Testing quantum and gravity …

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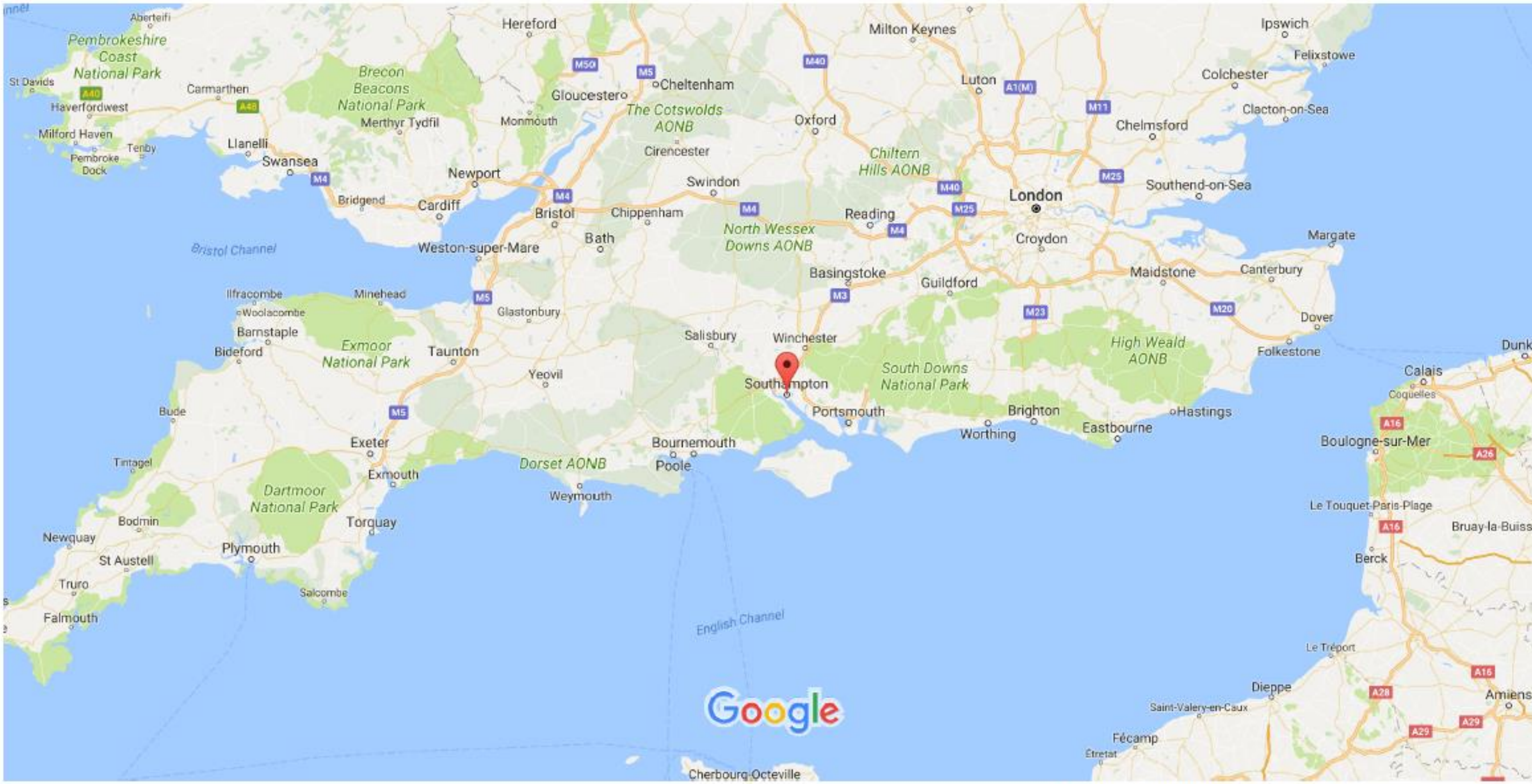
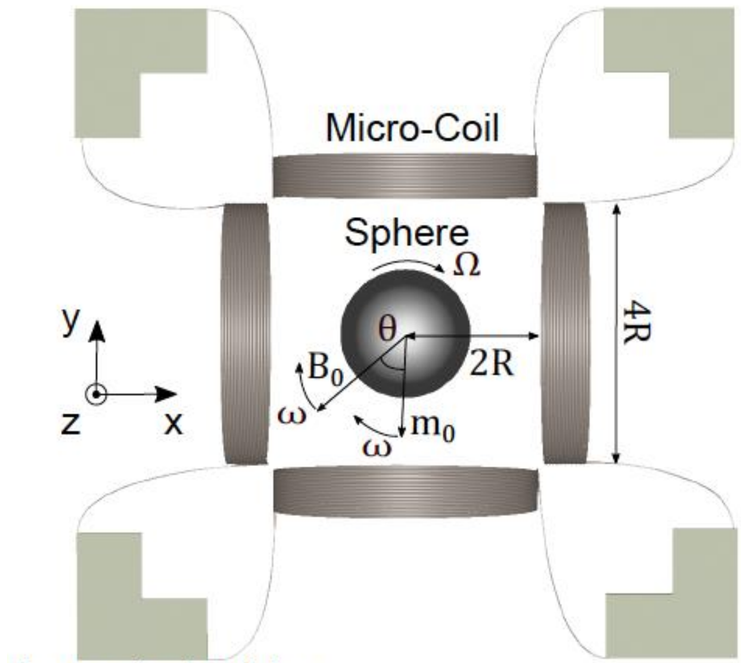
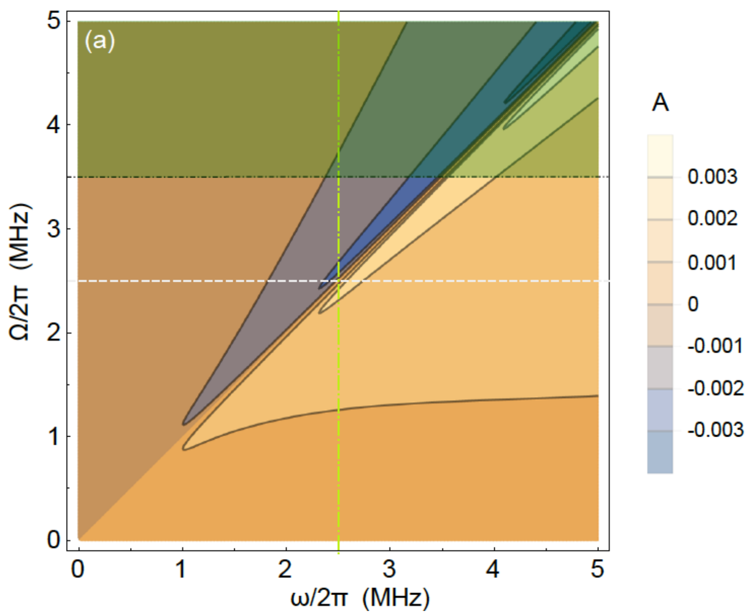


Map data ©2017 Google 20 km

Zel'dovich amplification of electro-magnetic field scattered of a spinning metal sphere:

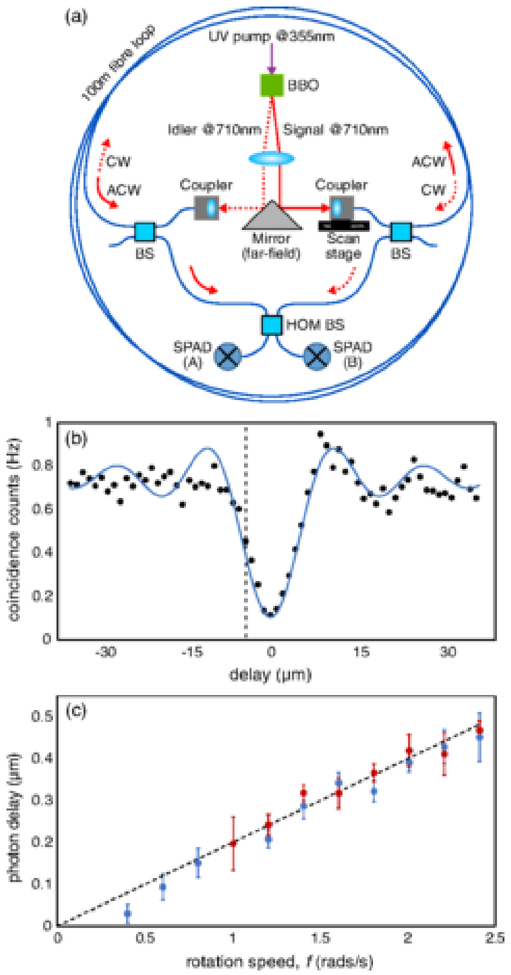




Analog to (Penrose superradiance) gravity effect of waves interacting with a rotating black hole.

Braidotti, M. C., A. Vinante, G. Gasbarri, D. Faccio, and H. Ulbricht, ***Zel'dovich amplification in a superconducting circuit,*** *Phys. Rev. Lett.* ***125****, 140801 (2020),*

QM in non-inertial frames



Photon bunching in a rotating reference frame
S Restuccia, M Toroš, GM Gibson, H Ulbricht, D Faccio, MJ Padgett
Physical Review Letters 123 (11), 110401 (2019).

Revealing and concealing entanglement with noninertial motion
M Toroš, S Restuccia, GM Gibson, M Cromb,
H Ulbricht, M Padgett, D Faccio
Physical Review A 101 (4), 043837 (2020).

PHYSICS QUESTIONS:

Testing collapse models

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

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

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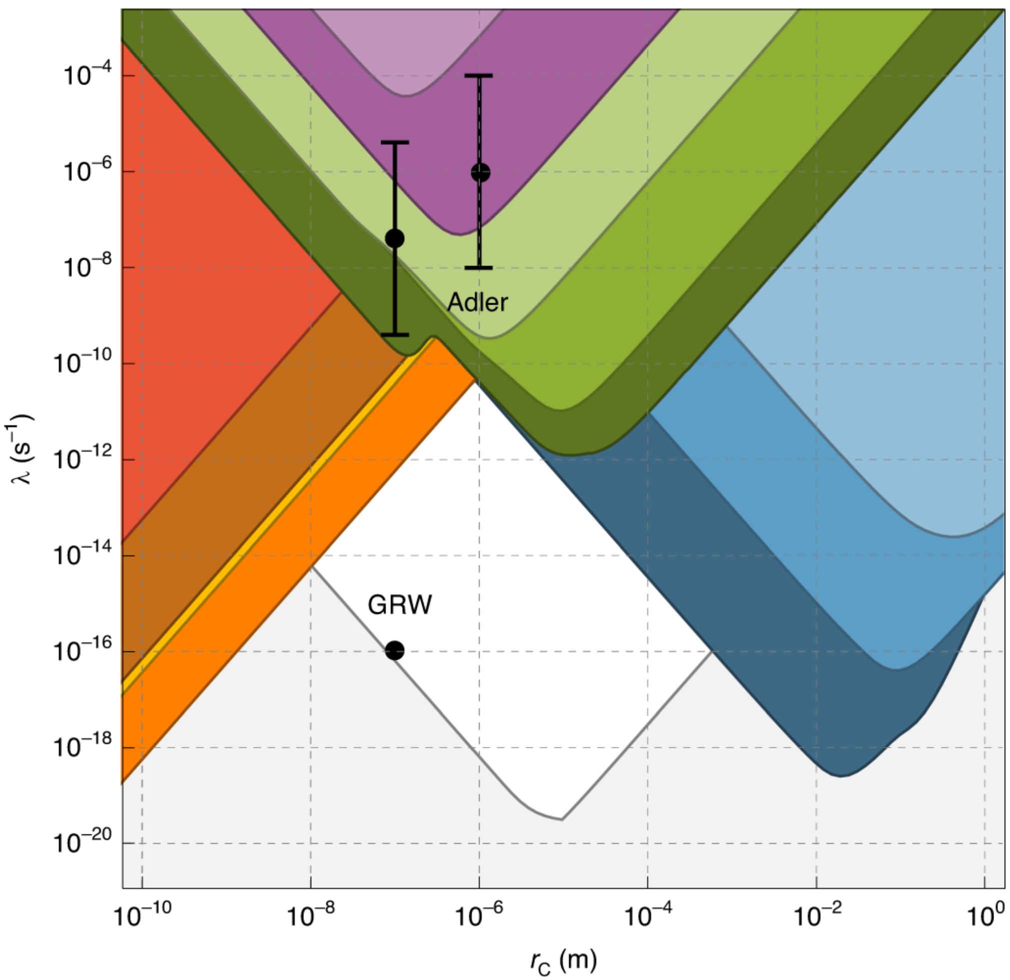
(published 2 April 2013)

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

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).

Mass-proportional collapse models: CSL

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

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

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

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**

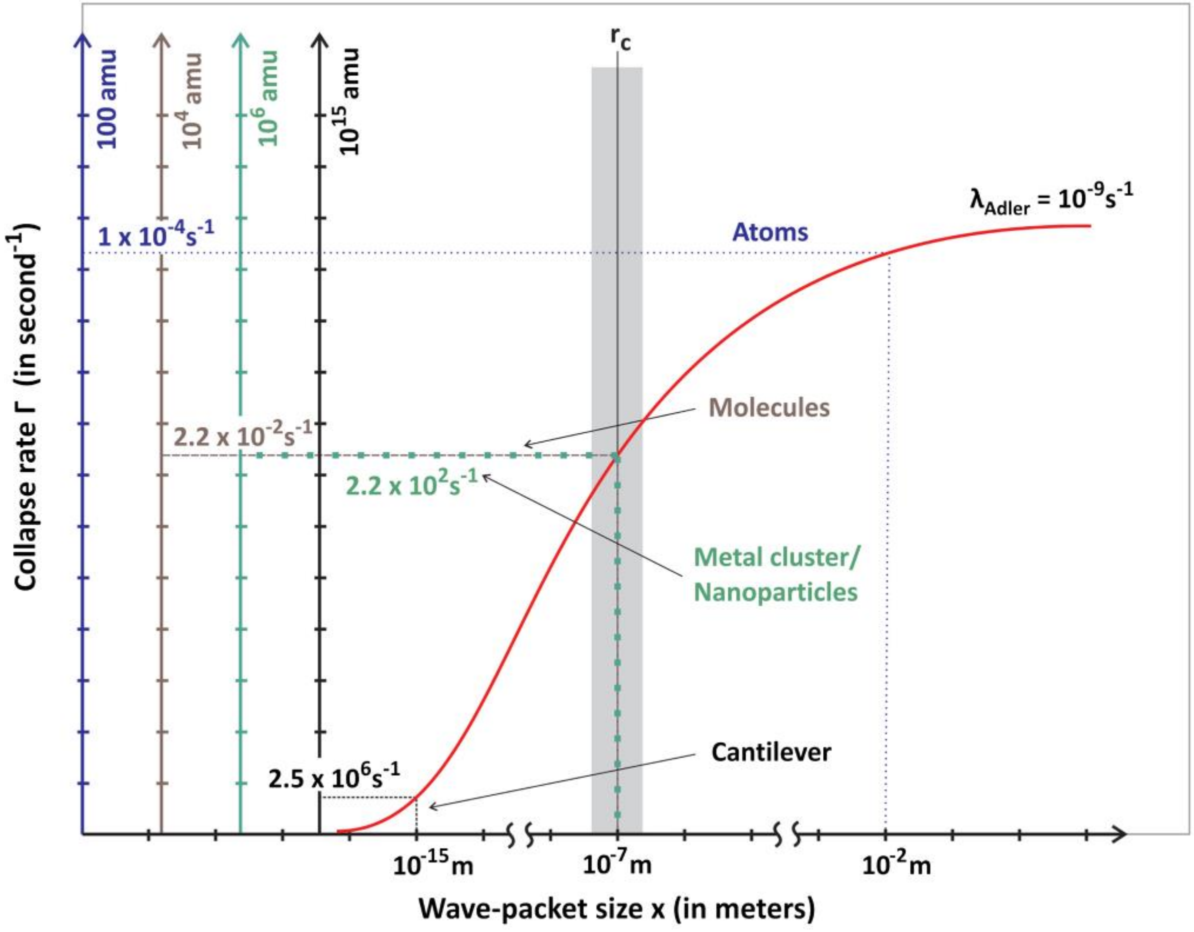
P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

What system parameters do we need for testing macroscopic quantum superpositions?

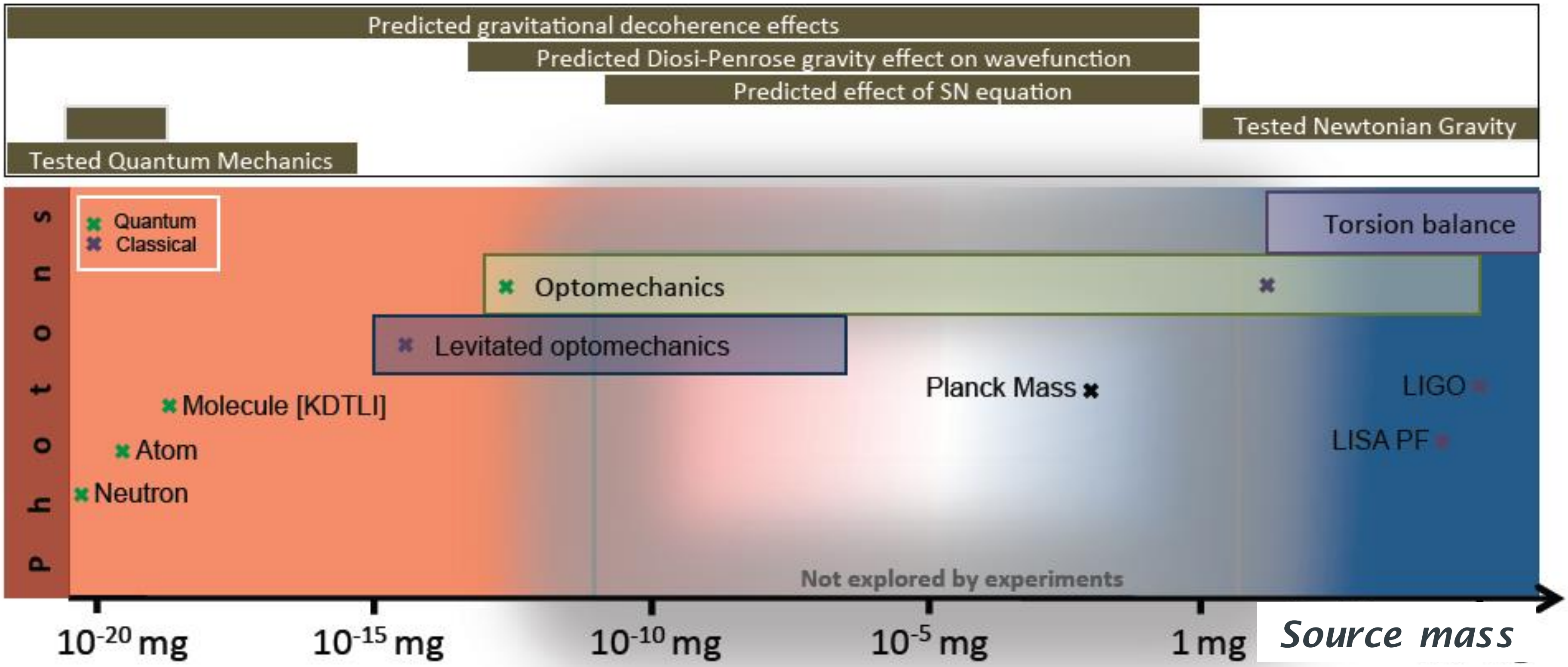
- Large mass
- Larger spatial separation/ size of superposition state
- Large time for the superposition state to exist

$$\frac{d}{dt}\rho_t(x,y) = -\frac{i}{\hbar}[H,\rho_t(x,y)] - \Gamma_{\rm CSL}(x,y)\rho_t(x,y)$$

$$\Gamma_{\rm CSL}(x) = \lambda[1 - e^{-x^2/4r_c^2}],$$



Testing gravity & quantum interplay: low energy regime



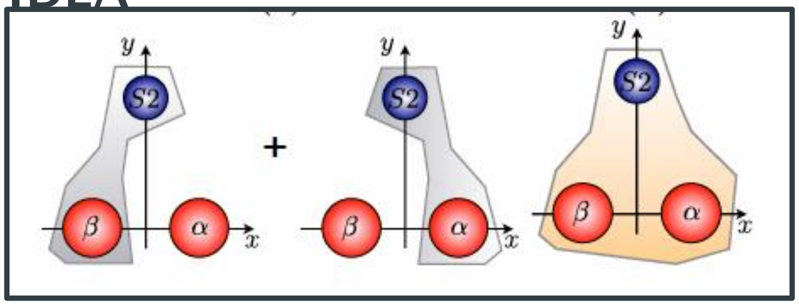
Smallest source mass where Newtonian gravity is confirmed by experiment: mg
What if the source mass is even smaller and in a spatial superposition?
How does the gravitational field look like then?

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

Testing the gravitational field generated by a superposition state.

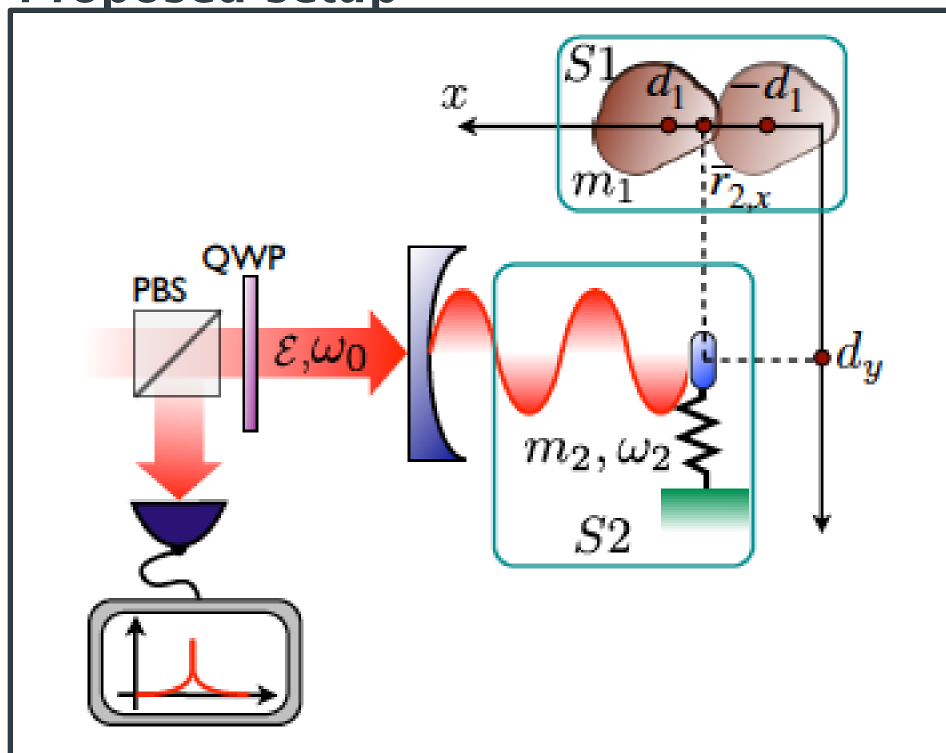
Challenge: *find two (sufficiently large) masses at sufficiently close proximity, where the source mass is in quantum state (super-position) and the test mass is sufficiently sensitive to probe the gravity field generated by source.*
Answer: *Optomechanics.*

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**

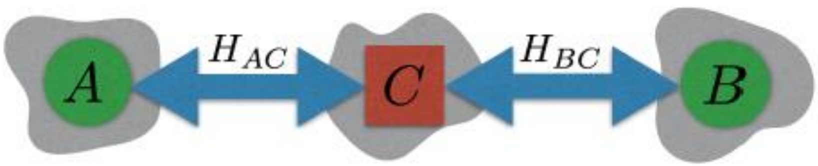
Proposed setup



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

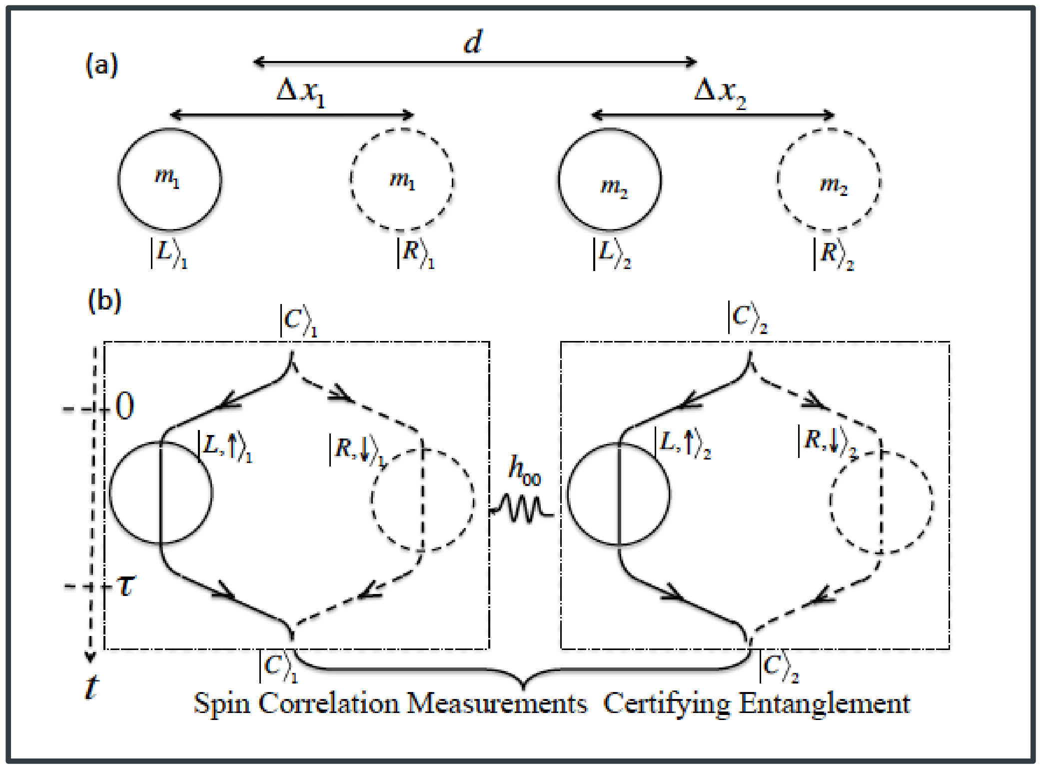
Gravity as entangler: … or any other coherent interaction

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:

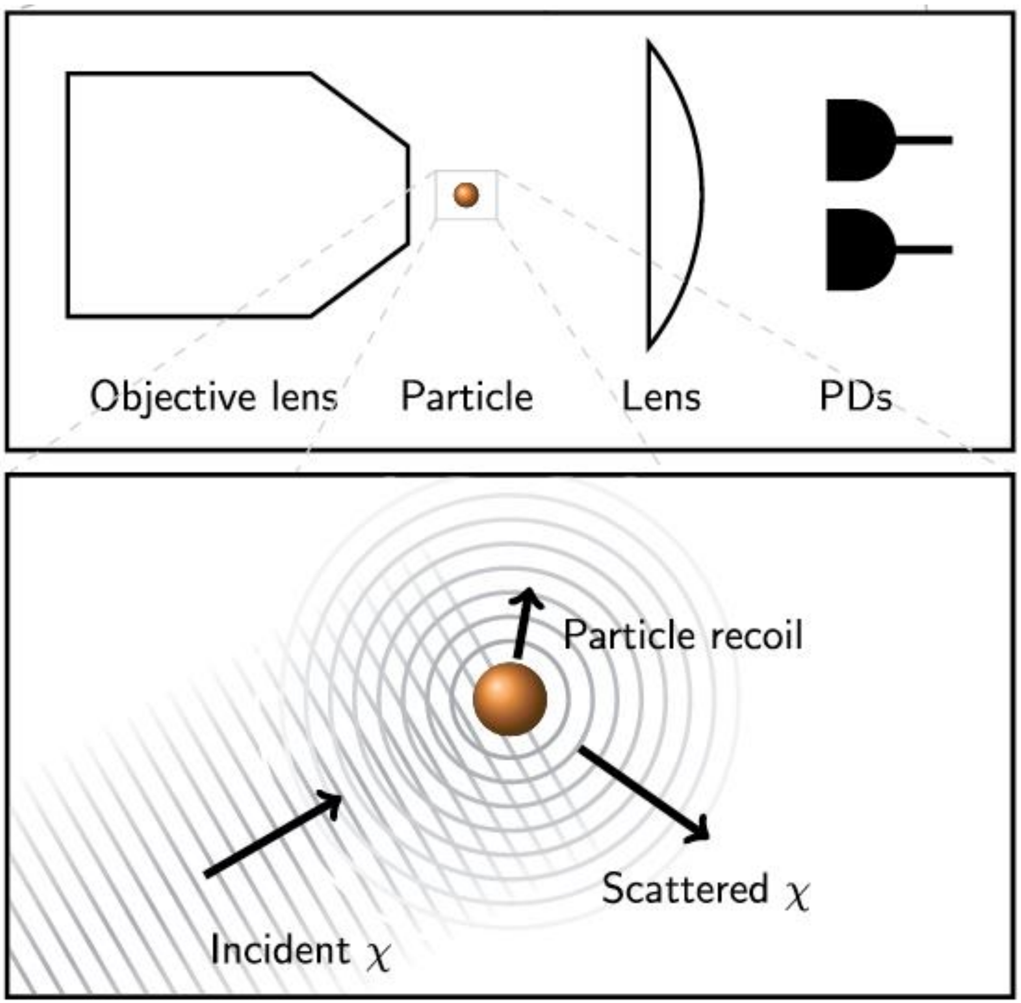
Masses:	10^{-14} kg
Superposition size:	250 μm
Separation (closest approach):	200 μm
Free fall time:	3.5 s
Magnetic field gradient:	10^6 T/m
Temperature (internal):	77 K
Vacuum:	10^{-17} mbar



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).

Testing new fields and particles, Dark Matter: beyond Standard model of particle physics



Mechanical harmonic oscillator (HO) system [levitated or clamped membrane/cantilever]

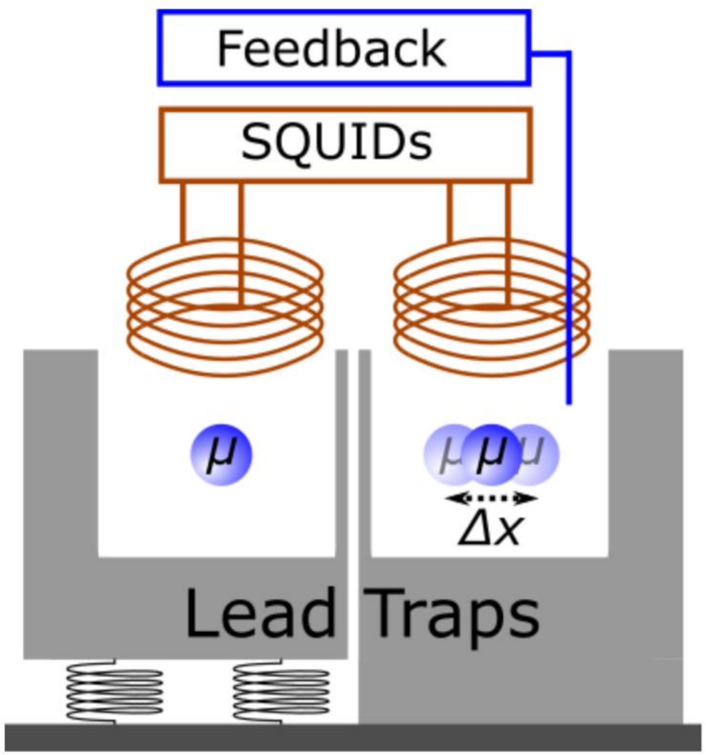
-> HO hit by many DM particles
-> elastic scattering
-> acceleration detected as Brownian like motion

Mechanical oscillators are **superb force/torque sensors**:

- $F_{min} = 10^{-20}$ N/sqrt(Hz) [1]
- $M_{min} = 10^{-31}$ Nm/sqrt(Hz) [2]

Bateman, J., I. McHardy, A. Merle, T.R.Morris, H.Ulbricht, ***On the Existence of low-mass Dark Matter and its direct detection, Nature Scientific Reports*** 5, 8058 (2015).
[1] Hempston, D., et al., ***Force sensing with an optically levitated charged***, Appl. Phys. Lett. **111**, 133111(2017).
[2] Rashid, M., et al., ***Precession Motion in Levitated Optomechanics***, Phys. Rev. Lett. **121**, 253601 (2018).

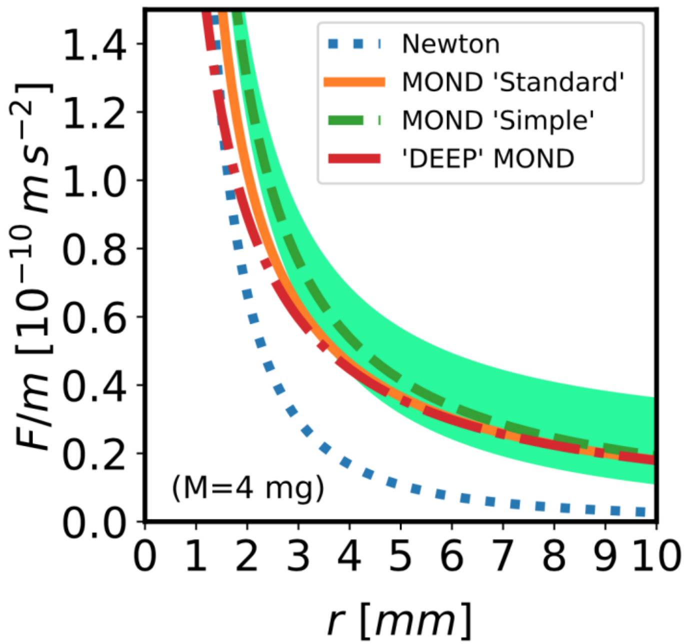
Testing variations of gravity: two masses



2-mass experiment based on levitated mechanics

- *mg* masses
- 0.5 mm
- 300 mK
- cm separation
- 30 Hz

- Experimental confirmed: 1e-9 m/s^2 @ 5K & Q=5500



Timberlake, C., A. Vinante, F. Shankar, A. Lapi, and H. Ulbricht, ***Probing Modified gravity with magnetically levitated resonantors***, PRD (2022).

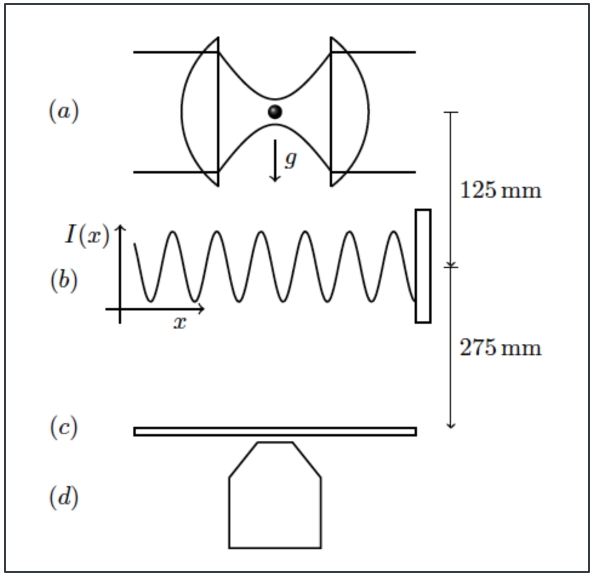
Experiments which can enter the regime to test all that physics

- Levitated mechanical systems
  - Optical
  - Magnetic
  - Paul electrodynamic

- Objective: Nano – and microparticles in quantum coherent state

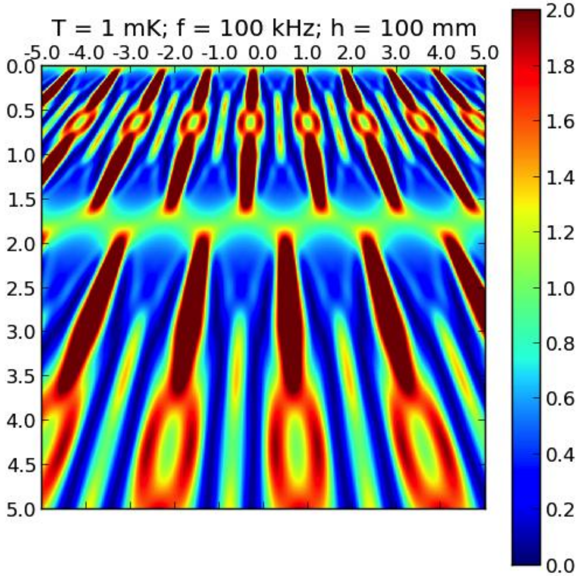
INTERFEROMETRIC VS. NON-INTERFEROMETRIC:

Nanoparticle Interferometer: testing quantum superposition



Quantum carpet:

expected interference pattern

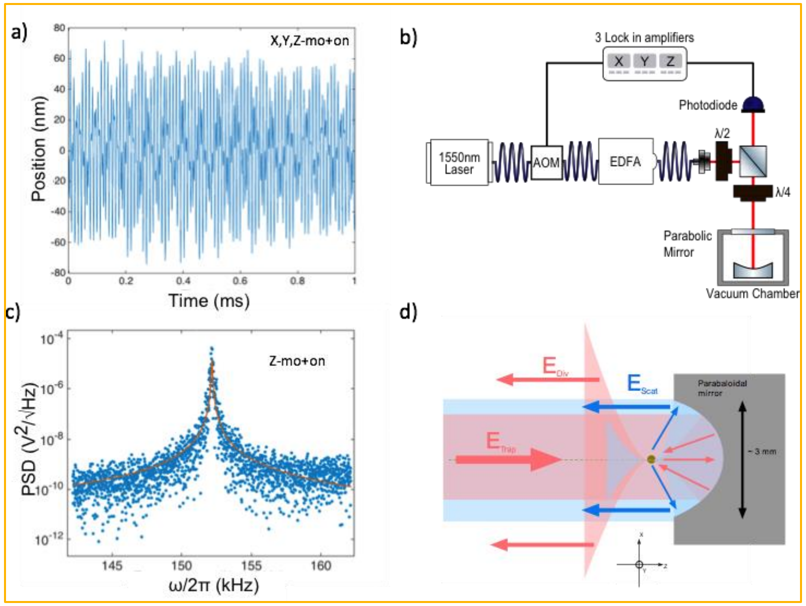


Step 1 - proposal: **Spatial superposition of particle of mass:** 10^6 -10^7 amu (20 nm in diameter)

- Wigner function model to calculate Quantum Carpet.
- **CSL-type and gravity induced collapse (independent Penrose and Diosi ideas) are tested.**

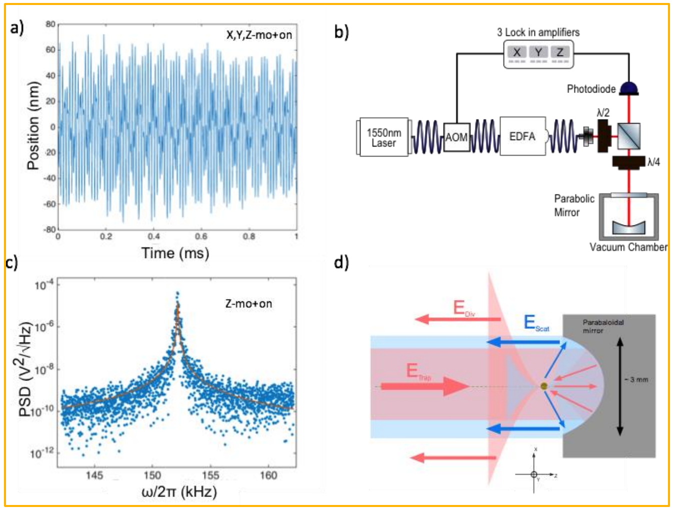
-> Thermal and collisional decoherence are negligible.

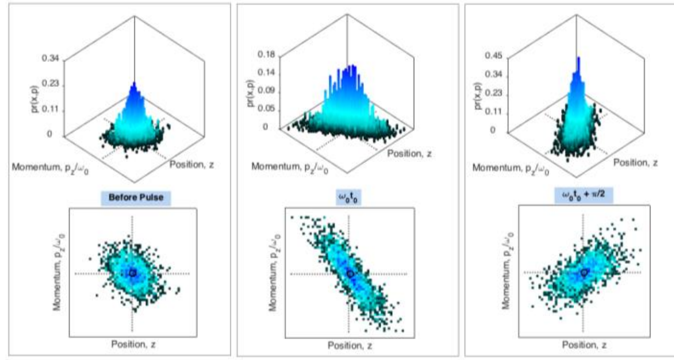
Step 2 – Experiment: **Particle source has been Implemented by particle levitation**

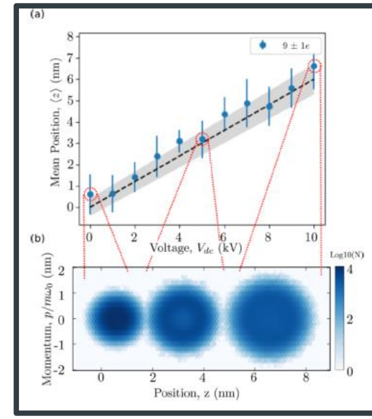


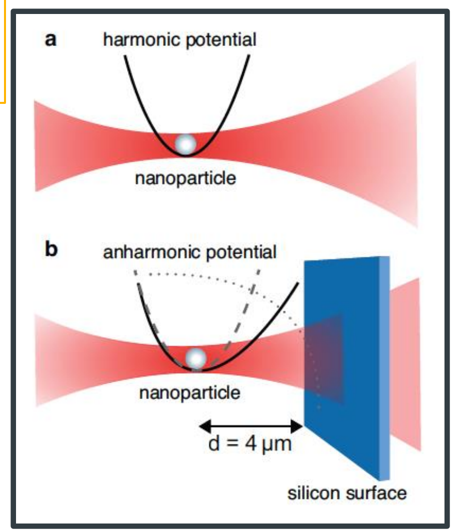
Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht
Near-field interferometry of a free-falling nanoparticle from a point-like source
Nature Communications 4, 4788 (2014).

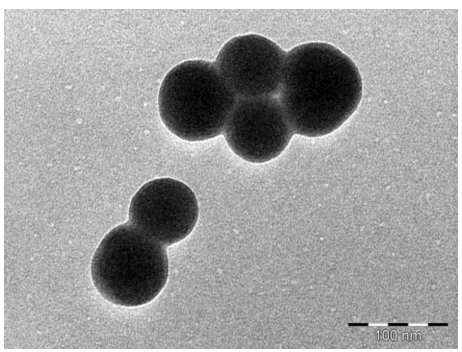
Levitated Opto-Mechanics:

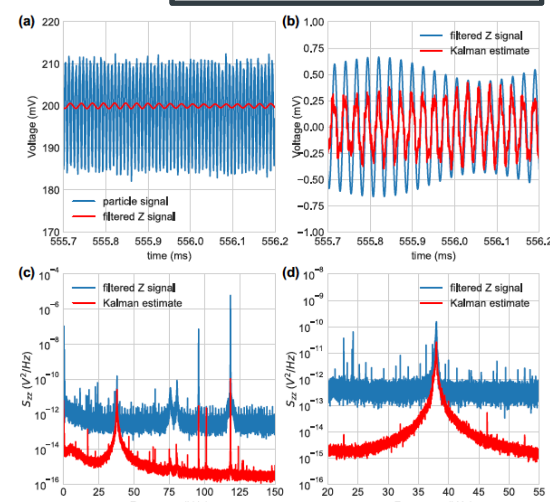










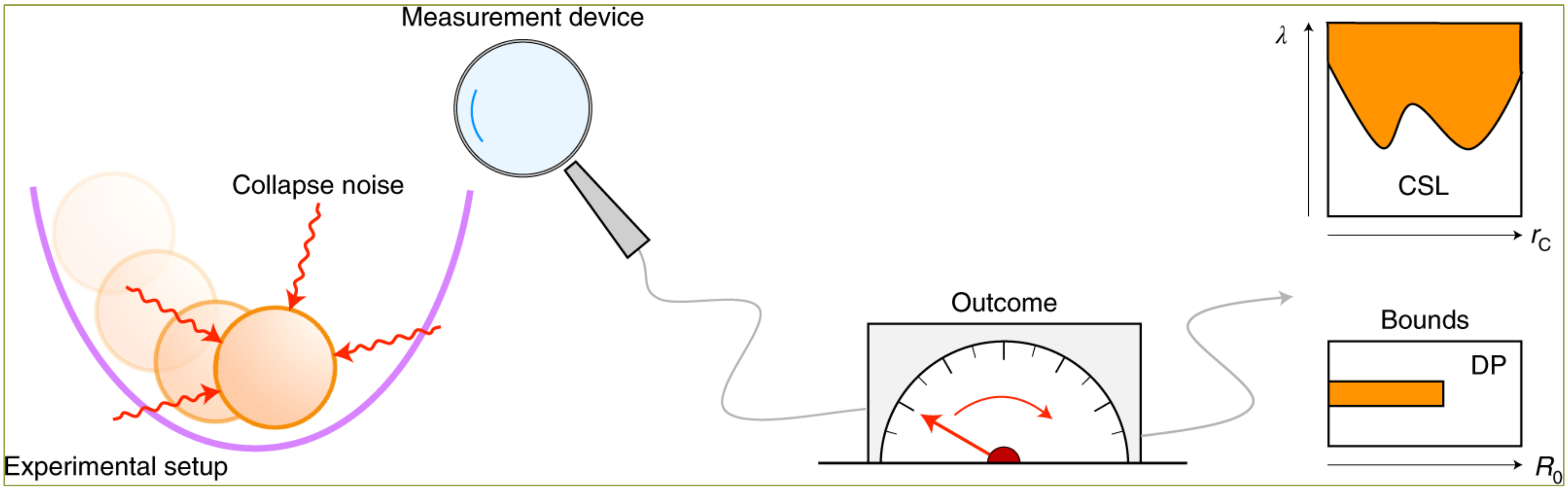


Rashid, M., M. Toroš, A. Setter, H. Ulbricht [Precession Motion in Levitated Optomechanics, PRL] 121, 253601 [(2018).]

Hempston, D., J. Vovrosh, M. Toroš, M. Rashid, and H. Ulbricht, **Force sensing with an optically levitated charged nanoparticle**, Appl. Phys. Lett. **111**, 133111 (2017)

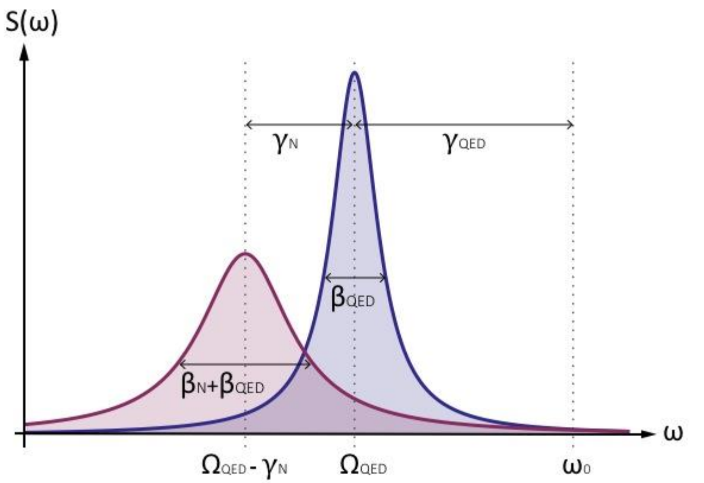
Rashid, M., T. Tufarelli, J. Bateman, J. Vovrosh, D. Hempston, M. S. Kim, and H. Ulbricht, ***Experimental Realization of a Thermal Squeezed State of Levitated Optomechanics***, PRL 117, 273601 (2016).

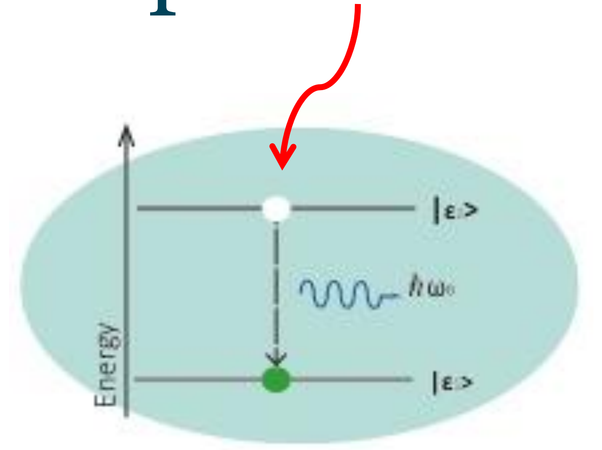
Non-interferometric tests of quantum superposition: looking for the noise (is there any?)



Present status and future challenges of non-interferometric tests of collapse models
M Carlesso, S Donadi, L Ferialdi, M Paternostro, H Ulbricht, A Bassi
Nature Physics 18 (3), 243-250 (2021).

Spectroscopy tests: Generic broadening of spectral line-width from collapse **noise**:





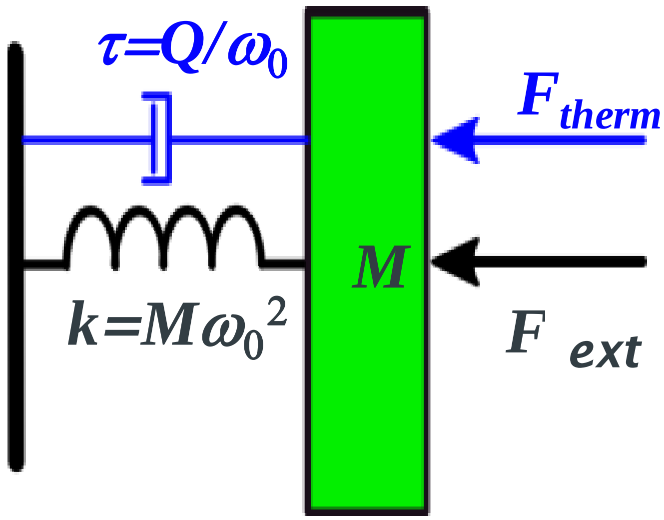
System	β_N (s^{-1})	Ω_N (s^{-1})
Hydrogen-like Atoms	$10^{-20} - 10^{-18}$	$\sim 10^{-53}$
Harmonic oscillator	$\frac{3\Lambda}{4}\left(\frac{\mu\, x_0}{m_0\, r_C}\right)^2$	$\frac{\Lambda^2}{32\omega_0}\left(\frac{\mu\, x_0}{m_0\, r_C}\right)^4$
$\mu = 1\,\text{amu and } \omega_0 = 10^{10}\text{s}^{-1}$	5.3×10^{-13}	6.2×10^{-36}
$\mu = 10^7\,\text{amu and } \omega_0 = 1.7 \times 10^8\text{s}^{-1}$	3.1×10^{-4}	1.3×10^{-16}
Double-well	$\frac{\Lambda}{8}\left(\frac{\mu\, q_0}{m_0\, r_C}\right)^2$	$\frac{\Lambda^2}{128\,\omega_0}\left(\frac{\mu\, q_0}{m_0\, r_C}\right)^4$
$\mu = m_e = 5.5 \times 10^{-4}\,\text{amu and } q_0 = 1\text{Å}$	4.2×10^{-23}	$10^{-57} - 10^{-55}$
$\mu = 1\,\text{amu and } q_0 = 1\text{Å}$	1.4×10^{-16}	$10^{-44} - 10^{-42}$
$\mu = 10^7\,\text{amu and } q_0 = 1\text{Å}$	0.014	$10^{-16} - 10^{-18}$

Bahrami, M., A. Bassi, and H. Ulbricht
Testing the quantum superposition principle in the frequency domain
Phys. Rev. **A 89**, 032127 (2014)]

Force (noise) in harmonic oscillator:

Thermal bath affect minimum force measured:

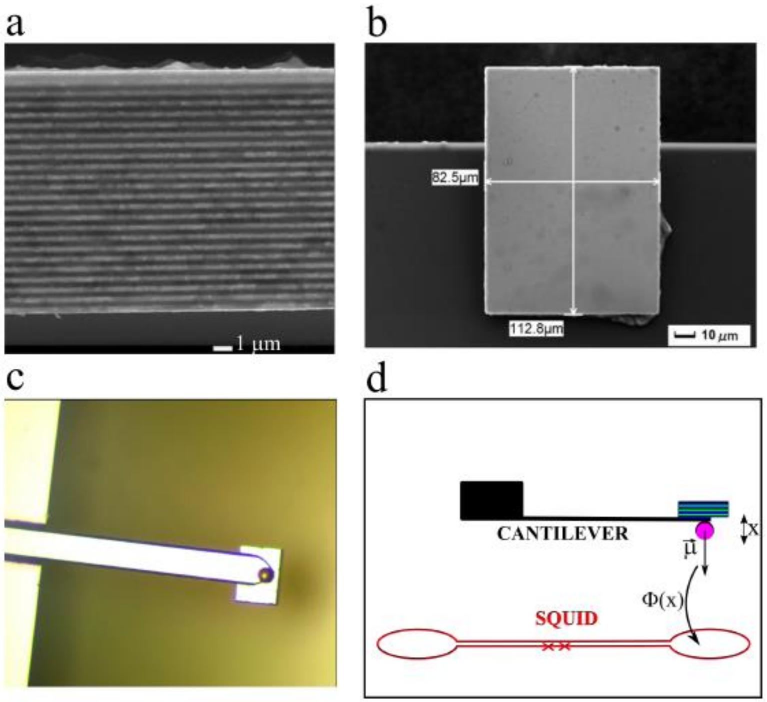
$$F_{min} = \sqrt{\frac{4k_B T_0 m\omega_0}{Q\tau}},$$

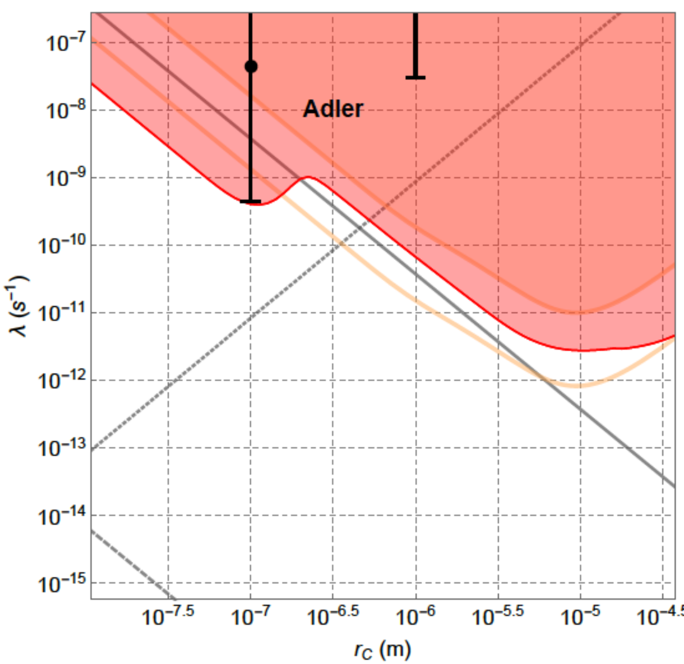


M. Bahrami et al, PRL **112** 210404 (2014)
S. Nimmrichter et al, PRL **113** 020045 (2014)
L. Diosi, PRL **114**, 050403 (2015)
D. Goldwater et al. Phys. Rev. **A 94**, 010104 (2015)
A. Vinante et al, PRL **116**, 090402 (2016)

Mass at cantilever: multi-layered mass amplifying noise

- **Sandwich of 40 layers of Tungsten-oxid and glass**
- **Mechanical temperature of cantilever at 10 mK**
- **Detection of motion by SQUID**
- **Substantial challenge of Adler's CSL values**

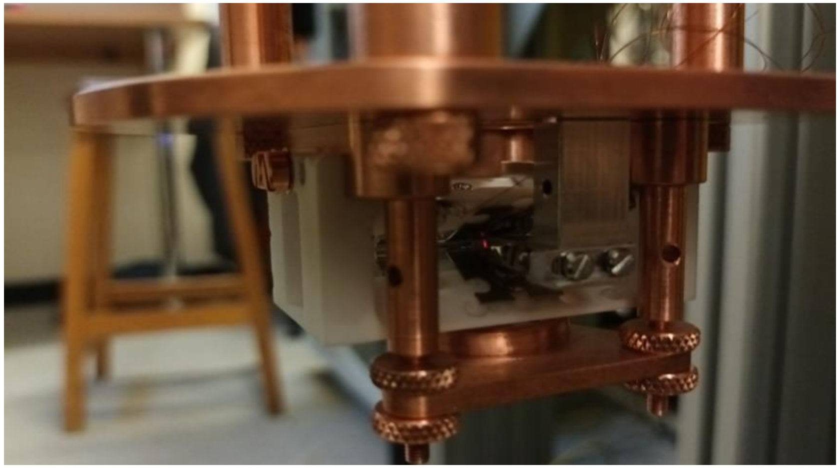


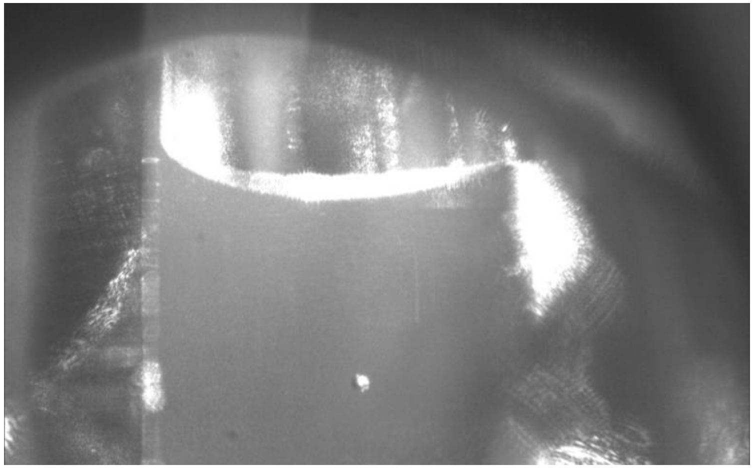


Vinante, A., M. Carlesso, A. Bassi, A. Chiasera, S. Varas, P. Falferi, B. Margesin, R. Mezzena, and H. Ulbricht. "Narrowing the parameter space of collapse models with ultracold layered force sensors.", *Phys. Rev. Lett.* **125**, 100404 (2020).

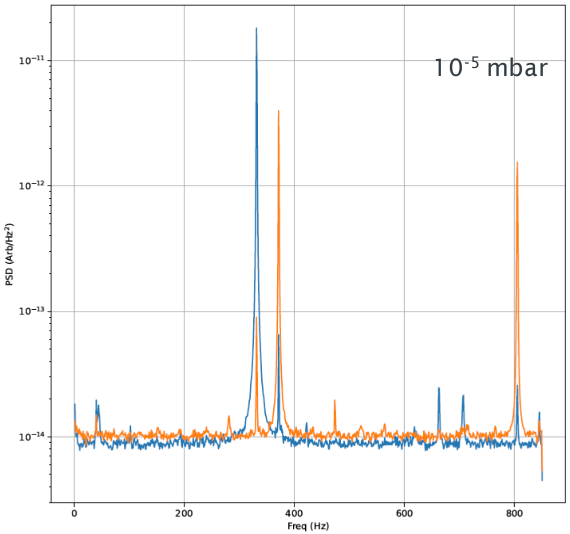
The Paul trap

University of Southampton



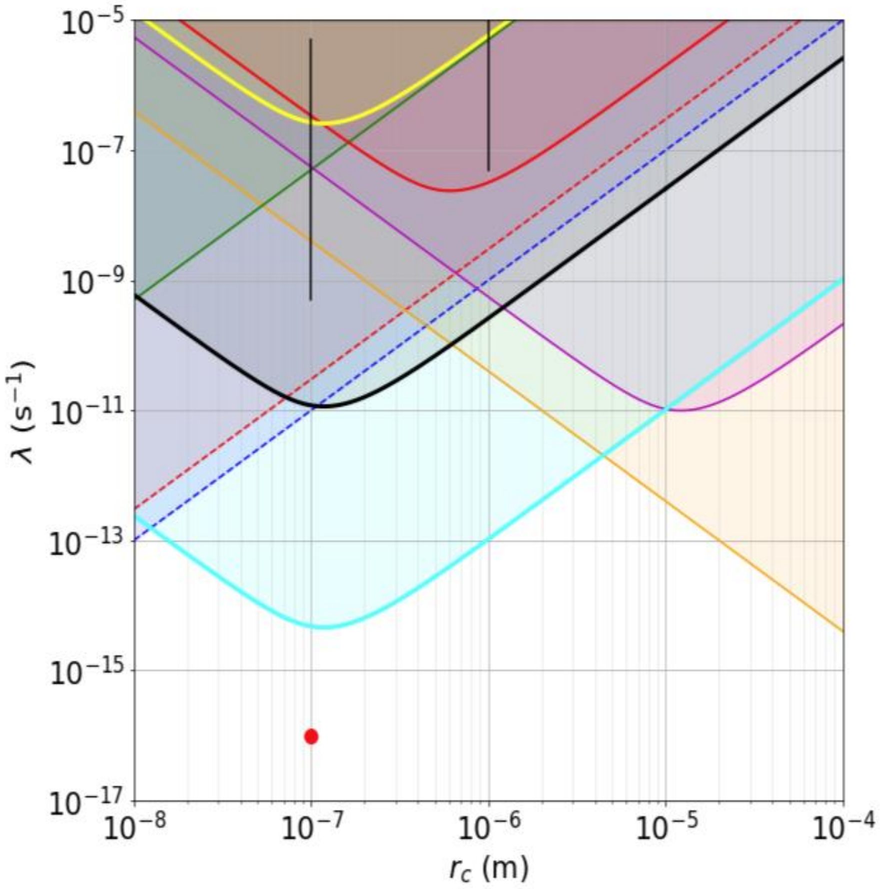


- Paul trap attached to cryostat.
- Particle trapped at room temperature (for weeks).
- Particle detected by camera method.



Room temperature results from Paul trap

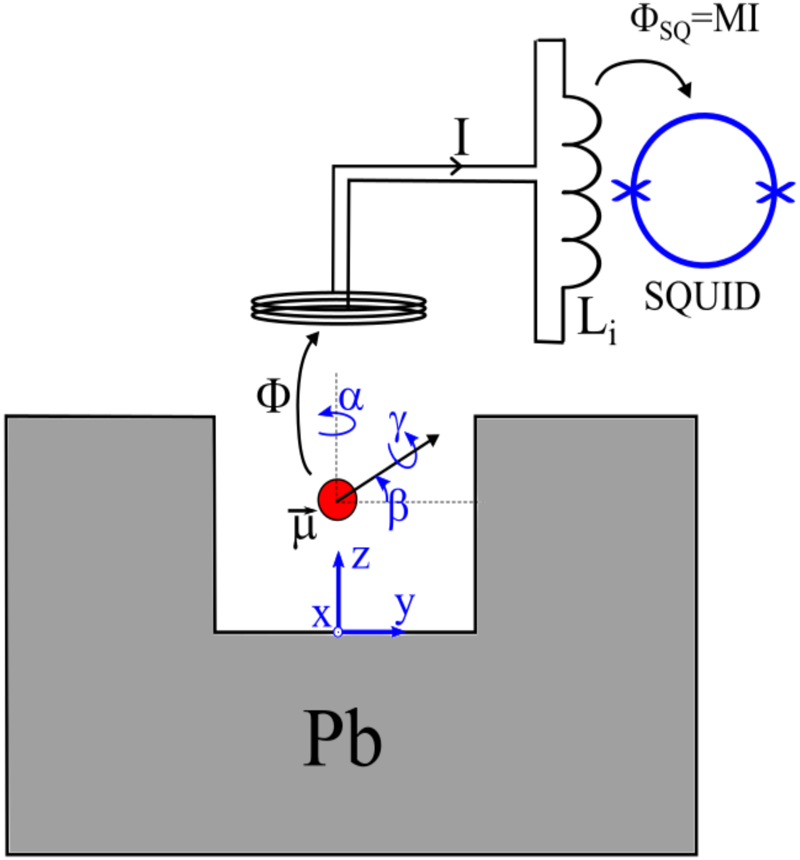
- Yellow curve: actual room temperature experiment
- Targeted next:
  - black curve for 50e charges at 300 mK
  - Cyan curve: 1e at 300 mK

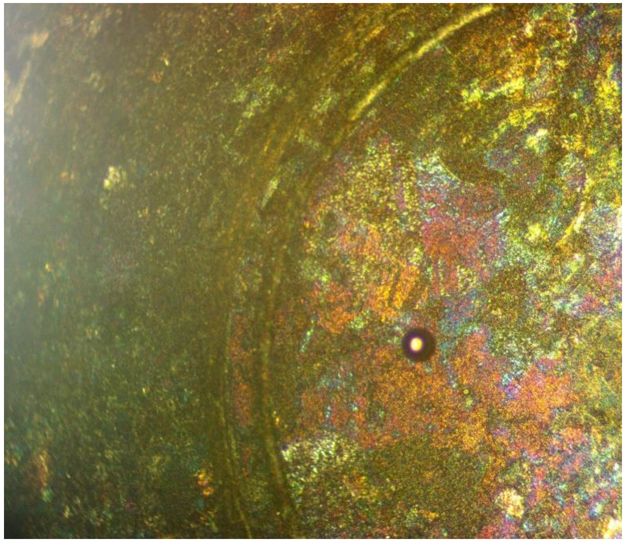


EXPERIMENTAL RESULTS:

Meissner levitation with SQUID readout

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

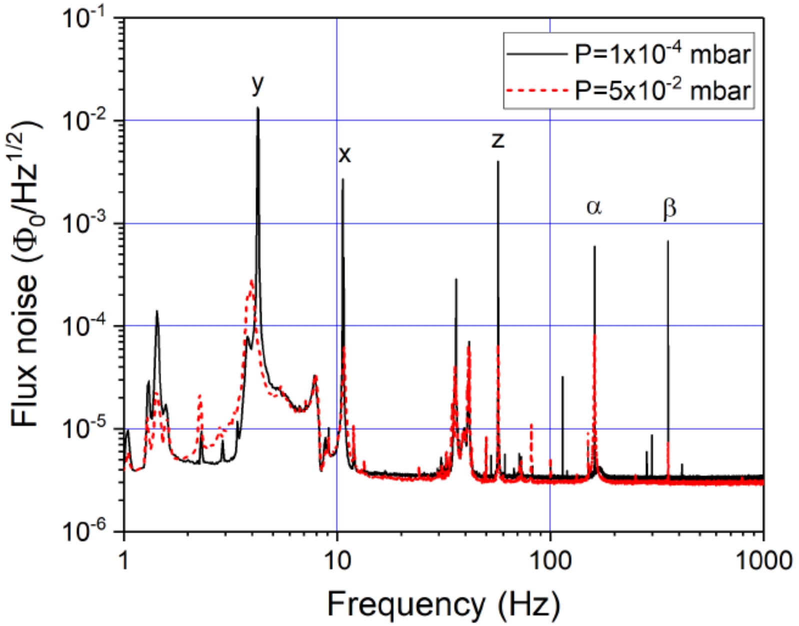




NdFeB microsphere
Radius = 27 um
Trap Radius = 2 mm

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)

Some results of magnetic trapping:



Beta-mode: libration motion

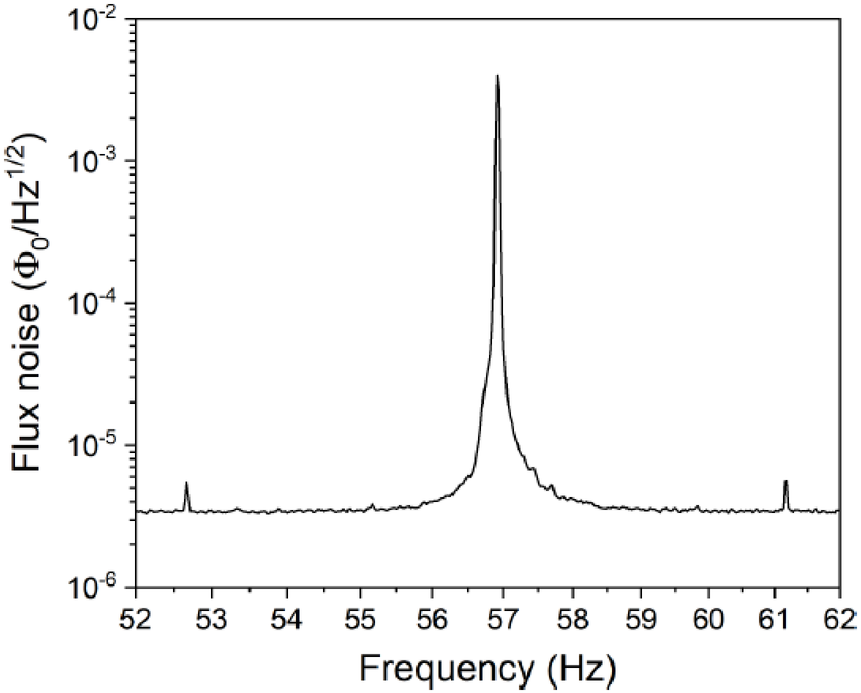
$$P \sim 10^{-5}\ \text{mbar}$$
$$Q = 1.34 \times 10^{7}.$$

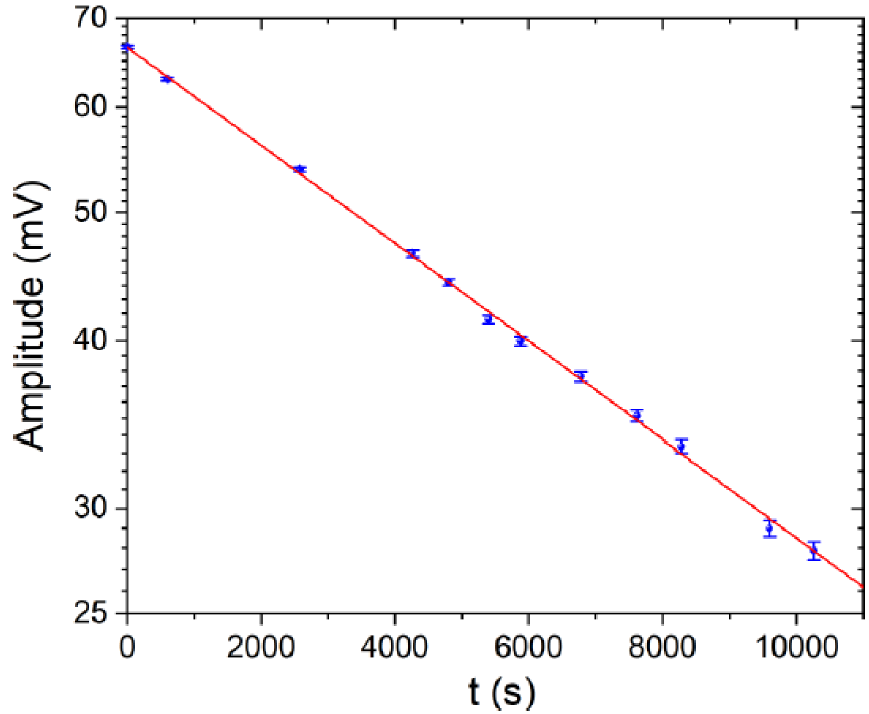
- **Peaks identified by finite element simulations**
- **z – and beta modes are studied in more detail**
- **All experiments so far a 4 K.**

$$\sqrt{S_T} = 1.00 \times 10^{-20}\ \text{Nm}/\sqrt{\text{Hz}}.$$

$$\sqrt{S_B} \approx 1\ \text{fT}/\sqrt{\text{Hz}} \quad \sqrt{S_f} \approx 1\ \text{aN}/\sqrt{\text{Hz}} \text{ for the } z \text{ mode}$$

Some results from magnetic trapping: 4K





Sensitivities extracted from force noise:

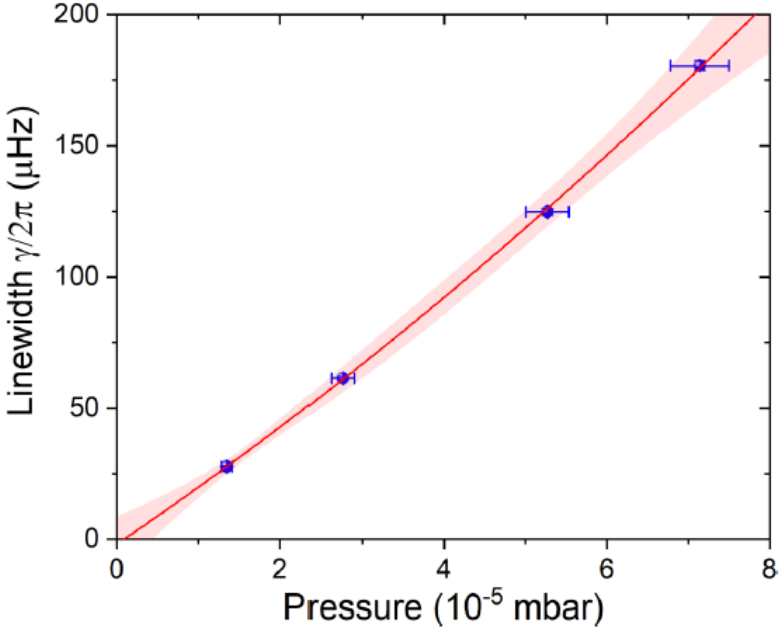
$$\sqrt{S_\mathcal{T}} = 1.00 \times 10^{-20}\ \mathrm{Nm}/\sqrt{\mathrm{Hz}}.$$

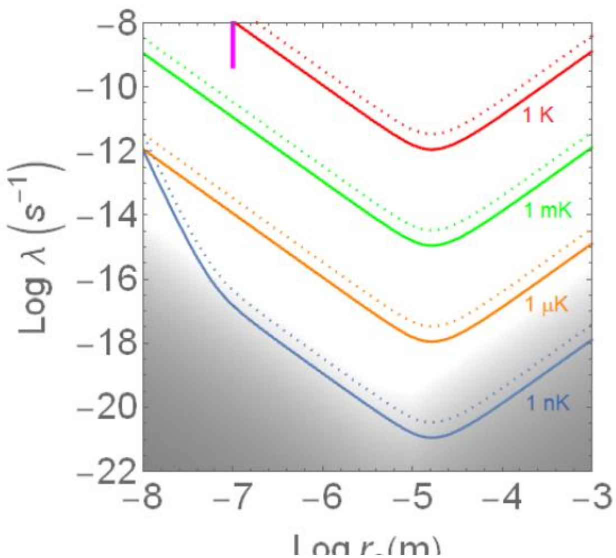
$$\sqrt{S_B} \approx 1\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$$

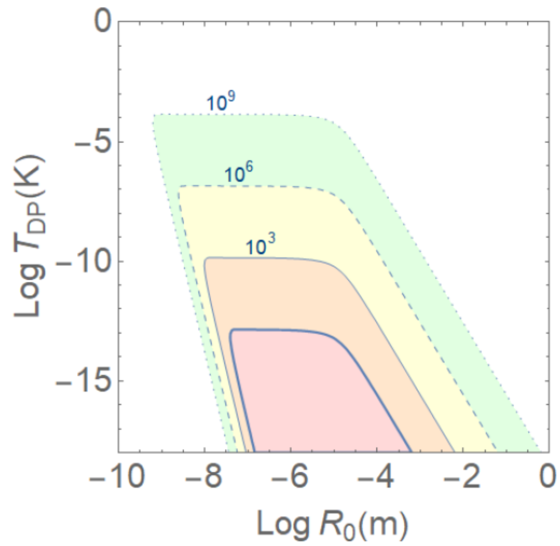
$$\sqrt{S_f} \approx 1\ \mathrm{aN}/\sqrt{\mathrm{Hz}} \text{ for the } z \text{ mode}$$

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)

Dissipative collapse models tested: dCSL, dDP



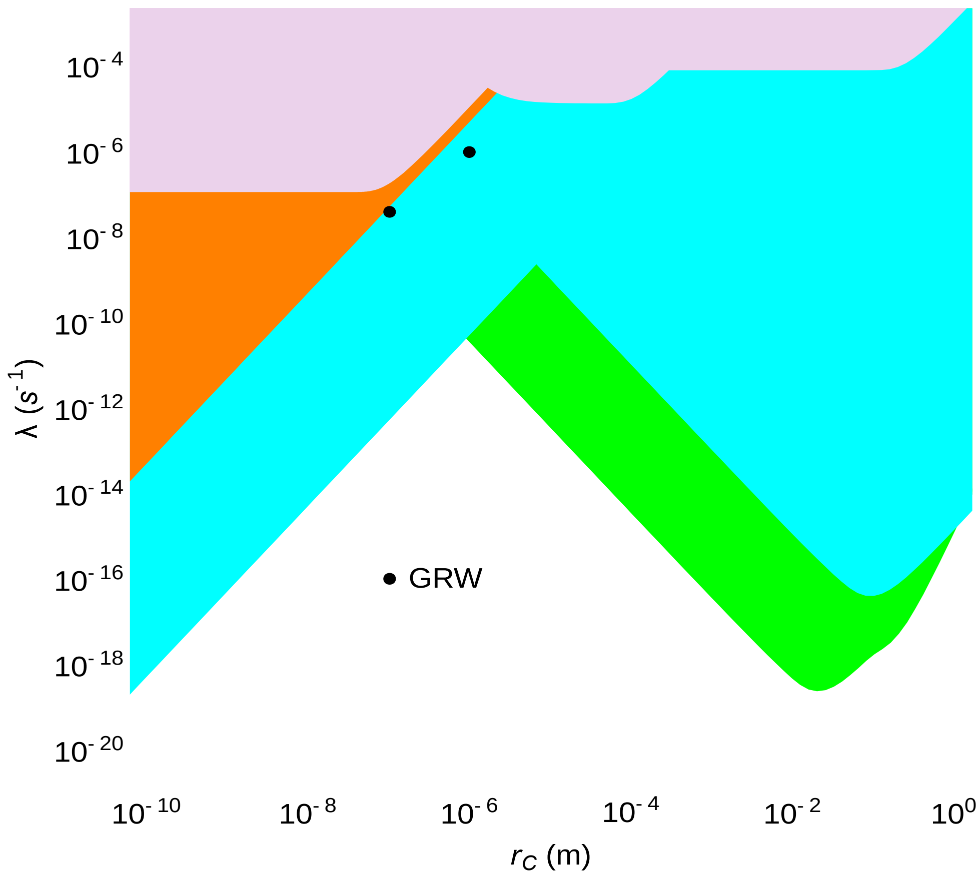




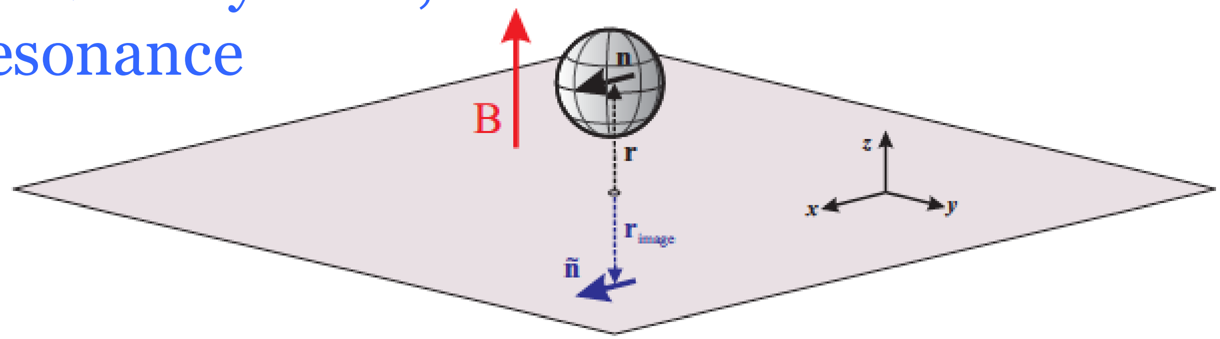
Vinante, A., G. Gasbarri, C. Timberlake, M. Toroš, and H. Ulbricht, Testing Dissipative Collapse Models with a Levitated Micromagnet, Phys. Rev. Research 2, 043229 (2020)

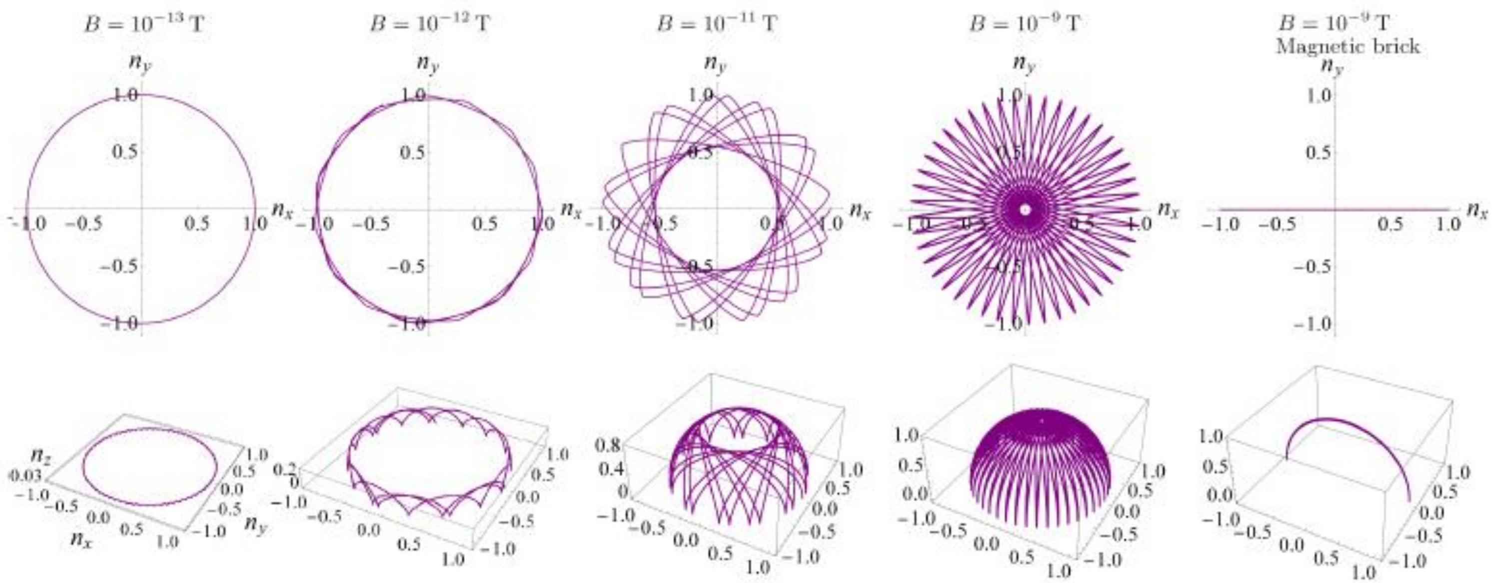
Next experiment: Disc in Meissner trap

- Larger, non-spherical particles are promising to test CSL: disc and rod geometries
- Based on previous theory publication (with TP)
- Dashed black line for libration motion of a 200 μm diameter disc.



Ferromagnetic gyroscope: Precession and nutation motion to probe tiny force, Macroscopic Spin Resonance

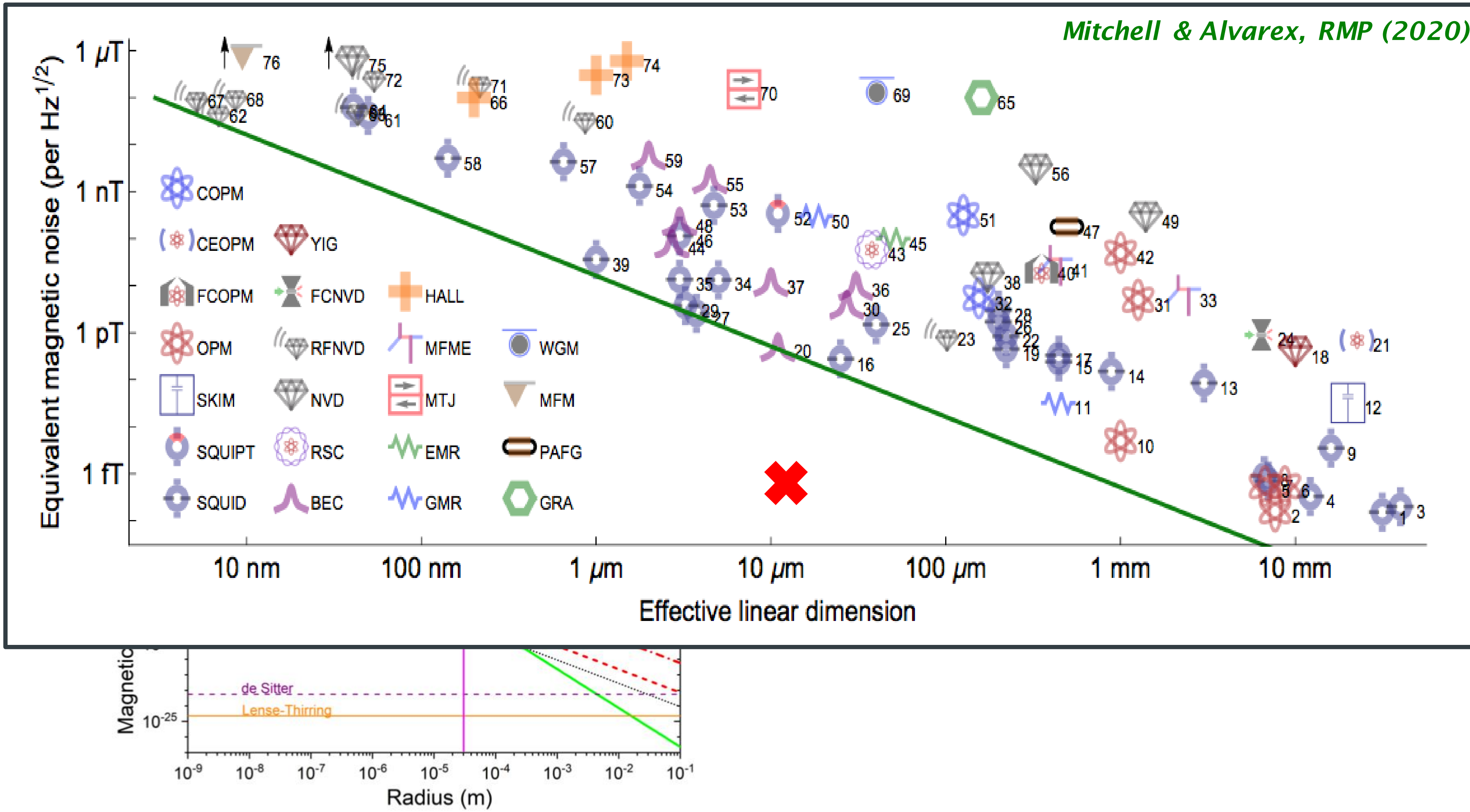




To test physics beyond the standard model: e.g. speculative pseudo-scalar mediated dipole-dipole interaction between electron Spins.

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).*

Beating ERL in magnetic field sensing



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),

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