Searching for non-Newtonian forces with optically levitated microspheres

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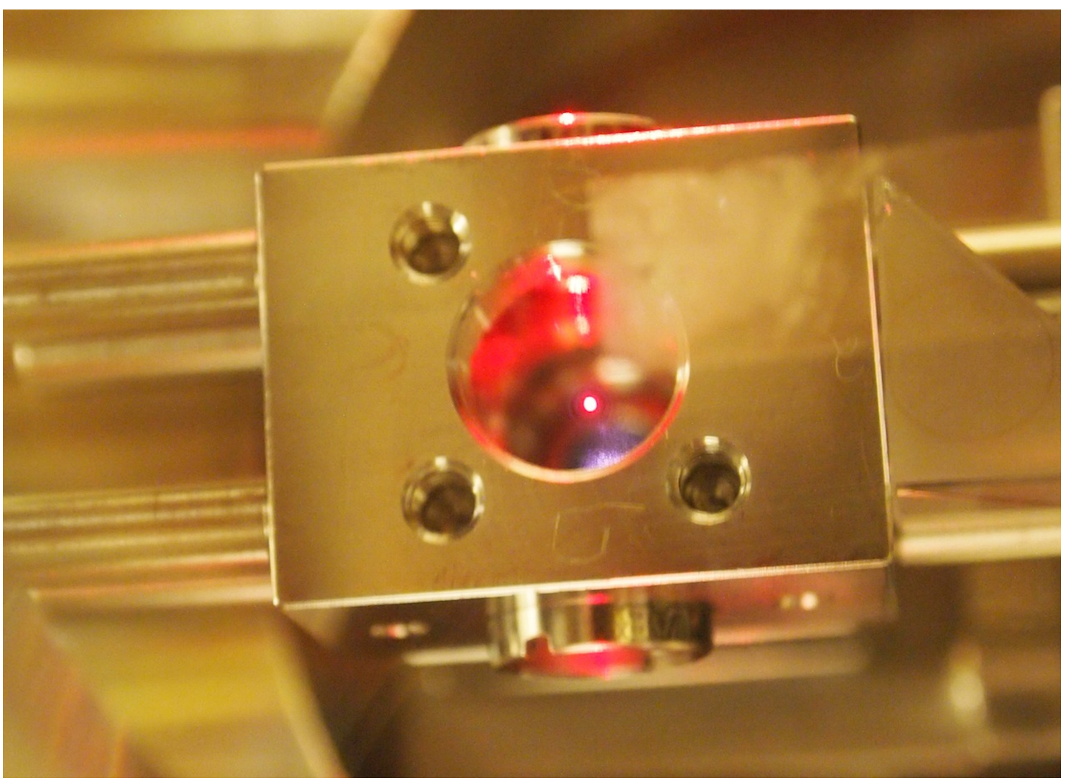
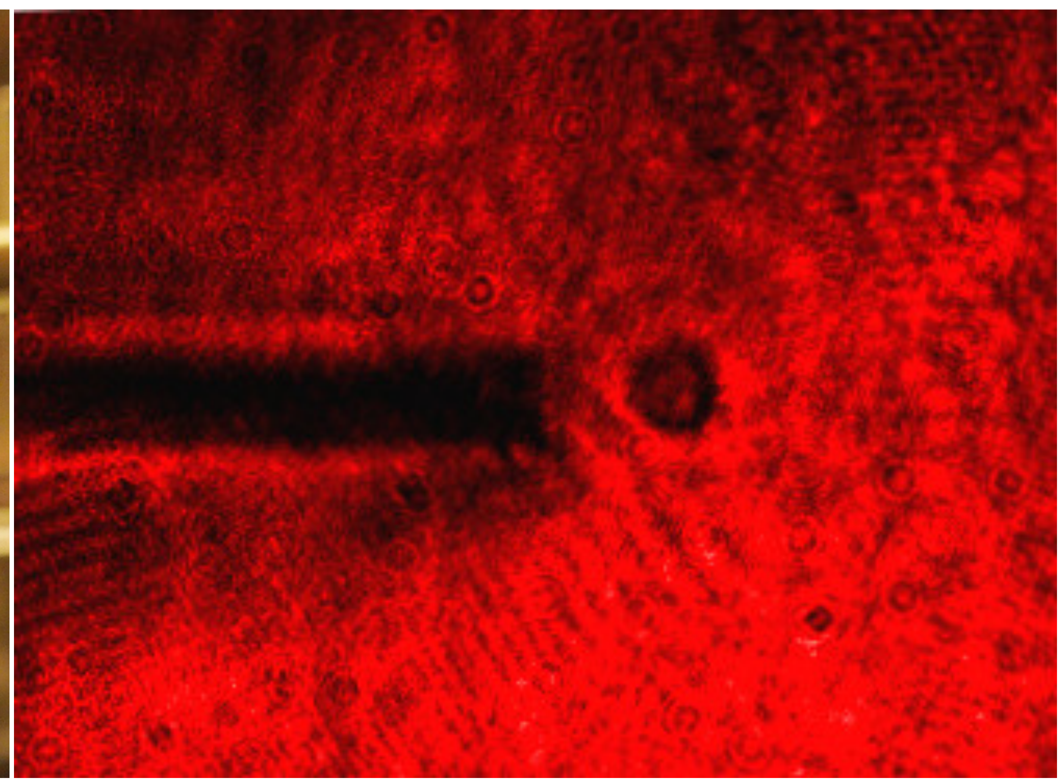
Testing Gravity 2015

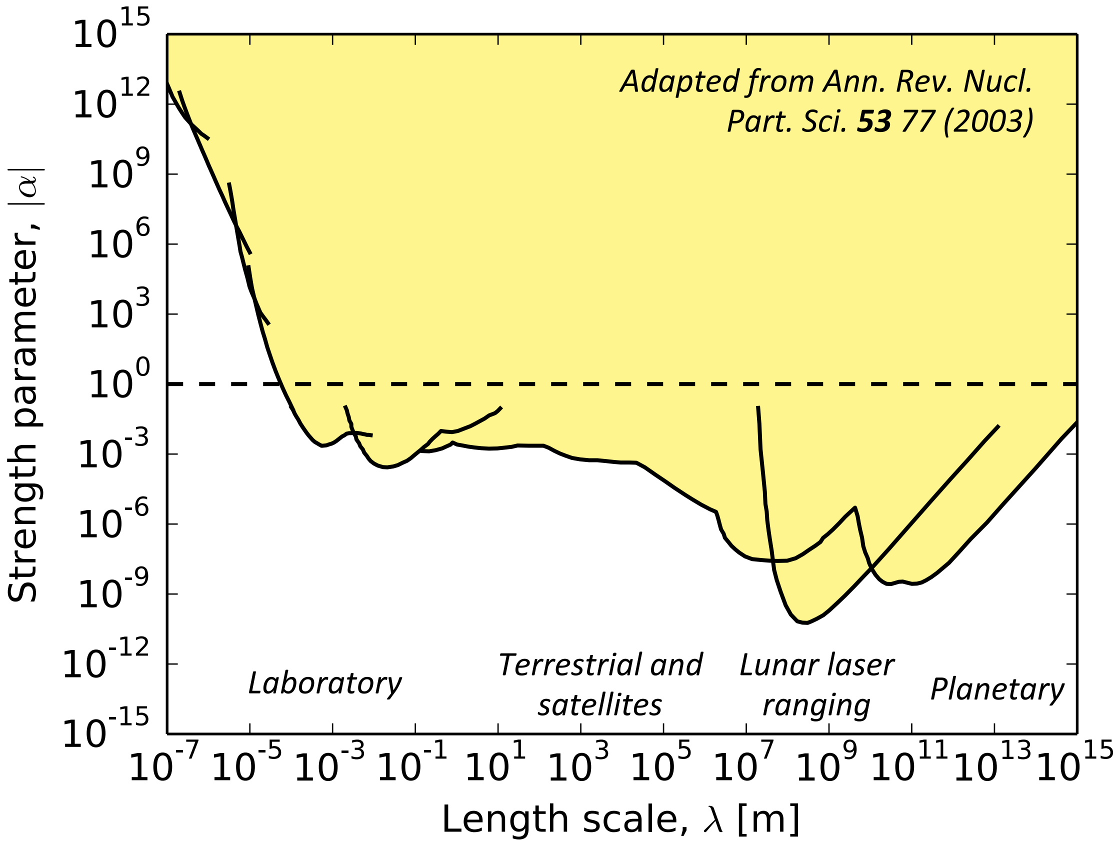



Introduction

- Searches for new short range forces can probe a variety of models of new physics that are difficult to test with other techniques
- Typically parameterize resulting non-Newtonian potential with Yukawa form:

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

Current experimental constraints on non-Newtonian forces:



- Strong limits from terrestrial and astrophysical tests exist at large distance
- For short length scales, constraints are much weaker: $\alpha \lesssim 10^{10}$ for $\lambda = 1\ \mu m$
- May be possible to significantly improve sensitivity at micron length scales

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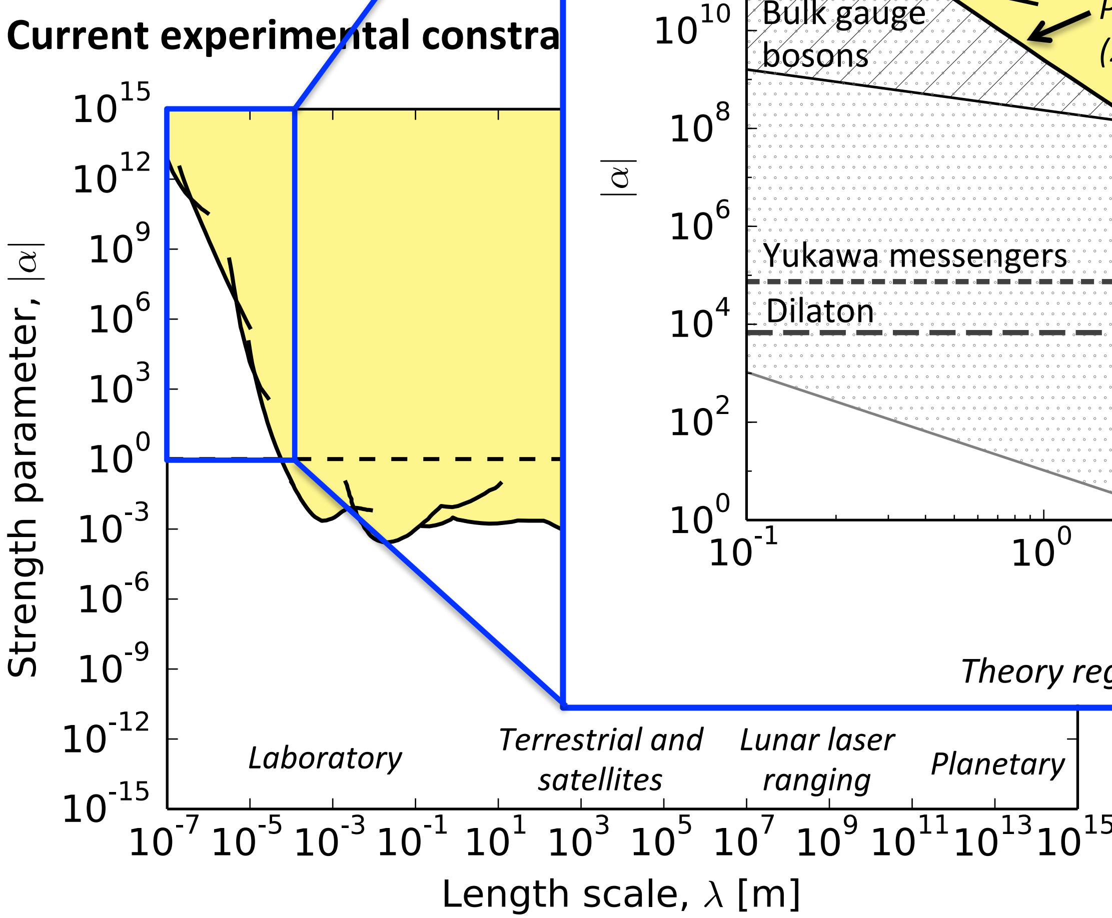

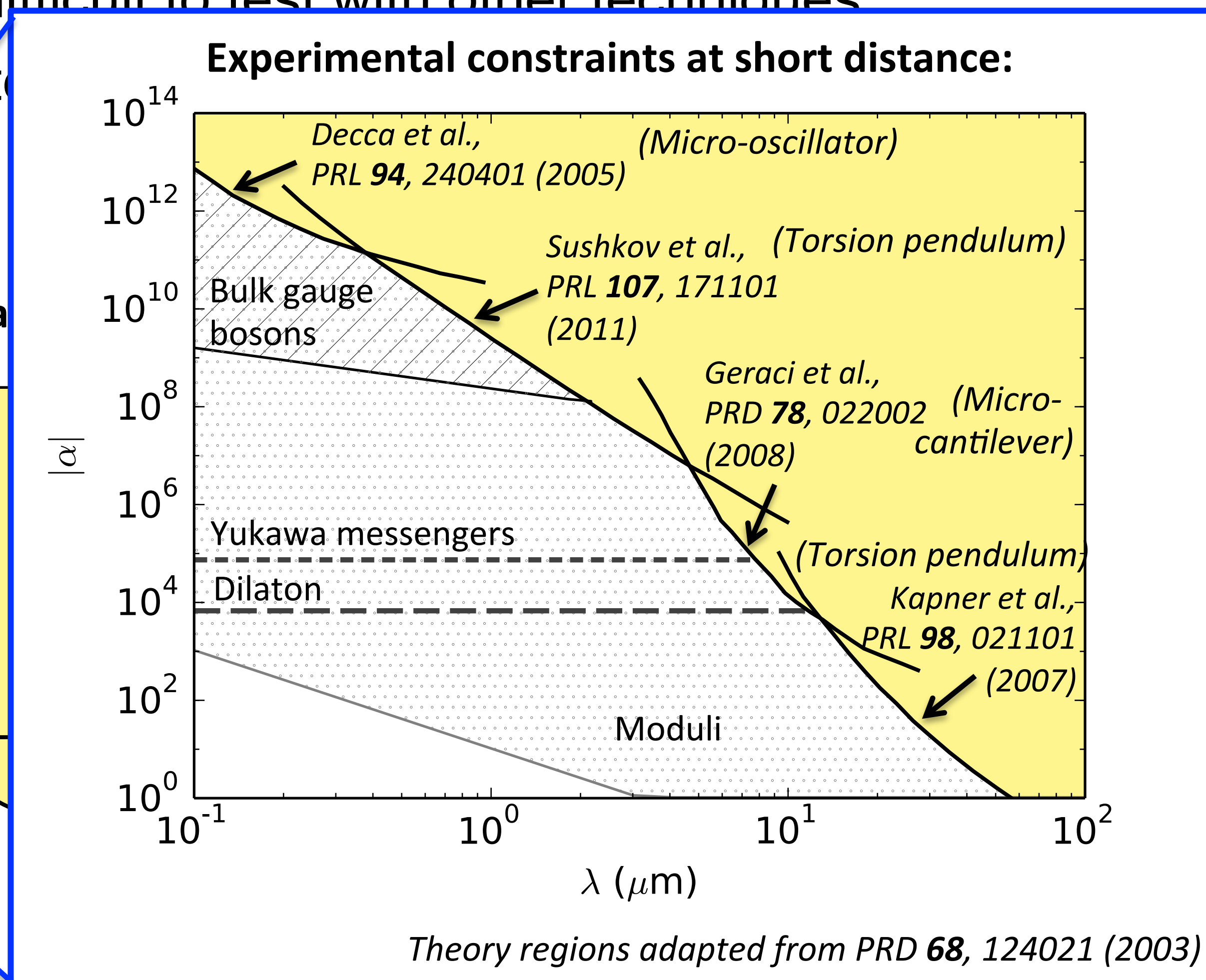

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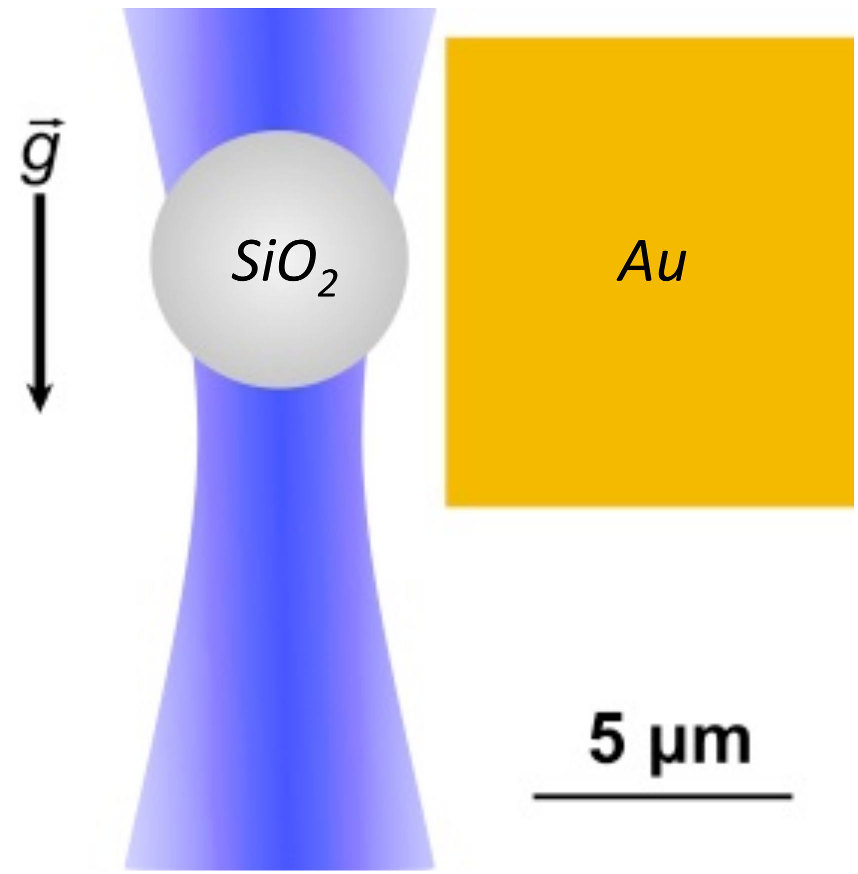
Optical levitation

- Previous measurements at short distance have used mechanical springs as force sensors (e.g. torsion pendulums, micromachined cantilevers)
- Suspending test mass with an "optical spring" offers several advantages:
  - Thermal and vibrational noise from mechanical support minimized
  - At high vacuum, test mass can be isolated from surroundings and cooled optically (without cryogenics)
  - Test mass position can be controlled and measured precisely with optics
  - Control of optical potential and motion in all 3 DOF allows powerful differential measurements
  - Dielectric spheres with a wide range of sizes (~10 nm – 10 μm) can be used
  - Extremely low dissipation is possible: $Q \sim 10^{12}$ at 10^{-10} mbar

Schematic of optical levitation technique:

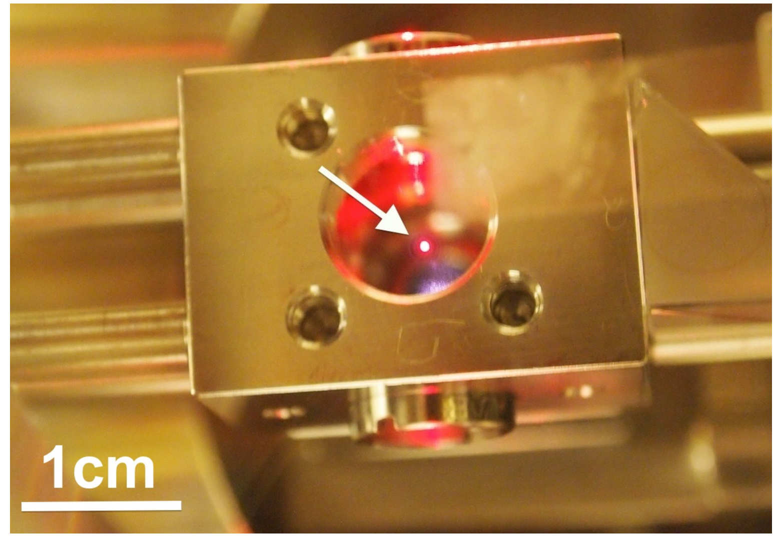


Geraci et al., PRL ***105****, 101101 (2010)*

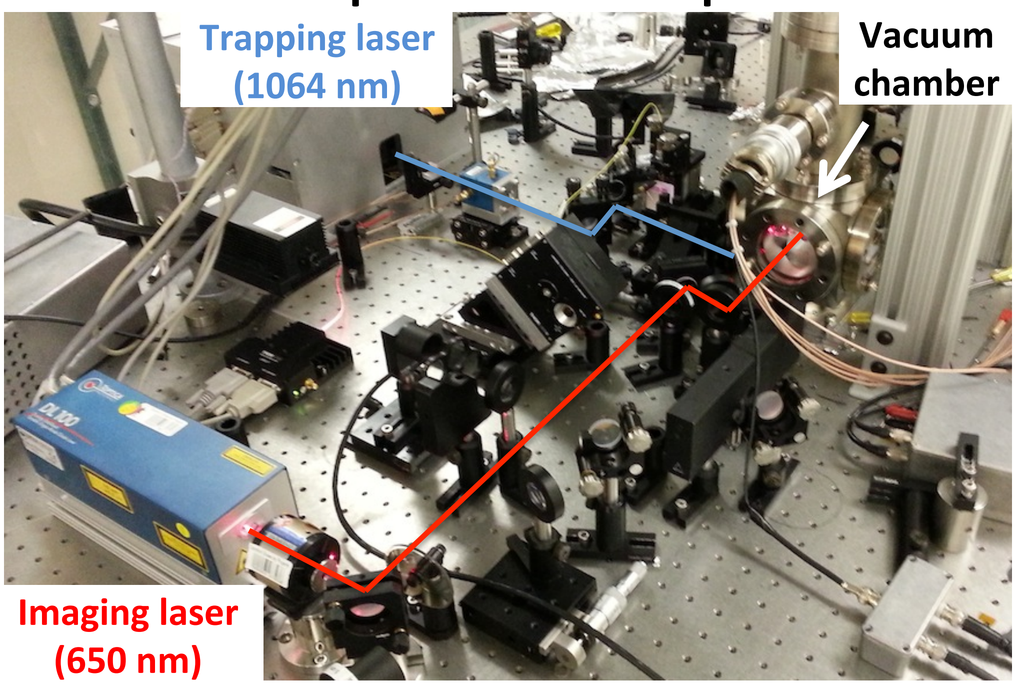
Experimental setup

- Developed setup capable of levitating SiO_2 microspheres with r = 0.5-5 μm
- Microspheres are levitated in UHV chamber with λ = 1064 nm, ~few mW trapping laser
- Imaged by additional λ = 650 nm beams
- Have stably trapped a single microsphere at ~10^{-7} mbar for >100 hrs

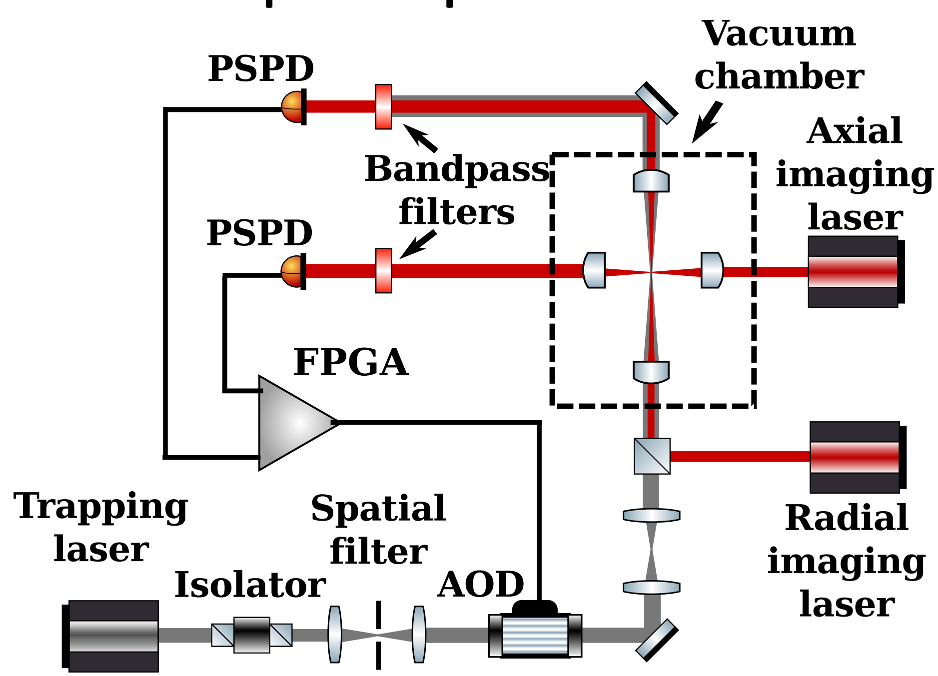
Photograph of trapped microsphere:



Experimental setup:



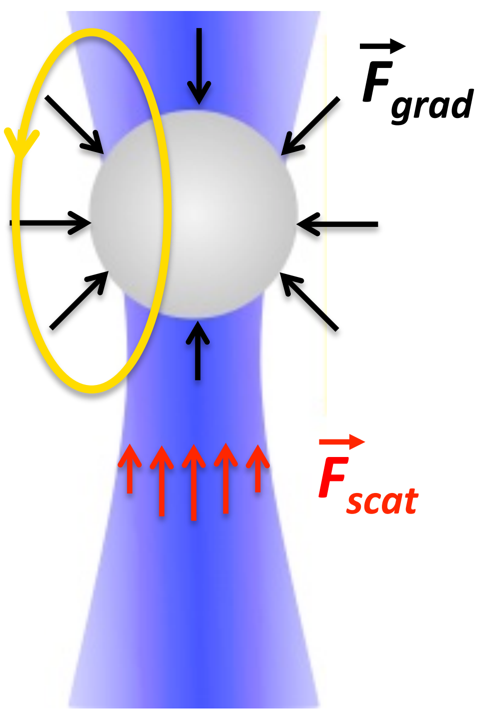
Simplified optical schematic:



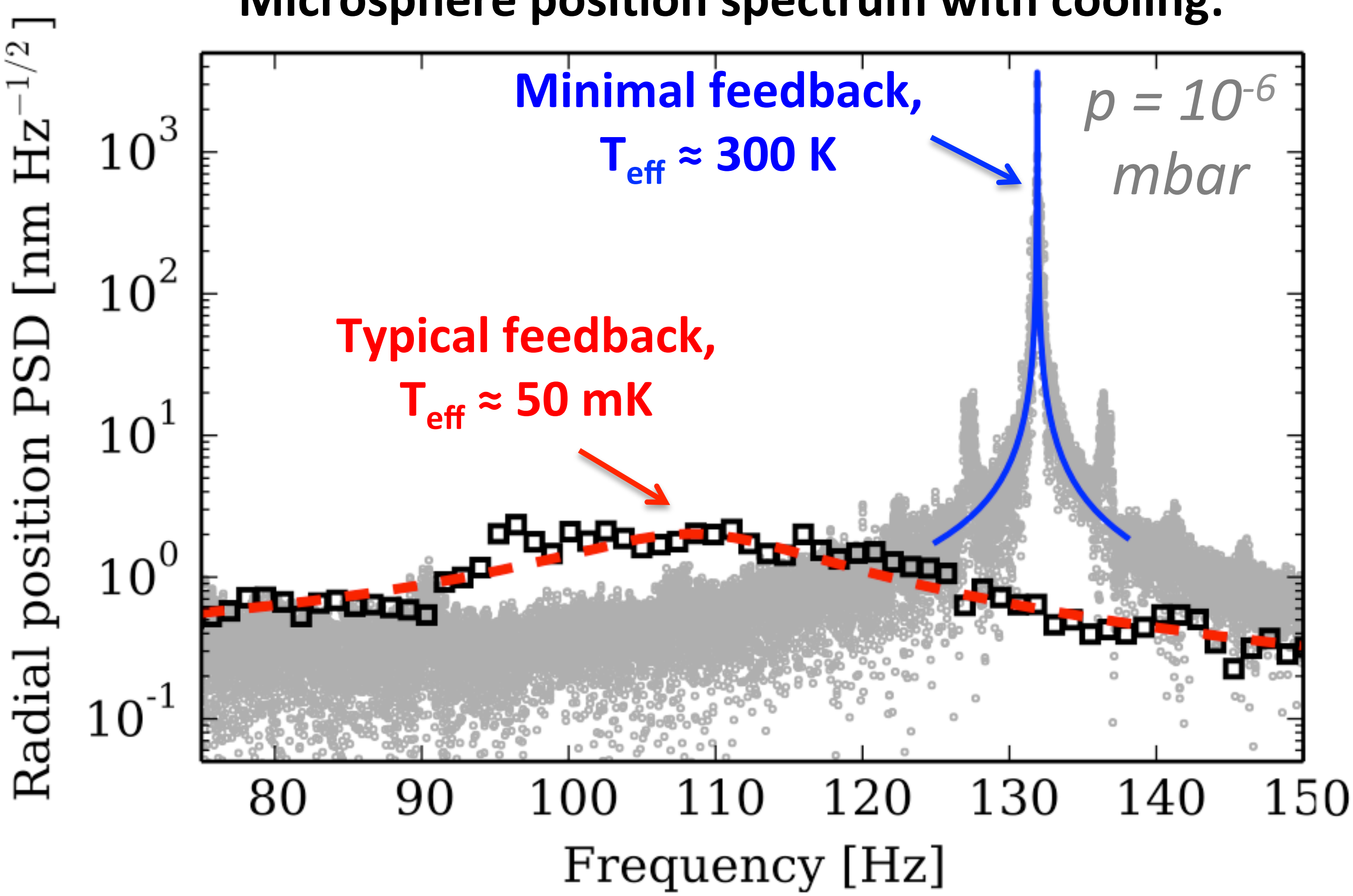
Microsphere cooling

- Below ~1 mbar, active feedback cooling is needed to maintain stable trapping
- Monitor position of microsphere and apply feedback by modulating amplitude and pointing of the trapping beam (using FPGA and AOD)
- Can cool center of mass motion to <50 mK in all 3 DOF

Mechanism for laser heating:



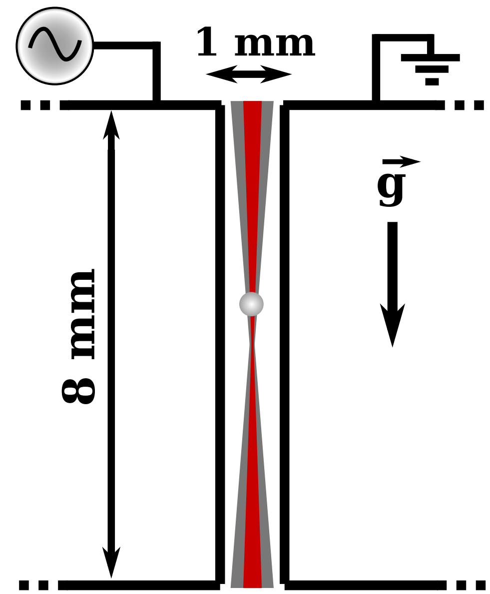
Microsphere position spectrum with cooling:



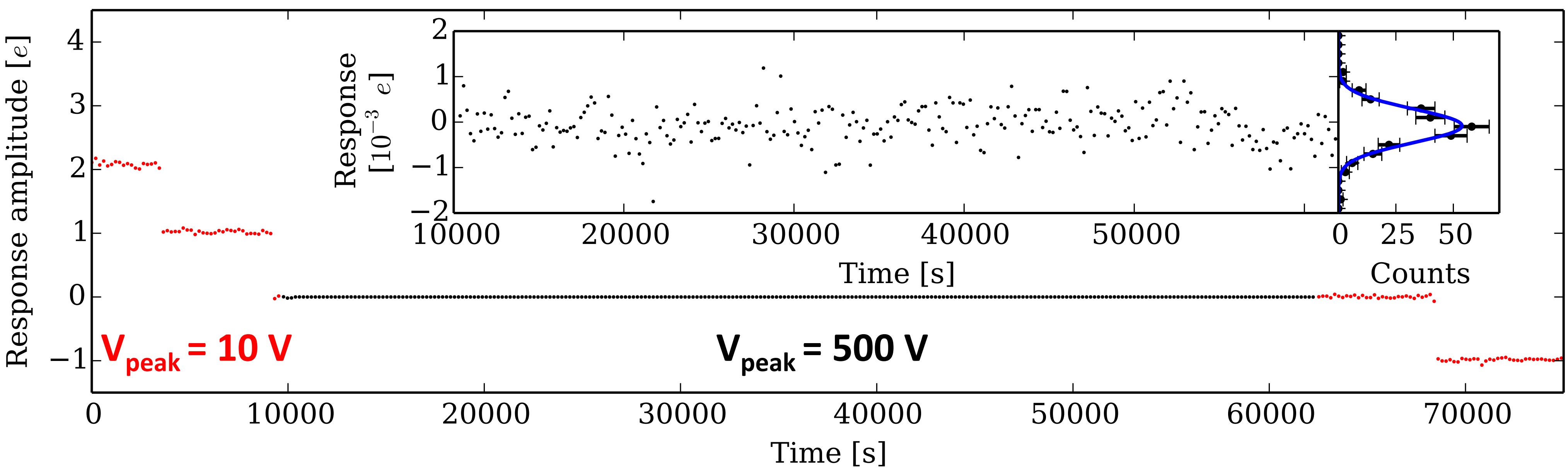
Microsphere neutralization

- Electromagnetic backgrounds can overwhelm signal from new short-range forces
- Microsphere can be discharged by flashing with UV light from Xe flash lamp
- Have demonstrated controlled discharging with single e precision
- Once neutral, microspheres have not spontaneously charged in total integration time of more than 5 x 10^5 s

Electrode configuration:



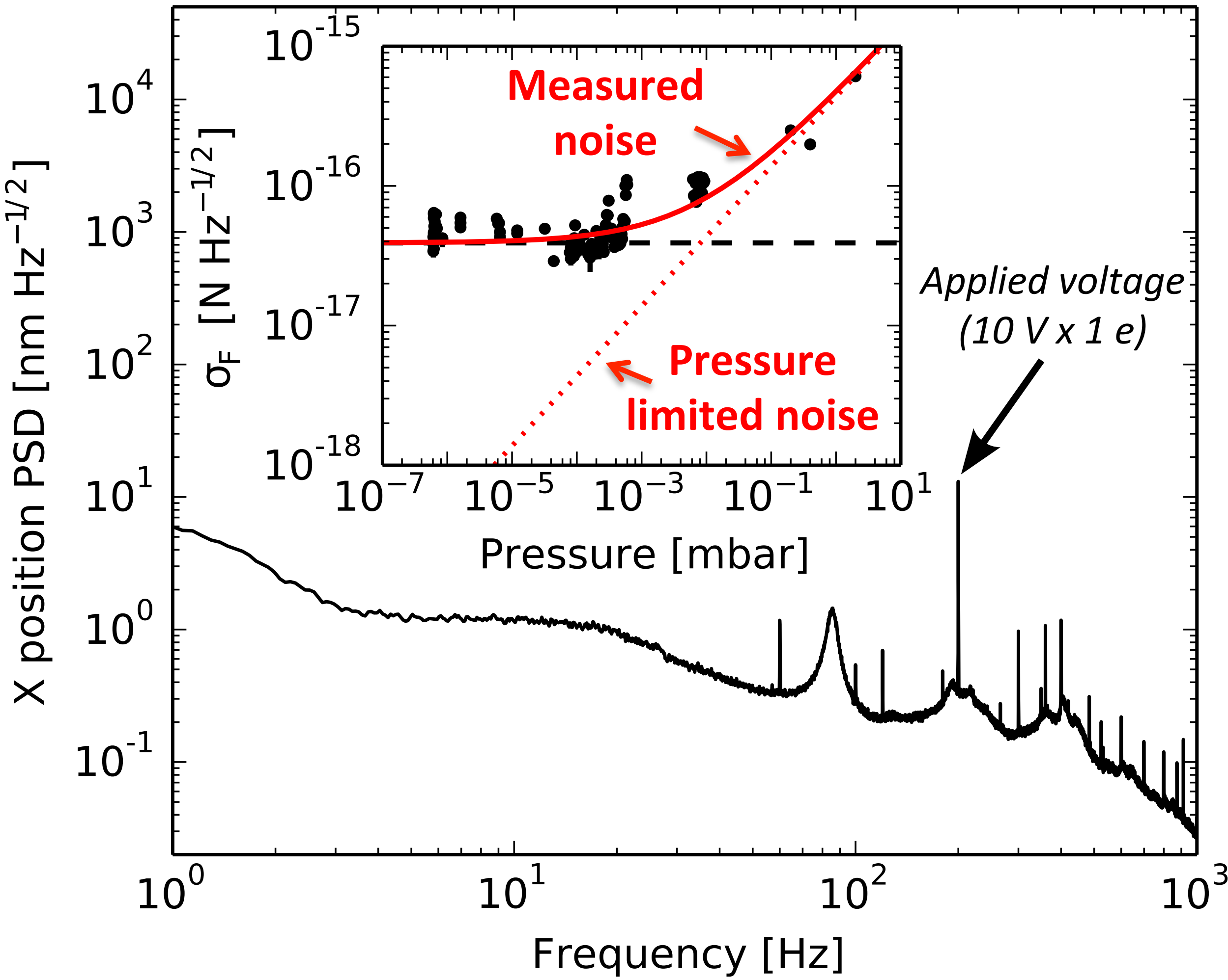
Example of discharging process:



Force sensitivity

- Can also use observed single e steps to perform absolute calibration of force sensitivity for each microsphere *in situ*
- At high pressure, sensitivity limited by residual gas damping
- Below 10^{-3} mbar, force sensitivity limited to $\sigma_F = 5 \times 10^{-17}$ N Hz$^{-1/2}$
- Current sensitivity limited by non-fundamental sources of noise (imaging and laser jitter)
- Significant improvement possible – pressure limited sensitivity at 10^{-9} mbar ~ 10^{-20} N Hz$^{-1/2}$

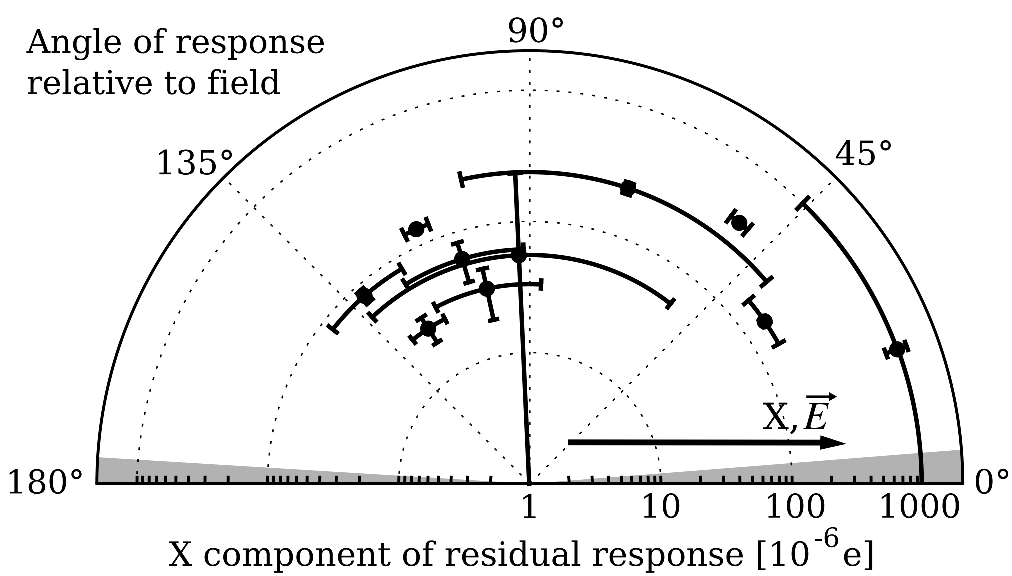
Calibration of force sensitivity:



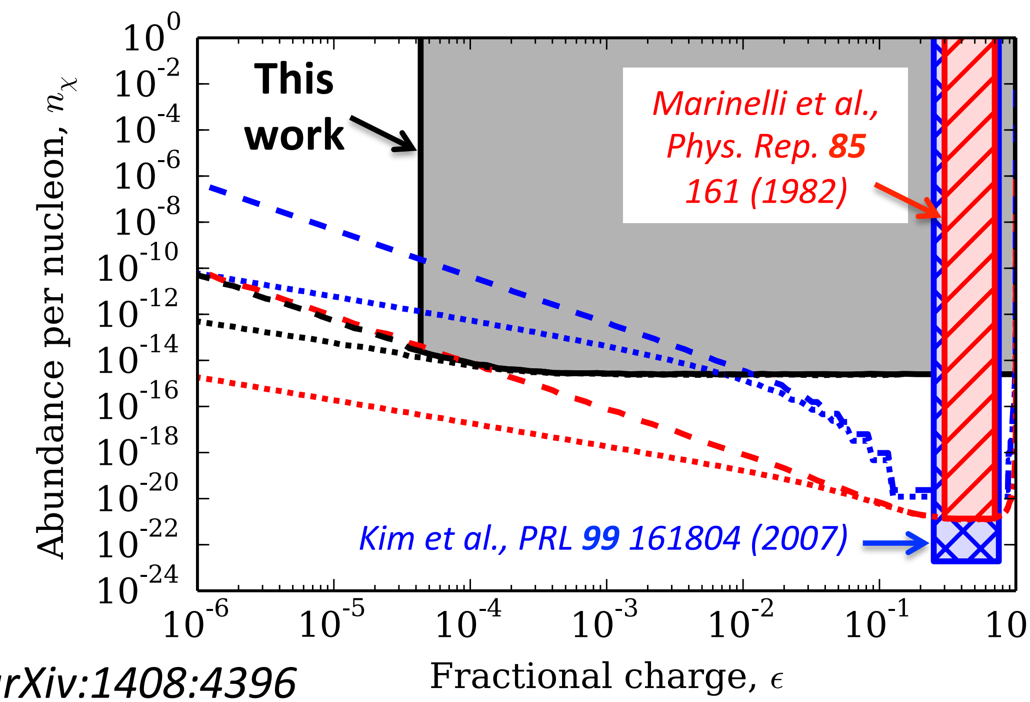
Search for millicharged particles

- As a first application of this force sensing technique, we have performed a search for millicharged particles (|q| << 1e) bound in the microspheres
- Sensitive to single fractional charges as small as 5 x 10^{-5} e
- Current sensitivity (<1 aN) limited by residual response due to microsphere inhomogeneities that couple to E-field gradients

Measured residual response:



Limits on abundance of millicharged particles:

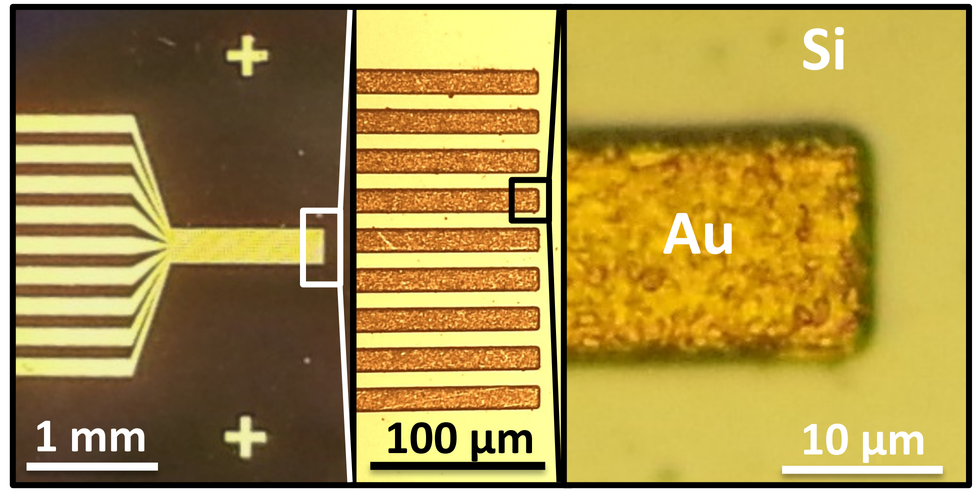


*Moore et al., PRL **113** 251801 (2014), arXiv:1408:4396*

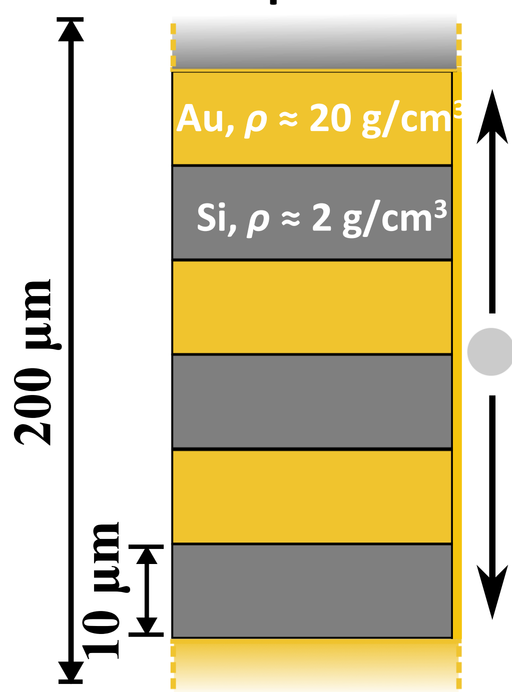
Attractor design

- Short-range force measurements require gravitational attractor that can be positioned near microsphere
- Attractor with spatially varying density allows reduction of many backgrounds
- Have begun fabrication of Au and Si test mass arrays
- Au shielding layer screens electromagnetic backgrounds that vary with composition

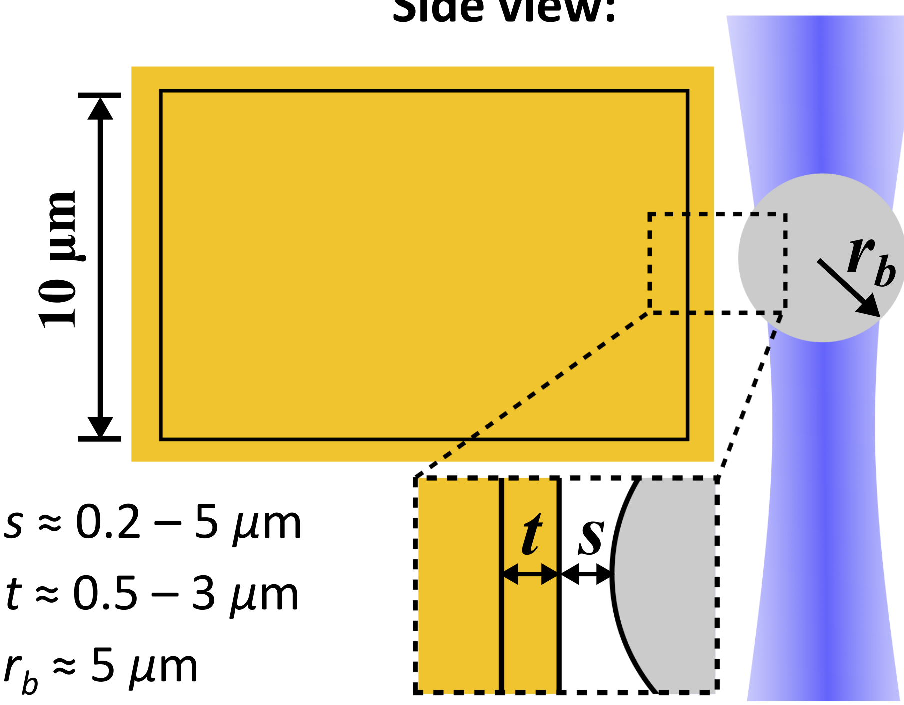
Images of preliminary fabrication tests:



Top view:



Side view:



$s \approx 0.2 - 5\ \mu m$

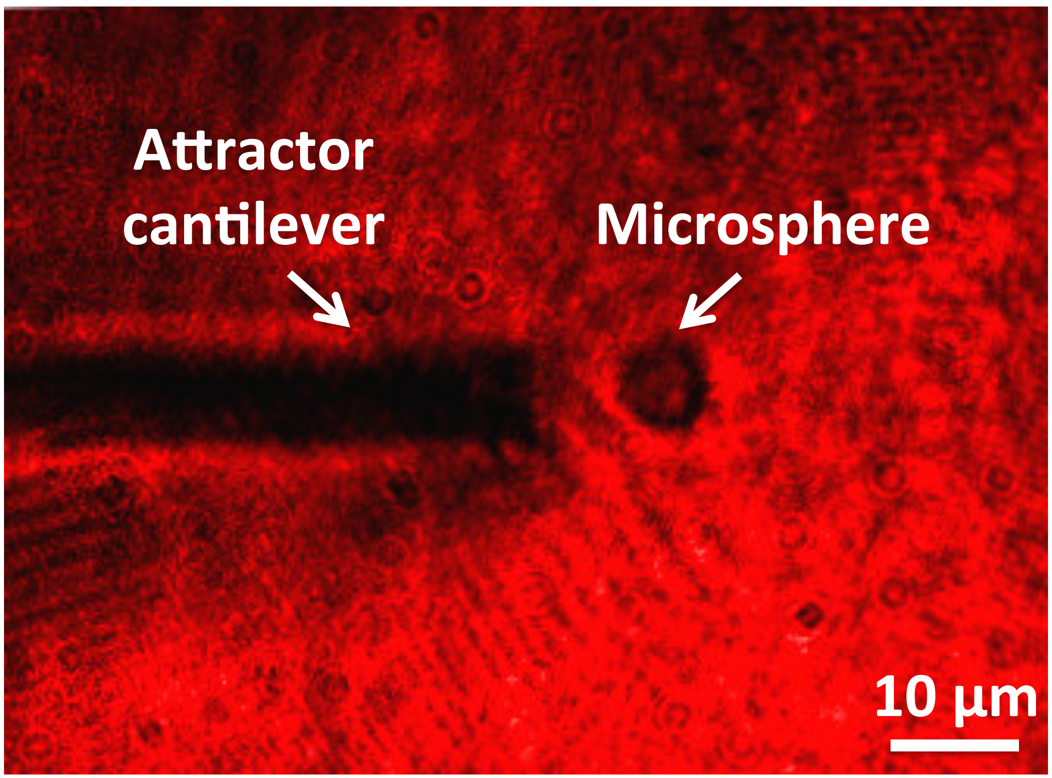
$t \approx 0.5 - 3\ \mu m$

$r_b \approx 5\ \mu m$

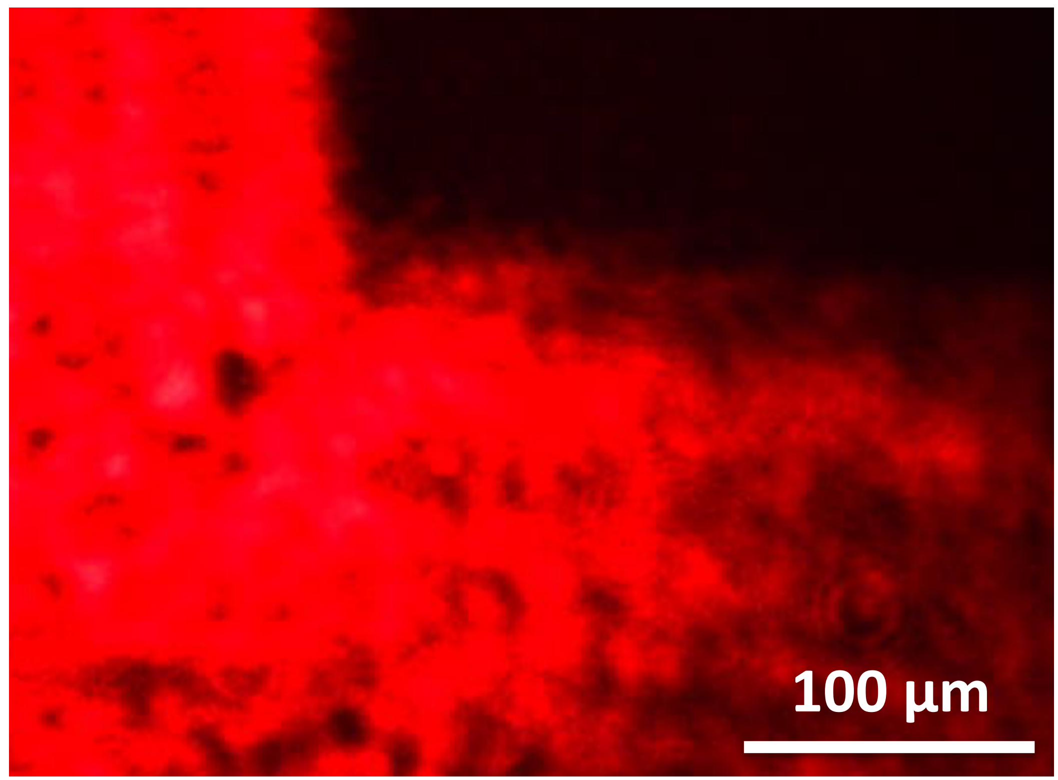
Microsphere positioning

- The position of the microsphere can be precisely controlled via the optical potential
- Acousto-optic deflector (AOD) is used to position microsphere with ~µm separations from attractor mass
- Microsphere can be moved along the attractor face to produce an oscillation in density near the microsphere at up to ~200 Hz

Side view of microsphere near attractor:



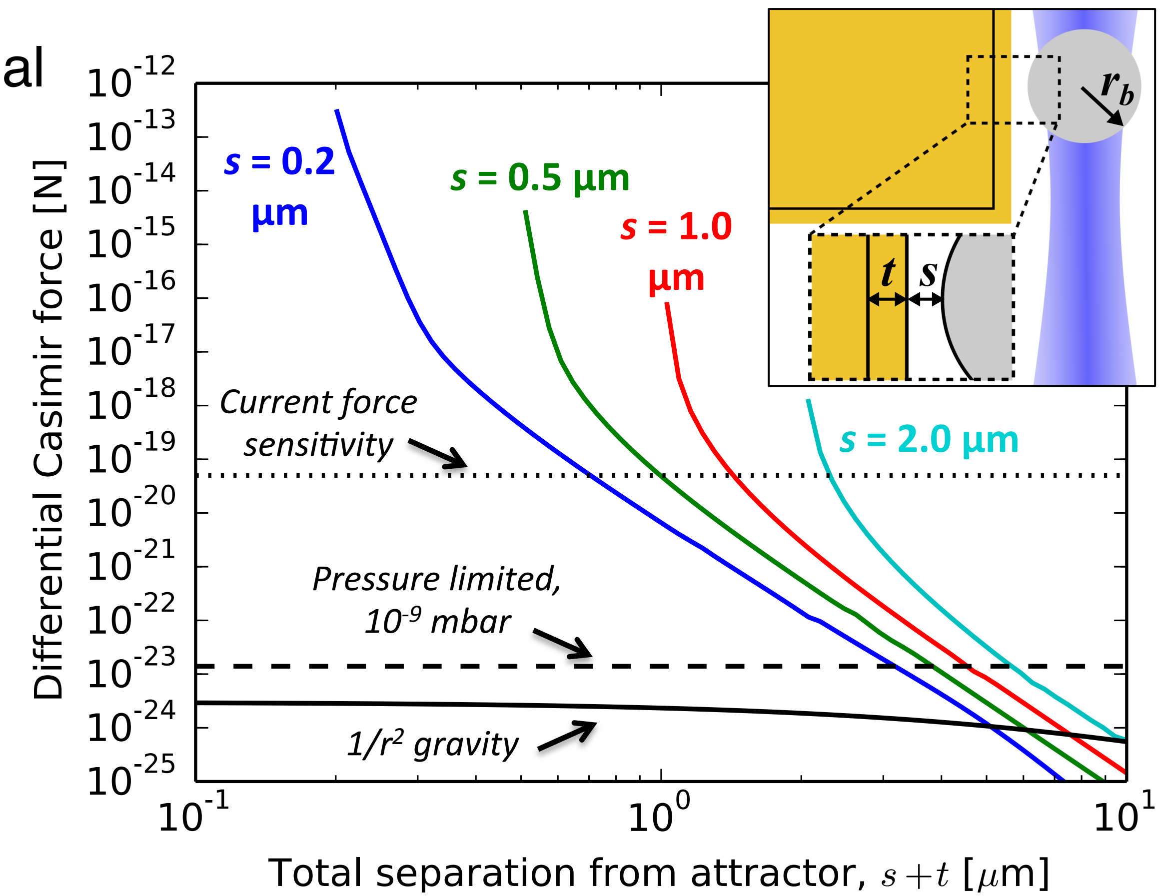
Top view of microsphere near attractor:



Expected backgrounds (Casimir)

- If unscreened, differential Casimir force between Au and Si can present dominant background
- Coating attractor with Au shield layer (0.5 to 3 μm thick) can sufficiently suppress this background
- Differential Casimir force modulates with the same spatial frequency as the expected signal
- Calculation assumes proximity force approximation (PFA)
- Full calculation without PFA for realistic 3D geometry is in progress

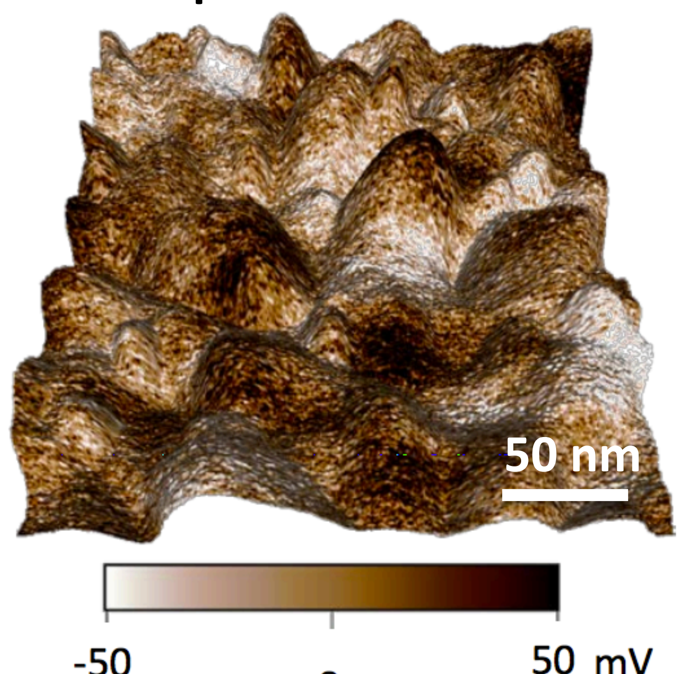
Calculation of differential Casimir force:



Expected backgrounds (Patch potentials)

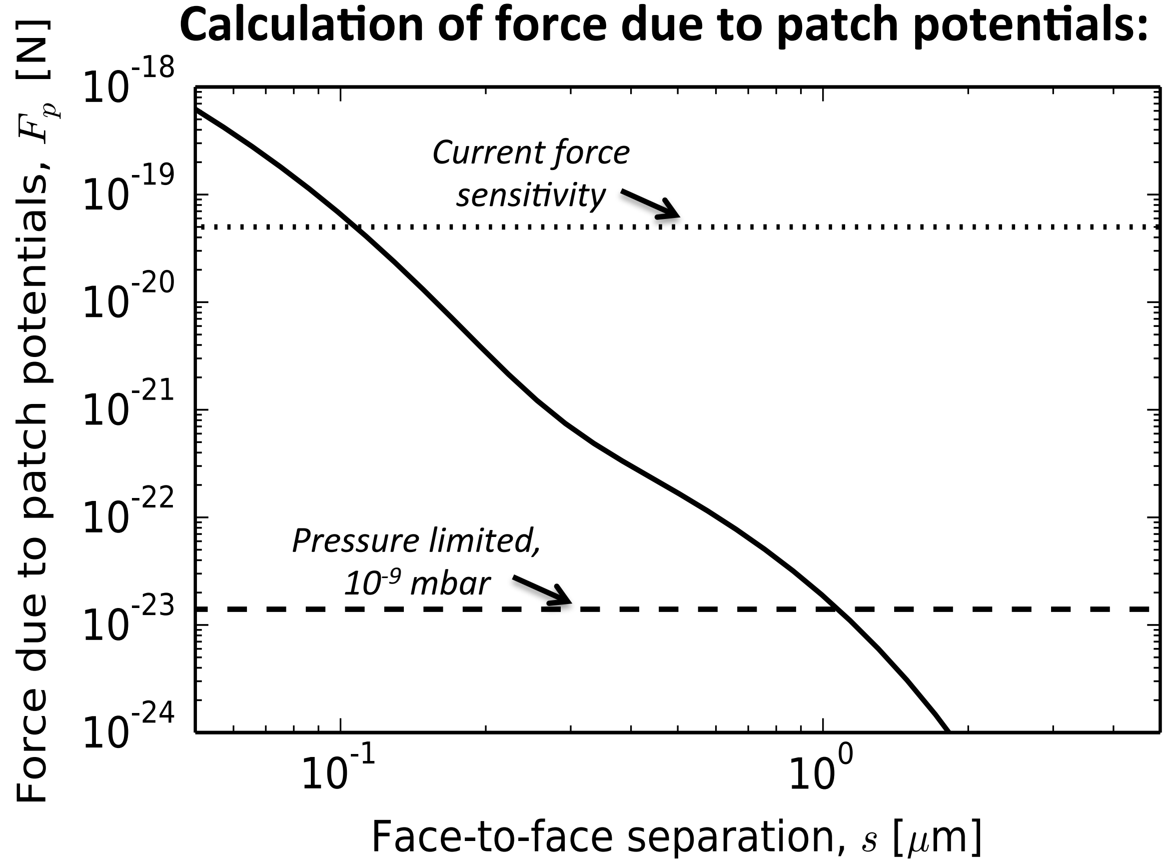
- Deposited metal films typically have potential variations ~10–100 mV over 10 nm–1 μm surface regions due to crystalline grains or impurities
- Such "patch potentials" have been studied extensively since they provide a significant background in Casimir force experiments
- Estimated background using recent patch measurements of Au films (only small component will be at same spatial frequency as attractor mass)

Topography and surface potential for sputtered Au film:



Garrett et al., arXiv:1409.5012

Calculation of force due to patch potentials:

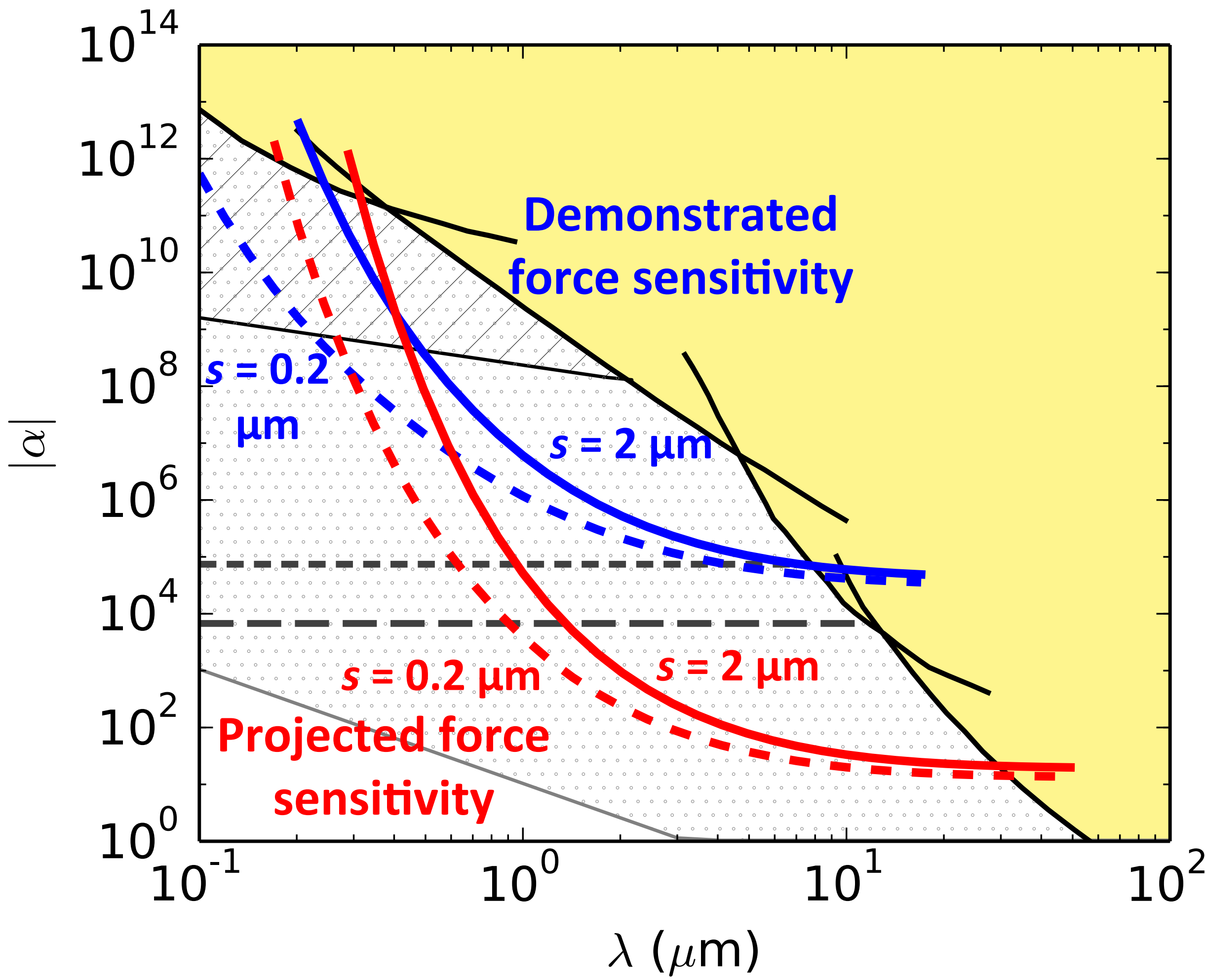


Expected sensitivity

- Have calculated expected sensitivity to Yukawa strength parameter, α, as a function of length scale, λ
- Assume face-to-face separation of s = 0.2 μm (dashed) or 2 μm (solid)

- Plot sensitivity for demonstrated $\sigma_F = 5\times10^{-17}$ N $Hz^{-1/2}$ (blue) and for pressure limited σ_F at 10^{-9} mbar (red)
- Assume Au shielding layer of sufficient thickness to make Casimir background negligible
- Improvement in sensitivity by several orders of magnitude over existing limits at 0.5–10 μm is possible
- Hatched regions, lines show selection of theoretical models from PRD **68** 124021 (2003)

Projected sensitivity to non-Newtonian forces:



Summary

- Have developed apparatus to optically levitate micron sized dielectric spheres in vacuum
- Force sensitivity << 10^{-18} N and our ability to precisely manipulate the microspheres near the attractor surface can enable unprecedented sensitivity to non-Newtonian forces at micron distances
- Have demonstrated force sensing technique in search for millicharged particles bound in the microspheres (sensitive to $q > 5 \times 10^{-5}\, e$)
- Currently fabricating spatially varying attractor masses that are needed for searches for short-range forces
- Sensitivity projections indicate that several orders of magnitude improvement is possible over existing constraints at 0.5-10 µm