

New/exotic Probes for Fundamental Physics

A sampler

Giorgio Gratta
Physics Dept, Stanford University

IASPPF, Hong Kong, Jan 2026

“My advice is to try crazy ideas and innovative experiments.”

Steve Weinberg, APS News Feb 2019

The physics of Fundamental Particles and Interaction has traditionally embraced disparate techniques to crack the riddles of Nature.

Some examples

- Rutherford scattering experiments using alphas, vacuum chambers and fluorescent screens
- Stern-Gerlach experiments on spins, using magnetic field gradients
- Cosmic rays! Θ - τ puzzle. Discovery of the positron.
- Radioactive sources and the measurement of neutrino helicity
- Mössbauer spectroscopy and the first measurement of gravitational red/blue shift
- Nuclear reactors and the discovery of neutrinos
- Cyclotrons and the discovery of antiprotons
- Nuclear demagnetization cooling and the discovery of parity violation
- Accelerators and bubble chambers and the exploration of hadron physics
- Many more results from ever increasing energy accelerators and ever more complex detectors
- Colliders and W, Z, Jet physics, the Higgs
- Low background detectors and solar neutrinos
- Cosmic rays, the Sun, reactors and the discovery of neutrino oscillations

Whither the path? There is no path where no one has gone before!

Faust, Goethe, 1808

Disclaimer/apology

This is a very large field and, by construction, nearly each experiment has its own technique that would require time to explain. In addition, the boundaries of the “field” are fuzzy, so that depending on the definitions one may intrude into other fields.

Hence, I will cover only a very modest set of examples. Deliberately left out are:

- Any sort of cosmic ray physics (here cosmic ray includes photons and neutrinos)
- Gravitational waves
- All of neutrino physics
- WIMP dark matter detection
- $g-2$
- Quantum simulation and other “mainstream” AMO
- Axions (see talks this afternoon)
- ...

And I will shamelessly spend most of my time on experiments done in my labs

Gravity is not part of the Standard Model of fundamental particles and interactions

- The inverse square law is generally assumed to work all the way down to the Planck length

$$R_P = \sqrt{\frac{G\hbar}{c^3}} = 1.6 \times 10^{-35} \text{ m.}$$

This is a bold assumption that requires experimental verification.

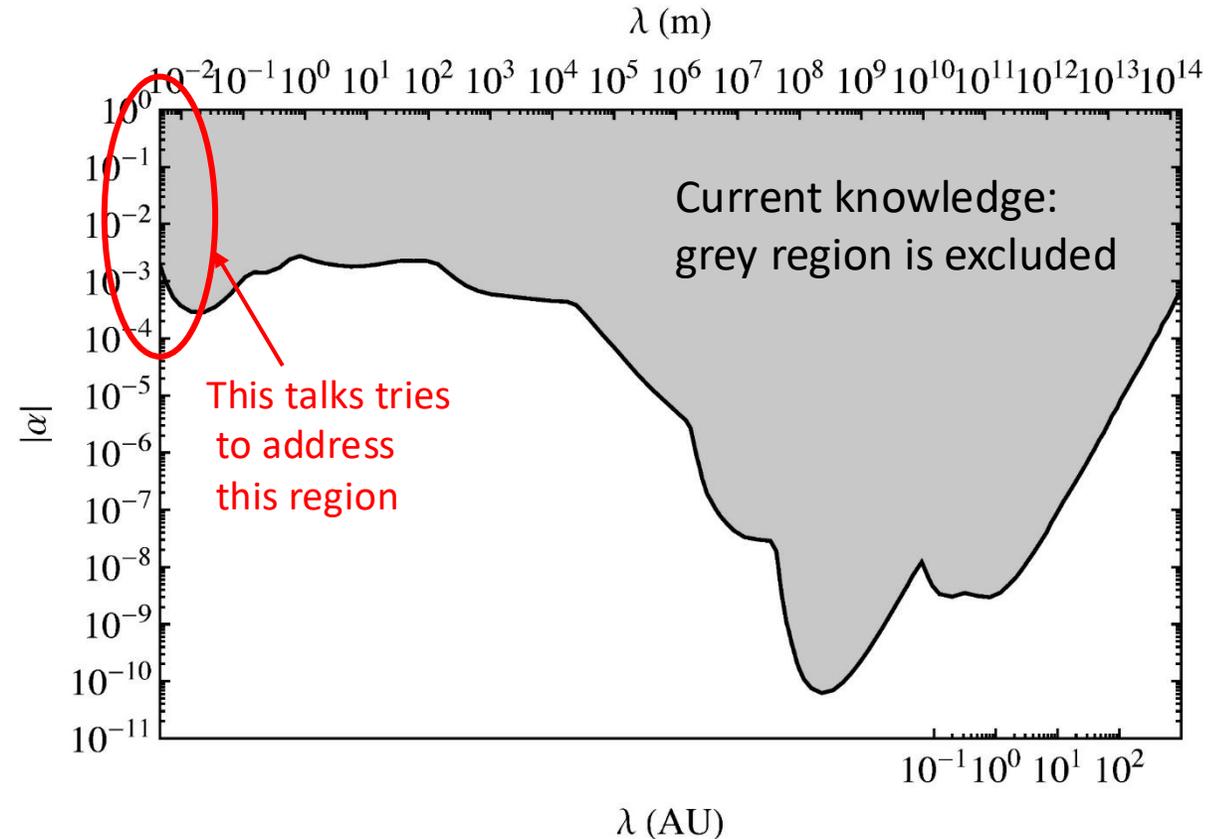
So, how well do we know that the inverse square law applies?

It is customary to express potential deviations from the $1/R^2$ law by modifying the potential with a Yukawa term:

$$V(R) = G \frac{M_1 M_2}{R} (1 + \alpha e^{-R/\lambda})$$

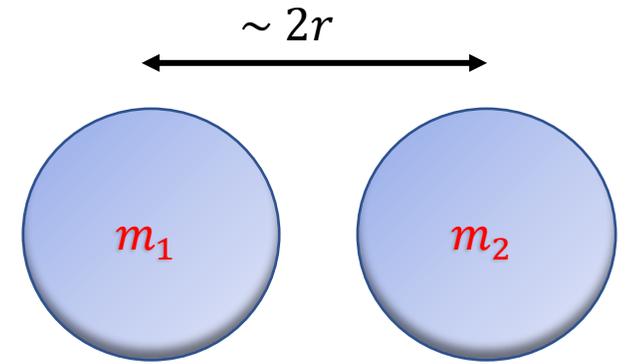
α : magnitude of the effect

λ : scale of the effect

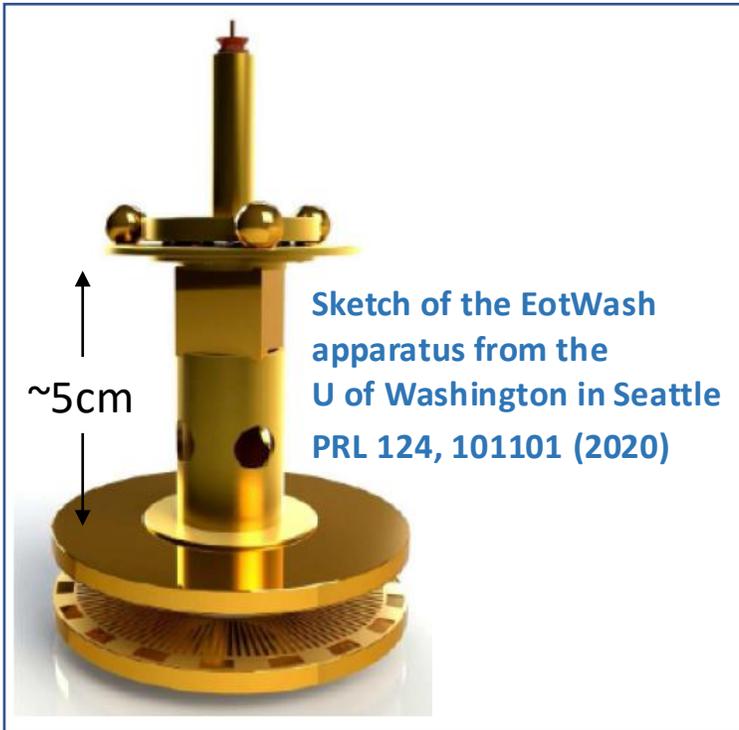


Experimental challenges

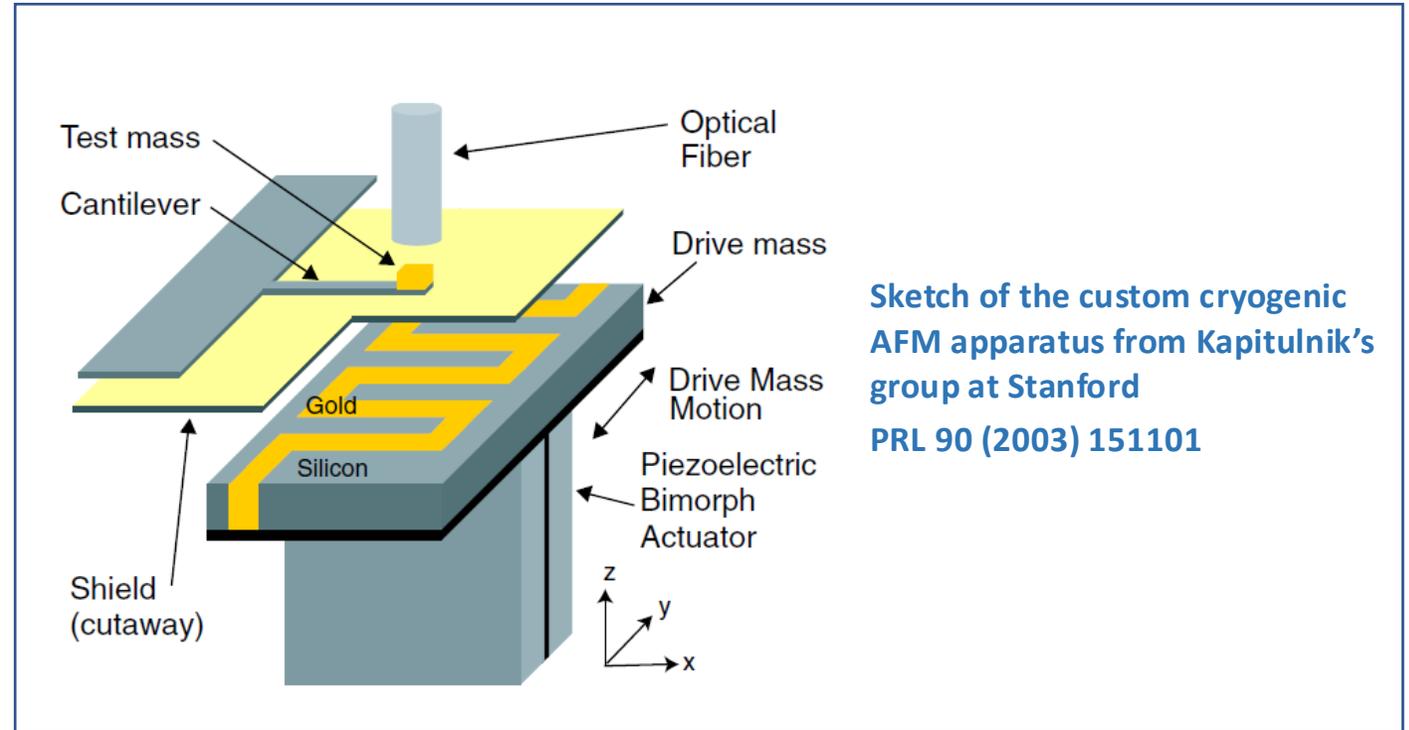
- Since $F = G \frac{M_1 M_2}{R^2} = G \frac{\rho_1 V_1 \rho_2 V_2}{R^2}$
for atomic materials $\rho_1 \sim \rho_2 < 20 \text{ g/cm}^3$, there is no silver bullet.
In addition, the volume $V \sim R^3$, so $F \sim G \frac{\rho^2 R^6}{R^2} \propto R^4$
- At distances $< 100 \mu\text{m}$ even neutral matter results in residual E&M interaction that are a dangerous background for the measurements.



$r \sim 10 \mu\text{m} \rightarrow F_N \sim 10^{-21} \text{N}$



Sketch of the EotWash apparatus from the U of Washington in Seattle
PRL 124, 101101 (2020)



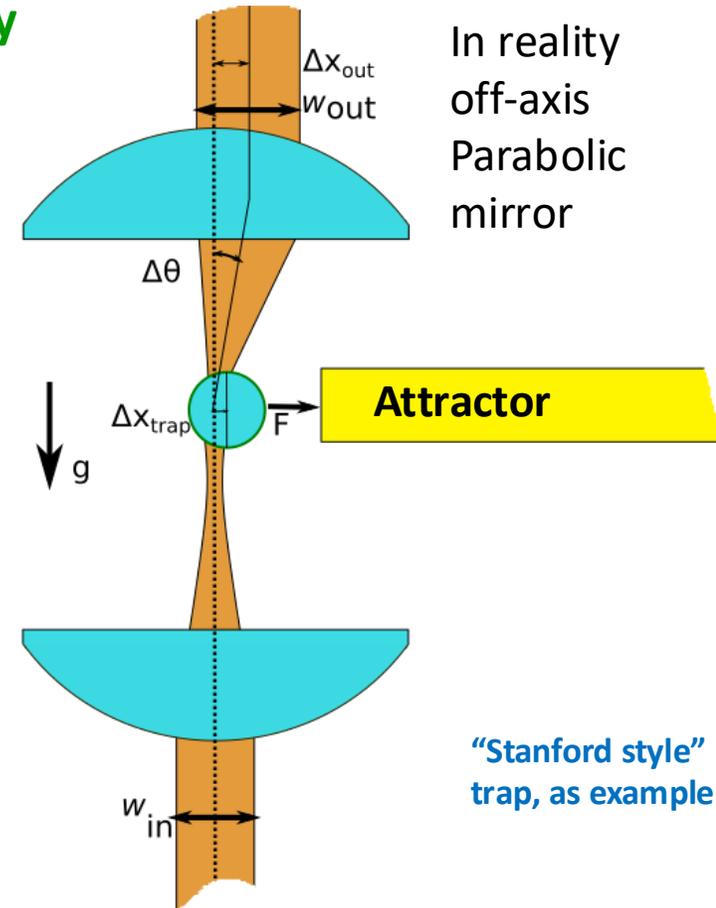
Sketch of the custom cryogenic AFM apparatus from Kapitulnik's group at Stanford
PRL 90 (2003) 151101



In the last 40 years, the technique of optical tweezers has matured, primarily in water with applications to biology

Microspheres optically trapped in vacuum make superb force sensors.

→ Optical, instead of mechanical, springs.
Effective C.O.M. temperature can be mK in a room temperature apparatus

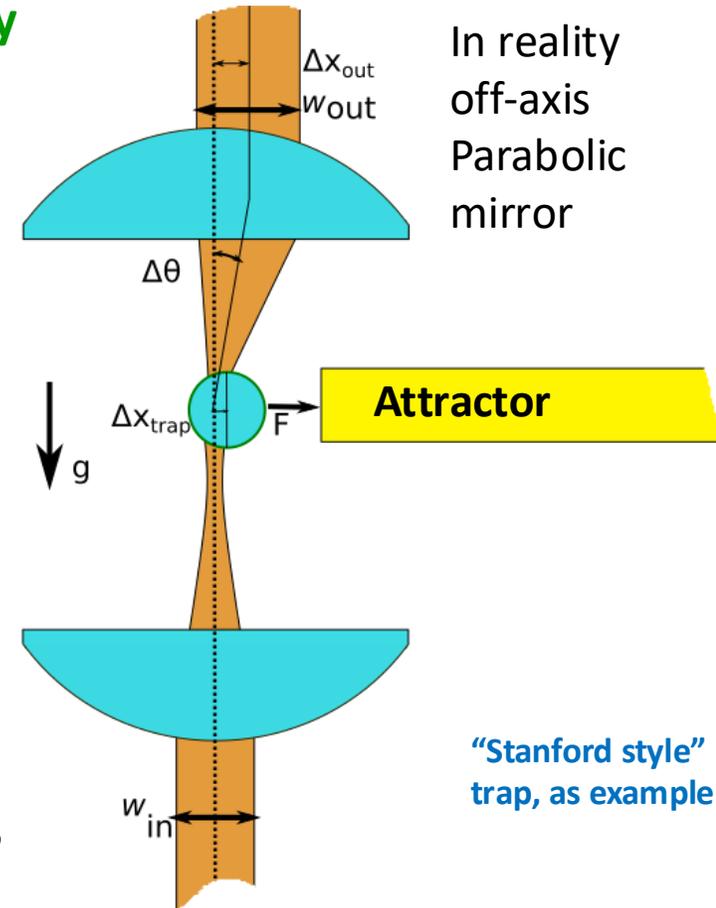
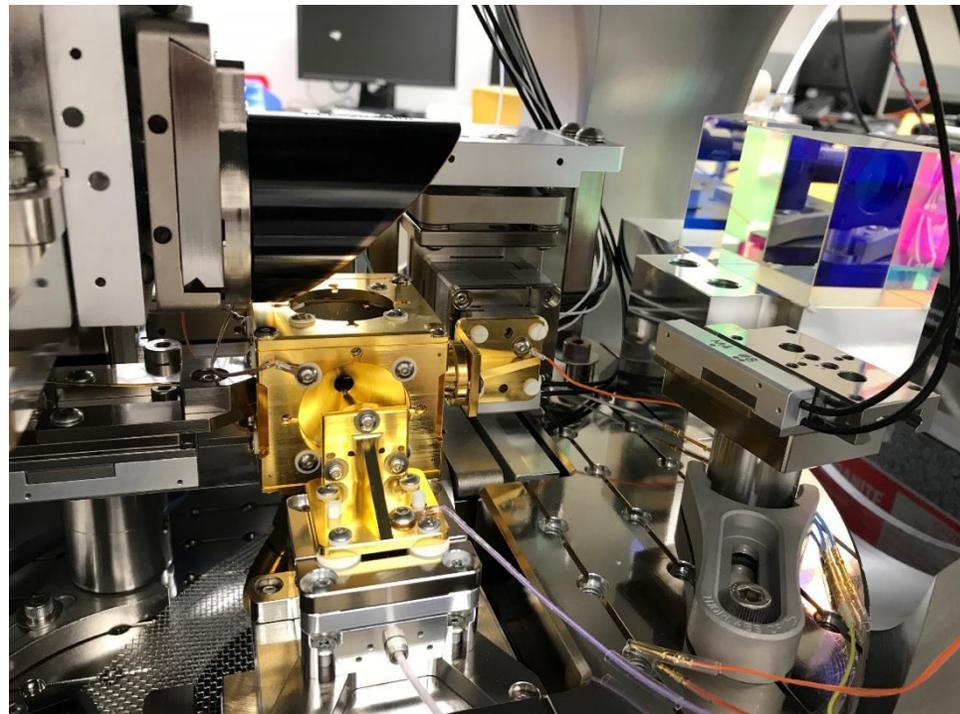




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~7.6 μm diameter silica microspheres

Mass ~420 pg

Force noise floor ~10 aN/ $\sqrt{\text{Hz}}$

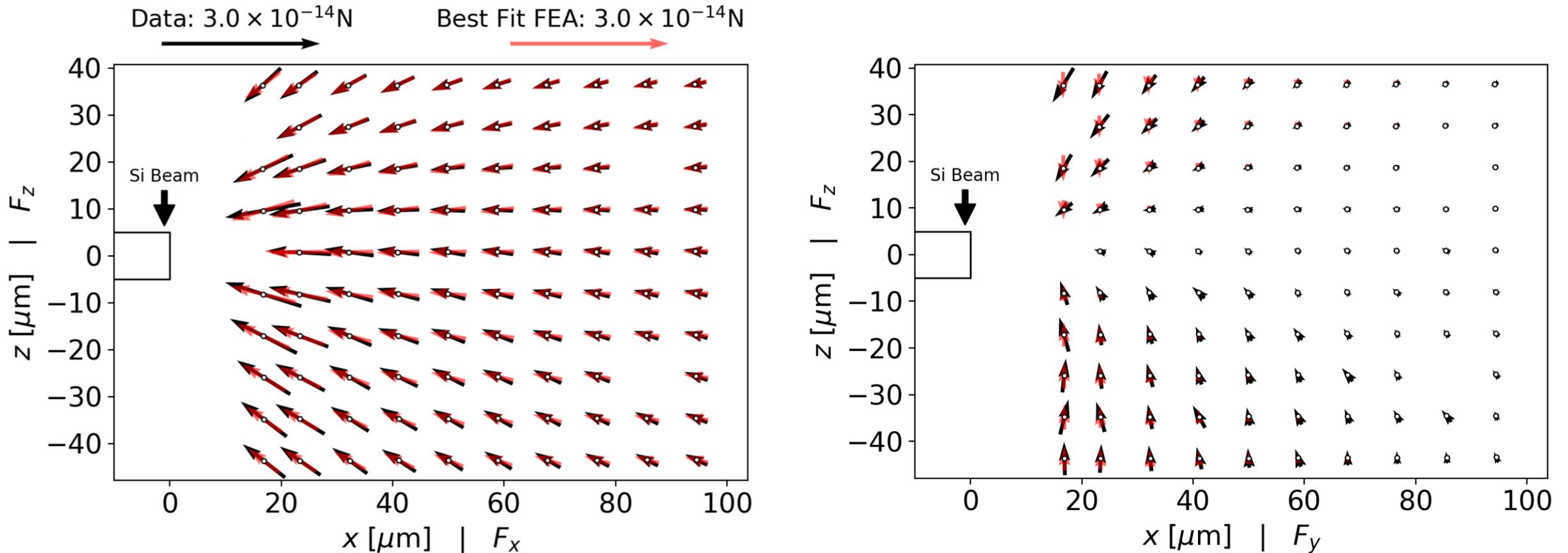
(to be improved)

Possible to bring objects to within ~1 μm

from the surface of the microsphere

The trapped microsphere (5-10 μm diameter) is an excellent force sensor, with full 3D, vector field mapping capability

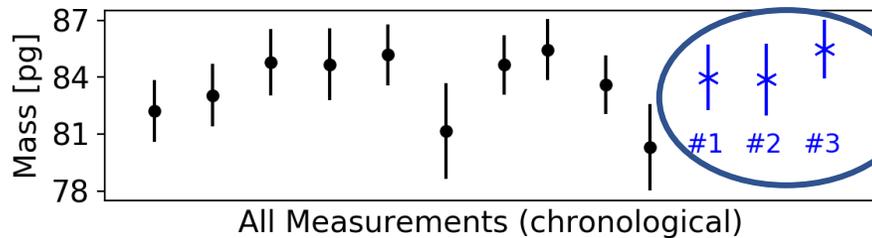
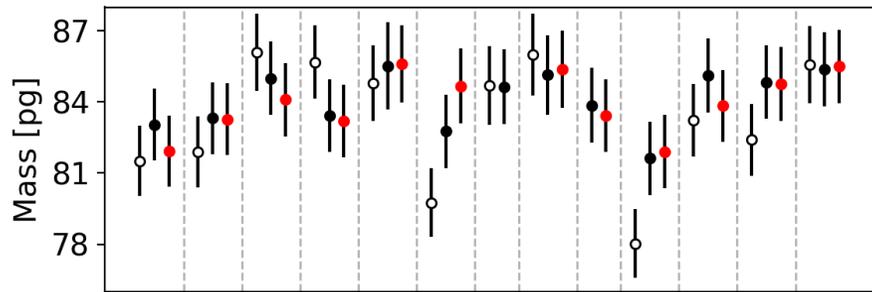
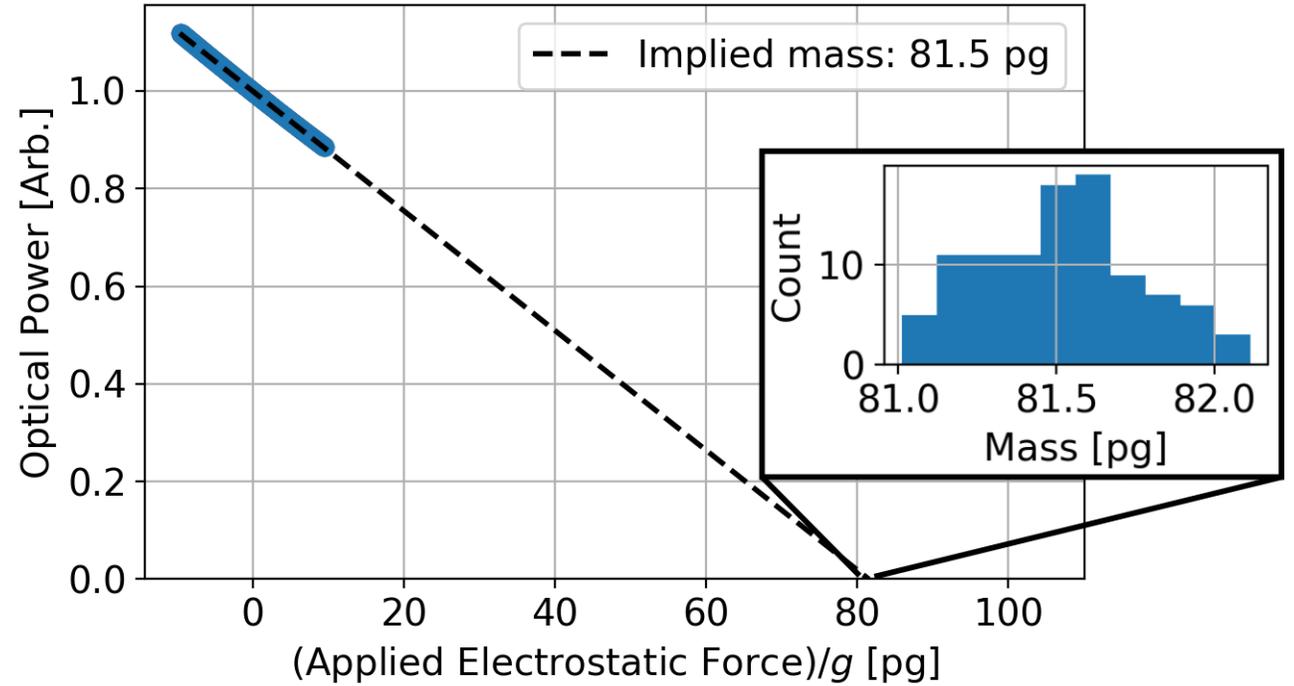
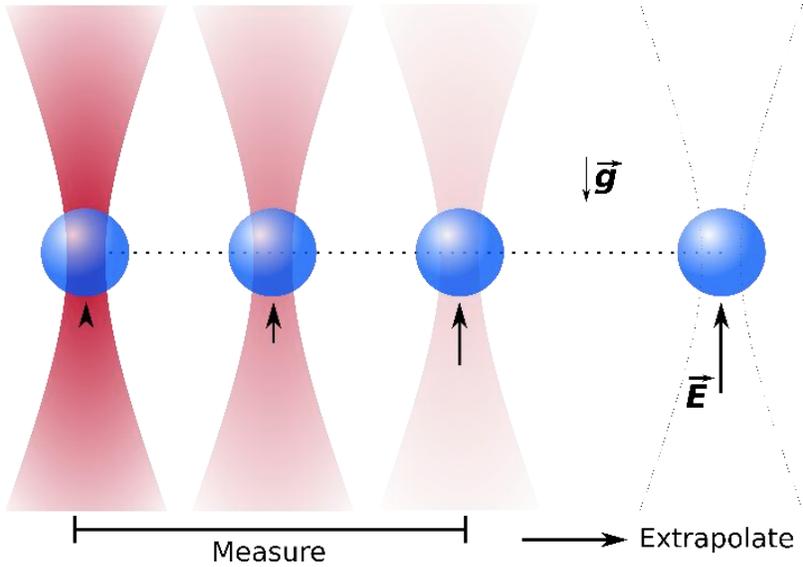
as can be shown/calibrated by measuring charged microspheres



C.Blakemore et al., Phys. Rev. A 99 (2019) 023816

Similar results in G.Winstone et al., Phys. Rev. A 98 (2018) 053831

Precision measurement of microsphere mass and density



This technique only requires the knowledge/measurement of the relative power needed to compensate for a certain electrostatic force. I.e, it only needs the linearity of a photodiode.

These three microspheres are then individually recovered and their diameter measured offline in an SEM

C.Blakemore et al., Phys. Rev. Appl. 12 (2019) 024037

Spinning trapped microspheres

Since microspheres have a electric dipole moments, a torque can be applied by a rotating external electric field.

A.Rider et al. Phys Rev A 99 (2019) 041802(R)

C.P.Blakemore et al. Phys Rev A 106 (2022) 023503

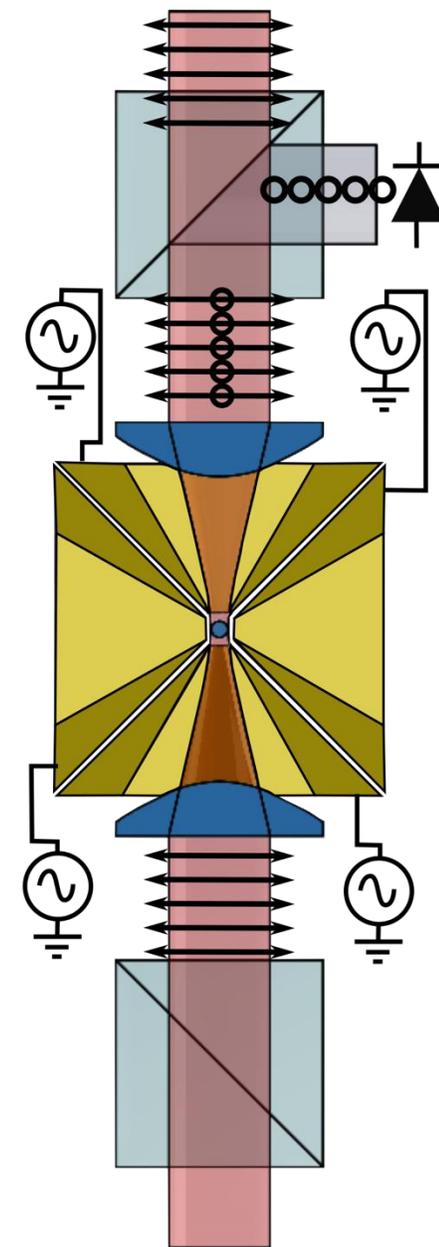
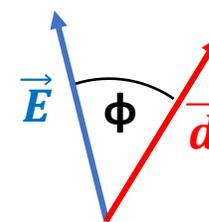
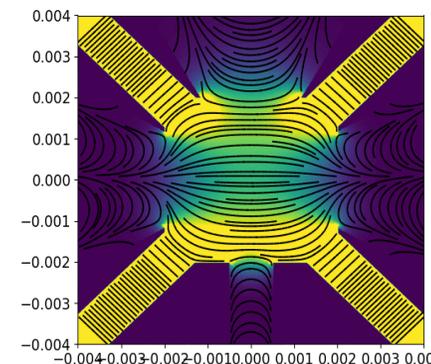
Application in vacuum sensing,

C. Blakemore at al, J. Vac. Sci. Technol. B 38, 024201 (2020)

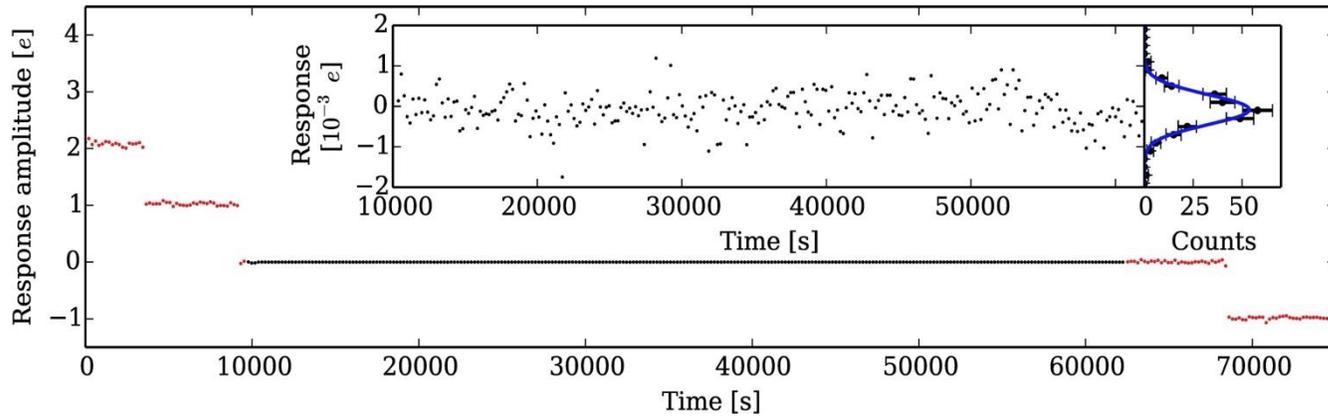
navigation,

and microsphere stabilization (lower noise).

But the dipole moment also couples to E-field gradients which can be minimized but not entirely eliminated.



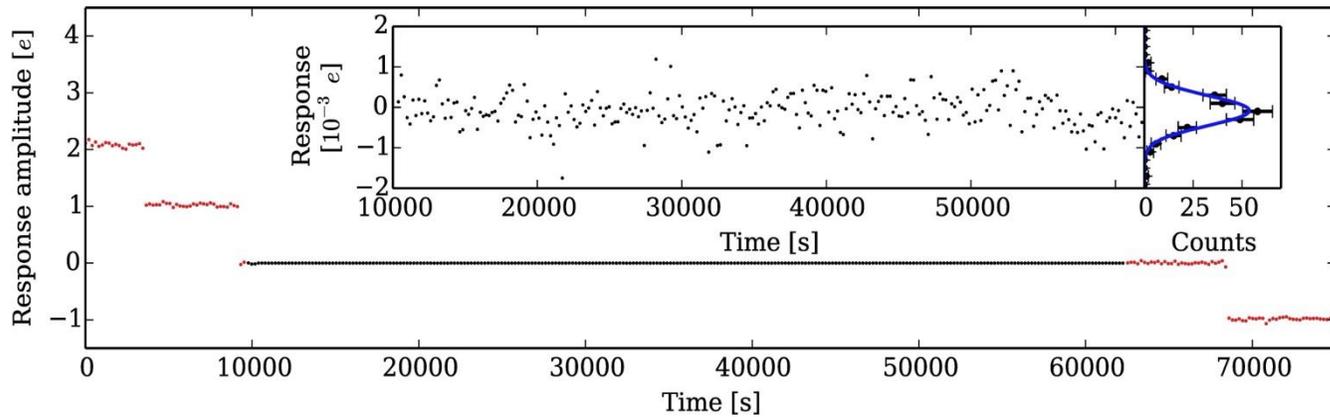
**Charge can be set to arbitrary (small) values (useful for force calibration)
including zero (useful for the measurement)**



In fact, searches for millicharges or tests of neutrality of matter are by-products of this work.

However, electric dipole moments of $\sim 100e \mu\text{m}$ are observed, producing background forces by coupling to E-field gradients.

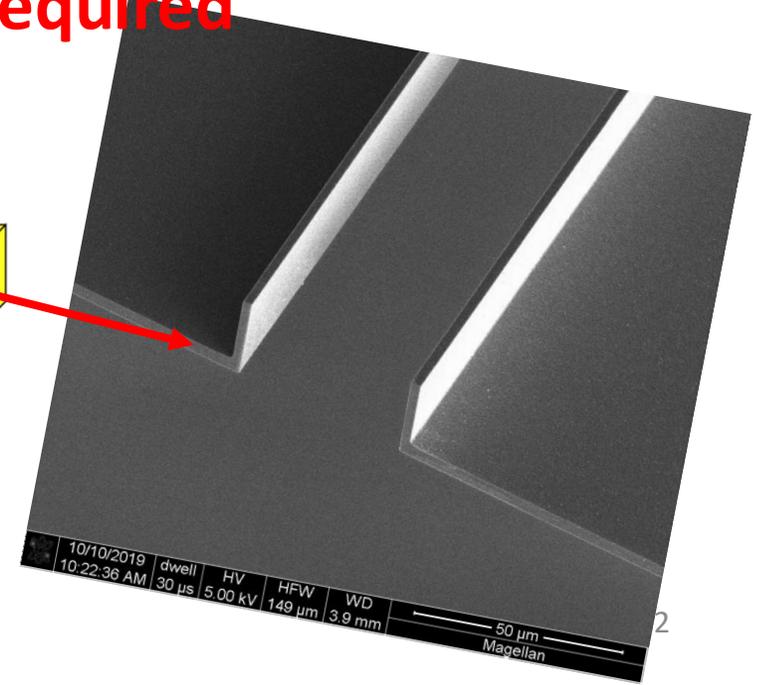
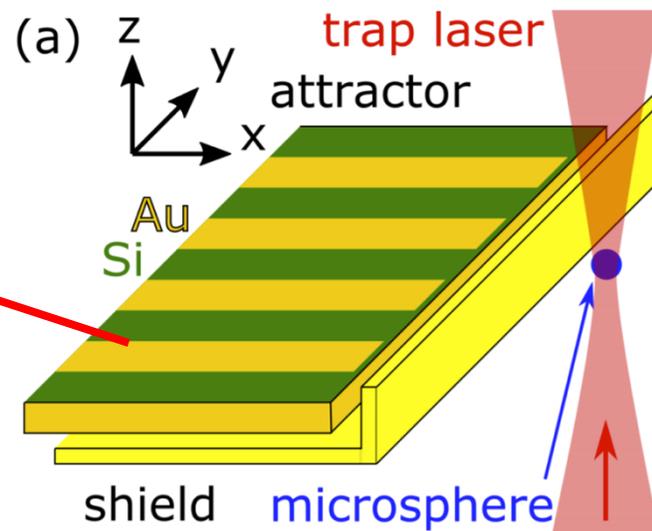
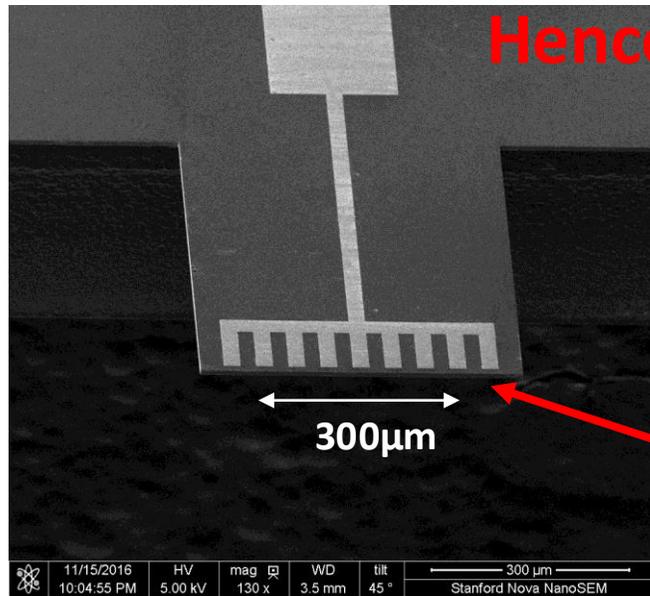
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In fact, searches for millicharges or tests of neutrality of matter are by-products of this work.

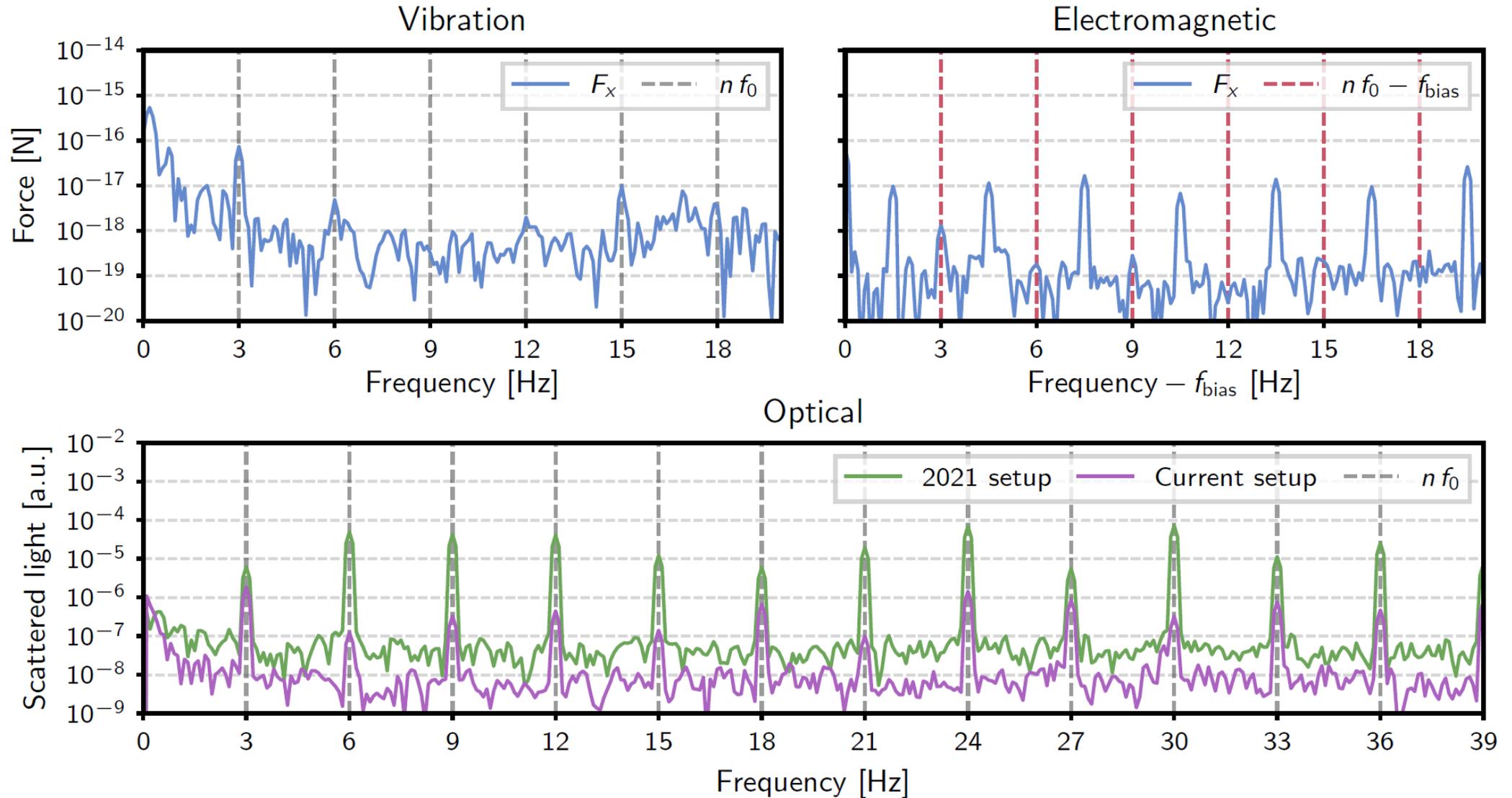
However, electric dipole moments of $\sim 100e \mu\text{m}$ are observed, producing background forces by coupling to E-field gradients.

Hence, a stationary shield is required

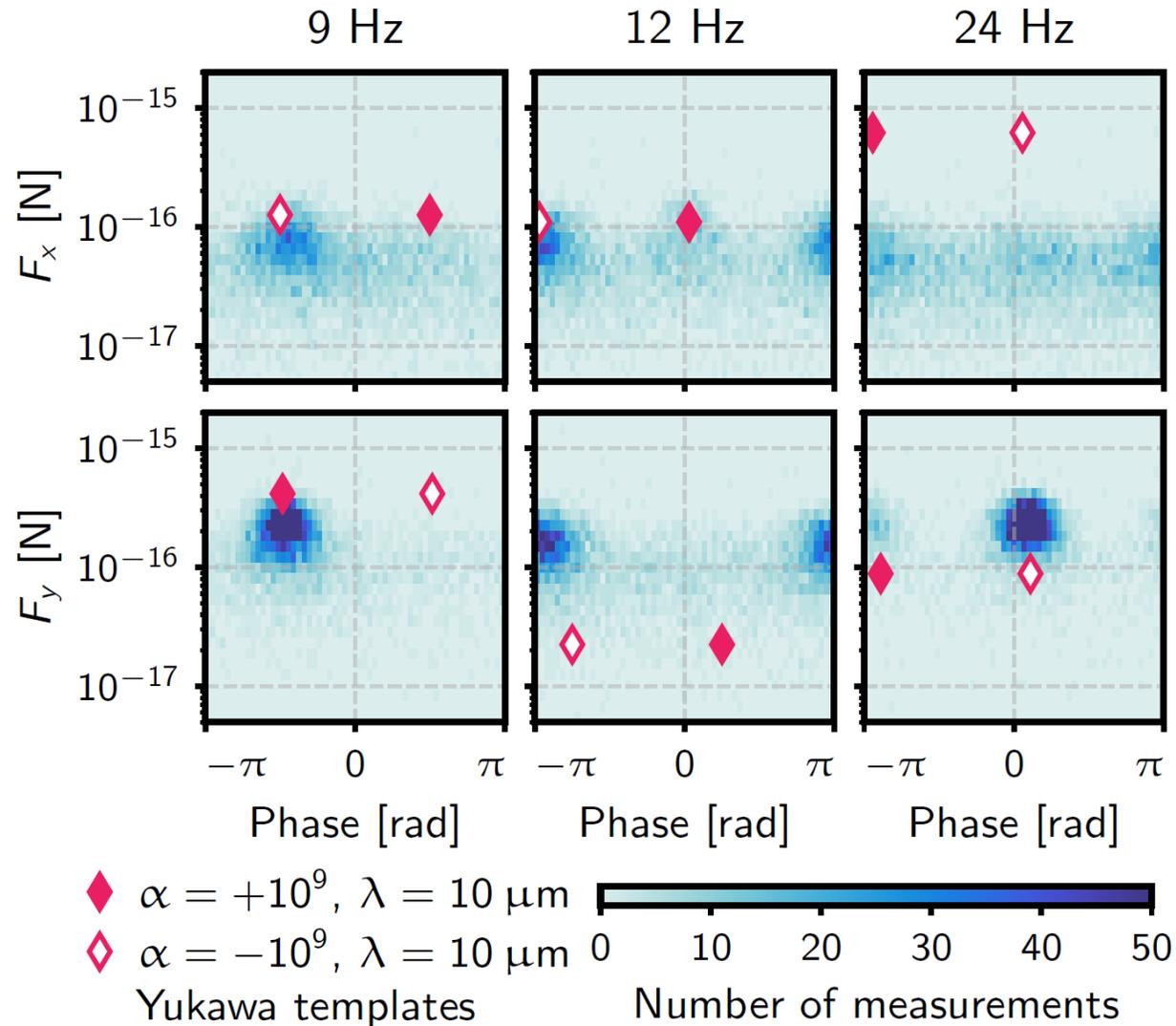


Backgrounds are still the most serious limitation to the sensitivity,

but, in the most recent science run, the dominant optical one was reduced by ~ 2 orders of magnitude

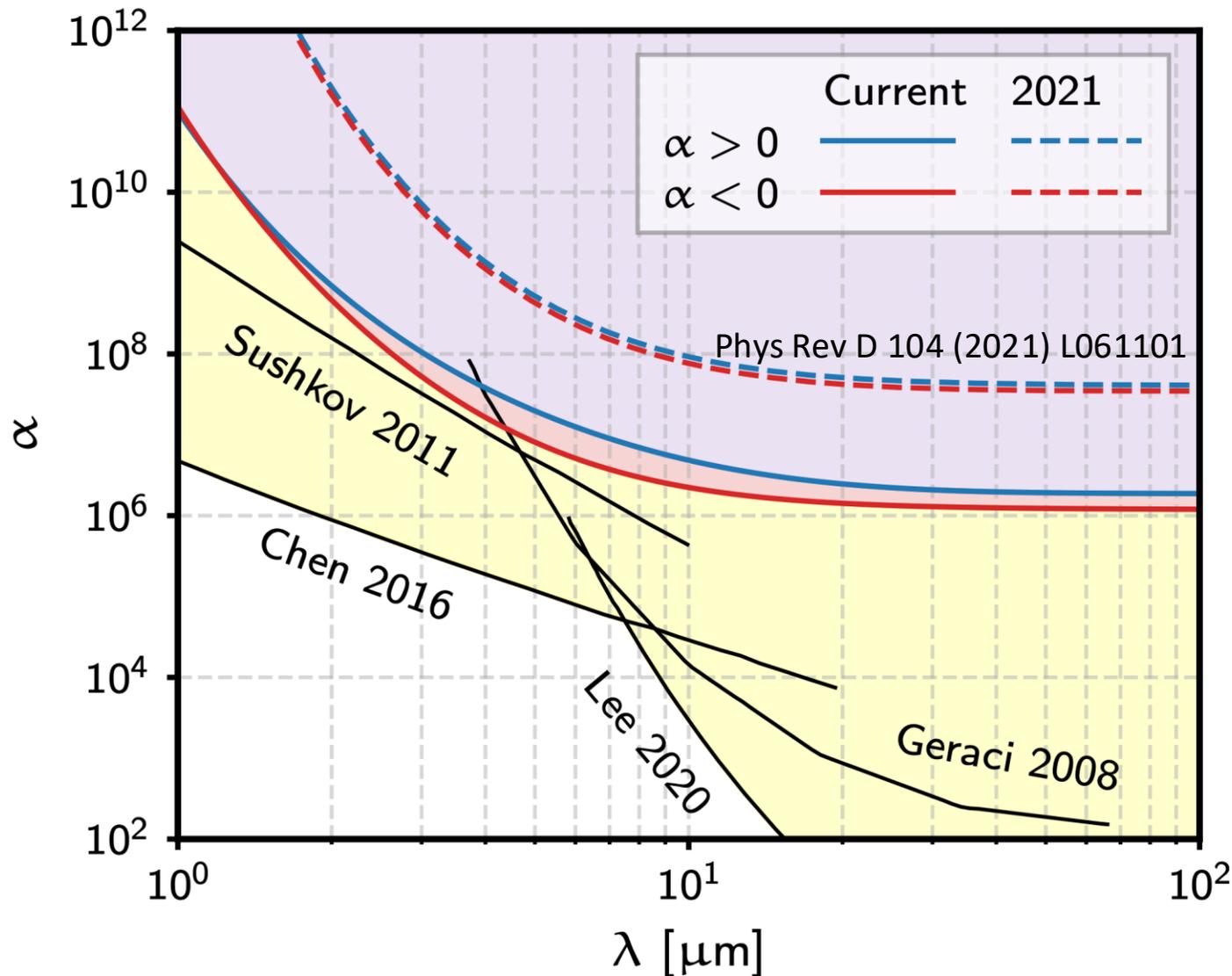


The force measurement in 2 coordinates (eventually 3), its phase, and the use of the six harmonics with the most power better constrains the measurement.



Result

<https://arxiv.org/abs/2412.13167>



- Limit is set using profile-likelihood
Better understanding and reduction of background:
➔ 100x improvement over our first result
- Setting limit on positive and negative coupling constants
- First measurement of the force vector
- Current sensitivity limited by diffuse light background (and, no doubt, other backgrounds are lurking under that)
- Working on more background abating techniques

G.Venugopalan et al., arXiv:2412.13167
to appear on *Scientific Reports*.

What about even shorter distances? Presumably, EM backgrounds become horrendous.

- Neutron Scattering is used, and one may be able to improve this further.
- Here I want to mention a new idea (GG, D.E. Kaplan, S. Rajendran, PR D 102 (2020) 115031)
Use nuclei (instead of atoms) as sensors: Nuclei are well protected affairs
(the fact that very long half lives, even for EM transitions, are readily observed is witness to this statement)
 - Nuclei have electric charge, but that is screened by the electron cloud and has little coupling to external E&M disturbances (Schiff screening).
 - In addition, nuclear level shifts due to E&M coupling occur through coupling to multipole moments and these are suppressed by the size of the nucleus.
 - And, this is further suppressed, for unpolarized nuclei, by \sqrt{N} , when looking for the shift of a spectroscopy line that is measured by N events.

→ **This is really new! Do not directly measure a force, but, rather, detect small shifts in nuclear γ transitions using Mössbauer spectroscopy.**
(Similarly to $0\nu\beta\beta$ decay) the observation of a shift is new physics, no matter of what theory may say. Relating the shift to the exact physics does require theory.



Glen Rebka at the basement station

Zeitschrift für Physik, Bd. 151, S. 124–143 (1958)

Aus dem Institut für Physik im Max-Planck-Institut für medizinische Forschung,
Heidelberg

Kernresonanzfluoreszenz von Gammastrahlung in Ir^{191}

Von

RUDOLF L. MÖSSBAUER*

Mit 8 Figuren im Text

(Eingegangen am 9. Januar 1958)

Mössbauer spectroscopy was used in an elegant experiment to detect, for the first time, gravitational red/blue shift of photons.

Pound & Rebka Physical Review Letters. 4 (1960) 337

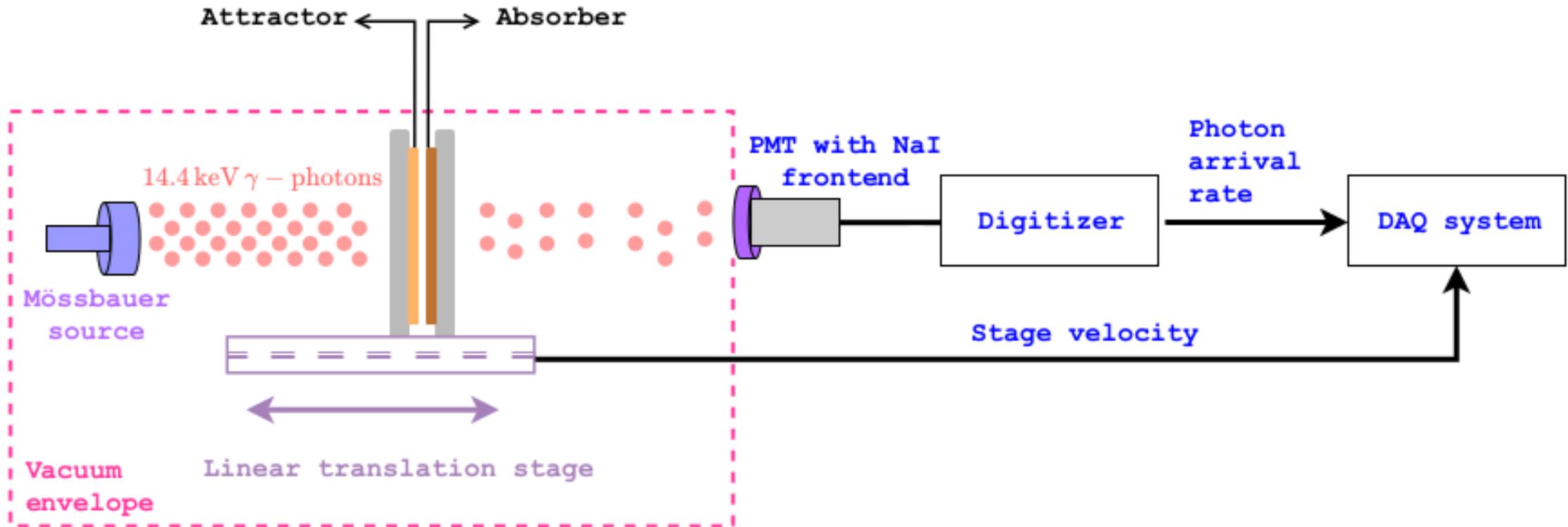
Somewhat disconcertingly, Mössbauer spectroscopy was then “appropriated” by Chemists!

→ It's time to reclaim it back for fundamental physics!

Incidentally ^{229}Th clock transition is a special case of this.

How to measure a force using nuclei? *Don't: measure instead a perturbation of the nuclear potential due to the addition of an external potential.*

The very narrow lines in Mössbauer spectroscopy provide the sensitivity.



Fantastic Mössbauer Resolution

Used mainly in chemistry

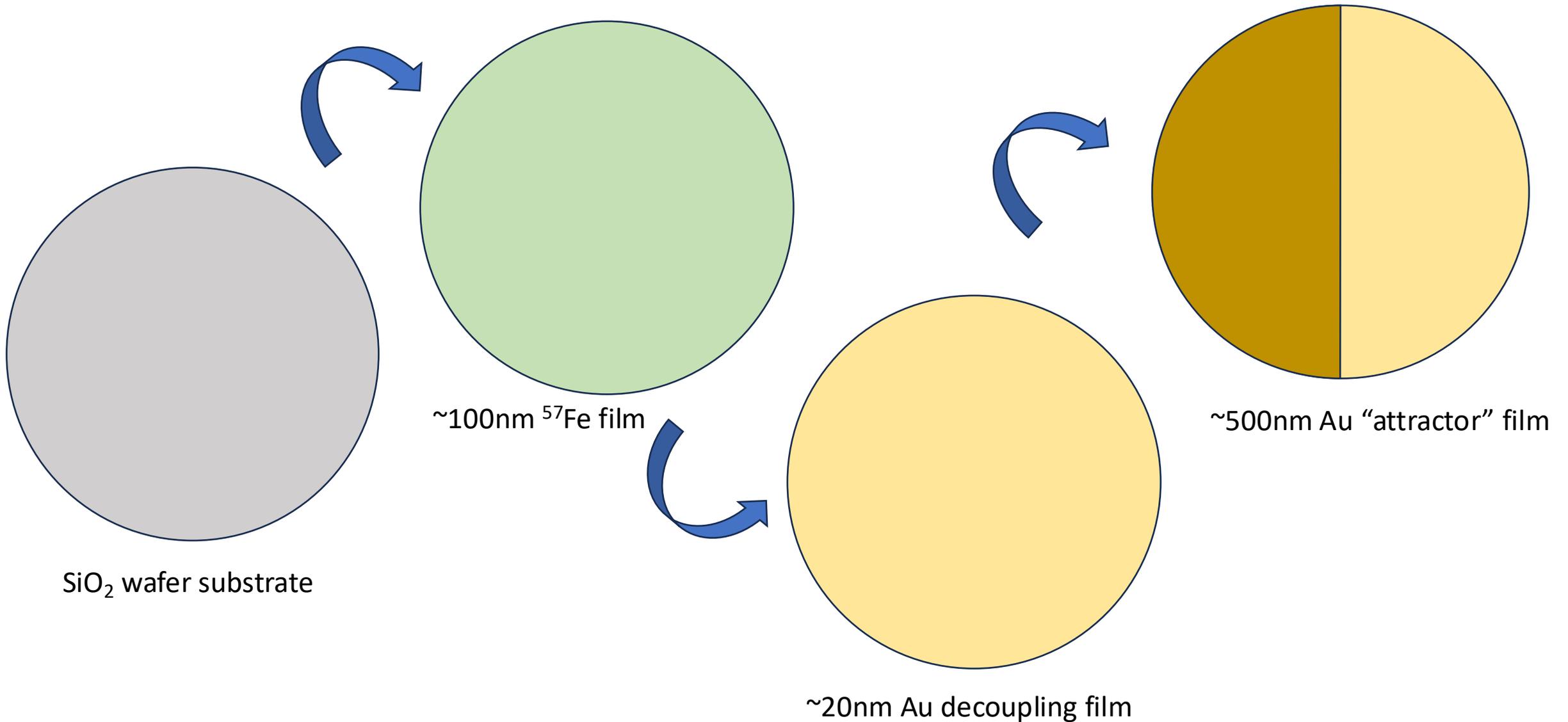
Nuclide	E (eV)	$T_{1/2}$	Γ (eV)	Γ/E
$^{57}_{26}\text{Fe}$	14,413	98.3 ns	4.7×10^{-9}	6.4×10^{-13}
$^{73}_{32}\text{Ge}$	13,328	2.92 μs	1.6×10^{-10}	1.2×10^{-14}
$^{181}_{73}\text{Ta}$	6,237	6.05 μs	7.5×10^{-11}	1.2×10^{-14}
$^{67}_{30}\text{Zn}$	93,300	9.07 μs	5.0×10^{-11}	5.4×10^{-16}
$^{45}_{21}\text{Sc}$	12,400	318 ms	1.4×10^{-15}	1.13×10^{-19}
$^{107}_{47}\text{Ag}$	93,125	44.3 s	1.03×10^{-17}	1.1×10^{-22}
$^{103}_{45}\text{Rh}$	39,753	56.1 min	1.36×10^{-19}	3.4×10^{-24}
$^{189}_{76}\text{Os}$	30,814	5.8 hr	2.2×10^{-20}	7.0×10^{-25}

Essentially unexplored



For reference, aLIGO strain sensitivity:
 $\delta l/l \sim 10^{-23}/\sqrt{\text{Hz}}$

First version of the experiment



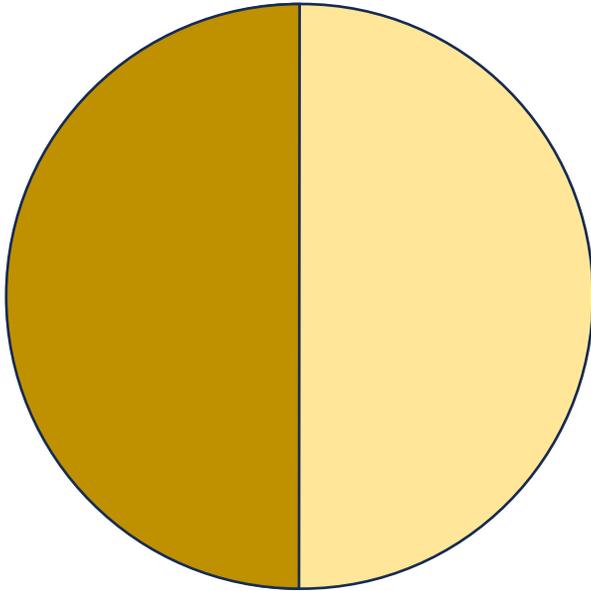
SiO_2 wafer substrate

$\sim 100\text{nm}$ ^{57}Fe film

$\sim 20\text{nm}$ Au decoupling film

$\sim 500\text{nm}$ Au "attractor" film

Variable-distance device



Multi-layer device

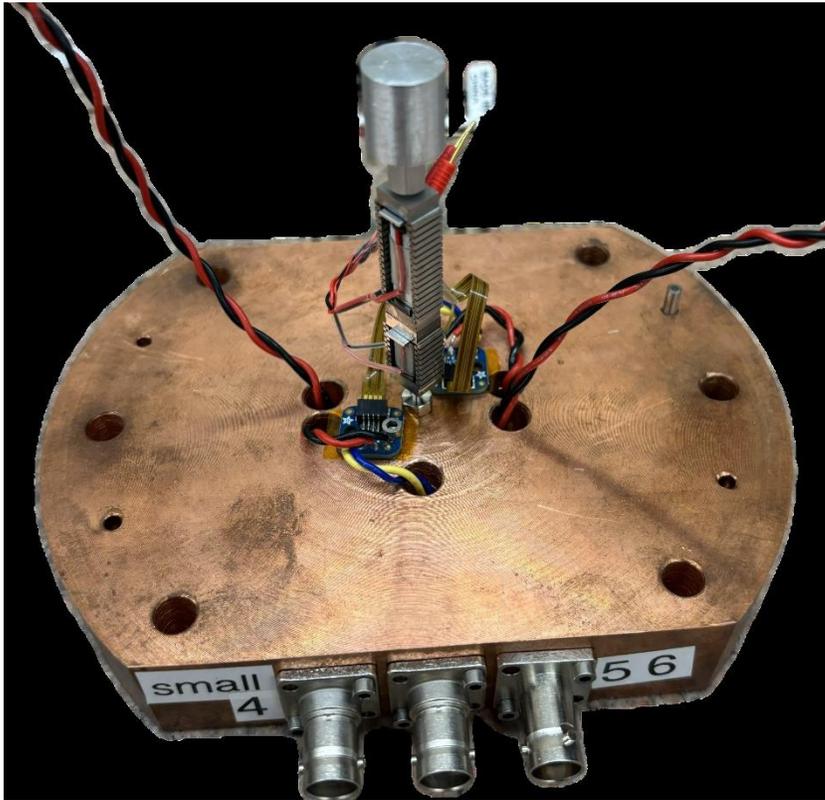


A variable-distance setup has the advantage of allowing for a change in distance during the experiment.

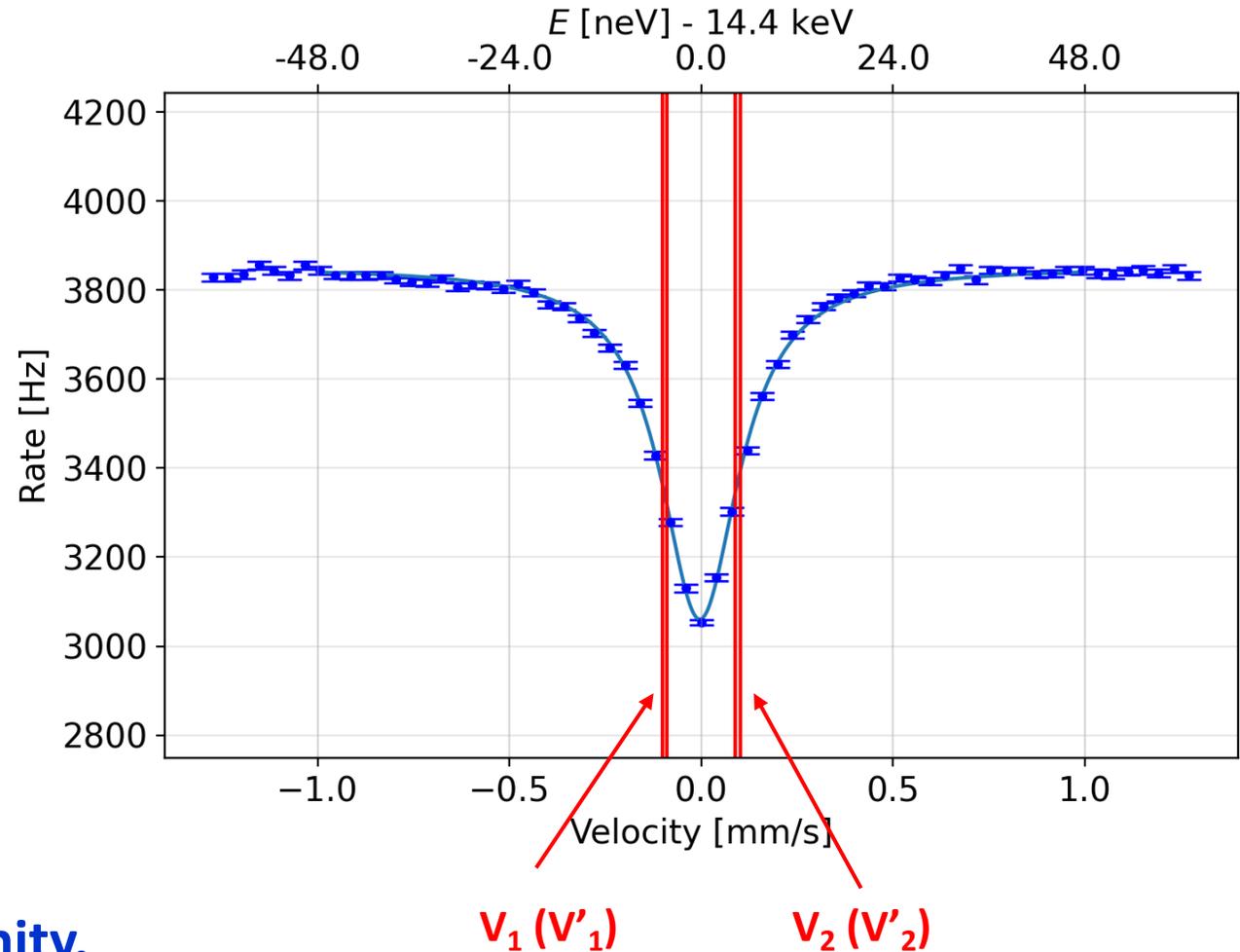
→ Complex mechanics

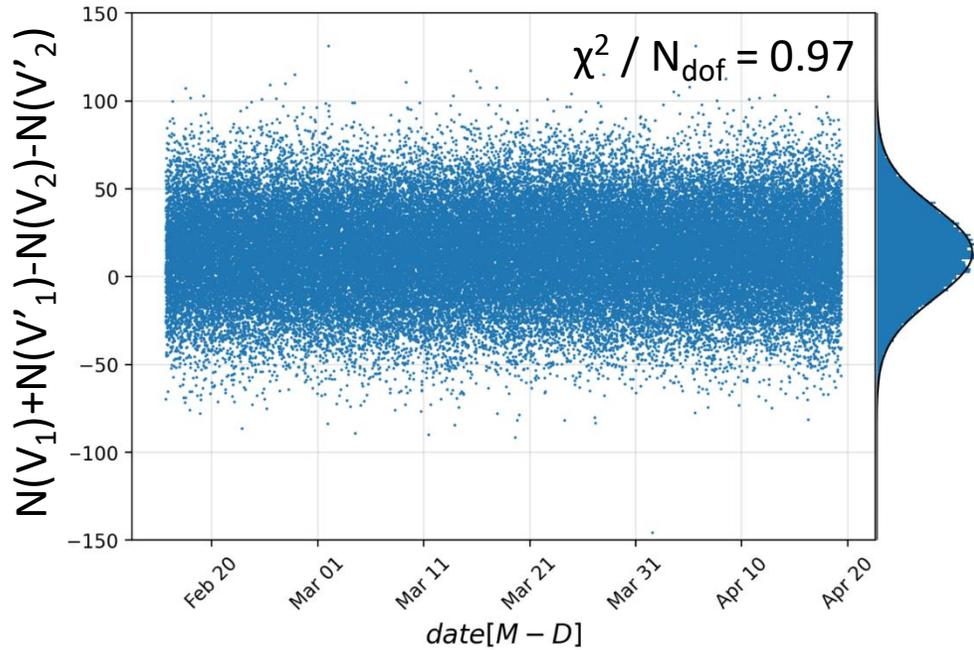
→ To be developed after a positive signal is observed!

Custom piezoelectric spectrometer



Use statistics optimally to measure the position of the resonance, and for temperature stability and uniformity.

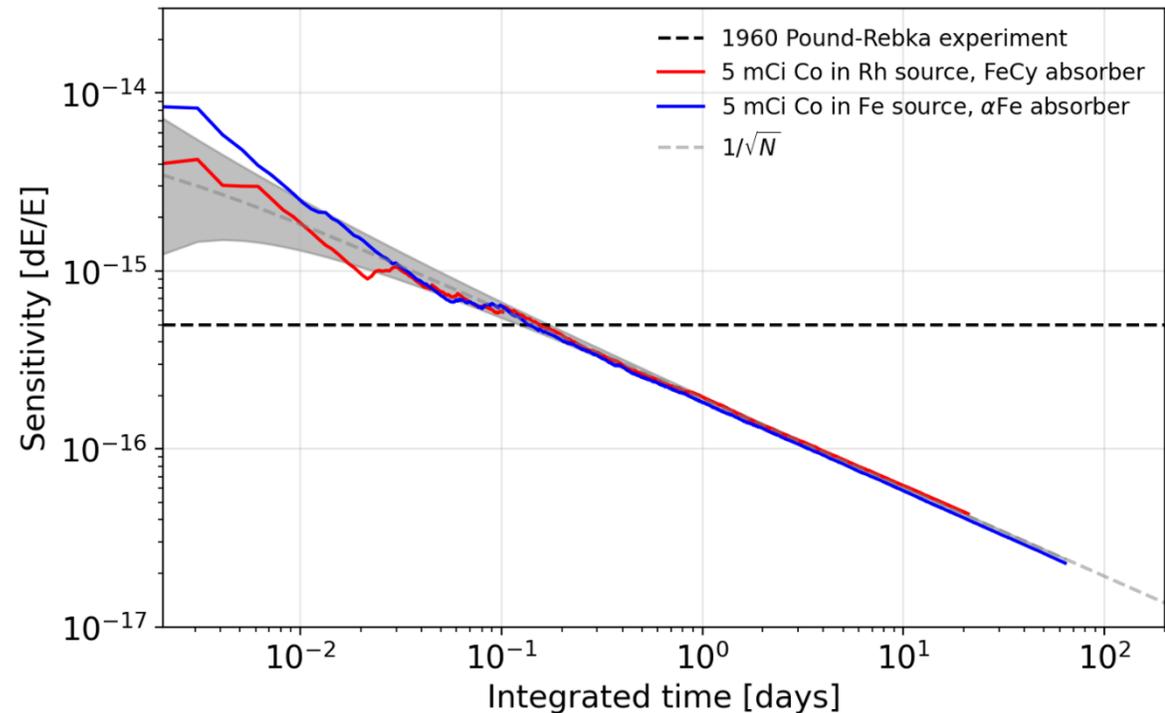




The energy is stable to 2×10^{-17} , similar to the best optical clocks.

Required statistics $\times 10^4$
(largest improvement from a hotter source).

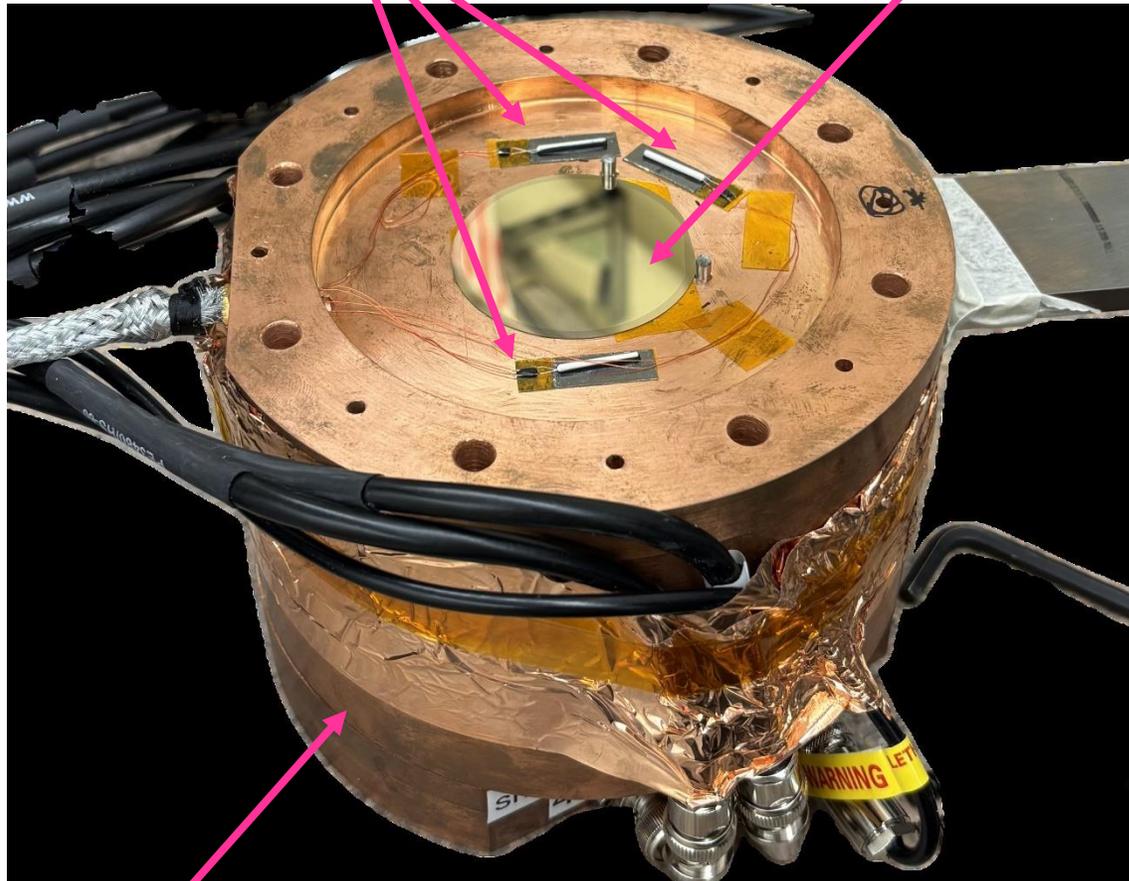
Test with >60 days of data with the 5mCi ^{57}Co source in α -iron lattice:
 → so far the energy shift sensitivity follows the \sqrt{N} behavior.



High-rate camera goes on top

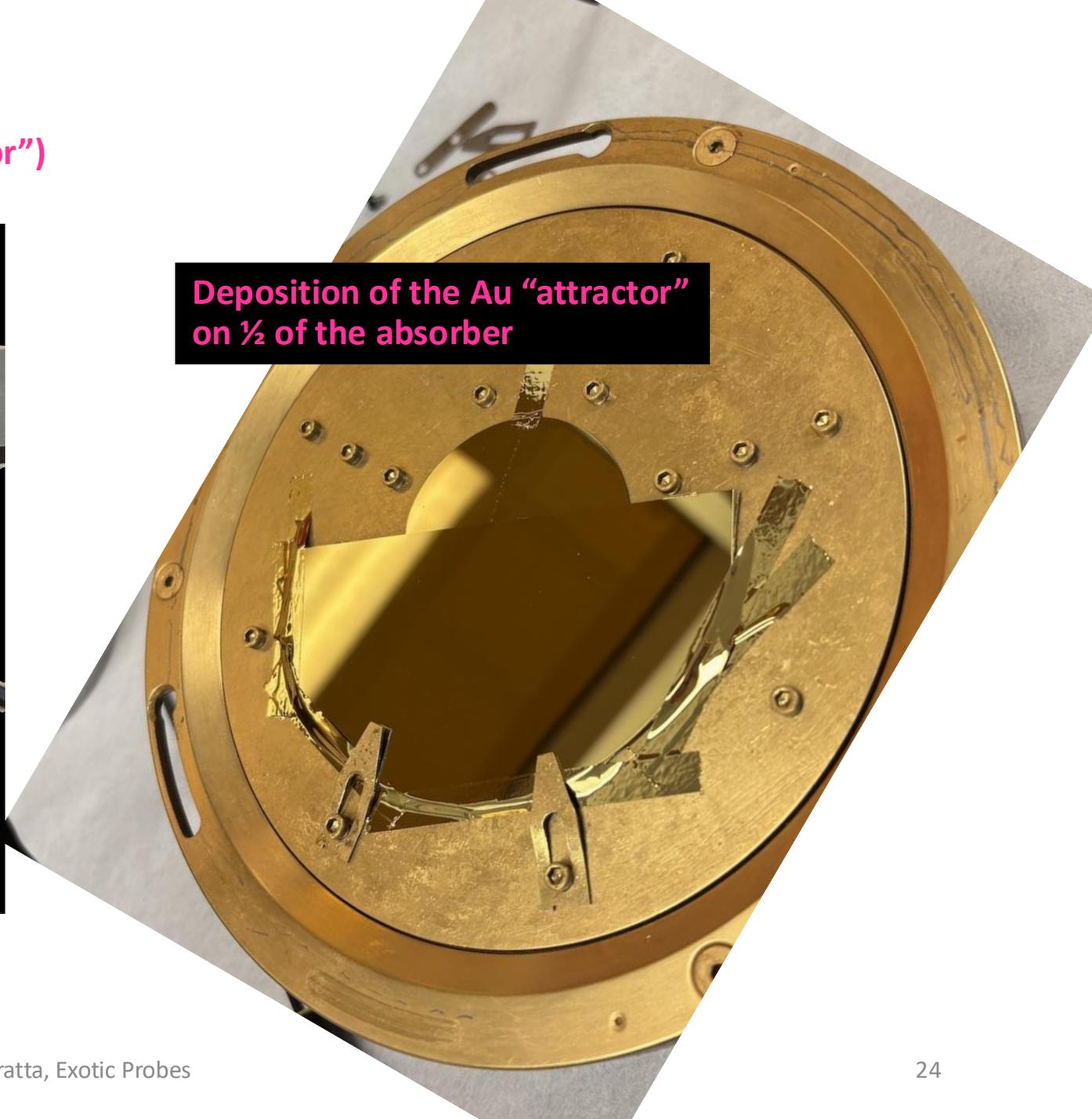
Precision RTDs

^{57}Fe absorber (no "attractor")



Source and piezo drives inside

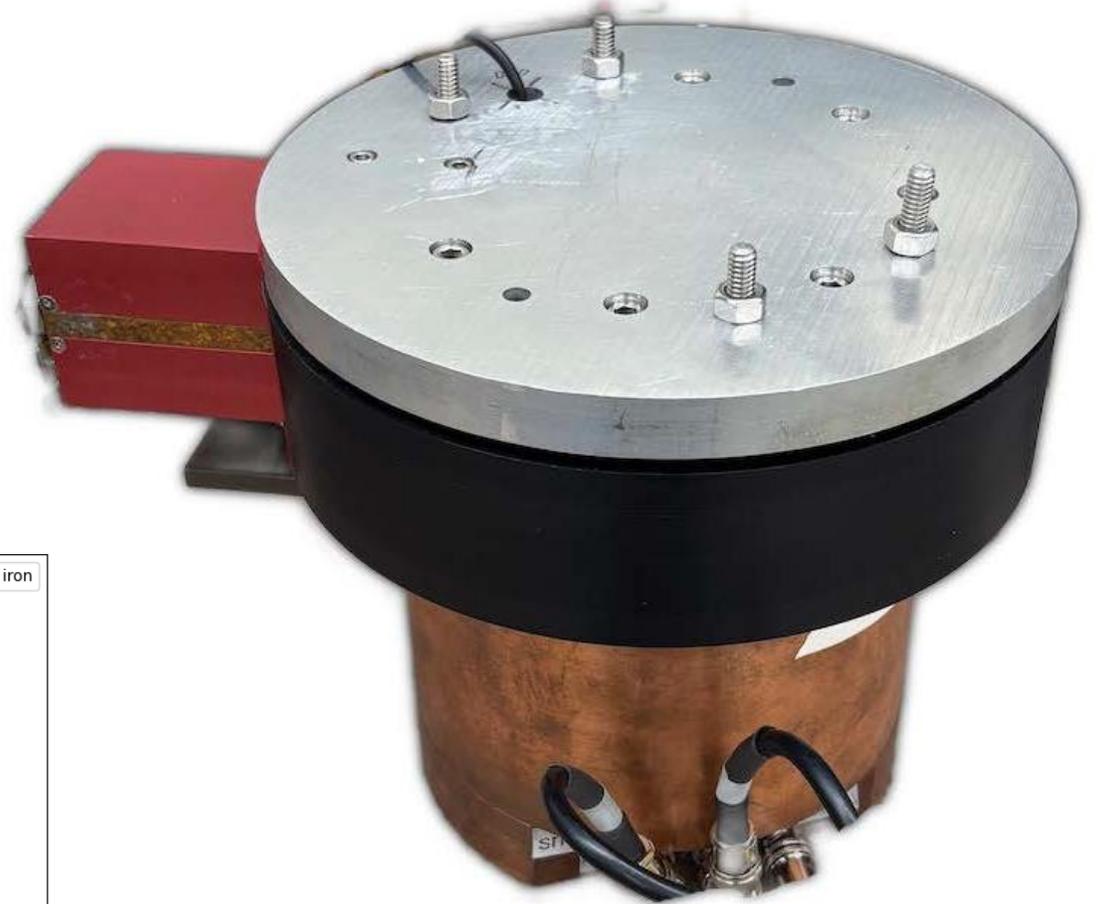
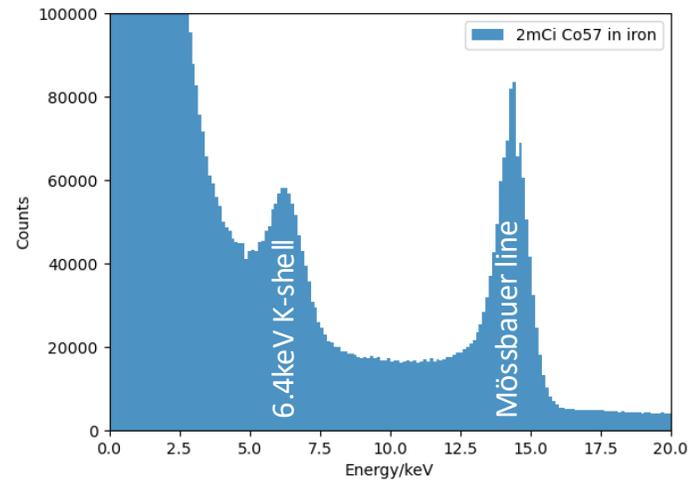
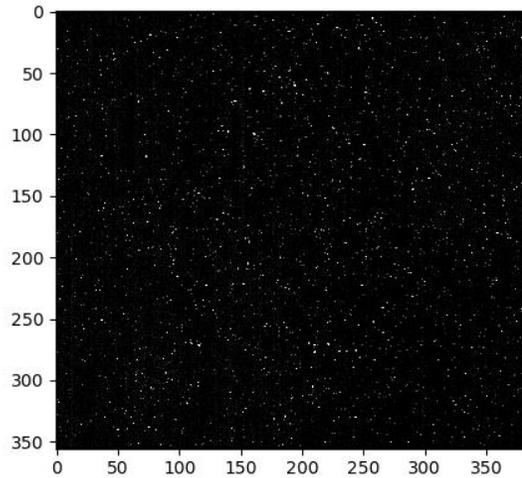
Deposition of the Au "attractor" on $\frac{1}{2}$ of the absorber



First science run started in Dec 2025 with a 50mCi source: use a 2Mpixel X-ray camera



KPIX detector originally designed/built by SLAC for synchrotron light detection at LCLS.



Beyond the first experiments

- Narrower sources being worked on: ^{181}Ta , ^{73}Ge
- Can also do an experiment where the absorber is an alloy of the Mössbauer nucleus and a nucleus available in two very different masses. E.g. ^{122}Te and ^{130}Te .

Accelerator-produced photons can be used to directly excite the nuclear isomeric states.

- *Access a much broader set of isotopes/isomeric states, some way narrower.*
- *Absorber and emitter can be the same species, great simplification.*
- *Can also use the pulsed structure of the exciting beam to suppress backgrounds.*

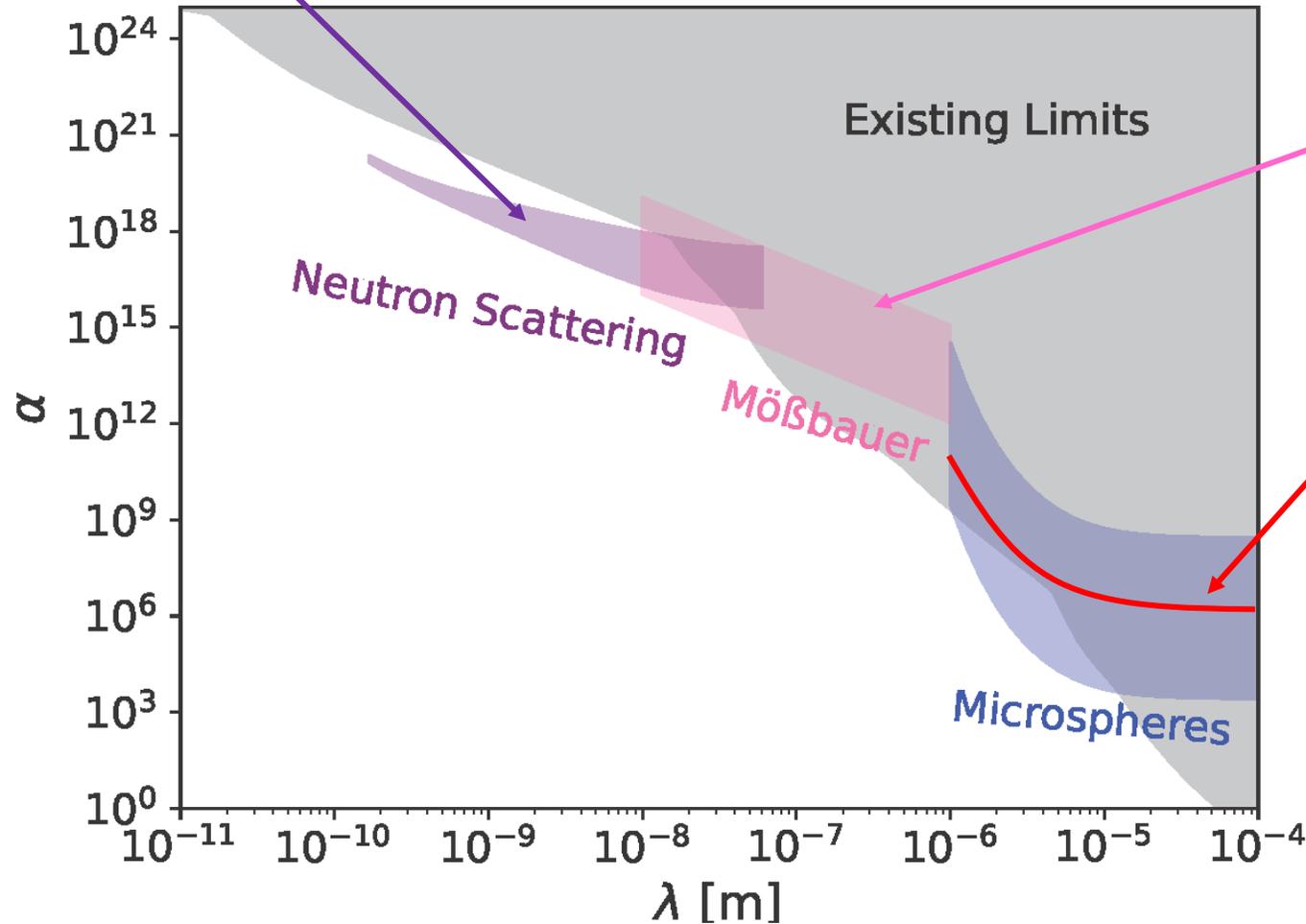
(Also pursued by others)

→ ***Nuclear Quantum Optics!***

Aspirations of our program (the bands are projections)

“Xenon 1g” Z. Bogorad, P. Graham, GG,
Phys Rev D 108 (2023) 055005

Also a motivation to “nuclear quantum optics”, with various potential applications.
GG, D.E. Kaplan, S. Rajendran,
Phys Rev D 102 (2020) 115031.

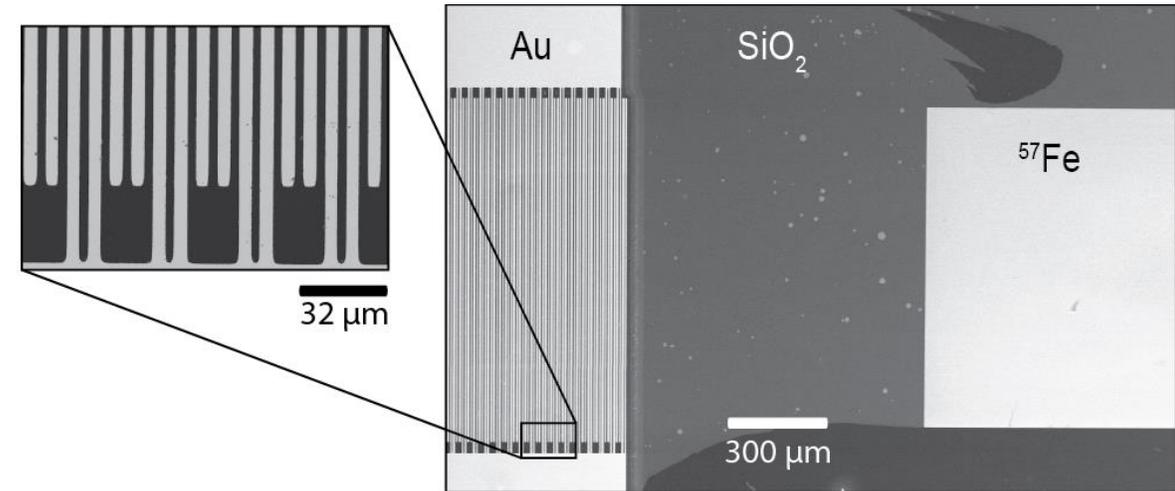
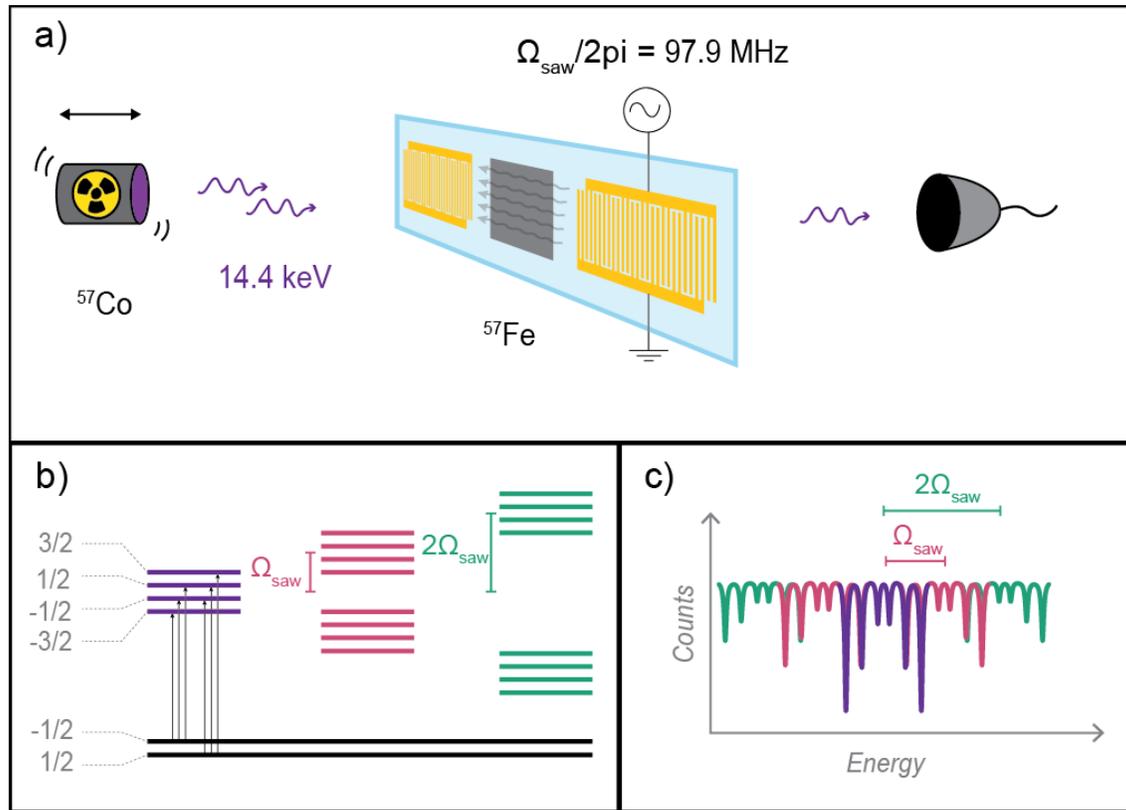


Recent result:

G.Venugopalan et al. *arXiv:2412.13167*
Also, application to neutrality of matter,
inertial sensing, quantum S&T

It is also desirable to have some overlap between techniques, convenient in case of a discovery.

A first example: a gamma-ray acousto-optic modulator

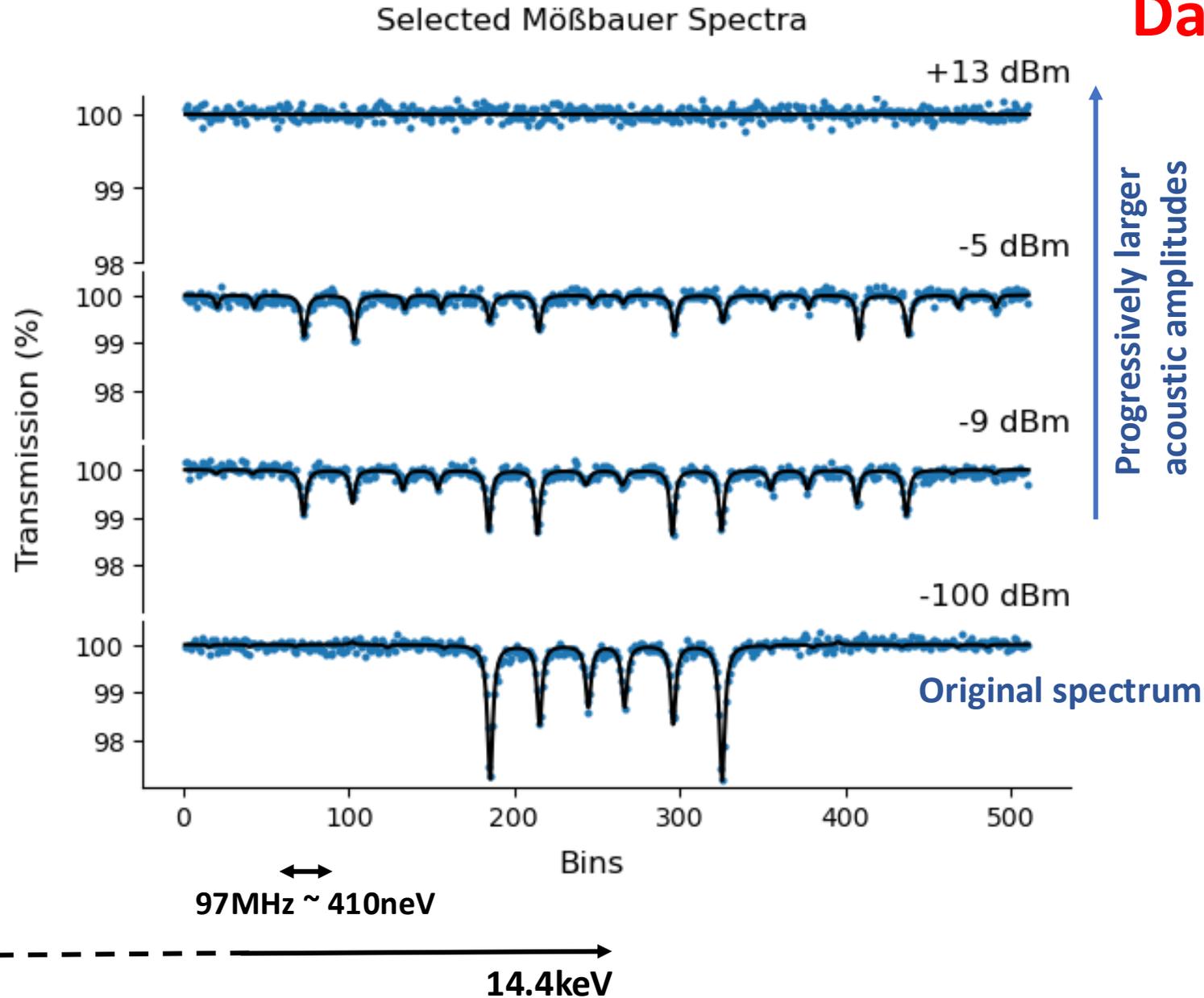


Like in an AOM, phonons in the quartz transfer energy to the γ -rays, producing higher order modes.

This is happening in the regime where $\tau_{\text{SAW}} \sim 10\text{ns} < \tau_{\text{Fe-57}} \sim T_{1/2}/\sqrt{2} \sim 70\text{ns}$

This device: acoustic frequency, 97 MHz, is almost exactly the same as the energy difference between different m states, producing various degeneracies.

Data: a tunable γ -ray source!



Note that the integral of counts is constant in the different spectra.

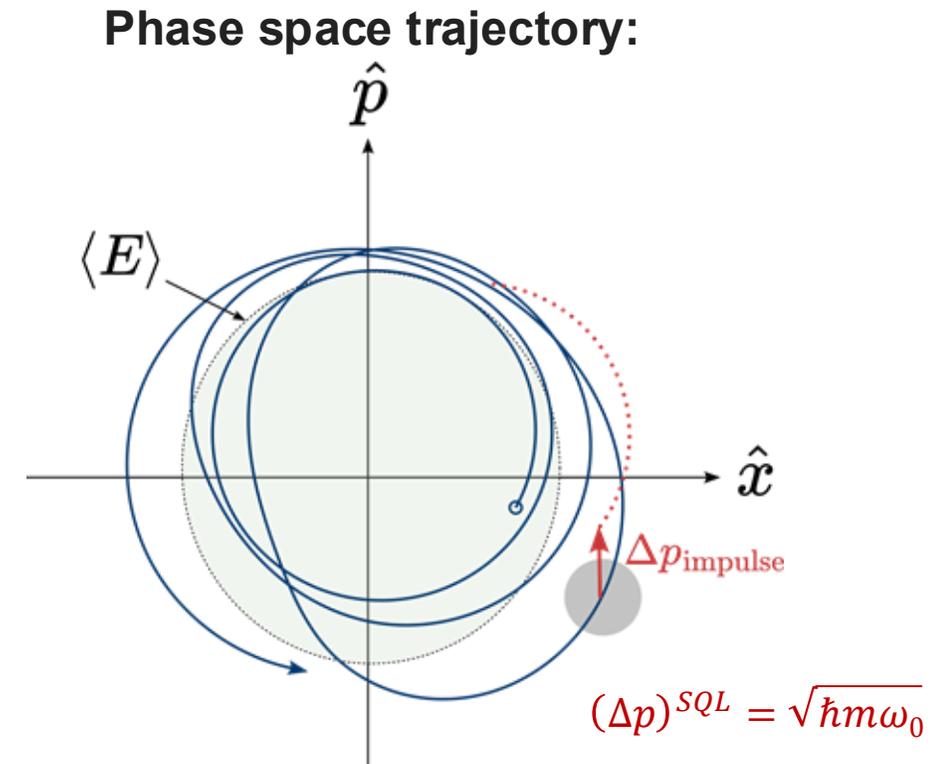
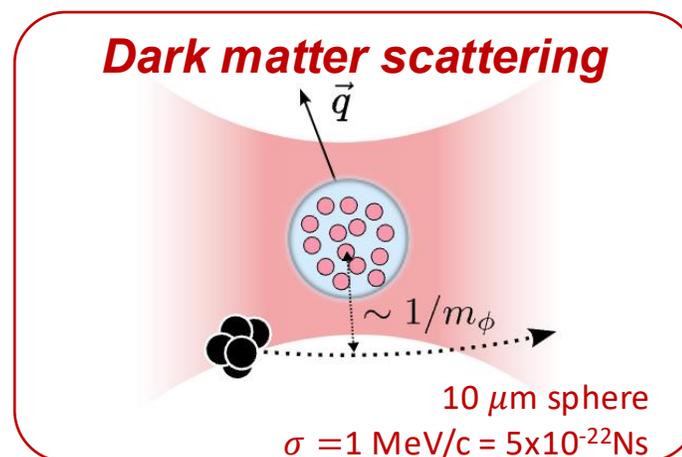
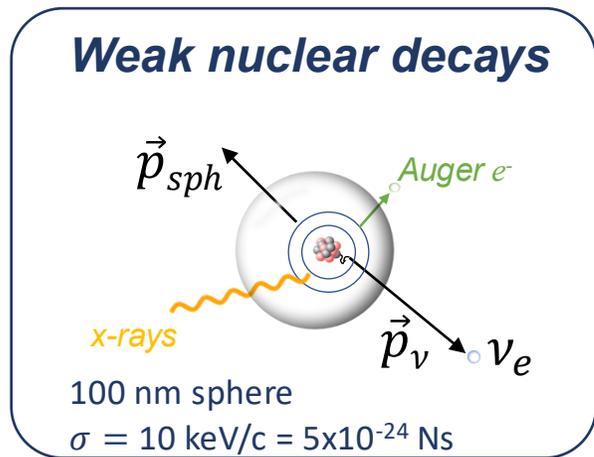
As the acoustic amplitude increases, a larger fraction of the integral is contributed by sidebands away from the center.

Note that at max amplitude, the counts are all in far away sidebands (out of range for the spectrometer).

Recoiling micro/nano-spheres (work mainly by D.Moore's group, Yale)

- Levitated sensors are reaching sensitivity to the tiny forces from single sub-atomic particles
 - For weak decays, allows the momentum of each ν to be reconstructed on an event-by-event basis
 - Can also enable new searches for dark matter scattering via a long range force

Example force measurements relevant for fundamental physics:



PRL133, 023602 (2024), arXiv:2402.13257
 PRX Q 4, 010315 (2023), arXiv:2207.05883

PRL 128, 101301 (2022), arXiv:2111.03597
 PRL 127, 061804 (2021), arXiv:2104.05737
 PRL 125, 181102 (2020), arXiv:2007.12067

See, also, e.g.:

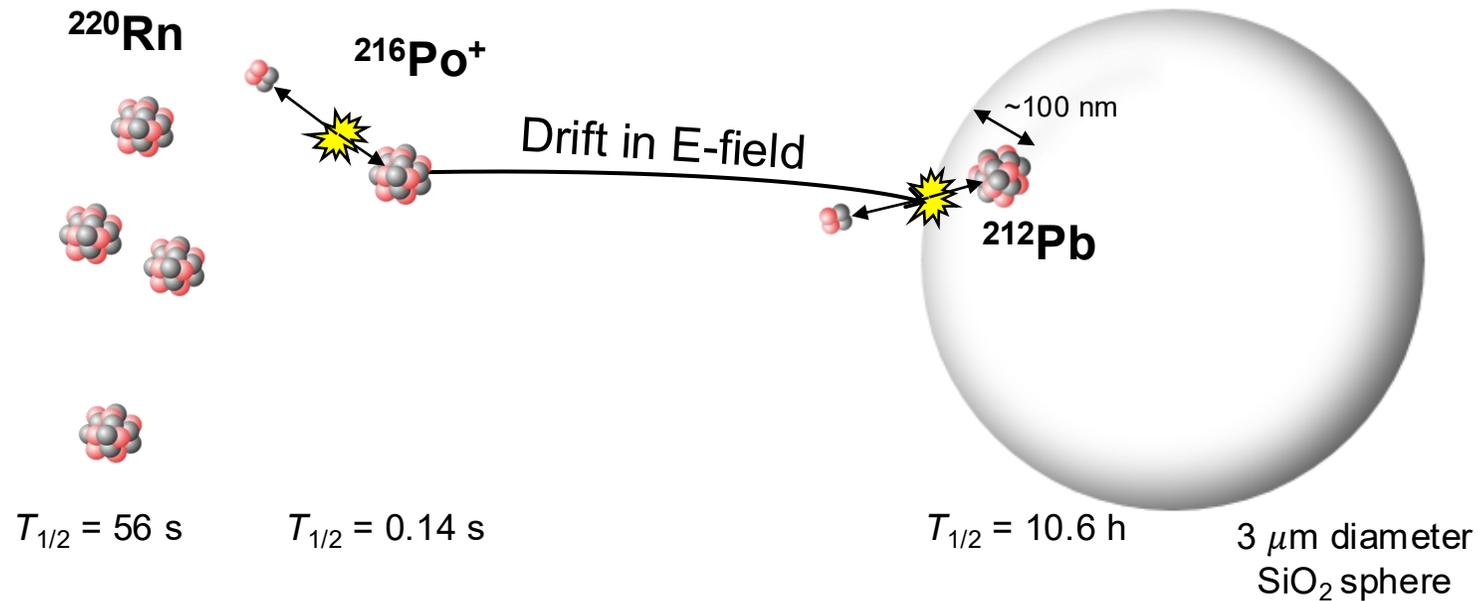
Magrini et al., Nature 595, 373 (2021)

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

Proof of principle (α decays)

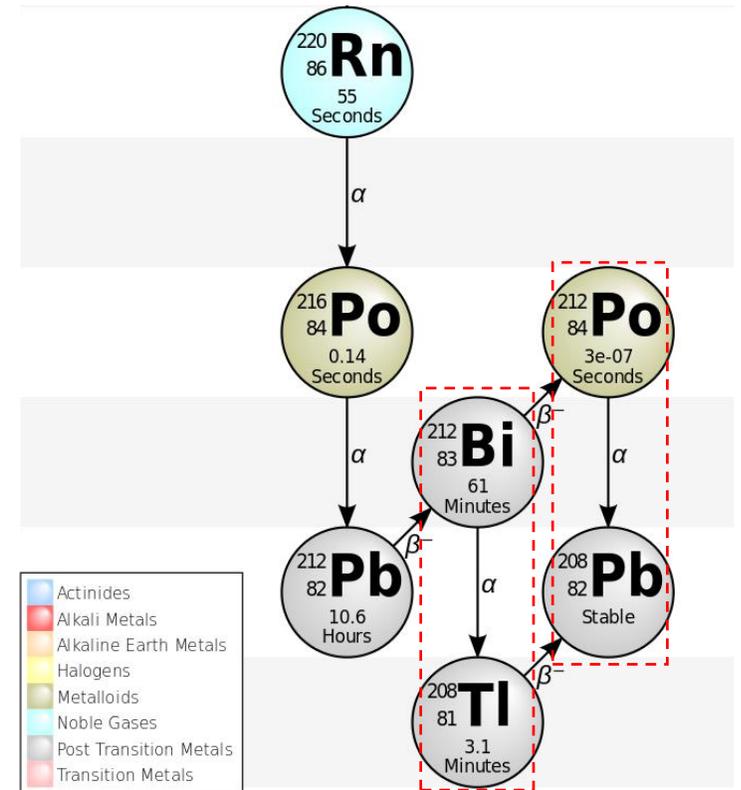
- As a proof-of-principle, we have detected single α decays with $>\mu\text{m}$ sized spheres
 - Momentum is $\sim 200 \text{ MeV}/c$ (compared to $0.1\text{-}1 \text{ MeV}/c$ for typical ν, γ)
- Have demonstrated loading of small quantities of ^{212}Pb into trapped microspheres

Schematic of loading scheme:



J. Wang et al, PRL133, 023602 (2024), arXiv:2402.13257

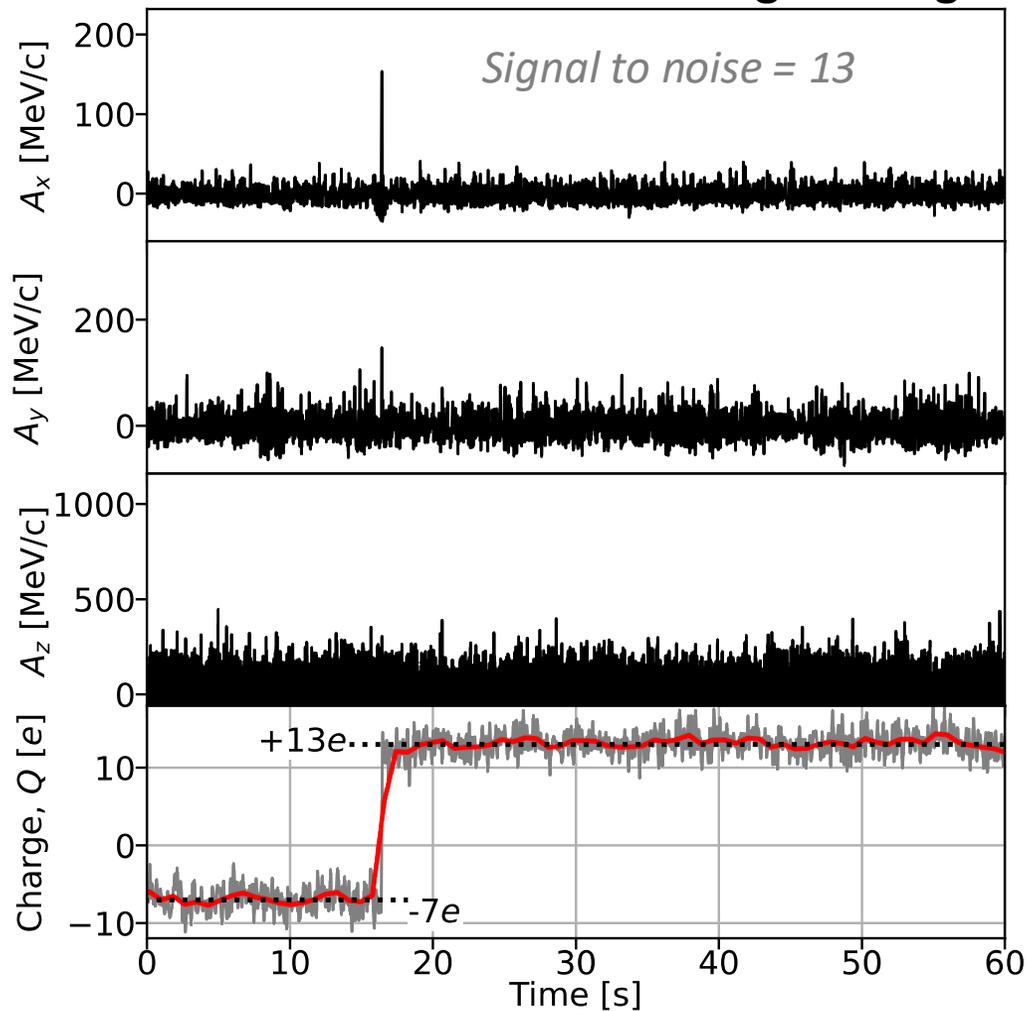
Rn-220 decay chain:



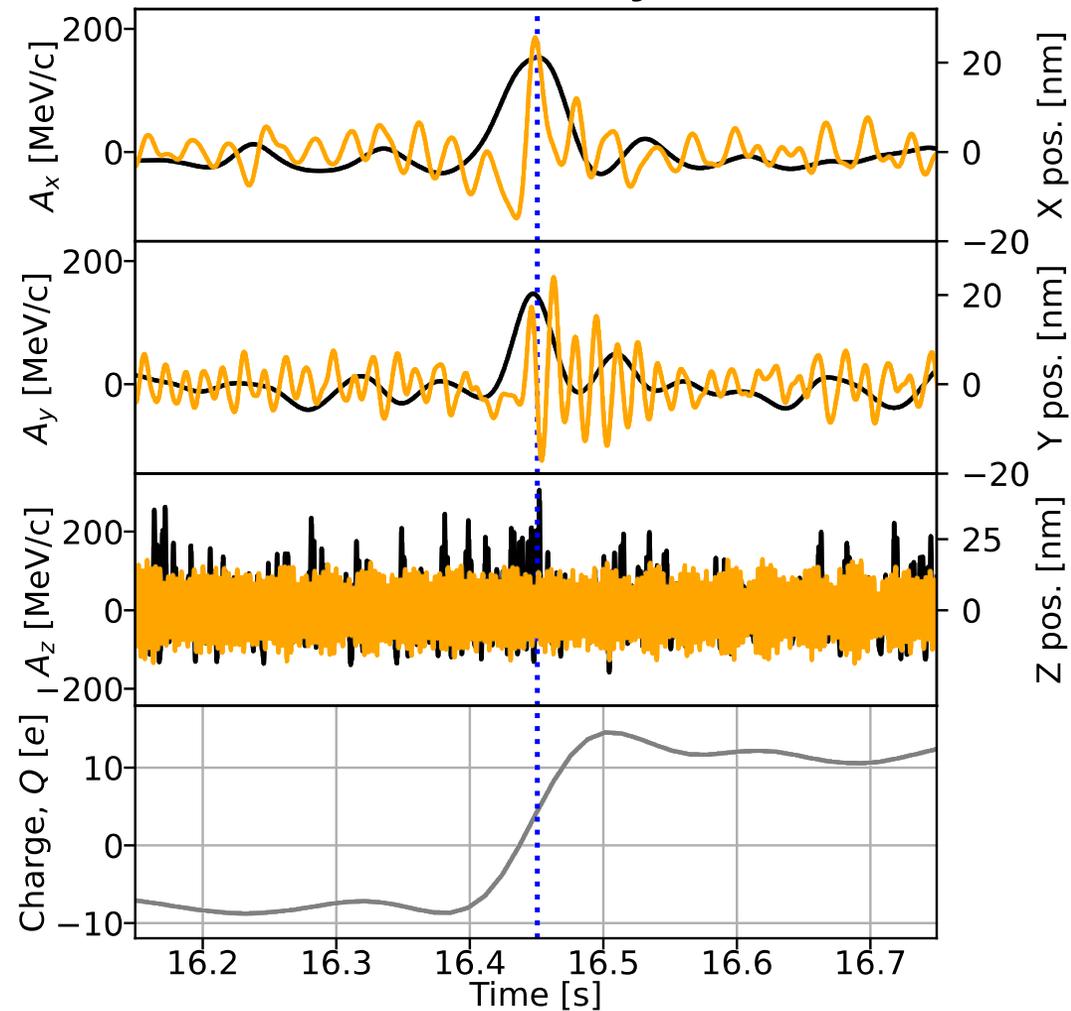
Detection of single nuclear decays

- Reconstruct recoil of the particle correlated with the decay time (identified by charge change)

Recoil coincident with charge change:



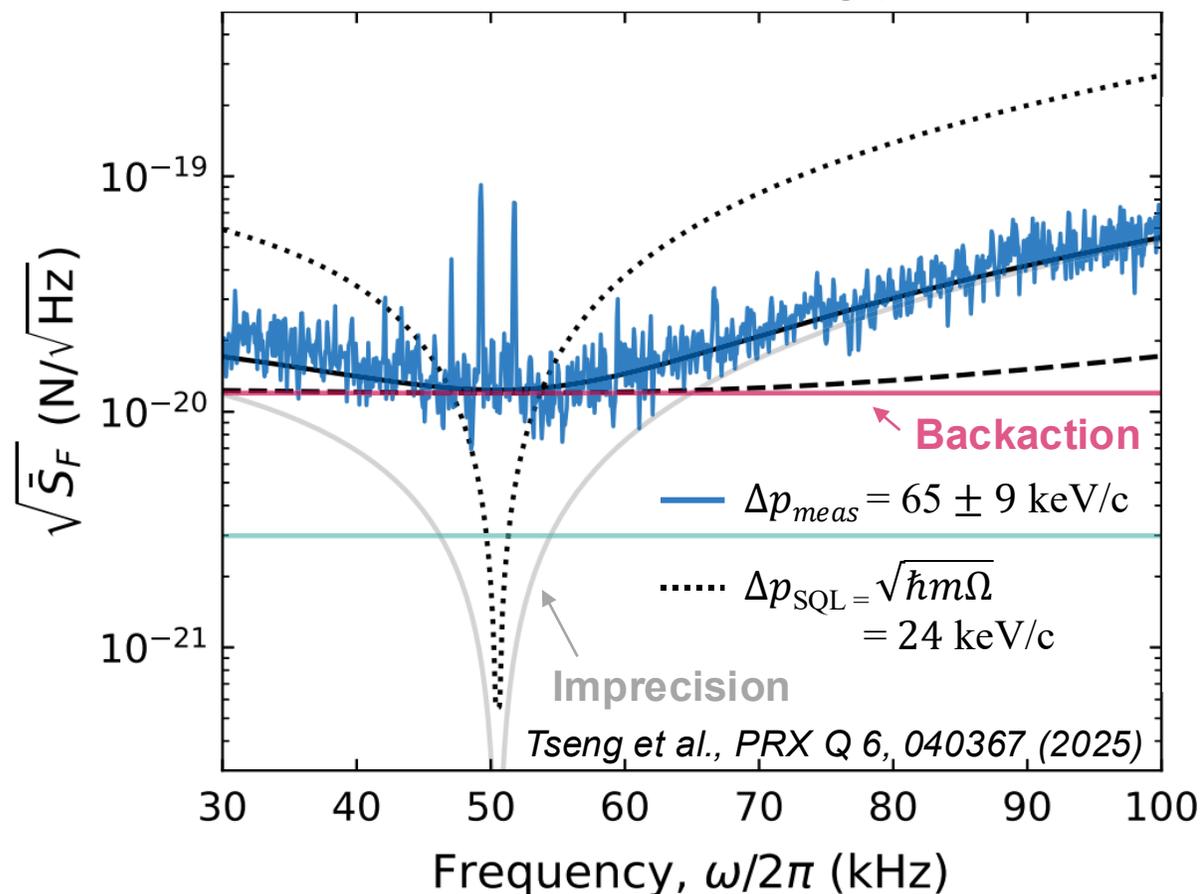
Zoom to decay time:



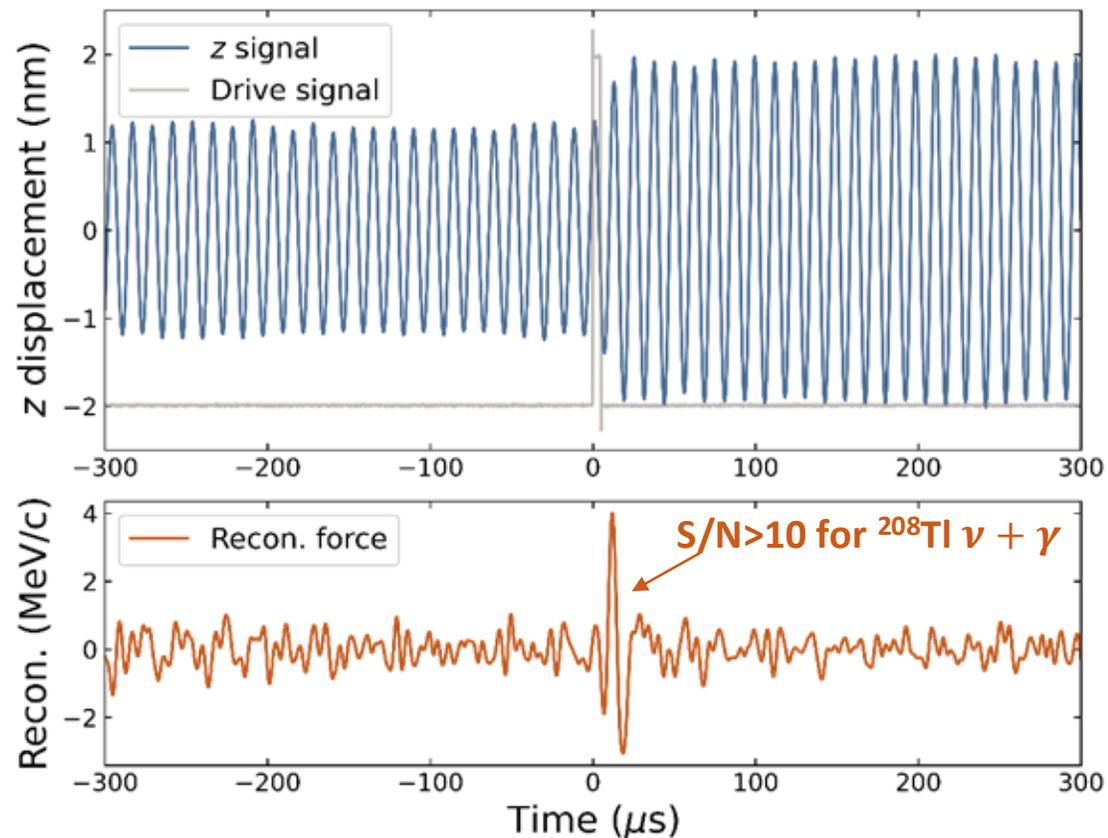
Smaller spheres (fg mass)

- In parallel, have reached required sensitivity to detect neutrinos with high signal-to-noise with ~ 150 nm diameter spheres
- Resolution within $< 3x$ of “Standard Quantum Limit” (SQL), limited by measurement backaction

Measured force noise, 5 fg particle:



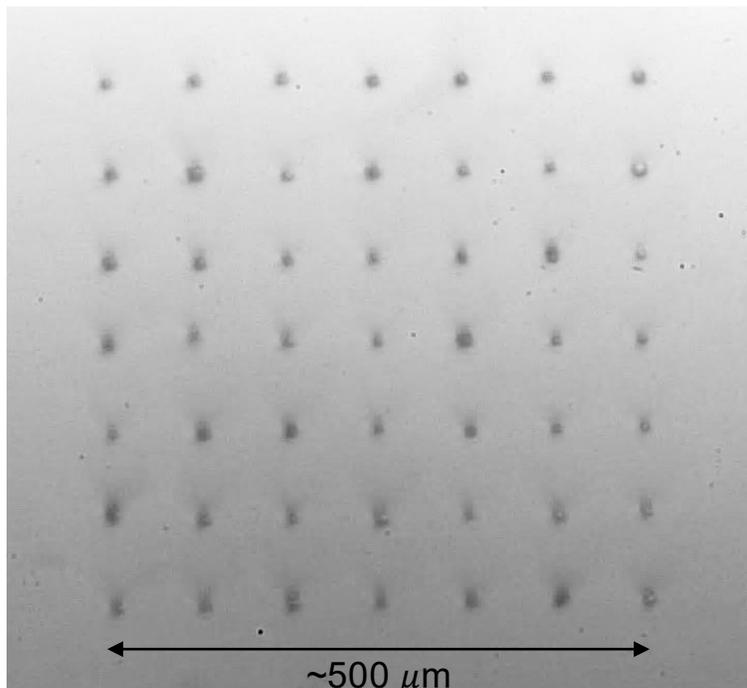
Calibrated response, 5 fg particle (4 MeV/c):



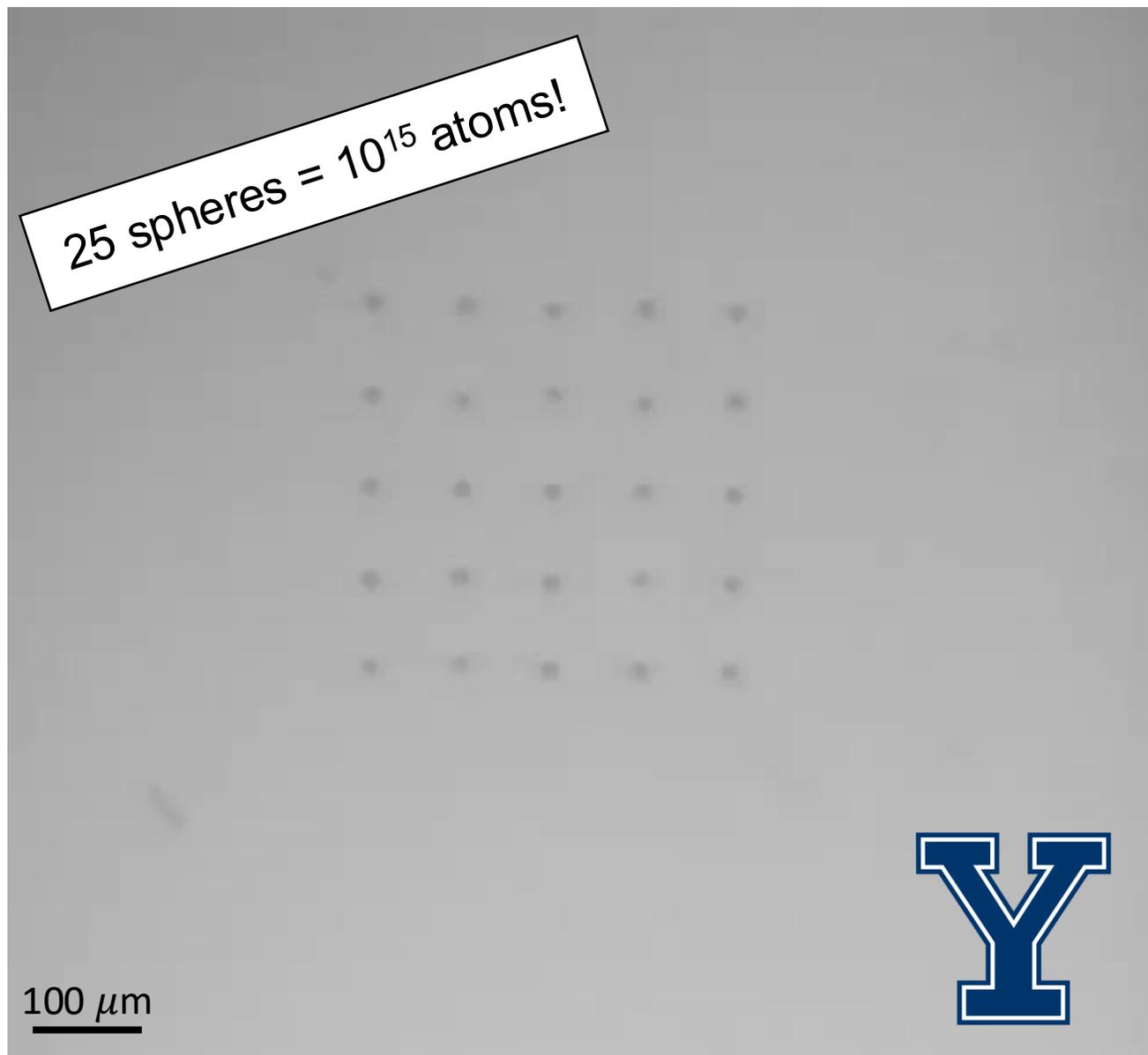
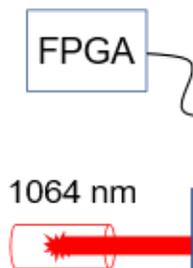
Microsphere arrays

- Microsphere trap at Yale has been upgraded to allow up to $\sim 10 \times 10$ arrays
- Similar technology to tweezer arrays for
→ Real time control over trap position

7x7 array of spheres in vacuum:



Siegel et al. PRA 111, 033514 (2025)

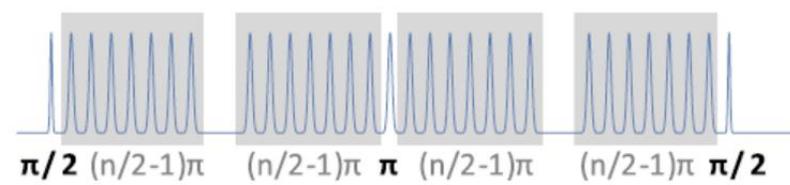
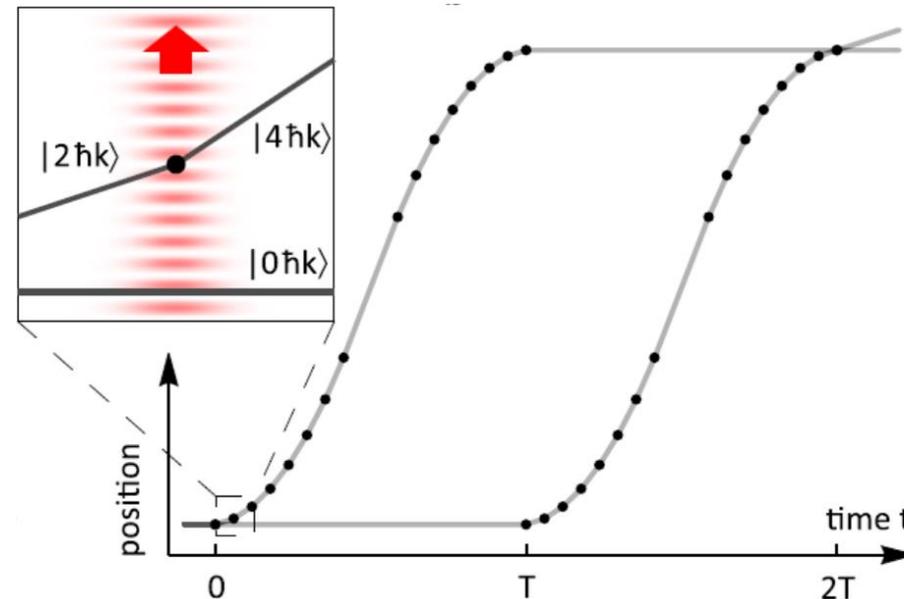
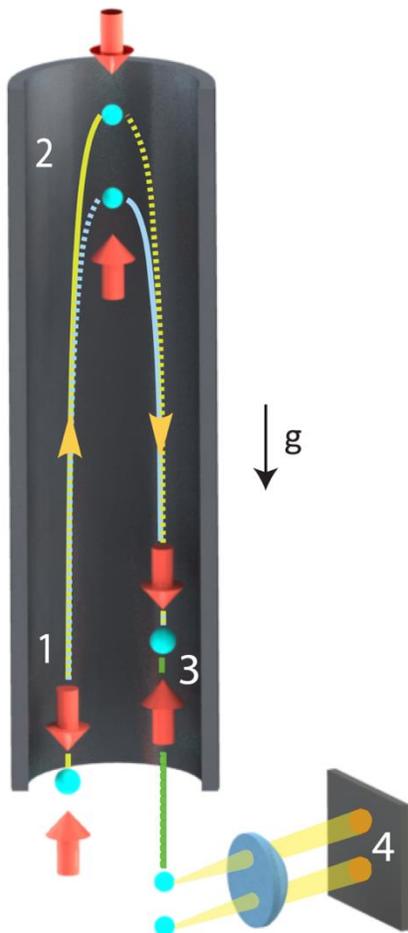


Played at 8x speed

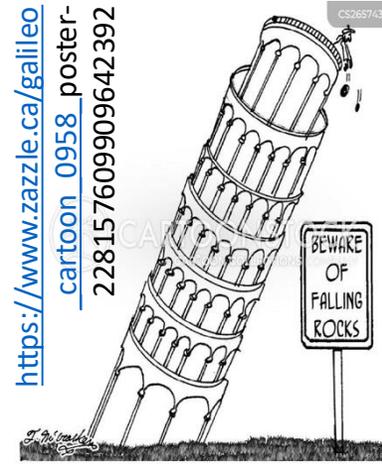
Testing the equivalence principle 450 years after Galileo:

Interferometry, when feasible, wins!

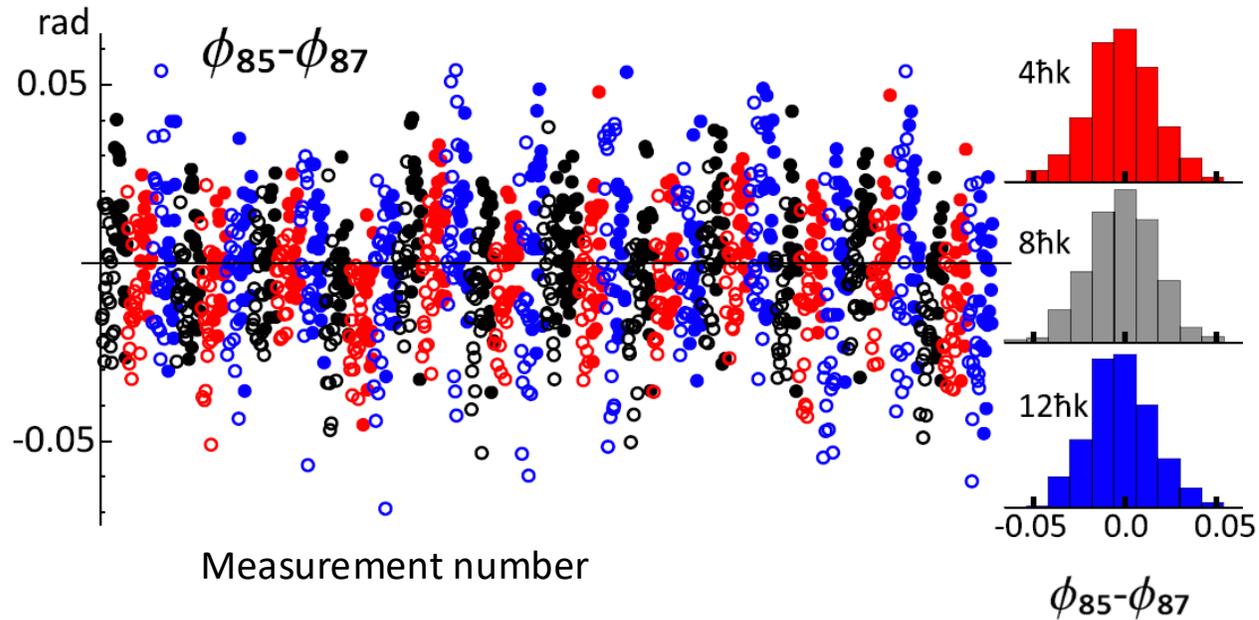
$^{87}\text{Rb}/^{85}\text{Rb}$ free fall interferometer



A sequence of light pulses coherently divide, re-direct and recombine atomic wavepackets



The differential accelerations of ^{85}Rb and ^{87}Rb are inferred by comparing phase shifts for atom interferometers.



Parameter	Shift	Uncertainty
Total kinematic	1.5	2.0
Δz		1.0
Δv_z	1.5	0.7
Δx		0.04
Δv_x		0.04
Δy		0.2
Δv_y		0.2
Width		1.6
ac-Stark shift		<u>2.7</u>
Magnetic gradient	-5.9	0.5
Pulse timing		0.04
Blackbody radiation		0.01
Total systematic	-4.4	3.4
Statistical		1.8

$$\eta = [1.6 \pm 1.8(\text{stat}) \pm 3.4(\text{syst})] \times 10^{-12}$$

P.Asembaum et al, Phys. Rev. Lett. 125, 191101 (2020)

Other competitive results: $\sim 10^{-13}$ (torsion balance) and 10^{-14} (Microscope spacecraft)

In the Standard Model the Electric Dipole Moment (EDM) of elementary particles is extremely small and not measurable in the near future.

A number of New Physics ideas can render the EDM much larger

→ Searches for EDM are searches for New Physics.

A large class of experiments, generally using subtle and beautiful techniques.

Some general comments:

The measurement requires subjecting the particle to a large E-field

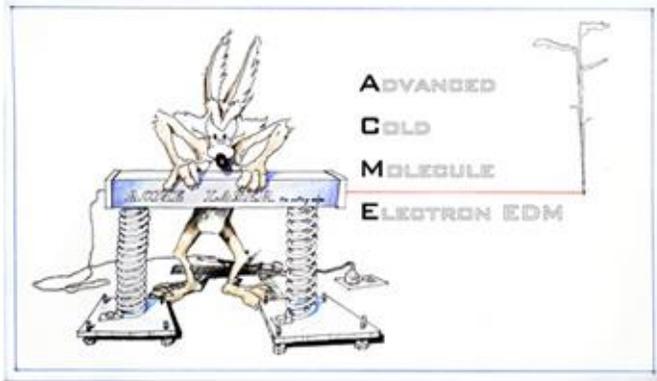
→ Charged particles are swept away, unless they are actually stored in a specifically designed storage ring (this is a new technique).

→ EDM of charged particles (such as e^- or p) can be studied in atoms or molecules (there are loopholes in Schiff screening, after all).

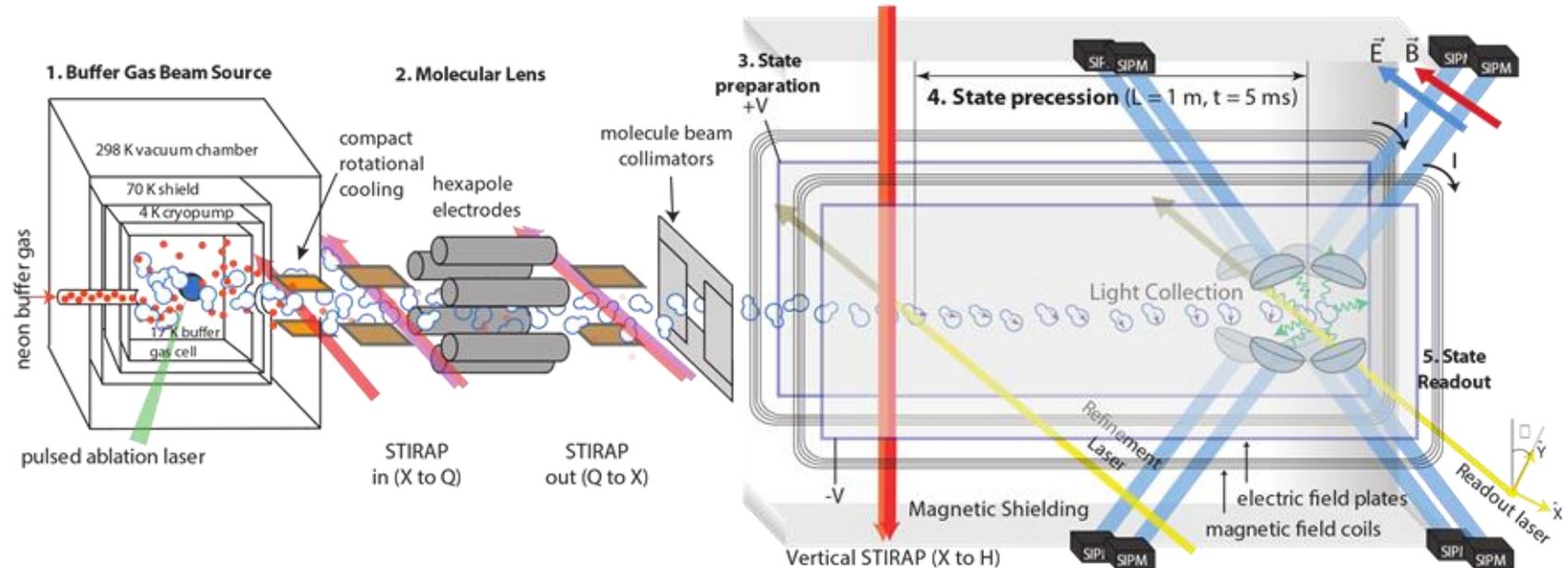
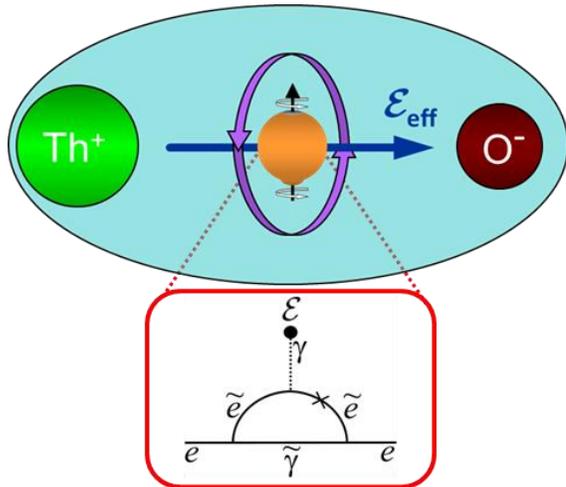
→ Free neutrons can be used (Ultracold neutrons in modern experiments) and they provide the simplest measurements to interpret.

All measurements are limited by statistical as well as systematical effects.

EDM measurements for e^- or p in atoms or molecules use changes in spectroscopy when the E field is applied



- Electron experiences huge (80 GV/cm) effective E-field in ThO molecule
- Cold, slow molecular beam \rightarrow excellent statistics, long spin coherence time
- Powerful rejection of systematics from particular molecular structure: “internal co-magnetometer”, suppressed magnetic sensitivity



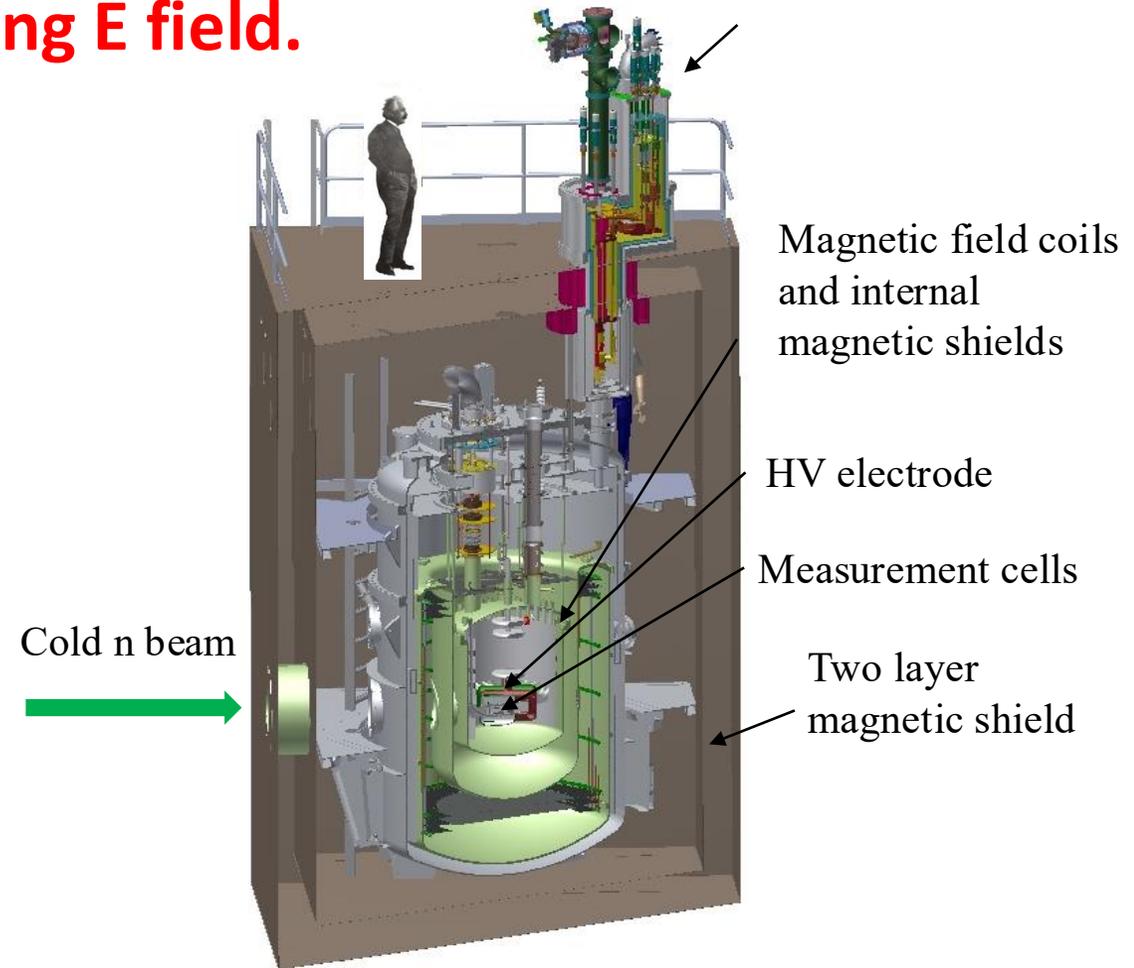
ACME III projected sensitivity $\sim 1.3 \times 10^{-31}$ e·cm (30-fold improvement)

Neutron EDM is generally measured as a change in the spin precession frequency when applying a strong E field.

- **Statistical uncertainties:** “neutrons don’t exist”
 - experiments being designed to do the measurement in Superfluid He
 - Lower n losses → Higher neutron density
 - Higher HV possible
- **Systematics:** most important is residual mag fields (~ 1 pTesla/cm “=“ 10^{-28} e-cm)
 - “Co-Magnetometry”
 - Lots of redundancy

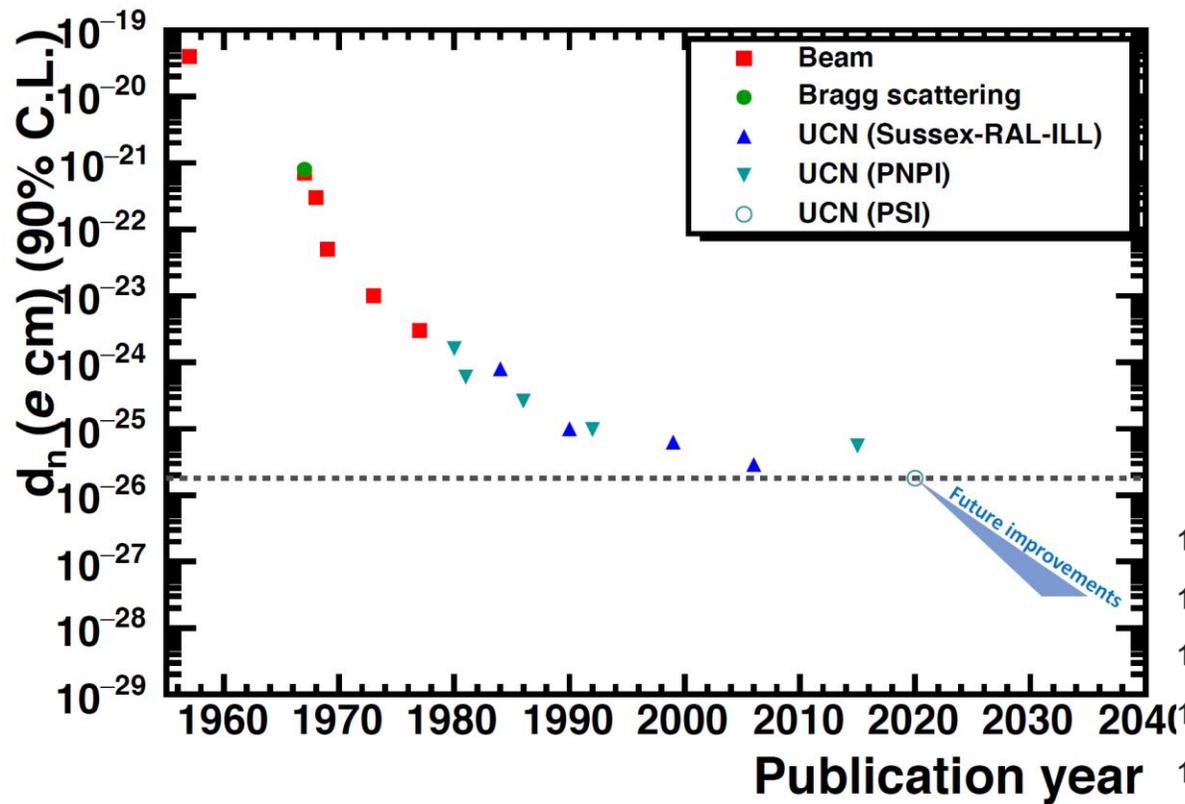
Expected sensitivity: $\sim 3 \times 10^{-28}$ e-cm

Standard Model says $d_n \sim 10^{-32}$ e-cm

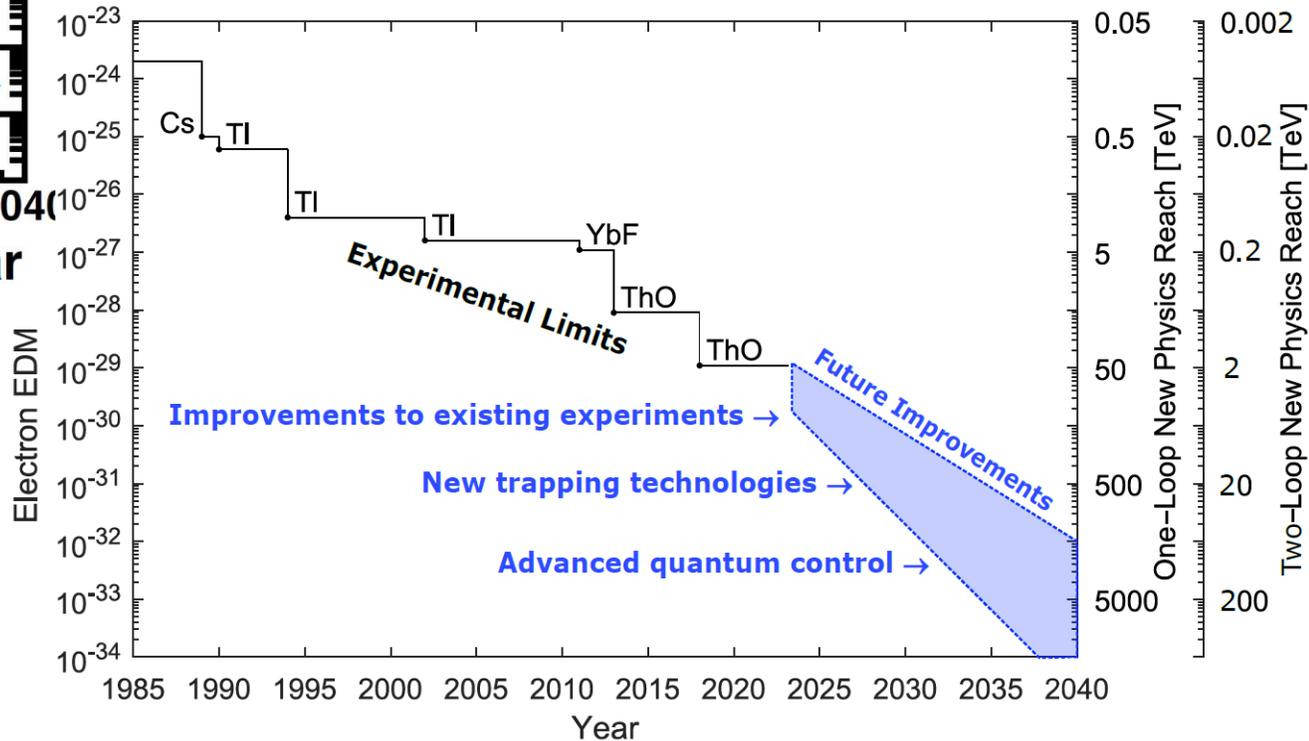


Example: NDM@SNS

Concept by R. Golub & S. K. Lamoreaux,
Phys. Rep. 237, 1 (1994)



EDM sensitivity with neutrons and atom/molecule, compared



Finally, a note of caution

This field is not unlike exploring a jungle.

Particle physicists are used to:

- Backgrounds that are “perfectly” simulated by GEANT *et al.*
- Many measurements dominated by statistical errors which are easy to compute (and at times “overcomputed”)
- A very mature field expecting very high-quality standard for results

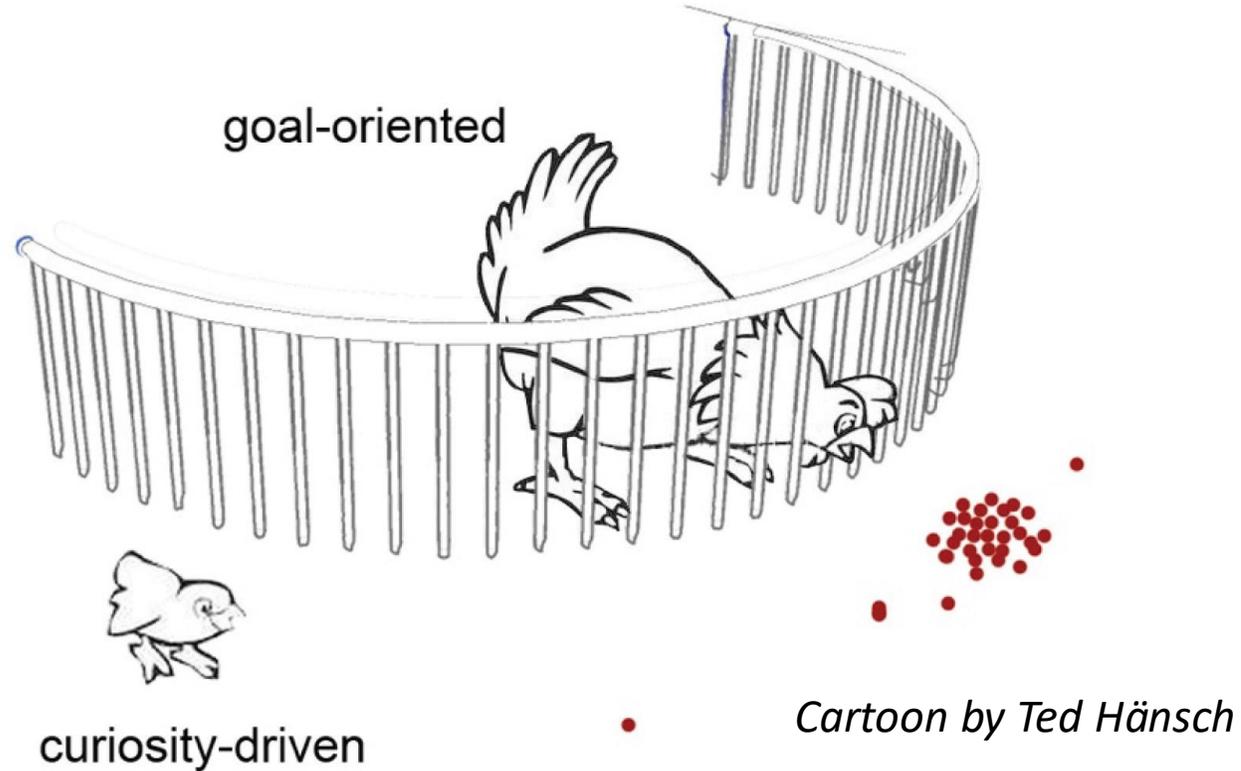
The jungle works differently, and experiments tend to be dominated by systematics, some of which are difficult to quantify. Some experiments may have dubious discovery potential, at least in the pioneering phase.

But discoveries change fields.

When I started working in low energy neutrino physics “low background” was a rather qualitative term. Now we have “perfect” simulations, like in colliders.

So, we should keep in mind that some redundancy is healthy.

Conclusion



*Thanking many colleagues, in particular:
Vincenzo Cirigliano, Brad Filippone, Mark Kasevich, Dave DeMille, Dave Moore*

Most importantly, thanks to the members of my group and our sponsors



Most importantly, thanks to the members of my group and our sponsors



And, as usual... capable and enthusiastic postdocs sought!