

Levitation for large-mass superpositions

Bas Hensen | 16-9-2026



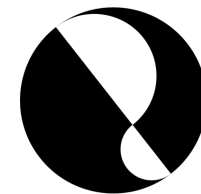
**Universiteit
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The Netherlands



European Research Council



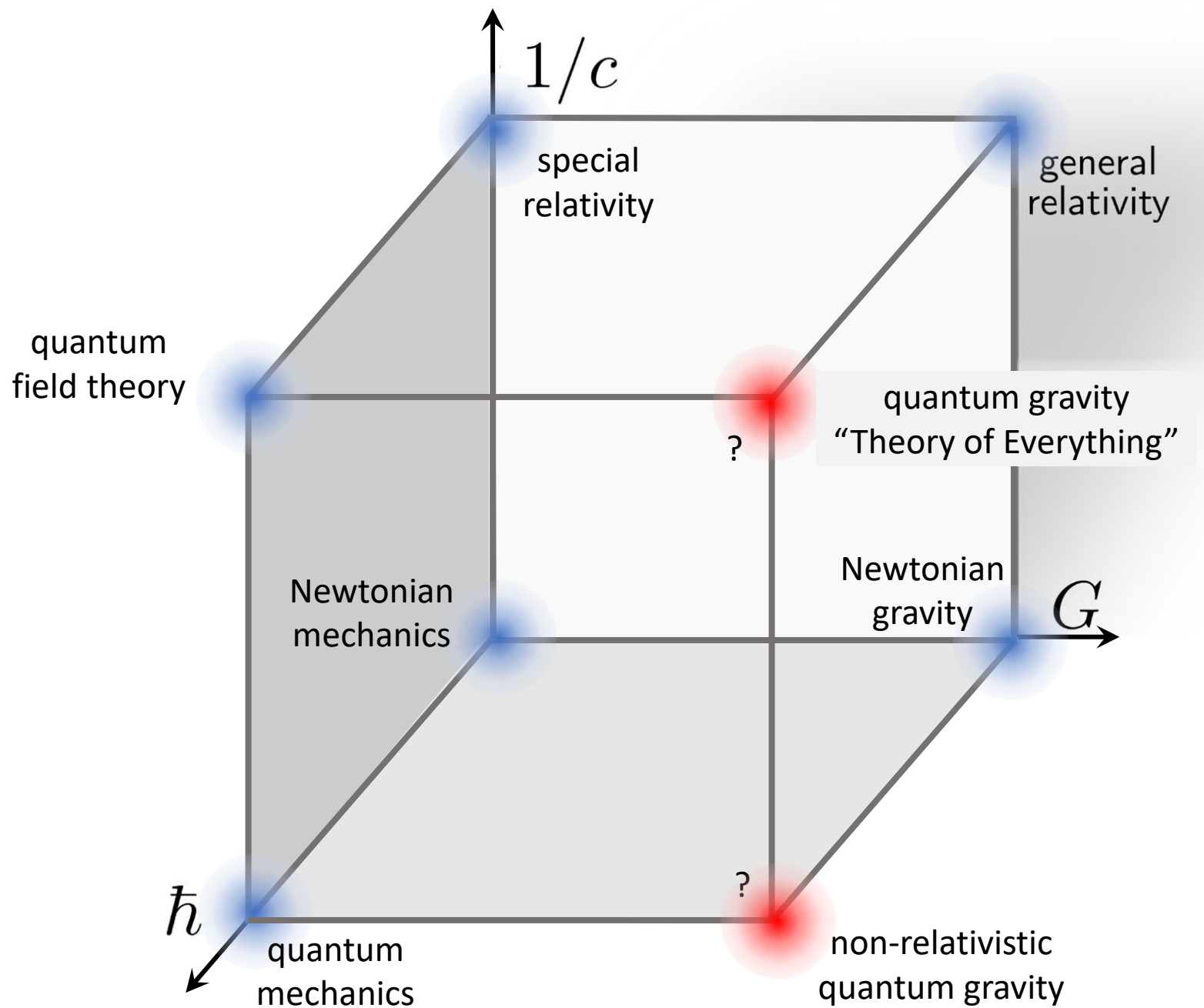
**Einstein Telescope
for business**



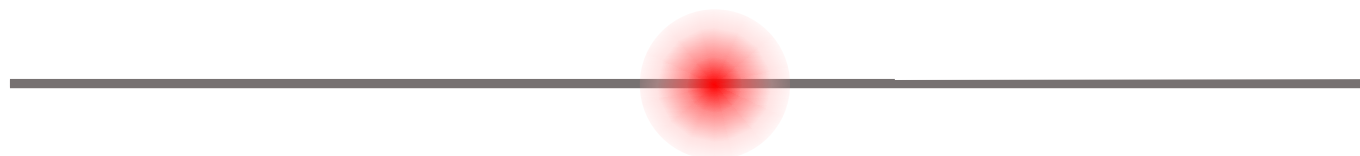
**Quantum
Delta NL**



Discover the world at Leiden University



quantum
mechanics

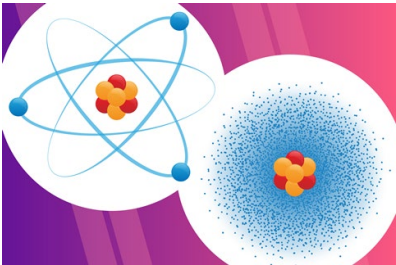


Newtonian
gravity

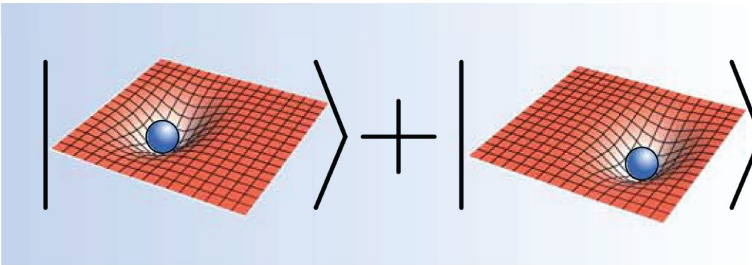
How massive can a quantum state be?

How small can a gravitational source mass be?

quantum
mechanics



Single atoms, ions



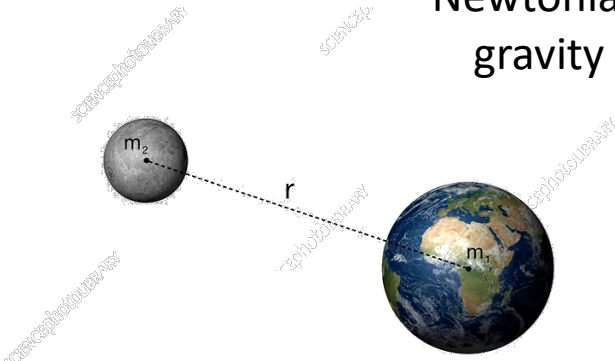
Is gravity quantum?

→ gravity mediated entanglement test

Or not?

→ gravitationally induced wafefunction collapse

Newtonian
gravity



Planetary motion

10^{-27} kg
1 fm

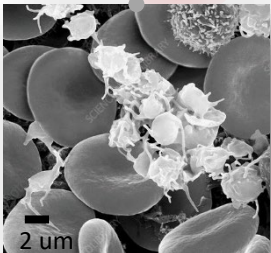
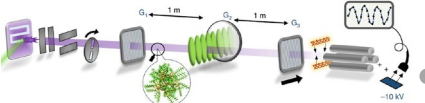
10^{-20} kg
1 nm

10^{-4} kg
1 mm

10^{24} kg
1000 km

Matter-wave interferometry

Fein, ..., Arndt, *Nat. Phys.* **15**, 1242 (2019)



www.sciencephoto.com
/media/873644

Torsion pendulum experiments

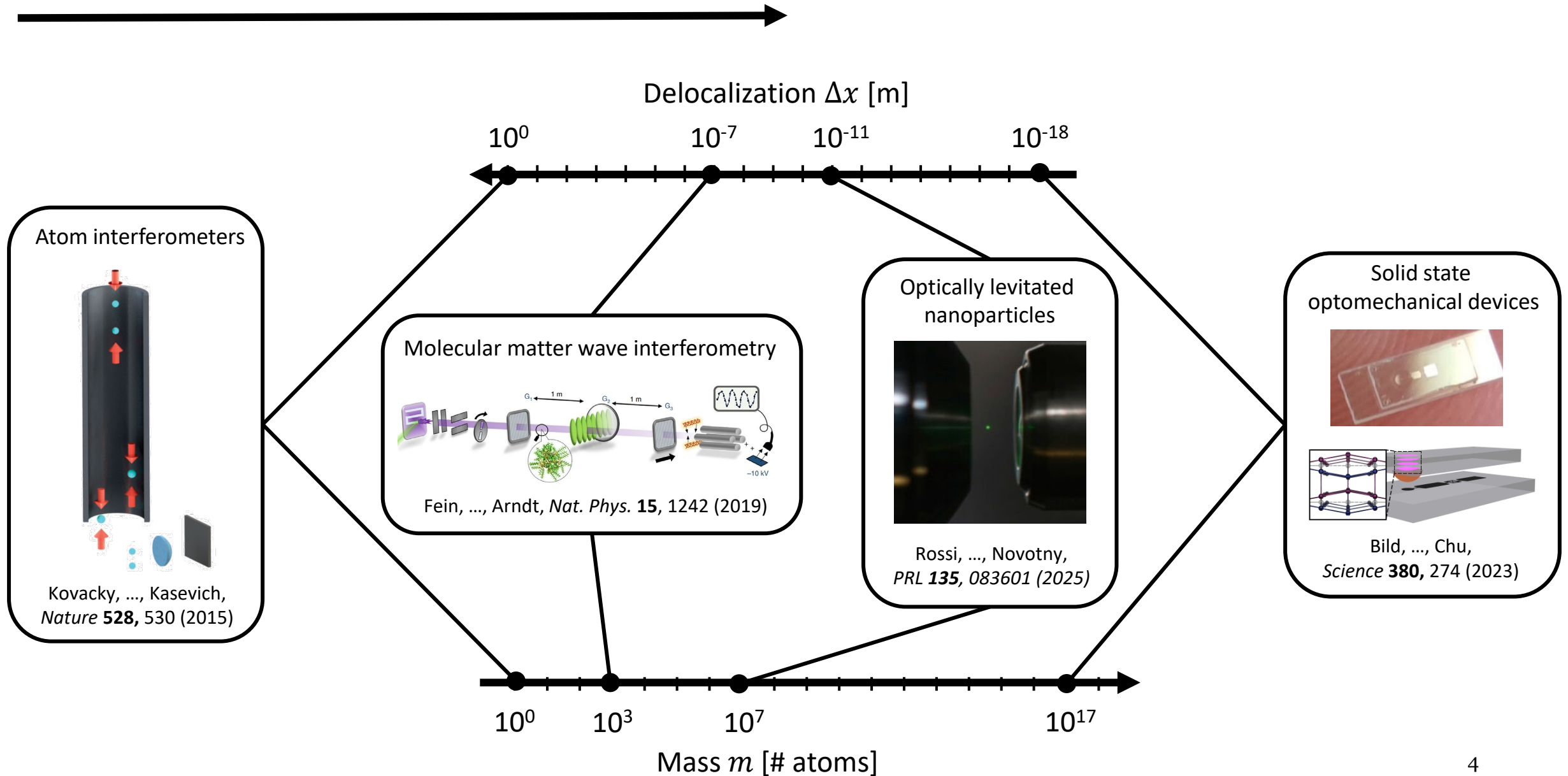
Westphal, ..., Aspelmeier, *Nature* **591**, 225 (2021)



How massive can a quantum state be?

e.g. superposition size

Macroscopic: large mass and large delocalization



How massive can a quantum state be?

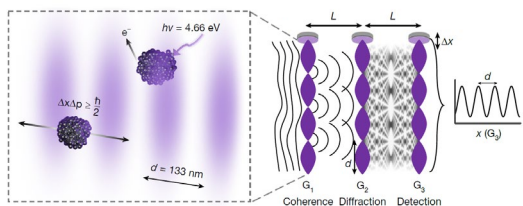
Macroscopic: large mass and large delocalization

e.g. superposition size

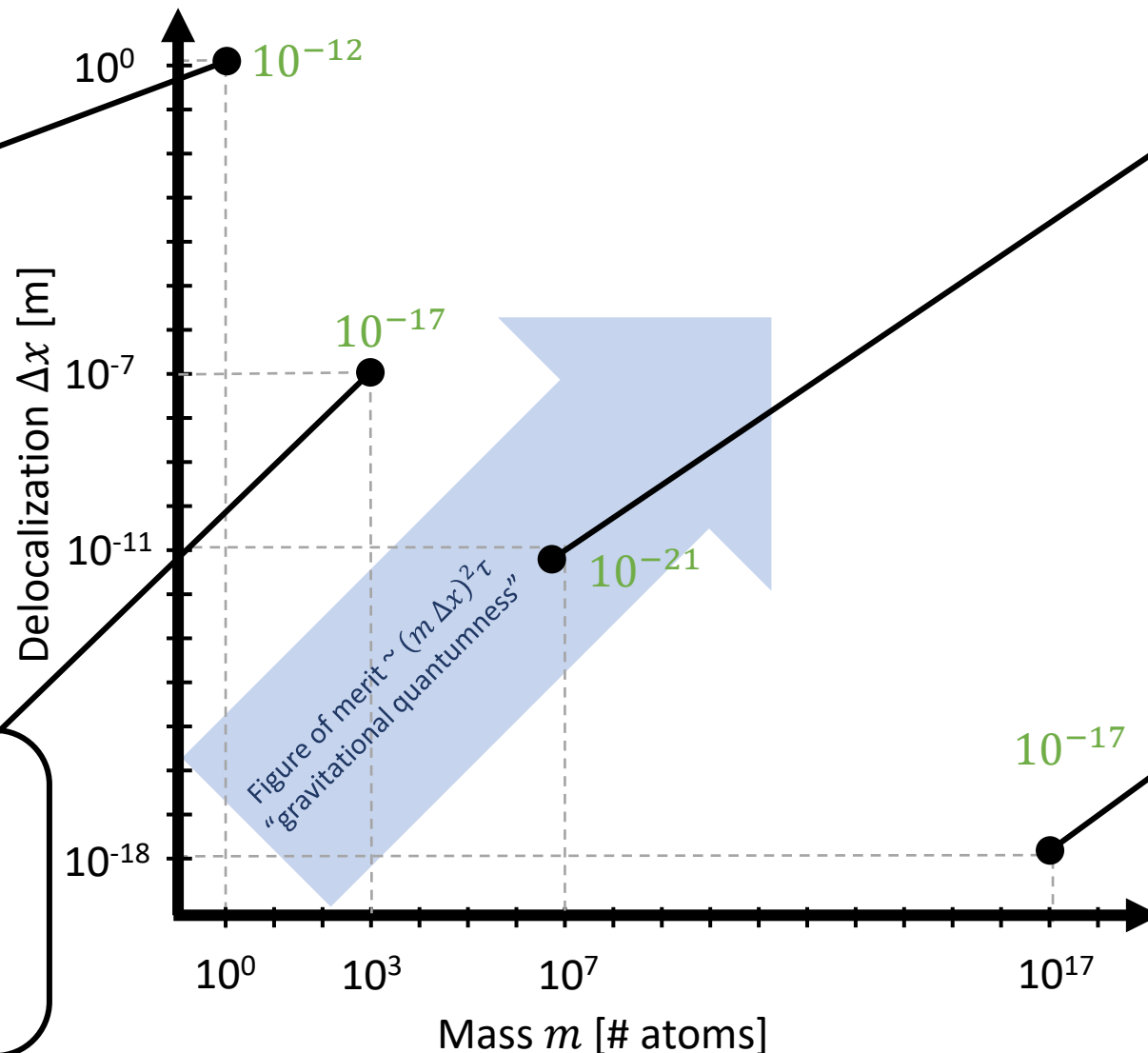
Atom interferometers



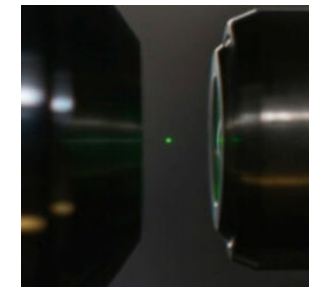
Kovacky, ..., Kasevich,
Nature **528**, 530 (2015)



Pedalino, ..., Arndt & Gerlich,
Nature **649**, 866 (2026)

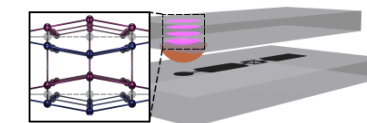


Optically levitated nanoparticles



Rossi, ..., Novotny,
PRL **135**, 083601 (2025)

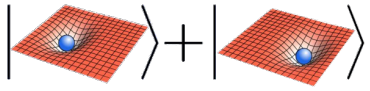
Solid state optomechanical devices



Bild, ..., Chu,
Science **380**, 274 (2023)

Green: Concurrence C for example
 $d = 10 \mu\text{m}$. Target: $C = O[1]$

Larger mass leads to smaller delocalisation



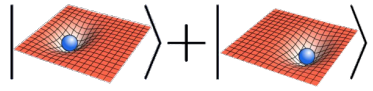
=

① Initialization in a pure state

② Prepare superposition

③ Verification of superposition

Larger mass leads to smaller delocalisation

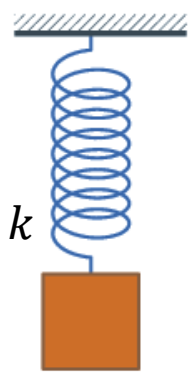


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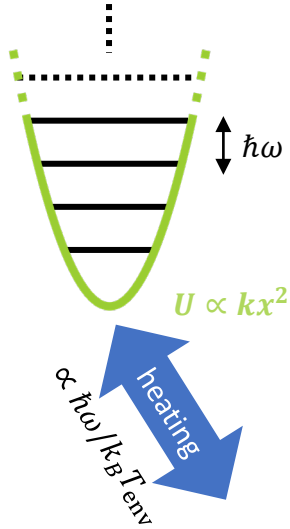
① Initialization in a pure state

② Prepare superposition

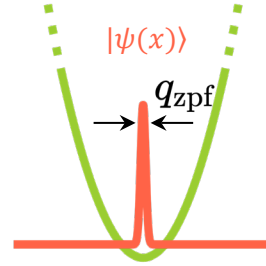
③ Verification of superposition



m



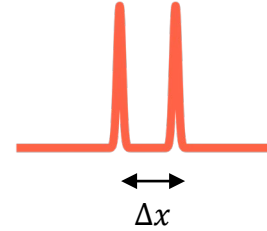
environment



$$q_{\text{zpf}} = \sqrt{\frac{\hbar}{2m\omega_m}}$$



→ pm-fm



Few phonon superposition size
→ Delocalization $\Delta x \approx O[1] \cdot q_{\text{zpf}}$

$$\omega_m = \sqrt{k/m}$$

The power of levitation: dynamical control of the confining potential

$$|\text{state 1}\rangle + |\text{state 2}\rangle$$

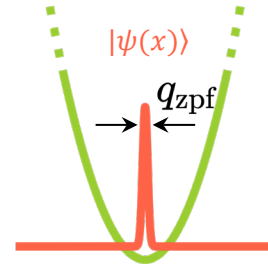
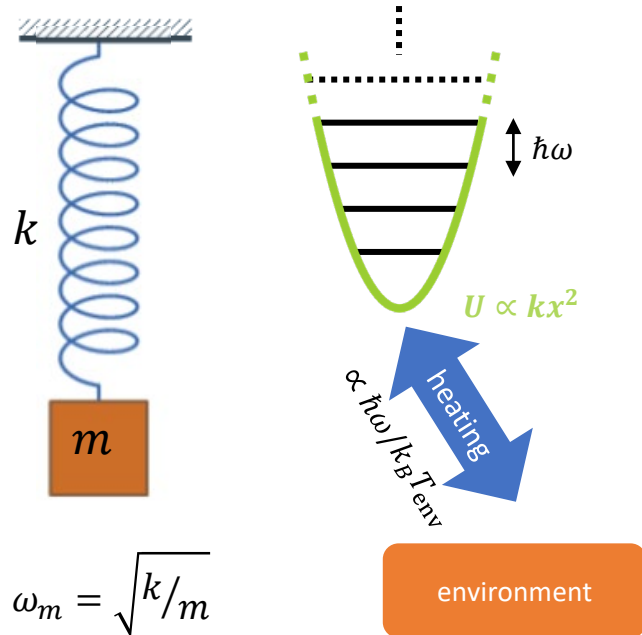
=

① Initialization in a pure state

② a Coherent expansion

② Prepare superposition

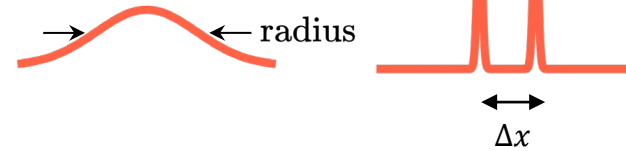
③ Verification of superposition



$$q_{\text{zpf}} = \sqrt{\frac{\hbar}{2m\omega_m}}$$



→ pm-fm



→ Delocalization ~~$\Delta x \approx O[1] \cdot q_{\text{zpf}}$~~

$$\Delta x \approx O[t^2] \cdot q_{\text{zpf}}$$



$\propto \mu\text{m}$

① Stiff potential:

- + reduced heating rate
- + increased sideband resolution (for cavity coupled systems)

② Weak/inverted/non-linear potential:

- + fast (free) wavefunction expansion
- + non-linear potentials
- + increased interaction with ancillary quantum systems

③ Stiff potential:

- + for readout or next iteration

Using levitation:

Optical levitation

Electrical levitation

Magnetic levitation

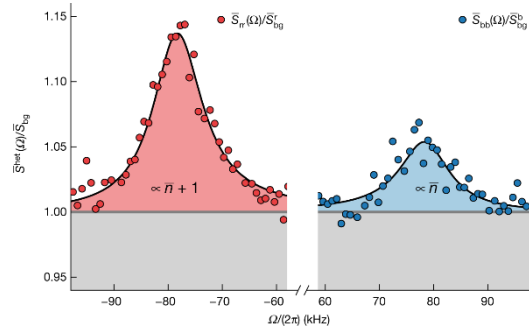
Table 1. Advantages (✓) and drawbacks (✗) of optical, electrical, and magnetic interactions in terms of levitation, control, and measurement of the particle.

	Optical	Electrical	Magnetic
Levitation	✓ High trapping frequencies (>100 kHz) ✓ Charged or neutral particles ✓/✗ Large distance from surfaces ✗ Laser recoil heating ✗ Internal heating due to absorption ✗ Limited to ultralow-absorption, high-temperature-resistant particles	✓ No internal heating ✓ Applicable to a wide range of charged particles ✓ Large potential depth ✓ On-chip integration ✓ Compatible with optical manipulation ✗ Low trapping frequencies (<10 kHz) ✗ Highly charged particles (sensitive to decoherence) ✗ Poor spatial confinement	✓ No internal heating ✓ Potentials created by static fields ✓ Applicable to very large particles ✓ On-chip integration ✓/✗ Advanced cryogenics required for superconducting traps or particles ✗ Low trapping frequencies (<1 kHz) ✗ Dissipation and decoherence mechanisms not fully understood
Control	✓ Cooling via active and passive feedback ✓ Potentials can be easily engineered and reconfigured ✓ Control of rotational degrees of freedom ✗ Coherent control limited by decoherence due to light scattering	✓ Cooling via active and passive feedback ✓ Simple implementation of cold damping ✓ Particles with internal degrees of freedom (quantum emitters) ✗ Proximity to surfaces (sensitive to stray fields)	✓ Cooling via active and passive feedback ✓ Easy access to other degrees of freedom (e.g., magnetization) ✗ Static potentials
Measurement	✓ Shot-noise-limited measurements ✗ Laser recoil heating	✓ No need for bulk optical elements ✗ Requires the detection of very weak currents	✓ Sensitive readout with magnetometers (e.g., SQUIDs) or superconducting circuits (cavities, qubits) ✗ Low compatibility with optical measurements

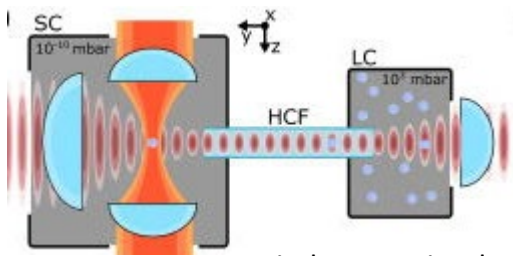
Gonzalez-Ballester et al, *Levitodynamics: Levitation and control of microscopic objects in vacuum*.

Science **374**, eabg3027 (2021) <https://www.science.org/doi/10.1126/science.abg3027>

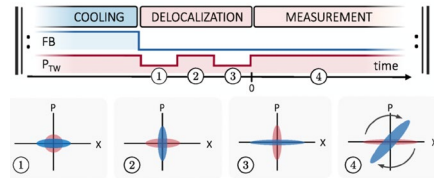
Optical levitation



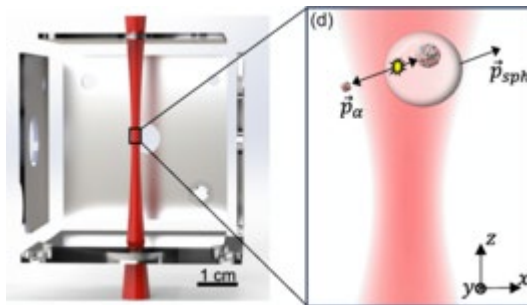
Tebbenjohanns, ..., Novotny, *Nature* **595**, 378 (2021)
 Delić, ..., Aspelmeyer, *Science* **367**, 892 (2020)
 Magrini, ..., Aspelmeyer, *Nature* **595**, 373 (2021)
 Ranfagni, ..., Marin, *PRR* **4**, 033051 (2022)
 Piotrowski, ..., Novotny, *Nat. Phys.* **19**, 1009 (2023)
 Troyer, ..., Arndt, *Nat. Phys.* **22**, 584–590 (2026)



Lindner, ..., Kiesel,
APL **124**, 143501 (2024)

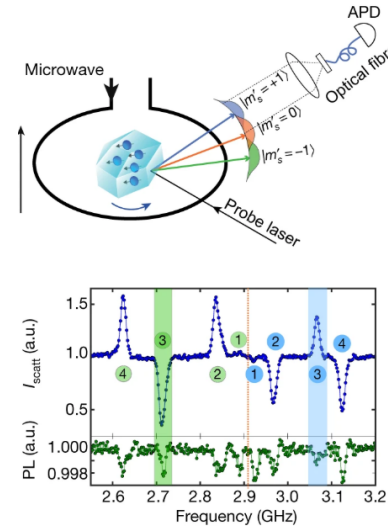


Rossi, ..., Novotny,
PRL **135**, 083601 (2025)

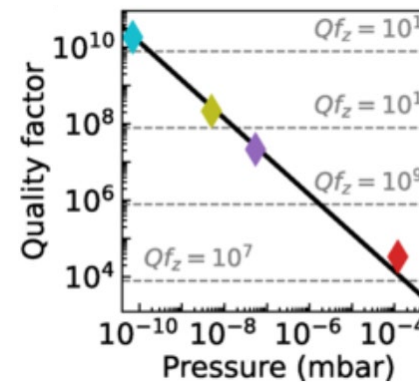


Wang, ..., Moore, *PRL* **133**, 023602 (2024)

Electrical levitation

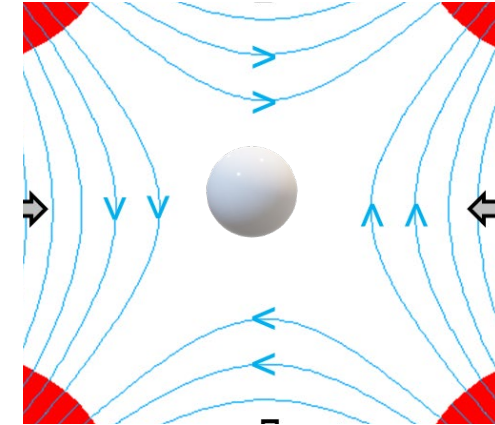


Delord, ..., Hétet,
Nature **580**, 56 (2020)



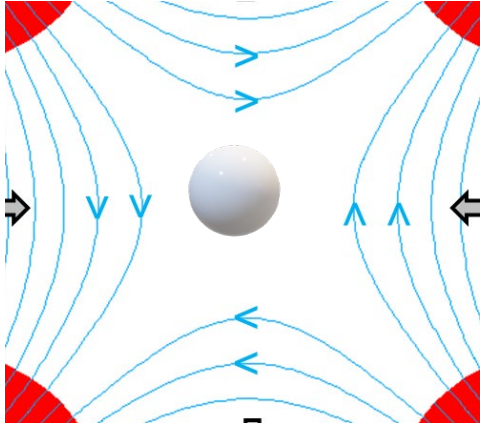
Dania, ..., Northup,
PRL **132**, 133602 (2024)

Magnetic levitation



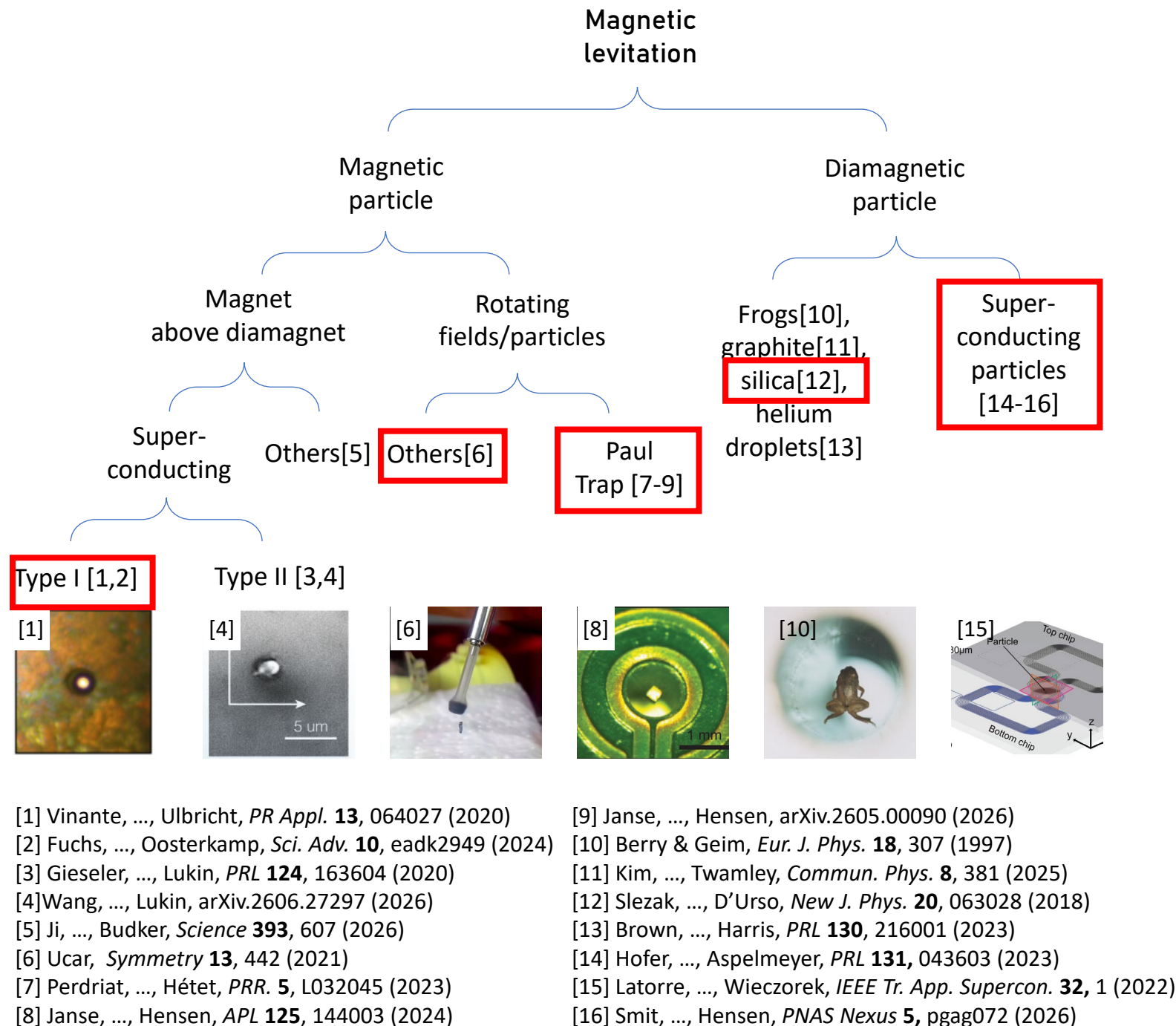
- + Charge-neutral particles
- + No trap-laser heating
- + Large masses
- + Direct coupling to spin qubits or squids
- Very low trapping frequencies
- Miniaturization: smaller particles & traps needed
- Challenging cryogenic operation
- Readout sensitivity to be improved

Magnetic levitation

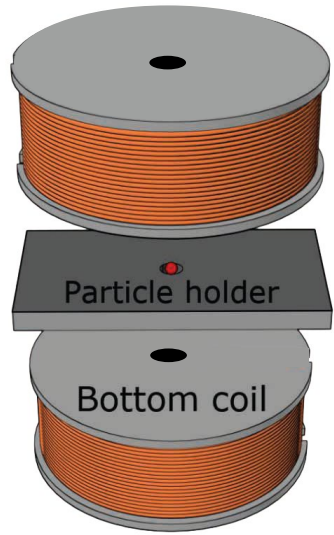


- + Charge-neutral particles
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- + Large masses
- + Direct coupling to spin qubits or squids

- Very low trapping frequencies
- Miniaturization: smaller particles & traps needed
- Challenging cryogenic operation
- Readout sensitivity to be improved

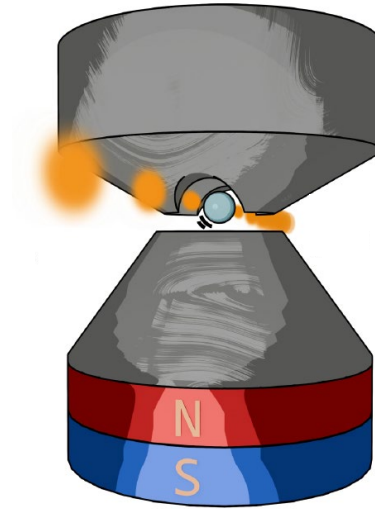


Magnetic levitation in our lab: stiffer potentials, miniaturization and readout



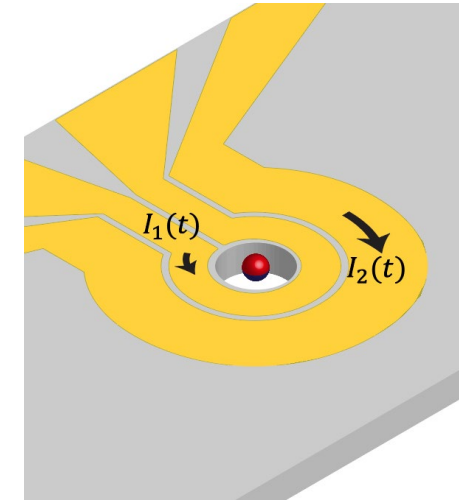
Poster:
Eli van der Bent

Superconducting particle @ mK



Poster:
M. Luisa Mattana

Silica particle @ RT

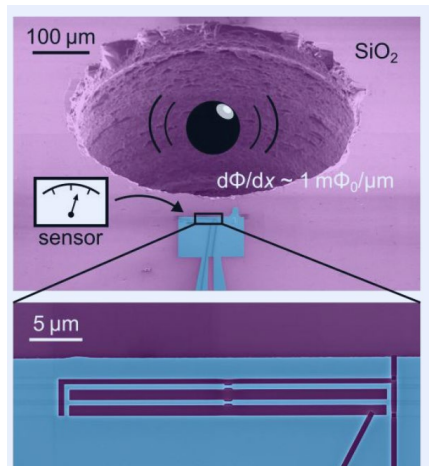


Rest of the talk

Magnetic particle @ RT



Kaveh Lahabi
@ Leiden

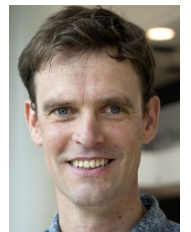
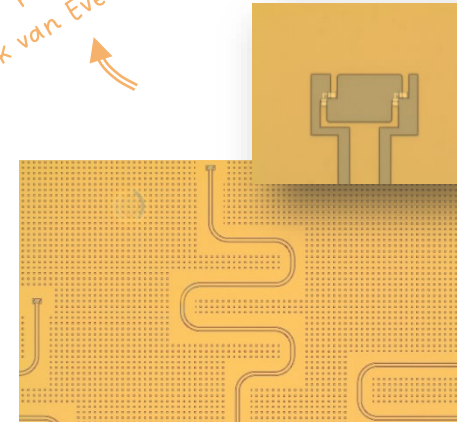


Poster:
Richard Wagner



Gary Steele
@ TU Delft

Poster:
Loek van Everdingen

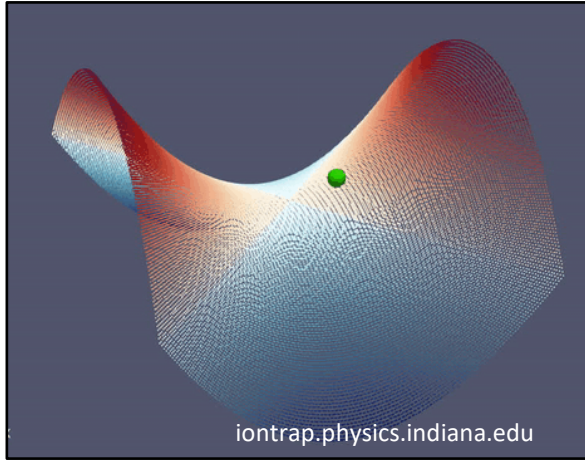


Tjerk
Oosterkamp
@Leiden

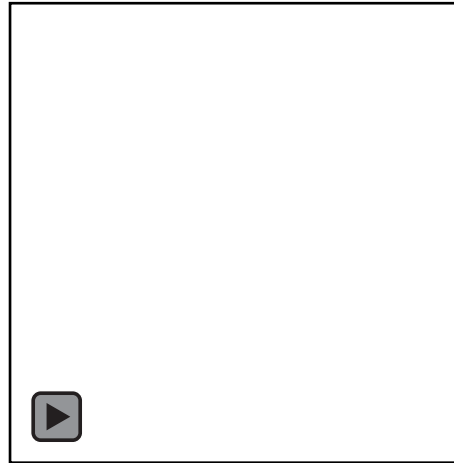
On-chip levitation of ferromagnetic microparticles

M. Janse, M. L. Mattana, J. van Doorn, E. van der Bent, R. Wagner, R. Smit & B. Hensen.
On-chip levitation of ferromagnetic microparticles. (2026).
doi:[10.48550/arXiv.2605.00090](https://doi.org/10.48550/arXiv.2605.00090).

Novel levitation platform – planar magnetic Paul trap



Concept: Perdriat, ..., Hétet,
PRR. **5**, L032045 (2023)



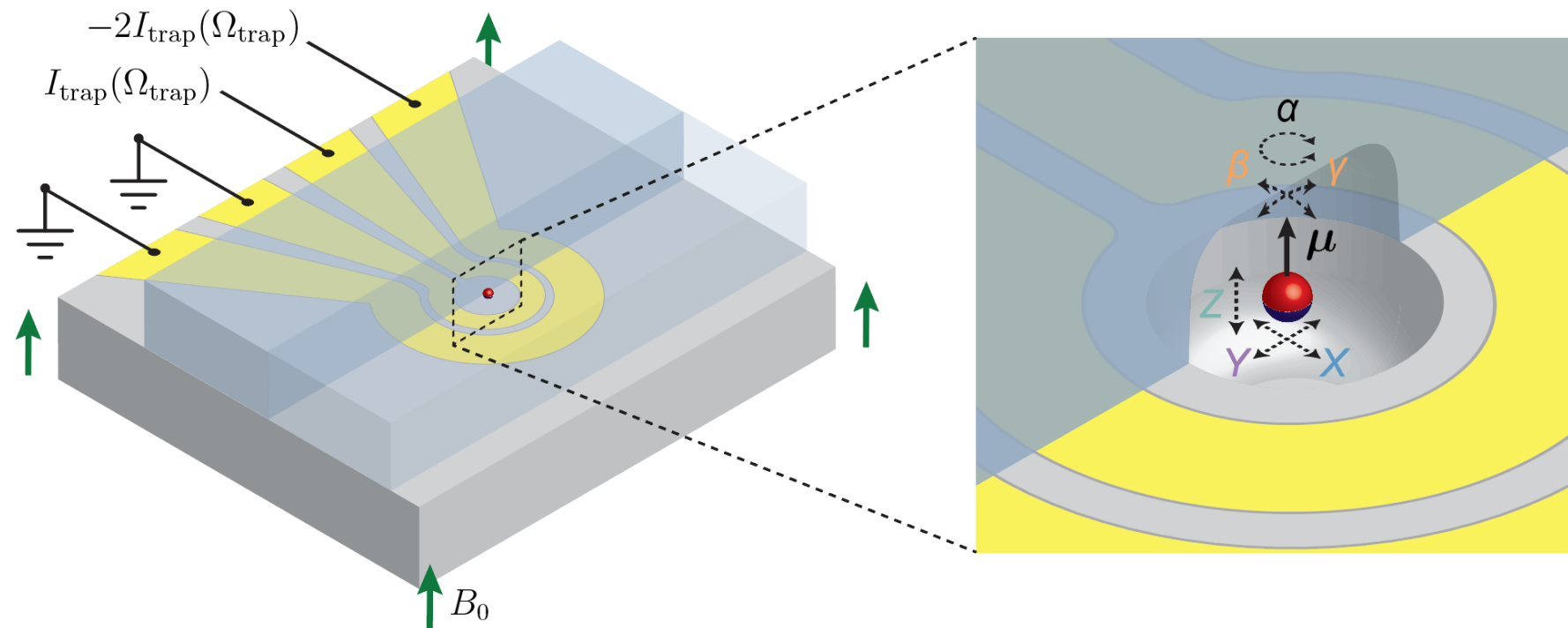
Experiment: Janse, ..., Hensen,
APL **125**, 144003 (2024)

250 μm
ferromagnet

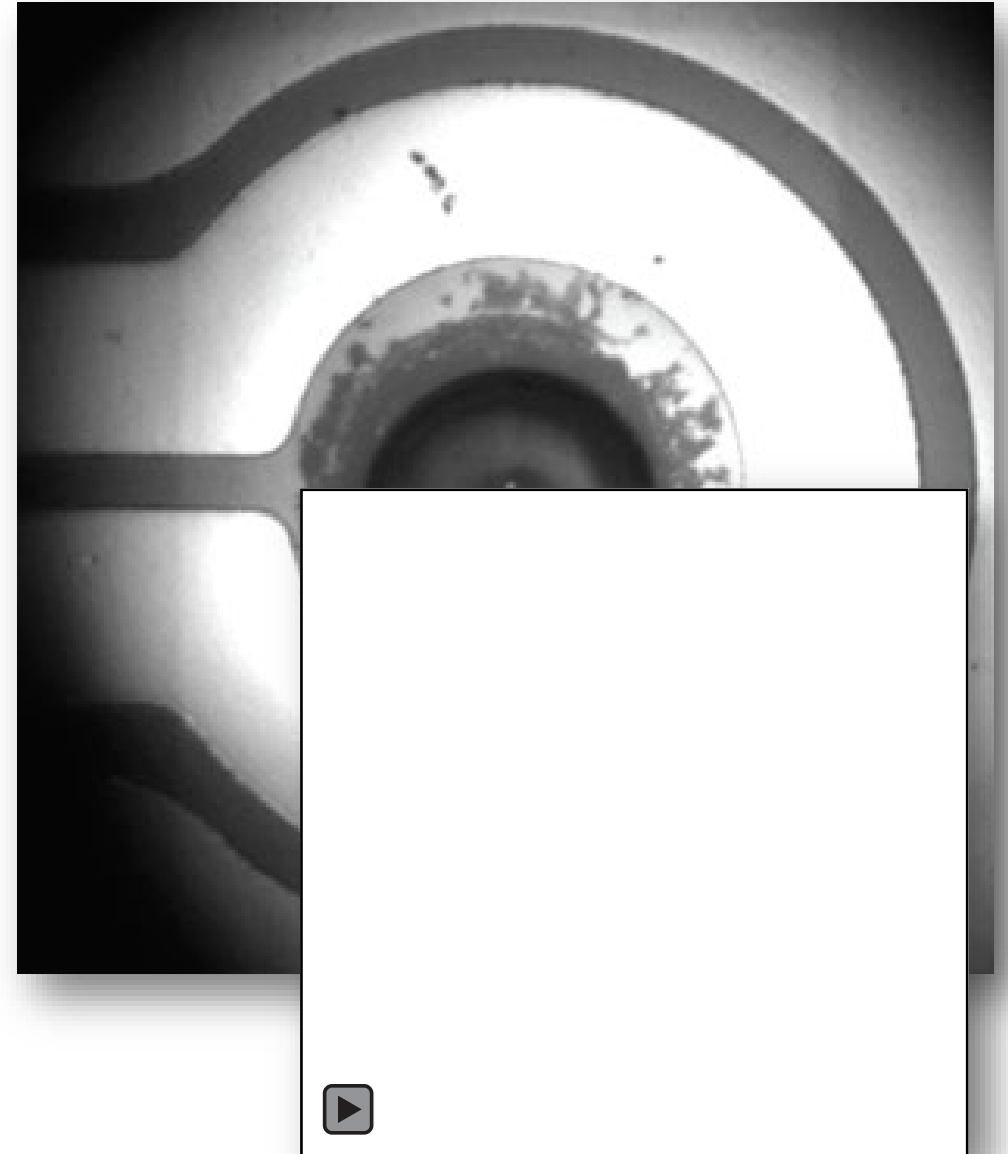
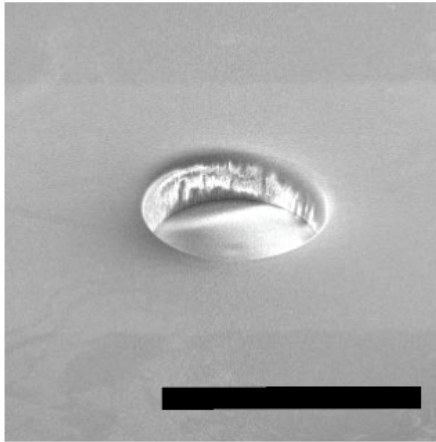
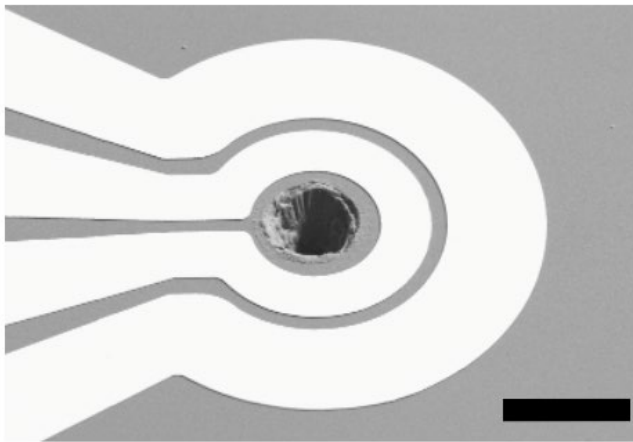
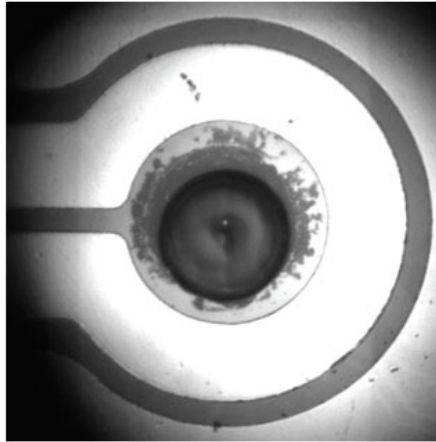
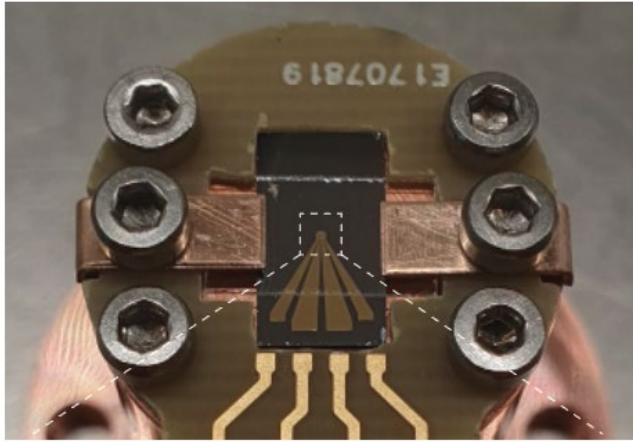
A new platform with:

- + no trapping laser absorption heating
- + charge-neutral particles
- + controlled libration: **'twisting'** modes
- + room-temperature (or 4K), no superconducting elements
- + direct magnetic coupling to **spin qubits**

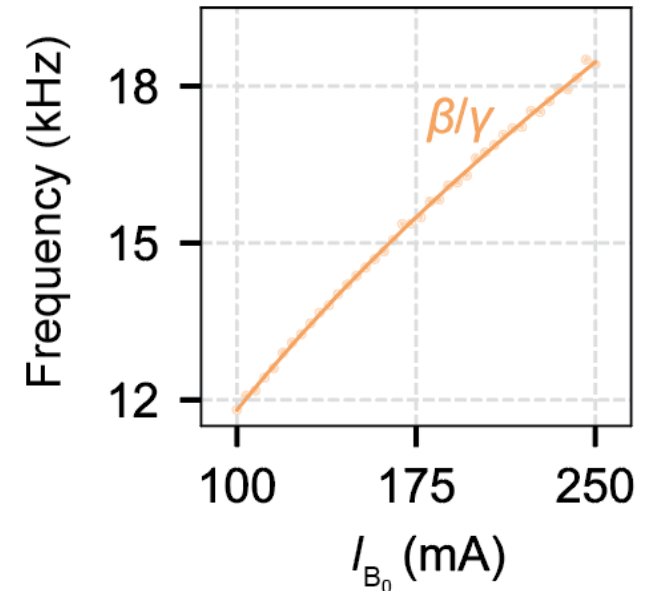
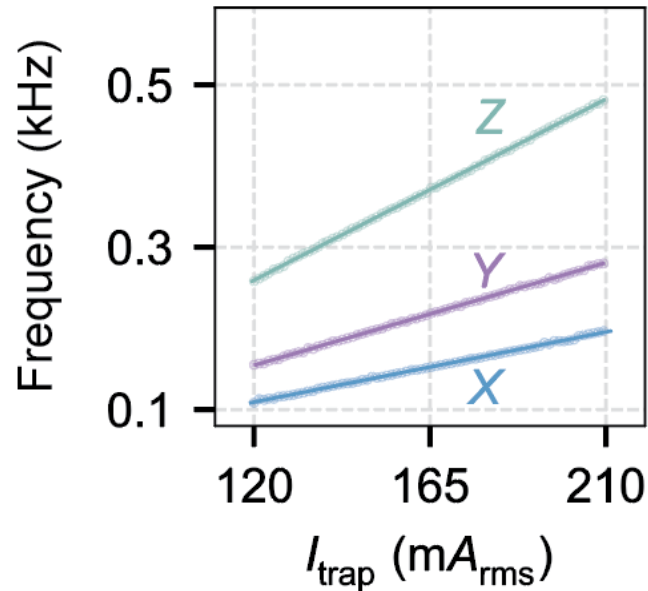
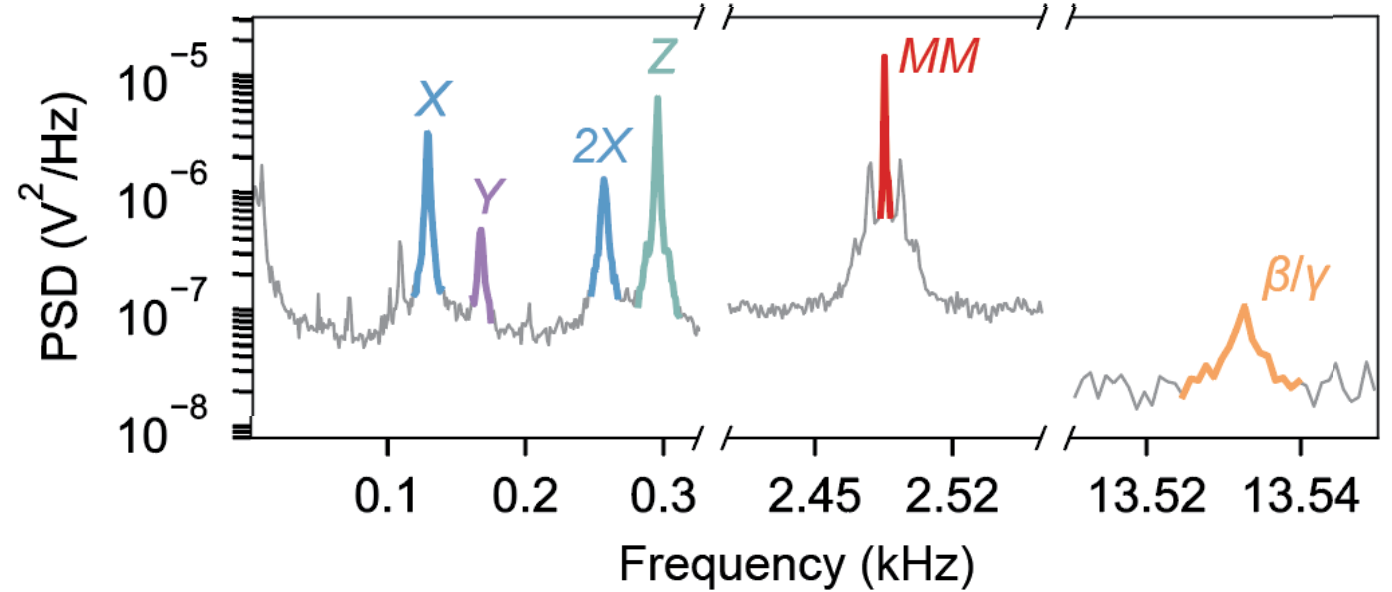
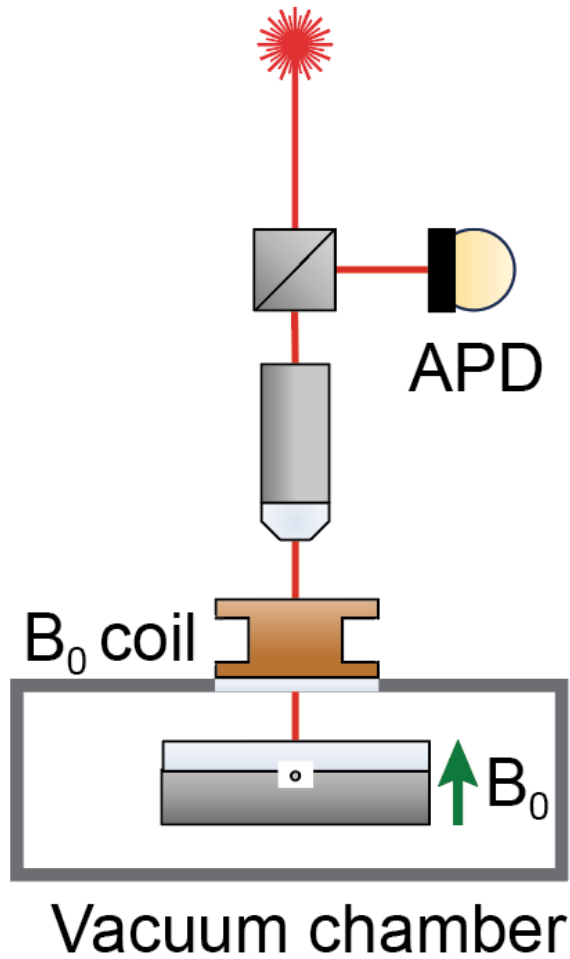
Towards sub-micron particles (and future spin-coupling): on-chip version



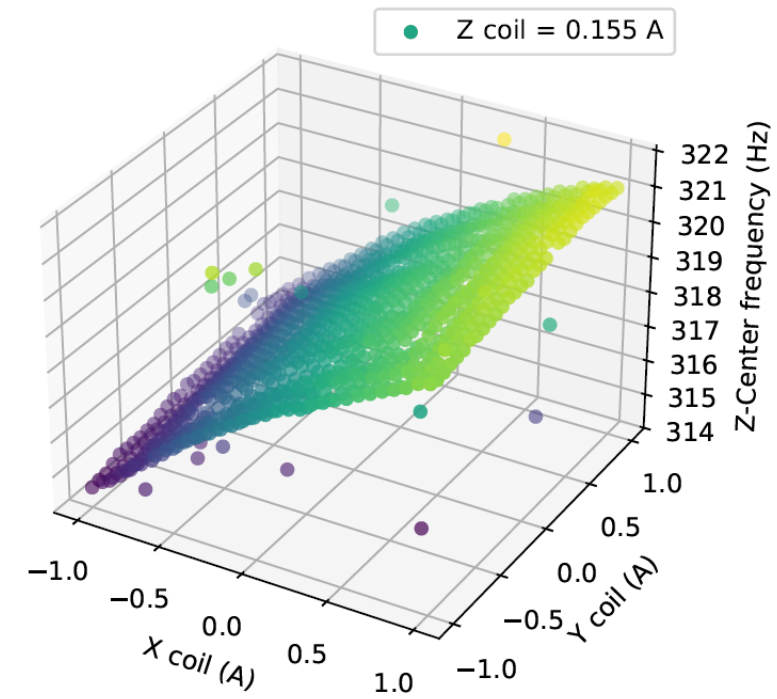
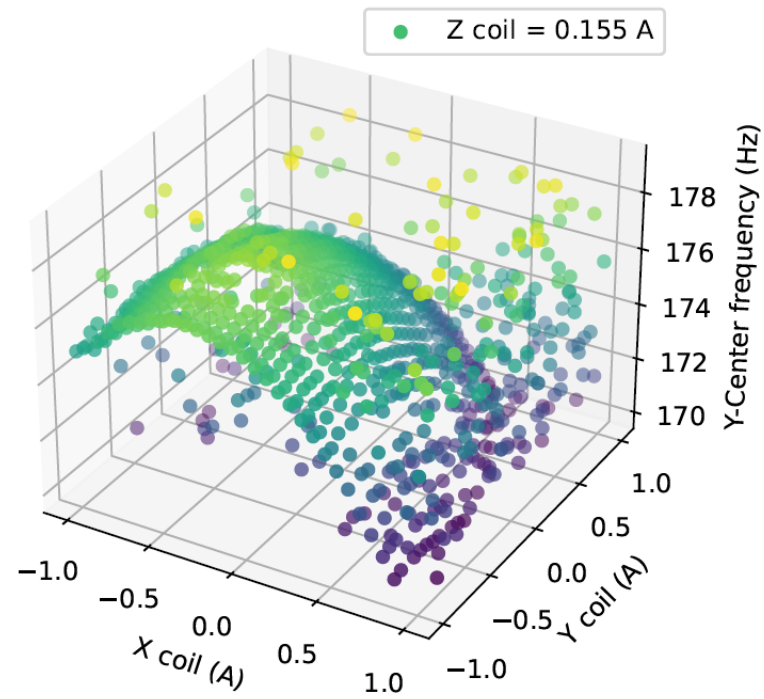
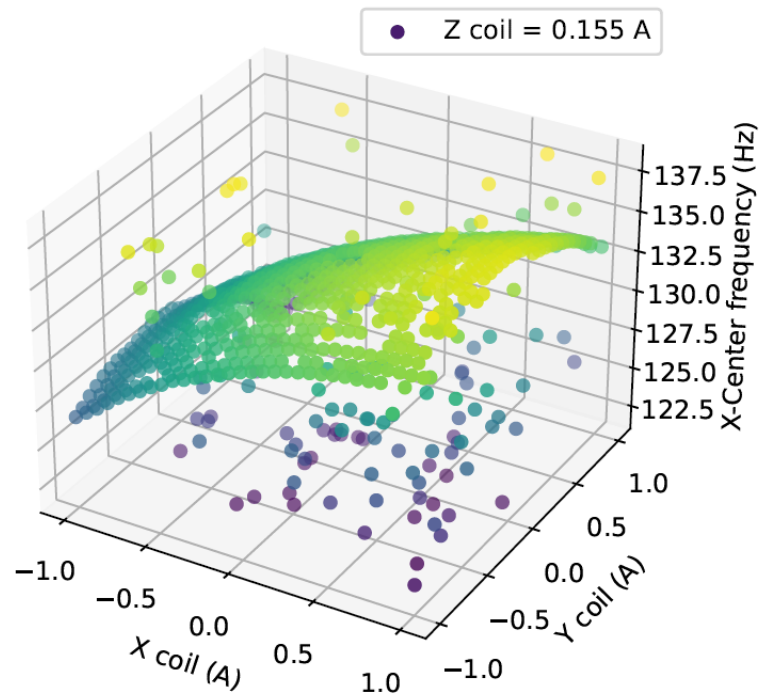
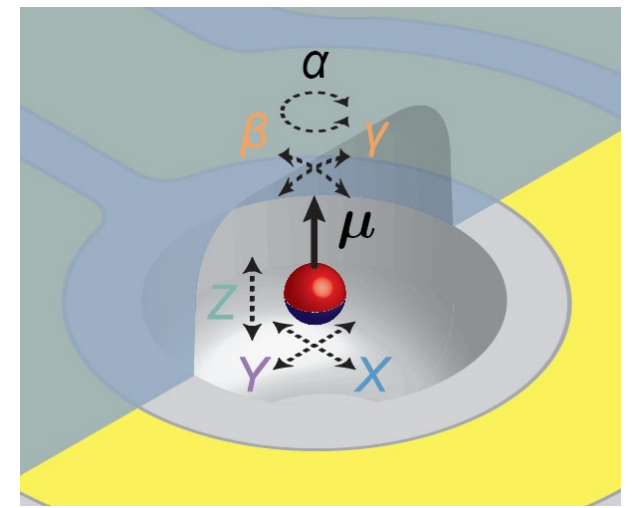
We implement an on-chip version with a flip-chip glass cover



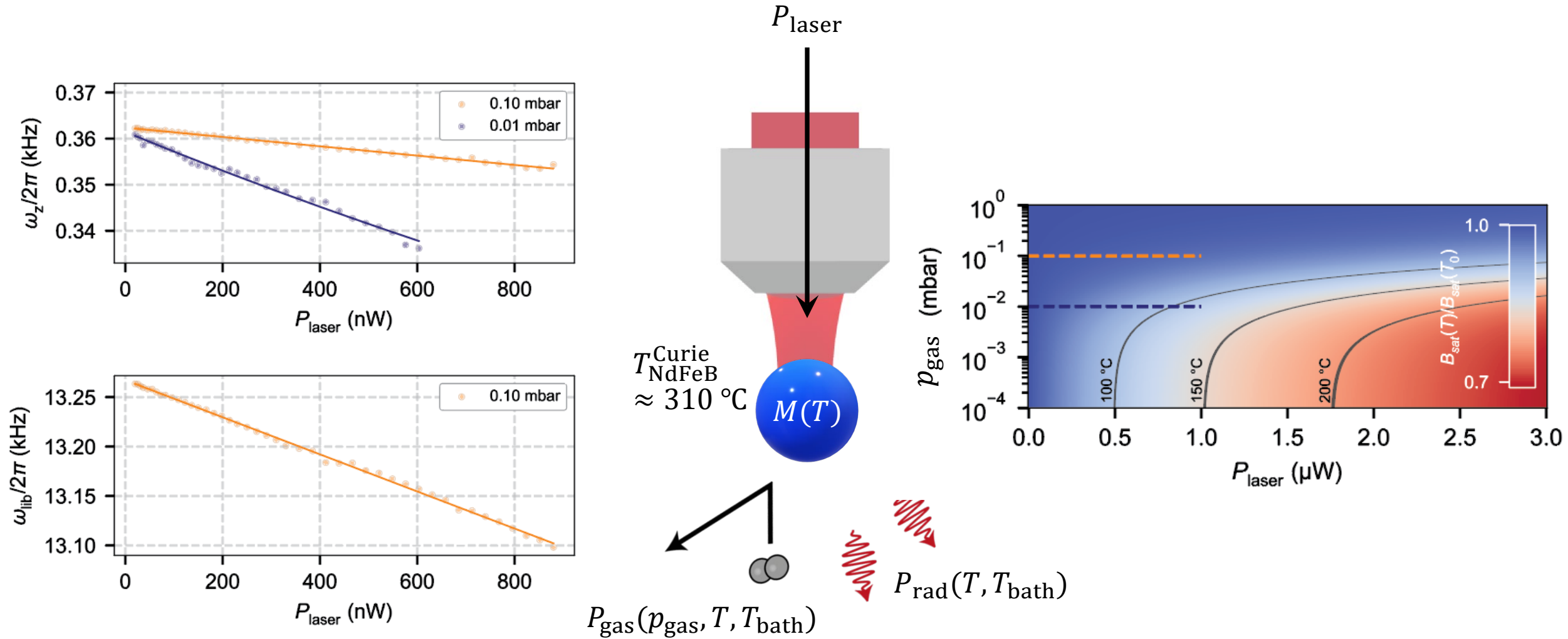
Eigenmotion follows Matthieu equations for Paul traps



Nontrivial frequency tuning for x/y compensation coils

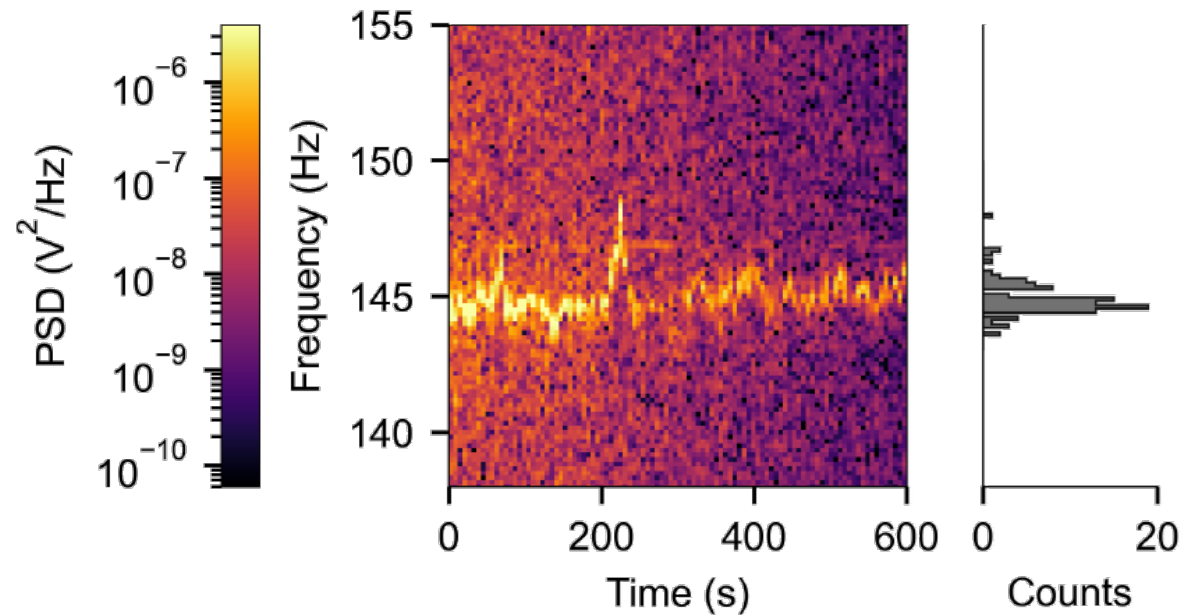
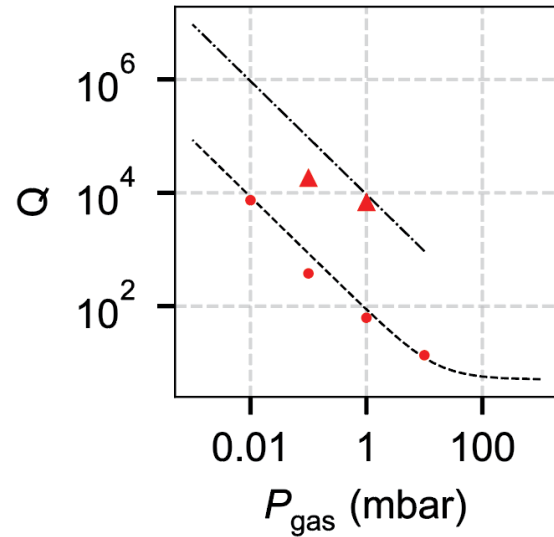
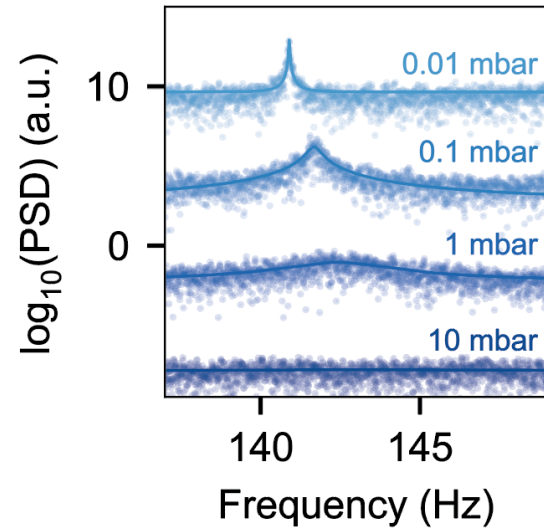


Readout laser heats the particle at low pressure: magnetisation thermodynamics

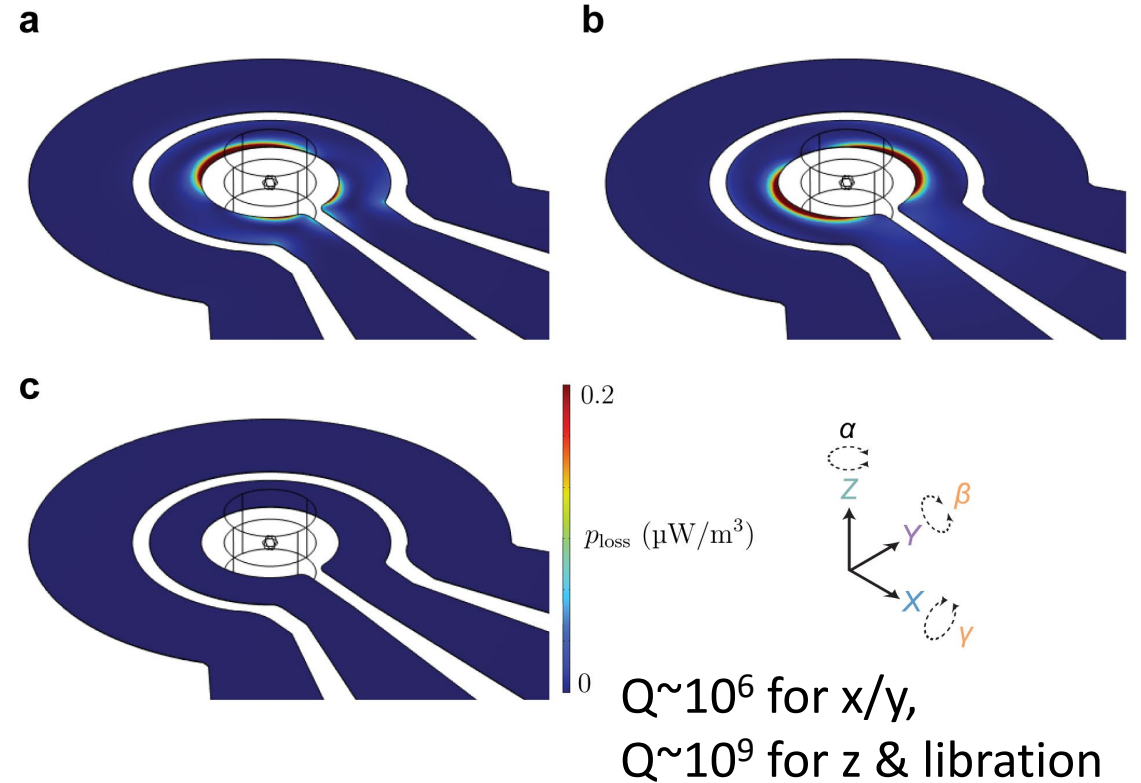


Solution: use avalanche photodetector

At lower pressure, the eigenfrequencies can be seen drifting around



Expected limits in quality factor from eddy current damping

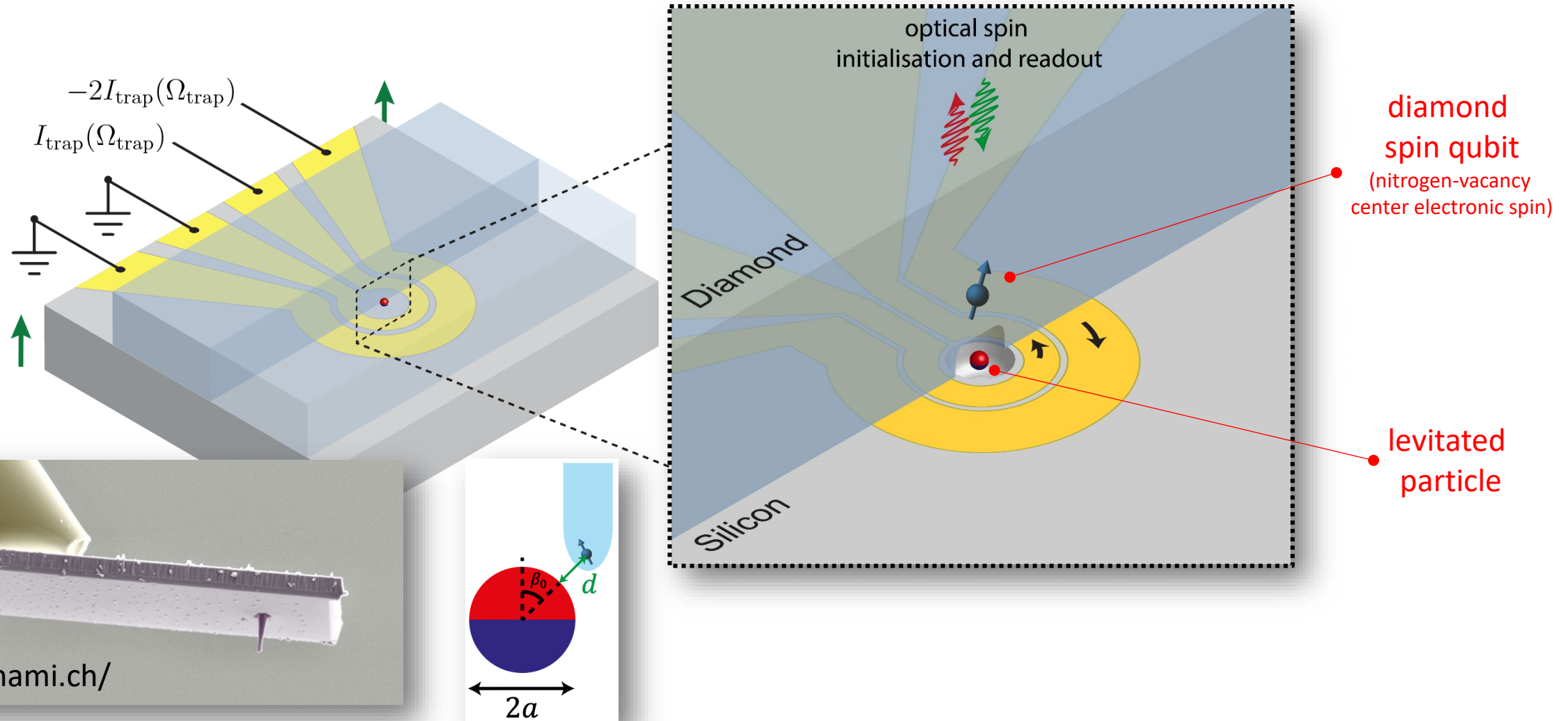


$Q \sim 10^6$ for x/y,
 $Q \sim 10^9$ for z & libration

Current plan:

- Trapping current stabilisation
- Cryogenic pumping
- Magnetic shielding

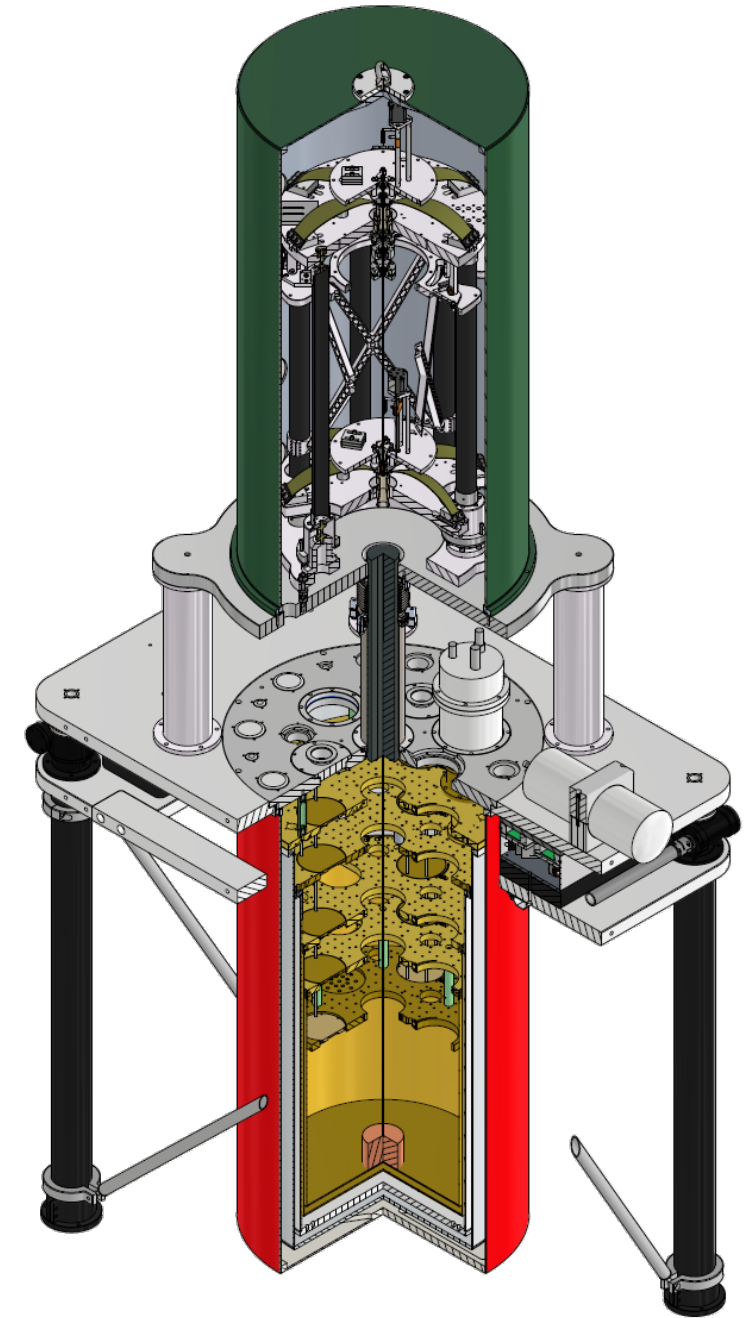
Vision: towards sub-micron particles coupled to solid state spins



Poster Juriaan Langendorf: Combining gravitational wave mirror vibration isolation with millikelvin temperatures



Einstein Telescope
for business



Hensen lab – Magnetic levitation for large-mass quantum superpositions



Hensen lab



Bas Hensen



Robert Smit
→ Florence



Martijn Janse



M. Luisa Mattana



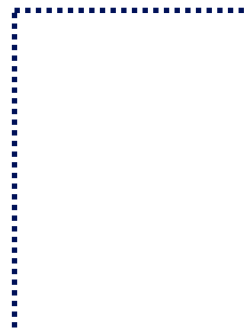
Richard Wagner



Eli van der Bent



Juriaan Langendorf



Bálint Bosman

Flux concentrator: Smit, ..., Hensen, *PNAS Nexus* 5, pgag072 (2026)
Magnetic Paul Trap: Janse, ..., Hensen, arXiv.2605.00090 (2026)

Collaborators



Tjerk Oosterkamp Kaveh Lahabi
@ Leiden



Joris van Heijningen
@ Nikhef



Universiteit
Leiden
The Netherlands



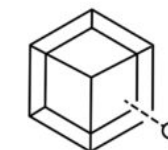
European Research Council



Einstein Telescope
for business



Netherlands Organisation
for Scientific Research



QUANTUM
LIMITS



Gary Steele
@ TU Delft



Quantum
Delta NL

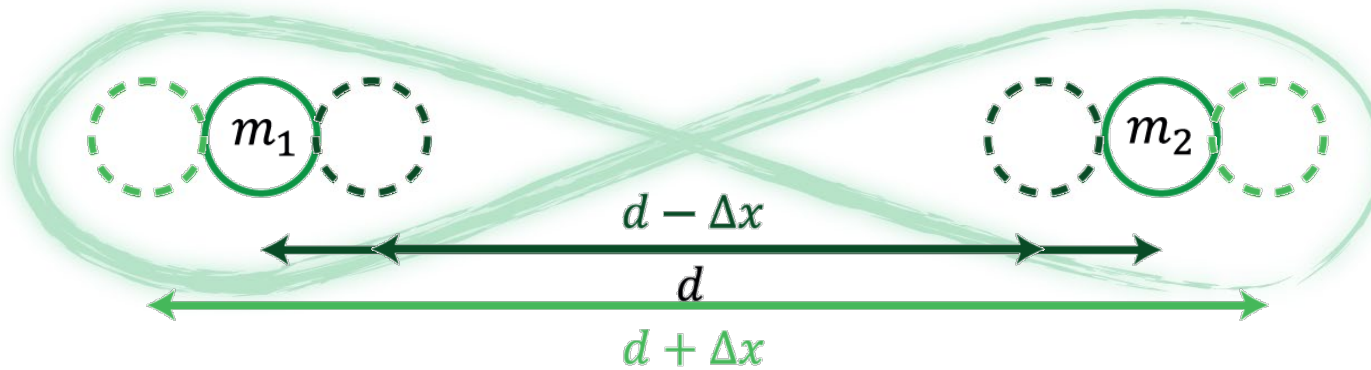
Questions?



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Gravity mediated entanglement



$$|\Psi\rangle = |\psi\rangle_1 \otimes |\psi\rangle_2 = |L\rangle_1 + |R\rangle_1 \otimes |L\rangle_2 + |R\rangle_2 \quad t = 0$$

$$e^{i\phi} \left\{ |L\rangle_1 \otimes (|L\rangle_2 + e^{i\phi_{\text{outer}}} |R\rangle_2) + |R\rangle_1 \otimes (e^{i\phi_{\text{inner}}} |L\rangle_2 + |R\rangle_2) \right\} \quad t = \tau$$

$$\rho_1 = \text{Tr}_2[|\Psi\rangle\langle\Psi|], \text{ concurrence } C = \sqrt{2(1 - \text{Tr}[\rho_1^2])} \propto (m\Delta x)^2 \tau / d^3$$

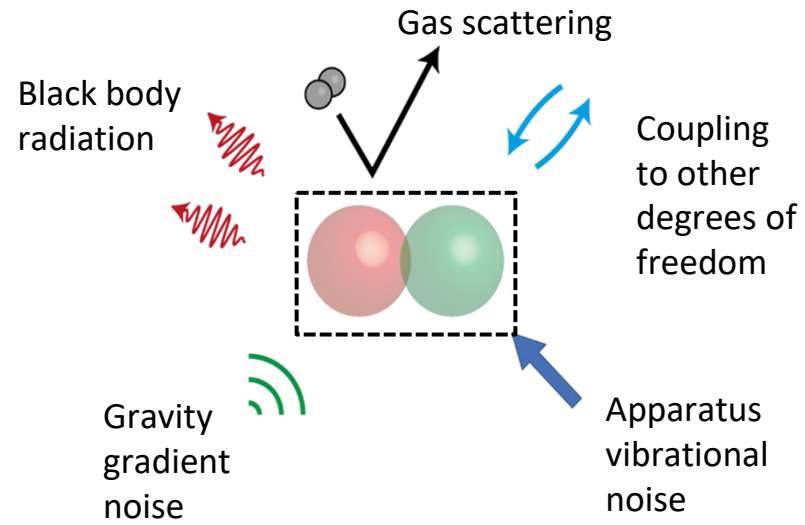
$$\phi_{\text{outer}} - \phi = \frac{Gm_1 m_2 \tau}{\hbar(d + \Delta x)}$$

$$\phi_{\text{inner}} - \phi = \frac{Gm_1 m_2 \tau}{\hbar(d - \Delta x)}$$

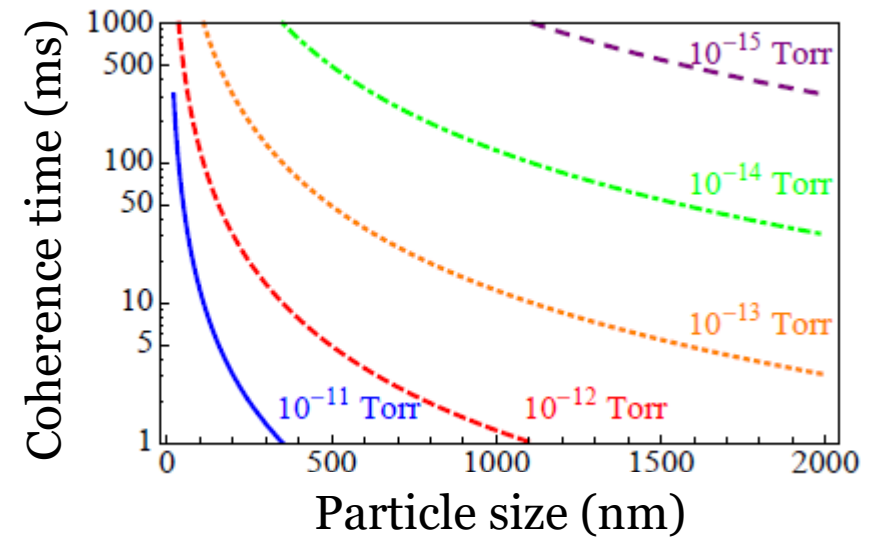
$$\phi = \frac{Gm_1 m_2 \tau}{\hbar d}$$

$$C = \left| \sin\left(\phi - \frac{\phi_{\text{inner}}}{2} - \frac{\phi_{\text{outer}}}{2}\right) \right| \approx \phi - \frac{\phi_{\text{inner}}}{2} - \frac{\phi_{\text{outer}}}{2} = Gm_1 m_2 \tau \frac{\Delta x^2}{d^3 - d\Delta x^2} \approx Gm_1 m_2 \tau \frac{\Delta x^2}{d^3}$$

Decoherence gets worse

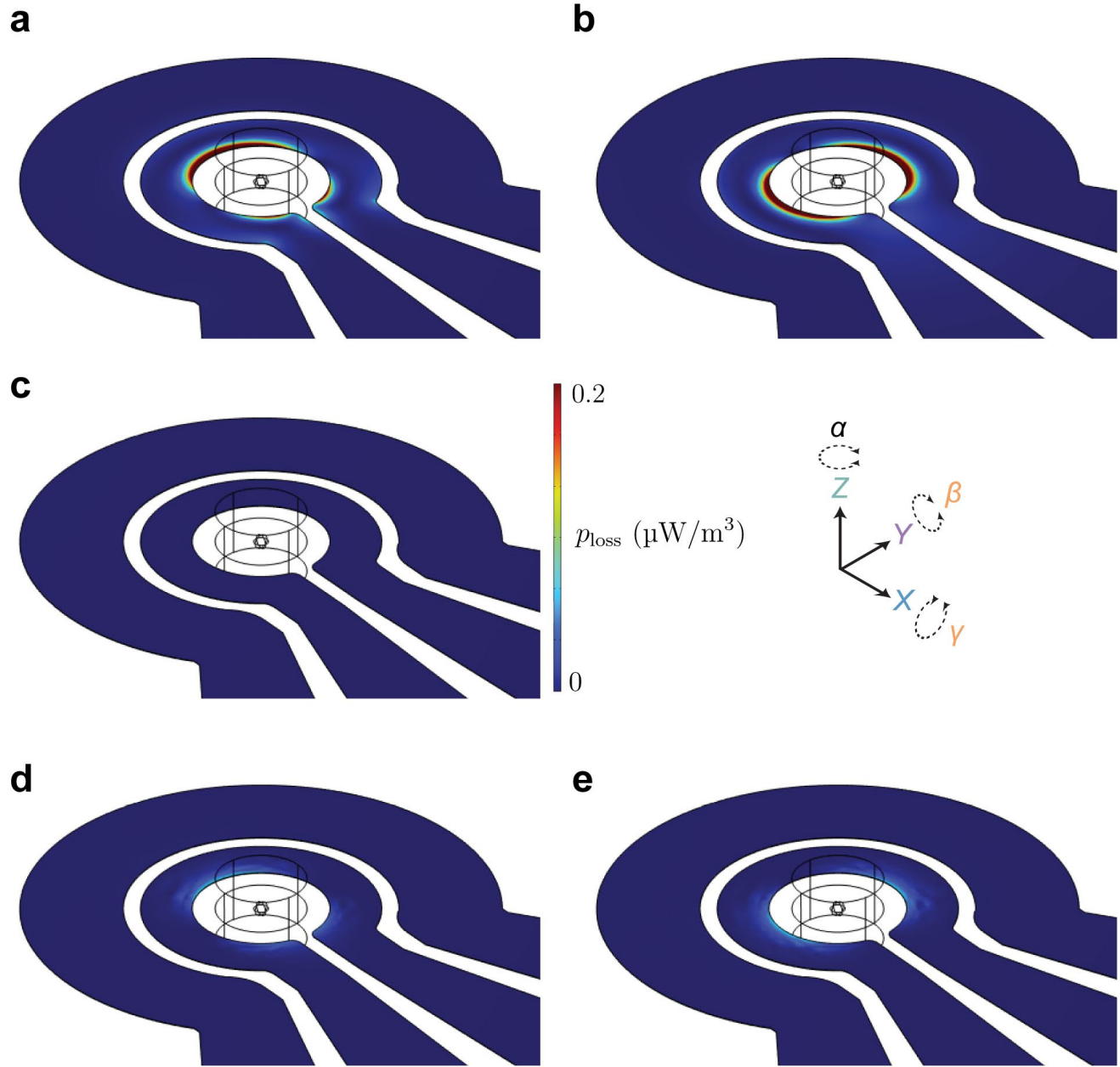


Decoherence due to gas collisions

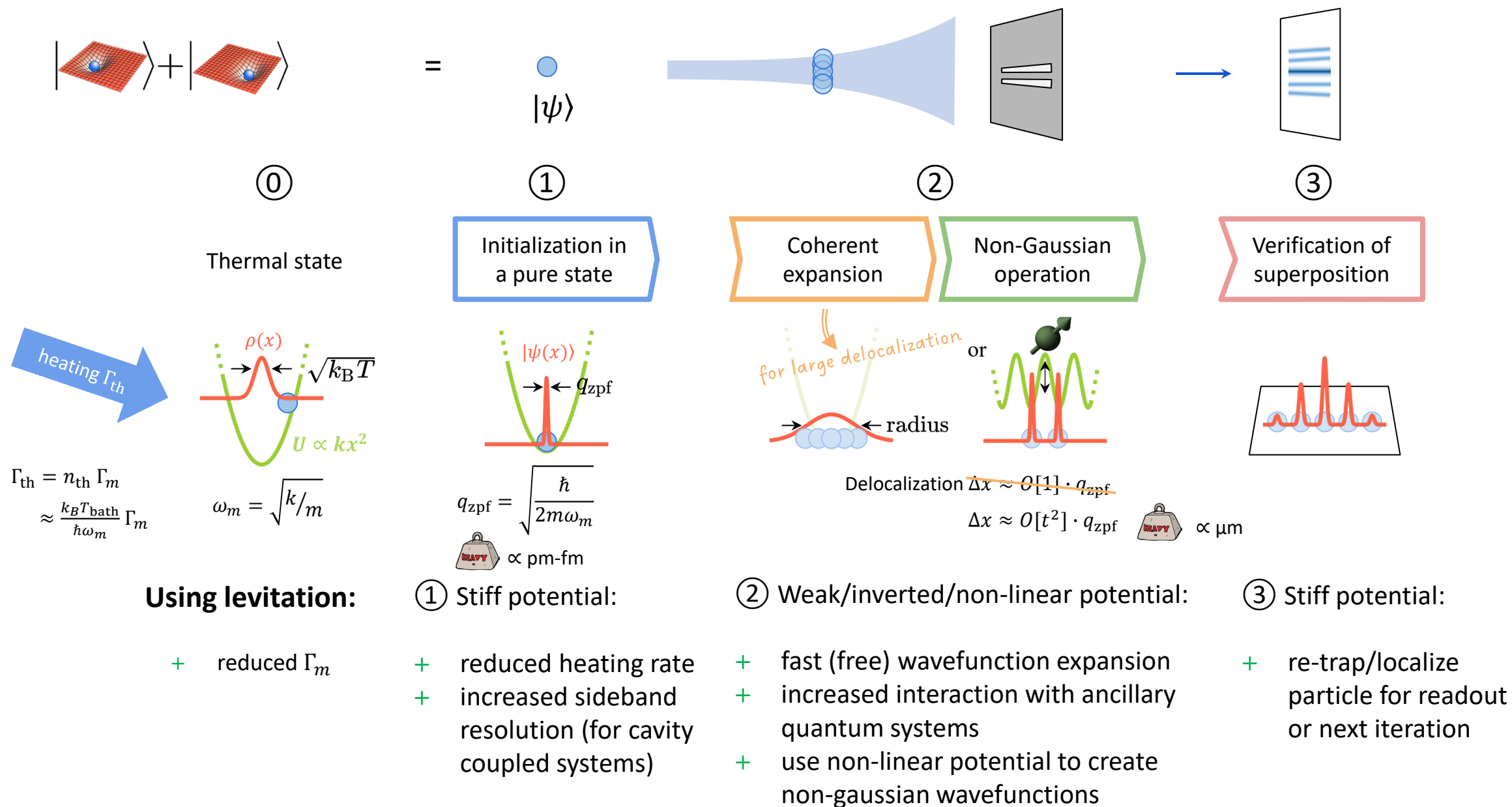


Expected limit in quality factor from eddy current damping:

$\sim 10^6$ for x/y,
 $\sim 10^9$ for z & libration



The power of levitation: dynamical control of the confining potential



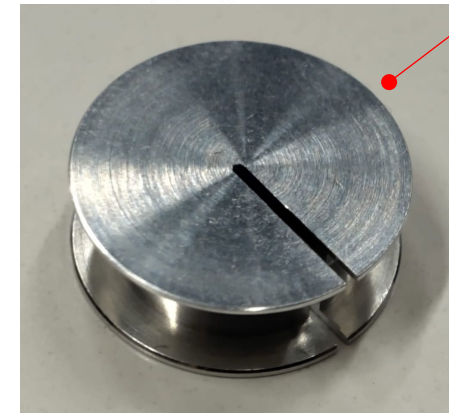
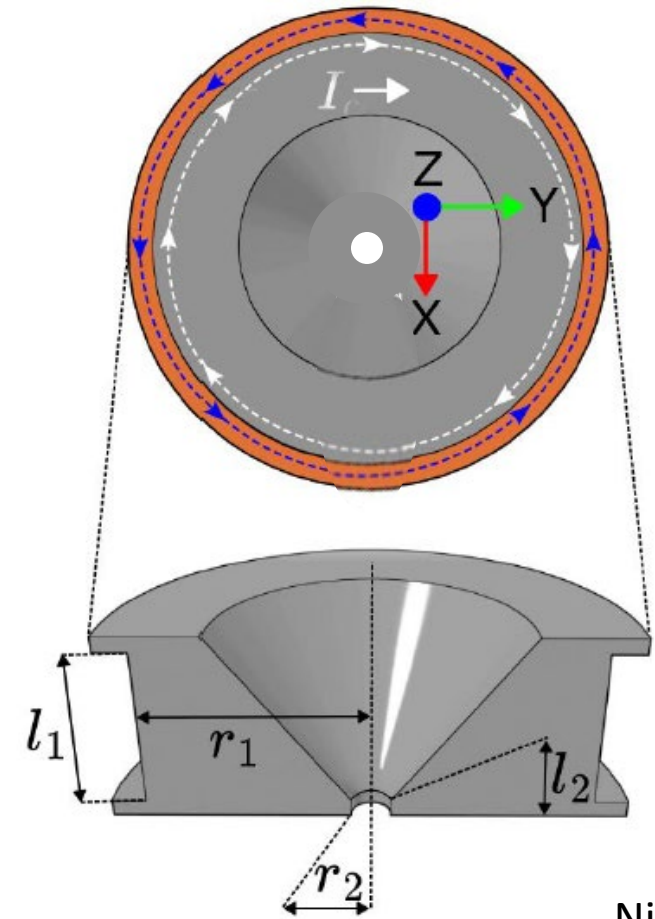
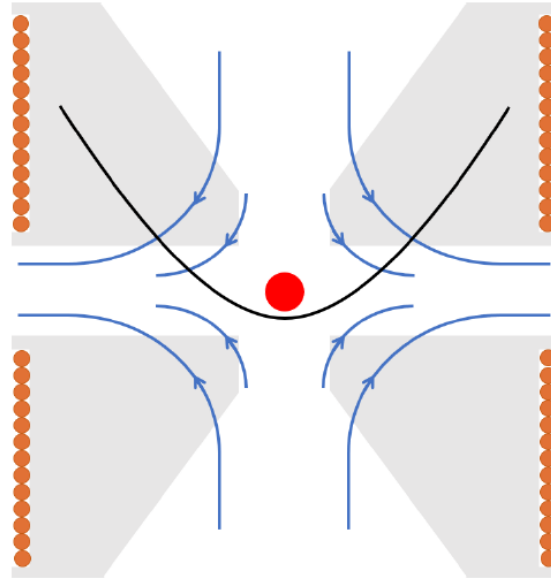
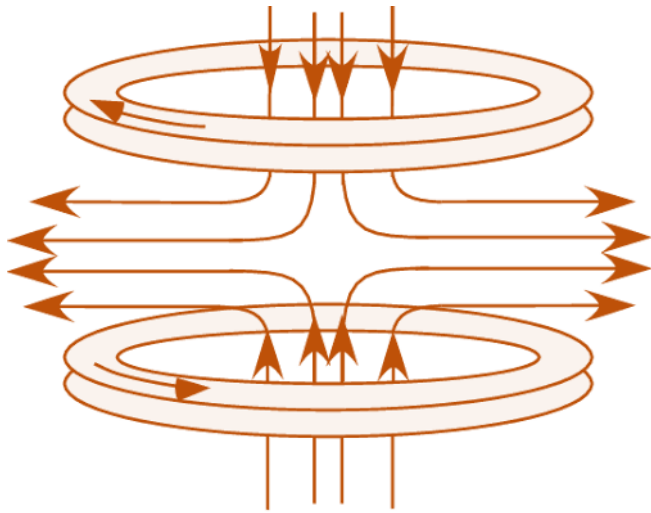
Part 1/3 Stiffer potentials: Superconducting flux concentrator

R. Smit, M. Janse, E. van der Bent, T. de Jong, K. Heeck, J. Plugge, T. Oosterkamp & B. Hensen.
Superconducting flux concentrator coils for levitation of particles in the Meissner state.

PNAS Nexus **5**, pgag072 (2026).

<https://doi.org/10.1093/pnasnexus/pgag072>

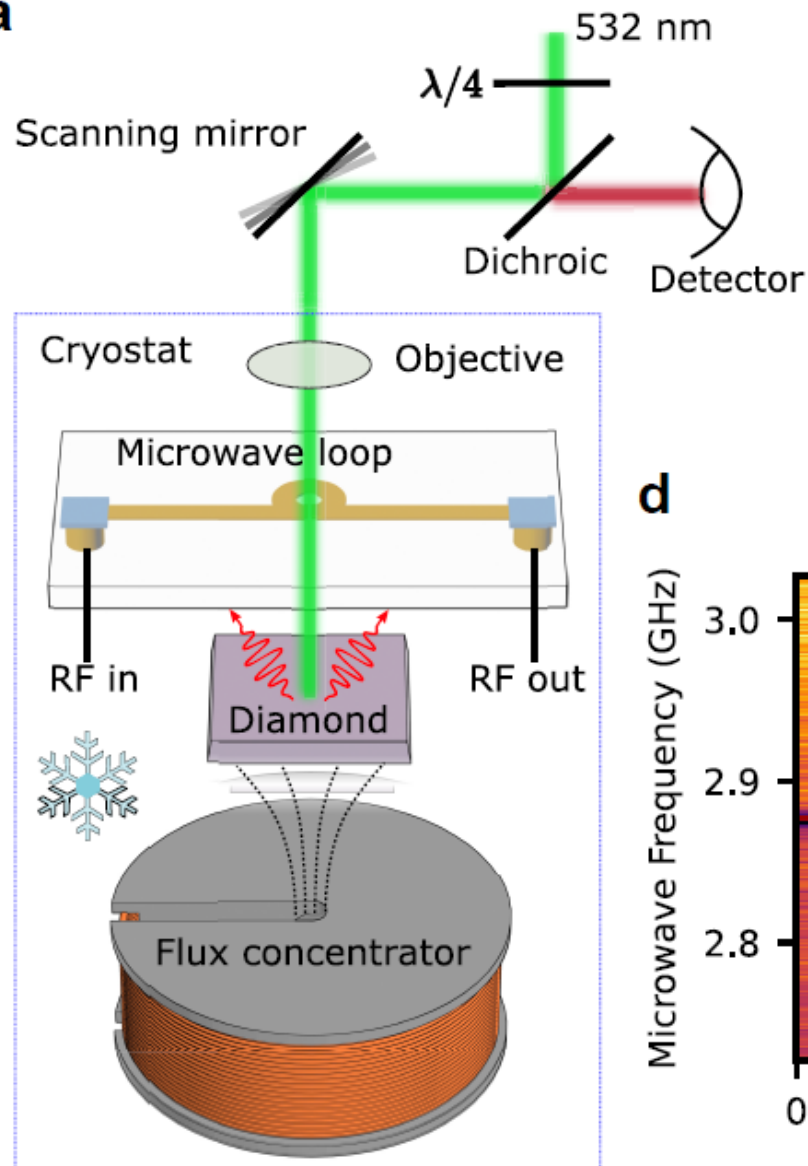
Flux focussing using a superconducting core



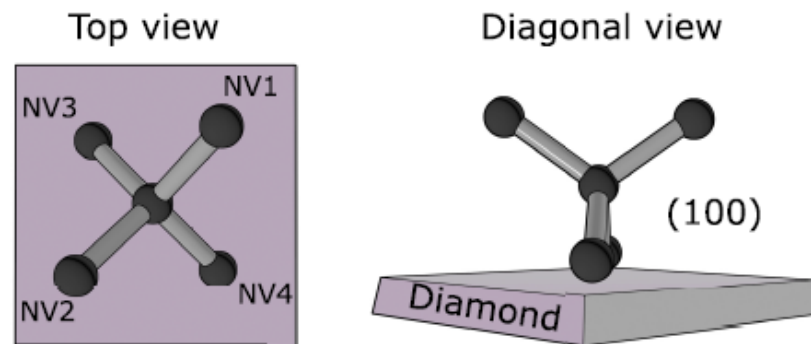
Niobium,
 $r_1 = 6.5 \text{ mm}$

Local magnetometry using NV spin defect in diamond confirms flux focussing

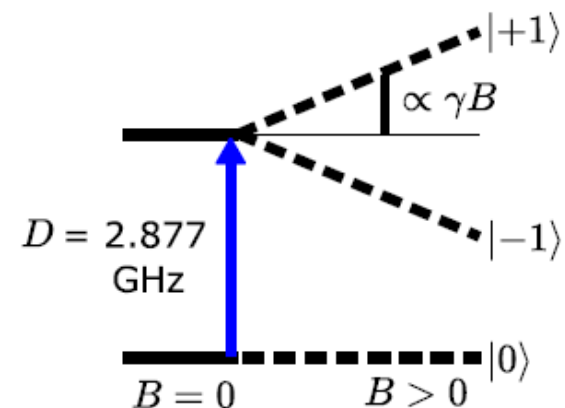
a



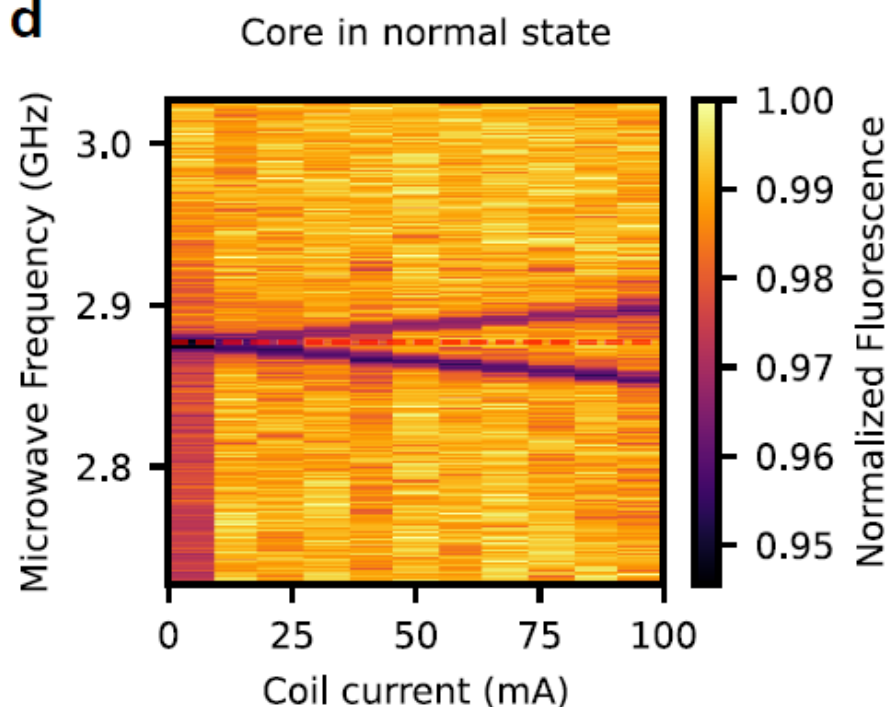
b



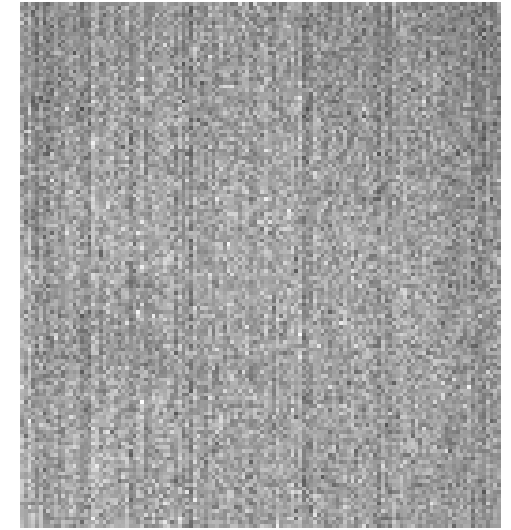
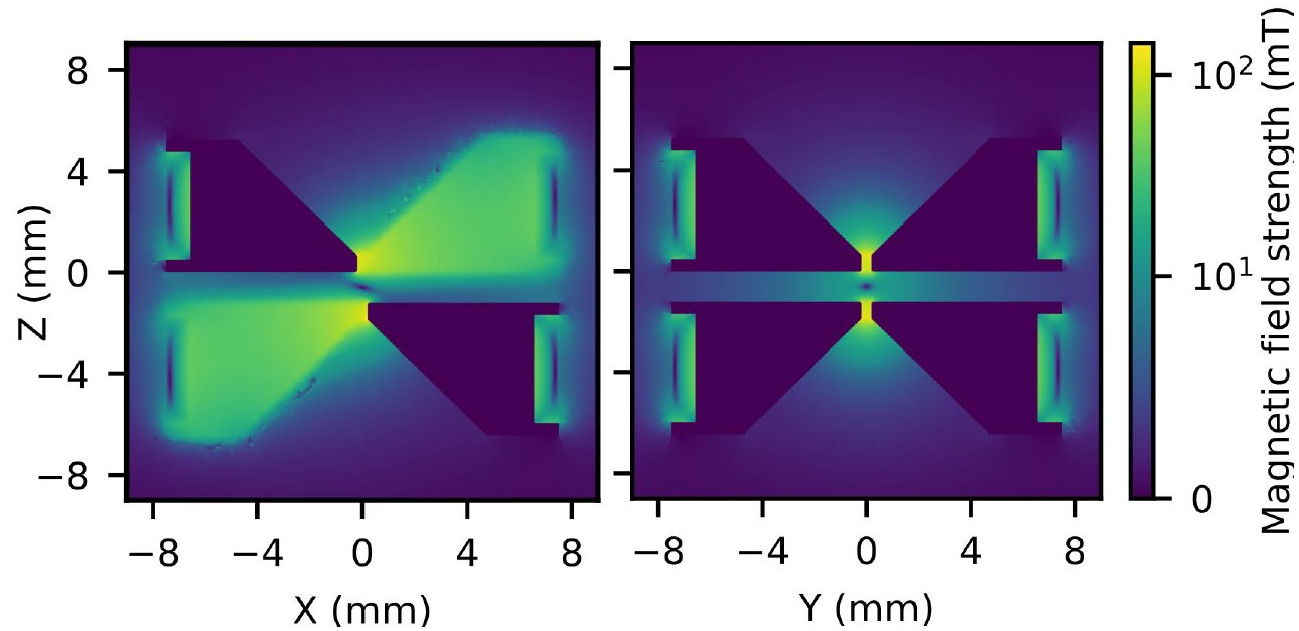
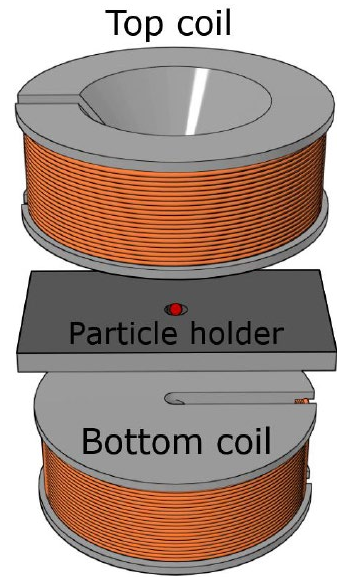
c



d

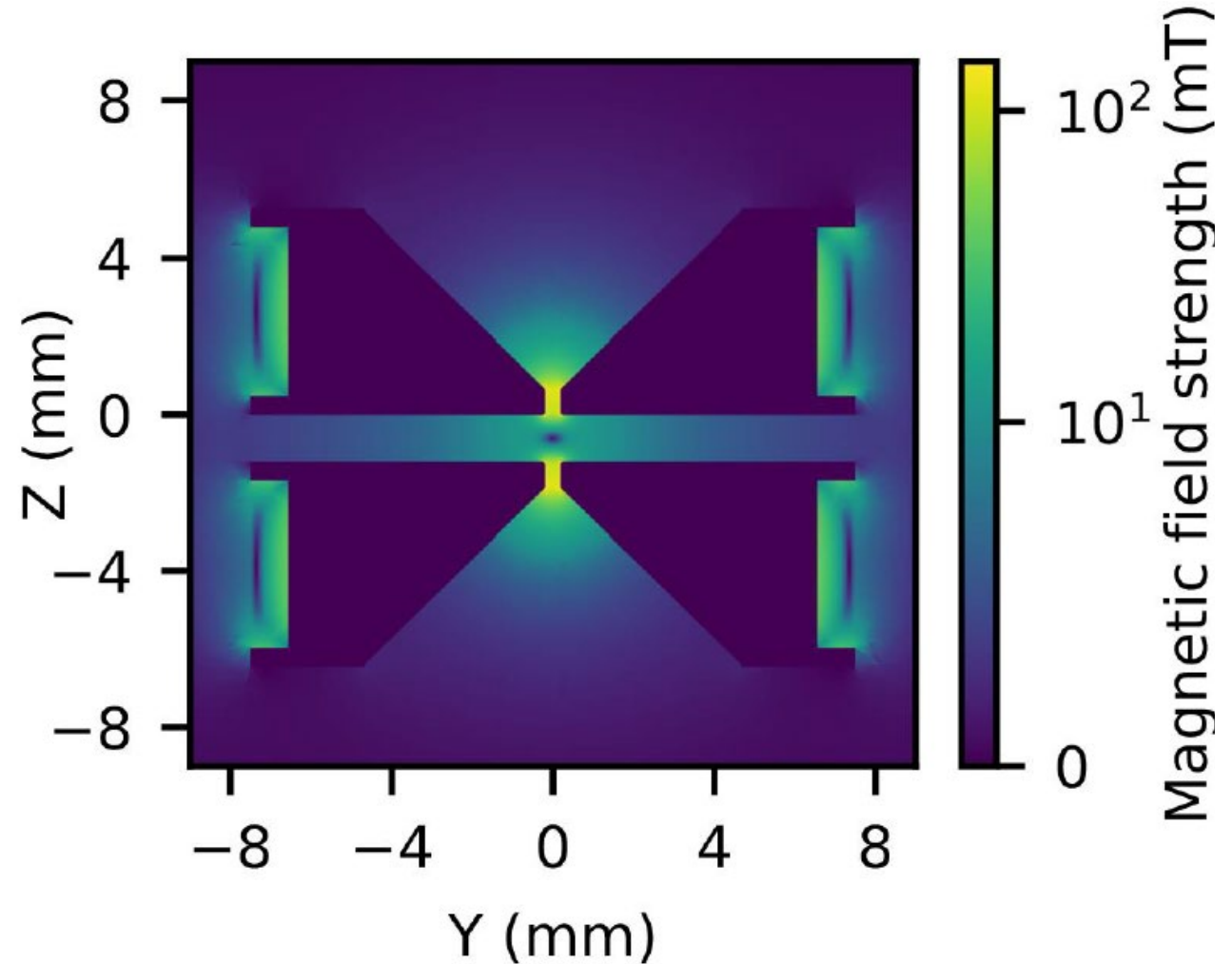
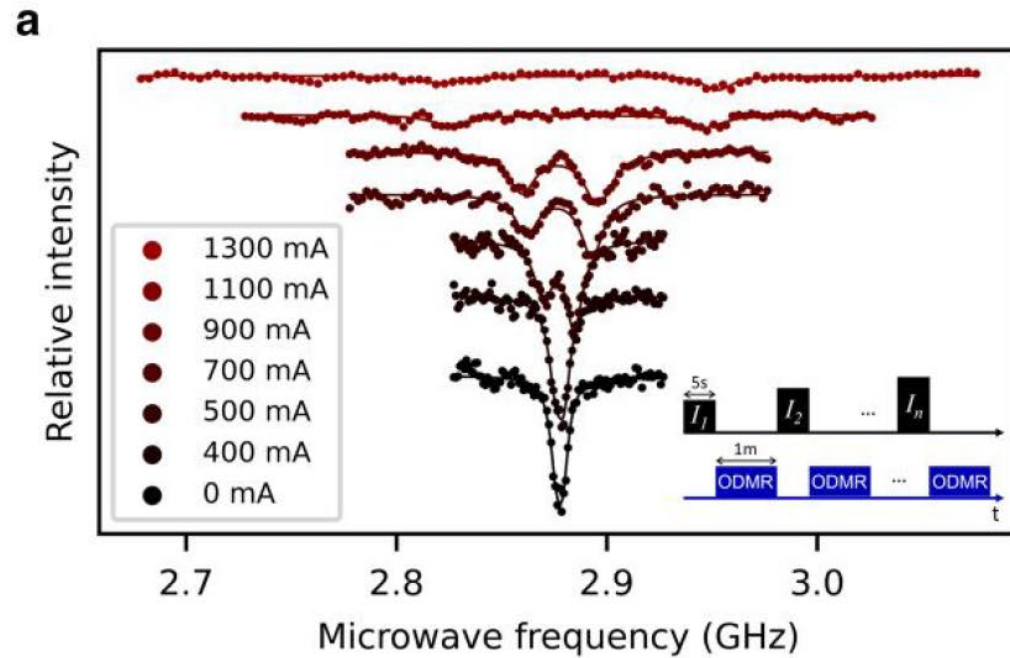


Superconducting particle levitation at millikelvin temperatures: limited Q

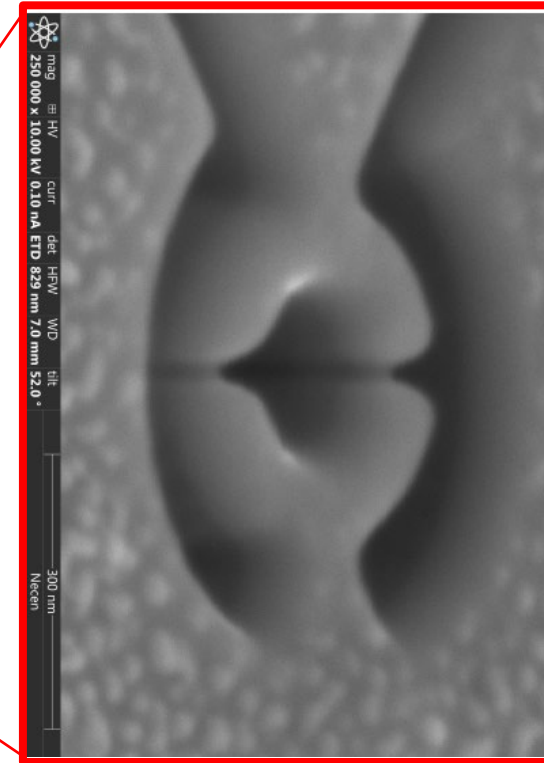
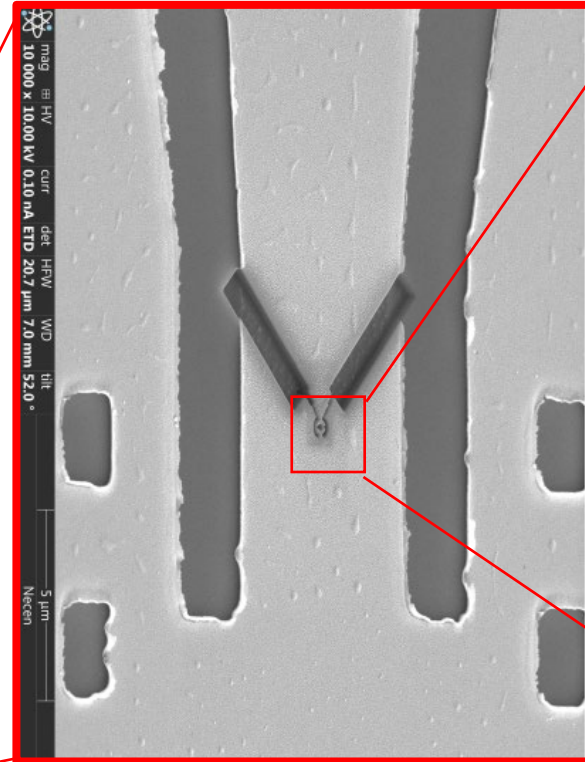
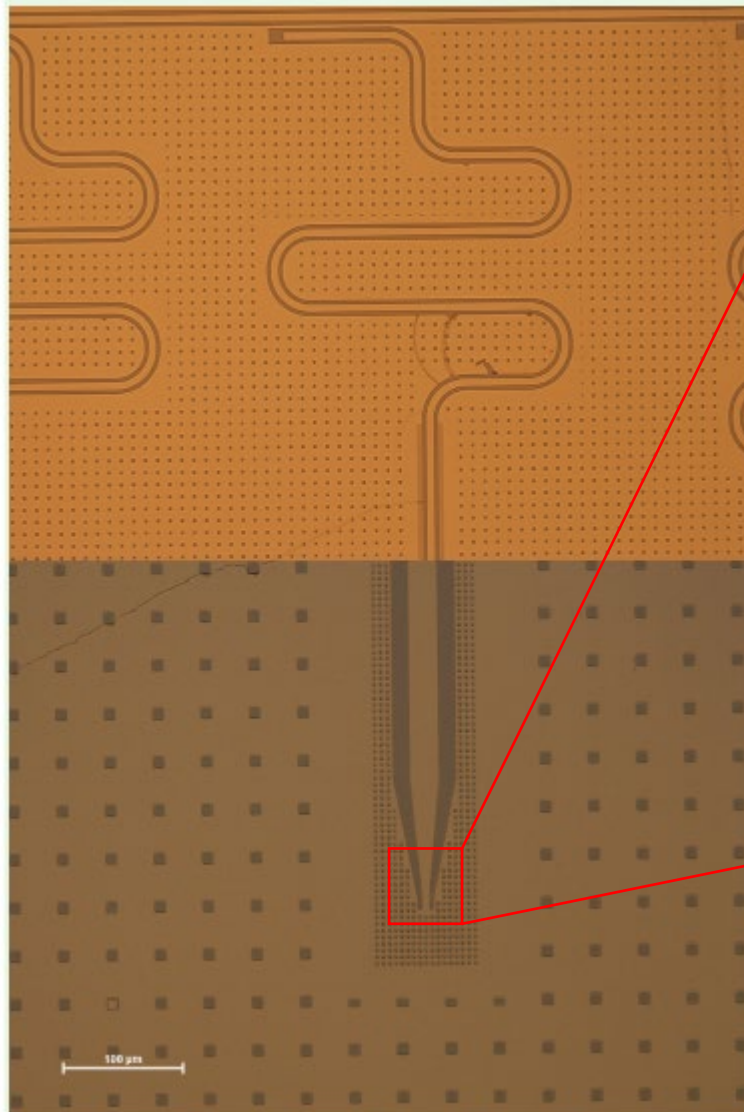


50 um PbSn at mK

Magnetic field in superconducting core persists after ramping down high applied currents



Integrated nanoSQUIDs for high magnetic field compatibility



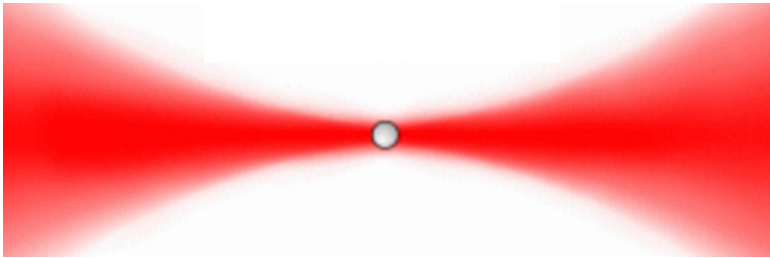
Richard Wagner
Is here!



Collaboration
Kaveh Lahabi
@ Leiden

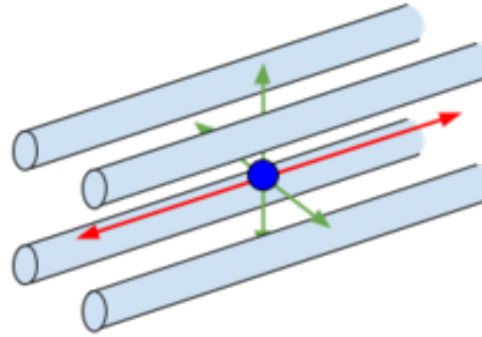
Why magnetic levitation?

Optical tweezers



- + High trapping frequencies
- + Cooling multiple modes to QGS

Electrical Paul trap



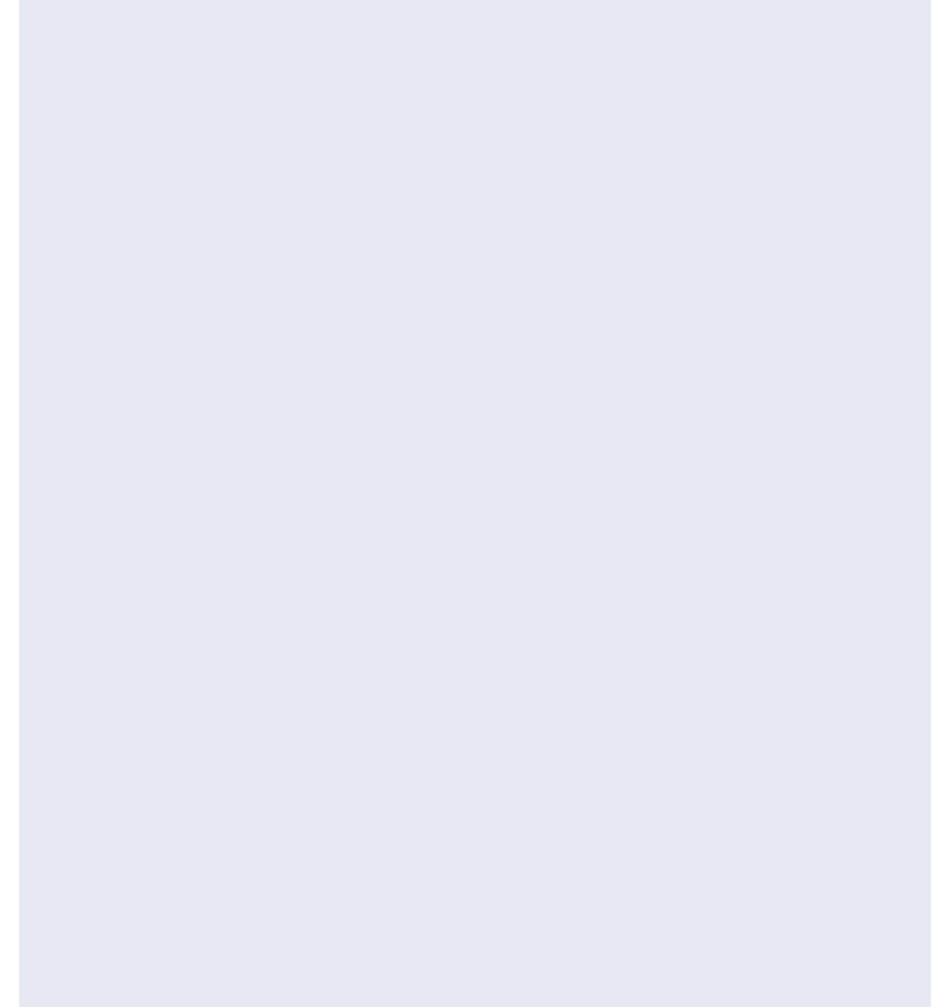
- + No laser induced internal heating
- + On-chip integration

(Dia)magnetic levitation



- + No charges & heating
- + Large masses
- Cryogenics (?)

Gonzalez-Ballestro et al., Science **374**, eabg3027 (2021)



Synergy with Einstein Telescope gravitational wave detector technology



Einstein Telescope for business



Universiteit
Leiden



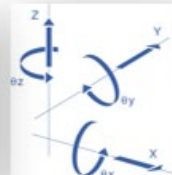
WP1 | Cryogenic superattenuators



WP2 | Cryogenic multi- axis feedback system



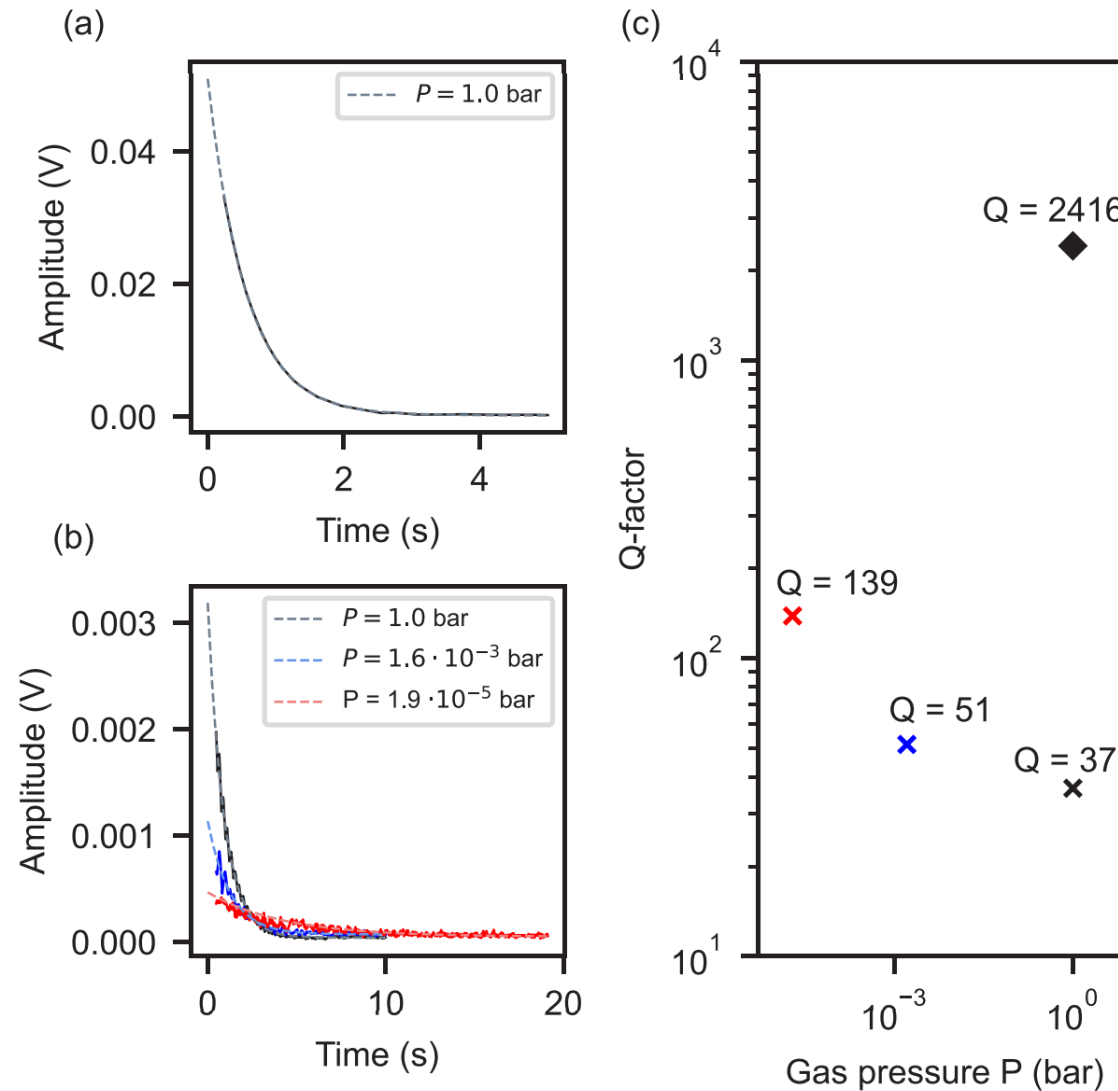
WP3 | Levitated 6D accelerometer



WP4 | Valorization: Quantum Microscopy



Q-factors are relatively low



Janse et al., APL **125**, 144003 (2024)

Still some challenges left for the magnetic Paul trap...

- + No charges & heating
- + Large masses
- + Larger magnetic moment than for induced dipole
- + Integration with optics possible (hybrid traps)
- Cryogenics ✓
- Unsuitable for miniaturization (to chip) ✓
- Low trapping frequencies (Hz)
- Low Q-factors

Paul traps

Breaking Earnshaw's theorem

 $\chi < 0$ (Meissner levitation)

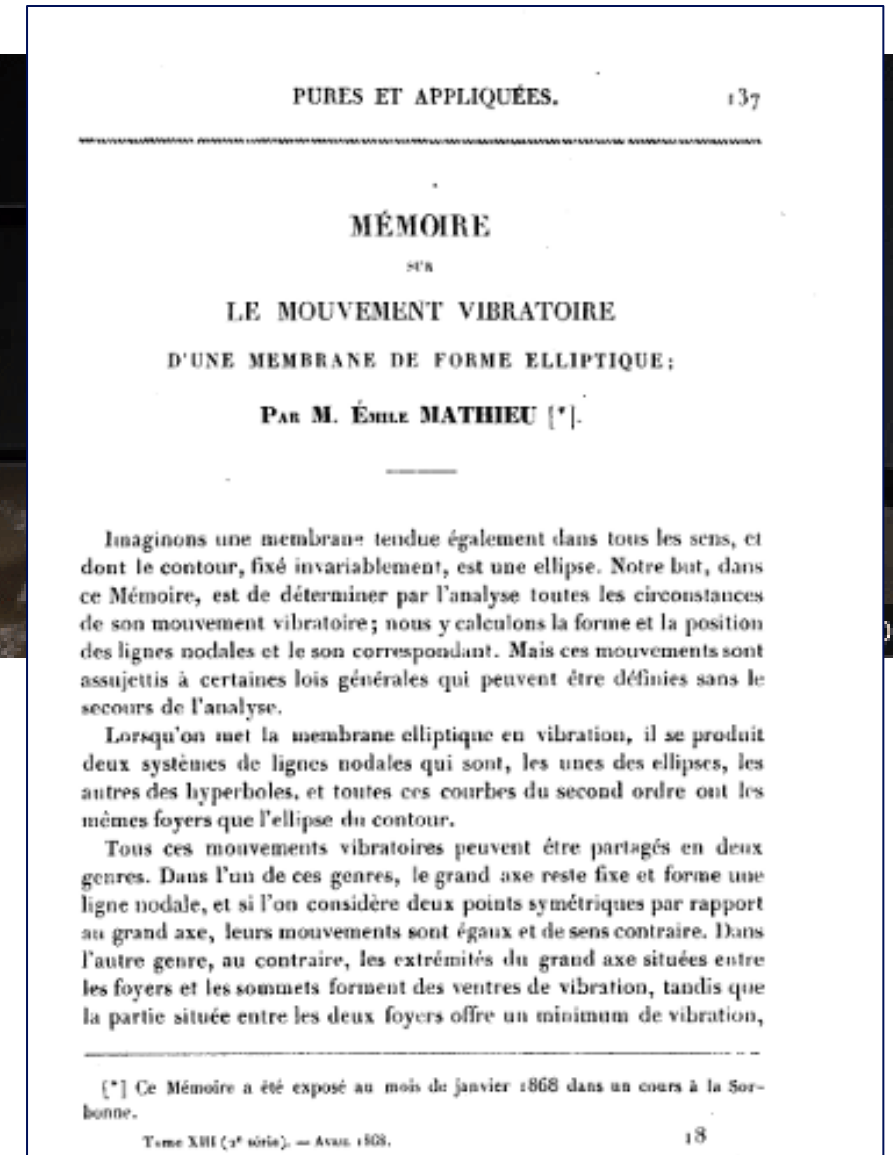
 AC fields

Mathieu equations

$$\frac{d^2u}{dt^2} + \frac{\Omega^2}{4}(a_u - 2q_u \cos \Omega t)u = 0 \text{ for } u = x, y, z$$

$$\text{where } a_x = -\frac{a_z}{2} = \frac{8eV_{DC}}{2r_0^2 m \Omega^2} \text{ and } q_x = -\frac{q_z}{2} = \frac{4eV_{AC}}{2r_0^2 m \Omega^2}$$

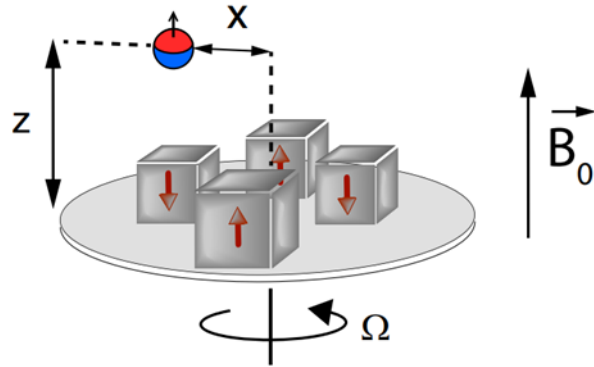
But can we build a magnetic version?



Dehmelt, Adv. Atom. Mol. Phys., **3**, 53-72 (1968)
Mathieu, J. Appl. Math., 137 (1868)

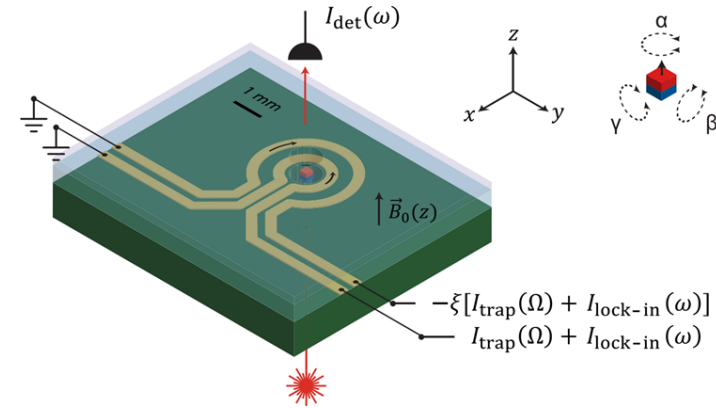
Summary

Magnetic Paul traps provide for magnetic levitation at room temperature.



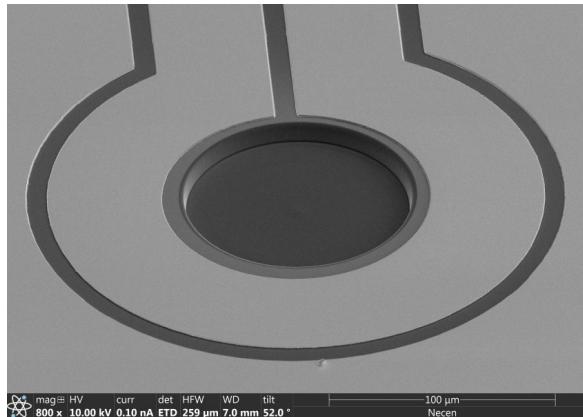
Perdriat et al., PRR **5**, L032045 (2023)

Planar AC magnetic Paul traps allow for miniaturization of the trap design, and thus higher eigenfrequencies.

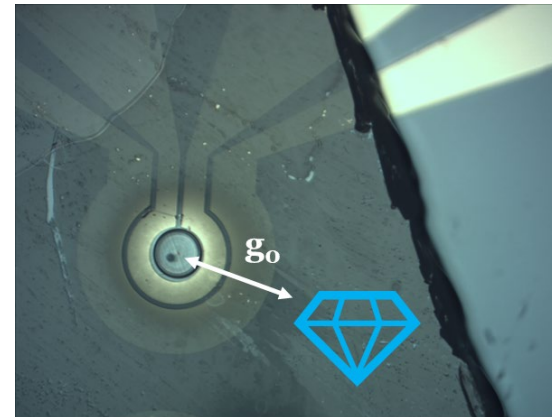


Janse et al., APL **125**, 144003 (2024)

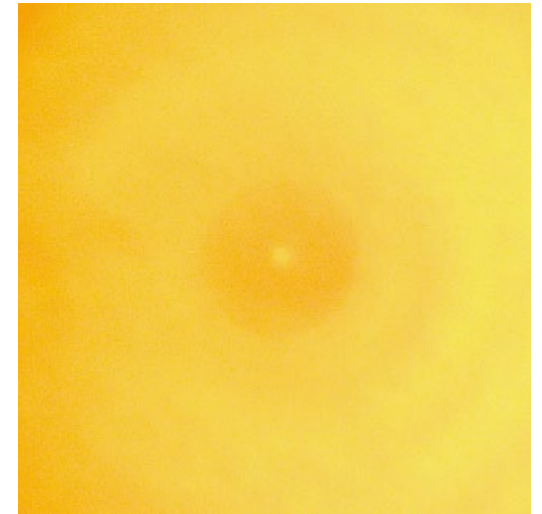
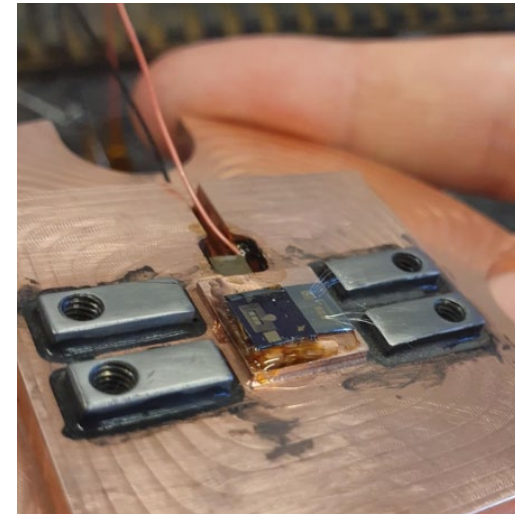
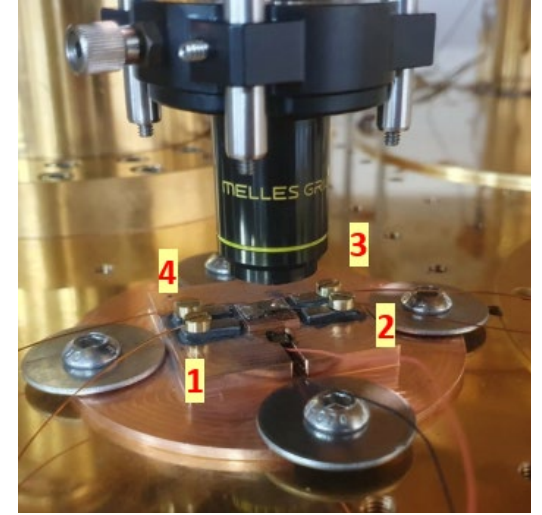
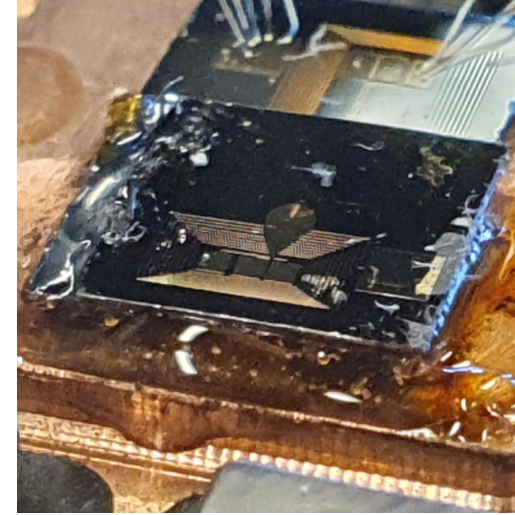
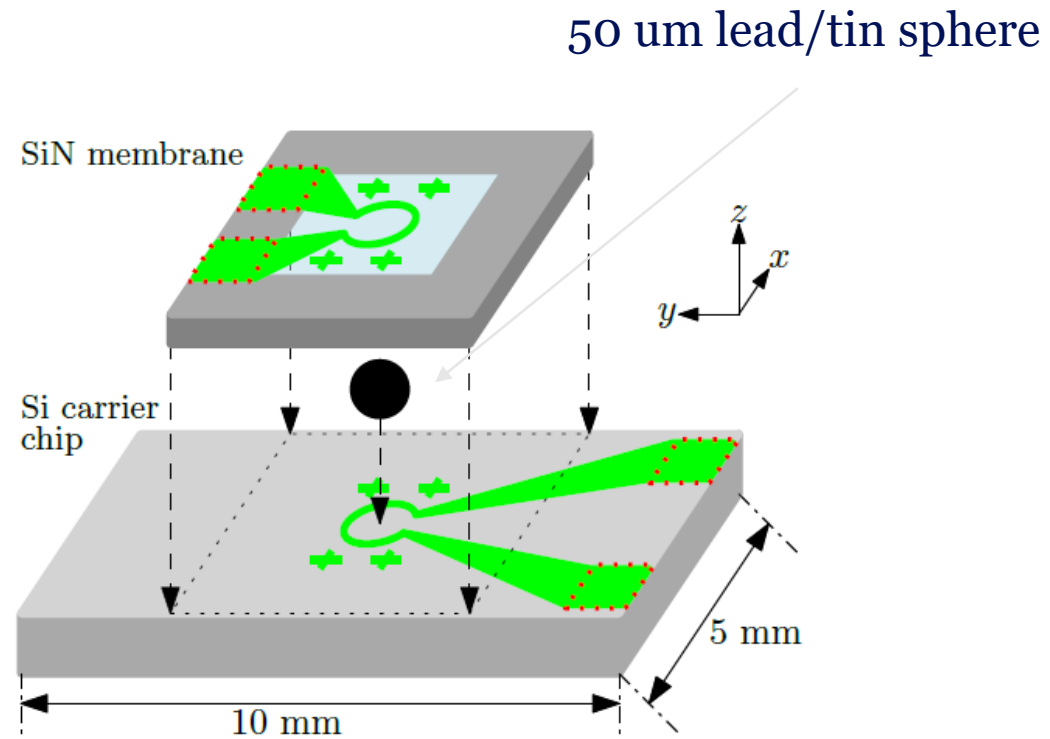
Librational eigenfrequencies of on-chip planar AC magnetic Paul traps reach up to 20 kHz.



Librational eigenmodes of ferromagnets may be cooled via optomechanical coupling to NV centers.



Miniaturization: On-chip traps for superconducting particle levitation



See also:

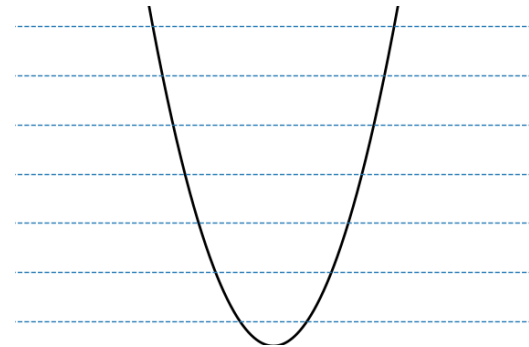
Hofer, ..., Aspelmeyer, *PRL* **131**, 043603 (2023)

Latorre, ..., Wieczorek, *IEEE Trans. Appl. Supercon.* **32**, 1–5 (2022)

The power of levitation

$$x_{\text{ZPF}} = \sqrt{\frac{\hbar}{2m_{\text{eff}}\Omega_m}}$$

$$q_{\text{zpf}} = \sqrt{\frac{\hbar}{2m\omega_m}}$$



① Stiffen potential,
increase
eigenenergies $\hbar\omega$

The power of levitation: dynamical control of the confining potential

