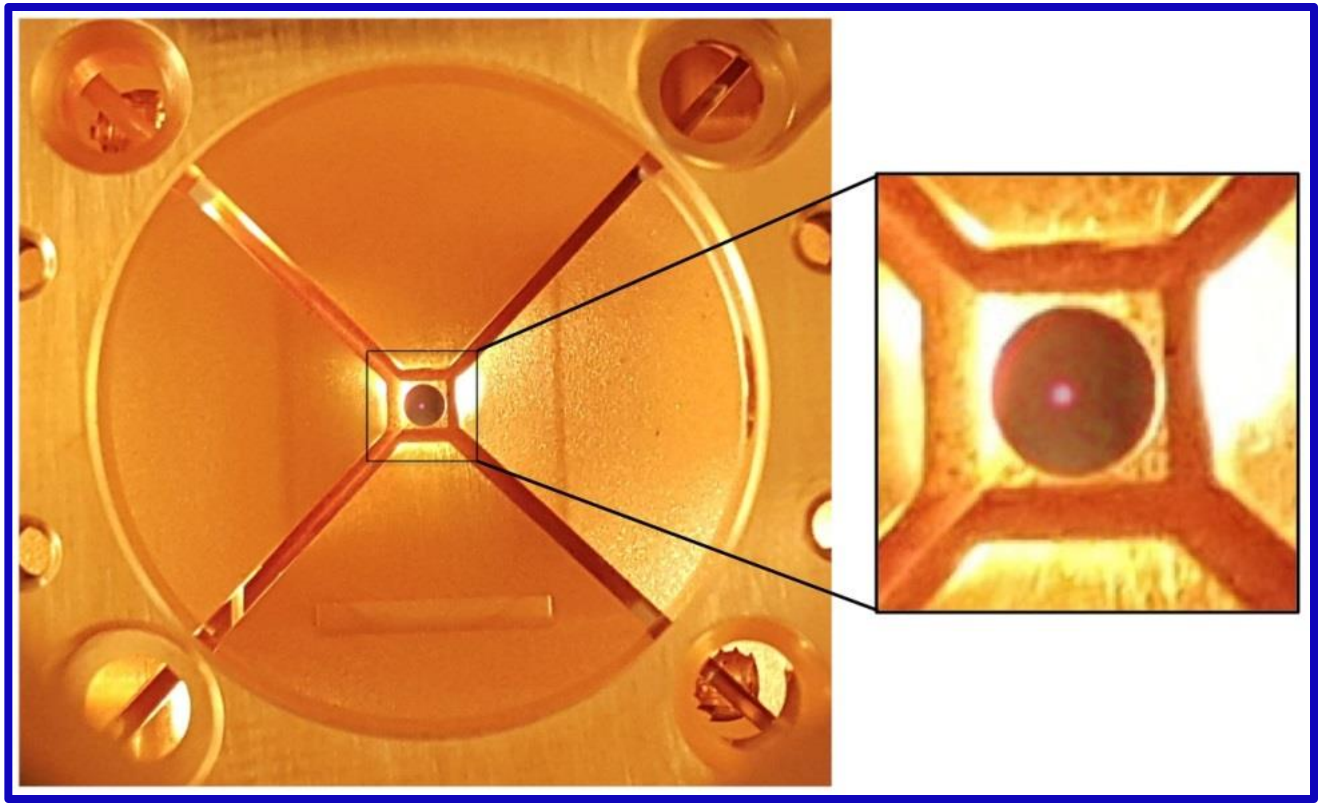
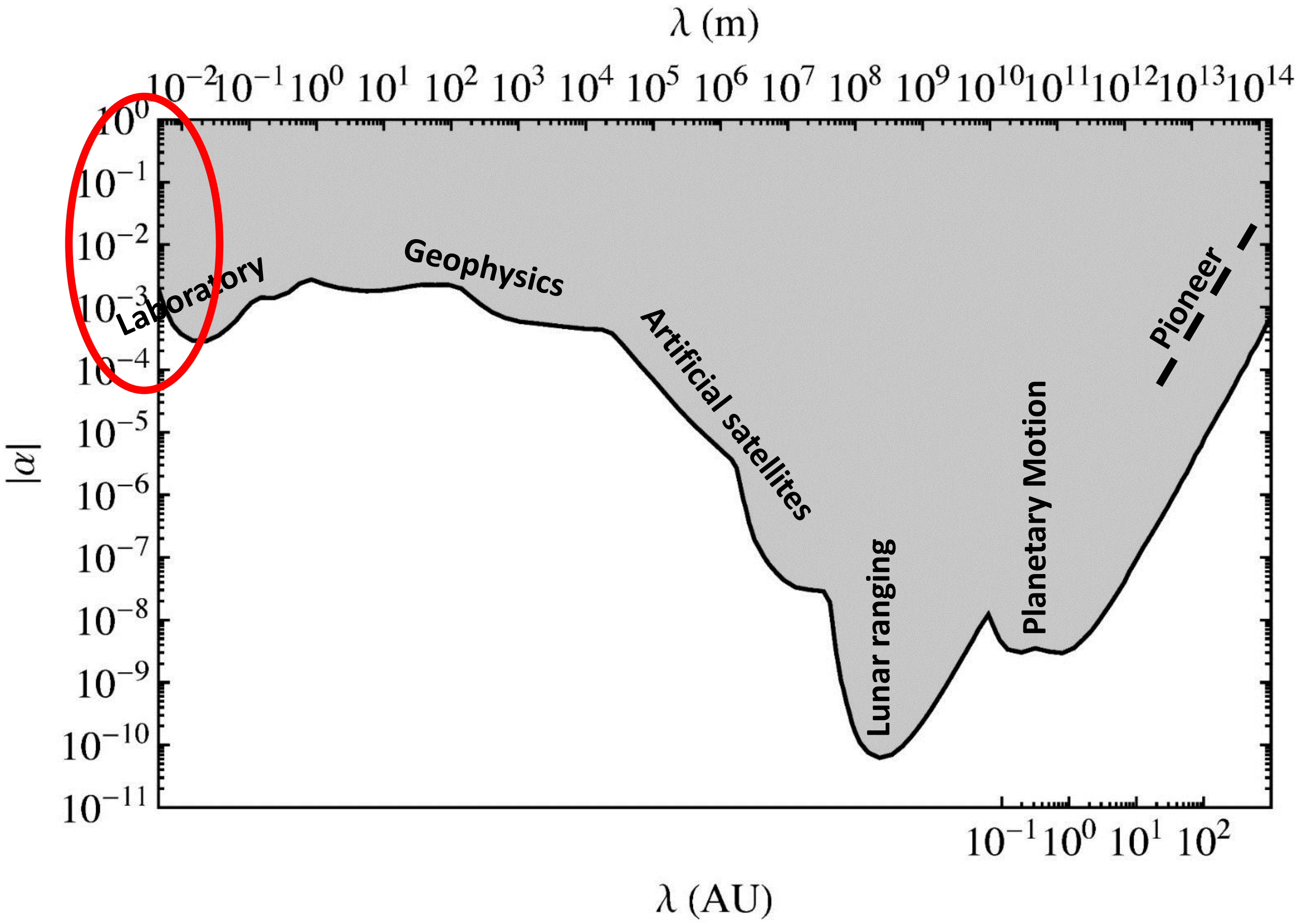
Tests of gravity using levitated microspheres



C. Blakemore, G. Gratta, M. Louis, M. Lu,
D. Moore, A. Rider, S. Roy
Stanford-Yale Collaboration

The current knowledge of the 1/R² law of gravity parameterized by the potential

$$\Psi(R) = \frac{GM}{R}\left(1 + \alpha e^{-\frac{R}{\lambda}}\right)$$

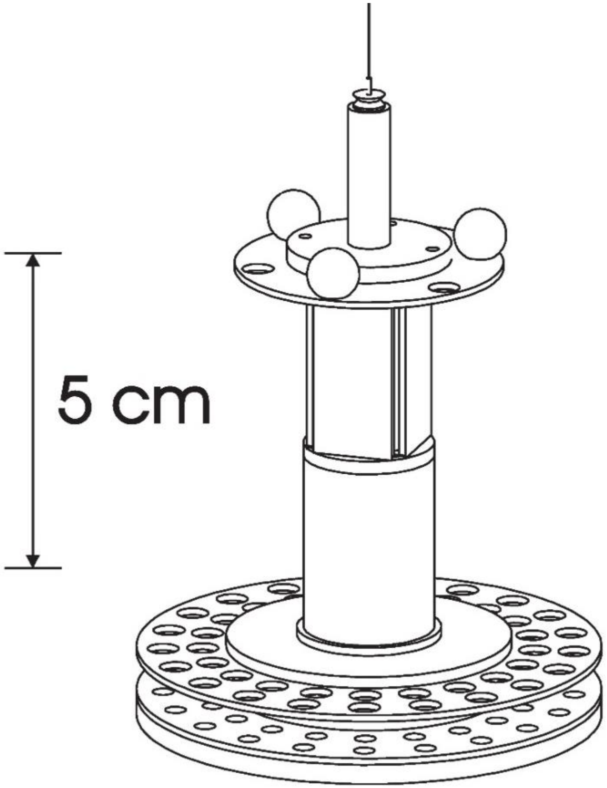


Short distance regime: the challenges

1. G is very small (gravity is very weak). Since gravity can't be shielded this is not obvious in very large objects.

2. Since $F = G\frac{M_1 M_1}{R^2} = G\frac{\rho_1 V_1 \rho_2 V_2}{R^2}$ for materials we have access to (no Neutron Stars here!) $\rho_1 \sim \rho_2 < 20$ g/cm^3, there is no silver bullet. In addition $V \sim R^3$, so $F \sim G\frac{\rho^2 R^6}{R^2}$ It is clear that measurements at short distance become exceedingly difficult. Often the measured quantity is the acceleration of the test mass: $a \sim G\frac{\rho R^3}{R^2} \sim G\rho R$

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



Sketch of the EotWash apparatus from the University of Washington in Seattle

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

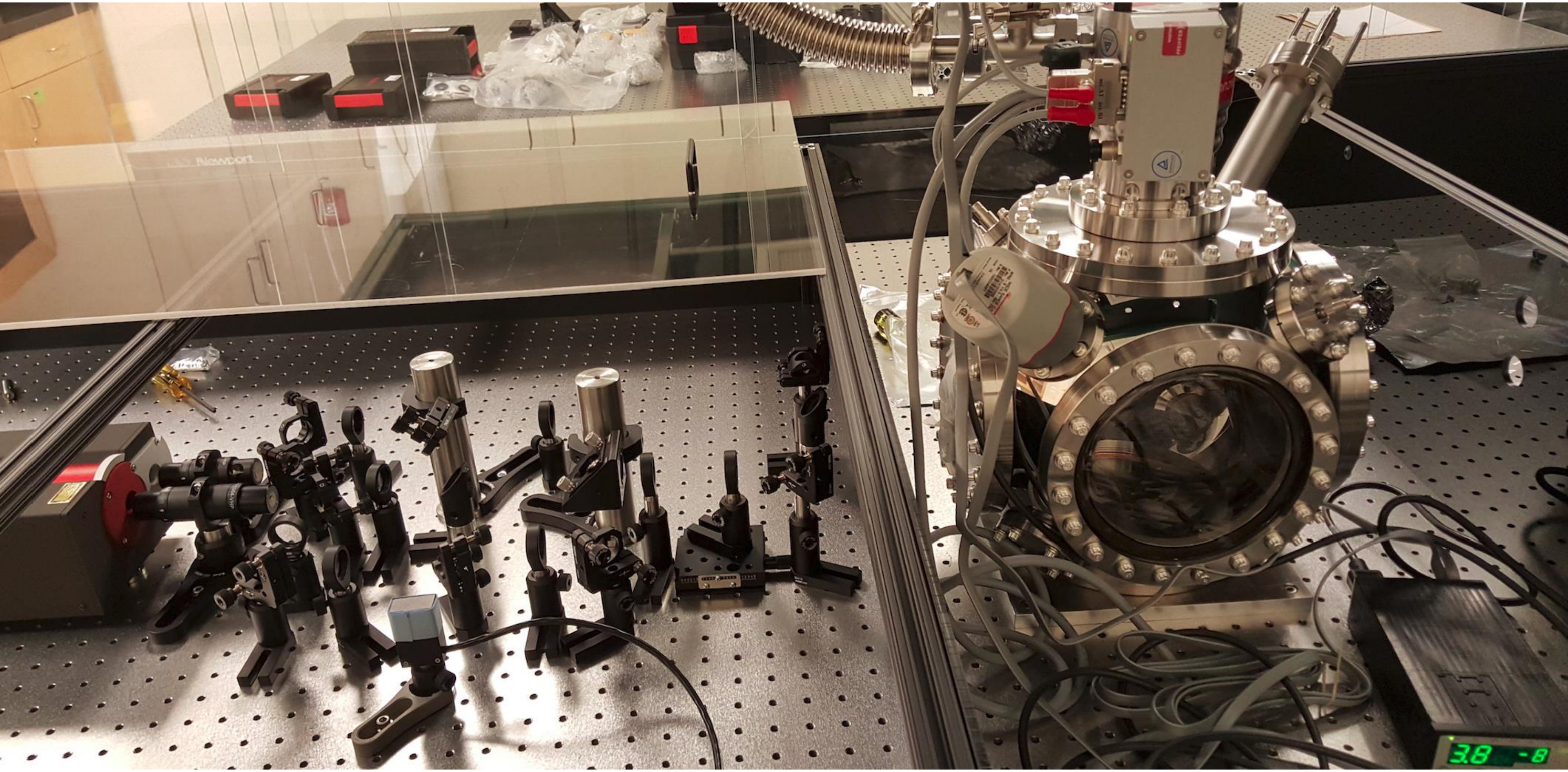
As distances become shorter substantial efforts have to do with "artificial" issues (e.g. how to machine a 5 cm diameter disk flat to µm level…).

In addition most previous measurements use mechanical springs.

We use a force sensor similar in size to the range of interest and use "optical springs" that are much more versatile than the mechanical ones.

[Note: The ideal probe for such a measurement would be a neutron, because its charge radius is ~1fm instead of ~1nm (for atoms). Unfortunately we do not know how to manipulate a neutron sufficiently well to use it for these measurements.]

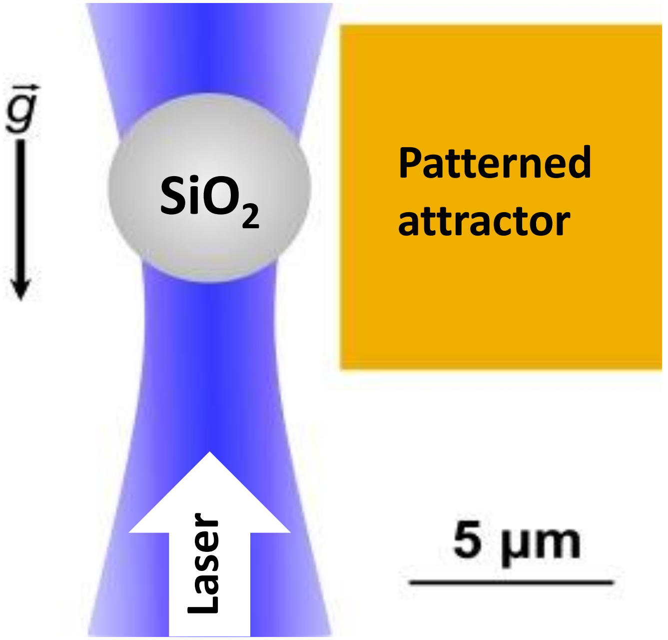
Table top! (Yale group)



New Stanford Lab

Optical traps offer important advantages

- In high vacuum can cool the force sensor (µsphere) with everything else at room temperature.
- Thermal and vibrational noise from mechanical support minimized.
- Test mass position can be controlled and measured precisely with optics.
- Trap parameters can be changed instantaneously.
- Control of optical potential and motion in all 3 DOF allows powerful differential measurements.
- Dielectric spheres from ~10 nm to 10 µm commercially available.
- Extremely low dissipation is possible: $Q \sim 10^{12}$ at 10^{-10} mbar

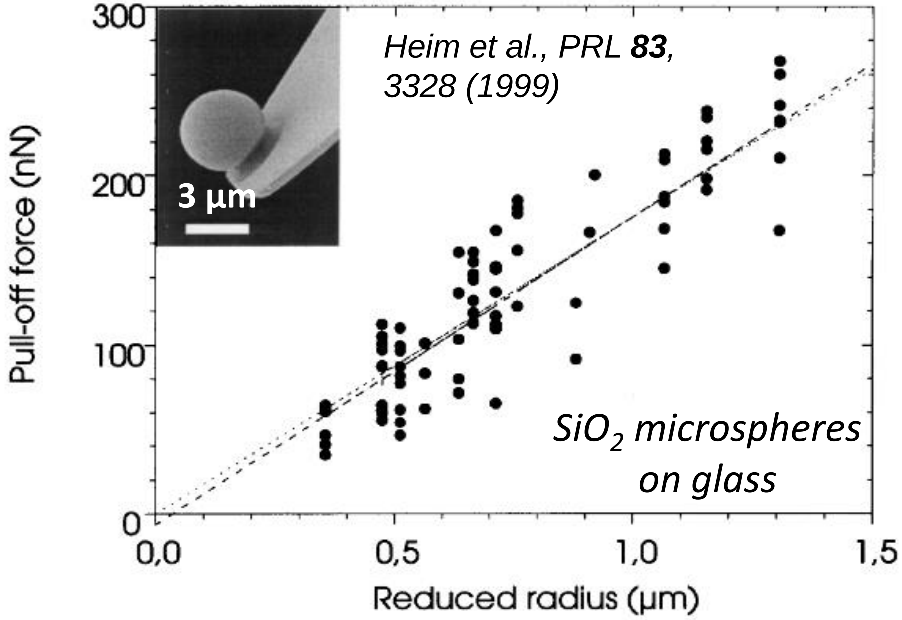


Ashkin & Dzierdzic, Appl.Phys.Lett. 19 (1971) 283
Geraci et al., PRL 105 (2010) 101101
Ranjit et al., Phys. Rev. A 91 (2015) 051805(R)

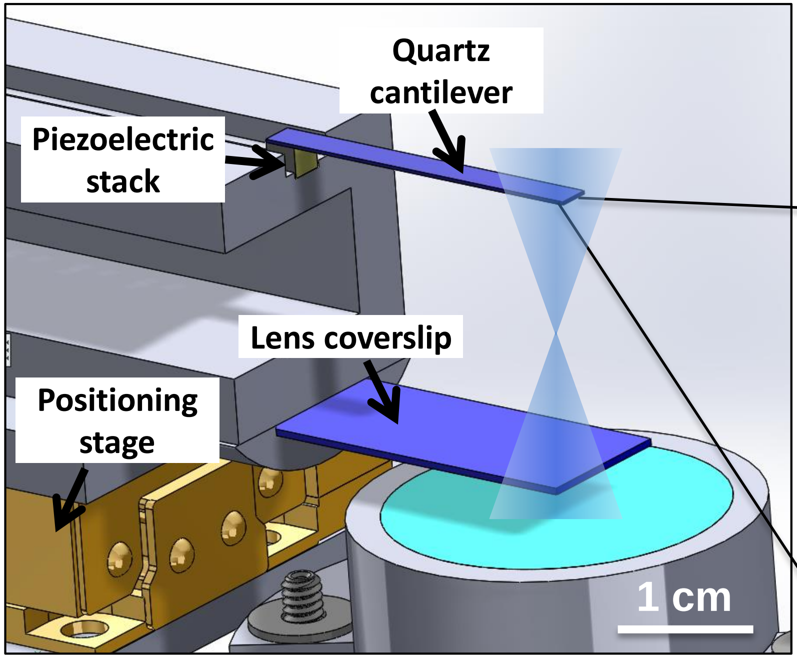
Trap loading

- Microspheres are launched from bottom surface of quartz cantilever
- Pull-off forces of ~100 nN require accelerations ~10^6 m/s^2
- Bottom coverslip protects lens and is retracted after trapping

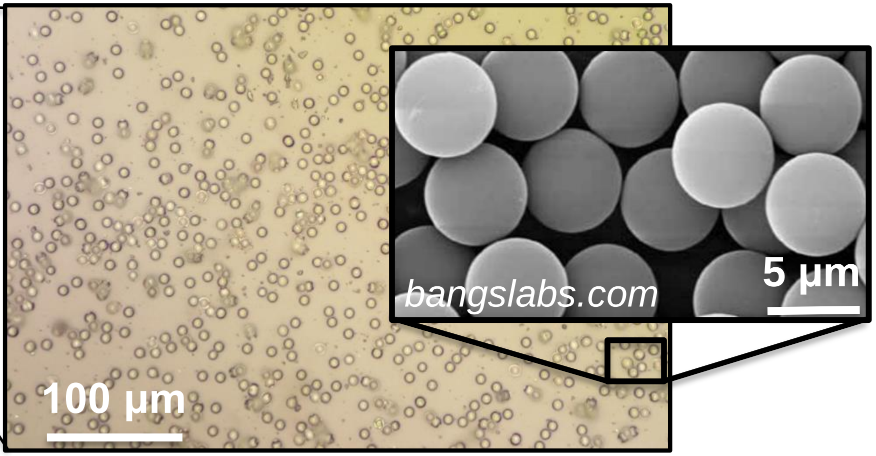
Pull-off force vs. microsphere radius:



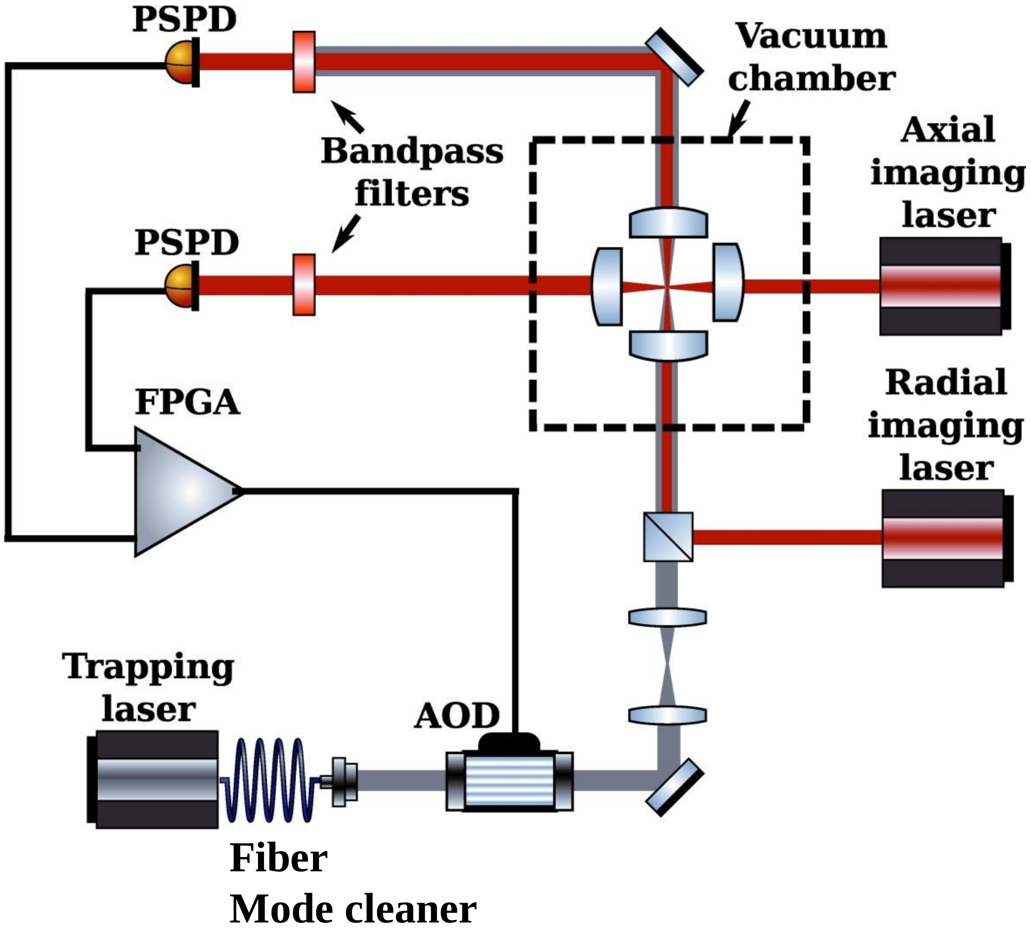
Schematic of microsphere dropper:



Microspheres on quartz surface:

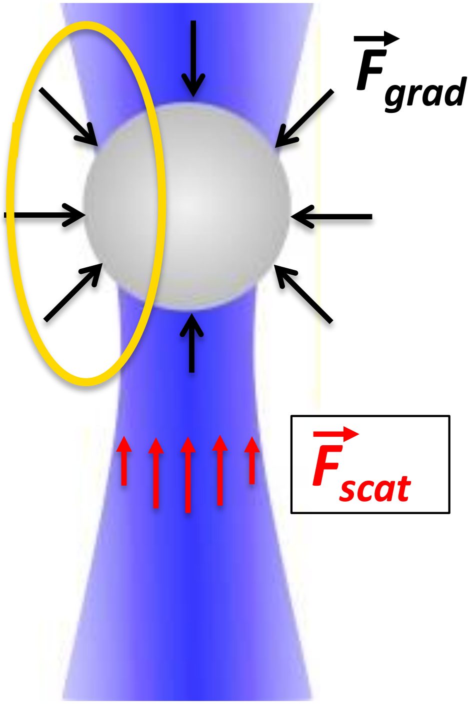


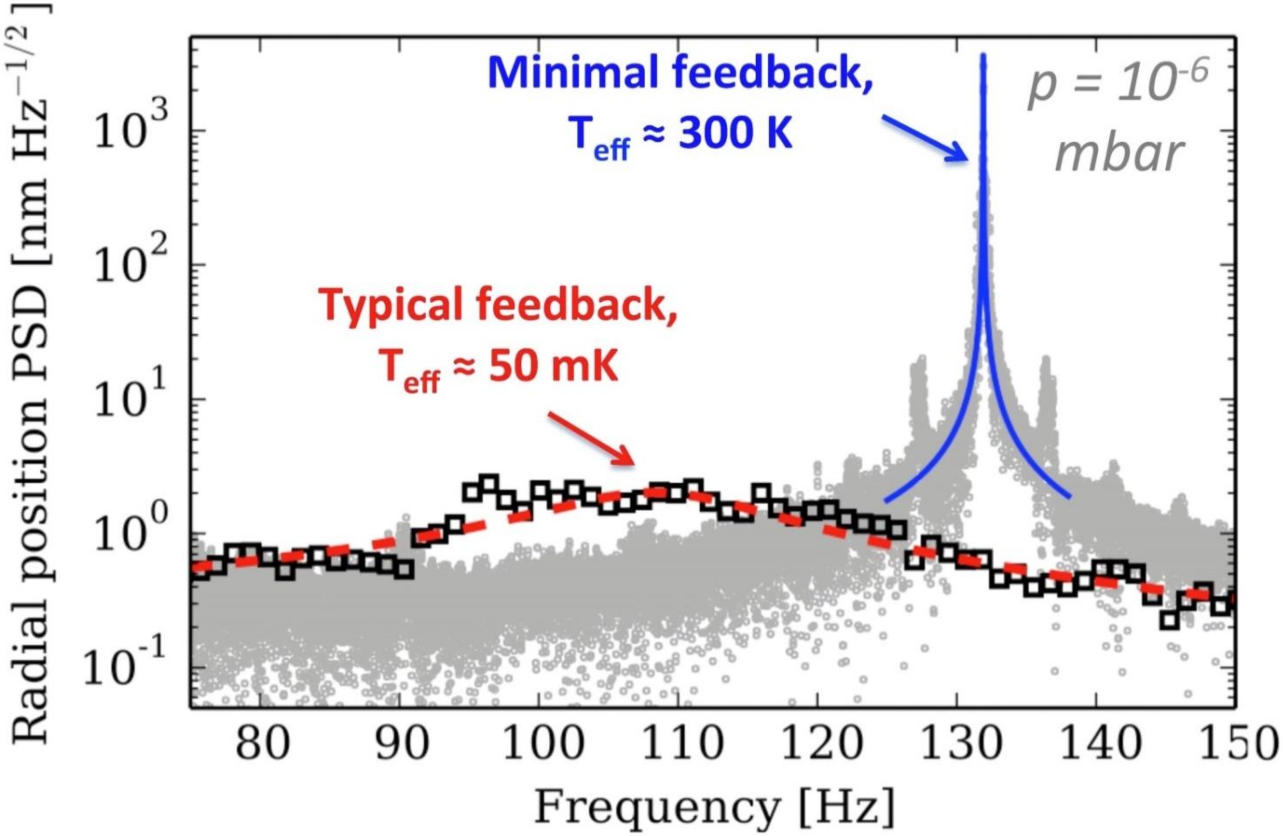
Initial, simplified optics setup



- 1064 nm trapping laser, up going using single mode fiber as spatial mode cleaner
- 650 nm imaging laser
- Position sensitive PD for high bandwidth feedback and CCD cameras for imaging
- FPGA forms feedback signals on the laser power (vertical) and beam steering (horizontal) DOFs
- μspheres are dropped in ~1 mbar N_2 from a vibrating quartz beam
- System pumped to ~10^{-6} mbar while starting the feedback cooling

Can readily cool μspheres to <100 mK, with everything else in the apparatus being at room temperature.

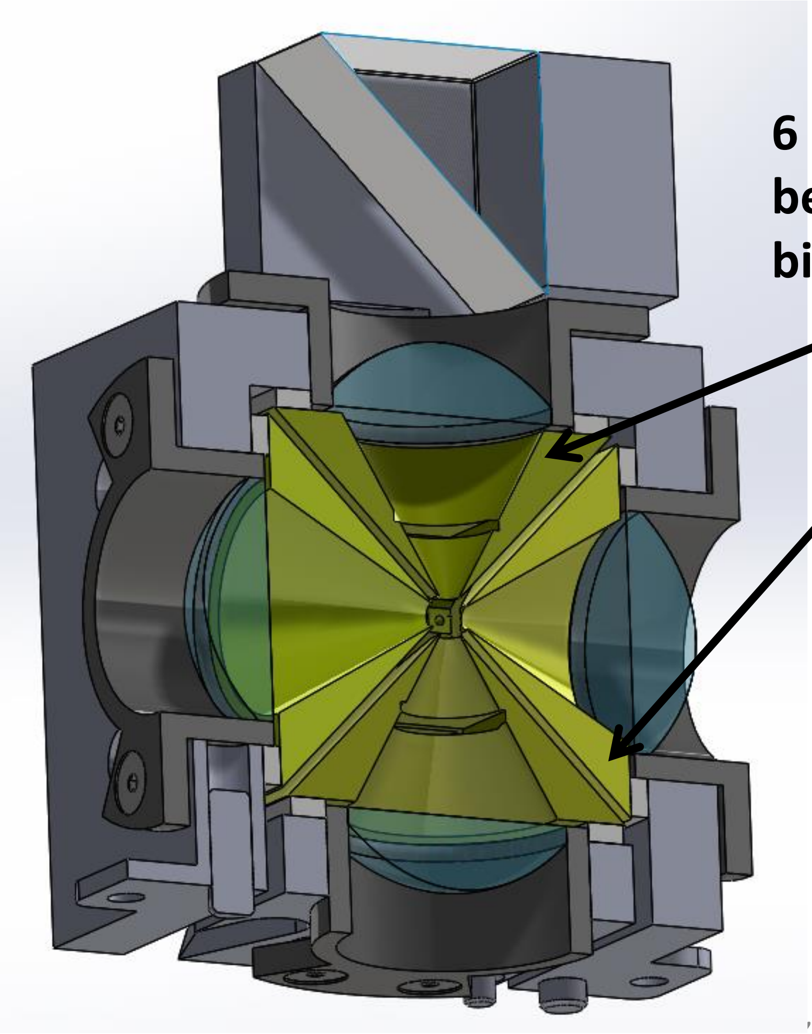




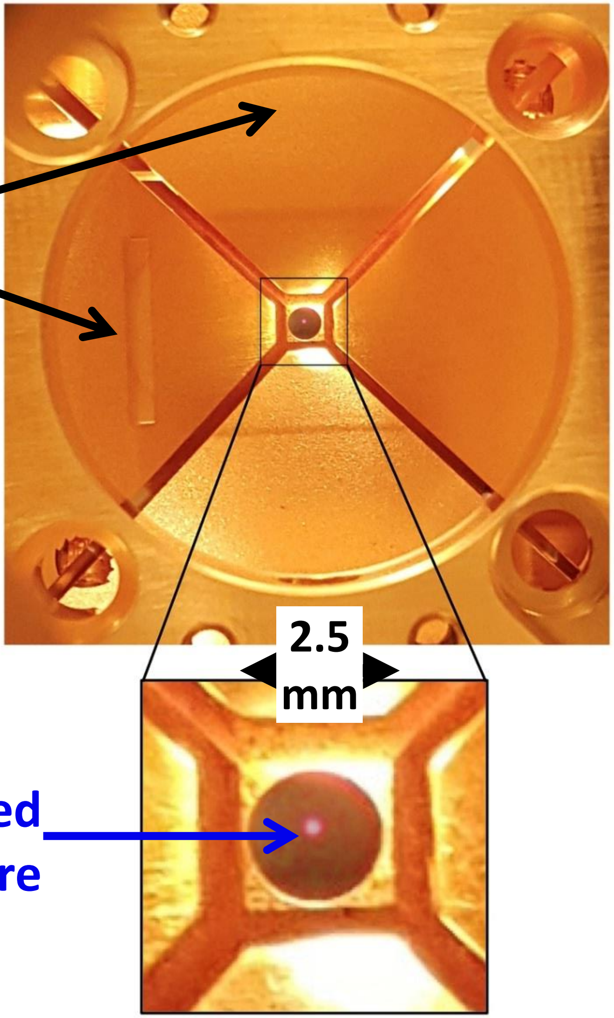
- ***Note that this is the "temperature" of the center-of-mass DOFs. We do not know the internal temperature of the μsphere.***
- ***Can maintain μspheres in this state for days.***

Important to provide good charge control around microsphere (even for microspheres that are overall neural)

- ➔ **Shield possible static charges on the trapping and imaging lenses**
- ➔ **Allow for the option of tweaking the potentials of each of the 6 sides of the**



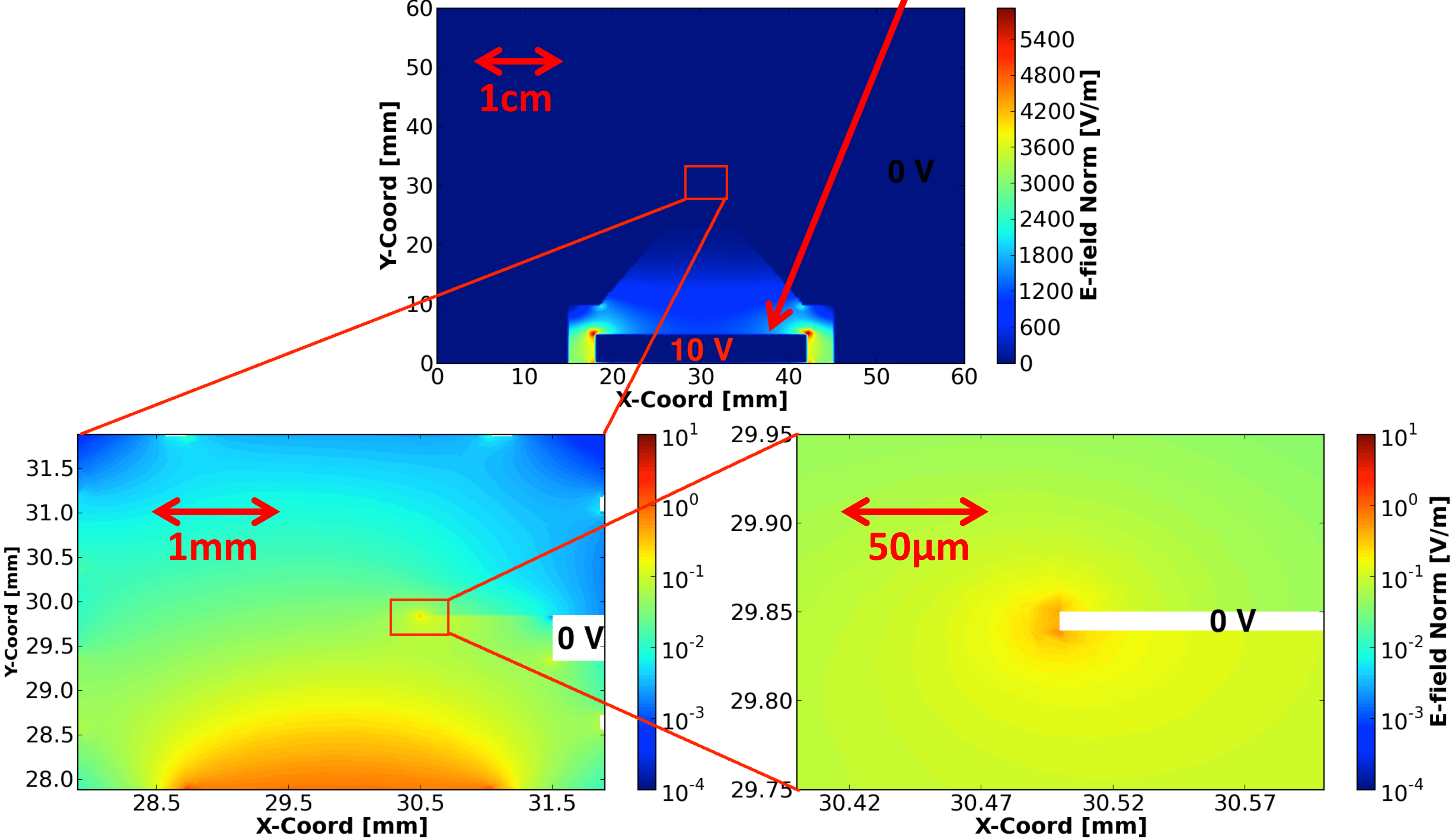
6 “funnels” can be independently biased.



Trapped µsphere

Each of the 6 funnels can be independently biased, but the shielding effect alone is dramatic.

Simulated field from
10 V on one of the lenses



Screened scalars: a "low-hanging fruit" along the way to gravity

Theories of Dark Energy introduce scalar fields that can get around the present limits on long range forces and go undetected because of screening in regions of high mass density ***(basically, the field has finite values only in vacuum)***

➔ Hence the name Chameleon for some of the scalars!

A. Joyce, B. Jain, J. Khoury, and M. Trodden, Phys. Rept. 568, 1 (2015), arXiv:1407.0059
D. F. Mota and D. J. Shaw, Phys. Rev. Lett. 97, 151102 (2006), arXiv:hep-ph/0606204
A. Upadhye, Phys. Rev. D 86, 102003 (2012), arXiv:1209.0211
C. Burrage, E. J. Copeland, and E. A. Hinds, JCAP 1503, 042 (2015), arXiv:1408.1409

By virtue of their small size the μspheres see a mostly unshielded field

Similar measurements have been obtained using atom interferometry

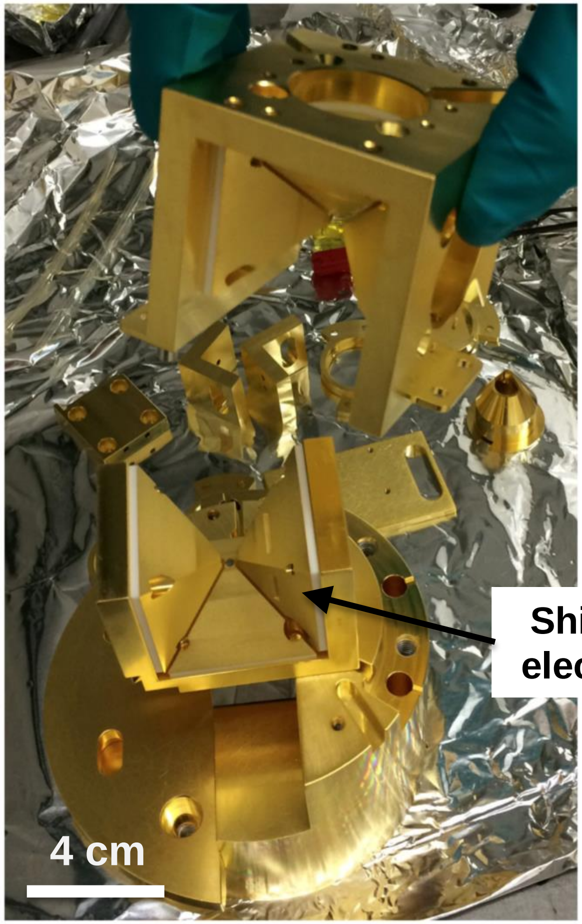
P. Hamilton, et al., Science 349, 849851 (2015), arXiv:1502.03888
B. Elder, et al., Phys. Rev. D 94, 044051 (2016), arXiv:1603.06587
M. Jaffe, et al., Nature Physics doi: 10.1038/nphys4189 *(2017), arXiv:1612.05171.*

…and neutrons

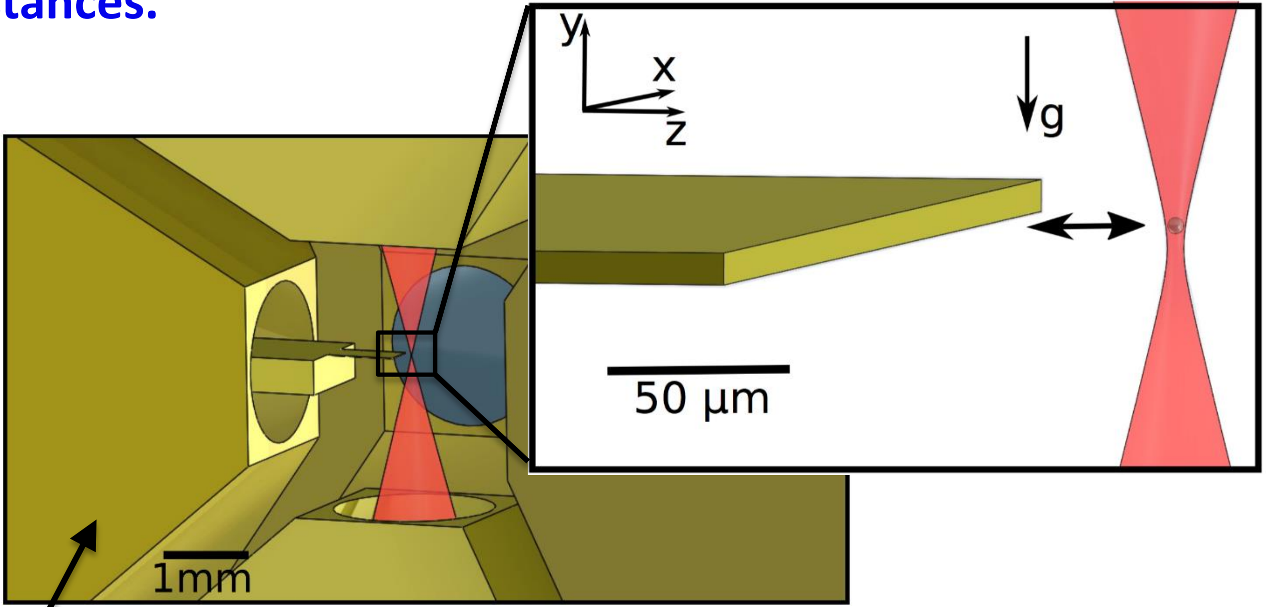
K. Li et al., Phys. Rev. D 93, 062001 (2016), arXiv:1601.06897.
H. Lemmel, et al., Phys. Lett. B 743, 310 (2015), arXiv:1502.06023.
T. Jenke et al., Phys. Rev. Lett. 112, 151105 (2014), arXiv:1404.4099.

Use a Au-coated Si diving board driven in and out with respect to the μsphere

➔ Background control is more challenging than for gravity (in/out motion!) but does not need patterning of the diving board and can use larger distances.



Shielding electrodes



Experimental parameters:

Microsphere radius [μm]	2.50 ± 0.24
Microsphere density [g/cm^3]	2.0
Cantilever thickness [μm]	10.4
Separation distance [μm]	20 - 230
Background pressure [mbar]	< 10^{-6}

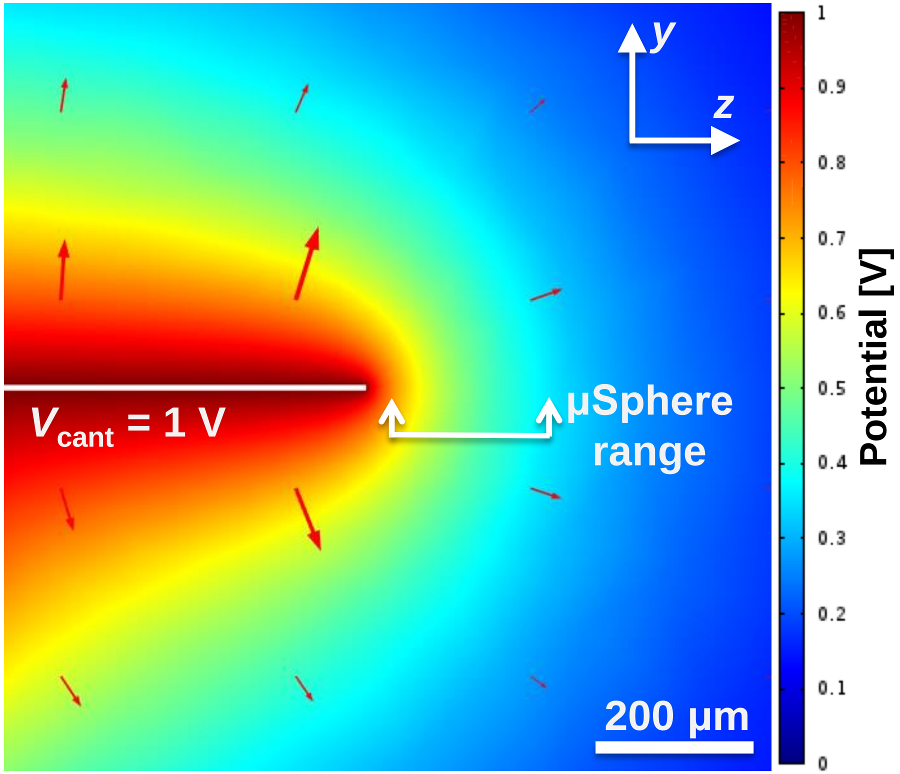
Electrostatic background

Neutral microspheres contain ~10^{14} electric charges and interact primarily as dipoles:

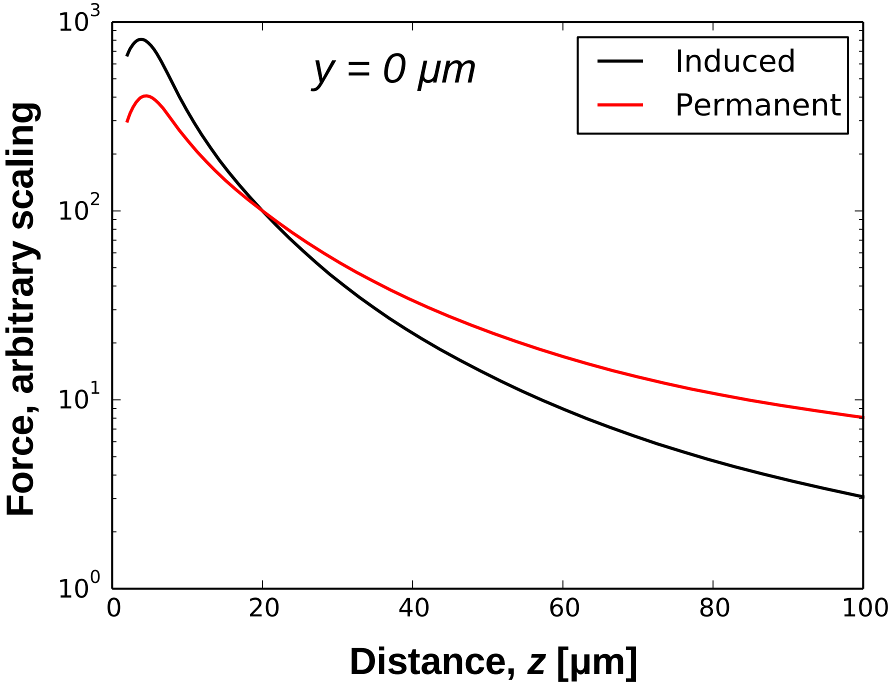
$$\vec{F} = (\vec{p}\cdot\vec{\nabla})\vec{E} \quad \Rightarrow \quad F_z \approx (p_{0z} + \alpha E_z)\frac{\partial E_z}{\partial z}$$

Permanent dipole **Induced dipole**

FEM calculation of electric potential:

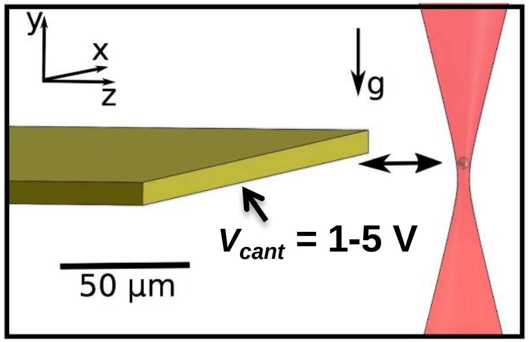


Force for permanent and induced dipole:

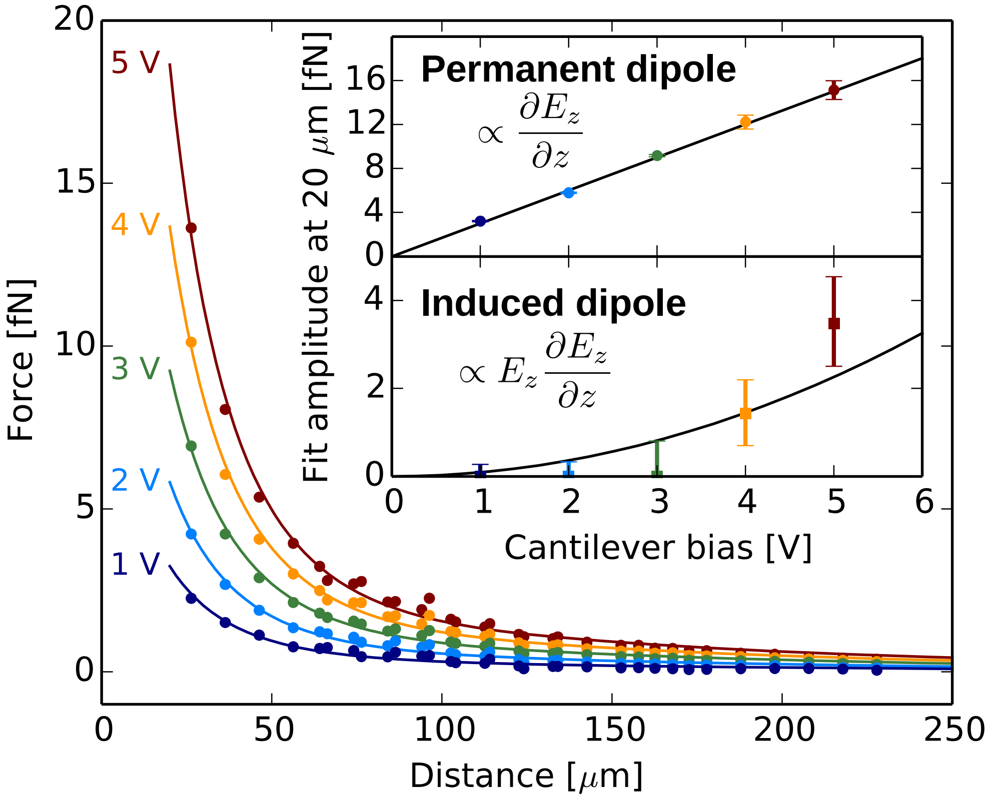


This background is measured:

- Bias cantilever to from 1 to 5 V and sweep its position
- Fits to distance dependence allow determination of permanent and induced dipole moments



Microsphere response vs. distance:



Fits to dipole response:

Microsphere	p_{0z} [$e\ \mu$m]	α/α_0
#1	151 ± 6	0.21 ± 0.13
#2	89 ± 10	0.00 ± 0.33
#3	192 ± 30	0.25 ± 0.14

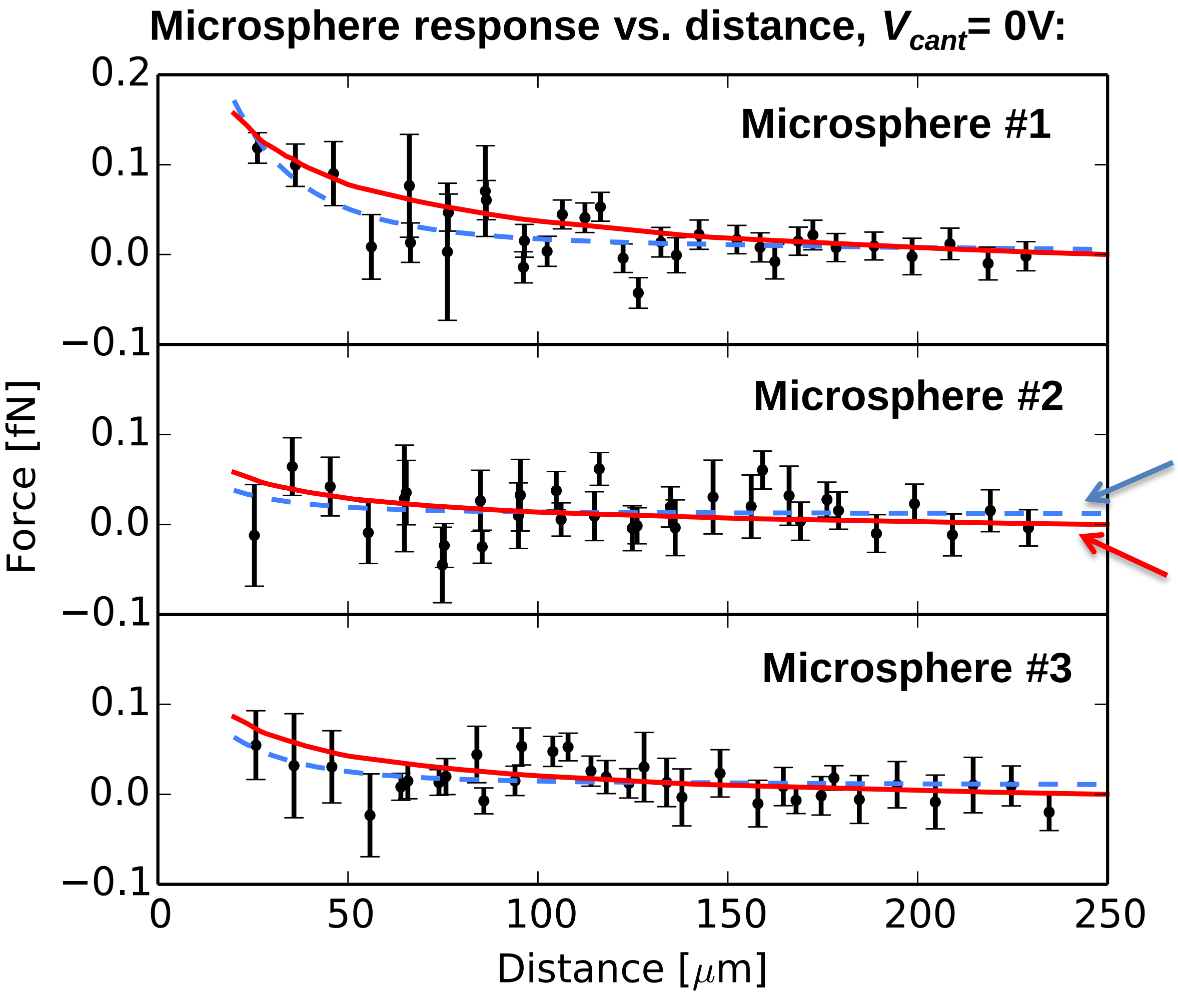
Polarizability, α, measured relative to:

$$\alpha_0 = 3\epsilon_0 \left(\frac{\epsilon_r - 1}{\epsilon_r + 2}\right)\left(\frac{4}{3}\pi r^3\right)$$

for $\epsilon_r \approx 3$, r = 2.5 μm (but our microspheres may not behave like bulk silica)

Then perform measurement with cantilever at “nominal 0 V”

Residual response consistent with <30 mV contact potentials

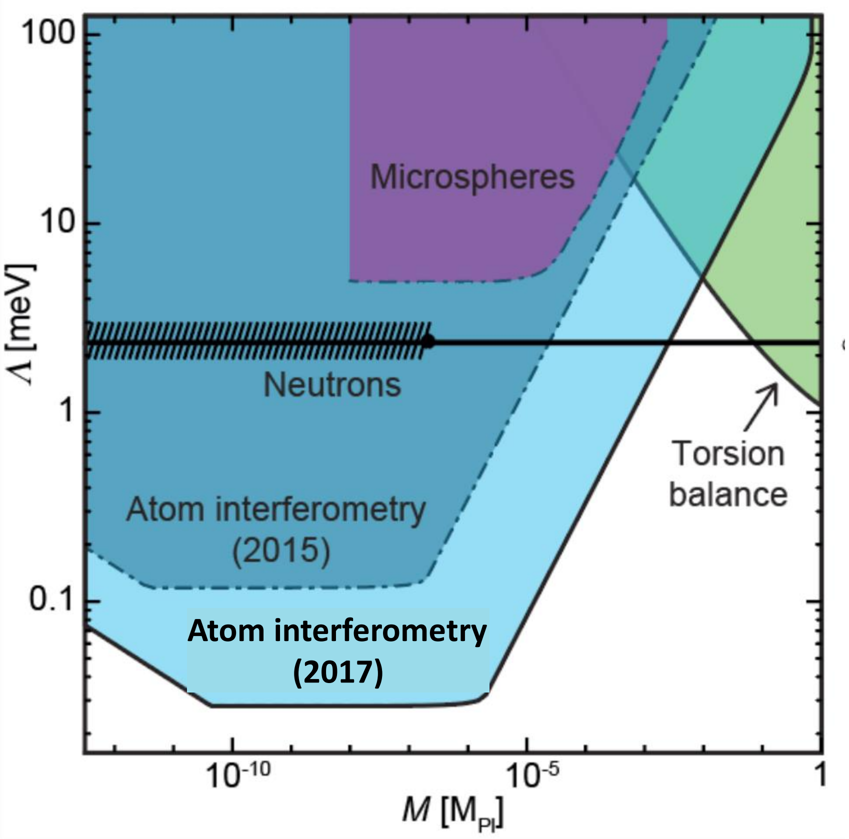


Background only fit

90% CL upper limit on screened scalar interaction

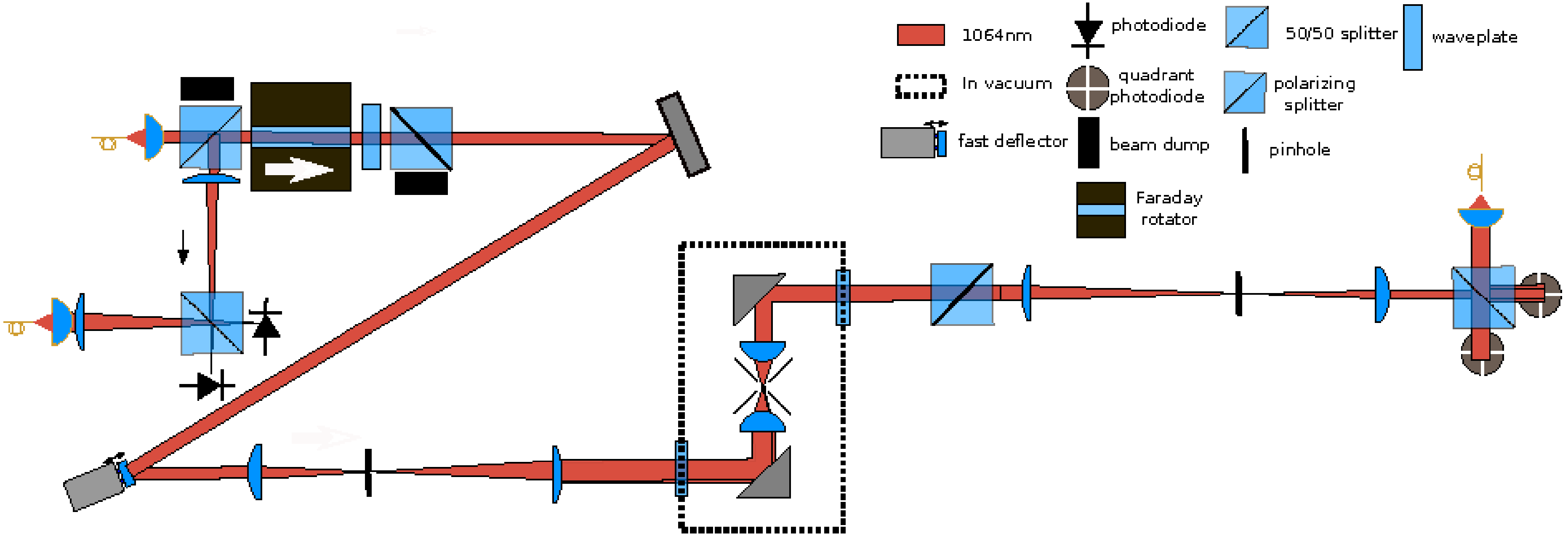
Results *(A.Rider et al. Phys. Rev. Lett. 117 (2016) 101101 arXiv:1604:04908, 17 April 2016)*

- **Consistent with background-only model at 90% CL**
- **Sensitivity limited by electrostatic backgrounds, and unable to constrain models with Λ = 2.4 meV due to self-screening**
- **Constraints can be set at Λ > 4.6 meV where self-screening is reduced**



Substantially better sensitivity should be achievable with better electrostatic control

A better optical setup with heterodyne/interferometric readout



- Suppress background scattered from near-by attractor (scattered light has wrong phase relationship)
- Absolutely calibrated vertical position (vertical DOF readout interferometrically from back-reflected light)
- True single-beam and single-frequency operation

Onwards to gravity…

Structured attractor can mitigate many backgrounds present for uniform cantilever (only move perpendicularly to the force direction)

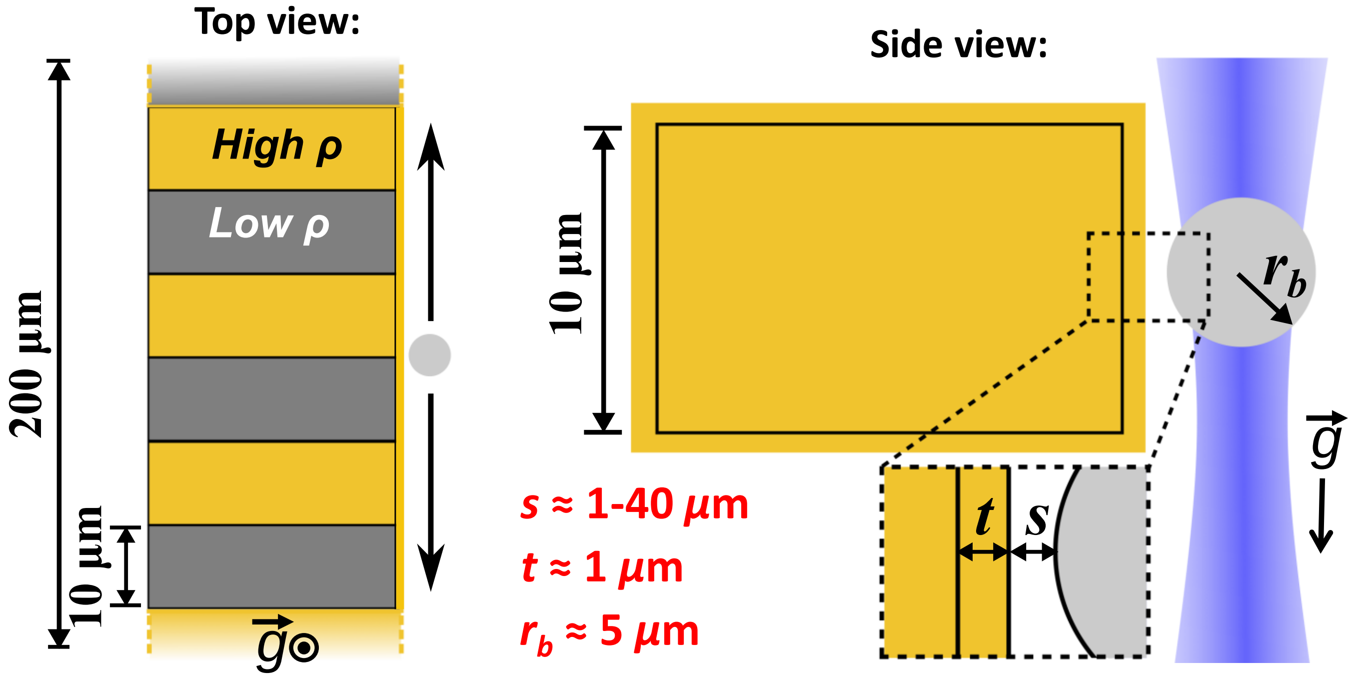
High ρ material:

Au, $\rho \approx 20$ g/cm^3

Low ρ materials:

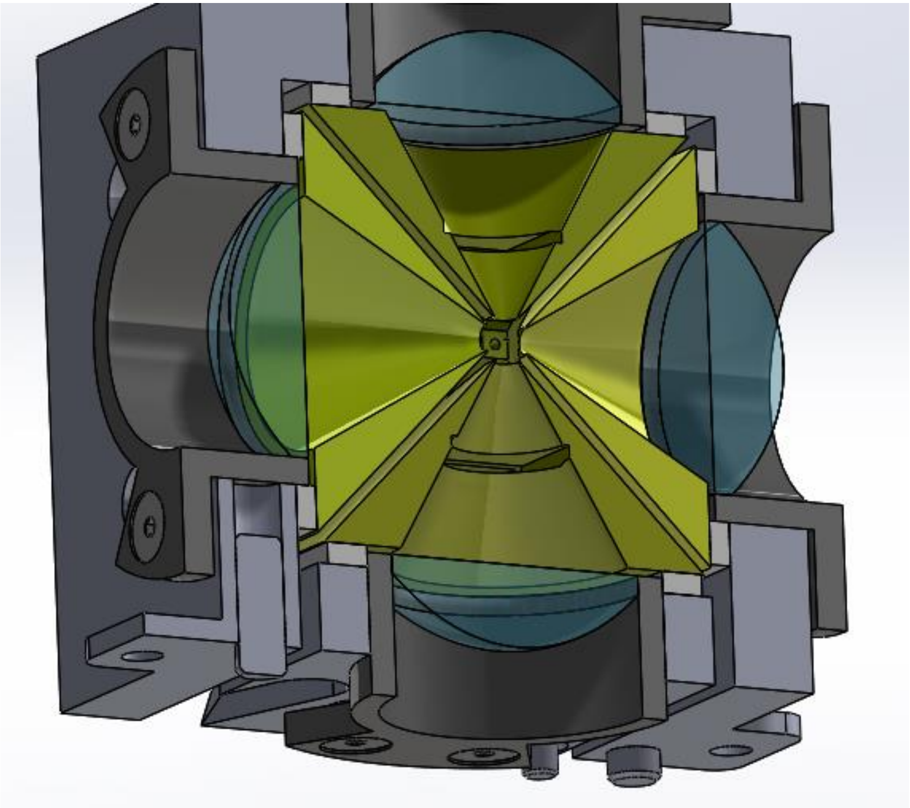
Cu, $\rho \approx 9$ g/cm^3
Si, $\rho \approx 2$ g/cm^3

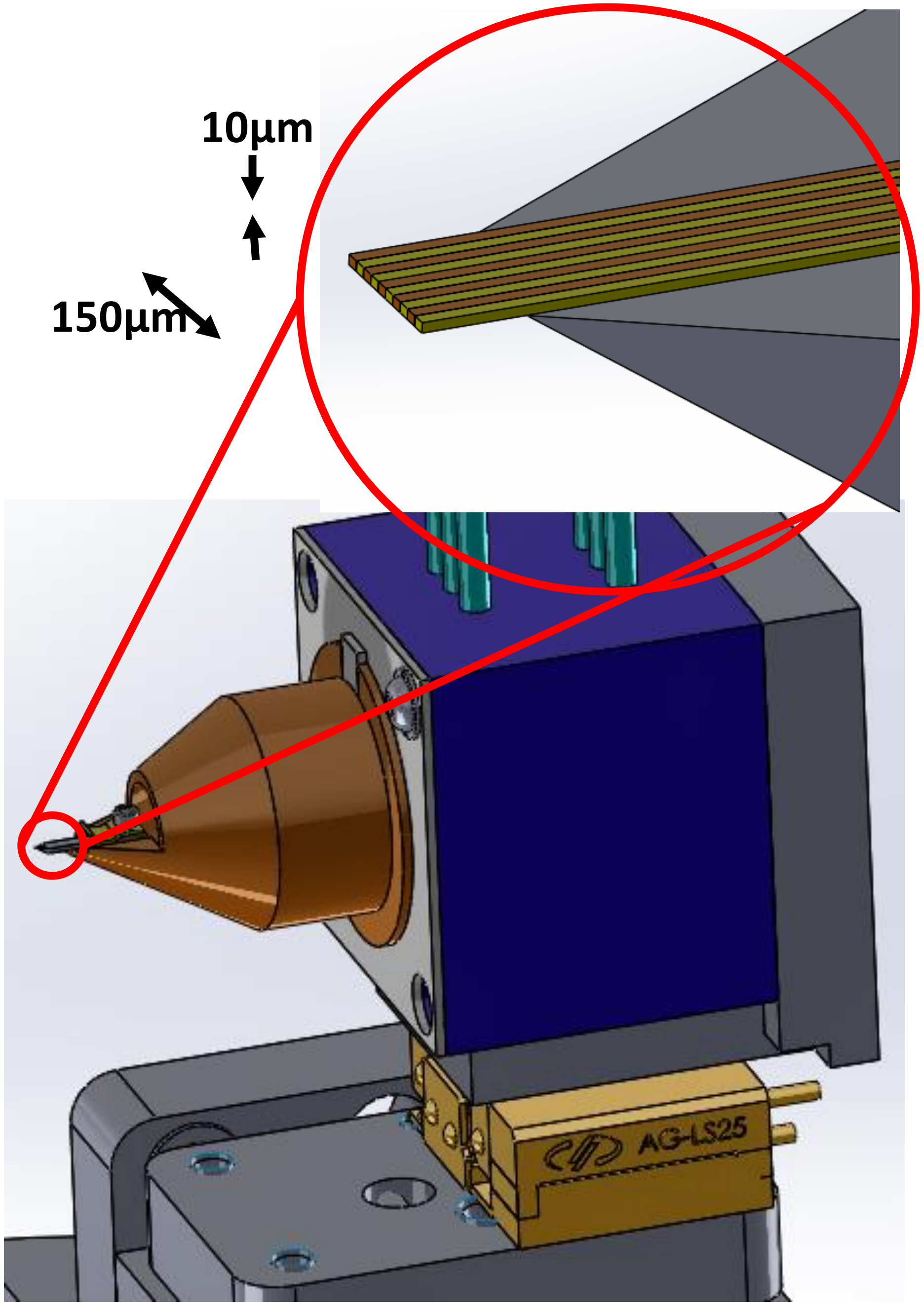
Schematic of density structured probe mass:



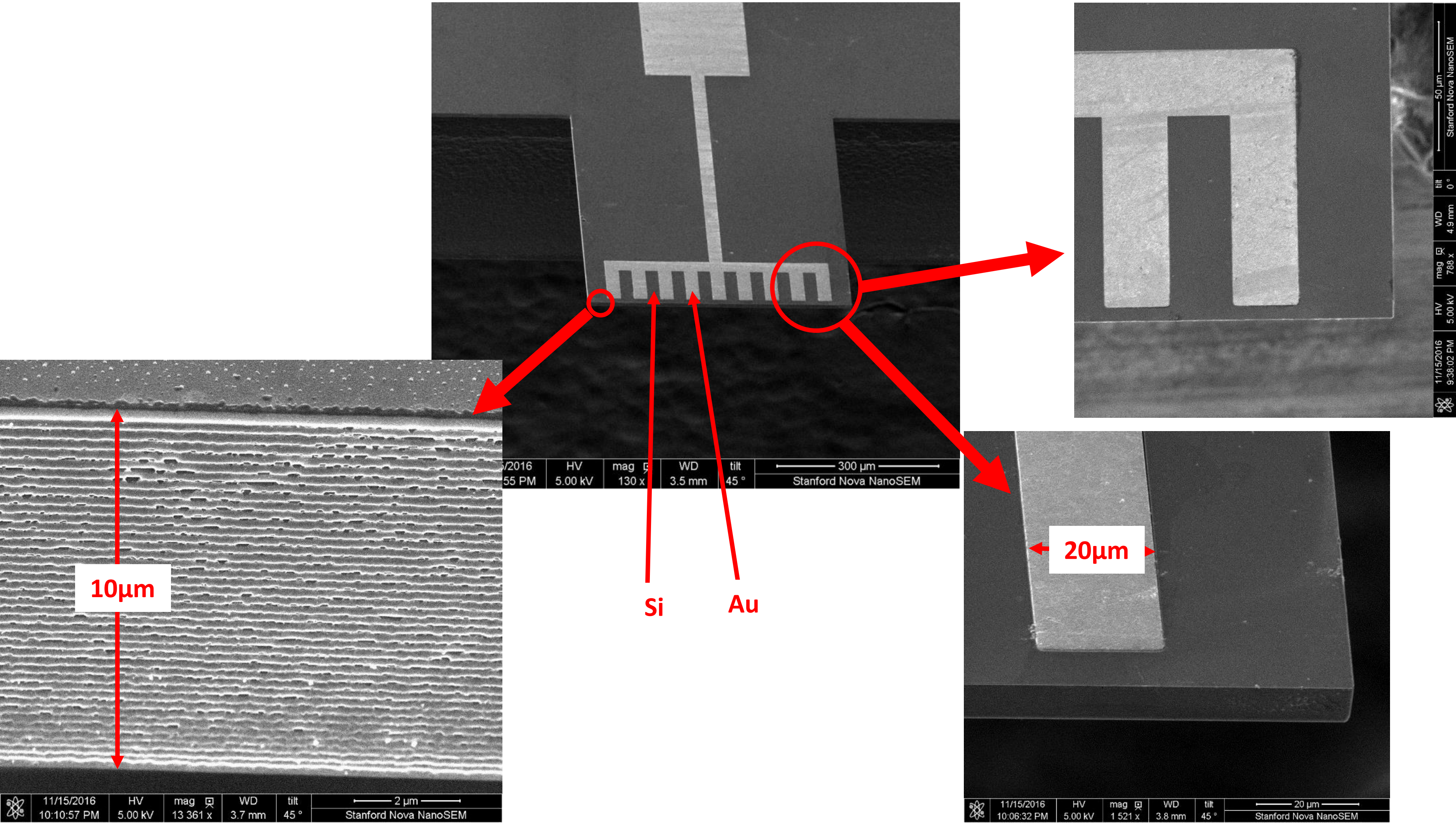
$s \approx 1\text{-}40\ \mu m$
$t \approx 1\ \mu m$
$r_b \approx 5\ \mu m$

This is mounted on a fast flexure stage to swing it in front of the μsphere.

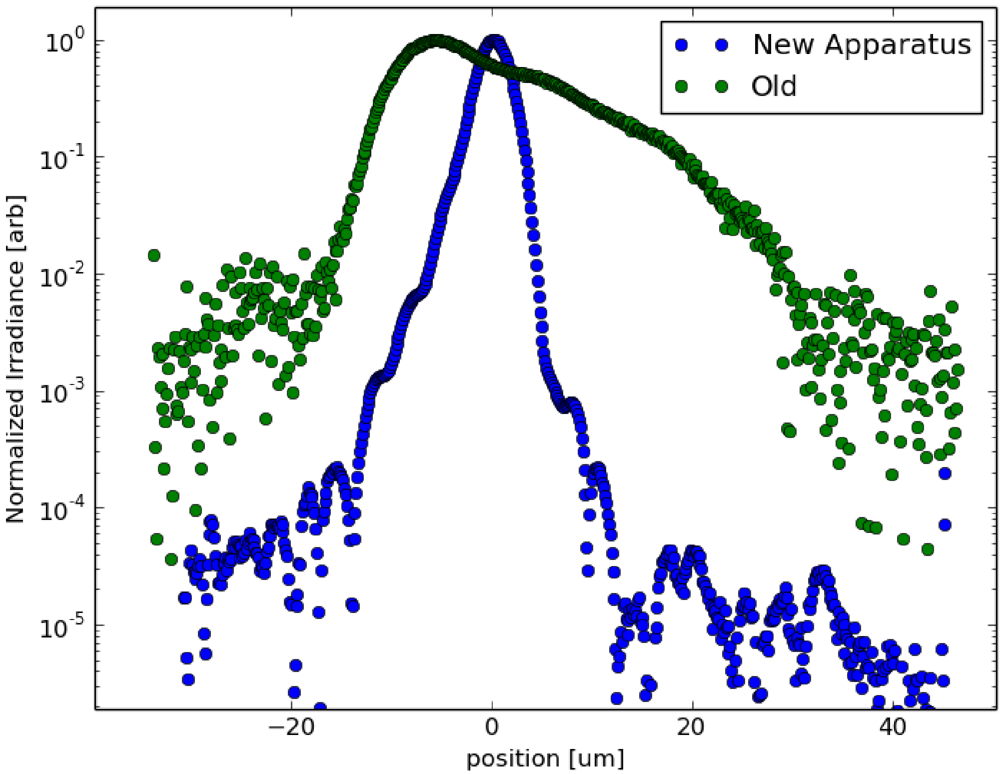




Si-Au attractors fabricated and ready for use

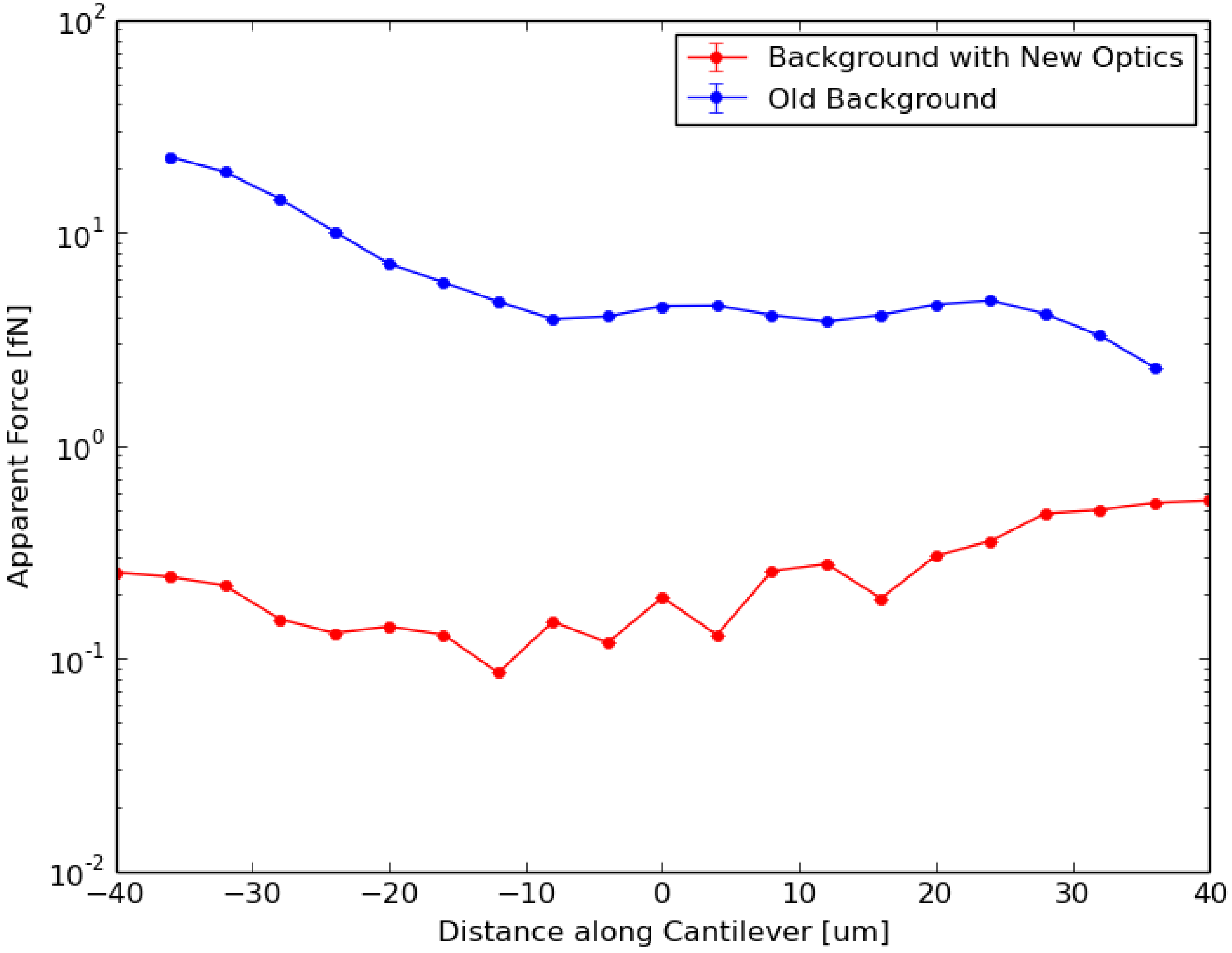


Better laser mode to limit light scattered from near-by attractor

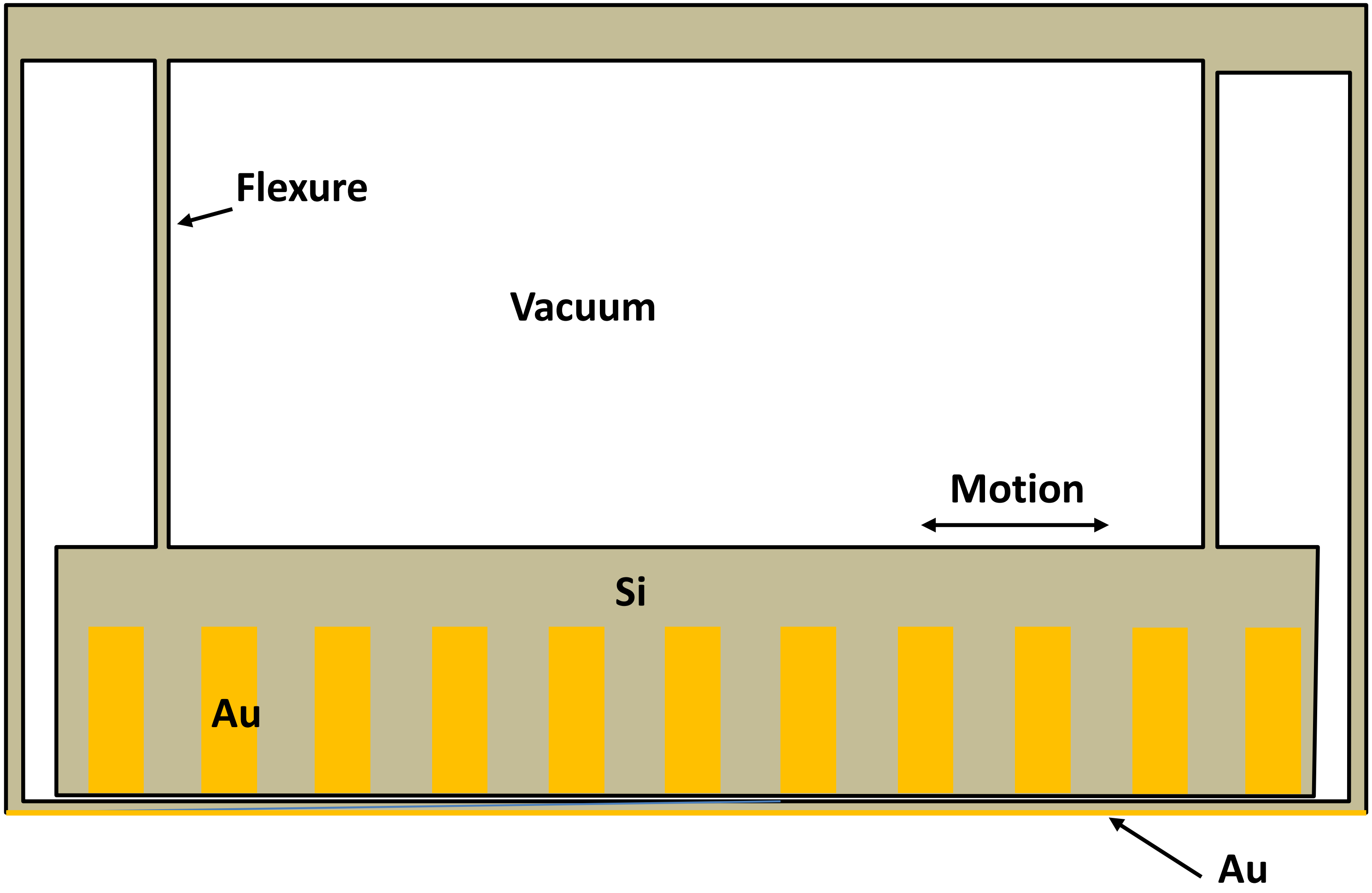


Radius of circular region at z_{trap} (μm)	Power in (new) beam halo (%)
2.5	0.7-0.8
5	0.5-0.6
10	0.2

Present blocked light background for S=10μm separation



Concept of attractor with stationary shield



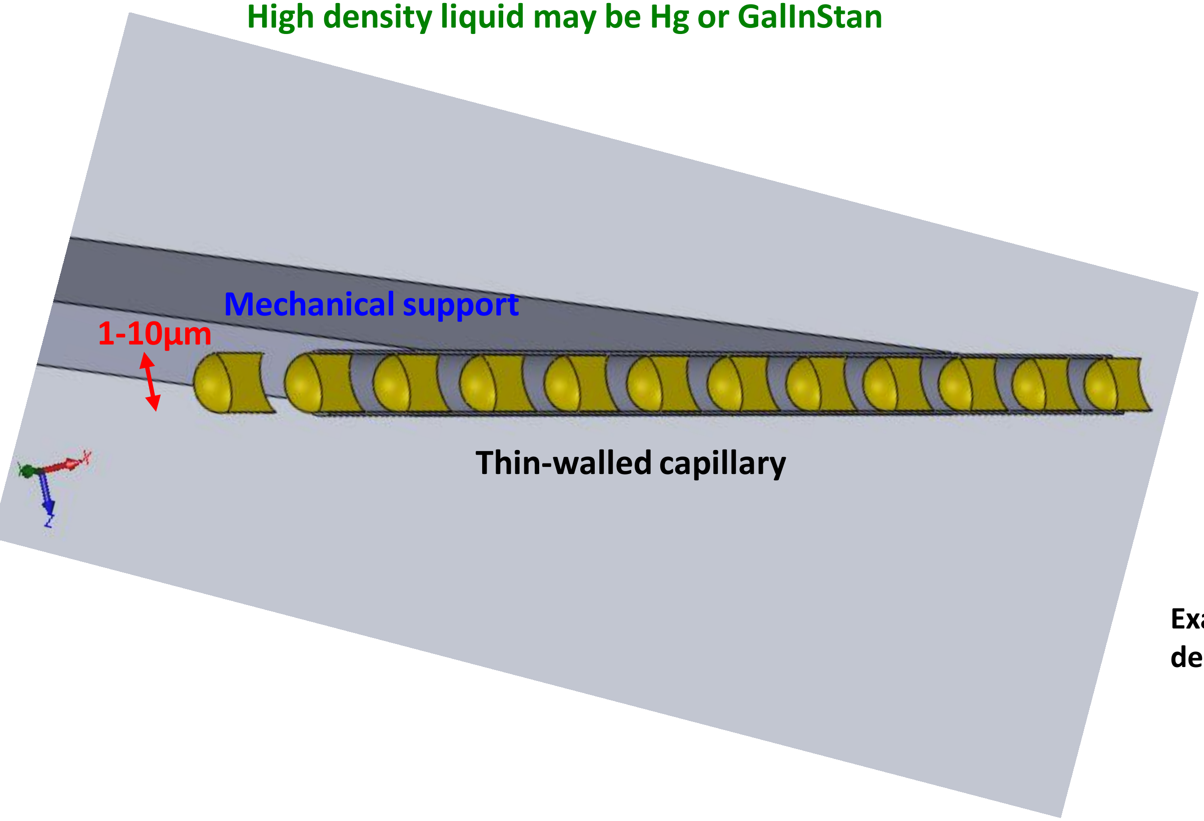
Fabrication technology very similar to the one already defined

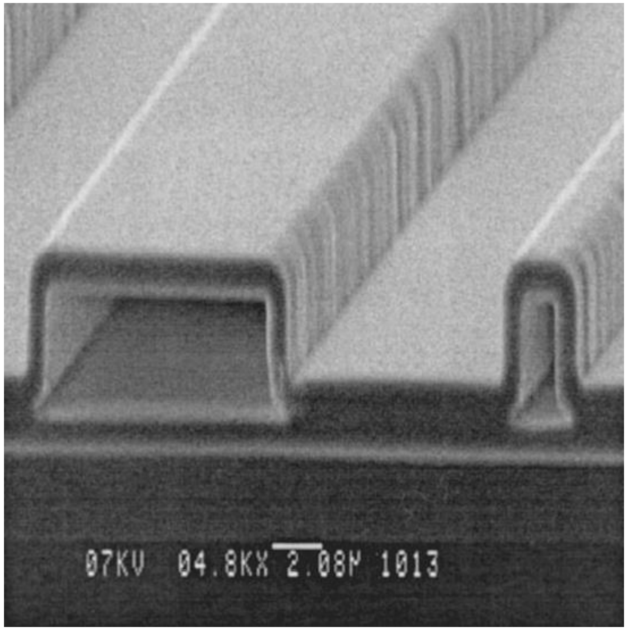
Drive mechanism not yet designed

Stationary shield can also be retrofitted on other, existing designs

Concepts for fluidic periodic attractors

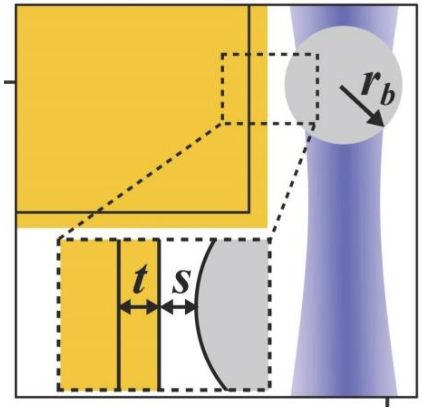
Alternating droplets of low and high density liquids
High density liquid may be Hg or GaInStan





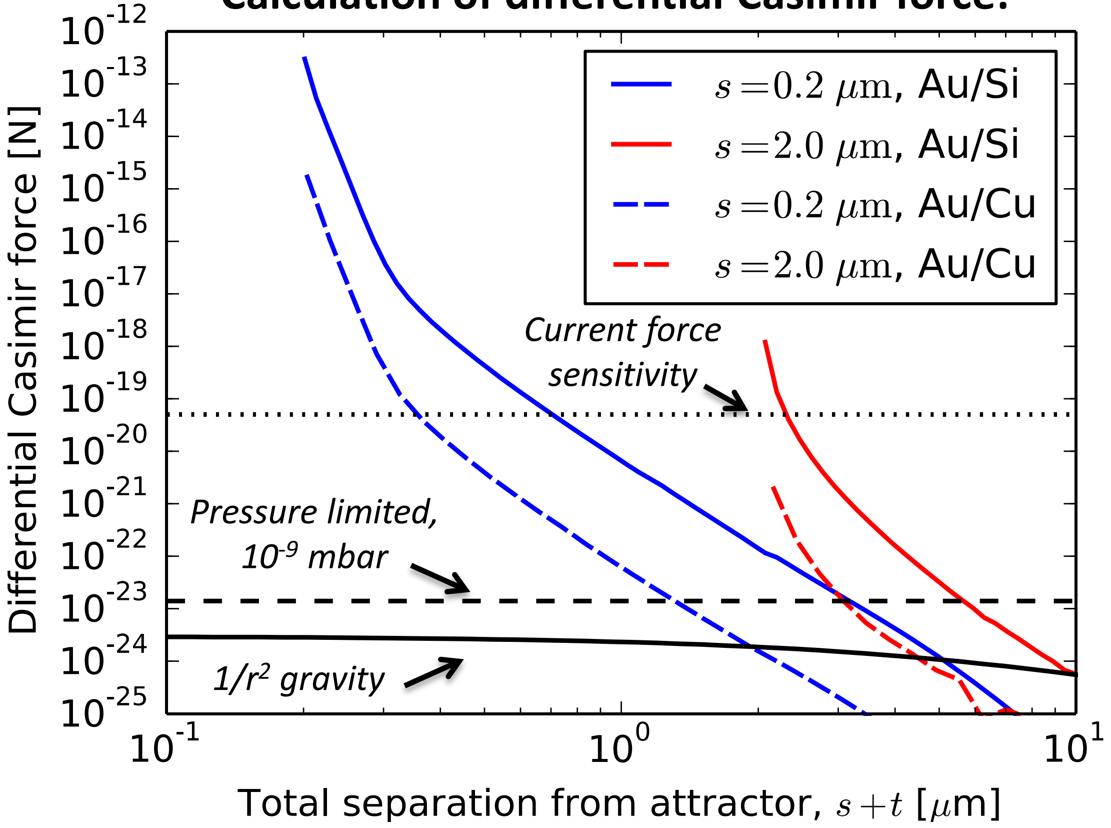
Example of microchannel in Si
deBoer et al J Microelectromechanical Sys 9 (2000) 94

Expected backgrounds: Casimir forces



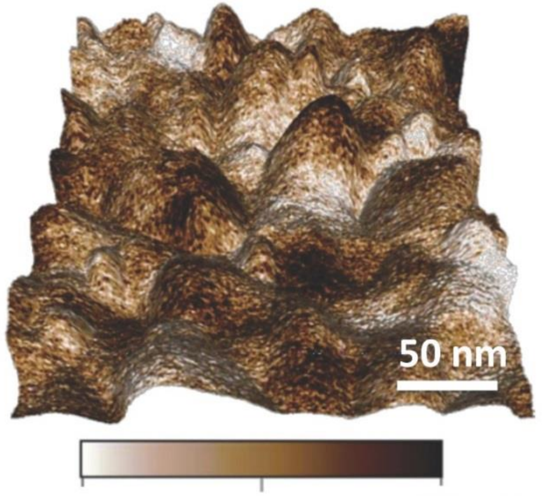
Coating the attractor with t = 0.5 – 3 µm thick Au should sufficiently suppress the differential Casimir force

Calculation of differential Casimir force:



Expected backgrounds: Patch potentials

Topography and surface potential for sputtered Au film:

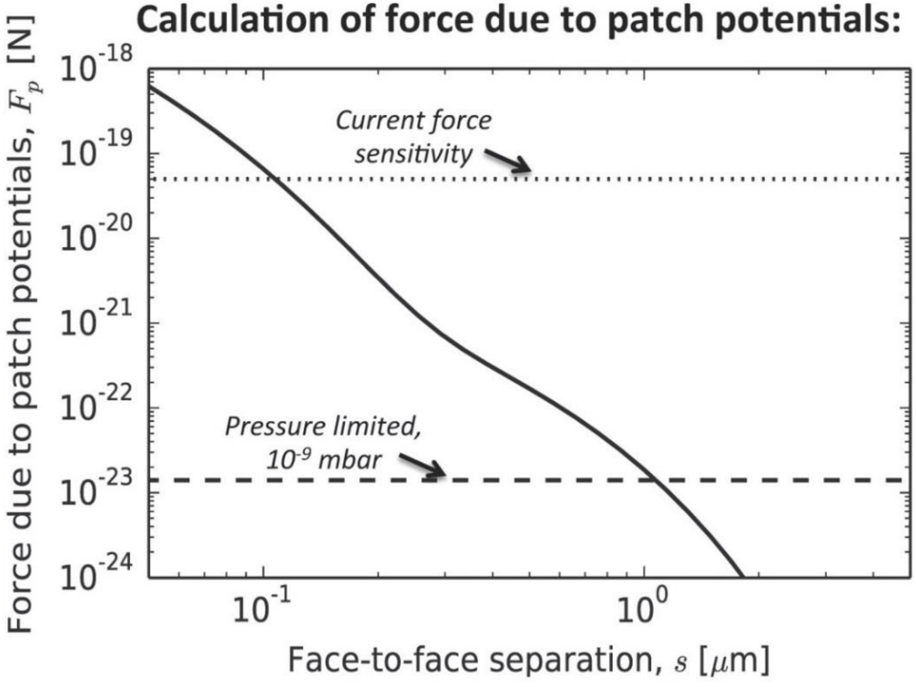


Garrett et al., arXiv:1409.5012

- **Deposited Au films typically have potential variations ~10–100 mV over 10-1000 nm surface regions**
- **Such “patch potentials” have been studied extensively in previous work**

- **Have estimated background using patch measurements of Au films**
- **Possibly amorphous graphite coatings have smaller patch potentials.**

Calculation of force due to patch potentials:



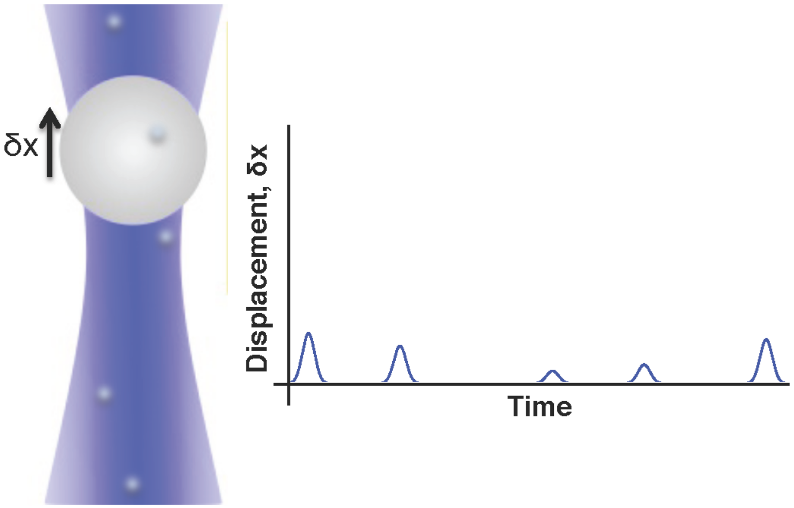
Note that a set of measurements with:

- **Different microsphere diameters**
- **Different distances from the attractor**
- **Rotating microspheres**

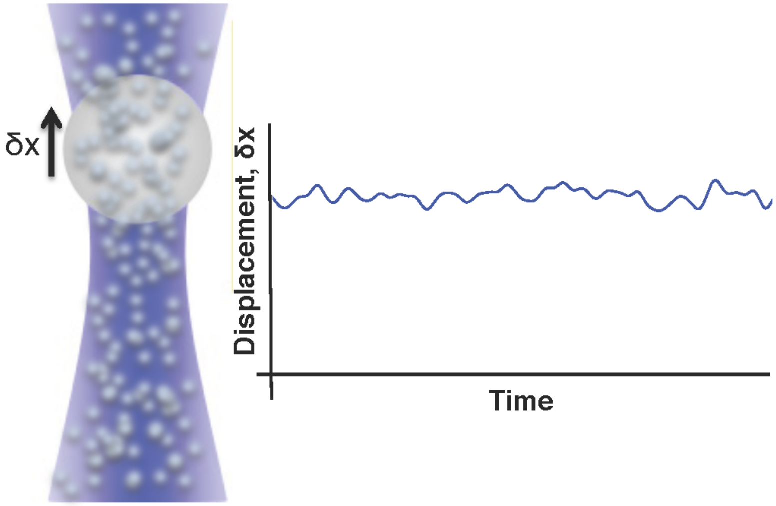
Should allow, to some extent, the discrimination of the electrical backgrounds

A limit to the force sensitivity arises from the Standard Quantum Limit

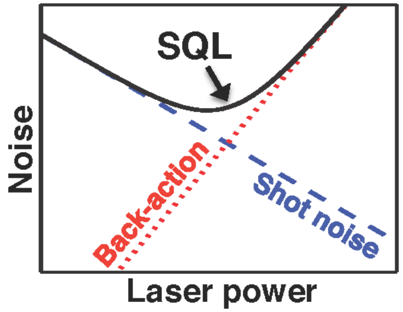
Shot noise limit:



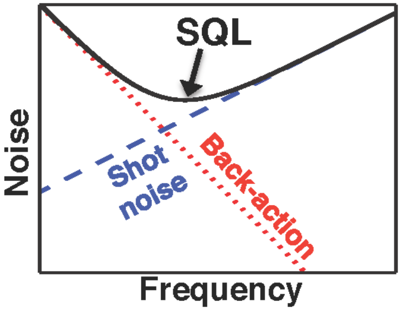
Back-action noise limit:



Fixed frequency:



Fixed power:



$\delta x \sim \sqrt{\frac{\hbar}{m\omega^2}}$ (at the SQL)

$\Rightarrow \delta F \sim 2 \times 10^{-21}\ \mathrm{N\ Hz}^{-1/2}$

for *d*=5 μm spheres at *P* ~ 0.2 mW

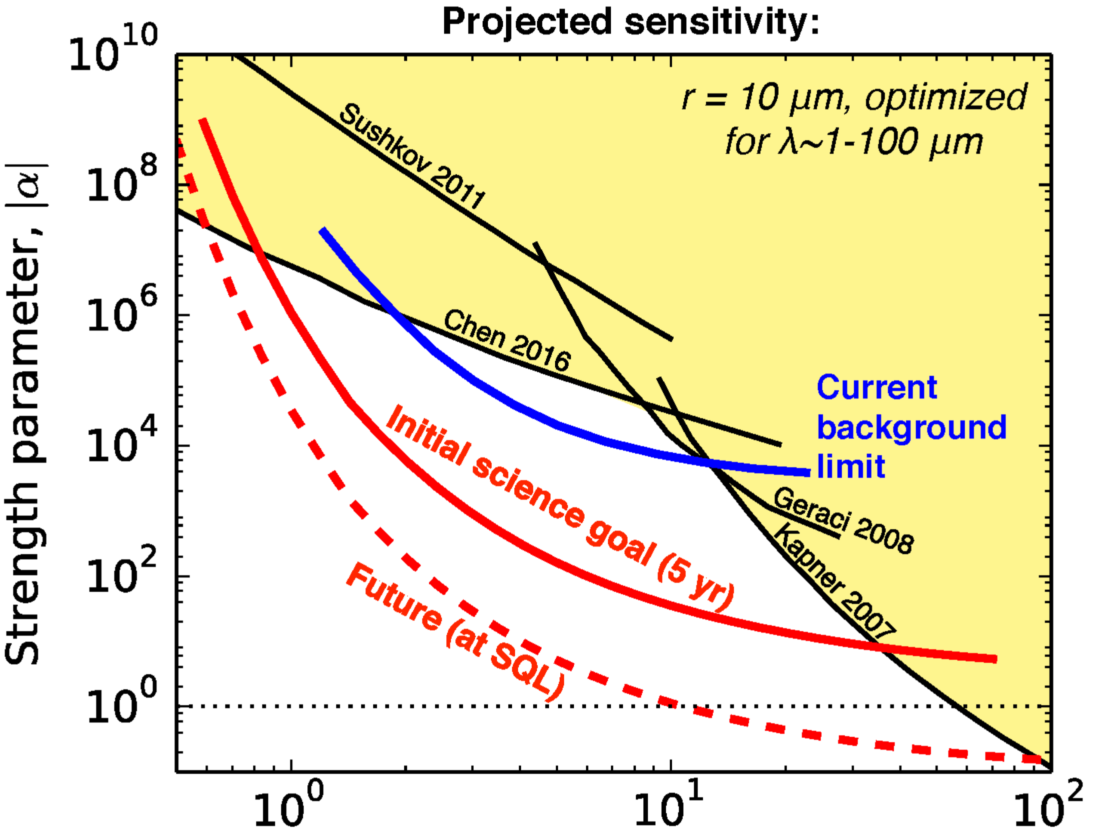
Projected sensitivity

- **Parametrization:** $$V(r) = -\frac{Gm_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

- **Assumptions:**

  Force sensitivity:
  $\sigma_F = 2 \times 10^{-17}$ N Hz$^{-1/2}$
  (already achieved)
  σ_F = pressure limited at
  10^{-9} mbar (red)
  10^5 s integration time
  Attractor distance s = 2μm

  Backgrounds:
  At or below noise level,
  Au shield thick enough to
  suppress Casimir background

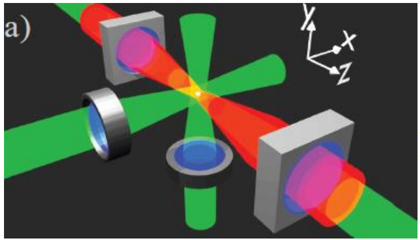


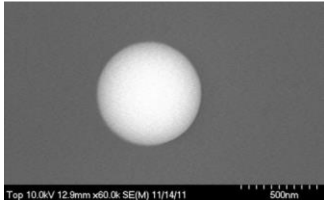
Existing limits are the envelope of:
Chen et al, PRL 116 (2016) 221102 (micromechanical torsion oscillator)
Sushkov et al, PRL 107 (2011) 171101 (torsion pendulum)
Geraci et al, PRD 78 (2008) 022002 (microcantilever)
Kapner et al, PRL 98 (2007) 021101 (torsion pendulum)

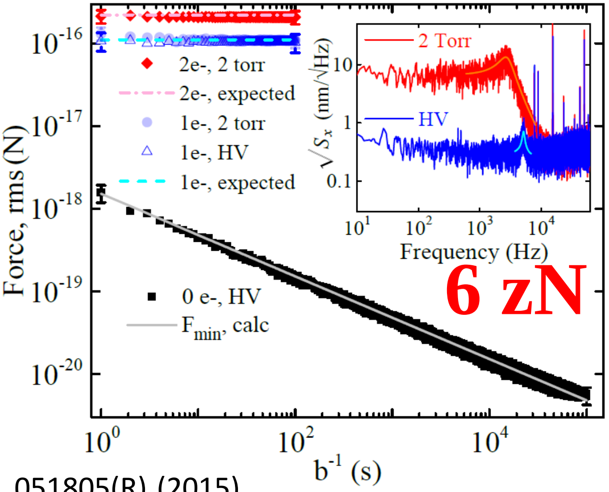
- **Substantial improvement over existing limits should be possible between 1 and 40 μm**

Zeptonewton force sensing

Laser-cooled 300 nm silica nanospheres in a standing-wave optical trap







G. Ranjit et.al., *Phys. Rev. A* **91**, 051805(R) (2015).

G. Ranjit, M. Cunningham, K. Casey, and AG, *Phys. Rev. A*, **93**, 053801 (2016).

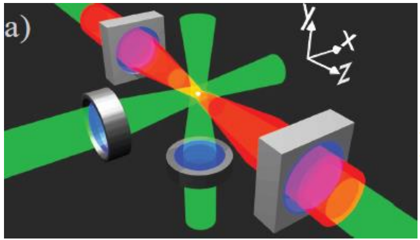
A. Geraci Lab

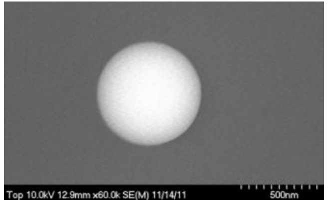
University of Nevada, Reno

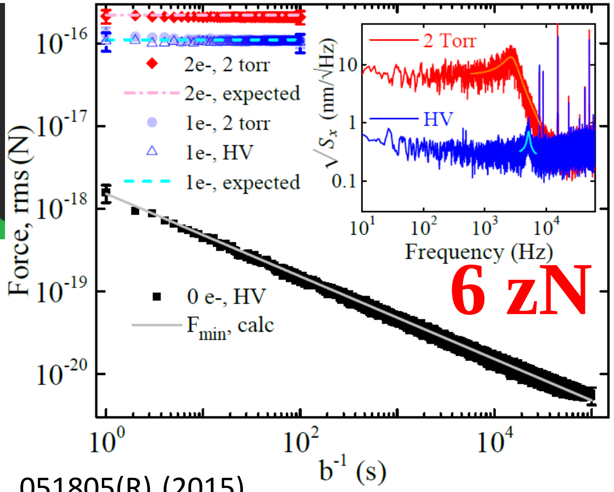
HEISING-SIMONS FOUNDATION

Zeptonewton force sensing

Laser-cooled 300 nm silica nanospheres in a standing-wave optical trap





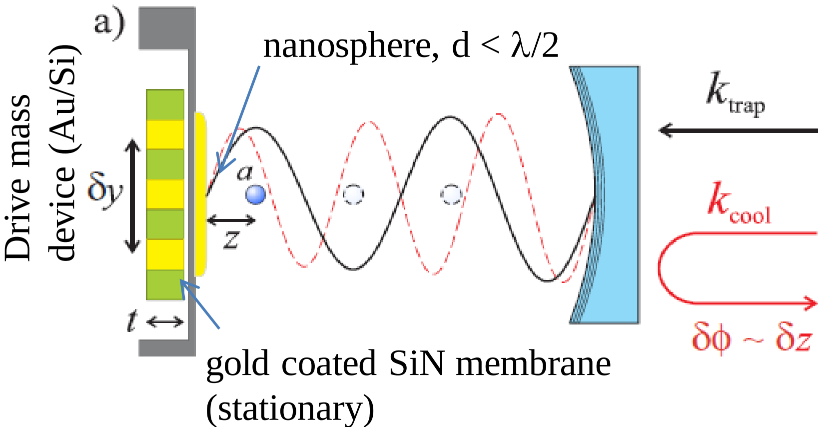


G. Ranjit et.al., *Phys. Rev. A* **91**, 051805(R) (2015).
G. Ranjit, M. Cunningham, K. Casey, and AG, *Phys. Rev. A*, **93**, 053801 (2016).

A. Geraci Lab

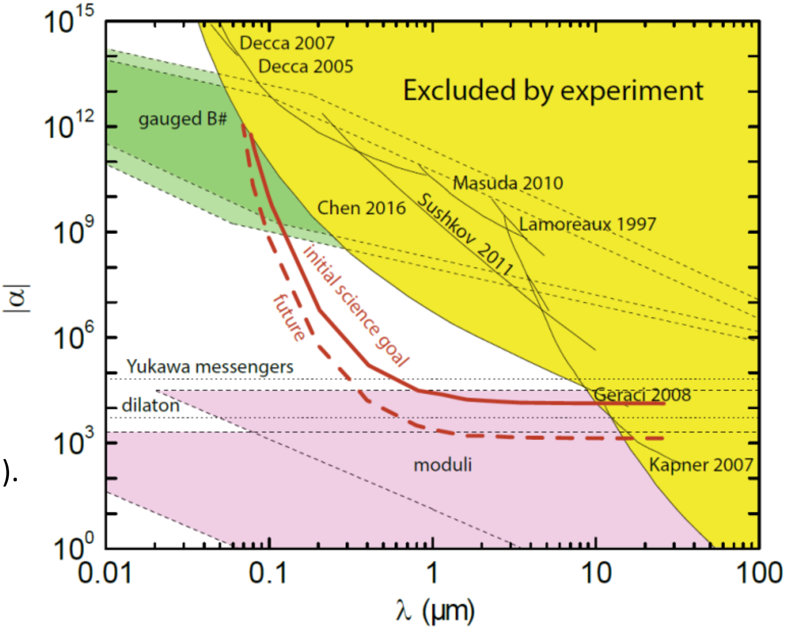
Gravity at micron scales

A.Geraci, S. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010).



Gravitational Waves

A.Arvanitaki and A.Geraci, *Phys. Rev. Lett*. **110**, 071105 (2013).



University of Nevada, Reno

HEISING-SIMONS FOUNDATION

Summary

- Dark Matter and Dark Energy, along with theoretical difficulties in quantum gravity suggest that gravity is the next frontier!
- The experimental study of gravity at extreme scales may reveal exciting physics beyond the SM.
- Developed a technique to measure very small forces at <50μm distance using dielectric μspheres and oprical tweezers.
- The power of the technique was demonstrated by searches for millicharge particles and screened scalars.
- Force measurements with this technique at the quantum limit may substantially advance our understanding of fundamental physics.