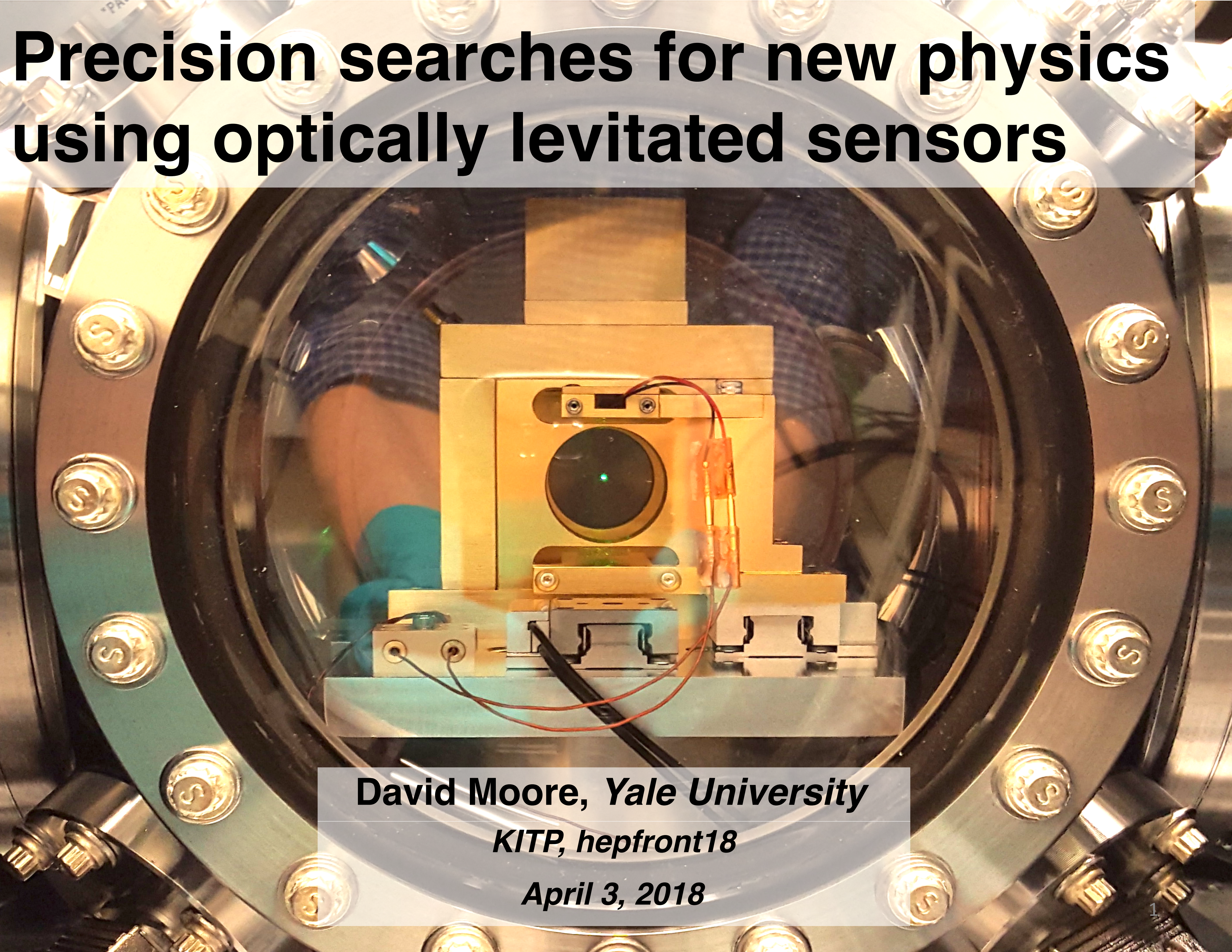
Precision searches for new physics using optically levitated sensors



David Moore, ***Yale University***

KITP, hepfront18

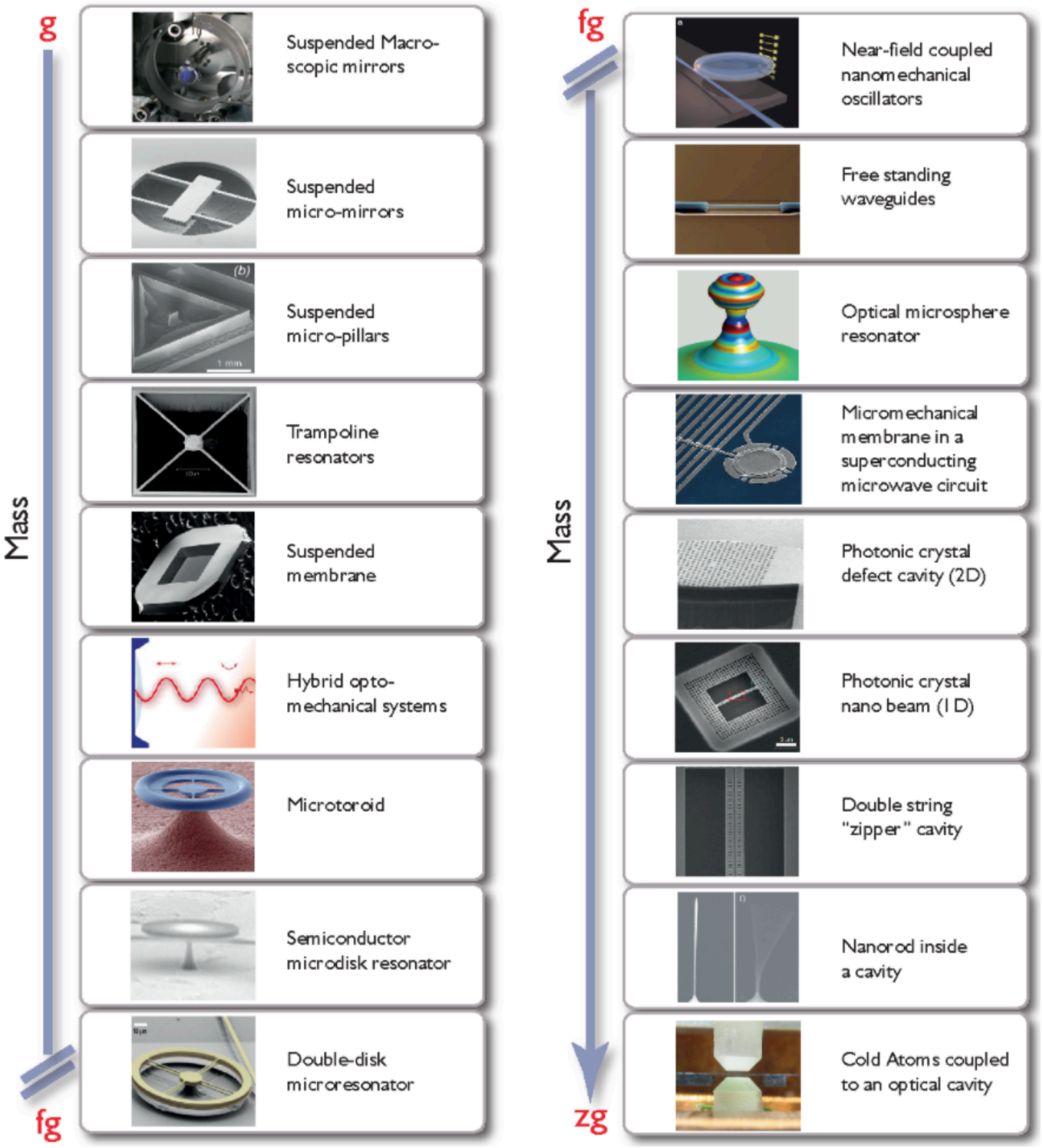
April 3, 2018

Precision force sensing

- New forces arise in a variety of proposed BSM models
- Forces can appear at weak couplings or short distance
- “Opto-mechanical” systems can enable precise force sensors
- Allow control and measurement of ~zg to ~kg scale test masses

Aspelmeyer, Kippenberg, and Marquardt, Rev. Mod. Phys. 86, 1391 (2014)

Example opto-mechanical systems:



Levitated microspheres

- Micron-sized dielectric masses can be levitated with ~few mW of laser power
- "Optical tweezers" are common tool in biophysics to measure ~pN forces
- At high vacuum, extremely low dissipation is possible:

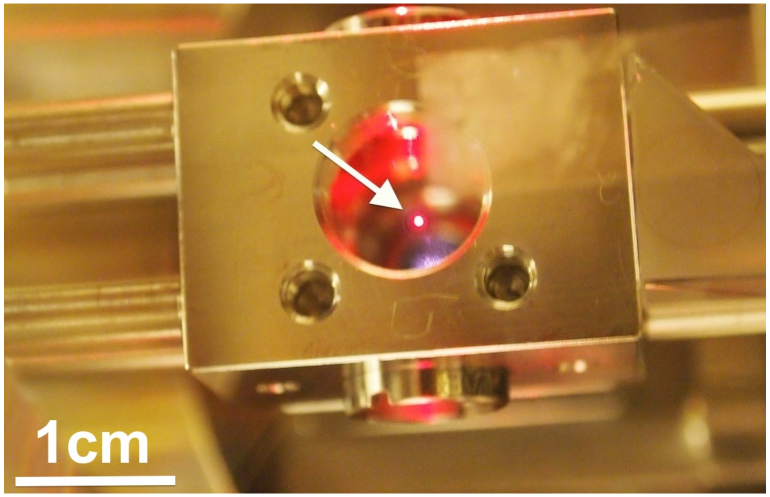
$$\sigma_F \sim 10^{-21}\ \mathrm{N\ Hz^{-1/2}}\ \text{at}\ 10^{-10}\ \mathrm{mbar}$$

$$(\sigma_a \sim 10^{-9}\ g\ \mathrm{Hz^{-1/2}})$$

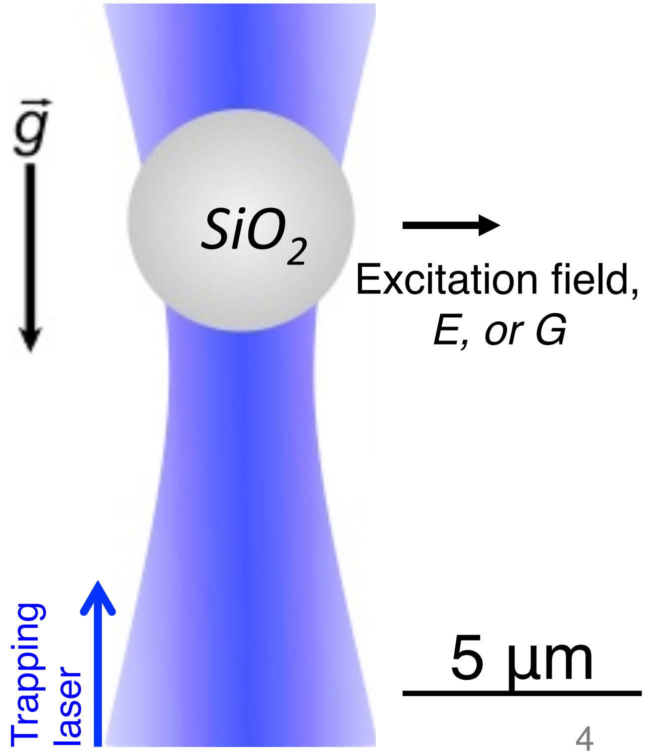
Ashkin & Dziedzic, Appl. Phys. Lett. ***19****, 283 (1971)*
Geraci et al., PRL ***105****, 101101 (2010)*

- Levitated masses are isolated both electrically and thermally

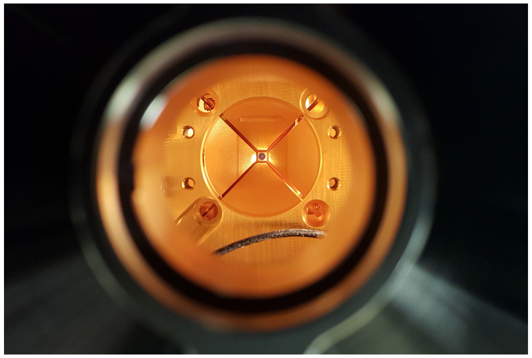
Photograph of trapped microsphere:



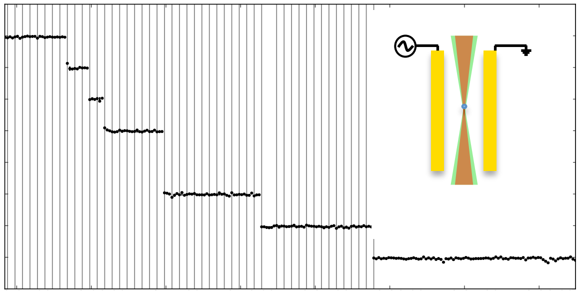
Schematic of optical levitation technique:



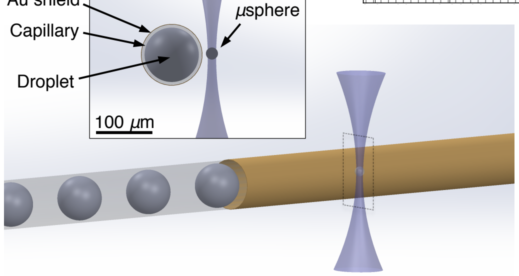
Outline



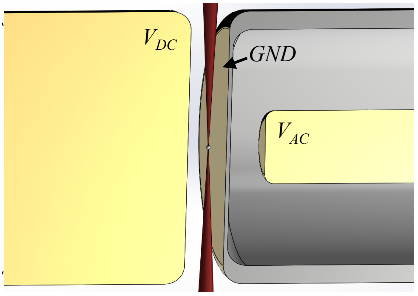
1. Optically levitated microspheres in high vacuum



2. Millicharged particles and the neutrality of matter



3. Tests of gravity and non-Newtonian forces



4. Tests of Coulomb's law and dark photons

Experimental setup

- Optical trap capable of levitating spheres with $r \sim 0.5$-15 μm
- Microspheres are trapped with ~1-100 mW trapping laser power
- Trapping times longer than one month at pressure ~10^{-7} mbar

Simplified optical schematic:

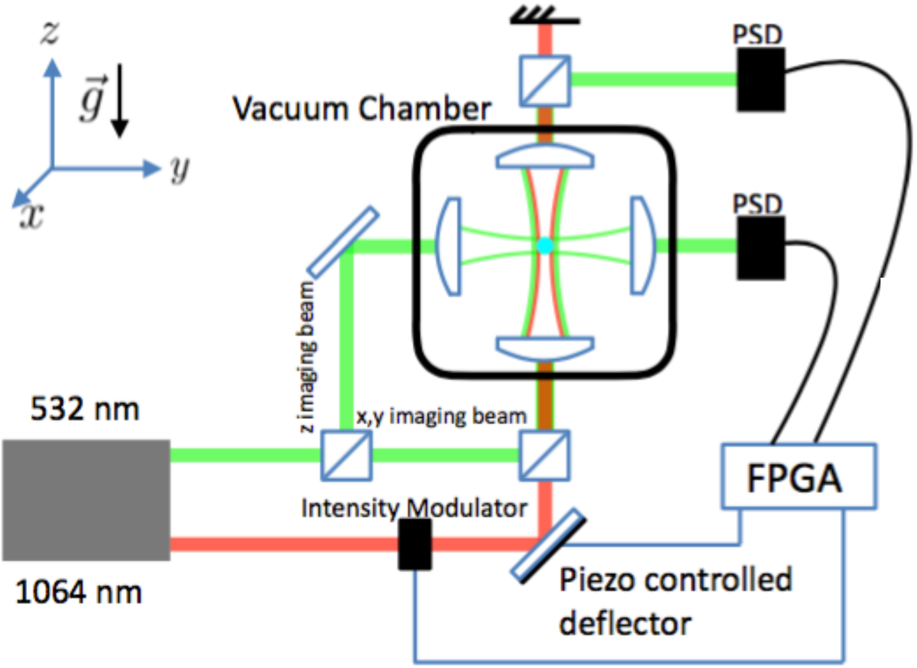
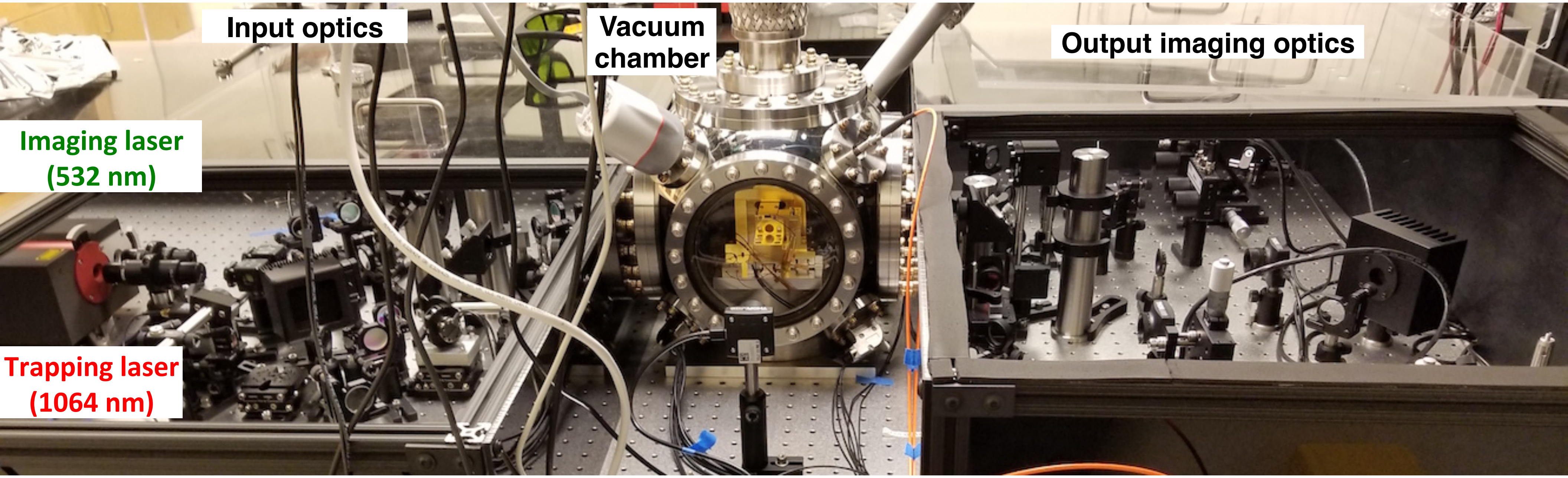


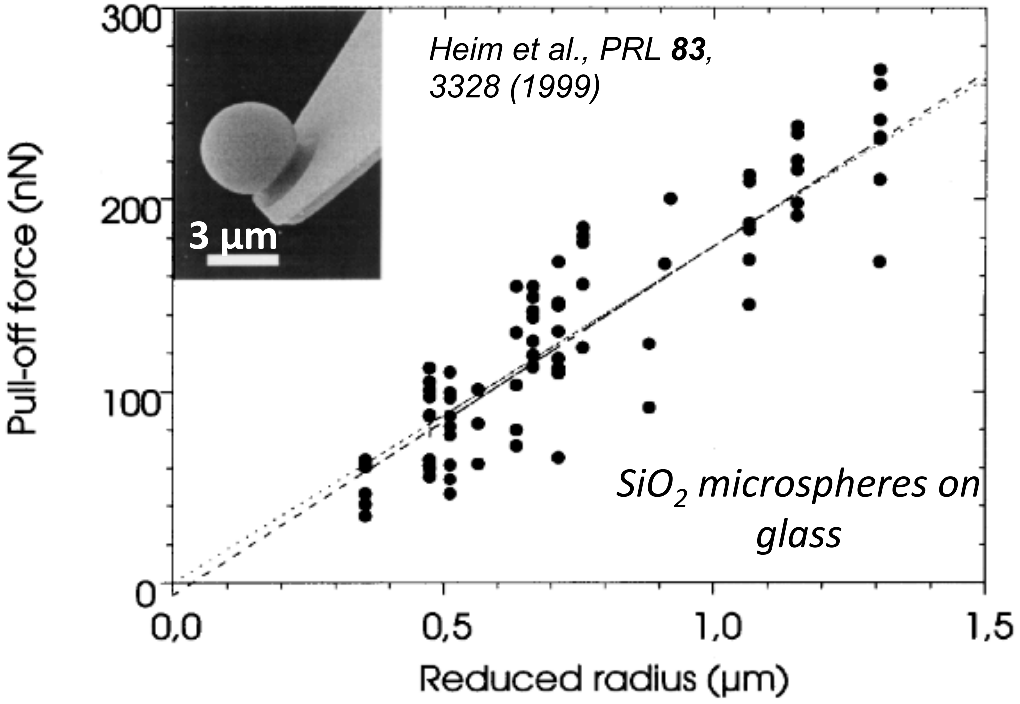
Photo of experimental setup:



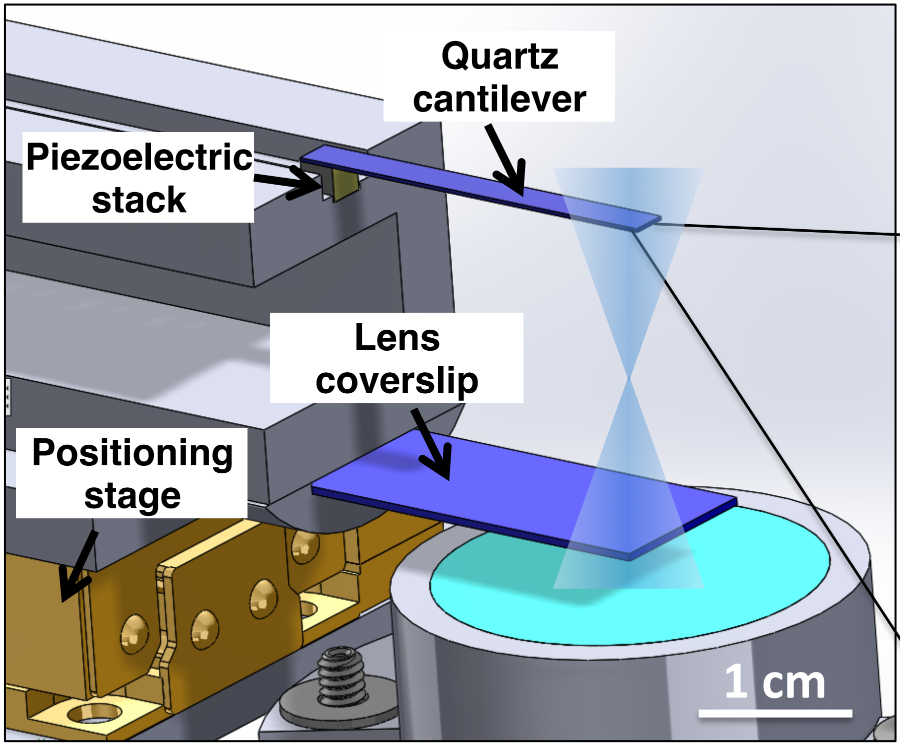
Trap loading

- 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

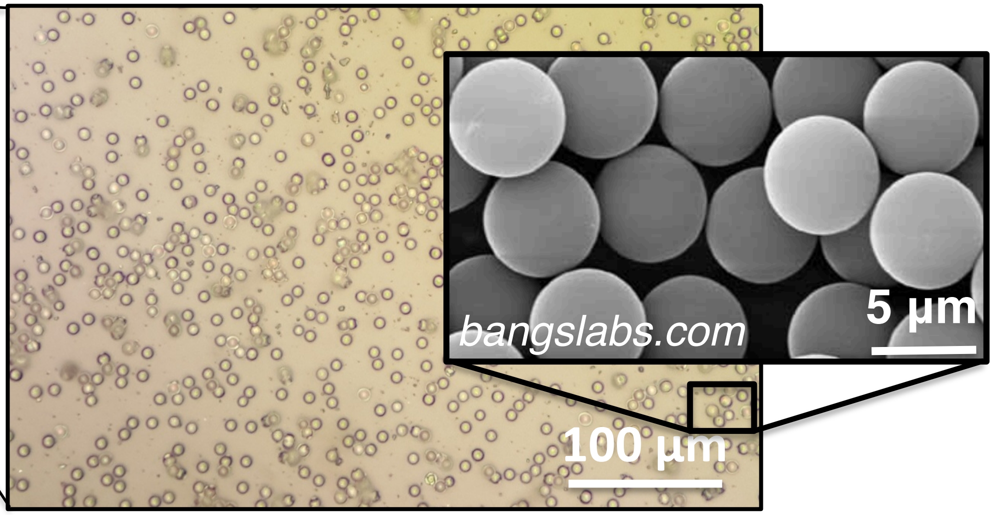
Pull-off force vs. microsphere radius:



Schematic of microsphere dropper:

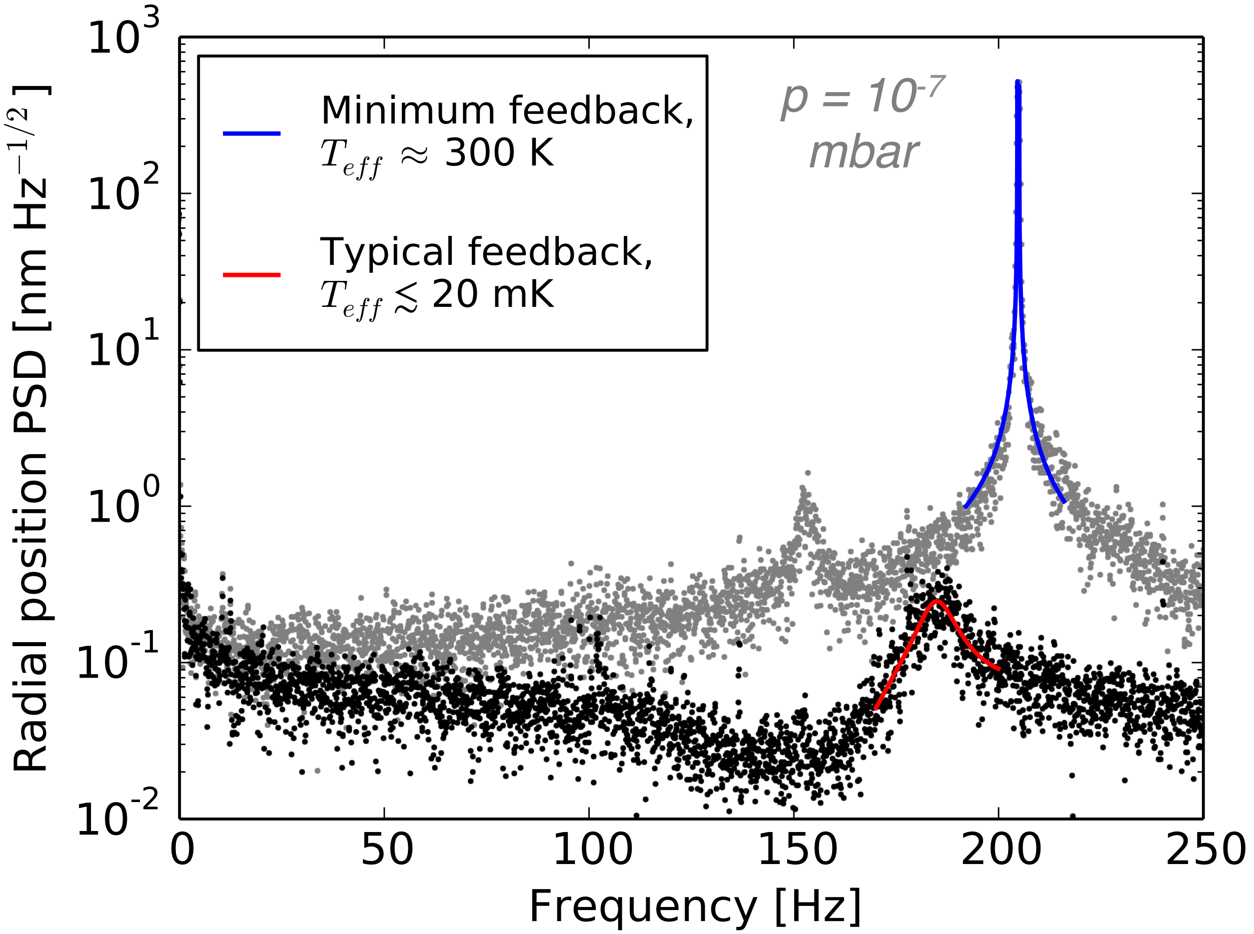


Microspheres on quartz surface:



Microsphere cooling

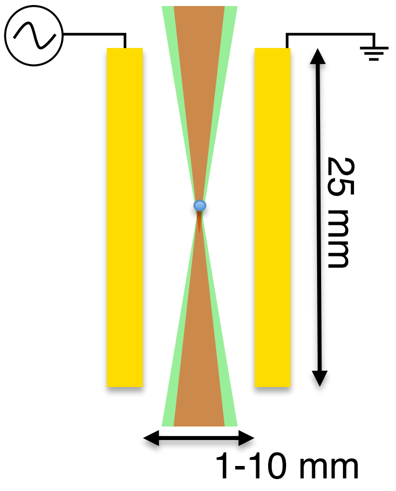
- Below ~1 mbar, active feedback cooling is needed for stable trapping
- Monitor position of microsphere and modulate amplitude and pointing of the trapping beam
- Can cool center of mass motion to $T_{eff} < 20$ mK in all 3 DOF



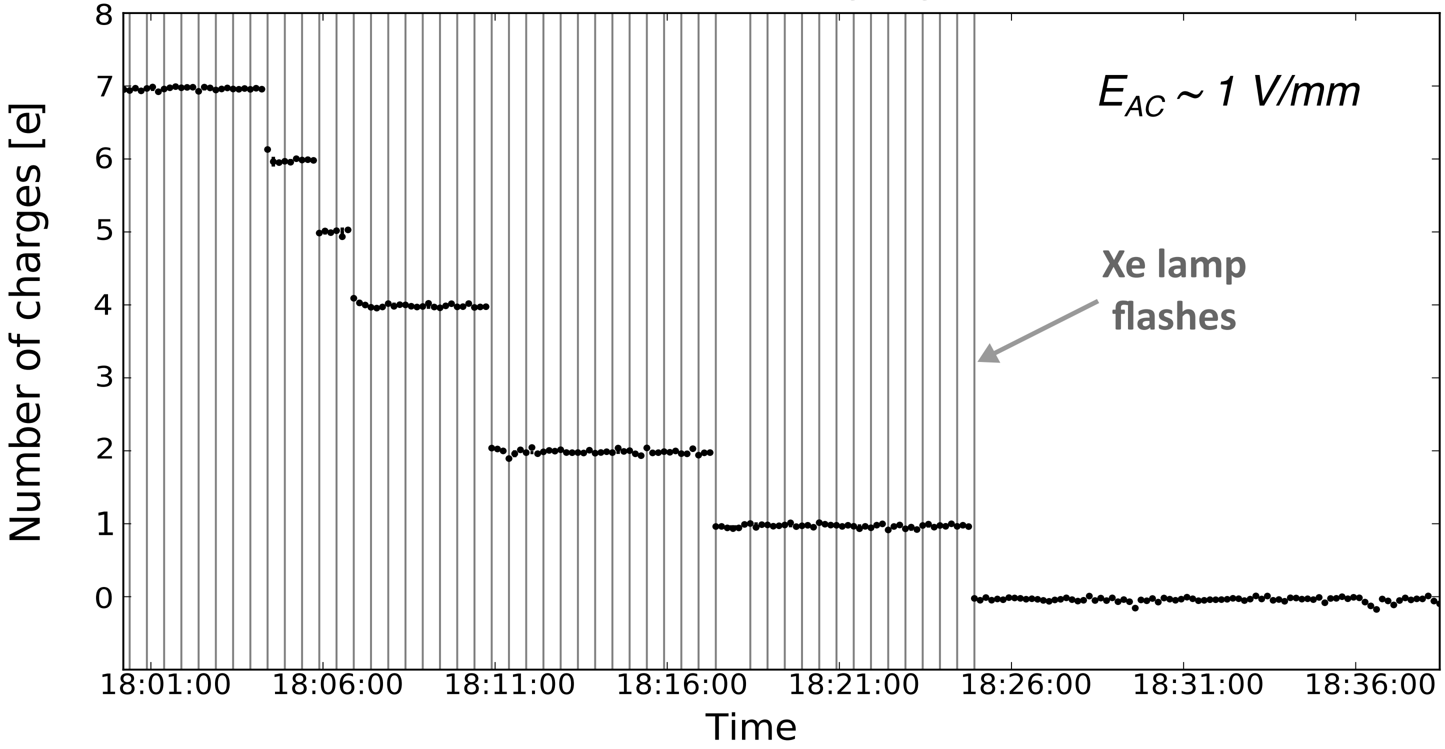
Microsphere neutralization

- Have demonstrated controlled discharging with single e precision
- Measure microsphere response to oscillating electric field while flashing with UV light
- Charging rates ~1 *e*/day (~1 yA) or lower, can be eliminated with DC field

Electrode cross-section:



Example of discharging process:

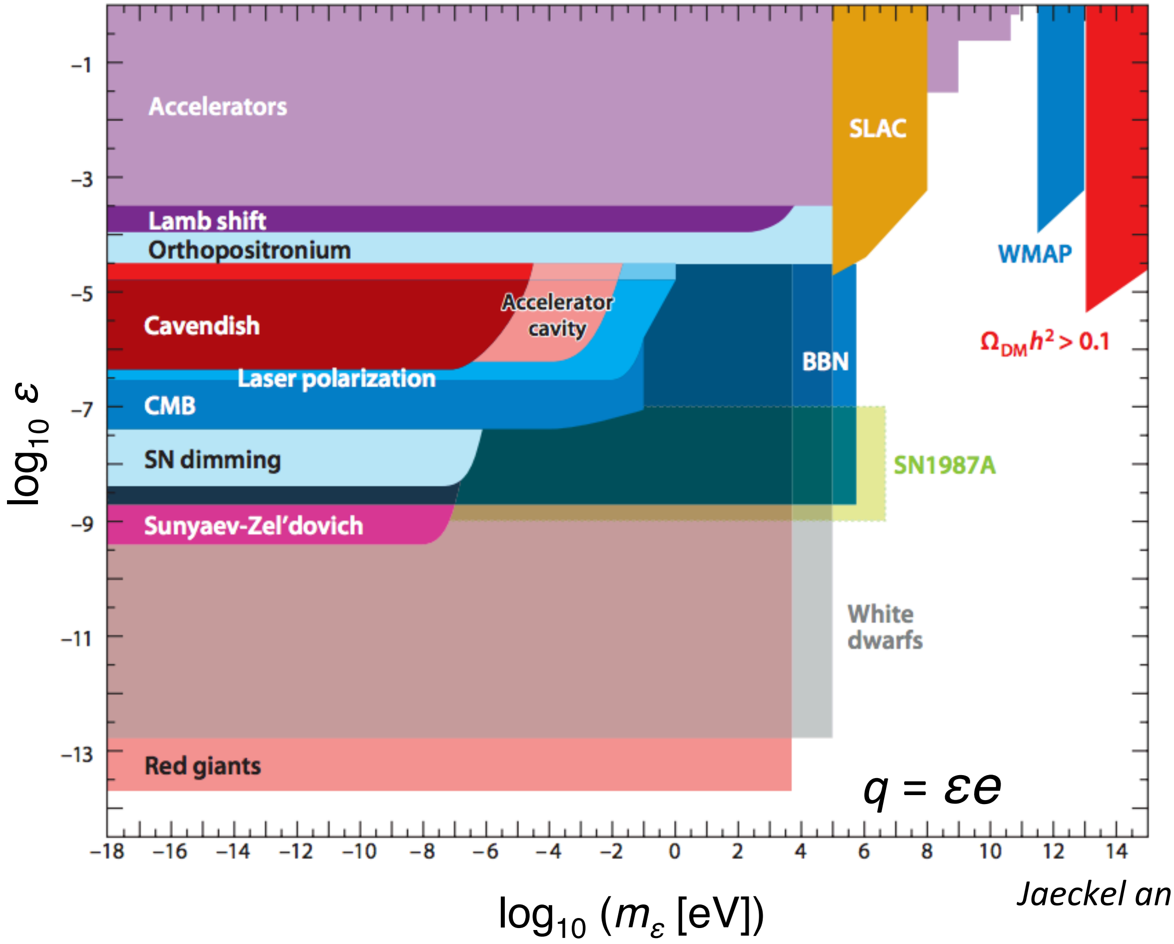


Millicharged particles and the neutrality of matter

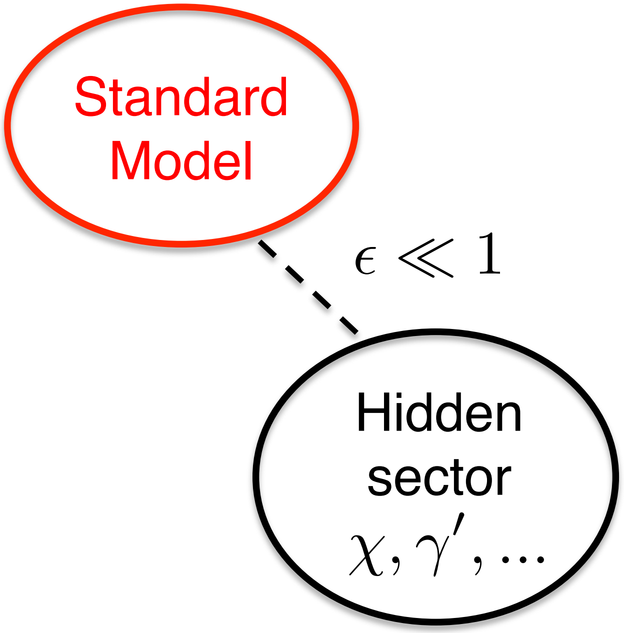
Matter neutrality

- Microspheres allow searches for tiny fractional charges in ~ng sized masses
- Sensitive to “millicharged” dark matter bound in matter or a difference in electron/proton charges

Constraints on millicharged particles:



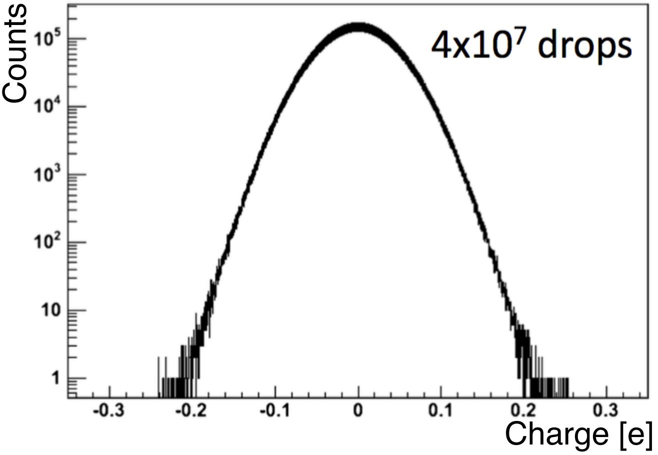
Jaeckel and Ringwald, Ann. Rev. Nucl. Part. Sci., 60, 405 (2010)



Searches in matter

Fractional charges

Automated Milliken oil drop experiment (2007):

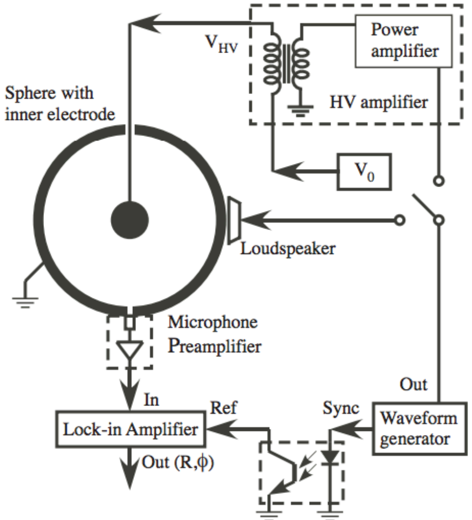


P. Kim et al., PRL 99, 161804 (2007)

No free quarks in 0.3 g of matter

Matter neutrality

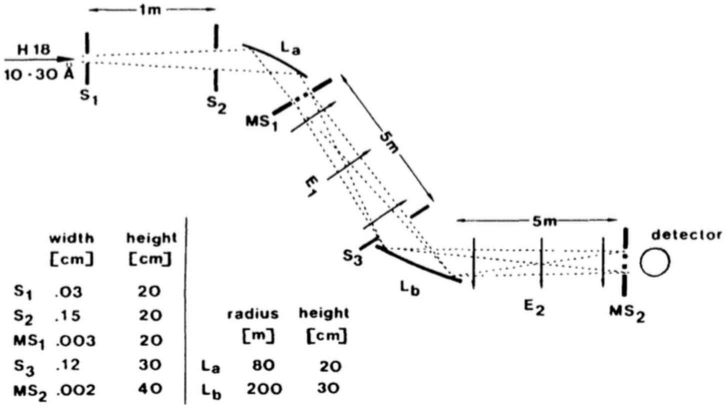
Acoustic resonator (2011):



G. Bressi et al., PRA 83, 052101 (2011)
H. Dylla et al., PRA 7, 1224 (1973)

$|q_e + q_p| < 10^{-21}$ *e*

Neutron beam deflection (1988):



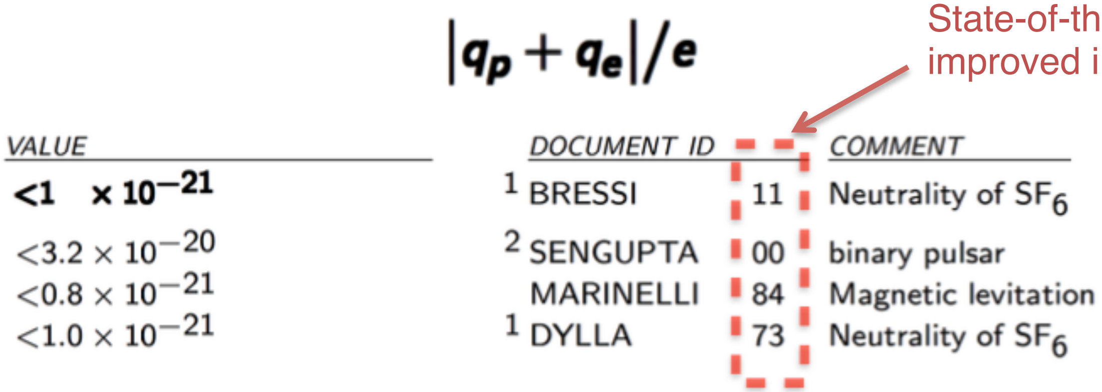
	width [cm]	height [cm]
S_1	.03	20
S_2	.15	20
MS_1	.003	20
S_3	.12	30
MS_2	.002	40

	radius [m]	height [cm]
L_a	80	20
L_b	200	30

J. Baumann et al., PRD 37, 3107 (1988)

$|q_n| < 10^{-21}$ *e*

Particle data group constraints (2017):



$$|q_p + q_e|/e$$

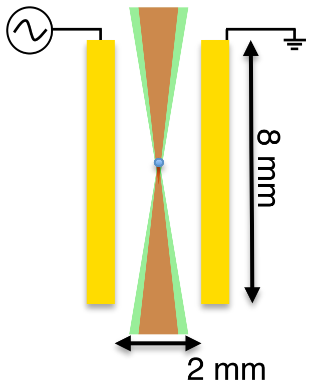
VALUE	DOCUMENT ID		COMMENT
$<1 \times 10^{-21}$	[1] BRESSI	11	Neutrality of SF_6
$<3.2 \times 10^{-20}$	[2] SENGUPTA	00	binary pulsar
$<0.8 \times 10^{-21}$	MARINELLI	84	Magnetic levitation
$<1.0 \times 10^{-21}$	[1] DYLLA	73	Neutrality of SF_6

State-of-the art not improved in ~45 yrs

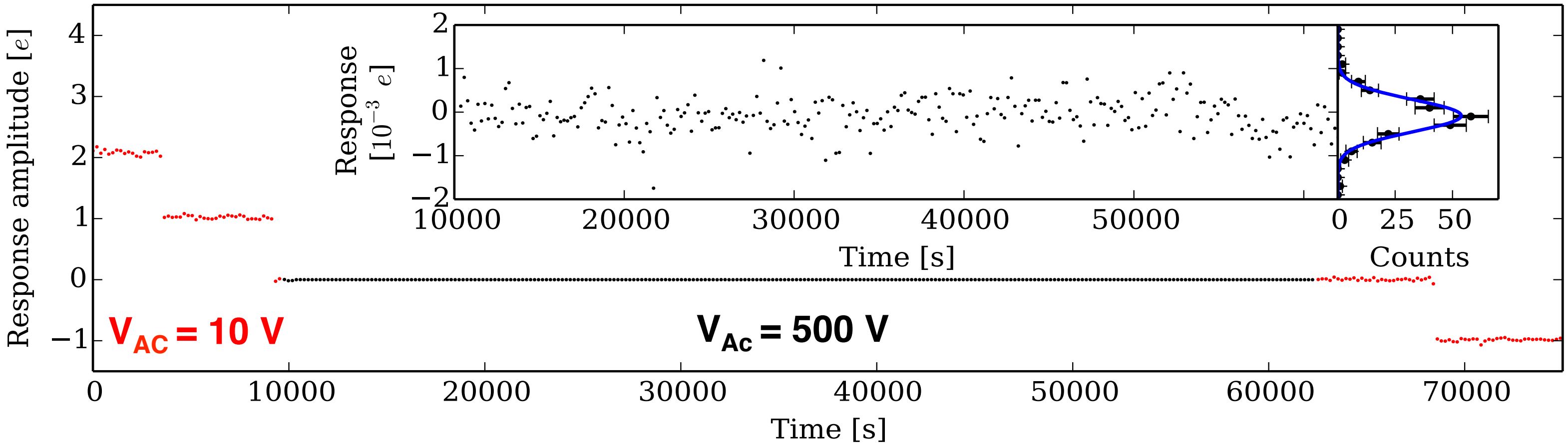
Initial search (2014)

- Neutralize microspheres (so that $n_e = n_p$) and search for residual charge

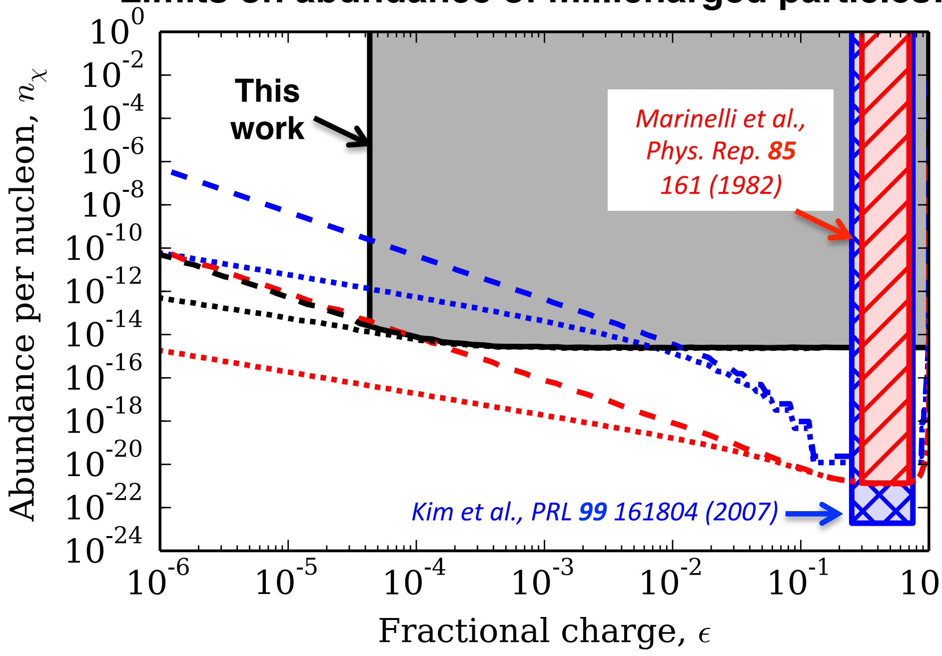
Electrode schematic:



Residual charge measurement for a typical microsphere:



Limits on abundance of millicharged particles:

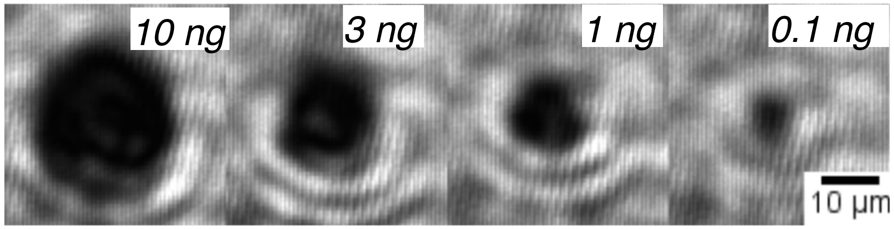


*Moore et al., PRL **113** 251801 (2014), arXiv:1408:4396*

- Repeated for 10 microspheres (total mass 0.1 ng)
- Residual response consistent with permanent dipole moments

Larger spheres

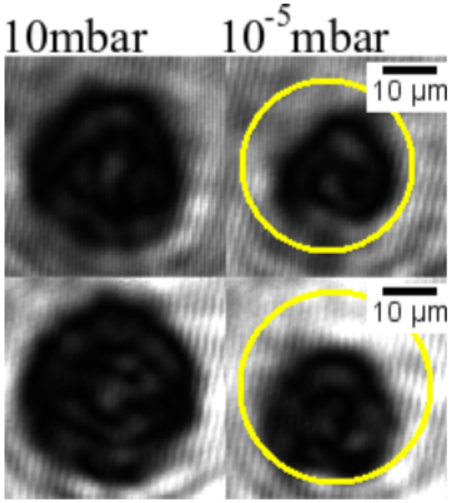
Images of trapped spheres of several sizes:



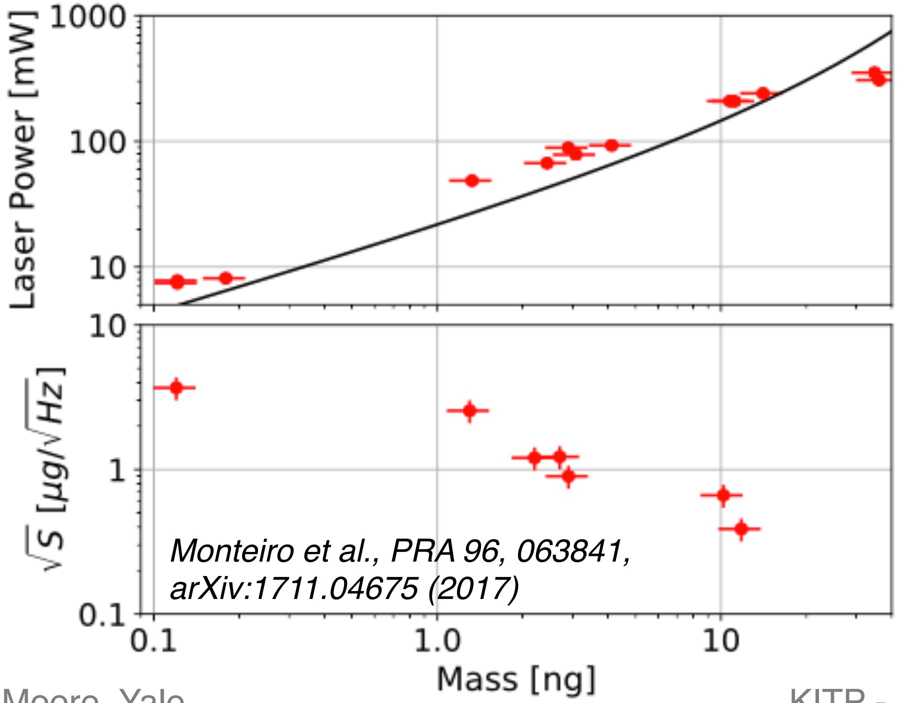
F. Monteiro

- Recently demonstrated the trapping of spheres between 0.1 – 30 ng
- 10 ng spheres have best acceleration sensitivity for levitated sensor by >30x
- Larger spheres vaporize, but may be possible with spheres that don't contain water

Vaporization of 30 ng spheres:

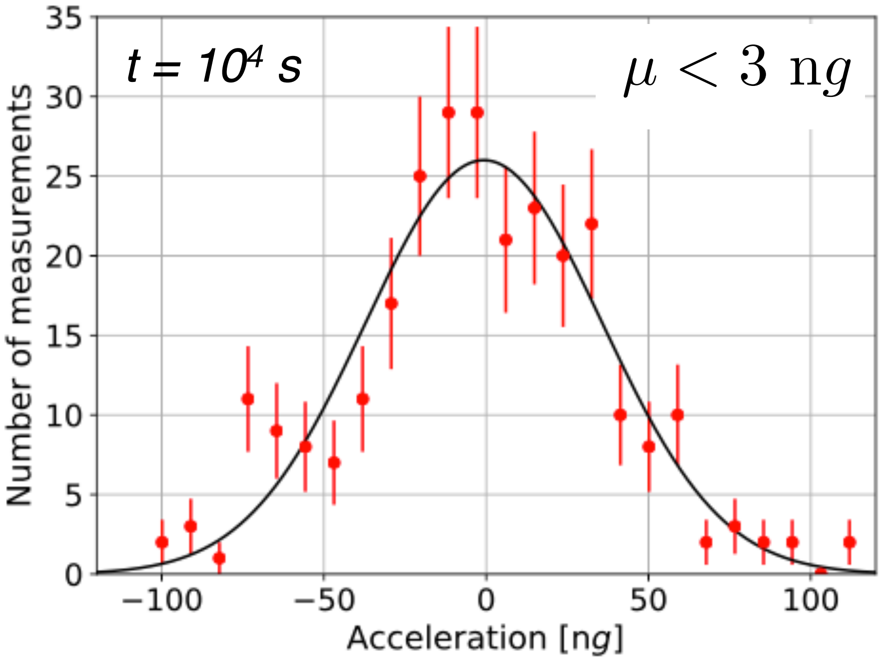


Acceleration sensitivity vs mass:



Monteiro et al., PRA 96, 063841, arXiv:1711.04675 (2017)

Measured acceleration (no ext. force):



Dipole backgrounds

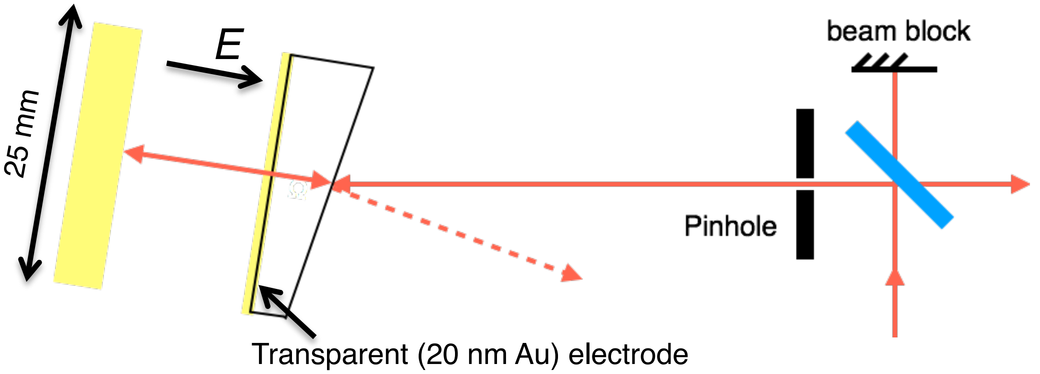
- Dipole backgrounds can be eliminated by minimizing electric field gradients

$$\vec{F} = (\vec{p}\cdot\vec{\nabla})\vec{E}$$

$$\vec{p} = \vec{p}_0 + \alpha\vec{E}$$

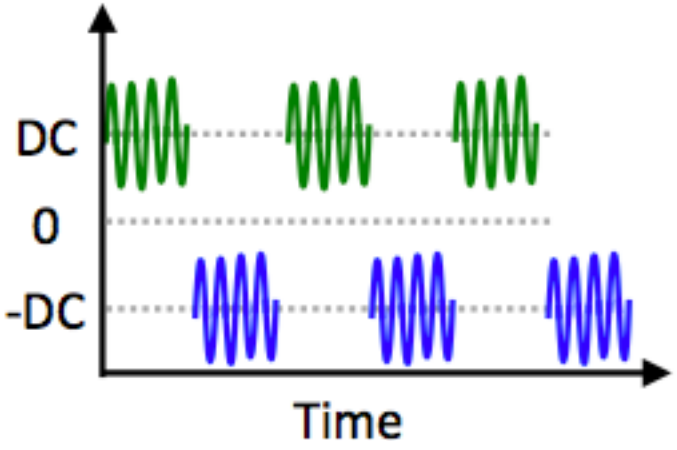
Permanent dipole
($|p_0| \sim 100\ e\ \mu$m, oscillates at ω_{AC})

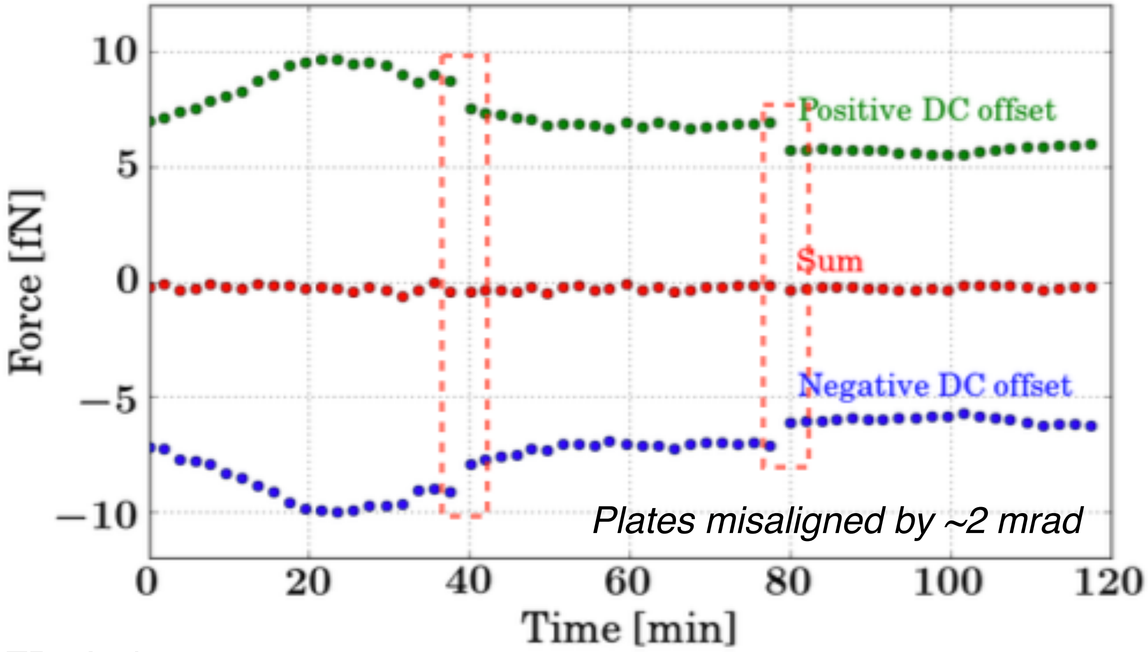
Induced dipole
(Oscillates at $2\omega_{AC}$)



Plates can be aligned in situ to ~100 μrad

- Any residual background can be further canceled by reversing DC field



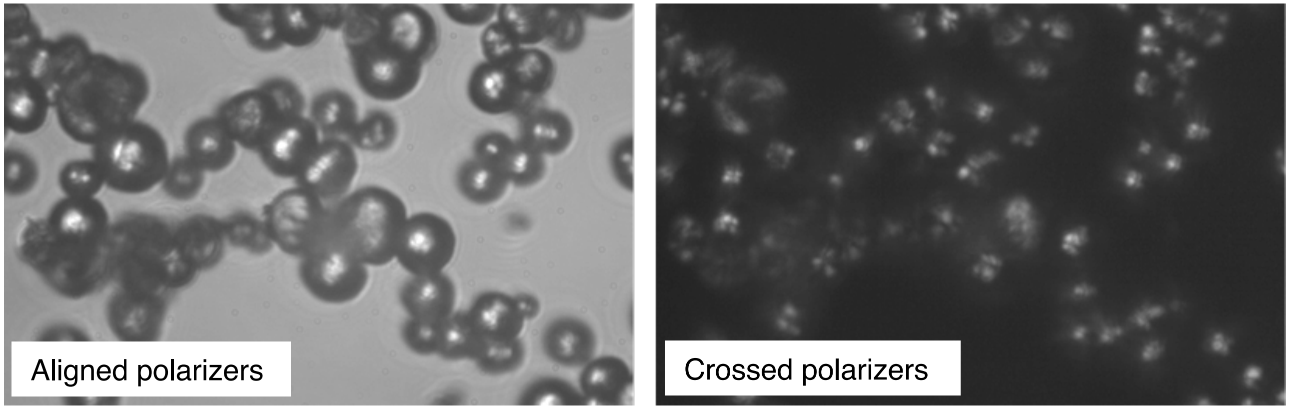


Plates misaligned by ~2 mrad

Background torques

- Even for perfectly uniform field, oscillating field still exerts torque and non-sphericity can produce apparent motion at ω_{AC}
- Developing techniques to rapidly rotate spheres about beam axis

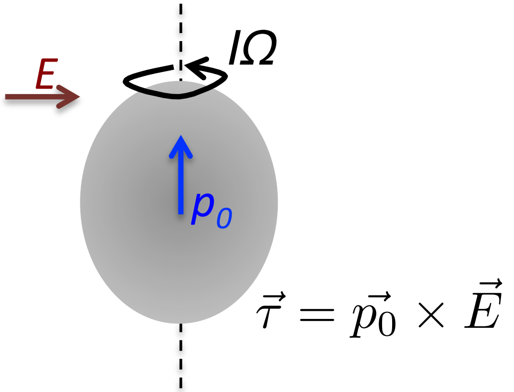
Birefringent (vaterite) microspheres:



Aligned polarizers

Crossed polarizers

S. Ghosh



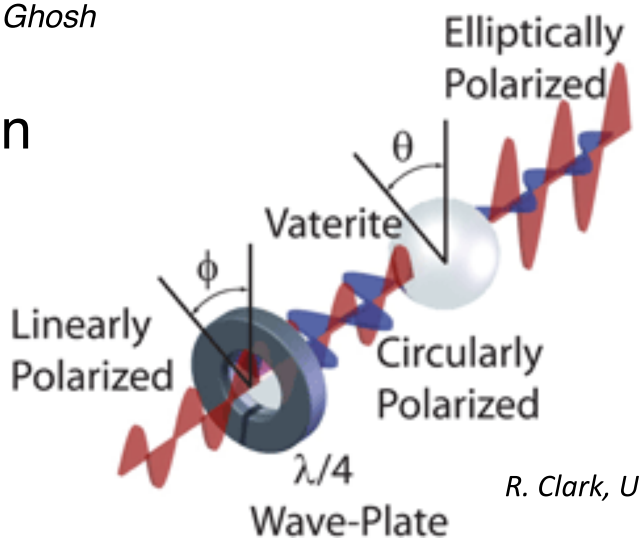
$$\vec{\tau} = \vec{p_0} \times \vec{E}$$

Background minimized for large Ω

- Circularly polarized light will exert torque on birefringent sphere

Friese et al., Nature 394, 348 (1998)

Donato et al., Sci. Rep. 6, 31977 (2016)

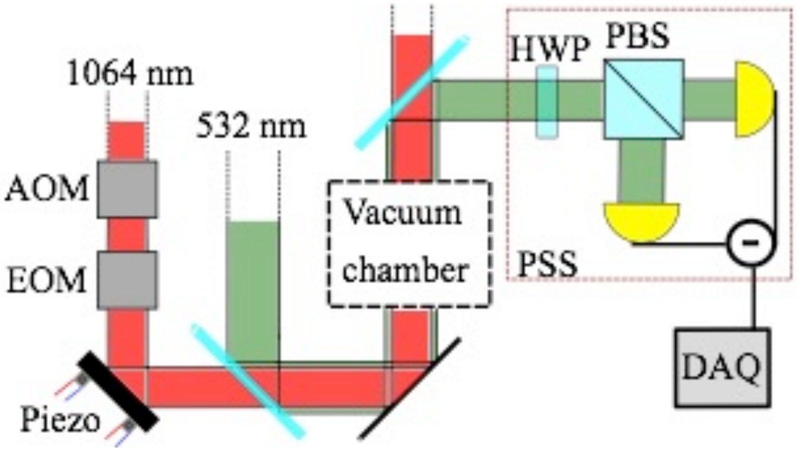


R. Clark, U. Rochester

Rotation in high vacuum

- Recently demonstrated rotation up to 6 MHz in high vacuum
- Spheres lost at higher rotation rates due to centrifugal stresses
- Rotation of amorphous SiO_2 spheres also observed

Polarization control and imaging:



Maximum angular acceleration:

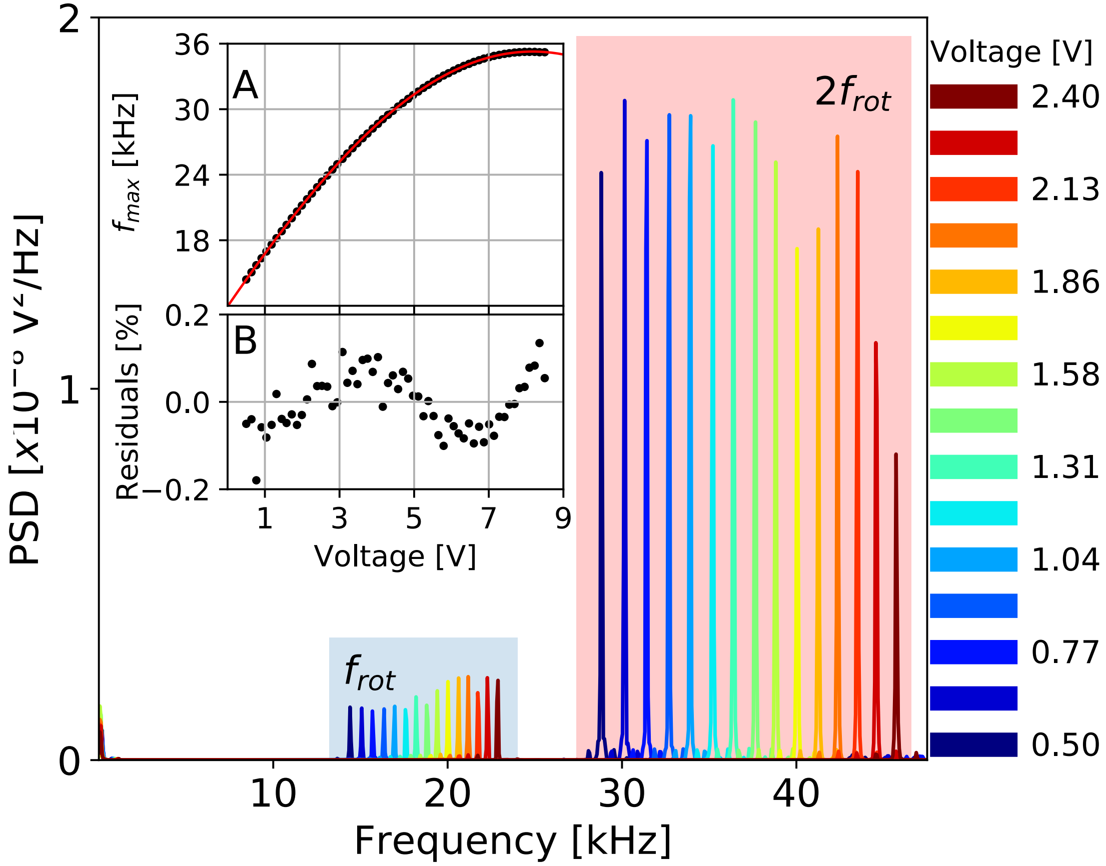
Vaterite, d=5 μm:

$$\alpha > 10^6 \ \mathrm{rad/s^2} \ (\tau > 300 \ \mathrm{fN}\,\mu\mathrm{m})$$

SiO_2, d=10 μm:

$$\alpha \sim 200 \ \mathrm{rad/s^2} \ (\tau \sim 3 \ \mathrm{fN}\,\mu\mathrm{m})$$

Rotation rate vs. polarization (10^{-2} mbar):

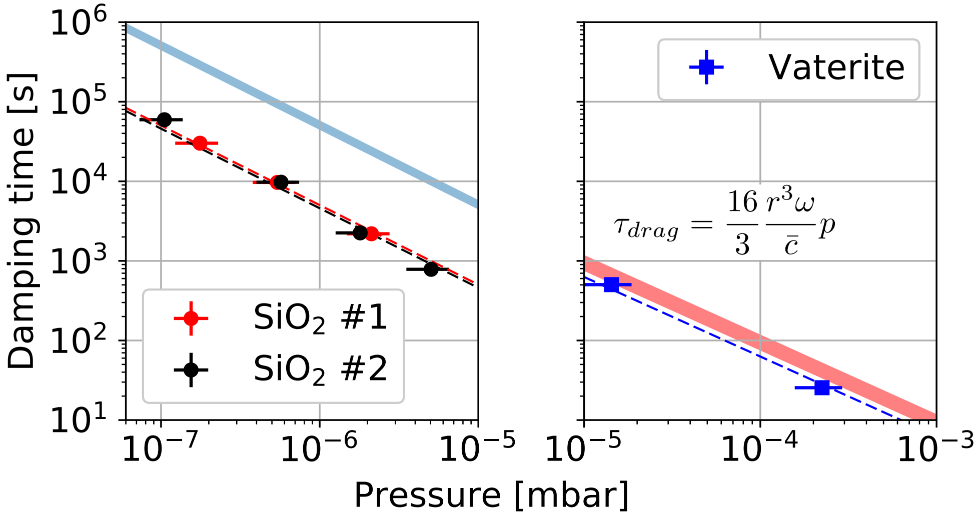


Monteiro et al., arXiv:1803.04297 (2018)

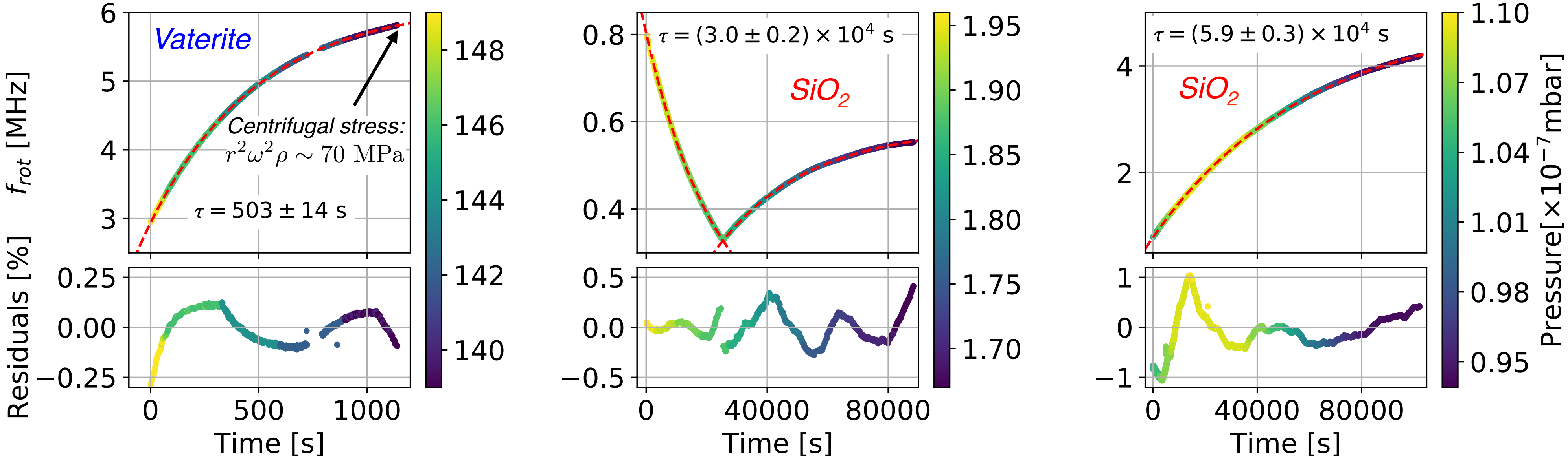
Rotation in high vacuum

- Measured damping time is ~1 day at 10^{-7} mbar
- Sphere rotates 10^{11} cycles in single damping time
- No dissipation above gas damping observed

Damping time versus pressure:



Measurement of damping time (rotation rate versus time):

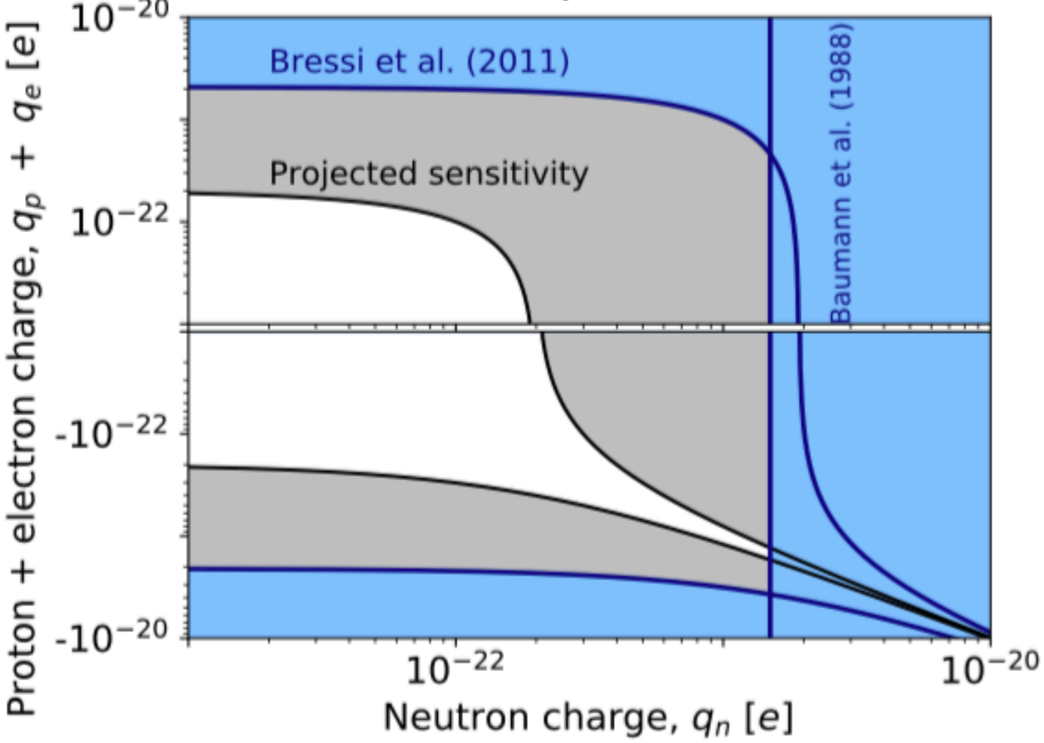


Monteiro et al., arXiv:1803.04297 (2018)

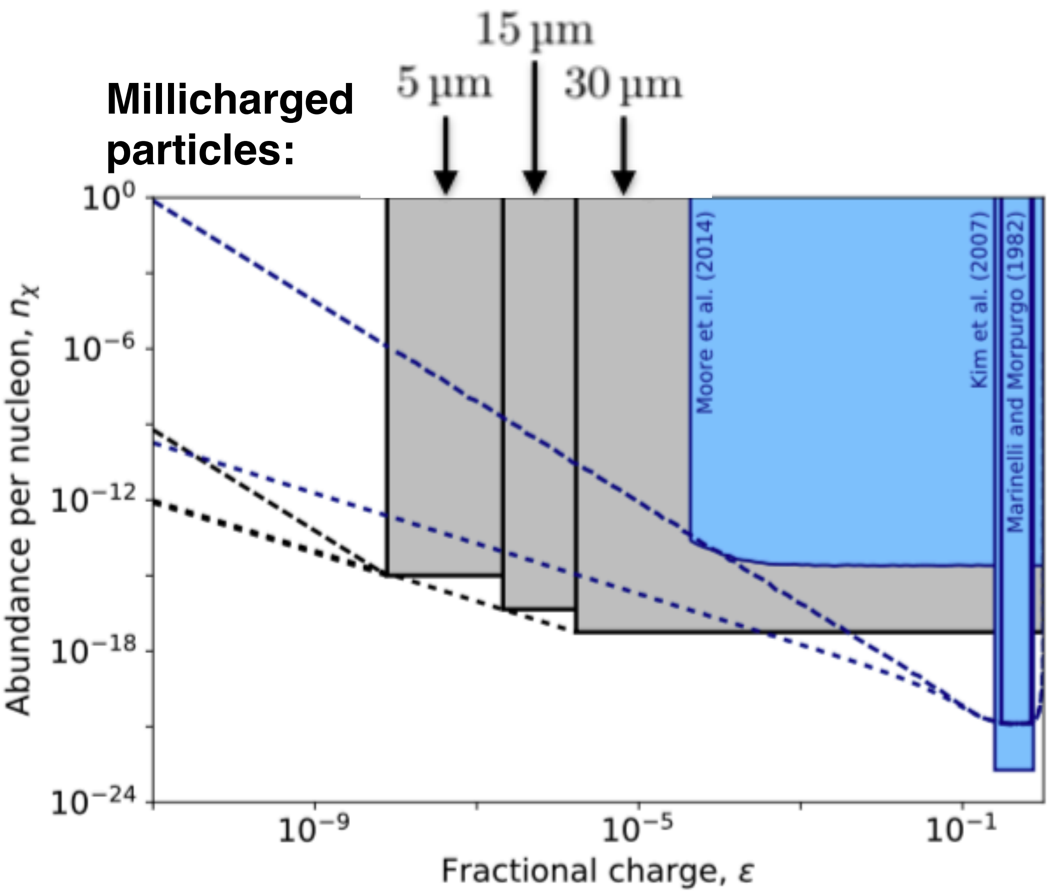
Projected sensitivity

- Current experiment aimed at reaching backgrounds below 10^{-19} N for d = 15 µm spheres
- Would allow improved searches for millicharged particles as well as tests of the neutrality of matter ($|q_p + q_e + q_n|$)

Neutrality of matter:



Millicharged particles:

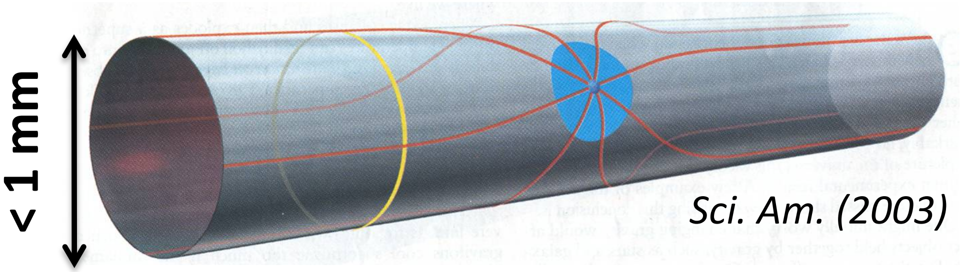


Searches for non-Newtonian forces at micron distances

Non-Newtonian forces

- Levitated microspheres can enable tests of gravity at the micron scale
- Theories attempting to account for the hierarchy problem, dark matter, or dark energy predict that there could new forces at << 1 mm

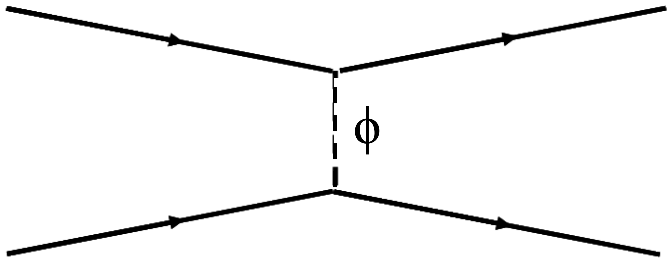
Large extra dimensions:



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)

Forces from new light 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 (screened scalars, modified gravity, …):

$\Lambda \sim 2$ meV
($\sim 80\ \mu$m)

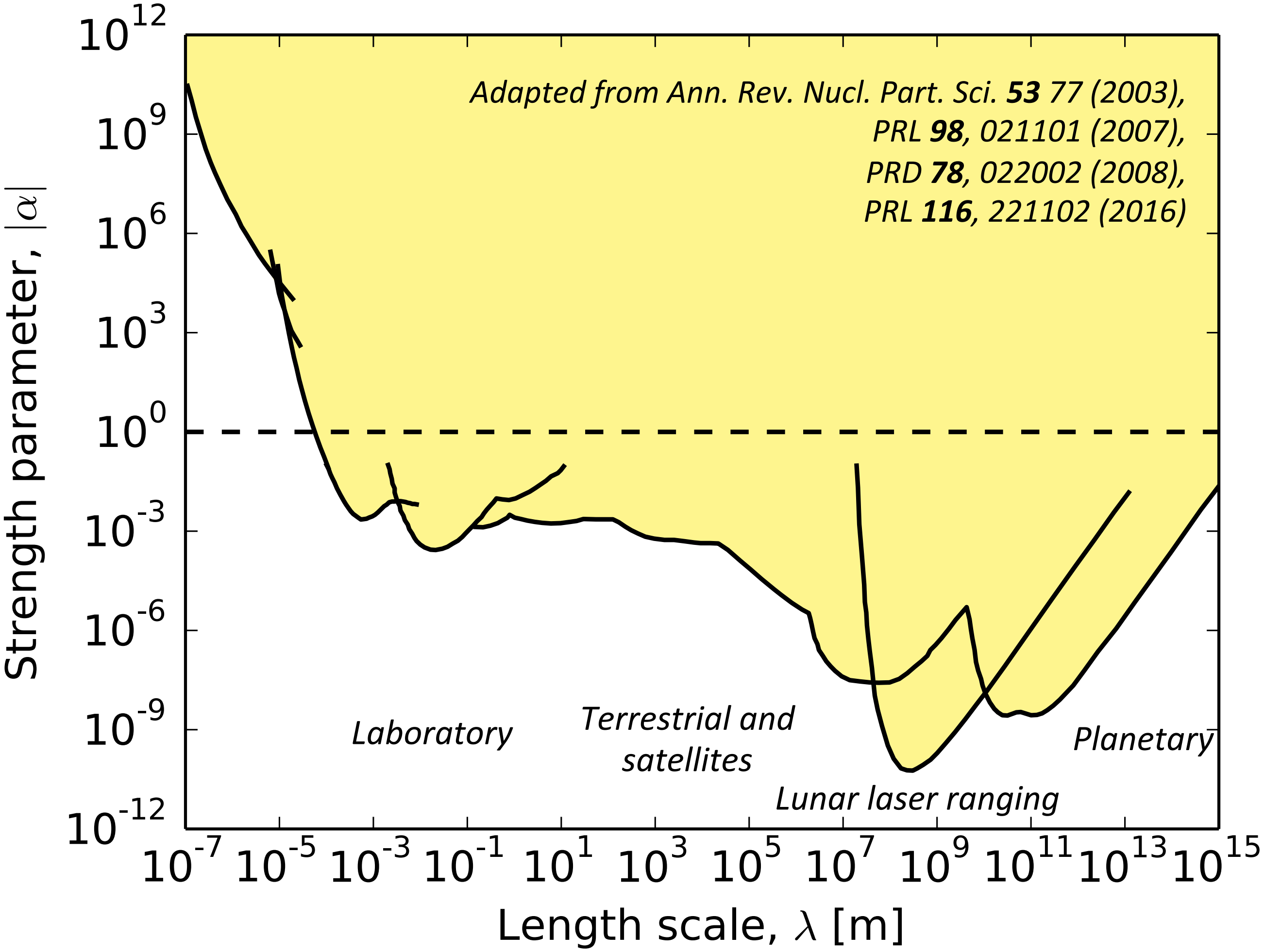
e.g., Sundrum, Phys. Rev. D **69**, 044014 (2004)
Khoury and Weltman, Phys. Rev. Lett. **93**, 171104 (2004)

Experimental constraints

- One convenient parameterization for the non-Newtonian potential is the Yukawa form:

$$V(r) = -\frac{Gm_1m_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

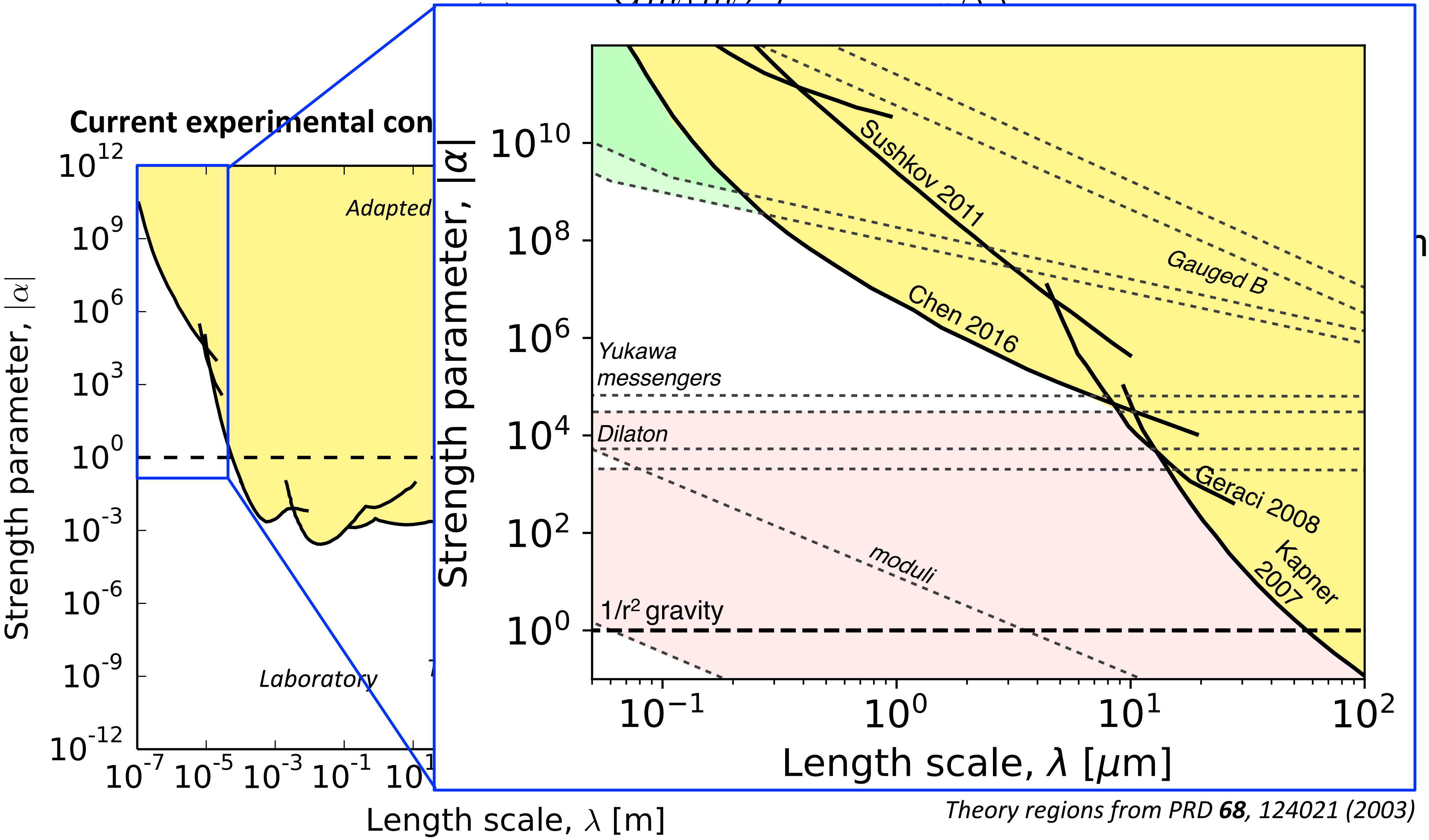
Current experimental constraints on non-Newtonian forces:



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

Experimental constraints

- One convenient parameterization for the non-Newtonian potential is the Yukawa form:

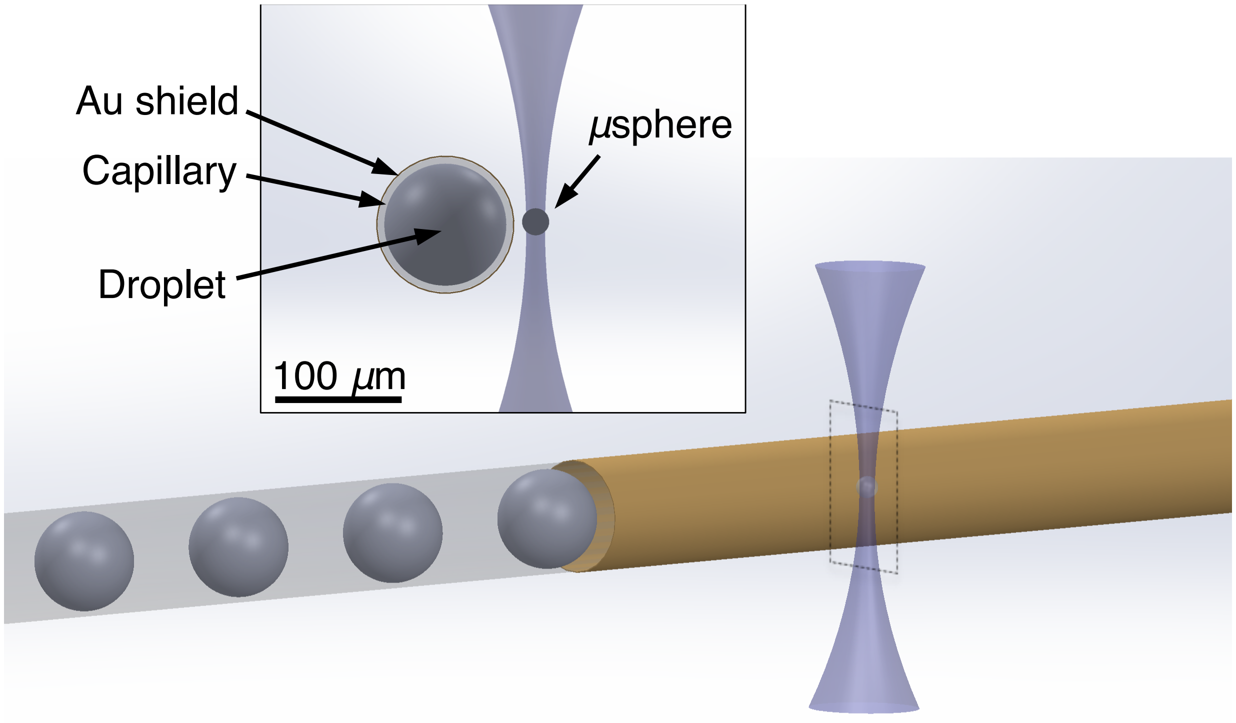


*Theory regions from PRD **68**, 124021 (2003)*

Gravitational attractor

- Investigating use of commercial microdroplet systems as attractors
- Density pattern created by dense fluid in carrier fluid (e.g. Ga/In eutectic alloy in oil)
- Au-coated, thin-walled capillary provides fully hermetic, stationary shield (minimizes electromagnetic backgrounds)

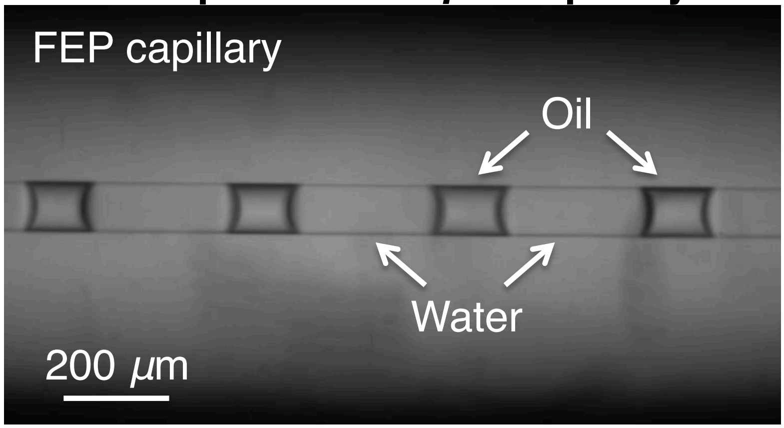
Schematic of microfluidic attractor concept:



Monodispersed microdroplets on chip:

dolomite-microfluidics.com

Droplets in 100 μm capillary:

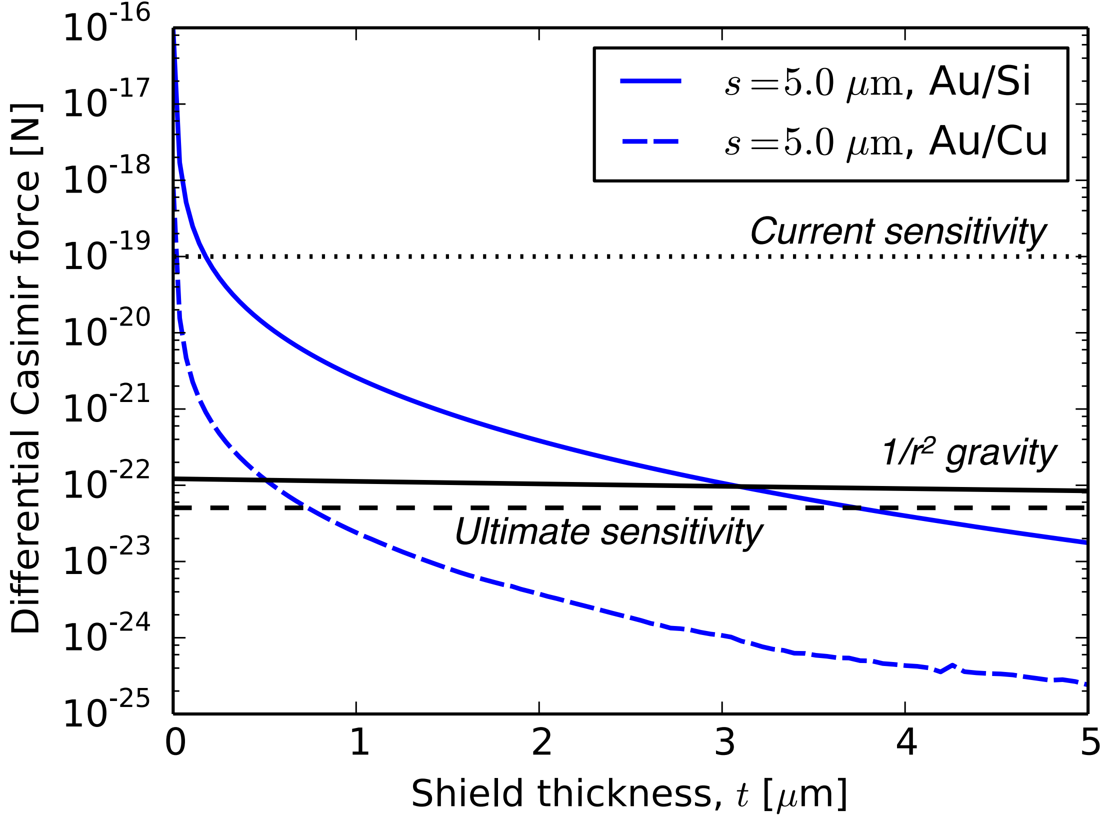


E. van Assendelft

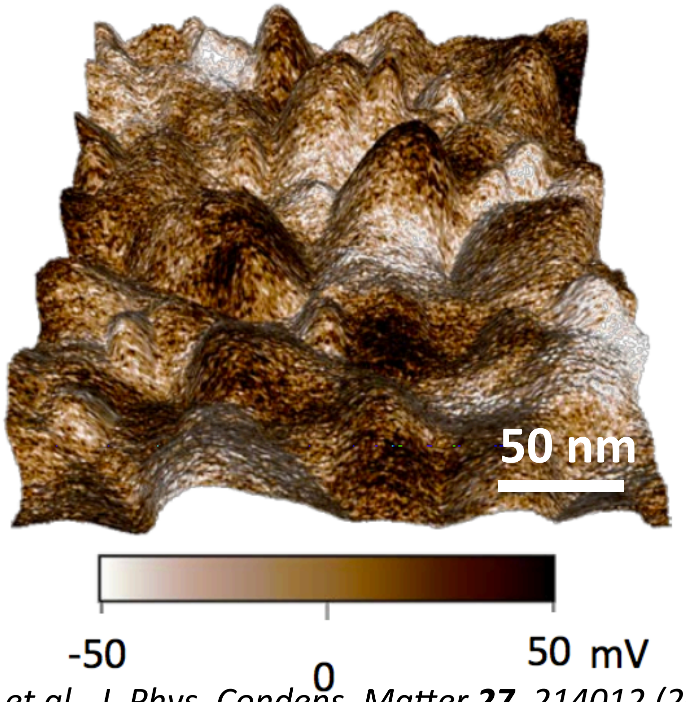
Backgrounds

- Primary challenge is to develop an attractor that eliminates electromagnetic backgrounds
- Au-coated capillary should significantly suppress backgrounds from the Casimir force and patch potentials
- Au/Si cantilever attractor also under development (Stanford)

Calculation of differential Casimir force:



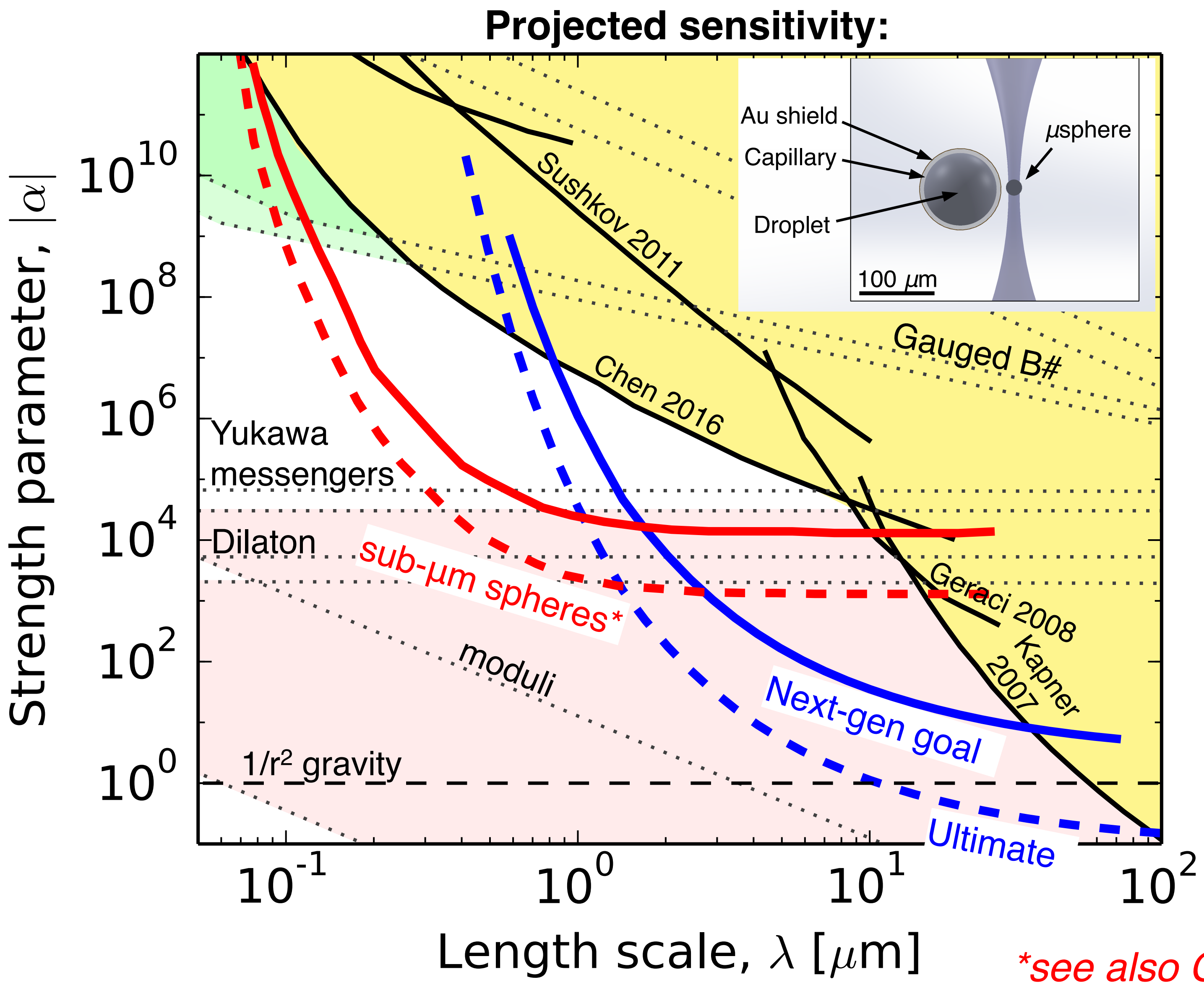
Topography and surface potential for sputtered Au film:



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

Projected sensitivity

- These techniques could allow substantial amount of unexplored parameter space to be searched for new gravity-like interactions!



Assumptions:

$r = 10$ μm, optimized for λ~2-100 μm

$r = 0.2$ μm, optimized for λ~0.1-1 μm

10^5 s integration

Next-gen goal:
$\sigma_F = 5 \times 10^{-19}$ N Hz$^{-1/2}$

Ultimate:
$\sigma_F = 2 \times 10^{-20}$ N Hz$^{-1/2}$

Assumes shielded attractors suppress backgrounds below projected noise level

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

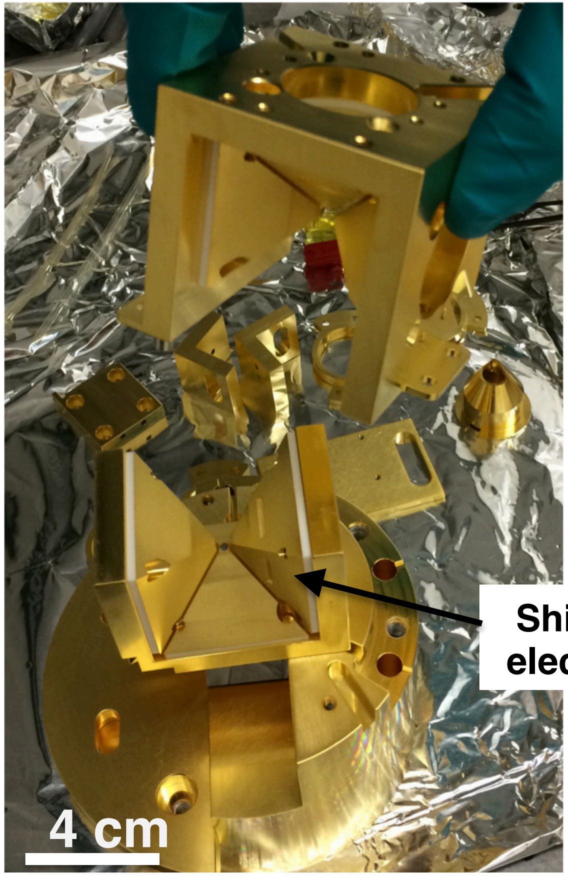
Screened scalar dark energy

- In certain screened scalar dark energy models new forces appear at:

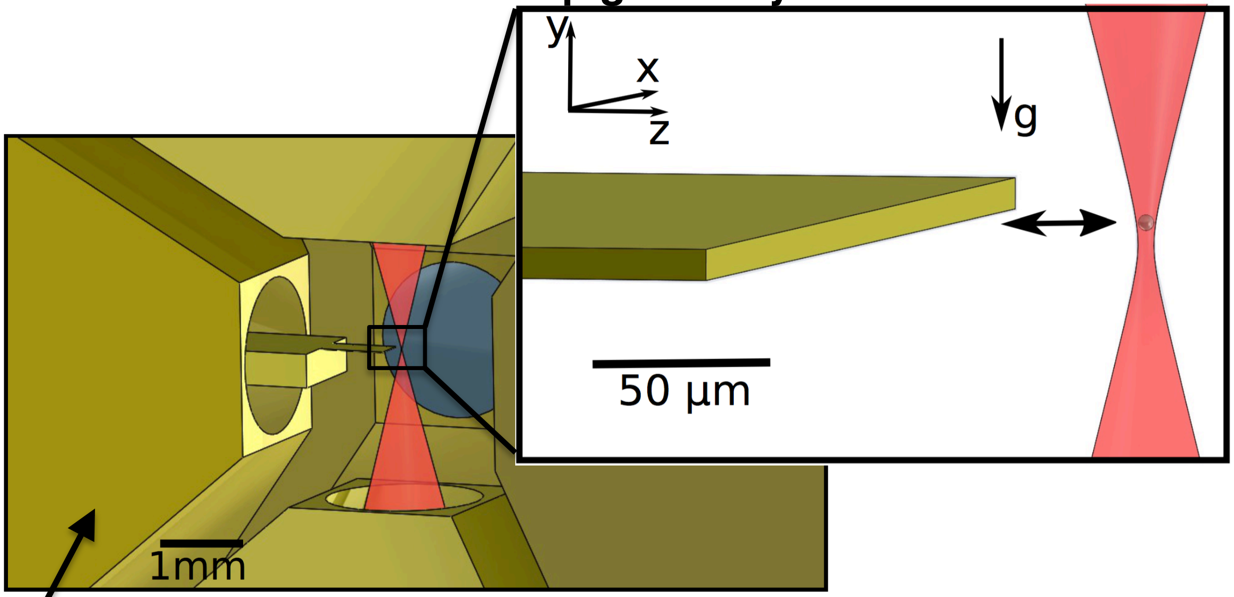
$$\Lambda = 2.4\ \mathrm{meV} \Rightarrow \hbar c/\Lambda \sim 80\ \mu\mathrm{m}$$

- To search for forces from screened scalars, oscillate mass density near the trap using a Au-plated Si cantilever

Photograph of electrodes:



Schematic of trap geometry:



Shielding electrodes

Experimental parameters:

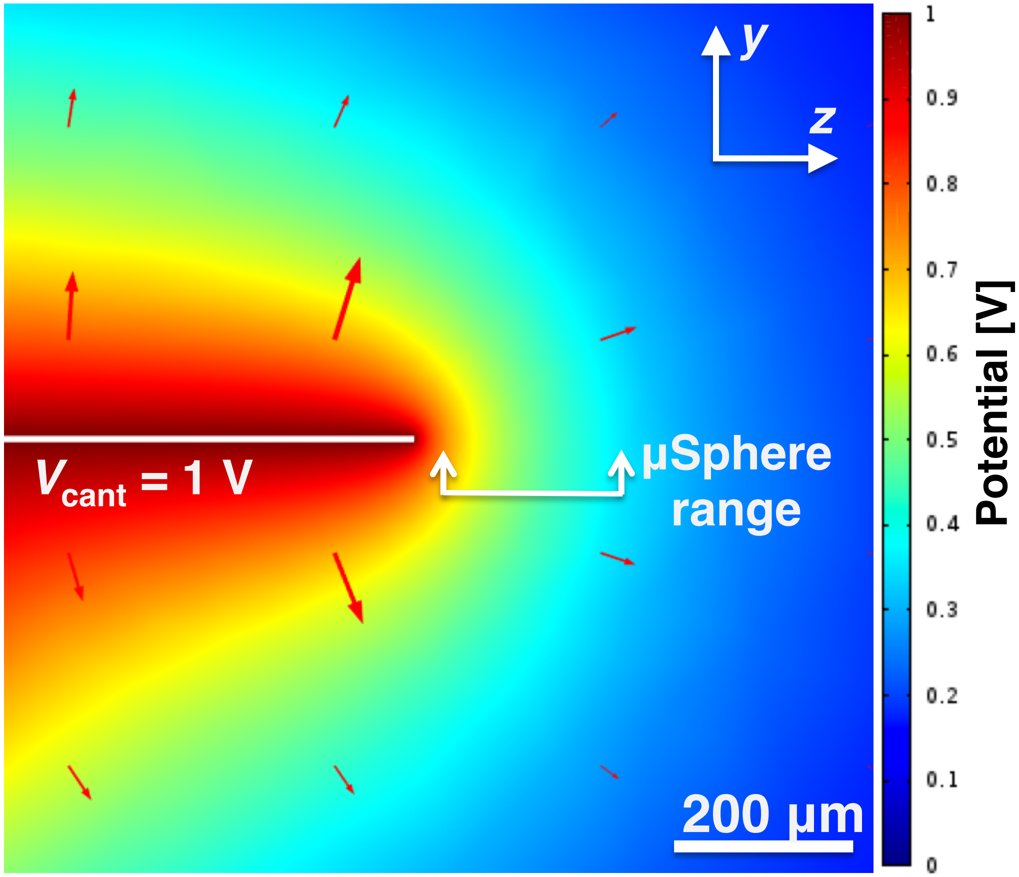
Microsphere radius [µm]	2.50 ± 0.24
Microsphere density [g/cm^3]	2.0
Cantilever thickness [µm]	10.4
Separation distance [µm]	20 - 230
Background pressure [mbar]	< 10^{-6}

Electrostatic calibration

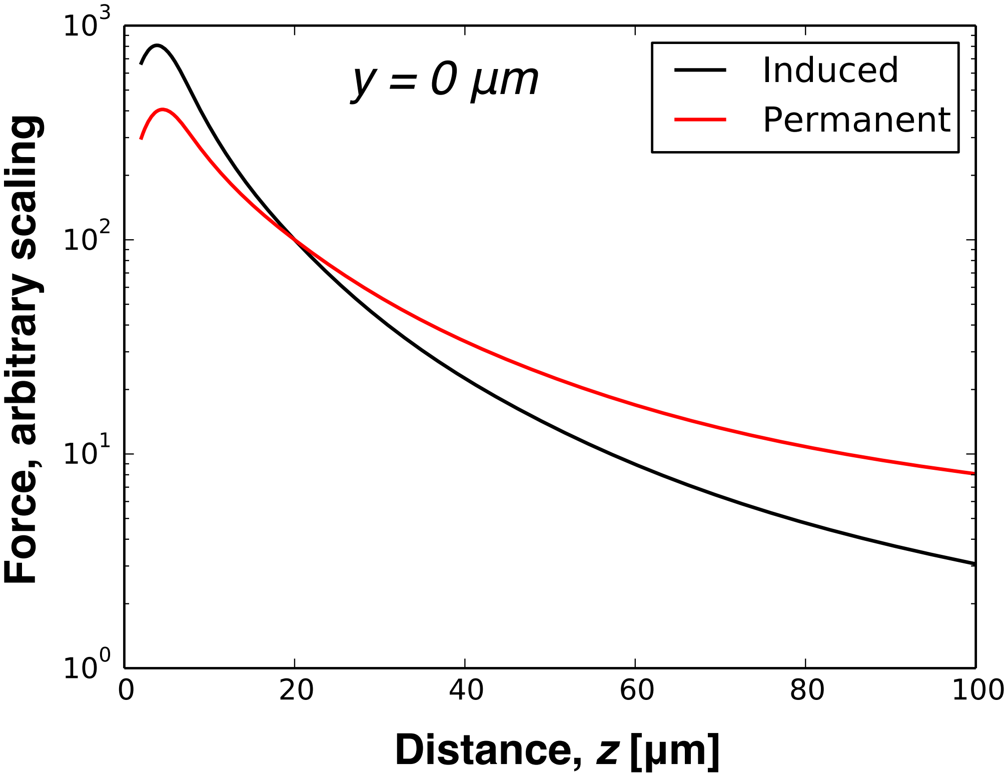
- Neutral microspheres contain ~10^{14} electric charges and interact primarily as dipoles: $\vec{F} = (\vec{p} \cdot \vec{\nabla})\vec{E} \quad \Rightarrow \quad F_z \approx (p_{0z} + \alpha E_z)\frac{\partial E_z}{\partial z}$

Permanent dipole **Induced dipole**

FEM calculation of electric potential:

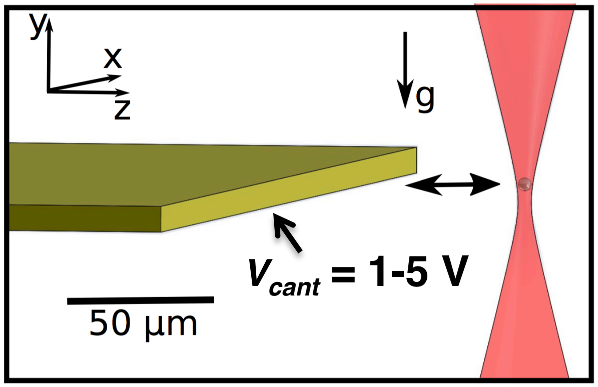


Force for permanent and induced dipole:

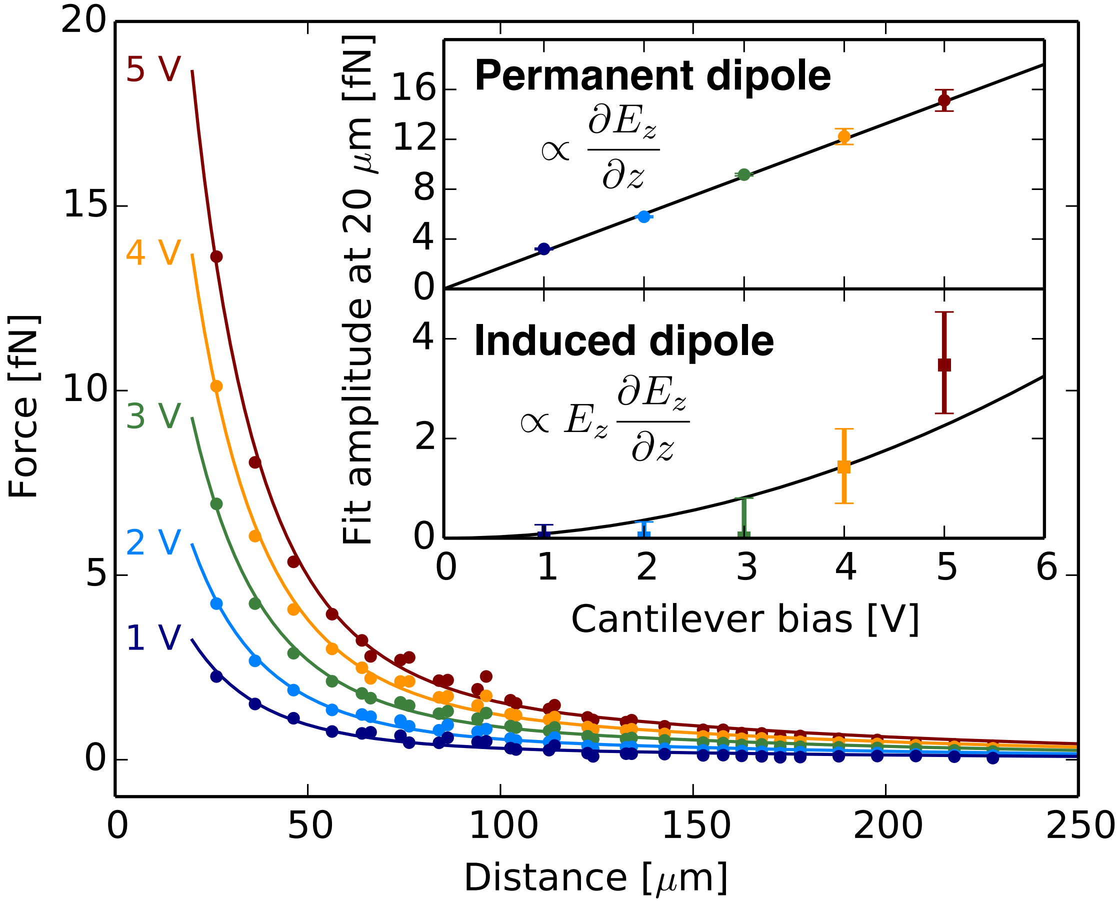


Electrostatic calibration

- 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 μm]	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:

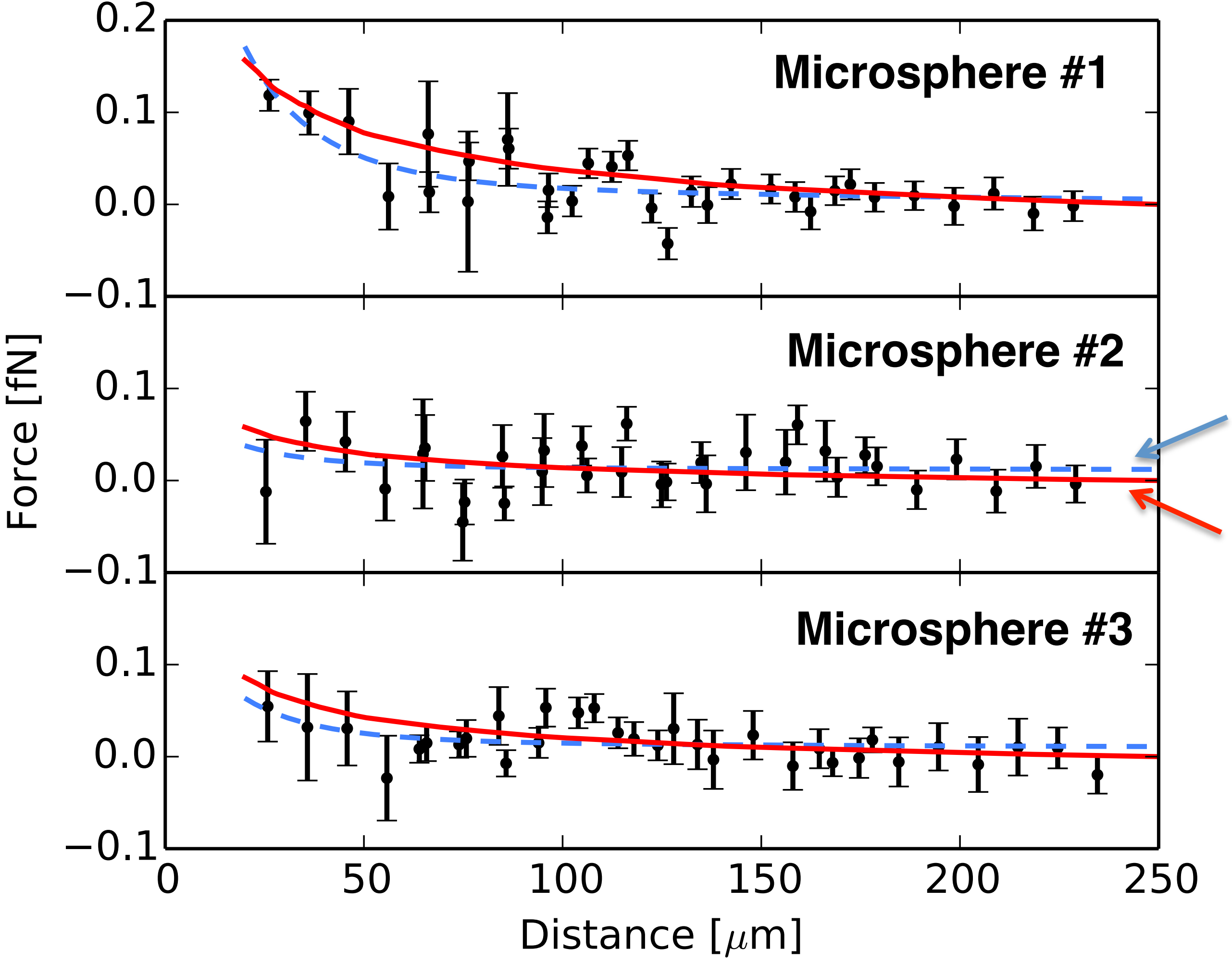
$$\alpha_0 = 3\epsilon_0 \left(\frac{\epsilon_r - 1}{\epsilon_r + 2}\right)\left(\frac{4}{3}\pi r^3\right)$$

for $\varepsilon_r \approx 3$, r = 2.5 μm

Residual response

- After measuring response to non-zero bias, set to nominal potential of 0 V
- Residual response consistent with <30 mV contact potentials

Microsphere response vs. distance, V_{cant}= 0V:



Background only fit

90% CL upper limit on screened scalar interaction

A. Rider, D. Moore, et al., PRL 117, 101101 (2016), arXiv:1604.04908

Tests of Coulomb’s law at micron distances

Coulomb’s law

- Can also search for new forces that couple to charge
- Similar to millicharged particles, new forces could arise from hidden sector dark matter models

Dark photons:

$$V(r) = \frac{e^2}{r}\left(1 + \chi^2 e^{-m_\Gamma r}\right)$$

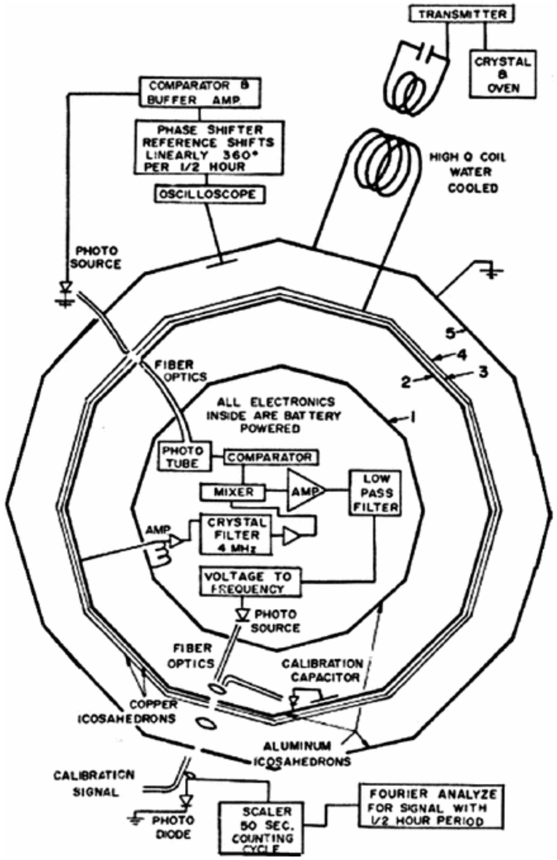
Light millicharged particles:

$$V(r) \approx \frac{\alpha}{r}\left[1 + \frac{\alpha\epsilon^2}{4\sqrt{\pi}}\frac{\exp(-2mr)}{(mr)^{\frac{3}{2}}}\right]$$

e.g. Jaeckel and Ringwald, Ann. Rev. Nucl. Part. Sci., ***60****, 405 (2010)*

- Previous laboratory tests searched for non-zero photon mass
- Most sensitive to ~μeV dark photons (~10 cm)
- Microspheres can search up to ~1 eV (~ µm)

Laboratory Coulomb’s law test (1971):

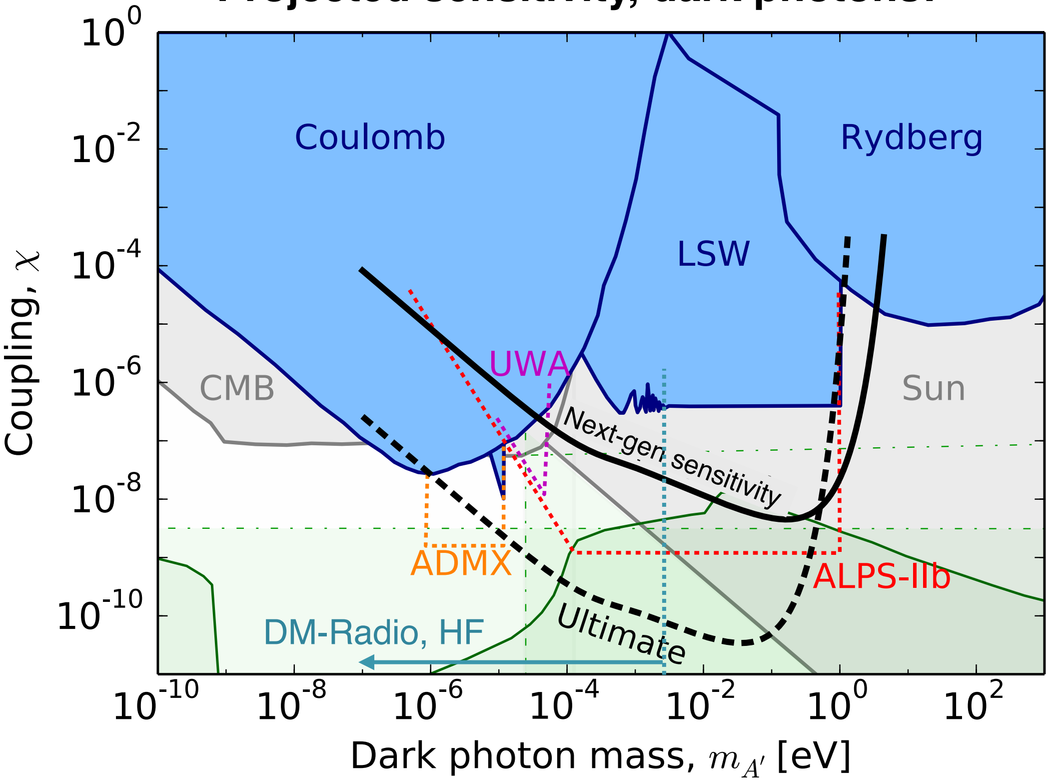


Williams et al., Phys. Rev. Lett. 26, 721 (1971)
Bartlett and Lögl, Phys. Rev. Lett. 61, 2285 (1988)

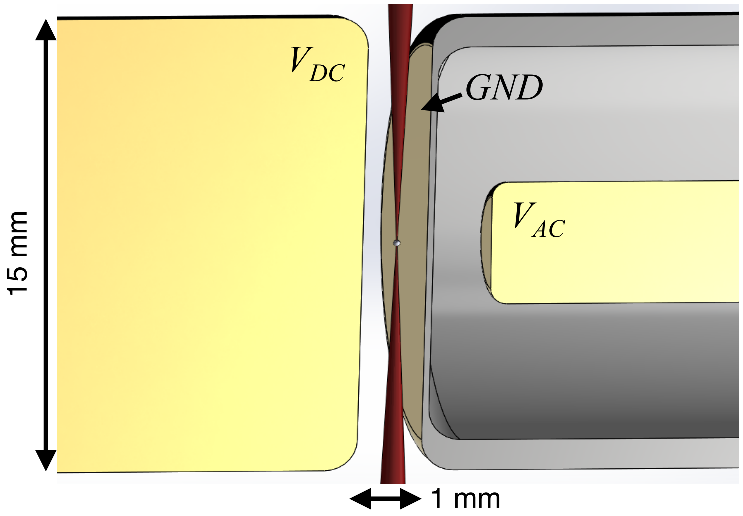
Dark photons

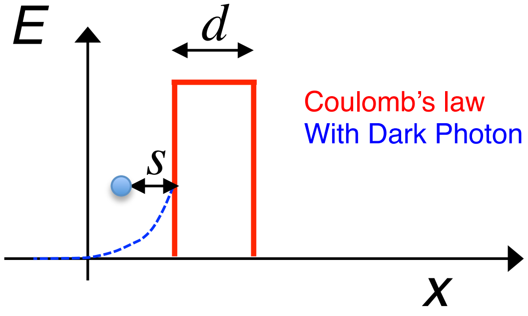
- Position highly charged (or polarized) microsphere next to shielded electric field
- Most sensitive to meV-eV mass range
- Complementary to “light shining through wall” experiments and DM-Radio

Projected sensitivity, dark photons:



Schematic of electrodes:



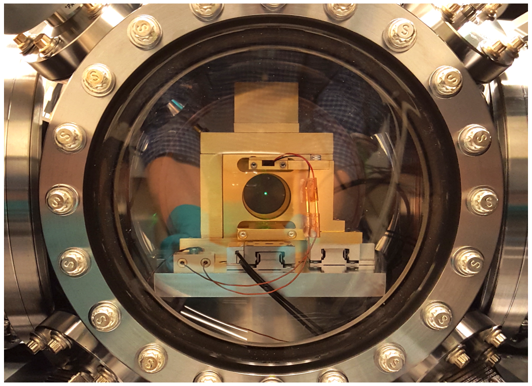


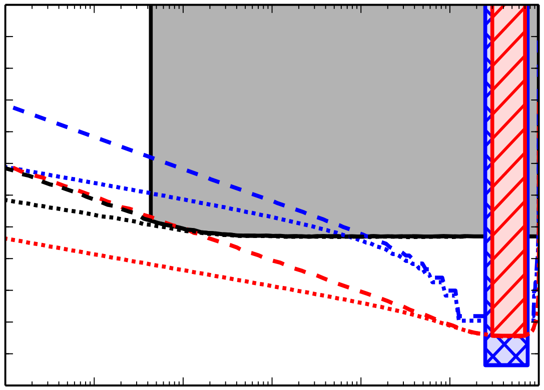
Requires: $d \gg 1/m_\chi$

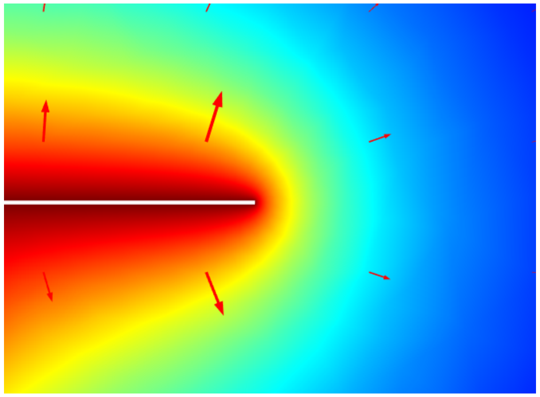
$s < 1/m_\chi$

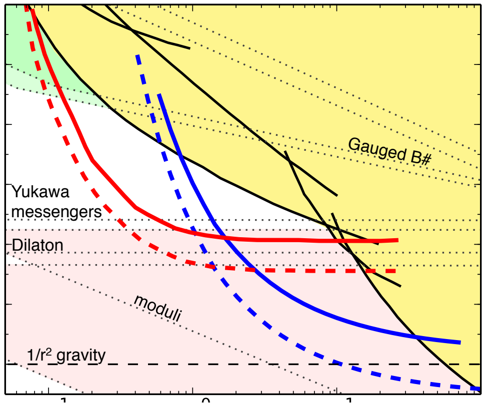
Summary

- Levitated microspheres in high vacuum can provide extremely sensitive force sensors
- Have already performed searches for screened scalar dark energy models and millicharged particles bound in matter
- Future work will enable new tests of matter neutrality, Newton’s, and Coulomb’s law at micron distances
- These and other experiments at the precision frontier could give our first hints of BSM physics!









Yale University:

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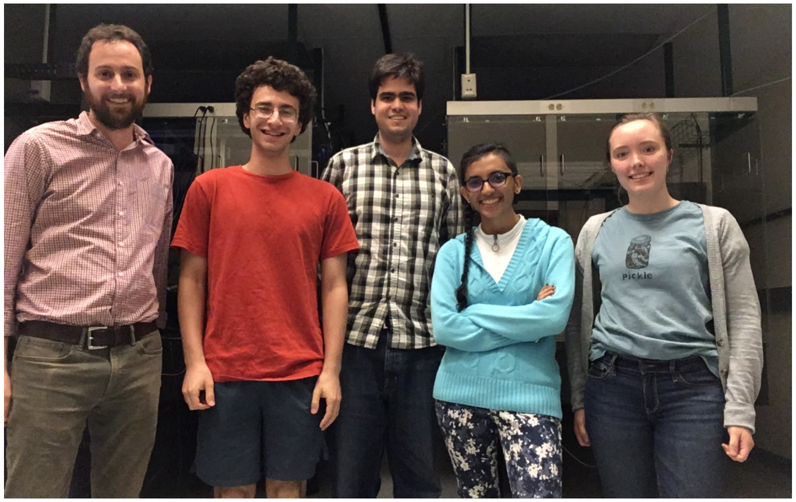
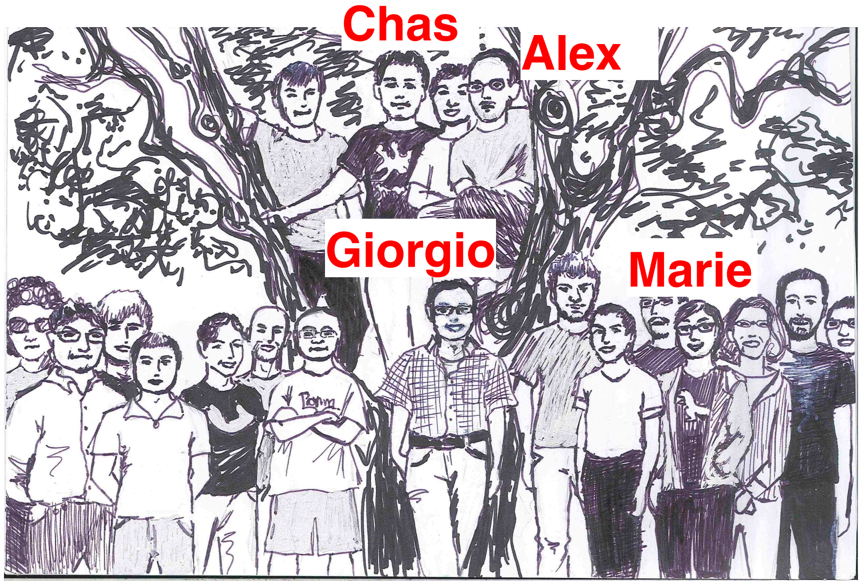
Adam Fine
Sumita Ghosh
Fernando Monteiro
David Moore



Stanford University:

Charles Blakemore
Akio Kawasaki
Maxime Louis
Marie Lu
Alexander Rider
Sandip Roy
Giorgio Gratta



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