Searching for new forces at micron scale and beyond

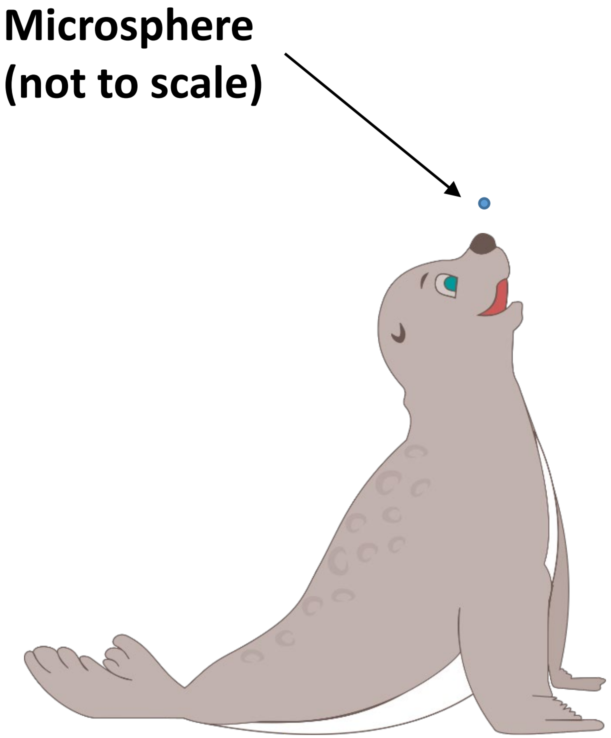
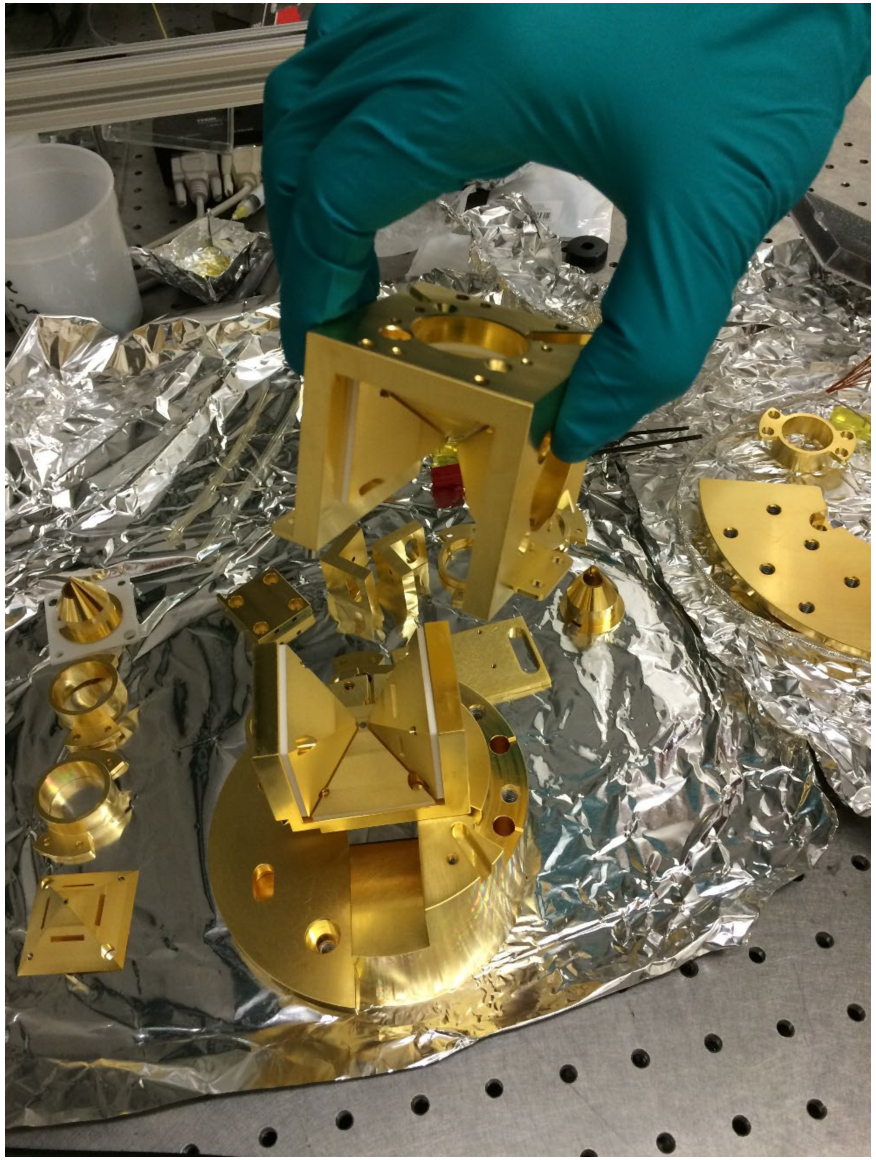


Image credit: Delia Gratta

Giorgio Gratta
Physics Dept, Stanford



Gravity is:

- the most evident
- the weakest
- the least well-known interaction in Nature

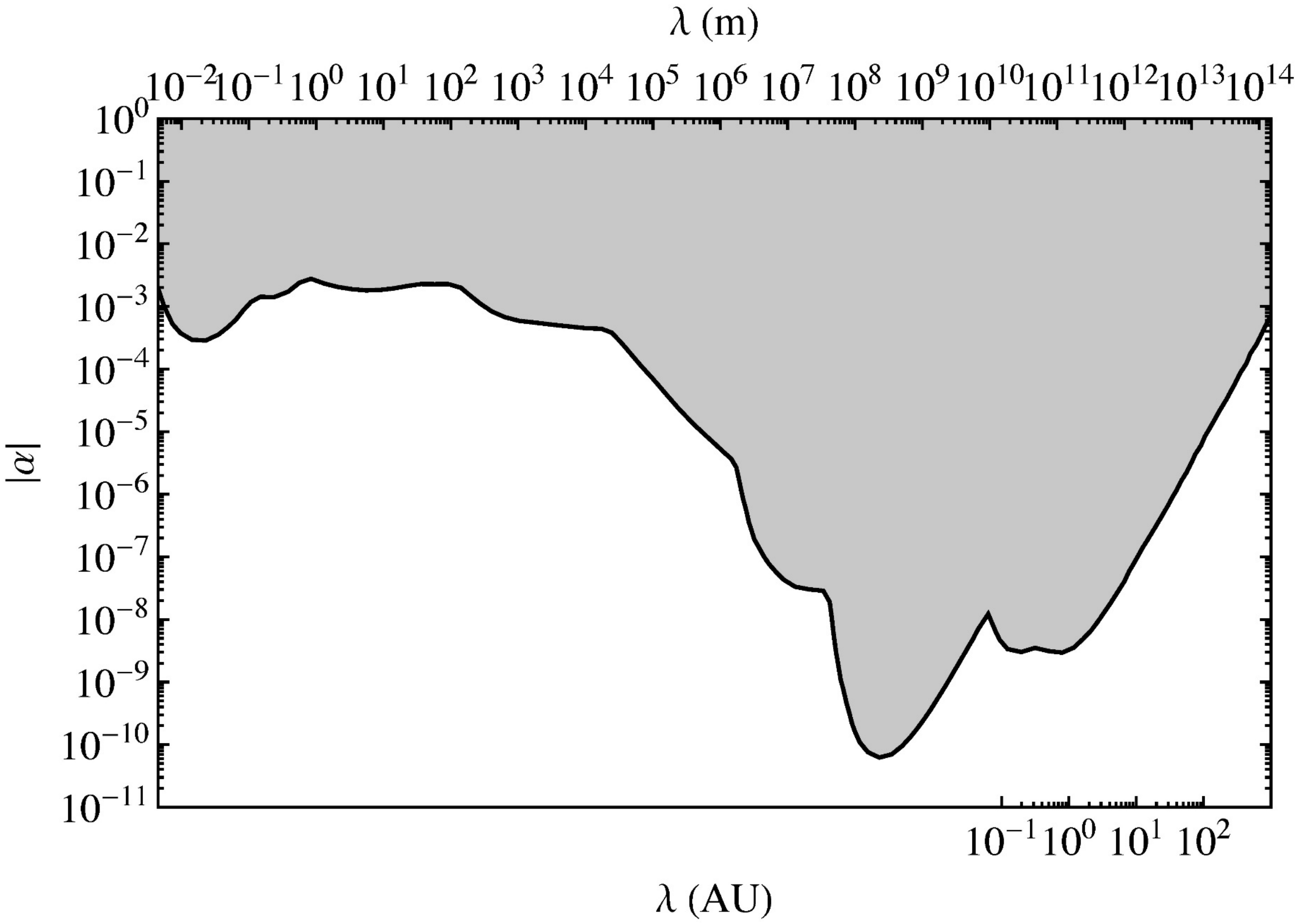
Fundamental interactions	Normalized Strength	Effective Range (m)
Strong Nuclear Force	10^{38}	10^{-15}
Electromagnetic Force	10^{36}	∞
Weak Nuclear Force	10^{25}	10^{-18}
Gravity	1	∞

Most of the empirical features of gravity and differences in phenomenology from the other interactions can be understood in terms of the parameters above.

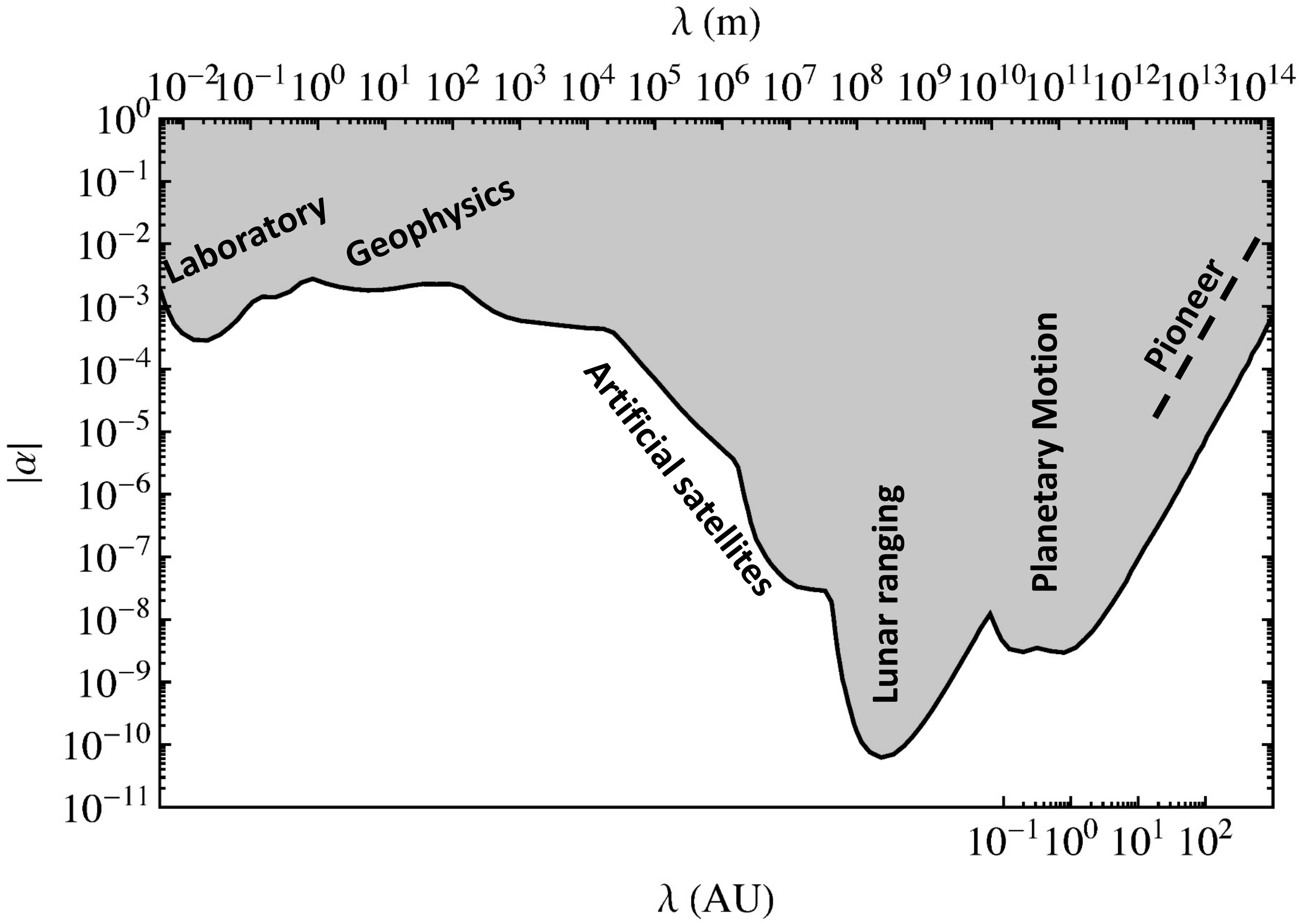
In addition, there is no such thing as "antigravity", so gravity cannot be shielded, which explains why this weakest force is so evident:

e.g. keeps the solar system together.

What do we empirically know

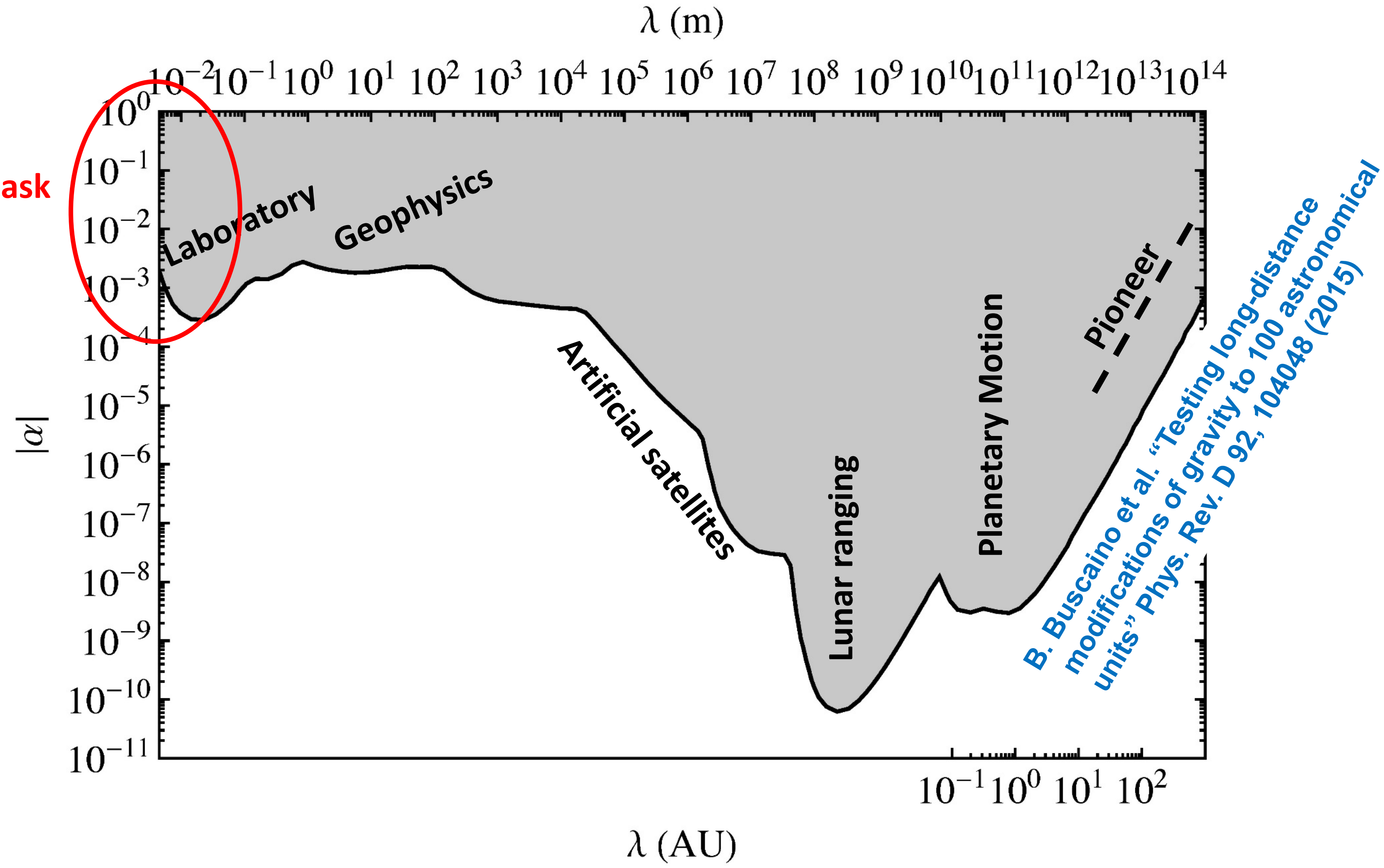


What do we empirically know



What do we empirically know

Today's primary task



B. Buscaino et al. "Testing long-distance modifications of gravity to 100 astronomical units" Phys. Rev. D 92, 104048 (2015)

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.

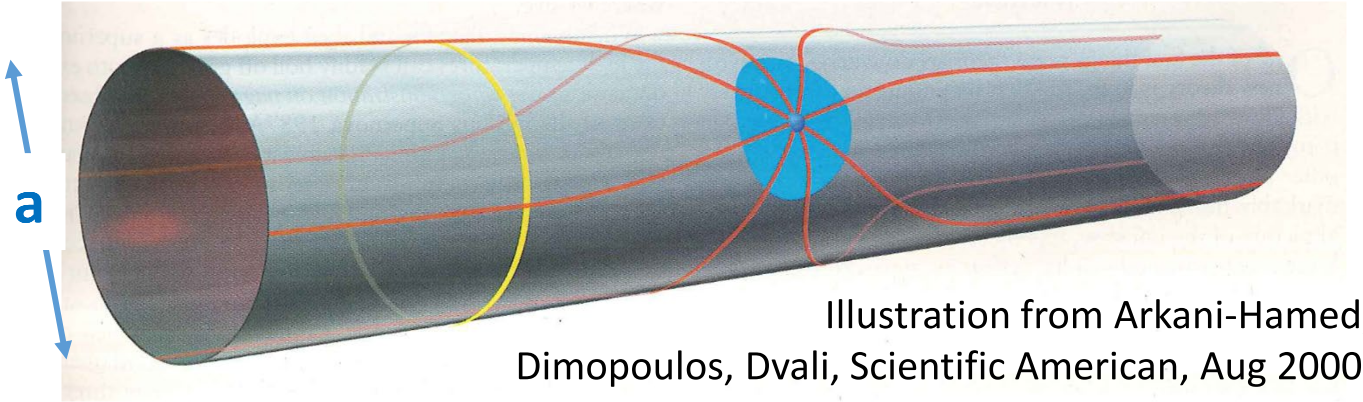


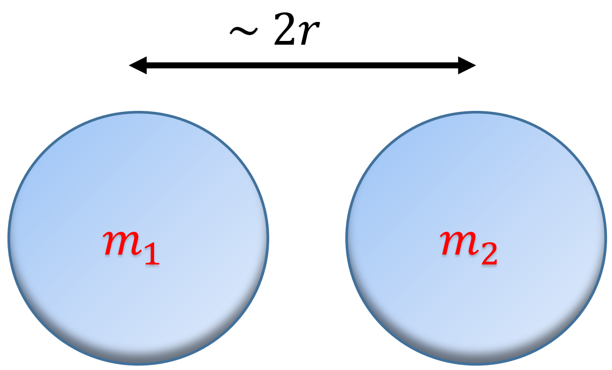
Illustration from Arkani-Hamed, Dimopoulos, Dvali, Scientific American, Aug 2000

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

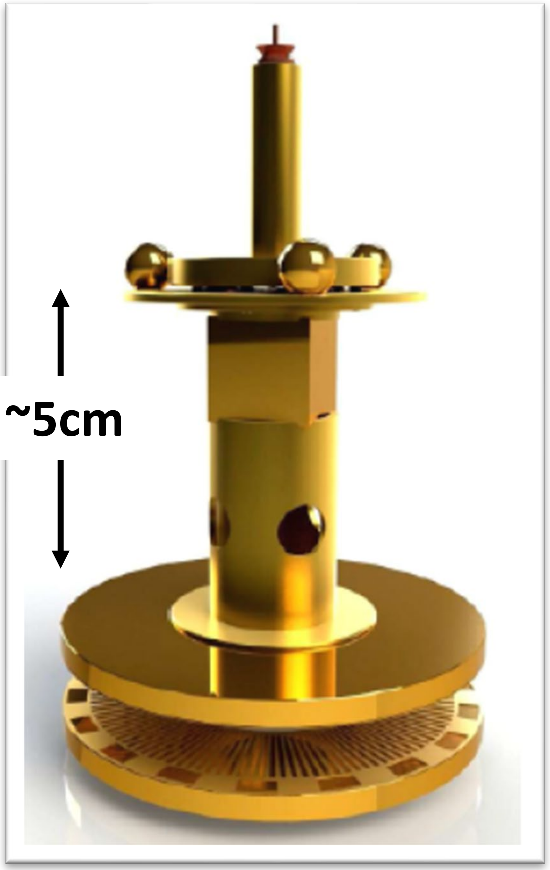
- Since $F = G\frac{M_1 M_1}{R^2} = G\frac{\rho_1 V_1 \rho_2 V_2}{R^2}$
  for atomic materials (we can't use Neutron Stars!)
  $\rho_1 \sim \rho_2 < 20$ g/cm^3, there is no silver bullet.
  In addition, the volume $V \sim R^3$, so $F \sim G\frac{\rho^2 R^6}{R^2}$
  and it is clear that measurements at short distance become exceedingly difficult.



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

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

- It is important not only to set limits but also to have discovery potentials.
  Would a positive observation be believable as such an important discovery?



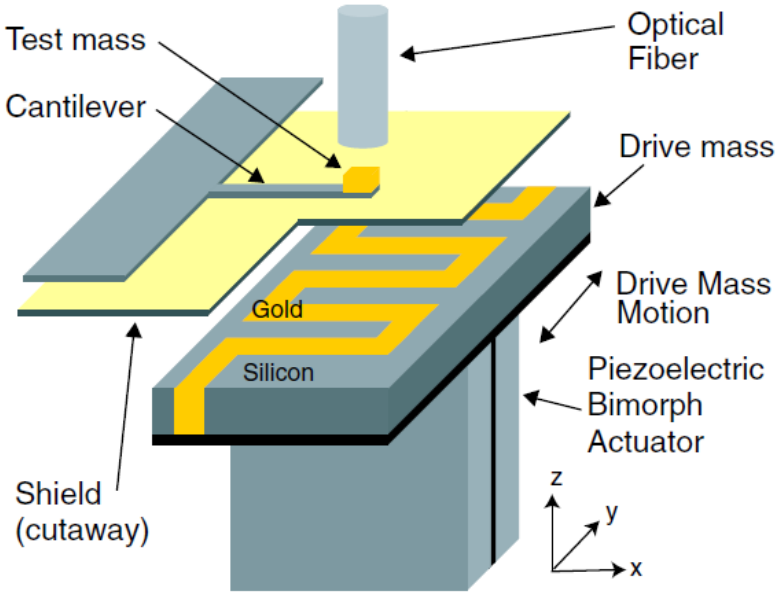
Most inverse-square law measurements are/have been done with wonderfully sophisticated versions of Cavendish's setup.

As distances become shorter, it is reasonable to seek experimental arrangements whereby the apparatus is similar in size to λ.

In any case, all these measurements are dominated by systematics and a program using different techniques is desirable, particular in the case of a discovery.

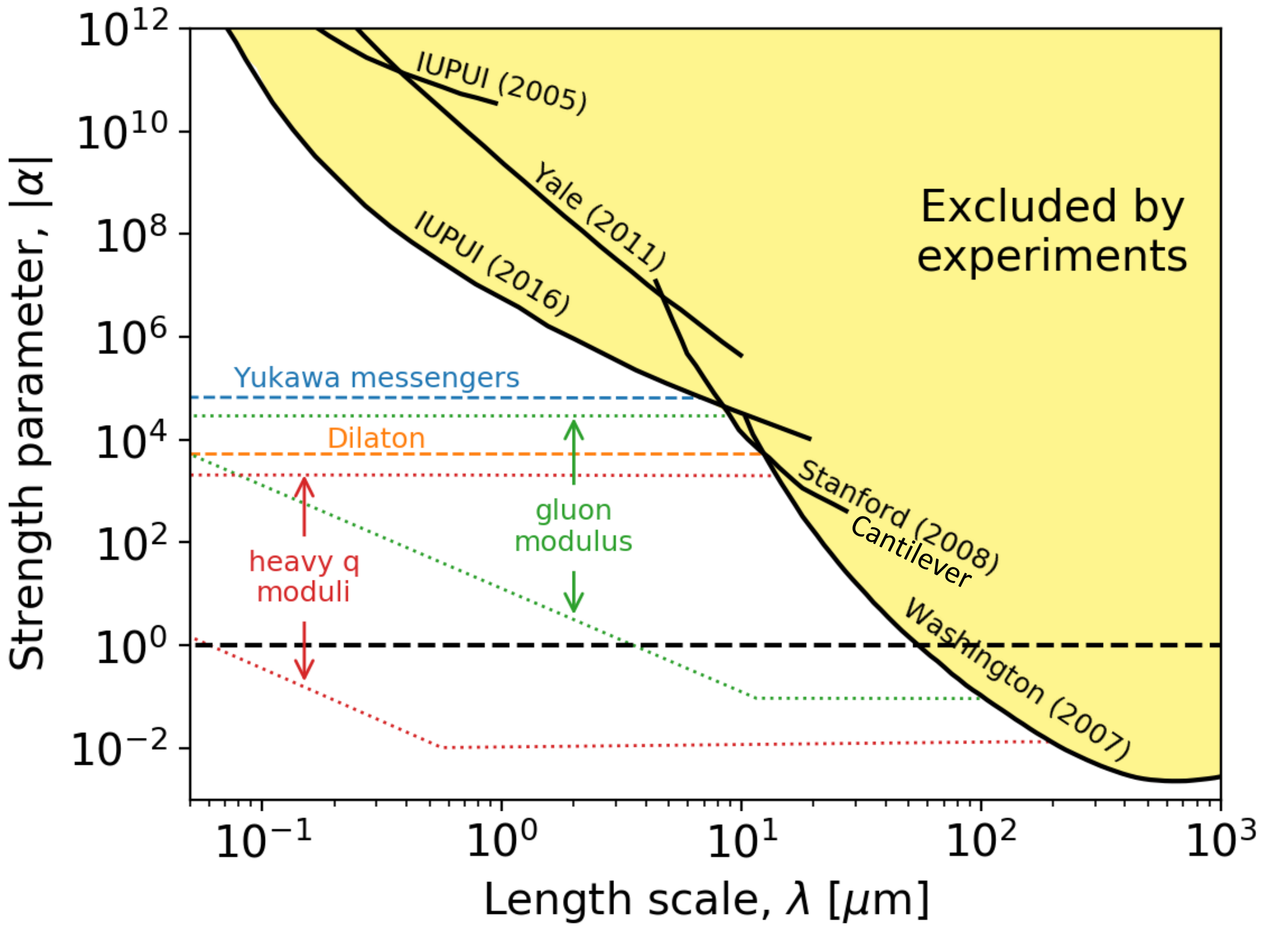
Sketch of the EotWash apparatus from the University of Washington in Seattle
Phys. Rev. Lett. 124, 101101 (2020)

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



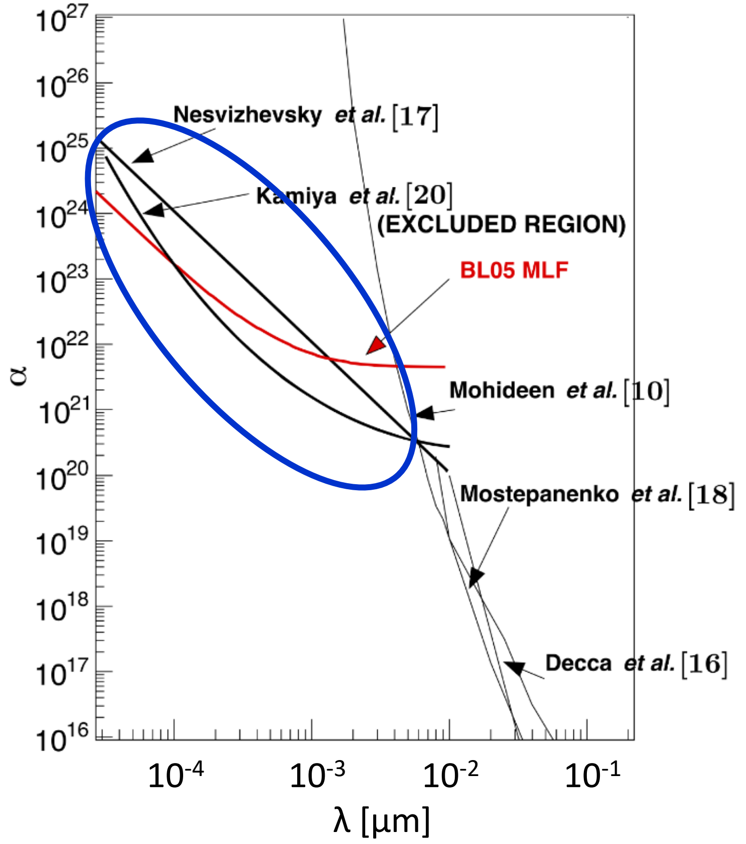
Sketch of the custom cryogenic AFM apparatus from Kapitulnik's group at Stanford
J.Chiaverini *et al.*, PRL 90 (2003) 151101

The current experimental situation on the α-λ plane



Note: The ideal probe for such a measurement is the neutron (charge radius is ~1fm instead of ~1nm).

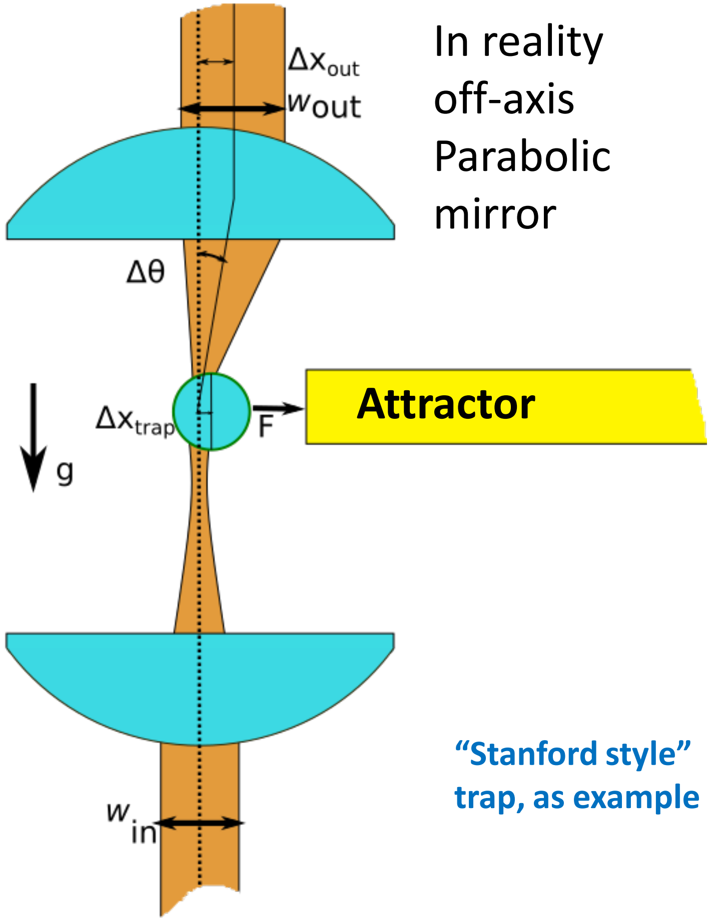
There may be new ways to do this, see Bogorad, Graham, GG, arXiv:2303.17744



C.C.Haddock et al., PRD 97 (2018) 062002
Y.Kamiya et al., PRL 114 (2015) 161101

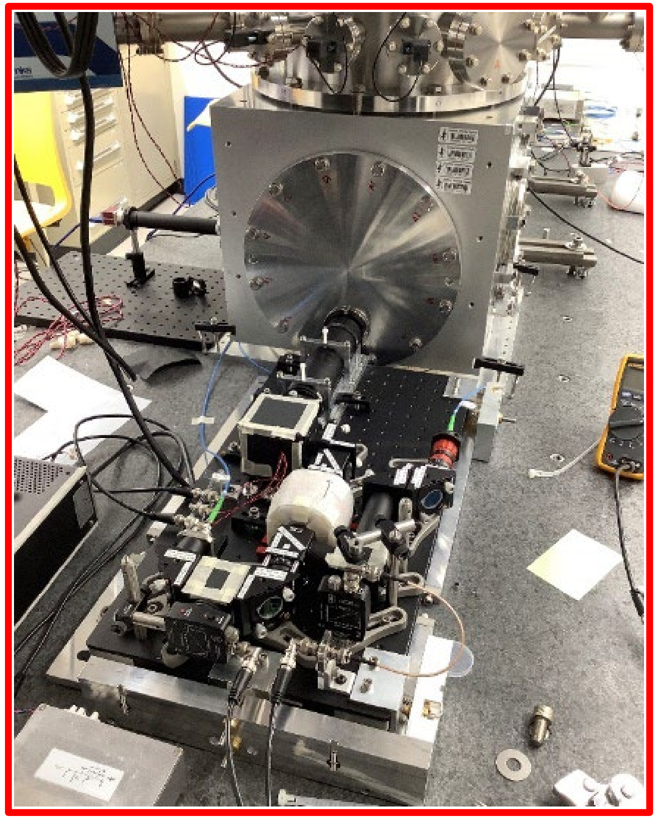
Optical tweezers in vacuum provide a new way to sense small forces doing away with mechanical springs

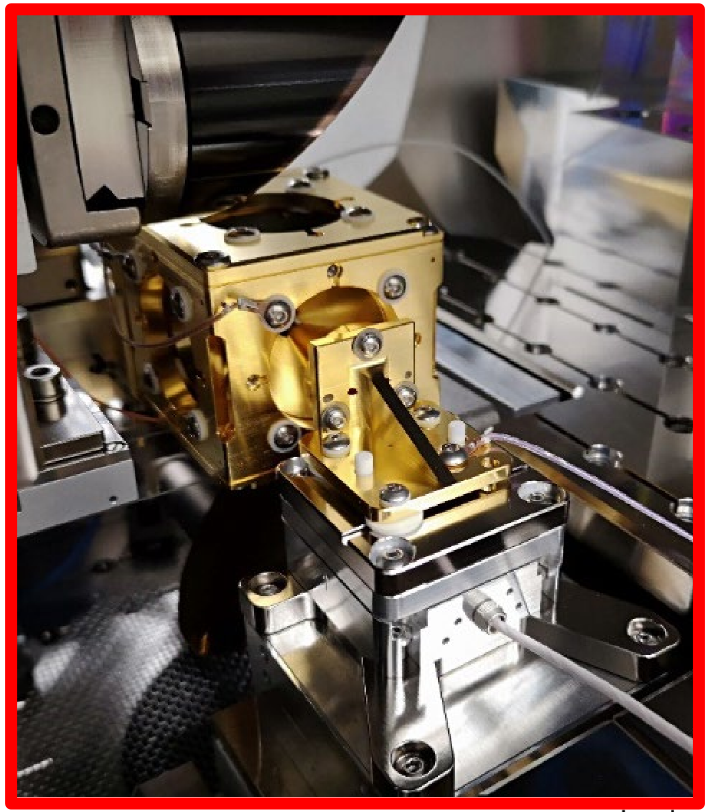
- In high vacuum we can cool the force sensor (µsphere) while everything else is at room temperature.
- Thermal and vibrational noise from mechanical support minimized.
- Trap parameters can be changed instantaneously.
- Control of optical potential and motion in all 3 DOF: great flexibility.
- Extremely low dissipation is possible: $Q \sim 10^{12}$ at 10^{-10} mbar.
- The noise quantum limit should be reachable
  (but it’s not required for the first gravity measurements).
- Microspheres are really isolated (in particular electrically).
- Unexplored: much risk and many opportunities!
- Many applications to other areas.

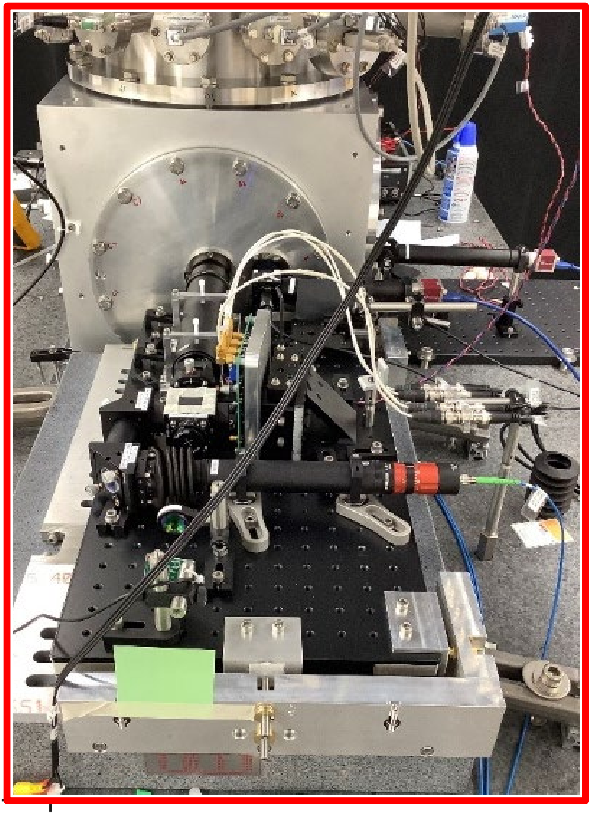


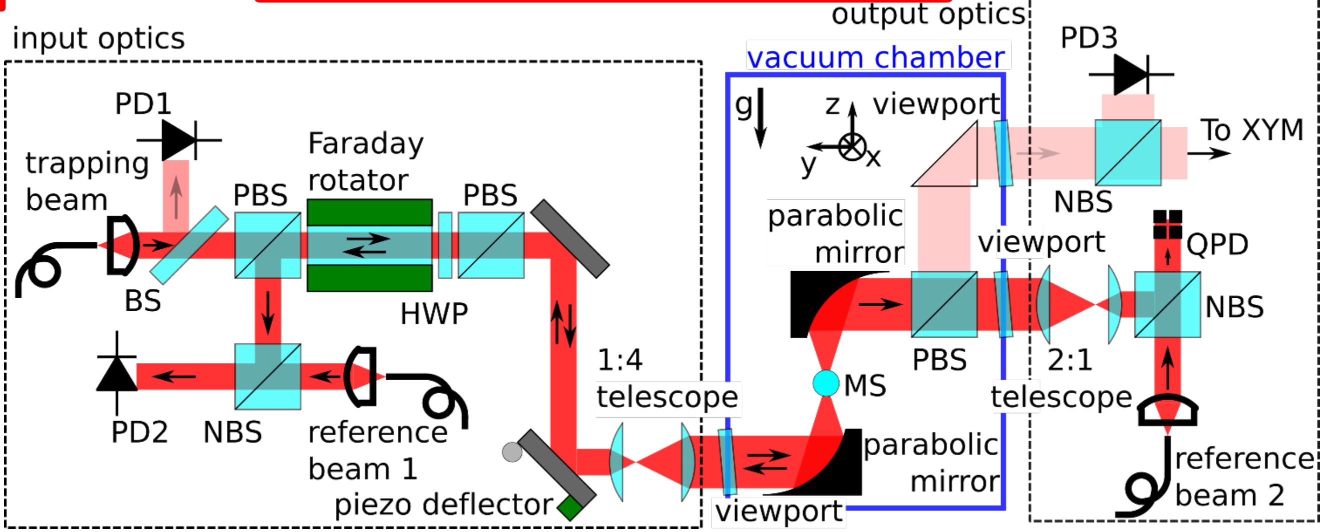
In reality
off-axis
Parabolic
mirror

“Stanford style”
trap, as example









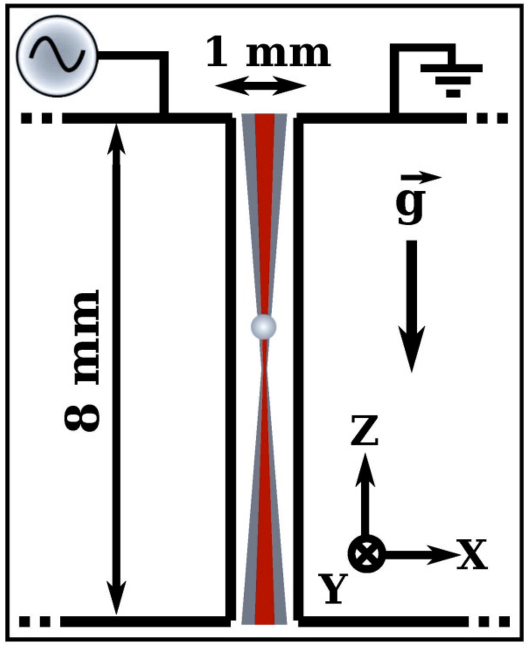
Rev. Sci. Instrum. *91, 083201 (2020)*

Compared with most work reported here, the main differences are:

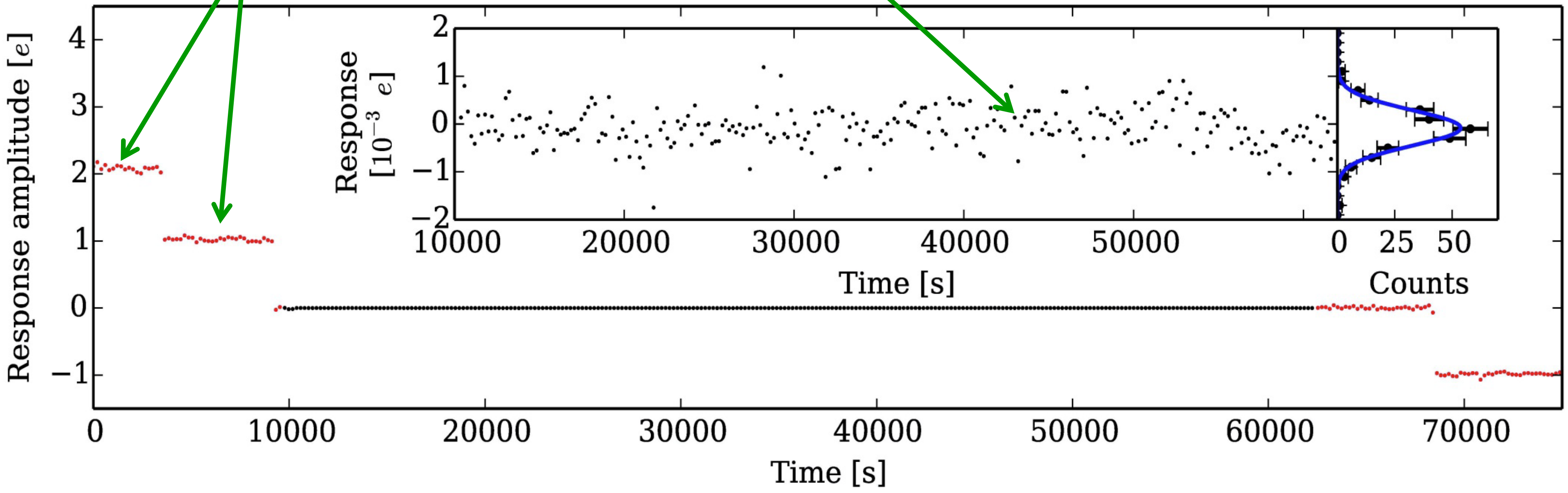
1) **We use μm size microspheres**
2) **We need to get very close to them, so, e.g. we abhor charges (except for calibration)**

As loaded in the trap, μspheres are usually charged (~500e)

➔ ***Their charge state can be changed at leisure (in both directions), using a UV light source***



The charge state can then be measured by applying an RF potential to a pair of electrodes

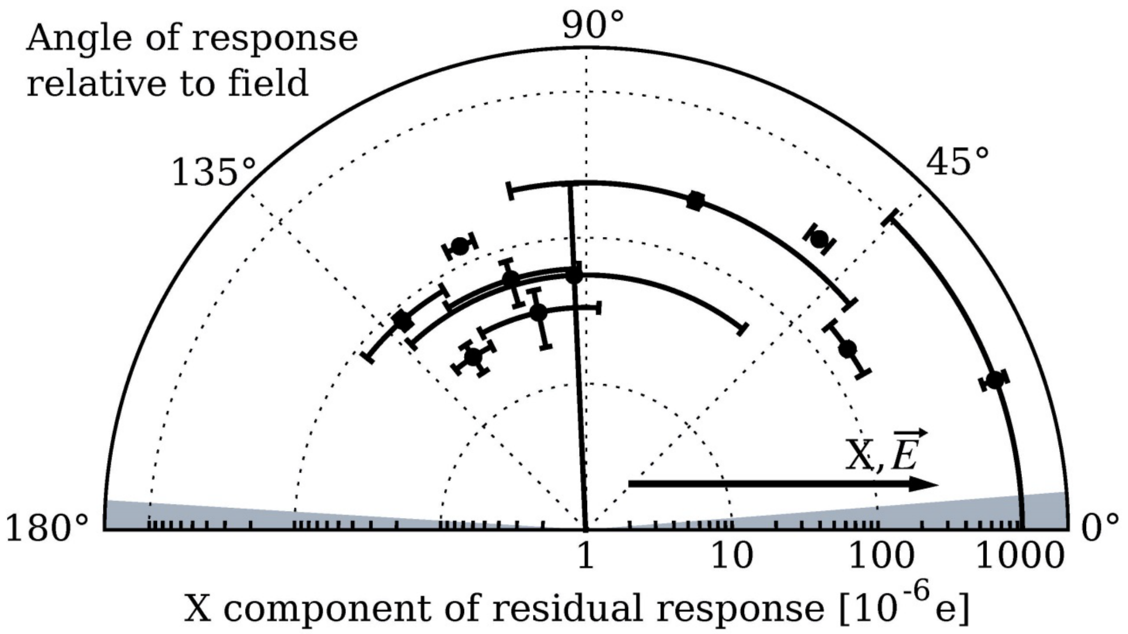


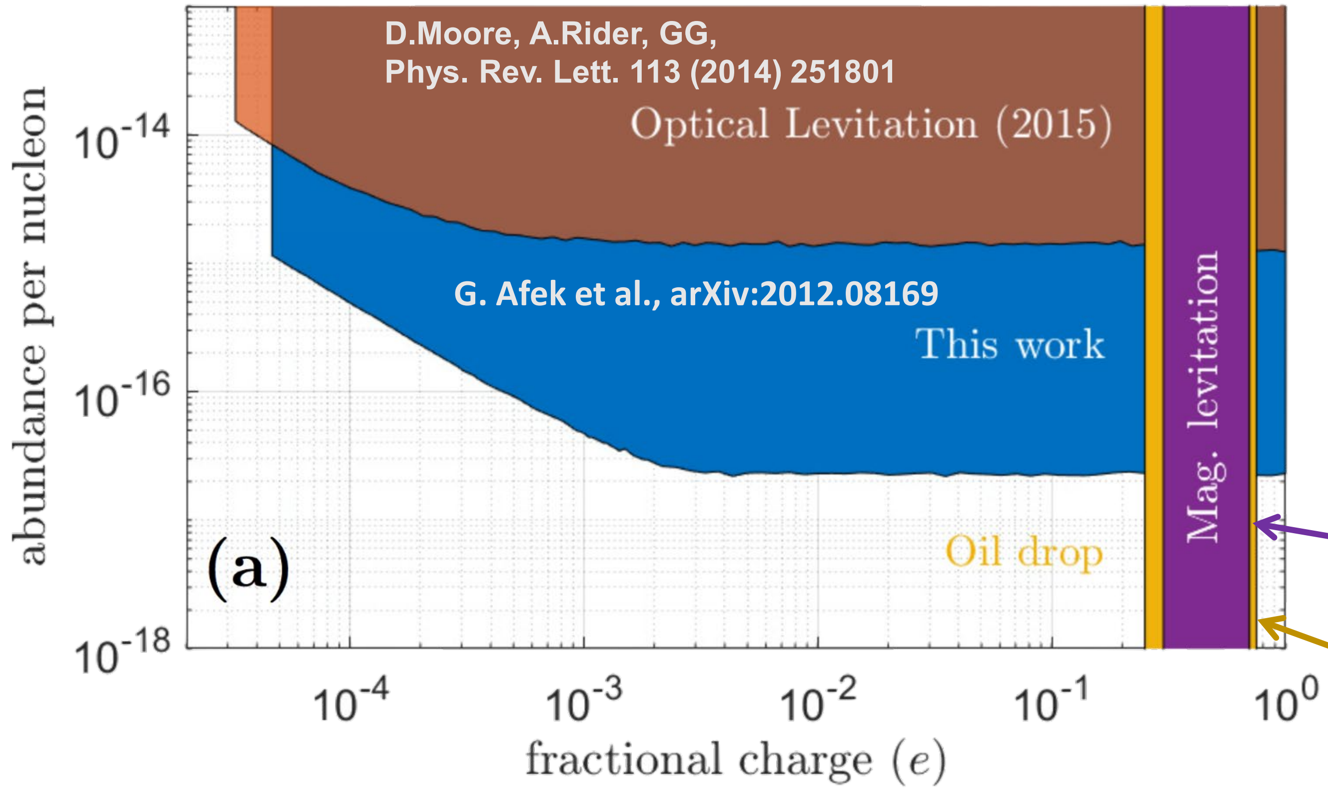
Quantized charge

"0 charge" with increased 500 V RF amplitude.

How close to 0 is “0 charge”?

There are small residuals but the response is not consistent with an effective charge.




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

G. Afek et al., arXiv:2012.08169

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

Kim et al., PRL 99 (2007) 161804

How to recognize permanent dipole backgrounds

At f_0:

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

This is subdominant and not yet well studied

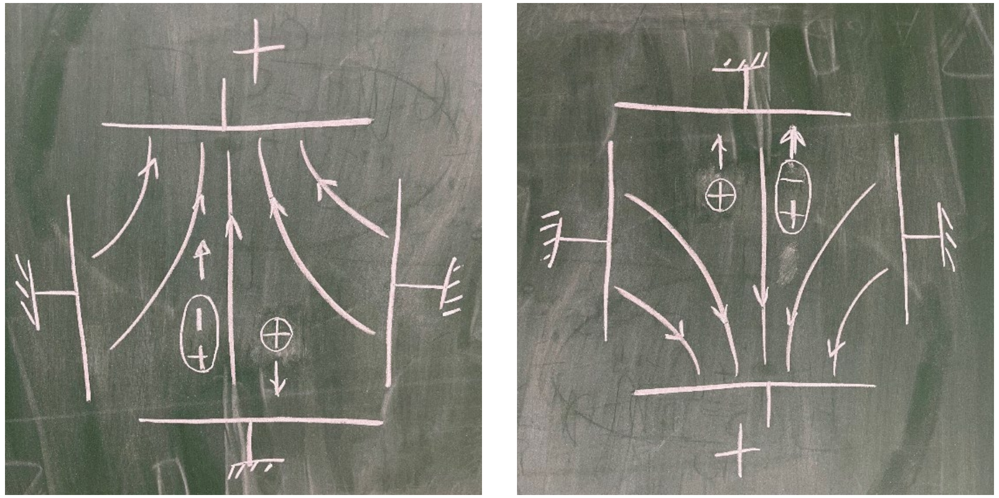
This is the term to worry about

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:

$$\boxed{A \equiv F^+ - \Omega F^- = 2qE^+ + (p^+_{\mathrm{ac}} - \Omega p^-_{\mathrm{ac}}) \frac{\partial E_{\mathrm{dc},z}}{\partial z}}$$

Describes the possible slight asymmetry between the two field directions



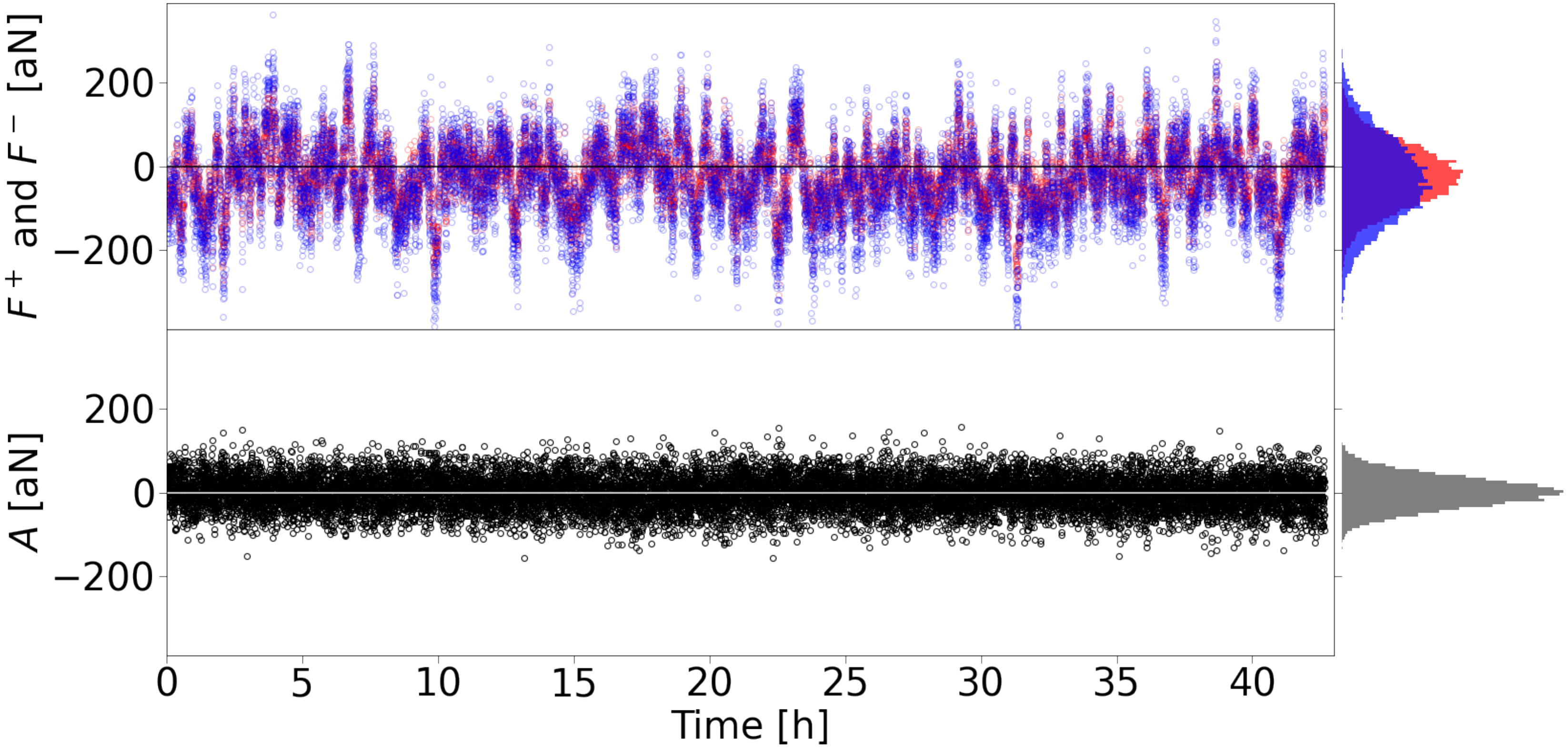
Note that the force switches direction for the monopole but not for the (permanent) dipole.

(blackboard courtesy of M. Aspelmeyer)

The cancellation works remarkably well!!

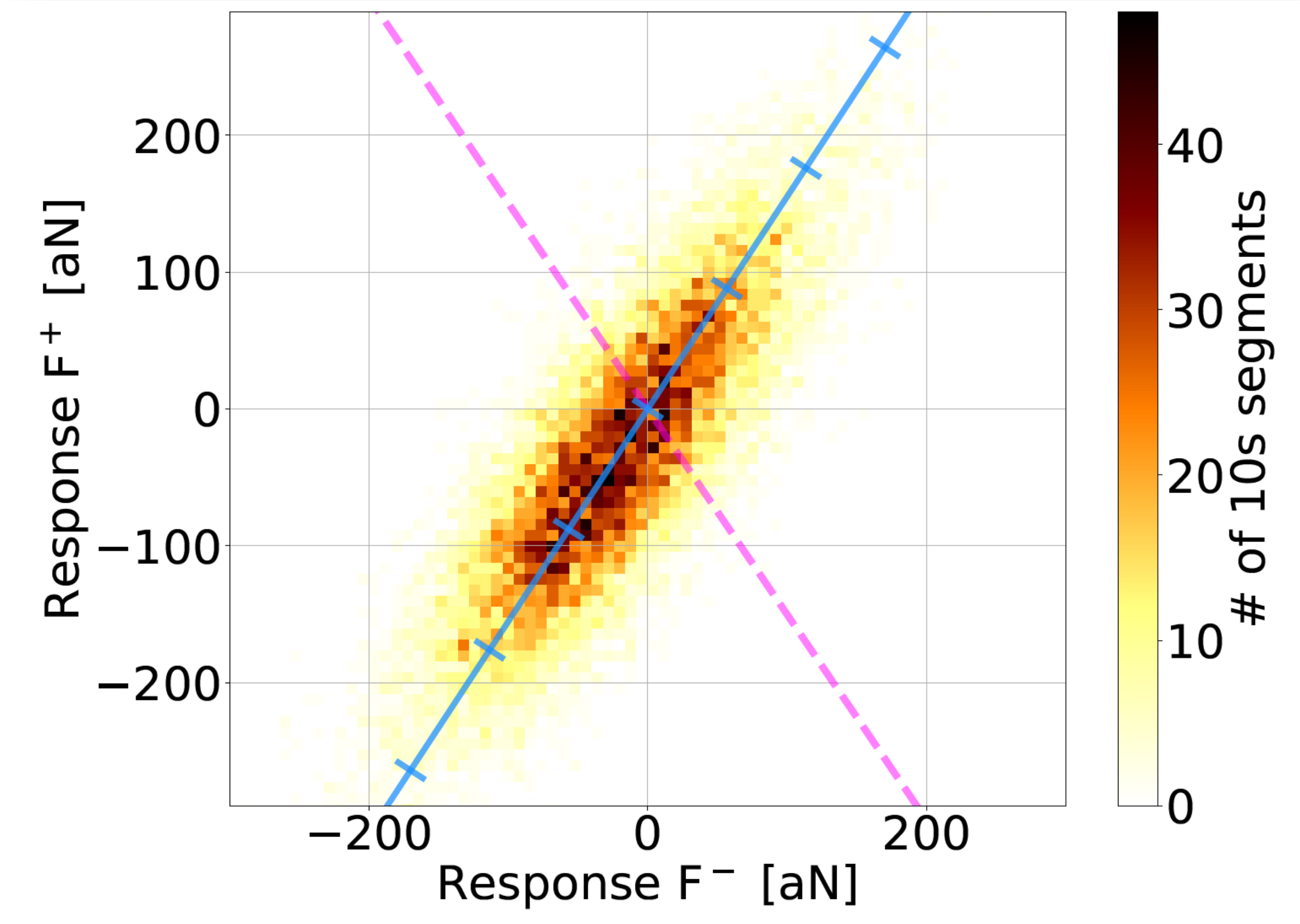
(here Ω is calculated with FEA, using the measured trap position with respect to the electrodes)

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



Note that the quantity *A* has no bias, within the extent of the noise.

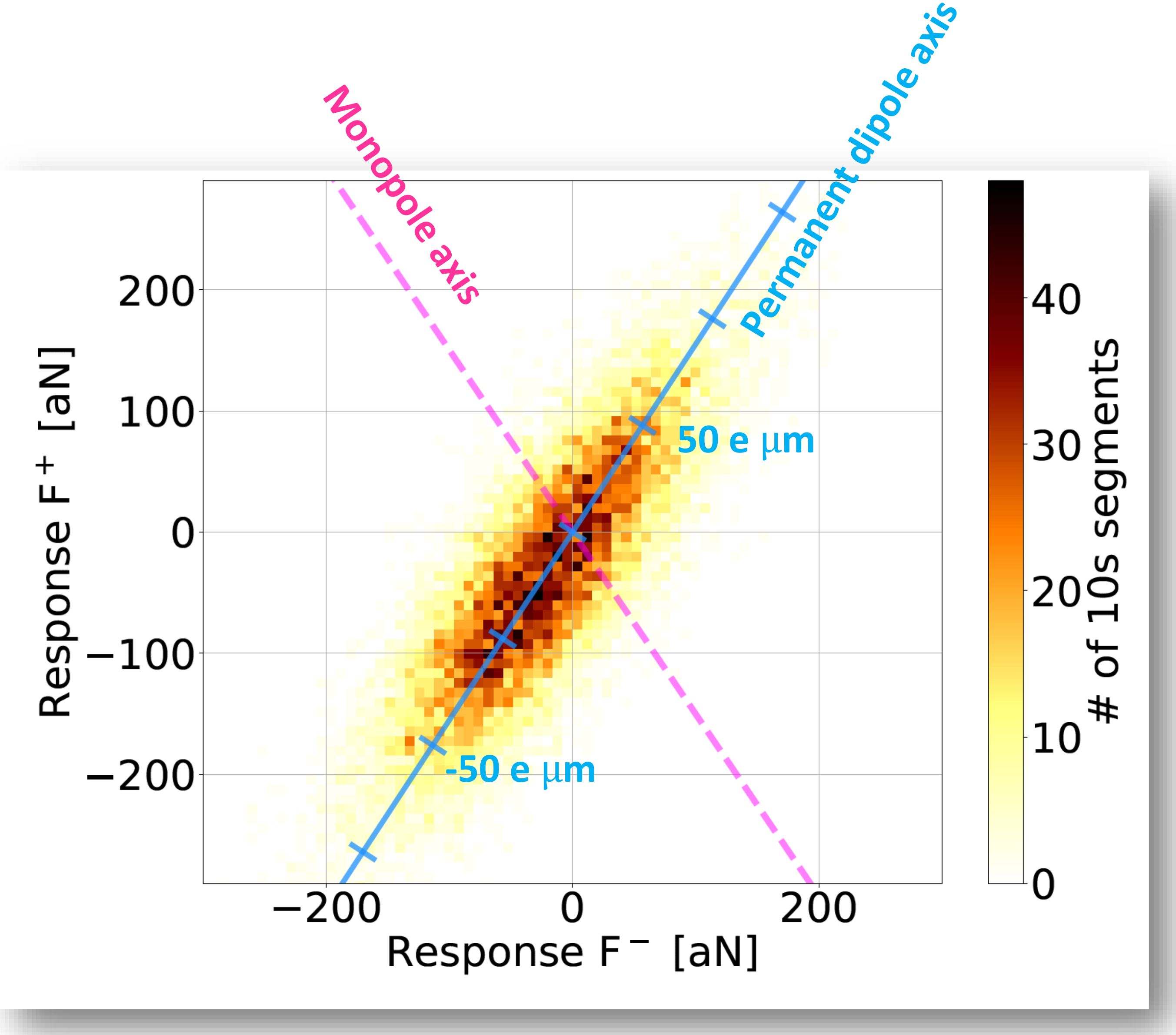
The correlation between F_+ and F_- contains more information!



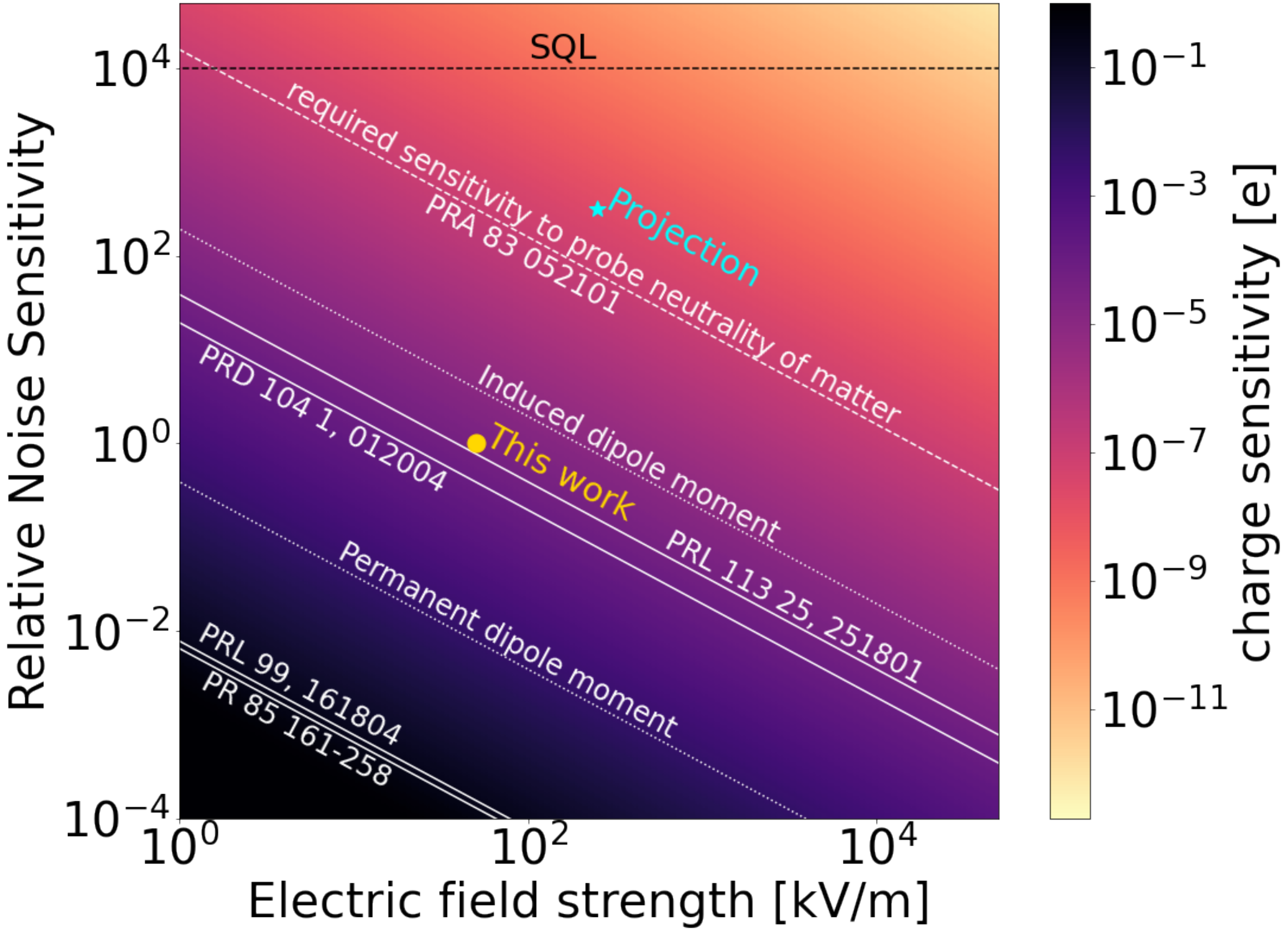
The correlation between F_+ and F_- contains more information!

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

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



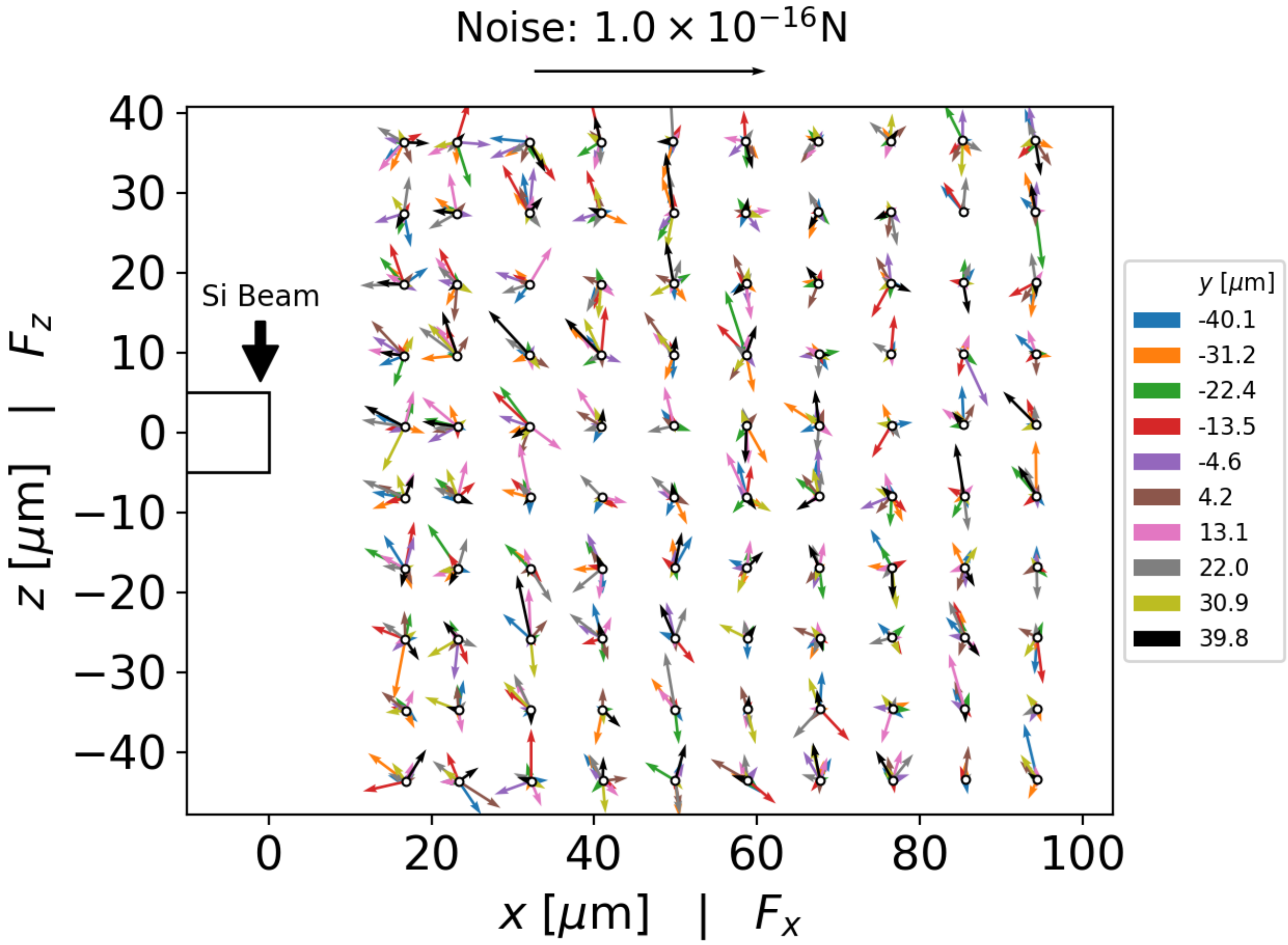
A look at the parameter space relevant for the measurement of small charges

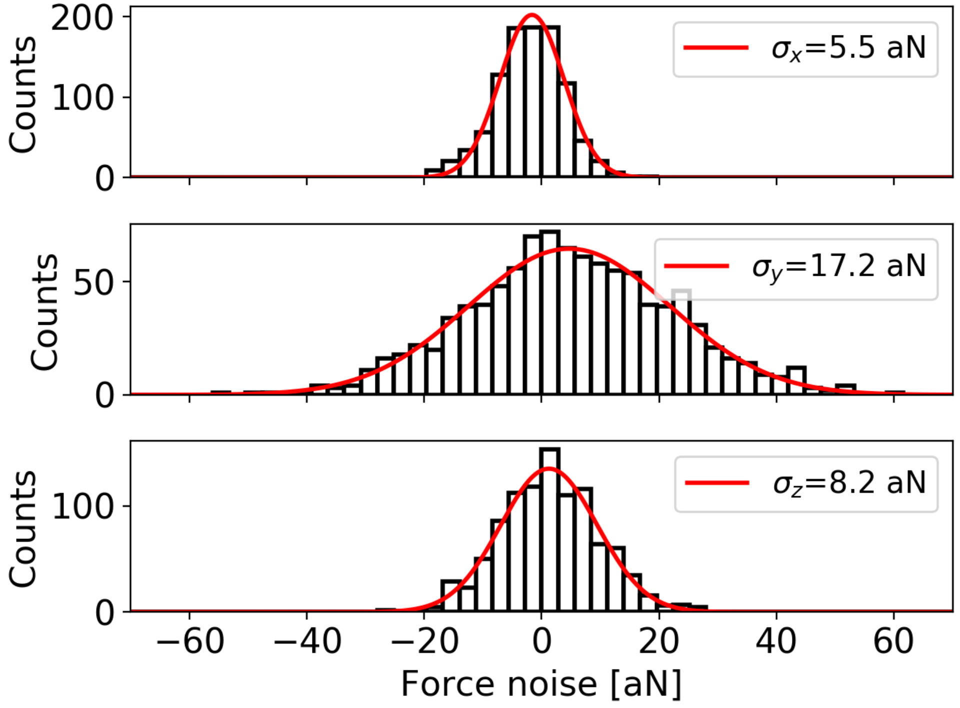


N. Priel, et al.,
"A background-free optically levitated charge sensor"
Sci. Adv. 8 eabo2361 (2022)

An improved search for minicharge particles or test of neutrality of matter is forthcoming

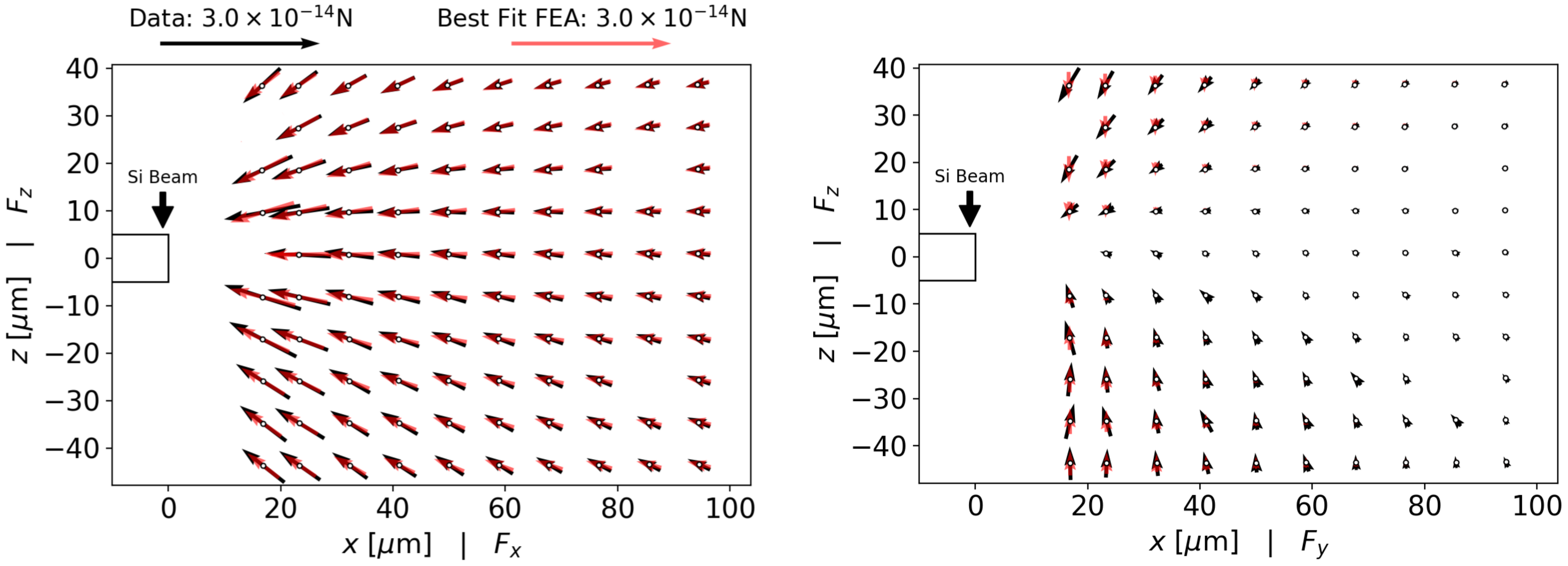
For a static attractor, the noise on the measurement is unaffected (and very small) -- even for a charged microsphere (~500e$^-$)





Closest approach for the plot is 15µm; by now below ~2µm (to the closest material object)

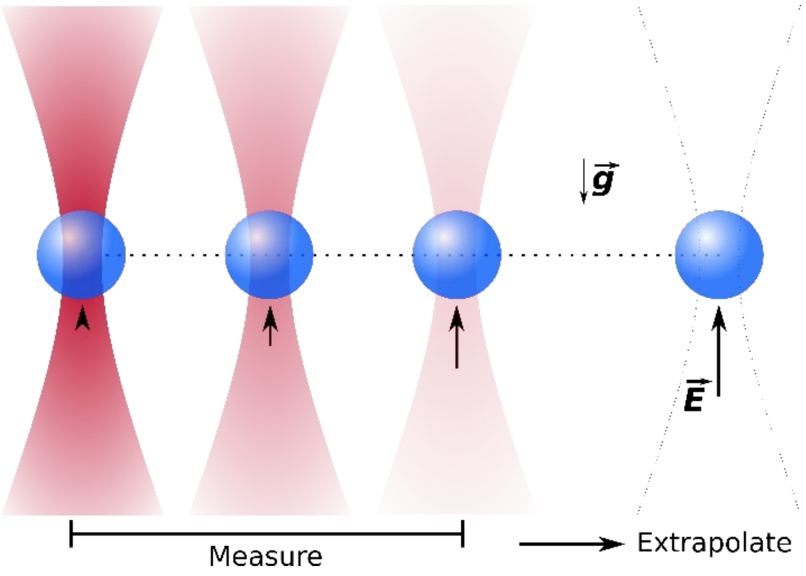
As a demo, full 3D vector mapping of the electric field of a biased attractor (100mV) --here compared to a FEA model

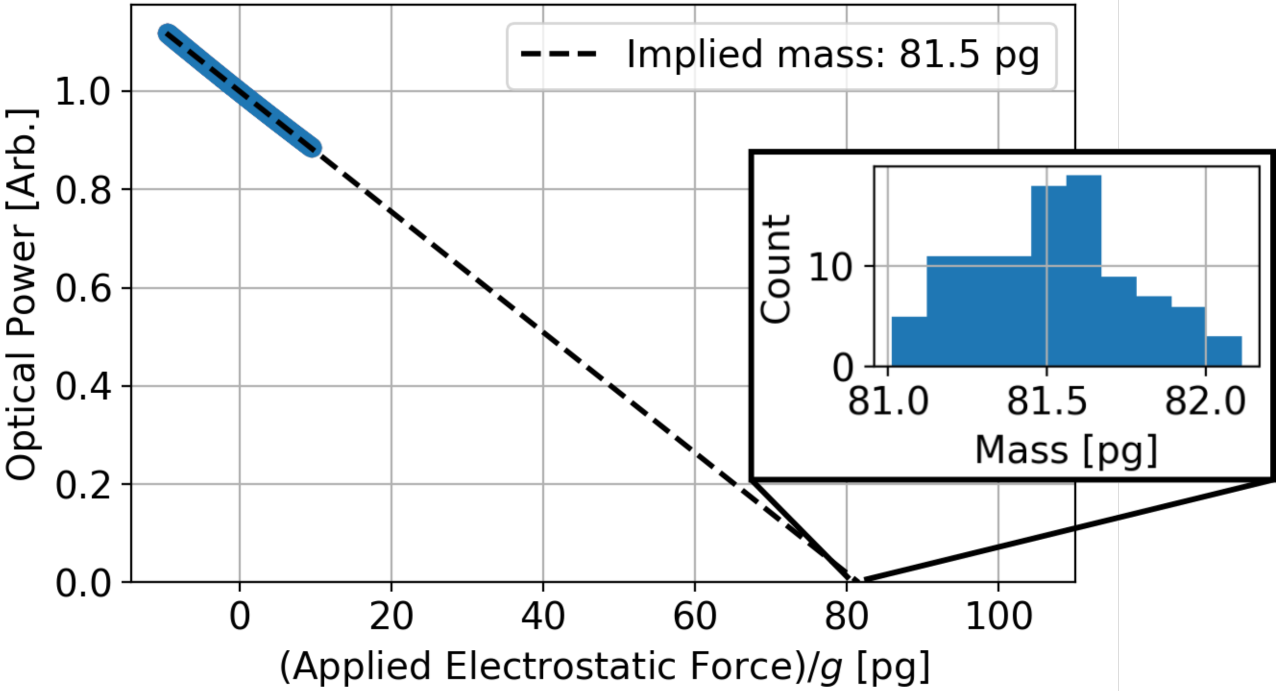


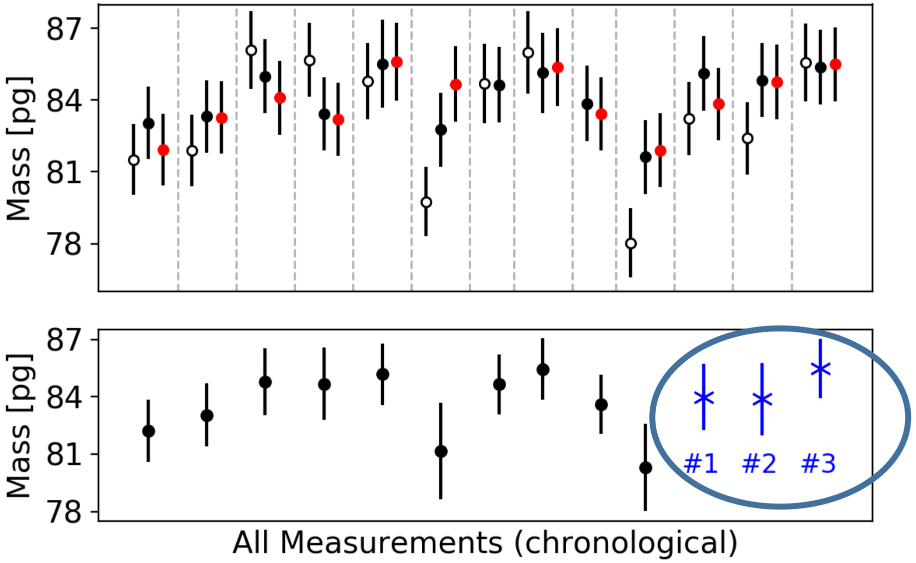
C.Blakemore et al., Phys. Rev. A 99 (2019) 023816

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

Precision measurement of microsphere mass and density

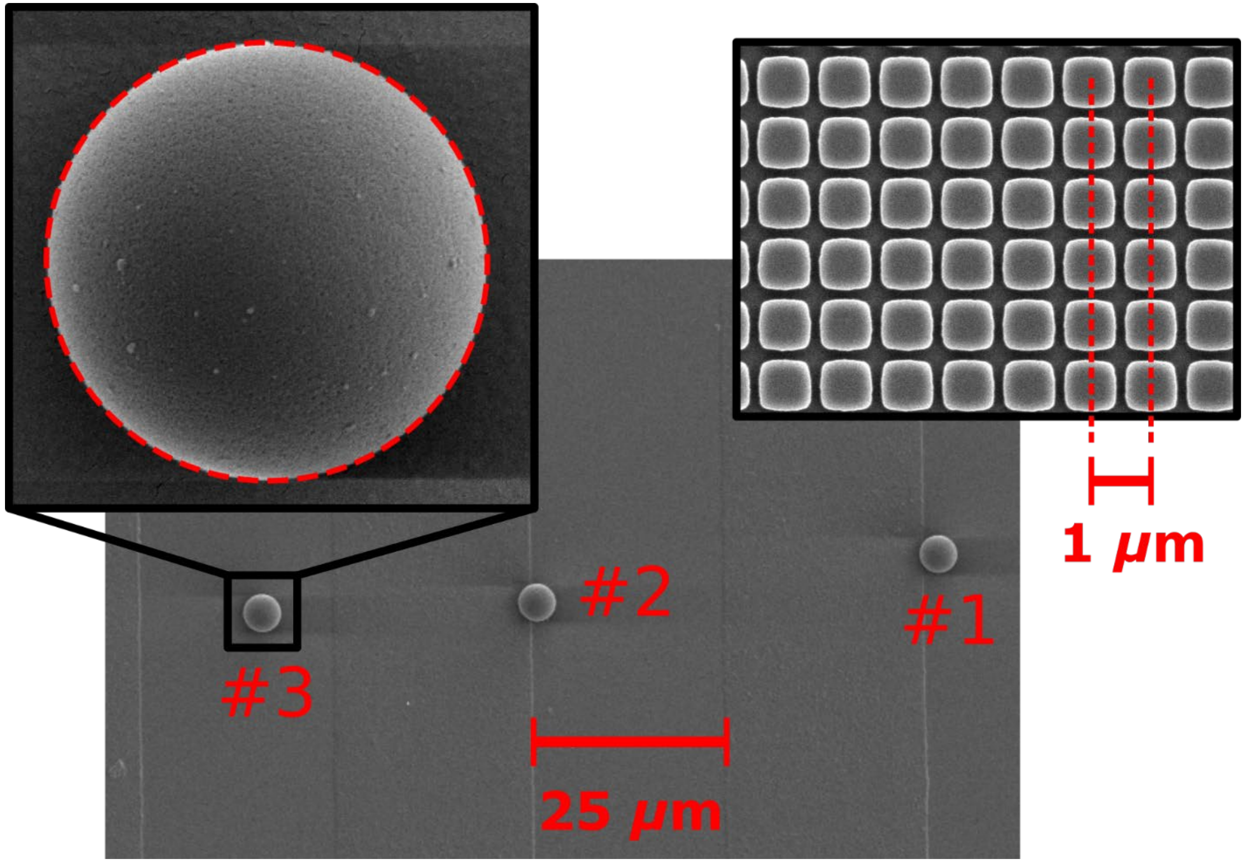


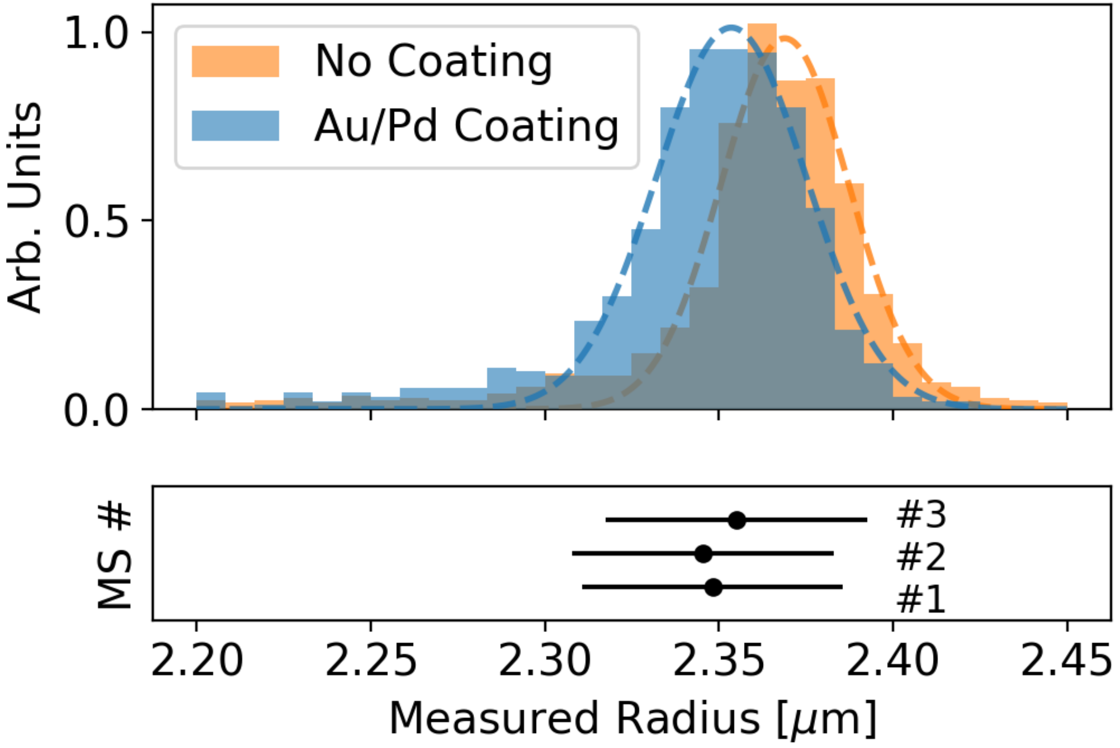




This technique only requires the knowledge/measurement of the relative power needed to compensate for a certain electrostatic force. Ie, it only needs the linearity of a photodiode

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





Extract $\rho_{MS} = 1.55 \pm 0.08$ g/cm^3
Density of fused silica is $\rho_{SiO2} = 2.2$ g/cm^3
➔ Presumably the microspheres have some non-trivial porosity

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

Spinning trapped microspheres

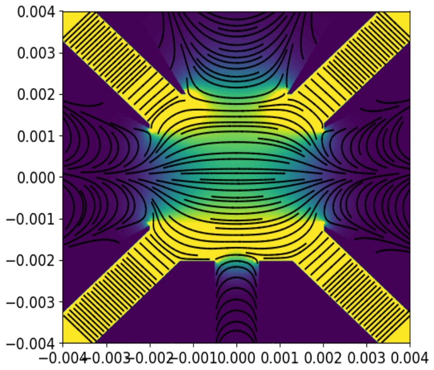
It has been demonstrated by others that birefringent microspheres can be spun up by applying a torque from a circularly polarized light beam. *e.g. Y. Arita et al., Anal. Chem. 83 (2011) 8855*
F. Monteiro et al., Phys. Rev. A 97 (2018) 051802

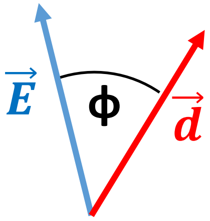
This technique can reach extremely high angular velocities (at the point of making the microspheres explode).

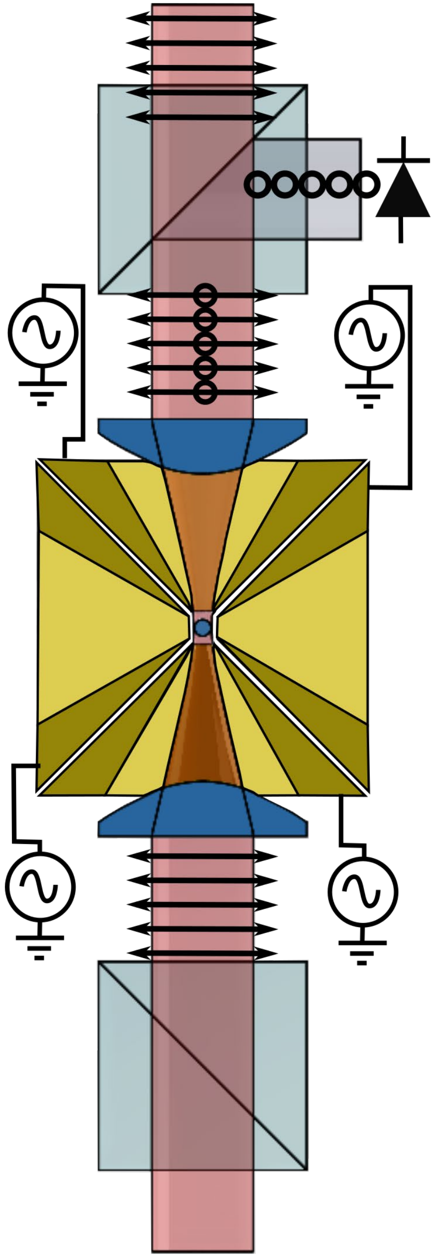
If the microsphere has an electric dipole moment, then a torque can be applied by a rotating external electric field.

We apply this through the 4 electrodes in the horizontal plane.

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

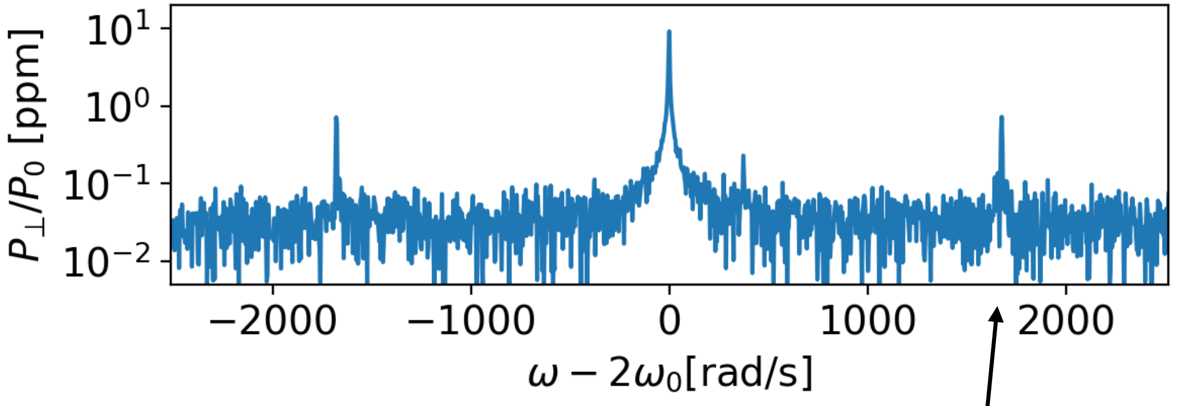




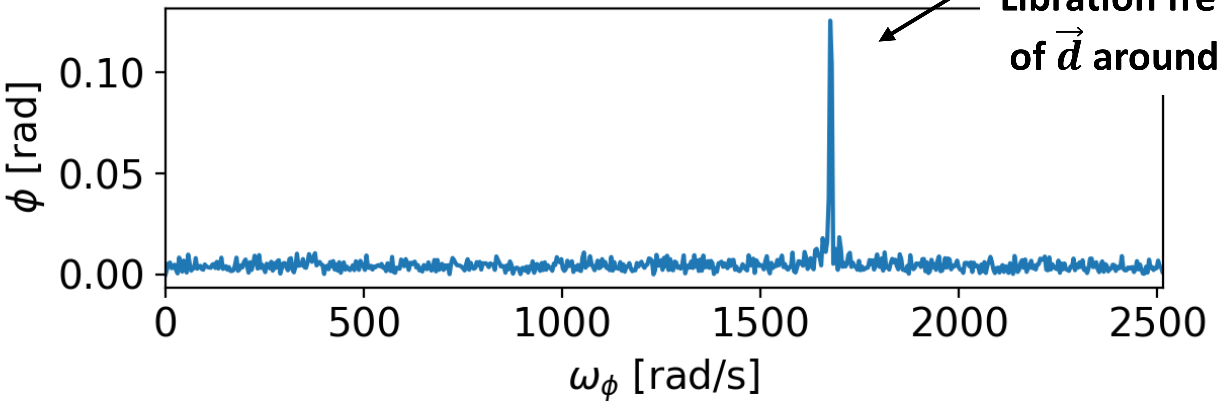


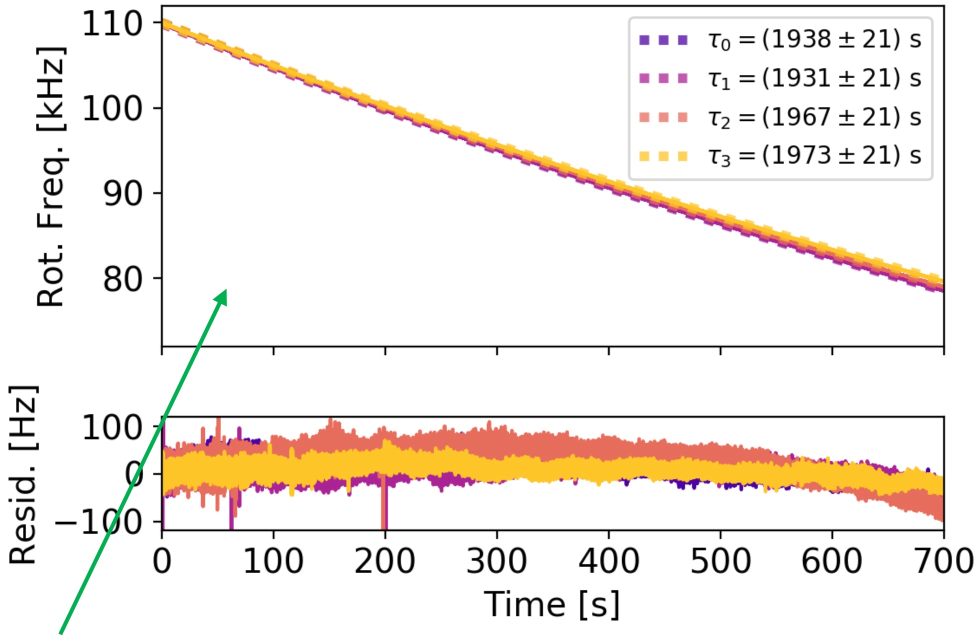
The rotation is read out using the small residual birefringence that the silica microspheres apparently have.

2x rotation frequency



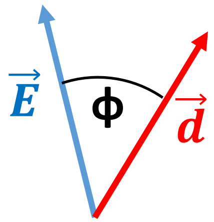
Libration frequency of $\vec{d}$ around $\vec{E}$





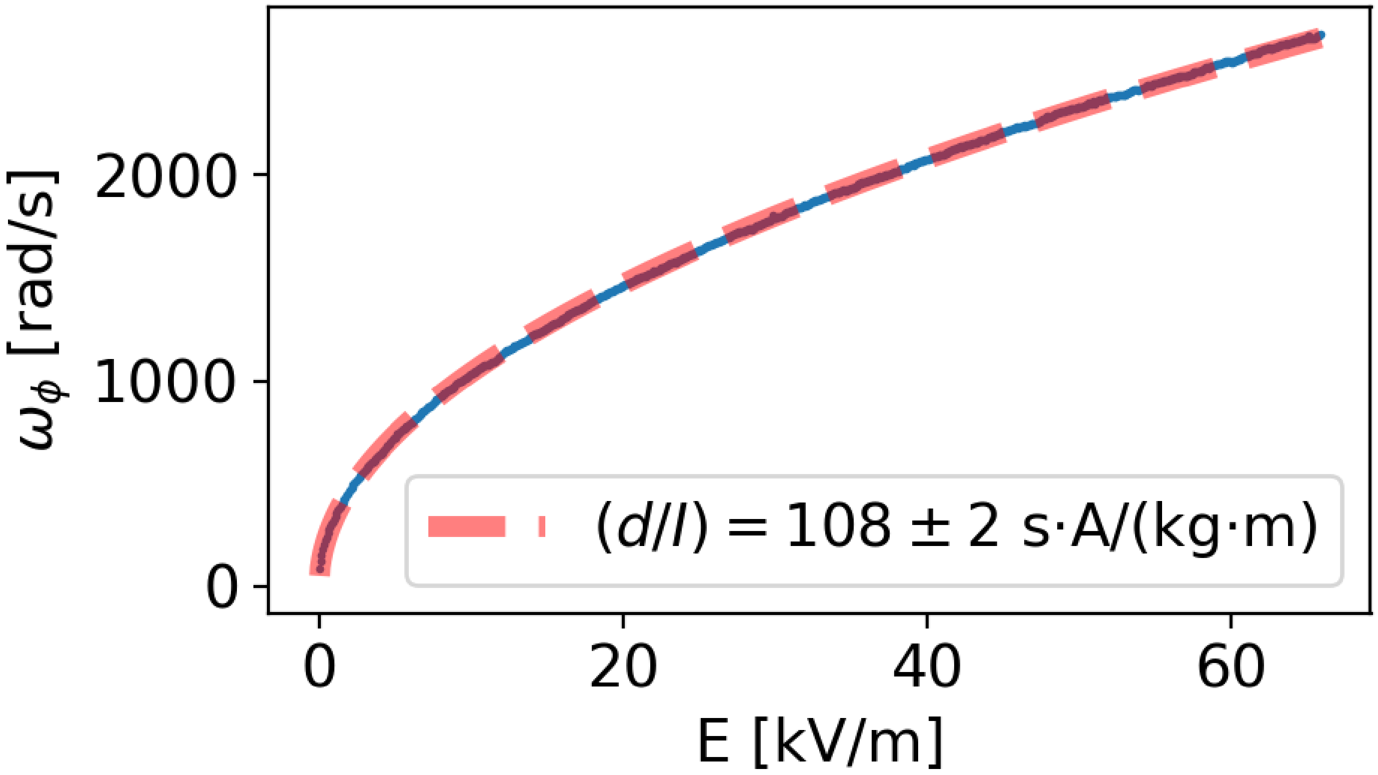
Stopping the driving field makes the microsphere gradually spin-down, initially with the expected exponential law. The time constant can be translated* into the pressure, like in a rotating ball vacuum gauge.

*** A.Cavalleri et al., Phys. Lett. A 374 (2010) 3365**



The libration frequency can be written as $\omega_\phi \cong \sqrt{cos\phi_{eq}\frac{Ed}{I}}$

and d/I can be extracted from a fit to the data



And, assuming I to be that of a homogeneous silica sphere, one gets $d = 127 \pm 14$ e µm

One can also measure the phase lag between the drive signal and the spinning readout

As expected the phase lag is a function of the pressure (i.e. of the gas drag).

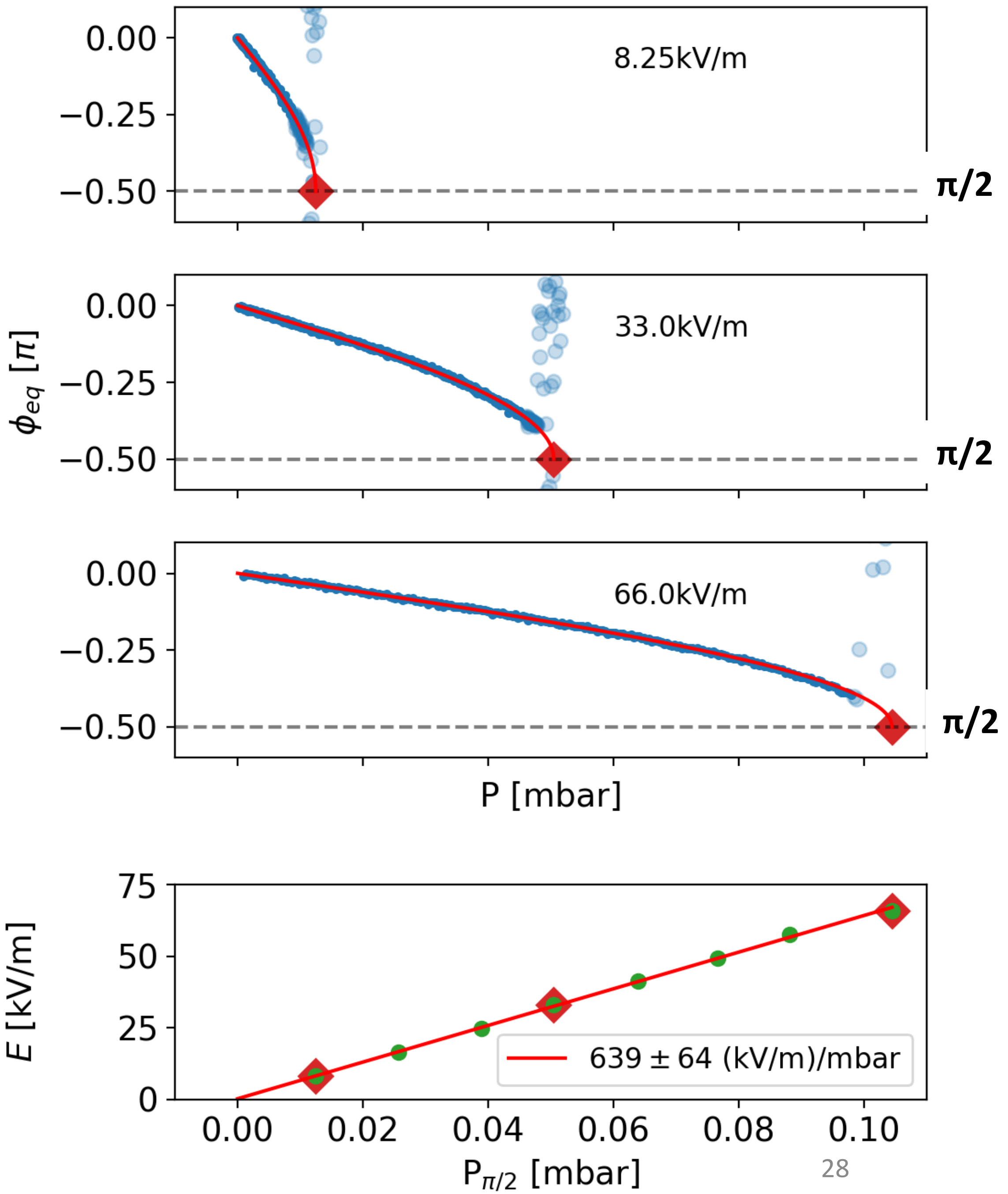
When the phase lag reaches π/2 the microsphere unlocks from the drive signal (phase → random).

The unlocking pressure depends on the amplitude of the drive signal.

From the fit and *d* measured above, one can extract the pressure at the microsphere.

- Absolute measurement
- Can go lower than a baratron (10^{-6}, and this can be improved)
- Local measurement! An array of traps can map the pressure.
- Independent from magnetic fields

(used in conventional rotating ball gauges)



The microsphere is a tiny gyroscope!

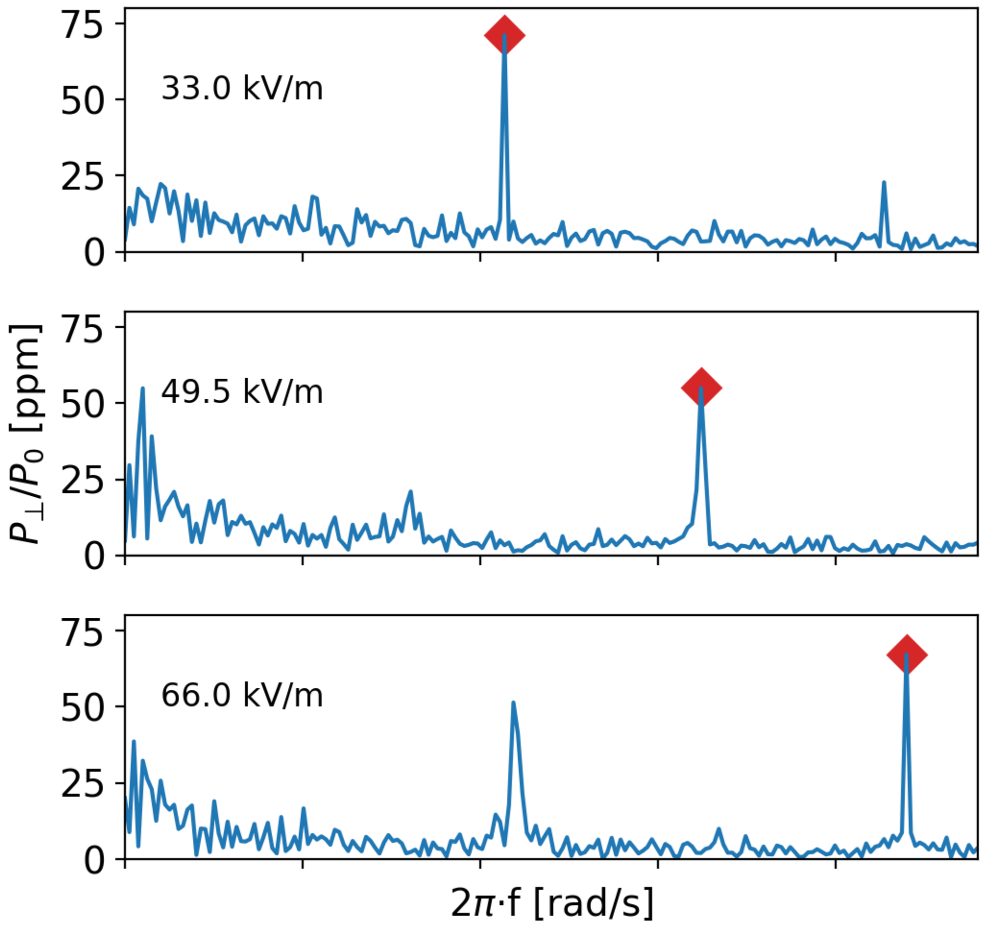
We can watch it precess. After spinning up, apply a torque in the plane orthogonal to that of rotation.

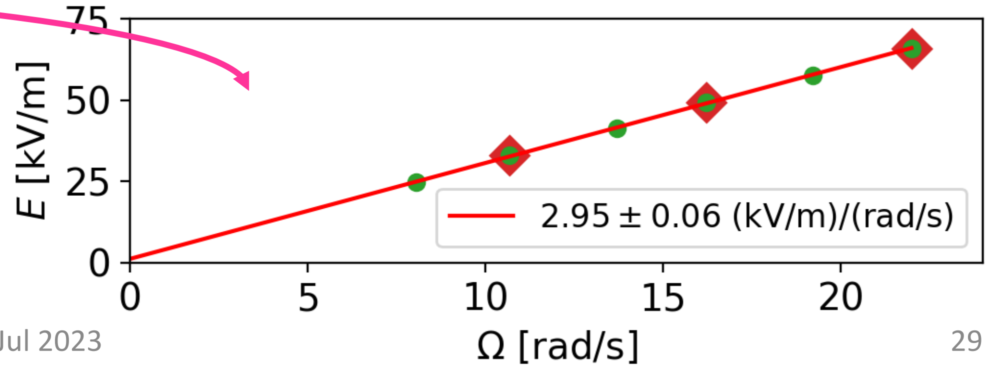
Suddenly making the E field turn in a plane perpendicular to the microsphere rotation results in precession with frequency Ω.

For $\Omega \ll \omega_0$ and neglecting dissipation,

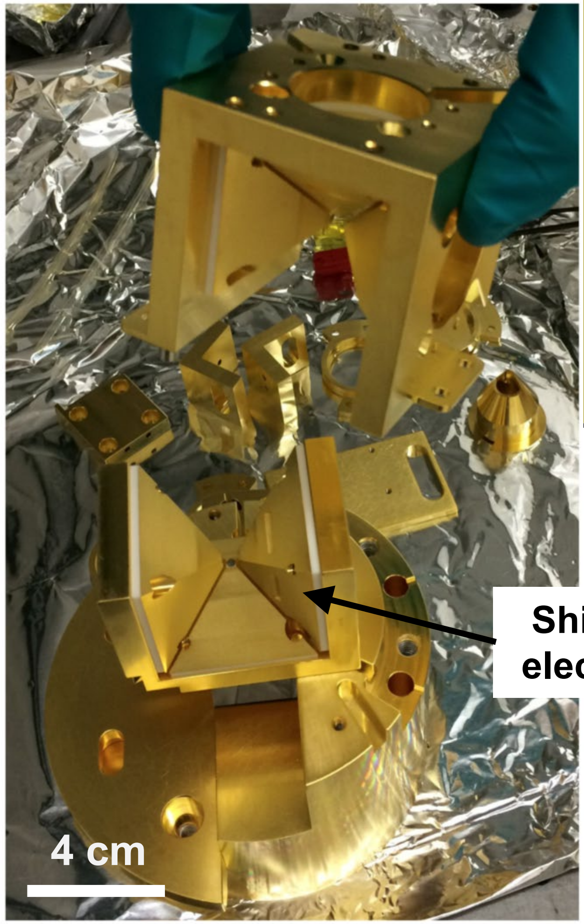
$$\frac{d}{I} = \frac{\Omega \cdot \omega_0}{E} = 106 \pm 2 \ \text{s A/(kg m)}$$

Indeed, data shows that $\Omega \propto E$ and the value of d/I is consistent with that obtained from libration data.

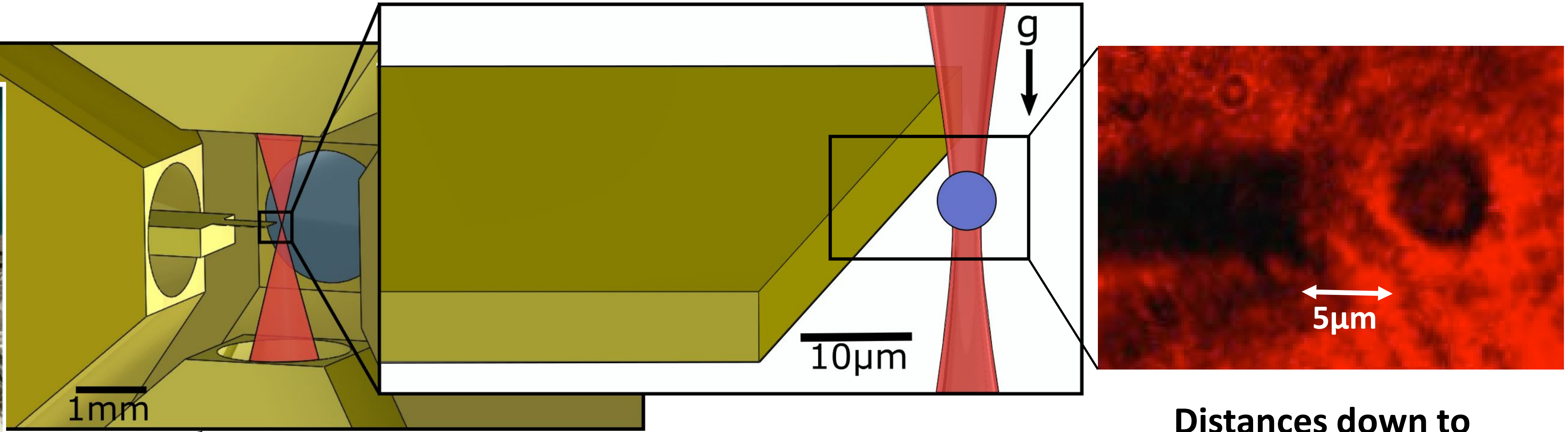




There are specific challenges in moving objects very close to the microsphere



Shielding electrodes

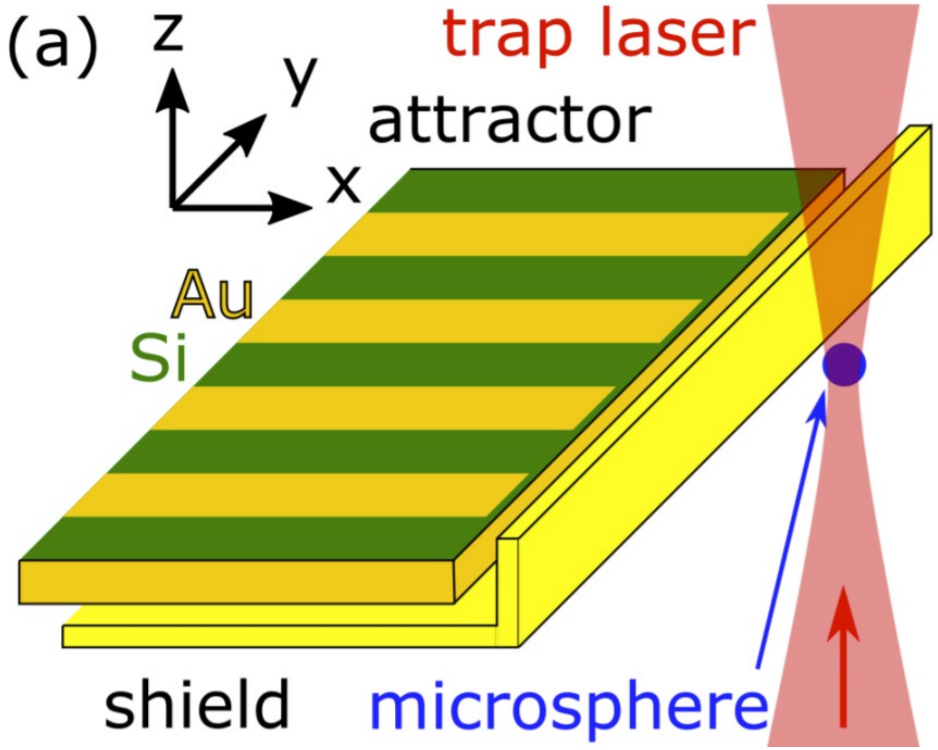


**Distances down to
A few μm have been
stably achieved**

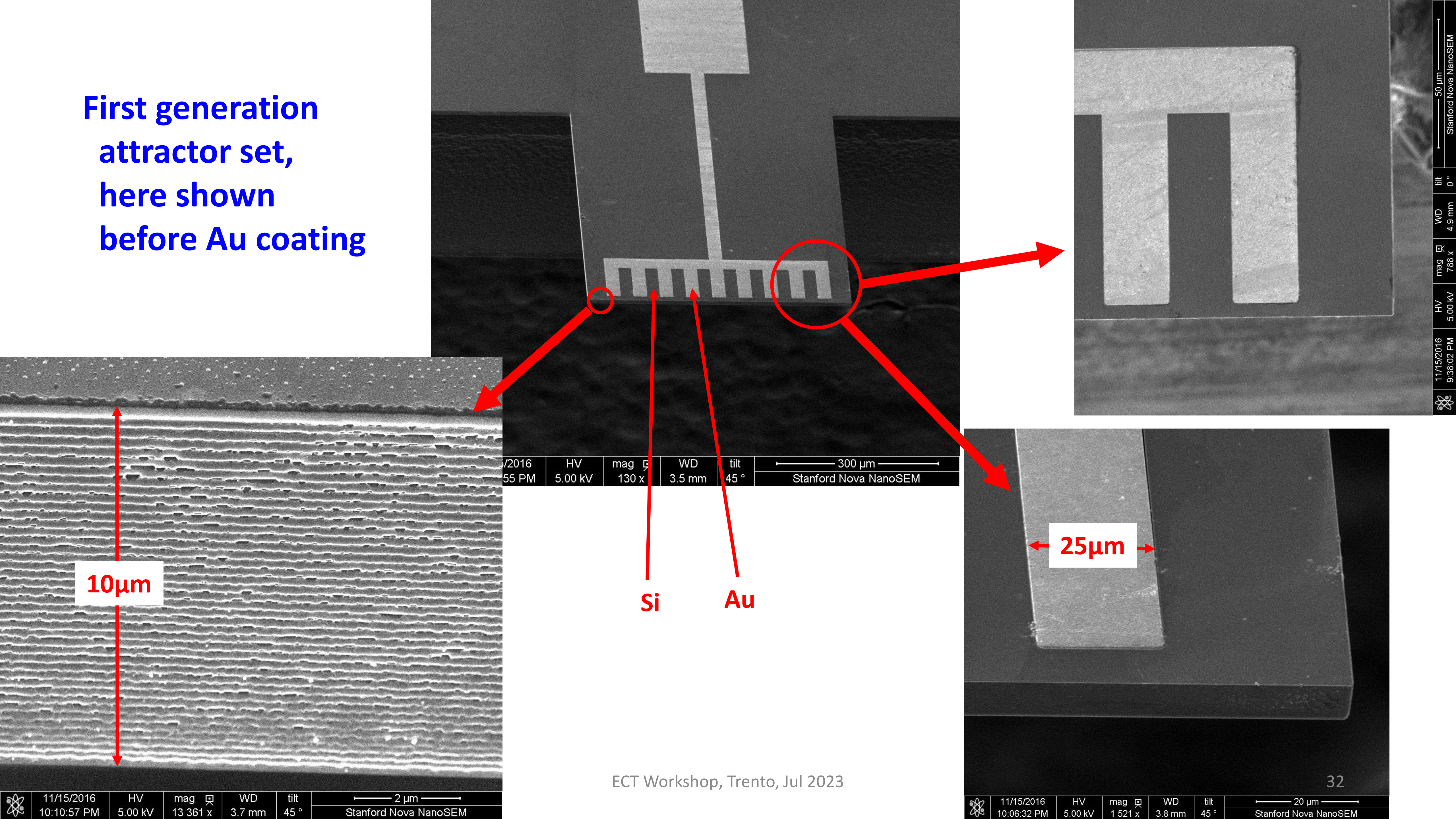
- **Perturbation of the optical mode of the trapping beam**
- **Residual electrostatic forces (typically gradients interacting with microsphere dipole moments)**
- **Below ~a μm Casimir forces (see later)**

First gravity run

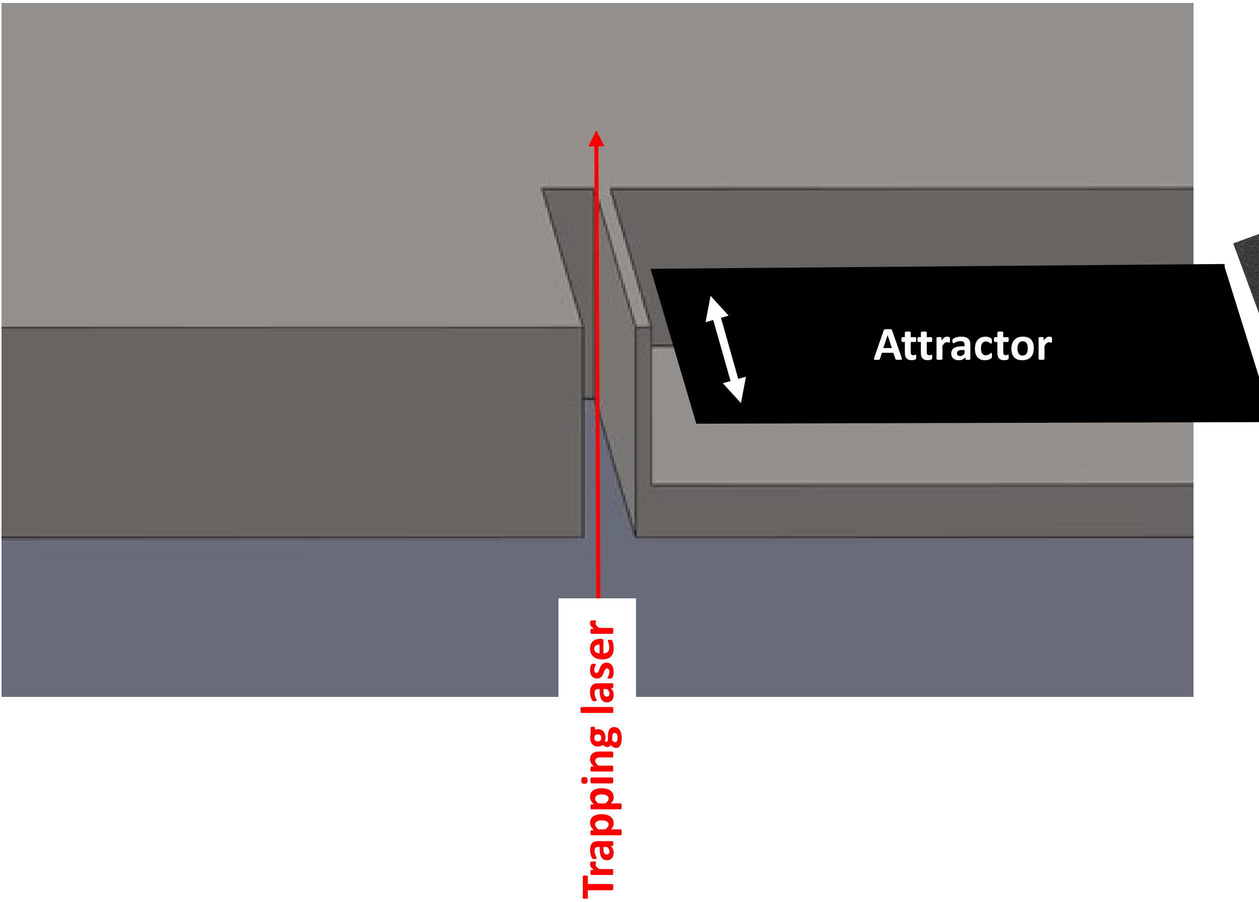
- 10^5 seconds
- 7.6 µm sphere (420 pg)
- 200 µm attractor stroke
- Using only Z channel
- Separation:
  - 13.9 um in X
  - 15.8 um in Z
- Background mitigation using
  - Shield
  - Drive attractor along density modula at f_0(3Hz), and observe correlated force at $f_0, 2f_0, 3f_0, 4f_0, \ldots$

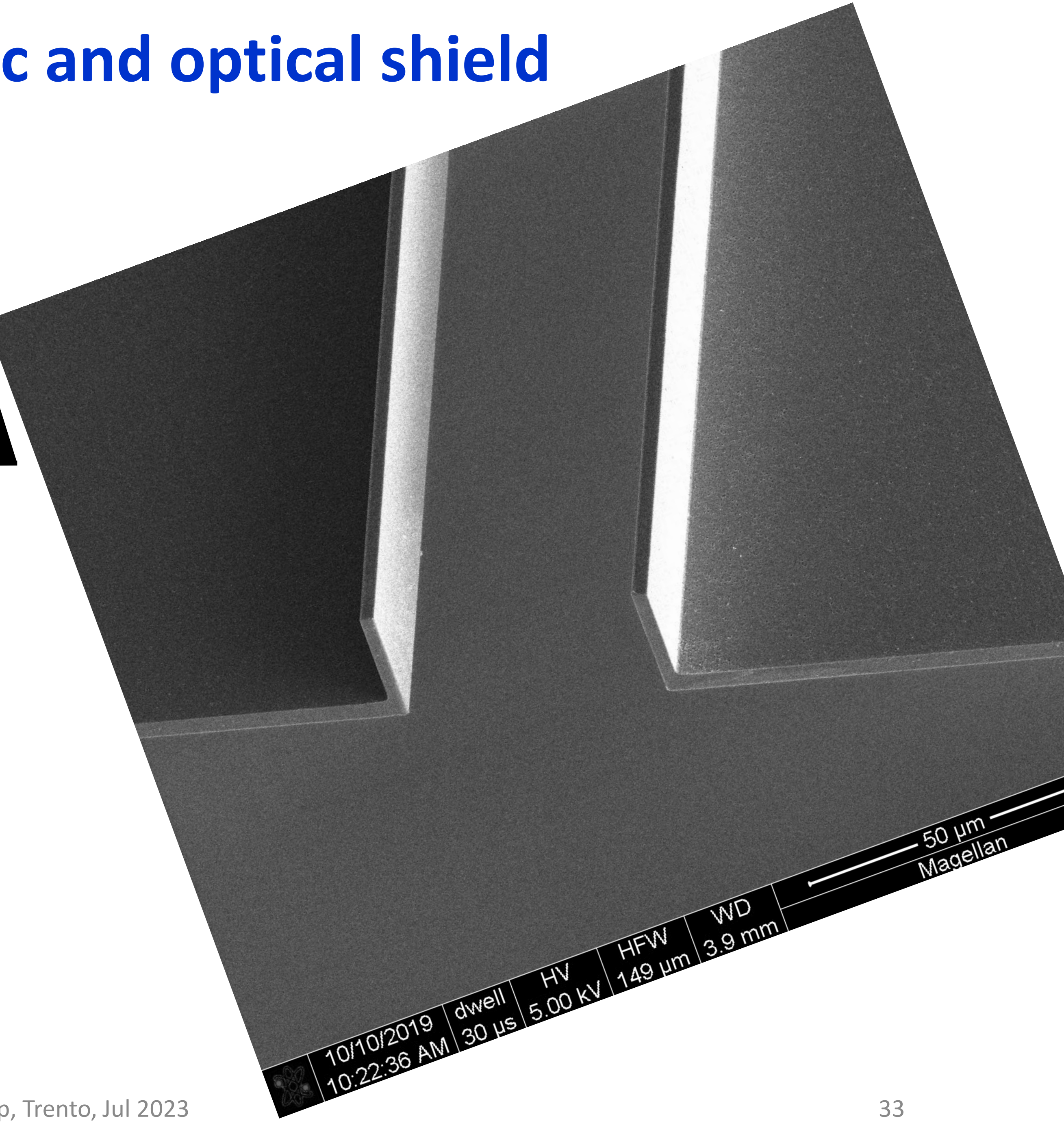


First generation attractor set, here shown before Au coating

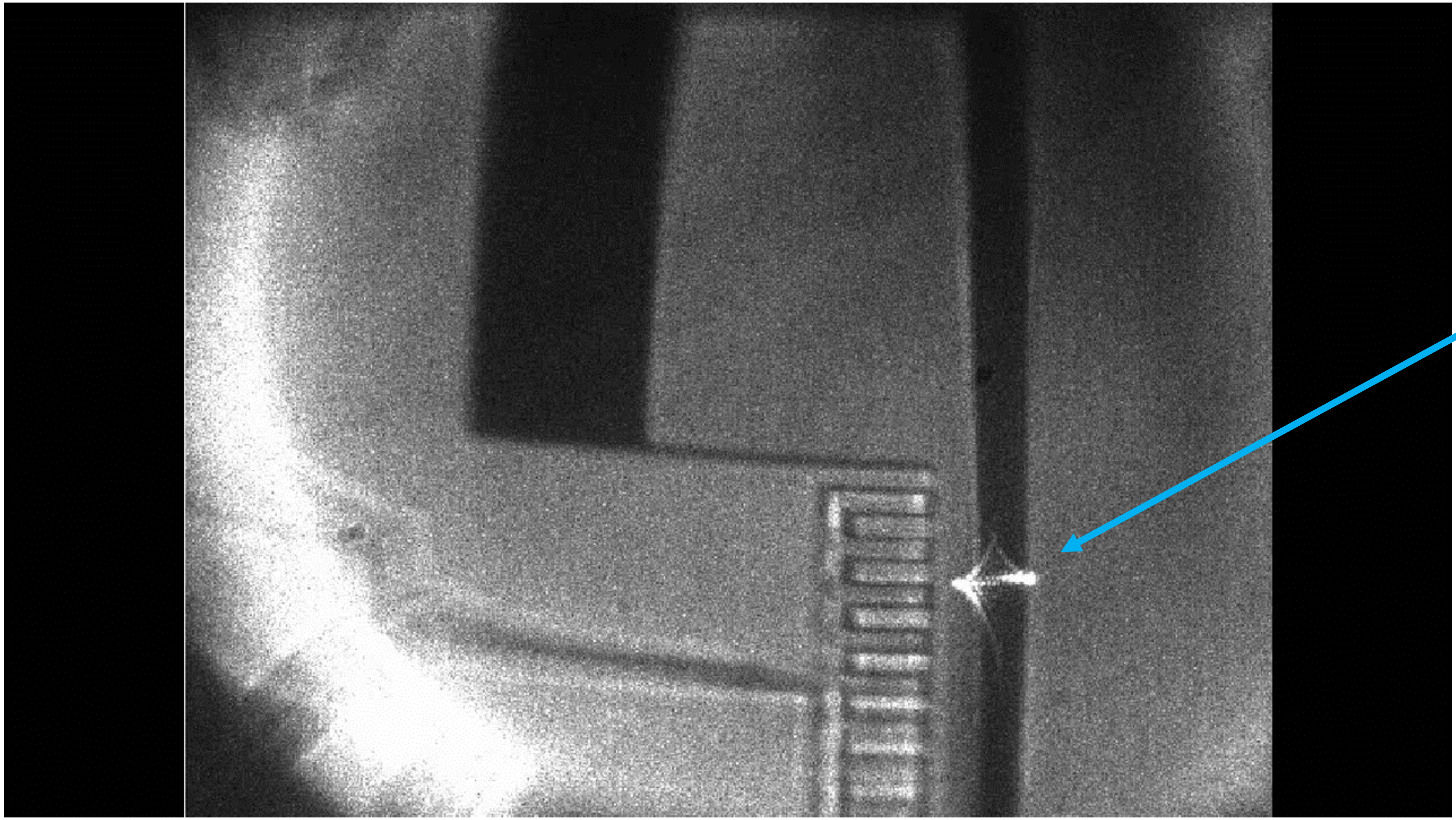


Standing electrostatic and optical shield





Example of scanning



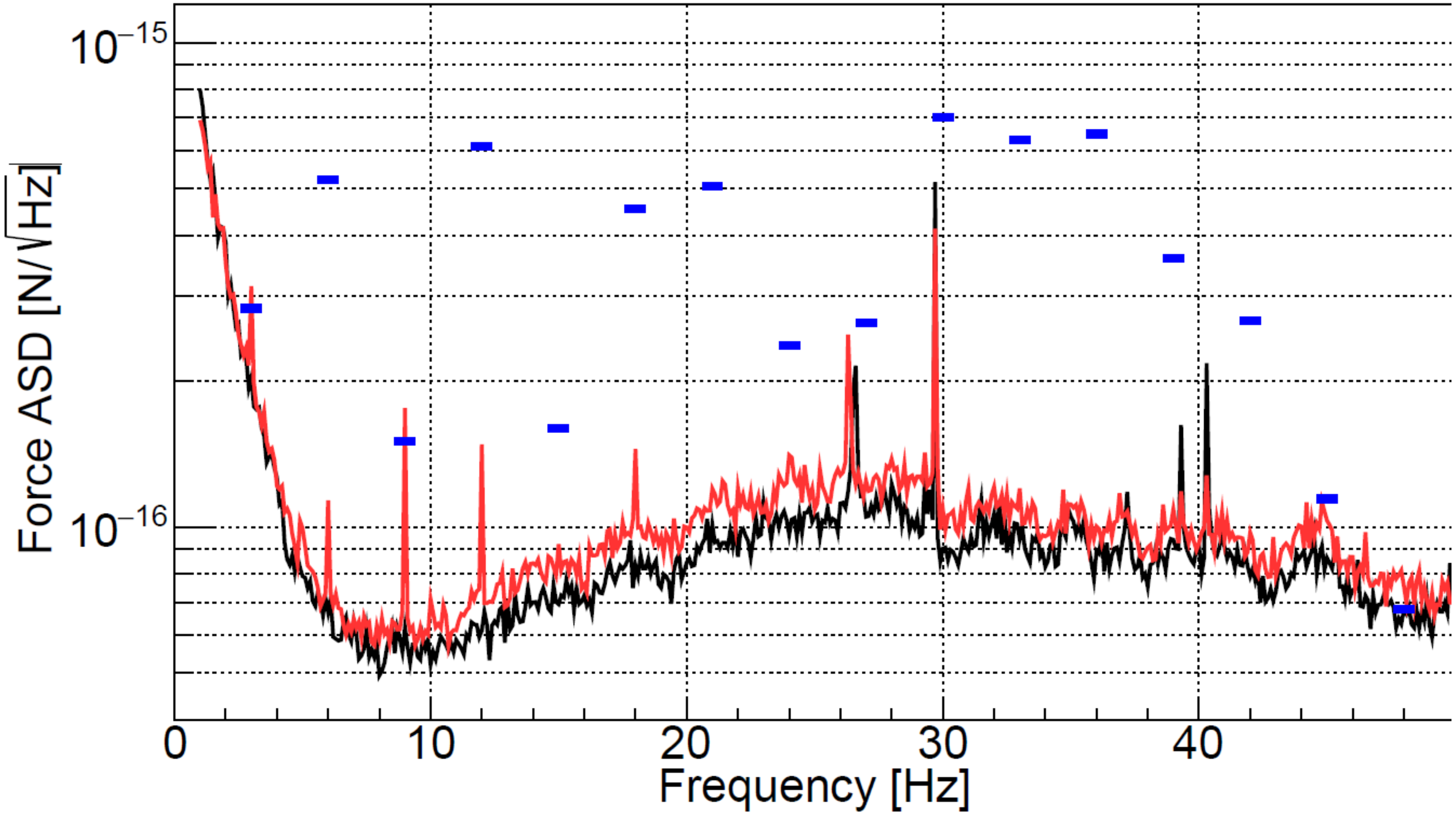
Trap with microsphere

Top view

$\vec{g}\odot$

Actual scan frequency: 3 Hz

First gravity run

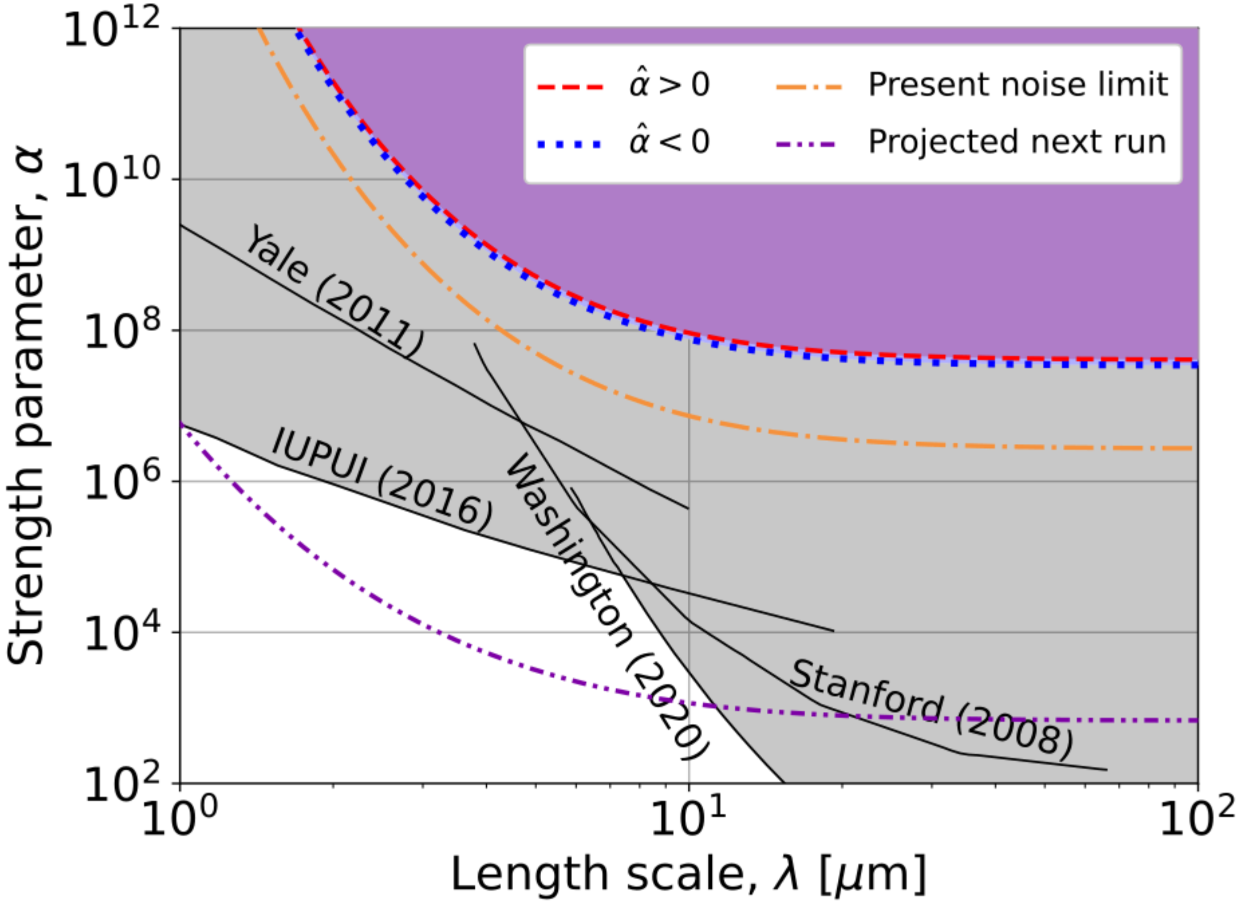


- ○ Force sensitivity of 10^{-16} N/$\sqrt{\mathrm{Hz}}$
- ○ Backgrounds
- ○ Black - response with stationary attractor
- ○ Red – response with moving attractor
- ○ Blue – expected response for $\alpha = 10^{10}$ and $\lambda = 10\mu m$

First 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: much work on this in the last 1.5 years**

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



Backgrounds, noise and ongoing upgrades

- **Vibrations**

✓ Rebuilt some parts for improved rigidity
- Rotary attractor (collaboration with EPFL)

- **Optical backgrounds**

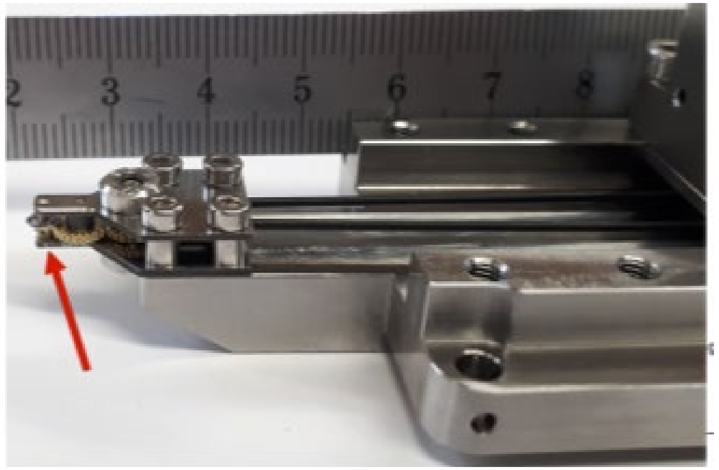
✓ Fast camera to detect x-y signal and advanced image analysis
- x-y readout in reflection
- Better masking and black coatings

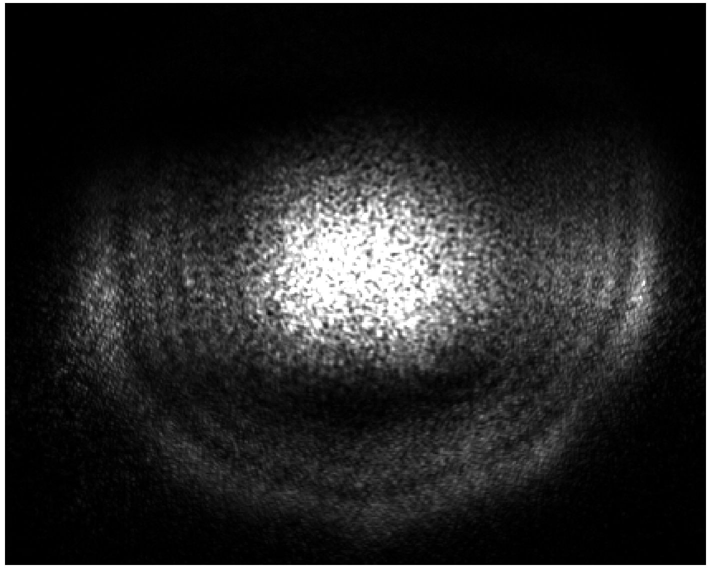
- **EDM backgrounds**

✓ Realign everything and make sure attractor and shield are properly positioned
✓ Modeling with help of applied potentials and gradients
✓ Apply nulling potential between attractor and shield

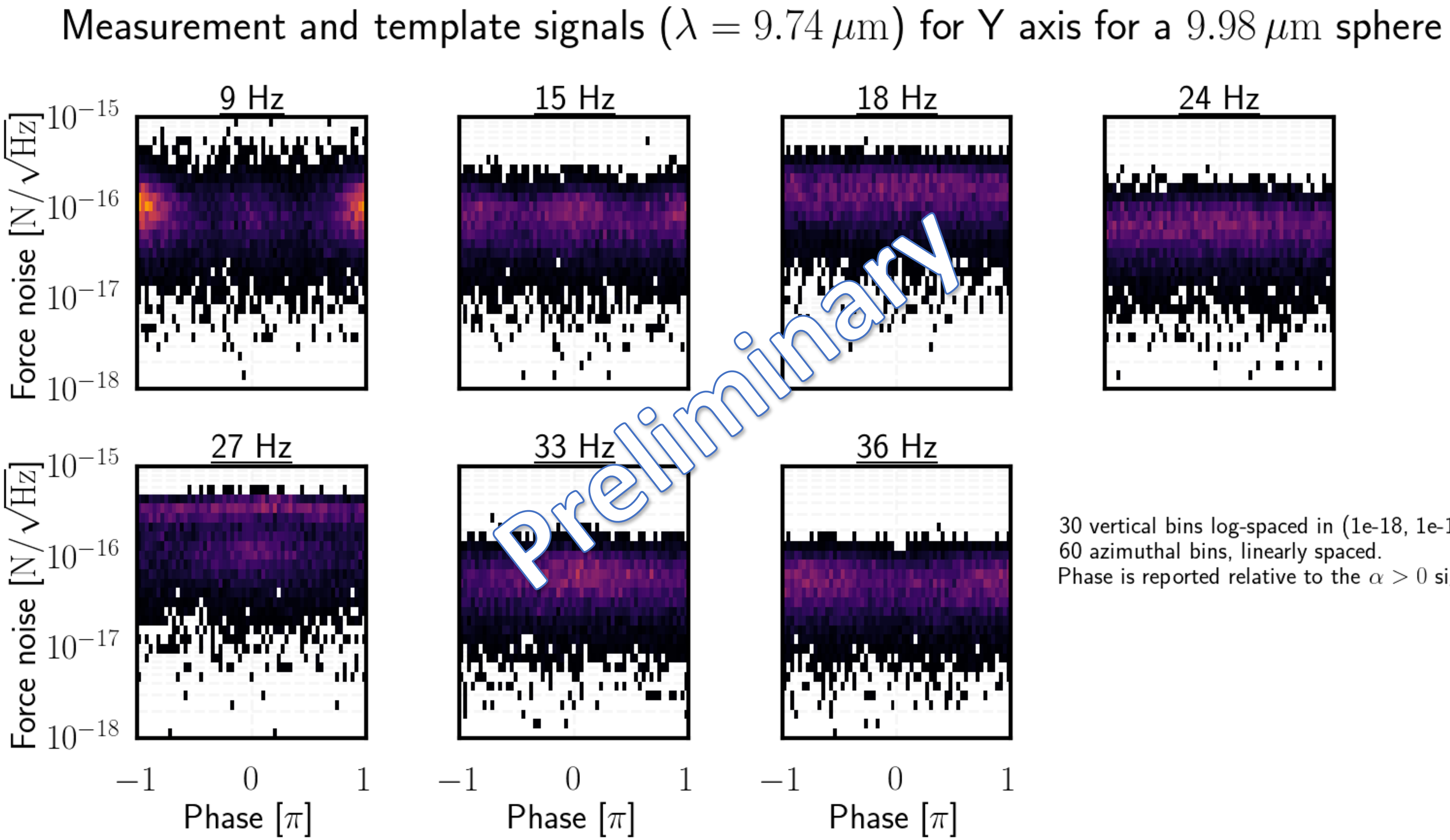
- **Pointing & readout noise**

- Non-interferometric readout channel
- In air optics → in He optics



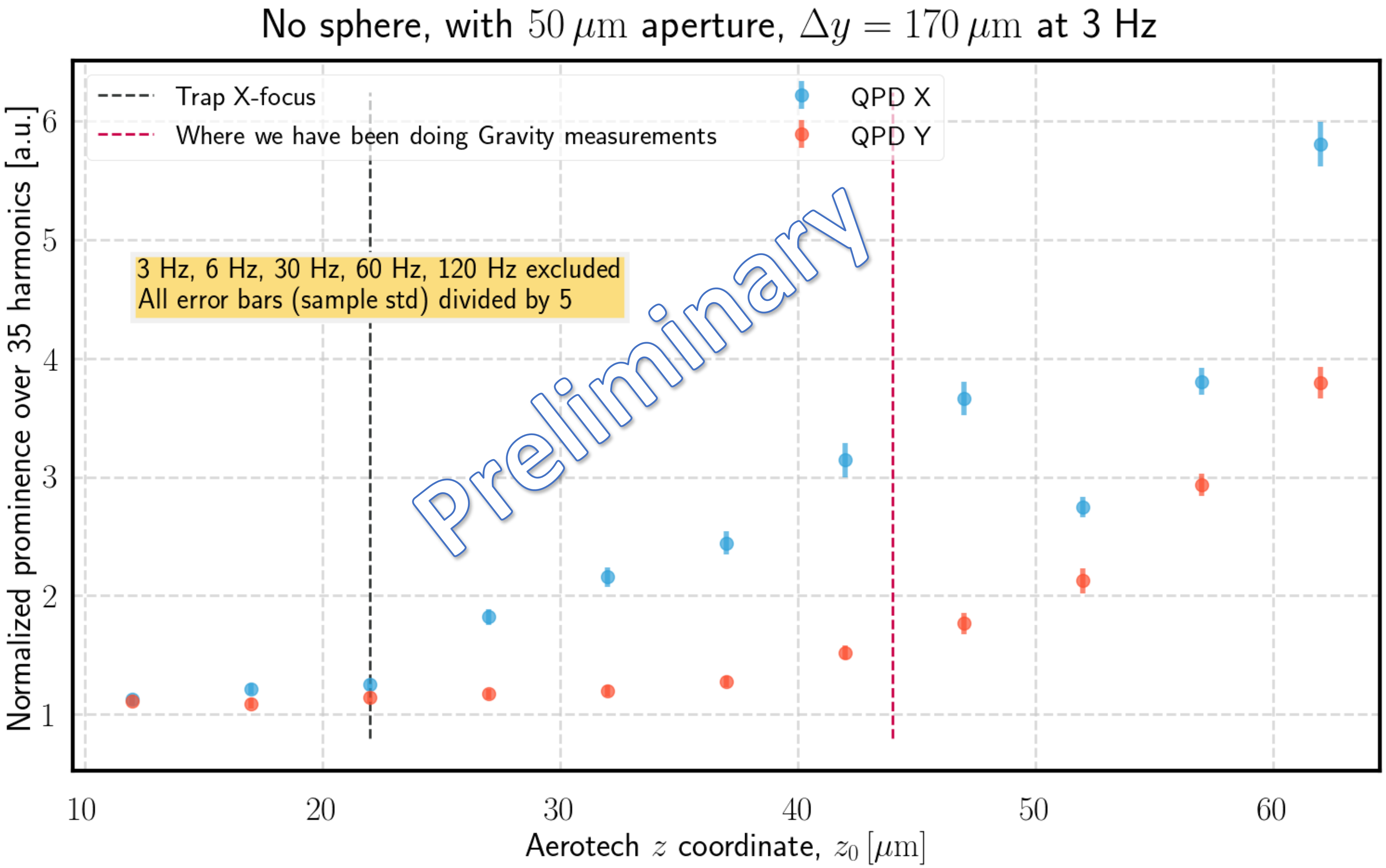


Background now substantially smaller than before and NOT dominated by EM effects.



30 vertical bins log-spaced in (1e-18, 1e-15) N.
60 azimuthal bins, linearly spaced.
Phase is reported relative to the $\alpha > 0$ signal template.

In fact, much of the background is there even without microsphere, but being at the focus helps…



Conclusions

- After >200 years of mechanical springs, the $1/R^2$ behavior of gravity around 10µm is now tested with optically levitated microspheres.
- New technique: takes time to establish but…
- Along the way we have discovered a wealth of tricks and applications to other areas of physics.
- Having a variety of very different techniques is really important, particularly if a discovery is made.
- A new measurement with improved sensitivity should be available soon.
- Same for a new test of neutrality of matter.

The (recent) cast

… and Dimitri Ntounis
Yuqi Zhu (missing)

From the previous generation:
Chas Blakemore
Alex Fieguth
Emmett Hough
Nadav Priel

Kenneth Kohn
Clarke Hardy
Gautam Venugopalan
Lorenzo Magrini

Also thanks to our “alter egos” at Yale: Dave Moore, Thomas Penny, Ben Siegel, Yu-Han Tseng, Jiaxiang Wang, Molly Watts

…and at EPFL: Aurelio Bay and Florian Bernard

The (recent) cast

… and Dimitri Ntounis
Yuqi Zhu (missing)

From the previous generation:
Chas Blakemore
Alex Fieguth
Emmett Hough
Nadav Priel

Last but not least: postdocs sought for various activities in the group. This includes:

- **the work described here,**
- **a search for new interactions using Mössbauer spectroscopy and**
- **the nEXO neutrinoless double-beta decay experiment**

http://grattalab3.stanford.edu/neutrino/index.html