Magneto-Gravitational Trapping of SiC Particles Containing Si-Vacancy Centers

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Challenges for Witnessing Quantum Aspects of Gravity in a Lab
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Motivation: Tabletop Gravitational Measurements

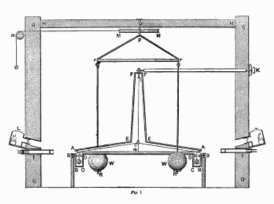
- Tests of macroscopic quantum mechanics.
- Precision measurements ($G \approx 6.67 \times 10^{-11}\ \mathrm{m^3 s^{-2} kg^{-1}}$).
- High-sensitivity force measurements.

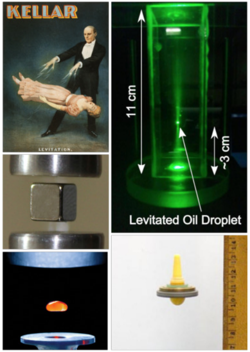
Why levitated optomechanics?

- Cold atoms: tiny mass $\rightarrow$ gravitational forces are weak.
- Micro/nano-mechanical systems: clamping adds loss.
- Trapping: “spheres” are (ideally) simple geometry.

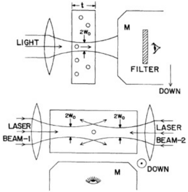
Why are these measurements hard?

- The force of gravity is weak!
- There is no way to shield against gravity.
- Equivalence principle: acceleration indistinguishable from gravity $\rightarrow$ sensitivity to non-inertial reference frame.



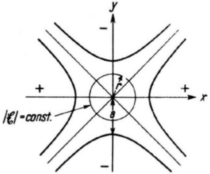


Approaches to Levitated Optomechanics



Optical (Dynamic Electromagnetic) Traps

- “Acceleration and Trapping of Particles by Radiation Pressure”, Arthur Ashkin, Physical Review Letters (1970).
- Nobel Prize in Physics (2018), “…for the optical tweezers and their application to biological systems.”



Paul (Electrodynamic) Traps

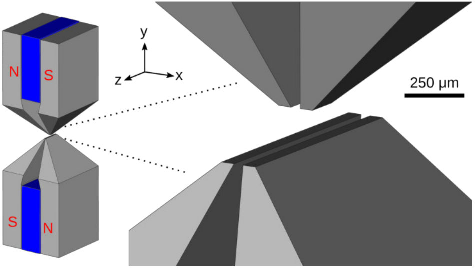
- “Ein neues Massenspektrometer ohne Magnetfeld”, Wolfgang Paul, and H. Steinwedel, Z. Naturforsch. A. (1953).
- Nobel Prize in Physics (1989, with Hans Dehmelt), “…for the development of the ion trap technique.”

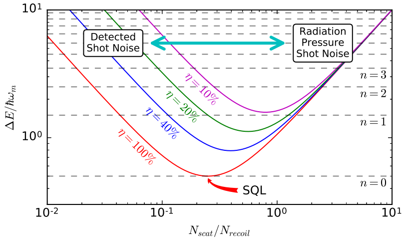
Diamagnetic (Magnetostatic) Traps

- “Of Flying Frogs and Levitrons”, Michael V. Berry and Andre K. Geim, Eur. J. Phys. (1997).
- Ig Nobel Prize (2000, A. K. Geim and M. V. Berry), “…for using magnets to levitate both a frog and sumo wrestler.”

Overview

- Introduction to magneto-gravitational traps.
- Towards the standard quantum limit (SQL). But which one?
- Classical measurements of gravity and acceleration.
- Adding a quantum handle with SiC and putting it all together.

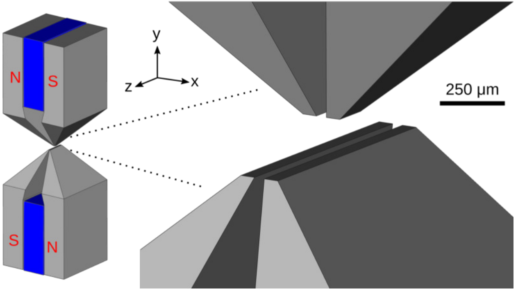


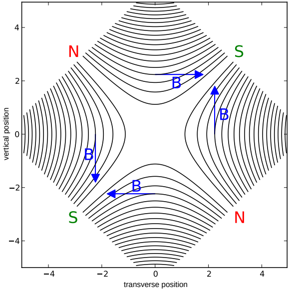


Magneto-Gravitational Trap for Optomechanics

- Vertical field gradient $\approx 1\,\mathrm{T}/100\,\mu\mathrm{m}$.
- Curved 2-D magnetic quadrupole + Earth's gravity creates a 3-D trap.[1]
- Directions: x = transverse, y = vertical, z = axial.

$$\frac{U}{m} = gy - \frac{\chi B^2}{2\rho\mu_0} = gy - \frac{\chi}{2\rho\mu_0}\left|A_x \Delta x\,\hat{y} + \left(B_0 + A_y \Delta y + A_z \Delta z^2\right)\hat{x}\right|^2$$



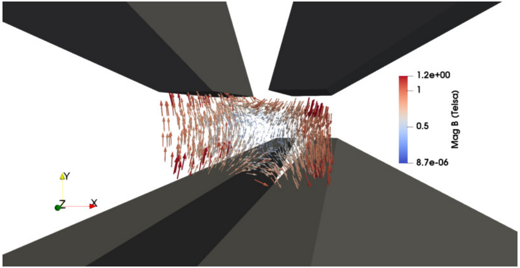


[1] J.-F. Hsu, P. Ji, C. W. Lewandowski, B. D'Urso, Sci. Rep. (2016)

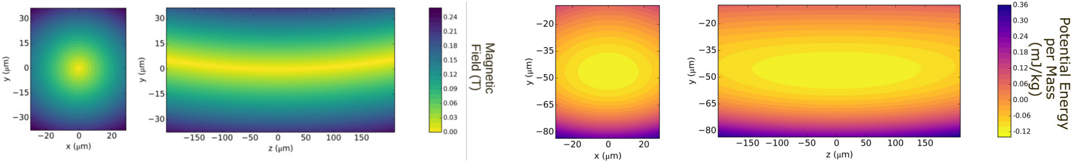
Modeling the Magneto-Gravitational Trap

We use two models of our traps:

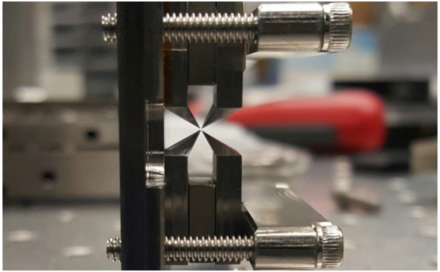
1. Finite element calculations of magnetic, electric, and gravitational fields.

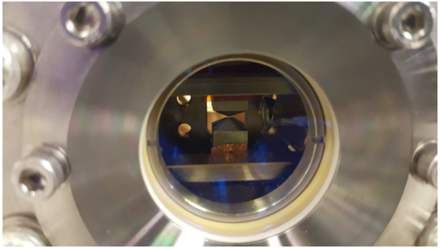


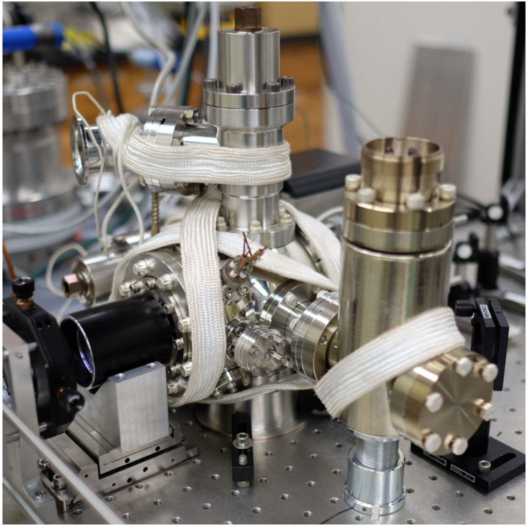
2. 3-term spherical harmonic expansion of magnetic field.



Trap and Vacuum Chamber Construction

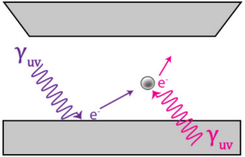


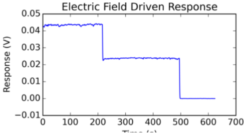


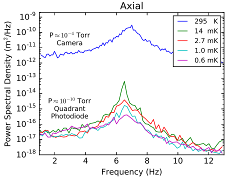


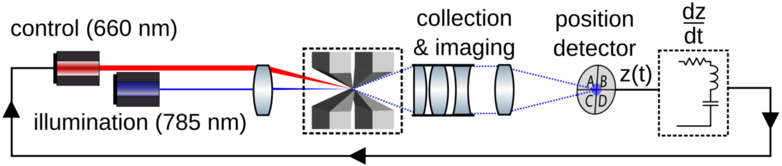
Established Features of Magneto-Gravitational Trapping

- Trap particles ≈ 1 to $65\,\mu$m diameter.
- Particle materials: SiO_2, SiC, diamond, water, oils, ...
- Low oscillation frequencies:
  - Axial ≈ 0.1 to 10 Hz.
  - Transverse/Vertical ≈ 50 to 120 Hz.
- Trapping in UHV ($< 1 \times 10^{-10}$ Torr).
- Perfect (zero e^-) electric monopole neutralization.
- Linear feedback cooling to $\approx 140\,\mu$K (axial).
- 3-D cooling with multiple sensors and cooling beams.

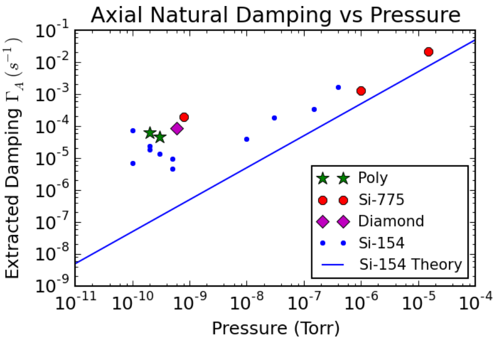


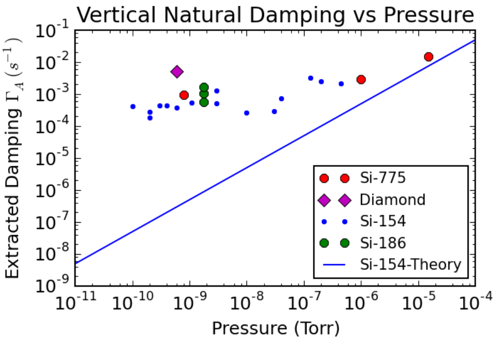






Inferred Damping Across Many Particles

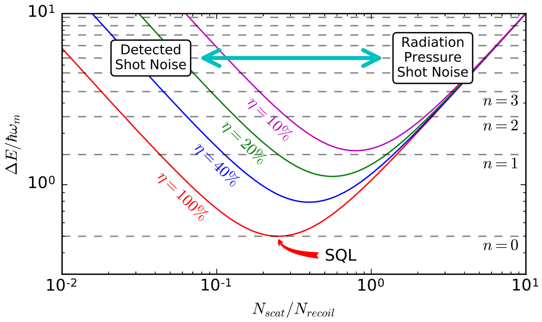




calculated $\Gamma_A \leqslant \Gamma_{\mathrm{feedback}} \frac{T_{\mathrm{feedback}}}{T_A}$

Cooling to the Quantum Ground State?

- We are still far from the ground state: $\bar{n}_z \approx 3 \times 10^5$.
- Limited by: vacuum, noise, vibration, rotation…???
- Increase optical power to make radiation pressure shot noise relevant $\rightarrow$ faster measurement.
- Problem: quantum decoherence time is less than one oscillation period.
- Can we make pulsed measurements in the free-particle limit?



Quantum efficiency needed for cooling to $\bar{n} < 1$ is $\eta > \frac{1}{9}$.

Pulsed Measurement Fundamental Noise Sources

- **Radiation pressure shot noise**
  Scatter N_λ photons $\rightarrow$ a momentum kick with:

$$\Delta p_z = \frac{2\pi\hbar f_z\sqrt{N_\lambda}}{\lambda}$$

- **Detected shot noise**
  Heisenberg uncertainty minimum $\rightarrow$ position uncertainty:

$$\Delta z_\lambda = \frac{\lambda}{4\pi f_z\sqrt{N_\lambda}}$$

- **Thermal noise**
  - Thermal displacement and velocity are too large. Subtract them off.
  - Use a series of 3 position measurements separated by τ with $z_c = z_3 - 2z_2 + z_1$ $\rightarrow$ thermal noise:

$$\Delta_T z_c = \sigma_{\beta T}\sqrt{\frac{4k_B T\omega_z}{mQ}}\tau^{\frac{3}{2}}$$

Pulsed Measurement Combined Noise

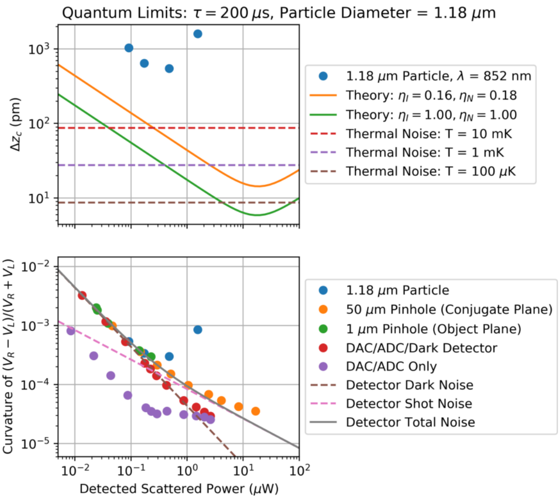
- Noise (quantum + thermal) for the three measurement sequence as a function of the detected number of photons N_D is:

$$\Delta_{\text{total}} z_c = \sqrt{\frac{3\lambda^2}{8\pi^2 f_z^2 \eta_I N_D} + \frac{4\pi^2\hbar^2 f_z^2 N_D}{m^2\lambda^2\eta_N}\tau^2 + \sigma_{\beta T}^2 \frac{4k_B T\omega_z}{mQ}\tau^3}$$

- Several parameters are calculated numerically:
  - Particle geometry (Mie scattering)
    $\rightarrow f_z \approx 0.324$
  - Photon collection & detection efficiency (Mie scattering & Fourier optics)
    $\rightarrow \eta_N \approx 0.59$ (maximum), $\eta_I \approx 0.16$ (2-segment detector).
  - Thermal force numerical calculation
    $\rightarrow \sigma_{\beta T} \approx 0.74$

Towards Position Measurements at the SQL

- New camera-based cooling scheme for all 3 translational degrees of freedom.
- New 2-segment detector and digitizer built and qualified.
- High-power illumination can be pulsed on.
- What is going wrong?
- Likely source of problems: Ellipsoidal particle $+$ uncontrolled particle rotation $\rightarrow$ fluctuating radiation pressure.



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Measuring the Newtonian Constant of Gravitation "G"

- Measure G from an oscillation frequency shift with or without field masses M.
- Horizontal oscillation frequency:

$$\omega_{\text{near}} = \sqrt{\frac{k}{m} - \frac{4GM}{d^3}}.$$

- For $M = \frac{4\pi}{3}\rho R^3$ and $d = 2R$, $\Delta f = -\frac{\rho G}{12\pi f_{\text{far}}}$.
- For tungsten alloy with $f_{\text{far}} \sim 0.01\,\text{Hz} \to \Delta f \sim 3 \times 10^{-6}$ Hz.

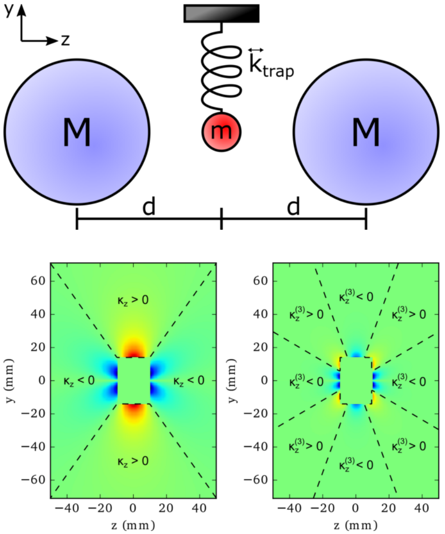
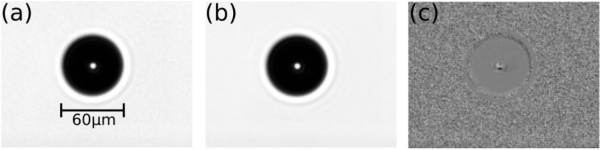
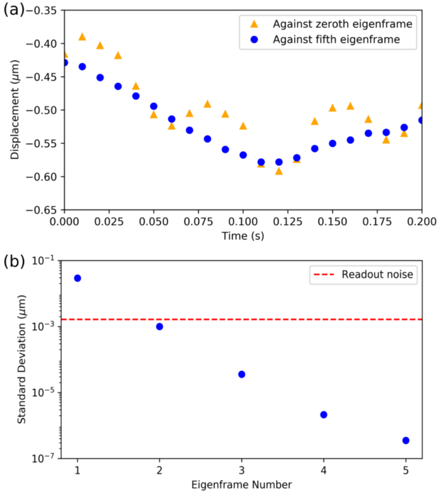


Image-Based Position Detection

- Measure displacement of particle by cross-correlation of images over time.
- Effect of image noise greatly reduced by building up an averaged “eigenframe” in Fourier space.
- Attained precision ≈ 1.6 nm per image (pixel size is 1.15 μm).[2]

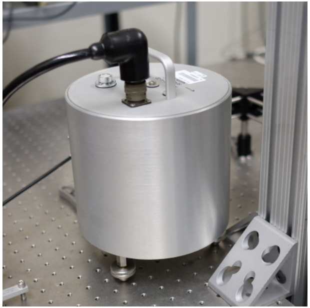


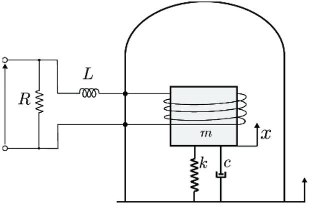


[2] C. Lewandowski et al, Phys. Rev. Appl. 15, 014050 (2021)

Trapped Particle As an Accelerometer

- A harmonic oscillator (resonance frequency ω_0) can be used as an accelerometer:
  - If $\omega \gg \omega_0$, the environment moves but the proof mass stays still $\rightarrow$ acceleration is detected.
  - If $\omega \approx \omega_0$, the environment and proof mass move with different phases $\rightarrow$ acceleration is detected (enhanced by Q).
  - If $\omega \ll \omega_0$, the environment and proof mass move together $\rightarrow$ acceleration is not detected.
- In our system, the signal originates from the relative *displacement* of the particle and detector.
- In a geophone, the signal originates from the relative *velocity* of the proof mass and coil.

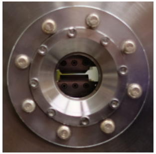


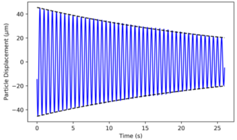


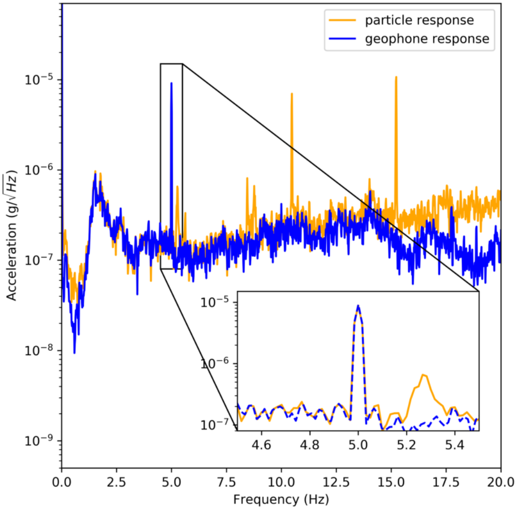
Acceleration Sensing: Particle vs. Geophone

Divide out harmonic oscillator response to get acceleration:

- Particle:
  - Measure camera magnification.
  - Analyze ring-down to get frequency and damping.
- Geophone:
  - Factory calibration of frequency, damping, gain.
- Response to drive matches $\pm 3\,\%$.

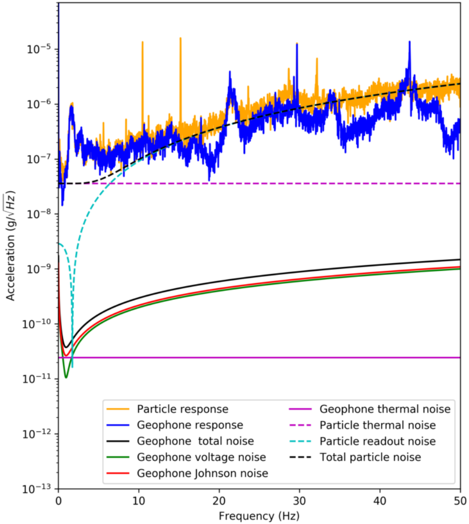






Noise Analysis: Particle vs. Geophone

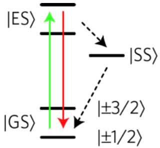
- Particle noise dominated by image readout noise:
  - $\approx 1.6\,\mathrm{nm}$ per image ($160\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$).
  - Near shot noise limit.
- Thermal noise ($\approx 10\,\mathrm{K}$ or less) may limit low-frequency sensitivity.
- Feedback noise is *computationally* limited.
- Particle gives similar results with 4×10^9 lower mass than geophone (particle noise is higher in principle).[3]

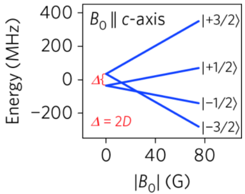


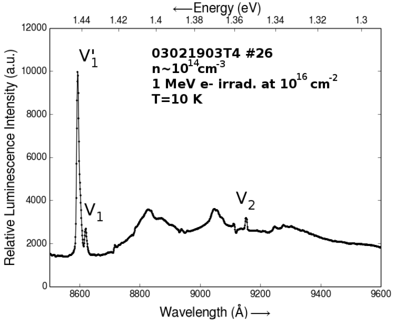
[3] C. W. Lewandowski, T. D. Knowles, Z. B. Etienne, B. D'Urso, Phys. Rev. Applied 15, 014050 (2021)

V_{Si}^{-} (V2) Defect in 4H-SiC

- The V_{Si}^{-} (V2) center in 4H-SiC has much in common with the NV center in diamond.
- SiC is transparent, commercially produced, and stable.
- Two possible sites for V_{Si}^{-} (V2).[4]
  - *V1* (ZPL at 861 nm).
  - *V2* (ZPL at 916 nm).
- Intrinsic defect: create with irradiation.
- Room-temperature properties of V_{Si}^{-} (V2):
  - $S = 3/2$ (sense $|B|$ and direction).
  - Efficient excitation 720 - 800 nm.[4]
  - Excited state lifetime $\tau \approx 6.3$ ns.[4]
  - Zero field splitting $\Delta \approx 70$ MHz.[5]
  - Spin coherence time $T_2 \approx 100$ μs.[5]





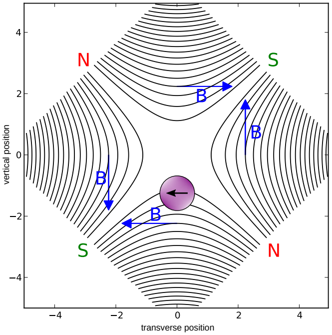


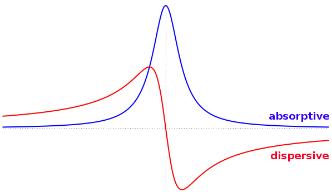
[4] Dissertation of F. Fuchs, Würzburg (2015)

[5] Widmann et al, Nat. Mat. 14, 164 (2015)

V_{Si}^{-} (V2) in a Trapped 4H-SiC Particle

- Two approaches to Electron Spin Resonance (ESR) in trapped particles:
  1. Optically Detected Magnetic Resonance (ODMR): collect spin-dependent photoluminescence (less than 1% contrast, other challenges).
  2. Mechanically resonant Stern-Gerlach:
     - 2.1 (Re)initialize spin to $|m_s = \pm 1/2\rangle$ with 785 nm pump.
     - 2.2 Drive $|m_s = +1/2\rangle \leftrightarrow |m_s = +3/2\rangle$ or $|m_s = -1/2\rangle \leftrightarrow |m_s = -3/2\rangle$ with μ-wave drive frequency-modulated at ω_y.
     - 2.3 Response: vertical motion with dispersive lineshape when varying μ-wave center frequency.
- Map out trap magnetic field with ESR.
- Measure rotation of trapped particles with ESR.





Prospects for Witnessing Quantum Aspects of Gravity

Soon (Maybe)

- Position detection approaching the SQL on $\sim 100\,\mu\mathrm{s}$ timescales. (Testing gravitational collapse models?)
- Steps on the way to superposition states:
  - Mechanically resonant Stern-Gerlach detection.
  - Magnetic field detection/mapping.
  - Rotation sensing.

Long-Term

- Position detection at the SQL for longer times and larger particles.
- Integration of pulsed ESR with high-speed SQL position detection.
- Spin superposition states
  $\rightarrow$ mechanical superposition states
  $\rightarrow$ interference, detected with pulsed measurements.

Acknowledgements

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- Undergraduate students: Samuel Fritsch, Noelle Dean; [Joshua Bartkoske, William Hotzfield, Silas Andrews, Emilyn Kracher, Norhan Fathy, Dominic Bair]
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