First search for new long range forces at the micron scale using optically levitated microspheres

Charles Blakemore, Stanford University

10 June 2021

Challenges for Witnessing Quantum Aspects of Gravity in a Lab, ICTP-SAIFR

EVERYTHING IS A TEAM EFFORT

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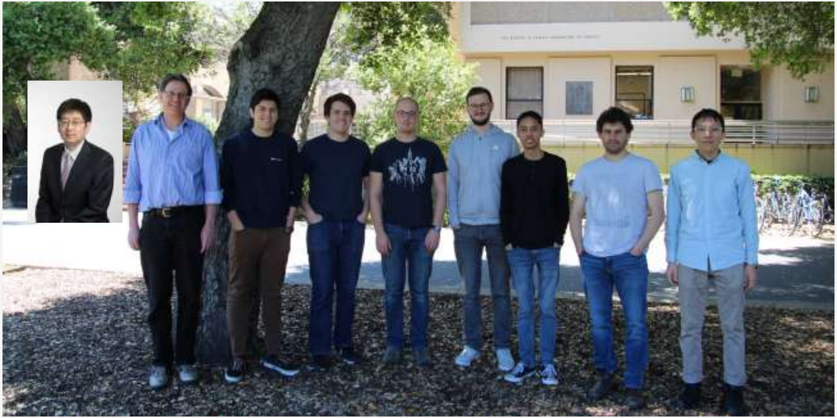

NSF
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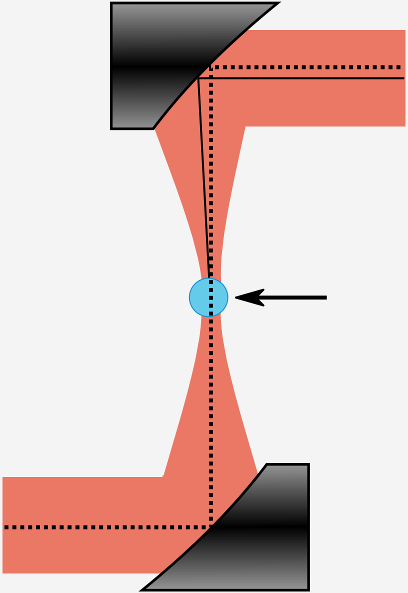
OVERVIEW

1. Introduction
   - Measuring gravity at short range
   - Optical tweezers and our system
2. Test- and source-mass characterization
   - Mass/radius measurements
   - Attractor and shield fabrication
3. Searching for non-Newtonian gravity
   - The measurement, the backgrounds, and resultant limits
   - Future improvements



MODIFICATIONS TO GRAVITY

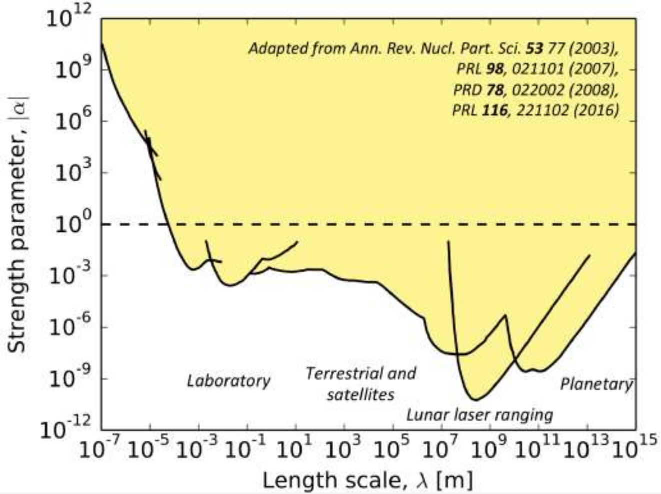
- Assume classical Newtonian gravity, add another term
- If force carrier is massive $\rightarrow$ Yukawa potential
- Between two point masses m_1 and m_2:

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

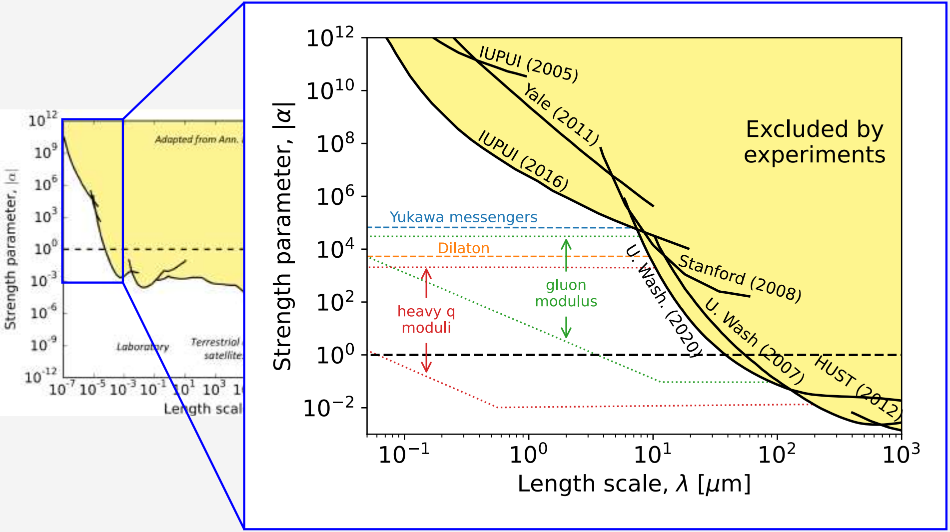
- Strength: α, length-scale: λ
  - Just a particular parameterization
  - Allows comparison across a huge number of scales
  - Investigating any deviations from $V \propto (1/R)$ is interesting

THE LANDSCAPE OF MEASUREMENTS

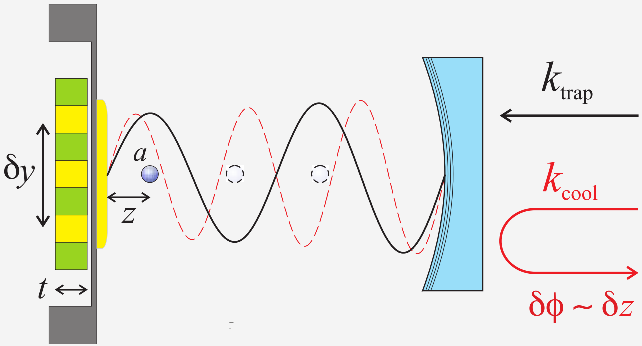
- Slightly outdated, but tells most of the story



MEASURING GRAVITY (AT SHORT RANGE)



- Proposed by **Geraci *et al.***
- Position a microsphere within an optical cavity
- Introduce a source mass with modulated density
- Move the source mass and look for a correlated signal



PRL ***105****, 101101 (2010)*

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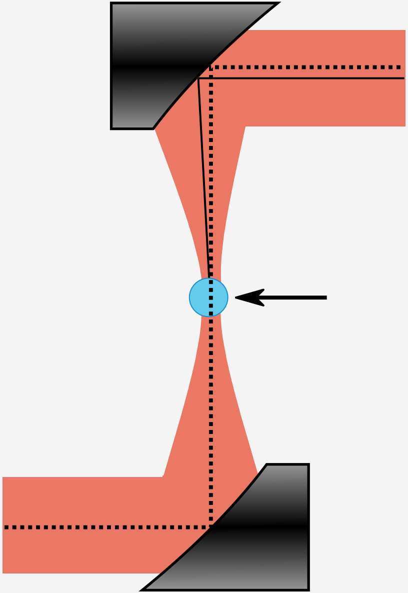
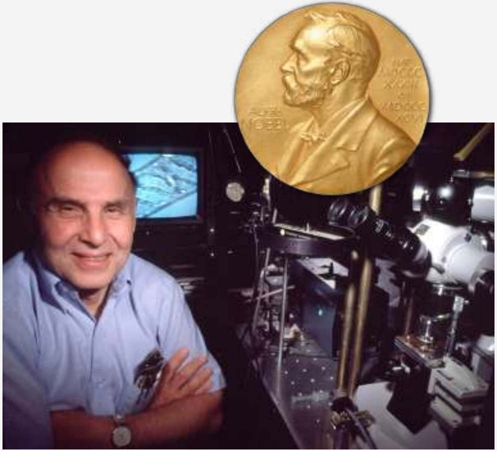


OPTICAL TWEEZERS

- Invented by Arthur Ashkin at Bell Labs in the early 1970s
  - First trapped particles in a liquid
  - Suggested vacuum operation, then demonstrated
  - First implementation of feedback
  - Predicted all sorts of things

are still free to rotate. Thus optical levitation with feedback has many potential applications, for example, in laser fusion experiments,[2] construction of ultracentrifuges, study of photoemission,[5] and measurement of gravity forces. This feedback scheme has features in

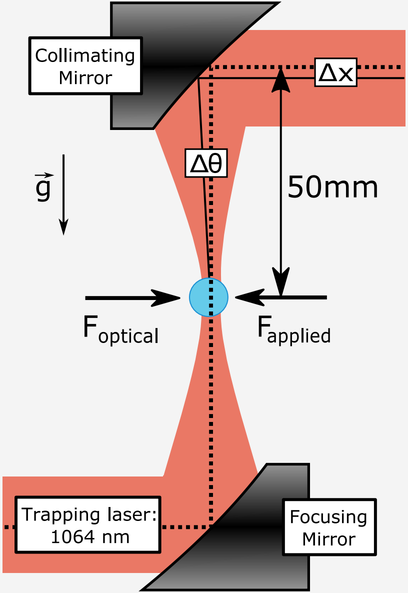
Appl. Phys. Lett. ***30***, *202 (1977)*



OPTICAL TWEEZERS, ASHKIN STYLE

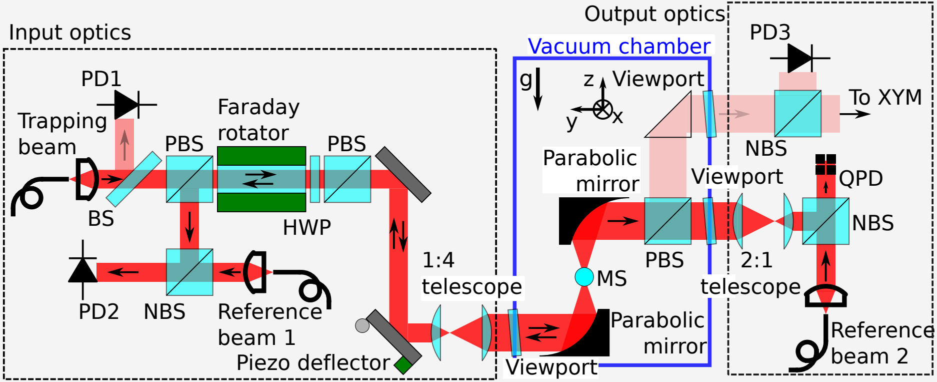
- Vertically oriented optical trap
  - For our system:
  - Single-beam, 1064 nm
  - $r = 2.5 - 3.8\ \mu$m silica microspheres
- Gravity stabilizes vertical direction
- Radial forces deflect outgoing beam
  - Use microsphere as test mass

$$F_{opt} \approx \epsilon \frac{P_{opt}}{c} \Delta\theta \sim 1\,\mathrm{fN} \left(\frac{P_{opt}}{\mathrm{mW}}\right) \left(\frac{\Delta\theta}{\mathrm{mrad}}\right)$$



THE FULL OPTICAL SYSTEM

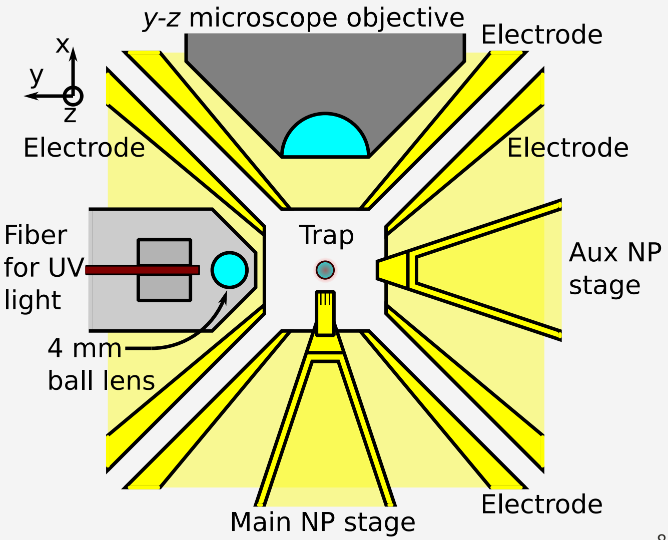
- One beam to rule them all: trapping, feedback, imaging
- Two interferometric measurements for transmitted and retroreflected light



Rev. Sci. Instrum. ***91****, 083201 (2020)*

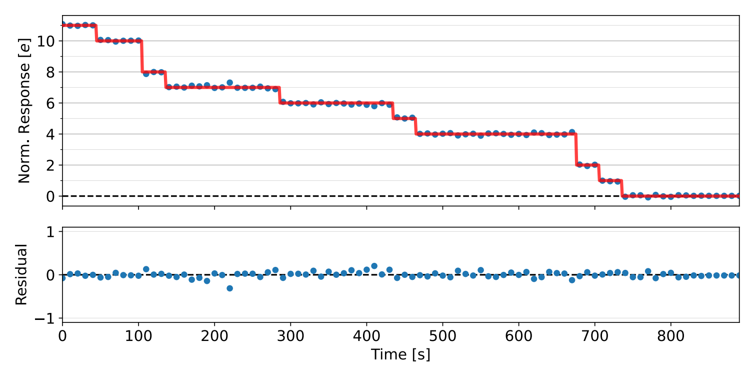
ELECTROSTATIC SHIELDING

- Stray electric fields represent a significant background
- There are six identical shielding electrodes making a cubical cavity
- Bore holes for optical and mechanical access
- Can drive known electric fields to calibrate microsphere response



CALIBRATING THE SYSTEM

- Microsphere is usually charged after trapping → Discharge with UV photons
- Can see response to an oscillating electric field decrease in steps
- Unit step size corresponds to a single electron



PRL ***113****, 251801 (2014)*

INSIDE THE CHAMBER

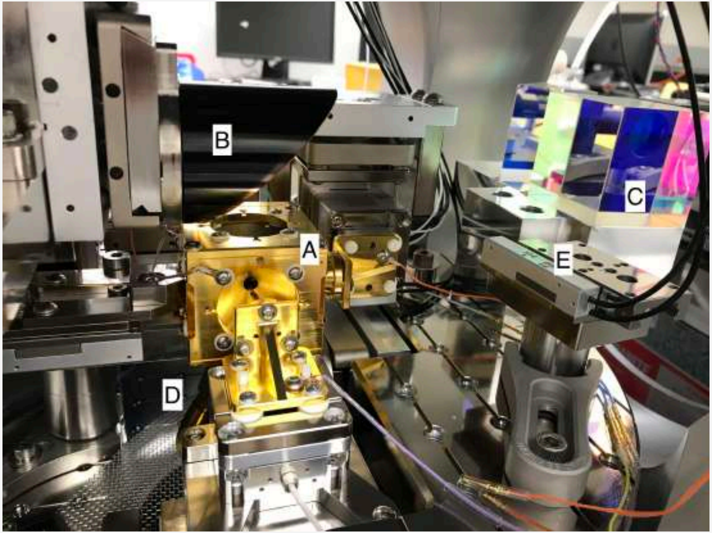
A Electrode housing

B Collimating parabolic mirror

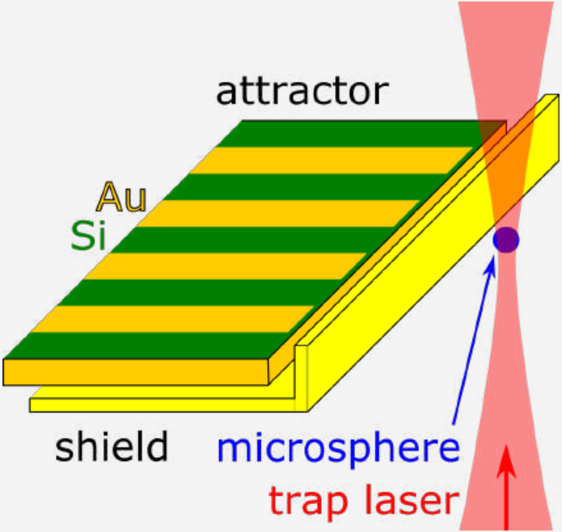
C PBS Cube

D Focusing parabolic mirror

E Bead dropper



SCHEMATIC DEPICTION OF A SHORT-RANGE FORCE MEASUREMENT



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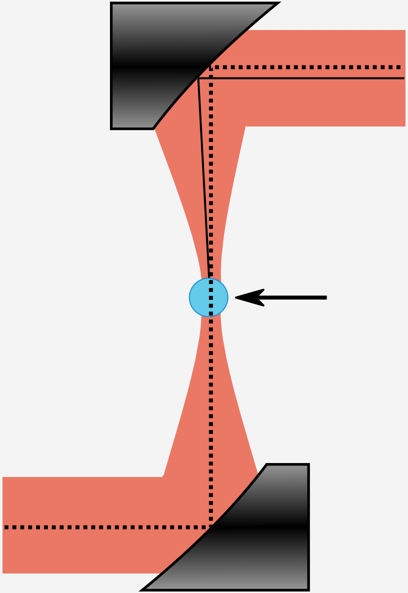
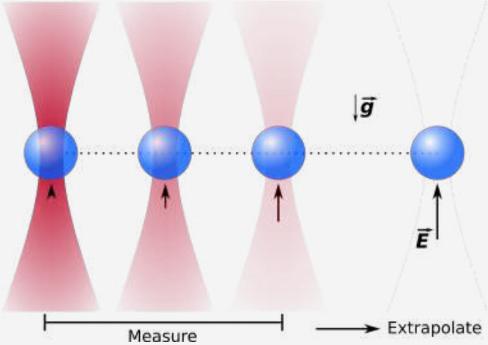
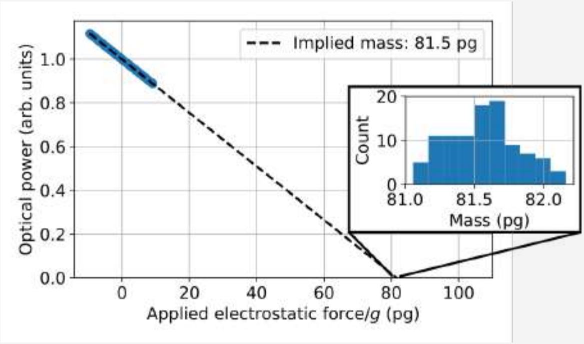


MICROSPHERE MASS MEASUREMENT

- Co-levitate with electrostatic field, extrapolate to find mass

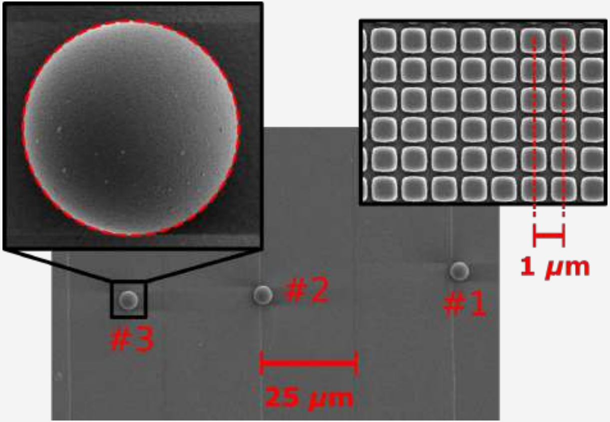
$$\sum F_z = F_{\mathrm{opt},z}(t) + qE_z(t) - mg = 0$$





PRApplied ***12*** *024037 (2019)*

- “Catch” microspheres after they’re trapped (surprisingly hard)
- Transfer to SEM on a mechanical probe, normally used for inducing forces



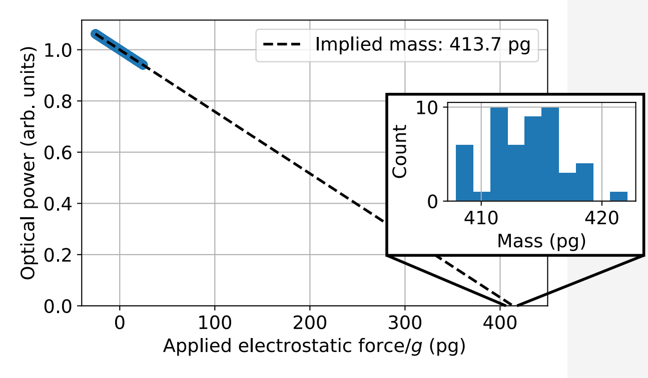
CALCULATION OF DENSITY

- First direct characterization of levitated particle density
- Much different than fused silica and manufacturer provided number
  - $\rho_{\mathrm{SiO_2}} = 2.2 - 2.4\ \mathrm{g/cm^3}$ and $\rho_{\mathrm{Bangs}} = 1.8\ \mathrm{g/cm^3}$

MS	m (pg)	r (μm)	ρ ($\mathrm{g/cm^3}$)
No. 1	$84.04 \pm 0.80\,(\mathrm{stat.}) \pm 1.52\,(\mathrm{sys.})$	2.348 ± 0.038	$\mathbf{1.550 \pm 0.080}$
No. 2	$83.87 \pm 1.14\,(\mathrm{stat.}) \pm 1.51\,(\mathrm{sys.})$	2.345 ± 0.037	$\mathbf{1.554 \pm 0.079}$
No. 3	$85.48 \pm 0.17\,(\mathrm{stat.}) \pm 1.54\,(\mathrm{sys.})$	2.355 ± 0.038	$\mathbf{1.562 \pm 0.081}$

DECIDED TO USE LARGER MICROSPHERES

- Expected radius seems to be consistent with manufacturer (they sell them by size)
    - Given: $r = 3.78 \pm 0.1\ \mu$m
    - Meas: $r = 3.76 \pm 0.1\ \mu$m
- Implies $\rho \approx 1.85$ g/cm^3
- Thus, just need to measure the mass and we “know everything”



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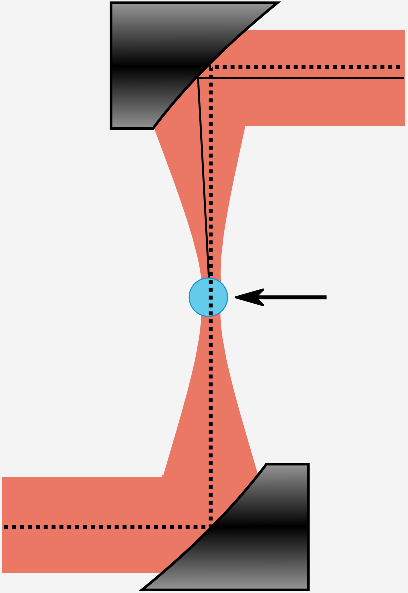
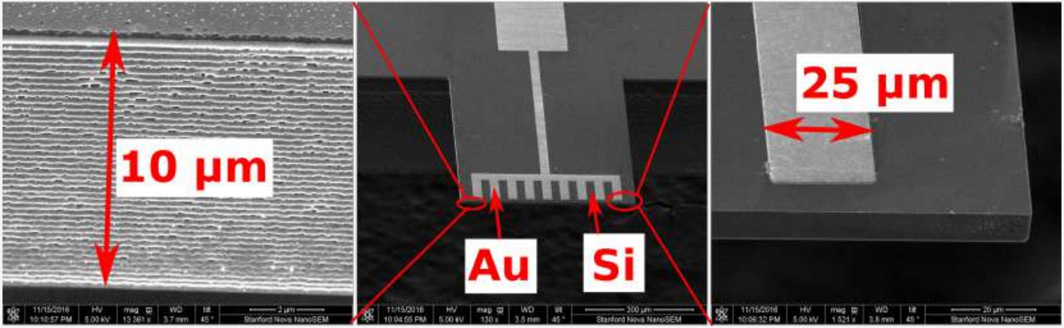


ATTRACTOR TO PROBE GRAVITATIONAL INTERACTIONS

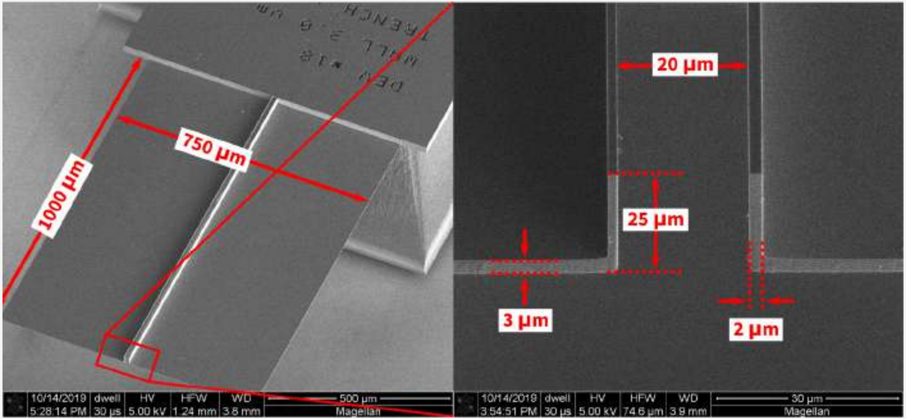
- Custom, in-house fabrication of attractor
  - Au-filled trenches in Si cantilever
- Sputter gold layer over the surface to minimize residual electrostatics



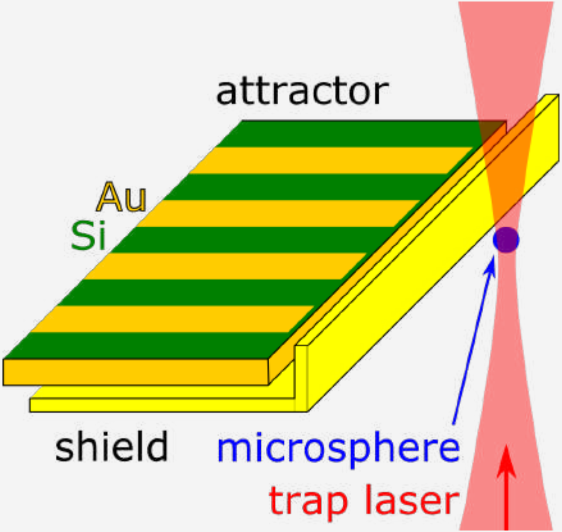
IEEE ECTC ***274*** *(2017)*

ANOTHER ELECTROSTATIC SHIELD

- Similar in-house fabrication of all-silicon shield
- Sputtered gold layer for equipotential

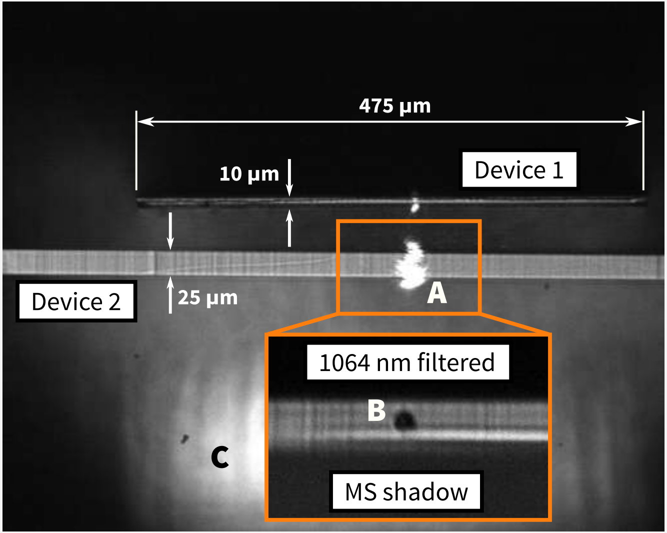


RECALL…



THE ATTRACTOR, SHIELD, AND MICROSPHERE

- It helps to actually see relative positions between the objects
- Remove the redundant 'pocket' feature of the shield to expose microsphere
- Can align and calibrate positions of mechanical devices



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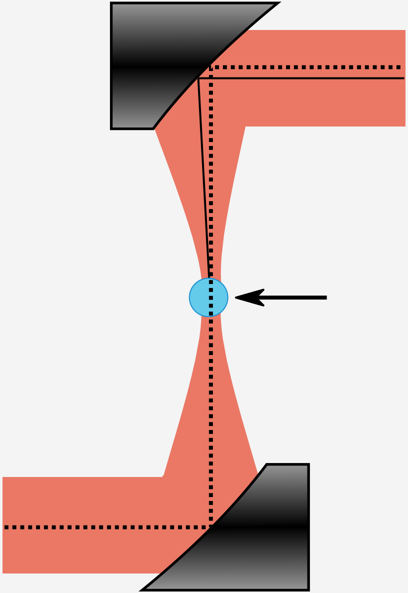
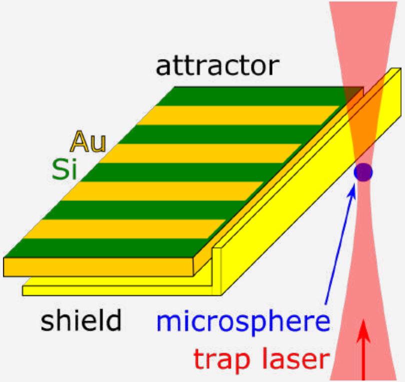


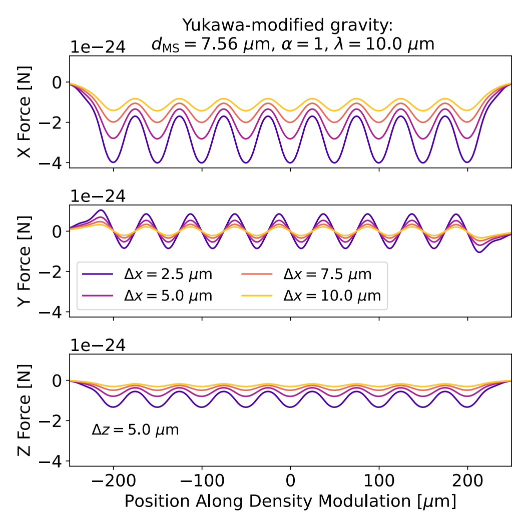
A SCRIPT FOR THE MEASUREMENT

1. Trap microsphere
2. Discharge/calibrate
3. Position devices near MS
4. Drive attractor along density modulation to excite signal
5. Once microsphere is lost, register positions of devices relative to trapping



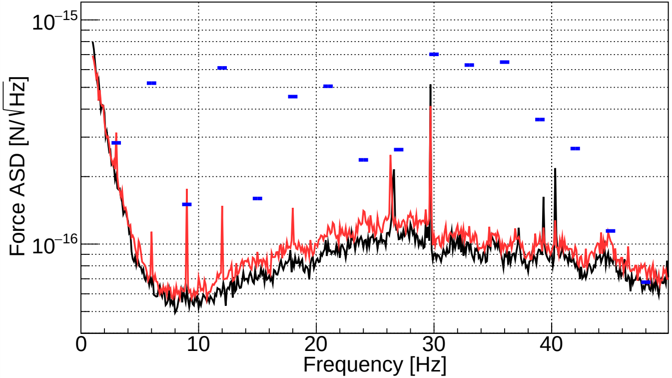
THE SIMULATED SIGNAL

- Analytic function for yukawa-modified gravity between sphere and point mass
- Partition attractor mass into unit cells (point masses)
- Add up signal from all unit cells



A TYPICAL AMPLITUDE SPECTRAL DENSITY

- Attractor driven at a frequency $f_0 = 3$ Hz
- Expected response appears at harmonics of f_0
- Repeat 10 s measurement 10^4 times
- Plot shows average of 100 such meas.



NO ATTRACTOR MOTION vs ATTRACTOR MOVING

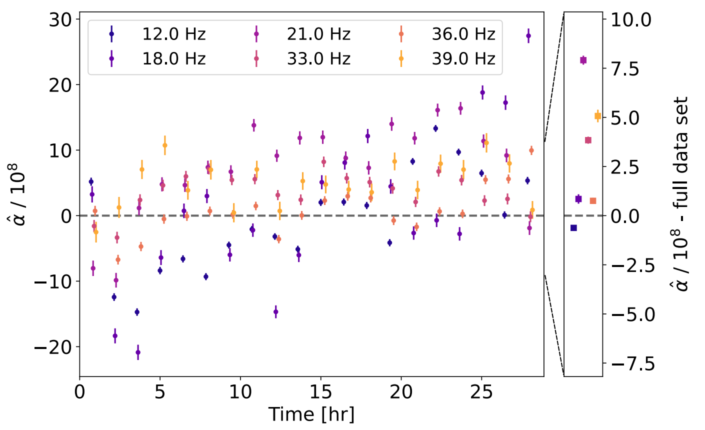
EXPECTED MOD. GRAV. RESPONSE

INTERPRETING THE MEASURED RESPONSE

- Clearly there is a background visible in some harmonics...
- Pick harmonics where signal strength is greater than strength of fundamental
  - Ignore f_0, $2f_0$ (non-linearity), and 30 Hz
  - Left with 6 harmonics, each an independent measurement
- Using a maximum likelihood parameter estimation, determine best-fit values of α, for each λ and harmonic f_i

A DRIFTING BACKGROUND

- We see a background force
- Does NOT look like gravity
- Different $\hat{\alpha}$ for different harmonics
- Drifts in time



WHAT DO YOU DO WITH A BACKGROUND?

BEST	Mitigate the underlying problem
OKAY	Include well-informed background model into parameter estimation
UNFORTUNATE	**Make conservative estimate acknowledging presence of and limitation induced by the background**
UNACCEPTABLE	Subtract the background

- Basic procedure is testing a null hypothesis: do we see a signal consistent with a new interaction? or just noise?
- With a robust background model, a profile-likelihood procedure is ideal
- Have to modify the test-statistic to acknowledge presence of background, but without a well-defined background model:

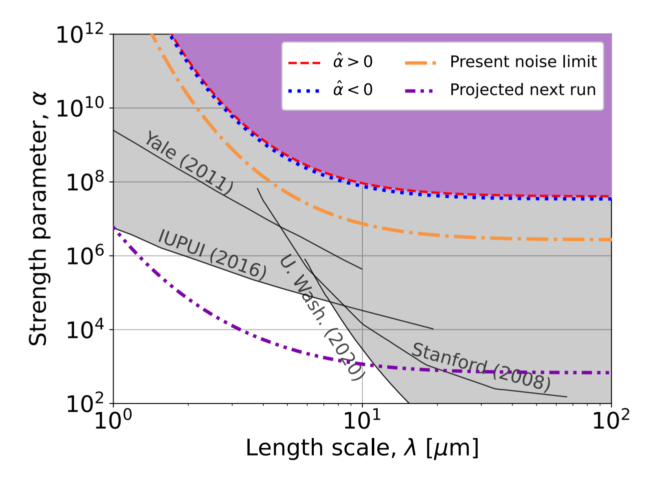
$$q_{\alpha,i} = \begin{cases} -2\log\left(\frac{\mathcal{L}_i(\alpha,\lambda)}{\mathcal{L}_i(\hat{\alpha}_i,\lambda)}\right) & \alpha \geq \hat{\alpha}_i \\ 0 & \alpha < \hat{\alpha}_i \end{cases}, \tag{1}$$

arXiv:2102.06848v1

Eur. Phys. J. C ***71****, 1554 (2011)*

LIMIT IN $\alpha - \lambda$ PARAMETER SPACE

- Eliminating backgrounds immediately gets us an order of magnitude
- Many near-term improvements planned



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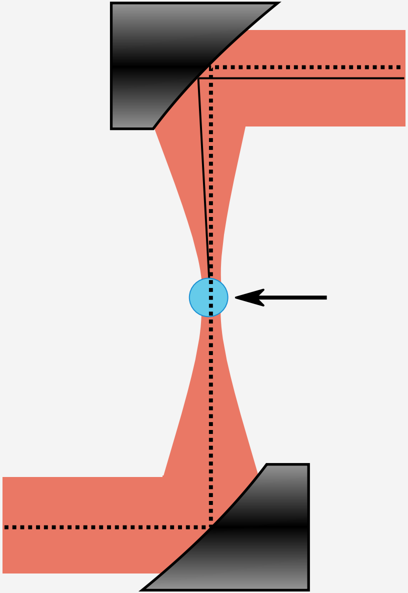
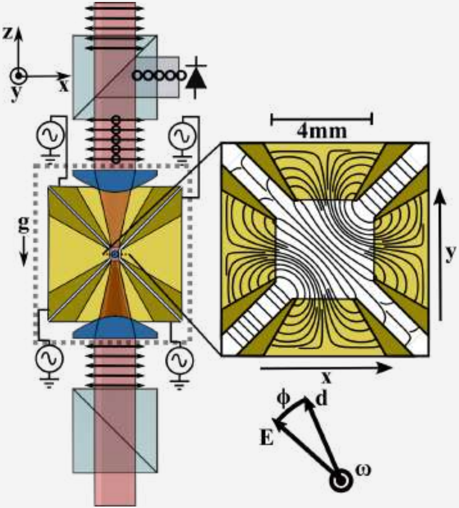
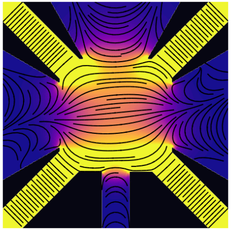


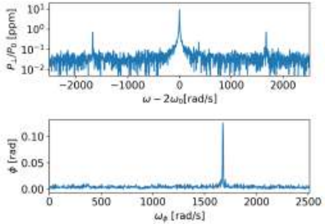
ELECTRICALLY DRIVEN ROTATION



*PRA **97** 041802(R) (2019)*

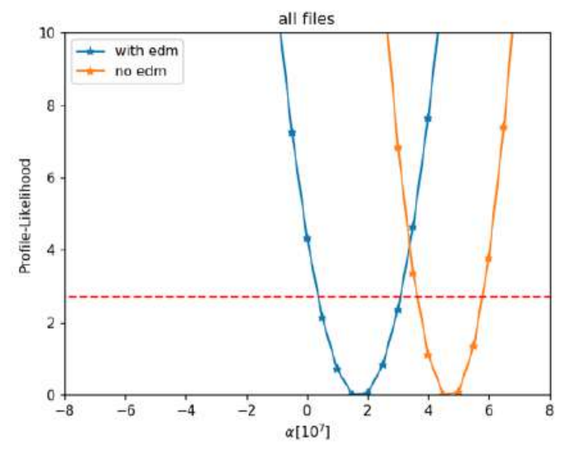
- **Residual dipole moment**
  - Dipole aligns with field
  - Rotate field $\rightarrow$ rotate microsphere
- **Residual birefringence**
  - Modulation of cross-polarized power at $2 \cdot \omega_0$





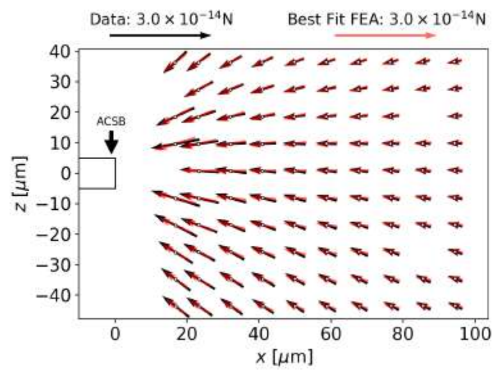
UNDERSTANDING THE ELECTROSTATIC BACKGROUND

- Assume freely-spinning dipole
- Time-average couples to gradient induced by contact potential on attractor
- Include in profile-likelihood estimation
- Reduces tensions with prior “null” measurements



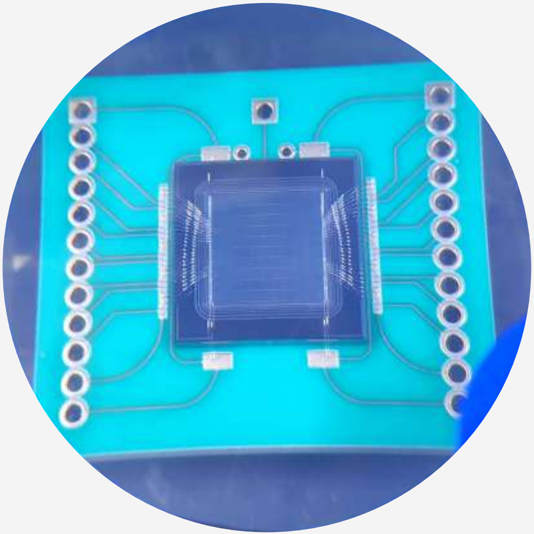
FORCE-FIELD MICROSCOPY

- Microsphere response known in all 3 directions
- Change positions (and biases) of attractor and shield
  - Measure full vector force-field: $\vec{F}(x, y, z)$
- With and without spinning



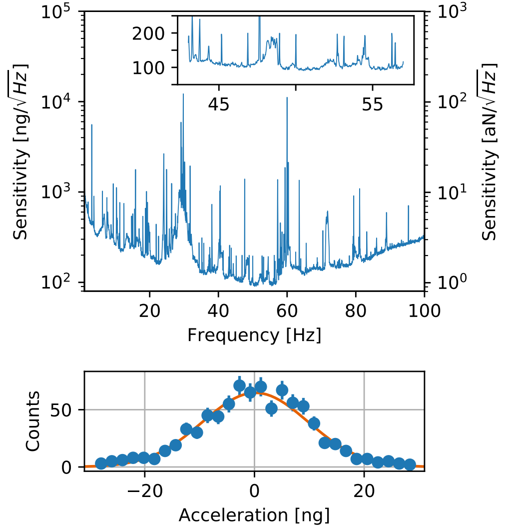
*PRA **99** 023816 (2019)*

- Develop a rudimentary image of the scattered light
- May allow discrimination between actual motion and light scattered by motion of nearby objects (i.e. the attractor)

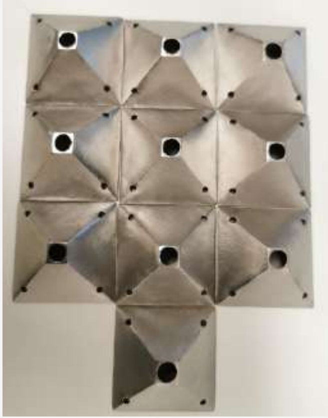


- Similar apparatuses have demonstrated exceptional performance recently
- Assuming same acceleration sensitivity for our sphere sizes
- $\sigma_F \leq 1 \times 10^{-18}\ \mathrm{N}/\sqrt{\mathrm{Hz}}$

PRA ***101****, 053835 (2021)*



- Cover surfaces with optically black coatings
- Colloidal graphite
- Vacuum deposition of porous metal matrices

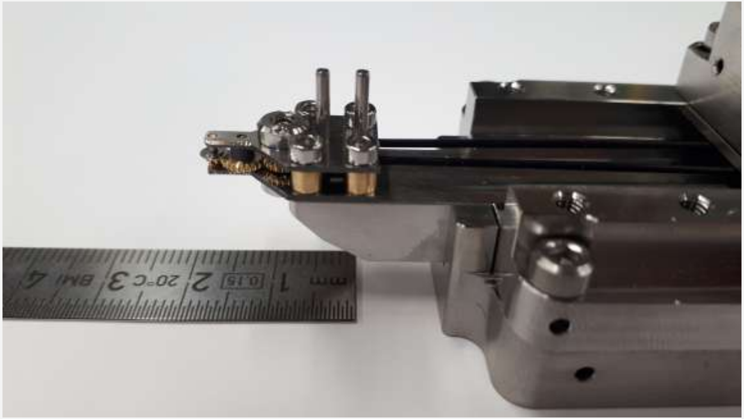


PASSIVE MECHANICAL STABILIZATION (READ: LOTS OF STEEL)

- Improve flanges and optical windows
- Stabilize mechanical supports within chamber

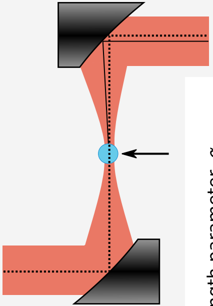
ROTARY ATTRACTOR

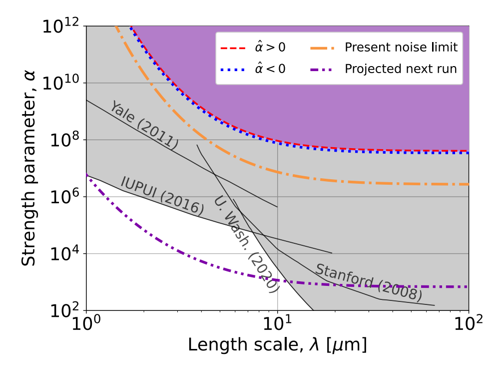
- Reciprocating motion seems to cause too many backgrounds
- Take advantage of rotation
- Get to collaborate with watch makers!



SUMMARY

- Optically levitated microsphere used as a precision force sensor
- First test of gravity with this type of apparatus
- Many improvements to be made!





THANK YOU FOR YOUR ATTENTION!

QUESTIONS?