Investigating the Breakdown of Newton's Law at Submicron Length-Scales

Christopher Gerig[1] and J.C. Davis[1,2]

1. LASSP, Cornell University, 2. Brookhaven National Lab

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Hiro Miyake
Vikram Gadagkar
Tien-Ming Chuang

Motivation

In recent years, *String Theory* **has proposed the existence of extra spatial dimensions, in addition to the familiar three, which are "curled up" at every point in space. The presence of these extra dimensions would alter Newton's Law by introducing a 'Yukawa potential' into the depicted force-equation and thereby formulating non-Newtonian forces. Other considerations, such as hierarchy problems and the Cosmological Constant Problem, have also motivated our tests of the gravitational inverse-square law in the previously inaccessible regime [1].**

Here, the additional Yukawa-term gives the total potential

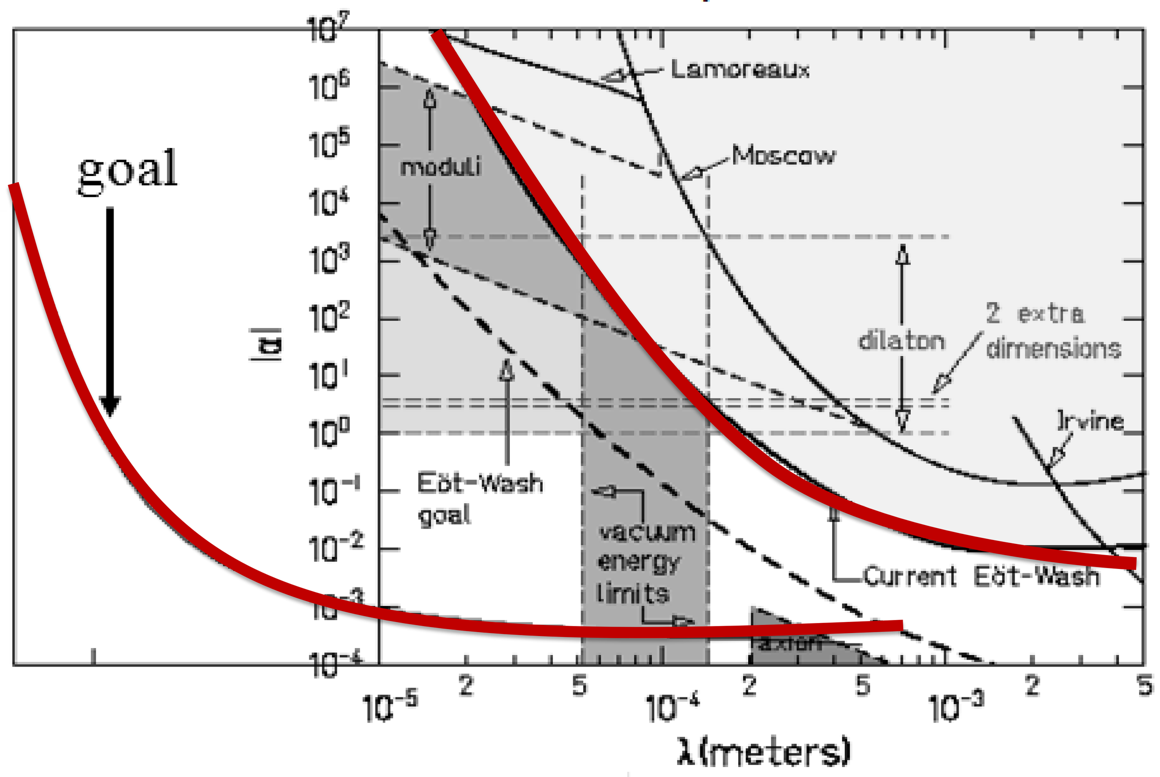
$$V = -\frac{GmM}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

where α is the characteristic strength and λ is the characteristic length. There has been no experimental evidence as of today to support these theories or to even observe the gravitational force at length-scales below 100µm [2,3,4]. Experiments to detect such a modification to the gravitational force on a test mass are performed and fitted for the variables λ and α. The yellow area in the figure is the region where non-Newtonian effects have been excluded.

Scope

We are studying the ultimate limits of force/position-sensing with nano-mechanical systems and SQUID-based classical accelerometers at extremely low temperatures, with a view towards developing new force-sensing tests for fundamental physics. Of immediate interest is a type of Cavendish experiment which is designed to detect gravity at micron-scale distances and measure departures from Newton's Law of Universal Gravitation into the nanometer range.

Newton's Law: $\vec{F} = m\vec{g} = -\frac{GmM}{r^2}\hat{r}$



We plan to measure displacements produced by these forces with the technique of high-Q resonant force detection using a superconducting quantum interference device (SQUID) based position sensor. This will be applied to a nano-Cavendish experiment. Our design should have sufficient sensitivity to detect non-Newtonian forces at distance scales shorter than one micron. Thus this research will either provide evidence for non-Newtonian forces and the associated theories, or will vastly extend the region of knowledge where it is known that Newton's Law holds.

Experiment & Apparatus

The underlying concept of our experiment is the detection of the gravitationally-induced oscillation of a test mass from the driven oscillation of a nearby source mass. This is a low-distance analog of the classical Cavendish experiment.

Masses will be evaporated on two capacitive membranes, separated by a few microns.

Given a voltage V_o between two plates, the pressure on the top plate is $\frac{\varepsilon_0 V_0^2}{2d^2}$ (attractive).
By applying a voltage to the source capacitive membrane, the electrostatic force will deflect the membrane. Therefore, oscillating the voltage will directly oscillate the membrane/mass.

An applied DC bias voltage will allow for the discrete movement of the equilibrium separation distance between the two masses.

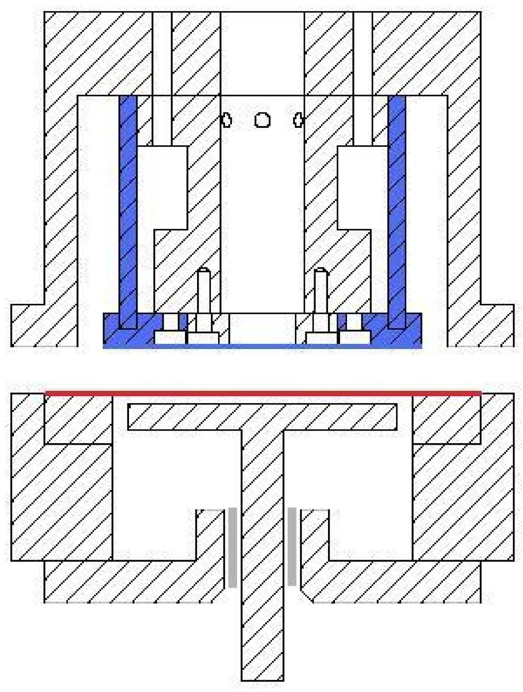
To suppress electromagnetic interactions, a thin superconducting sheet will be placed in between the two masses. Due to the Meissner Effect, this shield will deflect magnetic fields.

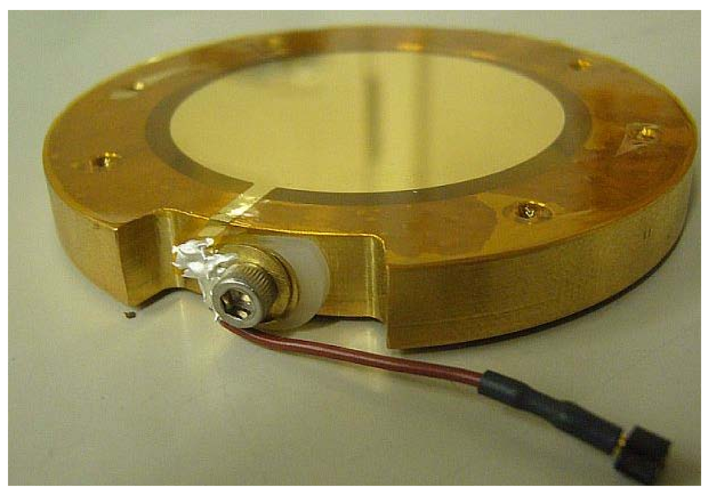
Yukawa Force between plates:

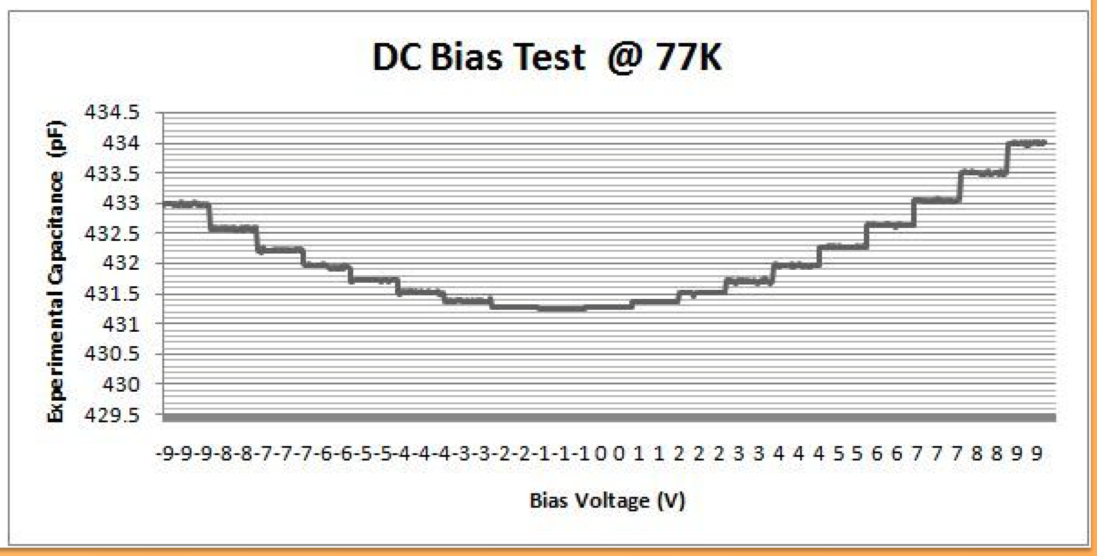
$$F_Y = -4\pi G\rho m\alpha\lambda^2 \frac{1}{t_{SiN}} \sinh\left(\frac{t_{kapton}}{\lambda}\right) e^{-\frac{h+t_{kapton}}{\lambda}} \left(1 - e^{-\frac{t_{SiN}}{\lambda}}\right)$$

Expected displacement (driven harmonic oscillator):

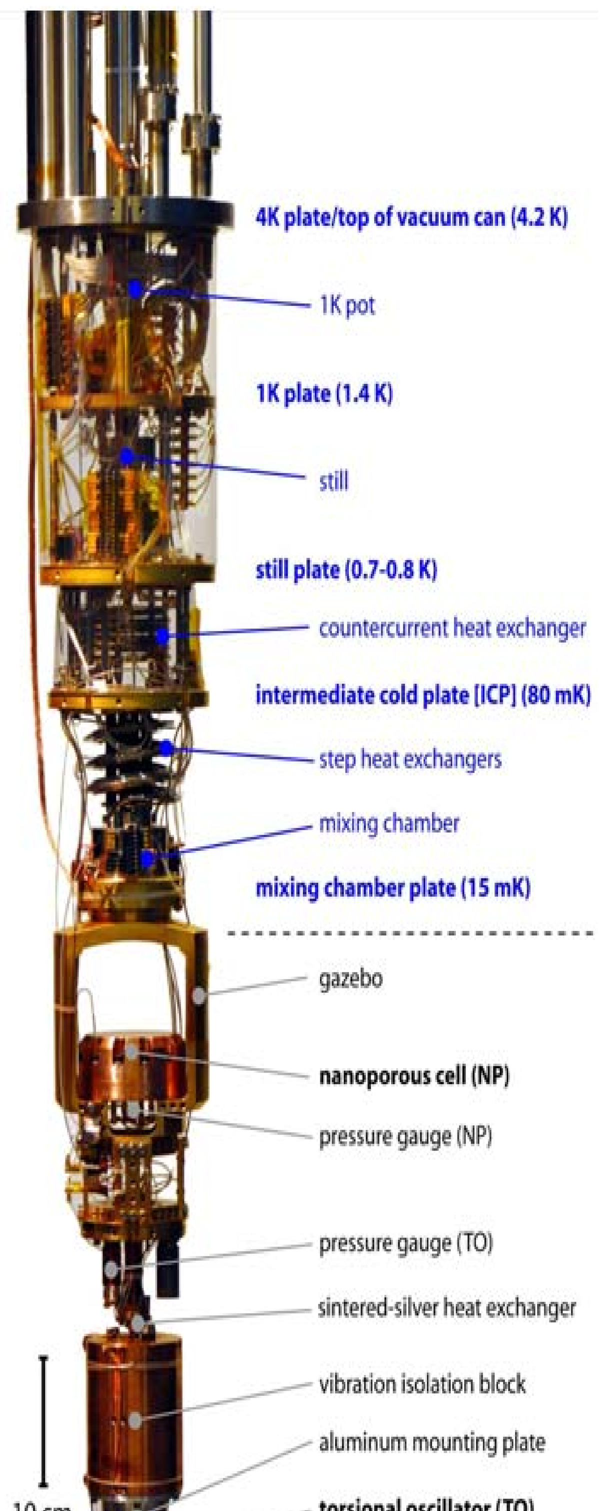
$$\delta x = \frac{2\pi G m A\sigma\alpha\lambda^{-1} e^{-x_0/\lambda}}{\sqrt{\left(2\pi G m\alpha\lambda^{-1}\sigma e^{-\frac{x_0}{\lambda}}\right)^2 + \frac{m^2\omega_0^4}{Q^2}}} \approx 10^{-14} m$$



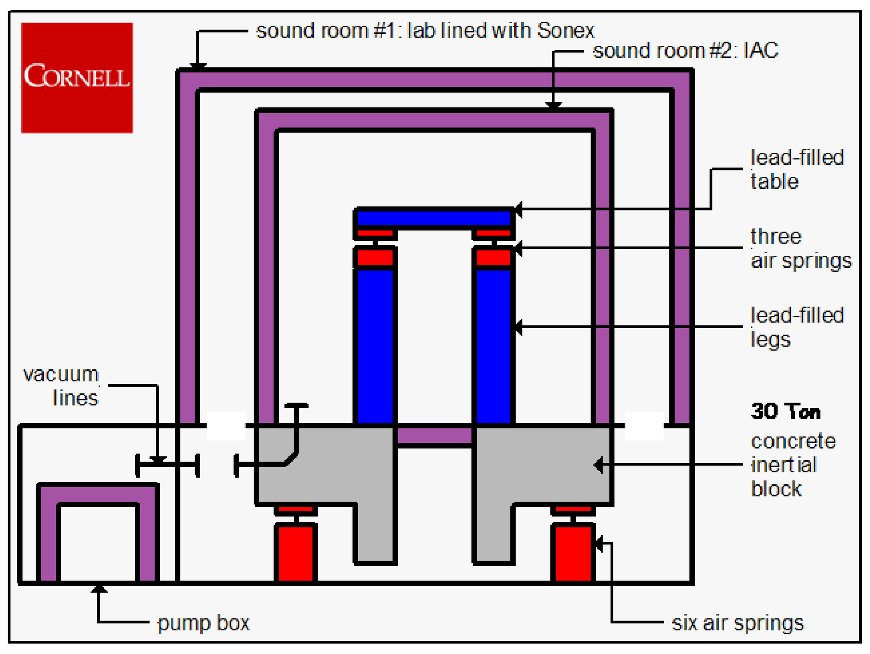




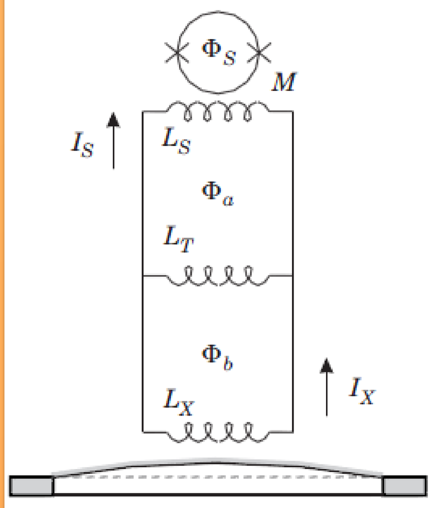
Cryogenics, Vibration Isolation, and Detection

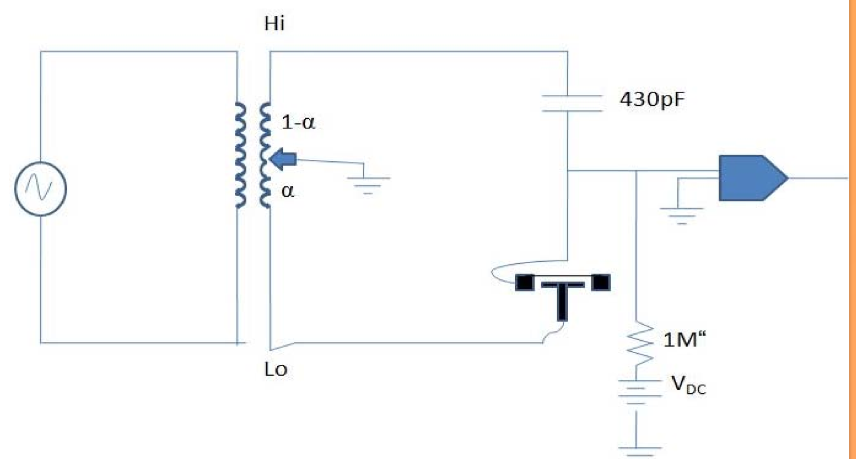


We need an ultra low temperature environment to suppress intrinsic thermomechanical noise of the system, and an ultra low vibration environment to suppress background vibration noise that can overwhelm our signal. Our apparatus will be suspended in a cryogenic vibration isolation assembly on an ultralow noise dilution refrigerator, housed in an ultralow vibration and radio-frequency shielded laboratory. This room is floated by air springs which serve as passive vibration isolators. We will operate at a temperature of ~10mK. Consequently, precautions must be taken when cooling from room temperature to 10mK because thermal cycling of the material can easily collapse the system. The dilution refrigerator gives a resolution of 10^{-16}m/√Hz at 20mK [5].



As for circuitry, we will detect changes in membrane amplitude (i.e. changes in capacitance) via a capacitance bridge. In the future we will replace the test mass capacitive membrane with a high-Q nitride membrane and will use a SQUID-based detection scheme. The capacitance bridge scheme will be able to detect Newtonian forces, allowing us to first confirm that the proposed method works.





References:
[1] E. Adelberger *et al., Tests of the Gravitational Inverse-Square Law*, Annu. Rev. Nucl. Part. Sci. 53 (2003)
[2] J. Chiaverini *et al., New Experimental Constraints on Non-Newtonian Forces below 100µm*, Phys. Rev. Let. 90 (2003)
[3] D. Kapner *et al., Tests of the Gravitational Inverse-Square Law below the Dark-Energy Length Scale*, Phys. Rev. Let. 98 (2007)
[4] D. Weld *et al., New Apparatus for Detecting Micron-scale Deviations from Newtonian Gravity*, Phys. Rev. D77 (2008)
[5] B. Hunt *et al., Evidence for a Superglass State in Solid ^{4}He*, Science Vol 324 (2009)

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