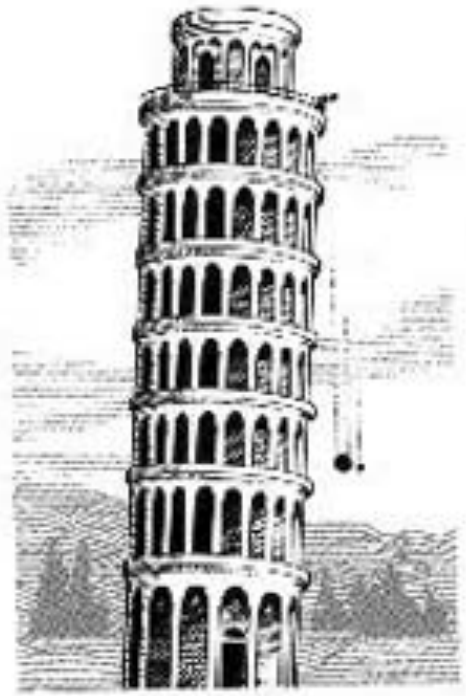
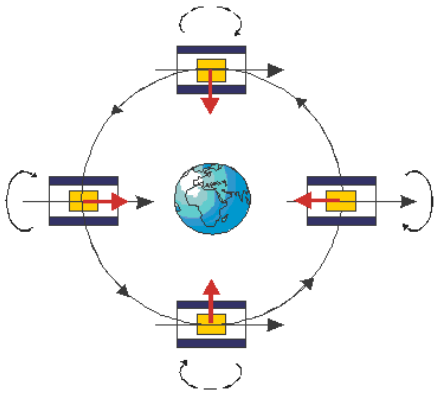
Why Test the Equivalence Principle ?

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(Einstein) Equivalence "Principle" (EP)

- Not a basic principle of physics

- A heuristic generalization of an experimental fact: "hypothesis of equivalence" (Einstein)

$\longrightarrow$ very successful in building General Relativity (GR)

- GR is based on two basic postulates:
  - **(1)** EP: Universal coupling of matter to gravity $(\eta_{\mu\nu} \to g_{\mu\nu}(x))$ plus usual coupling constants of special relativistic physics
  - **(2)** Dynamics of the gravitational field $g_{\mu\nu}(x)$

$$S = S_{\rm matter}[\psi, A, \phi; g_{\mu\nu}; g_a, Y, \lambda, \mu] + \int d^4x \sqrt{g}\, \frac{R(g_{\mu\nu})}{16\pi G}$$

Special Relativistic Physics (SM, MSSM, . . .)

$$S_{\rm SM}[\psi, A, \phi; \eta_{\mu\nu}; g_a, Y, \lambda, \mu]$$

based on two types of absolute structures

Space-time structure: $\eta_{\mu\nu}$

Coupling constants:

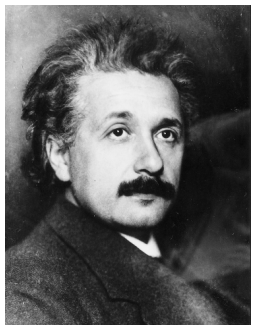
gauge couplings	g_1, g_2, g_3
scalar boson (BEH) parameters	μ, λ
Yukawa couplings	Y_{ij}
UV cut-off	$\Lambda_{\rm UV}$

about 20 parameters in SM and $\sim$ 100 in MSSM

What determines the coupling constants? (I)

• Very unsatisfactory to put them by hand: this is against the "principle of reason" nihil est sine ratione (Leibniz)

• The history of physics suggests that there are no absolute structures in physics



Einstein's GR:

$$\eta_{\mu\nu} \longrightarrow g_{\mu\nu}(x)$$

absolute, rigid spacetime

elastic spacetime, dynamically influenced by matter

What determines the coupling constants? (II)

Kaluza-Klein's idea:

$$g_1 \quad \text{or} \quad \alpha_{\rm em} \simeq \frac{3}{8}\frac{g_1^2}{4\pi\hbar c} \simeq \frac{1}{137} \quad \longrightarrow \quad g_{55}(x)$$

higher-dimensional elastic spacetime





Dynamical symmetry breaking (BEH): the vacuum state minimizes the energy $V(\phi)$ which dynamically determines

$$\langle\phi\rangle \sim \frac{\mu}{\sqrt{\lambda}} \longrightarrow m_e \sim Y_e\langle\phi\rangle \sim Y_e\frac{\mu}{\sqrt{\lambda}}$$

Origin of the mass scales in the SM?

• A striking property of the SM: its "near conformal" invariance. The primary source of conformal-invariance breaking is the mass scale μ in the scalar (BEH) sector. Then $m_{\rm quarks}$ and $m_{\rm leptons}$ α μ.

• On the other hand, $m_{\rm hadrons} \sim \Lambda_{\rm QCD} \simeq \Lambda_{\rm UV}\, e^{-\frac{c}{g^2_{\rm UV}}}$ "dimensional transmutation" (Coleman, Weinberg '73).

• Quantum breaking of classical conformal invariance as possible origin of mass scale of quarks and leptons (Meissner, Nicolai '07): extended scalar sector

$$V_{\rm scalar}(\Phi,\varphi) = \frac{\lambda_1}{4}\,(\Phi^\dagger\Phi)^2 + \frac{\lambda_2}{2}\,\varphi^2(\Phi^\dagger\Phi) + \frac{\lambda_3}{4}\,\varphi^4$$

quantum corrections (Coleman-Weinberg) modify $V_{\rm scalar}(\Phi,\varphi)$ and introduce a scale coming from $\Lambda_{\rm UV}$, $\lambda_i^{\rm UV}$:

$$m_{\rm leptons} \text{ and } m_{\rm quarks} \propto \Lambda_{\rm UV}\, f(\lambda_i^{\rm UV})$$

In both cases "external" dynamical effects determine the structure of local "vacuum"

$$\eta_{\mu\nu} = g_{\mu\nu}(x)$$

$$\alpha_{\rm em} \sim g_{55}(x) \qquad \text{(if KK)}$$

$$m_A \sim Y_A \frac{\mu}{\sqrt{\lambda}}$$

Then if any of the coupling constants of local physics (e.g., $\alpha_{\rm em}$, m_e/m_p, m_q/m_p, ...) is x-dependent

$\Longrightarrow$ violation of (weak) equivalence principle (Dicke 1962)

Notably violation of universality of free fall

$$S_{\rm m_A} = -\int m_A[\alpha(x), \ldots] \sqrt{-g_{\mu\nu}(x)\, dx^\mu\, dx^\nu}$$

Composition-dependent acceleration

$$\vec{a}_A = \vec{g} - \vec{\nabla}\, \ell n\, m_A[\alpha(x), \ldots] = \vec{g} - \frac{\partial\, \ell n\, m_A}{\partial\, \alpha} \vec{\nabla}\, \alpha - \ldots$$

String-inspired motivation for EP violation

String theory:

- "magically" unites Relativistic Quantum Theory with GR

$$\{\eta_{\mu\nu} + \text{string} + \hbar\} \longrightarrow \text{dynamical } g_{\mu\nu}(x)$$

- naturally unifies gauge-theories (A_μ) with gravity $(g_{\mu\nu})$, and more generally matter, interactions and space-time

- at face value, string theory contains no arbitrary coupling constants, and is a vast generalization of the Kaluza-Klein idea

$$g_a^{D=4} = f(\langle\phi_1(x)\rangle, \langle\phi_2(x)\rangle, \ldots, \langle\phi_n(x)\rangle, \ldots)$$

many scalar (moduli) fields of dynamical origin: compactified dimensions, brane positions,...

General dilaton-like model of EP violations

Assume general dependence of coupling "constants" on some "dilaton" field φ: $\alpha_{EM}(\varphi), (m_q/\Lambda_{QCD})(\varphi), (m_e/\Lambda_{QCD})(\varphi), \cdots$. Then the dependence of m_A upon fundamental coupling constants:

$$m_A = \Lambda_{QCD} \hat{m}_A(\alpha_{EM}, \frac{m_u}{\Lambda_{QCD}}, \frac{m_d}{\Lambda_{QCD}}, \frac{m_e}{\Lambda_{QCD}})$$

$\rightarrow$ a φ dependence of m_A and a corresponding dilaton coupling to m_A

$$\alpha_A = \frac{\partial \ln m_A(\varphi)}{\partial \varphi}$$

Composition-dependent modification of Newtonian interaction

$$V(r) = -G \frac{m_A m_B}{r} (1 + \alpha_A \alpha_B e^{-m_\varphi r})$$

If inverse range of φ: $m_\varphi = 0$. $\rightarrow$ Weak EP violation

$$\eta_{AB} = \left(\frac{\Delta a}{a}\right)_{AB} \simeq (\alpha_A - \alpha_B)\alpha_E$$

Composition-dependence of scalar-induced EP violations

General possible (dilaton-like) phenomenology (Damour-Polyakov'94, Dent'08, Damour-Donoghue'10) contain four different couplings , which are expected to be well approximated by two effects ($A \equiv N + Z$)

$$\left(\frac{\Delta a}{a}\right)_{AB} \simeq \left[\frac{c_1}{A^{1/3}} + c_2 \frac{Z^2}{A^{4/3}}\right]_{AB}$$

Two dominant EP signals, linked to nuclear physics (variation of $m_q/\Lambda_{\rm QCD}$) and Coulomb effects (variation of $\alpha_{\rm EM} = e^2/\hbar c$)

Two material pairs suffice to constrain the two dominant EP parameters c_1, c_2

Dilaton-like models allow to a priori compare the sensitivity of various EP tests: e.g. the "dilaton charge vector" of the pair Rb^{85}, Rb^{87} can be compared to that of Pt, Ti and is found to be $\sim 10^{-2}$ smaller.

Composition-dependence of vector-induced EP violations

General possible vector-like phenomenology (Fayet $\geq$ 81; spin-1, long-range U boson). $Q_U = Q + \alpha B + \beta L + \cdots$ Two dominant EP signals on electrically neutral bodies

$$\left(\frac{\Delta a}{a}\right)_{AB} = \left[c_1 \frac{N}{M} + c_2 \frac{Z}{M}\right]_{AB}$$

Two material pairs suffice to constrain the two dominant EP parameters c_1, c_2, and to distinguish vector models from scalar models

Can moduli fields be nearly massless ?

The dynamical nature of all coupling constants (and mass ratios) in string theory a priori suggests the presence of EP violations.

However, it seems (in the weak coupling domain) that if the moduli fields stay massless, the level of EP violation would be phenomenologically too large (and would also jeopardize inflation)

Majority view: try to find "string vacua" which stabilize all moduli fields at the minimum of some effective potential $V(\phi_1, \phi_2, \ldots)$

$\Longrightarrow$ all moduli acquire a mass $m_a^2 \sim \partial^2 V / \partial \phi_a^2$ (see Denef2008)

EP tests are important because they test an assumption commonly made in string theory, and could refute it.

String-inspired cosmological attractor mechanism

A different scenario for trying to reconcile the existence of (massless) moduli with phenomenology (Damour-Polyakov, Damour-Piazza-Veneziano).

Modulo some assumption about the (strong-field) behaviour of the coupling functions $g_a(\phi)$ of moduli, ϕ might be cosmologically attracted towards a value ϕ_* where ϕ_* decouples from matter; i.e.

$\alpha_A(\phi) \to \alpha_A(\phi_*) = 0$ during cosmological expansion

This mechanism naturally generates $\Delta a/a \ll 1$ without using small parameters.

It gives an "existence proof" of an EP violation which is naturally below the currently tested level $\Delta a/a \sim 10^{-13}$

- Dilaton run-away scenario (DPV) dilaton Φ:

$$\mathcal{L}_{\rm eff} = B_R(\Phi)\, R(g) + B_\Phi(\Phi)(\nabla\Phi)^2 + B_F(\Phi)\, F^2_{\mu\nu} + \dots$$

where $B_i(\Phi)$ = various dilaton coupling functions.

- Assume $B_i(\Phi) = C_i + O(e^{-2\Phi})$ as $\Phi \to +\infty$ (strong coupling domain).

Then, during cosmological expansion, because of the $B(\Phi)$-induced Φ-dependence of the matter density, the dilaton Φ is attracted towards large positive values ($\Phi_* = +\infty$).

- $\Longrightarrow$ coupling of Φ to matter $\propto \frac{\partial\, B_i}{\partial\, \Phi} = O(e^{-2\Phi})$ is naturally driven to small values.

- Many observational consequences today.

Relations between the various observational consequences of the dilaton-runaway scenario

• Link between weak EP violation and Cosmology (assuming inflationary potential $V(\chi) = \lambda(\Phi)\,\chi^n$ with $n = 2$)

$$\frac{\Delta a}{a} \sim 5 \times 10^{-4} \left(\frac{b_F}{b_\lambda c}\right)^2 \left(\frac{\delta\rho}{\rho}\right)^2 \sim \left(\frac{b_F}{b_\lambda c}\right)^2 \times 10^{-12}$$

Link between EP violation and variation of constants:$\dot{\alpha}_{\rm EM}/\alpha_{\rm EM}, \ldots$ ($\alpha_{\rm EM} = e^2/\hbar c$

$$\frac{d\ \ln\ \alpha_{\rm EM}}{dt} \sim \pm 10^{-16} \sqrt{1 + q_0 - \frac{3}{2}\,\Omega_m}\, \sqrt{10^{12}\,\frac{\Delta a}{a}}\ yr^{-1}$$

• Link between EP and tests of (PN) gravity

$$\frac{\Delta a}{a} \sim 10^{-2}\,\frac{d_q}{d_g}\,\frac{1 - \gamma^{\rm PPN}}{2}$$

Other motivations for weakly coupled light particles

• The observation of dark energy $\rho_{\rm vac} \sim 10^{-123}\ m^4_{\rm Planck} \neq 0$ poses a challenge May be it is an indication of a $V(\phi)$ relaxing towards zero ("quintessence", Wetterich, ..., Steinhardt, ...), which suggests the existence of EP violations linked to the nearly massless ϕ.

• If dark matter is some light (sub eV) particle, it might have EP-violating coherent couplings to ordinary matter.
• Example leading to EP violations: sub-eV scalar dark matter with "scalar portal" coupling (Piazza, Pospelov 2010) $\mathcal{L} \ni A\phi H^\dagger H$: *super-renormalizable* coupling: avoid the unnaturalness of a very light ϕ in presence of quantum WEP (only logarithmically divergent corrections to m_φ).
• after symmetry breaking $\varphi = \phi + \frac{A\, v_H^2}{2\, m_\varphi^2}$ mediates a fifth force of range m_φ^{-1}.

Anthropic-type argument for EP violation (Damour-Donoghue 2010)

Independently of any specific theoretical model one might argue (along the "anthropic" approach to the vast "multiverse" of cosmological and/or string backgrounds) that:

(i) the EP is not a fundamental symmetry principle of Nature

(ii) the level $\eta \sim \Delta a/a$ of EP violation can be expected to vary, quasi-randomly, within some range of order unity over the full multiverse

(iii) as there is probably a maximal level of EP-violation, say $\eta_* \neq 0$ [currently bounded to be $< 10^{-9}$], which is compatible with the development of life (and physicists), one should a priori expect to observe, in our local environment, an EP violation η of order η_*.

Awaiting surprising for tests of gravity in space?

• "Chameleon" mechanism (Khoury, Weltman '04, ..., Brax, ...) combining the attractor mechanism (which uses φ-dependence of Lagrangian couplings e.g. $B(\phi) = e^{\beta\,\Phi/MP}$) with a quintessence-like potential $V(\phi) = M^{4+n}\,\phi^{-n}$

$\Rightarrow \;\; V_{\rm eff}(\phi) = V(\phi) + \rho\, B(\phi)$

$\Rightarrow$ environment-dependent $m_\phi = m_\phi(\rho)$

• m_ϕ in the near vacuum of space could be much smaller than m_ϕ in Earth-bound experiments.

• Existence proof that space experiments could measure larger deviations from usual gravity than extrapolated from ground experiments: e.g. for value of G, or EP-violation η_{AB}.

Conclusions

• EP is intimately connected with some of the basic aspects of modern physics, and of the unification of gravity with particle physics.

• The historical tendency of physics to discard any absolute structures, as well as the generalized Kaluza-Klein aspects (moduli) of string theory a priori suggests there could exist EP violations.

• $\exists$ no firm prediction for level of EP violation, but some phenomenological models show that the violation could naturally be just below the currently tested level.

• Experimental tests of the EP well below the present $\sim 10^{-13}$ level (such as the Microscope space mission; 10^{-15} EP test) might discover a well-needed clue beyond our current knowledge of gravity