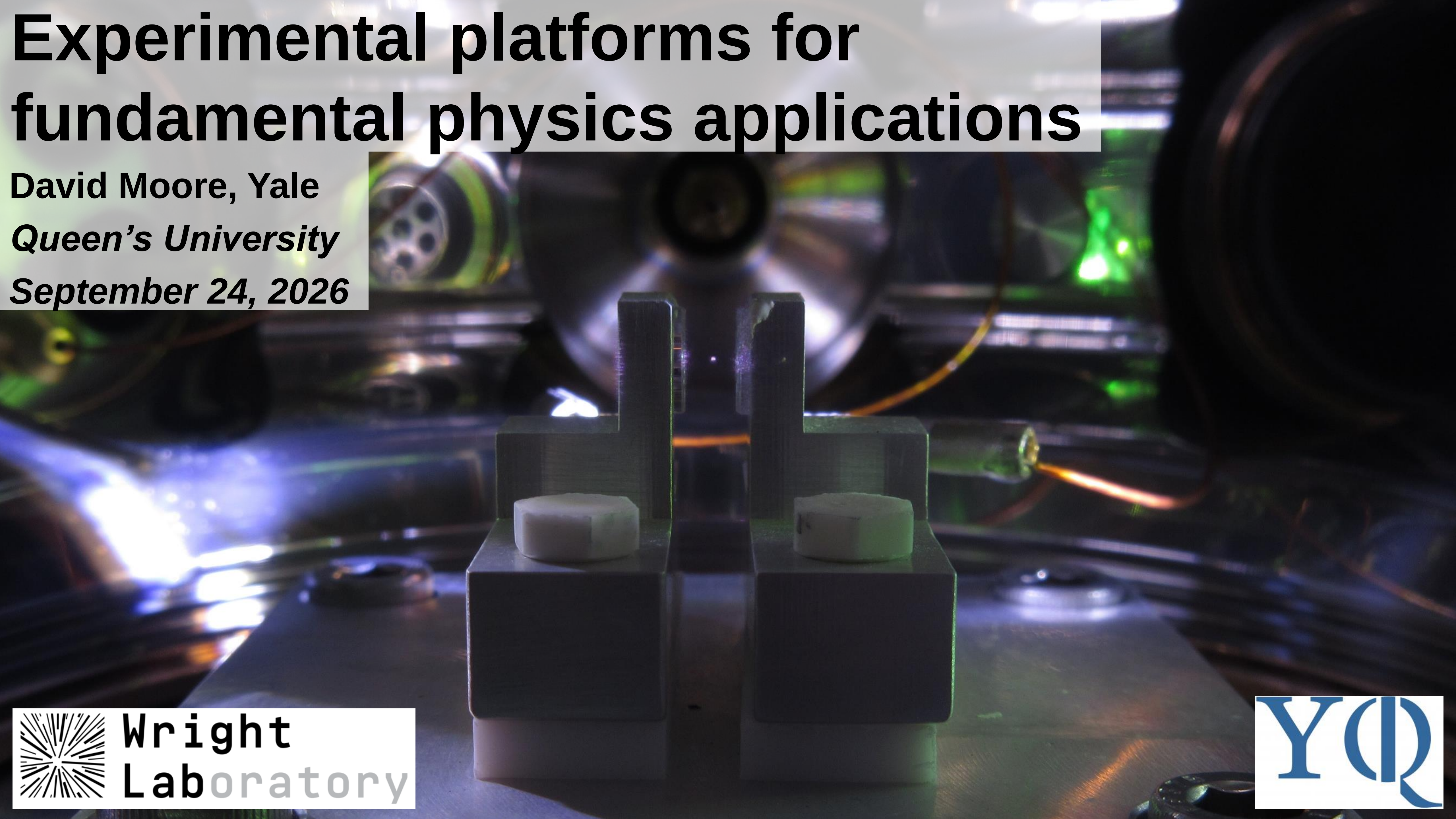
Experimental platforms for fundamental physics applications



David Moore, Yale

Queen’s University

September 24, 2026

Wright Laboratory

Mechanical systems

- A wide variety of mechanical quantum systems are revolutionizing how we measure tiny forces
- Huge variety of systems now allow mechanical DOF to be read out in the quantum regime
- These sensors can detect extremely tiny forces or accelerations
  - In the large mass range, excellent accelerometers (e.g. gravity, dark matter, …)
  - In the sub-ng range, reaching sensitivity to the forces imparted by single sub-atomic particles
- See also yesterday's talk by Zhen Liu for theory motivation

See also, e.g.:

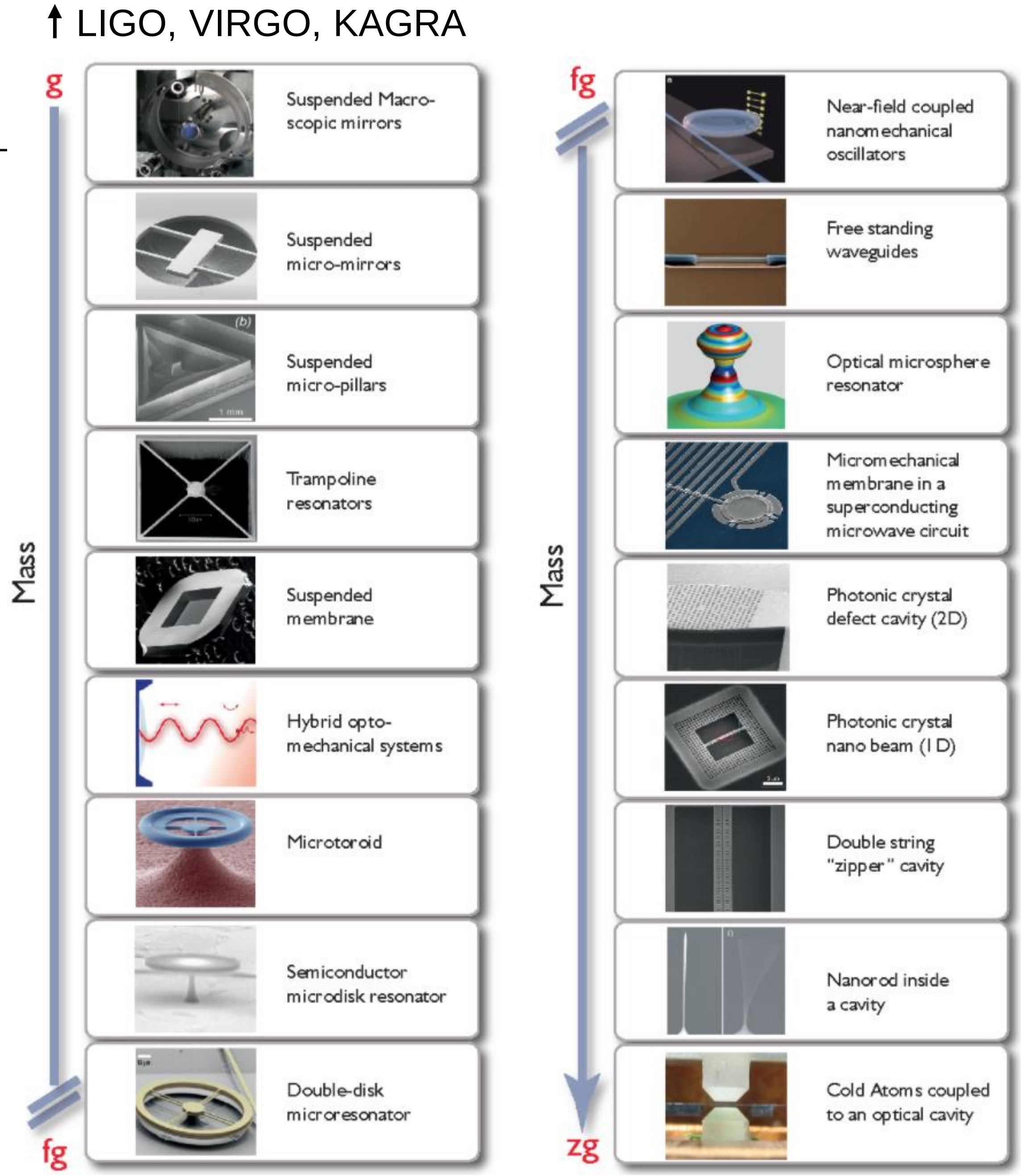
"Snowmass 2021: Quantum Sensors for HEP Science," arXiv:2203.07250.

"Mechanical Quantum Sensing in the Search for Dark Matter," Quant. Sci. Tech. 6 024002 (2021), arXiv:2008.06074

"Searching for new physics using optically levitated sensors," Quant. Sci. Tech. 6 014008 (2021), arXiv:2008.13197

"Quantum sensing for particle physics," Nature Reviews Physics 6, 329 (2024)

…

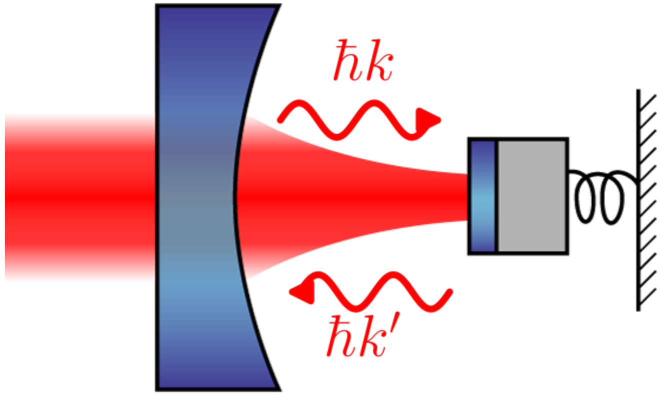


Aspelmeyer et al., Rev. Mod. Phys. 86, 1391 (2014)

Noise and sensitivity

- To make a precise sensor with a mechanical system, need two things:
  - Need to have enough precision to detect tiny changes in its motion (“***displacement sensitivity***”)
  - Need to minimize any forces acting on the mass that could otherwise obscure what we want to sense (“***force noise***”)
- Many sources of noise can contribute to these (e.g. thermal noise, noisy electronics, …), but noise from the measurement itself is a fundamental contributor to both:

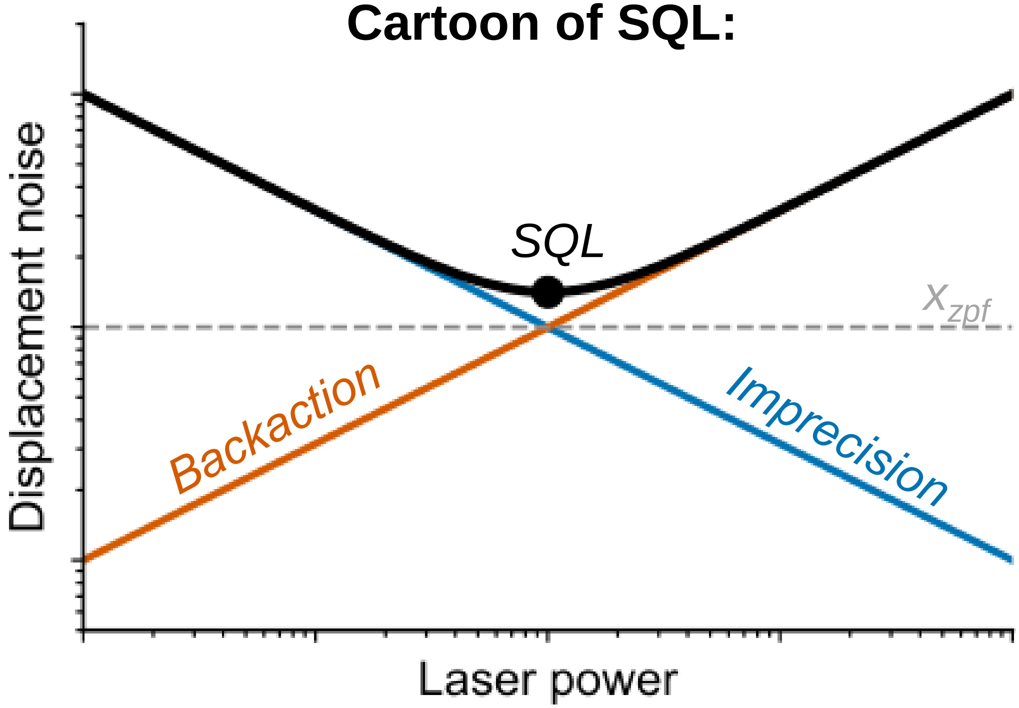
“Canonical” optomechanical system:



Imprecision: Uncertainty in mirror position due to shot noise fluctuations in measured phase

Backaction: Fluctuations in mirror position due to shot noise in radiation pressure

Cartoon of SQL:

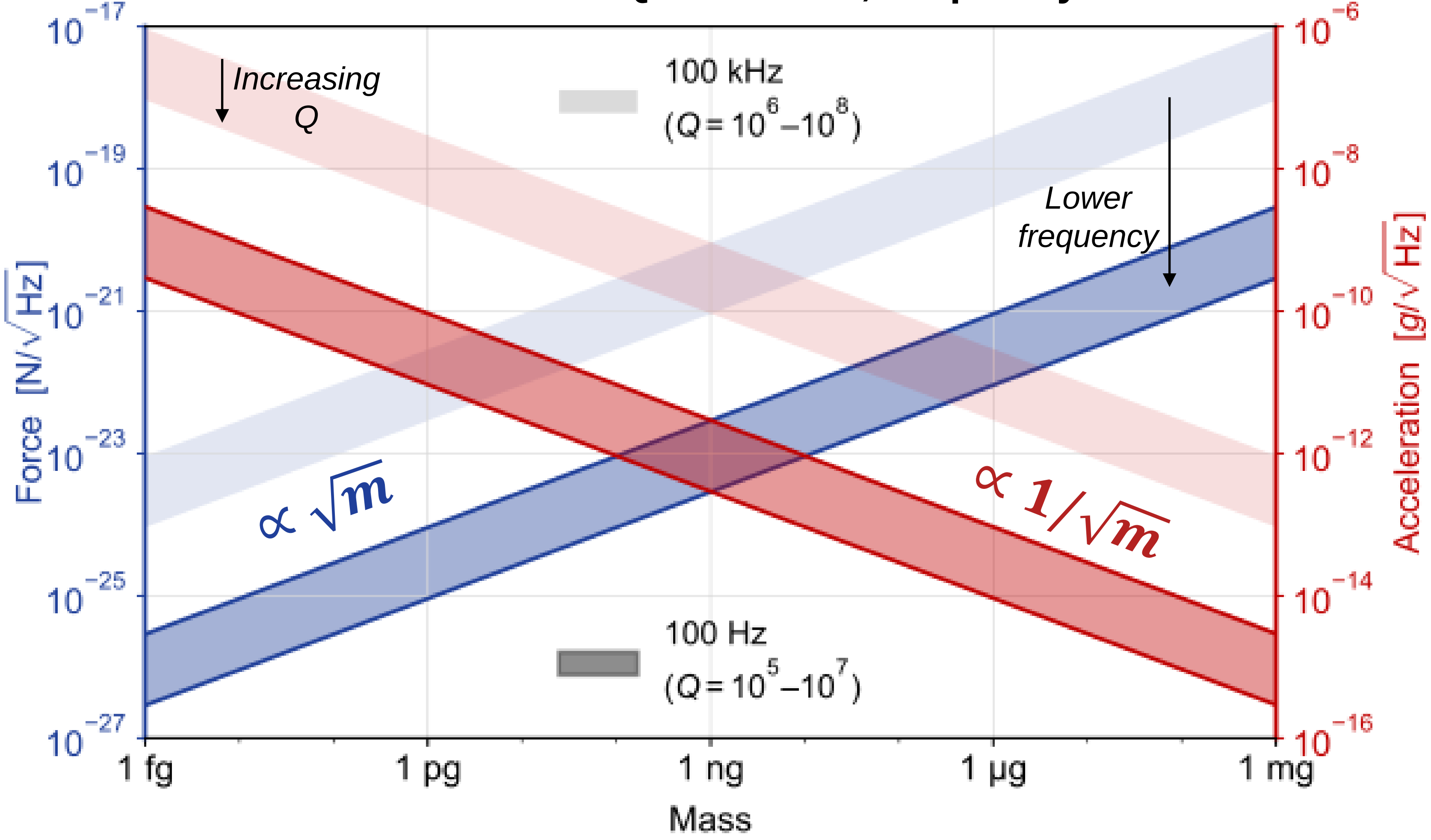


Sensitivity at SQL

- While not a fundamental limit (see e.g. talks by M. Rossi, V. Sudhir), the standard quantum limit (SQL) represents a sensitivity benchmark that is often of interest

Example physics targets:
- *Forces from fundamental particles*
- *Particle dark matter*
- *Neutrinos*
- *…*

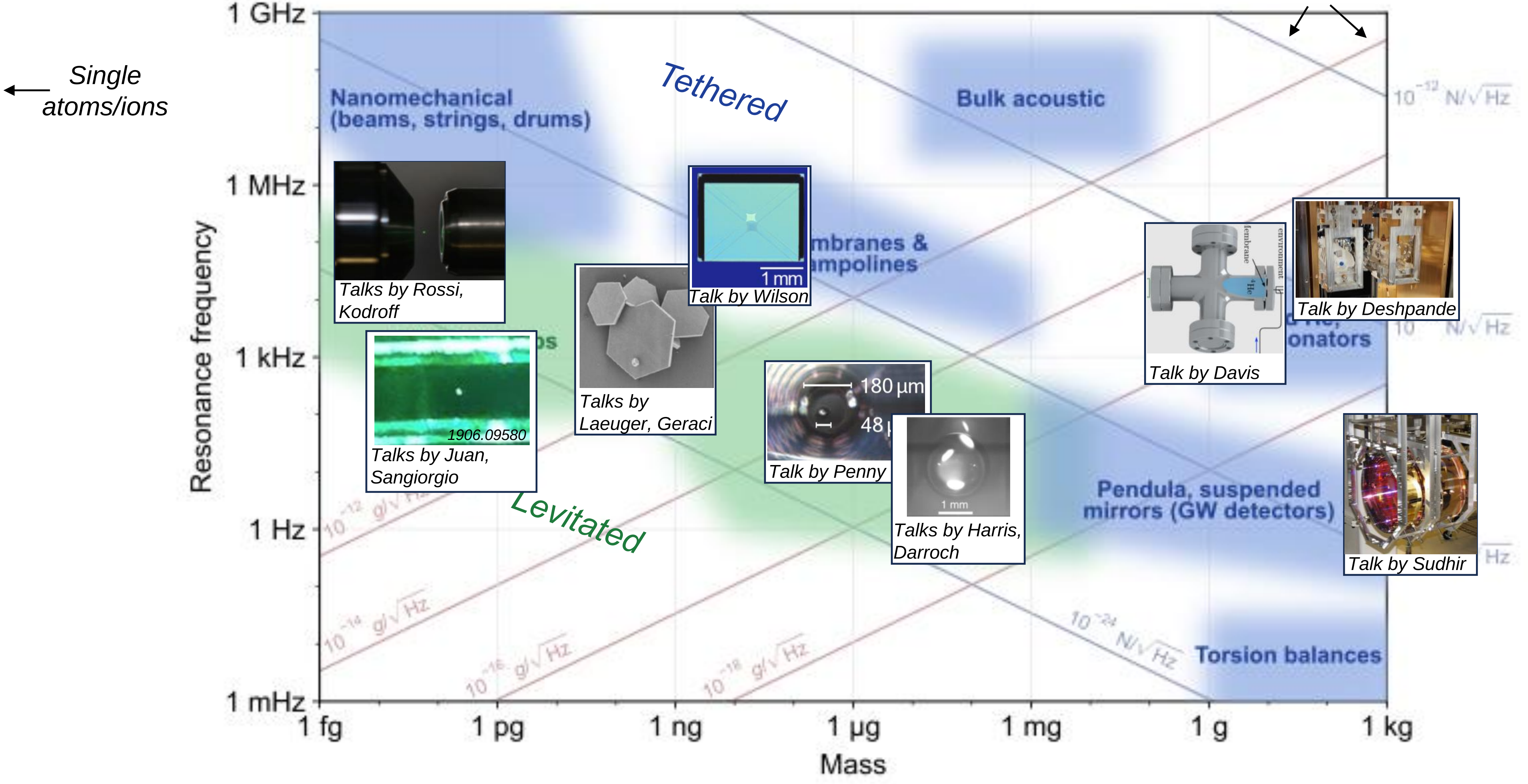
On-resonance SQL vs. mass, frequency:



Example physics targets:
- *Gravity*
- *Ultra-light dark matter*
- *Gravitational waves*
- *…*

Survey of experimental systems

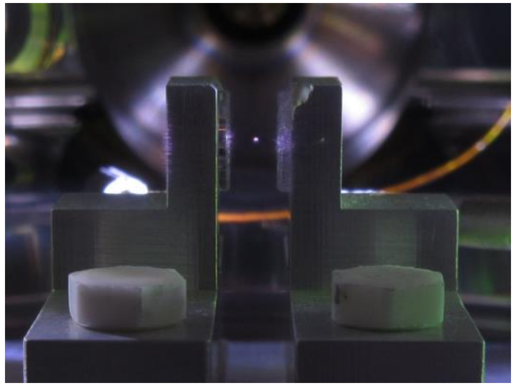
Summary of experimental platforms:

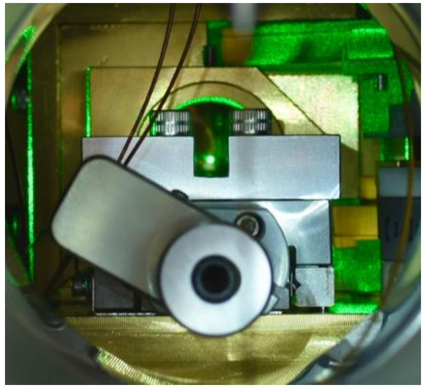


Optical levitation

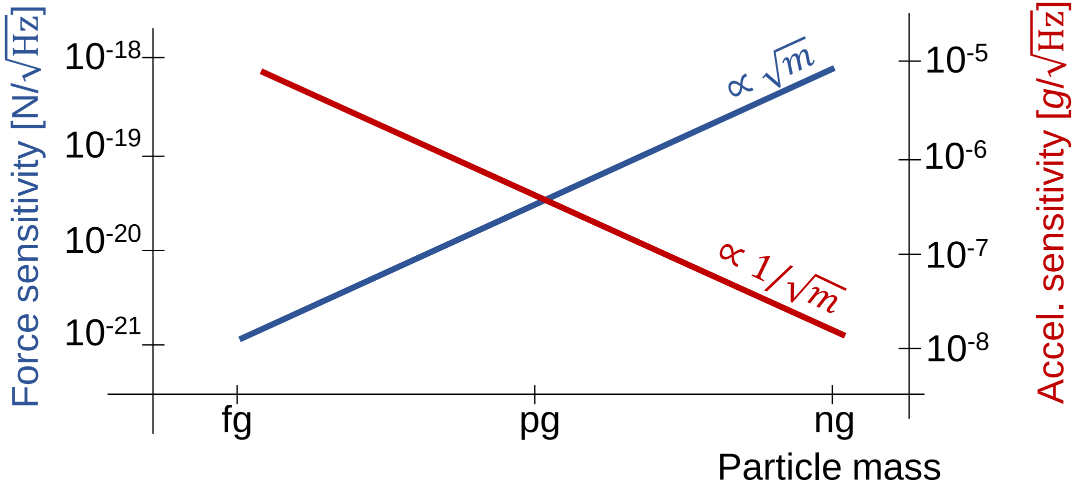
- Nano- to micro-sized dielectric masses can be optically trapped with ~100 mW of laser power
- Levitated masses are isolated both electrically and thermally
  - Ultra-low decoherence allows quantum control of motional degrees of freedom
  - Force sensitivities at the zN level, with acceleration sensitivities near a nano-g

Photographs of trapped nano/micro particles at Yale:

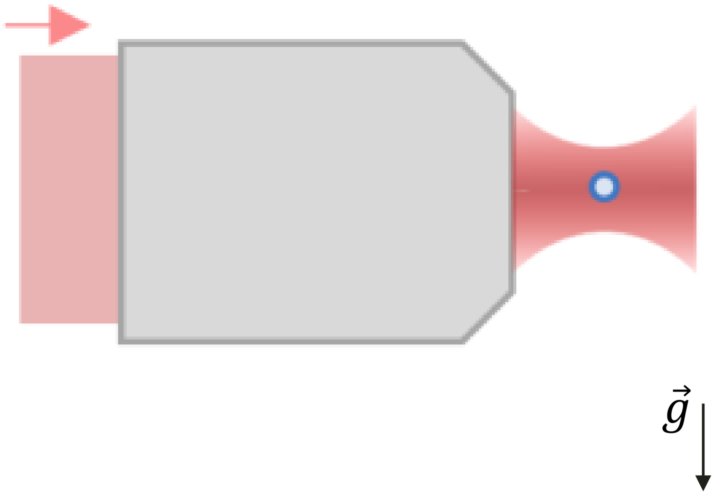




Force and acceleration sensitivity vs particle mass:



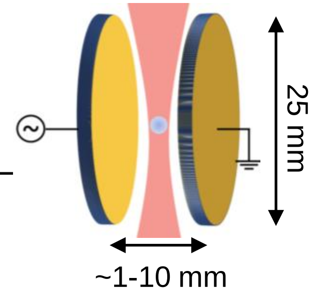
Highly focused tweezers (~0.1 – 1μm):
~1 fg – 1 pg



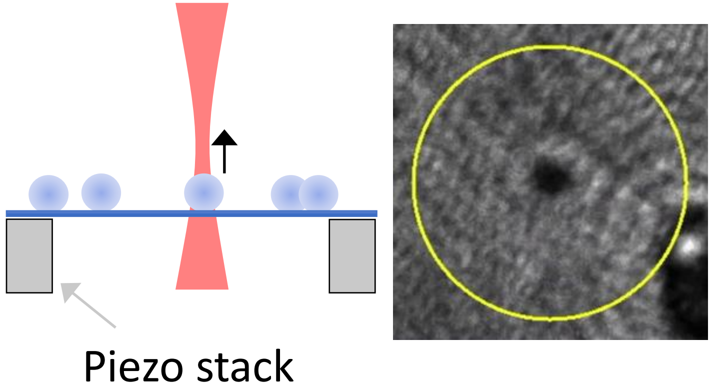
Levitation trap (~1 – 30 μm):
~1 pg – 30 ng

Moore and Geraci, Quantum Sci. Technol. 6 014008 (2021)

Experimental sequence (>ng spheres)



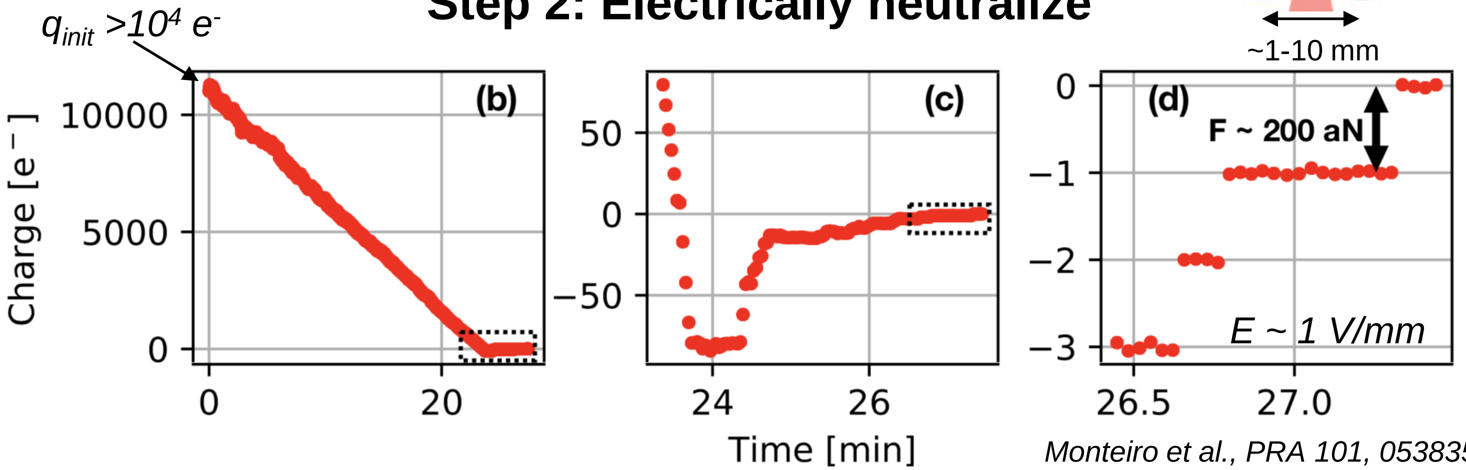
Step 1: Trap sphere (~1 mbar)



Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)

Pump to $\lesssim 10^{-7}$ mbar

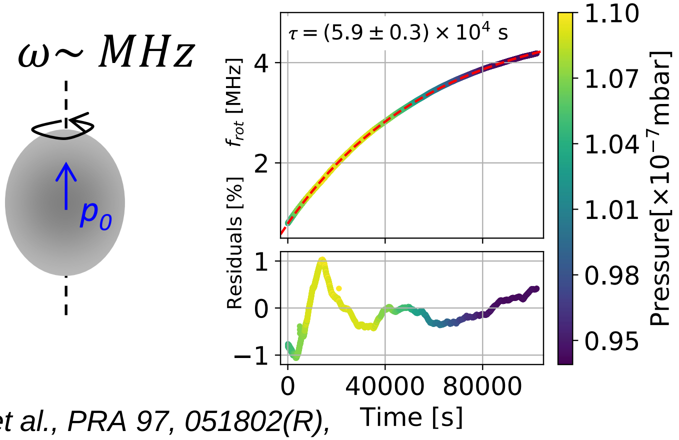
Step 2: Electrically neutralize



Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)

Step 3: Stabilize spin

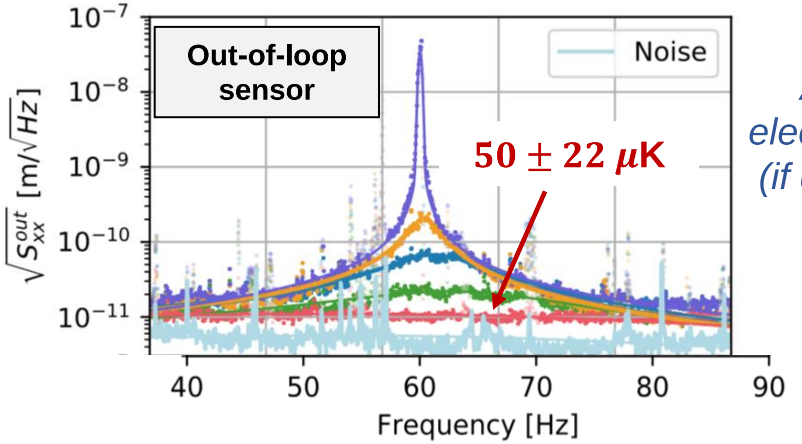
Optically spin to >MHz frequency



Monteiro et al., PRA 97, 051802(R), arXiv:1803.04297 (2018)

Active feedback cooling to μK temperatures

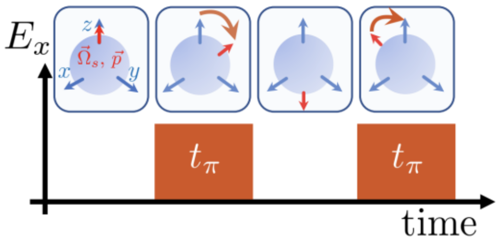
Step 4: Cool center-of-mass mode



Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)
Monteiro et al., PRA 96, 063841, arXiv:1711.04675 (2017)

Step 5: Orient electric dipole moment

Apply electric field (if desired)

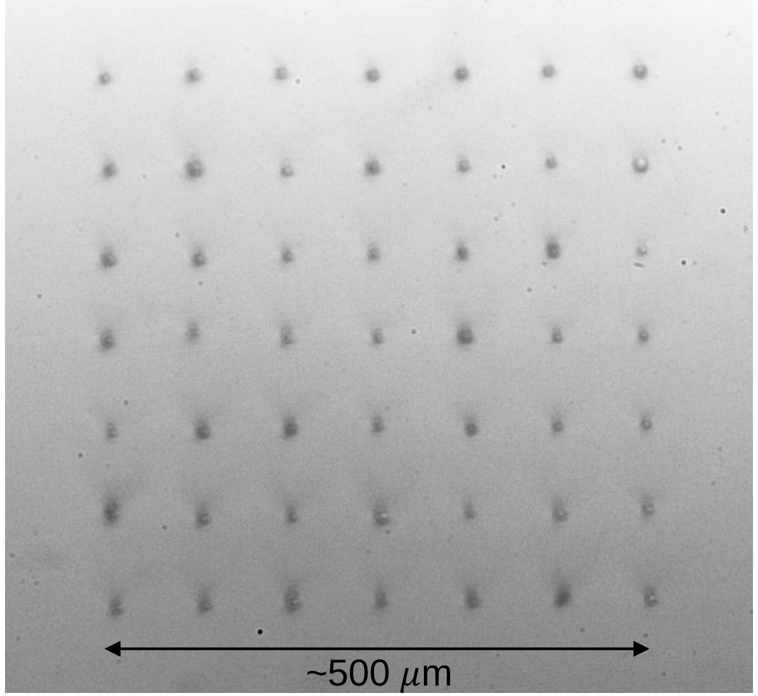


Afek et al., PRA 104, 053512, arXiv:2108.04406 (2021)

Microsphere arrays

- Also upgraded our system with high po
microparticle arrays up to ~10 x 10 in v
- Similar technology to tweezer arrays fo
  → Additionally require closed loop fee

7x7 array of spheres in vacuum:



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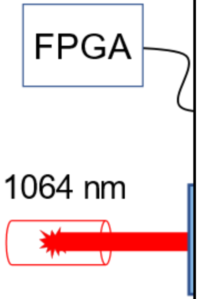
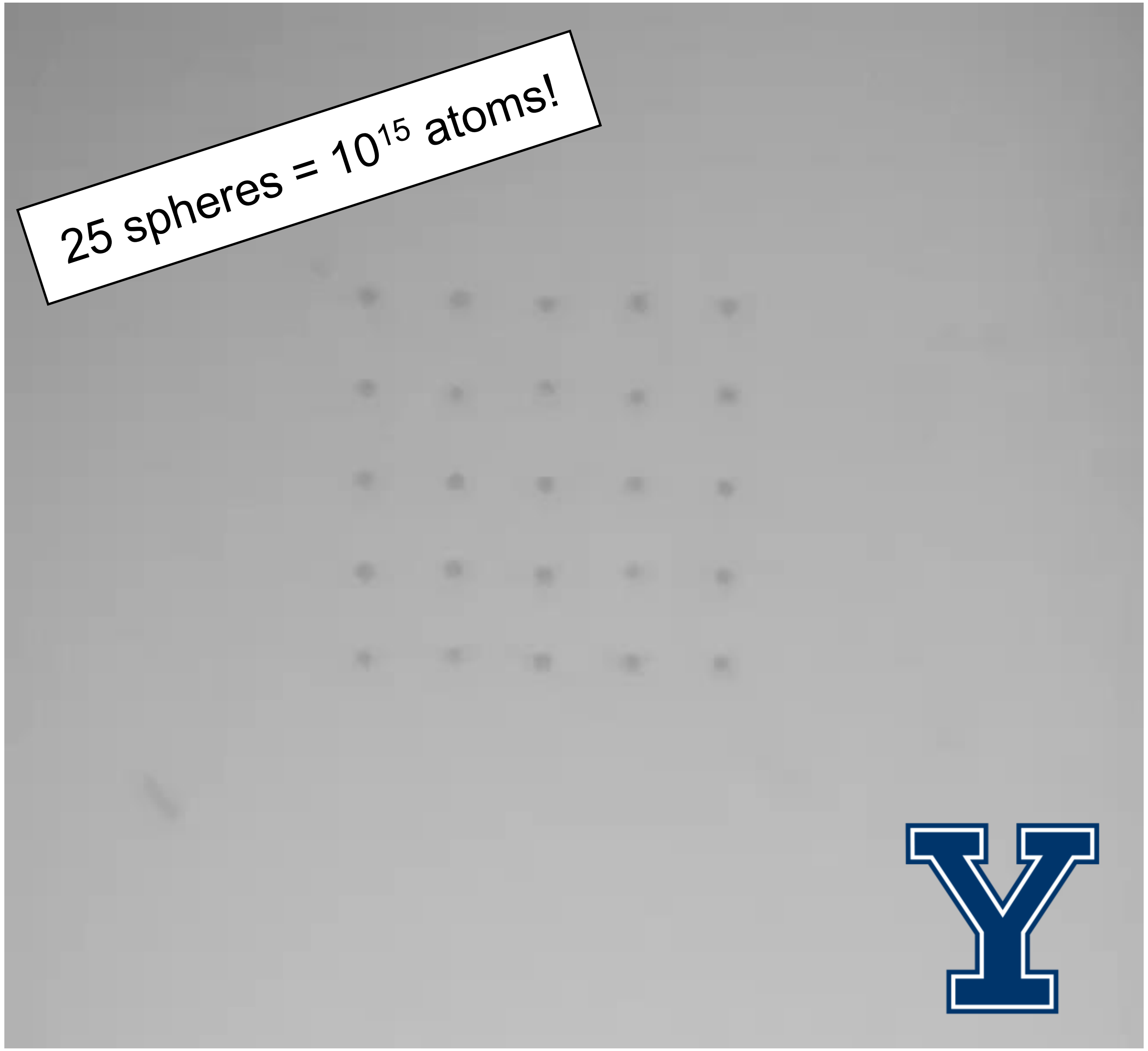


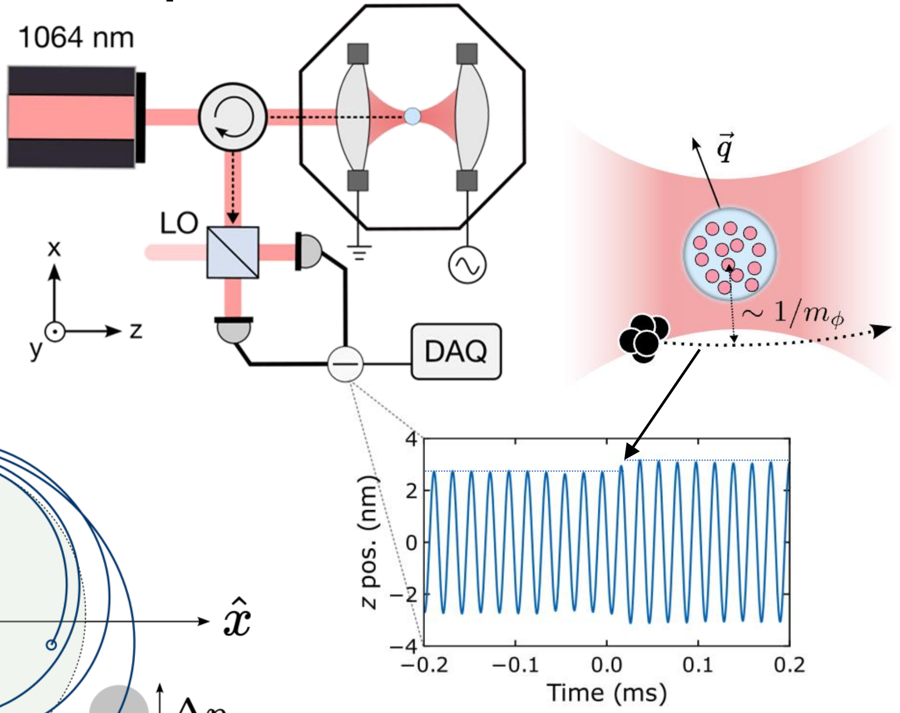


Played at 8x speed

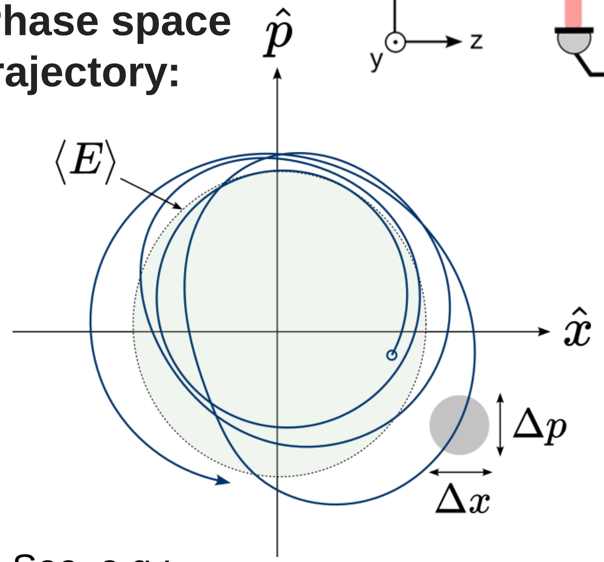
Impulse sensing

- Levitated sensors are now reaching sufficient sensitivity to detect the tiny forces imparted by single sub-atomic particles

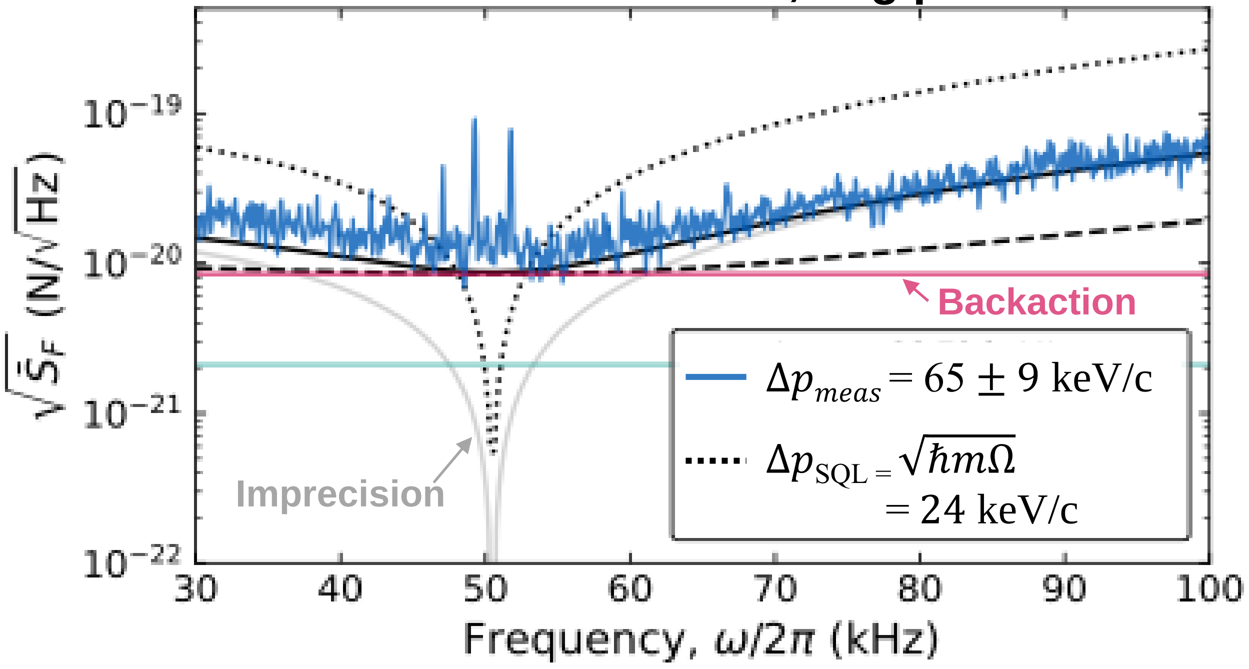
Schematic of impulse measurement:



Phase space trajectory:



Measured force noise, 5 fg particle:



PRX Quantum 6, 040367 (2025), arXiv:2508.00815

See, e.g.:

Magrini et al., Nature 595, 373 (2021)
Tebbenjohanns et al., Nature 595, 378 (2021)

See talk by M. Rossi for how to do even better!
→ Also applications in talks by S. Sangiorgio, D. Kodroff

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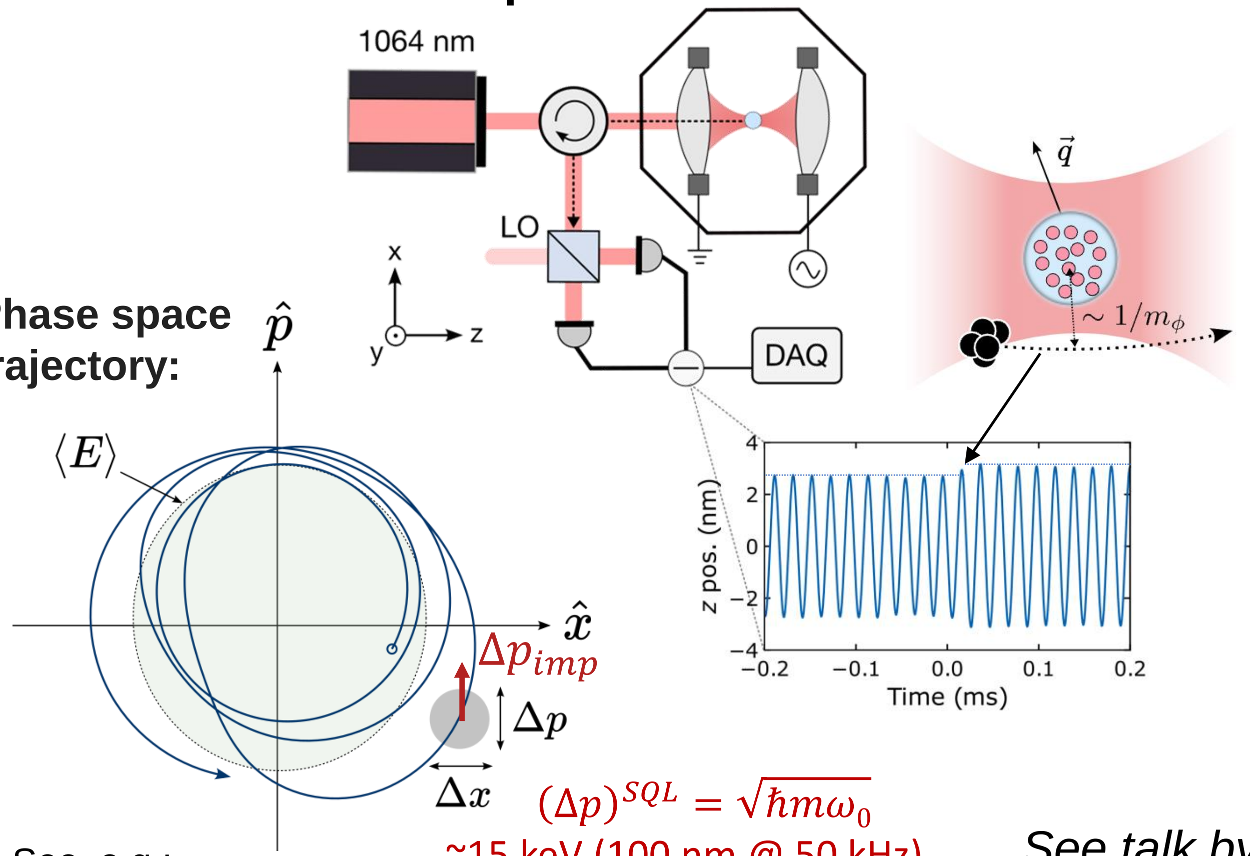
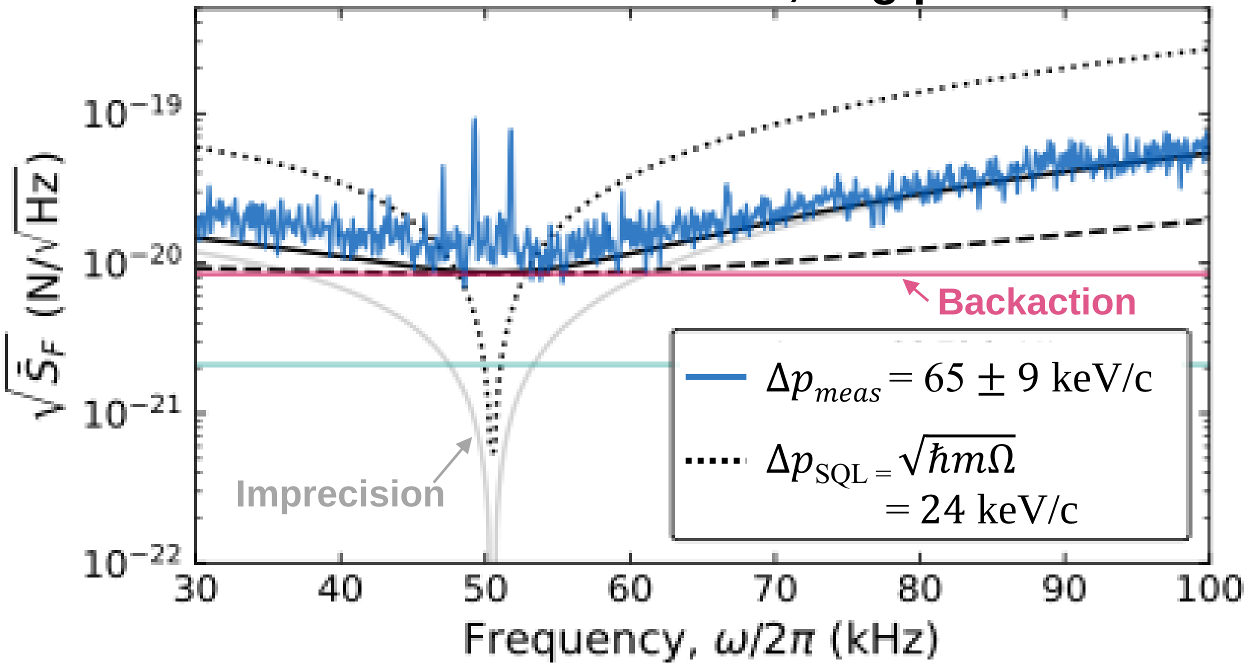


$(\Delta p)^{SQL} = \sqrt{\hbar m \omega_0}$

~15 keV (100 nm @ 50 kHz)

Measured force noise, 5 fg particle:



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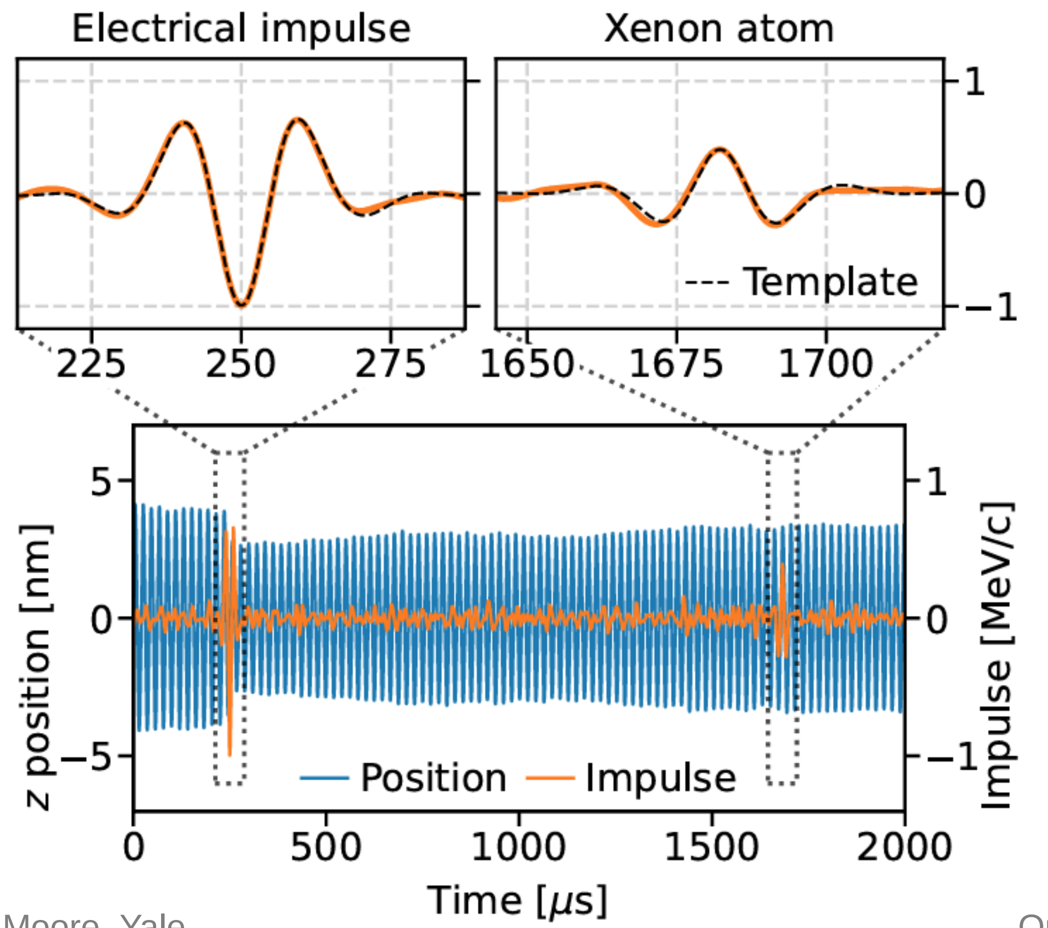
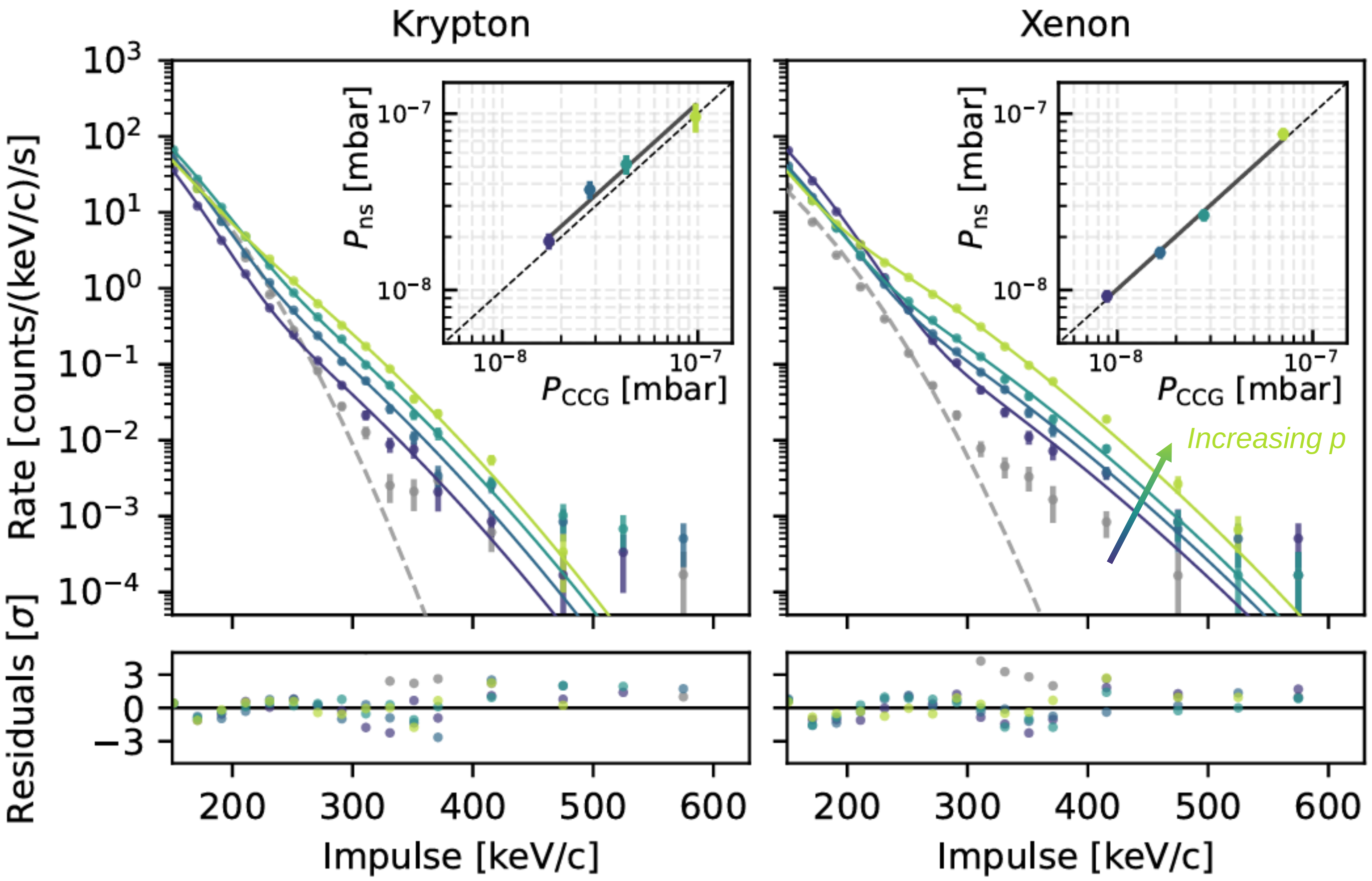
Proof-of-principle (gas collisions)

- Sensitivity needed to see single room temperature gas molecules collide with the particle similar to ν
  - Injected trace levels of heavy gases (Kr, Xe, SF_6) and reconstructed the momentum transfers from individual collisions

Example measured gas collision:



Collision spectrum vs. pressure:

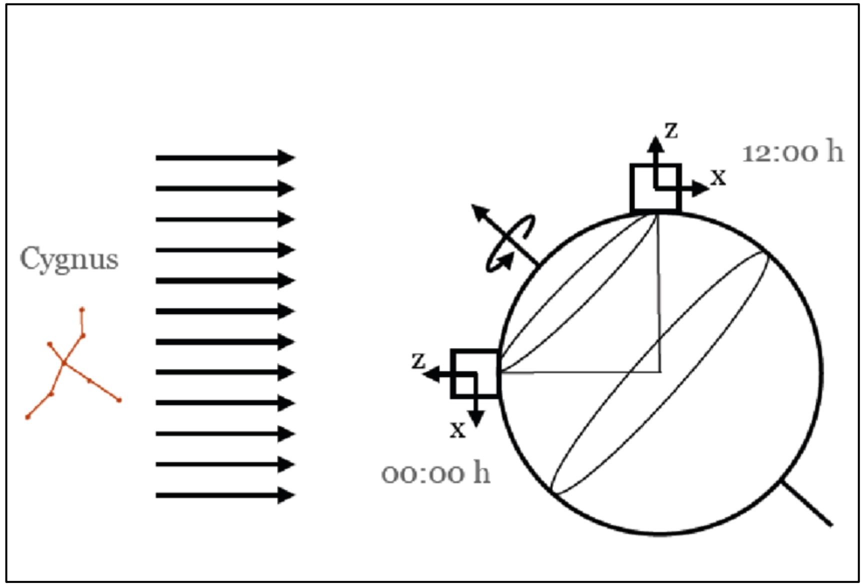


arXiv:2604.18371

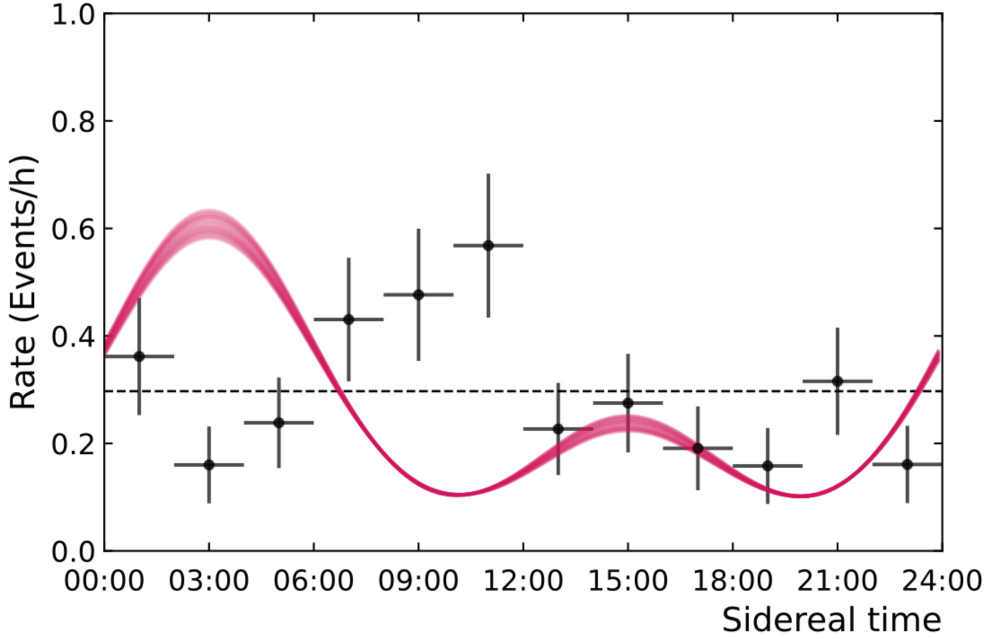
Dark m

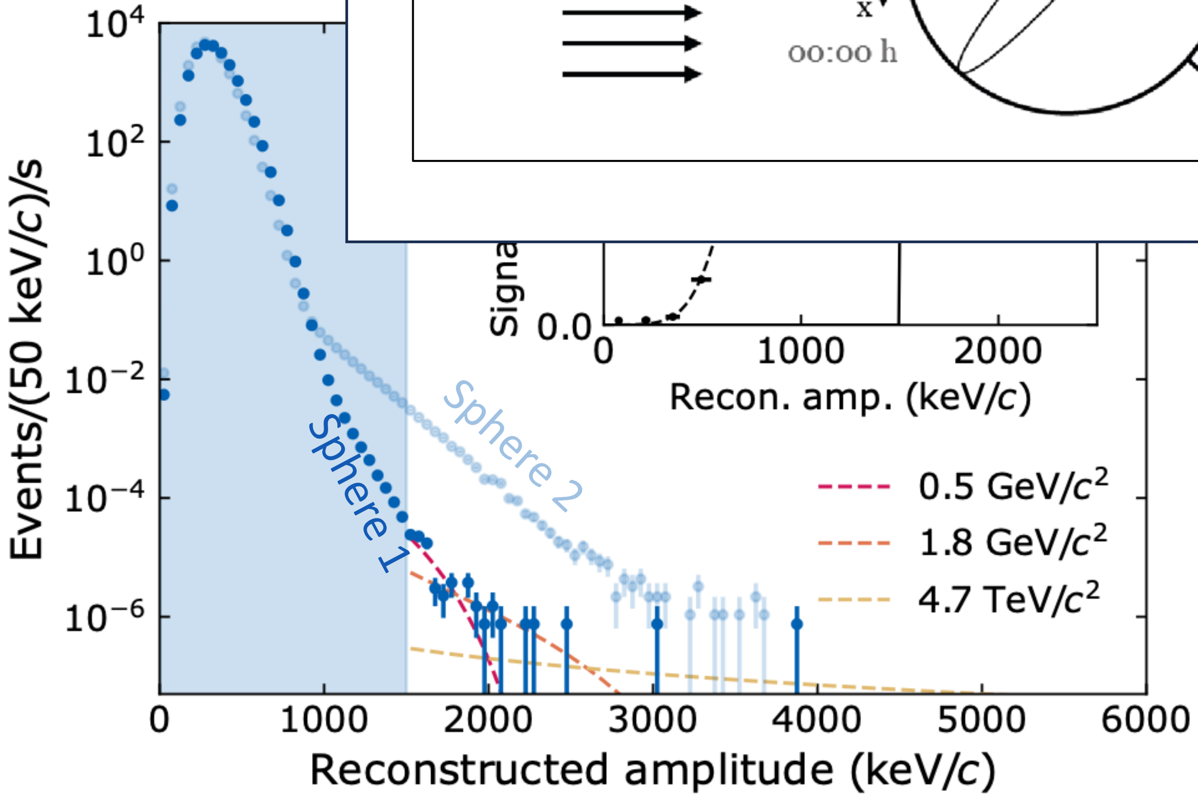
- Performed
  - Tail of
  - Conser
    matter

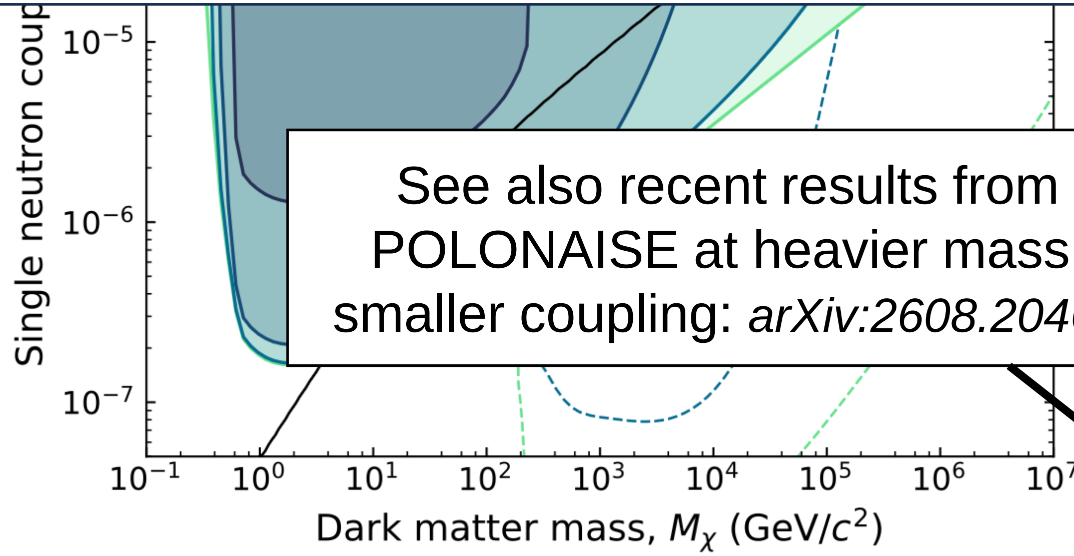
Natural directionality → any detection would be definitive!



Event rate vs sidereal time:







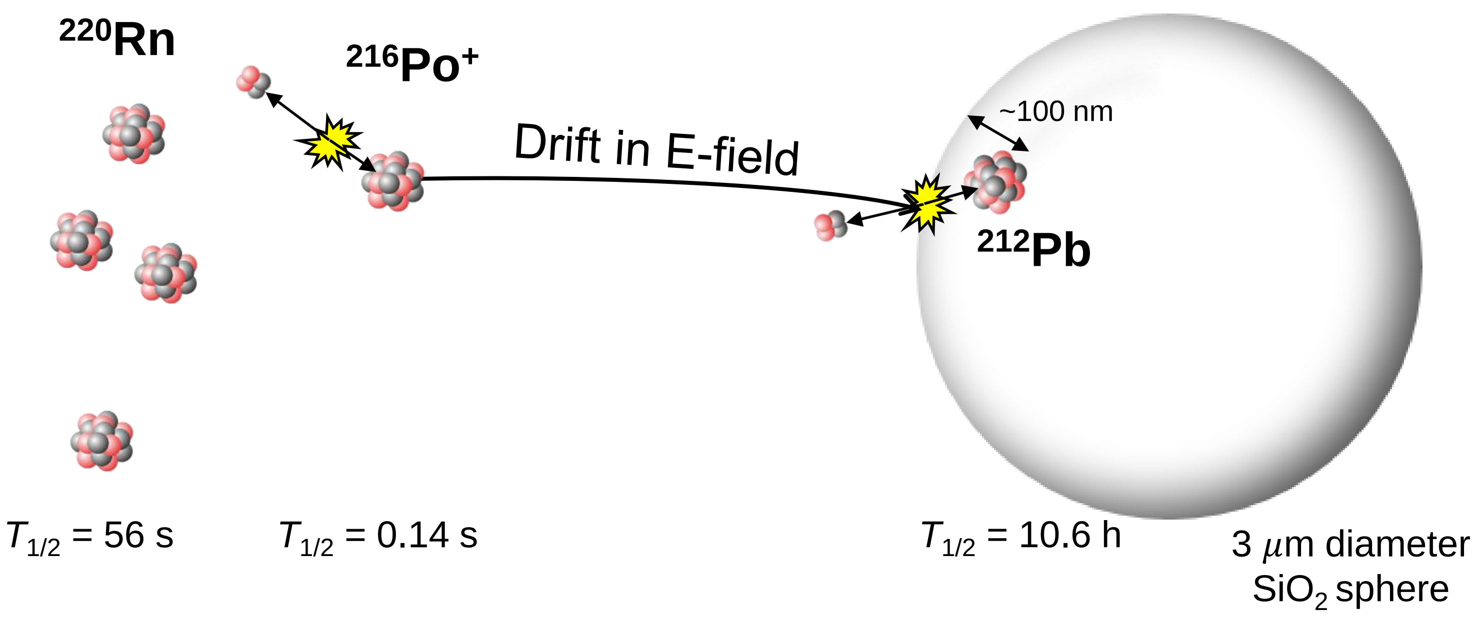
See also recent results from POLONAISE at heavier mass, smaller coupling: *arXiv:2608.20464*

PRX Quantum 6, 040367 (2025), arXiv:2508.00815

Radioisotope loading (α decays)

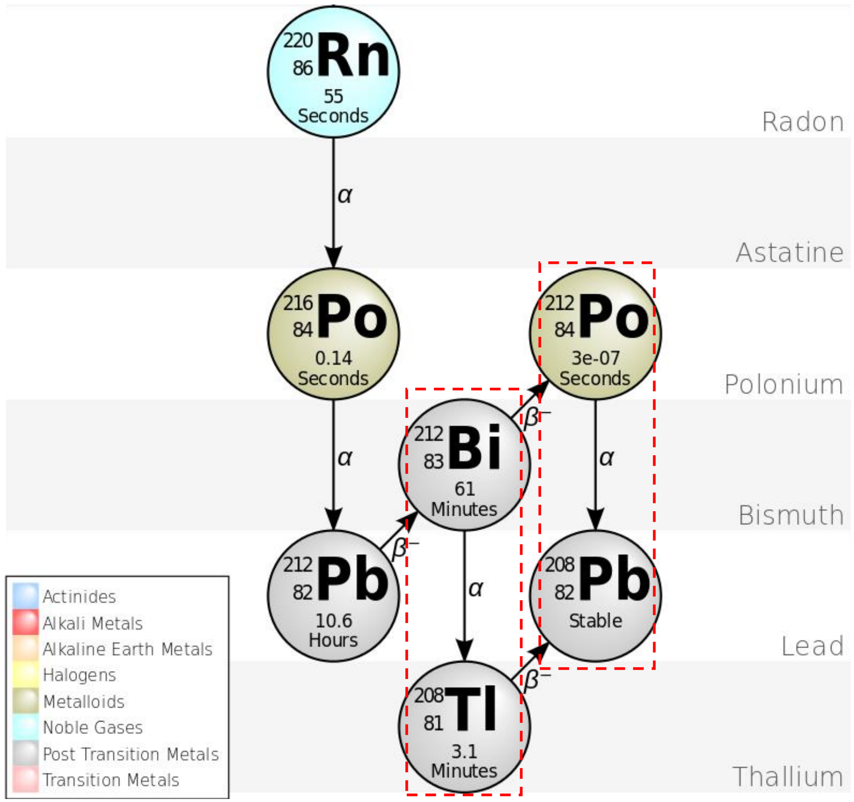
- As a proof-of-principle, we have detected single α decays with >μm sized spheres
  - Momentum is ~200 MeV/c (compared to 0.1-1 MeV/c for typical ν, γ)
- Have demonstrated loading of small quantities of ^{212}Pb into trapped microspheres

Schematic of loading scheme:



PRL133, 023602 (2024), arXiv:2402.13257

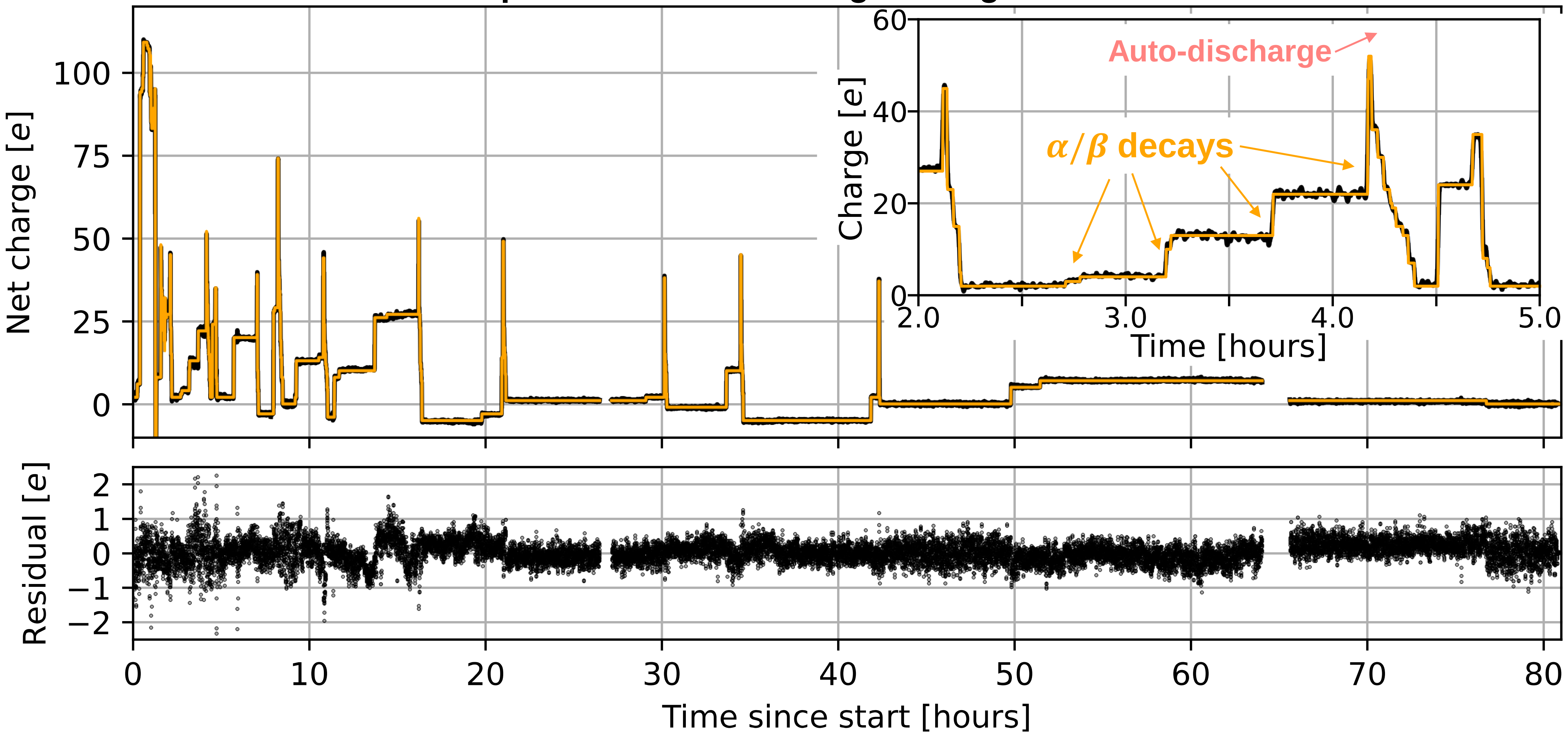
Rn-220 decay chain:



Detection of single nuclear decays (charge)

- Can detect single nuclear decays through the change in net charge of the particle

Example of measured charge changes vs. time:

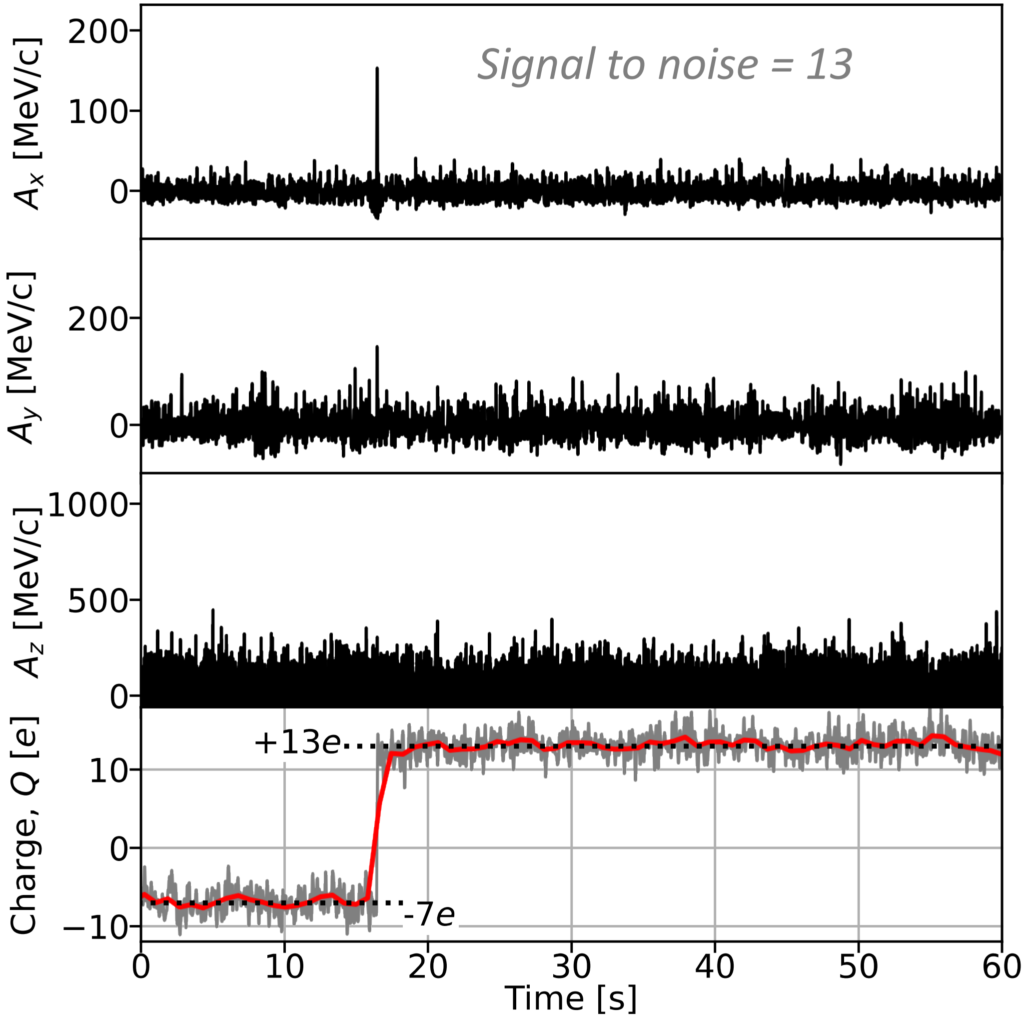


PRL133, 023602 (2024), arXiv:2402.13257

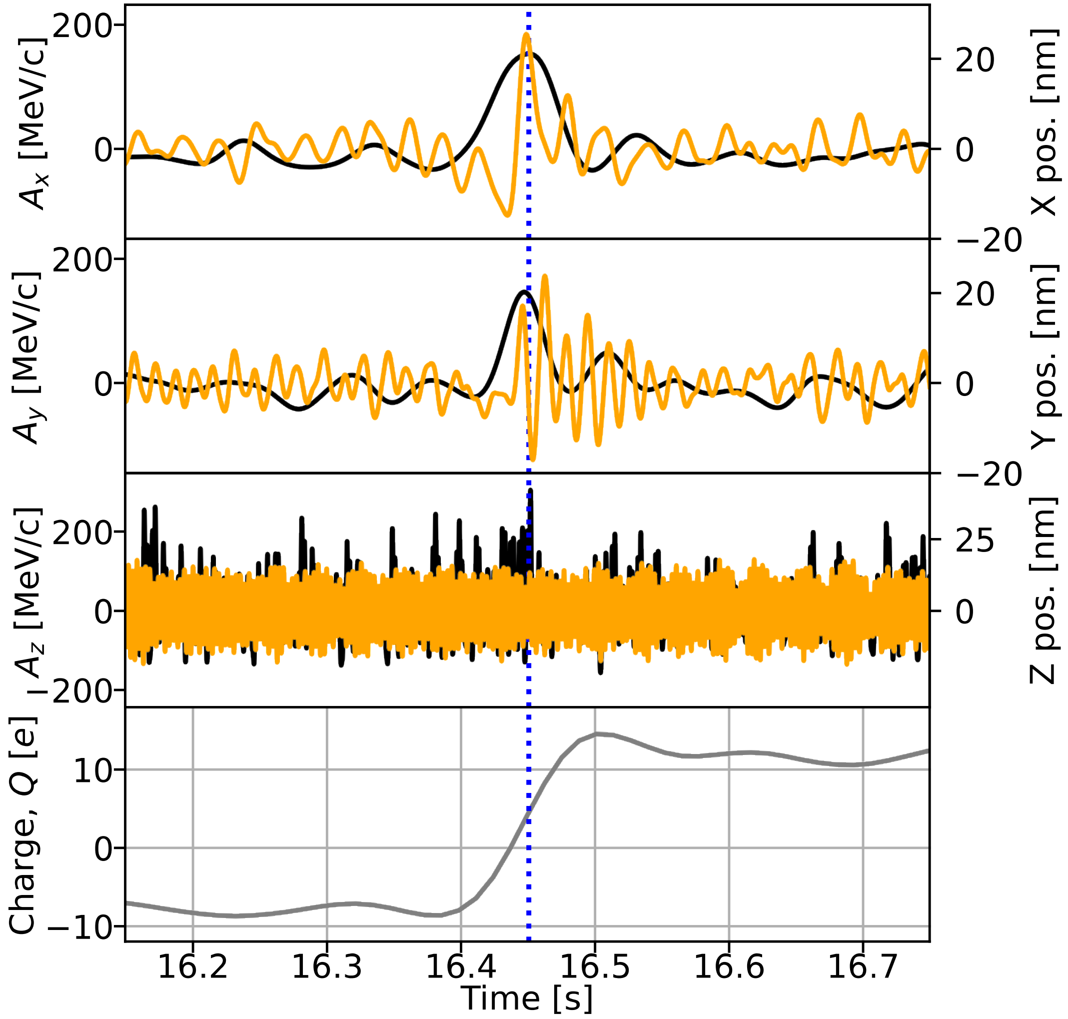
Detection of single nuclear decays (recoil)

- Reconstruct recoil of the entire particle correlated with the decay time

Recoil coincident with charge change:



Zoom to decay time:

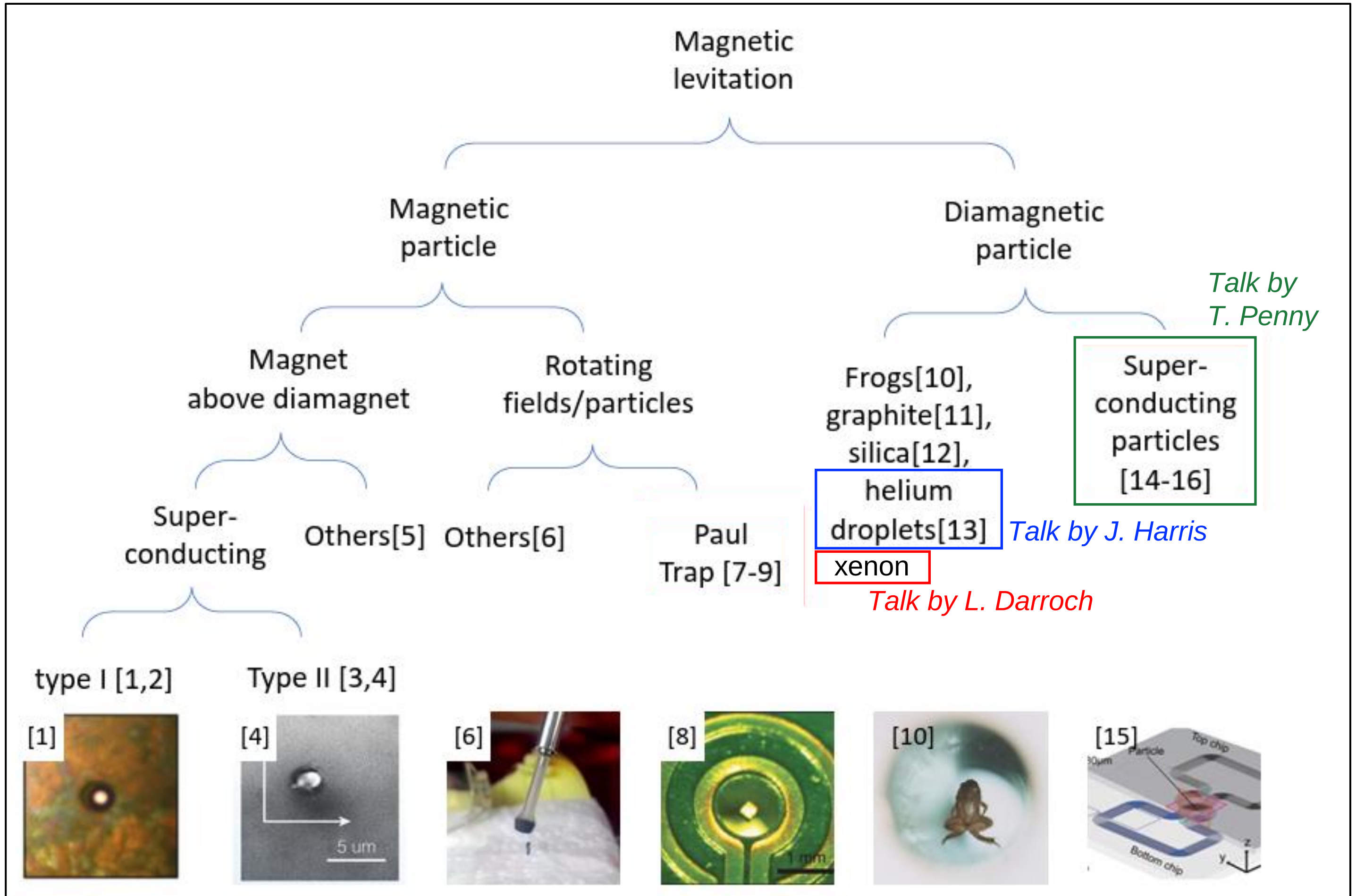


PRL133, 023602 (2024), arXiv:2402.13257

Magnetic levitation

- Magnetic levitation typically allows larger objects to be trapped:
  - *μg-mg up to "frog scale"*
- Diverse set of platforms now exist, giving lots of engineering freedom
- **Benefits:**
  - Can trap charge neutral particles (unlike RF traps, similar to optical traps)
  - No need for a laser (and associated heating)
  - Possibly read out directly with superconducting circuits (*see talks by M. Juan, T. Penny*)
- **Possible challenges:**
  - Displacement sensitivity (at least to date)
  - Some options need cryogenics (+ low vibrations)
  - Low trapping frequencies (similar to others in this mass range)

Family tree of magnetic trapping techniques (from Bas Hensen):

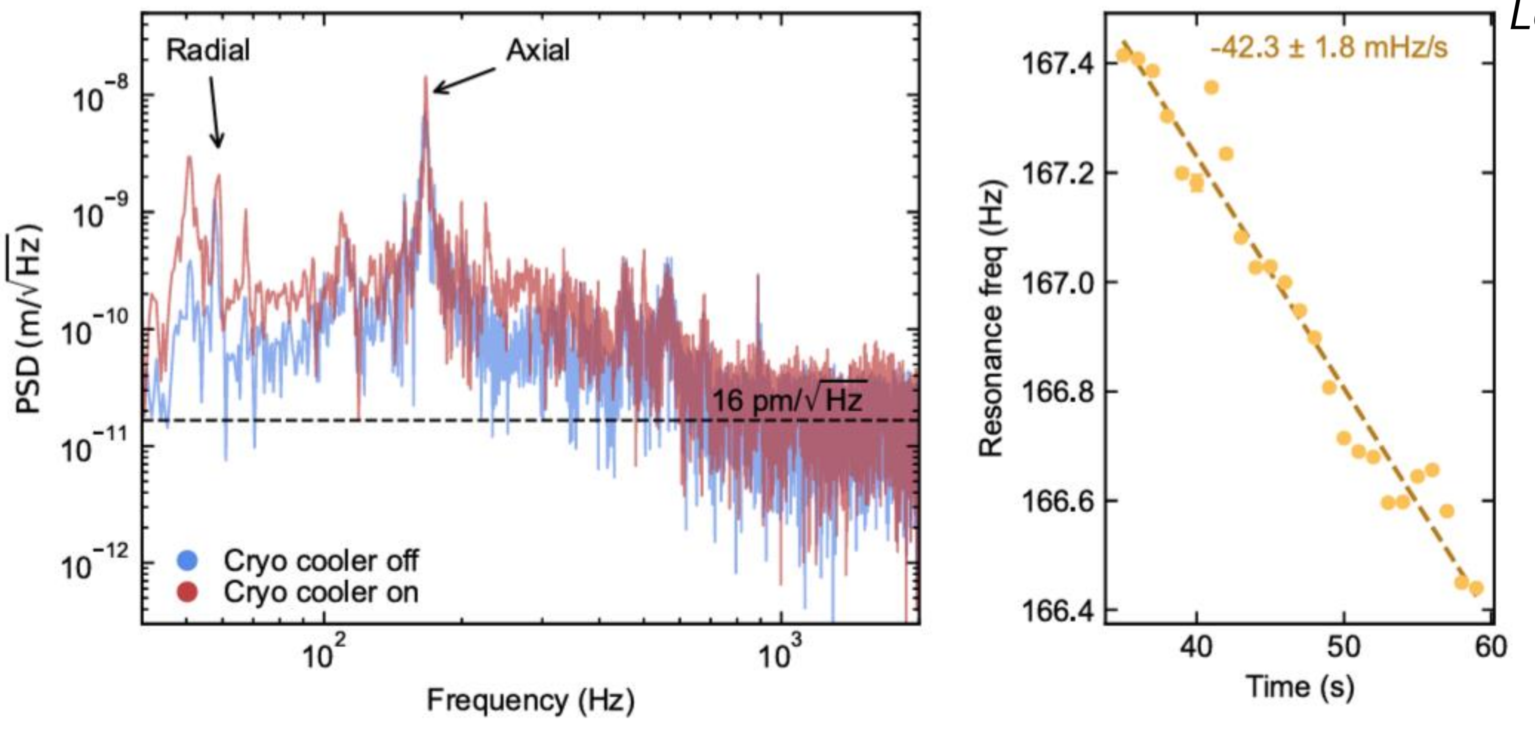


[1] Vinante, ..., Ulbricht, *PR Appl.* **13**, 064027 (2020)
[2] Fuchs, ..., Oosterkamp, *Sci. Adv.* **10**, eadk2949 (2024)
[3] Gieseler, ..., Lukin, *PRL* **124**, 163604 (2020)
[4]Wang, ..., Lukin, arXiv.2606.27297 (2026)
[5] Ji, ..., Budker, *Science* **393**, 607 (2026)
[6] Ucar, *Symmetry* **13**, 442 (2021)
[7] Perdriat, ..., Hétet, *PRR.* **5**, L032045 (2023)
[8] Janse, ..., Hensen, *APL* **125**, 144003 (2024)
[9] Janse, ..., Hensen, arXiv.2605.00090 (2026)
[10] Berry & Geim, *Eur. J. Phys.* **18**, 307 (1997)
[11] Kim, ..., Twamley, *Commun. Phys.* **8**, 381 (2025)
[12] Slezak, ..., D'Urso, *New J. Phys.* **20**, 063028 (2018)
[13] Brown, ..., Harris, *PRL* **130**, 216001 (2023)
[14] Hofer, ..., Aspelmeyer, *PRL* **131**, 043603 (2023)
[15] Latorre, ..., Wieczorek, *IEEE Tr. App. Supercon.* **32,** 1 (2022)
[16] Smit, ..., Hensen, *PNAS Nexus* **5,** pgag072 (2026)

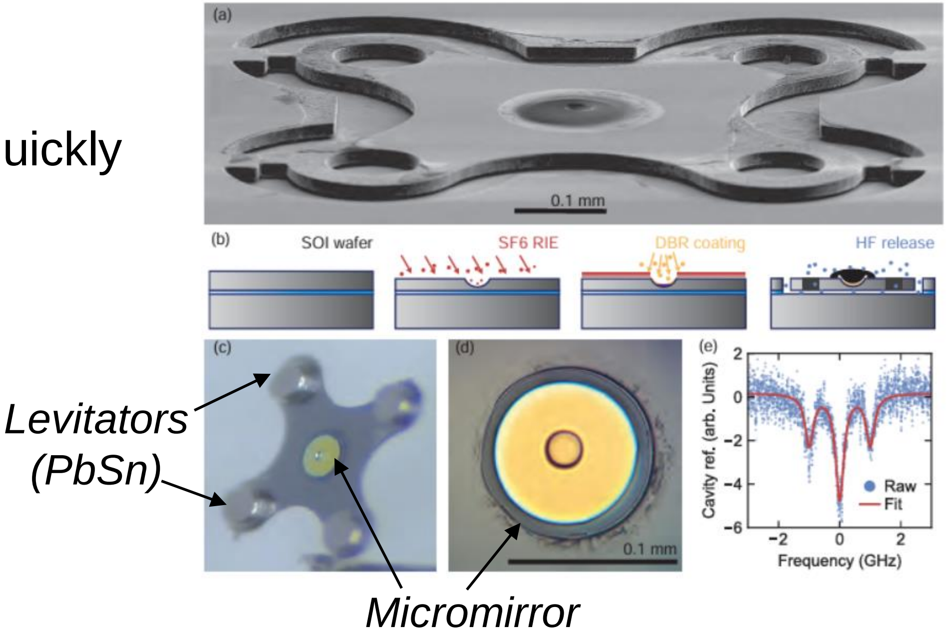
Magnetic levitation (optical detection)

- Vienna group has recently demonstrated optical detection of the motion of a levitated micromirror
  - Previous work shining lasers directly on a superconductor quickly heats it and the particle drops

Displacement sensitivity at ~10 pm/$\sqrt{\mathrm{Hz}}$:



Magnetically levitated mirror ($m \approx 30\mu$g):



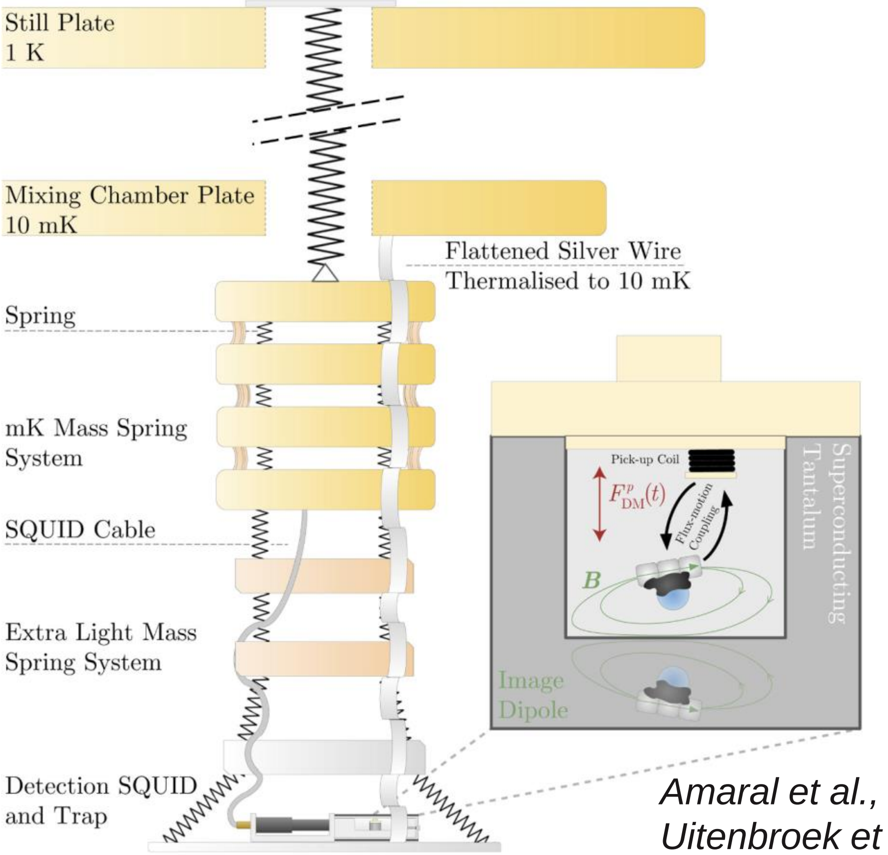
- To cool to ground state (or reach broadband SQL at this freq) requires ~10^{-17} m/$\sqrt{\mathrm{Hz}}$:
- To keep improving need:
  - Higher reflectivity
  - More laser power
  - Optical cavity
- Or non-optical readout with sufficiently strong coupling (?)

Koller et al., arXiv:2609.17787 (2026)

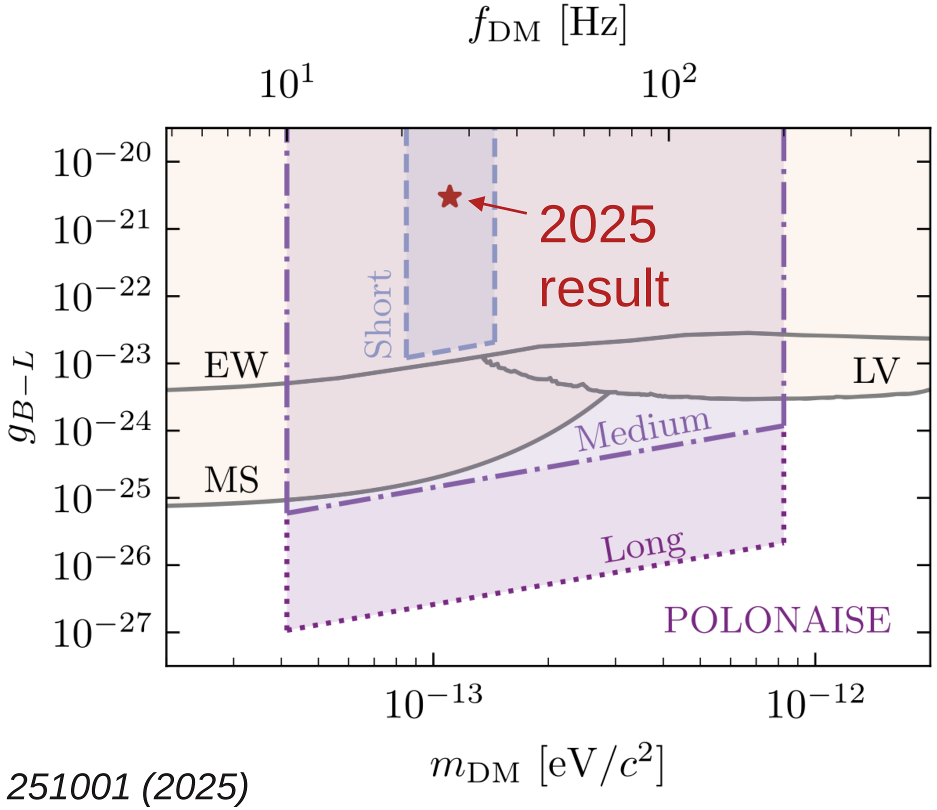
Vibration isolation + ULDM (POLONAISE)

- Additional challenge in many cryogenic setups is vibrations from cryostat
- POLONAISE/Leiden group have reached 110 to 130 dB vibration isolation at 27 Hz resonance (acceleration noise at ~$10^{-11}\ g/\sqrt{\text{Hz}}$)
- Vibrations are about 20 dB above thermal noise at 50 mK, 40 dB above off-res SQL

Magnetically levitated 400 μg mass:



Current and projected ULDM sensitivity:

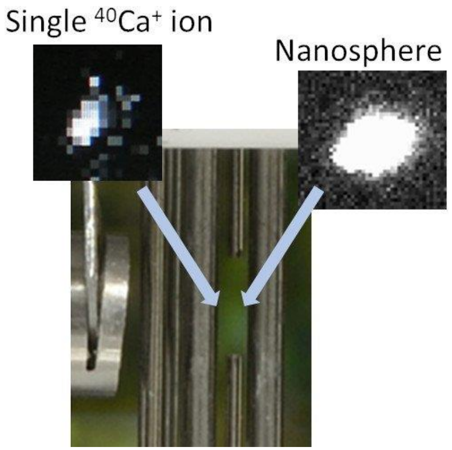


Amaral et al., PRL 134, 251001 (2025)
Uitenbroek et al., arXiv:2605.28479 (2026)

Charged particle trapping (Paul traps)

- For charged particles, also possible to levitate with RF fields (see talks by M. Juan, S. Sangiorgio)
- Additional examples (not comprehensive, see also Barker group [UCL], Millen group [KCL]):

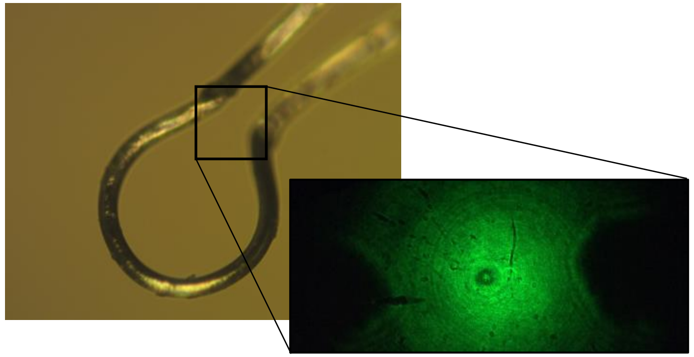
Northup group (Innsbruck):



- Co-trapping of nanosphere + ion
- Demonstrated ultra-high $Q = 10^{10}$

*See e.g. PRL **132**, 133602 (2024)*

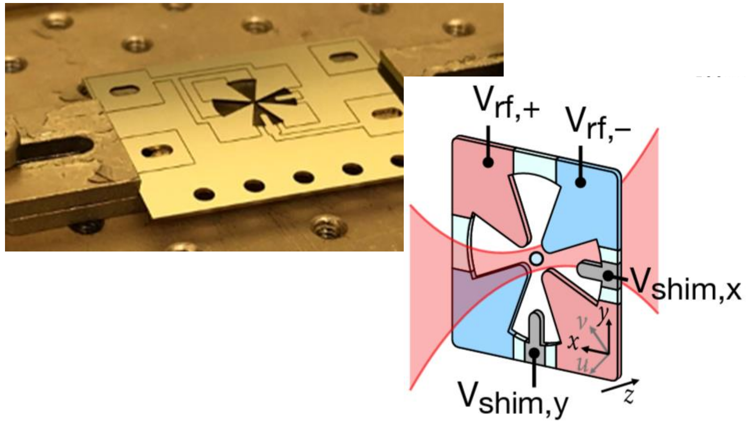
Hétet group (ENS Paris):



- Trap microdiamonds with NVs while avoiding heating
- Spin cooling of diamond libration

See e.g. Nature 580, 56 (2020), as well as work by T. Li (Purdue)

Novotny group (ETH Zurich):



- Hybrid RF + optical trap
- Aim for large state expansion in dark trap (no photon recoil)

See e.g. PRL 132, 253602 (2024)

Benefits:

- Deep, large traps for a range of particle sizes (from ions to microparticles)
- Dark traps are possible, with no recoil heating or internal heating from laser
  - Alternatively, can combine with optical detection or trapping
- Co-trapping with ions possible (Northup group)

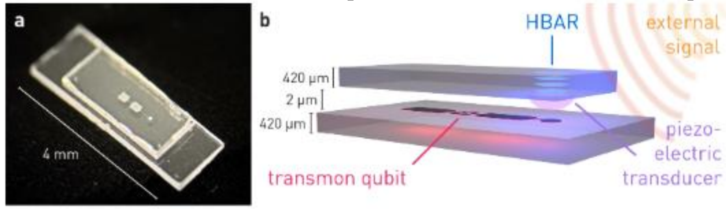
Possible challenges:

- Particles are electrically charged and may couple to stray fields
- Charge changes (e.g. from nuclear decays) can produce impulses

Tethered oscillators (isolation without levitation)

- Levitation is only one method for decoupling force noise (thermal noise, vibrations, etc)
- Tethered systems also reach extreme performance with a number of techniques, e.g.:
  - Cool environment to low temperatures (10 mK ~ 200 MHz)

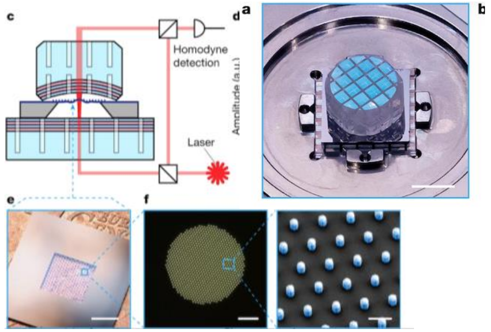
Bulk acoustics (Chu, ETH Zurich):



Excited state population ~1e-5 in GHz modes, PRL 136, 180802 (2026)

  - Decouple from phonon bath using a phononic crystal (with bandgap)

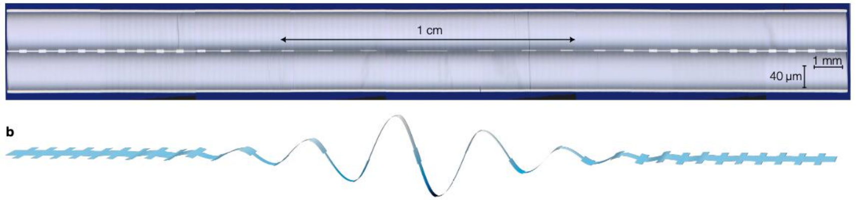
Membranes at room temp (Kippenberg, EPFL):



Isolated membrane near ground state at room temp, Nature 626, 512 (2024)

  - Reach extremely high Q (e.g. via dissipation dilution and soft clamping, *see talk by D. Wilson*)

Ultra-high aspect ratio Si_3N_4 strings (Norte, Delft):

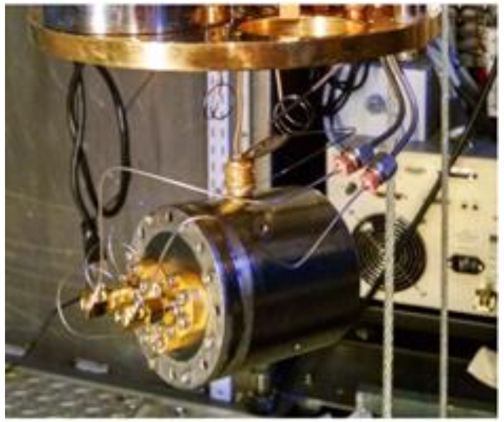


3 cm long, 70 nm thick string with Q = 6.6x10^9, Nat Commun 15, 4255 (2024)

Tethered oscillators (cont'd)

- Use extremely low-loss materials (e.g., superfluid He, high-purity sapphire/quartz, etc, *see talks by J. Davis, J. Harris, T. Deshpande*)

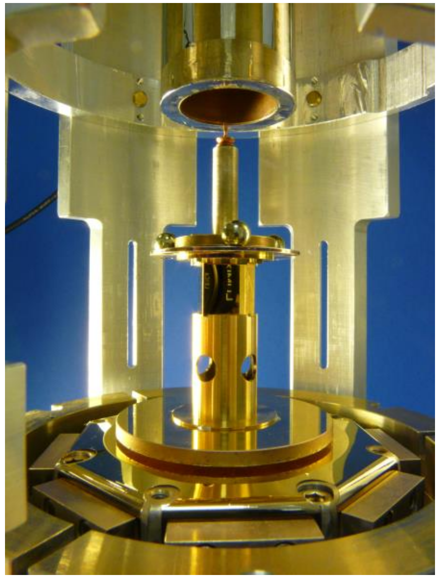
High-Q superfluid He resonator (Schwab, Caltech):



Q >10^8 for acoustic modes in superfluid He, J. Low Temp. Phys. 186, 233 (2017)

- "Win with mass"
  - Especially for accelerations, classical masses can significantly outperform smaller "quantum limited" masses
    - Anyone who has ever tried to "beat Eot-Wash" in a fundamental physics measurement probably knows this
  - Tethers often allow much larger masses to be used

Eot-Wash Torsion Balance:



(Differential) acceleration sensitivity ~10^{-14} g/$\sqrt{\text{Hz}}$ at mHz frequencies for ~cm scale mass

Summary

- Optomechanical systems are revolutionizing how we measure tiny forces and accelerations acting on masses in the lab
- These systems have significant potential to impact searches for various weakly coupled phenomena in fundamental physics, with many applications already underway
- There is a huge experimental toolbox already developed, which is likely only to grow in its capabilities in future years
- Many of the best ideas are likely still to be identified, so excellent time to be creative