

Searching for new forces at micron scale and other fun tricks with levitated microspheres

Microsphere
(not to scale)

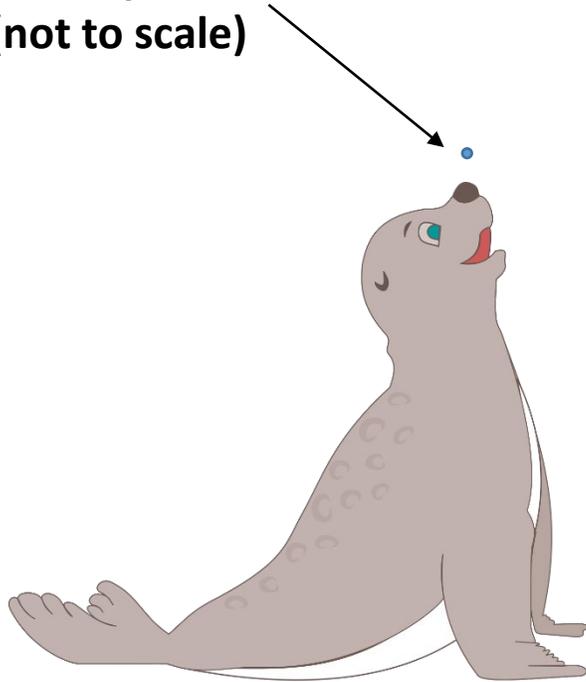
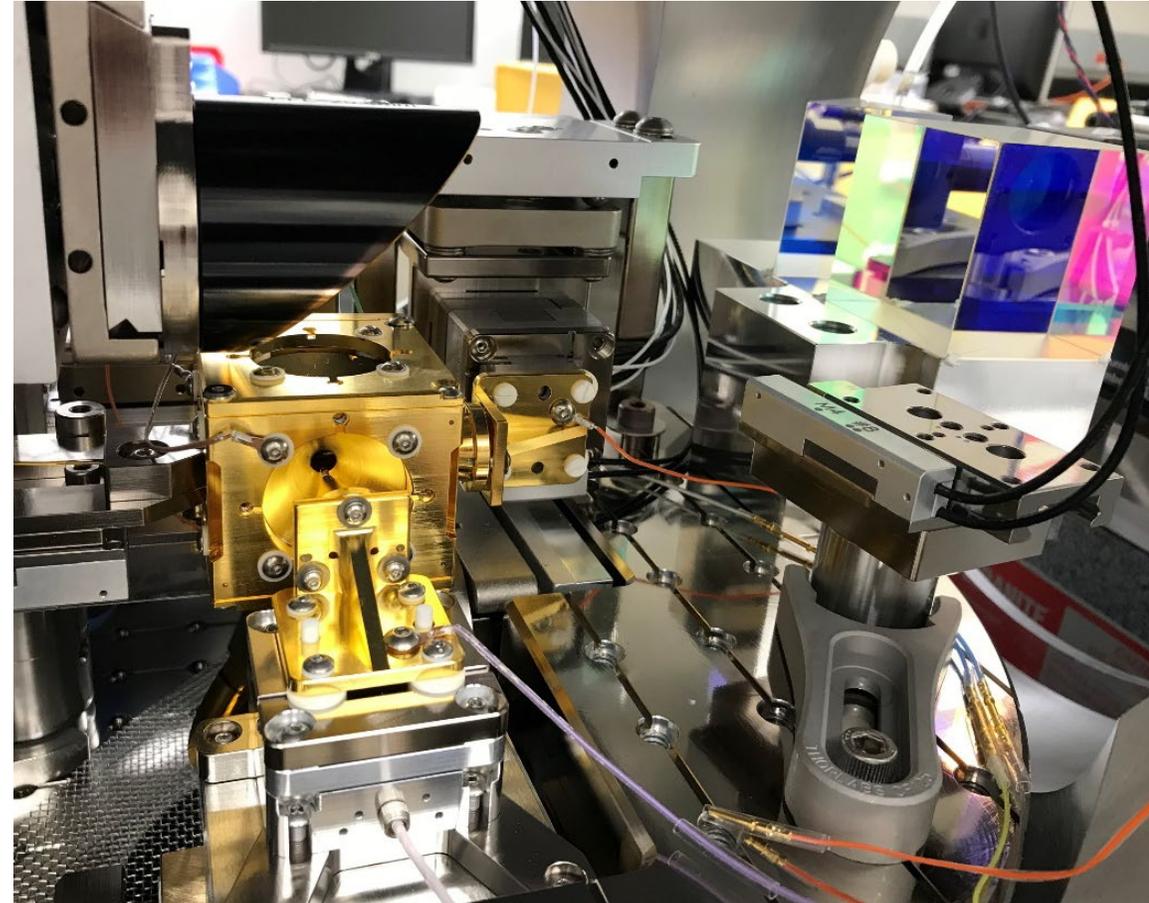


Image credit: Delia Gratta

Giorgio Gratta
Physics Dept,
Stanford University



See also: Tue 3:54 PM E03.00005: C.Blakemore "Librational feedback cooling with spinning silica microspheres"
Tue 4:06 PM E03.00006: N.Priel "A background-free optically levitated charge sensor"
Tue 4:18 PM E03.00007: E.Hough "Novel Technique to Measure μm -Scale Forces Using a Non-Linear Attractor"

- Gravity is not part of the Standard Model of fundamental particles and interactions

- The inverse square law is generally assumed to work all the way down to the Planck length

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

This is a bold assumption that requires experimental verification.

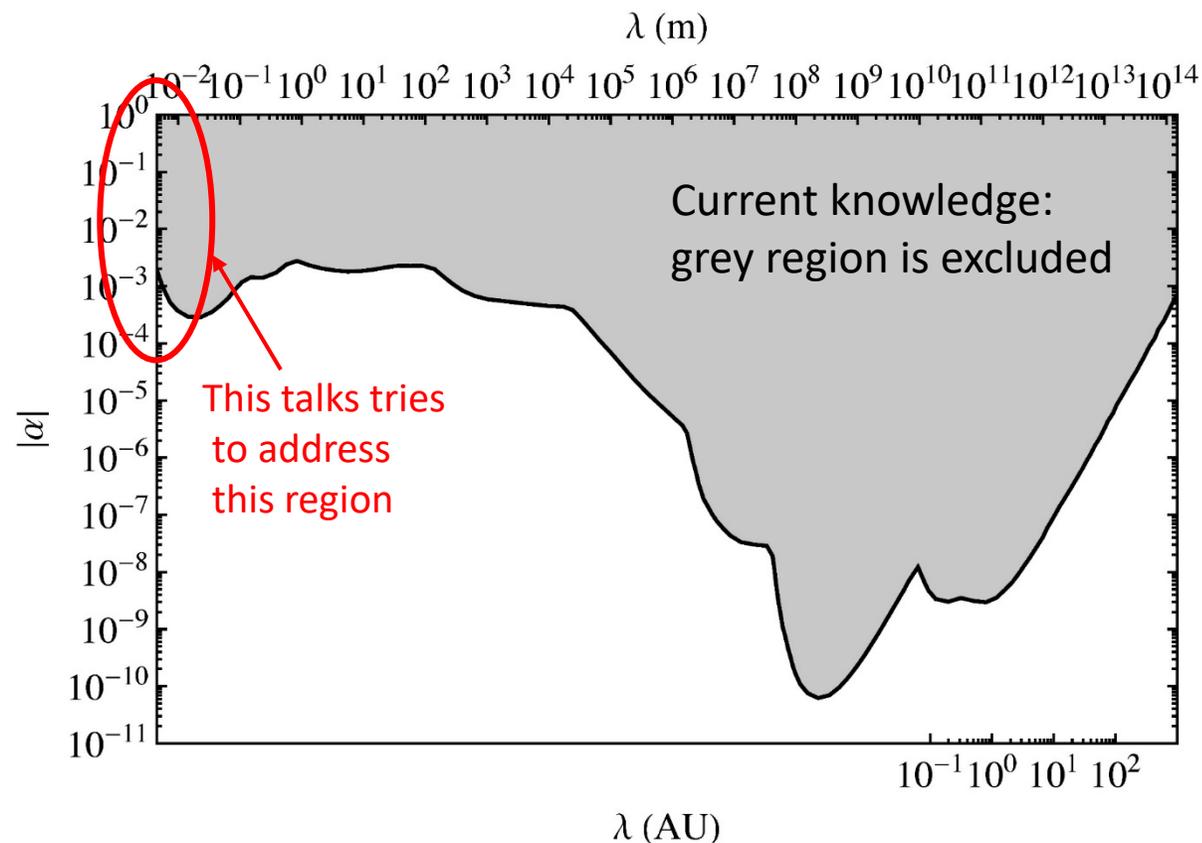
So, how well do we know that the inverse square law applies?

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

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

α : magnitude of the effect

λ : scale of the effect



Experimental challenges

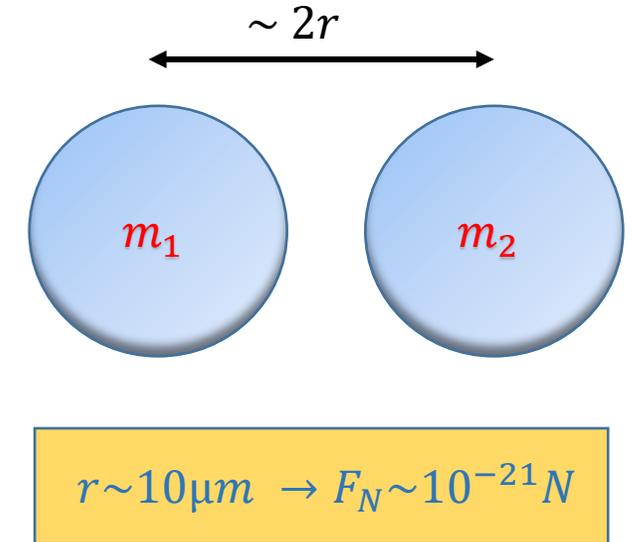
- Since $F = G \frac{M_1 M_2}{R^2} = G \frac{\rho_1 V_1 \rho_2 V_2}{R^2}$

for atomic materials (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 $F \sim G \frac{\rho^2 R^6}{R^2}$

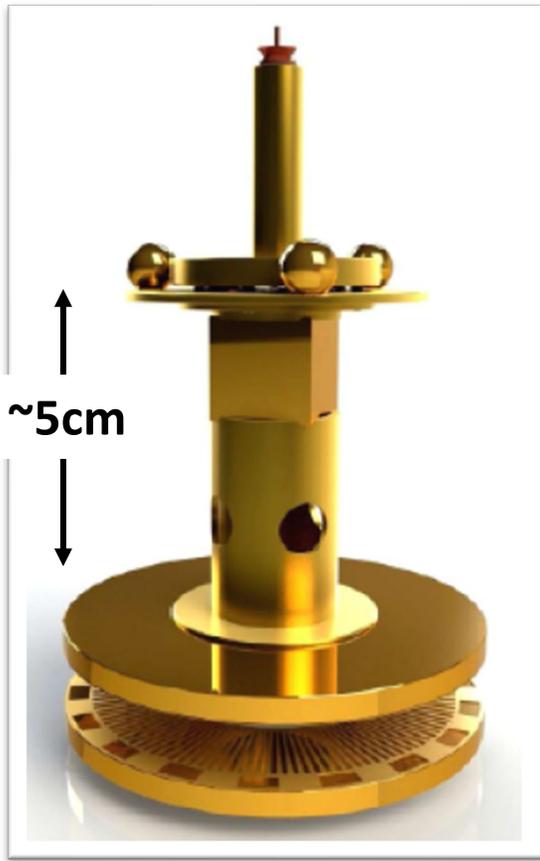
and it is clear that measurements at short distance become exceedingly difficult.



- 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.

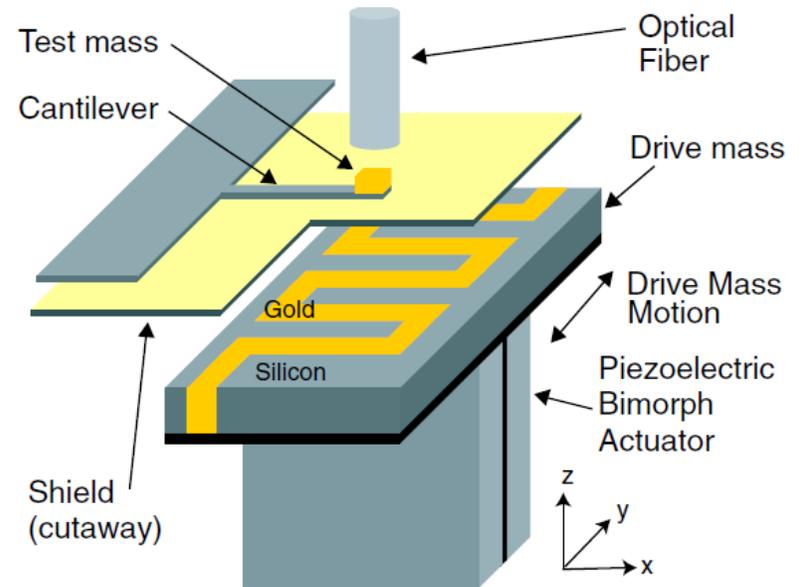
Most inverse-square law measurements are/have been done with wonderfully sophisticated versions of Cavendish's setup.

As distances become shorter, this approach becomes more difficult and new techniques are desirable.



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)



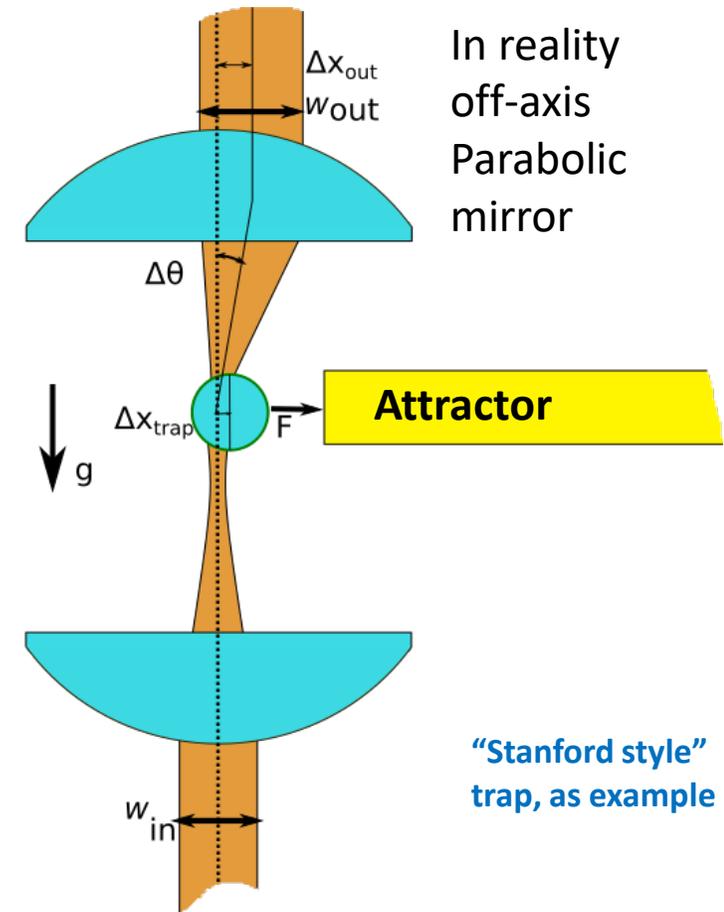
Sketch of the custom cryogenic AFM apparatus from Kapitulnik's group at Stanford
J. Chiaverini et al., PRL 90 (2003) 151101



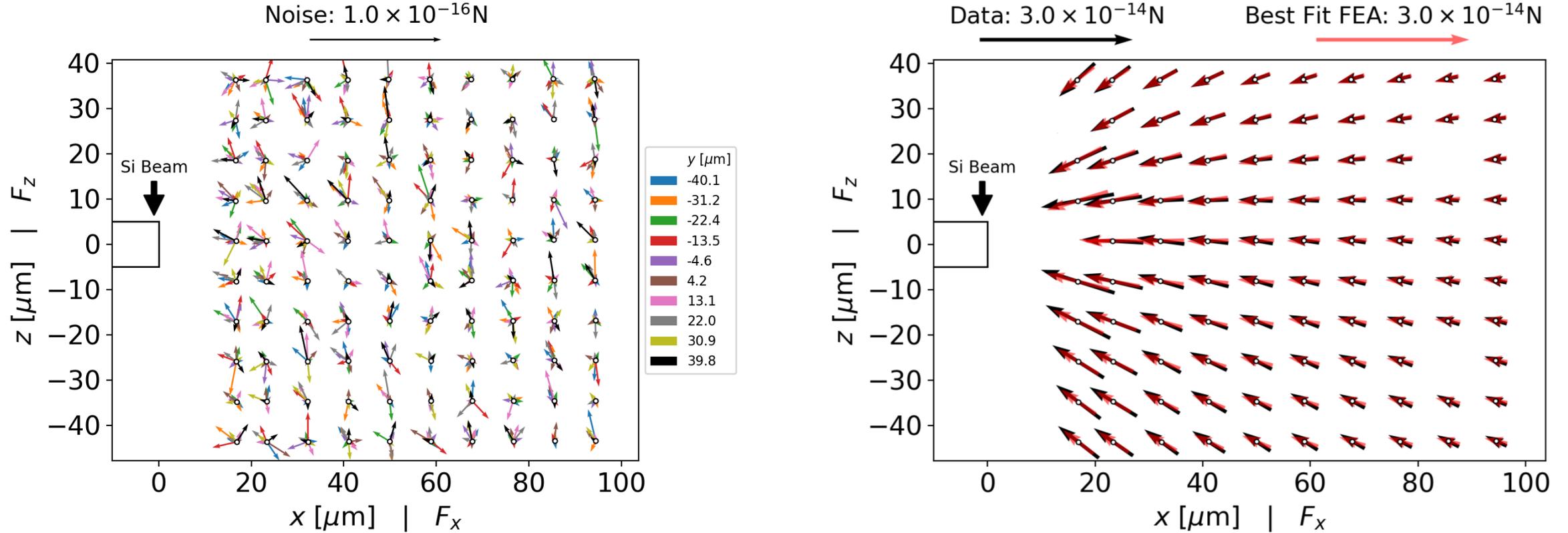
In the last 40 years, the technique of optical tweezers has matured, primarily in water with applications to biology

Microspheres optically trapped in vacuum make superb force sensors

- In high vacuum we can cool the force sensor (μ sphere) while everything else is at room temperature.
- Microspheres are really isolated (in particular electrically).
- Trap parameters can be changed instantaneously.
- Extremely low dissipation is possible: $Q \sim 10^{12}$ at 10^{-10} mbar.
- Control of optical potential and motion in all 3 DOF: great flexibility.
- The quantum noise limit has been reached (for smaller spheres: U.Delic et al, Science 367 (2020) 892) --not required for early gravity measurements.
- New chance to understand and reject background forces.
- Unexplored: much risk and many opportunities!
- Many applications to other areas.



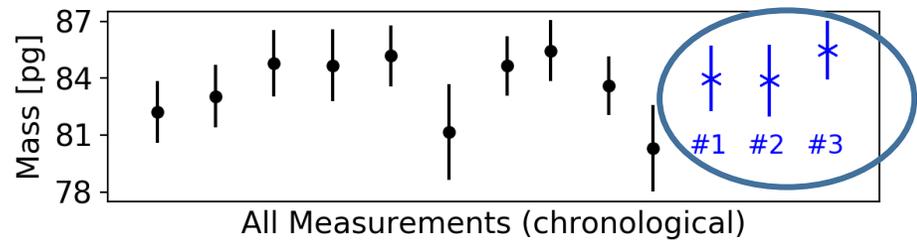
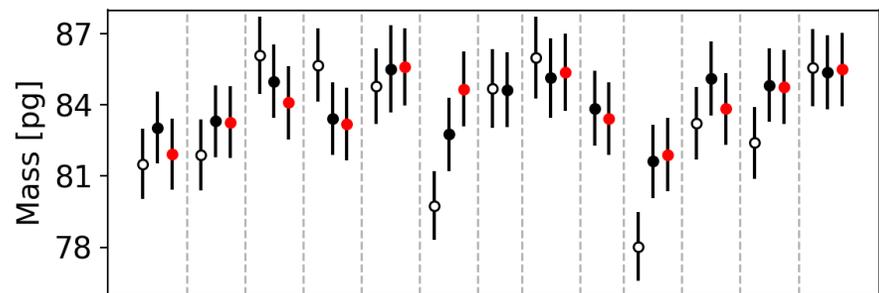
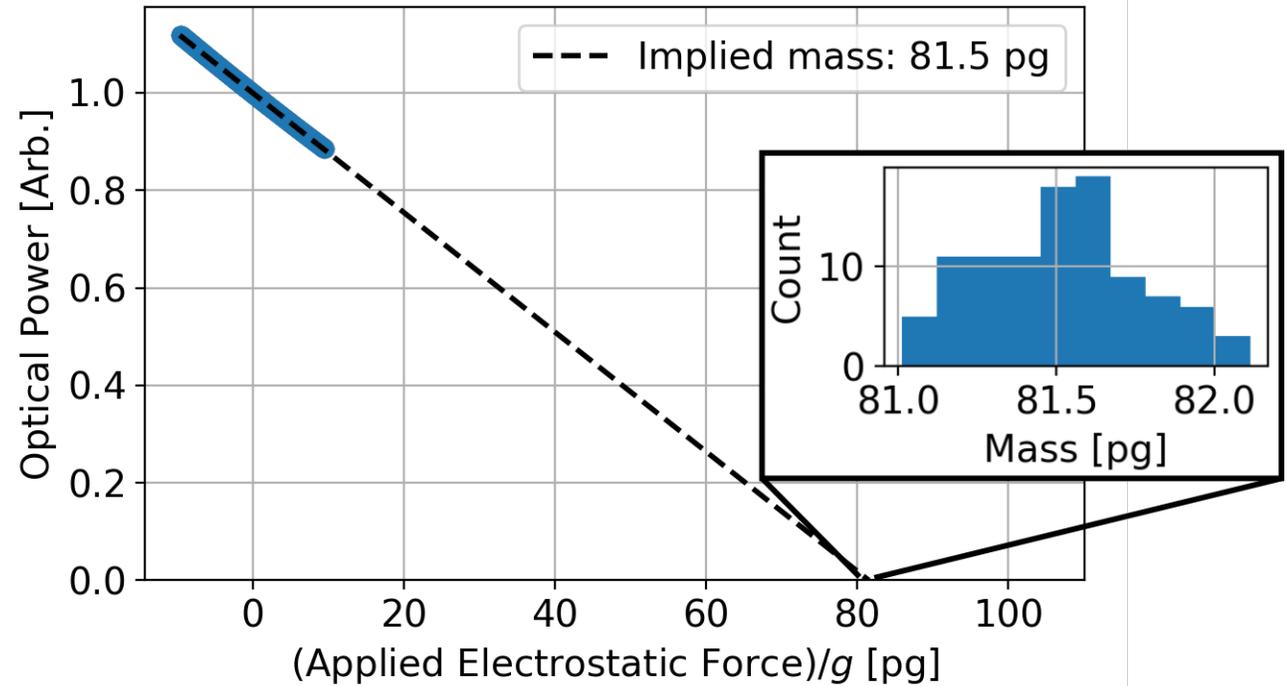
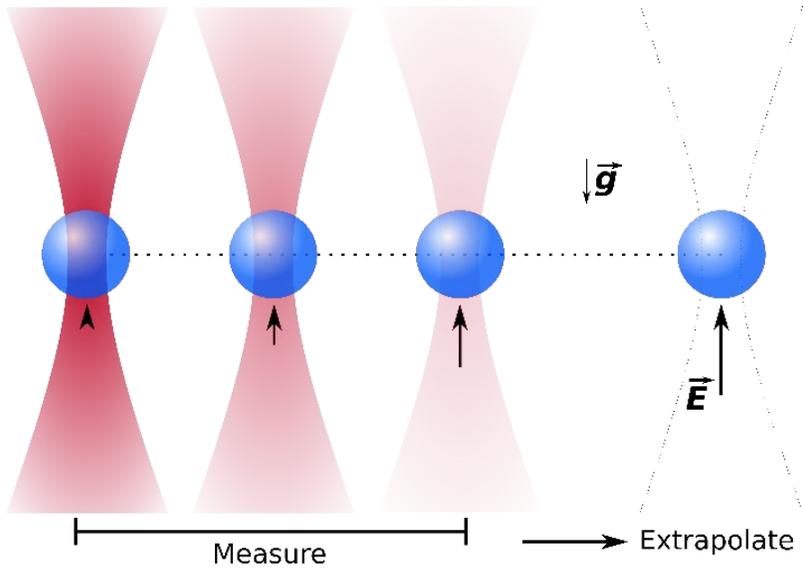
The microsphere is an excellent force sensor, with current noise $\sim 10 \text{ aN}/\sqrt{\text{Hz}}$ and easy to calibrate in absolute units by adding/removing known charges and applying an AC field. Can measure a vector field over a 3D array of positions.



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

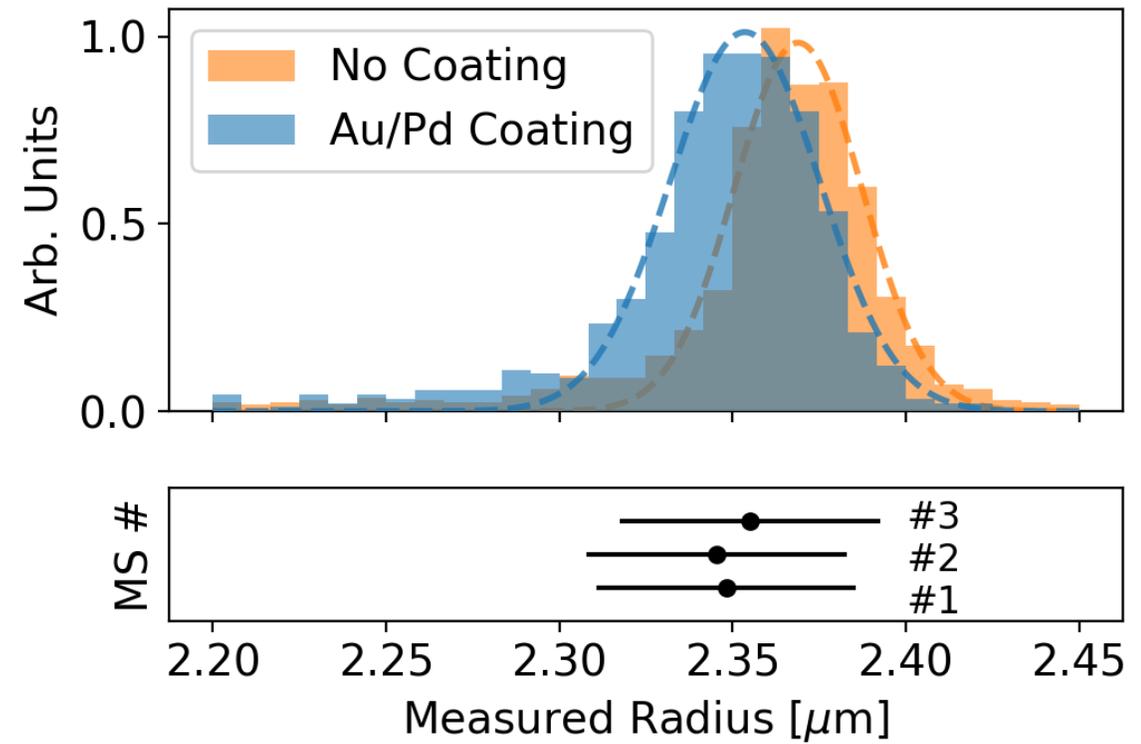
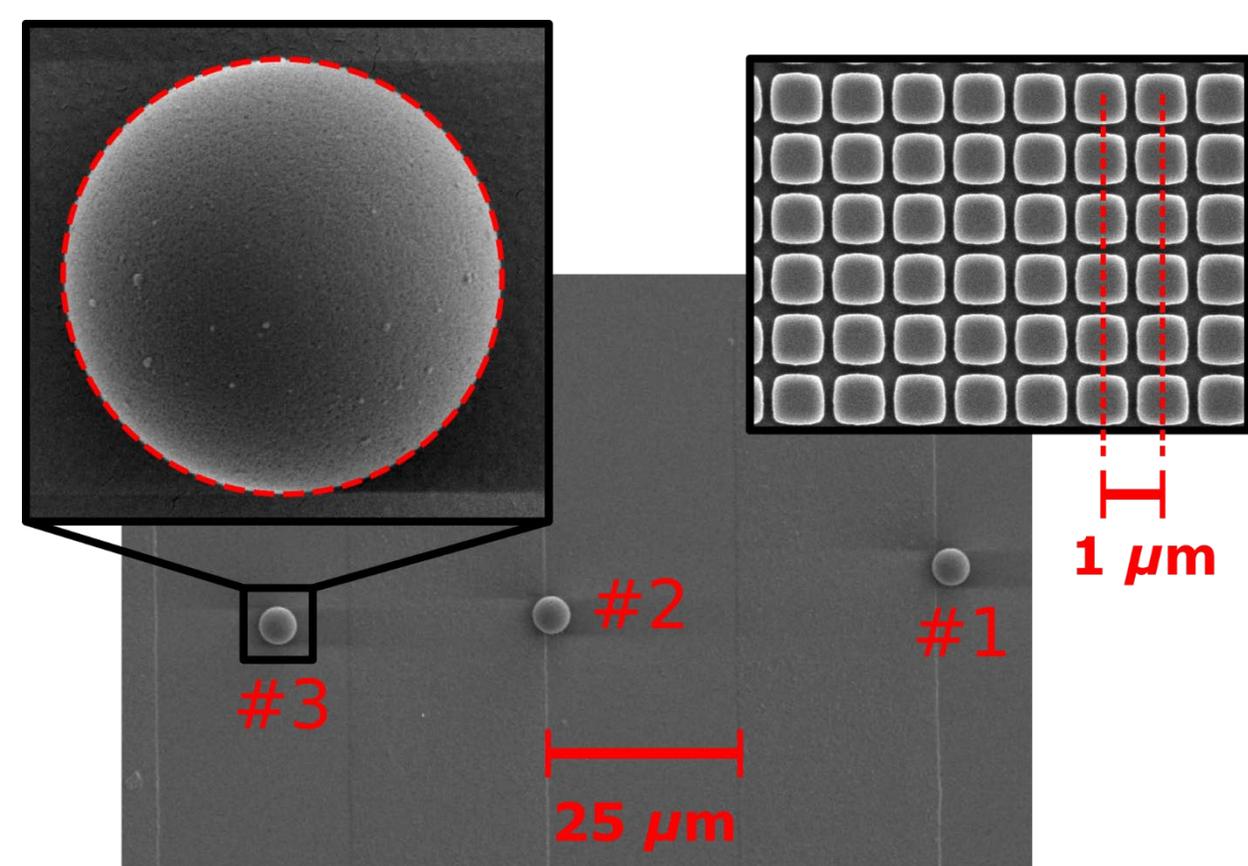
Similar results in G.Winstone et al., Phys. Rev. A 98 (2018) 053831

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 (Stober process) 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

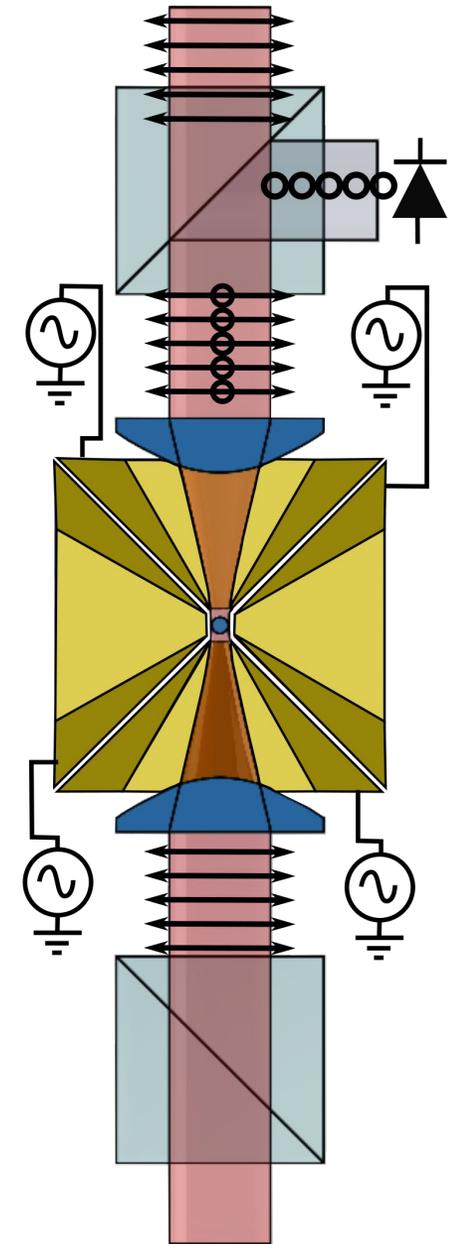
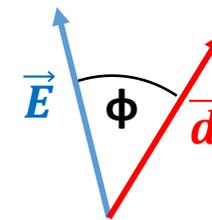
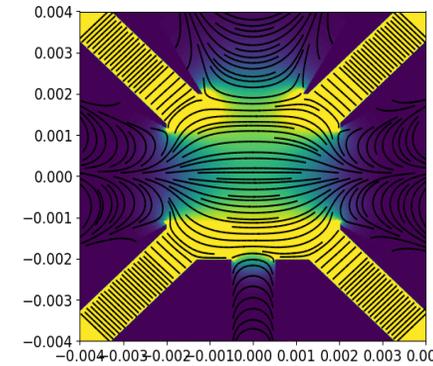
F. Monteiro et al., Phys. Rev. A 97 (2018) 051802

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

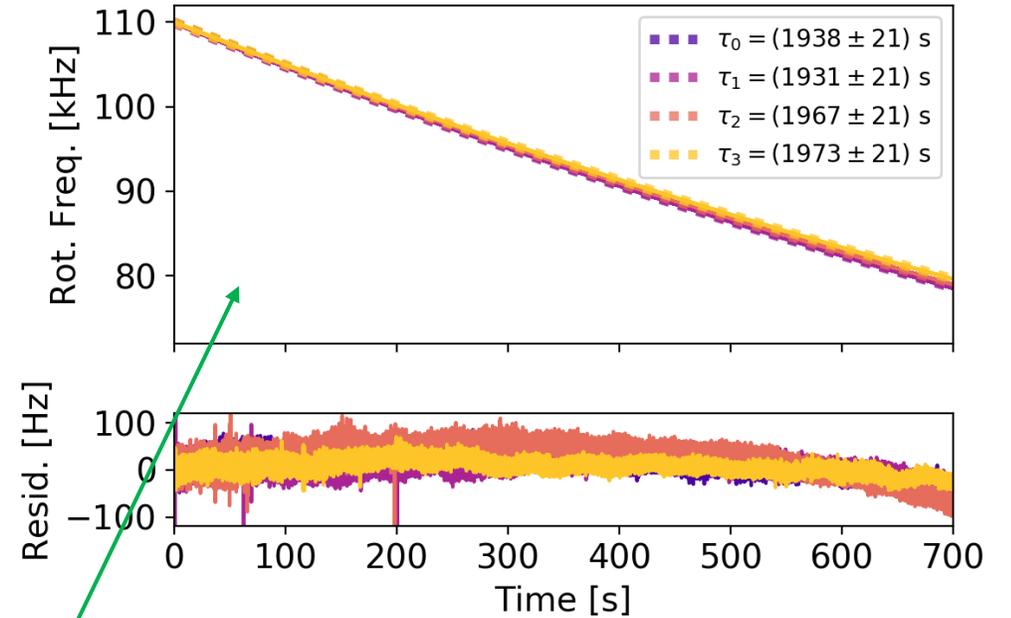
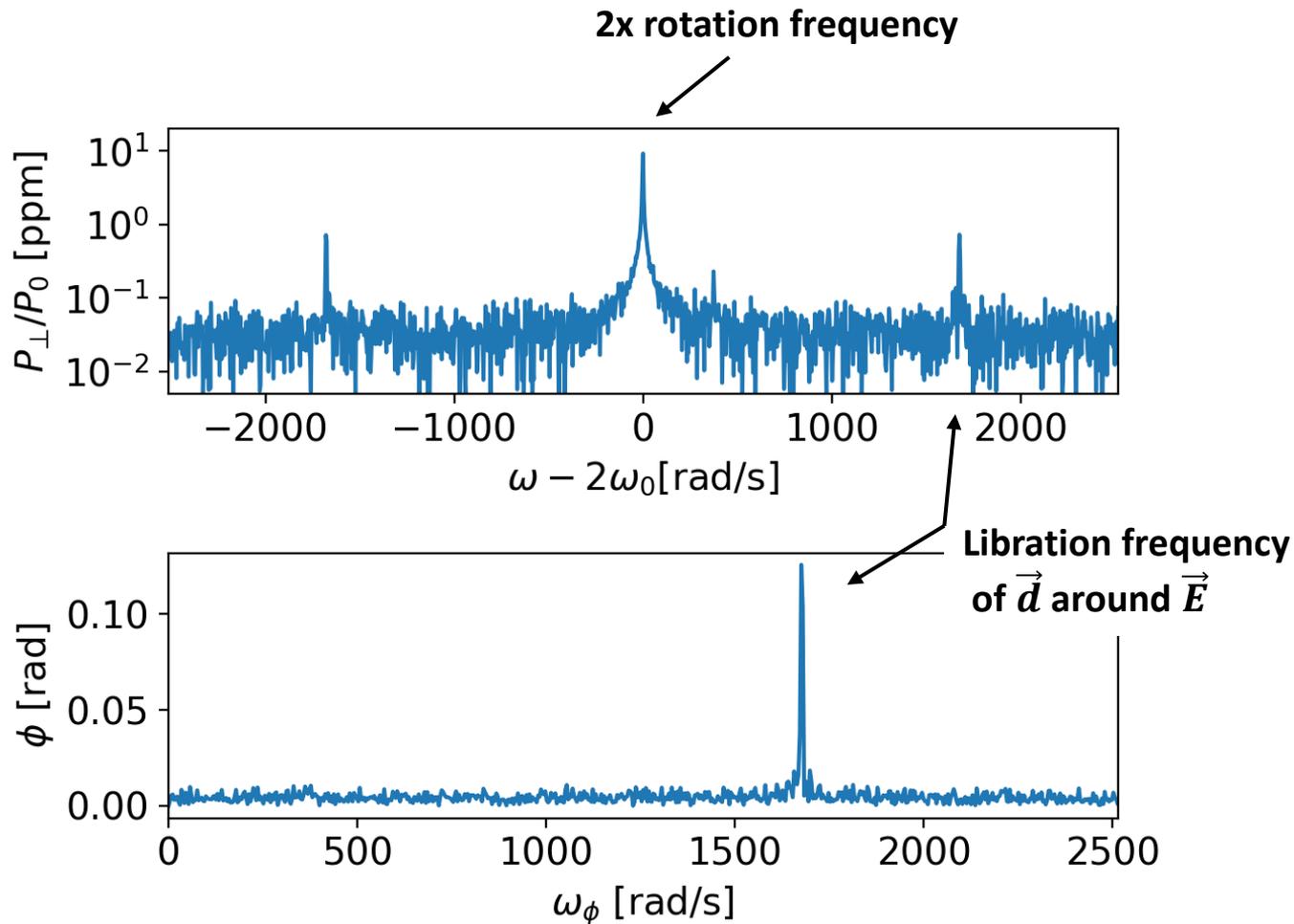
If the microsphere has an electric dipole moment, then a torque can be applied by a rotating external electric field.

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

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

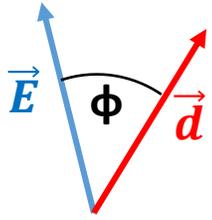


The rotation is read out using the small residual birefringence that the silica microspheres apparently have.

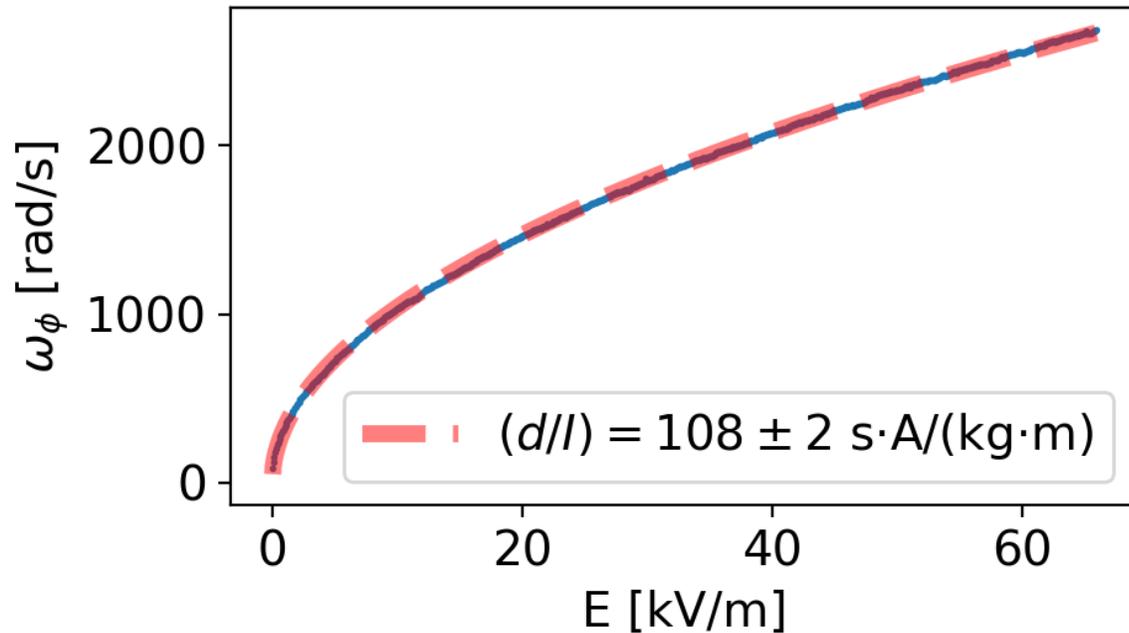


Stopping the driving field makes the microsphere gradually spin-down, with the expected exponential law. The time constant can be translated* into the pressure, like in a rotating ball vacuum gauge.

* 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



Assuming I to be that of a homogeneous silica sphere, we get $d = 127 \pm 14 \text{ e } \mu\text{m}$

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

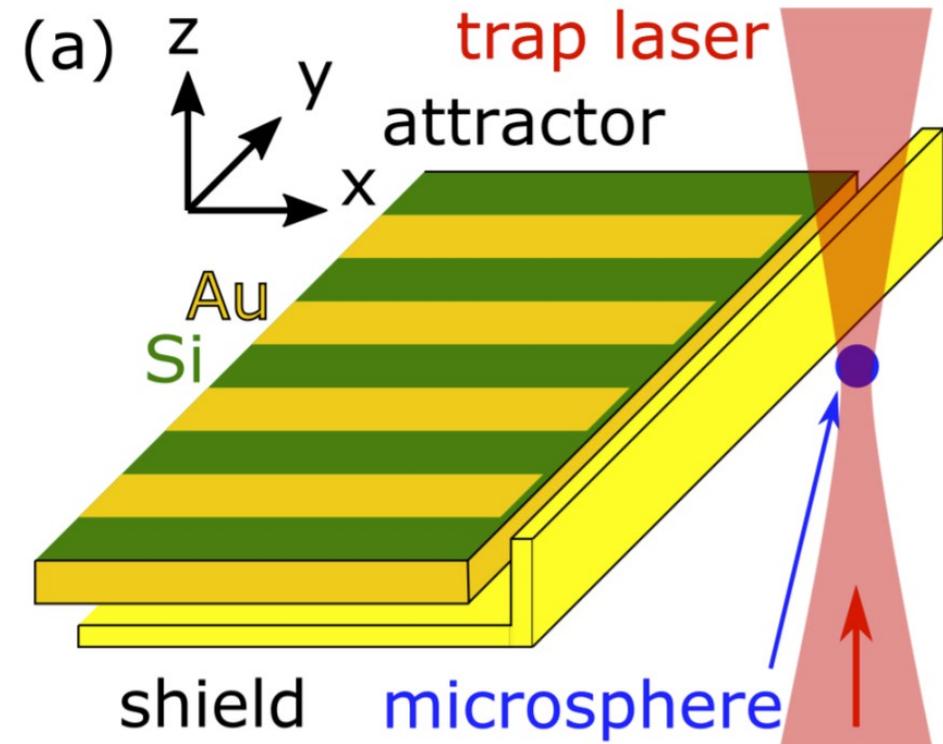
More recently, we achieved the first successful feedback cooling of the libration DOF

C.P. Blakemore et al., "Librational Feedback Cooling", arXiv:2203.11390v1, Mar 2022

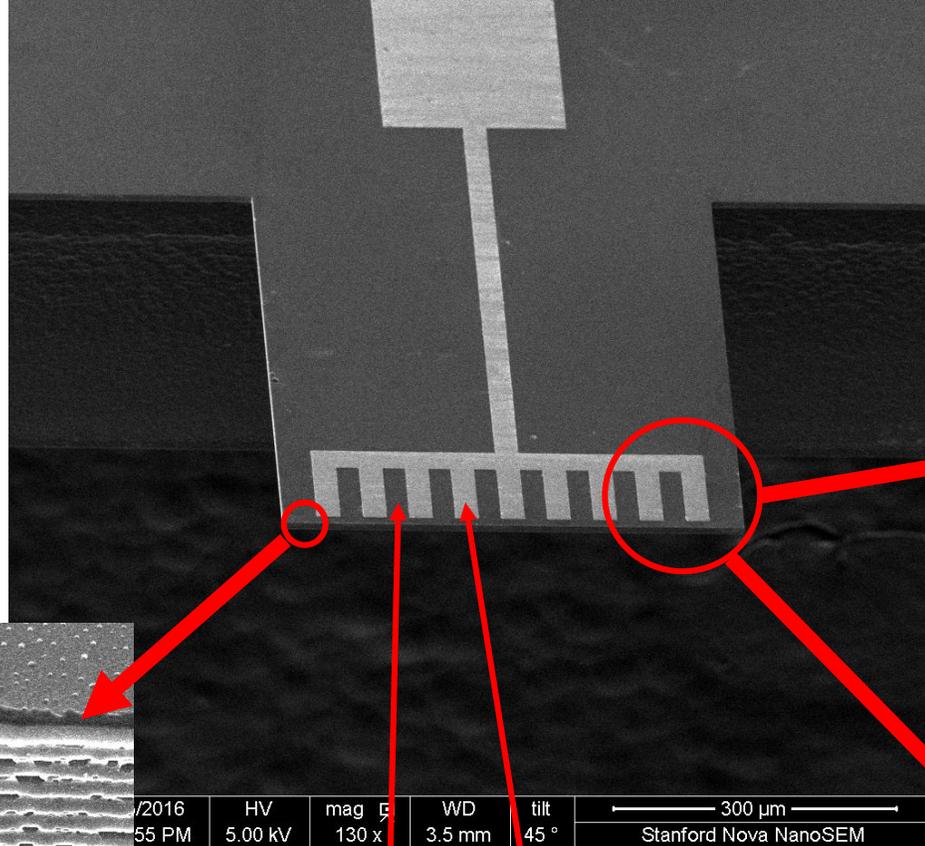
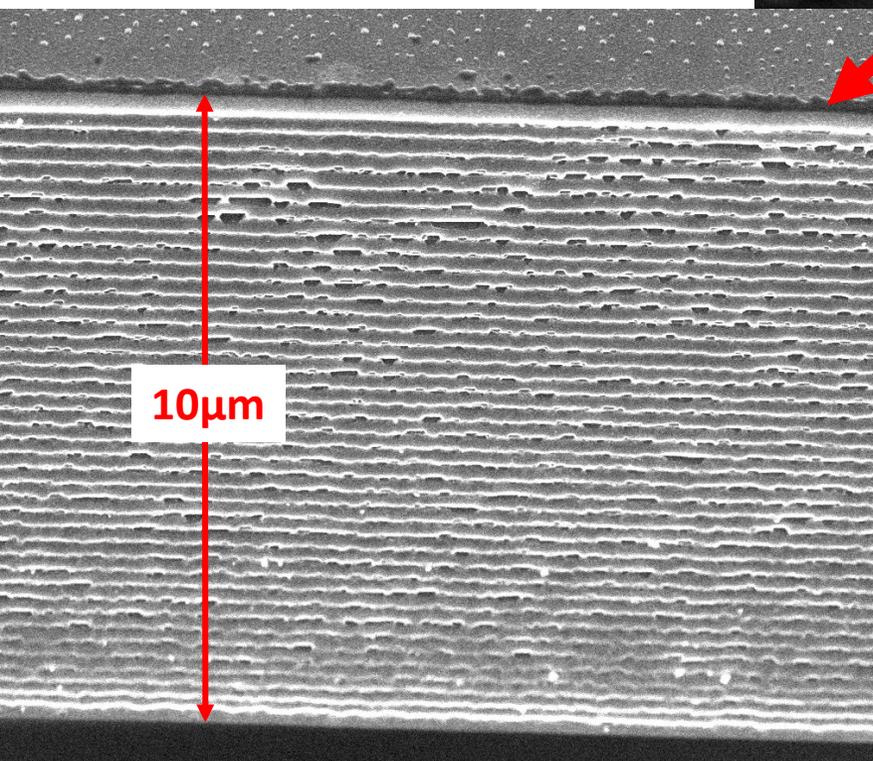
See also: Tue 3:54 PM E03.00005: C.Blakemore "Librational feedback cooling with spinning silica microspheres"

First search for new forces

- $\sim 10^5$ seconds run
- 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), observe correlated force at $f_0, 2f_0, 3f_0, 4f_0, \dots$

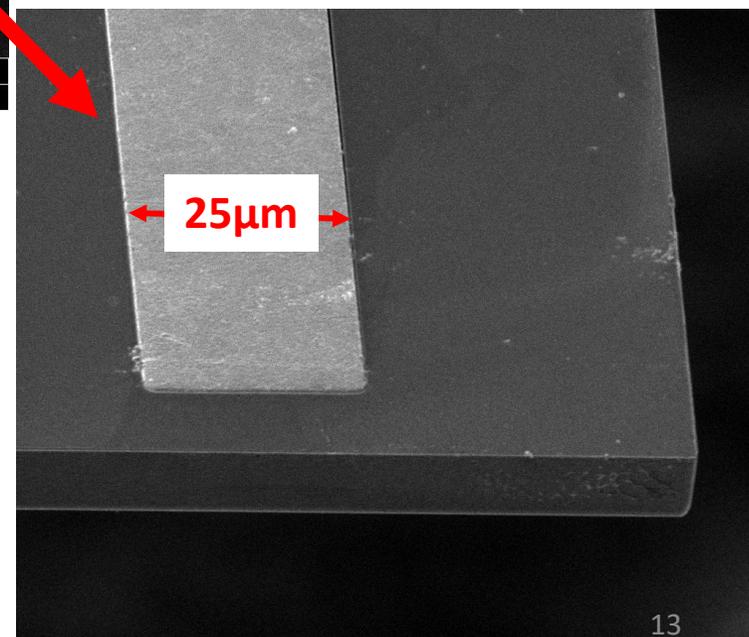
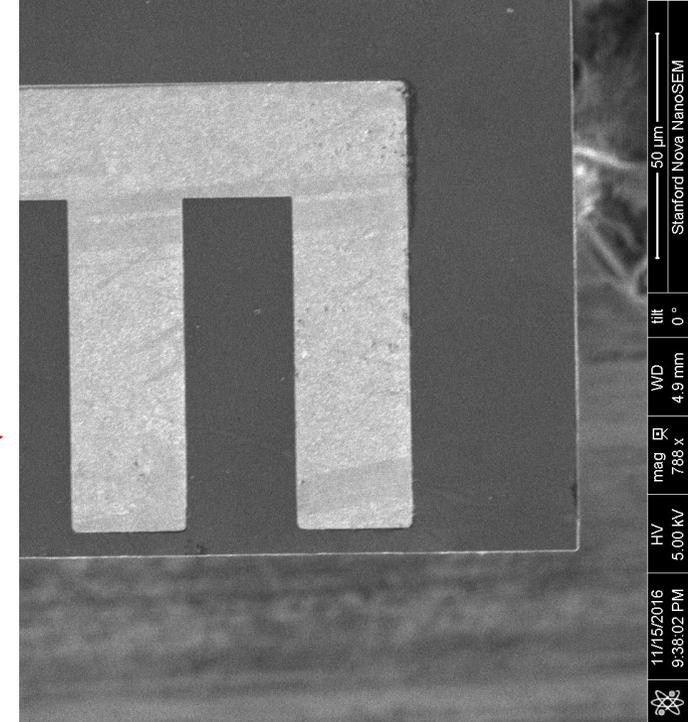


First generation
attractor set,
here shown
before Au coating



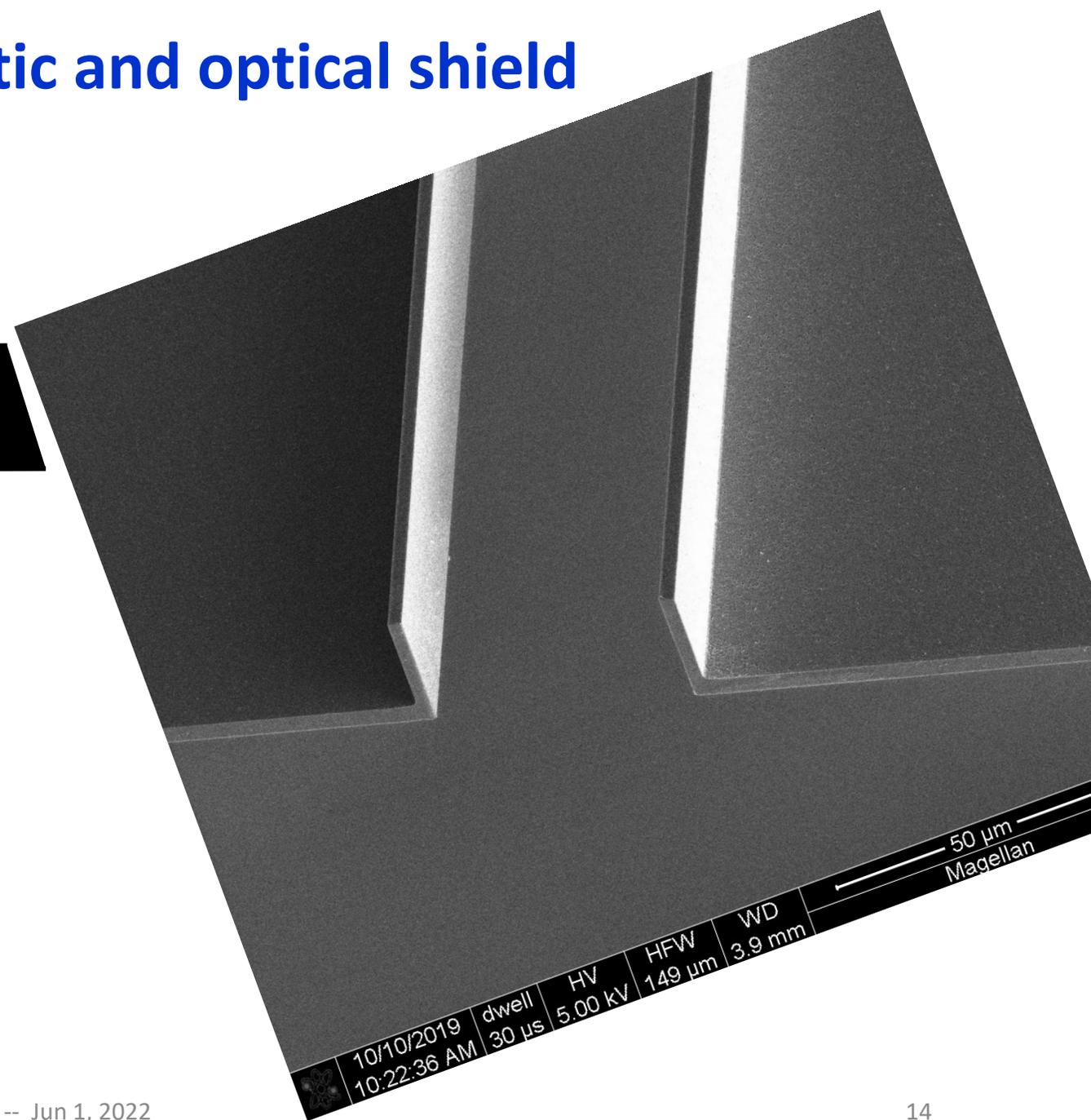
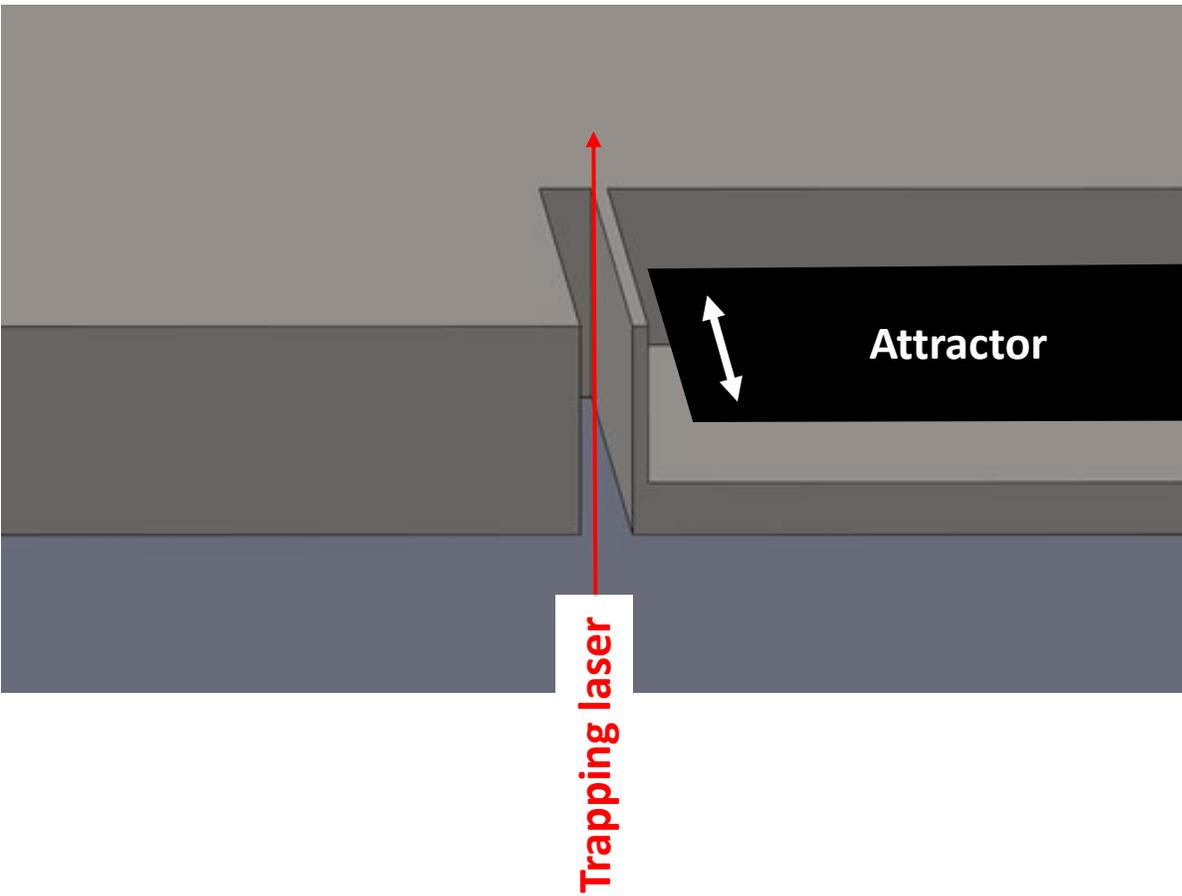
| | | | | | |
|------------|---------|-------|--------|------|-----------------------|
| 11/15/2016 | HV | mag | WD | tilt | 300 µm |
| 10:55 PM | 5.00 kV | 130 x | 3.5 mm | 45 ° | Stanford Nova NanoSEM |

Si Au

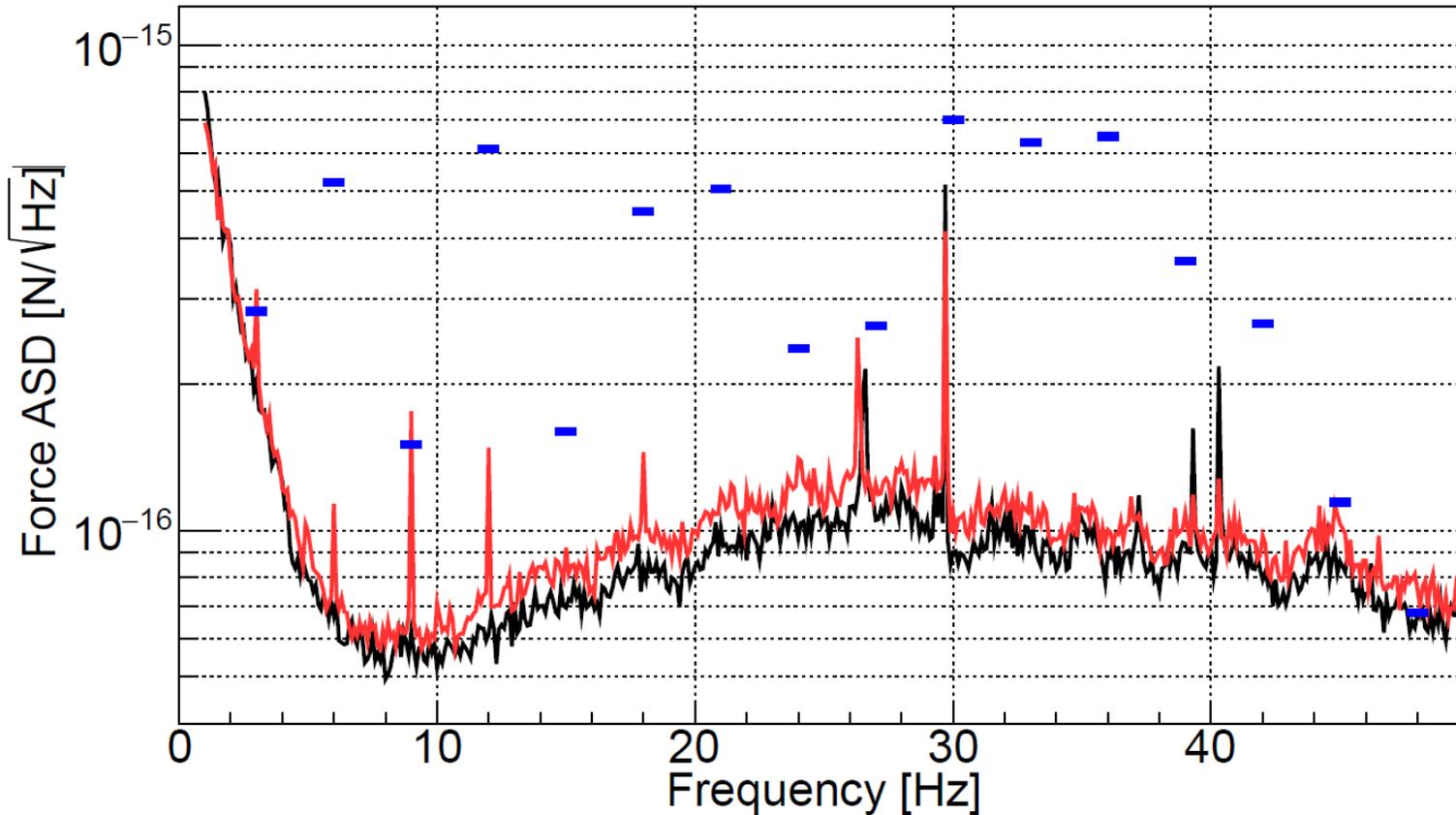


| | | | | | |
|-------------|---------|---------|--------|------|-----------------------|
| 11/15/2016 | HV | mag | WD | tilt | 20 µm |
| 10:06:32 PM | 5.00 kV | 1 521 x | 3.8 mm | 45 ° | Stanford Nova NanoSEM |

Standing electrostatic and optical shield



Results from the first run



Measured force sensitivity:

$$10^{-16} \text{ N}/\sqrt{\text{Hz}}$$

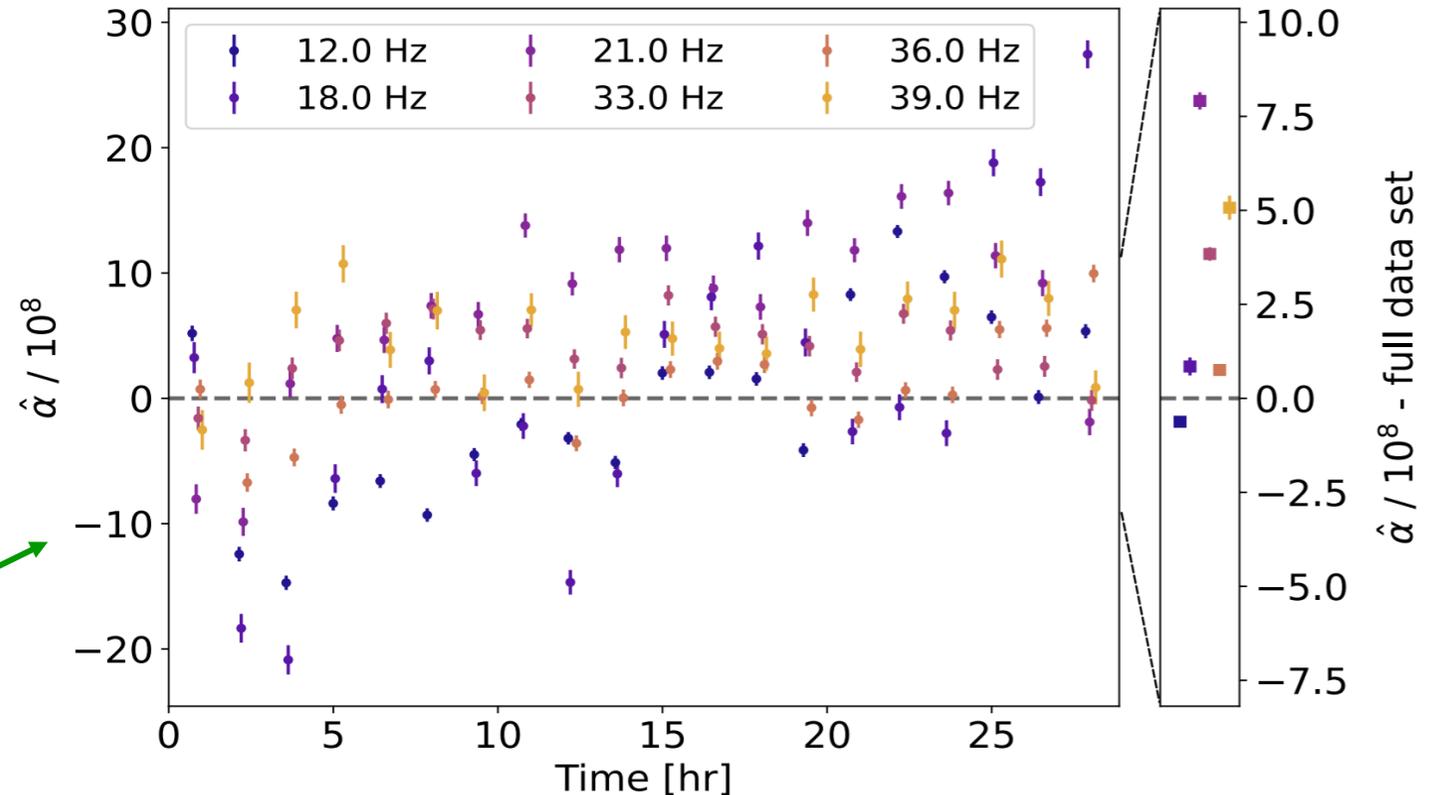
- Black - response with stationary attractor
- Red – response with moving attractor
- Blue – expected response for $\alpha = 10^{10}$ and $\lambda = 10\mu\text{m}$

Results from the first run

- Z-channel is used (defined *a-priori*) due to X-channel background level
- Fitting signal model on harmonic-by-harmonic basis
- 6 harmonics used
- Phase info also used (this will become more important with all 3 DOFs)
- There is a finite effect, but the data is clearly not “signal-like”
- Each harmonic is fit with using

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

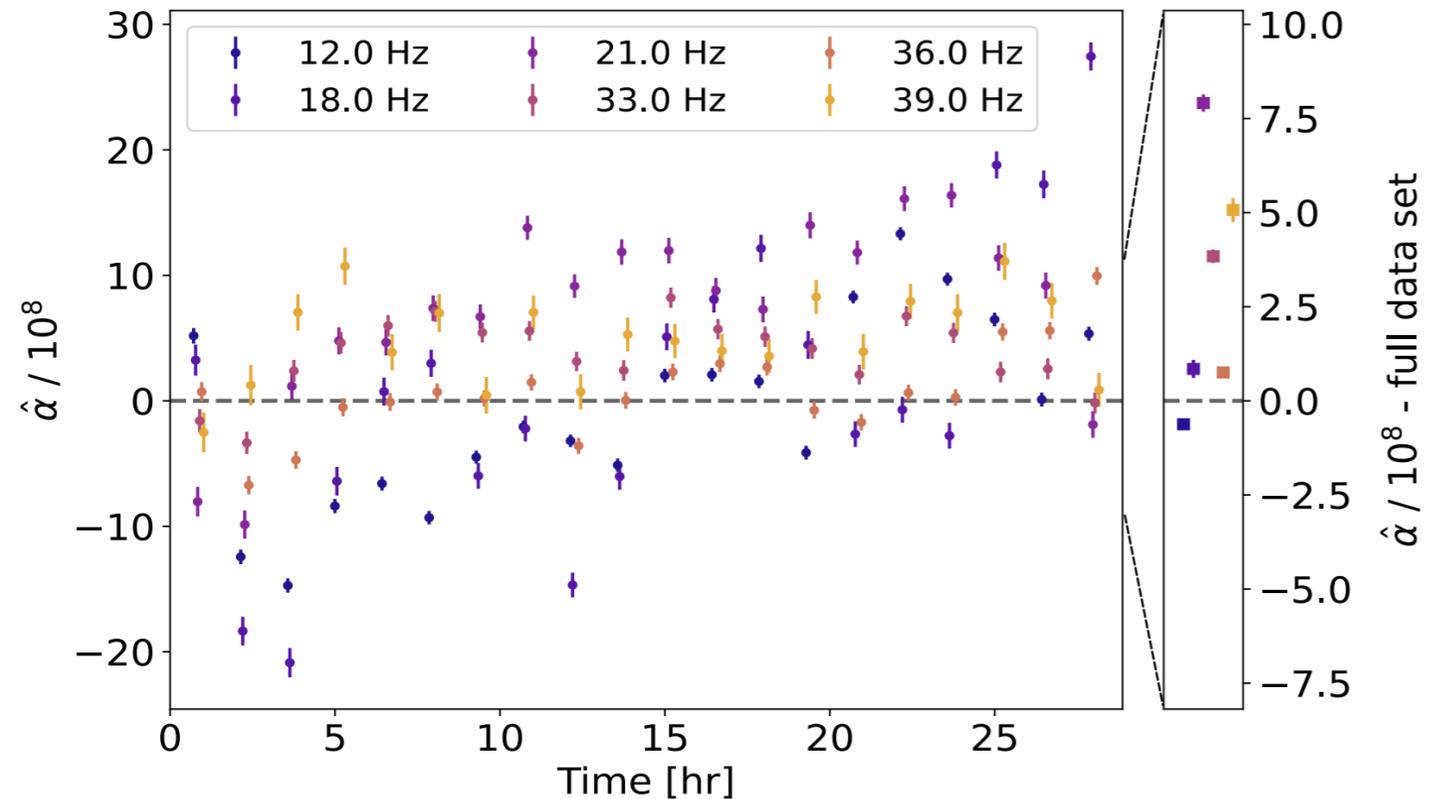
- These are produced for each harmonic every 5000 s



Results from the first run

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

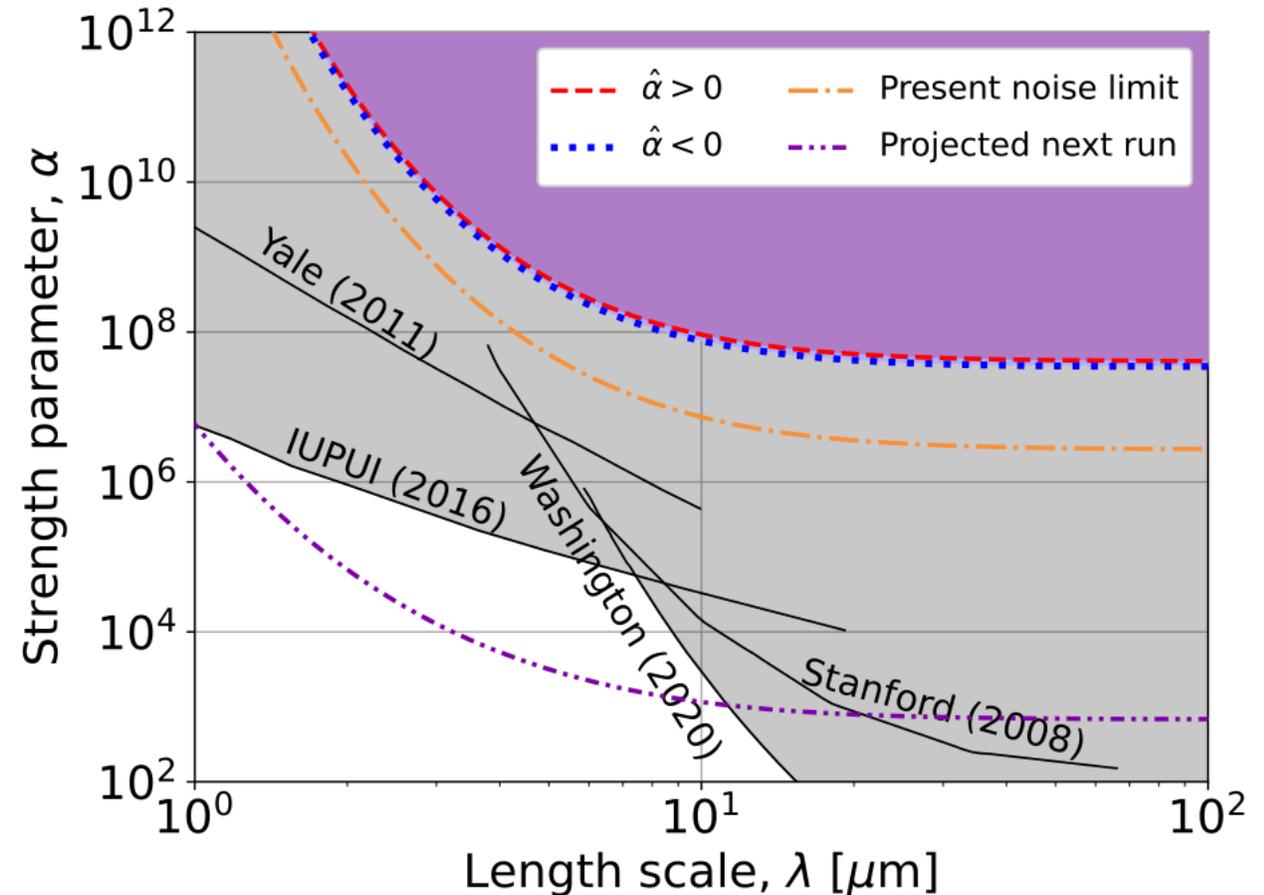
| Effect ϵ | $\Delta\epsilon$ | $\Delta\alpha/\alpha$ |
|-----------------------------|-----------------------|-----------------------|
| Drift of amplitude response | 10% | 10% |
| Attractor thickness | 1 μm | 11% |
| Phase response | ~ 0.1 rad | 12% |
| Distances in Y | < 0.2 μm | $< 3\%$ |
| Distances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



Results from the first run

- 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 by injecting fake signals and using dedicated MC.
- The sensitivity is limited by backgrounds. Most important are likely to be EM interactions between the gradient from contact potential between attractor and shield and μ sphere electric dipole moment.
- Other backgrounds arise from stray light, vibrations.
- Further down is the noise, primarily from pointing of the trapping beam.

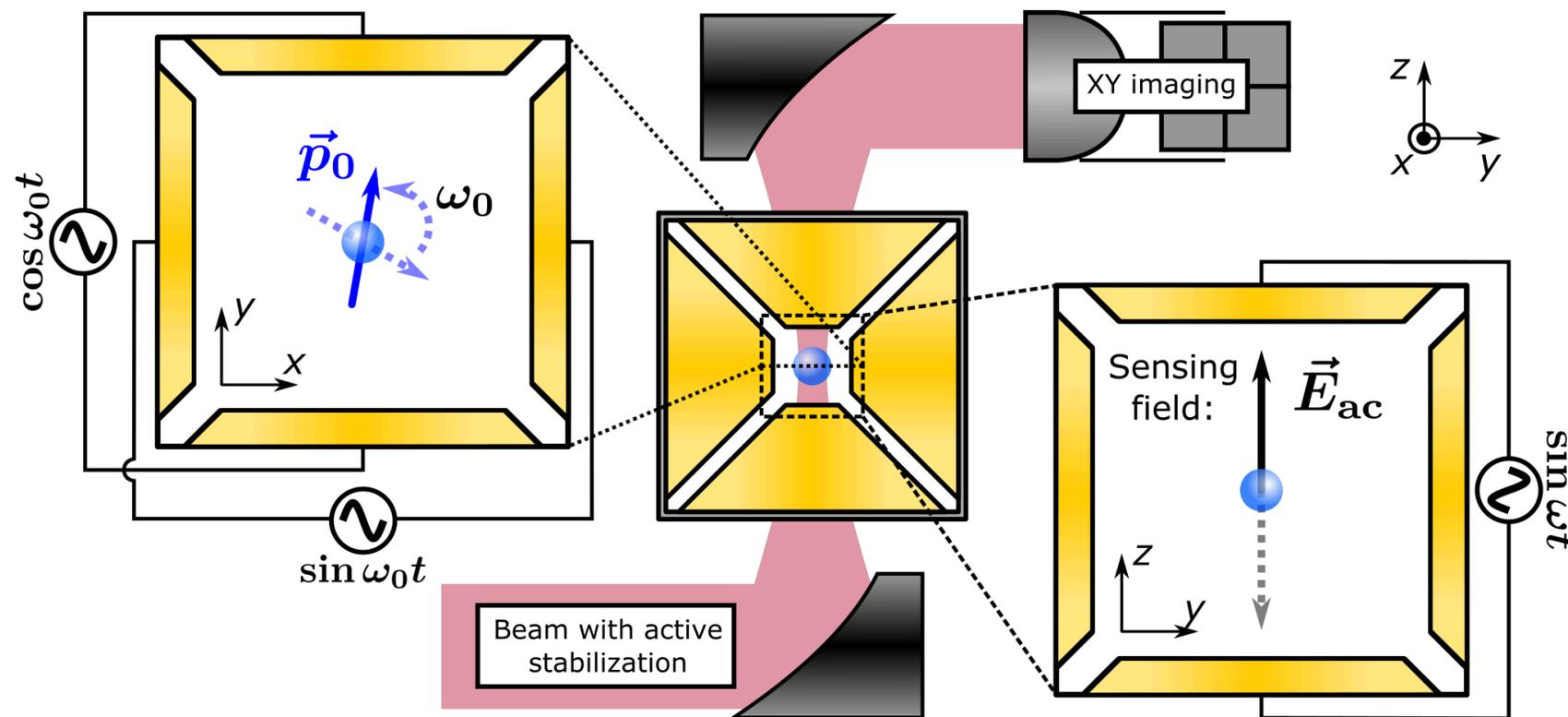
C.Blakemore *et al.*, "Search for non-Newtonian interactions at micrometer scale with a levitated test mass"
Phys Rev D 104 (2021) L061101



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. $q_{\text{proton}} = q_{\text{electron}}$)

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



How to recognize permanent dipole backgrounds

At f_0 :

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

This is subdominant and not yet well studied

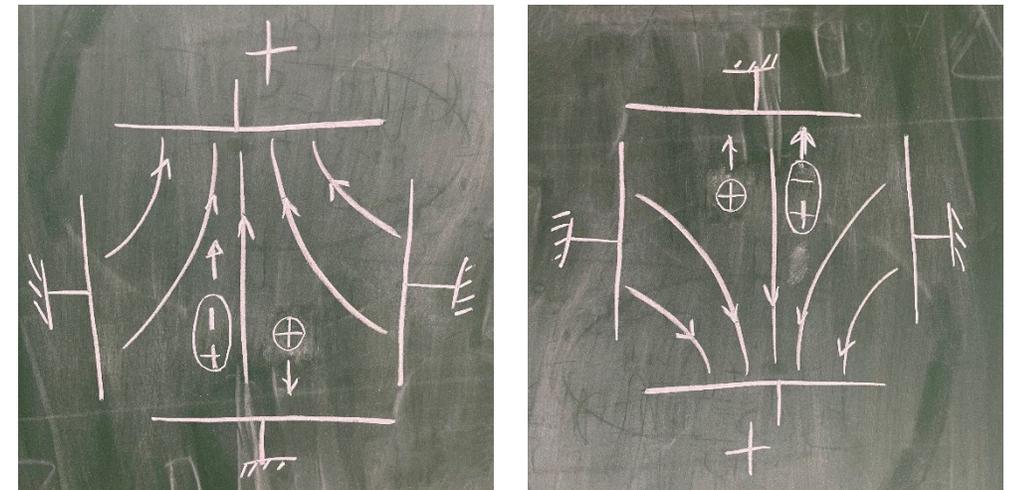
This is the term to worry about

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

At first order the dipole term cancels for the quantity:

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

Describes the possible slight asymmetry between the two field directions

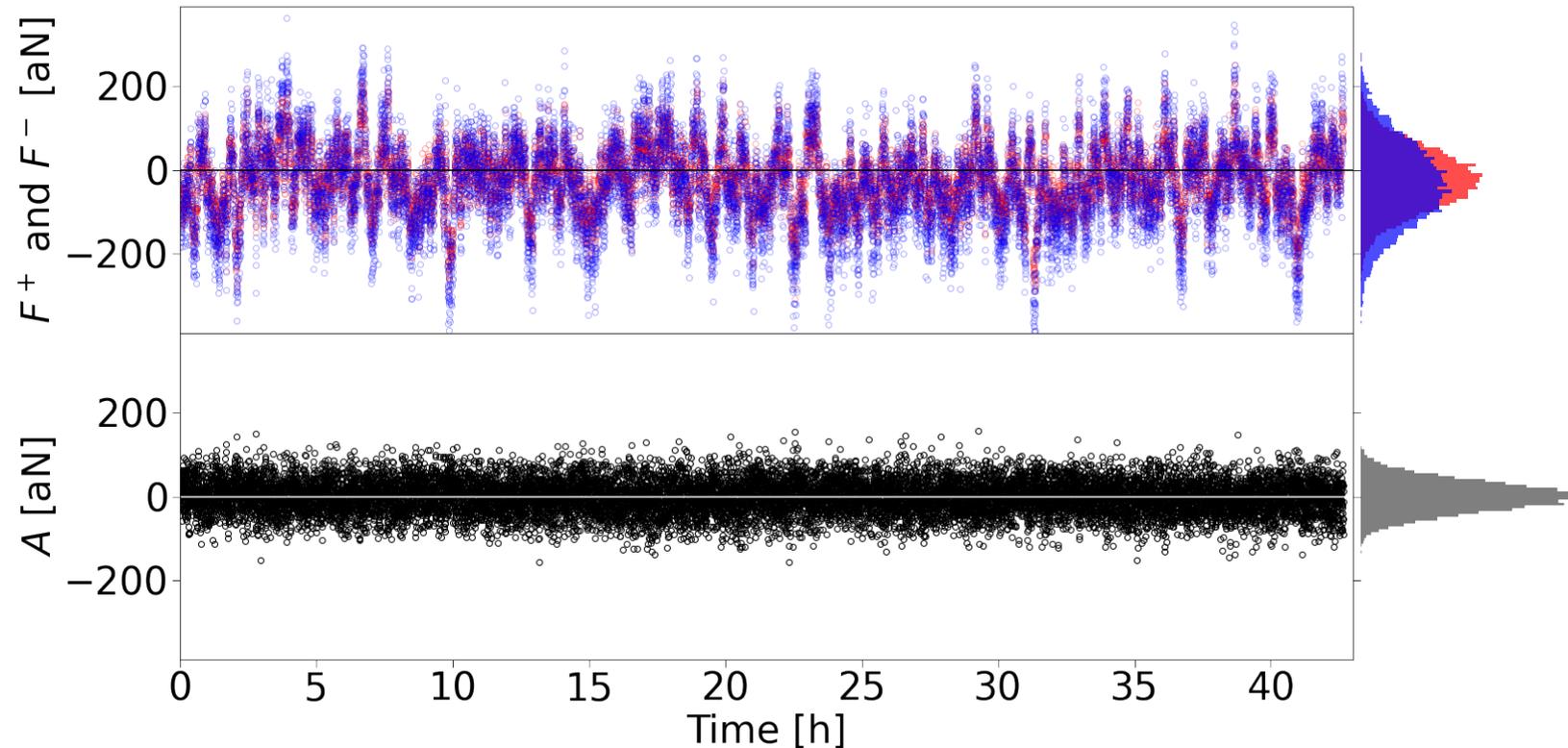


Note that the force switches direction for the monopole but not for the (permanent) dipole. (blackboard courtesy of M. Aspelmeyer)

The cancellation works remarkably well!!

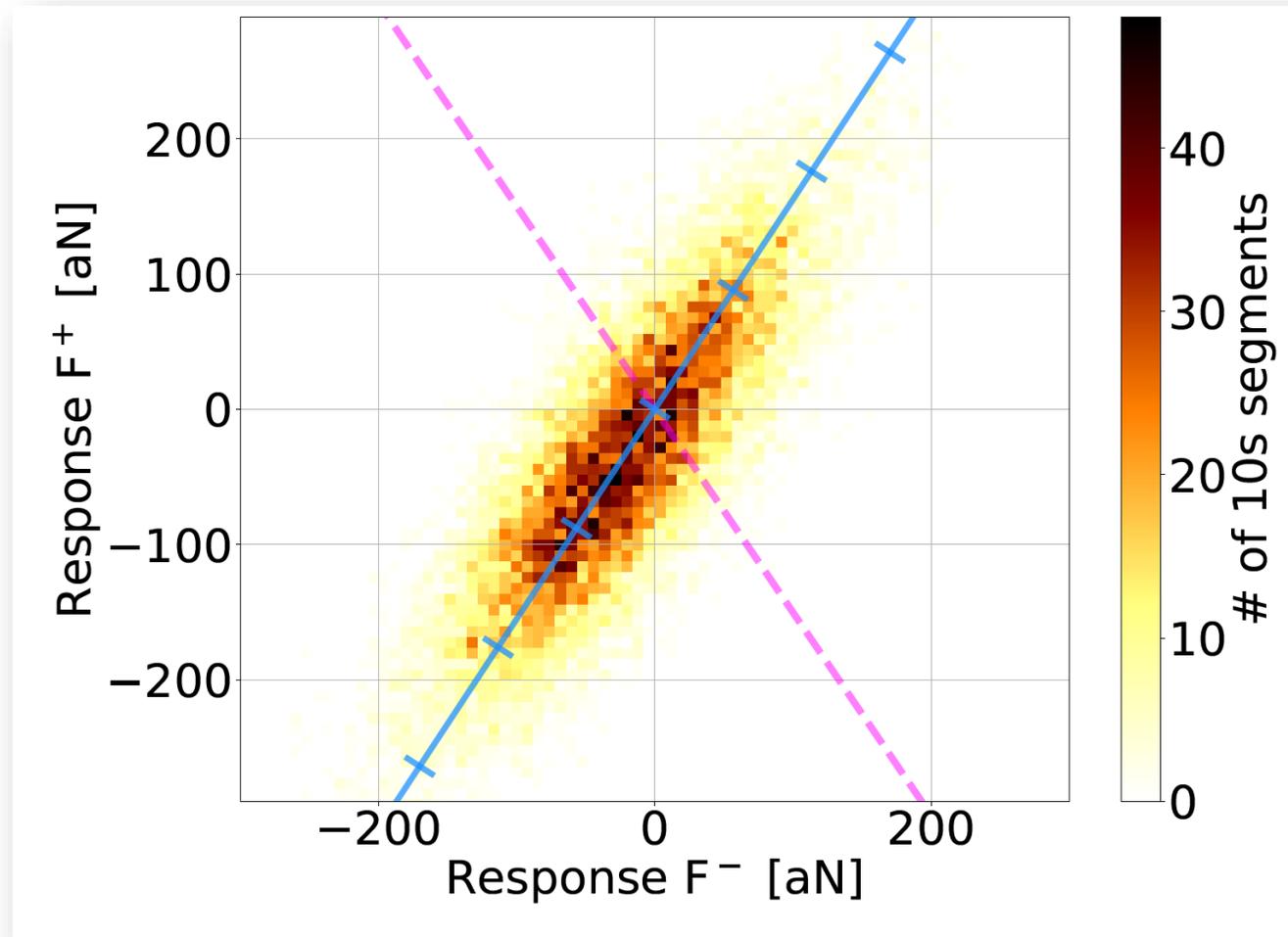
(here Ω is calculated with FEA, using the measured trap position with respect to the electrodes)

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



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

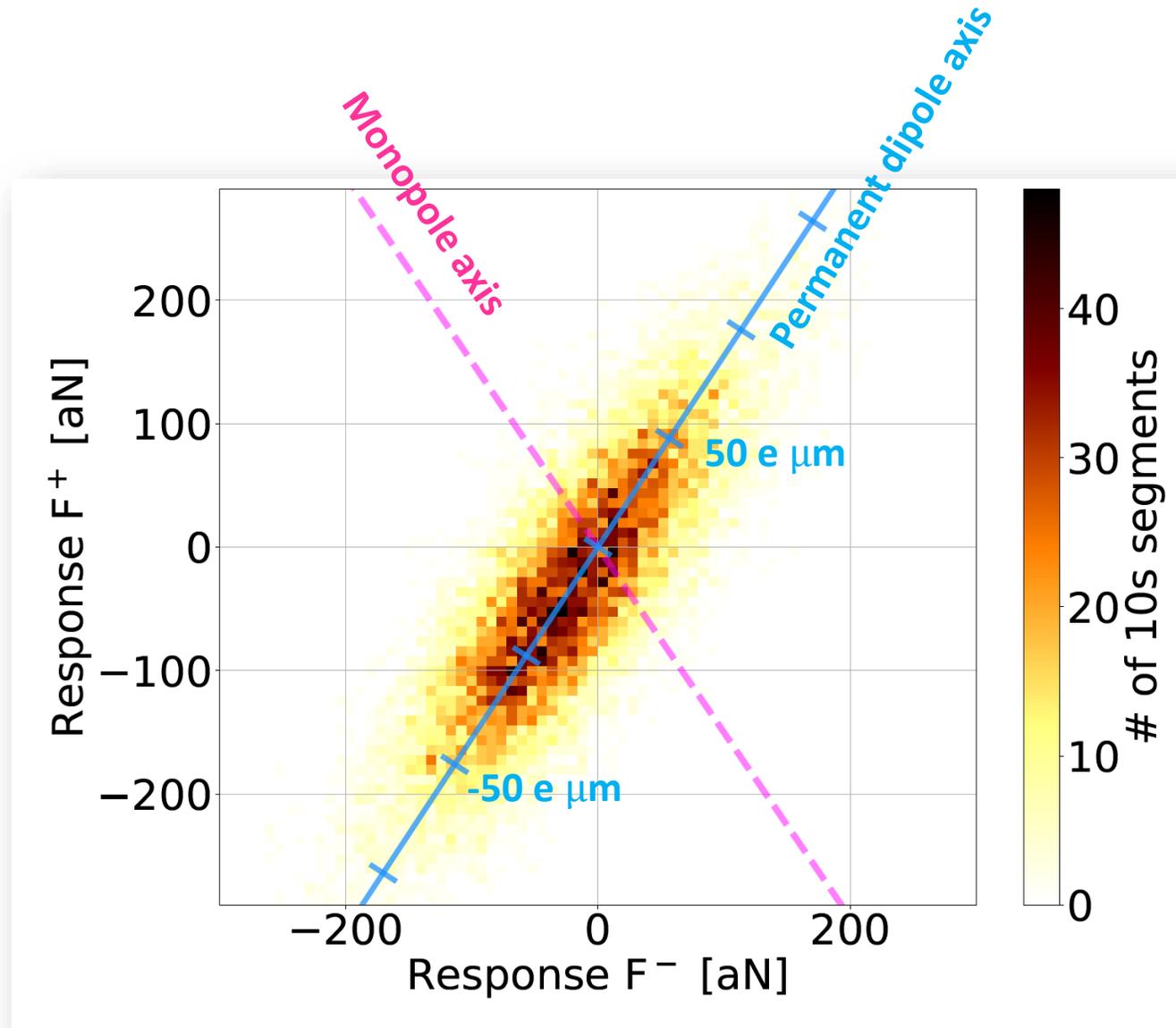
The correlation between F_+ and F_- contains more information!



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

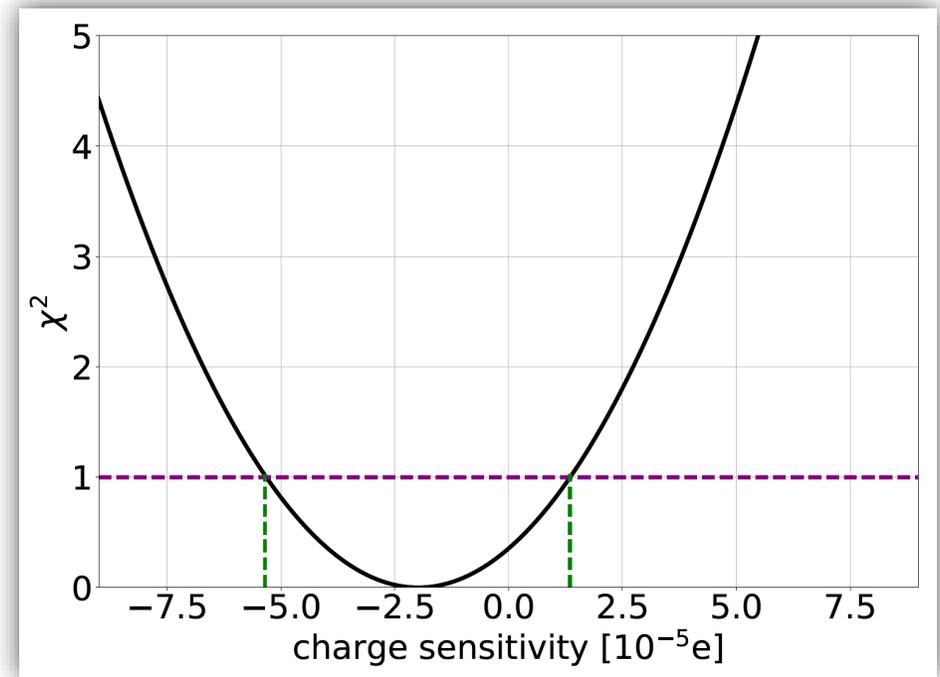
Again, note that there is no bias along the monopole axis.

But there is a finite permanent dipole measured (about 20 $e \mu\text{m}$ here). Quantitatively, this does not mean much, because the dipole changes with time)



Charge sensitivity

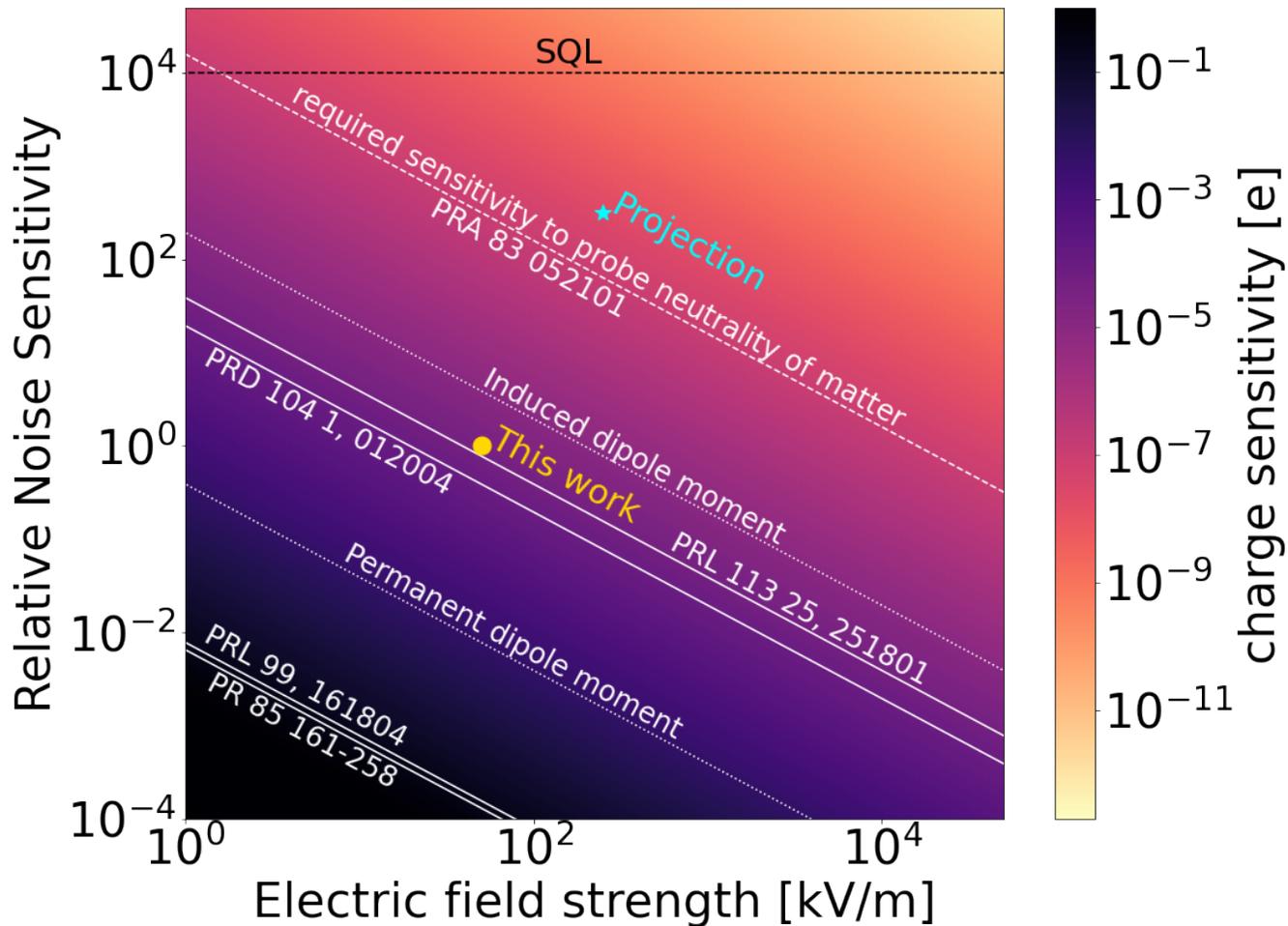
- 3 spheres with different electric field configurations: consistent results.
- No residual backgrounds: **improved accuracy by two orders of magnitude**



| 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 $3.3 \times 10^{-5} e$**
- **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)*

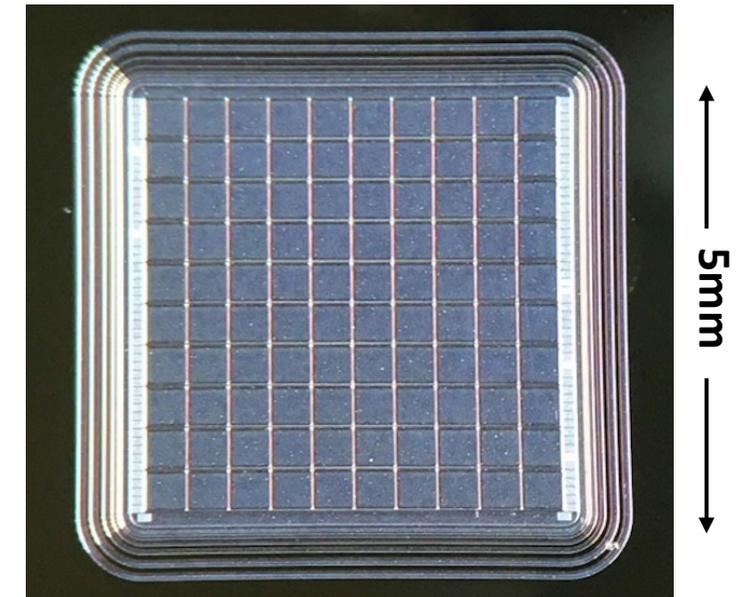
See also: Tue 4:06 PM E03.00006: N.Priel "A background-free optically levitated charge sensor"

What comes next

- **Recommissioning trap after a number of upgrades**
- **For next measurements:**
 - EDM backgrounds (modeling and scanning with attractor and nulling the contact potential)
 - Reduce stray light effects
 - **Work on pointing noise**
- **In the works, in parallel:**
 - **Rotary attractor**
 - Less vibration at the fundamental frequency
 - Different systematics
 - In collaboration with EPFL
 - **Multi-pixel (100) x-y readout**
 - Provide crude imaging, helpful with stray light of non-Gauss modes
 - Deep depletion / excellent q_e at 1064nm
 - In collaboration with SLAC

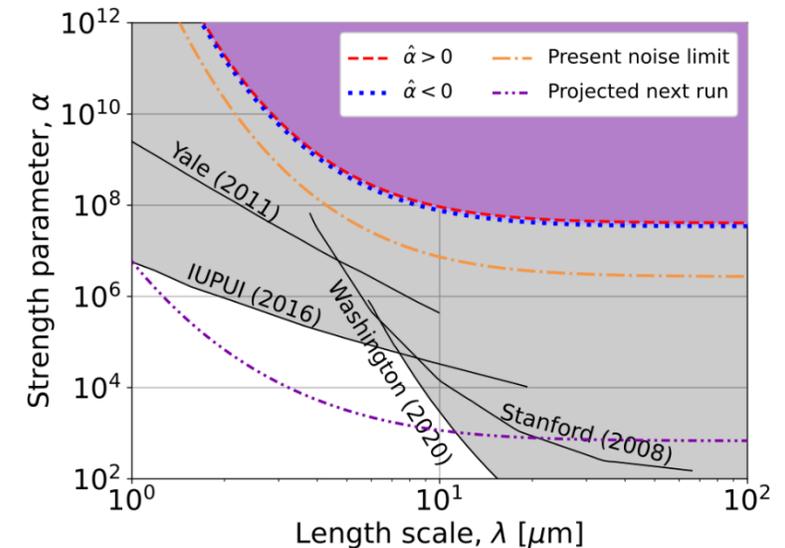


See also: Tue 4:18 PM E03.00007: E.Hough "Novel Technique to Measure μm -Scale Forces Using a Non-Linear Attractor"



Conclusions

- After >200 years of mechanical springs, the $1/R^2$ behavior of gravity <50 μm 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 then proceeded to measure and suppress.
- A number of system upgrades are in progress, and we just restarted data taking, striving for much improved sensitivity.





The cast



Also thank our "alter egos" at Yale:

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

