Title: Measuring gravity at micron scale and other fun tricks with optically levitated microspheres

Speakers: Giorgio Gratta

Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 21, 2022 - 2:00 PM

URL: https://pirsa.org/22090017

Abstract: I will describe a new program of measurements in fundamental physics using optically levitated dielectric microspheres. The focus of the talk will be the recently completed first search for new, gravity-like interactions at micron scale using this novel technique. I will also show an array of other results, including searches for millicharged particles, Chameleon fields and techniques to manipulate the various degrees of freedom of the trapped microspheres.

Measuring gravity at short distances

and other fun tricks with levitated microspheres

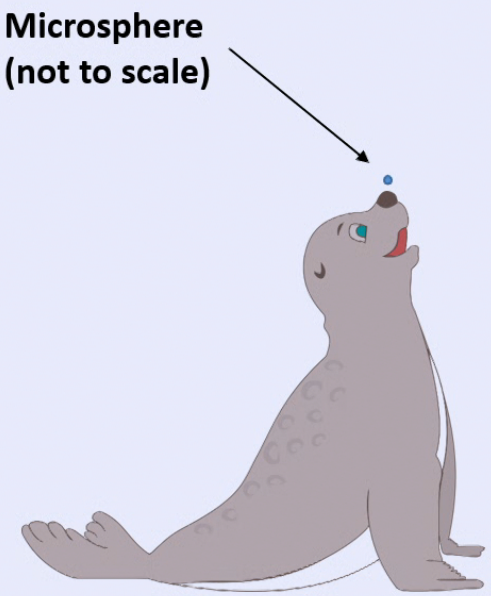
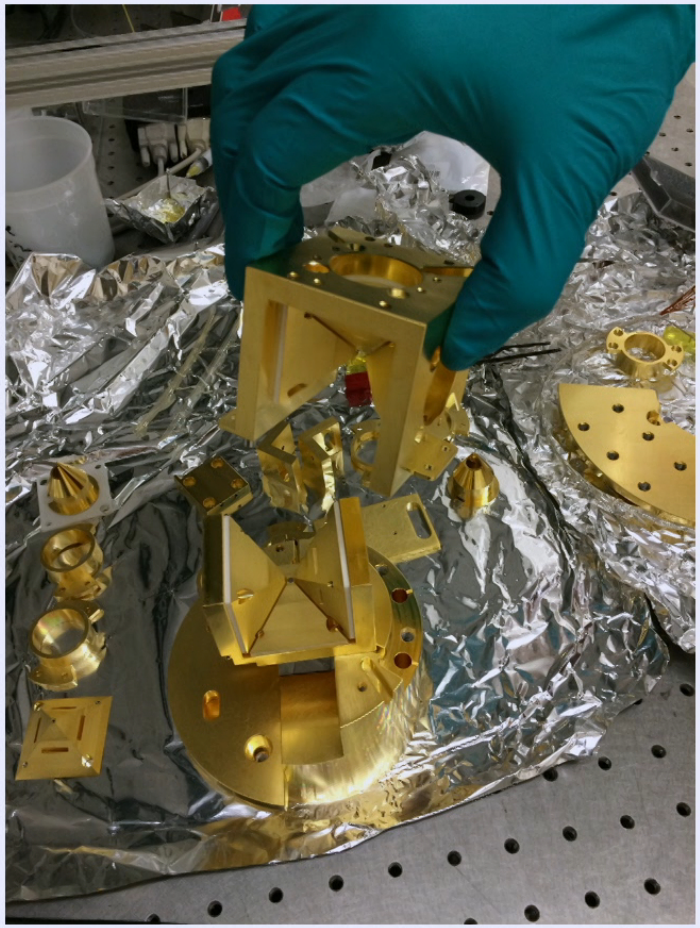


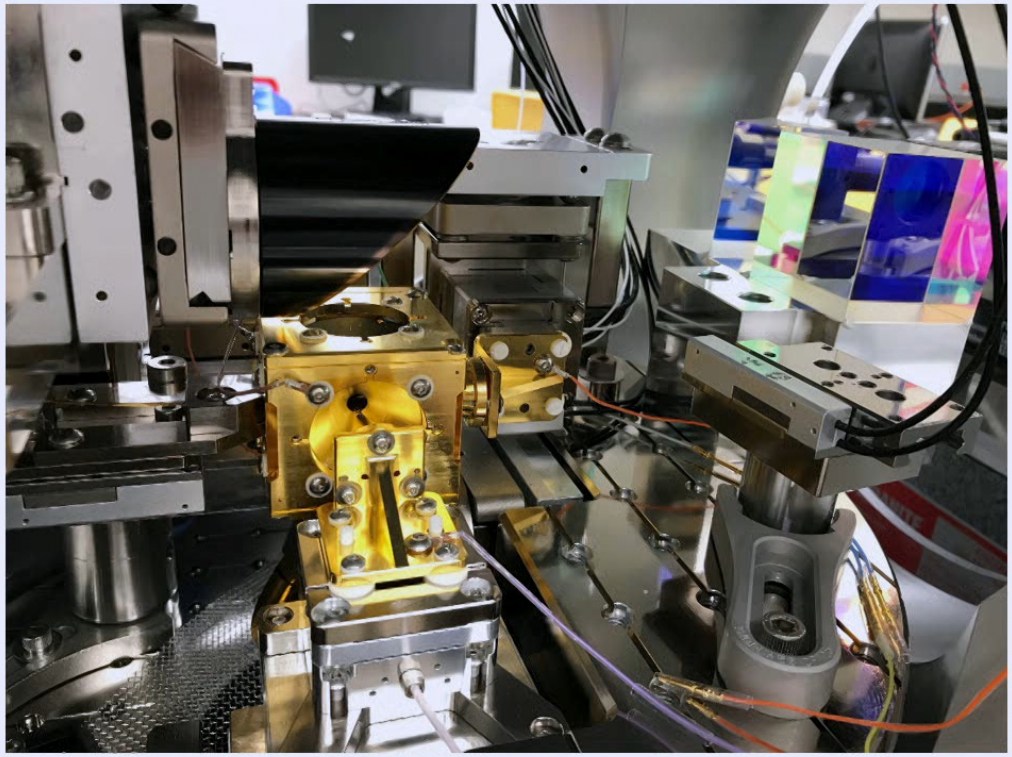
Image credit: Delia Gratta

Giorgio Gratta
Physics Dept, Stanford



Plan

- Measuring gravity at short distance, new physics opportunities
- The physics of optically levitated dielectric microspheres
- (non-gravity) results in particle physics
- New technical developments
- First gravity measurement in the 1 - 50μm range
- A new technique to measure and reject "all" EM backgrounds!



The goal is to convince you that we are developing a truly wonderful new technique with many exciting applications, not just in the area of short distance gravity. Indeed, there are now several groups active in levitated optomechanics, worldwide.

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	∞

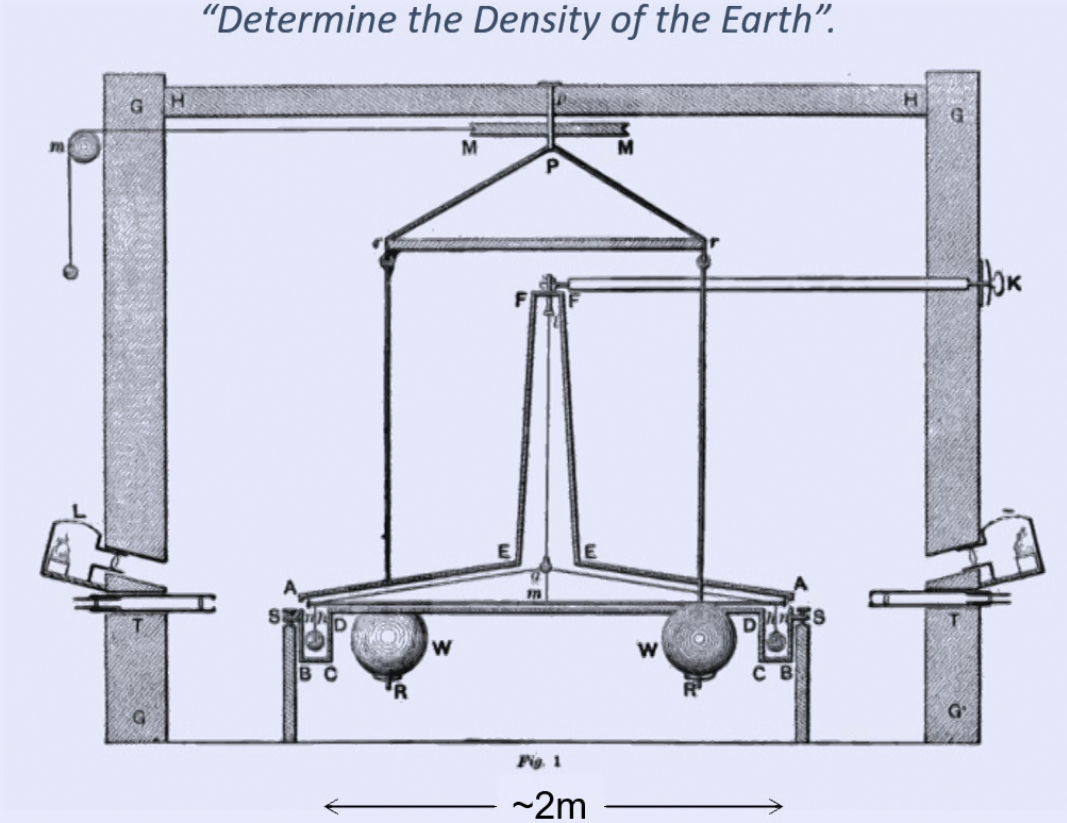
Most of the empirical features of gravity and differences in phenomenology from the other interactions can be understood in terms of the parameters above.

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".

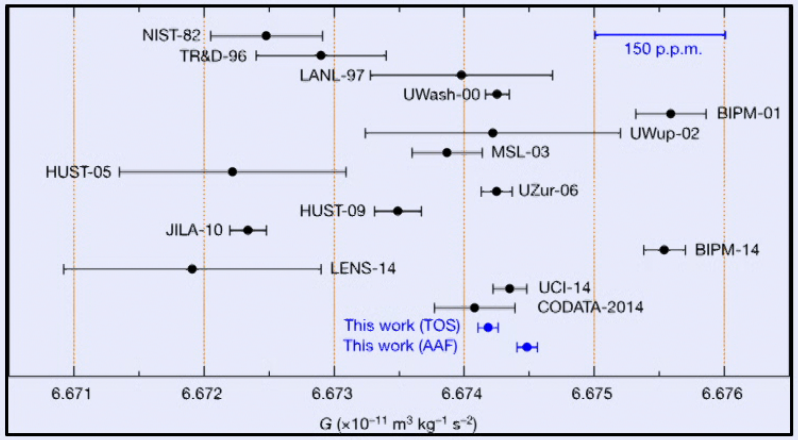


H.Cavendish, Phil. Trans. Royal Soc. London (part II) 88, p469-526 (21 Jun 1798, 220 years ago!)

Cavendish's measurement, in terms of G, gives

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

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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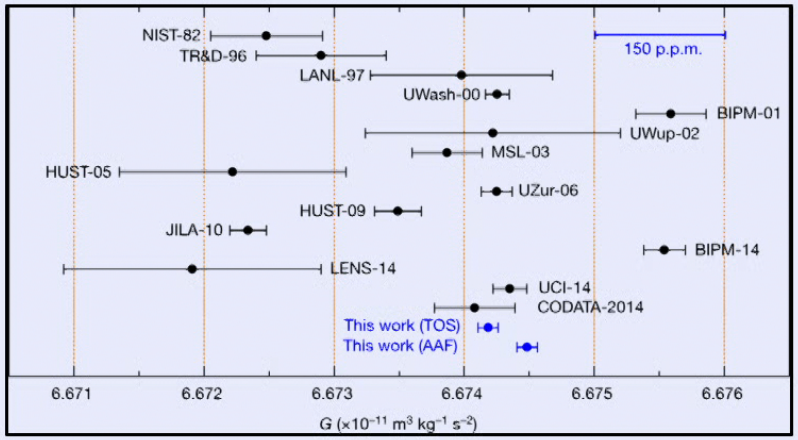

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- the QED coupling constant, α, to 0.23ppb
- the weak coupling constant, G_F, to 0.5ppm

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 $1/R^2$ 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 $R_P = \sqrt{\frac{G\hbar}{c^3}} = 1.6 \times 10^{-35}\mathrm{m}$**

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

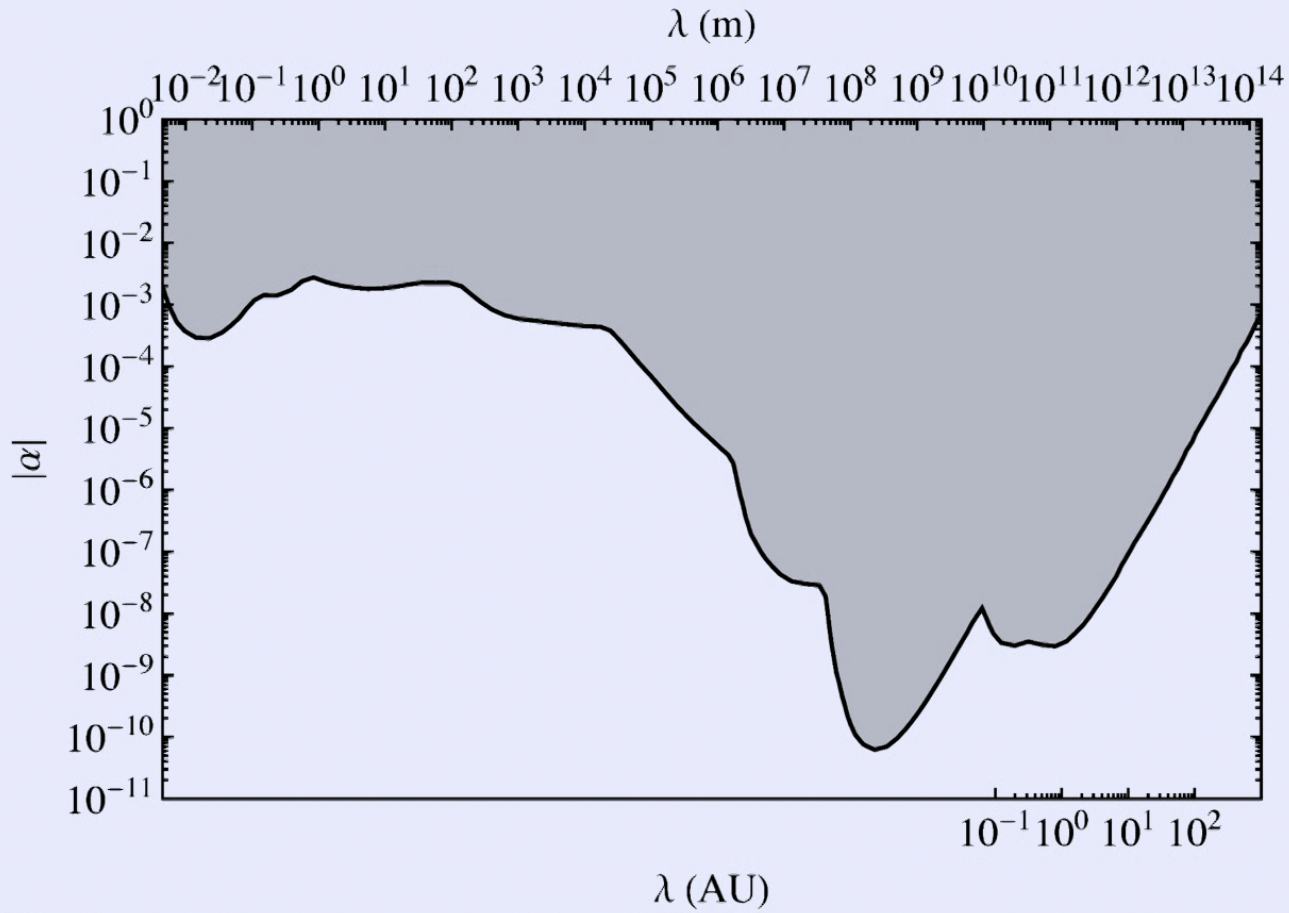
So, how well do we know that the inverse square law applies?

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



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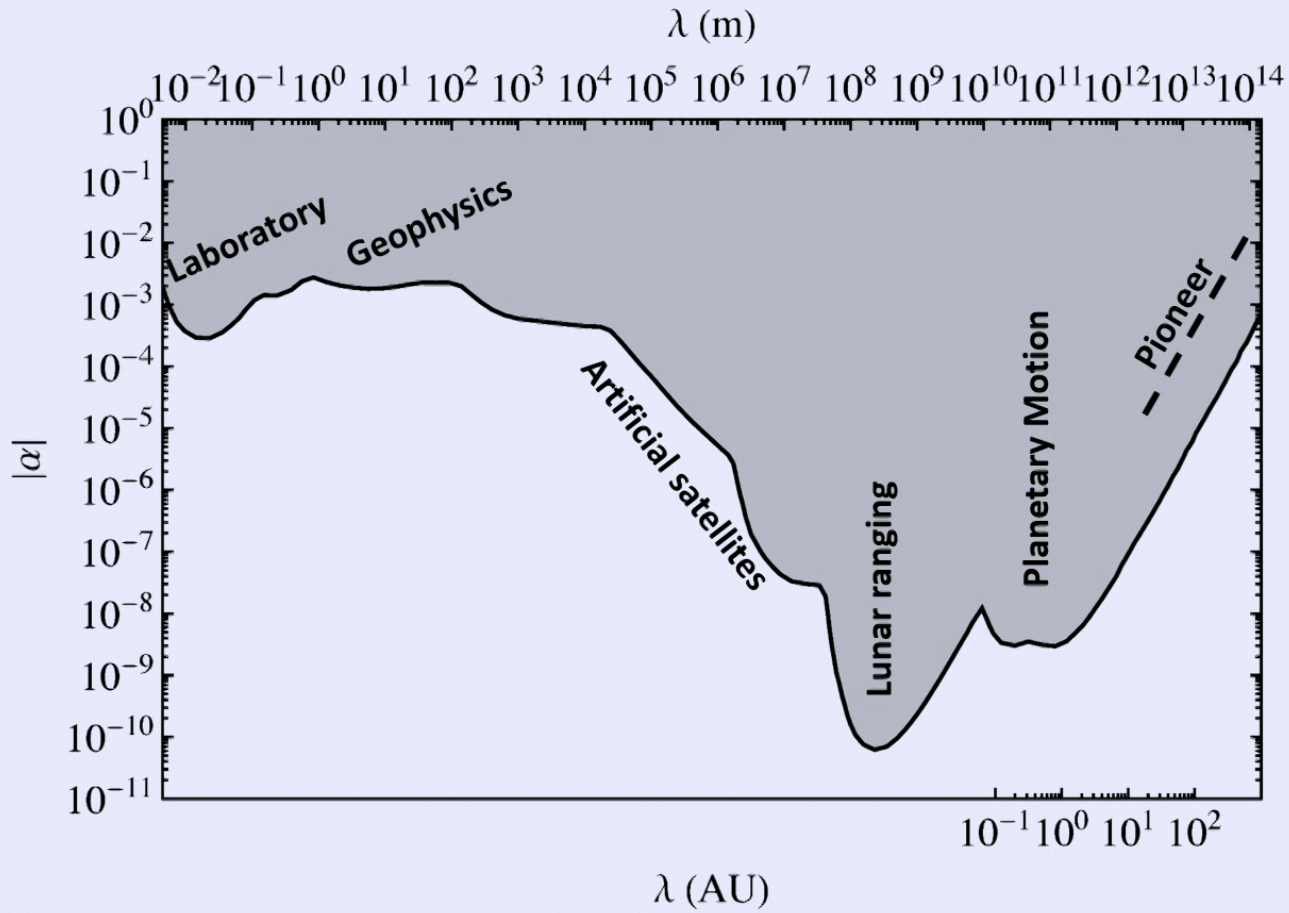


One can take the point of view that exploring the law of gravity at any distance is such an important endeavor that should be carried out irrespective of theoretical prejudice.

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.

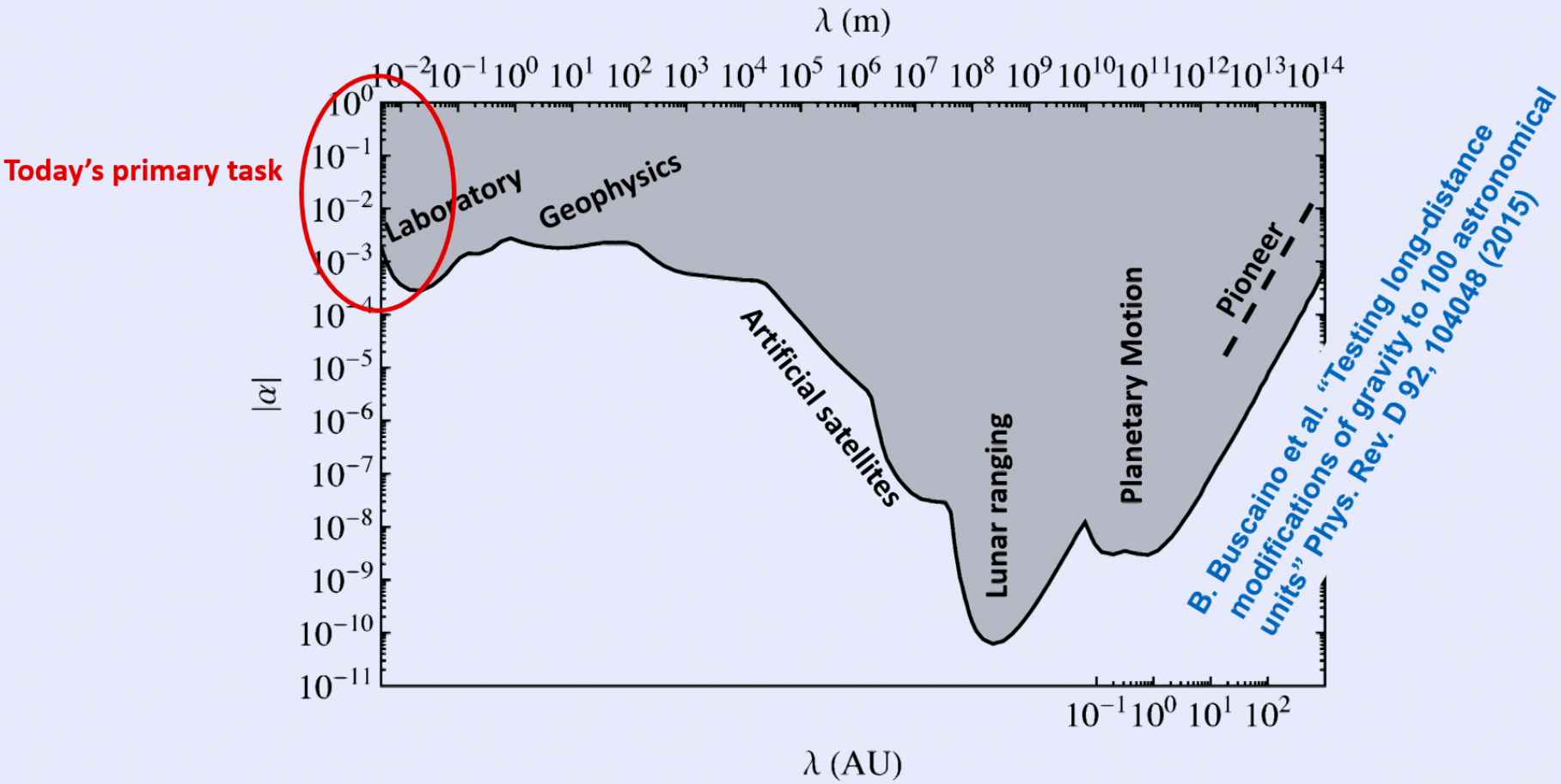
➔ After all, it is quite arrogant to assume that gravity behaves as we know it, all the way down to the Planck scale!

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.

What do we empirically know



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As an example, several authors have suggested that the dimensionality of the physical universe may be 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.

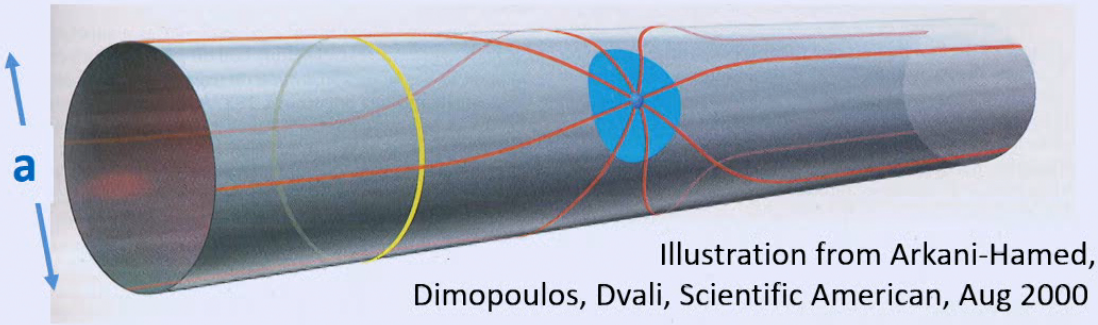


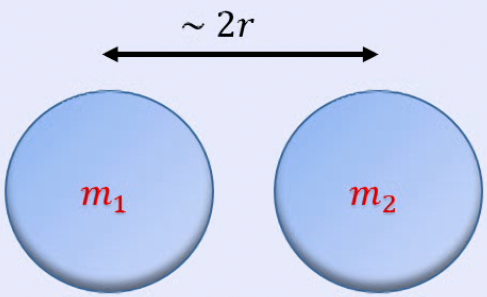
Illustration from Arkani-Hamed, Dimopoulos, Dvali, Scientific American, Aug 2000

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 forces related to intrinsic properties of matter (e.g. baryon number) may appear as modifications to Newtonian gravity.

Experimental challenges

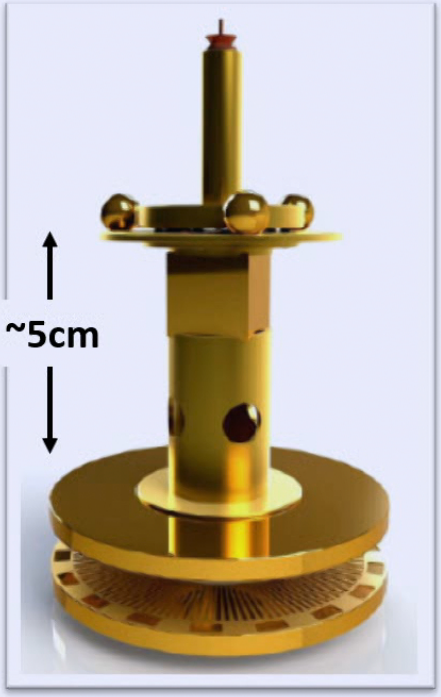
- Since $F = G\frac{M_1 M_1}{R^2} = G\frac{\rho_1 V_1 \rho_2 V_2}{R^2}$
  for atomic materials (we can't use Neutron Stars!)
  $\rho_1 \sim \rho_2 < 20$ g/cm³, there is no silver bullet.
  In addition, the volume $V \sim R^3$, so $F \sim G\frac{\rho^2 R^6}{R^2}$
  and it is clear that measurements at 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 the measurements.

- Experiments should have discovery potential, in addition to the ability of setting limits. This may naturally evolve after an early indication, but more techniques to obtain robust results from the get-go and/or cross check results are required.

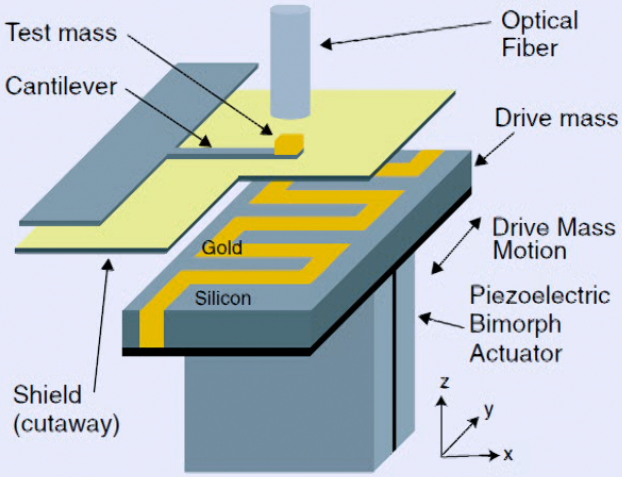


Sketch of the EotWash apparatus from the University of Washington in Seattle
Phys. Rev. Lett. 124, 101101 (2020)

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

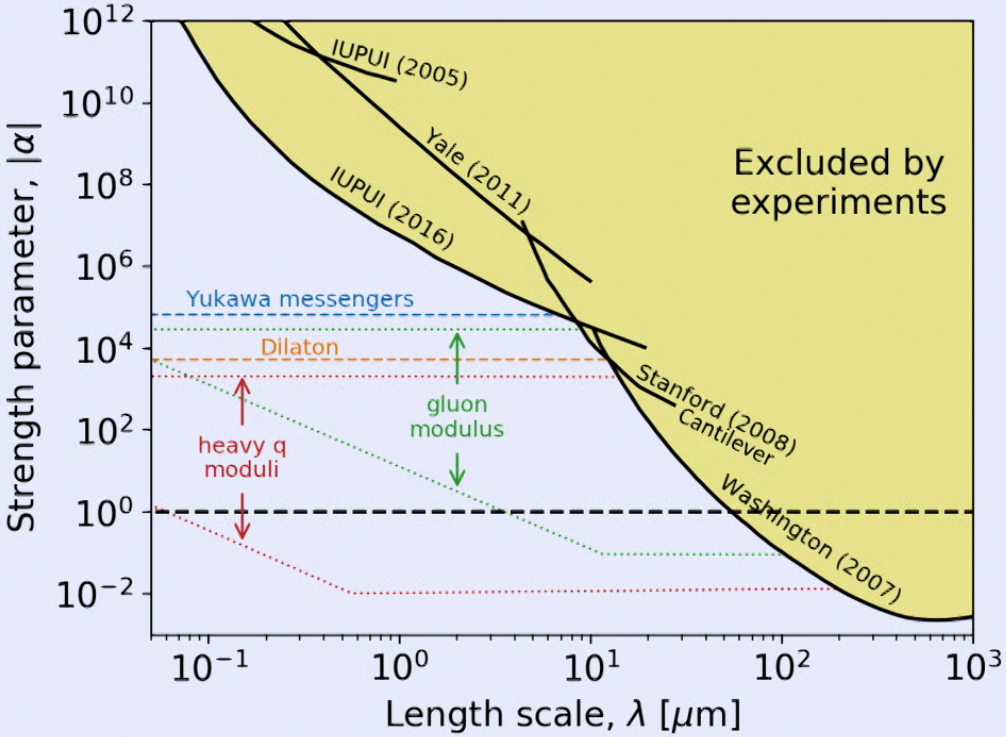
As distances become shorter, this approach becomes clumsy and substantial efforts have to do with "artificial" issues (e.g. how to machine a 5 cm diameter disk flat to μm level…).

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

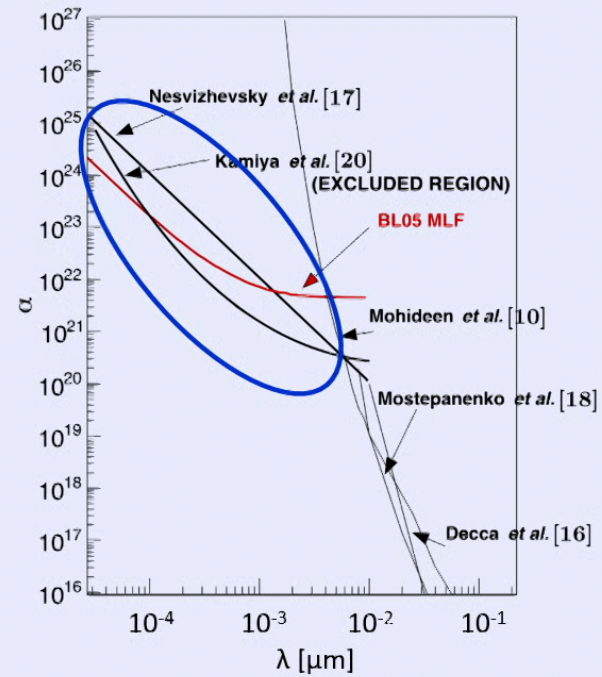


Sketch of the custom cryogenic AFM apparatus from Kapitulnik's group at Stanford
J.Chiaverini *et al.*, PRL 90 (2003) 151101

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). For the same reasons the manipulation of neutrons is hard and results are only interesting at ultra short distance (where there no other option)



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

Given the small strength of gravity we need to measure really small forces

Some orders of magnitude of more or less familiar forces (weighs)

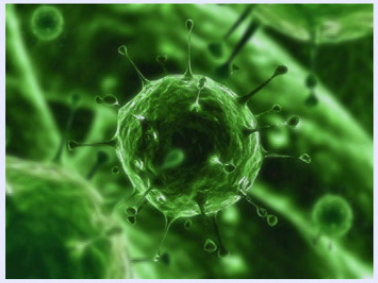
A bathroom scale resolves ~1 *N*

100 kg ~ 1kN

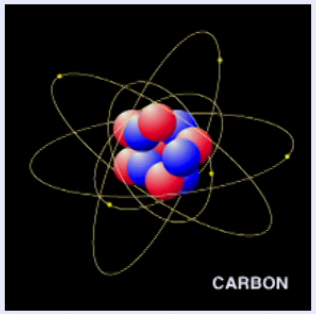
A dust mite 10^{-7} N

E. coli 10^{-14} N

Virus 10^{-19} N



Carbon atom 10^{-25} N



Conventional AFM measures 10^{-12} N

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

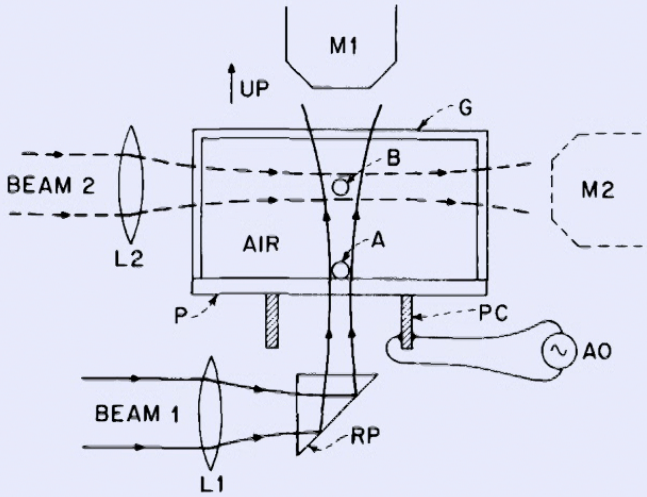
A “new and old” technique to explore the short distance behavior

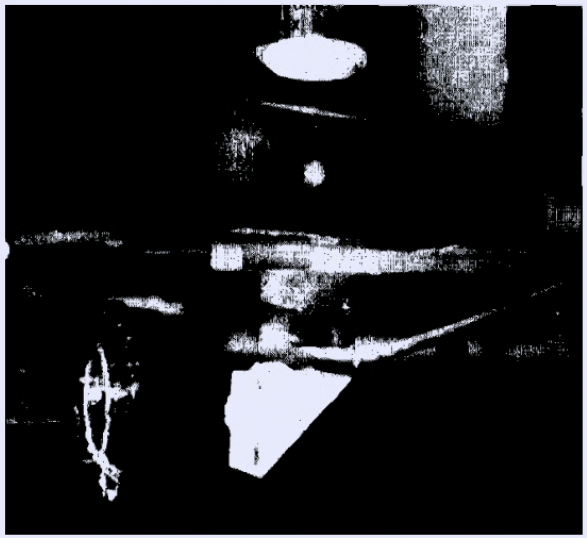
APPLIED PHYSICS LETTERS VOLUME 19, NUMBER 8 15 OCTOBER 1971

Optical Levitation by Radiation Pressure

A. Ashkin and J. M. Dziedzic
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 14 June 1971; in final form 13 August 1971)

The stable levitation of small transparent glass spheres by the forces of radiation pressure has been demonstrated experimentally in air and vacuum down to pressures ~1 Torr. A single vertically directed focused TEM_{00}-mode cw laser beam of ~250 mW is sufficient to support stably a ~20-μ glass sphere. The restoring forces acting on a particle trapped in an optical potential well were probed optically by a second laser beam. At low pressures, effects arising from residual radiometric forces were seen. Possible applications are mentioned.

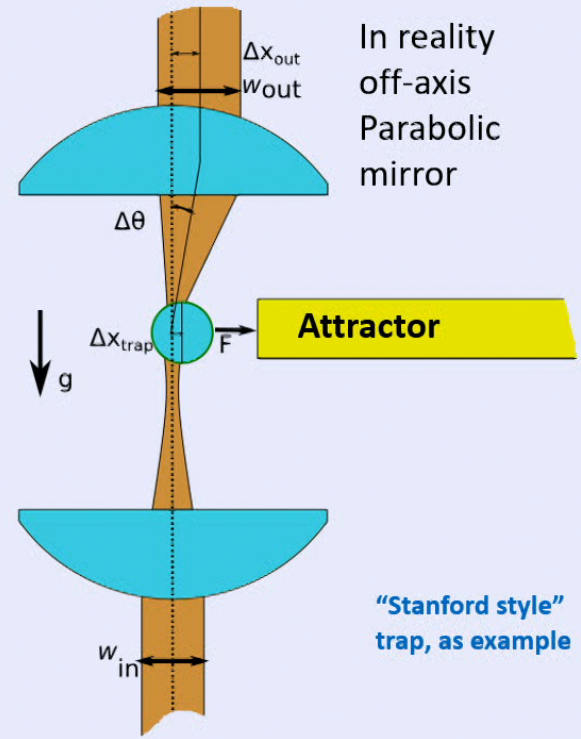


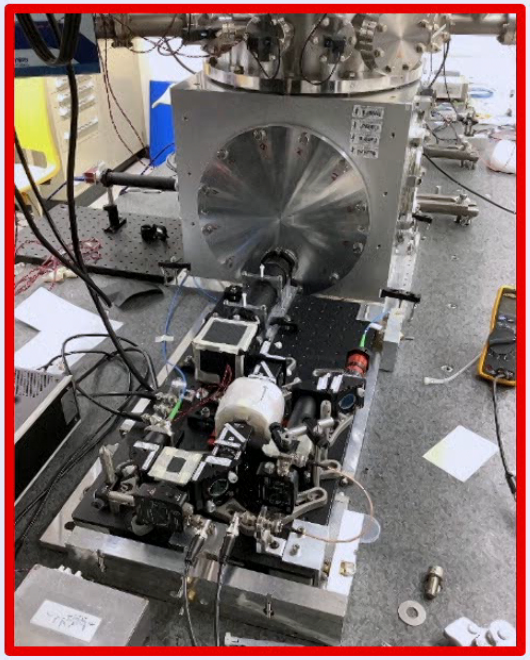


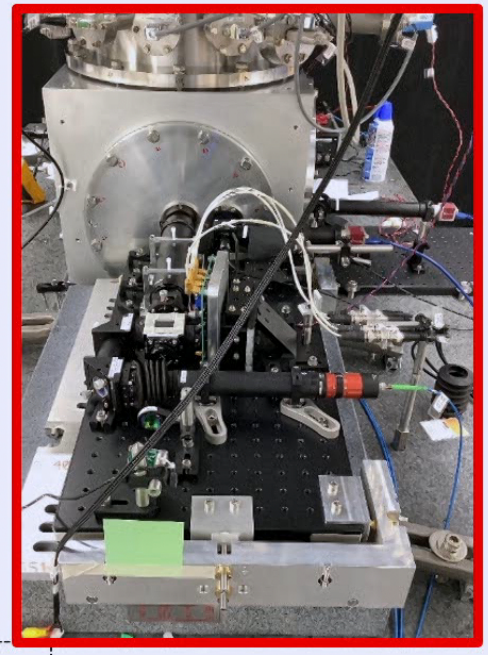
In the last 50 years, the technique has matured, under the name of optical tweezers, primarily in water with applications to biology

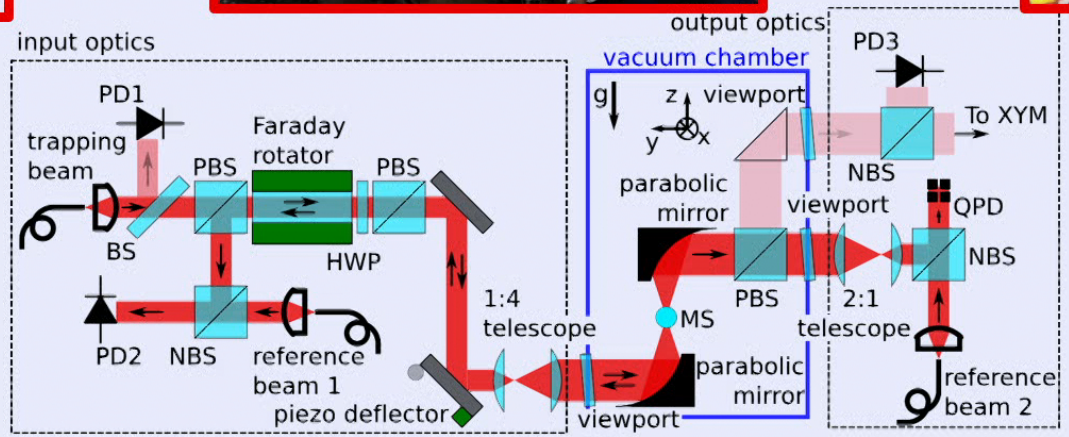
Microspheres optically trapped in vacuum make superb force sensors

- 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 quantum noise limit has been reached (for smaller spheres: U.Delic et al, Science 367 (2020) 892) --this is 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.





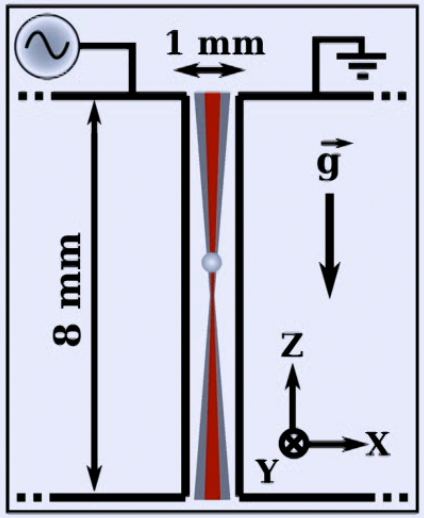




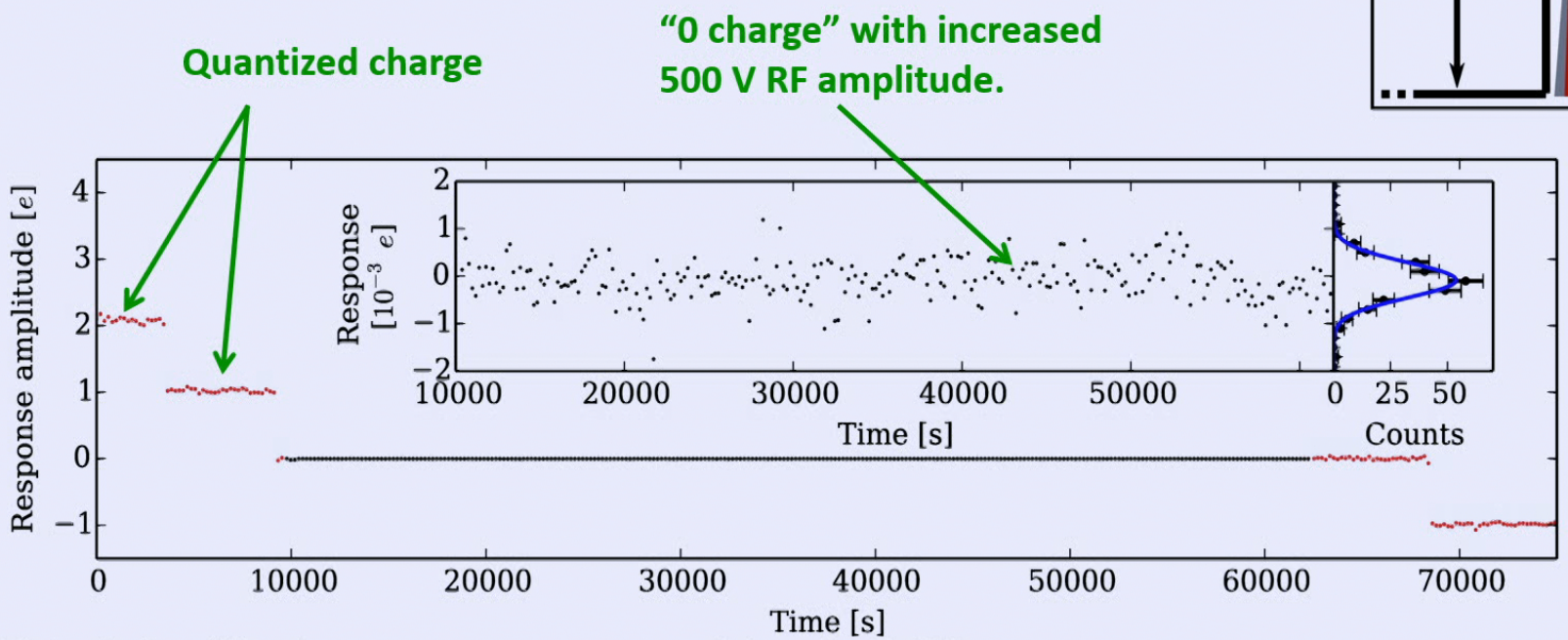
Rev. Sci. Instrum. 91, 083201 (2020)

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

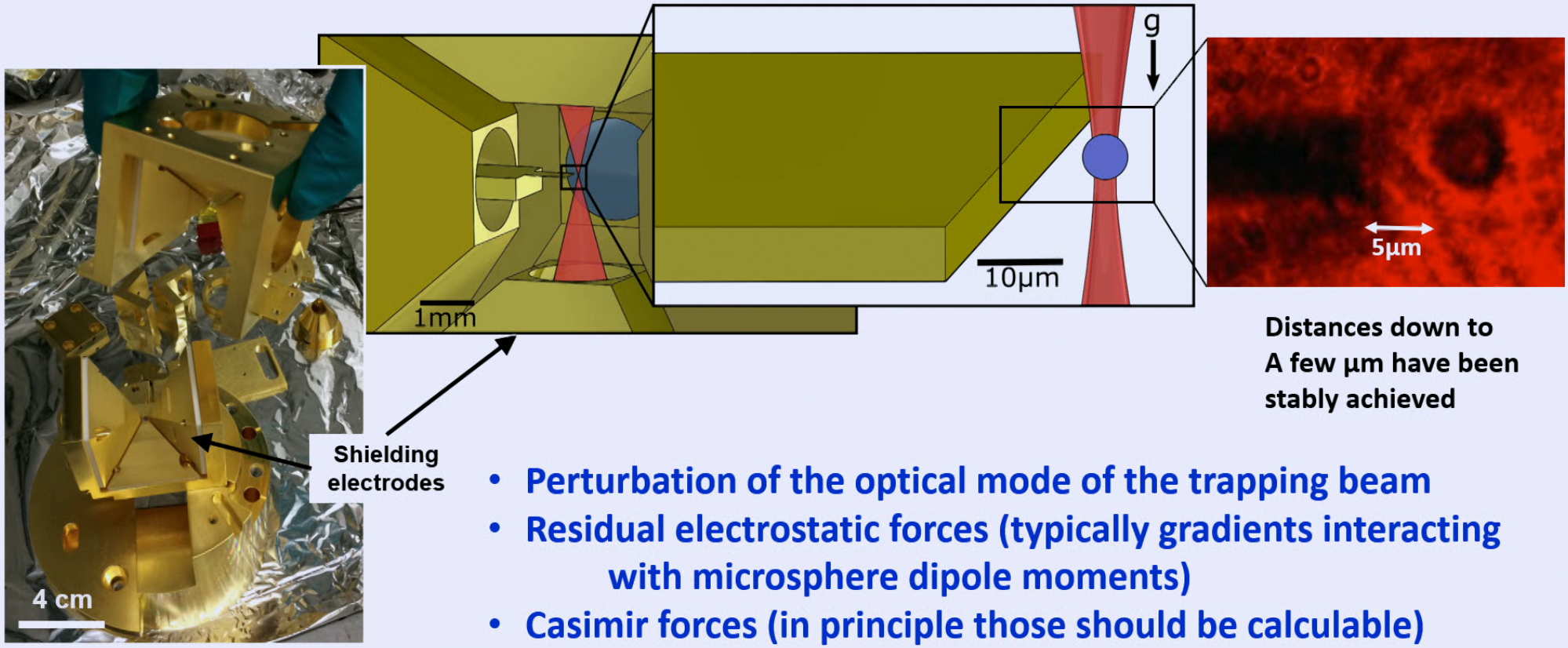
➔ ***Their charge state can be changed at leisure (in both directions), using a UV light source***



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



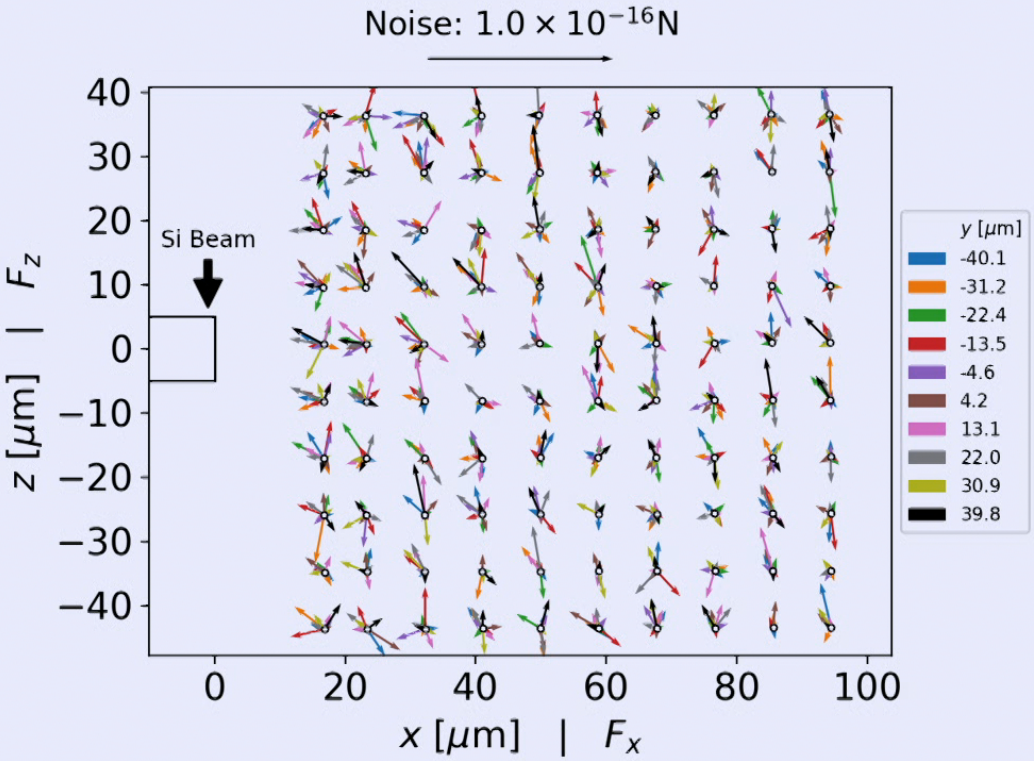
There are specific challenges in moving objects very close to the microsphere

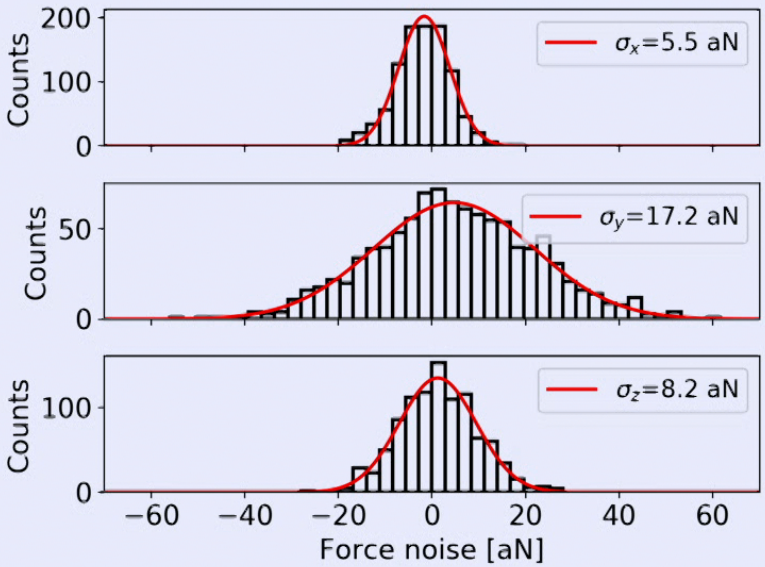


Distances down to A few µm have been stably achieved

- Perturbation of the optical mode of the trapping beam
- Residual electrostatic forces (typically gradients interacting with microsphere dipole moments)
- Casimir forces (in principle those should be calculable)

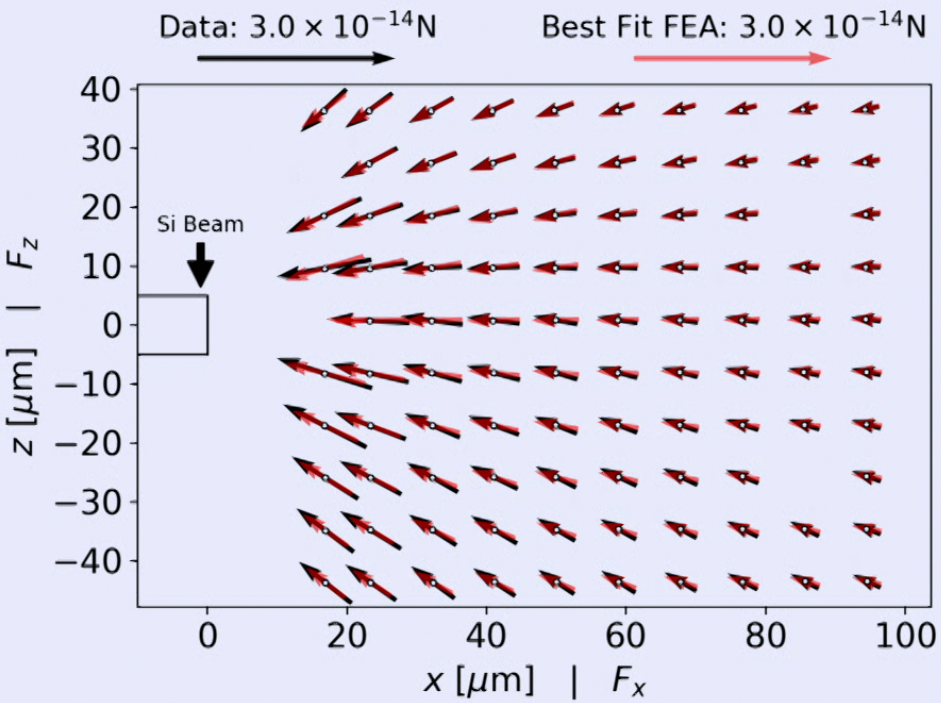
For a static attractor, the noise on the measurement is unaffected (and very small) -- even for a charged microsphere (~500e$^-$)

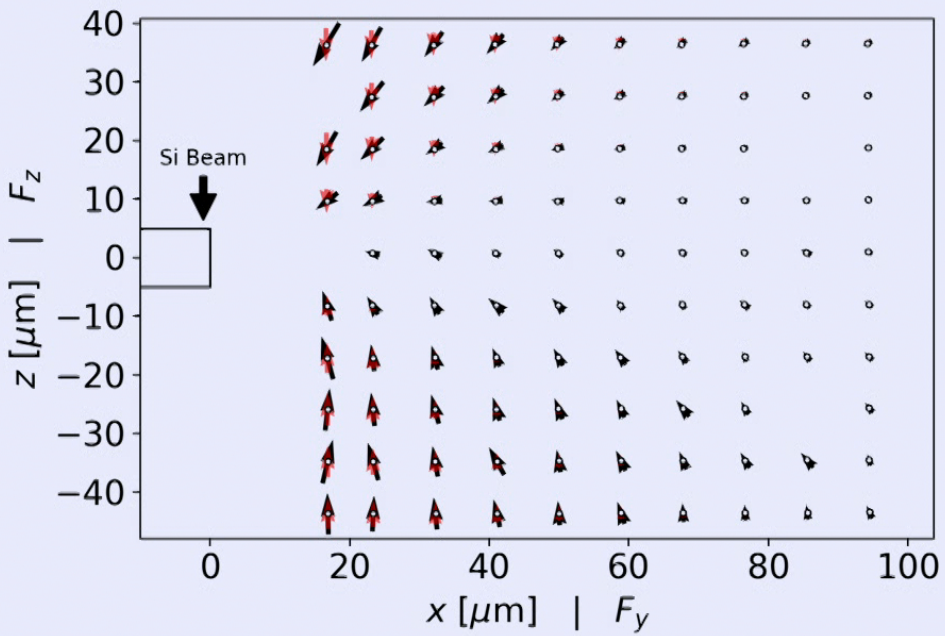




Closest approach for the plot is 15µm; substantially smaller distances are possible now.

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

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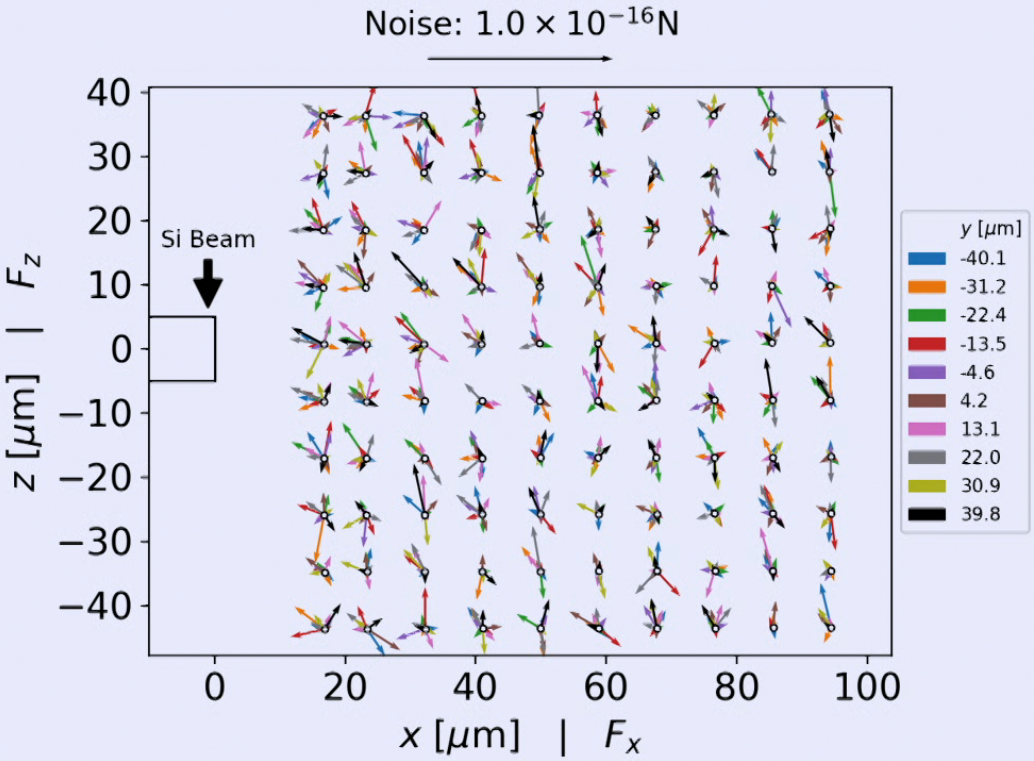

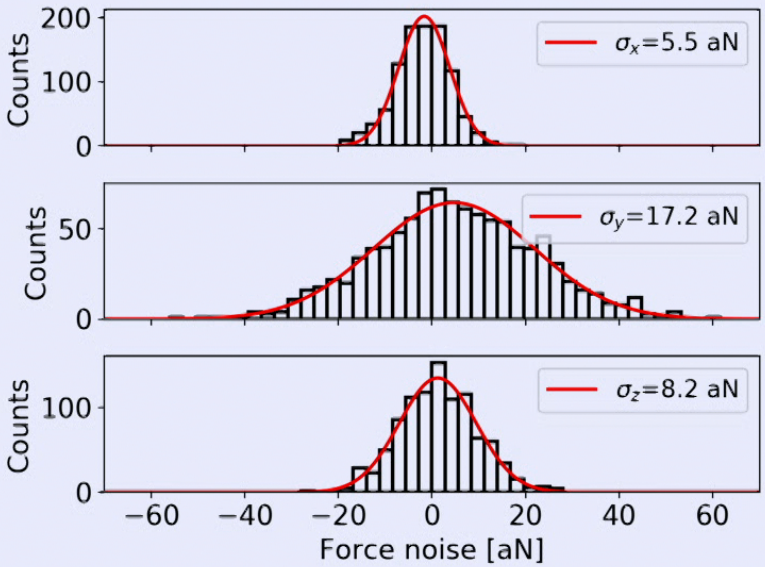

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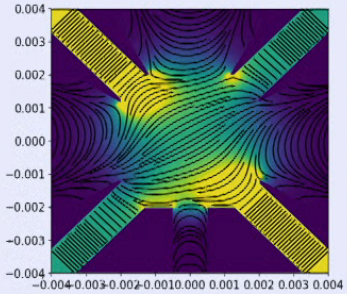
Spinning trapped microspheres

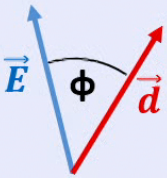
It has been demonstrated by others that birefringent microspheres can be spun up by applying a torque from a circularly polarized light beam. *e.g. Y. Arita et al., Anal. Chem. 83 (2011) 8855*
F. Monteiro et al., Phys. Rev. A 97 (2018) 051802

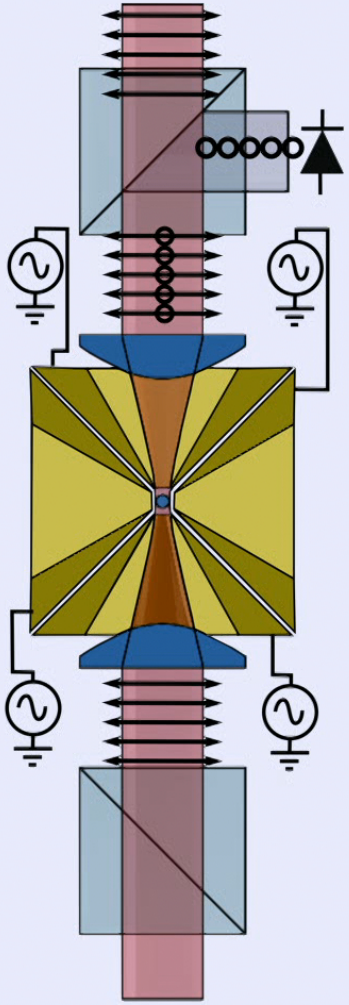
This technique can reach extremely high angular velocities (at the point of making the microspheres explode).



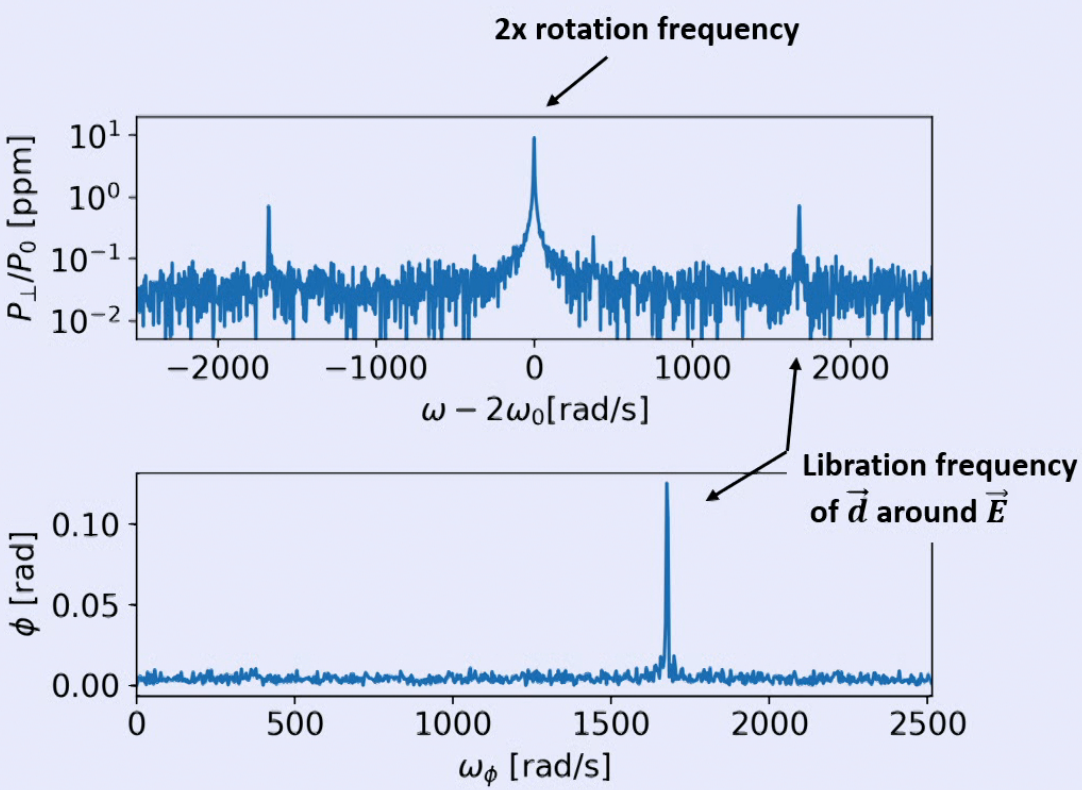
If the microsphere has an electric dipole moment, then a torque can be applied by a rotating external electric field.
We apply this through the 4 electrodes in the horizontal plane.

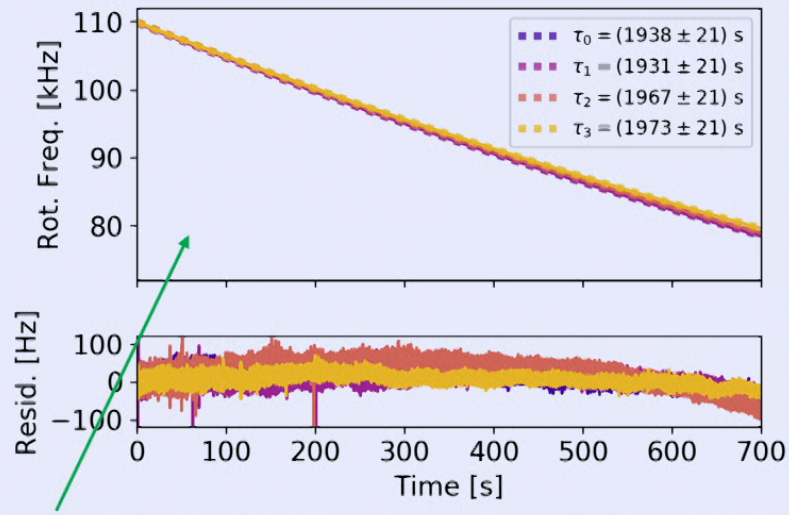
A.Rider et al. Phys Rev A 99 (2019) 041802(R)





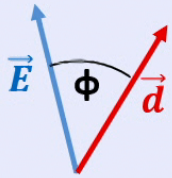
The rotation is read out using the small residual birefringence that the silica microspheres apparently have.





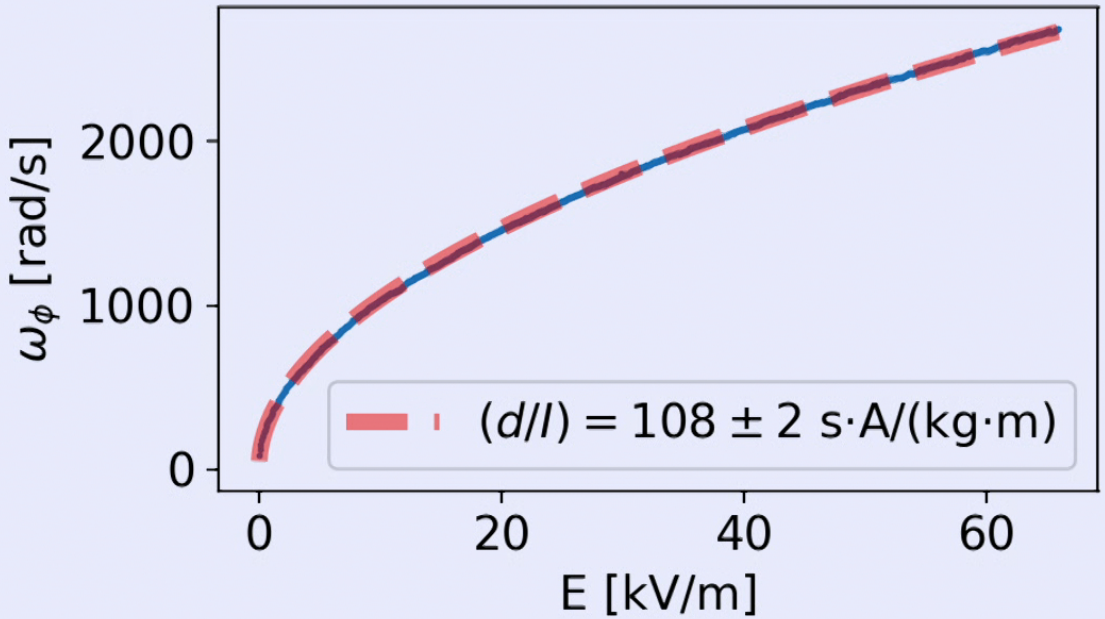
Stopping the driving field makes the microsphere gradually spin-down, with the expected exponential law. The time constant can be translated* into the pressure, like in a rotating ball vacuum gauge.

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



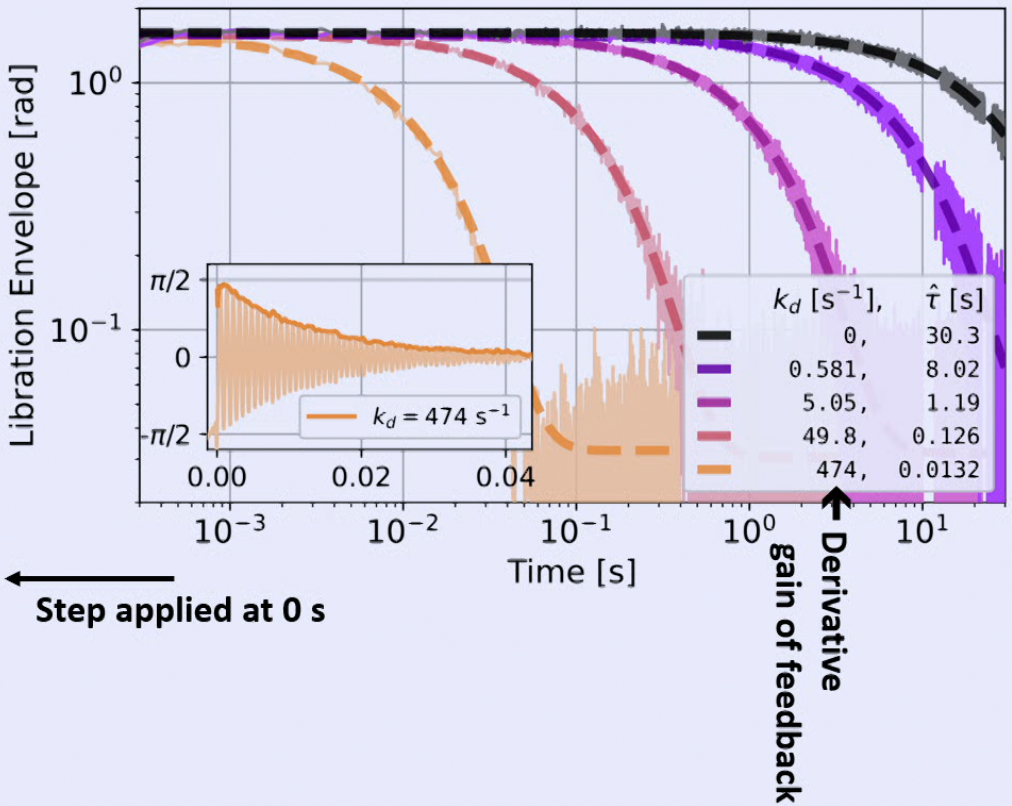
The libration frequency can be written as $\omega_\phi \cong \sqrt{cos\phi_{eq}\frac{Ed}{I}}$

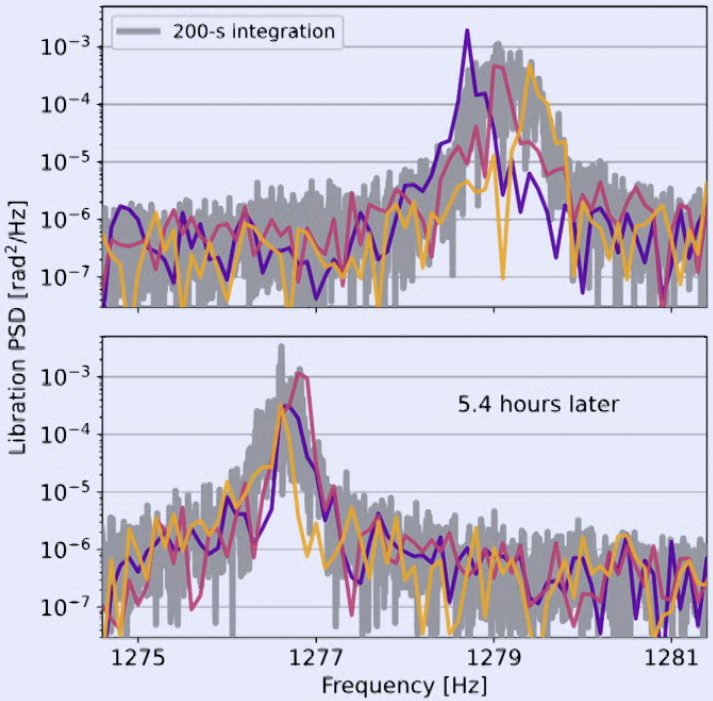
and d/I can be extracted from a fit to the data



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

First successful feedback cooling of the librational degree of freedom





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

But, the value of the d/I changes in time.
(d=electric dipole moment, I=moment of inertia)
presumably this is because charges redistribute in/on the microsphere in time.

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).

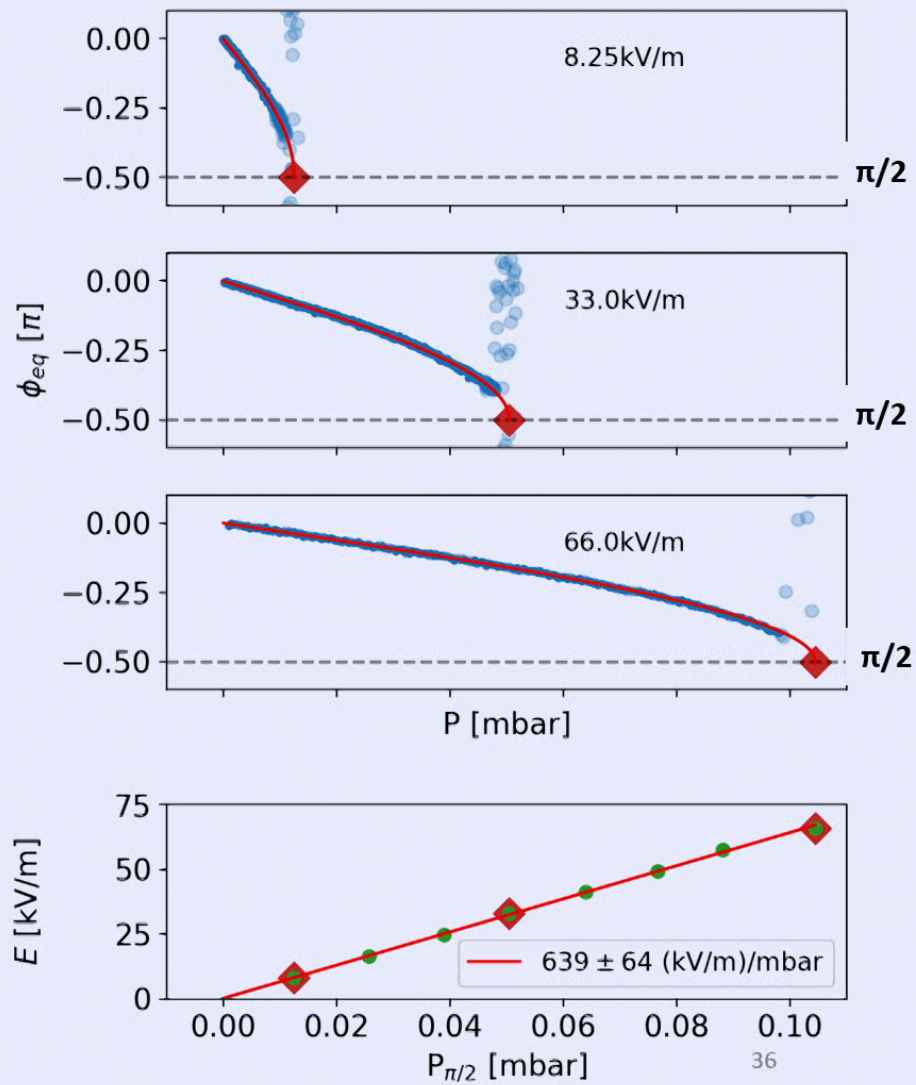
When the phase lag reaches π/2 the microsphere unlocks from the drive signal (phase → random).

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

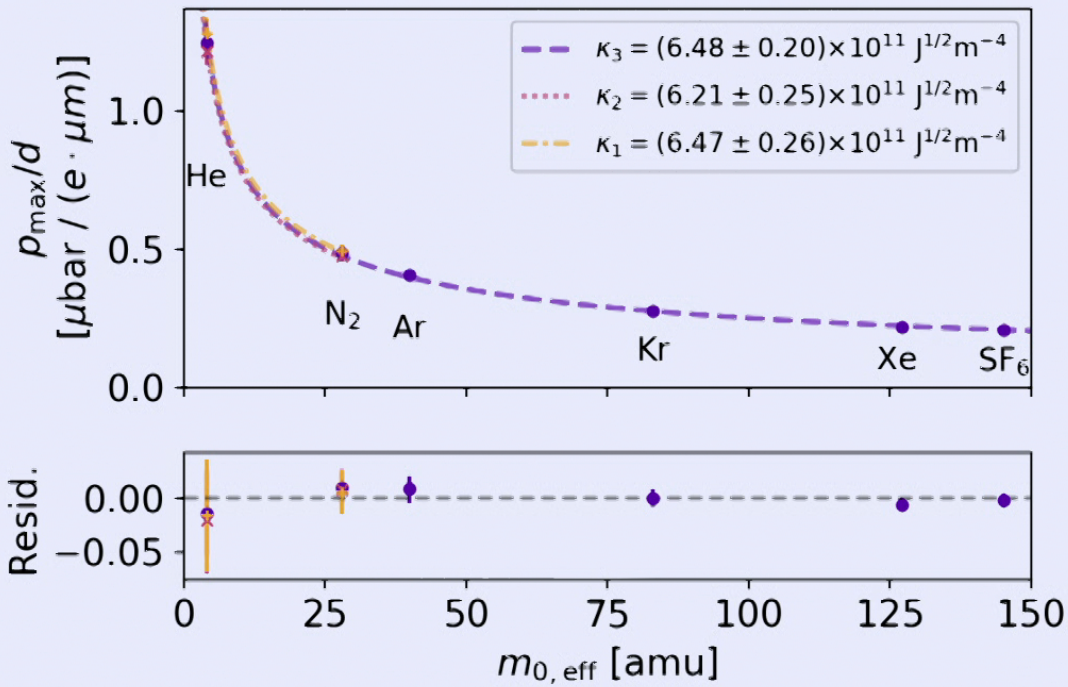
From the fit and *d* measured above, one can extract the pressure at the microsphere.

- **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 unlocking pressure depends on the molecular mass in a known way*



Measurements with a substantial array of masses verify this statement.

This also means that, if the pressure is measured otherwise, the microsphere rotation can be used to detect the gas species.

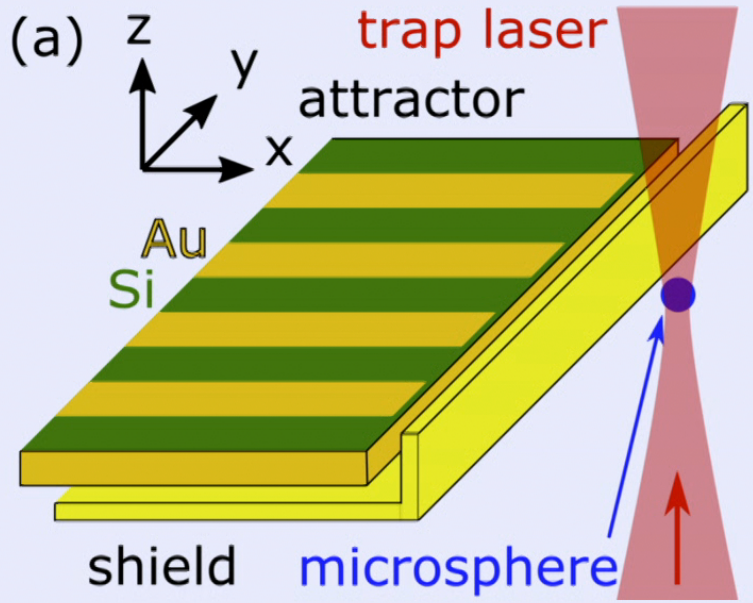
☺ **An RGA without ionization!**
☺ **An RGA at high pressure!**
☹ **Not really an RGA, because one only measures one "effective" mass**

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

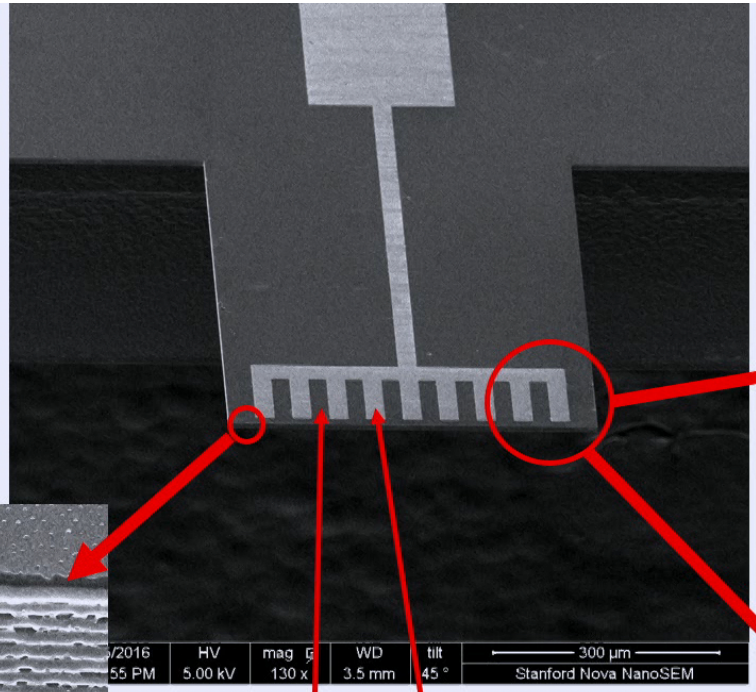
** e.g. A.Cavalleri et al., Phys. Lett. A 374 (2010) 3365*

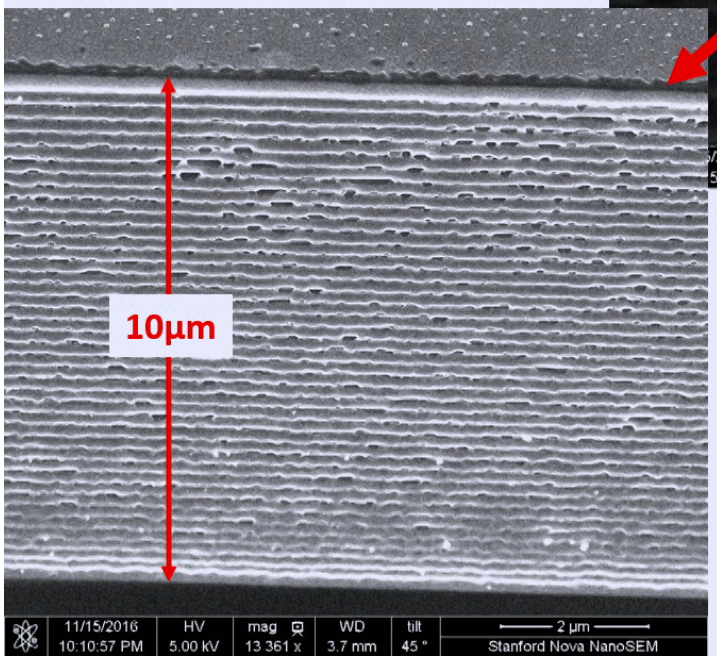
First gravity run

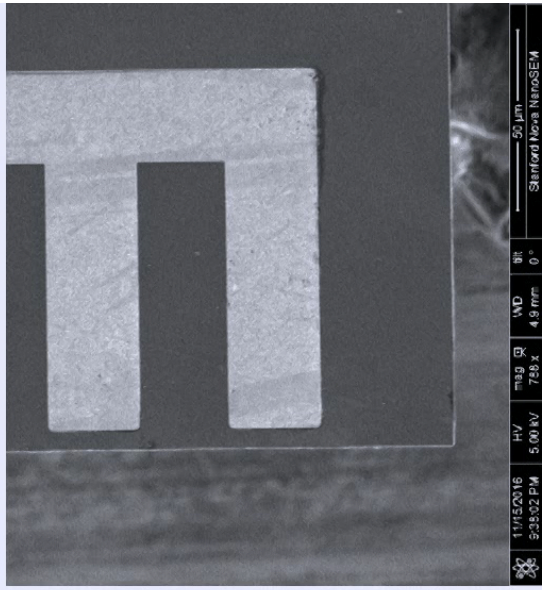
- 10^5 seconds
- 7.6 µm sphere (420 pg)
- 200 µm attractor stroke
- Using only Z channel
- Separation:
  - 13.9 um in X
  - 15.8 um in Z
- Background mitigation using
  - Shield
  - Drive attractor along density modulation at f_0(3Hz), and observe correlated force at f_0, $2f_0$, $3f_0$, $4f_0$, …

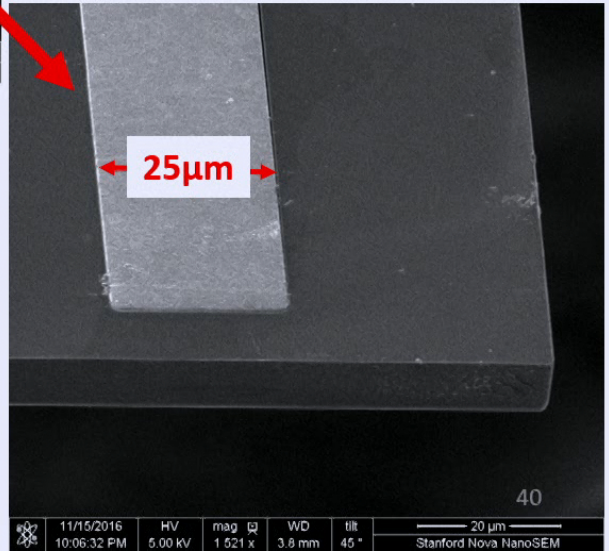


First generation attractor set, here shown before Au coating





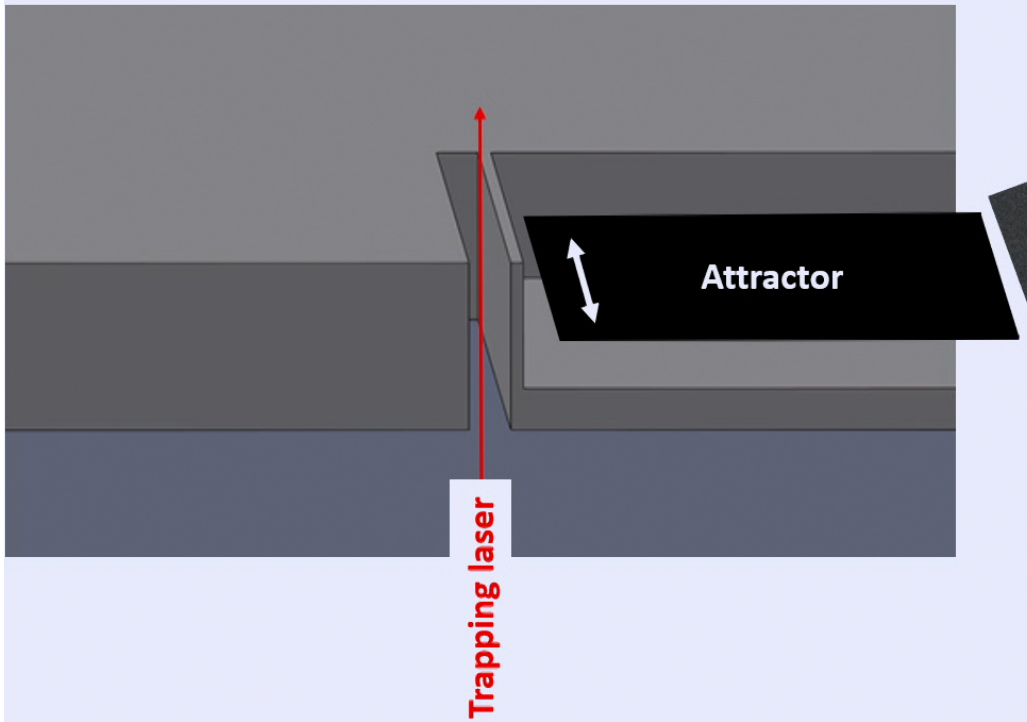


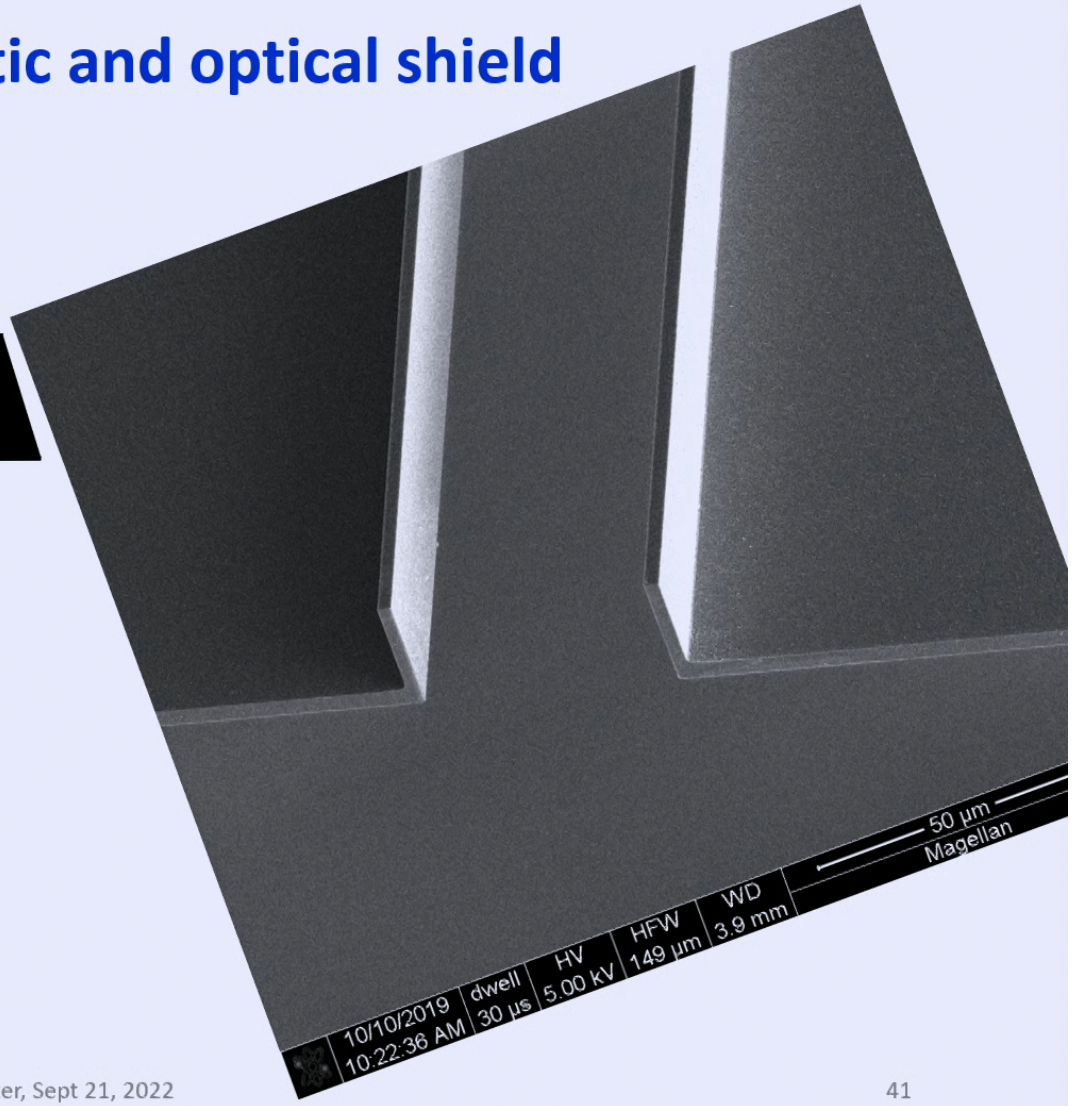


Si

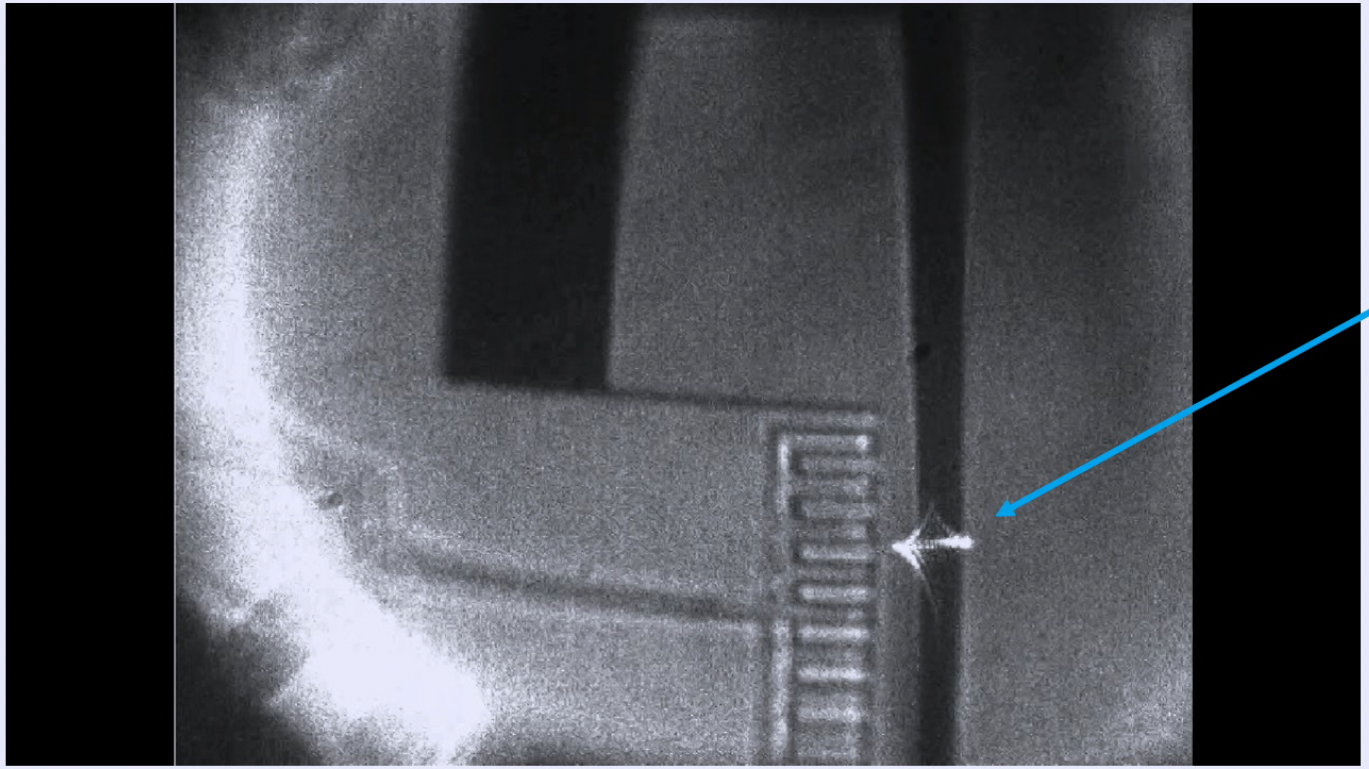
Au

Standing electrostatic and optical shield





Example of scanning



Trap with microsphere

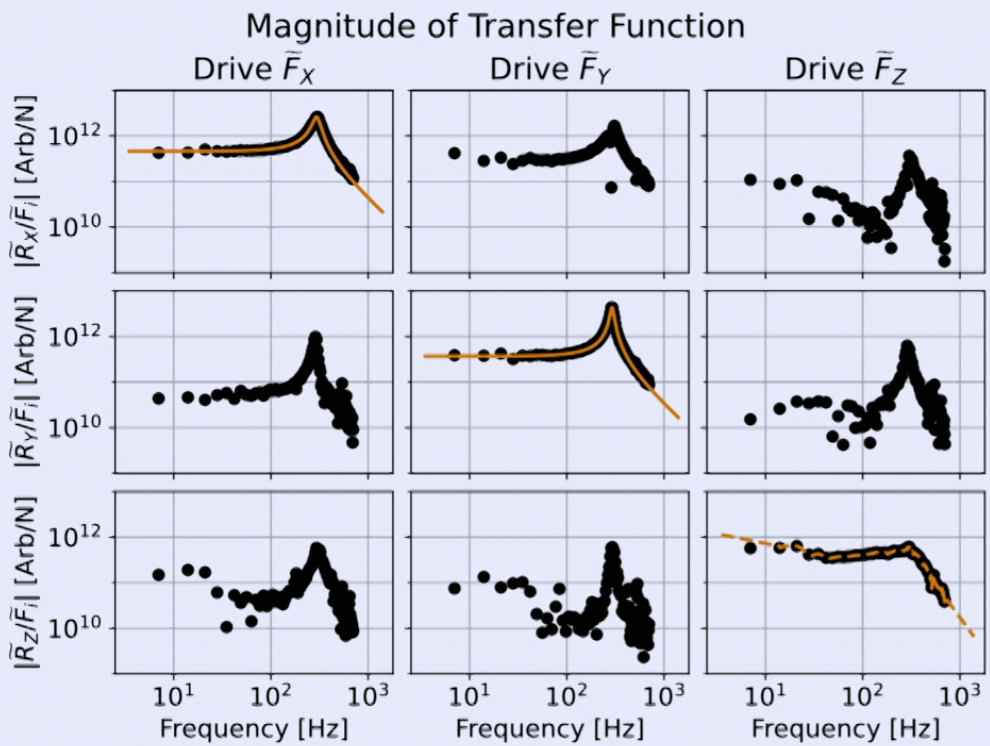
Top view

$\vec{g}\odot$

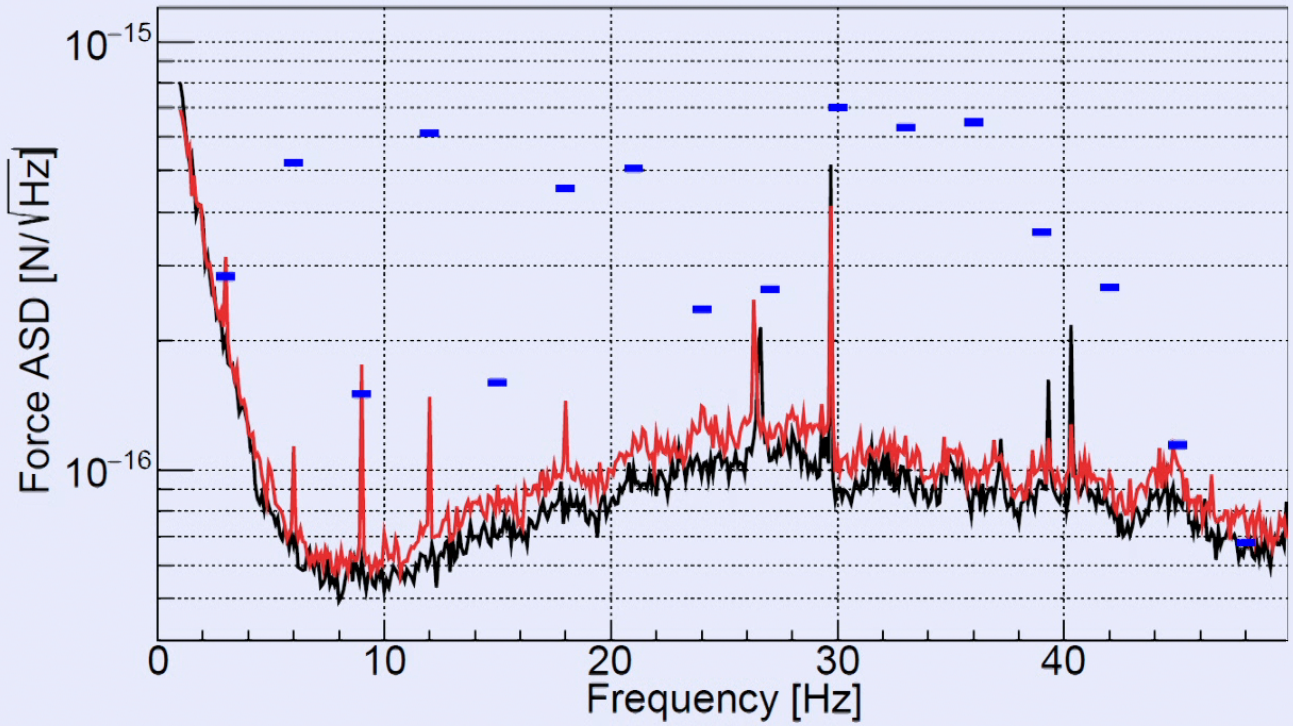
Actual frequency: 13 Hz
For this test, distance attractor – microsphere center: 85 um

Force calibration

- Sphere is prepared with a know charge state.
- Apply electric field in the form of frequency comb.
- Extract the amplitude and phase for each frequency.
- Cross talk measured.
- Discharge sphere down to zero again and take gravity data.



First gravity run



Force sensitivity: 10^{-16} N/$\sqrt{Hz}$

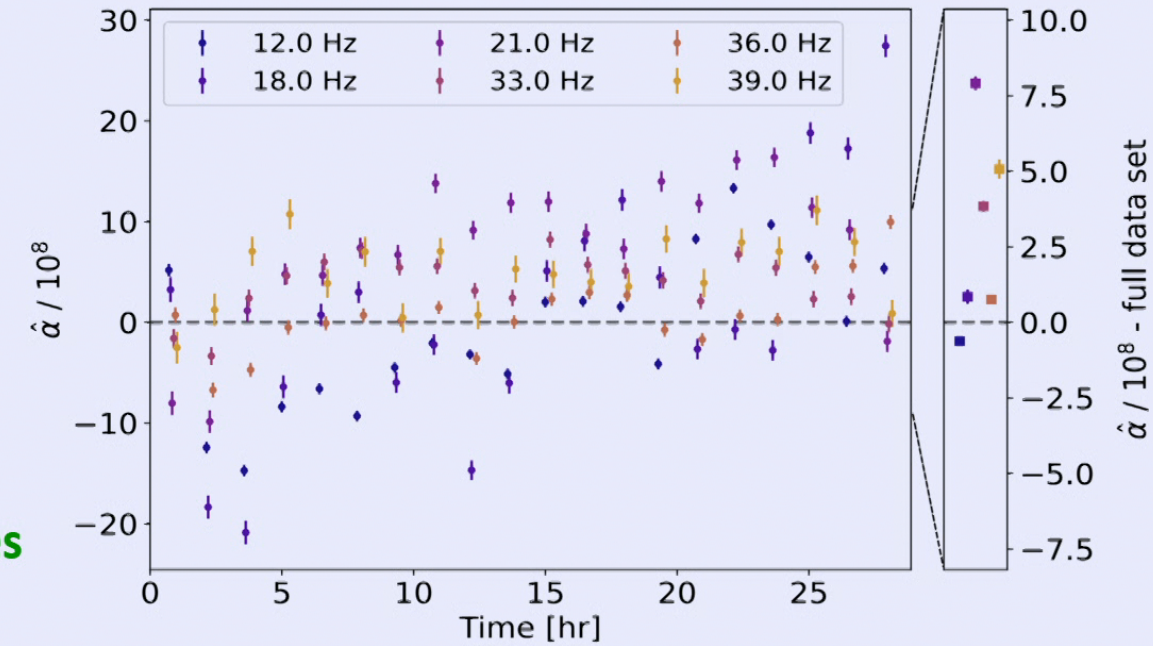
- **Black - response with stationary attractor**
- **Red – response with moving attractor**
- **Blue – expected response for $\alpha = 10^{10}$ and $\lambda = 10\mu m$**

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**

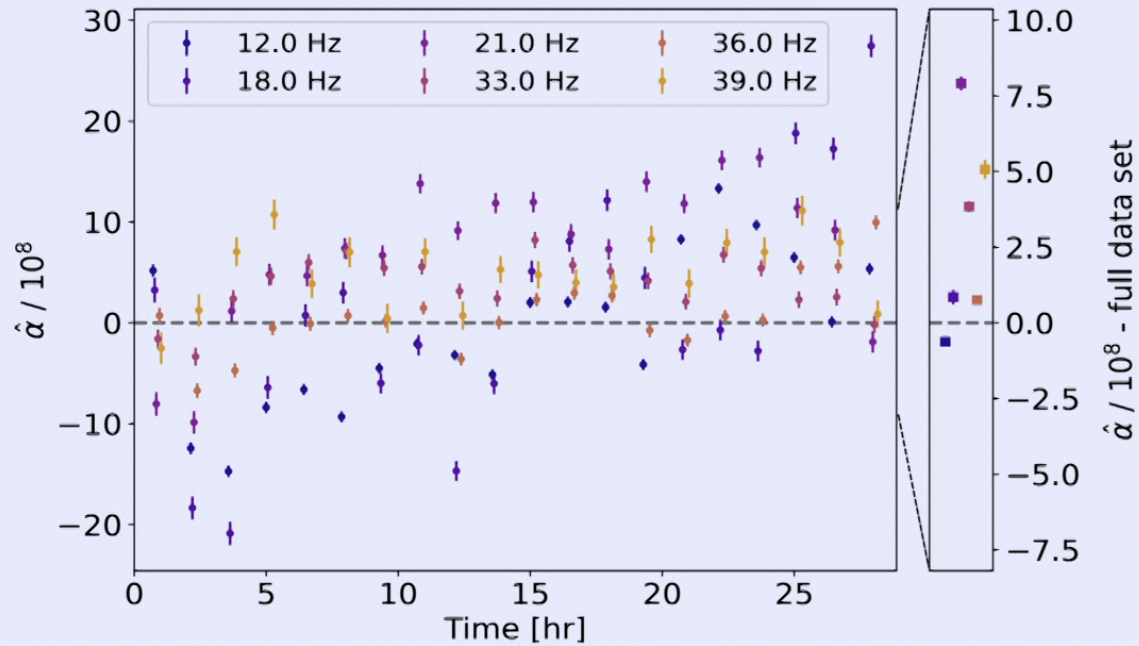
$$\mathcal{L}_i(\alpha,\lambda) = \prod_j \frac{1}{\sqrt{2\pi\sigma_j}} e^{-(F_j-\tau(\alpha,\lambda,\mathbf{x}_j))^2/2\sigma_j^2}$$

- **This can be used to extract MLEs and for statistical inference purposes**



Exhaustive systematic study shows that drifts in the response can not explain the observed data

Effect ϵ	$\Delta\epsilon$	$\Delta\alpha/\alpha$
Drift of amplitude response	10%	10%
Attractor thickness	1 μm	11%
Phase response	~0.1 rad	12%
Distances in Y	<0.2 μm	< 3%
Distances in Z	<0.9 μm	< 6%
Distances in X	1.5 μm	30%
MS weight	15 pg	3.5%

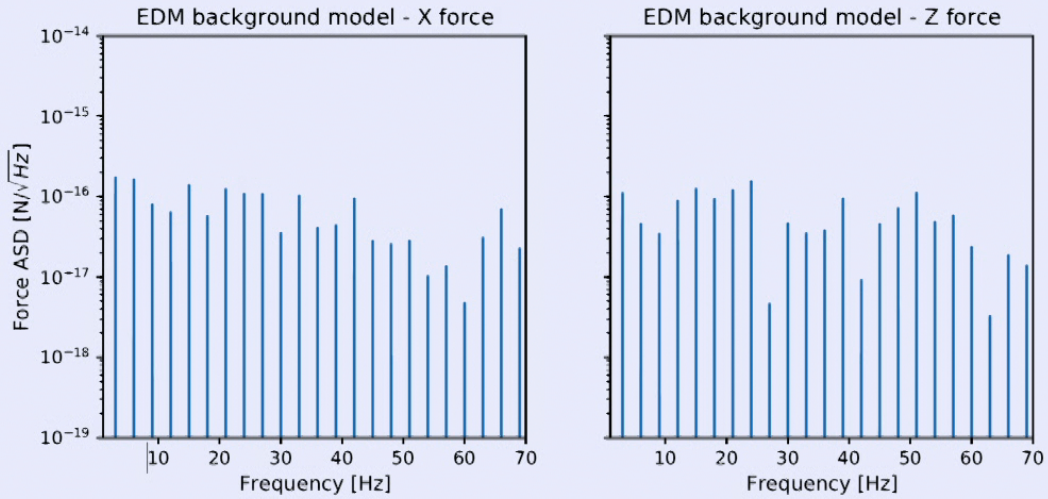


EDM backgrounds

- **Electric field gradients are not fully suppressed by the shield and create backgrounds due to coupling to the dipole moments**

$$\vec{F}=(\vec{d}\cdot\vec{\nabla})\vec{E}$$

- **A background is calculated using a constant EDM of [1000, 0, 0] e µm and a 50 mV contact potential**

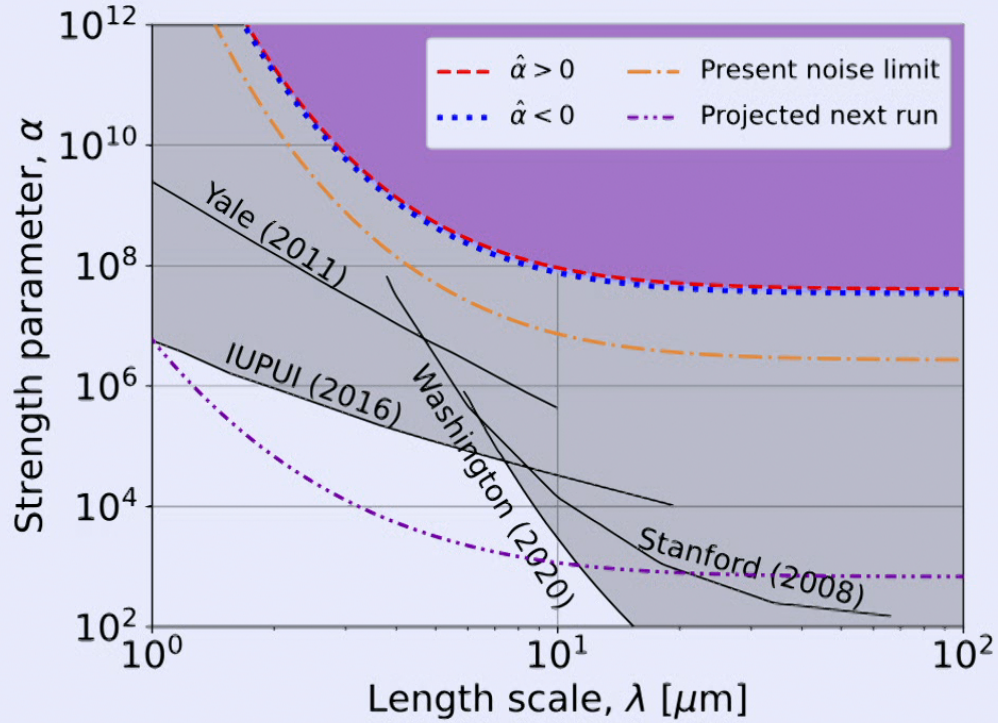


The effect detected fits well to this model and adding contributions for the three components of the EDM produces a fit where α is consistent with zero.

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 and great progress is being made to understand and directly measure this.

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

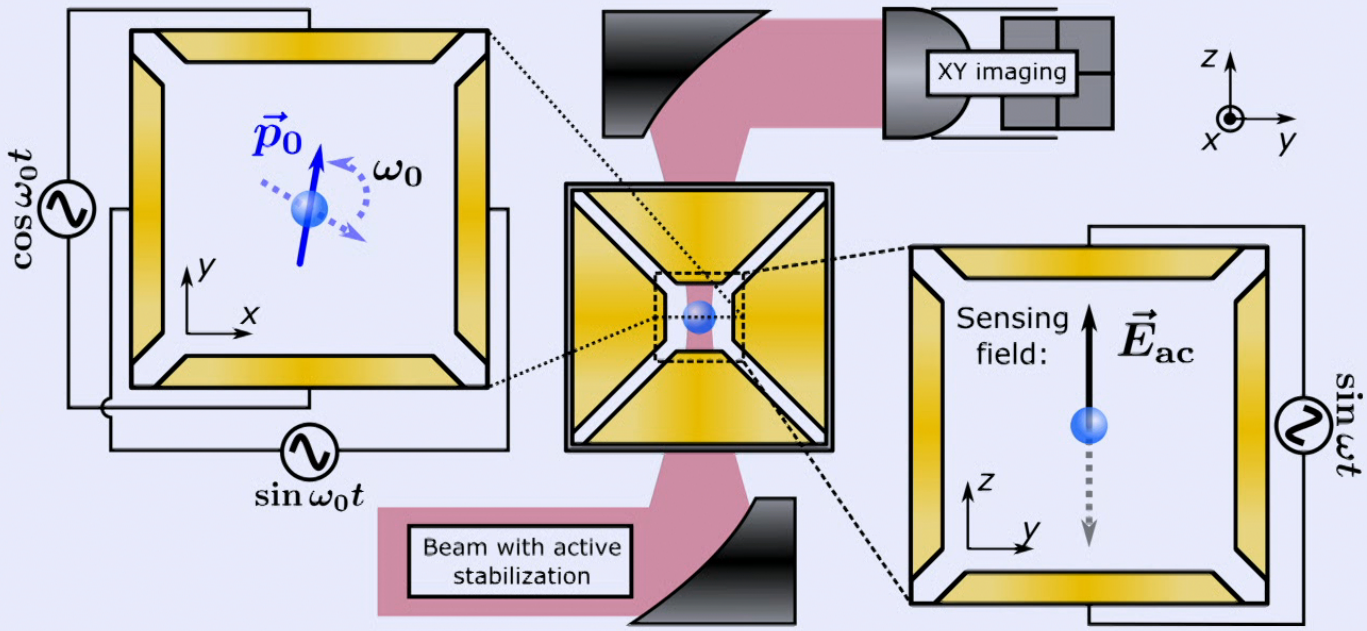


A substantial step forward in the understanding of EM interactions

➔ EM backgrounds limit many areas of experimental physics

➔ As a test, this will produce a new result in the area of "Minicharge" particles and Neutrality of matter (i.e. $q_{proton} = q_{electron}$)

The rotation alone, suppresses the dipole contribution to the force by a factor 10-100 with respect to the non-spinning case



Permanent dipole backgrounds

At f_0:

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

This is about contact potentials and is usually negligible

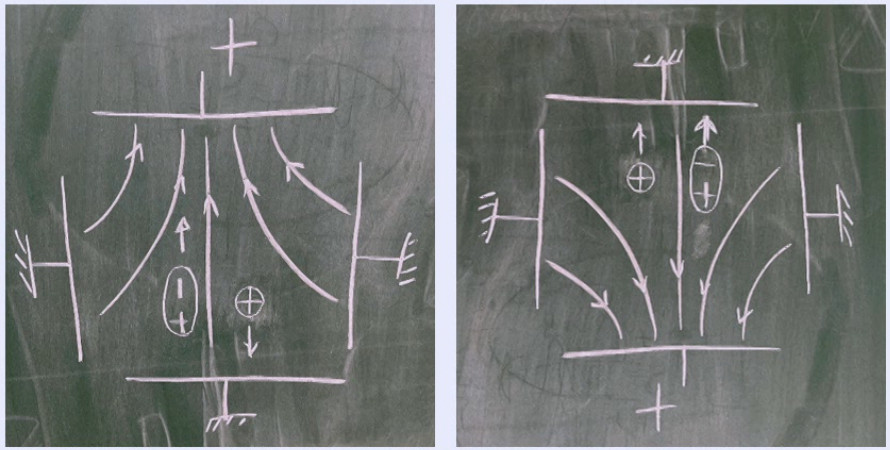
This is the term to worry about

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

At first order the dipole term cancels for the quantity:

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

Describes the possible slight asymmetry between the two field directions

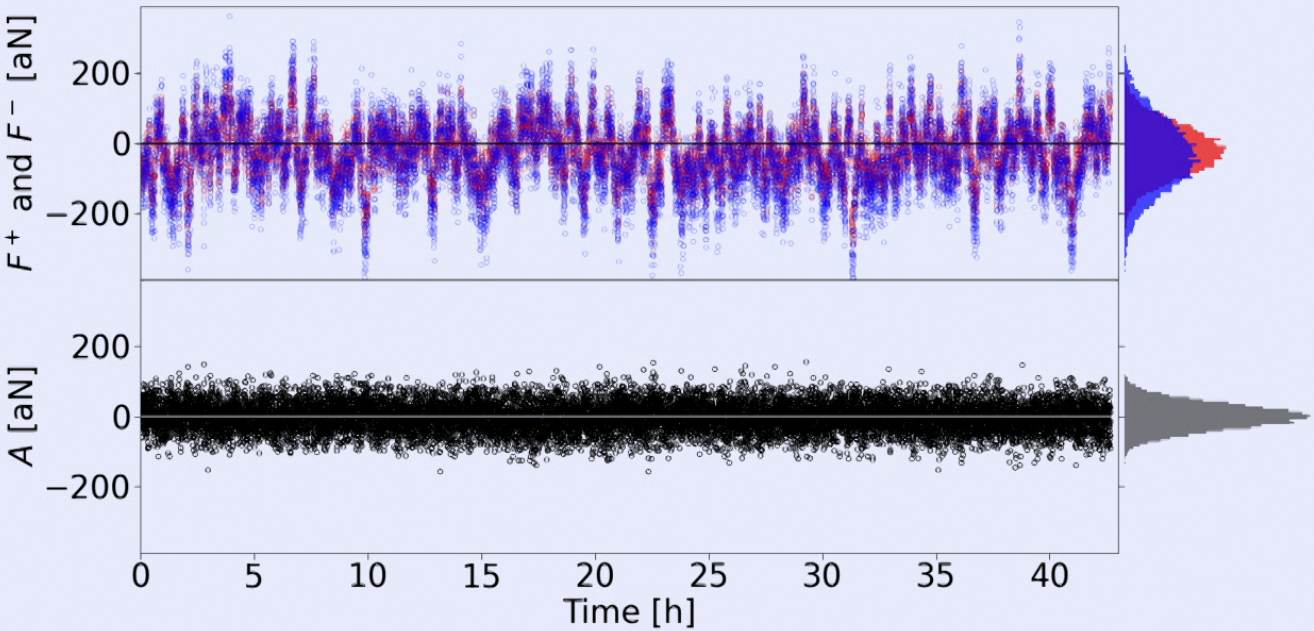


Note that the force switches direction for the monopole but not for the (permanent) dipole

(thanks to M. Aspelmeyer for the use of the blackboard)

The cancellation works remarkably well!!

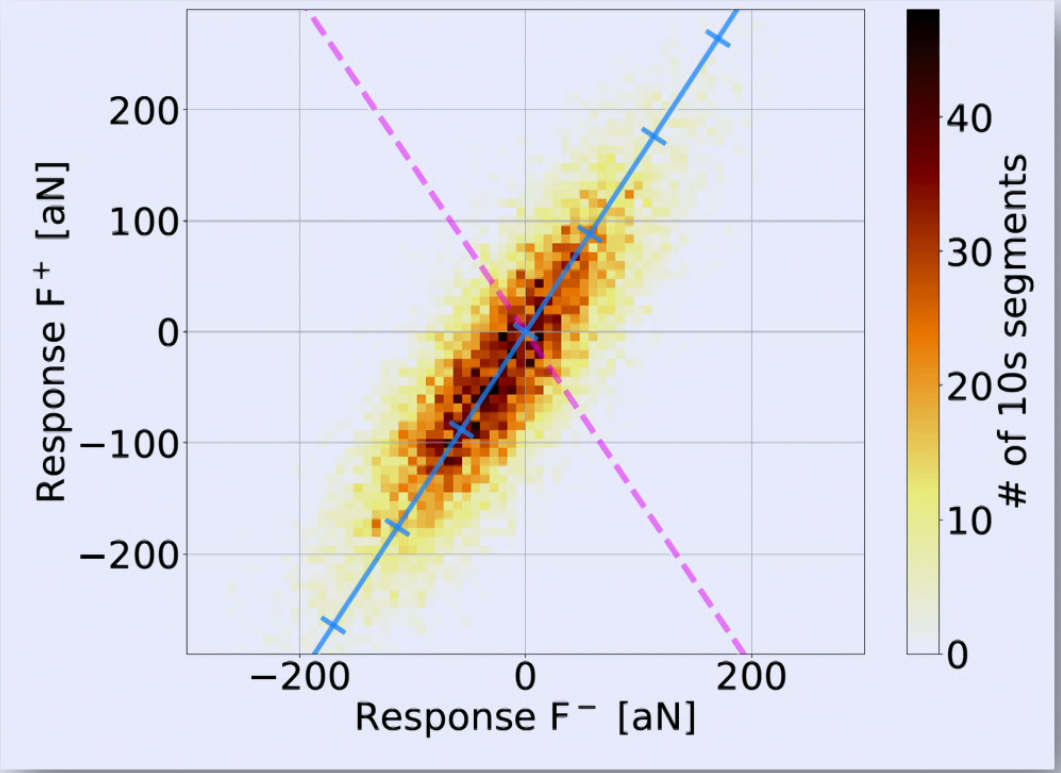
(here Ω is calculated with FEA, using the measured trap position with respect to the electrodes)



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

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

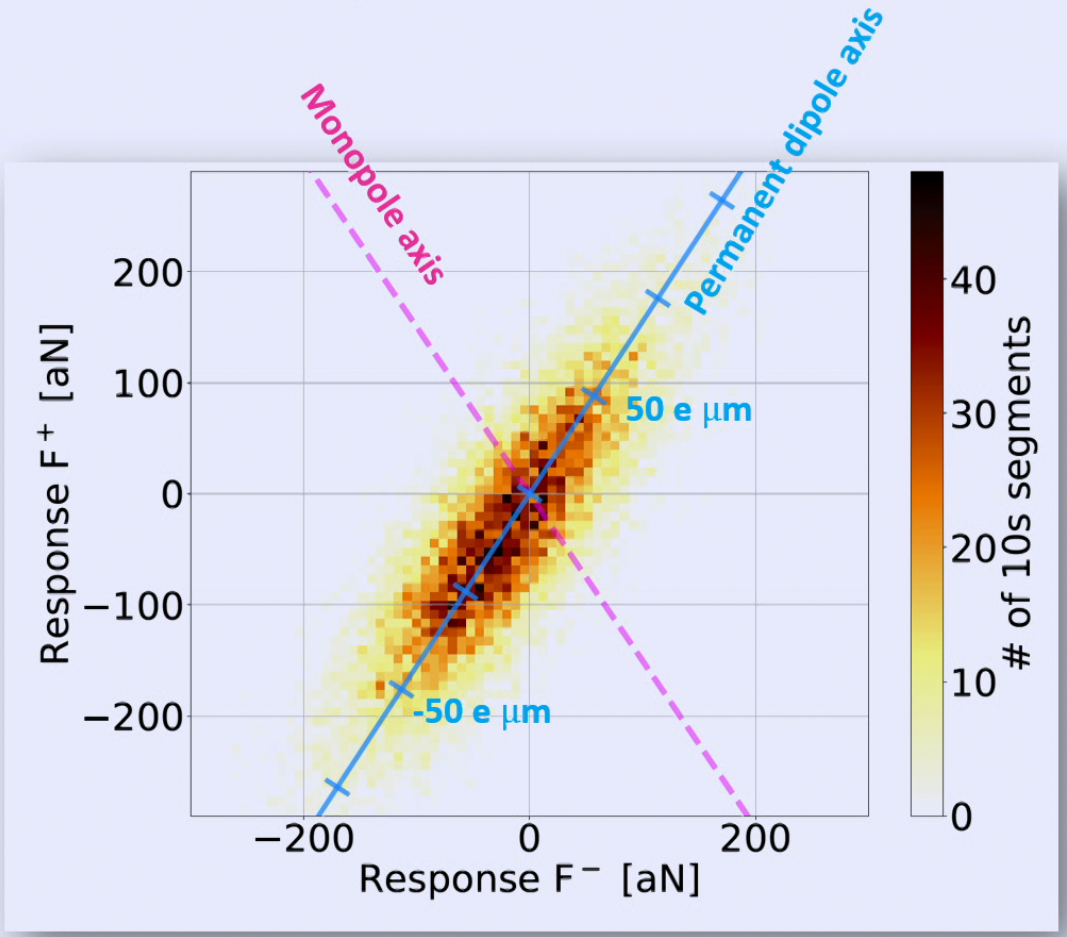
The correlation between F_+ and F_- contains more information!



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 we have seen that the dipole changes with time)



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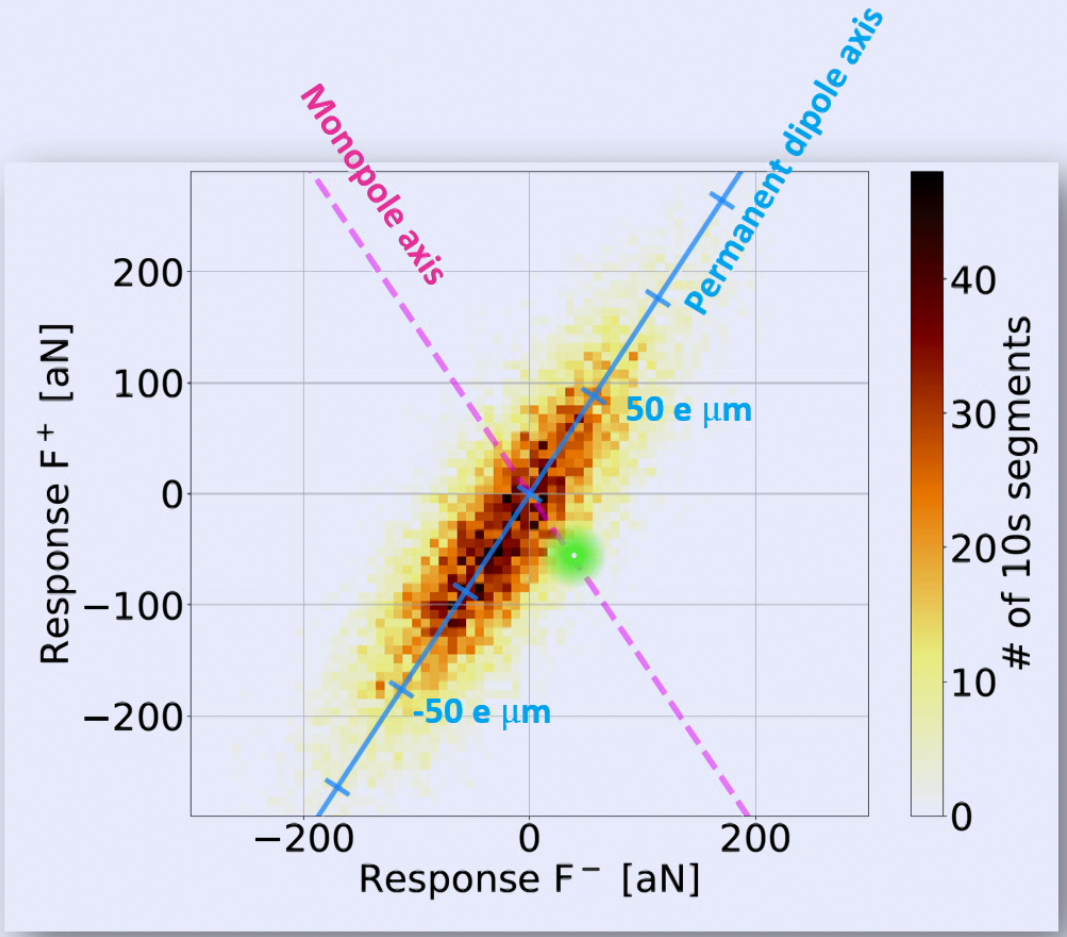


The induced dipole interacting with the changing gradient shows up at $2f_0$

Induced dipoles can originate from the polarizability of the sphere or from excursions to the spin and are cancelled in a second quantity:

$$B \equiv G^+ - \Omega^2 G^- \simeq -\frac{1}{2}\left(p_{\rm ac}^+ - \Omega p_{\rm ac}^-\right)\frac{\partial E^+}{\partial z}$$

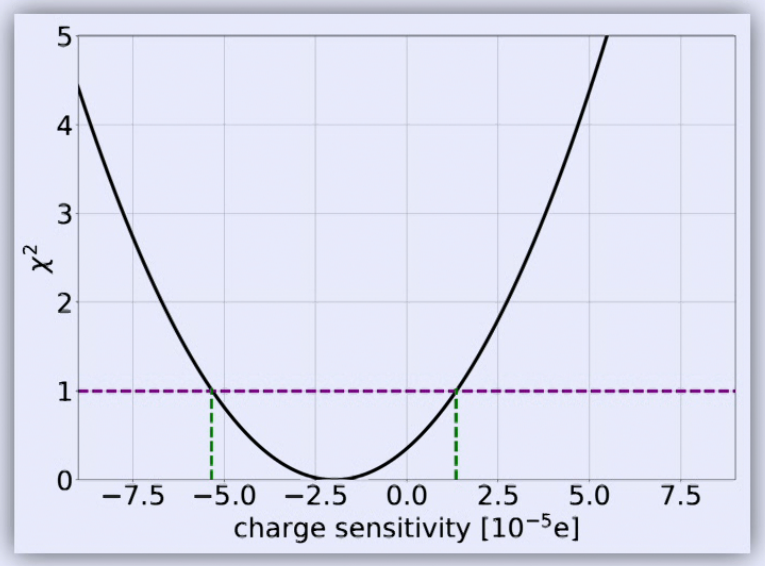
B can then be used to write a full expression for the monopole term:

$$2qE^+ \simeq A + 2B\frac{(\partial_z E_{{\rm dc},z})}{(\partial_z E^+)}$$

Although in the second term is negligible for the current measurement.
Properties of the polarizability of the microspheres can be extracted from this process, although more work is needed in this direction.

Charge sensitivity

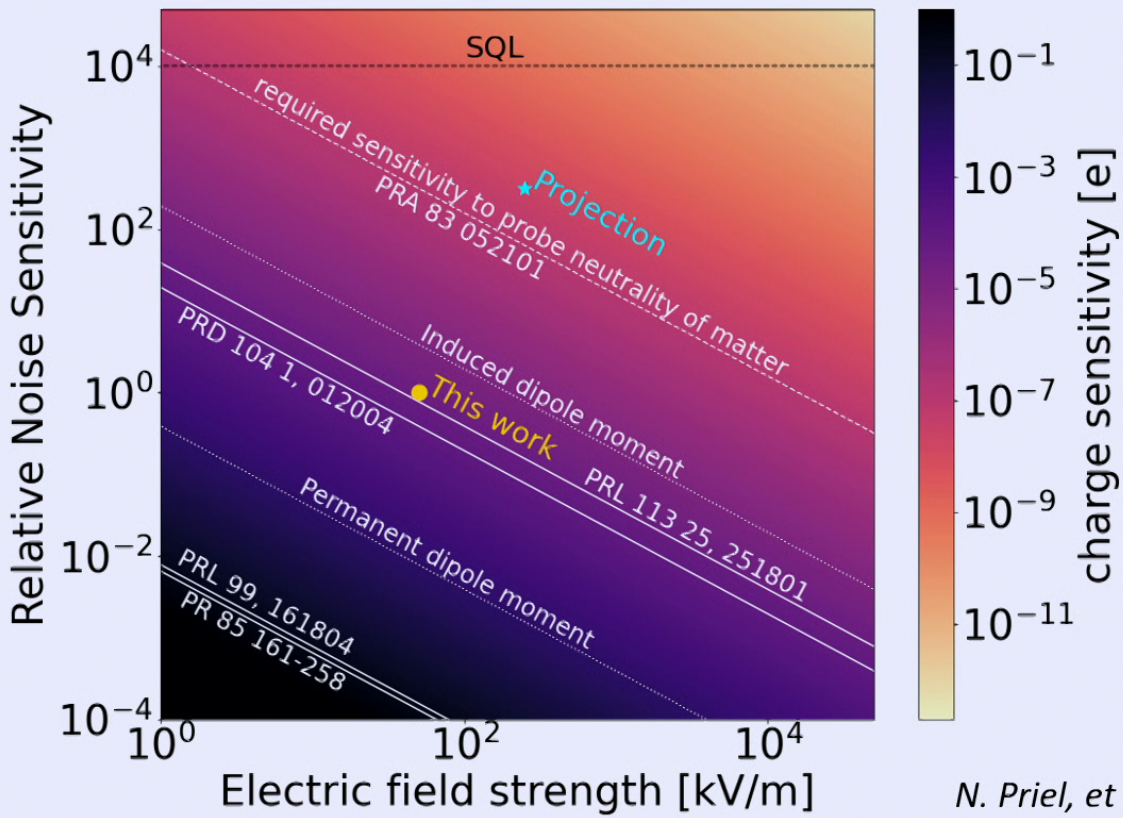
- 3 spheres with different electric field configurations: consistent results.
- No residual backgrounds: **improved accuracy by two orders of magnitude**



	Oscillating field					
MS	Voltage	Frequency	Axis	Electrodes seperation	Integration time	Charge sensitivity
1	20 V	71 Hz	x	8 mm	27 h	$4.5 \times 10^{-4}\,e$
2	200 V	71 Hz	y	8 mm	28 h	$7.7 \times 10^{-5}\,e$
3	200 V	139 Hz	z	4 mm	92 h	$3.9 \times 10^{-5}\,e$

- **Combined limit is 3.3×10^{-5} e**
- **Can easily be improved**

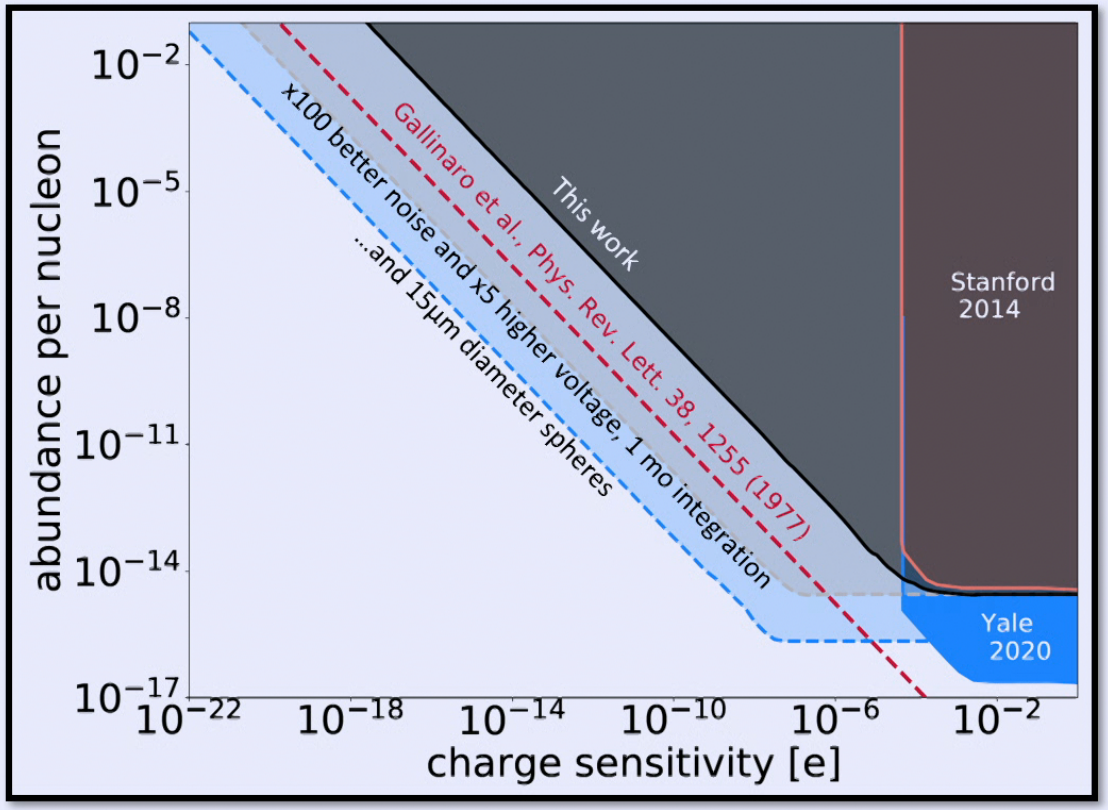
A look at the parameter space relevant for the measurement of small charges



N. Priel, et al.,
"A background-free optically levitated charge sensor"
arXiv:2112.10383v1 (20 Dec 2021), soon on Science Advances

MiniCharged Particle and Neutrality of Matter interpretation

- Limits on mini-charged particles bound to matter
- Assuming only positive or only negative charges
- Can be compared with a naïve translation from neutrality of matter experiment
- Need to further *assume* production mechanism and binding mechanism to translate to mass vs. charge parameter space
- (More caveats)



Other background sources (in order of likely importance):

- **Stray light,** **producing a shift on the QPD that is interpreted as a shift of the microsphere**
- **Vibrations induced by the attractor motion**
- **Laser pointing noise**
- **Casimir forces**

Ongoing upgrades

Done/near future improvements:

- **Stray light campaign**
- **EDM backgrounds (modeling and scanning with attractor and nulling the contact potential)**
- **System rigidity**
- **In air optics → in He optics**

Ongoing upgrades

Done/near future improvements:

- **Stray light campaign**
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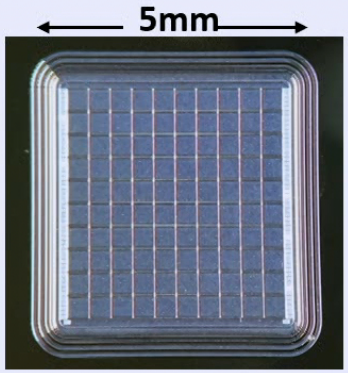
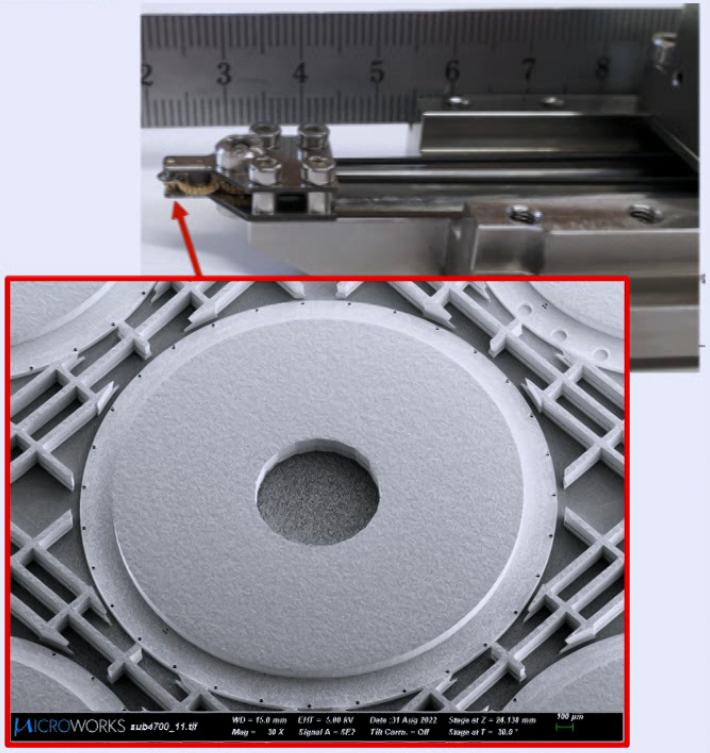
- Multi-pixel photodiode (100 pixels)
- Need to design electronics
- FPGA-based real time processing
- 100% QE at 1064nm
- In collaboration with SLAC



A few months later

- Rotary attractor
- Less (no) vibration at the fundamental frequency
- Fit the existing trap
- Can mitigate existing backgrounds
- In collaboration with EPFL



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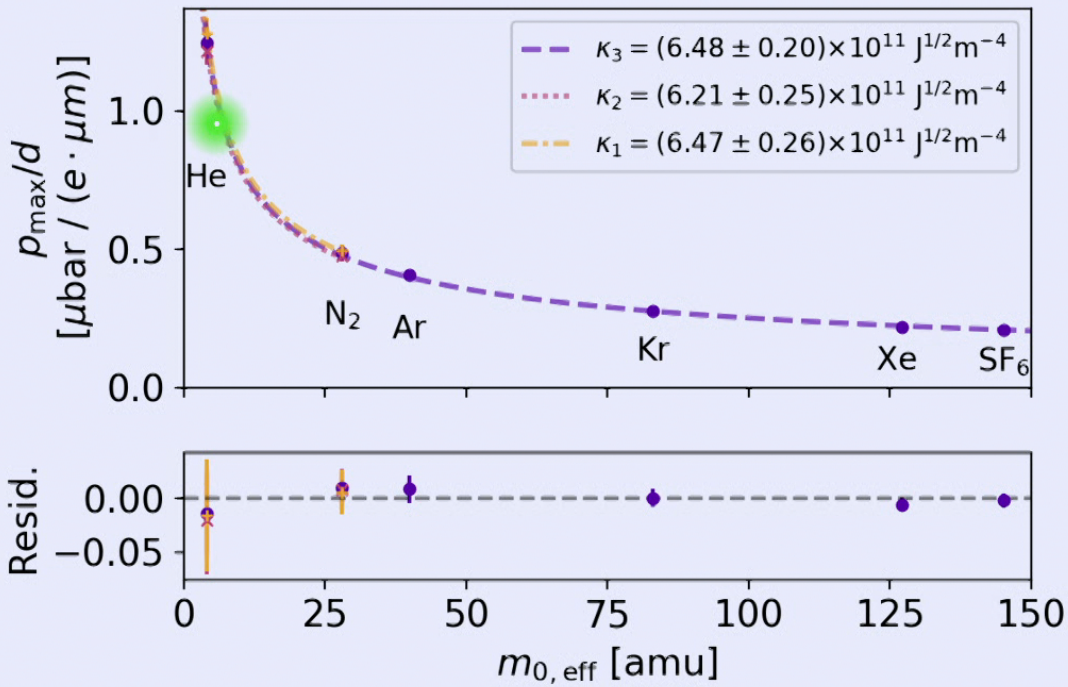

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C. Blakemore at al, J. Vac. Sci. Technol. B 38, 024201 (2020)

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