

Measuring gravity at short distances *and other fun tricks* *with levitated microspheres*

Microsphere
(not to scale)

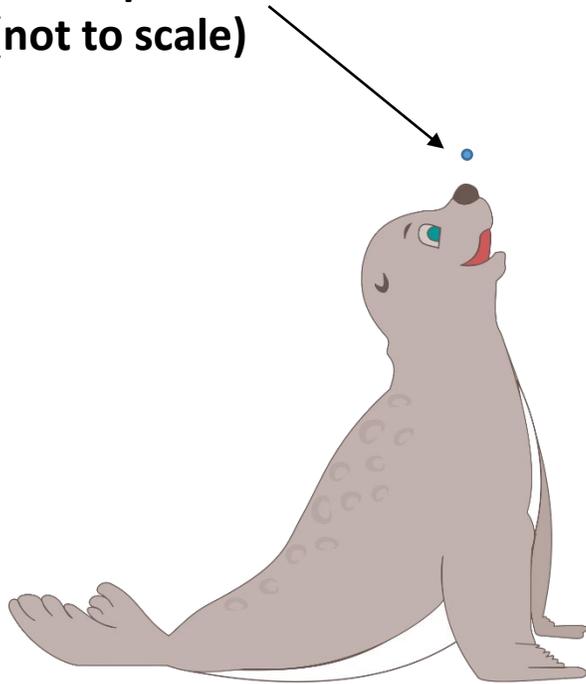
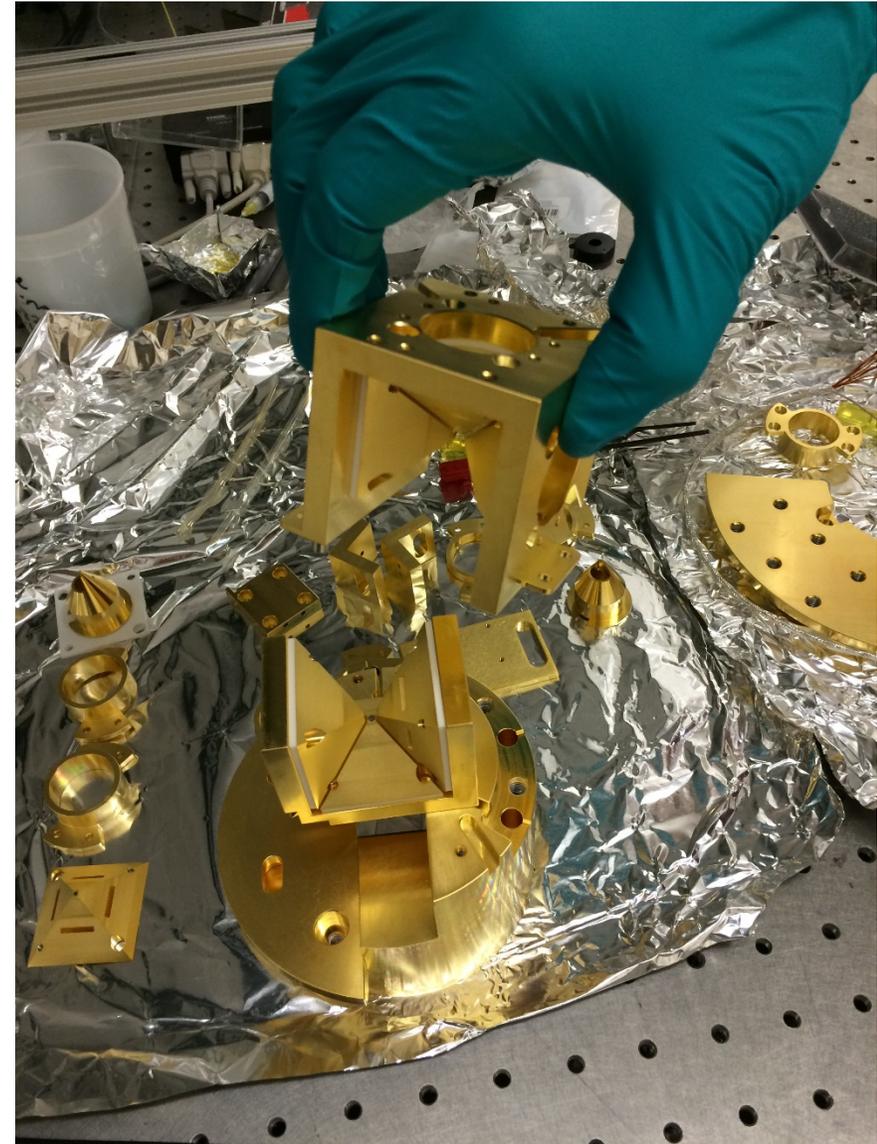


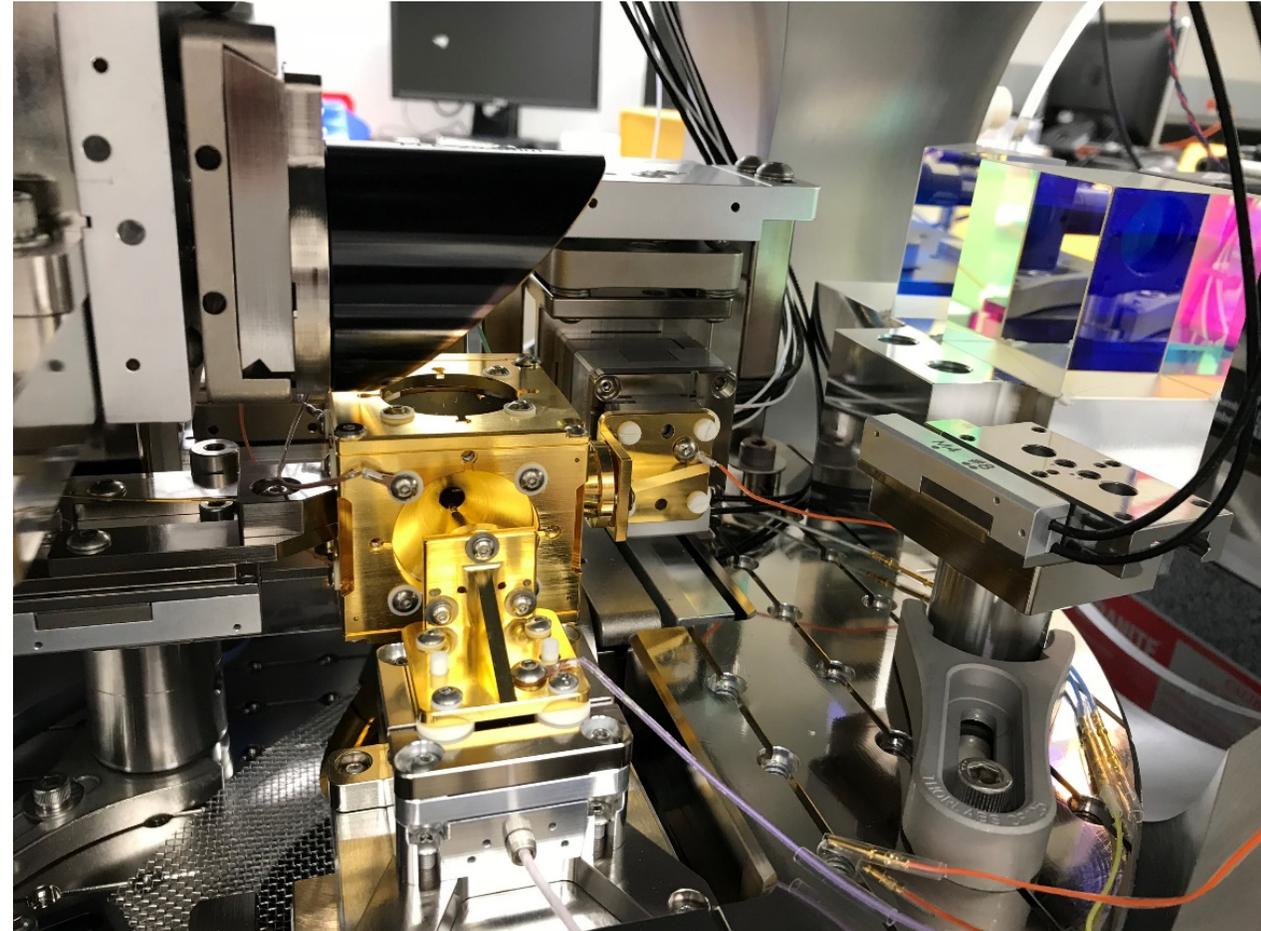
Image credit: Delia Gratta

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 - 50 μ m range



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".



John Mitchell

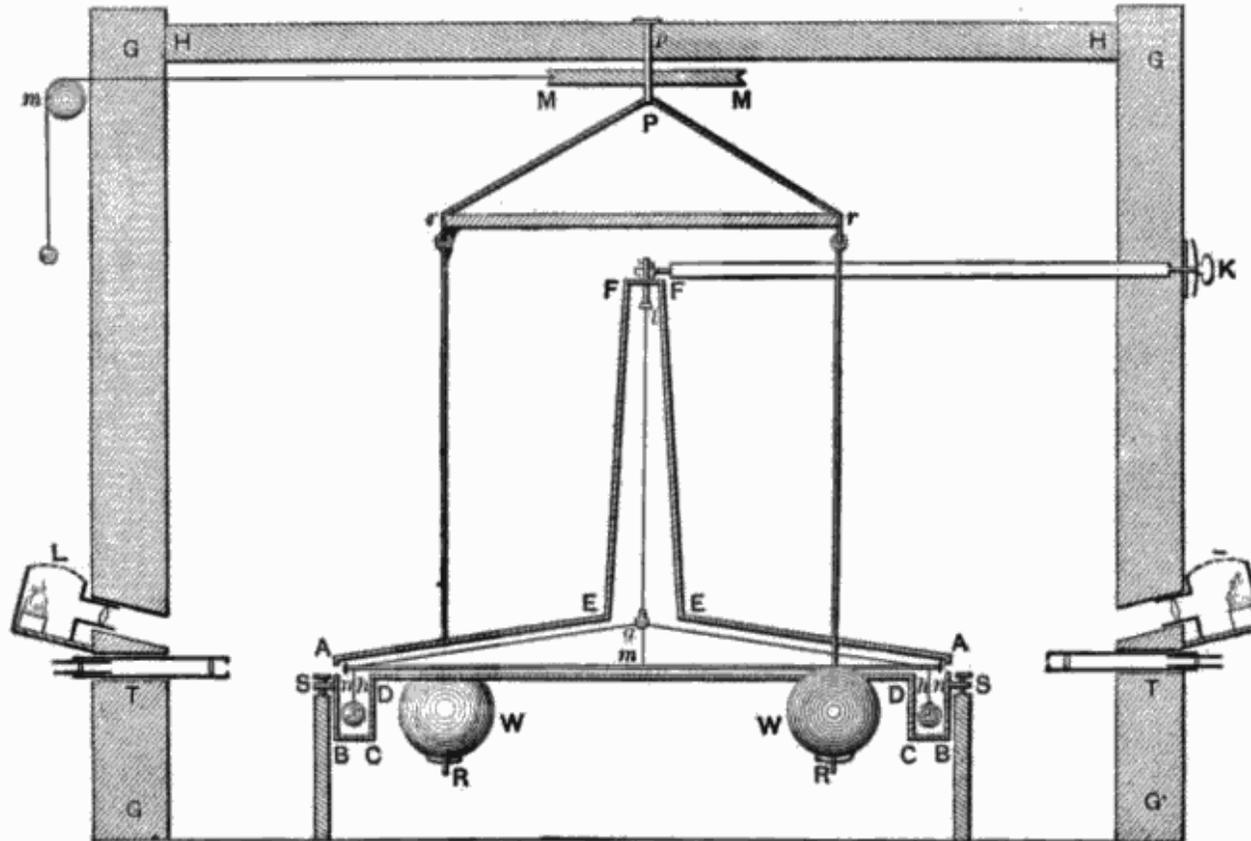


Fig. 1

← ~2m →



H. Cavendish

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

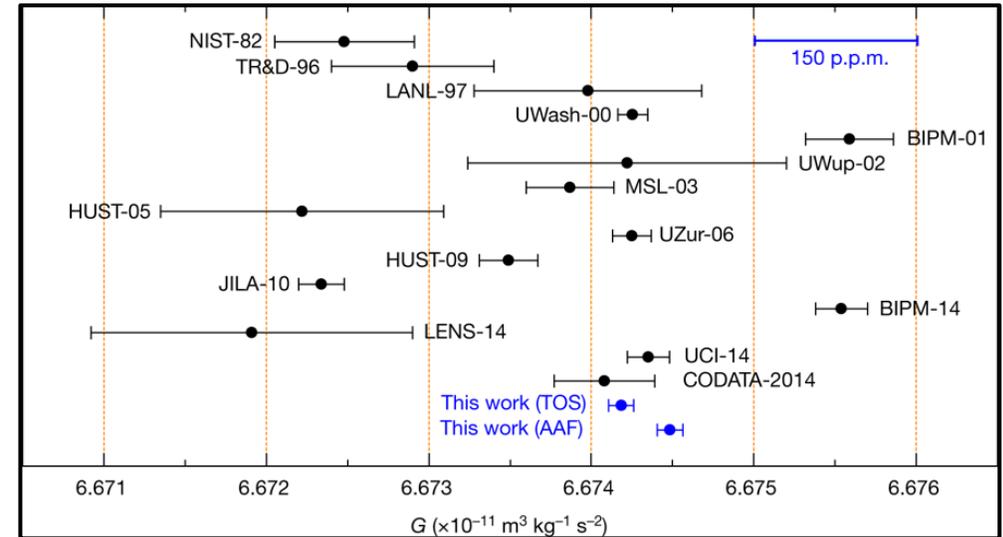
Cavendish's measurement, in terms of G , gives

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

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



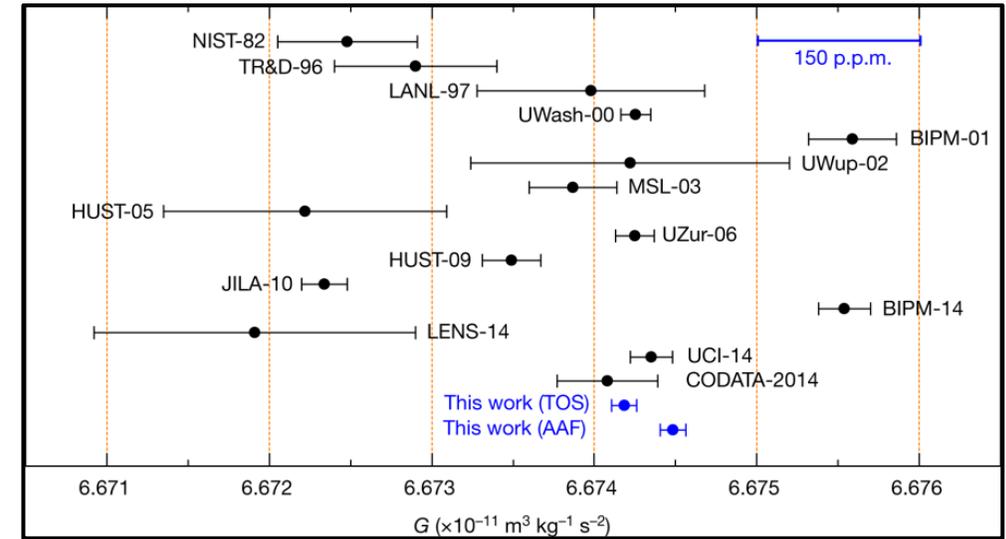
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However, since we do not know how to calculate G from other quantities in physics,
we do not expect to find new physics in the absolute value of G .

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

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

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

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

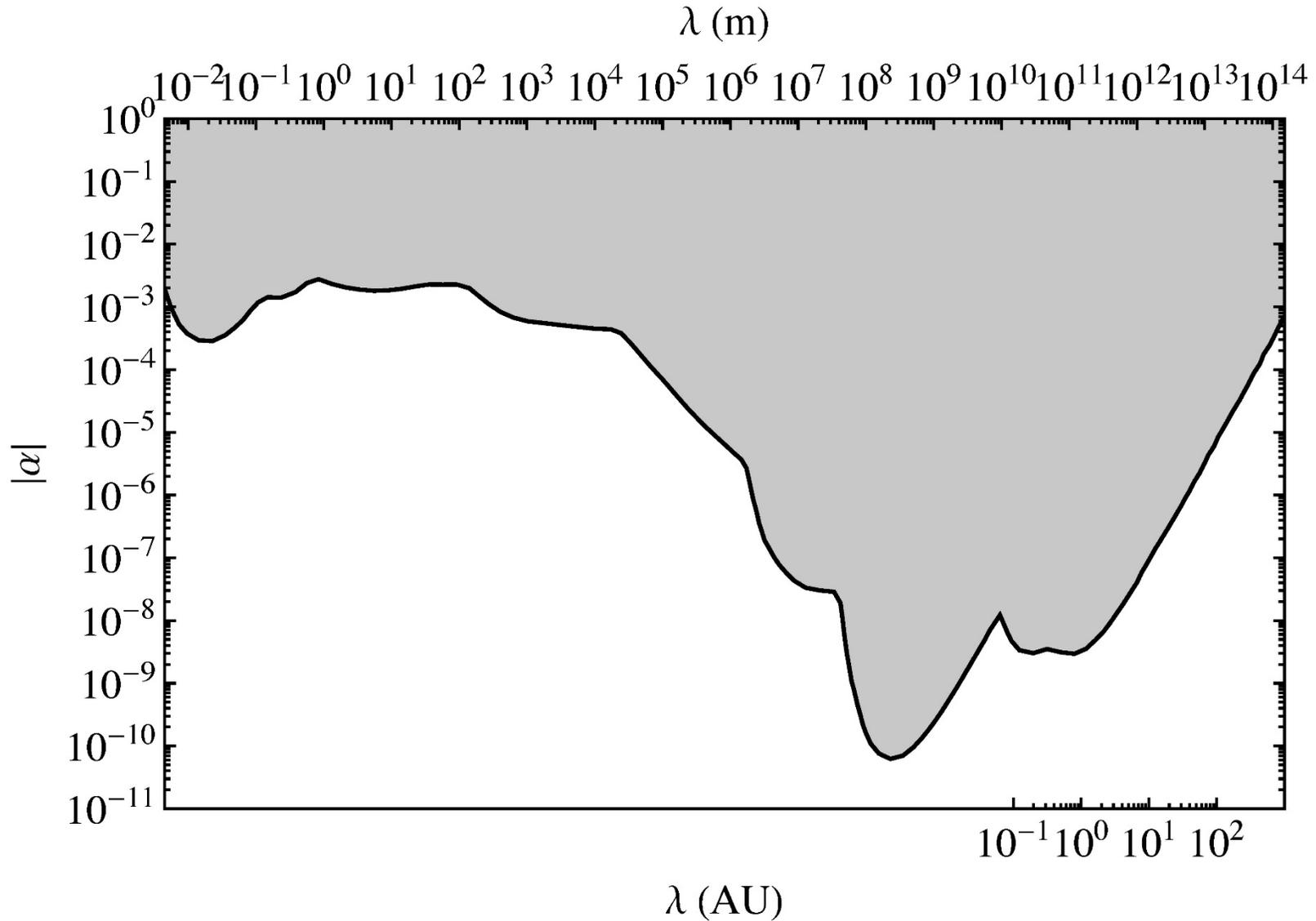
It is customary to express potential deviations from the $1/R^2$ law by modifying the potential with a Yukawa term, obtaining:

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

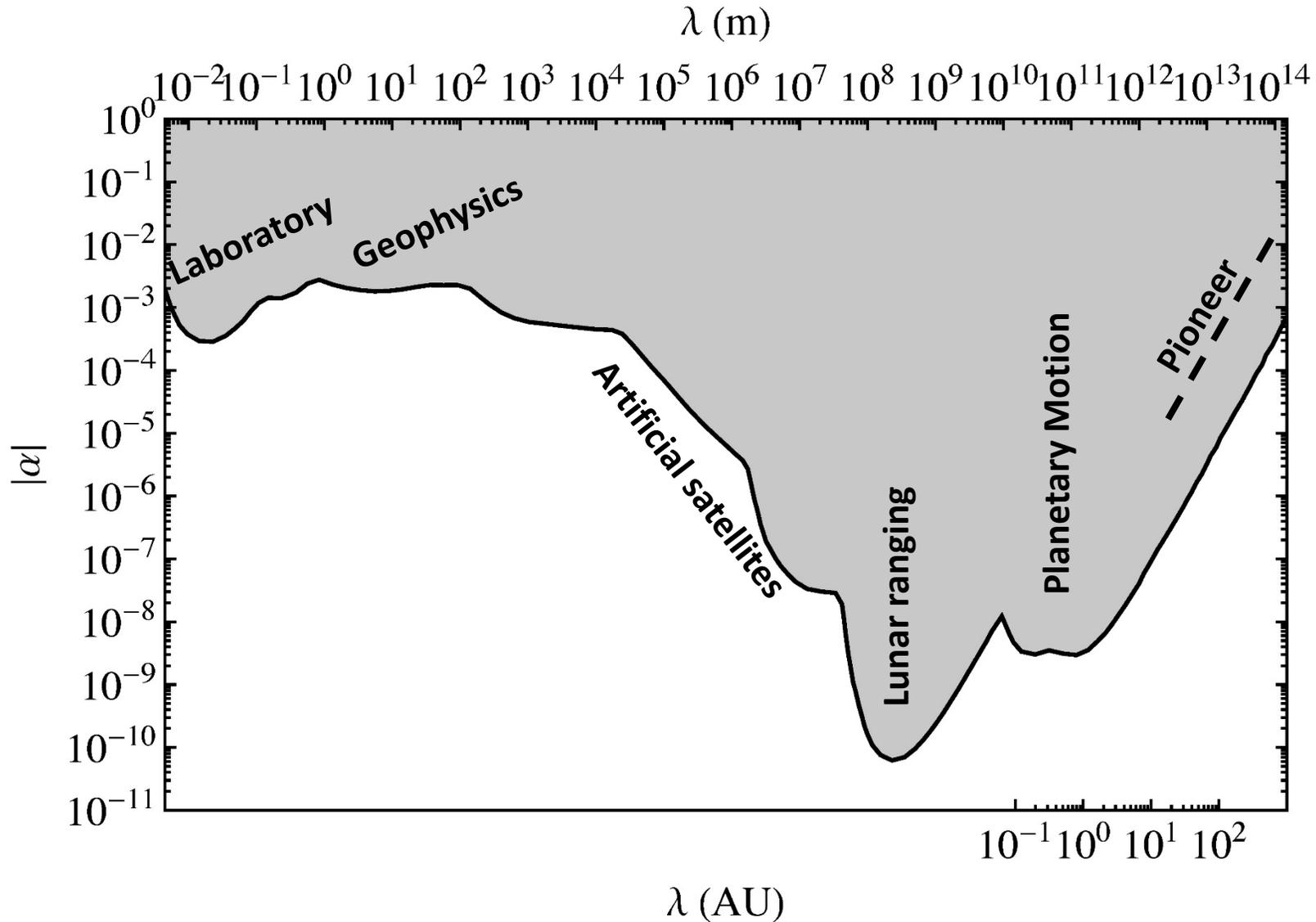
α : magnitude of the effect

λ : scale of the effect

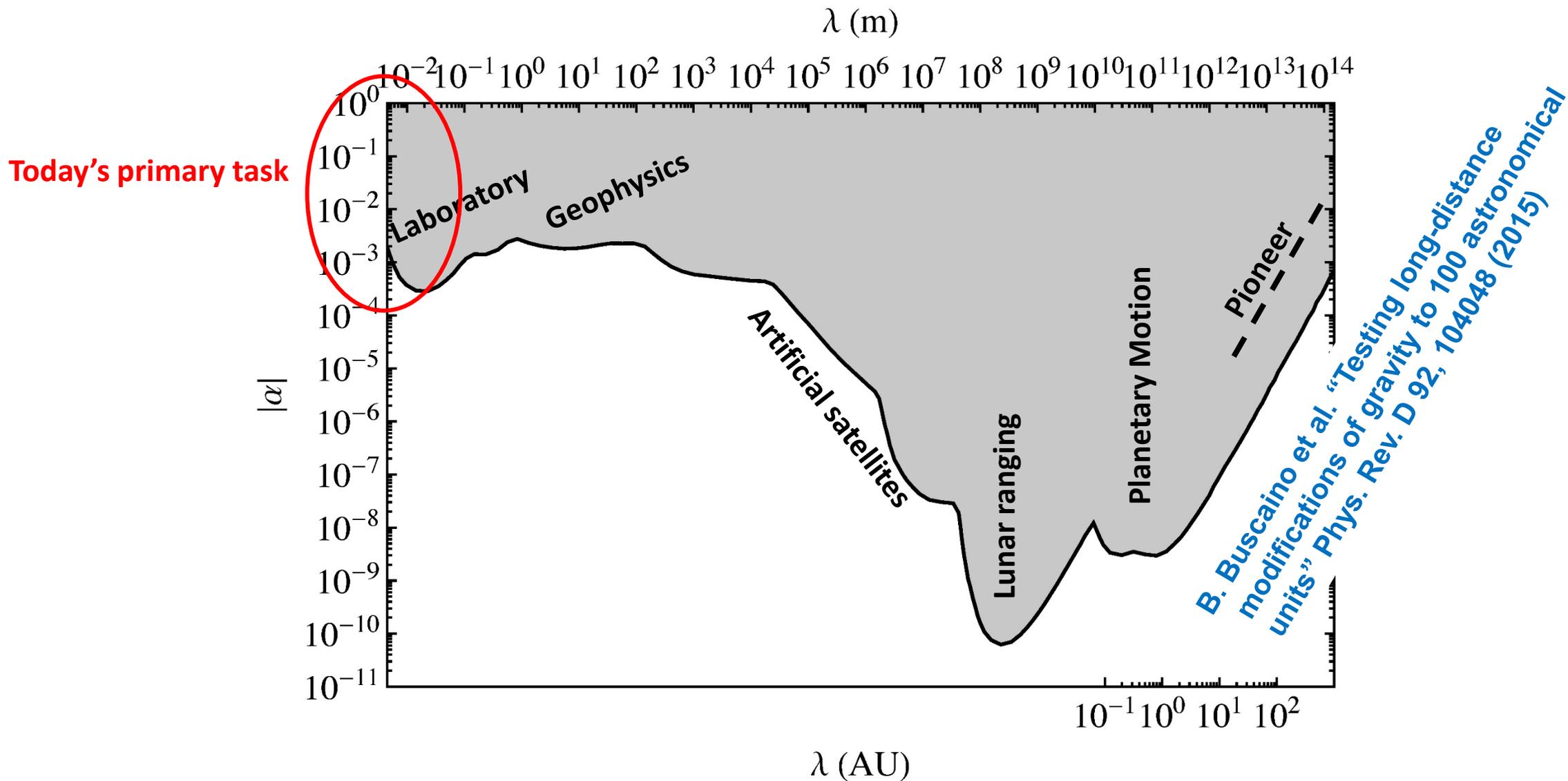
What do we empirically know



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 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 $R \ll a$ and as a constant for $R \gg a$.

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.

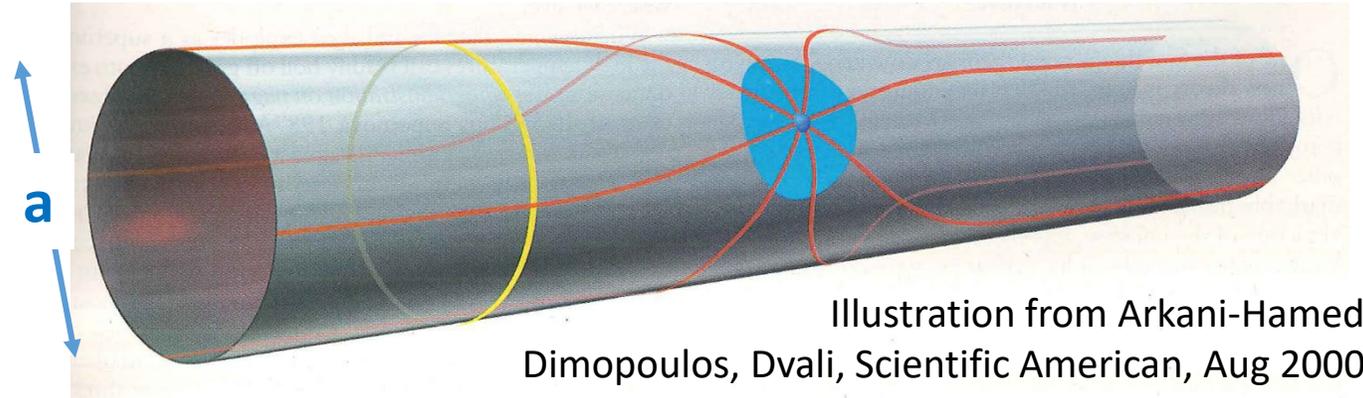
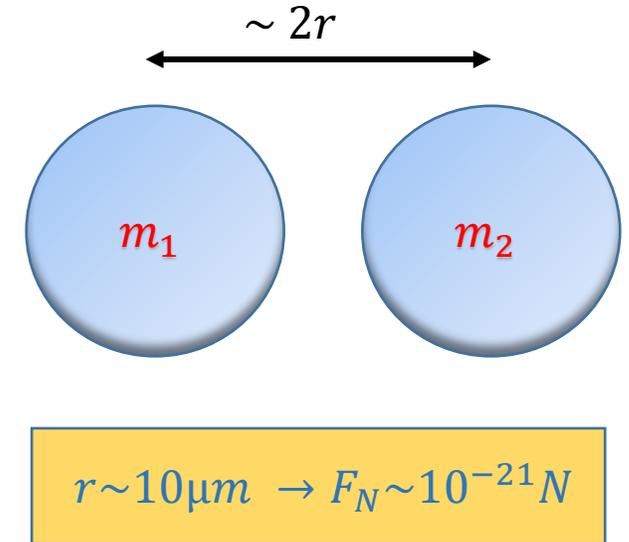


Illustration from Arkani-Hamed, Dimopoulos, Dvali, Scientific American, Aug 2000

But, also, any new, long-range forces related to intrinsic properties of matter (e.g. baryon number) may appear as modifications to Newtonian gravity.

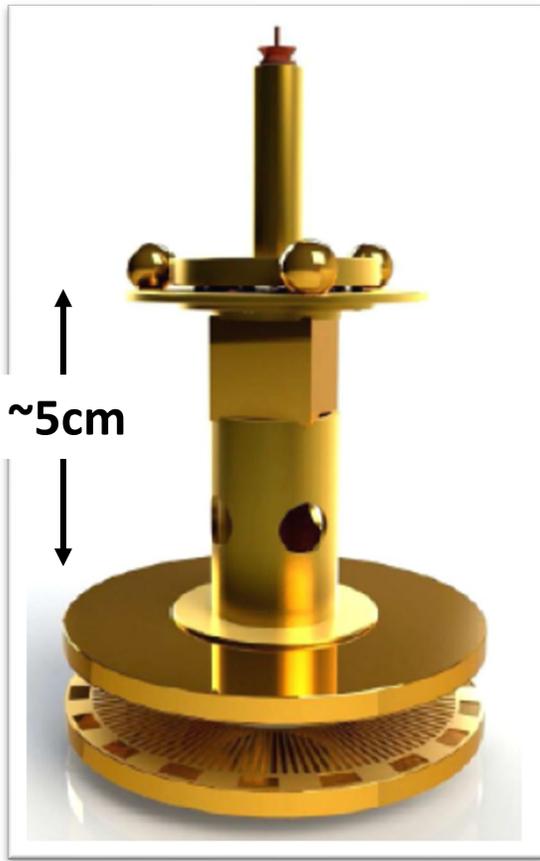
Experimental challenges

- Since $F = G \frac{M_1 M_2}{R^2} = G \frac{\rho_1 V_1 \rho_2 V_2}{R^2}$
for atomic materials (we can't use Neutron Stars!)
 $\rho_1 \sim \rho_2 < 20 \text{ g/cm}^3$, there is no silver bullet.
In addition, the volume $V \sim R^3$, so $F \sim G \frac{\rho^2 R^6}{R^2}$
and it is clear that measurements at short
distance become exceedingly difficult.
- At distances $< 100 \mu\text{m}$ 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.



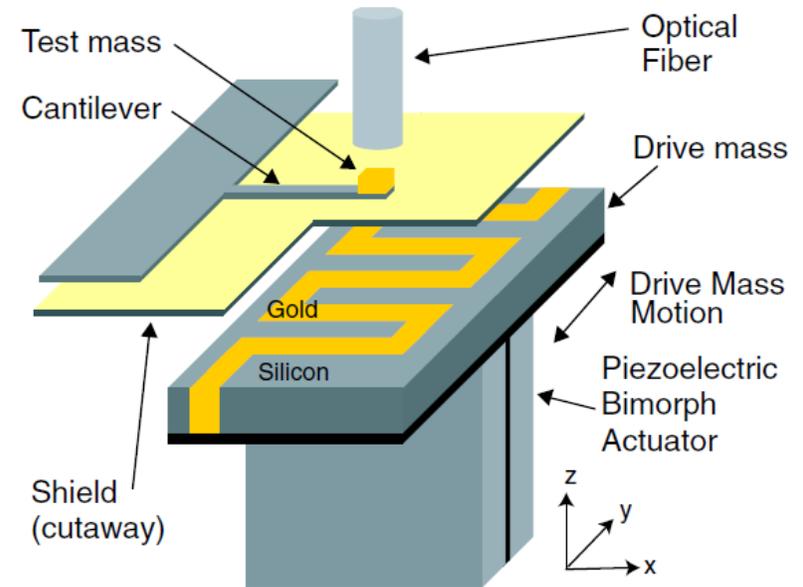
Most inverse-square law measurements are/have been done with wonderfully sophisticated versions of Cavendish's setup.

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...).



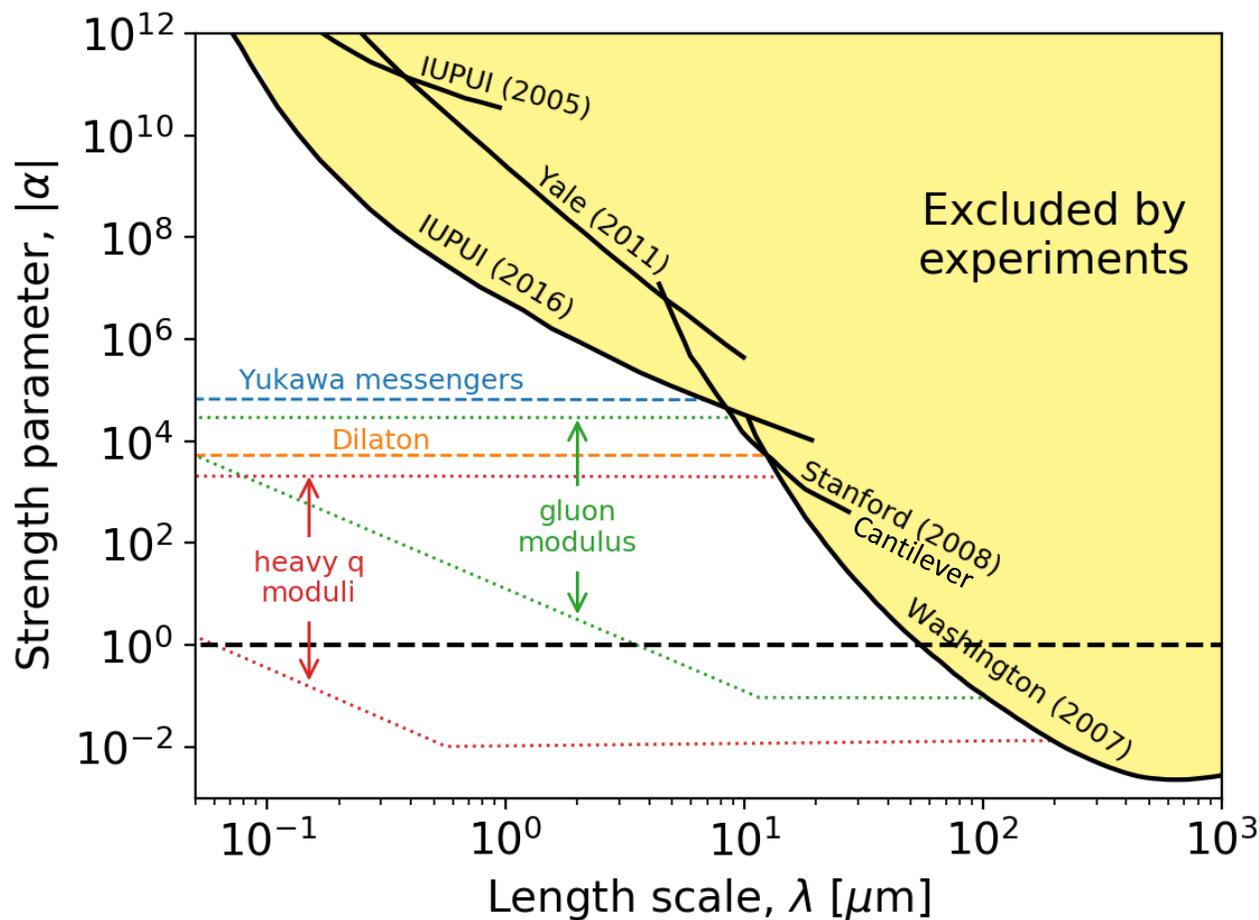
Sketch of the EotWash apparatus from the University of Washington in Seattle
Phys. Rev. Lett. 124, 101101 (2020)

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

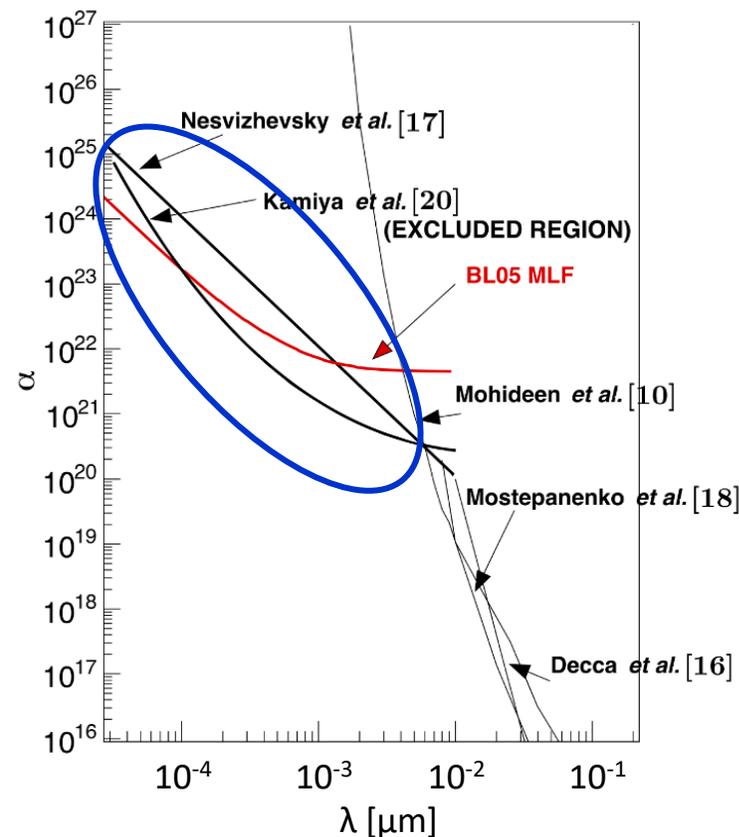


Sketch of the custom cryogenic AFM apparatus from Kapitulnik's group at Stanford
J. Chiaverini et al., PRL 90 (2003) 151101

The current experimental situation on the α - λ plane

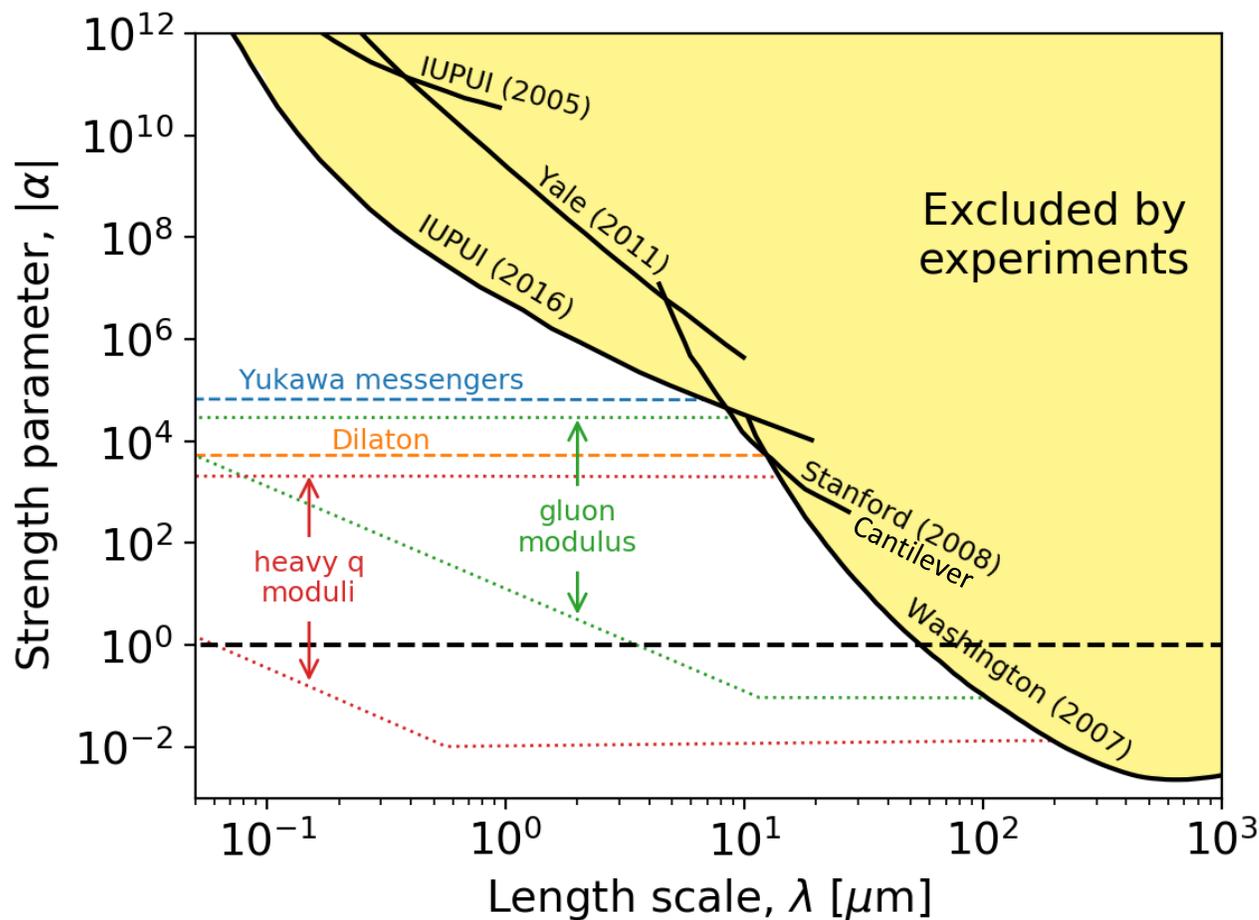


Note: The ideal probe for such a measurement is the neutron (charge radius is $\sim 1\text{fm}$ instead of $\sim 1\text{nm}$). For the same reasons the manipulation of neutrons is hard and results are only interesting at ultra short distance (where there no other option)



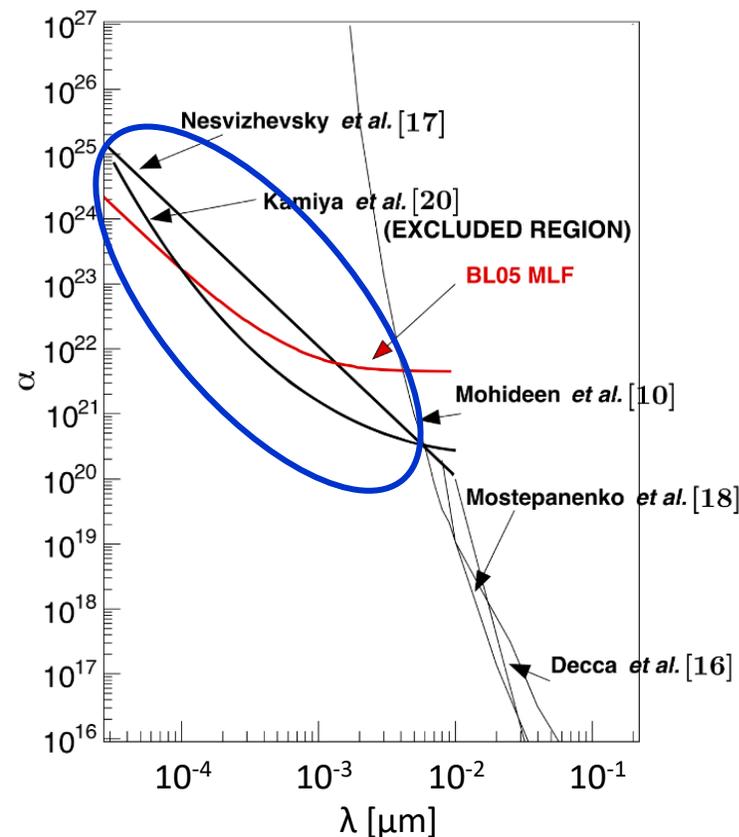
C.C.Haddock *et al.*, PRD 97 (2018) 062002
Y.Kamiya *et al.*, PRL 114 (2015) 161101

The current experimental situation on the α - λ plane



Lots of phase-space for new physics to explore

Note: The ideal probe for such a measurement is the neutron (charge radius is $\sim 1\text{fm}$ instead of $\sim 1\text{nm}$). 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 (weights)

A bathroom scale
resolves $\sim 1\text{ N}$

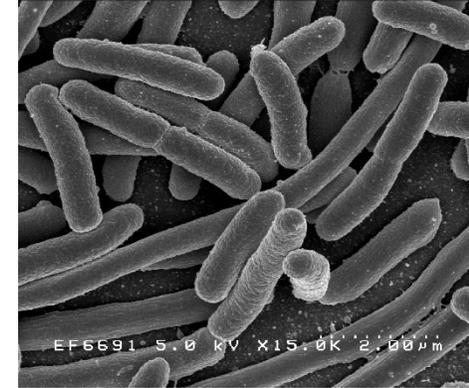


100 kg $\sim 1\text{ kN}$

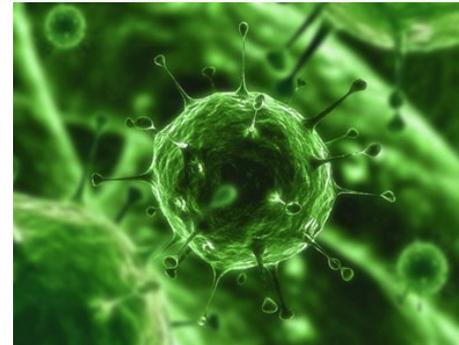
A dust mite 10^{-7} N



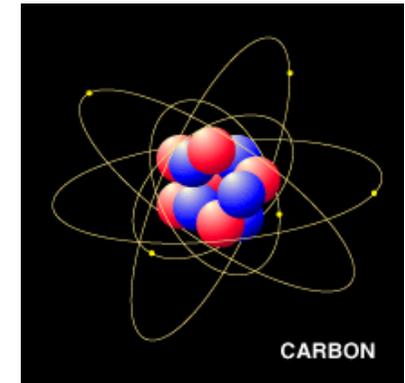
E. coli 10^{-14} N



Virus 10^{-19} N



Carbon atom 10^{-25} N



Conventional AFM measures
 10^{-12} N

Specialized, cryogenic setups
can result in $\sim 10^{-16}\text{ N}/\sqrt{\text{Hz}}$
noise floors

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

APPLIED PHYSICS LETTERS

VOLUME 19, NUMBER 8

15 OCTOBER 1971

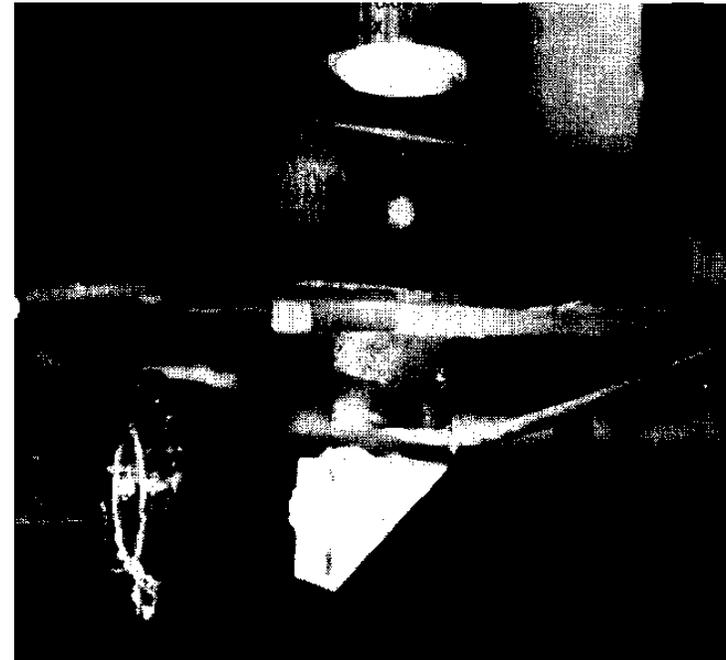
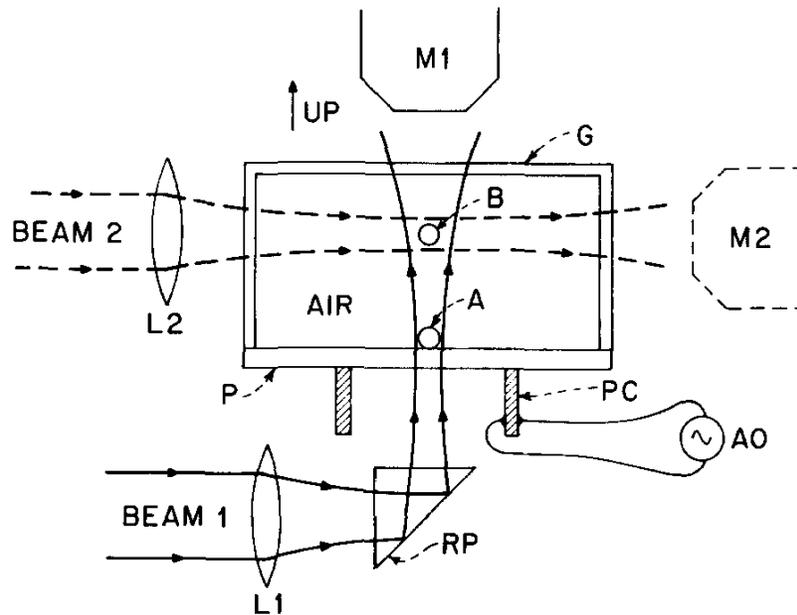
Optical Levitation by Radiation Pressure

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 TEM₀₀-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.

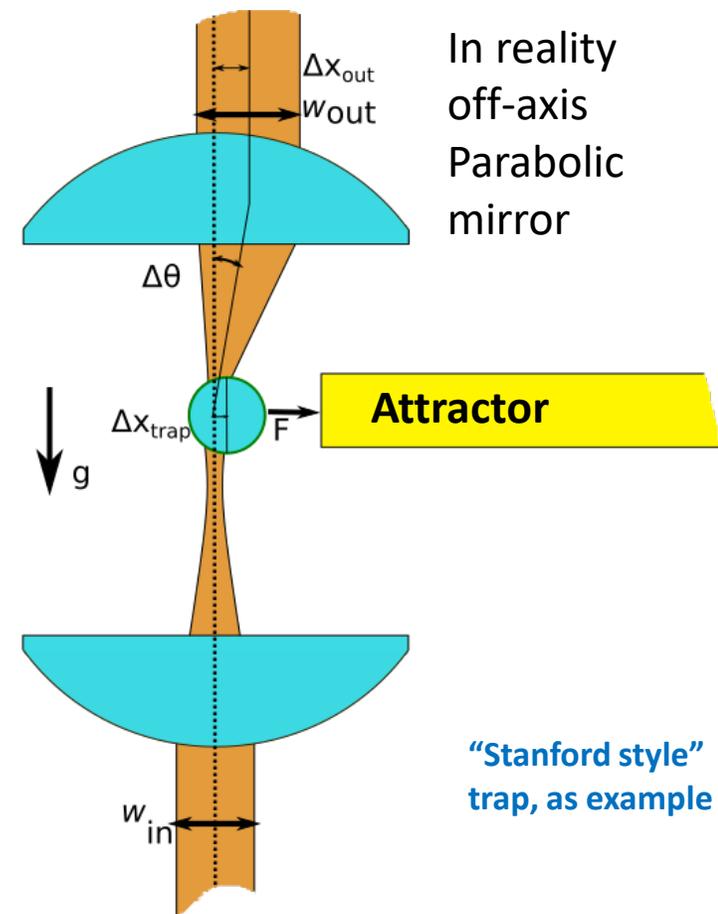


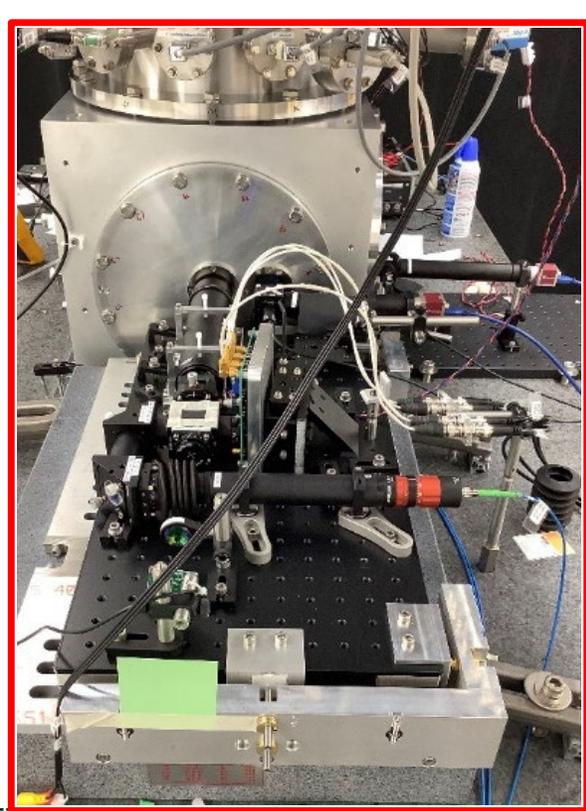
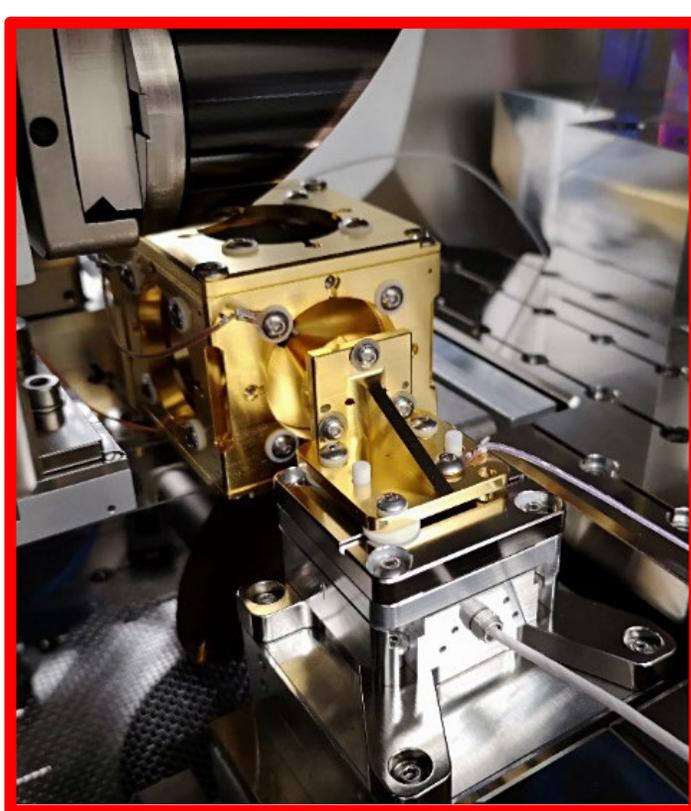
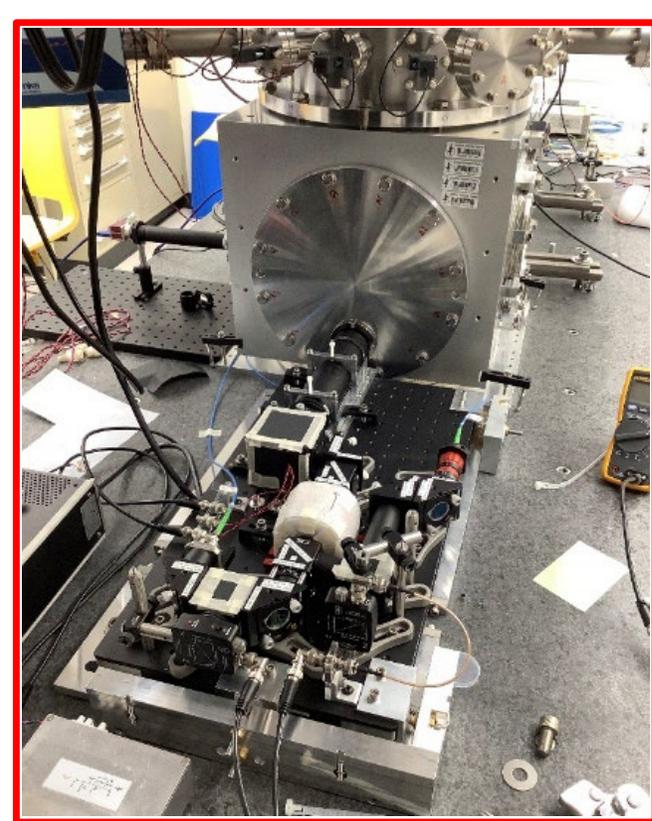


In the last 40 years, the technique has matured, under the name of optical tweezers, primarily in water with applications to biology

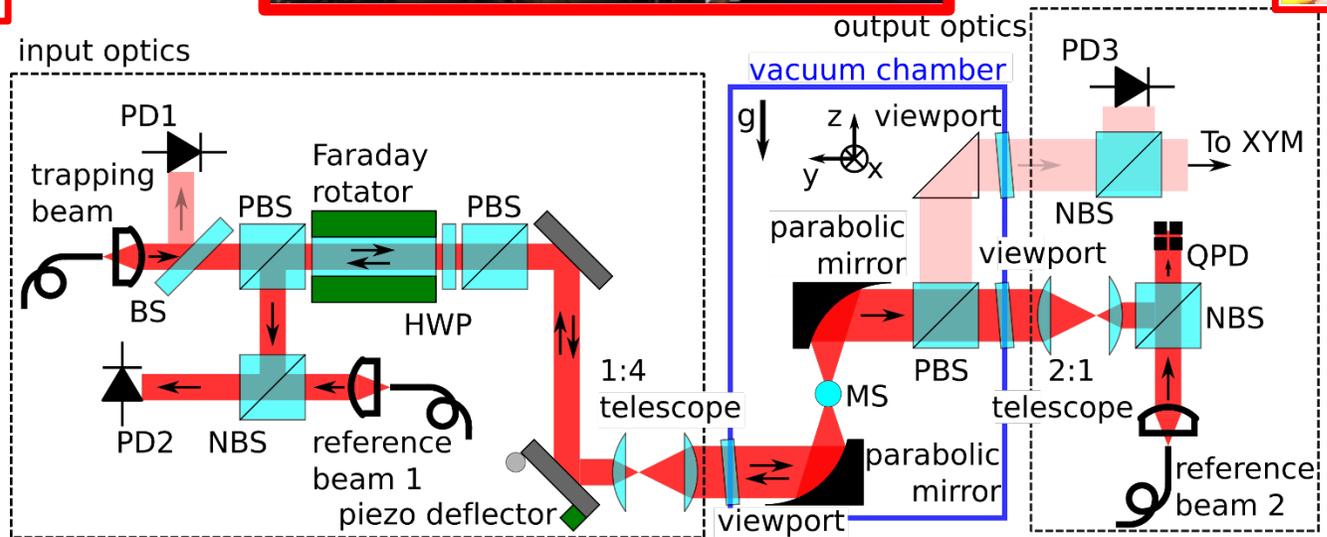
Microspheres optically trapped in vacuum make superb force sensors

- In high vacuum we can cool the force sensor (μ sphere) 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.



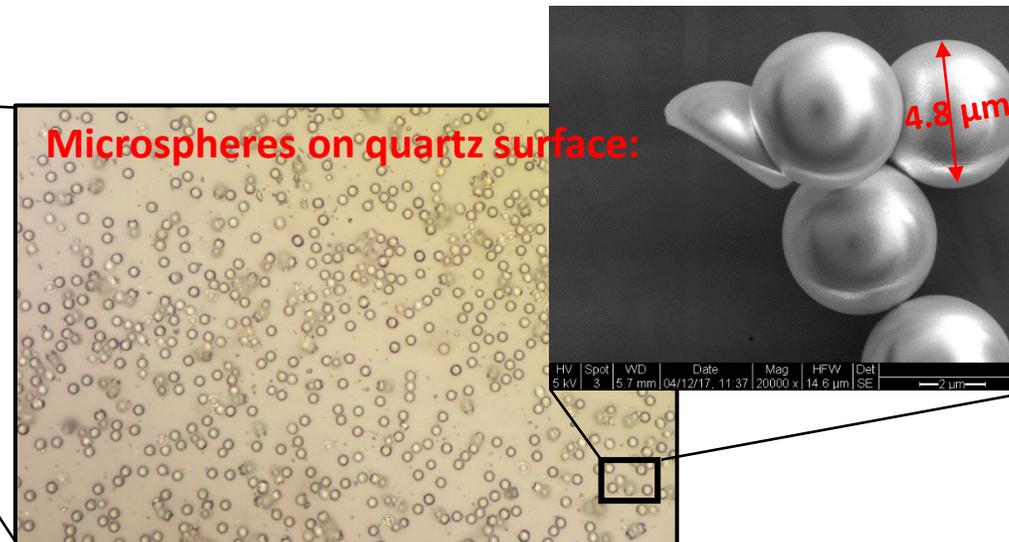
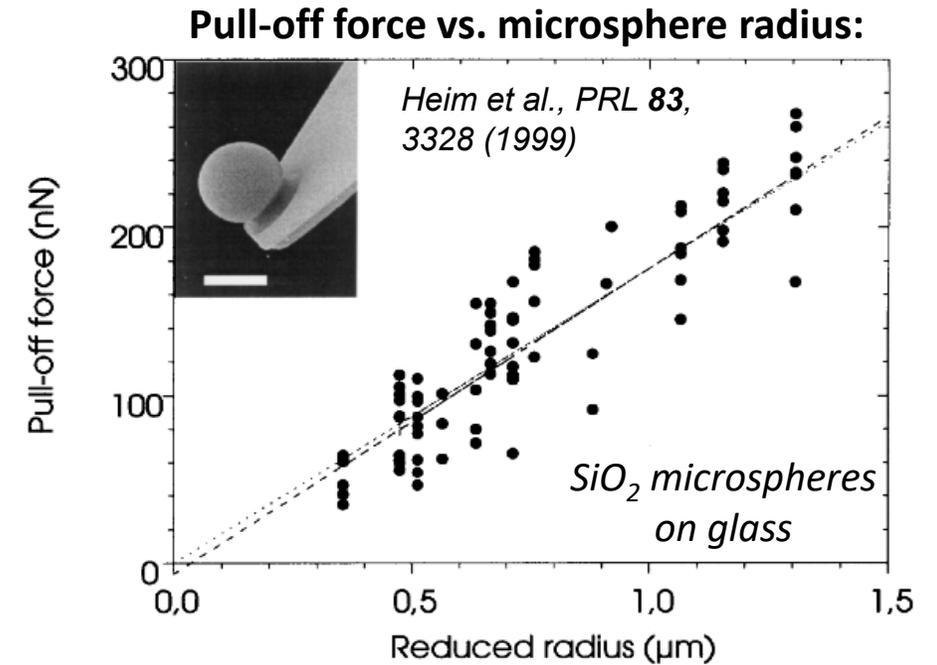
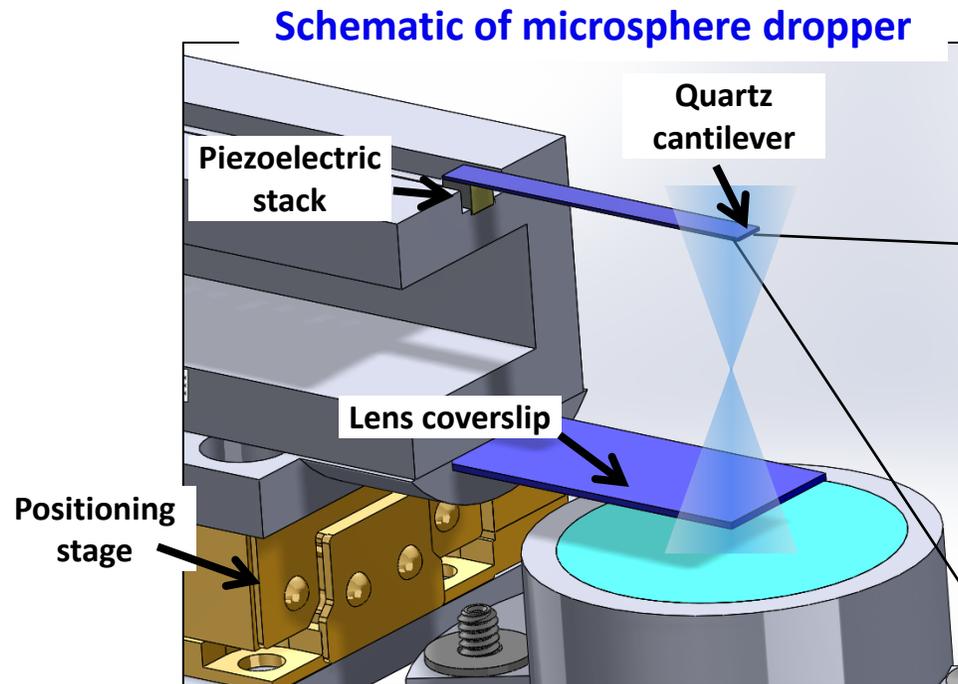


Rev. Sci. Instrum.
 91, 083201 (2020)



Trap loading

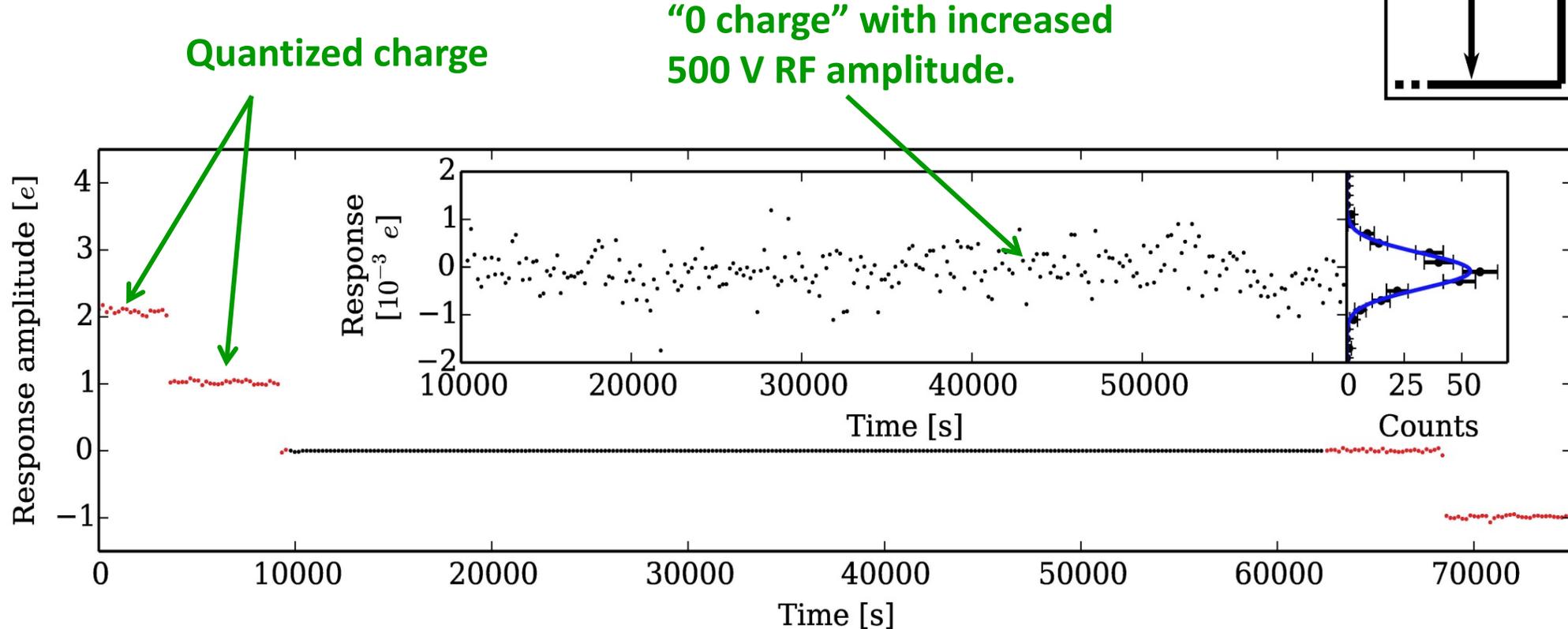
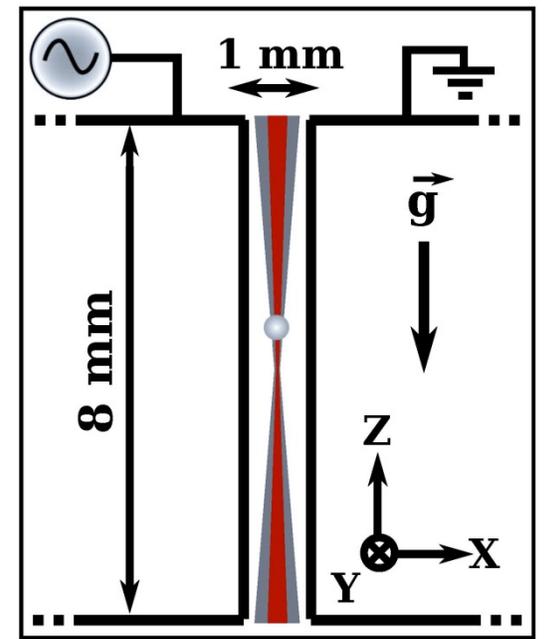
- $\sim 5\mu\text{m}$ diameter microspheres are launched from the bottom surface of quartz cantilever in a few torr atmosphere
- Pull-off forces of ~ 100 nN require accelerations $\sim 10^6$ m/s²
- Bottom coverslip protects optics and is retracted after trapping
- Once a μsphere is trapped, the buffer gas is slowly removed and the feedback cooling turned on.



As loaded in the trap, μ spheres are usually charged ($\sim 500e$)

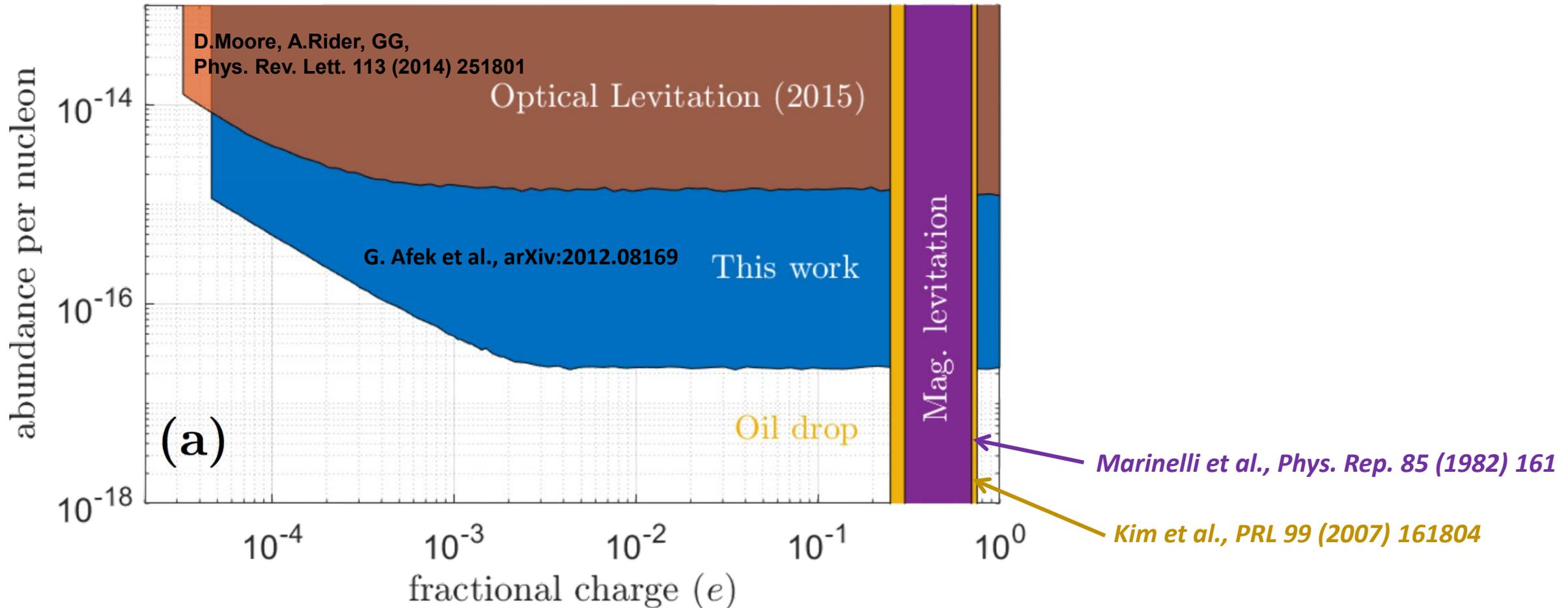
→ Their charge state can be changed at leisure (in both directions), using a UV light source

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

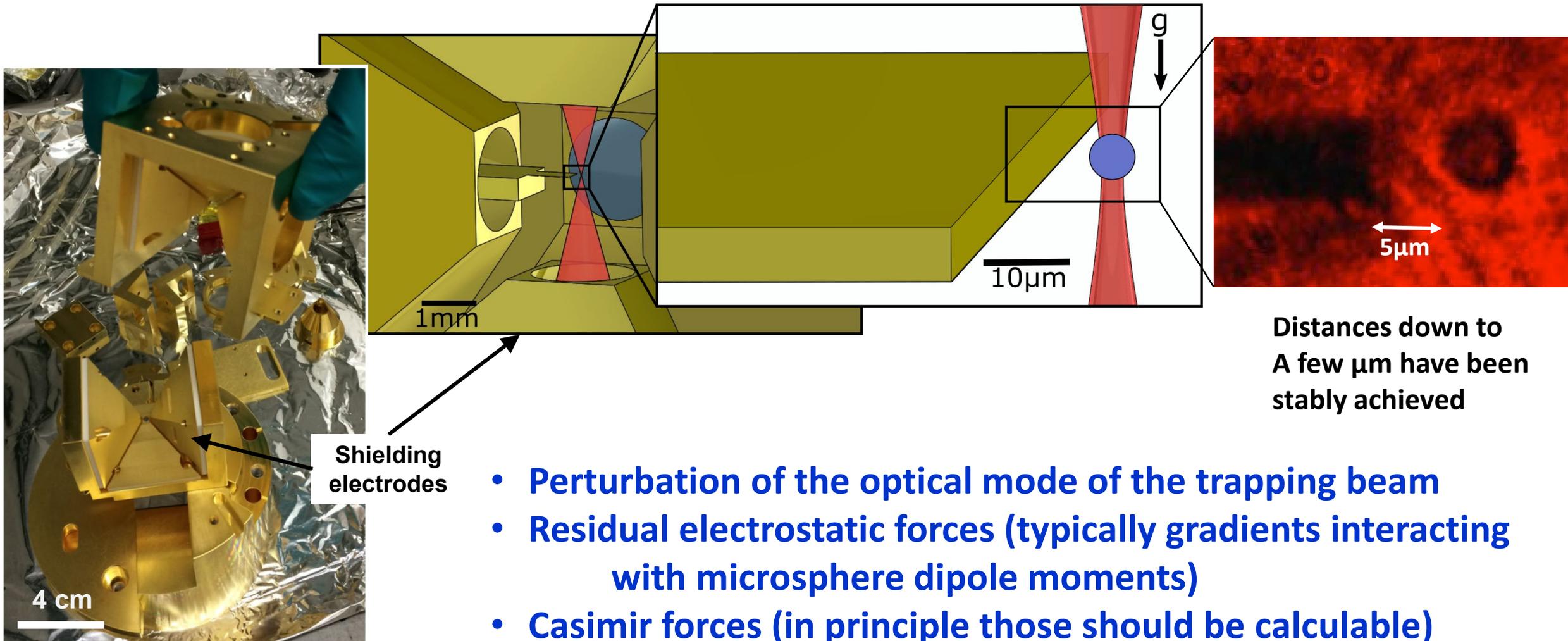


How close to 0 is “0 charge”?

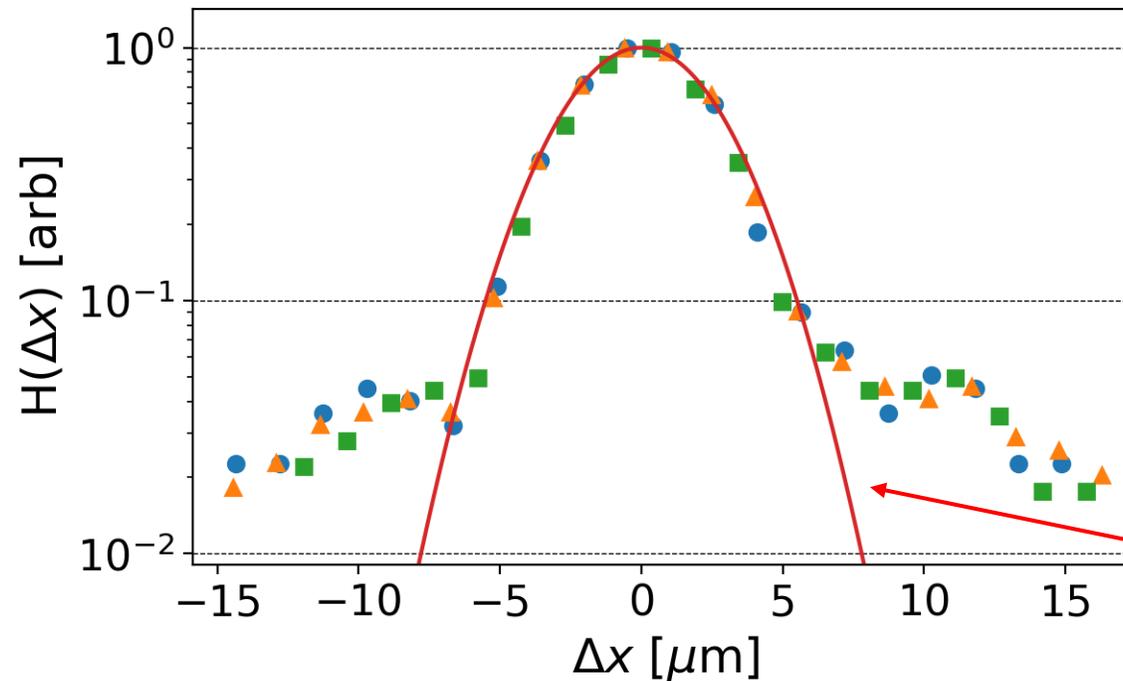
There are small residuals but the response is not consistent with an effective charge.



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



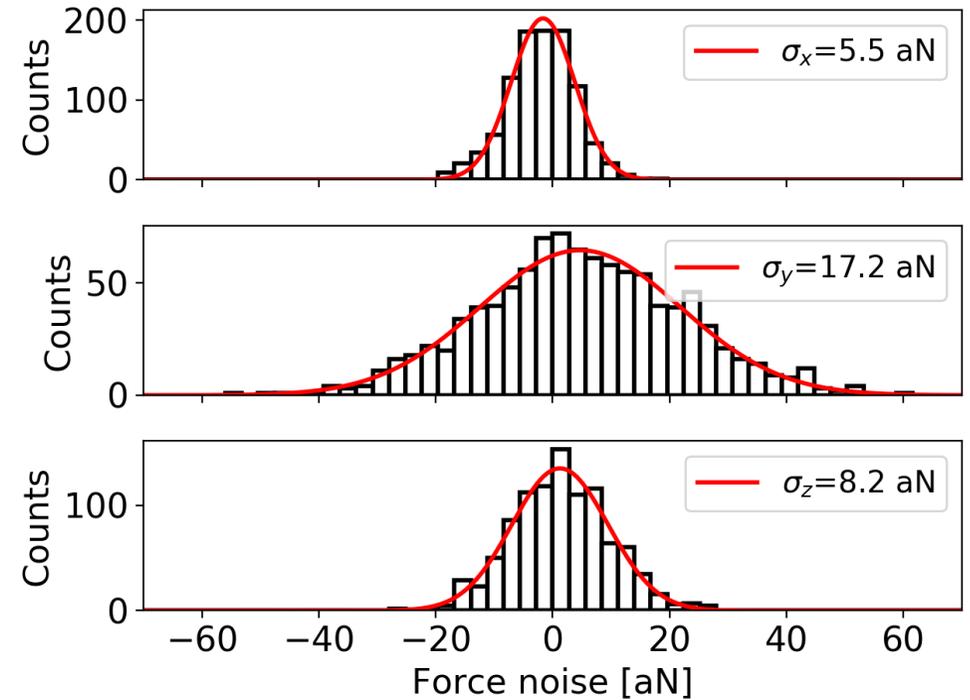
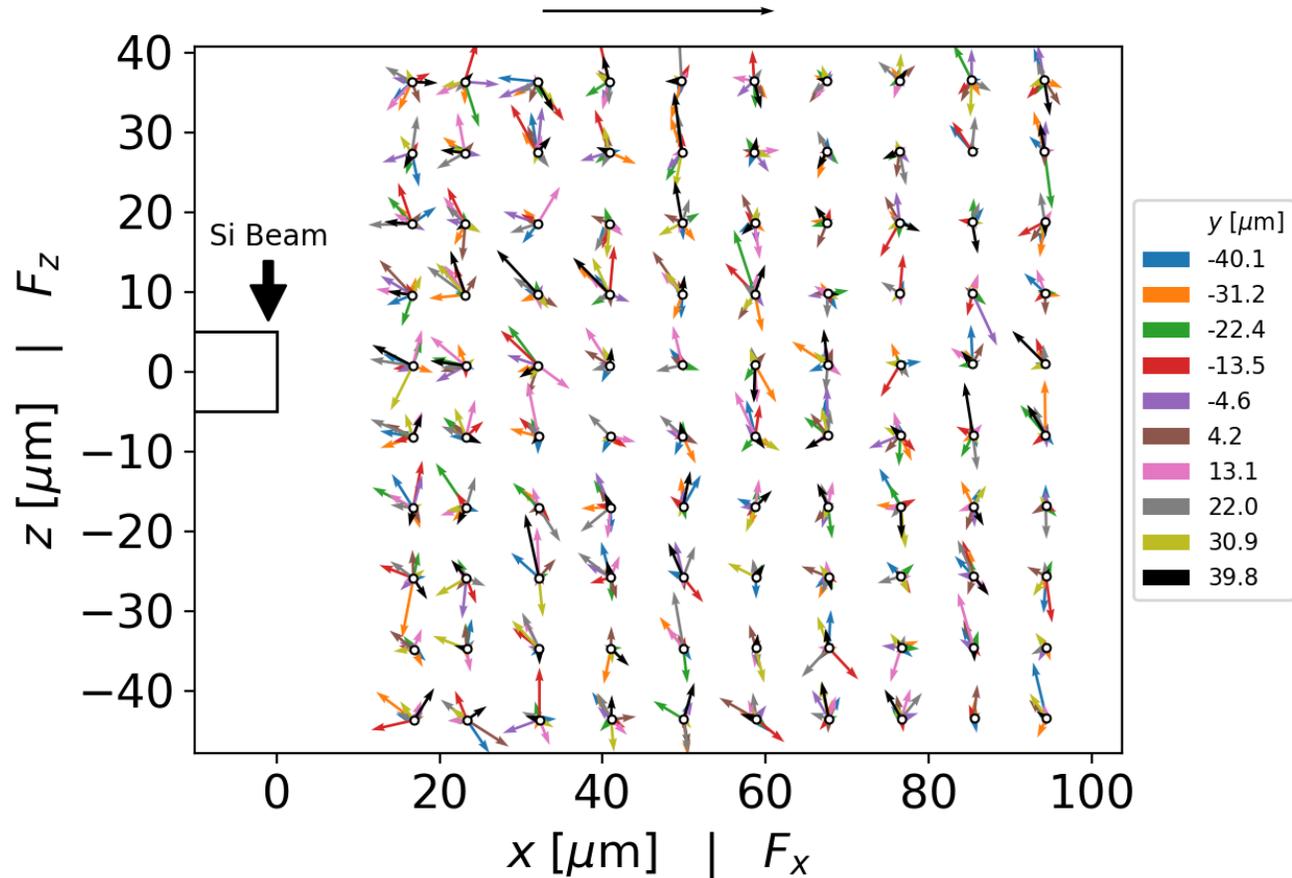
Reasonable Gaussian mode and suppression of scattered light from interferometry *(yet, this needs improving, see later)*



**A priori model from
beam parameters
(only free parameters:
normalization
and centering)**

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

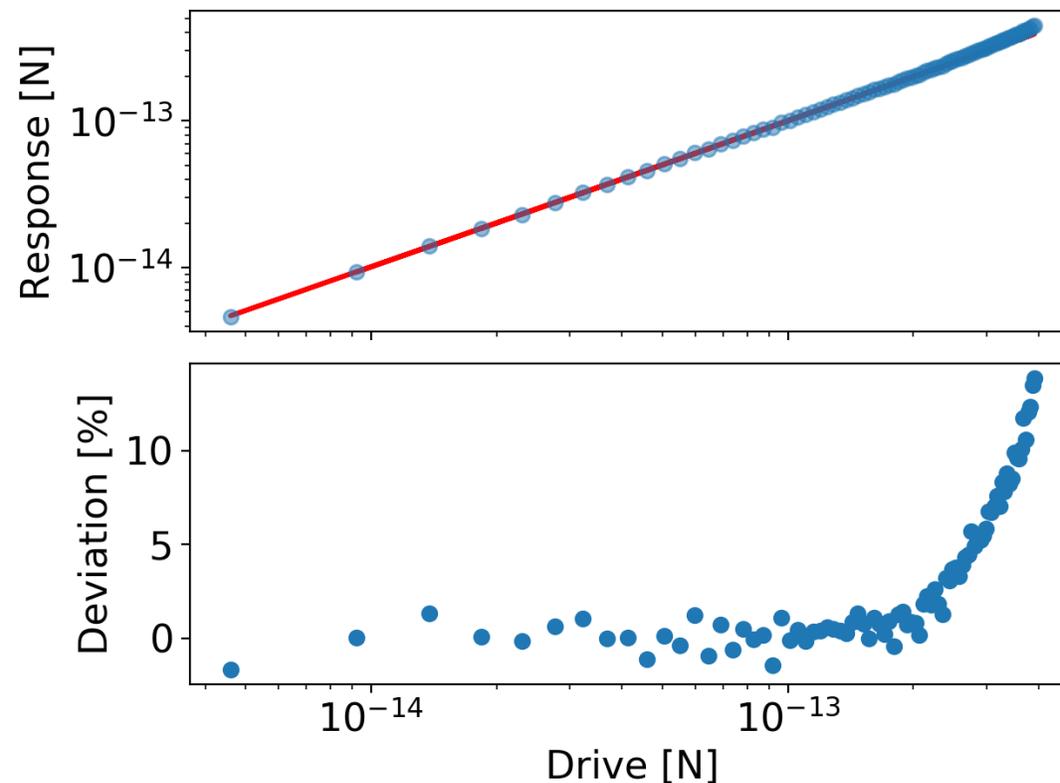
Noise: $1.0 \times 10^{-16} \text{N}$



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

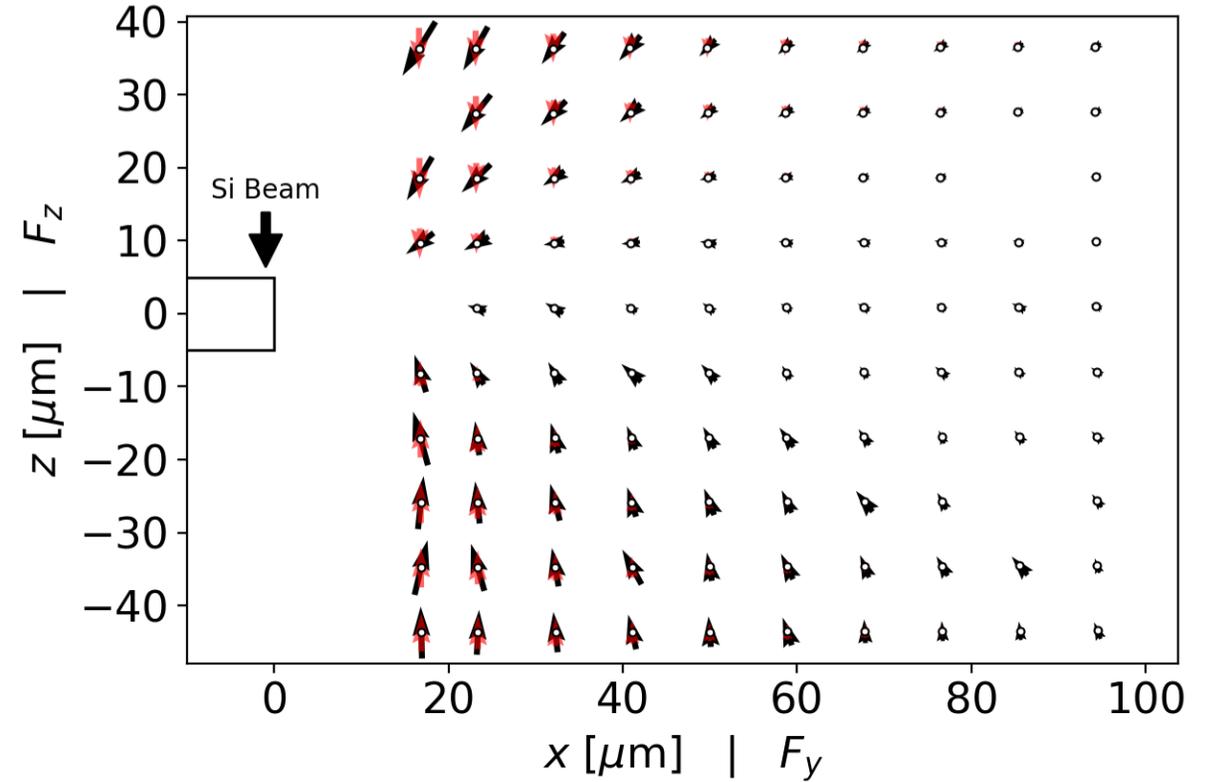
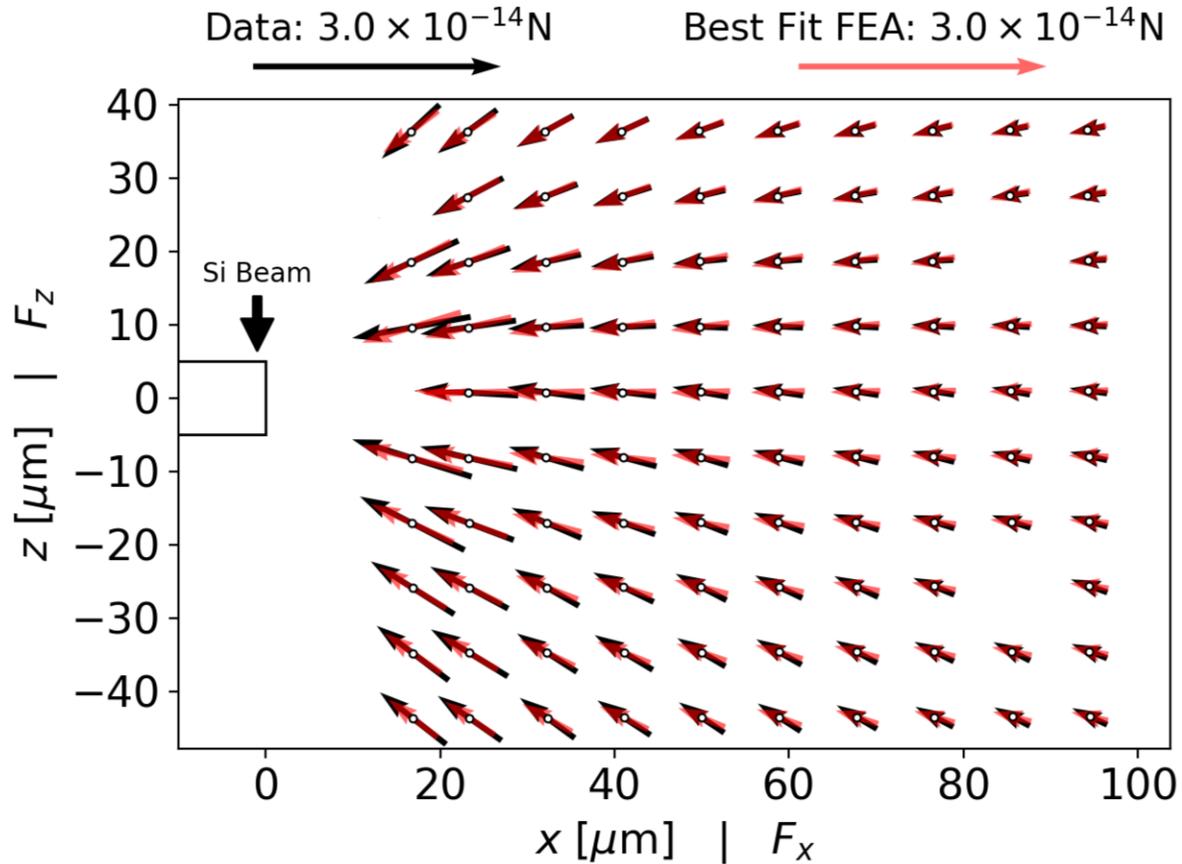
The force sensitivity is linear over several orders of magnitude, so that the microsphere can be used to sense different interactions, with

- state of the art noise
- good linearity
- 3D vector measurement
- relatively large sensitive volume
($80 \times 80 \times 80 \mu\text{m}^3$, limited by the range of the current positioning stage)



**Can't get as close as AFM,
but noise is similar to cryo AFM
and this is a fully 3D measurements in a large volume of space**

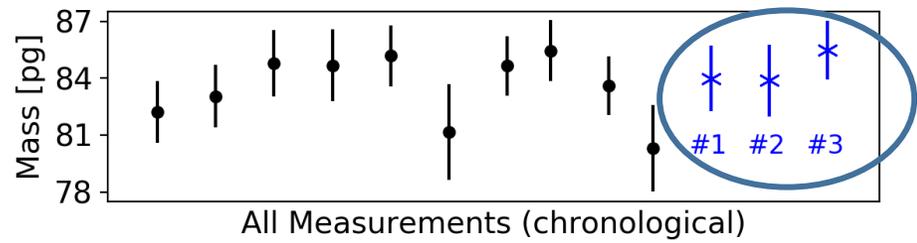
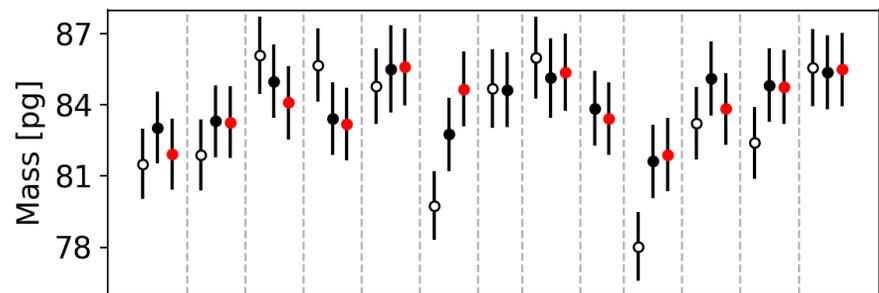
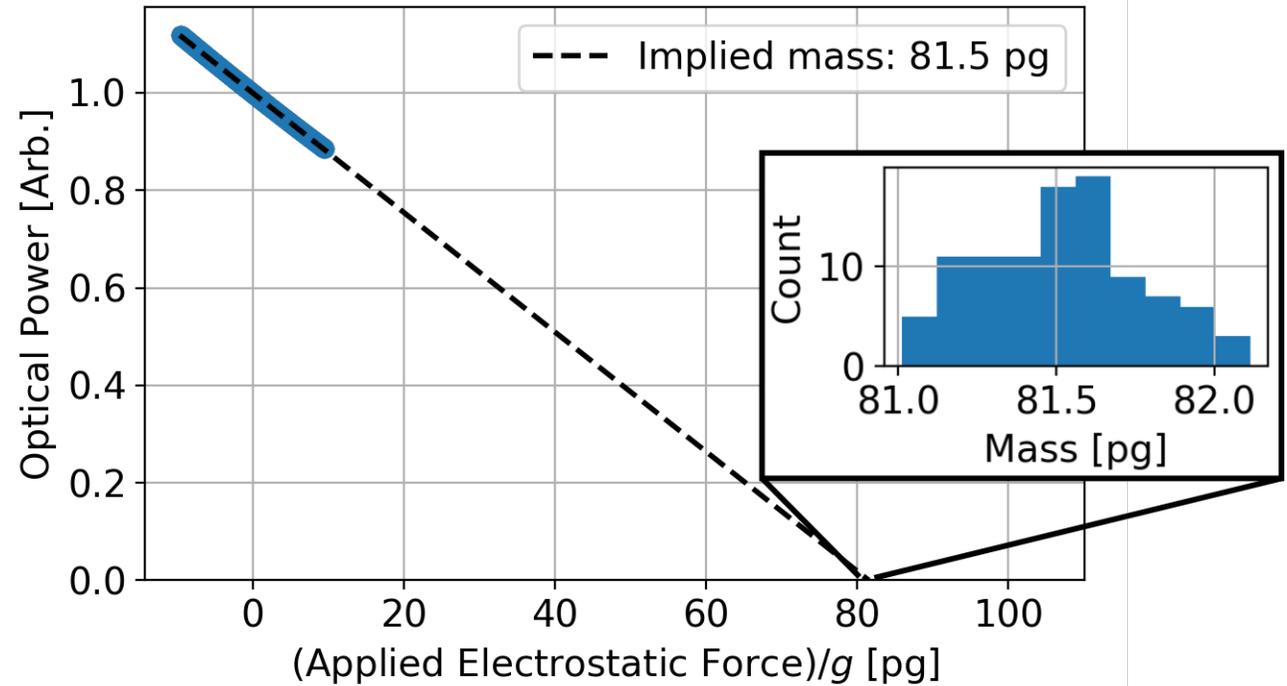
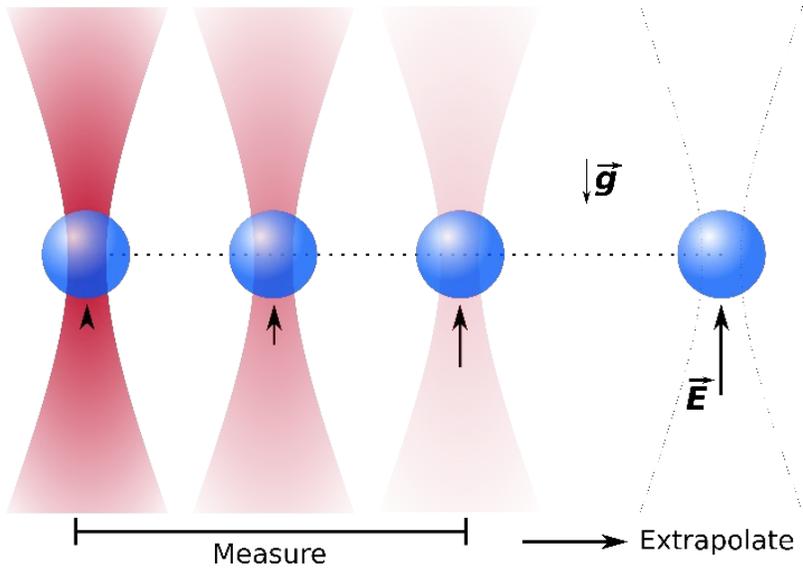
As a demo, full 3D vector mapping of the electric field of a biased attractor (100mV) --here compared to a FEA model



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

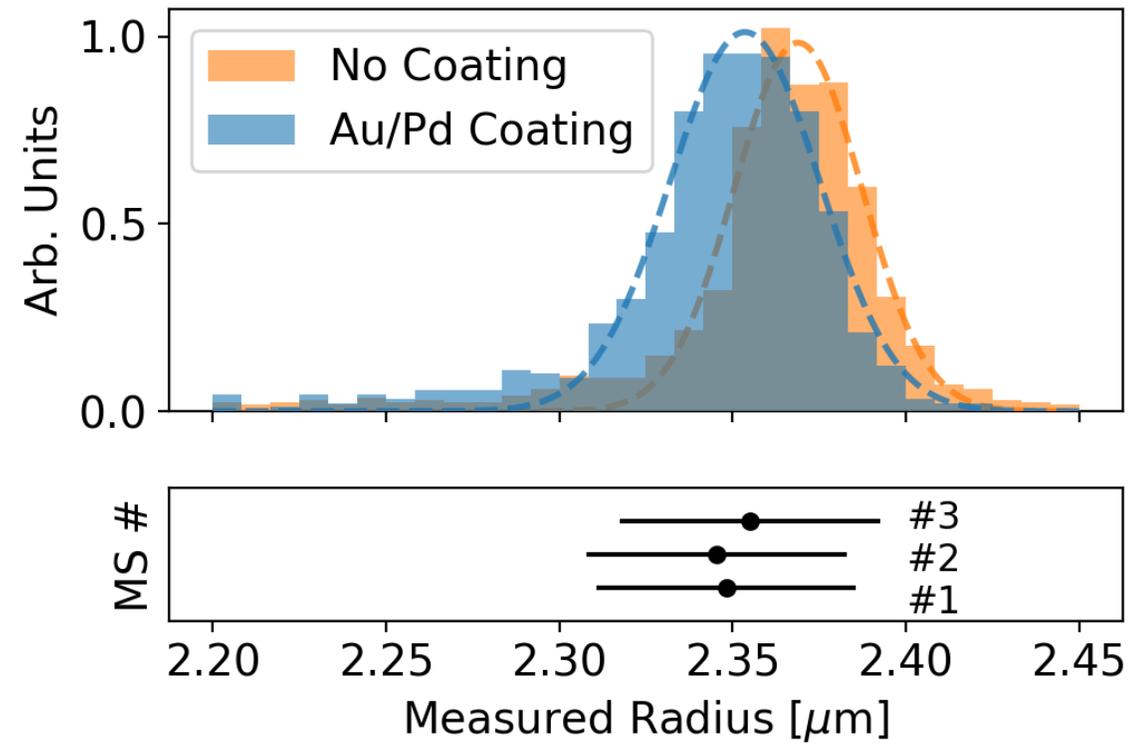
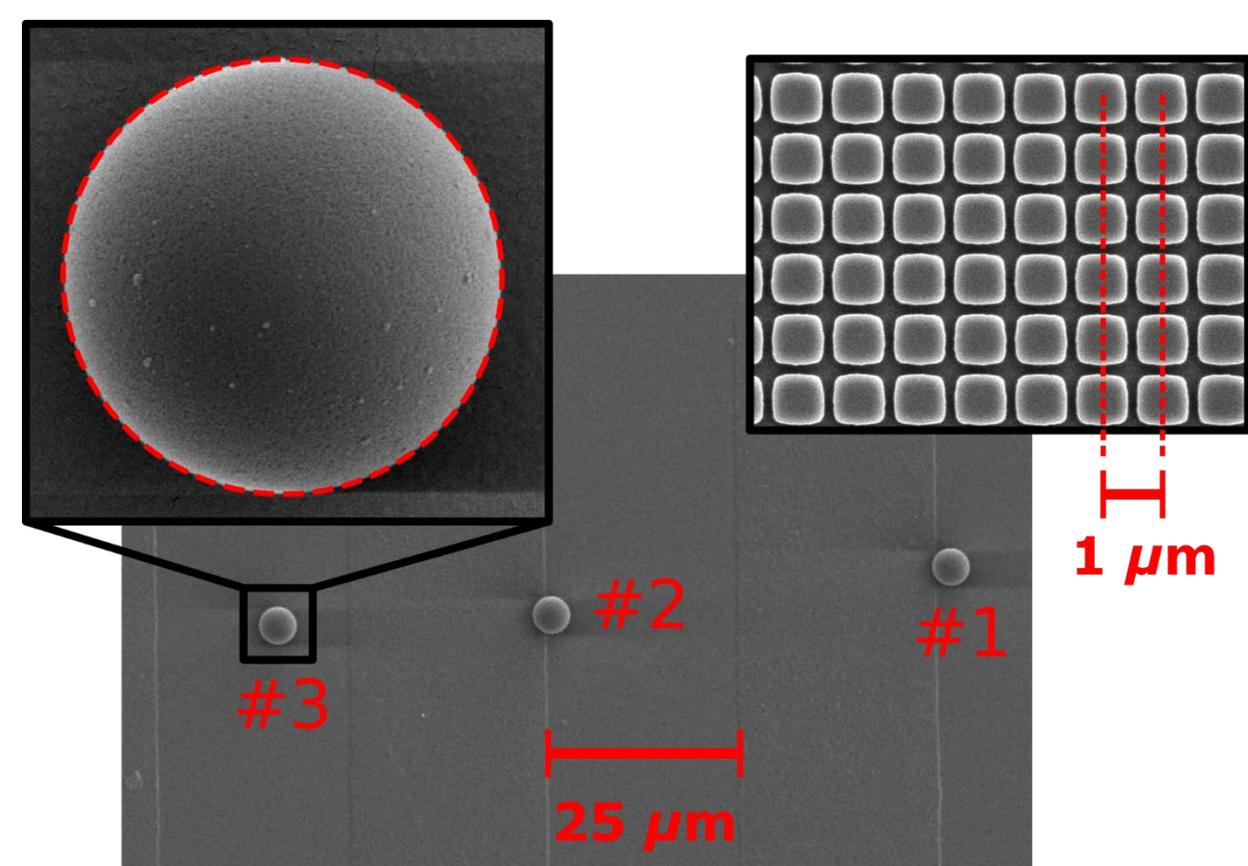
Similar results in G.Winstone et al., Phys. Rev. A 98 (2018) 053831

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 $\rho_{MS} = 1.55 \pm 0.08 \text{ g/cm}^3$
 Density of fused silica is $\rho_{SiO_2} = 2.2 \text{ g/cm}^3$
 → 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

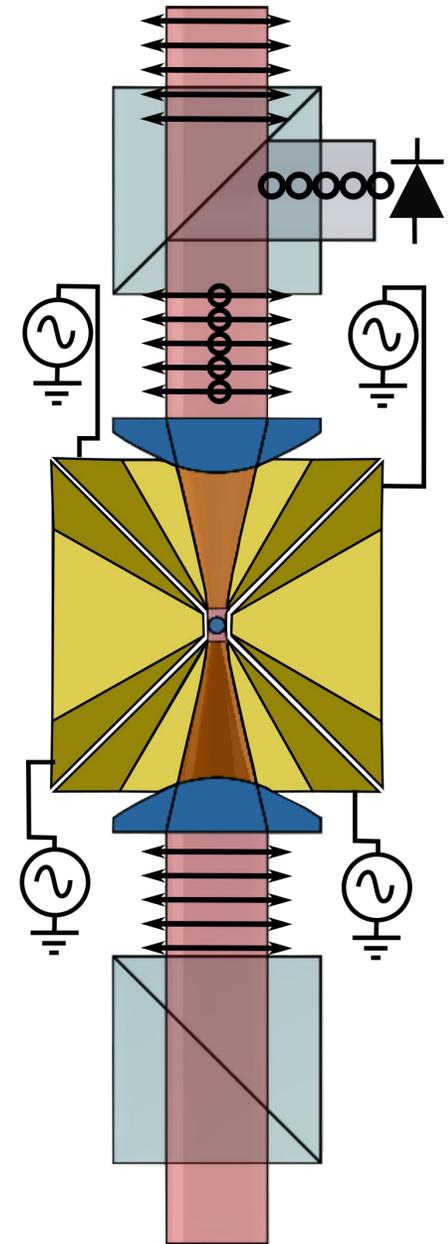
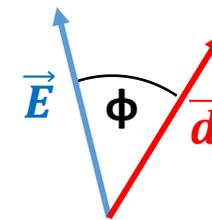
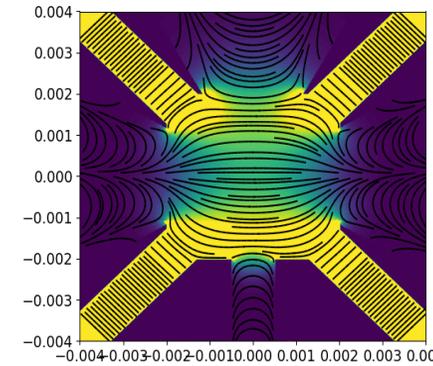
F. Monteiro et al., *Phys. Rev. A* 97 (2018) 051802

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

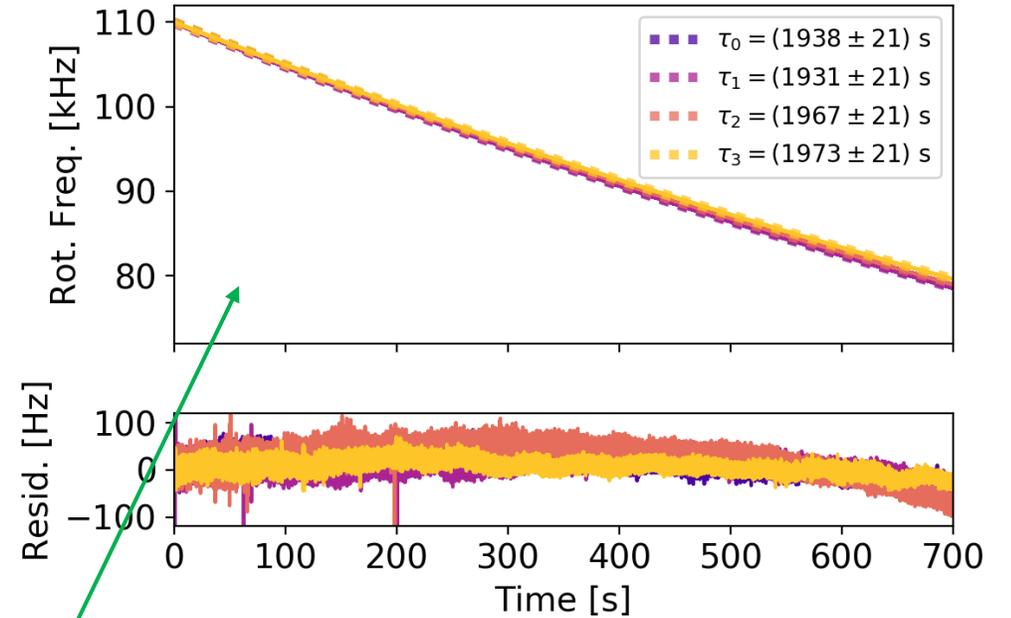
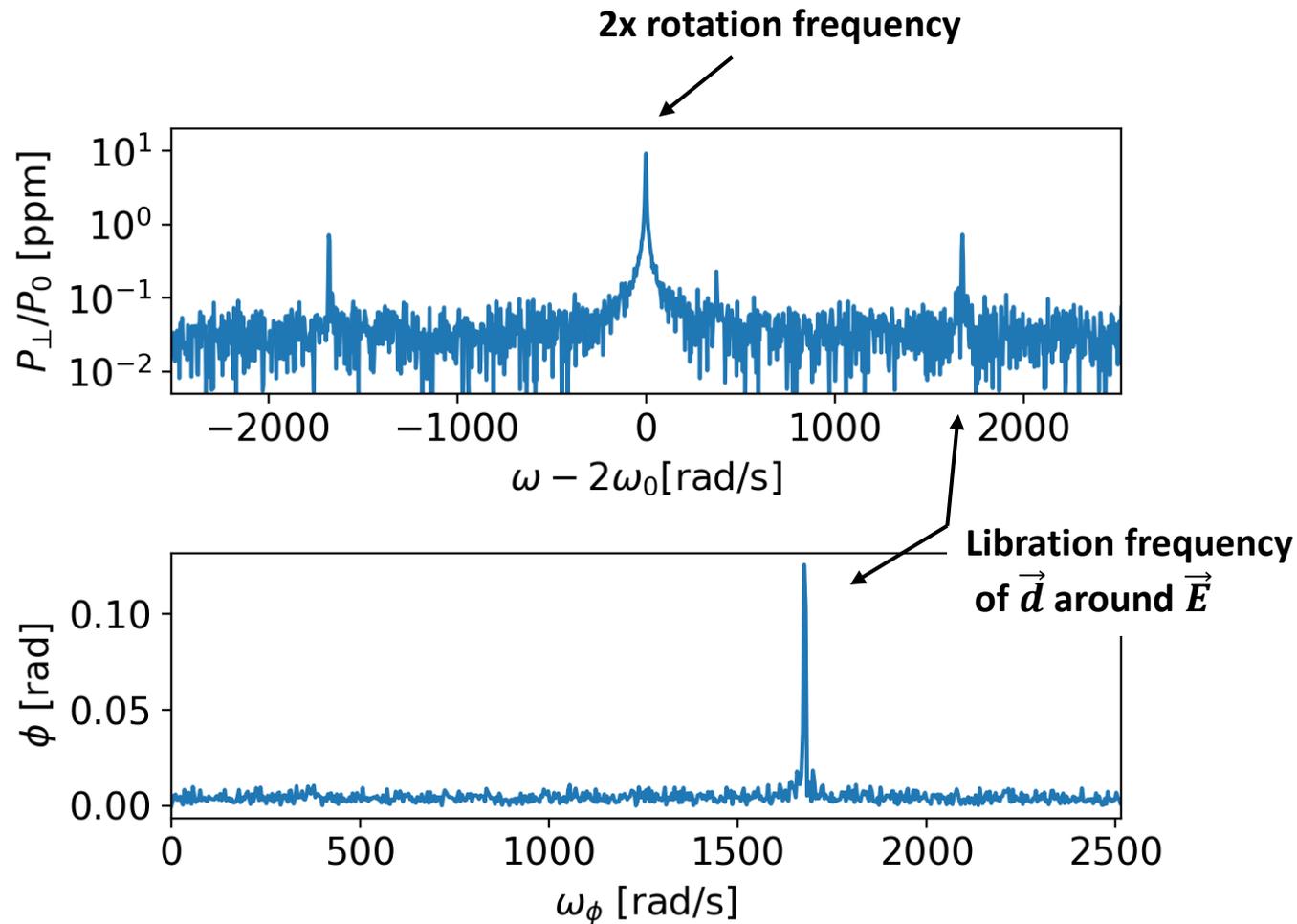
If the microsphere has an electric dipole moment, then a torque can be applied by a rotating external electric field.

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

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

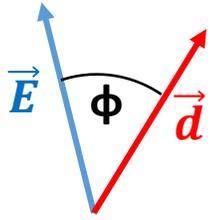


The rotation is read out using the small residual birefringence that the silica microspheres apparently have.

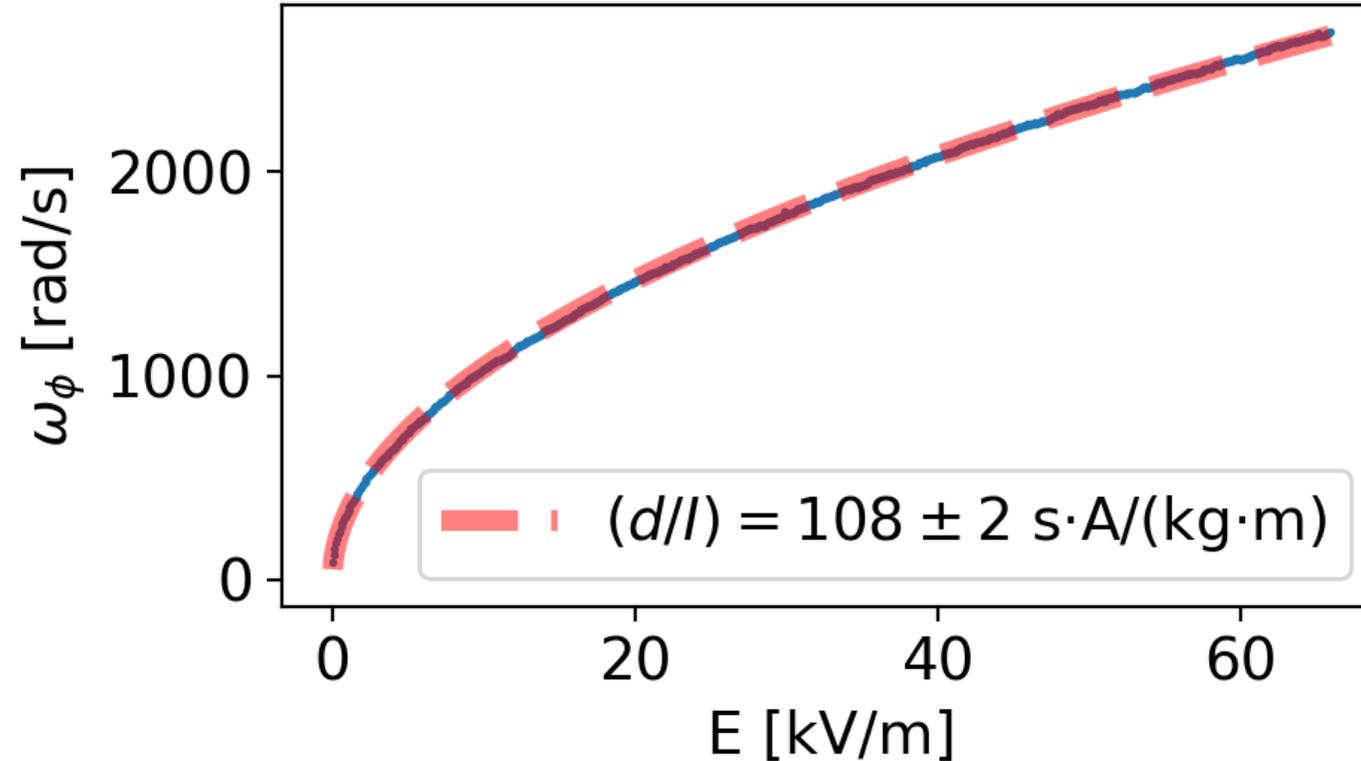


Stopping the driving field makes the microsphere gradually spin-down, with the expected exponential law. The time constant can be translated* into the pressure, like in a rotating ball vacuum gauge.

* 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 $d = 127 \pm 14 \text{ e } \mu\text{m}$

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).

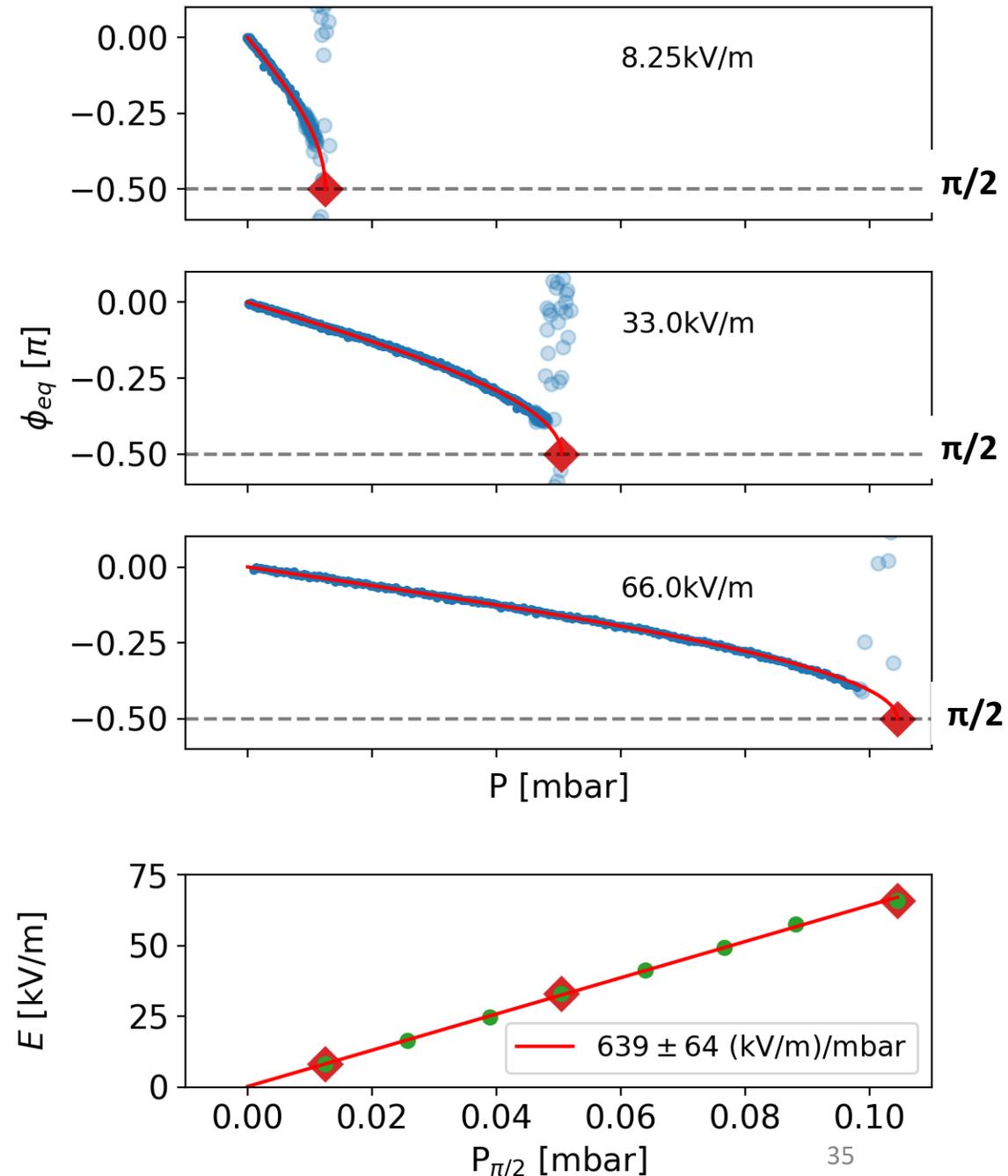
When the phase lag reaches $\pi/2$ the microsphere unlocks from the drive signal (phase \rightarrow random).

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

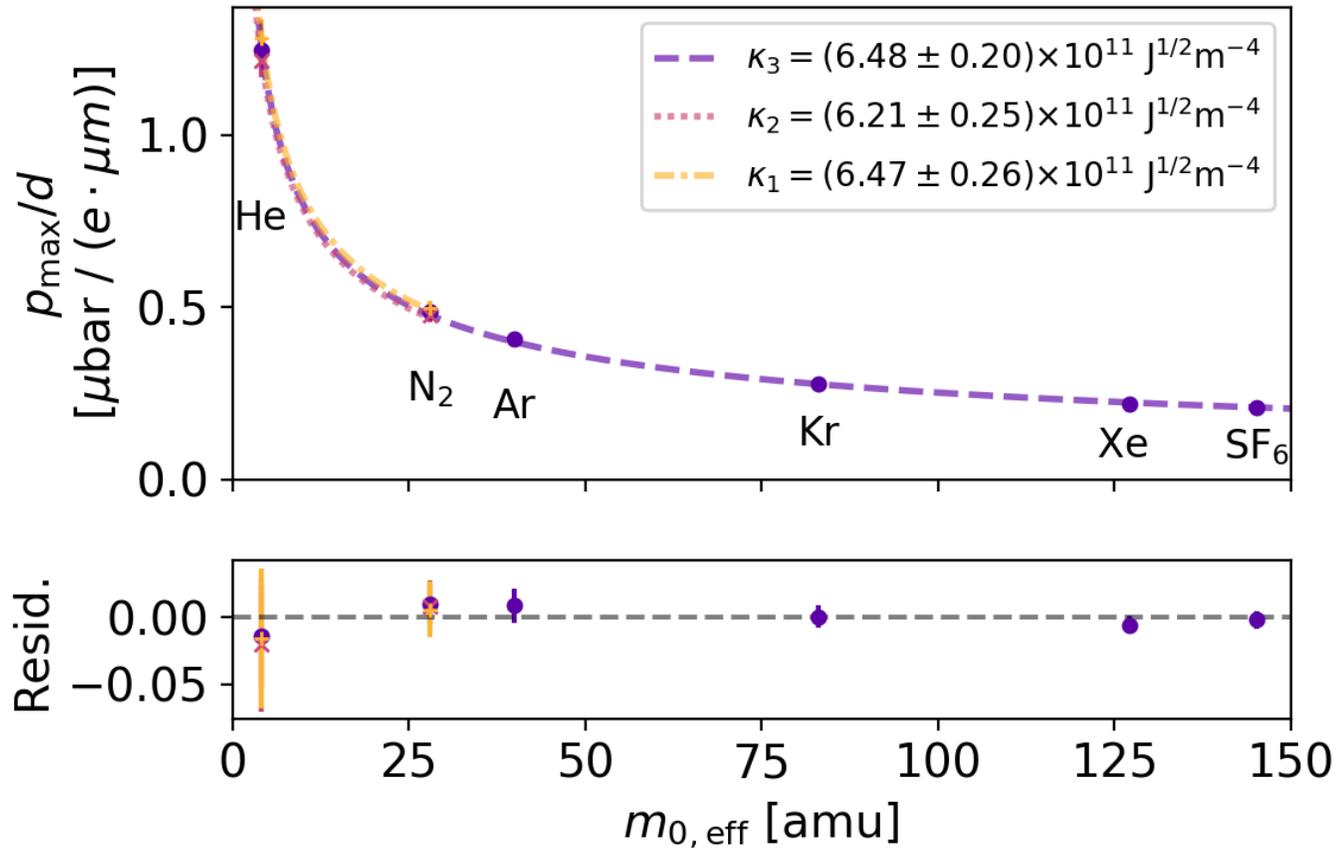
From the fit and d measured above, one can extract the pressure at the microsphere.

- 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 et al, J. Vac. Sci. Technol. B 38, 024201 (2020)

The microsphere is a tiny gyroscope!

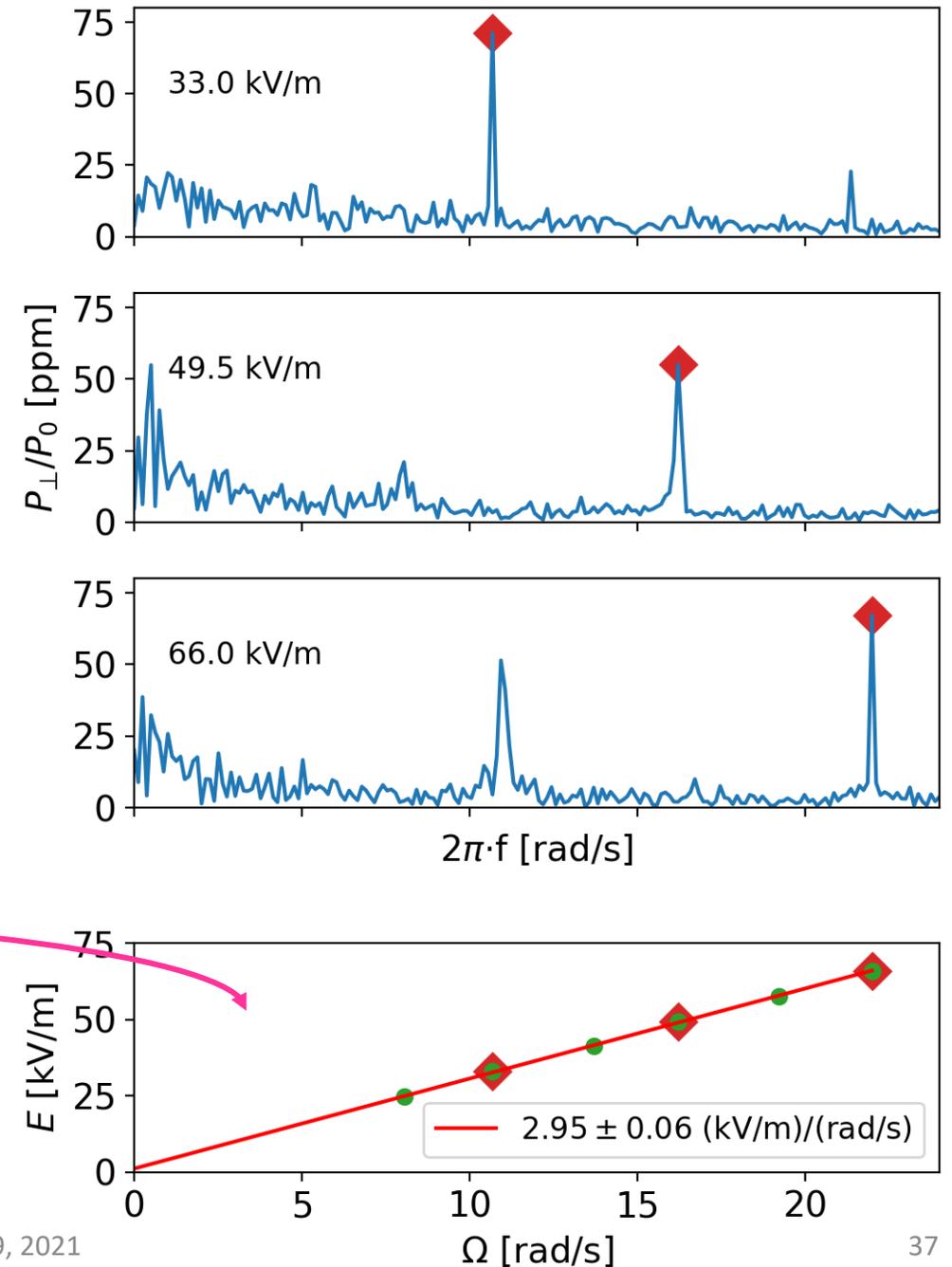
We can watch it precess. After spinning up, apply a torque in the plane orthogonal to that of rotation.

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,

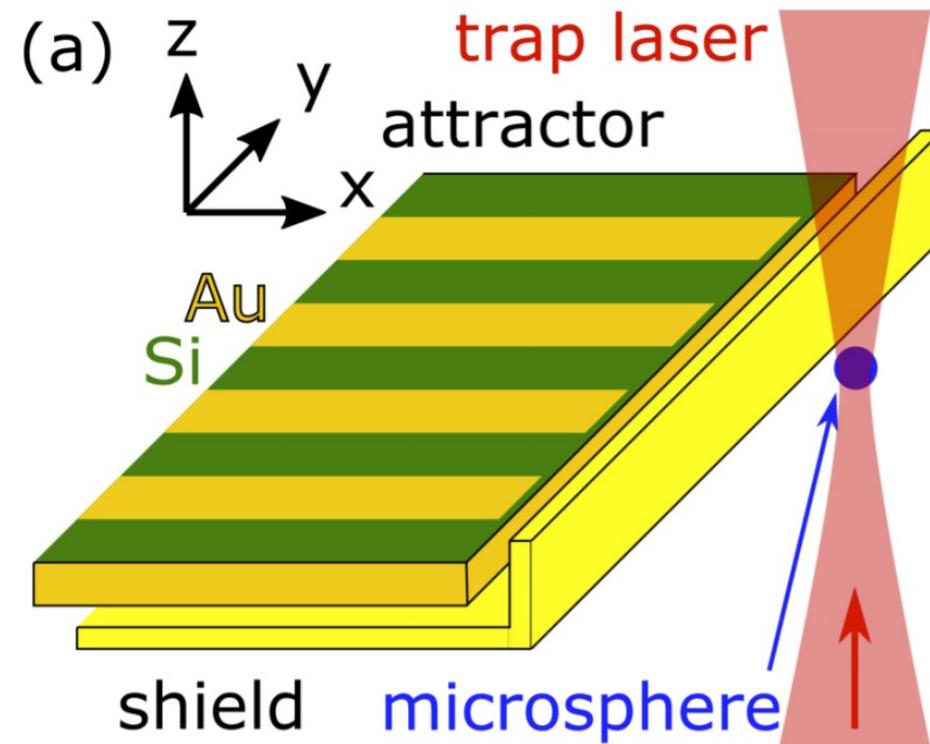
$$\frac{d}{I} = \frac{\Omega \cdot \omega_0}{E} = 106 \pm 2 \text{ s A}/(\text{kg m})$$

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

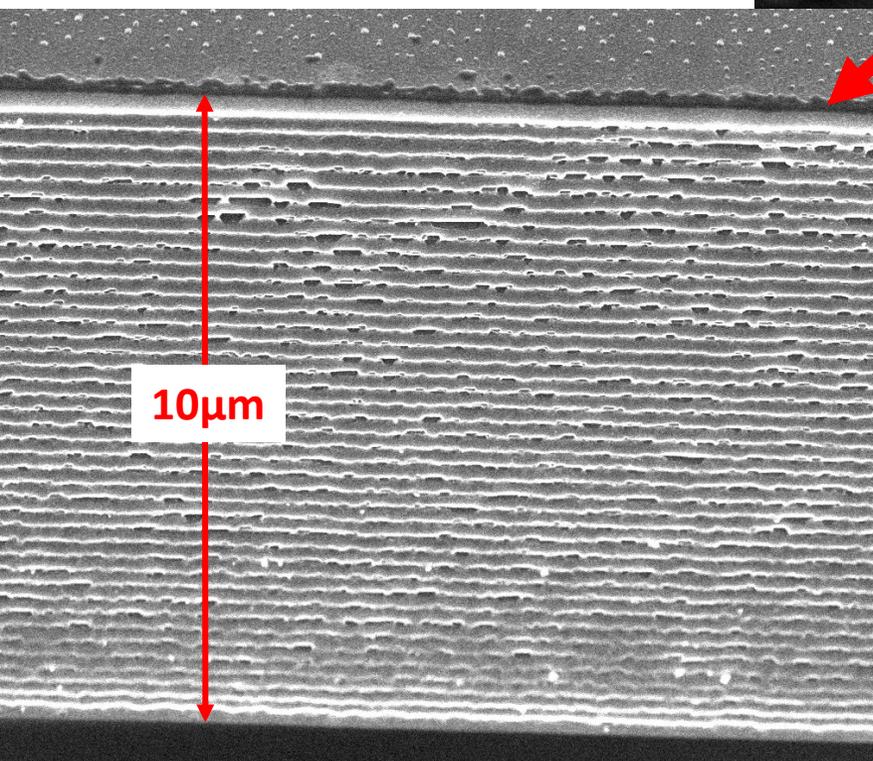
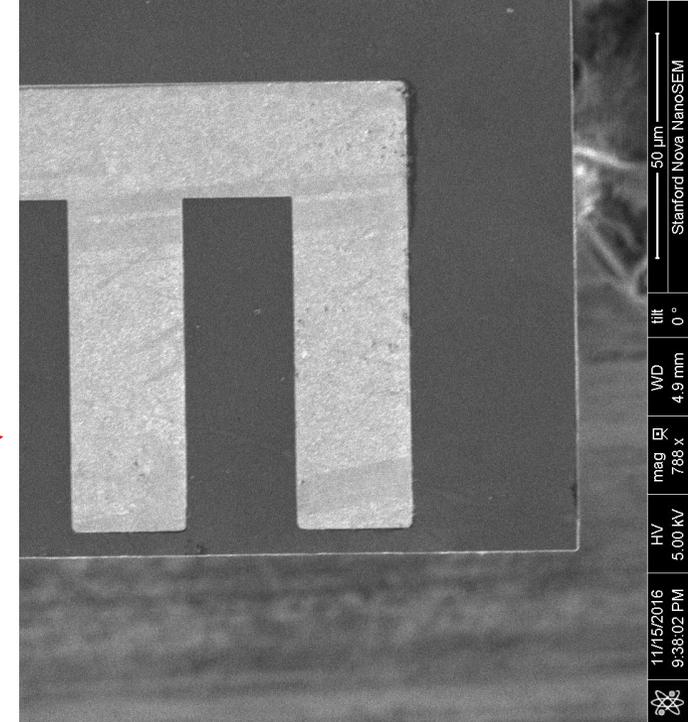
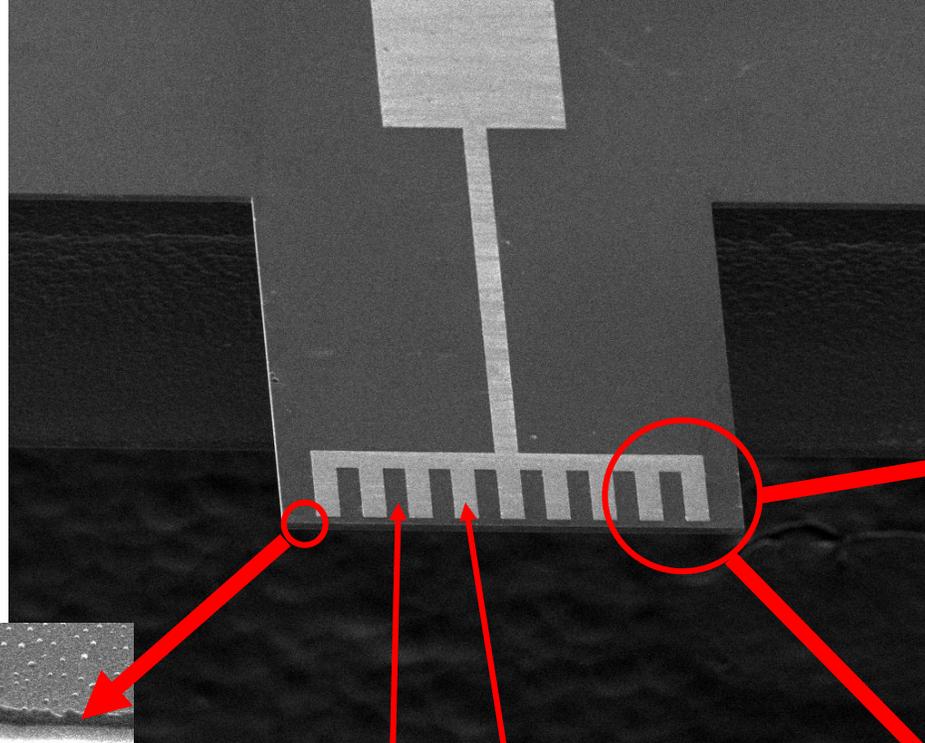


First gravity run

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



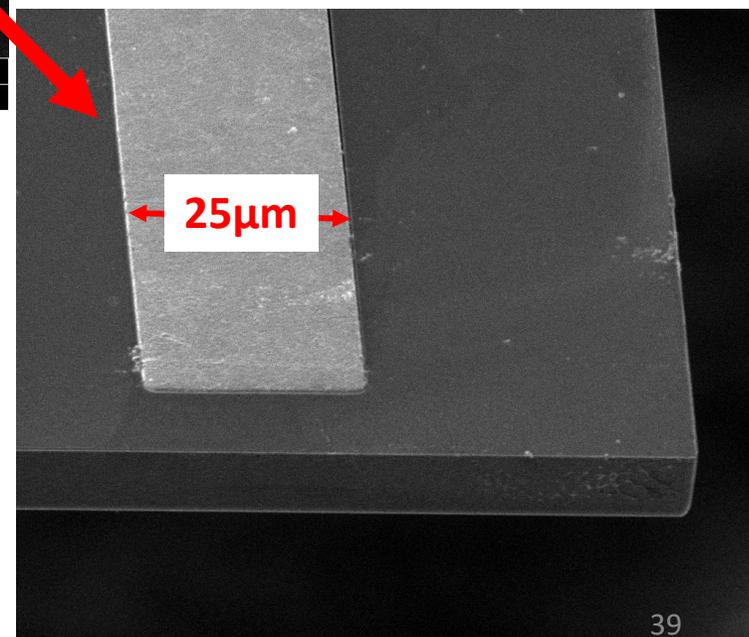
First generation attractor set, here shown before Au coating



11/15/2016 5:55 PM HV 5.00 kV mag 130 x WD 3.5 mm tilt 45° 300 μm Stanford Nova NanoSEM

Si

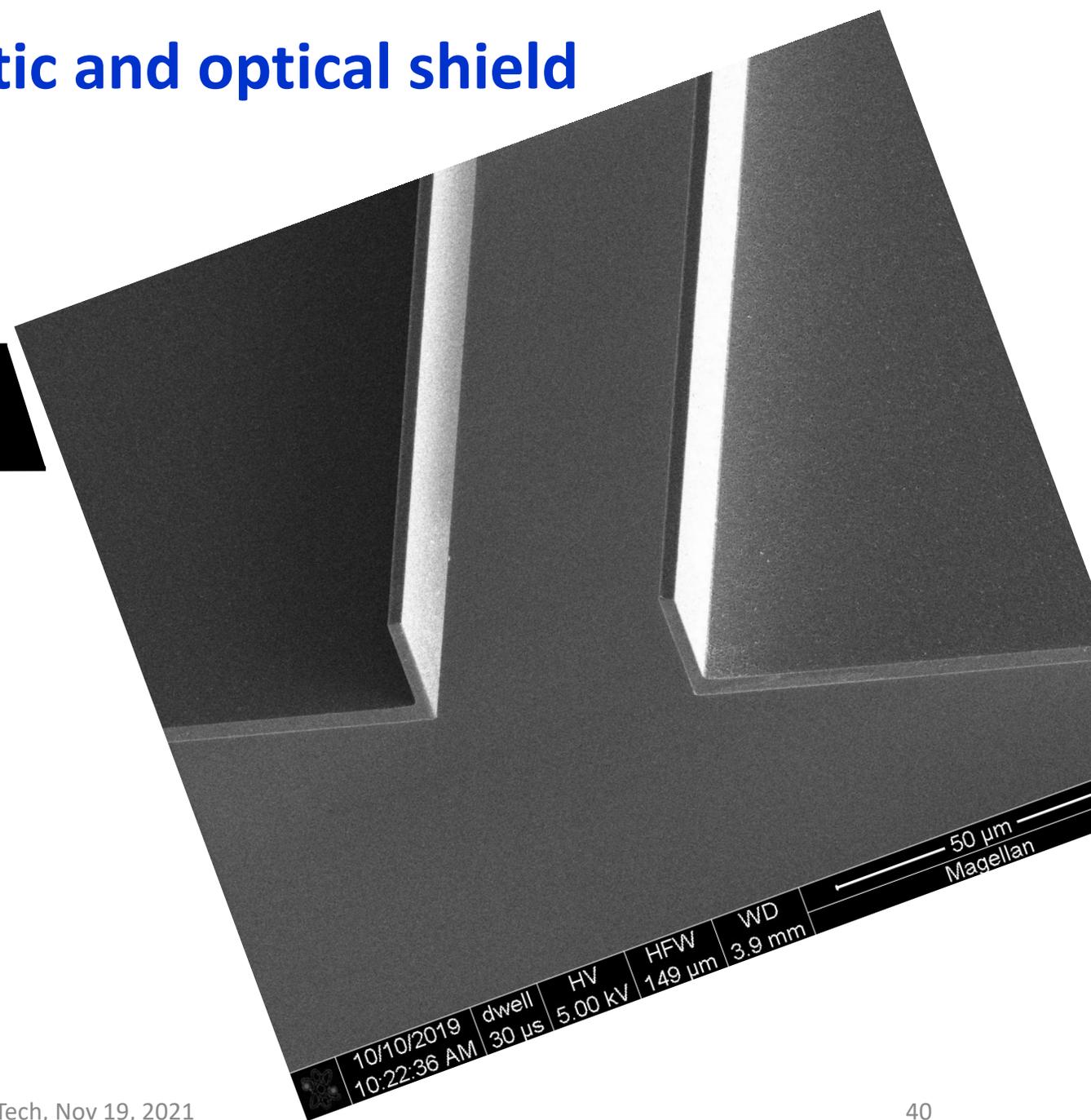
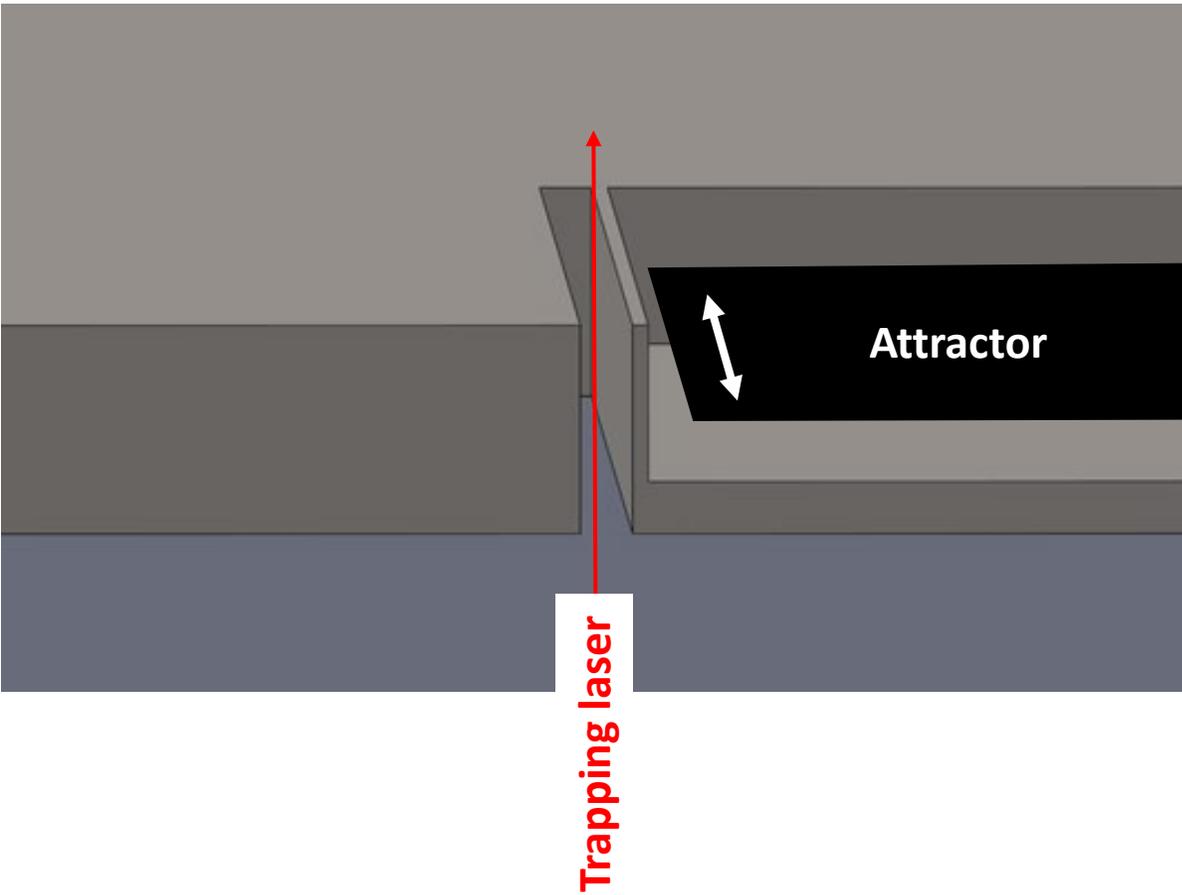
Au



11/15/2016 10:10:57 PM HV 5.00 kV mag 13361 x WD 3.7 mm tilt 45° 2 μm Stanford Nova NanoSEM

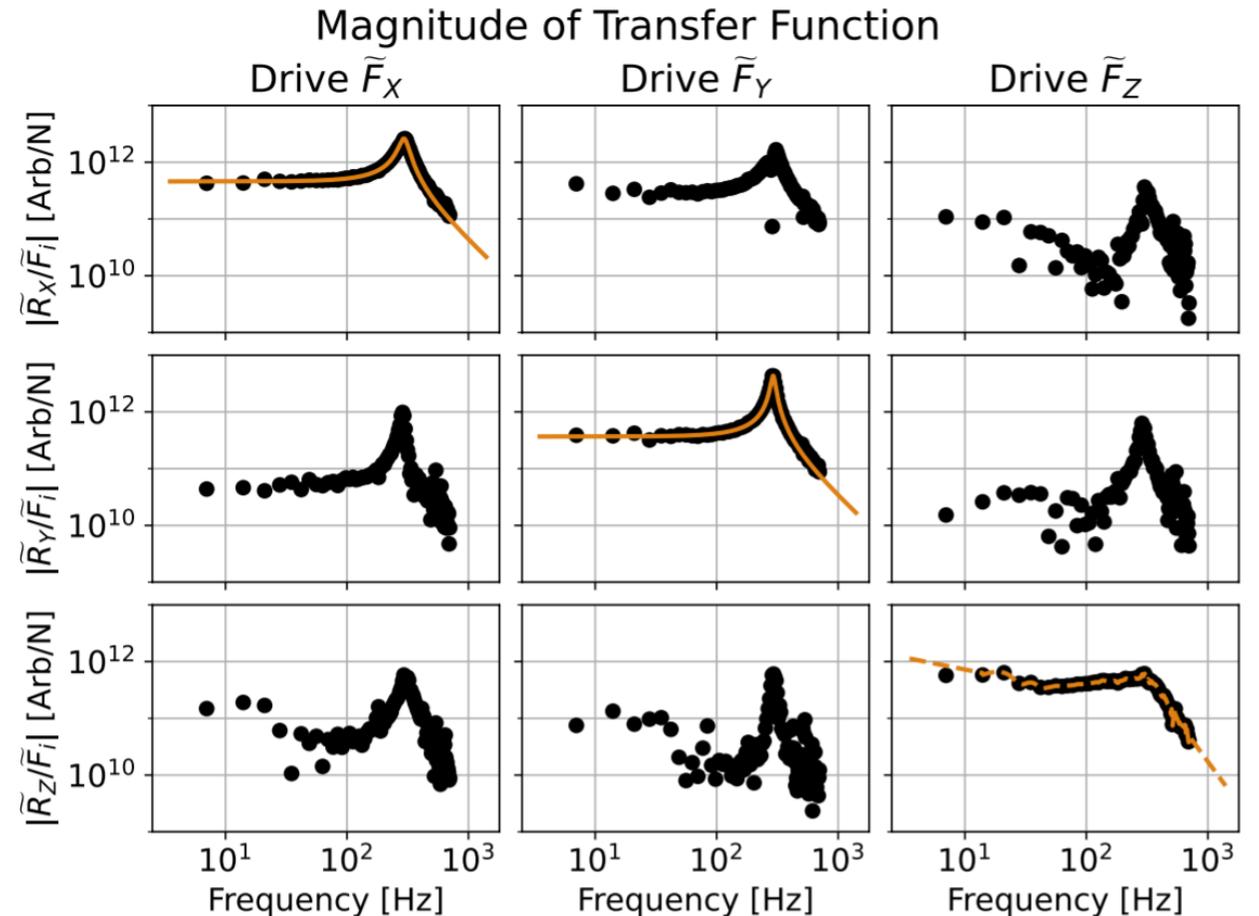
11/15/2016 10:06:32 PM HV 5.00 kV mag 1521 x WD 3.8 mm tilt 45° 20 μm Stanford Nova NanoSEM

Standing electrostatic and optical shield

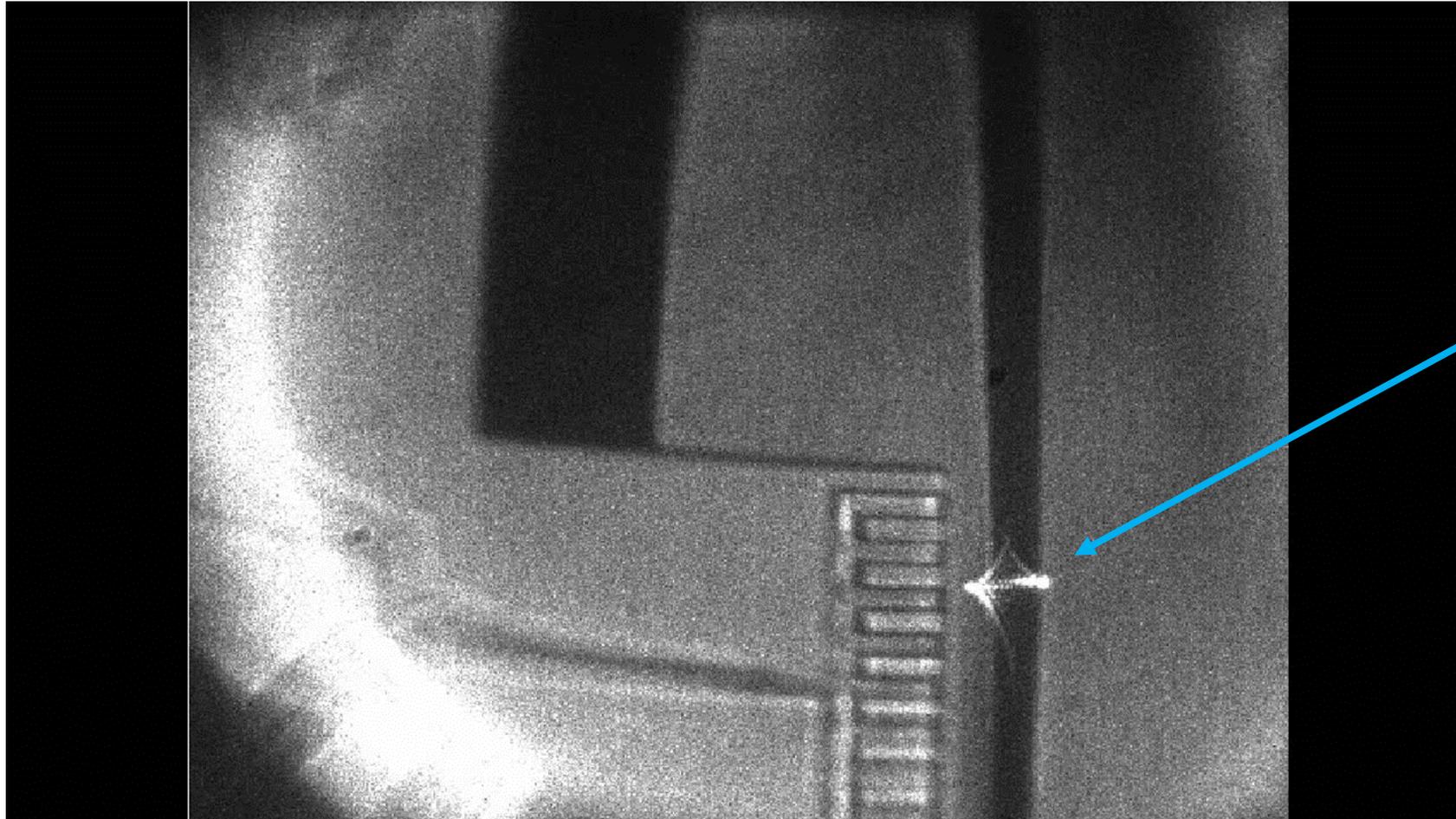


Force calibration

- Sphere is prepared with a known 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



Example of scanning



Trap with
microsphere

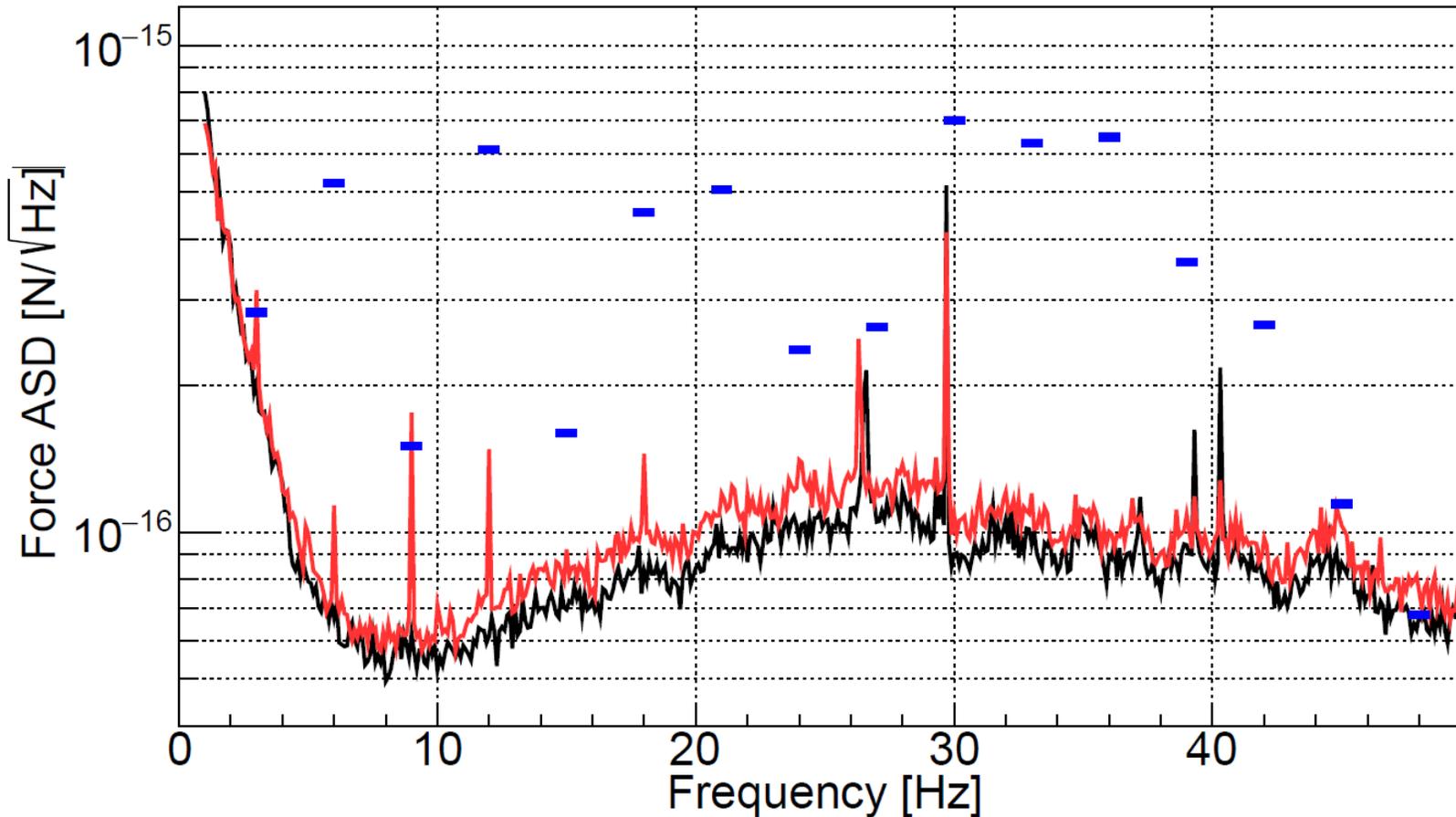
Top view

$\vec{g} \odot$

Actual frequency: 13 Hz

For this test, distance attractor – microsphere center: 85 μm

First gravity run

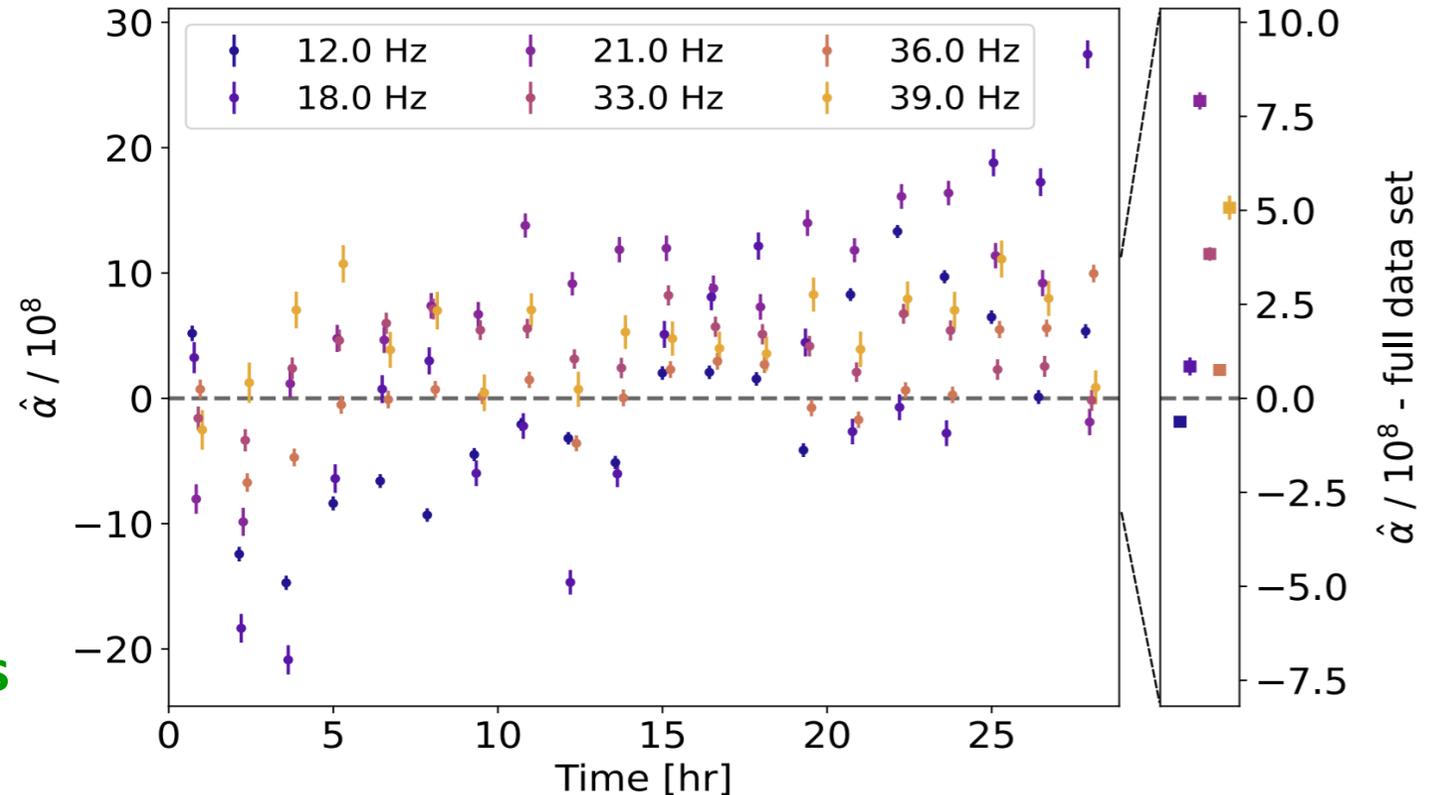


Force sensitivity: 10^{-16} N/ \sqrt{Hz}

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

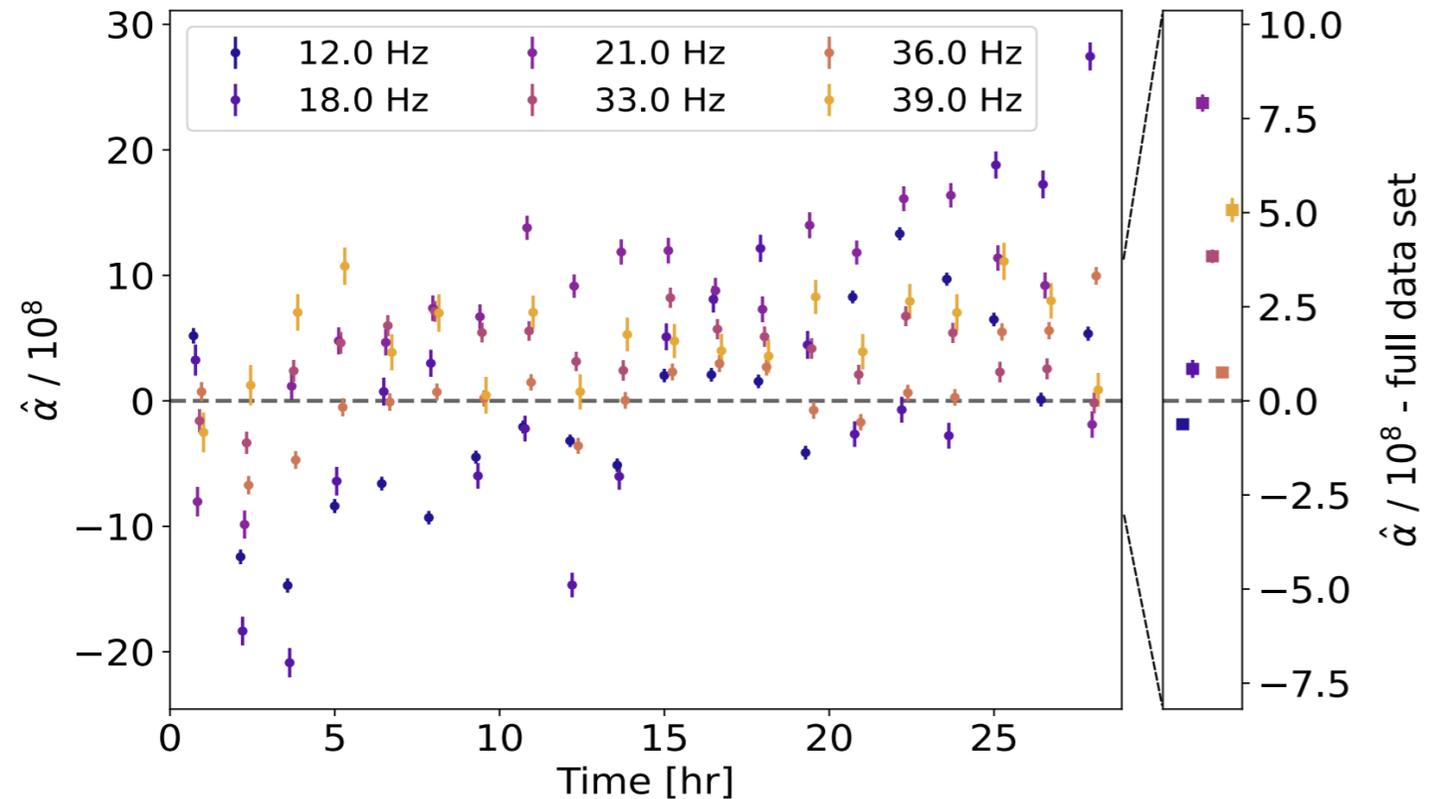
Z channel data

- 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

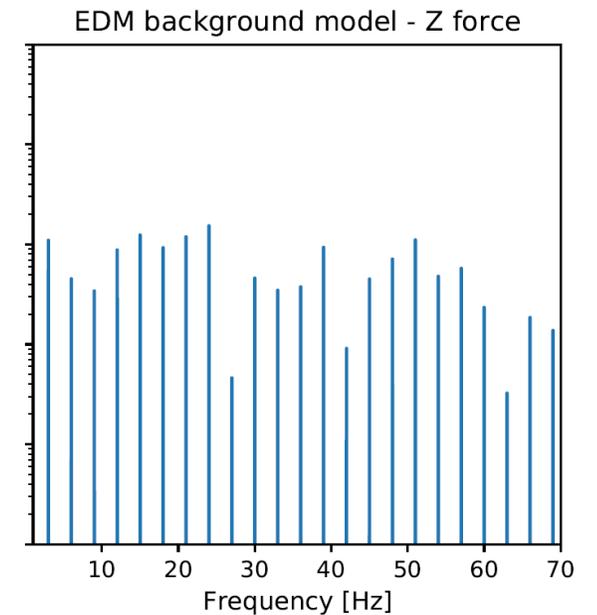
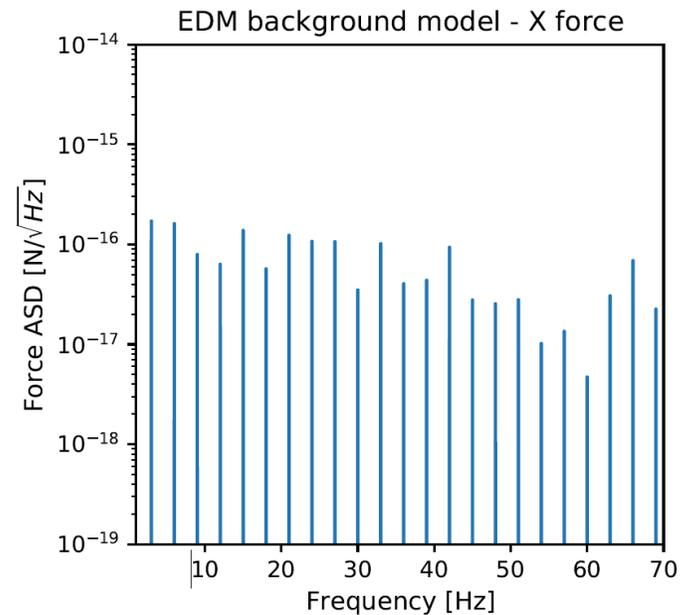


- Field gradients are not fully suppressed by the shield and create backgrounds due to coupling to the dipole moments

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

- 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.



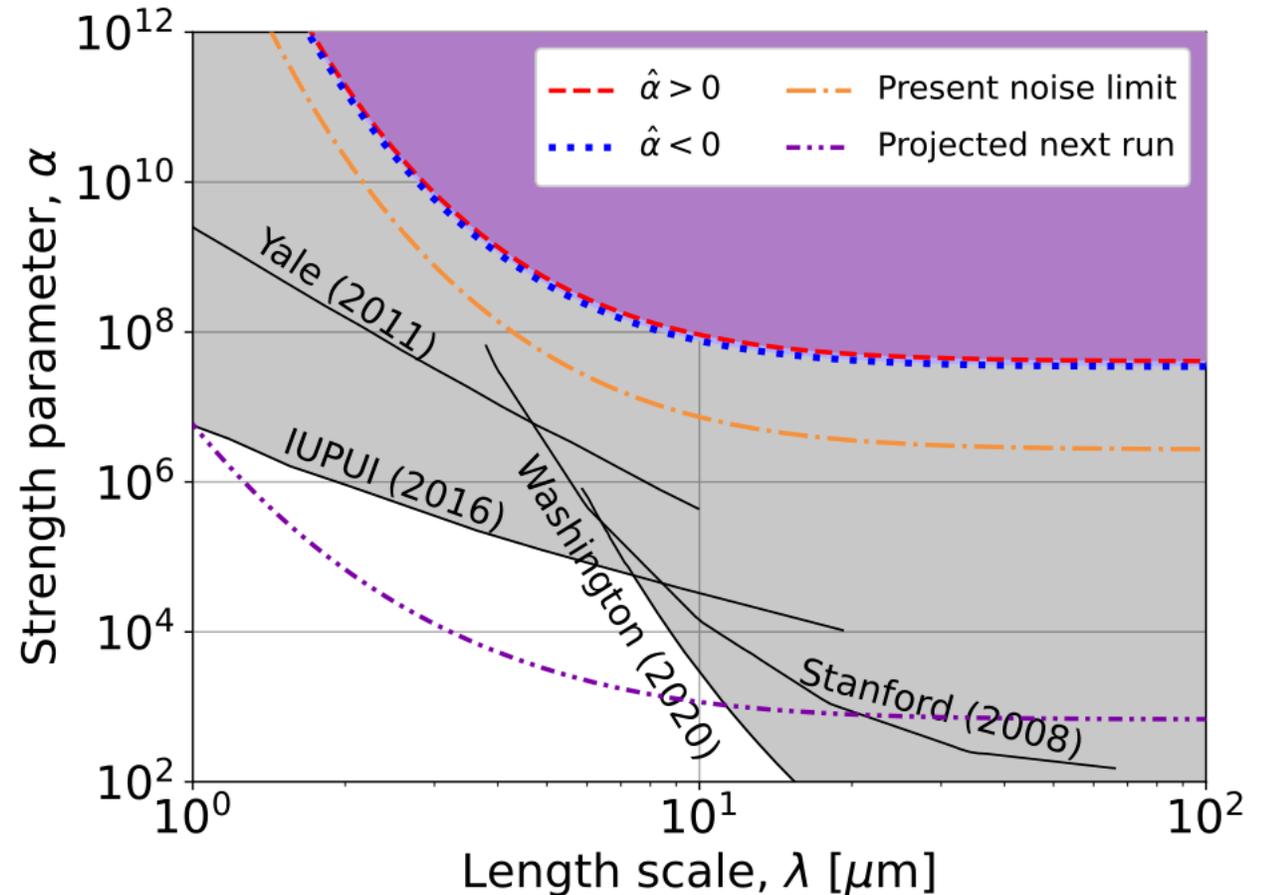
Other background sources (in order of likely importance):

- **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

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.
- Beyond this, need to reduce the pointing noise.

C.Blakemore *et al.*, arXiv:2102.06848 (2021)
to appear on Phys. Rev. D



Ongoing upgrades

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

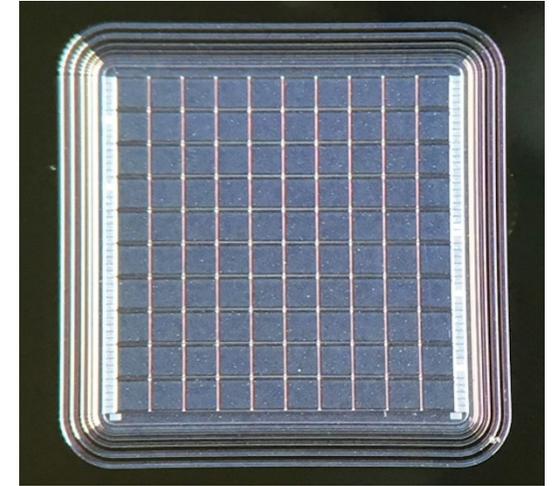
Near future improvements:

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

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

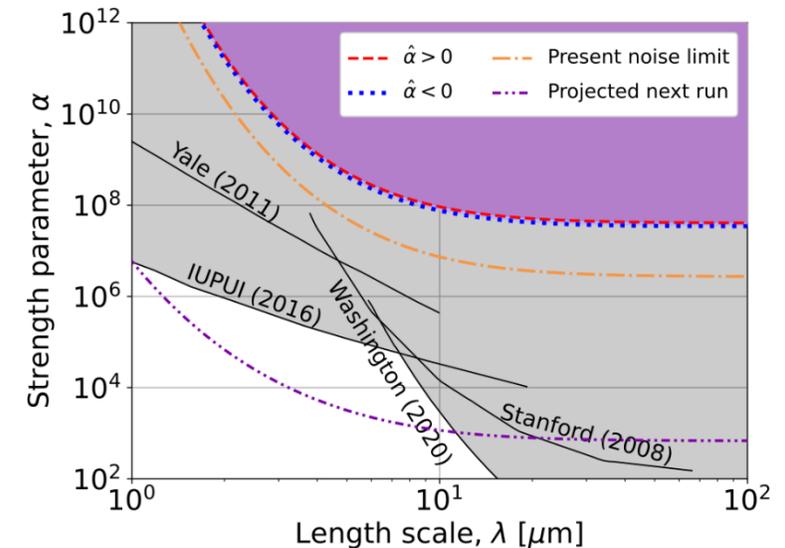
- Rotary attractor
- Less (no) vibration at the fundamental frequency
- Fit the existing trap
- Can mitigate existing backgrounds
- In collaboration with EPFL

← 5mm →



Conclusions

- After >200 years of mechanical springs, the $1/R^2$ behavior of gravity $50\mu\text{m}$ is now tested with optically levitated microspheres.
- It took a few years to establish this new technique and...
- Along the way we have discovered a wealth of tricks and applications to other areas of physics.
- A first measurement is now available, resulting in a conservative limit.
- All scales in this new measurement are in the μm range.
- The measurement is limited by backgrounds that we now start understanding well.
- A number of system upgrades are in progress and we hope to restart data taking in the late summer, with much improved sensitivity.





The cast



Also thank our "alter egos" at Yale:

G. Afek, D. Moore, B. Siegel, J. Wang, M. Watts

