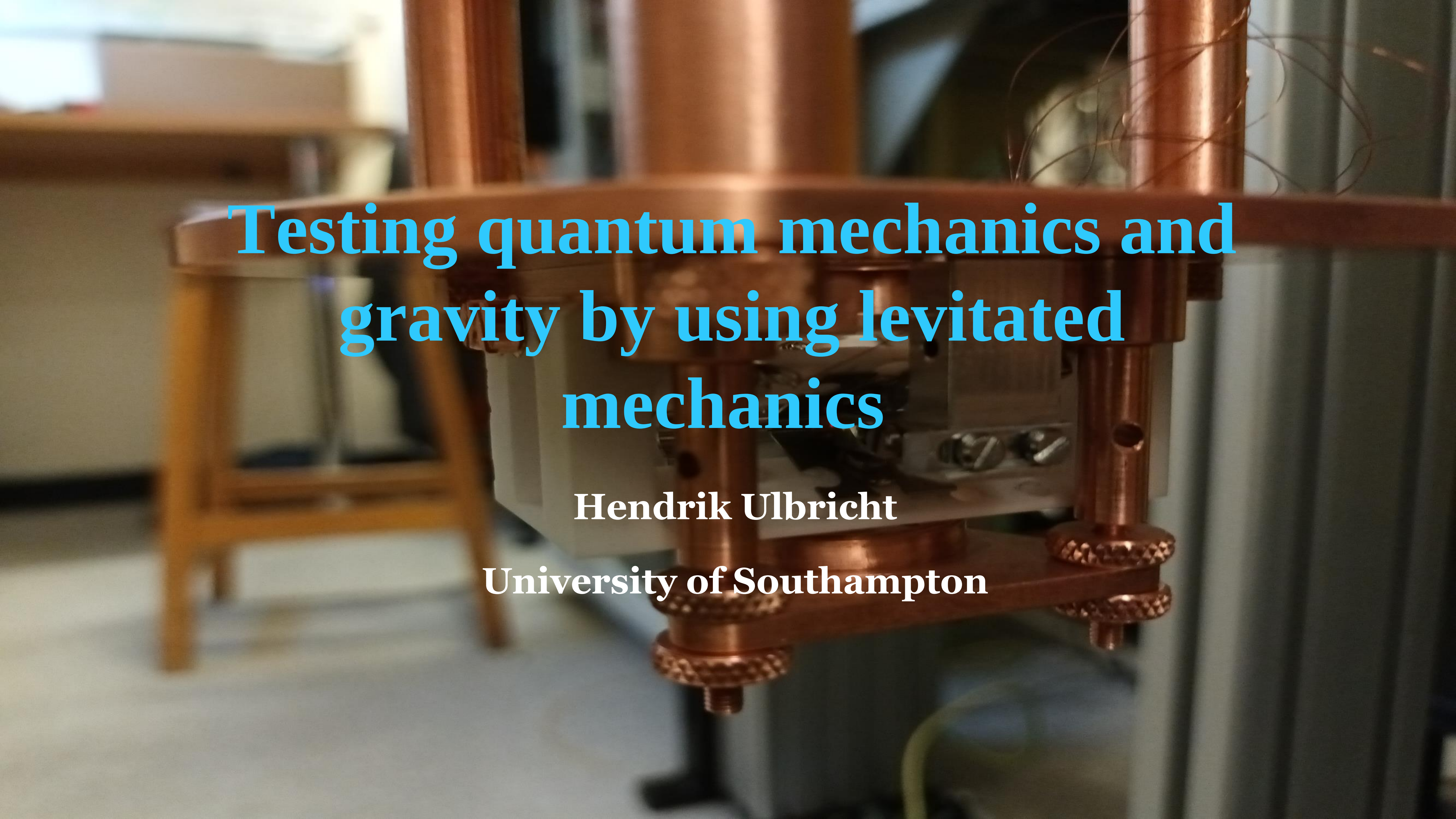


Testing quantum mechanics and gravity by using levitated mechanics

Hendrik Ulbricht

University of Southampton

Thanks to …

Group at Southampton: Tim Fuchs, Chris Timberlake, Marion Cromb, Jack Homans, Elliot Simcox, Jakub Wardak, Laura Barbara, Amy Smith, Charlotte Bridgett. *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, Matteo Carlesso, Angelo Bassi.

Experiments, applications & space: Peter Barker, Tjerk Oosterkamp, Andrea Vinante, Alessio Belenchia, Jize Yan, Maria Chiara Braidotti, Daniele Faccio.

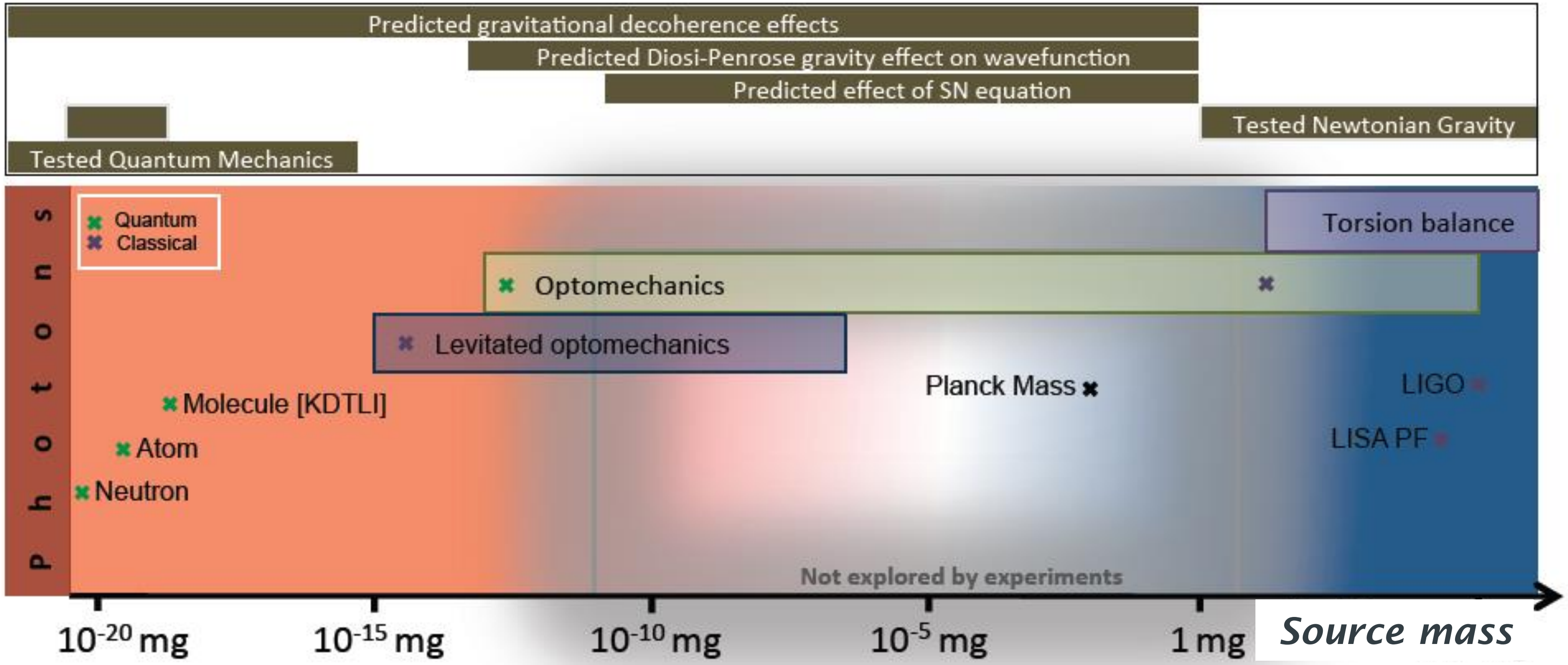
Community: Optomechanics seminar series *UniKORN*, Optomechanics space mission consortium *MAQRO*, ESA Payload Masters *Op-To-Space*, EPSRC international networks *LeviNet & INQST*, Space South Central and Programme *JUPITER*.

Support from: UK EPSRC & STFC, EU Horizon2020 FET-Open project *TeQ*, EU HorizonEurope EIC Pathfinder *QuCoM*, EU QuantERA project *LEMAQUME*, Leverhulme Trust, John F Templeton Foundation, FQXi, Royal Society, EU COST action *QTSpace*, Research England SPRINT project *SIGMA*, UKSA IBF project *A3S*, STFC IAA *JOVAIN-1*.

Main menu

- Testing macroscopic (large-mass) quantum.
- Testing small-mass gravity.
- Amplification of elm fields by mechanical rotation.

Test gravity & quantum interplay in low energy regime



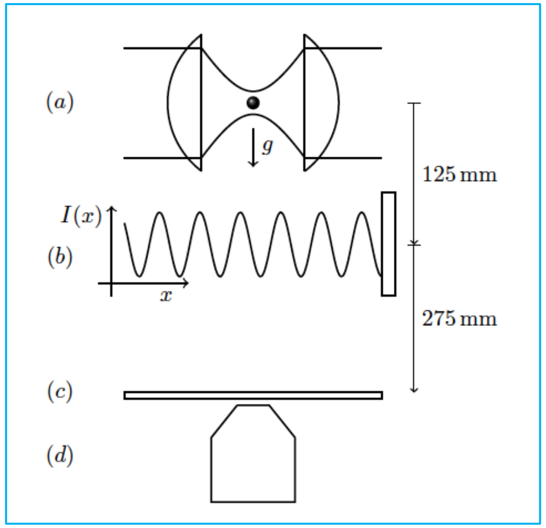
Smallest source mass where Newtonian gravity is confirmed by experiment: ~100 mg
What if the source mass is even smaller and in a spatial superposition?
How does the gravitational field look like then?

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

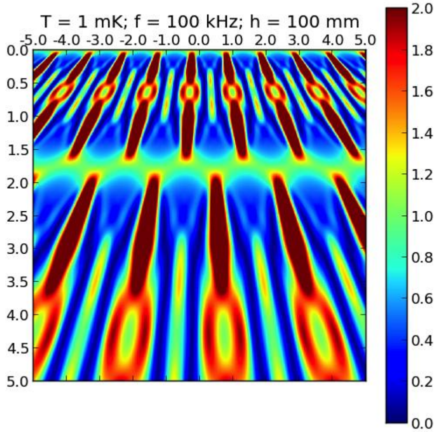
EXERIMENTS: LEVITATED MECHANICAL SYSTEMS

Nanoparticle Talbot interferometer (NaTali):

directly testing macroscopic quantum superpositions



Quantum carpet:
Simulated interference pattern



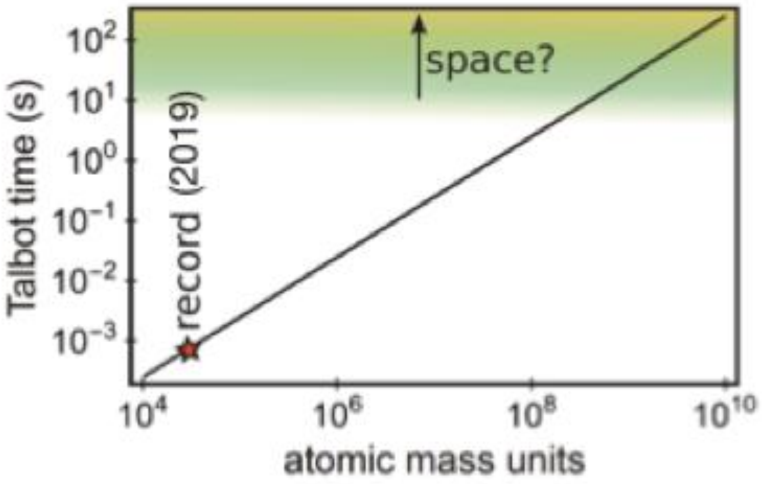
Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht
Near-field interferometry of a free-falling nanoparticle from a point-like source
Nature Communications 4, 4788 (2014).

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.

✓

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

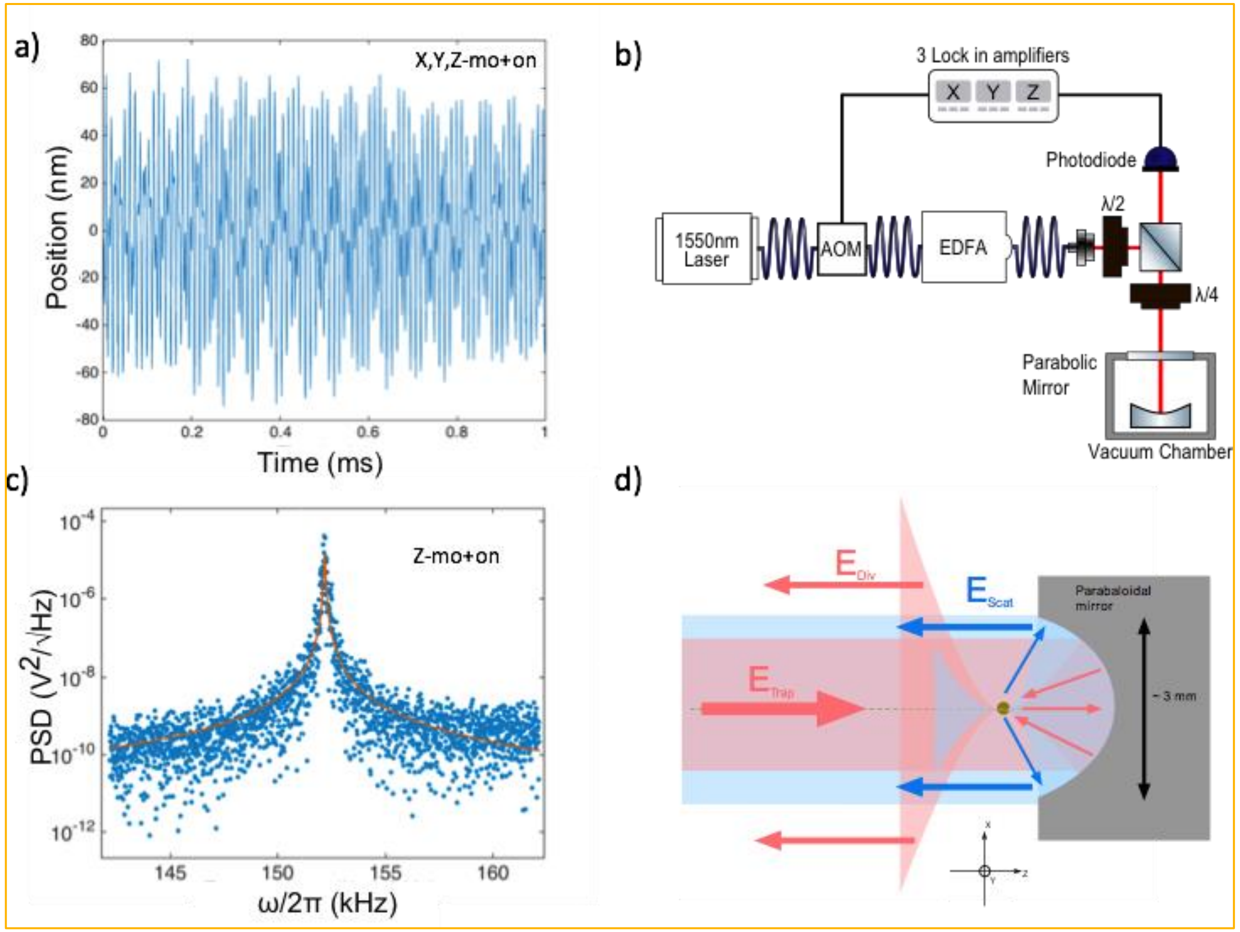


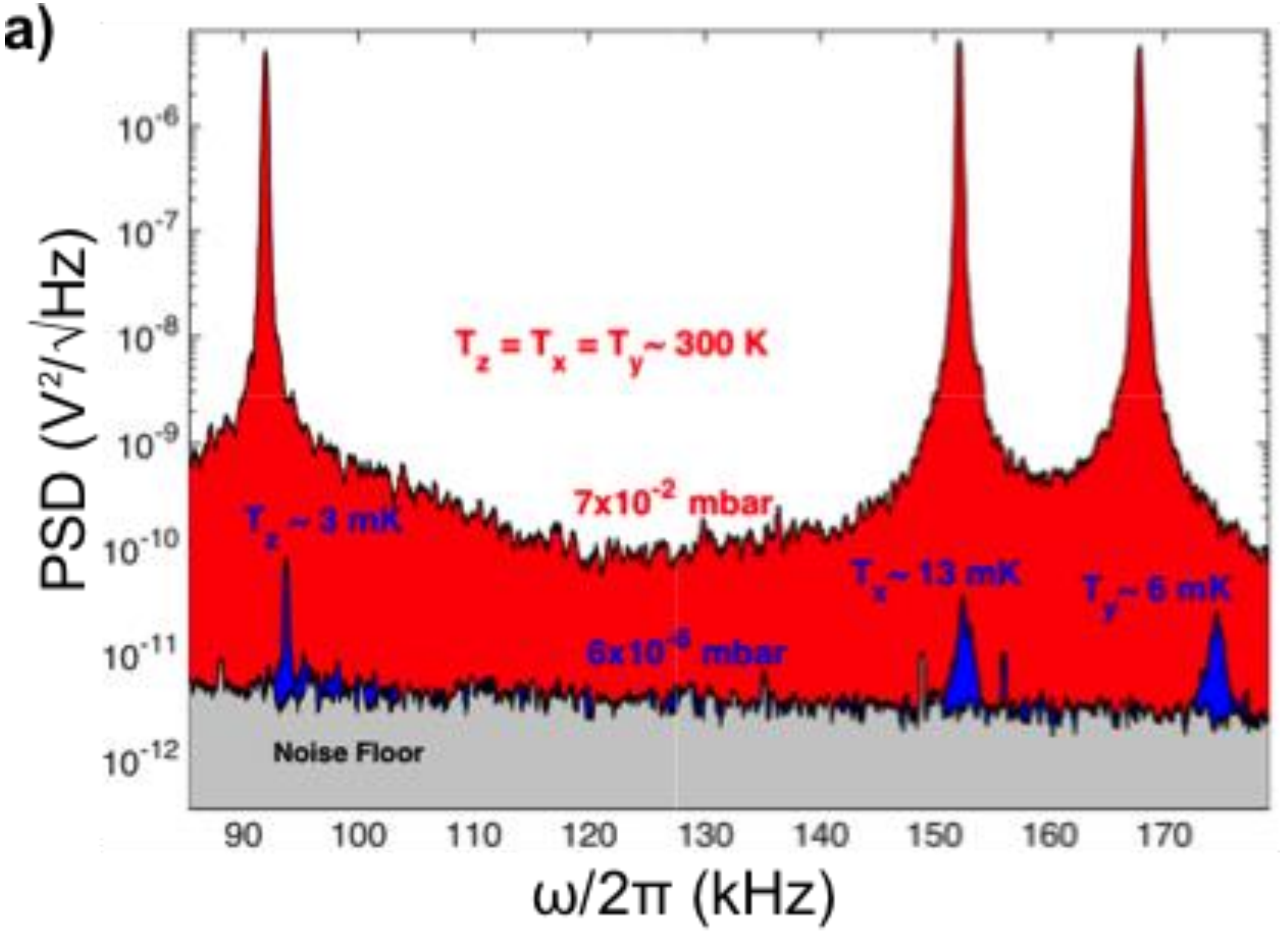
Belenchia, A., Carlesso, M., Donadi, S., Gasbarri, G., Ulbricht, H., Bassi, A. and Paternostro, M., 2021. Test quantum mechanics in space. *Nature*, *596*(7870), pp.32-34.

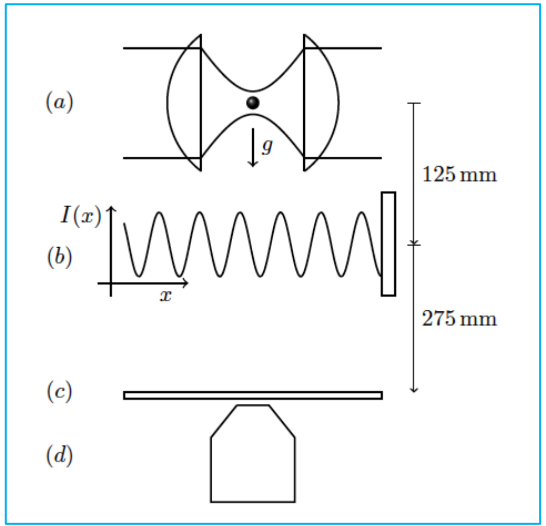
Trap and measure position, then feedback cool to ~1mK

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

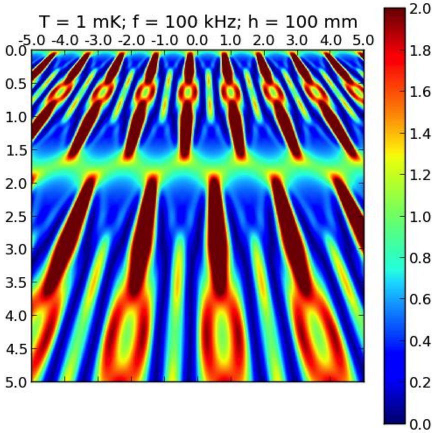
Power spectral density: $S_x(\omega) = \frac{k_B T_0}{\pi m} \frac{\Gamma_0}{([\omega_0 + \delta\omega]^2 - \omega^2)^2 + \omega^2 [\Gamma_0 + \delta\Gamma]^2}$







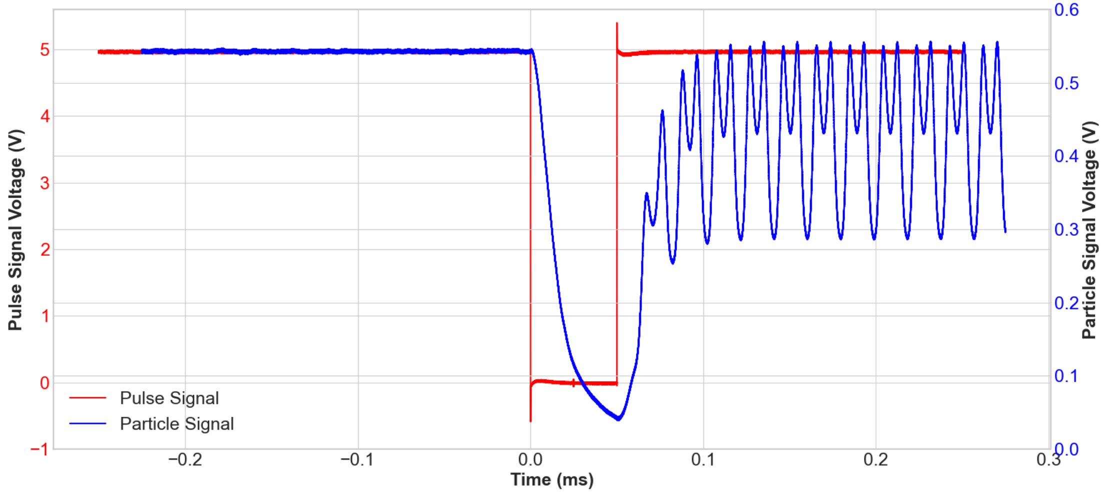
Quantum carpet:
Simulated interference pattern

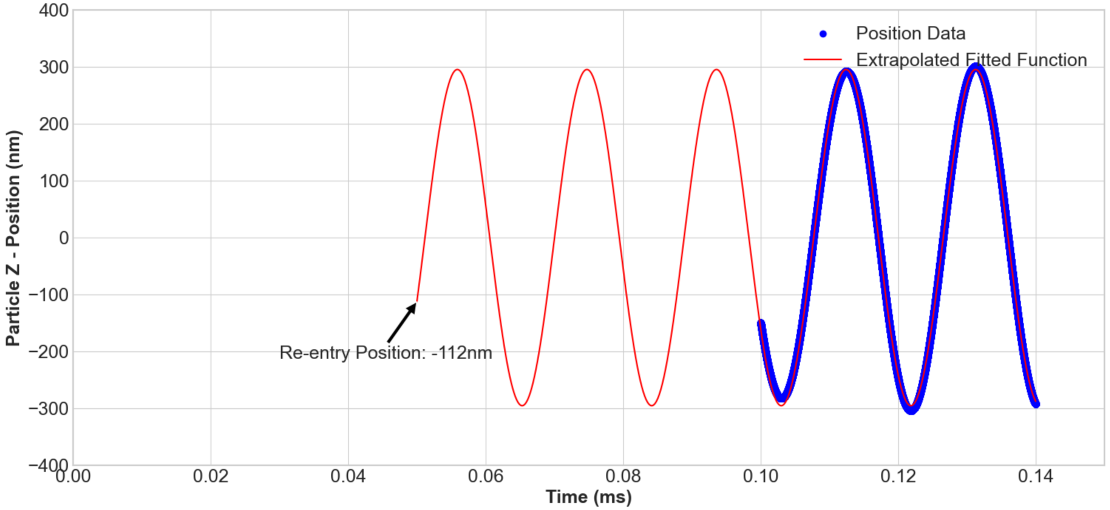


LONG FREE COHERENT EVOLUTION TIME

Freefall scheme: recapture in trap gives 500 microsecs

- Re-entry position can be detected by filtering and extrapolating particle signal close to re-entry.
- Data from turning trap off/on and detecting position as proof of concept.
- Needs proper tracking model and filtering (Jason Ralph)





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.

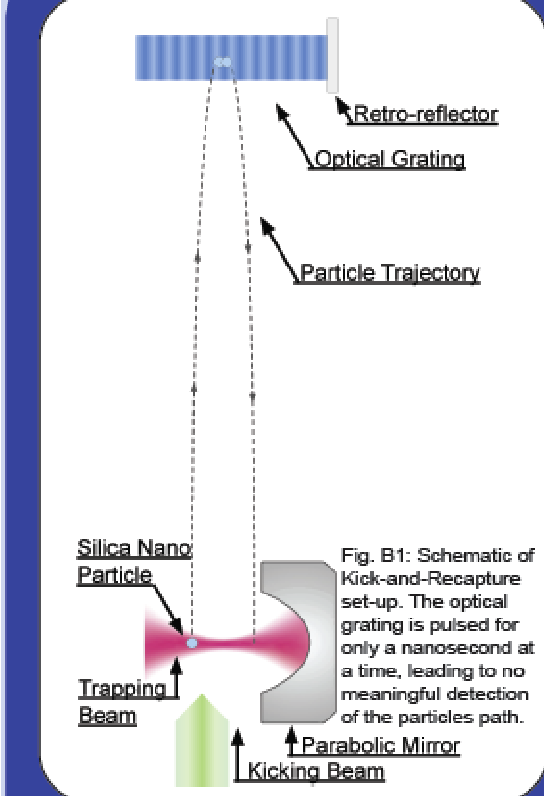


Fig. B1: Schematic of Kick-and-Recapture set-up. The optical grating is pulsed for only a nanosecond at a time, leading to no meaningful detection of the particles path.

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.

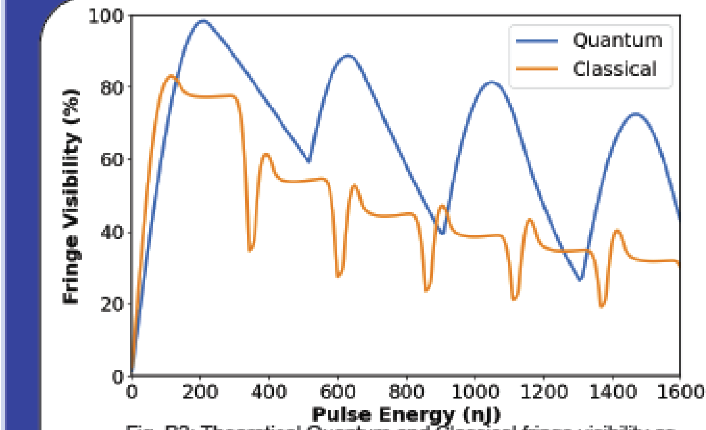


Fig. B2: Theoretical Quantum and Classical fringe visibility as function of optical grating intensity. A SiO2 particle, m = 10^8 AMU, cooled down to 1 mK C.O.M. motion was assumed. P = 10^-10mbar, T_{flight} 58 ms or 1.6 cm flight height.

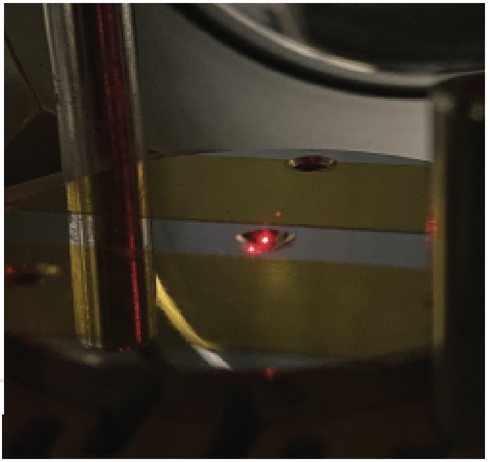
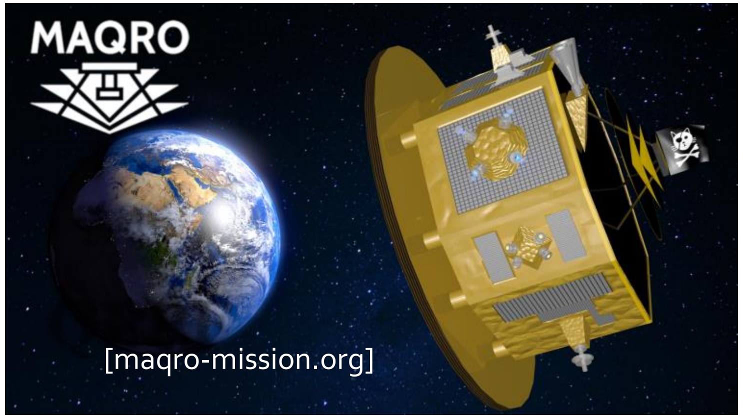
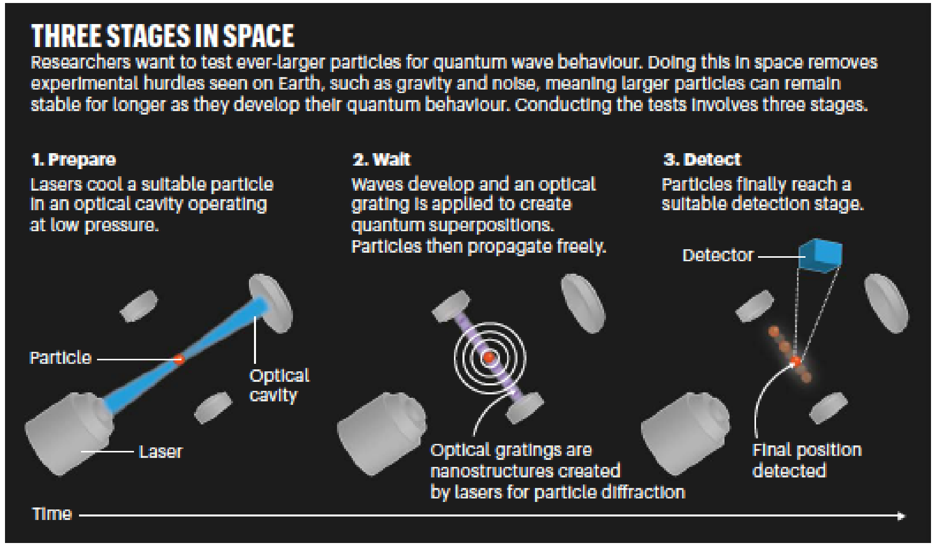


Fig. B3: Photo of a particle trapped above the parabolic mirror, illuminated by a red laser.

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





THREE STAGES IN SPACE

Researchers want to test ever-larger particles for quantum wave behaviour. Doing this in space removes experimental hurdles seen on Earth, such as gravity and noise, meaning larger particles can remain stable for longer as they develop their quantum behaviour. Conducting the tests involves three stages.

1. Prepare
Lasers cool a suitable particle in an optical cavity operating at low pressure.

2. Wait
Waves develop and an optical grating is applied to create quantum superpositions.
Particles then propagate freely.

3. Detect
Particles finally reach a suitable detection stage.

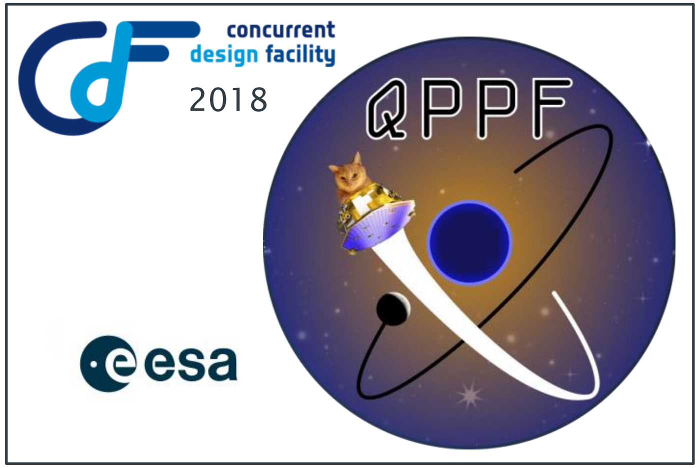
Theoretical foundations

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).

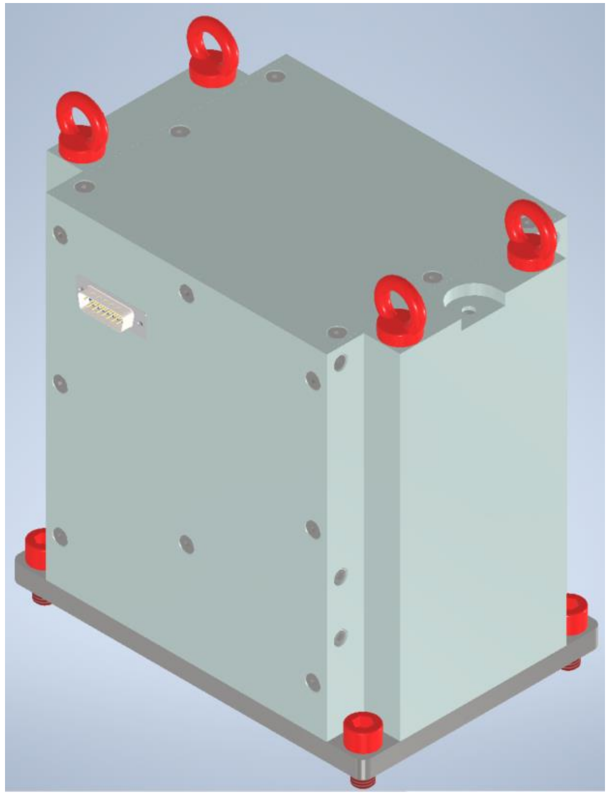


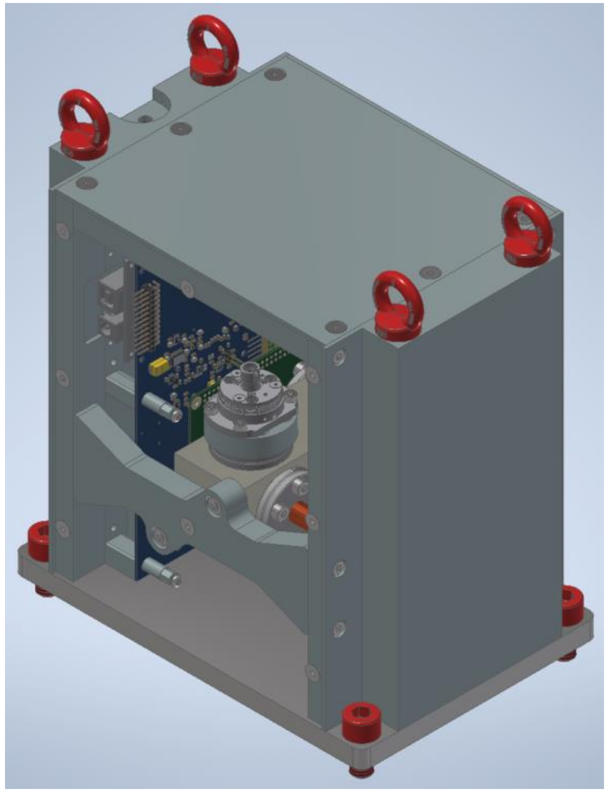
TWIN PARADOX LABS SURREY SPACE CENTRE bias ZARM University of Southampton

Levitated mechanics in free fall – satellite launch June 2025

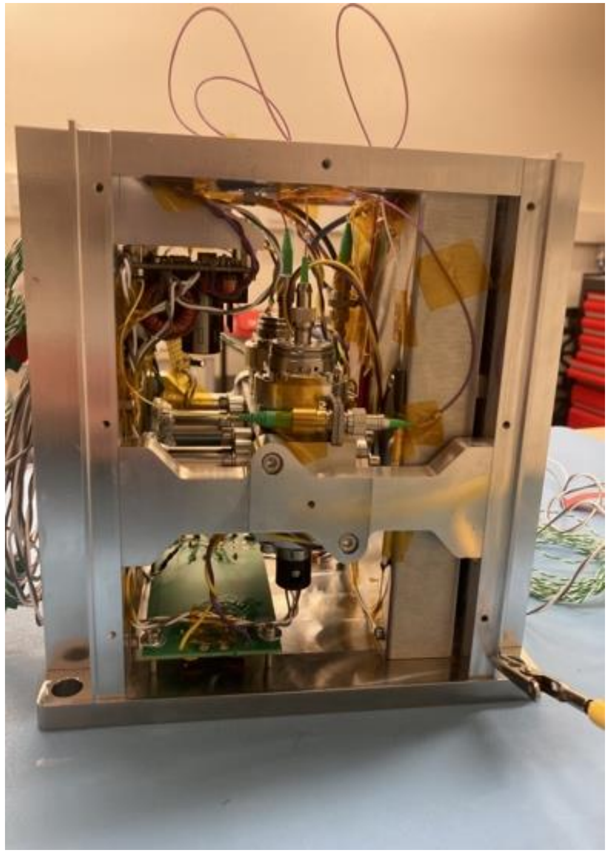
Payload box:

- 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).

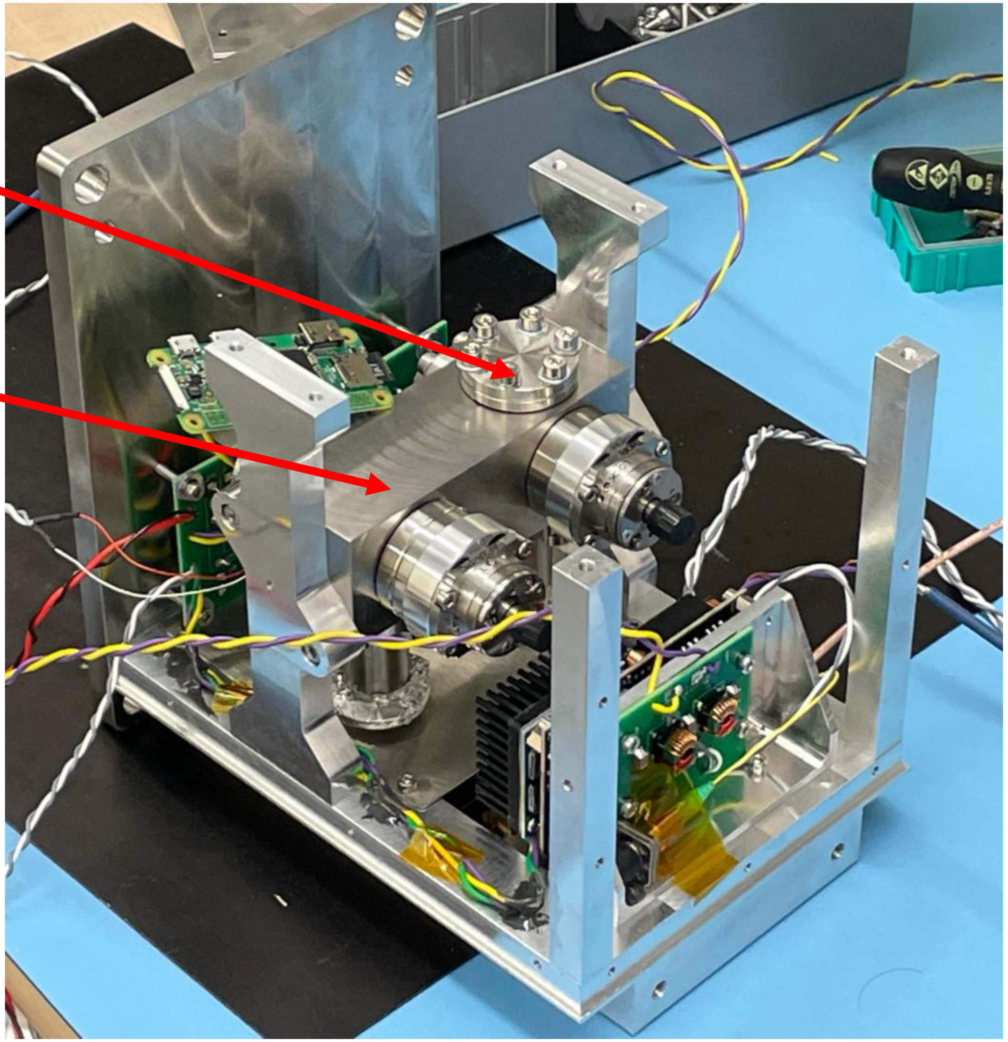




BIAS
Southampton
Op-To-Space
ZARM
Surrey



What is inside the box?

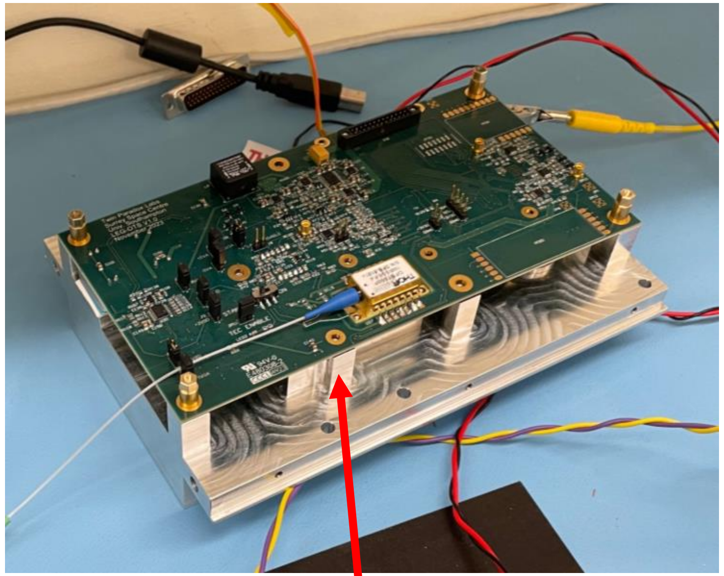


Optical trap for silica particles

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.

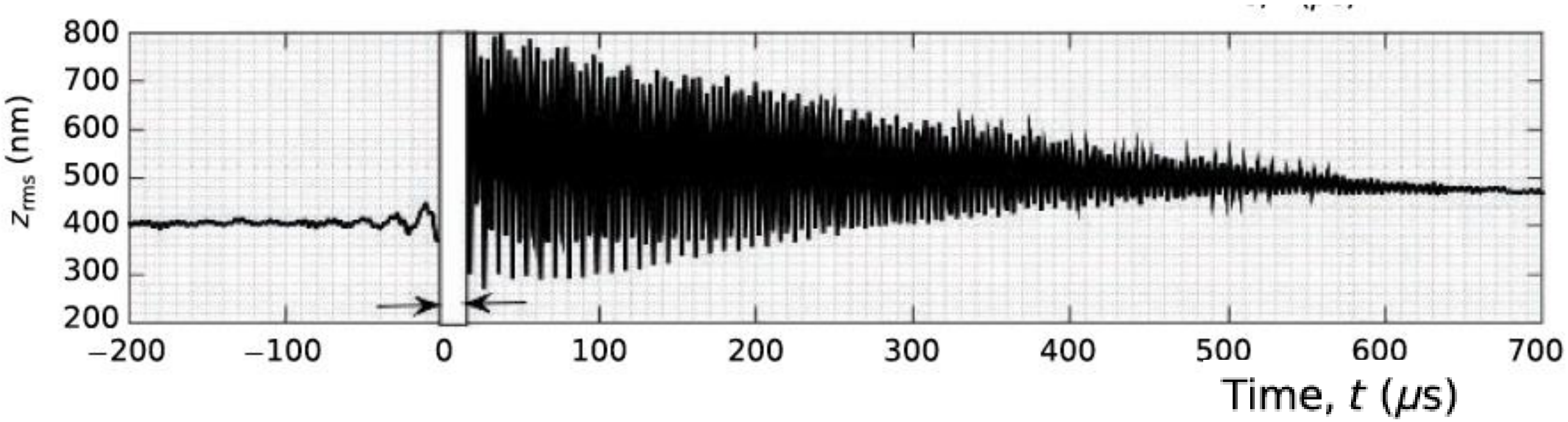
Fully autonomous operation

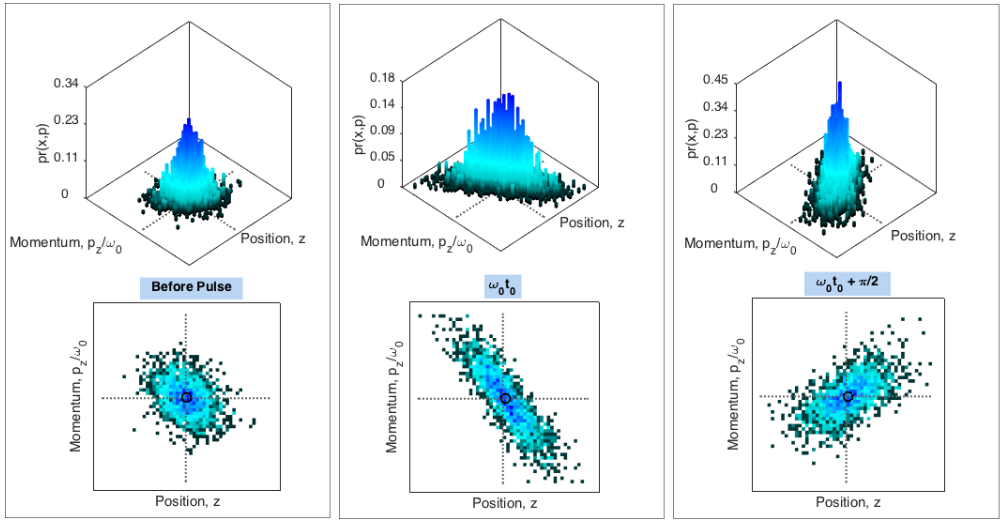
OR

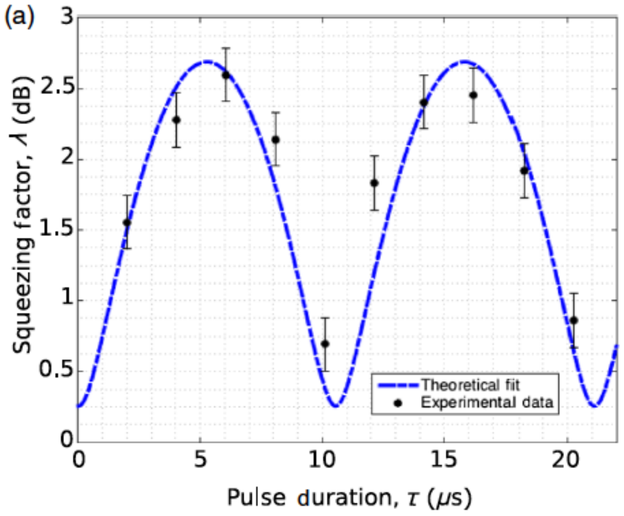
ACCELERATE EVOLUTION OF QUANTUM STATE COHERENTLY

Squeezing the thermal motion by frequency jump

Time trace:

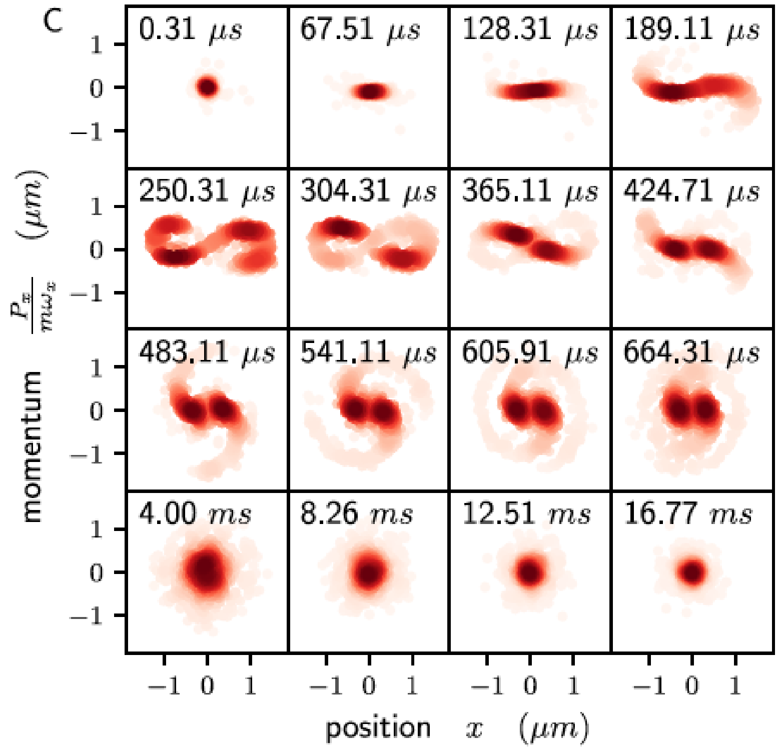


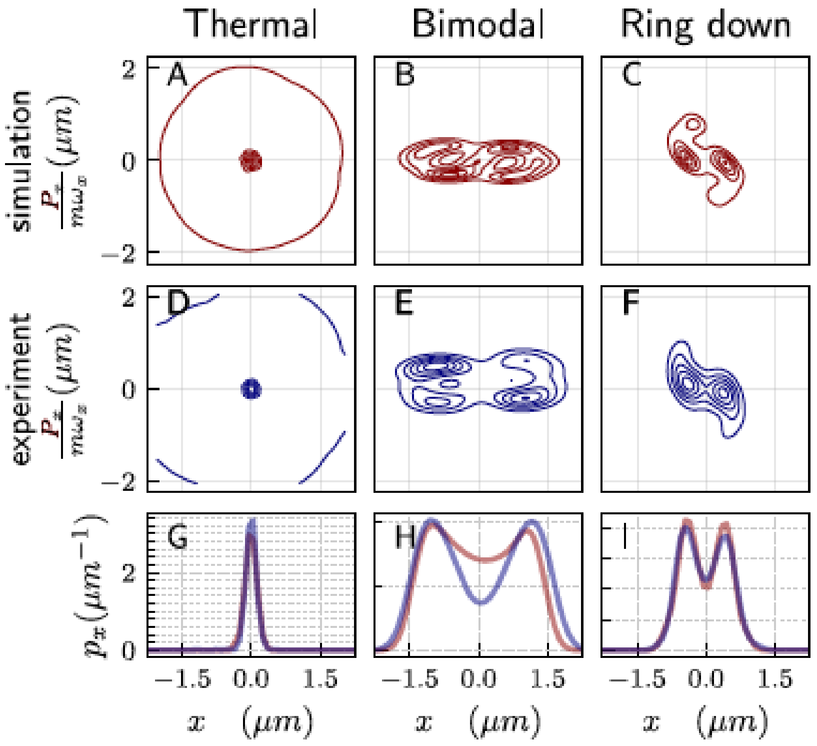




Rashid, M., T. Tufarelli, J. Bateman, J. Vovrosh, D. Hempston, M. S. Kim, and H. Ulbricht, ***Experimental Realization of a Thermal Squeezed State of Levitated Optomechanics***, PRL 117, 273601 (2016).

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

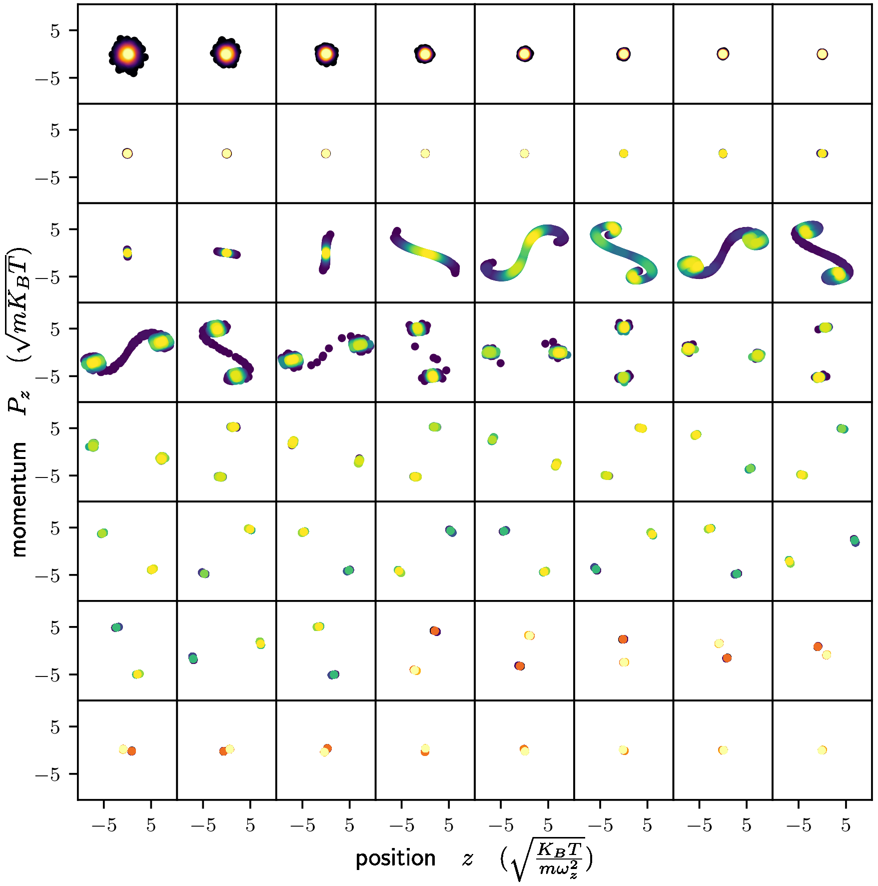


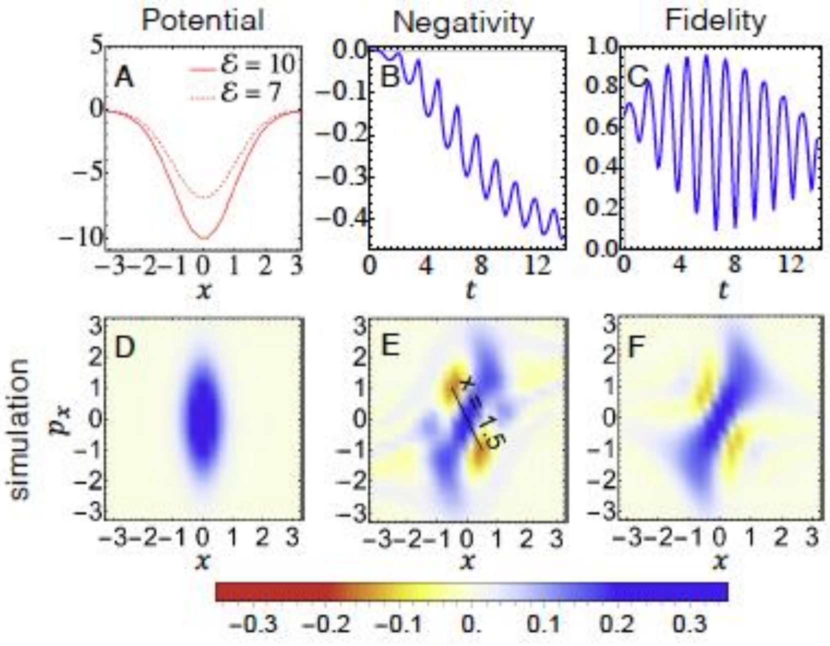


Muffato, R., Georgescu, T., Homans, J., Guerreiro, T., Wu, Q., Chisholm, D., Carlesso, M., Paternostro, M. and Ulbricht, H., 2024.
Generation of classical non-Gaussian distributions by squeezing a thermal state into non-linear motion of levitated optomechanics. *arXiv preprint arXiv:2401.04066*.

Simulation: Non-Gaussian states by squeezing thermal state:

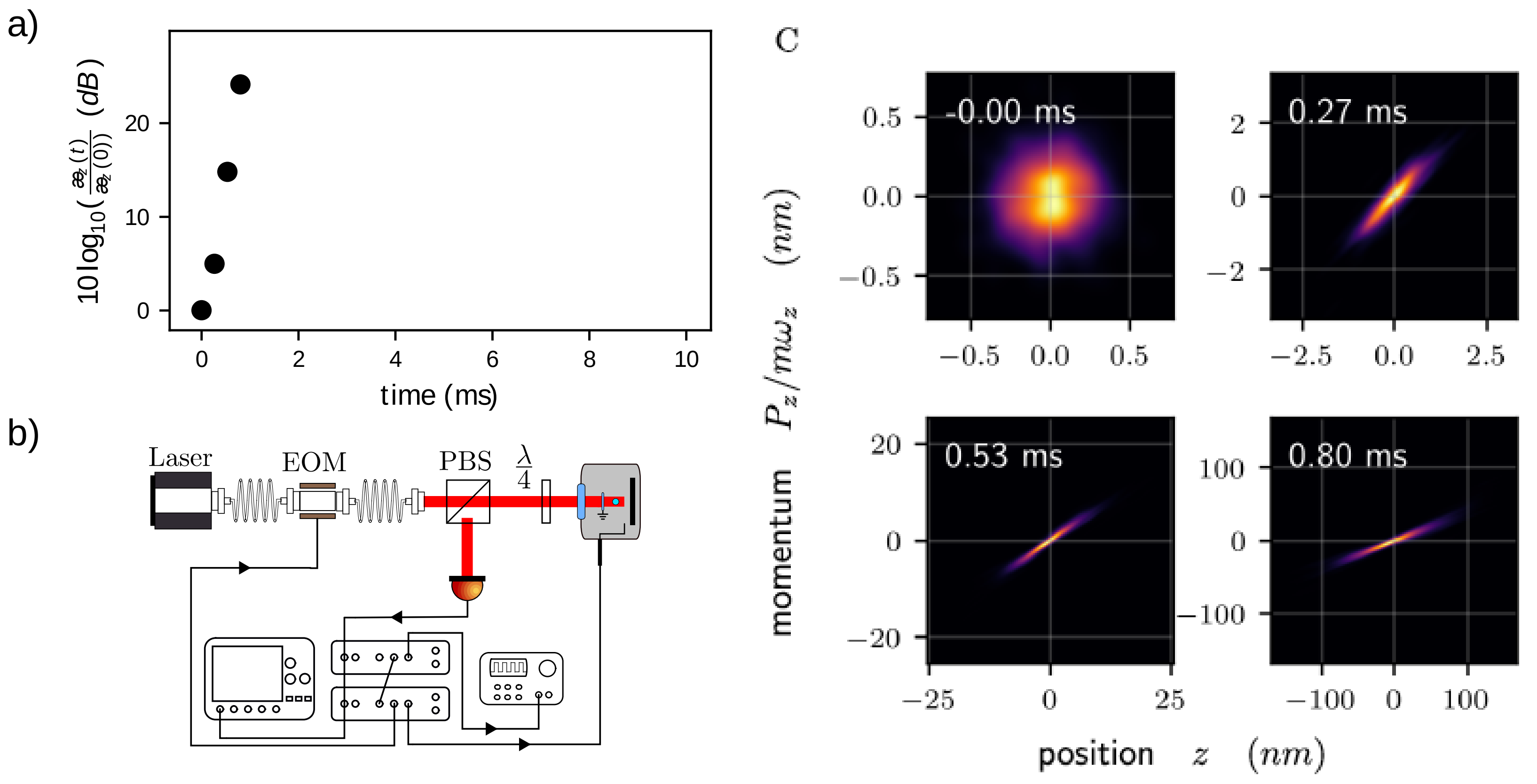
squeezing + cooling + non-linearity





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*.

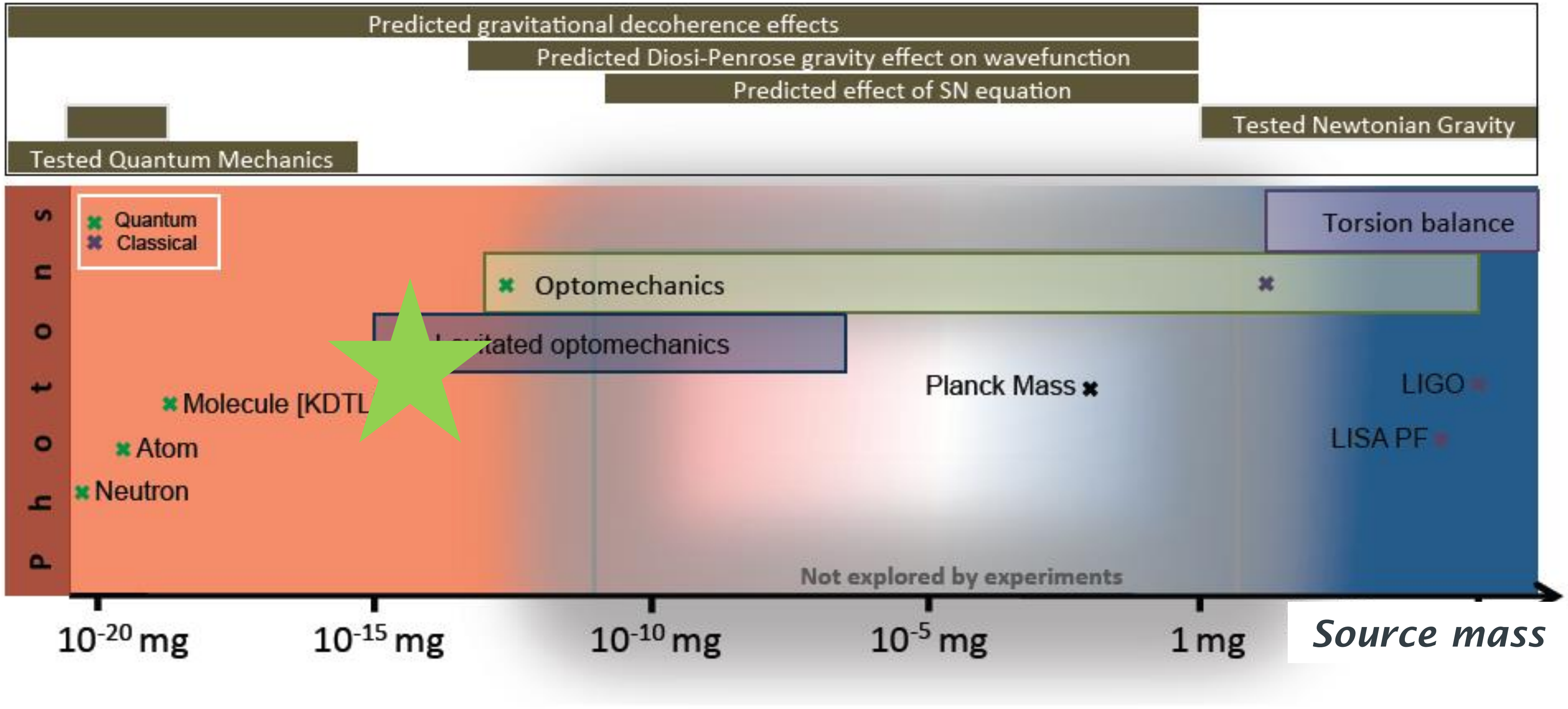
Experiment results: the other option …. coherent expanding the motional state:



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

Macroscopic quantum: where are we?

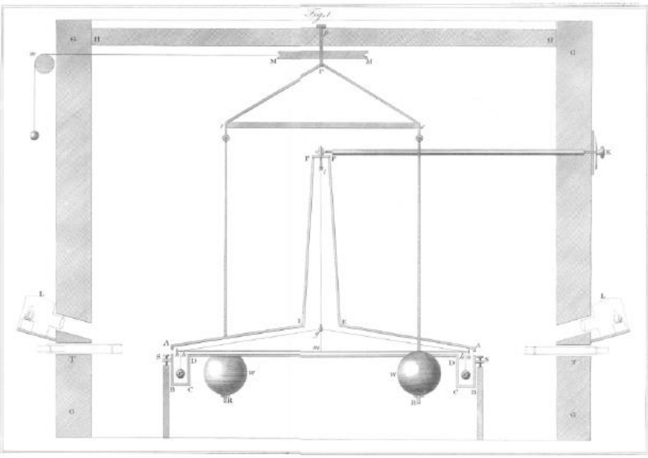
Experimental target with levitated particles at the moment (100 nm particle)
[*Superposition size larger than the size of the particle*]

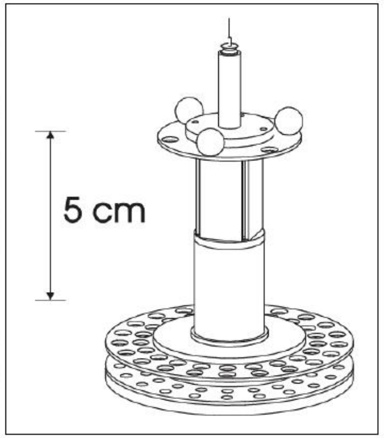


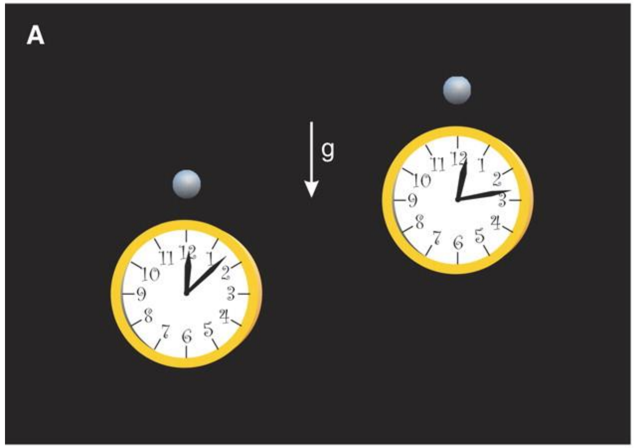
Bassi, A., A. Grossardt, and H. Ulbricht, ***Gravitation Decoherence***, Class. Quantum Grav. **34**, 193002 (2017).

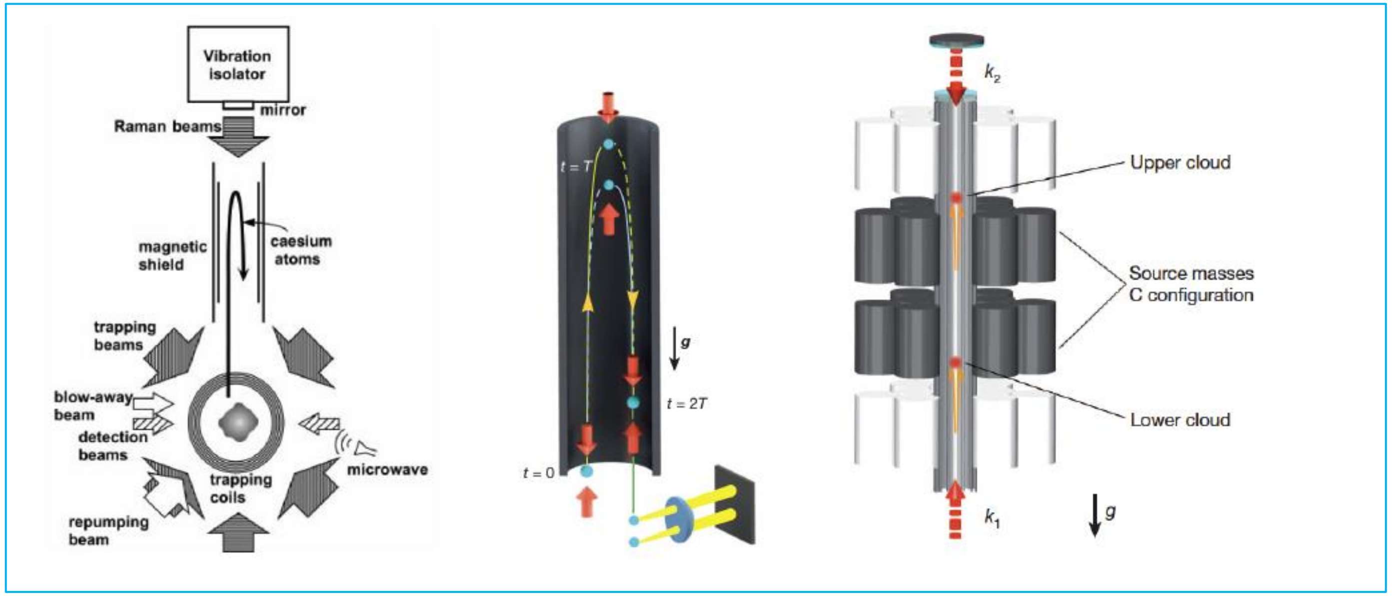
MEASURING TWO-MASS GRAVITY

How do we measure gravity?







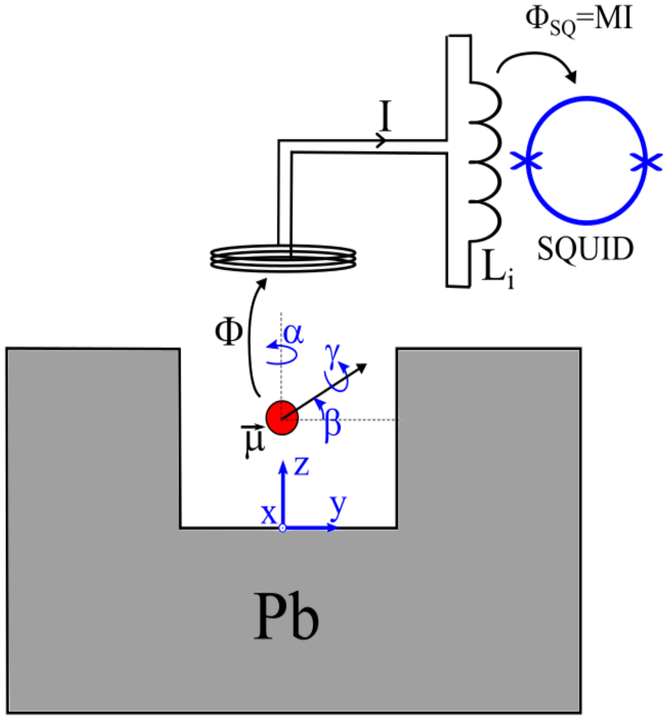


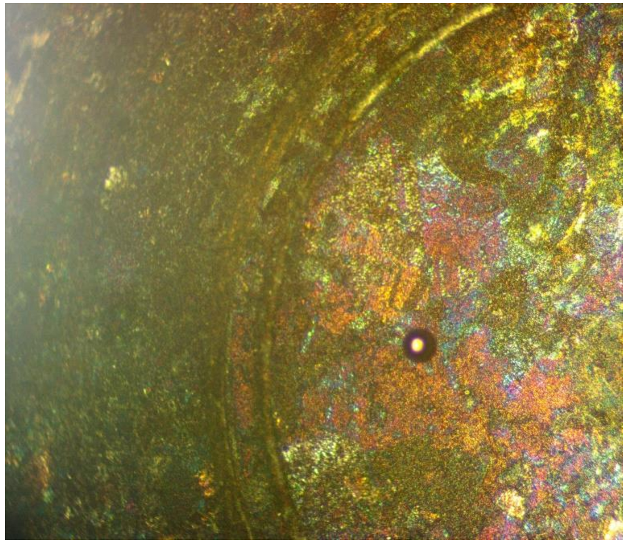
- Torsion pendulum
- Atom interferometer
- Optomechanics: LIGO
- Clocks for GR effects

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

Levitated small mass experiments: Meissner trapping of ferromagnets

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



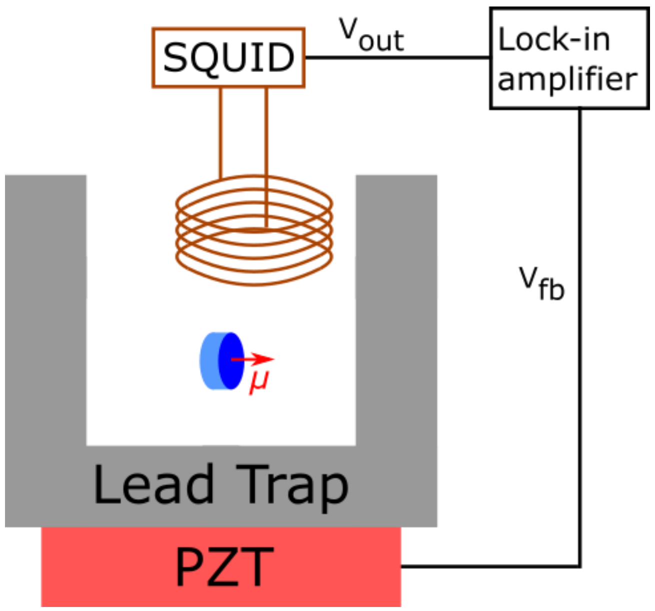


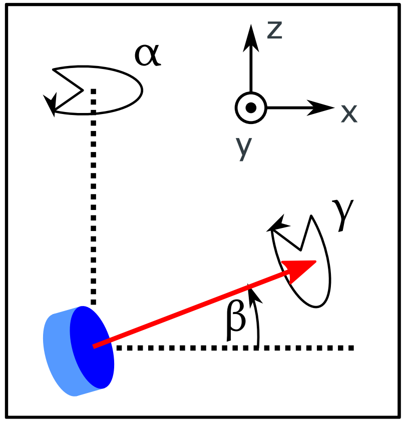
NdFeB microsphere radius = 27 um
Trap Radius = 2 mm

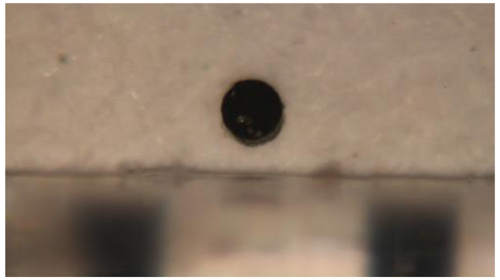
Vinante, A., P. Falferi, G. Gasbarri, A. Setter, C. Timberlake, and H. Ulbricht, Ultrahigh mechanical quality factor with Meissner-levitated ferromagnetic microparticles,Phys. Rev. Appl. 13, 064027 (2020)

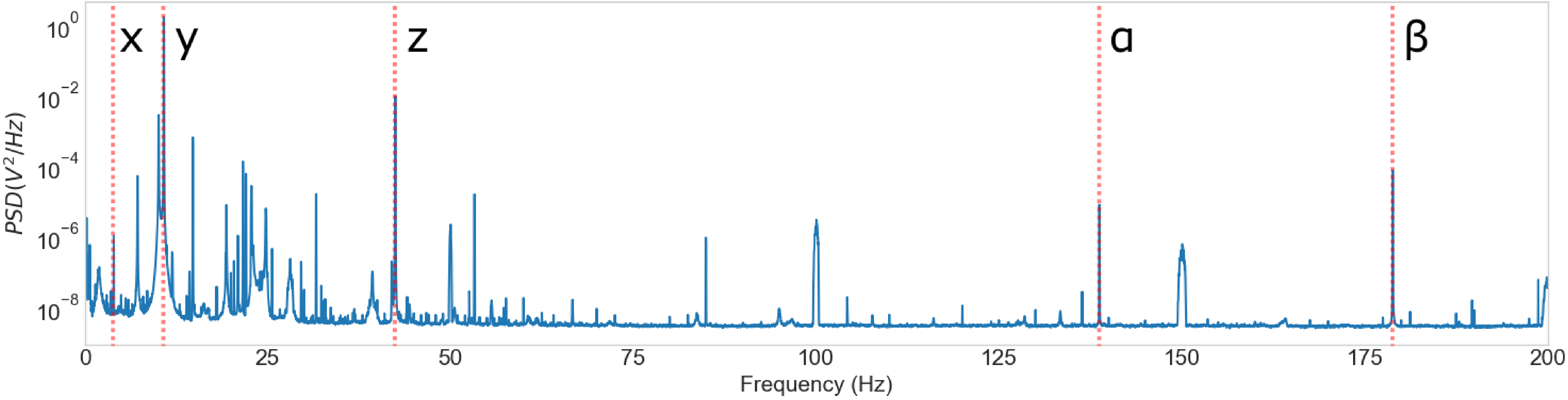
Feedback Cooling: PZT kicks

- 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





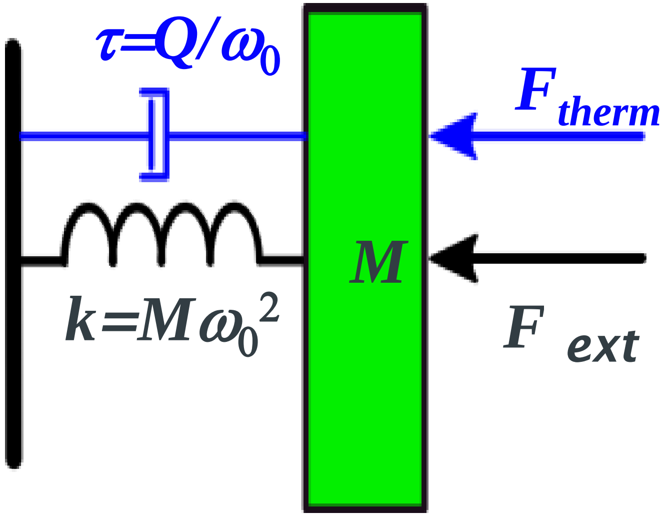




Force (noise) in harmonic oscillator:

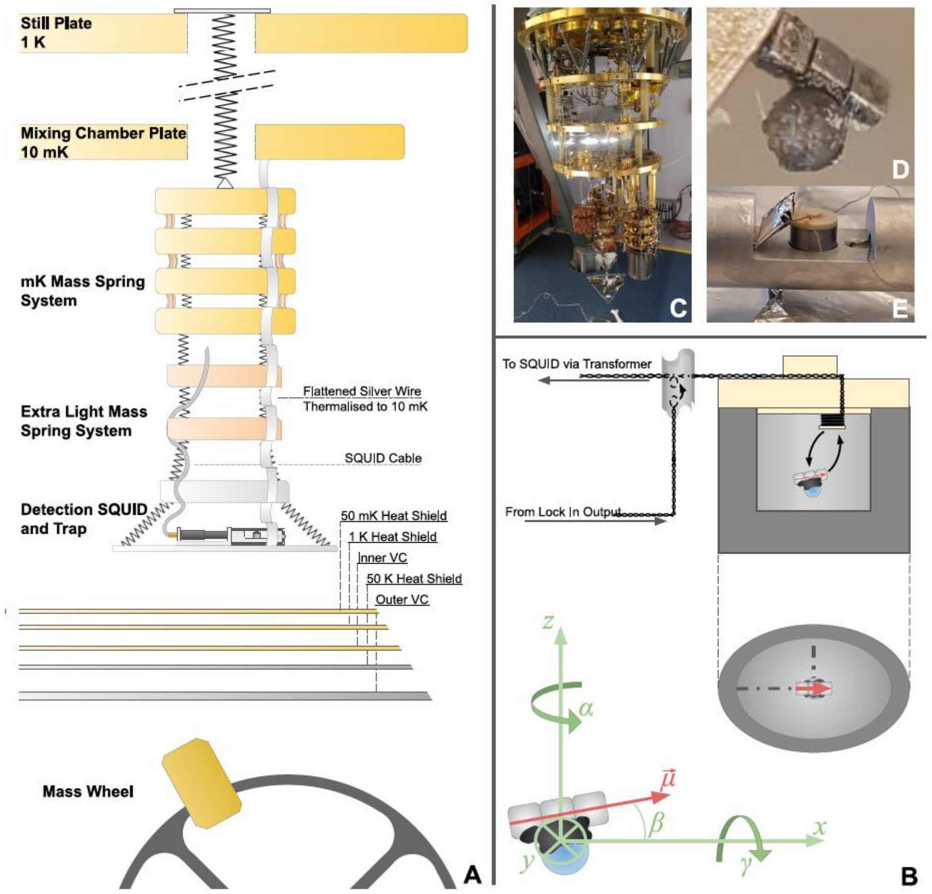
Thermal bath affect minimum force measured:

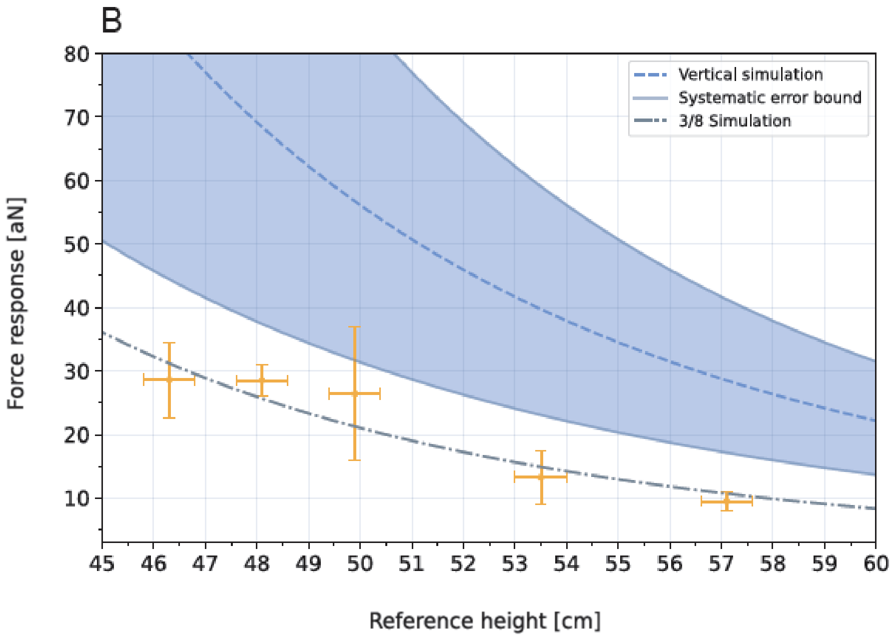
$$F_{min} = \sqrt{\frac{4k_BT_0m\omega_0}{Q\tau}},$$



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.

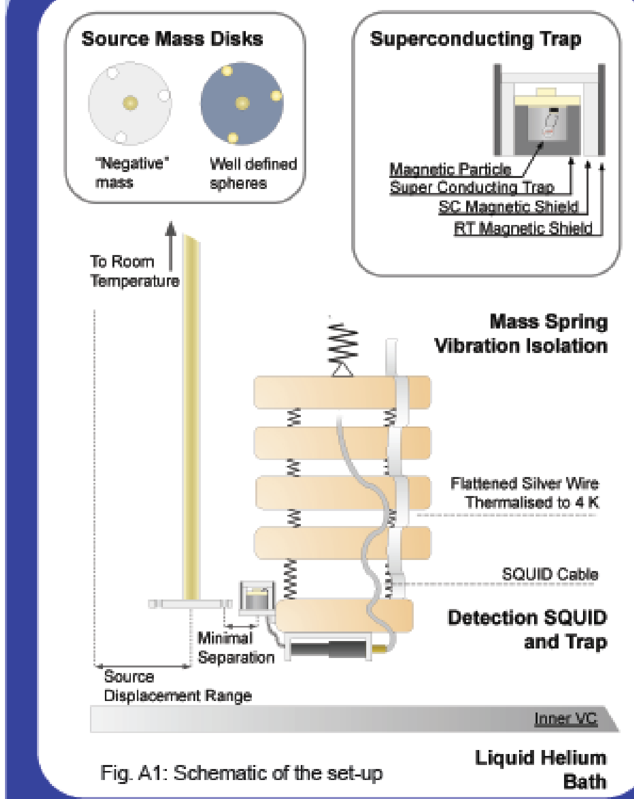


Fig. A1: Schematic of the set-up

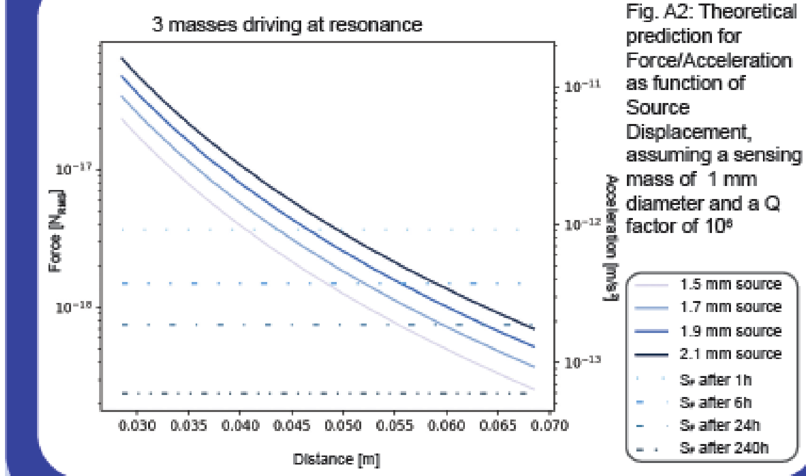
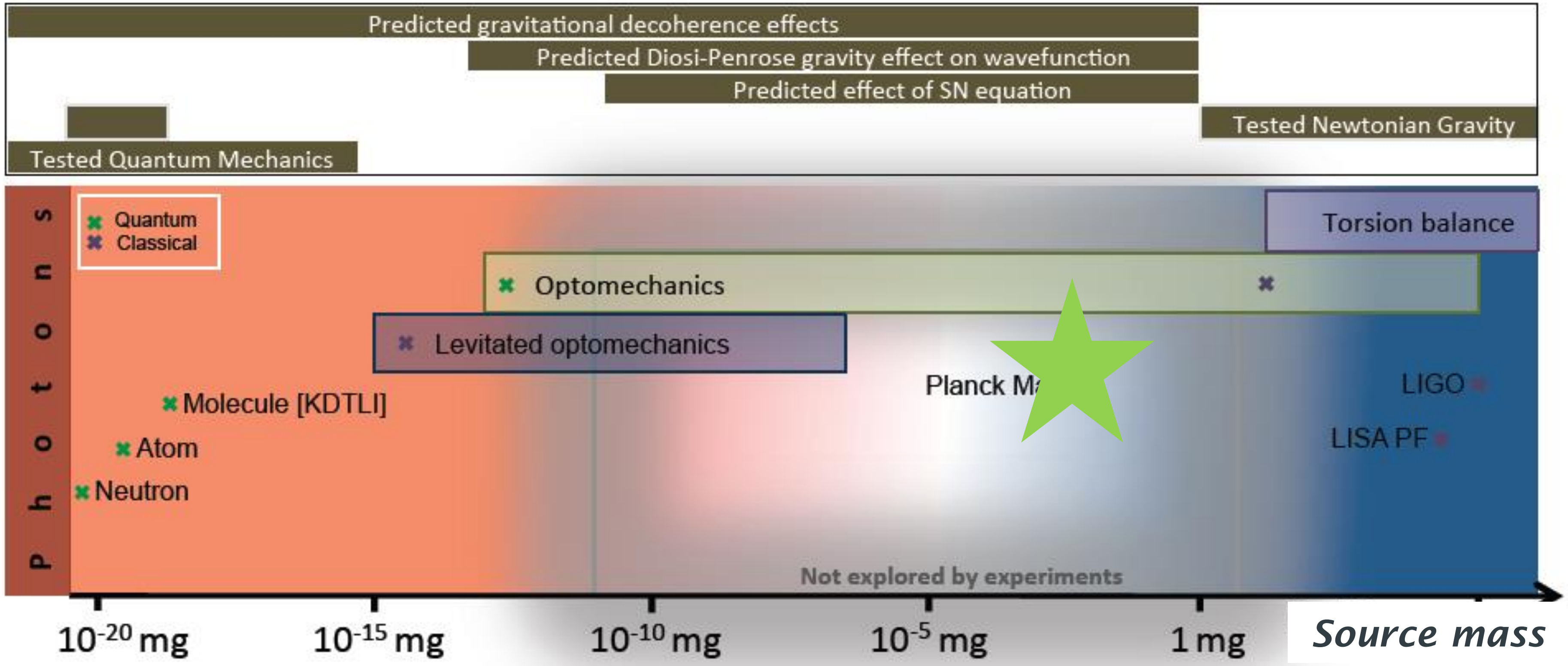


Fig. A2: Theoretical prediction for Force/Acceleration as function of Source Displacement, assuming a sensing mass of 1 mm diameter and a Q factor of 10^6

Small mass gravity: where are we?

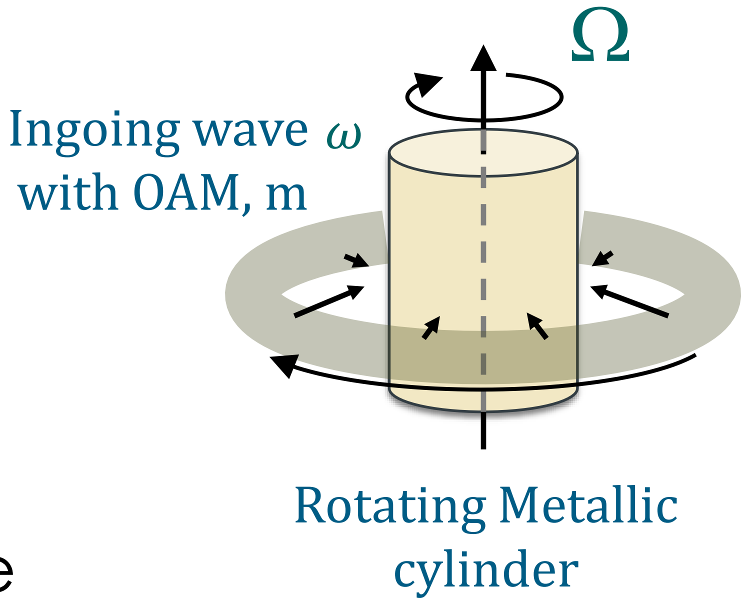
Current experimental target with probing by levitated particle (10 microgram)



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

ZEL’DOVICH EFFECT

Rotating absorbers can amplify waves that have angular momentum



Waves of frequency $\boldsymbol{\omega}$ and angular momentum order *m* should become amplified after interacting with an absorber co-rotating at Ω when:

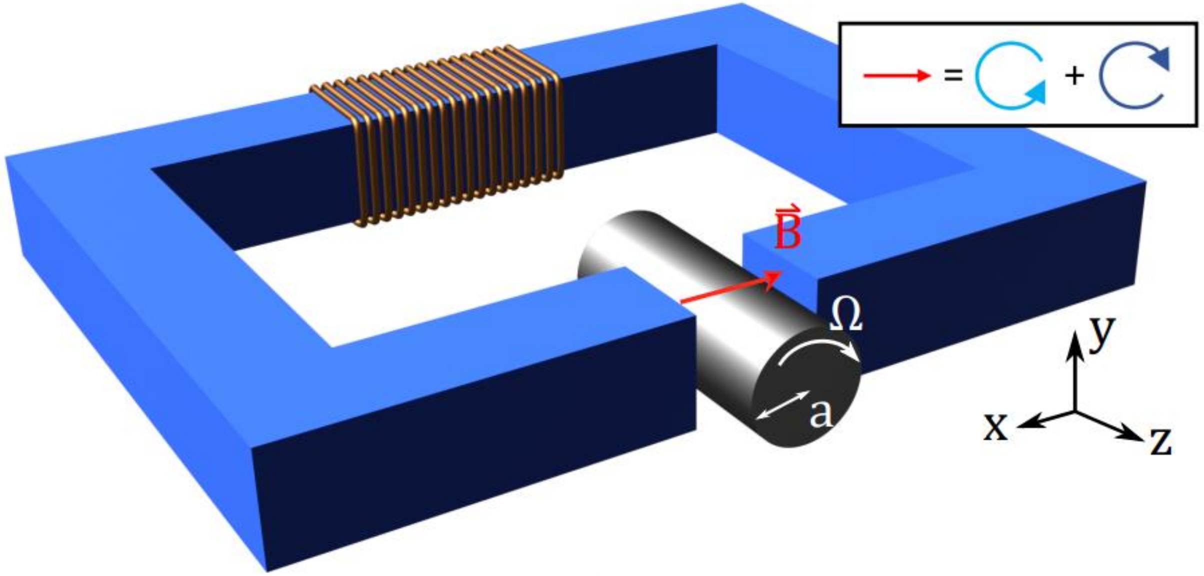
$$(\boldsymbol{\omega} - \boldsymbol{m\Omega}) < \boldsymbol{0}$$

Ya.B. Zel'dovich. *JETP Lett*. 14, 180 (1971) Ya.B. Zel'dovich. *JETP* 35.6, 1085 (1972)

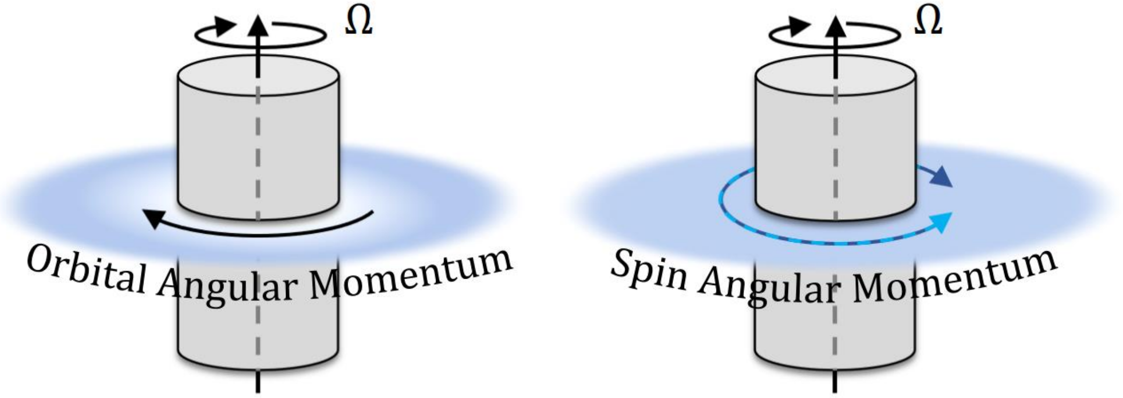
Zel’dovich Effect with EM

doi.org/10.1038/s41467-024-49689-w

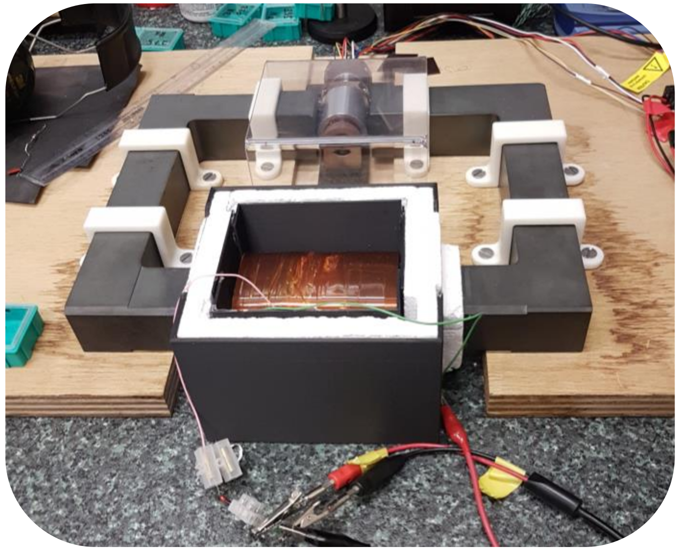
- Resonant LC circuits (frequency ω) forming magnetic fields interacting with a rotating metal cylinder (frequency Ω)



$$\mathbf{B_0} = I\beta(1,0,0)^T e^{i\omega t}$$
$$= \frac{1}{2} I\beta\left[(1,i,0)^T + (1,-i,0)^T\right] e^{i\omega t}$$



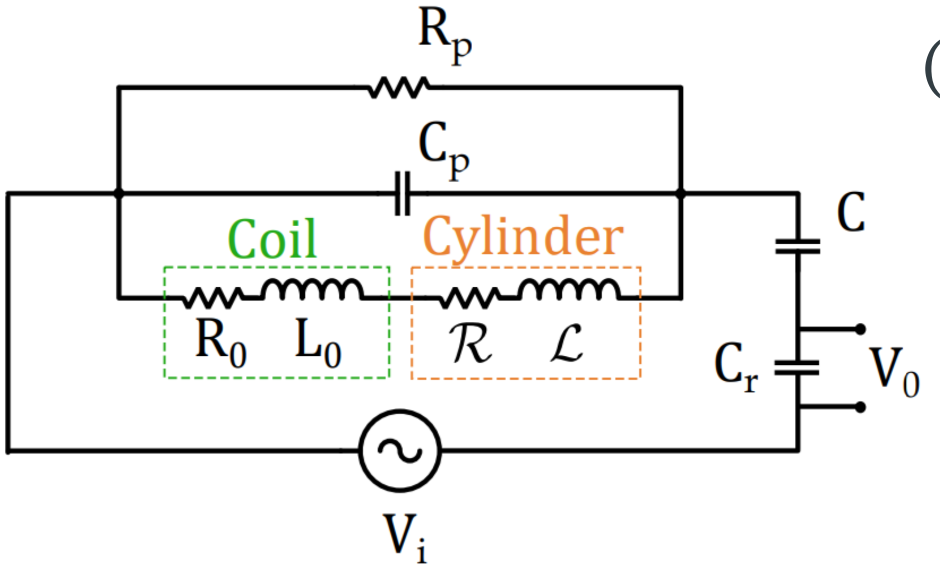
$$(\omega - \ell\Omega) < 0 \Rightarrow (\omega - s\Omega) < 0$$



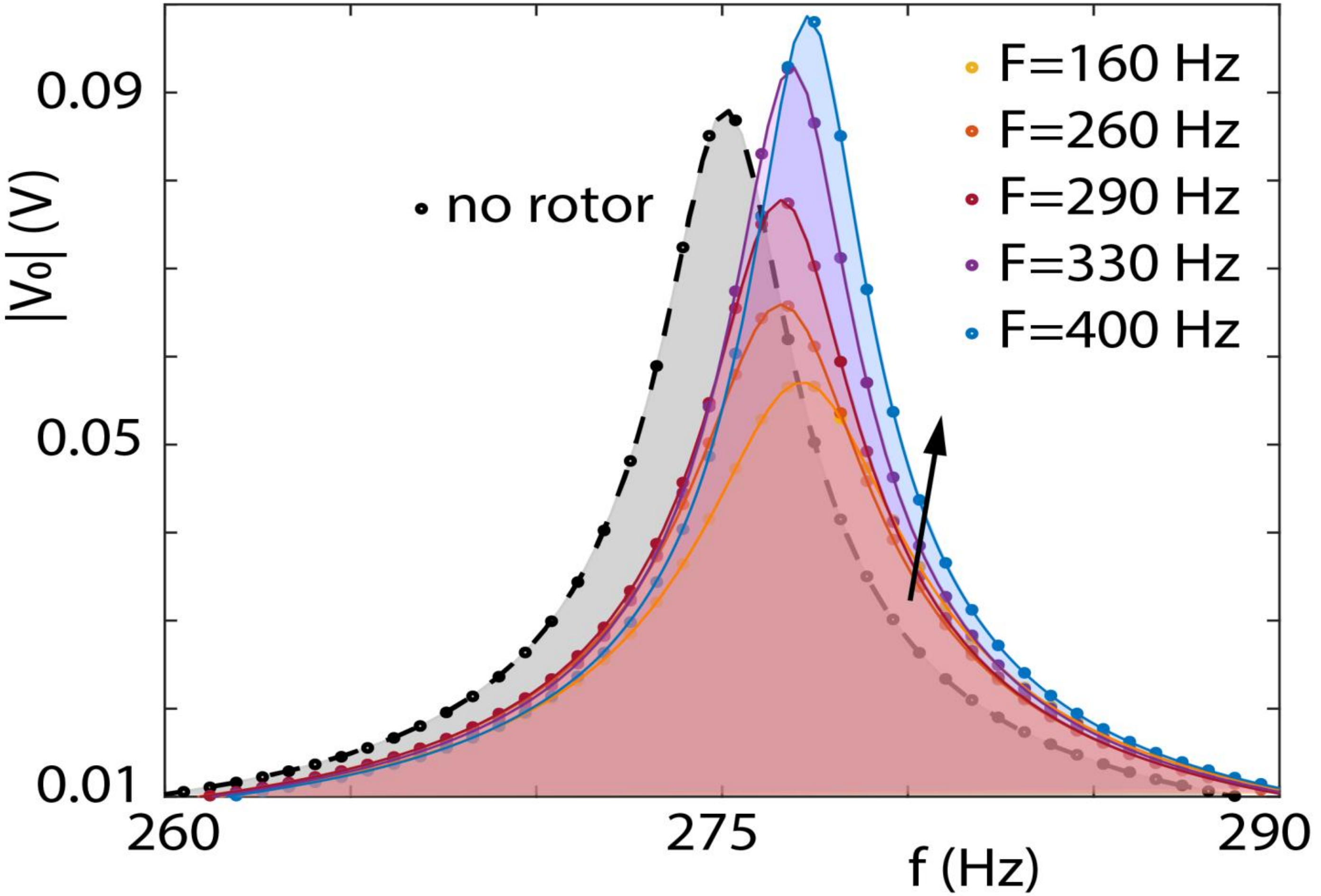
doi.org/10.1038/s41467-024-49689-w

rdcu.be/dL5K7

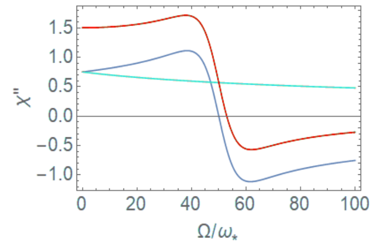
$$\mathcal{R} = Re[V/I] = \omega\beta^2\left[\chi''(\omega-\Omega)+\chi''(\omega+\Omega)\right]$$



(β is a coupling factor that depends on the system geometry)



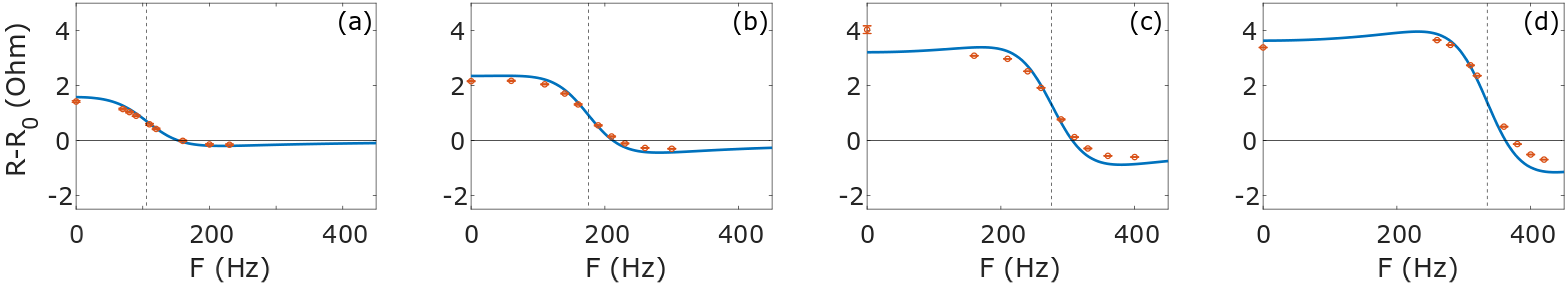
Amplification threshold rotation frequency F_{th} slightly higher than resonant circuit frequency f_0, due to presence of lossy counter-rotating component



doi.org/10.1038/s41467-024-49689-w

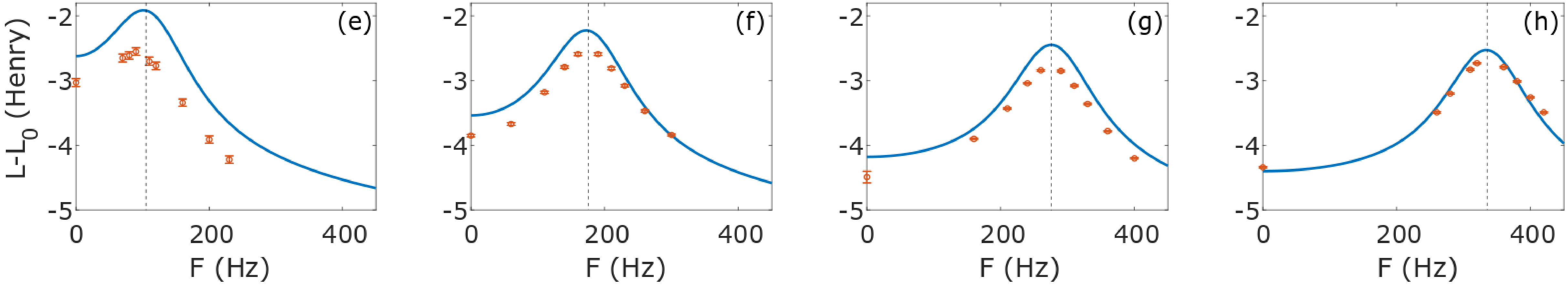
rdcu.be/dL5K7

$$\mathcal{R} = Re[V/I] = \omega\beta^2\left[\chi''(\omega-\Omega)+\chi''(\omega+\Omega)\right]$$



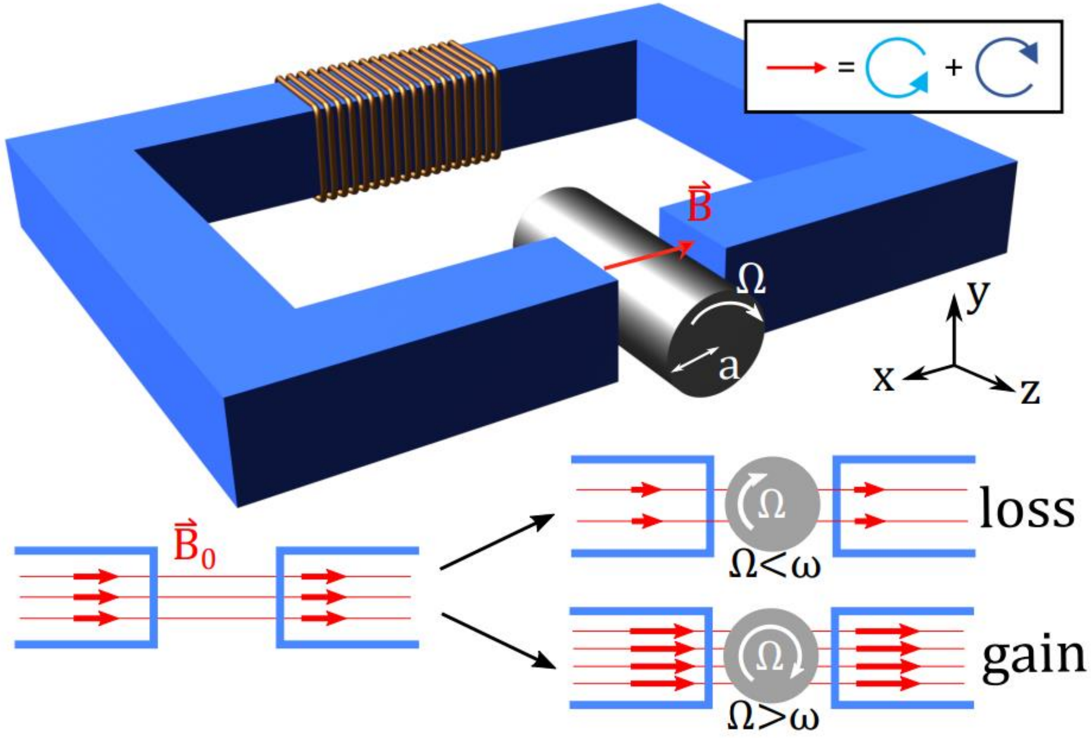
Changing capacitors gives different resonant frequencies of the circuit (dotted vertical line). Bigger effects at higher frequencies

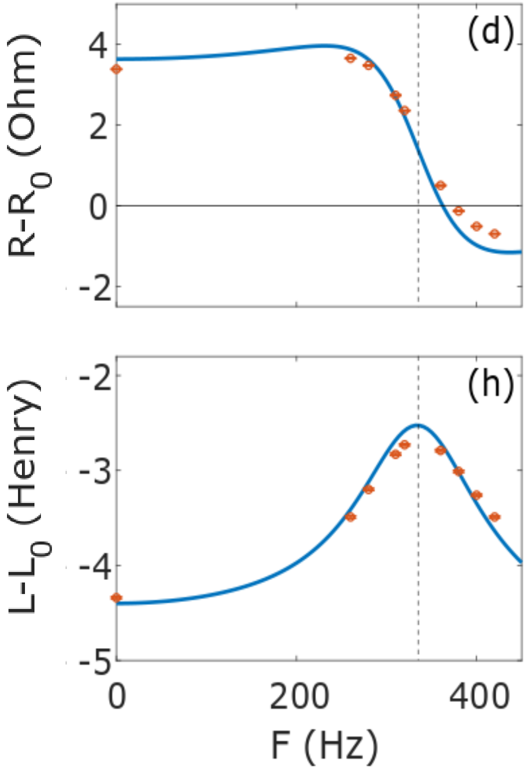
$$\mathcal{L} = Re[\Phi/I] = \beta^2\left[\chi'(\omega-\Omega)+\chi'(\omega+\Omega)\right]$$



doi.org/10.1038/s41467-024-49689-w

rdcu.be/dL5K7





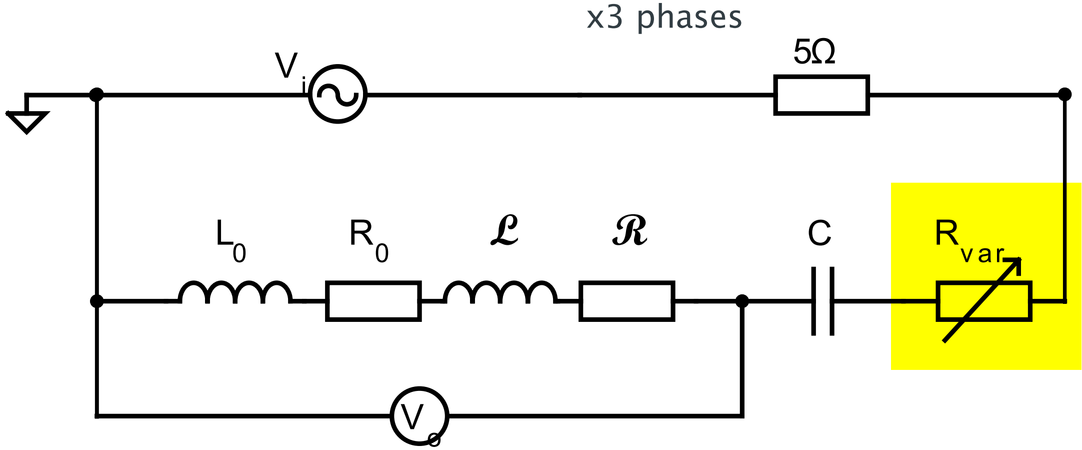
$R_0 = 2.03\ \text{k}\Omega$

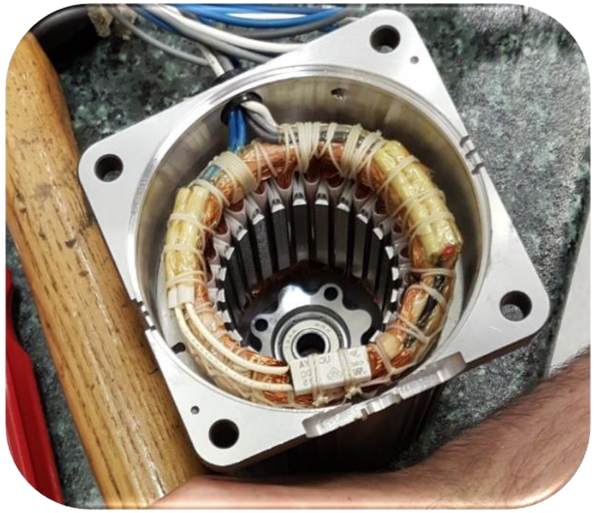
$L_0 = 263\ \text{H}$

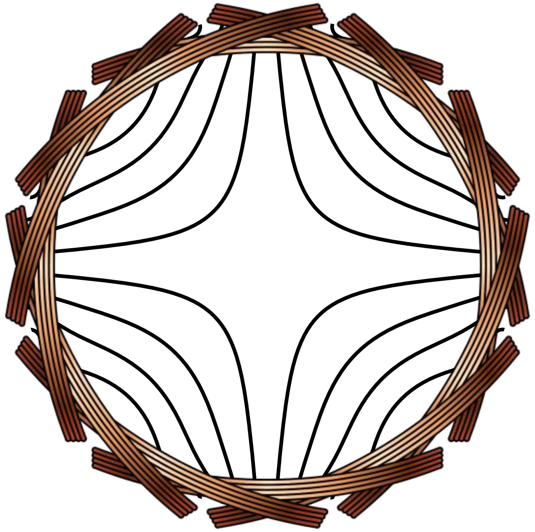
- New-found links to induction generators

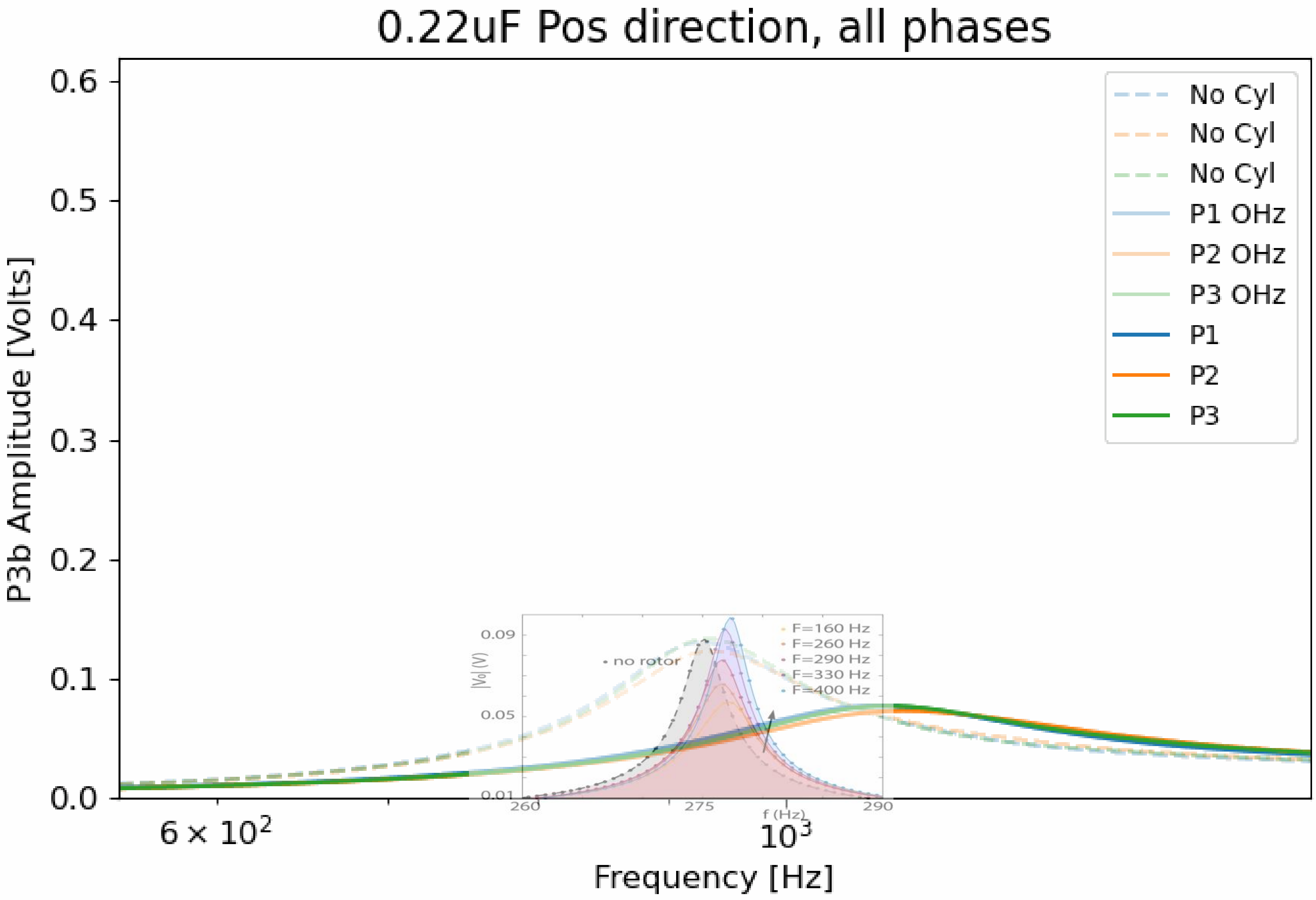
Zel’dovich Effect with EM: 3-phase configuration

- Resonant LC circuits from induction motor coils forming a **rotating magnetic field** interacting with a rotating metal cylinder
  - Previous: coupling low, extra counter-rotating component, overall circuit resistance (2kOhm) much bigger than change due to effect.(2-6Ohm)
- This: high coupling, rotating (quadrupole) magnetic field, lower overall circuit resistance (~80 Ohm) on same order as change

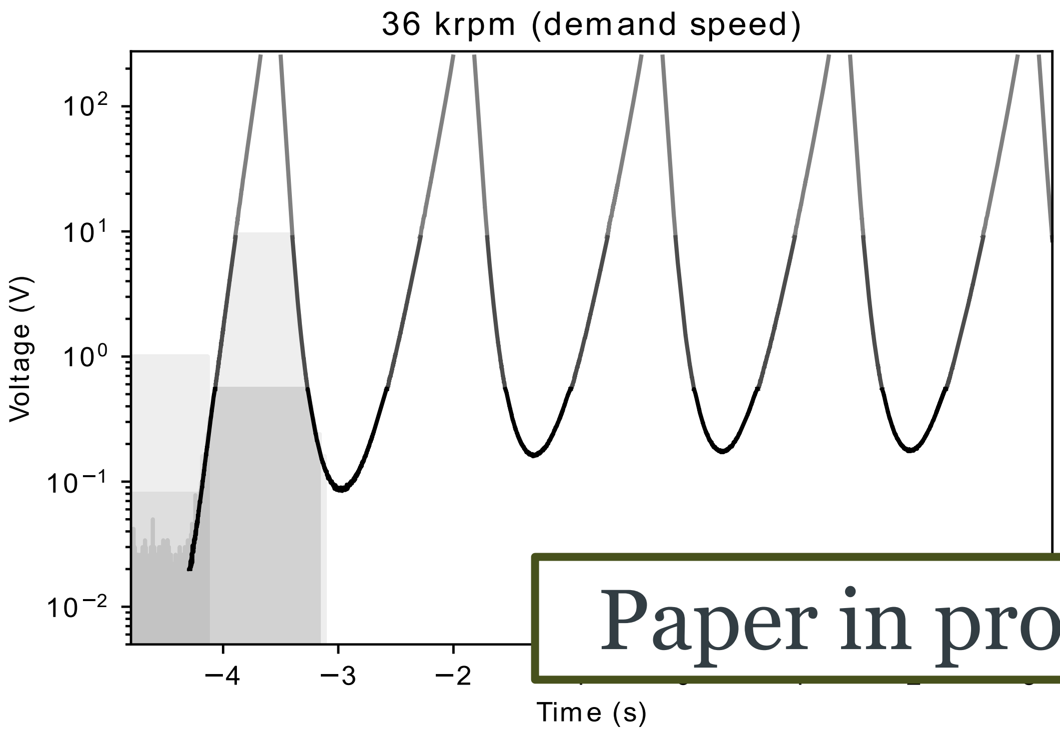




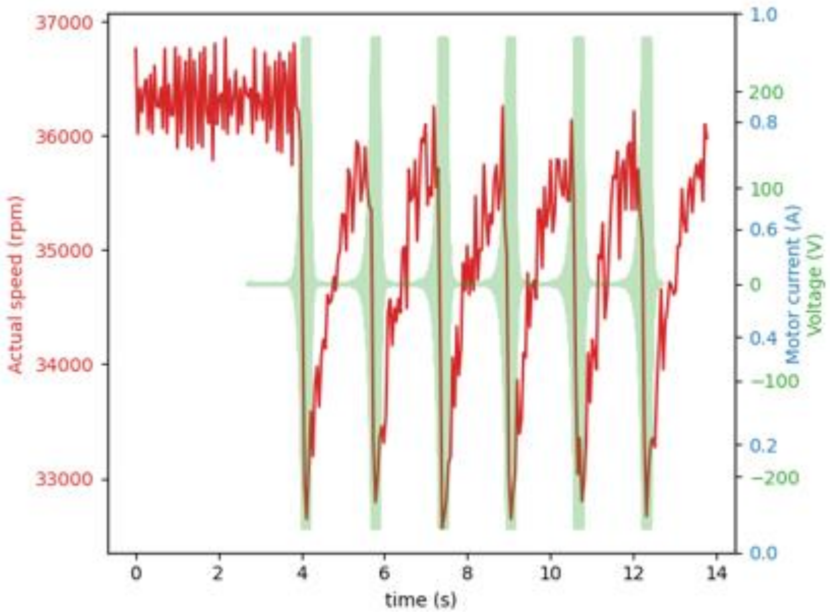


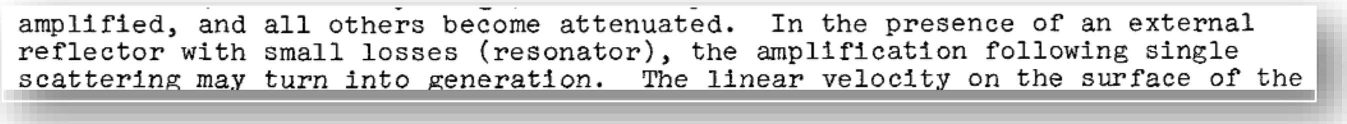

0.22uF Pos direction, all phases
P3b Amplitude [Volts]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
6×10^2
10^3
Frequency [Hz]
No Cyl
No Cyl
No Cyl
P1 OHz
P2 OHz
P3 OHz
P1
P2
P3
|V₀| (V)
0.09
0.05
0.01
260
275
290
f (Hz)
no rotor
F=160 Hz
F=260 Hz
F=290 Hz
F=330 Hz
F=400 Hz

Generation regime – seeded by thermal/electronic noise



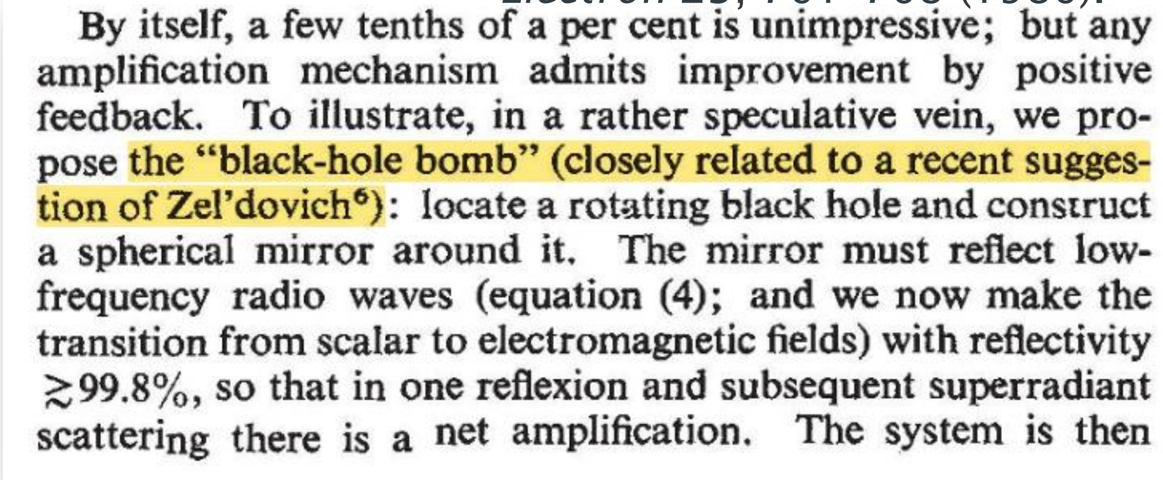
Paper in progress……




amplified, and all others become attenuated. In the presence of an external reflector with small losses (resonator), the amplification following single scattering may turn into generation. The linear velocity on the surface of the

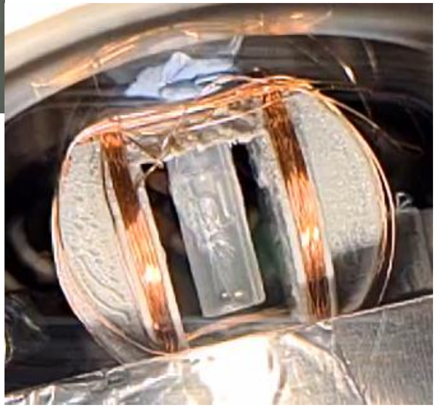
Ya.B. Zel'dovich. *JETP Lett.* 14, 180 (1971)

Zel'dovich, Ya. B., Rozhanskii, L. V. & Starobinskii, A. A. *Radiophys Quantum Electron* **29**, 761–768 (1986).


By itself, a few tenths of a per cent is unimpressive; but any amplification mechanism admits improvement by positive feedback. To illustrate, in a rather speculative vein, we propose the "black-hole bomb" (closely related to a recent suggestion of Zel'dovich[6]): locate a rotating black hole and construct a spherical mirror around it. The mirror must reflect low-frequency radio waves (equation (4); and we now make the transition from scalar to electromagnetic fields) with reflectivity $\gtrsim$99.8%, so that in one reflexion and subsequent superradiant scattering there is a net amplification. The system is then

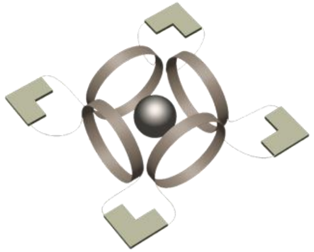
Press and Teukolsky, 'Floating Orbits, Superradiant Scattering and the Black-Hole Bomb'. Nature 238 (1972)

Project: Zel’dovich Effect with EM



Future: possible routes to the quantum realm

- Levitated microsphere spinning at MHz or more (?)
- Interacts with surrounding superconducting circuit
- GHz rotation could move test to the quantum spontaneous generation regime



M. C. Braidotti, A. Vinante, G. Gasbarri, D. Faccio, & H. Ulbricht, *Phys. Rev. Lett.* **125**, 140801 (2020).
10.1103/PhysRevLett.125.140801

Summary of talk

- Pushing on gravity and quantum experiments.
- Testing macroscopic quantum.
- Testing small-mass gravity.
- Then both: gravity in superpositions. [did not manage in time]

IDEAS FOR GRAVITY IN QUANTUM SUPERPOSITIONS

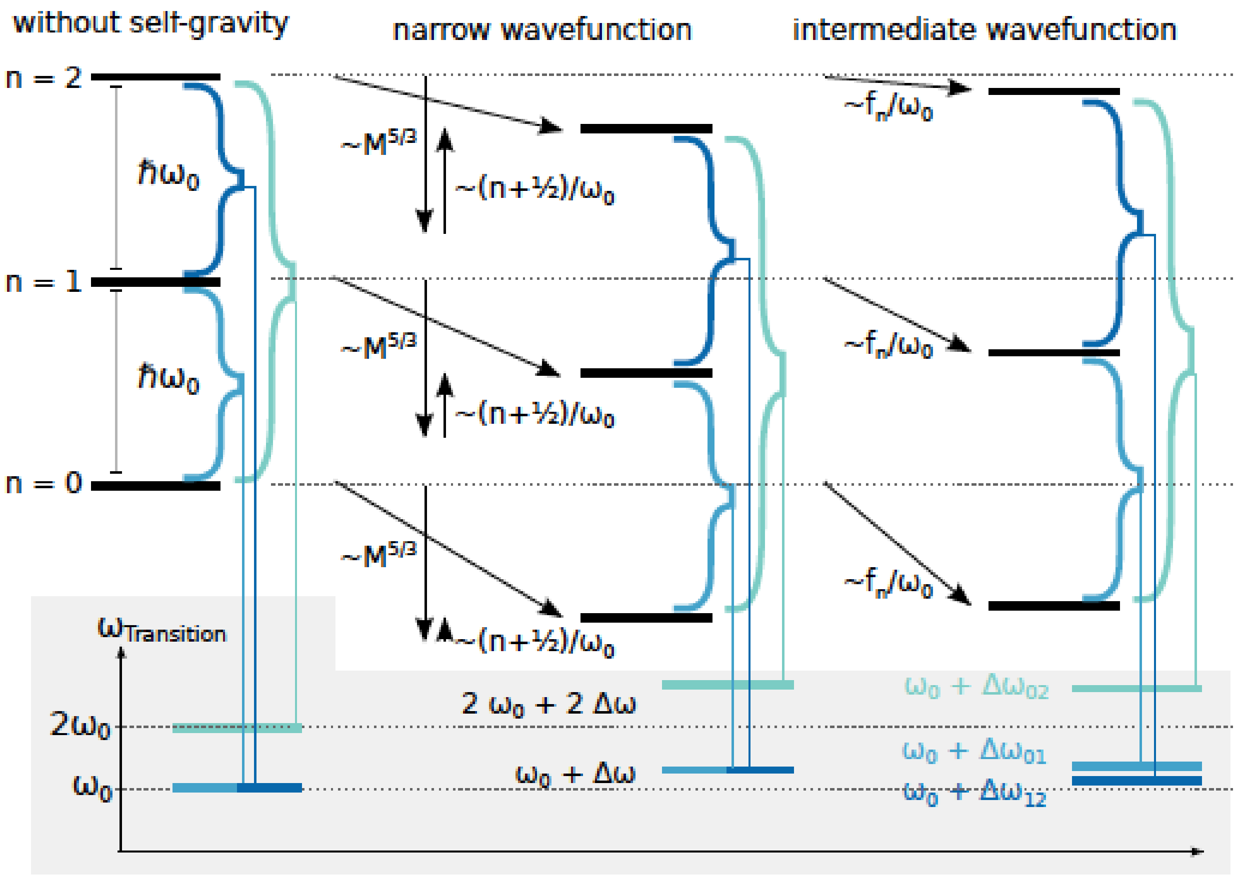
Schroedinger-Newton (SN): semi-classical gravity

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

$$\boxed{\begin{aligned} \mathrm{i}\hbar \frac{\partial}{\partial t} \psi(t, \mathbf{r}) &= \left(\frac{\hbar^2}{2\,M} \nabla^2 + V_{\mathrm{ext}} + V_g[\psi] \right) \psi(t, \mathbf{r}) \\ V_g[\psi](t, \mathbf{r}) &= -G \int \mathrm{d}^3 r' \, |\psi(t, \mathbf{r}')|^2 \, I_{\rho_c}(\mathbf{r} - \mathbf{r}') \, . \end{aligned}}$$

Obvious option for test: study free wavefunction expansion

Predicted shifts of energy levels according to SN



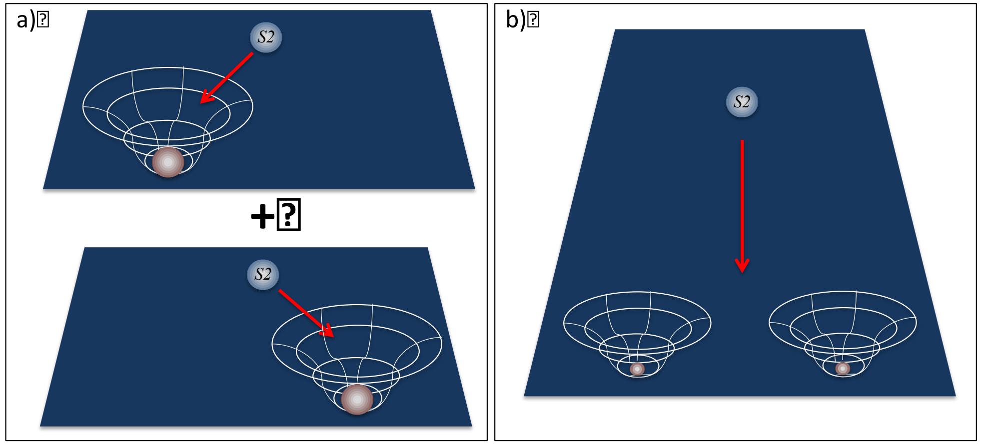
- SN shift of energy levels of mechanical harmonic oscillator
- Feasible for a test with existing tech

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?

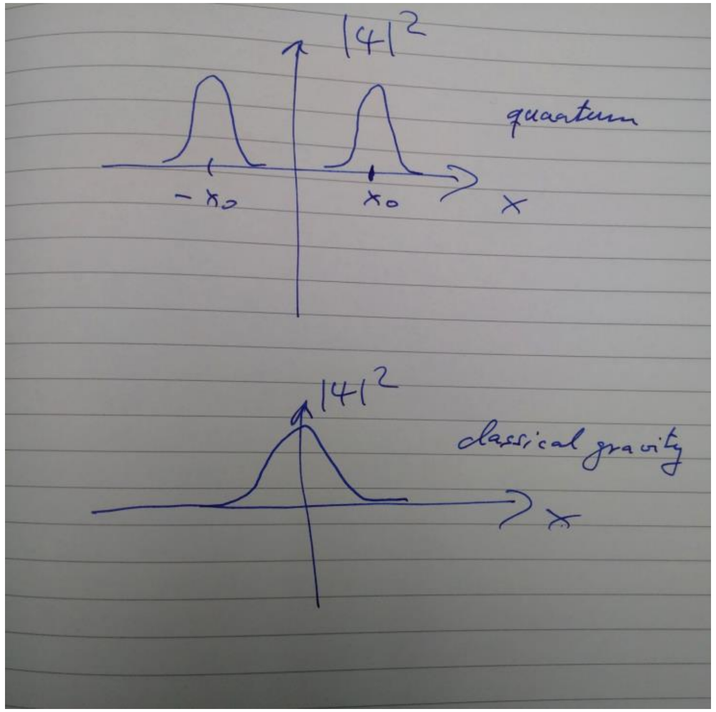
Concept of experiment:



quantum

(semi)-classical

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



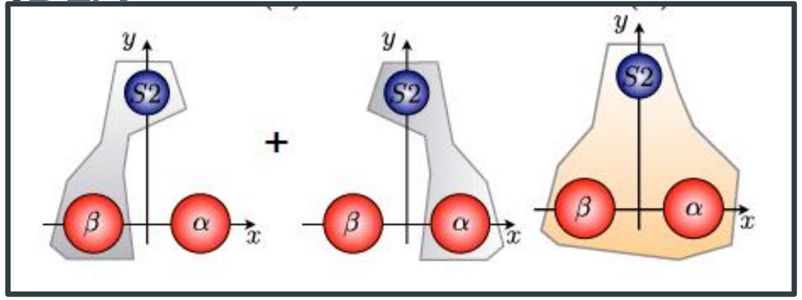
Quantum and (semi)-classical gravity have distinctively different outcome of the experiment.

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.

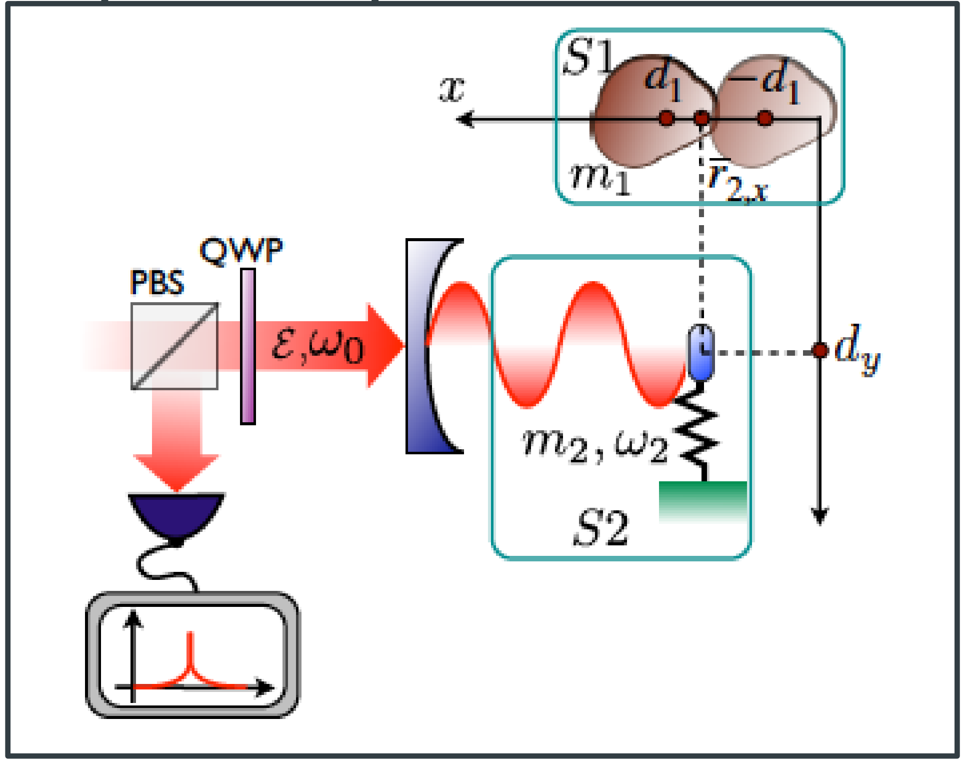
Challenge: *find two (sufficiently large) masses at sufficiently close proximity, where the source mass is in quantum state (super-position) and the test mass is sufficiently sensitive to probe the gravity field generated by source.*
Answer: *Optomechanics.*

IDEA



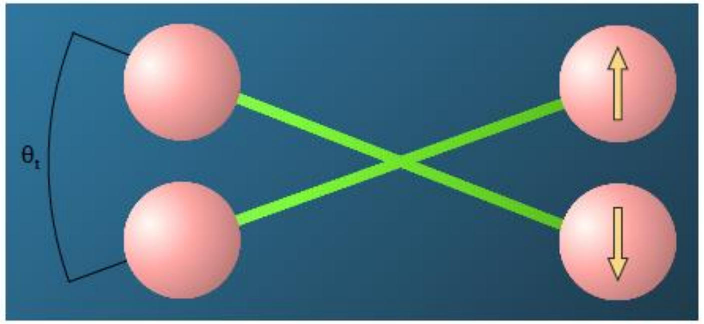
- **Testing by direct measurement of density noise spectrum**
- **or by indirect measurement of (quantum) correlations in optical field.**
- **Biggest challenge: Van der Waals+Casimir-Polder**

Proposed setup



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

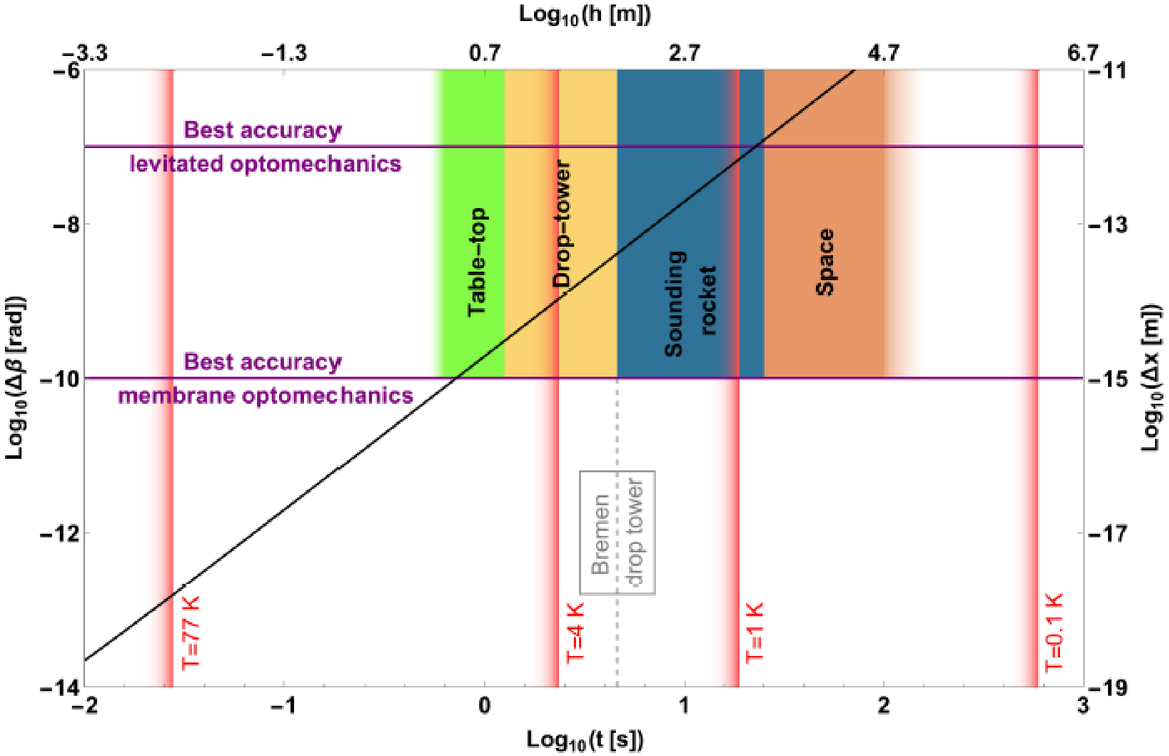
Angular superposition: Does **gravity** destroy the superposition?



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

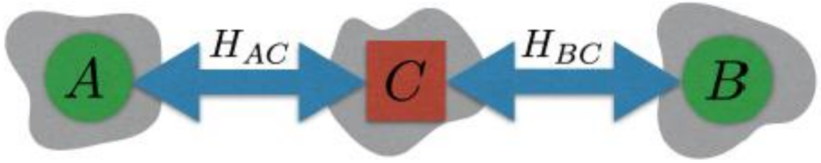


For practical purposes:
libration/rotation degree of freedom is favorable.

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

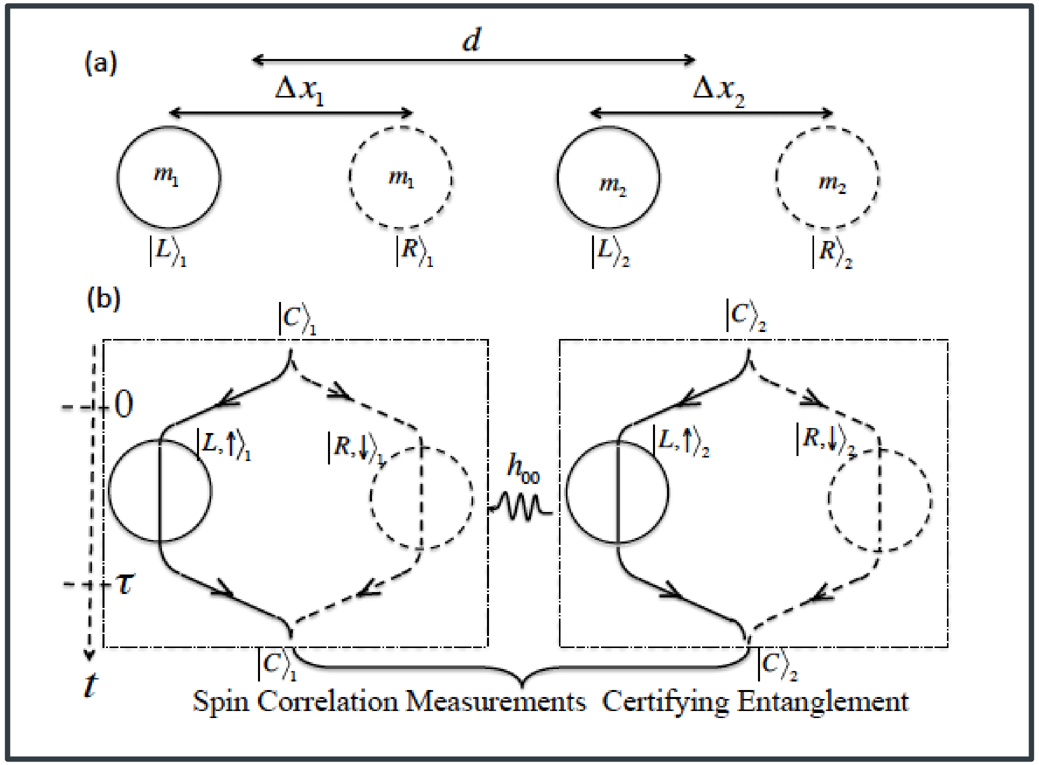
Gravity as entangler: What does it tell about gravity?

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).

MEASURING B-FIELDS

How do we measure magnetic fields?

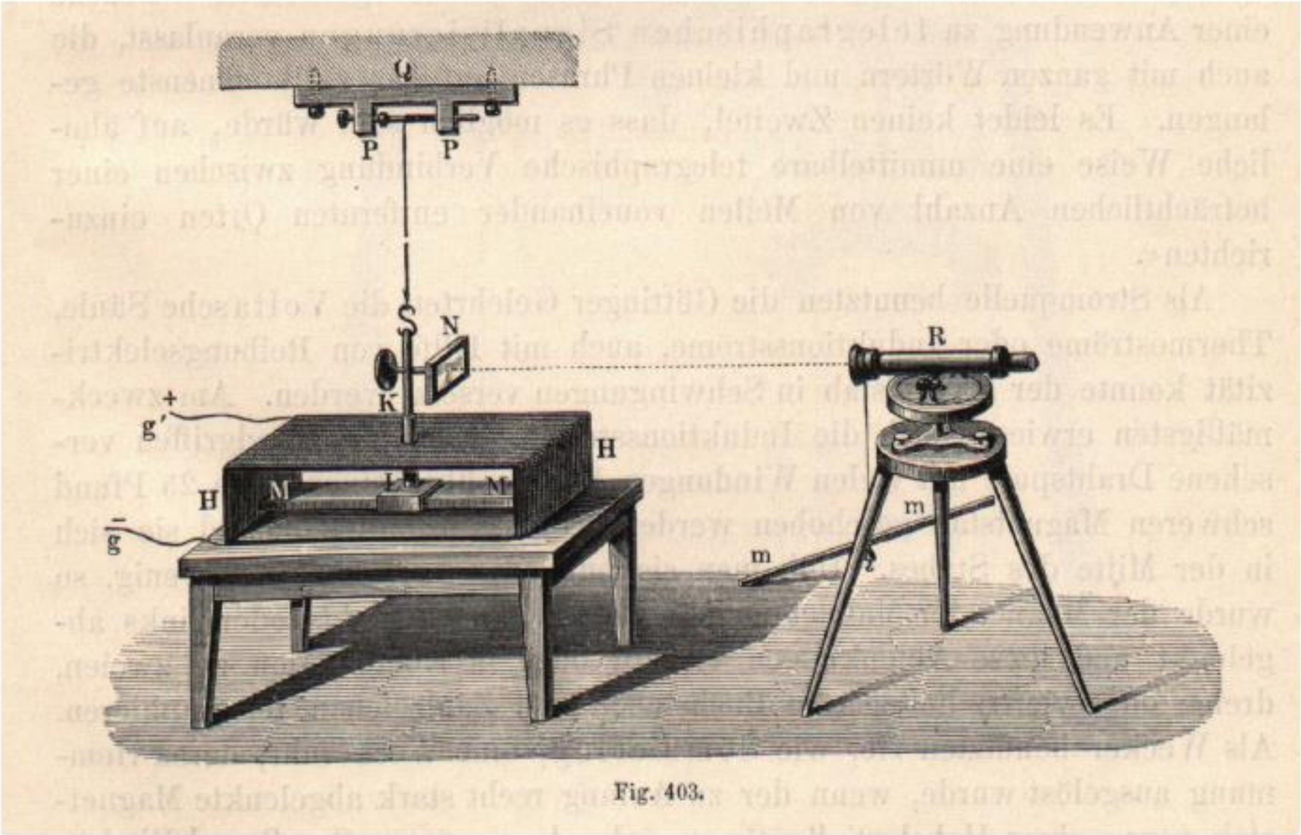
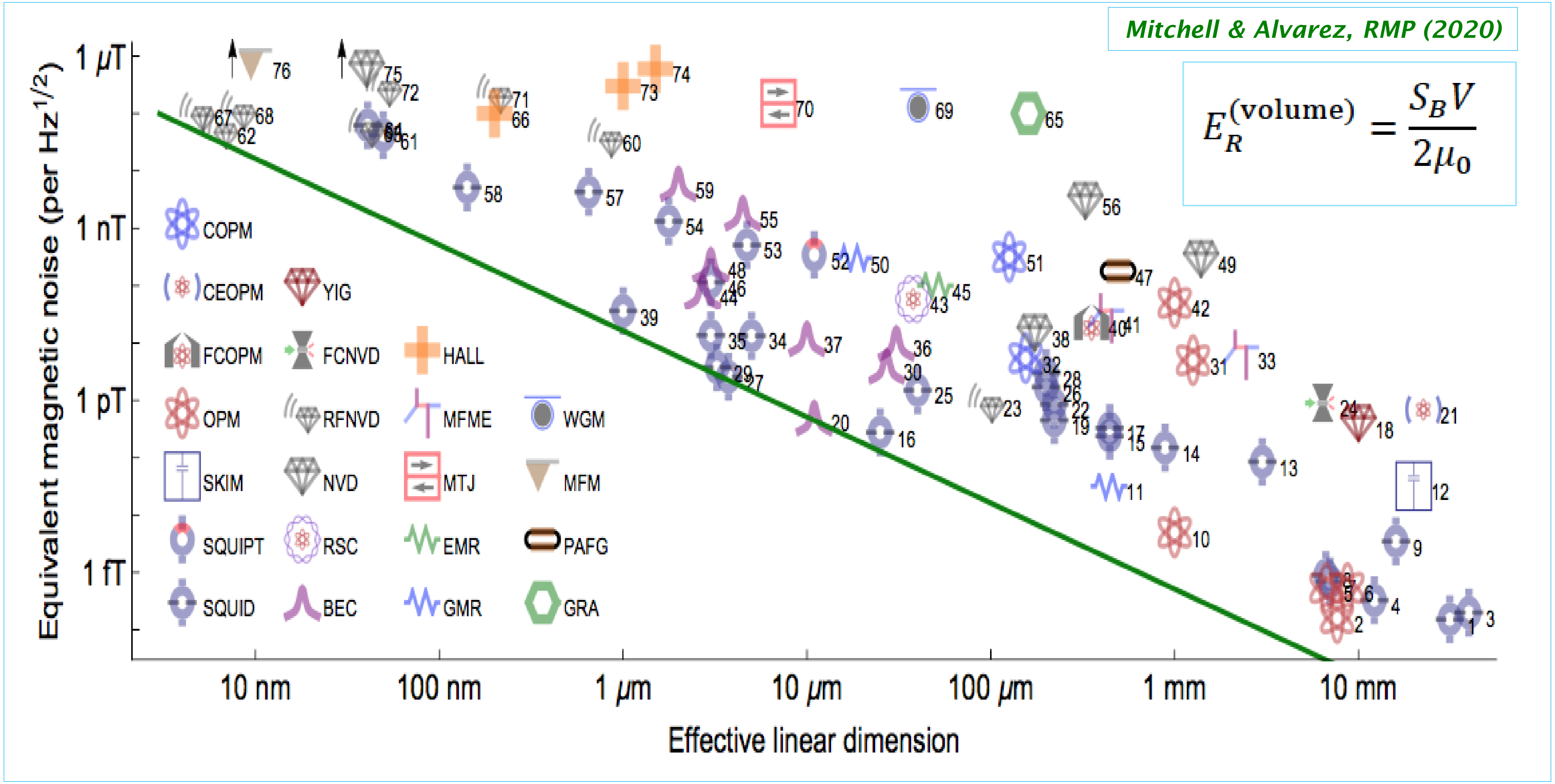


Fig. 403.

C.F. Gauss, *Intensitas vis magnetica et terrestris ad mensuram absolutam revocata*, Göttingen,1833

Empirical result: energy resolution limit (ERL) in B-field sensing applies universally.

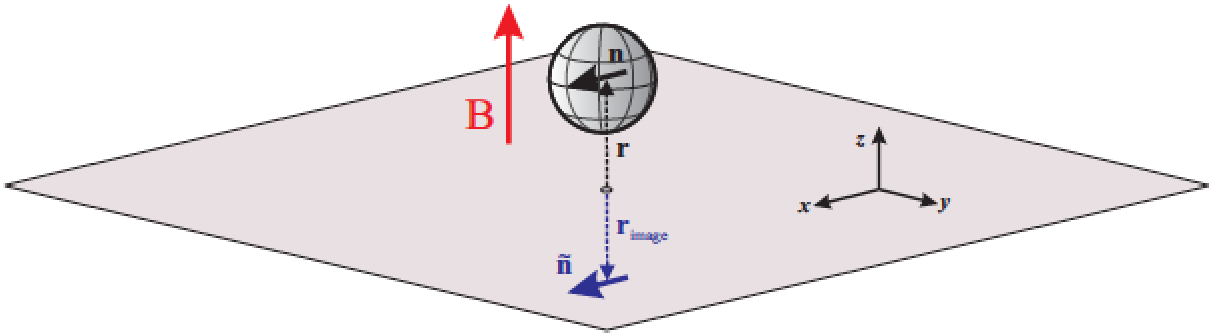


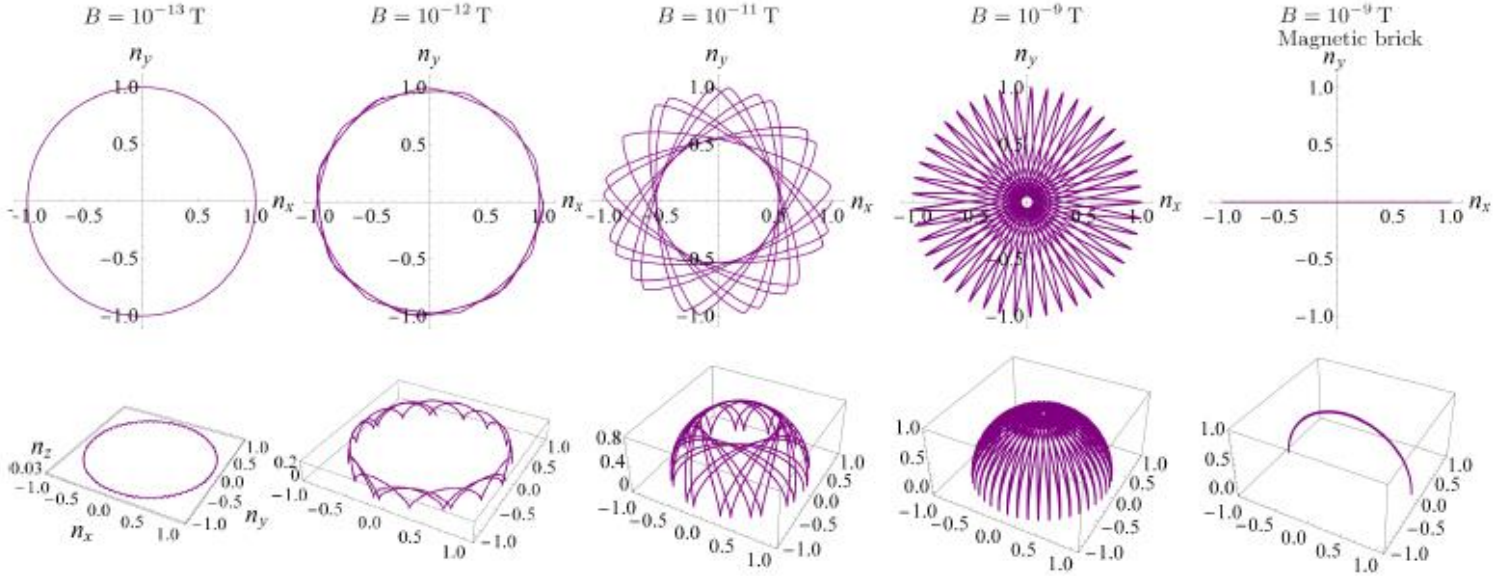
Mitchell & Alvarez, RMP (2020)

$$E_R^{(\text{volume})} = \frac{S_B V}{2\mu_0}$$

C.D. Tesche, and J. Clarke,
J. Low Temp. Phys. **29**, 301 (1977)

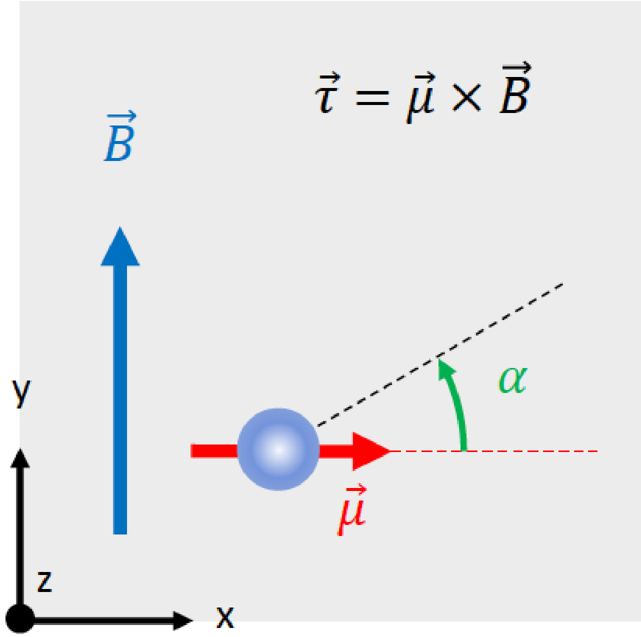
A realization of B-field sensor by ferromagnetic gyroscope: Precession and nutation motion to probe tiny force, Einstein-de Haas effect

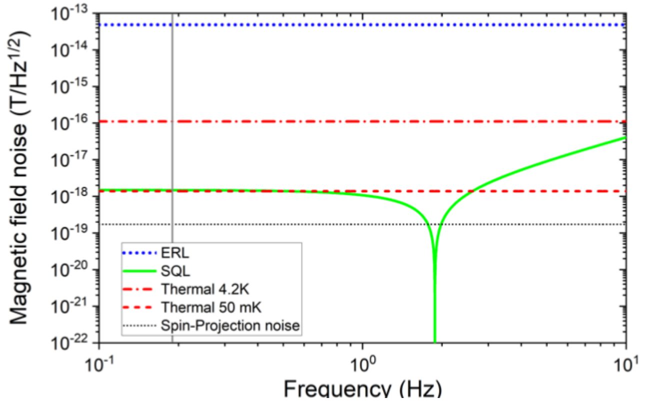




Fadeev, P., C. Timberlake, T. Wang, A. Vinante, Y. B. Band, D. Budker, A. O. Sushkov, H. Ulbricht, and D. F. J. Kimball Ferromagnetic Gyroscopes for Tests of Fundamental Physics, Quantum Sci. Technol ***6****, 024006 (2021).*

How to evaluate ERL with levitated micromagnets





Thermal torque noise:

$$S_{\tau,\mathrm{thermal}} = 4k_{\mathrm{B}}TI\frac{\omega_\alpha}{Q_\alpha}$$

Standard Quantum Limit torque noise:

$$S_{\tau,\mathrm{SQL}} = \frac{4mr^2}{5}\hbar\sqrt{(\omega_\alpha^2 - \omega^2)^2 + \left(\frac{\omega\omega_\alpha}{Q_\alpha}\right)^2}$$

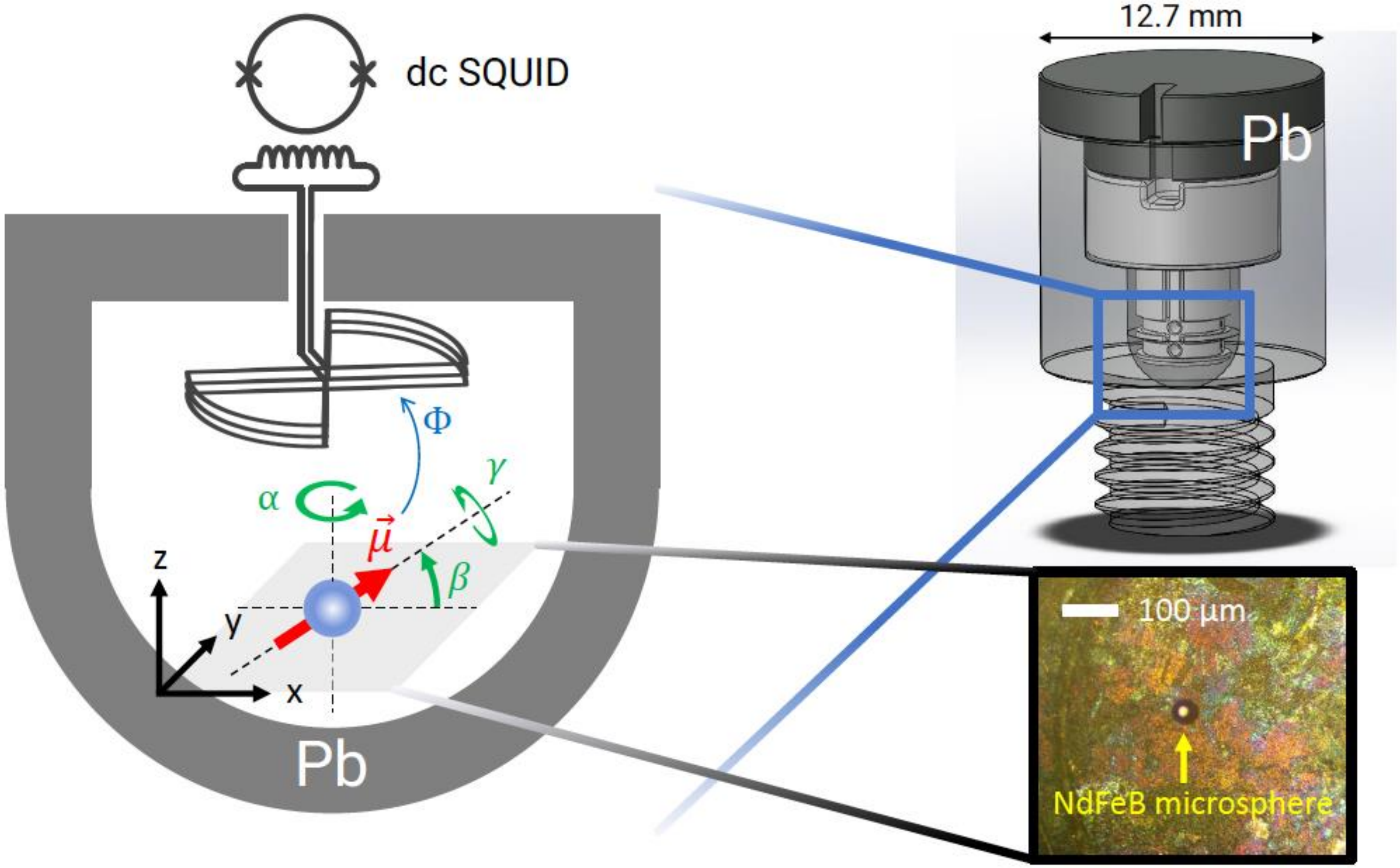
Typical set-up: $S_{\tau,\mathrm{thermal}} \gg S_{\tau,\mathrm{SQL}}$ @ 4.2 K

⇒ Magnetic noise: $S_{B,\mathrm{thermal}} = \frac{S_{\tau,\mathrm{thermal}}}{\mu^2} = \frac{12k_{\mathrm{B}}T\rho f_\alpha}{5M^2rQ_\alpha} \ll S_{B,\mathrm{ERL}}$

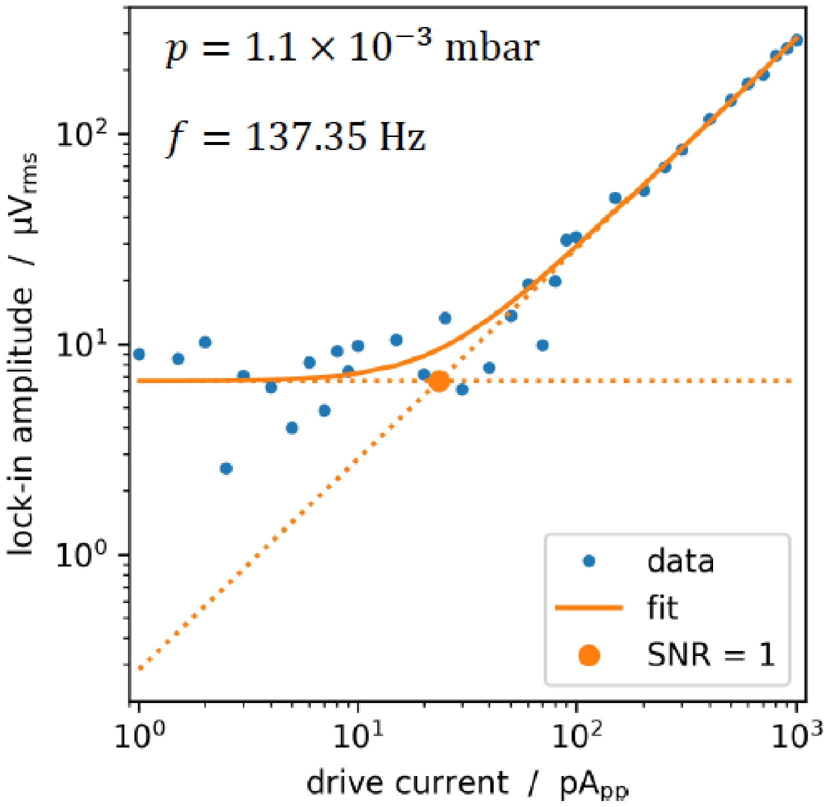
Vinante, A., C. Timberlake, D. Budker, D. J. Kimball, A. O. Sushkov, and H. Ulbricht, Surpassing the Energy Resolution Limit with ferromagnetic torque sensors, Phys. Rev. Lett. 127, 070801 (2021).

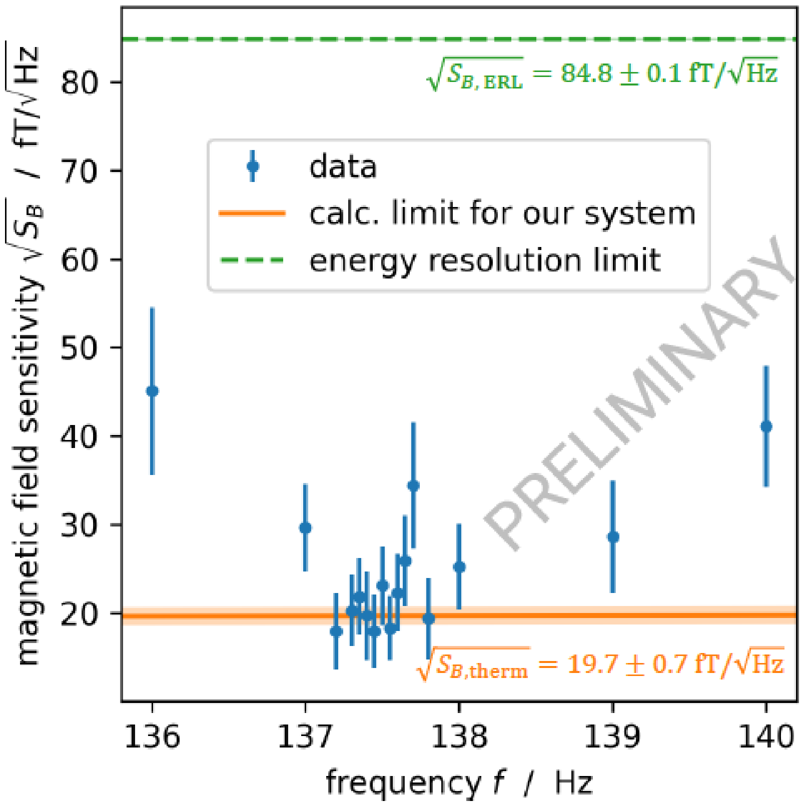
Experimental Set-up (in Trento)

Felix Ahrens & Andrea Vinante



Experimental results: magnetic field sensitivity @ 4K

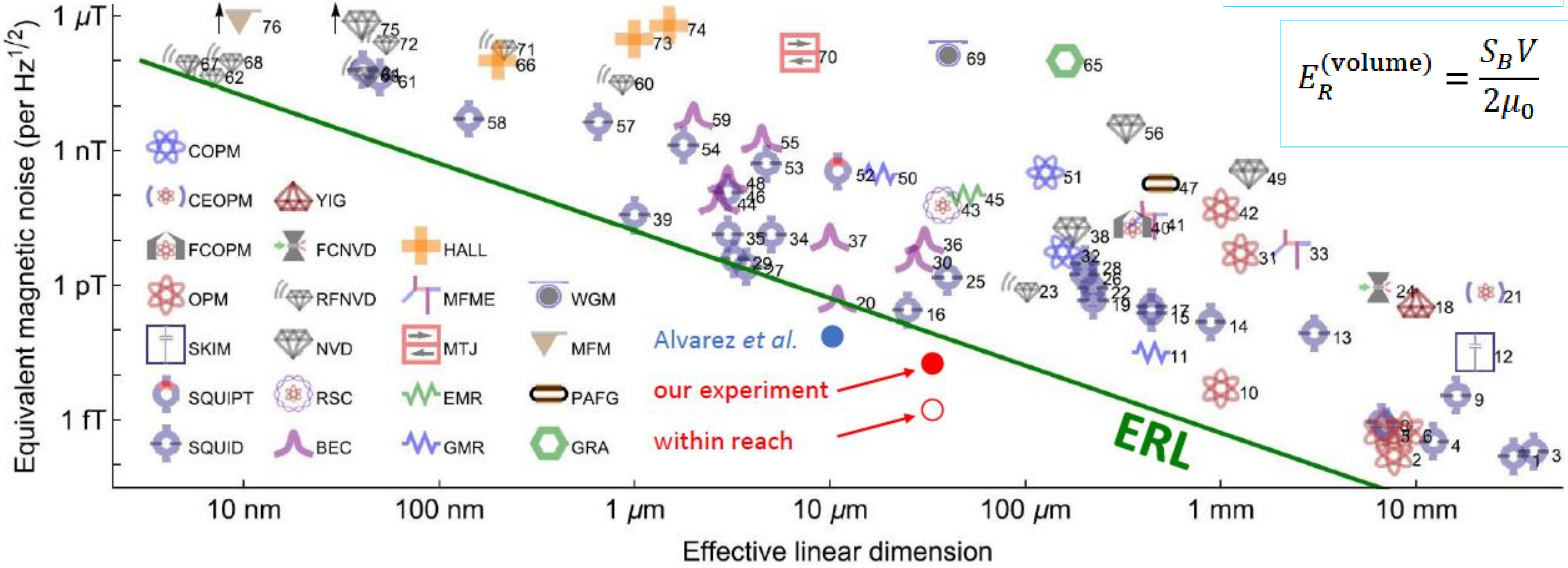




Experimental result: B-field sensing below ERL

Mitchell & Alvarez, RMP (2020)

$$E_R^{(\mathrm{volume})} = \frac{S_B V}{2\mu_0}$$



Alvarez et al., *Proc. Natl. Acad. Sci. USA*, 119, e2115339119 (2022)

Ahrens, F., Ji, W., Budker, D., Timberlake, C., Ulbricht, H., & Vinante, A. (2024).
Levitated ferromagnetic magnetometer with energy resolution well below $\hbar$. *arXiv preprint arXiv:2401.03774*.