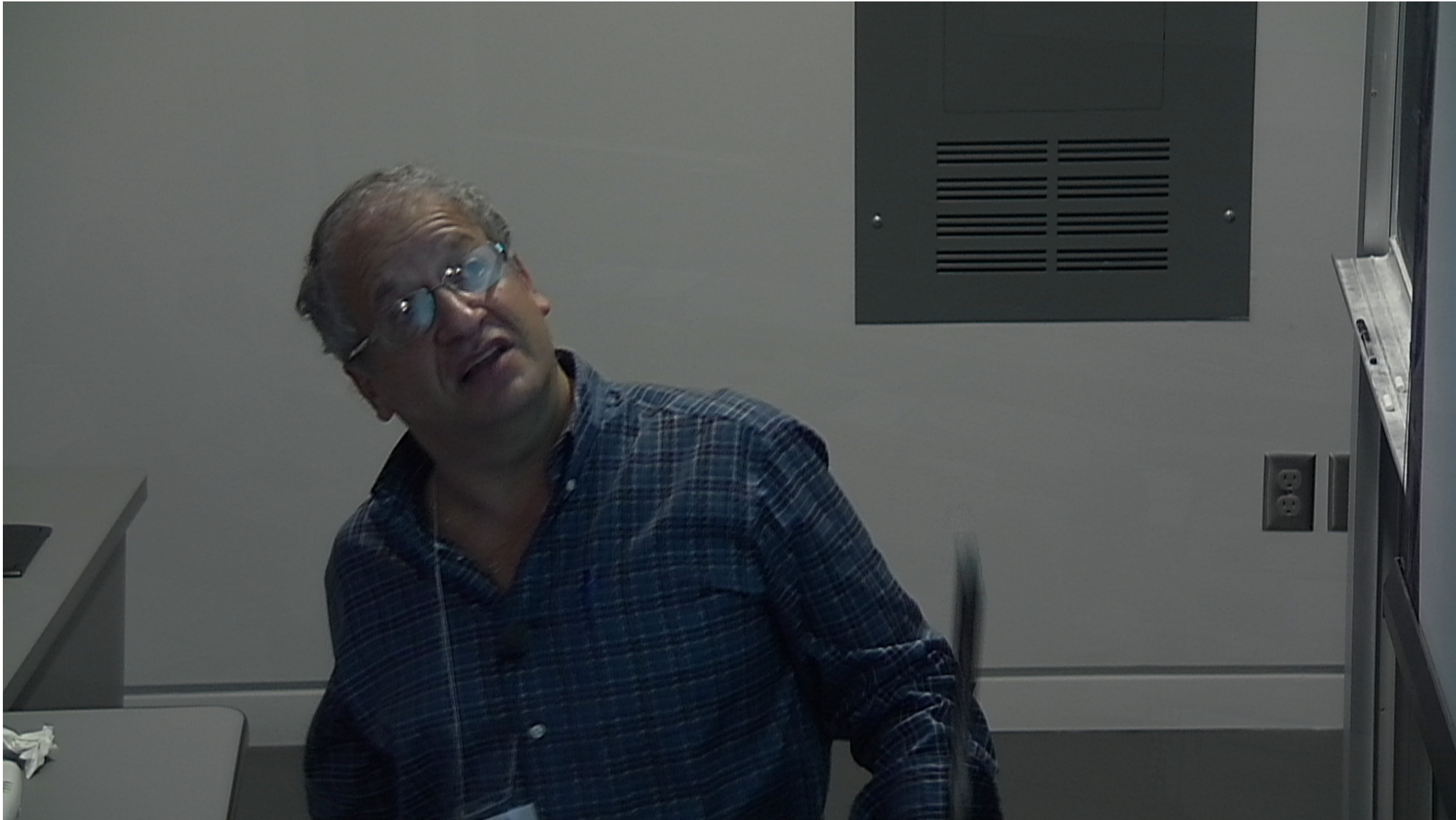


Title: Improved test of the Equivalence Principle as a probe of quantum gravity

Date: Oct 22, 2012 10:35 AM

URL: <http://pirsa.org/12100127>

Abstract: Current approaches to the problems of dark energy and unification generically predict the existence of new fields (quintessence dilatons etc.) that will in principle couple with different strengths to different standard-model fields. These different coupling strengths will cause test materials of different compositions to fall at different rates in the same gravitational field violating the Equivalence Principle the foundation of General Relativity. A sufficiently sensitive measurement of the relative accelerations of different test bodies in orbit around the earth could detect or rule out these new fields complementing existing or proposed experiments in high-energy physics (colliders) and observational cosmology (space telescopes). To do this convincingly such an experiment needs at least three test materials spanning the largest possible volume in the space of atomic and molecular properties and a sensitivity to EP violations of as little as a part in 10^{18} (attainable only in space and at low temperatures). I discuss one such experiment the Satellite Test of the Equivalence Principle which has reached an advanced stage of prototype development and is currently awaiting a path toward a flight program.



Test of the Equivalence Principle

Expositors: James Overduin, Towson University,

Experimental Searches for QG Phenomenology: The hard facts.
October 22, 2012

The Equivalence Principle:

The EP is at the HEART, not just of GR, but of **Inertia**:

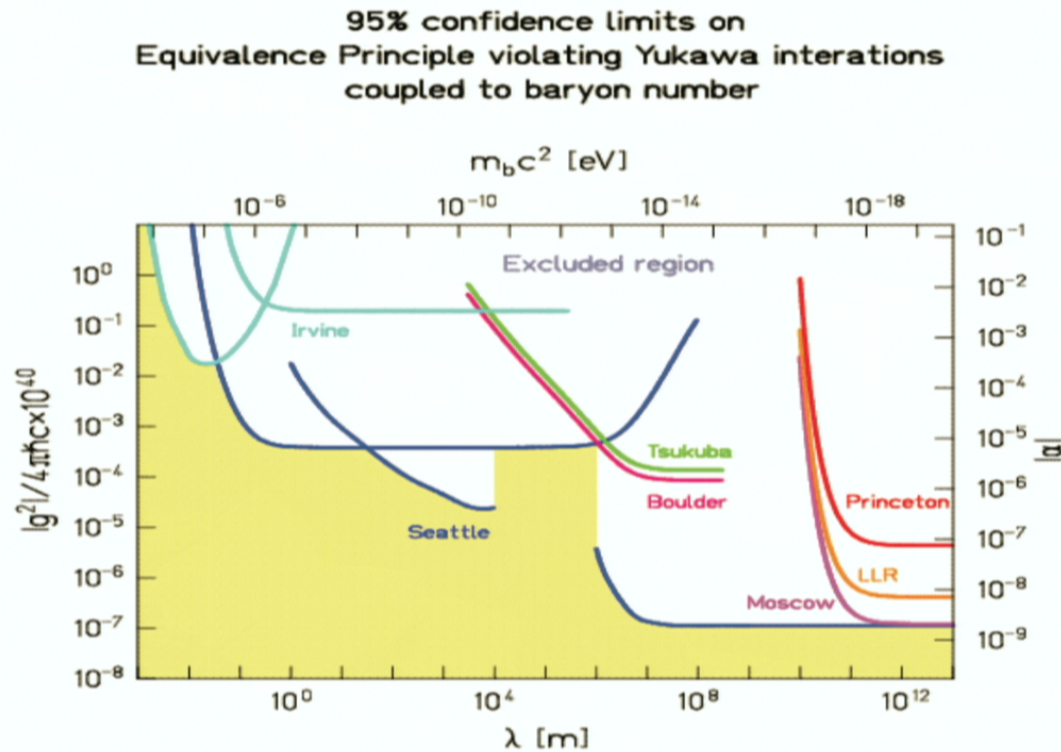
What is **operationally** an inertial frame ? A: **Def:** One where 2 “free” particles moving non- co linearly, do move inertially.....

The LAW OF INERTIA : all other free particles move inertially.

Now: **What are free particles?** (We can make sure they are outside the range of nuclear forces, and have no electric charge or magnetic moment, but we can not turn off Gravity).

The EP is then what makes the above definition work: Simply ignore Gravity: i.e. free falling frames ARE the only **operationally accessible** inertial frames.

Testing EP: Long tradition Gauss, Eötvös, Dicke, etc... and since the mid 1980's with the 5th Force case, much improved tests: $\Delta a/a$ for different objects. (basically stable chemical elements).



There are various versions, WEP, EEP, and SEP, but, in principle, there are several versions regarding their extendibility to quantum systems: (Callender & Okon, Eur. Jour. of Phil. of Sci (2011)).

EP1: Universality of free fall of test bodies.

EP2: Equiv of homogenous Grav. field and accelerated frames.

EP3: Universality of the behavior of systems in small enough regions of space-time

EP4: Universal and minimal coupling of matter fields to gravity.

Classically: Ohanian Objection: The shape of a self gravitating drop of liquid is not spherical if $R^a_{bcd} \neq 0$, even as the size the drop $\rightarrow 0$.

In the Quantum Context, one needs to find the appropriate one. There is often confusion in the fact that the mass does not drop in Schrödinger equation:

$$i\frac{\partial\psi}{\partial t} = -\frac{\nabla^2}{2M}\psi + M\Phi\psi.$$

This has been tested with Neutrons (COW , Grenoble). Some people regard this as a violation of the EP!!.

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Einsteinian Gravity is Emergent:

At the fundamental level, it might be described by something completely different... perhaps some pre-metric structure, but even if we are very very conservative, at the quantum level it is described by other variables... Spin foams, causal sets, strings..., or, quite likely, something else.

It is hard to see how that some exactly valid version of EP could be emergent from some underlying non-metric structure.

In fact it seems hard even if what we have is a highly complex fundamental metric structure:

True objects **ARE NOT** point-like: Quantum Objects are never fully localized, and, thus, it is not clear to what extent they can be considered point like.... (in the **GR** sense), even if they do not have internal structure.

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For instance: Photons are “known” to violate the letter: Drummond and Hathrell (PRD 1980) have shown that curvature affects the path of photons in a EP violating manner! This is “understood” to be a result of a certain non localization of the photon: due to electron-positron dressing it acquires a “size” of order e^2/m_e .

In fact, Papapetrou has shown that, even classically, particles with spin do not move along geodesics!!!.

A sobering fact: So far, we know of no elementary particles without spin!. Can we state, **operationally**, some **version of the EP** that we might hope to be exact ?

We ’ ll hear about a proposal for an improved test (satellite based. Up to 10^{-18}) motivated in part, by the search for new fields coupling to matter.

Can this be distinguished from “real” from EP violations?

Improved tests of the Equivalence Principle as a probe of quantum gravity

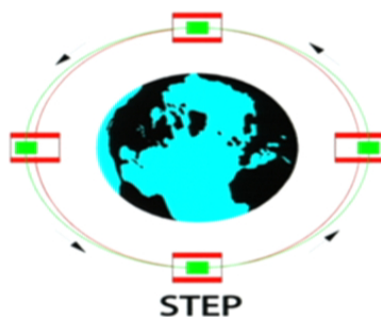
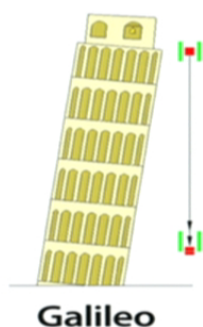
James Overduin (Towson University, Johns Hopkins University)

Experimental search for quantum gravity: the hard facts

Oct. 22, 2012

Satellite Test of the EP (STEP)

- Essentially an orbiting version of Galileo's “drop-tower” experiment

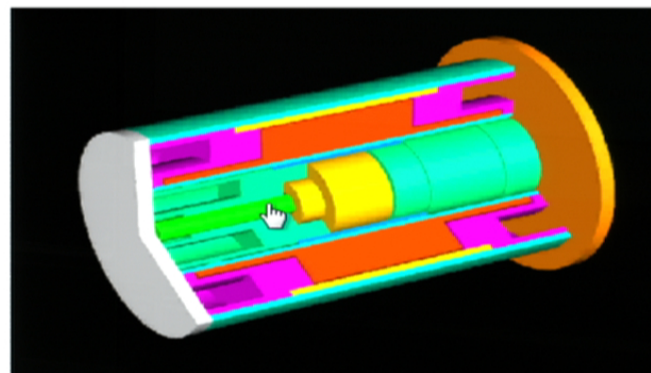
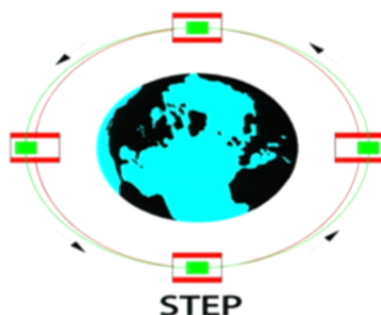
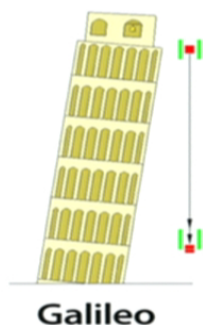


- More time for separation to build, and signal is *periodic*
- Larger driving acceleration and quieter “seismic” environment allow for improvement of 5-6 orders of magnitude over terrestrial tests
- Inherits key technologies from Gravity Probe B: drag-free control, cryogenic SQUID readout, electrostatic positioning system, others



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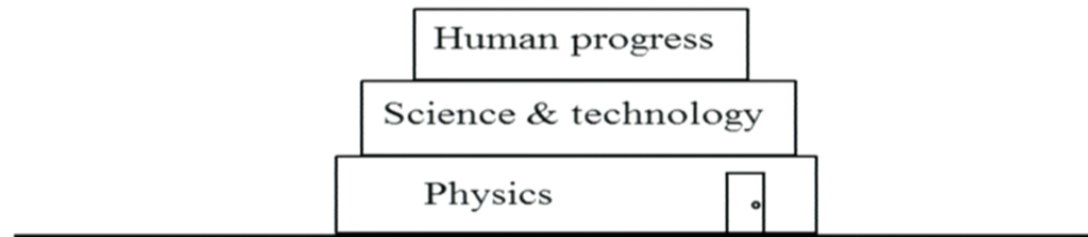
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A fundamental test

- STEP tests the *foundation*---not a prediction---of Einstein's theory of general relativity, which holds up half of present-day physics:



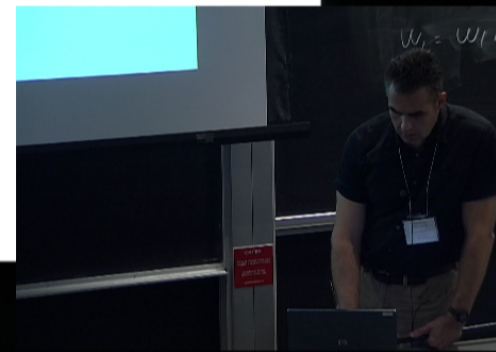
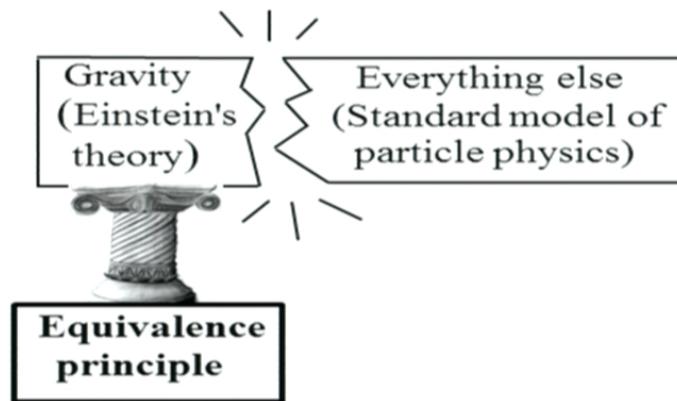
(Theorist's view -
not to scale)

Crisis and unification in physics

- Einstein's geometrical theory of gravity based on the Equivalence Principle fundamentally inconsistent with the rest of physics (standard model)

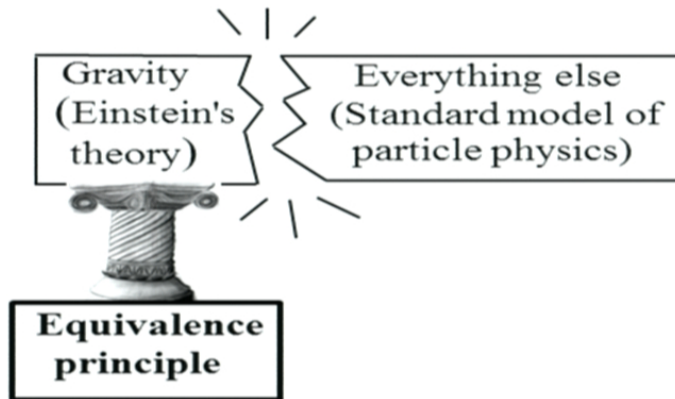
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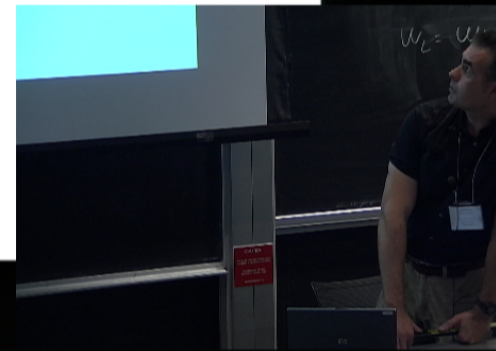
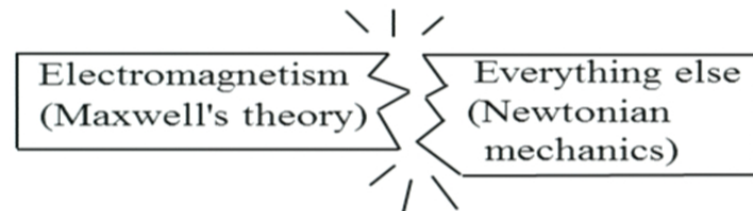


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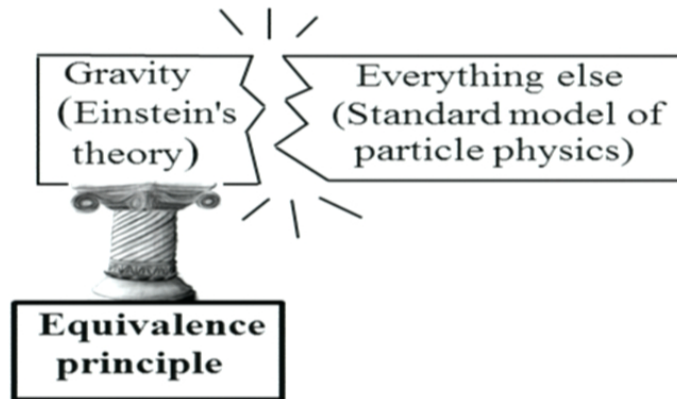


- Physics in crisis, circa 1900:

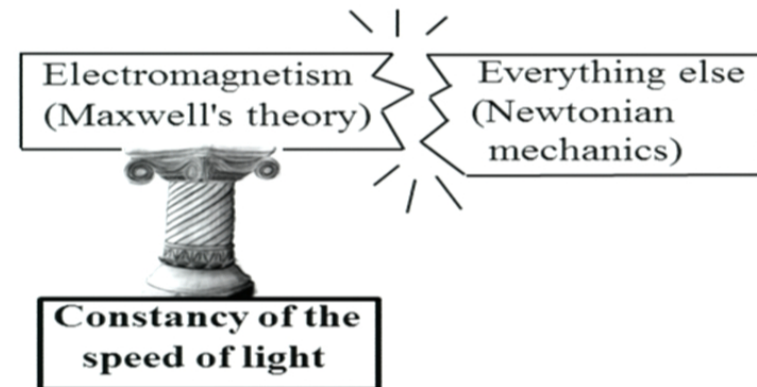


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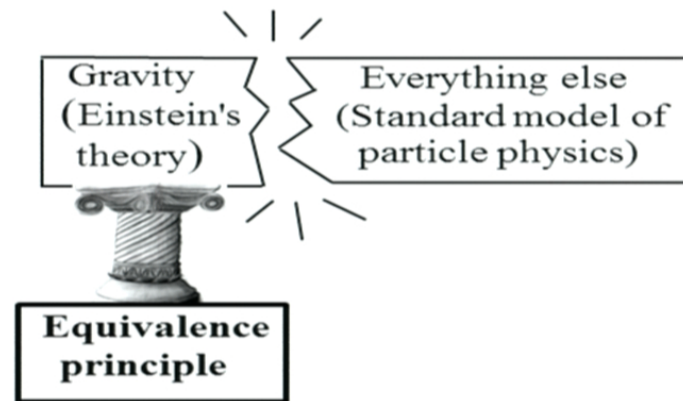
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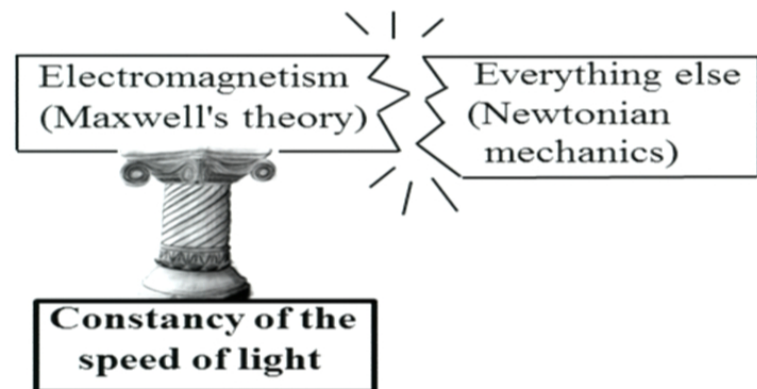


**?
STEP**
↓
Theory of everything?

Crucial
experiment:

Resulting
unified
theory:

- Physics in crisis, circa 1900:



**✓
Michelson-Morley experiment**

↓
Special relativity

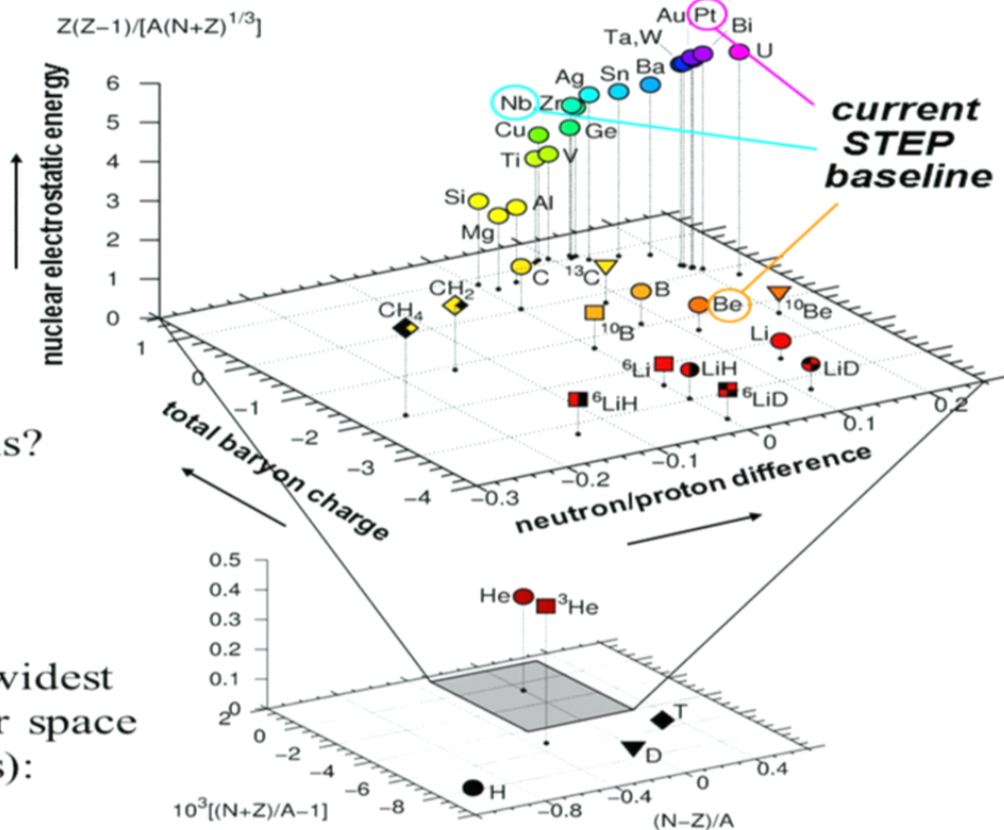


-
- The figure is a 3D plot showing the nuclear electrostatic energy (Y-axis, ranging from 0 to 6) as a function of total baryon charge (X-axis, ranging from -4 to 0.2) and neutron/proton difference (Z-axis, ranging from -0.8 to 0.4). The plot displays various isotopes and molecules, including CH_4 , CH_2 , C , ^{13}C , ^{10}B , ^{10}Be , ^6Li , ^6LiH , ^6LiD , ^3He , ^4He , H , D , T , Si , Mg , Al , Ti , V , Cu , Nb , Zr , Ag , Sn , Ba , Ta , W , Au , Pt , Bi , and U . The plot is labeled with the formula $Z(Z-1)/[A(N+Z)^{1/3}]$ at the top. A zoomed-in view of the lightest nuclei is shown in the bottom right corner, with axes labeled $10^3[(N+Z)/A-1]$ and $(N-Z)/A$.



- heavy vs. light elements?
 - baryons vs. leptons?
 - different particle generations?
 - matter vs. antimatter?
 - fermions vs. bosons?
 - matter vs. *dark* matter?
-
- in a first experiment, span widest possible region in parameter space (e.g. Blaser, Damour, others):

What to drop?



A probe of quantum gravity

- **DIMENSIONAL ARGUMENT:** any attempt to combine gravity with quantum field theory generically predicts new effects above some *characteristic energy scale* E (Adler 2006):

$$\text{predicted} = \text{standard} \left[1 + \xi \left(\frac{E}{m_{\text{qg}} c^2} \right) + \mathcal{O} \left(\frac{E}{m_{\text{qg}} c^2} \right)^2 \right]$$

where $\xi \sim \mathcal{O}(1)$ and:

$$\frac{E}{m_{\text{qg}} c^2} = \begin{cases} \frac{m_{\text{Higgs}}}{m_{\text{gut}}} \sim \frac{100 \text{ GeV}}{10^{16} \text{ GeV}} \sim 10^{-14} \\ \frac{m_{\text{nuc}}}{m_{\text{Pl}}} \sim \frac{1 \text{ GeV}}{10^{19} \text{ GeV}} \sim 10^{-19} \end{cases}$$

Importance of a null result

- **GENERIC APPROACH:** supplement standard model with simplest possible new field: one scalar field ϕ (as motivated by dark energy, string theory dilaton or supersymmetric moduli fields)
- ϕ couples to standard-model matter via dimensionless couplings β_k
- standard calculations (Carroll 1998 and others) show that if

$$\frac{\Delta a}{a} \lesssim 10^{-12} \quad \text{then:} \quad \beta_k \lesssim 10^{-6} \quad (\text{current constraint})$$

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10^{-18} **10^{-9} (STEP sensitivity)**



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10^{-18} (red arrow from 10^{-12}) 10^{-9} (red arrow from 10^{-6}) **(STEP sensitivity)**

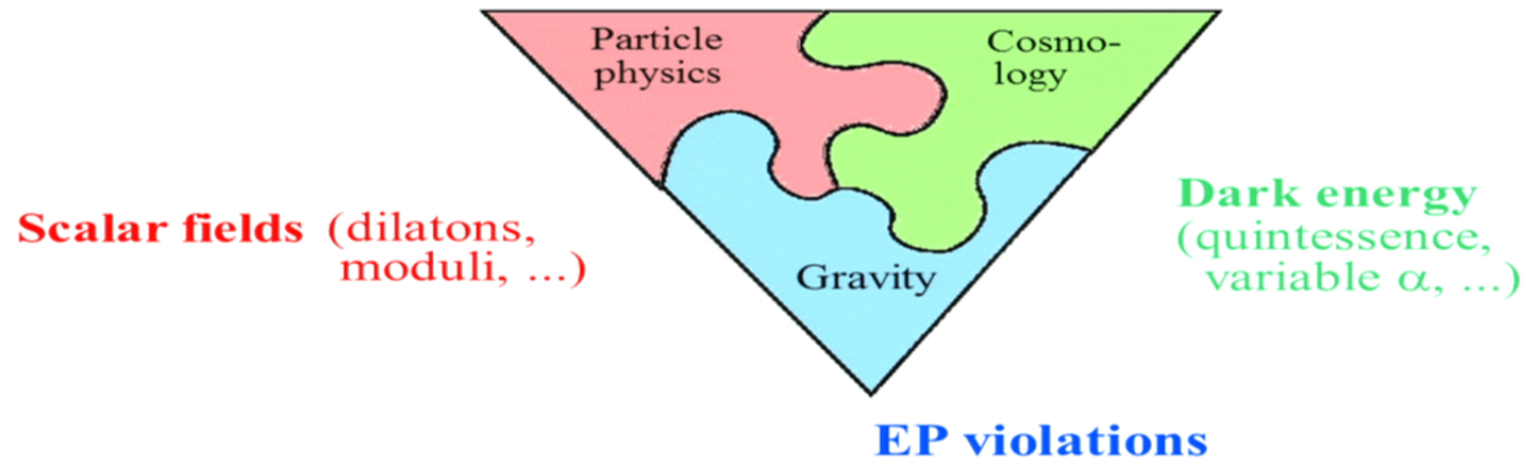
- dimensionless couplings as small as 10^{-6} are natural – *barely!* (cf. $\frac{\alpha_{\text{em}}^2}{16\pi}$)
- couplings smaller than 10^{-9} are not! (cf. “strong CP problem”)
- Ed Witten (2000): ***“It would be surprising if ϕ exists and would not be detected in an experiment that improves bounds on EP violations by 6 orders of magnitude”***
- a null result *closes the door* on new fields of the kind generically predicted by unified field theories, implying that a gravity really is purely geometrical and a more radical approach is required to unify it with the standard model

In a nutshell

- All or most approaches to quantum gravity involve new fields with non-universal couplings to SM fields
- The corresponding dimensionless coupling strengths (β) translate into violations of the EP ($\Delta a/a$)
- Below a certain point, nonzero coupling strengths β are inherently unnatural
- An null EP detection over the corresponding range of $\Delta a/a$ then becomes an experimental test of quantum gravity
- (A positive detection is of course something else altogether)
- A space test offers the surest way to reach both the required sensitivity and do so with a diverse set of test materials (spanning the largest possible volume of SM phase space)

Complementarity

Fundamental physics triangle:



Extra slides - theory