Universality of Free Fall and General Relativity

(The Eötvös-Pekár-Fekete experiments and their lasting effects)

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Topics to be covered

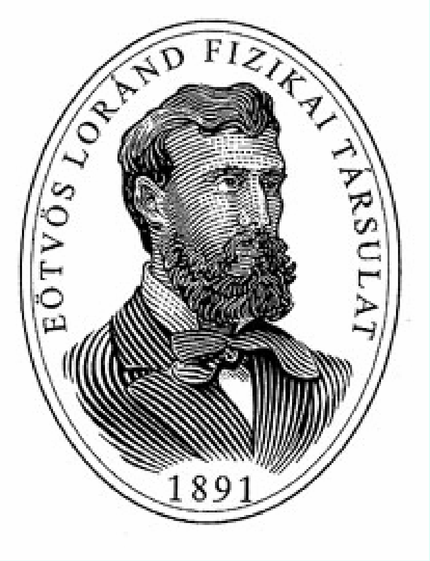
- Loránd (Roland) Eötvös and his innovative gravity research
- Universality of Free Fall (UFF), Equivalence Principles (EP)
- Einstein's „belated proposal" for Eötvös-type experiments
- Renewed interest in gravity experiments in the early 60's
- Fischbach's Fifth Force, and reinterpreted EPF experiments
- Composition- and modified distance-dependence of gravity?
- Exotic matter, exotic gravity laws, and the validity of the EP
- Eöt-Wash group in Seattle, recent and planned experiments

1907,
a memorable year for Eötvös
and for gravity research

What happened 100 years ago?

1. A large annual government grant was donated to the Experimental Physics Department of Budapest University that allowed Eötvös to extend his gravity research both in laboratory and in geophysical applications. Instrumentation built from that grant served as the basis for today's Eötvös Loránd Geophysical Institute.
2. Eötvös and his assistants, D. Pekár and J. Fekete started a new series of experiments on the proportionality of inertial and gravitational masses (or UFF). Their work was awarded the Beneke prize of Göttingen University in 1909.
3. Albert Einstein formulated his Equivalence Principle that served as the foundation of GR. He considered it later as his „happiest thought" (or rather: „der glücklichste Gedanke meines Lebens").

Emblems of the Hungarian Geophysical Institute
(celebrating its centenary)
and of the Physical and Geophysical Societies,
all named after Eötvös.



Centenary exhibition
of the Geophysical
Institute (ELGI), with
several instruments
of the Eötvös era
on display.

Loránd Eötvös (1848-1919), as president of the Hungarian Academy (1889-1905), and in his office, after the EPF experiments

Karl Runge (1856-1927)

It was Karl Runge (University of Göttingen) who was in charge of the Beneke Foundation that offered a prize for new tests on the UFF, taking into account recent progress in various fields of physics.

Runge was the head of the first applied mathematics department in the world. He studied spectral lines, numerical methods, and was a good friend and co-worker of Max Planck, and thesis adviser of Max Born.

Early work of Eötvös
on capillarity and on gravity

Some important instruments and results of Eötvös before the EPF experiments of 1907 to 1908

• 1886: the Eötvös-law on capillarity was published after a long, careful study of surface tension under controlled conditions. Early work of Einstein was also influenced by those results.

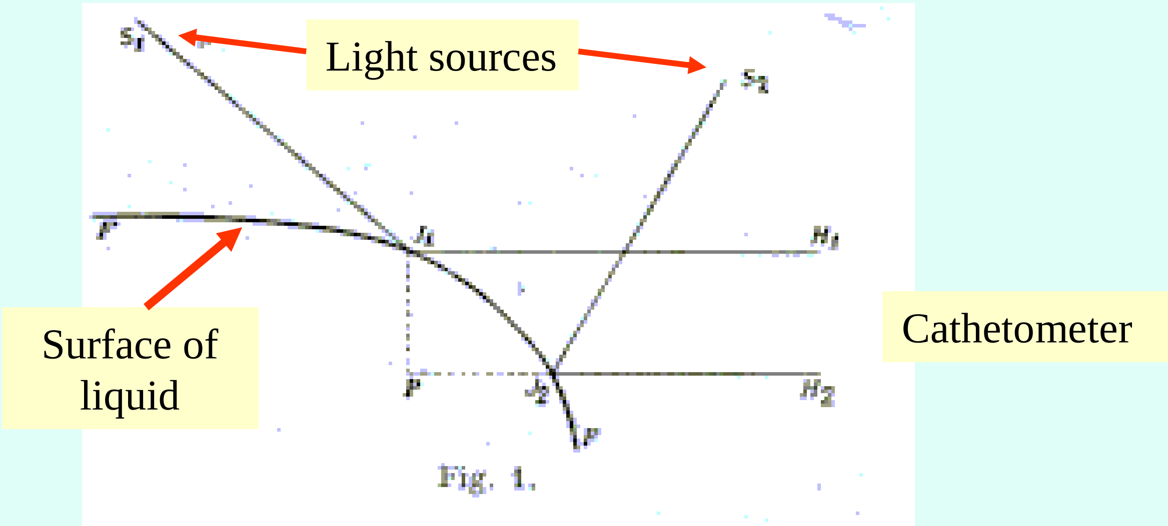
• 1887 to 1890: preparatory work with torsion balances, both in the lab and outdoors. Tested UFF with 400 times better precision than Bessel for various pairs of substances, measured the slope of his garden, effects of walls in lab, and the mass of Gellért Hill.

•1891 to 1906: Measured G in lab, gravity anomalies on an old volcanic cone, on the ice of lake Balaton, and both gravity and magnetic anomalies on various terrains. Costructed new devices.

Common features of capillary and gravitational studies by Eötvös

Very precise analysis of the local properties (e.g. curvature) of a surface. In capillarity, he was able to establish very general laws of temperature dependence.

He started to study gravity possibly in connection with the shape of the Earth, best defined by an equipotential surface fitted to the level of oceans, and continued as virtual „sea level" to the continents. He measured very local features of that surface.

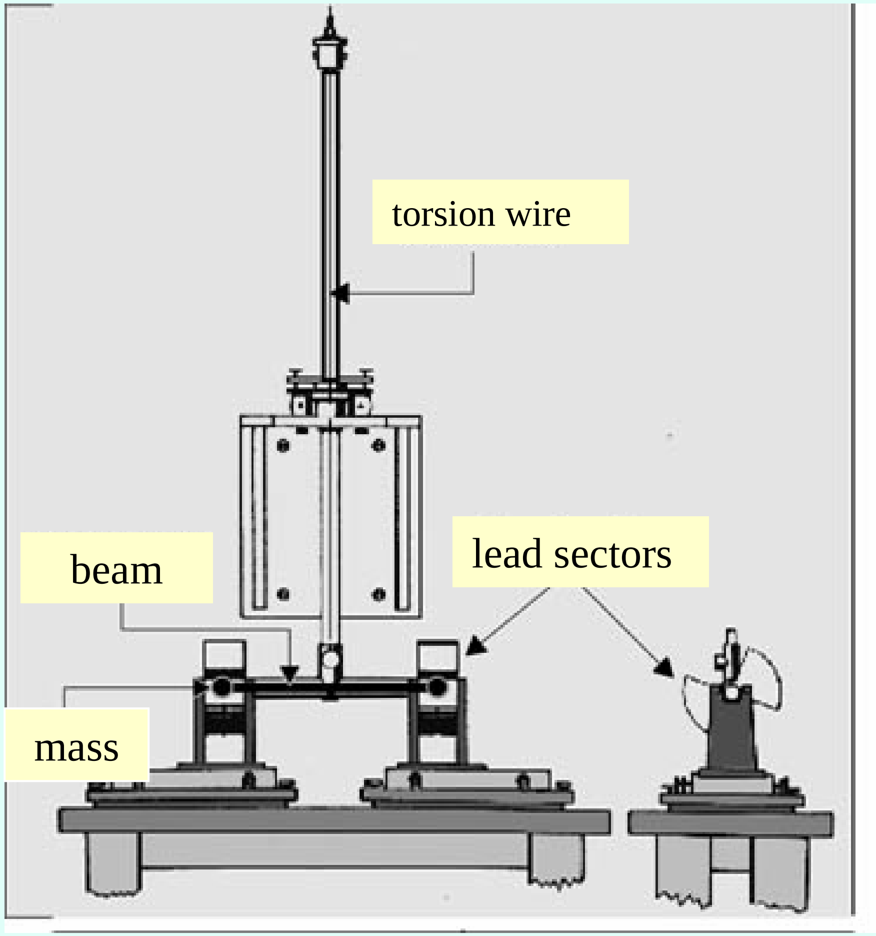


Reflection method of capillary measurements of Eötvös

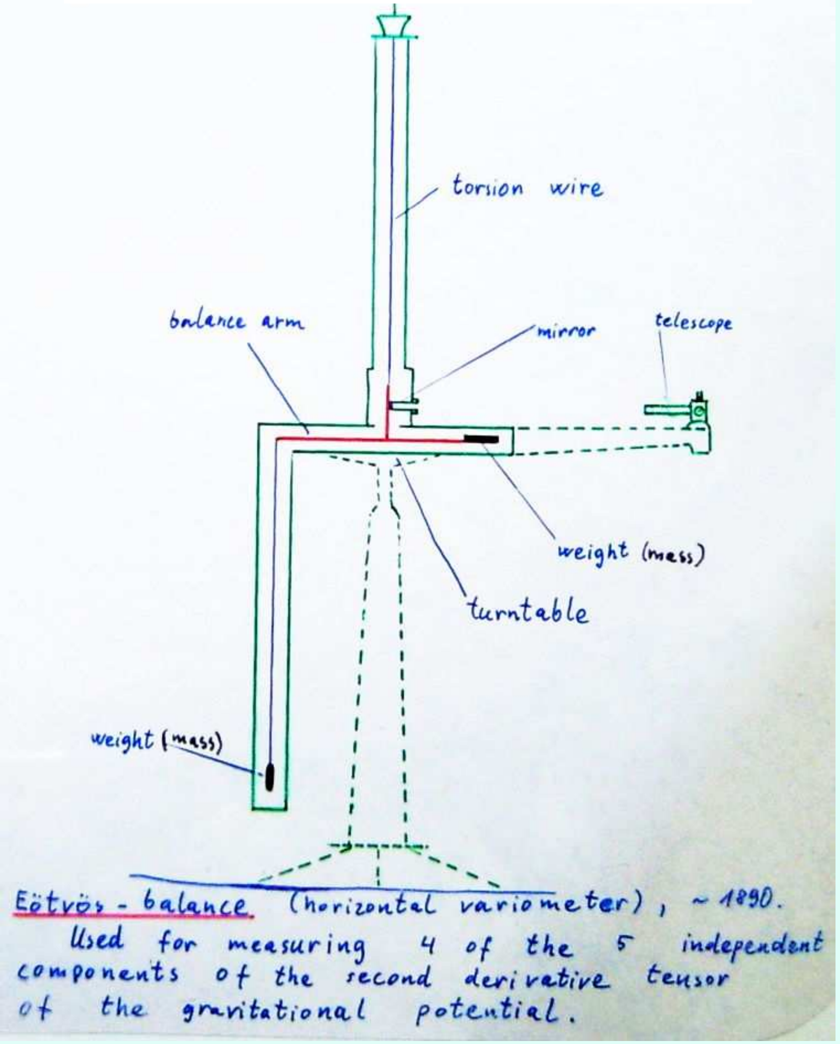
Eötvös law (or rule) for capillarity:

The rate of change of molar surface energy with temperature is a constant for all liquids. That constant is as fundamental for liquids as the universal gas constant is for gases.

Enhancement of the sensitivity of a „curvature variometer" by rotatable lead sectors



Eötvös balance (or pendulum)



Horizontal variometer of Eötvös, now usually called Eötvös balance.

By this instrument he could measure 4 of the 5 independent second derivatives of the local gravitational potential on the surface of Earth.

For measuring very local variations in gravity, both test masses were made of platinum.

For checks on UFF, one of the two test masses was made of some other material.

Eötvös measured G by a torsion pendulum between two brick walls. He used the different oscillation periods of parallel and perpendicular rods.

Box 4. Gravitational Attraction Experiments: The Newtonian Constant of Gravitation

One of the oldest fundamental constants is the Newtonian constant of gravitation G, which gives the strength of the gravitational force of attraction between any two objects according to the familiar formula

$$F = G\frac{m_1 m_2}{r^2},$$

where m_1 and m_2 are the masses of the two objects and r is the distance between them (assumed to be large compared to their extent). In effect measured by Henry Cavendish in 1798, this constant has shown resistance to improvement over the years. In fact, it is the only constant whose recommended value in the 1998 adjustment has a larger uncertainty than its recommended value in the prior 1986 adjustment. The reason for the increased uncertainty is that after the 1986 value was recommended, a new, highly credible experiment reported a value for G that disagreed significantly with the recommended value.[10] Furthermore, a small, but previously unknown, anharmonicity was found in the suspension of torsion balances, such as the one used in the experiment on which the 1986 value was based. These facts suggested that the gravity experiments were not understood as well as was believed. Thus, the 1986 value was retained as the 1998 recommended value, but its uncertainty was increased by about a factor of 12 to recognize these issues and to alert users to the problem. As a result of these considerations, the 1998 recommended value is

$$G = 6.673(10) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}.$$

Recently, a precise result of a new experiment that is in relatively good agreement (within two standard deviations) with the 1986 recommended value has been reported[11] (see PHYSICS TODAY, July 2000, page 21).

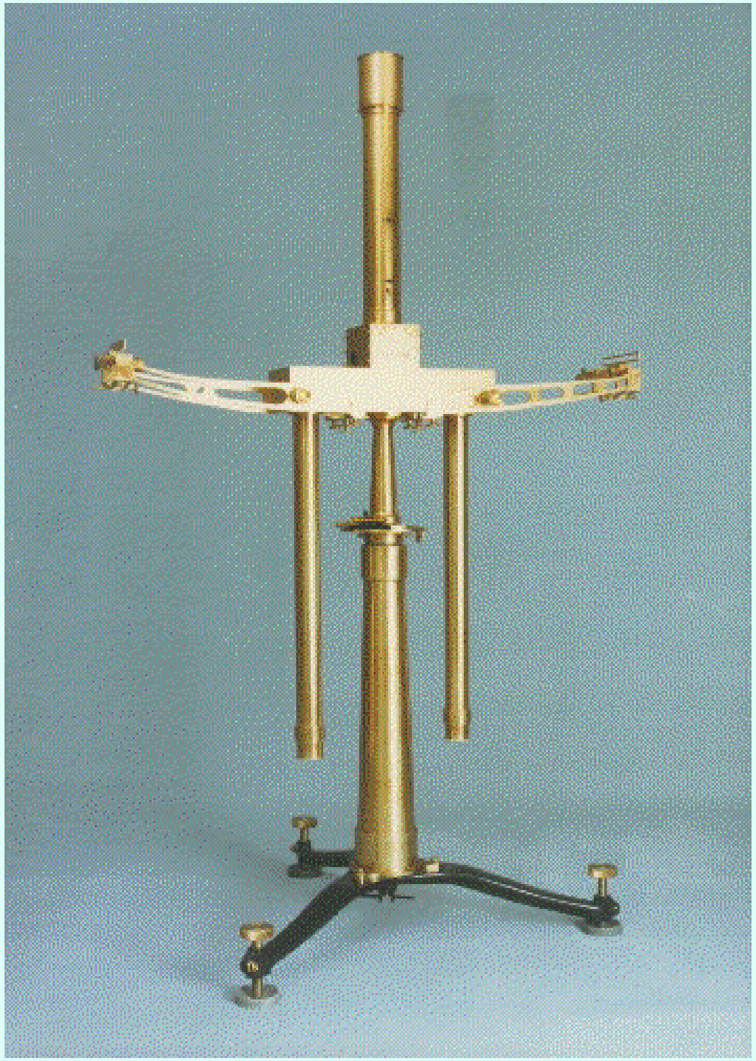
Eötvös's results in 1896: $G = 6.650\ (138) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$

Double Eötvös balance:

A combination of two simple Eötvös balances.

For outdoors measurements, it allowed to cover one site in a single night.

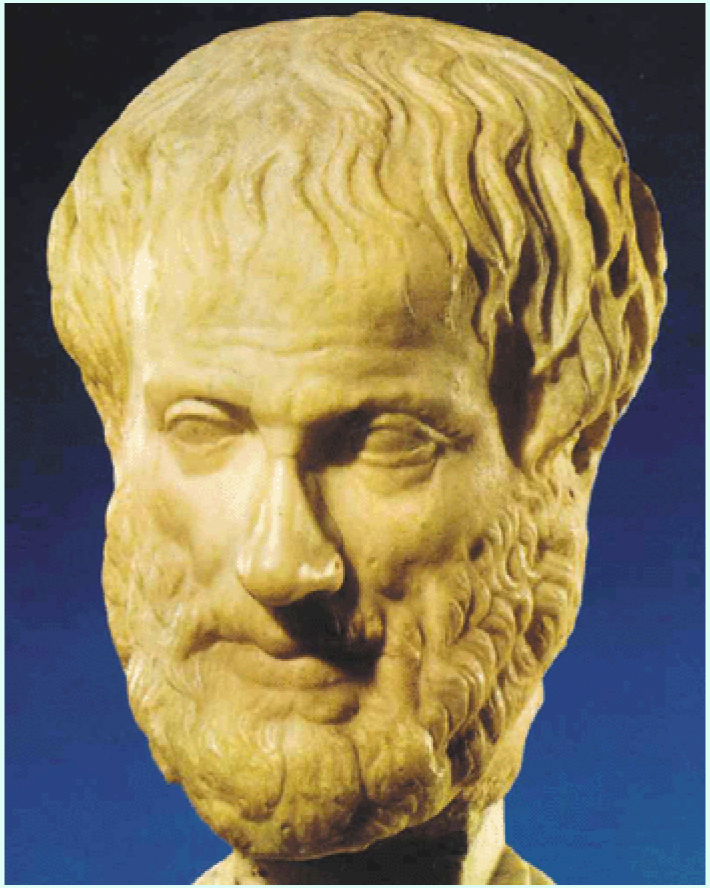
For the EPF experiments it allowed to eliminate effects of the environment when comparing two masses of different material.



Eötvös's poetical description of his balance in 1901

"The means I use is a simple, straight stick with masses attached to each end, and encased in metal, so that it will not be disturbed by the movement of air or differences in temperature. All mass near or far has an attracting influence on the stick, but the fibre, from which it is hung, resists this effect and twists in the opposite direction, producing by its twisting the exact measurements of the forces imposed upon it. This is nothing but an adapted version of the Coulomb instrument. ***It is simple as Hamlet's flute, if you know how to play on it. Just as the musician can coax entrancing melodies from his instrument, so the physicist, with equal delight, can measure the finest variations of gravity.*** "

Short historical overview of UFF and of the equivalence principles



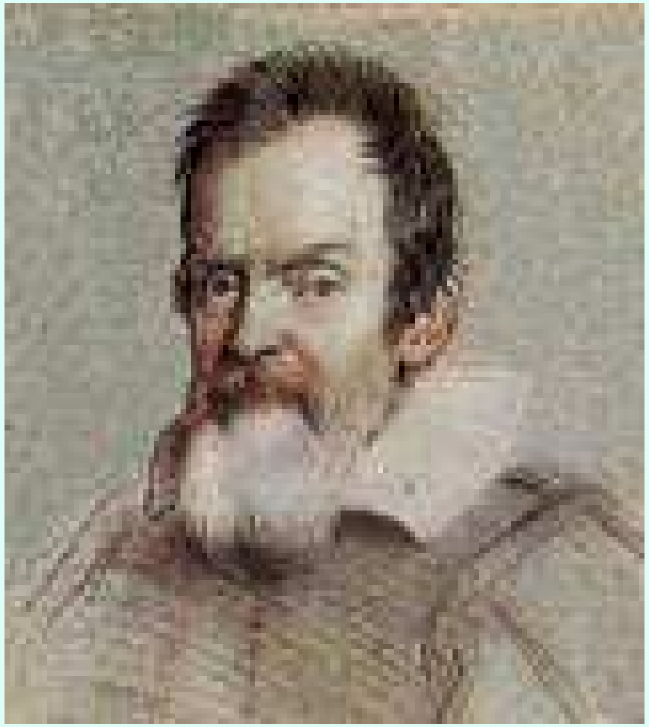
Aristoteles (384-322 BC)

Was Aristoteles totally wrong when he said heavier objects fall faster?

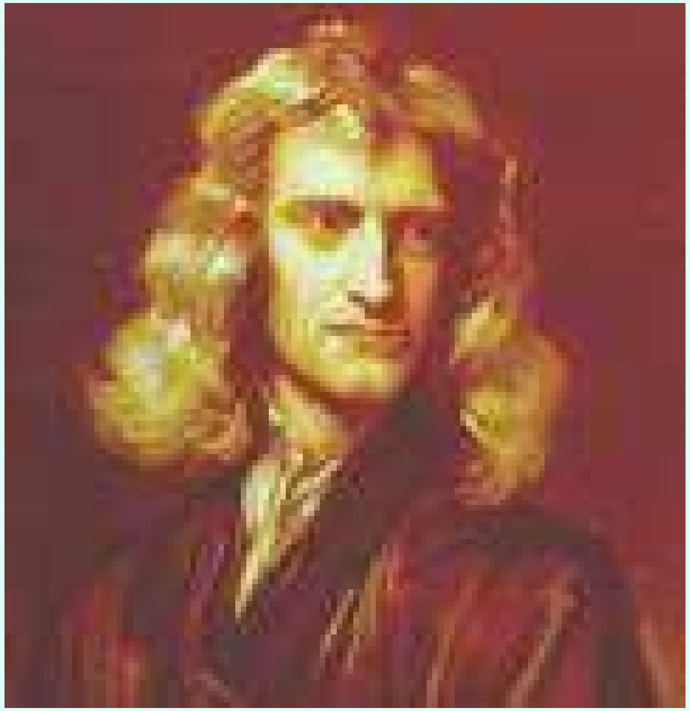
His rules applied quite well for objects falling e.g. in water, where „terminal speed” is more easy to reach than in air.

At that time, acceleration was a too tricky concept, and real vacuum was nonexistent.

The fathers of the concept of the Universality of Free Fall



Galileo Galilei (1564-1642)



Isaac Newton (1642-1727)

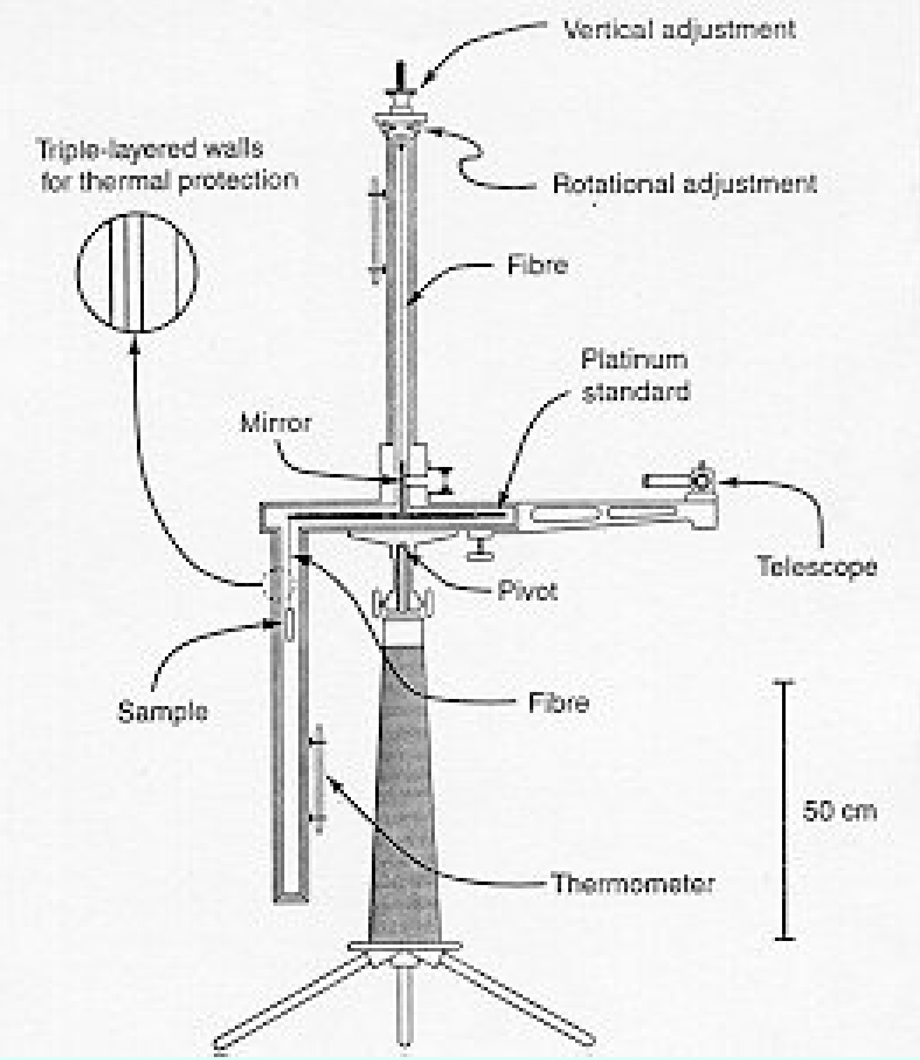
•**Weak Equivalence Principle (WEP):** inertial and gravitational masses are proportional (or: mass and weight are proportional). Or: falling objects follow the same trajectory (University of Free Fall, UFF).

•**Einstein Equivalence Principle (EEP):** 1. WEP is valid; 2. any non-gravitational experiment gives the same results in freely falling frames; 3. The results are independent of when and where in the Universe the experiment is done. Thus physical constants should also be the same always and everywhere. EEP probably also implies that gravity can be described in terms of a curved spacetime geometry.

•**Strong Equivalence Principle:** Objects with self-gravity (e.g. stars, planets and moons) also fall in the same way. That would not be true if attraction was different for the gravitational binding energy.

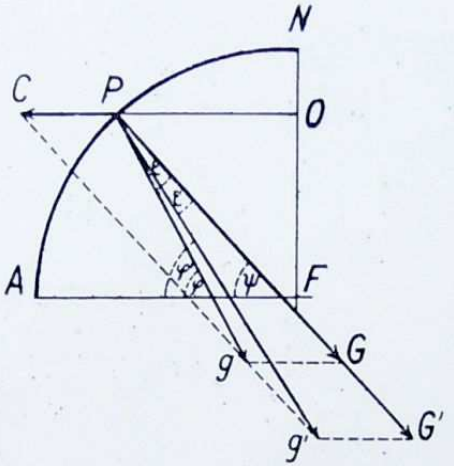
•It is now questioned whether dark matter and energy should also fall in the same way as ordinary, baryonic matter.

The EPF experiments



Eötvös-balance as used for UFF tests

If inertial and gravitating masses were different



$$g = G\cos\varepsilon - C\cos\phi$$

$$C\sin\phi = G\sin\phi$$

$$tg\varepsilon = \frac{C\sin\phi}{g + C\cos\phi}$$

Similar equations apply to the primed quantities.
Let

$$G' = G(1+\kappa).$$

Then

$$\eta = \varepsilon - \varepsilon' = \frac{G}{g}\kappa \sin\ \varepsilon .$$

The EPF experiments restricted that angle to less than 2 10^{-4} arc seconds. „Ocean levels” of the two materials aligned at the equator would then not deviate by more than a hair’s width at the poles!

Principles of UFF tests on the rotating Earth by torsion balances

Suppose two bodies have the same inertial but different gravitational masses. Then gravity acts on them with different forces (G, G’), and their weights (gravity + centrifugal) will be different (g, g’), both in magnitude and in direction.

This small difference in direction exerts a torque on the Eötvös balance, and can be separated from gravity gradient effects, if a sufficient number of measurements is made in different azimuthal directions.

Co-authors of Eötvös in the EPF paper

Dezső Pekár (1873-1953). Worked with Eötvös from 1895 to 1919, and also led his geophysical measurements. He established and led the Loránd Eötvös Geophysical Institute until 1934, made several improvements to the Eötvös balance, and also led some prospecting expeditions abroad (e.g. in India).

Jenő Fekete (1880-1943) worked with Eötvös for 15 years. After the death of Eötvös (in 1919) he went to Texas, Mexico, and Venezuela, and helped to find oil there with Eötvös balances. From 1934 he led the Loránd Eötvös Geophysical Institute.

In 1922 they jointly published the EPF paper in Annalen der Physik.

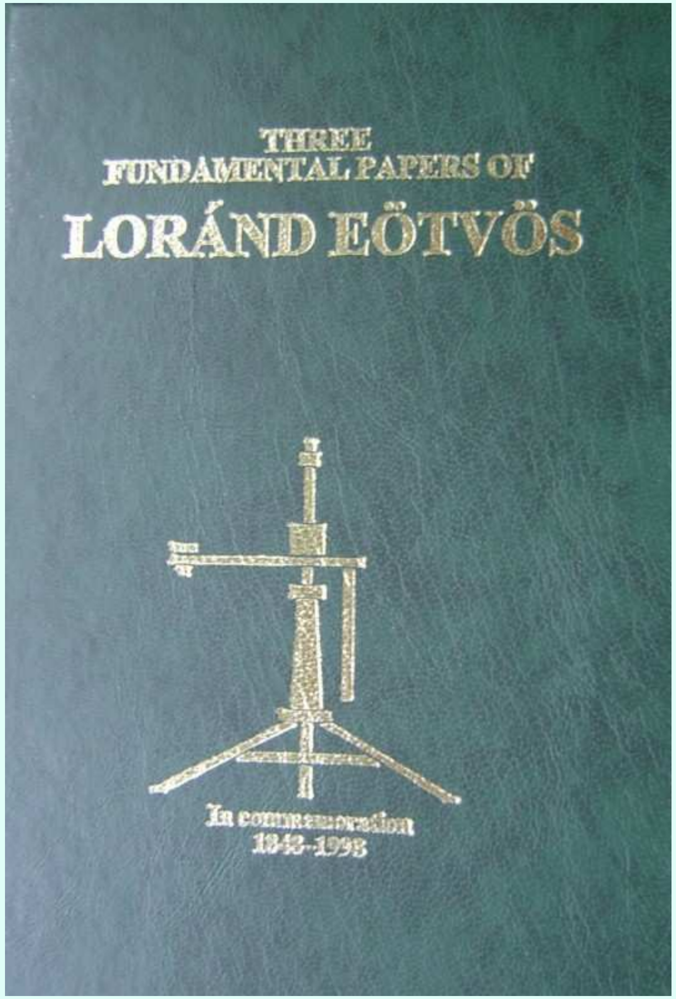
Results of the EPF experiments:

•No systematic deviation from UFF was found for any pair of materials, not even for gases and for radioactive substances.

•The upper limits for violations of UFF were found for most solids as $5x10^{-9}$.

•For most pairs the Earth was used as the attracting agent, in some cases the Sun.

•No shielding of gravity was found.
•The authors concluded that a still higher precision could be reached with similar methods, but: ***„Ars longa, vita brevis”*.**



Einstein and Eötvös

Einstein und der Eötvös-Versuch: Ein Brief Albert Einsteins an Willy Wien

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Zusammenfassung

Das Aequivalenzprinzip wurde von Einstein erst 1907 in Worte gefasst. Er wendete sich 1912 brieflich an W. Wien mit der Bitte, den Unterschied der Schwingungsdauer eines Uranpendels und eines Bleipendels sowie die Proportionalität der trägen und schweren Massen eines Blei- und eines Urangewichts auszumessen, und zwar mit einer Drehwage. Der Brief macht es klar, dass Einstein bei der Aufstellung des Aequivalenzprinzips von dem Eötvös-Versuch nichts wusste, und als es ihm nötig schien, das Prinzip experimentell zu prüfen, hat er den Versuch neuentdeckt.

Summary

The principle of equivalence was first formulated by Einstein in 1907. In 1912 he turned by letter to W. Wien with the request to measure the difference between the periods of oscillation of pendulums made of uranium and lead, as well as the proportionality of inertial and gravitational masses of a uranium and a lead weight, respectively, namely with a torsion balance. The letter testifies that Einstein was not aware of the Eötvös experiment when he formulated the principle of equivalence and as soon as he needed an experimental test of it, he reinvented the experiment.

Was Einstein aware of the early UFF results of Eötvös, when he formulated his EP in 1907?

If not, when did he feel it necessary to check his assumptions?

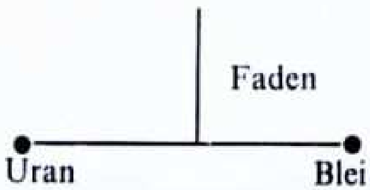
A letter of Einstein to Wilhelm Wien in 1912 gives some indications.

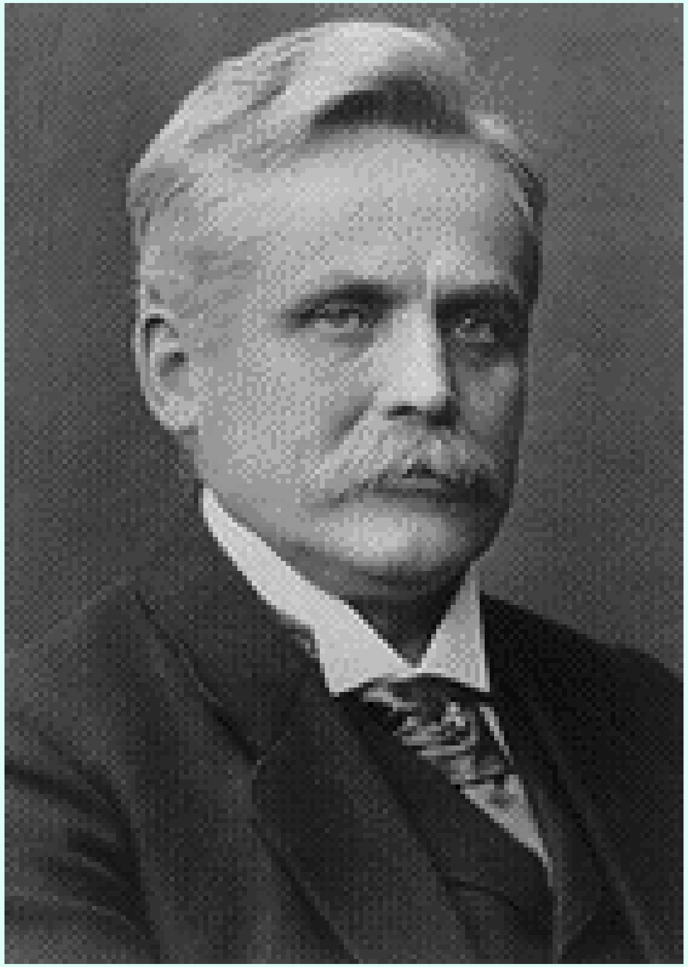
Einstein's proposal to Wien, how to check the EP for α decay

From J. Illy 1989:

Es ist ganz klar, hätte Einstein etwas über den Eötvös-Versuch gewusst, so hätte er nicht an Wien geschrieben. Doch der Brief endet nicht mit der Unterschrift:

> *Post-Scriptum.* Es kam mir nachträglich eine viel empfindlichere Methode in den Sinn, um eine nicht genaue Proportionalität der trägen und der schweren Masse von Uran und Blei zu konstatieren, falls es eine solche gibt. Es wäre nämlich in diesem Falle die auf die Körper infolge der Erddrehung wirkende Zentrifugalkraft nicht für alle Körper der Schwere proportional. Die scheinbare Lotrichtung eines Uran-Lotes und eines Blei-Lotes müssten voneinander abweichen. Es müsste ferner eine Drehwage, an deren Balken ein Uranstück bezw. Bleistück angebracht ist, ein Drehmoment erfahren, wenn die Wagebalken in die West-Ost-Richtung gebracht wird, welches Drehmoment bei Kommutieren der Wage um 180° sein Vorzeichen ändern würde. Dieser Effekt wäre, wie ich mich durch Rechnung überzeugte ganz bequem messbar. Vielleicht hätten Sie die Güte, diesen einfachen Versuch ausführen zu lassen, der die Bedeutung eines experimentum crucis hätte.[4]

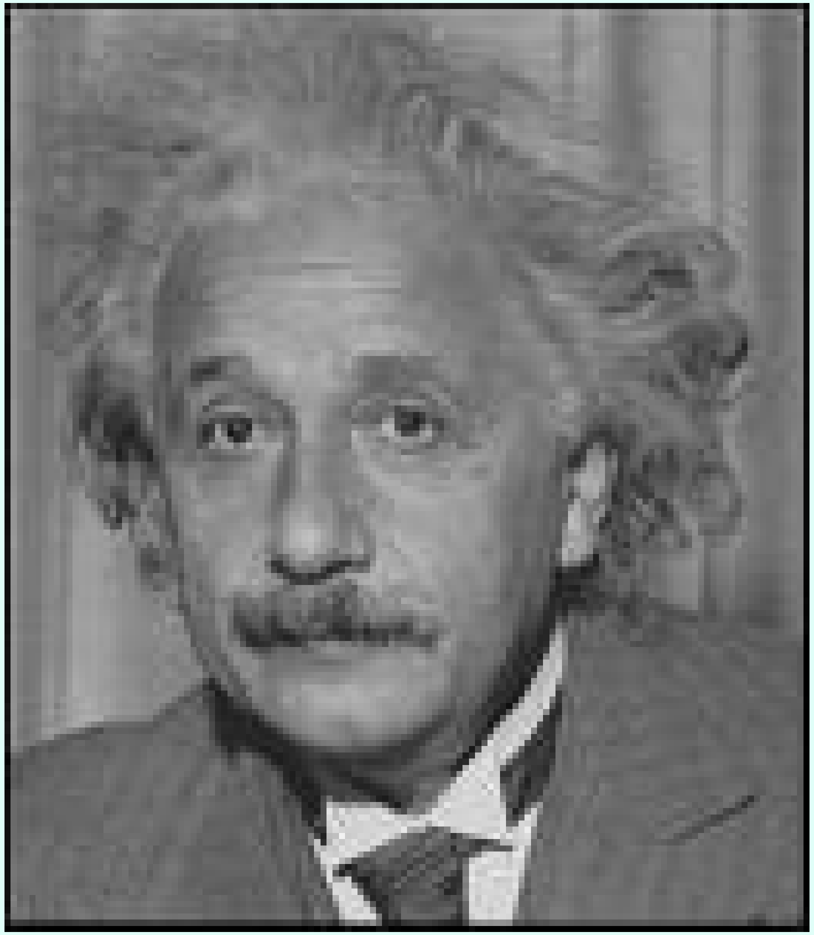




Wilhelm Wien (1864-1928)

Wilhelm Wien received the Nobel prize in 1911 for his work on the black-body radiation. It greatly helped Planck to suggest quanta.

After receiving Einstein’s letter, he may have informed Einstein that the proposed experiment was done by Eötvös more than 20 years earlier. Next year Einstein and Marcel Grossmann referred to the early Eötvös paper, but they were probably not aware of the later, more precise EPF experiments.



Albert Einstein (1879-1955)

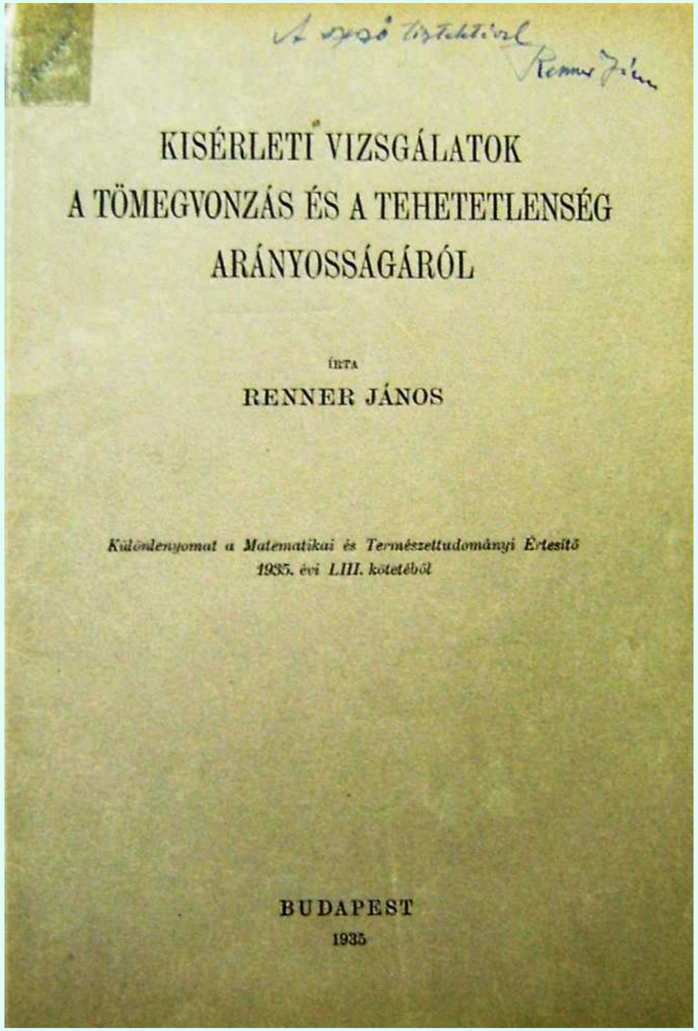
“I was sitting on a chair in my patent office in Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his weight. … It was what led me to the theory of gravity.”

Einstein in Kyoto, 1922

“The general theory of relativity owes its existence in the first place to the empirical fact of the numerical equality of the inertial and gravitational mass of bodies.”

Einstein, Lecture at King’s College, London, 1921

Tests of the Equivalence Principles between 1930 and 1970

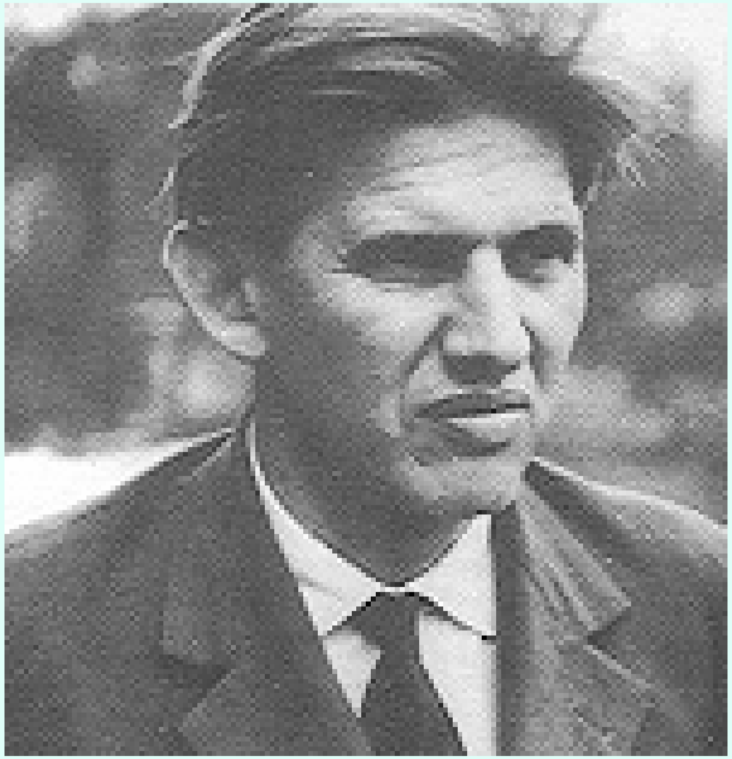


In the 1930's János Renner, an earlier assistent of Eötvös, made a long and careful set of new tests on the UFF. He used very similar methods and devices as EPF, but had more time and some better calibrated Eötvös balances.

Again, no deviations from the UFF were found for a variety of substances, but he improved the upper limits by about one order of magnitude, to 5×10^{-10}.

Although not widely known, his limits were considered as best up to the 1960's.

Letter of Bruno Bertotti to Jánossy about Renner, and about Dicke's plans



Lajos Jánossy (1912-1978)

Prof. L. Jánossy
Department of Physics
University of Budapest
Budapest /Hungary/

Princeton, January 31, 1961.

Dear Professor Jánossy;

I am interested in the experimental confirmation of the principle of equivalence and I recently came across with the little known paper by John Renner published in 1935 in the proceedings of the Hungarian Academy of Sciencex. He performed Eötvös' experiment with a technique even more refined and obtained results which about an order of magnitude better than his predecessor's. Because of the outstanding importance of this experiment, I would like to know more about his work and wonder if you know whether Dr. Renner is still alive and where he lives. His work was done in your department, anyway and may have you heard already about it directly; what is your opinion in this case? One would like to know, for example, what is the meaning of the statement made in par. III according to which he was able to determine 1/40 of a millimeter in the scale in the optical arrangement; in par. IV, in fact, he states that the statistical error in such reading was ,0022 millimiters, which is less than the one you can compute if you assume that the error in each measurement is equal to 1/40 millimiter.

You might be interested in knowing that the Eötvös' experiment is being repeated with refined electronic tehcnique here in Princeton by professor Dicke and his collaborators.

I wonder if you carried more experiments on the interference of weak beams of light; I read with interest your papers of 1957; can you send me reprints of your theoretical papers /in the Nuovo Cimento, I believe/ on this and related topics?

Thank you very much.

Yours truly:

Bruno Bertotti.

Robert H. Dicke (1916-1997)

Dicke’s Princeton group performed the first modern test of the UFF, and achieved a relative precision of 10^{-11}. Instead of Earth, the Sun was the attracting center, while the role of Earth was to smoothly rotate the torsion balance each day.

Dicke’s group checked the results and methods of Renner, and concluded that his error analysis was not quite correct.

Lunar Laser Ranging results (from 1970 on) show the validity of the strong EP, including that of gravitational binding energy.

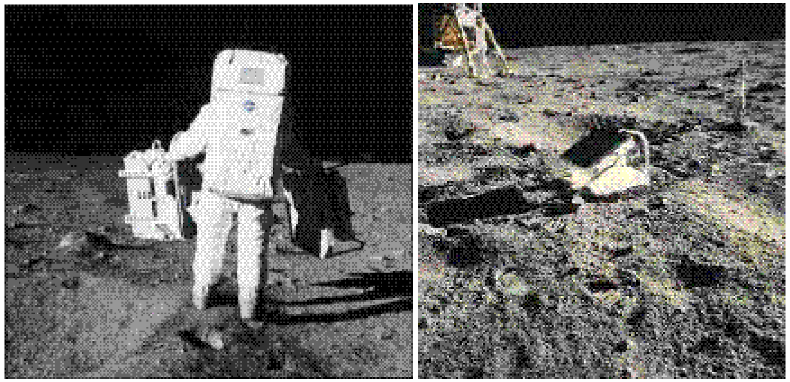


Figure 1: (a) The LLR retroreflector, at Buzz Aldrin's right side, being carried across the lunar surface by the Apollo 11 astronaut. (b) Apollo 11 laser retroreflector array.

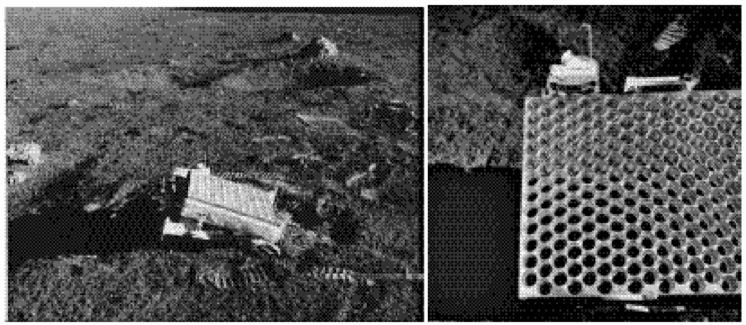
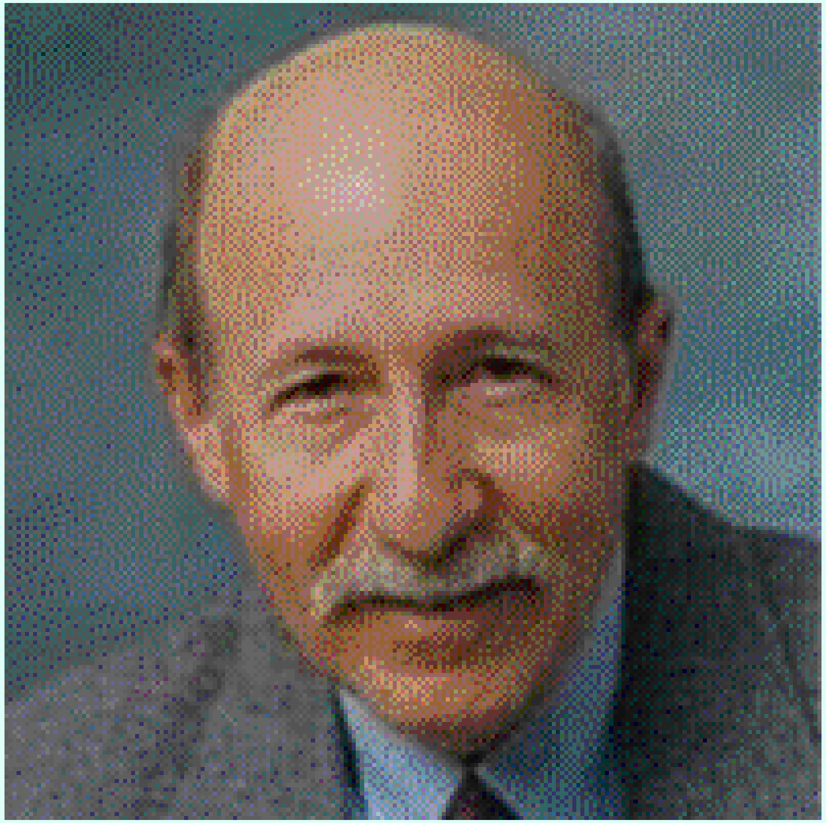


Figure 2: Apollo 14 (left) and Apollo 15 (right) LLR retroreflector arrays.

Retroreflectors left on the moon by Apollo astronauts are illuminated by laser beams from Earth. Moon orbit is determined to cm precision.

Gravitational binding energy has been shown to be consistent with GR to a precision of 1 in 1000. Further improvement on lasers and reflectors may further improve those limits.

The Fifth Force proposal of Ephraim Fischbach



Ephraim Fischbach

Fischbach et al. published the ‘Fifth Force’ hypothesis in 1986. Their claim was mainly based on the old EPF results, interpreted from a new point of view.

The Fifth Force was claimed much weeker than gravity, with a range of hundreds of meters, and its source was barion number or hypercharge.

First paper on Ephraim Fischbach's „Fifth Force" claim

PHYSICAL REVIEW LETTERS

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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.

A huge experimental activity followed the Fischbach paper

*(Phys Rev. Letts **56**, 1, 1986)*

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

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

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]

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

How do small residuals of EPF results relate to barion number?

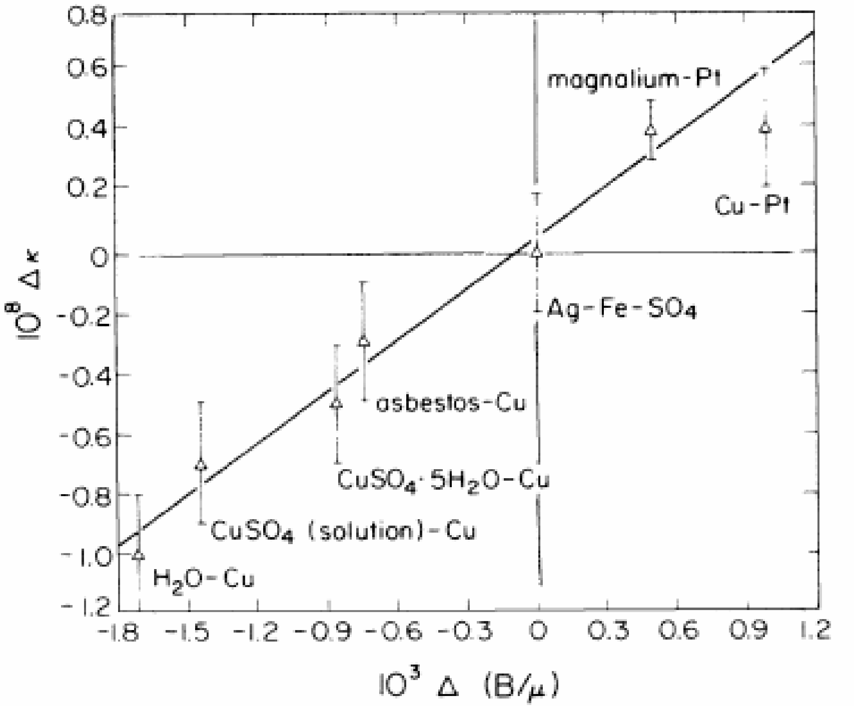
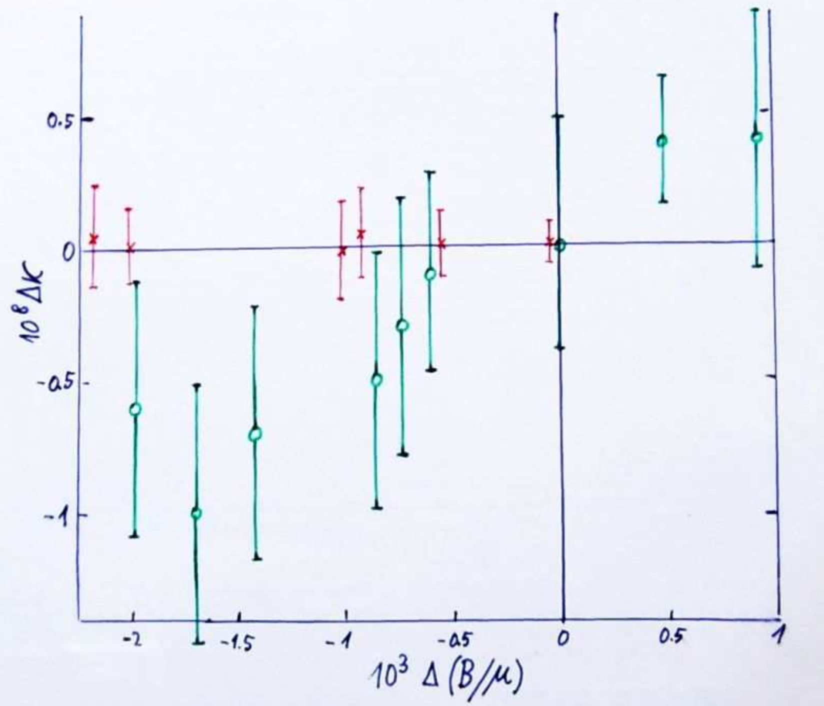


FIG. 1. Plot of $\Delta\kappa$ vs $\Delta(B/\mu)$ using the data in Table I. Ag-Fe-SO_4 refers to the reactants before and after the chemical reaction described by Eq. (7). The solid line represents the results of a least-squares fit to the data.

EPF and Renner results compared to barion number differences



Differential accelerations measured by Eötvös, Pekár and Fekete (EPF) and by Renner (1930-35). standard deviations are 2.4 times larger than given by the authors!

My own contemporary calculations of the residuals for EPF and Renner.

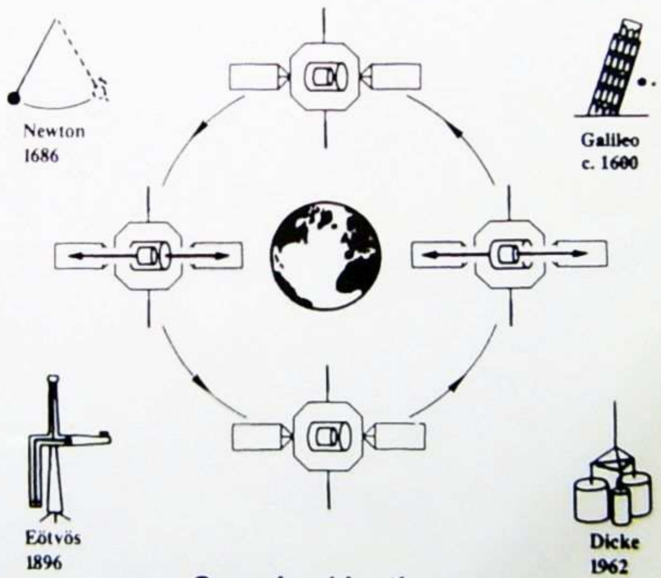
The apparently more precise Renner data contradicted the Fischbach hypothesis.

Planned space experiments

STEP Symposium

Testing the Equivalence
Principle in Space

6-8 April 1993 Pisa, Italy



Organised by the
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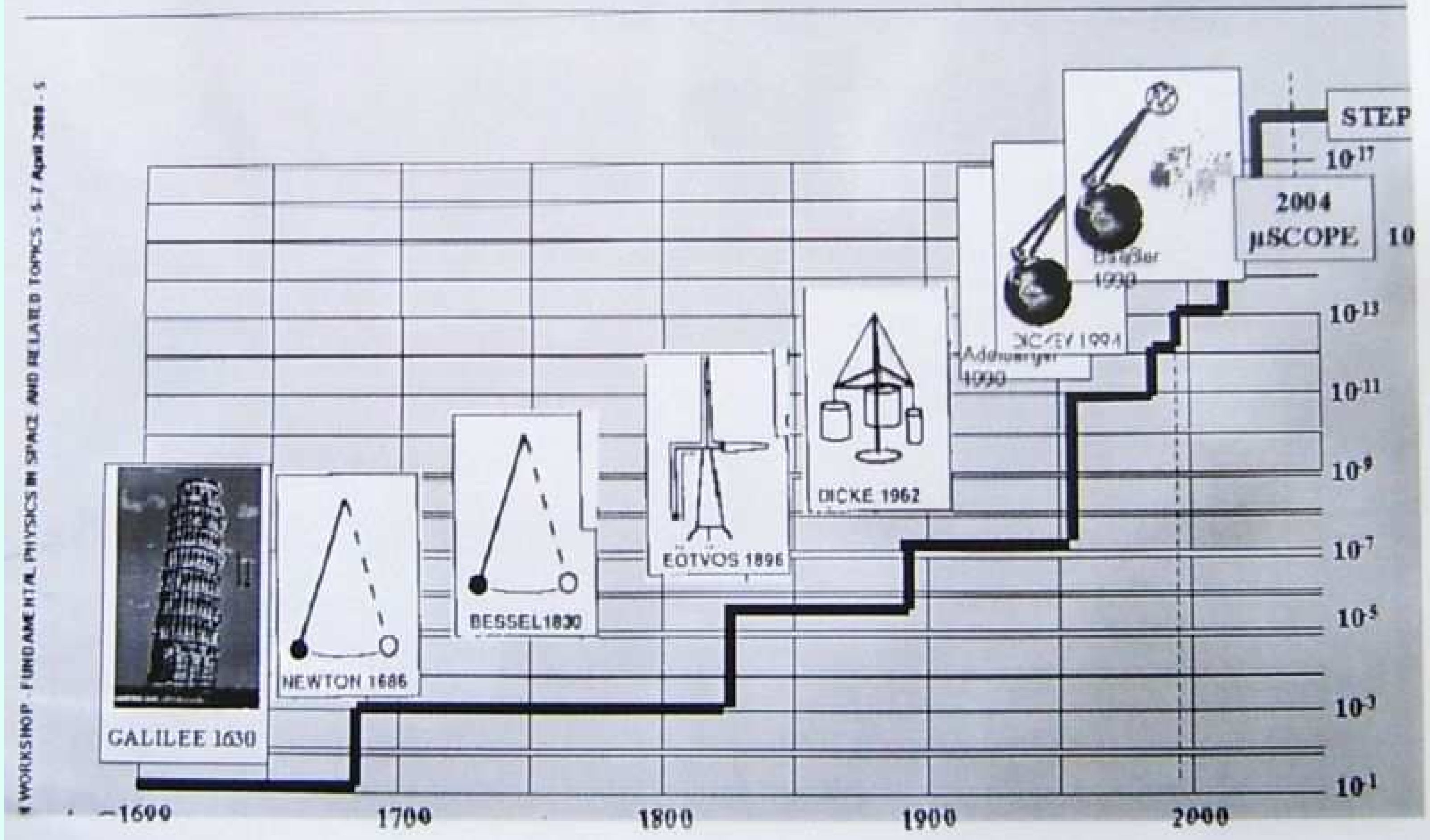
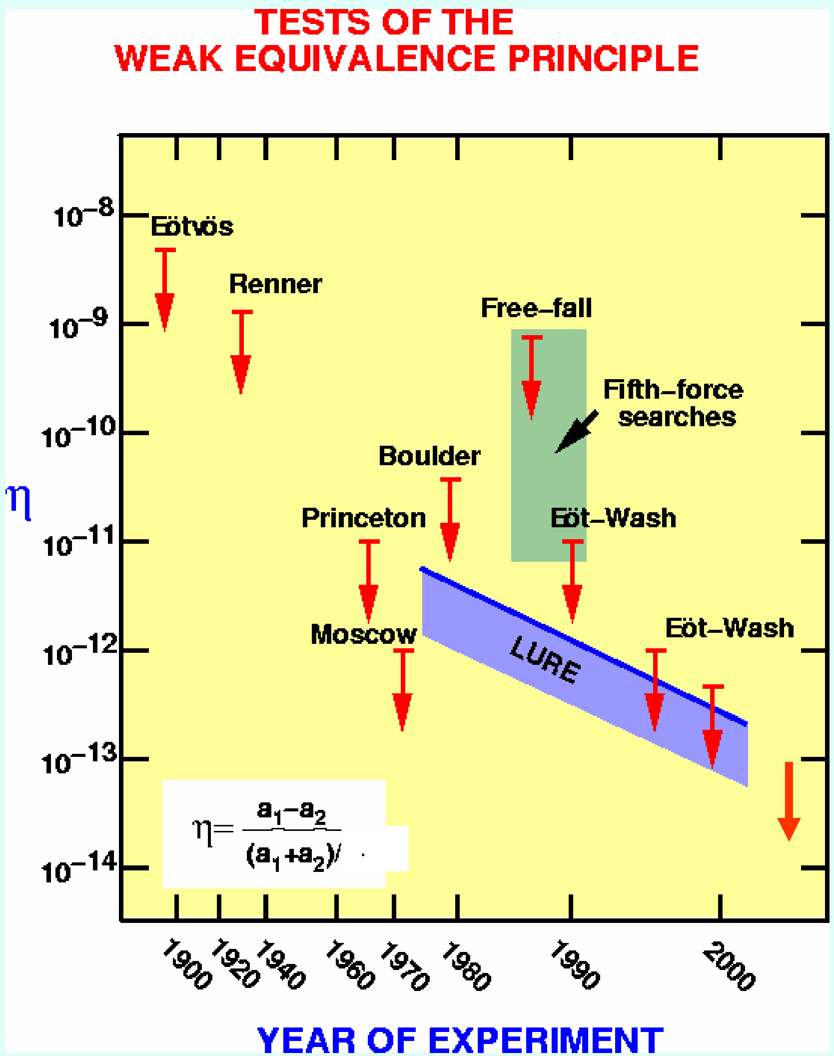
Eötvös and *STEP*

Baron Roland Eötvös of Vásárosnamény
1848 — 1919

Increasing precision of UFF tests



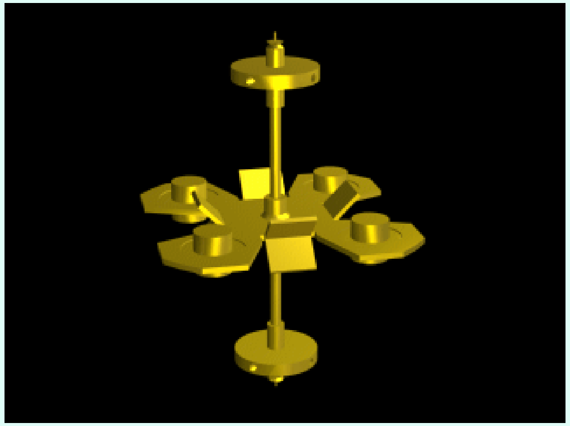


How upper limits on possible violations of the UFF decreased in 100 years, since the EPF experiments.

1/r^2 law at small and very large distances

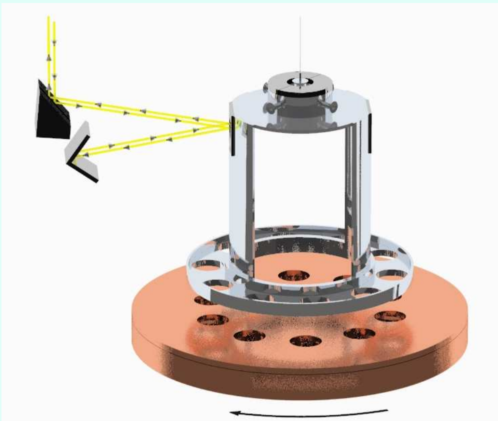
Eric G. Adelberger, University of Washington, Seattle.
He was the founder of the „Eöt-Wash” group in 1987.

Modern torsion balances of the Eöt-Wash Group

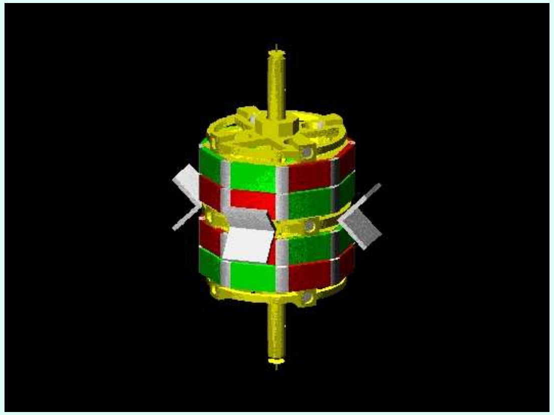


Rot-Wash, continuously rotating

UFF test for 4 pairs of substances

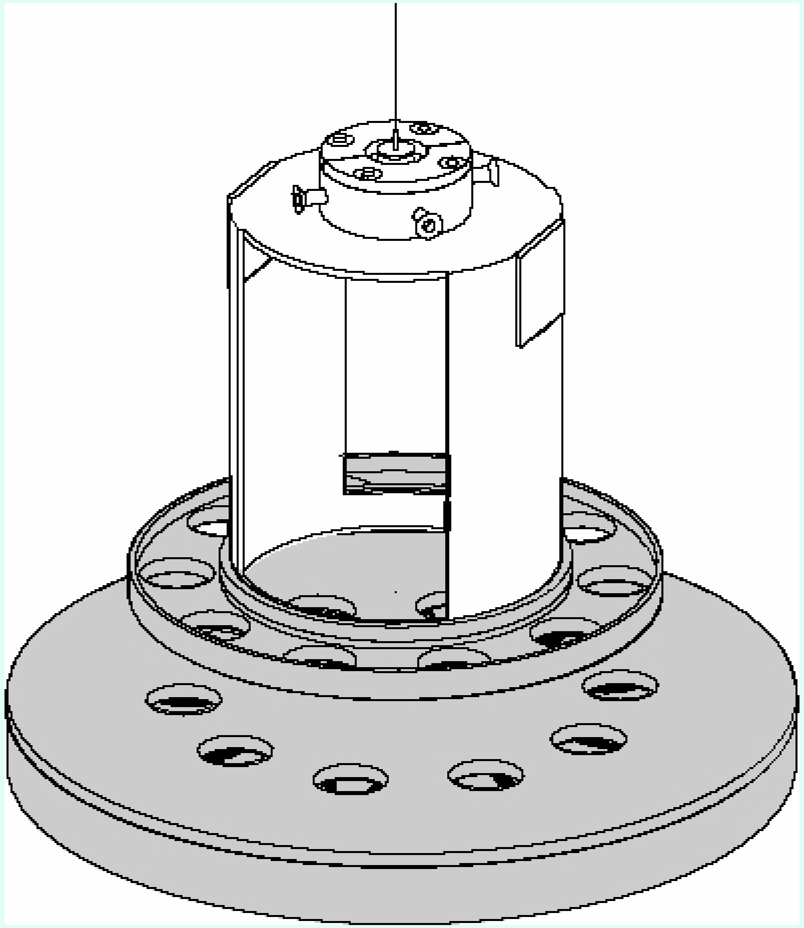


$1/r^2$ law at small distances



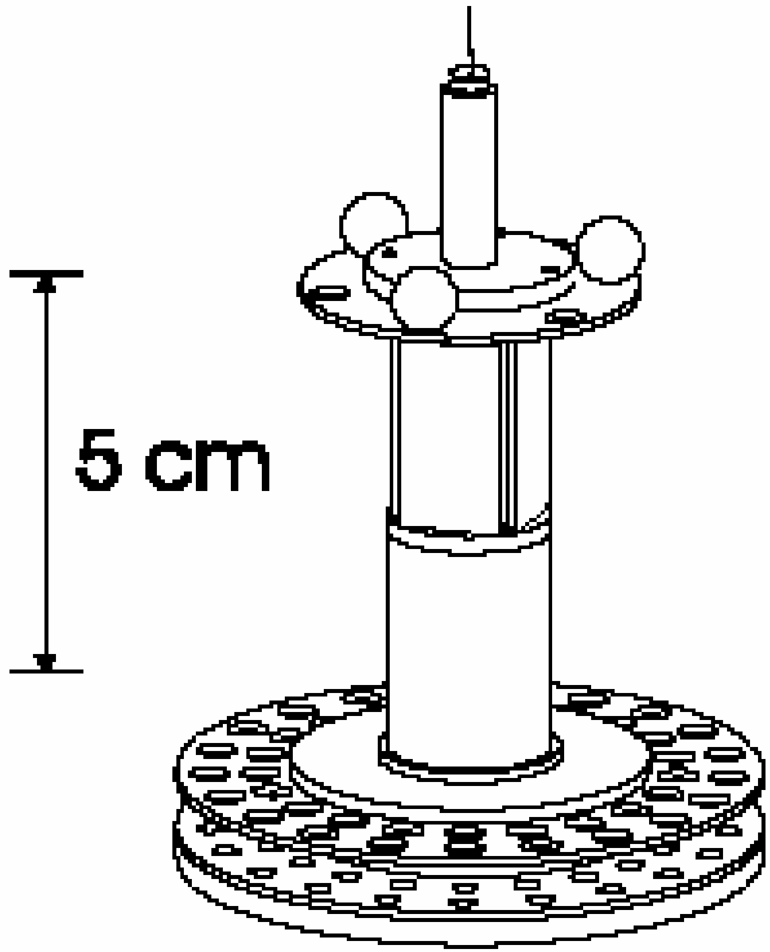
For testing spin - mass interaction

First Eöt-Wash torsion balance for testing $1/r^2$ law

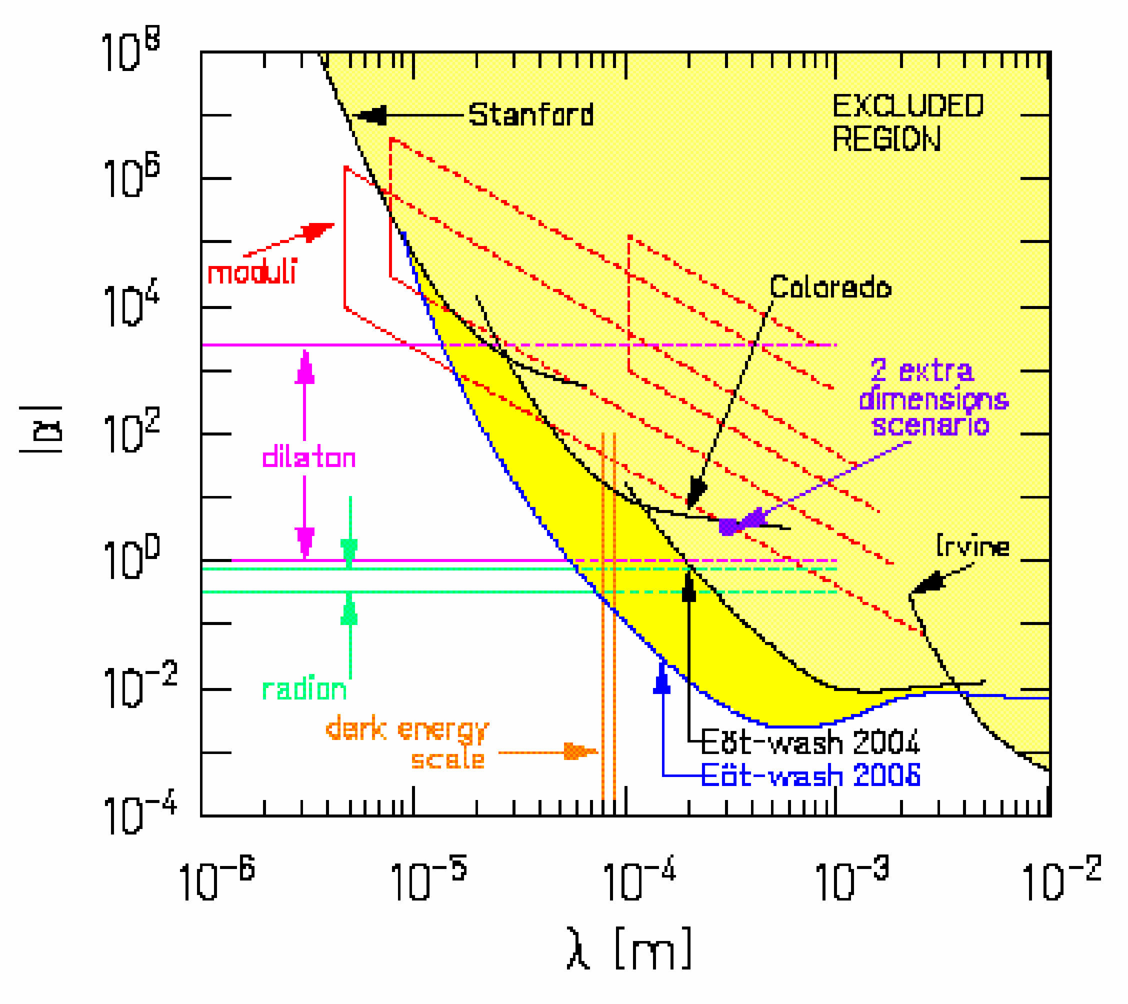


Most recent torsion balance of the „Eöt-Wash” group that checked the validity of the $1/r^2$ law of gravitational attraction down to about 50 micrometers.

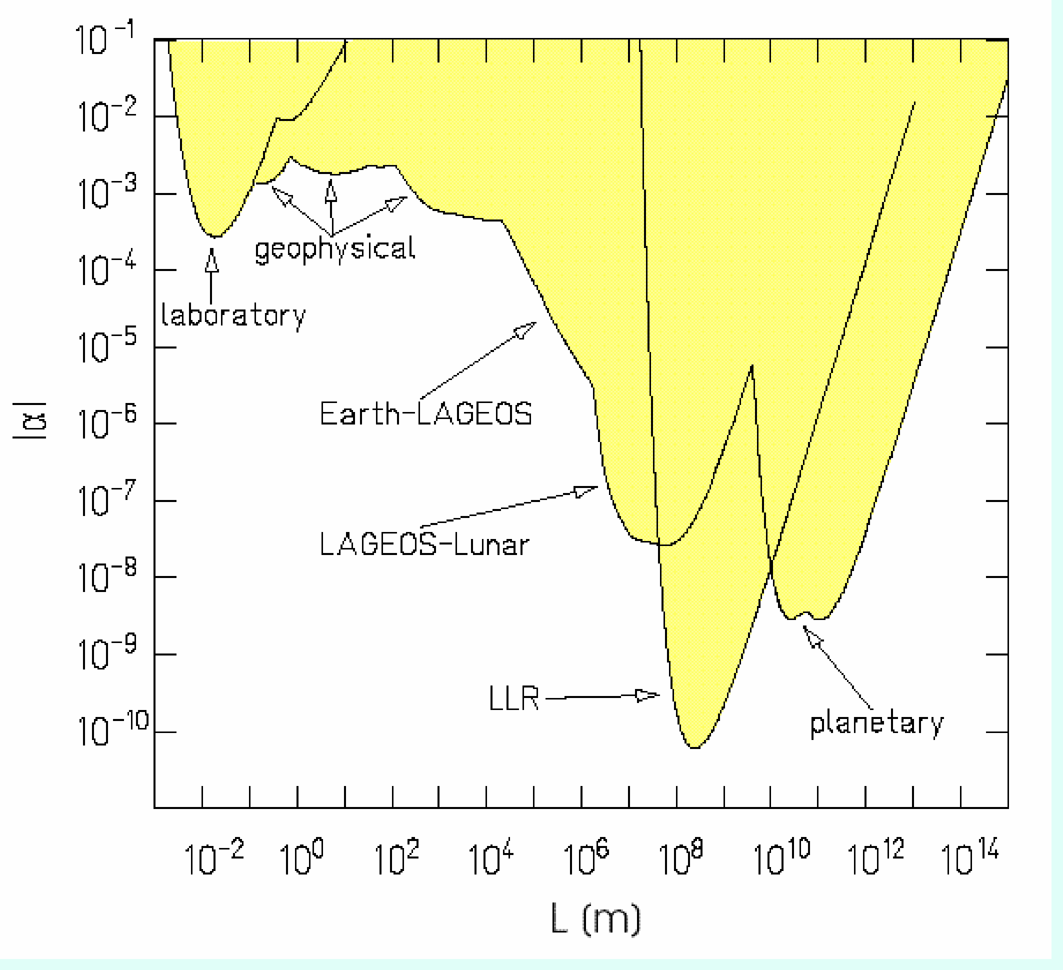
Predictions for a vacuum fluctuation origin of „dark energy” suggest that the law would change below about 85 micrometers.



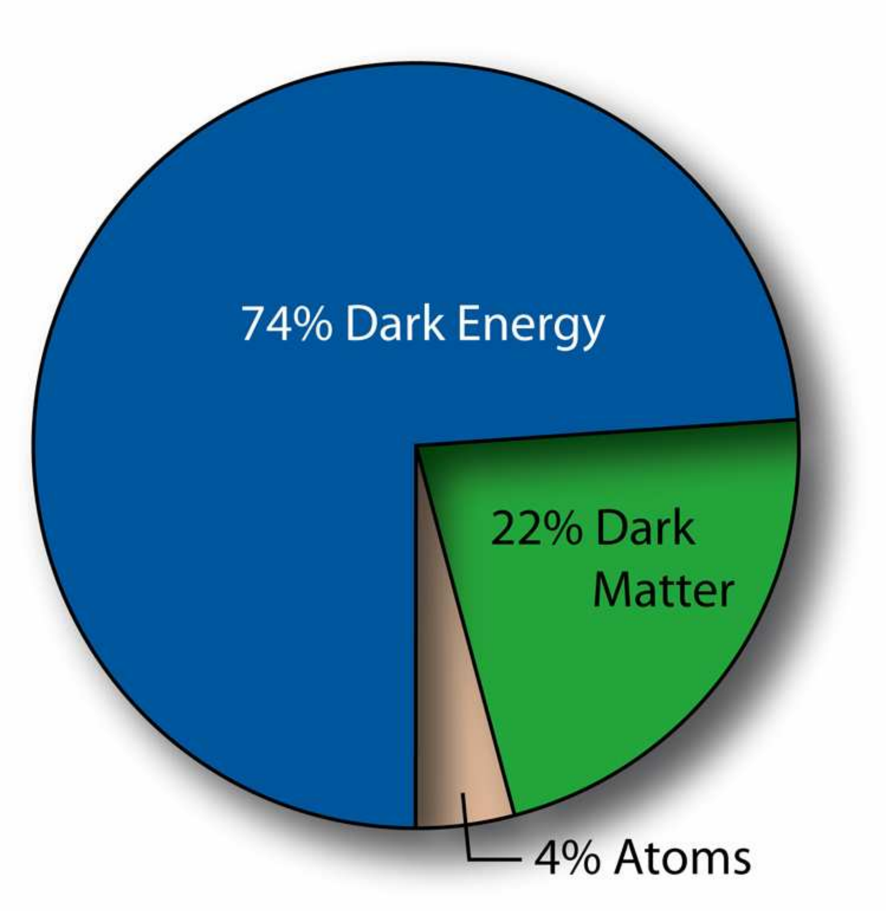
„Fifth Force" strengths now excluded at small distances



Fifth Force strengths excluded at larger distances

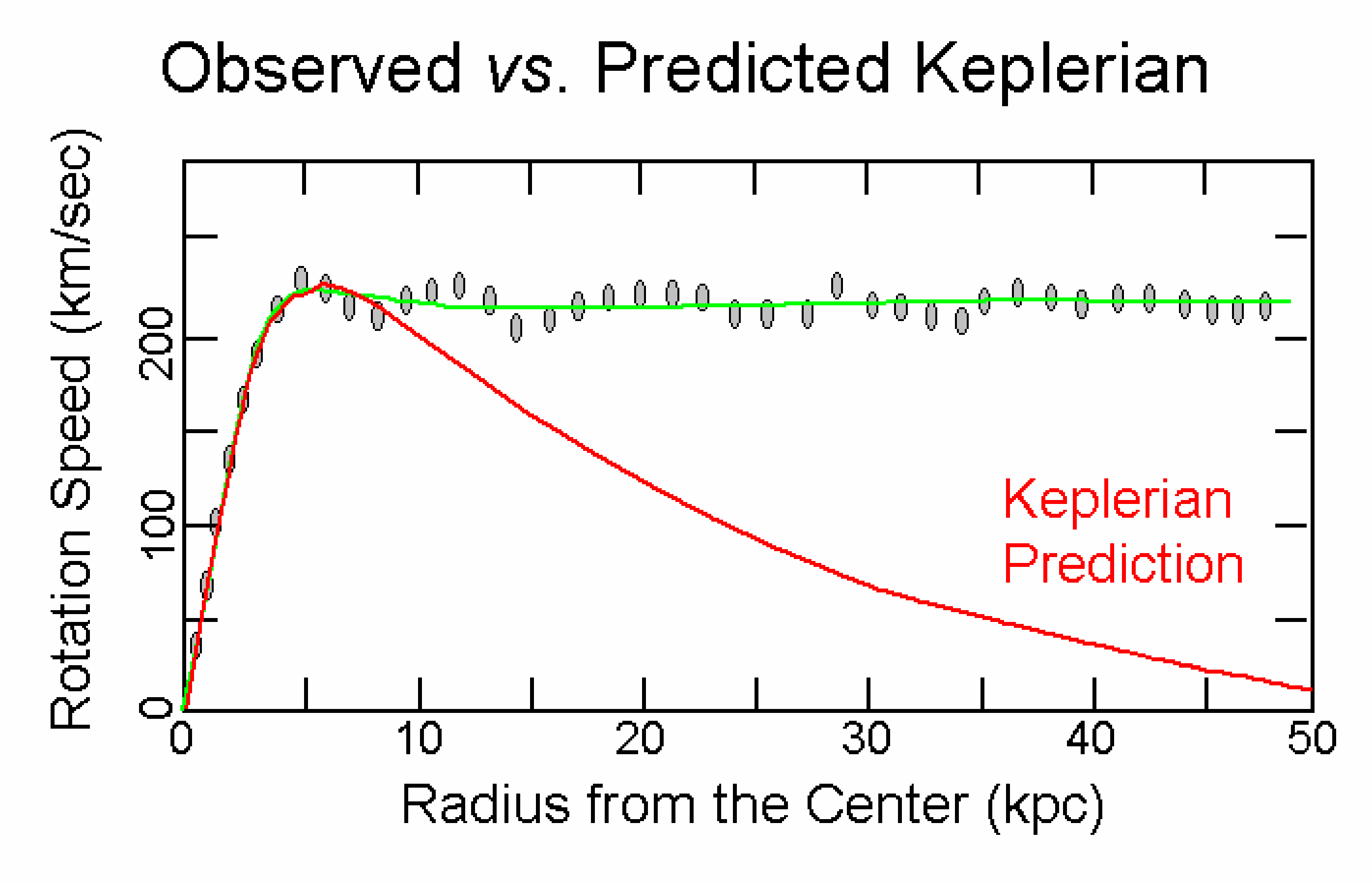


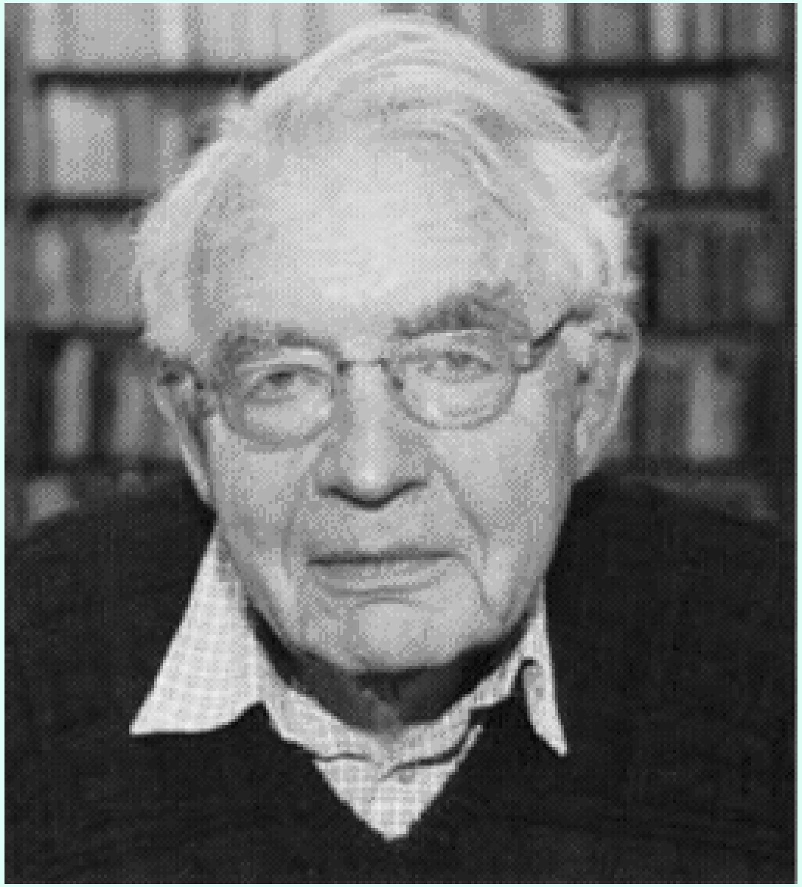
What is our Universe made of?



The relative amount of the different forms of matter is thought to be well known, but not understood.

Dark matter in galaxies may cause flat rotation curves.





Hendrik Casimir (1909-2000)

The Casimir effect – due to vacuum fluctuations - gives rise to strong forces between good conductors sufficiently close to each other.

That effect makes it difficult to check the $1/r^2$ dependence of gravitational forces below some tens of micrometers.

Summary

•More and more precise tests on the UFF are still in the forefront of research, and torsion balances, first used by Eötvös for that purpose, are still competitive devices.

•Tests of Einsteinian general relativity have so far fully confirmed its predictions. There is some chance, however, that either more precise tests on UFF, or tests on the inverse square law at very small or very long range will find some deviation, and point the way toward a more complete, unified theory.

•The structure of the Universe is poorly understood both on very small and on very large scales. Table-top experiments of the Eötvös type might be competitive with huge accelerators and telescopes in finding a way out of the present trap of incompatible „standard theories”.

A poem by the young Eötvös that shows how keenly he wanted success.

Laurels beckoned us, so we started out
With Nightingale towards a mountain height.
While I grappled with the sheer cliffs below,
She seized her prize in easy, graceful flight.

What I may perhaps never ever reach,
Took but a brief moment for the bird;
O Heaven don't be so unjust, I plead,
Grant me wings too. Let my prayer be heard.

Does dark energy define a new fundamental length scale in physics?

$$\rho_{\mathrm{d}} \approx 3.8 \ \mathrm{keV/cm^3}$$

$$\lambda_{\mathrm{d}} = \sqrt[4]{\hbar c/\rho_{\mathrm{d}}} \approx 85 \ \mu\mathrm{m}$$

a second "Planck length"?