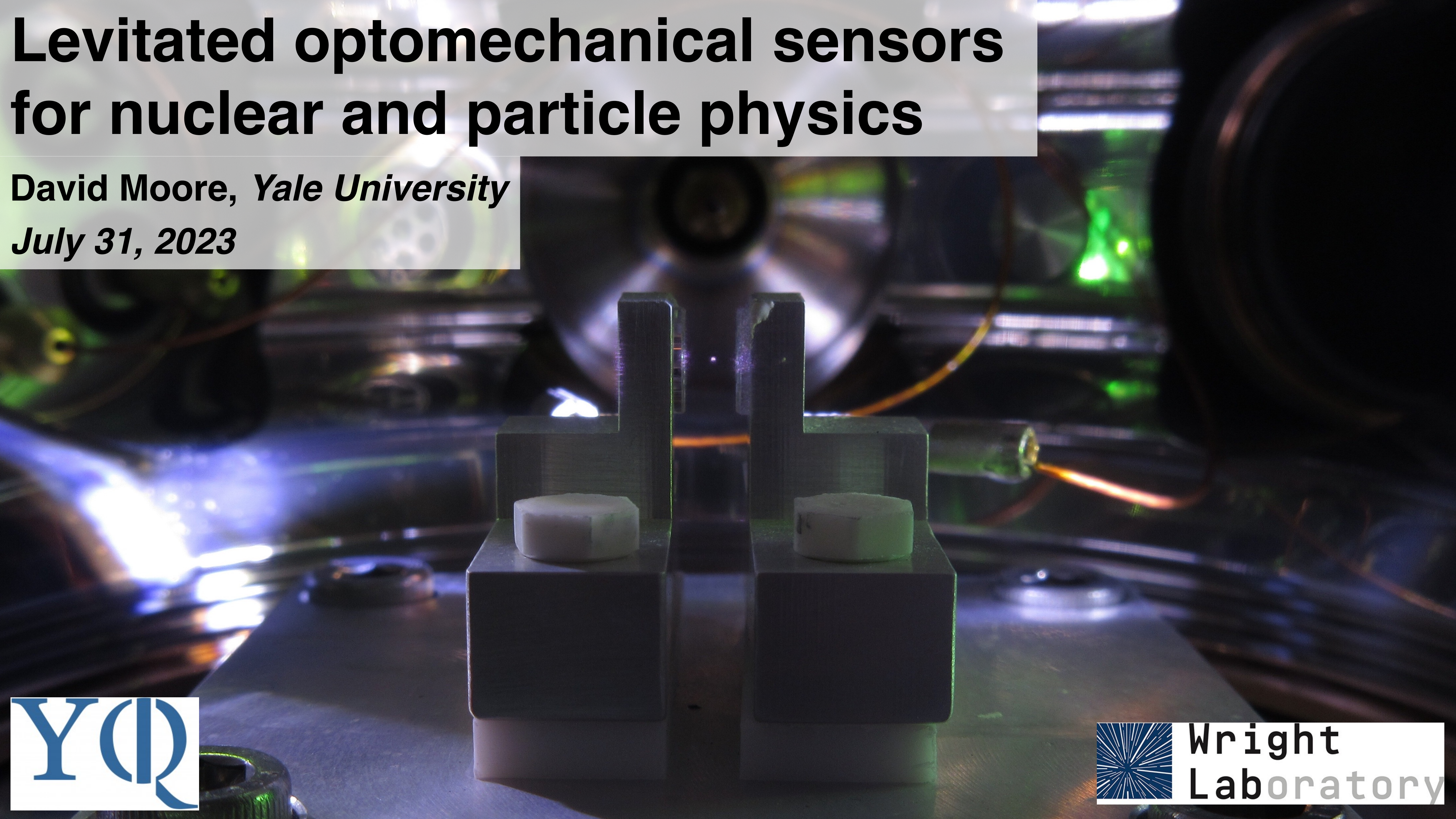
Levitated optomechanical sensors for nuclear and particle physics

David Moore, ***Yale University***

July 31, 2023

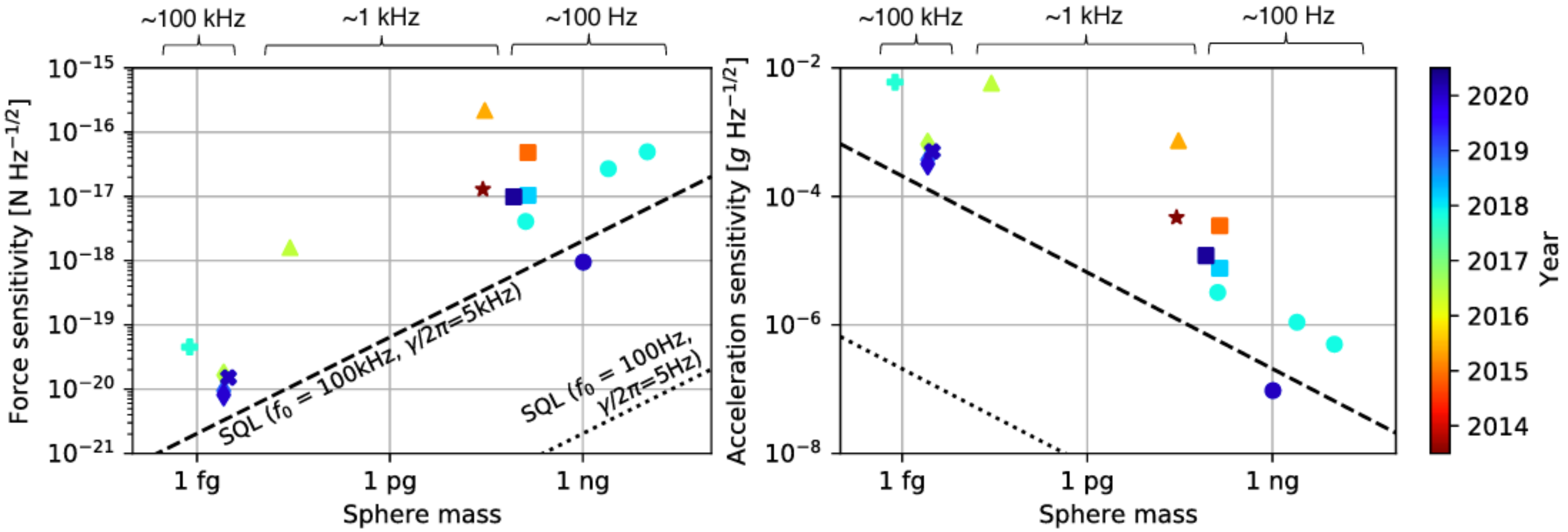


Wright Laboratory

Optical trapping (1 fg – 30 ng)

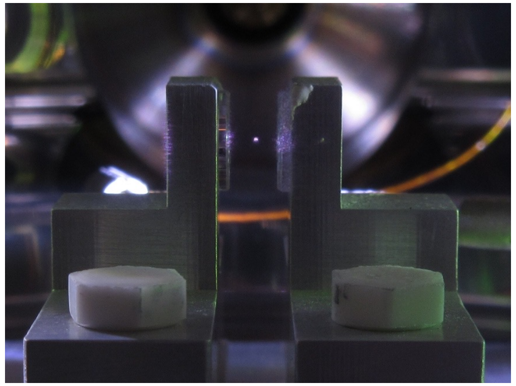
- Nano- to micro-sized dielectric masses can be optically trapped over a wide range of masses
- Forces sensitivities at the zN/$\sqrt{\text{Hz}}$ (~100 nm particles) to aN/$\sqrt{\text{Hz}}$ (~10 μm particles) scale
- In high vacuum, masses are isolated thermally and electrically

Force sensitivity vs sphere mass: **Acceleration sensitivity vs sphere mass:**

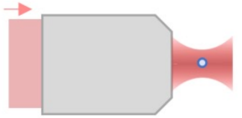


DCM and A. Geraci, Quantum Sci. Technol. 6 014008 (2021), arXiv:2008.13197

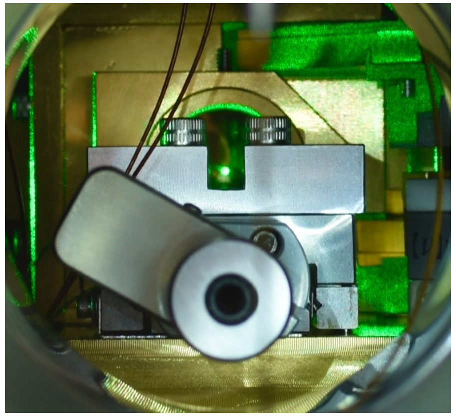
Examples of trapped nano/micro particles at Yale:

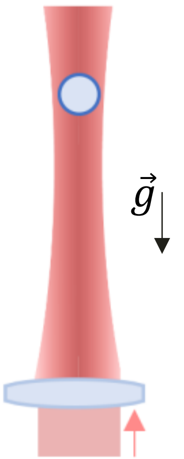


Tightly focused tweezers (~0.1 – 1μm):
~1 fg – 1 pg

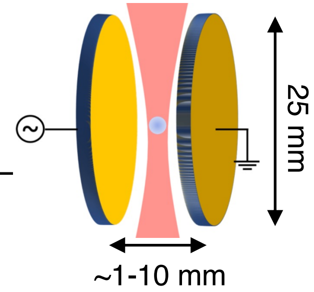


Levitation trap (~1 – 30 μm):
~1 pg – 30 ng

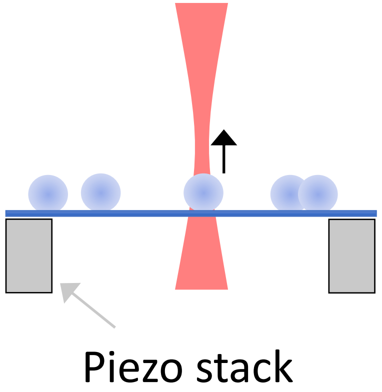


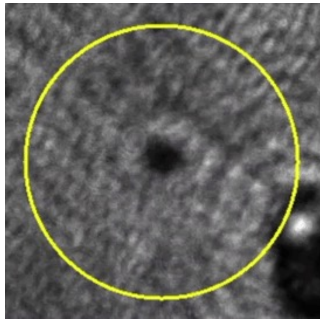


Experimental sequence (>μm spheres)



Step 1: Trap sphere (~1 mbar)

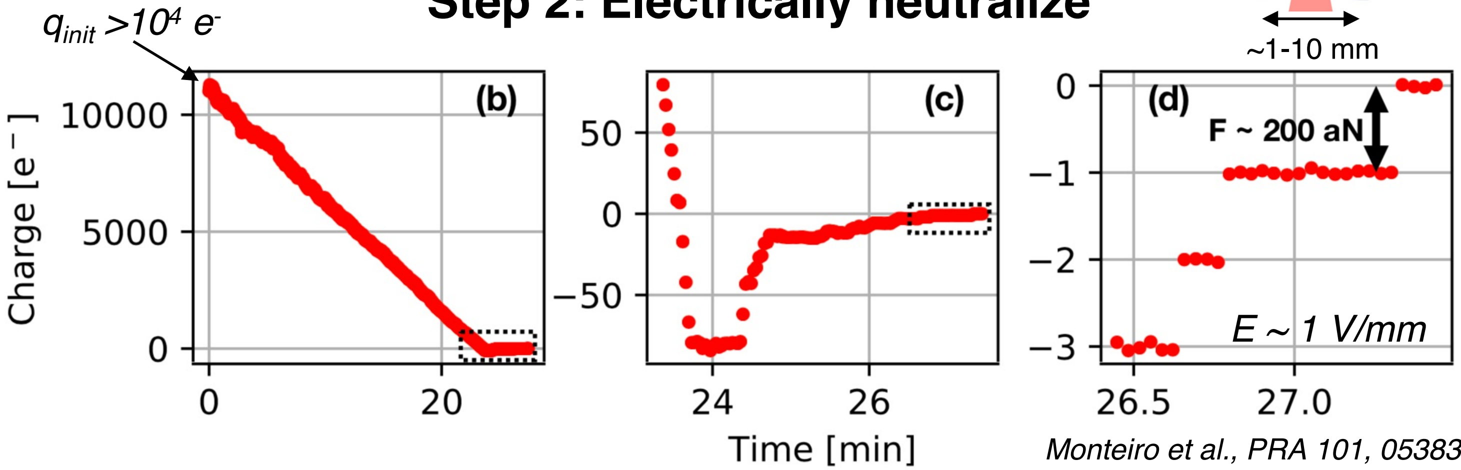




Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)

Pump to
≲10^{-7} mbar

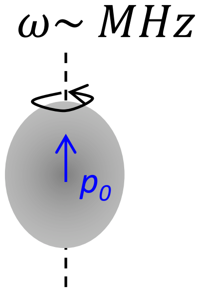
Step 2: Electrically neutralize

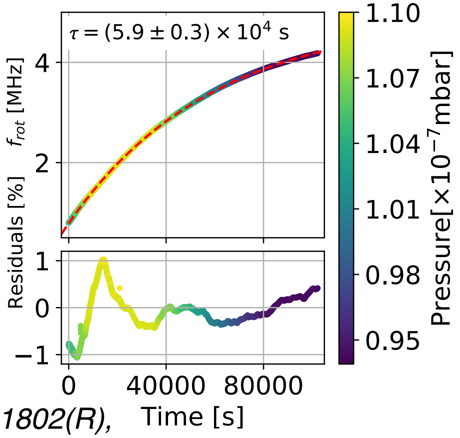


Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)

Step 3: Stabilize spin

Optically spin to >MHz frequency

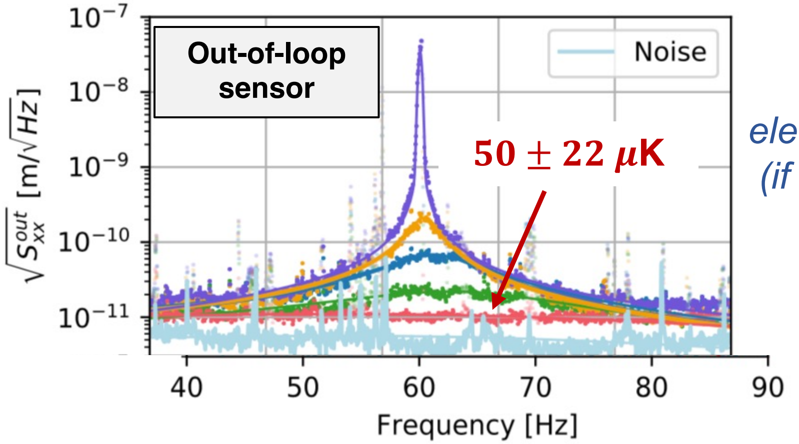




Monteiro et al., PRA 97, 051802(R), arXiv:1803.04297 (2018)

Active feedback cooling to <100 μK

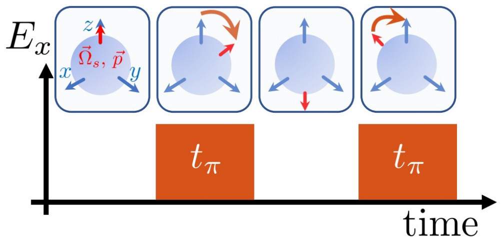
Step 4: Cool center-of-mass mode



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)



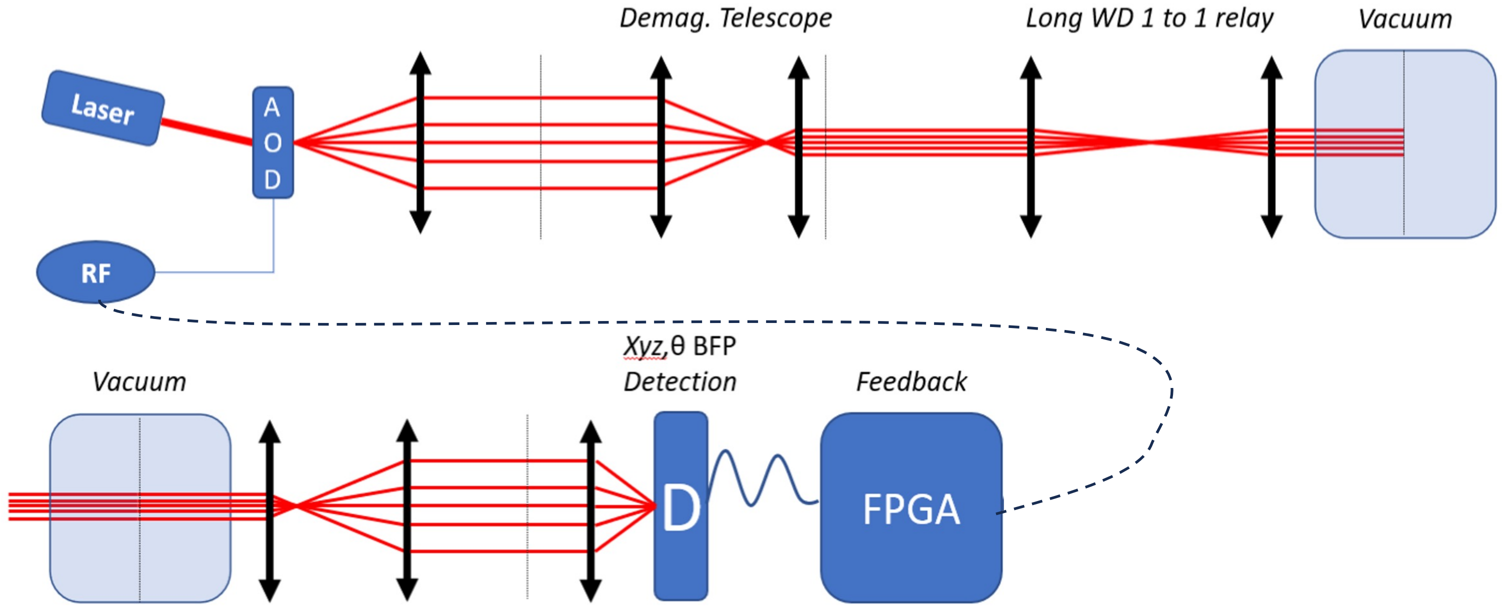
Afek et al., PRA 104, 053512, arXiv:2108.04406 (2021)

Microsphere arrays

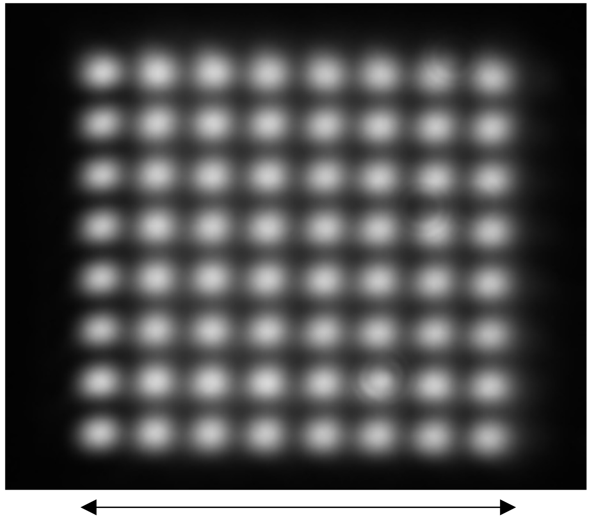
- Microsphere trap has been upgraded with high power laser (100 W) to allow up to ~10 x 10 arrays
- FPGA code developed for time/frequency multiplexing of RF signal driving AOD
  - Low trap frequencies (~100 Hz) permit time multiplexing which simplifies near term implementation

Trapping schematic:

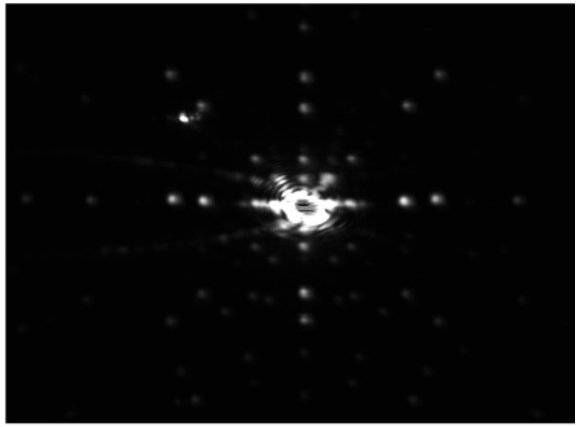
Detection schematic:



8x8 array of traps (laser only):



Time sharing of multiple traps:



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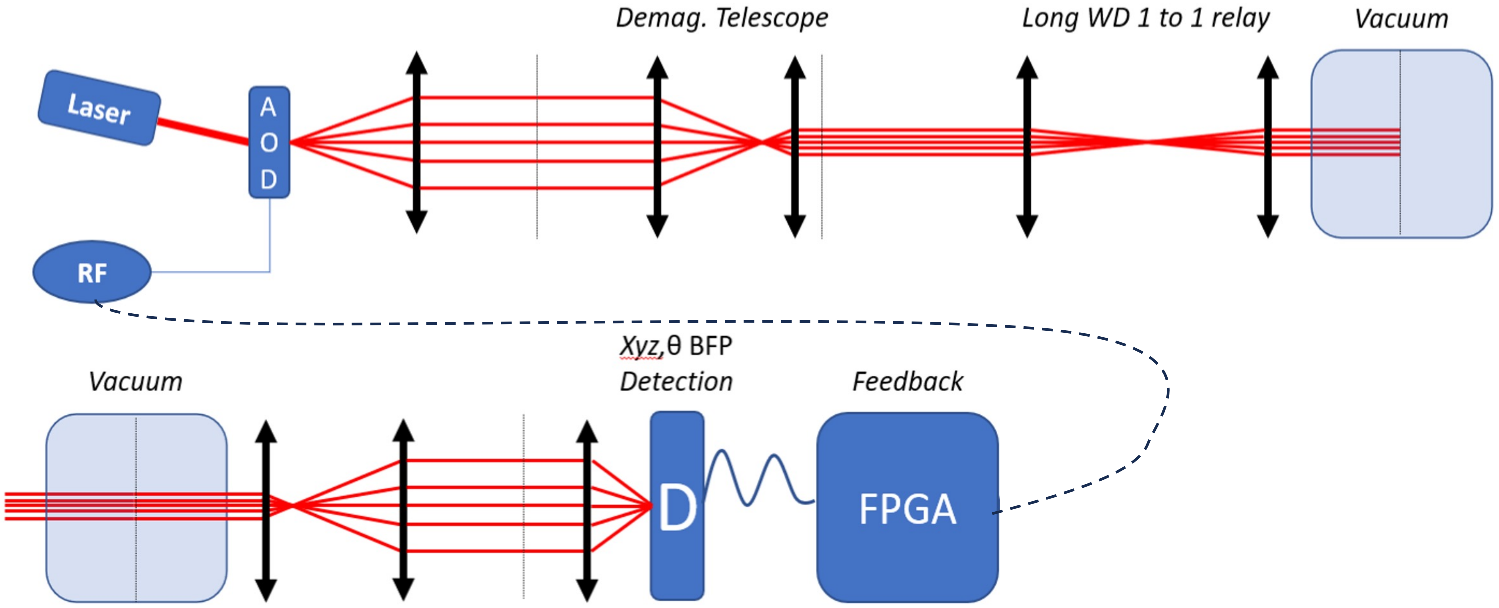
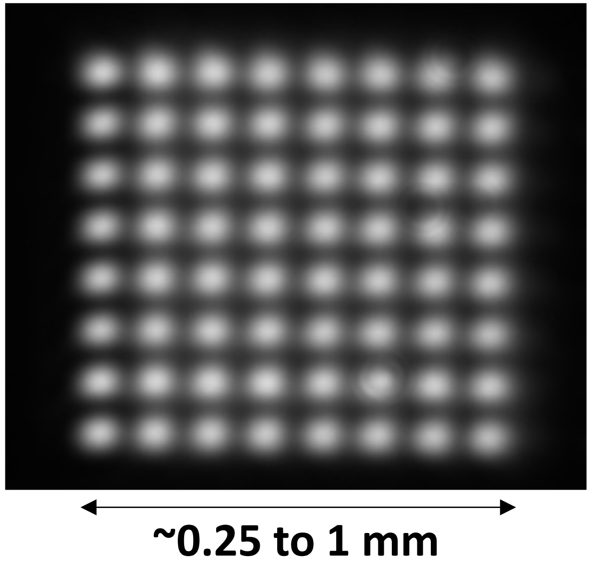
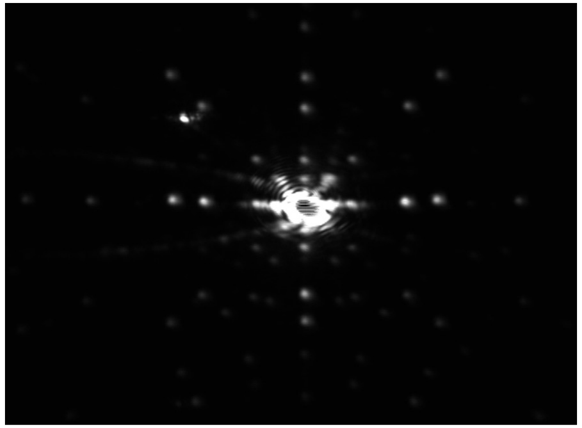


8x8 array of traps (laser only):



Time sharing of multiple traps:

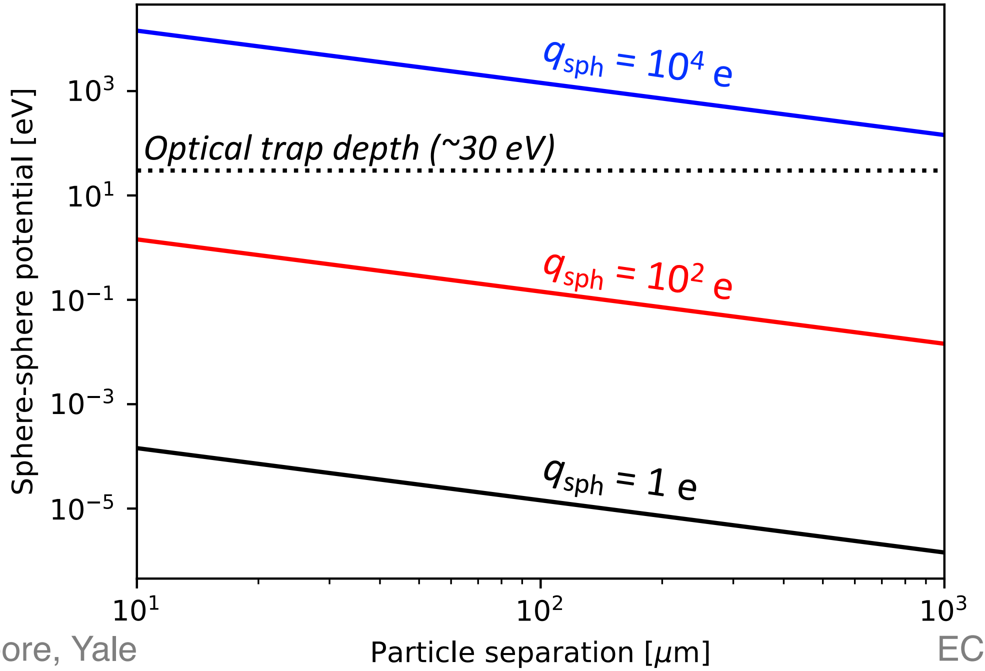


Array loading

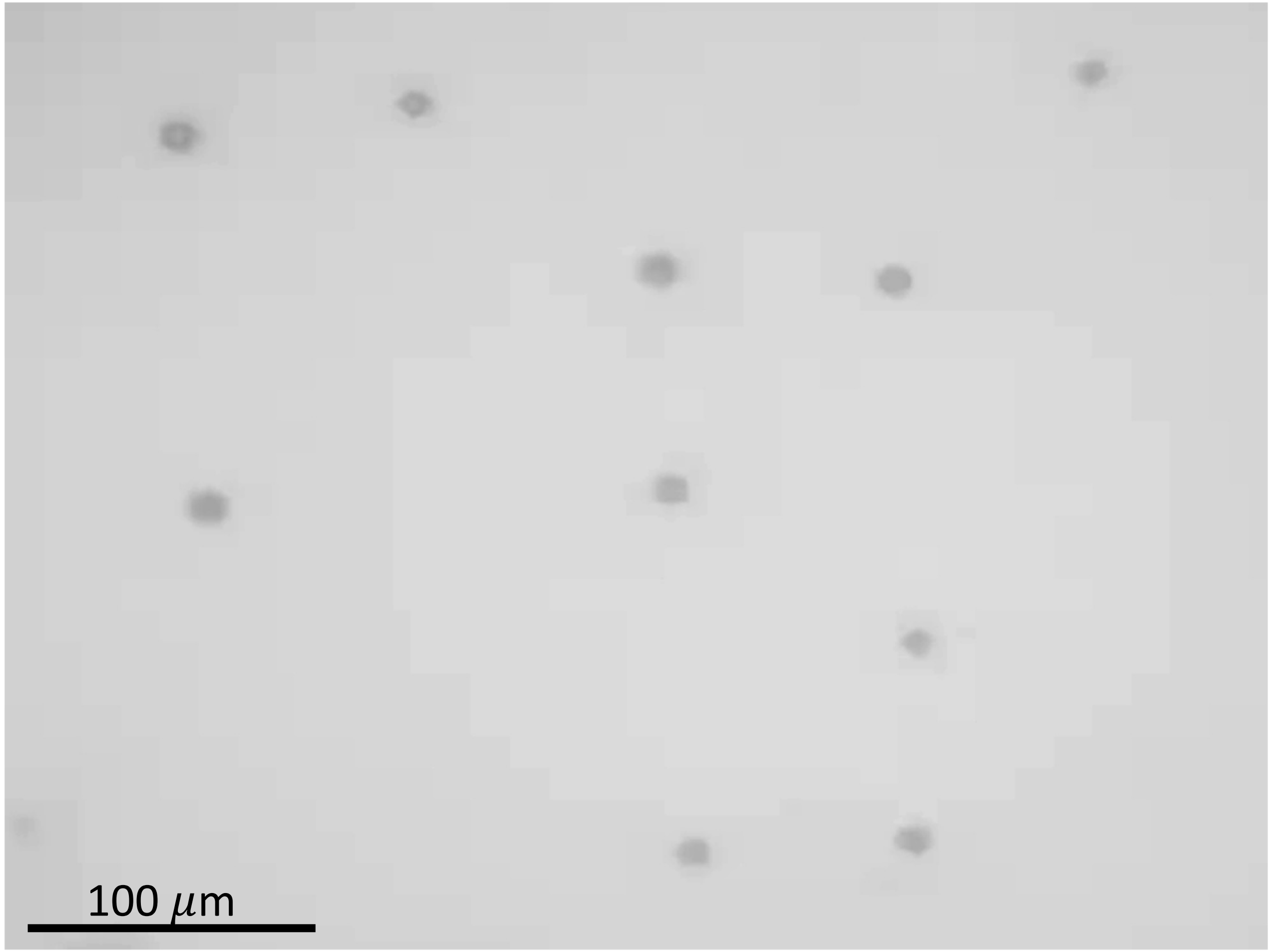
- Coulomb forces between spheres can make loading a dense array challenging
- Loading of ~10 element arrays is possible with our standard loading techniques
- Still working to improve loading efficiency

→ Neutralize first then move into array

Coulomb potential vs separation:



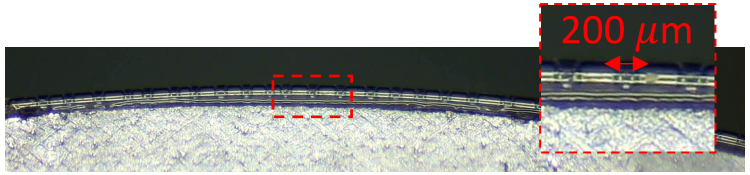
Example of array loading (10 μm spheres @ ~1 mbar):

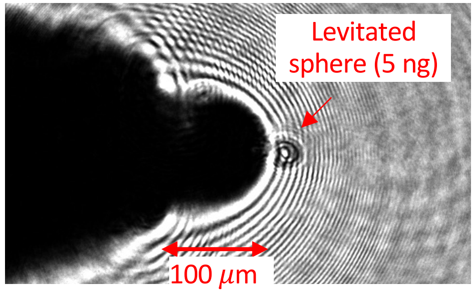


Applications to fundamental physics

- **Searches for "fifth forces":**
  - Tests of Newton's law

    -> See previous talk by Giorgio Gratta
  - Tests of Coulomb's law

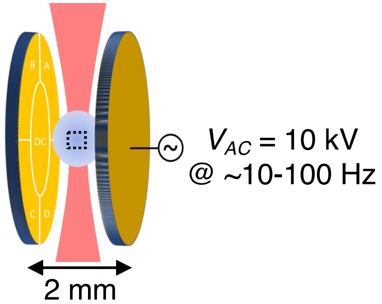


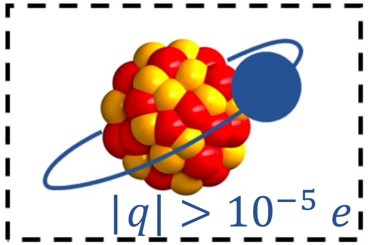


See also: PRL 117, 101101, arXiv:1604.04908 (2016)

- **Neutrality of matter**:
  - Millicharged dark matter particles

    Afek et al., Phys. Rev. D 104, 012004 (2021), arXiv:2012.08169
  - Charge quantization





*See also: PRL **113** 251801, arXiv:1408:4396 (2014)*

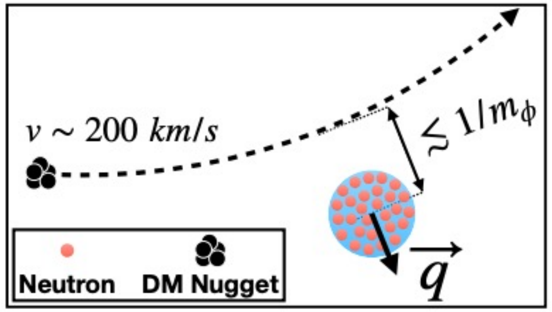
- **Detection of small impulses:**
  - Nuclear recoils from α/β decays

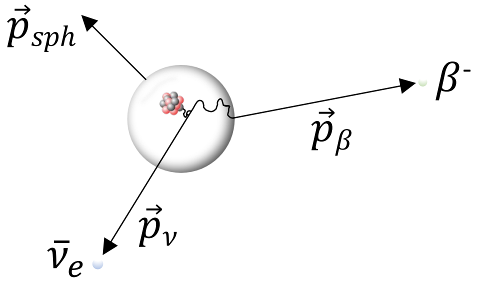
    D. Carney, K. Leach, and DCM, PRX Quantum *4*, 010315 (2023), arXiv:2207.05883
  - Kinematic detection of dark matter

    Monteiro et al., Phys. Rev. Lett. 125, 181102 (2020), arXiv:2007.12067

    Carney et al., Phys. Rev. Lett. 127, 061804 (2021), arXiv:2104.05737

    Afek et al., Phys. Rev. Lett. 128, 101301 (2022), arXiv:2111.03597



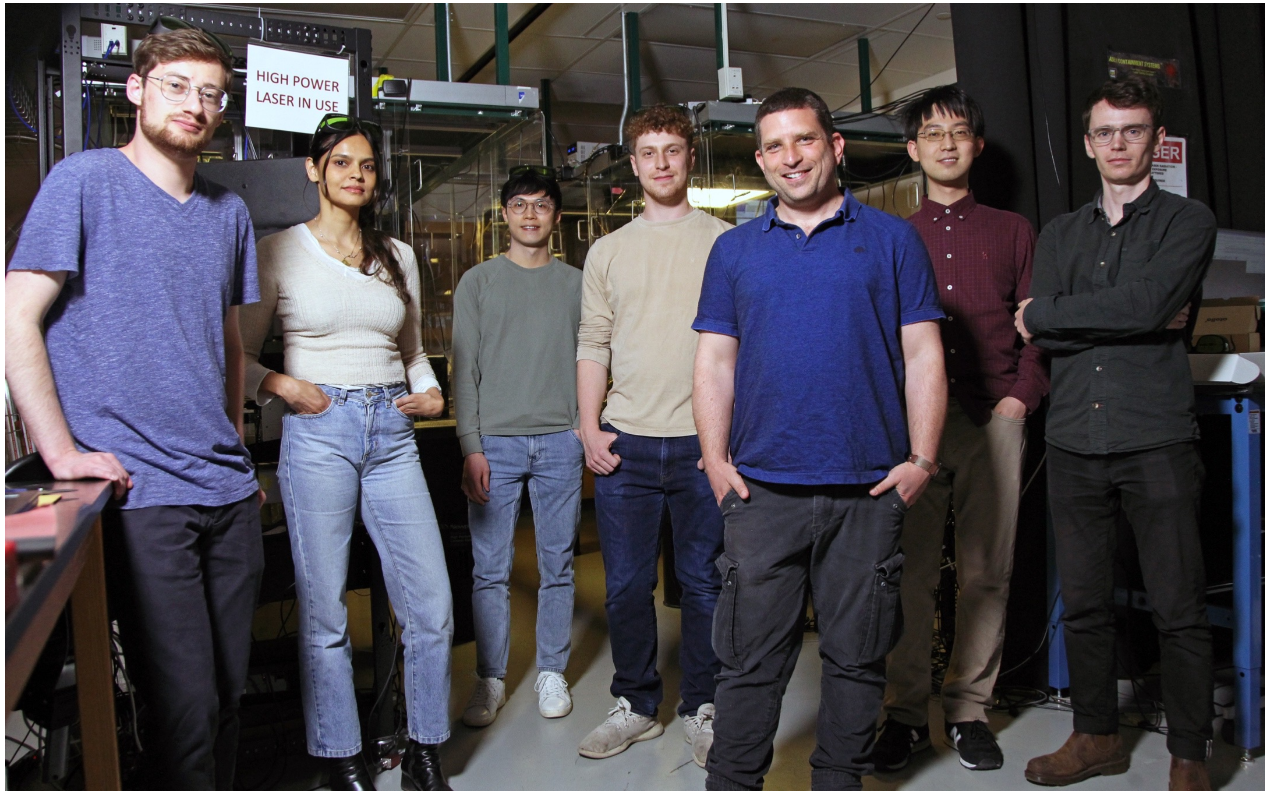


*See also: Malyzhenkov et al., PRA **98**, 052103 (2018)*

The SIMPLE team at Yale:

(Search for new Interactions in a Microsphere Precision Levitation Experiment)

Imam Mian
David Moore
Tom Penny
Ben Siegel
Yu-Han Tseng
Jiaxiang Wang
Molly Watts



Wright Laboratory

YQ

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ONR
Science & Technology

U.S. DEPARTMENT OF
ENERGY
Office of Science

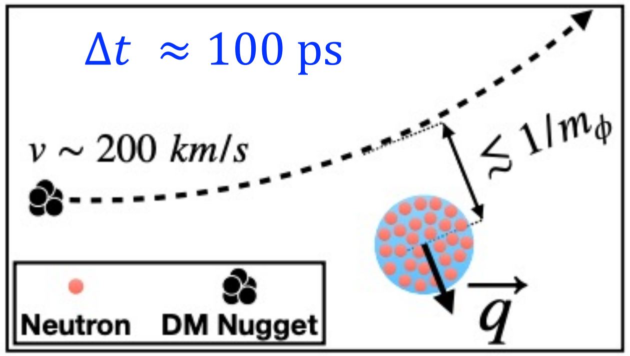
Impulse detection

- Signals of interest here are momentum impulses (i.e. essentially instantaneous forces):

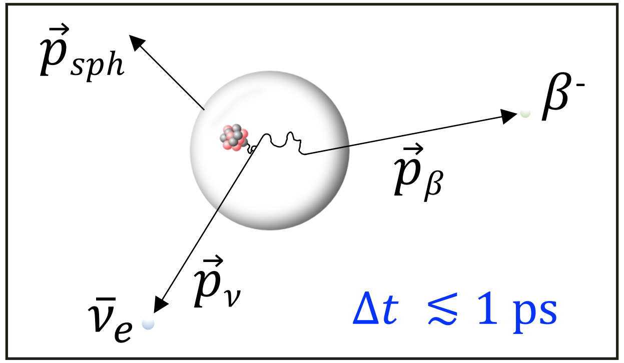
$$\Delta p = F\Delta t, \qquad \text{for interaction time } \Delta t \ll 1/\omega_0$$

Examples:

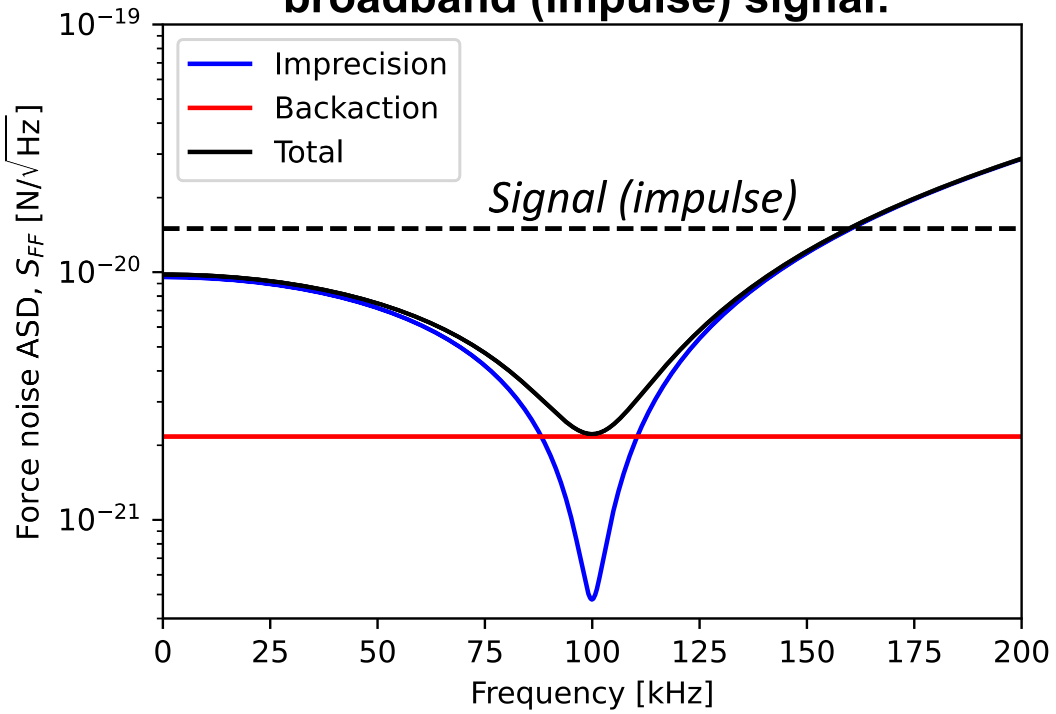
Dark matter scattering:



Nuclear decays:



Schematic of measurement noise for a broadband (impulse) signal:



"Standard quantum limit" for an impulse:

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

See, e.g., A. Clerk, PRB 70, 245306 (2004)

$\Longrightarrow$ 0.5 MeV/c (1 ng @ 100 Hz)

└→ 10 μm sphere

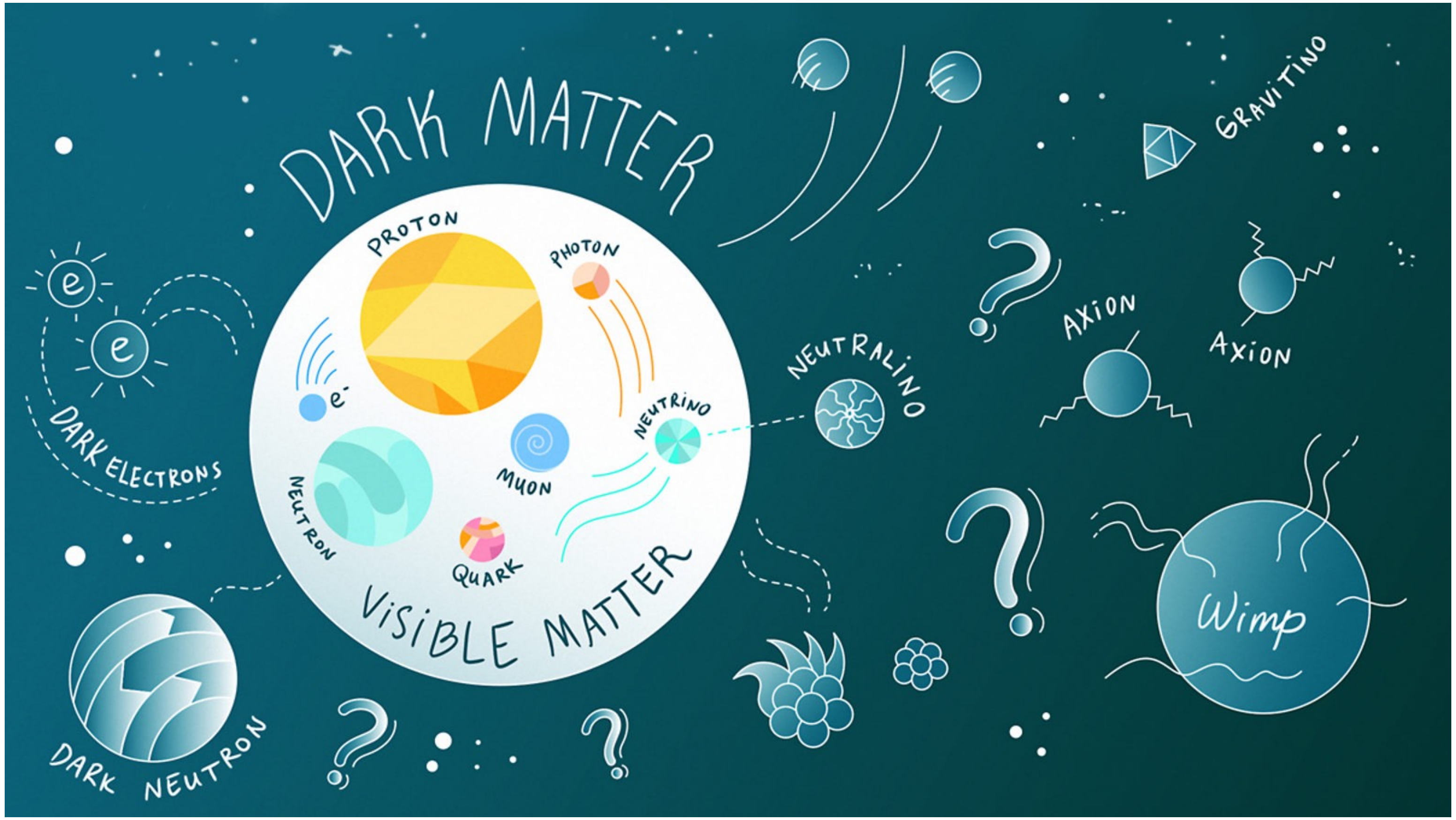
15 keV/c (1 fg @ 100 kHz)

└→ 100 nm sphere

For a non-unity detection efficiency, η:

$$\Delta p \lesssim \eta^{-1/4}(\Delta p)^{SQL}$$

Dark matter

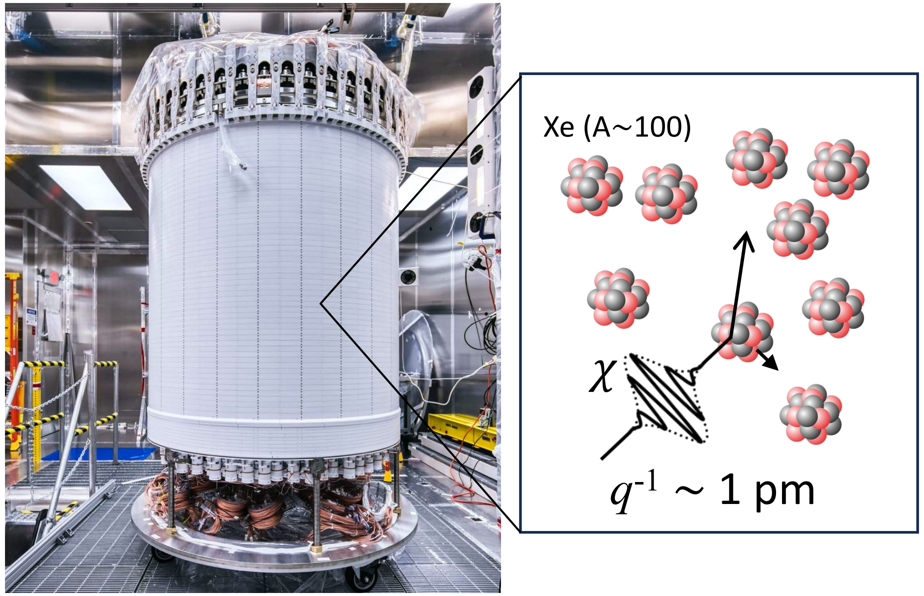


https://www.symmetrymagazine.org/article/december-2013/four-things-you-might-not-know-about-dark-matter

Kinematic detection of (particle) dark matter

- While the momentum sensitivity is sufficient to detect dark matter scatters, the rate of scatters can be very small
- Most sensitive to dark matter models that primarily interact coherently with entire objects

Ton-scale WIMP detectors (e.g. LZ, XENON, PandaX):

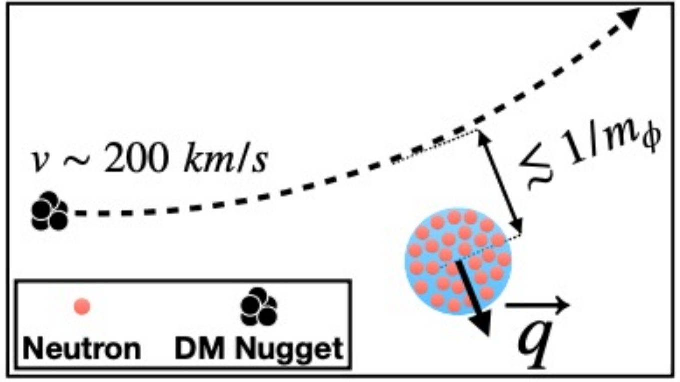


Coherence only over a single nucleus:

$$\text{Rate} \propto \underset{\gg 10^{23}}{\underset{\nearrow}{N_T}}\,\underset{\sim 10^{4}}{\underset{\nwarrow}{A^2}}\,\sigma_n$$

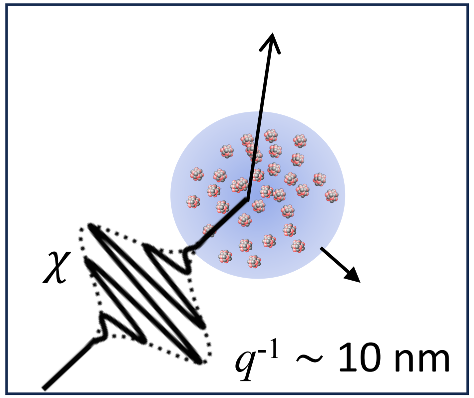
fg-ng scale trapped objects:

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:

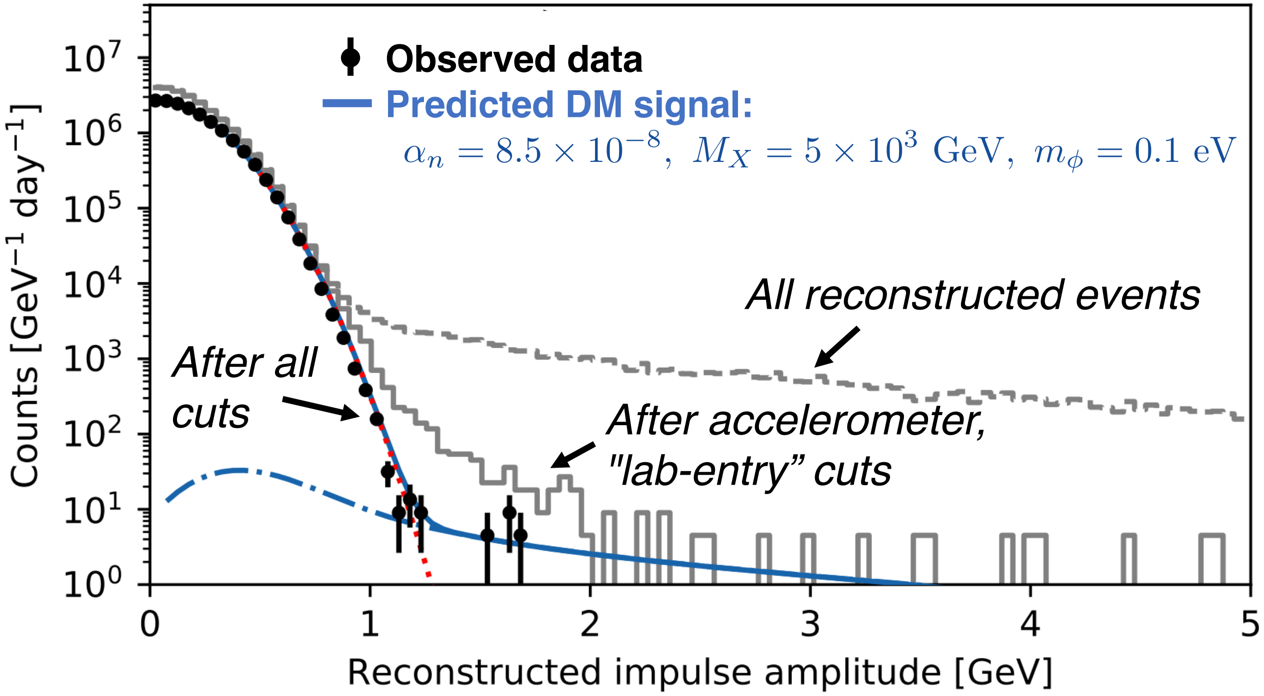
$$\text{Rate} \propto \underset{\sim (10^9)^2 \text{ to } (10^{14})^2}{\underset{\nearrow}{(N_T)^2}}\sigma_n$$

Can rival Avogadro's number!

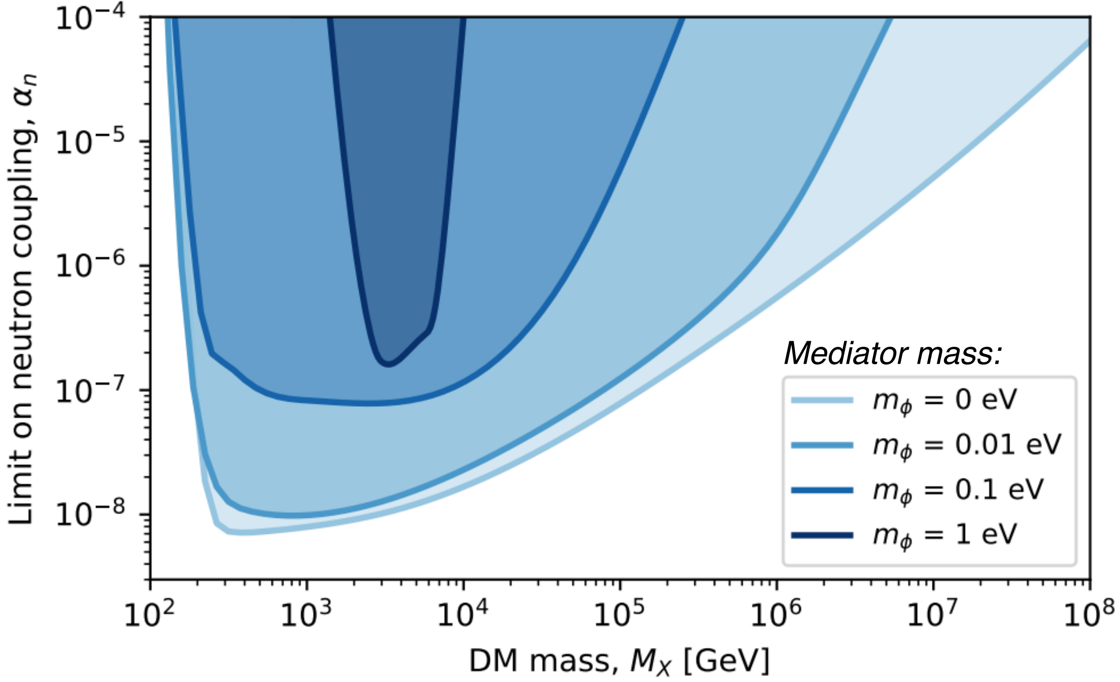
Dark matter search (long range force)

- Acquired 5 days of dark matter search data in June 2020, four candidate events remain in non-Gaussian tail of distribution after all cuts
- Conservatively set limits on neutron coupling assuming candidates could arise from DM

Measured spectrum of impulses:



Limits on generic DM-neutron coupling:

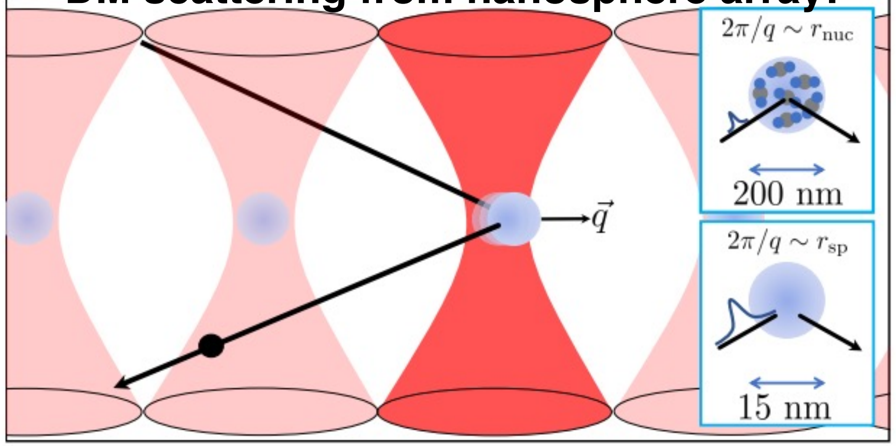


Monteiro et al., PRL 125, 181102 (2020), arXiv:2007.12067

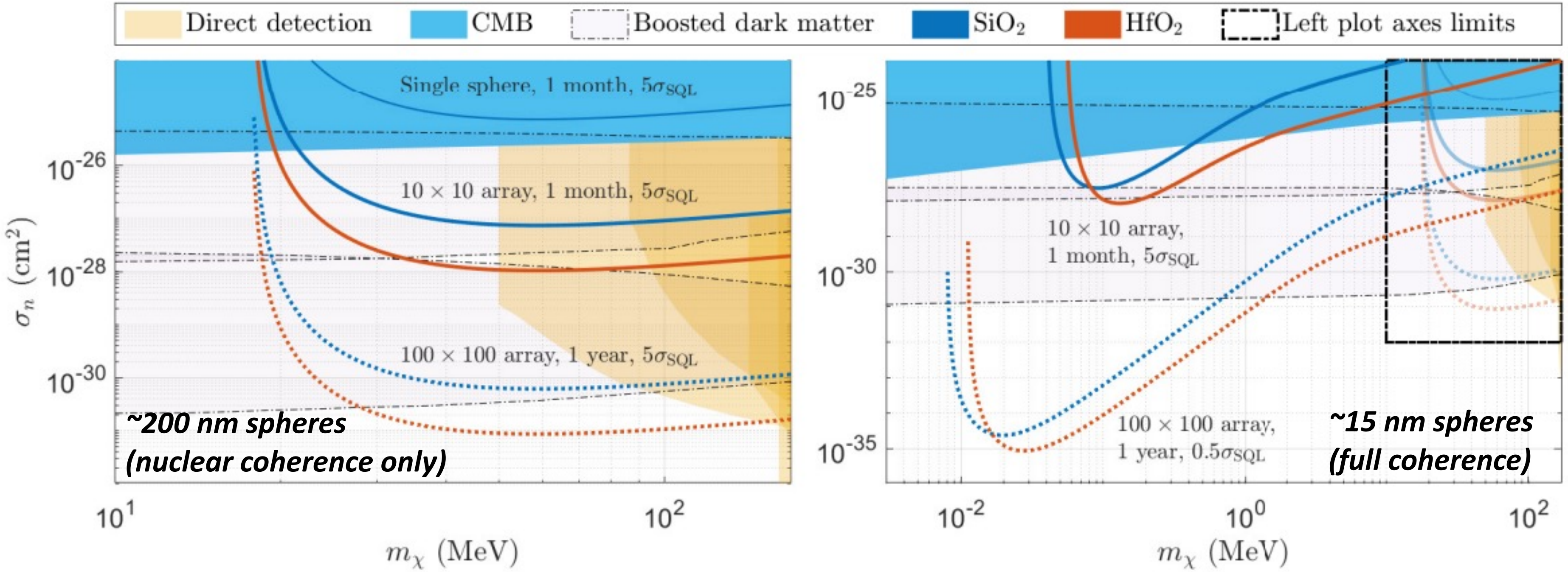
Coherent scattering from nanospheres

- For smaller spheres, much lower recoil thresholds can be obtained (at the cost of reduced target mass)
- Coherence over entire sphere possible even for short-range interactions for ~15 nm spheres

DM scattering from nanosphere array:



Projected low-mass DM sensitivity:



~200 nm spheres (nuclear coherence only)

~15 nm spheres (full coherence)

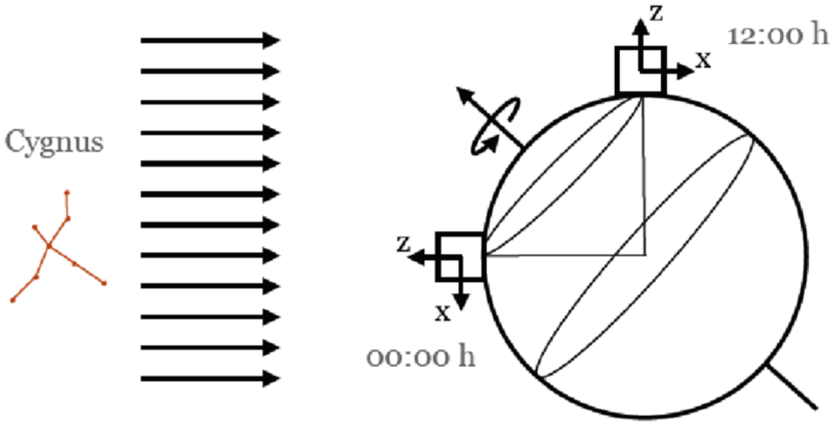
Afek et al., Phys. Rev. Lett. 128, 101301 (2022) ,arXiv:2111.03597

Physics "Viewpoint": https://physics.aps.org/articles/v15/32

Future sensitivity

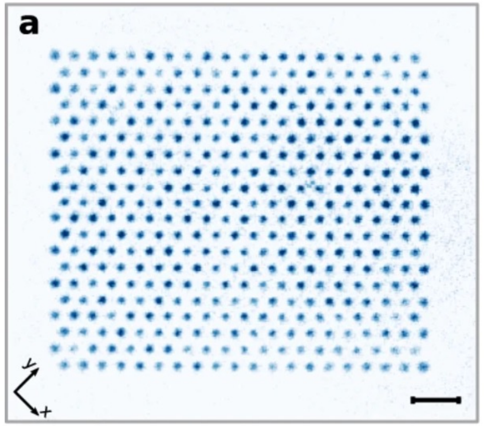
- This first proof-of-principle search for DM with mechanical d beyond existing searches for certain classes of models
- Next steps:
    - Continue to push towards SQL (and possibly beyond?)
    - Develop large arrays of sensors, and longer exposures

Natural directionality → any detection would be definitive!



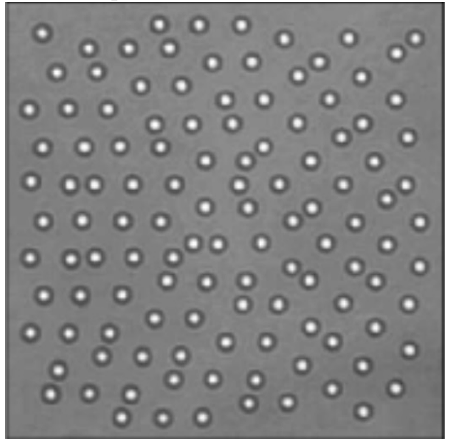
Tweezer arrays:

Atoms:



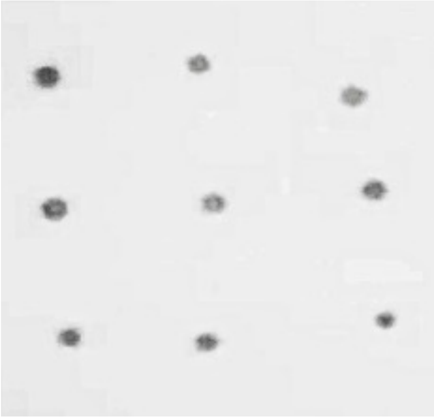
Wang et al. npj Quantum Inf 6, 54 (2020)

μspheres (fluid):



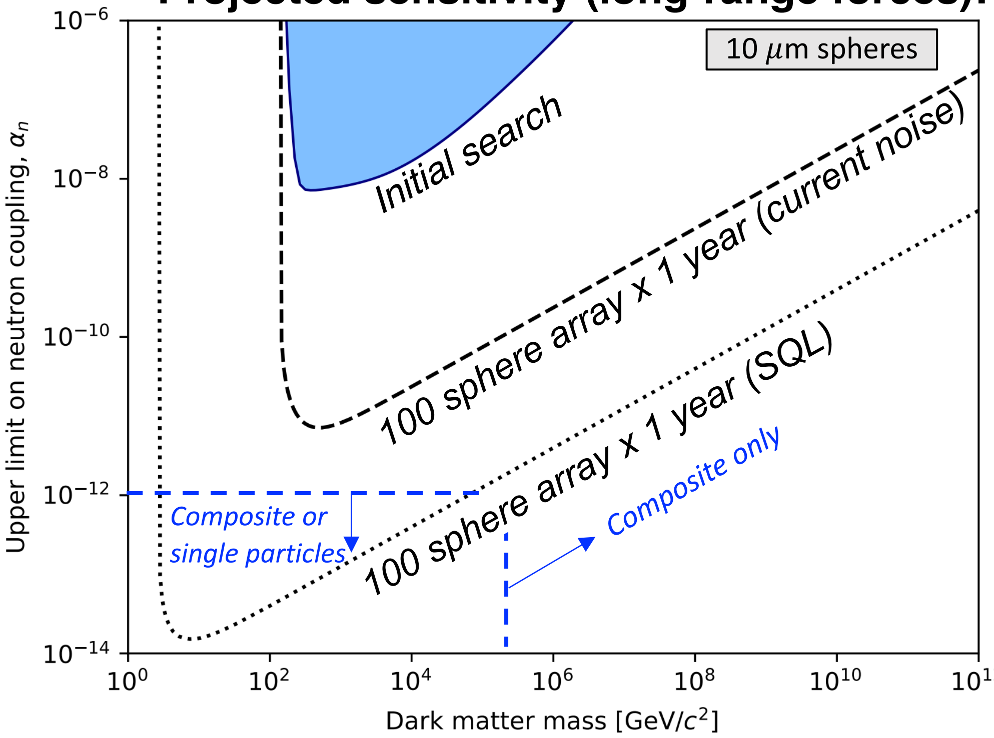
D. Grier and Y. Roichman Appl. Optics 45, 880 (2006)

μspheres (vacuum):



B. Siegel (Yale)

Projected sensitivity (long-range forces):



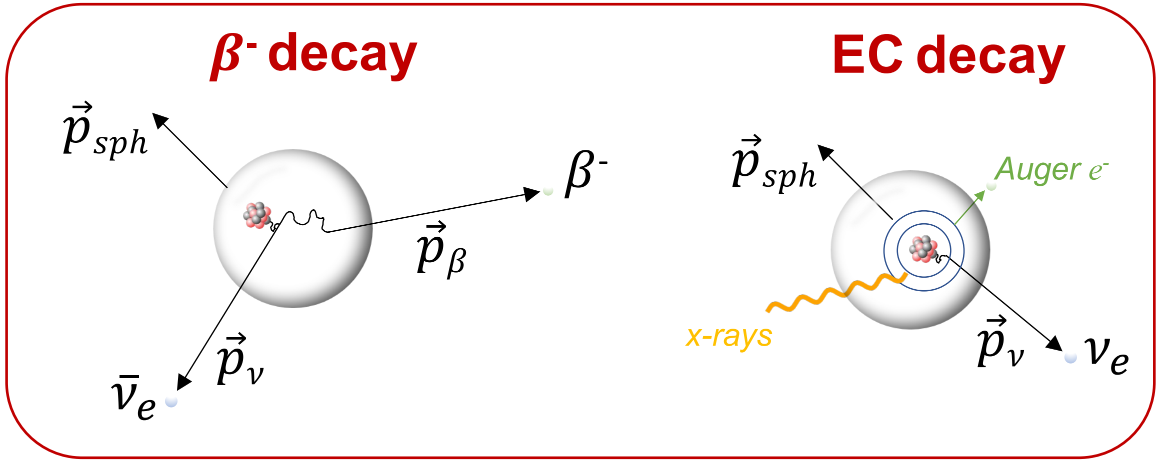
DCM and A. Geraci, Quantum Sci. Tech. 6 014008 (2021), arXiv:2008.13197

Sterile neutrinos

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

Nuclear decays in mechanical sensors

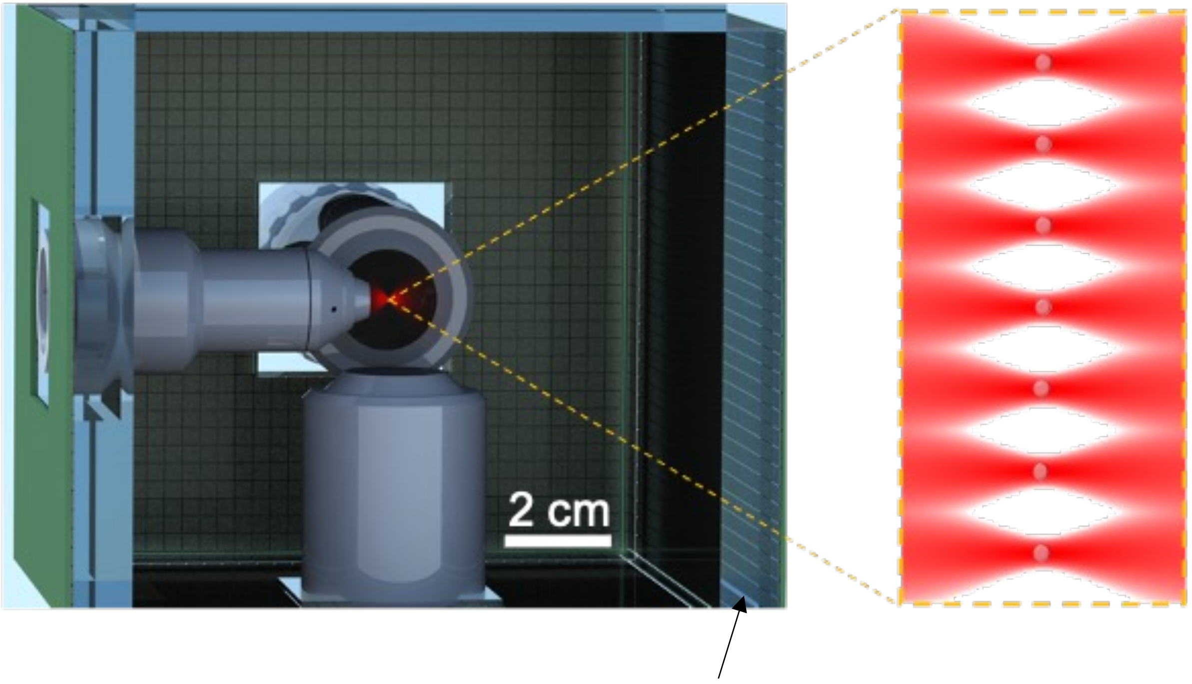
- Reconstructing the momentum of the recoiling nucleus from a nuclear decay embedded in a nanoparticle can provide sensitivity to massive neutral particles emitted in the decay
- For weak decays, the ν momentum can be reconstructed on an event-by-event basis providing sensitivity to keV-MeV mass sterile neutrinos
    - May also be of interest for other “invisible” particles (e.g. axions, dark photons, $\bar{n}$, …)



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

See also: BeEST collaboration, PRL 126, 021803 (2021), arXiv:2010.09603

Detector concept:

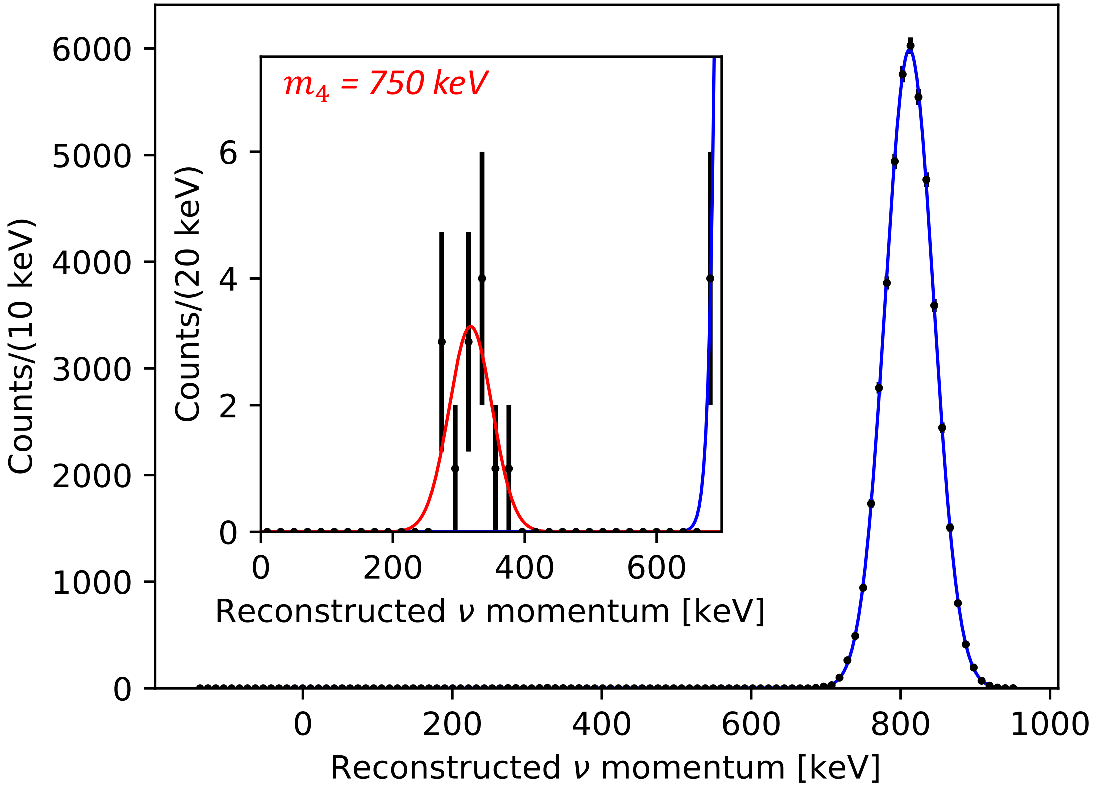


Nanosphere array

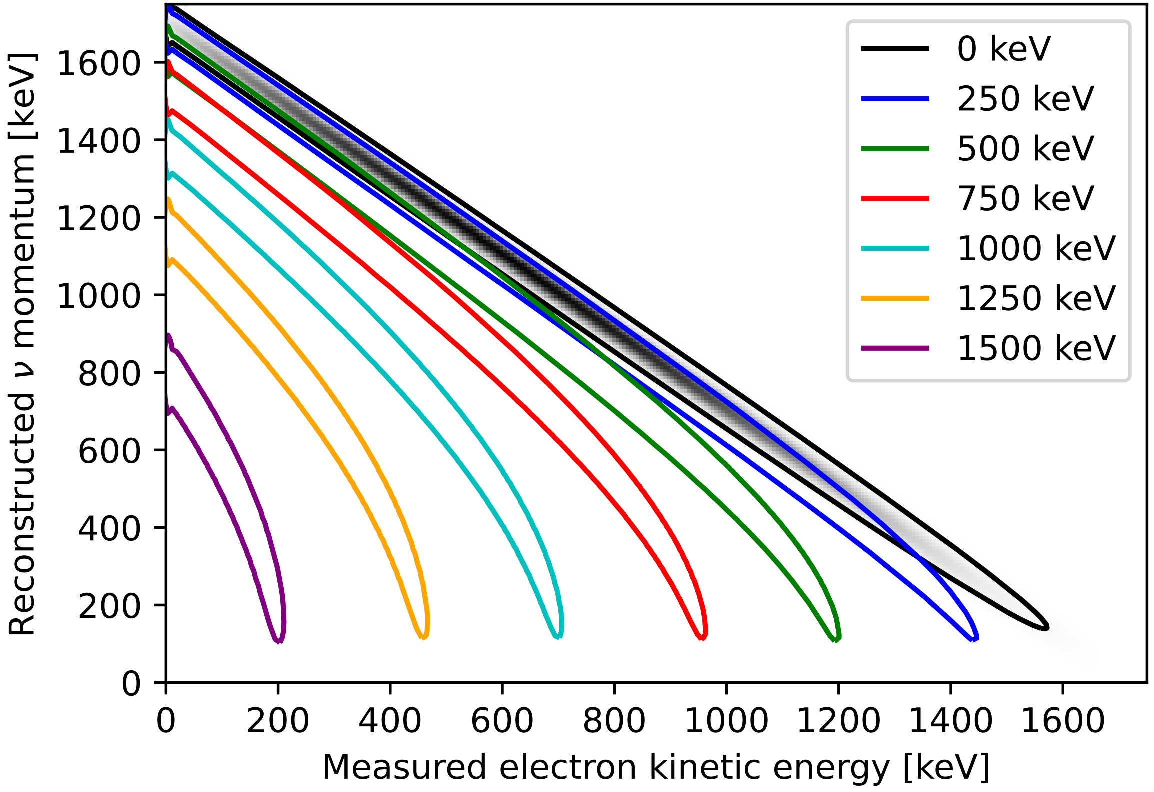
Scintillator + SiPM arrays

Experimental signature

- If a keV – MeV mass sterile ν mixes with the light ν, then expect small fraction of decays to emit a heavy ν
- Momentum difference between heavy and light state is largest for non-relativistic neutrinos, i.e., $E_\nu \approx m_\nu$



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



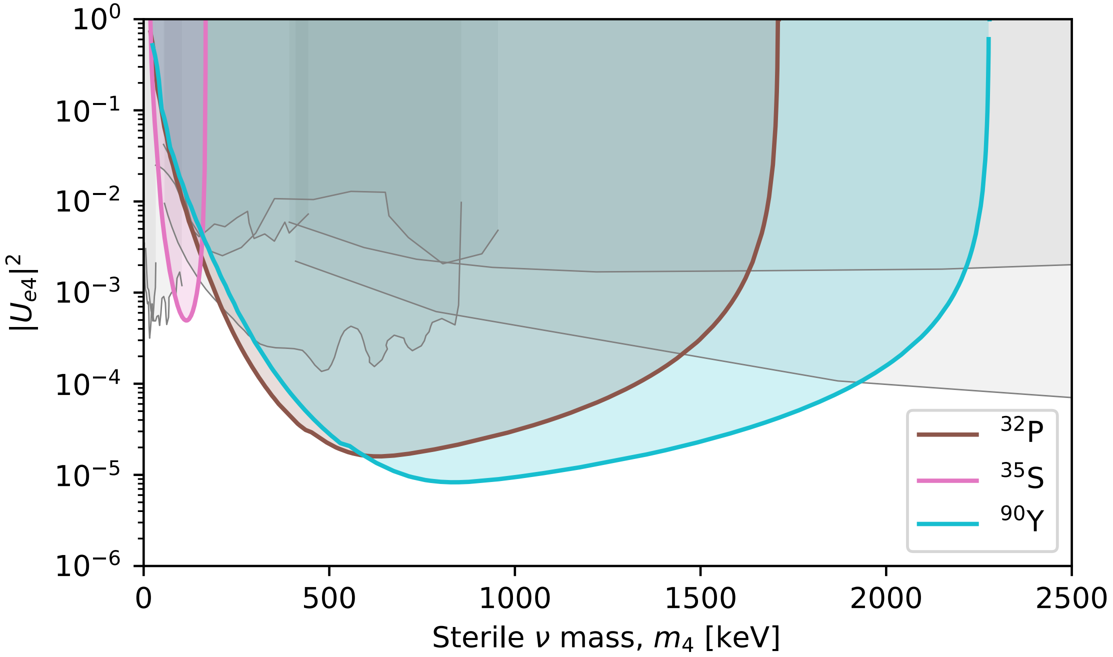
Example β^- decay (^{32}P):

arXiv:2207.05883

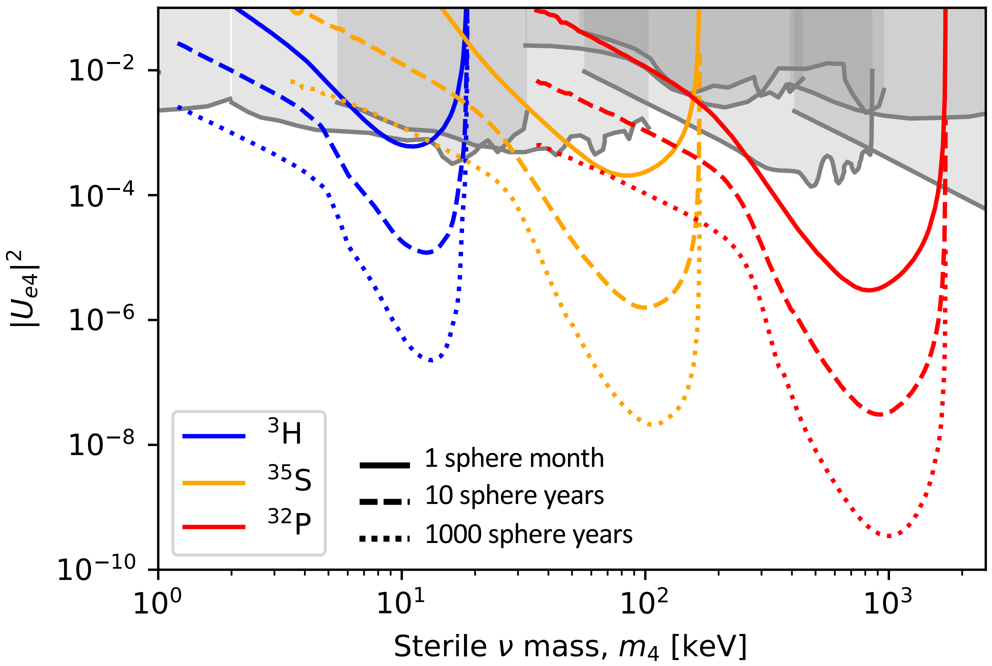
Projected sensitivity

- A single nanosphere at existing sensitivity could search well beyond existing laboratory constraints on heavy sterile ν in ~1 month
- Larger arrays and smaller particles could reach many orders of magnitude further sensitivity
- Backgrounds can be mitigated through triple coincidence (sphere recoil, secondary particle, sphere charge change)

Example β^- isotopes (1 sphere x 1 month):



Projected sensitivity versus livetime:



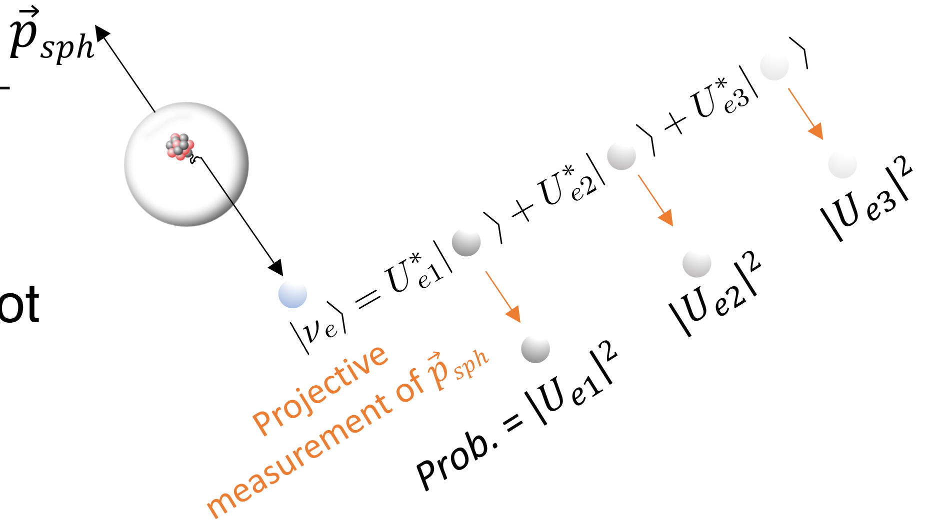
arXiv:2207.05883

Light ν

- Reaching a projective measurement of light ν masses would require measurements deep in the quantum regime
- A fixed solid source localizing nuclei at atomic distances cannot produce ν with sufficiently well defined momenta:

$$\Delta x \Delta p > \frac{\hbar}{2} \quad \Rightarrow \Delta x \gtrsim (100 \text{ meV})^{-1} = 2 \ \mu\text{m}$$

Projective measurement of sphere momentum:

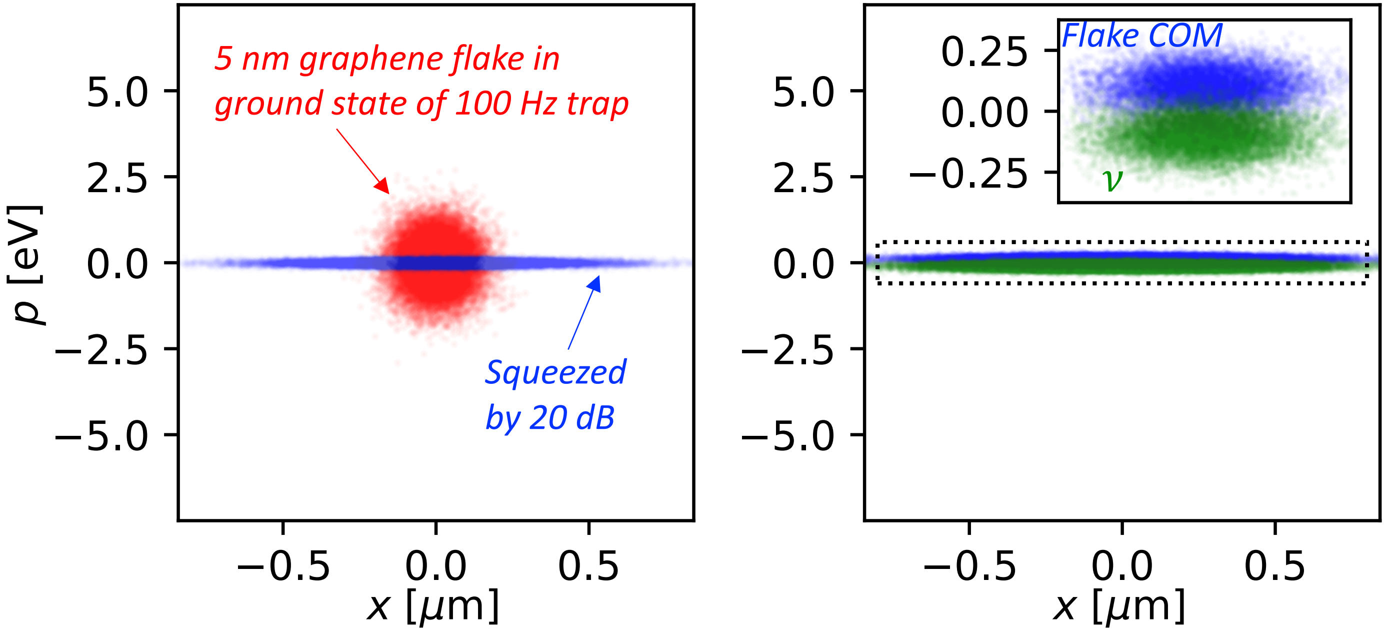


Relevance of Heisenberg Uncertainty also recently pointed out for PTOLEMY (CνB):

See, e.g., Cheipesh et al., PRD 104, 116004 (2021)
Apponi et al. (PTOLEMY), arXiv:2203.11228 (2022)

- Delocalizing COM of solid nanoparticle could allow required state-preparation
- Substantially beyond state-of-the-art, but rapid progress is being made!

Example of requirements on state preparation and measurement:

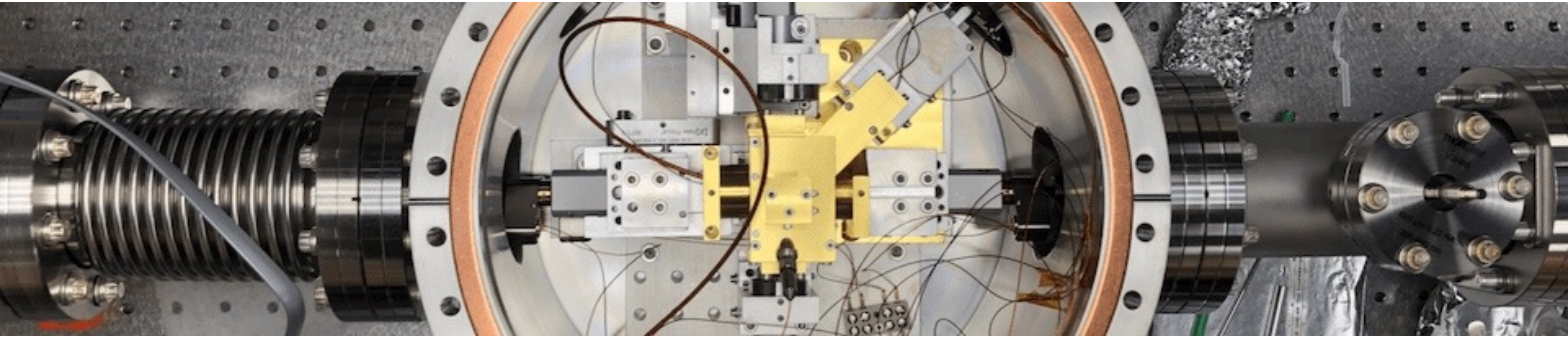


Summary

- Levitated optomechanical systems provide extremely precise sensors for forces and accelerations, and are reaching quantum measurement regimes

- We have recently performed searches for mechanical recoils from passing dark matter and are developing techniques to search for sterile ν

- Ambitious future extensions of these techniques are possible, and may provide new tools at the precision frontier of nuclear and particle physics!



Constraints on sterile ν

- A wide variety of searches have been performed for sterile ν:

Mass range (laboratory):

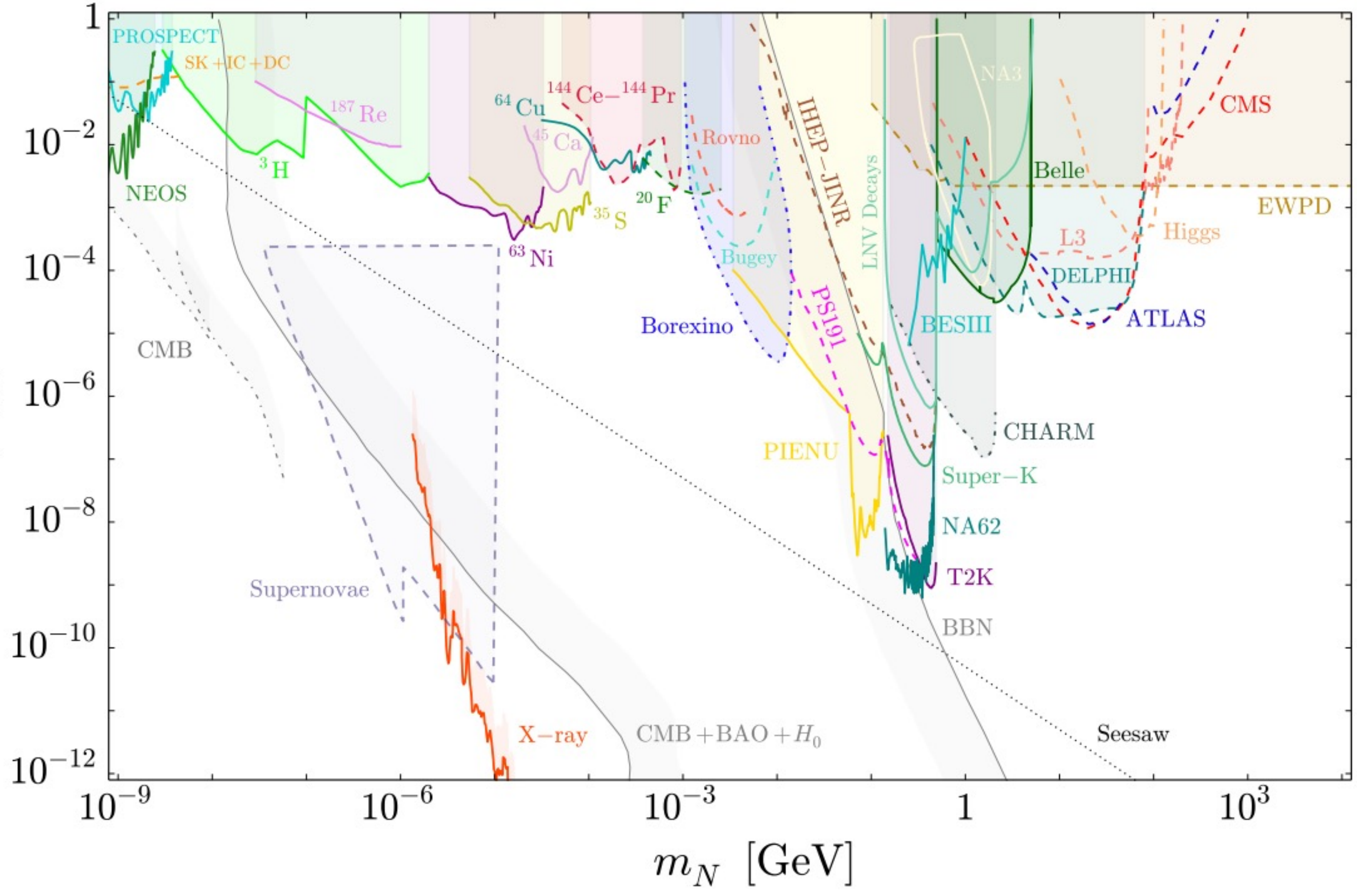
~eV: Short-baseline oscillations, reactors, ^{3}H spectrum

~keV – MeV: Beta decay spectra

>MeV: Heavy neutral leptons at accelerators

- If sterile ν constitute significant fraction of DM, strong x-ray constraints exist
- ~keV sterile ν with mixing ~10^{-10} are a viable DM candidate

Experimental limits on sterile ν mixing with ν_e:



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