Rencontres de Moriond and the 5th Force

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The Fifth Force: A Personal History

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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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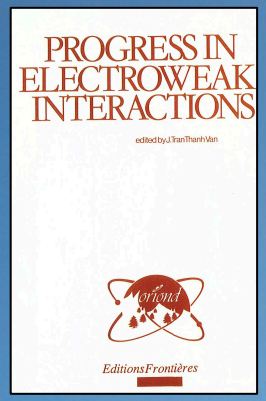
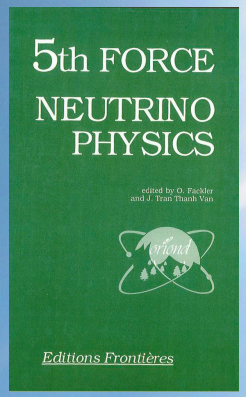
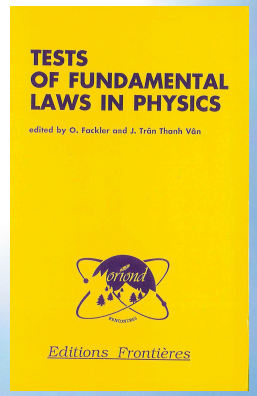
4 Reflections

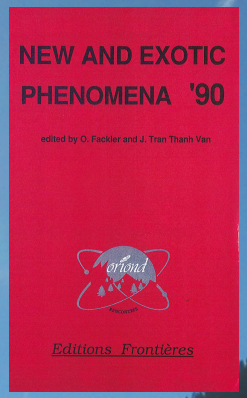
4.1 The Moriond Conferences

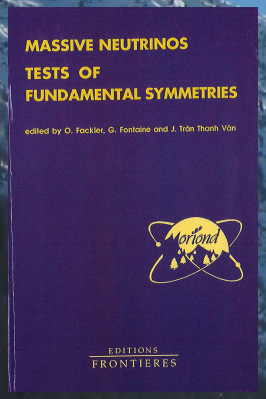
No organizational effort contributed more to searches for non-Newtonian gravity (and other related exotic phenomena) than the Rencontres de Moriond under the leadership of J. Trân Than Vân. ,

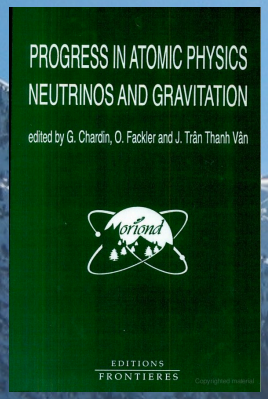


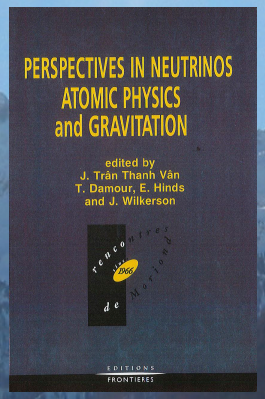


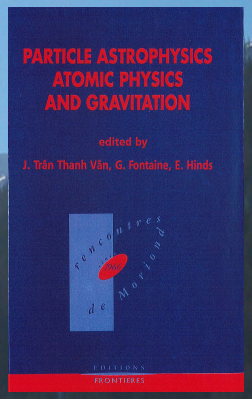


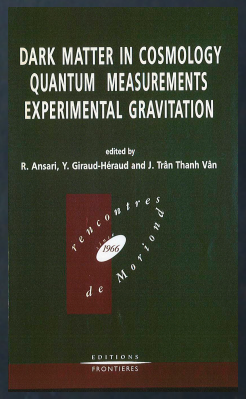


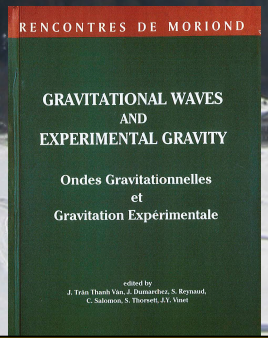


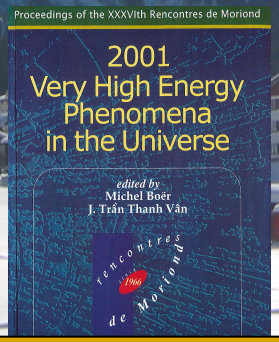


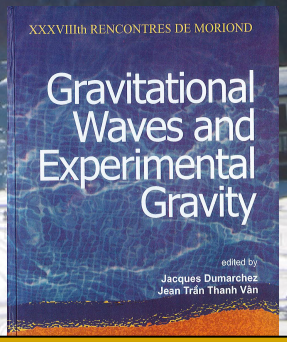


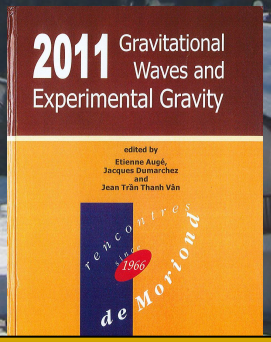












PURDUE UNIVERSITY

Ephraim Fischbach
Rencontres de Moriond, March 2015

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

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

Conservation of Heavy Particles and Generalized Gauge Transformations

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AND

C. N. YANG, *Institute for Advanced Study, Princeton, New Jersey*

(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

$$\psi_N \rightarrow e^{i\alpha}\psi_N, \quad \psi_P \rightarrow e^{i\alpha}\psi_P, \tag{1}$$

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:

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

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).

The Search for New Macroscopic Forces: Pre-1986

NATURE PHYSICAL SCIENCE VOL. 234 NOVEMBER 1 1971

Dilaton and Possible Non-Newtonian Gravity

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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 $\kappa^2 = (3/8) G F_\theta^2$, 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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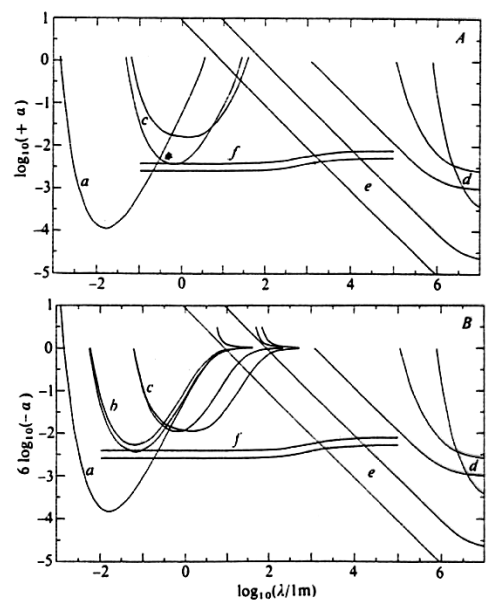
Theories which attempt to unify gravity with the other forces of nature can be coarsely classified according to the mass scale of the new particles they introduce or equivalently the length scale at which new phenomena occur. This mass scale can be expressed as $m_p(m_H/m_p)^n$, where m_H is a typical 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

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



The 5th Force

PURDUE UNIVERSITY
Ephraim Fischbach
Rencontres de Moriond, March 2015

Reanalysis of the Eötvös Experiment

PHYSICAL REVIEW LETTERS

VOLUME 56 | 6 JANUARY 1986 | NUMBER 1

Reanalysis of the Eötvös Experiment

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(Received 7 November 1985)

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

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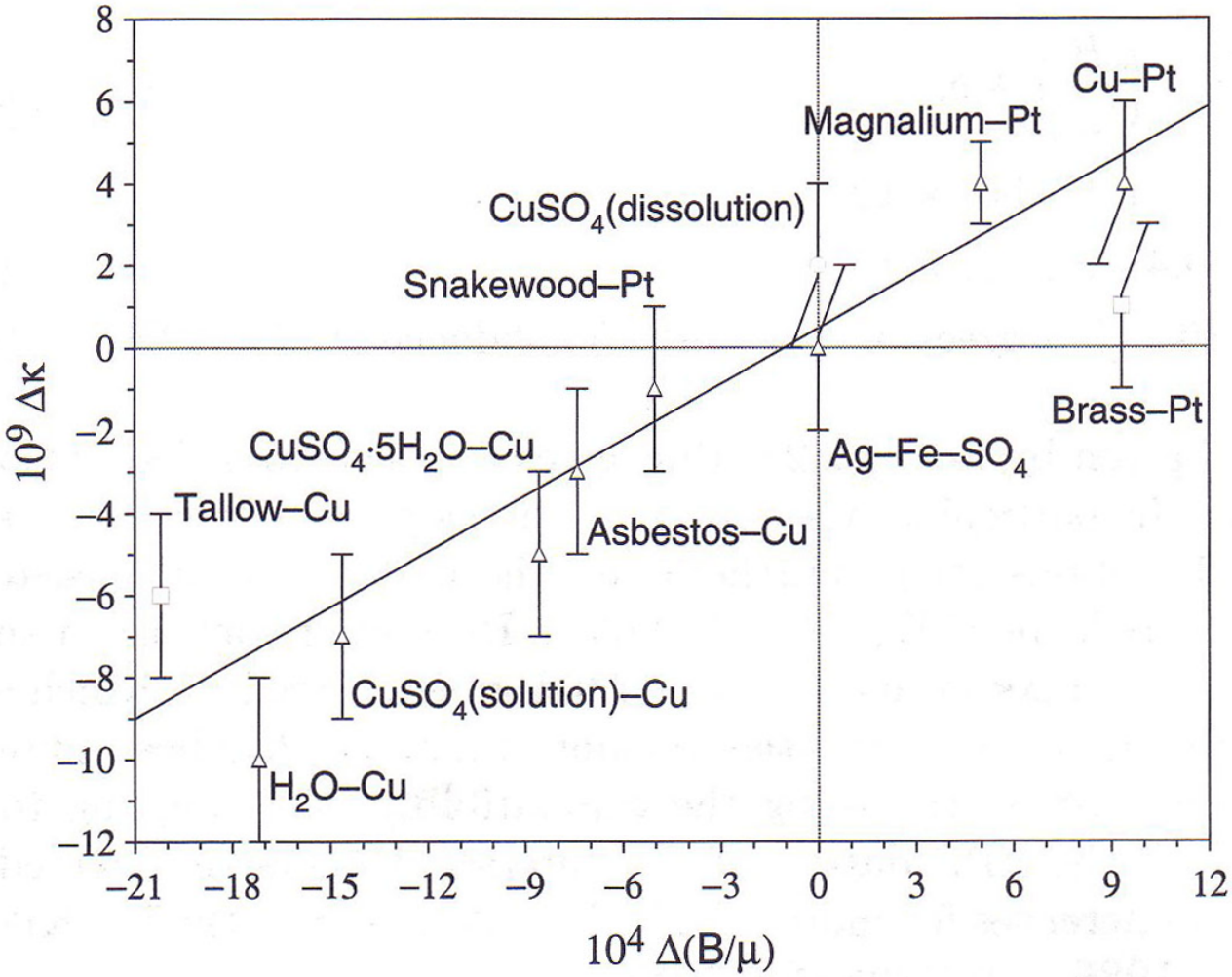
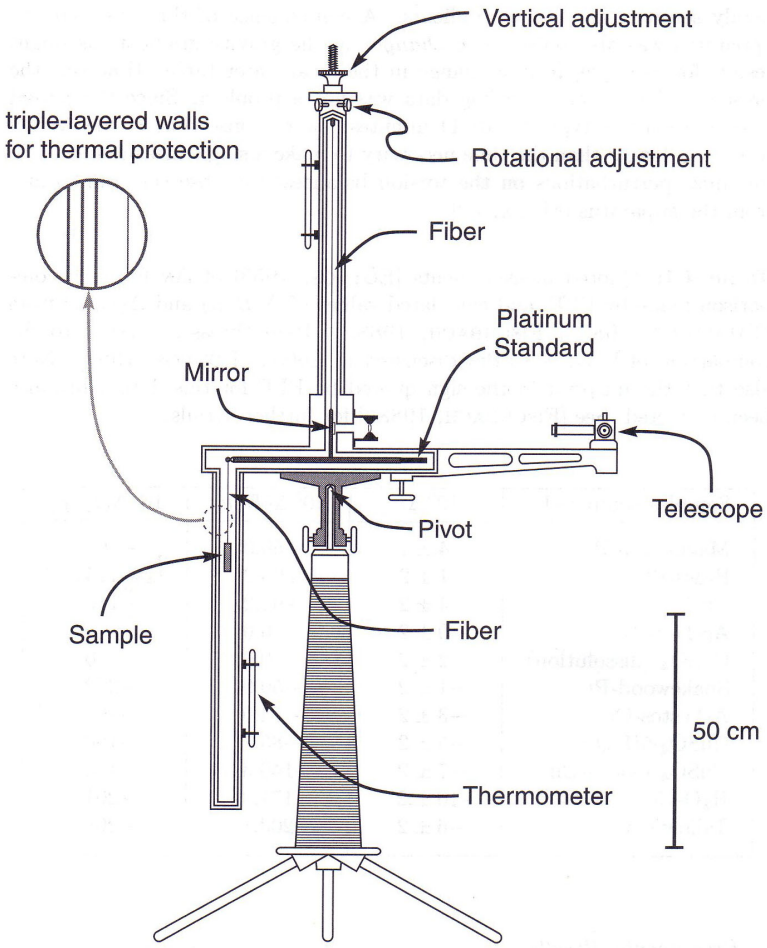
Eötvös Results



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

The New York Times

WATER METER USE IN ALL DWELLINGS PROPOSED BY KOCH

WHITE HOUSE GETS WEINBERGER STUDY ON ARMS RESPONSE

PRESIDENT BREAKS ALL ECONOMIC TIES WITH THE LIBYANS

QADDAFI 'A PARIAH'

Reagan Tells Americans in Country to Leave, Warning of Penalty

Hints of 5th Force in Universe Challenge Galileo's Findings

Why Reagan Shuns Attack

A Fifth Force?

Safety Violations at Nuclear Plant Were Cited by U.S. in '85 Report

Many Tourists Resuming Plans In Fear of Terrorism, Experts Say

For Pennzoil, A Surging Stock but No Deal

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.

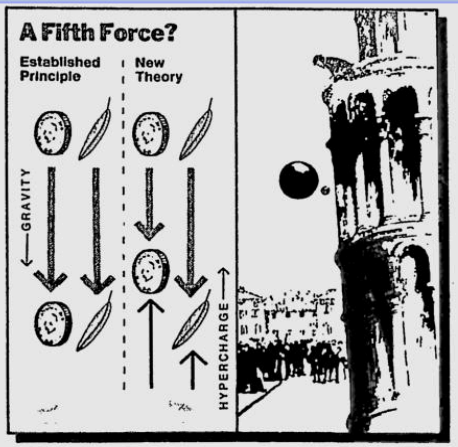
Newton relied on Galileo's work in formulating his theory of gravity in the late 17th century, and Einstein, re-enforced by the Hungarian experiments, also made the assumption that all bodies fall at the same rate in a uniform gravitational field in enunciating his general theory of relativity in 1916.

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 York Times

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.

Phenomenology

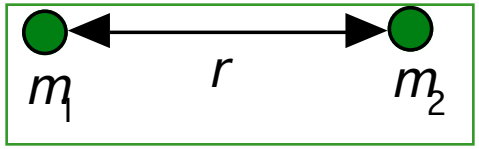
Summary of Newtonian Gravity

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

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

or

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

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

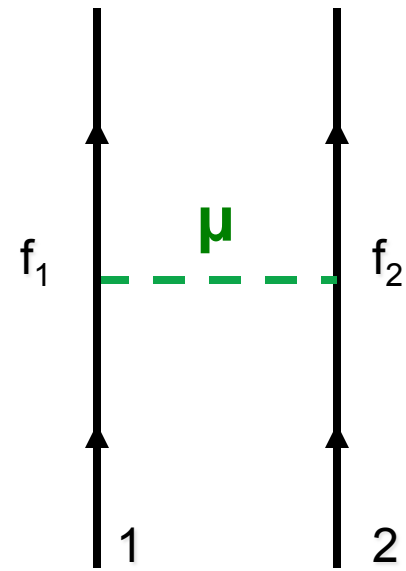
Hence, new interactions like the fifth force may be natural consequences of many models.

New Yukawa Forces

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

Yukawa Phenomenology:

$$V_{\text{Yukawa}}(r) = \alpha \left(\frac{G M_1 M_2}{r} \right) e^{-r/\lambda}$$



Strength Relative to Gravity: α

Range: $\lambda = \dfrac{\hbar}{\mu c}$ $(\mu = \text{ boson mass})$

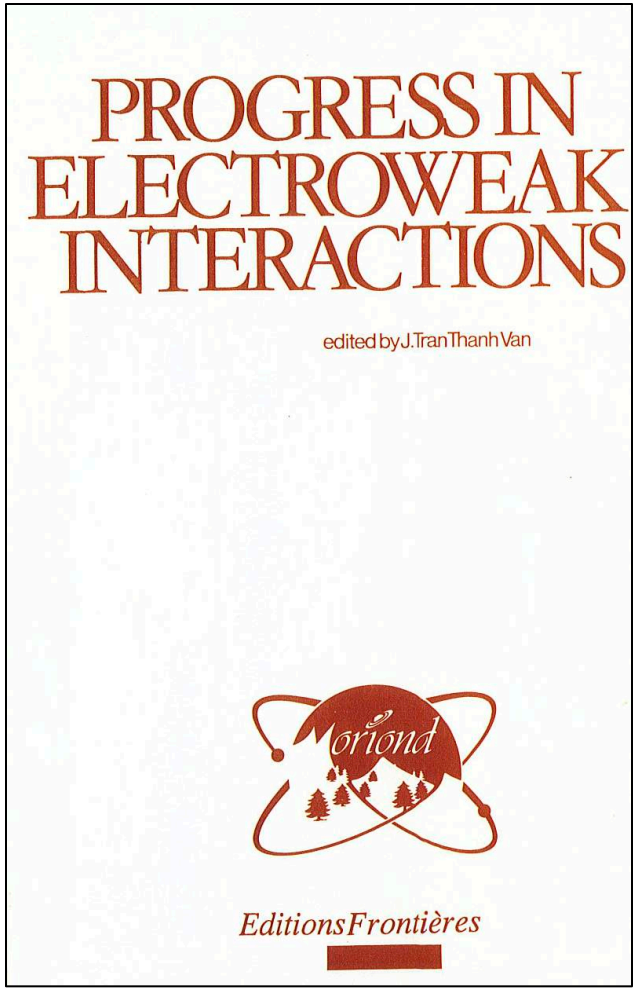
5th Force at Moriond

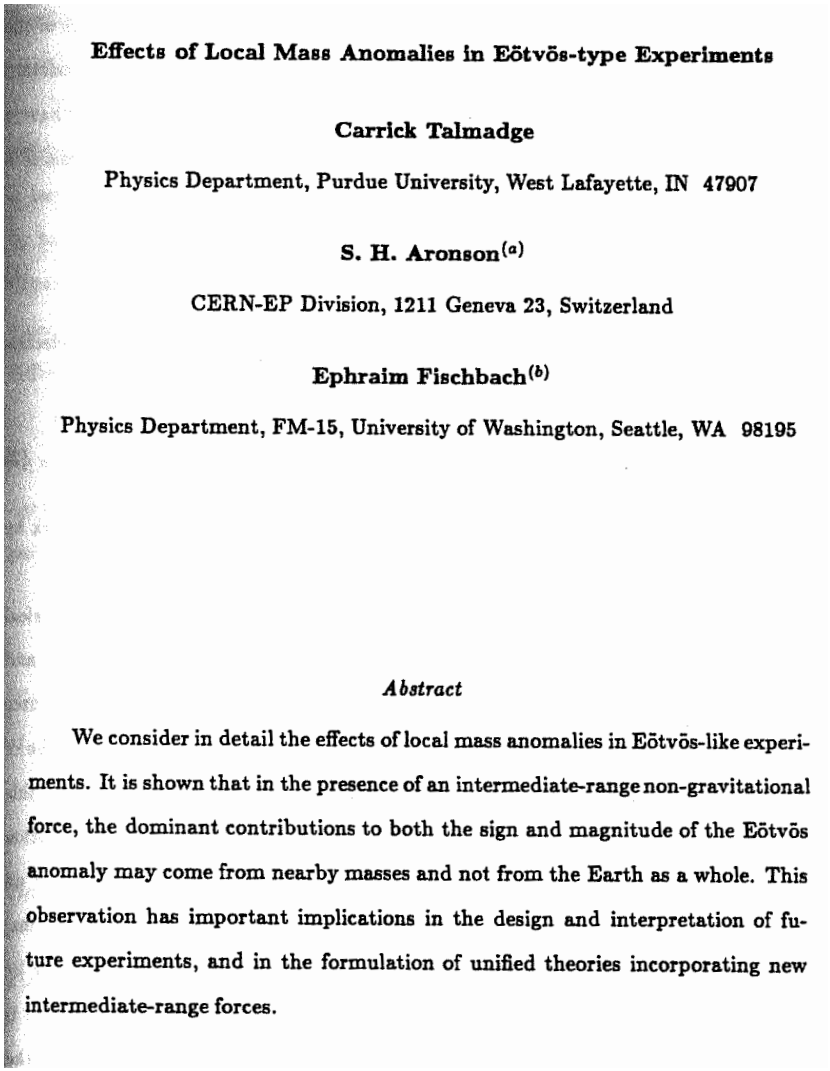
PURDUE UNIVERSITY

Ephraim Fischbach

Rencontres de Moriond, March 2015

1986





Effects of Local Mass Anomalies in Eötvös-type Experiments

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S. H. Aronson[a]

CERN-EP Division, 1211 Geneva 23, Switzerland

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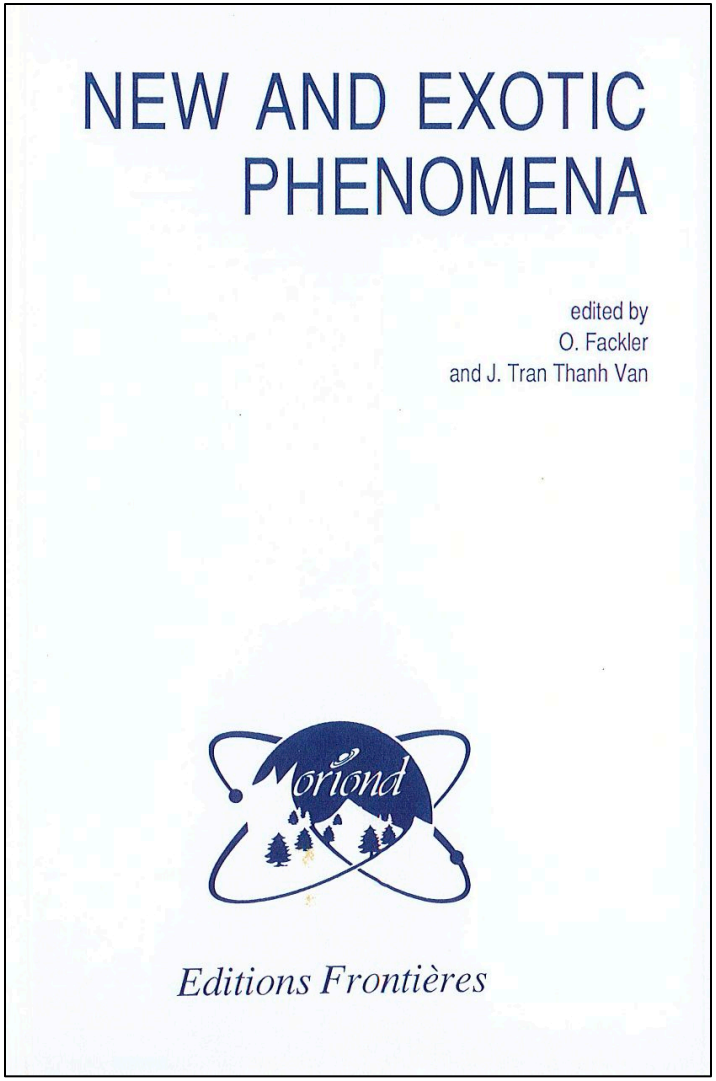
Physics Department, FM-15, University of Washington, Seattle, WA 98195

Abstract

We consider in detail the effects of local mass anomalies in Eötvös-like experiments. It is shown that in the presence of an intermediate-range non-gravitational force, the dominant contributions to both the sign and magnitude of the Eötvös anomaly may come from nearby masses and not from the Earth as a whole. This observation has important implications in the design and interpretation of future experiments, and in the formulation of unified theories incorporating new intermediate-range forces.

1987



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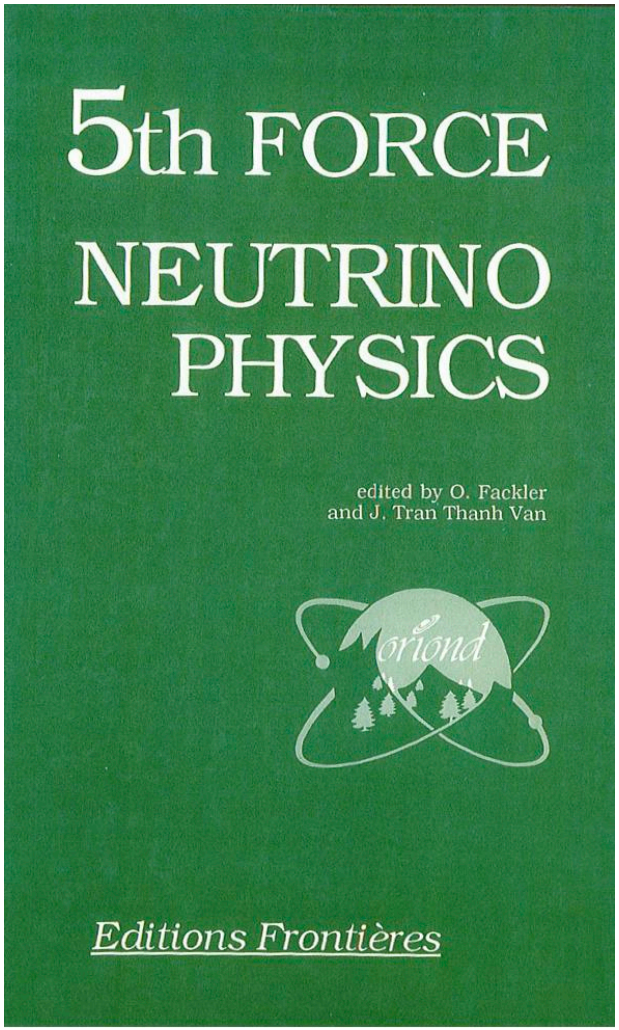
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NEUTRINO
PHYSICS
edited by O. Fackler
and J. Tran Thanh Van
moriond
Editions Frontières

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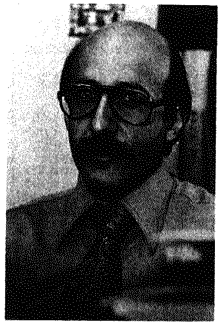
1988

THE FIFTH FORCE: AN INTRODUCTION TO CURRENT RESEARCH*

Ephraim Fischbach and Carrick Talmadge

Physics Department, Purdue University, West Lafayette, IN 47907 USA



(Presented by E. Fischbach)

ABSTRACT

We review the present status of research on the fifth force in the framework of a simple phenomenological picture. The principal theoretical and experimental questions are outlined, and a summary of the ongoing fifth force experiments is given.

* Work supported in part by the United States Department of Energy

THE COMPATIBILITY OF GRAVITY AND KAON RESULTS IN THE SEARCH FOR NEW FORCES

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and

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Purdue University
West Lafayette, IN 47907, USA

ABSTRACT

The existing data on energy-dependences of the fundamental parameters of the K^0-$\bar{K}^0$ system, and the limits on the decay $K^+ \to \pi^+$ + (invisible neutrals), are used in conjunction with geophysical data to explore the coupling of the putative fifth force to quantities other than baryon number.

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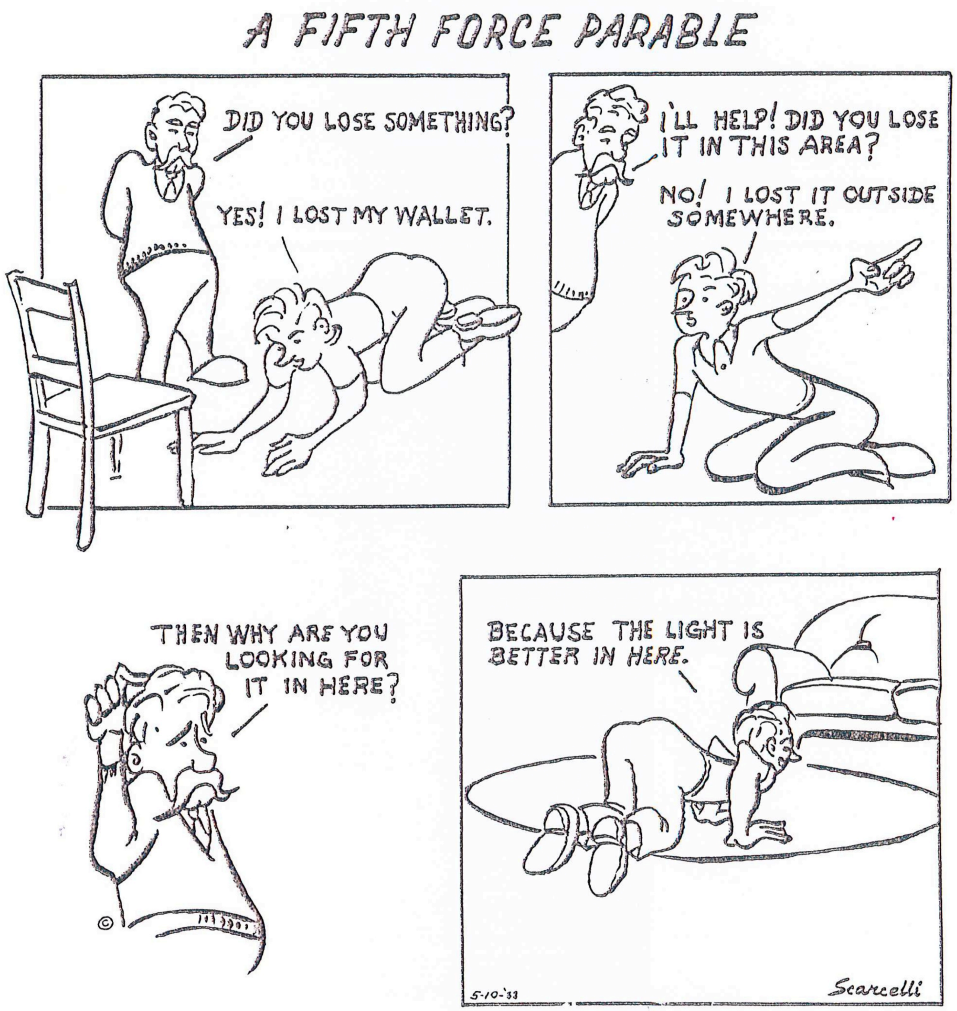
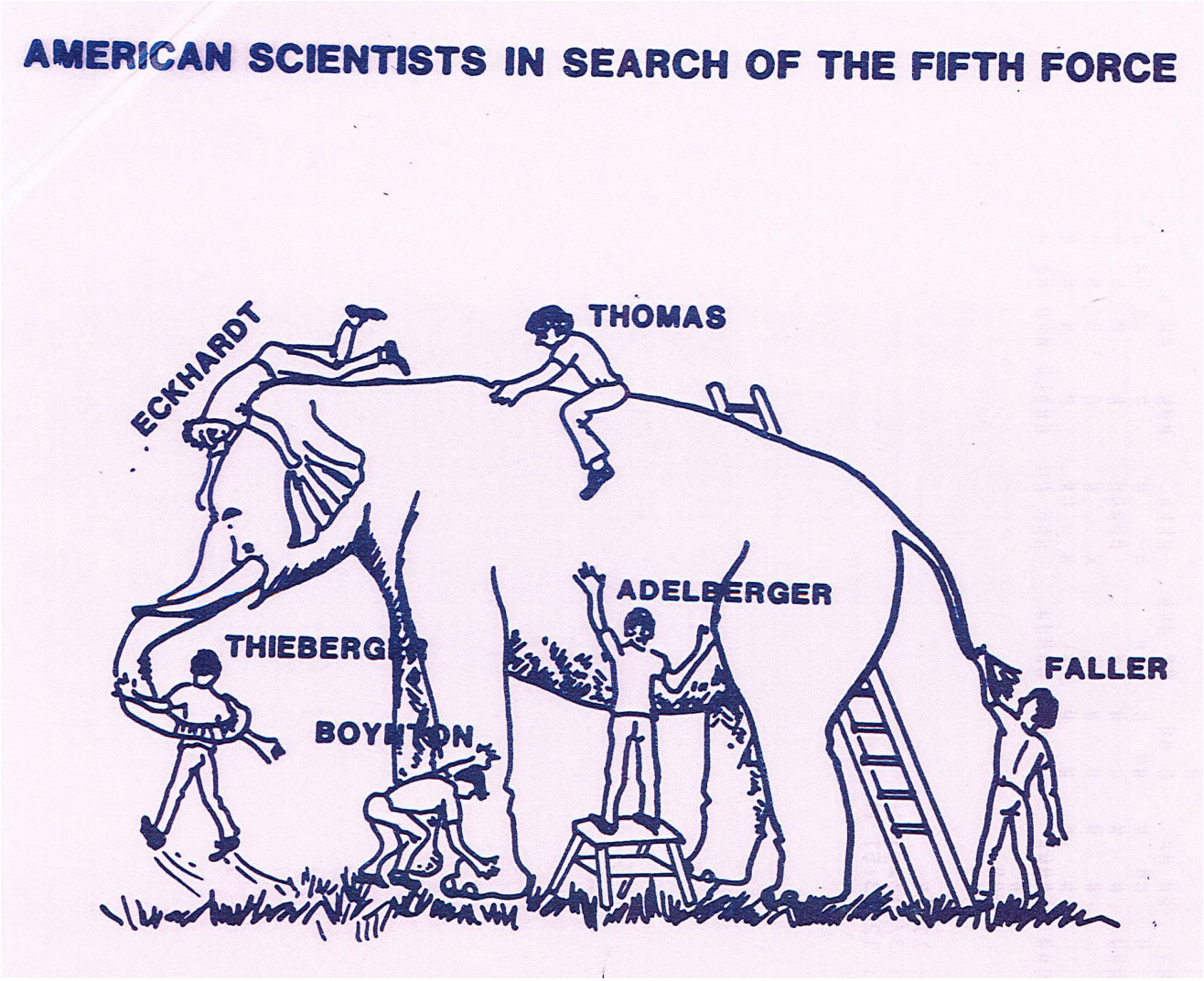
1988


A FIFTH FORCE PARABLE
DID YOU LOSE SOMETHING?
YES! I LOST MY WALLET.
I'LL HELP! DID YOU LOSE IT IN THIS AREA?
NO! I LOST IT OUTSIDE SOMEWHERE.
THEN WHY ARE YOU LOOKING FOR IT IN HERE?
BECAUSE THE LIGHT IS BETTER IN HERE.
5-10-'83
Scarcelli

1988


AMERICAN SCIENTISTS IN SEARCH OF THE FIFTH FORCE
ECKHARDT
THOMAS
ADELBERGER
THIEBERGER
BOYETON
FALLER

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.

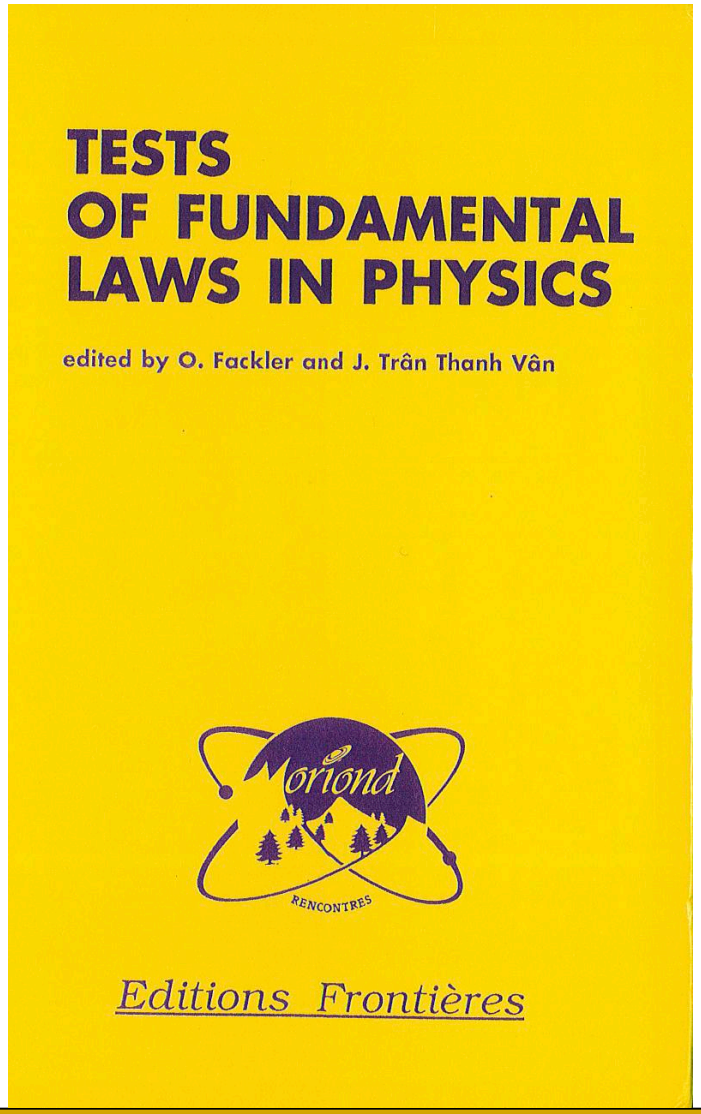
Much the same has emerged from an analysis of past measurements of the position of planetary orbits conducted by C. Talmadge from Purdue University and three colleagues at the Jet Propulsion Laboratory at Pasadena, California. The argument is simple: if the force between a planet and the Sun is not a 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.

John Maddox

1989


TESTS
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1989

ALTERNATIVE MODELS OF THE FIFTH FORCE*

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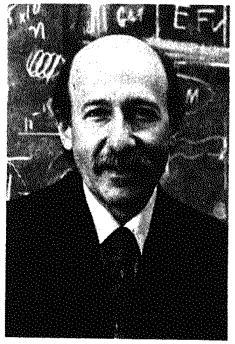
Physics Department, Purdue University, West Lafayette, IN 47907 USA



(Presented by E. Fischbach)

ABSTRACT

The fifth force is conventionally described in terms of a Yukawa potential, $V_5(r) = f^2 Q_1 Q_2 \exp(-r/\lambda)/r$, which is the form that would arise from the exchange of a single quantum with mass $m = \hbar/\lambda c$. We show that under certain circumstances the fifth force would actually be described by an exponential, $V_5(r) = f^2 Q_1 Q_2 \exp(-r/\lambda)/\lambda$. Viewed from the perspective of an exponential potential, the current experimental situation appears quite different from what would be inferred from a Yukawa. We discuss the phenomenological implications of an exponential model, with particular emphasis on composition-dependent experiments. Our analysis suggests that the exponential model may provide a consistent picture of the existing data.

RARE K DECAYS AND LIMITS ON NEW FORCES

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E. FISCHBACH[d)] and C. TALMADGE[d)]

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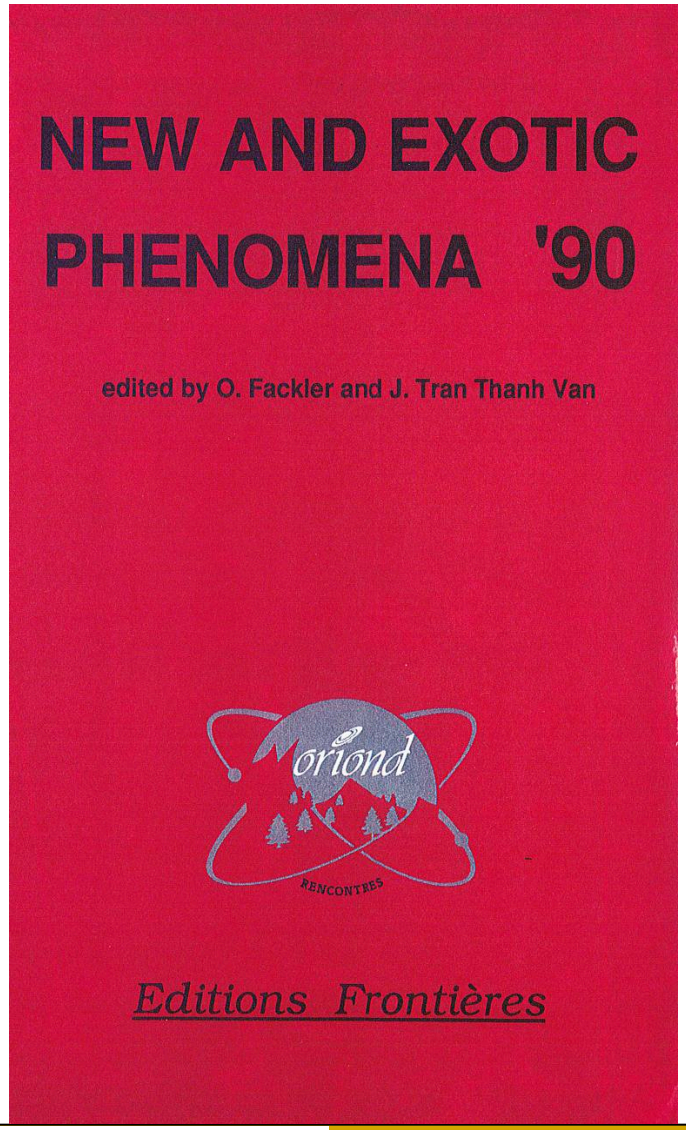
c) Institute of Physics, Academia Sinica, Nankang, Taipei, Taiwan, ROC
d) Physics Department, Purdue University, West Lafayette, Indiana 47907

ABSTRACT

We reconsider the possible detection of hyperphotons (γ_Y) in the decay mode, $K_L \to \pi^+\pi^-\gamma_Y$. We find it to have certain advantages over $K^+ \to \pi^+\gamma_Y$ in setting limits on new forces coupling to hypercharge. The prospects for studying this decay mode in the near future are discussed.

1990



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FINITE-SIZE EFFECTS IN EÖTVÖS-TYPE EXPERIMENTS*

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(Presented by E. Fischbach)

ABSTRACT

We discuss a new class of experiments in which searches for composition-dependent deviations from Newtonian gravity can be used to set limits on composition-independent effects as well. These experiments utilize the observation that objects with different charge or mass distributions, will couple differently to the (non-vanishing) Laplacian of a non-Newtonian potential.

SUMMARY OF FIFTH FORCE EXPERIMENTS

1990

ANOMALOUS EFFECT SEEN		NO ANOMALY SEEN
• Eötvos, et al.	7.8σ	• Adelberger et al. (3 expts.)
• Stacey, et al.	> 2σ	• Faller, et al. * (free-fall)
• Thieberger	3.0σ	• Fitch, et al
• Hsui	?	• Kuroda & Mio *
• Boynton, et al.	3.6σ	• Speake & Quinn *
• Eckhardt, et al.	14σ	• Bizzeti
• Ander, et al.	?	

* No anomaly expected at indicated sensitivity level

1990

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New Test of Quantum Mechanics: Is Planck's Constant Unique?

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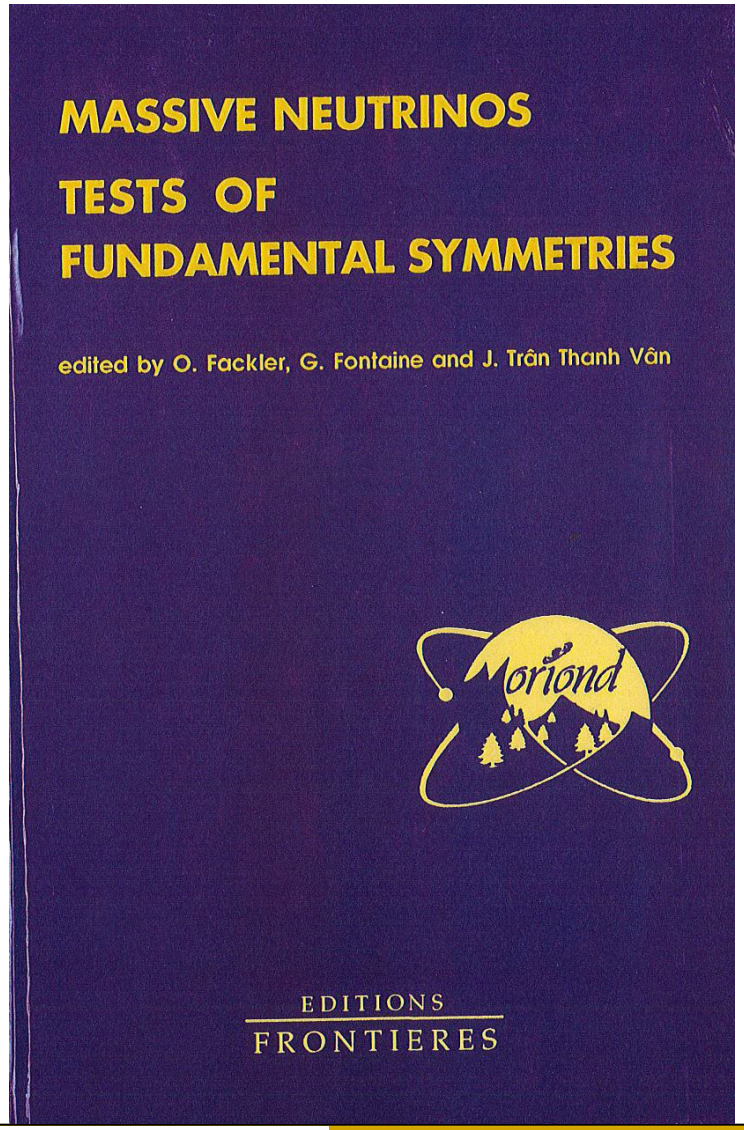
Geoffrey L. Greene
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

Richard J. Hughes
Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 20 August 1990)

We discuss the possibility that different realms of physics are described by distinct quantization constants. From the consistency of existing data, we infer limits on the differences between hypothetically distinct quantization constants for different elementary particles. Since the existence of multiple Planck constants implies violations of space-time symmetries, these limits may be viewed as precise tests of fundamental conservation laws, including the conservation of linear momentum and energy.

1991



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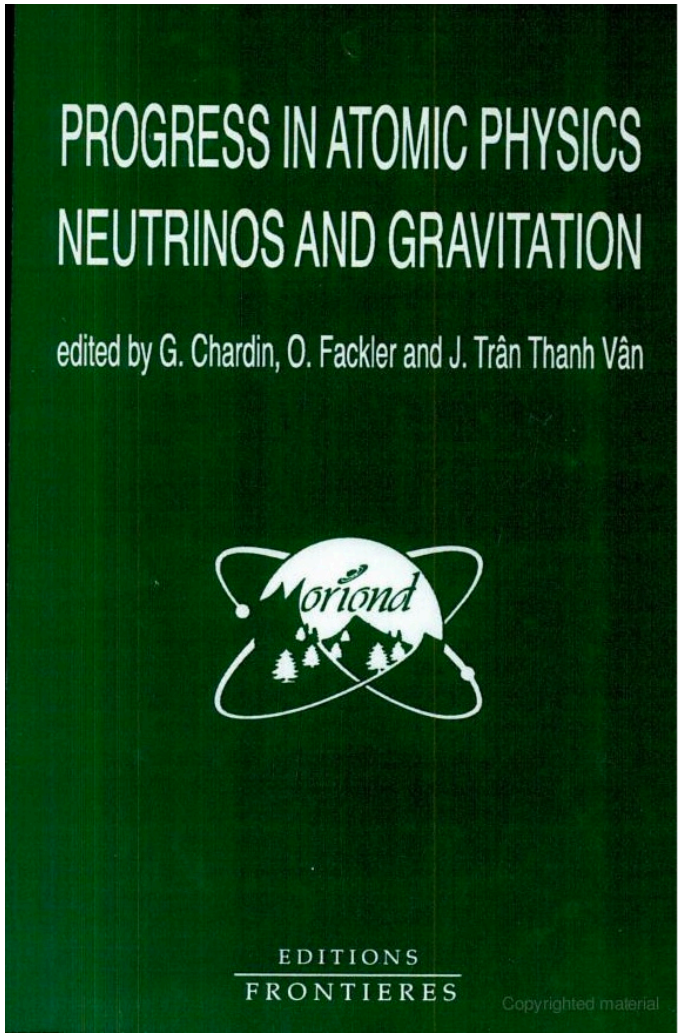
1992



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1992

THE FIFTH FORCE IN ELECTROMAGNETISM AND GRAVITY

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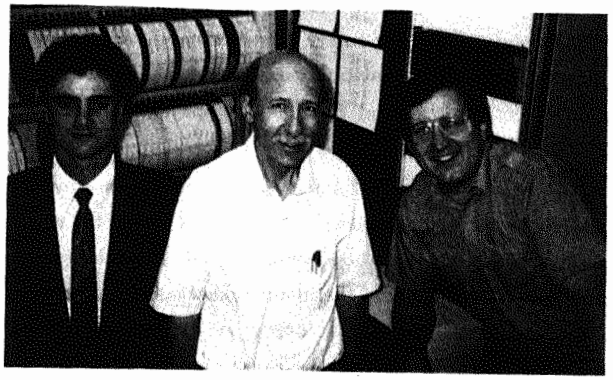
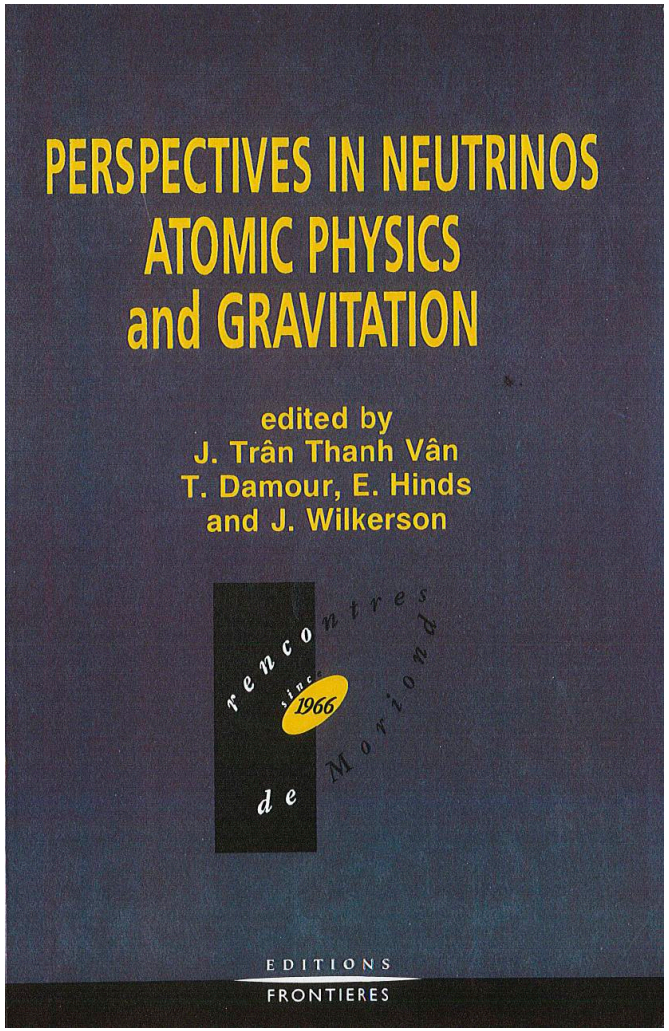


ABSTRACT

Recent interest in the "fifth force" has focused on new intermediate range interactions whose presence could lead to apparent deviations from the predictions of Newtonian gravity. Here we draw attention to the possibility that the *same* forces could also lead to apparent anomalies in electromagnetic interactions, for appropriate values of the range and coupling constant. We contrast the phenomenology of searches for gravitational and electromagnetic signals for the fifth force, and we present new experimental limits for each case.

1993



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THE SECOND COMING OF TOWER GRAVITY: AN UPDATE

Donald H. Eckhardt, Anestis J. Romaides, Roger W. Sands, and Christopher Jekeli
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ABSTRACT

The Phillips Laboratory and Purdue University are conducting a tower gravity experiment near the town of Inverness, MS. Gravity is measured at six elevations on the 610 m WABG-TV tower as well as on the surface in an 8 km radius about the tower. These data are combined with archived data extending to 300 km. Using previously devised techniques, the surface data are analytically continued and compared with the observations. The current difference at the highest tower elevation surveyed so far, 493 m, is 34 μGal.

NEWMAN (EÖTVÖS) VERSUS NEWMAN (SPIN)

1993

1. Torsion balance technology	1. Torsion balance technology
2. Sensitive to torques at $\sim 10^{-4} \times$ gravity	2. Sensitive to torques at $\sim 10^{-2}$ gravity
3. Lab experiment	3. Lab experiment
4. electromagnetic backgrounds small	4. electromagnetic backgrounds can be large
5. $g_V^2 \lesssim 10^{-41}$ ←	5. $g_P^2 \lesssim 4 \times 10^{-10}$ ←

VOLUME 82, NUMBER 24 PHYSICAL REVIEW LETTERS 14 JUNE 1999

New Limits on the Couplings of Light Pseudoscalars from Equivalence Principle Experiments

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(Received 11 January 1999)

The exchange of light pseudoscalar quanta between fermions leads to long-range spin-dependent forces in order g^2, where g is the pseudoscalar-fermion coupling constant. We demonstrate that laboratory bounds on the Yukawa couplings of pseudoscalars to nucleons can be significantly improved using results from recent equivalence principle experiments, which are sensitive to the spin-independent long-range forces that arise in order g^4 from two-pseudoscalar exchange. [S0031-9007(99)09397-7]

VOLUME 83, NUMBER 18 PHYSICAL REVIEW LETTERS 1 NOVEMBER 1999

Constraints on Light Pseudoscalars Implied by Tests of the Gravitational Inverse-Square Law

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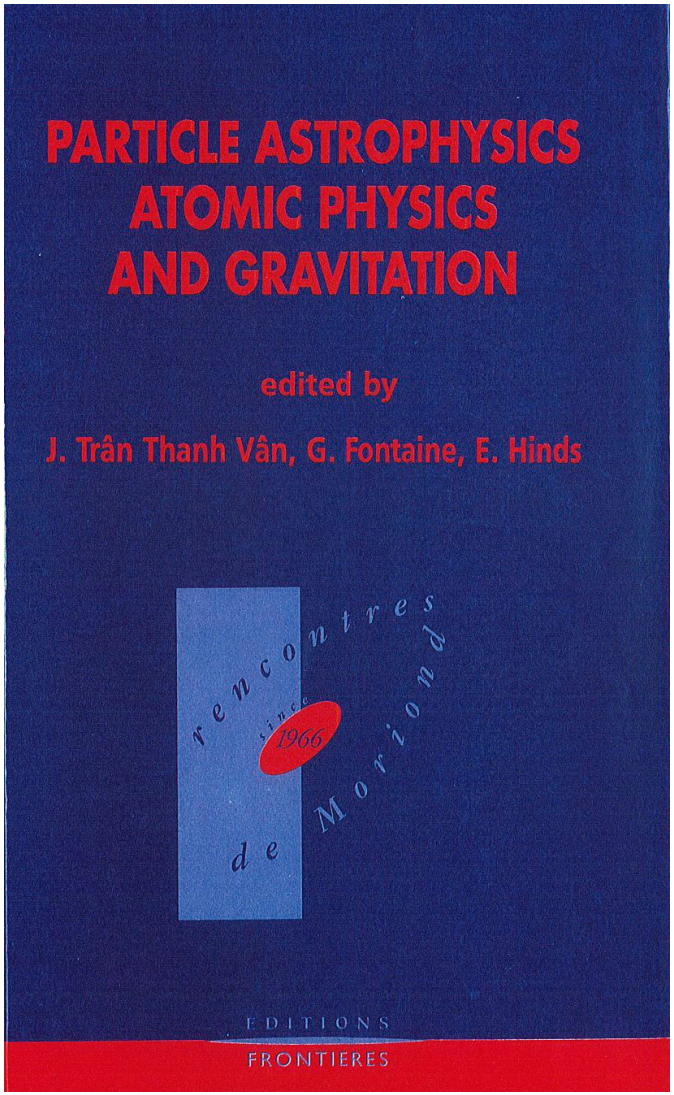
(Received 3 June 1999)

The exchange of light pseudoscalars between fermions leads to a spin-independent potential in order g^4, where g is the Yukawa pseudoscalar-fermion coupling constant. This potential gives rise to detectable violations of both the weak equivalence principle (WEP) and the gravitational inverse-square law (ISL), even if g is quite small. We show that when previously derived WEP constraints are combined with those arising from ISL tests, a direct experimental limit on the Yukawa coupling of light pseudoscalars to neutrons can be inferred for the first time ($g_n^2/4\pi \lesssim 1.6 \times 10^{-7}$), along with a new (and significantly improved) limit on the coupling of light pseudoscalars to protons.

1994



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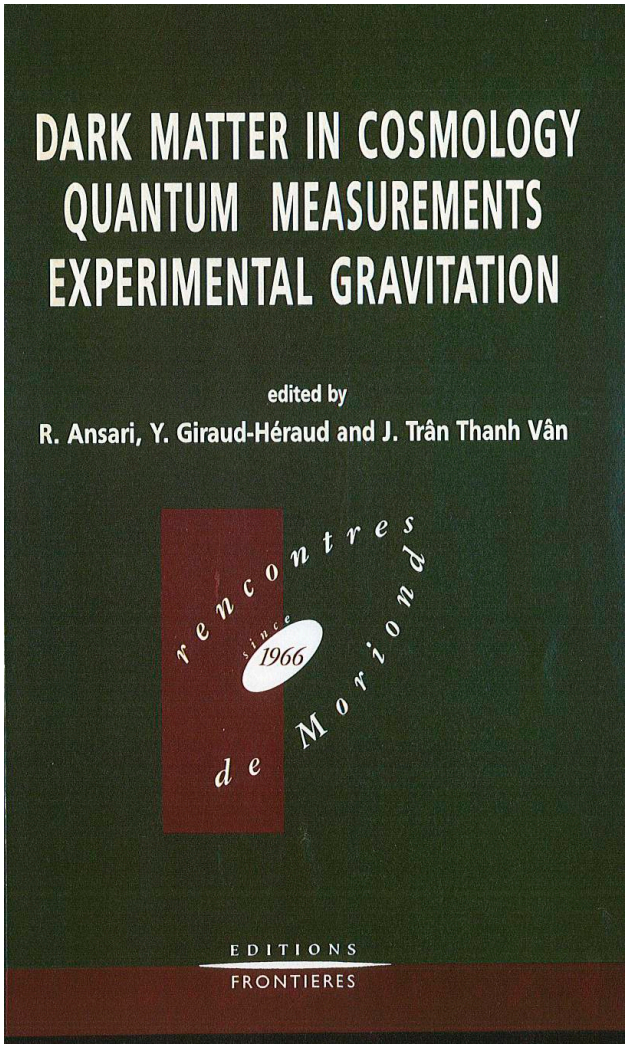
1996



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1996

TEN YEARS OF THE FIFTH FORCE*

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ABSTRACT

The suggestion in 1986 of a possible gravity-like "fifth" fundamental force renewed interest in the question of whether new macroscopic forces are present in nature. Such forces are predicted in many theories which unify gravity with the other known forces, and their presence can be detected by searching for apparent deviations from the predictions of Newtonian gravity. We review the phenomenology behind searches for a "fifth force", and present a summary of the existing experimental constraints.

A LOWER BOUND ON NEUTRINO MASS?*

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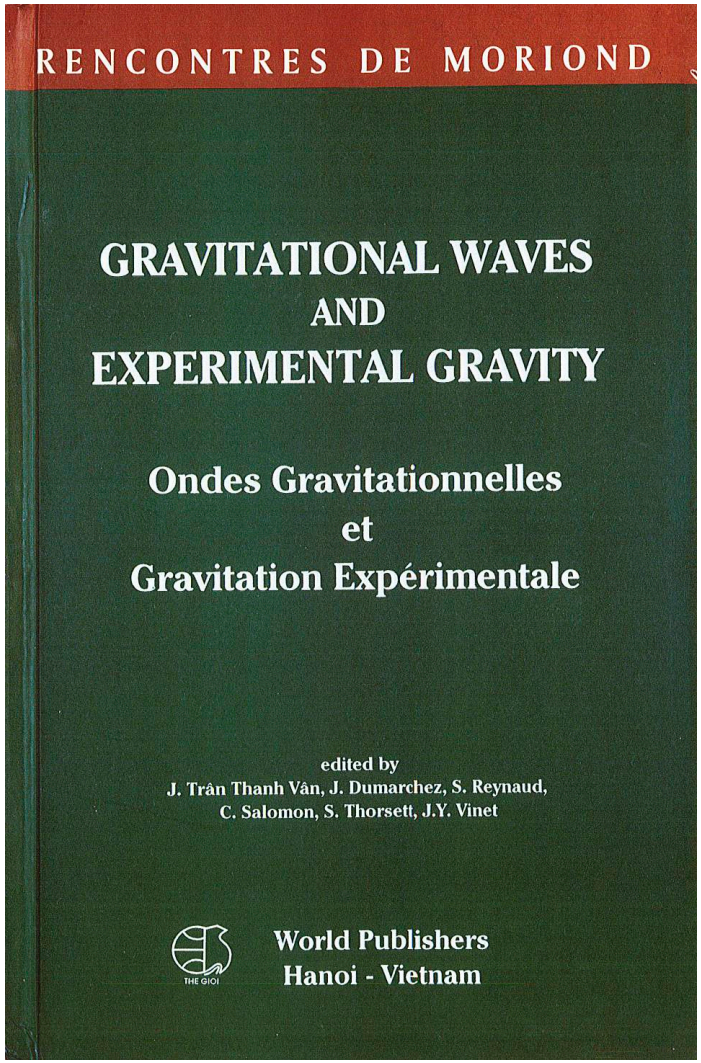
ABSTRACT

The exchange of massless neutrinos between heavy fermions (e.g. e, p, n) gives rise to a long-range 2-body force. It is shown that the analogous many-body force can lead to an unphysically large energy density in white dwarfs and neutron stars. To reduce the energy density to a physically acceptable value, the neutrino must have a *minimum* mass, which is approximately 0.4 eV/c^2. Some recent questions relating to the derivation of this bound are also discussed.

2000



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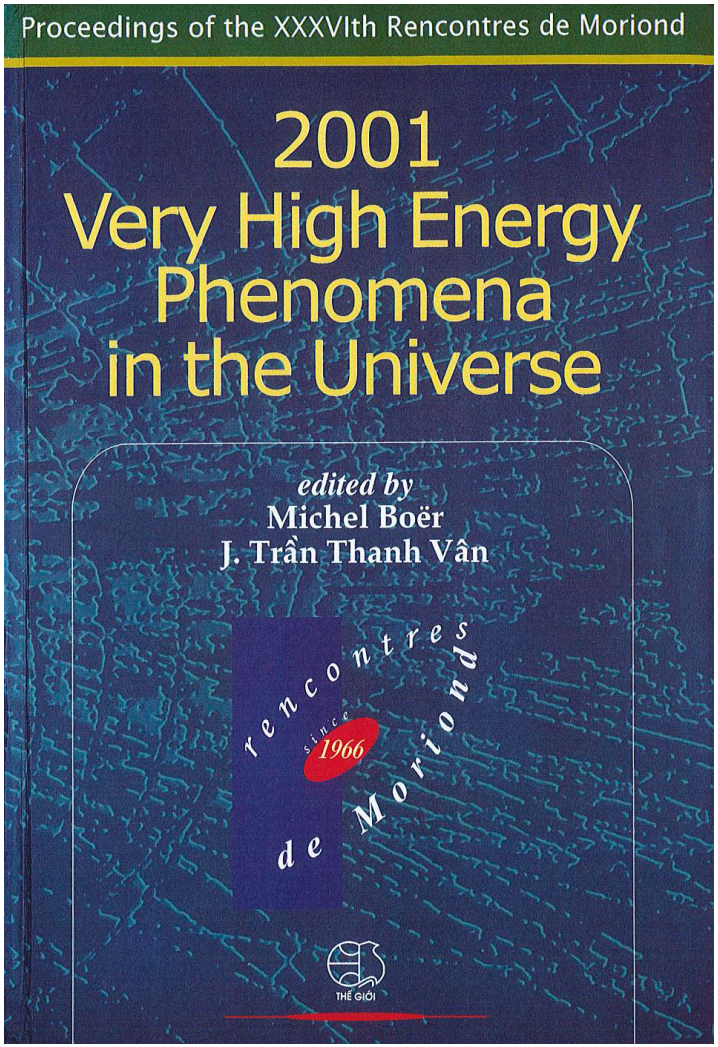
2001



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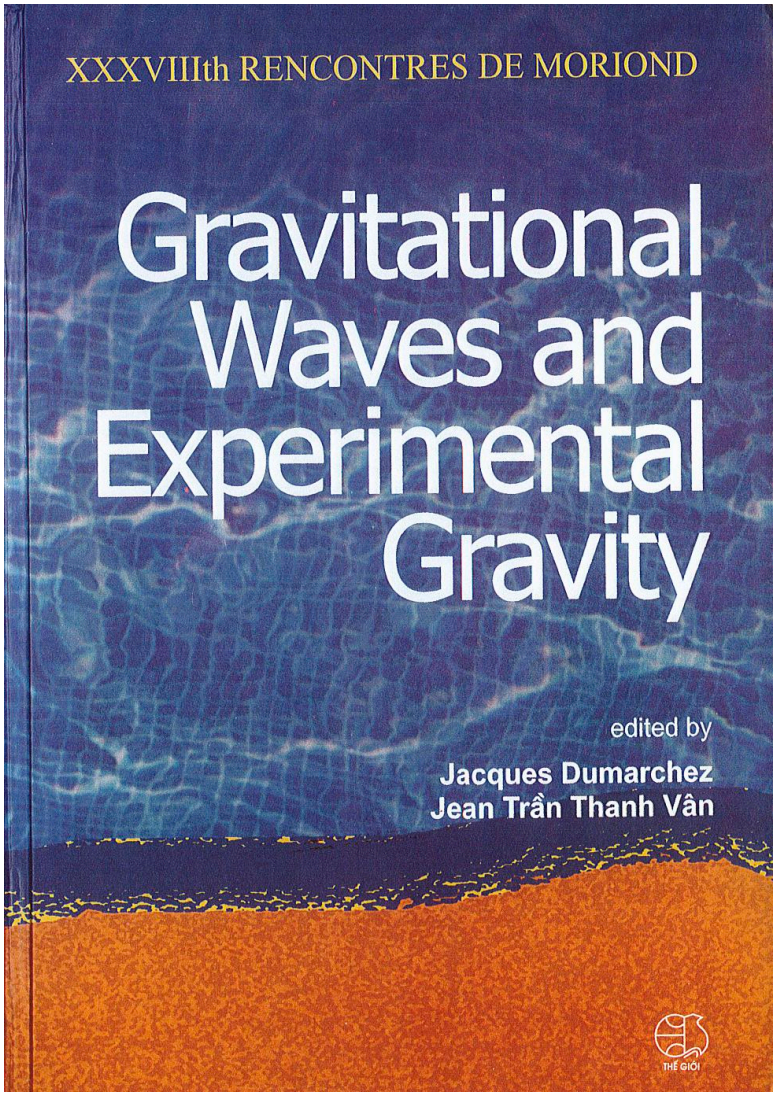
2003



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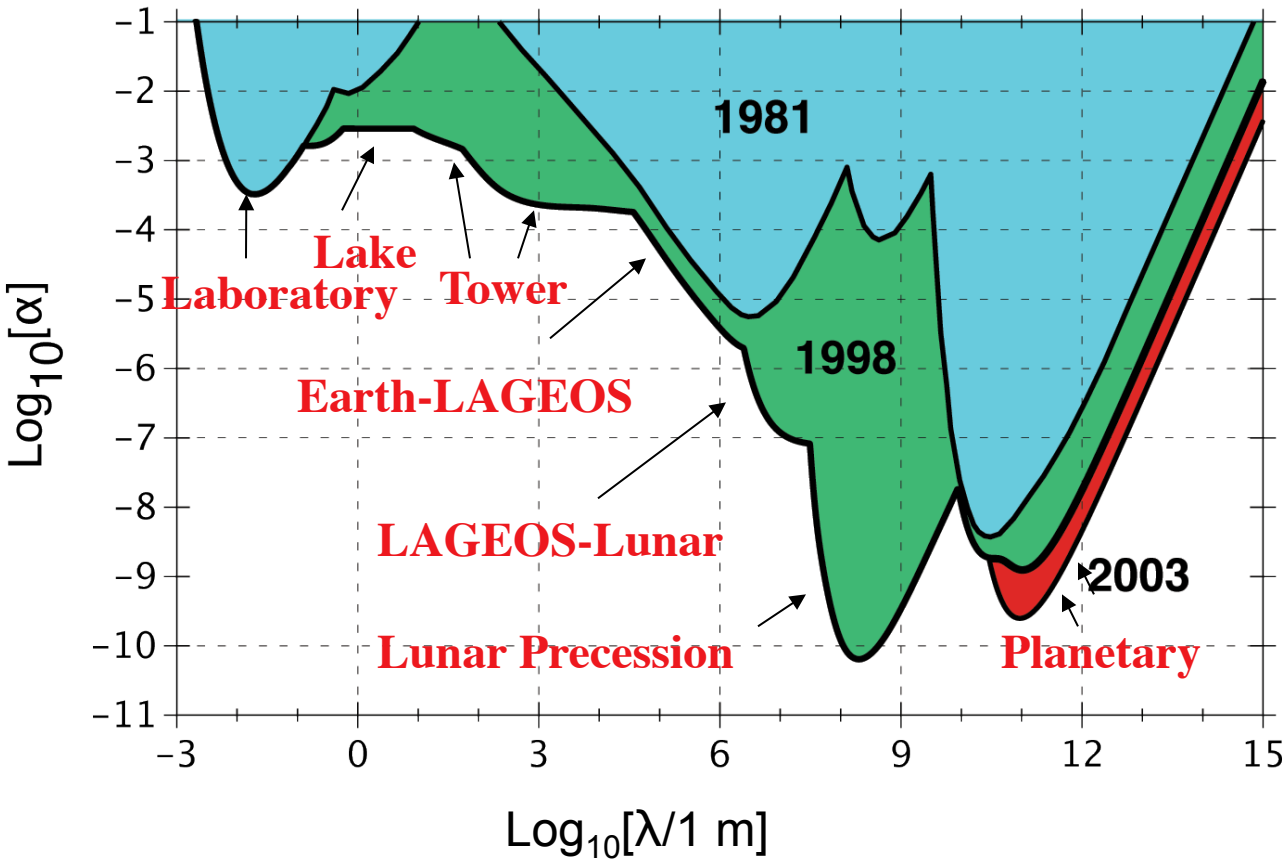
Limits on Yukawa Forces:
Long-Range Limits

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



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

2003

EXTRA DIMENSIONS, NEW FORCES, AND NON-NEWTONIAN GRAVITY

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We review the theoretical motivation and phenomenology used to constrain new forces and extra spatial dimensions via tests of Newtonian gravity. We then use a simple model of a single compact dimension to illustrate how extra dimensions modify the law of gravity.

1 Introduction

Tests of Newtonian gravity have become important tools in constraining possible extensions of the Standard Model. Over the past twenty years, many experiments have tested the inverse-square law (ISL) and the Weak Equivalence Principle (WEP) on distance scales ranging from millimeters to astronomical units without finding any deviations from the predictions of Newton's law of gravity.[1] Still, very little is known about gravity between 0.1 mm and the Planck length $L_{\rm Pl} \sim 10^{-35}$ m, where quantum gravitational effects are expected to become important. The possibility that new physics lies within this unexplored territory has motivated new experiments to probe gravity at sub-millimeter scales. Here we begin by describing the phenomenology used to characterize the modifications of Newtonian gravity caused by the presence of new macroscopic forces and extra spatial dimensions. We then describe in some detail how extra compact dimensions affect the law of gravity using a model with one additional compact dimension.

2 Phenomenology

For separations $\gtrsim 10^{-5}$ m, the dominant force between neutral, non-magnetic bodies is the gravitational force. Therefore, direct attempts to detect new forces using macroscopic test bodies at these separations become gravity experiments, since one searches for deviations from the predictions of Newton's law. While one might imagine *a priori* that there is a limitless number of possible modifications of law of gravity, this is not the case in practice. One finds that only two general classes of modifications arise in most theories—Yukawa and power-law forces.

To see this, let us begin by considering the forces that might arise between two point masses m_1 and m_2 separated by a distance r. In addition to the gravitational force, a new force arising from the exchange of a single light boson of mass μ could appear. In this case, the total potential

NEW EXPERIMENTAL LIMITS ON THE EXISTENCE OF STRONGLY INTERACTING DARK MATTER PARTICLES

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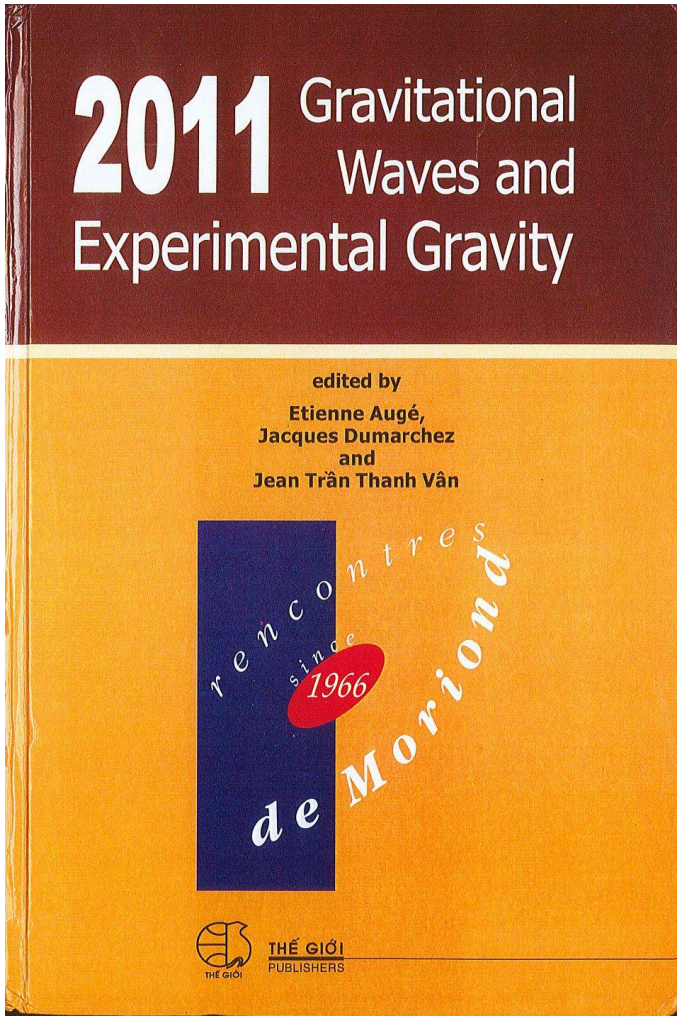
We report the results from an experimental search for strongly interacting massive dark matter particles bound to gold nuclei. A scan for heavy gold isotopes with masses ranging from 186.3–325.9 GeV/c^2 was performed on laboratory gold and gold from western Australia using PRIME Lab, the Purdue Accelerator Mass Spectrometer facility. If such particles exist in this mass range their abundances must be less than 10^{-11}–10^{-10}. These results provide significant new constraints on current models which predict the existence of such particles.

1 Introduction

A number of recent theoretical arguments and experimental results have raised the possibility that strongly interacting massive particles (SIMPs) exist in nature[1–5]. These particles are typically stable neutral fermions, whose existence could help resolve a number of outstanding problems, as we discuss below. Since any new strongly interacting particle could in principle bind to nuclei, SIMPs may manifest themselves as superheavy isotopes of ordinary elements. We report here the results of a recent search for SIMPs with mass M_S bound to gold nuclei, forming a new isotope of $_{79}$Au denoted by $_{79}X$ with mass M_X, where gold has been chosen for several reasons: To start with, previous searches have focused on SIMPs bound to light nuclei[6,7], but no comparable limits exist for heavy nuclei. Moreover, SIMPs may bind preferentially to heavy nuclei, since the presence of a larger (in radius) nuclear potential well implies a smaller kinetic energy (and hence more binding) via the uncertainty principle[1]. In addition, gold can be found in sites relatively close to the surface of the Earth, where the extent of the gold's exposure to SIMPs can be estimated using geological considerations. Finally, gold readily forms negative ions, which a tandem electrostatic accelerator requires in the initial acceleration stage.

Since a SIMP's particle-antiparticle annihilation cross section $\sigma_{S\bar{S}}$ determines its relic density[3], different models providing estimates of $\sigma_{S\bar{S}}$ make predictions as to whether SIMPs can appear in sufficient abundance to saturate the galactic halo[1]. Models that predict saturation of the upper bound on (galactic halo) dark matter are restricted by a number of experiments, as reviewed by Starkman *et al.*[2]. If the relic SIMP abundance is roughly proportional to $(\sigma_{\bar{S}S} M_S)^{-1}$, the bound is not saturated as $\sigma_{\bar{S}S}$ moves beyond $\sigma_{\bar{S}S}^{\rm min} \sim 10^{-36}$ cm^2 and the limits of Starkman *et al.*[2] do not apply. Thus a neutral SIMP with mass $M_S \leq 100$ GeV/c^2 may exist and still have gone undetected. Supersymmetry (SUSY) provides another motivation for SIMPs. Raby[4]

2011



II. Experimental Gravity

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Particle Data Group

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.

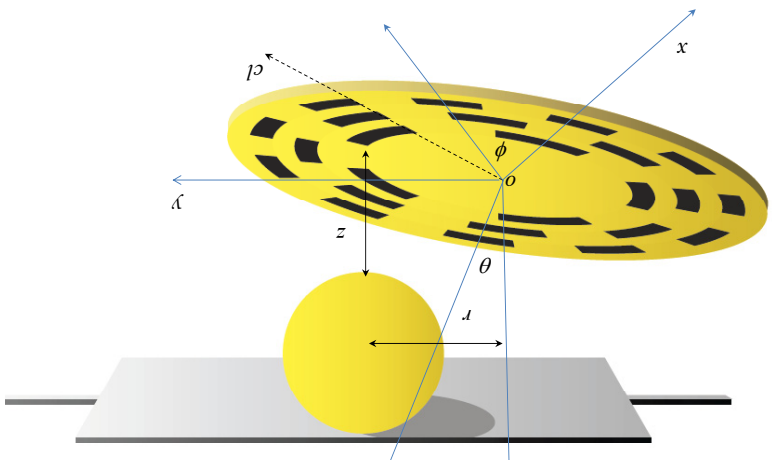
[13] CHIAVERINI 03 search for new forces, probing α above 10^4 and λ down to 3μm, finding no signal. See their Fig. 4 for details on the bound. This bound does not place limits on the size of extra flat dimensions.

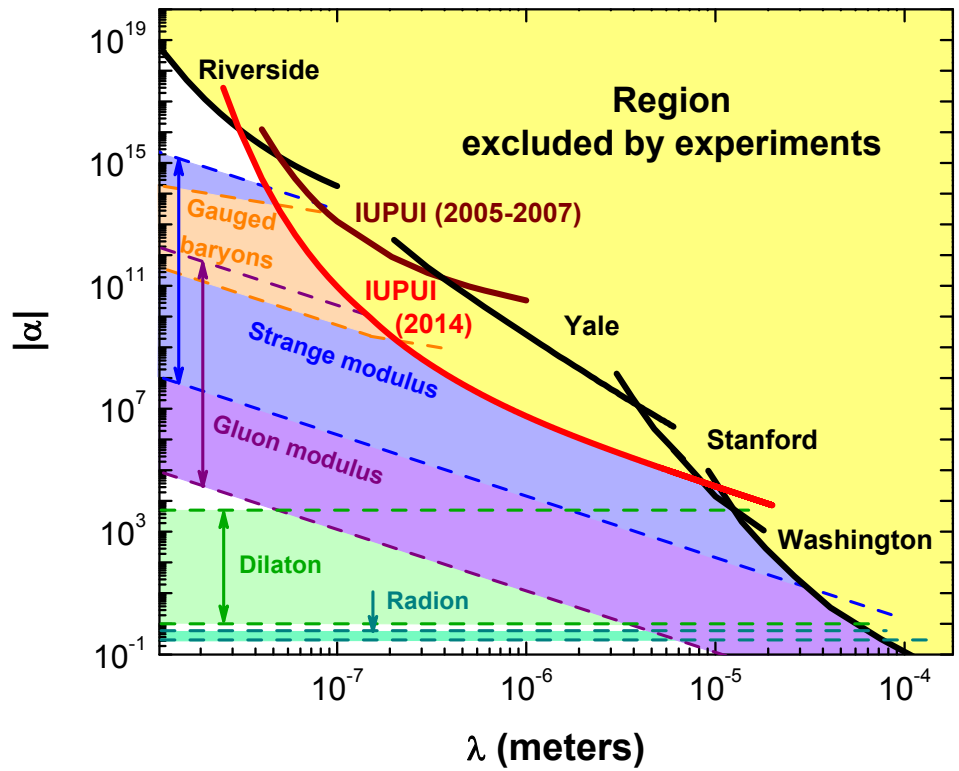
[14] LONG 03 search for new forces, probing α down to 3, and distances down to about 10μm. See their Fig. 4 for details on the bound.

[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.

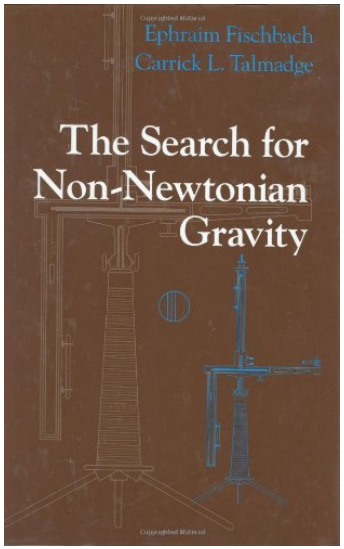
New Limits on New Submicron Forces

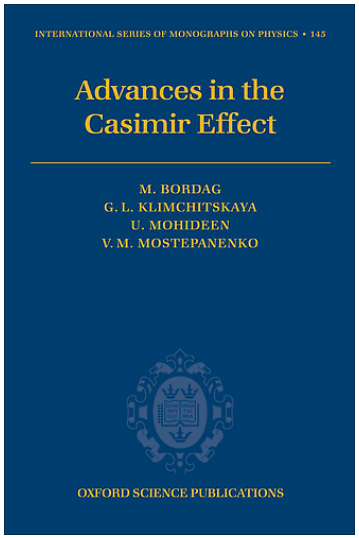


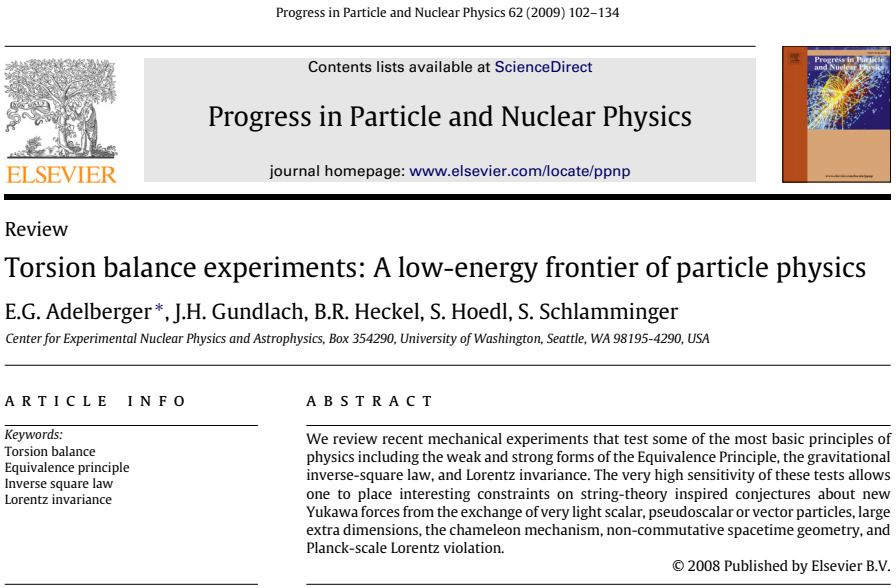


Reference: Y.-J. Chen, W. K. Tham, D. E. Krause, D. López, Ephraim Fischbach, and R. S. Decca, arXiv:1410.7267

General References







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Review

Torsion balance experiments: A low-energy frontier of particle physics

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ABSTRACT

We review recent mechanical experiments that test some of the most basic principles of physics including the weak and strong forms of the Equivalence Principle, the gravitational inverse-square law, and Lorentz invariance. The very high sensitivity of these tests allows one to place interesting constraints on string-theory inspired conjectures about new Yukawa forces from the exchange of very light scalar, pseudoscalar or vector particles, large extra dimensions, the chameleon mechanism, non-commutative spacetime geometry, and Planck-scale Lorentz violation.

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The End

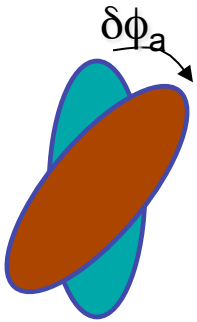
Long-Range Tests

(composition-independent)

Inverse-Square Law: Solar System Tests

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

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

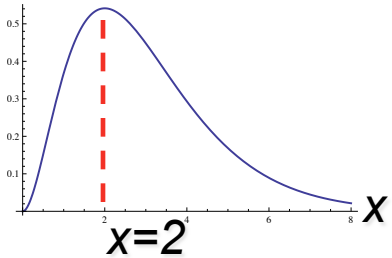


a) Planetary Precession:

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

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

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



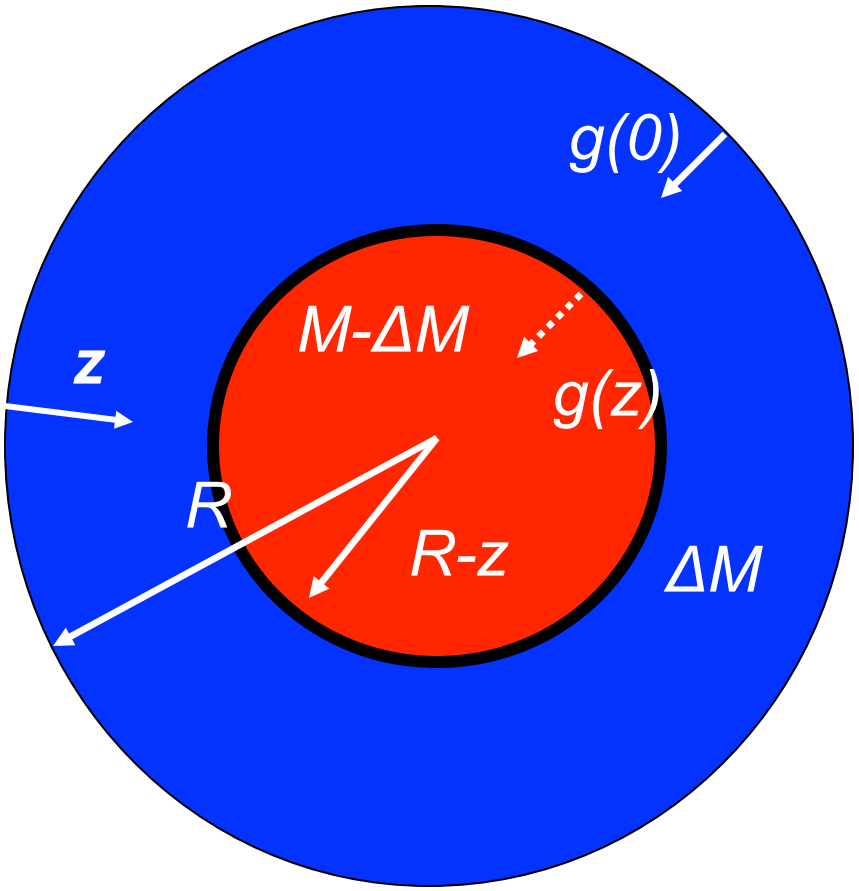
b) Variation of GM_{sun} :

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

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

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

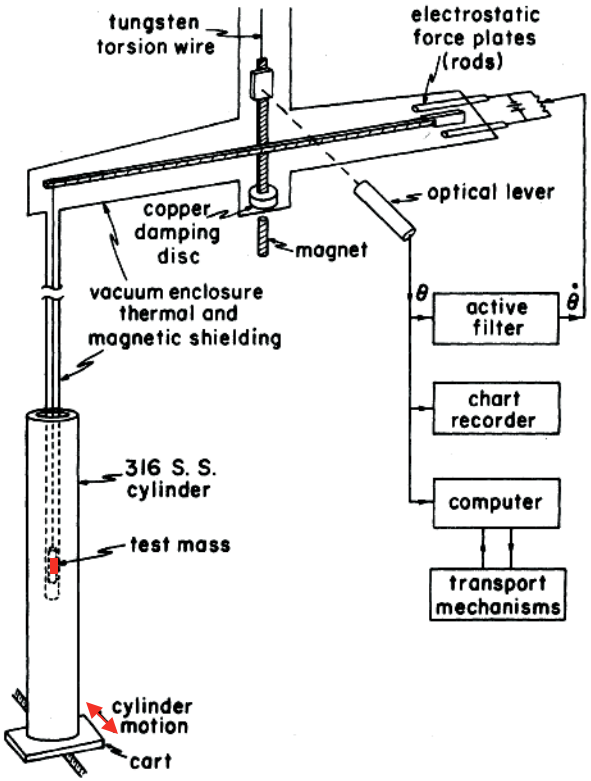
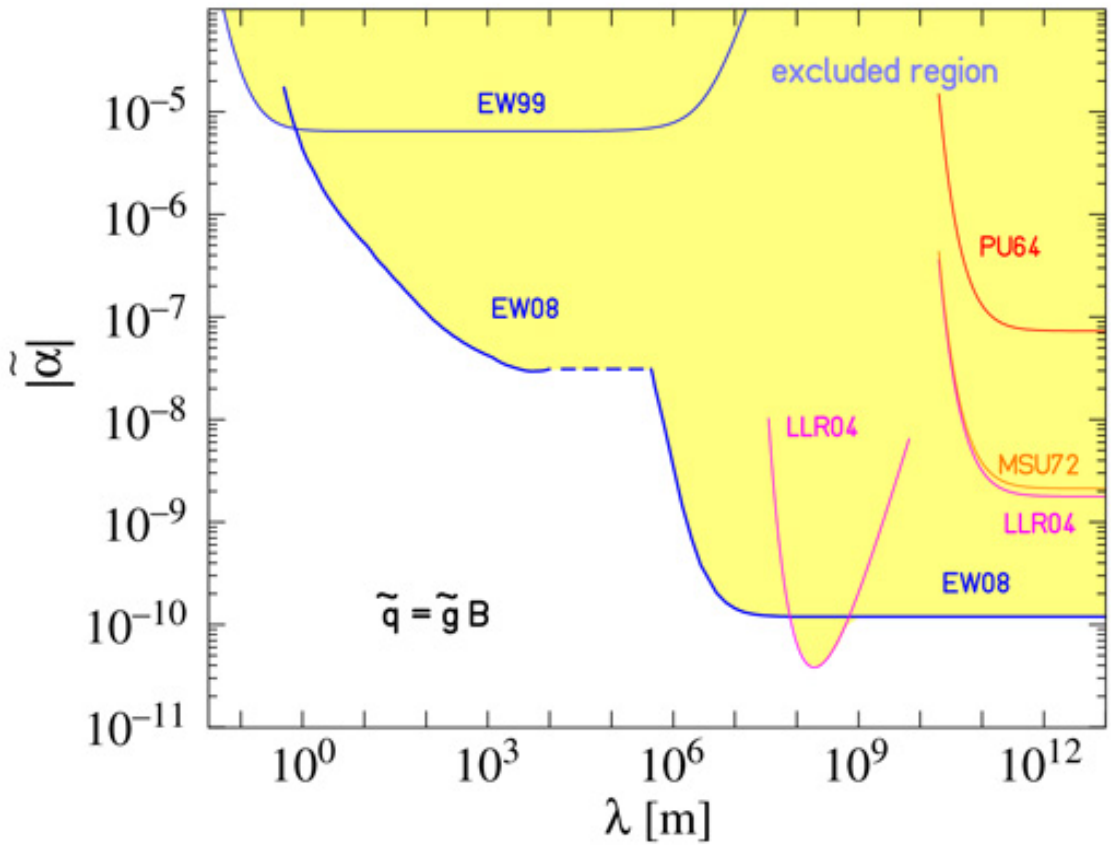


FIG. 1. Schematic of the experimental apparatus.

Long-Range Tests

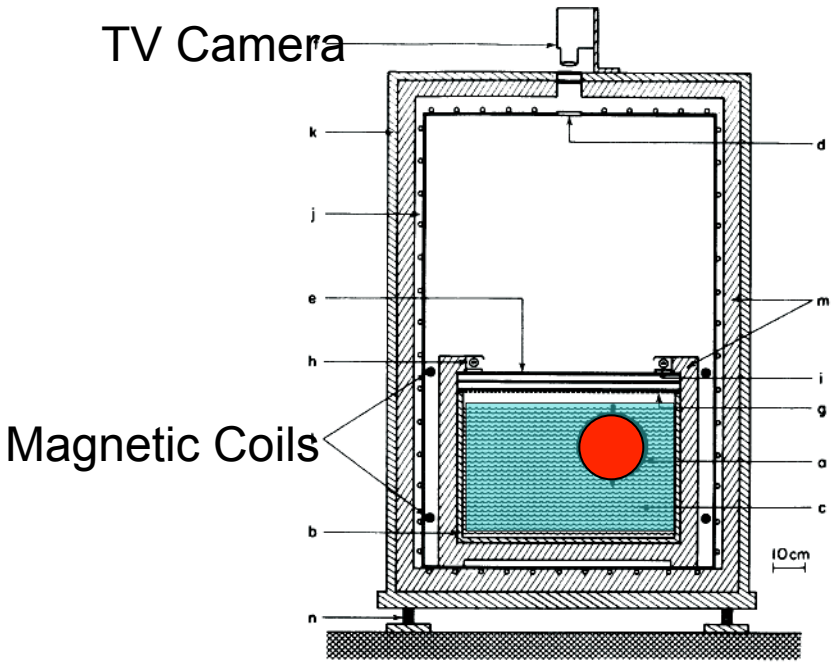
(composition-dependent)

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



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

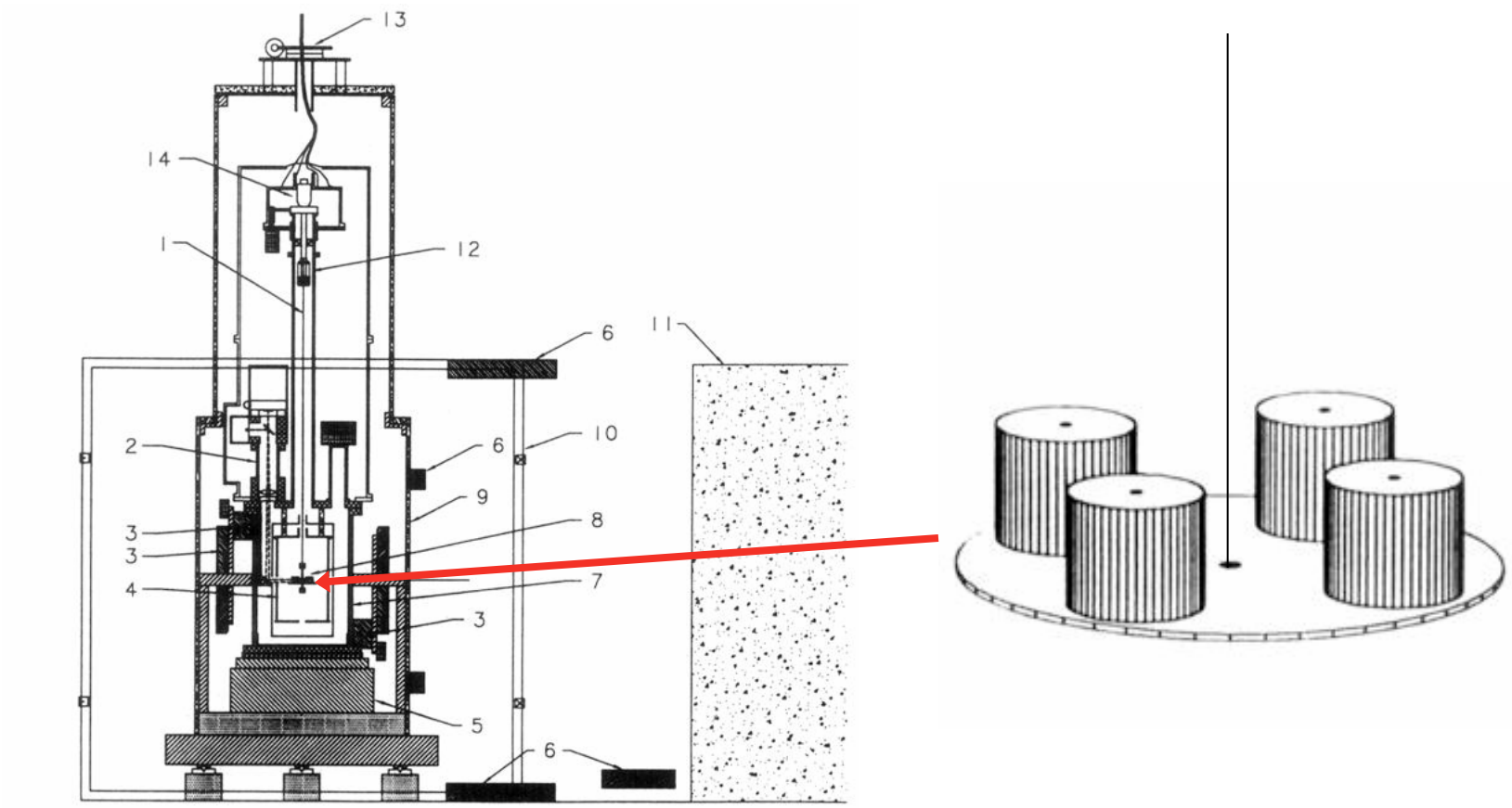
Composition-Dependent Tests: (Thieberger 1987)



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

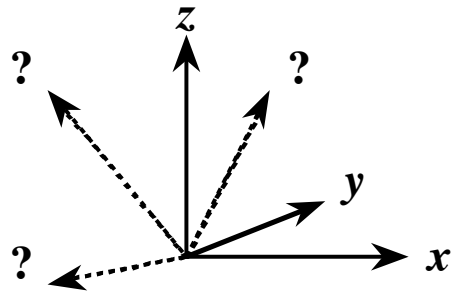
There is at present no credible evidence for any deviations from the predictions of Newtonian gravity on any length scale.

Short-Range Phenomenology

Ephraim Fischbach

Rencontres de Moriond, March 2015

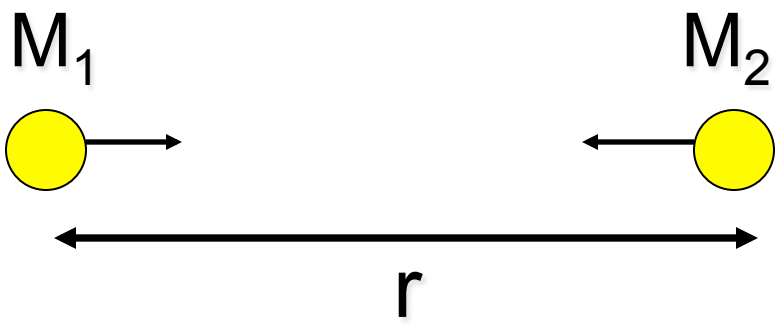
Extra Dimensions



Theories:

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

Gravity in 3 + *n* Non-Compact Dimensions

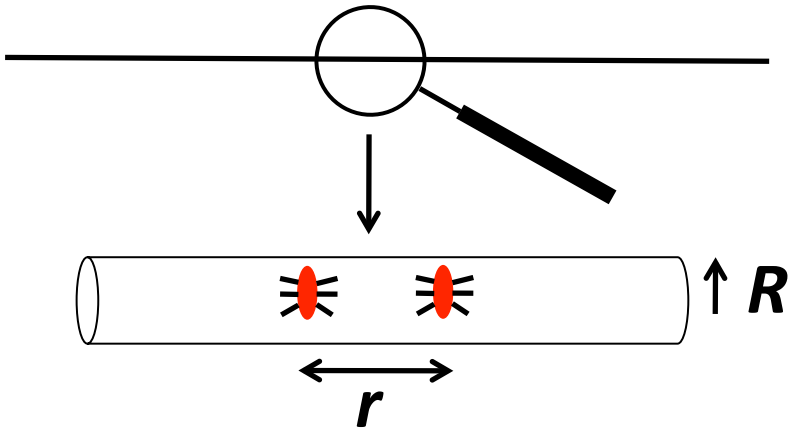


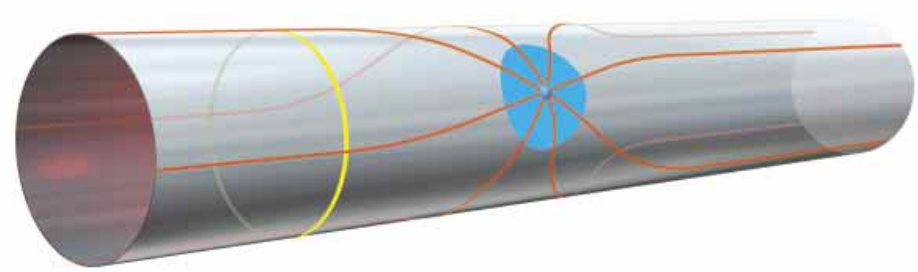
Potential Energy:

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

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

Gravity with *n* Compact Extra Dimensions of Size R

Newtonian Gravity

Yukawa Correction

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

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**

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

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 $M_{4+n} \sim 1$ TeV by assumption
We then solve:

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

$$R(n) \approx 2 \times 10^{(32/n-17)}\ \mathrm{cm}$$

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

Limit on Largest Extra Dimension R ≤ 44 μm

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

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- "Extra Dimensions," Review of Particle Physics, Particle Data Group
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- A. Pérez-Lorenzana, arXiv:hep-ph/0503177
- N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Rev. D **59**, 086004 (1999)
- I. Antoniadis, N. Arkani-Hamed, S. Dimopoulus, G. Dvali, Phys. Lett. B **436**, 257 (1998)
- L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999); **83**, 4690 (1999)
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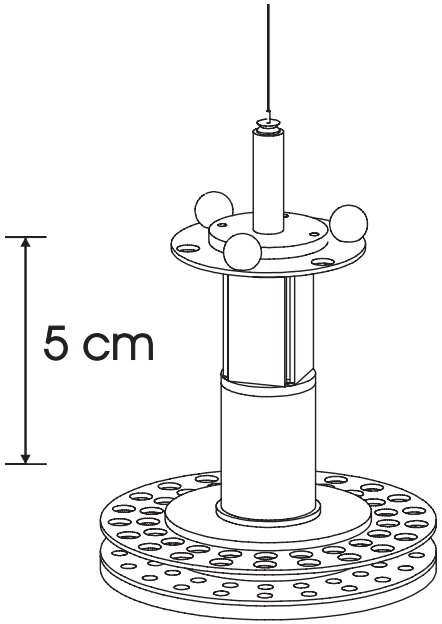
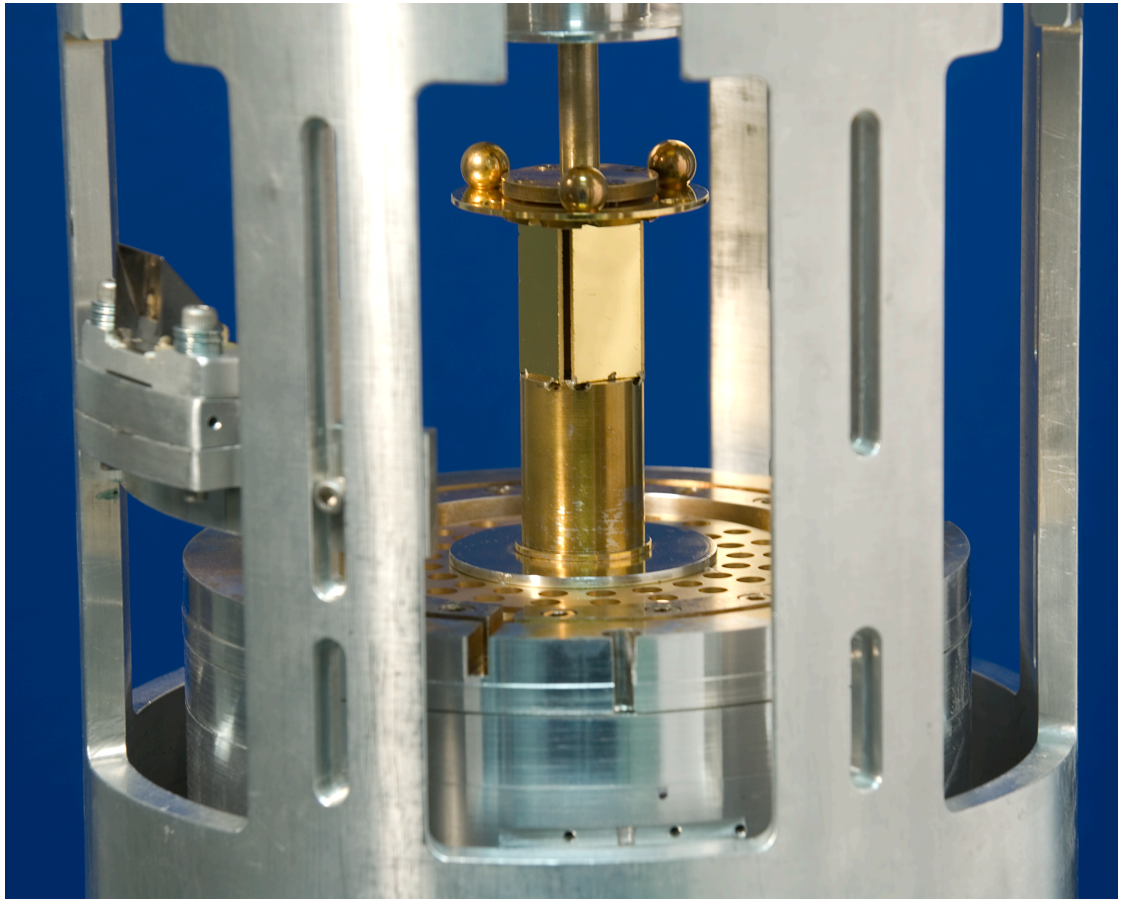
Short-Range Experiments

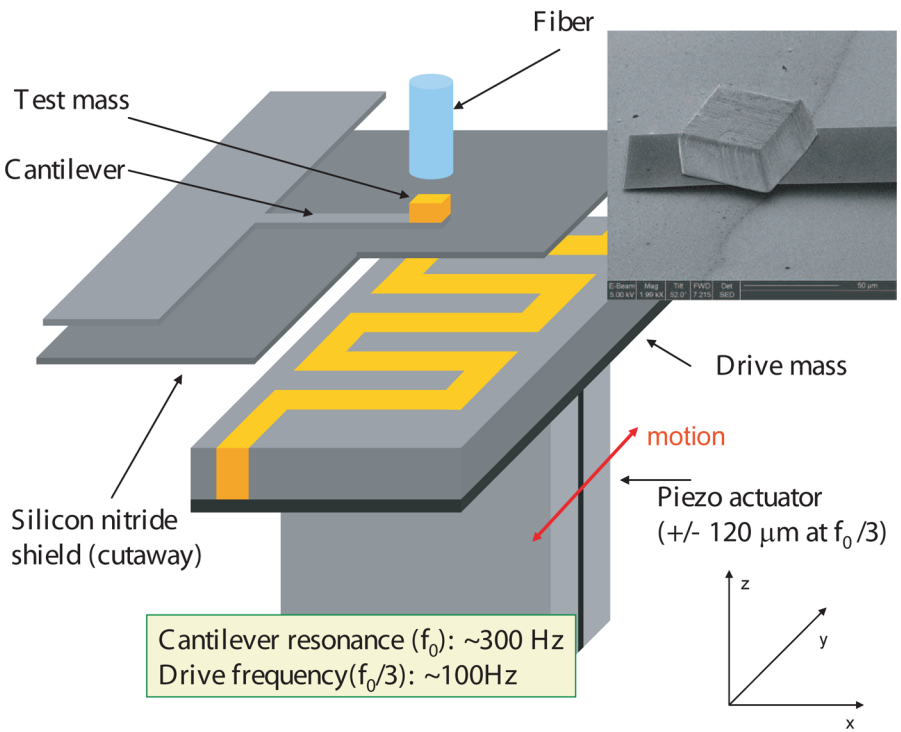
Eöt-Wash Short-Distance Experiment





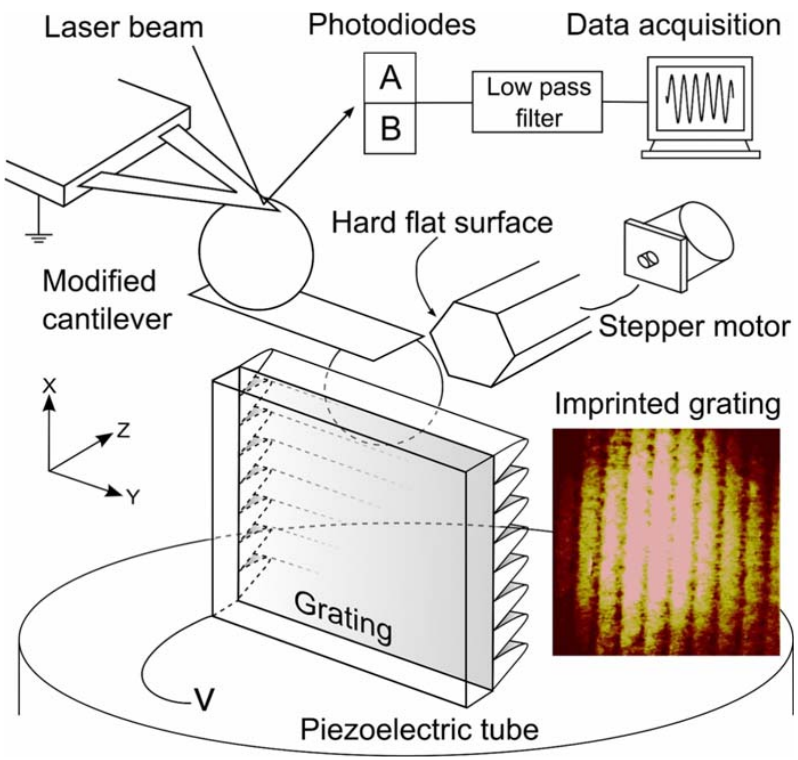
D. J. Kapner, et al., Phys. Rev. Lett. 98, 021101 (2007)

Stanford Short-Distance Experiment



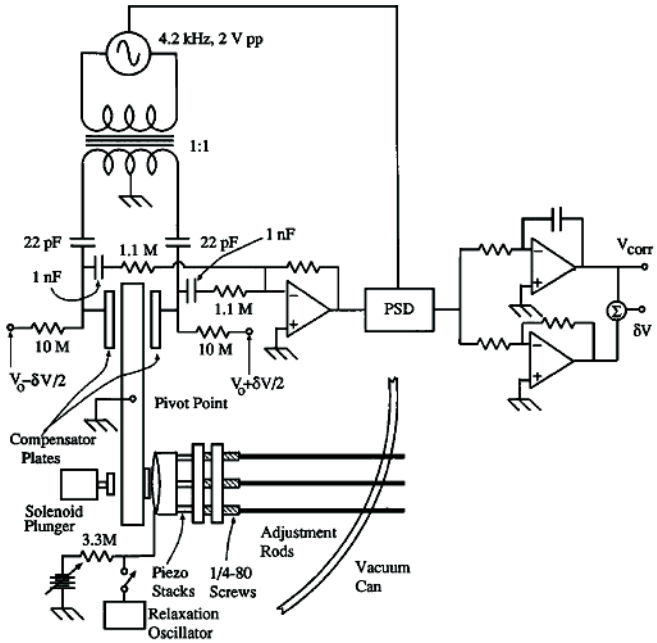
Reference: A.A. Geraci, et al., PRD, **78**, 022002 (2008)

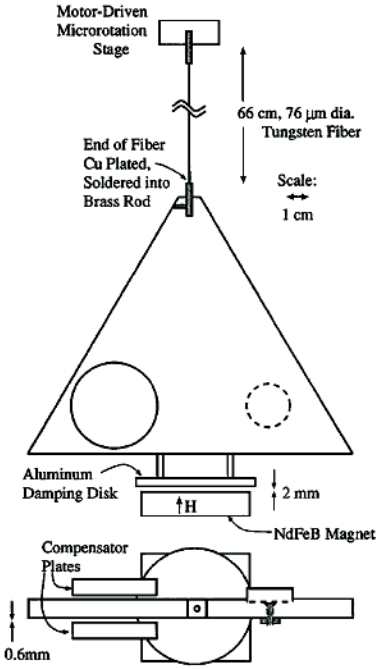
Riverside Lateral Casimir Force Experiment



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

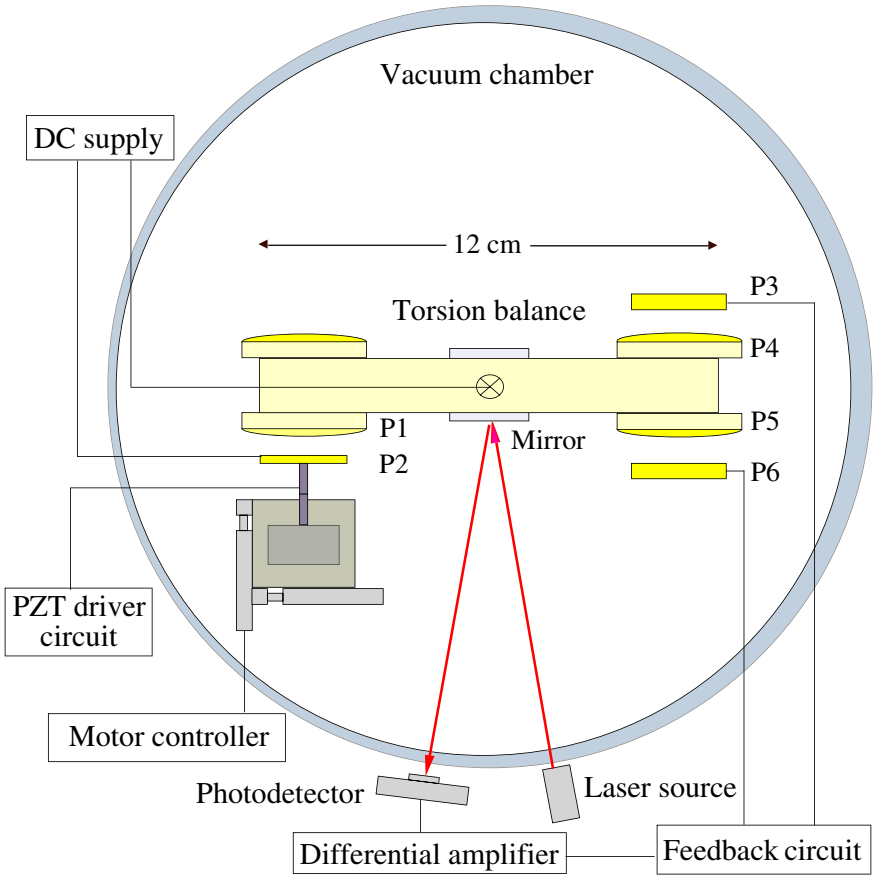
Lamoreaux Short-Distance Experiment





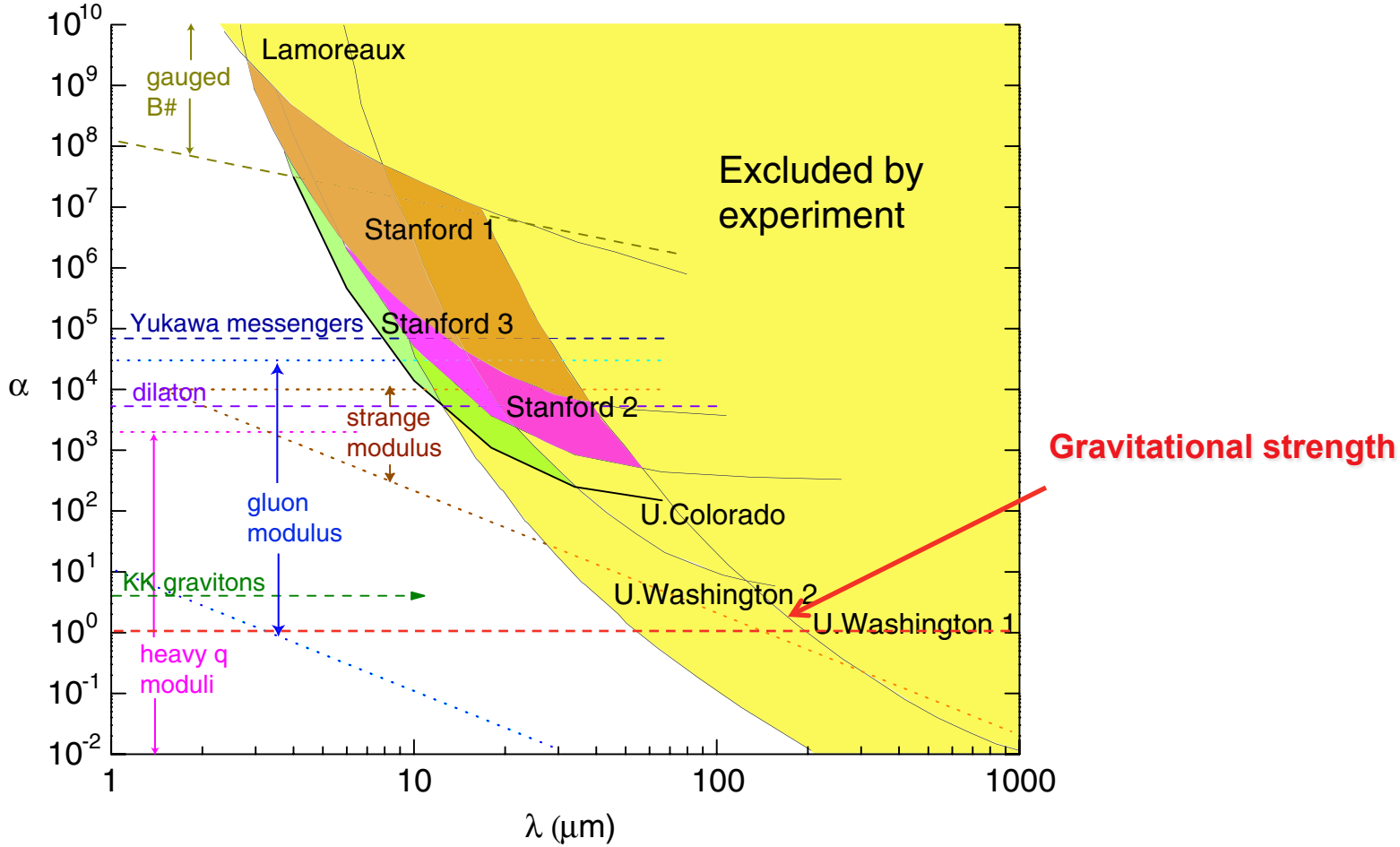
Reference: S. K. Lamoreaux, Phys. Rev. Lett. **78**, 5 (1997)

Tokyo Casimir Experiment



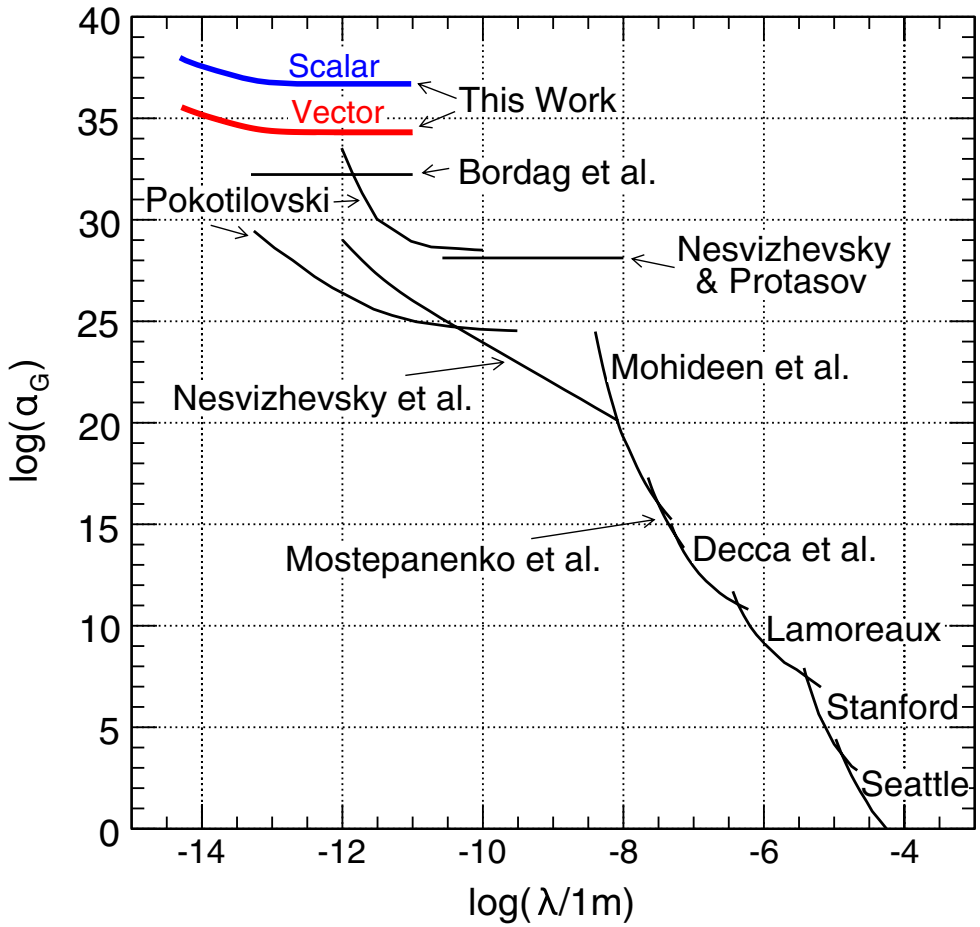
Reference: M. Masuda and M. Sasaki, Phys. Rev. Lett. **102**, 171101 (2009)

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



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

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:

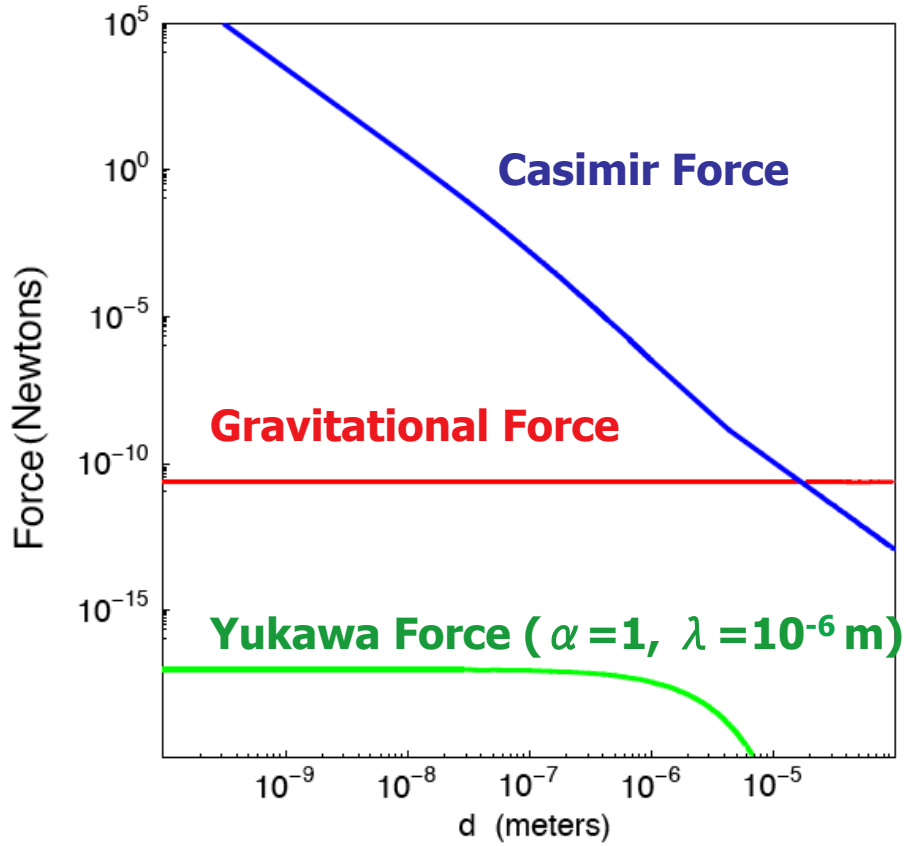
1. **Strong Background Forces**

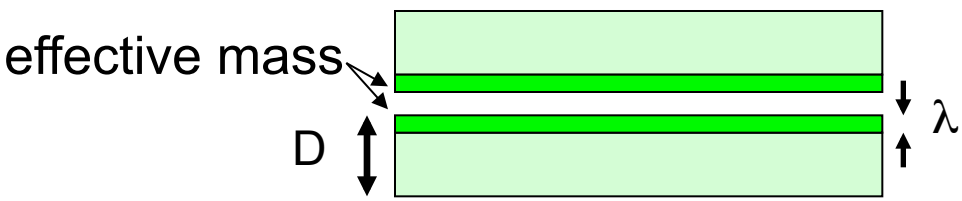
   Casimir force dominates when 10^{-10} m < separation < 10^{-6} m

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





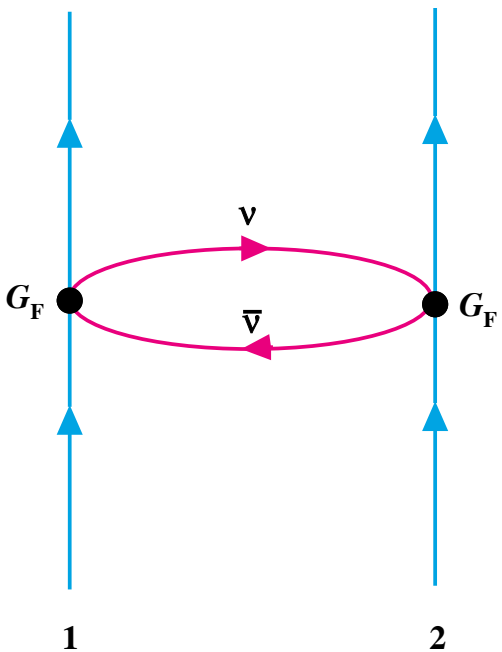
$$\frac{F_{\text{Yukawa}}}{F_{\text{Gravity}}} = \alpha \left(\frac{\lambda}{D} \right)^2$$

Power Law Forces

Various mechanisms lead to inverse power-law potentials:

$$V_n(r) = -\alpha_n \left(\frac{GM_1M_2}{r} \right) \left(\frac{r_0}{r} \right)^{n-1},$$

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



- ***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

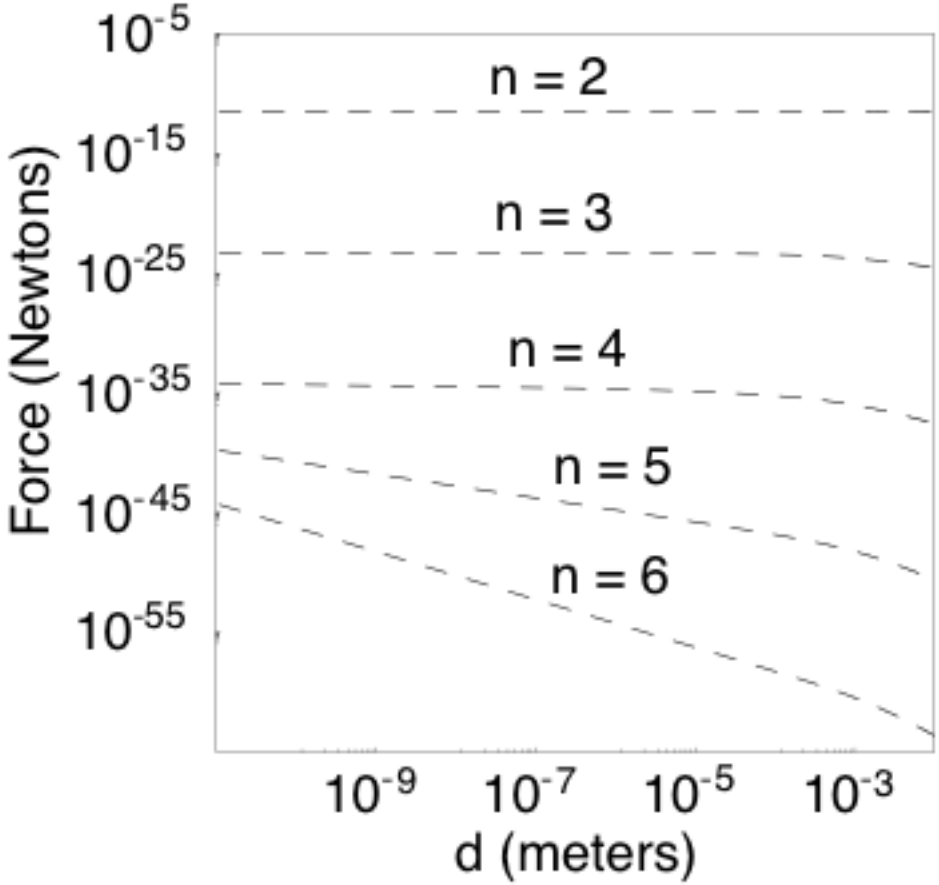
$$V_n(r) = -\beta_n \left(\frac{GM_1M_2}{r}\right)\left(\frac{1\ \text{mm}}{r}\right)^{n-1}$$

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

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

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.

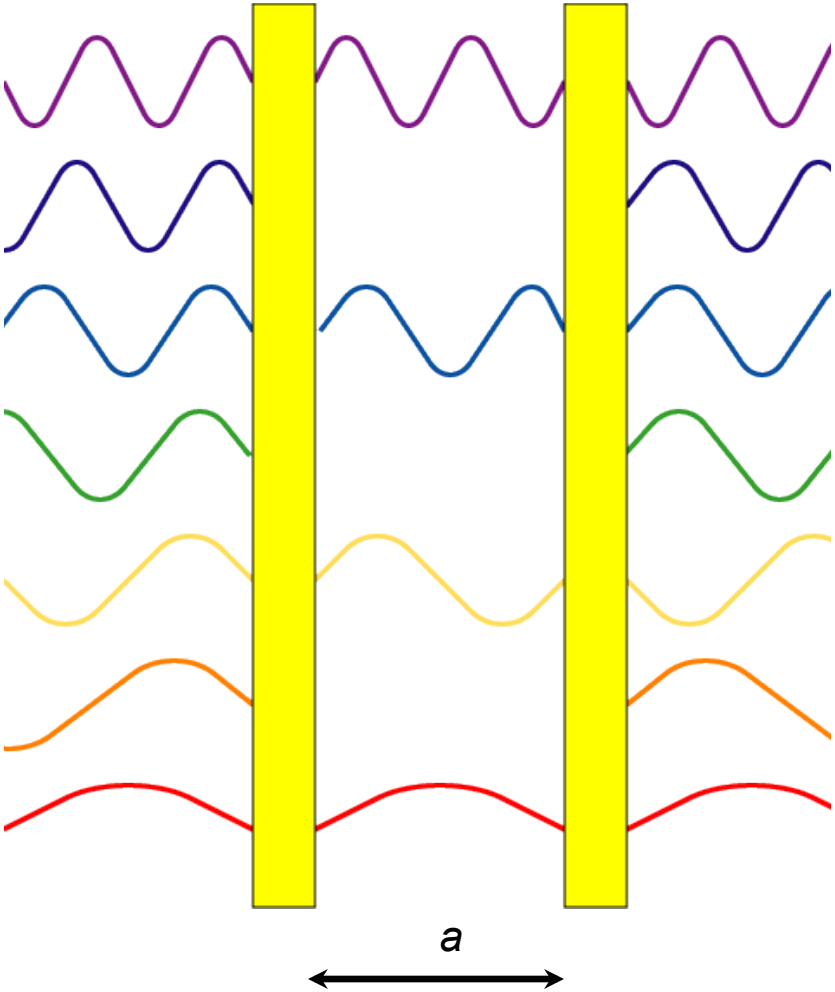
Background forces increase faster than new power-law forces as separation decreases.

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

The Casimir Force



$$\langle 0|\vec{E}|0\rangle = \langle 0|\vec{B}|0\rangle = 0$$

$$\frac{1}{2}\langle 0|\vec{E}^2 + \vec{B}^2|0\rangle = \langle 0|\vec{E}^2|0\rangle = \frac{1}{2\Omega}\sum_{\omega,\mathbf{k}}\omega_k$$

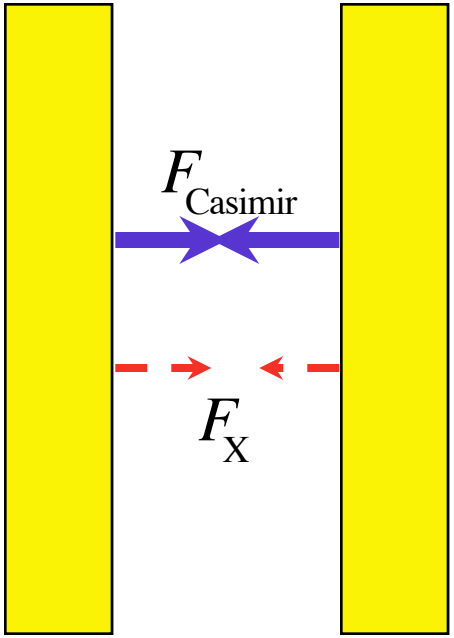
Attractive force!

$$P_C = -\frac{\pi^2}{240}\frac{\hbar c}{a^4}$$

- Dominant electronic force at small (~ 1 nm) separations
- Non-retarded: van der Waals
- Retarded: Casimir

No mode restriction on the outside

Searching for New Forces/Dimensions using Casimir Force Experiments



Measure Casimir force and compare result with theory:

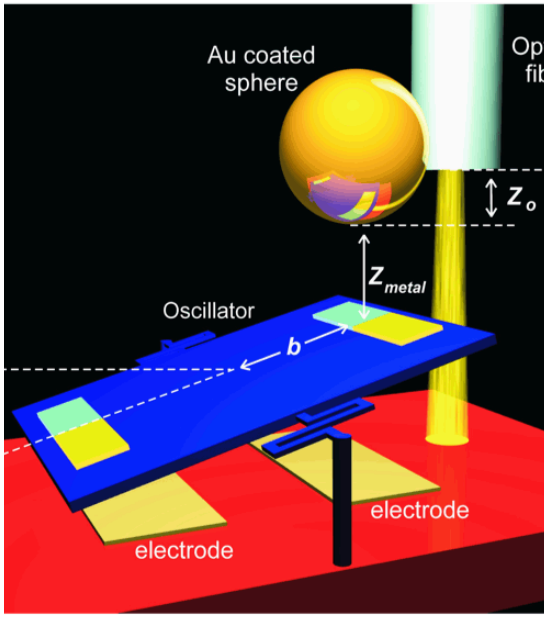
$$\left|F_X\right| \leq \left|F_{\text{Casimir}}^{\text{Measured}} - F_{\text{Casimir}}^{\text{Theory}}\right|$$

Corrections from Ideal:

- Temperature-Dependence
- Roughness Corrections
- Finite-Conductivity

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

IUPUI Experiment
(Decca, Lopéz, Fischbach, Krause)



Experimental Parameters:

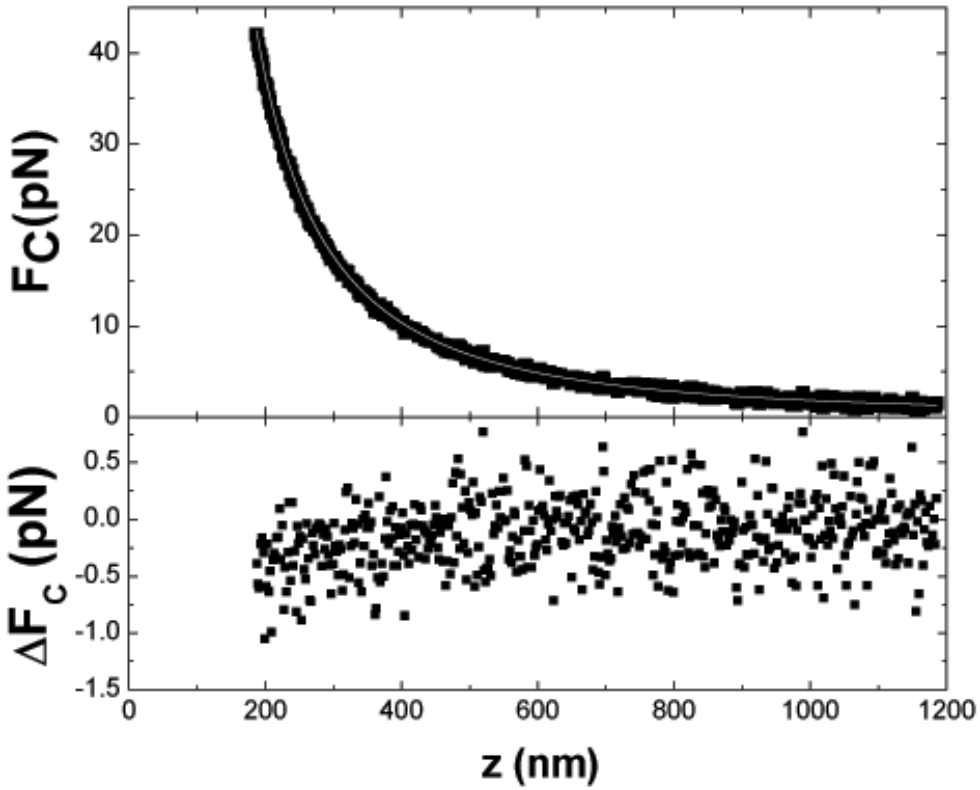
Plate: 500 μm × 500 μm × 3.5 μm

Sphere Radius: ~50 μm

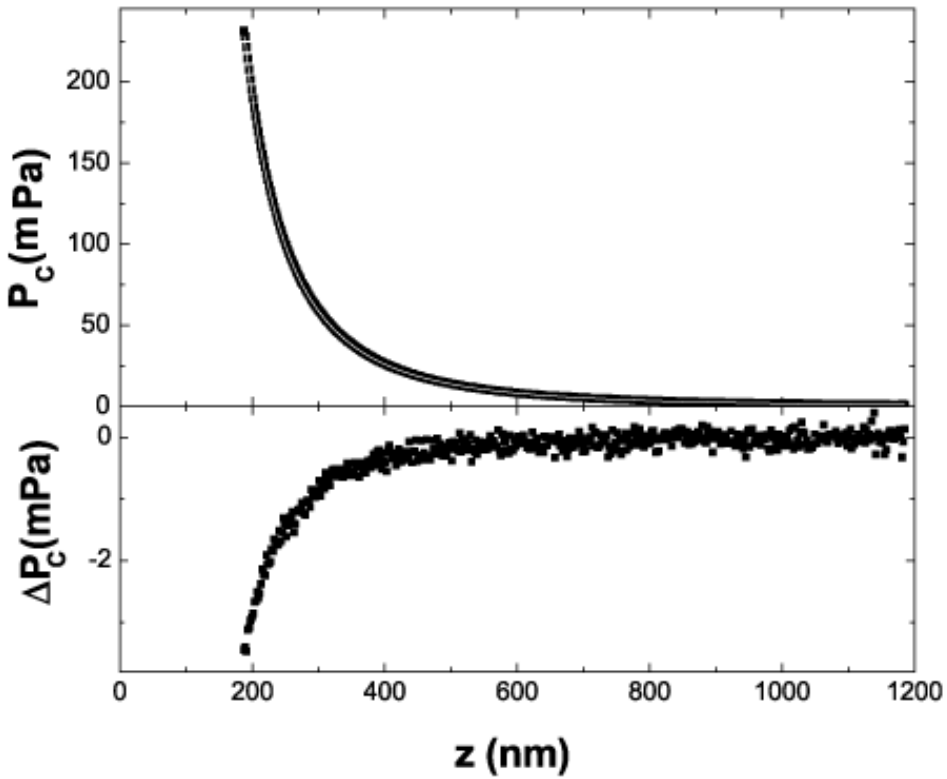
Sphere/Plate Separation: 150-500 nm

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

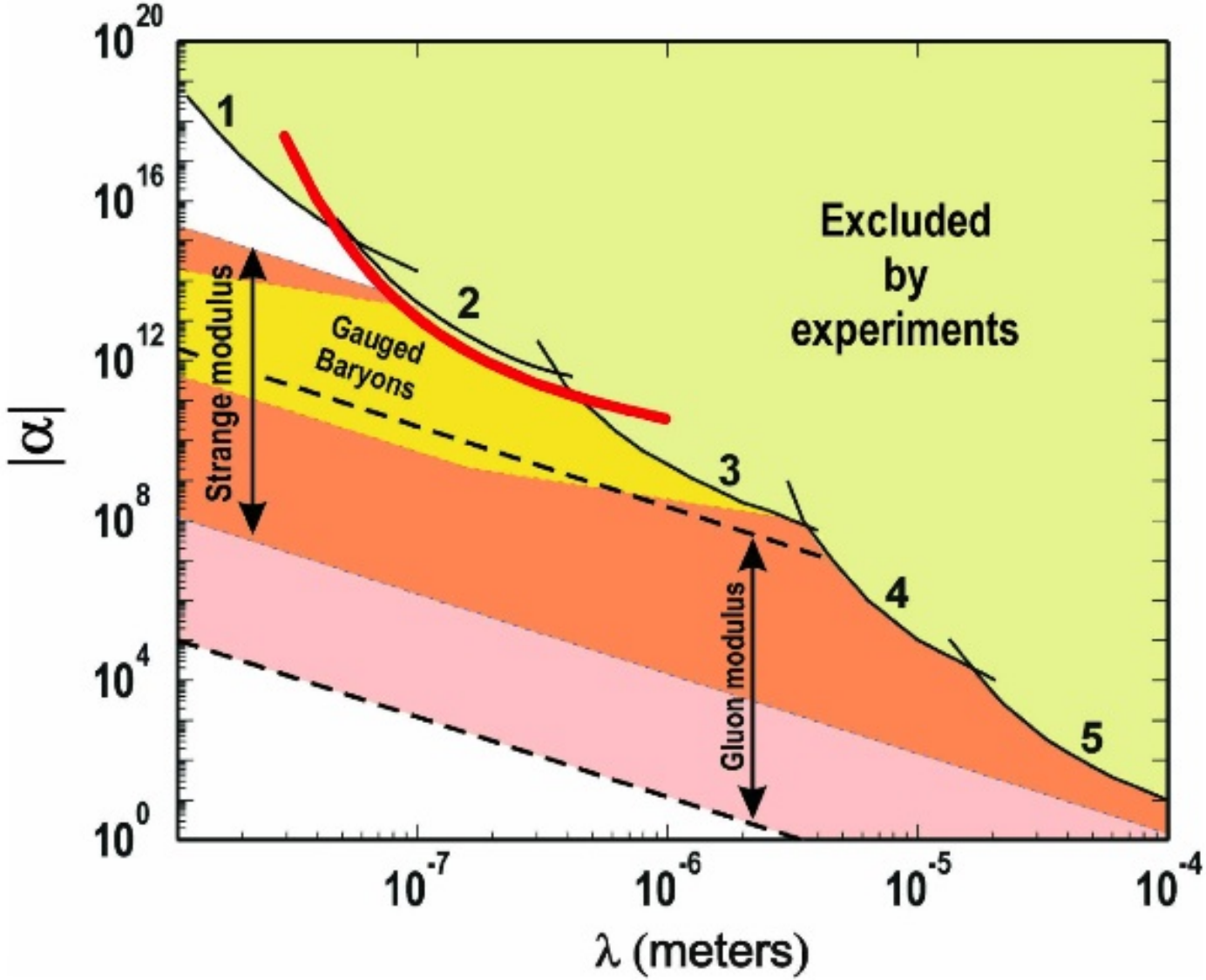
Casimir Force:
Static Measurement



Casimir Pressure:
Gradient Measurement

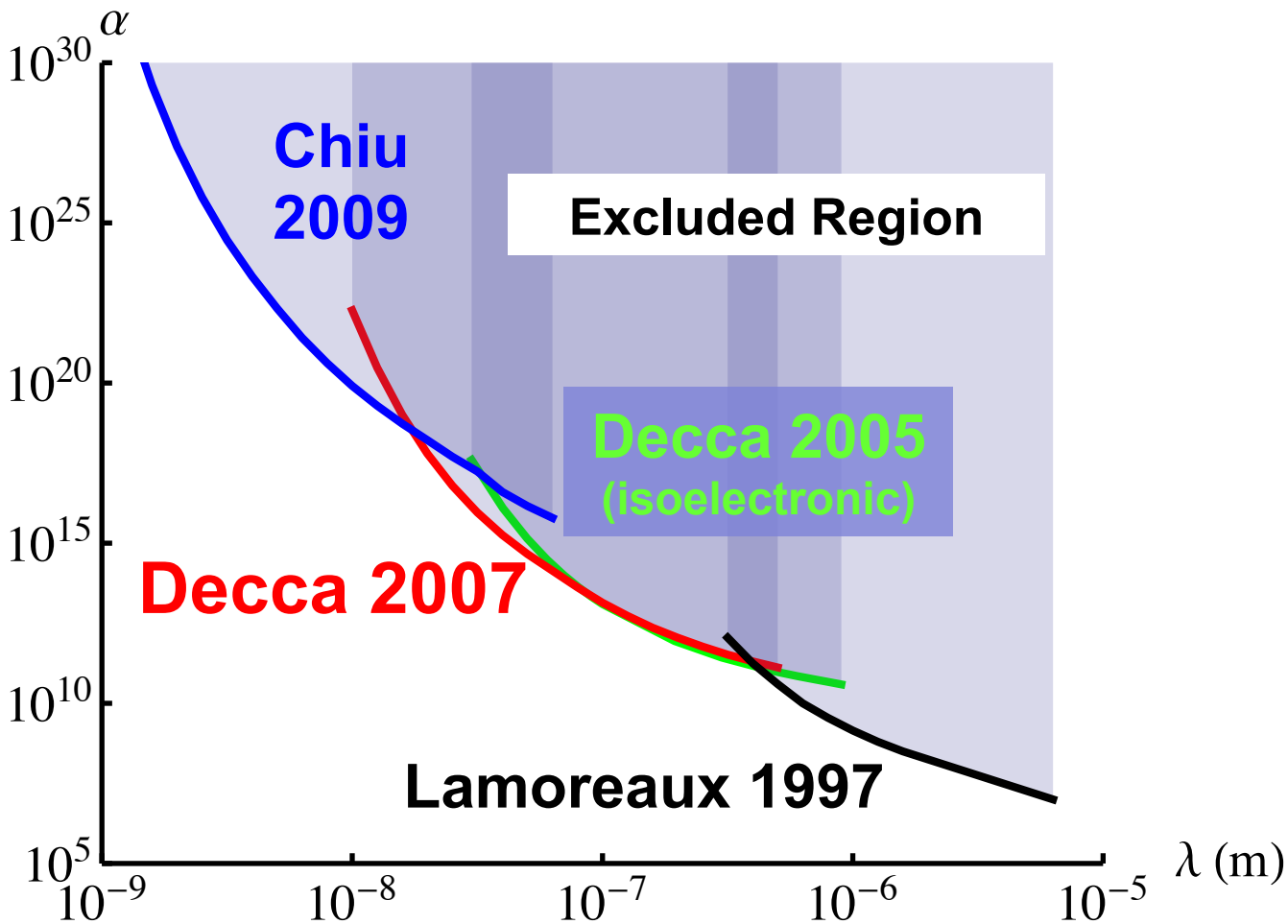


Theories at Sub-Micron Distances



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.
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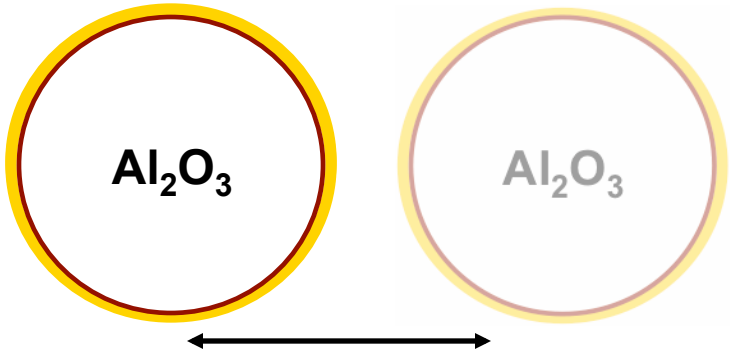
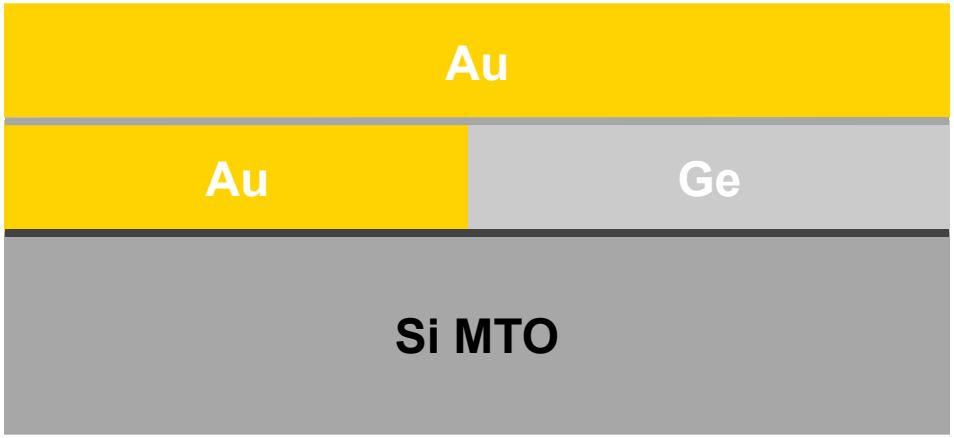
“Casimir-less” experiments

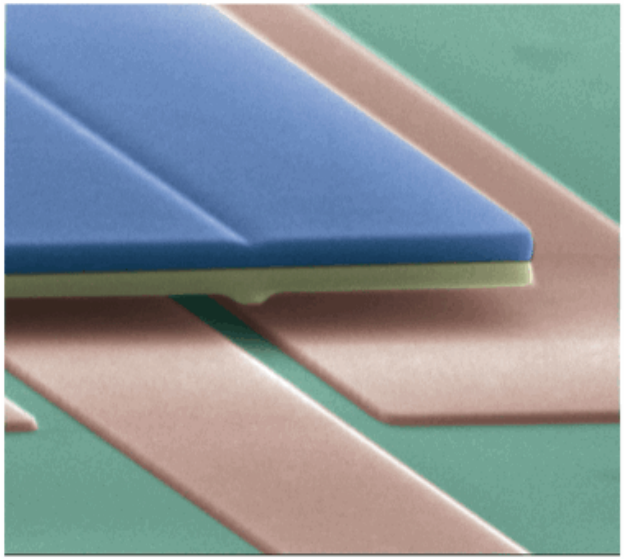
$$\Delta F^{\text{Casimir}} = F_{12'}^{\text{Casimir}} - F_{12}^{\text{Casimir}} \approx 0$$

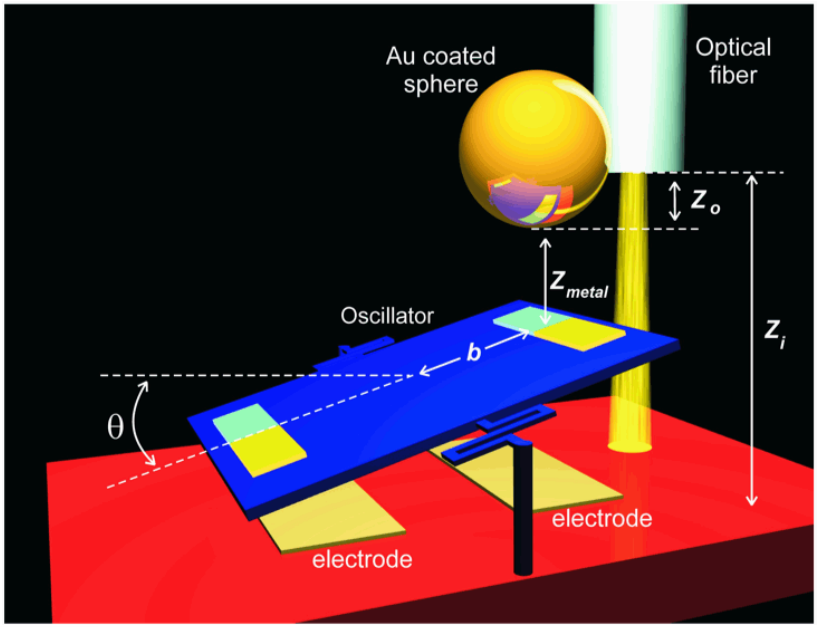
$$\Delta F^{\text{Hyp}} = F_{12'}^{\text{Hyp}} - F_{12}^{\text{Hyp}} \neq 0$$

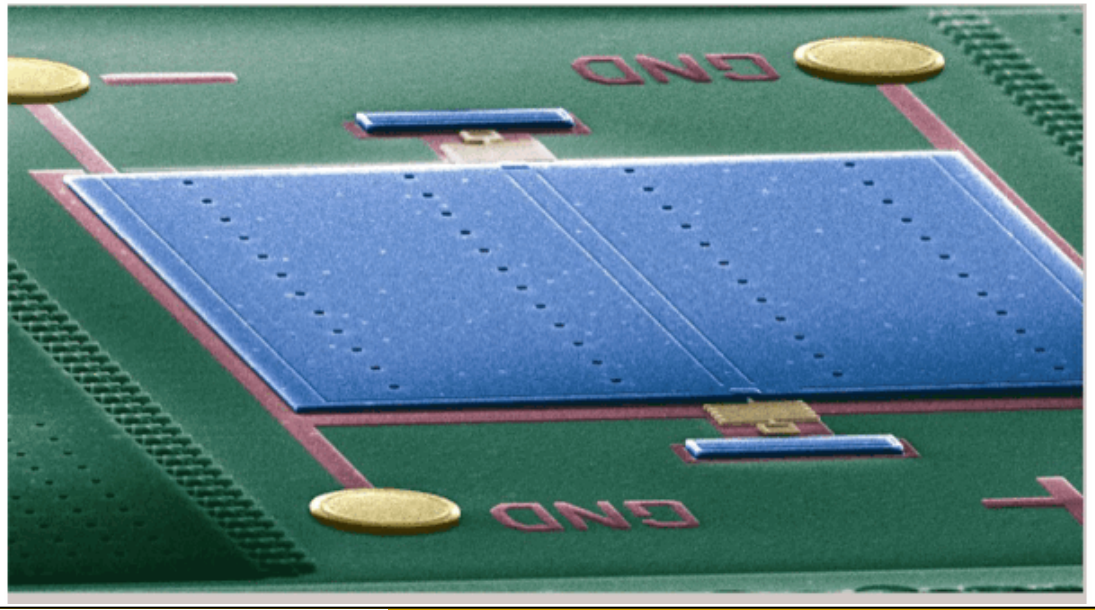


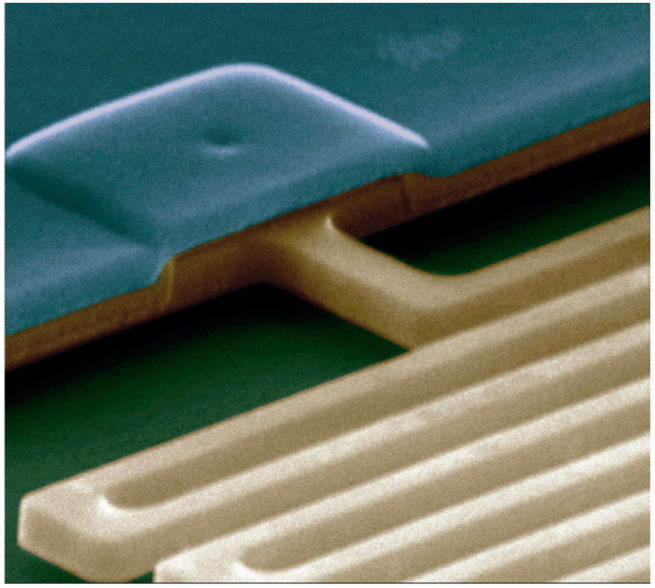


Experimental setup

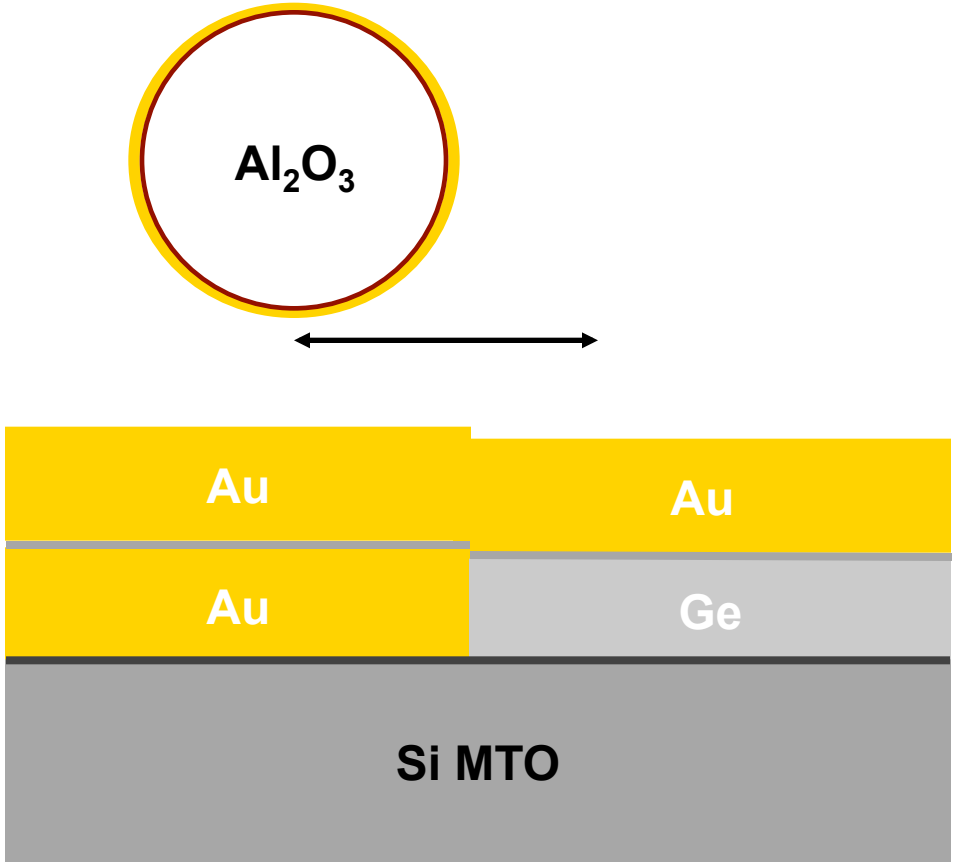








Problems



- **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

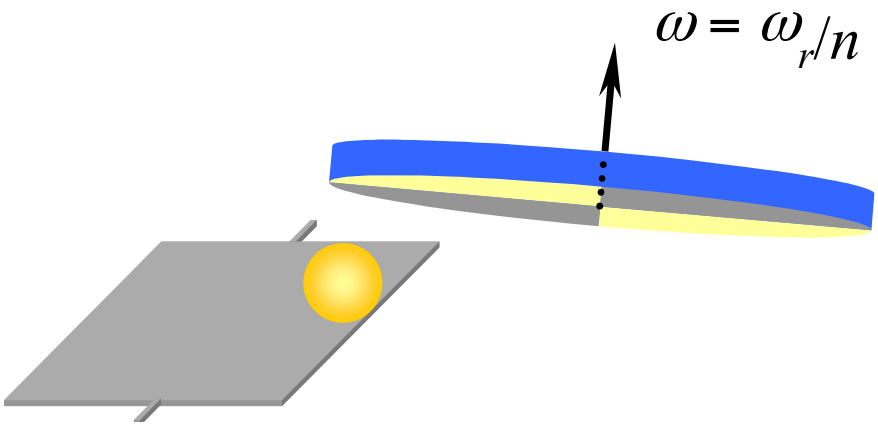
Ephraim Fischbach

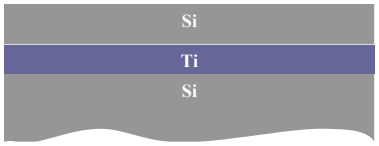
Rencontres de Moriond, March 2015

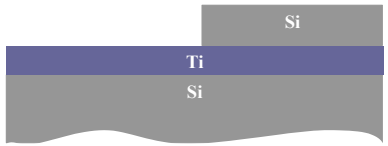
What next?

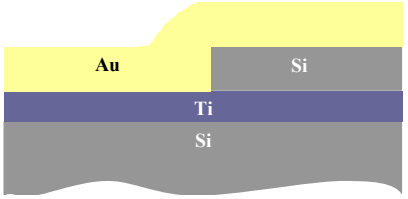
-Improve signal

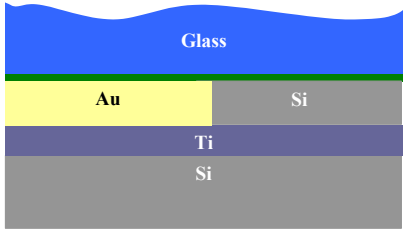
-Reduce background

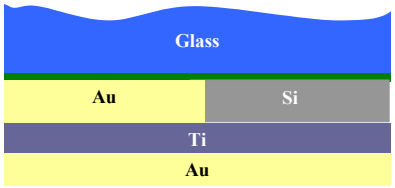




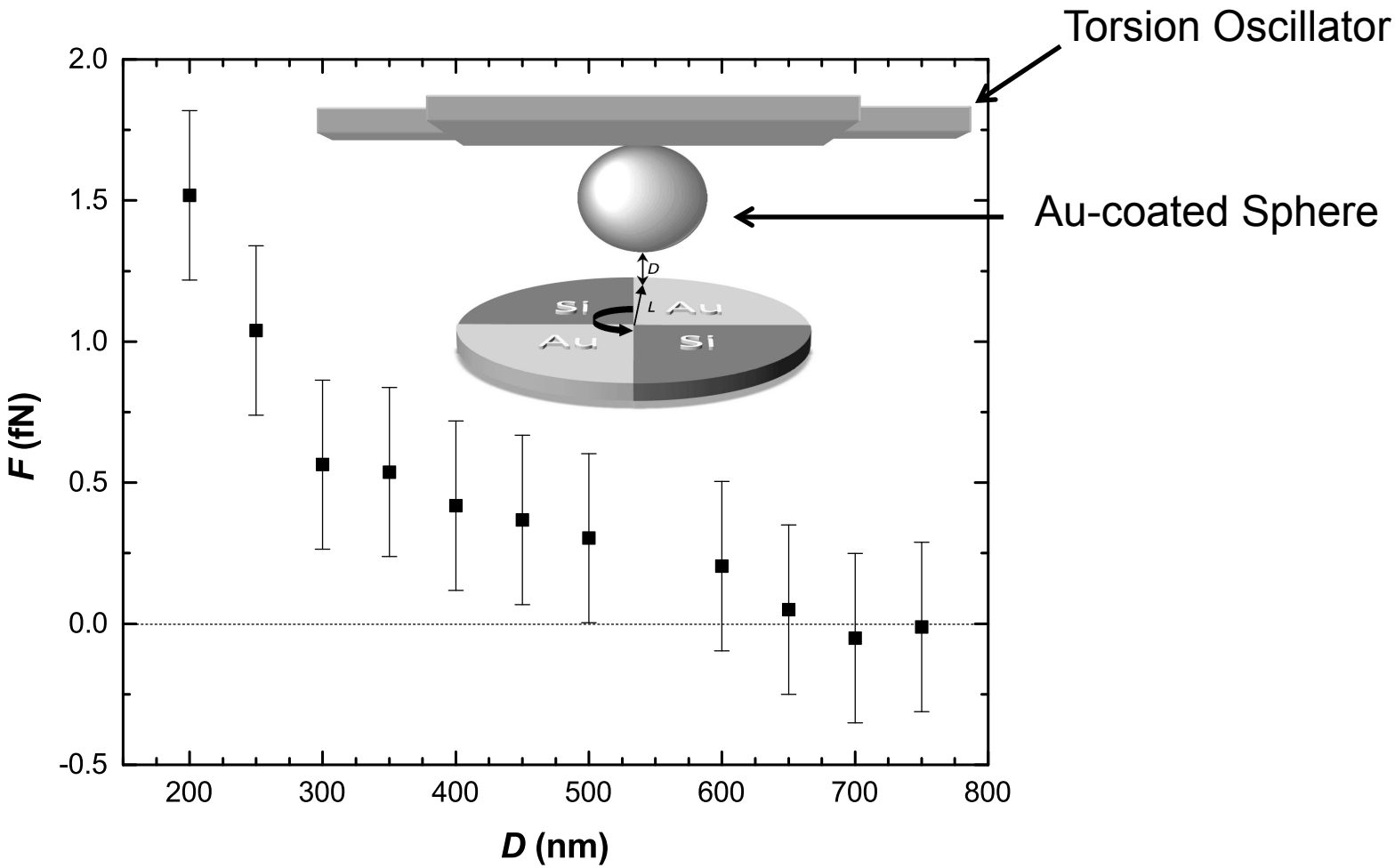




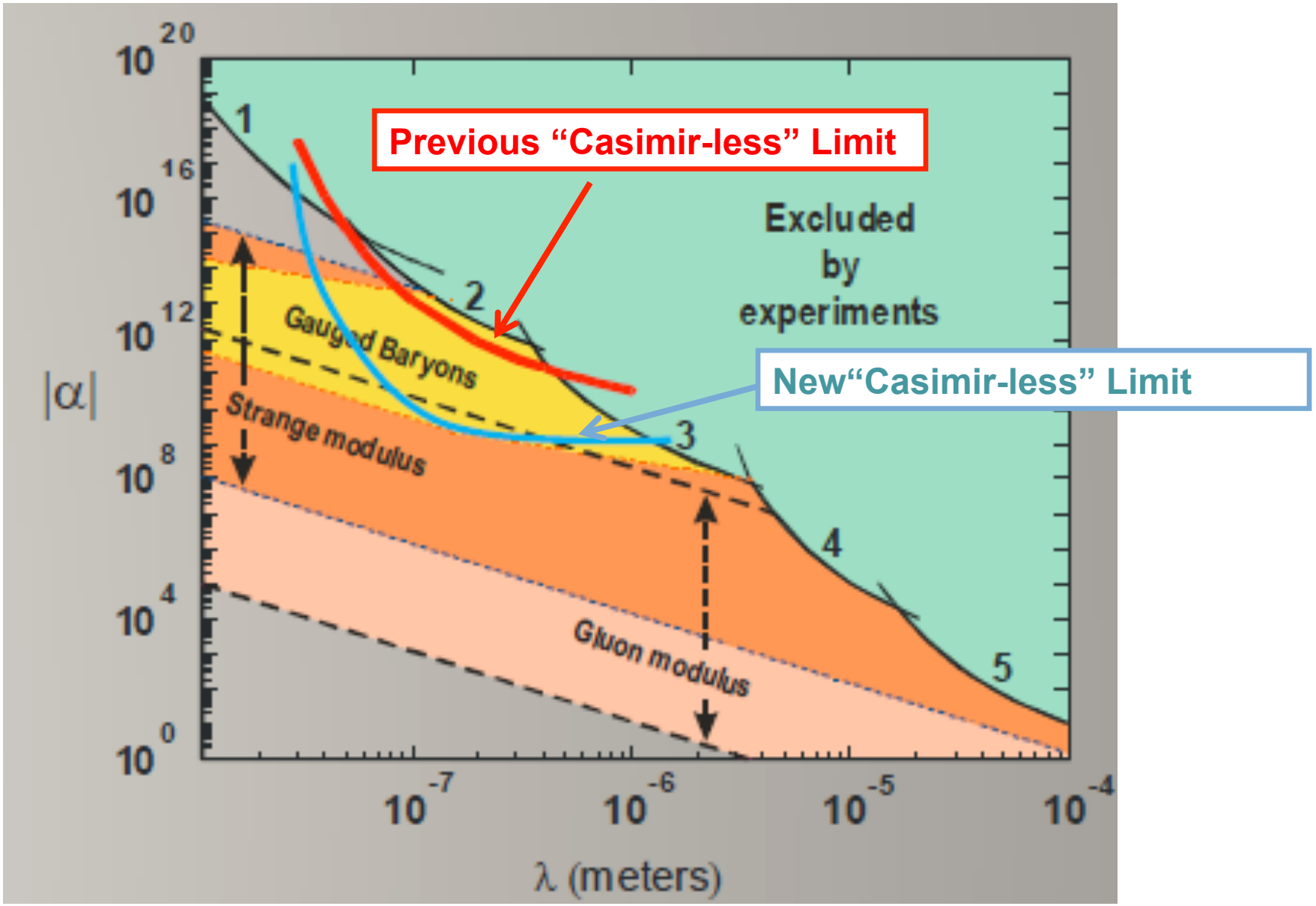




Schematic of Experimental Setup with Measured Force



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
|α|
λ (meters)
10^20
10^16
10^12
10^8
10^4
10^0
10^-7
10^-6
10^-5
10^-4

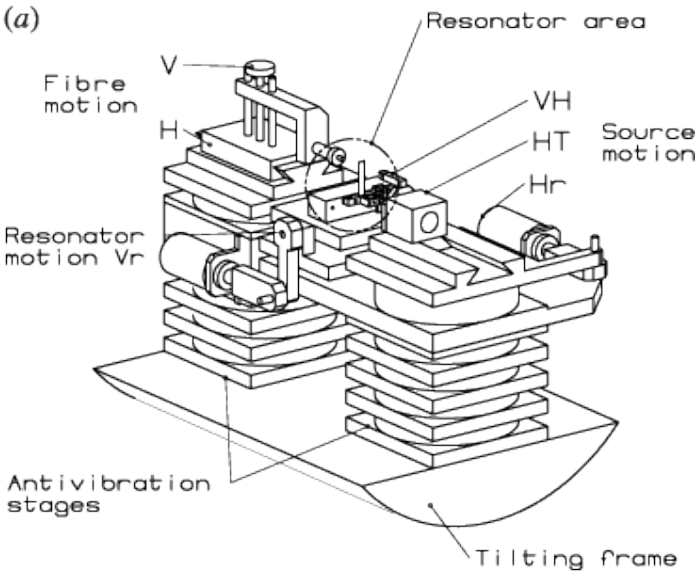
Outlook

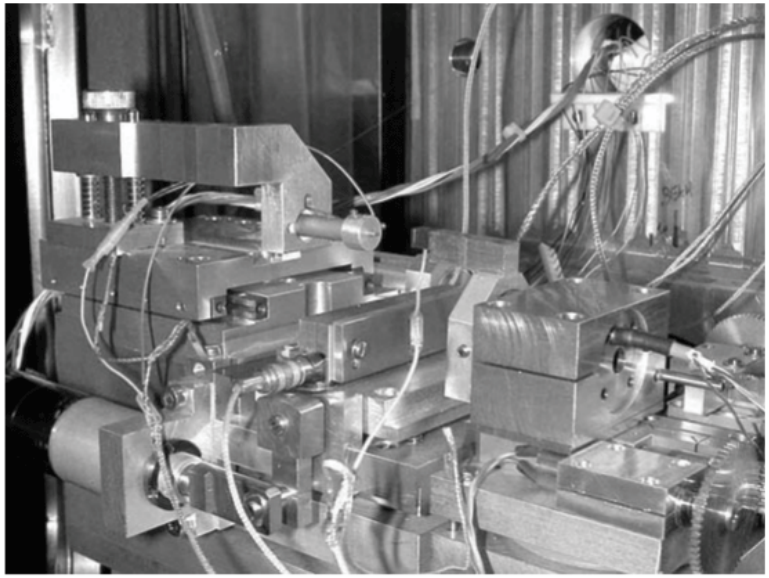
- **New Experiments**
  - ✓ Levitated Microspheres (Geraci)
  - ✓ Micro-cantilever (Long)
  - ✓ Neutrons (Nesvizhevsky, Jenke)
  - ✓ Superconducting Torsion Balance (Chalkley)
  - ✓ Atom Interferometry—FORCA-G (Pelle)
  - ✓ Casimir (Reynaud)

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

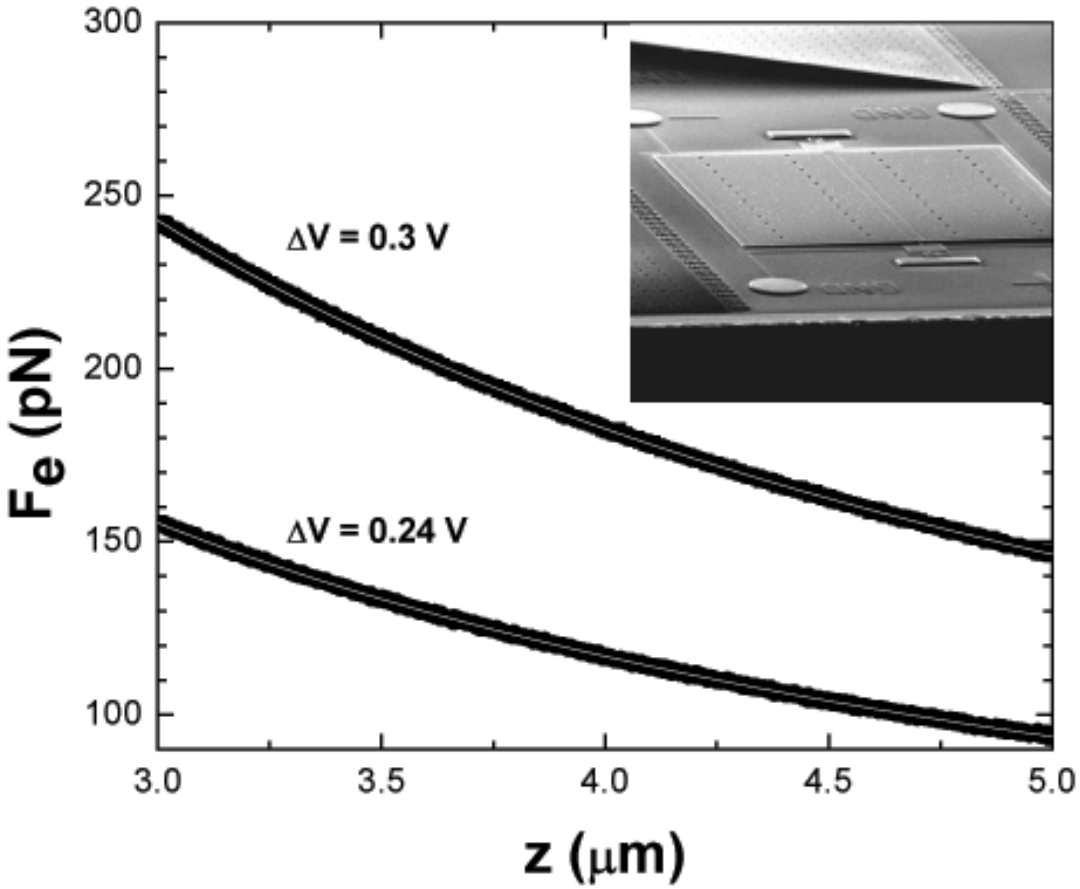
The End

Present:
Padova Short-Distance Experiment

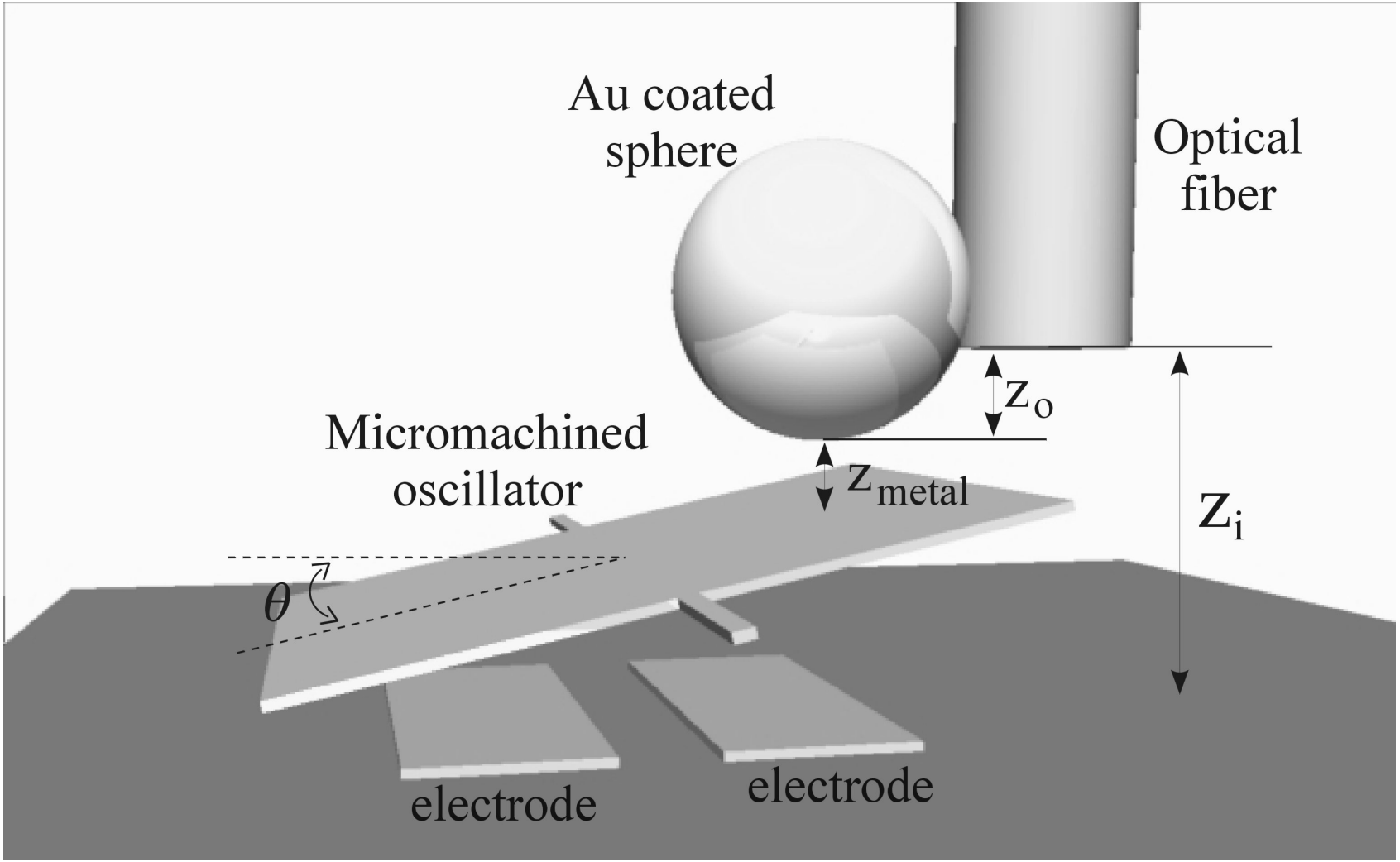




Electrostatic Force Measurements



IUPUI Experiment
(Decca, Lopéz, Fischbach, Krause)



Separation measurement

z_{meas} is determined using a known interaction

z_i, Θ are measured for each position

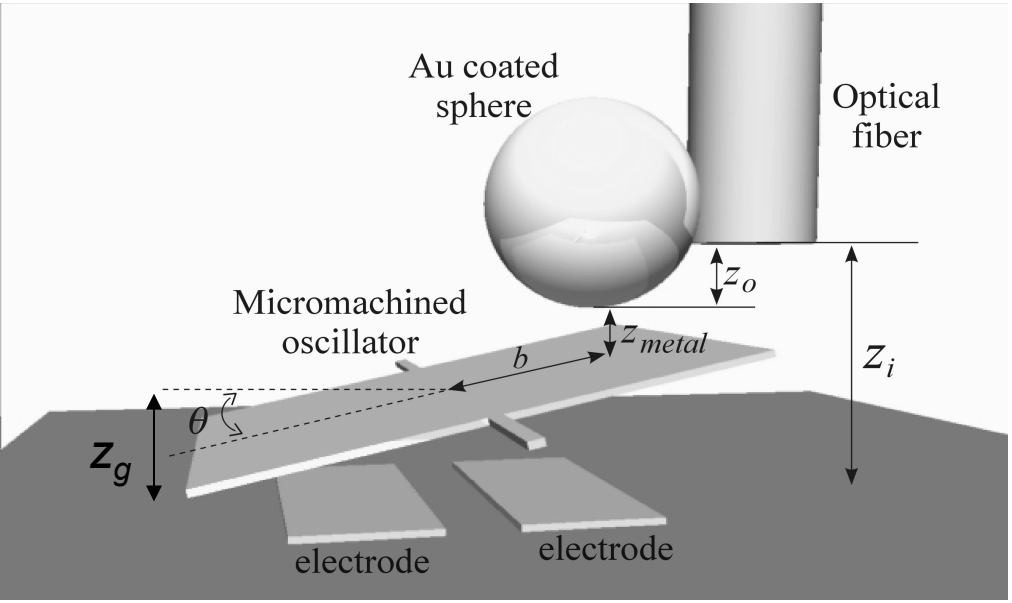
z_g = ~(1500.0 ± 0.1) nm, interferometer

z_i = ~(30000.0 ± 0.2) nm, absolute interferometer

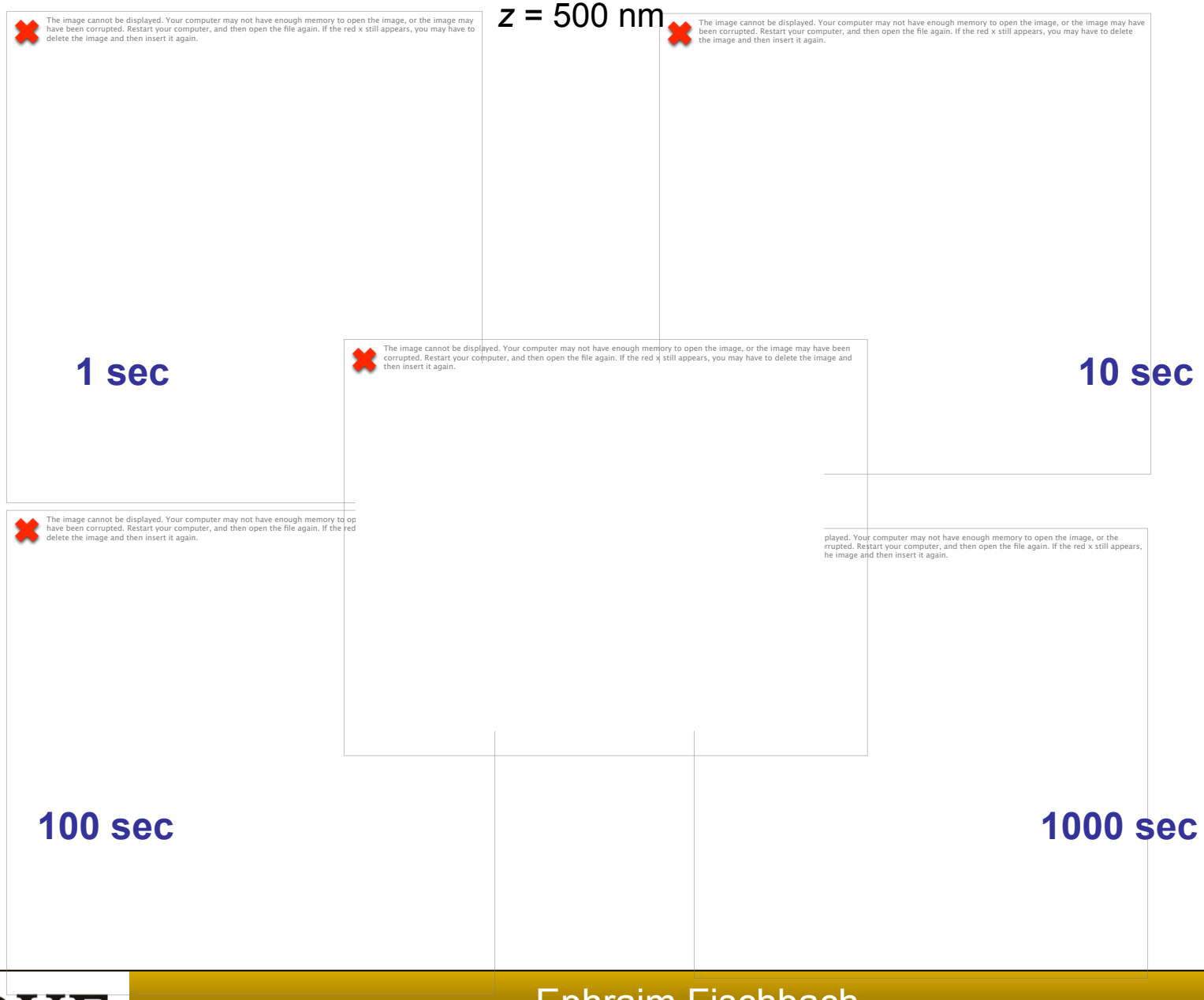
z_o = ~(20000.0 ± 0.5) nm, electrostatic calibration

b = ~(210 ± 3) μm, optical microscope

Θ = ~(1.000 ± 0.001) μrad



z = 500 nm



"Casimir-less" experiments

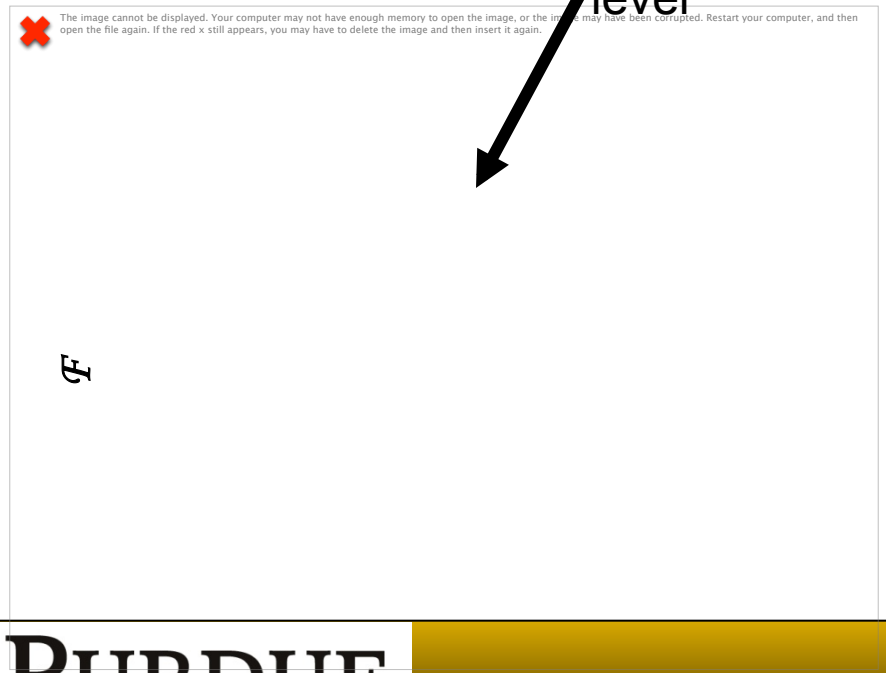
Signal optimization:
Work at w_o!!!

Oscillate plate at f_1, sphere at f_2 such that $f_1 + f_2 = f_o$

$$e^{-z/\lambda} \propto \cos(2\pi f_1 t); \rho_{Au} - \rho_{Ge} \propto \cos(2\pi f_2 t)$$

$$\Delta F_{hyp} \propto \cos(2\pi f_o t)$$

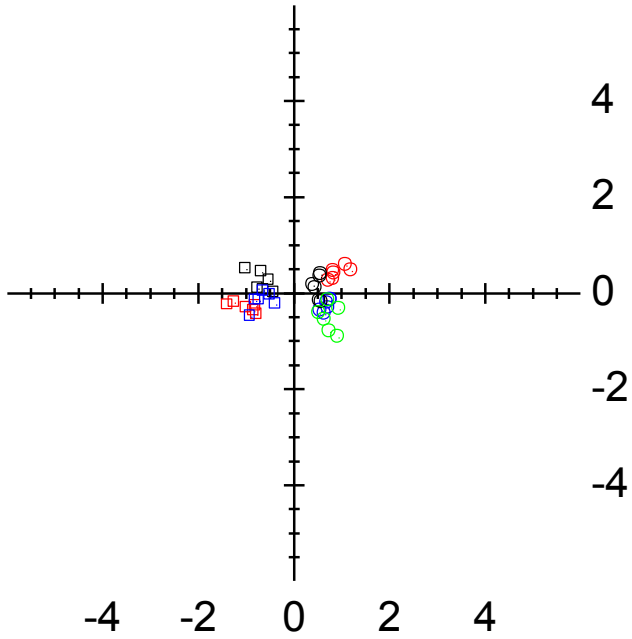
95% confidence level



Net force!

“Casimir-less” experiments

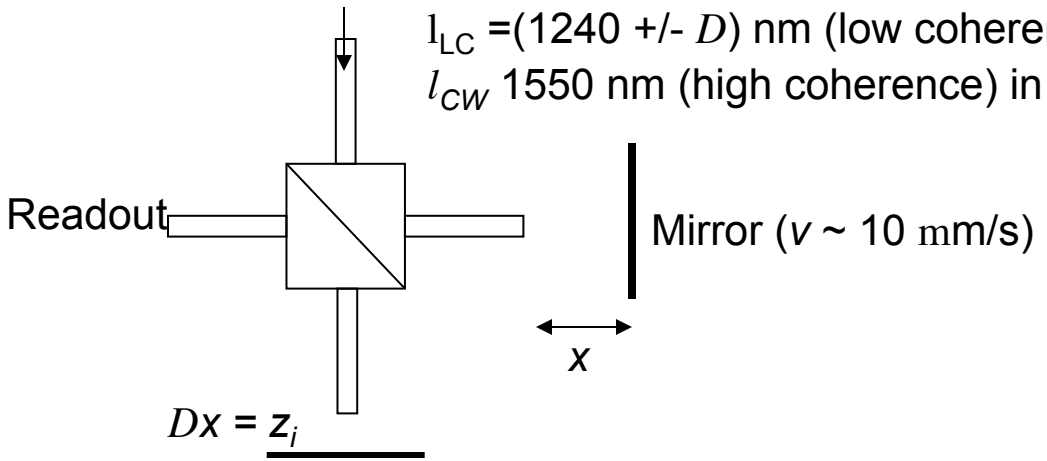
Sanity check: more samples!



Distance measurement

Interferometer (Yang *et al.*, Opt. Lett. **27**, 77 (2005

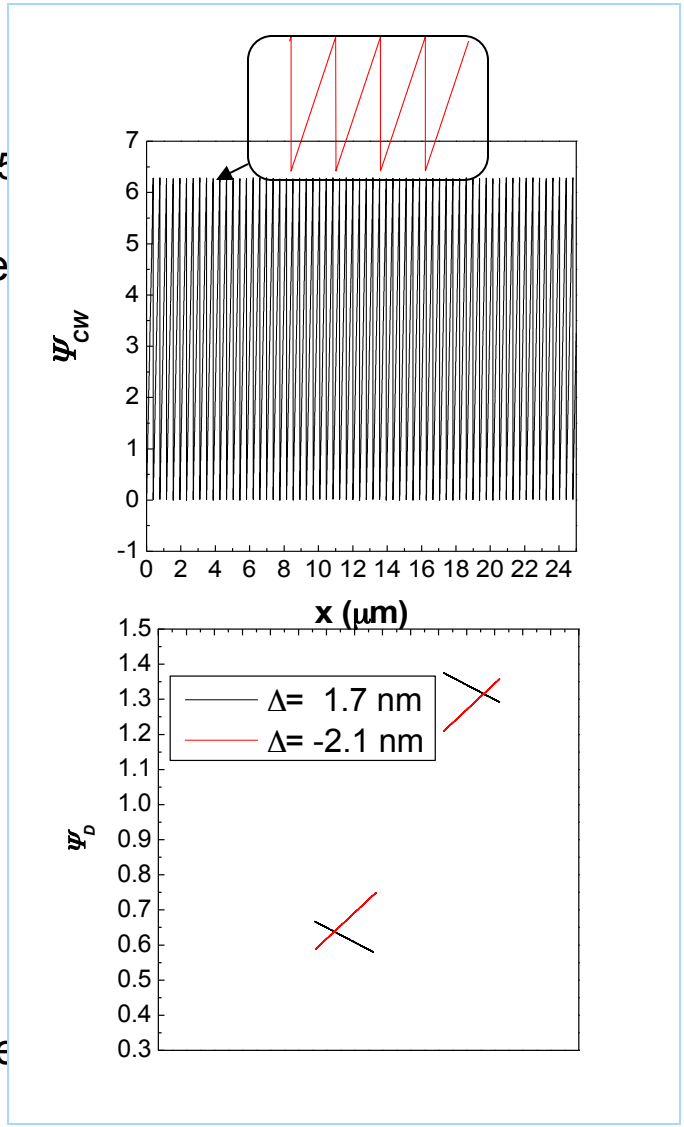
l_{LC} =(1240 +/- D) nm (low coherence
l_{CW} 1550 nm (high coherence) in



$$\psi_D = \psi_{LC} - \tfrac{4}{5}\psi_{CW}$$

$$z_i = \frac{\lambda_{CW}}{4}\left[\mathrm{int}\left(S_{fringe}\right) + S_{phase}\right]$$

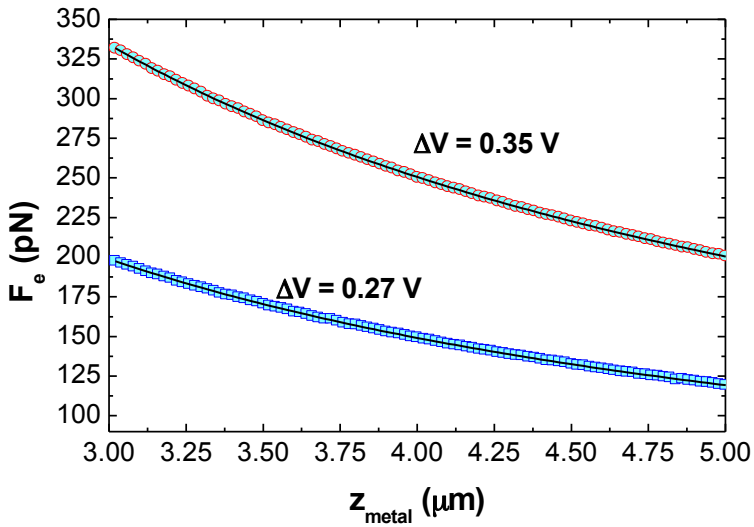
$$S_{phase} = \left(\psi_D(x_1) - \psi_D(x_2)\right)(\mathrm{mod}\, 2\pi)$$

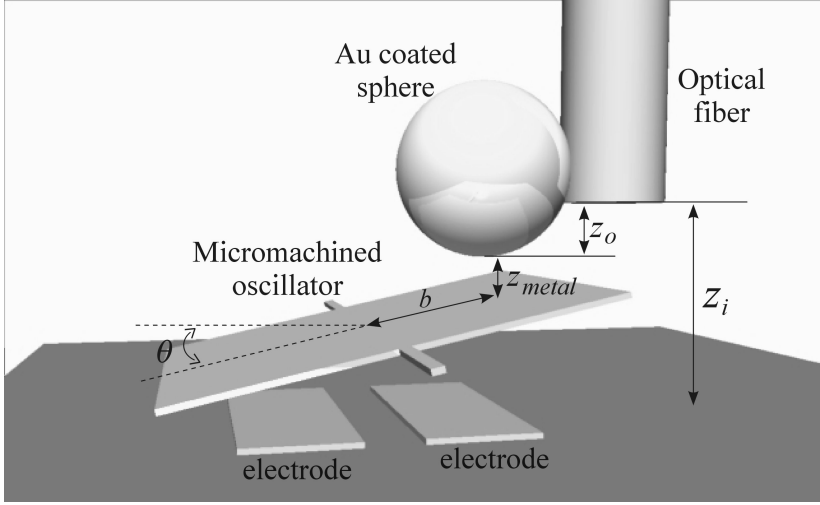


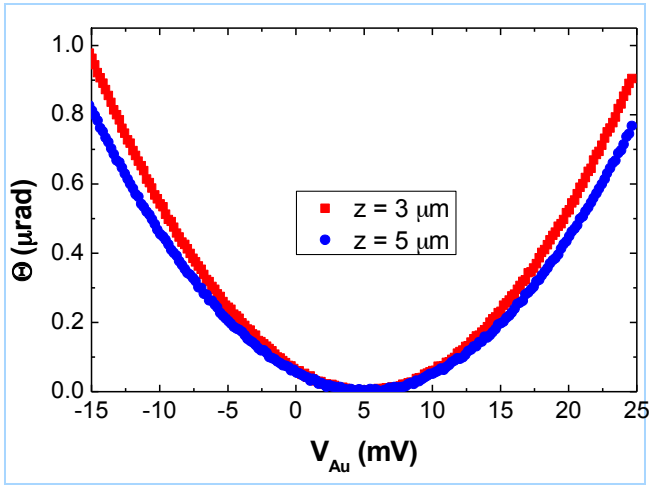
-Phases obtained doing a Hilbert transform of the amplitude
-Changes in D (about 2 nm) give different curves.
Intersections provide Dx
-Quite insensitive to jitter. Only $2DDx'/(l_{CW})^2$
Instead of $2Dx'/l_{CW}$

Separation measurement

Electrostatic force calibration





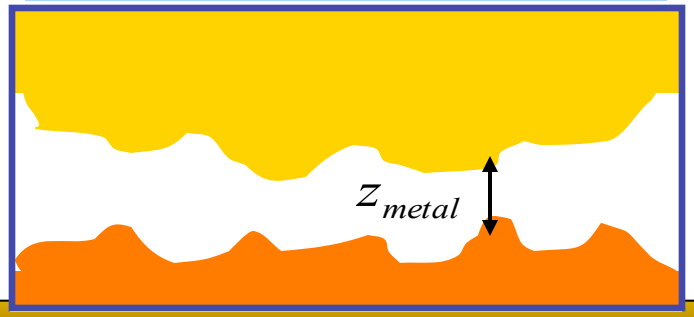


$$F_e = -2\pi\varepsilon_o (V - V_{Au})^2 \sum_n \frac{\coth u - n \coth nu}{\sinh nu} \sim$$

$$-2\pi\varepsilon_o (V - V_{Au})^2 \sum_0^7 A_i \left(\frac{R}{(z_{metal} + \bar{z})} \right)^{1-i}$$

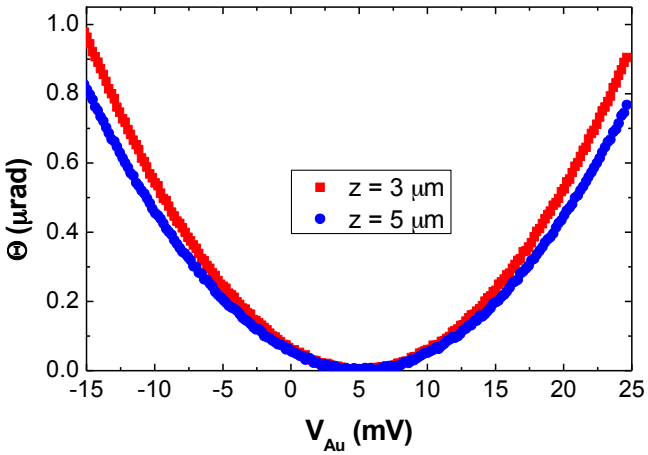
$$u = 1 + \frac{(z_{metal} + \bar{z})}{R}$$

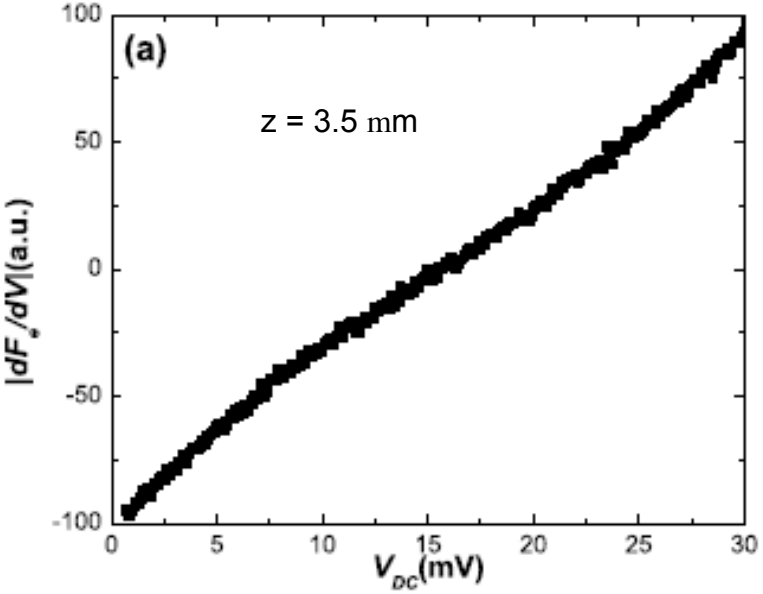
Originally using the whole expression,
lately using the 8 term fit found by Mohideen

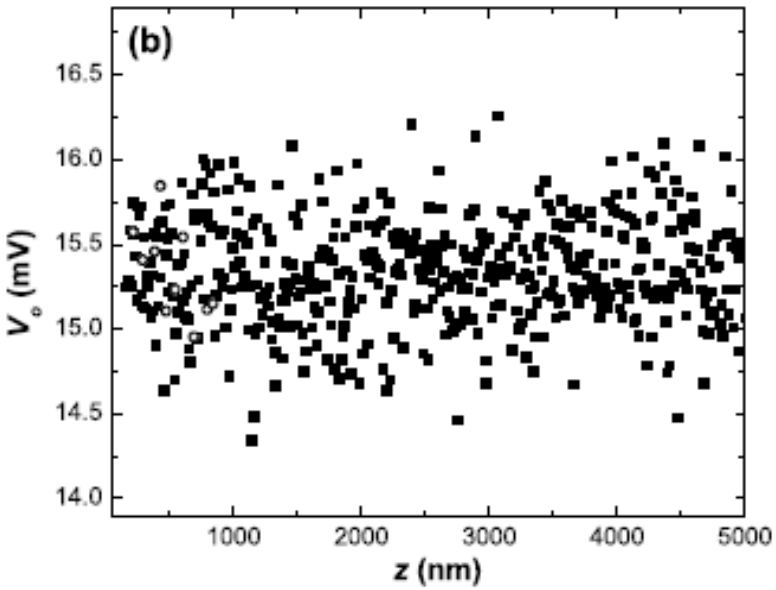


Separation measurement

Electrostatic force calibration







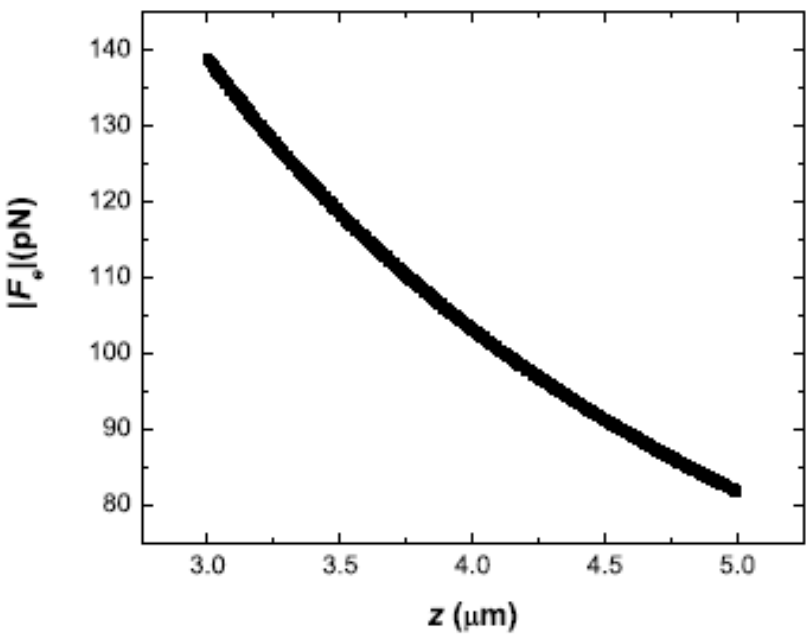
Separation measurement

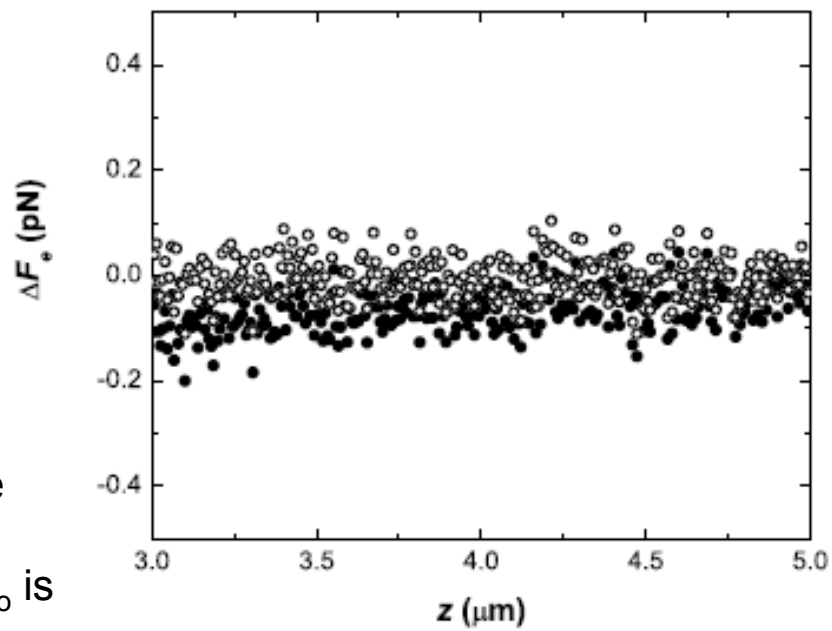
Electrostatic force calibration

$$F_e = -2\pi\varepsilon_o (V - V_{Au})^2 \sum_n \frac{\coth u - n \coth nu}{\sinh nu} \sim$$

$$-2\pi\varepsilon_o (V - V_{Au})^2 \sum_0^7 A_i \left(\frac{R}{(z_{metal} + \bar{z})} \right)^{1-i}$$

$$u = 1 + \frac{(z_{metal} + \bar{z})}{R}$$



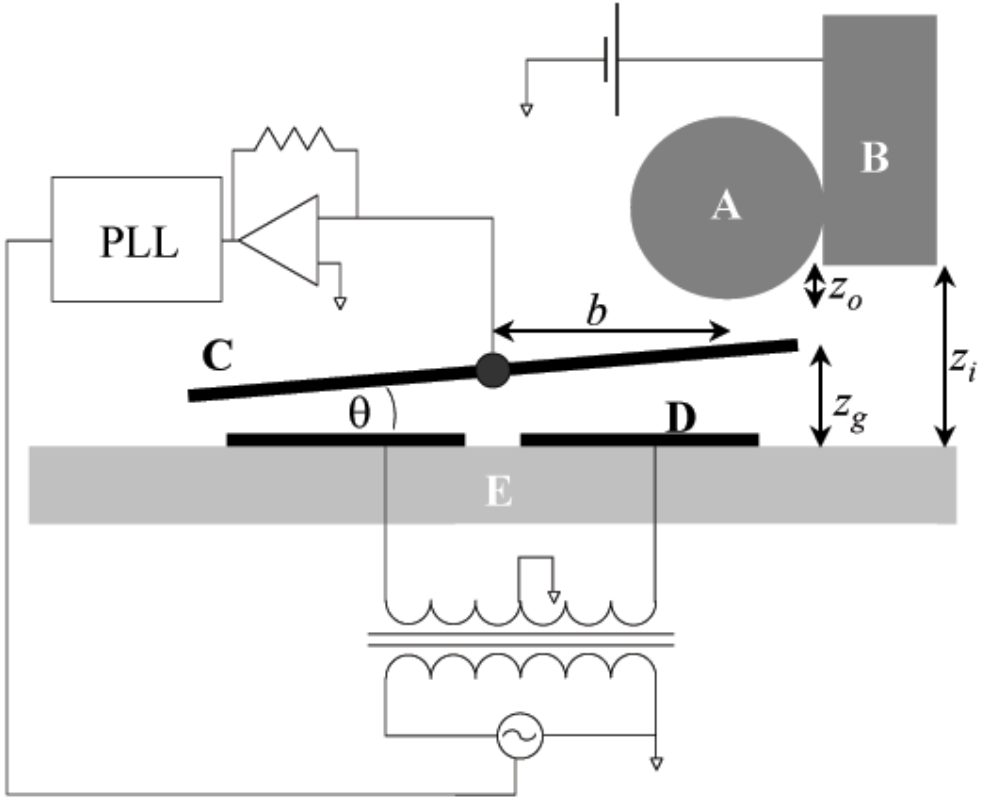


-After measuring the deflection (expressed as force here), we adjust for the unknown separation.

-The figure shows the ΔF_e for the optimal $\bar{z}$ and one off by 1.5 nm

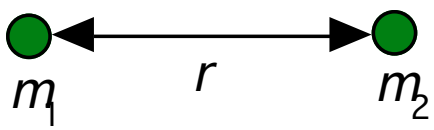
-The error in the force associated with the error in V_o is < 1 fN.

Experimental Setup for Casimir Force Measurement between Dissimilar Materials



Non-Newtonian Gravity

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



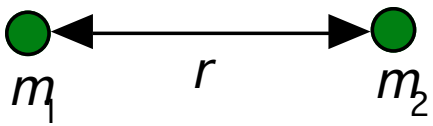
$$F(r) = -\frac{G(r)m_1m_2}{r^2}\hat{r}$$ → doesn't vary as $1/r^2$ *

$$G(r) = G[1 + \alpha_{12}e^{-r/\lambda}(1 + r/\lambda)]$$ → not independent of 1 or 2 *

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

Summary of Newtonian Gravity

$$V(r) = -\frac{Gm_1 m_2}{r}$$



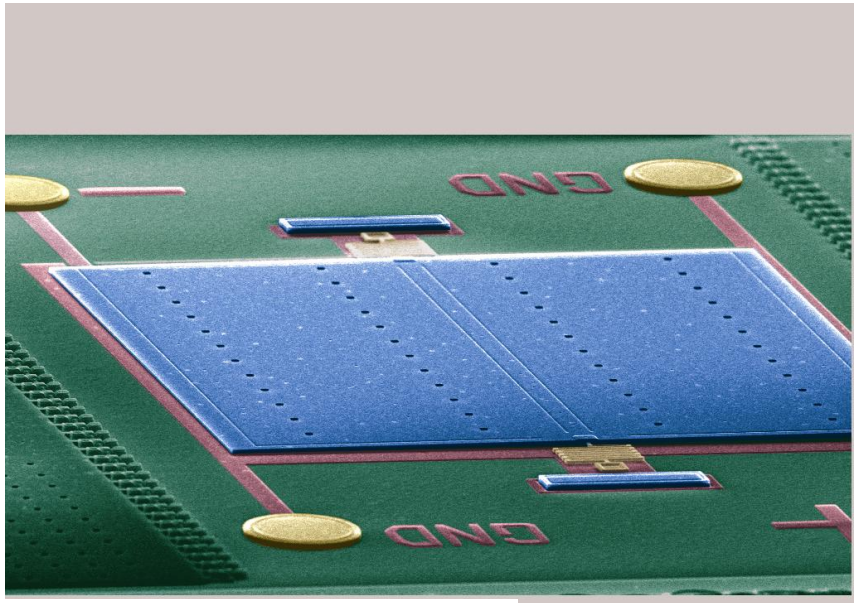
$$\vec{F}(r) = -\frac{G\cancel{m}_1 m_2}{r^2}\hat{r} = \cancel{m}_1 \vec{a}_1$$

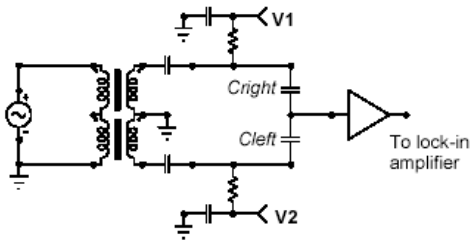
$$\vec{a}_1 = -\frac{Gm_2}{r^2}\hat{r}$$

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

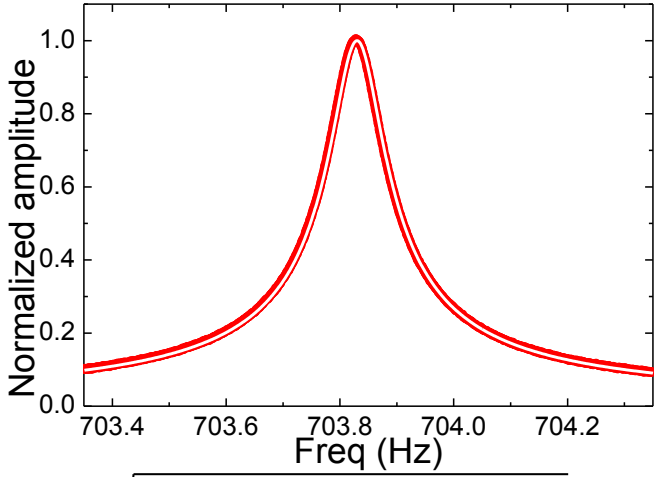
b) varies as $1/r^2$

Experimental setup



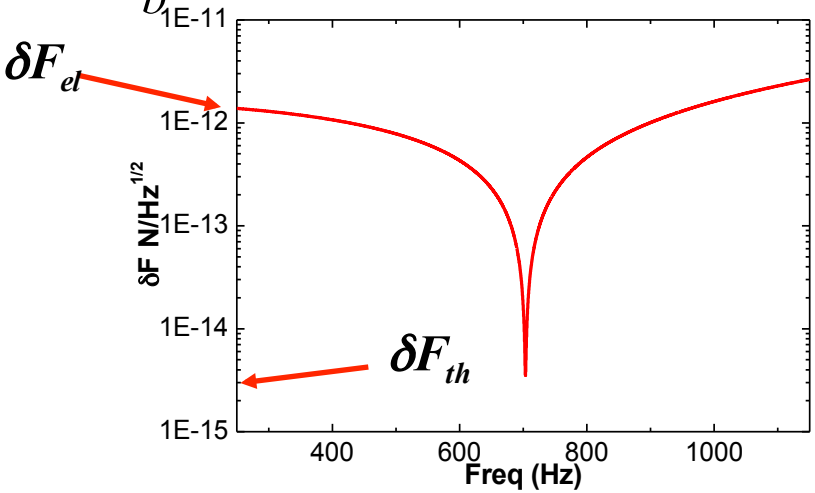


$$\delta\theta \approx 10^{-9}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$$

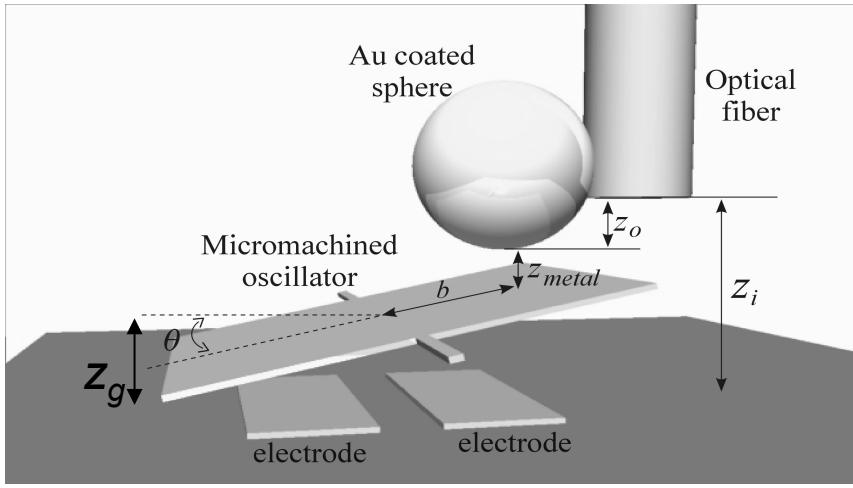


$$\delta F = \frac{1}{b}\sqrt{\left(\frac{4k_B T\kappa}{\omega_o Q}\right) + \left(\frac{\delta\theta_{el}\kappa}{A(\omega)}\right)^2}$$

$$= \frac{1}{b}\sqrt{\delta F_{th}^{\ 2} + \delta F_{el}^{\ 2}}$$

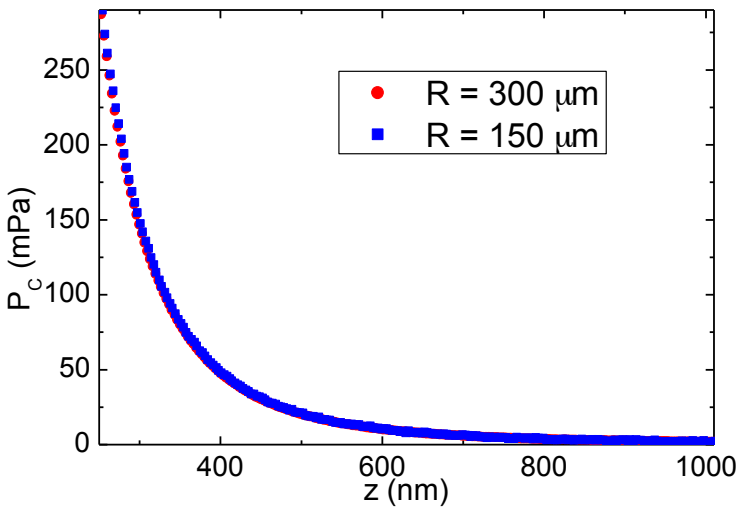


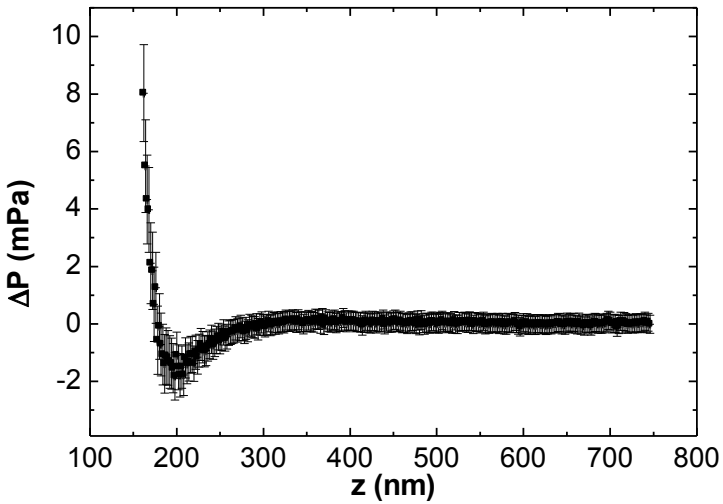
Dynamic measurements



$$\omega_r^2 = \omega_o^2\left(1 - \frac{b^2}{I\omega_o^2}\frac{\partial F_C}{\partial z}\right)$$

$$F_C = 2\pi R \times E_C \Rightarrow \frac{\partial F_C}{\partial z} = 2\pi R \times P_C$$

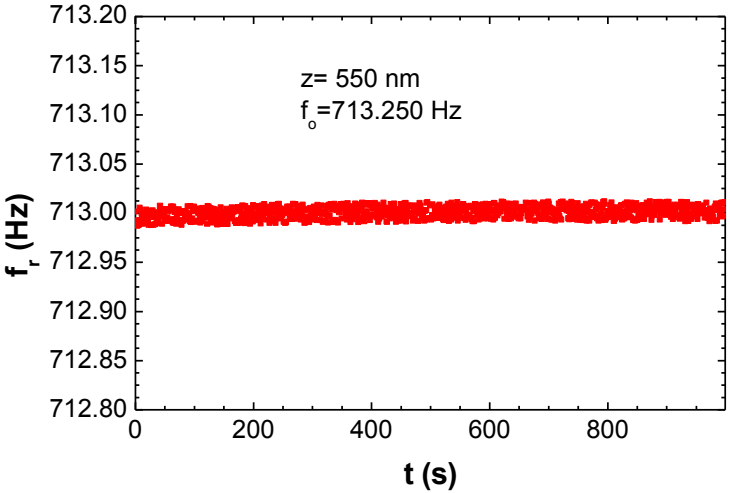


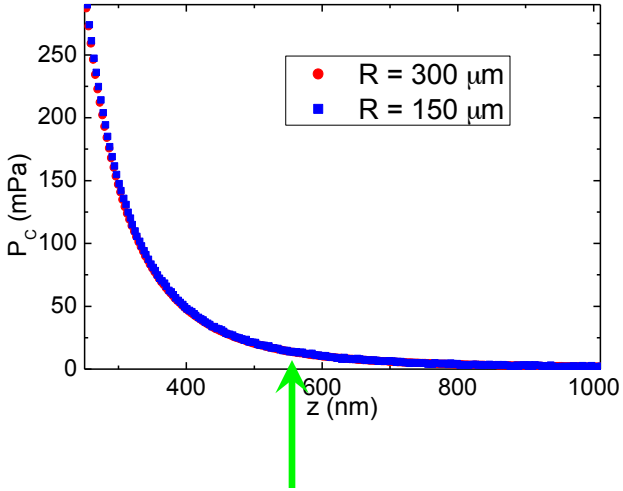


Pressure determination

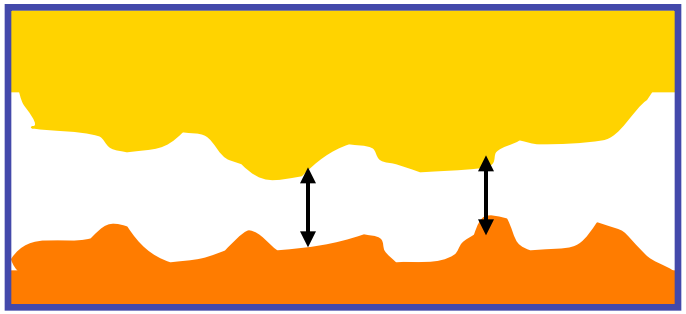
$$\omega_r^2 = \omega_o^2\left(1 - \frac{b^2}{I\omega_o^2}\frac{\partial F_C}{\partial z}\right)$$

$$F_C = 2\pi R \times E_C \Rightarrow \frac{\partial F_C}{\partial z} = 2\pi R \times P_C$$





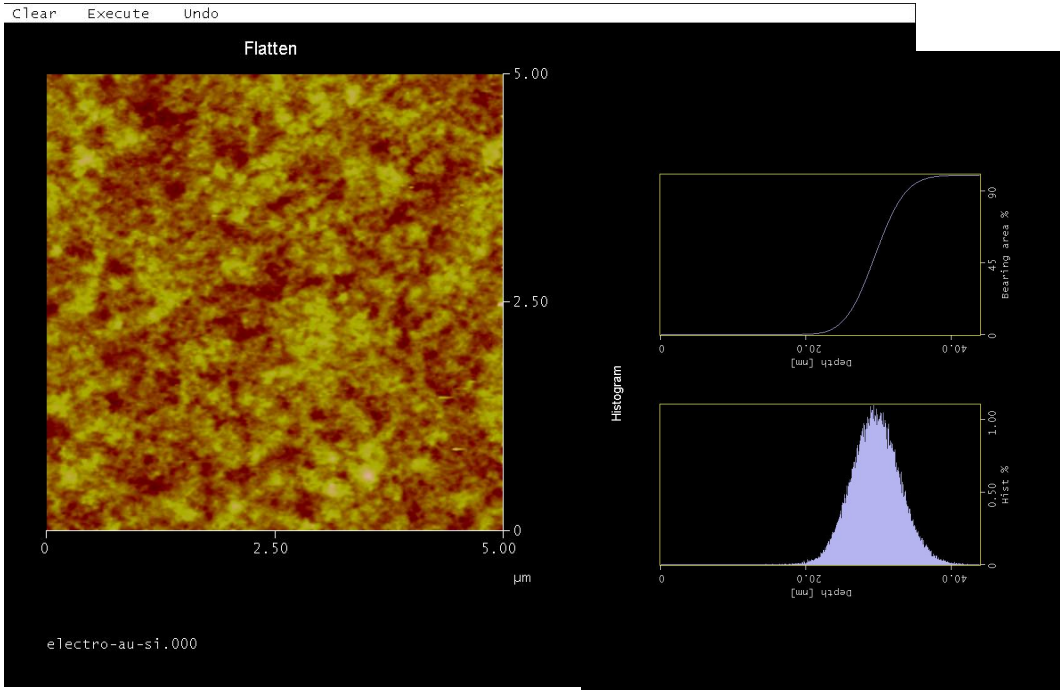
Comparison with theory



$$F_C = \sum_i v_i F_{CS}(z)$$

v_i: Fraction of the sample at separation zi

AFM image of the Au plane

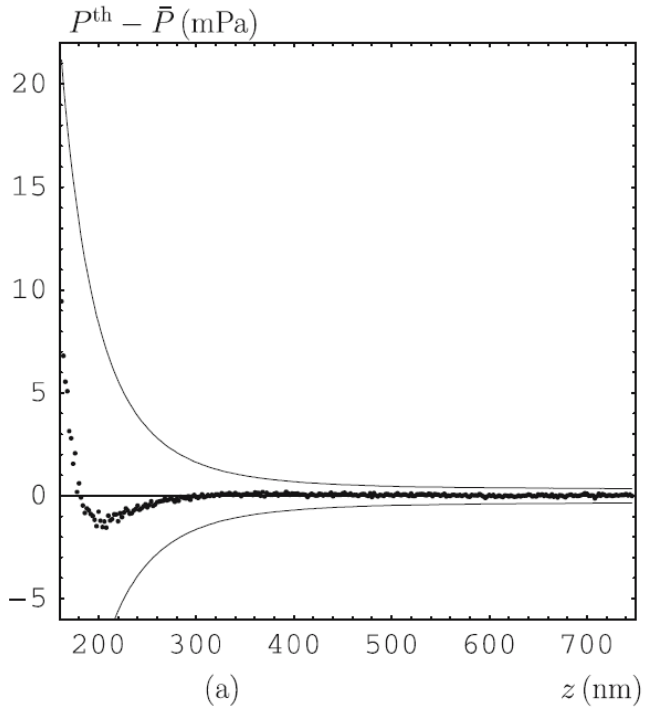


$$F_{CS}(z) = \frac{\square}{2\pi c^2} R \int_0^\infty \xi^2 d\xi \int_1^\infty p \left\{ \ln\left[1 - \frac{(s_1 - p)(s_2 - p)}{(s_1 + p)(s_2 + p)} e^{-2p\xi z/c}\right] + \ln\left[1 - \frac{(s_1 - \varepsilon_1 p)(s_2 - \varepsilon_1 p)}{(s_1 + \varepsilon_2 p)(s_2 + \varepsilon_2 p)} e^{-2p\xi z/c}\right] \right\} dp$$

$$F_C = \sum_i v_i F_{CS}(z)$$

$$s_i = \sqrt{\varepsilon_i - 1 + p^2}$$

Comparison with theory



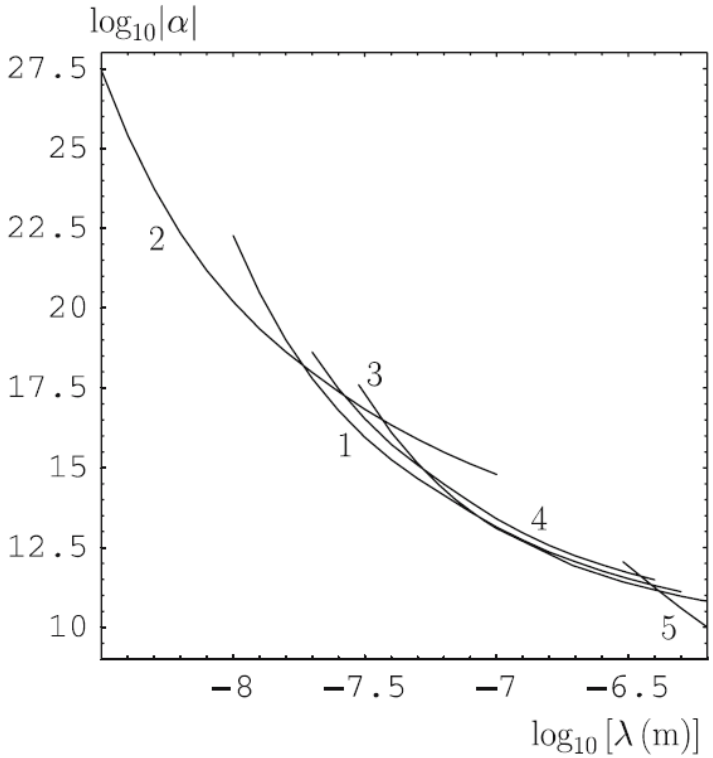
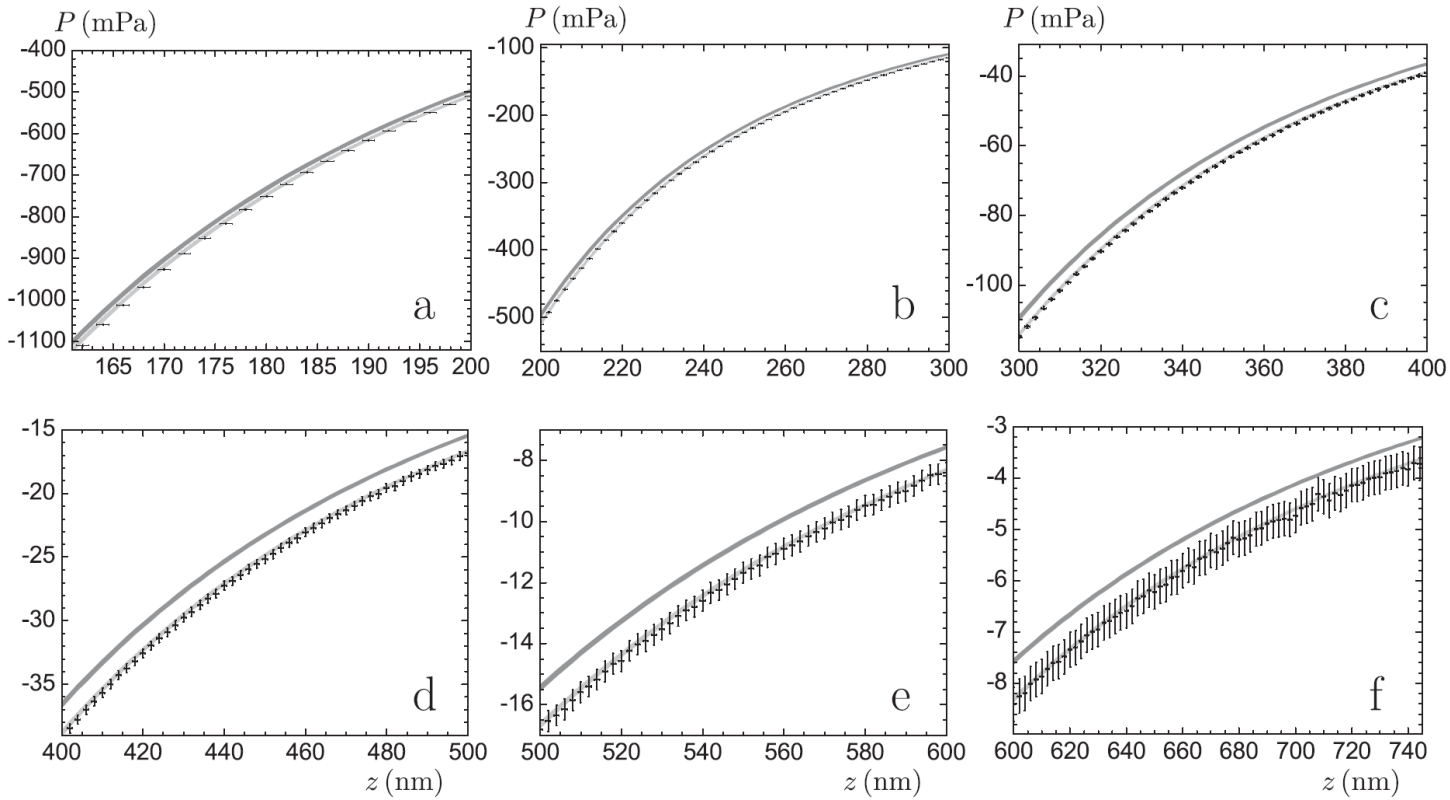


Fig. 4. Differences between theoretical Casimir pressures computed using the generalized plasma model approach (**a**) and the Leontovich surface impedance approach (**b**) and mean experimental Casimir pressures (*dots*) versus separation. *Solid lines* indicate the limits of the 95% confidence intervals

Comparison with theory

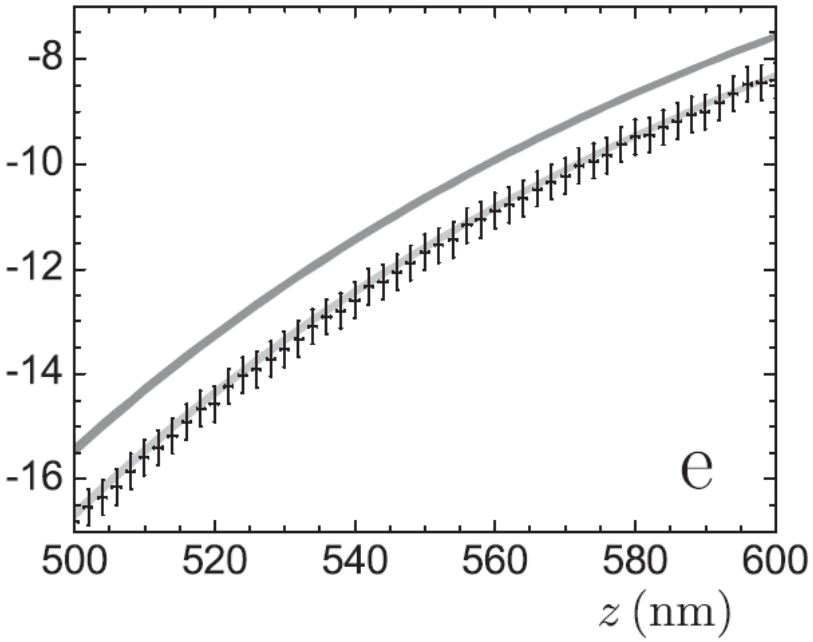
PRD **75**, 077101



-Dark grey, Drude model approach
-Light grey, Leontovich impedance approach

Comparison with theory

PRD **75**, 077101



There is a significant issue: Drude does not agree with the data
-Experimental problem?
-Theoretical problem?
-Theory not applied to the right experiment?

Theoretical errors:
-Sample dependence: 0.5%
-Separation dependence: 1.5% (162 nm)
0.32%(750 nm)

-Dark grey, Drude model approach
-Light grey, impedance approach

~19 mPa @162 nm (Exp: ~2.5 mPa @162 nm)

"Casimir-less" experiments

$$\Delta F_{hyp} = -4\pi^2 G\alpha\lambda^3 e^{-z/\lambda} R K_s K_p$$

$$K_s = \left[\rho_{Au} - (\rho_{Au} - \rho_{Cr}) e^{-d^s_{Au}/\lambda} - (\rho_{Cr} - \rho_s) e^{-(d^s_{Au} + d_{Cr})/\lambda}\right]$$

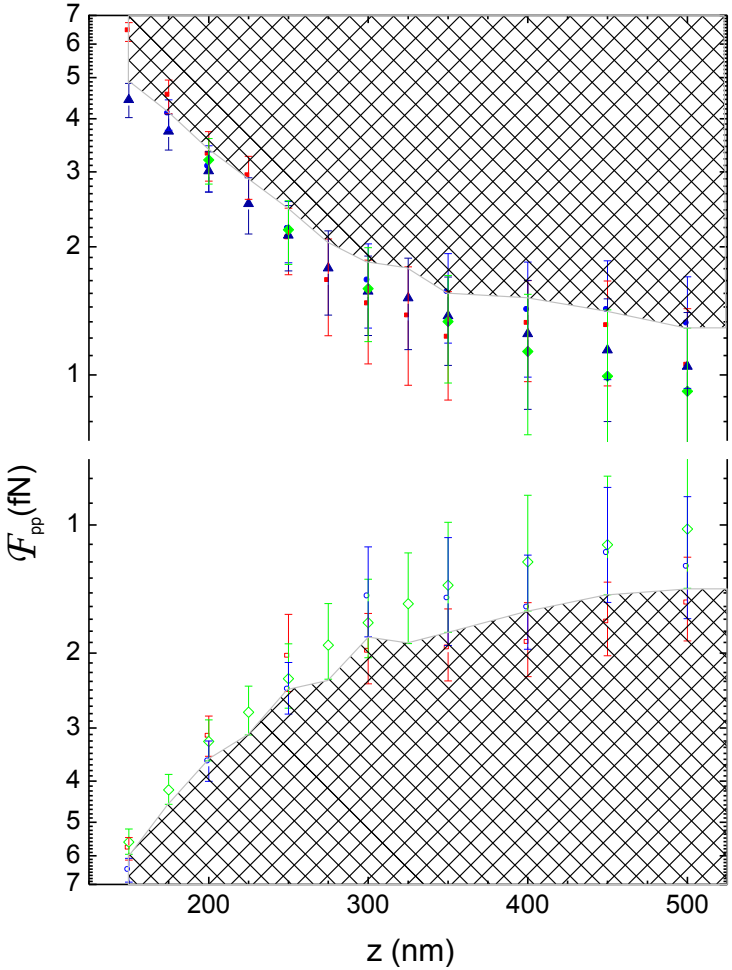
$$K_p = \left[(\rho_{Au} - \rho_{Ge}) e^{-(d^p_{Au} + d_{Pt})/\lambda} \left(1 - e^{-(d_{Ge})/\lambda}\right)\right]$$

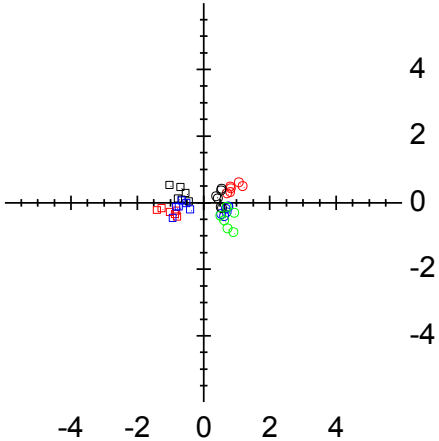
Signal optimization:
Work at w_o!!!

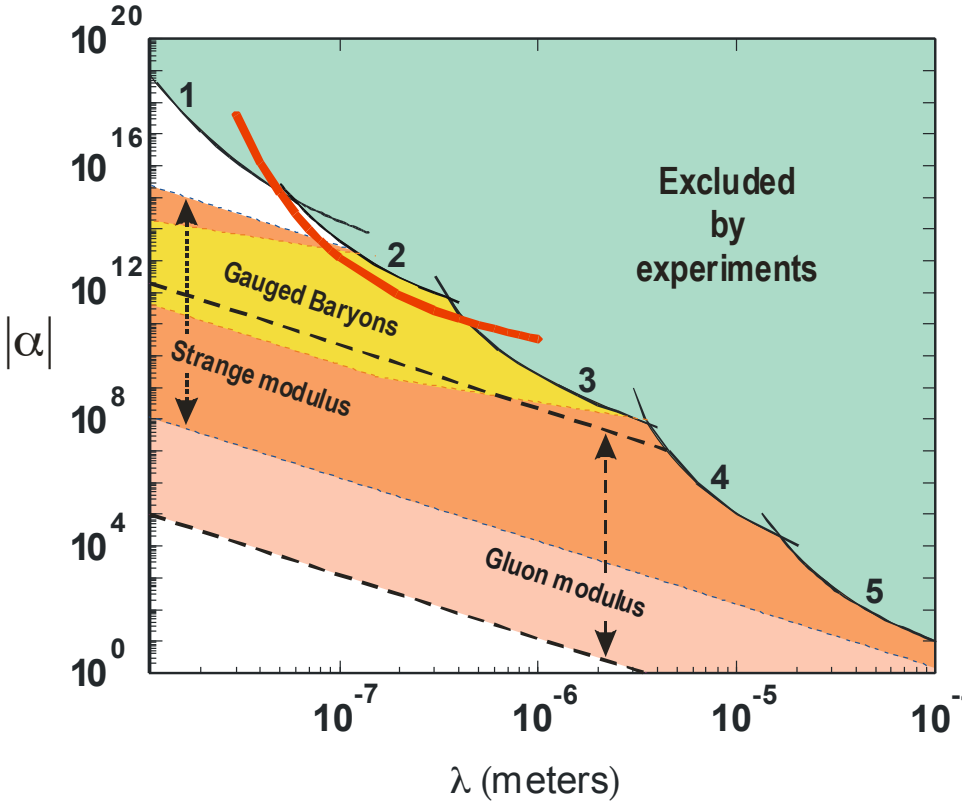
Heterodyne
Oscillate plate at f_1, sphere at f_2
such that $f_1 + f_2 = f_o$

$$e^{-z/\lambda} \propto \cos(2\pi f_1 t); \rho_{Au} - \rho_{Ge} \propto \cos(2\pi f_2 t)$$

$$\Delta F_{hyp} \propto \cos(2\pi f_o t)$$


$\mathcal{F}_{pp}$ (fN)
z (nm)

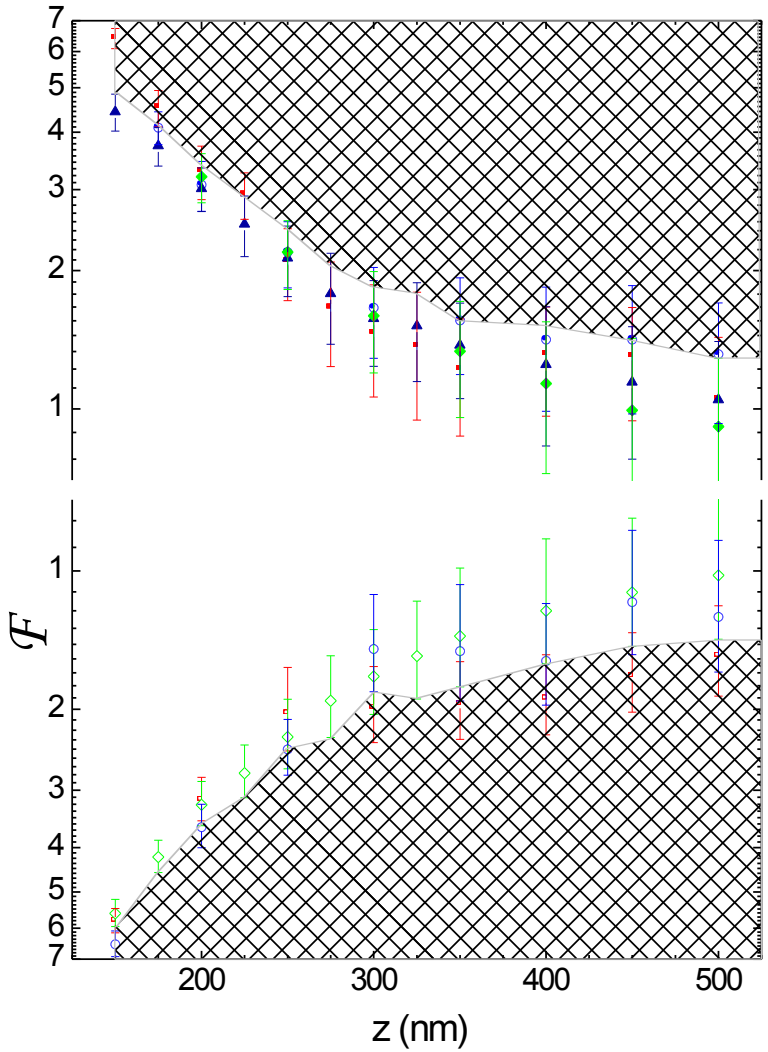


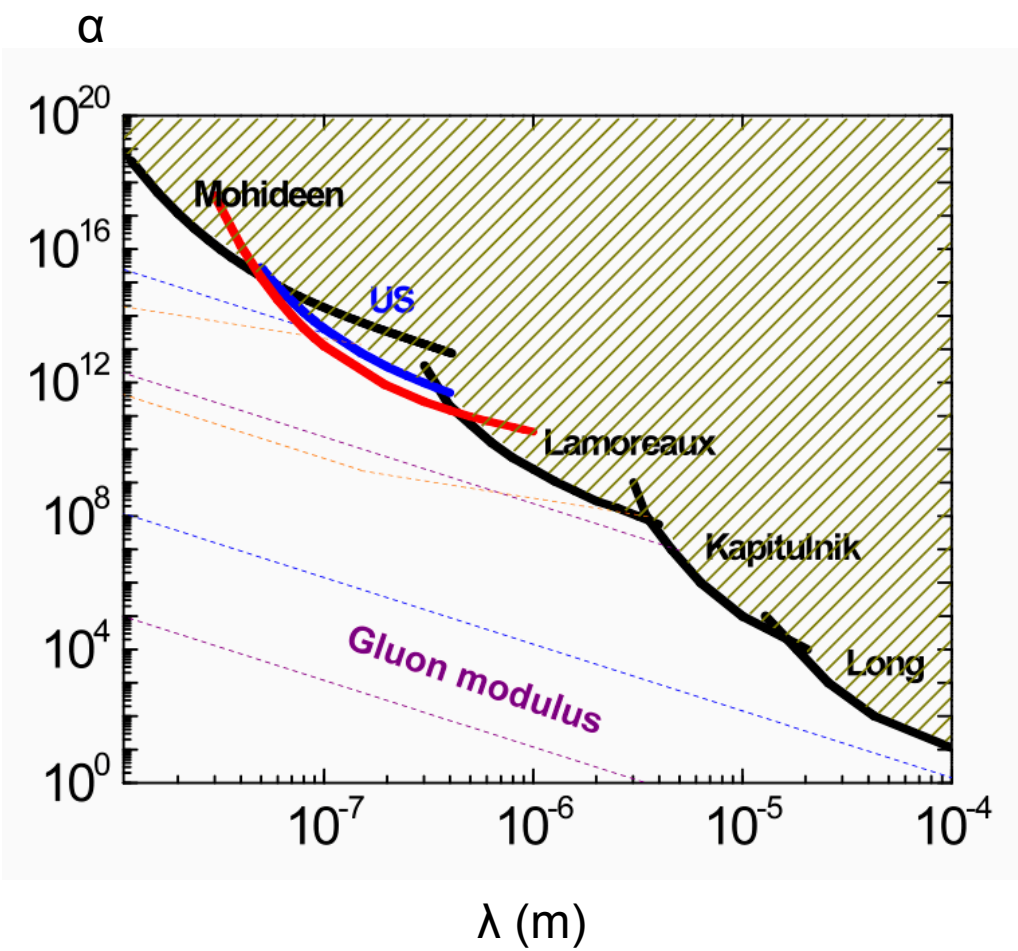

Excluded by experiments
Gauged Baryons
Strange modulus
Gluon modulus
|α|
λ (meters)

Conclusions

- **Most sensitive measurements** of the Casimir Force and Casimir Pressure
- **Unprecedented agreement with theory**
- **First realization** of a **"Casimir-less"** experiment
- **Improvement** of about **three orders of magnitude** in Yukawa-like hypothetical forces

"Casimirless" Capped 2-Material Experiment: Results





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