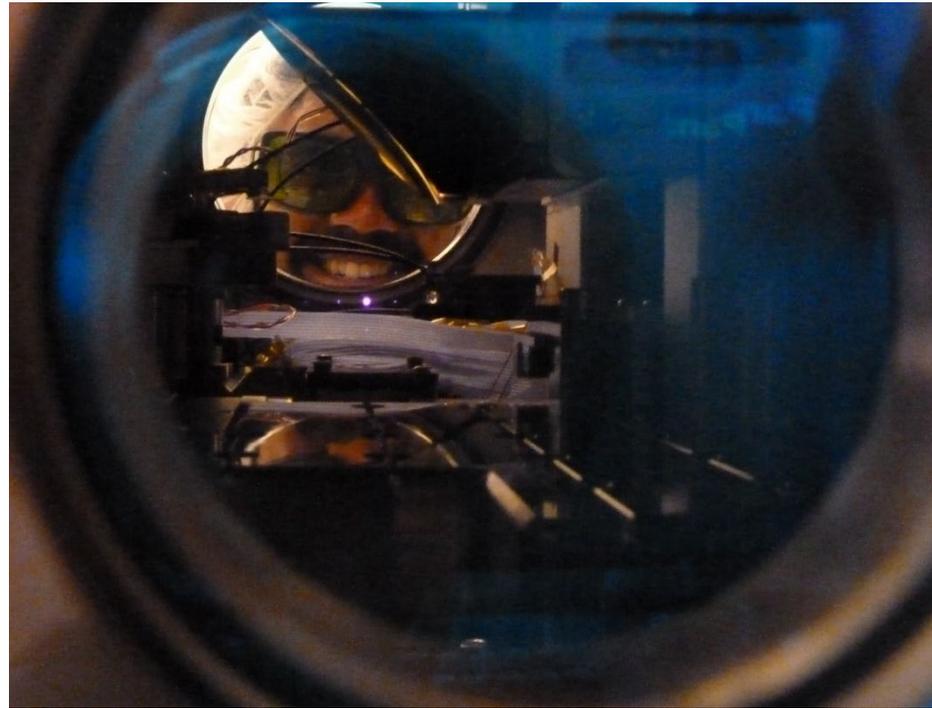# Testing Gravity at Ever Shorter Scale
a trip into exotic experimental physics

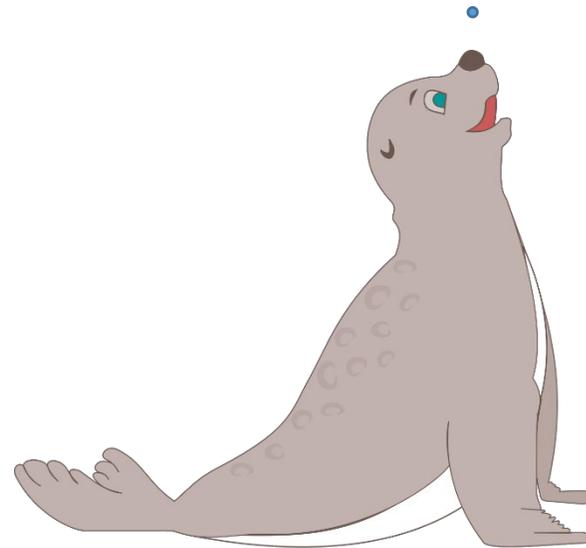*Giorgio Gratta*
Physics Dept, Stanford

Image credit: Delia Gratta

"My advice is to try crazy ideas and innovative experiments."

Steven 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

Plan

- **Measuring gravity at short distance, new physics opportunities**
- **The physics of optically levitated dielectric microspheres**
- **First results in the 1 - 50μm range**
- **Mössbauer spectroscopy and the quest for new physics**
- **Initial technical developments**
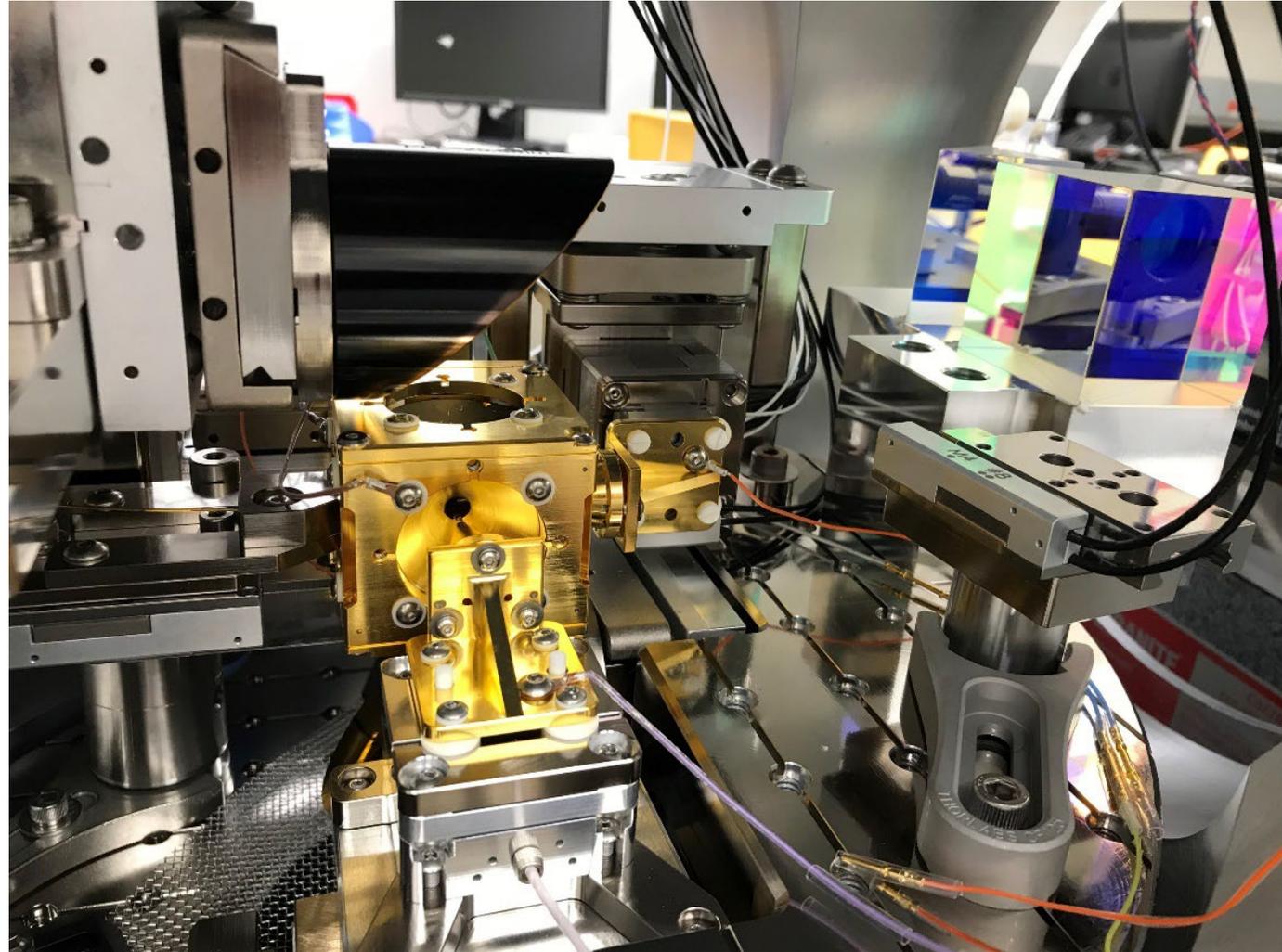
Gravity is:
- the most evident
- the weakest
- the least well-known interaction in Nature

Fundamental interactions	Normalized Strength	Effective Range (m)
Strong Nuclear Force	10^{38}	10^{-15}
Electromagnetic Force	10^{36}	∞
Weak Nuclear Force	10^{25}	10^{-18}
Gravity	**1**	**∞**

Most of the empirical features of gravity and differences in phenomenology from the other interactions can be understood in terms of the parameters above.
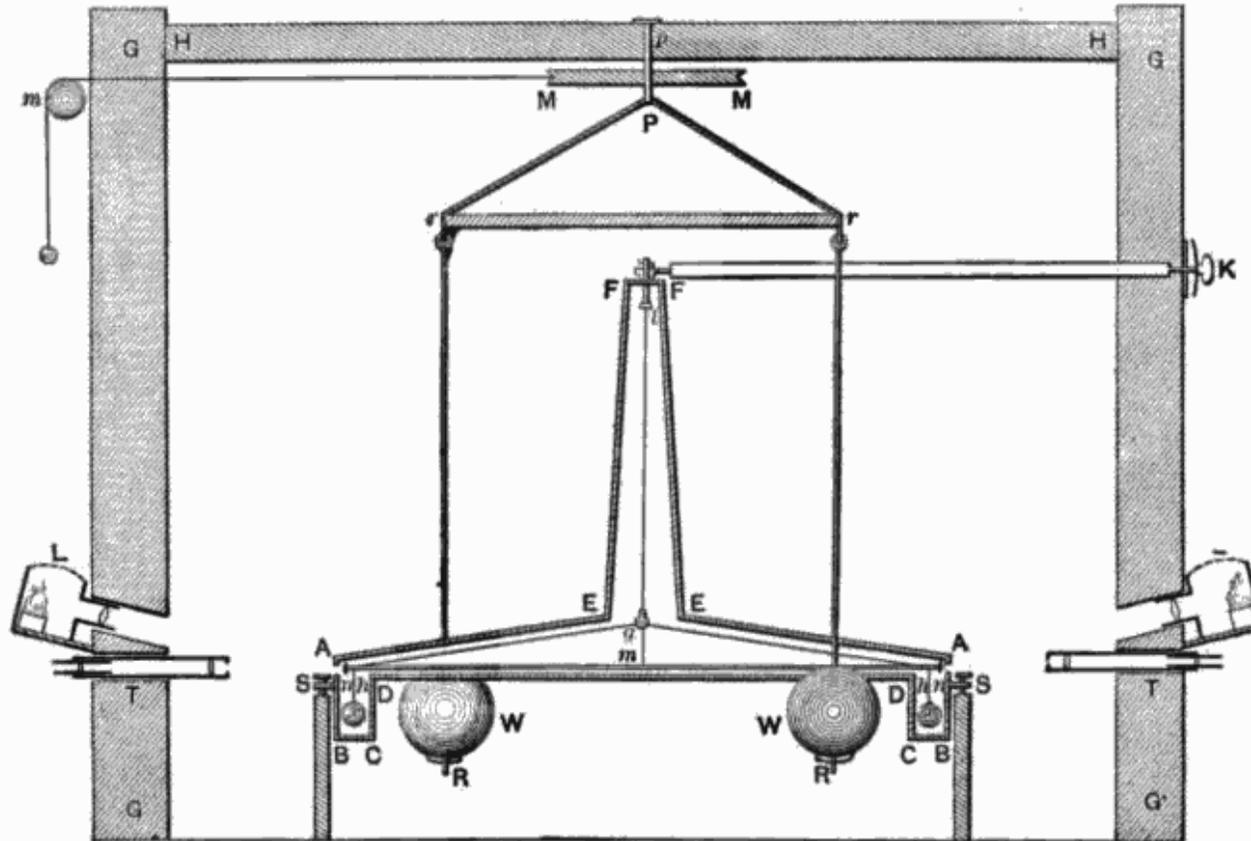
In addition, there is no such thing as "antigravity", so gravity cannot be shielded, which explains why this weakest force is so evident:
e.g. keeps the solar system together.

The first laboratory experiment on gravity

Apparatus by Rev. John Mitchell, used by Henry Cavendish to "Determine the Density of the Earth".

~2m

**H.Cavendish, Phil. Trans. Royal Soc. London (part II) 88, p469-526 (21 Jun 1798, 225 years ago!)**

Cavendish's measurement, in terms of G, gives

$$G = (6.74 \pm 0.04) \cdot 10^{-11} \, \text{m}^3 \text{kg}^{-1} \text{s}^{-2} \quad \sim 0.6\%, \quad (1798)$$

**Current measurements have 11 ppm uncertainty,
    but there is a few sigma disagreement between the two
    most recent ones (Li et al., Nature 560 (2018) 582)**

At the same time we know
- **the QED coupling constant, α, to 0.23ppb**
- **the weak coupling constant, G_F, to 0.5ppm**
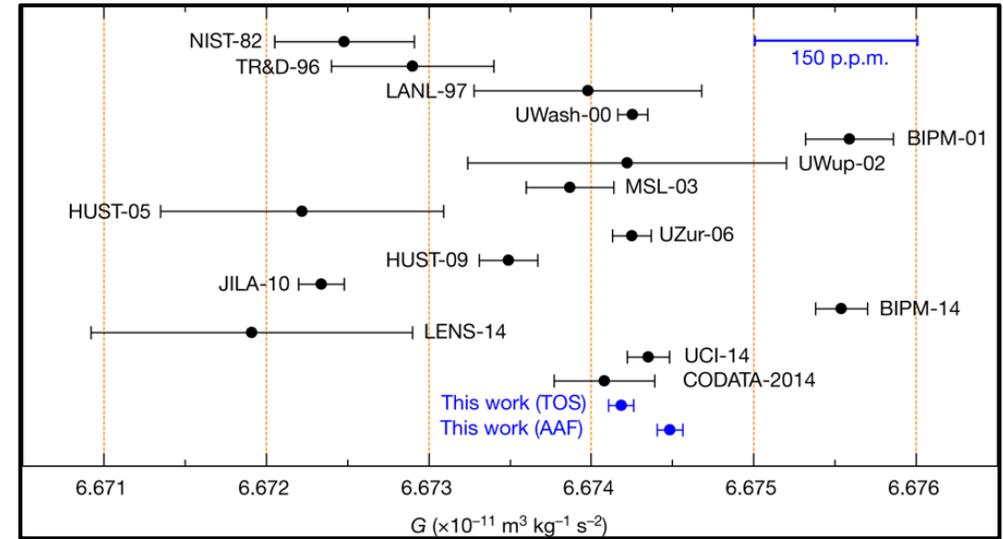
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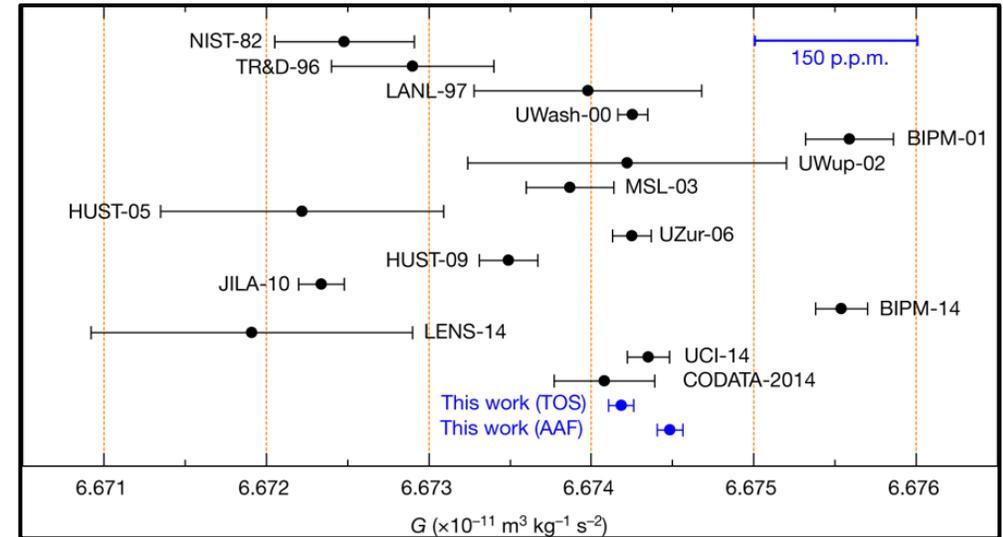- the weak coupling constant, G_F, to 0.5ppm

However, since we do not know how to calculate G from other quantities in physics, we do not expect to find new physics in the absolute value of G.

More interesting is to test if there are deviations from the 1/R² law for gravity.

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

  Of course, this is a bold assumption that requires experimental verification.

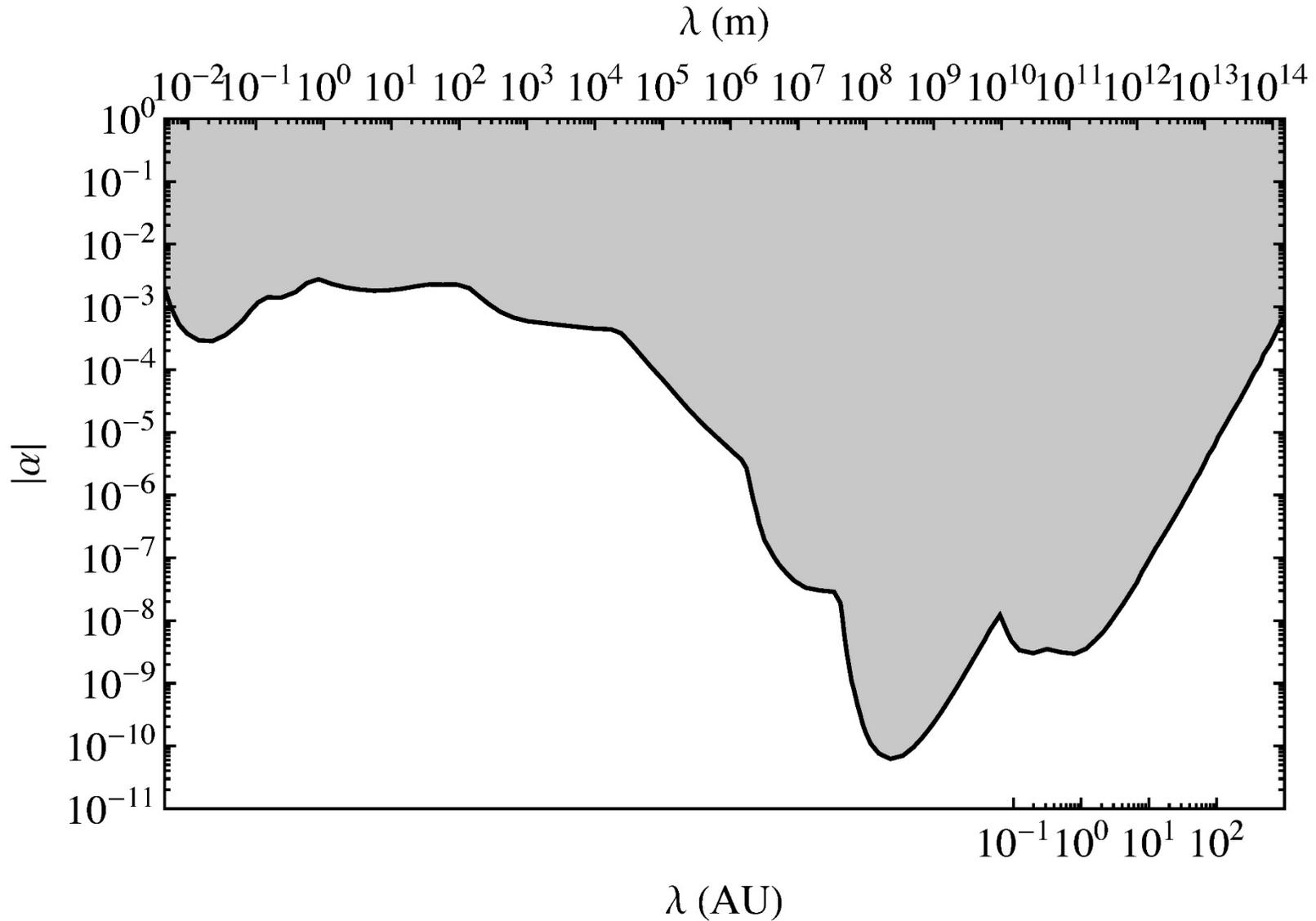# So, how well do we know that the inverse square law applies?

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

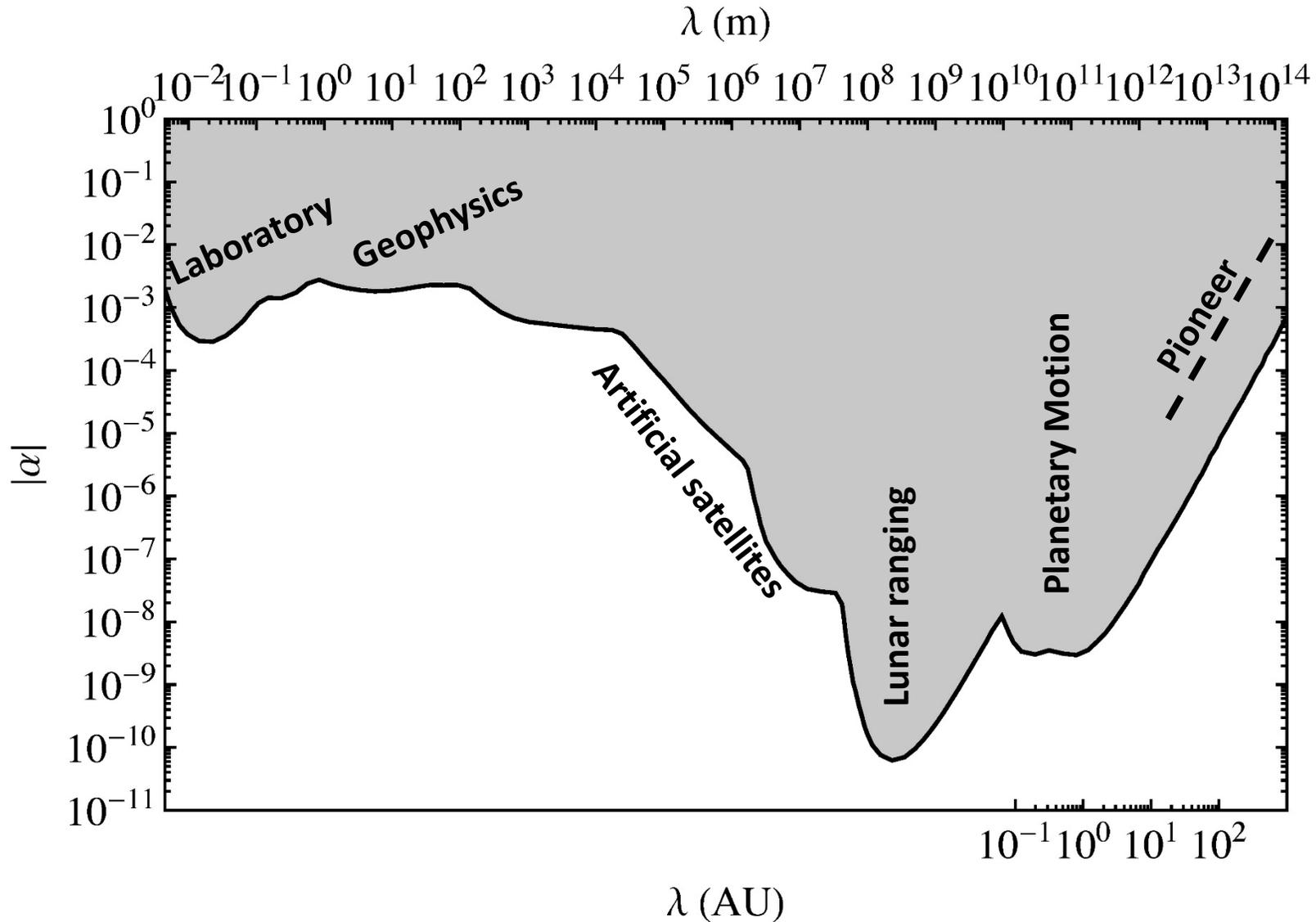$$V(R) = G\frac{M_1 M_2}{R}\left(1 + \alpha e^{-R/\lambda}\right)$$

α: magnitude of the effect
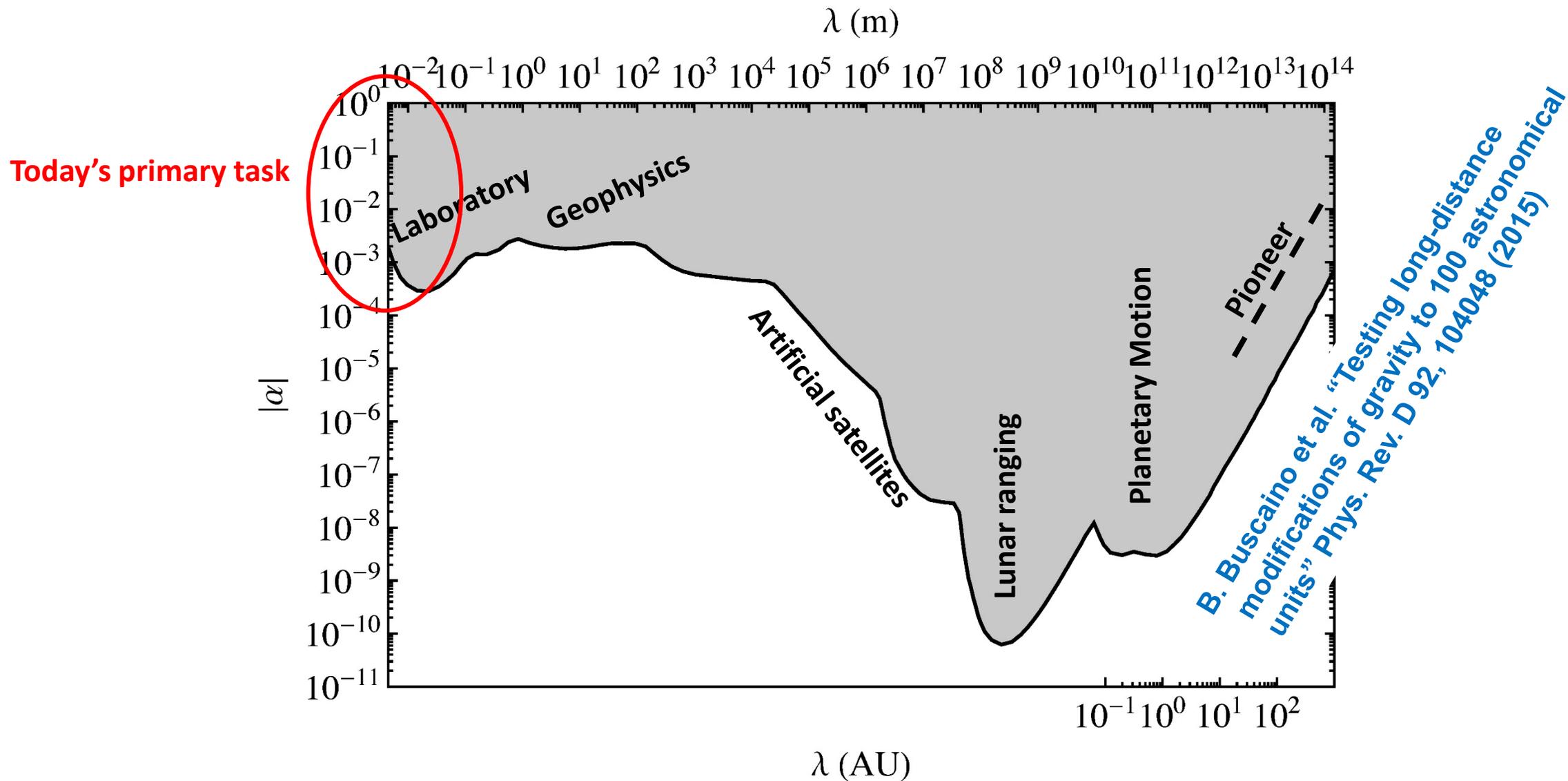λ: scale of the effect

What do we empirically know

What do we empirically know

What do we empirically know

One can take the point of view that exploring the law of gravity at any distance is such an important endeavor that should be carried out irrespective of theoretical prejudice.

In addition, there are important theoretical reasons to suspect that deviation from $1/R^2$ may actually arise naturally and be more than just plausible.

Gravity is a notoriously rebellious interaction. We do not have a good framework to treat the theory of gravity in a quantum-mechanical context.

And gravity at ordinary energies/distances is so much weaker than any of the other fundamental interactions.

Why? Are those issues related to each other?

Will the solutions of these puzzles simultaneously solve other modern puzzles in physics, such as those of Dark Matter or Dark Energy.

As an example, several authors have suggested that the dimensionality of the physical universe may at the root of some of these problems.

Many theories naturally include more than the ordinary 3 space dimensions. Since the ordinary physical space is clearly 3-dimensional, it is often assumed that the dimensions in excess of 3 are somehow curled up at very small scale, so that they have no effect at larger scales.

E.g. here the field scales as 1/R for R<<a and as a constant for R>>a.

Illustration from Arkani-Hamed, Dimopoulos, Dvali, Scientific American, Aug 2000

Some versions of this scenario substantially reduce the scale gap from electroweak physics to gravity, making gravity stronger at energy scales that are not as extreme as would result from a plain $1/R^2$ trend.
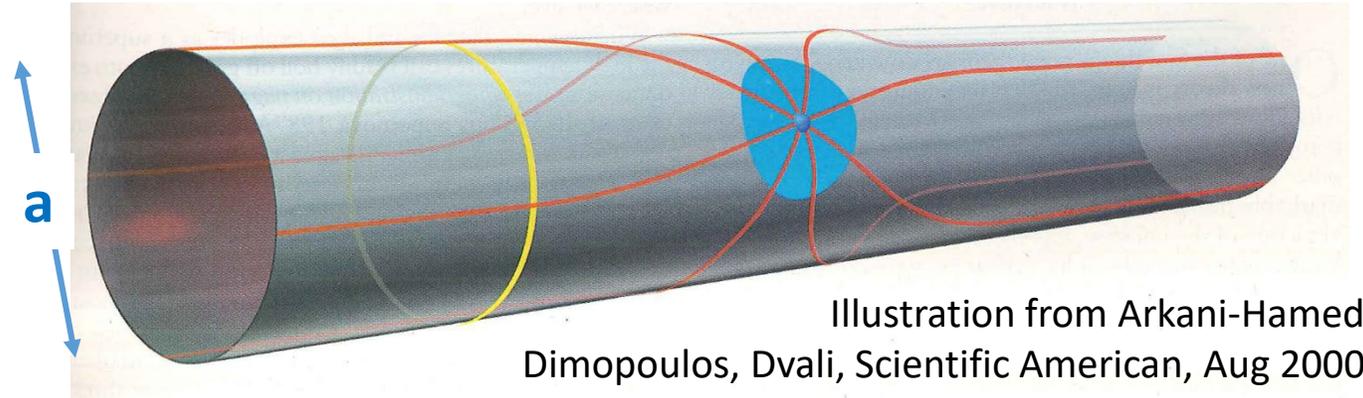
But, also, any new, long range force related to intrinsic properties (e.g. baryon number) may appear as a modification to Newtonian gravity.

Experimental challenges

- Since $F = G\dfrac{M_1 M_1}{R^2} = G\dfrac{\rho_1 V_1 \rho_2 V_2}{R^2}$

  for atomic materials (we can't use Neutron Stars!)
  $\rho_1 \sim \rho_2 < 20$ g/cm³, there is no silver bullet.

  In addition, the volume $V \sim R^3$, so $F \sim G\dfrac{\rho^2 R^6}{R^2}$

  and it is clear that measurements at short
  distance become exceedingly difficult.

- At distances <100μm even neutral matter results
  in residual E&M interaction that are a dangerous
  background for these measurements

$\sim 2r$

m_1 m_2

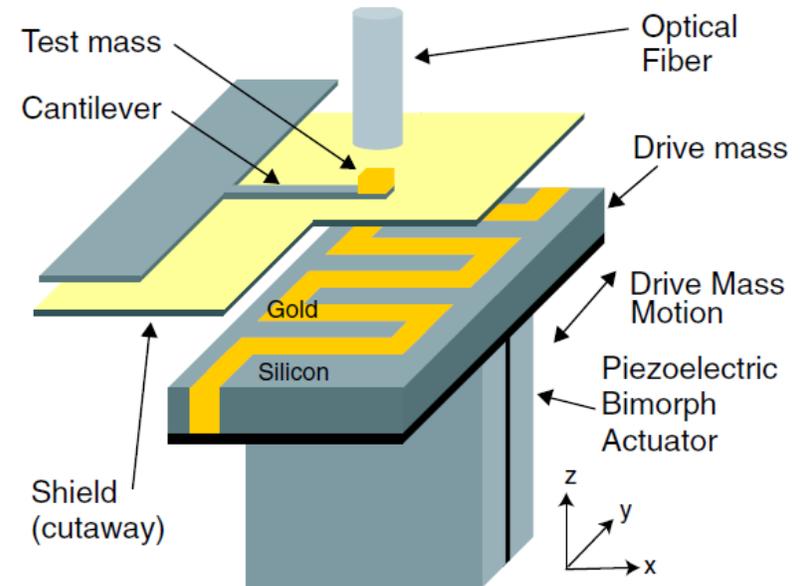$r \sim 10\mathrm{\mu m} \;\rightarrow\; F_N \sim 10^{-21} N$
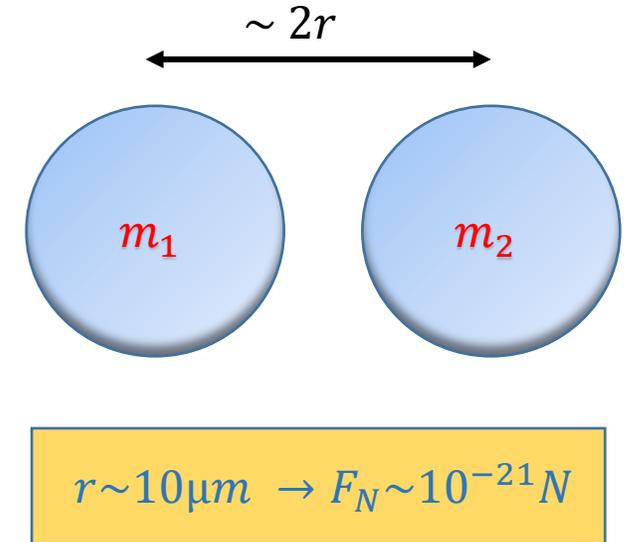
Most inverse-square law measurements are/have been done with wonderfully sophisticated versions of Cavendish's setup.

As distances become shorter, this approach becomes clumsy and substantial efforts have to do with "artificial" issues (e.g. how to machine a 5 cm diameter disk flat to µm level…).

~5cm
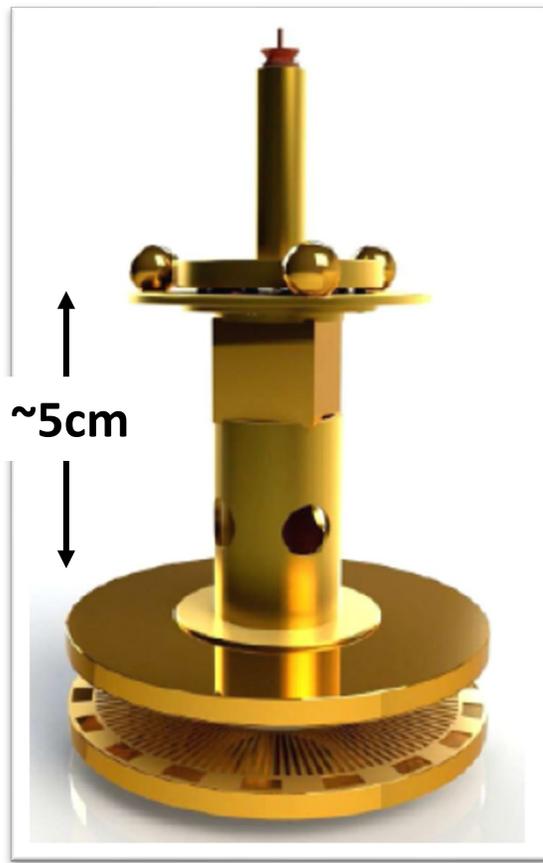
Sketch of the EotWash apparatus from the University of Washington in Seattle

Phys. Rev. Lett. 124, 101101 (2020)

In recent times, some new measurements have been made using AFM techniques (but, still, these use mechanical springs)

Test mass
Cantilever
Optical Fiber
Drive mass
Gold
Silicon
Drive Mass Motion
Piezoelectric Bimorph Actuator
Shield (cutaway)
z
y
x

Sketch of the custom cryogenic AFM apparatus from Kapitulnik's group at Stanford

J.Chiaverini *et al.*, PRL 90 (2003) 151101

The current experimental situation at short distance on the α-λ plane
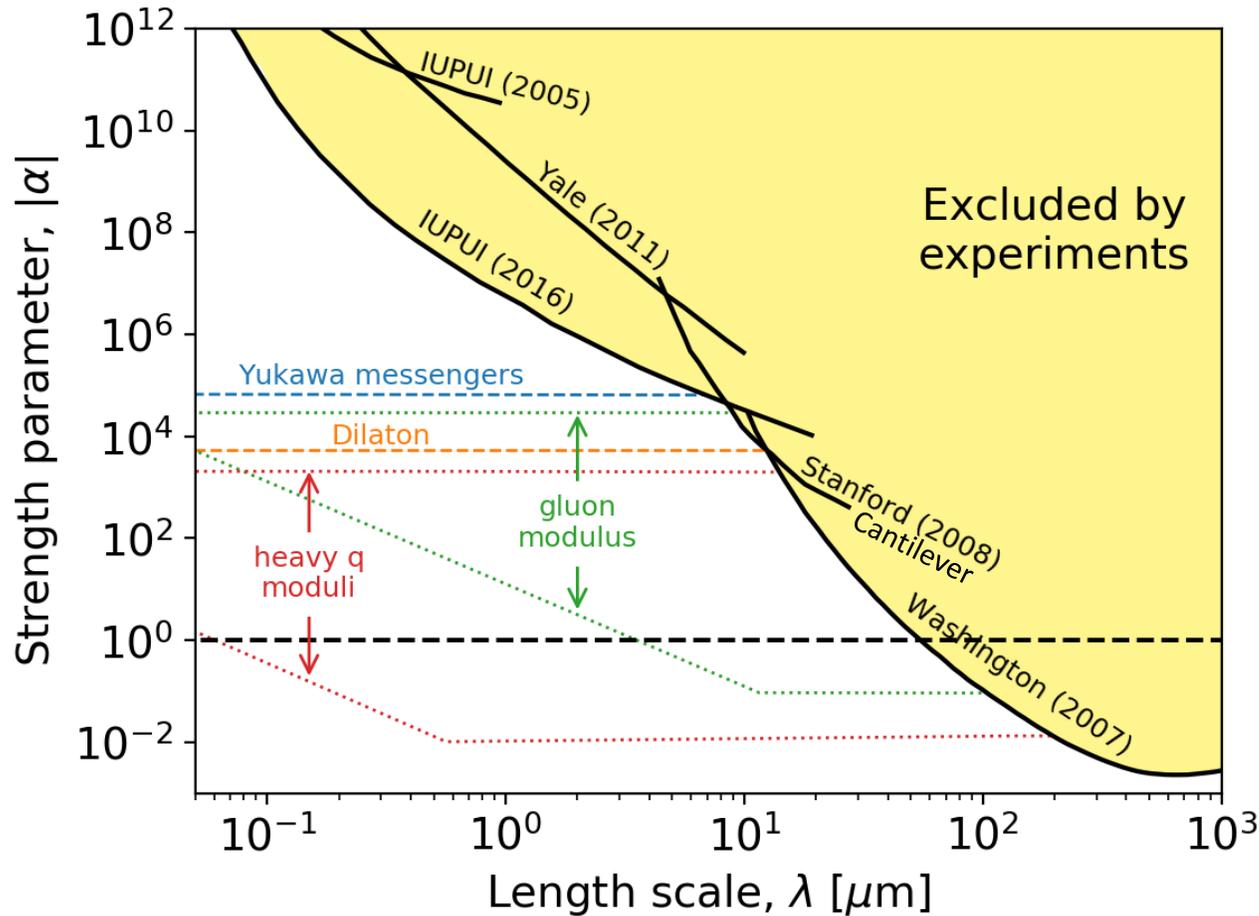
Note: The ideal probe for such a measurement is the neutron (charge radius is ~1fm instead of ~1nm).

➔ *More on this later*
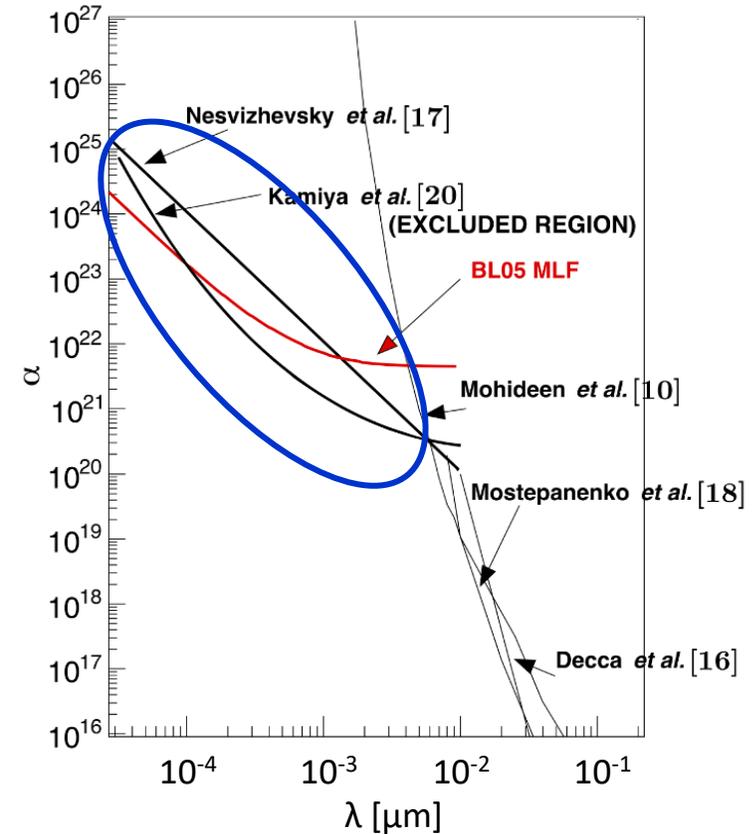
Given the small strength of gravity we need to measure really small forces

Some orders of magnitude of more or less familiar forces (weighs)
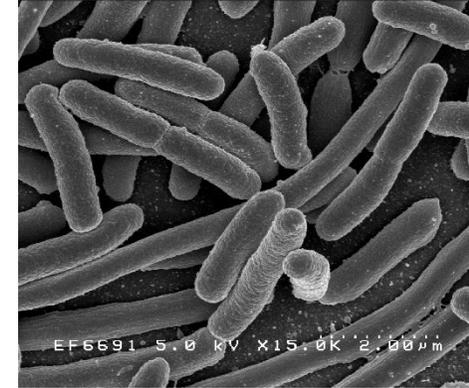
A bathroom scale resolves ~1 N

A dust mite 10^{-7} N

E. coli 10^{-14} N
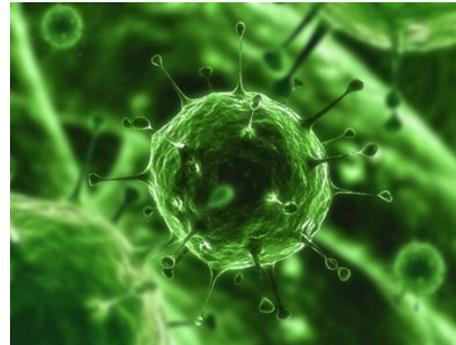
100 kg ~ 1kN

Conventional AFM measures 10^{-12} N

Specialized, cryogenic setups can result in ~10^{-16} N/√Hz noise floors

Virus 10^{-19} N

Carbon atom 10^{-25} N

In the last 50 years, optical tweezers have developed into broad field, primarily applied to biology, in water.

Microspheres optically trapped in vacuum make superb force sensors. **No mechanical springs!**
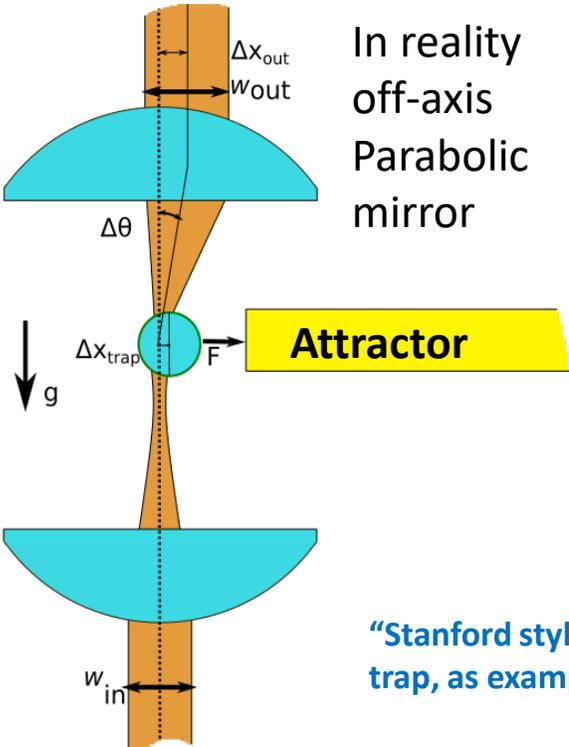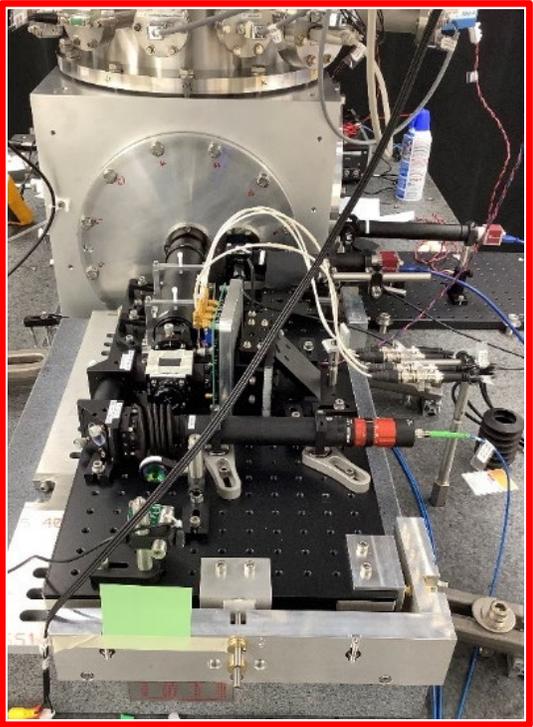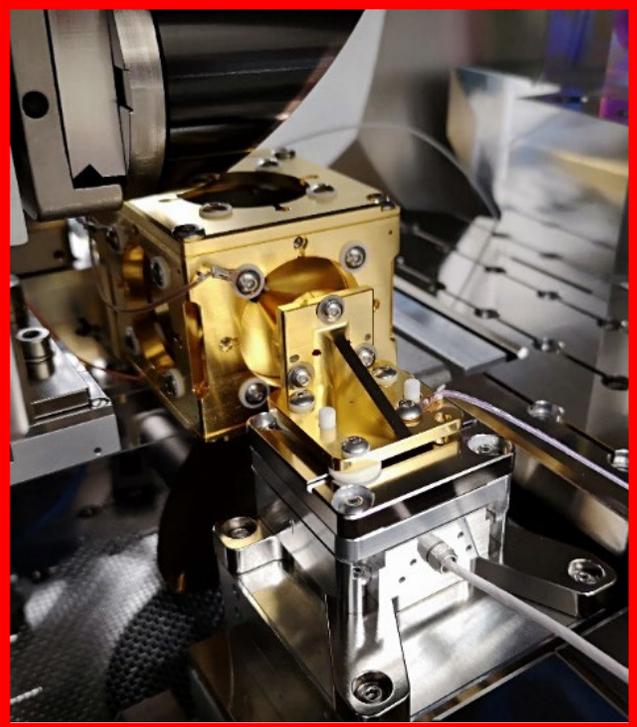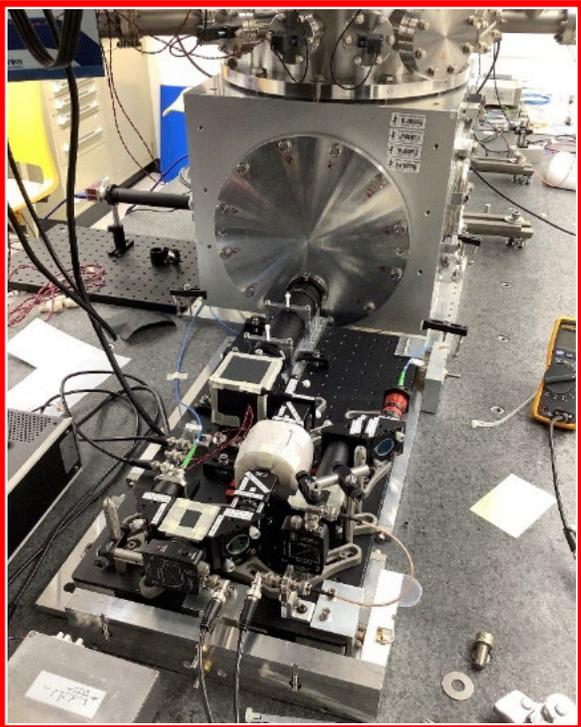
In reality off-axis Parabolic mirror

Attractor

"Stanford style" trap, as example

Rev. Sci. Instrum. 91, 083201 (2020)

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

as can be shown/calibrated by measuring charged microspheres
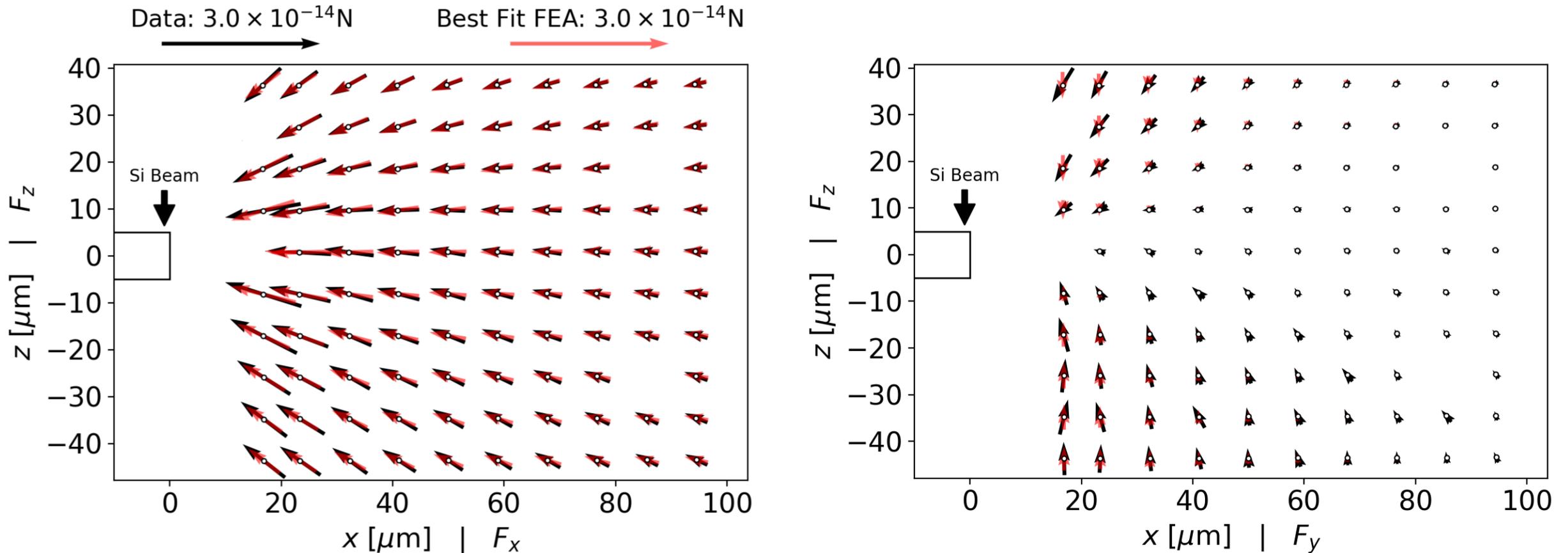
C.Blakemore et al., Phys. Rev. A 99 (2019) 023816
Similar results in G.Winstone et al., Phys. Rev. A 98 (2018) 053831

Precision measurement of microsphere mass and density

Implied mass: 81.5 pg
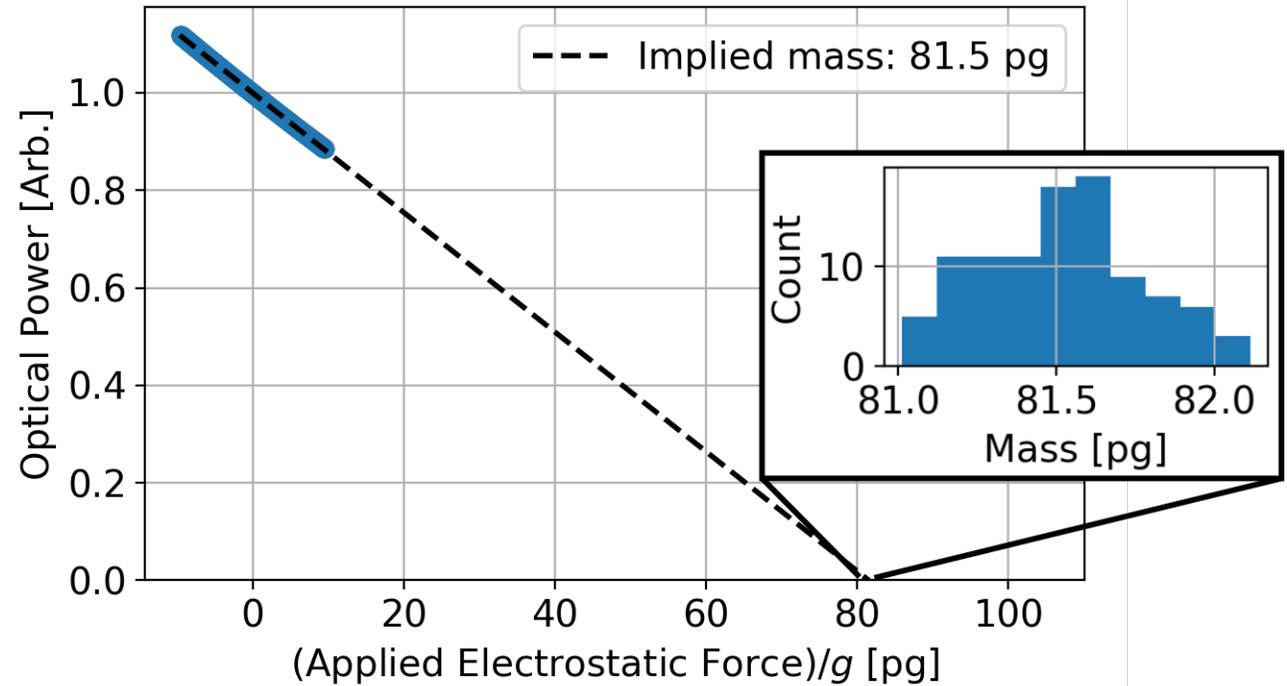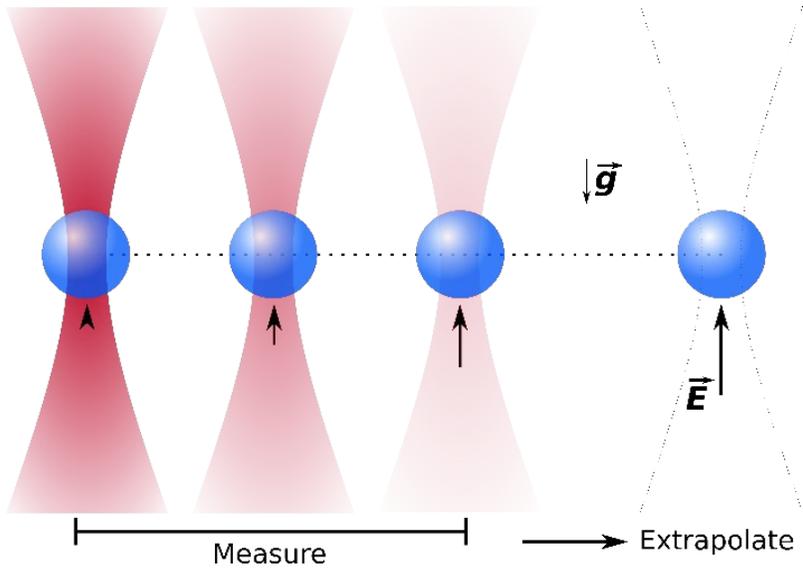
This technique only requires the knowledge/measurement of the relative power needed to compensate for a certain electrostatic force. Ie, it only needs the linearity of a photodiode.
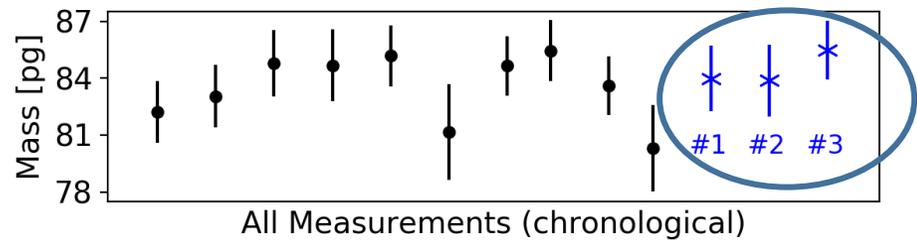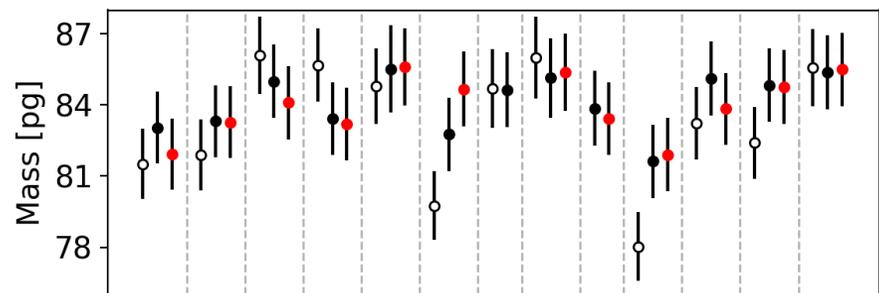
These three microspheres are then individually recovered and their diameter measured offline in an SEM

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.
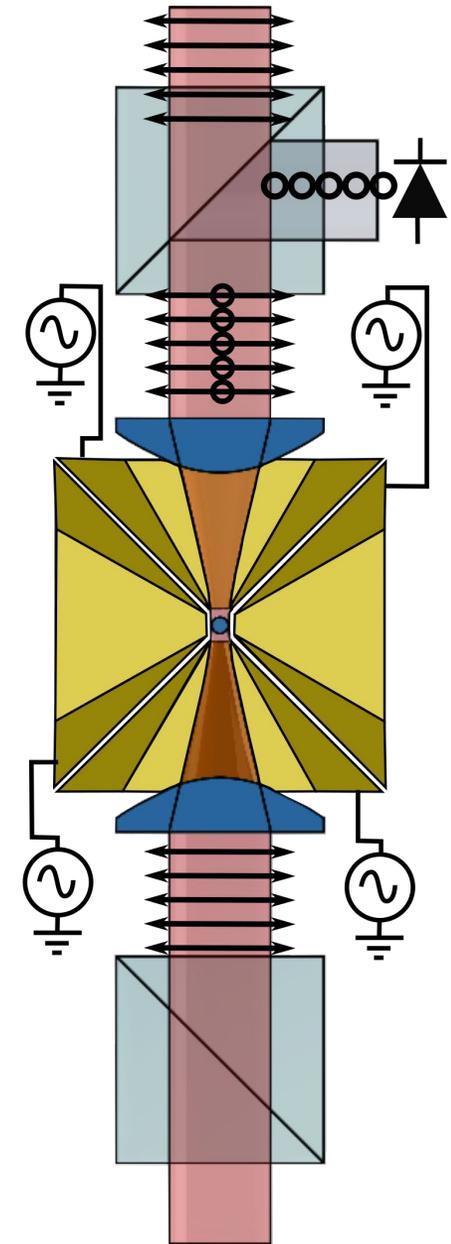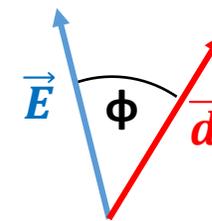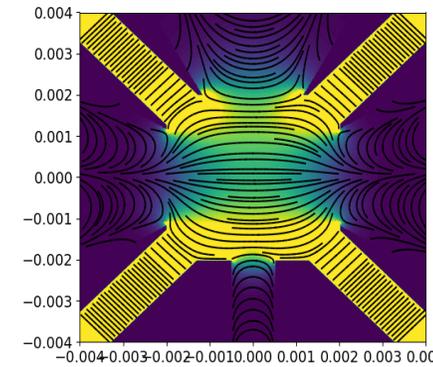
The possibility of setting the charge of the microsphere at leisure, opens the opportunity to search for very small charges (<<1me-) or, more interestingly, search for deviations from neutrality of matter.

Quantized charge

"0 charge" with increased 500 V RF amplitude.
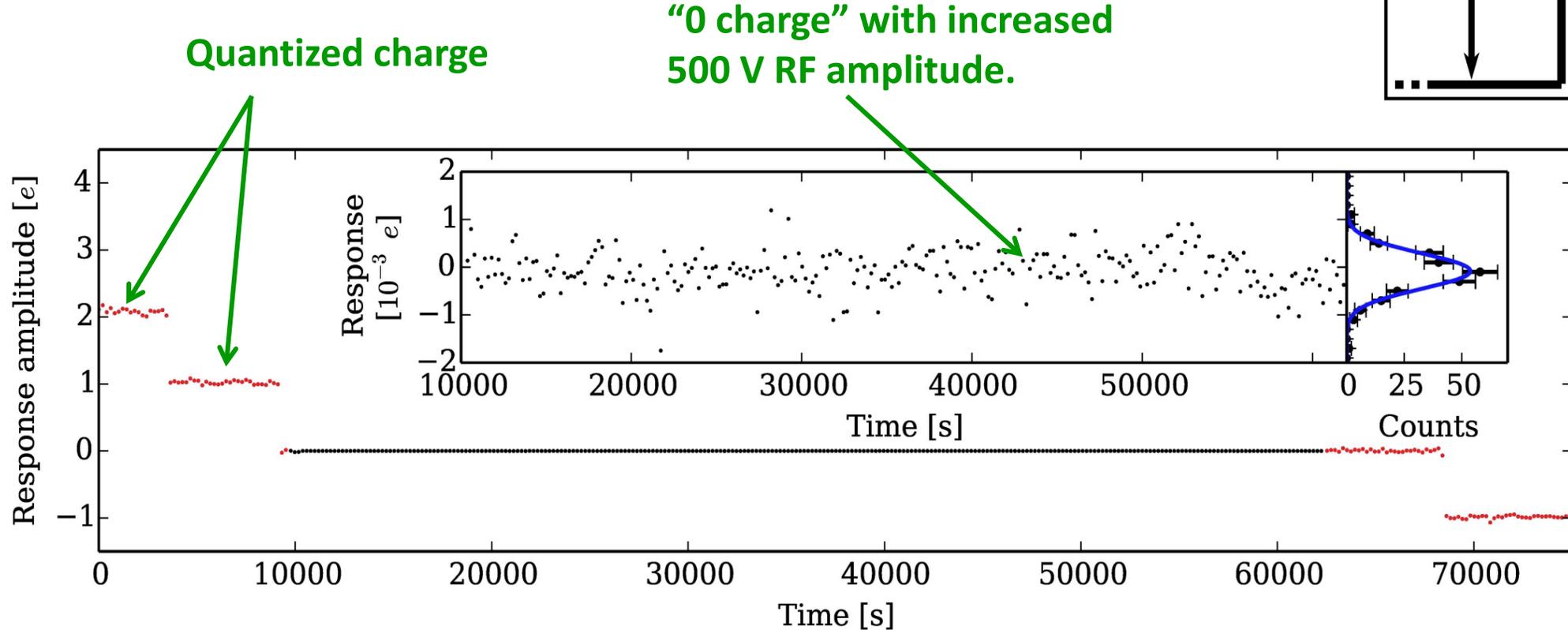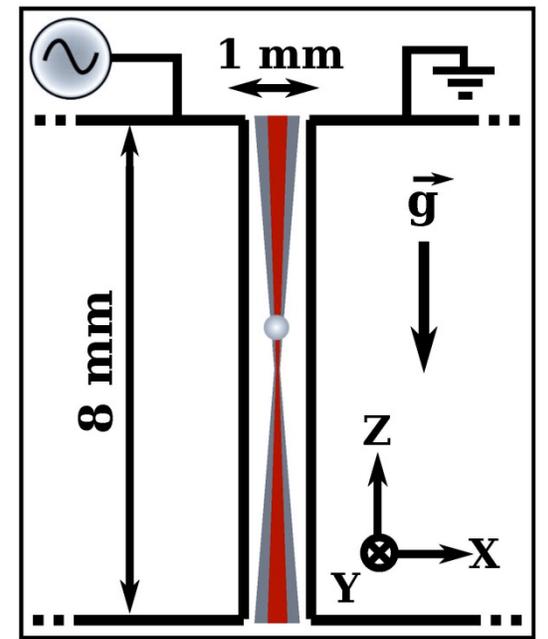
Existing millicharge or neutrality limits

D.Moore, A.Rider, GG,
Phys. Rev. Lett. 113 (2014) 251801 (first microsphere paper)

Optical Levitation (2015)
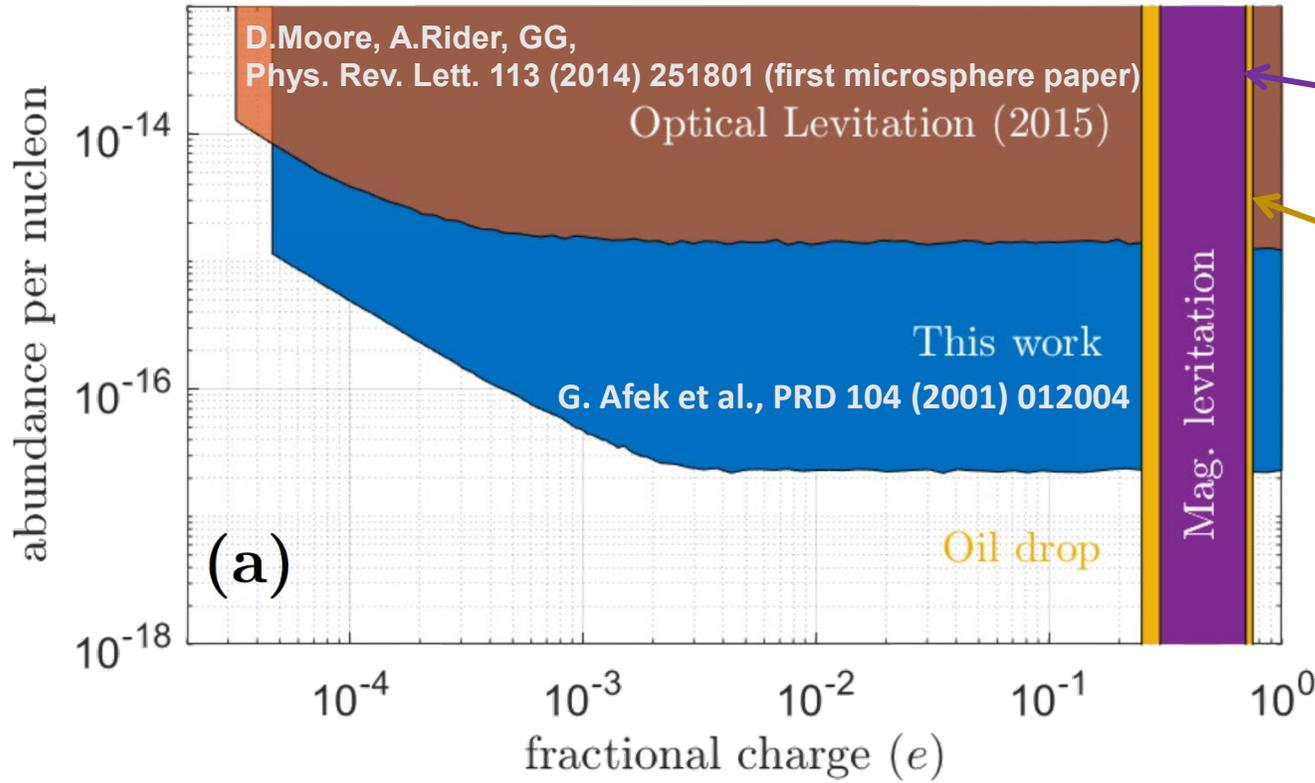
Marinelli et al., Phys. Rep. 85 (1982) 161

Kim et al., PRL 99 (2007) 161804

This work

G. Afek et al., PRD 104 (2001) 012004

Mag. levitation

Oil drop

(a)

abundance per nucleon

fractional charge (e)
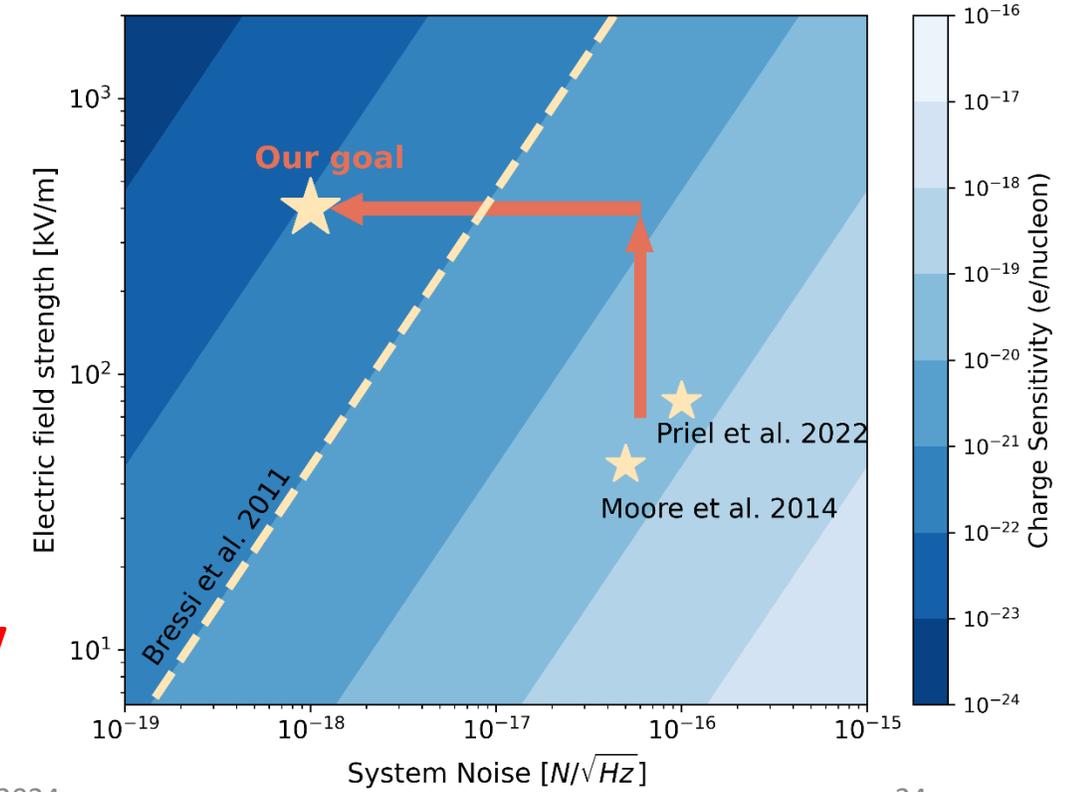
and expected sensitivity

Our goal

Priel et al. 2022

Moore et al. 2014

Bressi et al. 2011

Electric field strength [kV/m]

System Noise [$N/\sqrt{Hz}$]

Charge Sensitivity (e/nucleon)

How to recognize permanent dipole backgrounds

At f_0:

$$\mathbf{F} = \underbrace{q\mathbf{E}_{ac}}_{\text{Monopole}} + \underbrace{\mathbf{p}_{dc} \cdot \nabla \mathbf{E}_{ac}}_{\text{Permanent dipole}} + \underbrace{\mathbf{p}_{ac} \cdot \nabla \mathbf{E}_{dc}}_{\text{Induced dipole}}$$

This is subdominant
and not yet well studied

This is the term to worry about

Let's make the gradients as large as we like, but always run with pairs of field configurations

At first order the dipole term cancels for the quantity:

$$A \equiv F^+ - \Omega F^- = 2qE^+ + \left(p_{ac}^+ - \Omega p_{ac}^-\right)\frac{\partial E_{dc,z}}{\partial z}$$

Describes the possible slight asymmetry between the two field directions
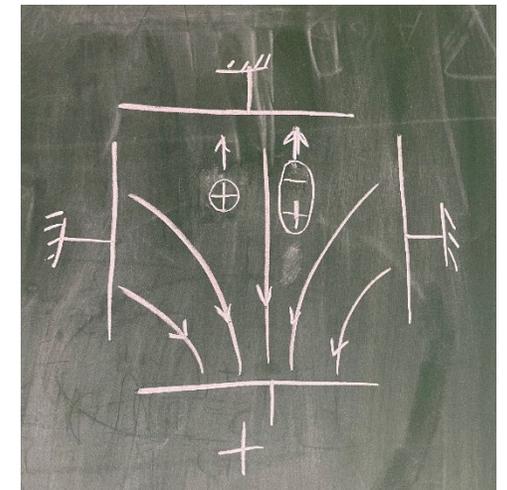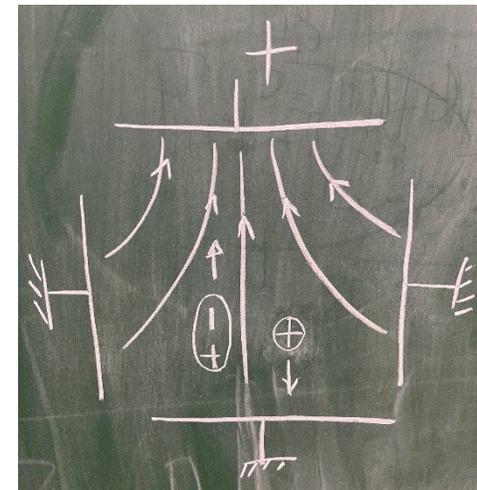
Note that the force switches direction for the monopole but not for the (permanent) dipole.
(blackboard courtesy of M. Aspelmeyer)

The cancellation works remarkably well!!
(here Ω is calculated with FEA, using the measured trap position with respect to the electrodes)

$$A \equiv F^+ - \Omega F^- = 2qE^+ + \left(p_{ac}^+ - \Omega p_{ac}^-\right)\frac{\partial E_{dc,z}}{\partial z}$$
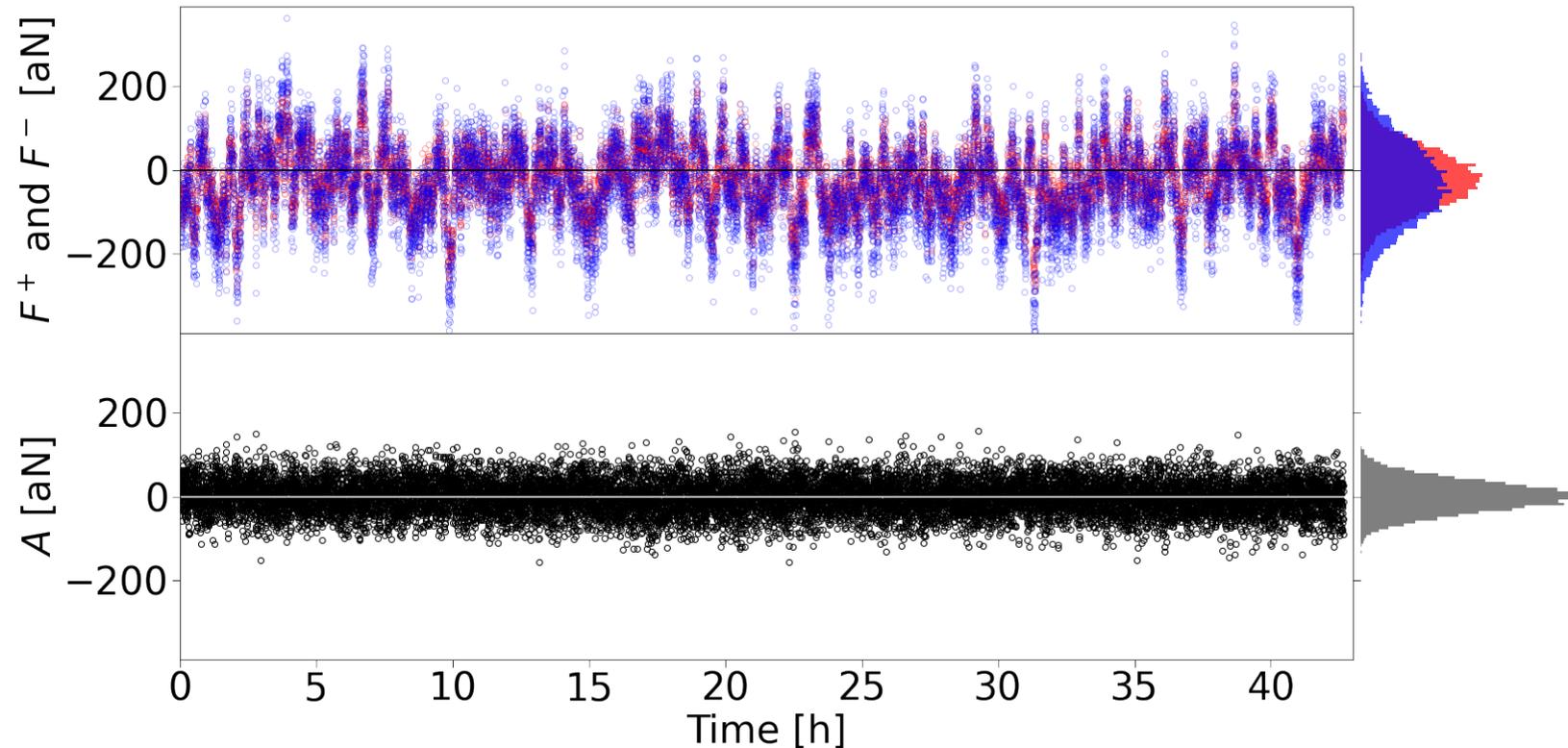
Note that the quantity *A* has no bias, within the extent of the noise.

The correlation between F_+ and F_- contains more information!

Again, note that there is no bias along the monopole axis.

But there is a finite permanent dipole measured
(~20 e μm here.   Quantitatively, this does not mean much, because the dipole changes with time)

N. Priel et al.
  Science Advances 8 Issue 41 (2022) 2361
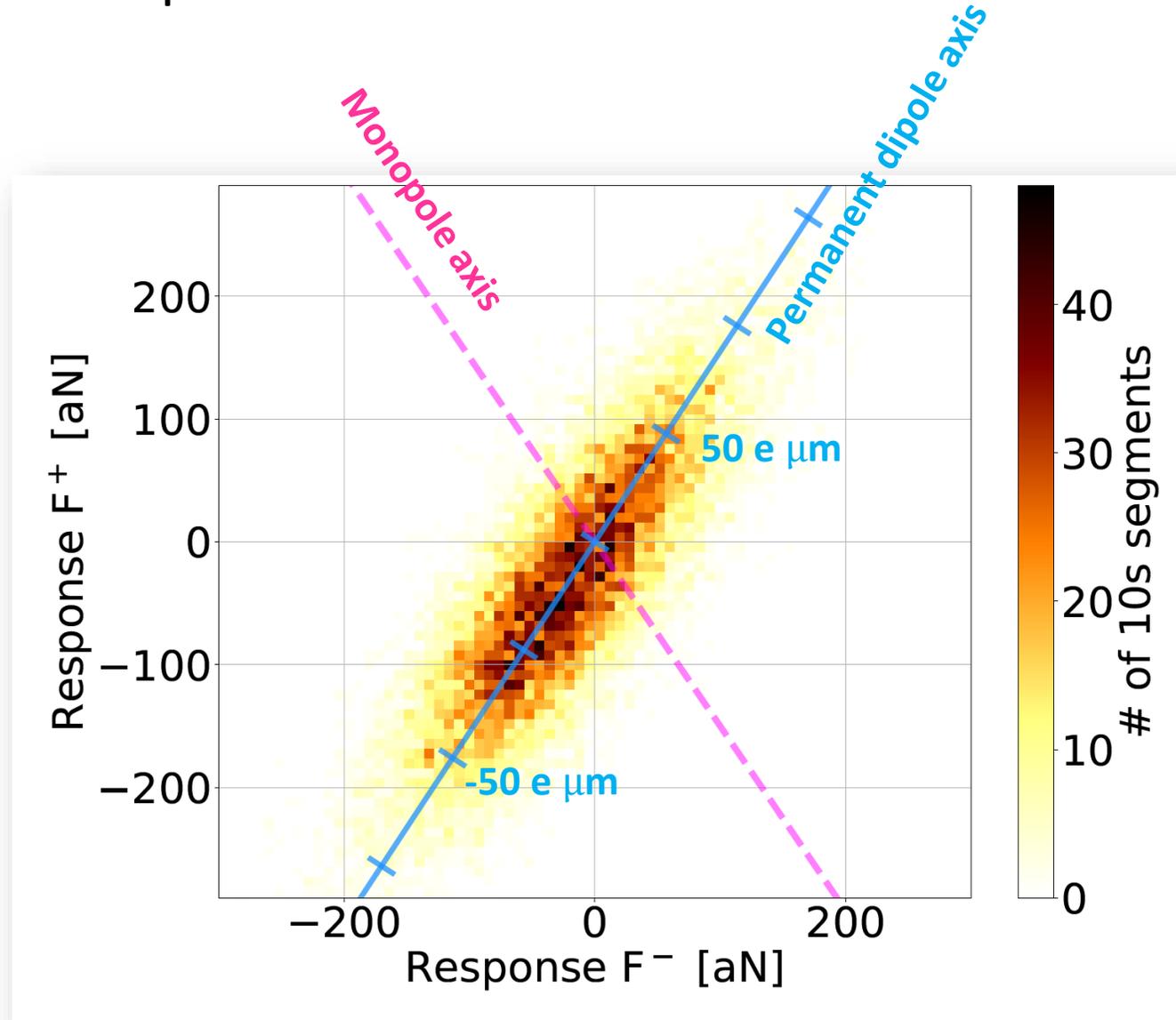
First gravity run

- 10^5 seconds

- 7.6 μm sphere (420 pg)

- 200 μm attractor stroke

- Using only Z channel

- Separation:
  - 13.9 um in X
  - 15.8 um in Z

- Background mitigation using
  - Shield
  - Drive attractor along density modula
    at f_0(3Hz), and observe correlated force
    at f_0, $2f_0$, $3f_0$, $4f_0$, …
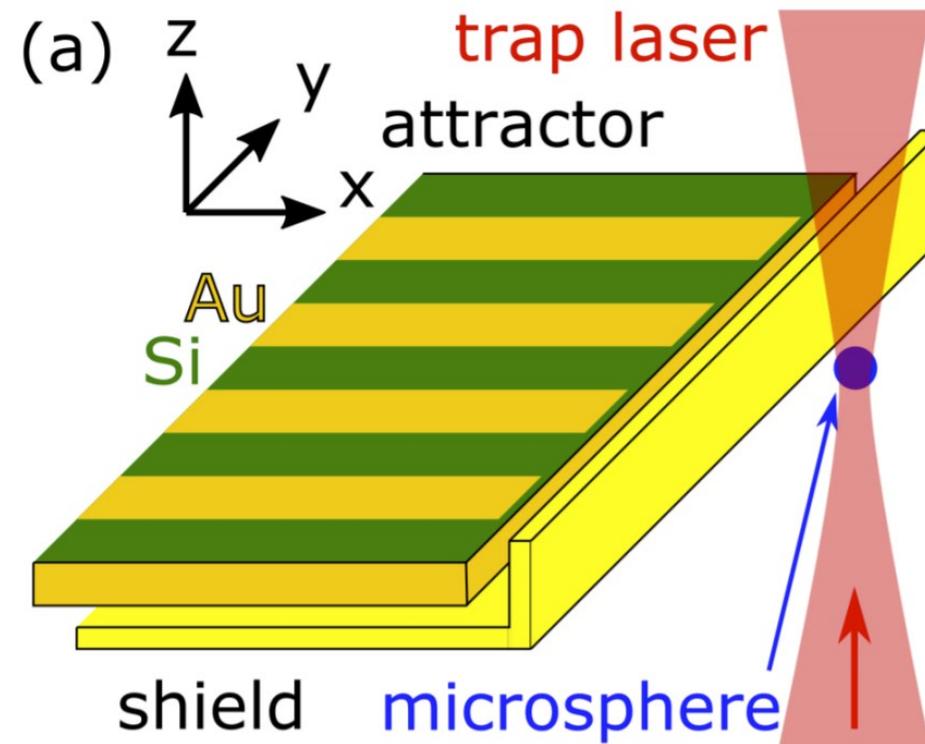
First generation attractor set, here shown before Au coating
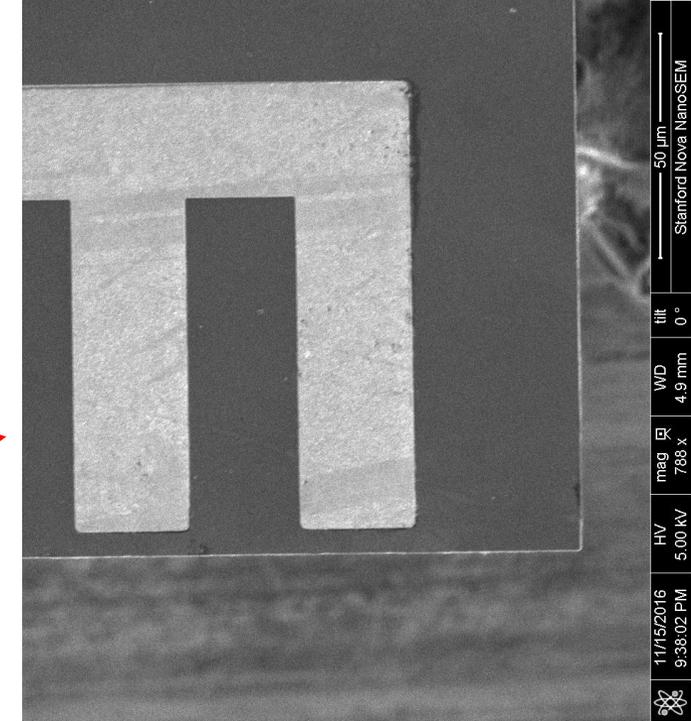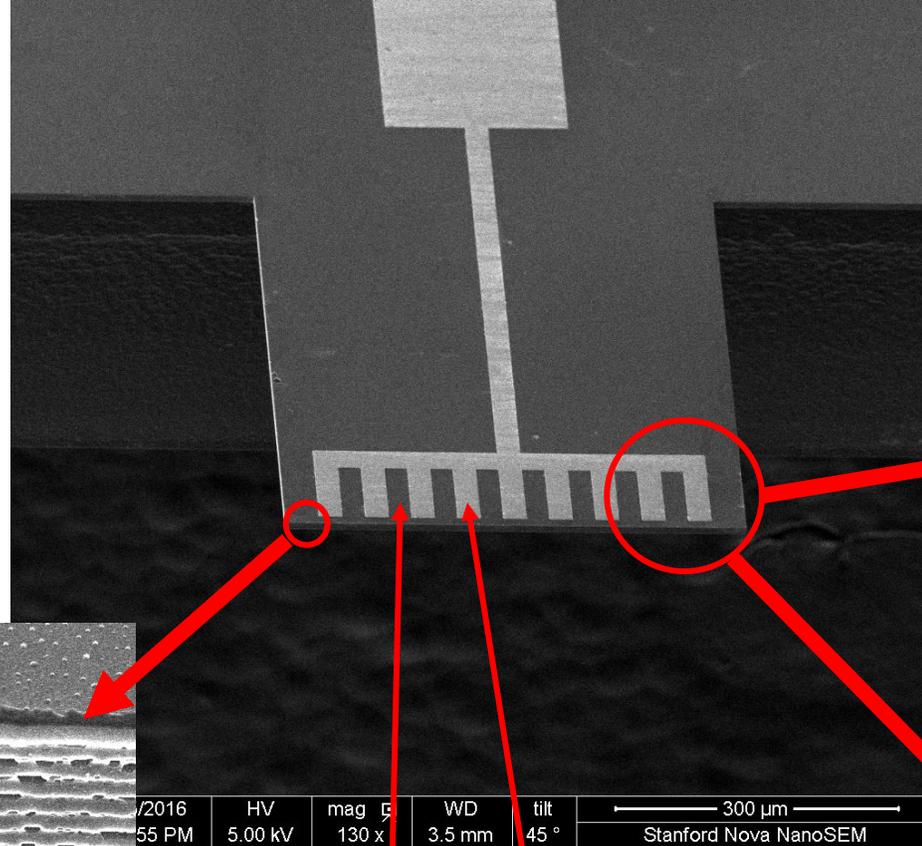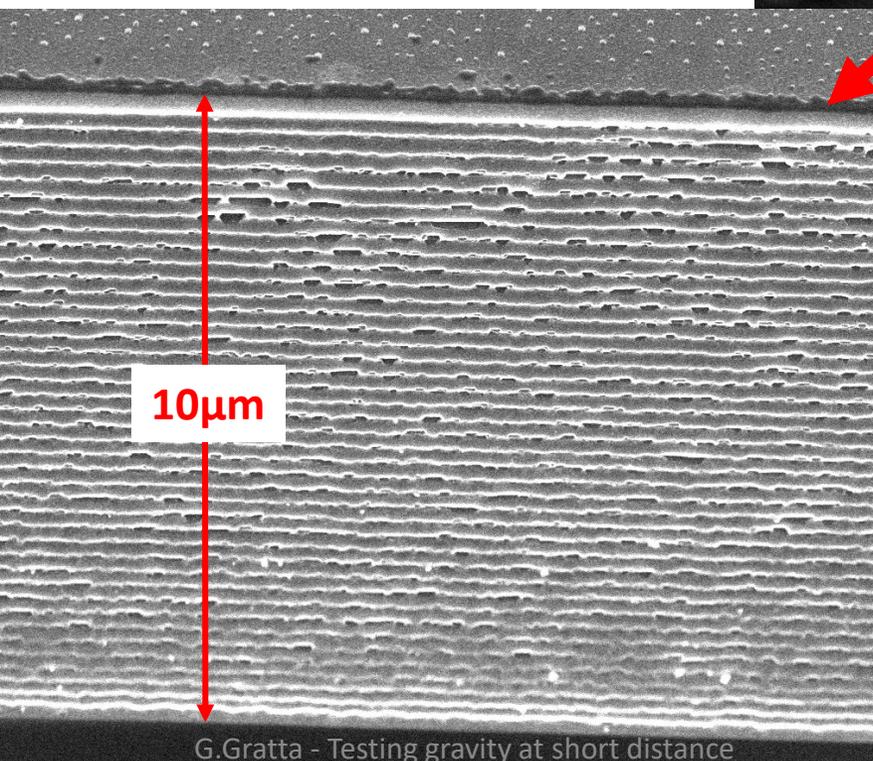
10μm

Si   Au
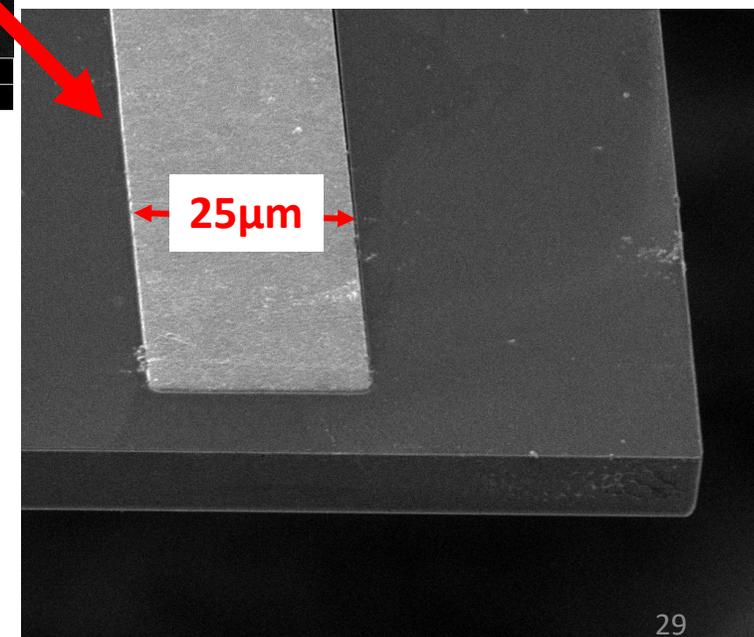
25μm

Standing electrostatic and optical shield

Attractor

Trapping laser
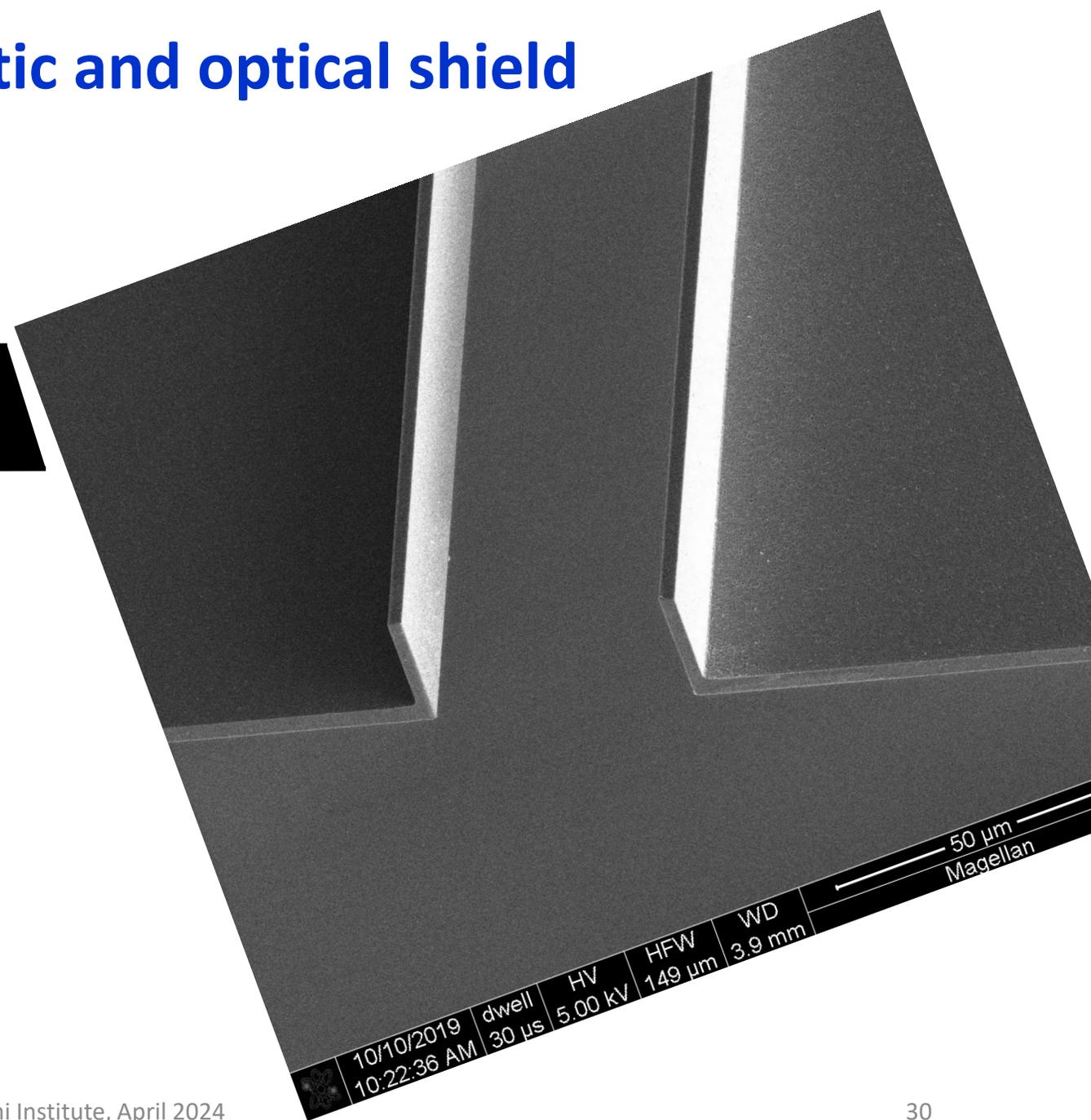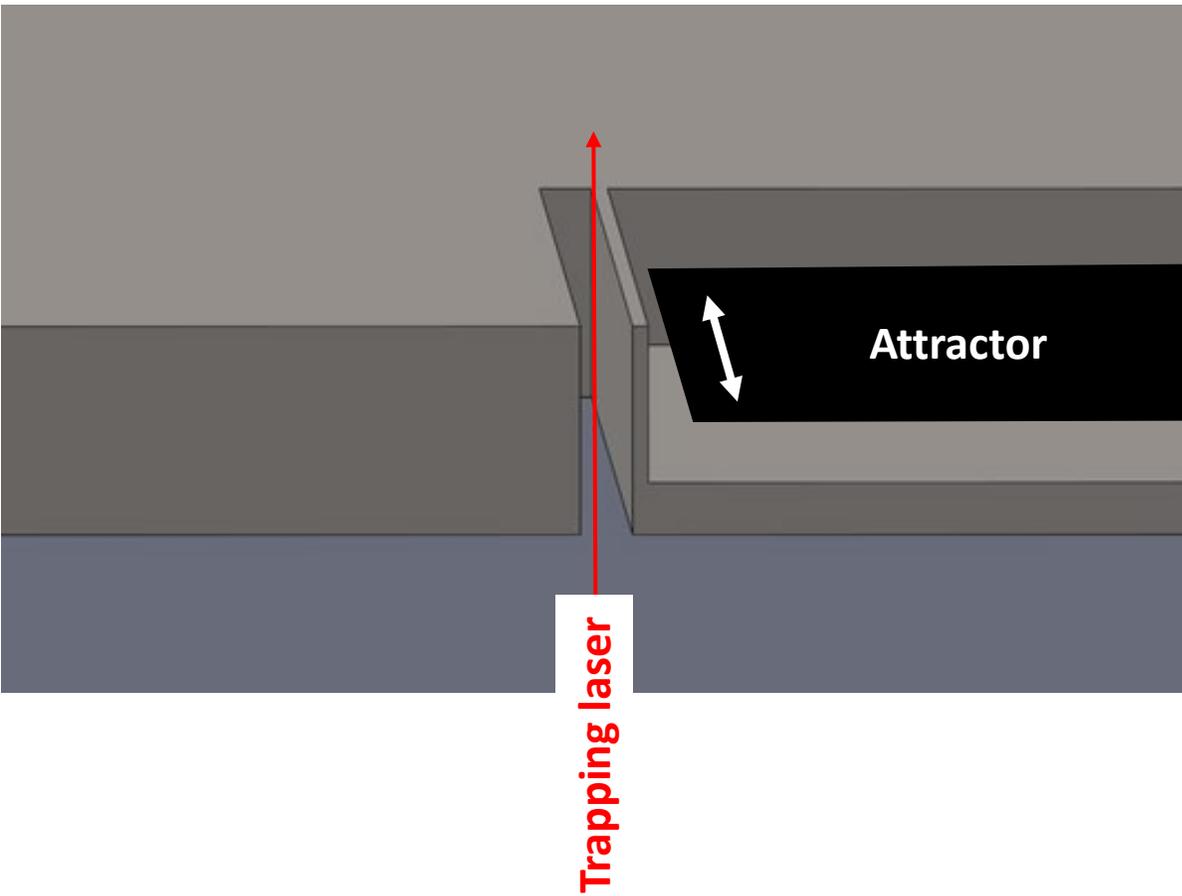
First gravity run
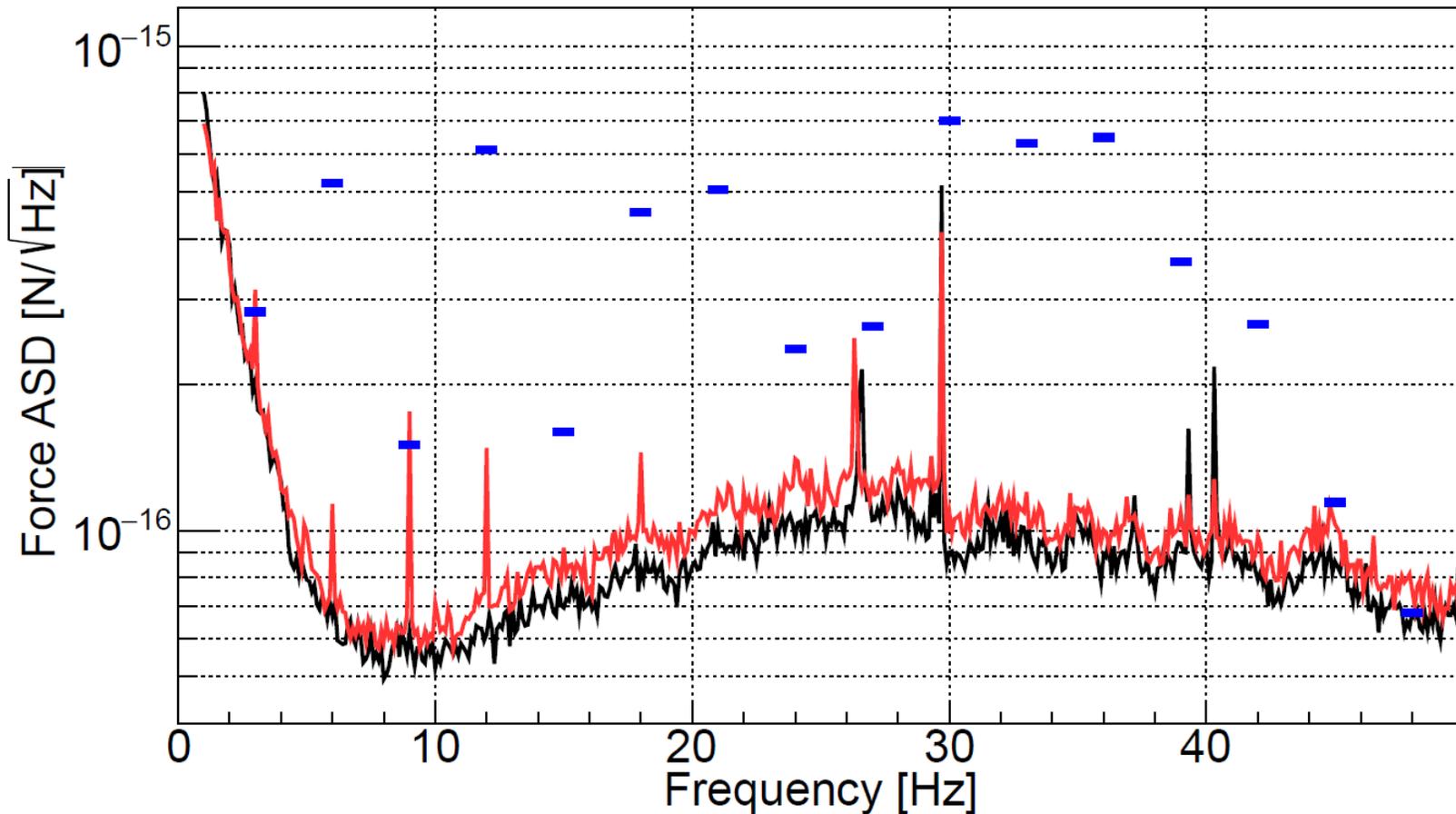
o Force sensitivity of 10^{-16} N/$\sqrt{\text{Hz}}$

o Backgrounds

o Black – response with stationary attractor

o Red – response with moving attractor

o Blue – expected response for $\alpha = 10^{10}$ and $\lambda = 10\mu m$

Z channel data

- **Z-channel is used (defined *a-priori*) due to X-channel background level**
- **Fitting signal model on harmonic-by-harmonic basis**
- **6 harmonics used**
- **There is a finite effect, but the data is clearly not "signal-like"**
- **Each harmonic is fit with using**

$$\mathcal{L}_i(\alpha, \lambda) = \prod_j \frac{1}{\sqrt{2\pi}\sigma_j} e^{-(F_j - \tau(\alpha, \lambda, \mathbf{x}_j))^2 / 2\sigma_j^2}$$

- **This can be used to extract MLEs and for statistical inference purposes**
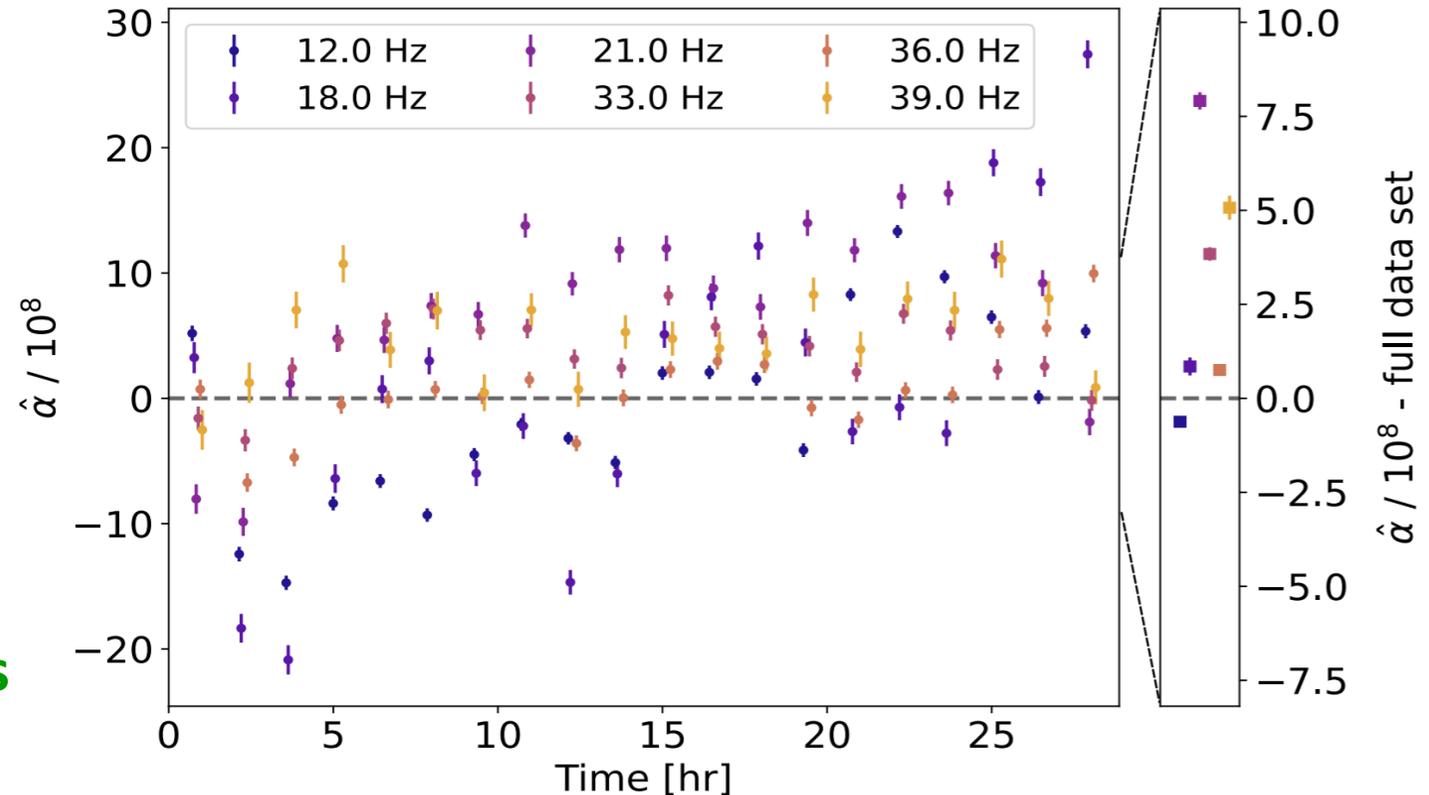
First new force limit with microspheres

- **Limit is set using profile-likelihood approach**
- **No background model used, and no background is subtracted**
- **Setting limit on positive and negative non-Newtonian gravity separately**
- **Method was investigated using a dedicated MC**
- **The sensitivity is limited by backgrounds and great progress is being made to understand and directly measure them.**
- **Beyond this, need to reduce the pointing noise.**
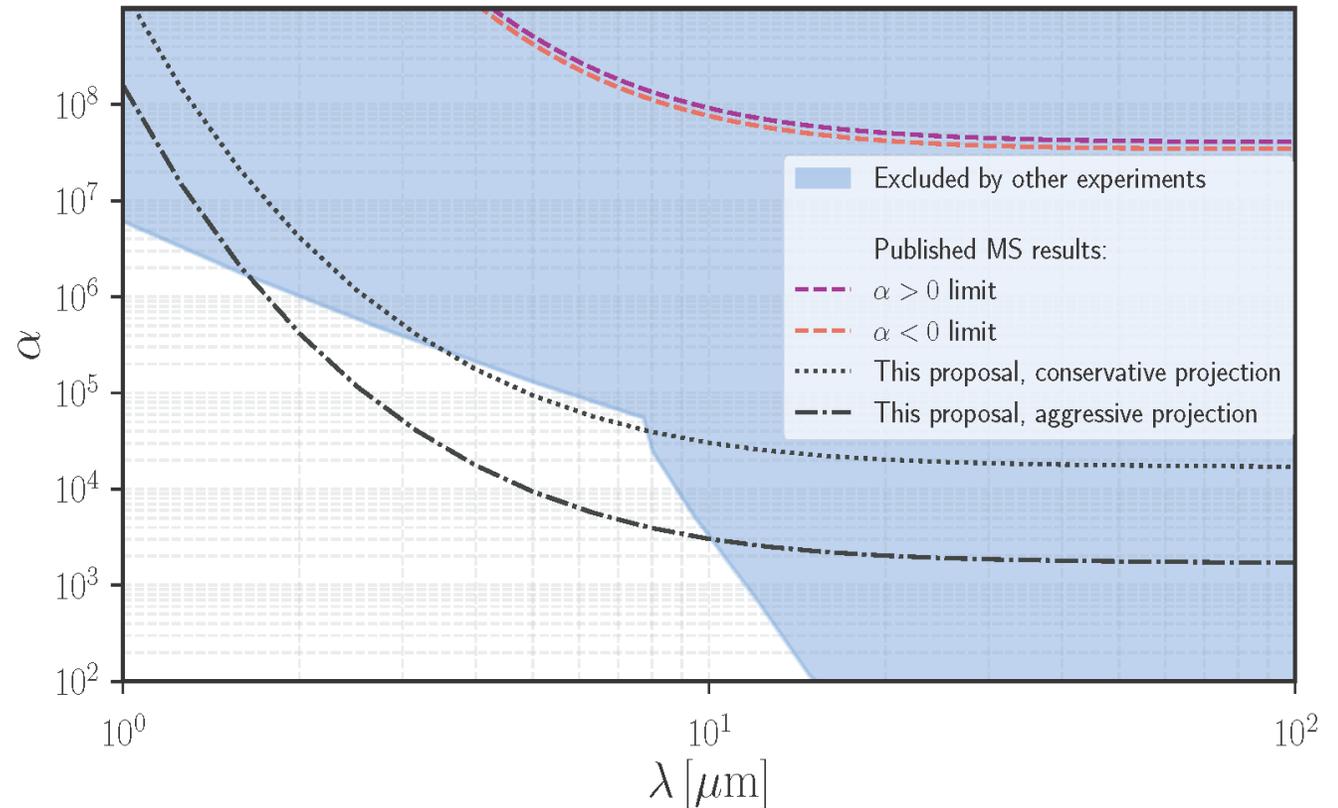
C.Blakemore et al., Phys Rev D 104 (2021) L061101

Currently, the dominant background appears to be due to stray light modulated by mechanical and optical features on the attractor
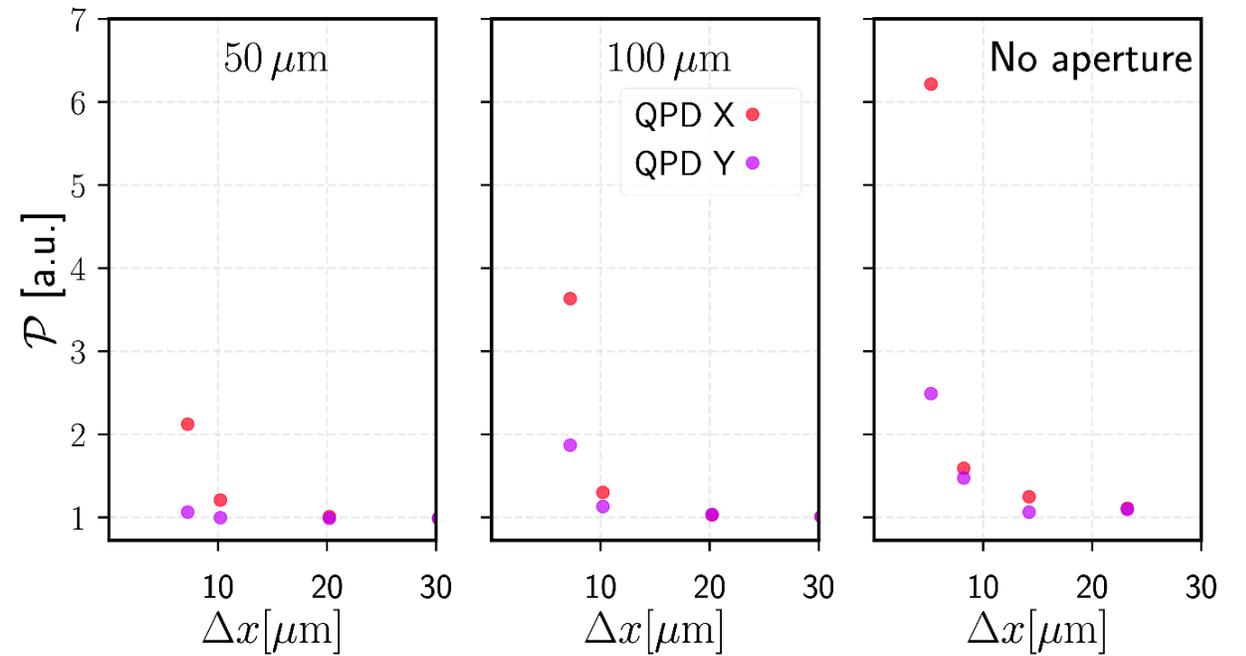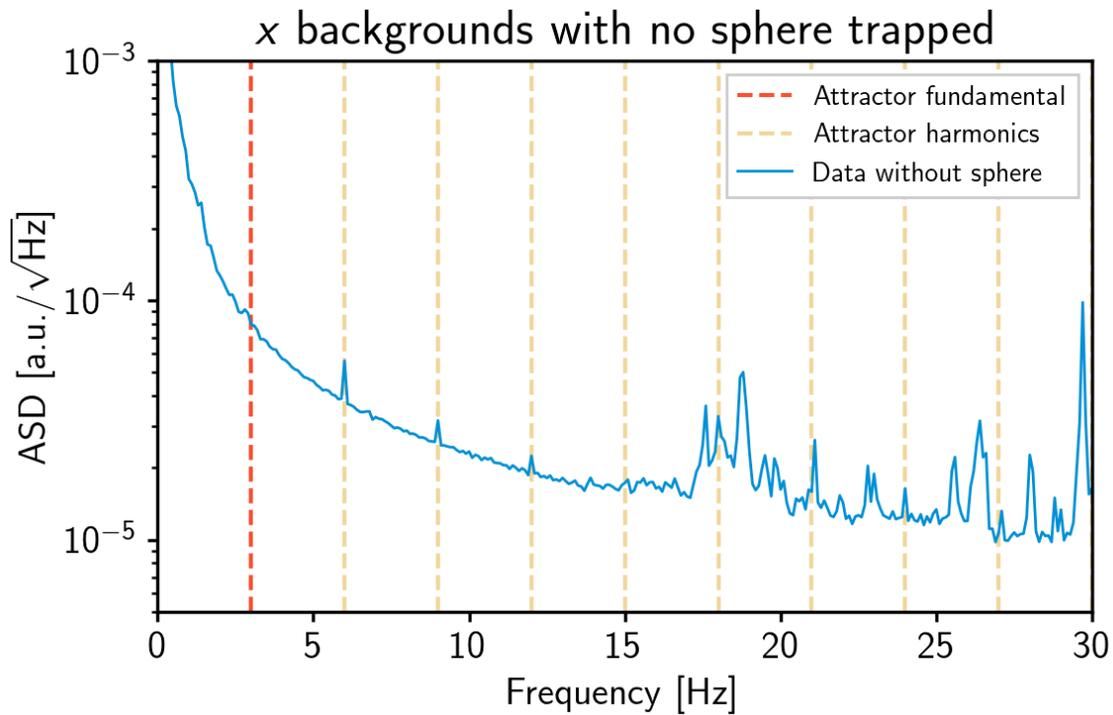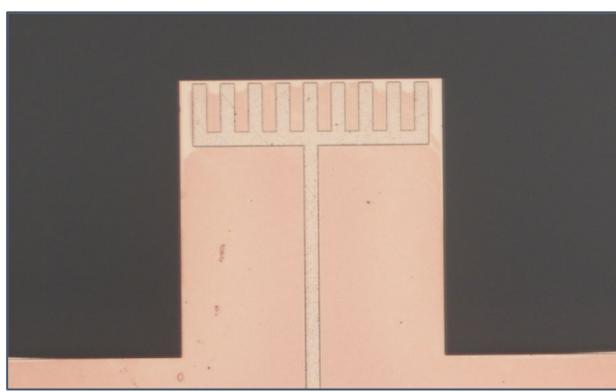
Indeed, some background is present even when scanning the attractor but no microsphere in the trap.

*Next run will use attractors electroplated
with "Platinum Black" which we managed to produce.*

Aquadag
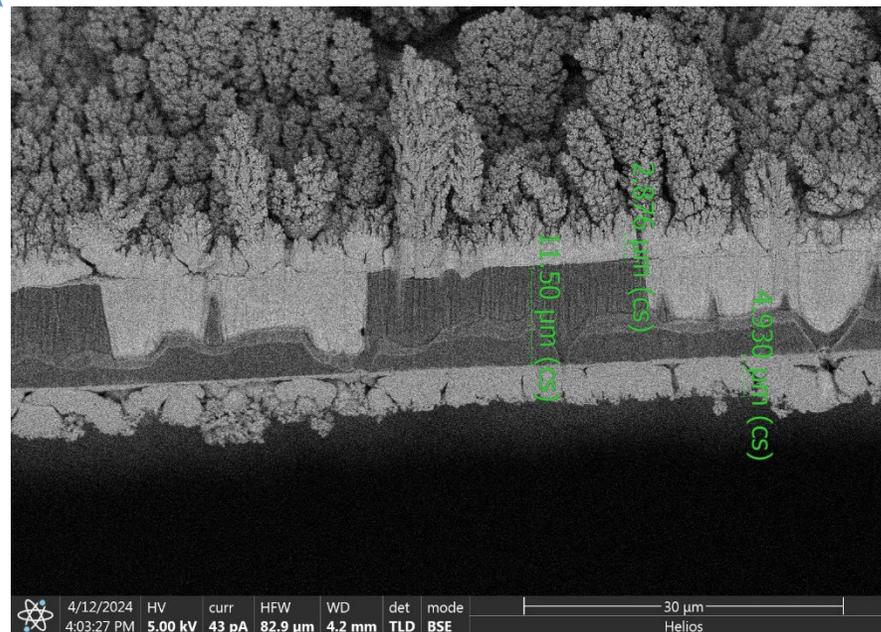
Also improving trapping laser pointing noise, directly reflected in the force noise
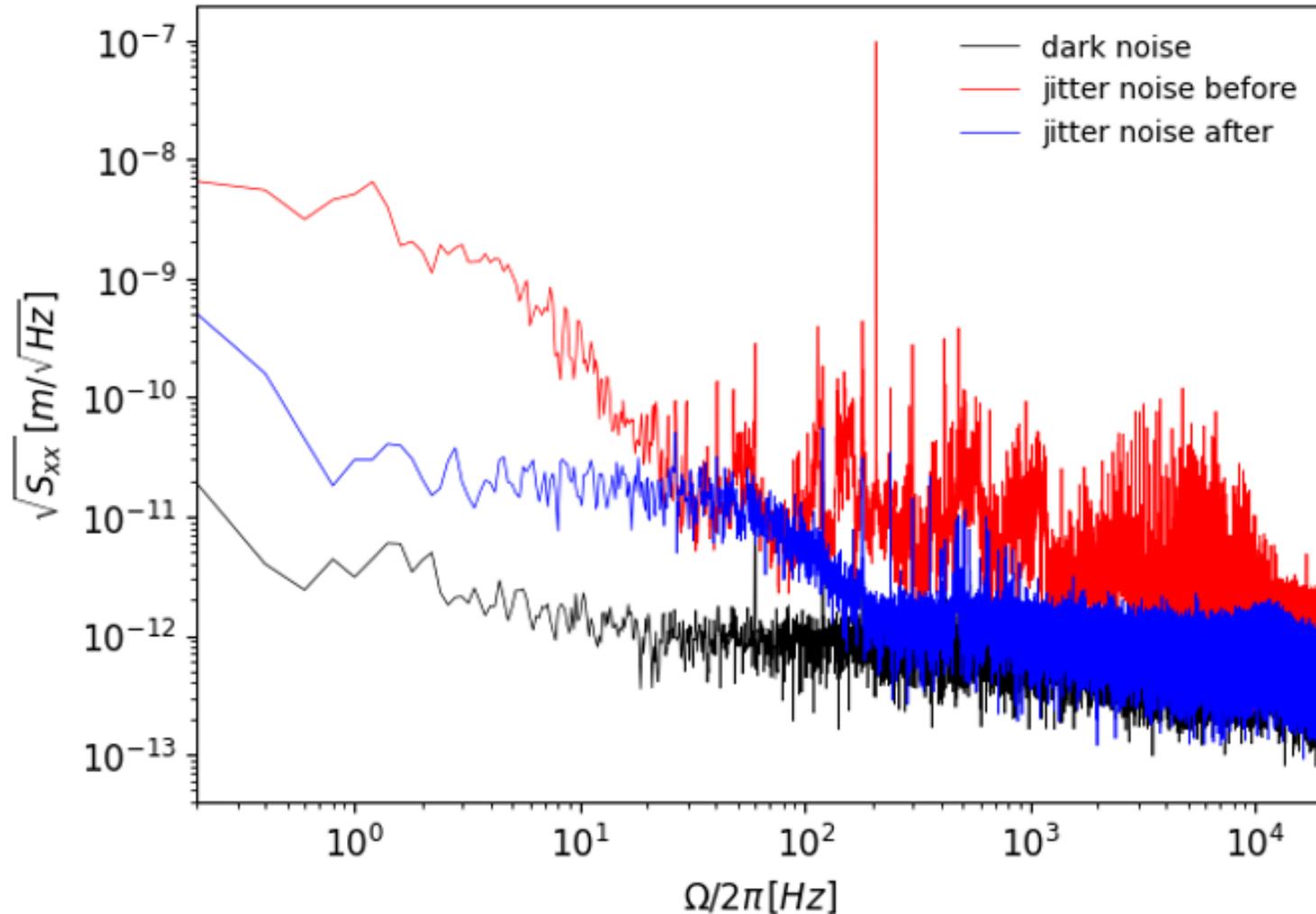
Still, as the range tested decreases, electromagnetic backgrounds on atomic matter sensitivity
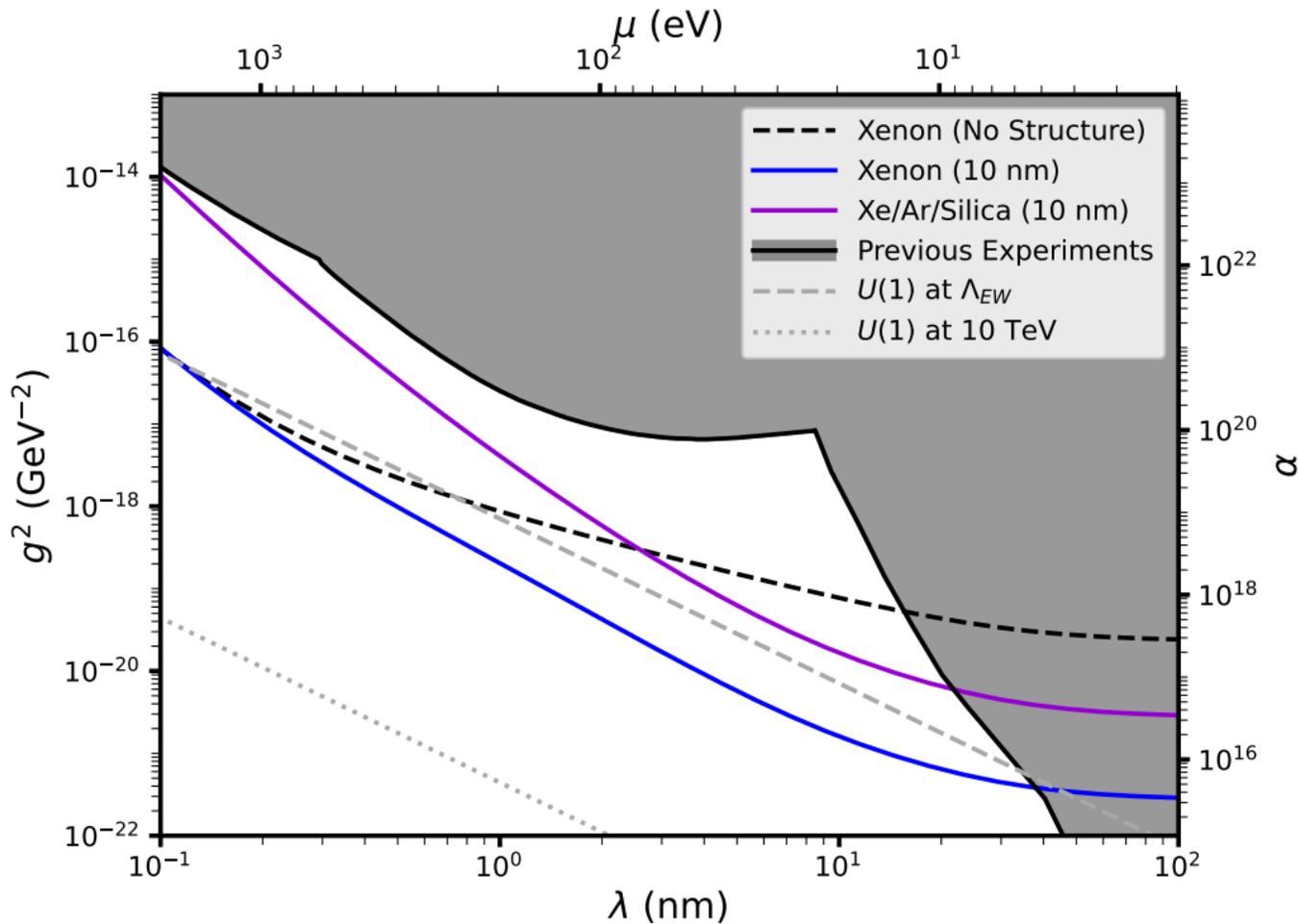
Indeed, neutrons, with a smaller charge radius than atoms can be an ideal probe, although, essentially for the same reason, neutrons are hard to handle.

Recent work suggests that better sensitivity could be obtained using ultra-low angle scattering off porous or composite materials, mitigating backgrounds from strong interactions.

Z.Bogorad, P.Graham, G.G, Phys. Rev. D 108 (2023) 055005

Here, I want to describe a different technique, using nuclei (as opposed to atoms) as force sensors

GG, D.E. Kaplan, S. Rajendran, Phys Rev D 102 (2020) 115031.

"Nuclei are well-protected affairs"

They have electric charge, but that is screened by the electron cloud and so has little coupling to external E&M disturbances.

In addition, nuclear level shifts due to E&M coupling, occurs through coupling to multipole (mainly dipole) moments and these are suppressed by the size of the nucleus.

And, this is further suppressed, in the case of unpolarized nuclei, by $\sqrt{N}$, when looking for the shift of a spectroscopy line that is measured by N events.

➡ **Can nuclear (gamma) spectroscopy used to investigate new forces?**
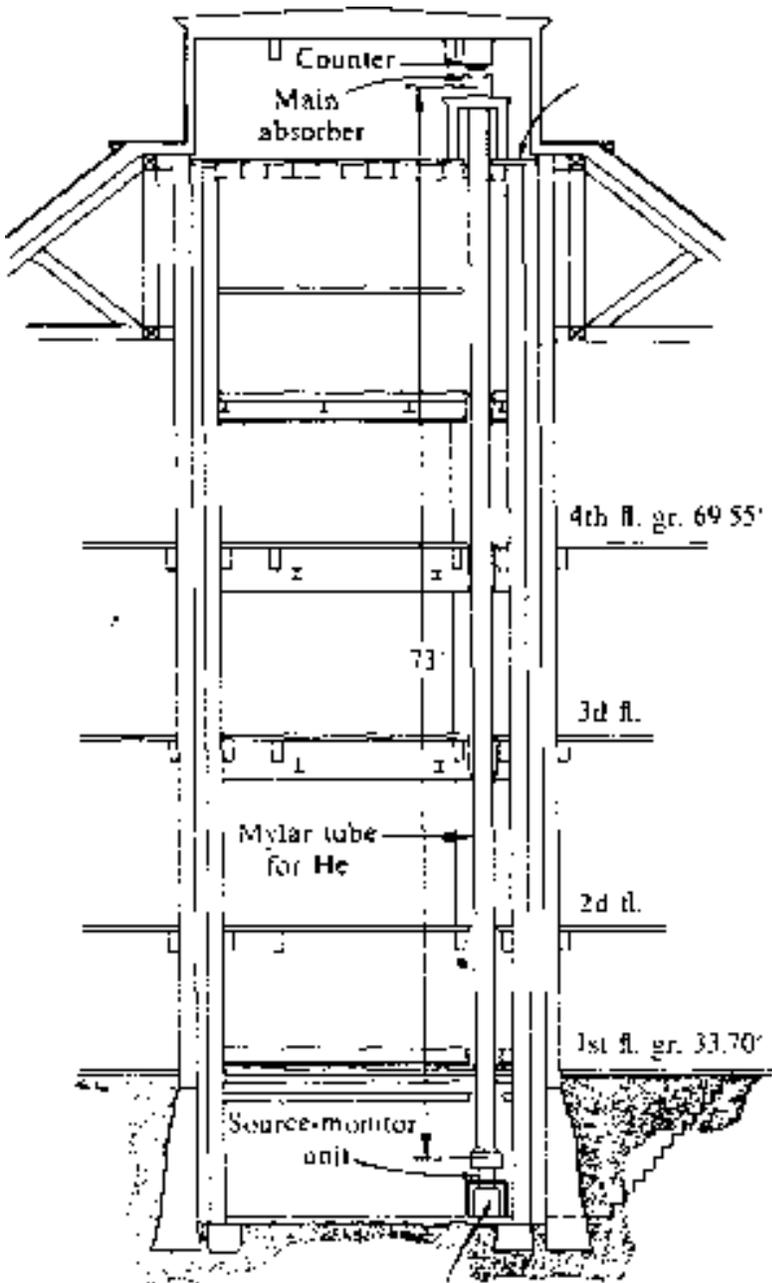
Mössbauer spectroscopy was used in a very elegant experiment to detect, for the first time, gavitational red/blue shift of photons.

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

Somewhat disconcertingly, Mössbauer spectroscopy was the ``appropriated'' by Chemists!

➔ *Time to reclaim it back for measurements of fundamental physics!*

Recoils in atomic and nuclear spectroscopy

In atomic physics, we are used to the fact that a photon emitted by an atom can be re-absorbed by another atom of the same species:

The fact that this works is kind of accidental, because the emitted photon is somewhat red shifted by the recoil of the emitting atom and, for the same reason, it needs to be a bit blue shifted to excite the absorbing one.

Quantitatively the energy of the emitted photon is: $E_\gamma = \Delta E \left(1 - \frac{\Delta E}{2Mc^2} \right)$

And, to be absorbed the energy has to be $E_\gamma = \Delta E \left(1 + \frac{\Delta E}{2Mc^2} \right)$

where ΔE is the energy difference between the two states and M is the mass of the atom.

This only works if the relative linewidth $\frac{\Gamma}{E_\gamma} > \frac{\Delta E}{Mc^2}$

Atomic physics example:

Natural linewidth for Na D$_1$ line: $\tau = 16\text{ns}$, $\delta\nu = 10\text{MHz}$ and $\dfrac{\Gamma}{E_\gamma} = \dfrac{\delta\nu}{\nu} = 2 \cdot 10^{-8}$

$$\frac{\Delta E}{Mc^2} = \frac{2.1eV}{23 \cdot 1GeV} \cong 10^{-10}$$

so $\dfrac{\Gamma}{E_\gamma} > \dfrac{\Delta E}{Mc^2}$ **(in reality this is even better because the line is broadened by collisions and thermal motion --which is the reason why state of the art clocks use cooled atoms and atomic fountains)**

Nuclear physics examples:

Natural linewidth for ^{152}Sm ~900 keV transition: $T_{1/2} = 28\text{fs}$, $\dfrac{\Gamma}{E_\gamma} = \dfrac{1.6 \cdot 10^{-2}}{9 \cdot 10^5} = \mathbf{1.7 \cdot 10^{-8}}$

$$\frac{\Delta E}{Mc^2} = \frac{9 \cdot 10^5 eV}{152 \cdot 10^9 eV} \cong \mathbf{6 \cdot 10^{-6}}$$

Now $\dfrac{\Gamma}{E_\gamma} < \dfrac{\Delta E}{Mc^2}$ and the photons emitted by a piece of Sm cannot be resonantly absorbed by another piece of Sm.

(you may remember that this issue was used in the experiment to measure the helicity of the neutrino, exactly by requiring that a previous recoil would boost the Sm nucleus and make the resonant absorption possible)

Things get even worse with e.g. the ^{137}Ba 661 keV transition (the very common "^{137}Cs" source).

Here $T_{1/2} = 2.55\text{min}$, $\dfrac{\Gamma}{E_\gamma} = \dfrac{2.9 \cdot 10^{-8}}{6.6 \cdot 10^5} = \mathbf{4.4 \cdot 10^{-24}}$

$$\frac{\Delta E}{Mc^2} = \frac{6.6 \cdot 10^5 eV}{137 \cdot 10^9 eV} \cong \mathbf{4.8 \cdot 10^{-6}}$$

In other words, the recoil moves the lines soooo far apart that there is no hope to see resonant absorption.

Note, incidentally, that the very long half-lives actually observed in nuclear physics occur because:
"nuclei are protected affairs"!

Mössbauer spectroscopy

In condensed matter, however, there are conditions in which what recoils is not the nucleus but the entire crystal.

➔ In this case the exceedingly narrow width of some transitions can be used in a resonant absorption setup.

f **Lamb-Mossbauer factor: the fraction of gammas emitted or absorbed recoillessly**

At high temperature ($T > \Theta$, Θ is the Debye temperature)

$$f(T) = exp\left[-\frac{3E_\gamma^2 T}{k_B \Theta^2 M c^2}\right]$$

so you want low T, large Θ and small E_γ.

In practice, for metals, $f(T) \approx 70\%$ at room temperature if $E_\gamma < 20$keV

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

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.
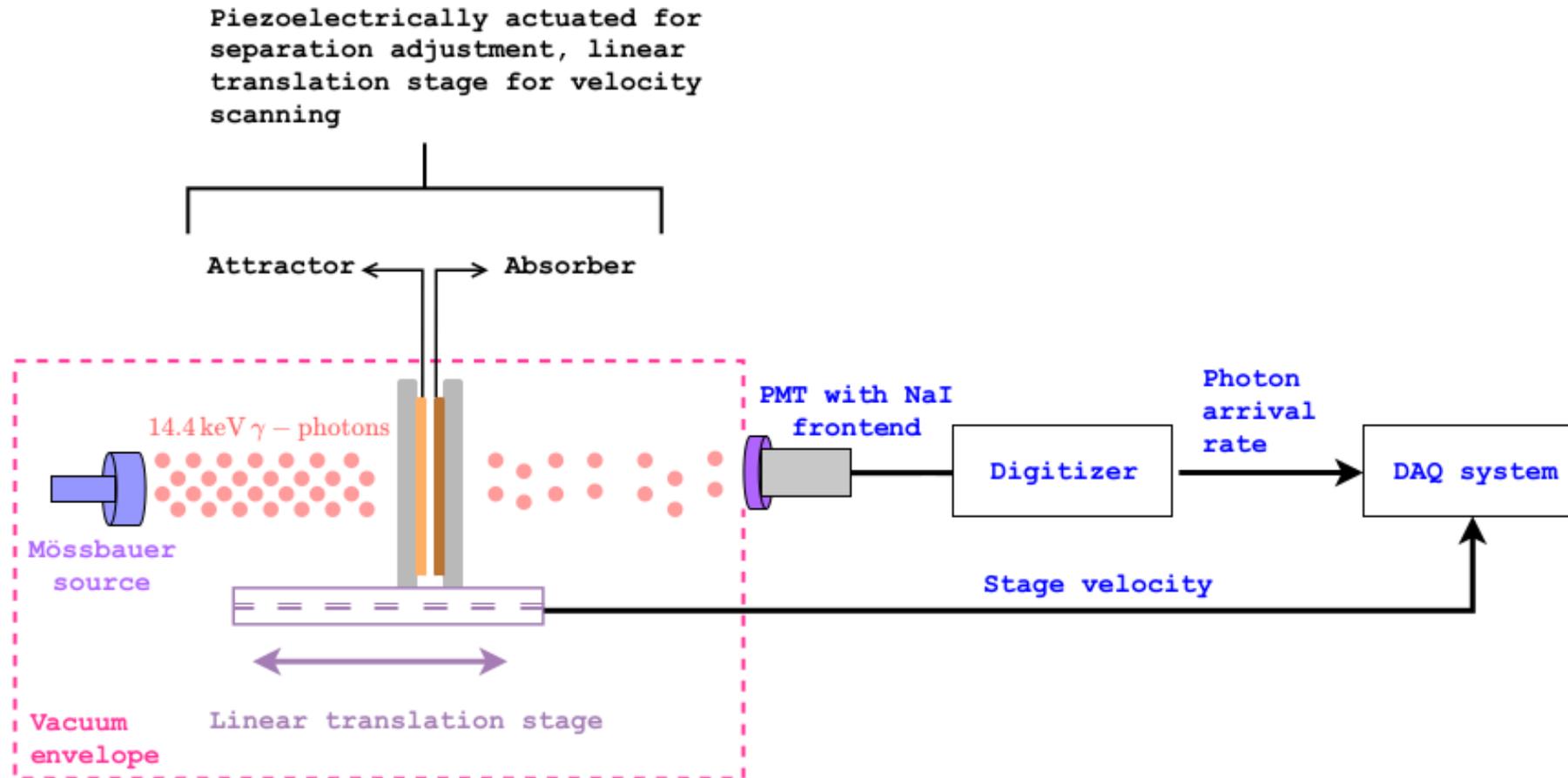
The new, hypothetical interaction, perturbs the isomeric state, slightly changing the position of the line.

By design, the experiment is insensitive to vector interactions, highly suppressing EM backgrounds.

Note that we search for the new interaction by measuring the effect of the field on a bound state, *and not by sensing a force!*

This is a rather new concept of measurement.

Unfortunately, there is nuclear physics between a measured effect and the line shift potentially observed by an experiment.
Yet, a line shift, as long as real, IS A BIG DISCOVERY, irrespective of the nuclear physics.

…reminds me of neutrinoless double beta decay!

14.4 keV photons

100 nm

To photon counter

Au or Pt

Fe-57

Be windows (1.25" dia)
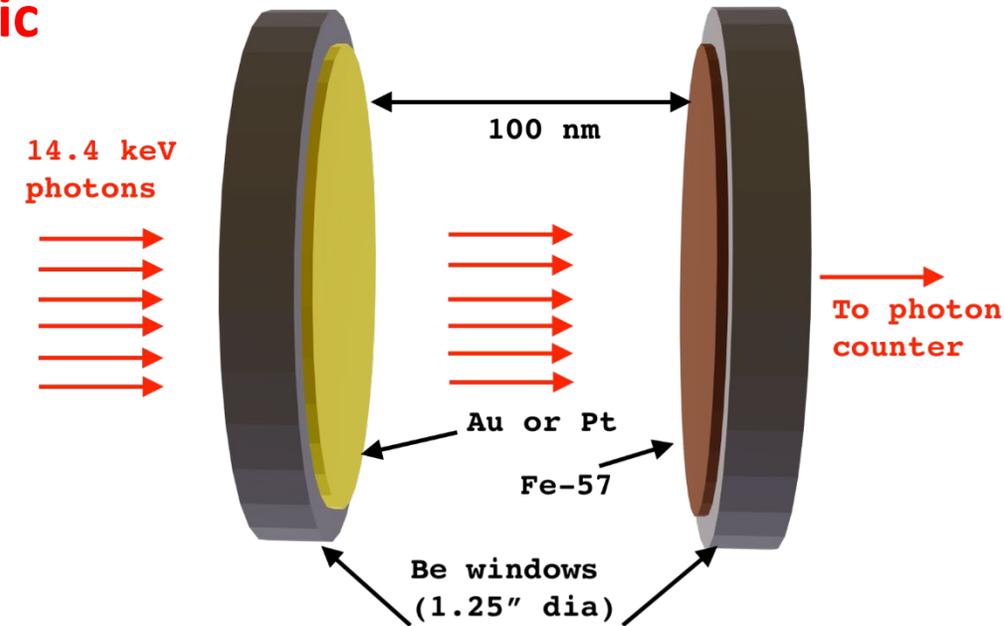
The resonant absorber material needs to have a resonant absorption length of the order of the range of the force being tested

			Mössbauer Decay					
N_M	E	Γ	Γ_{EXP}	Γ_{EXP}/Γ	Ref.	β	ℓ	η
	(eV)	(eV)	(eV)				(nm)	
$^{57}_{26}$Fe	14,413	4.7×10^{-9}	$\approx 5 \times 10^{-9}$	≈ 1	[19]	8.56	48	0.89
$^{73}_{32}$Ge	13,328	1.6×10^{-10}	1.6×10^{-10}	≈ 1	[20]	1.12×10^3	3.2×10^4	1
$^{181}_{73}$Ta	6,237	7.5×10^{-11}	5.5×10^{-10}	7.5	[21]	70.5	180	1
$^{67}_{30}$Zn	93,300	5.0×10^{-11}	7.5×10^{-11}	1.5	[18]	0.87	3.3×10^3	1
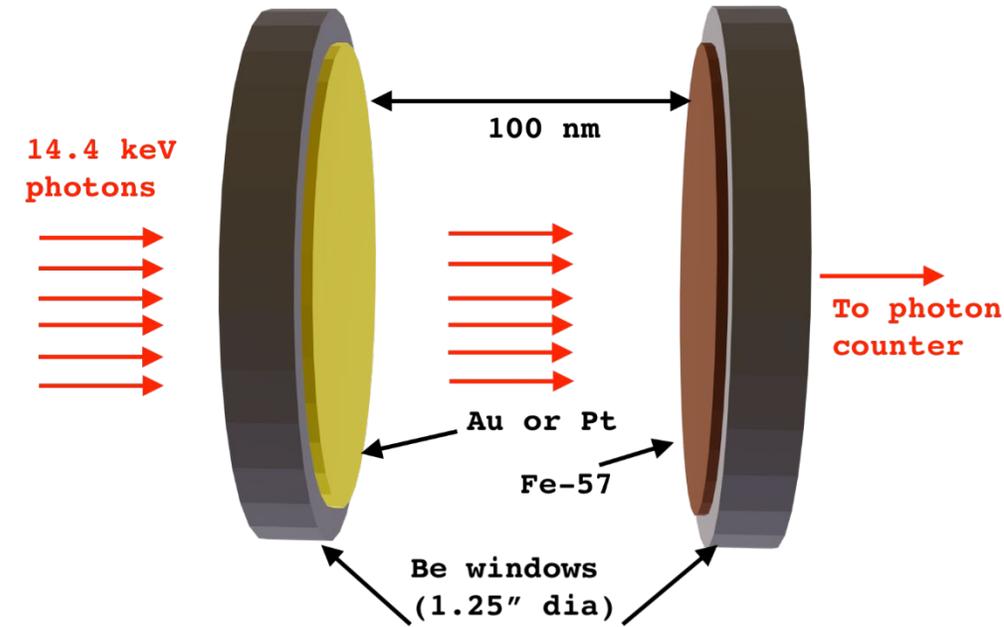
Although one may be able to perturb the source instead of the absorber.

Instead of bringing the attractor closer to the absorber (or source) one could condense layers of "attractor" material. Xe is particularly appropriate, because of the large mass, high condensation temperature and the possibility of using different isotopes.

Ultra polished Be substrates
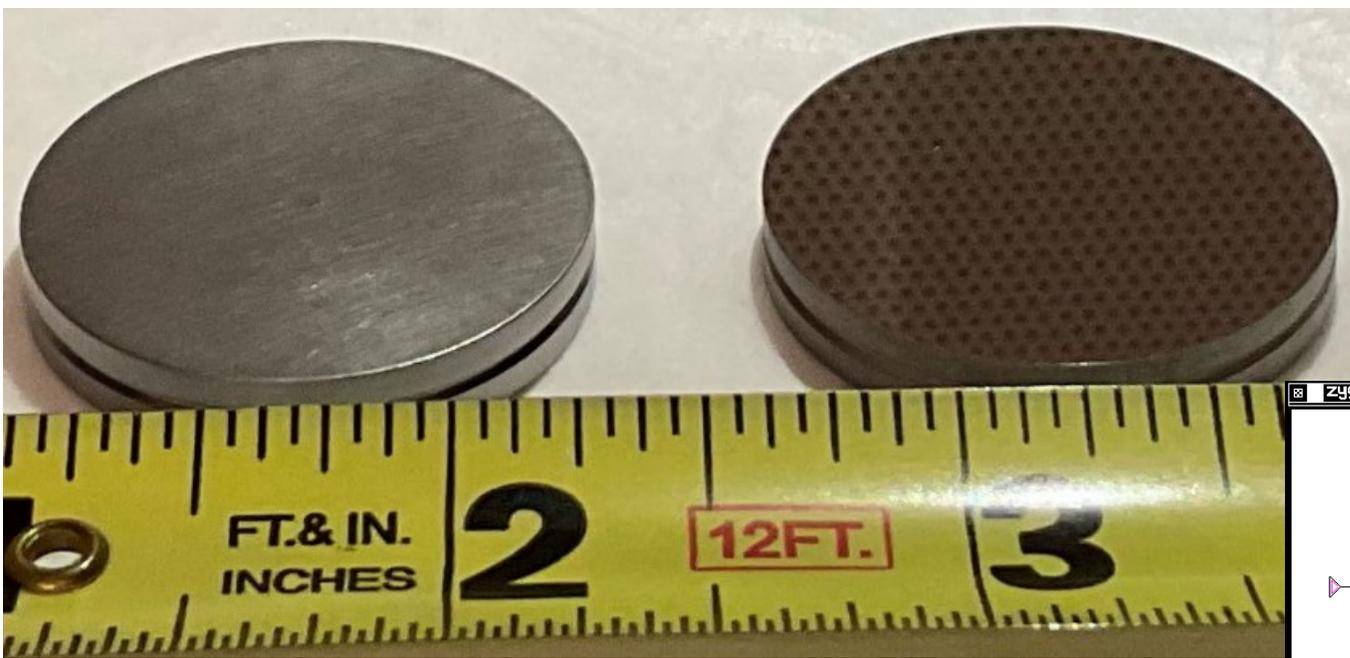
- *Minimum absorption of 14 keV photons*
- *Stiff*
- *Technology to polish them to a very high figure is (almost) standard (±15 nm flats in hand)*
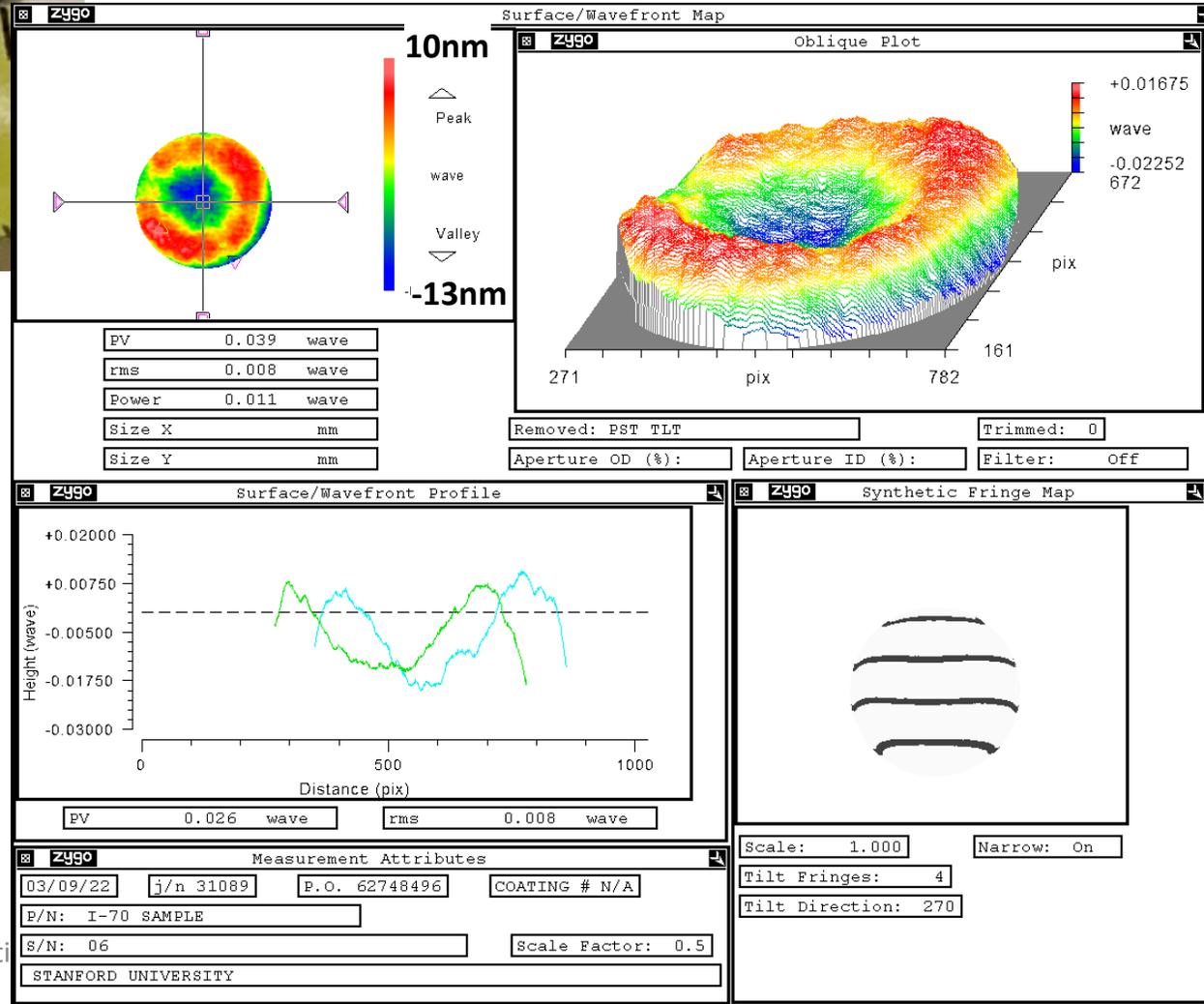
Interestingly, 3 DOF for the separation and coplanarity of the two metallic disks can be measured with a single-channel capacitive measurements (and three absolutely calibrated piezo actuators).
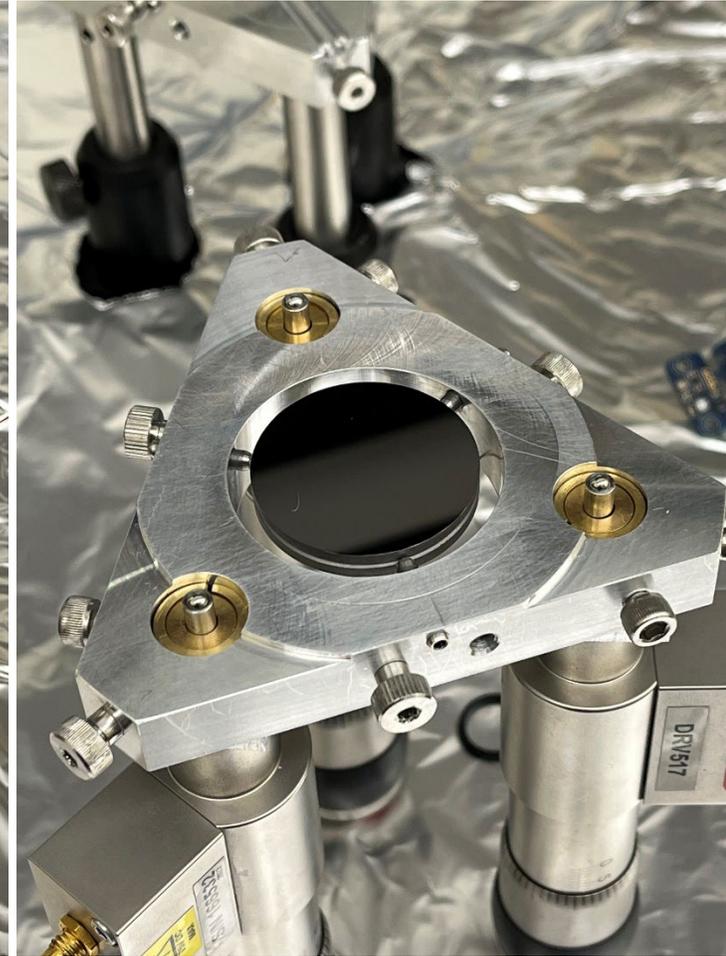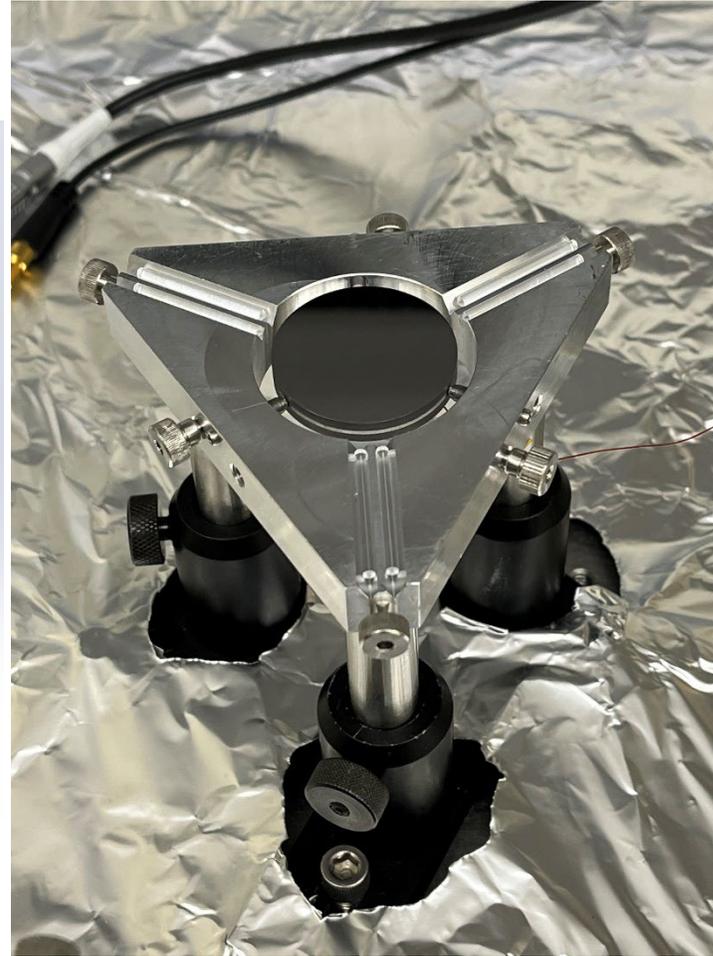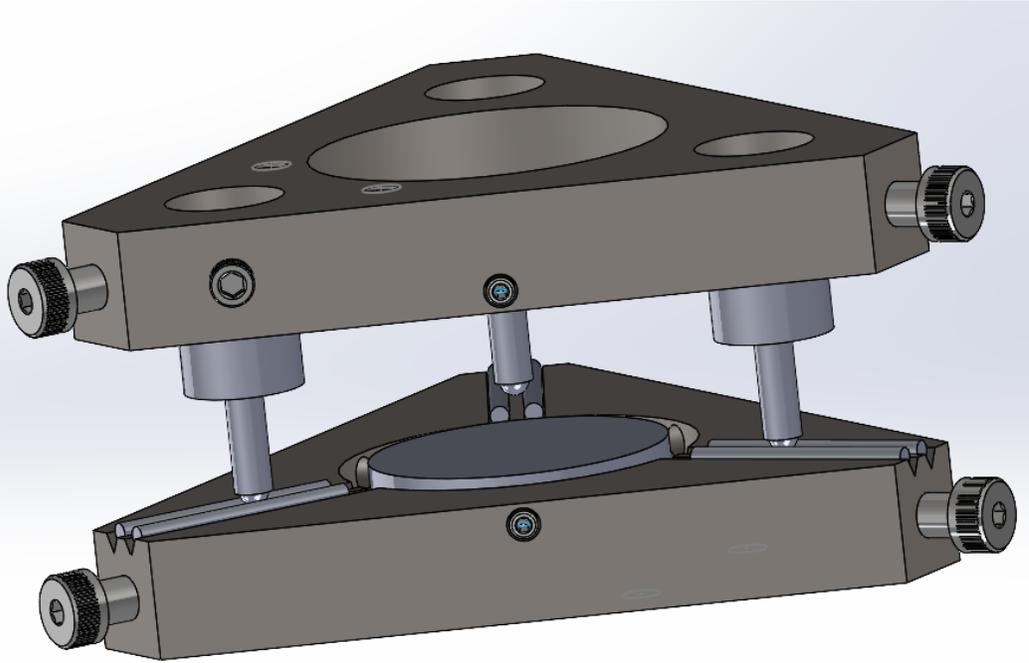
2 angle co-planarization and 1 distance measurement with single-channel capacitive measurement.

2 independent distance measurements.

$$C = \epsilon_0 \frac{\pi R^2}{d}\left(1 + \frac{R^2(\theta - \theta_0)^2}{4d^2}\right)$$

$$\downarrow$$

$$C = A + B(\theta - \theta_0)^2$$

Model

Real data

2.6 μm

3.3 μm

10.6 μm
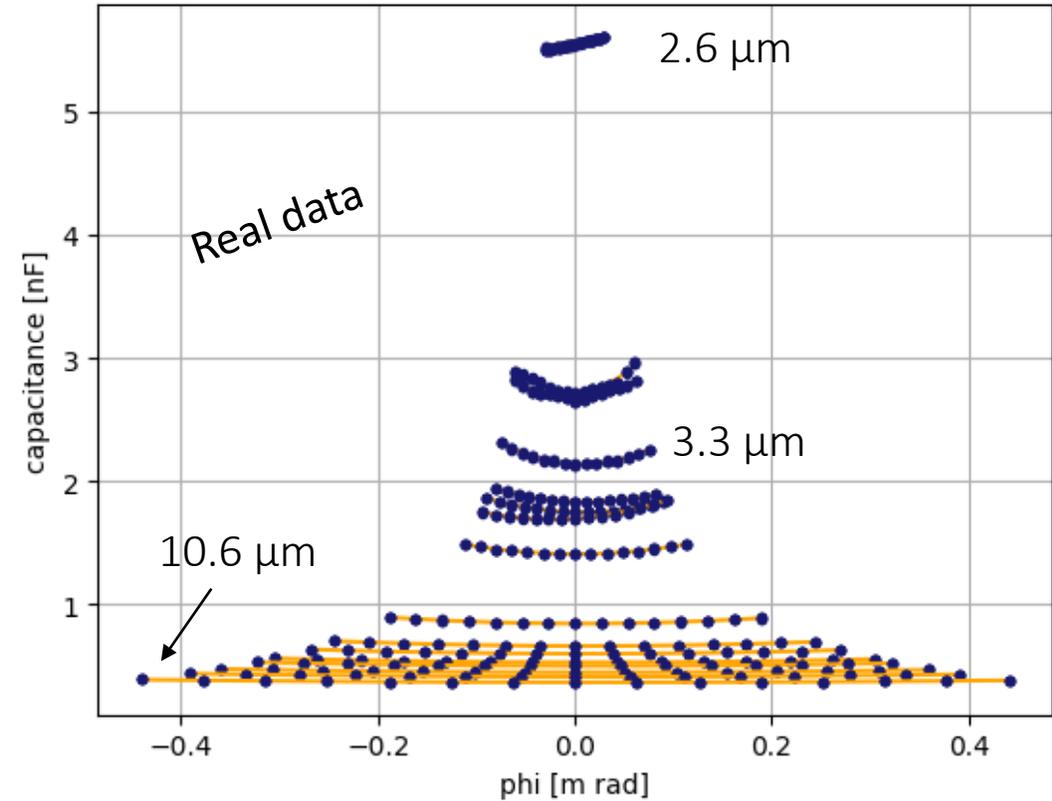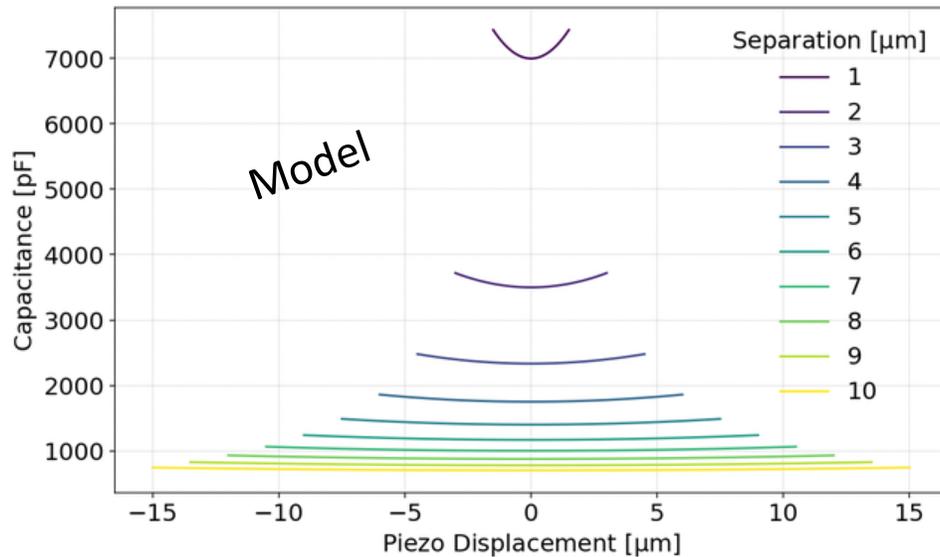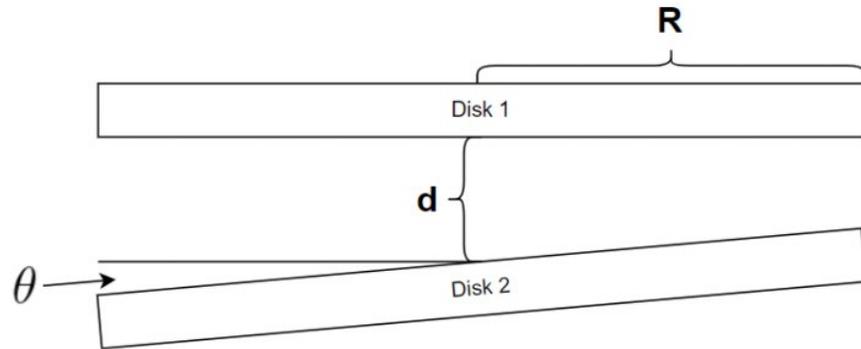
The peak scanning strategy is different from that of conventional Mössbauer spectroscopy.
- To optimize statistics only run at

FPGA Selects 14keV

Digitizer CH0

Digitizer CH1

Pos/Negative Velocity Switch

DAQ Gate
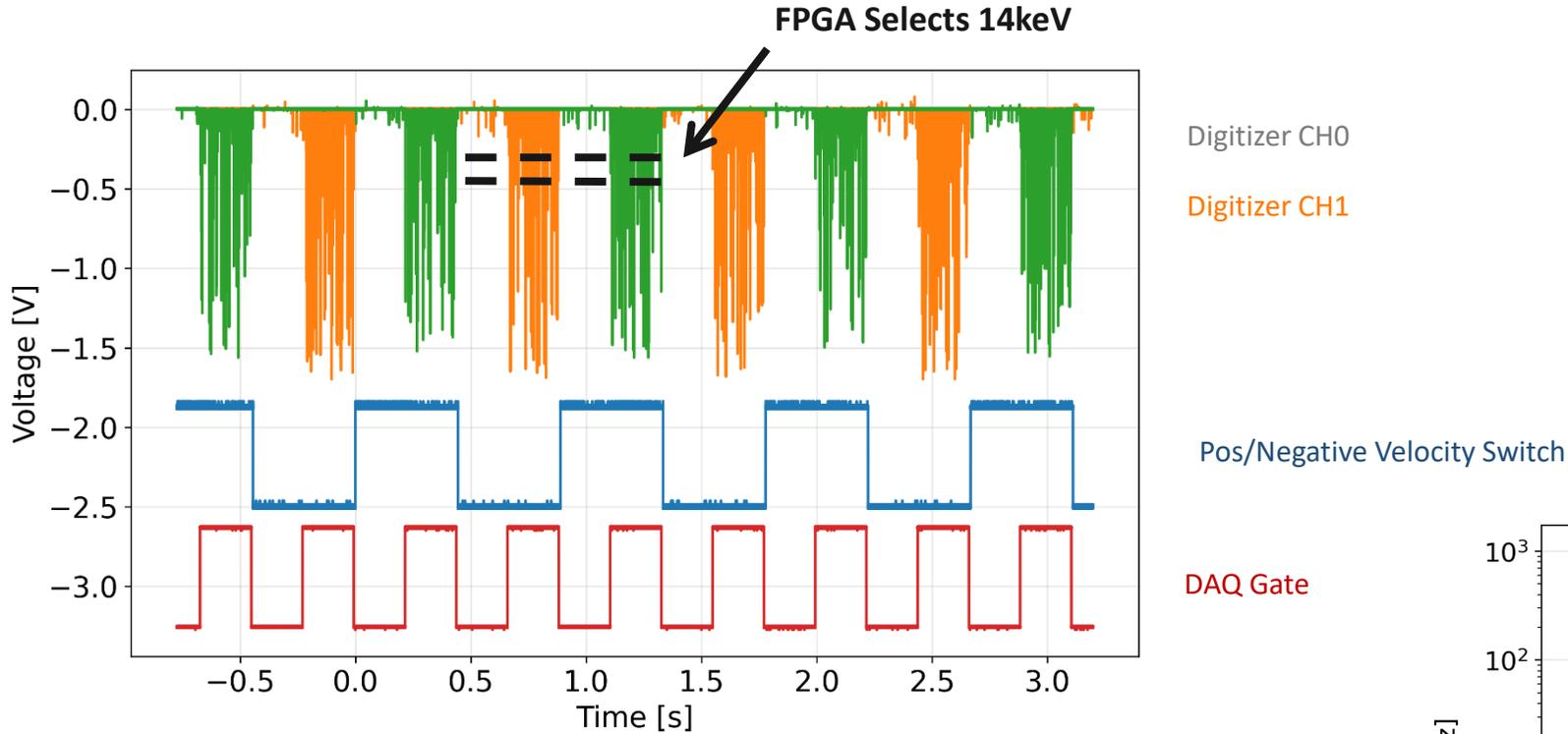
- **Max rate: 1 MHz**

- **Current SNR: 7**
- **Optimized SNR: 20**

6 keV   14.4 keV   122 keV
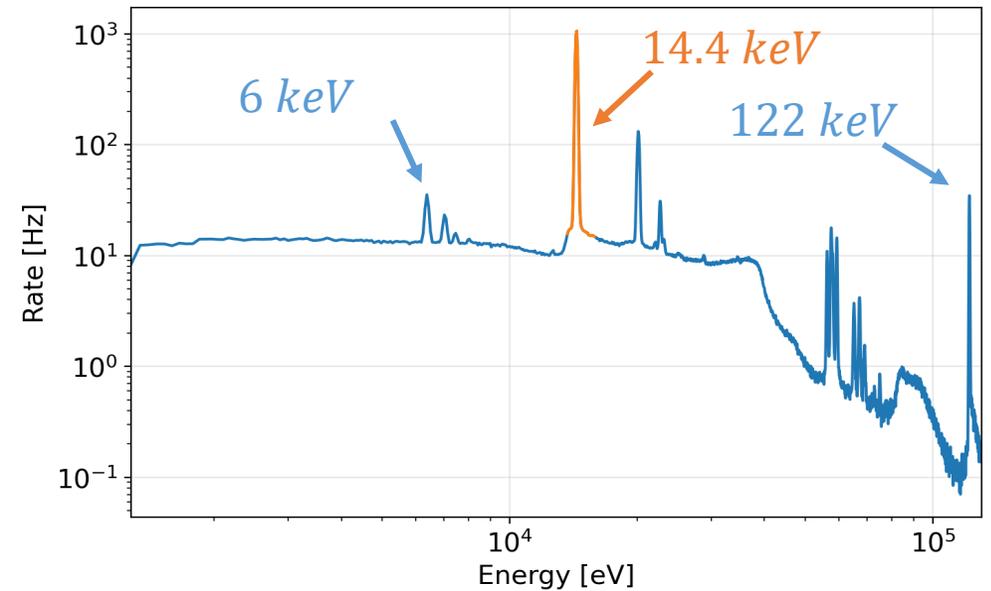
To optimize the use of statistics, only scan at the two optimal velocities ±v (unlike conventional Mössbauer spectroscopy, where the scal as a sine-wave drive).

Since the acceleration part of the cycle is wasted, low velocity is desirable.

And, counterintuitively, 6-line spectrum works best.
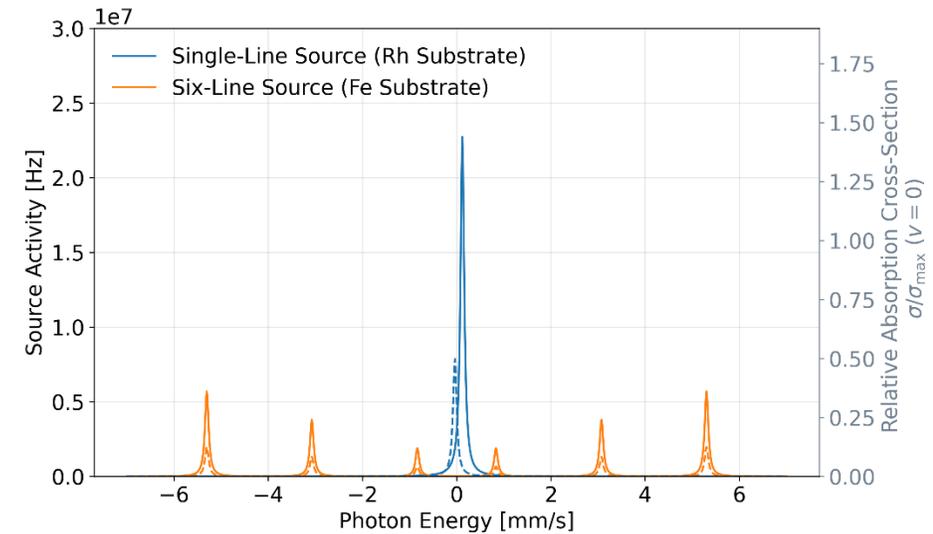
Source	Absorber (100 nm, enriched)	Differential Resonance Velocity (mm/s)	Thickness (mean free paths in 100nm)	Fraction of resonance used	Figure of merit
[57]Co - Rhodium matrix	Potassium Ferrocyanide*	0.159	0.01	1.00	0.01
[57]Co - Rhodium matrix	α-Iron	5	2	0.25	0.50
[57]Co - Rhodium matrix	α-Iron	1	2	0.08	0.16
[57]Co - Iron matrix	α-Iron	<0.1**	2	0.19	0.38

*   *Potassium ferrocyanide is also harder to provide as a thin coating*
** *Very advantageous to scan at low velocity and around 0 mm/s*
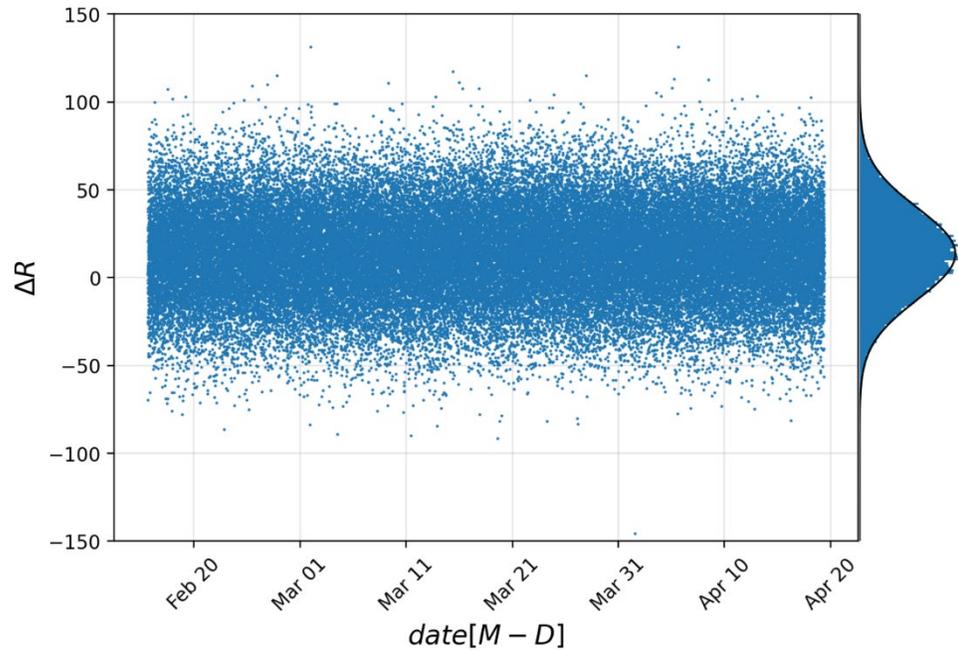
Does this really work?

Required improvement:
$$100\text{x } \left(10^4 \text{ in statistics}\right)$$
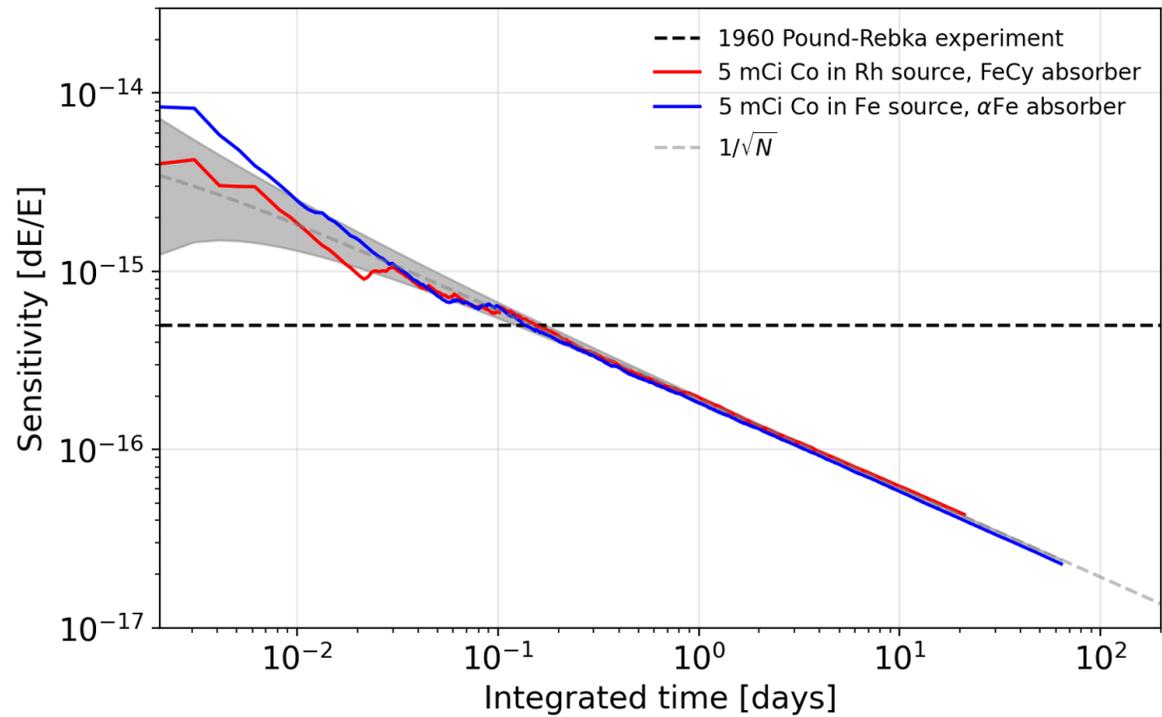
Preliminary summary of systematics

Express them as an estimated spurious shift, δE. Assume that the measurement is done with $N_\gamma \approx 10^{13}$ decays

EM coupling to the attractor. For unpolarized nuclei these are all suppressed by $\sqrt{N_\gamma}$

- **Casimir interactions** $\quad \delta E \approx 10^{-13}$ **eV**
- **Patch potentials** $\qquad \delta E \approx 10^{-15}$ **eV**
- **Magnetic domains** $\quad \delta E \approx 10^{-10}$ **eV**

$$\text{so, the worst of these is } 3 \cdot 10^{-17} \text{ eV}$$

Second order EM effects: external EM fields shifts the electron clouds that change the overlap with the nuclei.
Those <u>do not</u> average down with $\sqrt{N_\gamma}$ (but they are second order).

- **Dominant is Casimir effect:** $\quad \delta E \approx 3 \cdot 10^{-15} \left(\frac{10nm}{d}\right)^4$ **eV**

Temperature effects.

- Second order Doppler: thermal motion of nuclei results in time dilatation and a line shift. Of course, it is not that the
  attractor changes the temperature of the source or absorber. The effects scales as $\delta E \approx 10^{-11}(\frac{T}{300K})^3$,
  so e.g. at 30K one needs the temperature (of source and absorber) to be stable to better than 100mK, not hard.

- The Lamb-Mossbauer factor (the fraction of recoilless events) changes with temperature. This is not a line shift,
  but, we are crude and just measure the rate
  for $E_\gamma \approx 10$ keV, $\theta_D \approx 400$ K the temperature coefficient of the resonant rate is 10^{-4} K^{-1} , so one needs to
  keep the 30 K temperature constant to 3 mK between attractor in and attractor out.
  This is more challenging, but can be mitigated by measuring the resonance by 3 (or more) points
  (that hurts a bit the statistical power), or by bringing the attractor in a out many times.

Estimated sensitivity

	Activity (mCi)	collimation	ΔE (eV)	Comment
^{57}Fe	100	±10°	10^{-15}	Conservative, Stat dominated
^{181}Ta	1000	2π	10^{-17}	Aggressive, Syst dominated

Estimated sensitivity
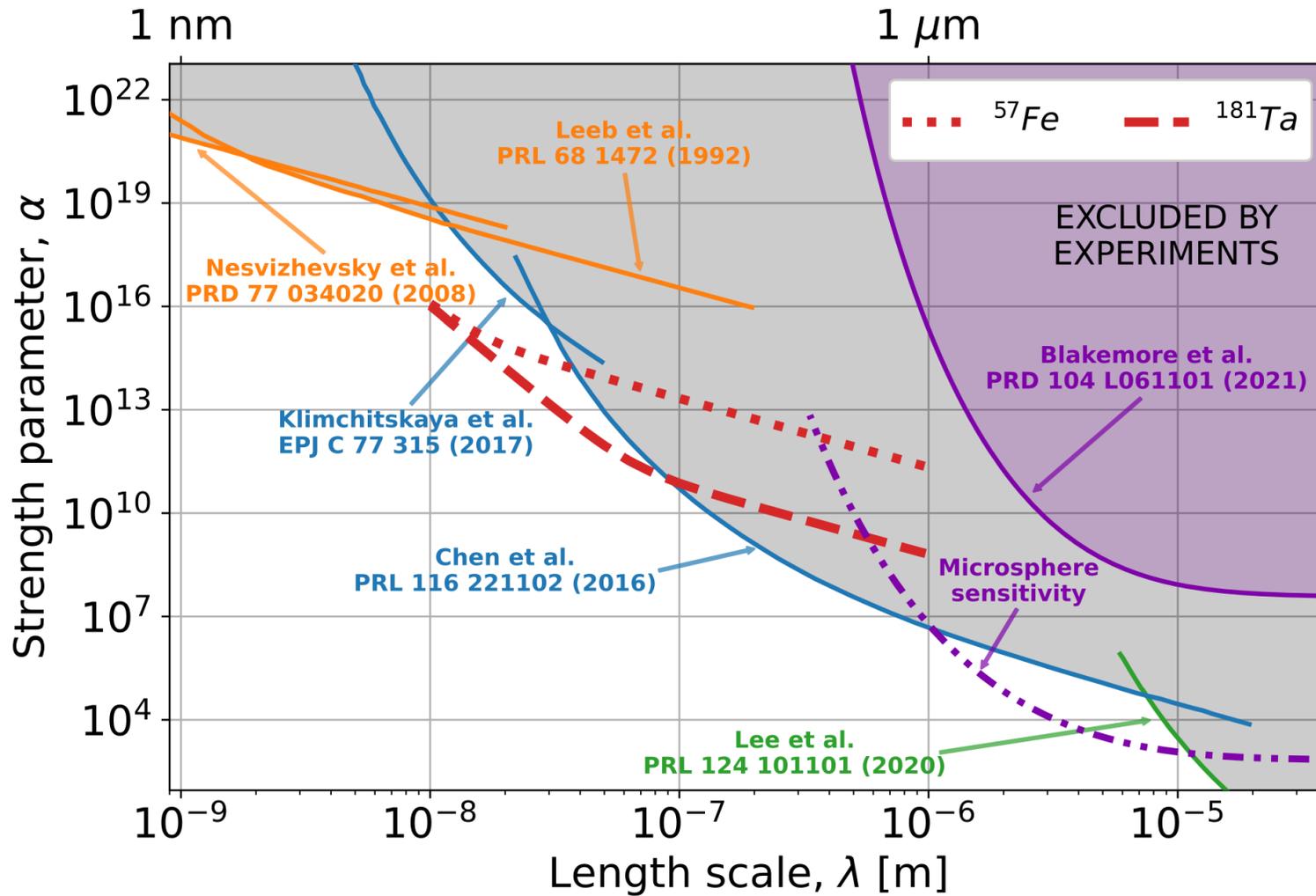
It is customary to express potential deviations from the 1/R² law by modifying the potential with a Yukawa term, obtaining:

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

α: magnitude of the effect
λ: scale of the effect

Neutrons

Cantilevers (Casimir)

Torsion balances

Levitated microspheres

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 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

The quick brown fox jumps over the lazy dog. The quick brown fox jumps over the lazy dog.

Conclusion

goal-oriented

curiosity-driven
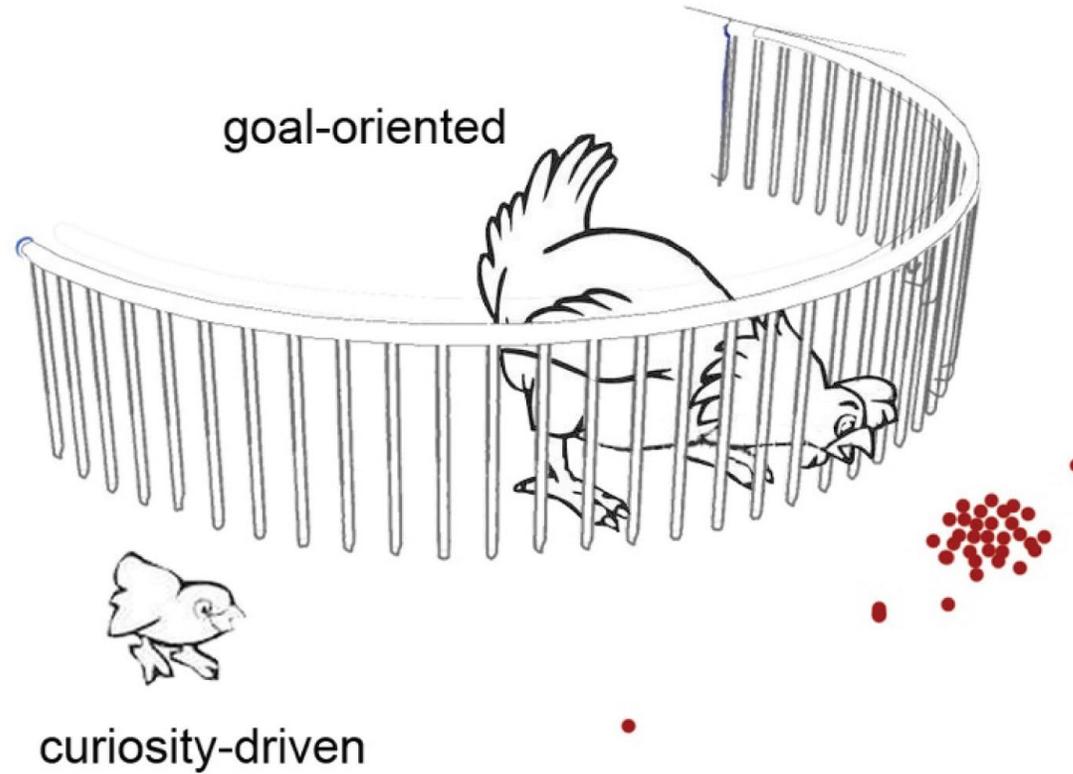
Cartoon by Ted Hänsch

The current cast