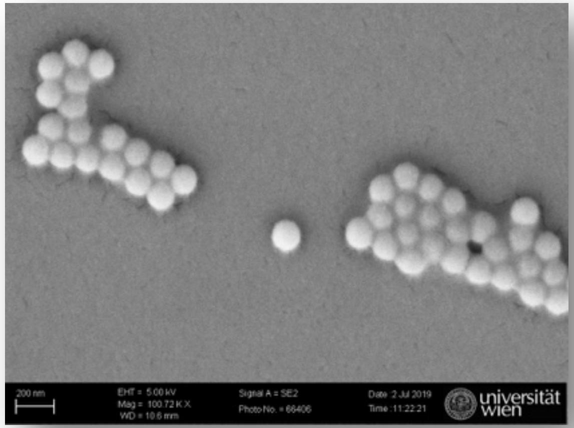
α: Re{Polarizability}

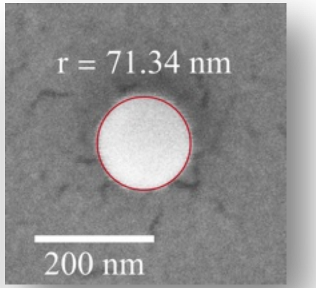
E: optical trapping field

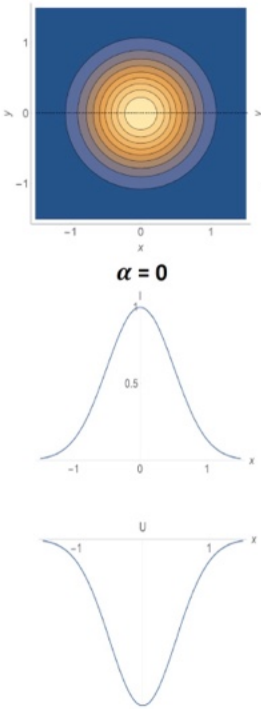
↳ beam intensity

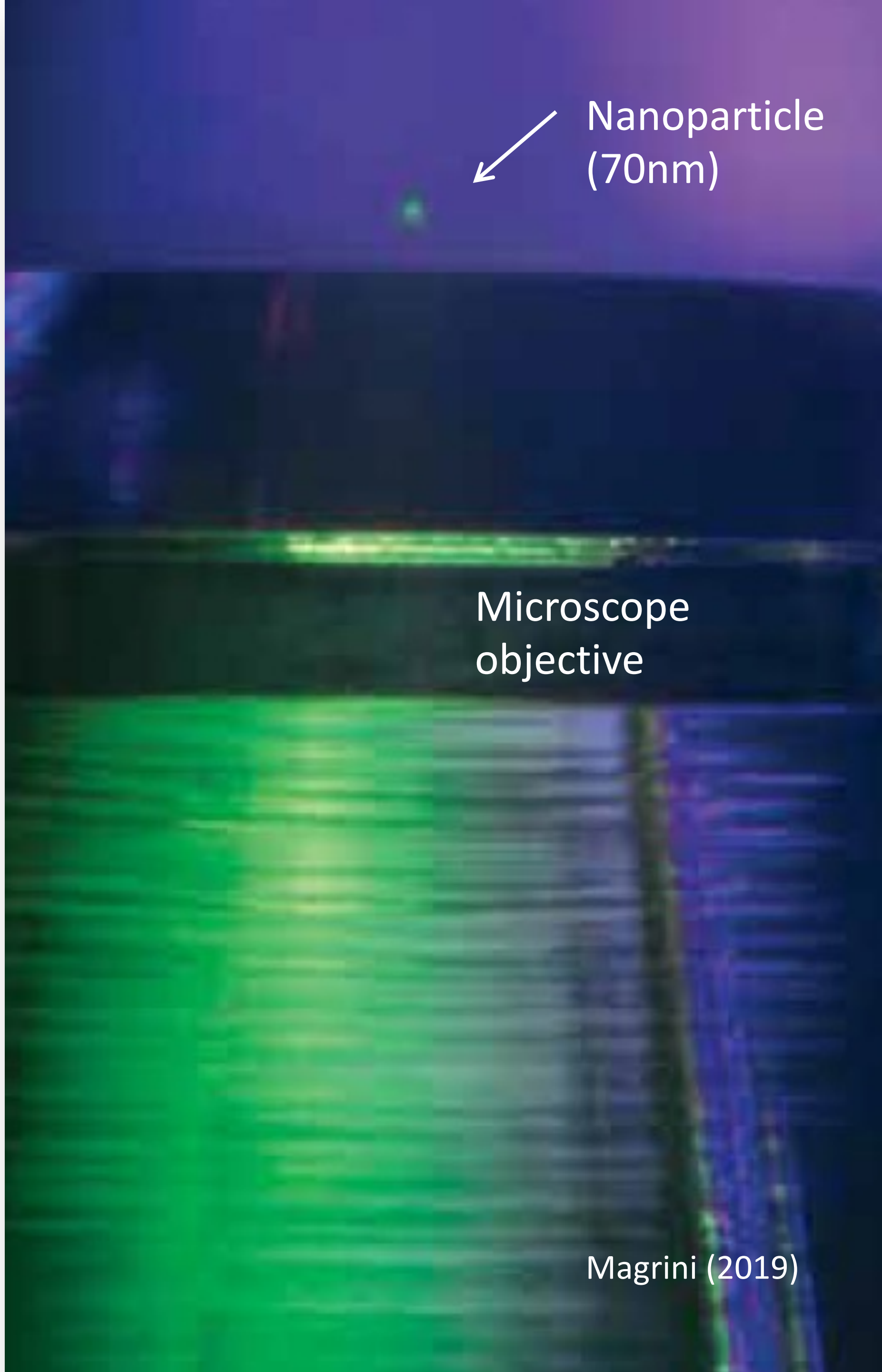
→ GRADIENT FORCE $F \propto (\nabla E^2) \cdot \alpha$











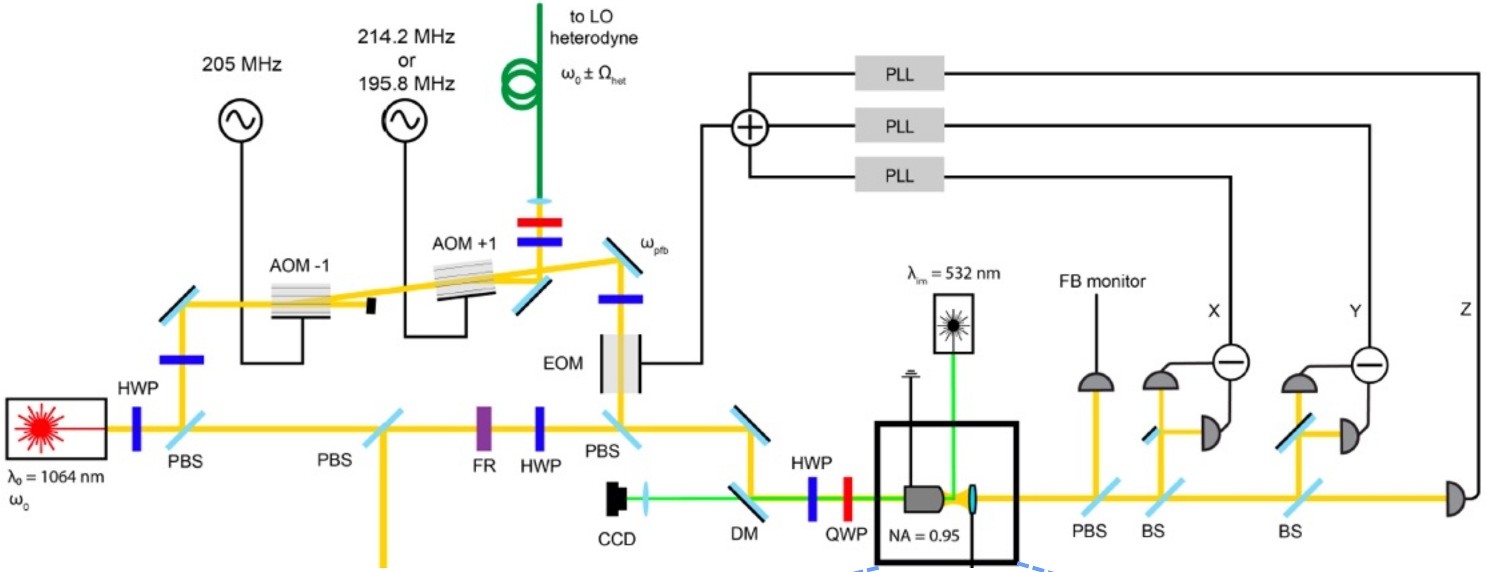
Pioneering work by Ashkin:

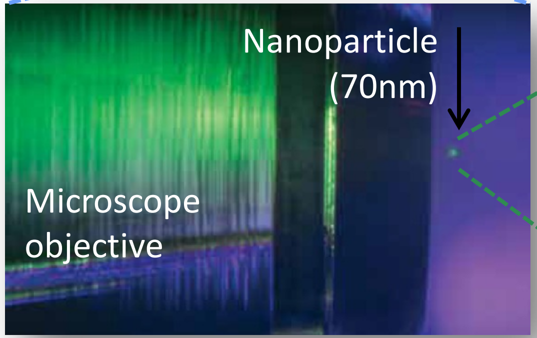
A. Ashkin, PRL 24, 156 (1970).

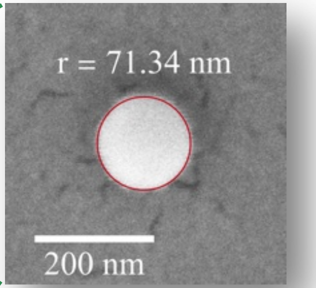
A. Ashkin, J. M. Dziedzic, APL 28, 333 (1976).

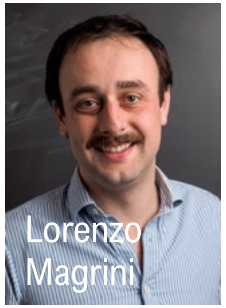
Keeping a particle in high vacuum: feedback control

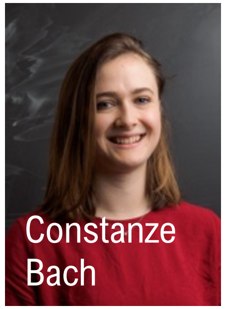
Magrini et al., Nature 595, 373 (2021)
see also
F. Tebbenjohanns et al., PRL 124, 013603 (2020)
F. Tebbenjohanns et al., Nature 595, 378 (2021)











3d parametric feedback stabilizes the particle @ 9e-9 mbar

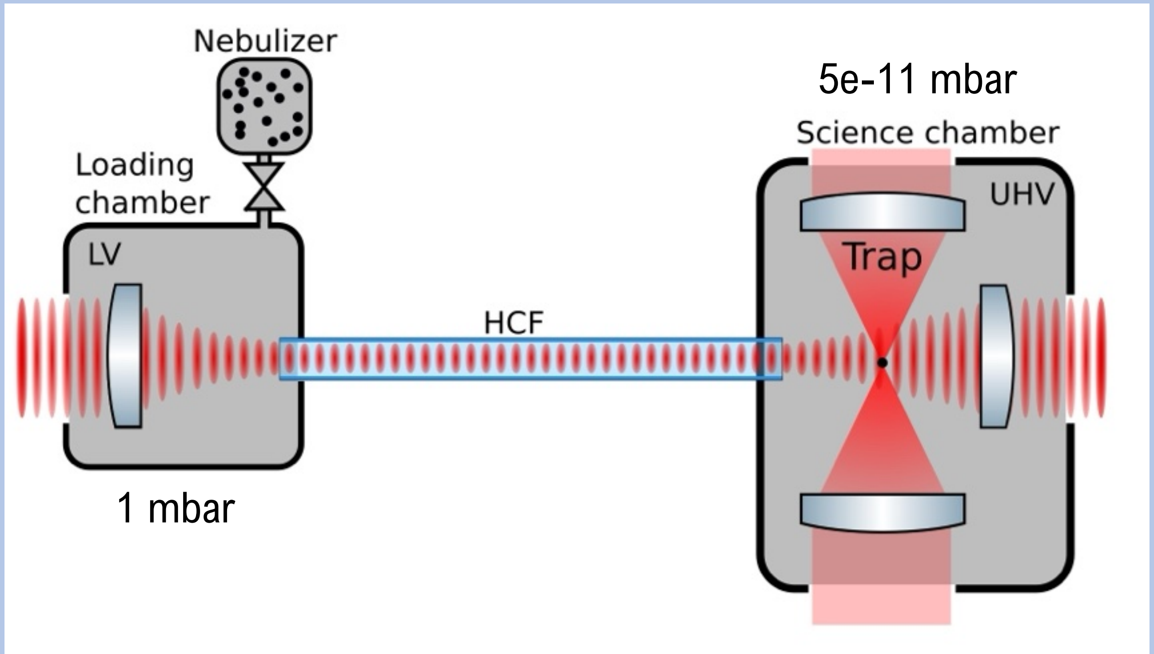
see also Gieseler et al., Phys. Rev. Lett. 109, 103603 (2012)

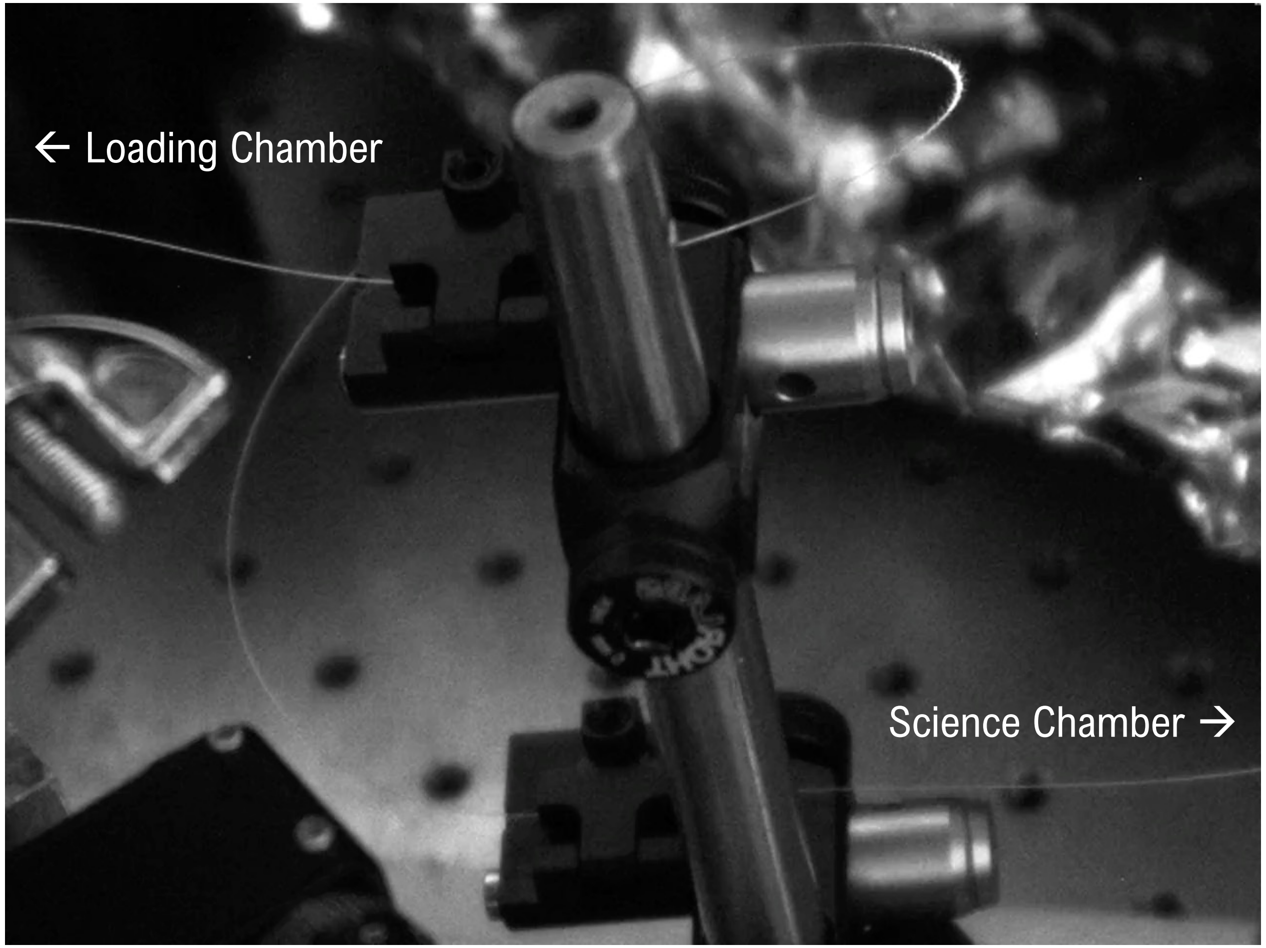
Lorenzo Magrini, Constanze Bach
P. Rosenzweig, A. Deutschmann, A. Kugi (TU Wien)

Trapping, transport and handover with a photonic crystal hollow core fiber

- particle trapping and transport through a 1064nm optical conveyor belt inside a photonic crystal hollow core fiber
- handover to a 1550nm standing wave trap @ < 1e-10 mbar

HCF loading scheme



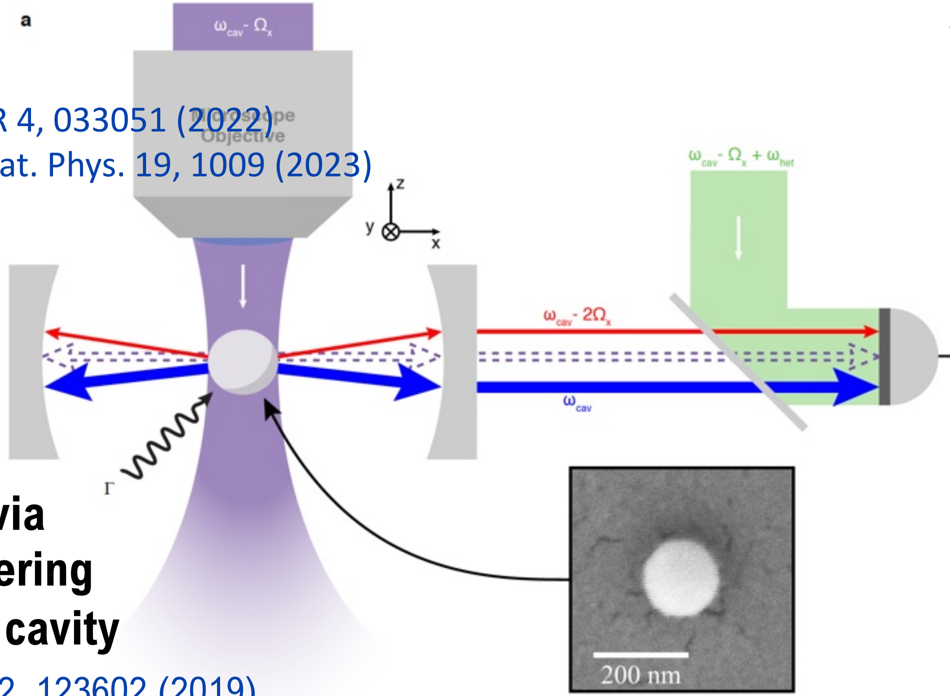


in preparation; see also Grass et al., APL 108, 221103 (2016)

Motional Quantum Ground State of a Levitated Nanoparticle

Delić et al., Science **367**, 892 (2020)

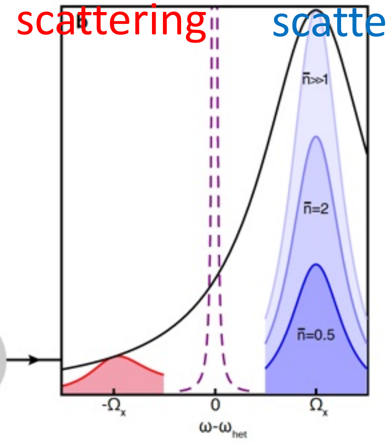
2d:
Ranfagni et al., PRR 4, 033051 (2022)
Piotrowski et al., Nat. Phys. 19, 1009 (2023)

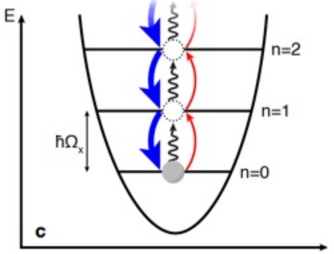


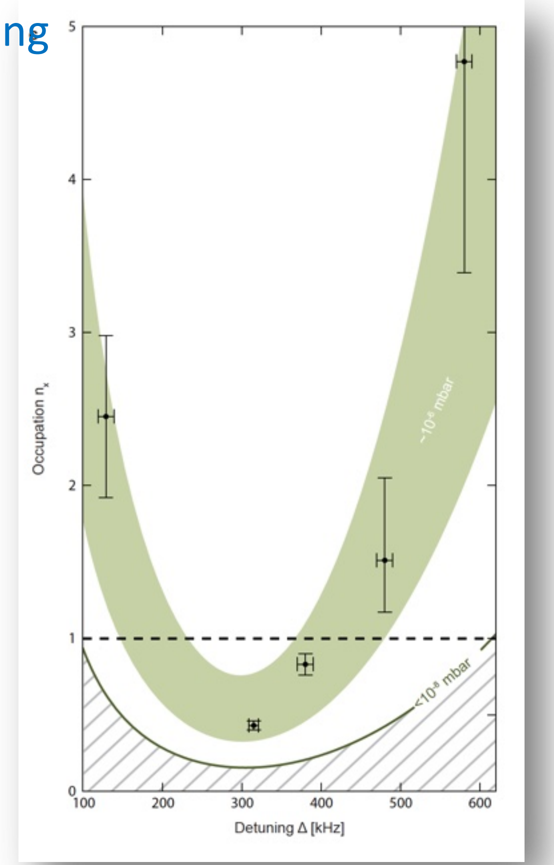
Laser cooling via coherent scattering into an optical cavity

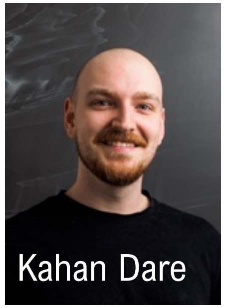
Delic et al., PRL 122, 123602 (2019)
Windey et al., PRL 122, 123601 (2019)

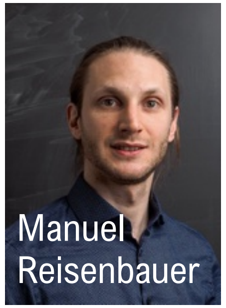
Stokes scattering | **anti-Stokes scattering**











Vladan Vuletic @ MIT

$\omega_x \approx 2\pi{\times}305$ kHz

$\omega_z \approx 2\pi{\times}80$ kHz

$\omega_y \approx 2\pi{\times}275$ kHz

$\kappa = 2\pi{\times}193$ kHz

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

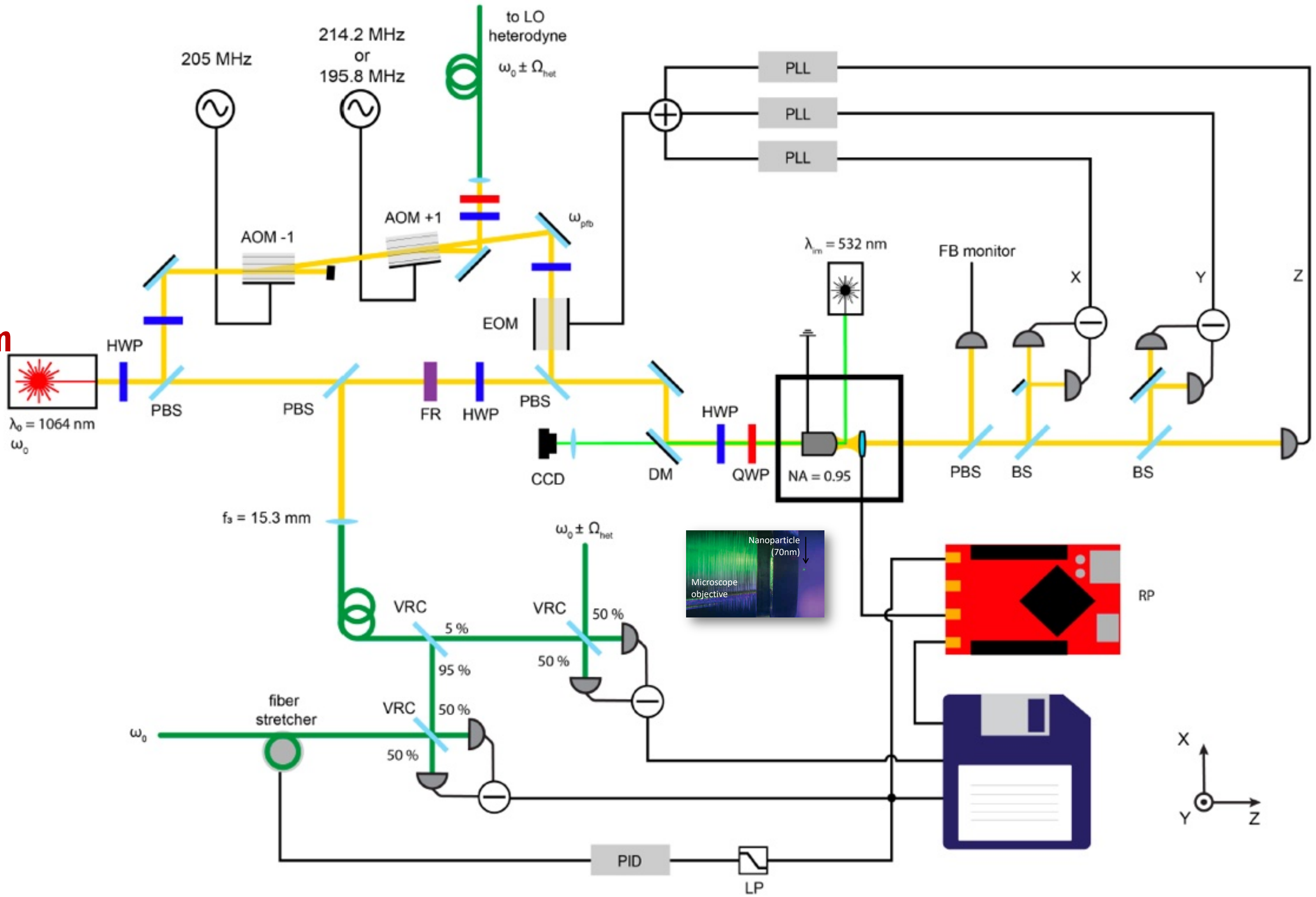
n_x **< 0.5** (ground state probability **> 2/3**)
Center-of-mass Tc = 12uK; environment Te > 300K
$g_x = 2\pi$ x 71 kHz, Cooperativity C = 5

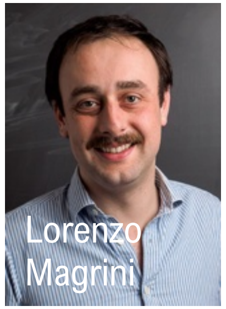
based on:
Hechenblaikner et al., PRA 58, 3030 (1998)
Vuletic & Chu, PRL 84, 3787 (2000)
Leibrandt et al., PRL 103, 103001 (2009)
Hosseini et al., PRL 118, 183601 (2017)

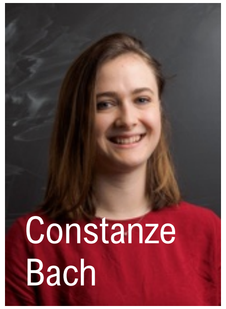
Quantum Kalman Control: ground-state cooling

Magrini et al., Nature 595, 373 (2021)
see also
F. Tebbenjohanns et al., PRL 124, 013603 (2020)
F. Tebbenjohanns et al., Nature 595, 378 (2021)

- **Confocal backplane imaging** allows **quantum limited position measurement @ 1.7 x Heisenberg limit** (1e-14 m/sqrt{Hz})
- **Kalman filtering** allows **real-time tracking of the quantum trajectory @ 1.3 x zero-point motion**
- **Optimal feedback (LQR)** allows to stabilize particle motion in its **quantum ground state (<n> = 0.5) in a room temperature environment**







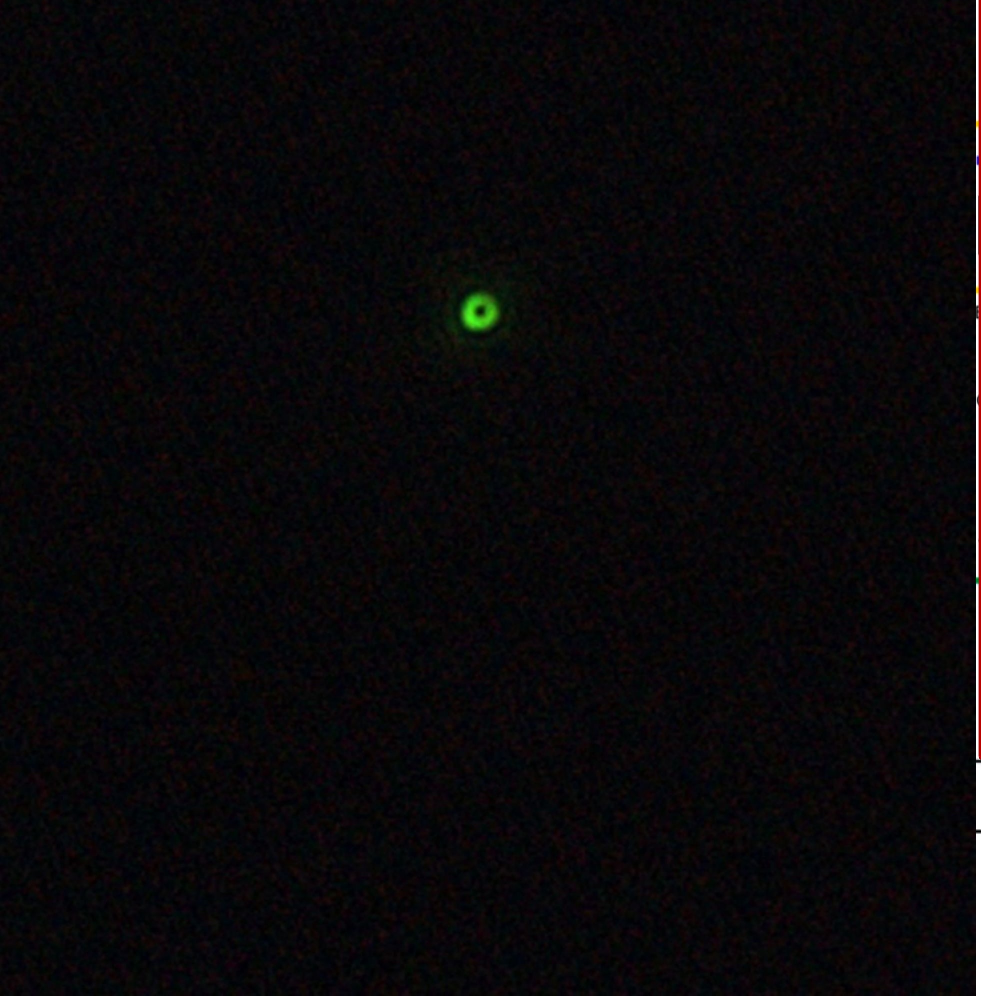
Lorenzo Magrini, Constanze Bach, Nikolai Kiesel
P. Rosenzweig, A. Deutschmann, A. Kugi (TU Wien)

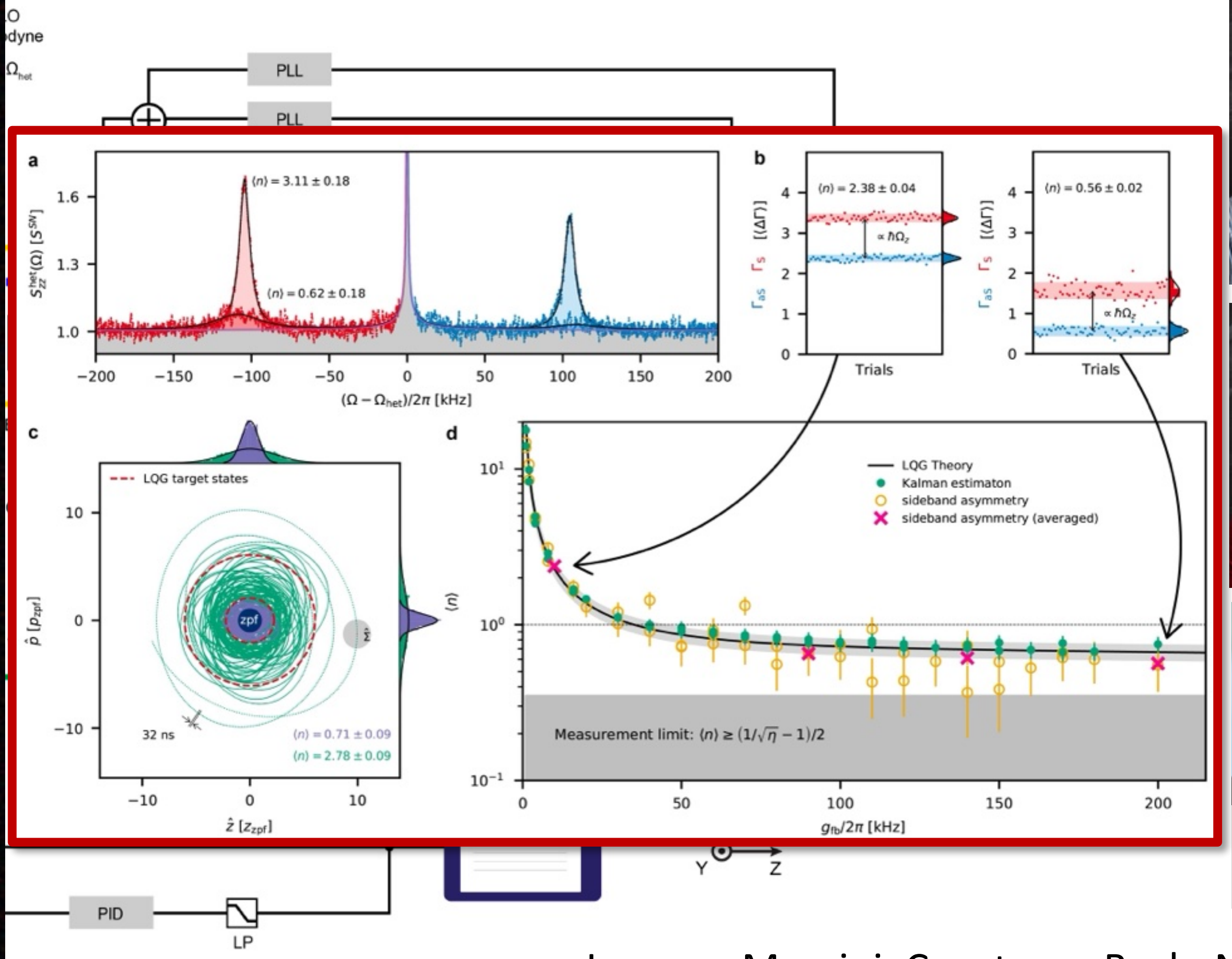
related:
Wieczorek et al., PRL 114, 223601 (2015)
Rossi et al., PRL 123, 163601 (2019)

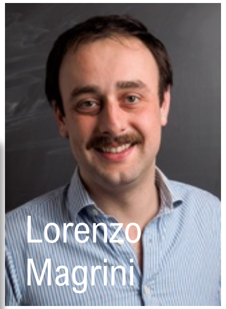
ground-state cooling

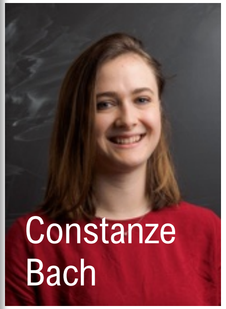
Magrini et al., Nature 595, 373 (2021)
see also
F. Tebbenjohanns et al., PRL 124, 013603 (2020)
F. Tebbenjohanns et al., Nature 595, 378 (2021)

Image of a 150nm glass sphere in its quantum ground state of motion at a room temperature environment



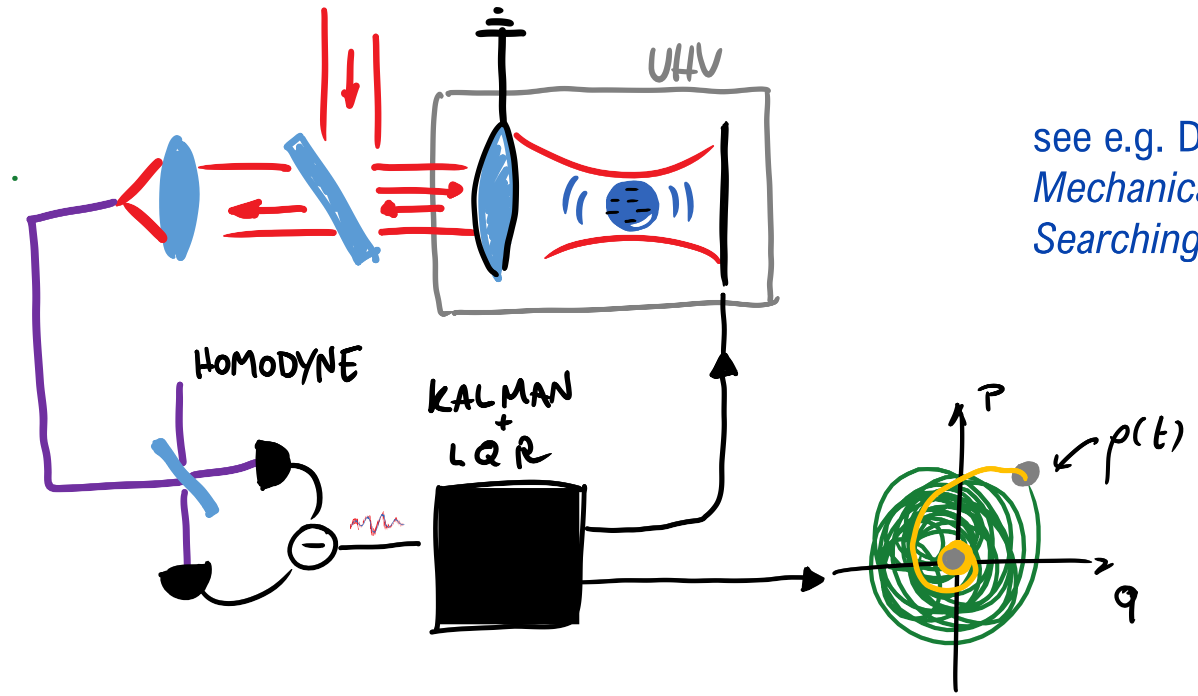






Lorenzo Magrini, Constanze Bach, Nikolai Kiesel
P. Rosenzweig, A. Deutschmann, A. Kugi (TU Wien)

Real-time state estimation: mechanical sensing of weak transient forces

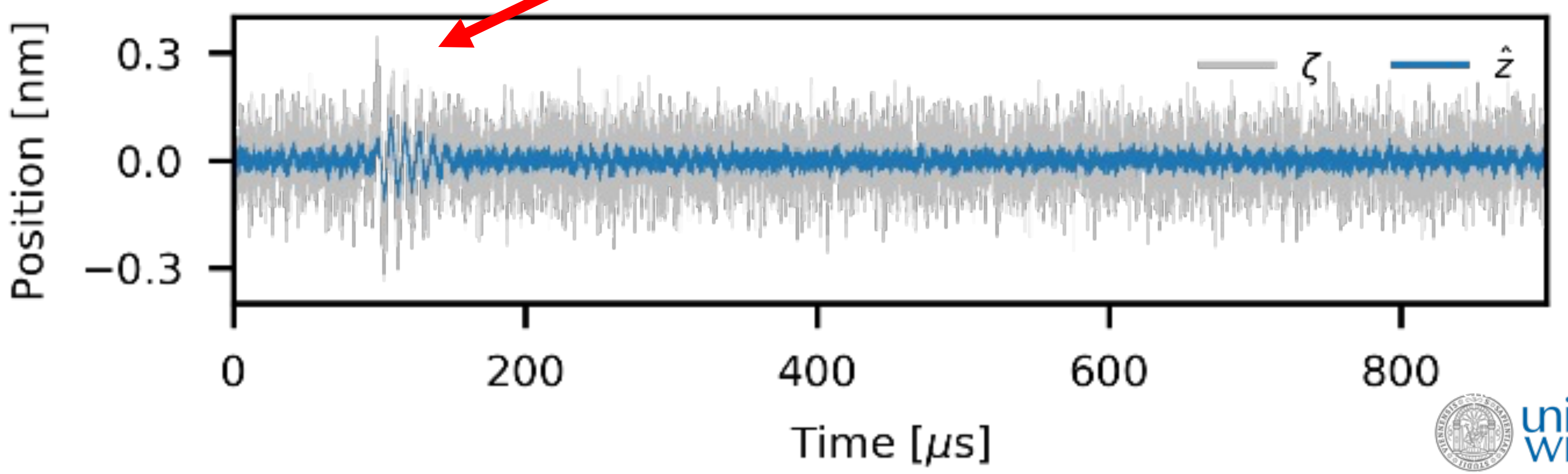


see e.g. David Moore group (Yale):
Mechanical detection of nuclear decays, arXiv:2402.13257
Searching for new physics using optically levitated sensors, QST 6, 014008 (2021)

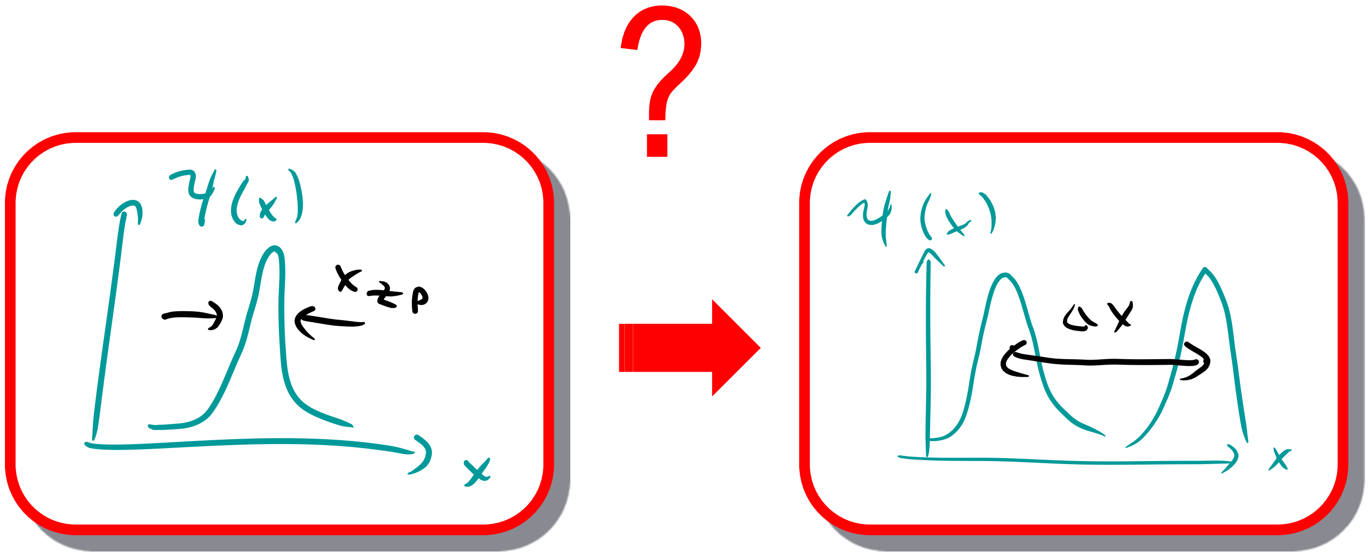
Measuring the kick of a single gas molecule?

$$\Delta p \sim 7p_{\mathrm{zpf}} \sim 7\times10^{-23}\ kg\ m\ s^{-1}$$

(ca. 100 keV/c)



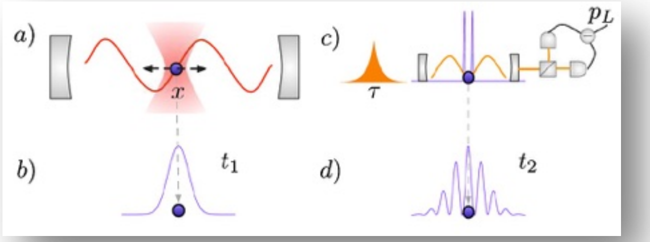
Towards „large“ quantum superposition states?



How to prepare “macroscopic superpositions”?

funded by ERC Synergy Grant, with
Oriol Romero-Isart (Innsbruck)
Lukas Novotny (ETH)
Romain Quidant (ETH)

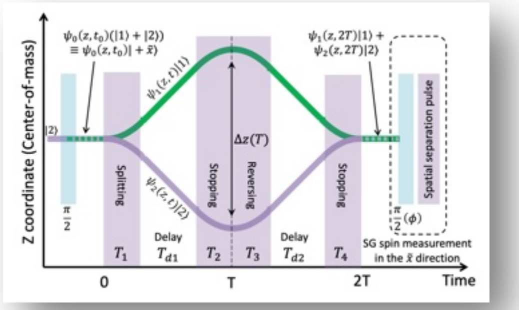
free-fall + quantum measurement



Romero-Isart et al., PRL 107, 020405 (2011)
Pinot et al., arxiv 1603.01553 (2016)

OR

internal degrees of freedom



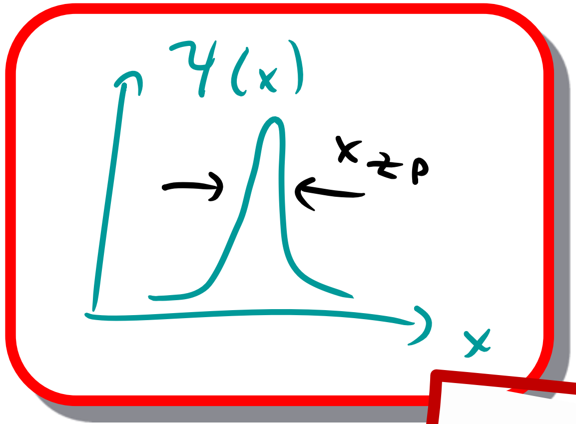
Folman et al., arxiv 2011.10928, 2105.01094

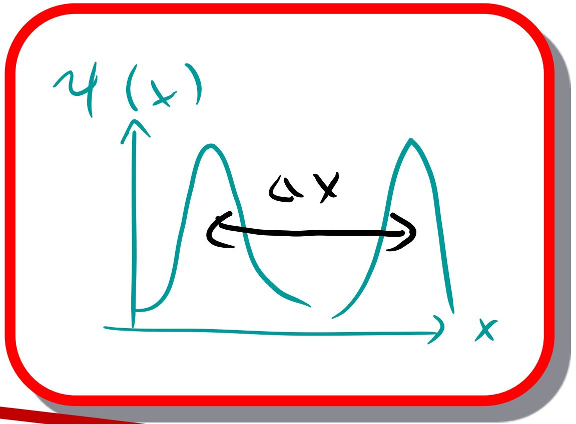
OR

in-trap coherent dynamics

Towards „large“ quantum superposition states?

Neumeier et al., arXiv:2207.12539 (PNAS 2024)
related: Roda-Llordes et al., PRL 132, 023601 (2024)

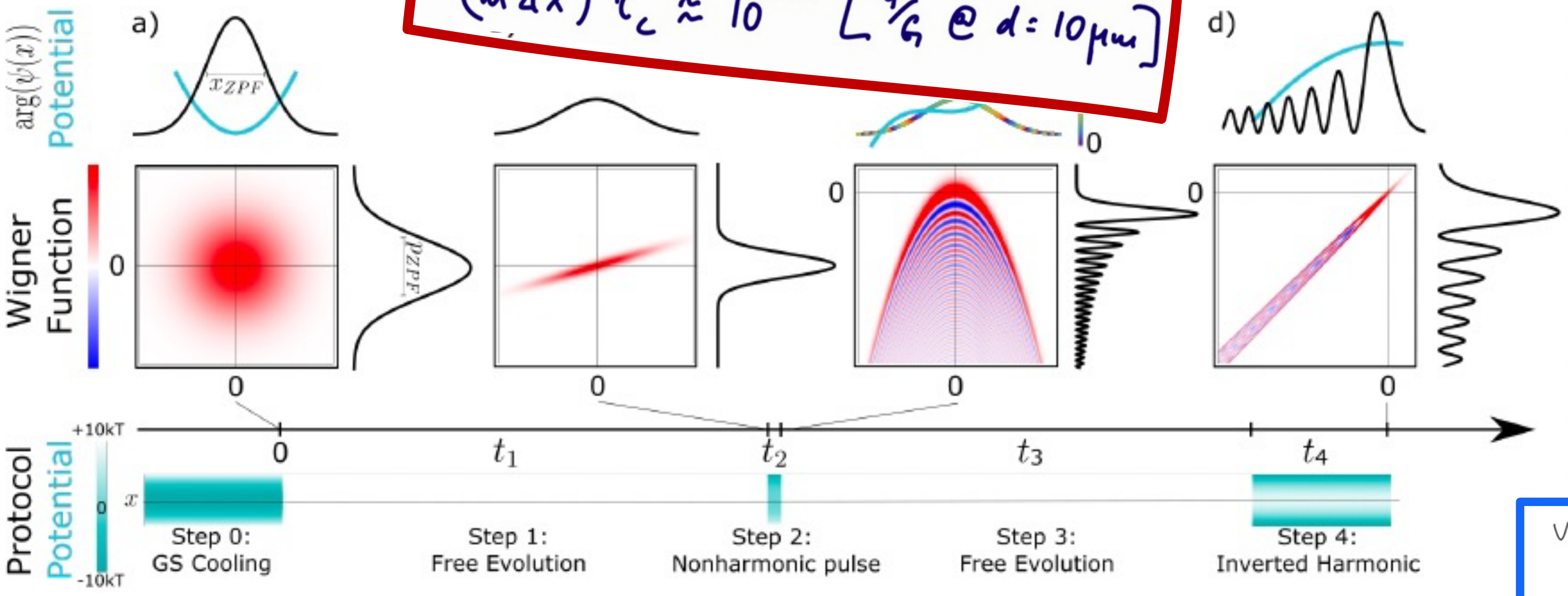


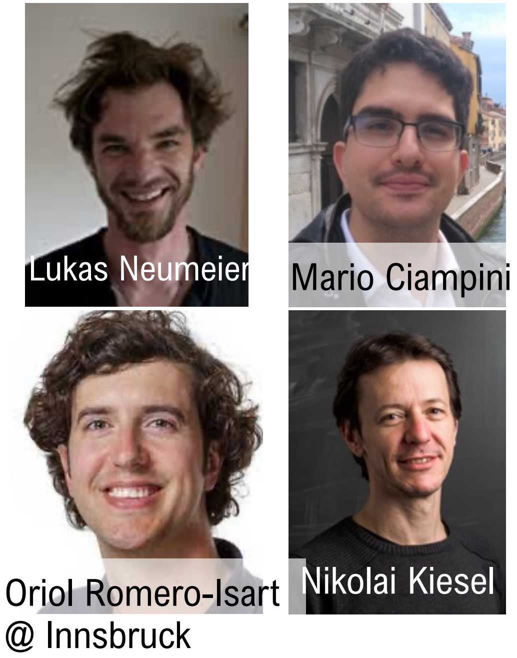


$(m \Delta x)^2 \tau_c \approx 10^{-10} \, [\hbar / G \; @ \; d = 10\mu m]$

The SUPER-MARIO protocol:

- **all-optical state control via potential modulation**
- **Particle is levitated all the time (no free-fall)**
- **Expectation: nm-sized quantum interference of a 50nm particle at 300K and UHV within milliseconds**



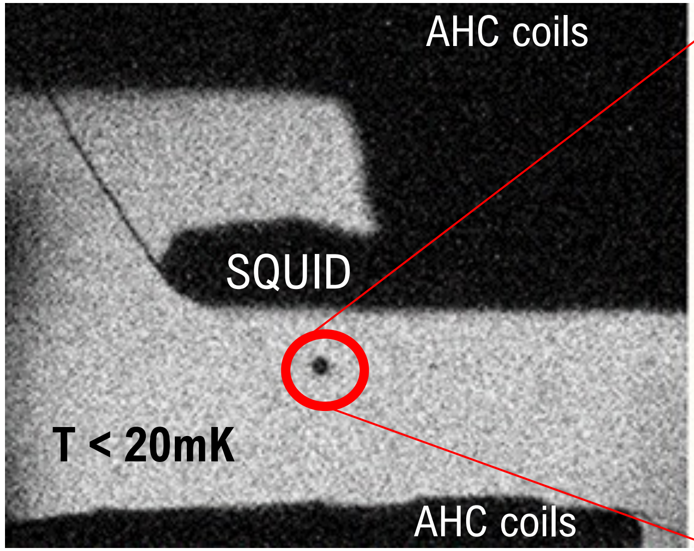


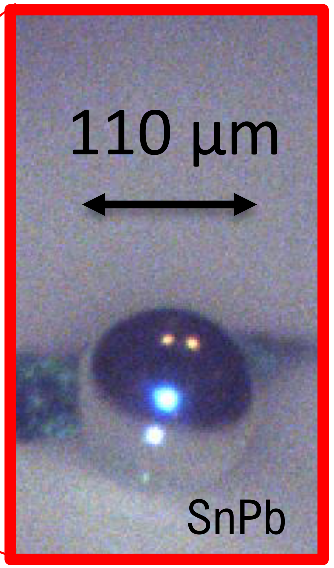
$V(x) \propto I(x)$

SHORT PULSE $I(x)$: $\psi(x) \to \psi(x) \exp\{-\frac{i}{\hbar} V(x) t\}$

Hofer et al., PRL 131, 043603 (2023)

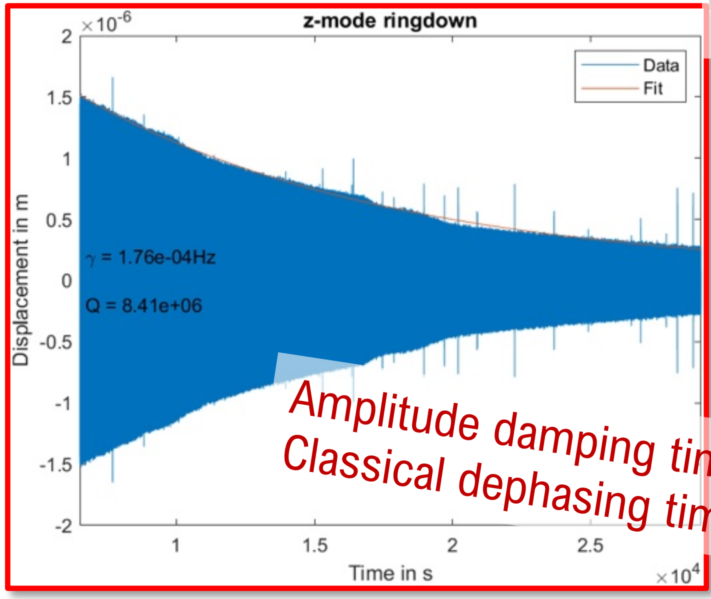
Towards larger masses: superconducting levitation





ca. Planck mass

- **stable levitation of a 5.6µg superconducting SnPb sphere at 15mK (Q > 1e7 at 200Hz)**
- **DC-SQUID readout of particle motion allows for 3D magnetic feedback**
- **cryogenic vibration isolation attenuates seismic noise by seven orders of magnitude**



Amplitude damping time > 40,000 sec
Classical dephasing time > 80 sec

Oosterkamp & Hensen group (Leiden) / Wieczorek group (Chalmers)

- B. van Waarde, The lead zeppelin : a force sensor without a handle, Ph.D. thesis, Leiden University (2016)
- Gutierrez Latorre et al., PR Applied 19, 054047 (2024)

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WMI, BAdW
UTübingen

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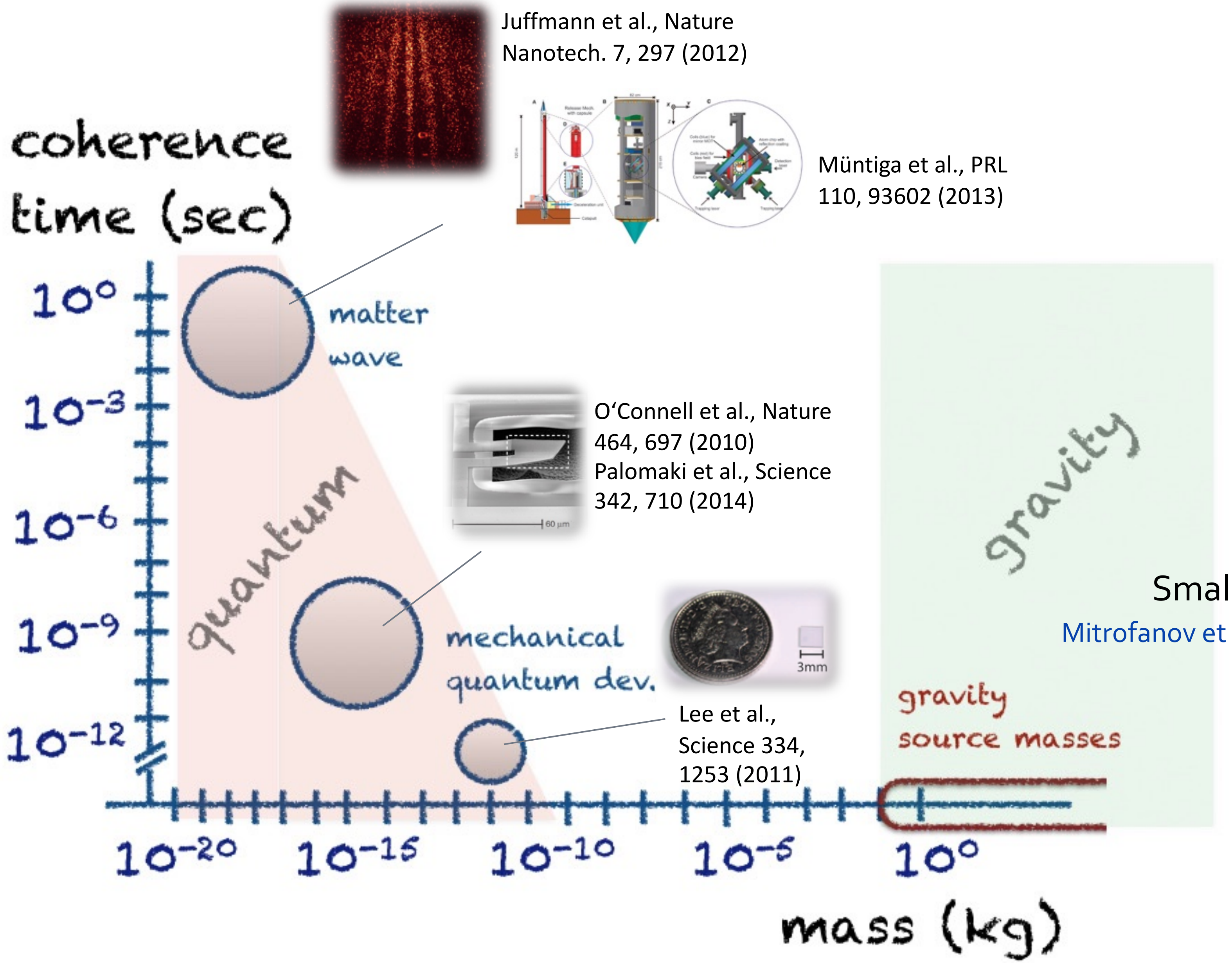
Reality check: quantum systems as gravitational source masses?

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



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

Mitrofanov et al., Zh. Eksp. Teor. Fiz. 94,16-22 (1988)

Lee et al., PRL 124, 101101 (2020)

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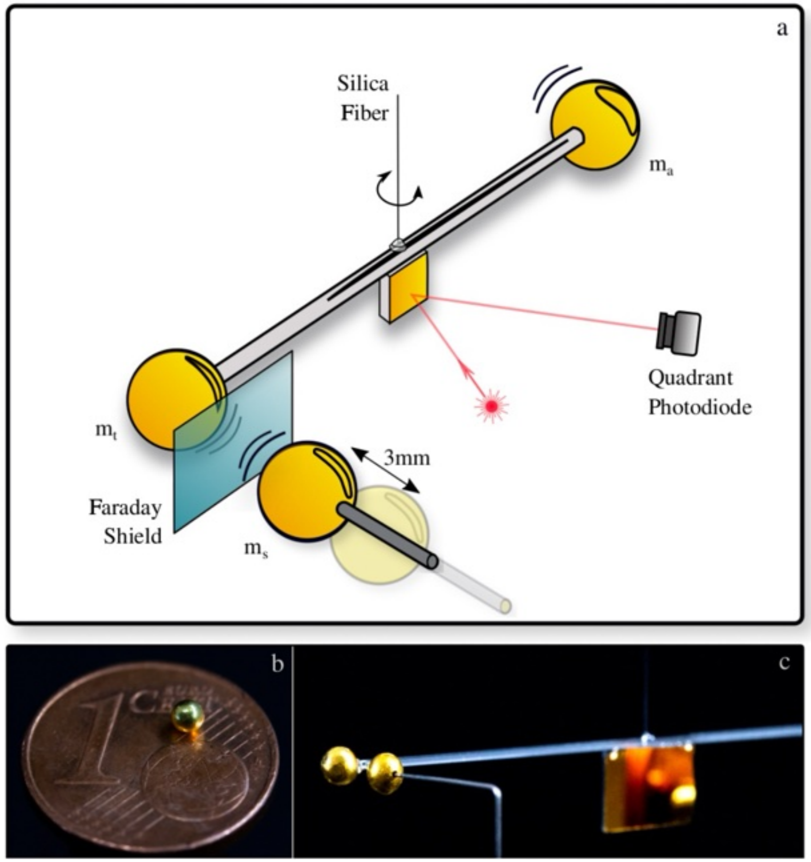
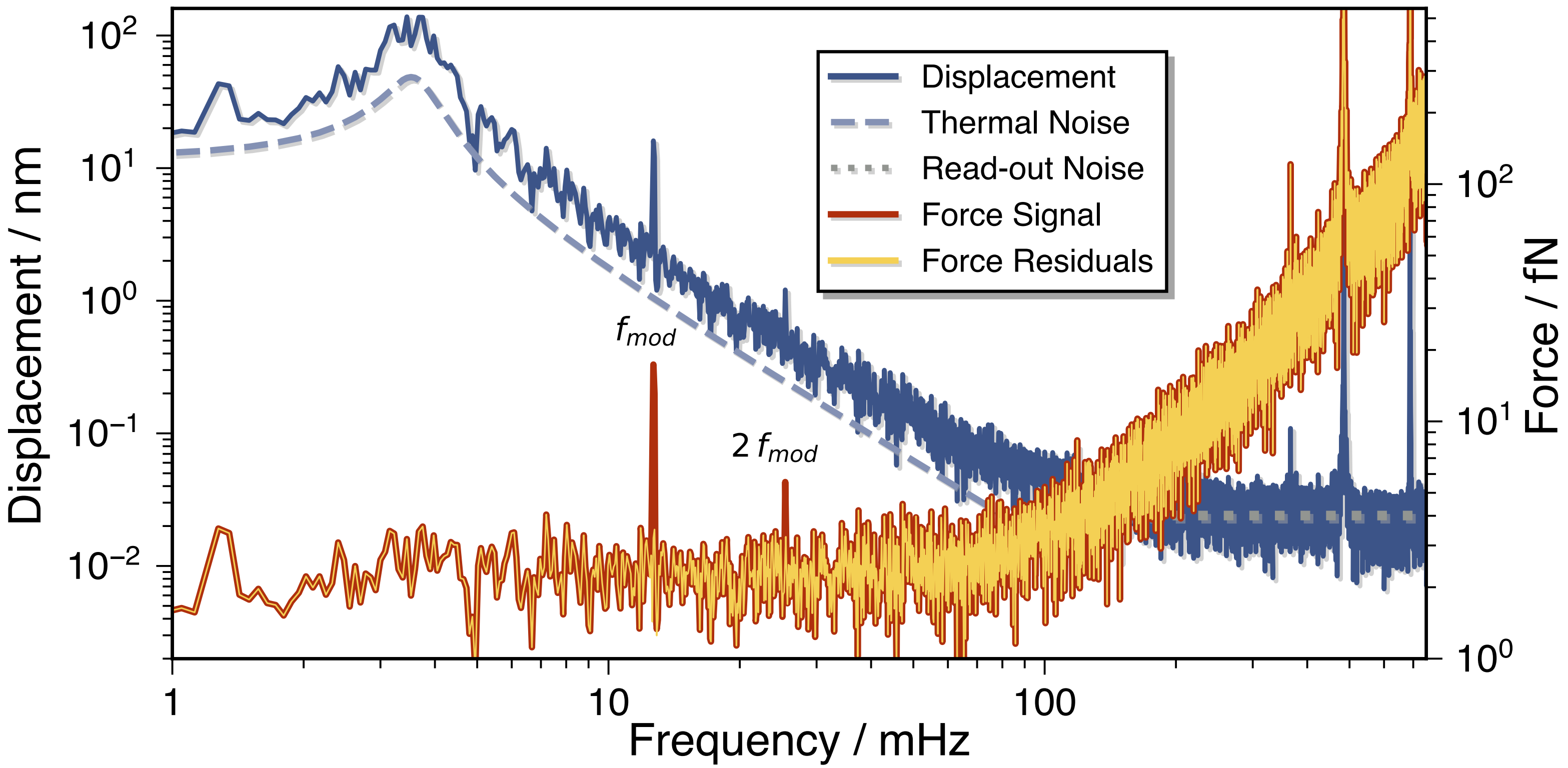
Silent Christmas Nights...

Westphal et al.,
Nature 591, 225 (2021)





- We observe a linear and quadratic acceleration modulation (at f_mod and 2f_mod) produced from a **90mg source mass**
- We resolve an **acceleration modulation of 3e-10 m/s^2** with an accuracy of 10% and a **precision of 1% (3e-12 m/s^2)**
- The observed coupling deviates from the CODATA value for Newton's constant by 9%, which is covered in the known systematic uncertainties of our experiment (i.e. interaction is >90% gravitational)

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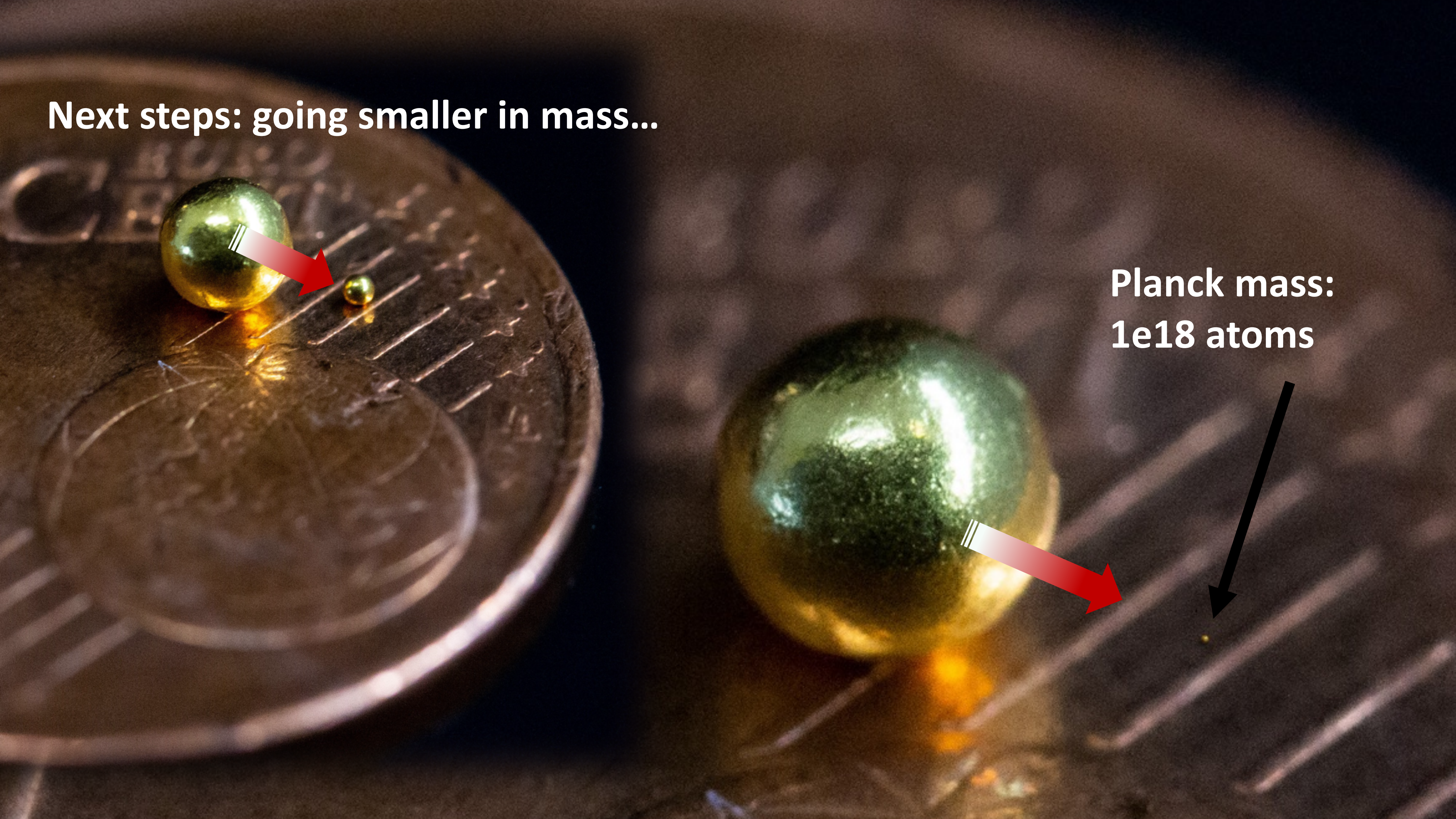

Next steps: going smaller in mass…
Planck mass:
1e18 atoms

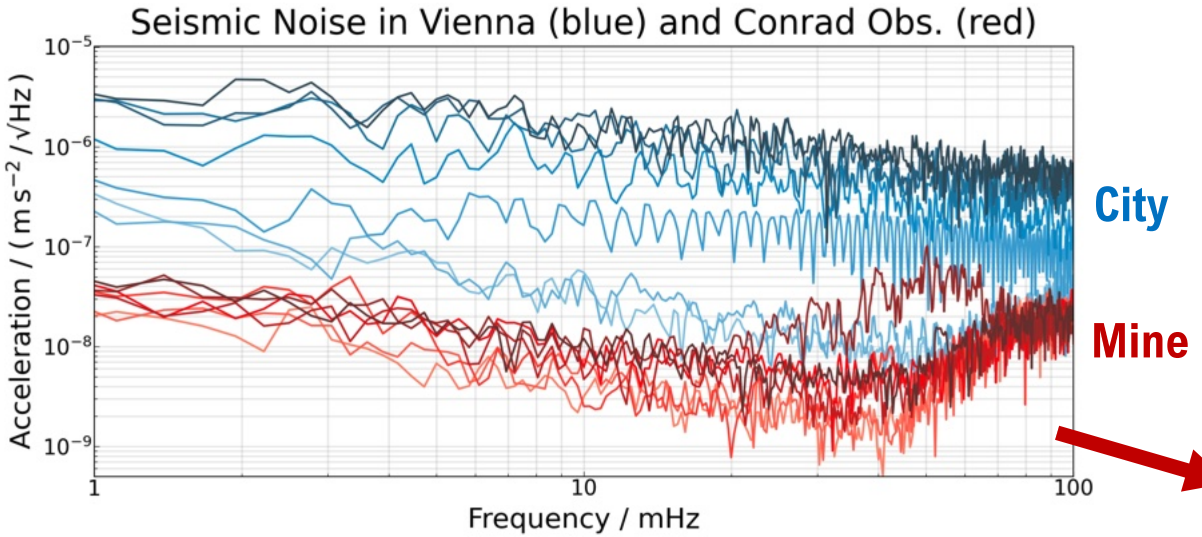
... by going underground

ZAMG
Zentralanstalt für Meteorologie und Geodynamik

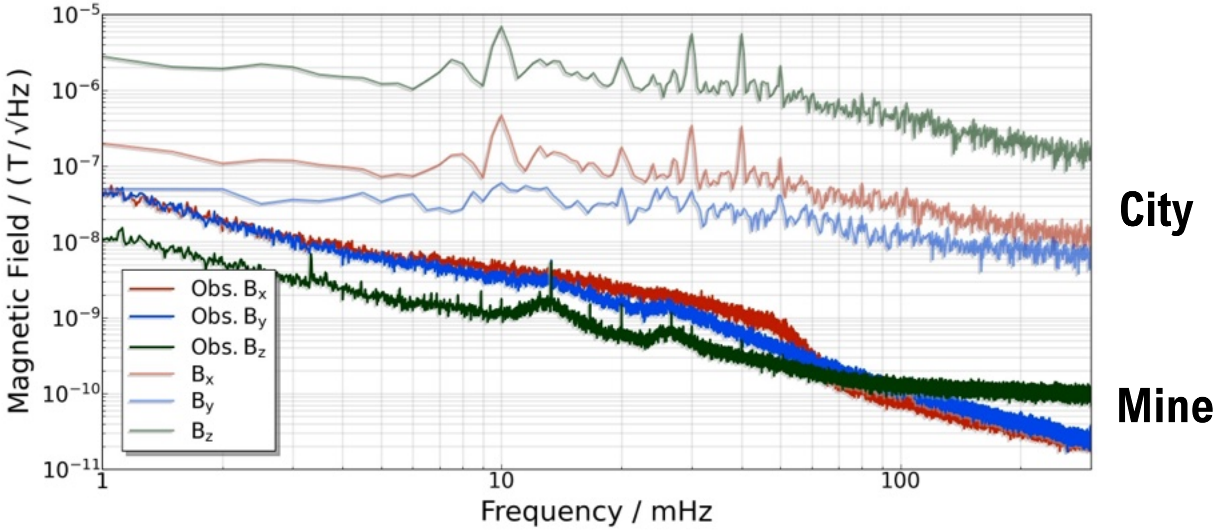
Conrad Observatory, Trafelberg, Austria

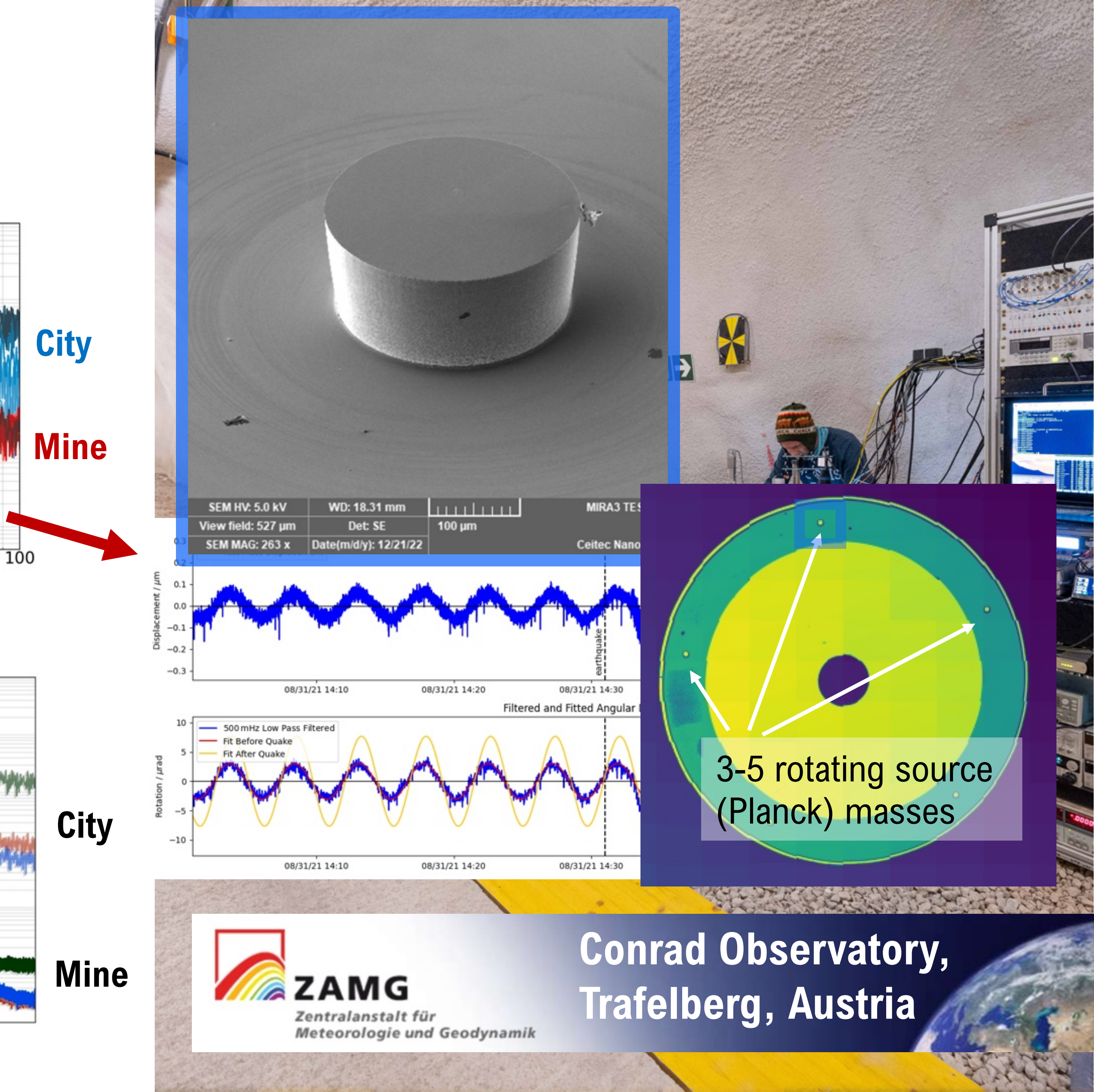
Improved noise performance...

Seismic

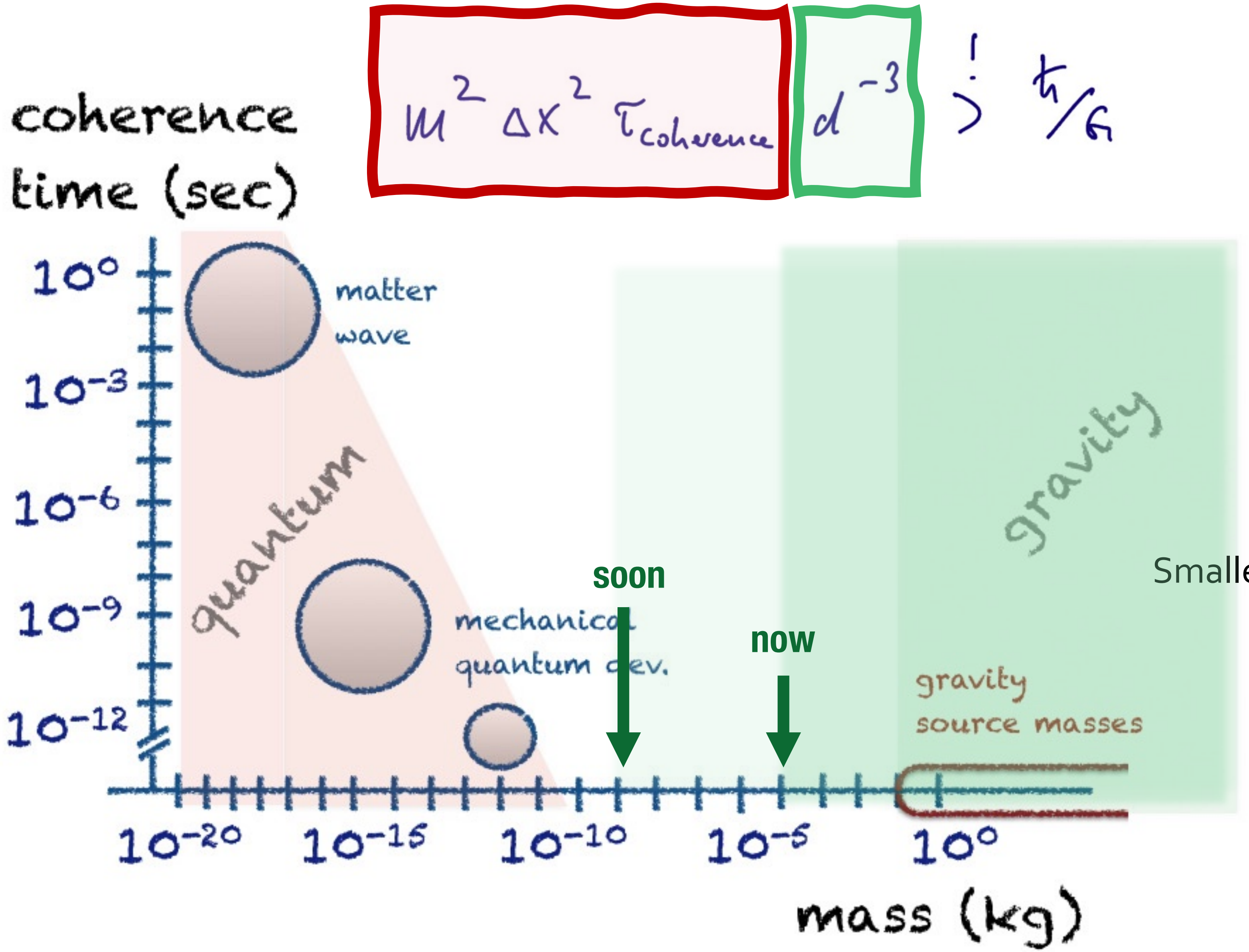


Magnetic





Reality check: quantum systems as gravitational source masses?



- How small can we make a source mass?
- How massive can we make a quantum system?

Smallest source mass to date: **0.09 g**

Westphal et al., Nature 591, 225 (2021)

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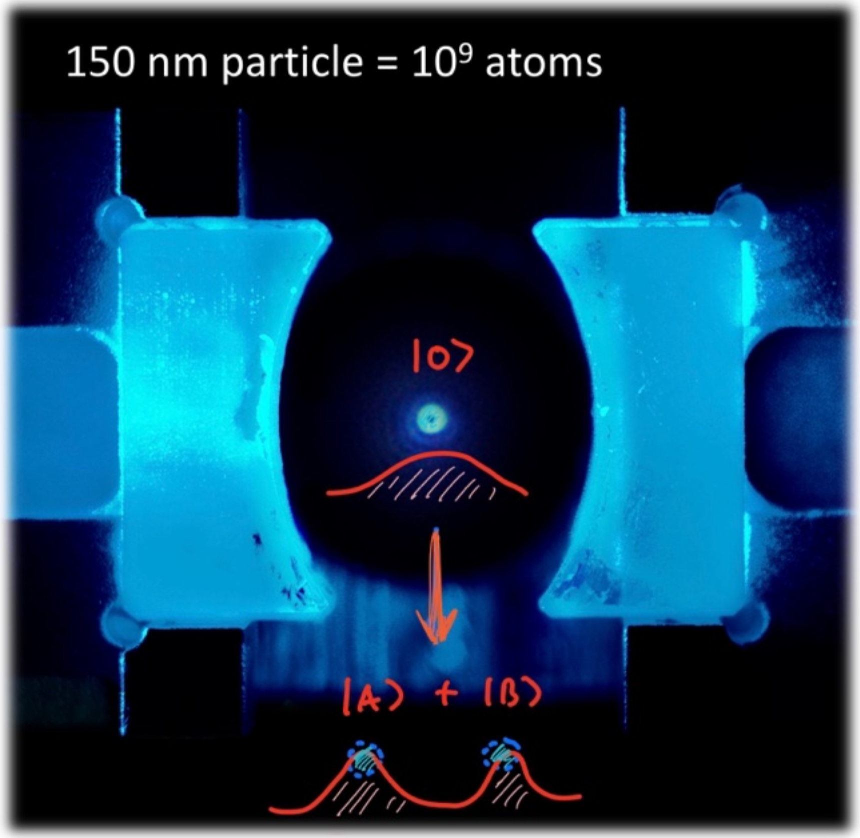
Summary

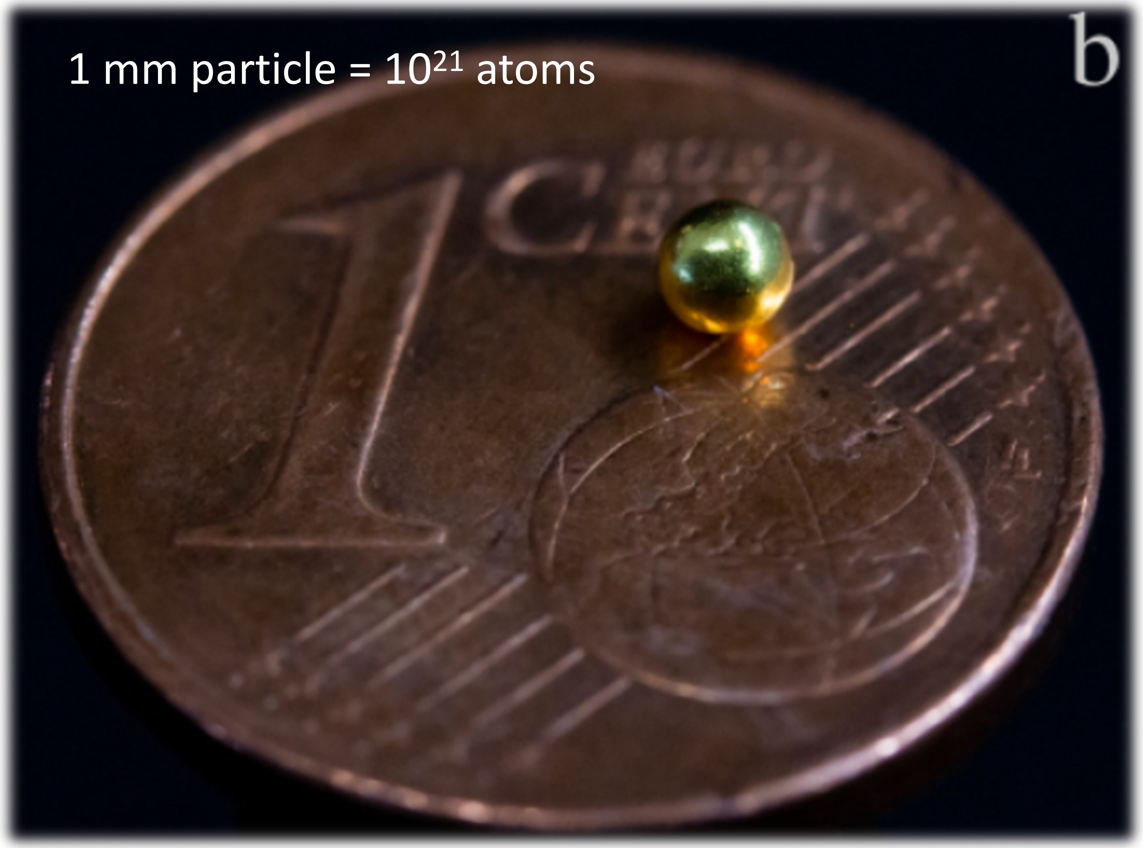
- Levitated quantum control in the regime of large mass and long coherence times
- Bottom-Up: Quantum regime of nanoparticles
- Top-Down: Gravitational coupling of mm-sized particles

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



Largest quantum mass in our lab: Quantum motion of a silica nanosphere at room temperature

Delic et al., Science 367, 892 (2020)
Magrini et al., Nature 595, 373 (2021)



Smallest gravitational source mass to date (1mm gold sphere = 4,000 times the Planck mass)

Westphal et al., Nature 591, 225 (2021)

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What do we (not) learn from observing entanglement generated by gravity

The generation of gravitationally induced entanglement…

- … is inconsistent with assuming gravity is described by a classical field theory
- … does not tell us anything about the quantization of gravity
- … is consistent with a low-energy linearized quantum field theory of gravity
- … excludes by principle all gravitational "collapse" models
- … requires quantization of gravity to avoid conflict with causality and complementarity

  IF observed together with retardation

e.g. Belenchia, Wald, et al., *Phys. Rev. D* **98**, 126009 (2018)
Danielson et al., Phys. Rev. D **105**, 086001 (2022)
Martín-Martínez, Perche, arXiv:2208.09489 (2022)

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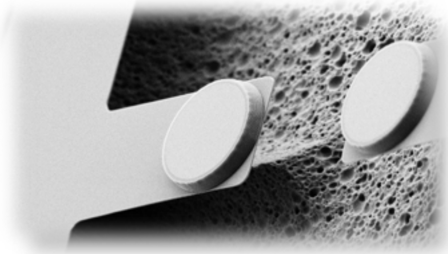
Ars longa, vita brevis

2004 2006 2008 2010 2012 2014

2004-2014 Quantum optomechanics

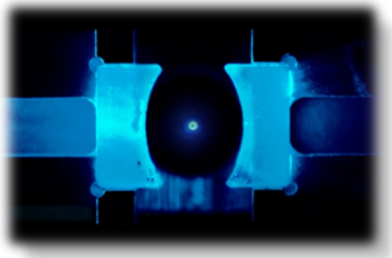
- (2004) motivation: Paolo Tombesi, Anton Zeilinger
- laser cooling of micromechanics (2006)
- strong optomechanical coupling (2009)
- quantum ground state micromechanics (2011)
- Cavity cooling of levitated solid (2013)



2014 2016 2018 2020 2022 2024

2014-2024 Combining quantum and gravity

- (2014) ERC grant: towards entangle-ment by gravity
- non-Gaussian quantum states of nanomechanics (2016-2018)
- quantum ground state levitated solid (2020)
- quantum control of levitated solid (2021)
- 1mm gravitational source mass (2021)



2024 2026 2028 2030 2032 2034

2024- ? Quantum sources of gravity

- delocalization of small masses (1e-9 M_P)
- delocalization of cold, small masses (1e-9 M_P)
- delocalization of cold, large masses (1e-3 M_P)
- 1M_P gravitational source mass
- gravity at 10um scale
- 1e-3 M_P source mass at 10um scale

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erc European Research Council

Alexander von Humboldt Stiftung/Foundation

FWF Der Wissenschaftsfonds.

cQOM

OMT OPTOMECHANICAL TECHNOLOGIES

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