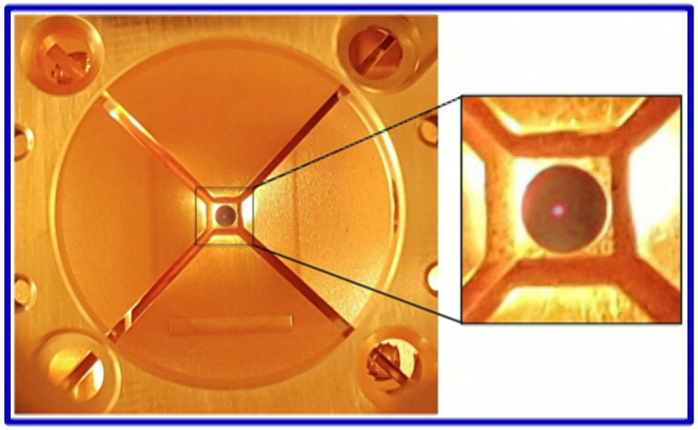
Title: Testing Gravity at Extreme Scales

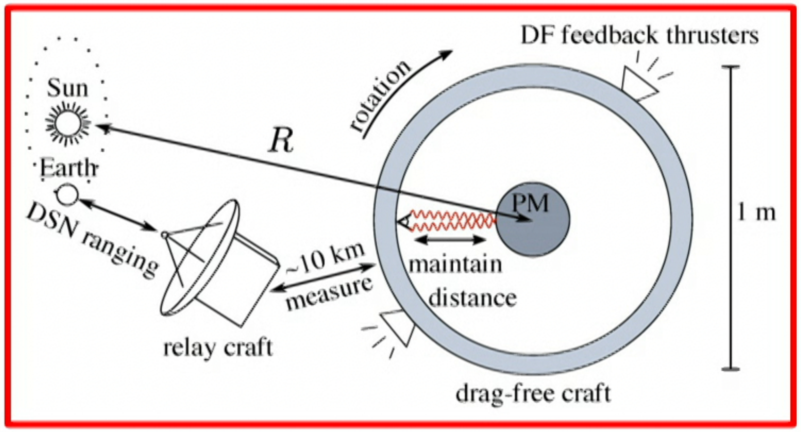
Date: Aug 22, 2017 09:30 AM

URL: http://pirsa.org/17080023

Abstract:

Probing gravity at extreme scales

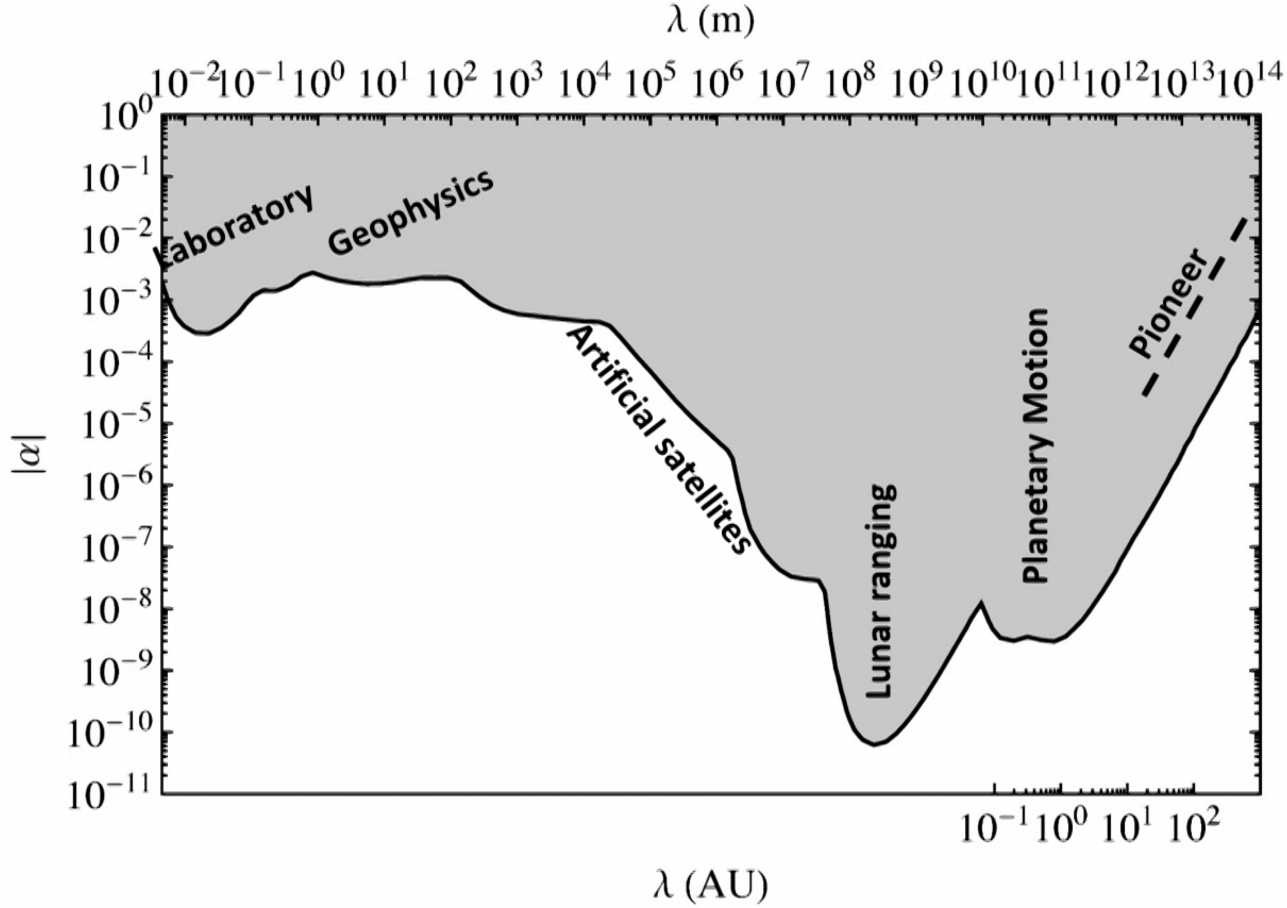




Giorgio Gratta

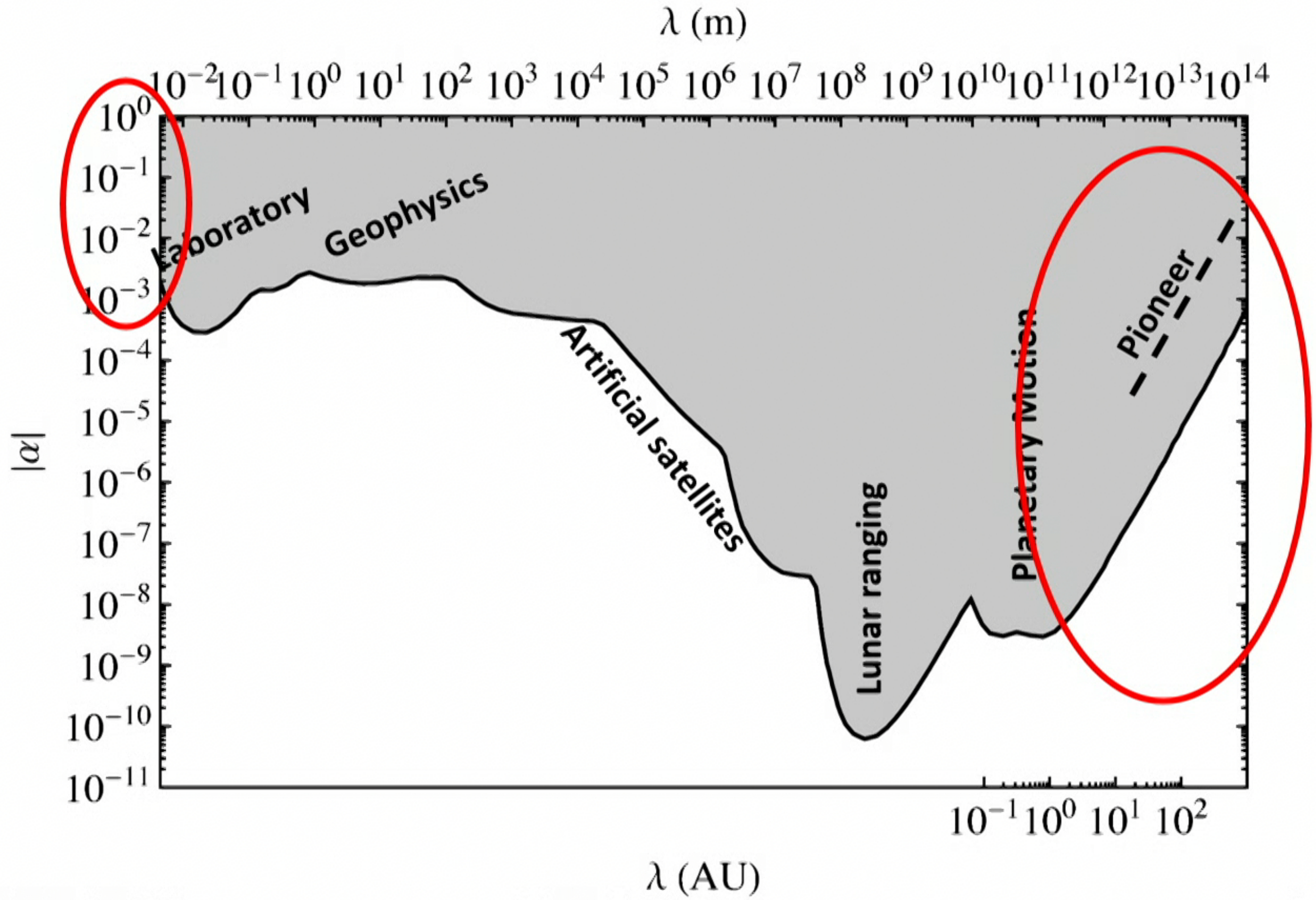
Physics Dept. Stanford University

What do we know



Adapted from E.G.Adelberger, B.R.Heckel and A.E.Nelson, ARNPS 53 (2003) 77

I will briefly discuss a couple of (very different) ideas to extend the measurement react at the two extremes of the scale.



The long distance regime

There is really nothing like "going there".

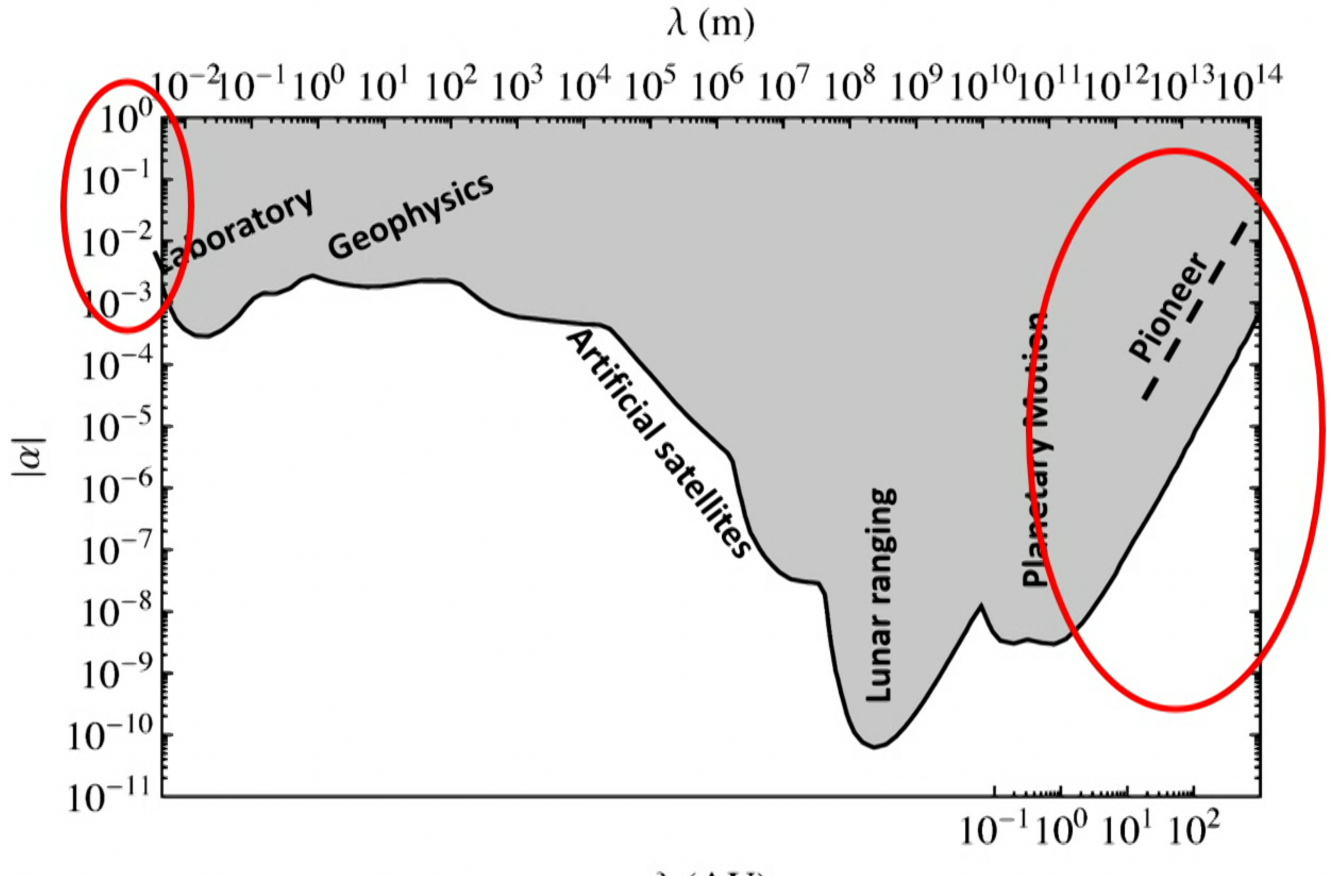
So the plots showing limits on an extra Yukawa terms only tell part of the story.

True modifications of gravity like DGP or MOND are very different and not well described by an extra Yukawa term. And these are models motivated by the Dark Matter and Dark Energy puzzles (even if they may not work well yet)

So "going there" possibly allows to test for the most relevant physics!

B.Buscaino, D.DeBra, P.W. Graham, GG, T.D. Wiser, Phys. Rev. D 92 (2015) 104048

I will briefly discuss a couple of (very different) ideas to extend the measurement react at the two extremes of the scale.



The long distance regime

Important challenges and requirements:

1) Getting there!
Requires a light payload, heavy launcher, gravitational assists

2) Drag-free system to minimize interactions with the outside (except for the gravity from solar system's bodies).
➔ Spacecraft flies around a "Proof Mass" that is truly ballistic

3) Further identify/fit away interactions of Proof Mass with spacecraft by rotating the spacecraft perpendicularly to the Sun's direction.

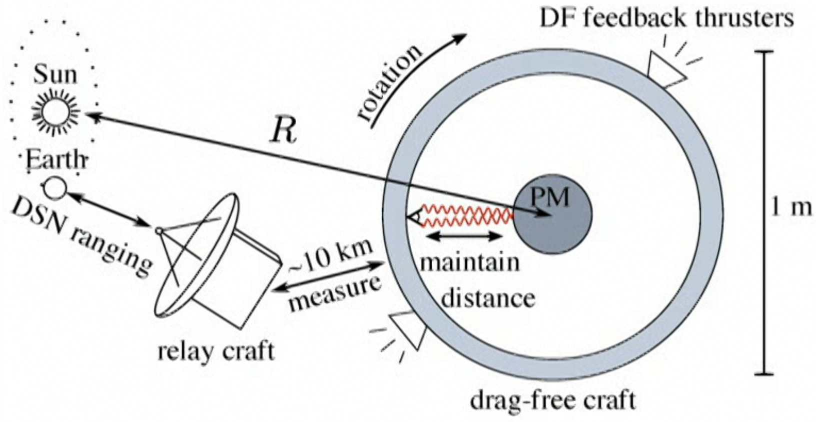
4) Good quality telemetry (R(t) and v(t)). Because of distance and spacecraft rotation, require a relay craft, trailing the science instrument by ~10km.

5) Reliable (10yr lifetime) drag-free system micro-thrusters.

Instrument/flight parameters

Parameter	Value
Drag Free spacecraft mass	200 kg
Experiment duration	7 yr
Distance reached	100 AU
Proof mass	1 kg
Proof mass radius (Pt)	5 cm
Thruster bandwidth	10^{-2} Hz
Proof mass sensing deadband	10 µm
Correction period	100 s
Ranging measurement period	20 day
Proof mass discharging period	2 day
Micro-thrusters fuel mass (FEEPs)	<50g
Spacecraft angular velocity	0.1 Hz
Spacecraft radial initial velocity	14 AU/yr
Relay craft distance	~10 km
RTG power	<1 kW

Red is technically challenging



Assume that a mission to 100AU with a ~2yr maneuvering phase and a ~5yr coast is feasible

[from R.A. Mewaldt et al., Acta Astron. 35 (1995) 267]

Realistic navigation with realistic launch windows needs to be designed by experts

Assume ~100 AU max distance

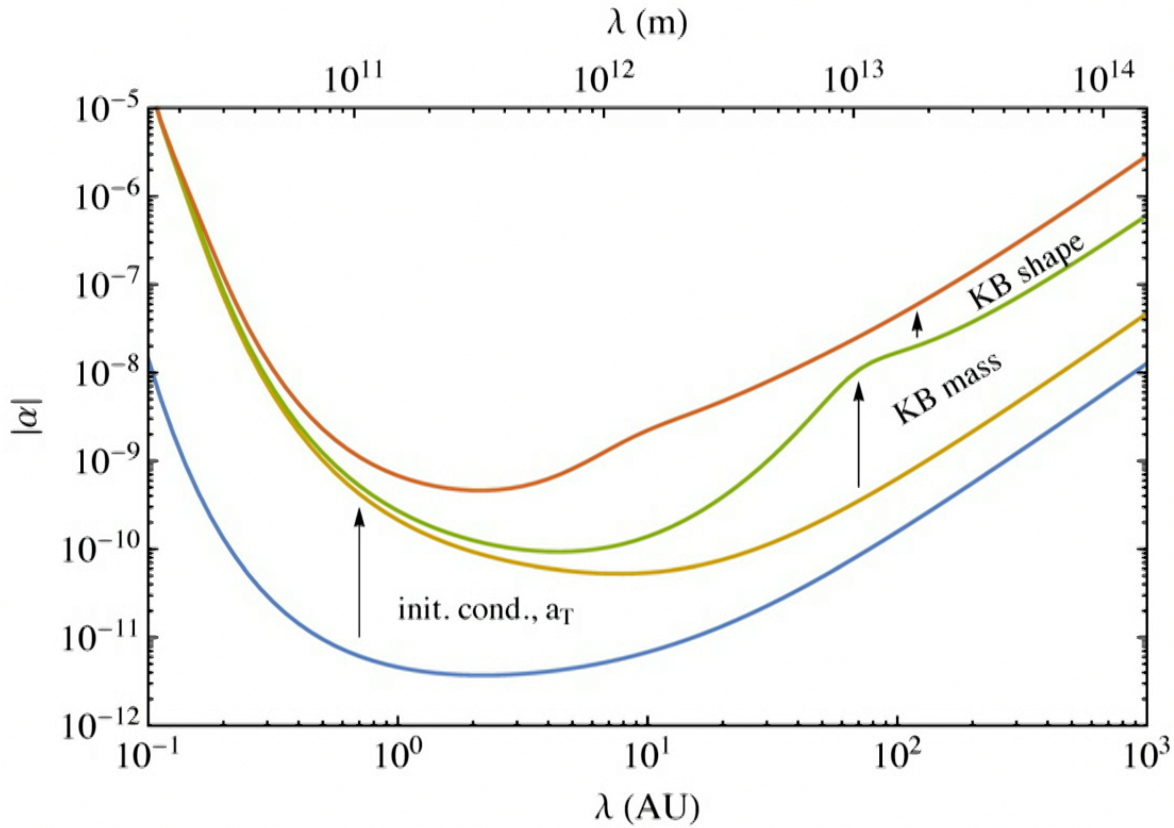
Maneuvering propulsion stage jettisoned before coast (when relay craft undocks and proof mass is released).

Dominant systematics

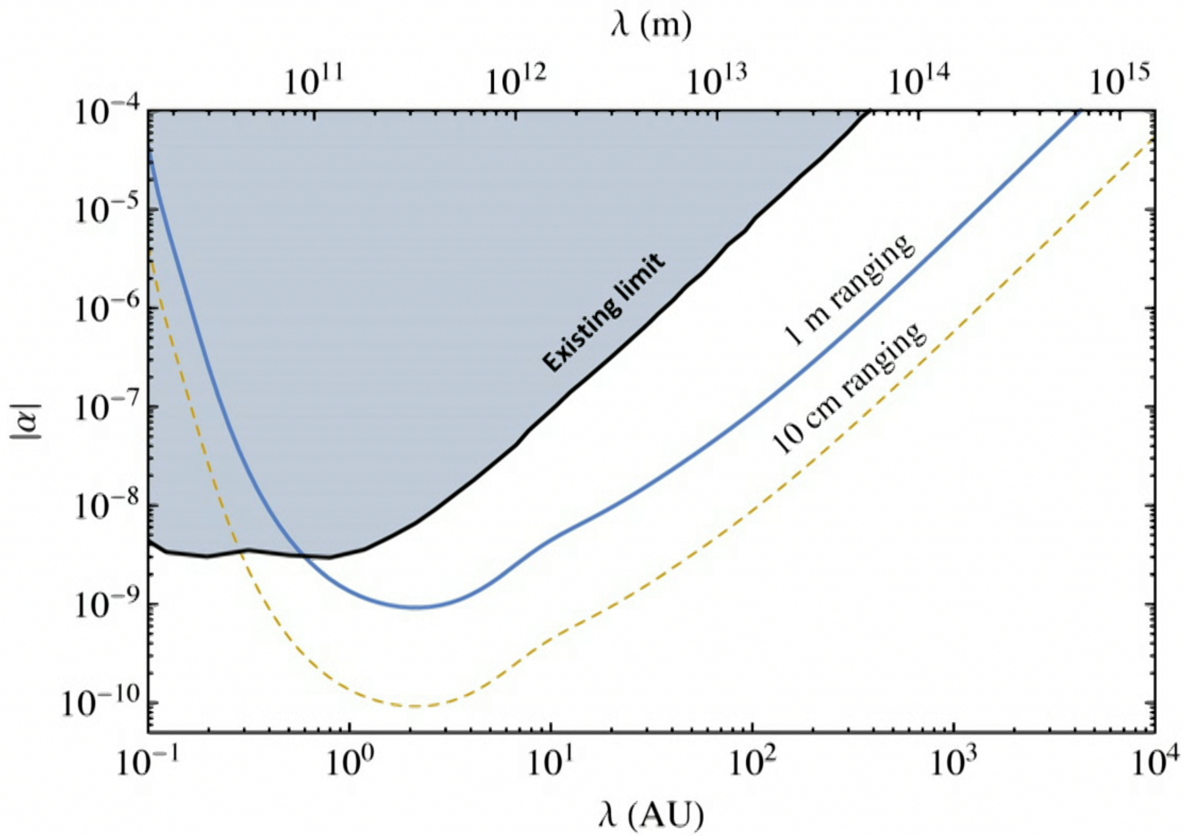
- Non-solar gravity in the solar system
  - Mass and density distribution of Kuiper Belt very poorly known
  - Best trajectory is polar; this can be achieved with one last gravitational assist designed to deflect the craft $\perp$ to the ecliptic plane (unique viewpoint of the Solar System!)
  - As a by-product the mission would measure $\delta GM_{KB} \sim 5\text{x}10^{-4}\, GM_{Earth} = 0.5\%$ @ $GM_{KB}^{MAX} = 0.1 GM_{Earth}$ and KB's mass weighed radius and ecliptic plane offset

- Ranging accuracy
  - Assume 1 m accuracy (this is conservative; feasible now with NASA DSN and "off the shelf" transponders)
  - Also use an aggressive option with 10 cm accuracy (possible with laser ranging under development)

Effect of the Kuiper Belt with a 1 m ranging accuracy, polar trajectory



Projected accuracy for Yukawa parameters



... and for non-Yukawa modification of gravity going to 100 AU is key.

If we are lucky we'll start a better study in the fall with JPL

Possible improvements:

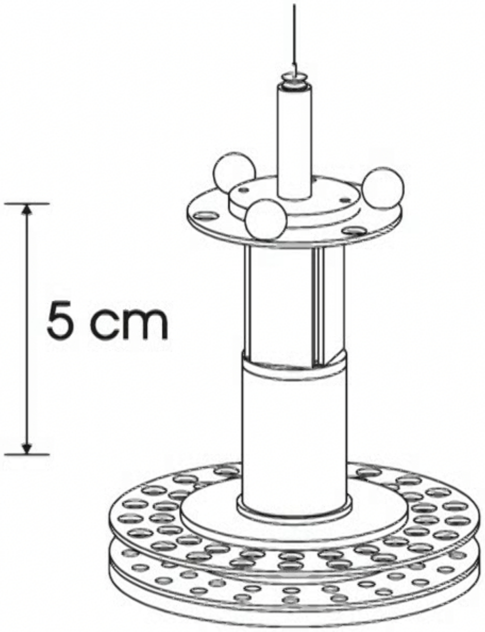
- ***Maybe they can go to 500AU in a reasonable time (this involves scary, very short distance flybys…)***
- ***Maybe the 10cm ranging accuracy is conservative and 1cm is aggressive.***
- ***Some engineering by someone who knows this stuff!***

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/cm³, 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…).

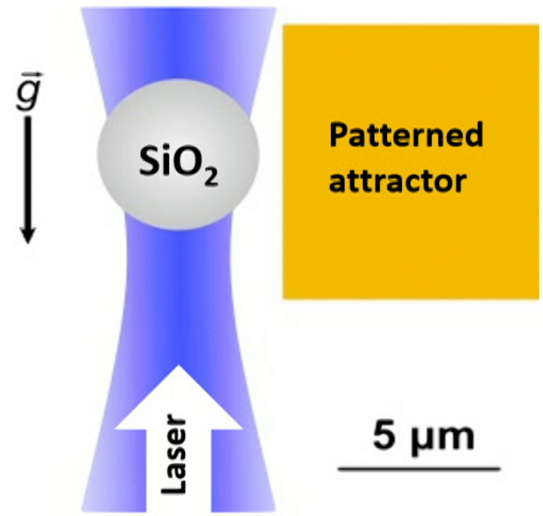
In addition most previous measurements use mechanical springs.

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.]

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

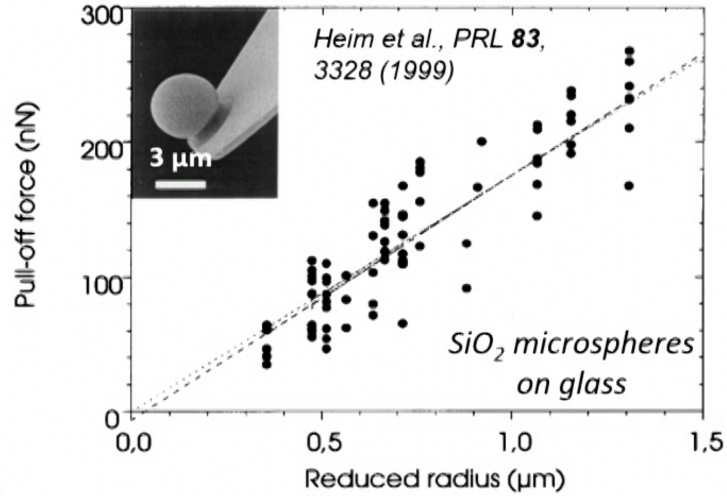


Ashkin & Dzierdzic, Appl.Phys.Lett. 19 (1971) 283
Geraci et al., PRL 105 (2010) 101101
Ranjit et al., Phys. Rev. A 91 (2015) 051805(R)

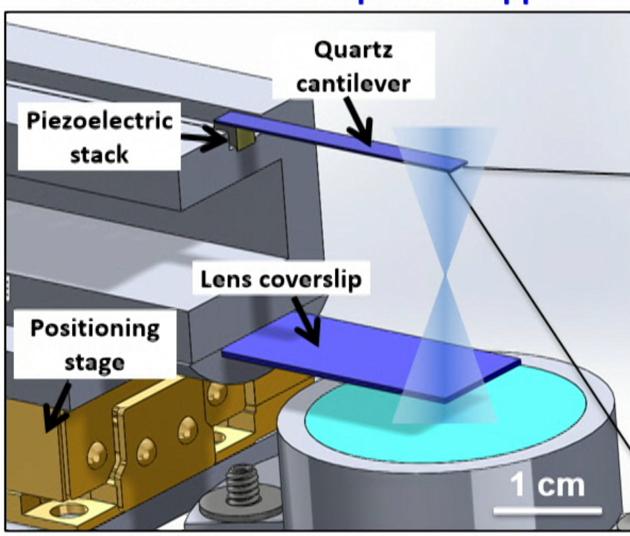
Trap loading

- 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

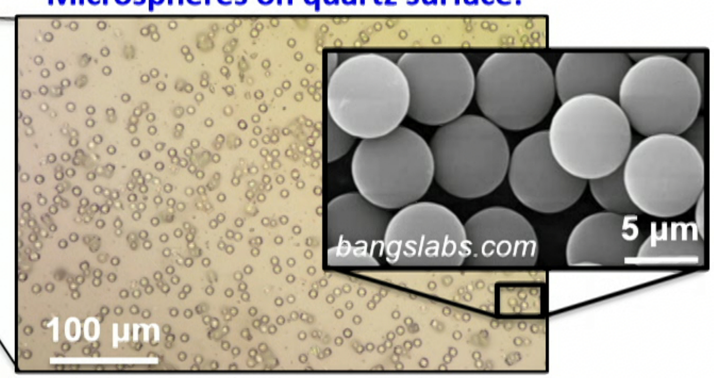
Pull-off force vs. microsphere radius:



Schematic of microsphere dropper:



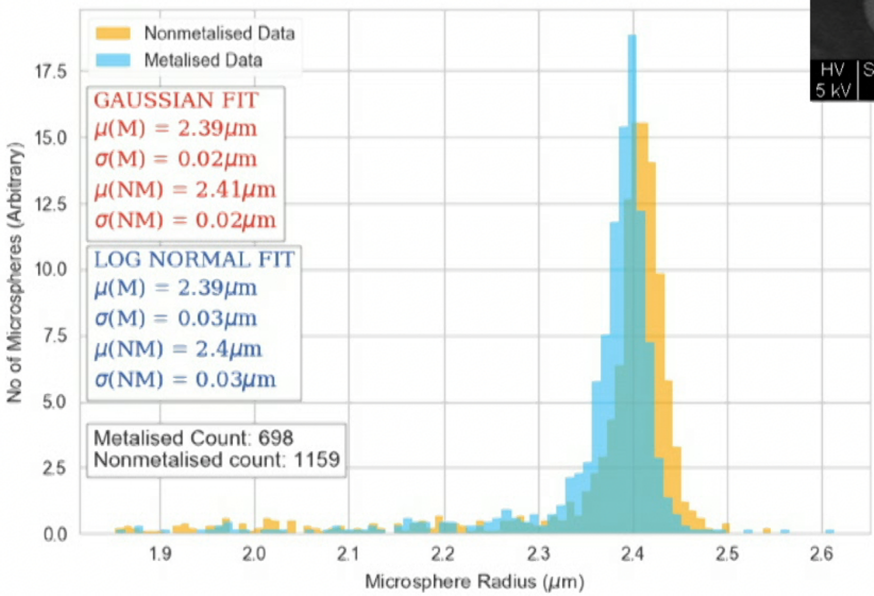
Microspheres on quartz surface:

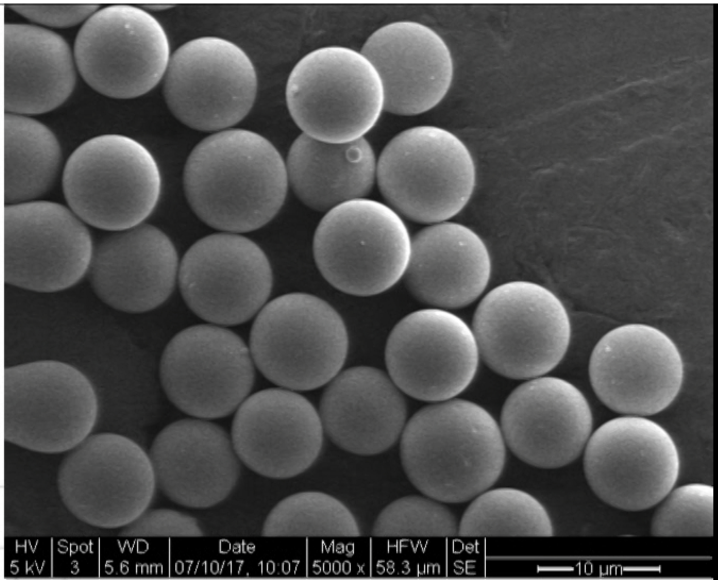


Our SEM analysis of 5μm diameter solution-grown silica microspheres

σ(R)/R ~ 1%

$$e = \sqrt{1 - \left(\frac{R-\epsilon}{R+\epsilon}\right)^2} \rightarrow \sigma(e) \sim 5\%$$

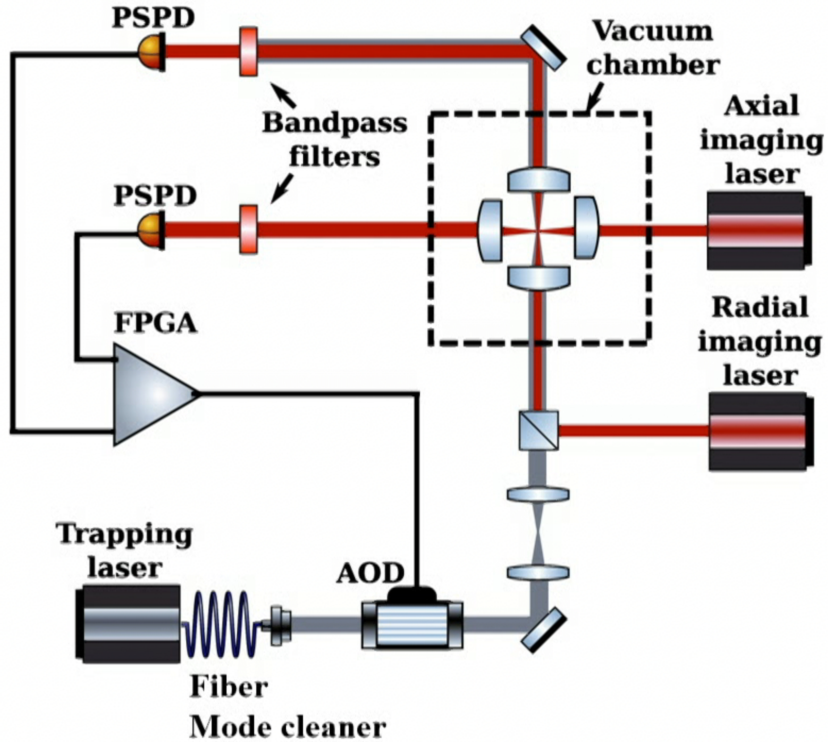




Microspheres also exist made of fused silica, titania, zirconia, sapphire and various plastics.

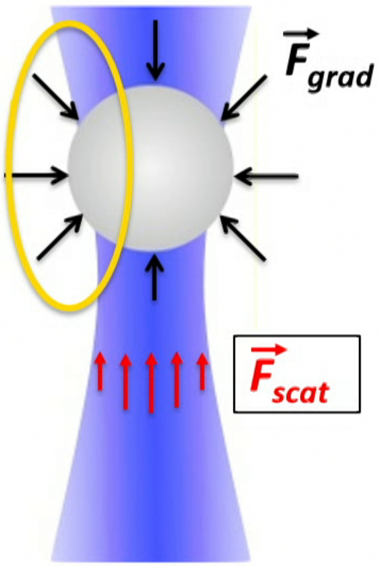
They can also have functional groups (COOH, NH_2) attached to their surface.

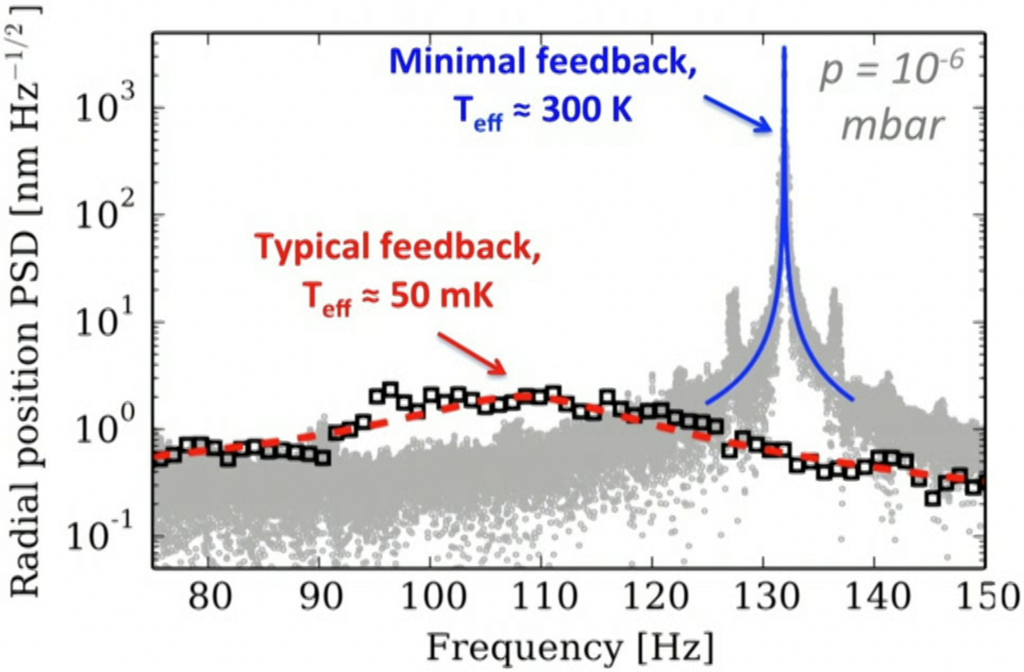
Initial, simplified optics setup



- 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.

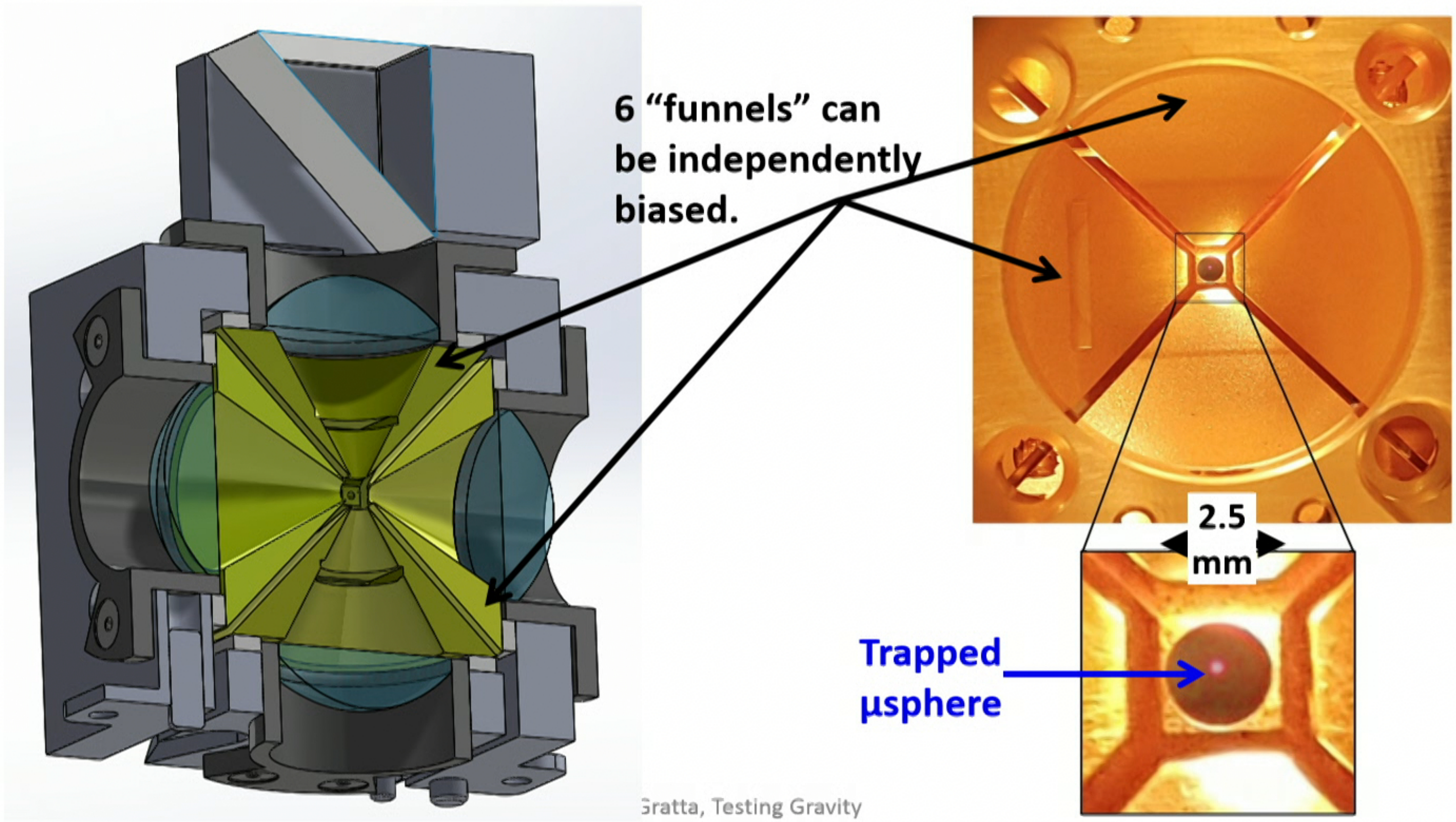




- ***Note that this is the "temperature" of the center-of-mass DOFs. We do not know the internal temperature of the µsphere.***
- ***Can maintain µspheres in this state for days.***

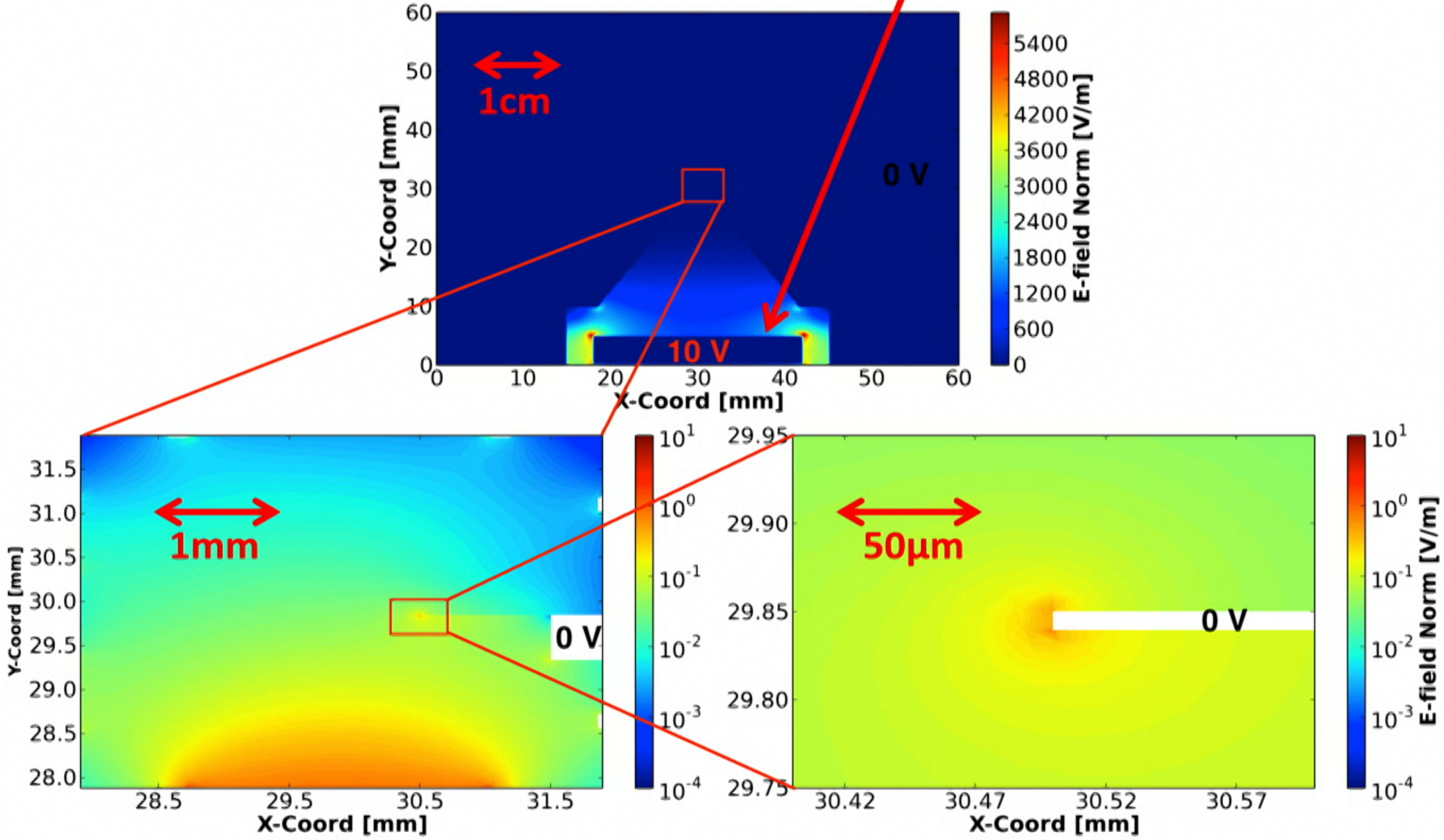
Important to provide good charge control around microsphere (even for microspheres that are overall neural)

- ➔ **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**



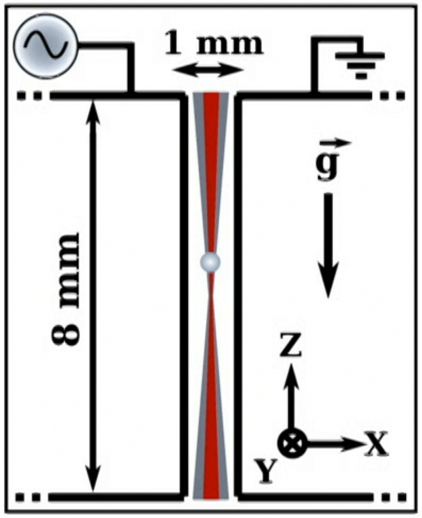
Each of the 6 funnels can be independently biased, but the shielding effect alone is dramatic.

Simulated field from 10 V on one of the lenses



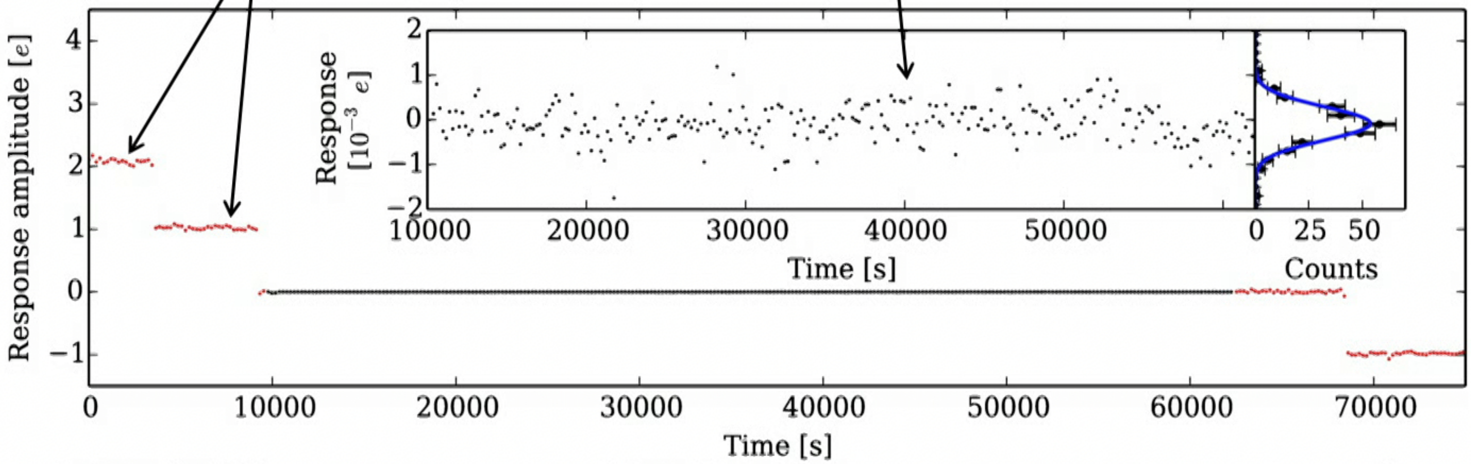
µspheres are often left in a charged state after being trapped.

- This can be measured by applying an RF potential to a set of plates
- µspheres are discharged by flashing a UV light.
- Probably this means that one can't use UV for the trapping laser



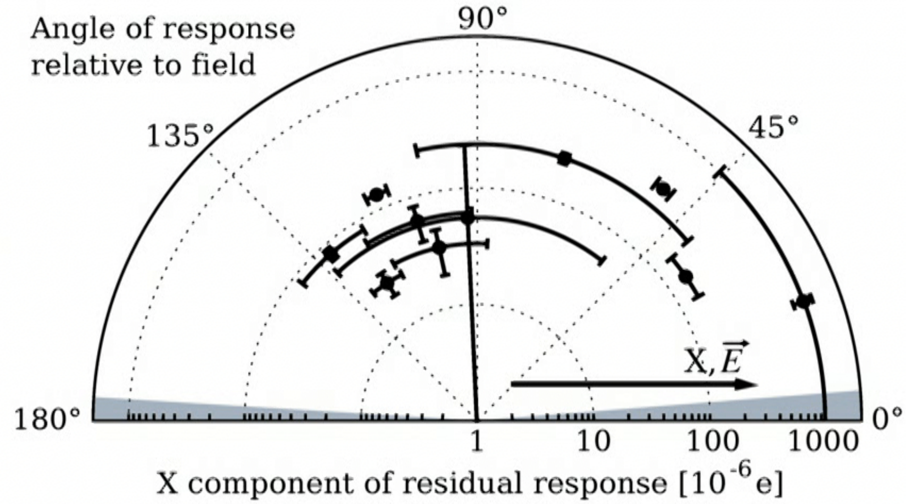
Quantized charge

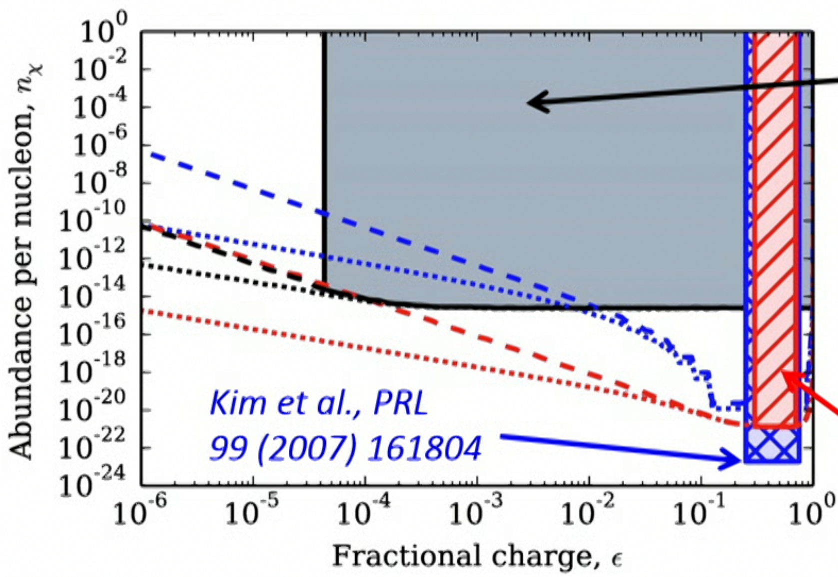
"0 charge" with increased 500 V RF amplitude.



How close to 0 is “0 charge”?

There are small residuals but the response is not consistent with an effective charge.





The largest residual can be conservatively used as a limit to particles with a “millicharge” bound into/onto the μspheres.

D.Moore, A.Rider, GG
Phys Rev Lett 113, 251801 (2014)

Marinelli et al., Phys. Rep. 85 (1982) 161

y

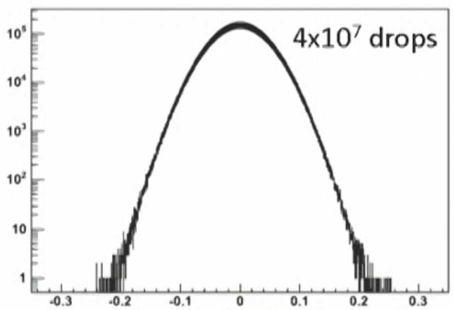
A continuation of this work is in progress of Dave Moore's lab at Yale

Previous measurements

Fractional charges

Previous Searches:Free Quarks

Astrophysical, bulk matter,
Accelerators..

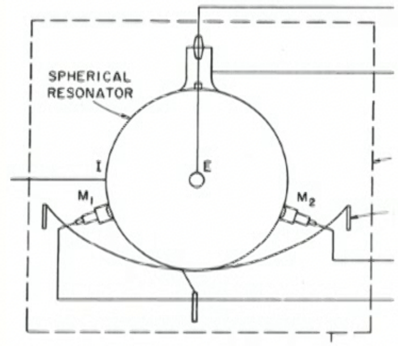


The q_c charge distribution in units of e

0.3g of matter were tested.
No evidence of millicharge was found.

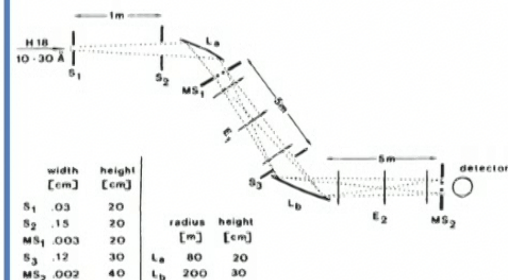
P. Kim et al.,PRL **99,** 161804 (2007)

Neutrality of Matter



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

H. Dylla et al., PRA 7, 1224 (1973)



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

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

4

F.Monteiro, MIT Workshop, Aug 2017

Neutrality of Matter

100 year old field, no improved sensitivity in the past 40 years

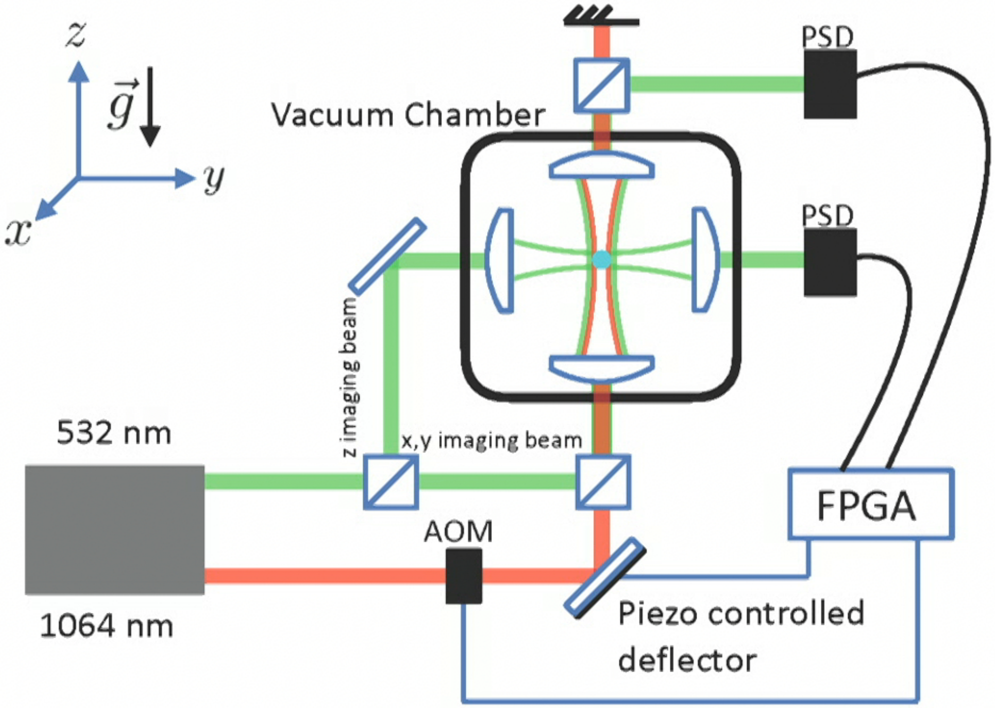
$$|q_p + q_e|/e$$

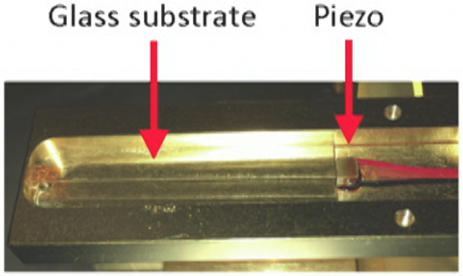
VALUE	DOCUMENT ID		COMMENT
$<1 \times 10^{-21}$	[1] BRESSI	11	Neutrality of SF_6
$<3.2 \times 10^{-20}$	[2] SENGUPTA	00	binary pulsar
$<0.8 \times 10^{-21}$	MARINELLI	84	Magnetic levitation
$<1.0 \times 10^{-21}$	[1] DYLLA	73	Neutrality of SF_6

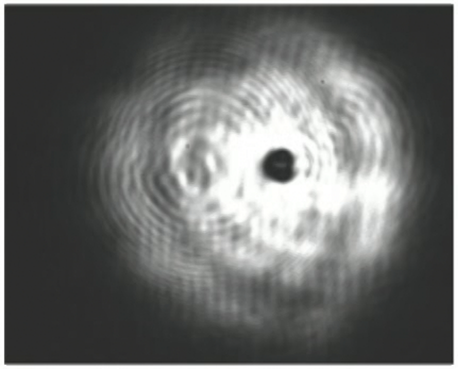
Year

Particle Data Group 2017

5





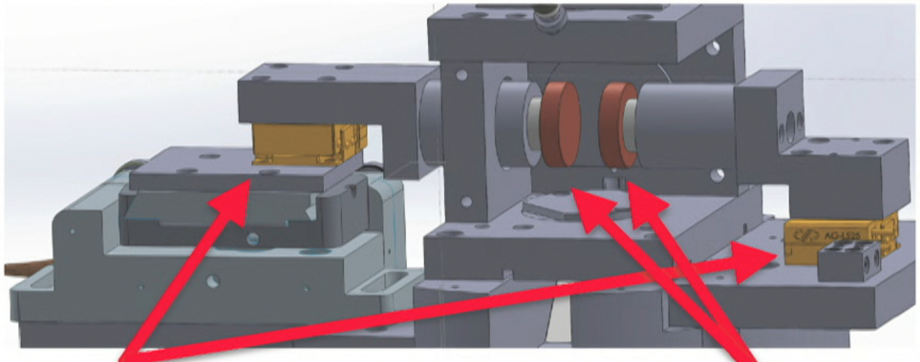


Useful to determine the size of the trapped sphere (15 μm).

Cool down the x,y,z degrees of motion.

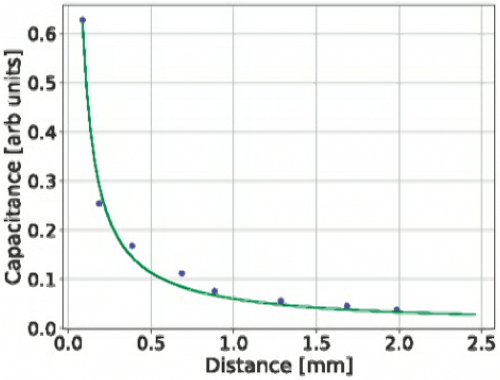
8

F.Monteiro, MIT Workshop, Aug 2017



- Adjustable position and angle
- < 1mm apart

- Mirror quality electrodes



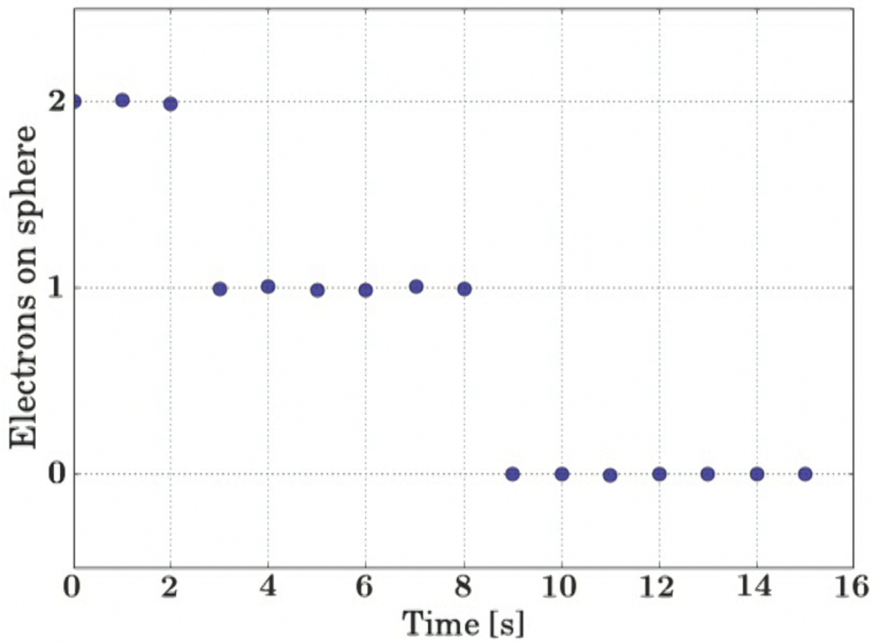
- 2 kV in between electrodes
  - > 10^6 V/m

9

F.Monteiro, MIT Workshop, Aug 2017

Sphere Discharge

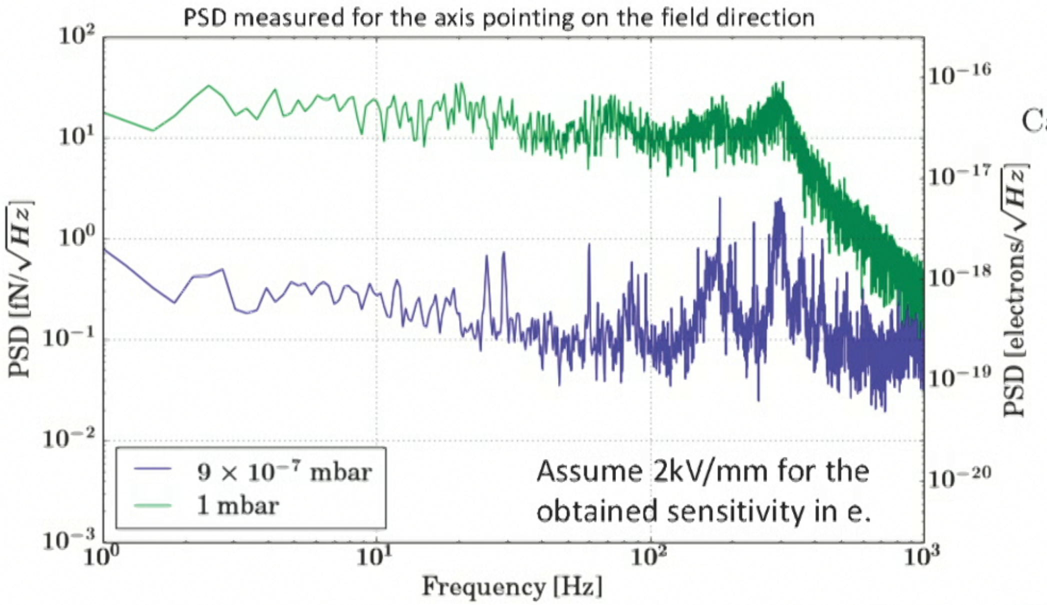
We have demonstrated controlled discharging with single electron precision.



- Measure microsphere response to an AC electric field while flashing with UV light.
- Week time-scale to charge.

F.Monteiro, MIT Workshop, Aug 2017

10



Calibration made with 1 electron

$\mathrm{d} = 15\,\mu\mathrm{m}$

$\mathrm{m} \approx 4 \times 10^{-12}\,\mathrm{kg}$

$\#\ \mathrm{protons} \approx 10^{15}$

Resonance around 300 Hz

Sensitivity → $3 \times 10^{-19}\,\mathrm{e}/\sqrt{\mathrm{Hz}}$

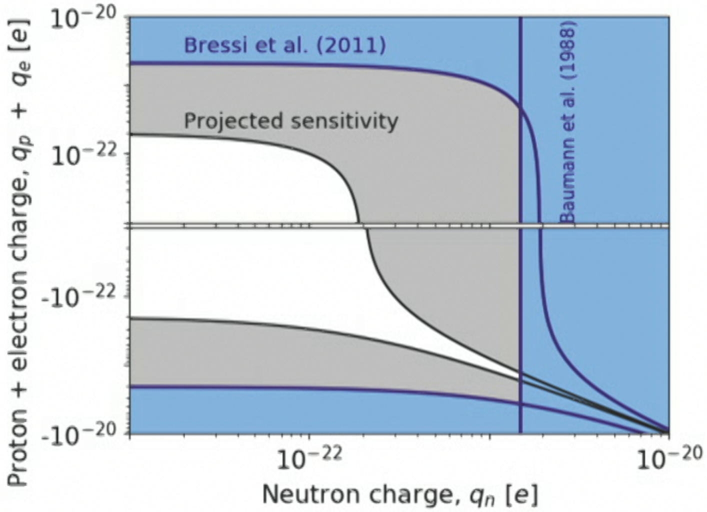
1 day of measurement → $1 \times 10^{-21}\,\mathrm{e}$

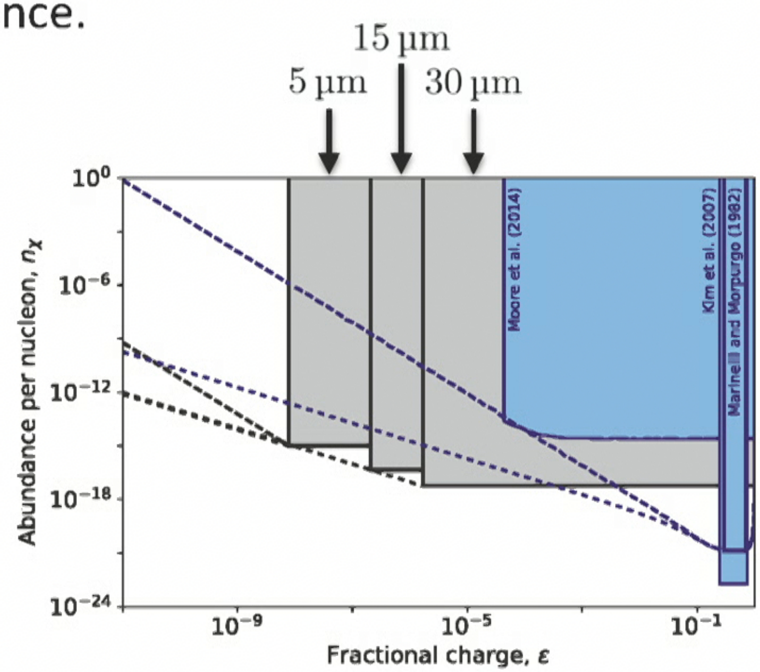
11

F.Monteiro, MIT Workshop, Aug 2017

Sensitivity Projection

- We expect to improve the current bounds on the neutrality of matter and millicharge abundance.



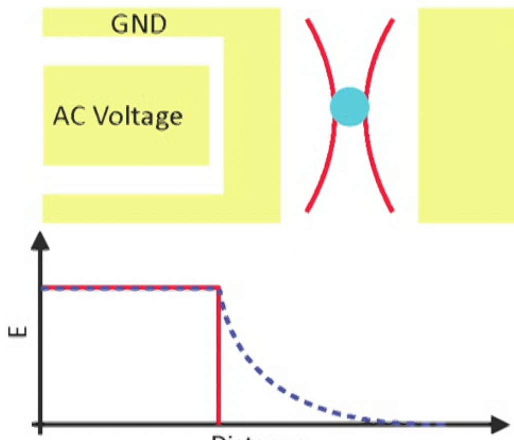


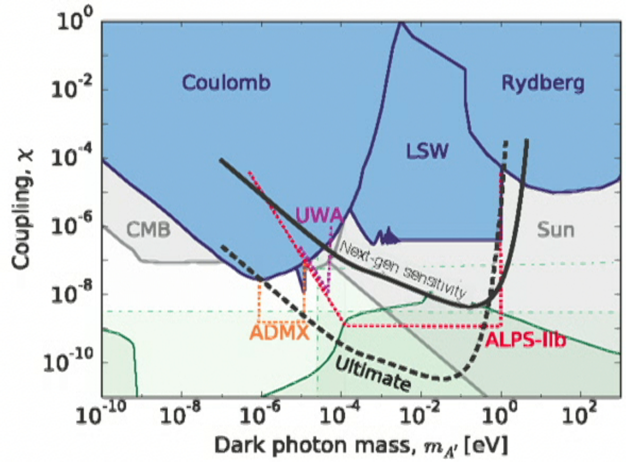
F.Monteiro, MIT Workshop, Aug 2017

Hidden Photons and Coulomb law deviations

Hidden photons modifies the Coulomb potential:

$$V(r) = \frac{\alpha}{r}(1 + \chi^2 e^{-m_{\gamma'} r})$$





Jaeckel et al., Ann. Rev. Nucl. Part. Sci., 60, 405 (2010)
R. Essig et al., arXiv:1311.0029 (2013)

18

F.Monteiro, MIT Workshop, Aug 2017

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

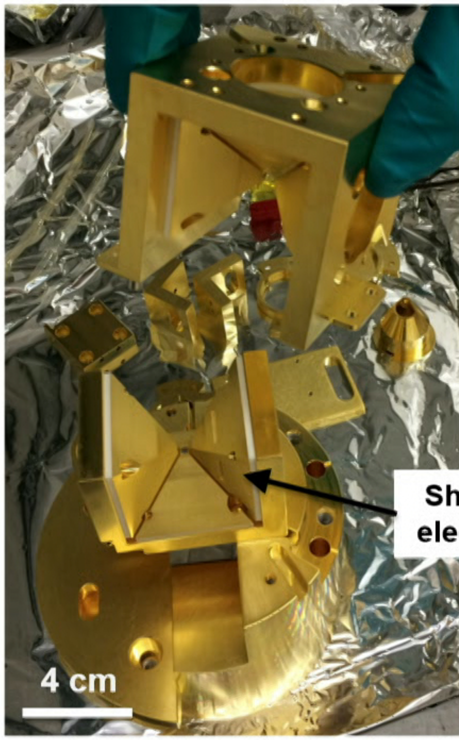
P. Hamilton, et al., Science 349, 849851 (2015), arXiv:1502.03888
B. Elder, et al., Phys. Rev. D 94, 044051 (2016), arXiv:1603.06587
M. Jaffe, et al., Nature Physics doi: 10.1038/nphys4189 *(2017), arXiv:1612.05171.*

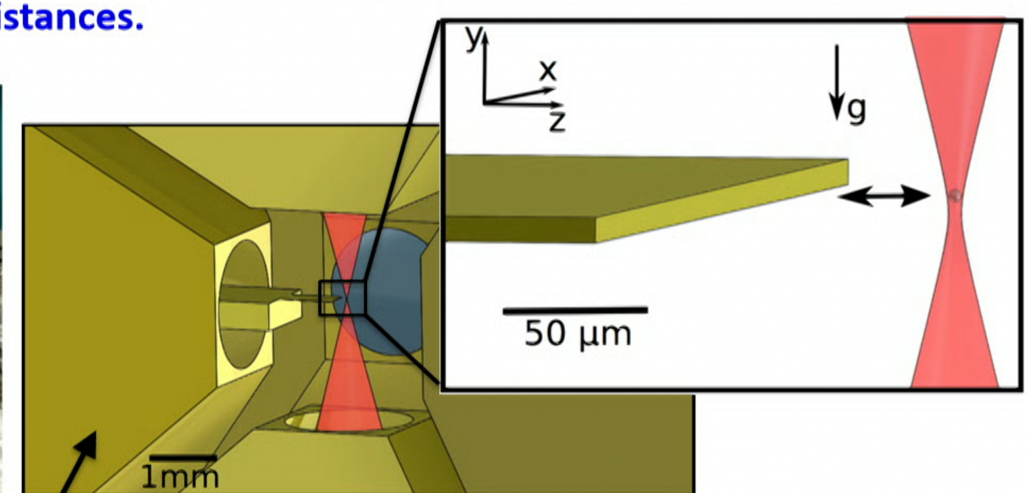
…and neutrons

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.





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}

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

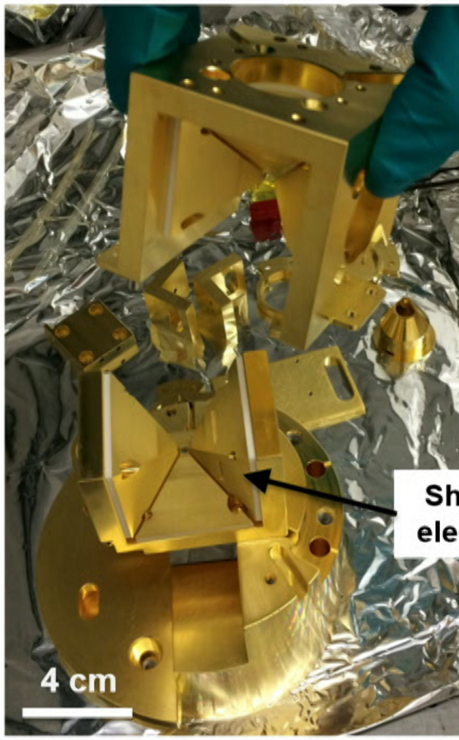
P. Hamilton, et al., Science 349, 849851 (2015), arXiv:1502.03888
B. Elder, et al., Phys. Rev. D 94, 044051 (2016), arXiv:1603.06587
M. Jaffe, et al., Nature Physics doi: 10.1038/nphys4189 *(2017), arXiv:1612.05171.*

…and neutrons

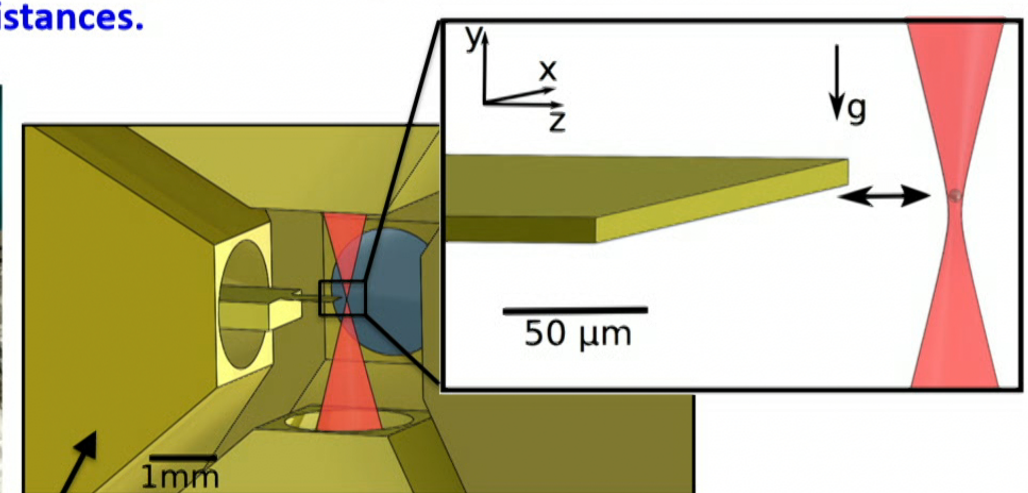
K. Li et al., Phys. Rev. D 93, 062001 (2016), arXiv:1601.06897.
H. Lemmel, et al., Phys. Lett. B 743, 310 (2015), arXiv:1502.06023.
T. Jenke et al., Phys. Rev. Lett. 112, 151105 (2014), arXiv:1404.4099.

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}

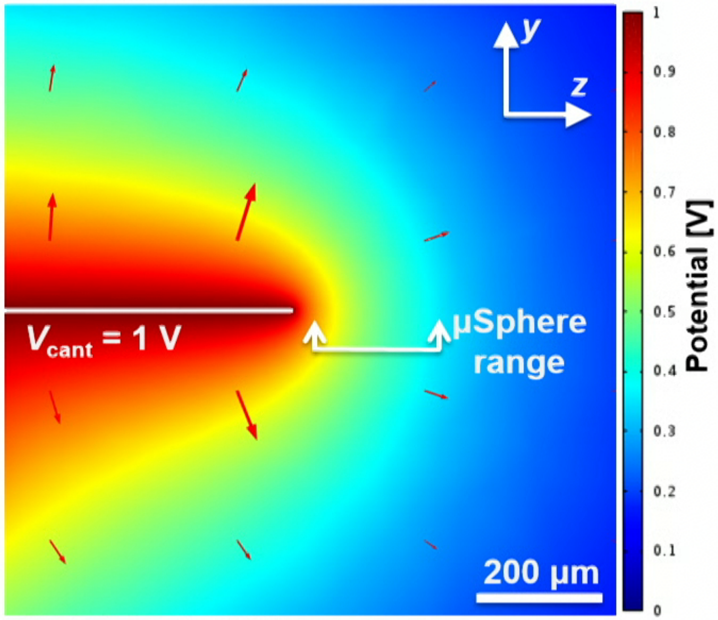
Electrostatic background

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

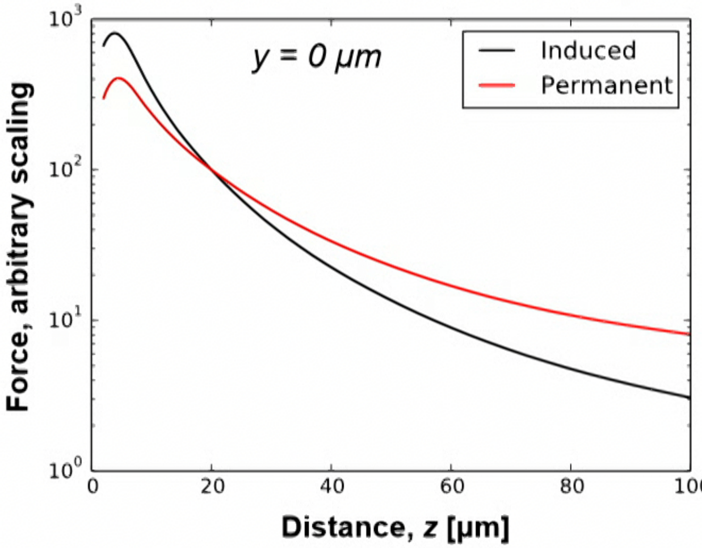
$$\vec{F} = (\vec{p} \cdot \vec{\nabla})\vec{E} \quad \Rightarrow \quad F_z \approx (p_{0z} + \alpha E_z)\frac{\partial E_z}{\partial z}$$

Permanent dipole **Induced dipole**

FEM calculation of electric potential:

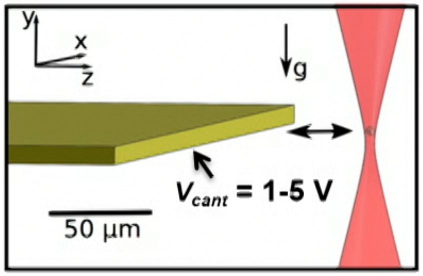


Force for permanent and induced dipole:

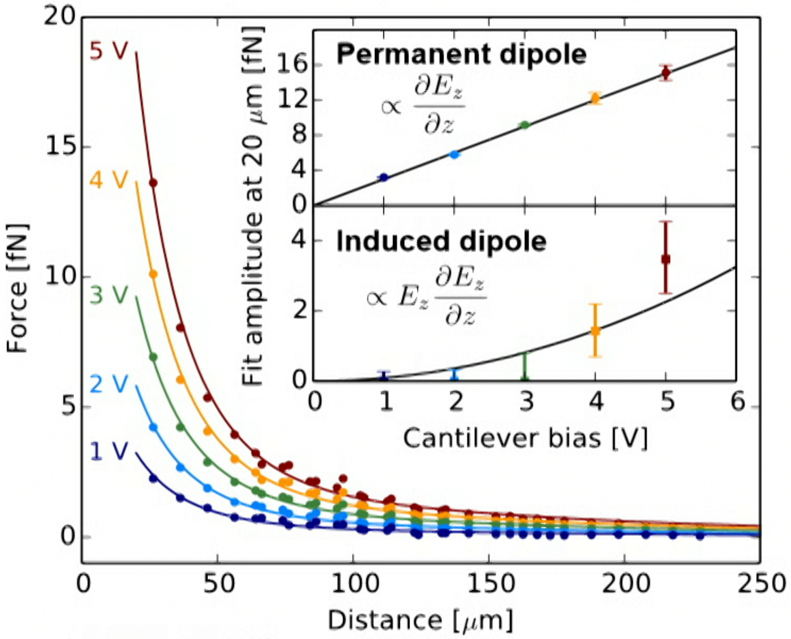


This background is measured:

- 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 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

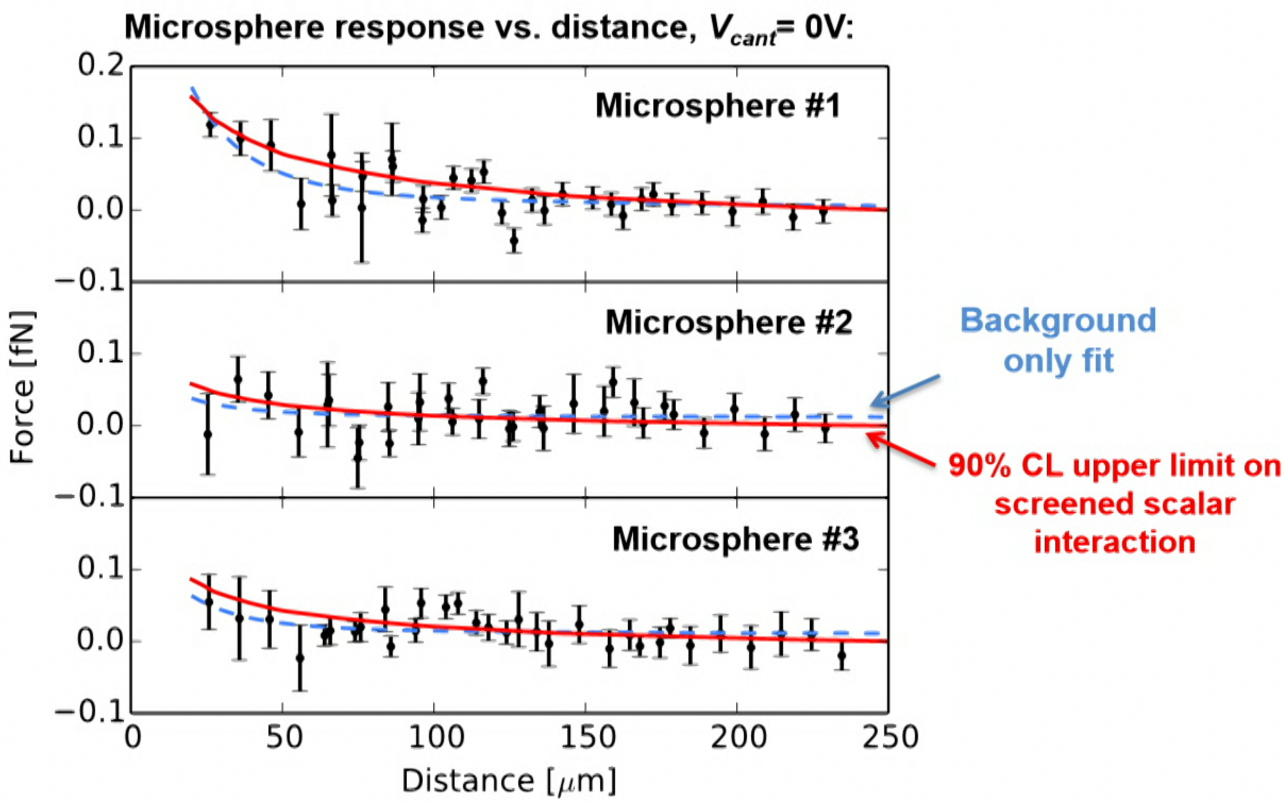
Polarizability, α, measured relative to:

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

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

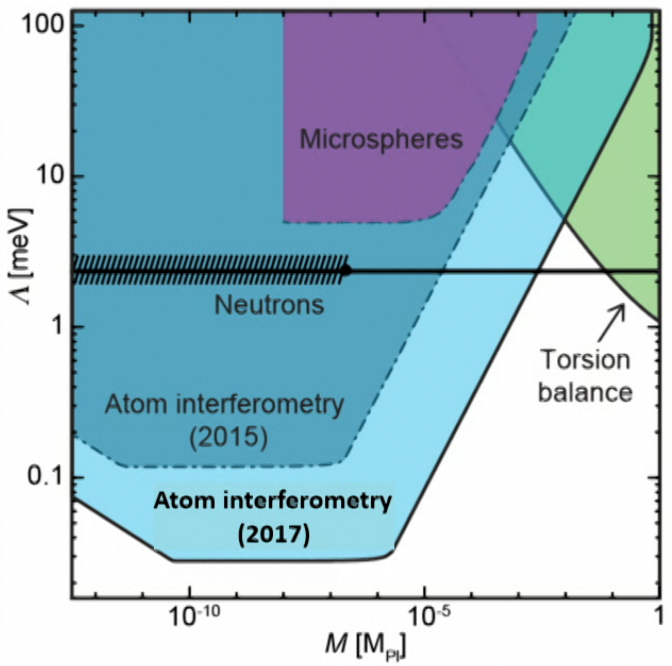
Then perform measurement with cantilever at "nominal 0 V"

Residual response consistent with <30 mV contact potentials



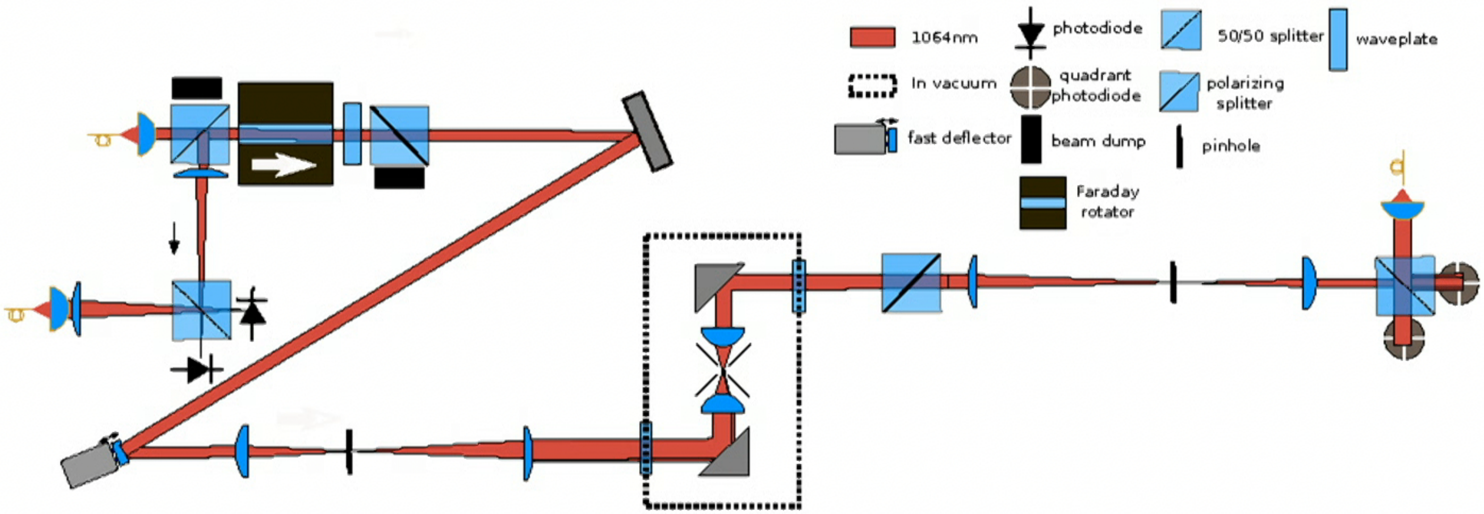
Results *(A.Rider et al. Phys. Rev. Lett. 117 (2016) 101101)*

- **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)

Schematic of density structured probe mass:

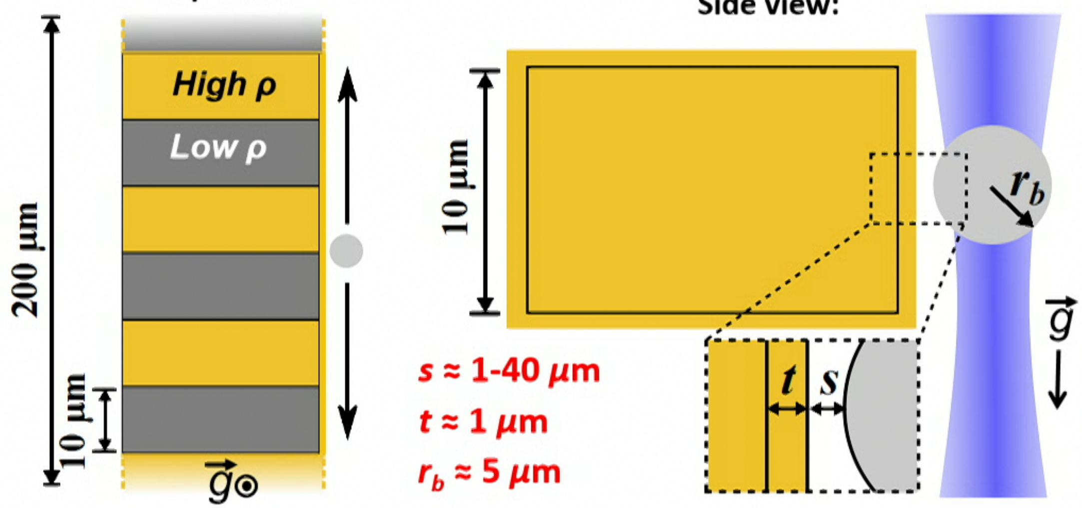
High ρ material:

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

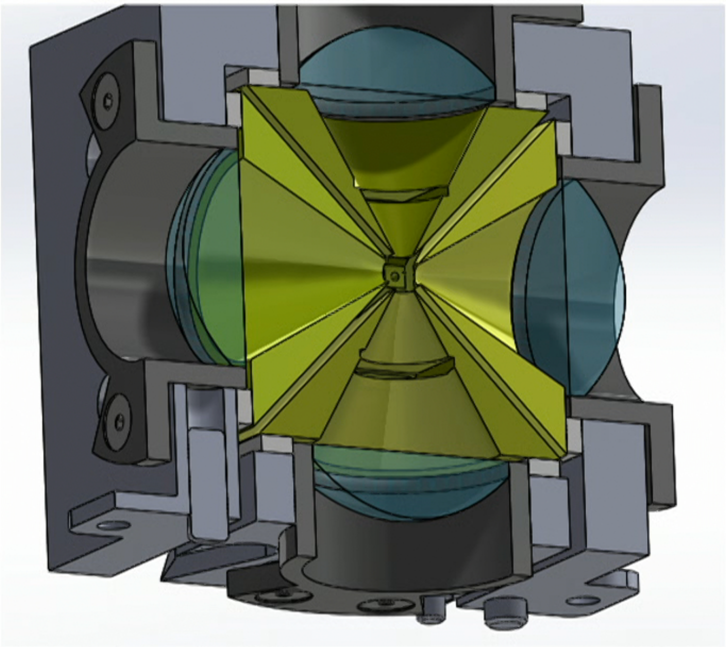
Low ρ materials:

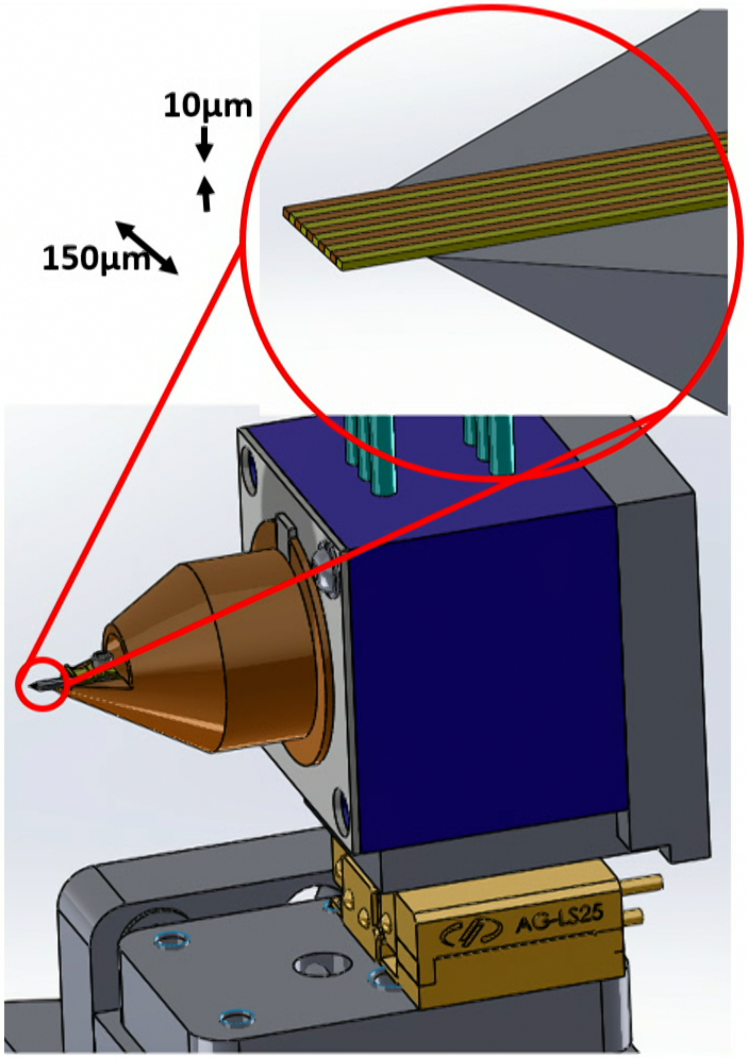
Cu, $\rho \approx 9$ g/cm^3

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

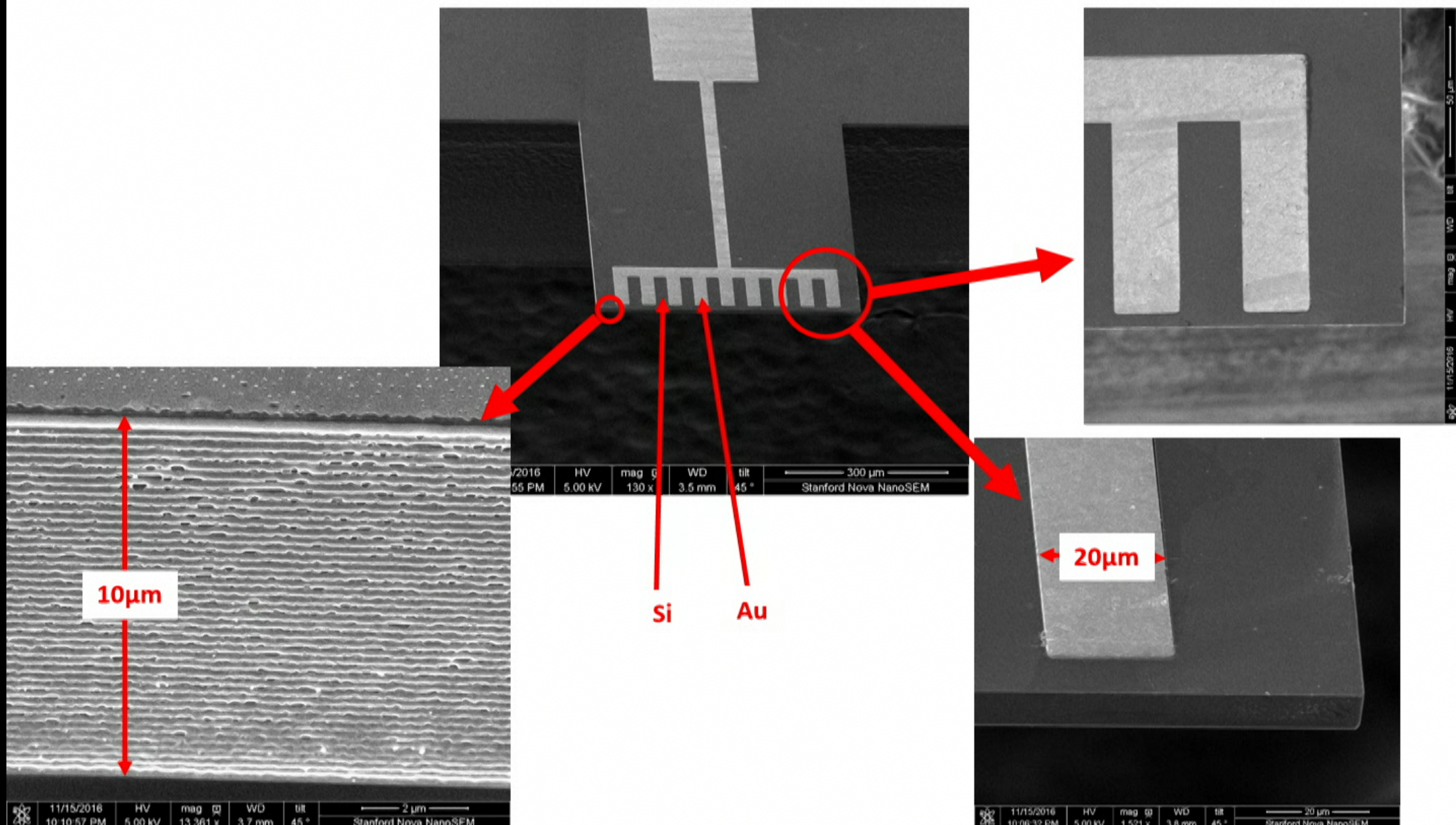


This is mounted on a fast flexure stage
to swing it in front of the μsphere.

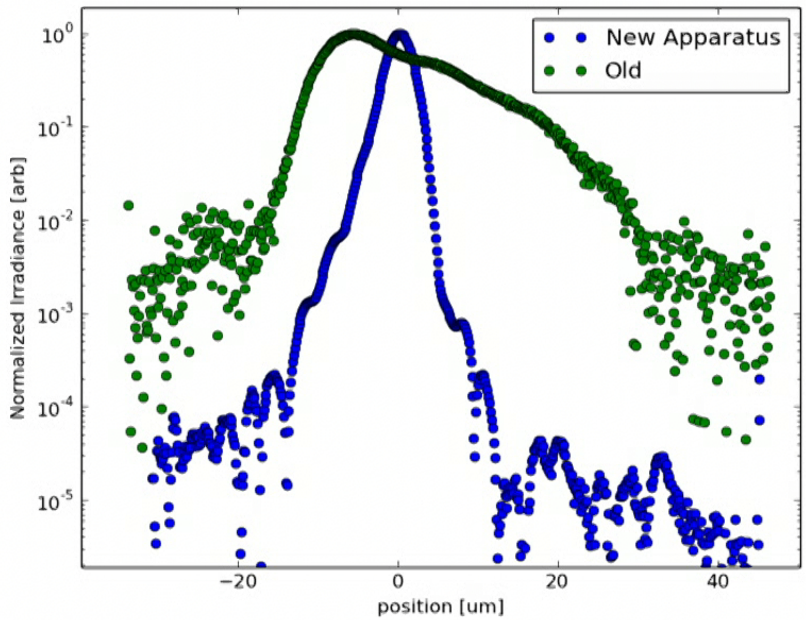




Si-Au attractors fabricated and ready for use

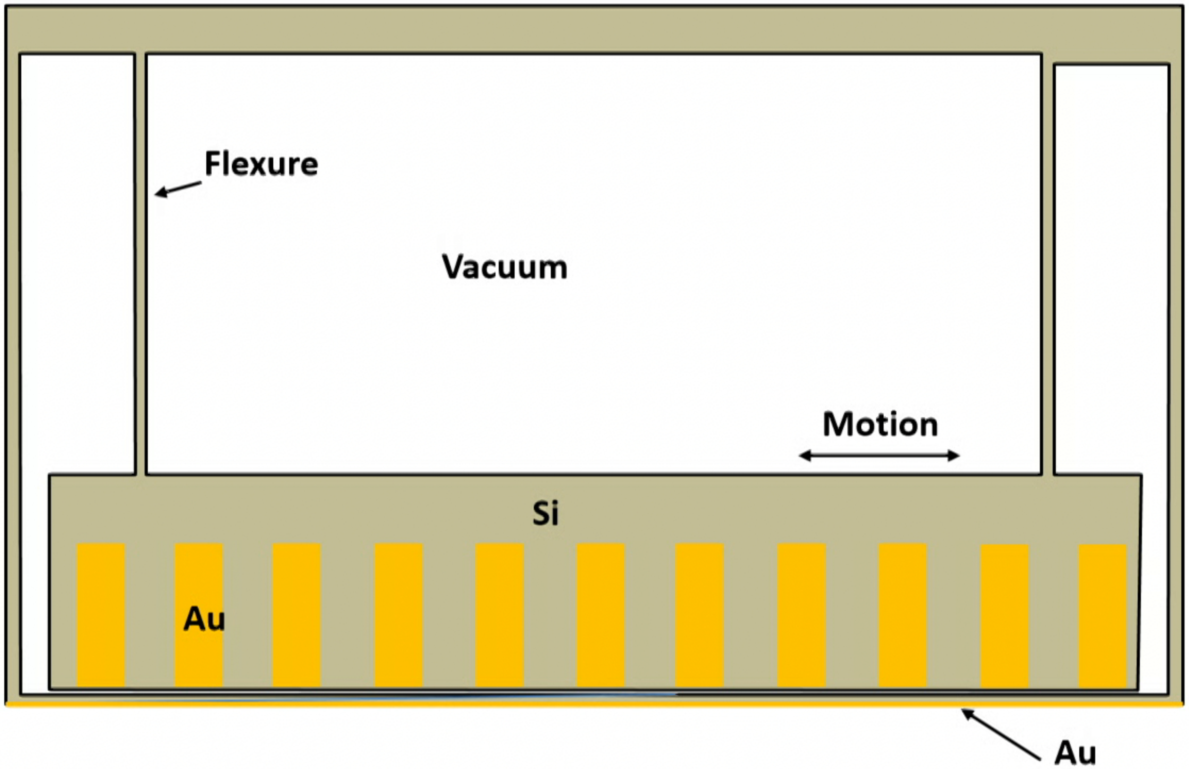


Better laser mode to limit light scattered from near-by attractor



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

Concept of attractor with stationary shield



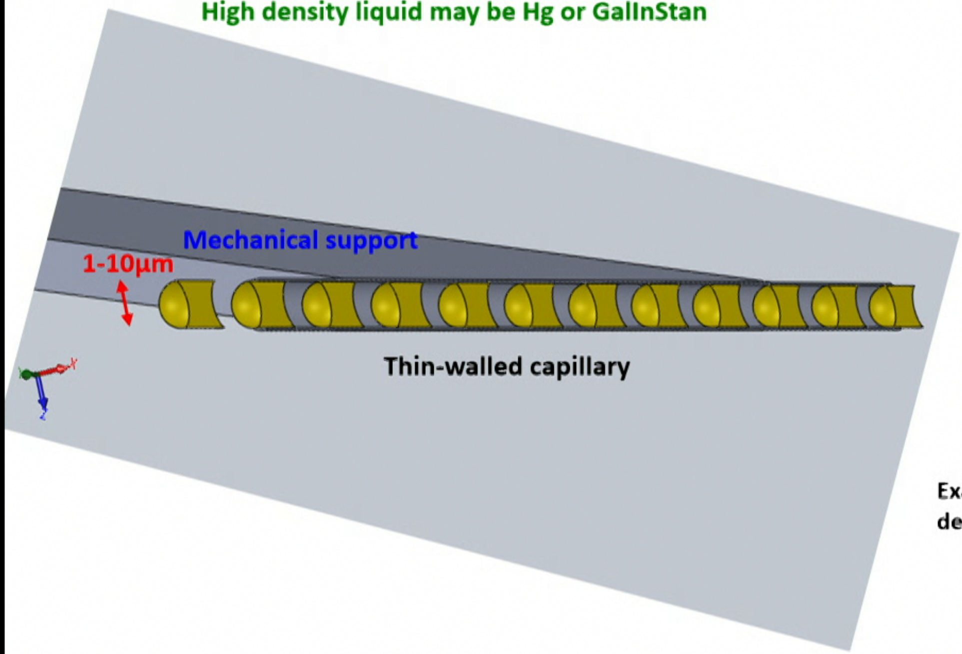
Fabrication technology very similar to the one already defined

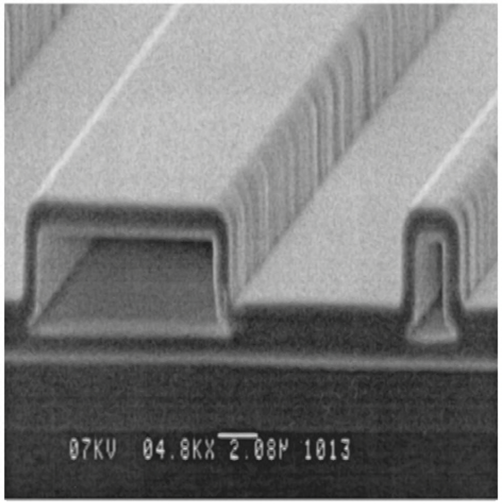
Drive mechanism not yet designed

Stationary shield can also be retrofitted on other, existing designs

Concepts for fluidic periodic attractors

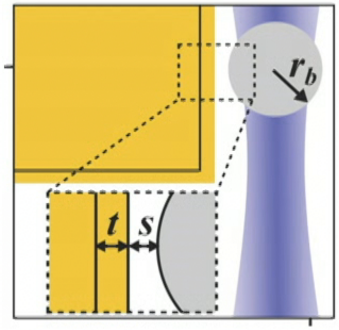
Alternating droplets of low and high density liquids
High density liquid may be Hg or GalInStan



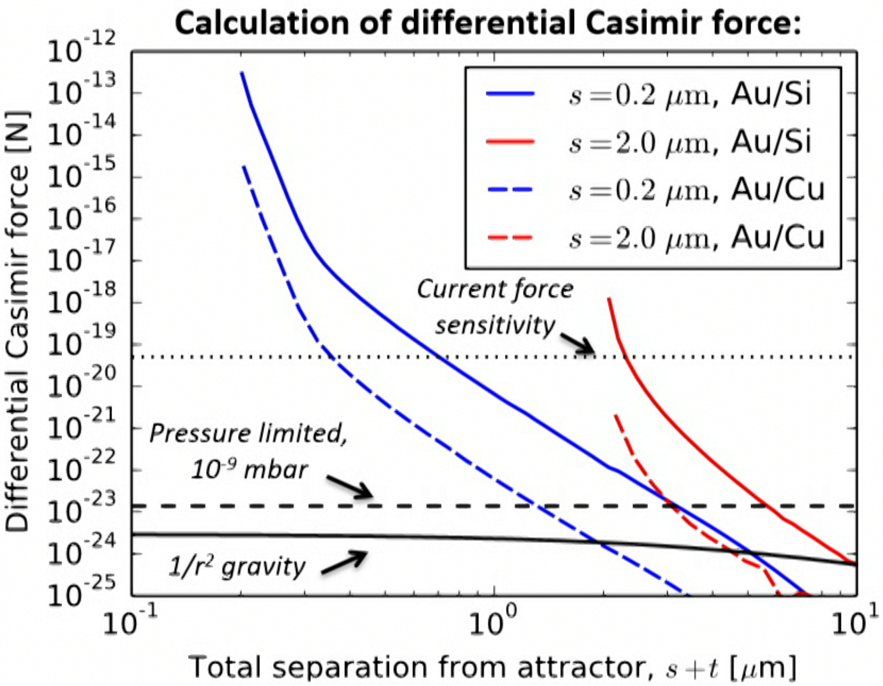


Example of microchannel in Si
deBoer et al J Microelectromechanical Sys 9 (2000) 94

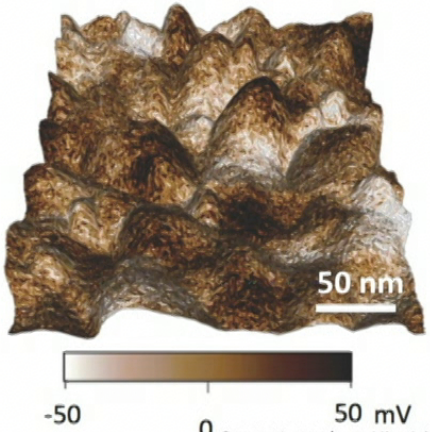
Expected backgrounds: Casimir forces



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



Topography and surface potential for sputtered Au film:



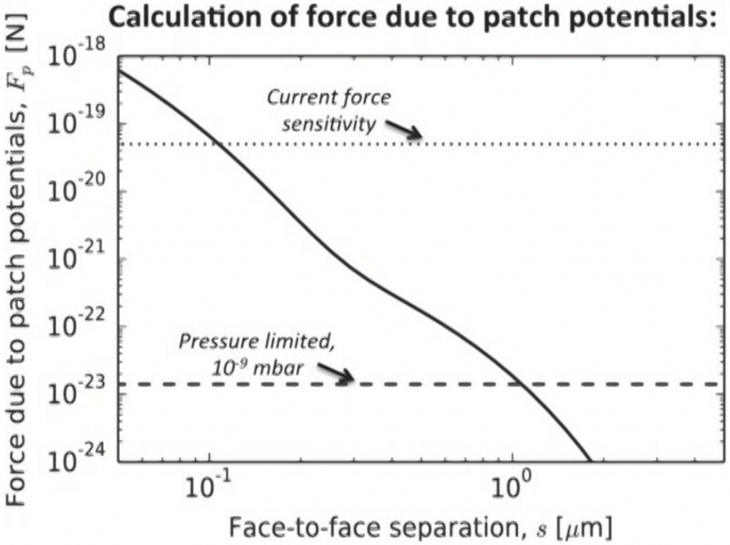
Garrett et al., arXiv:1409.5012

Expected backgrounds: Patch potentials

- **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:



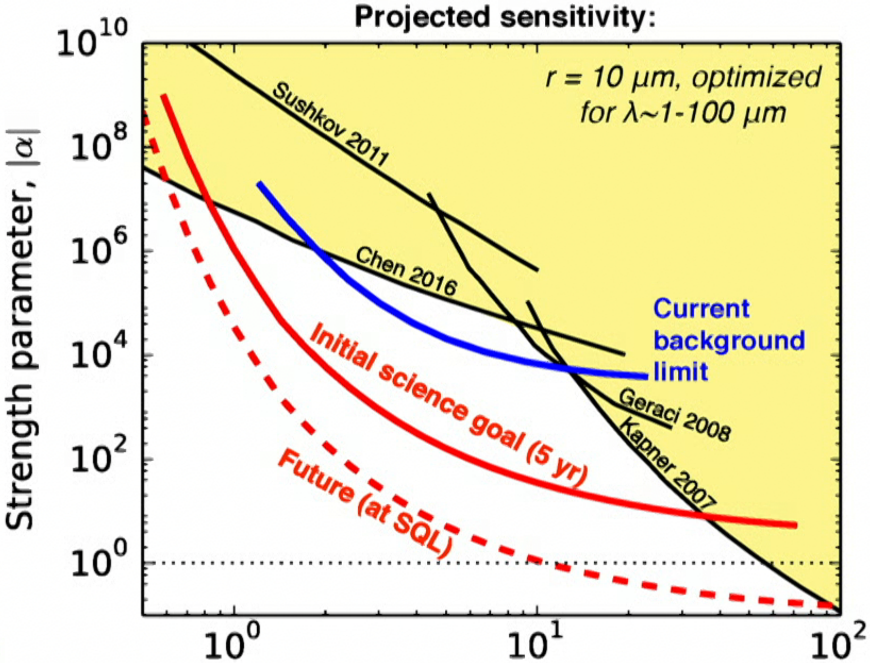
Projected sensitivity

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

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



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)

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 optical 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 (see also Andy's talk!)
- There are more applications to fundamental measurements, some known, some unknown! Help us figure out what else to use this for!

C.van Assendelft[3], B.Buscaino[1], D.DeBra[1], C.Blakemore[1],
A.Fine[3], S.Ghosh[3], P.W.Graham[1], N.Kurinsky[1],
M.Louis[2], M.Lu[1], F.Monteiro[3], D.C.Moore[3],
A.D.Rider[1], S.Roy[1], T.D.Wiser[1]

[1]*Physics Department, Stanford University*
[2]*Ecole Polytechnique*
[3]*Physics Department, Yale University*