Optomechanical sensors for fundamental physics

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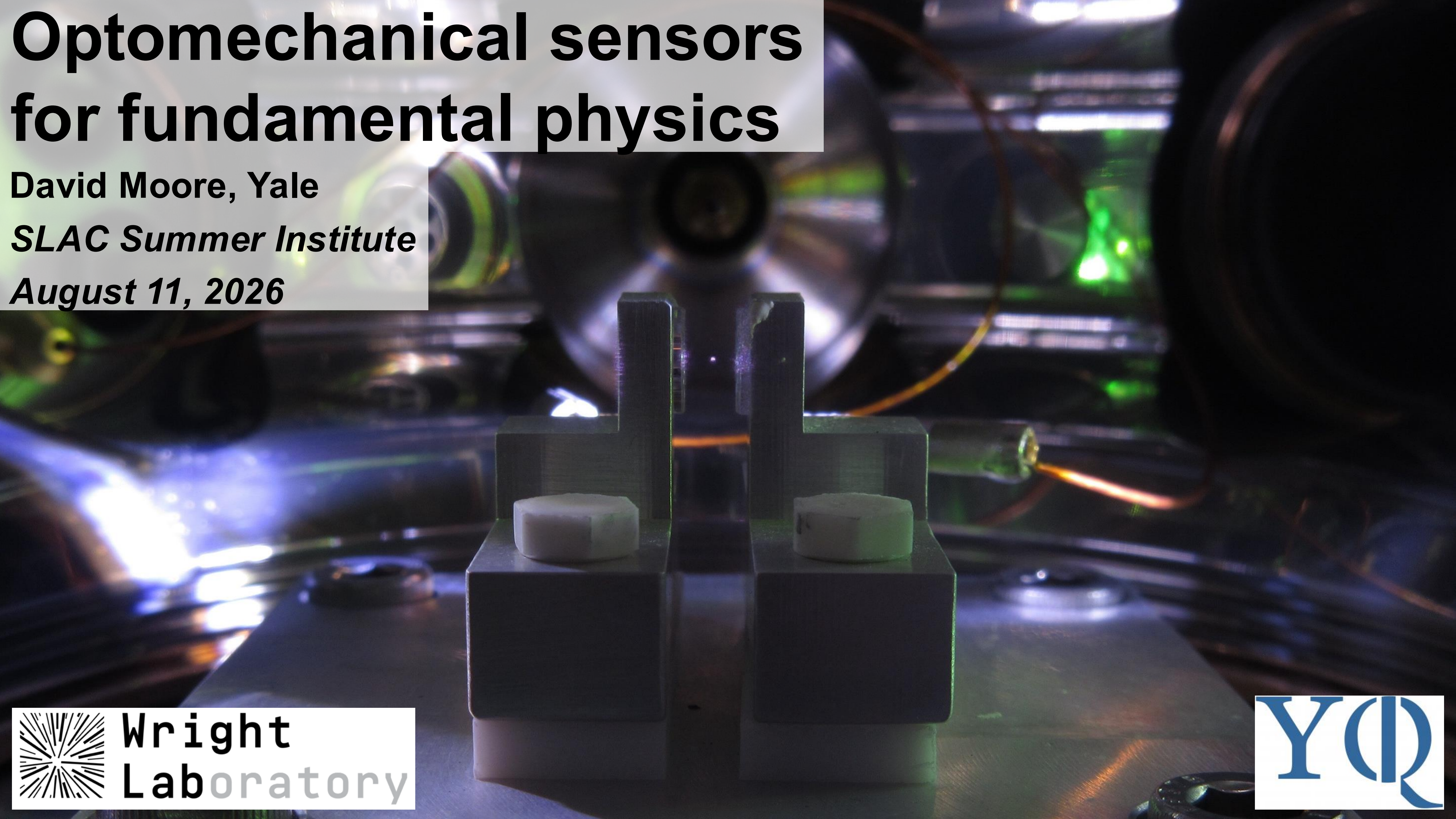
SLAC Summer Institute

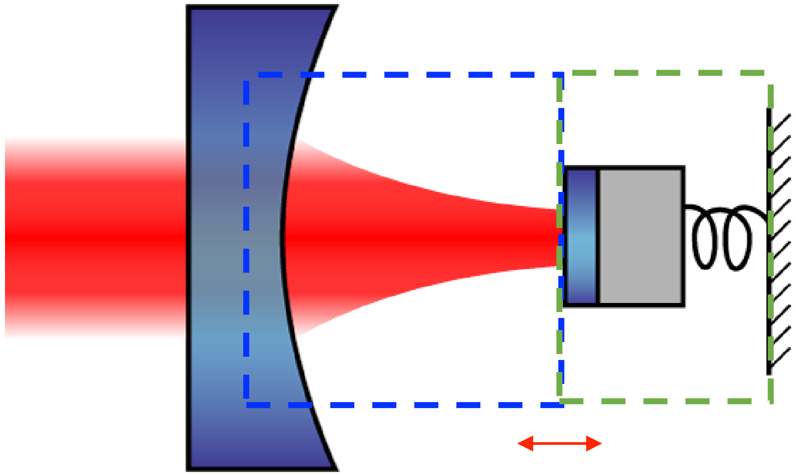
August 11, 2026



Wright Laboratory

Optomechanics primer

- An optomechanical system is a mass whose motion is controlled and read out through light
- The canonical system is an optical cavity where one mirror is free to move:



Energy per photon

Energy per phonon

Phonon number (mechanical resonator)

Mirror displacement

$$\hat{H} = \hbar\omega_c \hat{a}^\dagger\hat{a} + \hbar\Omega_m \hat{b}^\dagger\hat{b} - \hbar g_0 \hat{a}^\dagger\hat{a}\left(\hat{b} + \hat{b}^\dagger\right)$$

Photon number (optical cavity)

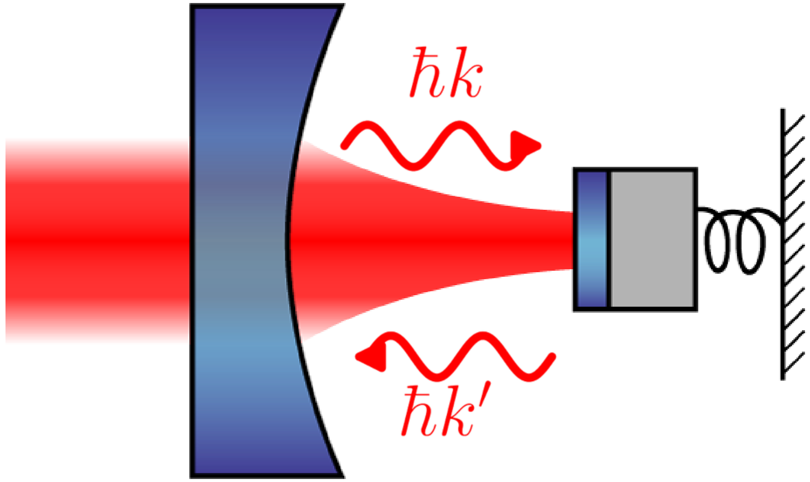
Optomechanical coupling

$\omega_c \sim 100$ THz
$\Omega_m \sim$ kHz – GHz
$g_0 \sim$ Hz-kHz (coupling per γ)

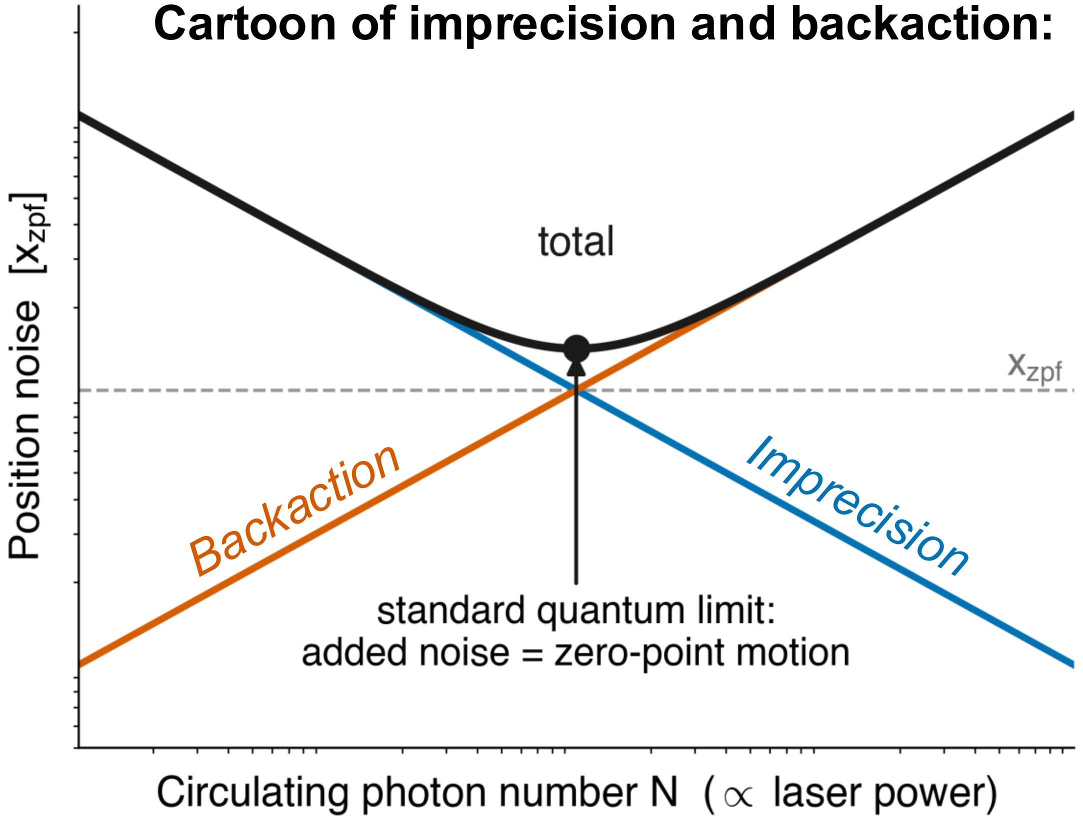
- Two coupled harmonic oscillators (light and mechanical motion)
  - Each photon exerts a tiny force on the mirror, and mirror’s motion imprints phase on light
- As we’ll see in a minute, many other systems that at first appear very different in geometry have this same basic quantum description

How well can you measure a mass this way?

- The phase of the light leaving the cavity encodes the mirror's position
- If we get rid of all sources of noise other than the measurement itself (thermal noise, noisy electronics, …), we are still limited by quantum noise:
  - ***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 imprecision and backaction:



Noise added by measurement at SQL:

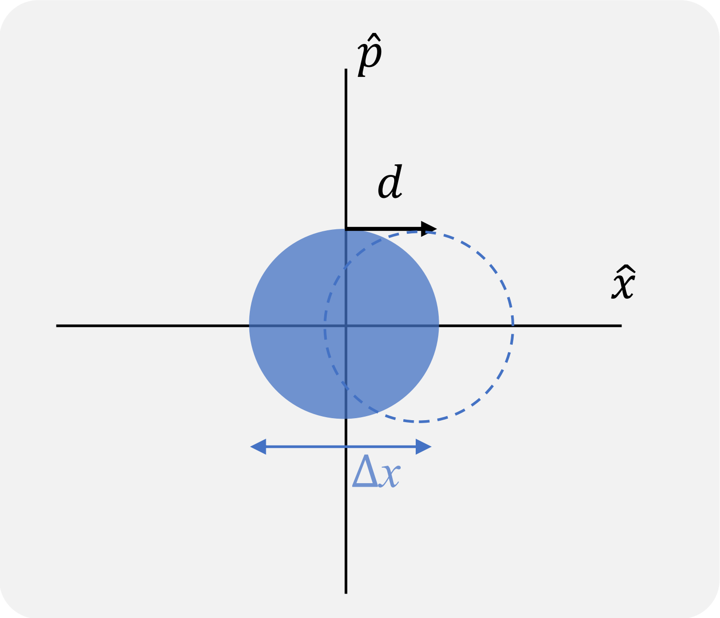
$$\Delta x_{\mathrm{SQL}} = x_{\mathrm{zpf}} = \sqrt{\frac{\hbar}{2m\Omega_m}}$$

Beyond the SQL

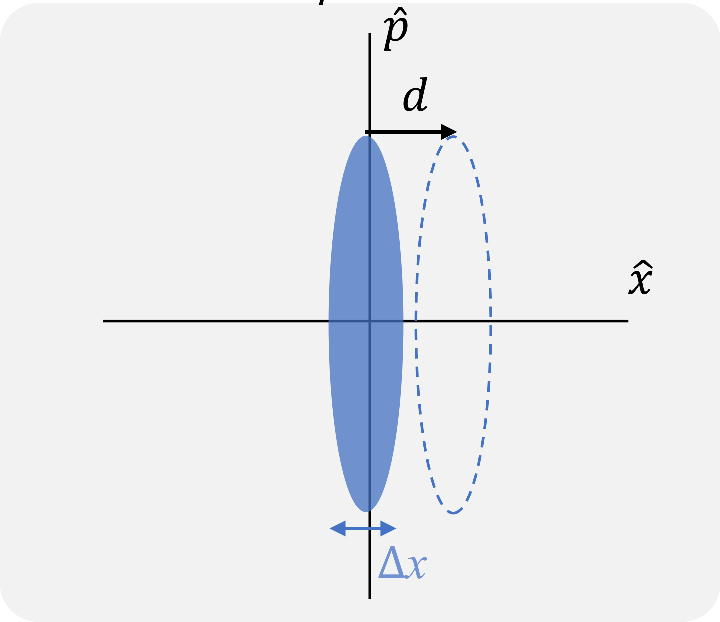
- The SQL is not a fundamental limit, but represents a constraint on a weak, continuous measurement of both the position and momentum
  - E.g., a strong, projective measurement can localize much smaller in Δx (at the cost of a large uncertainty in Δp, which can interfere with subsequent measurements)
  - More generally, we can squeeze light (or possibly mechanical DOFs) to achieve measurements beyond SQL

Cartoon of squeezed position measurement:

Unsqueezed



Squeezed

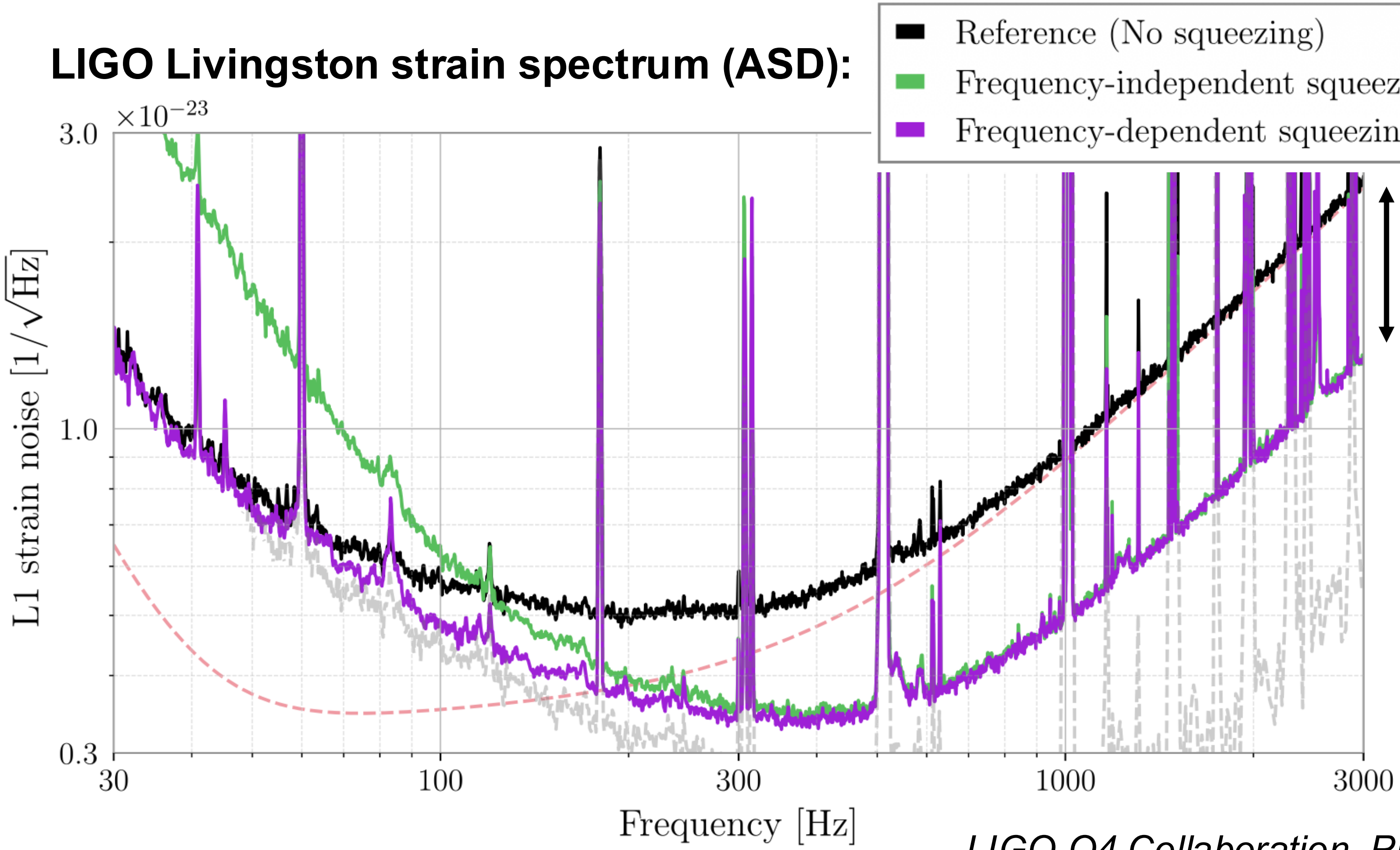


Always obey $\Delta x \Delta p \geq \frac{\hbar}{2}$ but push noise into quadrature we're not interested in

Squeezing in LIGO

- Gravitational wave detectors have pioneered many of these techniques, and are now using squeezing to enhance sensitivity
    - Notably, first exhausted “classical” sensitivity improvements at high frequency (e.g. more laser power)

LIGO Livingston strain spectrum (ASD):



~6dB squeezing ~(2x lower amplitude noise)

→ ≈ 8x larger observing volume

LIGO O4 Collaboration, PRX 13, 041021 (2023)

Other optomechanical systems

- A wide variety of optomechanical systems are revolutionizing how we measure tiny forces
- Many types of systems are reaching quantum regime following pioneering work by the gravitational wave community
- These sensors are 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

For more details see, e.g.:

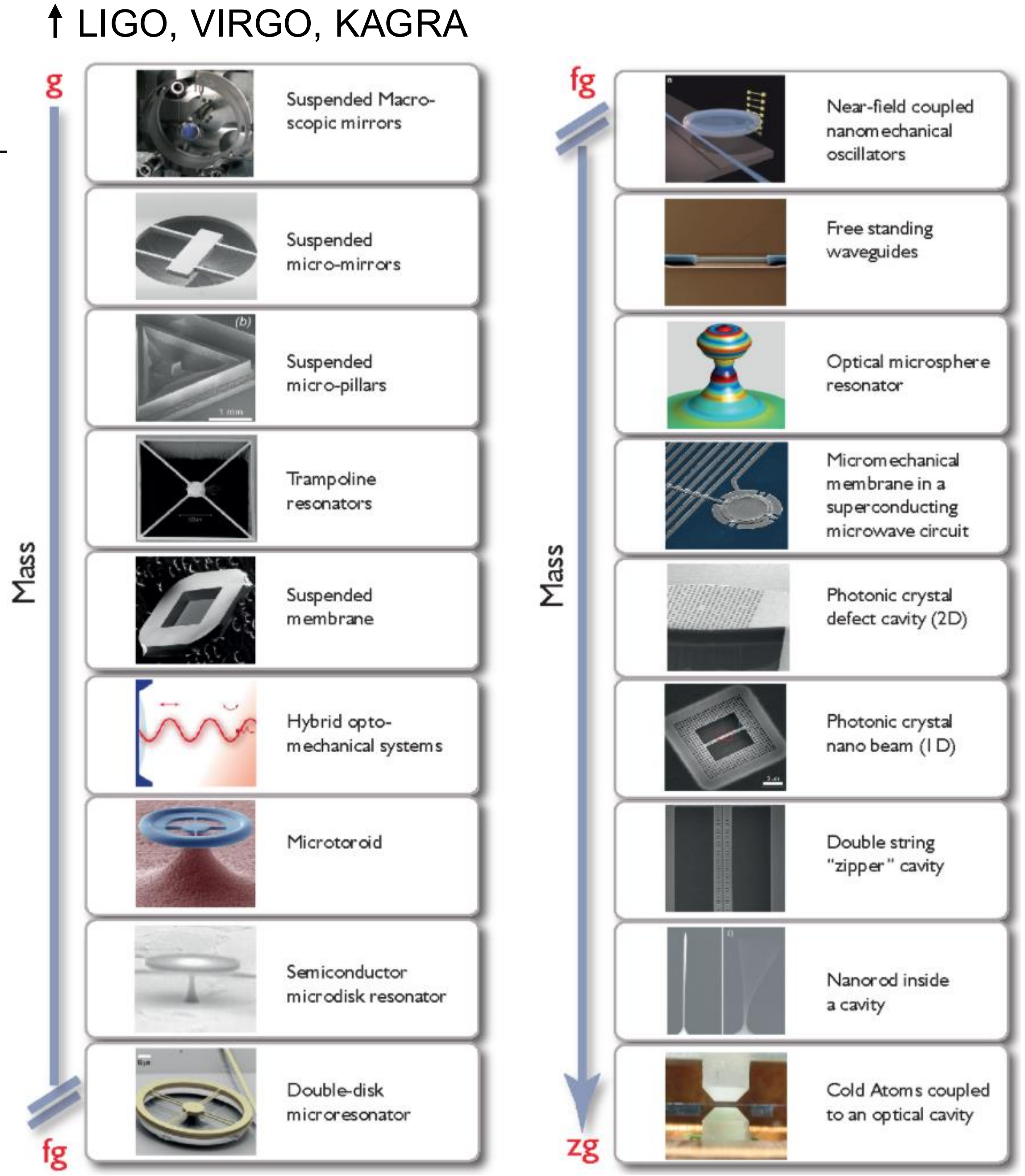
"Snowmass 2021: Quantum Sensors for HEP Science," arXiv:2203.07250.

"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)

…

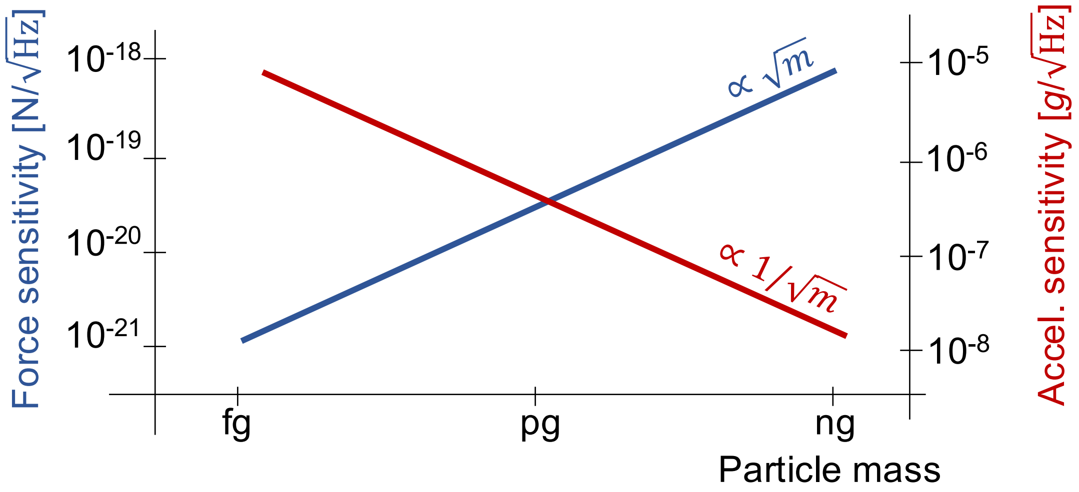


Aspelmeyer et al., Rev. Mod. Phys. 86, 1391 (2014)

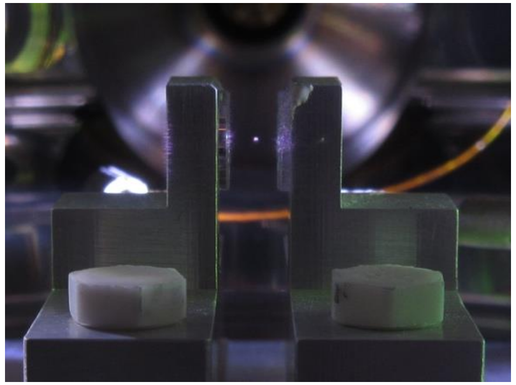
Levitated optomechanics

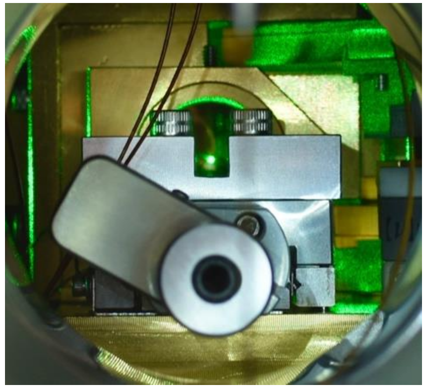
- Nano- to micro-sized dielectric masses can be optically trapped with ~100 mW of laser power
- Levitated masses are isolated both electrically and thermally
  - Ultra-low decoherence allows quantum control of motional degrees of freedom
  - Force sensitivities at the zN level, with acceleration sensitivities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

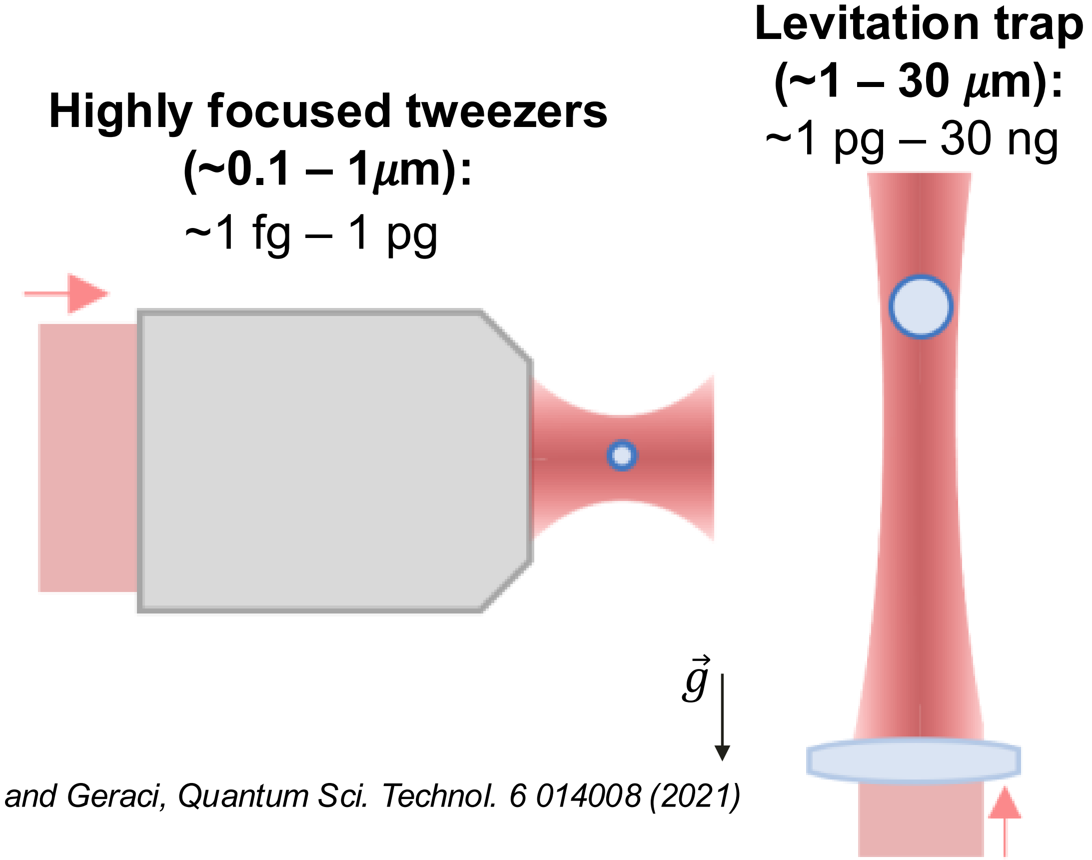
Force and acceleration sensitivity vs particle mass:



Photographs of trapped nano/micro particles at Yale:

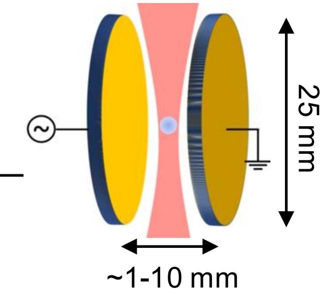




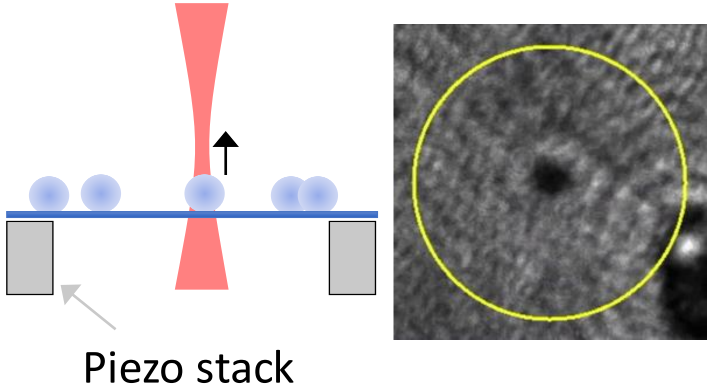


Moore and Geraci, Quantum Sci. Technol. 6 014008 (2021)

Experimental sequence (>ng spheres)



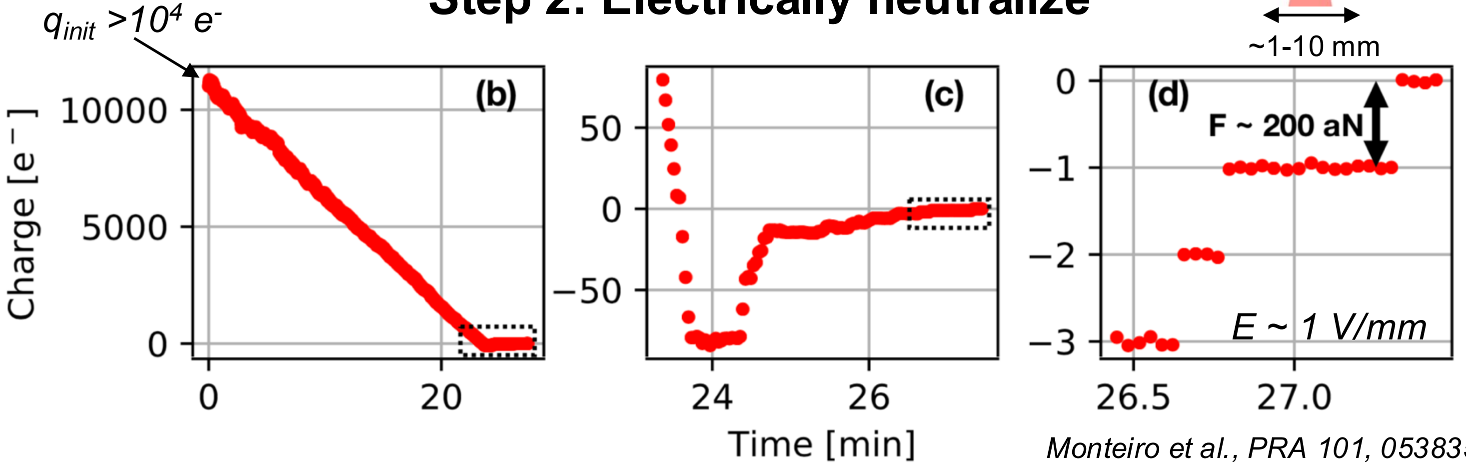
Step 1: Trap sphere (~1 mbar)



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

Pump to ≲10^{-7} mbar

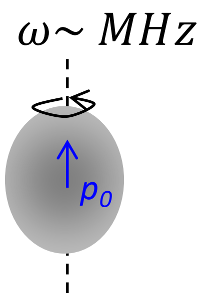
Step 2: Electrically neutralize

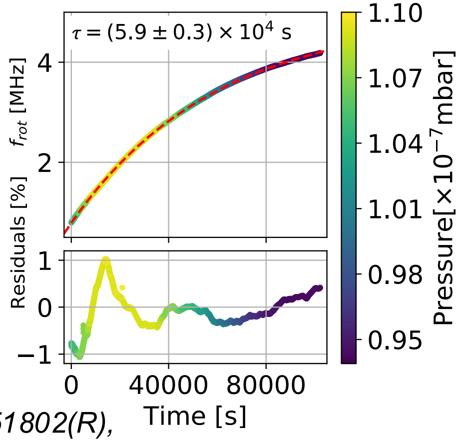


Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)

Step 3: Stabilize spin

Optically spin to >MHz frequency

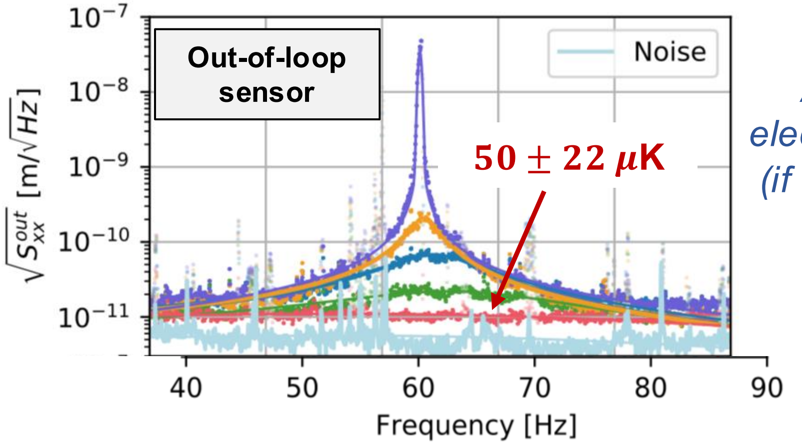




Monteiro et al., PRA 97, 051802(R), arXiv:1803.04297 (2018)

Active feedback cooling to μK temperatures

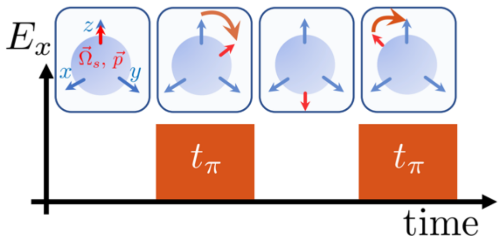
Step 4: Cool center-of-mass mode



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)

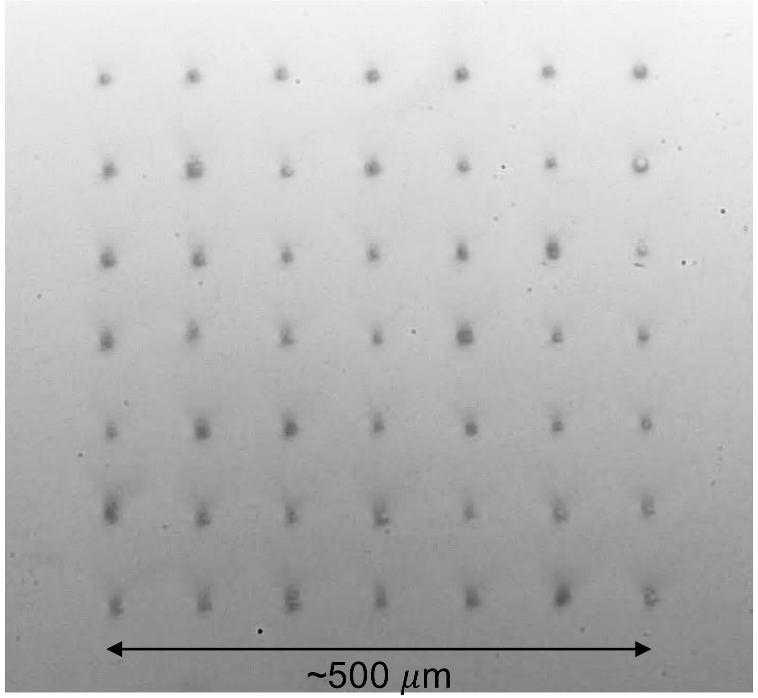


Afek et al., PRA 104, 053512, arXiv:2108.04406 (2021)

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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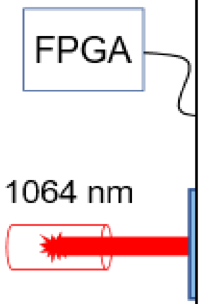
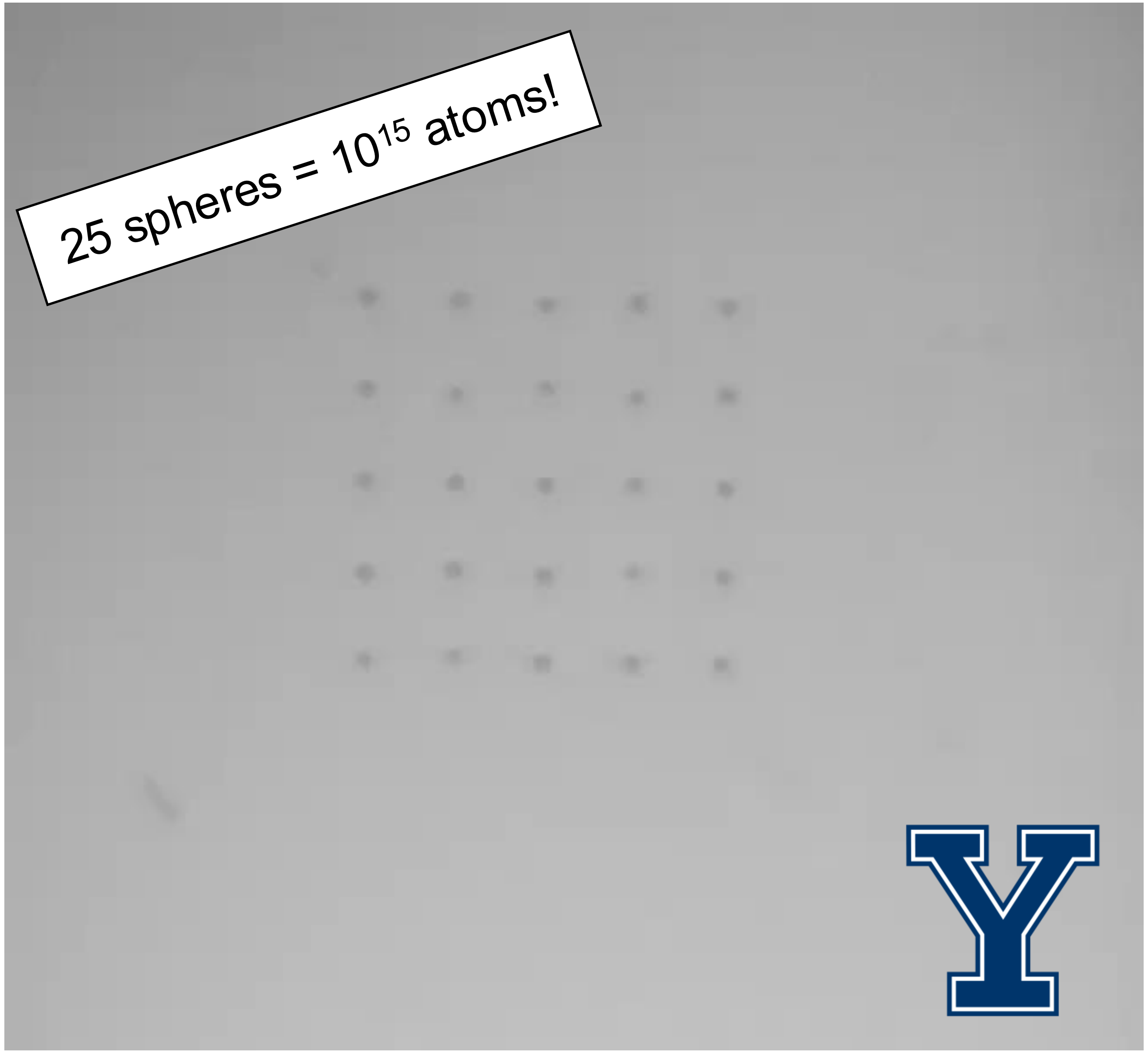




Played at 8x speed

9

Optomechanical sensors for the "invisible" Universe

Dark matter

https://www.symmetrymagazine.org/article/december-2013/four-things-you-might-not-know-about-dark-matter

What is the nature of dark matter?

Can we detect forces imparted by dark matter interactions in the lab?

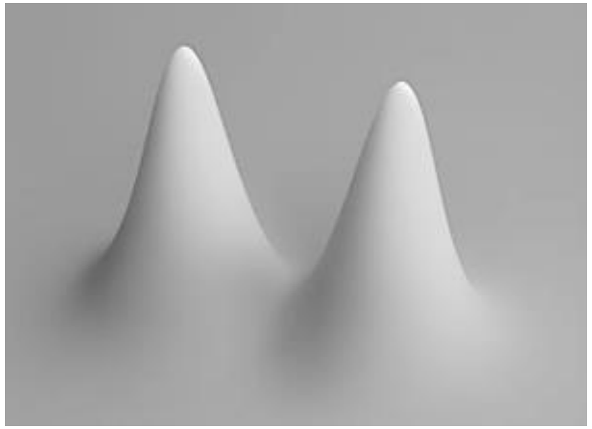
Neutrinos

https://www.symmetrymagazine.org/article/the-hidden-neutrino

Are there heavy, right-handed neutrinos that haven't been observed?

What are the masses of the light neutrinos?

Gravity

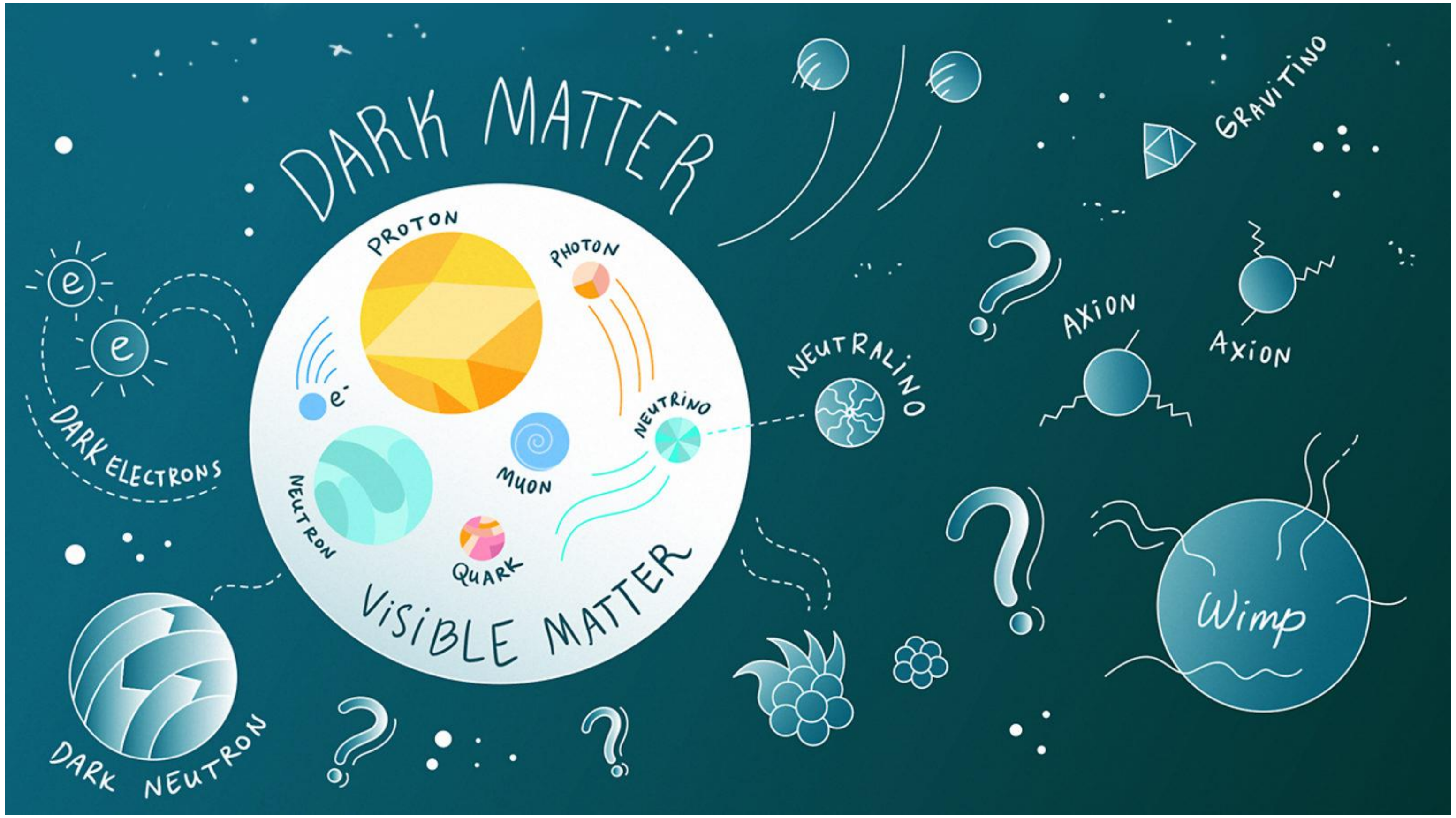


What is the gravitational field sourced by a massive, delocalized particle?

Are there BSM sources of high frequency gravitational waves?

- These questions remain unanswered largely due to the extremely weak interactions of interest
  - → Quantum measurement/control of much larger masses than single atoms/ions may allow new tools to prove these phenomena
- Optomechanical systems are ideal for searching for new interactions that couple to massive objects (compare e.g. to sensors for couplings to E&M fields [*talk by D. Speller*])

Dark matter

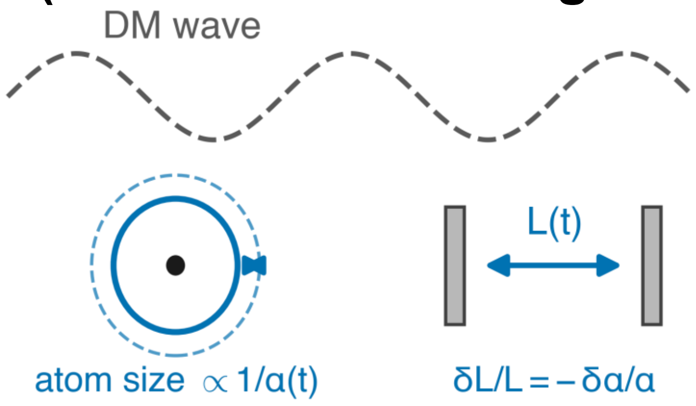


https://www.symmetrymagazine.org/article/december-2013/four-things-you-might-not-know-about-dark-matter

Ultralight dark matter

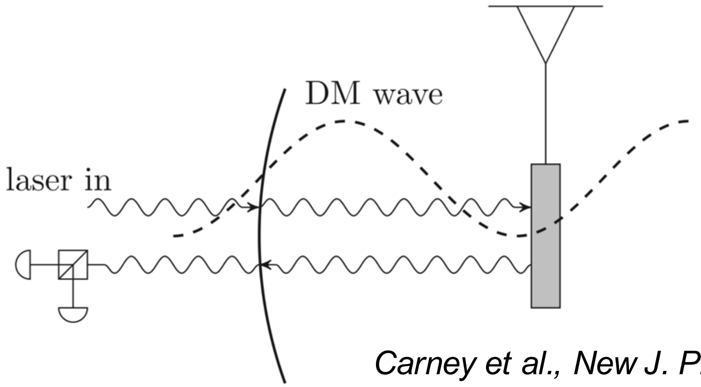
- Dark matter with mass $\lesssim$1 eV would have a number density per cubic wavelength $\gg$ 1
  - Leads to "wave-like" dark matter, which can impart classical forces (*see talk by Y. Kahn*)

Scalar (search for oscillating constants):



Can use clocks, optical cavites, etc. (see talk by V. Xu)

Vector (search for oscillating force on mass):



Carney et al., New J. Phys. 23 023041 (2021)

E.g., coupling to B-L pushes on neutrons:

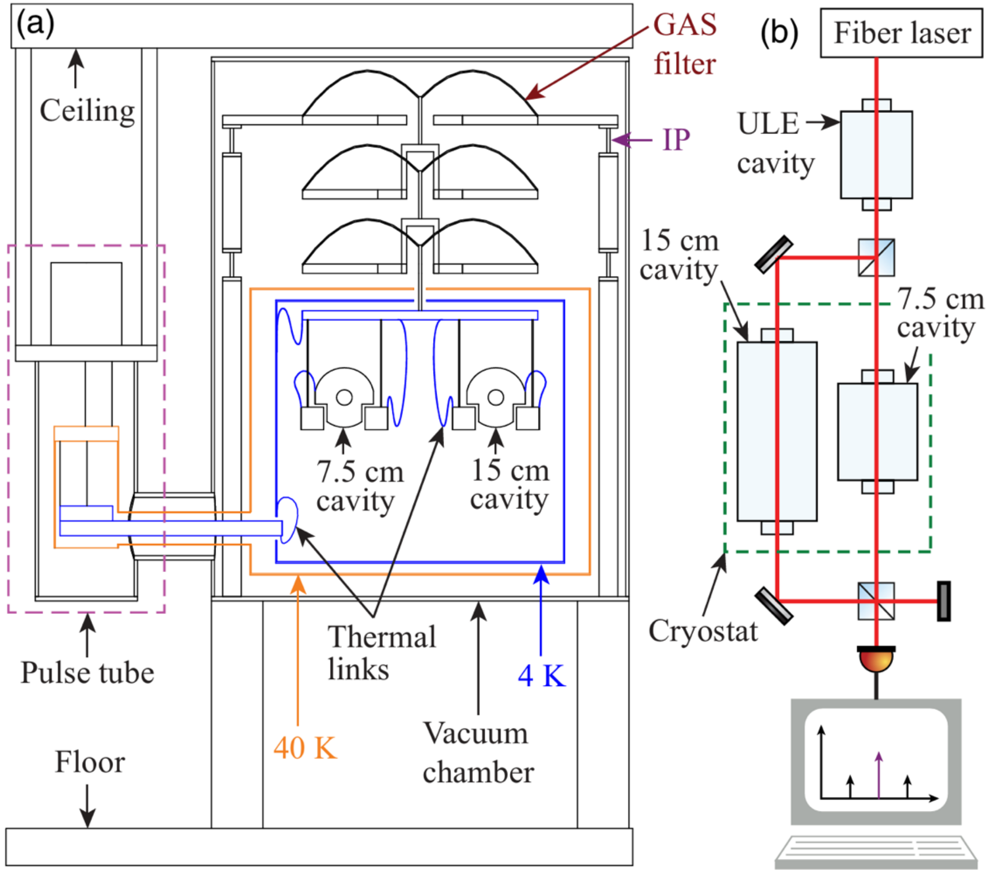
a $\lesssim 10^{-11}$ m/s^2 at 10 kHz [i.e., 10^{-20} N on a μg mass]

- In both cases, signal oscillates at $\omega \sim m_\phi$ and is coherent over ~10^6 cycles (*see talk by K. Lehnert*):
  - Aim to detect oscillating length change or force above thermal and measurement noise
  - Typically need resonant enhancement, require tuning over many masses

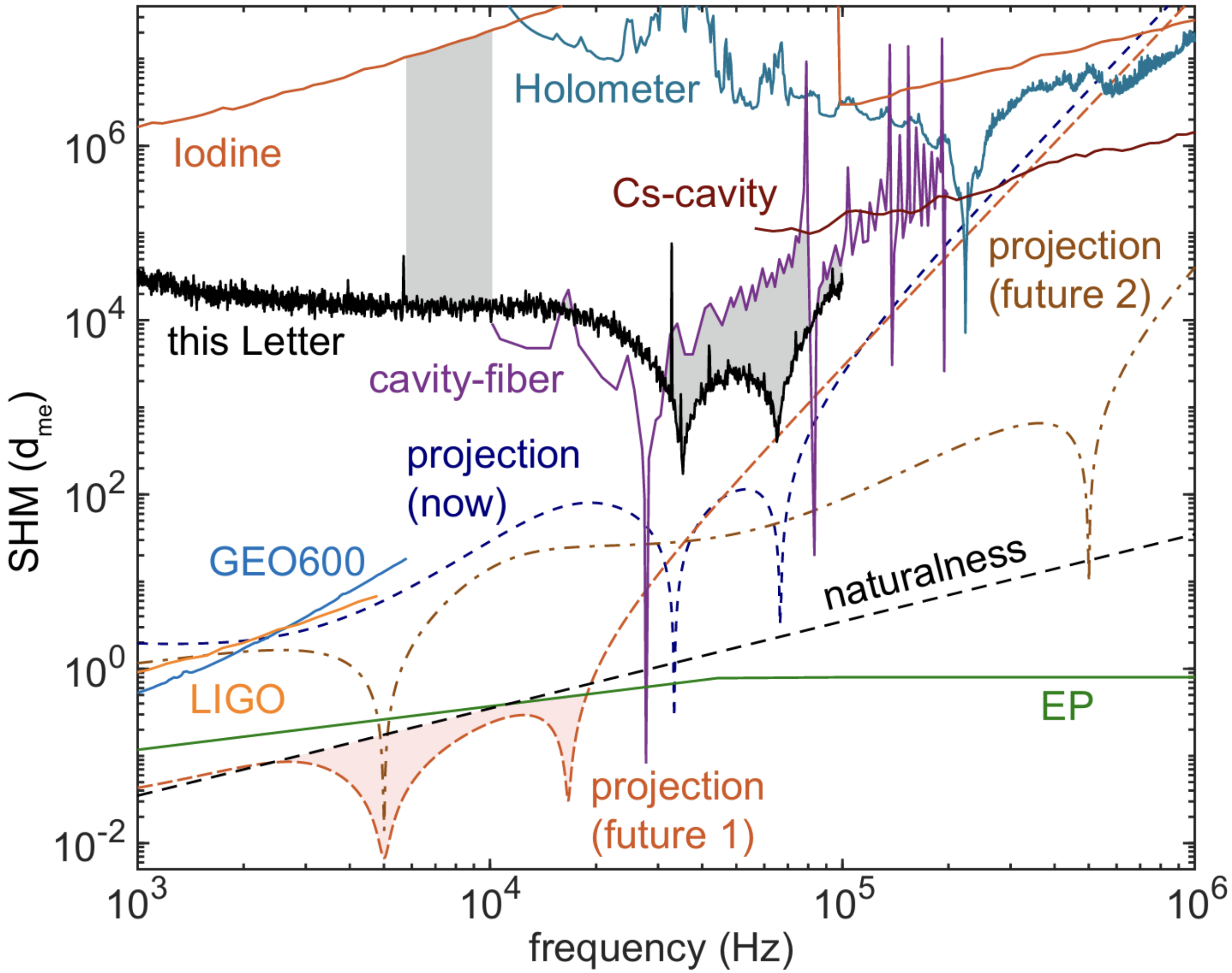
Ultralight dark matter (Optical cavities)

- Several experiments are now pursuing these models
  - Optical cavity comparisons (Northwestern):

Comparison of two cryogenic cavities:



Current and projected sensitivity:

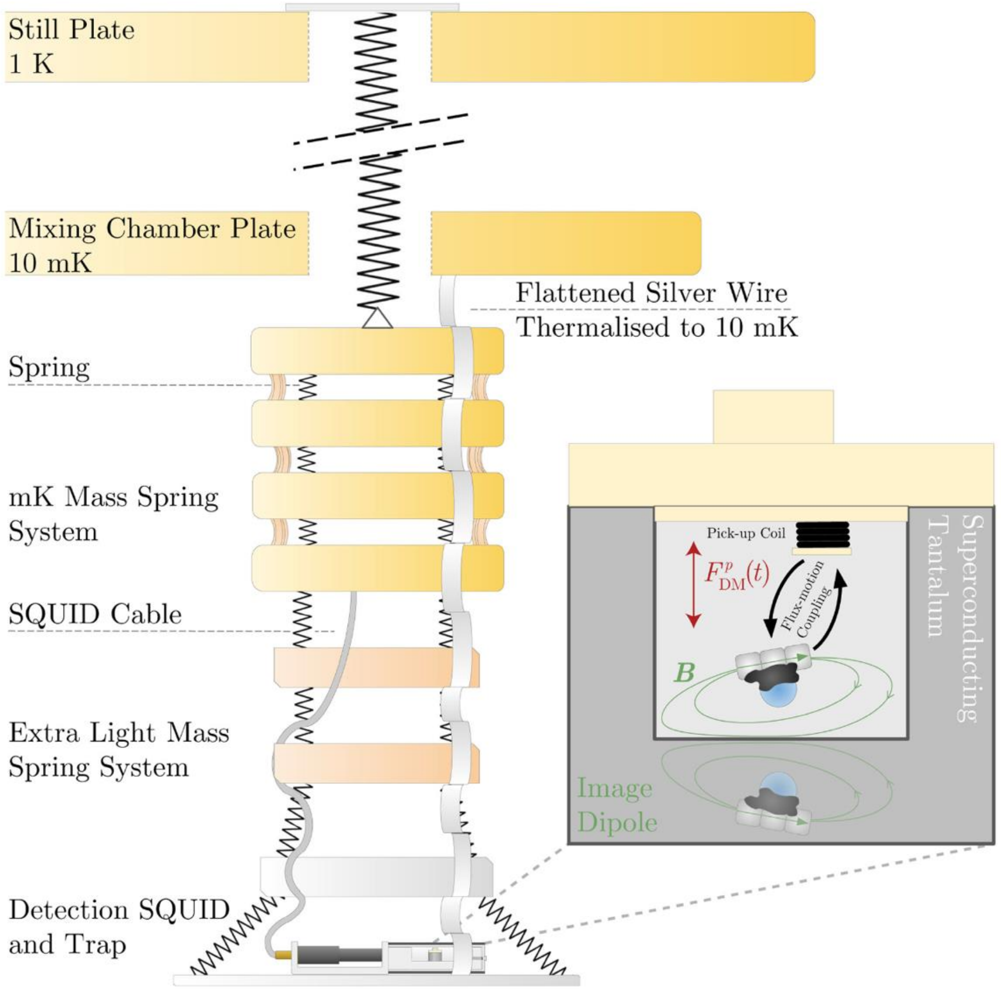


Deshpande et al., PRL 135, 261001 (2025)

Ultralight dark matter (POLONAISE)

- POLONAISE:

Magnetically levitated 400 ug mass:



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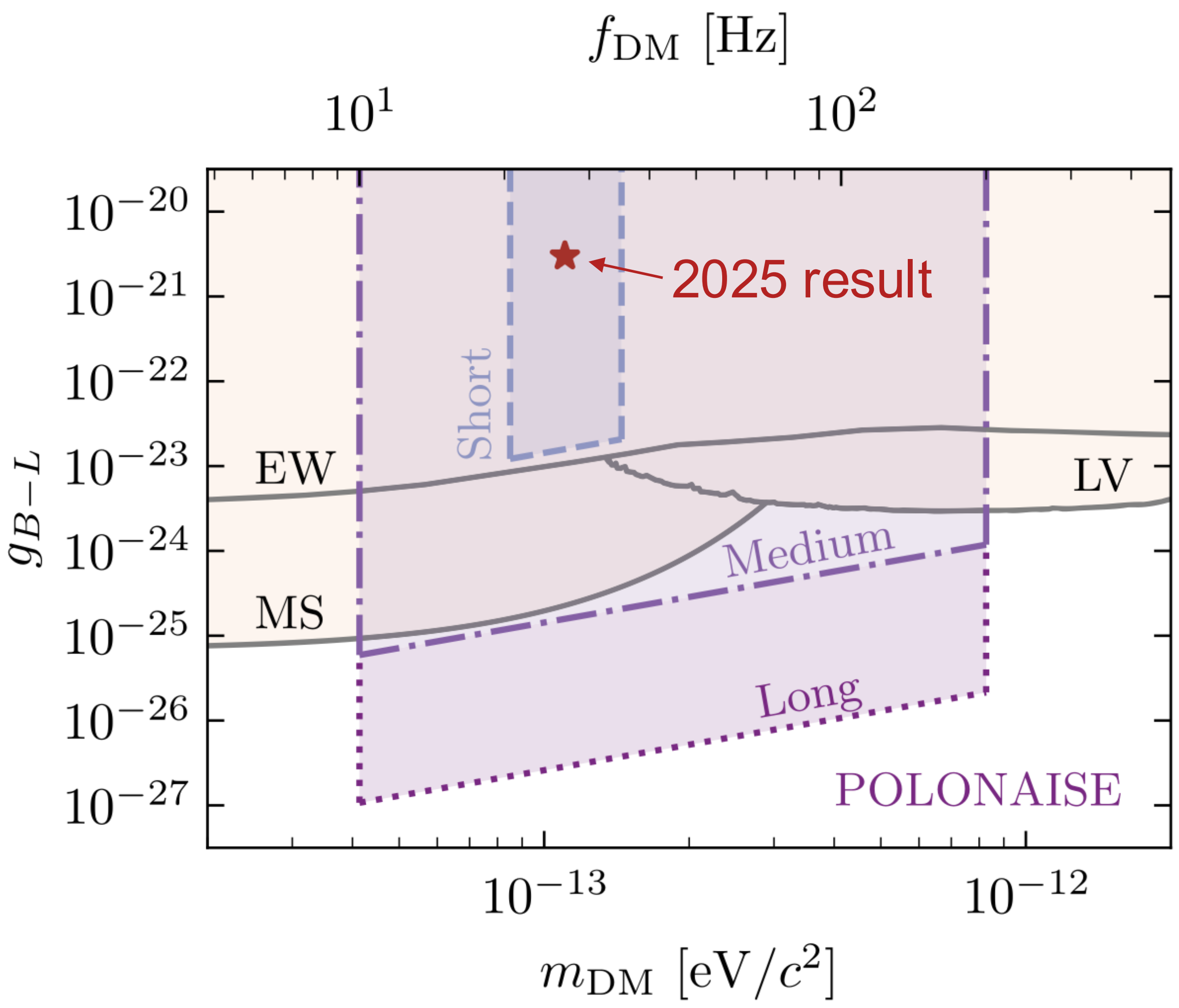
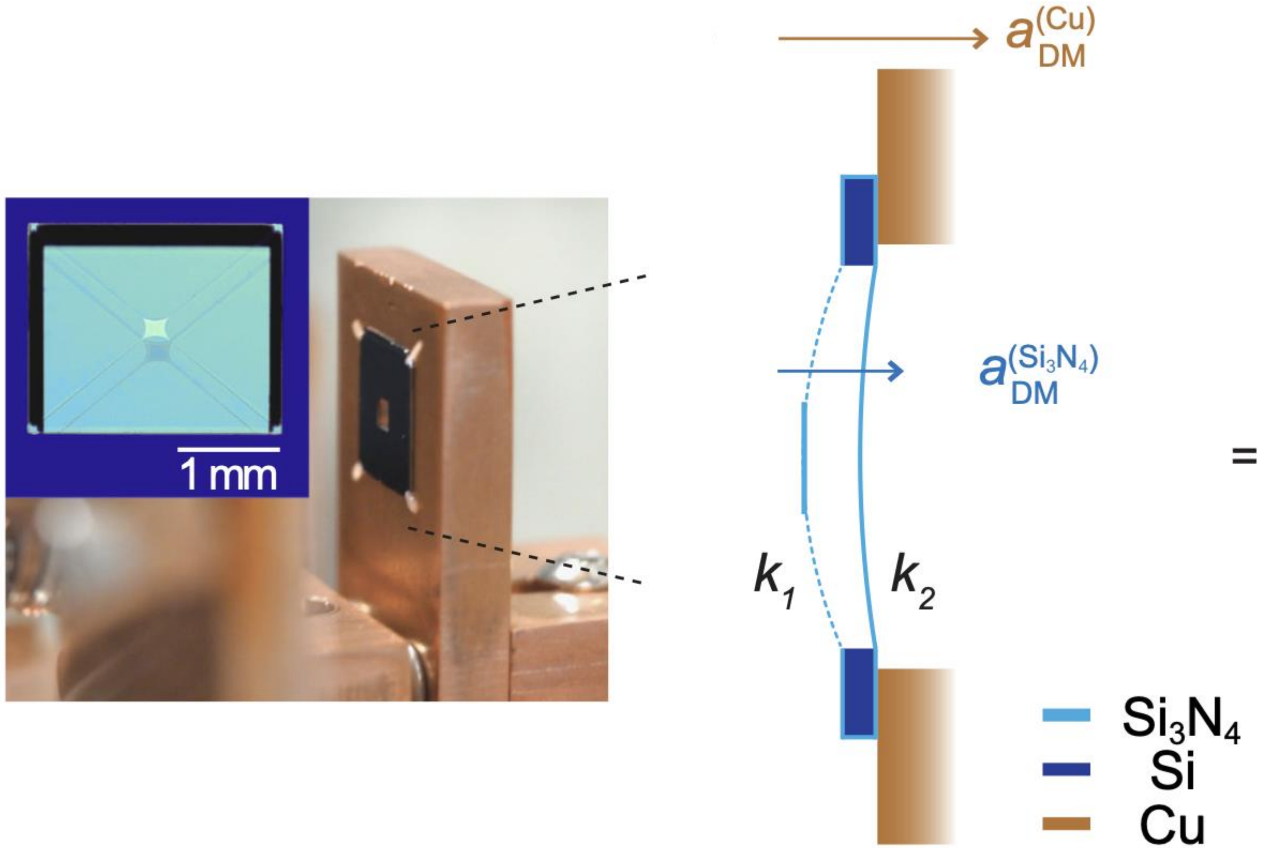


Amaral et al., PRL 134, 251001 (2025)

Ultralight dark matter (Trampoline oscillators)

- Membrane oscillators (U Arizona/NIST):

Tethered trampoline membrane oscillator:



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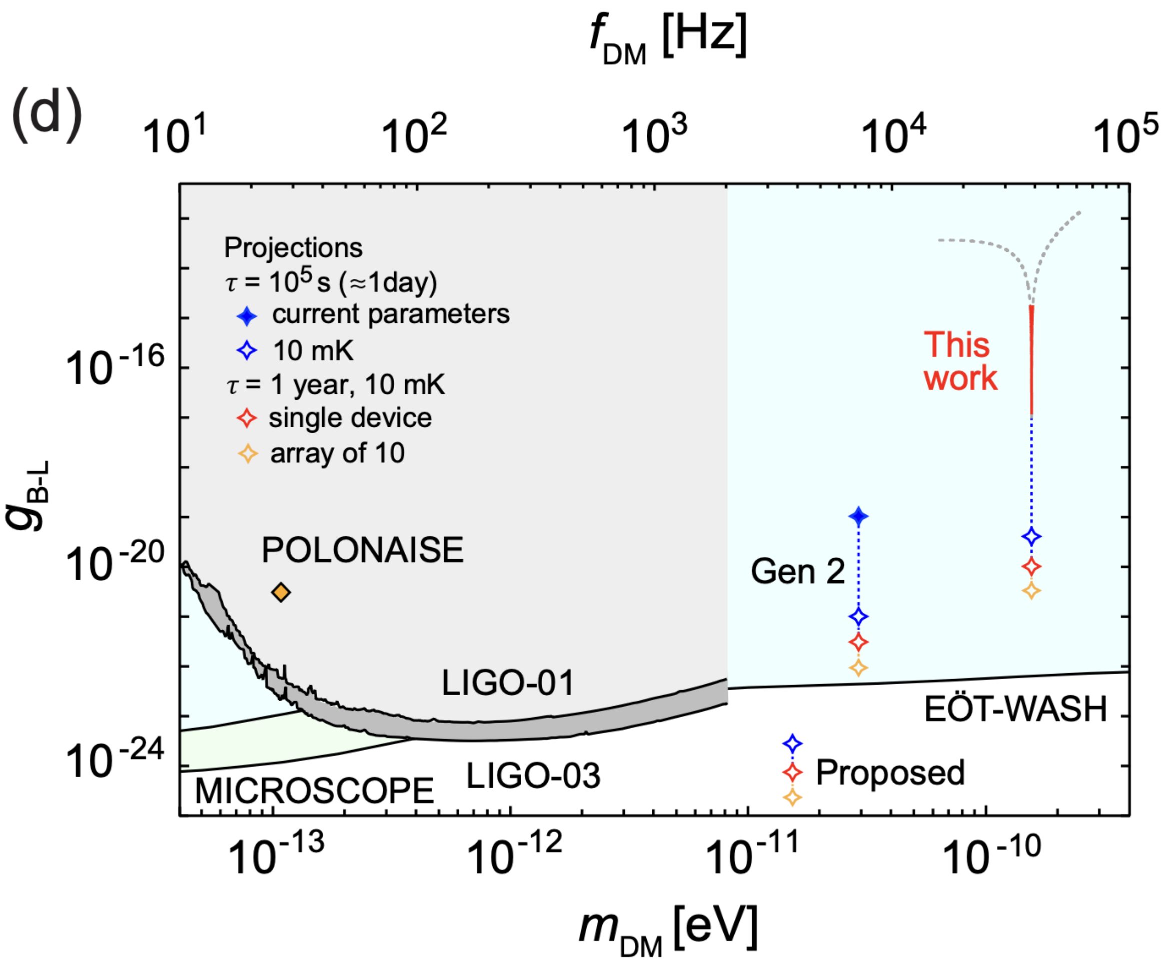
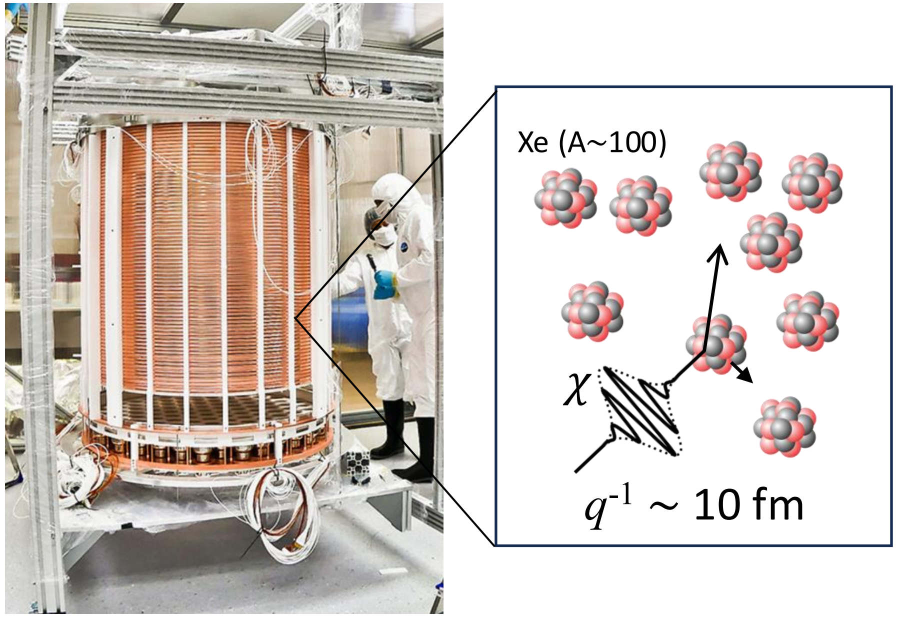


Chowdhury et al, PRD 113, L121303 (2026)

Kinematic detection of (particle) dark matter

- For masses ≳eV, DM interacts as "particles," i.e. discrete collisions (*see talk by T. Lin*)
- Mechanical sensors could be sensitive to dark matter models that primarily interact coherently with entire objects, rather than single nuclei or electrons

Ton-scale WIMP detectors (e.g. LZ, XENONnT,…):



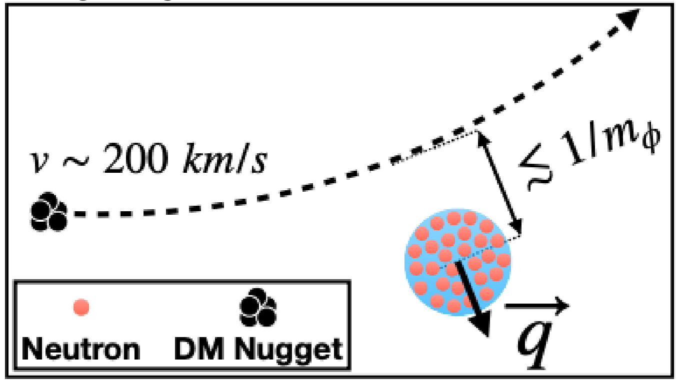
Coherence only over a single nucleus:

$$\text{Rate} \propto N_T\, A^2\, \sigma_n$$

N_T: ≫10^{23} ; A^2: ~10^4

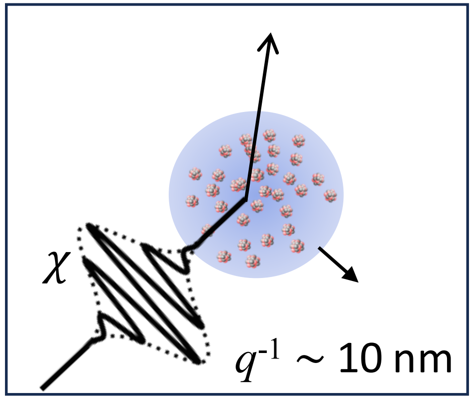
fg-ng scale trapped objects:

Long range force:



Monteiro et al., PRL 125, 181102 (2020), arXiv:2007.12067

Low momentum transfer:



Afek et al., PRL 128, 101301 (2022), arXiv:2111.03597

Coherence over an entire nano- or micro-sized object:

$$\text{Rate} \propto (N_T)^2 \sigma_n$$

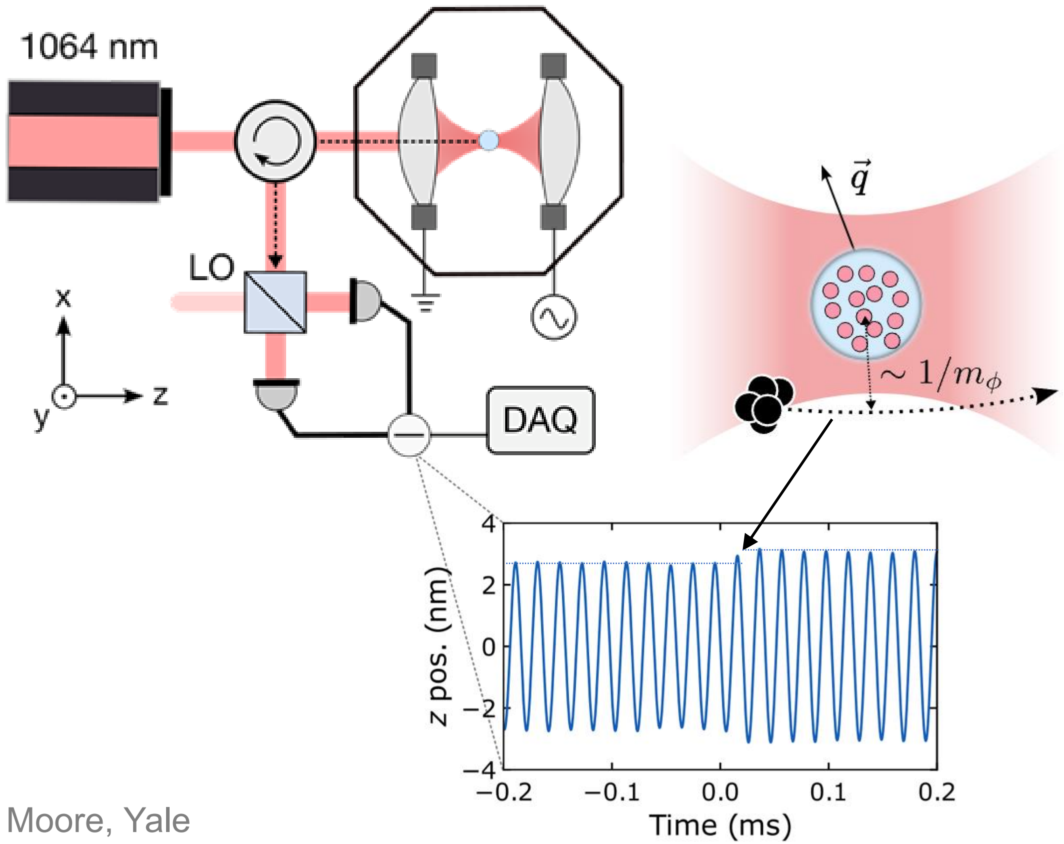
$(N_T)^2$: ~ $(10^9)^2$ to $(10^{14})^2$

Can rival Avogadro's number!

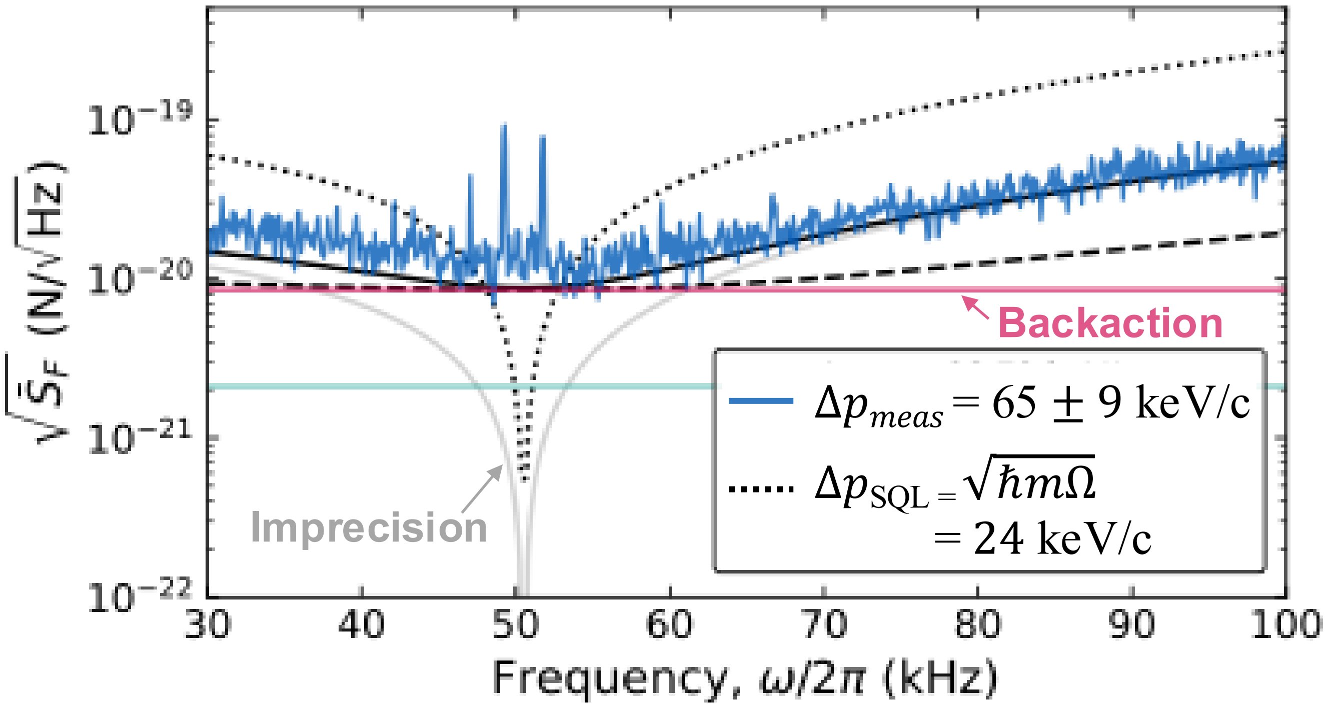
Impulses with nanospheres (Yale)

- Recently demonstrated impulse sensing within ≲3x of the SQL for ~100 nm diameter (~fg mass) spheres
  - Performed most sensitive search to date for certain classes of dark matter that primarily interact with the entire nanosphere
  - Resolution ≲50 keV/c sufficient to detect ν with momentum of 1 MeV/c with SNR ~ 20

Schematic of impulse measurement:



Measured force noise, 5 fg particle:

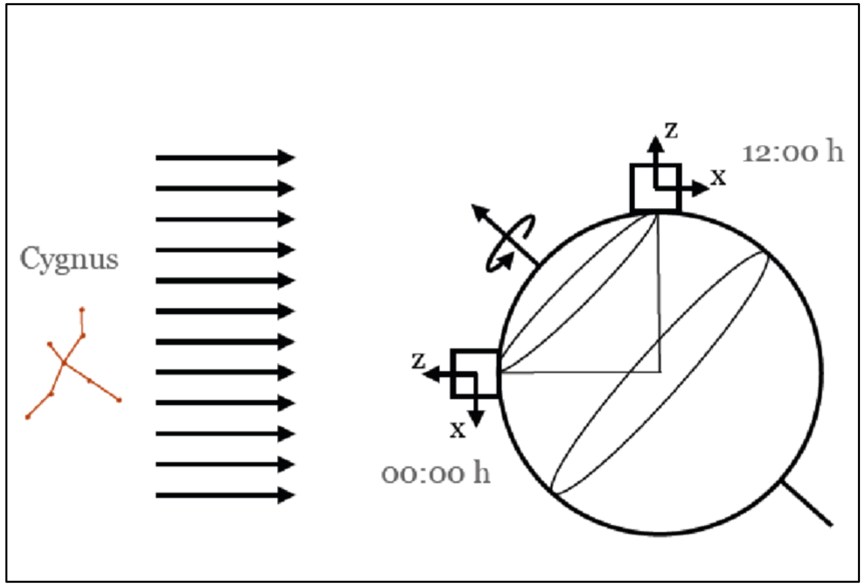


PRX Quantum 6, 040367 (2025), arXiv:2508.00815

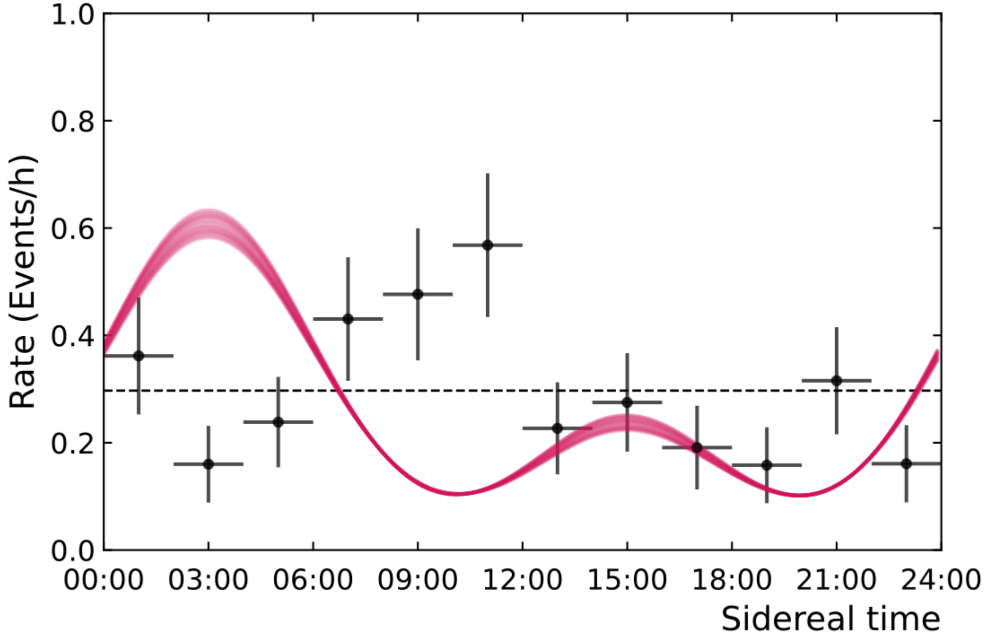
Dark m

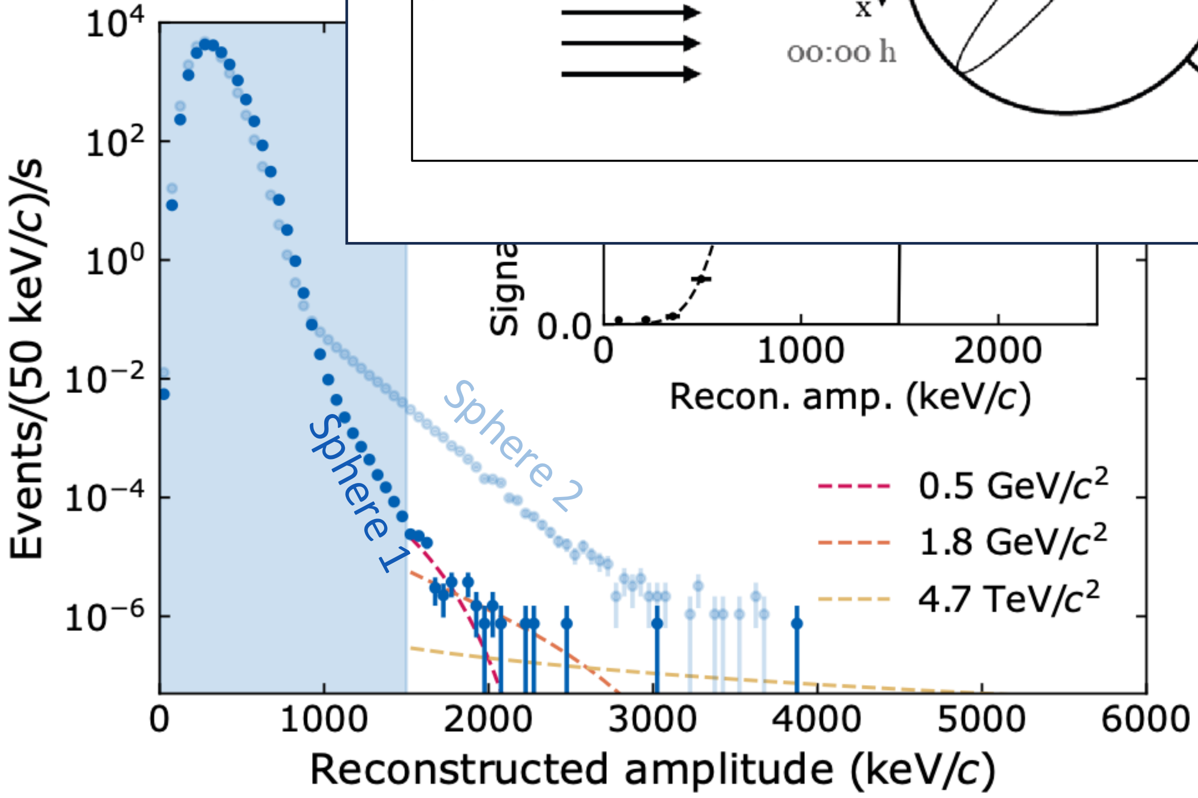
- Performed s
  - Tail of e
  - Conser matter

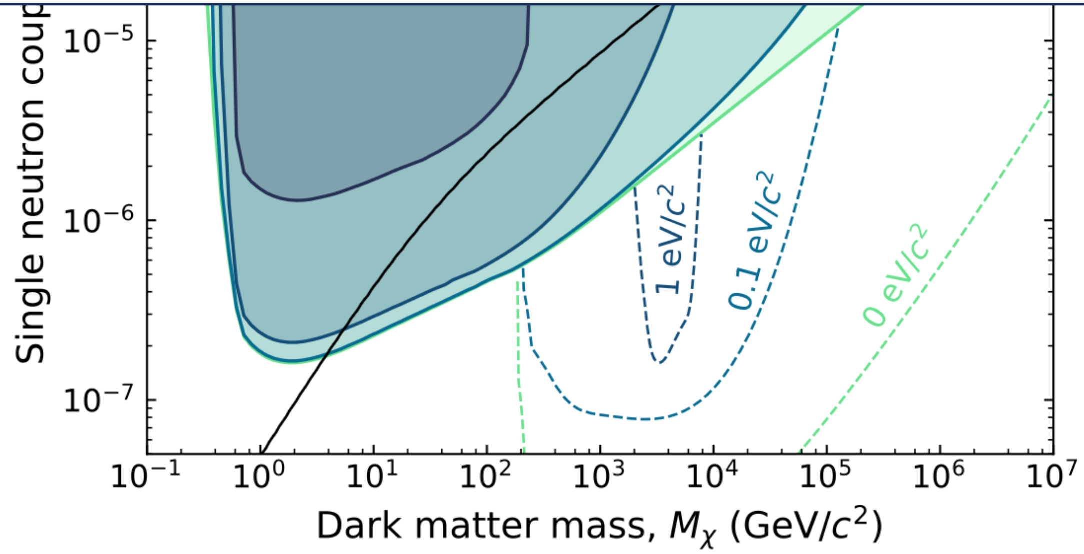
Natural directionality → any detection would be definitive!



Event rate vs sidereal time:







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

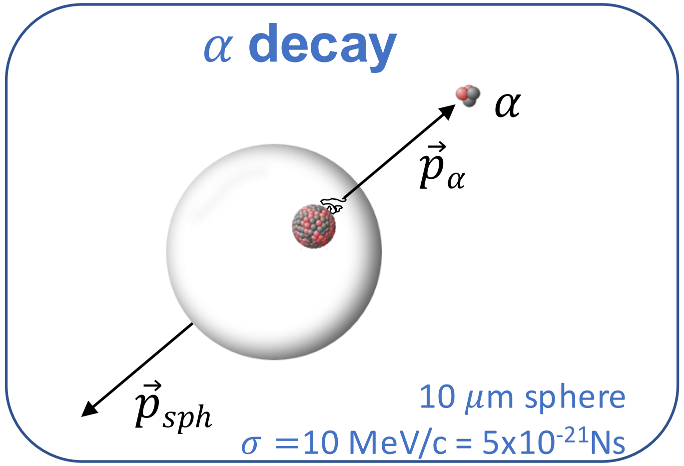
Neutrinos

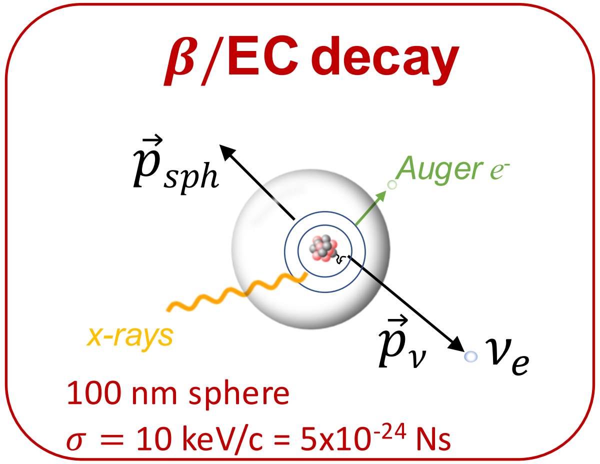
https://www.symmetrymagazine.org/article/the-hidden-neutrino

Nuclear decays in mechanical sensors

- Levitated sensors are now reaching sufficient sensitivity to detect the miniscule forces imparted by single sub-atomic particles
  - For weak decays, allows the momentum of each neutrino to be reconstructed on an event-by-event basis

Example force measurements for nuclear decay:

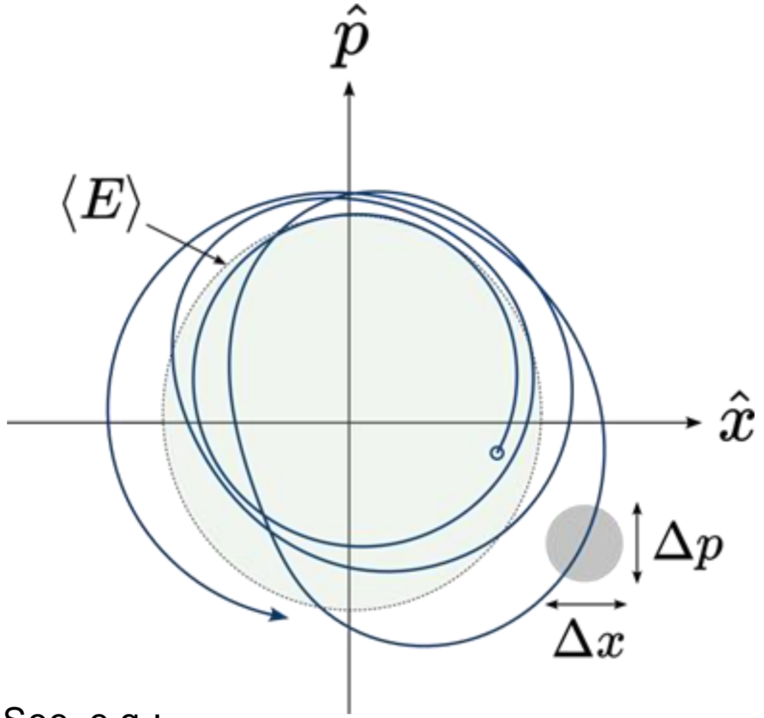




D. Carney, K. Leach, and DCM, "Searches for massive neutrinos with mechanical quantum sensors," PRX Quantum 4, 010315 (2023) arXiv:2207.05883

J. Wang et al., "Mechanical detection of nuclear decays," Phys. Rev. Lett. 133, 023602 (2024), arXiv:2402.13257

Phase space trajectory:



See, e.g.:
Magrini et al., Nature 595, 373 (2021)
Tebbenjohanns et al., Nature 595, 378 (2021)

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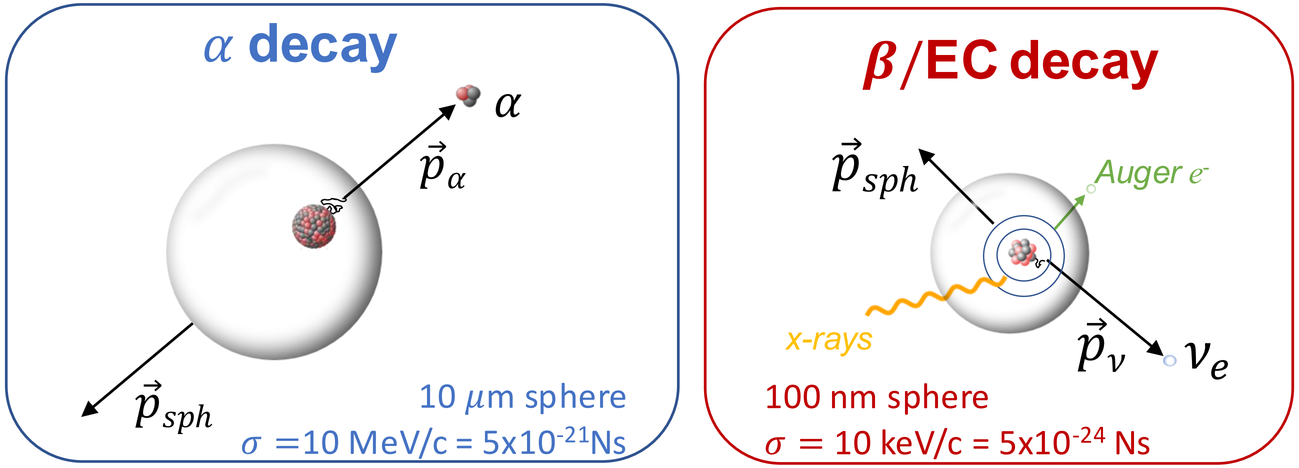

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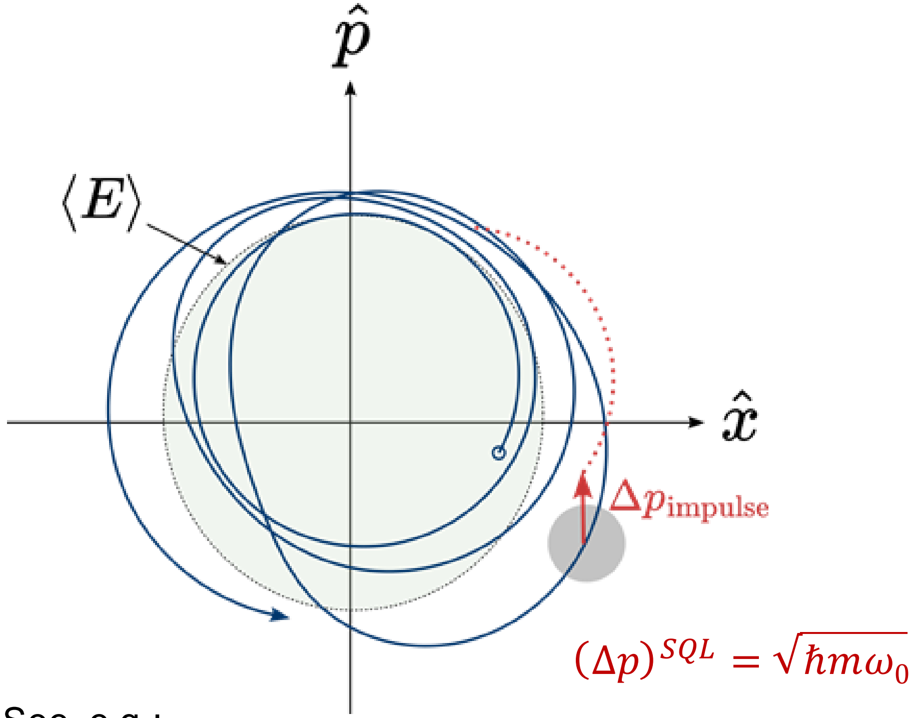


See, e.g.:

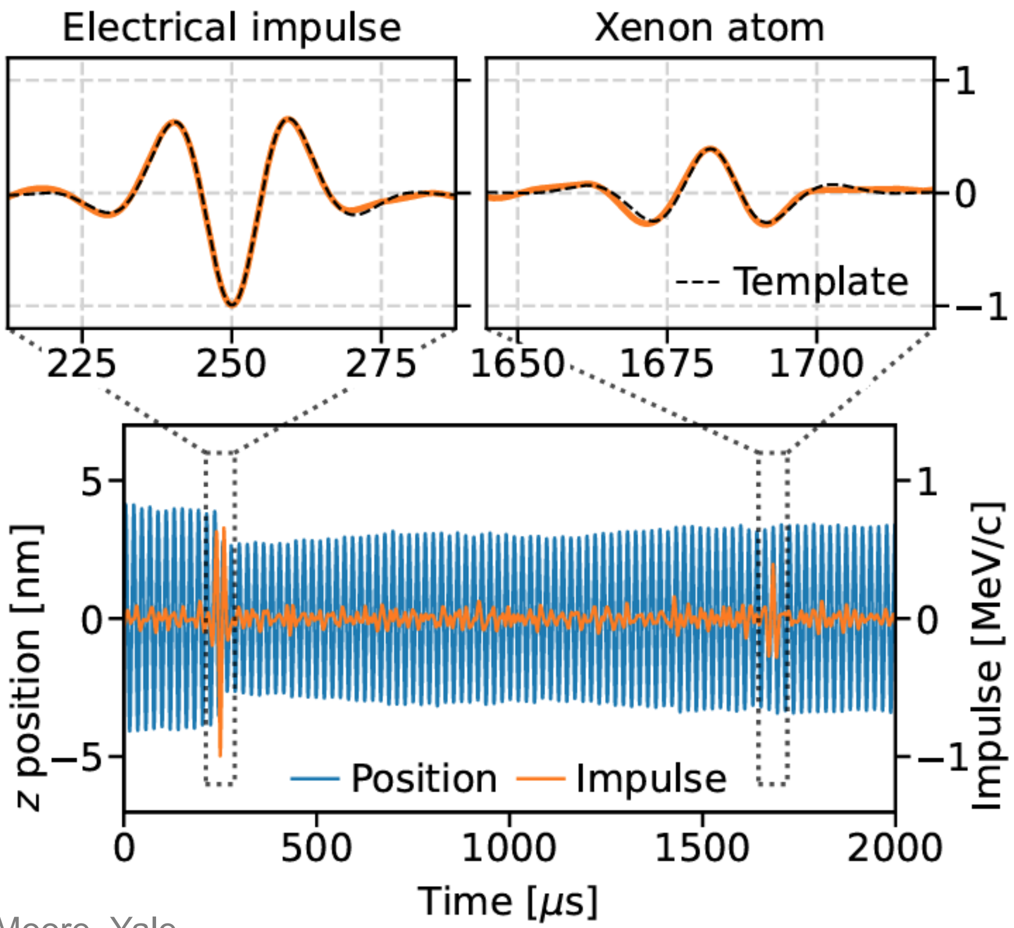
Magrini et al., Nature 595, 373 (2021)

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

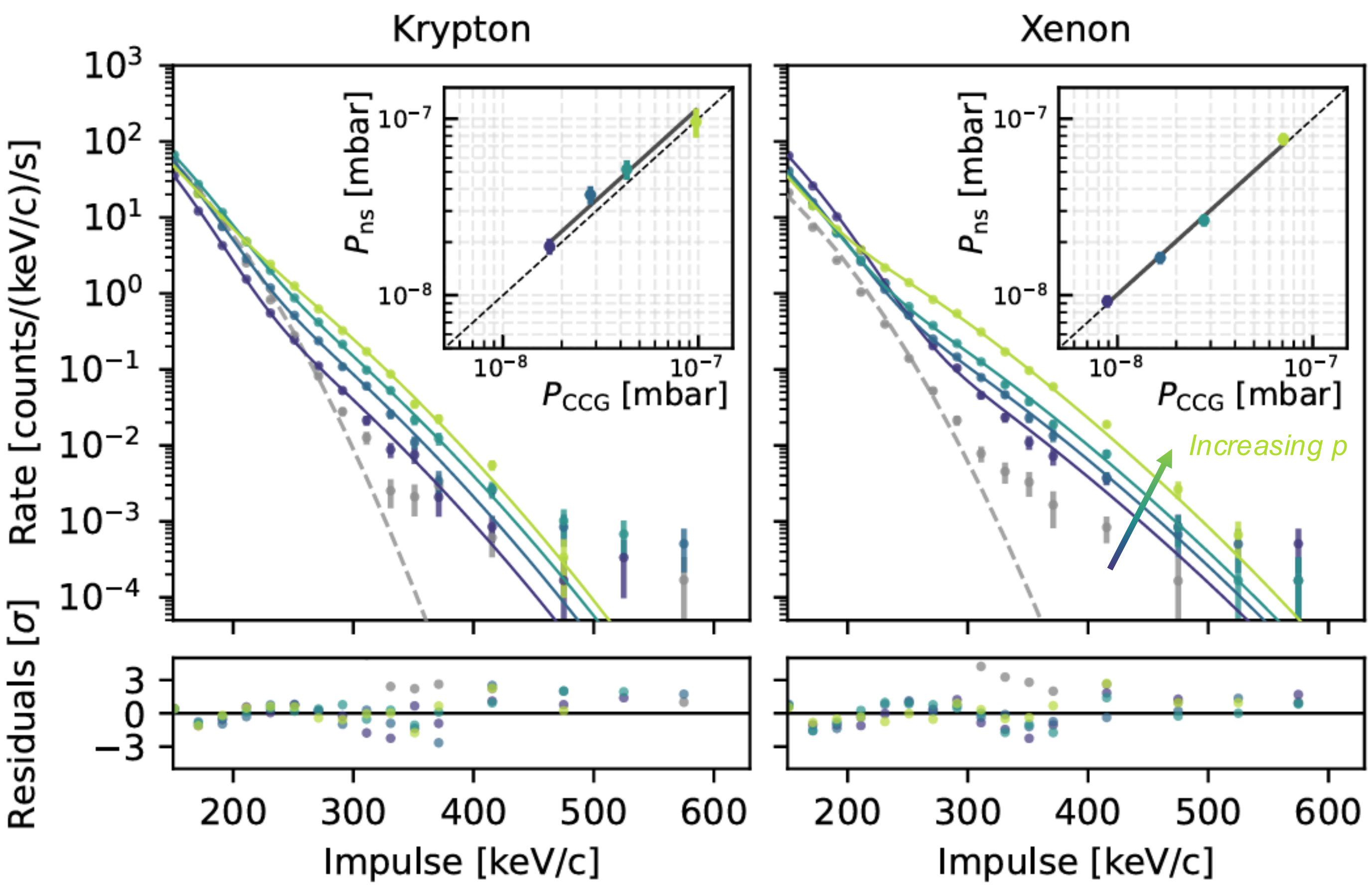
Proof-of-principle (gas collisions)

- 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:

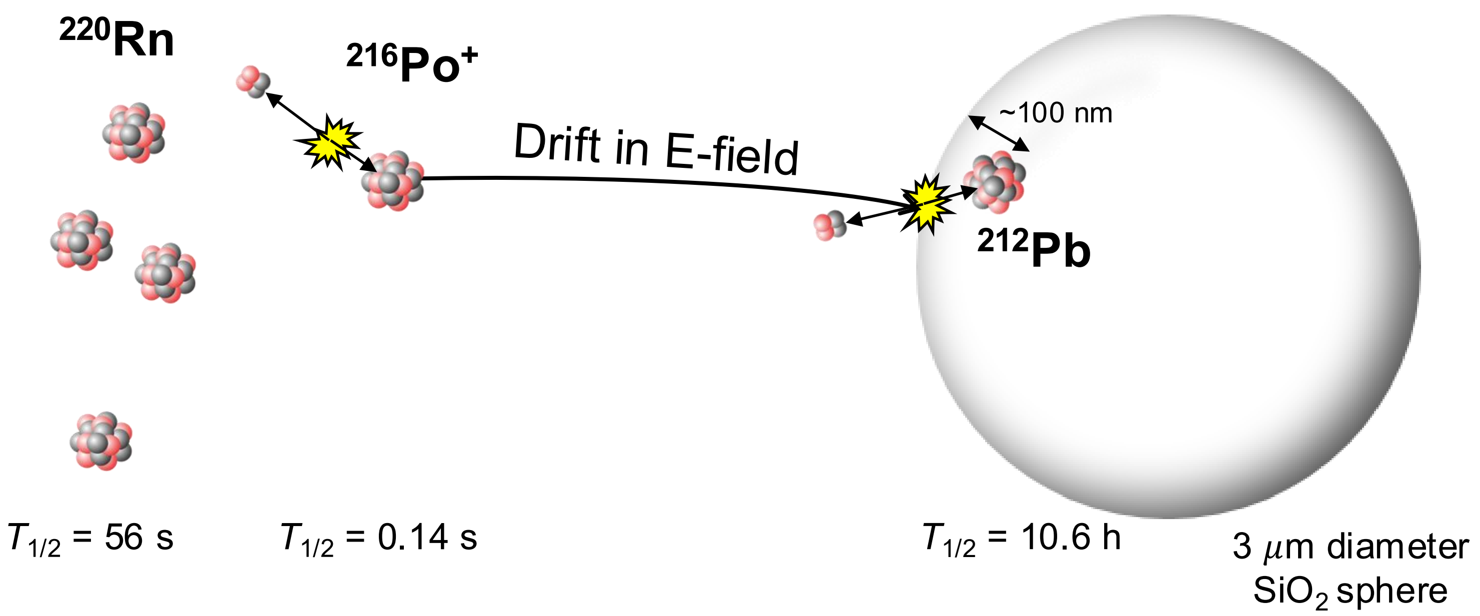


arXiv:2604.18371

Radioisotope loading (α decays)

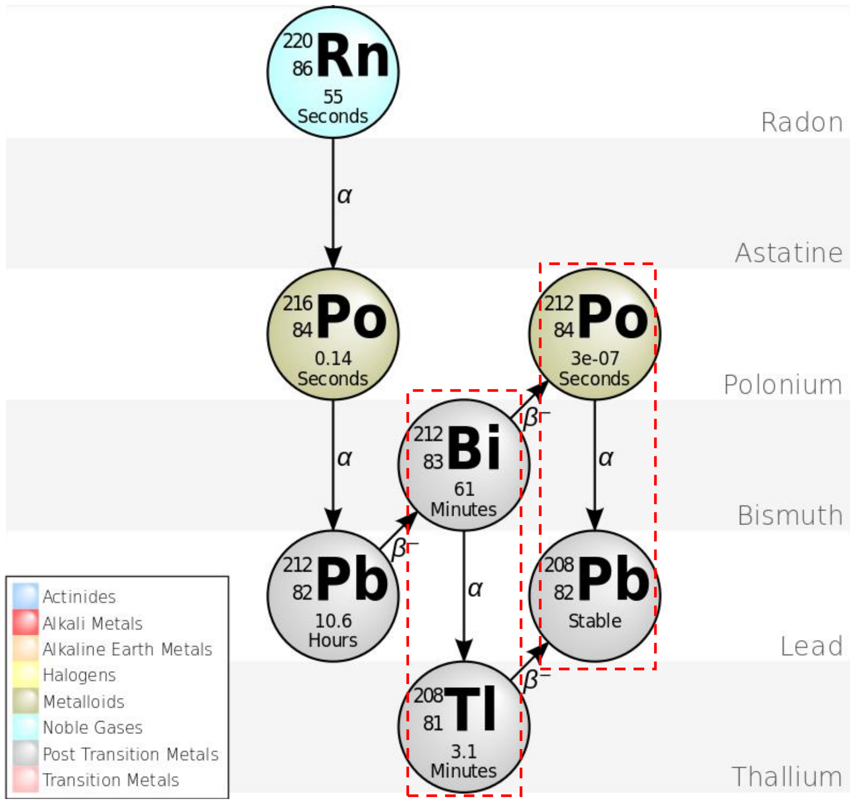
- As a proof-of-principle, we have detected single α decays with $>\mu$m sized spheres
  - Momentum is ~200 MeV/c (compared to 0.1-1 MeV/c for typical ν, γ)
- Have demonstrated loading of small quantities of ^{212}Pb into trapped microspheres

Schematic of loading scheme:



PRL133, 023602 (2024), arXiv:2402.13257

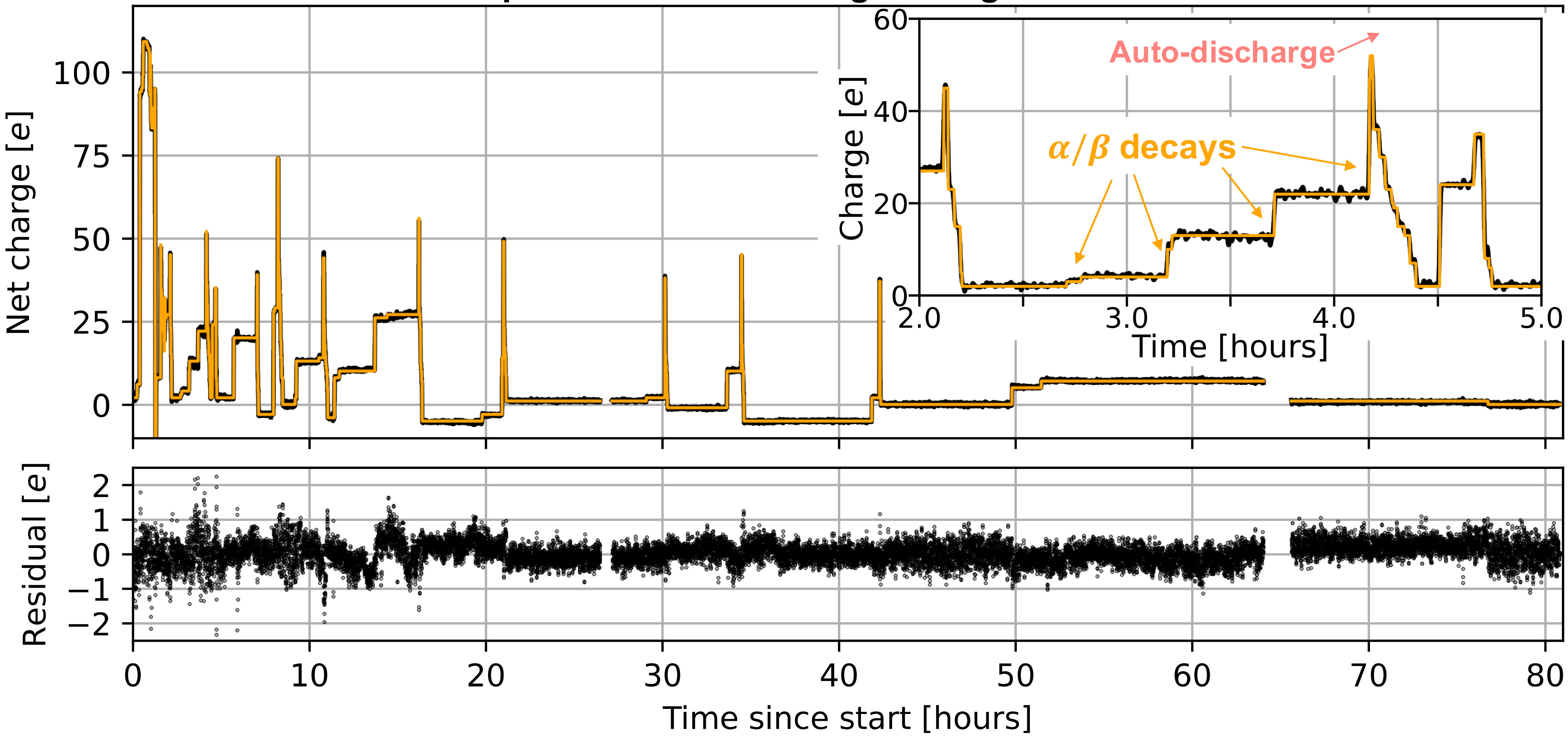
Rn-220 decay chain:



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:

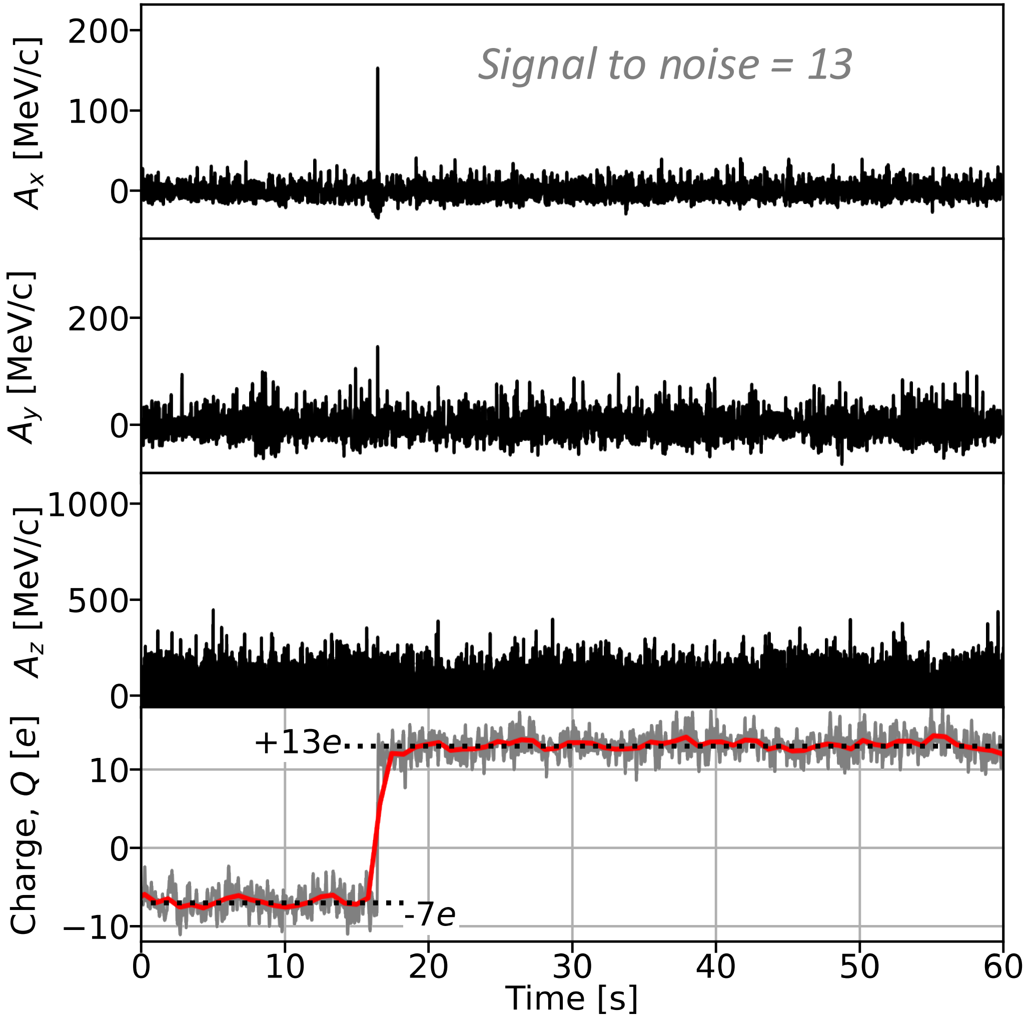


PRL133, 023602 (2024), arXiv:2402.13257

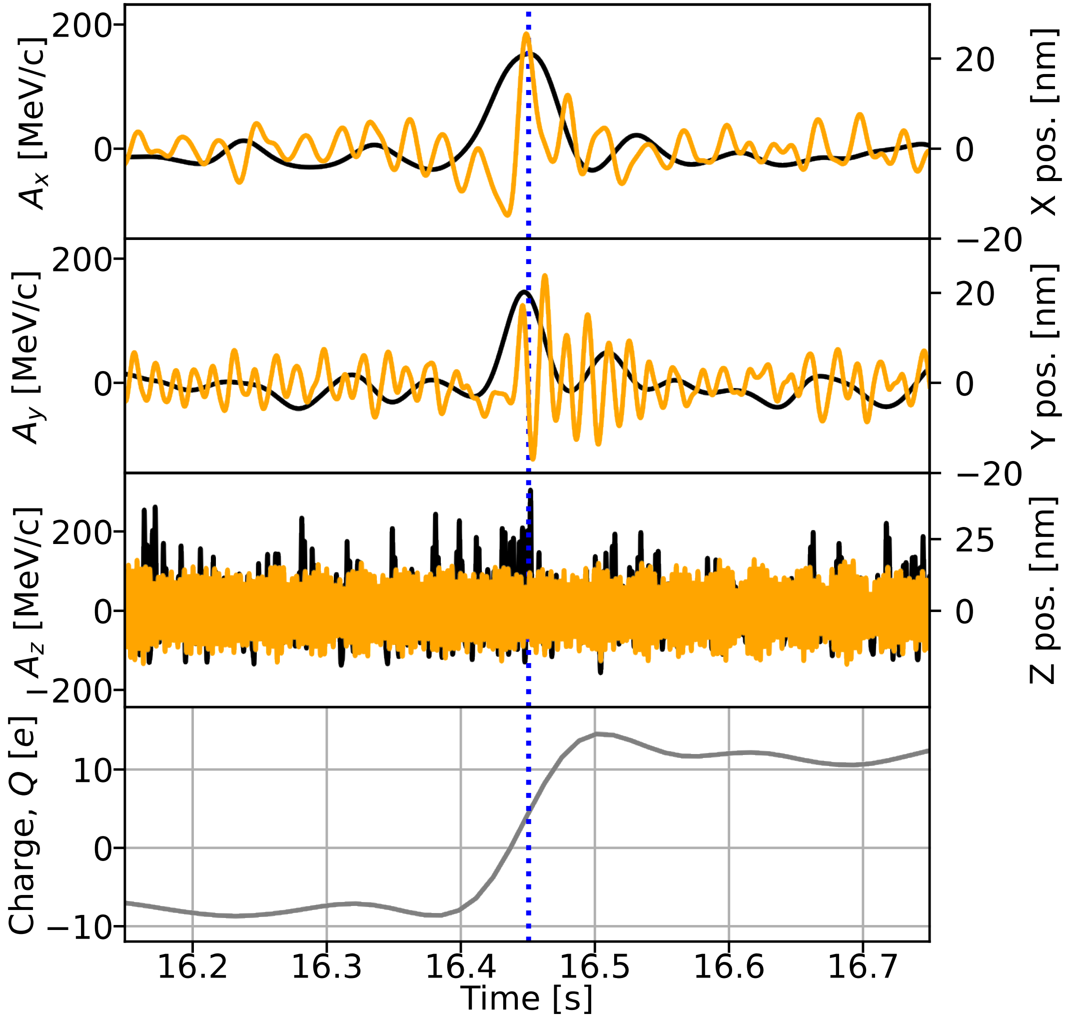
Detection of single nuclear decays (recoil)

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

Recoil coincident with charge change:

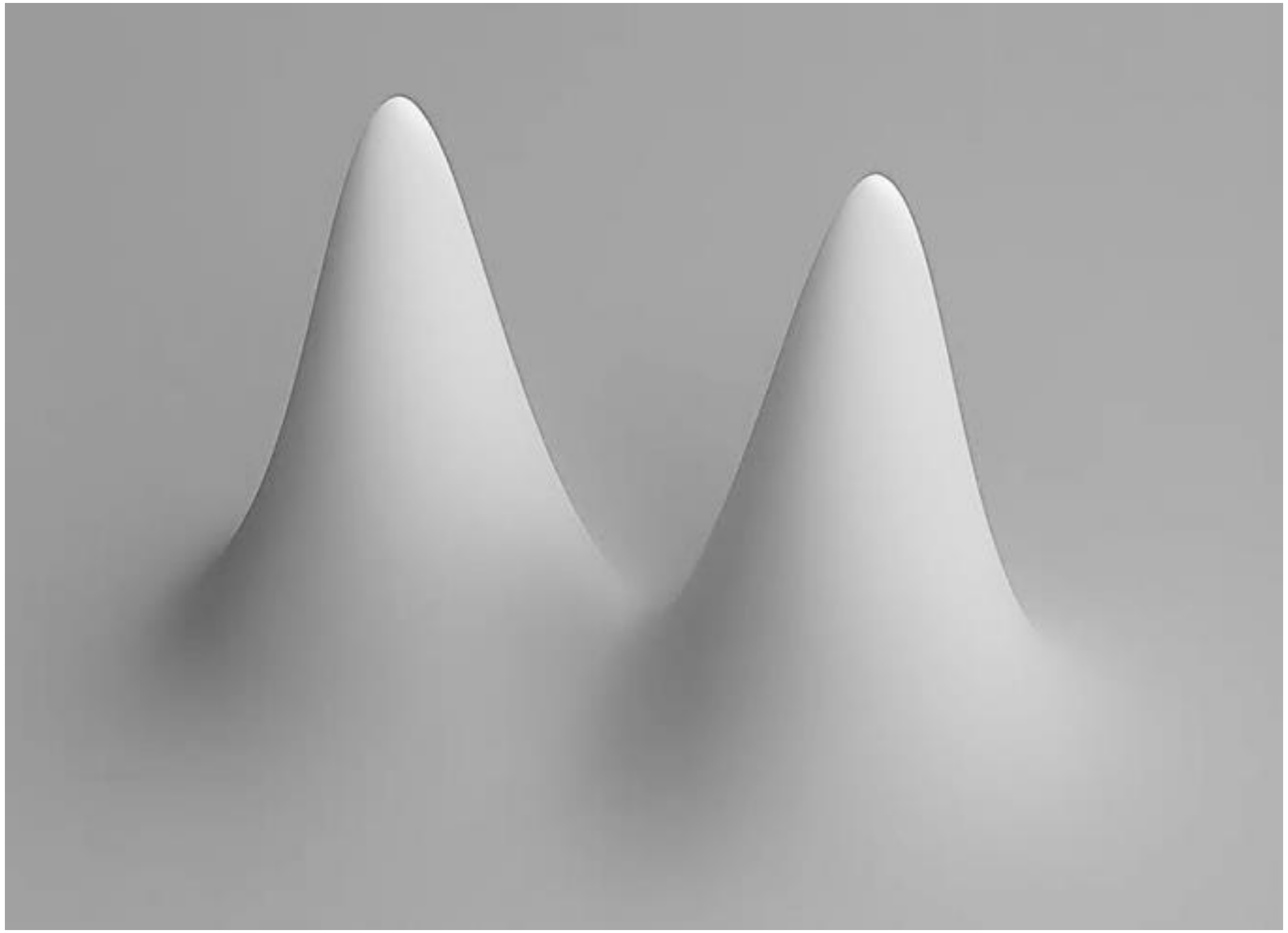


Zoom to decay time:



PRL133, 023602 (2024), arXiv:2402.13257

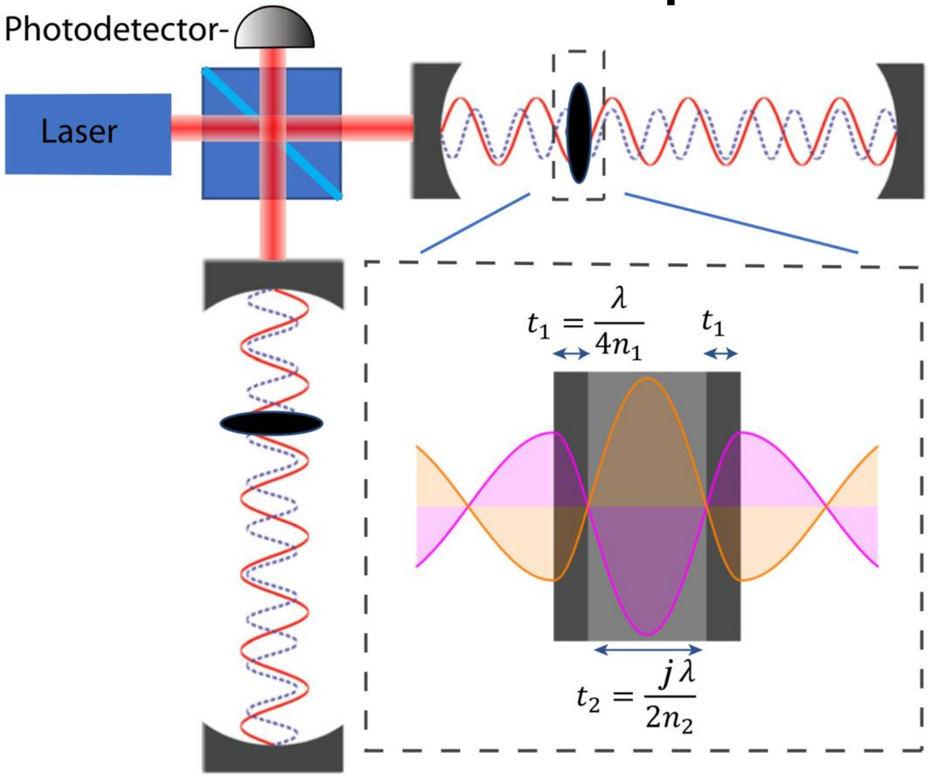
Gravity



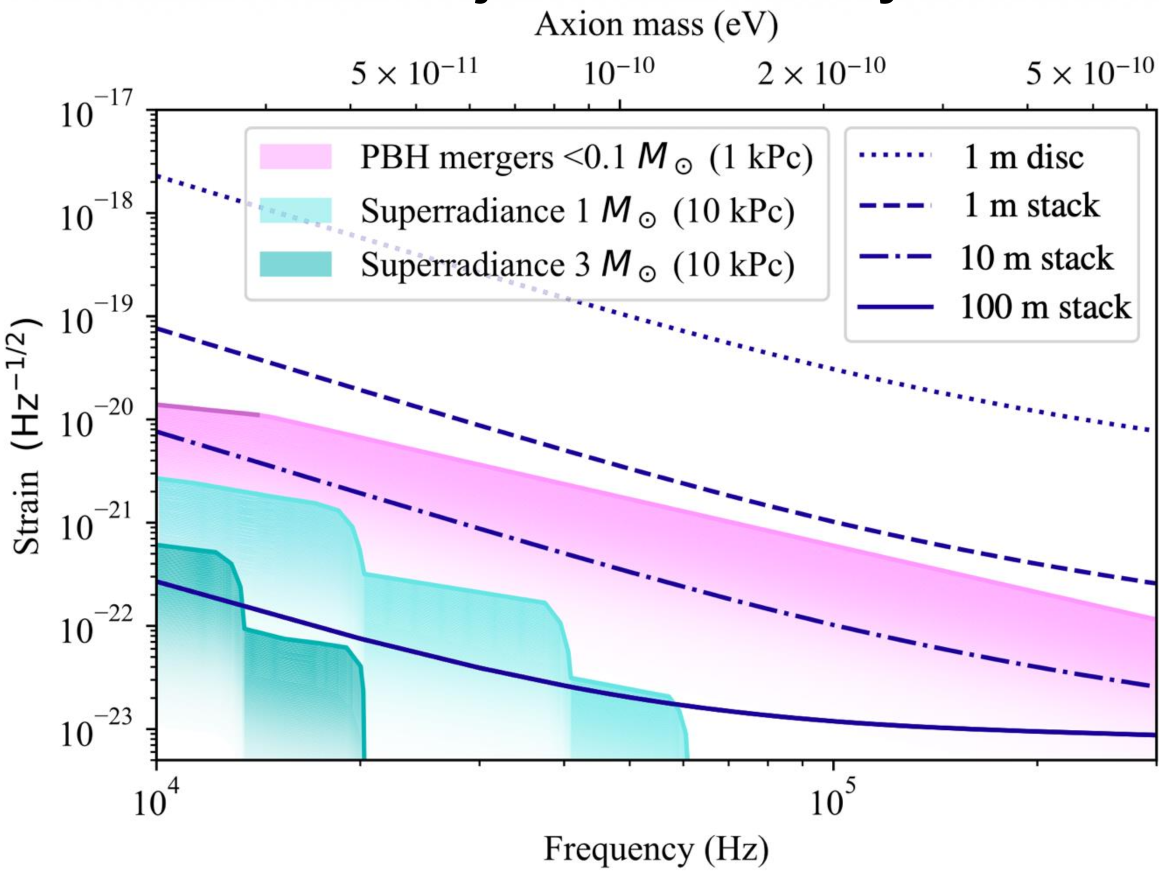
High frequency gravitational waves

- By incorporating levitated particle in Michelson interferometer, can use high Qs to potentially resonantly enhance high frequency GW signals (10s - 100s of kHz)
- Currently under development by Levitated Sensor Detector (LSD) collaboration

LSD Concept:



Projected sensitivity:



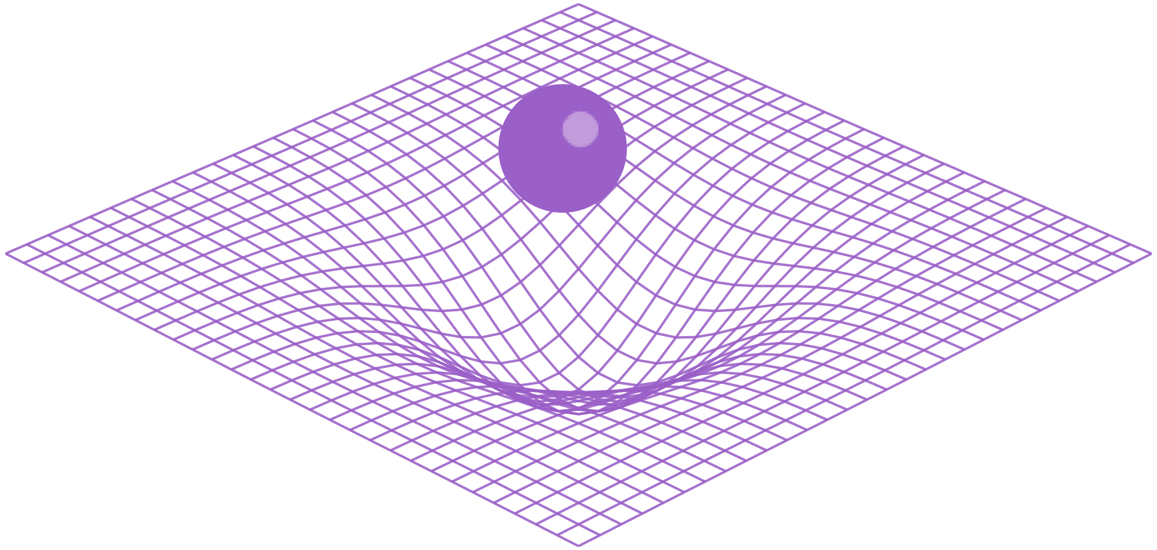
Aggarwal et al., PRL 128, 111101 (2022)

Is gravity "quantum"?

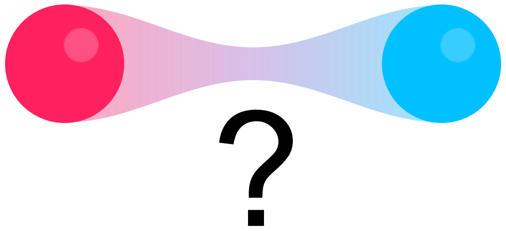
See also talk by D. Carney

- Can we experimentally probe fundamental questions about gravity with micron-scale particles:

Gravitational field sourced by classical mass:



Spatial superposition:



What is the gravitational field sourced by a spatial superposition?

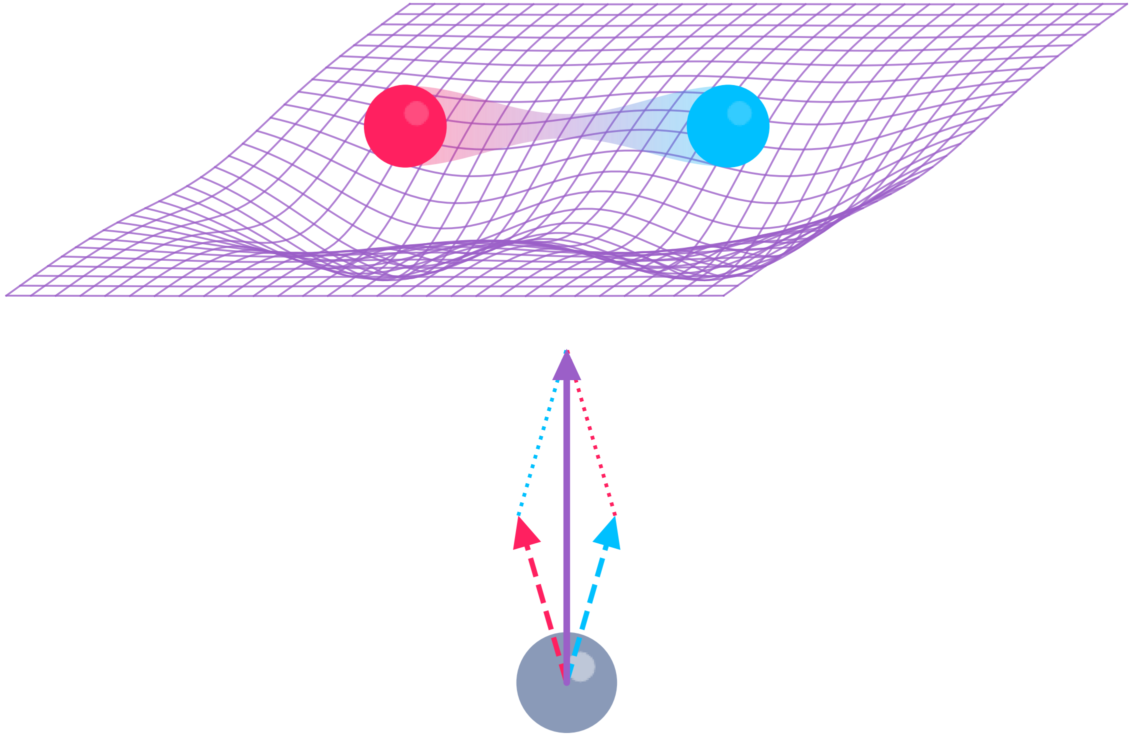
Figures from A. Markowitz

Is gravity “quantum”?

See also talk by D. Carney

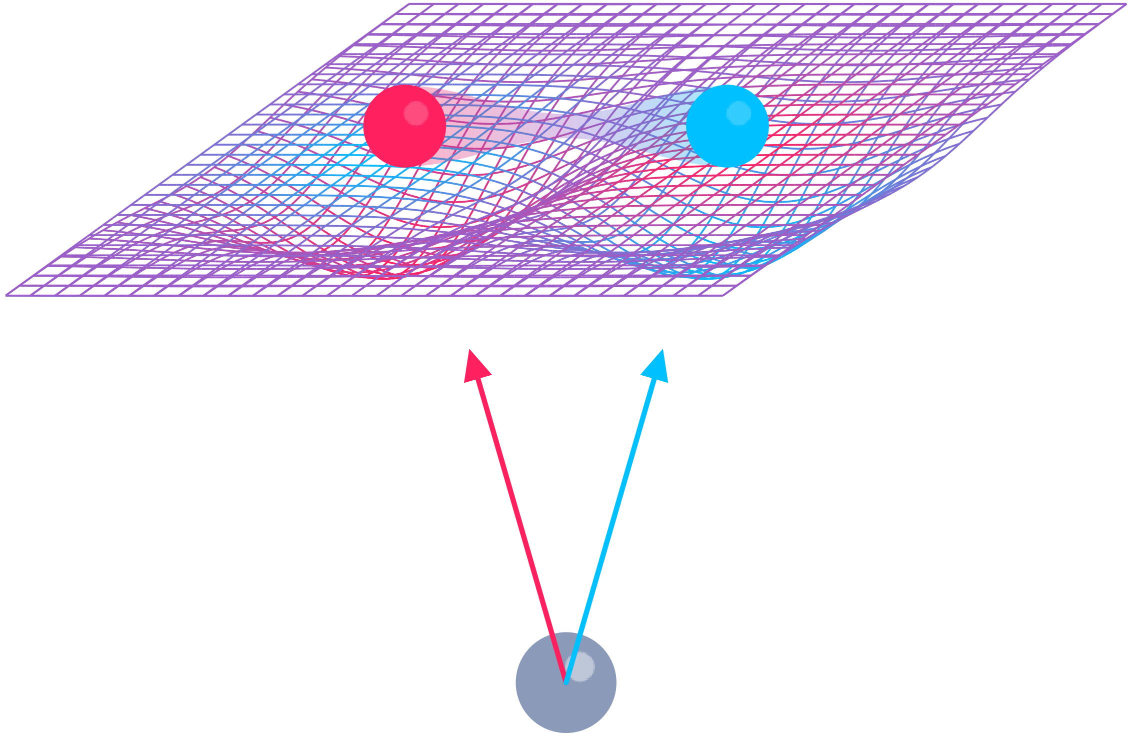
- Can we experimentally probe fundamental questions about gravity with micron-scale particles:

Semiclassical View:



No entanglement, classical potential

Quantum View:



Potential depends on wavefunction, masses entangled

Semiclassical gravity review: Miki et al., PRD 111, 104084 (2025)

Weak field gravity quantized by Bronstein (1936):
Physikalische Zeitschrift der Sowjetunion, 9, 2–3, p140–157 (1936)

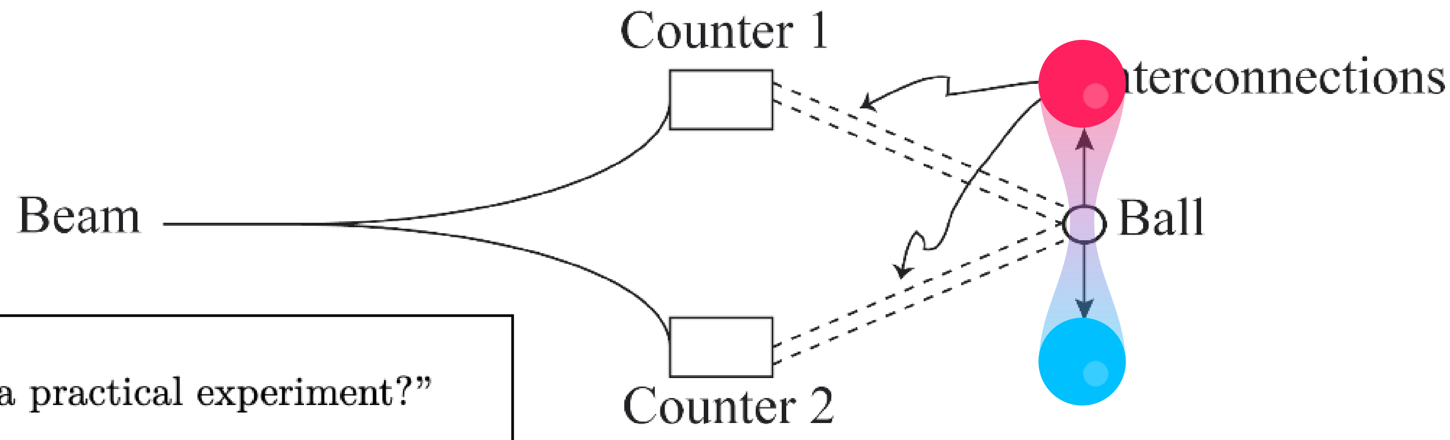
Canonical thought experiment

- As more and more massive systems allow us to control them in quantum states, can we imagine testing this?
  - Long history of considering these sorts of questions, going back at least to the 1957 Chapel Hill Conference

The Role of Gravitation in Physics

Report from the 1957 Chapel Hill Conference

Feynman's thought experiment:



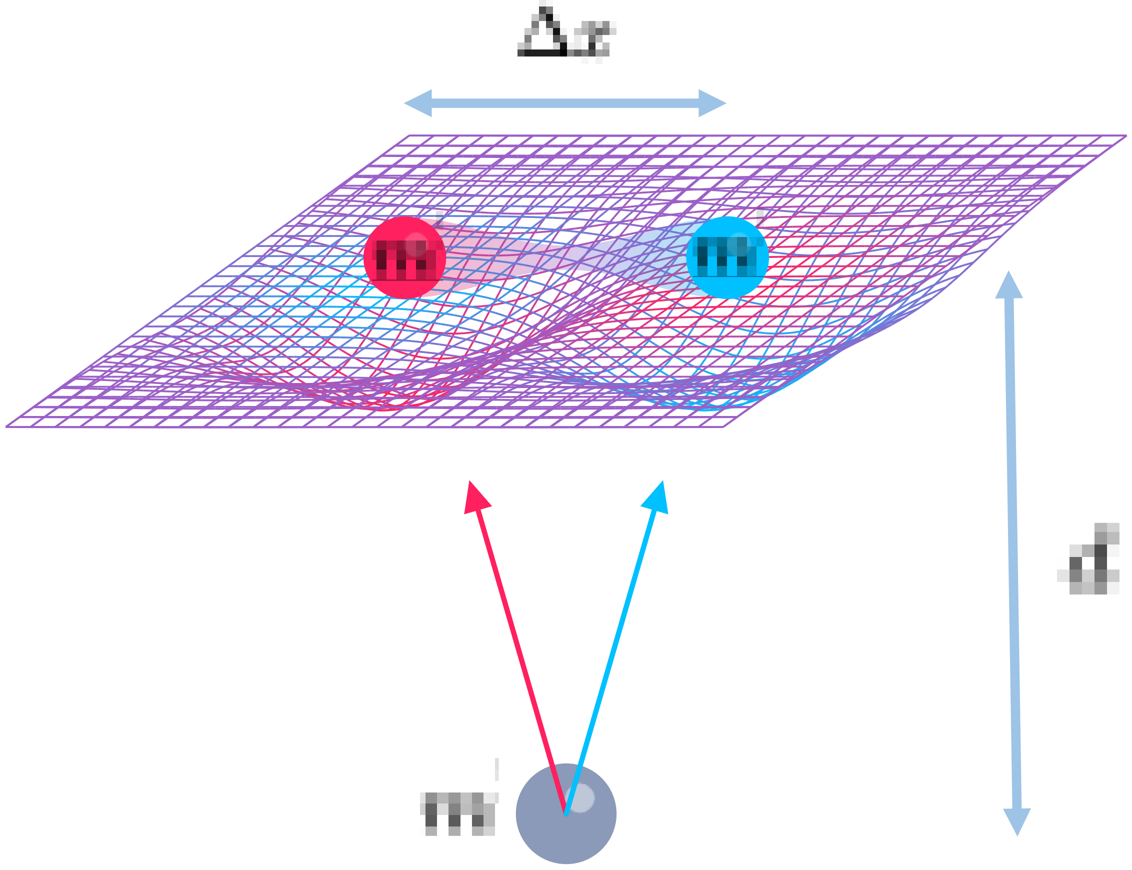
WITTEN: "What prevents this from becoming a practical experiment?"

FEYNMAN: "Well, it's a question of what goes on at the level where the ball flips one way or the other. In the amplifying apparatus there's already an uncertainty - loss of electrons in the amplifier, noise, etc. - so

Decoherence! (and backgrounds)

Key figures of merit

1. Massive objects in quantum states Γ_G
2. Small decoherence Γ_d
3. Small electromagnetic interactions Γ_{EM}



Gravitational potential

Tidal coupling

Gravitational entanglement rate

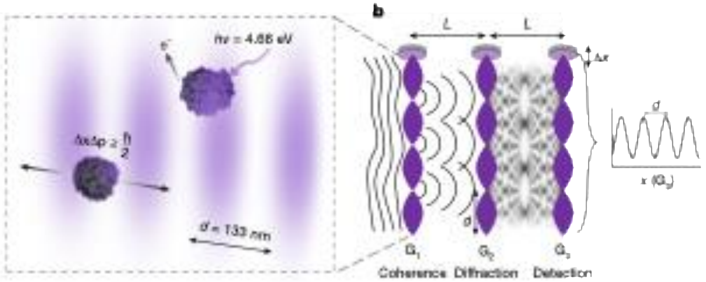
$$\Gamma_G = \frac{1}{\hbar}\frac{Gm^2}{d}\frac{\Delta x^2}{d^2}$$

$$\Gamma_d, \Gamma_{EM} < \Gamma_G$$

Which massive system should we use?

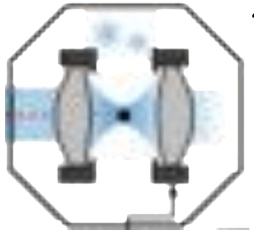
T. Kovachy e.a. Nature 528, 530-533 (2015)

atoms



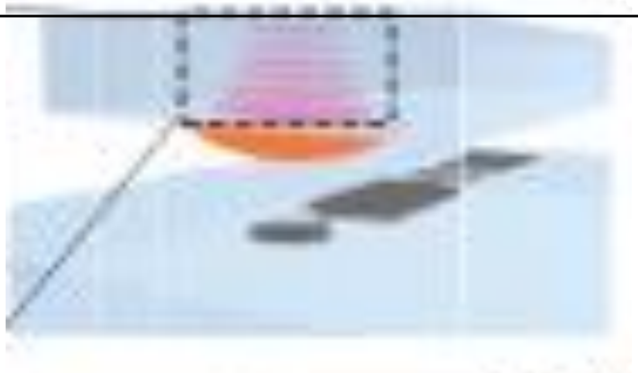
Pedalino, S., … Gerlich, S. *Nature* **649**, 866–870 (2026).

macromolecules, metallic clusters



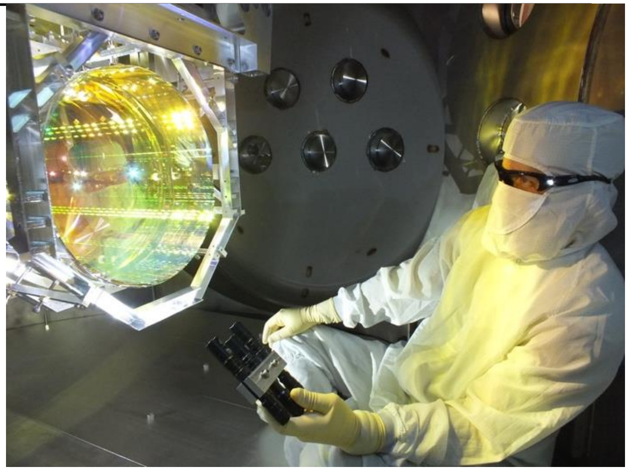
Rossi, M., …, Novotny, L. PRL 135, 083601 (2025)

levitated nanoparticles



Bild, M., … Yang, Y. Science 380, 274-278 (2023)

Solid state acoustics



Whittle, C… Zweizig, J. Science (2021)

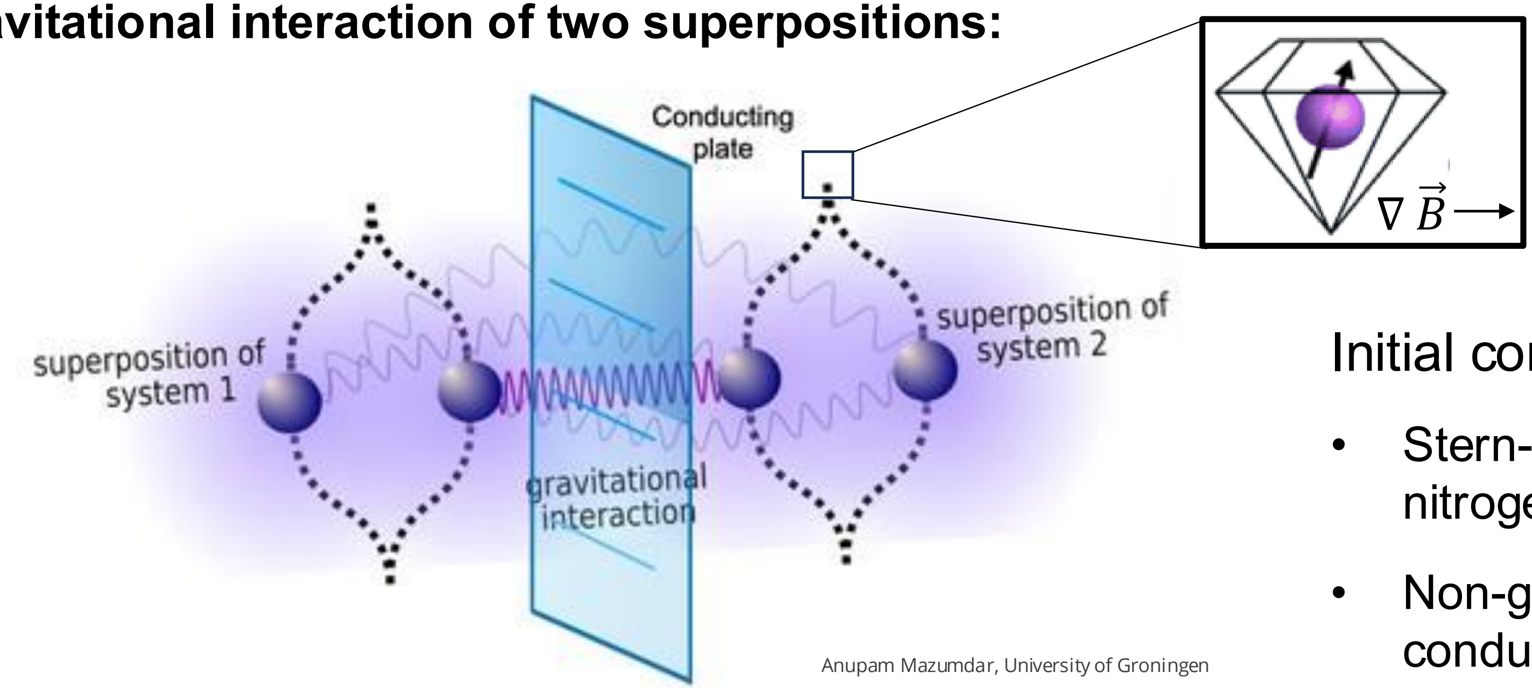
Gravitational Wave Observatories

Δx	0.5 m	1e-7 m	1.2e-10 m	1e-18 m	1e-19 m	delocalization
$\frac{m^2 \Delta x^2}{d^2} \frac{G}{\hbar} \frac{1}{\Gamma_d}$	**1e-12**	**1e-19**	**1e-22**	**1e-18**	**1e-11**	**Fig of merit**
m	9e-26 kg	2.8e-22 kg	1e-18 kg	2e-8 kg	10 kg	mass

Microdiamond concept

- Several recent proposals to realize this type of concept, typically with levitated objects*

Gravitational interaction of two superpositions:

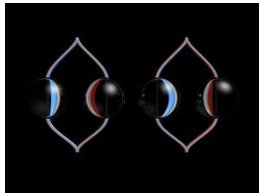


Anupam Mazumdar, University of Groningen

Bose et al. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.240401 (2017)
Marletto and Vedral, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.240402 (2017)

**Also some proposals with tethered ~mm sized masses (MIT, ISTA Austria)*

MAST-QG:
(*Macroscopic Superpositions Towards Witnessing the Quantum nature of Gravity*)



WARWICK THE UNIVERSITY OF WARWICK · Northwestern University · UCL · university of groningen · Yale · GORDON AND BETTY MOORE FOUNDATION · ALFRED P. SLOAN FOUNDATION

Initial concept:

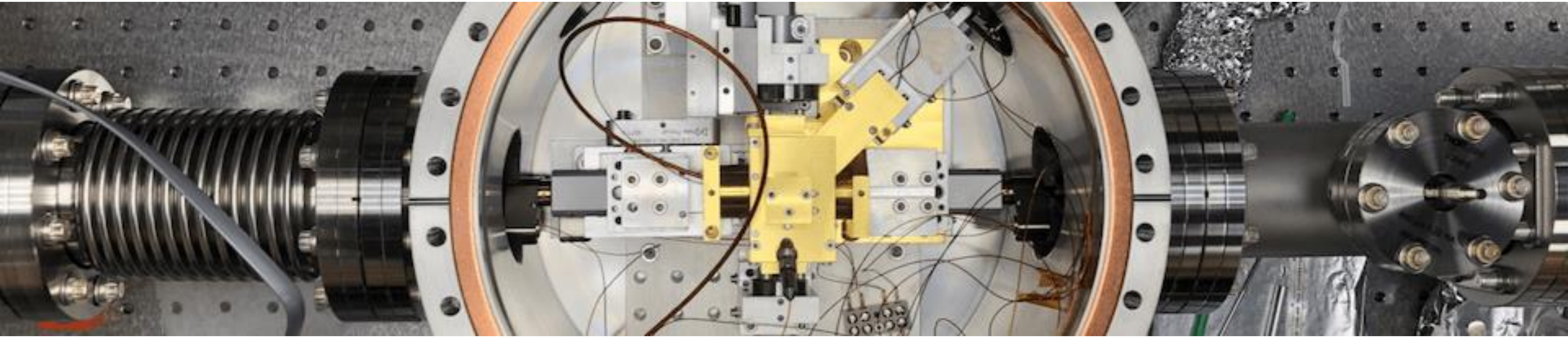
- Stern-Gerlach interferometer using single nitrogen-vacancy center in a nanodiamond
- Non-gravitational interactions shielded by conducting sheet
- Conceptual experimental parameters:
  - Particle mass $\approx$ 10 pg (μm diameter)
  - Superposition size $\approx$ 50 μm
  - Particle separation $\approx$ 30 μm

Summary

- Optomechanical systems are revolutionizing how we measure tiny forces and accelerations acting on masses in the lab

- Many weakly interacting phenomena of interest in fundamental physics may produce such forces

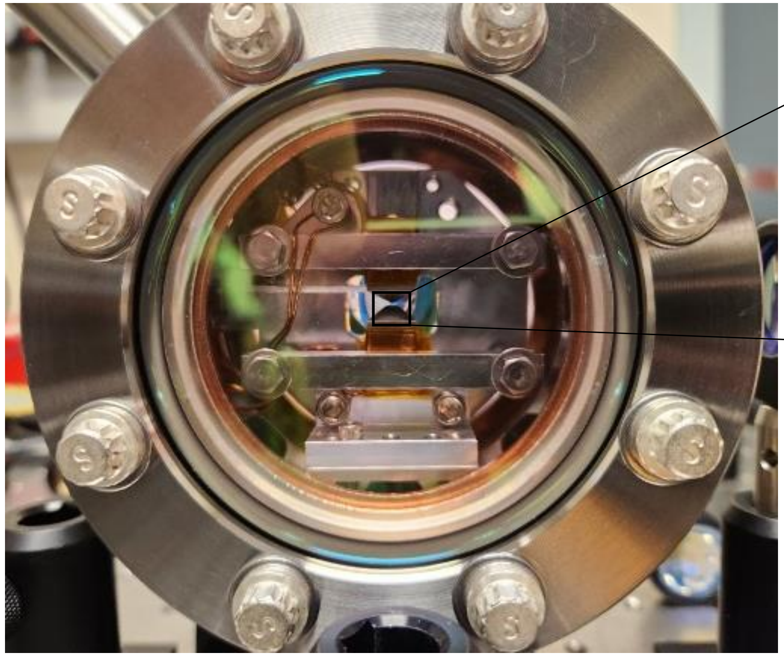
- A wide variety of new systems are currently under development, with applications to weakly interacting phenomena such as dark matter, neutrinos, and gravity



Diamagnetic trap for microdiamonds

- Have developed hybrid magnetic/optical trap for nano- and micro-diamonds based on design by Brian D'Urso's group (MSU)
- Diamagnetic trapping with optical readout and control, allowing multiple diamonds to be co-trapped

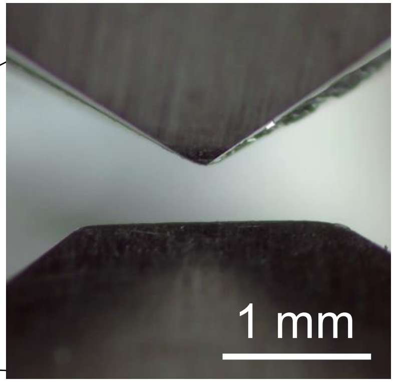
Photo of trapping chamber:



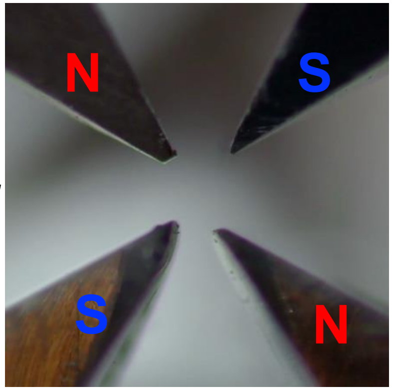
Trap design based on: Sci Rep 6, 30125 (2016), [B. D'Urso group]

Zoom to trap:

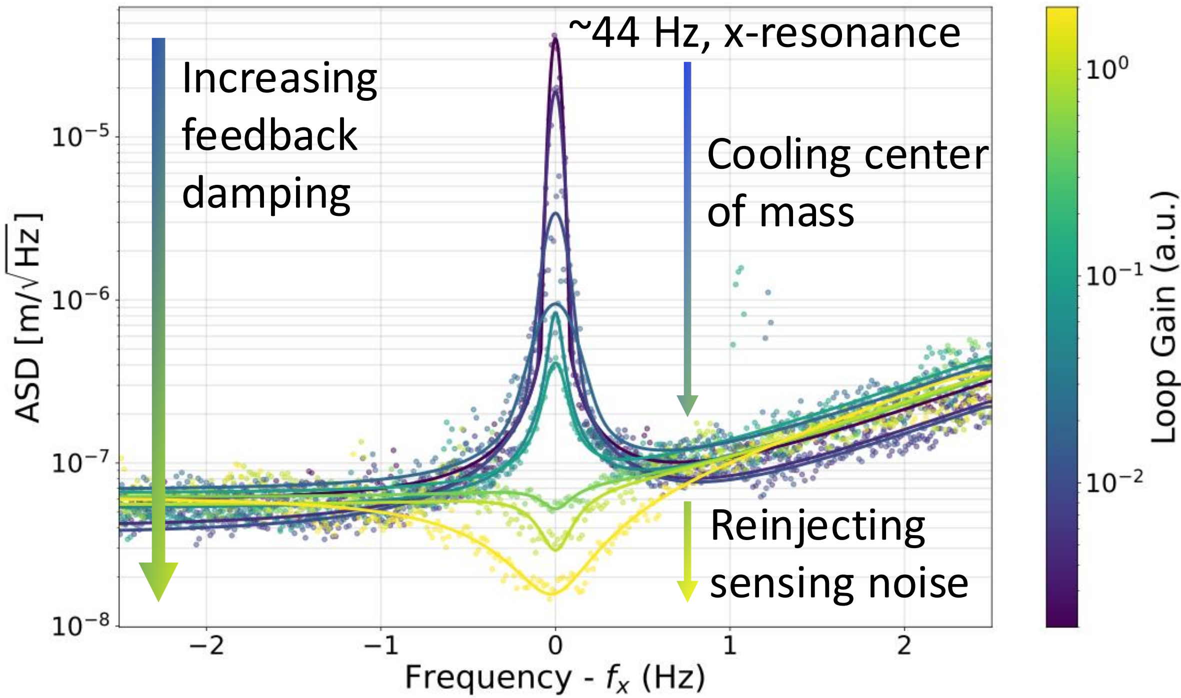
Front view:



Side view:



Feedback cooling to sub-K temperatures:



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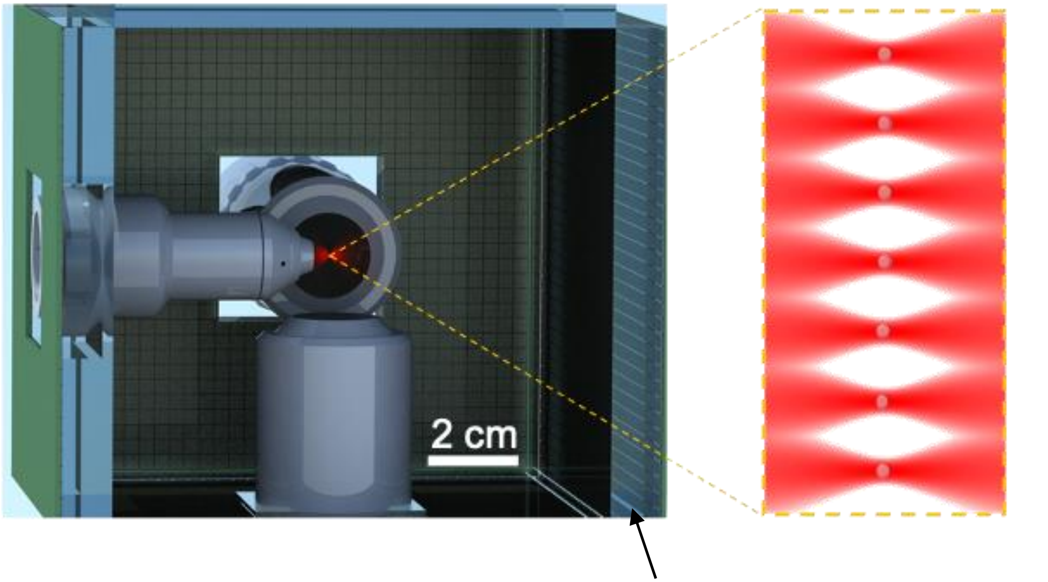
Plots and figures from A. Markowitz

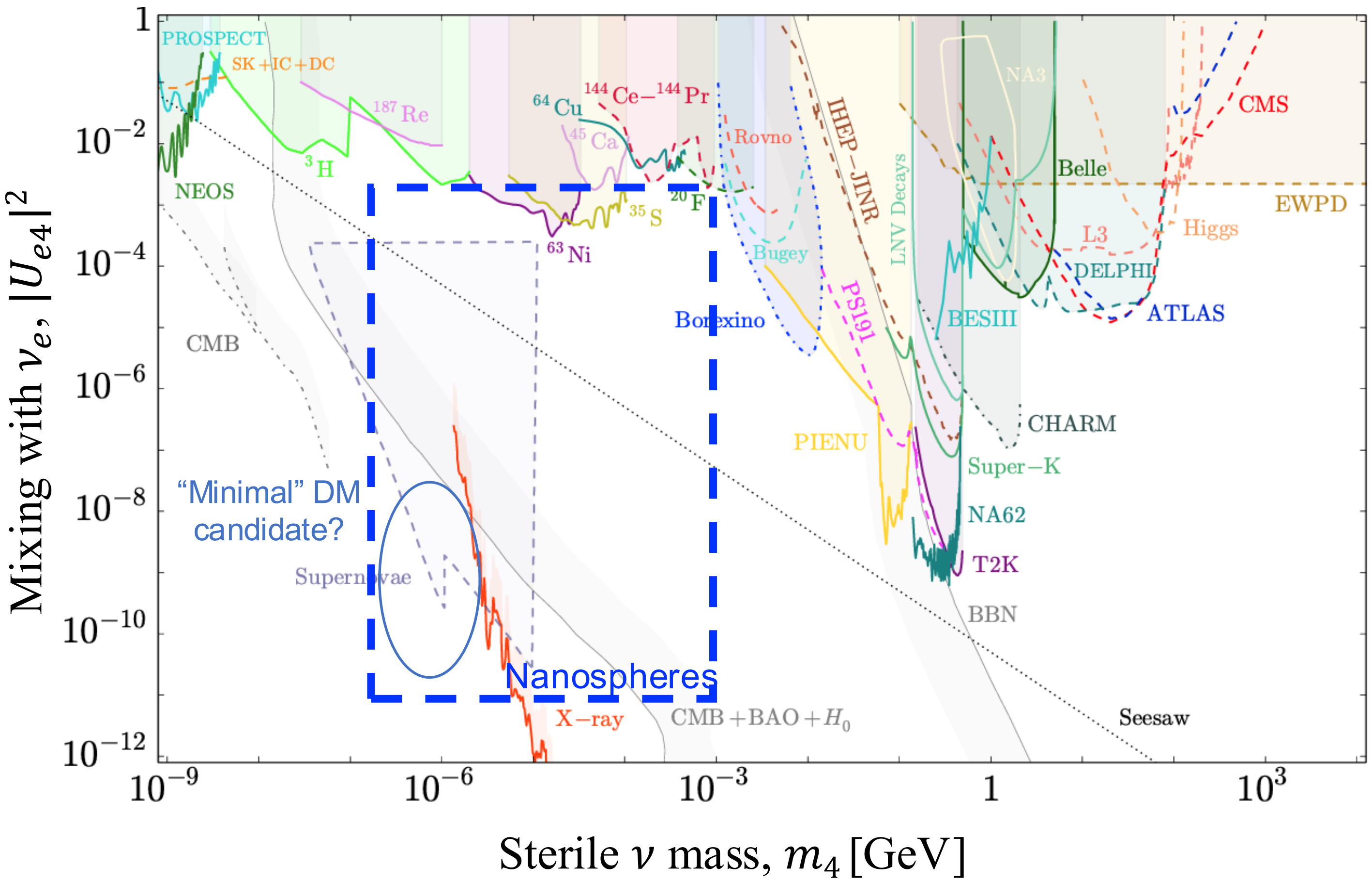
Sterile ν

- Search for keV-MeV steriles by reconstructing recoil momentum in weak decays
- If sterile mixes with ν_e, would observe "wrong momentum" in fraction $|U_{e4}|^2$ of decays
- Surround array of spheres with position sensitive detectors to reconstruct β momentum

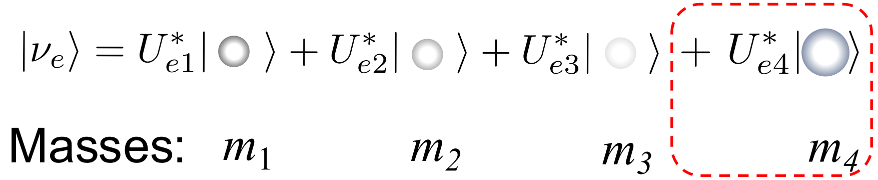
Detector concept:



Experimental limits on sterile ν mixing with ν_e:



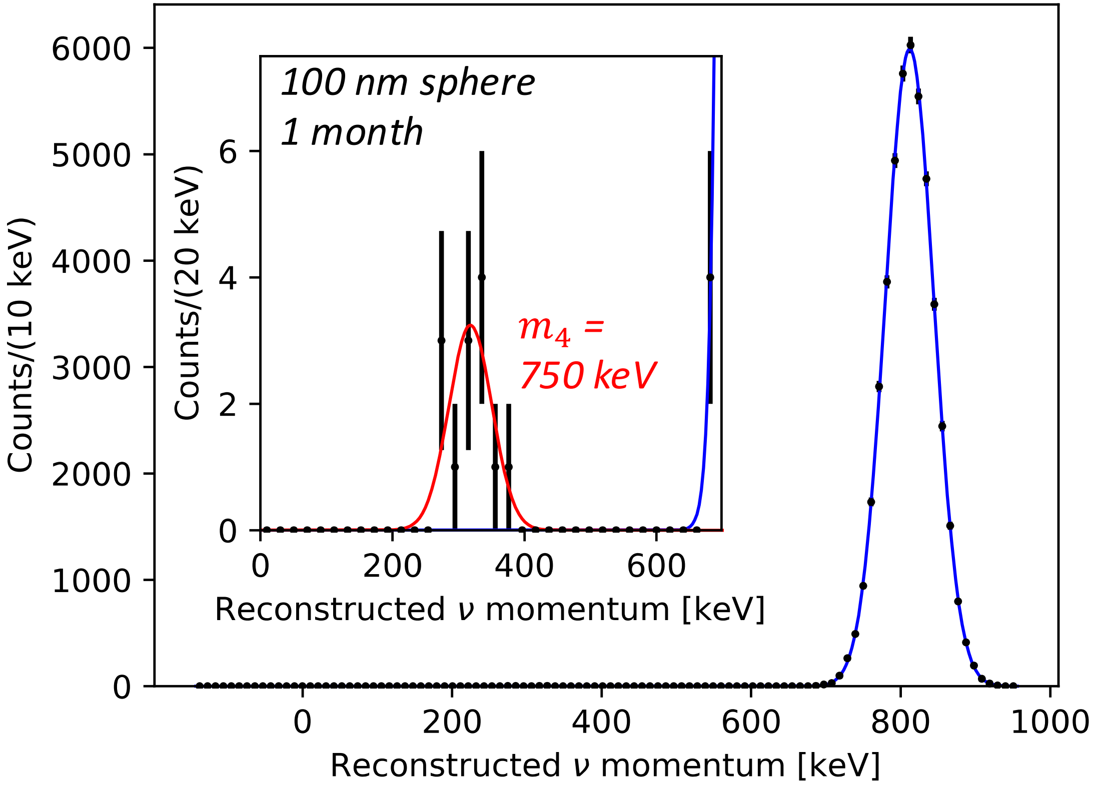
Bolton et al., JHEP 2020, 170 (2020), arXiv:1912.03058



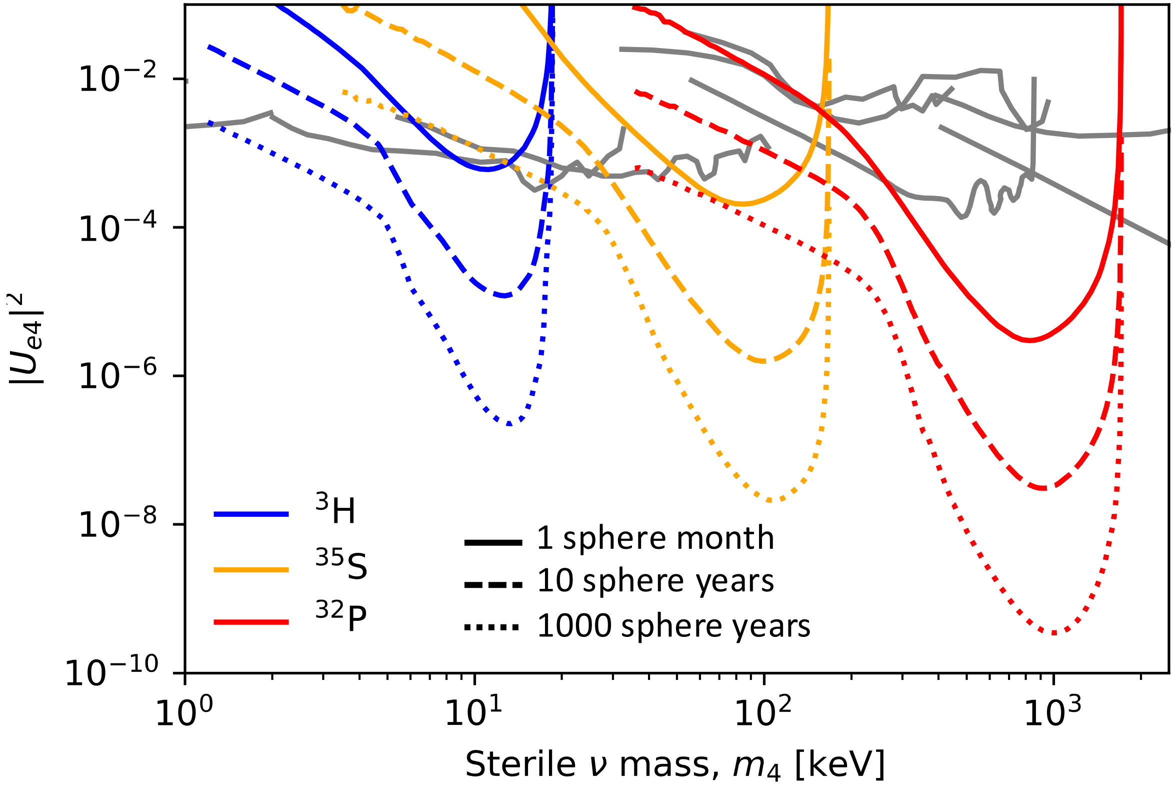
Projected sensitivity

- If a keV – MeV mass sterile ν mixes with the light ν, then expect small fraction of decays to emit a heavy ν
- Possibility to probe many orders of magnitude beyond best existing experiments with mechanical sensors

Example electron capture decay (^{37}Ar):



Projected sensitivity versus livetime:



PRX Q 4, 010315 (2023) arXiv:2207.05883