Large Mass Quantum Systems for Testing the overlap between Quantum Mechanics & Gravity – a Quantum to Classical Transition?

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Thanks to …

www.quantumnano.org

Group at Southampton: Tim Fuchs, Chris Timberlake, Marion Cromb, Jack Homans, Elliot Simcox, Jakub Wardak, Laura Barbara, Amy Smith, Charlotte Bridgett, Frank Parker, Rounak Naskar (soon). *Former members:* Tiberius Georgescu, Rafael Mufato, Hailong Pi, Chuang Sun, Andrea Vinante, James Bateman, Nathan Cooper, Jamie Vovrosh, David Hempston, Luca Ferialdi, Muddassar Rashid, Marko Toroś, George Winstone, Giulio Gasbarri, Ashley Setter.

Quantum Optics theory and Foundations of Physics: TP Singh, Mauro Paternostro, Sougato Bose, Dipankar Home, Matteo Carlesso, Angelo Bassi, Kinjalk Lochan.

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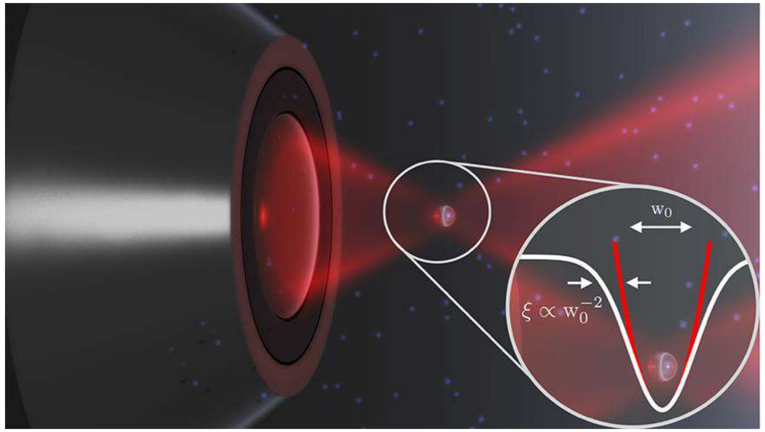
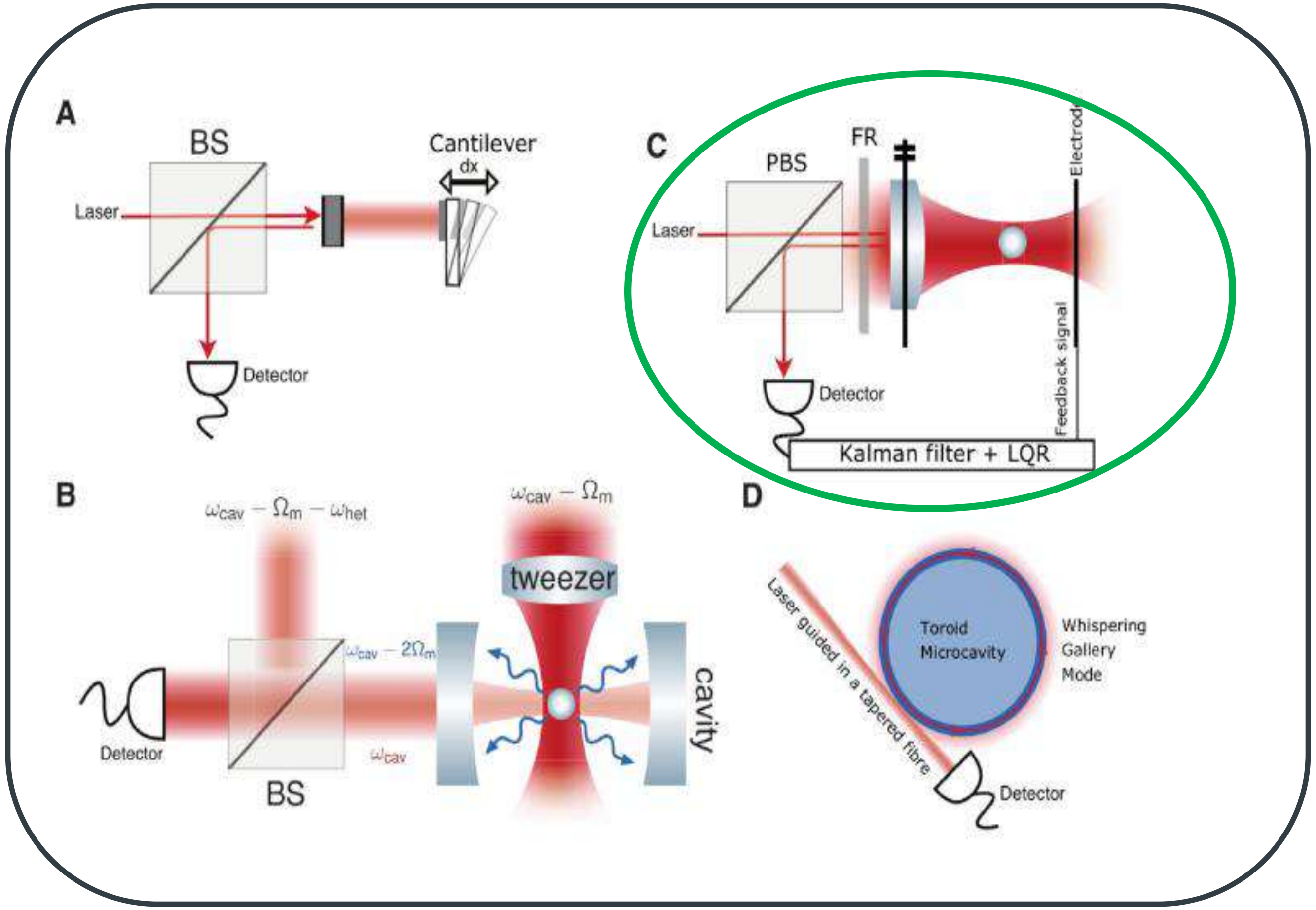
Outline of lecture

- Theoretical ideas and physics to test with large-mass quantum systems, testing aspects of quantum mechanics and gravity, testing fundamental physics.
- Experimental platforms: optical levitation and magnetic levitation of nanoparticle and even larger particles, state of the art experiments.

Optomechanical systems: Quantum Technology

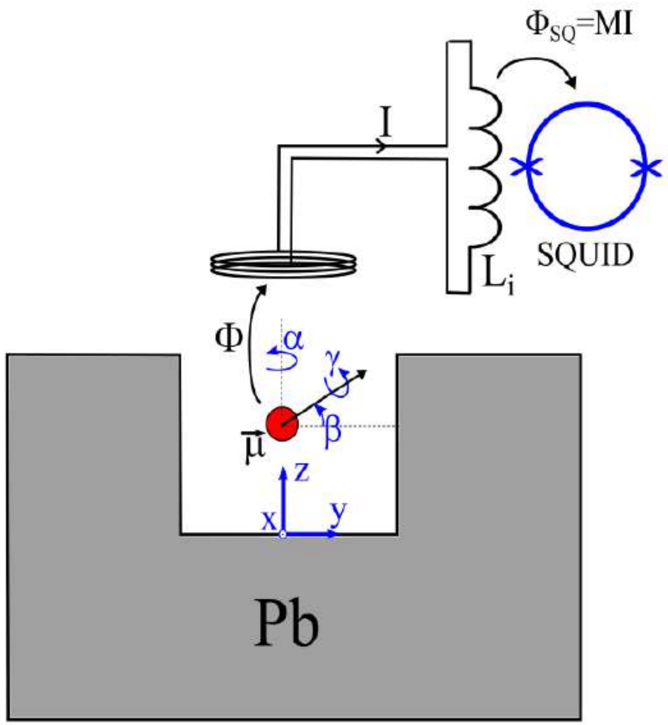
- Light is coupled to mechanics
  - Ultra-precise sensors
  - Frequency conversion
- Macroscopic quantum states

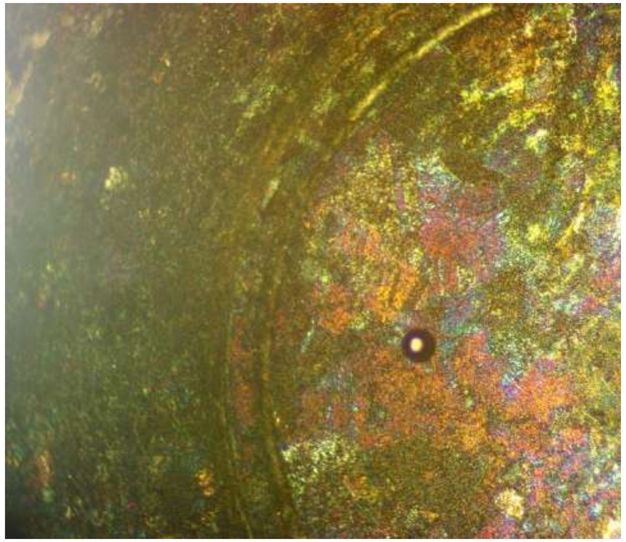




Meissner trapping of ferromagnets with SQUID readout:
low temperature

Simple passive trap: particle in the hole:
Lateral surface provides x,y confinement





NdFeB microsphere radius = 27 um
Trap Radius = 2 mm

Vinante, A., P. Falferi, G. Gasbarri, A. Setter, C. Timberlake, and H. Ulbricht, Ultrahigh mechanical quality factor with Meissner-levitated ferromagnetic microparticles,Phys. Rev. Appl. 13, 064027 (2020)

THEORY AND IDEAS

Testing quantum mechanics

REVIEWS OF MODERN PHYSICS, VOLUME 85, APRIL–JUNE 2013

Models of wave-function collapse, underlying theories, and experimental tests

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(published 2 April 2013)

Quantum mechanics is an extremely successful theory that agrees with every experimental test. However, the principle of linear superposition, a central tenet of the theory, apparently contradicts a commonplace observation: macroscopic objects are never found in a linear superposition of position states. Moreover, the theory does not explain why during a quantum measurement, deterministic evolution is replaced by probabilistic evolution, whose random outcomes obey the Born probability rule. In this article a review is given of an experimentally falsifiable phenomenological proposal, known as continuous spontaneous collapse: a stochastic nonlinear modification of the Schrödinger equation, which resolves these problems, while giving the same experimental results as quantum theory in the microscopic regime. Two underlying theories for this phenomenology are reviewed: trace dynamics and gravity-induced collapse. As the macroscopic scale is approached, predictions of this proposal begin to differ appreciably from those of quantum theory and are being confronted by ongoing laboratory experiments that include molecular interferometry and optomechanics. These experiments, which test the validity of linear superposition for large systems, are reviewed here, and their technical challenges, current results, and future prospects summarized. It is likely that over the next two decades or so, these experiments can verify or rule out the proposed stochastic modification of quantum theory.

DOI: 10.1103/RevModPhys.85.471 PACS numbers: 03.65.Ta, 03.65.Ud, 03.65.Yz, 42.50.Xa

Mass-proportional collapse models: CSL

$$\frac{d}{dt}|\psi_t\rangle = \Big[-\frac{i}{\hbar}H + \frac{\sqrt{\gamma}}{m_0}\int d^3x\,(M(\mathbf{x}) - \langle M(\mathbf{x})\rangle_t)\,dW_t(\mathbf{x})$$
$$-\frac{\gamma}{2m_0^2}\int\int d^3x d^3y\,G(\mathbf{x}-\mathbf{y})\,(M(\mathbf{x}) - \langle M(\mathbf{x})\rangle_t)\,(M(\mathbf{y}) - \langle M(\mathbf{y})\rangle_t)\Big]\,|\psi_t\rangle$$

$$M(\mathbf{x}) = ma^\dagger(\mathbf{x})a(\mathbf{x}) \qquad G(\mathbf{x}) = \frac{1}{(4\pi r_C)^{3/2}}\,\exp[-(\mathbf{x})^2/4r_C^2]$$

$$w_t(\mathbf{x}) \equiv \frac{d}{dt}W_t(\mathbf{x}) = \text{noise} \quad \mathbb{E}[w_t(\mathbf{x})] = 0 \quad \mathbb{E}[w_t(\mathbf{x})w_s(\mathbf{y})] = \delta(t-s)G(\mathbf{x}-\mathbf{y})$$

Two parameters

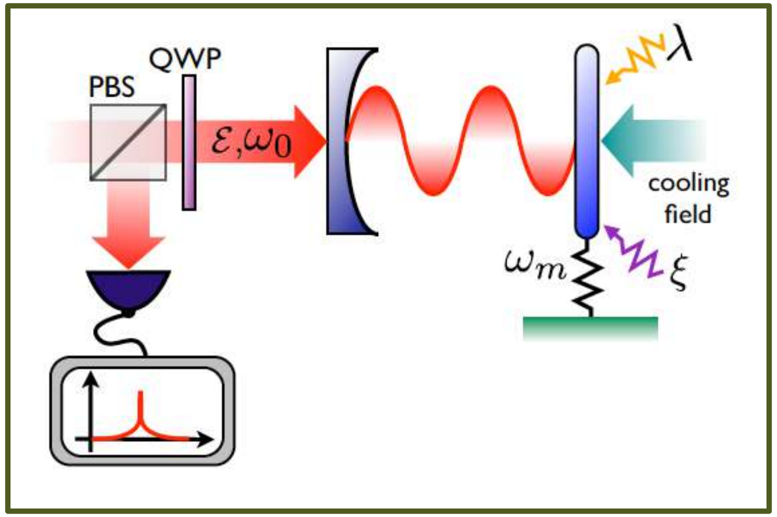
$\gamma =$ collapse strength $\qquad r_C =$ localization resolution

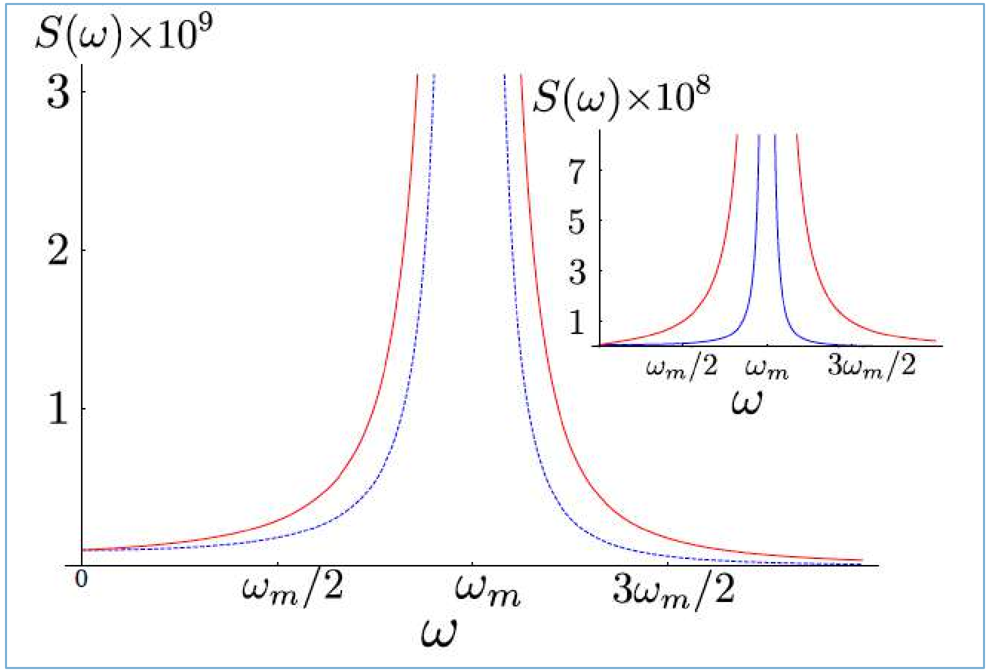
$\lambda = \gamma/(4\pi r_C^2)^{3/2} =$ collapse rate

- **Classical**
- **Random**
- **Non-linear**

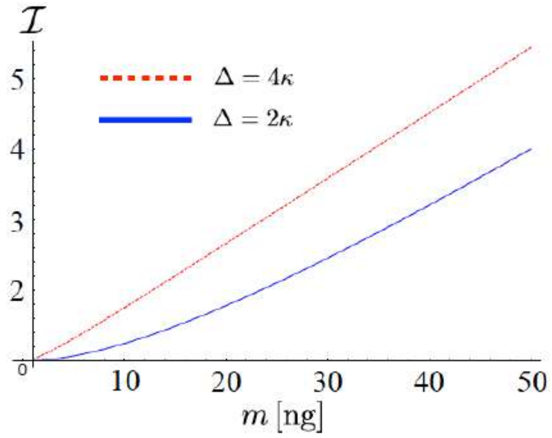
P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

Non-interferometric: Optomechanics



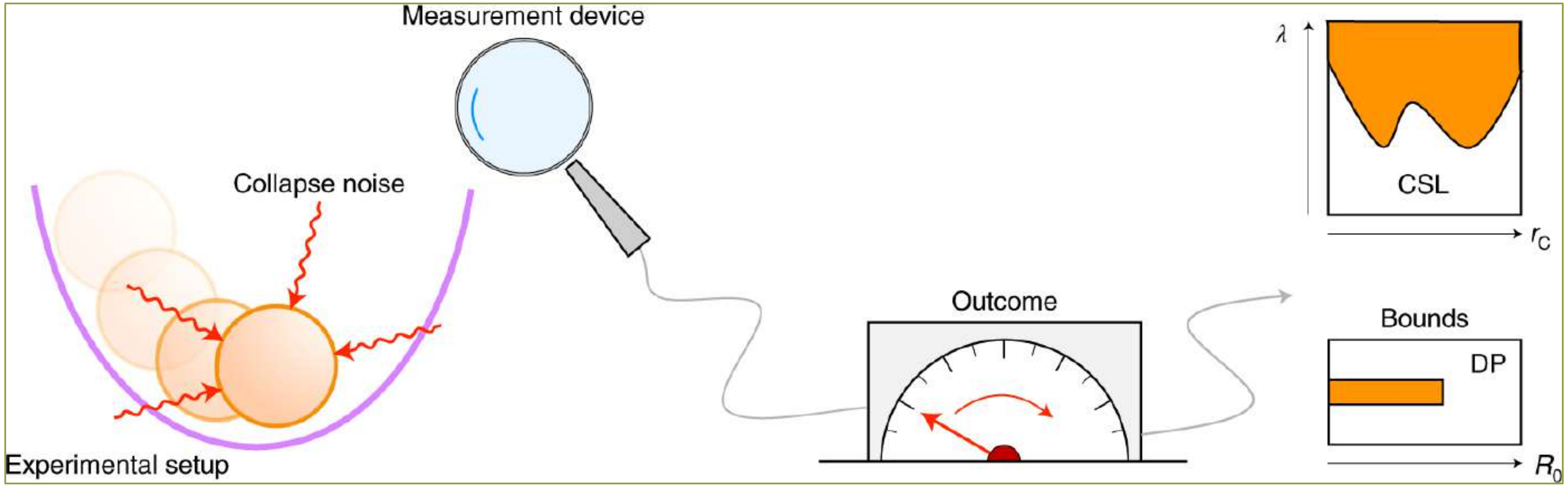


- Collapse noise affects mechanical motion of opto-mechanical system, read out by optics
- Broadening effect modeled by input/output theory of opto-mechanics.



M. Bahrami, M. Paternostro, A. Bassi and H. Ulbricht
Proposal for Non-interferometric Test of Collapse Models in Optomechanical Systems, *PRL* **112**, 210404 *(2014).*

Non-interferometric tests of quantum superposition



nature physics

REVIEW ARTICLE

https://doi.org/10.1038/s41567-021-01489-5

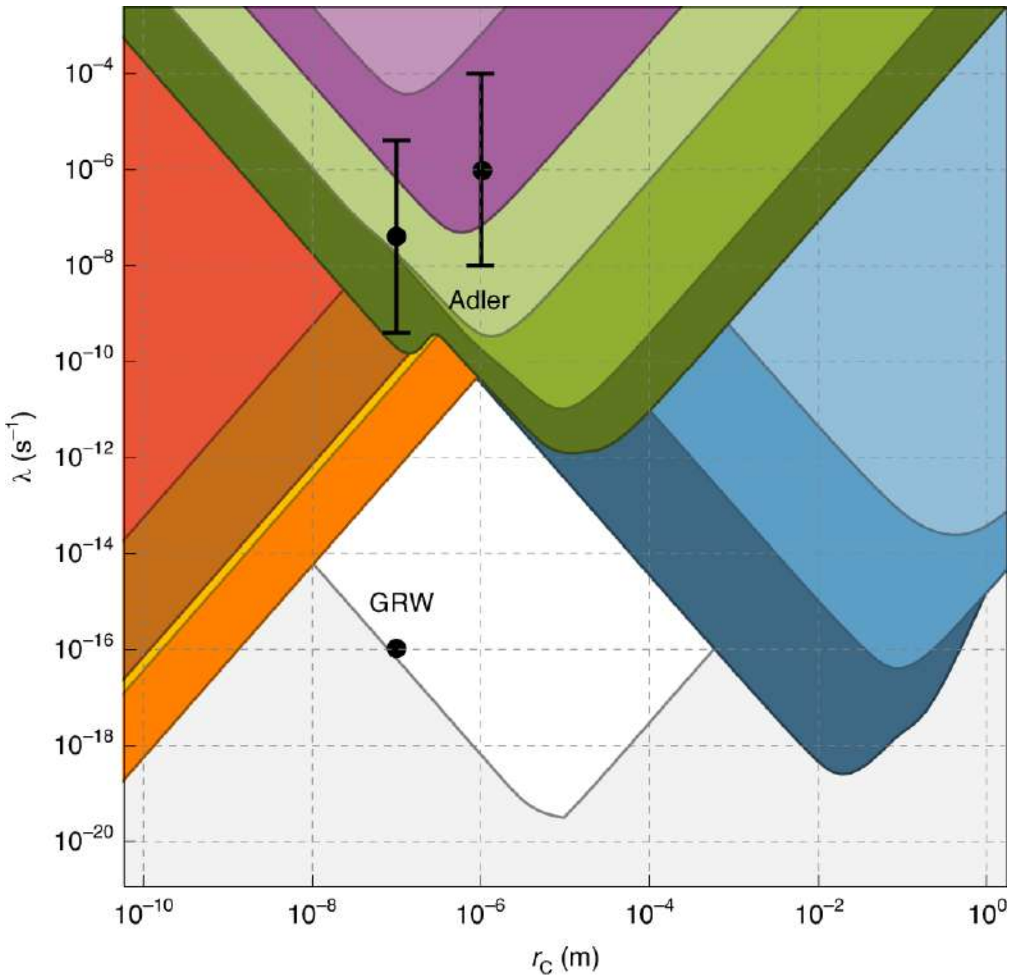
Check for updates

Present status and future challenges of non-interferometric tests of collapse models

Matteo Carlesso[1], Sandro Donadi[2], Luca Ferialdi[2,3], Mauro Paternostro[1], Hendrik Ulbricht[4] and Angelo Bassi[2,3]✉

The superposition principle is the cornerstone of quantum mechanics, leading to a variety of genuinely quantum effects. Whether the principle applies also to macroscopic systems or, instead, there is a progressive breakdown when moving to larger scales is a fundamental and still open question. Spontaneous wavefunction collapse models predict the latter option, thus questioning the universality of quantum mechanics. Technological advances allow to increasingly challenge collapse models and

Testing quantum mechanics: quantum superposition principle, measurement problem

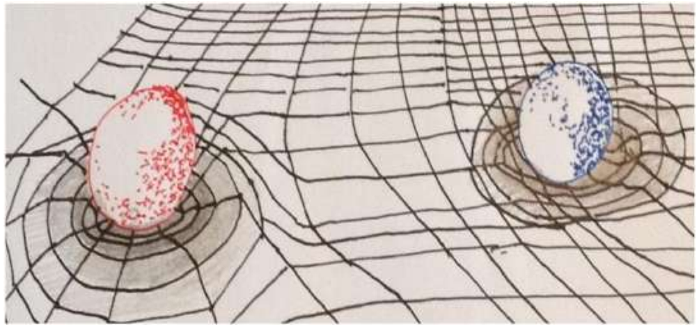


Bassi, A., K. Lochan, S. Satin, TP. Singh, and H. Ulbricht, Rev. Mod. Phys. 85, 471 (2013).

QUANTUM MECHANICS & GRAVITY

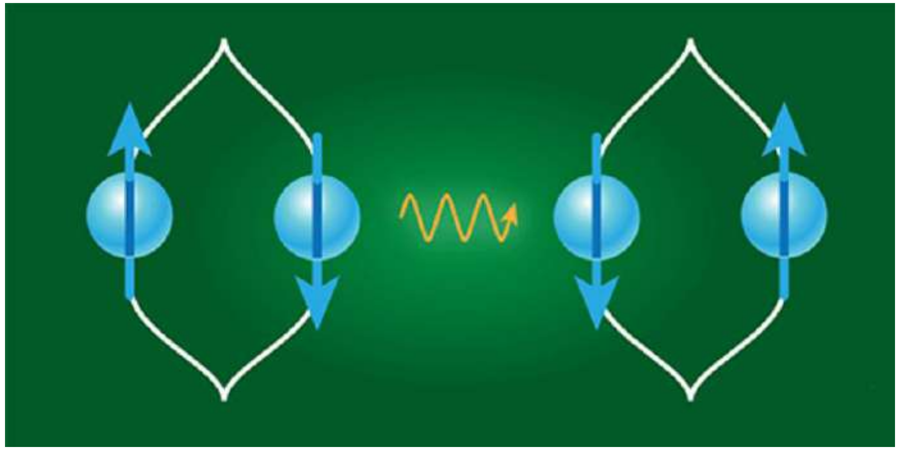
Long Term Goals: fundamental physics experiments

What is the gravitational field of a mass in superposition?



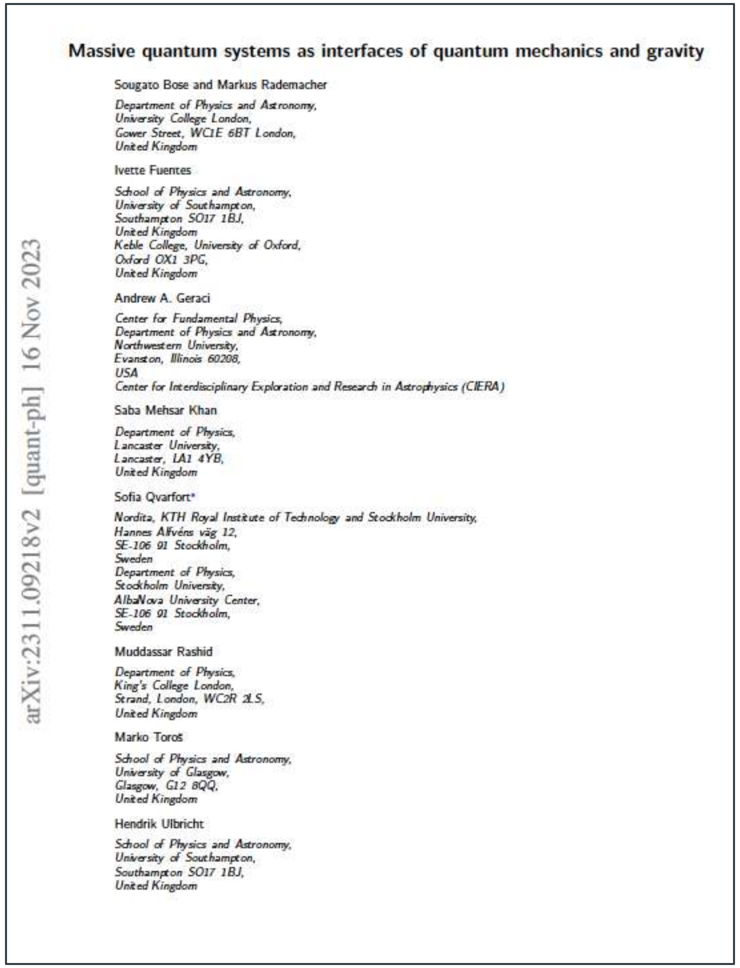
[npj Quantum Information volume 3, Article number: 41 (2017)]

Does gravity entangle quantum properties?



[G. W. Morley/University of Warwick and APS/Alan Stonebraker]
[Bose et. Al. Phys. Rev. Lett. 119, 240401]

Review article on testing gravity with large-mass quantum systems



arXiv:2311.09218v2 [quant-ph] 16 Nov 2023

Massive quantum systems as interfaces of quantum mechanics and gravity

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The traditional view from particle physics is that quantum gravity effects should only become detectable at extremely high energies and small length scales. Due to the significant technological challenges involved, there has been limited progress in identifying experimentally detectable effects that can be accessed in the foreseeable future. However, in recent decades, the size and mass of quantum systems that can be controlled in the laboratory have reached unprecedented scales, enabled by advances in ground-state cooling and quantum-control techniques. Preparations of massive systems in quantum states paves the way for the explorations of a low-energy regime in which gravity can be both sourced and probed by quantum systems. Such approaches constitute an increasingly viable alternative to accelerator-based, laser-interferometric, torsion-balance, and cosmological tests of gravity. In this review, we provide an overview of proposals where massive quantum systems act as interfaces between quantum mechanics and gravity. We discuss conceptual difficulties in the theoretical description of quantum systems in the presence of gravity, review tools for modeling massive quantum systems in the laboratory, and provide an overview of the current state-of-the-art experimental landscape. Proposals covered in this review include, among others, precision tests of gravity, tests of gravitationally-induced wavefunction collapse and decoherence, as well as gravity-mediated entanglement. We conclude the review with an outlook and discussion of future questions.

CONTENTS

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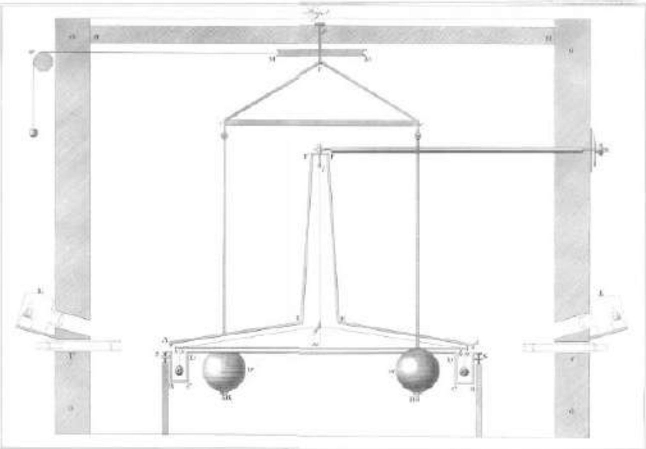
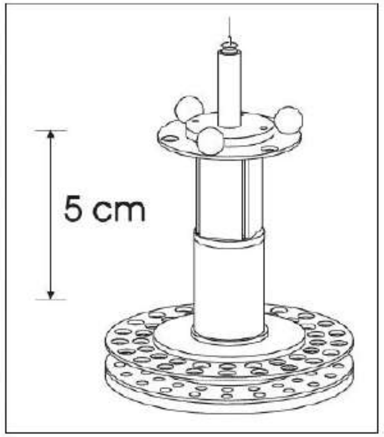
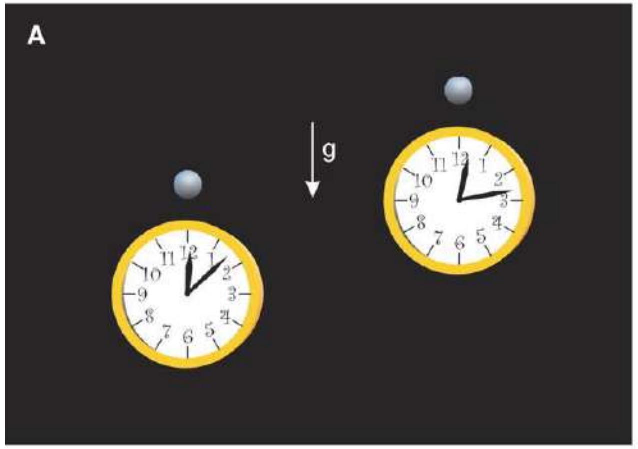
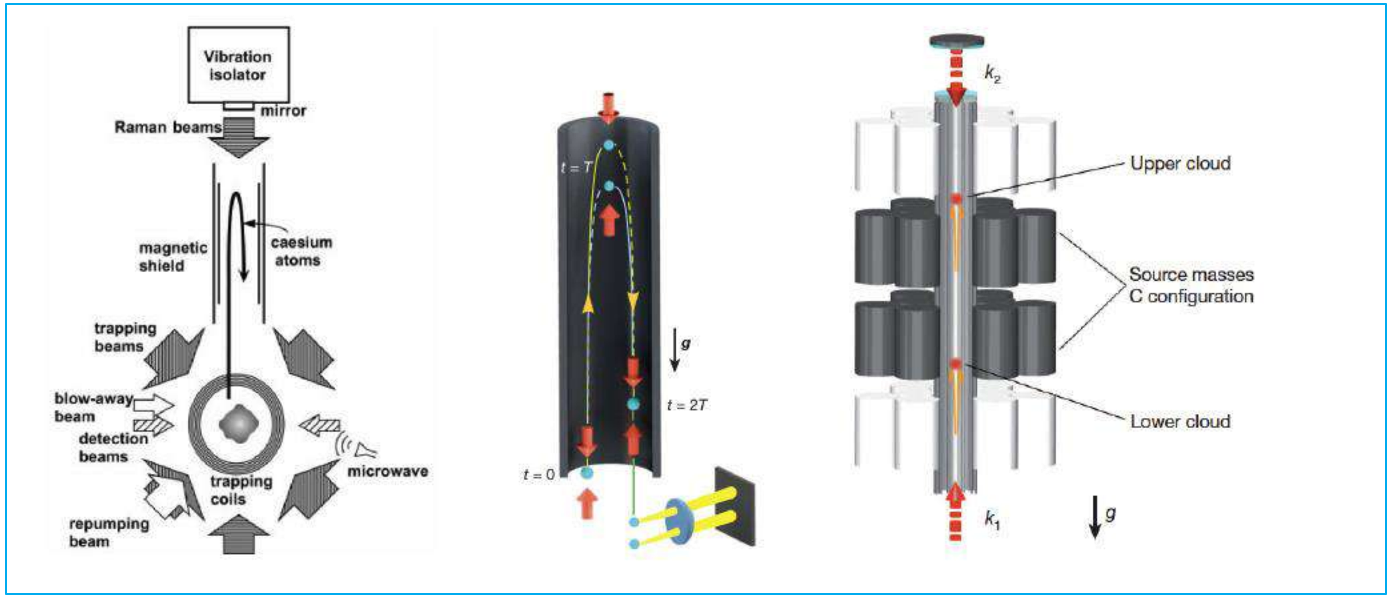
How do we measure gravity?





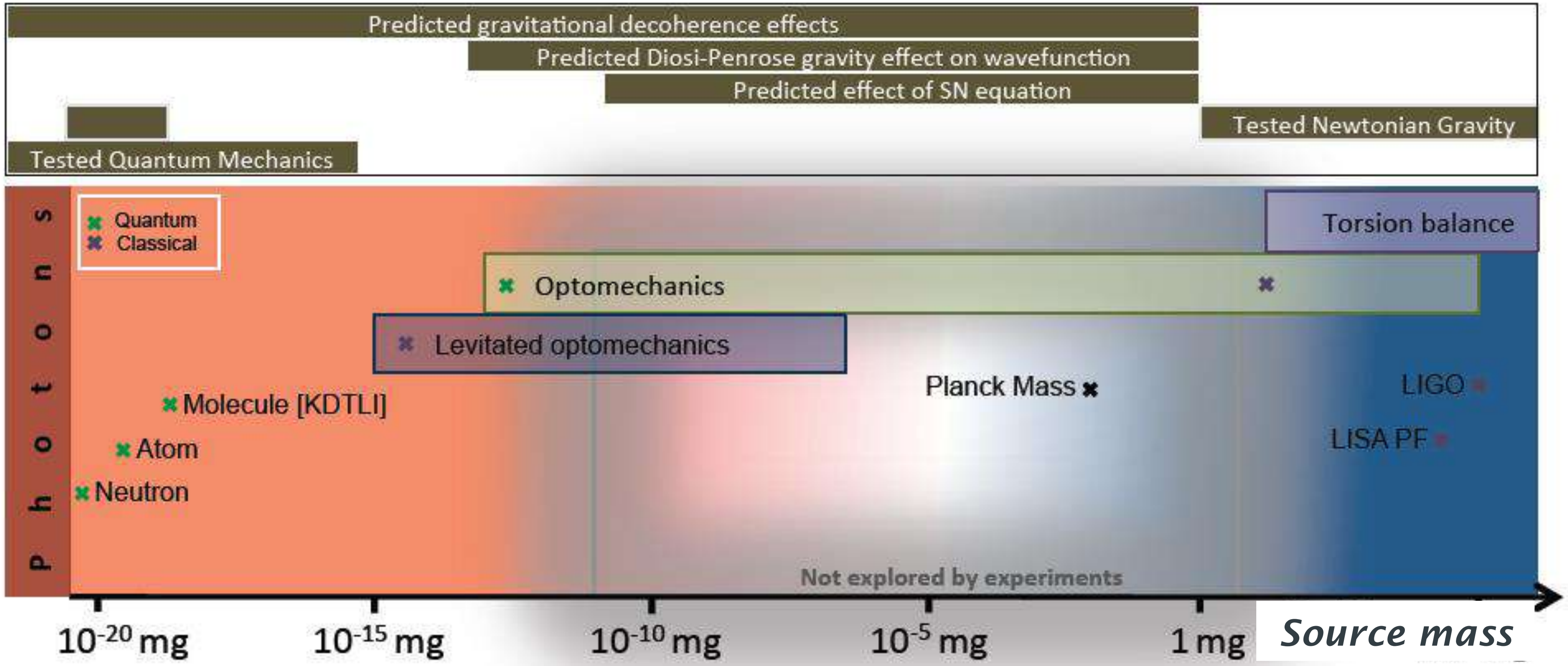




- Torsion pendulum
- Atom interferometer
- Optomechanics: LIGO
- Clocks for GR effects

Bassi, A., A. Grossardt, and H. Ulbricht, ***Gravitation Decoherence***, Class. Quantum Grav. **34**, 193002 (2017).

Test gravity & quantum interplay in low energy regime



Smallest source mass where Newtonian gravity is confirmed by experiment: ~100 mg
What if the source mass is even smaller and in a spatial superposition?
How does the gravitational field look like then?

Bassi, A., A. Grossardt, and H. Ulbricht, ***Gravitation Decoherence***, Class. Quantum Grav. **34**, 193002 (2017).

Schrödinger-Newton (SN): semi-classical gravity

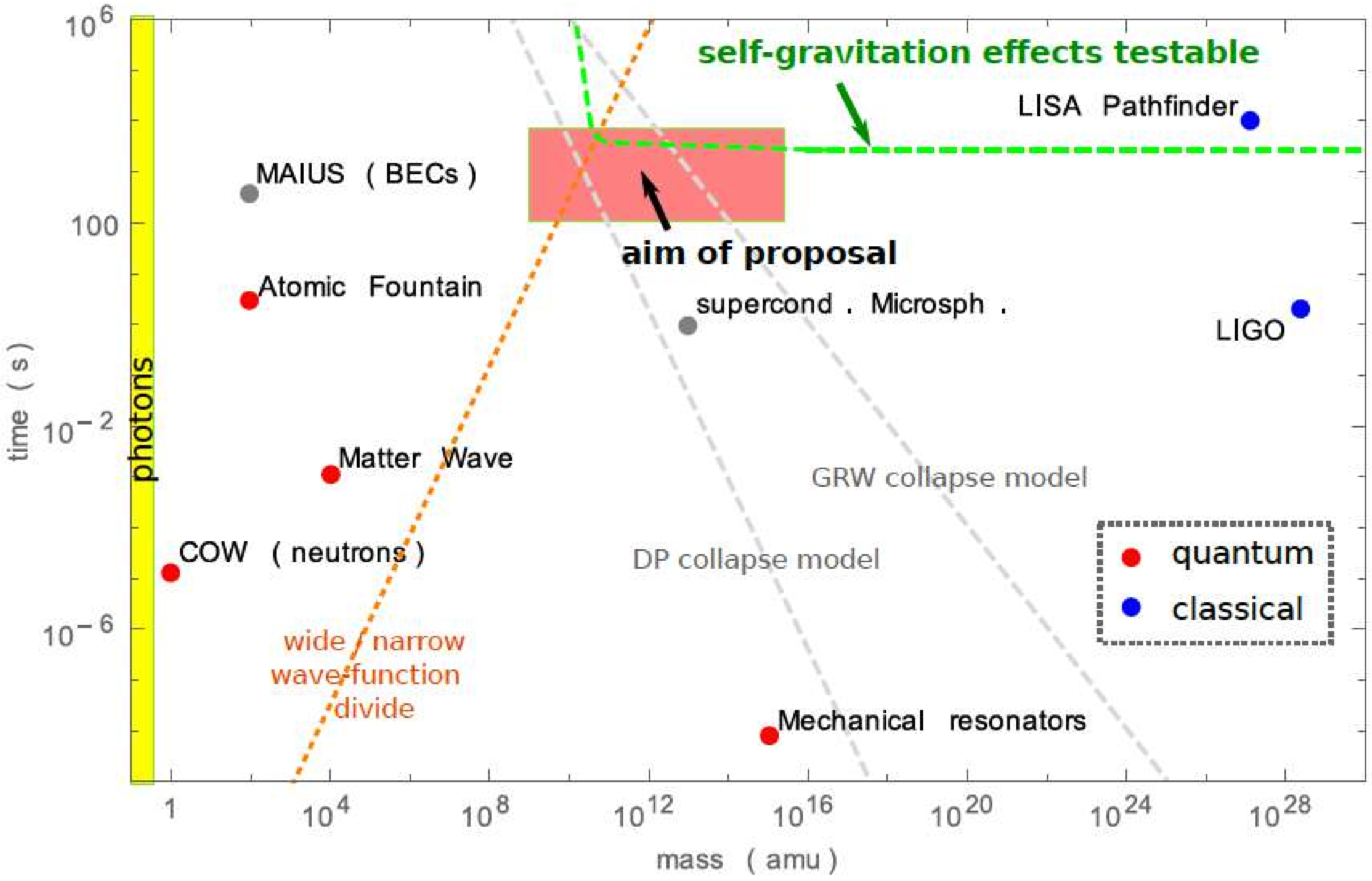
$$R_{\mu\nu} + \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} \langle \Psi | \hat{T}_{\mu\nu} | \Psi \rangle \, .$$

$$\mathrm{i}\hbar \frac{\partial}{\partial t} \psi(t, \mathbf{r}) = \left(\frac{\hbar^2}{2\,M} \nabla^2 + V_{\mathrm{ext}} + V_g[\psi] \right) \psi(t, \mathbf{r})$$

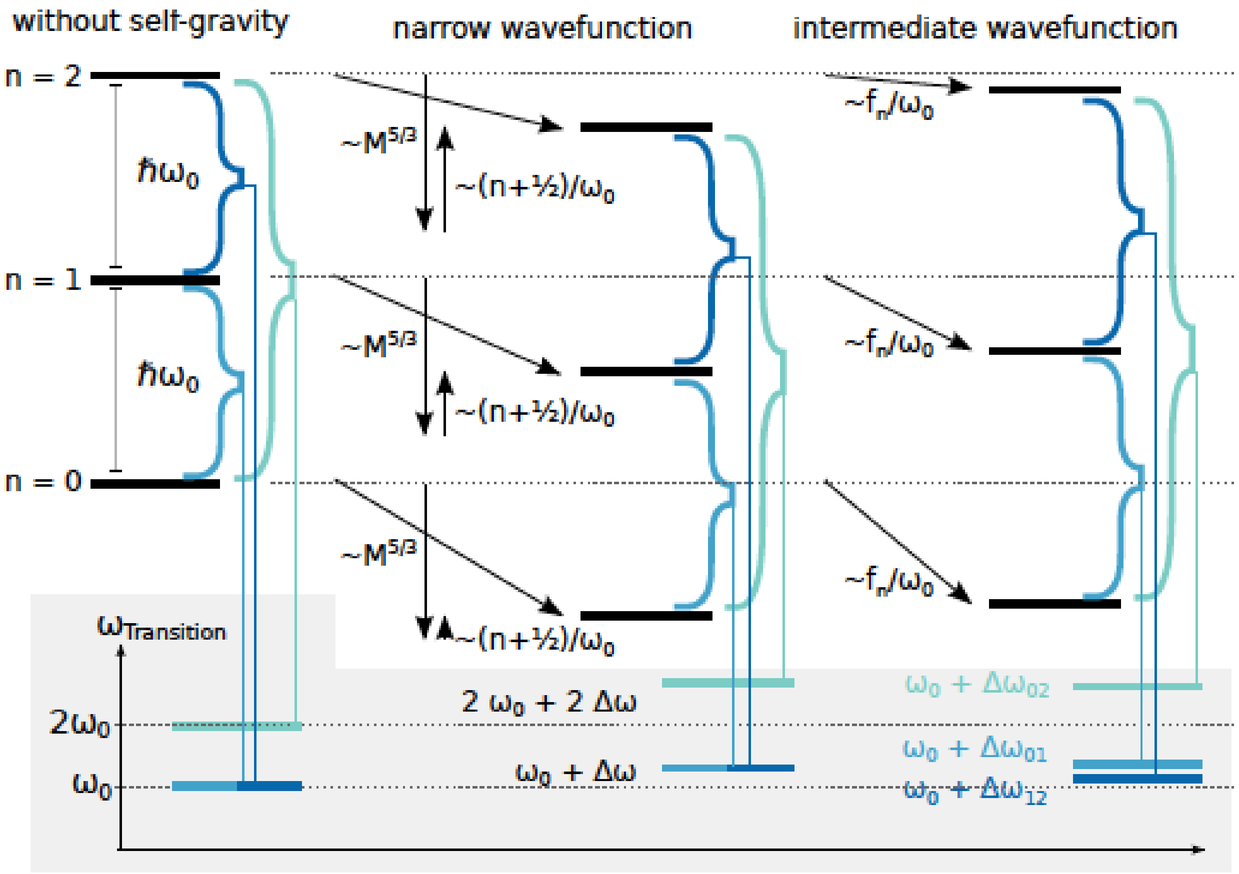
$$V_g[\psi](t, \mathbf{r}) = -G \int \mathrm{d}^3 r' \, |\psi(t, \mathbf{r}')|^2 \, I_{\rho_c}(\mathbf{r} - \mathbf{r}') \, .$$

Obvious option for test: study free wavefunction expansion

Free wavefunction expansion: a case for space?



Predicted shifts of energy levels according to SN



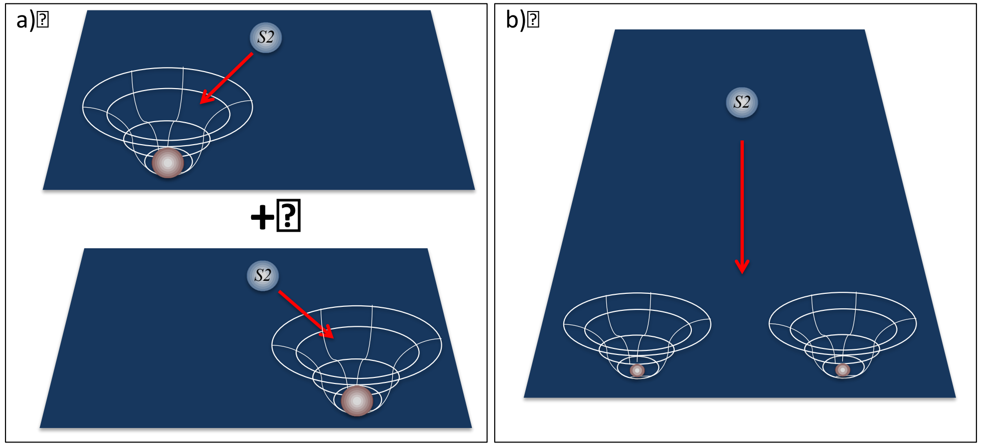
- SN shift of energy levels of mechanical harmonic oscillator
- Feasible for a test with existing tech

A Großardt, J Bateman, H Ulbricht, A Bassi, ***Optomechanical test of the Schrodinger-Newton equation,*** *Phys. Rev. D 93, 096003 (2016).*

Feynman's (Bronstein's) old question ...

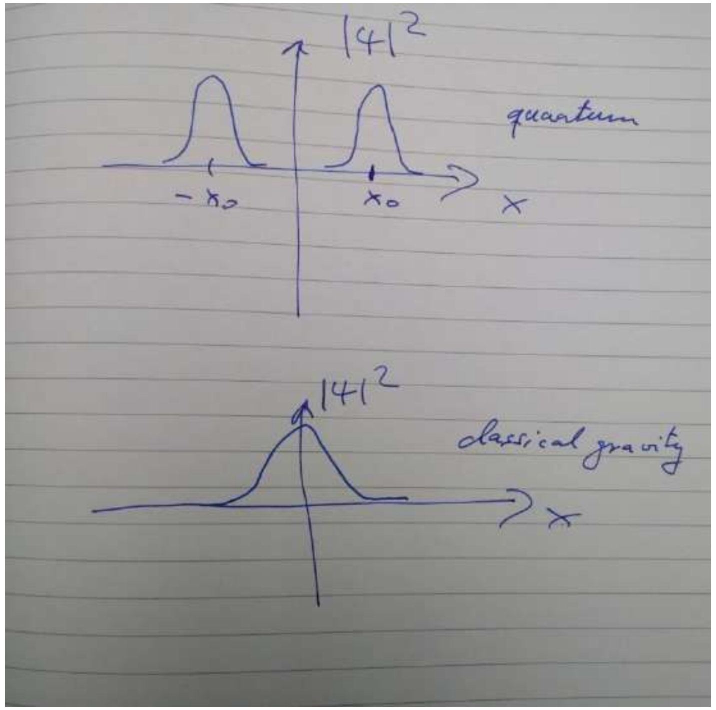
How does the gravitational field of a spatial quantum superposition state look like?

Concept of experiment:



quantum *(semi)-classical*

Expected experimental outcome,
Multiple measurements of probe/test Mass:



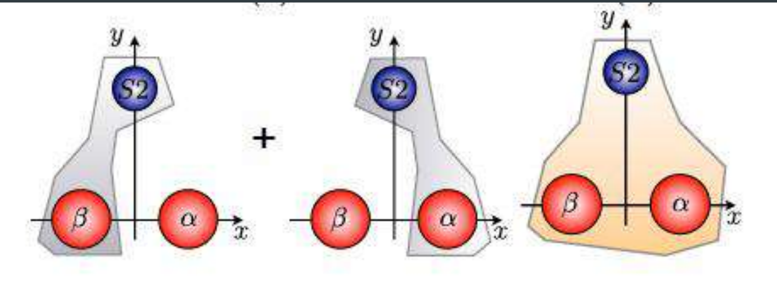
Quantum and (semi)-classical gravity have distinctively different outcome of the experiment.

M. Bahrami, A. Bassi, S. McMillen, M. Paternostro, H. Ulbricht, ***Is Gravity Quantum?,*** *arXiv:1507.05733 (2015).*

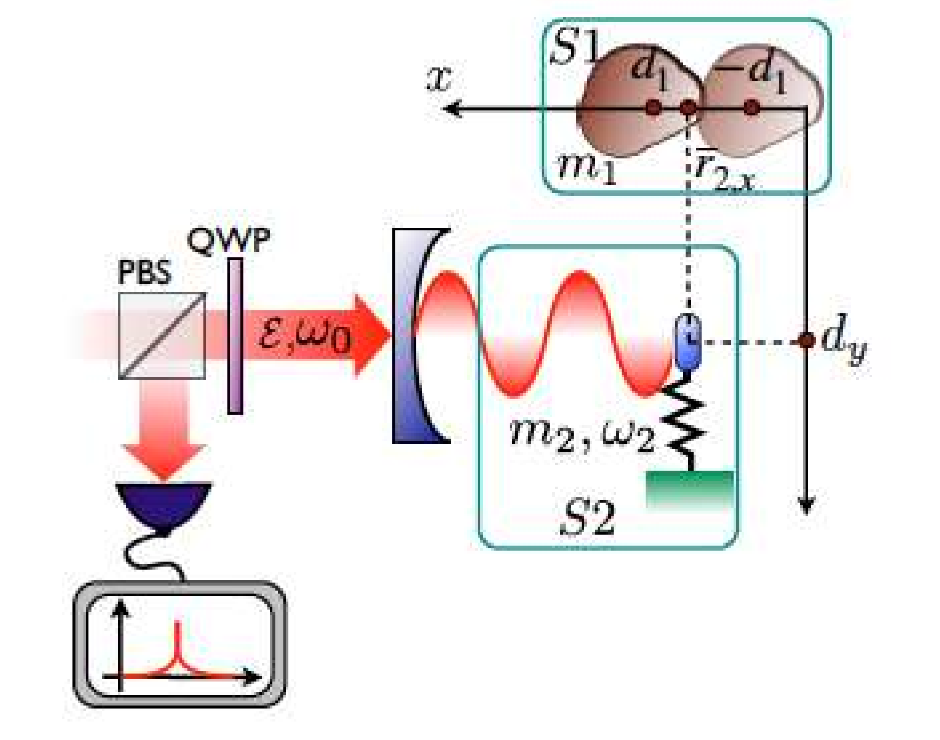
Testing the gravitational field generated by a superposition state.

Challenge: *find two (sufficiently large) masses at sufficiently close proximity, where the source mass is in quantum state (super-position) and the test mass is sufficiently sensitive to probe the gravity field generated by source.*
Answer: *Optomechanics.*

IDEA



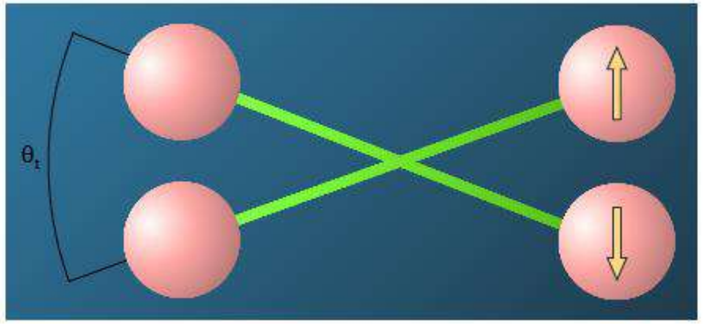
Proposed setup



- **Testing by direct measurement of density noise spectrum**
- **or by indirect measurement of (quantum) correlations in optical field.**
- **Biggest challenge: Van der Waals+Casimir-Polder**

Matteo Carlesso, Angelo Bassi, Mauro Paternostro, Hendrik Ulbricht
Testing the gravitational field generated by a quantum superposition, *New Journal of Physics 21, 093052 (2019).*

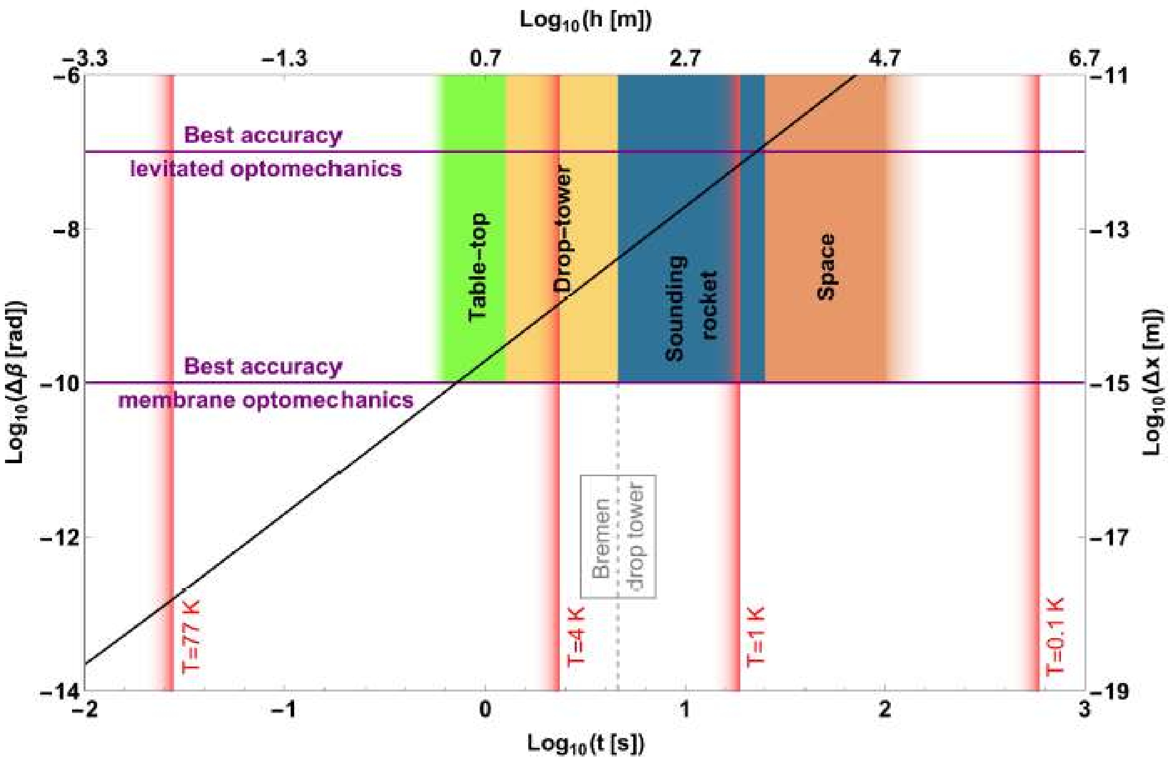
Angular superposition: Does **gravity** destroy the superposition?



4 seconds of free fall required.
-> drop tower, Einstein elevator or space experiment
-> no interactions based on QFT.

Parameter of proposal:

Mass:	10^{-20} kg
Length of handle:	10 μm
Angle separation:	10^{-4} rad
H-field gradient:	10^{6} T/m
Free fall time:	4 s
Temperature:	1 K
Vacuum:	10^{-14} mbar

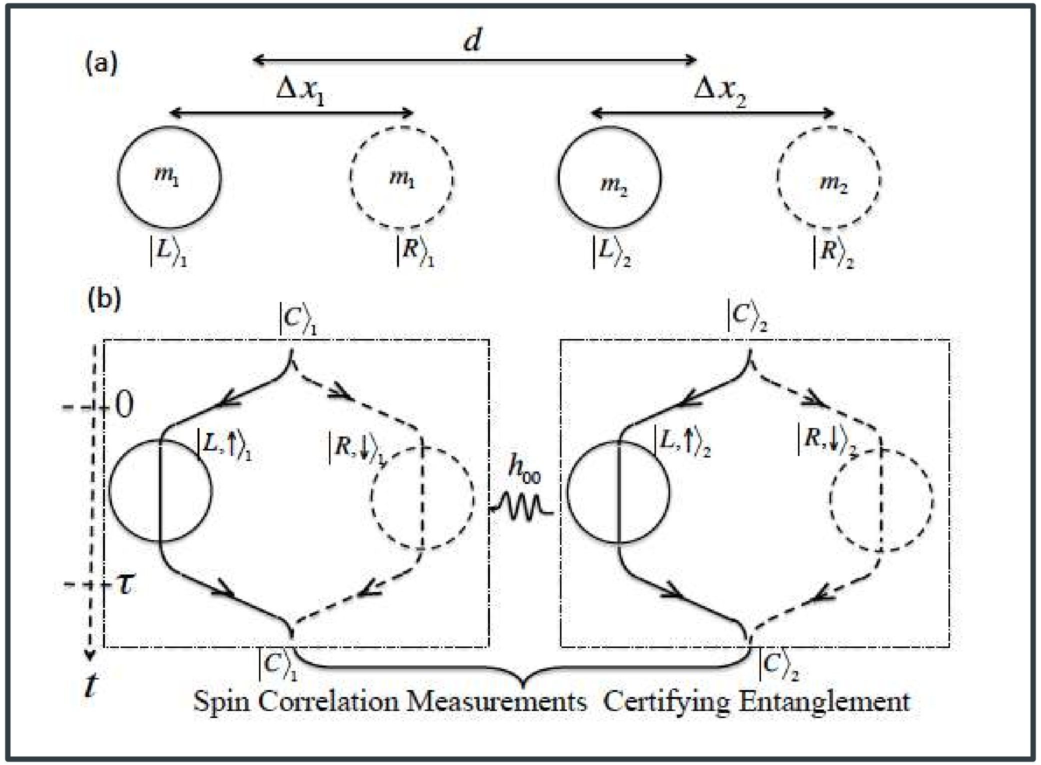


For practical purposes:
libration/rotation degree of freedom is favorable.

M. Carlesso, M. Paternostro, H. Ulbricht, and A. Bassi, arXiv1710.08695 (2017).

Gravity as entangler: What does it tell about gravity?

Proposed experiment: use NV-centre electron Spin as witness of entangling two particles which only interact by gravity, … formalized as ABC model



Parameter of proposal:

Masses:	10^{-14} kg
Superposition size:	250 μm
Separation (closest approach):	200 μm
Free fall time:	3.5 s
Magnetic field gradient:	10^6 T/m
Temperature (internal):	77 K
Vacuum:	10^{-17} mbar

Bose, S., A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. Geraci, P. Barker, M. S. Kim, G. Milburn, **A Spin Entanglement Witness for Quantum Gravity**, Phys. Rev. Lett. 119, 240401 (2017).

Krisnanda, T., M. Zuppardo, M. Paternostro, T. Paterek, **Revealing non-classicality of inaccessible objects,** Phys. Rev. Lett. 119, 120402 (2017).

Measurement based ideas: including using the nature of a quantum measurement

PHYSICAL REVIEW LETTERS **133,** 180201 (2024)

Testing Whether Gravity Acts as a Quantum Entity When Measured

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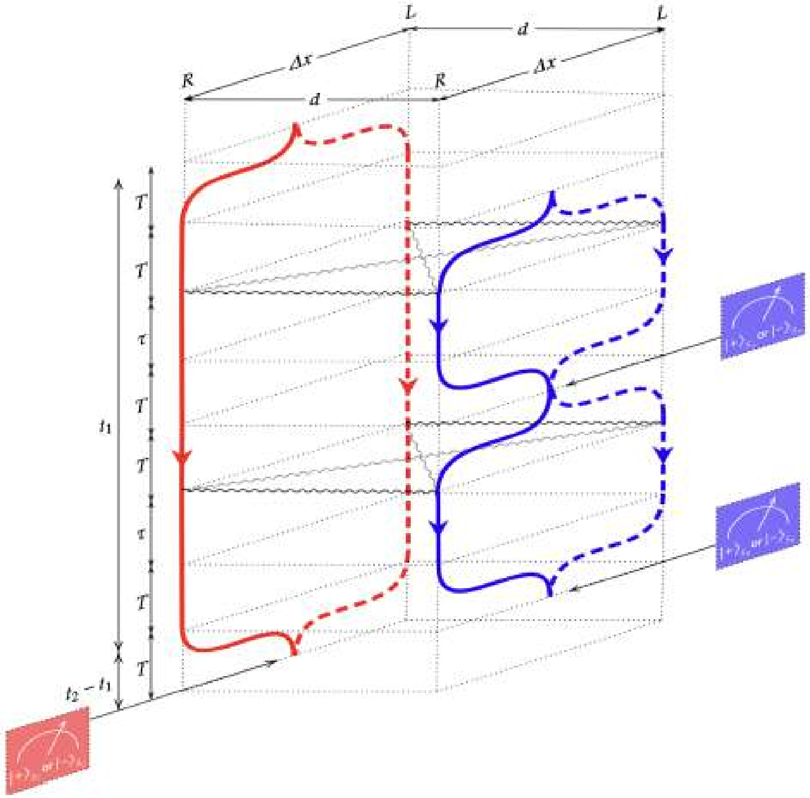
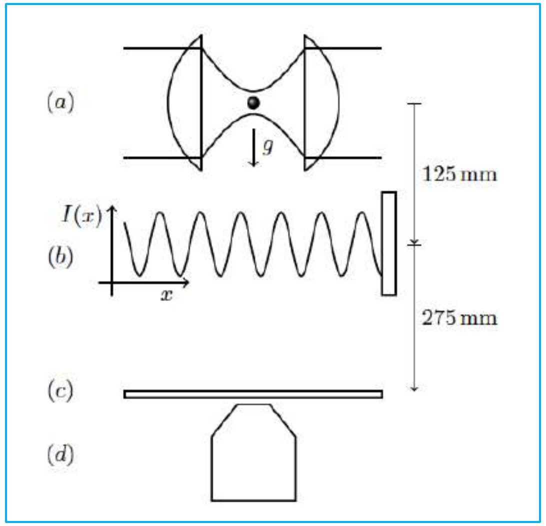


FIG. 2. The gravitational field generated by the interferometric source mass (red) is measured sequentially by a pair of massive interferometric probes (blue), where the gravitational interactions are indicated by wavy lines. Finally, the source mass superposition is closed and a measurement is performed on the embedded spin of the source mass.

EXPERIMENTS ON SUPERPOSITION: LEVITATED MECHANICS

Nanoparticle Talbot interferometer (NaTali):

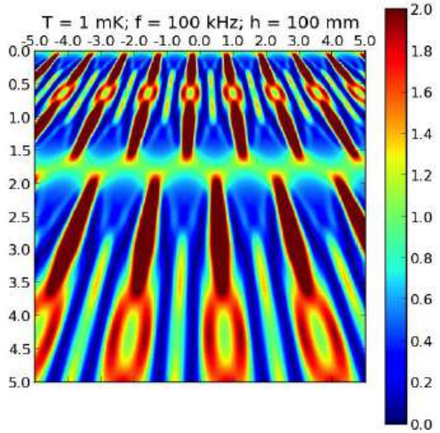
directly testing macroscopic quantum superpositions



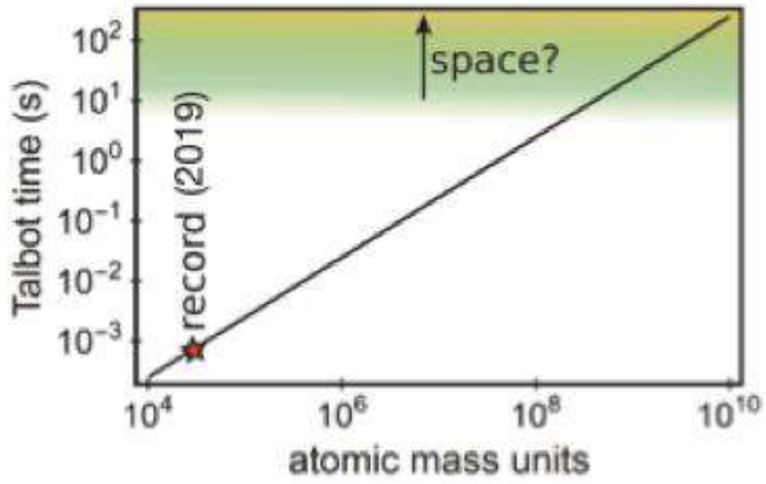
Step 1 - simulation: Spatial superposition of particle of mass: 10^6 -10^7 amu (20 nm in diameter)

- Wigner function model to calculate quantum carpet.
  -> Thermal and collisional decoherence are negligible.

Quantum carpet:
Simulated interference pattern



Step 2 – Experiment: Particle source has been realized by particle levitation & cooling, grating implementation ongoing



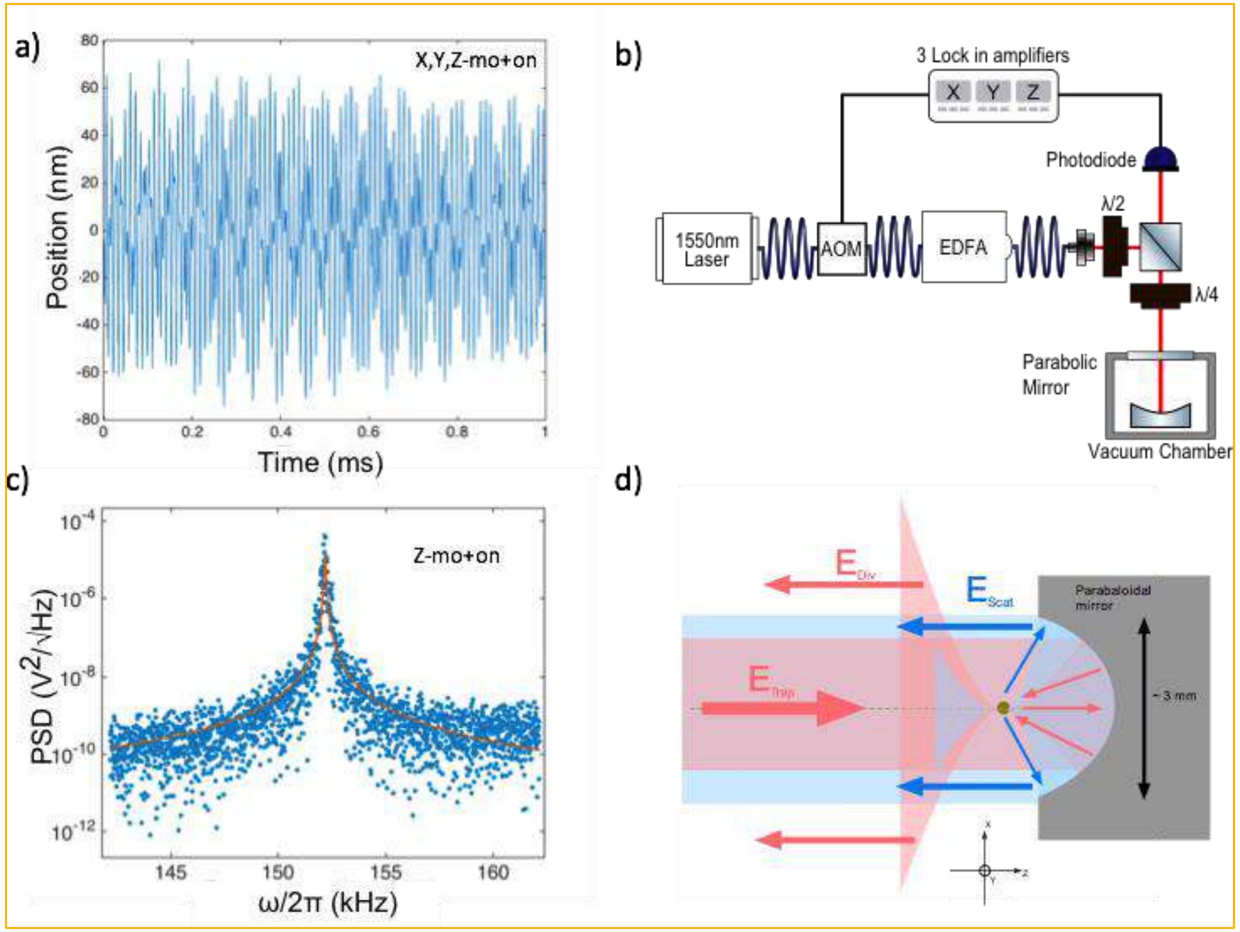
Belenchia, A., Carlesso, M., Donadi, S., Gasbarri, G., Ulbricht, H., Bassi, A. and Paternostro, M., 2021. Test quantum mechanics in space. *Nature*, *596*(7870), pp.32-34.

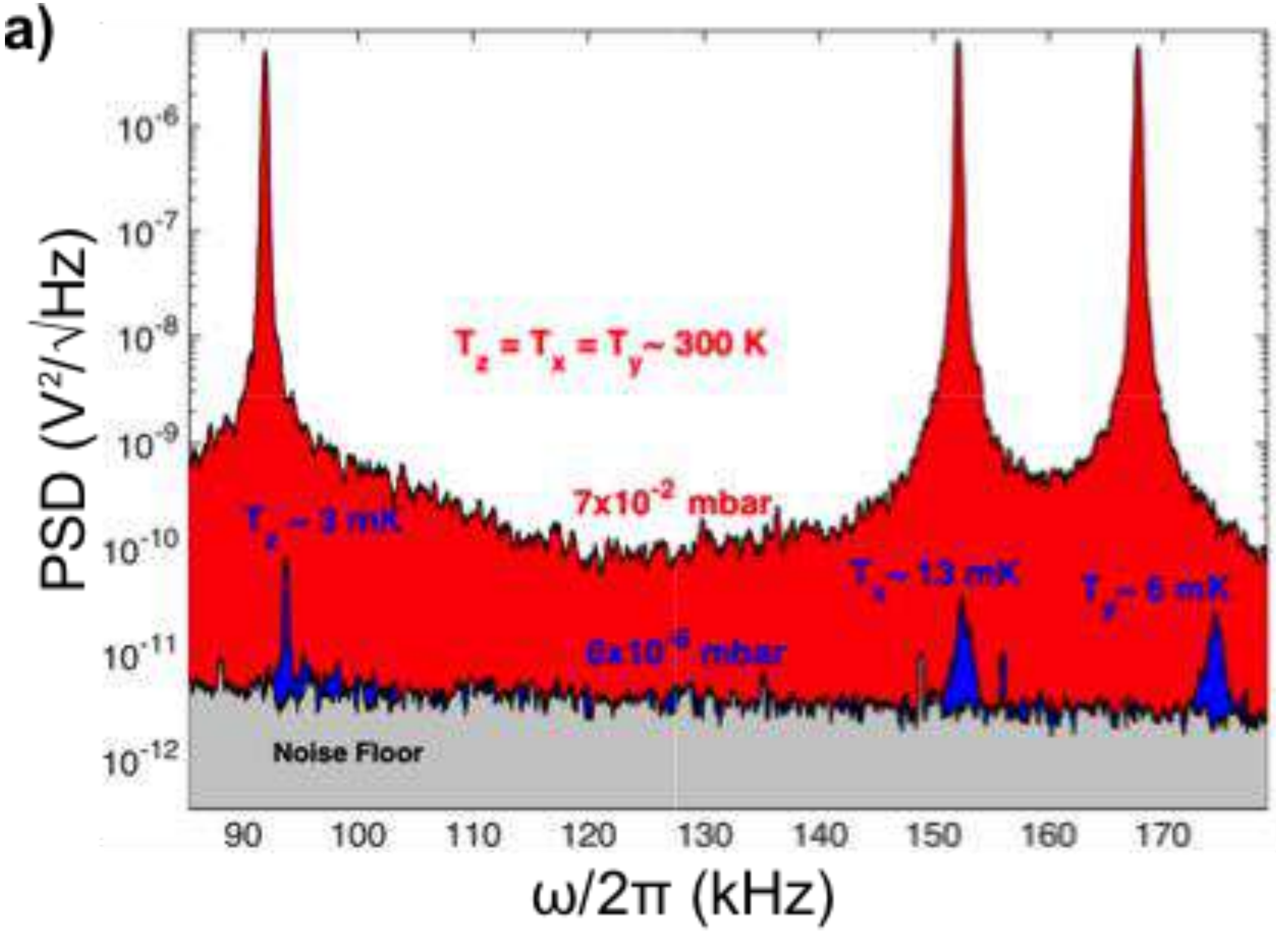
Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht
Near-field interferometry of a free-falling nanoparticle from a point-like source
Nature Communications 4, 4788 (2014).

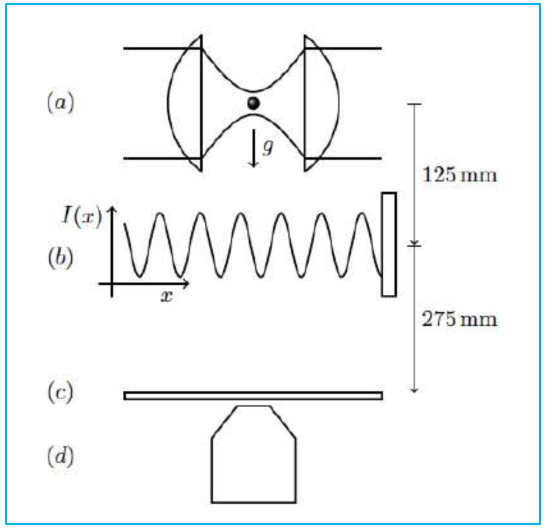
Trap and measure position, then feedback cool to ~1mK

Equation of motion: $\ddot{x}(t) + \Gamma_0 \dot{x}(t) + \omega_0^2 x(t) = \frac{1}{m}[F_{\text{fluct}}(t) + F_{\text{feed}}(t)]$

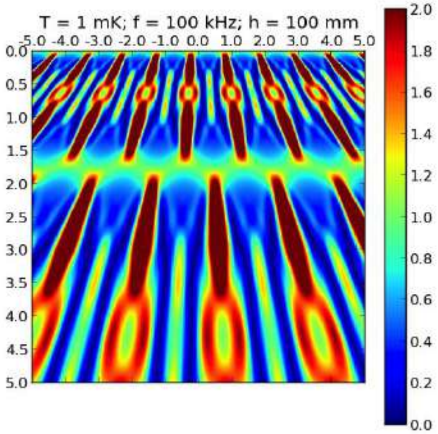
Power spectral density: $S_x(\omega) = \frac{k_B T_0}{\pi m} \frac{\Gamma_0}{([\omega_0 + \delta\omega]^2 - \omega^2)^2 + \omega^2[\Gamma_0 + \delta\Gamma]^2}$







Quantum carpet:
Simulated interference pattern



LONG FREE COHERENT EVOLUTION TIME

More free evolution time by Throw and Catch:

up to 100 millisecs

Wardak, J., Georgescu, T., Gasbarri, G., Belenchia, A. and Ulbricht, H., 2024. Nanoparticle Interferometer by Throw and Catch. *Atoms*, *12*(2), p.7.

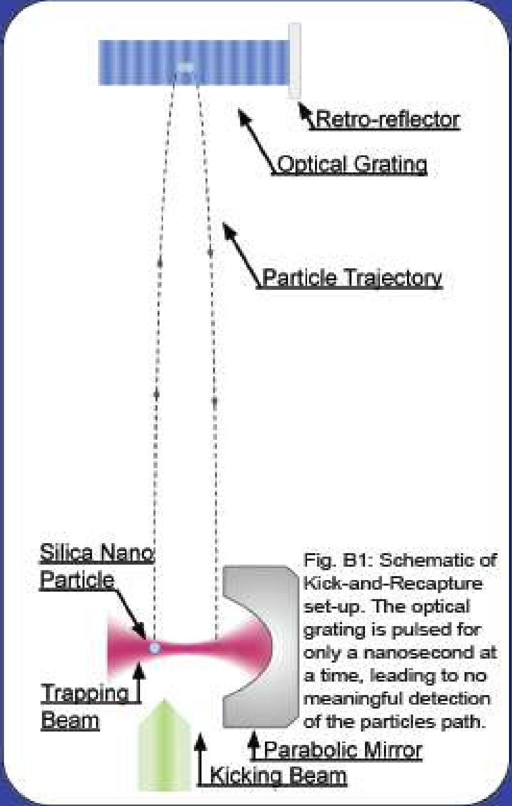


Fig. B1: Schematic of Kick-and-Recapture set-up. The optical grating is pulsed for only a nanosecond at a time, leading to no meaningful detection of the particles path.

Large Scale Quantum

Molecules up to 10^5 AMU have been shown to still display quantum interference during free evolution. Launching SiO2 nanospheres from an optical trap through an optical gratings we aim to demonstrate Talbot-Lau interference [2].

The 100 nm particles (10^{10} AMU) are cooled down to near the ground-state through parametric feedback cooling, after which they are kicked using a YAG laser.

Interference during free-fall is reconstructed after the particle travels through an optical UV grating and is recaptured into the trap. The recapture position is retraced, reconstructing the interference pattern of the same particle over many kick and recaptures.

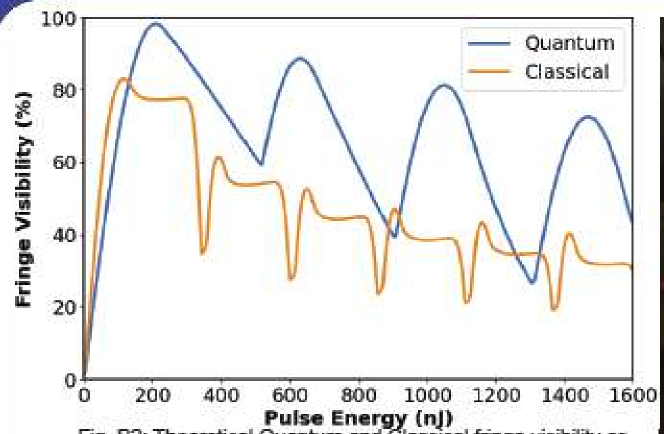


Fig. B2: Theoretical Quantum and Classical fringe visibility as function of optical grating intensity. A SiO2 particle, m = 10^8 AMU, cooled down to 1 mK C.O.M. motion was assumed. P = 10^-10mbar, T_{flight} 58 ms or 1.6 cm flight height.

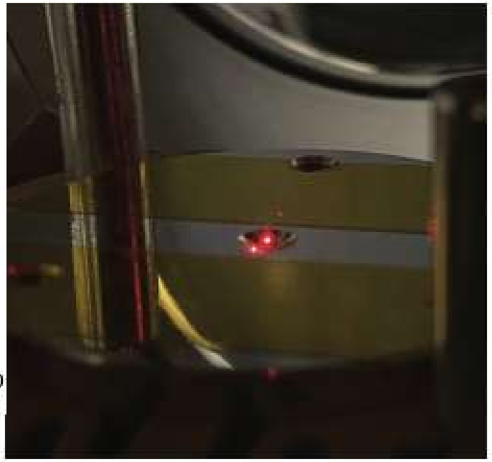
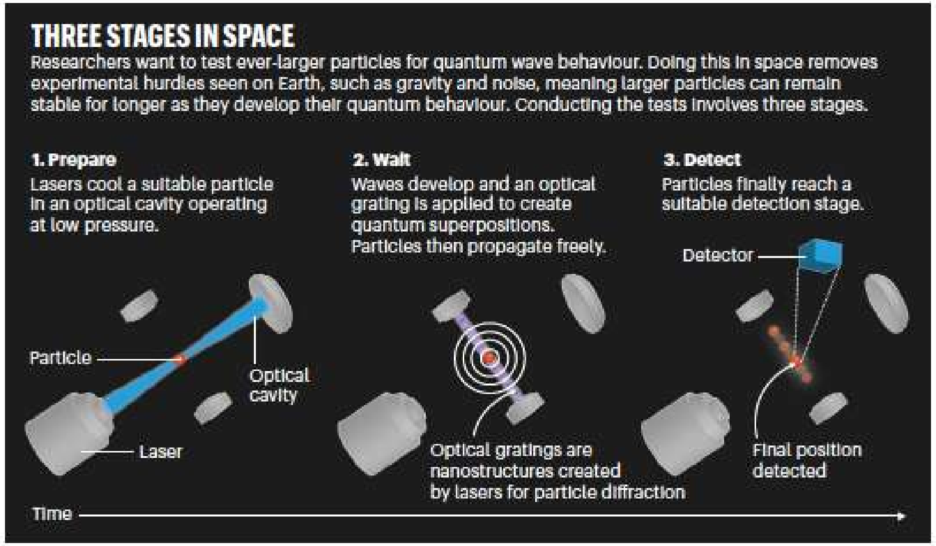


Fig. B3: Photo of a particle trapped above the parabolic mirror, illuminated by a red laser.

Satellite for long free evolution time: 100 secs (in free fall)

- **Main objective:** Generate macroscopic quantum superposition of a 100 nm+ particle.
- **Space advantage:** Long free-evolution time



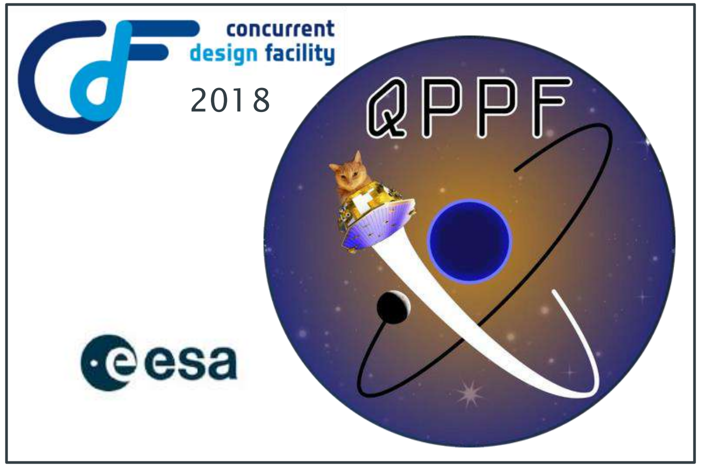
Theoretical foundations

Belenchia, A., et al., *Test quantum mechanics in space*, **Nature** 596, 32-34 (2021).

Belenchia, A., et al. *Quantum physics in space*, **Physics Reports** 951, 1-70 (2022).

Kaltenbaek, R., et al. *Research campaign: Macroscopic quantum resonators (MAQRO)*, **Quantum Science and Technology** 8, 014006 (2023).

Gasbarri, G., et al. *Testing the foundation of quantum physics in space via Interferometric and non-interferometric experiments with mesoscopic nanoparticles.* **Communications Physics** 4, 155 (2021).

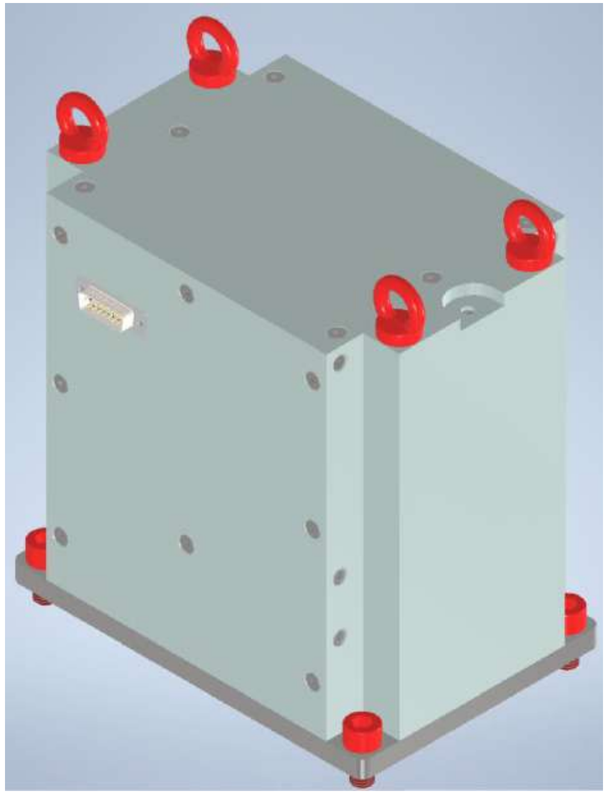


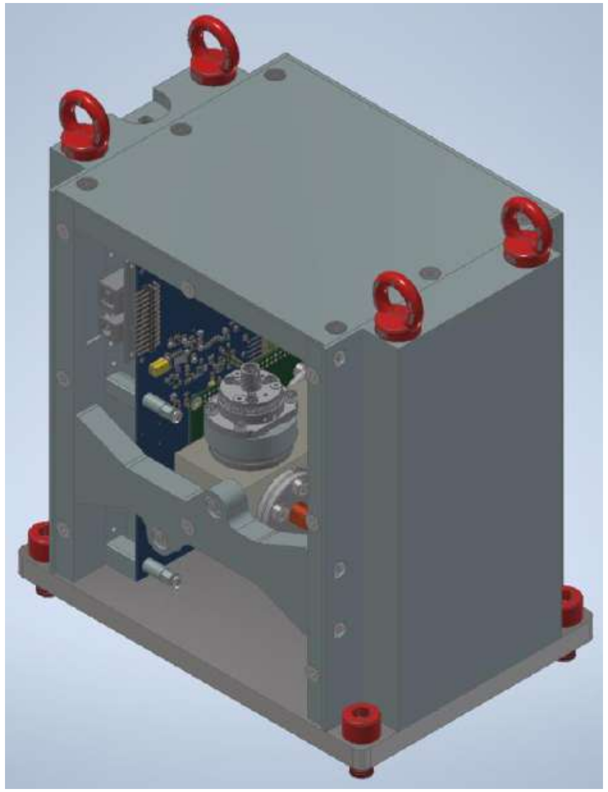
TWIN PARADOX LABS · SURREY SPACE CENTRE · bias · ZARM · University of Southampton

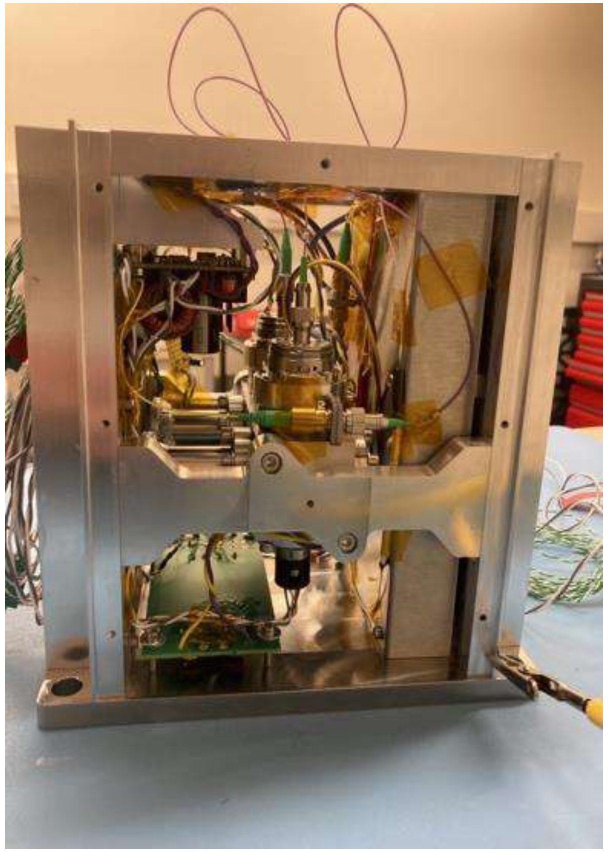
Levitated mechanics in free fall – satellite launch June 2025

Payload box:

- Size: 200 x 200 x 140 mm
- Weight: 10 kg
- 10 W power consumption (average)
- 1 optical trap, 1 diamagnetic trap, autonomous operation by FPGA and microcontroller.
- Tested for space: shock & vibration, thermal, EMC (next week).







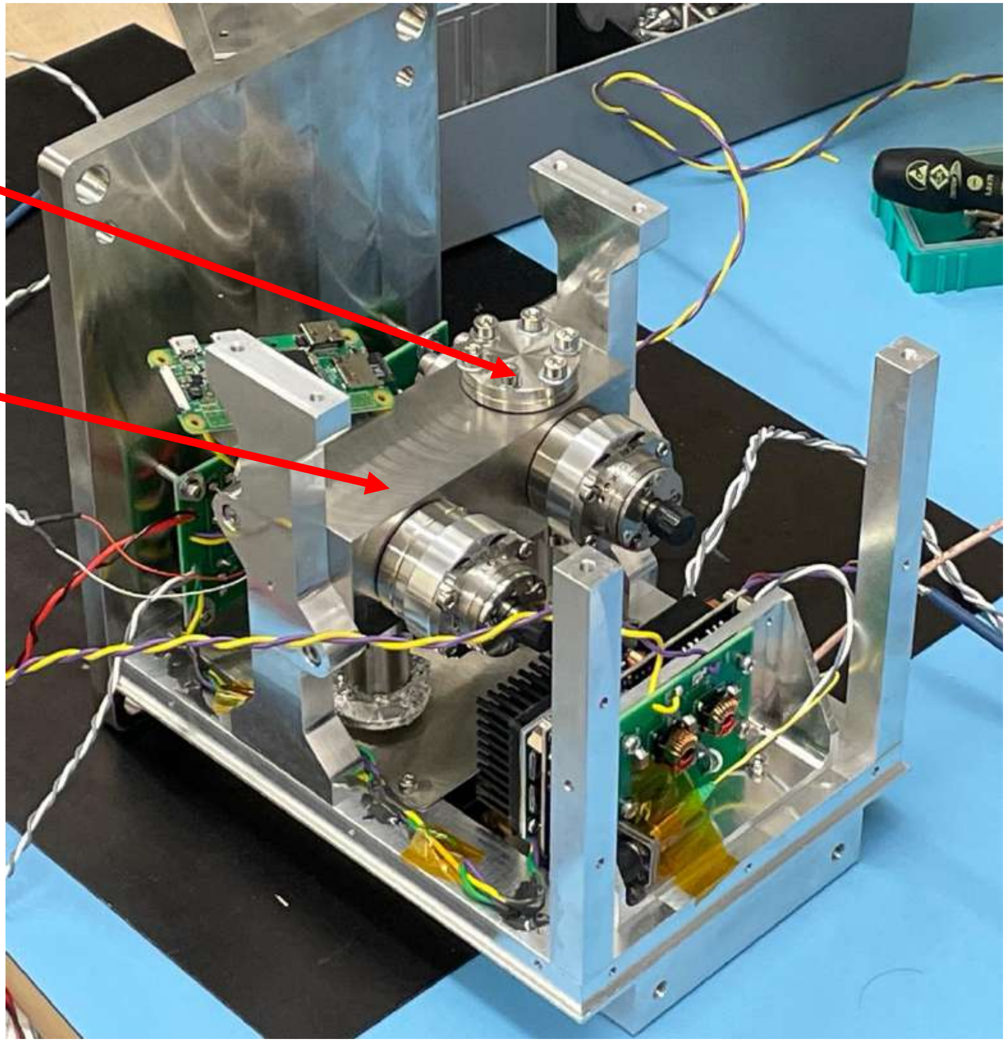
What is inside the box?

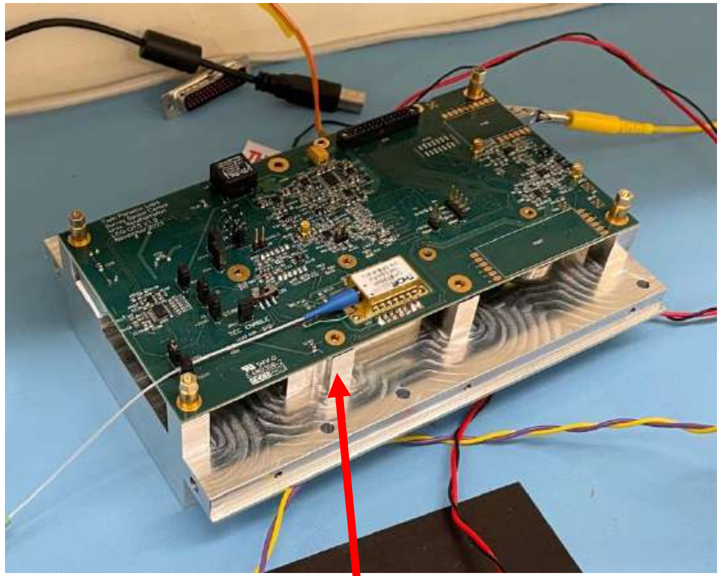
Optical trap for silica particles

Diamagnetic trap for graphite

Piezo-based particle loading system

Optical fiber system for detection,
UHV chambers (passively NEG pumped, 1e-9 mbar)

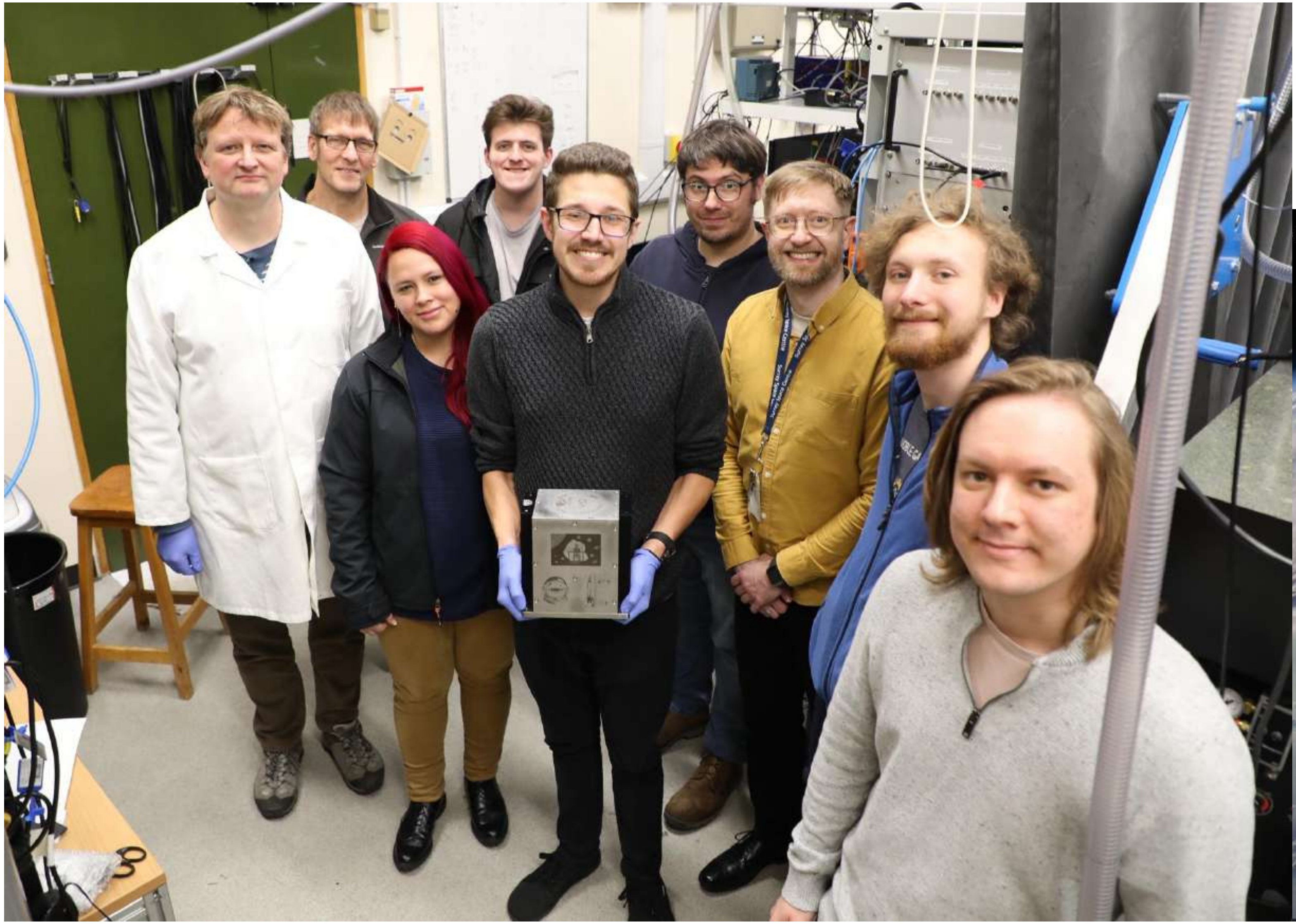


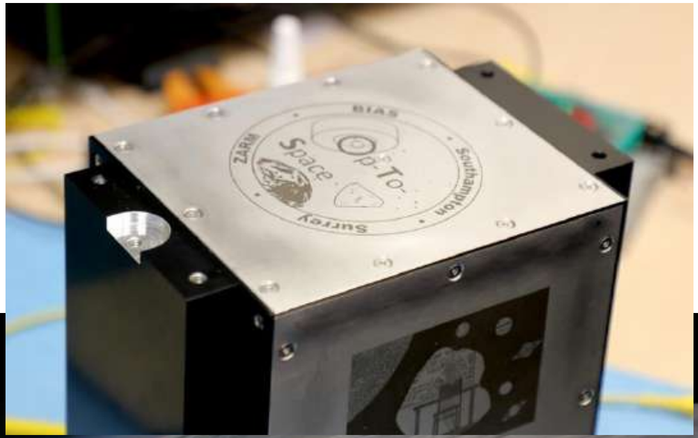


PCB with laser PID controller
FPGA for electronics
Microcontroller to operate Experiments and DAQ.

Fully autonomous operation

Payload delivery December 2024, launch 2025



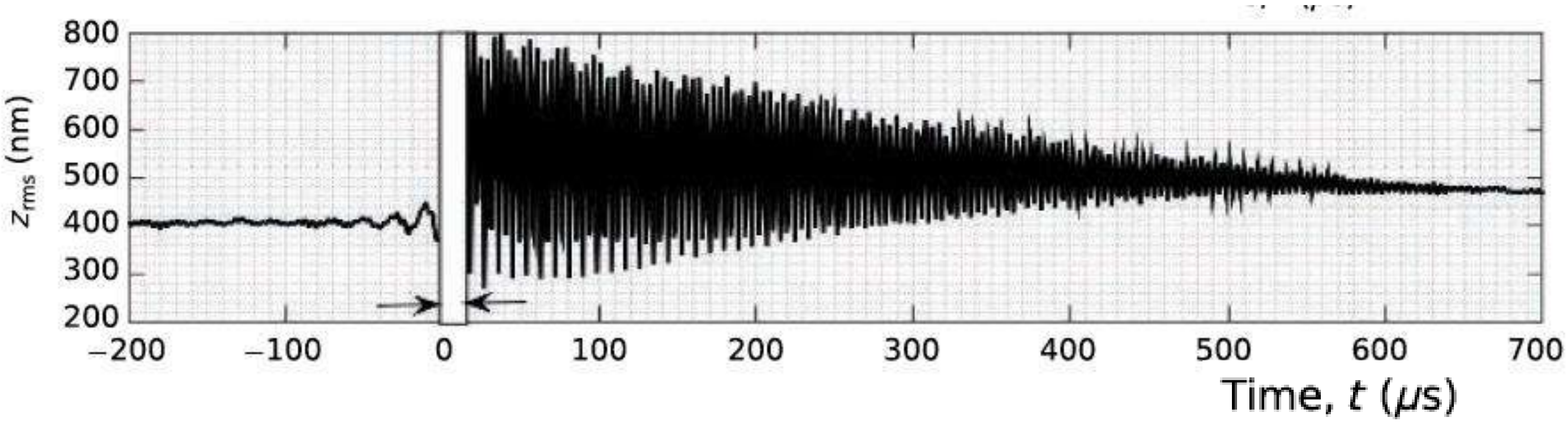


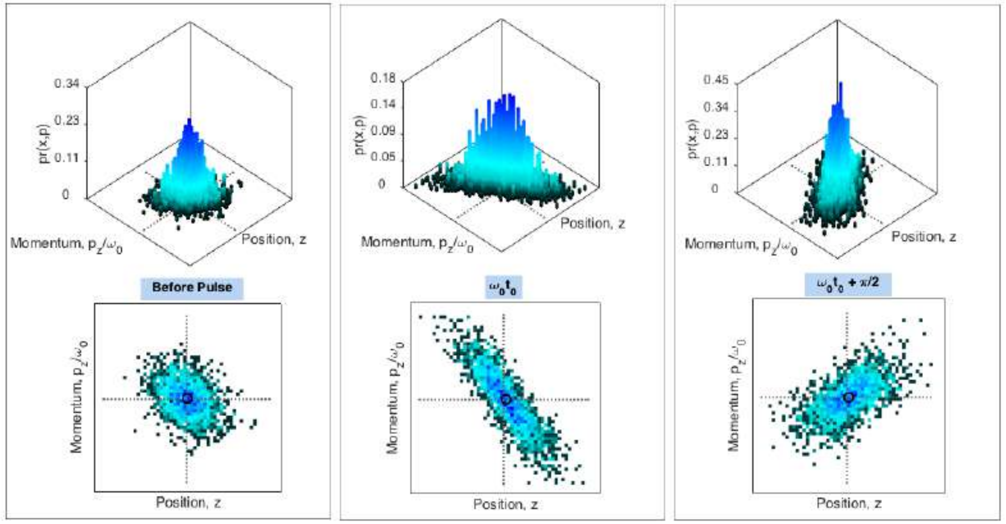
OR

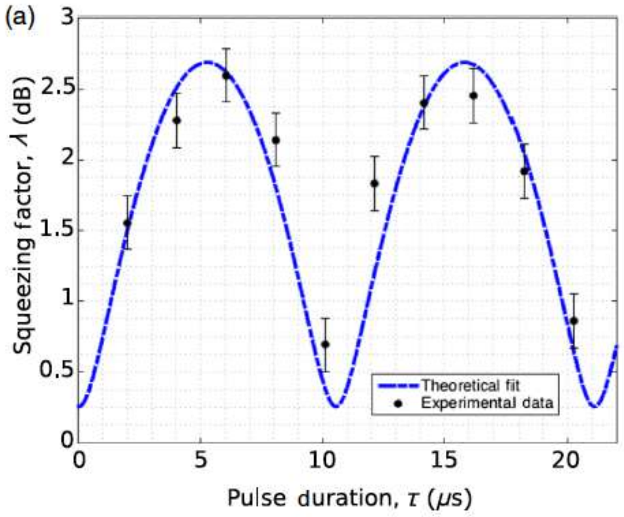
ACCELERATE EVOLUTION OF QUANTUM STATE COHERENTLY

Squeezing the thermal motion by frequency jump

Time trace:

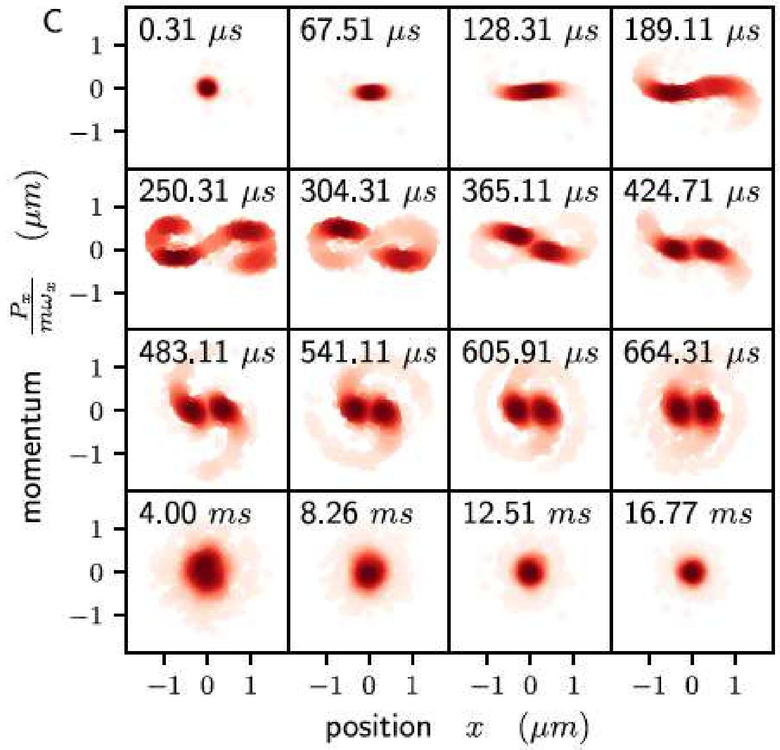


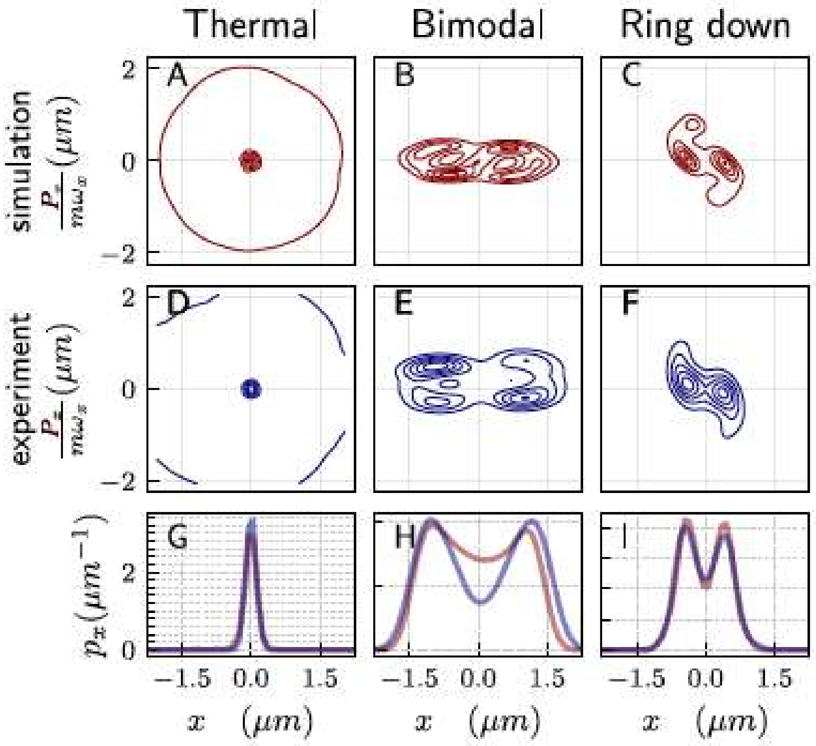




Rashid, M., T. Tufarelli, J. Bateman, J. Vovrosh, D. Hempston, M. S. Kim, and H. Ulbricht, ***Experimental Realization of a Thermal Squeezed State of Levitated Optomechanics***, PRL 117, 273601 (2016).

Experiment: Bi-modal distribution by squeezing thermal state: accessing x^4 Duffing trap non-linearity

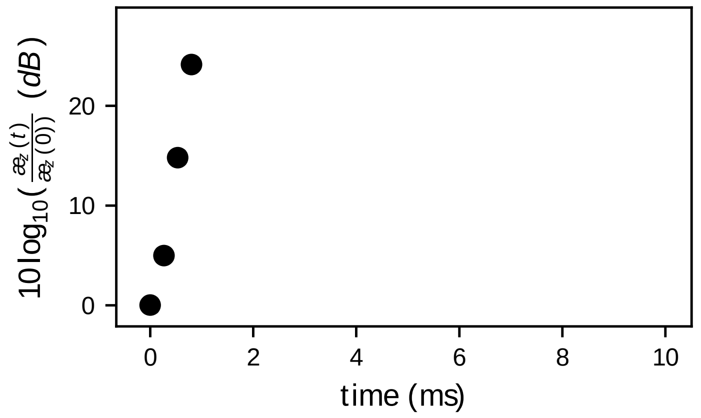




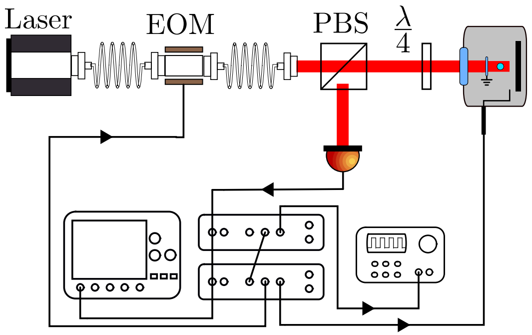
Muffato, R., Georgescu, T., Homans, J., Guerreiro, T., Wu, Q., Chisholm, D., Carlesso, M., Paternostro, M. and Ulbricht, H., 2024.
Generation of classical non-Gaussian distributions by squeezing a thermal state into non-linear motion of levitated optomechanics. *arXiv preprint arXiv:2401.04066*.

Experiment results: coherent expanding the motional state.

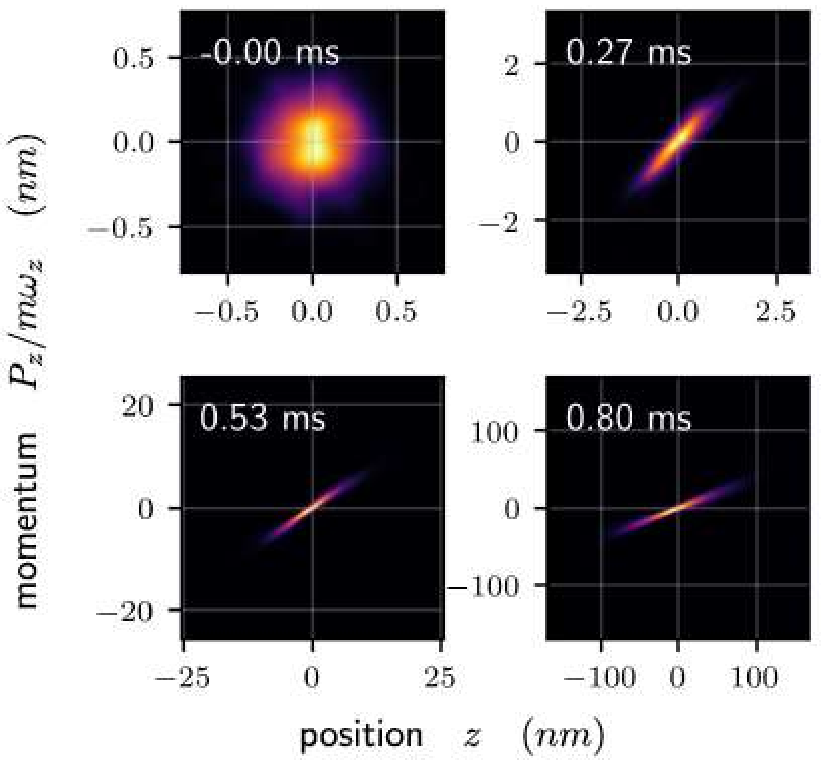
a)



b)



C

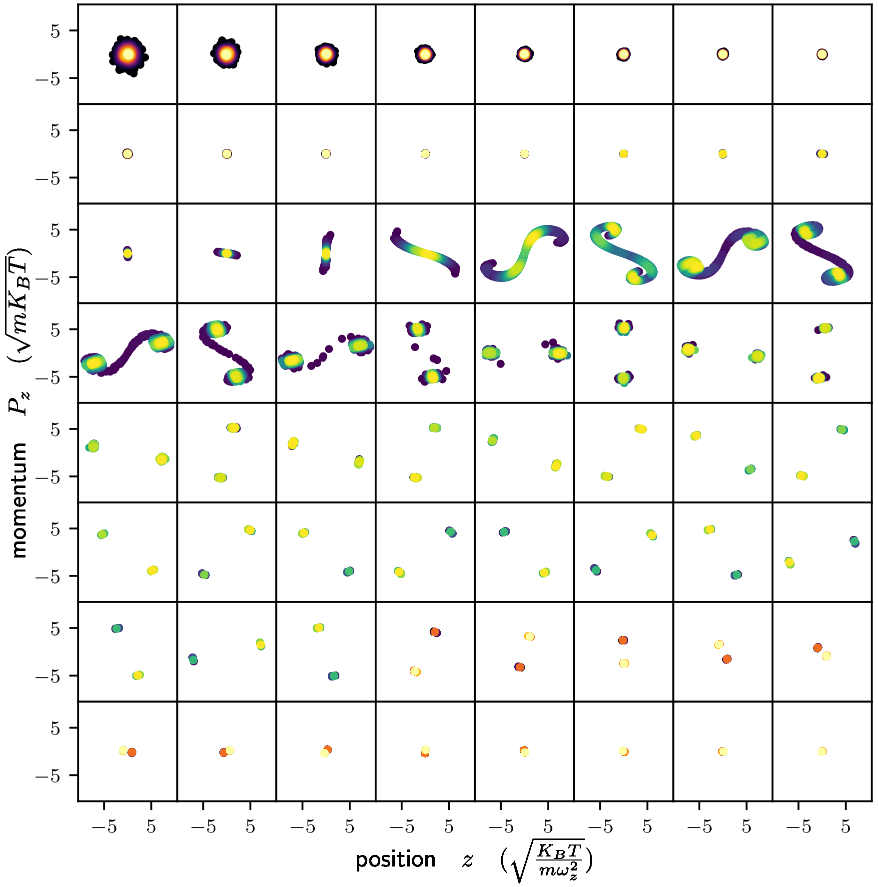


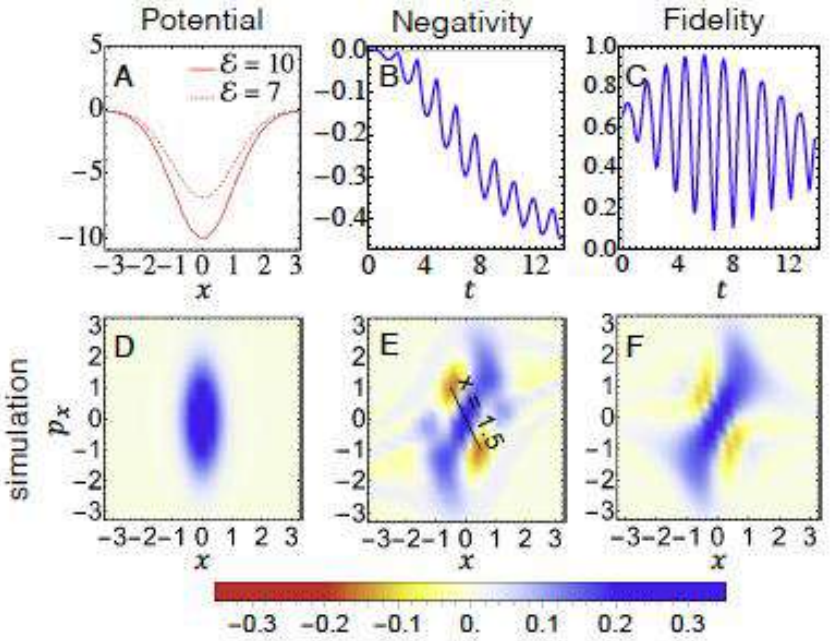
- Pre-cooled to 1000 phonons, then state expanded by trap modulation
- After 1ms of expansion, motional state is about the size of the particle

Muffato, R., et al., **Coherent expansion of the motional state of a massive nanoparticle beyond its linear dimensions**. *arXiv:2408.09596*.

Simulation: Non-Gaussian states by squeezing thermal state:

squeezing + cooling + non-linearity

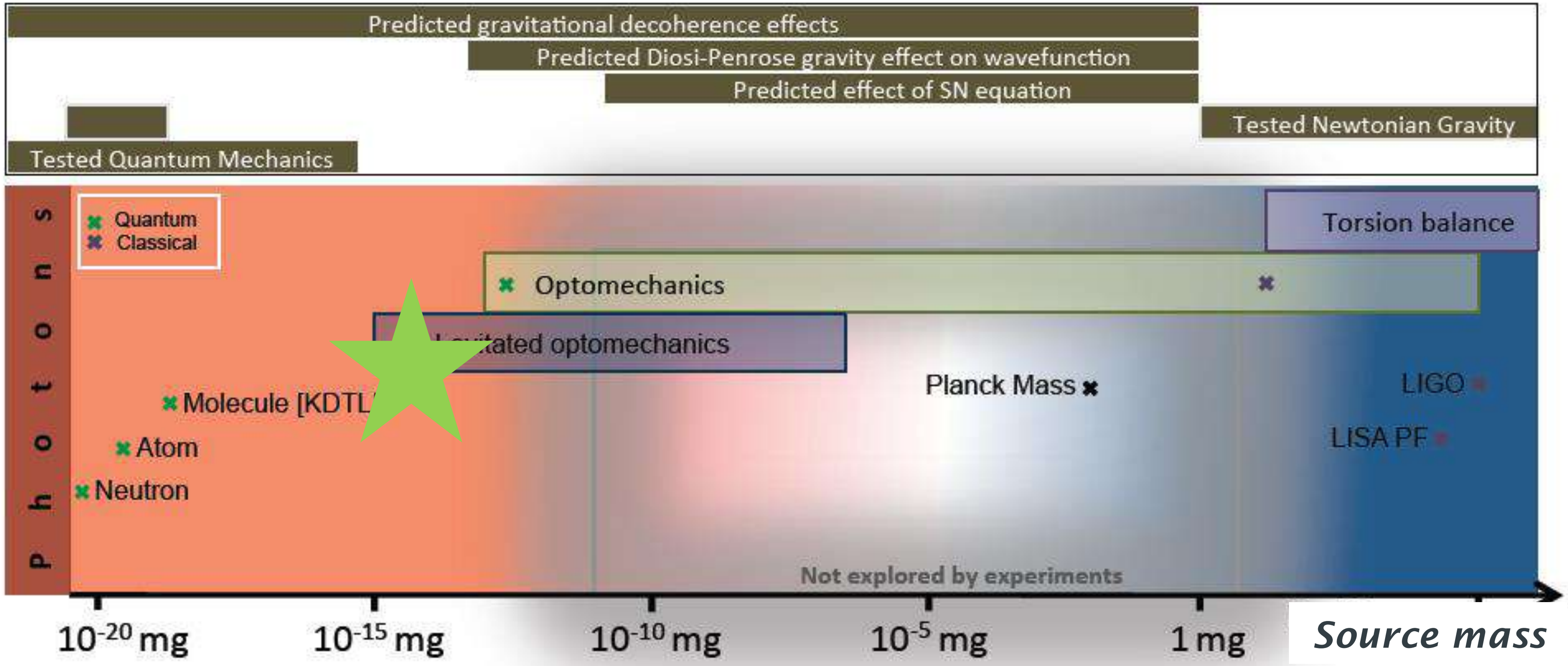




Wu, Q., et al., **Squeezing below the ground state of motion of a continuously monitored levitating nanoparticle.** Quantum Sci. Technol. 9 045038 (2024).

Macroscopic quantum: where are we?

Experimental target with levitated particles at the moment (100 nm particle)
[*Superposition size larger than the size of the particle*]

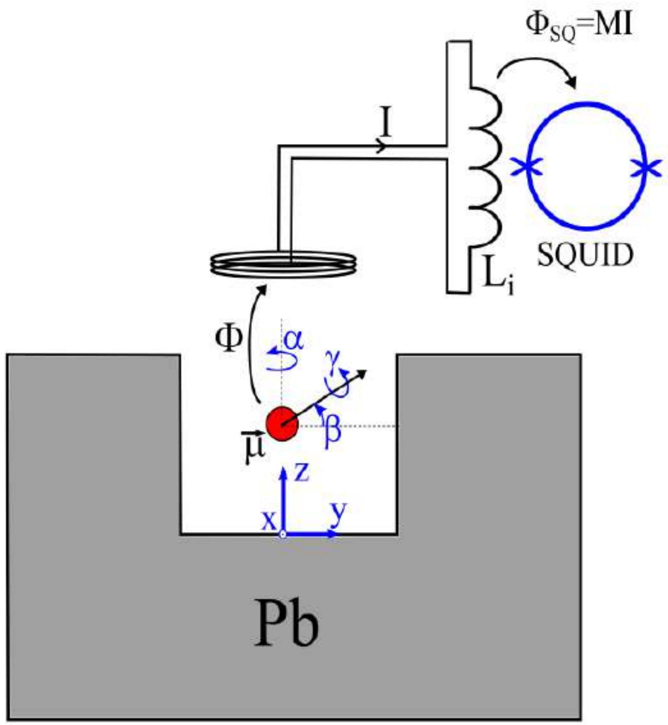


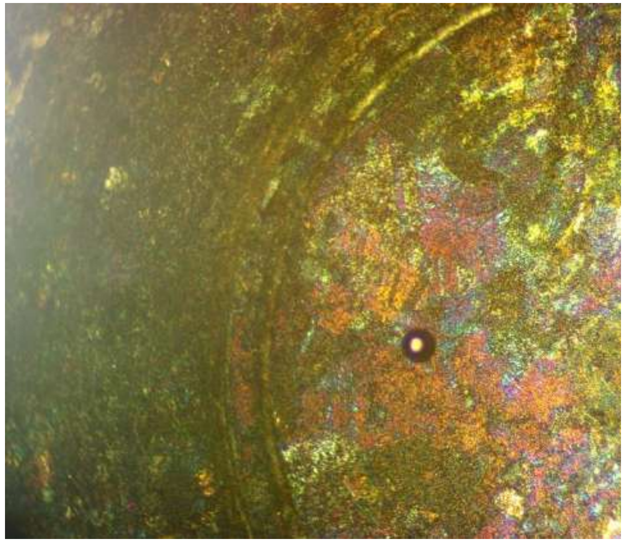
Bassi, A., A. Grossardt, and H. Ulbricht, ***Gravitation Decoherence***, Class. Quantum Grav. **34**, 193002 (2017).

MEASURING TWO-MASS GRAVITY

Levitated small mass experiments: Meissner trapping of ferromagnets

Simple passive trap: particle in the hole:
Lateral surface provides x,y confinement



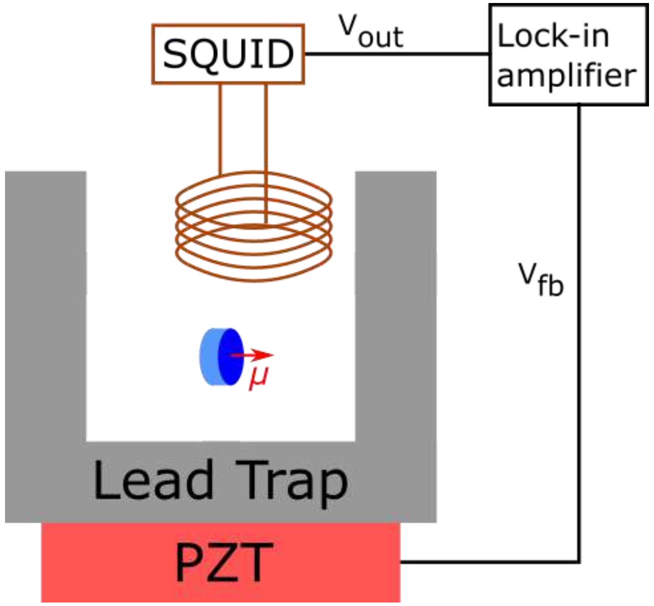


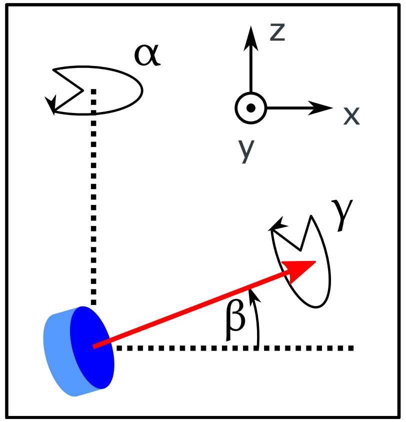
NdFeB microsphere radius = 27 um
Trap Radius = 2 mm

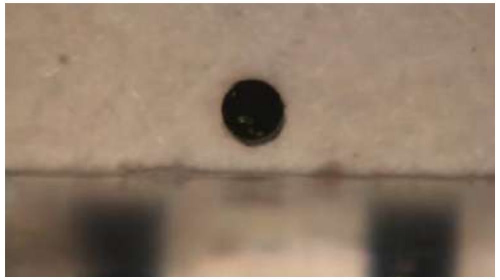
Vinante, A., P. Falferi, G. Gasbarri, A. Setter, C. Timberlake, and H. Ulbricht, Ultrahigh mechanical quality factor with Meissner-levitated ferromagnetic microparticles,Phys. Rev. Appl. 13, 064027 (2020)

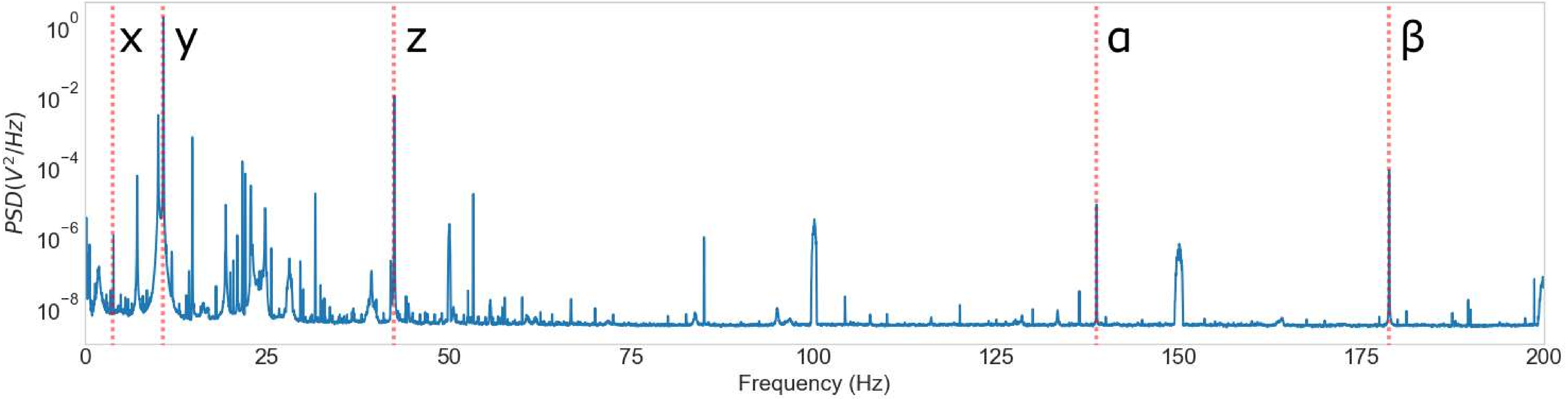
Feedback Cooling: PZT kicks

- 100 µm thickness x 200 µm diameter NdFeB magnet
- 3 translational (x, y, z) and 2 librational (α, β) modes
- Background temperature = 410 mK
- Gas pressure = 4 x 10^{-7} mbar





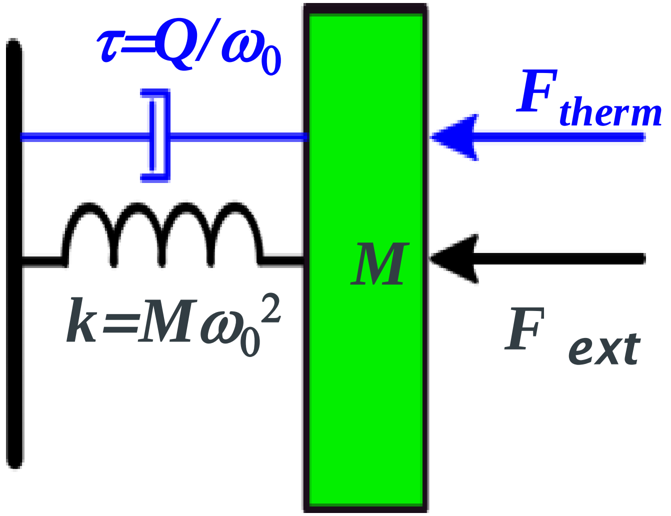




Force (noise) in harmonic oscillator:

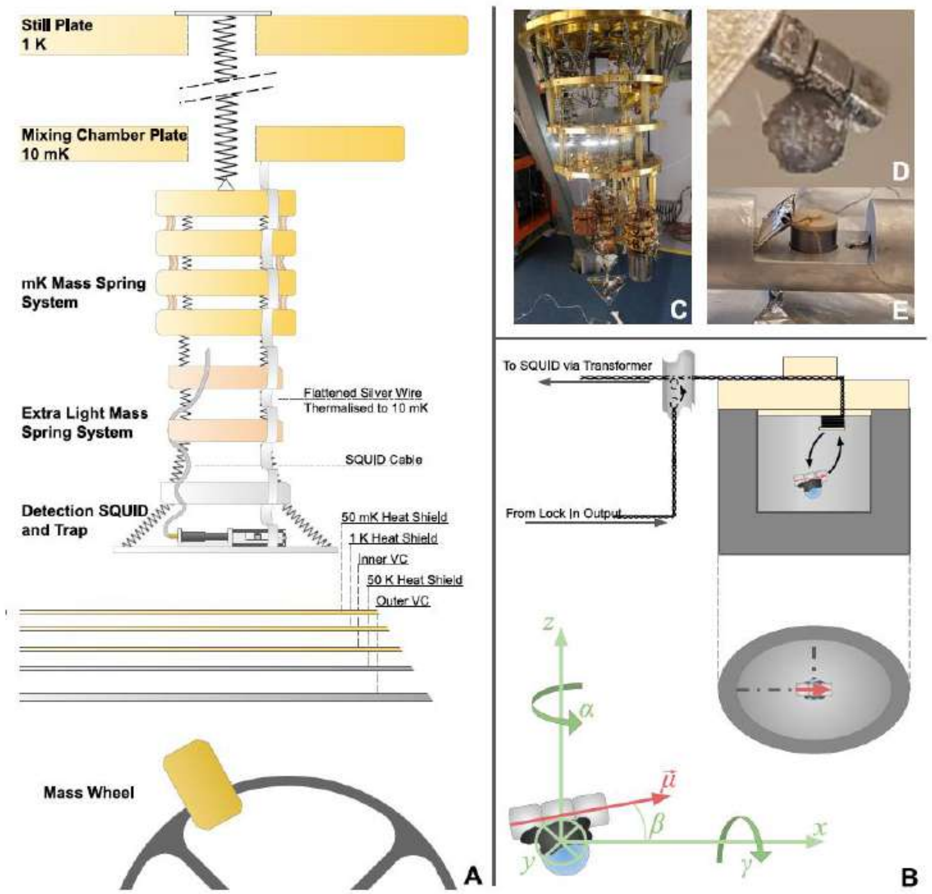
Thermal bath affect minimum force measured:

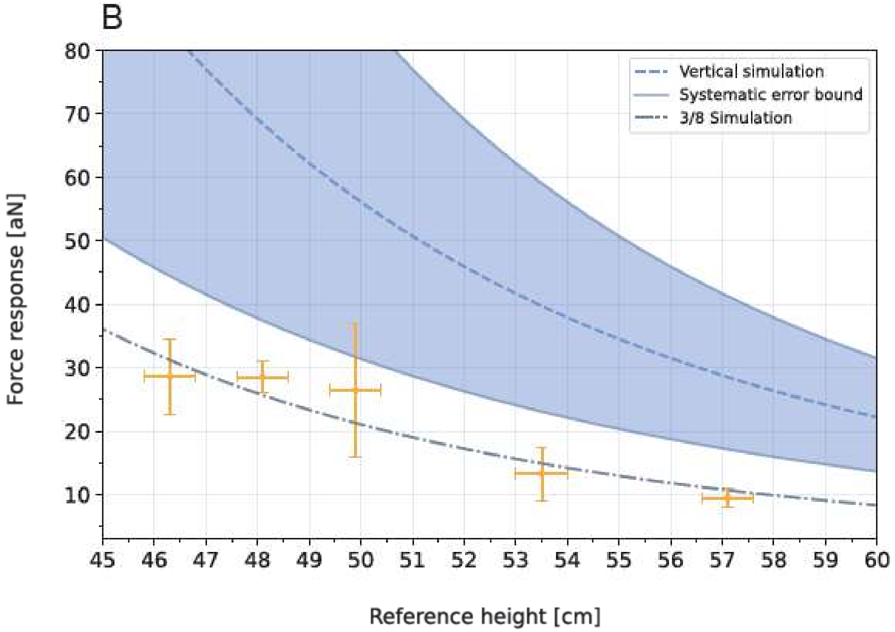
$$F_{min} = \sqrt{\frac{4k_B T_0 m\omega_0}{Q\tau}},$$



M. Bahrami et al, PRL **112** 210404 (2014)
S. Nimmrichter et al, PRL **113** 020045 (2014)
L. Diosi, PRL **114**, 050403 (2015)
D. Goldwater et al. Phys. Rev. **A 94**, 010104 (2015)
A. Vinante et al, PRL **116**, 090402 (2016)

Gravity testing with levitated ferromagnet (in Leiden)





- Probe mass: 0.43 mg
- Source mass: 2.45 kg (on wheel)
- Q = 10^7 @ 26 Hz
- 30 aN, 8 mHz linewidth
- 3/8 of expected Newtonian gravity

Fuchs, T.M., Uitenbroek, D.G., Plugge, J., van Halteren, N., van Soest, J.P., Vinante, A., Ulbricht, H. and Oosterkamp, T.H., 2024. Measuring gravity with milligram levitated masses. *Science Advances*, *10*(8), p.eadk2949.

Our next gravity experiment

Small Scale Gravity

To test the interplay between quantum mechanics and gravity, we must push gravitational detection to ever smaller scales, whilst pushing quantum mechanical effects to ever larger scales.

Passive levitation of magnets in superconducting traps offers great scalability, up from micrometer sized particles to centimeter sized objects. This allows us to push on both boundaries in the same set-up.

To detect gravitational coupling, we use 500 μm sized particles coupled to a cryogenic mass-wheel. From this, we will be able to detect gravitational coupling down to 10^{-13} g, an improvement from our previous work at roughly 10^{-11} g [1]. In this range, proposed theories of Modified Newtonian Gravity should deviate from classical predictions.

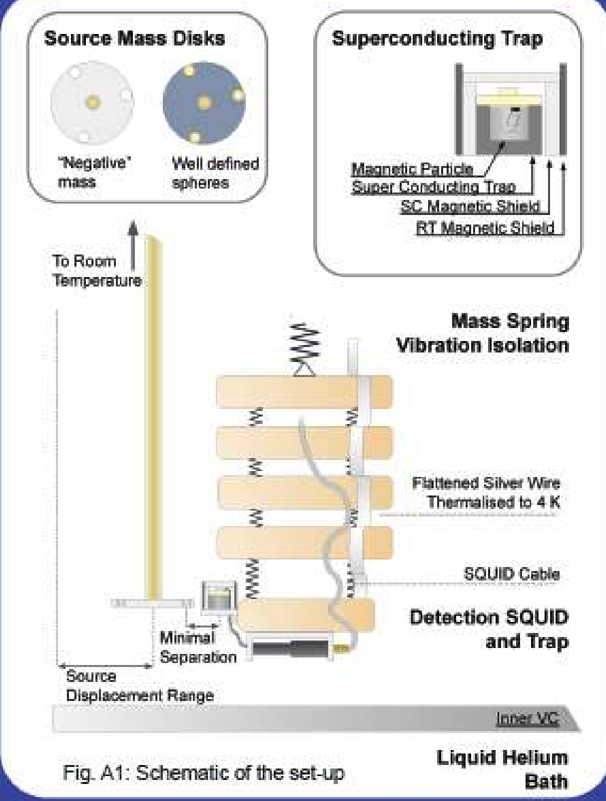


Fig. A1: Schematic of the set-up

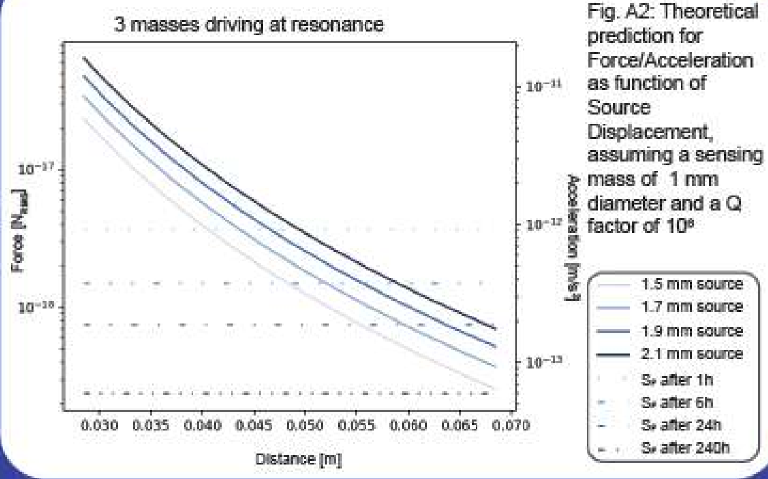
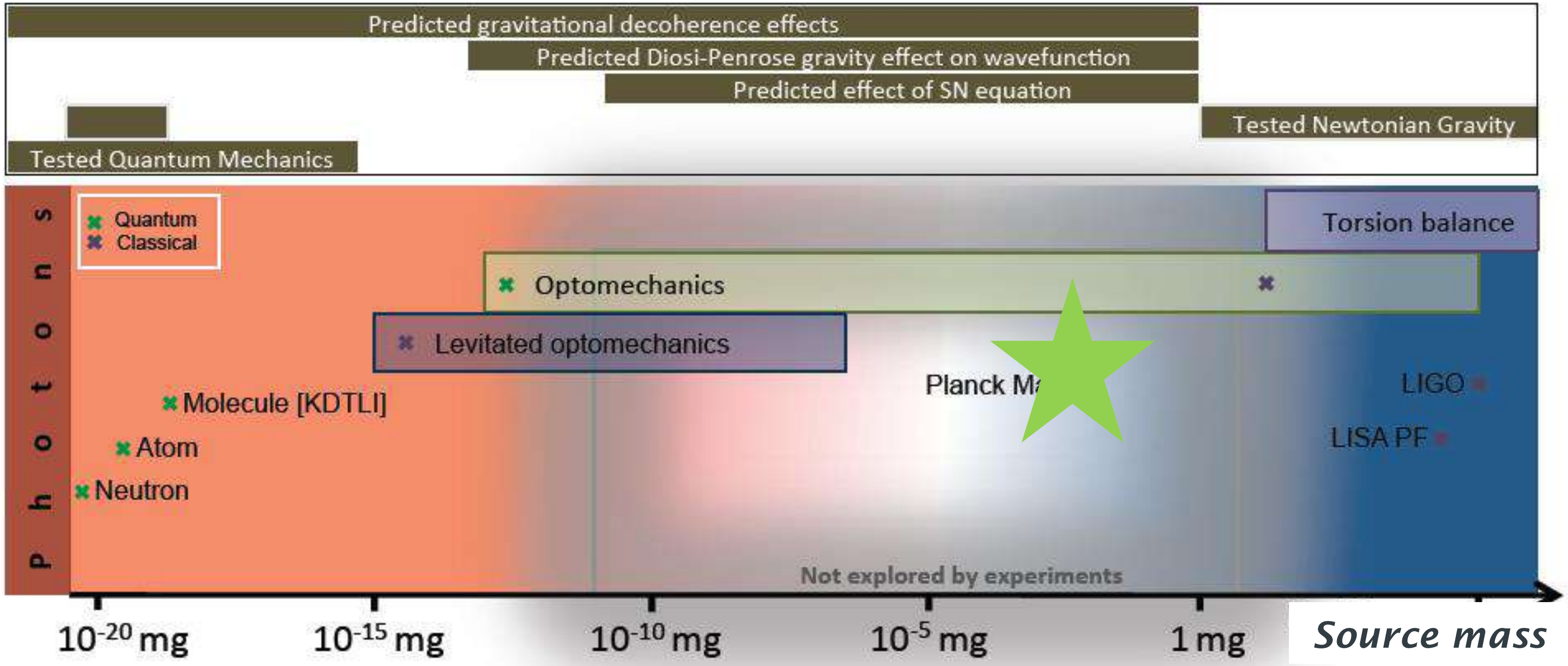


Fig. A2: Theoretical prediction for Force/Acceleration as function of Source Displacement, assuming a sensing mass of 1 mm diameter and a Q factor of 10^{6}

Small mass gravity: where are we?

Current experimental target with probing by levitated particle (10 microgram)



Bassi, A., A. Grossardt, and H. Ulbricht, ***Gravitation Decoherence***, Class. Quantum Grav. **34**, 193002 (2017).

Summary of talk

- Pushing on gravity and quantum experiments.
- Testing macroscopic quantum.
- Testing small-mass gravity.