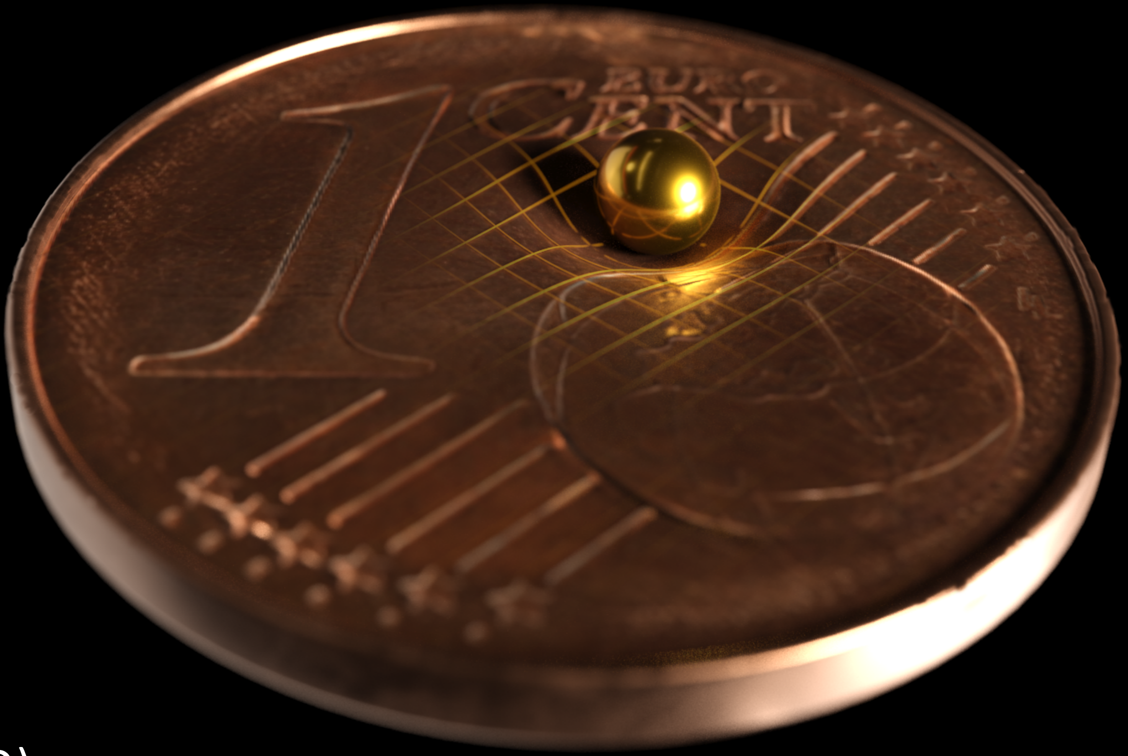
Humboldt Kolleg, Kitzbühel 2022

Gravitational Quantum Physics:
how to avoid the appearence of the 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

arxiv:2203.05587

Humboldt Kolleg, Kitzbühel 2022

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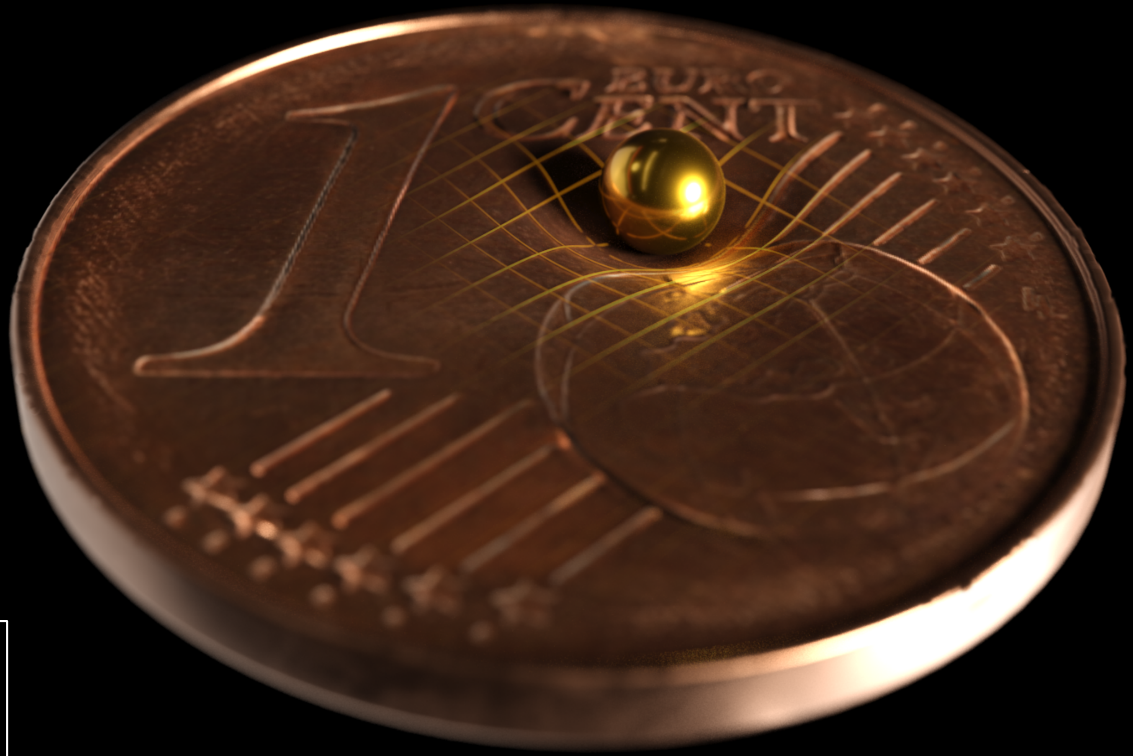


Peter Asenbaum

Talk on Friday:
Gravity in large quantum states and
the Aharonov-Bohm effect

IQOQI, Austrian Academy of Sciences

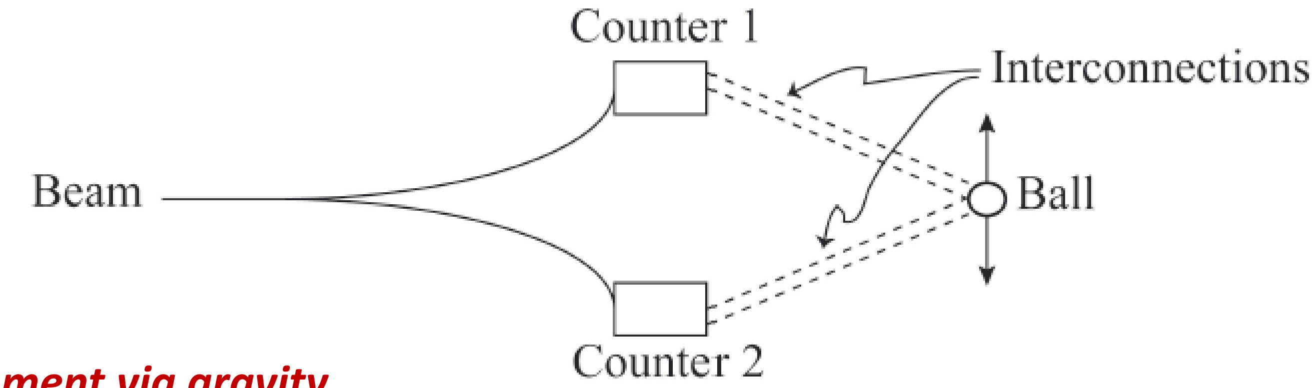
arxiv:2203.05587

Prelude: The 1957 Chapel Hill Conference

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



Quantum entanglement via gravity

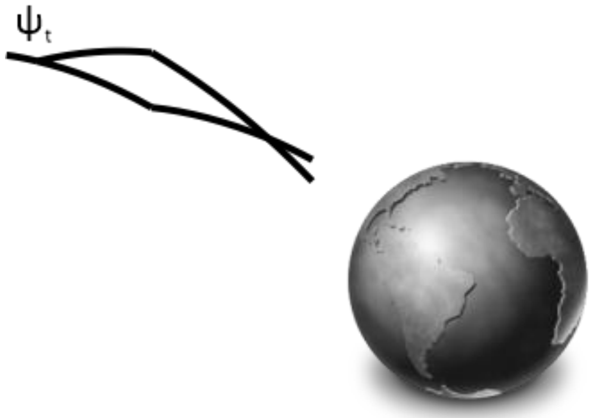
“…that we’re in trouble if we believe in quantum mechanics but don’t quantize gravitational theory”

„But aside from that possibility [that quantum mechanics fails], if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment.”

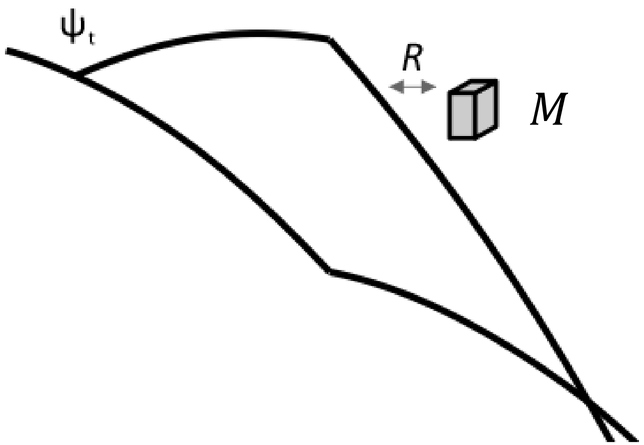
Here he explicitly refers to the ability to apply the superposition principle, i.e. probability amplitudes, to different gravitational field configurations, and not the necessity to invoke quanta of the field (gravitons).

arxiv:2203.05587

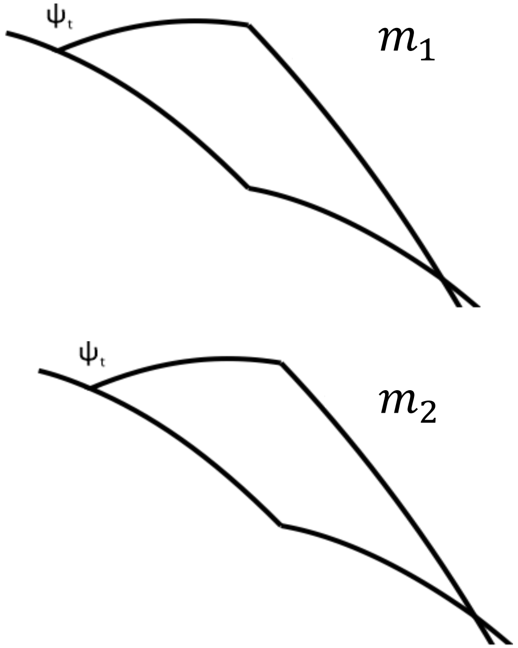
Gravity in Quantum Systems



classical



quantum



entanglement

$a_G = \frac{GM}{R^2}$ …source mass M

For two large quantum states:

Phase shift

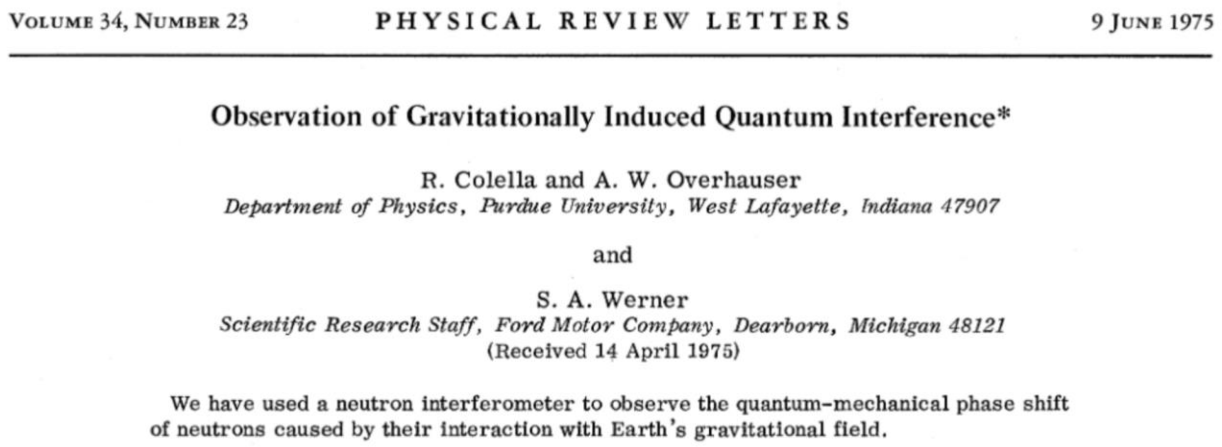
$$\phi = k\ a_G\ g\ \tau^2$$

$$\phi = \frac{m}{\hbar}\frac{GM}{R}\tau$$

$$\phi = \frac{m_1}{\hbar}\frac{Gm_2}{R}\tau$$

acceleration

Grav. Energy



VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

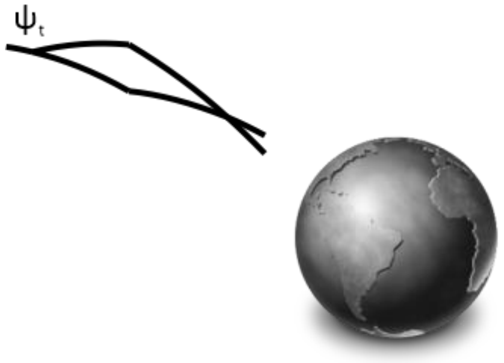
R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

and

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

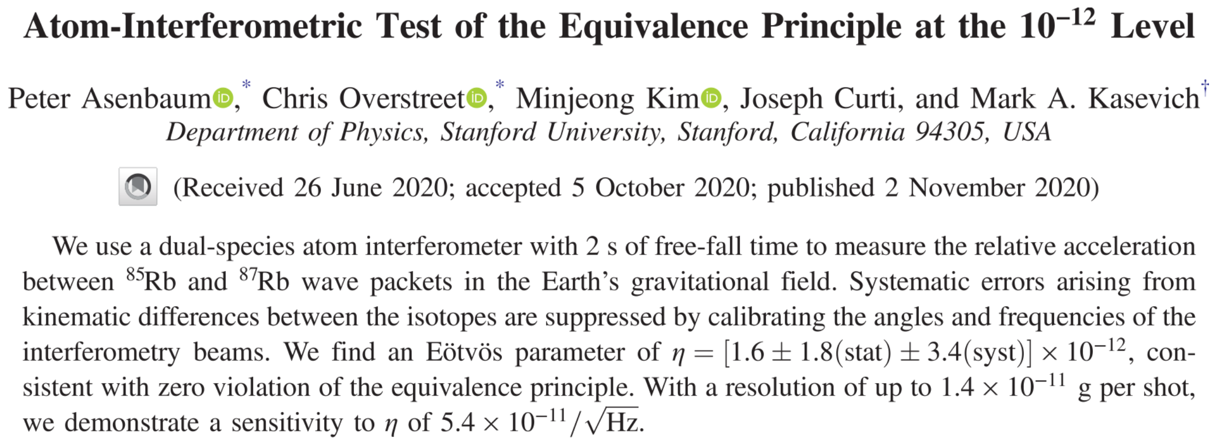
(Received 14 April 1975)

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



$$\phi = k\, g\, \tau^2$$

classical

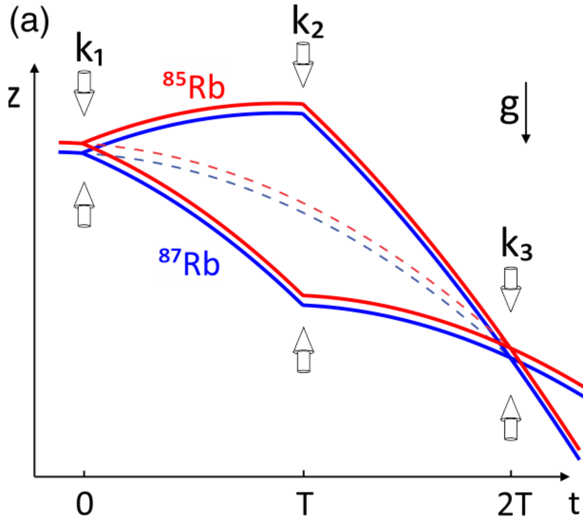


Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

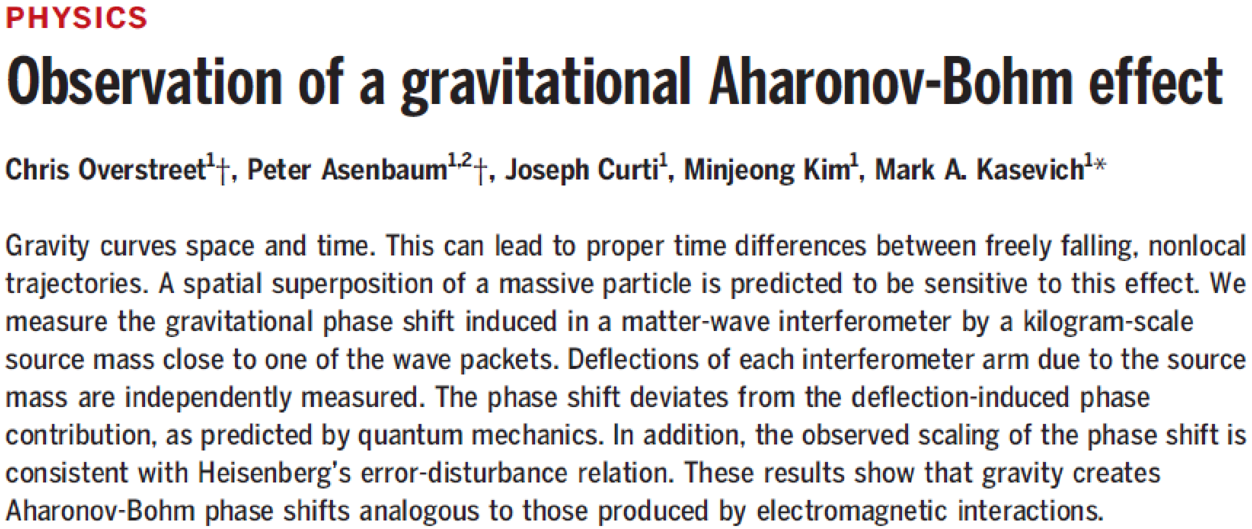
Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†
Department of Physics, Stanford University, Stanford, California 94305, USA

(Received 26 June 2020; accepted 5 October 2020; published 2 November 2020)

We use a dual-species atom interferometer with 2 s of free-fall time to measure the relative acceleration between ^{85}Rb and ^{87}Rb wave packets in the Earth's gravitational field. Systematic errors arising from kinematic differences between the isotopes are suppressed by calibrating the angles and frequencies of the interferometry beams. We find an Eötvös parameter of $\eta = [1.6 \pm 1.8(\mathrm{stat}) \pm 3.4(\mathrm{syst})] \times 10^{-12}$, consistent with zero violation of the equivalence principle. With a resolution of up to 1.4×10^{-11} g per shot, we demonstrate a sensitivity to η of $5.4 \times 10^{-11}/\sqrt{\mathrm{Hz}}$.



No mass dependence! QM satisfies Equivalence Principle!



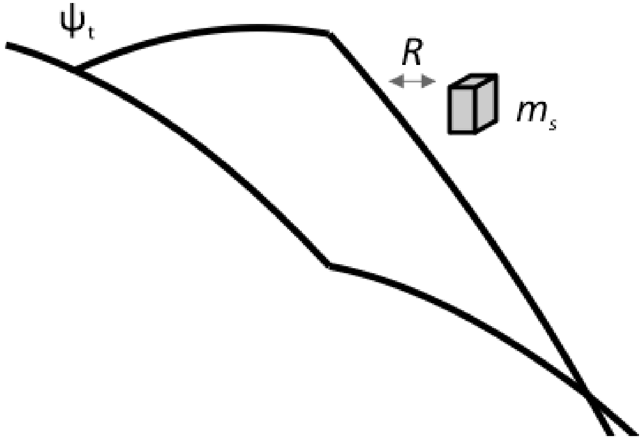
PHYSICS

Observation of a gravitational Aharonov-Bohm effect

Chris Overstreet[1]†, Peter Asenbaum[1,2]†, Joseph Curti[1], Minjeong Kim[1], Mark A. Kasevich[1]*

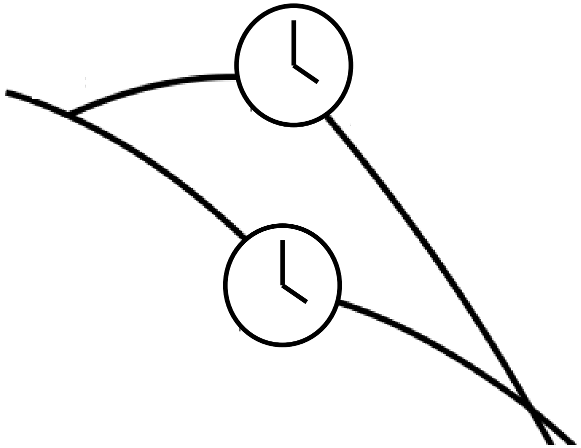
Gravity curves space and time. This can lead to proper time differences between freely falling, nonlocal trajectories. A spatial superposition of a massive particle is predicted to be sensitive to this effect. We measure the gravitational phase shift induced in a matter-wave interferometer by a kilogram-scale source mass close to one of the wave packets. Deflections of each interferometer arm due to the source mass are independently measured. The phase shift deviates from the deflection-induced phase contribution, as predicted by quantum mechanics. In addition, the observed scaling of the phase shift is consistent with Heisenberg's error-disturbance relation. These results show that gravity creates Aharonov-Bohm phase shifts analogous to those produced by electromagnetic interactions.

$$\phi = \frac{m}{\hbar}\frac{GM}{R}\tau$$



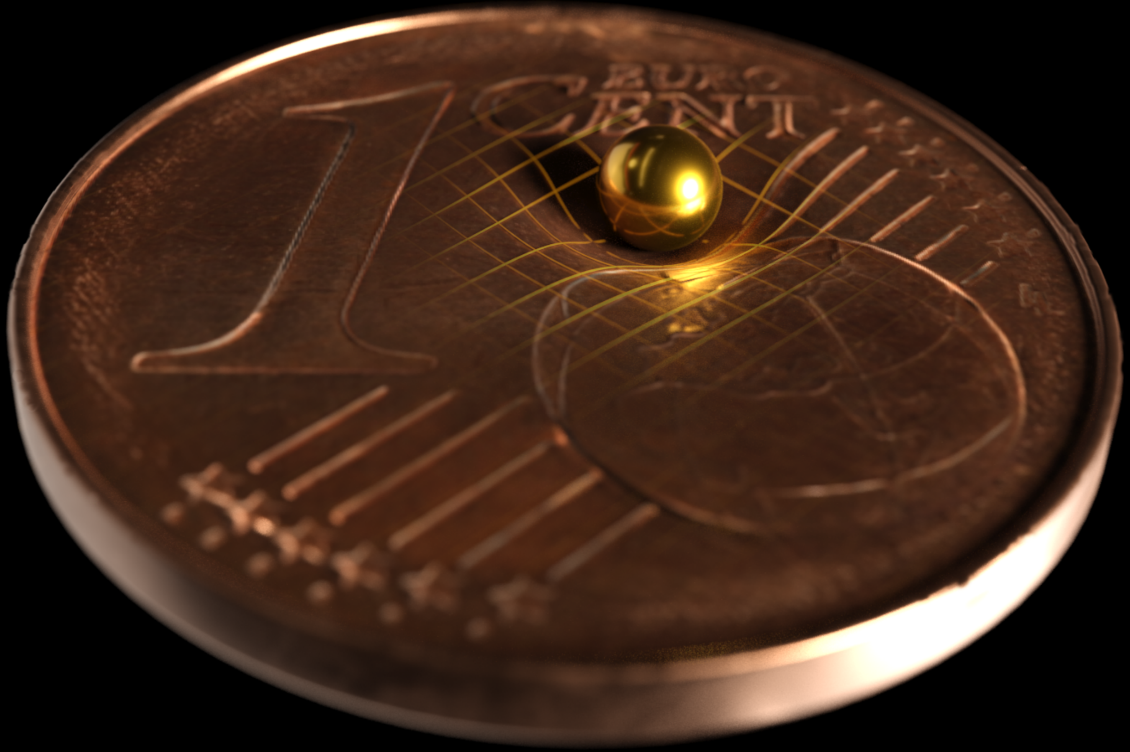
quantum

Two clocks measure hybrid between acceleration and energy



not high-sensitivity $\frac{\Delta m}{m} = 10^{-11}$

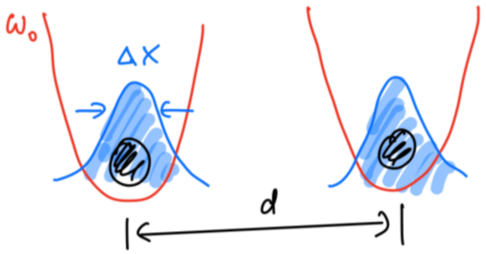
What about quantum systems as gravitational SOURCE masses?



- Source vs test mass
- In gravitational entanglement regime:

  each particle is sensor and source

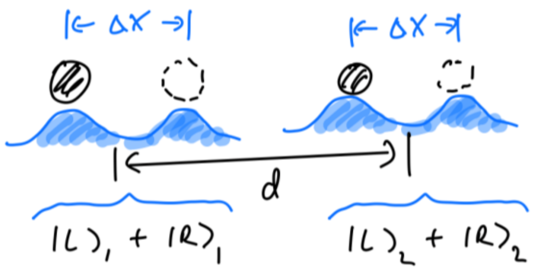
This rather be solid...



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

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

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



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

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

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

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)

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

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

$$\left.\begin{aligned} d &\sim 10^{-6}\,m \\ \frac{\Delta x}{d} &\sim 10^{-1} \end{aligned}\right\} \quad \begin{aligned} g &\approx 2\pi \cdot 10^{23} \cdot 10^{6} \cdot 10^{-2}\, m^2 \\ &\approx 6 \cdot 10^{27} \cdot m^2 \gtrsim \mathcal{O}(1) \end{aligned}$$

$$\leftrightarrow \quad m^2 \gtrsim (1.2 \cdot 10^{-14})^2$$

$$\rightarrow \quad \rho \approx \frac{m}{d^3} \gtrsim \frac{10^{-14}}{(10^{-6})^3} \sim 10^4 \frac{kg}{m^3} \equiv \text{SOLID-STATE}$$

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

The decoherence challenge...

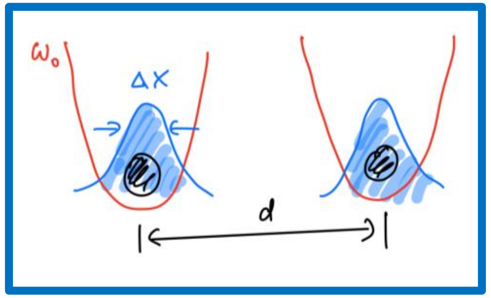
see also
O. Romero-Isart et al., PRL 107, 020405 (2011)
O. Romero-Isart, PRA 84, 052121 (2011)
S. Rijavec et al., New J. Phys. 23, 043040 (2021)
T. Weiss et al., PRL 127, 023601 (2021)

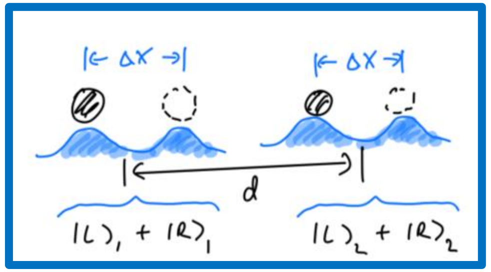
Examples:

	ΔX	squeezing	T_i	T_e
75 um glass sphere	> 2 μm	> 60 dB	4K	4K
Planck mass Pb sphere	> 12 um	> 60 dB	8K	6K
LIGO ($\mathcal{O}$(10 cm))	> 1 um	> 60 dB	4K	300 mK

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

assuming GAS SCATTERING & BLACKBODY radiation





arxiv:2203.05587 (2022)

Decoherence & the appearence of a classi

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

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)

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

Decoherence fron

$\lambda_{th} = 2\pi\hbar\,(\sqrt{2\pi}$

Decoherence from

$\lambda_{th} = \frac{\pi^{2/3}\,\hbar c}{k_B T_c} \sim 0($

Thermal decoherence

DECOHERENCE

(i) GAS DAMPING $\Gamma_g \simeq 2\cdot 10^{26}\, p R^2\, T_e^{-1/2}$

(ii) BLACKBODY SCATTERING $\Gamma_{b,s} \simeq 3\cdot 10^{36}\, R^6\, T_e^{9}\, \Delta x^2$

ABSORPTION $\Gamma_{b,a} \simeq 7\cdot 10^{25}\, R^3\, T_e^{6}\, \Delta x^2$

EMISSION $\Gamma_{b,e} \simeq 7\cdot 10^{25}\, R^3\, T_i^{6}\, \Delta x^2$

(iii) TRAP FLUCTUATIONS $\Gamma_x = \frac{\pi\omega_0^2}{4\sigma_0^2} S_x(\omega_0)$

(iv) FREQUENCY FLUCTUATIONS $\Gamma_\omega = \frac{\pi\omega_0^2}{16} S_\omega(2\omega_0)$

(v) THERMAL DECOHERENCE $\Gamma_{th} \simeq \frac{k_B T_e}{\hbar\omega_0}\gamma \simeq 10^{11}\cdot\frac{T_e}{\omega_0}\cdot\gamma$

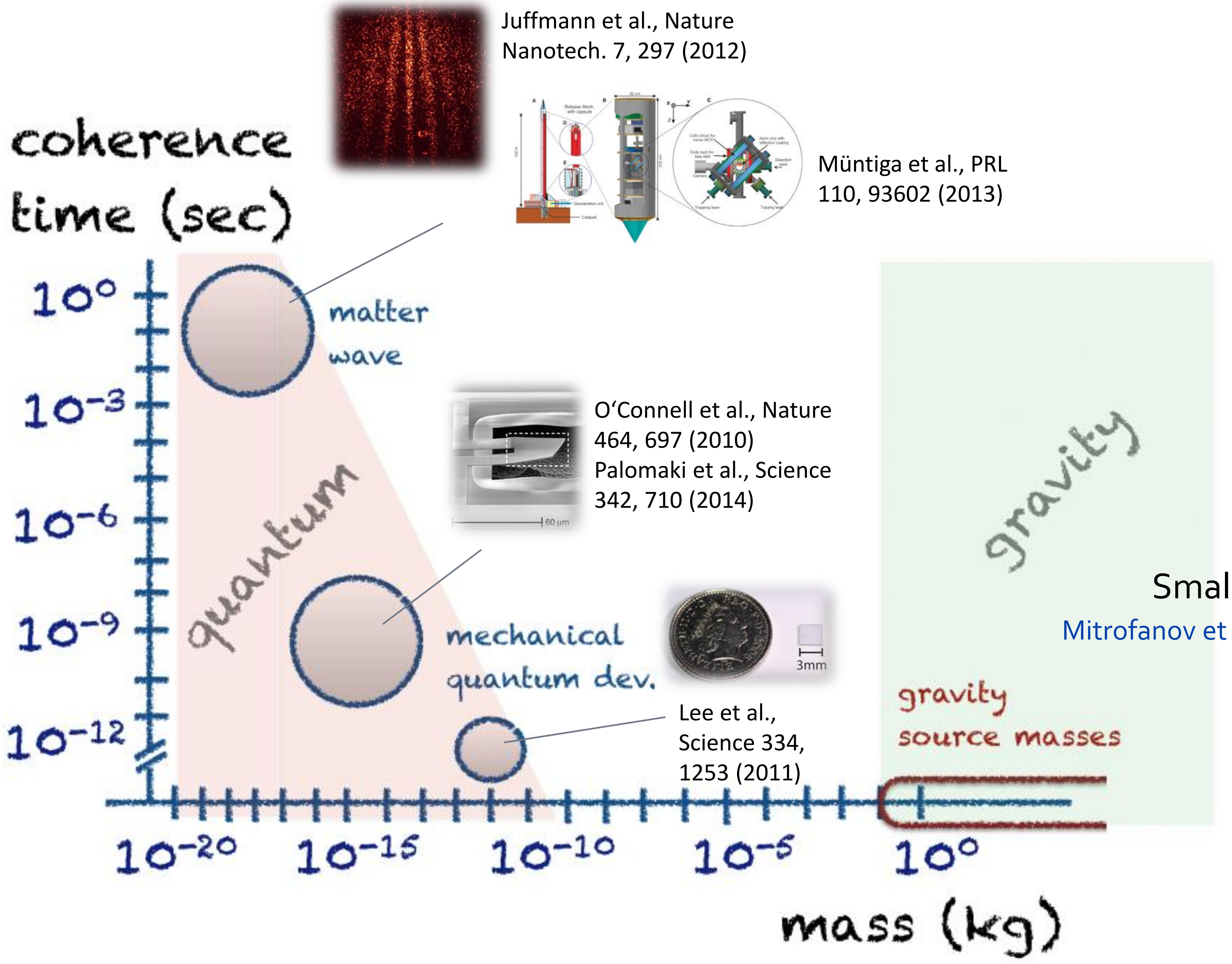
$$\Gamma_{gas} = \frac{\lambda_{th}}{\hbar}\,\frac{16\pi}{3}\, p R^2$$

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

BB emission
absorption

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

Reality check: quantum systems as gravitational source masses?



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

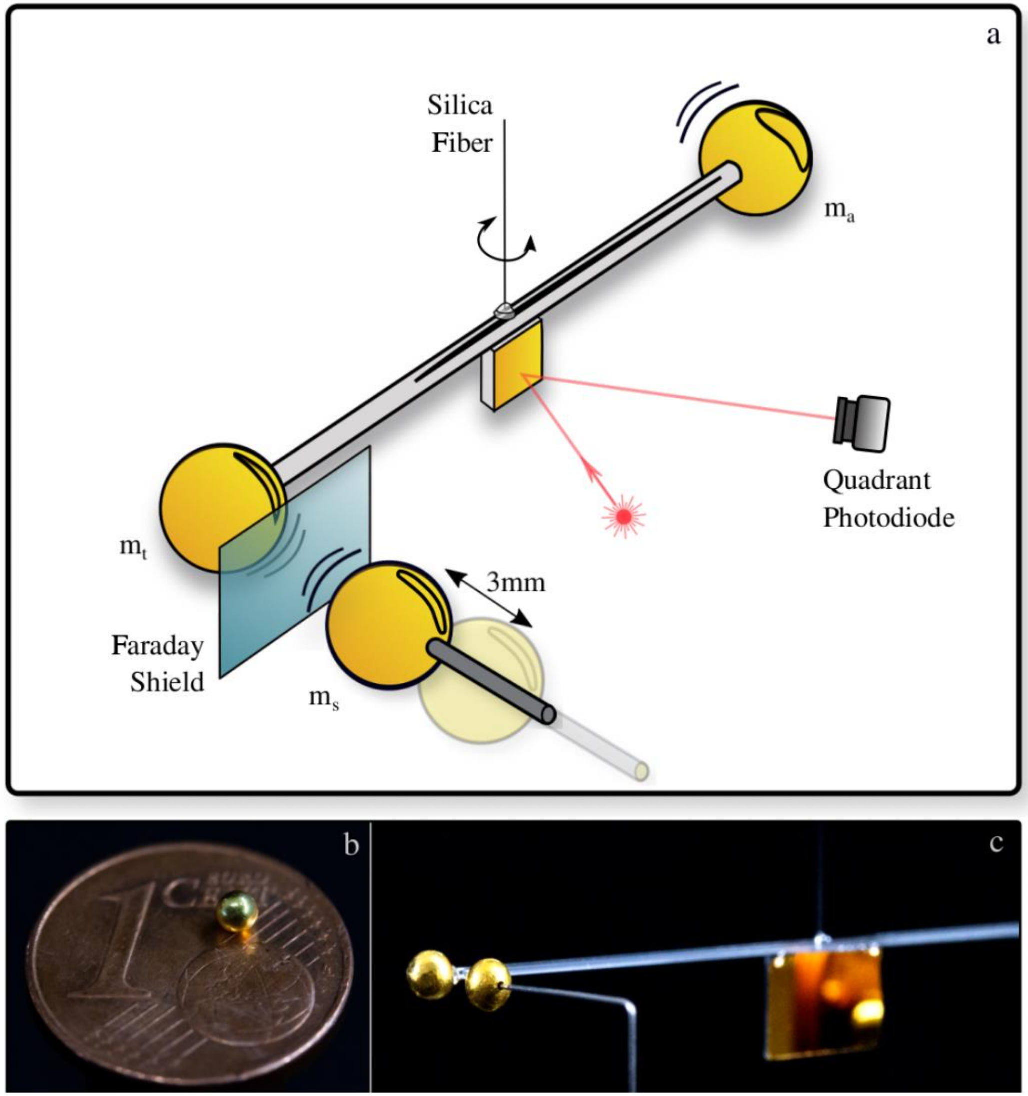
Smallest source mass to date: **0.7 g**

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

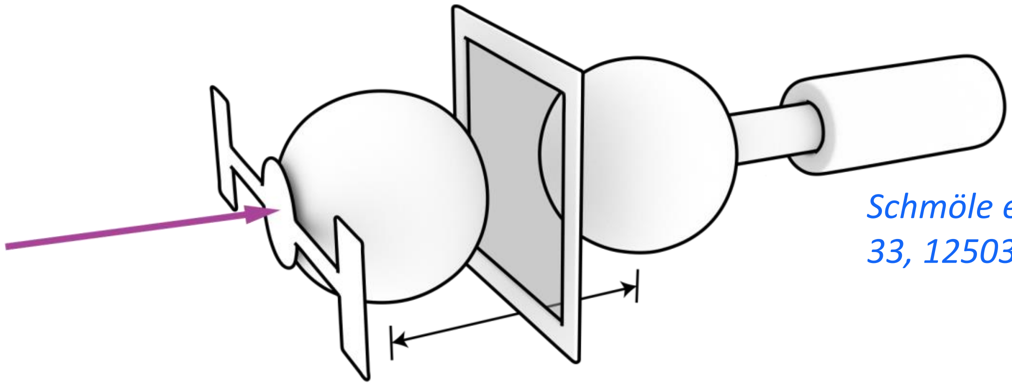
Lee et al., PRL 124, 101101 (2020)

1. Go small!
2. Go coherent!

How small can we go? The idea:



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



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

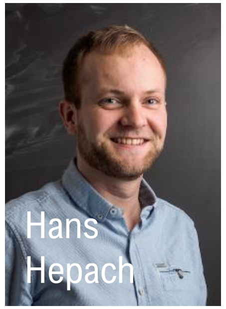
- periodic modulation of a source mass @ f_mod
- generates a test mass acceleration @ n x f_mod (n=1,2, …)
- fundamental limit: thermal noise of test mass oscillator

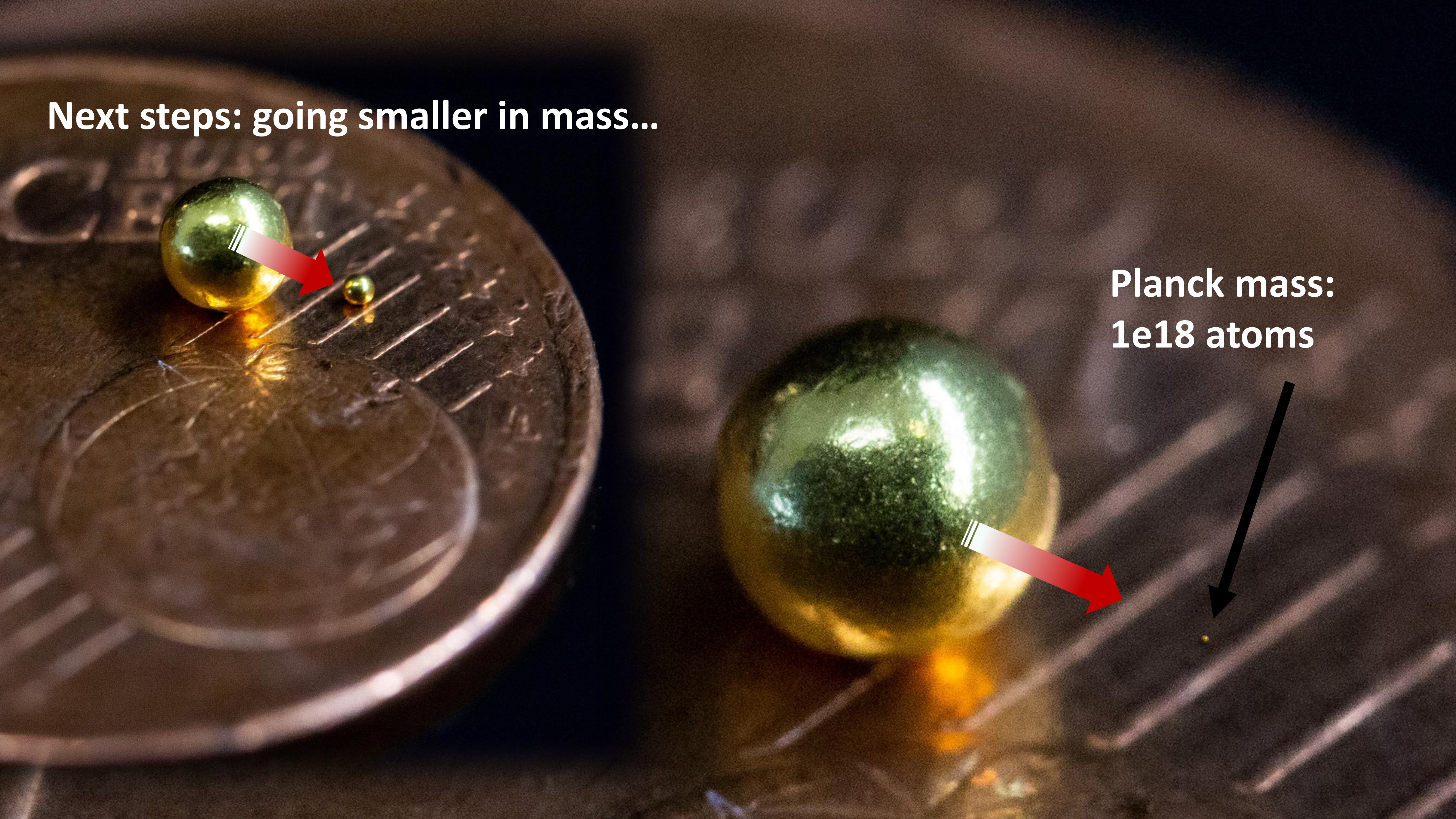
$$d(t) = d_0 + d_m \cos\Omega t$$

$$a(t) = G\frac{m}{d(t)^2} = G\frac{m}{d_0^2}\left(1 - 2\frac{d_m}{d_0}\cos\Omega t + 3\left(\frac{d_m}{d_0}\right)^2\cos^2\Omega t + \dots\right)$$

$$\left.\begin{aligned} m_s &\sim 9\cdot 10^{-5}\,\mathrm{kg} \\ d_0 &\sim 4\,\mathrm{mm} \\ d_m &\sim 1.6\,\mathrm{mm} \end{aligned}\right\} \quad a \sim 3\cdot 10^{-10}\,\frac{\mathrm{m}}{\mathrm{s}^2}$$

M=100 mg



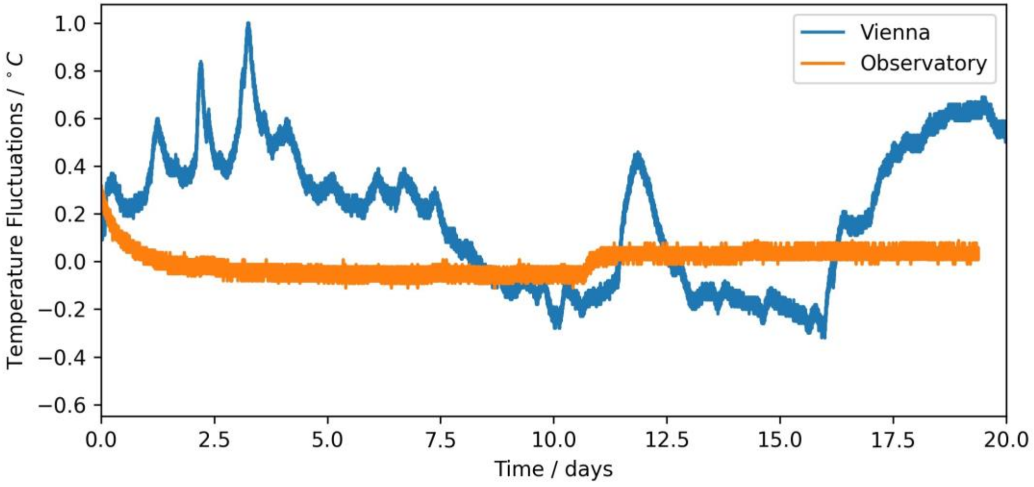


Next steps: going smaller in mass…

Planck mass:
1e18 atoms

Improved noise performance...

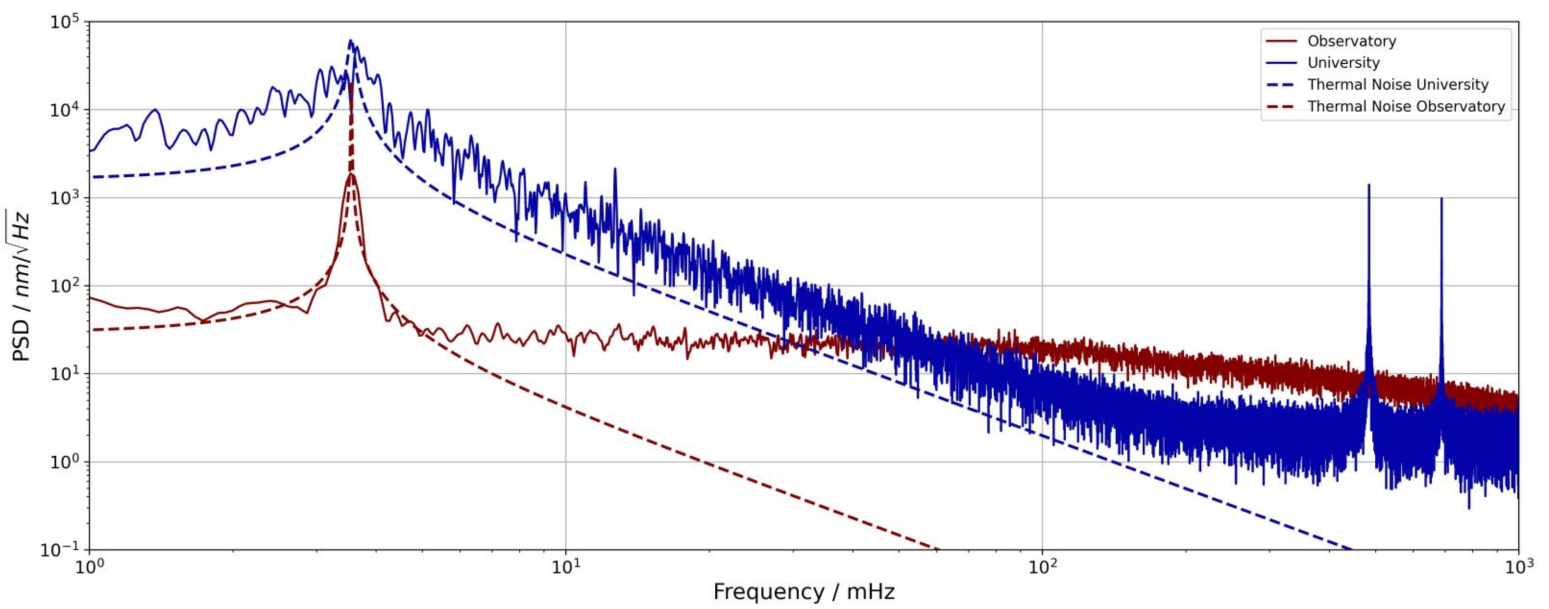
Temperature



City

Mine

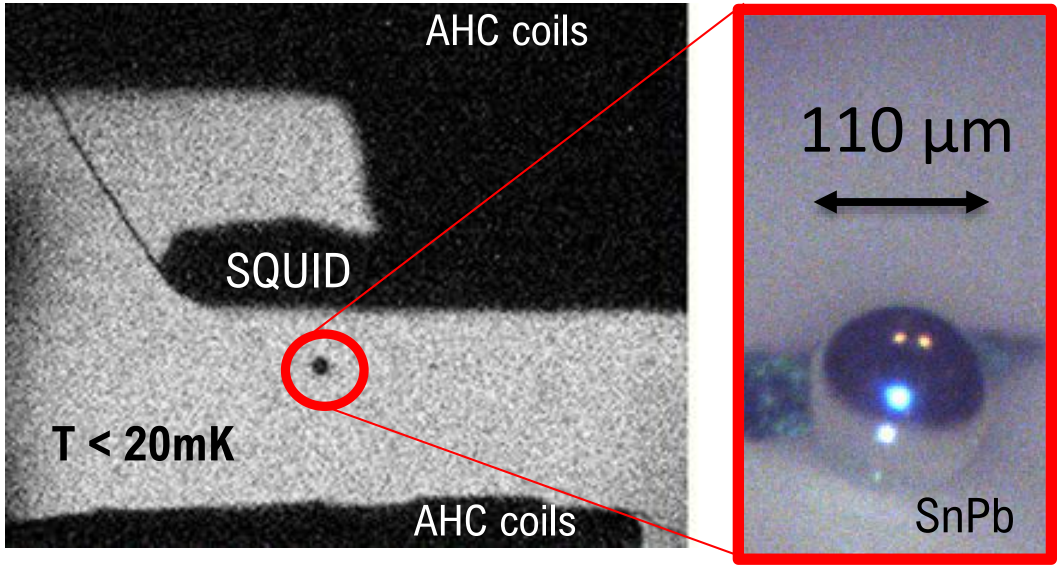
Displacement sensing



ZAMG
Zentralanstalt für Meteorologie und Geodynamik

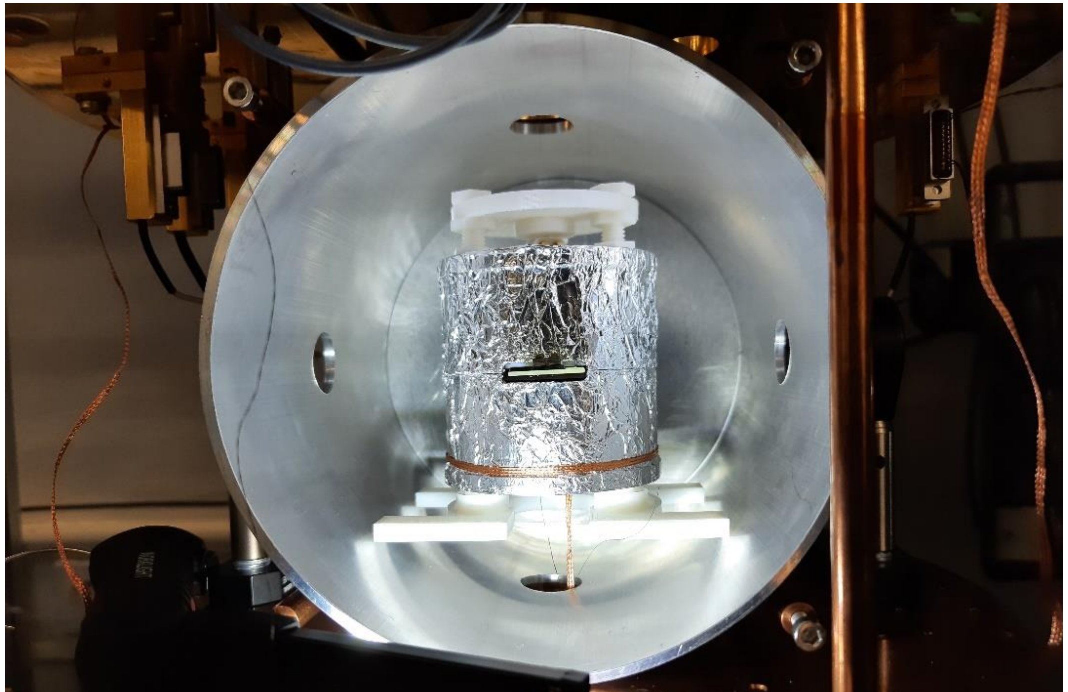
Conrad Observatory
Trafelberg, Austria

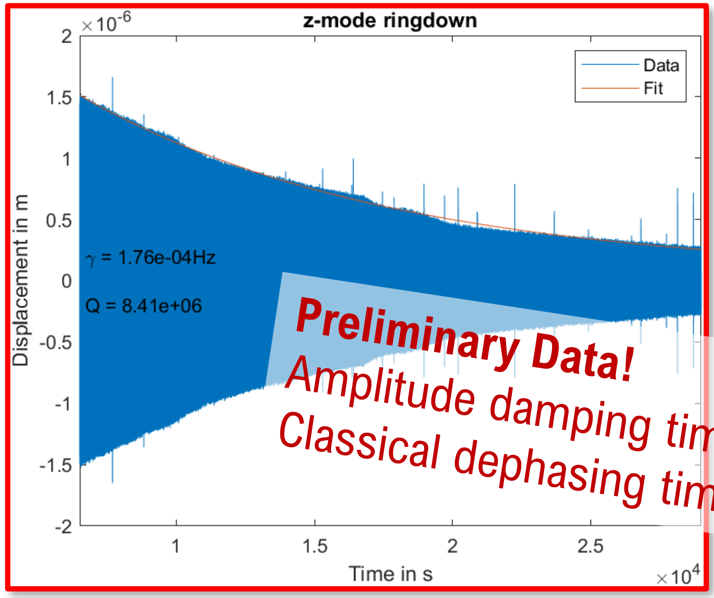
Go coherent: superconducting levitation



ca. Planck mass

Gerard Higgins





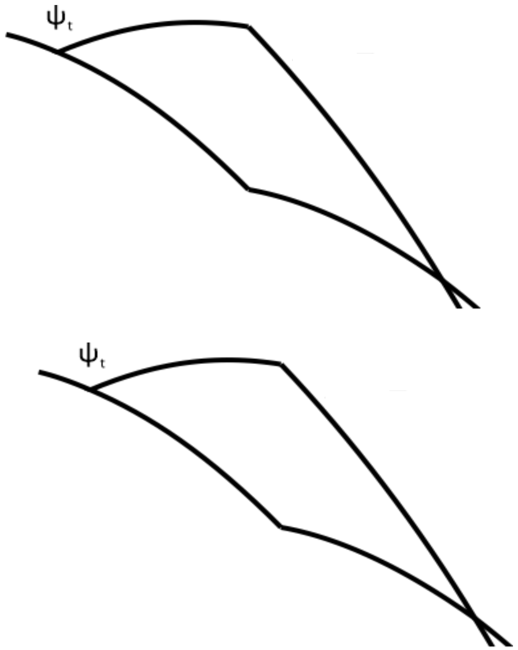
Preliminary Data!

Amplitude damping time > 40,000 sec

Classical dephasing time > 80 sec

Summary

Goal:



Grav. entanglement

Exp. parameters:

- Mass: 10^{-10} kg
- Pressure: 10^{-17} mbar
- Temperature: 1 K
- Sensitivity: 10^{-17}g
- Systematics:….

Implications:

- Gravity plays by quantum rules
- Grav. field clearly non-classical

BUT:

- Field can be ignored to predict experiment
- Superposition of field cannot be observed independently

Quantum-“Mechanics“ in Vienna: The Levitation Team 2022

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

erc European Research Council
Alexander von Humboldt Stiftung/Foundation
FWF Der Wissenschaftsfonds.
cQOM
OMT OPTOMECHANICAL TECHNOLOGIES