# Searching for new short range forces using optically levitated microspheres

David Moore, Alexander Rider, Marie Lu, Maxime Louis, Noah Kurinsky,
Charles Blakemore, Giorgio Gratta

Stanford University

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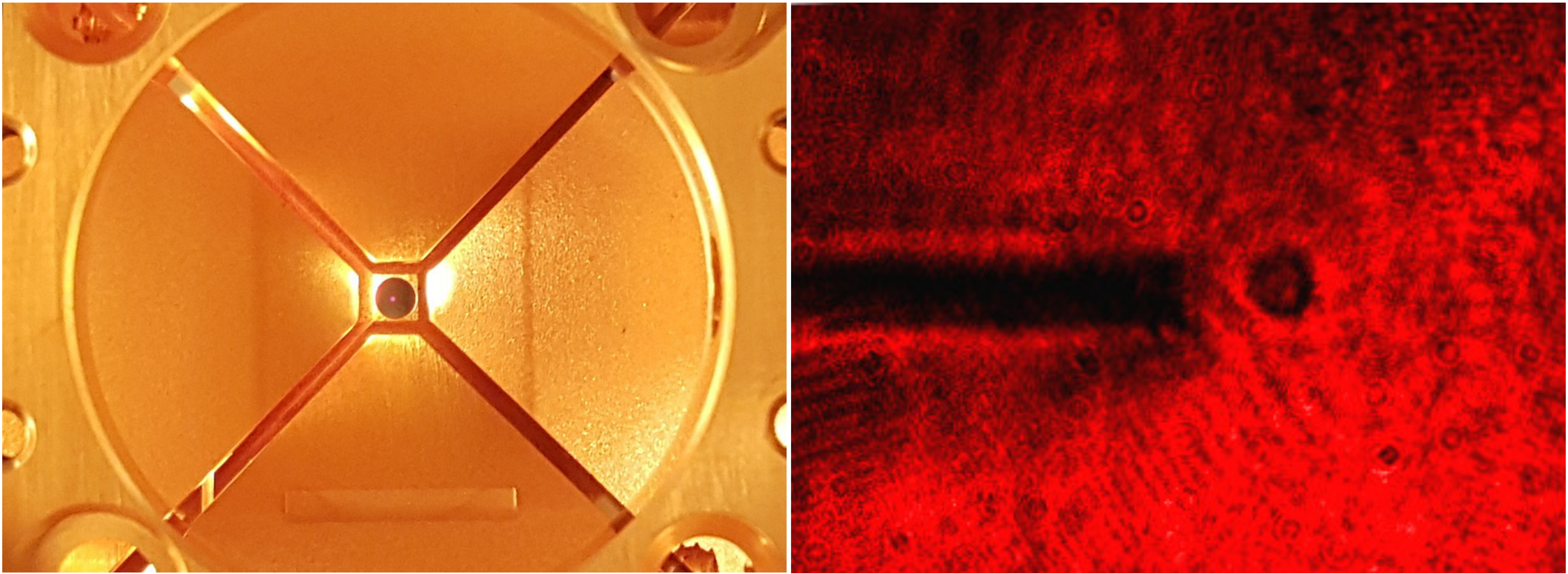
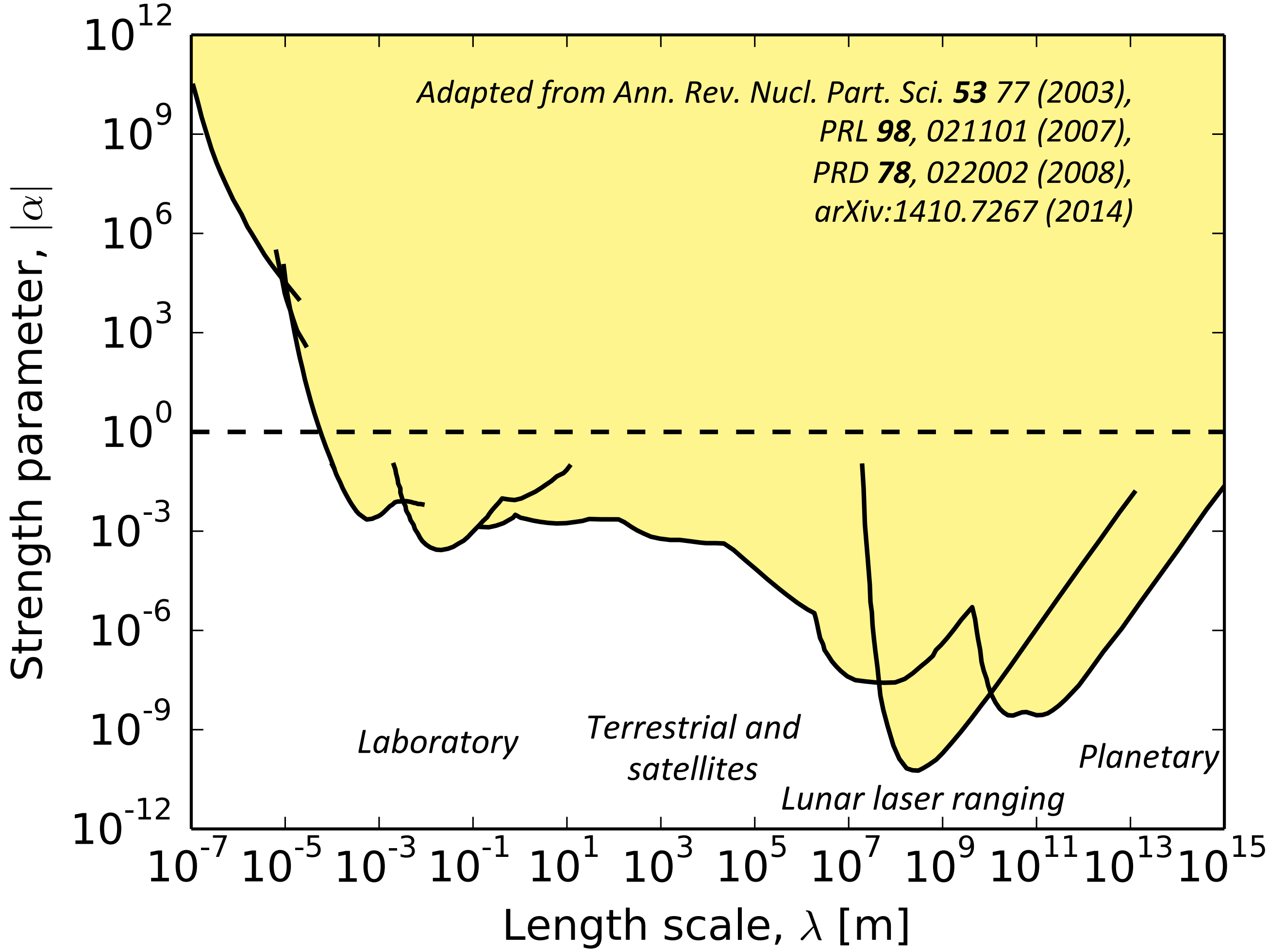


# Experimental constraints

- Searches for deviations from $1/r^2$ gravity can test a variety of models of new physics
- Typically parameterize potential as: $V(r) = -\frac{Gm_1m_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$

**Current experimental constraints on non-Newtonian forces:**



- Constraints weaken substantially at <<1 mm (e.g. $\alpha < 10^7$ for $\lambda = 1\ \mu\mathrm{m}$)
- New techniques may allow improved sensitivity at ~1 μm

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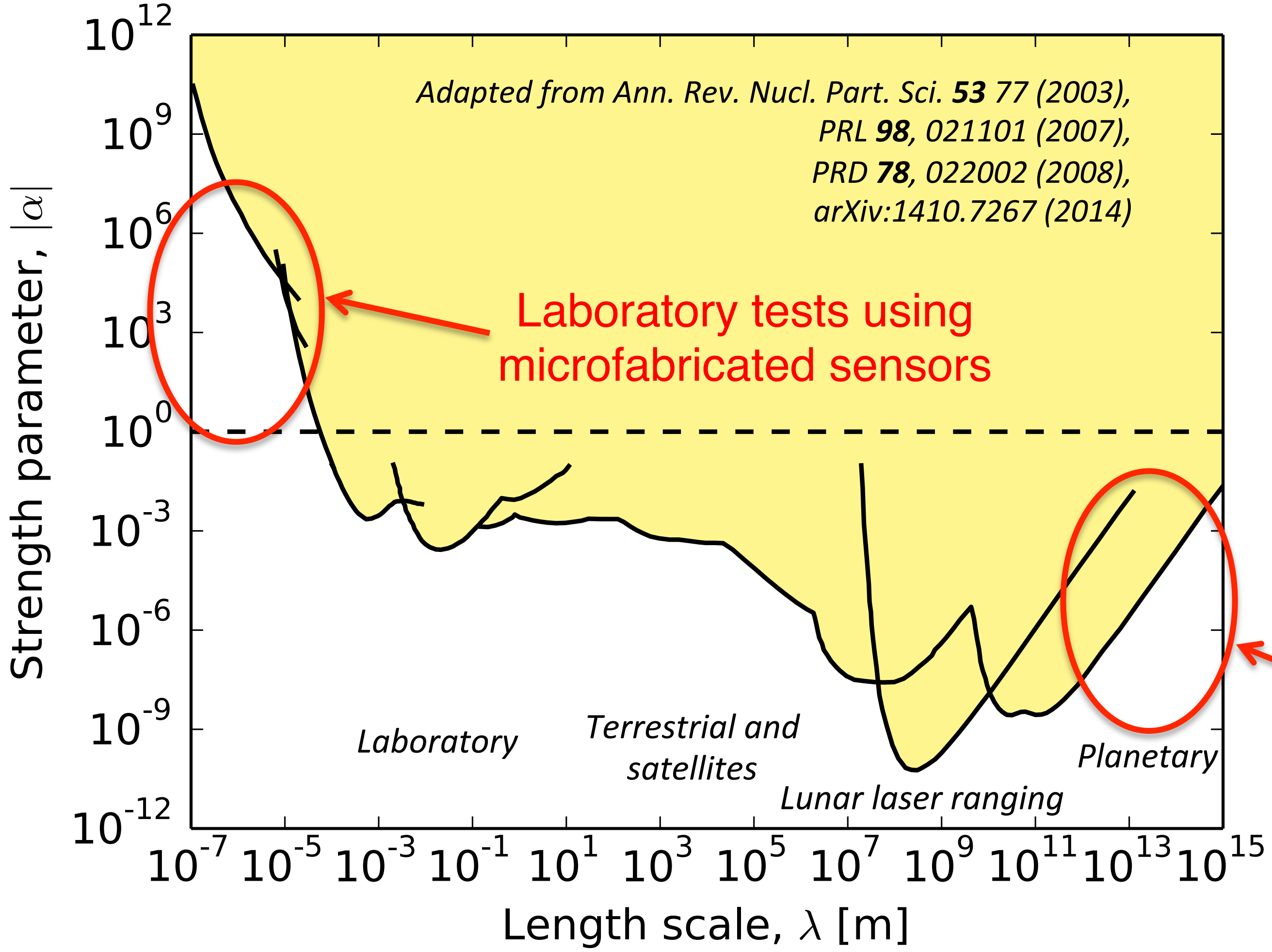


Laboratory tests using microfabricated sensors

Recent proposal for spacecraft with drag-free test mass at 1-100 AU

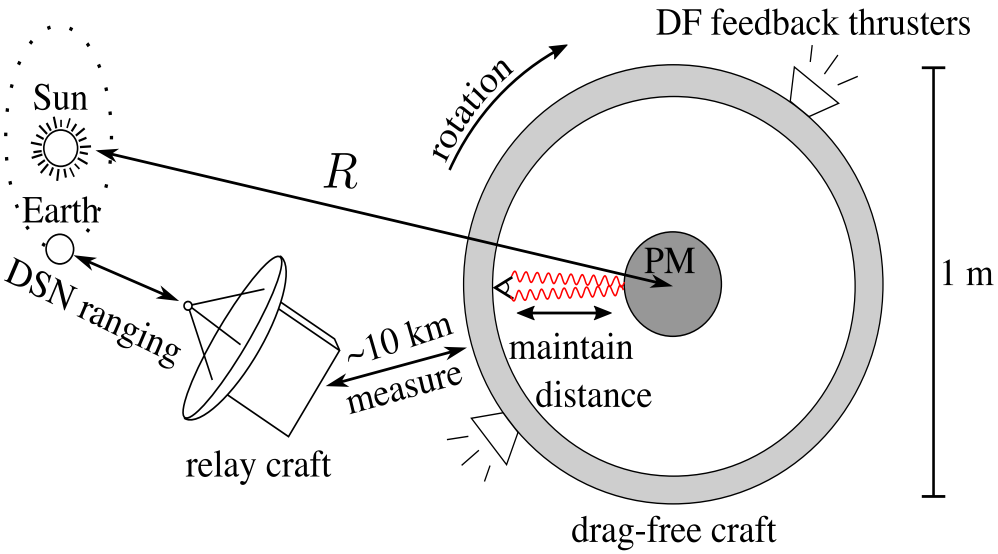
- Constraints weaken substantially at <<1 mm (e.g. $\alpha < 10^7$ for $\lambda = 1\ \mu\mathrm{m}$)
- New techniques may allow improved sensitivity at ~1 µm

# Long distance tests

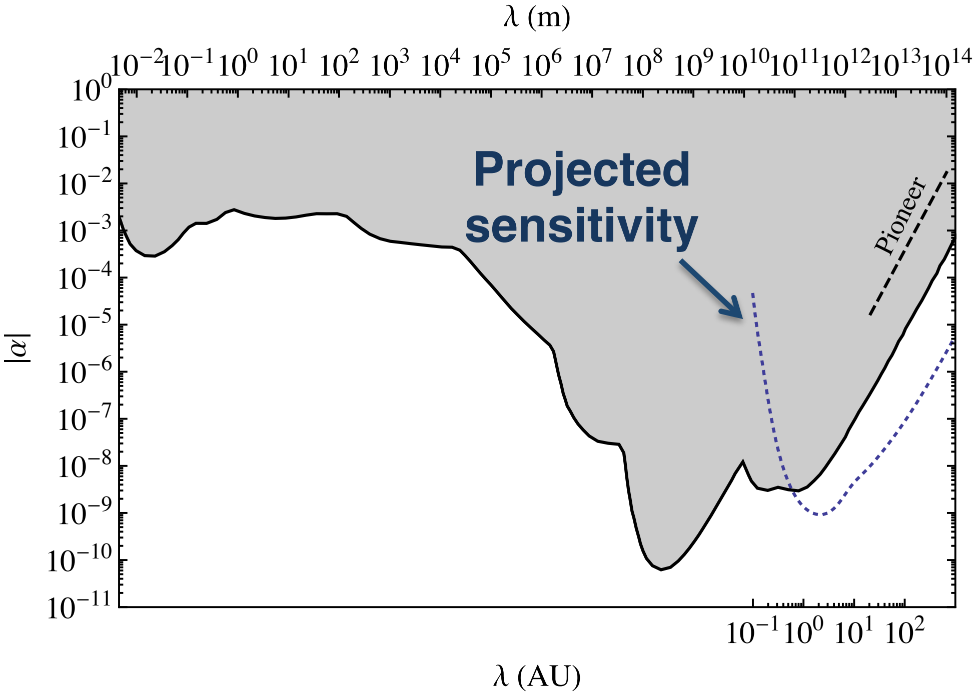
- Deviations at long distance could arise in models accounting for dark energy (e.g., Vainshtein-type mechanisms) or dark matter (MOND-like theories)
- Recent proposal to use spacecraft with drag free test mass at 1-100 AU:

*B. Buscaino, D. DeBra, P. Graham, G. Gratta, and T. Wiser,*
*Phys. Rev. D* ***92****,104048 (2015) arXiv:1508.06273*

**Schematic of experimental design:**



**Current and projected constraints:**

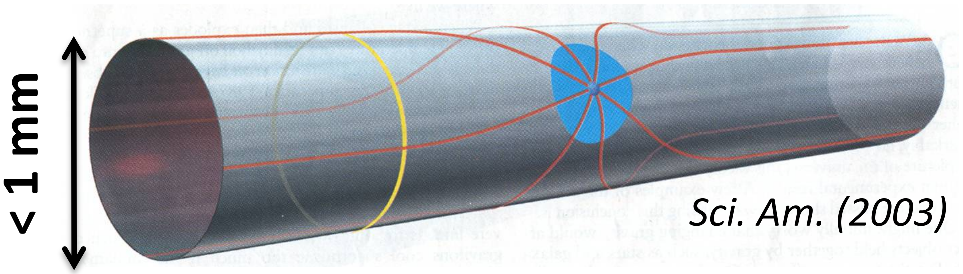


**Projected sensitivity**

# Short range forces

- In addition to new forces apparent at astrophysical distances, non-Newtonian forces can be searched for in the laboratory
- Theories attempting to account for the hierarchy problem, dark matter, or dark energy predict that there could new forces at << 1 mm

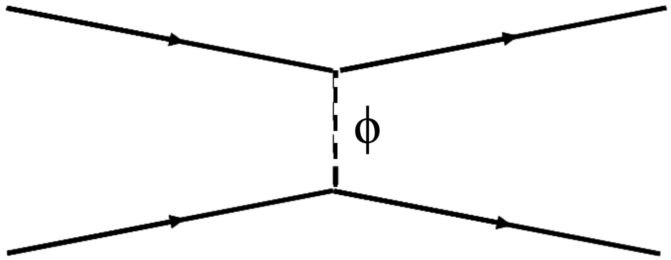
**Large extra dimensions:**



*Sci. Am. (2003)*

e.g., Arkani-Hamed et al., Phys. Lett. B 429, 263 (1998)
Randall and Sundrum, Phys. Rev. Lett. **83**, 3370 (1999); **83**, 4690 (1999)

**Exchange forces from new scalars (moduli, dilatons, …):**



e.g., Dimopoulos and Giudice, Phys. Lett. B **379** 105 (1996)
Kaplan and Wise, JHEP **08** 037 (2000)
Mantry et al., Phys. Rev. D **90**, 054016 (2014)

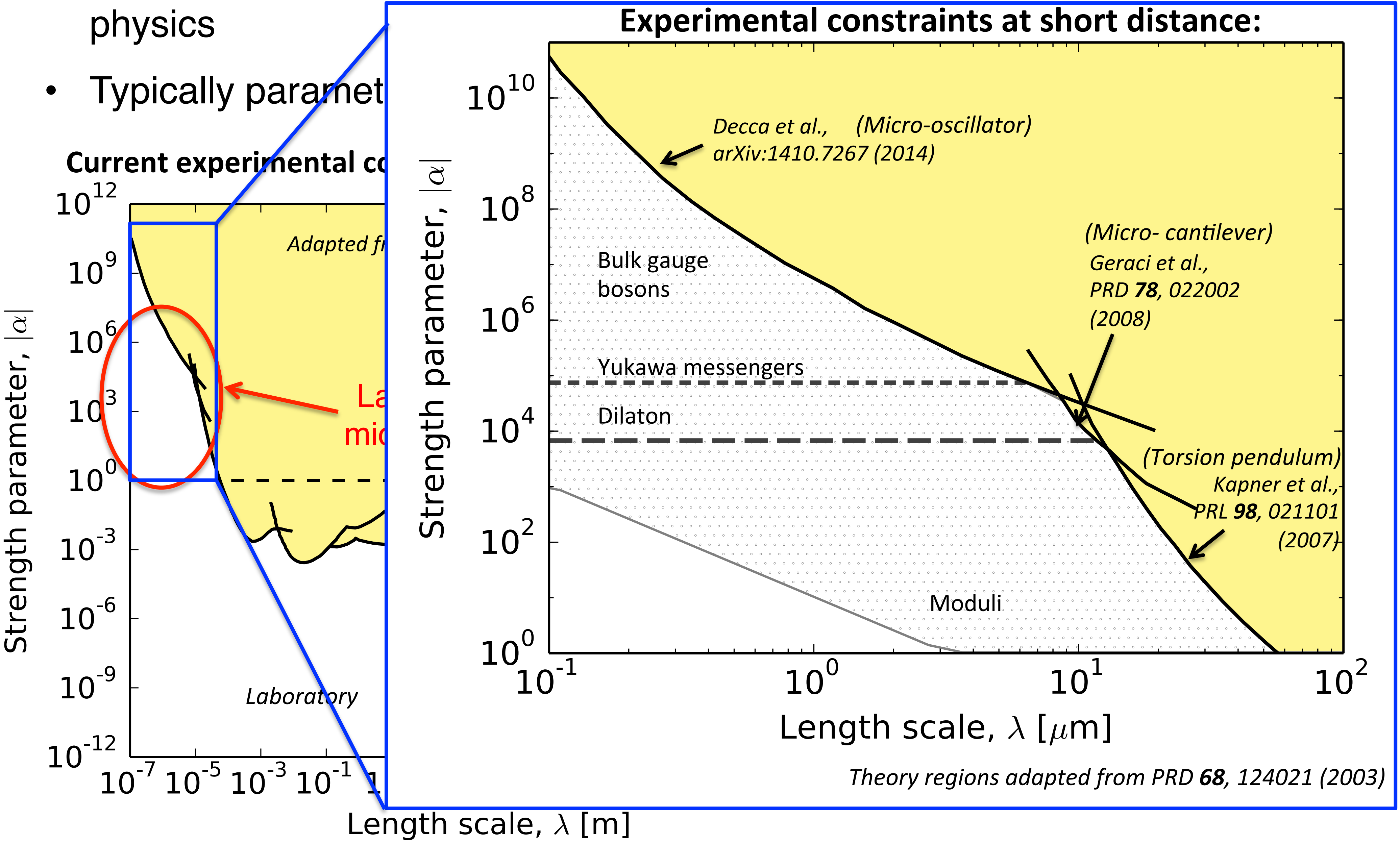
**Dark energy (“fat” gravitons, screened scalars, …):**

$\Lambda$ ~ 2 meV
(~ 80 μm)

e.g., Sundrum, Phys. Rev. D **69**, 044014 (2004)
Khoury and Weltman, Phys. Rev. Lett. **93**, 171104 (2004)

# Experimental constraints

- Searches for deviations from 1/r$^2$ gravity can test a variety of models of new physics
- Typically paramet



**Current experimental co**

**Experimental constraints at short distance:**

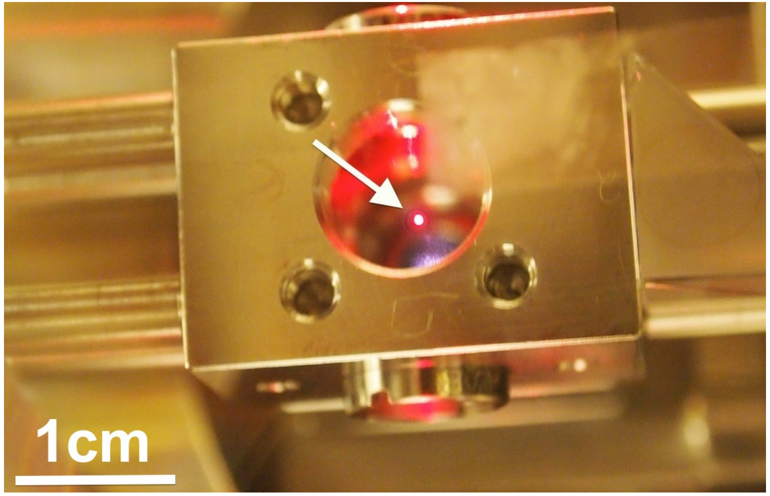
*Theory regions adapted from PRD **68**, 124021 (2003)*

# Optical levitation

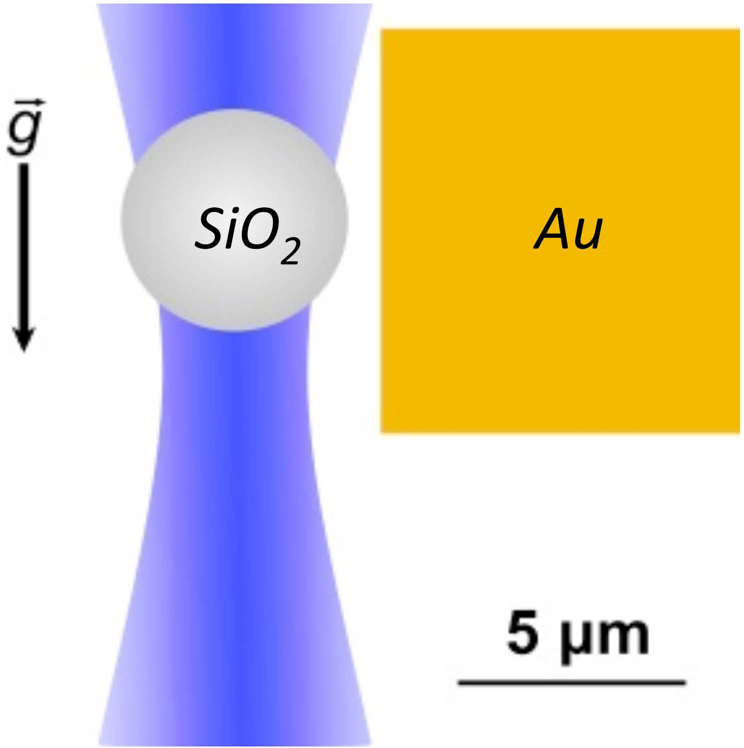
- Suspending test mass with an “optical spring” offers several advantages:
  - Test mass can be isolated from surroundings and cooled optically
  - Dielectric spheres between ~10 nm – 10 µm can be used
  - Position can be controlled and measured precisely with optics
  - Control over 3D optical potential enables differential measurements
  - At high vacuum, extremely low dissipation is possible: $Q \sim 10^{12}$ at $10^{-10}$ mbar

*Ashkin & Dziedzic, Appl. Phys. Lett.* ***19****, 283 (1971)*
*Geraci et al., PRL* ***105****, 101101 (2010)*

**Photograph of trapped microsphere:**



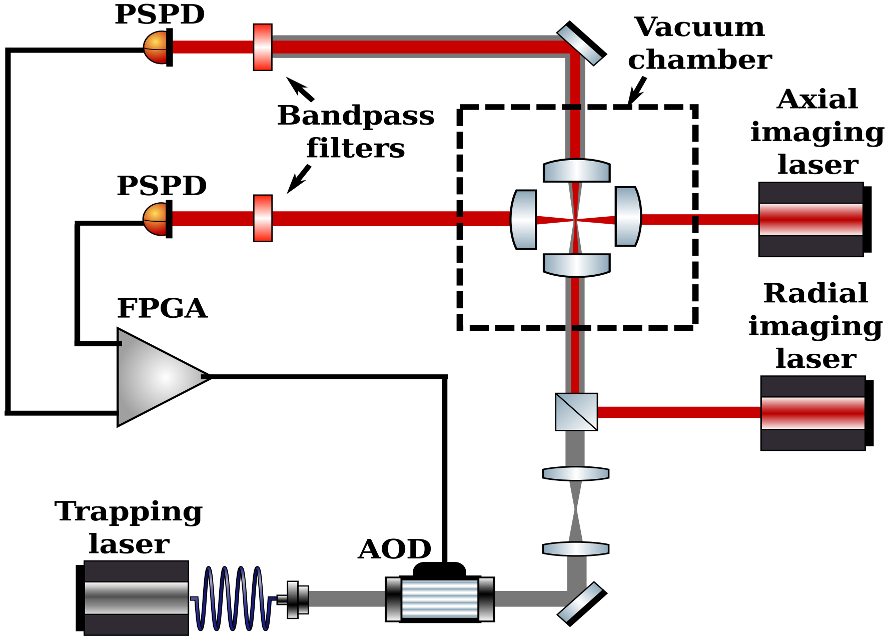
**Schematic of optical levitation technique:**



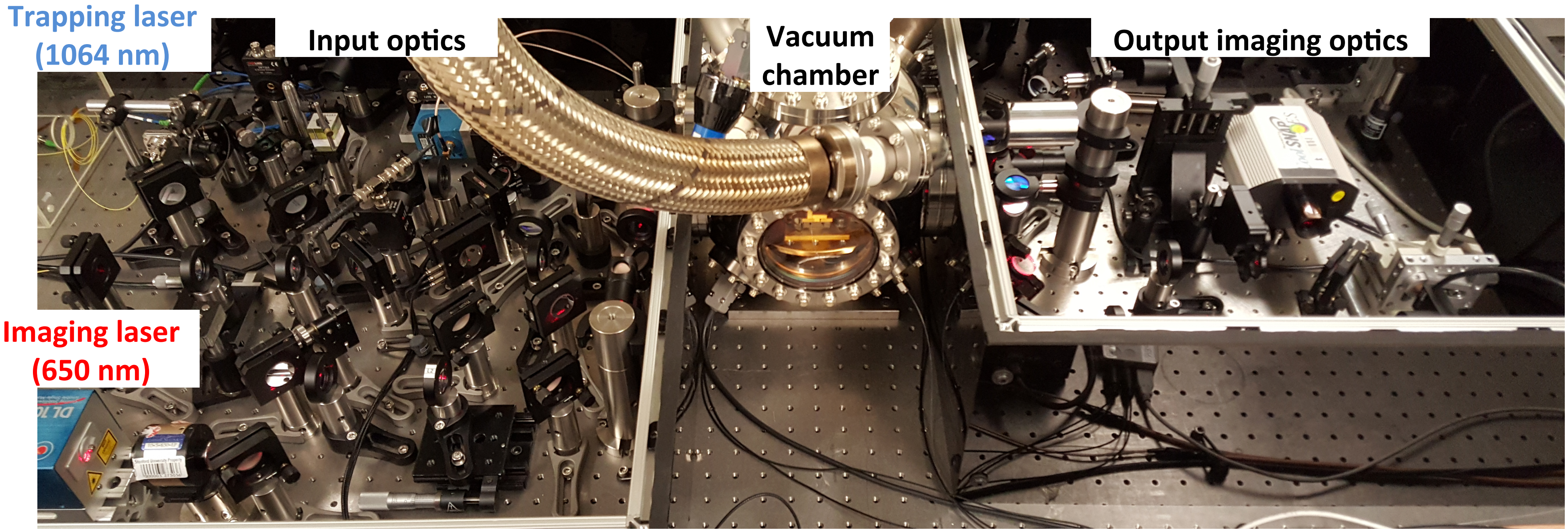
# Experimental setup

- Developed setup capable of levitating $SiO_2$ microspheres with $r = 0.5\text{-}5$ μm
- Microspheres are levitated in vacuum chamber with $\lambda = 1064$ nm, ~few mW trapping laser
- Have demonstrated trapping times of >10 days at ~$10^{-7}$ mbar

**Simplified optical schematic:**



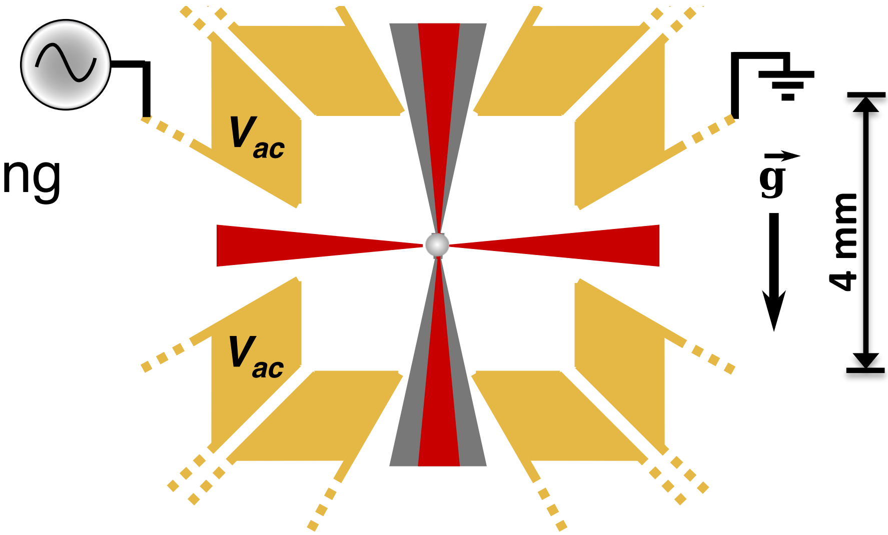
**Photograph of experimental setup:**



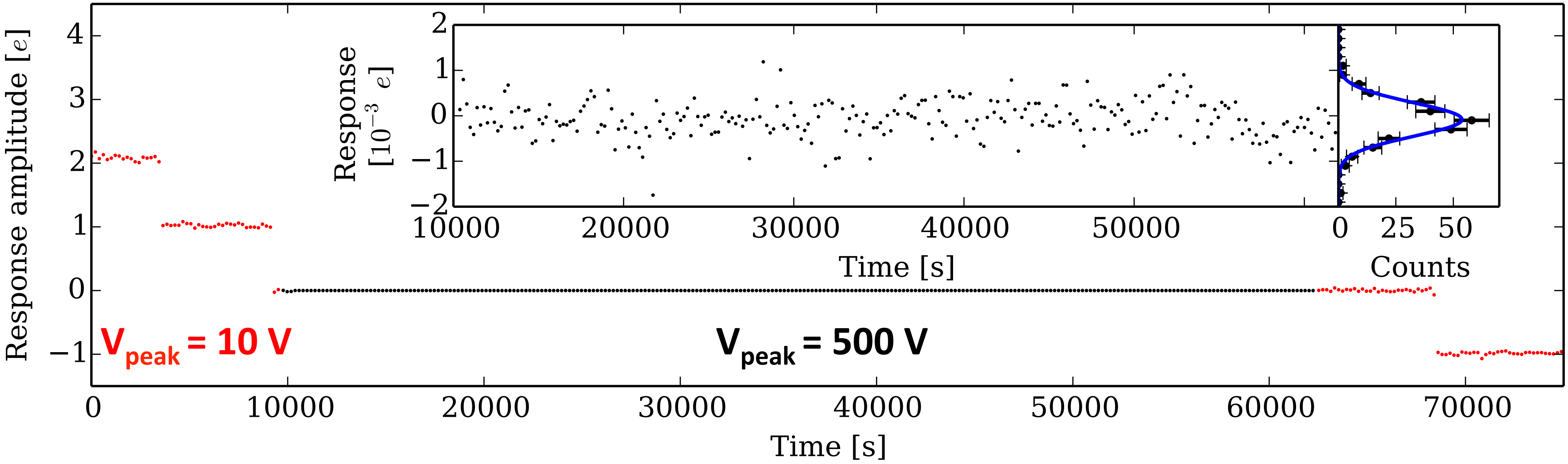
# Microsphere neutralization

- Have demonstrated controlled discharging with single $e$ precision
- Measure microsphere response to oscillating electric field while flashing with UV light
- Once neutral, have not observed spontaneous charging in more than $10^6$ s

**Electrode cross-section:**



**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*

- Low pressure force sensitivity limited to: **$\sigma_F = 5 \times 10^{-17}$ N Hz$^{-1/2}$**

- Currently limited by laser jitter and imaging noise

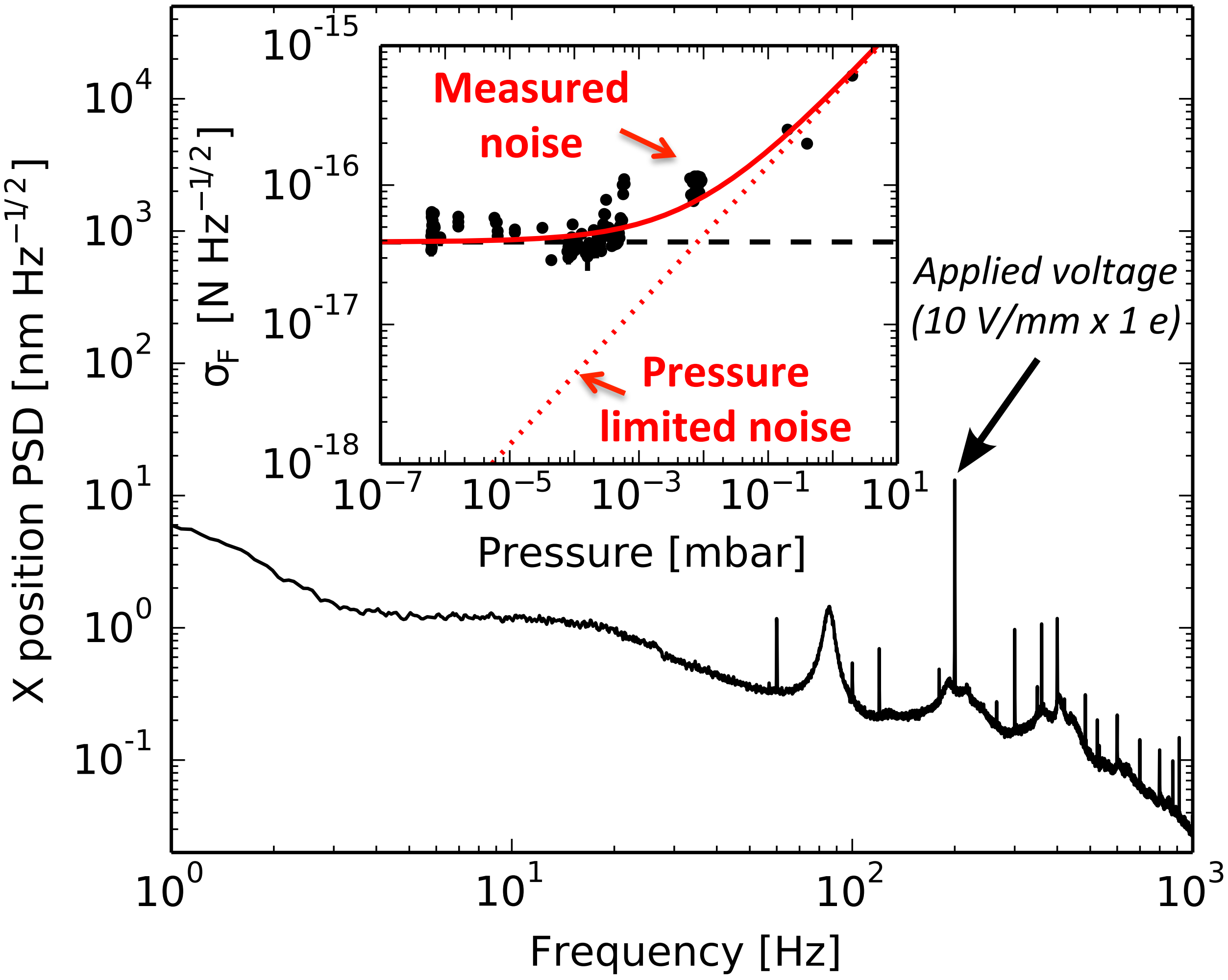
- Pressure limited sensitivity at $10^{-9}$ mbar:

**$\sigma_F \sim 10^{-21}$ N Hz$^{-1/2}$**

i.e., near the quantum limit:

$$\sigma_F \sim \sqrt{\hbar(m\omega^2)}$$

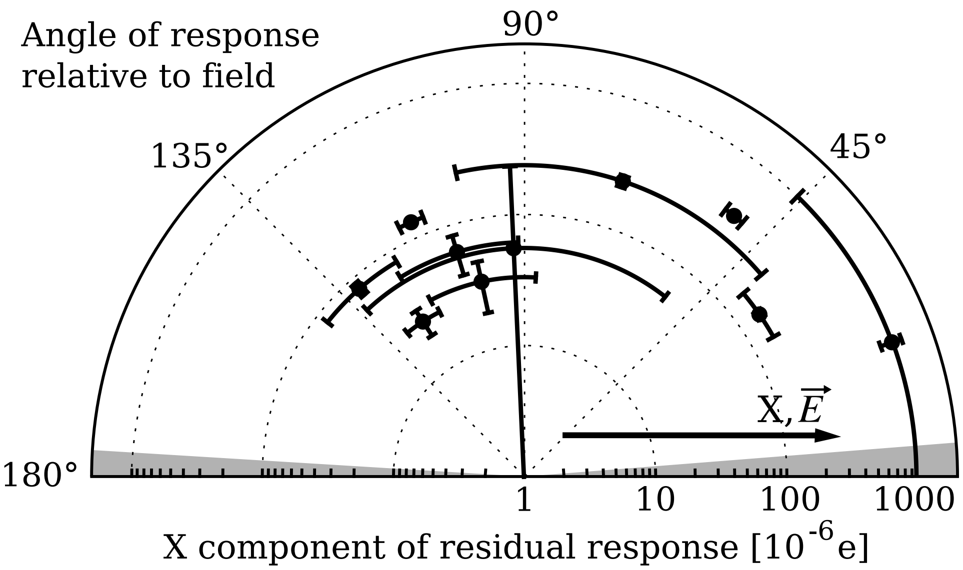
**Calibration of force sensitivity:**



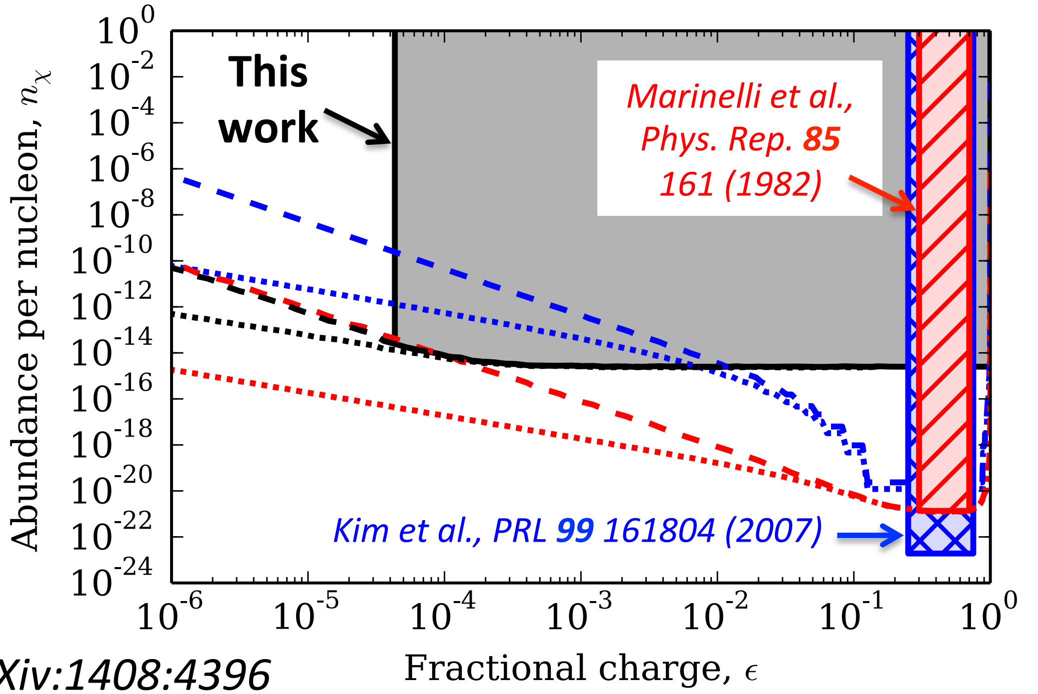
# Search for millicharged particles

- As a first application of this force sensing technique, we have performed a search for millicharged particles (|q| << 1$e$) 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:**

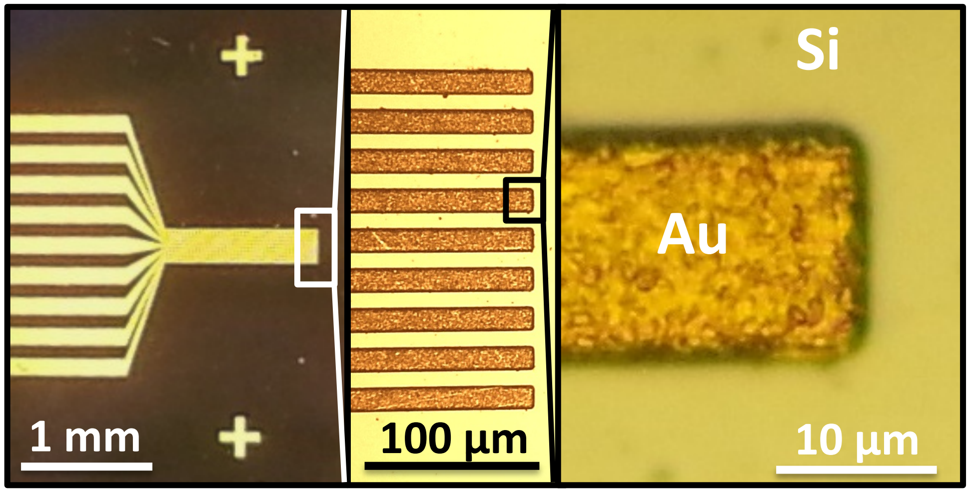


*Moore et al., PRL **113** 251801 (2014), arXiv:1408:4396*

# Attractor design

- Need attractor that can be placed at ~µm separations from microsphere
- Spatially varying density allows reduction of backgrounds
- Initial test mass arrays will be Au/Cu, also investigating Au/Si

**Images of preliminary fabrication tests:**



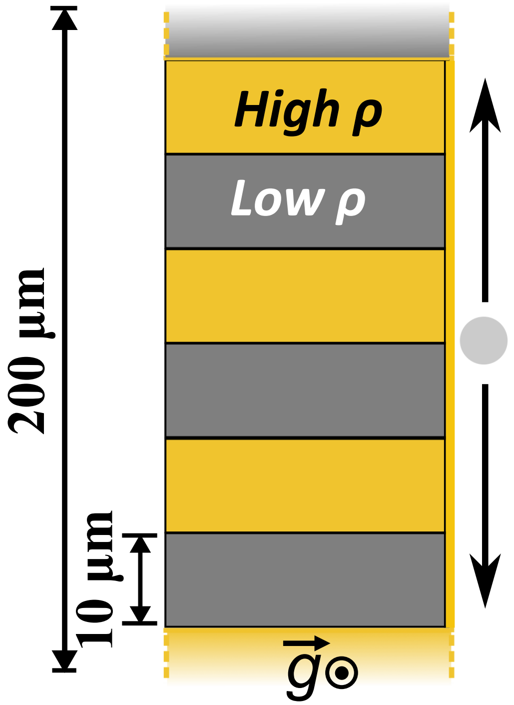
***High ρ material:***

**Au, $\rho \approx 20\ \mathrm{g/cm^3}$**

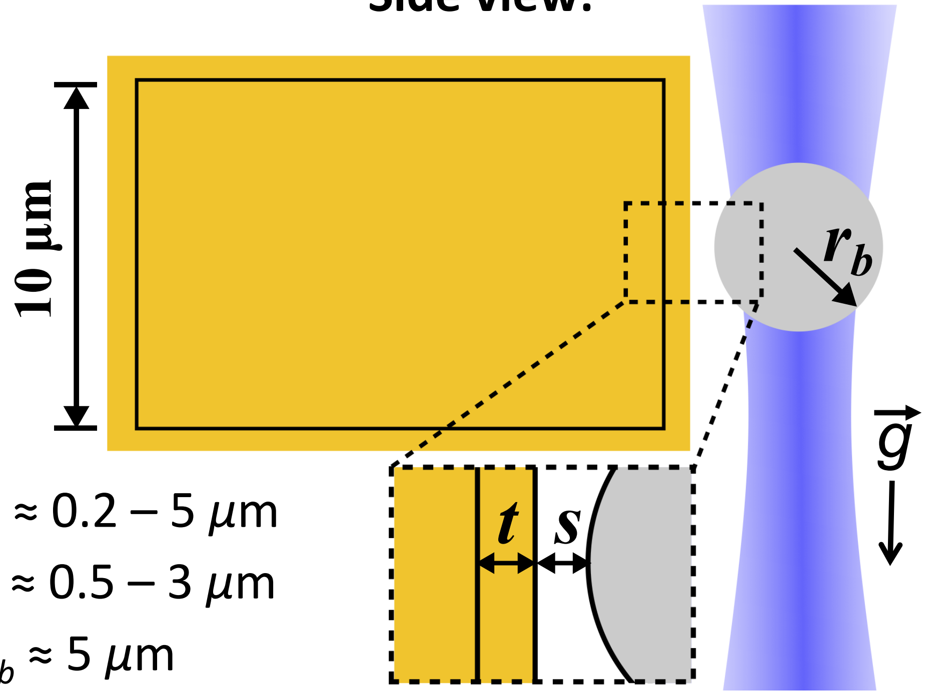
***Low ρ materials:***

**Cu, $\rho \approx 9\ \mathrm{g/cm^3}$**
**Si, $\rho \approx 2\ \mathrm{g/cm^3}$**

**Top view:**



**Side view:**

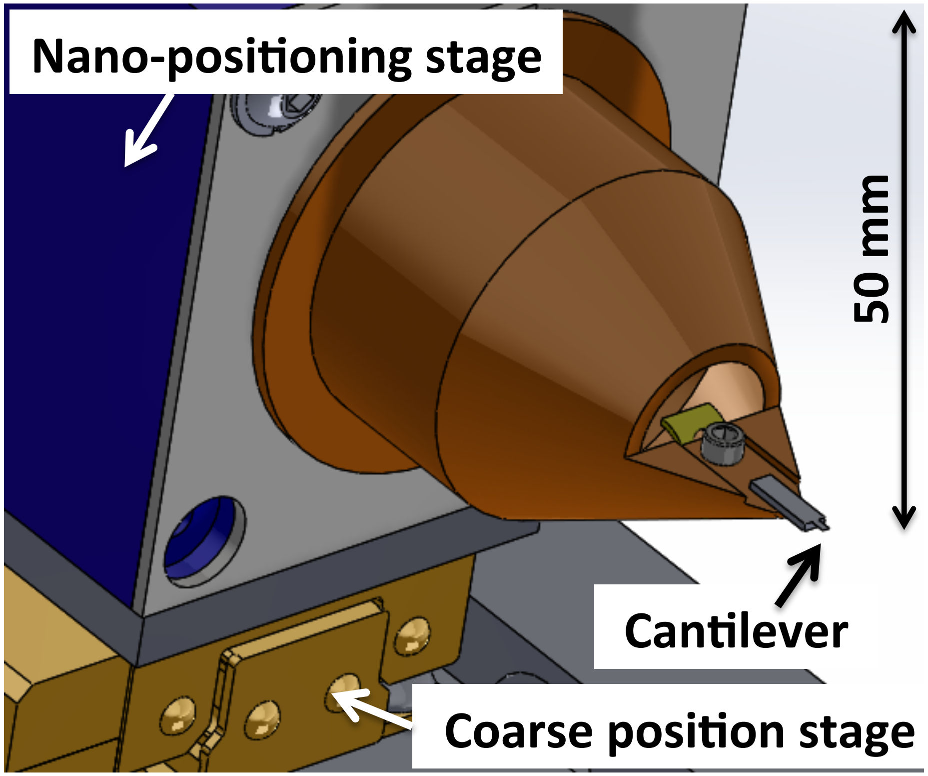


$s \approx 0.2 - 5\ \mu m$
$t \approx 0.5 - 3\ \mu m$
$r_b \approx 5\ \mu m$

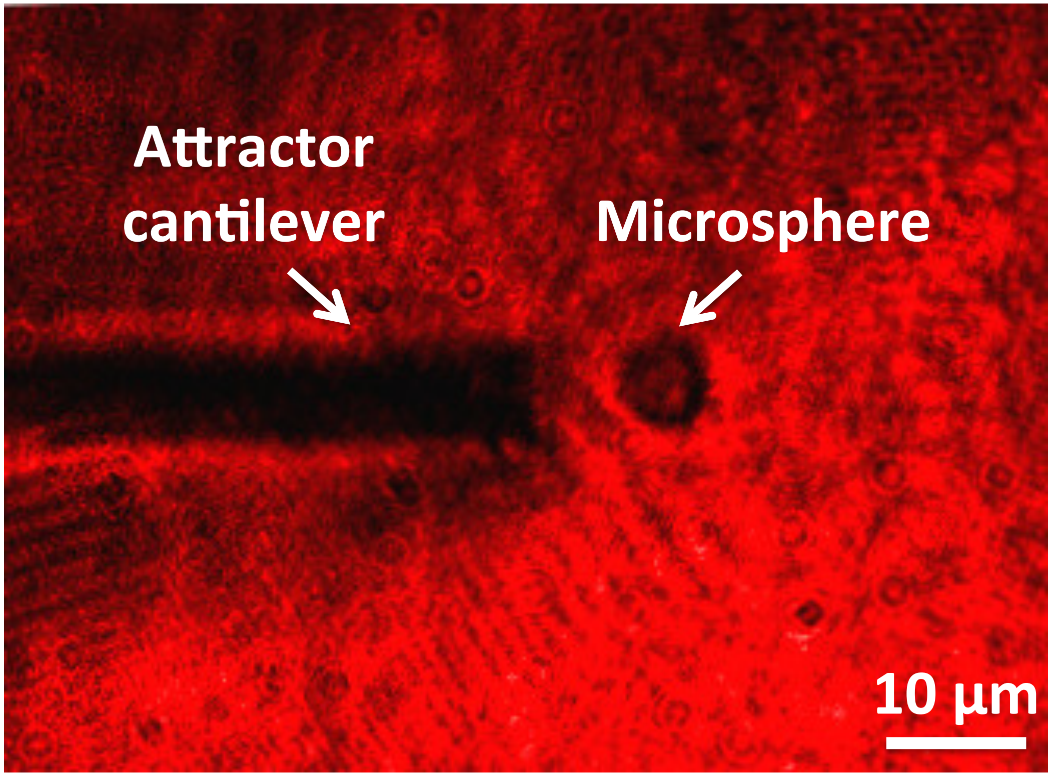
# Microsphere positioning

- Cantilever is mounted on nano-positioning stage and can be precisely positioned next to the trap
- Stage allows cantilever to be swept ~100 µm in all 3 DOF at >10 Hz
- Microsphere position can also be controlled optically using the AOD

**Schematic of nano-positioning stage:**



**Side view of microsphere near attractor:**

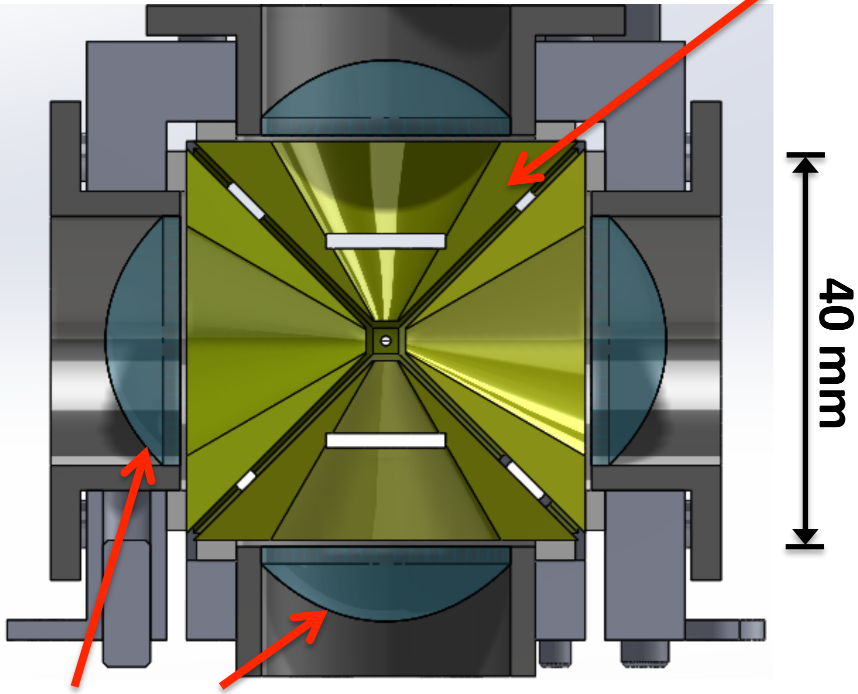


# Electrostatic shielding

- Trap is surrounded by shielding cones to attenuate stray electric fields
- Stray fields can cause large electric field gradients near attractor tip
- Even for neutral microspheres, stray fields will polarize microspheres which can couple to residual field gradients

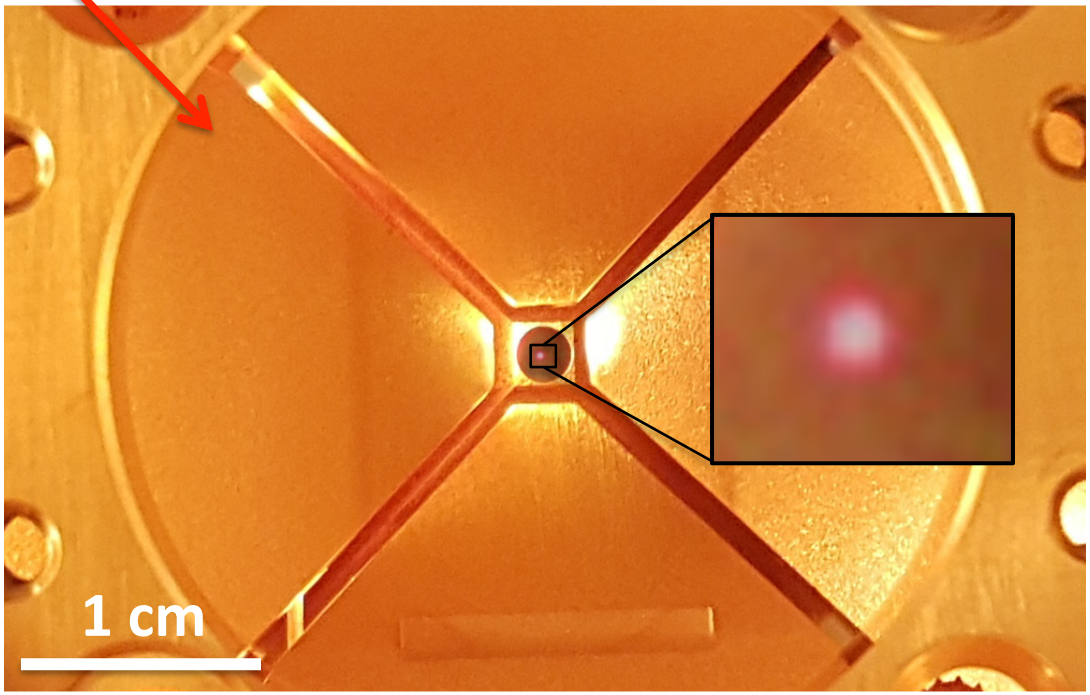
**Cross section of lens holders and shielding cones:**

*Each cone can be biased individually*



Focusing lenses

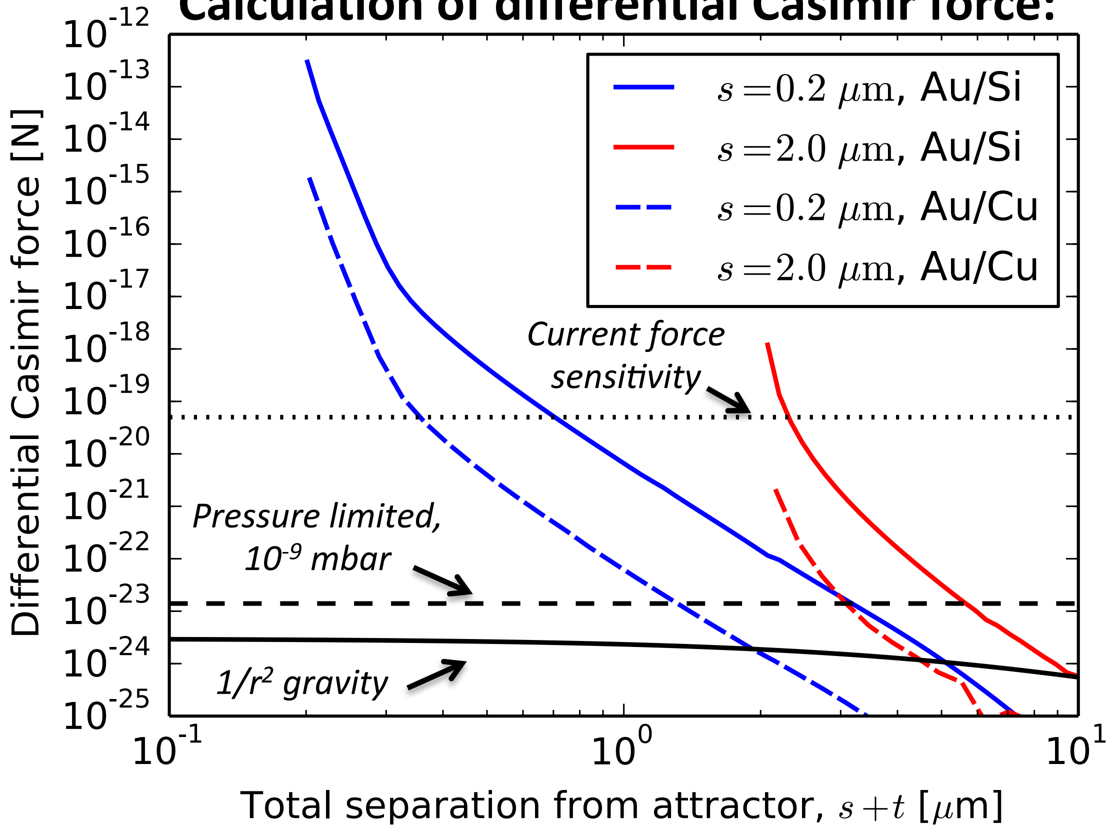
**Image of trapped microsphere:**



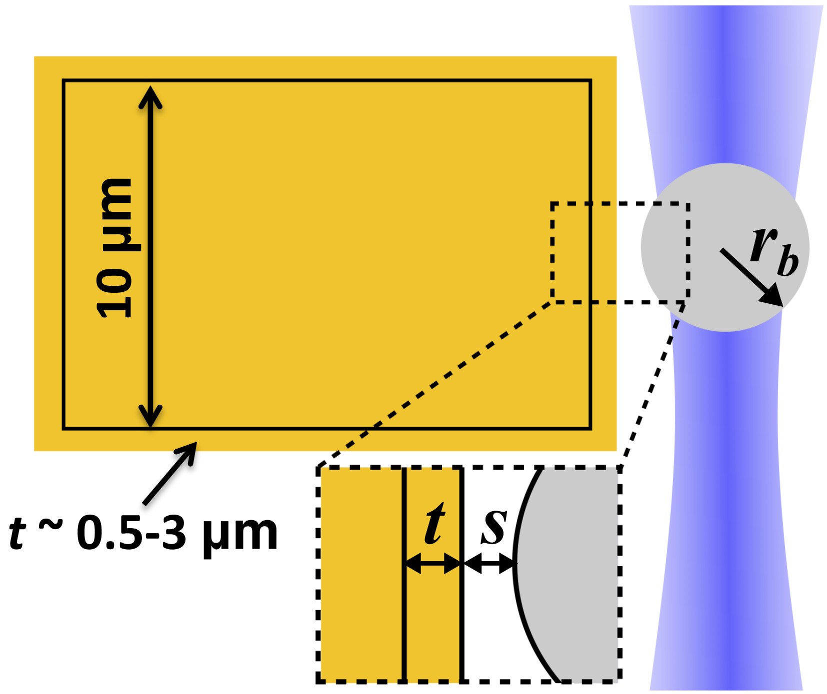
# Casimir backgrounds

- Even for neutral, unpolarized microspheres, electromagnetic backgrounds will still be present
- If unscreened, differential Casimir force between Au and Si/Cu can present dominant background
- Coating attractor with Au shield layer (0.5 to 3 µm thick) can sufficiently suppress this background

**Calculation of differential Casimir force:**



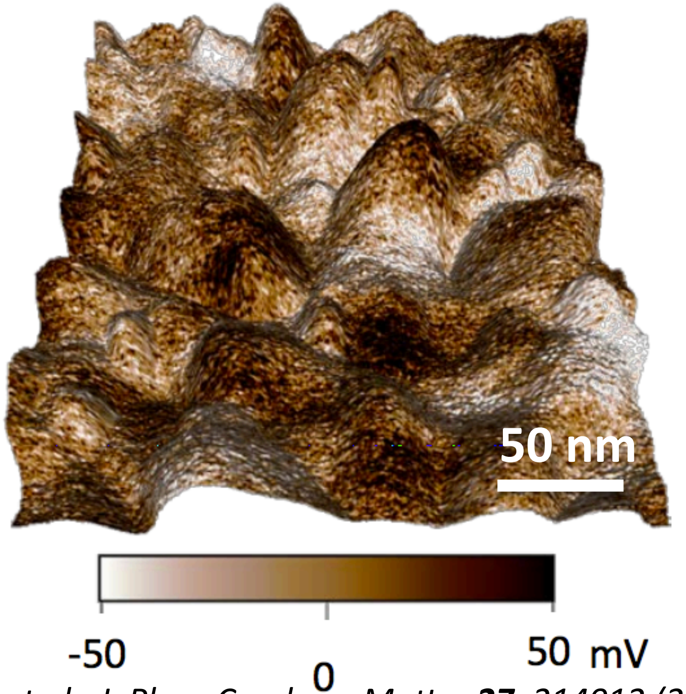
**Schematic of shielding layer:**



# Patch potentials

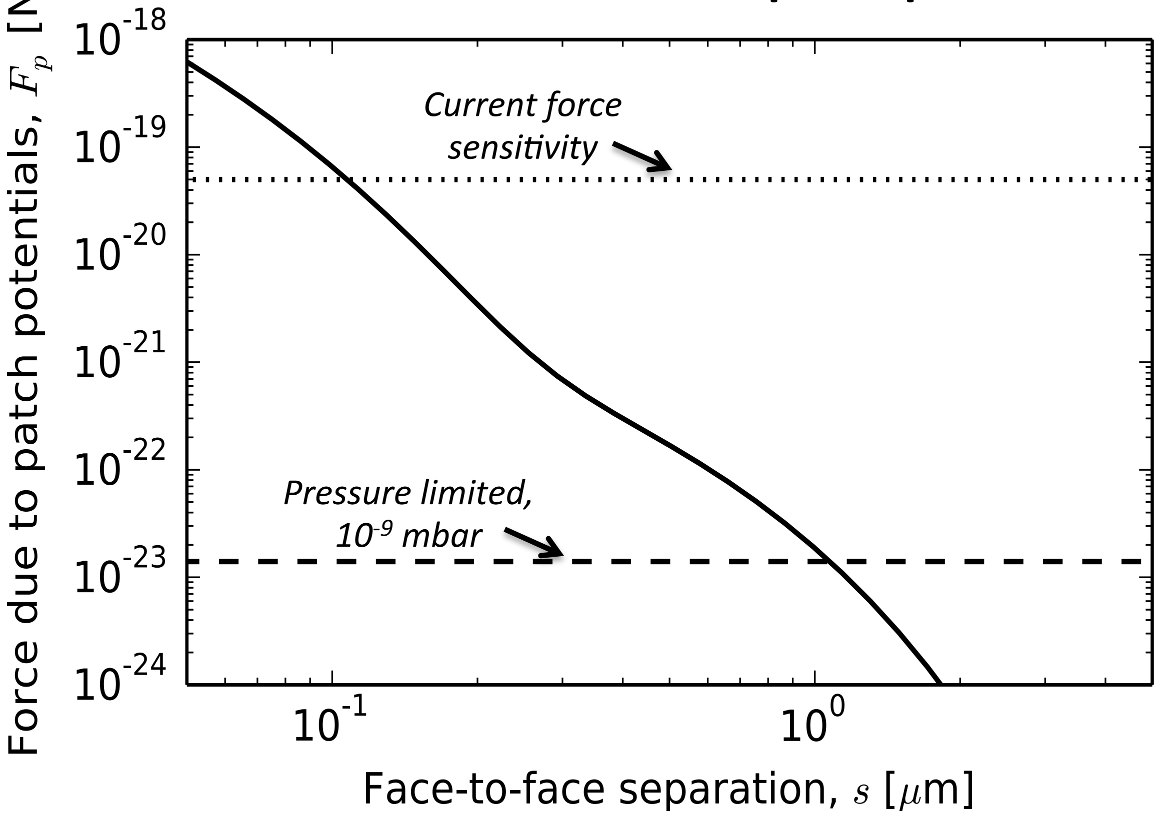
- Deposited Au films typically have potential variations ~10–100 mV over 10 nm–1 µm surface regions
- Such “patch potentials” have been studied extensively in previous work
- Have estimated background using recent patch measurements of Au films

**Topography and surface potential for sputtered Au film:**



*Garrett et al., J. Phys. Condens. Matter **27**, 214012 (2015)*

**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
- Assumptions:

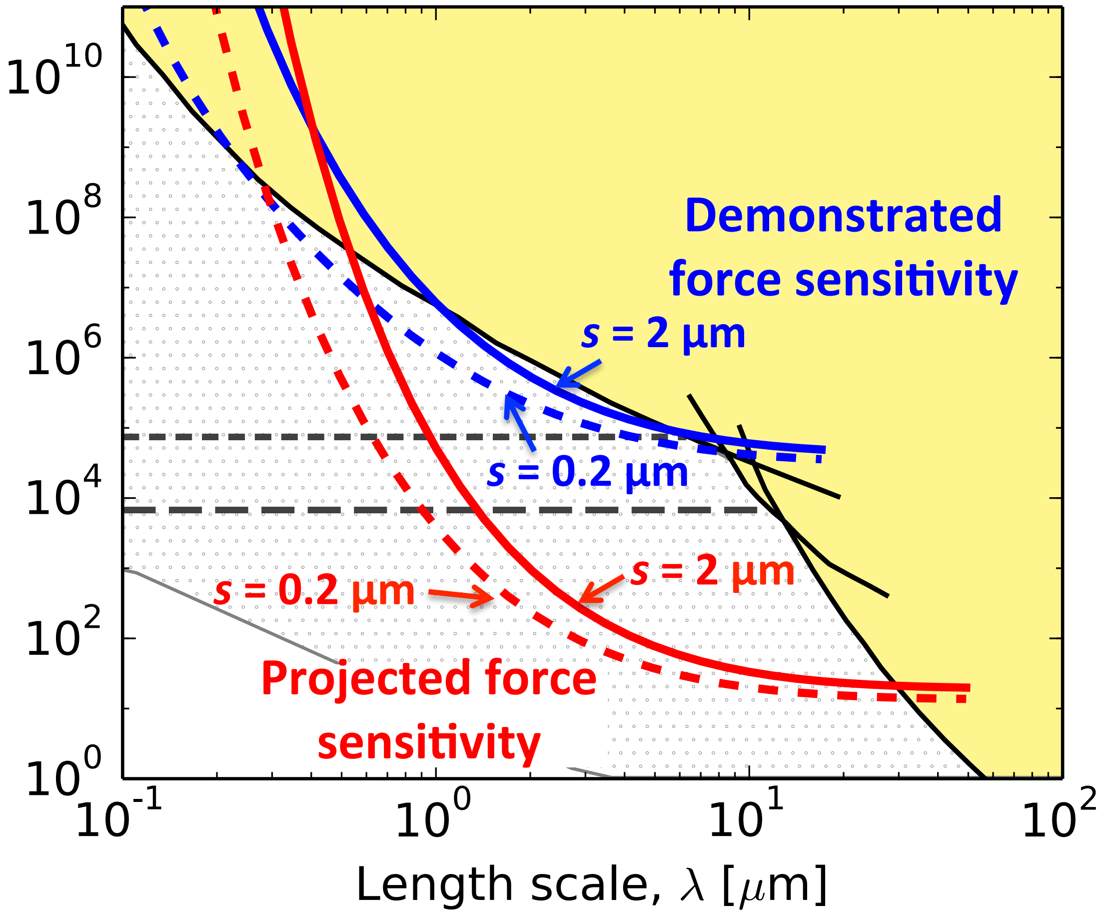
  **Face-to-face separation, *s*:**
  0.2 µm (dashed) or 2 µm (solid)

  **Force sensitivity:**
  $\sigma_F$ = 5 x $10^{-17}$ N $Hz^{-1/2}$ (blue)
  $\sigma_F$ = pressure limited at $10^{-9}$ mbar (red)
  $10^6$ s integration time

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

- Substantial improvement over existing limits may be possible at 0.5–40 µm

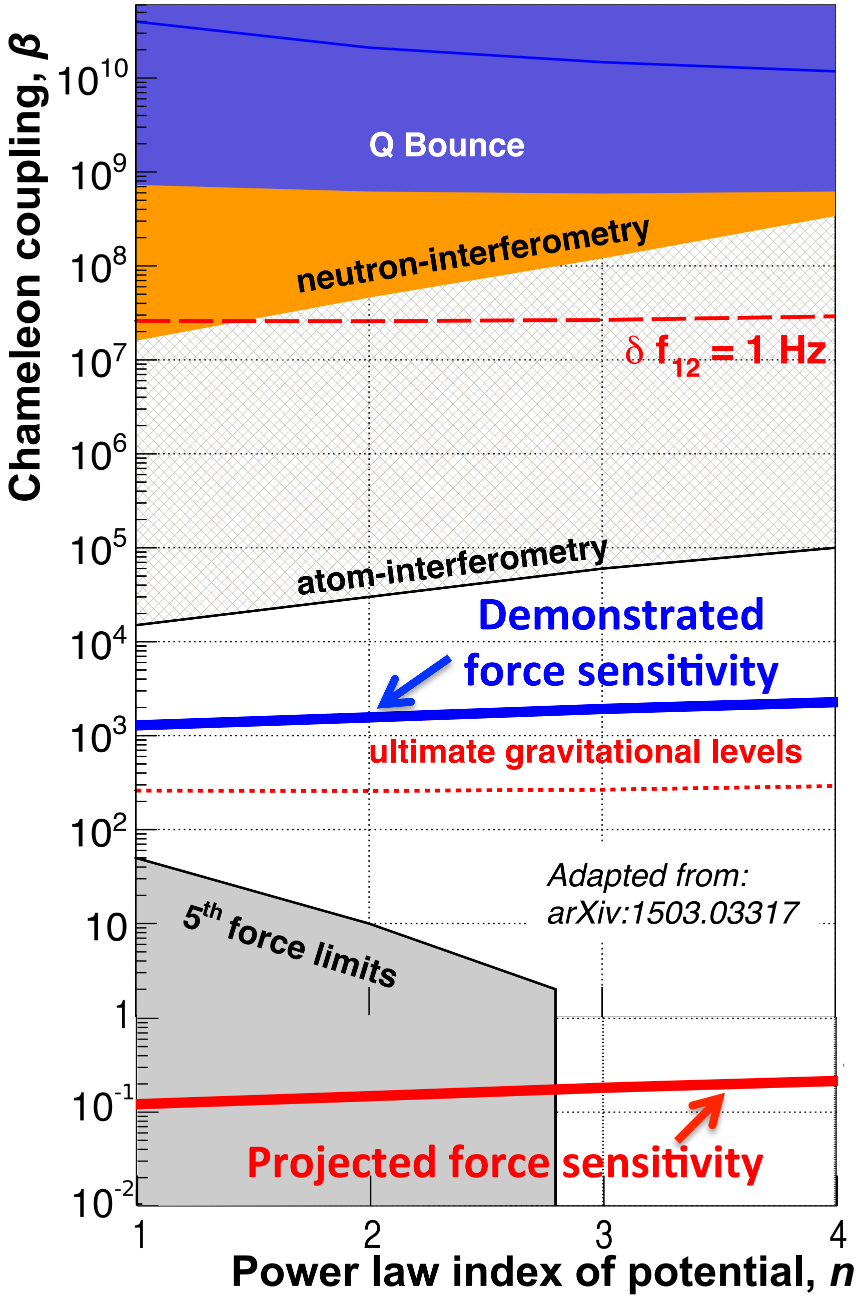
**Projected sensitivity to non-Newtonian forces:**



# Chameleons

- Recent theoretical interest in light scalars with screened interactions at short distances
- In the “chameleon” mechanism, the effective mass becomes large in high density regions
- Microspheres in our geometry are not substantially screened for $\beta < 10^8$
- Can search for new forces below dark energy length scale **$\Lambda \sim 80\ \mu m$**
- Allows sensitivity to larger couplings, $\beta$, than torsion pendula
- Could substantially improve on current constraints from neutron and atom interferometry

**Constraints on power law chameleons:**



*Adapted from: arXiv:1503.03317*

# Summary

- Levitated microspheres can enable novel searches for new forces at micron distances
- Ability to control charge state and optical potential allows precise measurement and mitigation of electrostatic backgrounds
- Have demonstrated force sensitivity <$10^{-18}$ N, but substantial improvement is possible
- Developing attractors necessary to search for non-Newtonian forces
- May be able to probe significant amounts of unexplored parameter space for new forces coupling to mass at length scales from 0.5 – 40 µm