The Enduring Significance of Eötvös' Most Famous Experiment

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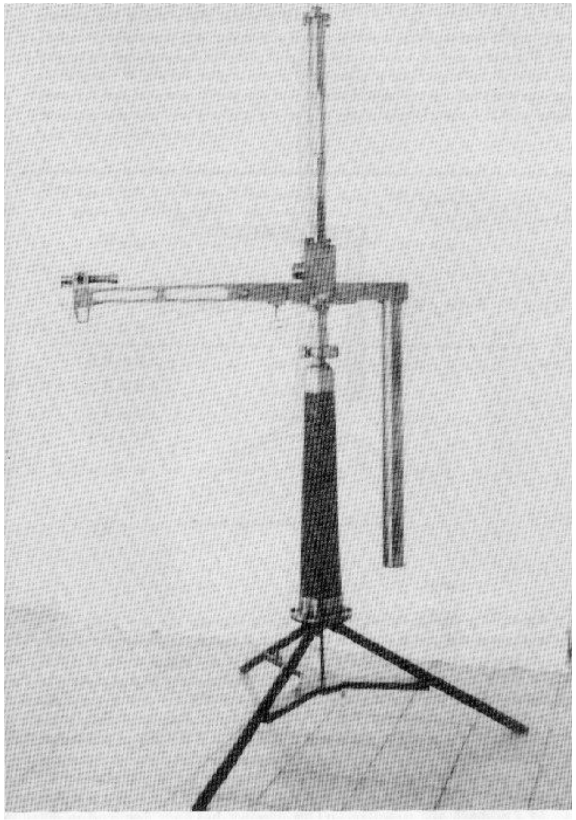

The Eötvös Paradox

1. The Eötvös Experiment was performed correctly.
2. The 1986 Reanalysis of the Eötvös Experiment leading to the suggested “5th Force” is correct.
3. The results of many experiments aimed at detecting the proposed “5th Force” have failed to confirm its existence.

Is it possible for all three of these statements to be true?

The Search for New Macroscopic Forces: Pre-1986

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

Conservation of Heavy Particles and Generalized Gauge Transformations

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(Received March 2, 1955)

The possibility of a heavy-particle gauge transformation is discussed.

THE conservation laws of nature fall into two distinct categories: those that are related to invariance under space-time displacements and rotations, and those that are not. In the former category there are the conservation laws of momentum, energy, and angular momentum. In the latter category we find the conservation laws of electric charge, of heavy particles, and the approximate conservation laws of isotopic spin, and perhaps others.[1] We notice that the best known within this second category, the conservation of electric charge, is related to invariance under gauge transformations,[2] which expresses the nonmeasurability of the phase of the complex wave function of a charged particle.

We want to ask here whether similar gauge invariances should be related to all conservation laws of the second category. This question has been discussed in connection with the conservation of isotopic spin by Yang and Mills.[3] We wish here to discuss the problem in connection with the conservation of heavy particles.

If we take the conservation of heavy particles to mean invariance under the transformation

$$\psi_N \rightarrow e^{i\alpha}\psi_N, \quad \psi_P \rightarrow e^{i\alpha}\psi_P, \qquad (1)$$

for the wave function of the heavy particles (neutrons and protons), a general gauge transformation (heavy-particle gauge transformation) is a transformation like (1) with the phase α an arbitrary function of space-time. Invariance under such a transformation means that the relative phase of the wave function of a heavy particle at two different space-time points is not measurable.

Such a gauge transformation is formally completely identical with the electromagnetic gauge transformation. Invariance under such a transformation therefore necessitates the existence of a neutral vector massless field coupled to all heavy particles. A nucleon would have a "heavy-particle charge" of $+\eta$ in such a field and an antinucleon would have a "heavy-particle charge" of $-\eta$. The force between two massive bodies therefore would contain a contribution from the Coulomb-like repulsion between such "heavy-particle charges." The total force including the gravitational attraction is:

$$\text{Force} = -G(M_1M_2/R^2) + \eta^2(A_1A_2/R^2). \qquad (2)$$

Here M_1, M_2, A_1, and A_2 are the inertia masses and mass numbers of the two bodies. There should also be a magnetic-dipole-like interaction between individual nuclei because the nucleons are in constant motion in a nucleus. But in a macroscopic object the nuclear spins average out so that (2) is correct unless the two bodies are spinning at high speeds.

Now the packing fraction of various atoms differ so that M/A varies fractional-wise from substance to substance by $\sim 10^{-3}$. This means that the observed gravitation mass [which contains a contribution from the η^2 term in (2)] divided by the inertia mass would vary fractional-wise from substance to substance by $10^{-3}\eta^2/G(M_P)^2$, where M_P is the mass of the proton[4] Very careful measurements by Eötvös and co-workers. have shown this variation to be $<10^{-8}$. Therefore

$$\eta^2/G(M_P)^2 < 10^{-5}.$$

It may be remarked that since the packing fraction differs most between hydrogen and, say, carbon, Eötvös' experiment could yield a more sensitive detection of η^2 by a factor of 10 if repeated with a comparison of hydrogen and carbon.

The assumption that leads to the above line of reasoning and the force expression (2) is that the phase factor α in (1) should be space-time-dependent. It should be noticed that in addition the assumption has also been made that the transformation that generates the conservation of heavy particles is of the specific form (1).

We wish to thank Dr. J. Robert Oppenheimer for an interesting discussion.

[1] See M. Gell-Mann and A. Pais, Proceedings of the Glasgow Conference, July, 1954 (to be published).
[2] W. Pauli, Revs. Modern Phys. 13, 203 (1941).
[3] C. N. Yang and R. L. Mills, Phys. Rev. 96, 191 (1954).
[4] Eötvös, Pekár, and Fekete, Ann. Physik 68, 11 (1922).

Reanalysis of the Eötvös Experiment

PHYSICAL REVIEW

LETTERS

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Reanalysis of the Eötvös Experiment

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We have carefully reexamined the results of the experiment of Eötvös, Pekár, and Fekete, which compared the accelerations of various materials to the Earth. We find that the Eötvös-Pekár-Fekete data are sensitive to the composition of the materials used, and that their results support the existence of an intermediate-range coupling to baryon number or hypercharge.

PACS numbers: 04.90.+e

Recent geophysical determinations of the Newtonian constant of gravitation G have reported values which are consistently higher than the laboratory value G_0.[1] With the assumption that the discrepancy between these two sets of values is a real effect, one interpretation of these results is that they are the manifestation of a non-Newtonian coupling of the form

$$V(r) = -G_\infty \frac{m_1 m_2}{r}(1+\alpha e^{-r/\lambda})$$

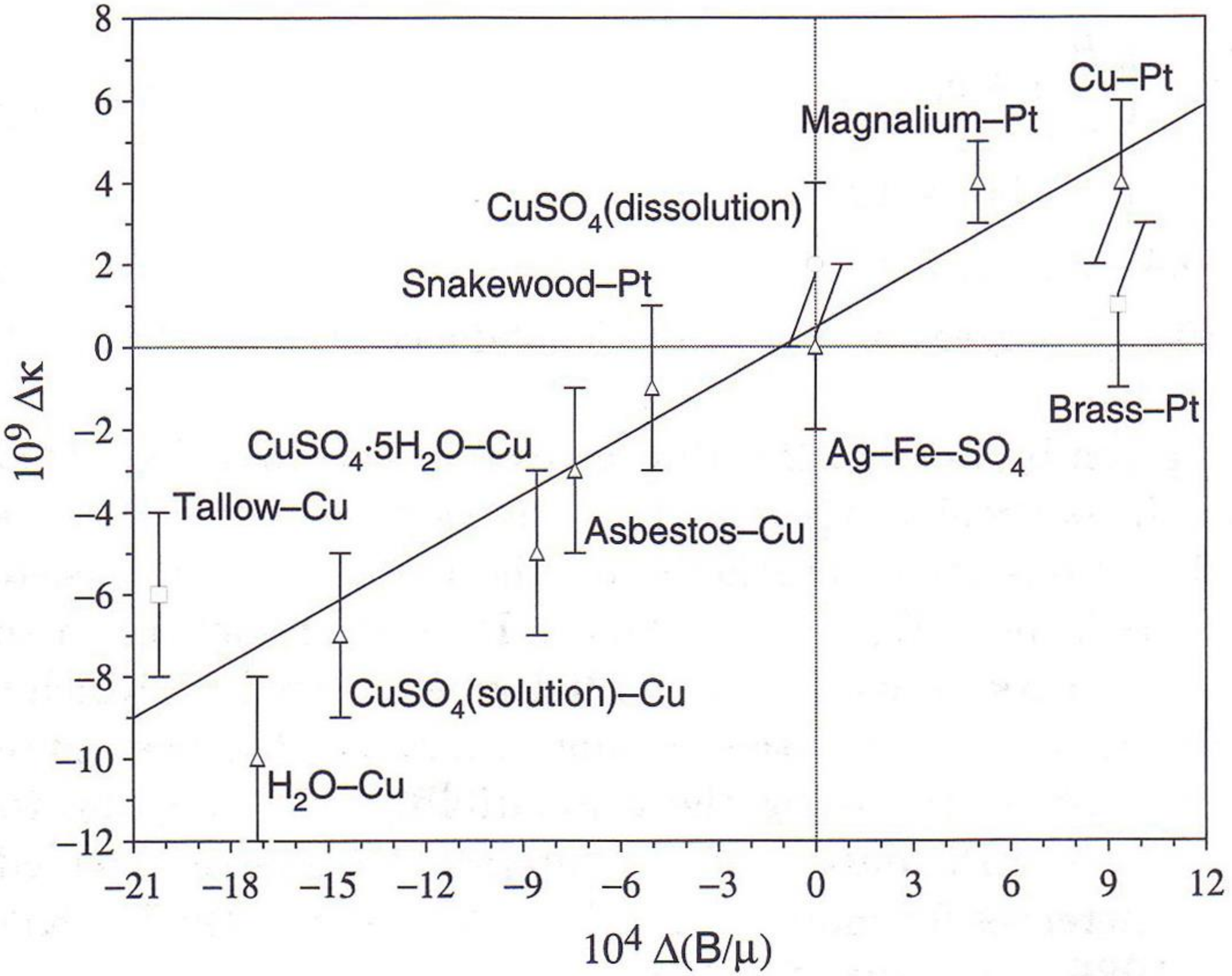
$$= V_N(r) + \Delta V(r). \qquad (1)$$

Here $V_N(r)$ is the usual Newtonian potential energy for two masses $m_{1,2}$ separated by a distance r, and G_∞ is the Newtonian constant of gravitation for $r \to \infty$. The geophysical data can then be accounted for quantitatively if α and λ have the values[2]

$$\alpha = -(7.2 \pm 3.6)\times 10^{-3}, \quad \lambda = 200 \pm 50 \text{ m}. \qquad (2)$$

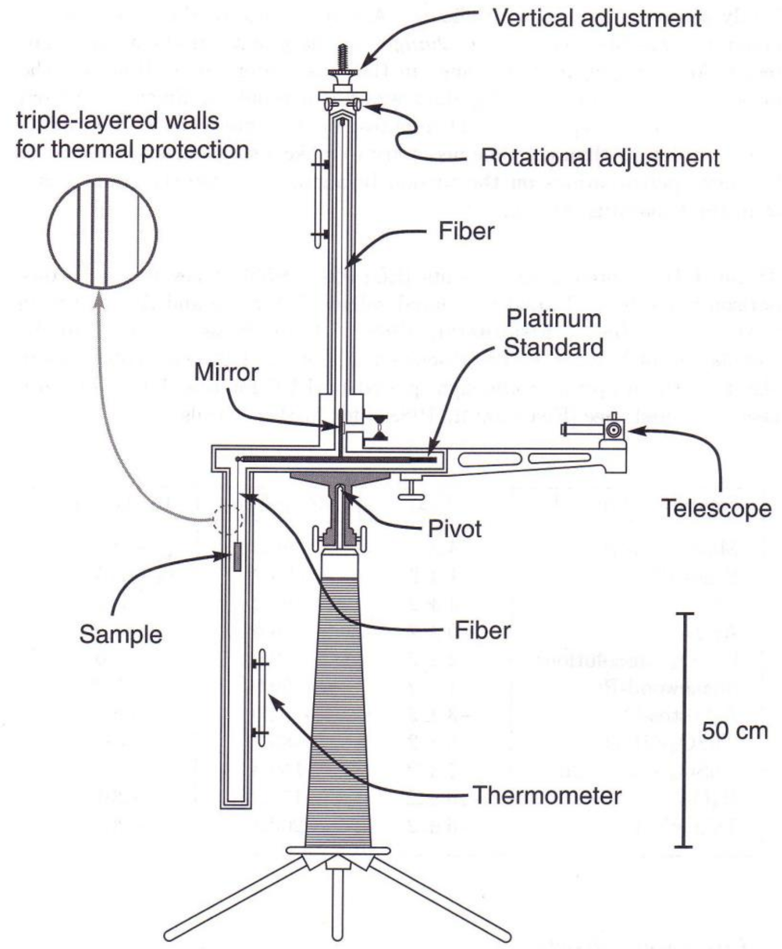
If $\Delta V(r)$ actually describes the effects of a new force, and is not just a parametrization of some other systematic effects, then its presence would be expected to manifest itself elsewhere as well. Recently, we have undertaken an exhaustive search for the presence of such a force in other systems. Our analysis, to be presented elsewhere,[3] leads to the conclusion that if such a force existed it would show up at present sensitivity levels in only three additional places: (i) the K^0-$\bar{K}^0$ system at high laboratory energies, where in fact anomalous effects have previously been reported[4]; (ii) a comparison of satellite and terrestrial determinations[5] of the local gravitational acceleration **g**; and (iii) the original Eötvös experiment[6] which compared the acceleration of various materials to the Earth. We note that the subsequent repetitions of the Eötvös experiment by Roll, Krotkov, and Dicke[7] and by Braginskii and Panov[8] compared the gravitational accelerations of a pair of test materials to the Sun, and hence would not have been sensitive to the intermediate-range force described by Eqs. (1) and (2). Motivated by our general analysis, we returned to the Eötvös experiment and asked whether there is evidence in their data of the presence of $\Delta V(r)$ in Eq. (1). Although the Eötvös experiment has been universally interpreted as having given null results, we find in fact that this is not the case. Furthermore, we will demonstrate explicitly that the published data of Eötvös, Pekár and

Eötvös Results



Reference: Fischbach, et al., Phys. Rev. Lett. **56**, 3 (1986)

Eötvös Apparatus



Reference: E. Fischbach and C. L. Talmadge, *The Search for Non-Newtonian Gravity* (AIP/Springer-Verlag, New York, 1999)

1986

New evidence hints of a possible 5th force

By JOHN NOBLE WILFORD
New York Times News Service

NEW YORK — A new analysis of early 20th-century experiments has produced results challenging both the findings of Galileo that all falling bodies accelerate at the same rate and a fundamental element of Einstein's general theory of relativity. This has led physicists to suspect that there may be a fifth, heretofore unidentified force at work in the universe.

Scientists said the new study, published in the Jan. 6 issue of Physical Review Letters, could have a profound influence on thinking in physics and cosmology, if the results can be substantiated by further experiments. Those who had examined the report said it appeared to be based on sound research.

Even though the new findings seemed to undermine a basic assumption made by Einstein, the principle of equivalence that stemmed from Galileo's work, scientists said the hypothesized new force, called the hypercharge, was so weak and local that, if it did exist, it should not fundamentally alter Einstein's principles as the basic tool of modern cosmology. The other known forces are electromagnetism, gravity, and the strong and weak forces governing nuclear structure.

The new analysis suggests that, contrary to Galileo's assertion, a feather would fall faster than a coin if dropped from the same height in a vacuum. This is because, in the new thinking, gravity is not the only force at work; there is also presumably something called hypercharge, which acts on objects of different compositions in ways to cause them to accelerate at slightly different rates.

In a telephone interview, Dr. Ephraim Fischbach, the leader of the team of scientists who made the study, said: "When you see something as fundamental as a new force, it's likely to change many things. We will have to rethink many views of particle physics and cosmology."

Fischbach, a professor of physics at Purdue University in Indiana, is a visiting professor this year at the Institute of Nuclear Theory at the University of Washington in Seattle. The other authors of the report are Daniel Sudarsky, Aaron Szafer and Carrick Talmadge of Purdue and S.H. Aronson of the Brookhaven National Laboratory at Upton, N.Y.

Dr. Robert H. Dicke, a Princeton University physicist and authority on Einstein's theories, said: "One has to be somewhat careful when you're dealing with something that's potentially revolutionary. But if this is right, it's extremely important. I can't pick any holes in the analysis."

Dicke, as other physicists who were asked to comment, emphasized the need to perform more exacting experimental tests of the effect of gravity, and possibly this hypothesized new force, on falling bodies. Modern techniques, he said, should make it possible to conduct tests in almost pure vacuums with uniform thermal conditions and an absence of outside vibrations.

Dr. Murray Gell-Mann, a theoretical physicist at the California Institute of Technology, said that if the conclusions of the study were correct, it was fair to speculate on the existence of a fifth force of intermediate range. Of the other known forces, gravity is the weakest; electromagnetism is responsible for the structure of atoms and the emission of light; the strong force binds the atomic nucleus together, and the weak force is responsible for certain kinds of radioactivity.

The prospect of another fundamental force comes at a time when most theoretical physicists are laboring mightily to conceive a single mathematical framework that describes all the forces, excepting possibly gravity, as different manifestations of one general force. These concepts are called grand unified theories, or GUT's.

Dr. Heinz R. Pagels, president of the New York Academy of Sciences, who is the author of books on particle physics, noted that scientists have speculated about the possible existence of the hypercharge force for more than 20 years. "One remains skeptical until further experiments are done," he said.

What Fischbach and his team did was re-examine the data from experiments conducted by Roland von Eotvos, a Hungarian scientist, over a period of more than two decades and reported in 1922.

The experiments, involving the suspension of objects of different composition and mass from a torsion balance, appeared to confirm Galileo's observation in the early 17th century. In the familiar, though probably apocryphal, story, Galileo is supposed to have dropped cannon balls from the Leaning Tower of Pisa and thereby determined that all objects fall under gravity with the same acceleration, if differences attributed to wind resistance are ignored.

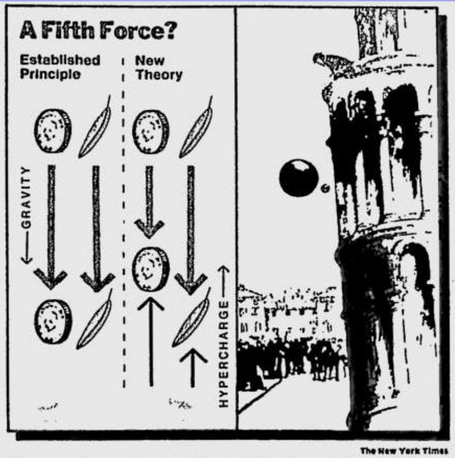
Newton relied on Galileo's work in formulating his theory of gravity in the late 17th century, and Einstein, re-enforced by the Hungarian experiments, also made the assumption that all bodies fall at the same rate in a uniform gravitational field in enunciating his general theory of relativity in 1916.

However, according to Fischbach, even the Hungarian experimenters noted some discrepancies in their results but chose to ignore them as being statistically insignificant. Upon detailed examination, Fischbach found the discrepancies in the group's "raw" experimental data to be large enough to suggest that some other force, besides gravity, might be acting on the bodies.

Fischbach was led to a review of the Eotvos experiment because of some "funny things" — his term for the apparent effect of another force — scientists had been seeing in recent work at the Fermi National Accelerator Laboratory in Illinois and in gravity studies by Frank Stacey deep in Australian mines.

In the report in Physical Review Letters, a journal of the American Physical Society, Fischbach's group concluded, "Although the Eotvos experiment has been universally interpreted as having given null results, we find in fact that this is not the case." In other words, something seemed to be causing objects to fall at slightly different rates.

The group said, moreover, that the results supported the existence of an intermediate-range force, called hypercharge.



The new theory proposes that a fifth force called hypercharge pushes up against falling objects, working against the force of gravity. The force of the hypercharge is a function of the mass and the atomic composition of a given object; it is greater for a copper coin than for a feather. Thus, if a feather and a penny were dropped through a vacuum the feather would fall slightly faster than the coin. That contradicts established principle, shown by Galileo at Tower of Pisa, asserting that they would fall at the same rate.

Evidence that the Eötvös Experiment was performed correctly

1. Care was taken to exclude temperature effects along with those arising from electromagnetic fields.
2. Correction for gravity gradients in
$$AgSO_4 + 2FeSO_4 \rightarrow 2Ag + Fe_2(SO_4)_3$$
3. $CuSO_4 \bullet 5\,H_2O$—Cu comparison gives a 5σ "signal" for an anomalous result
4. Why did Eötvös not publish his results between 1908 and 1919? His results improved over those of Bessel by more than a factor of 300.

And finally, the most compelling evidence that the Eötvös Experiment was performed correctly…

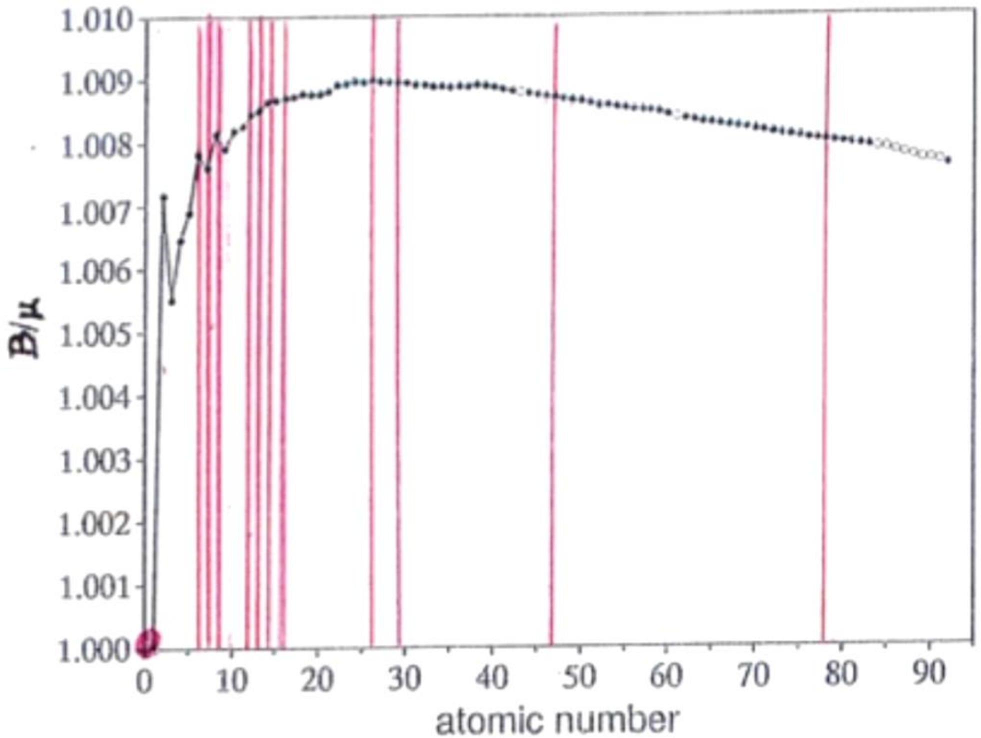


Figure 2.1: Plot of B/μ versus atomic number, where B denotes the baryon number, μ the mass in units of $m({}_1\mathrm{H}^1)$, and where the average over isotopes is evaluated using Eq. (2.2.4). For elements with no stable isotopes, the value of the longest-lived isotope is plotted. Elements with at least one stable isotope are plotted using a filled circle, and elements which have no stable isotopes are plotted using an open circle.

Phenomenology

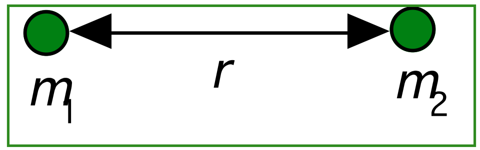
Summary of Newtonian Gravity

- Newtonian Gravity

$$V(r) = -\frac{Gm_1m_2}{r}$$

- Non-Newtonian Gravity

$$V(r) = -\frac{Gm_1m_2}{r}\left\{1+\alpha_{12}e^{-r/\lambda}\right\}$$



$$\vec{F}(r) = -\frac{G\cancel{m_1}m_2}{r^2}\hat{r} = \cancel{m_1}\vec{a}_1$$

$$\vec{F}(r) = -\frac{G(r)m_1m_2}{r^2}\hat{r}$$

doesn't vary as $1/r^2$ *

$$\vec{a}_1 = -\frac{Gm_2}{r^2}\hat{r}$$

a) independent of the nature of m_1 (Equivalence Principle)

b) varies as $1/r^2$

$$G(r) = G[1+\alpha_{12}e^{-r/\lambda}(1+r/\lambda)]$$

not independent of 1 or 2 *

* Evidence for either of these would point to a new fundamental force in nature.

The "Generic" Fifth Force Theory

Many specific theories lead to new weak forces of intermediate range. These theories derive from 2 observations:

1\.
$$\left.\begin{aligned} m_{hadron} &\sim 1\ \mathrm{GeV} \\ m_{Planck} &\sim 10^{19}\ \mathrm{GeV} \end{aligned}\right\} \Rightarrow \qquad \boxed{f = \frac{m_{hadron}}{m_{Planck}} \approx 10^{-19}}$$

2a.
$$\left.\begin{aligned} f &\approx 10^{-19} \\ m_{hadron} &\sim 1\ \mathrm{GeV} \end{aligned}\right\} \Rightarrow \qquad \boxed{\begin{aligned} &\mu = f\, m_{hadron} \approx 10^{-10}\ \mathrm{eV} \\ &(\lambda = 1/\mu \approx 2\ \mathrm{km}) \end{aligned}}$$

or

2b.
$$\left.\begin{aligned} f &\approx 10^{-19} \\ \langle \phi \rangle_{GSW} &\approx 240\ \mathrm{GeV} \end{aligned}\right\} \Rightarrow \qquad \boxed{\begin{aligned} &\mu = f \langle \phi \rangle \approx 2.4 \times 10^{-8}\ \mathrm{eV} \\ &(\lambda = 1/\mu \approx 8\ \mathrm{m}) \end{aligned}}$$

These parameters [f ~10^{-19}; λ ~ 10 m - 10 km] are typical of the values suggested by various theories.

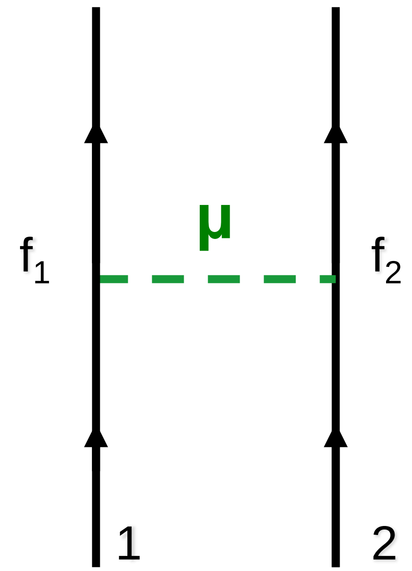
Hence, new interactions like the fifth force may be natural consequences of many models.

New Yukawa Forces

Many extensions to the Standard Model include new light bosons: (moduli, dilatons, scalar axions, hyperphotons, radions, KK gravitons, …)

Yukawa Phenomenology:

$$\boxed{V_{\text{Yukawa}}(r) = \alpha\left(\frac{GM_1M_2}{r}\right)e^{-r/\lambda}}$$



Strength Relative to Gravity: $\boxed{\alpha}$

Range: $\boxed{\lambda = \frac{\hbar}{mc}}$ ($m =$ boson mass)

1988

NATURE VOL. 335 29 SEPTEMBER 1988

The stimulation of the fifth force

Nearly three years of ingenious searching may not yet have uncovered evidence that the fifth force, a kind of correction of newtonian gravity, is real, but the search itself has been rewarding.

THE reality or otherwise of the fifth force, the supposed short-range correction to newtonian gravitation, may still be an open question, but there is little doubt that the search for evidence mounted in the past three years has been extraordinarily stimulating. Both experimentalists and theoreticians have done wonders of ingenuity. The flurry of excitement shows vividly how the publication of arresting inferences from intriguing data can have a value going beyond the interest of the original claims. No doubt it is a necessary condition for this benefit that the data should be convincing and the inferences made from them inherently plausible, conditions amply satisfied by Fischbach's re-examination of the Eötvos data of the 1920s.

On balance, the experimentalists seem to have responded the more ingeniously to the challenge of the fifth force. There have been novel designs of torsion balances and, more particularly, novel ways of placing them near perturbing masses, on cliff faces or on the edges of dry docks, for example. But a measurement now reported by C.C. Speake and T.J. Quinn, from the International Bureau of Weights and Measures in Paris (*Phys. Rev. Lett.* **61**, 1340; 1988) seems to point the way to more sensitive measurements of the gravitational attraction between masses separated by laboratory distances. That could be important because Newton's constant of gravitation, G, is one of the least accurately known of the fundamental constants.

Speake and Quinn have been operating on a huge scale, at least by the standards of most precision measurements, having arranged to measure the gravitational attraction between objects of different composition (lead, carbon and copper), each of mass 2–3 kg, and moveable attracting objects with mass no less than 1–78 tonnes (and made, alternately, of lead and brass). As the fifth force is supposed to depend on the composition of the attracting materials, it is necessary to be able to ring changes such as are made possible by this array of materials.

The alternative attracting masses apparently consist of motorized trolleys that can be trundled into position beneath a sealed tank containing the balance. The balance itself consists of a rigid beam with equal arms. The novelty is the suspension for the beam, which pivots on flexible strips rather than a knife-edge, thus avoiding the familiar problems in precision measurement of knowing just what allowance to make for the elasticity of a supposedly rigid support.

The enclosing tank is first evacuated and then filled with nitrogen at roughly atmospheric pressure, chiefly so as to damp oscillations of the balance. Test objects are weighed under the influence of one or other of the attracting masses. To minimize the effects of geometrical shape, the trolleys made of lead (in reality, there are two each, each carrying nearly half a tonne) consist of layers of lead interspersed with wood to give them nearly the same geometrical shape. Similarly, the 2–3 kg test masses are enclosed in stainless-steel cans of nearly equal shape so as to reduce the corrections due to buoyancy. There is a system of gimbals to ensure that masses can be interchanged accurately (and automatically) on the balance pans.

In essence, the measurement is a null measurement: the balance beam is kept horizontal by a servo-system, regulating electrical currents passed through two coils interacting with two magnets mounted at each end of the beam. Known sources of vibration are reduced as far as possible by the design and then at least partially excluded by filtering the output from the servo-system.

Even so, the system seems not to have been entirely free from trouble. Outgassing from the stainless-steel cans seems always to have been a problem (accounting for changes of pressure of the order of one per cent an hour). But the most persistent source of uncertainty in four series of measurements seems to have been the difficulty of excluding dynamical changes caused by external sources of heat. The wooden layers interleaved with lead insulated that pair of trolleys more efficiently than the brass trolleys from the laboratory floor, providing a systematic difference with composition that might have trapped less careful investigators. Speake and Quinn estimate that their mass differences have a sensitivity of 1 nanogram, corresponding to a force of 10^{-11} N.

The authors are no doubt right to say that their measurements should be readily capable of improvement, and that a tenfold improvement of sensitivity should be possible by paying more attention to the exclusion of design of the effects of external heat. And the result of what they have done so far? Sadly, the persisting errors are comparable with the mean values, which is another way of saying that they are not significant. The authors claim that they can only exclude the possibility that the fifth force at short distances is greater than about one per cent of ordinary gravitation, which of itself does not do much to advance the cause.

Much the same has emerged from an analysis of past measurements of the position of planetary orbits conducted by C. Talmadge from Purdue University and three colleagues at the Jet Propulsion Laboratory at Pasadena, California. The argument is simple: if the force between a planet and the Sun is not a simple inverse function of the square of the distance, Kepler's Third Law (relating orbital period to semi-major axis and, crucially, in which the mass of the planet does not enter) should not be strictly correct. In practice, Talmadge and his colleagues say, Kepler's Law is rarely verified directly; people measure the orbital period of a planet directly, then calculate the semi-major axis from the supposed value of the constant in the equation — the product of the solar mass and the gravitational constant.

The group seizes the opportunity of using accurate data for the positions of planets derived from sighting shots by passing spacecraft as well as from the longer series of data based on radar-ranging measurements of the objects of the Solar System. Evidently there is a substantial volume of data not fully made use of in previous analyses. One of the unexpected byproducts of the exercise is the discovery that the data can be made to yield more accurate estimates of the anomalous rates of precession of the orbits of the planets out to and including Jupiter.

But, sadly, the outcome for the main purpose of the calculation is again disappointing. From information about the distance of the orbit of a particular planet, it is obviously possible to obtain information about the strength of the fifth force in some region spanned by the average position of the orbit. Sadly, again, the estimated errors of the estimates Talmadge and his colleagues have derived are comparable with, or greater than, the estimates themselves, so that only extreme values of the parameters defining the fifth force (if there is one) can be confidently excluded. But, in a sense, "So what?". Observers will remark that the hunt for this still elusive phenomenon has already been worthwhile, whatever the eventual outcome.

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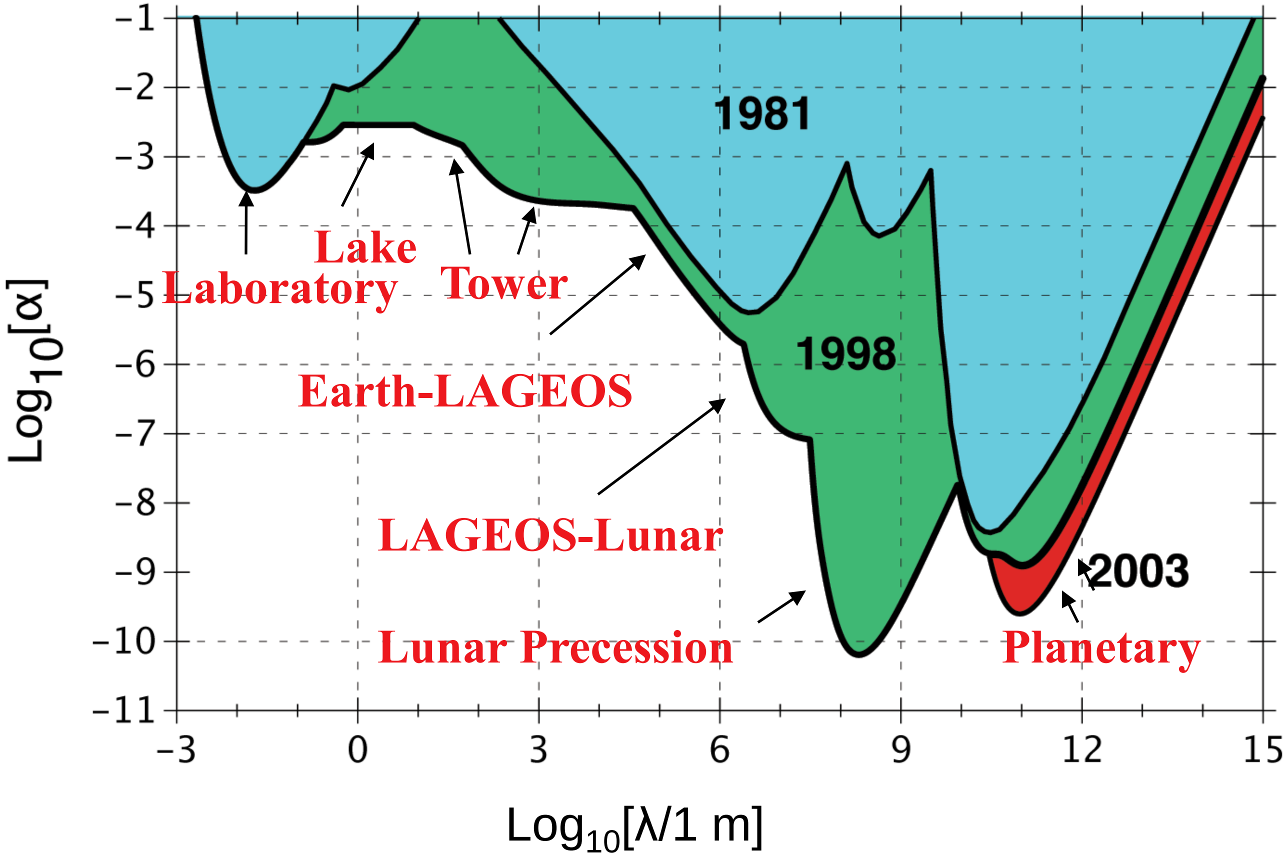
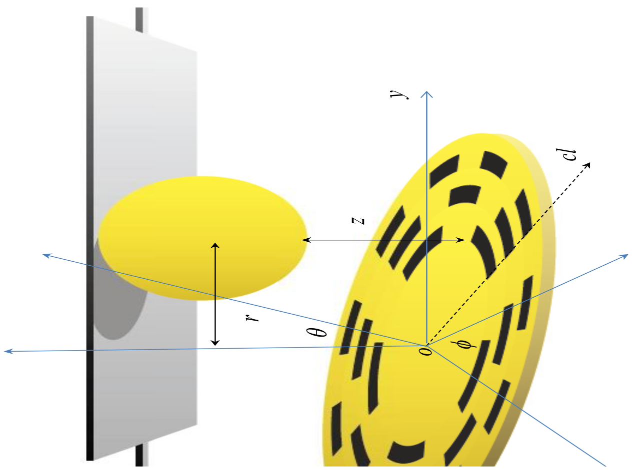
Limits on Yukawa Forces:
Long-Range Limits

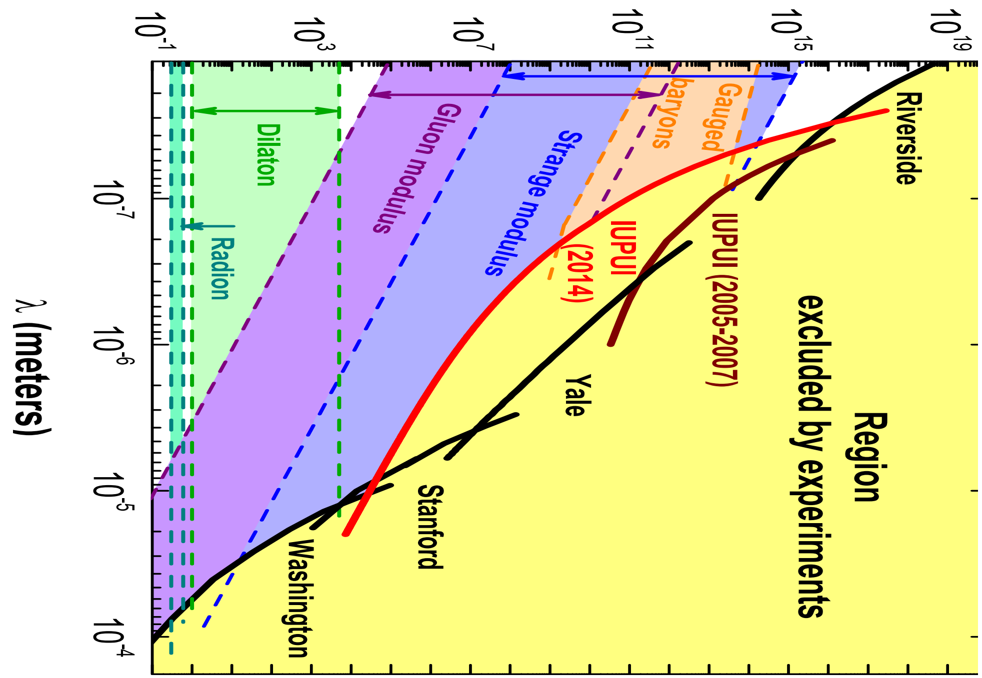
$$V(r) = -G\frac{m_1 m_2}{r}\left(1+\alpha\times e^{-r/\lambda}\right)$$



Reference: Coy, Fischbach, Hellings, Standish & Talmadge (2003)

New Limits on New Submicron Forces



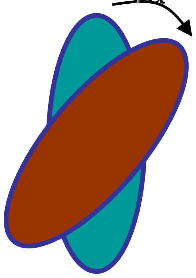


Reference: Y.-J. Chen, W. K. Tham, D. E. Krause, D. López, Ephraim Fischbach, and R. S. Decca, arXiv:1410.7267

Inverse-Square Law: Solar System Tests

The presence of the non-Newtonian contribution leads to 2 measurable effects:

$$V_5(r) = -\alpha \frac{G_\infty m_1 m_2 e^{-r/\lambda}}{r}$$

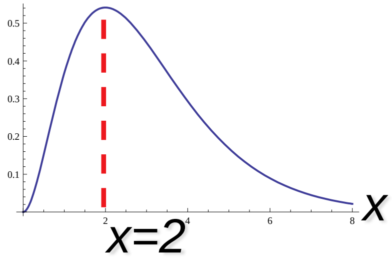


a) Planetary Precession:

$$\delta\phi_a \cong +\pi\alpha (a/\lambda)^2 e^{-a/\lambda} \text{ rad/rev} \equiv \pi\alpha\, x^2 e^{-x}$$

$$a = \text{ mean value of semi-major axis}$$

$\delta\phi_a = cx^2e^{-x}$ has a maximum at $x = 2$



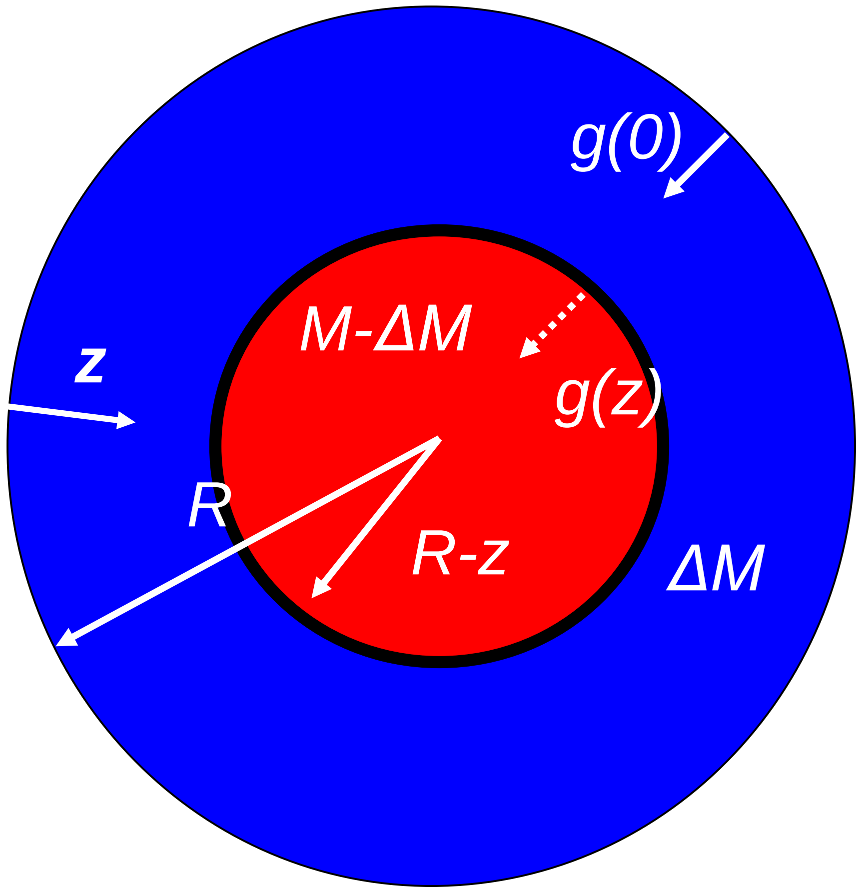
b) Variation of GM_{sun} :

$$V_5(r) \Rightarrow \quad G(r) = G_\infty[1 + \alpha(1 + r/\lambda)e^{-r/\lambda}] \neq \text{ constant}$$

$$\therefore \quad 4\pi^2 \frac{a_p^3}{T_p^2} = G(a)M_{sun} \neq \text{ constant}$$

Mikkelson & Newman (1977); de Rujula (1986); Talmadge, Berthias, Hellings, & Standish (1988); Coy, Fischbach, Hellings, Standish & Talmadge (2003)

Inverse-Square Law Tests:
Airy Method (Stacey 1984)



Inverse-Square Law Tests: Spero 1980

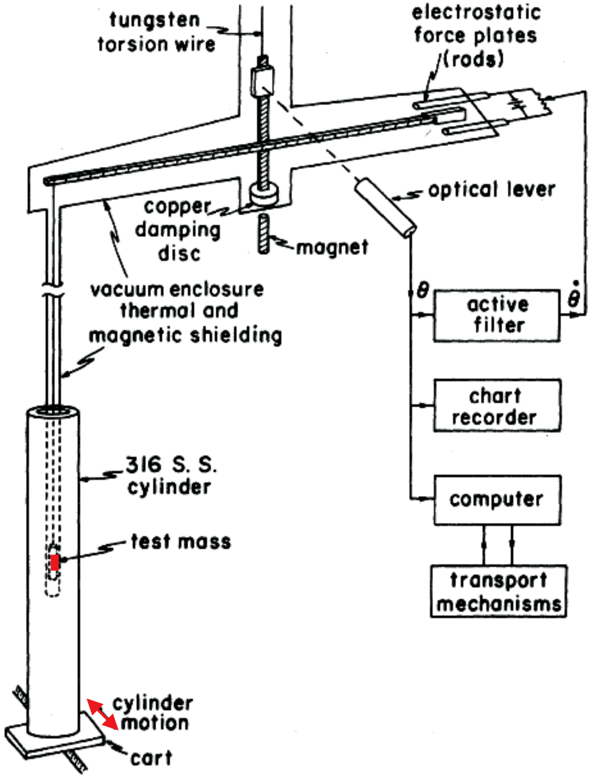
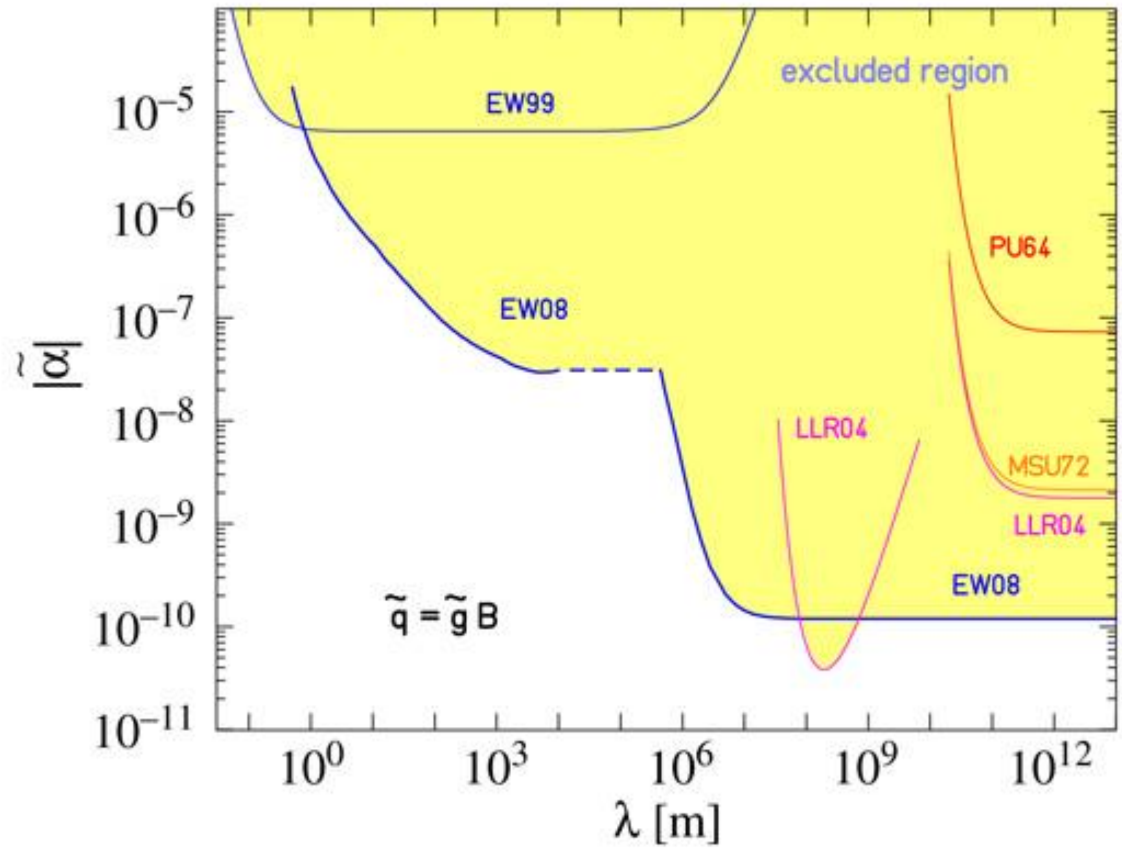


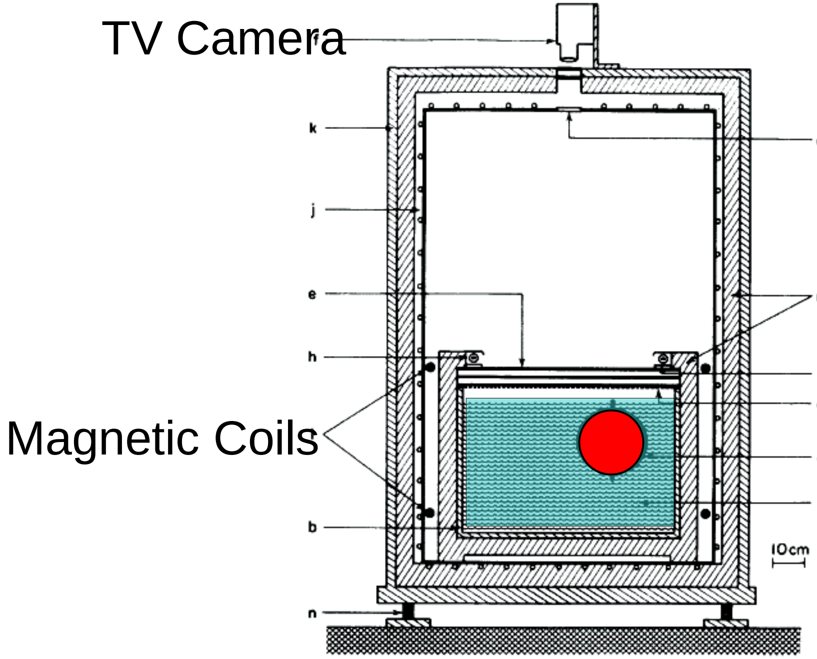
FIG. 1. Schematic of the experimental apparatus.

Limits on Extra Dimensions and New Forces: Long-Range Composition-Dependent Limits



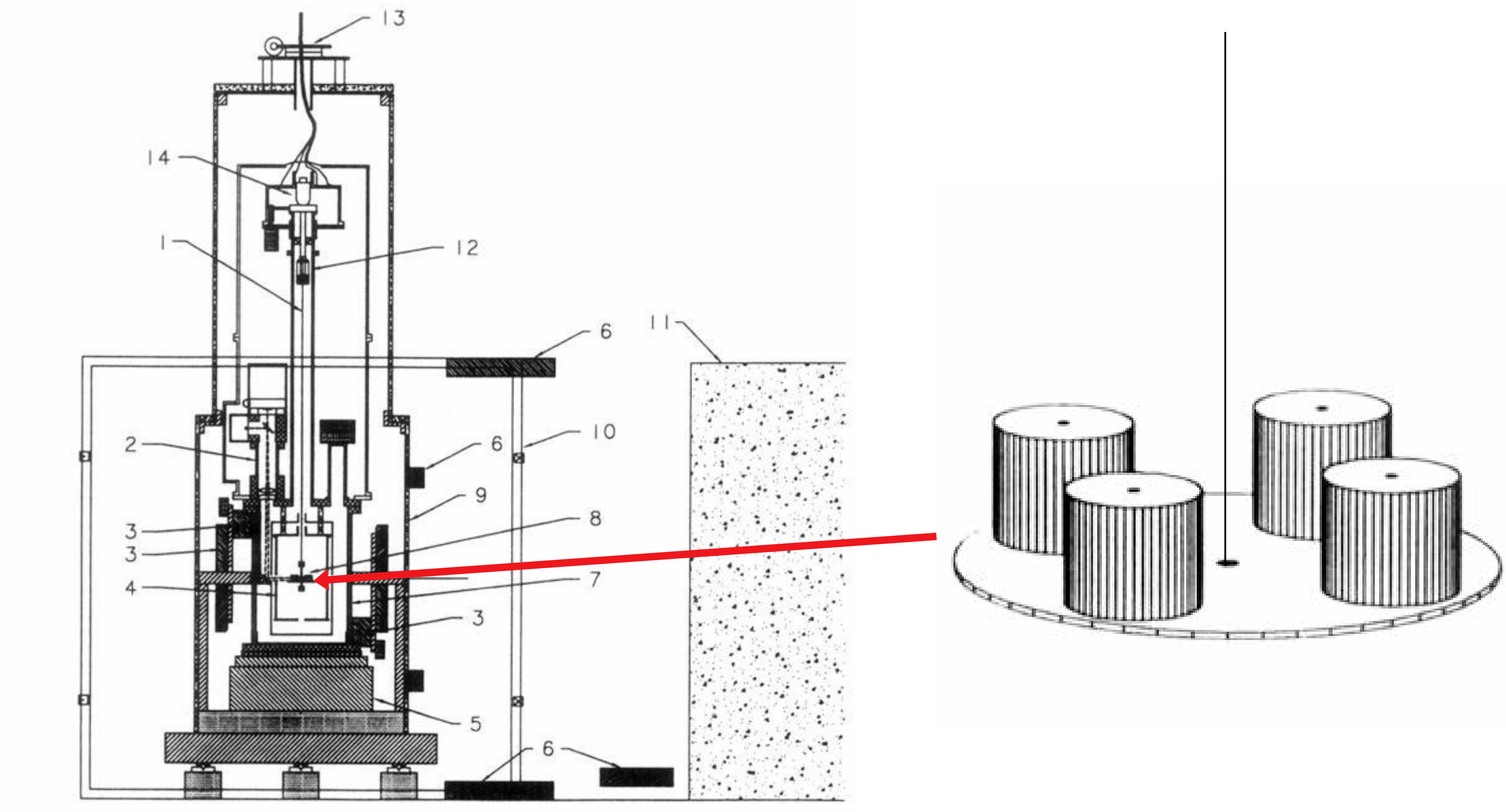
Reference: E. G. Adelberger, Prog. Part. Nucl. Phys. 62, 102 (2009)

Composition-Dependent Tests:
(Thieberger 1987)



Temperature of water is kept at (4.0±0.2)° C (maximum water density)

Composition-Dependent Tests:
(Eöt-Wash, 1994)



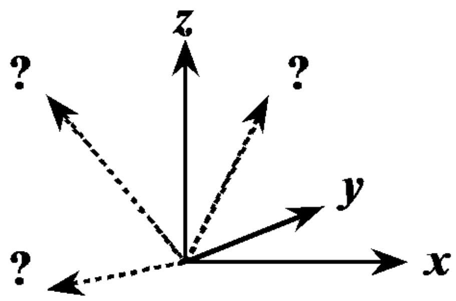
Reference: Y. Su, et al., Phys. Rev. D **50**, 3614 (1994)

Summary of Non-Null Results

Experiment	Disposition
Eötvös (1922)	???
Long (1976)	Tilt Problems
Stacey (1981)	Terrain Bias
Aronson (1982)	?
Thieberger (1987)	?
Hsui (1987)	Unknown Systematics
Boynton (1987)	Magnetic Contamination
Eckhardt (1988)	Terrain Bias
Ander (1989)	Gravitational Anomalies

There is at present no credible evidence for any deviations from the predictions of Newtonian gravity on any length scale.

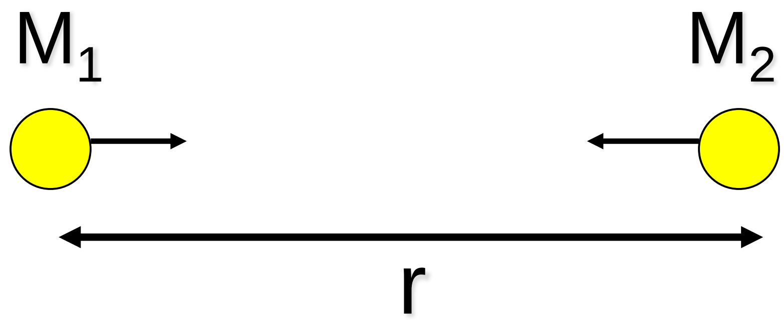
Extra Dimensions



Theories:

- **Kaluza-Klein Theories (1920s)**
- **Supergravity**
- **String Theory**

Gravity in 3 + *n* Non-Compact Dimensions

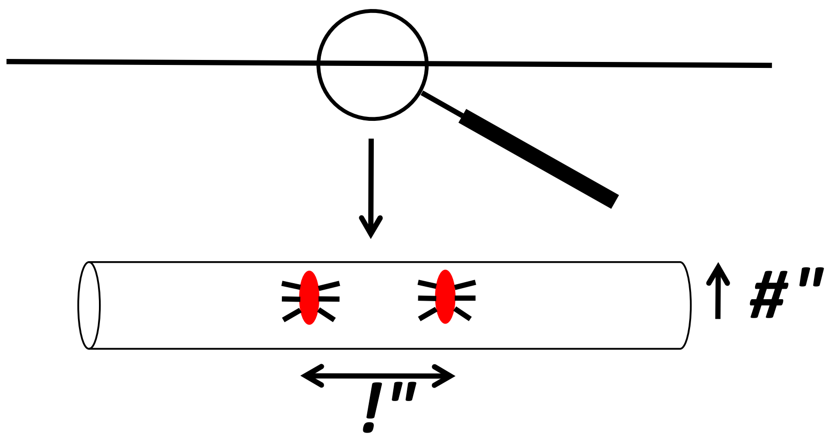


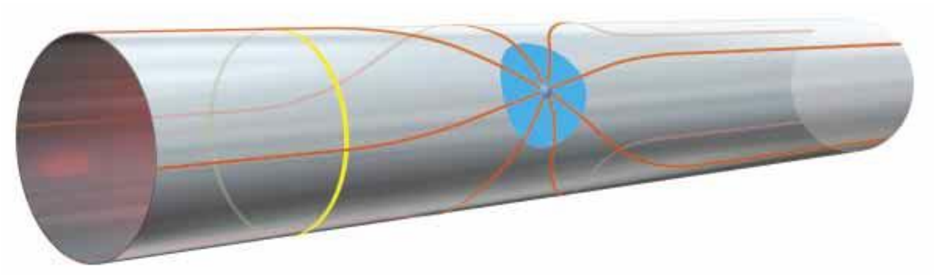
Potential Energy:

$$\boxed{V_{\text{Gravity}}(r) = -\frac{G_{4+n} M_1 M_2}{r^{1+n}}}$$

Observations ➔ n = 0

Compact Spatial Dimensions





ADD, Sci. Am., 2000

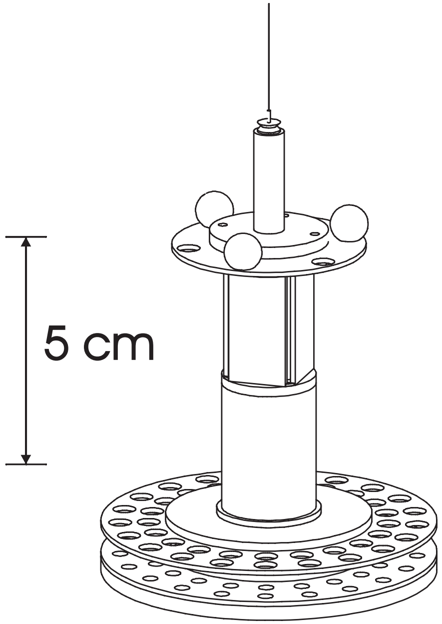
r* >> *R (**Space appears 3-D**

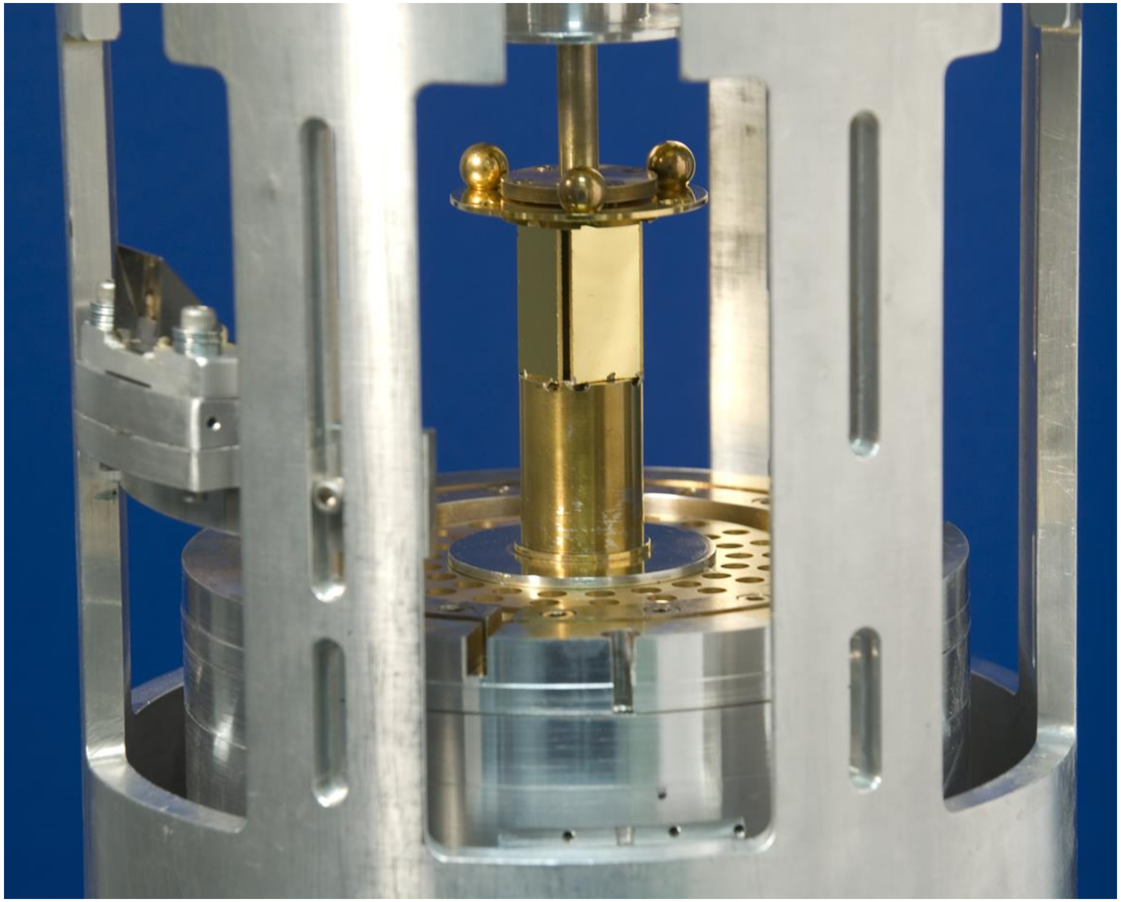
r* < *R (**Extra dimensions appear**

Experiment:

- **All matter sees extra dims if *R*< 10^{-15} m**
- **Only gravity sees extra dims if *R*< 10^{-4} m**

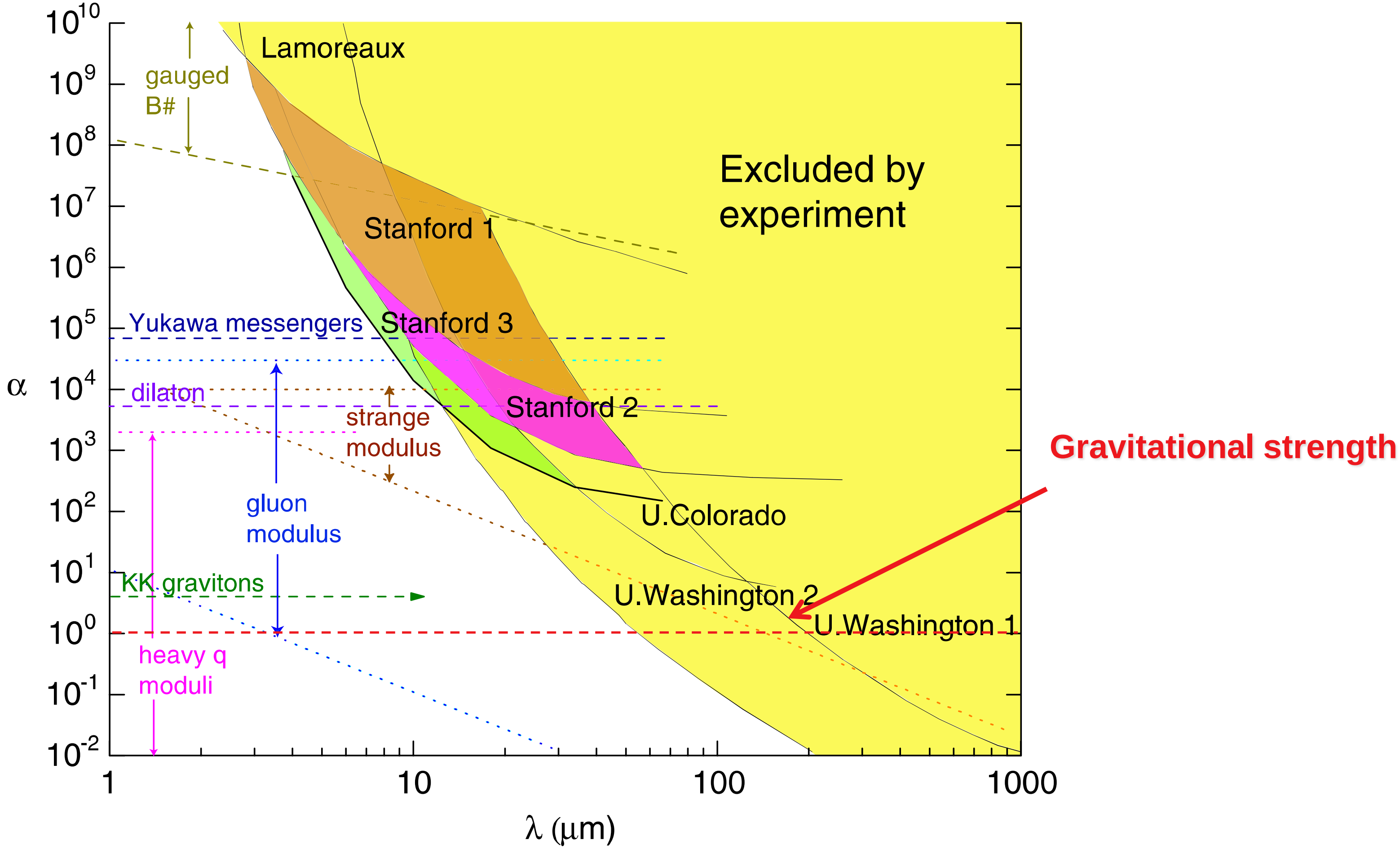
Eöt-Wash Short-Distance Experiment





D. J. Kapner, et al., Phys. Rev. Lett. 98, 021101 (2007)

Limits on Extra Dimensions and New Forces:
Short-Range Limits



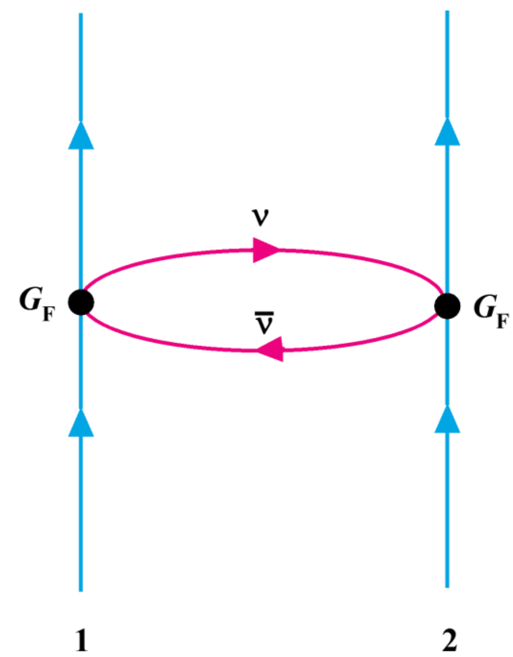
Reference: A. A. Geraci, et al., PRD **78**, 022002 (2008)

Power Law Forces

Various mechanisms lead to inverse power-law potentials:

$$V_n(r) = -\alpha_n \left(\frac{G M_1 M_2}{r} \right) \left(\frac{r_0}{r} \right)^{n-1},$$

$$r_0 \equiv 10^{-15}\ \text{m}$$



- ***n* = 2** 2-photon exchange; 2-scalar exchange
- ***n* = 3** 2-pseudoscalar exchange, Randall-Sundrum model with warped infinite dimensions
- ***n* = 5** 2-neutrino-exchange; 2-axion exchange

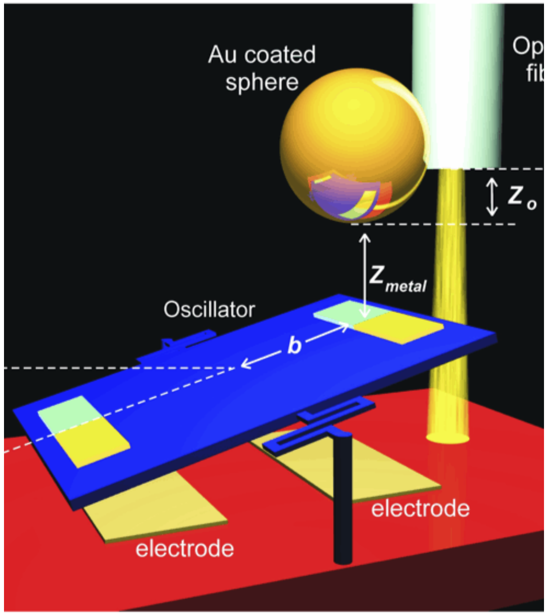
Limits on Power Law Forces from Short-Distance (~ cm) Gravity Experiments

$$V_n(r) = -\beta_n \left(\frac{GM_1 M_2}{r}\right)\left(\frac{1\ \text{mm}}{r}\right)^{n-1}$$

n	$\lvert\beta_n\rvert$
2	$\mathbf{4.5 \times 10^{-4}}$
3	$\mathbf{1.3 \times 10^{-4}}$
4	$\mathbf{4.9 \times 10^{-5}}$
5	$\mathbf{1.5 \times 10^{-5}}$

Reference: E. G. Adelberger, et al., Prog. Part. Nucl. Phys. **62**, 102 (2009).

IUPUI Experiment
(Decca, Lopéz, Fischbach, Krause)



Experimental Parameters:

Plate: 500 μm × 500 μm × 3.5 μm

Sphere Radius: ~50 μm

Sphere/Plate Separation: 150-500 nm

Image: R. S. Decca, et al., Phys. Rev. Lett**. 94**, 240401 (2005)

Towards a resolution of the Eötvös Paradox

The most likely resolution of the paradox probably lies in our group’s reanalysis of the Eötvös experiment:

- Although this paper is completely correct, there may be other models which could also account for the Eötvös data which would suggest a different family of experiments that have yet to be performed.
- In fact, it is likely that any interaction whose “charge: is baryon number (B) or hypercharge (Y) could work.

Towards a resolution of the Eötvös Paradox: Some Possibilities

- Baryonic neutrinos
- Baryonic force is somehow “activated” or “catalyzed” by the Earth’s rotation
- New force-gravitation interference enhancement
- New Non-Yukawa baryonic interaction
- Scalar-Vector Yukawa baryonic interactions
- A feature of the Eötvös experiment “hiding in plain sight”?
- Combination of puzzles (neutrino physics, dark energy, dark matter) may hold the answer

The End

EPJ manuscript No.
(will be inserted by the editor)

The Fifth Force: A Personal History

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Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA

Abstract. Insert your abstract here.

1 Introduction

At approximately 11AM on Monday, January 6, 1986 I received a call from John Noble Wilford of the N.Y. Times inquiring about a paper of mine which had just been published in Physical Review Letters [?]. As a subscriber to the Times I knew who John was, and so it was exciting to find myself speaking to him in person. My excitement was tempered by the fact that I had returned the day before to Seattle with a major cold which made it difficult for me to talk to him or anybody else. Two days later a front page story appeared in the Times by John under the headline "Hints of Fifth Force in Universe Challenge Findings of Galileo", accompanied by a sketch of Galileo's supposed experiment on the Leaning Tower of Pisa. Thus was born the concept of a "fifth force" which, as used now, generically refers to a gravity-like long-range force co-existing with gravity, presumably arising from the exchange of any of the ultra-light quanta whose existence is predicted by various unification theories such as supersymmetry. Depending on the specific characteristics of this hypothesized force, it could manifest itself in various experiments as an apparent deviations from the predictions of Newtonian gravity.

Our paper in Physical Review Letters (PRL) entitled "Reanalysis of the Eötvös Experiment" [?], was co-authored by my three graduate students Carrick Talmadge, Daniel Sudarsky, and Aaron Szafer, along with my long-time friend and collaborator Sam Aronson. As the title suggests, our paper re-analyzed the data obtained from what is now known as the "Eötvös Experiment", one of the most well-known experiments in the field of gravity. [2]. The authors of that 1922 paper, Baron Lorand v. Eötvös, Desiderius Pekar, and Eugen Fekete (EPF), had carried out what was then the most precise test of whether the behavior of objects in a gravitational field was the same independent of their different chemical compositions. Their conclusion, that it was, provided experimental support for what is now known as the Weak Equivalence Principles (WEP), which is one of the key assumptions underlying Einstein's General Theory of Relativity [3]. However, the result of our reanalysis [1] of the EPF paper [2] was that the EPF data were in fact "...sensitive to the composition of the material used.", in contrast to what EPF themselves had claimed. If the EPF data and our

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4 Reflections

4.1 The Moriond Conferences

No organizational effort contributed more to searches for non-Newtonian gravity (and other related exotic phenomena) than the Rencontres de Moriond under the leadership of J. Trân Than Vân.]
,

Outline

I. Prehistory:
- Early Motivation
- Generic Theories of Non-Newtonian Gravity

II. Re-analysis of the the Eötvös Experiment

III. The 5th Force and Rencontres de Moriond
- Original 5th Force
- Spin-Dependent Forces
- String-inspired Short-Distance Forces
  - ✓ Extra Dimensions
  - ✓ Casimir Forces

IV. Conclusions

Pre-History

The Search for New Macroscopic Forces: Pre-1986

NATURE PHYSICAL SCIENCE VOL. 234 NOVEMBER 1 1971 5

Dilaton and Possible Non-Newtonian Gravity

YASUNORI FUJII

Institute of Physics, College of General Education, University of Tokyo, Komaba, Tokyo 153

A model is proposed which allows a dilaton to show up in a possible non-Newtonian part of the gravitational force. By examining the available observational facts it can be shown that the force-range of the additional force, if it exists, will be either between 10 m and 1 km or smaller than ~1 cm.

A DILATON—a Nambu-Goldstone boson of dilatation invariance[1-6]—will, if it exists, couple to the graviton, because the dilaton dominates the energy-momentum tensor which is supposed to be a source of the graviton. The fact that the dilaton is a scalar particle does not prevent it from coupling to the graviton, which is described by a symmetric tensor field, but is not a genuine spin-2 particle because of its masslessness. As a consequence the dilaton may affect the gravitational force between two masses.

If the dilaton mass is of the order of hadronic masses, any modifications will occur only within the distances of the order of fm. The dilaton mass could be, on the other hand, of the order of $\kappa \sim [G\alpha'^{-2}]^{1/2}$ which is a typical combination of two fundamental constants in the gravitational and strong inter-

We have an order of magnitude estimate of the constant F_θ[7,9]

$$F_\theta \sim \alpha'^{-1} \tag{1}$$

The θ-graviton mixing problem is then resolved to give a gravity potential

$$V(r) = -\frac{3}{4} G \frac{1}{r}\left[1 + \frac{1}{3}\left(\cos \kappa r - \frac{1 - t_\theta/2\kappa^2}{\sqrt{-D}} \sin \kappa r\right) e^{-\kappa\sqrt{-D}\,r}\right] \tag{2}$$

where $\kappa^2 = (3/8)GF_\theta^2$, and $-D = t_\theta/\kappa^2 - 1$ with the restriction $t_\theta > \kappa^2$. From (1), with $G = 6.67 \times 10^{-8}$ cm^3 g^{-1} s^{-2} from the Cavendish experiment, we obtain $\kappa \sim 10^{-20}\, m_{N'}$ or $\kappa^{-1} \sim 10^5$ cm $= 1$ km.

If the "bare" dilaton mass squared (t_θ) vanishes, that is, dilatation invariance is strict, there is no change in the gravitational interaction. If t_θ is of the order of a hadronic mass squared, then $\kappa\sqrt{-D} \sim \sqrt{t_\theta}$ in the exponent in (2), because $t_\theta \gg \kappa^2$. The finite-range part vanishes for any macroscopic distance. On the other hand, t_θ may be of the same order of, but still larger than, κ^2. We obtain $\kappa\sqrt{-D} \sim \kappa$, because $-D \sim 1$. The force-range is of the order of $\kappa^{-1} \sim$ km. We have then an entirely new situation.

Consider the Cavendish experiment with the distance $r \sim 10$ cm. The potential (2) becomes

The Search for New Macroscopic Forces: Pre-1986

636 Nature Vol. 291 25 June 1981

LETTERS TO NATURE

Newtonian gravity measurements impose constraints on unification theories

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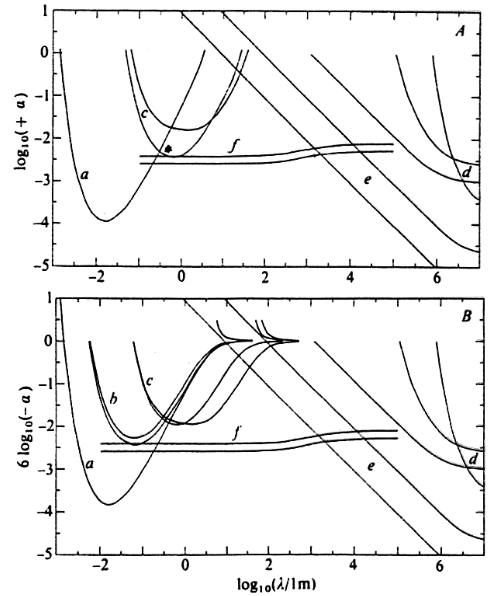
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, UK

Theories which attempt to unify gravity with the other forces of nature can be coarsely classified according to the mass scale of the new particles they introduce or equivalently the length scale at which new phenomena occur. This mass scale can be expressed as $m_p(m_H/m_p)^n$, where m_H is a typical hadron mass and m_p is the Planck mass. In most current theories n is 0 or 1. However, in some theories $n=2$, which offers the possibility of experimental consequences at kilometre scales. Here using satellite and geophysical data we place constraints on such theories and find that they are not viable unless $m_H > 10^3$ GeV.

geodesy measurements[21,22] together with the results of a recent mine experiment[23] and those in refs 18, 24 place stringent limits on the parameters appearing in theories of the Fujii or Scherk types.

If gravitation is due to the exchange of particles of Compton wavelength λ_i, and coupling α_i, the potential energy of two masses m and m' at a separation r is V where

$$V = -G_\infty \frac{mm'}{r}\left(1 + \sum_{i=1}^{N} \alpha_i \exp(-r/\lambda_i)\right) \quad (1)$$



PURDUE UNIVERSITY

The 5th Force

Particle Data Group

1645

Searches Particle Listings

Extra Dimensions

Limits on R from Deviations in Gravitational Force Law

This section includes limits on the size of extra dimensions from deviations in the Newtonian ($1/r^2$) gravitational force law at short distances. Deviations are parametrized by a gravitational potential of the form $V = -(G\ m\ m'/r)\ [1 + \alpha\ \exp(-r/R)]$. For δ toroidal extra dimensions of equal size, $\alpha = 8\delta/3$. Quoted bounds are for $\delta = 2$ unless otherwise noted.

VALUE (μm)	*CL%*	*DOCUMENT ID*		*COMMENT*
< 30	95	[1] KAPNER	07	Torsion pendulum
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[2] XU	13	Nuclei properties
		[3] BEZERRA	11	Torsion oscillator
		[4] SUSHKOV	11	Torsion pendulum
		[5] BEZERRA	10	Microcantilever
		[6] MASUDA	09	Torsion pendulum
		[7] GERACI	08	Microcantilever
		[8] TRENKEL	08	Newton's constant
		[9] DECCA	07A	Torsion oscillator
< 47	95	[10] TU	07	Torsion pendulum
		[11] SMULLIN	05	Microcantilever
<130	95	[12] HOYLE	04	Torsion pendulum
		[13] CHIAVERINI	03	Microcantilever
$\lesssim$200	95	[14] LONG	03	Microcantilever
<190	95	[15] HOYLE	01	Torsion pendulum
		[16] HOSKINS	85	Torsion pendulum

[1] KAPNER 07 search for new forces, probing a range of $\alpha \simeq 10^{-3}$–10^5 and length scales $R \simeq$ 10–1000 μm. For $\delta = 1$ the bound on R is 44 μm. For $\delta = 2$, the bound is expressed in terms of M_*, here translated to a bound on the radius. See their Fig. 6 for details on the bound.

[2] XU 13 obtain constraints on non-Newtonian forces with strengths $|\alpha| \simeq 10^{34}$–10^{36} and length scales $R \simeq$ 1–10 fm. See their Fig. 4 for more details. These constraints do not place limits on the size of extra flat dimensions.

[3] BEZERRA 11 obtain constraints on non-Newtonian forces with strengths $10^{11} \lesssim |\alpha| \lesssim 10^{18}$ and length scales $R =$ 30–1260 nm. See their Fig. 2 for more details. These constraints do not place limits on the size of extra flat dimensions.

[4] SUSHKOV 11 obtain improved limits on non-Newtonian forces with strengths $10^7 \lesssim |\alpha| \lesssim 10^{11}$ and length scales 0.4 μm < R < 4 μm (95% CL). See their Fig. 2. These bounds do not place limits on the size of extra flat dimensions. However, a model dependent bound of $M_* > 70$ TeV is obtained assuming gauge bosons that couple to baryon number also propagate in $(4 + \delta)$ dimensions.

[5] BEZERRA 10 obtain improved constraints on non-Newtonian forces with strengths $10^{19} \lesssim |\alpha| \lesssim 10^{29}$ and length scales $R =$ 1.6–14 nm (95% CL). See their Fig. 1. This bound does not place limits on the size of extra flat dimensions.

[6] MASUDA 09 obtain improved constraints on non-Newtonian forces with strengths $10^9 \lesssim |\alpha| \lesssim 10^{11}$ and length scales $R =$ 1.0–2.9 μm (95% CL). See their Fig. 3. This bound does not place limits on the size of extra flat dimensions.

[7] GERACI 08 obtain improved constraints on non-Newtonian forces with strengths $|\alpha| >$ 14,000 and length scales $R =$ 5–15 μm. See their Fig. 9. This bound does not place limits on the size of extra flat dimensions.

[8] TRENKEL 08 uses two independent measurements of Newton's constant G to constrain new forces with strength $|\alpha| \simeq 10^{-4}$ and length scales $R =$ 0.02–1 m. See their Fig. 1. This bound does not place limits on the size of extra flat dimensions.

[9] DECCA 07A search for new forces and obtain bounds in the region with strengths $|\alpha| \simeq 10^{13}$–10^{18} and length scales $R =$ 20–86 nm. See their Fig. 6. This bound does not place limits on the size of extra flat dimensions.

[10] TU 07 search for new forces probing a range of $|\alpha| \simeq 10^{-1}$–10^5 and length scales $R \simeq$ 20–1000 μm. For $\delta = 1$ the bound on R is 53 μm. See their Fig. 3 for details on the bound.

[11] SMULLIN 05 search for new forces, and obtain bounds in the region with strengths $\alpha \simeq 10^3$–10^8 and length scales $R =$ 6–20 μm. See their Figs. 1 and 16 for details on the bound. This work does not place limits on the size of extra flat dimensions.

[12] HOYLE 04 search for new forces, probing α down to 10^{-2} and distances down to 10μm. Quoted bound on R is for $\delta = 2$. For $\delta = 1$, bound goes to 160 μm. See their Fig. 34 for details on the bound.

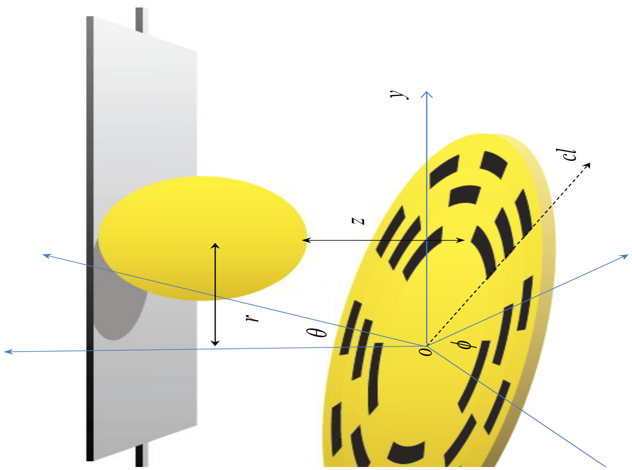
[13] CHIAVERINI 03 search for new forces, probing α above 10^4 and λ down to 3μm, finding no signal. See their Fig. 4 for details on the bound. This bound does not place limits on the size of extra flat dimensions.

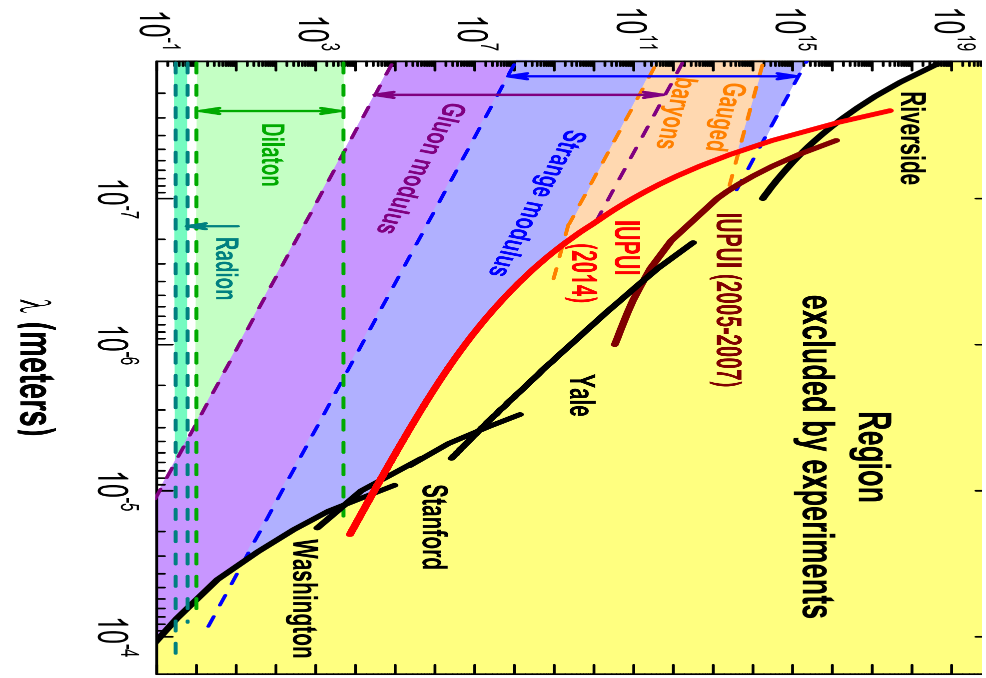
[14] LONG 03 search for new forces, probing α down to 3, and distances down to about 10μm. See their Fig. 4 for details on the bound.

[15] HOYLE 01 search for new forces, probing α down to 10^{-2} and distances down to 20μm. See their Fig. 4 for details on the bound. The quoted bound is for $\alpha \geq 3$.

[16] HOSKINS 85 search for new forces, probing distances down to 4 mm. See their Fig. 13 for details on the bound. This bound does not place limits on the size of extra flat dimensions.

New Limits on New Submicron Forces





Reference: Y.-J. Chen, W. K. Tham, D. E. Krause, D. López, Ephraim Fischbach, and R. S. Decca, arXiv:1410.7267

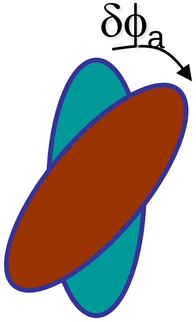
Long-Range Tests

(composition-independent)

Inverse-Square Law: Solar System Tests

$$V_5(r) = -\alpha \frac{G_\infty m_1 m_2 e^{-r/\lambda}}{r}$$

The presence of the non-Newtonian contribution leads to 2 measurable effects:

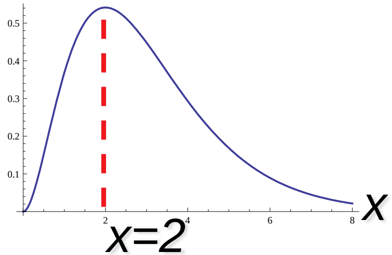


a) Planetary Precession:

$$\delta\phi_a \cong +\pi\alpha (a/\lambda)^2 e^{-a/\lambda} \text{ rad/rev} \propto \pi\alpha\, x^2 e^{-x}$$

$a =$ mean value of semi-major axis

$\delta\phi_a = cx^2 e^{-x}$ has a maximum at $x = 2$



b) Variation of GM_{sun} :

$$V_5(r) \Rightarrow \quad G(r) = G_\infty[1+\alpha(1+r/\lambda)e^{-r/\lambda}] \neq \text{ constant}$$

$$\therefore \quad 4\pi^2 \frac{a_p^3}{T_p^2} = G(a) M_{sun} \neq \text{ constant}$$

Mikkelson & Newman (1977); de Rujula (1986); Talmadge, Berthias, Hellings, & Standish (1988); Coy, Fischbach, Hellings, Standish & Talmadge (2003)

Long-Range Tests

(composition-dependent)

Short-Range Phenomenology

Gravity with *n* Compact Extra Dimensions of Size R

Newtonian Gravity

Yukawa Correction

$$V_{\text{Gravity}}(r) = \begin{cases} -\dfrac{G_4 M_1 M_2}{r}\left(1 + \alpha e^{-r/\lambda}\right), & r \gg R \\[2ex] -\dfrac{G_{4+n} M_1 M_2}{r^{1+n}}, & r \le R \end{cases}$$

Range of Yukawa: λ ~ R

Strength Constant: α ~ 1-10 (depends on n and compactification scheme)

Numerical Estimates

- It is convenient to introduce an energy scale set by the usual Newtonian constant $G = G_4$. This is the Planck mass $M_{Pl} = M_4$

  $M_4 = M_{Pl} = (\hbar c/G_4)^{1/2} = 2.18\times10^{-5}$ g $= 1.22\times10^{19}$ GeV/c^2

- In natural units ($\hbar = c = 1$) $M_4^2 = 1/G_4$

- The analog of the Planck mass in higher dimensions is called M_{4+n} where

$$M_4^2 \gg R^n(n) M_{4+n}^{n+2}$$

  where R(n) is the characteristic size of the compact dimension.

- This forms the basis for current experiments

How Big is M_{4+n}? How big is n?

1) The usual Planck mass M_4 and the associated length scale $\hbar/M_4c \approx 10^{-33}$ cm are the scales at which gravitational interactions become comparable in strength to other interactions, and hence can be unified with these interactions

2) It would be nice if this happened at a smaller energy scale bigger length scale.
A natural choice is ~ 1 TeV $= 10^{12}$ eV where supersymmetry breaks down

3) This can happen in some string theories with extra spatial dimensions if ordinary matter is confined to 3-dimensional walls ("branes"), and only gravity propagates in the extra dimensions

How Big is M_{4+n}? How big is n?

4) **In such theories $M_{4+n} \sim 1\ \mathrm{TeV}$ by assumption**
We then solve:

$$\underbrace{M_4^2}_{(10^{19}\ \mathrm{GeV})^2} \text{ » } R^n(n)\underbrace{M_{4+n}^{n+2}}_{(1\ \mathrm{TeV})^{n+2}}$$

$$R(n) \text{ » } 2 \text{ ´ } 10^{(32/n - 17)}\ \mathrm{cm}$$

***n* = 1** ⎝ $R(1) \approx 2 \times 10^{15}$ cm	**Excluded**
***n* = 2** ⎝ $R(2) \approx 0.2 = 2$ mm	**Highly Constrained**
***n* = 3** ⎝ $R(3) \approx 9 \times 10^{-7}$ cm	**Weakly Constrained**

Limit on Largest Extra Dimension R ≤ 44 μm

Reference: E. G. Adelberger, et al., Prog. Part. Nucl. Phys. **62**, 102 (2009).

Gravity and Extra Dimensions: Some References

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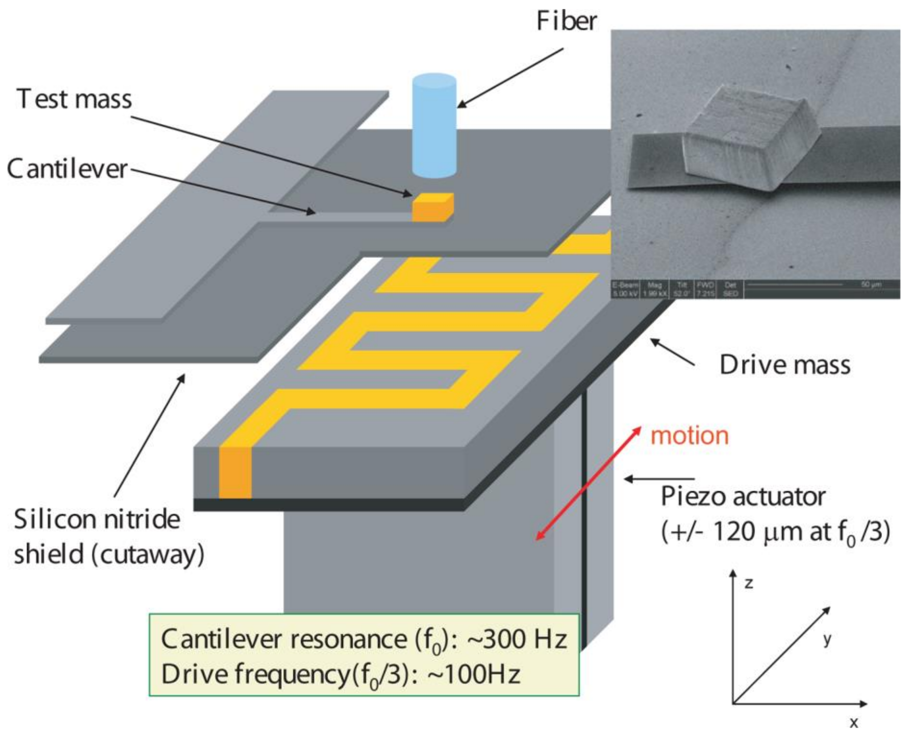
- L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999); **83**, 4690 (1999)
- A. Kehagias and K. Sfetsos, Phys. Lett. B **472**, 39 (2000); E. G. Floratos and G. K. Leontaris, Phys. Lett. B **465**, 95 (1999)

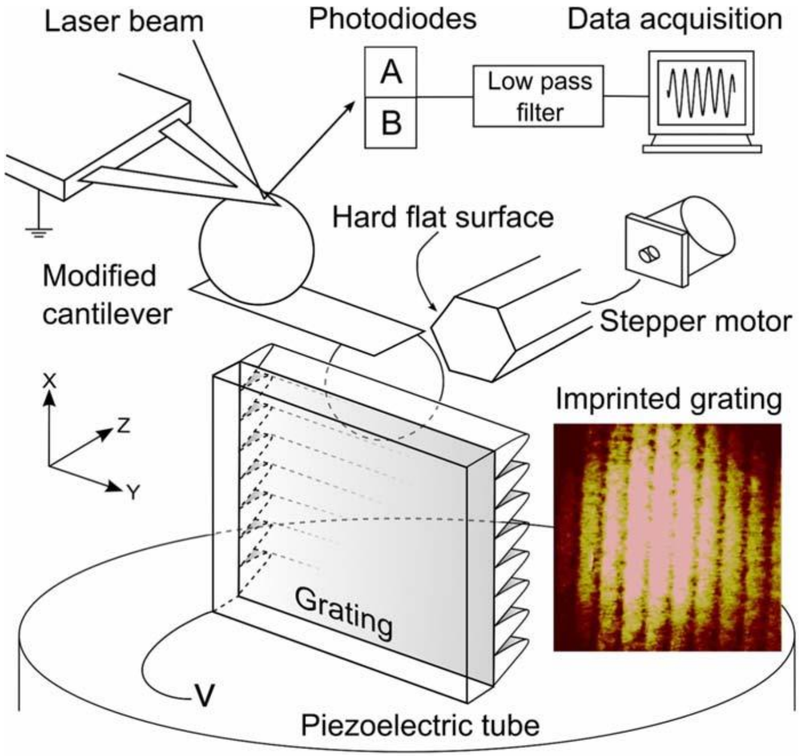
Short-Range Experiments

Stanford Short-Distance Experiment



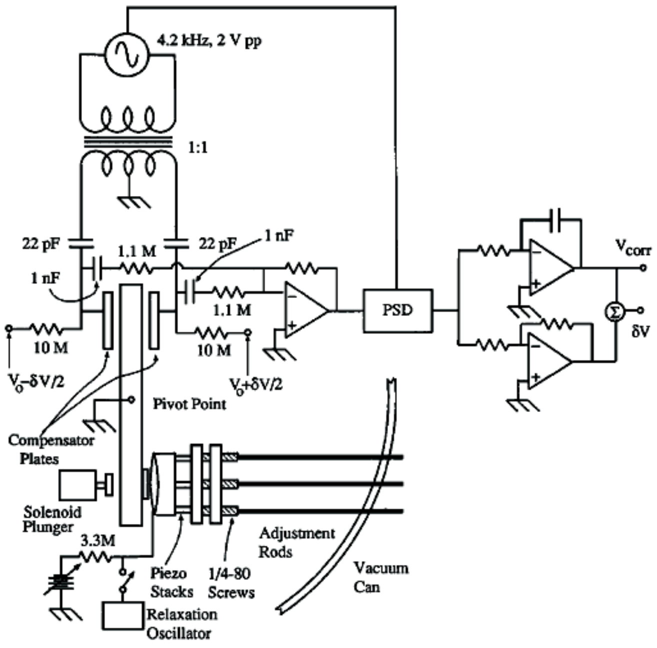
Reference: A.A. Geraci, et al., PRD, **78**, 022002 (2008)

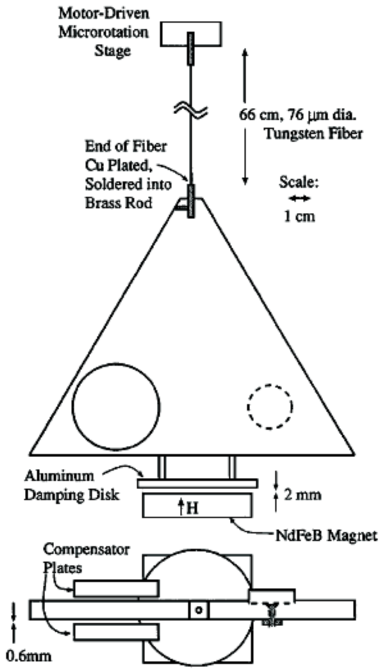
Riverside Lateral Casimir Force Experiment



Reference: H. –C Chiu, et al., Phys. Rev. B **80**, 121402(R) (2009)

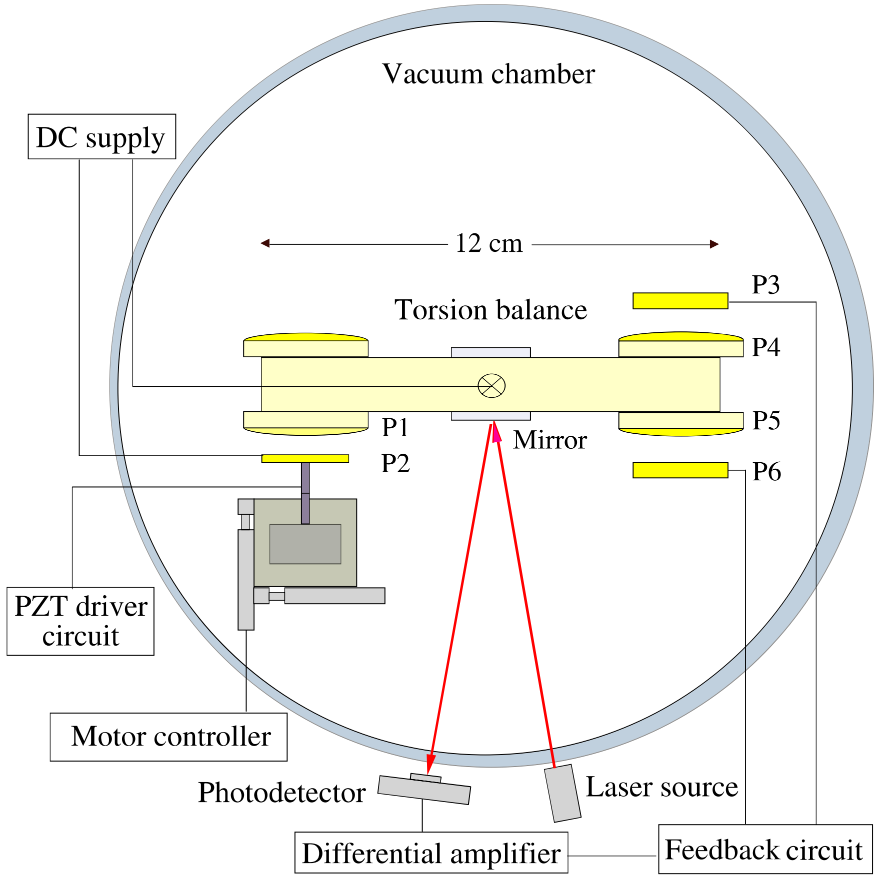
Lamoreaux Short-Distance Experiment





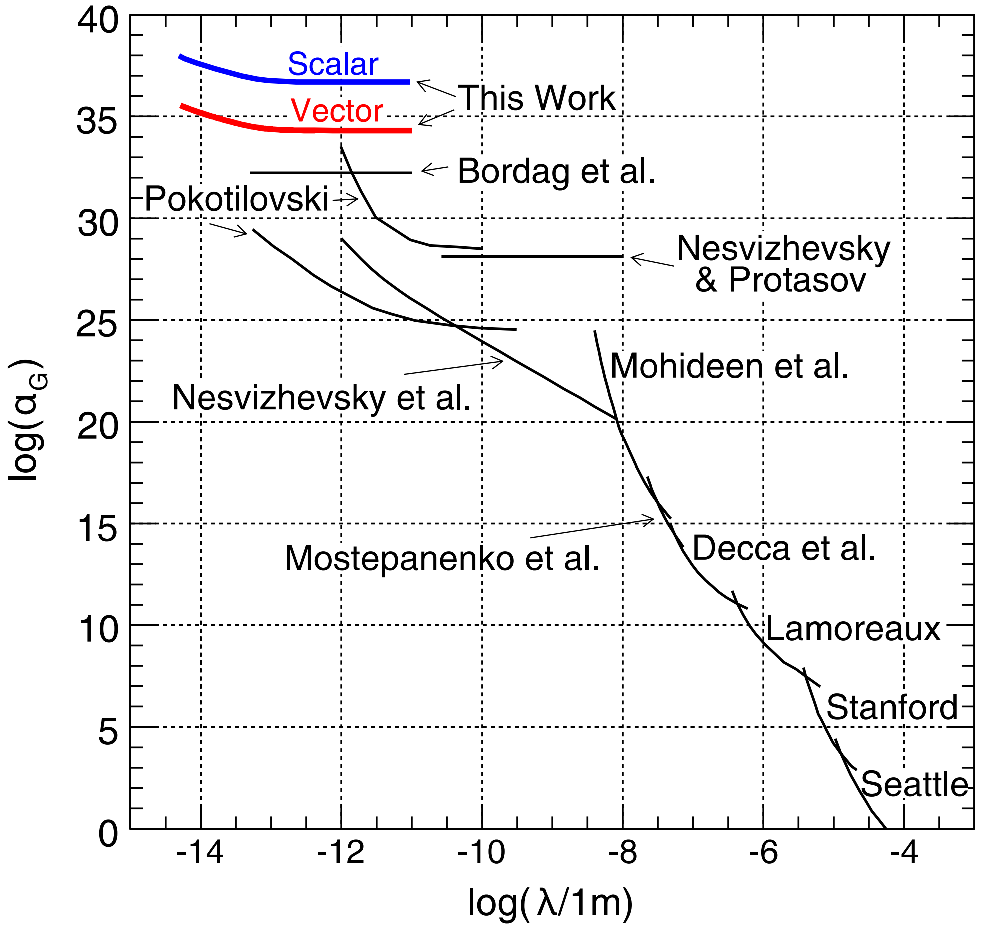
Reference: S. K. Lamoreaux, Phys. Rev. Lett. **78**, 5 (1997)

Tokyo Casimir Experiment



Reference: M. Masuda and M. Sasaki, Phys. Rev. Lett. **102**, 171101 (2009)

Limits on Extra Dimensions and New Forces:
Very Short-Range Limits



Reference: Y. Kamyshkov, et al., PRD **78**, 114029 (2008)

Why are Sub-micron Limits so Poor?

Problems:

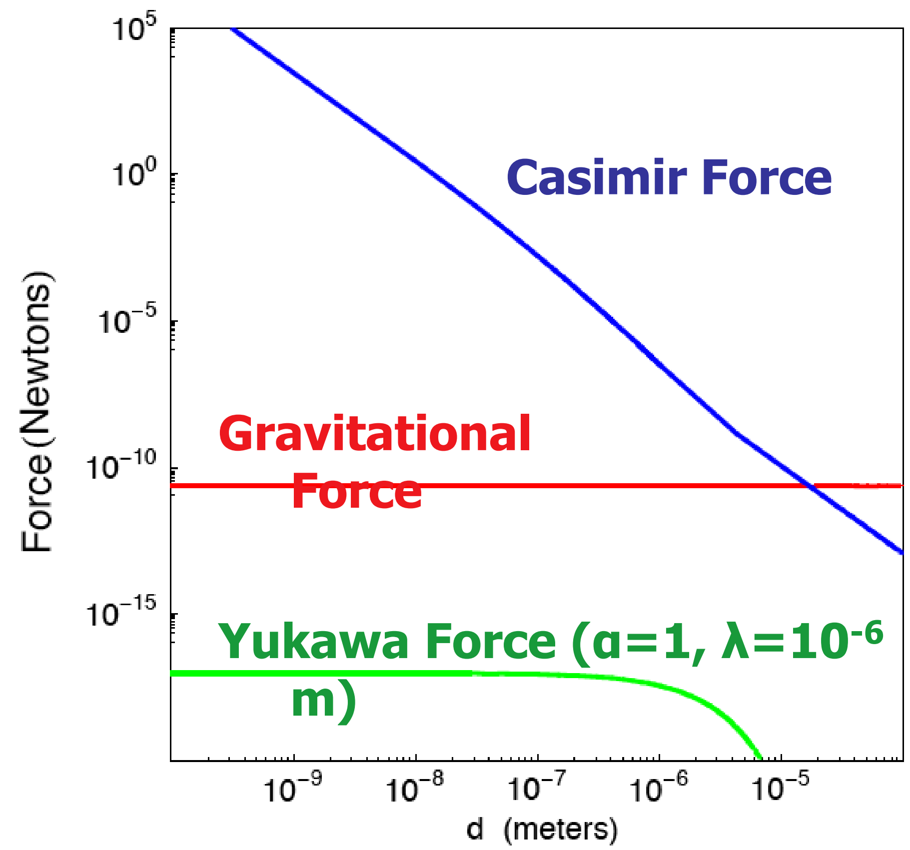
1. Strong Background Forces

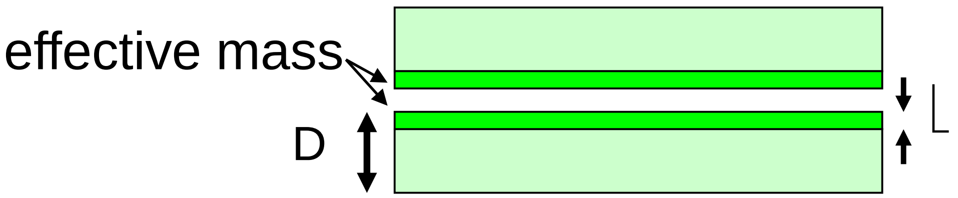
Casimir force dominates when 10^{-10} m < separation < 10^{-6} m

2. Small Fraction of Mass Contributes

Only mass within λ of surface contributes to Yukawa force between macroscopic bodies

Forces between two "pennies" at T = 300 K

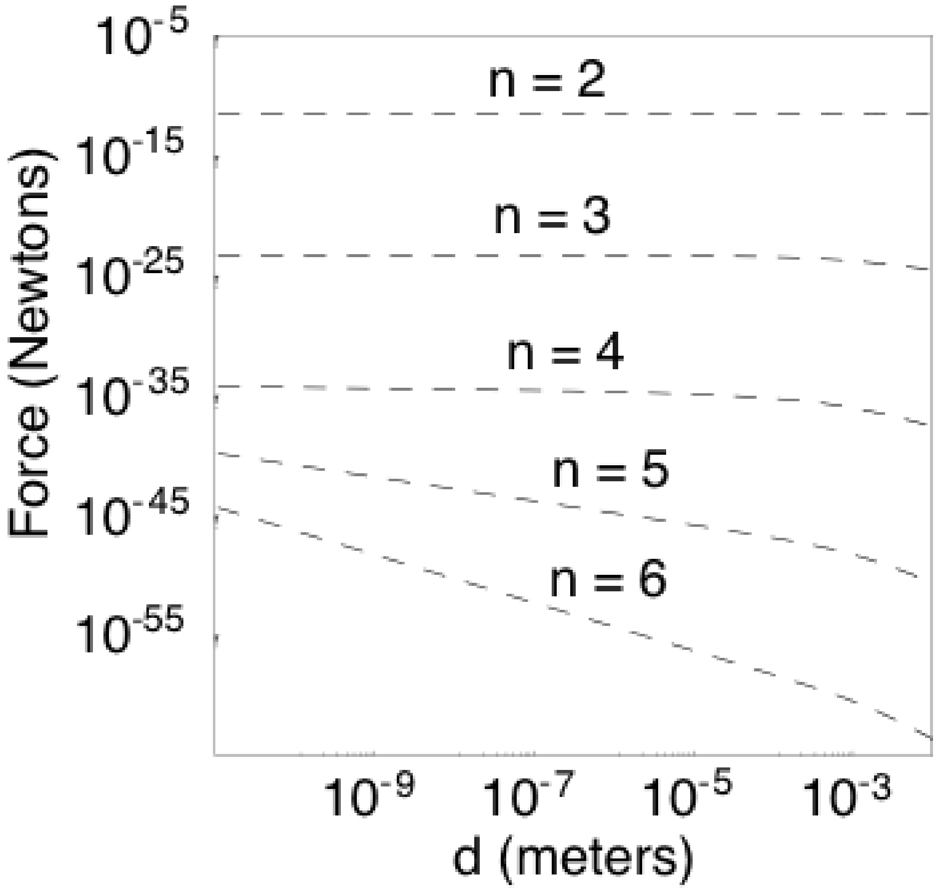




$$\frac{F_{\text{Yukawa}}}{F_{\text{Gravity}}} = \alpha \left(\frac{\lambda}{D} \right)^2$$

Finite-size Effect: New Power-law Forces

Power-law forces acting between two 1 cm × 1 cm × 1mm copper plates separated by distance d ($\alpha_n = 1$)



It is difficult to set limits on power-law forces at very short distances using macroscopic test bodies.

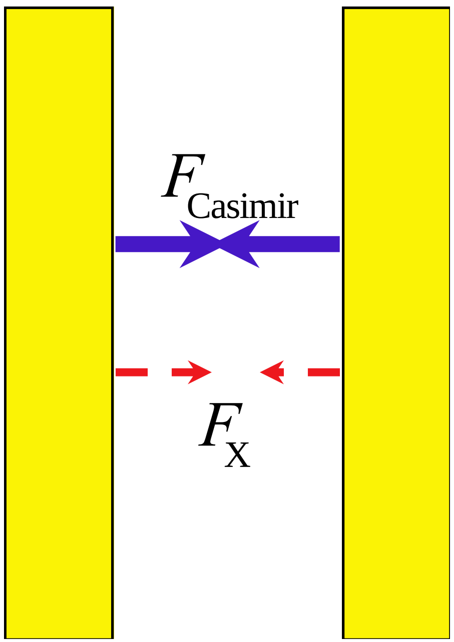
Background forces increase faster than new power-law forces as separation decreases.

Setting Limits on New Forces/New Extra Dimensions at Very Short Distances

- Extensions to the Standard Model of particle physics include new forces and extra dimensions that might appear at short distances.
- Many models predict that these effects appear as Yukawa or power-law corrections to Newtonian gravity.
- To set limits on Yukawa forces with ranges $\lambda < 10^{-6}$ m using force experiments, one must use test bodies separated by $< 10^{-6}$ m

Casimir Experiments

Searching for New Forces/Dimensions using Casimir Force Experiments



Measure Casimir force and compare result with theory:

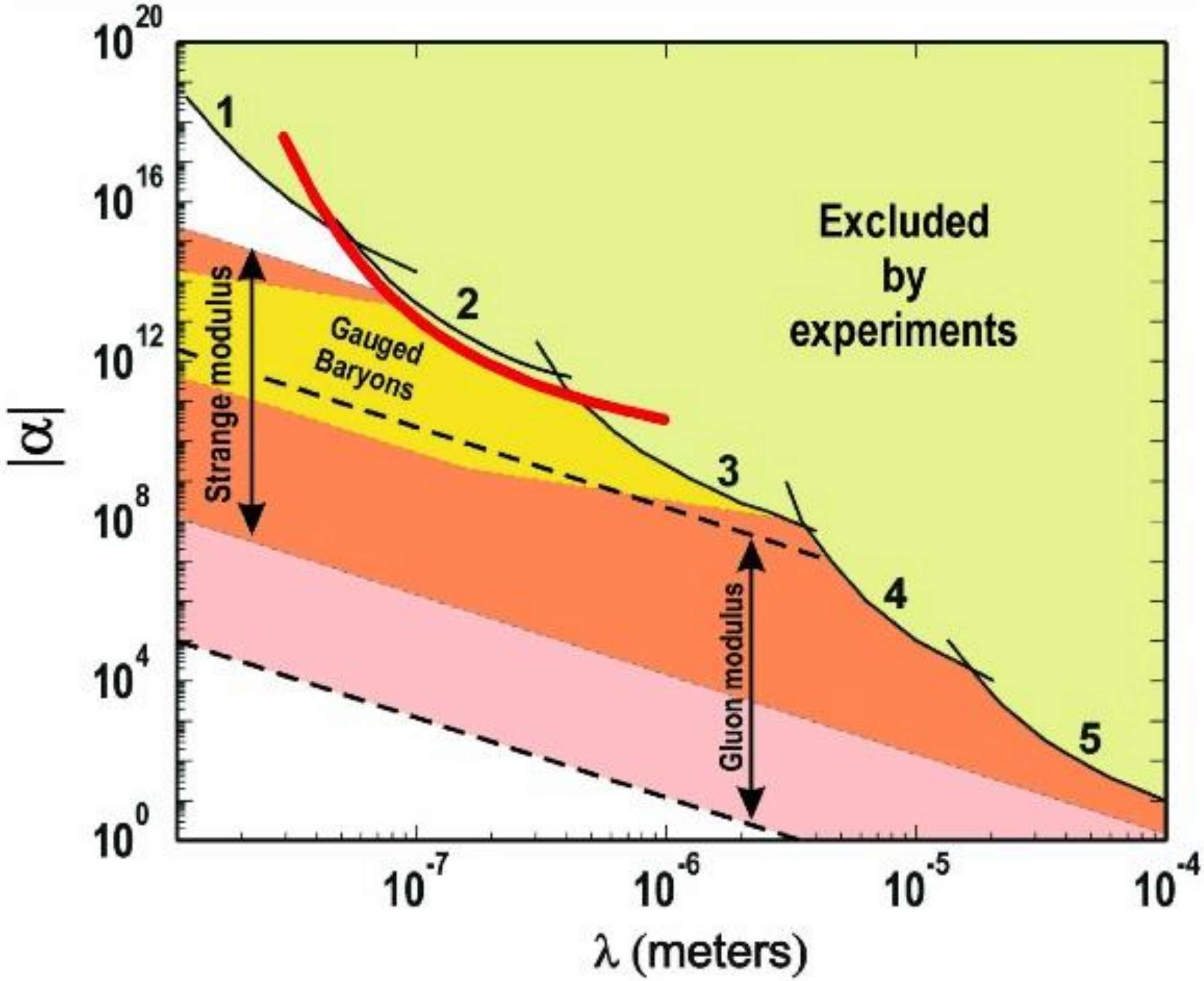
$$\left|F_X\right| \leq \left|F^{\text{Measured}}_{\text{Casimir}} - F^{\text{Theory}}_{\text{Casimir}}\right|$$

Corrections from Ideal:

- **Temperature-Dependence**
- **Roughness Corrections**
- **Finite-Conductivity**

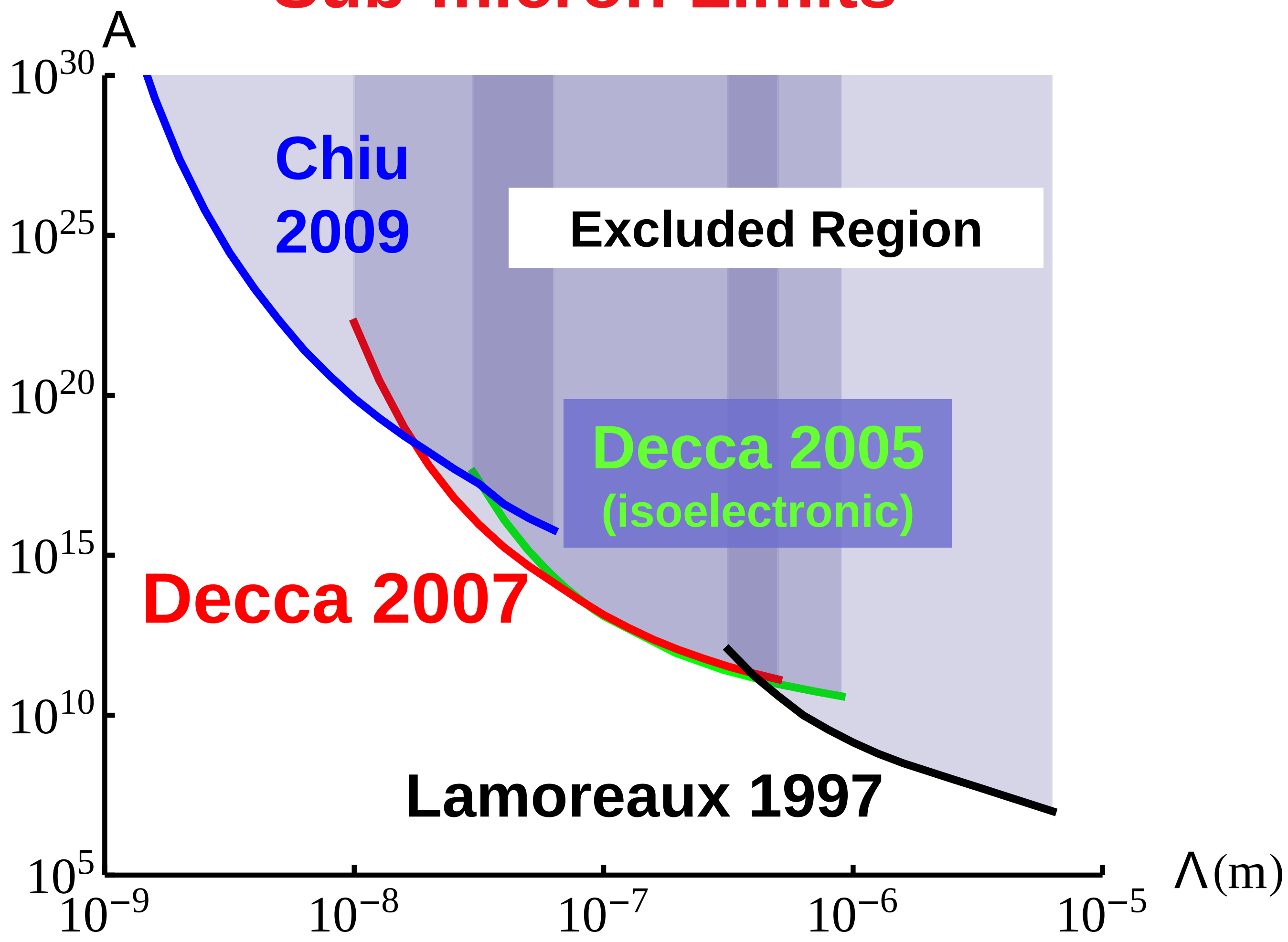
Reference: ***Advances in the Casimir Effect*** **by M. Bordag, et al.**

Theories at Sub-Micron Distances



Reference: R. S. Decca, et al., Phys. Rev. Lett**. 94**, 240401 (2005)

Limits on Extra Dimensions and New Forces:
Sub-micron Limits



Reference: V. M. Mostepanenko and G. L. Klimchitskaya

Iso-electronic (“Casimirless”) Experiments

Iso-electronic Effect

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Testing Newtonian gravity at the nanometer distance scale using the iso-electronic effect

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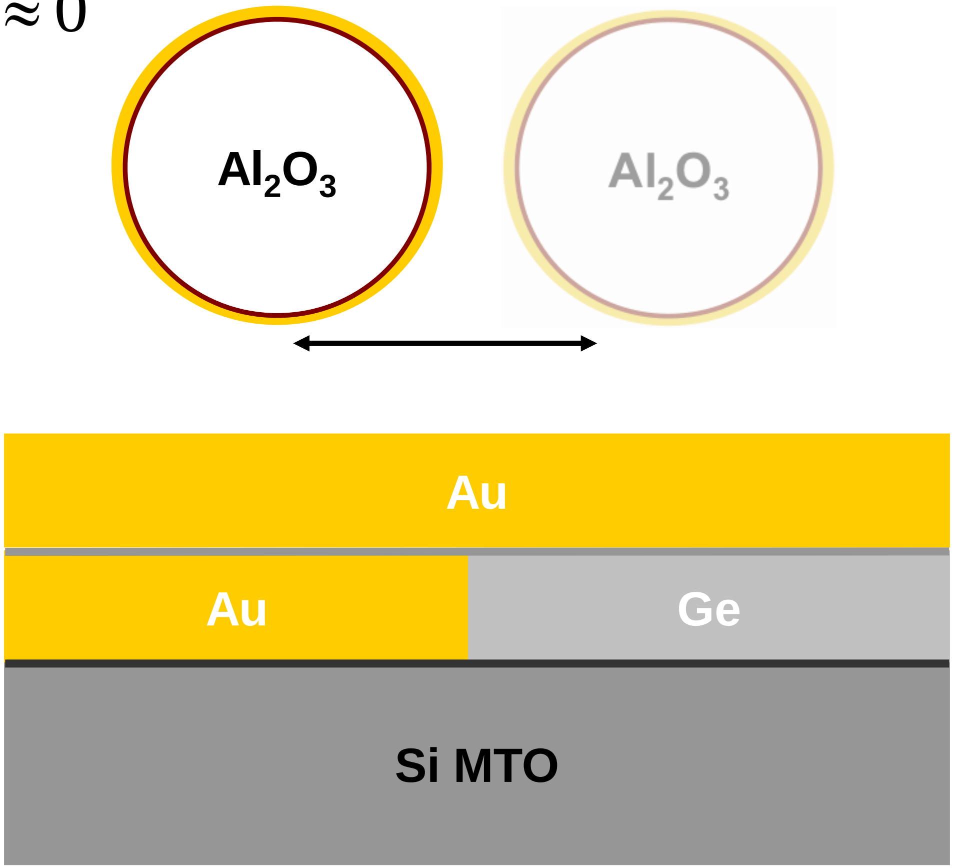
Abstract

We describe a new experimental and theoretical effort to search for new forces and extra spatial dimensions over nanometer distance scales. Since the Casimir force produces a large background over these distances, we plan to base our experiments on the iso-electronic effect. This utilizes the observation that the Casimir force depends primarily on the electronic properties of the test bodies, whereas new long-ranged forces also couple to nuclei. By measuring force *differences* between isotopes of the same element, we hope to greatly improve the current limits on new forces and extra dimensions at submicron separations.

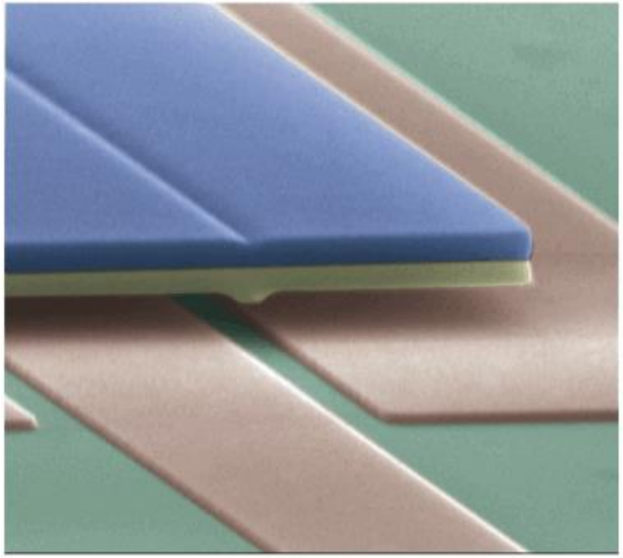
“Casimir-less” experiments

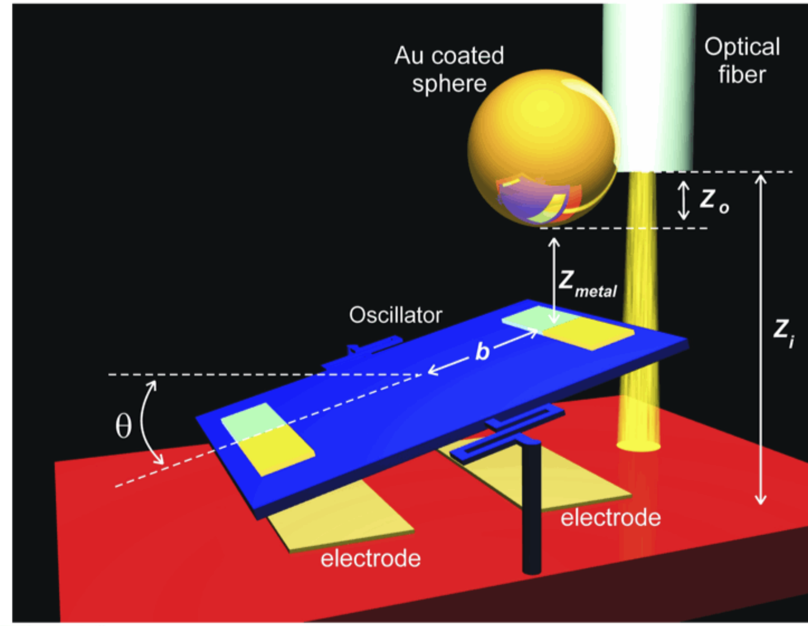
$$\Delta F^{\text{Casimir}} = F_{12'}^{\text{Casimir}} - F_{12}^{\text{Casimir}} \approx 0$$

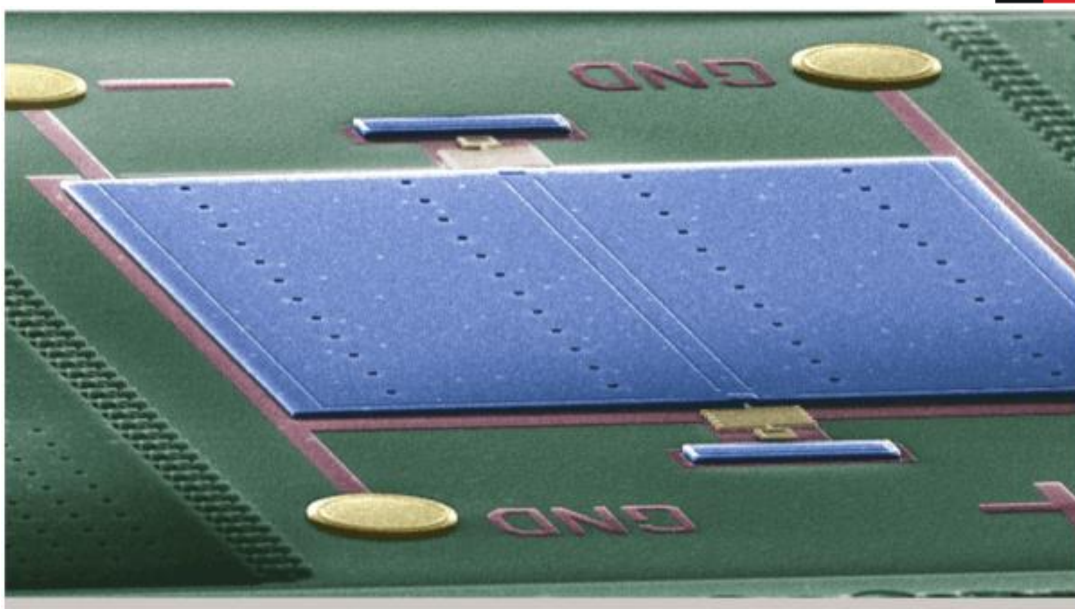
$$\Delta F^{\text{Hyp}} = F_{12'}^{\text{Hyp}} - F_{12}^{\text{Hyp}} \neq 0$$

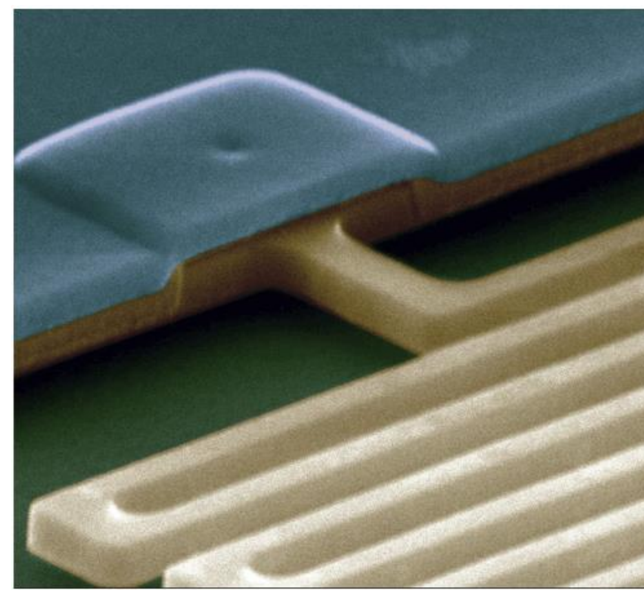


Experimental setup

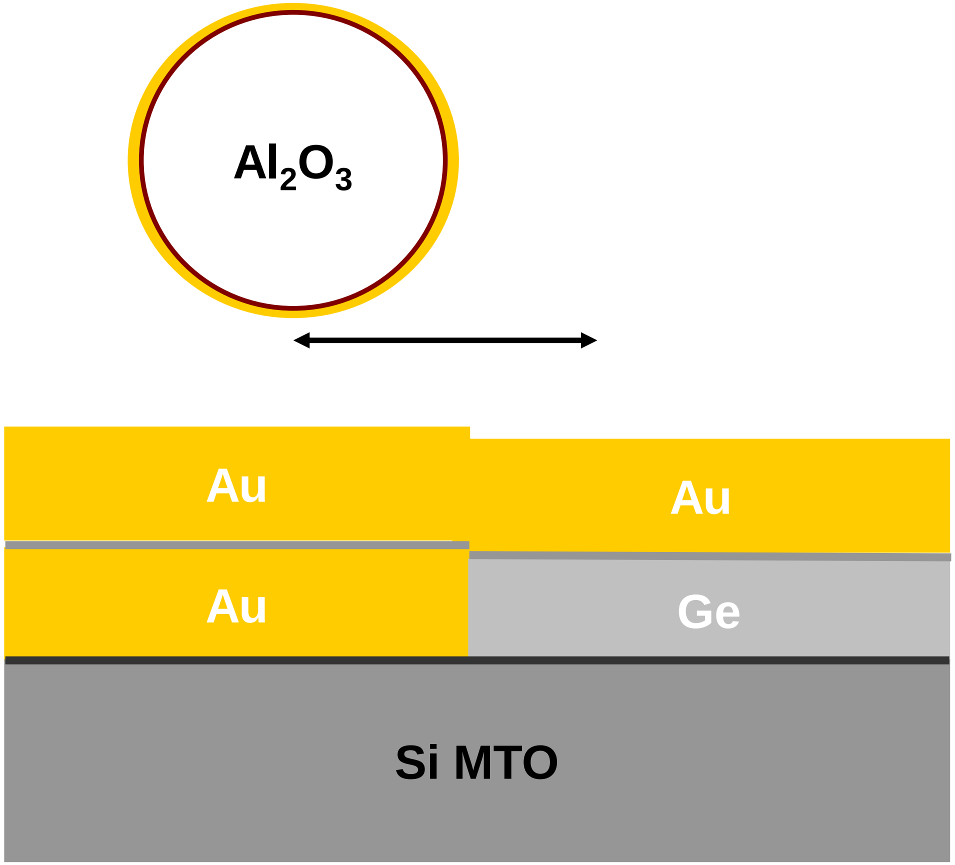








Problems



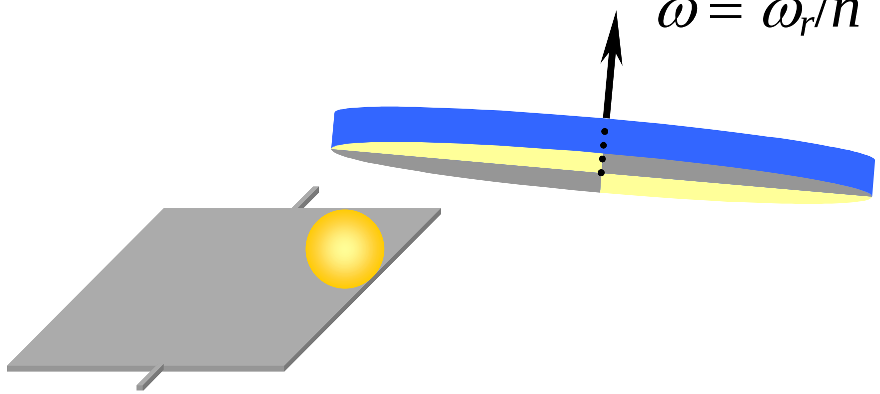
- **Motion not parallel to the axis**
  (too small)
- **Step**
  (0.1 nm needed)
- **Difference in electrostatic force**
  (0.1 mV needed)
- **Difference in Au coating**
  (unlikely)
- **Au coating not thick enough**
  (unlikely)

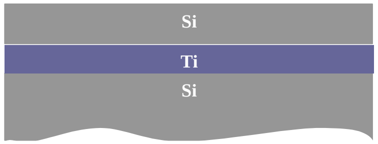
New “Casimirless” Experiments

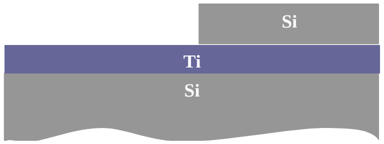
What next?

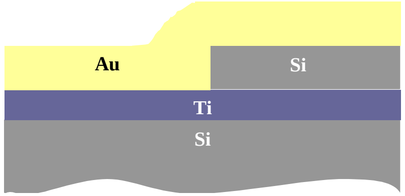
-Improve signal

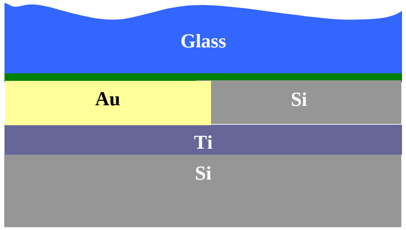
-Reduce background

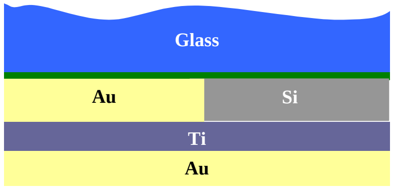




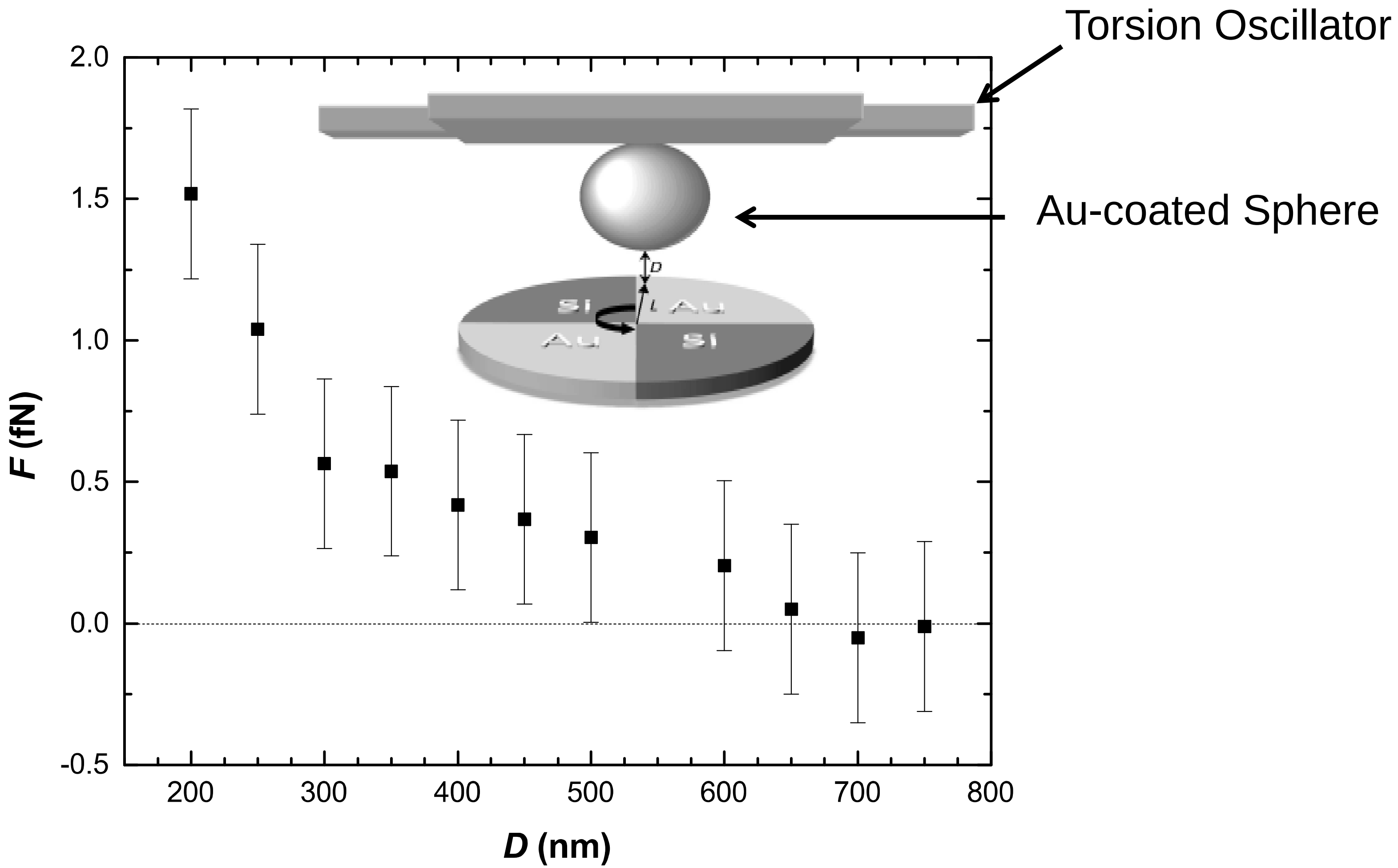




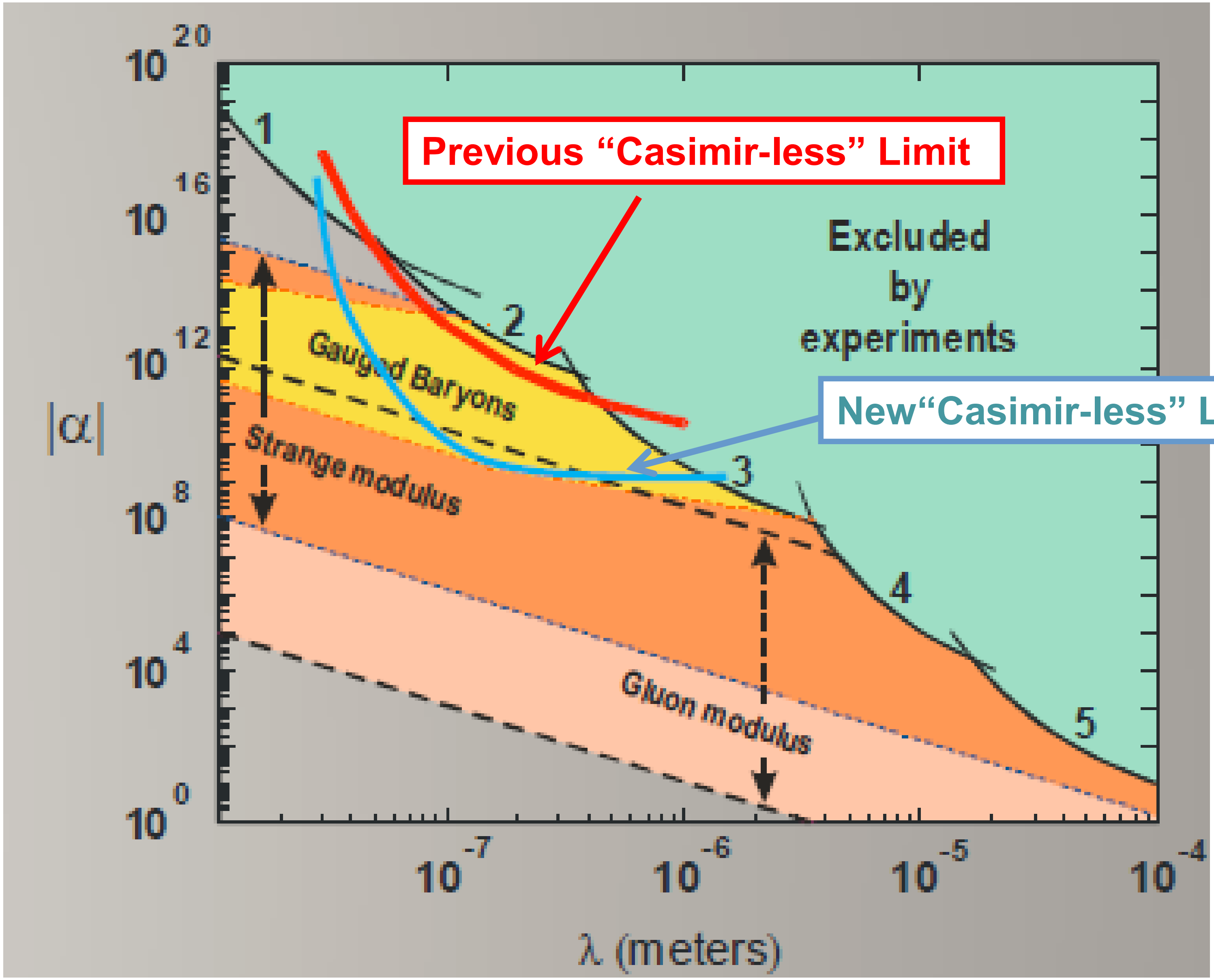




Schematic of Experimental Setup with Measured Force



Reference: R. S. Decca, Proceedings of the 6th Meeting on CPT and Lorentz Symmetry (CPT'13)



Previous "Casimir-less" Limit
New"Casimir-less" Limit
Excluded by experiments
Gauged Baryons
Strange modulus
Gluon modulus
1
2
3
4
5
$|\alpha|$
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
10^{0}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
λ (meters)

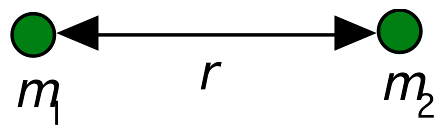
Outlook

- **New Experiments**
  - ✓ **Levitated Microspheres (Geraci)**
  - ✓ **Micro-cantilever (Long)**
  - ✓ **Neutrons (Nesvizhevsky, Jenke)**
  - ✓ **Superconducting Torsion Balance (Chalkley)**
  - ✓ **Atom Interferometry—FORCA-G (Pelle)**
  - ✓ **Casimir (Reynaud)**

- **Spin-Dependent Experiments**
- **Improved Iso-electronic experiments**
- **Improved understanding of the Casimir effect**

Non-Newtonian Gravity

$$V(r) = -\frac{Gm_1m_2}{r}\left\{1 + \alpha_{12}e^{-r/\lambda}\right\}$$



$$F(r) = -\frac{G(r)m_1m_2}{r^2}\hat{r}$$

$\longrightarrow$ doesn't vary as $1/r^2$ *

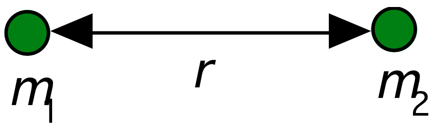
$$G(r) = G[1 + \alpha_{12}e^{-r/\lambda}(1 + r/\lambda)]$$

$\rightarrow$ not independent of 1 or 2 *

* Evidence for either of these would point to a new fundamental force in nature.

Summary of Newtonian Gravity

$$V(r) = -\frac{G m_1 m_2}{r}$$



$$\vec{F}(r) = -\frac{G \cancel{m_1} m_2}{r^2}\hat{r} = \cancel{m_1}\vec{a}_1$$

$$\vec{a}_1 = -\frac{G m_2}{r^2}\hat{r}$$

a) independent of the nature of m_1 (Equivalence Principle)

b) varies as $1/r^2$