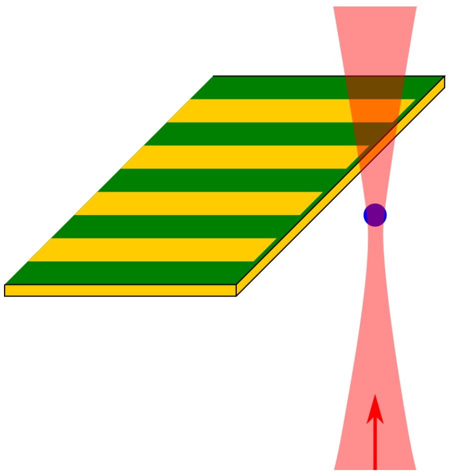
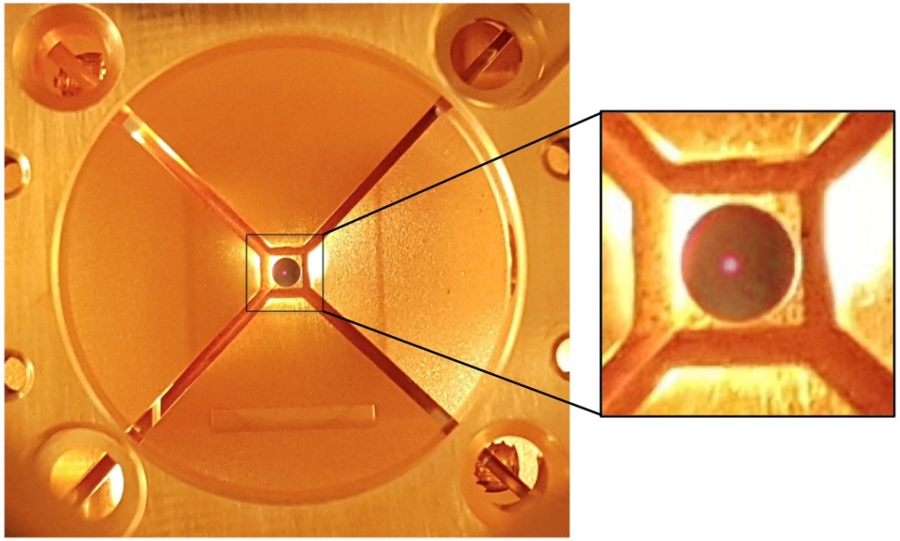
Search for non-Newtonian gravity at 10 μm scale by precision force measurements with optically-levitated microspheres





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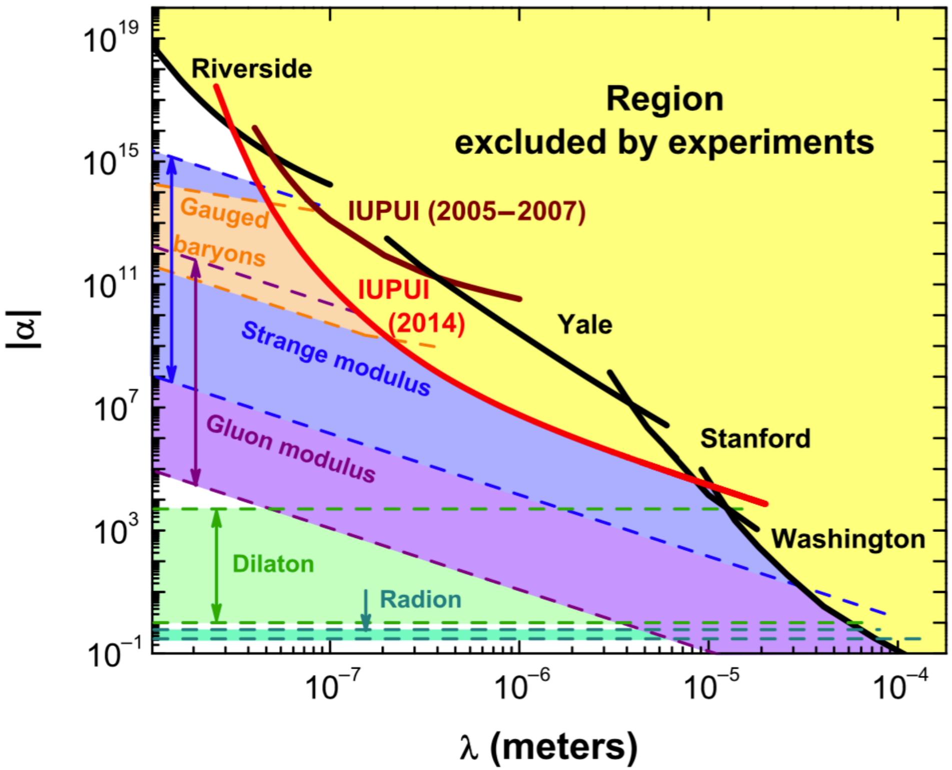
Modification to Newtonian Gravity

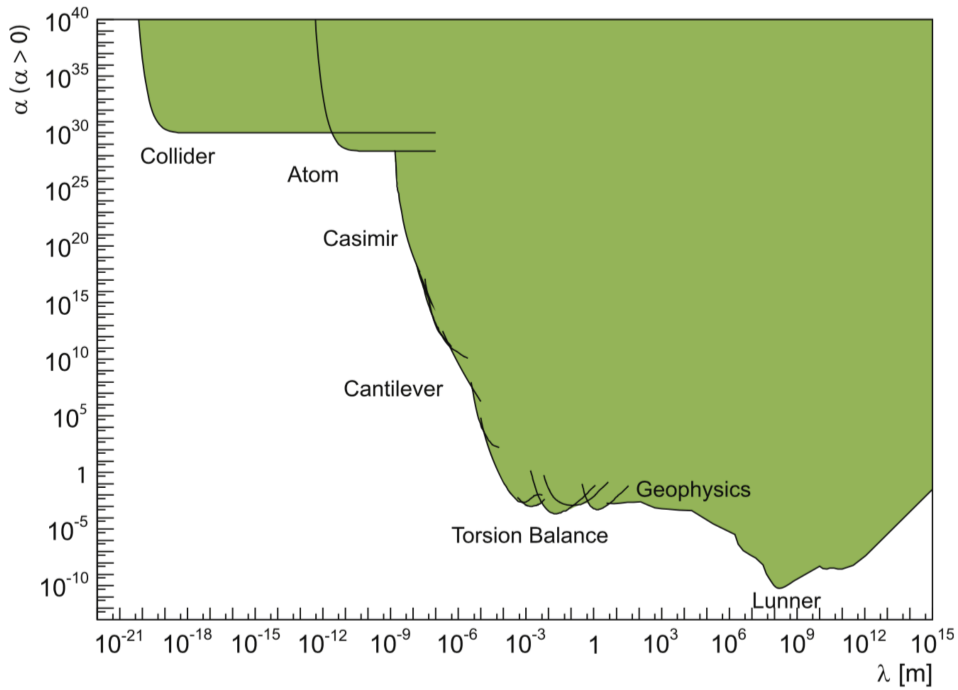
- Modified Newtonian gravity

$$V(r) = -\frac{GMm}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

- Current limit to the Yukawa term in α-λ space



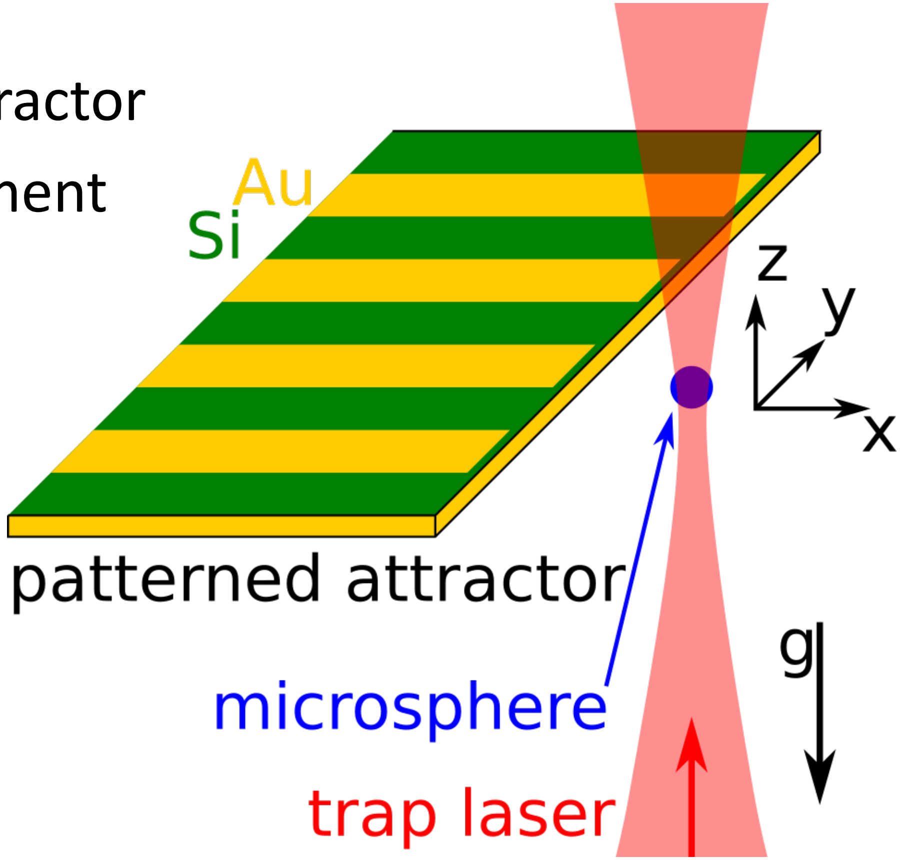
Y.-J. Chen, *et al.*: PRL **116**, 221102 (2016)



J. Murata, *et al.*:
Class. Quantum Grav. **32**, 033001 (2015)

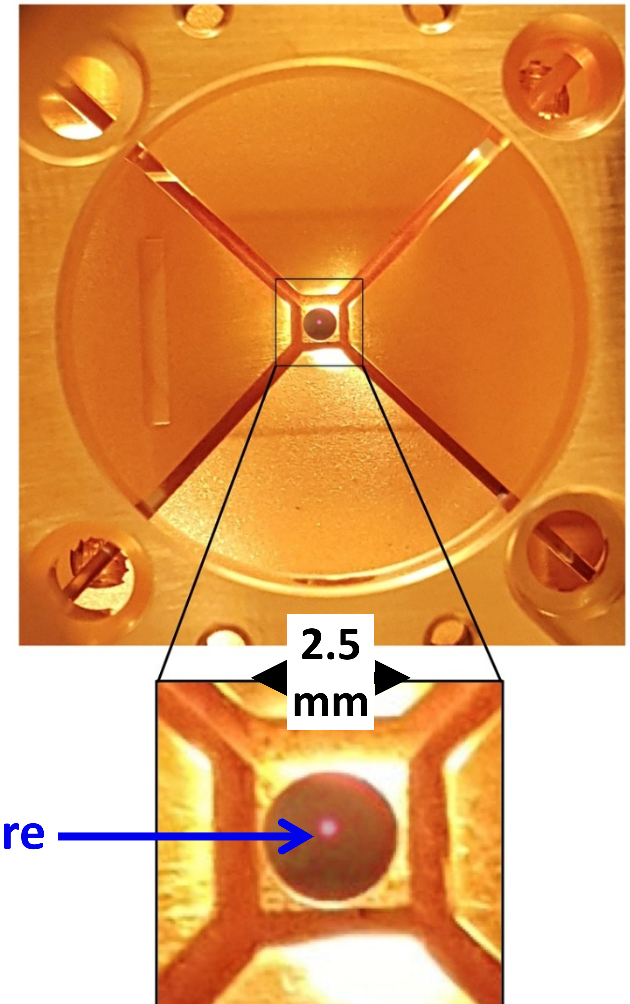
Our Approach: Optically Levitated Sphere

- 4.8 μm diameter sphere (~0.1 ng) made of silica is trapped by a single laser beam (1064 nm) in vacuum (~10^{-6} mbar).
- A cantelever with 50 μm period density modulation serves as an attractor
- The force on the sphere by the attractor is measured through the displacement of the sphere position.



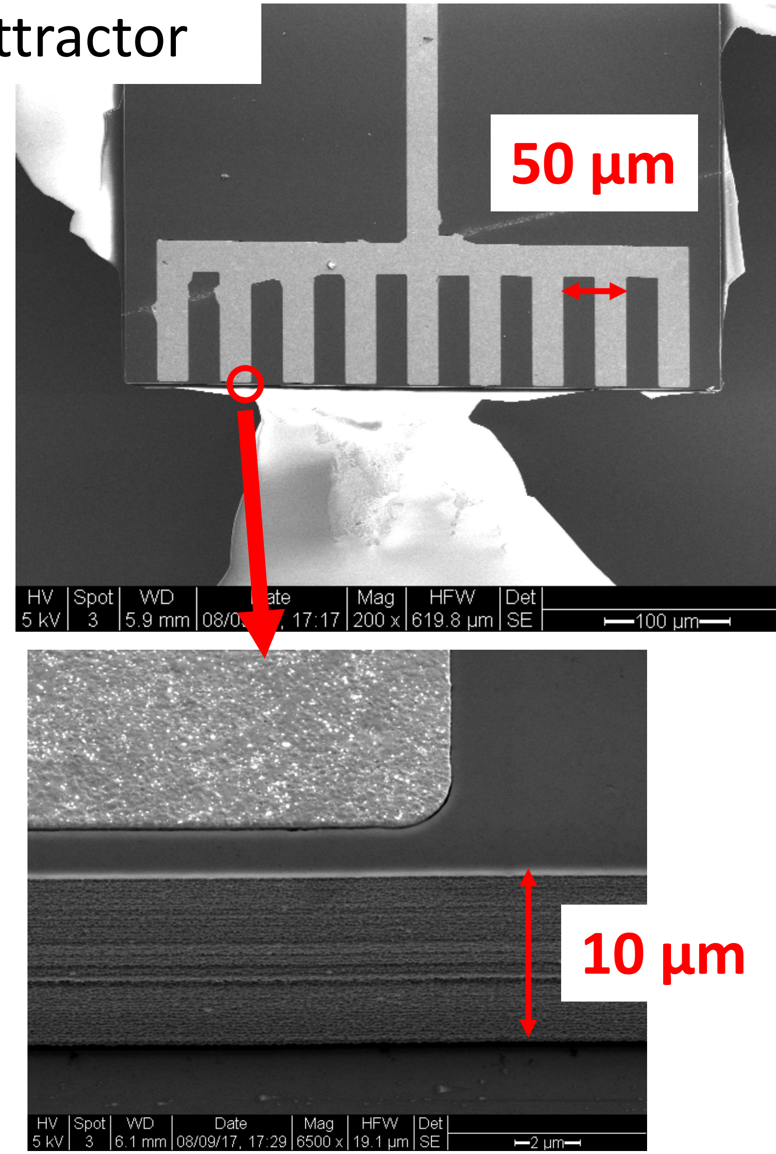
Apparatus

Trap and Electrode



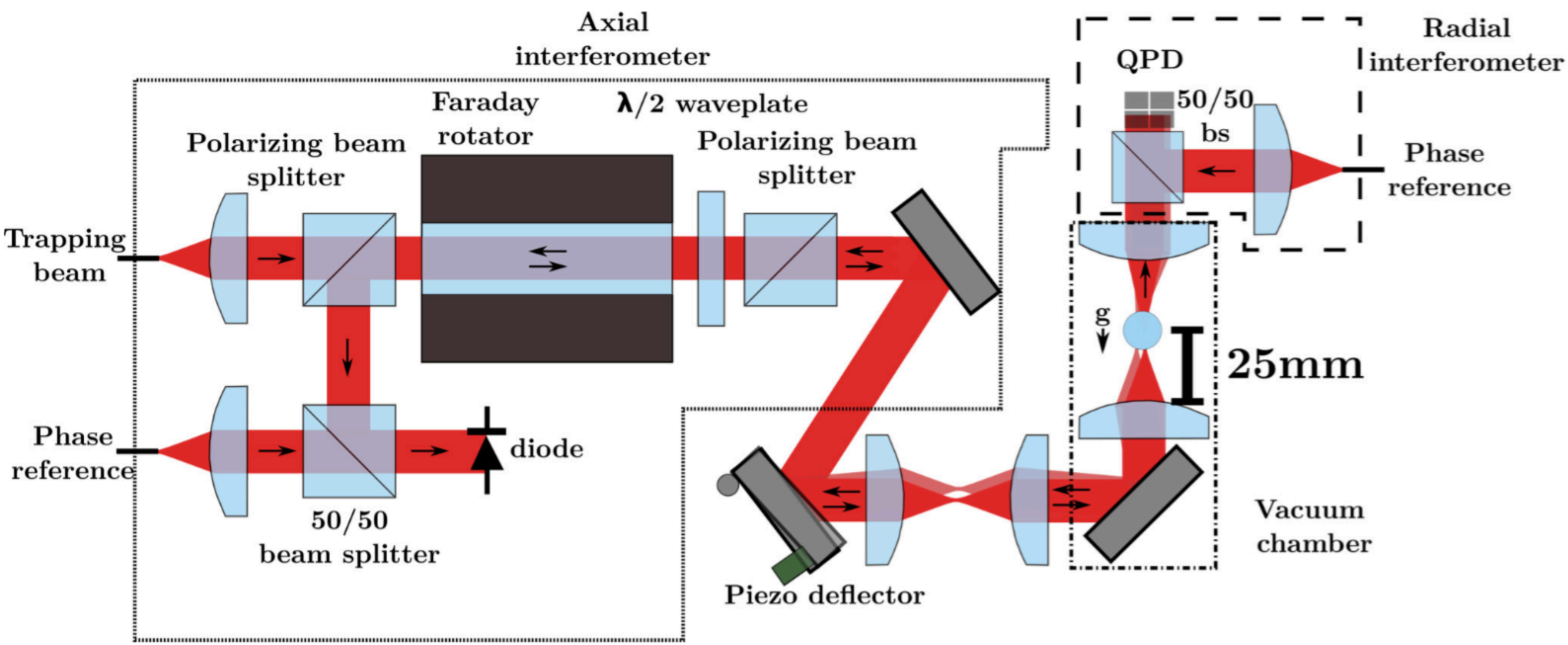
Trapped microsphere

Attractor



Heterodyne Measurement and Feedback

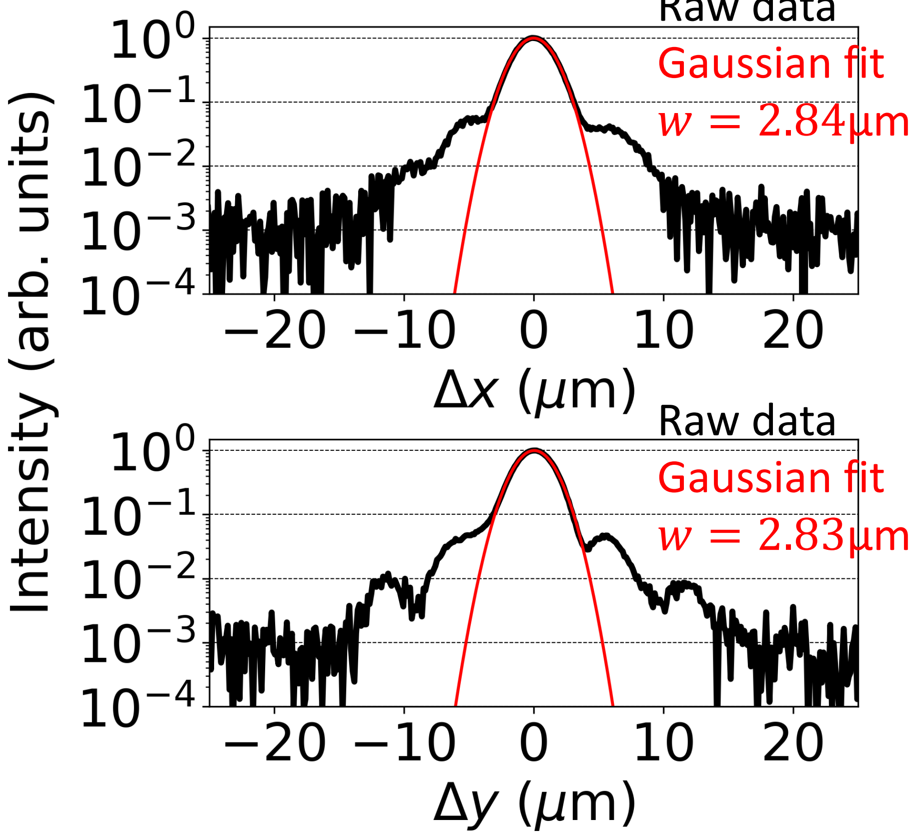
- Schematics of the trap, feedback, detection system



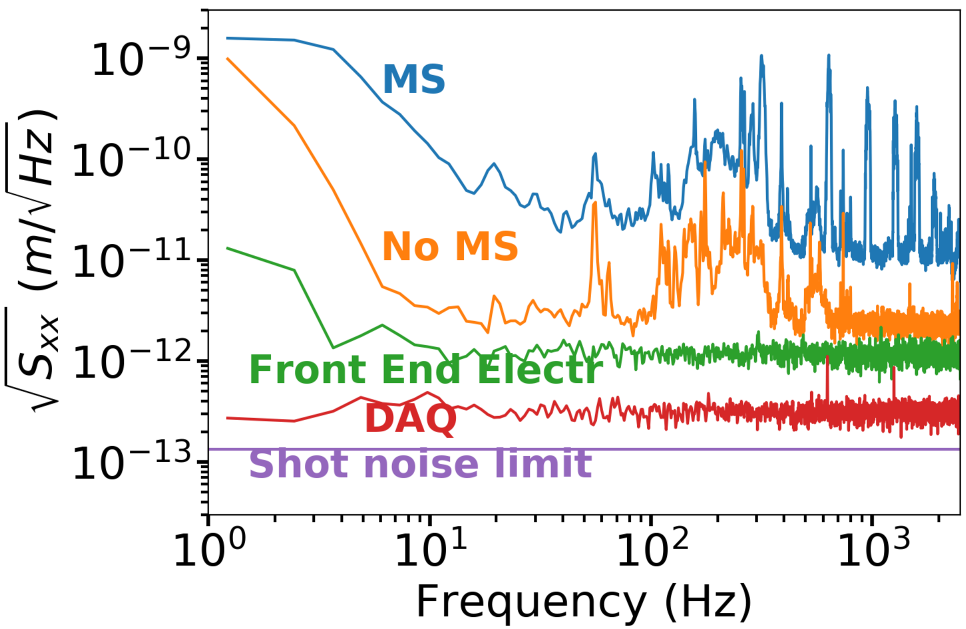
A. D. Rider, *et al.*: PRA **97**, 013842 (2018)

Performance of Heterodyne Measurement

Beam profile of x (top) and y (bottom) direction at the trap



Noise budget for the x direction position sensitivity
(y axis: noise spectral density of position)

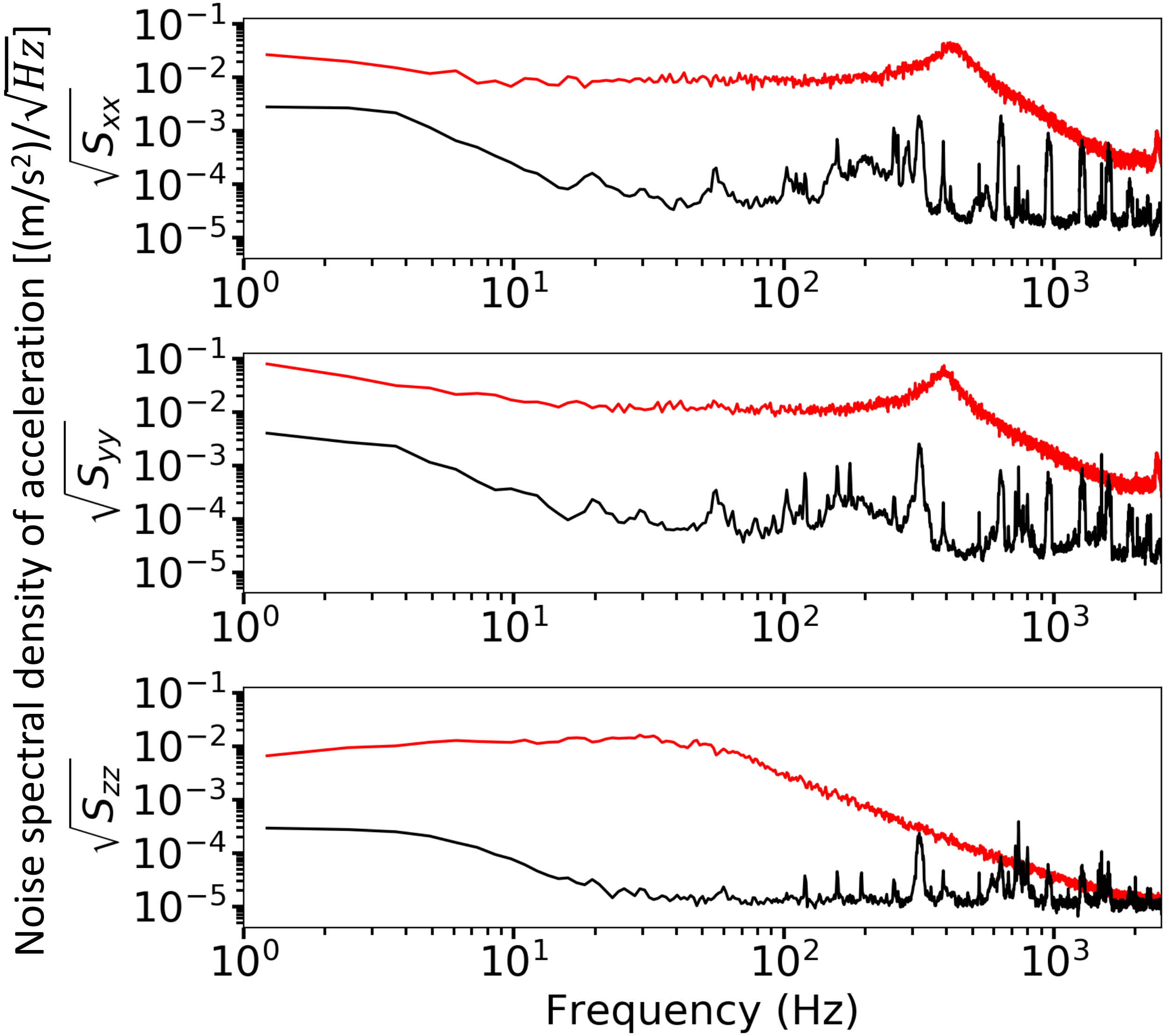


A. D. Rider, *et al.*: PRA **97**, 013842 (2018)

Acceleration Sensitivity

- This acceleration sensitivity gives force sensitivity of $8\times10^{-17}\ N/\sqrt{Hz}$.

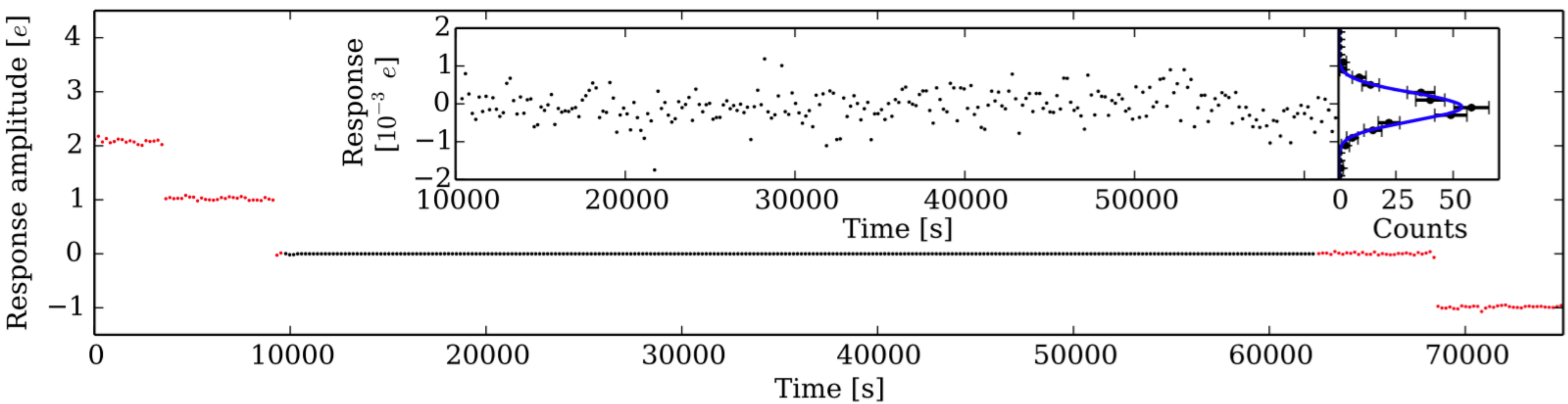
- Red line is at 1.5 mbar, without feedback cooling.
- Black line is at 10^{-6} mbar, with feedback cooling.



Discharge

- After a microsphere is trapped, feedback cooling is turned on, and the chamber is pumped down from ~1 mbar to ~10^{-6} mbar.
- Trapped sphere is charged, and we remove electrons by shining UV light onto the sphere.
- The process of the discharge of an electron by an electron is visible.

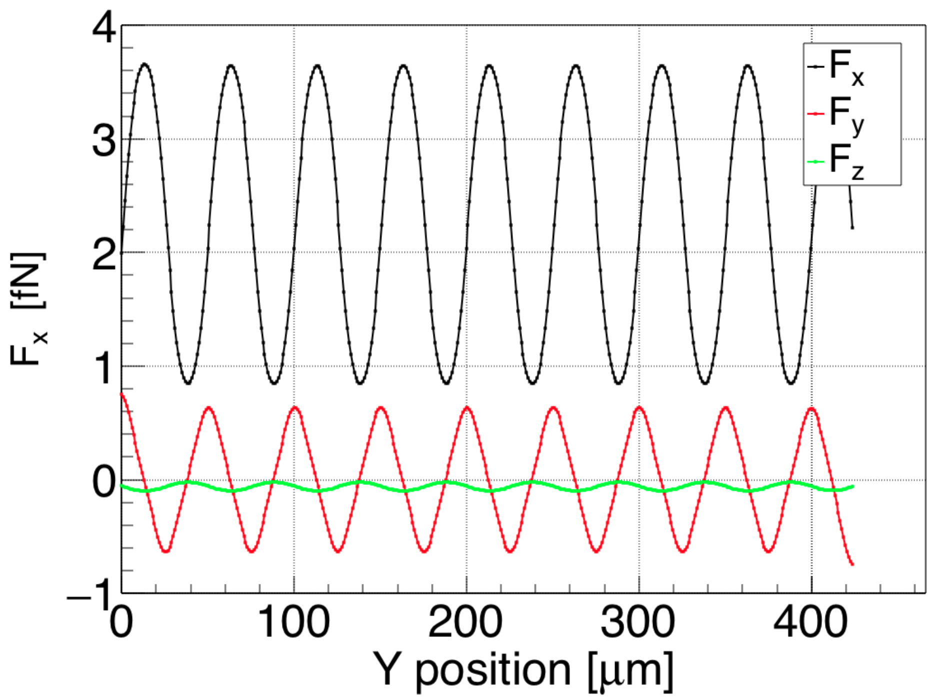
  →search for millicharge. (PRL **113**, 251801 (2014))

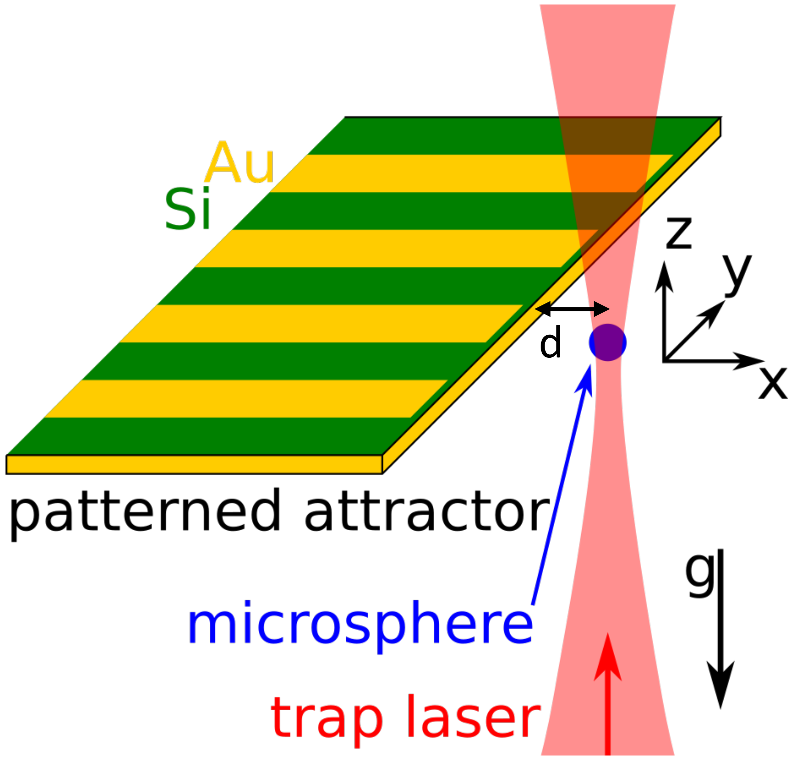


D. C. Moore, *et al.*: PRL **113**, 251801 (2014)

Data Taking Strategy

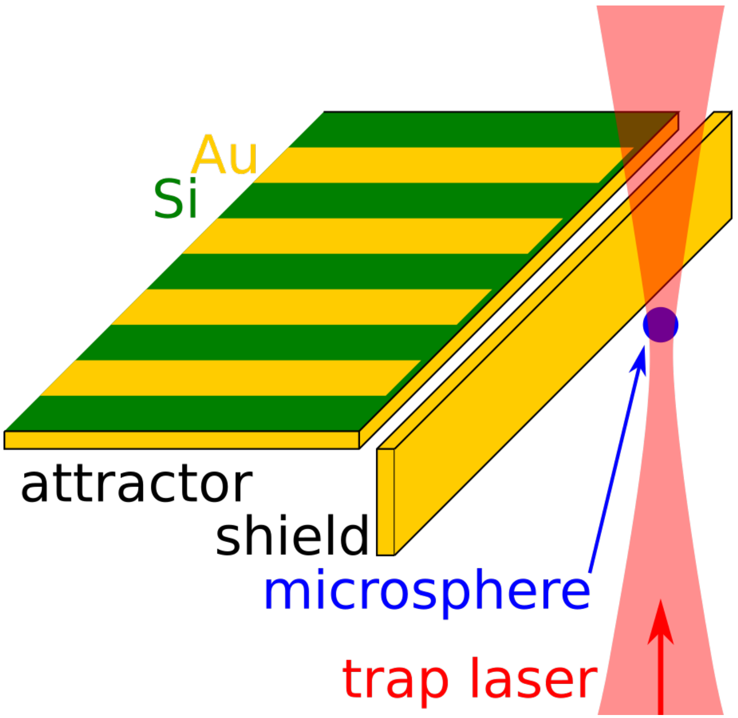
- Data are taken with the attractor's position driven with sinusoidal wave. The positions of the attractor and the microsphere are recorded.
- Simulated data for $d = 10\ \mu\text{m}$, $\alpha = 10^{10}$, $\lambda = 5\ \mu\text{m}$.



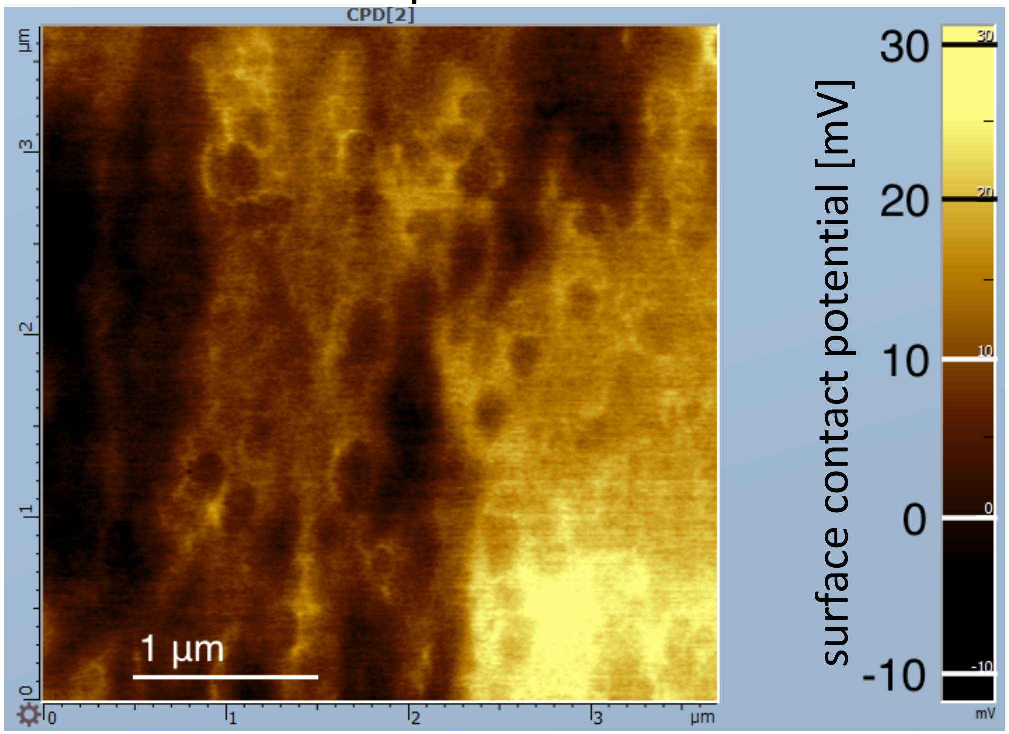


Background: Patch Potential

- Surface voltage of a metal is slightly different grain by grain, and this interacts with remaining permanent dipole moment on the sphere.
- To avoid this, we inserted a metal shield between the sphere and the attractor.

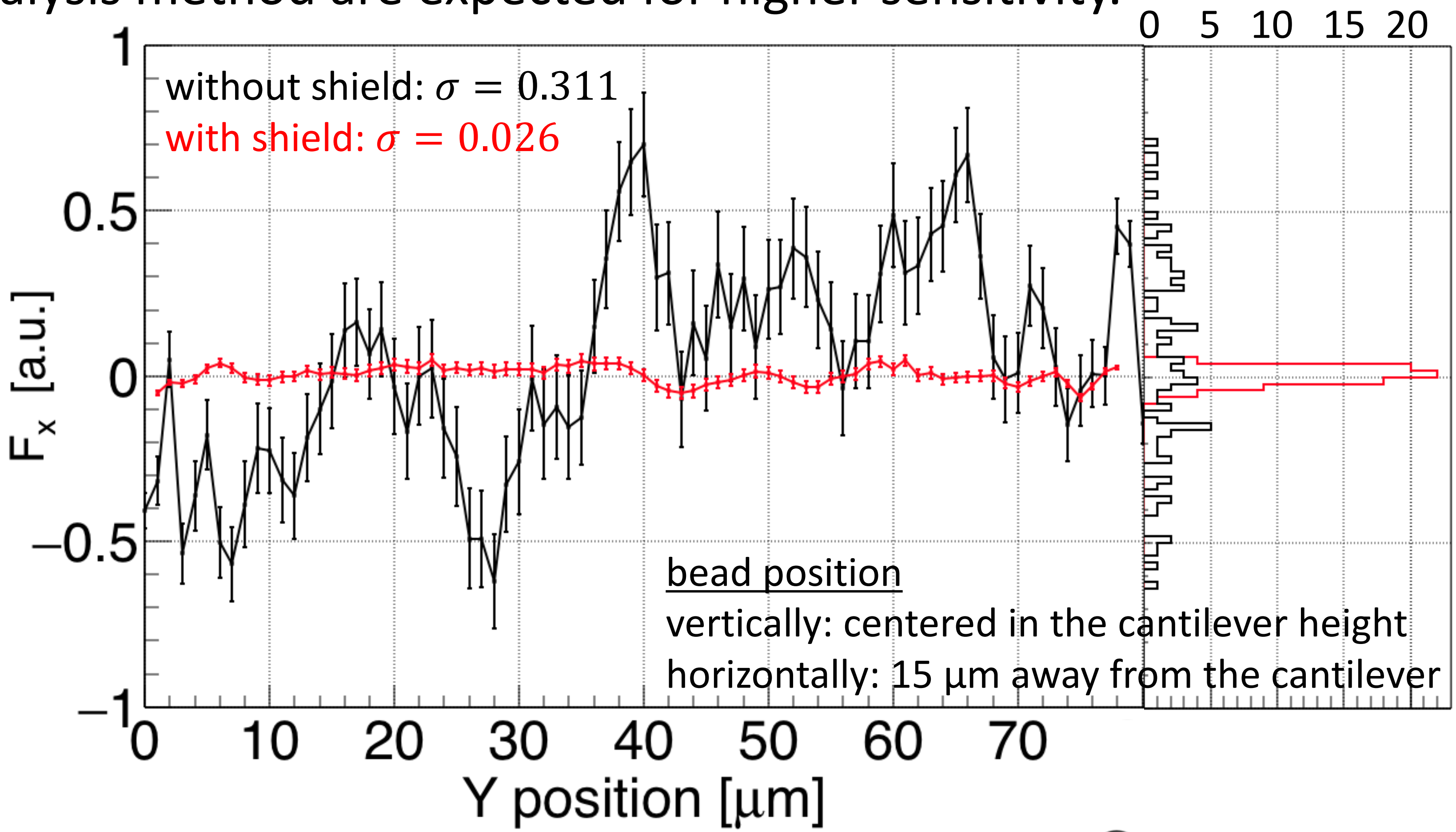


Kelvin probe force microscope measurement of surface contact potential



Background Reduction by the Shield

- The shield reduces the background by an order of magnitude.
- Further reduction of the background and improvement in the analysis method are expected for higher sensitivity.



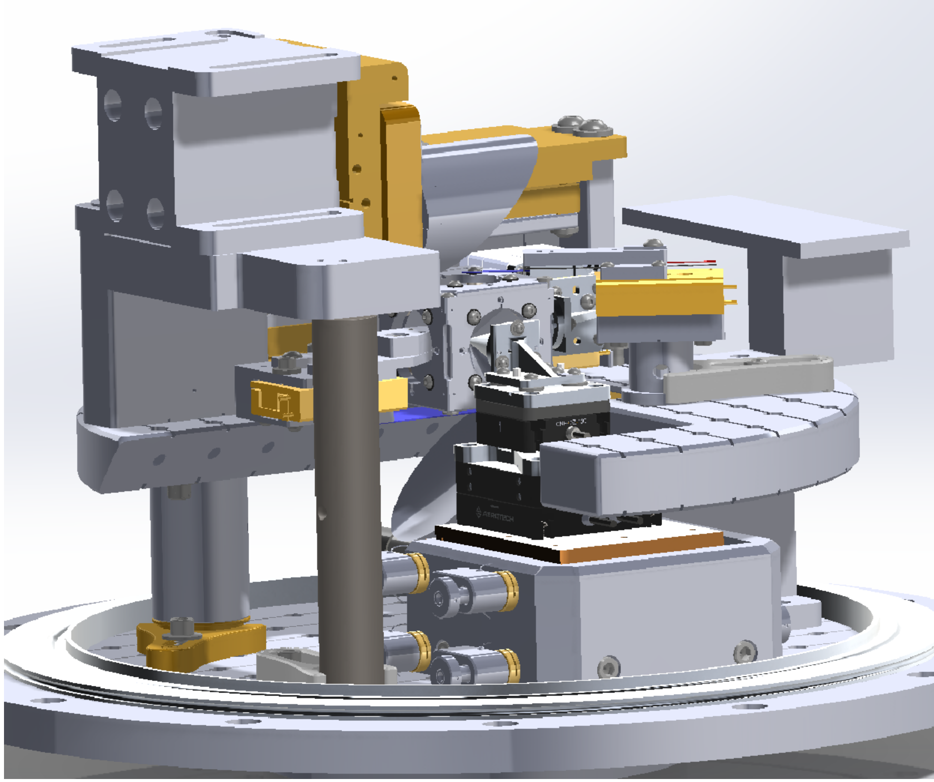
Conclusion and Outlook

Conclusion

- An apparatus to test Newtonian gravity with optically levitated sphere is built.
- First data is obtained, and we are working on analysis to extract best sensitivity to the gravitational force.

Outlook

- First result with current setup will come out in a near future.
- Upgraded new system is under construction.
  - Focusing by parabolic mirrors, instead of aspheric lenses.
  - Scanning the attractor over larger range.



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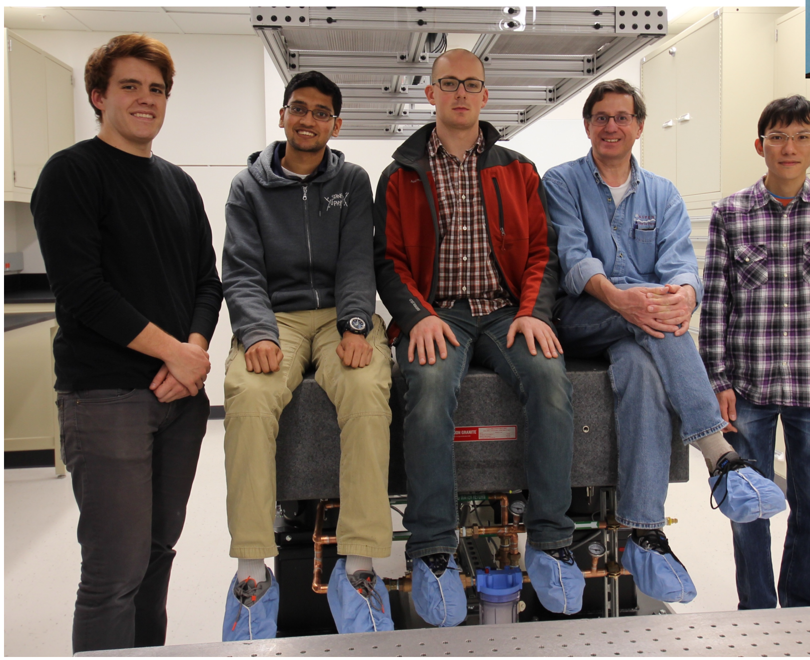
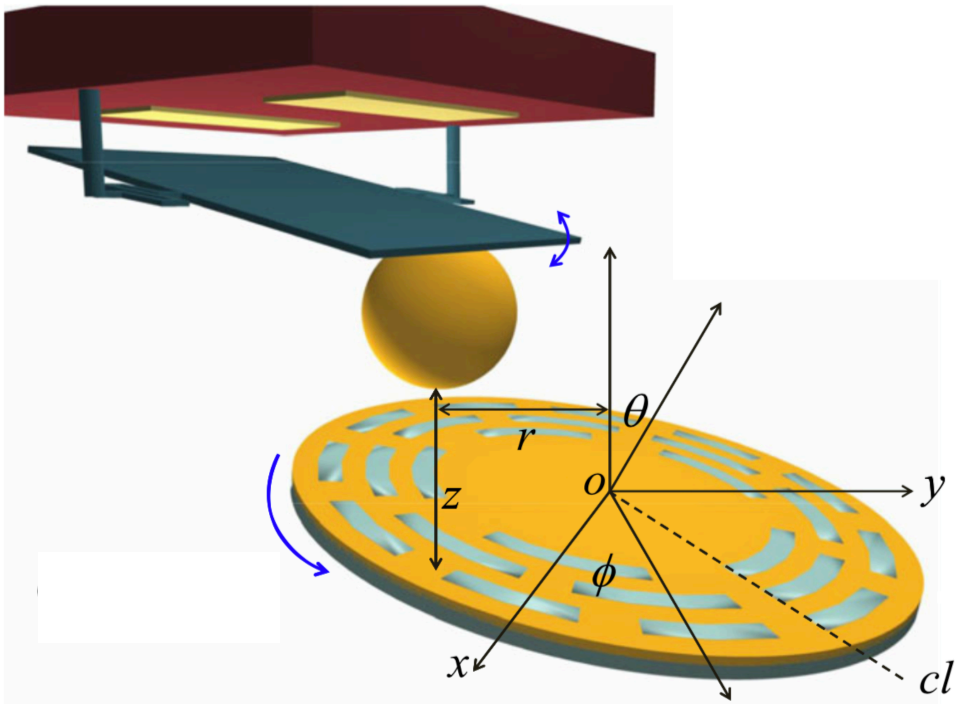
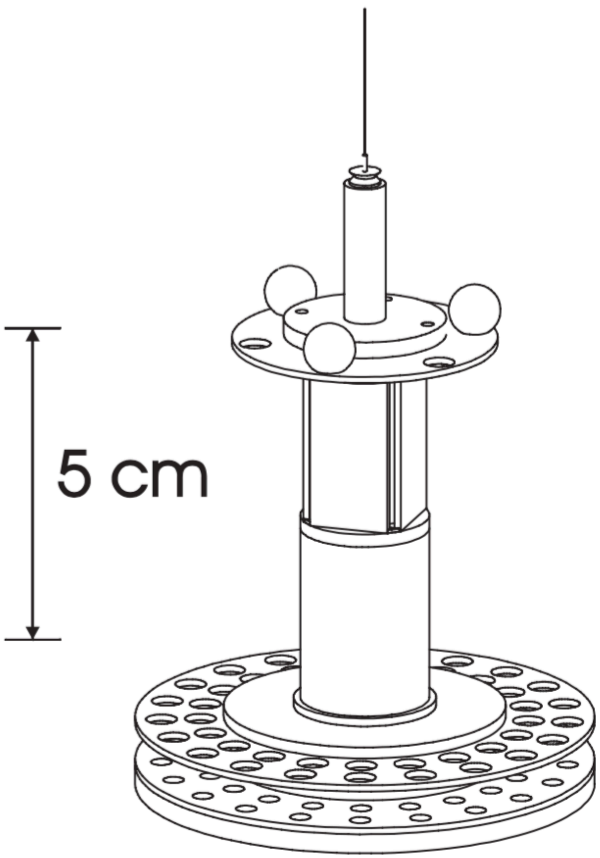


Backup Slides

Previous Measurements



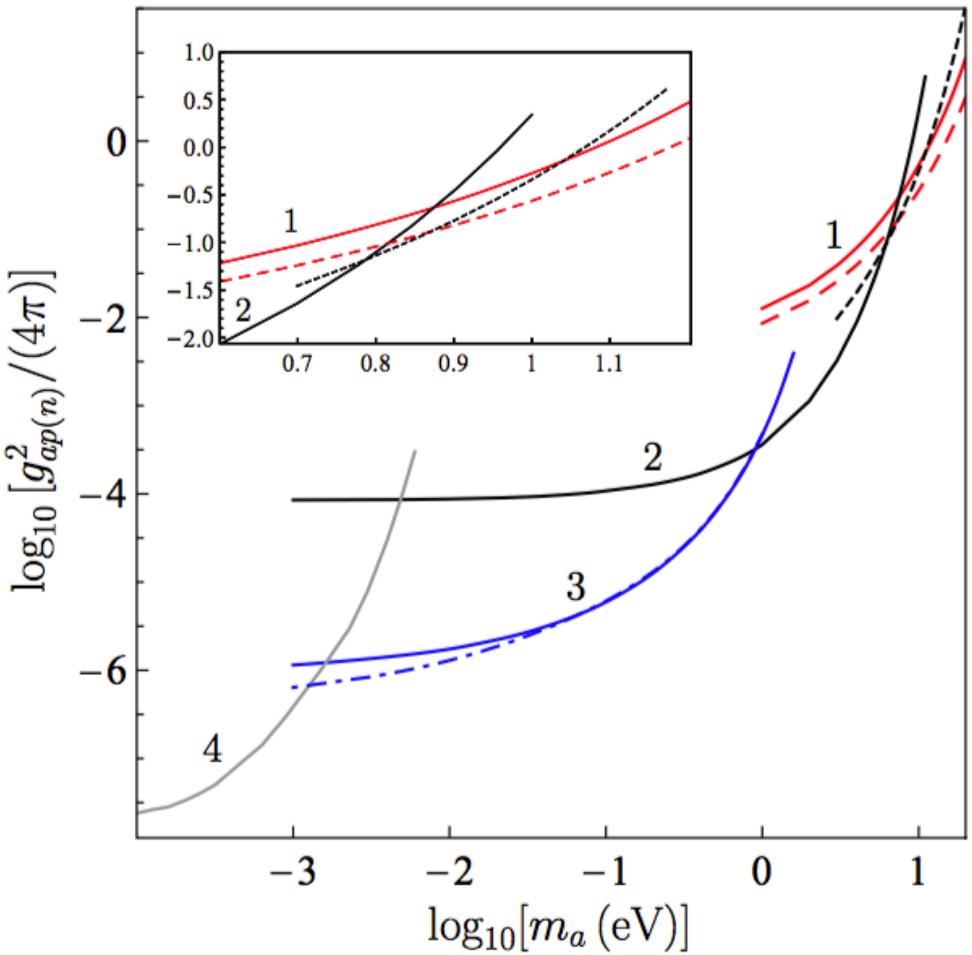
Y.-J. Chen, *et al.*: PRL **116**, 221102 (2016)



D. J. Kapner, *et al.*: PRL **98**, 021101 (2007)

Implication of the Modified Gravity

- Axion



G. L. Klimchitskaya: Eur. Phys. J. C **77**, 315 (2017)

Trapping a sphere

- Microspheres stick on a quartz surface by van der Waals force
- Spheres are shaken off from the quartz plate.
- Shaking continues until one of them is trapped.