Gravity, Strings and Supersymmetry Breaking, Pisa 2025

Quantum Signatures of Gravity in the Lab:

how to avoid the appearance of a classical world in gravity experiments?

Markus Aspelmeyer

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

A brief history of quantum optics:
does electromagnetism require a quantum description?

PHYSICAL REVIEW D VOLUME 9, NUMBER 4 15 FEBRUARY 1974

Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect*

John F. Clauser
Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 30 October 1973)

We have measured various coincidence rates between four photomultiplier tubes viewing cascade photons on opposite sides of dielectric beam splitters. This experimental configuration, we show, is sensitive to differences between the classical and quantum field-theoretic predictions for the photoelectric effect. The results, to a high degree of statistical accuracy, contradict the predictions by any classical or semiclassical theory in which the probability of photoemission is proportional to the classical intensity.

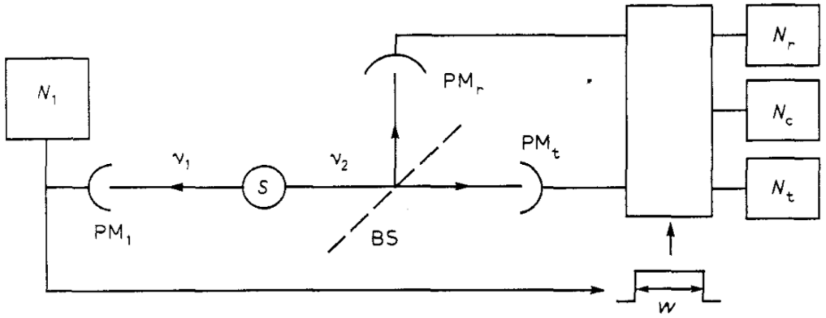
EUROPHYSICS LETTERS 15 February 1986
Europhys. Lett., 1 (4), pp. 173-179 (1986)

Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences.

P. Grangier, G. Roger and A. Aspect (*)
Institut d'Optique Théorique et Appliquée, B.P. 43 - F 91406 Orsay, France

(received 11 November 1985; accepted in final form 20 December 1985)

PACS. 42.10. – Propagation and transmission in homogeneous media.
PACS. 42.50. – Quantum optics.



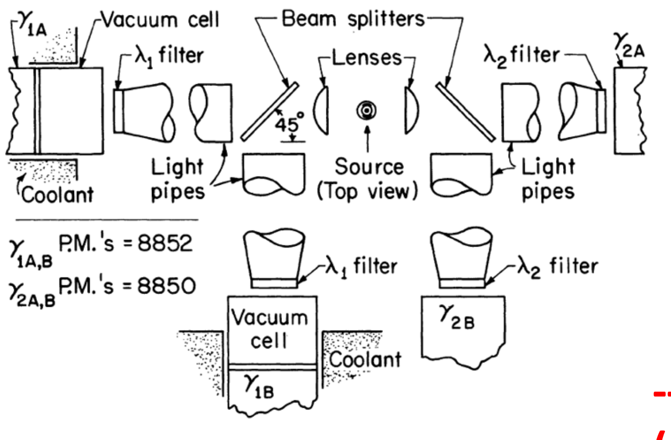
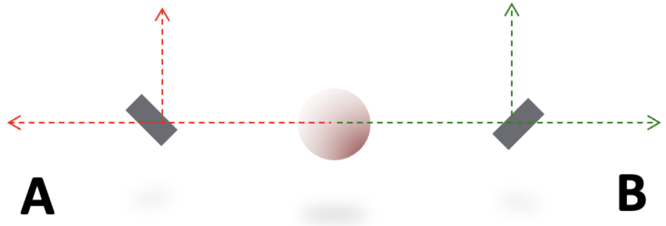


FIG. 2. Schematic diagram of our apparatus.

Cauchy-Schwarz: $g^{(2)}_{AB} \leq [g^{(2)}_{AA} \times g^{(2)}_{BB}]^{1/2}$



--> plus Bell tests: there is no (classical) alternative to QED!

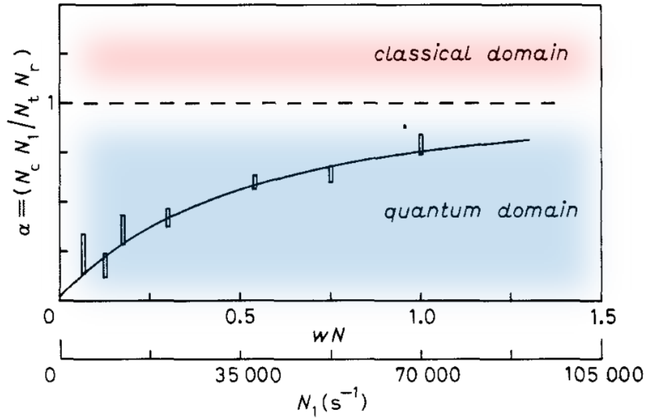


Fig. 2. – Anticorrelation parameter α as a function of wN (number of cascades emitted during the gate) and of N_1 (trigger rate). The indicated error bars are ± one standard deviation. The full-line curve is the theoretical prediction from eq. (8). The inequality $\alpha \geq 1$ characterizes the classical domain.

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)

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

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.

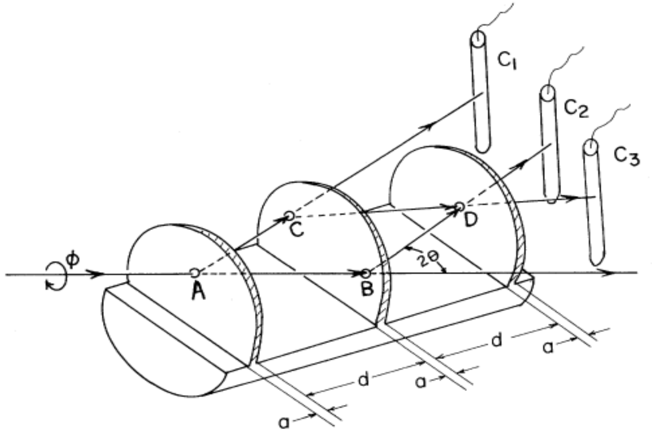
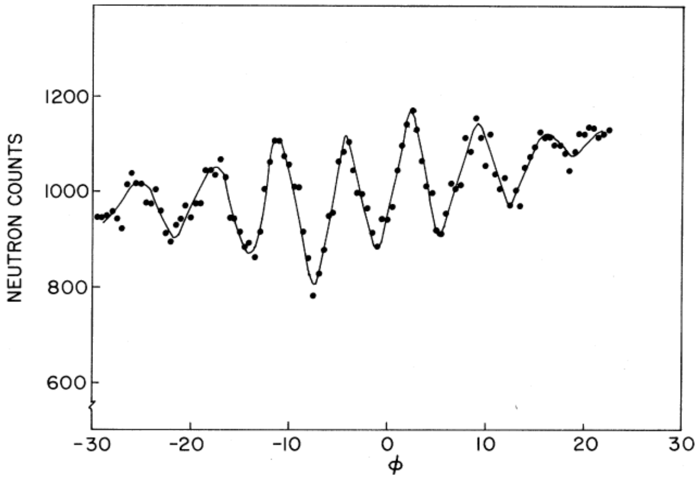
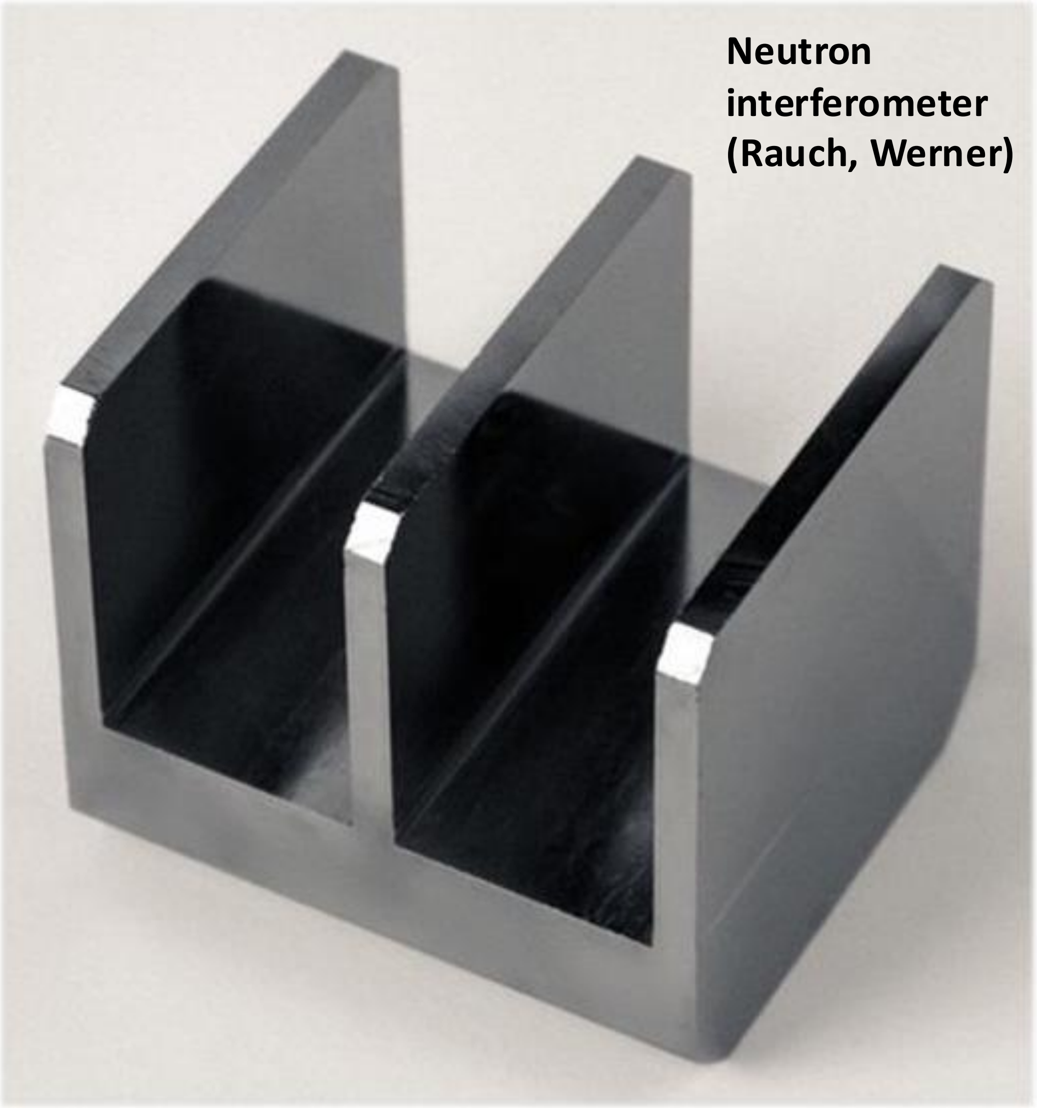


FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.

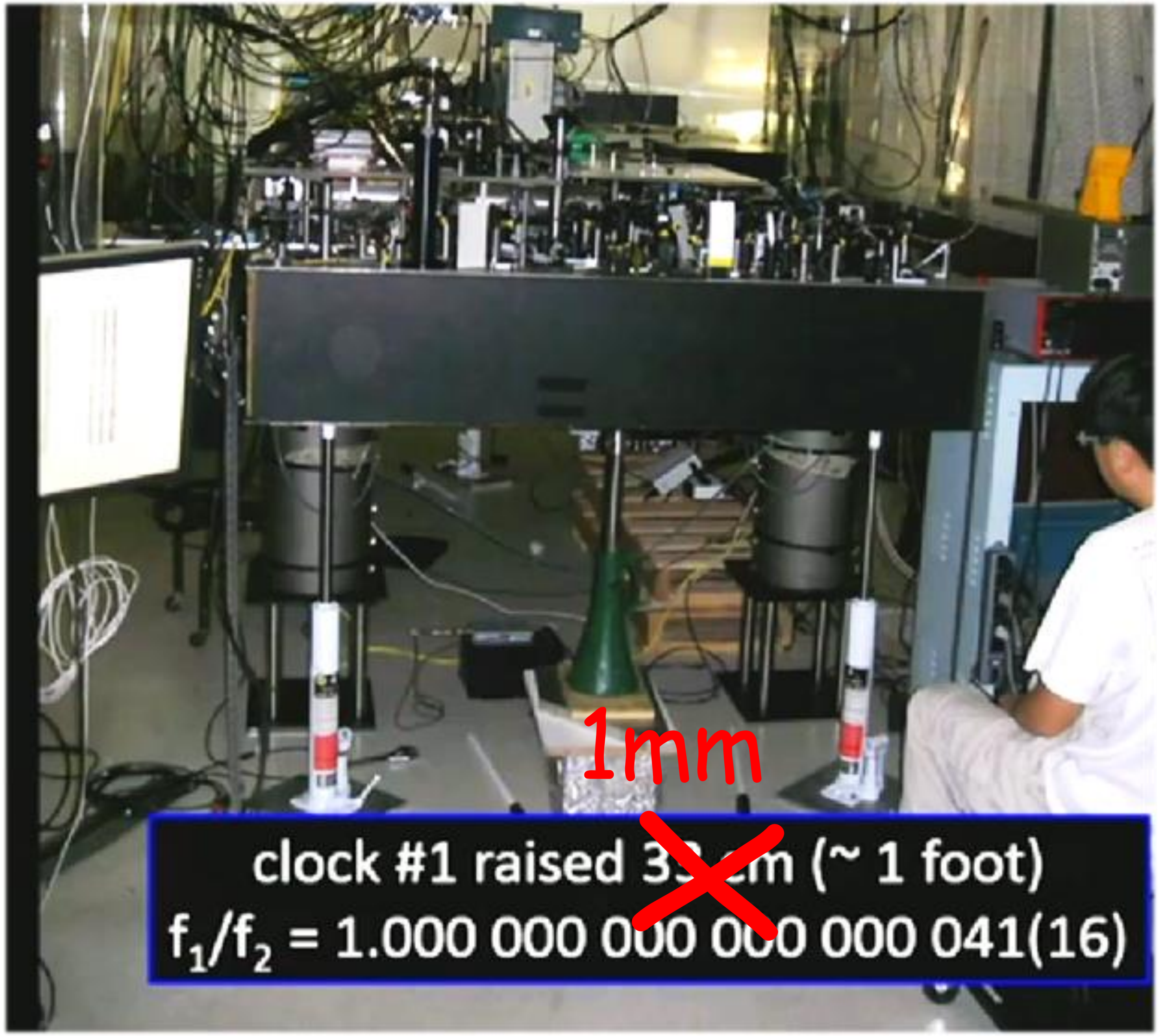




***Neutrons*: Earth's gravity impacts the wavefunction of a quantum particle**

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

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

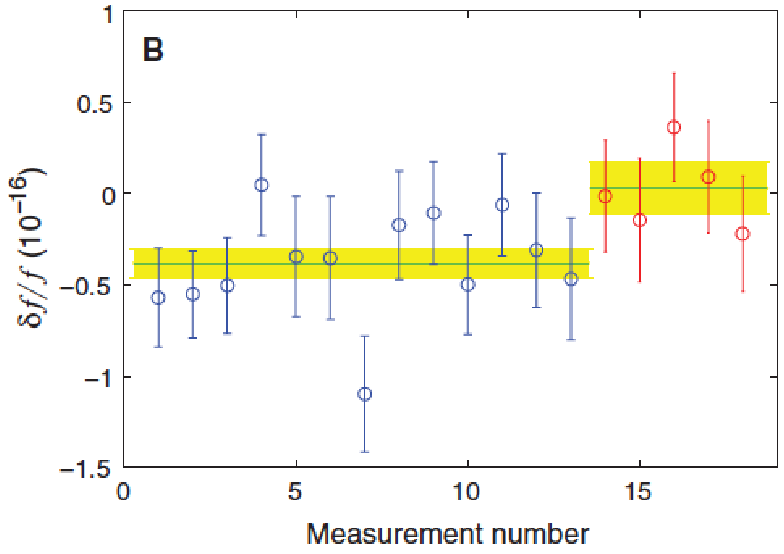


Optical Clocks and Relativity
C. W. Chou, *et al.*
Science **329**, 1630 (2010);
DOI: 10.1126/science.1192720

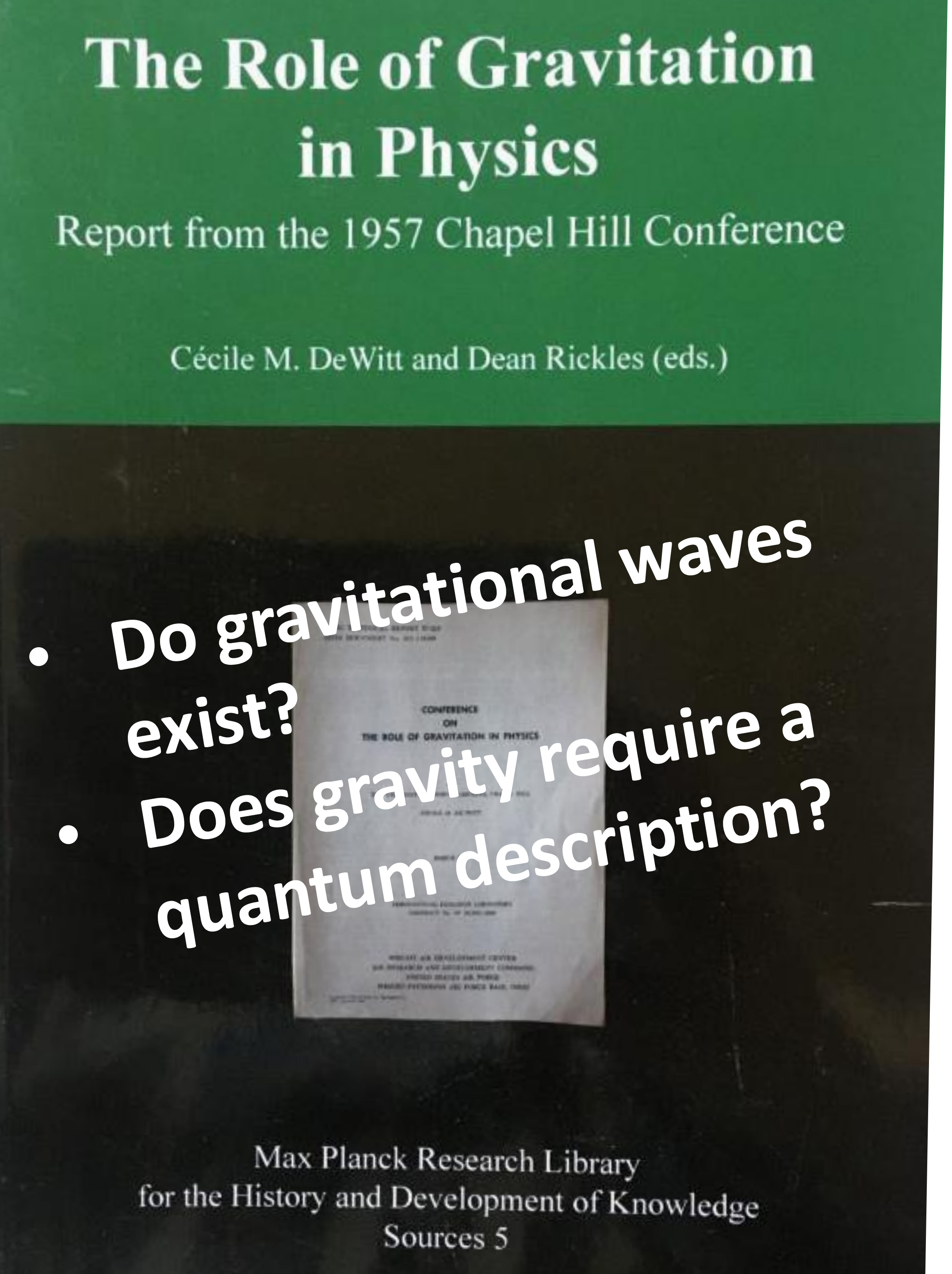
Optical Clocks and Relativity

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**



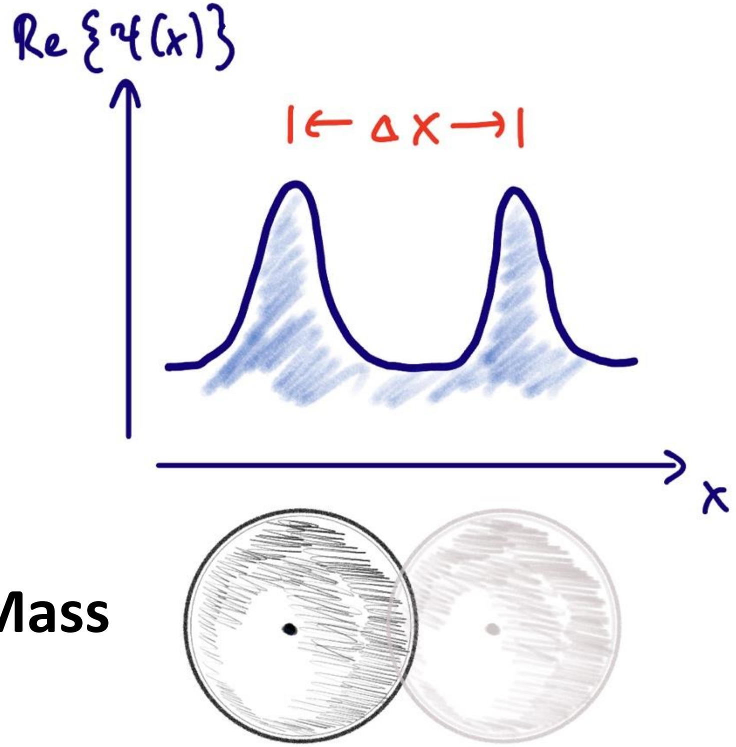
- **Do gravitational waves exist?**
- **Does gravity require a quantum description?**

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

FEYNMAN: **YES! Entangling two masses via gravity requires quantization!**

1957 Chapel Hill Conference

QUANTUM SOURCES OF GRAVITY cannot be described by GR

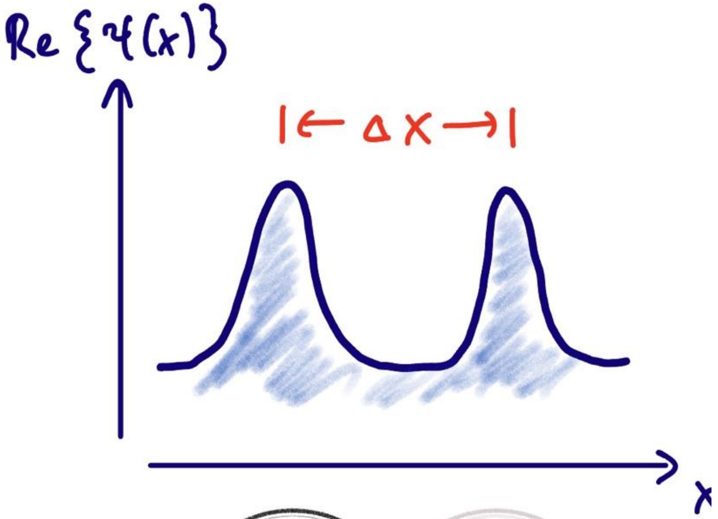


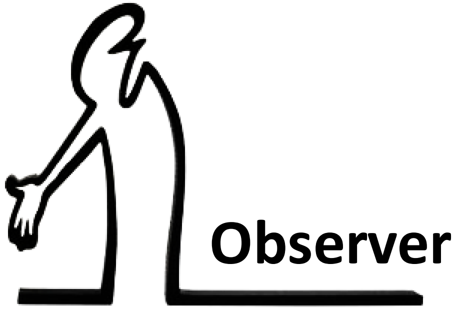
Mass

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

= Gravitational Schrödinger Cat

QUANTUM SOURCES OF GRAVITY cannot be described by GR





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

Mass

gravitional coupling to another system (e.g. test mass, clock) creates **entanglement**

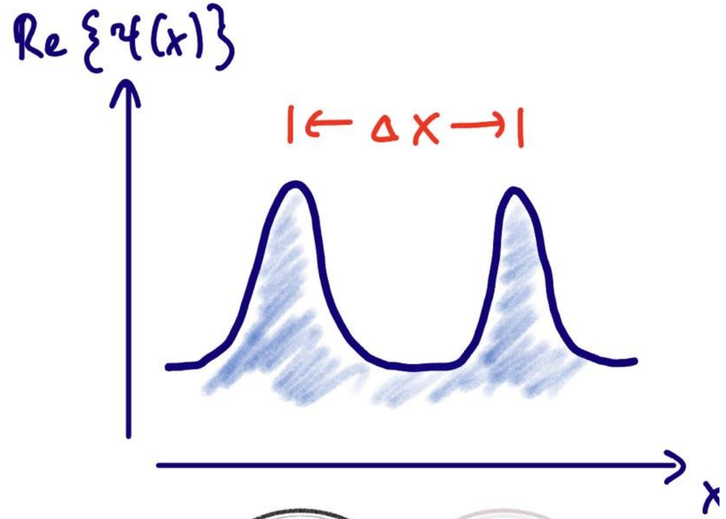
$$(|L\rangle_M + |R\rangle_M) \otimes |\tau\rangle_C$$

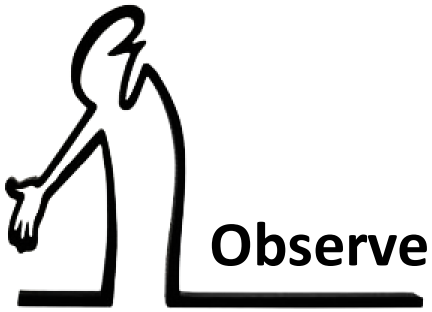
$\downarrow$ Gravity

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

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

QUANTUM SOURCES OF GRAVITY cannot be described by GR





Observer

> *if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment. (Feynman 1957)*

Mass

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

↓ Gravity

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

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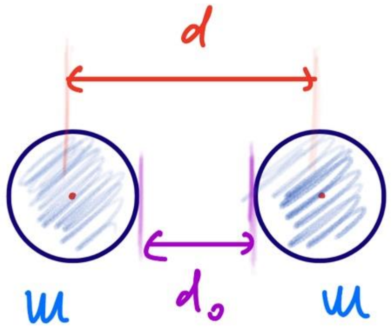
gravitional coupling to another system (e.g. test mass, clock) creates **entanglement**

QUANTUM SOURCES OF GRAVITY. What is the challenge?

We need **extreme regimes** of both **quantum** (large mass **m**, large delocalization **Δx**, long coherence time **τ**) and **gravity** experiments (short distance **d**, low noise), specifically

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

arxiv:2203.05587



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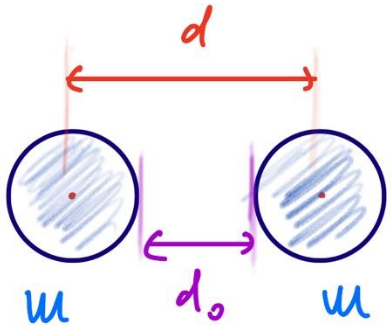
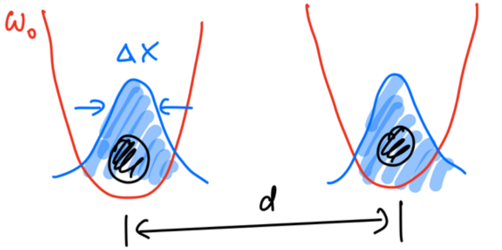
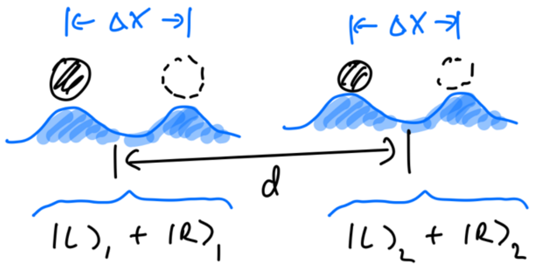




$$|\psi_0\rangle = |0\rangle_1 \otimes |0\rangle_2$$

$$\downarrow\ \hat{H}_{int} = -G\frac{m^2}{|\hat{r}|} \to -\hbar g \hat{x}_1 \hat{x}_2$$

$$|\psi_{ent.}\rangle$$



$$|\psi_0\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle_1 + |R\rangle_1\right) \otimes \frac{1}{\sqrt{2}}\left(|L\rangle_2 + |R\rangle_2\right)$$

$$\downarrow\ \varphi(t) = \frac{1}{\hbar}\int G\frac{m^2}{|\hat{r}|}dt$$

$$|\psi_{ent.}\rangle$$

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)

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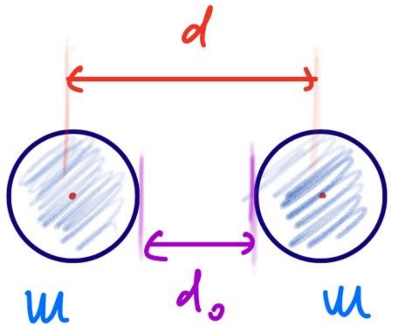
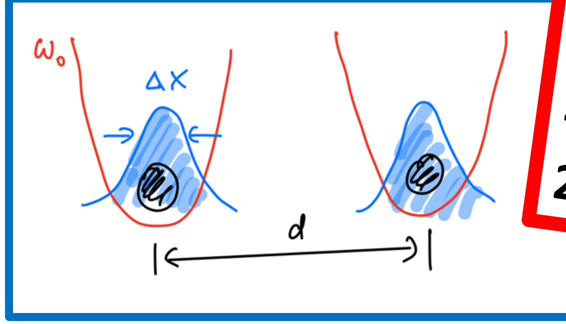
arxiv:2203.05587

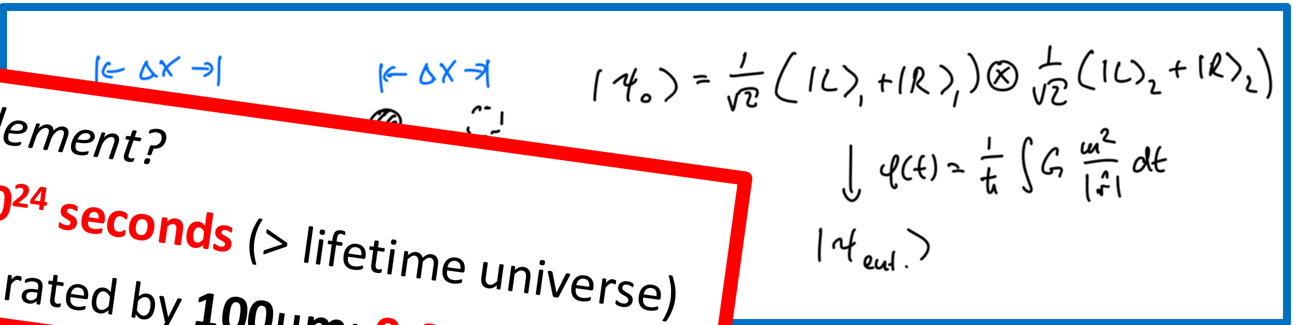




How long to generate entanglement?

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

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



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

QUANTUM SOURCES OF GRAVITY. Why solids?

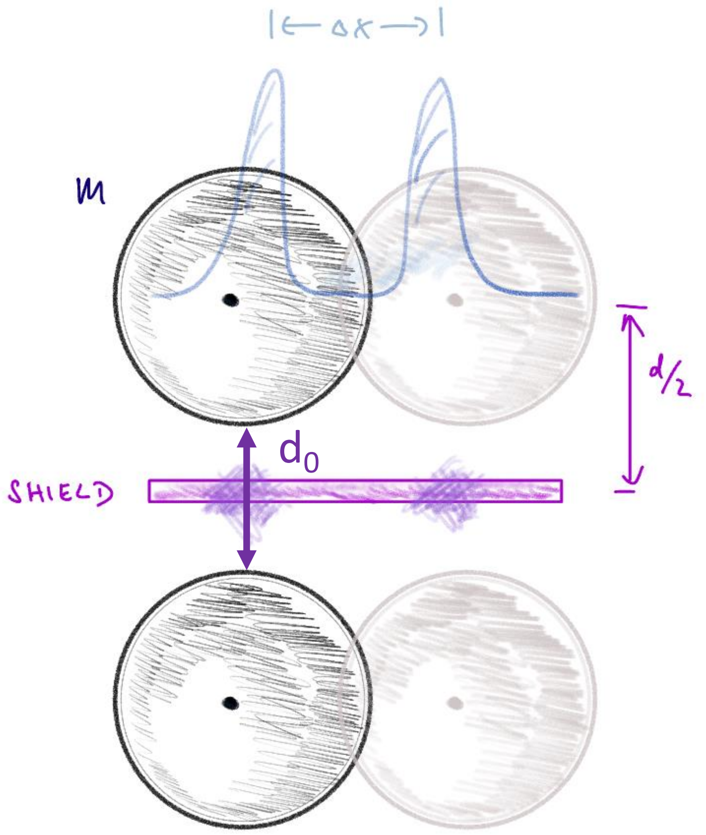
Experimental constraints

COHERENCE TIME $\tau \ll 1$ sec. , conservatively $\tau \lesssim 0.1$ sec.

SURFACE DISTANCE $d_0 = d - 2R \approx 10\,\mu m$, $d \gtrsim 10^{-5}\,m$

PRL 124, 101101 (2020)

IMAGE CHARGE DECOHERENCE $\propto \Delta x / d_0 \ll 1$, $\Delta x / d \ll 1$



$$\tau / d \; m^2 \gg m^2 \Delta x^2 \tau \, d^{-3} \gtrsim \hbar / G$$

$$m^2 \gg \frac{d}{\tau} \frac{\hbar}{G}$$

$$m \gg m_{PLANCK} \cdot \sqrt{\frac{d}{\tau c}} \gtrsim 10^{-6}\, m_{PLANCK}$$

$\sim 10^{-14}$ kg

$\sim 10^{13}$ a.m.u.

and within a volume $V \ll d^{-3}$

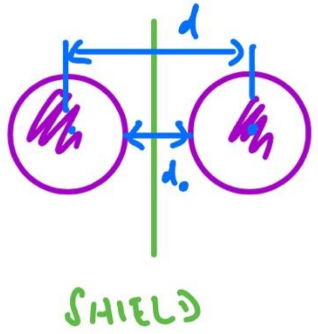
$$\Rightarrow \rho \gg \frac{m}{V} \sim 10\ kg/m^3$$

solid state densities

QUANTUM SOURCES OF GRAVITY in the presence of decoherence

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	
$\beta\,[M_p]$	$\gamma = (1+16\beta^{1/3})$	$\gamma^{3/2}$	Δx	r	T_a	$T_{e,i}$ [K]
1	17	70	$1.4\ 10^{-9}$	80 μm	7	11
10^{-1}	8.43	25	$4.9 \cdot 10^{-9}$	40 μm	9	11
10^{-2}	4.45	9.4	$19 \cdot 10^{-9}$	17 μm	11	10
10^{-3}	2.6	4.2	$84 \cdot 10^{-9}$	8 μm	13	9
10^{-4}	1.74	2.3	$460 \cdot 10^{-9}$	4 μm	15	8
10^{-5}	1.3	1.6	$3{,}1 \cdot 10^{-6}$	2 μm	16	6
	⋮	⋮	⋮	⋮	⋮	
10^{-9}	1,02	1,02	$2 \cdot 10^{-2}$	80 nm	18	1.5

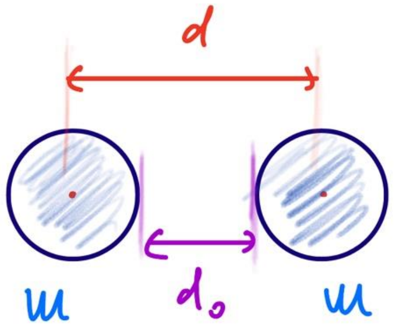
for $\bar{n} \sim 0.1$

assuming GAS SCATTERING & BLACKBODY radiation

QUANTUM SOURCES OF GRAVITY. Where do we stand?

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

Quantum Experiments



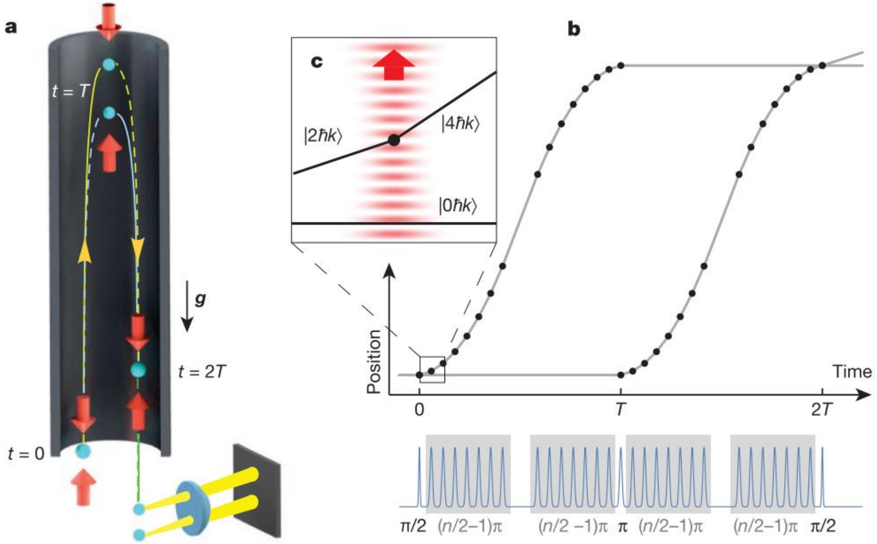
Current experiments involving delocalization of massive objects

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)

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

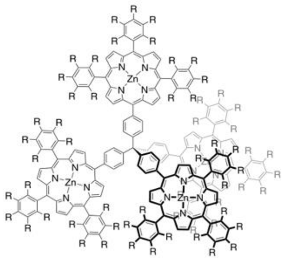


Macro-molecules

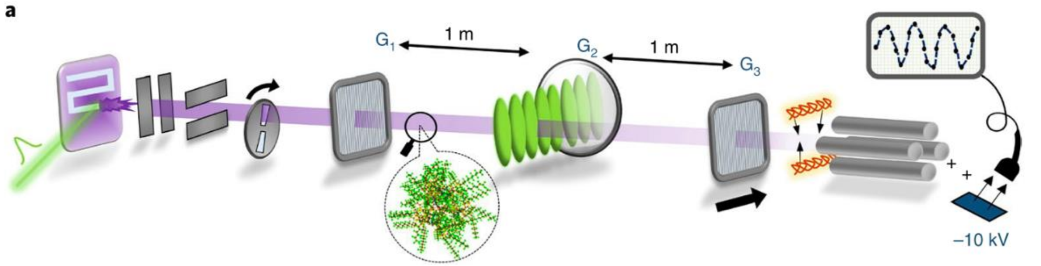
matter-wave interference; 2,000 atoms; M = 25,000 a.m.u. = 4e-23 kg; particle size D=5nm; superposition size $\Delta x > 500$ nm

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 $C_{10}H_4F_{17}S$

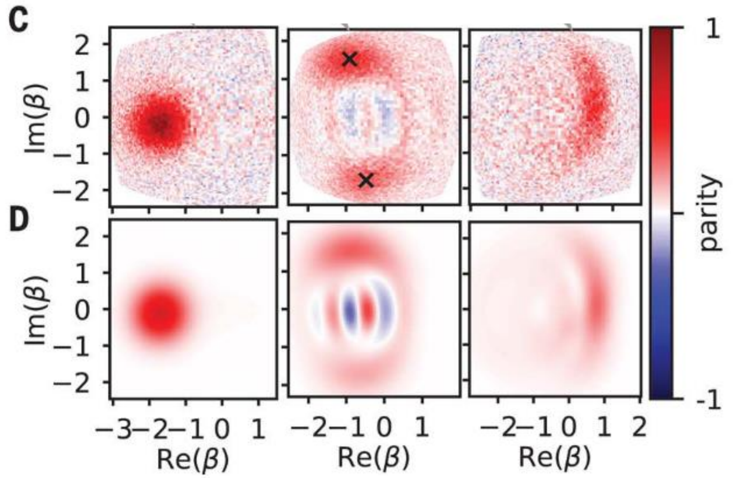


Current experiments involving delocalization of massive objects

Solid-state mechanical oscillators

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)



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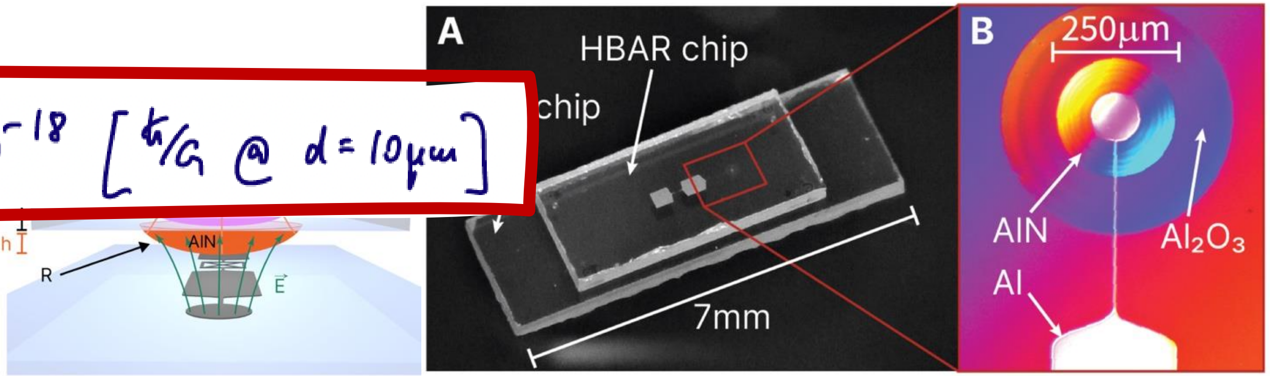
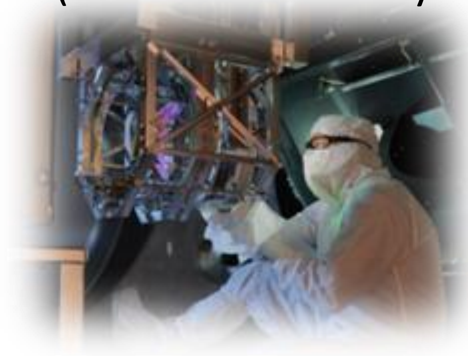


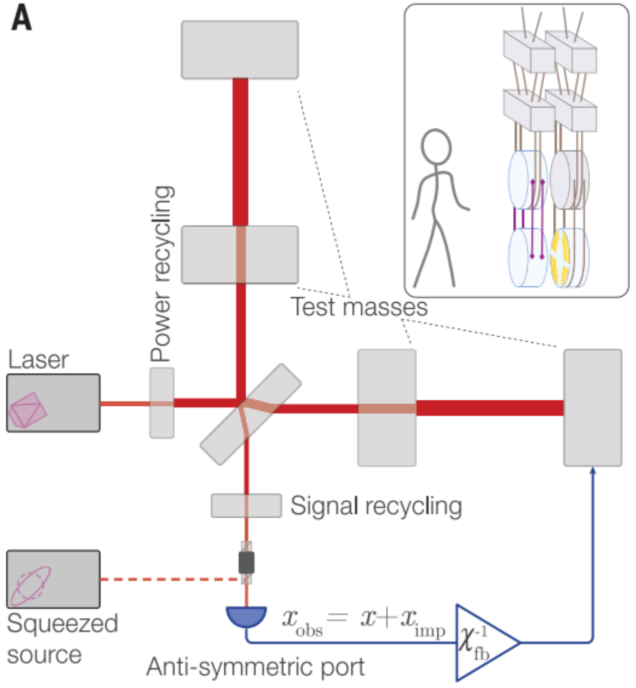
Motional quantum ground state

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)

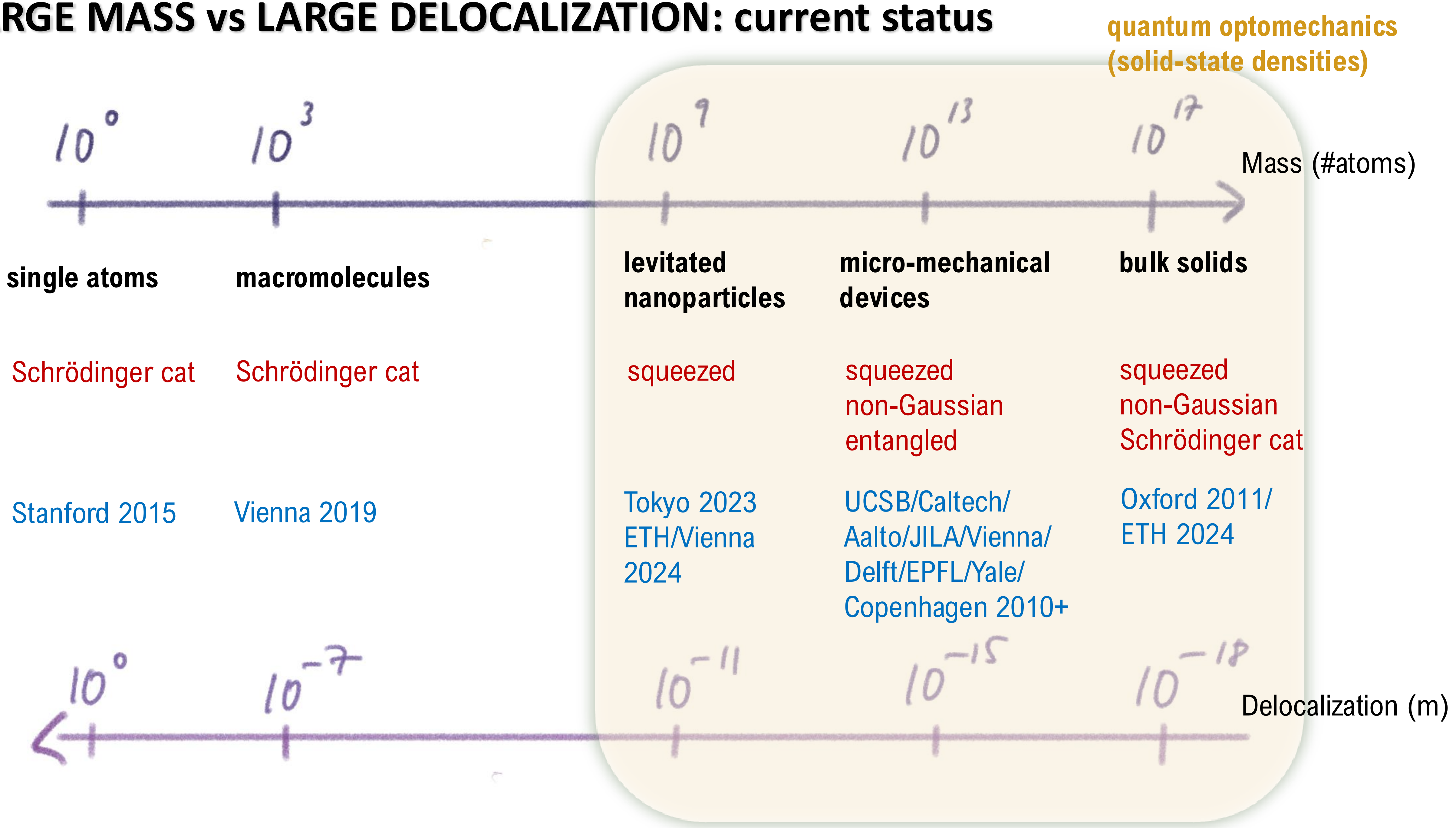
C. Whittle *et al.*, *Science* **372**, 1333–1336 (2021)

$$(m\,\Delta x)^2\,\tau \rightarrow 10^{-11}\ @\ d=10cm$$





LARGE MASS vs LARGE DELOCALIZATION: current status



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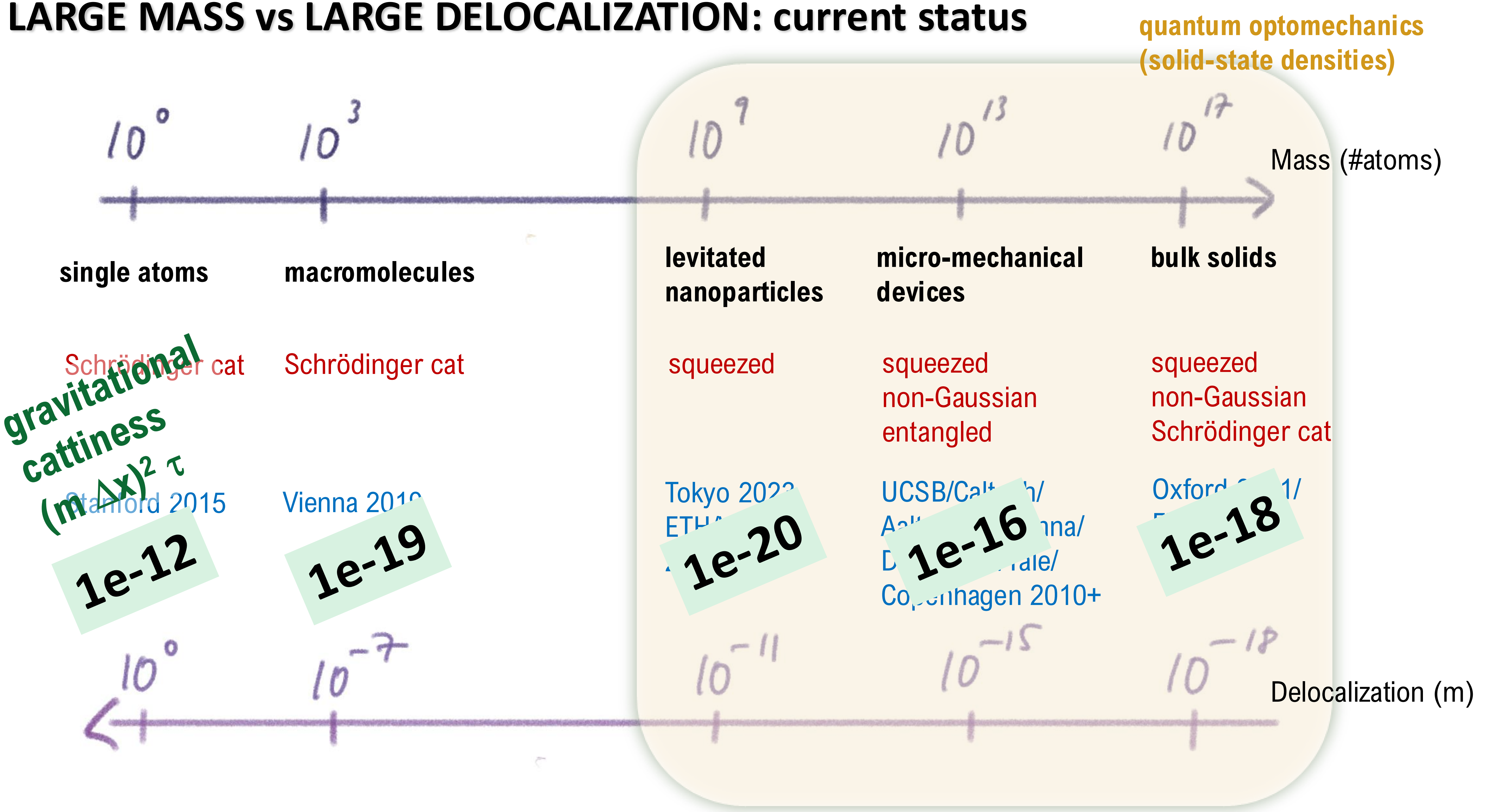

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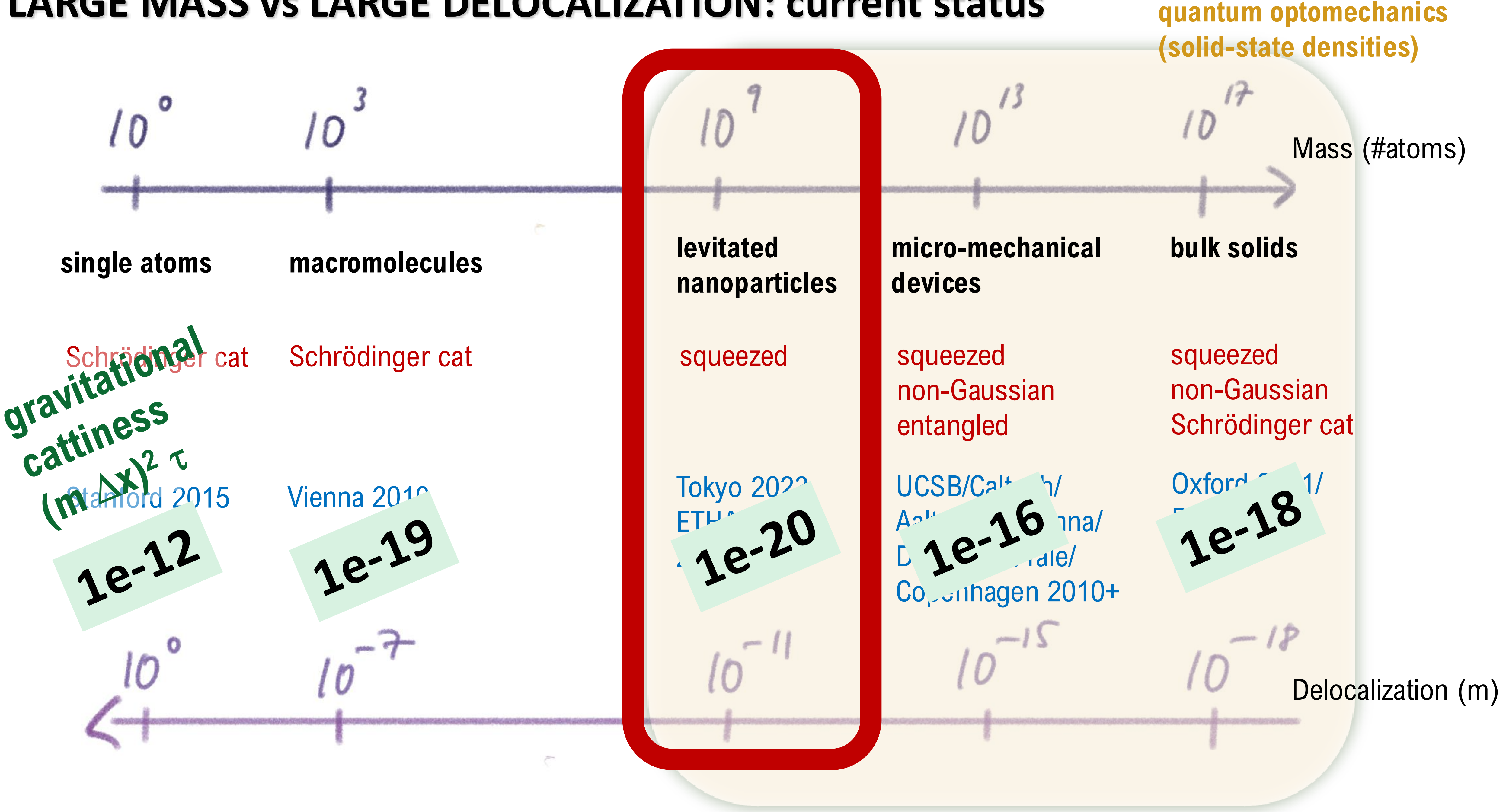
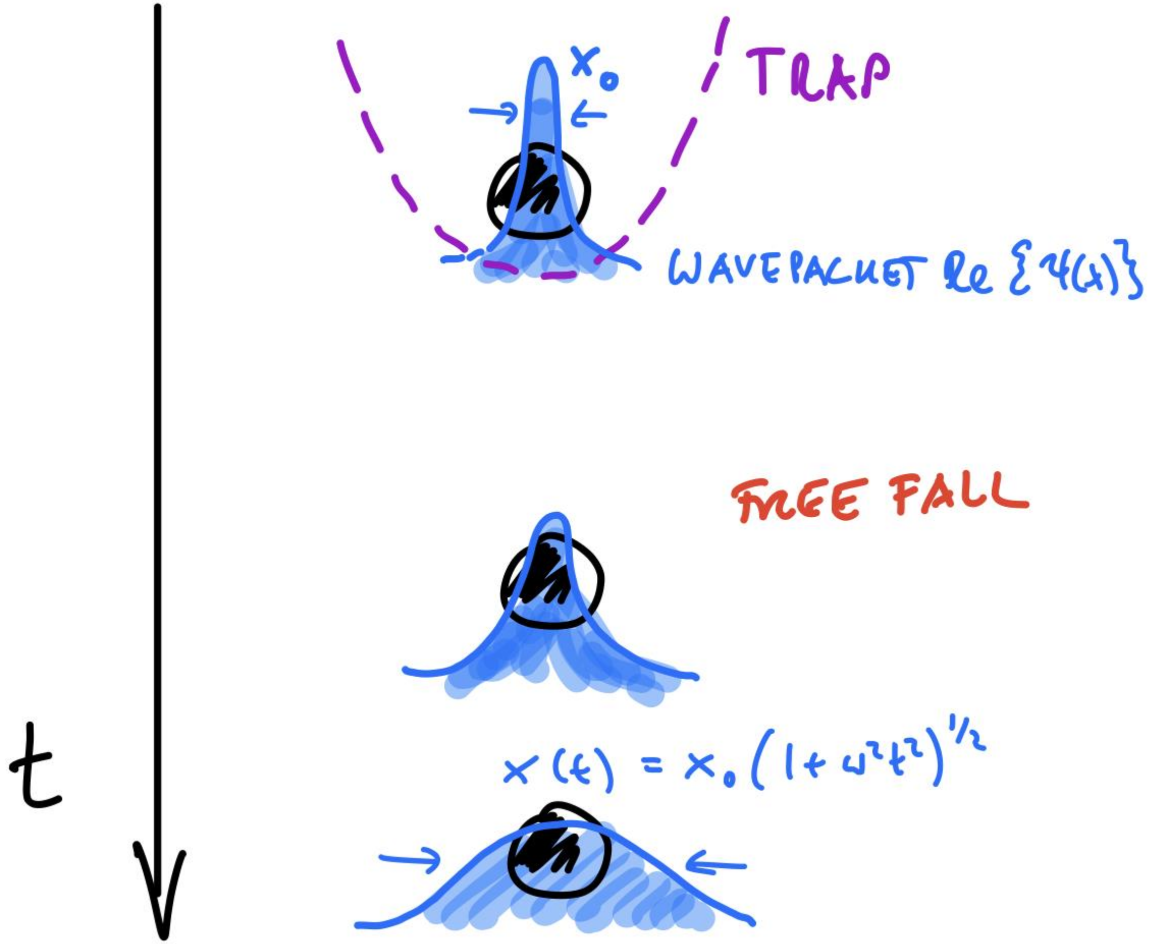


Towards „large“ quantum states?



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:

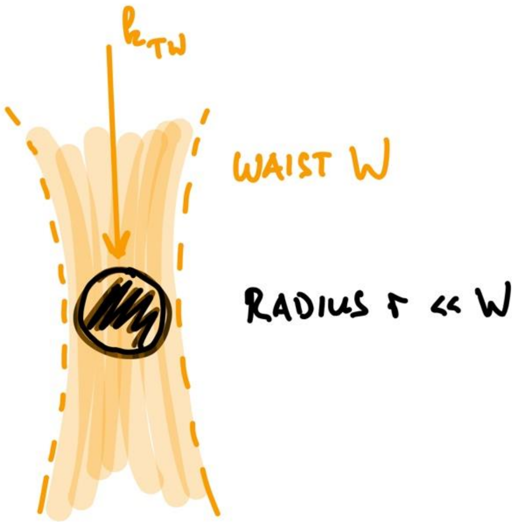
$\hat{H} \propto \underline{d} \cdot \underline{E} = \alpha \cdot E^2$

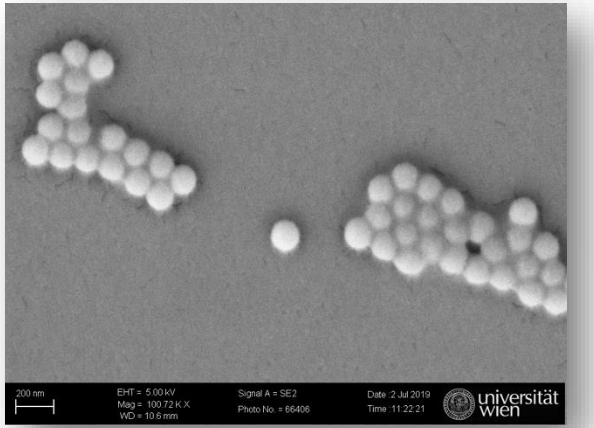
α: Re{Polarizability}

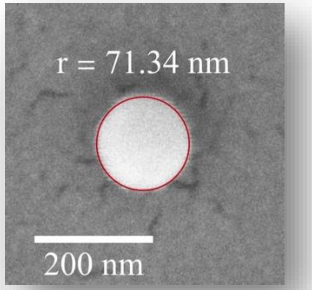
E: optical trapping field

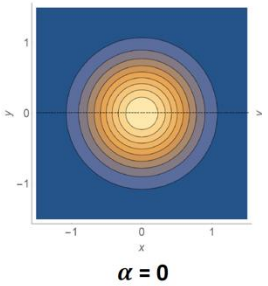
↳ beam intensity

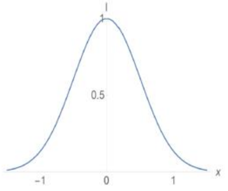
→ GRADIENT FORCE $F \propto (\nabla E^2) \cdot \alpha$

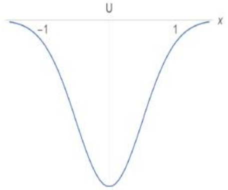


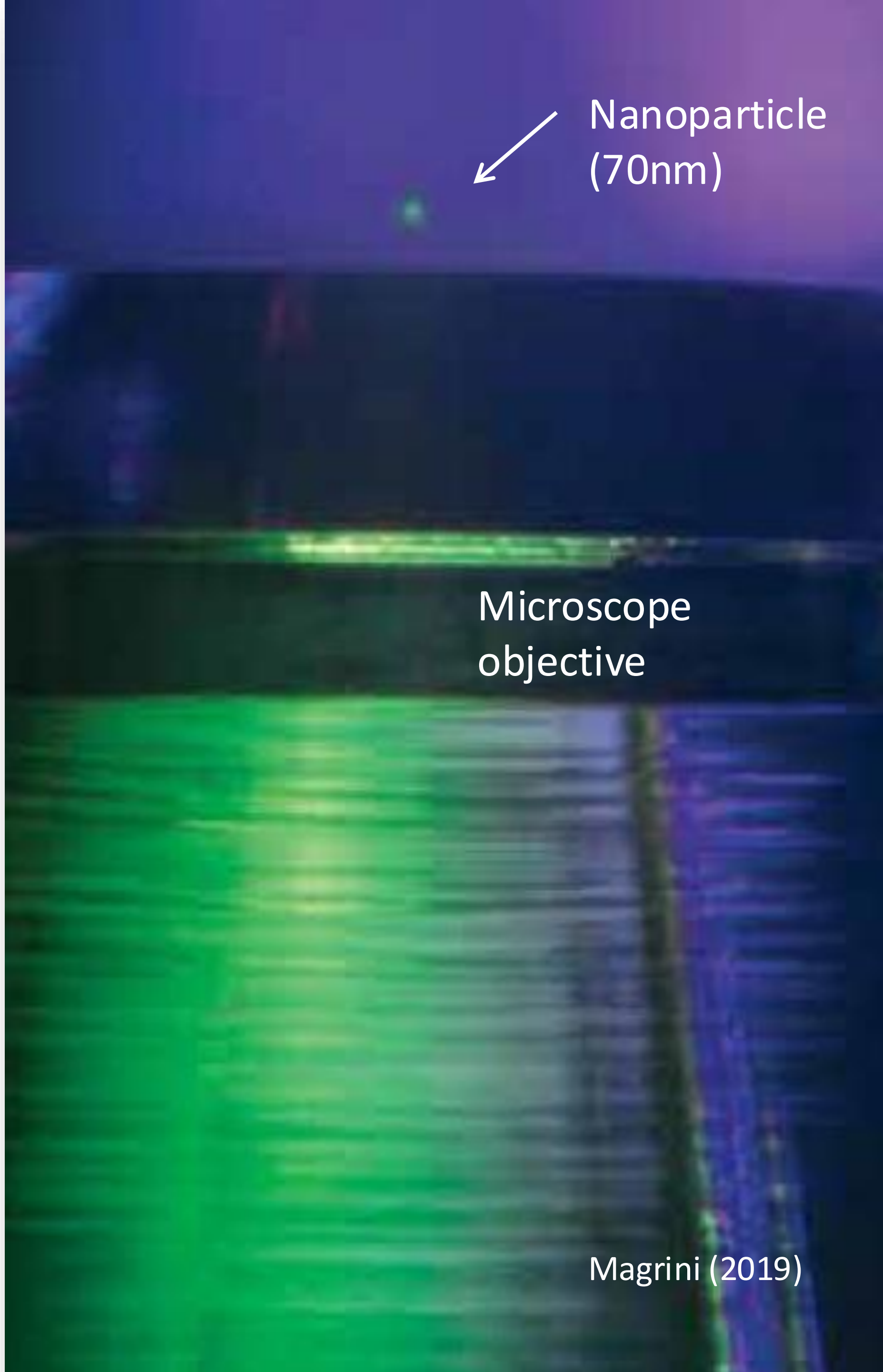












Pioneering work by Ashkin:

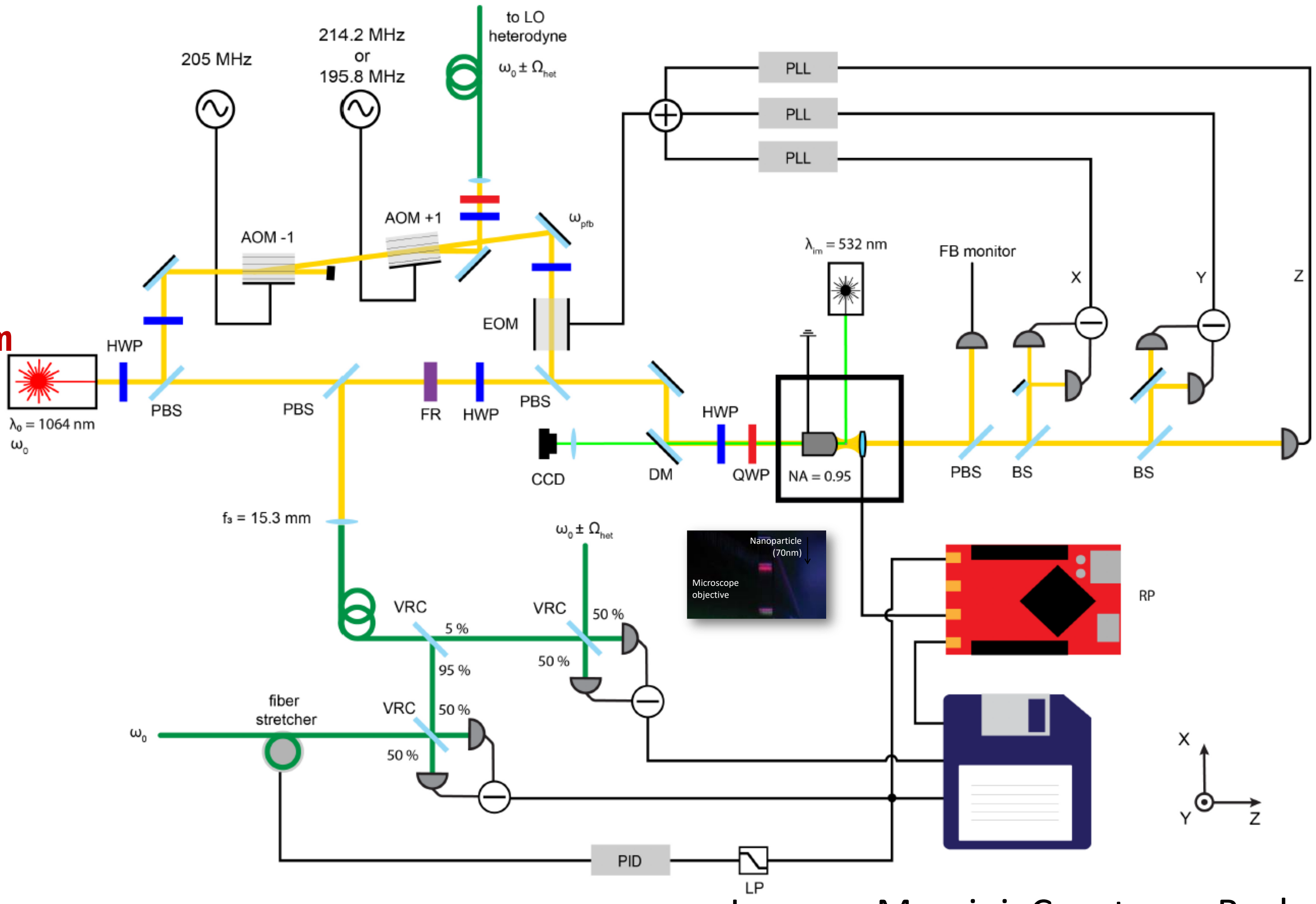
A. Ashkin, PRL 24, 156 (1970).

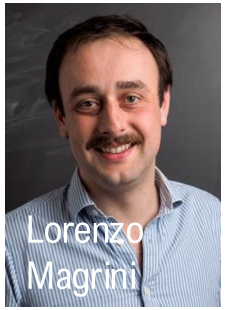
A. Ashkin, J. M. Dziedzic, APL 28, 333 (1976).

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**





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

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

ground-state cooling

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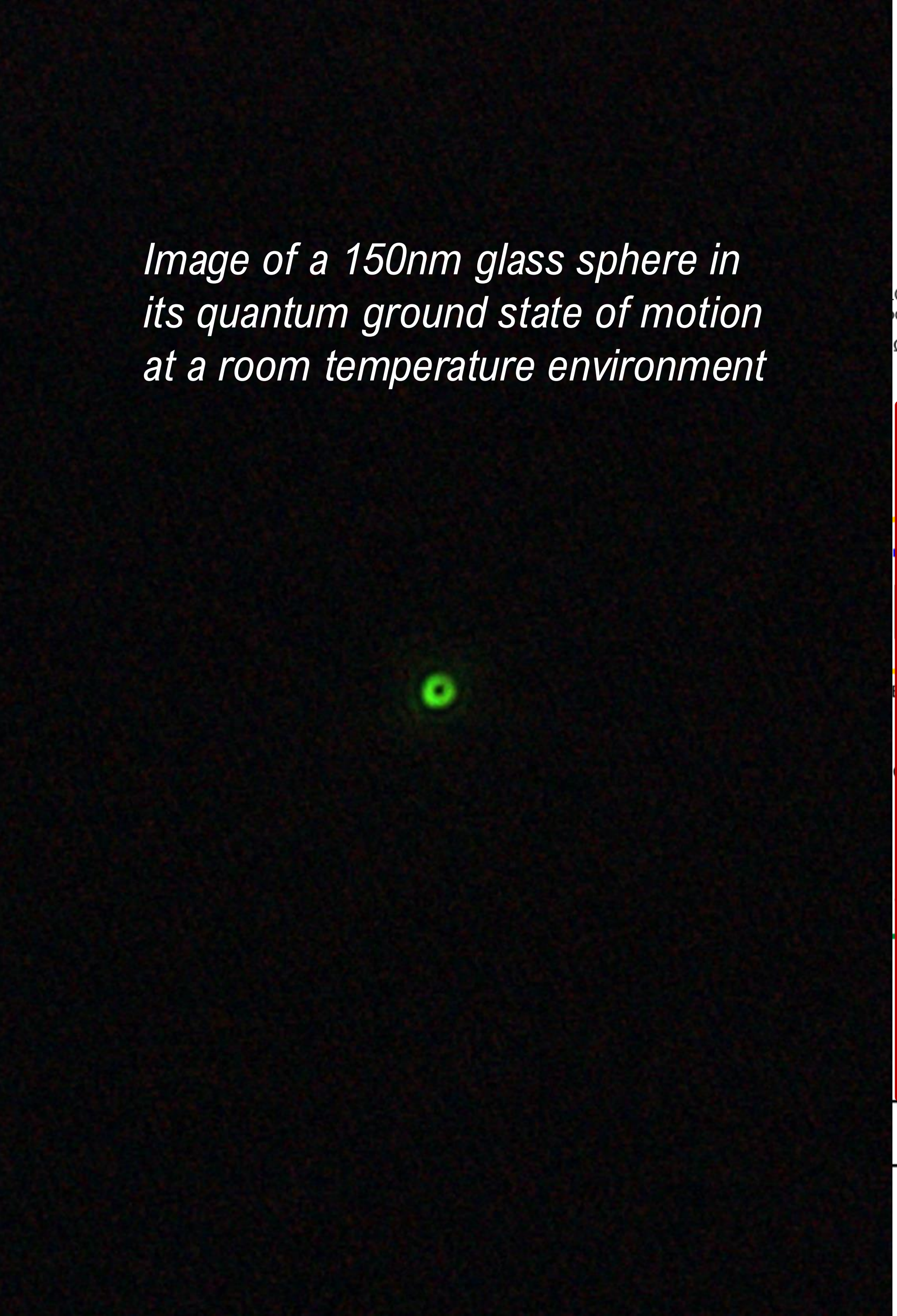
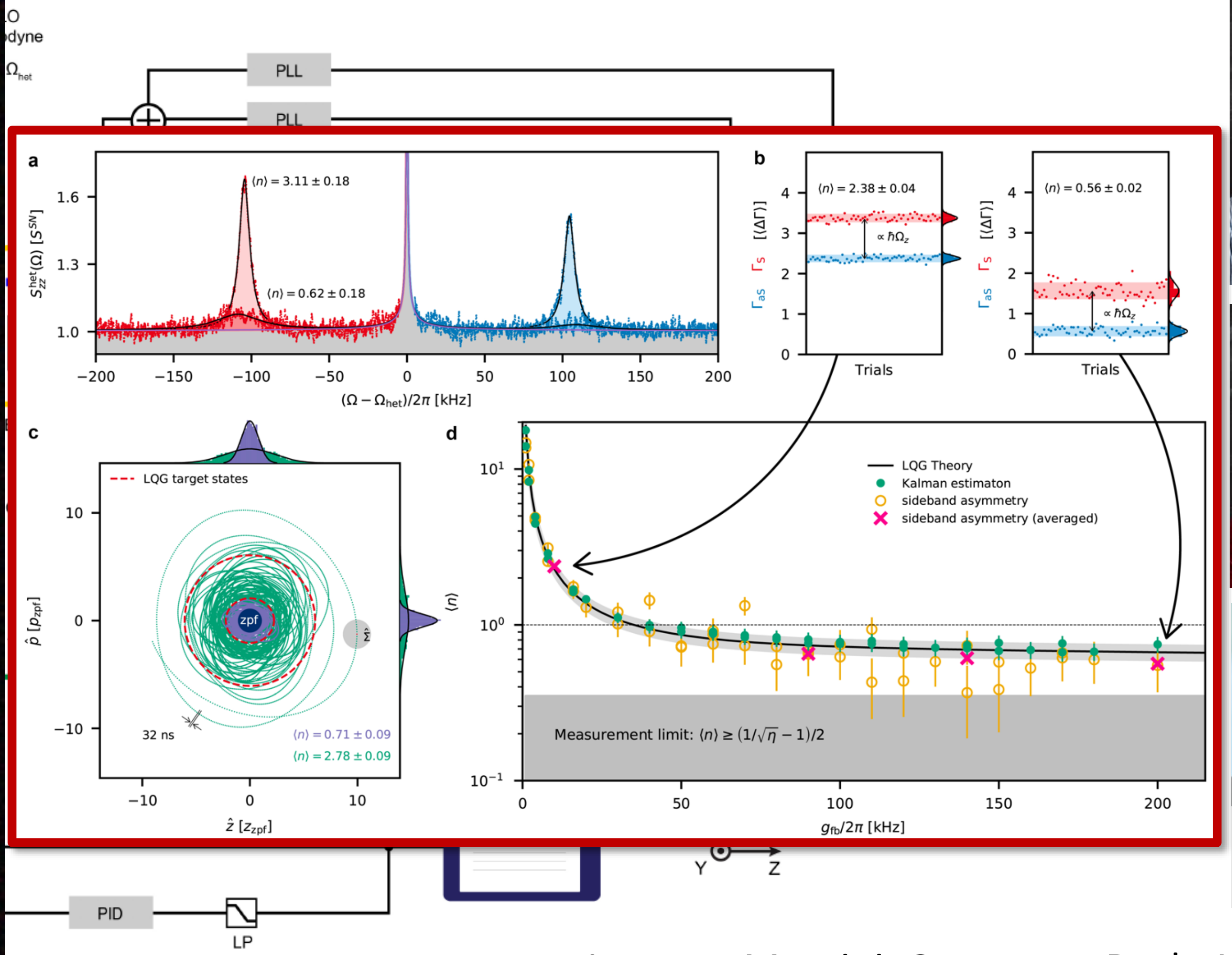
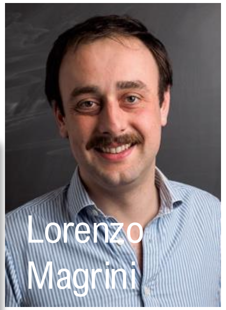
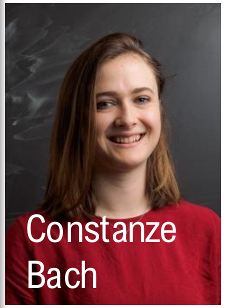


Image of a 150nm glass sphere in its quantum ground state of motion at a room temperature environment

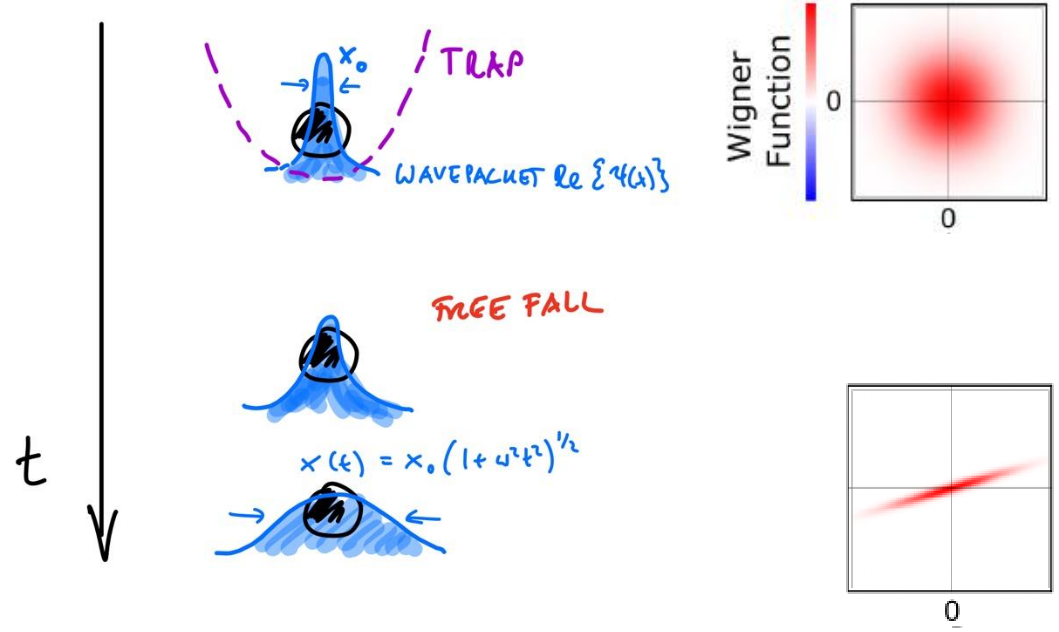






Lorenzo Magrini, Constanze Bach, Nikolai Kiesel
P. Rosenzweig, A. Deutschmann, A. Kugi (TU Wien)

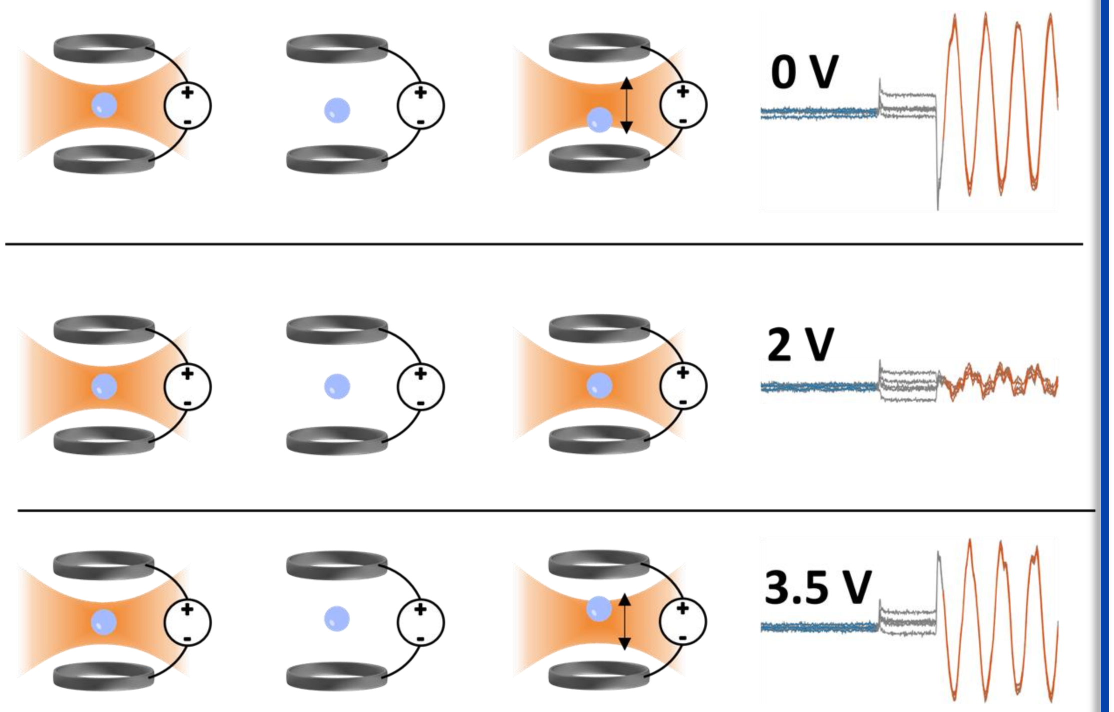
Towards large delocalization: free evolution



Free-falling wavepacket becomes delocalized

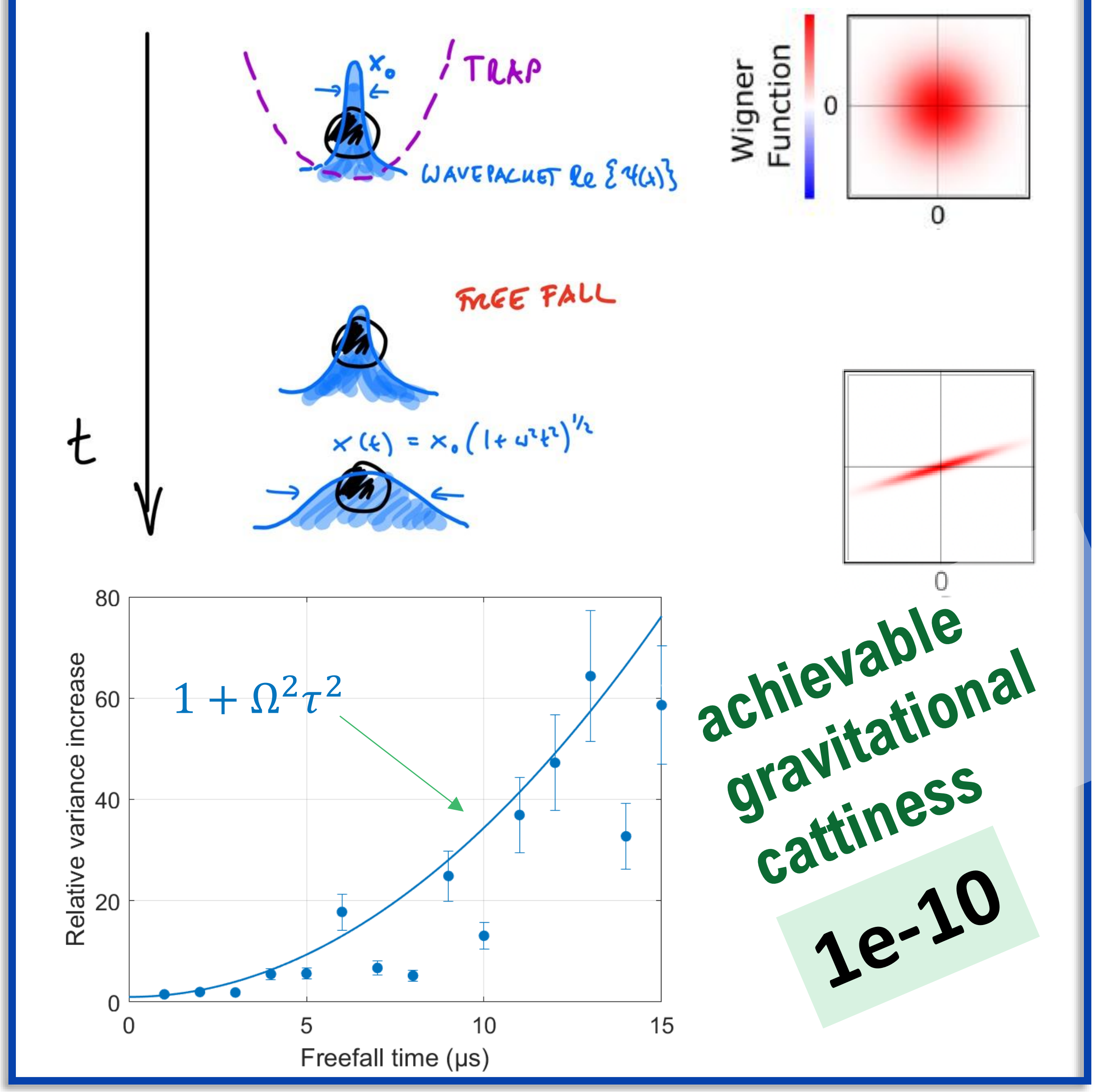
PRL 83, 4037 (1999): Cs atoms
PRL 131, 183602 (2023): neutral nanoparticle
related: arxiv:2408.01264 (2024)

3d electrostatic compensation allows free evolution without free fall (millisecond regime?)



- 3d electrodes, homodyne back detection, $\bar{n} \approx 100$
- Optimize voltages via free-fall recapture
  - Stray electric fields dominate over gravity
  - **Current record: 100 µs**

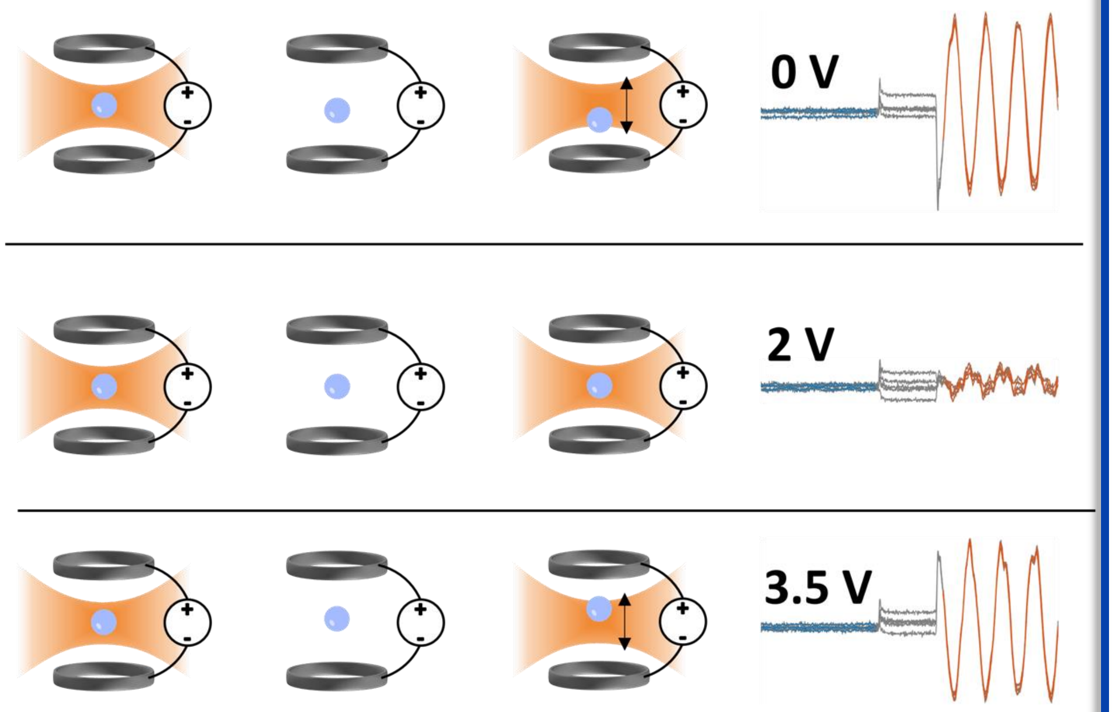
Towards large delocalization: free evolution



achievable gravitational cattiness

1e-10

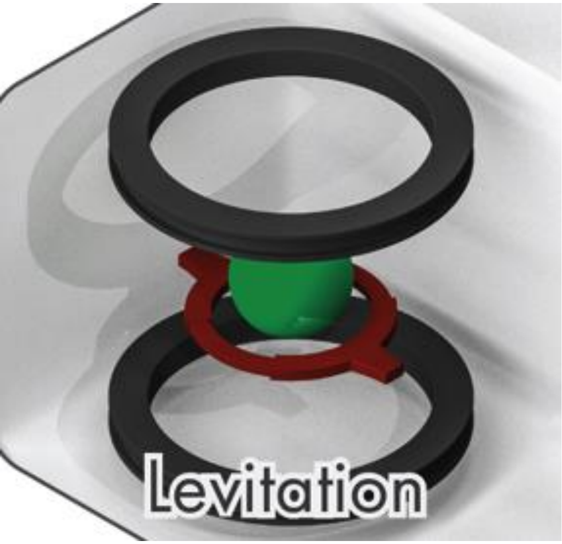
3d electrostatic compensation allows free evolution without free fall (millisecond regime?)

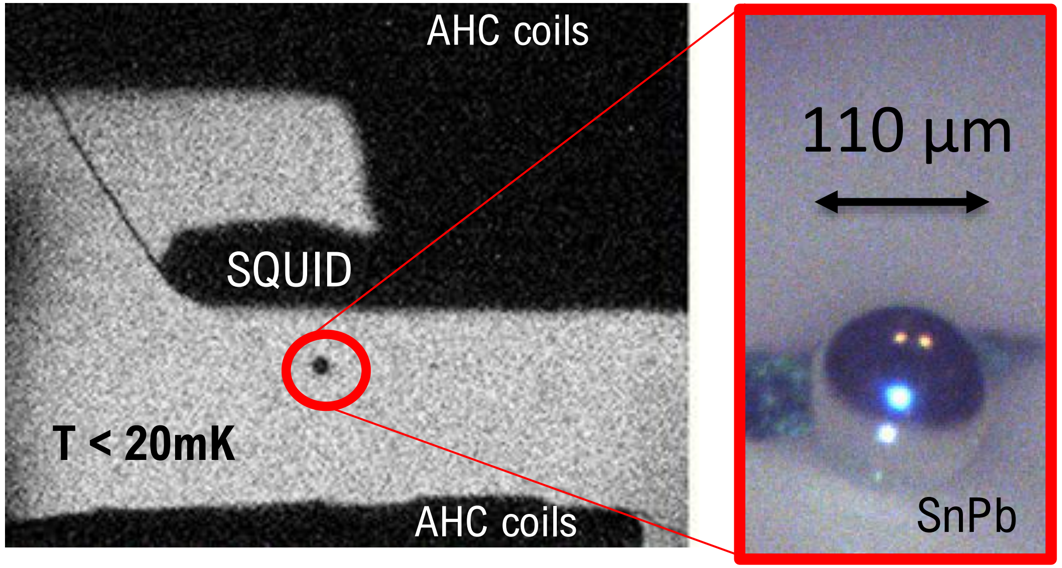


- 3d electrodes, homodyne back detection, $\bar{n} \approx 100$
- Optimize voltages via free-fall recapture
  - Stray electric fields dominate over gravity
  - **Current record: 100 µs**

Towards larger mass: superconducting levitation

Hofer et al., PRL 131, 043603 (2023)
Schmidt et al., Phys. Rev. Applied 22, 014078 (2024)





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

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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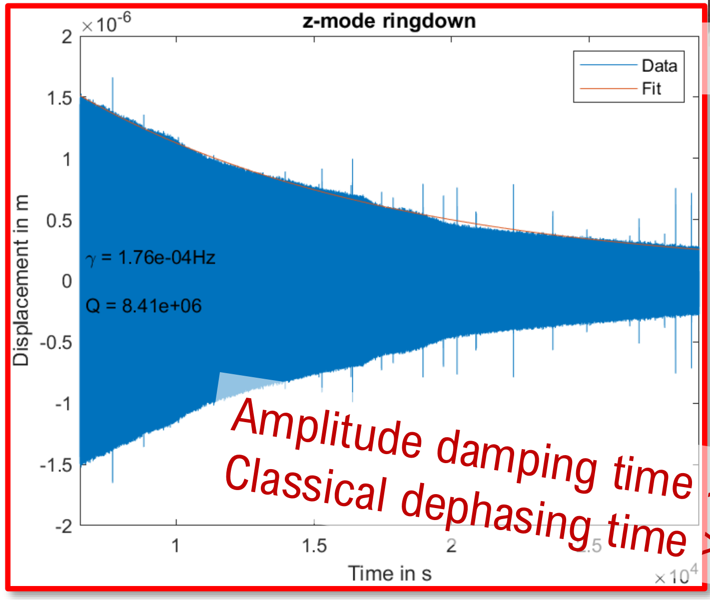
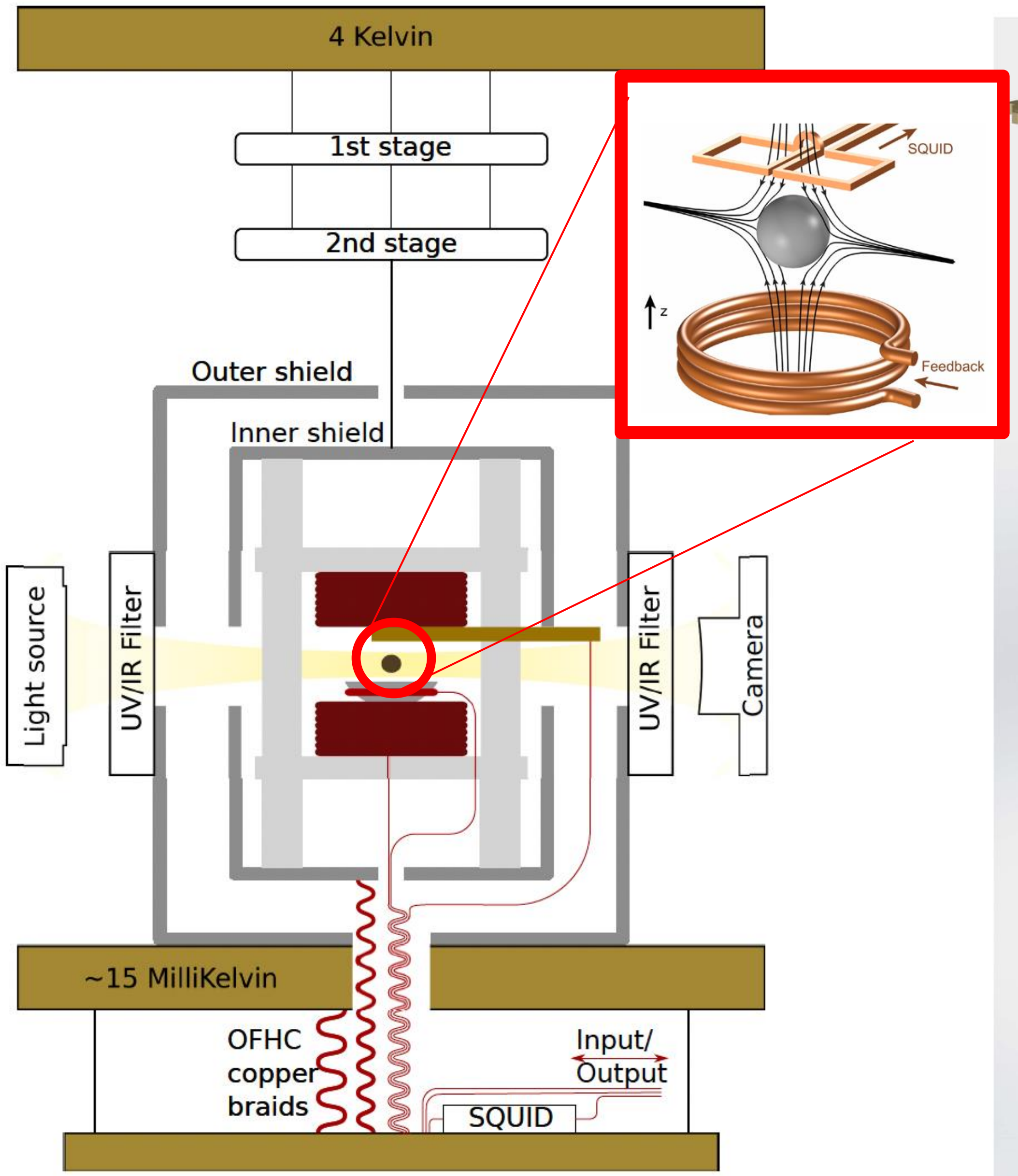


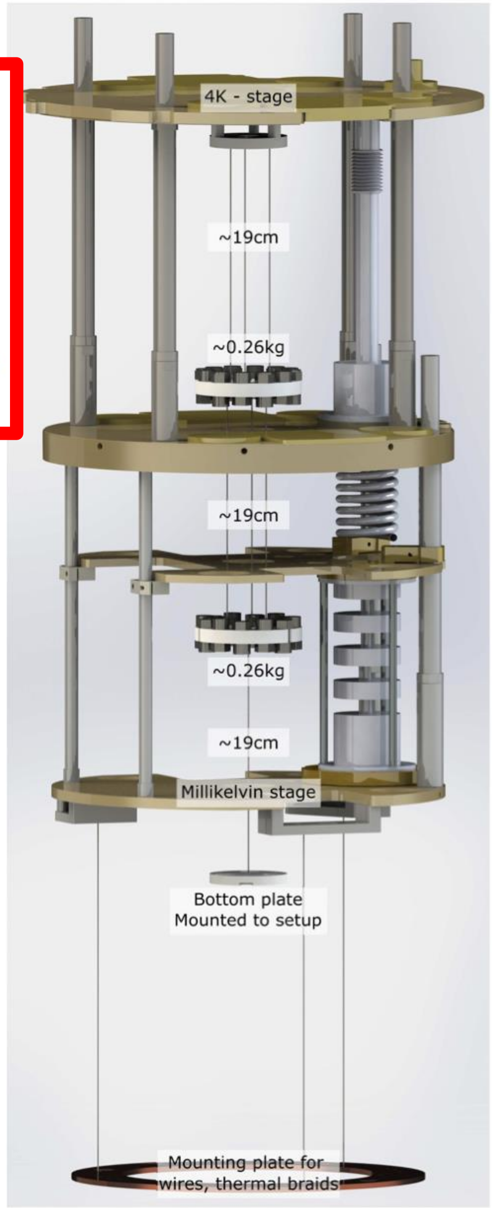
Amplitude damping time > 40,000 sec
Classical dephasing time > 80 sec

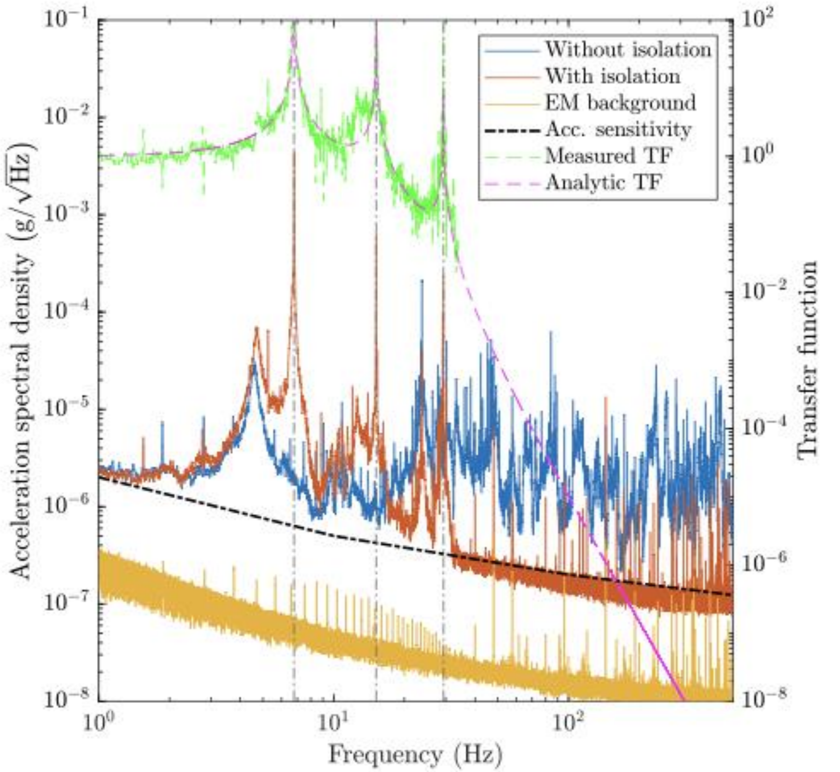
WMI, BAdW
UTübingen

Low-noise superconducting levitation at 20 mK

Hofer et al., PRL 131, 043603 (2023)
Schmidt et al., Phys. Rev. Applied 22, 014078 (2024)





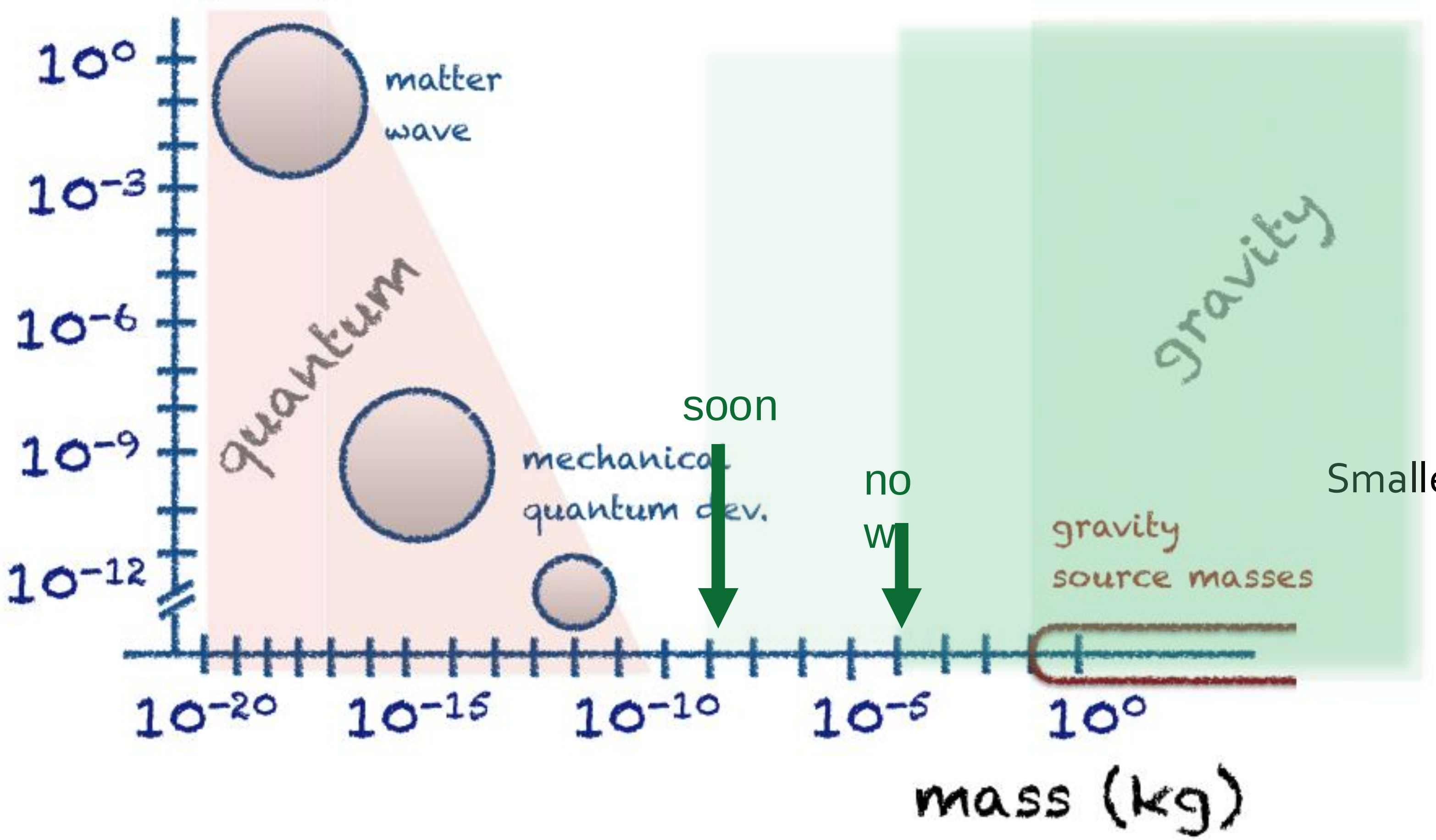


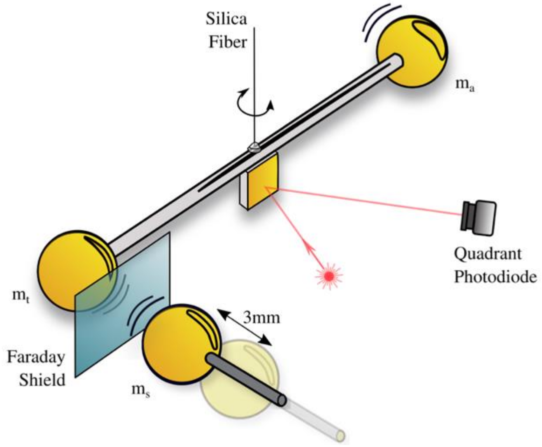
- next generation: superconducting cavities, improved coupling, quantum ground state (?)

What about gravity measurements?

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

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

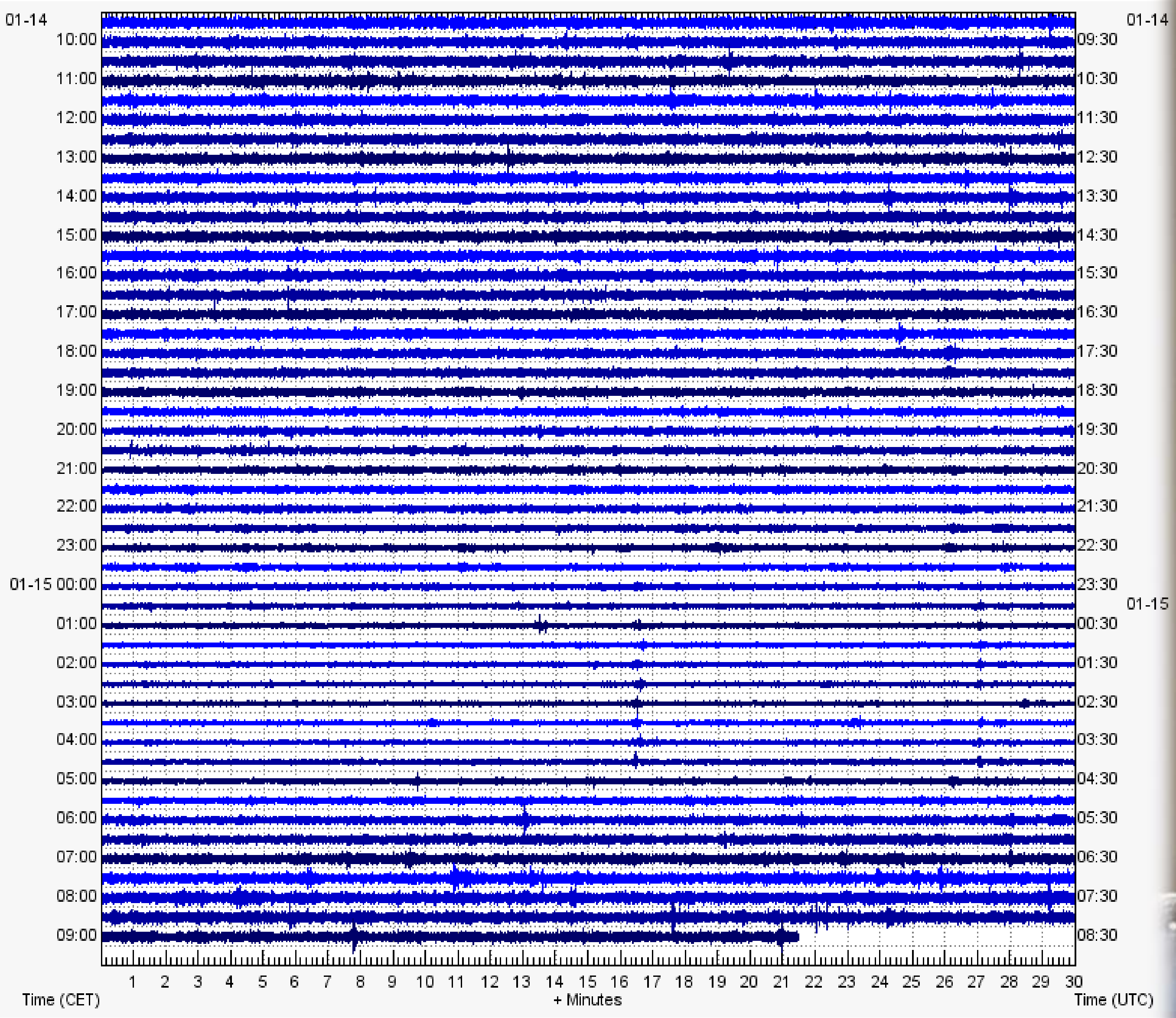


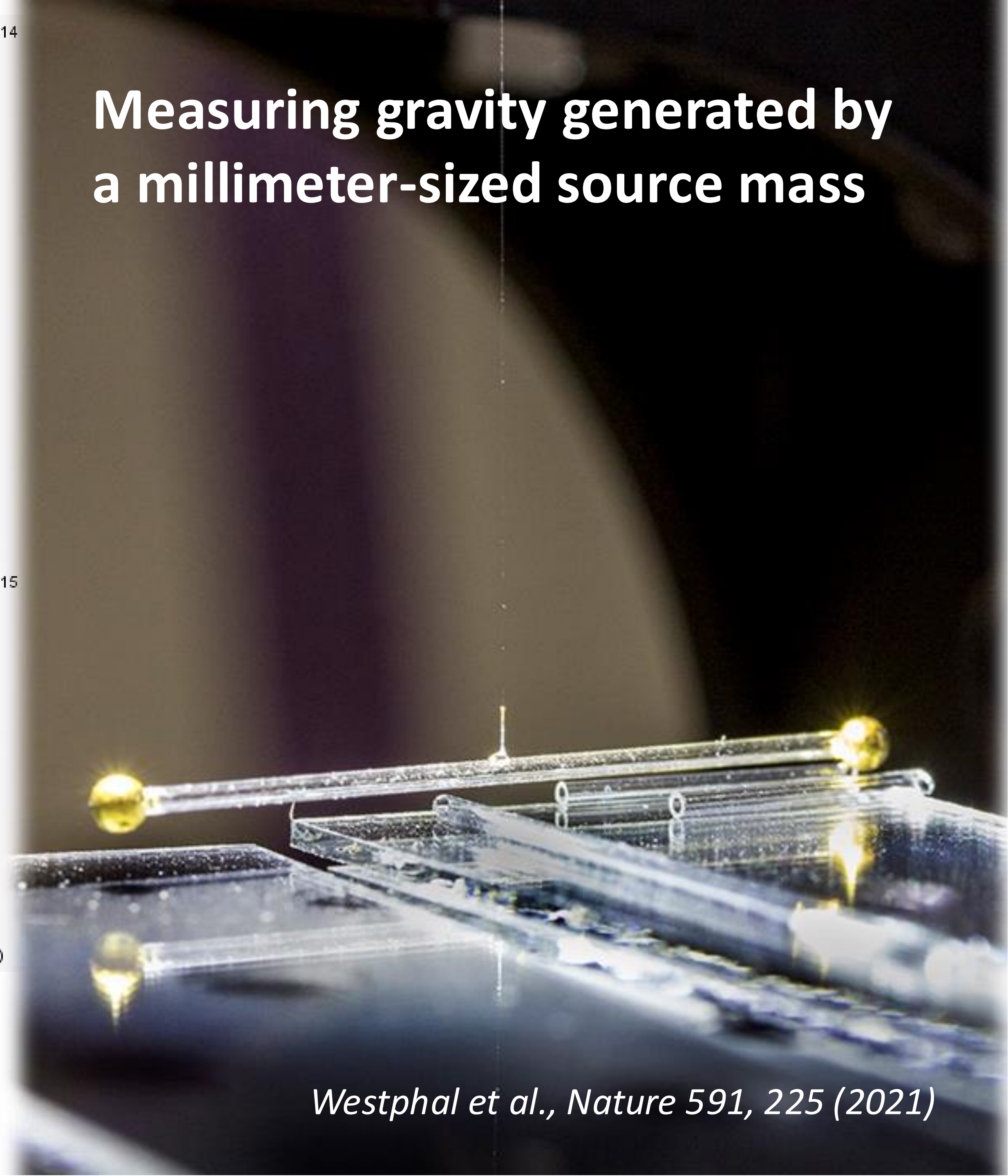


Smallest source mass to date: **0.09 g**

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

Measuring gravity generated by a millimeter-sized source mass



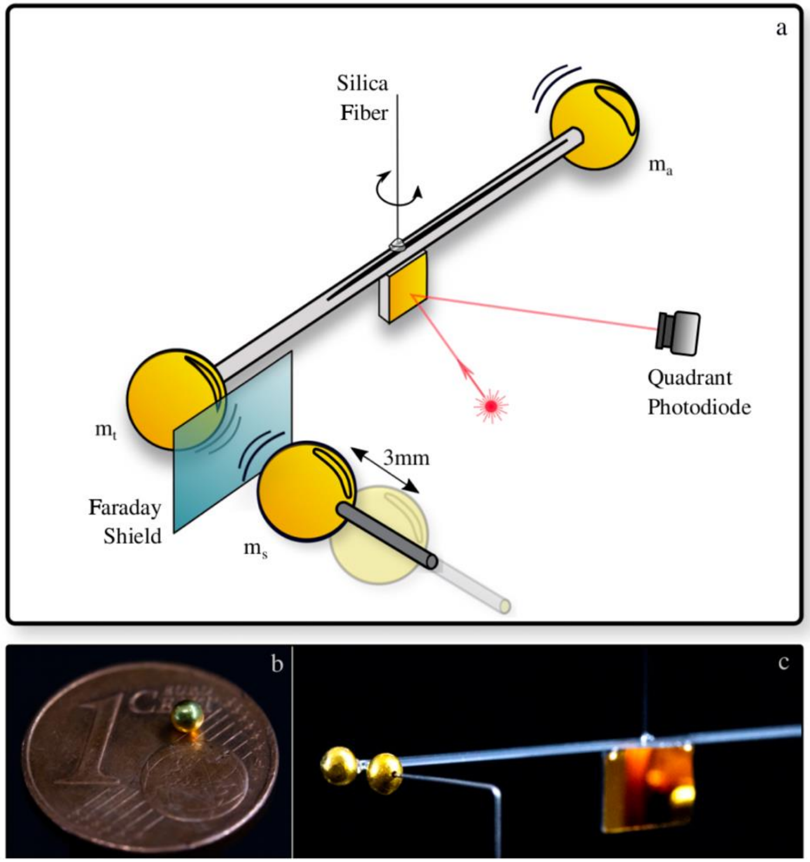


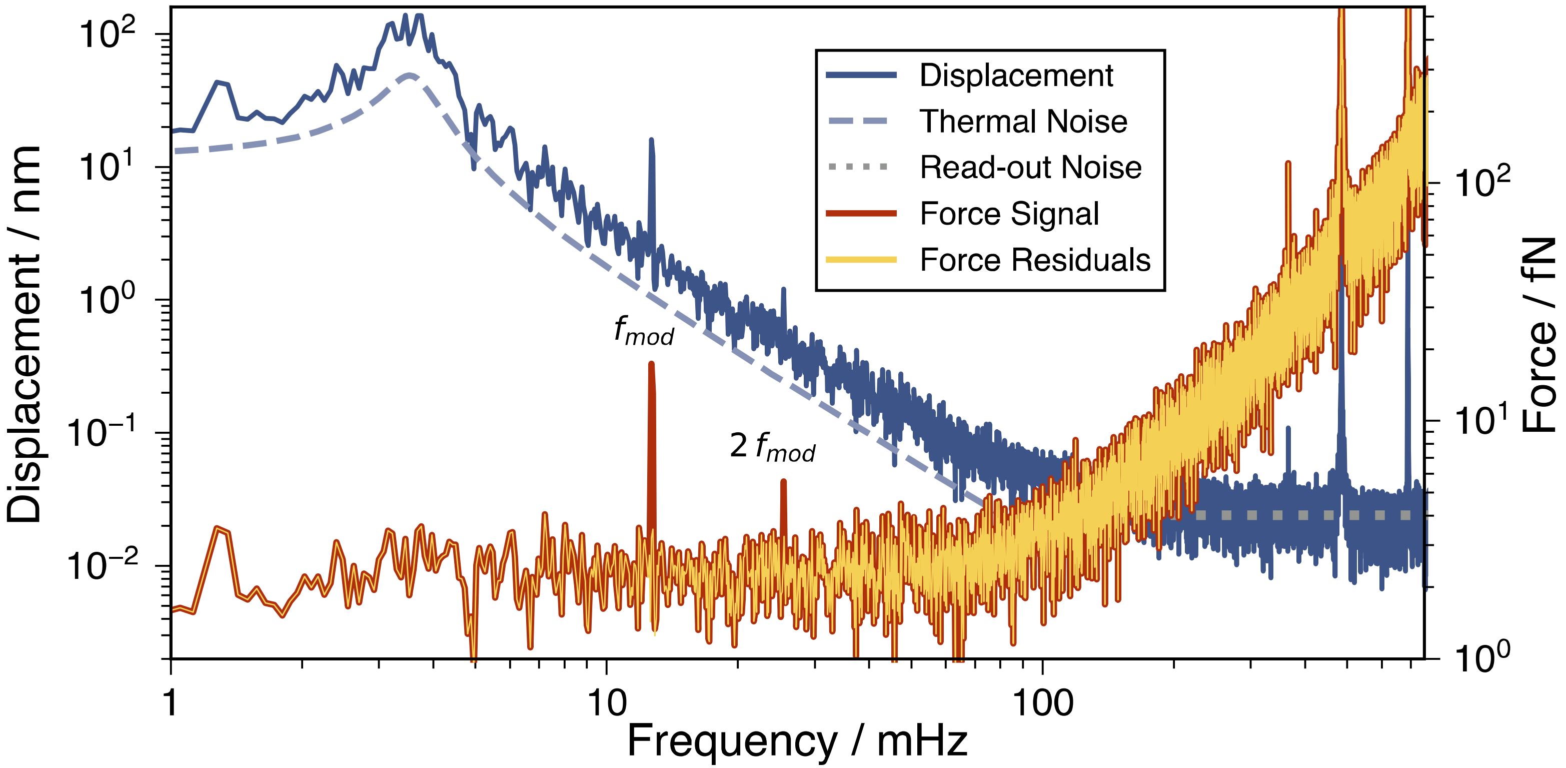
The challenge: how to NOT measure trams, marathon runners and night busses…

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

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

Silent Christmas Nights...





- 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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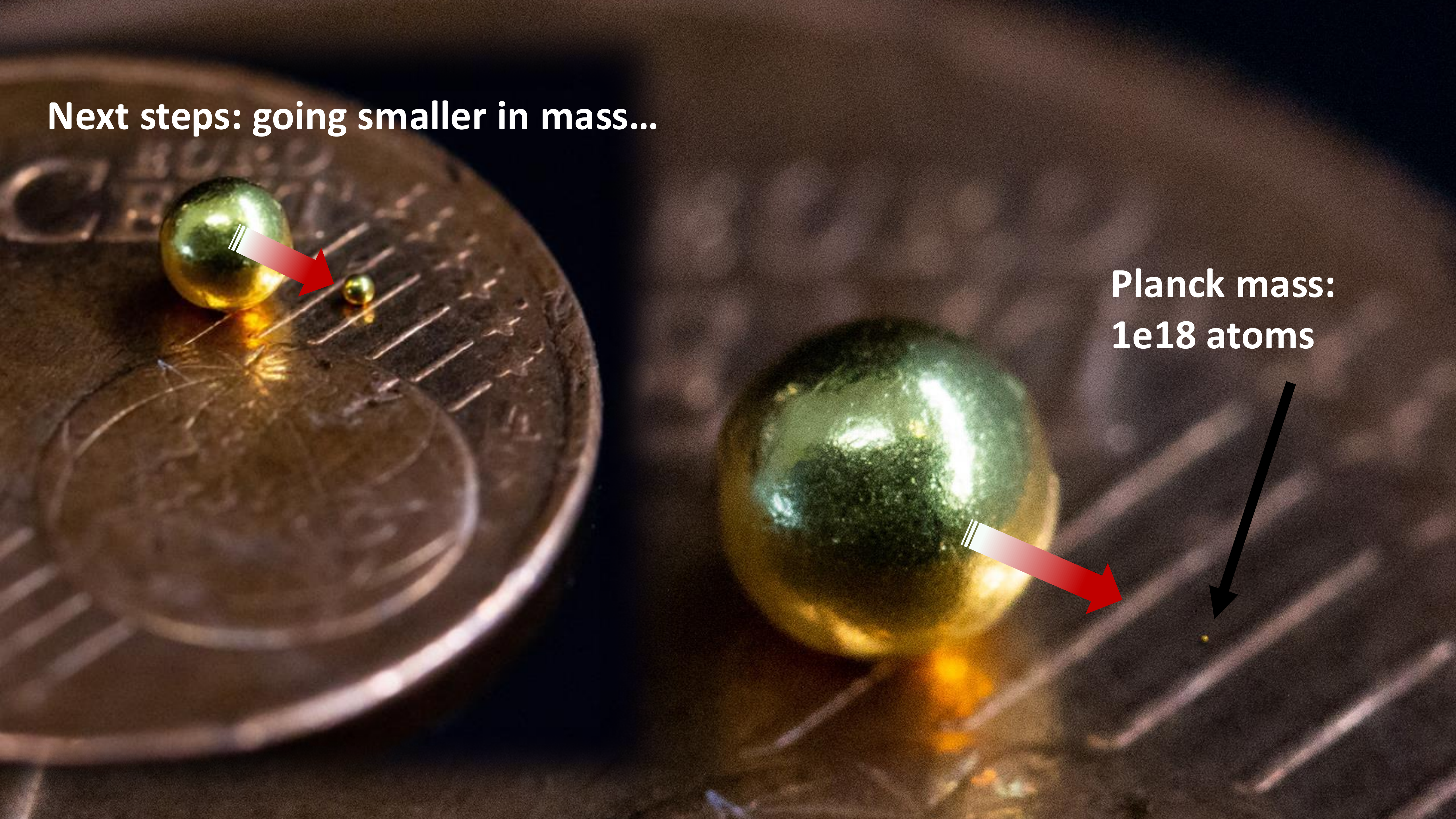

Next steps: going smaller in mass…
Planck mass:
1e18 atoms

... by going underground

ZAMG
Zentralanstalt für Meteorologie und Geodynamik

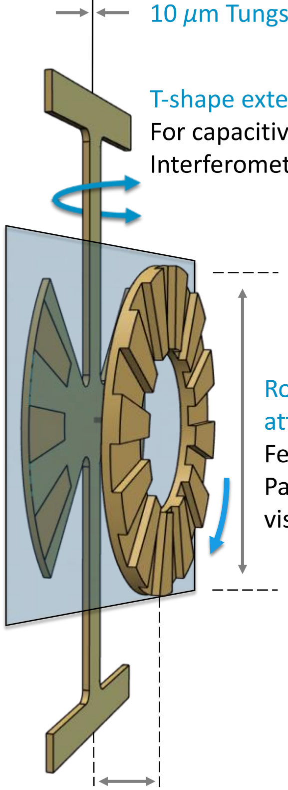
Conrad Observatory, Trafelberg, Austria

Going closer: gravity at short distances

Gravity experiments require electromagnetic shielding between masses:

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

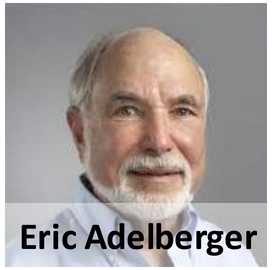
planned: d_0 > 10 μm [Vienna; in collaboration with Eric Adelberger]



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**



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Summary I: Quantum Sources of Gravity – why and how?

arXiv:2203.05587

Why?

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

FEYNMAN: „YES!“

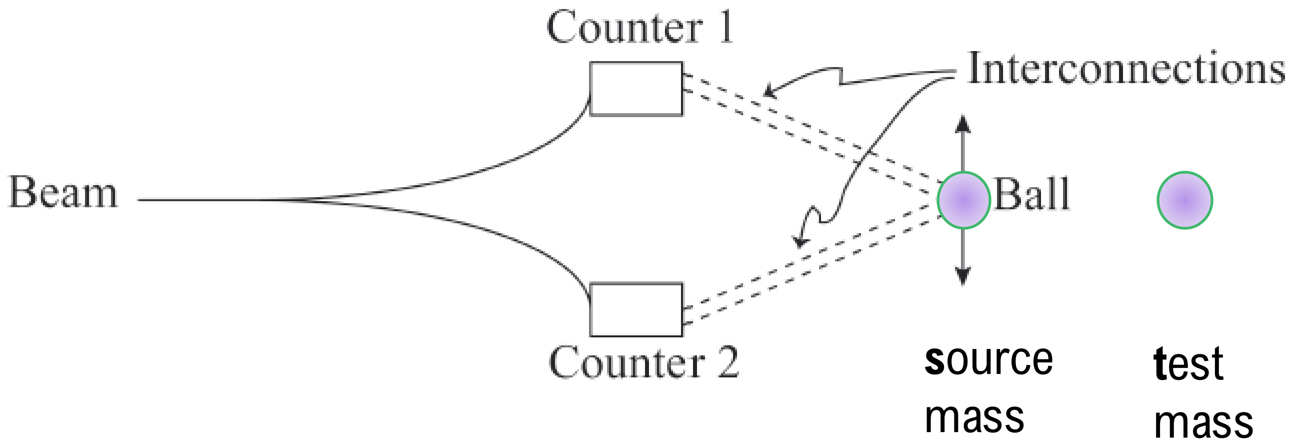
1957 Chapel Hill Conference

How?

R P Feynman

”One should think about designing an experiment which uses a gravitational link and at the same time shows quantum interference”

Chapel Hill Conference 1957



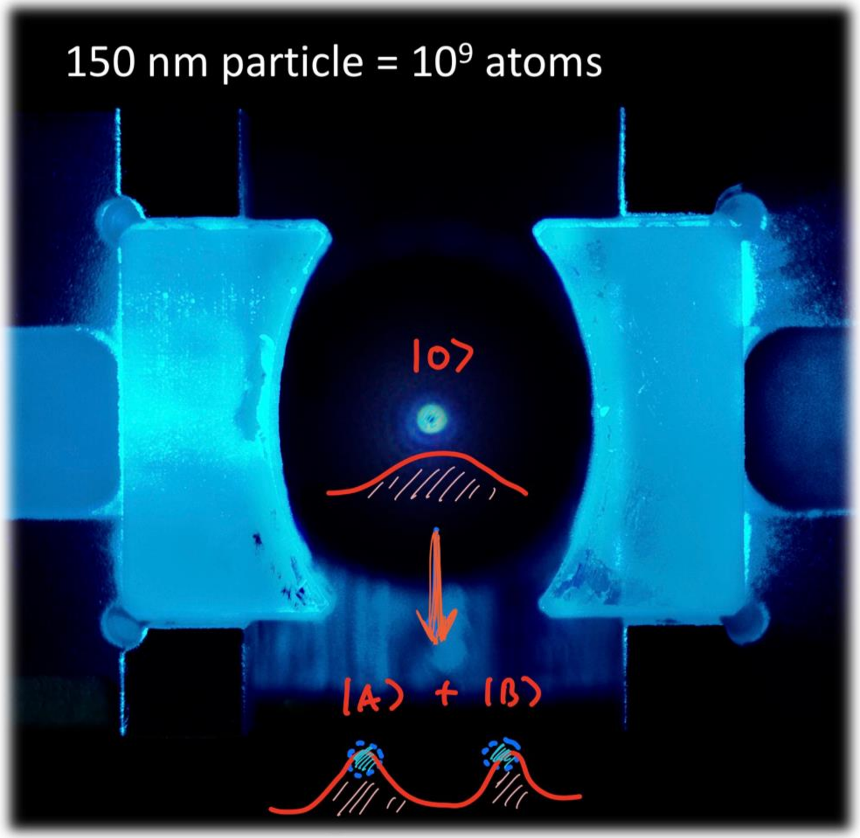
$$m^2 \Delta x^2 \tau_{coherence} d^{-3} \overset{!}{>} \hbar / G$$

Requires: **large mass** (>>1e-6 Planck Mass),
xtreme delocalization (>60dB),
long coherence (10ms),
sensitivity to gravity (<1e-14 g)

Summary II

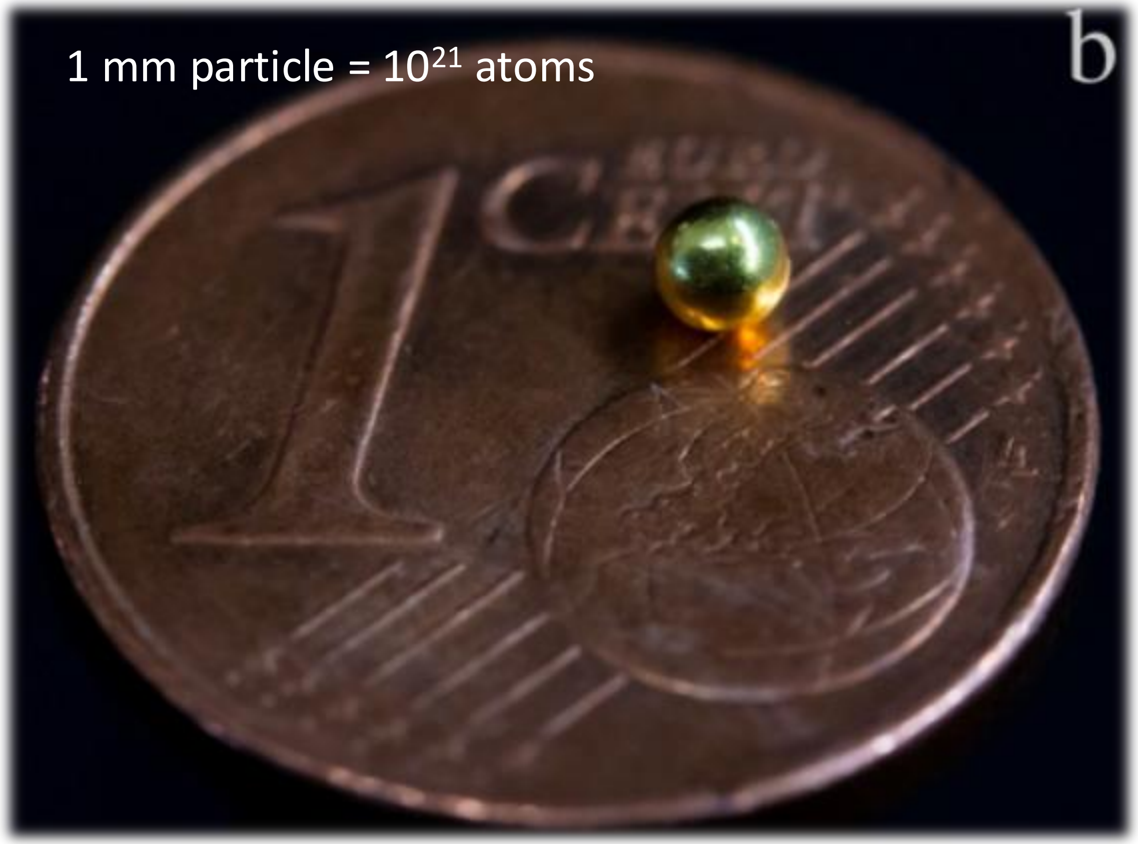
- Levitated quantum control in the regime of large mass and long coherence times
- Bottom-Up: Quantum regime of nanoparticles
- Top-Down: Gravitational coupling of mm-sized particles

- 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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Summary III:
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, *Phys. Rev. D* **108**, 101702 (2023)

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Quantum-“Mechanics“ in Vienna: The Levitation Team 2025

+ our collaboration partners:
The ERC Synergy team: Lukas Novotny, Romain Quidant (ETH) / Oriol Romero-Isart (Innsbruck)
Eric Adelberger (UWash) / Caslav Brukner (Vienna) / Rudolf Gross, Hans Hübl (WMI) / Andreas Kugi (TU Wien) /
Nikolai Kiesel (Vienna) / Monika Ritsch-Marte (Innsbruck) / Vladan Vuletic (MIT) / Robert Wald (UChicago) / Witlef Wieczorek (Chalmers)

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erc European Research Council
Alexander von Humboldt Stiftung/Foundation
FWF Der Wissenschaftsfonds.
cQOM
OMT OPTOMECHANICAL TECHNOLOGIES
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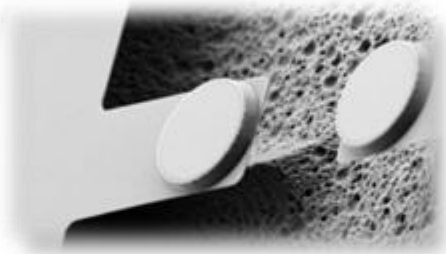
Ars longa, vita brevis

2004 2006 2008 2010 2012 2014

2004-2014 Quantum optomechanics

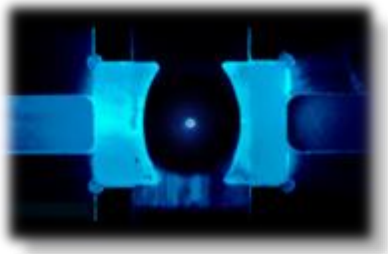
- (2004) motivation: Paolo Tombesi, Anton Zeilinger
- laser cooling of micromechanics (2006)
- strong optomechanical coupling (2009)
- quantum ground state micromechanics (2011)
- Cavity cooling of levitated solid (2013)



2014 2016 2018 2020 2022 2024

2014-2024 Combining quantum and gravity

- (2014) ERC grant: towards entanglement 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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