

Exotic Experiments in Particle Physics

A sampler

Giorgio Gratta
Physics Dept, Stanford University

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“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

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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
- ...

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.

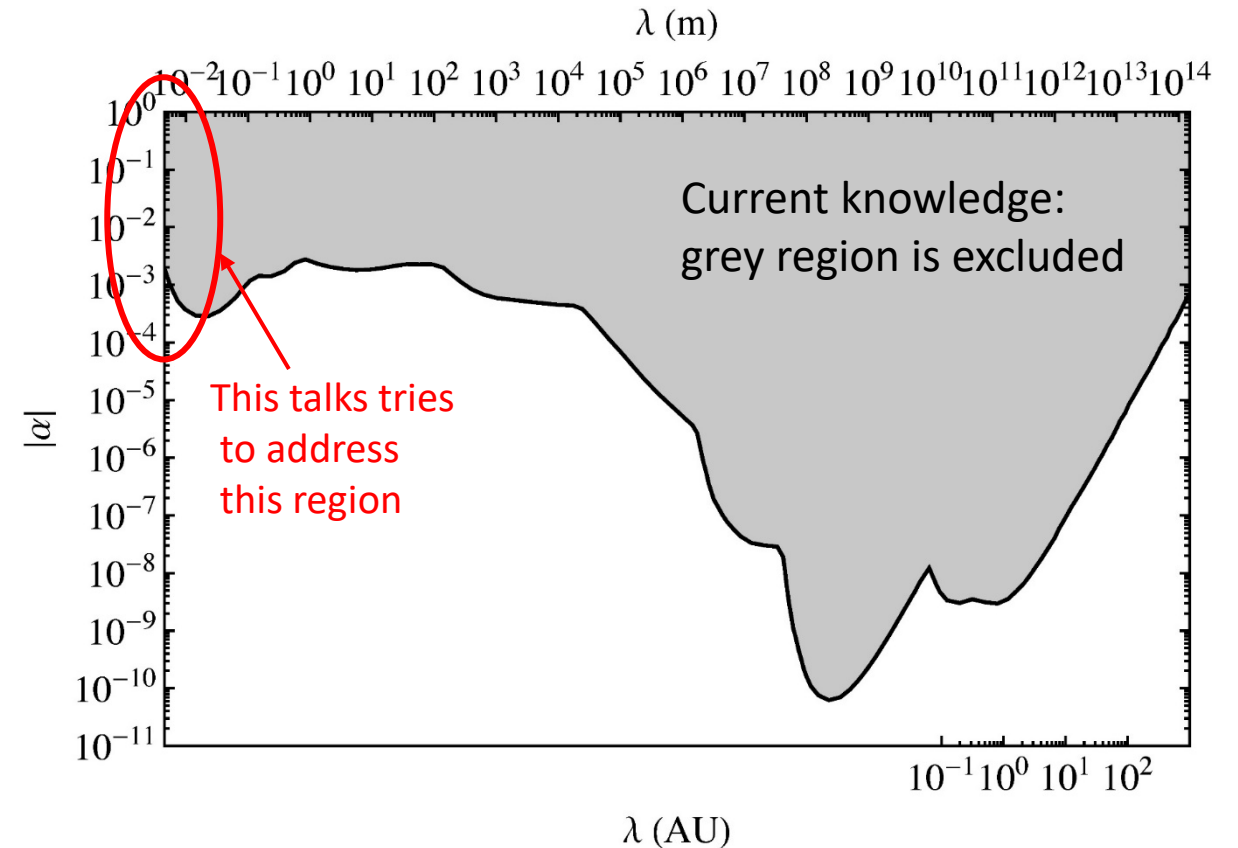
So, how well do we know that the inverse square law applies?

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

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

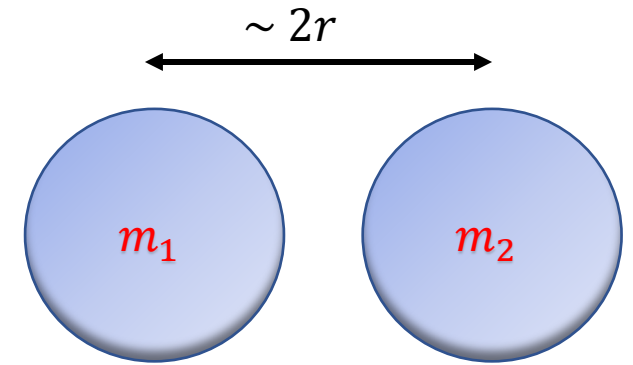
α : magnitude of the effect

λ : scale of the effect

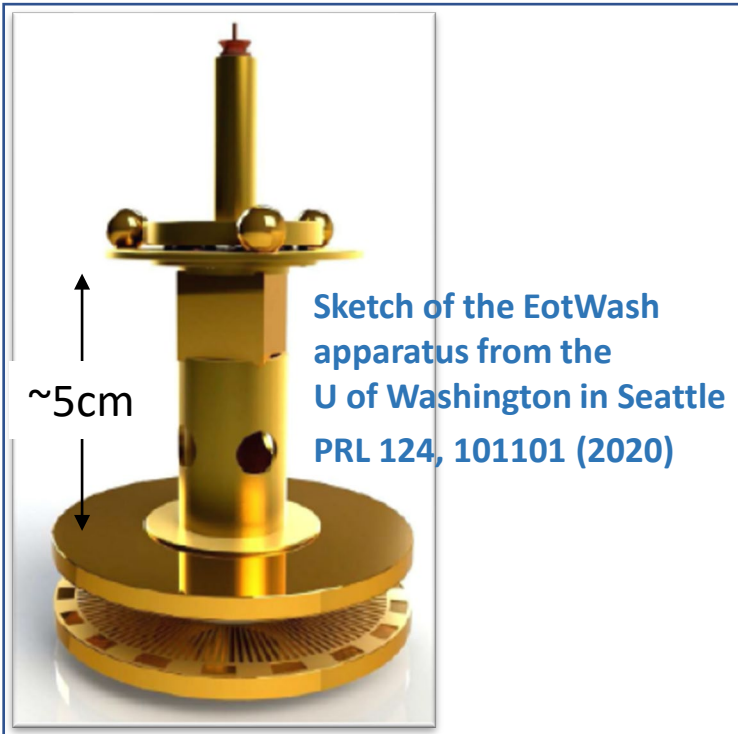


Experimental challenges

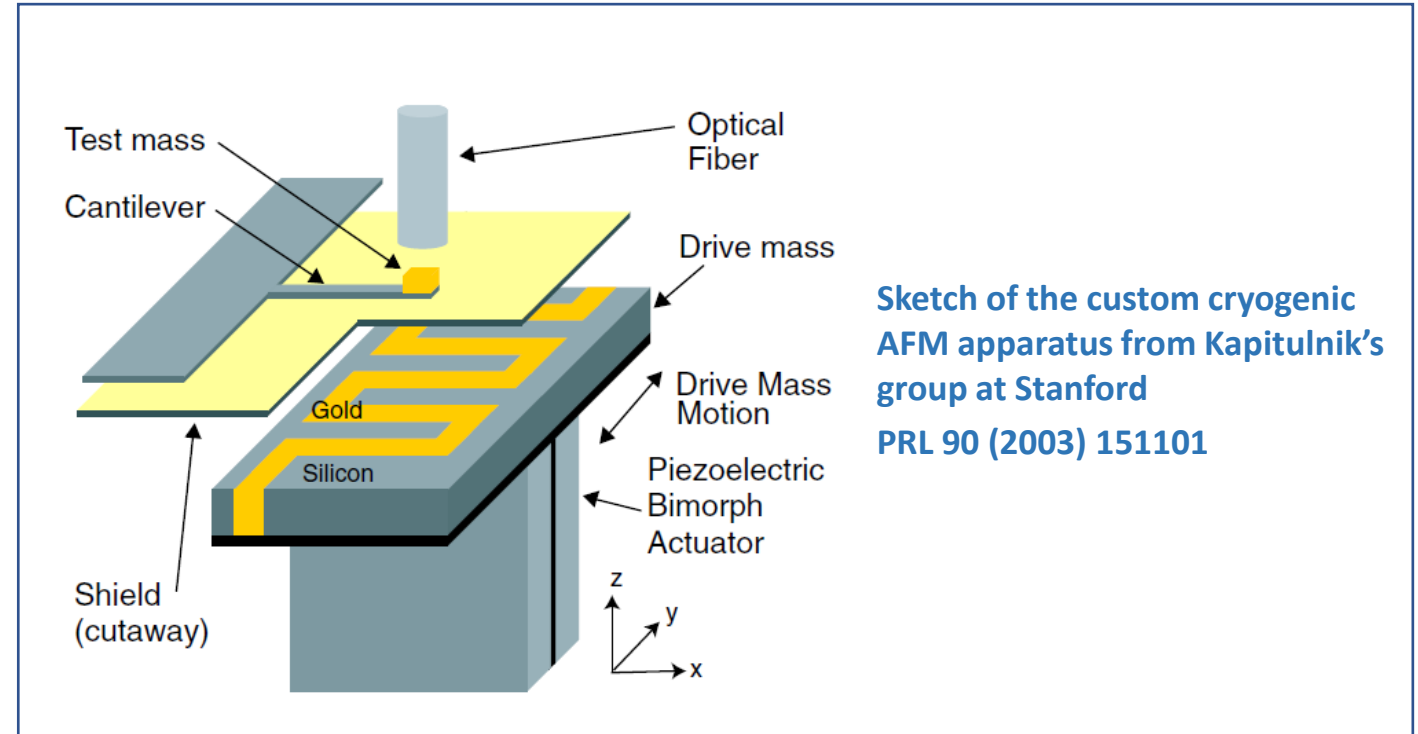
- Since $F = G \frac{M_1 M_2}{R^2} = G \frac{\rho_1 V_1 \rho_2 V_2}{R^2}$
for atomic materials $\rho_1 \sim \rho_2 < 20 \text{ g/cm}^3$, there is no silver bullet.
In addition, the volume $V \sim R^3$, so $F \sim G \frac{\rho^2 R^6}{R^2} \propto R^4$
- At distances $< 100 \mu\text{m}$ even neutral matter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



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



EPP 2024, April 2023



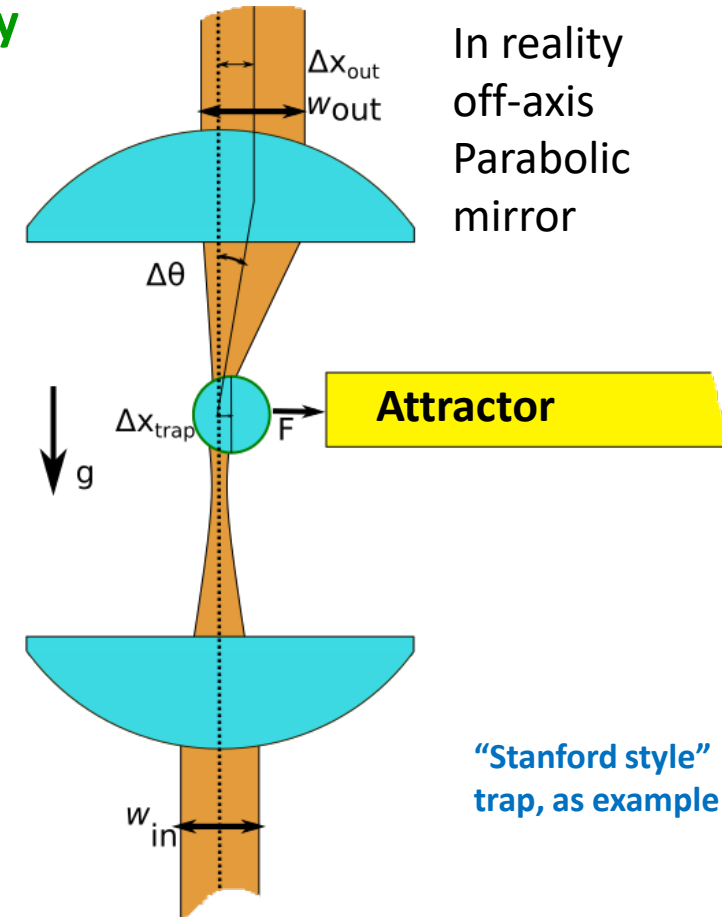
G.Gratta, Exotic Experiments



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**

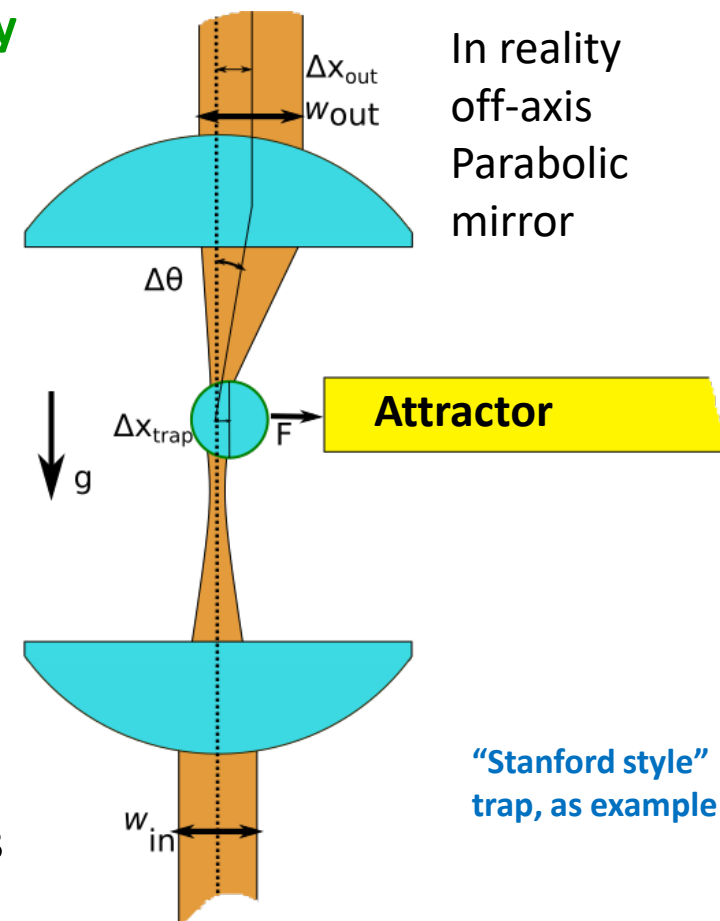
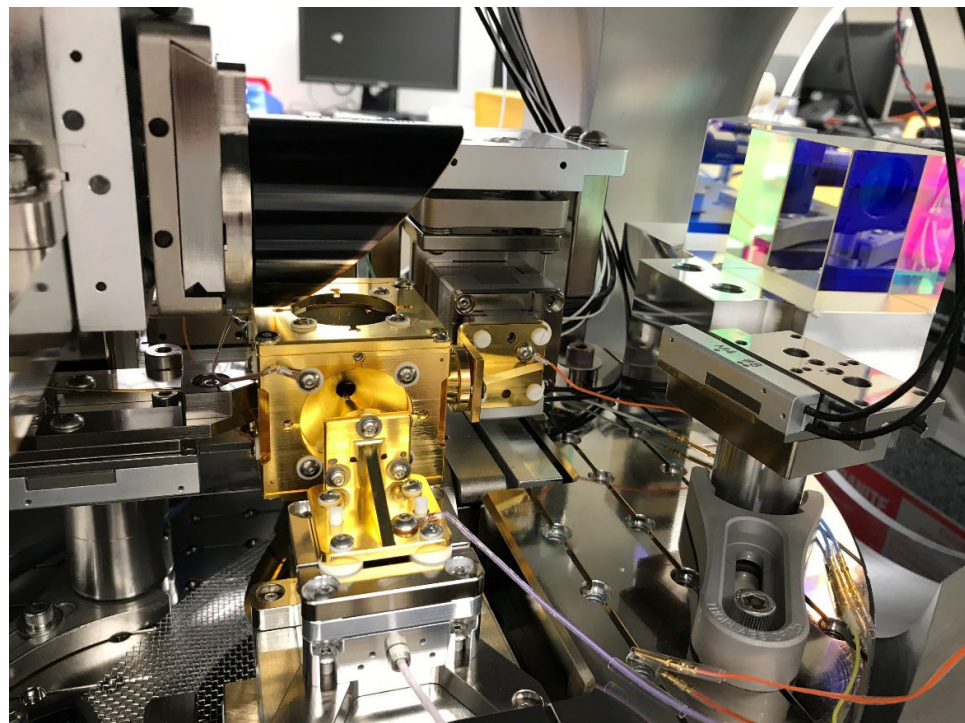




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~7.6 μm diameter silica microspheres

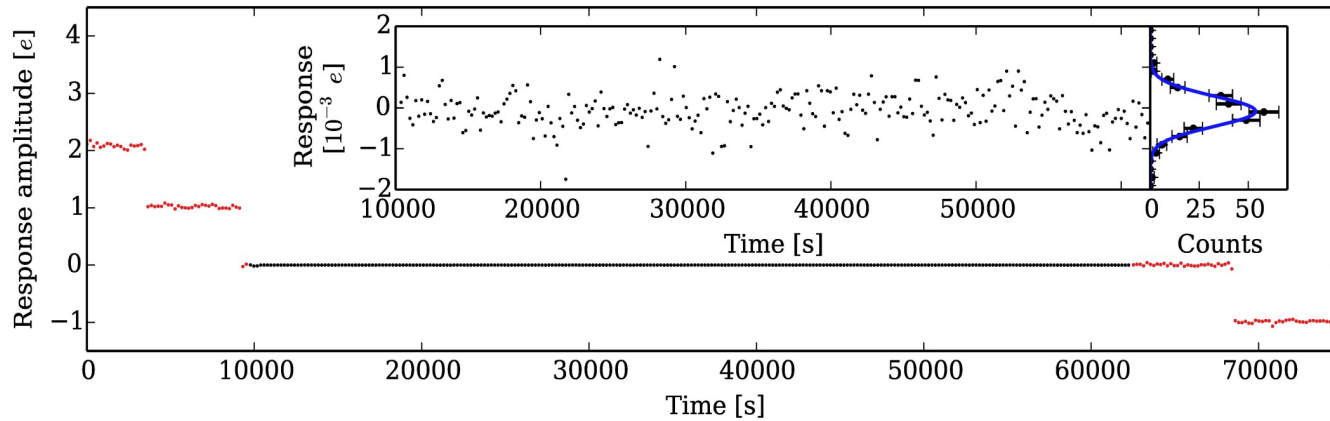
Mass ~420 pg

Force noise floor <0.1 fN/ $\sqrt{\text{Hz}}$

(to be improved)

**Possible to bring objects to within ~1 μm
from the surface of the microsphere**

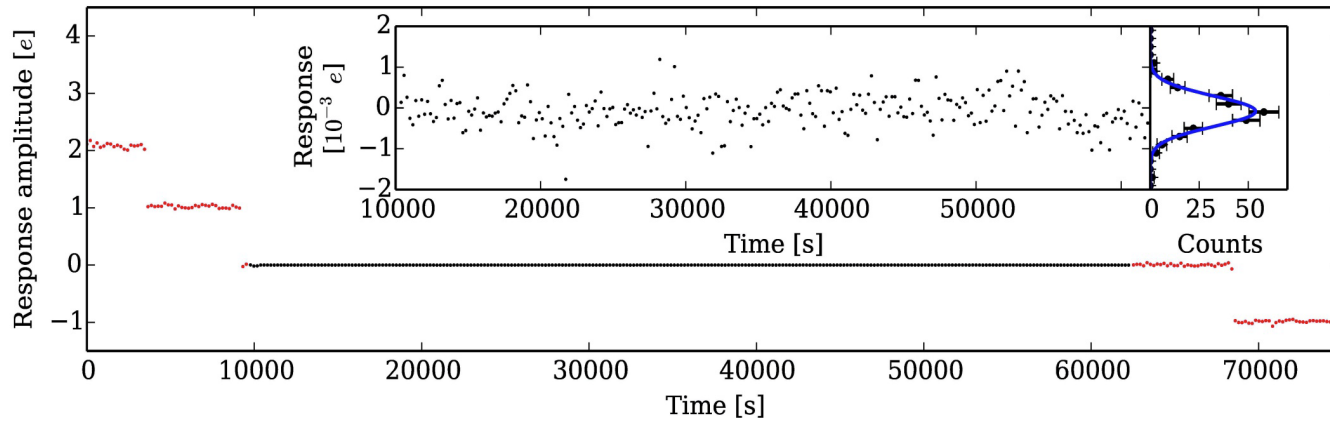
**Charge can be set to arbitrary (small) values (useful for force calibration)
including zero (useful for the measurement)**



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.

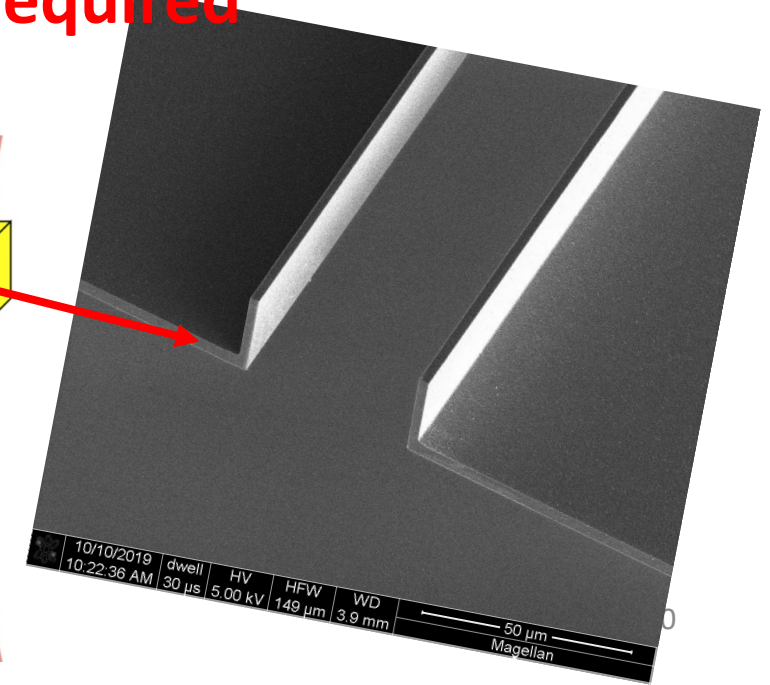
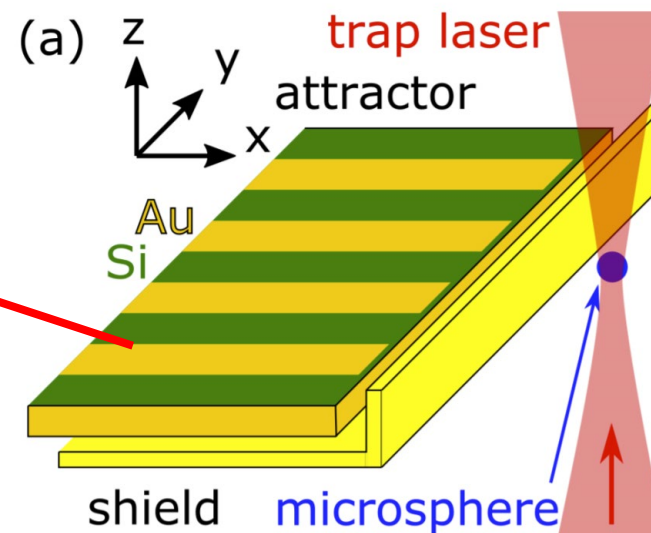
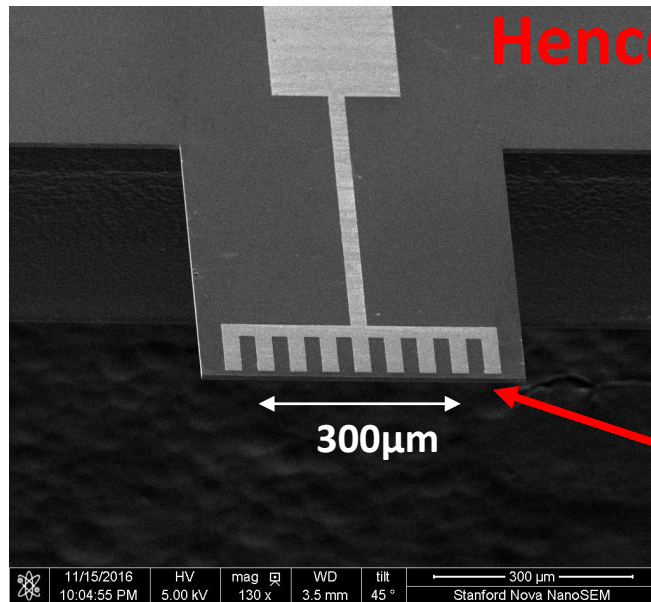
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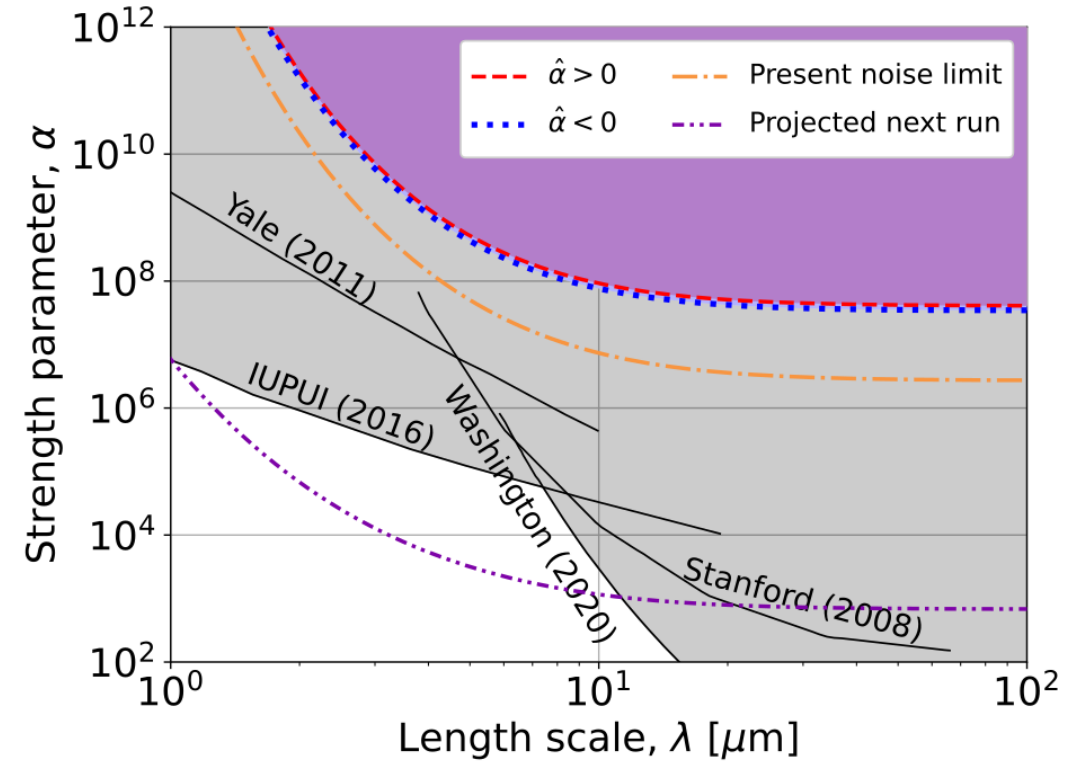
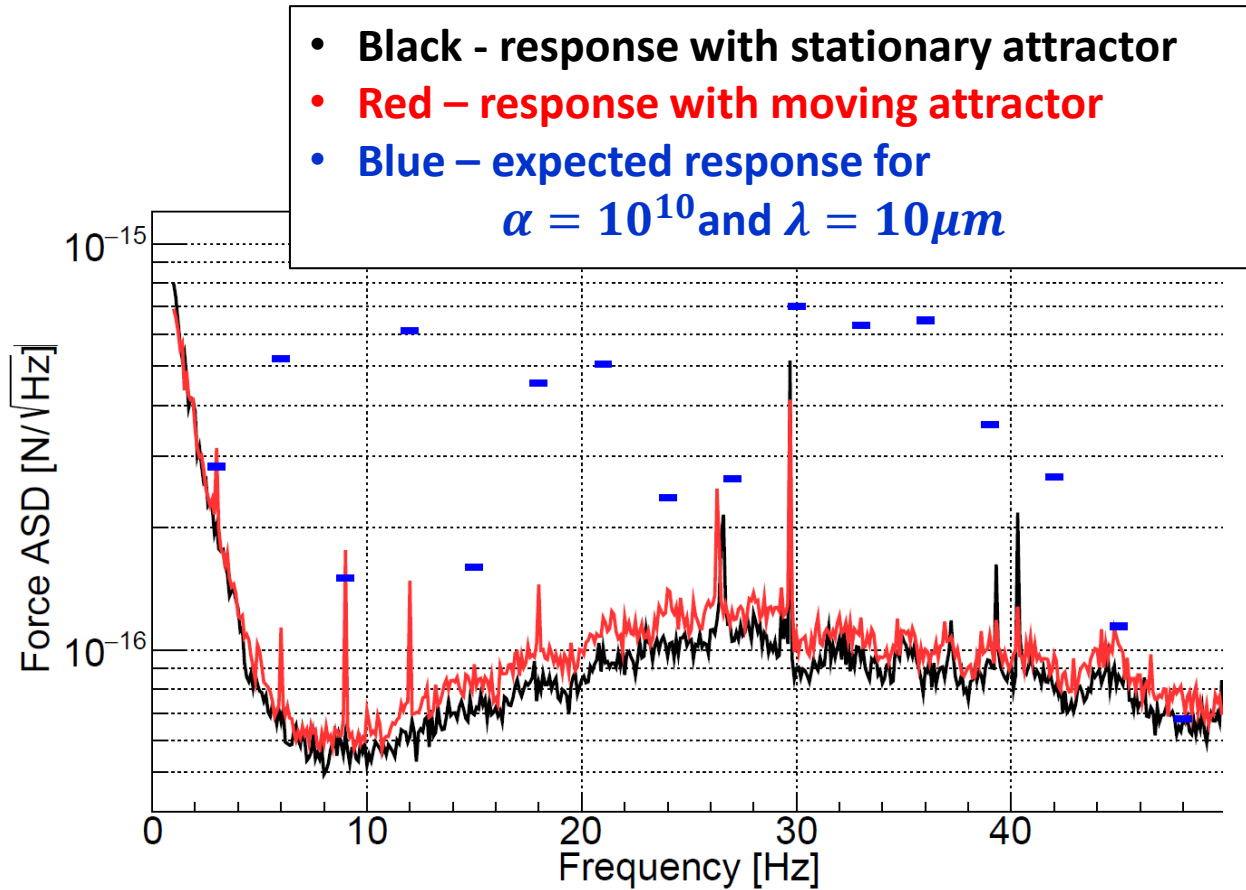
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However, electric dipole moments of $\sim 100e \mu\text{m}$ are observed, producing background forces by coupling to E-field gradients.

Hence, a stationary shield is required



Results from the first run



C.Blakemore *et al.*, Phys Rev D 104 (2021) L061101

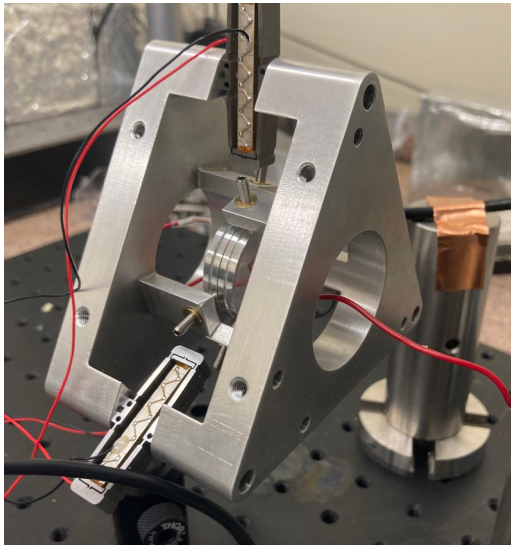
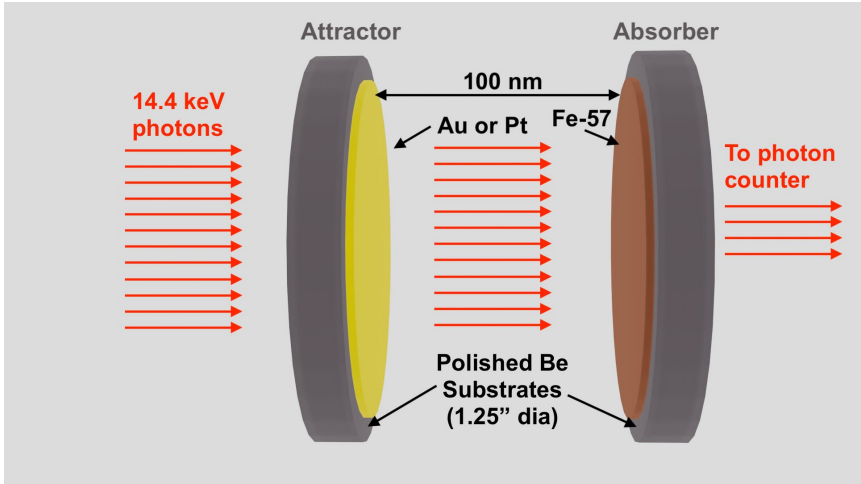
Still background dominated and only using one out of 3 DOFs.

Full measurement (taking data now) will have more redundancy than other techniques.

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

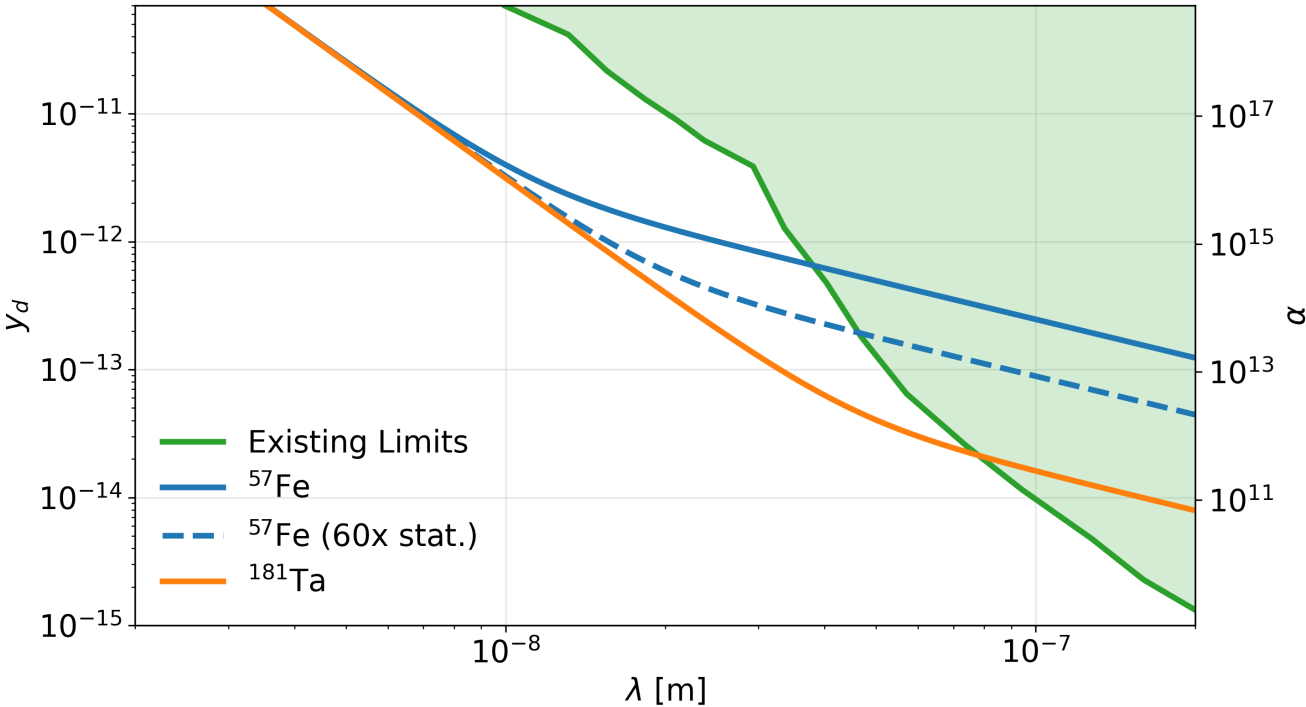
- Neutron Scattering is used, and one may be able to improve this further.
 - Here I want to mention a new idea (GG, D.E. Kaplan, S. Rajendran, PR D 102 (2020) 115031)
Use nuclei (instead of atoms) as sensors: Nuclei are well protected affairs
(the fact that very long half lives, even for EM transitions, 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.

The experiment requires bringing an attractor layer to <100 nm from a resonant absorber



Mössbauer spectroscopy, with ultra-narrow lines makes the measurement possible.

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	$2.92 \mu\text{s}$	1.6×10^{-10}	1.2×10^{-14}
$^{181}_{73}\text{Ta}$	6,237	$6.05 \mu\text{s}$	7.5×10^{-11}	1.2×10^{-14}
$^{67}_{30}\text{Zn}$	93,300	$9.07 \mu\text{s}$	5.0×10^{-11}	5.4×10^{-16}

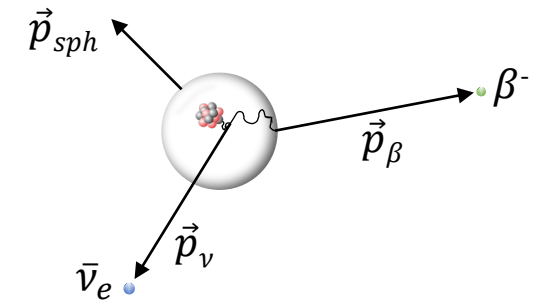


“Single shot” applications of levitated microspheres

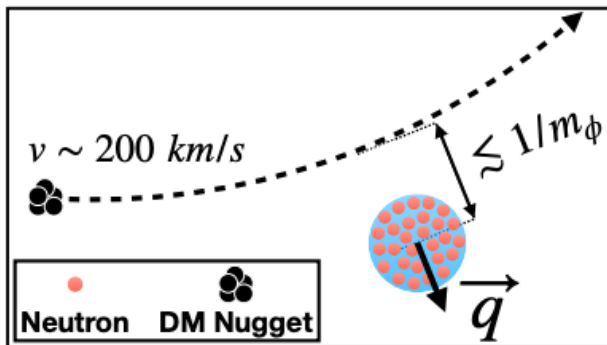
Carney et al., PRX Quantum 4, 010315 (2023) and references therein.

Detection of small impulses. Useful sensitivities for smaller spheres, ~ 100 nm size. At this size, the (nano)sphere motion can be cooled to the ground state of the harmonic oscillator (L. Magrini et al., Nature 595 (2021) 373)

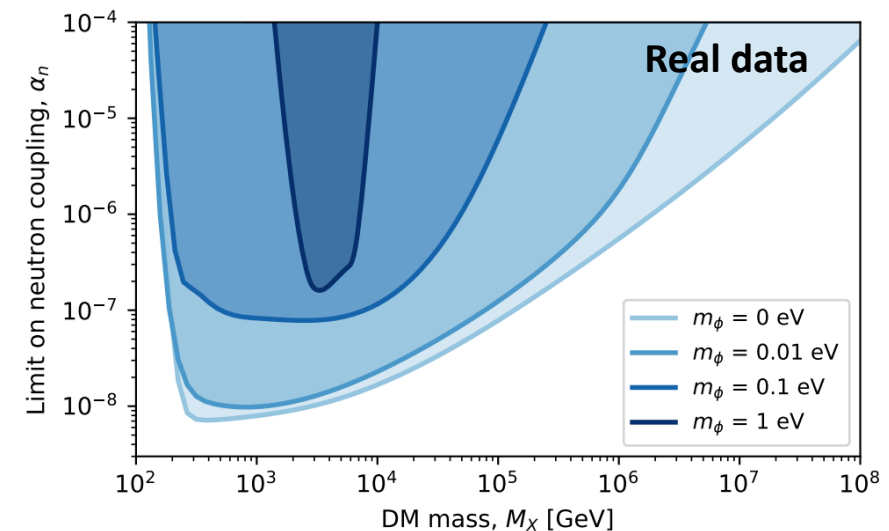
- Nuclear recoils from α/β decays of nuclides implanted in the nanosphere (great flexibility of nuclides).
Conventional detection of emerging particles $\rightarrow$ full closure of kinematics
 $\rightarrow$ An endpoint measurement becomes the measurement of a peak



- Kinematic detection of dark matter interacting with a new, long-range force $V = \alpha_n N_n \frac{e^{-m_\phi r}}{r}$ coupling to neutrons



Note that, in case of discovery, one gets the direction for free



Monteiro et al., PRL 125 (2020) 181102.

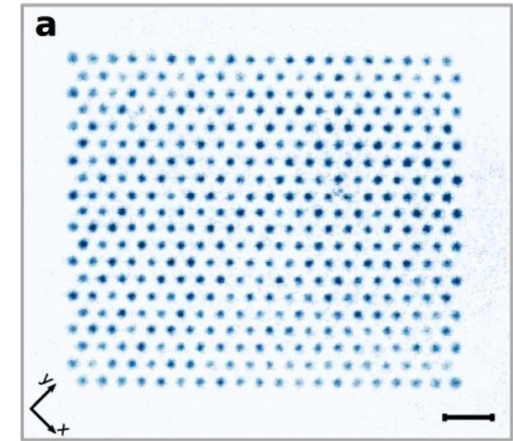
The sensitivity can be improved by:

- Reaching the quantum limit and moving beyond, with squeezing
- Building arrays of nanospheres

Both avenues are being pursued anyway in quantum optomechanics

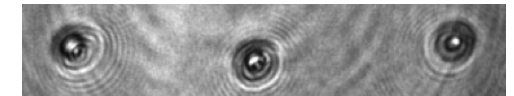
Tweezer arrays:

Atoms:



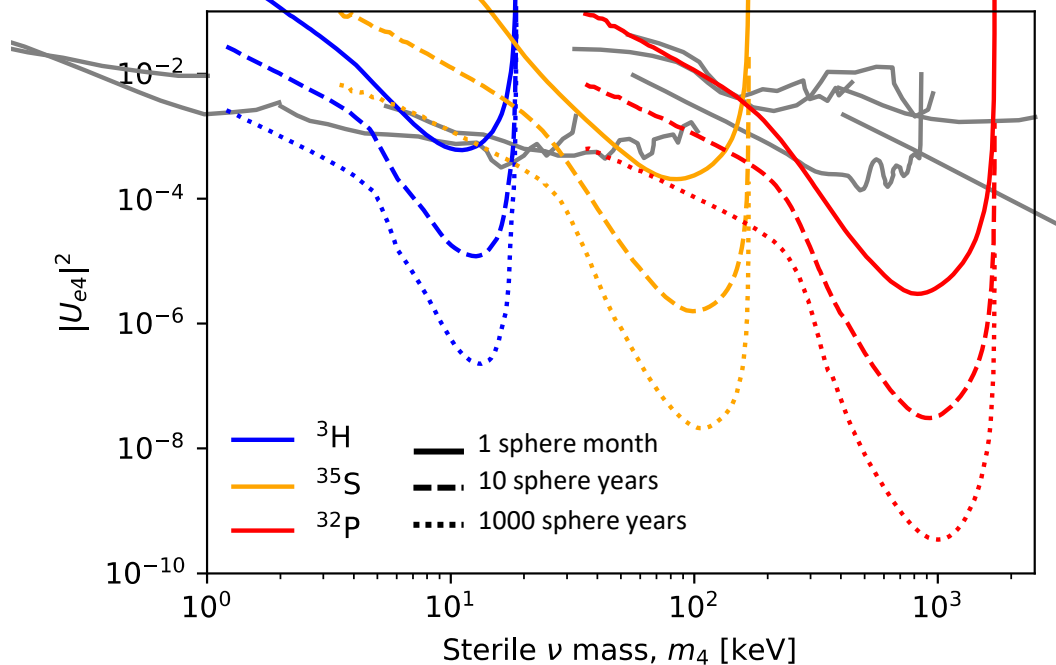
Wang et al. *npj Quantum Inf* 6, 54 (2020)

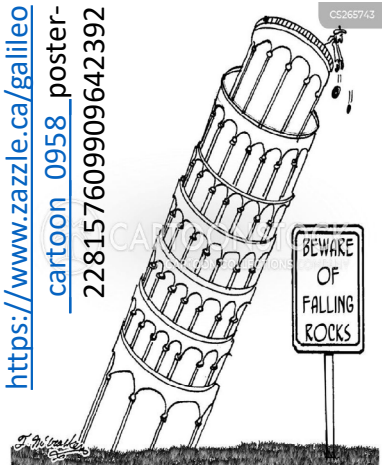
Microspheres, Yale:



Of course, this is all rather speculative, but so was the entire field of levitated optomechanics ~15 years ago!

Projected sensitivity versus exposure for decay into sterile neutrinos

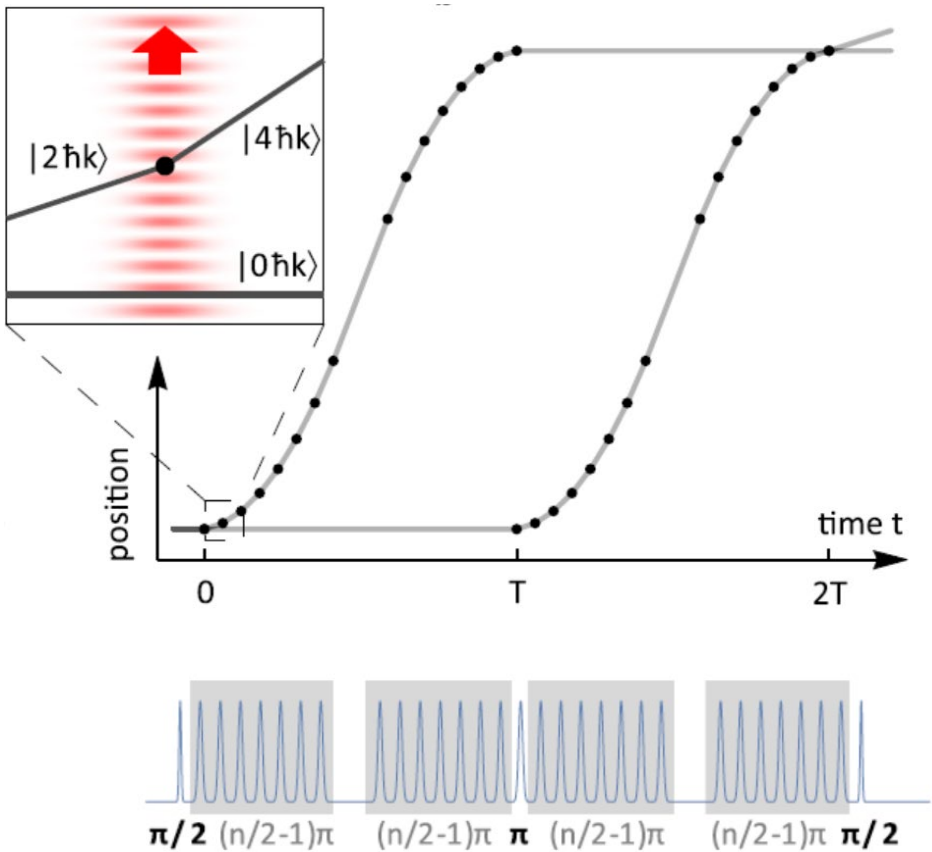
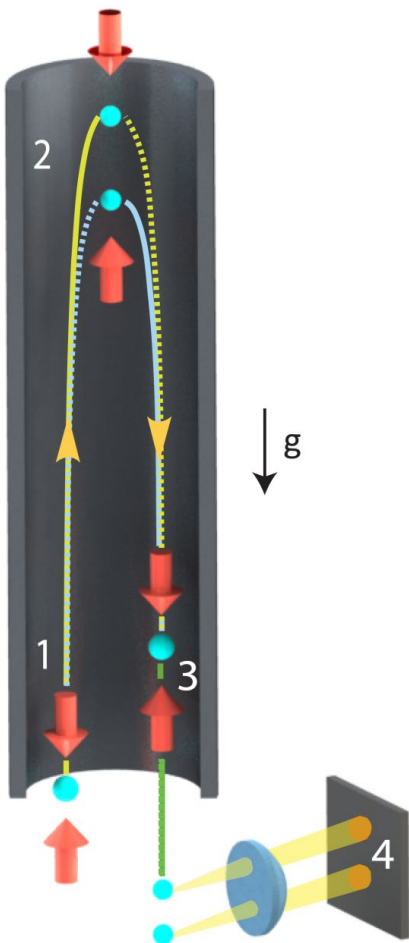




Testing the equivalence principle 450 years after Galileo:

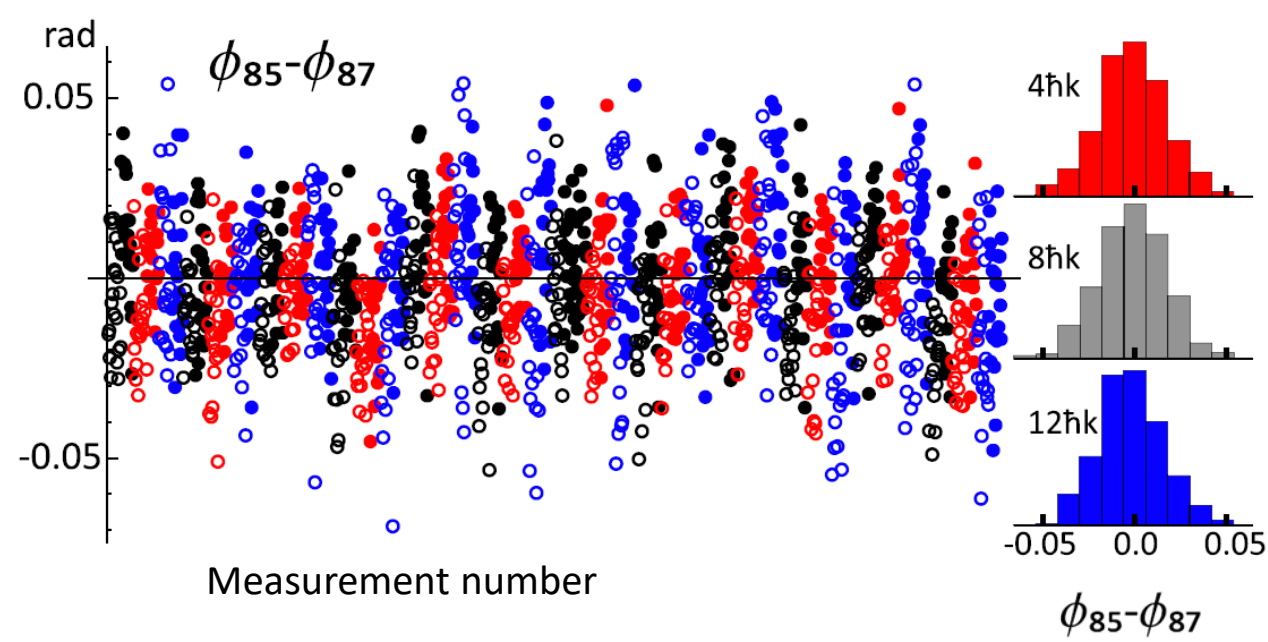
Interferometry, when feasible, wins!

⁸⁷Rb/⁸⁵Rb 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.

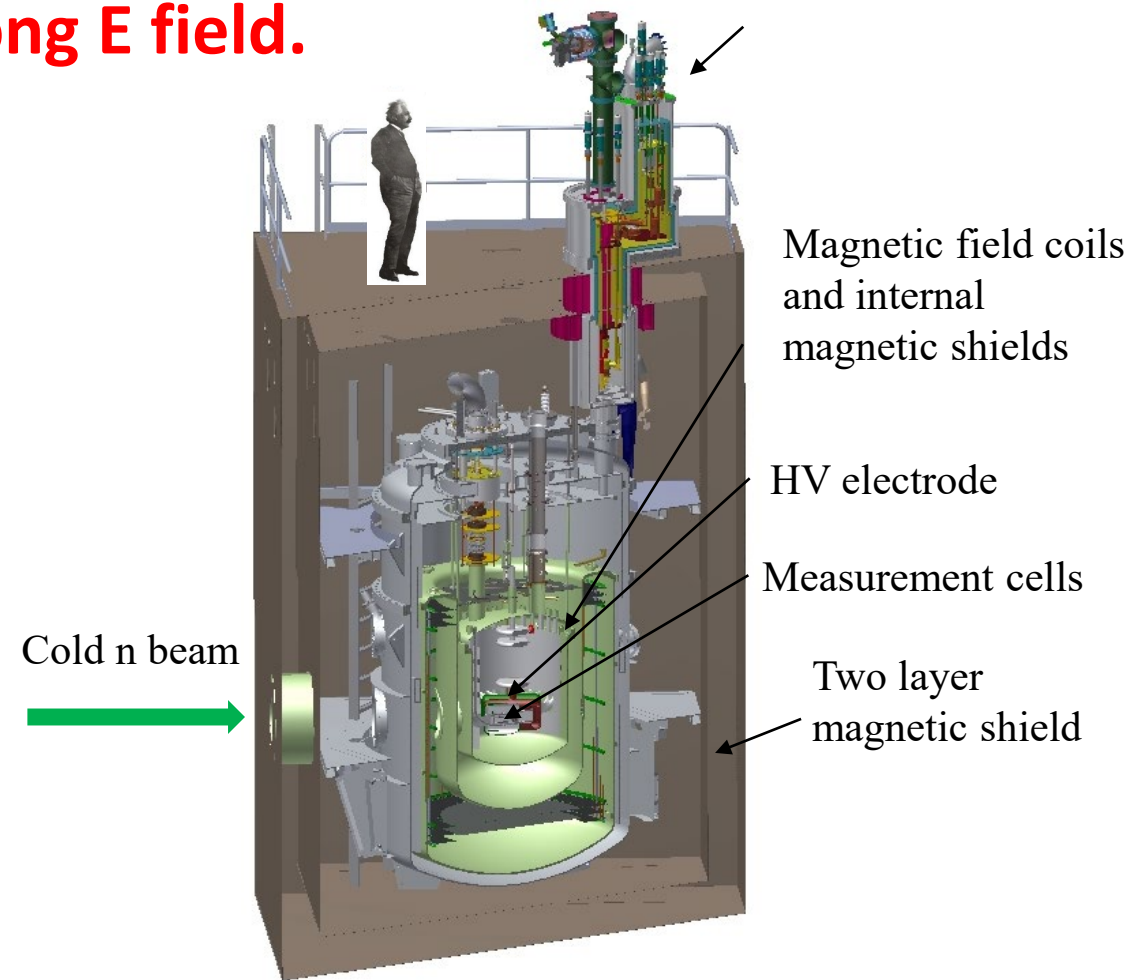
All measurements are limited by statistical as well as systematical effects.

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/built 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

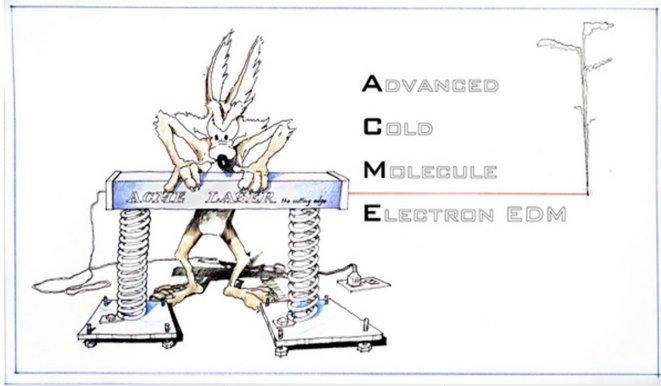


Example: NDM@SNS

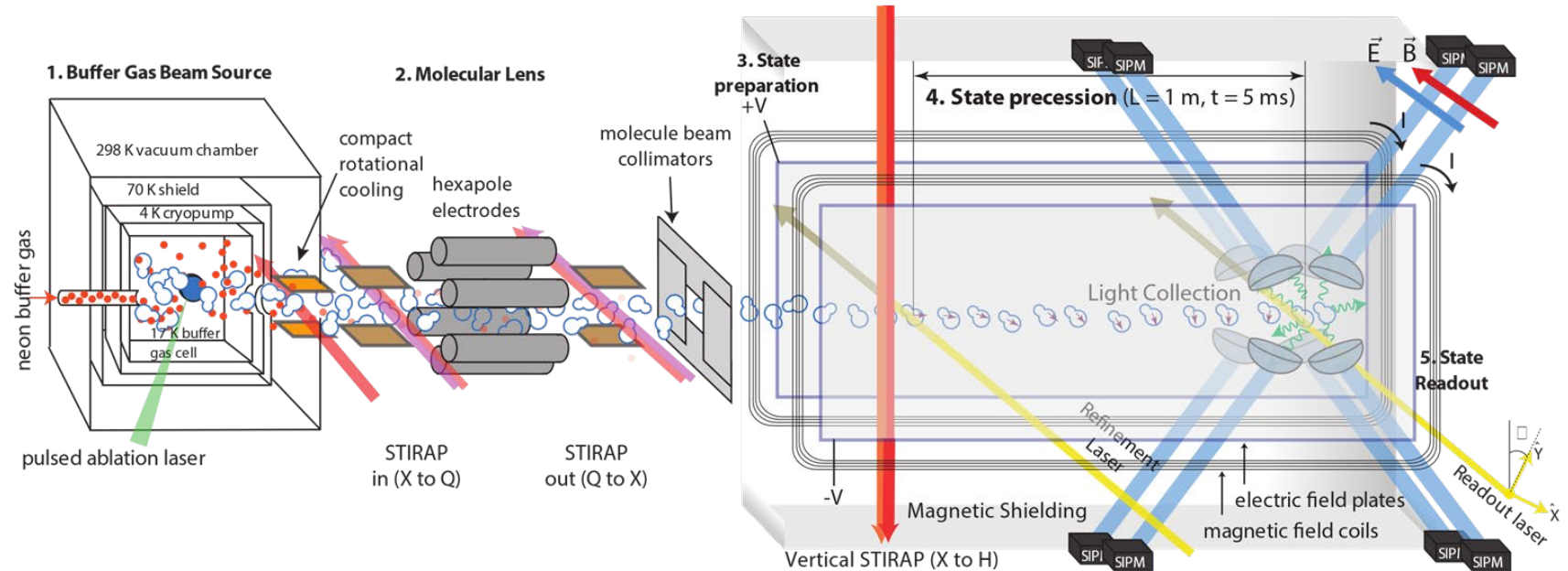
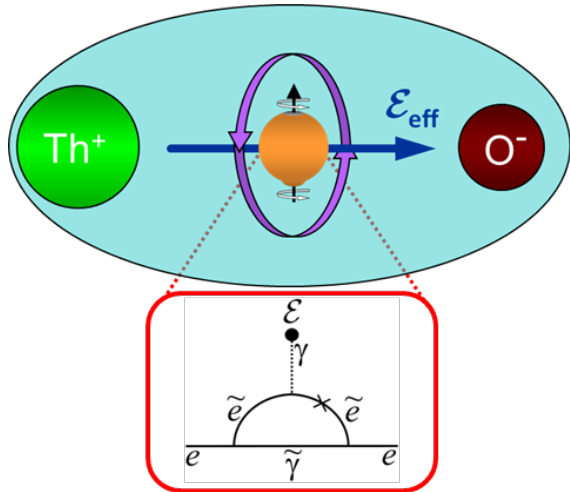
Concept by

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

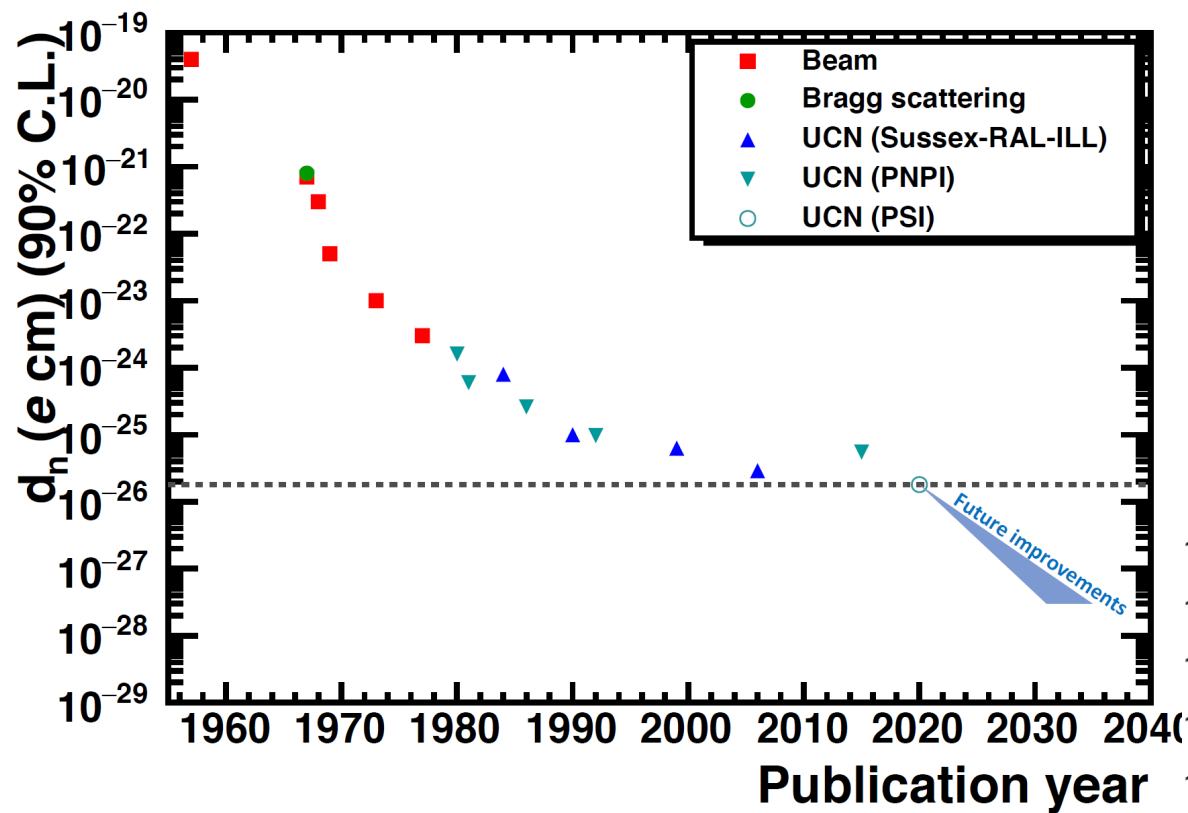
EDM measurements for e^- or p in atoms or molecules use changes in spectroscopy when the E field is applied



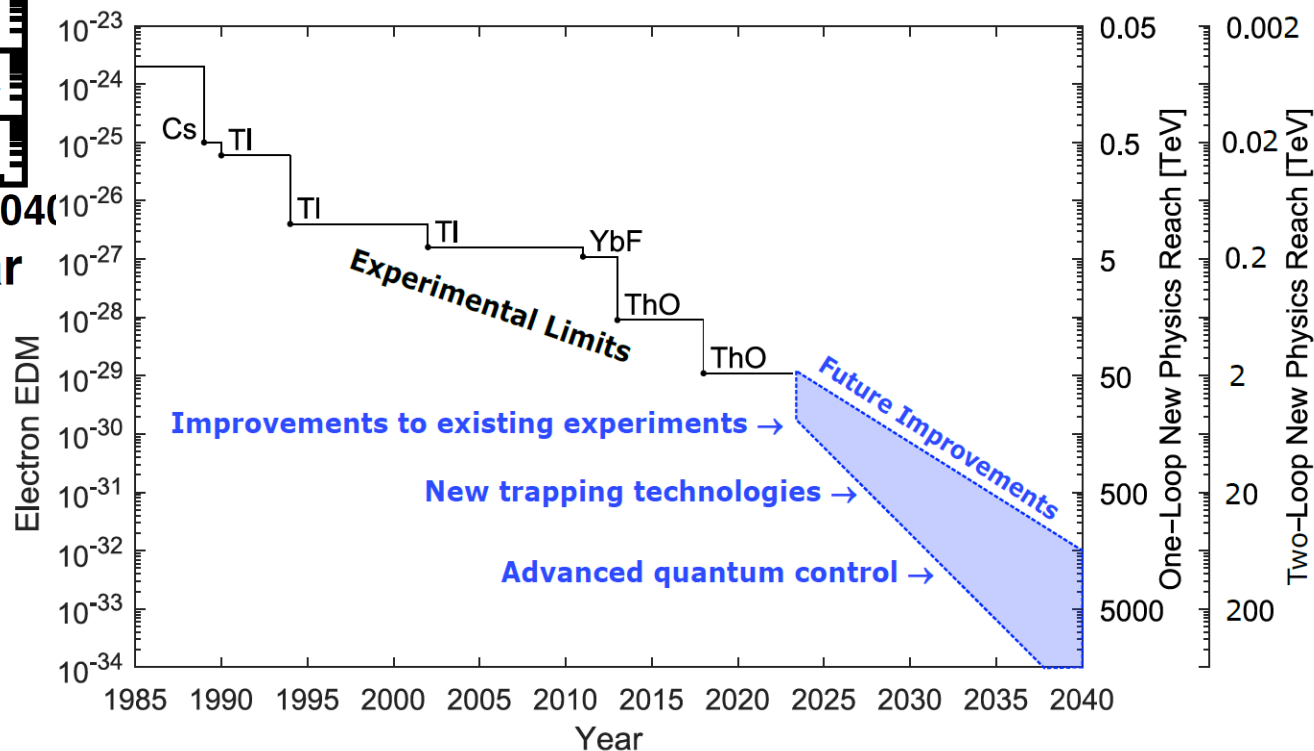
- Electron experiences huge (80 GV/cm) effective E-field in ThO molecule
- Cold, slow molecular beam $\rightarrow$ excellent statistics, long spin coherence time
- Powerful rejection of systematics from particular molecular structure: “internal co-magnetometer”, suppressed magnetic sensitivity



ACME III projected sensitivity $\sim 1.3 \times 10^{-31} \text{ e} \cdot \text{cm}$ (30-fold improvement), anticipated ~ 2024



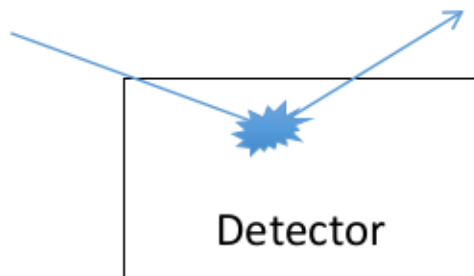
EDM sensitivity with neutrons and atom/molecule, compared



Particle and field-like Dark Matter

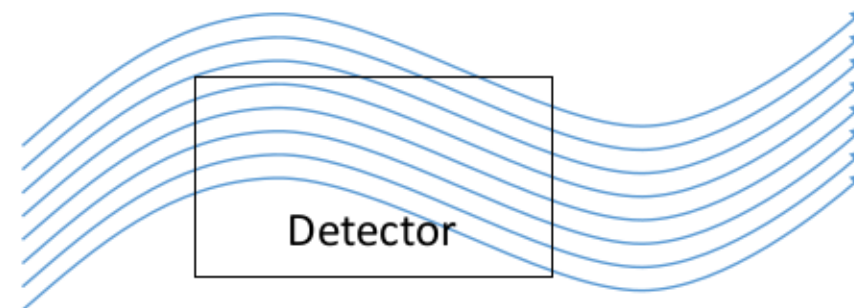
Heavy Particles

- Small number density (small occupation)
- No coherence at detector scale
- Look for individual scattering events (like a self-respecting particle physicist would do)
- Go underground
- Conventional WIMP detectors



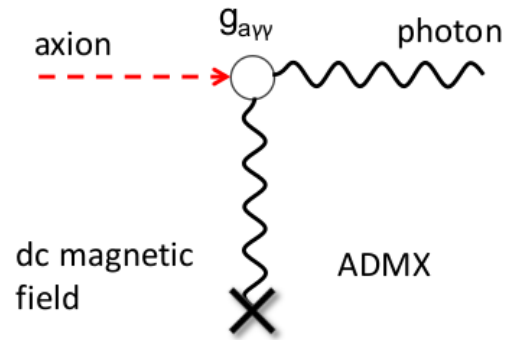
Light Field

- Large density (must be a boson)
- Long wavelength
- Coherent at the scale of the detector
- Only needs EM shielding
- Look for a classical, oscillating background field



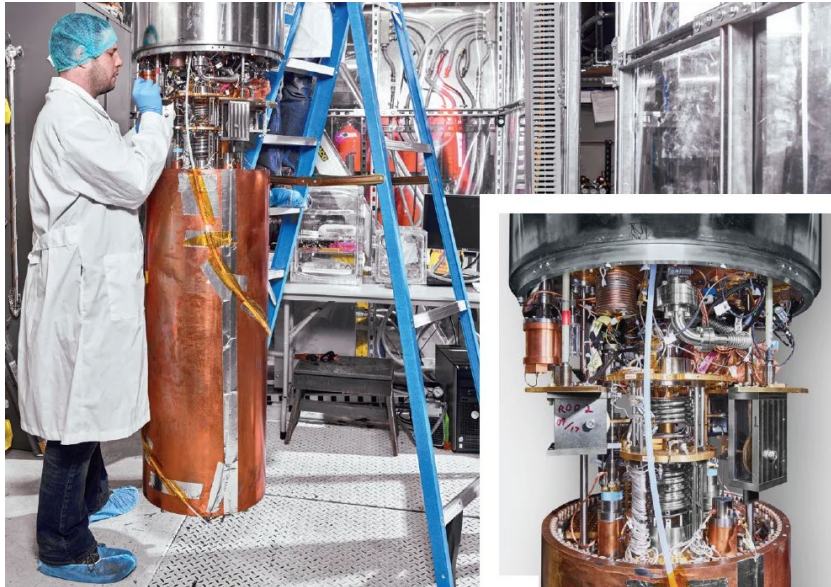
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An example is the axion, that couples to E&M with the help of an external field via the Primakoff effect (Sikivie 1983).



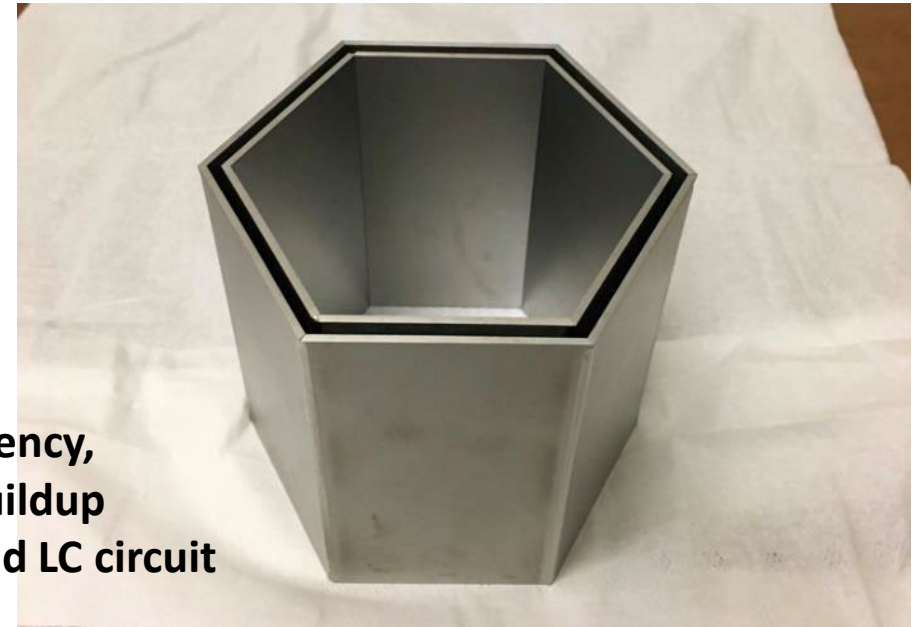
The detector is a superbly sensitive radio receiver installed “inside” a cavity providing shielding from the external EM radiation (axions couple little, so are not shielded), housed inside a magnet used for the conversion.

Since the mass of the particle is not known, the wavelength of the field is also unknown and the appropriate “radio technology” varies.

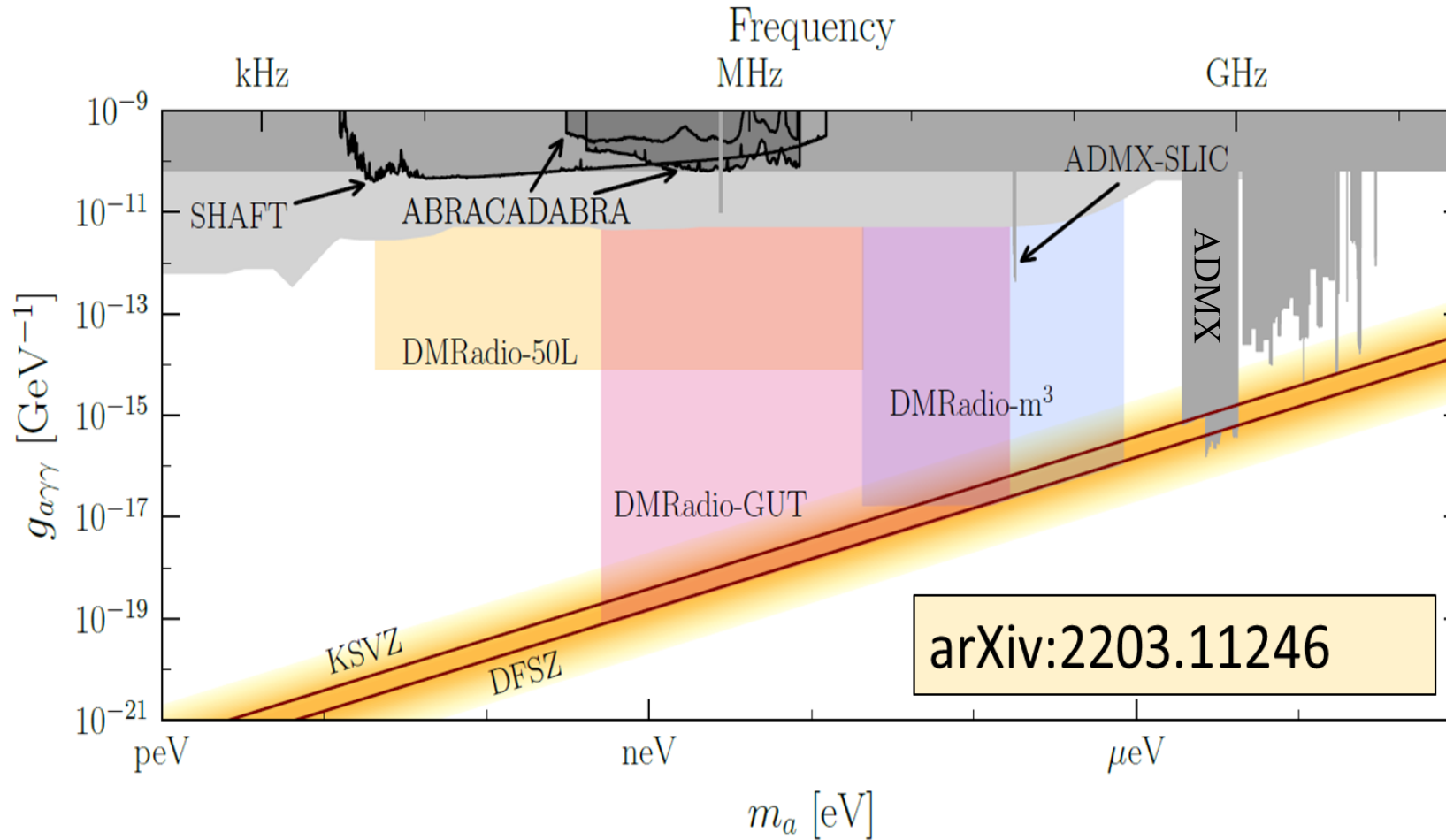


ADMX:
at high frequency,
the signal buildup
is in a (tunable) cavity

DM Radio:
at low frequency,
the signal buildup
is in a lumped LC circuit



Slowly but steadily closing the meV to peV region



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 that 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 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.

- The US has an oversize profile in this area of physics
- In part, this is due to the very diverse funding landscape
(NSF & DOE but also DoD, NASA, Private Foundations, and University startups)

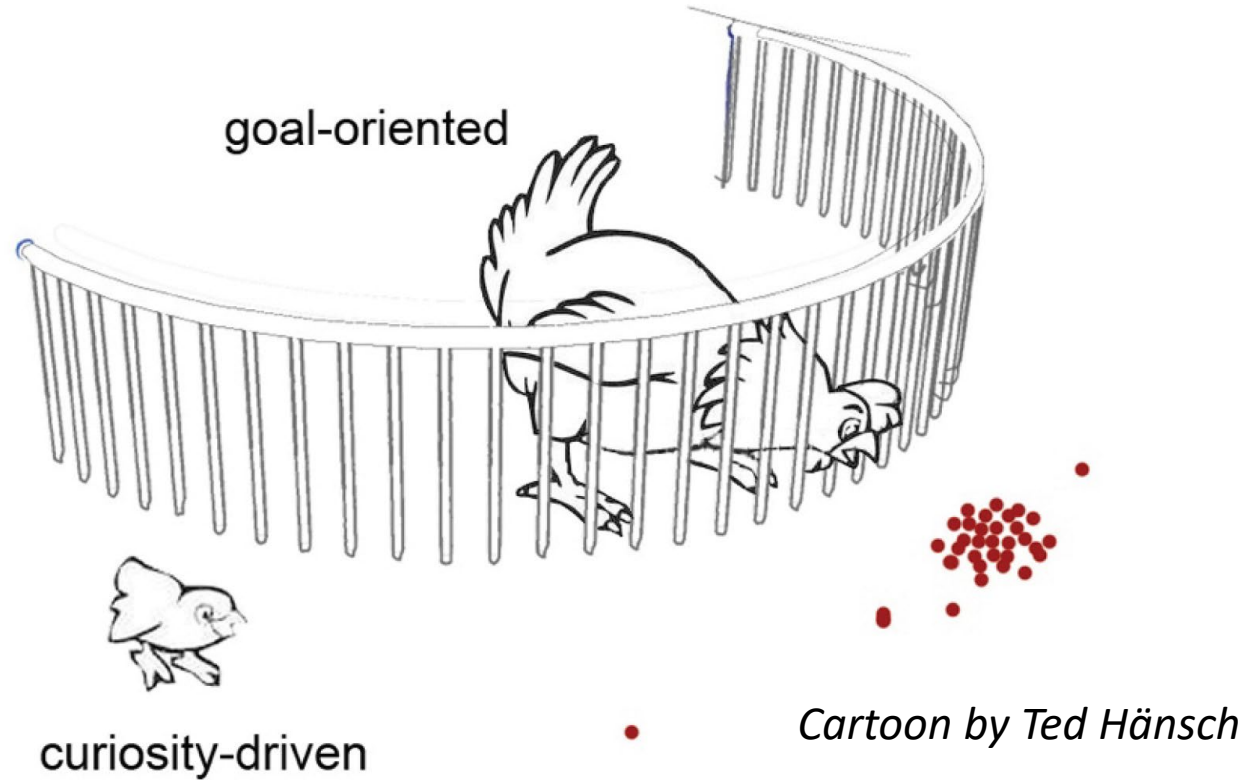
Coda:

Two random* problems that really bother me

- **How to detect relic Big Bang neutrinos**
- **Lower IceCube threshold to ~ 10 MeV and trace the “neutrino curve” of one Supernova/month**

*** Actually, they are not random: they share the distinction that they involve an assured discovery (or, a limit would be even more important than a discovery)**

Conclusion



Thanking many colleagues, in particular:

Vincenzo Cirigliano, Brad Filippone, Kent Irwin, Mark Kasevich, Dave DeMille, Dave Moore