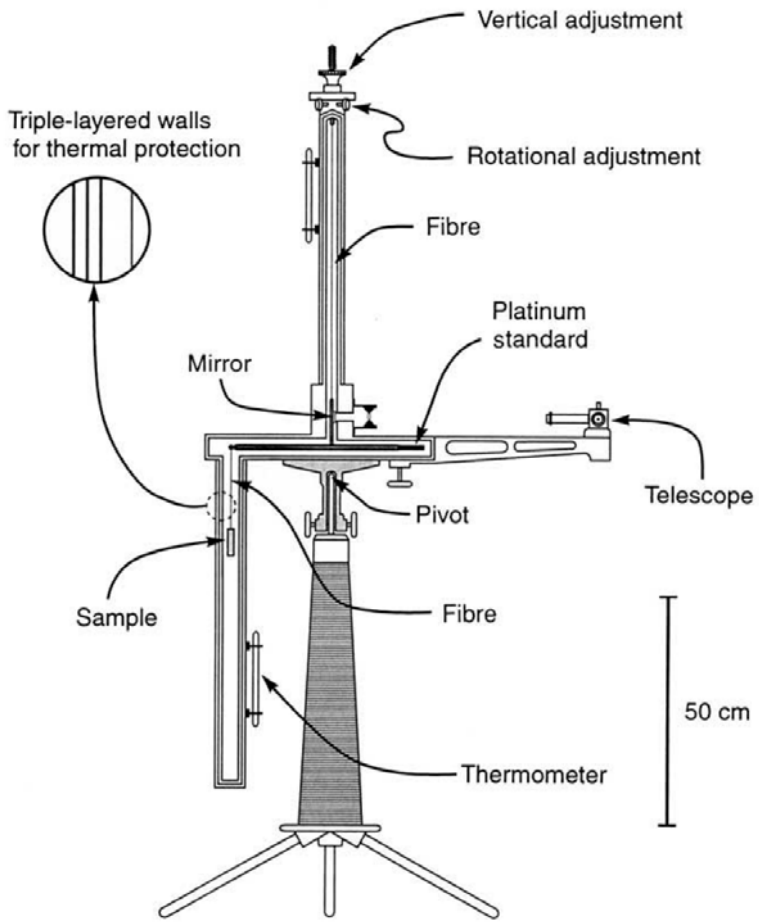
IHP 2006

Ground Based Tests of the Equivalence Principle



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Testing the Equivalence Principle

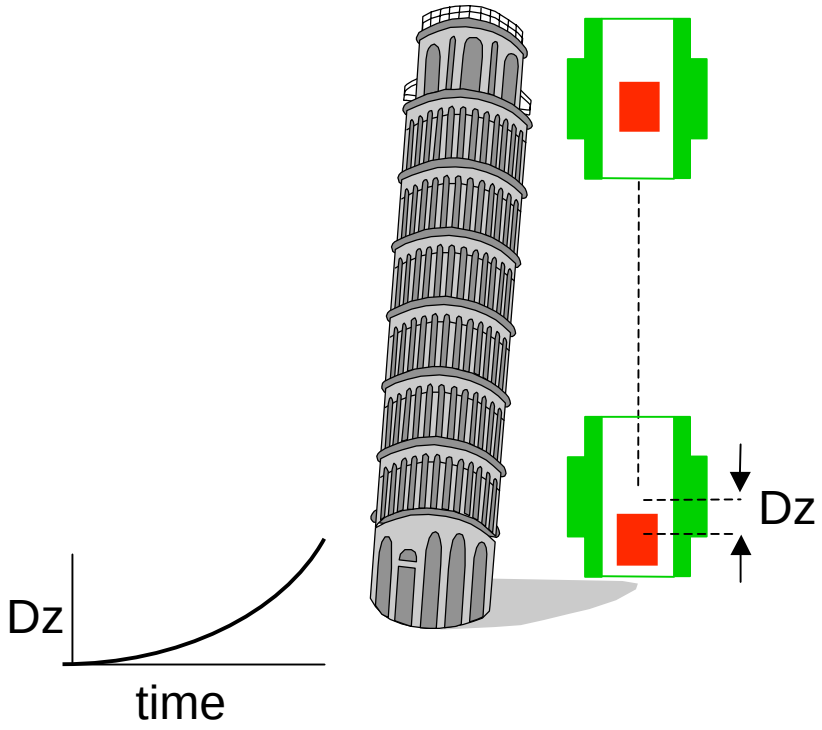
As formulated by Newton, the Equivalence Principle asserts the equivalence of gravitational mass m_g ($F = GMm_g/r^2$) and inertial mass m_i ($F = m_i a$). Generalized by Einstein, it is the foundation of general relativity.

A consequence of the Equivalence Principle is the Universality of Free Fall:
materials of different composition fall in a uniform gravitational field with the same acceleration.

Going back to Galileo's Leaning Tower experiment, equivalence has been tested over time with improving precision. Present limits are placed at a few parts in 10^{13} by ground based torsion balance experiments and lunar laser ranging.

Testing the Equivalence Principle

Newton's Mystery { $F = ma$ — mass - the receptacle of inertia
$F = GMm/r^2$ — mass - the source of gravitation

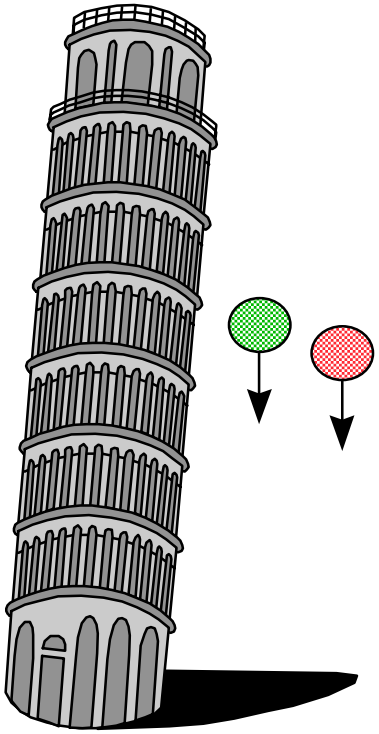


WEP => Universality of Free Fall

EP Is a postulate of General Relativity, its not explained by it.

Weak Equivalence Principle
UNIVERSALITY OF FREE FALL (UFF)

$$F = m_i a \qquad\qquad F = G\frac{m_g m_{earth}}{R^2}$$

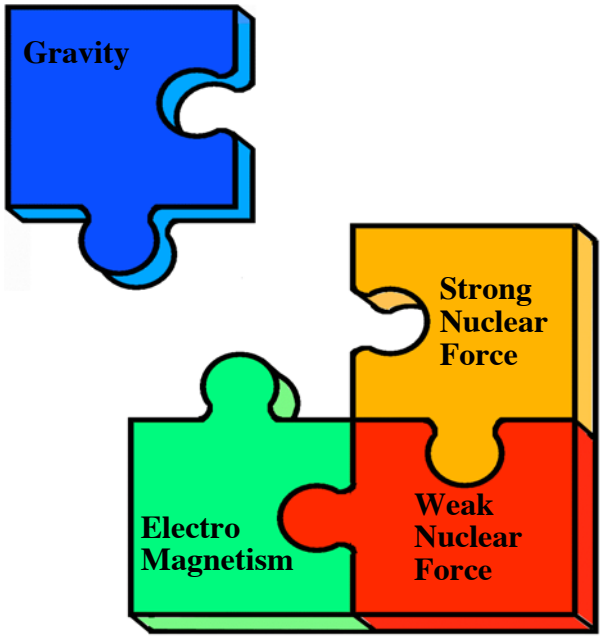


$$a = \frac{m_g}{m_i}\frac{G\,m_{earth}}{R^2}$$

$$a = \frac{m_g}{m_i}\frac{G\,m_{earth}}{R^2}$$

Is $\dfrac{m_g}{m_i}$ constant for all materials?

Can Gravity Be Made to Fit?



- **Unified Physics ?**
  - Problems with gravity
    - ➠ Resists Quantization
    - ➠ Hierarchy Problem

    Electro Weak Scale **/** Plank Scale ~10^{17}

- **Partial steps toward Grand Unification**
  - Strings/supersymmetry in early Universe scalar-tensor theory, not Einstein's
  - Damour - Polyakov: small Λ long range equivalence-violating dilaton

- **EP violations inherent in all known GU theories**
  - Runaway dilaton theories { (Witten) (Damour, Piazza, Veneziano) } η { >> 10^{-18} up to 10^{-14} }
  - 1 TeV Little String Theory (Antoniadis, Dimopoulos, Giveon) η ~ 10^{-15}

- **Observed(?) $\dot{\alpha}$ (Webb, et al.) (Dvali, Zaldarriga)** η > 10^{-17}

Space Based tests of EP take physics into new theoretical territory

A little more on EP violation predictions

The Equivalence Principle is a postulate of general relativity. Any violation of Equivalence implies either that the theory is in error or that there is a new force acting.

Early attempts at unification of gravity with electromagnetism implied violations of Equivalence.

Jordan showed that the Kaluza-Kline five-dimensional theory could be translated into a four-dimensional one with additional fields.
In addition to the tensor field of gravitation and the vector field of electromagnetism, a new scalar field appeared with a coupling strength close to that of gravitation.
In the original Jordan formulation this term drastically violated the Equivalence Principle.

To remedy this Fierz (1956) adjusted the couplings of the scalar field to produce a class of metrically coupled scalar-tensor gravitational theories that do satisfy Equivalence for *non-gravitational* mass-energy. An example theory in this class is the one-parameter theory further developed by C. Brans and R.H. Dicke.

However, even here- where the couplings were tuned to to preserve EP, one finds that while ordinary mass obeys Equivalence, the mass associated with gravitational self-energy does not. The result is a testable violation of what is sometimes called the 'strong' Equivalence Principle. Will return to this in the section on Lunar Laser ranging.

A little more on EP violation predictions 2

Modern approaches to unifying gravity with the other forces of nature (e.g. superstring and brane theories) also point to the existence of weak, long-range Equivalence Violating forces (mediated by dilatons, moduli) accompanying gravity.

In 1994, Damour and Polyakov found that while such forces would naturally have a magnitude comparable to gravity in the early Universe, as the Universe expands an "attractor-mechanism" may act, making the theory evolve toward, but never quite reach, Einstein's theory. A small residual long-range scalar force would survive, violating Equivalence.
Recently two lines of argument have emerged suggesting that violations may plausibly occur in the range 10^{-14} to 10^{-17} between the existing ground-based data and the region accessible to foreseeable space based experiments.

Antoniadis, Dimopoulos and Giveon "Little String Theory at a TeV", demonstrate that the Damour-Polyakov mechanism is an automatic consequence of one version of NS5-brane theories, and that such theories can lead to violations at the 10^{-16} level.

Dvali and Zaldarriaga[6] have shown that the recent evidence for a variation with time of the fine structure constant virtually requires a violation of Equivalence at a level that must exceed 10^{-17}.

EP and Dark Energy

Distances to Type I supernovae => universe expansion is accelerating
WMAP Measurements of CBM => universe is close to flat

74%	Dark Energy
22 %	Dark Matter
4%	ordinary Matter

Dark energy - negative pressure => acceleration
low density, 10^{-29} gm/cm^3 => difficult to detect in lab

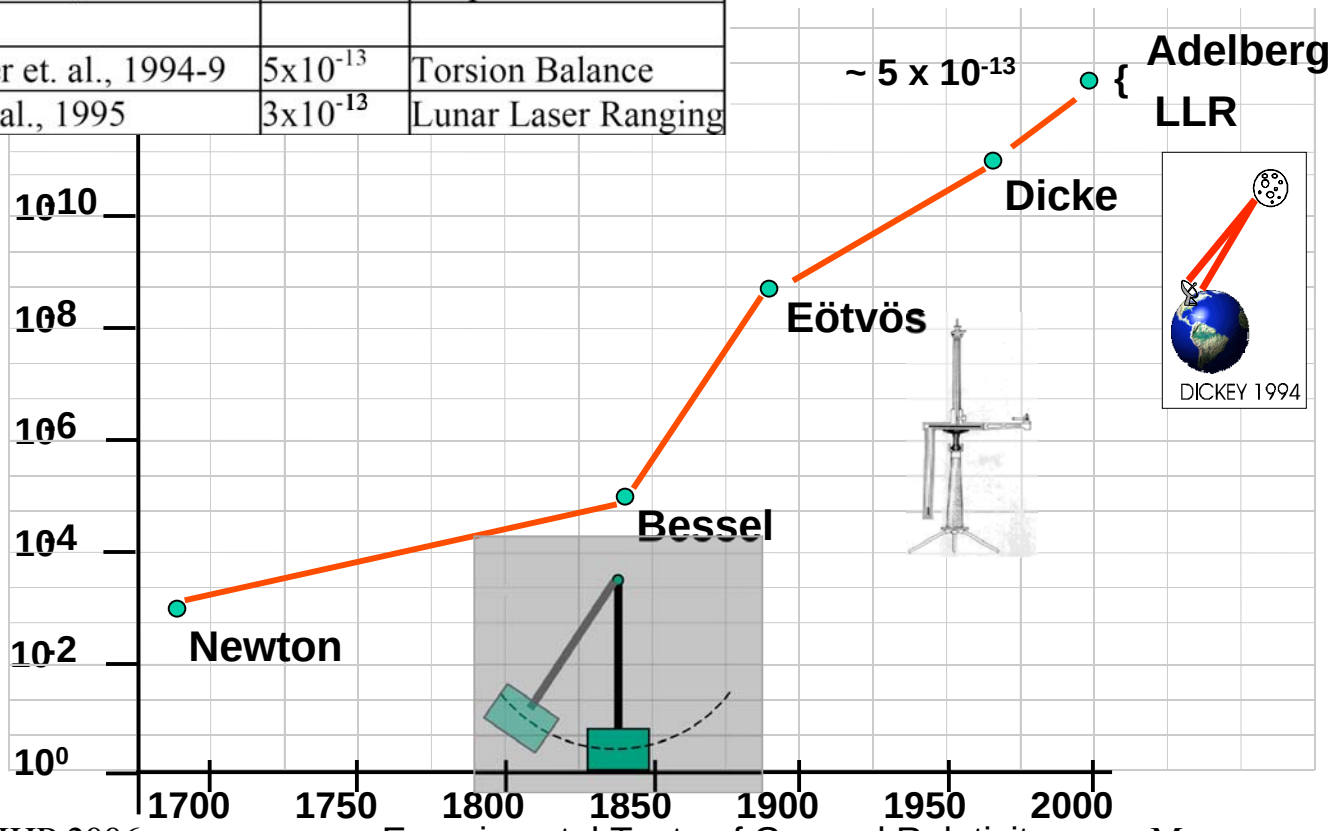
2 proposed forms of Dark Energy
- Cosmological Constant – constant, homogeneous energy density
- Quintessence – dynamical field

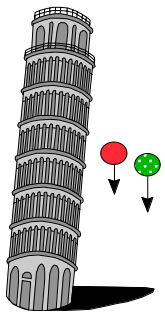
Couplings of Quintessence dynamical field => Equivalence violation

=> EP measurements can distinguish between Quintessence and Cosmological Constant alternatives

Historical Highlights of EP TESTS

Investigator	EP Limit	Method
Philiponus, ~500	"small"	Drop Tower
Galileo, ~1590	10^{-2}	Drop Tower
Newton, 1686	10^{-3}	Pendulum
Bessel, 1832	10^{-5}	Pendulum
Potter, 1923	10^{-6}	Pendulum
Eötvös, 1922	10^{-8}	Torsion Balance
Roll, Krotkov, Dicke, 1962	10^{-11}	Torsion Balance
Braginskii, Panov, 1972	10^{-12}	Torsion Balance
Shapiro et. al., 1976	10^{-12}	Lunar Laser Ranging
Keiser, Faller, 1981	10^{-10}	Fluid Support
Niebauer et. al., 1987	10^{-10}	Drop Tower
Adelberger et. al., 1994-9	$5x10^{-13}$	Torsion Balance
Dickey et.al., 1995	$3x10^{-13}$	Lunar Laser Ranging





EP History

Experimental tests of the Equivalence Principle go back at least to Galileo (and Dutch contemporary Simon Stevin)

Galileo's experiment (1592) demonstrated that a cannonball and a musket ball, dropped from the Leaning Tower of Pisa, hit the ground within a "hand's-breadth" of each other.
Galileo's aim was to publicly refute Aristotle's doctrine that heavy bodies fall faster than light ones. But showed that the acceleration is independent of, not only mass, but also the *composition* of the body. (the canon ball was stone, musket ball was lead)

Newton first saw how surprised one ought to be by this fact.

Newton made quantitative measurements with simple pendula-determining oscillation period as a function of material obtaining precision of of 0.1%. Bessel improved this to a part in 10^5.

The recent era of EP tests began with the torsion pendula measurements of Eötvös.

The Eötvös Experiment

Between 1889 and 1909 Eötvös and colleagues conducted a series of experiments to test the proportionality between inertial and gravitational mass.

To reach high sensitivity Eötvös developed a method based on the torsion pendulum.

Cavendish had first (1798) used this means of making gravitational measurements in his determination of the gravitational constant G(or equivalently the mass of the earth).

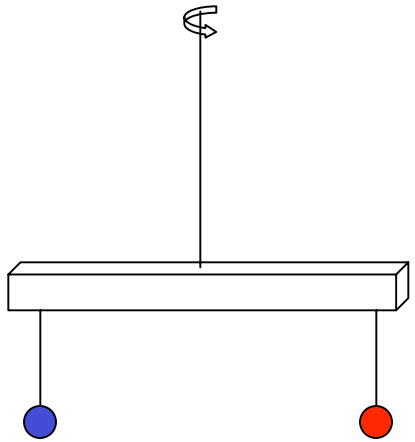
Masses under test were supported by a bar attached to a tungsten torsion fiber.

The small restoring force of the twist of the fiber leads to long periods (~2000 sec in Eötvös' case) and high sensitivity.

In the Eötvös experiment a difference in inertial and gravitational mass would produce a shift in the equilibrium position angle of the support bar in accordance with the balance between the acceleration of the gravity of the earth and the centripetal acceleration caused by the earth's rotation.

Eötvös measured the twist of the fiber optically

as a function of different test masses.



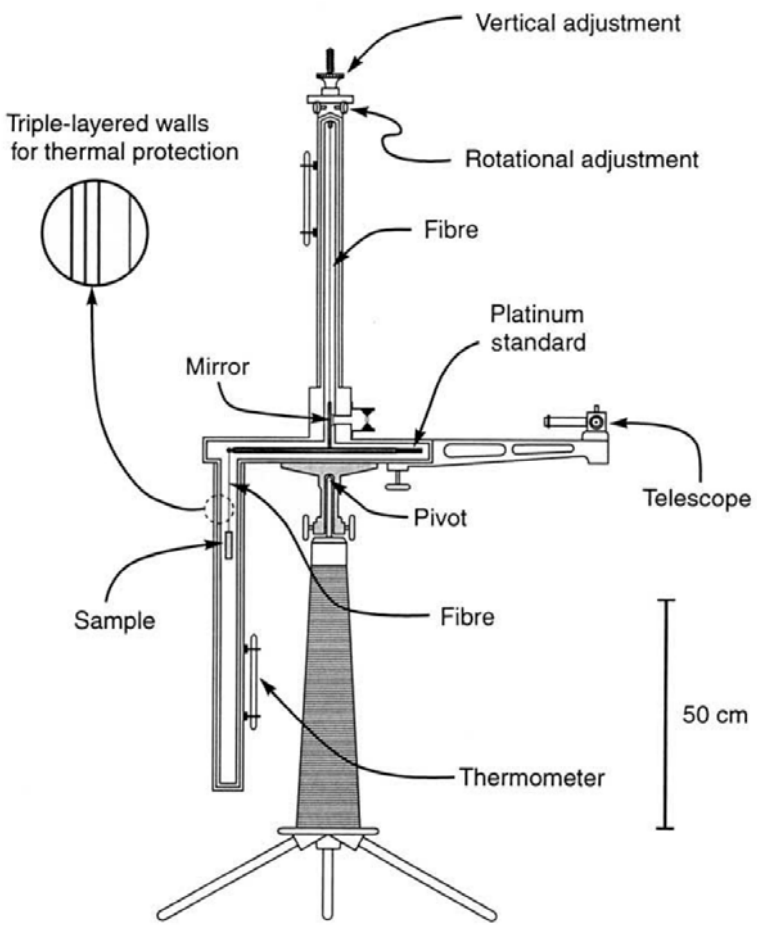
The diagram shows the Eötvös apparatus Fischbach and Talmadge, Nature 1992)

The telescope sights a mirror attached to the torsion fiber. The experimenter would make sightings quickly with respect to the natural period to avoid the disturbance caused by the gravitational attraction of himself.

This was particularly important for Eötvös who weighed ~ 300 pounds.

A variety of test mass materials were tested including:
Pt, Cu, Mg-Al alloy, Asbestos, Tallow, water, CuSo4 solution, and snakewood

Using this technique Eötvös claimed a precision of 1 part in 2×10^8



In the 1960's Robert Dicke, and later Braginsky improved on this technique by using the sun as the source of gravitational acceleration on the masses.

In this case a composition dependent difference would produce a signal modulated at a 24 hour period. Though at the earth's surface the acceleration of gravity due to the sun is only 1/1000 g this technique enabled the measurement precision to be improved to a part in 10^{11} or better - with no composition dependence detected.

Fifth Force

In 1986 Fischbach et al. (PRL 56 1 pg 3) published a reanalysis of the Eötvös data which reported a positive composition dependence correlated with the the hypercharge or Baryon number B/m of the materials. They claimed the analysis supported the existence of a possible fifth force of finite range that would lead to a modification of the gravitational potential to a form

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

With α ~5×10^{-6} and an interaction range of ~ λ = 200 meters.
The experiments of Dicke and Braginsky insensitive to this force since the the sun was the source in their tests.

The possible existence of a fifth force sparked renewed interest in EP measurement.

A group a the University of Washington founded by Blayne Heckel and Eric Adelberger (the Eöt-Wash group) have conducted a series of experiments which have pushed the precision of composition dependence effects to Parts in 10^{13} (and which see no positive effect)

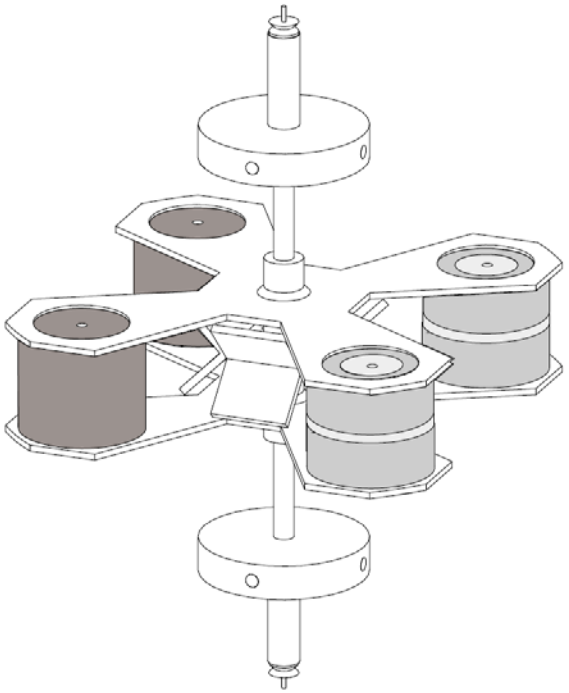
The University of Washington torsion pendulum systems rotate at periods on the order of 30 min to 1 hr to shift signal frequencies away from diurnal effects and employ co-rotating optical system to monitor the twist. Measurements are made with respect to the sun, local hillsides, lab masses and the galactic center.

The geometry of the pendula are constructed and tuned to minimize the first few gravitational multi-pole moments to minimize gravity gradient perturbations.

Eöt-Wash Torsion Pendula

8 test masses

4 Be, 4 Ti



Stainless Steel vs

quartz and magnesium alloy

to mimic earth-moon system

Short Range Tests of the Inverse Square Law

Recent theoretical attempts to explain the hierarchy problem – the weakness of gravity in comparison to the other forces – have given rise to possible new couplings of short range of the Yukawa type

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

with $\lambda \leq 1$mm. This would lead to deviation of the Newton inverse square law behavior at short distances. This likewise has sparked a series of measurements which have now extended the bounds for new interaction at short range.

A bit of motivation:
Why is Gravity so weak (force between e and p is 10^{-39} times electrostatic force)
Arkani-Hamed, Dimopoulis and Dvali's =>
could be that most of its strength leaks off into the extra dimensions
Only gravity sees these extra dimensions
Extra dimensions may be macroscopic (not Planck length 1.6 **x**10^{-33} cm)

In such a picture gravity would be stronger and fall off more quickly than $1/r^2$ at distances approaching the scale of the extra dimensions

Macroscopic curl-up of an extra dimension

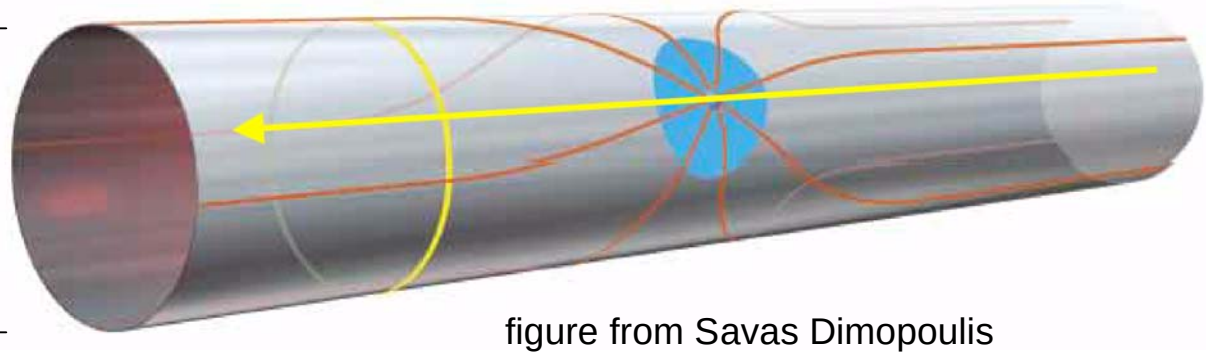
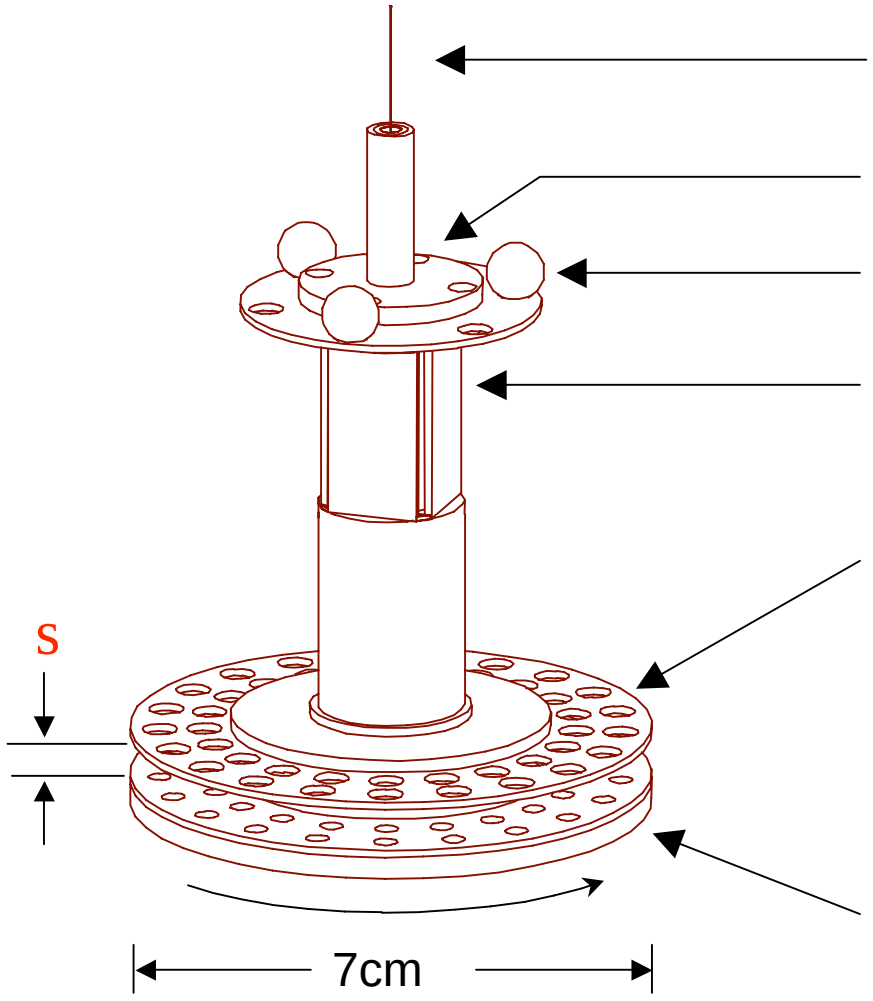


figure from Savas Dimopoulis

Surface is analog to normal 3 space dimensions

Eöt-Wash Short Range Test Torsion Pendulum

From Blayne Heckel



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

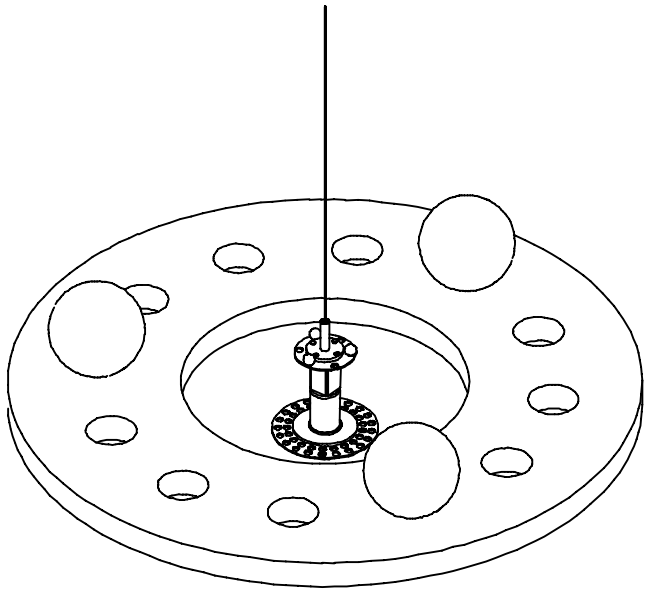
3 aluminum calibration spheres

4 mirrors for tracking deflection angle o

detector: 1mm thick molybdenum ring with 42 holes arranged in 21-fold rotational symmetry

not pictured, 10μm thick Au-coated BeCu membrane, electrostatic shield

attractor : **rotating pair** of discs with 21-fold rotational symmetry, holes in lower attractor out of phase with holes in upper attractor to **cancel Newtonian gravity**



≈1kg brass spheres rotate at a 6-inch radius to provide gravitational calibration torque.

The Stanford Short Range Test

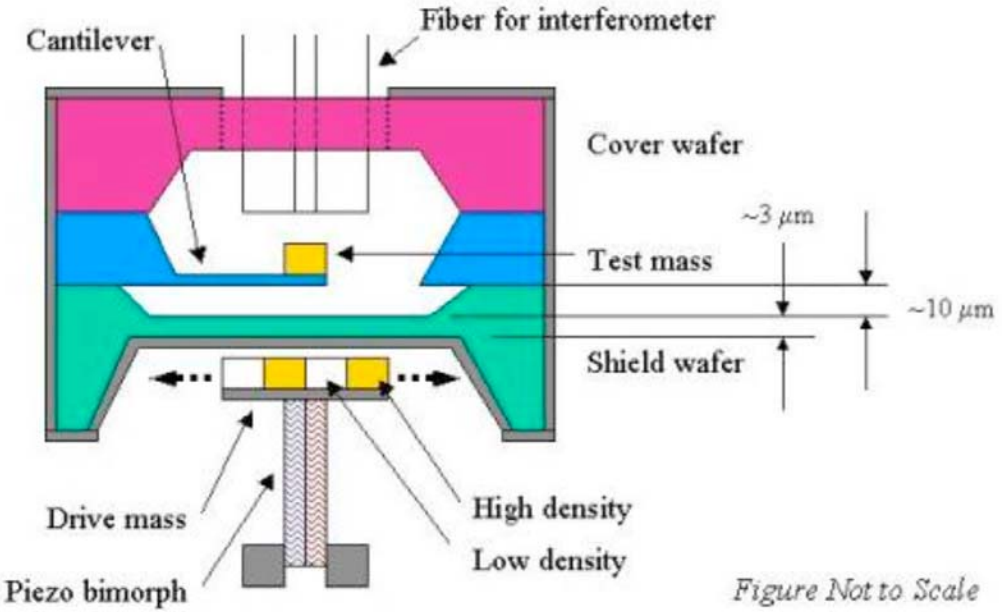
A group at Stanford University directed by Aharon Kapitulnik has developed a different technique

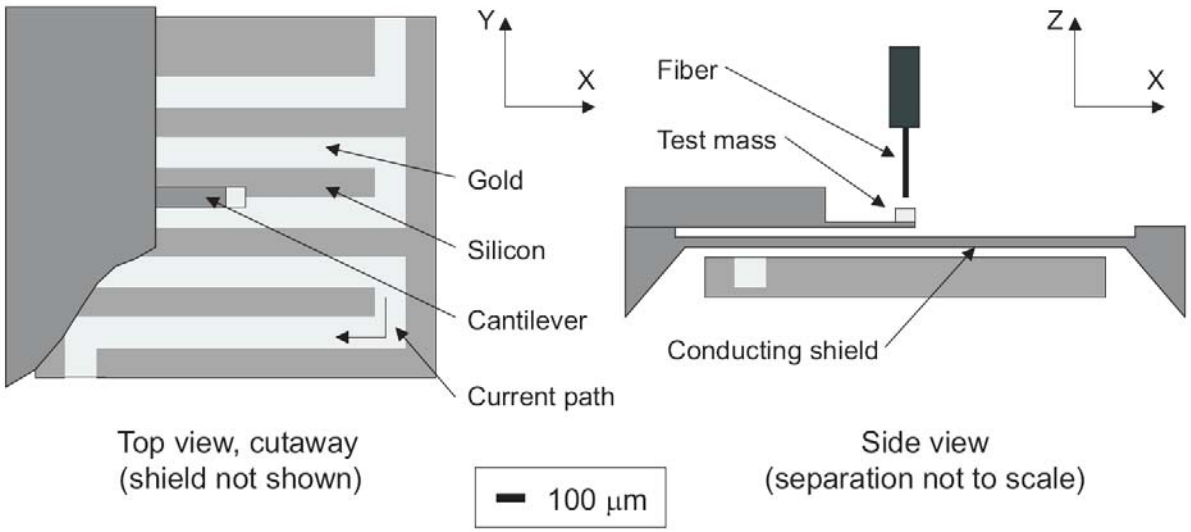
A mass is attached to a micro-cantilever fabricated using micromachining techniques

Fiber-optic interferometry is used to measure the deflection of the micro-cantilever as a drive mass constructed of ten bars: five gold bars alternating with five silicon bars moves horizontally beneath the cantilevered mass.

A sensitivity below 1×10^{-17} N (200 times the expected Newtonian gravitational force) was reached with a few hours of averaging.

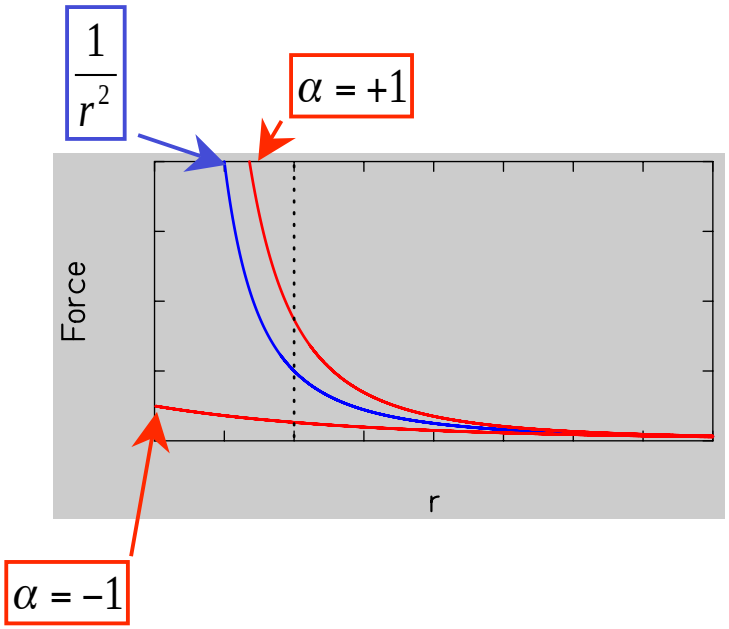
The Stanford Short Range Test Apparatus

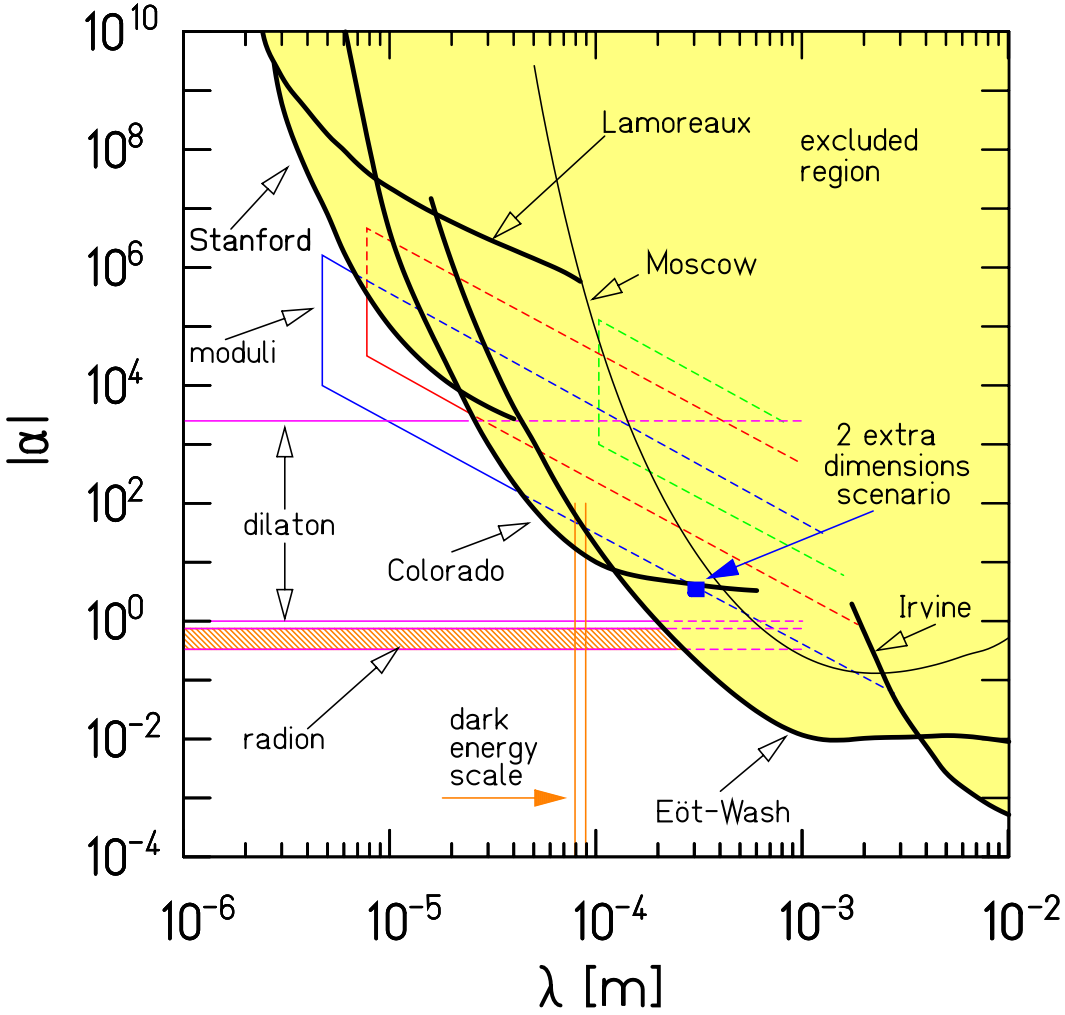




Present Limits On Short Range Tests

From Blayne Heckel





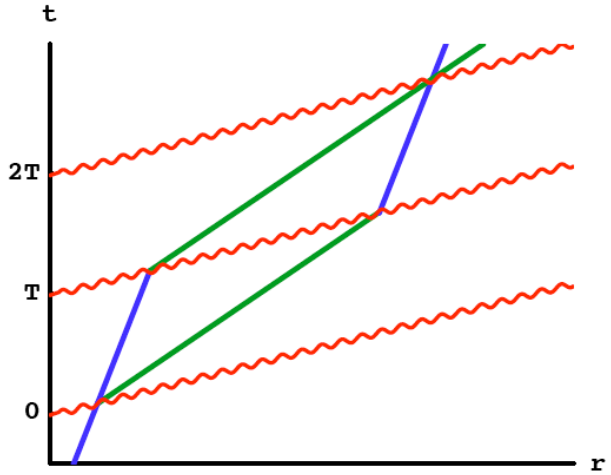
Irvine: PRD **32** 3084 (1985), Eot-Wash: PRD **70** 042004(2004), Colorado: Nature **421** 922(2003), Stanford: PRL **90** 15101(2003)

Future Ground Based EP Tests

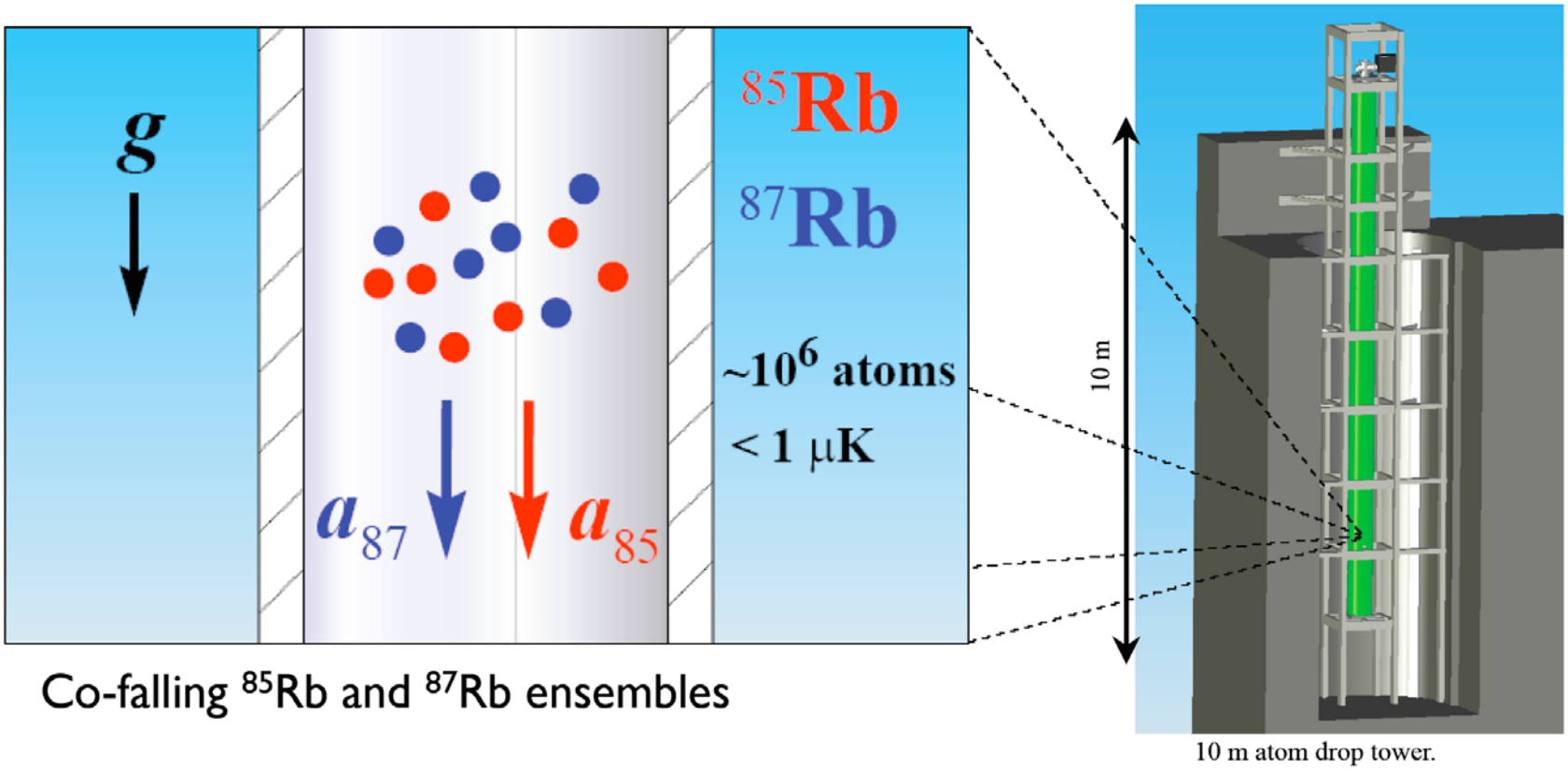
Recently Mark Kasevich of Stanford has proposed using atom interferometry to improve the present limits of Equivalence Principle measurement.

The concept: a cold ensemble of atoms is split into a superposition of two quantum states by a laser pulse, travels up a 10 meter tower.

It is then coherently reflected using a pi laser pulse, travels down the tower and then is recombined with a third pulse. The phase shift produced by the gravity field is detected. Two systems Rb85 and 87 can be run simultaneously. A difference in the gravitational acceleration will be detected by comparing the phase shifts.



Future Ground Based EP Tests



Co-falling ^{85}Rb and ^{87}Rb ensembles

10 m atom drop tower.

Initial results are expected within a year.