University of Southampton

Testing fundamental physics by levitated mechanics

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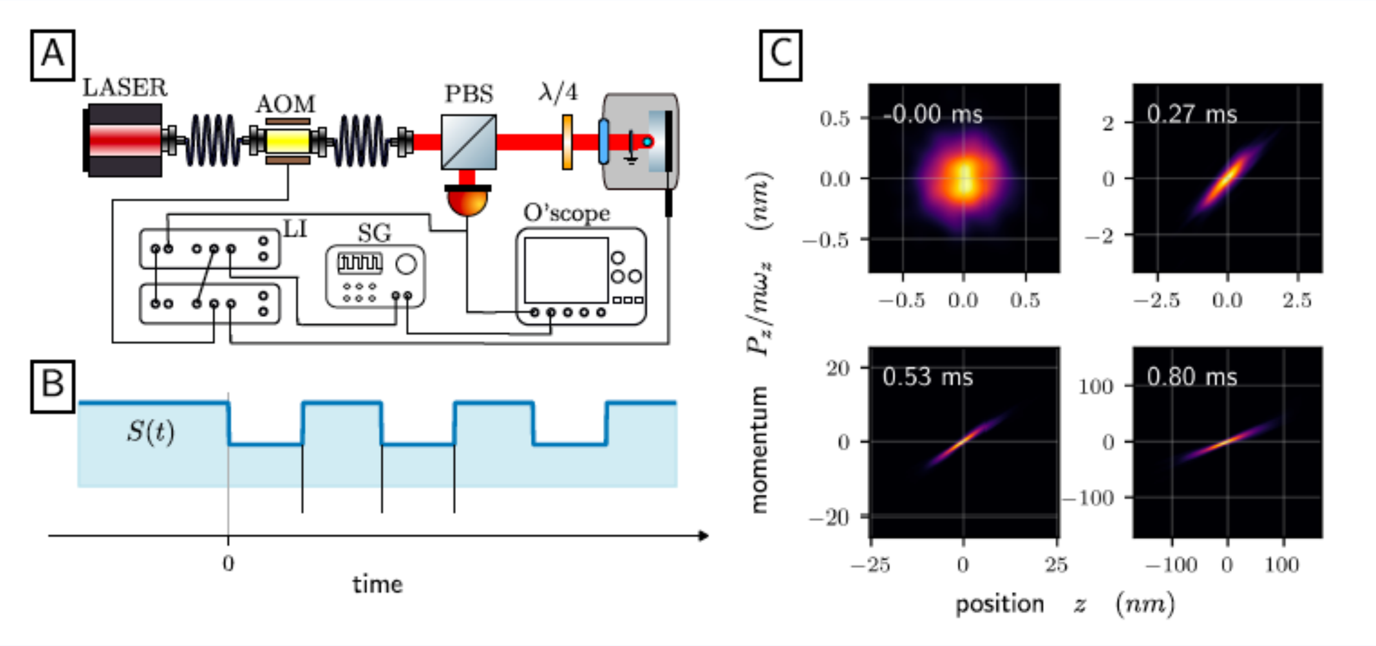
Outline

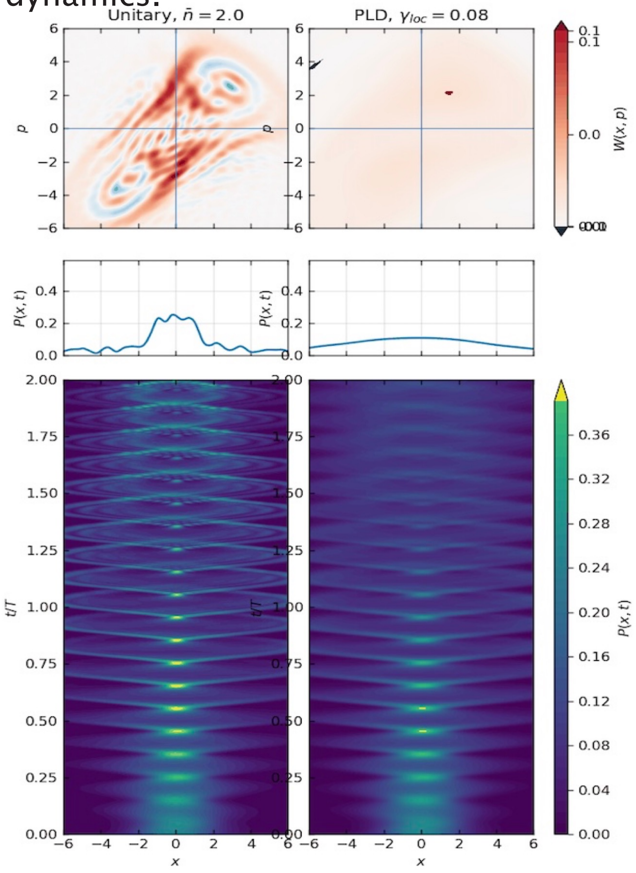
- Levitated mechanics as a probe for fundamental physics (QM, gravity, HEP stuff)
- Things measured already (mostly gravity, but also magnetic)
- Things on the horizon for measuring (gravity, bounds on DM & exotic interactions)
- G-LHC, that biggest challenge yet (deals with tiny accelerations)

State expansion in levitated optomechanics:

Generating macroscopic quantum states to probe fundamental physics



Wigner function of macroscopic quantum state generated by non-linear dynamics.

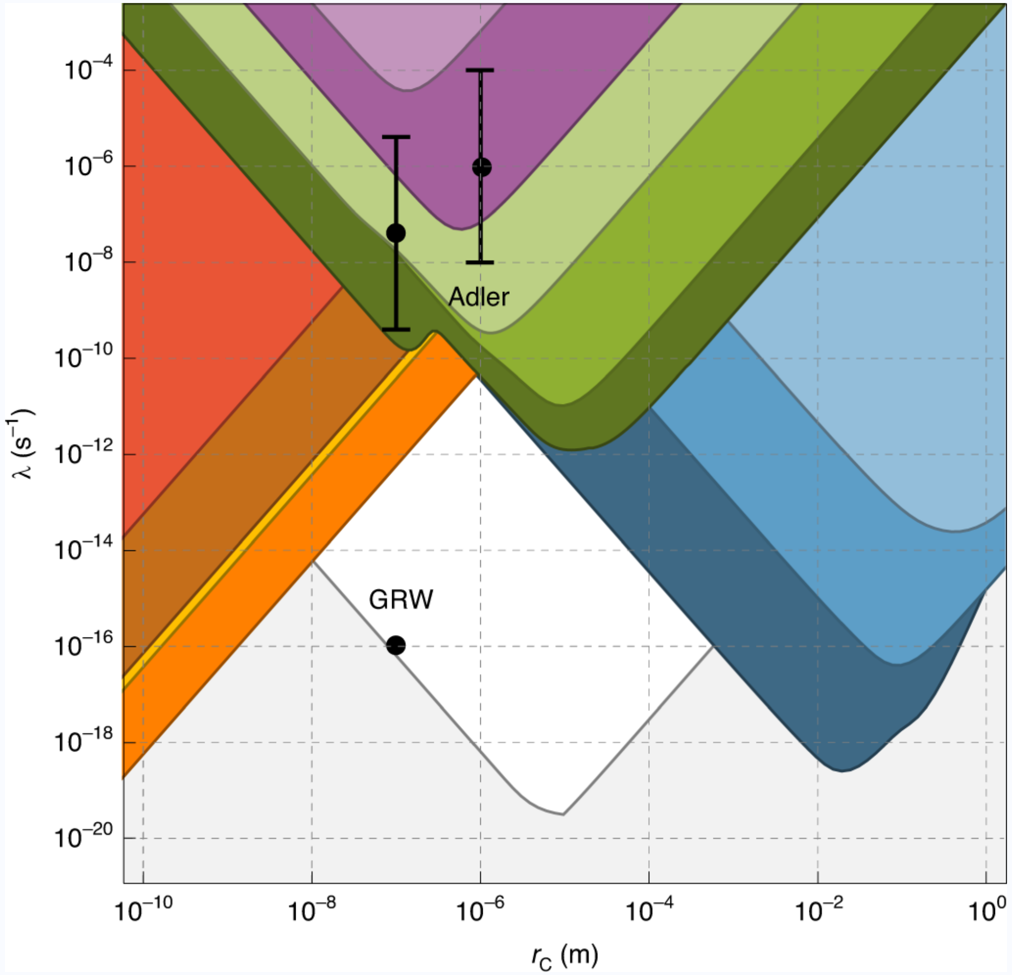


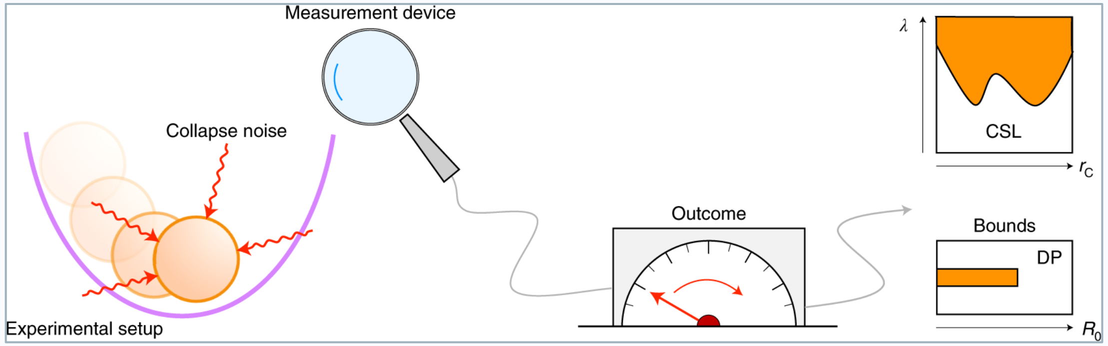
Experimental result:
Coherence and purity survive the expansion of the state from 0.5 nm to 250 nm.

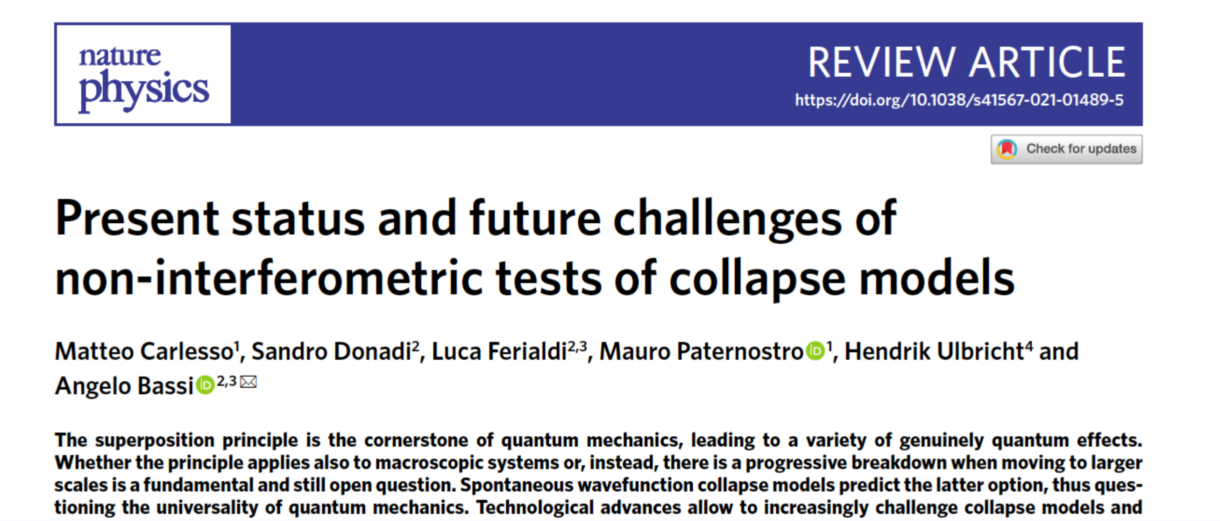
Muffato, R., Georgescu, T.S., Carlesso, M., Paternostro, M. and Ulbricht, H., 2024. **Coherent expansion of the motional state of a massive nanoparticle beyond its linear dimensions.** *arXiv preprint arXiv:2408.09596*.

Testing quantum superposition principle:

Non-interferometric and interferometric by comparing to model predictions







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]

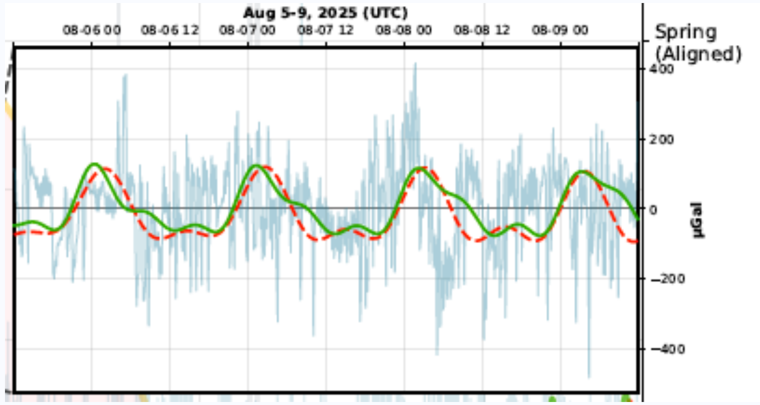
The superposition principle is the cornerstone of quantum mechanics, leading to a variety of genuinely quantum effects. Whether the principle applies also to macroscopic systems or, instead, there is a progressive breakdown when moving to larger scales is a fundamental and still open question. Spontaneous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

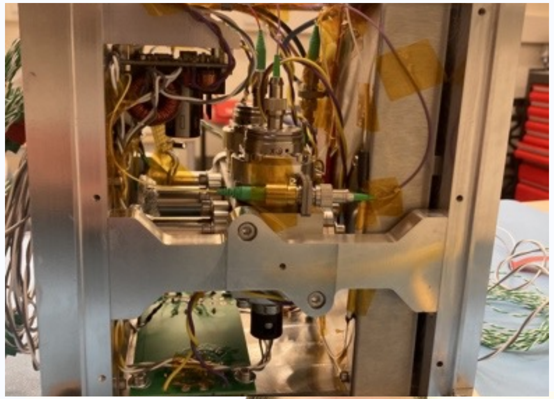
Previous review: Bassi, A., K. Lochan, S. Satin, TP. Singh, and H. Ulbricht, Rev. Mod. Phys. 85, 471 (2013).

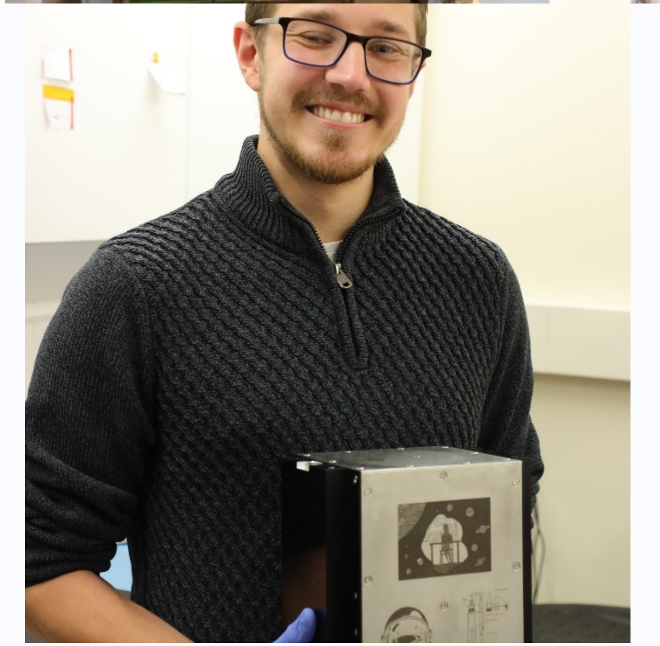
2025 – Credibility: LOMS in space

Space tech demo: 23/06/2025 LOMS launched with Falcon 9 from Vandenberg space port.

Gravimeter tech demo: LOMS gravimeter used to detect Earth tides at < 1 microGal.



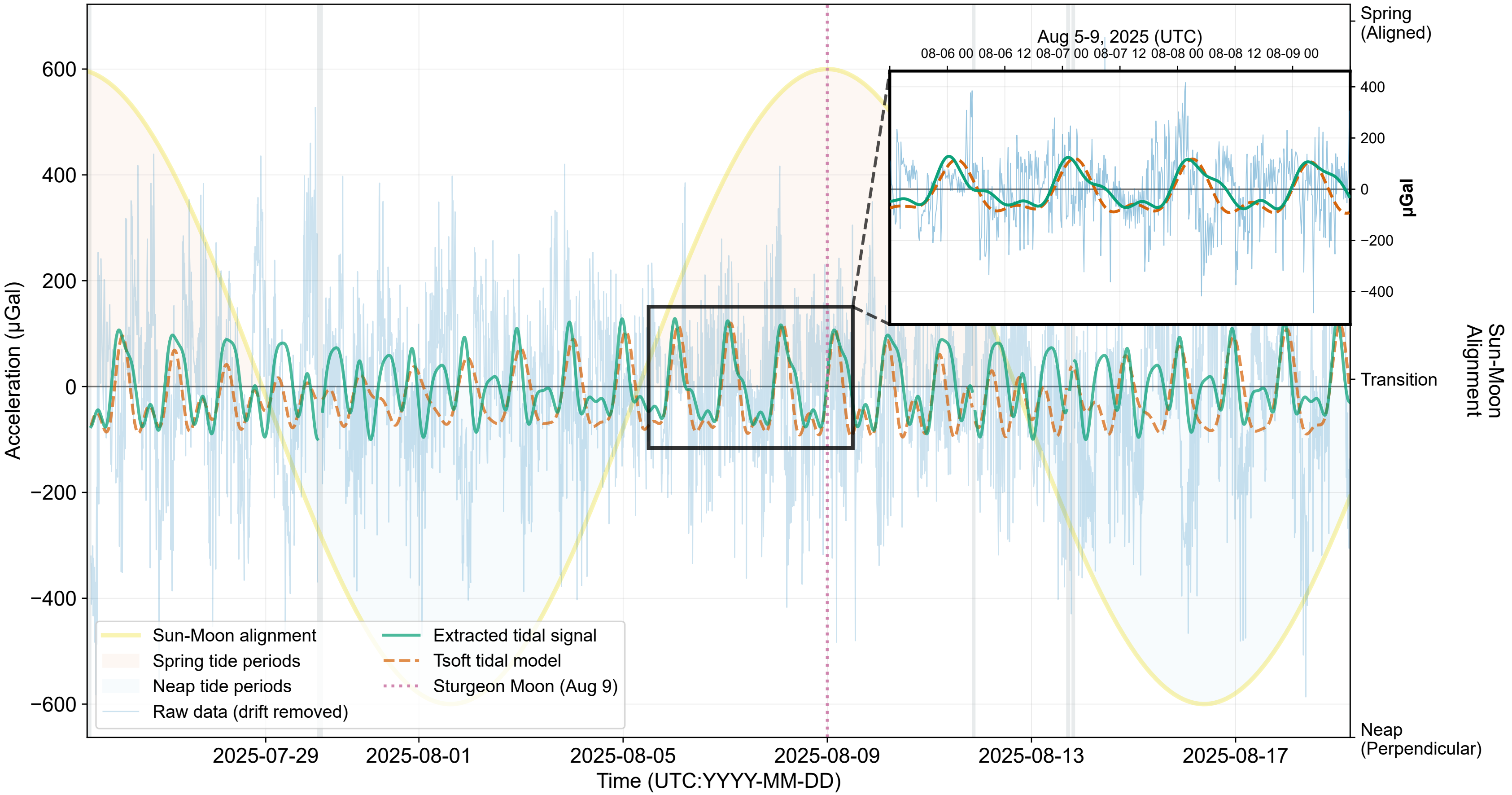




Homans, J., Simcox, E., Wardak, J., da Palma Barbara, L., Fuchs, T.M., Mufato, R., Concepcion, F., Dragomir, A., Vogt, C., Nisbet-Jones, P. and Bridges, C., 2025. **An experimental platform for levitated mechanics in space.** *Quantum Science and Technology*, *10*(3), p.035053.

TECHNOLOGY DEMONSTRATOR: EARTH TIDES @ SOUTHAMPTON

- Outperforming existing gravimeters
- Cheap, low weight, small footprint, low power consumption
- Commercialisation & spin-out, Innovate UK ICURe programme



APPLICATION AREA – 1: MATTER DETECTION & MONITORING, DUAL USE

- Reliable data production on mass position and mass movement for:

    1. **Discovery & extraction monitoring**: oil & gas, CO_2 management - net zero, blue & green hydrogen, fracking, minerals, underground water monitoring, moist of soil.
    2. **Monitoring effects of global warming**: ice melting in polar regions, sea water level rising, flooding and disaster forecasting, weather.
    3. **Monitoring geological processes**: volcano activities, tsunamis, earth- and sea-quake forecast, etc.
    4. **Civil engineering, security & defence:** detection & monitoring of underground caves & tunnels, buried utilities, pipes, sinkholes, mine shafts, water & fuel reservoirs.

- **Space-enabled example:** EO - satellite geodesy (swarm): high spatial & temporal resolution data with global context, complementary to optical and thermal data.

Science case: Nanoparticle interferometer

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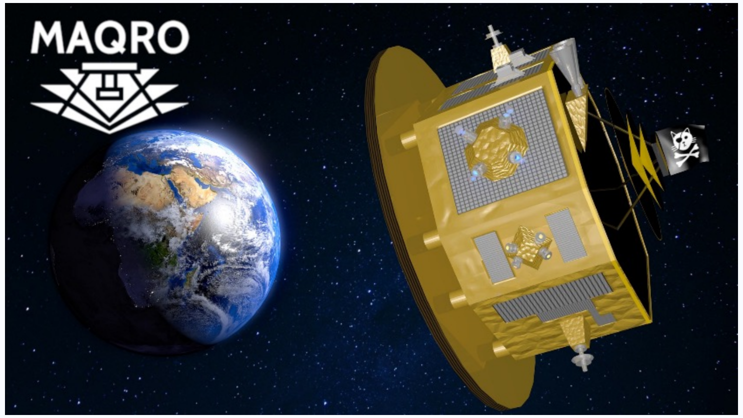
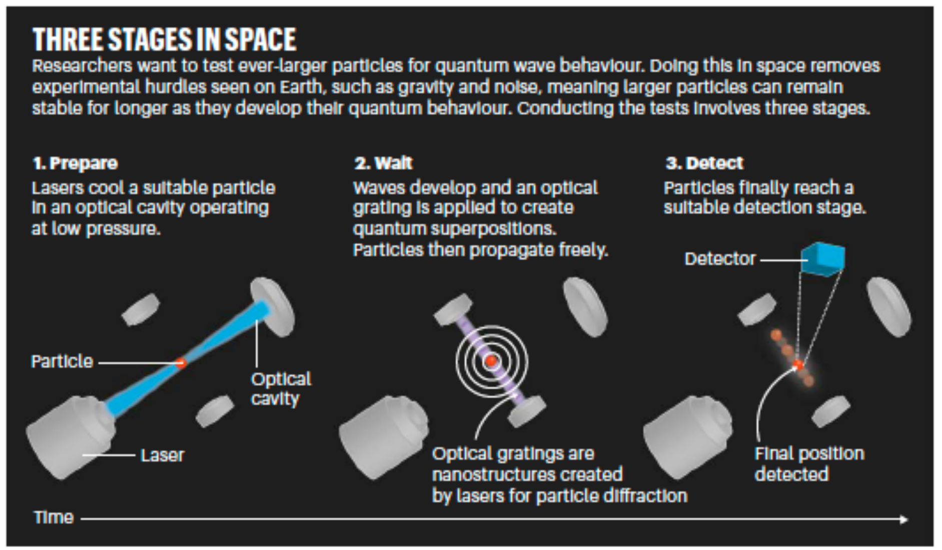
Objectives:

1. Enabling future tests of fundamental physics in space: Quantum theory, Gravity & gravitational waves, Dark Matter
   - ➢ A successful experiment would be the first ever macroscopic superposition with levitated nanoparticles, so new science is possible
2. Quantum Technology for space → satellite gravimetry (EO)





Theoretical foundations

ESA Voyage 2050 white paper on QT for space.

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).

A Bassi, et al. *A way forward for fundamental physics in space*, **npj Microgravity** 8 (1), 49 (2022).

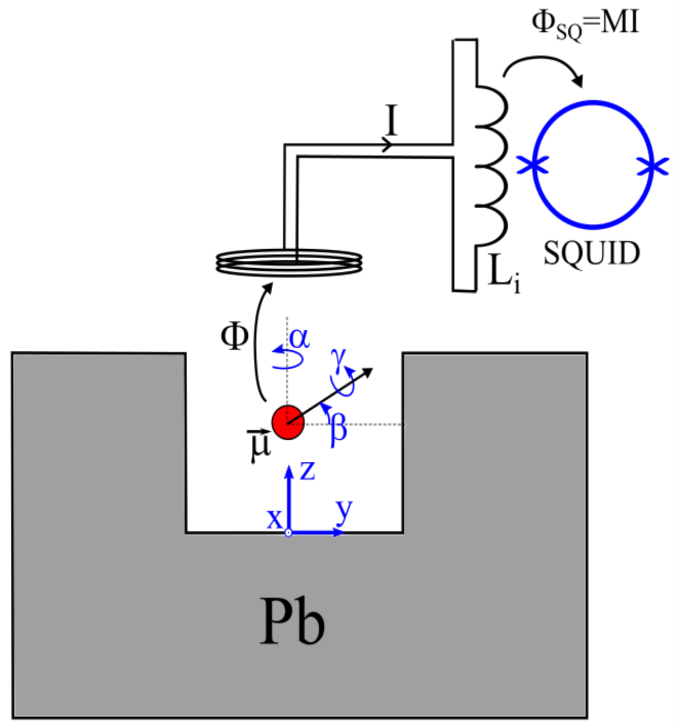
concurrent design facility 2018

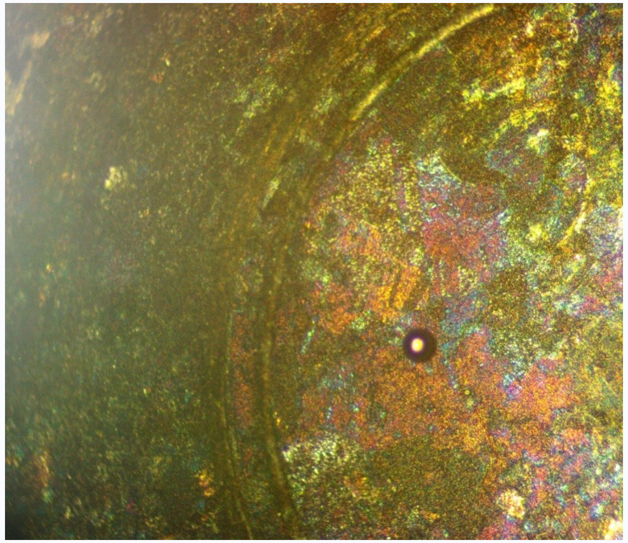
QPPF

esa

Levitated mechanics: Meissner trapping of ferromagnets

Passive trap: particle in the box:
Lateral surface provides x,y confinement





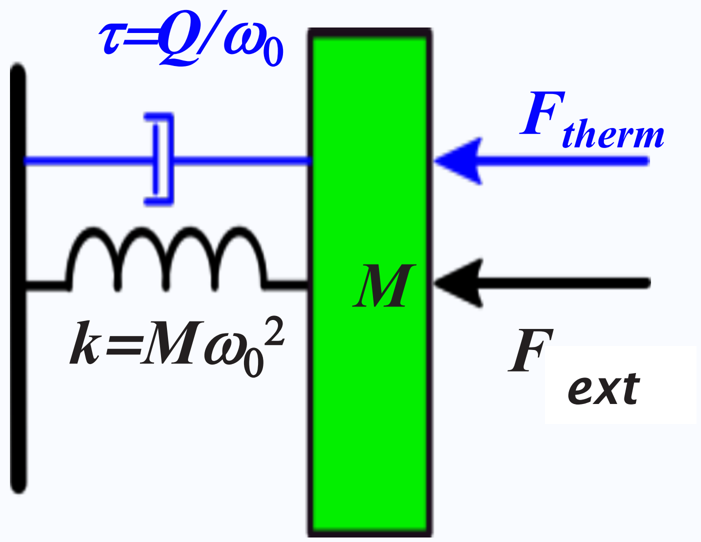
NdFeB microsphere radius = 27 um
Trap Radius = 2 mm

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)

Force (noise) in harmonic oscillator:

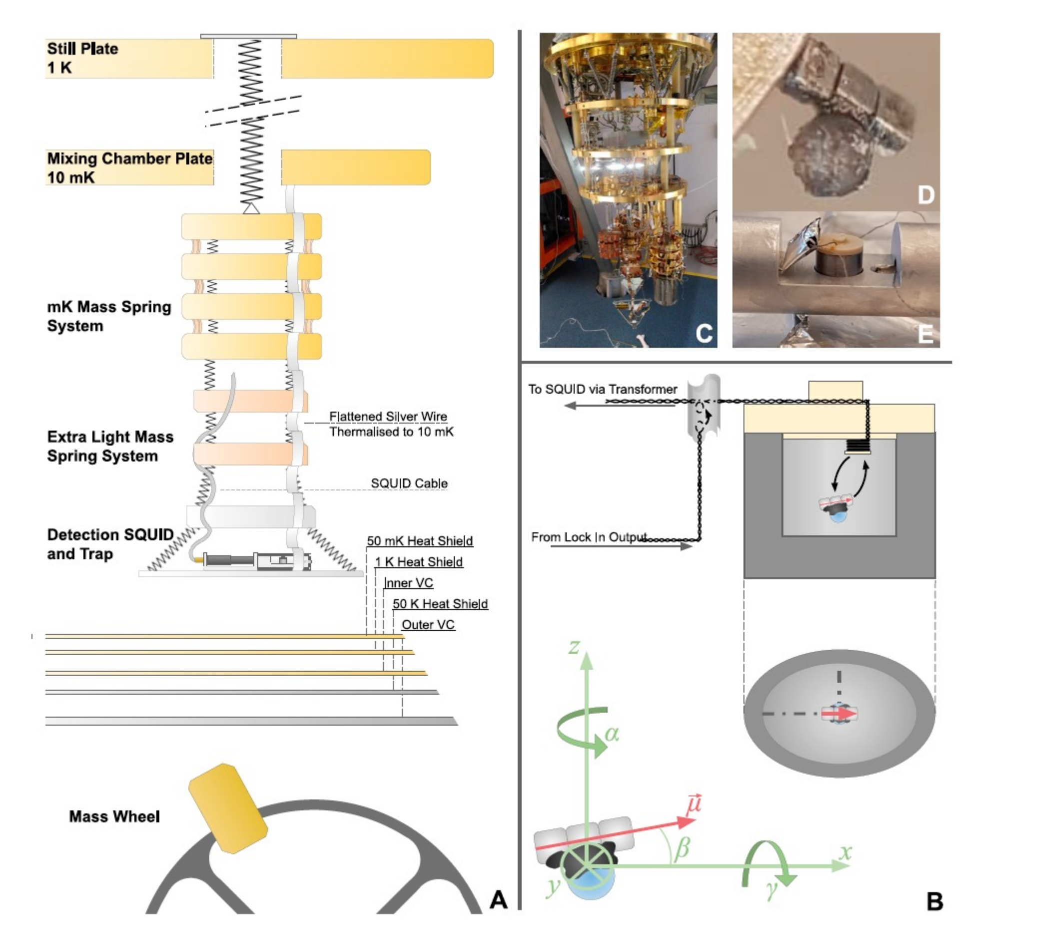
Thermal bath affect minimum force measured:

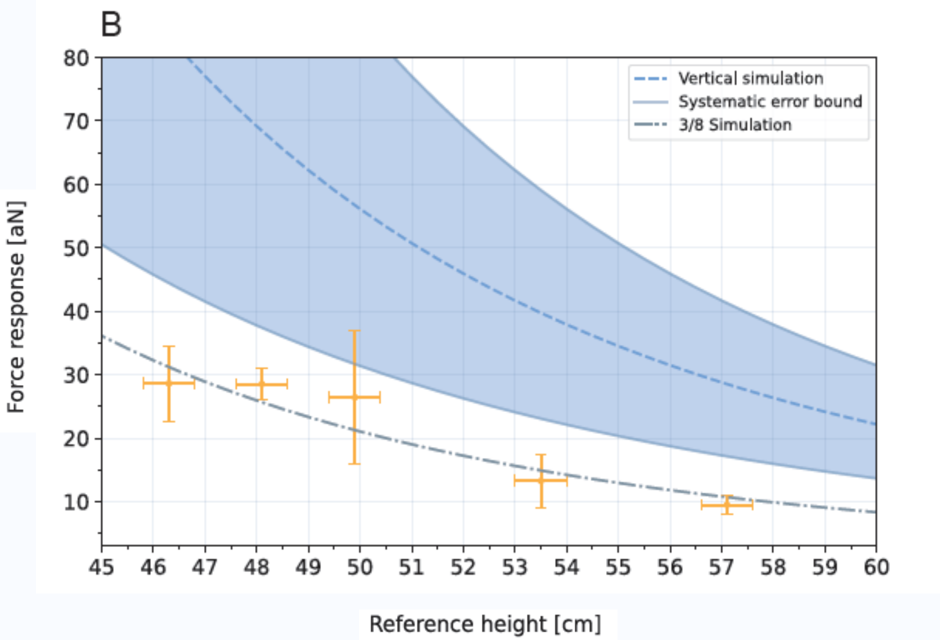
$$F_{min} = \sqrt{\frac{4k_B T_0 m\omega_0}{Q\tau}},$$



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.

Testing gravity in quantum systems and coherence in gravity

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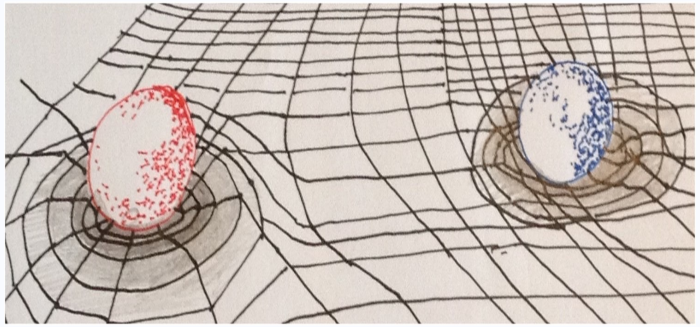
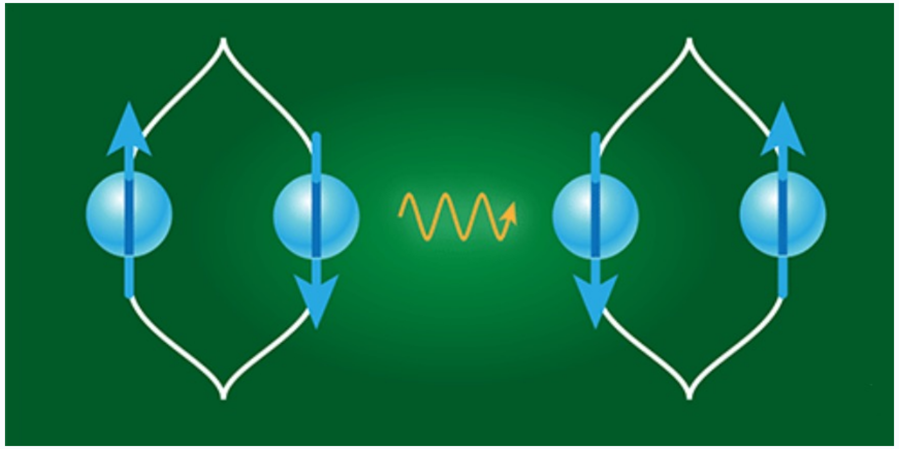
What is the gravitational field of a mass in superposition?



[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]

Bose, S., Fuentes, I., Geraci, A.A., Khan, S.M., Qvarfort, S., Rademacher, M., Rashid, M., Toroš, M., Ulbricht, H. and Wanjura, C.C., 2025. **Massive quantum systems as interfaces of quantum mechanics and gravity.** *Reviews of Modern Physics*, *97*(1), p.015003.

Bassi, A., Großardt, A. and Ulbricht, H., 2017. **Gravitational decoherence.** *Classical and Quantum Gravity*, *34*(19), p.193002.

Bose, S., Mazumdar, A., Morley, G.W., Ulbricht, H., Toroš, M., Paternostro, M., Geraci, A.A., Barker, P.F., Kim, M.S. and Milburn, G., 2017. **Spin entanglement witness for quantum gravity.** *Physical review letters*, *119*(24), p.240401.

Carlesso, M., Bassi, A., Paternostro, M. and Ulbricht, H., 2019. **Testing the gravitational field generated by a quantum superposition.** *New Journal of Physics*, *21*(9), p.093052.

ULDM search using gravity on levitated particle

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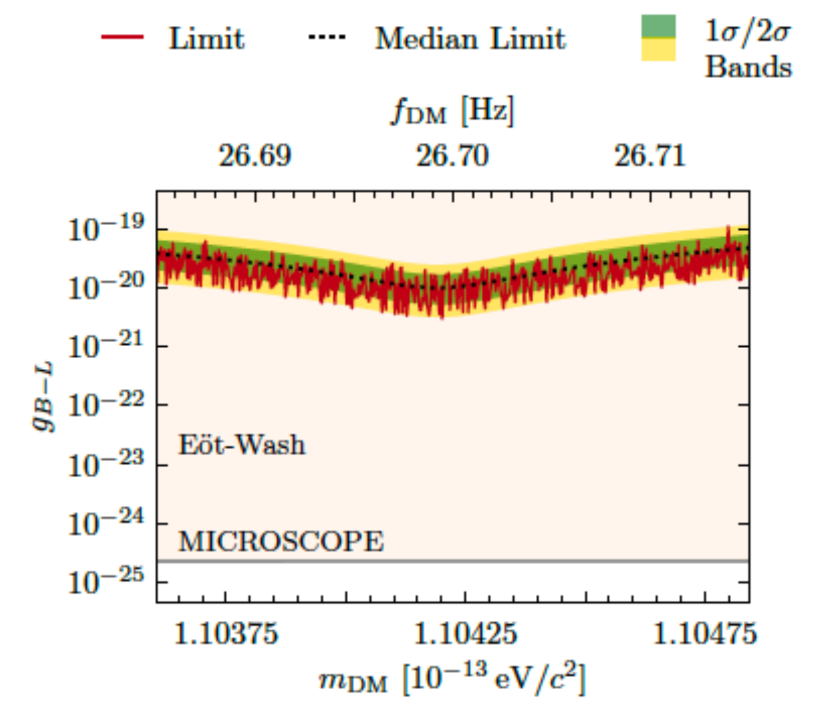
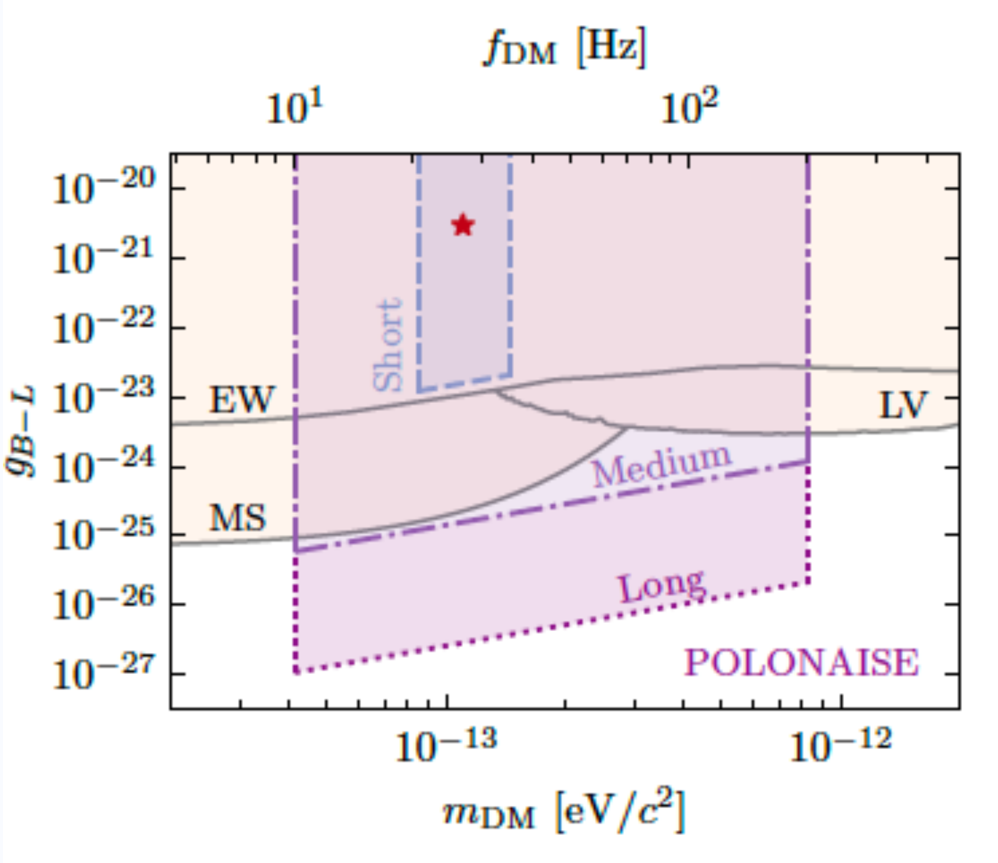
$$g_{B-L} = \frac{\kappa}{|\mathcal{R}_p - (\omega_0^2/\omega_{\mathrm{DM}}^2)\mathcal{R}_t|\, m_p a_0}\sqrt{\frac{2S_{FF}}{T_{\mathrm{obs}}}}$$

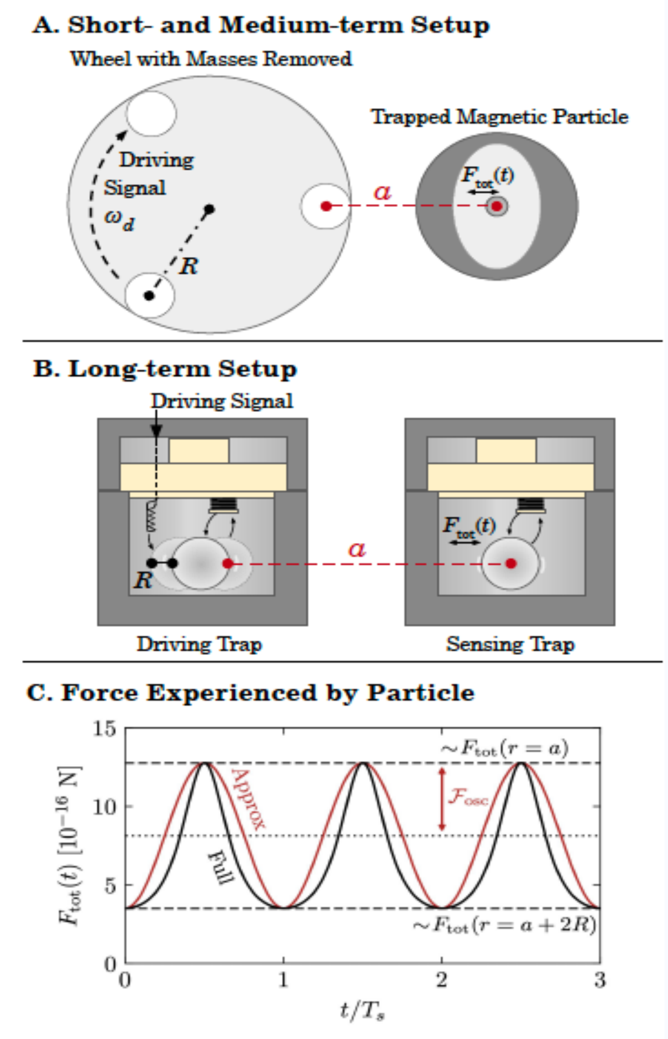


Future projection for optimized experiment



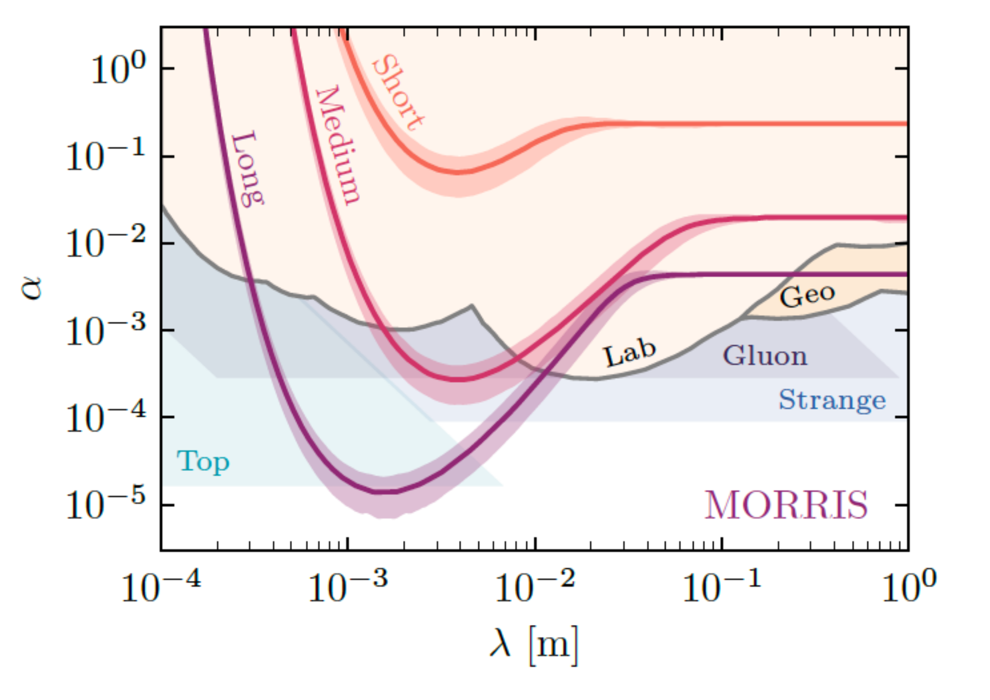
Amaral, D.W., Uitenbroek, D.G., Oosterkamp, T.H. and Tunnell, C.D., 2024. **First Search for Ultralight Dark Matter Using a Magnetically Levitated Particle.** *arXiv preprint arXiv:2409.03814*.

Probing modifications in gravity: MORRIS



Testing non-Newtonian gravity by Yukawa-type modification

$$U(r) \equiv -\frac{G_\infty m_s m_p}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



Amaral, D.W., Fuchs, T.M., Ulbricht, H. and Tunnell, C.D., 2026. **Magnetic levitation as a new probe of non-Newtonian gravity**. *Physical Review D*, *113*(2), p.L021101.

Exploring exotic interactions: directional fingerprint

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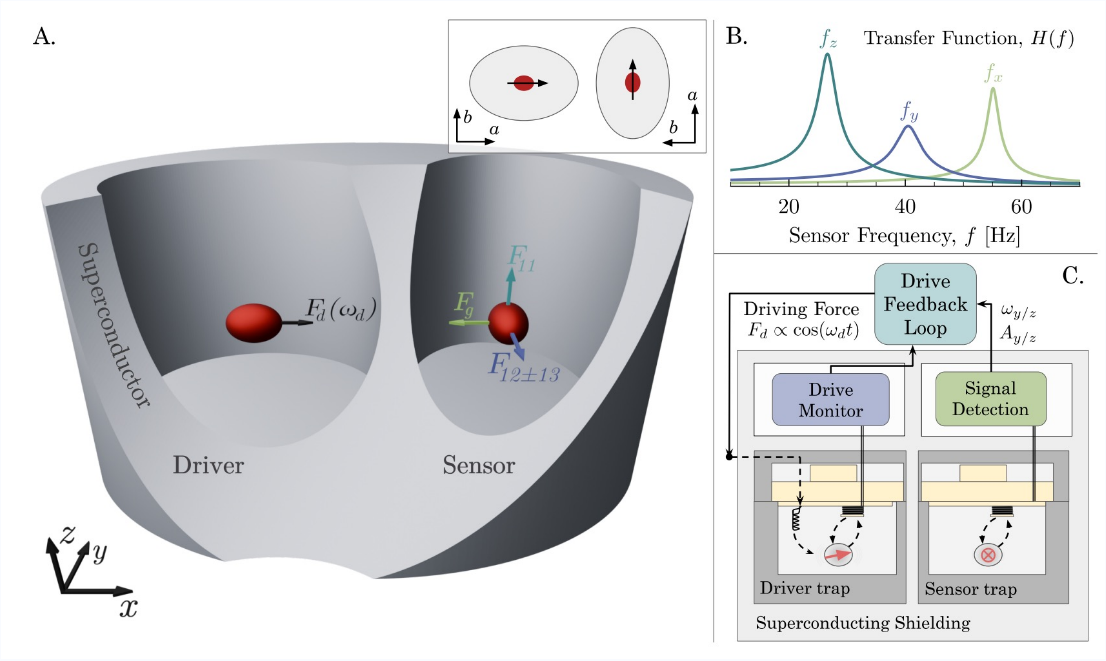
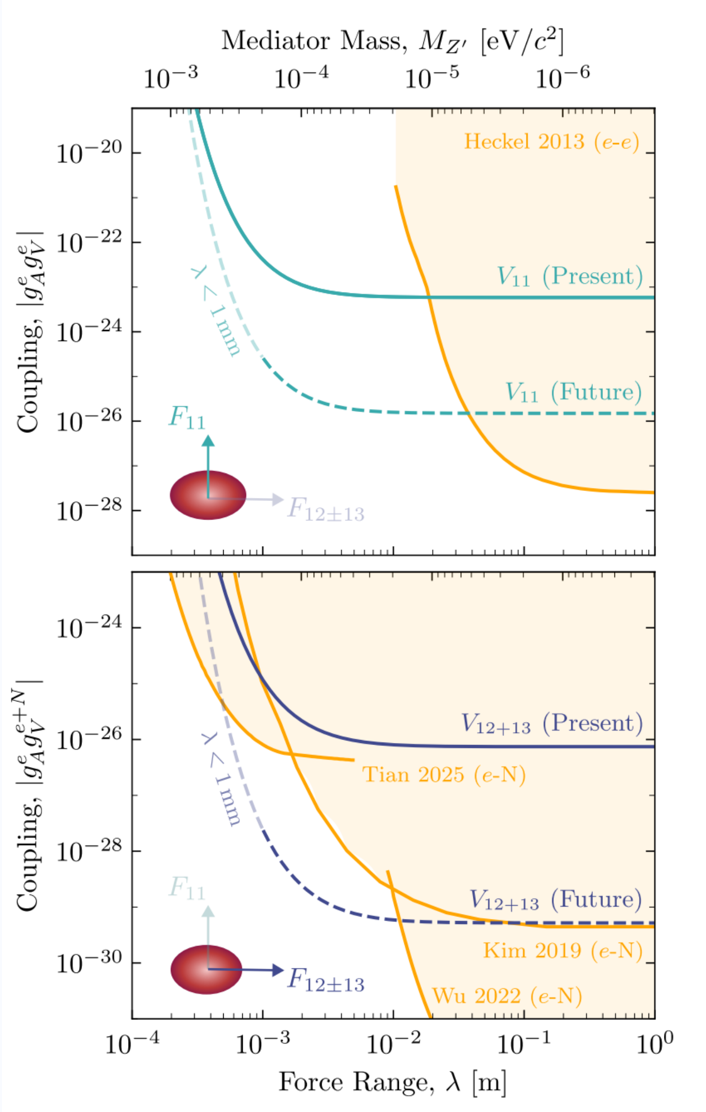


Amaral, D. W., Cong, L., Fuchs, T. M., Ulbricht, H., & Budker, D. (2026). **A Levitated-Magnet Vector Force Sensor for Spin-Dependent Exotic Interactions.** *arXiv preprint arXiv:2606.30781*.



Example, spin-spin interaction: Z' boson with parity-violating axial-vector – vector (AV) couplings induces distinguishable V_{12} and V_{11}

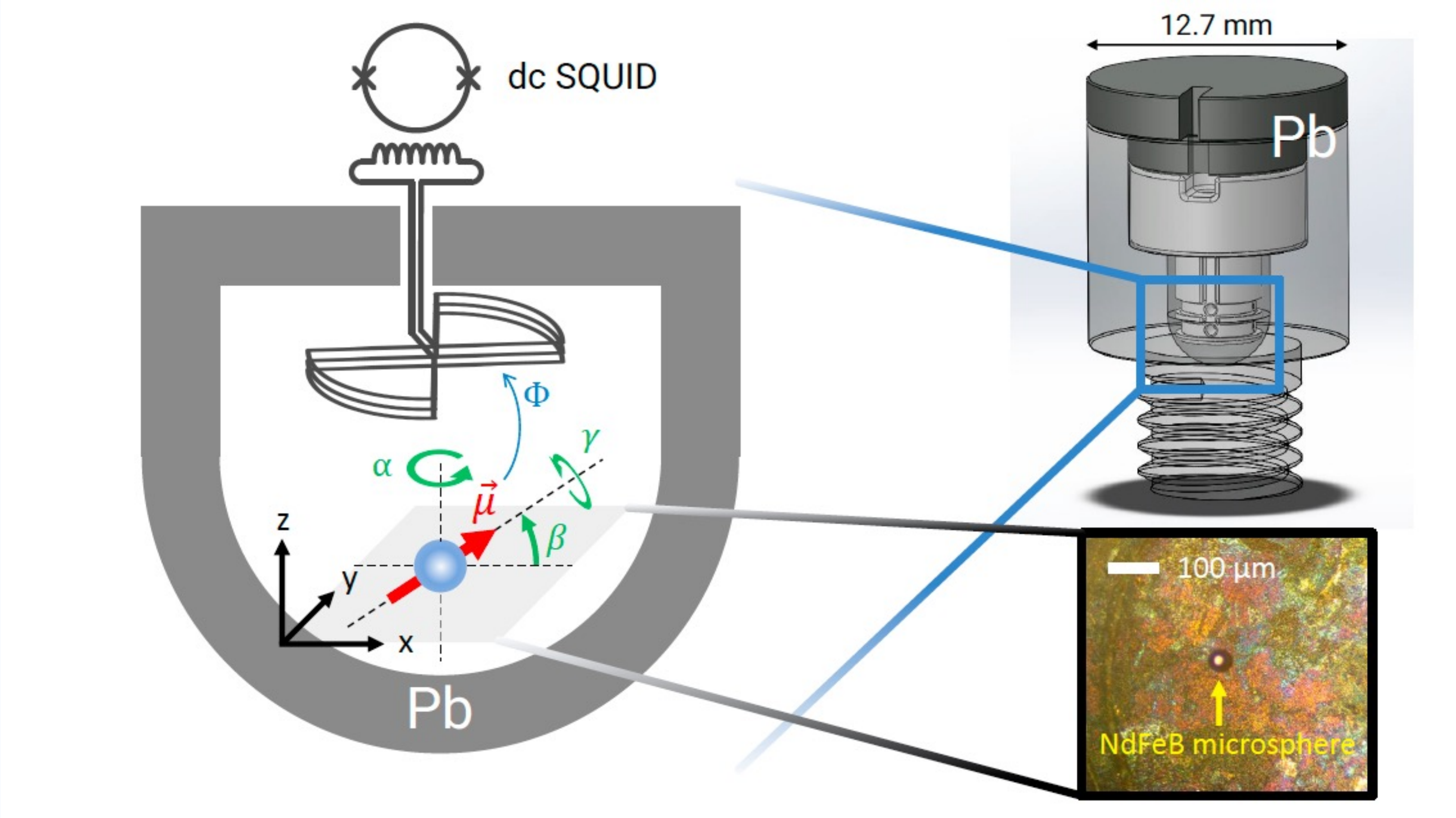
$$V_{AV}(\mathbf{r},\mathbf{v}) = \underbrace{-g_A^e g_V^e \frac{\hbar^2}{4\pi m_e}\left[(\boldsymbol{\sigma}_e \times \boldsymbol{\sigma}'_e)\cdot\hat{\mathbf{r}}\right]\left(\frac{1}{r^2}+\frac{1}{\lambda r}\right)e^{-r/\lambda}}_{V_{11}|_{AV}+V_{11}|_{VA}}$$

$$+\underbrace{g_A^e g_V^{e+N}\frac{\hbar}{4\pi}\left[(\boldsymbol{\sigma}_e - \boldsymbol{\sigma}'_e)\cdot\mathbf{v}\right]\frac{1}{r}e^{-r/\lambda}}_{V_{12+13}|_{AV}+V_{12-13}|_{AV}}\,. \qquad (1)$$

Electron spins

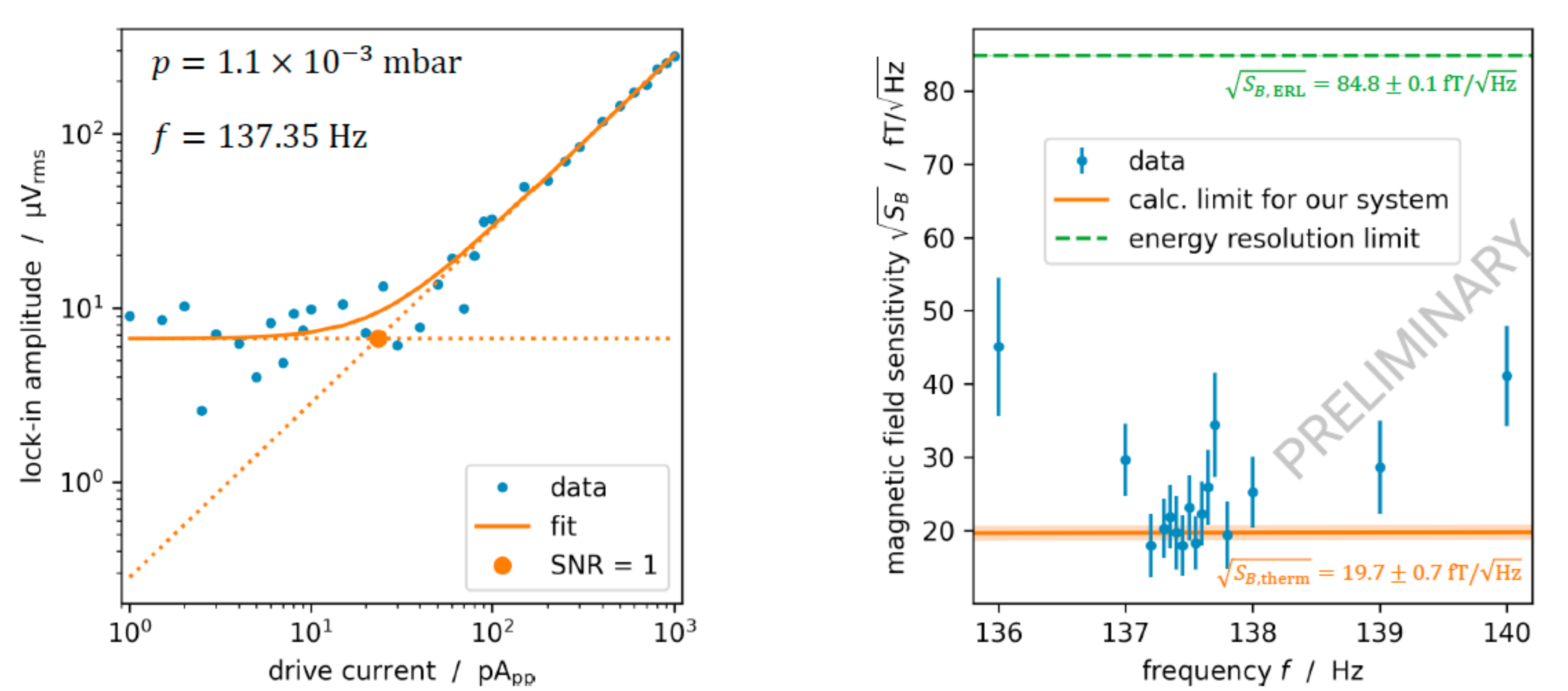
Electron+nuclear spins

Experimental Set-up (in Trento)



Felix Ahrens & Andrea Vinante

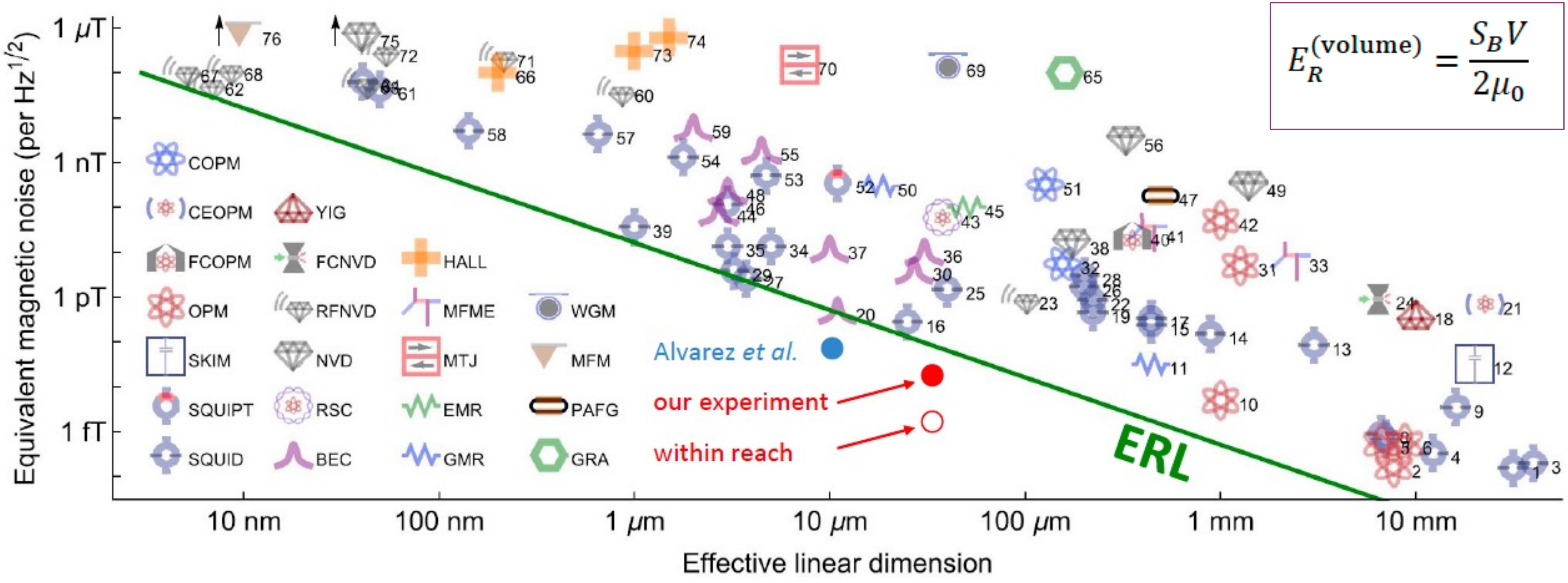
Experimental results: magnetic field detection



Ahrens, F., Ji, W., Budker, D., Timberlake, C., Ulbricht, H., & Vinante, A., **Levitated ferromagnetic magnetometer with energy resolution well below $\hbar$.** *PRL 134, 110801 (2025), and arXiv:2401.03774.*

Experimental result:

B-field sensing below quantum limit



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

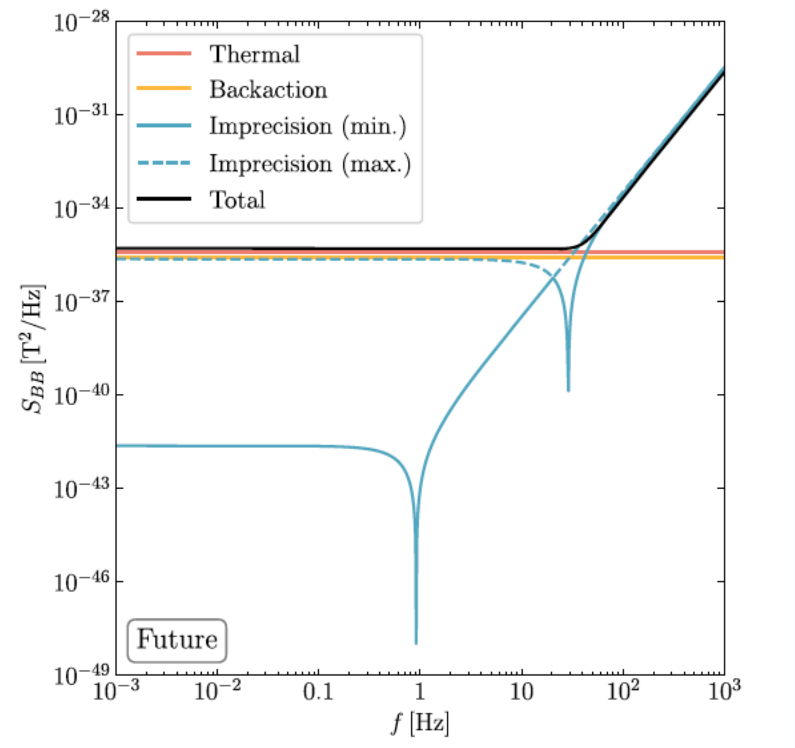
Alvarez et al., *Proc. Natl. Acad. Sci. USA*, 119, e2115339119 (2022)

Ahrens, F., Ji, W., Budker, D., Timberlake, C., Ulbricht, H., & Vinante, A., *PRL 134, 110801 (2025).*

ULDM detection with levitated magnetometer

Three different scenarios for experiment:

Parameter	Existing	Future	Freefall
Ferromagnet radius R	20 μm	2 mm	2 cm
Ferromagnet magnetization M		7×10^5 A/m	
Ferromagnet density ρ		7400 kg/m^3	
Temperature T	4 K	50 mK	300 K
Dissipation rate γ	10^{-2} Hz	2×10^{-6} Hz	10^{-10} Hz
Azimuthal trapping $V_{\phi\phi}$	10^{-14} J	$10^{-3} V_{\theta\theta}$	7×10^{-9} J
Energy resolution $\kappa_\theta = \kappa_\phi$	$1000\hbar$	$\hbar$	$\hbar$
Polar coupling $\tilde{\eta}_\theta$	$1.1 \times 10^{-7}\ \sqrt{\text{J}}$	$3.7 \times 10^{-3}\ \sqrt{\text{J}}$	$10^{-5}\ \sqrt{\text{J}}$
Azimuthal coupling $\tilde{\eta}_\phi$	$5 \times 10^{-9}\ \sqrt{\text{J}}$	$3.7 \times 10^{-3}\ \sqrt{\text{J}}$	$10^{-5}\ \sqrt{\text{J}}$
$\tilde{\eta}_\theta^{(\text{res})} = \tilde{\eta}_\phi^{(\text{res})}$	$9.1 \times 10^{-7}\ \sqrt{\text{J}}$	$4.6 \times 10^{-3}\ \sqrt{\text{J}}$	$2.5\ \sqrt{\text{J}}$
$\tilde{\eta}_\theta^{(\text{broad})}$	$6.4 \times 10^{-7}\ \sqrt{\text{J}}$	$3.6 \times 10^{-3}\ \sqrt{\text{J}}$	$10^{-5}\ \sqrt{\text{J}}$
$\tilde{\eta}_\phi^{(\text{broad})}$	$10^{-7}\ \sqrt{\text{J}}$	$1.1 \times 10^{-4}\ \sqrt{\text{J}}$	$10^{-5}\ \sqrt{\text{J}}$
ω_I	$2\pi \times 0.53$ Hz	$2\pi \times 5.3 \times 10^{-5}$ Hz	$2\pi \times 5.3 \times 10^{-7}$ Hz
$v_{\theta\theta}$	$2\pi \times 4.9 \times 10^5$ Hz	$2\pi \times 1.6 \times 10^7$ Hz	$2\pi \times 0.12$ Hz
$v_{\phi\phi}$	$2\pi \times 1.2 \times 10^4$ Hz	$2\pi \times 1.6 \times 10^4$ Hz	$2\pi \times 0.12$ Hz



Kalia, S., Budker, D., Kimball, D.F.J., Ji, W., Liu, Z., Sushkov, A.O., Timberlake, C., Ulbricht, H., Vinante, A. and Wang, T., 2024. **Ultralight dark matter detection with levitated ferromagnets.** *Physical Review D*, *110*(11), p.115029.

Three coupling cases: DM to magnetometer

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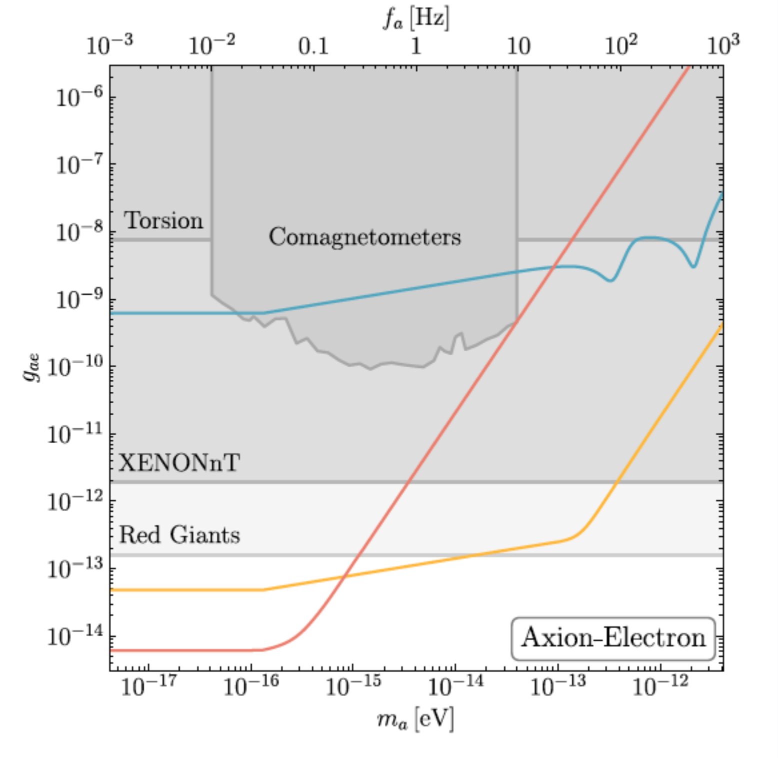
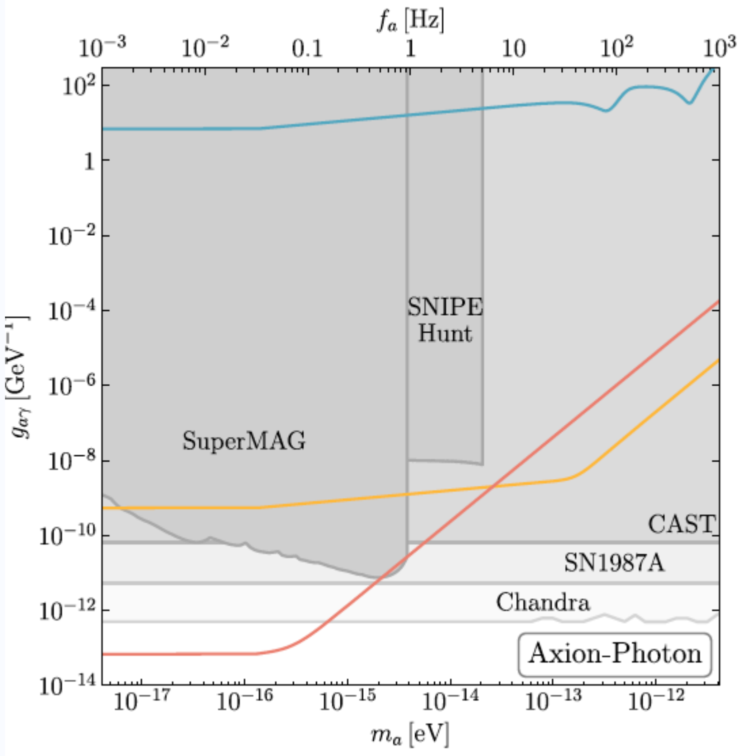
Axion-electron coupling

$$\mathcal{L}_{ae} \supset \frac{g_{ae}\sqrt{\hbar^3 c}}{2m_e}\partial_\mu a \bar{\psi}_e \gamma^\mu \gamma_5 \psi_e$$



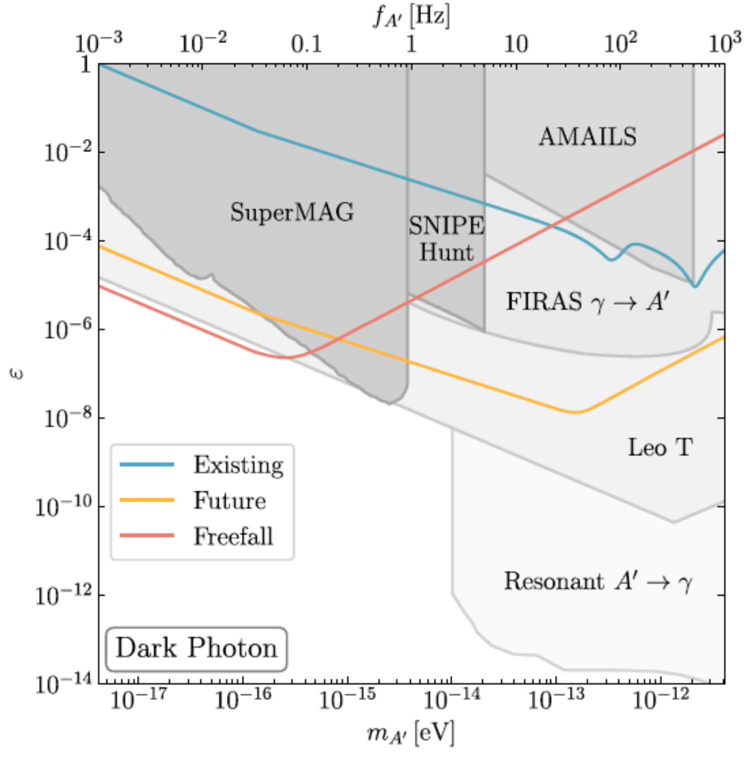
Axion-photon coupling

$$\mathcal{L} \supset \frac{g_{a\gamma}\sqrt{\hbar c^3}}{4\mu_0} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Dark-photon kinetic mixing

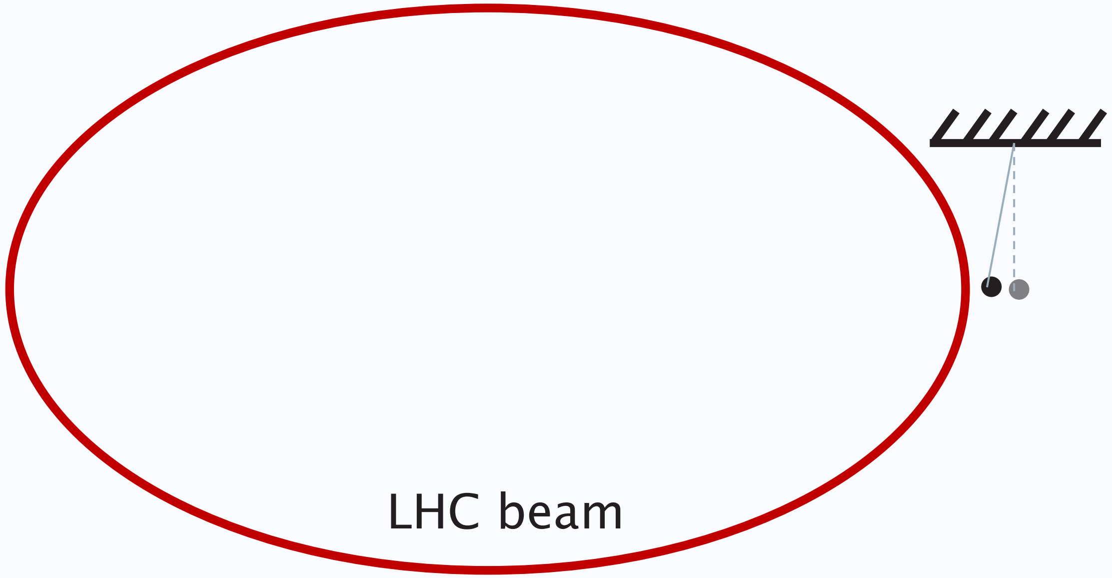
$$\mathcal{L}_{A'} \supset \frac{\varepsilon}{\mu_0}\left(\frac{m_{A'}c}{\hbar}\right)^2 A_\mu A'^\mu$$



Kalia, S., Budker, D., Kimball, D.F.J., Ji, W., Liu, Z., Sushkov, A.O., Timberlake, C., Ulbricht, H., Vinante, A. and Wang, T., 2024. **Ultralight dark matter detection with levitated ferromagnets.** *Physical Review D*, *110*(11), p.115029.

The G-LHC Project: part of DRD5

To measure the gravitational near field of the LHC proton beam



	P_{p}	$T_{\mathrm{p}}^{\mathrm{cav}}$	P_{avg}	w_{B}
pulses in cavity	$3 \cdot 10^{14}$ W	100 fs ·10 kHz $\frac{8 \cdot 10^5}{\omega_0}$	$2 \cdot 10^{10}$ W	$< 100\ \mu$m
cw cavity	$2 \cdot 10^{11}$ W	$\frac{\pi}{\omega_0}$	$1 \cdot 10^{11}$ W	$< 100\mu$m
LHC	10^{14} W	10^{-9} s	$3.8 \cdot 10^{12}$ W	16 μm

Lab-scale test of GR in entirely new parameter regime

- ultrarelativistic source of gravity (special relativity)

Non-relativistic acceleration sensor

- sensitive to T_{00} component
- Newtonian gravity, but source of gravity = almost pure kinetic energy rather than mass

Test alternative gravity theories against experiment

- e.g. Brans-Dicke theory
- theories with free energy as source
- in general, parametrized post-Newtonian theories

➔ **Experiment:** What counts is average power and distance from beam.

Radial acceleration of non-relativistic probe mass:

Best accelerometers: LISA Pathfinder 10^{-15} m/(s^2 Hz$^{1/2}$)

$$a_\rho = -\frac{4GP_{\mathrm{av}}}{c^3}\frac{1}{\rho} \simeq -1.9 \cdot 10^{-20}\,\mathrm{m/s^2} \text{ at } \rho = 2\,\mathrm{mm}$$

Braun, D., Cai, R., Hermes, P., Marchese, M.M., Nimmrichter, S., Pfeifer, C., Rätzel, D., Redaelli, S. and Ulbricht, H., 2025. **The path towards measuring the gravitational field of proton bunches at accelerators.** *arXiv preprint arXiv:2504.10942.*

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Thanks to

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External Experiment: Tjerk Oosterkamp, Andrea Vinante, Dmitry Budker, Derek Kimball, Sasha Sushkov, Gavin Morley.