BERN
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THEORETICAL MOTIVATION FOR TESTING THE EQUIVALENCE PRINCIPLE

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EQUIVALENCE 'PRINCIPLE'

- NOT A BASIC PRINCIPLE OF PHYSICS
- A HEURISTIC GENERALIZATION OF AN EXPERIMENTAL FACT: 'HYPOTHESIS OF EQUIVALENCE' (EINSTEIN)

→ VERY SUCCESFUL IN BUILDING GENERAL RELATIVITY (GR)

- GR IS BASED ON TWO BASIC POSTULATES:

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

UNIVERSAL COUPLING MATTER TO GRAVITY $\eta_{\mu\nu} \to g_{\mu\nu}(x)$

USUAL COUPLING CONSTANTS OF SPECIAL RELATISTIC PHYSICS

DYNAMICS OF THE GRAVITATIONAL FIELD

'EQUIVALENCE PRINCIPLE'

SPECIAL RELATIVISTIC PHYSICS (SM, MSSM...)

$$S_{SM} = \sum_{a=1,2,3} -\frac{1}{4g_a^2}\,\eta^{\alpha\rho}\eta^{\beta\nu}\,F^{(a)A}_{\alpha\beta}\,F^{(a)A}_{\rho\nu}$$

$U(1)\times SU(2)\times SU(3)$

$$+\sum_{3\times(q,\ell)} \bar{\psi}_i\,\gamma^\mu\left(\partial_\mu + \sum_a A^{(a)A}_\mu T^A_\psi\right)\psi_i$$

3 GENERATIONS OF QUARKS AND LEPTONS

$$-\eta^{\mu\nu}\left(\partial_\mu\phi + \sum_a A^{(a)A}_\mu T^A_\phi\right)\left(\partial_\nu\phi + \sum_a A^{(a)A}_\nu T^A_\phi\right)^*$$

$$+\mu^2\,\phi^*\phi - \lambda\,(\phi^*\phi)^2$$

HIGGS SECTOR

$$+\sum_{i,j} Y_{ij}\,\bar{\psi}_i\,\phi\,\psi_j$$

COUPLING HIGGS FERMIONS

ABSOLUTE STRUCTURES:

SPACE-TIME

$\eta^{\mu\nu}$

COUPLING CONSTANTS:

- GAUGE COUPLINGS g_1, g_2, g_3
- HIGGS PARAMETERS μ, λ
- YUKAWA COUPLINGS Y_{ij}
- UV CUT-OFF Λ_{UV}

ABOUT 20 PARAMETERS IN SM

AND ~ 100 IN MSSM

WHAT DETERMINES THE COUPLING CONSTANTS ?

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

$\eta_{\mu\nu}$: ABSOLUTE, RIGID SPACETIME

$g_{\mu\nu}(x)$: ELASTIC SPACETIME, DYNAMICALLY INFLUENCED BY MATTER

KALUZA-KLEIN'S IDEA:

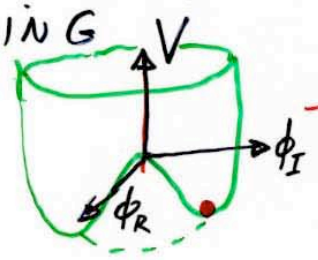
g_1 OR $\alpha_{em} \simeq \frac{3}{8}\frac{g_1^2}{4\pi\hbar c} \simeq \frac{1}{137} \longrightarrow g_{55}(x)$

HIGHER-DIMENSIONAL ELASTIC SPACETIME

DYNAMICAL SYMMETRY BREAKING

A PRIORI IN SM $m_e^{(0)} = \dots = m_{24}^{(0)} = 0$

BUT



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

Y_e: DYNAMICALLY DETERMINED: THE VACUUM STATE MINIMIZES THE ENERGY

IN BOTH CASES

'EXTERNAL' DYNAMICAL EFFECTS THAT DETERMINE THE STRUCTURE OF LOCAL 'VACUUM'

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

$\alpha_{em} \sim g_{55}(x)$ (IF KK)

$m_i \sim Y_i \frac{\nu}{\sqrt{\lambda}}$

THEN IF ANY OF THE COUPLING CONSTANTS OF LOCAL PHYSICS (EG., α_{em}, m_e/m_p, m_q/m_p, ...) IS x-DEPENDENT

$\Rightarrow$ VIOLATION OF EQUIVALENCE PRINCIPLE (Dicke 1962)

NOTABLY VIOLATION OF UNIVERSALITY OF FREE FALL

$$S_{mi} = -\int m_i[\alpha(x), \cdots] \sqrt{-g_{\mu\nu}(x)\, dx^\mu dx^\nu}$$

$\Rightarrow$ ACCELERATION

$$\vec{a}_i = \vec{g} - \vec{\nabla} \ln m_i[\alpha(x), \cdots]$$

$$= \vec{g} - \frac{\partial \ln m_i}{\partial \alpha} \vec{\nabla}\alpha - \cdots$$

COMPOSITION-DEPENDENT PART OF $\vec{a}_i$

COMPLEXITY OF COUPLING DEPENDENCE OF MASSES

$$m_{ATOM} = Z\, m_p + N\, m_n + Z\, m_e + E^{nucleus}_{SU(3)} + E^{nucleus}_{U(1)}$$

$$m_p = a\,\Lambda_{QCD}(g_3) + b_u m_u + b_d m_d + c_p\,\alpha_{em}\,\Lambda_{QCD}(g_3)$$

$$\Lambda_{QCD}(g_3) \sim \Lambda_{UV}\, e^{-\frac{c}{g_3^2}}$$

$$m_u \sim Y_u \langle\phi\rangle \sim Y_u \frac{\mu}{\sqrt{\lambda}}$$

$$m_e \sim Y_e \frac{\mu}{\sqrt{\lambda}}$$

$$E^{nucleus}_{SU(3)} \simeq (N+Z)\left[a_3^0 + \frac{\partial a_3}{\partial m_\pi^2} m_\pi^2\right] + (N+Z)^{2/3}\left[b_3^0 + \frac{\partial b_3}{\partial m_\pi^2} m_\pi^2\right]$$

$$m_\pi^2 \sim \Lambda_{QCD}\,(m_u + m_d)$$

$$E^{nucleus}_{U(1)} \sim \frac{Z(Z-1)}{(N+Z)^{1/3}} \frac{\alpha_{em}}{r_0\,(m_{u+d}/\Lambda_{QCD})}$$

$\Rightarrow$ COMPLEXITY OF COMPOSITION-DEPENDENCE OF EP VIOLATION (Damour Polyakov '94, ..., Dent '08, Damour Donoghue '08)

$$\frac{\vec{a}_i - \vec{a}_j}{\vec{g}} = c_A\left[\frac{Z(Z-1)}{(N+Z)^{1/3}M}\right]_{ij} + c_B\left[\frac{N+Z}{M}\right]_{ij} + c_D\left[\frac{N-Z}{M}\right]_{ij} + c'_B\left[\frac{(N+Z)^{2/3}}{M}\right]_{ij} + \cdots$$

$\rightarrow$ RICHNESS OF INFORMATION, IN CASE EP IS OBSERVED

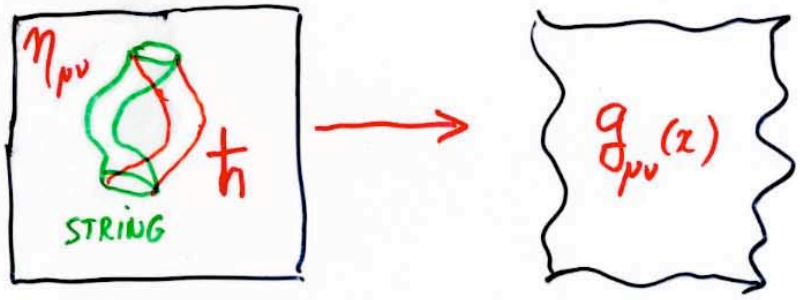
UP TO NOW, WE PRESENTED ONLY AN 'UPDATED' VERSION OF MOTIVATIONS KNOWN TO JORDAN, DICKE, ...

NEW MOTIVATIONS FROM MODERN PHYSICS ?

'STRING' THEORY :

A VAST THEORETICAL FRAMEWORK WHICH NATURALLY UNIFIES MANY FACTS AND IDEAS OF 20th CENTURY PHYSICS

- IT 'MAGICALLY' RECONCILES RELATIVISTIC QUANTUM THEORY WITH G.R.



- IT NATURALLY UNIFIES
  - GAUGE INTERACTIONS $A^A_\mu(x)$
  - GRAVITATIONAL INTERACTION $h_{\mu\nu}(x)$

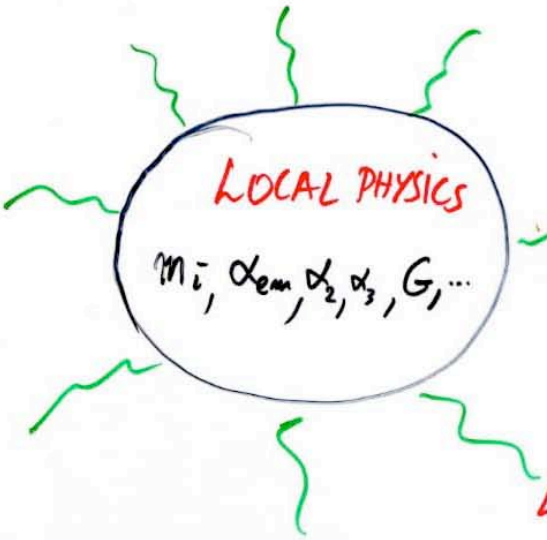
- IT PROMISES TO UNIFY MATTER, INTERACTIONS (FORCES), AND SPACE-TIME
  (MATTER ↔ INTERACTIONS: SUSY)

  ONLY ONE SUBSTRATUM (?)

  WHICH PROBABLY TRANSCENDS USUAL DISTINCTIONS

AT FACE VALUE, STRING THEORY CONTAINS NO ARBITRARY COUPLING CONSTANTS TO BE A PRIORI GIVEN

IT IS A VAST GENERALIZATION OF KALUZA-KLEIN IDEA IN THAT



'EXTERNAL' 'MODULI FIELDS' $\Phi_A(x)$

WHOSE VACUUM EXPECTATION VALUE (VEV) DETERMINE THE LOCAL VALUE OF COUPLING CONSTANTS

E.G.

IN $D=10$ SPACETIMES

$$g_{STRING} = \exp \langle \Phi(x) \rangle$$

IN COMPACTIFIED $D = 4 + 6$ (6 COMPACT)

$$g_a = f\left(\langle \Phi_1(x) \rangle, \langle \Phi_2(x) \rangle, \ldots\right)$$

MANY SCALAR (MODULI) FIELDS

MEASURING THE SHAPE AND SIZE OF COMPACTIFIED DIMENSIONS ($\sim g_{55}(x)$), TOGETHER WITH THE POSITION OF VARIOUS EXTENDED BRANES WRAPPING INTERNAL DIMENSIONS

EXCITING FOR ~~EP~~, BUT ALSO VERY WORRISOME:

LIKE $g_{55}(x)$ IN KALUZA-KLEIN, THE MODULI FIELD ARE A PRIORI MASSLESS

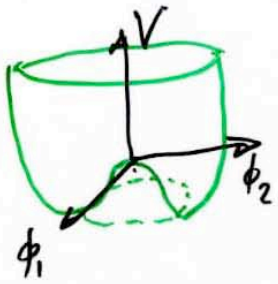
$\Rightarrow$ ALREADY EXPERIMENTALLY EXCLUDED

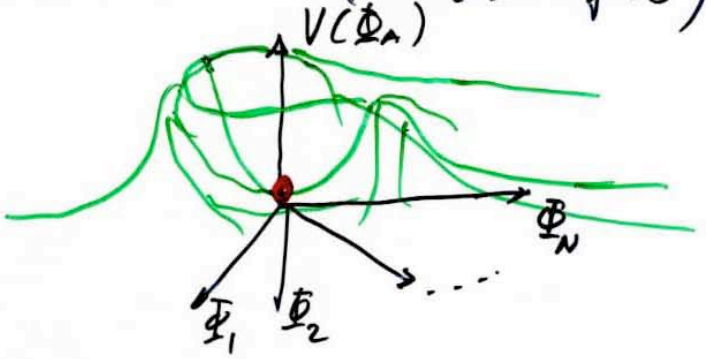
BECAUSE THE EP VIOLATIONS ARE MUCH TOO STRONG

$\Rightarrow$ MOST STRING THEORIST TRY TO FIND 'STRING VACUA'

WHICH IMPLY THE STABILIZATION OF MODULI FIELDS AT THE MINIMUM OF SOME EFFECTIVE POTENTIAL (see e.g. Denef 08)

SIMILARLY TO HIGGS STABILIZATION





$\Rightarrow$ ALL $\Phi_A(x)$ ARE 'PINNED' AROUND SOME VALUES

$\rightarrow$ NO LONGER MASSLESS, BUT $m_A^2 \sim \frac{\partial^2 V}{\partial \Phi_A}$

$\rightarrow$ Yukawa-exponential SUPPRESSION OF ANY ~~EP~~ VIOLATION OR MODIFICATION OF GRAVITY: $\propto e^{-m_A r}$

- COULD LEAVE SOME SHORT-RANGE MODIFICATION OF GRAVITY?

? POSSIBLY, BUT ONE THEN WORRIES ABOUT NATURALLY REALIZING INFLATION $\rightarrow$ NEED MOST MASSES TO BE $> H_{INFL}$

- IF WE FOLLOW THE MAJORITY VIEW THAT THE MODULI MUST BE STABILIZED IN THE REAL 'STRING VACUA', THIS DOES NOT IMPLY AT ALL THAT ONE SHOULD SHUN EP TESTS. ON THE CONTRARY EP TESTS BECOME TESTS OF AN IMPORTANT ASSUMPTION CURRENTLY MADE IN STRING THEORY

- ON THE OTHER HAND, AS THE CURRENT STRING REALIZATIONS OF MODULI STABILIZATION (KKLMMT...) ARE EXTREMELY COMPLEX, AND LOOK RATHER UNNATURAL, ONE CANNOT HELP THINKING THAT THERE MIGHT EXIST OTHER WAYS IN WHICH STRING THY CONNECTS WITH THE REAL WORLD, WITHOUT HAVING TO ASSUME THE STABILIZATION OF ALL MODULI.

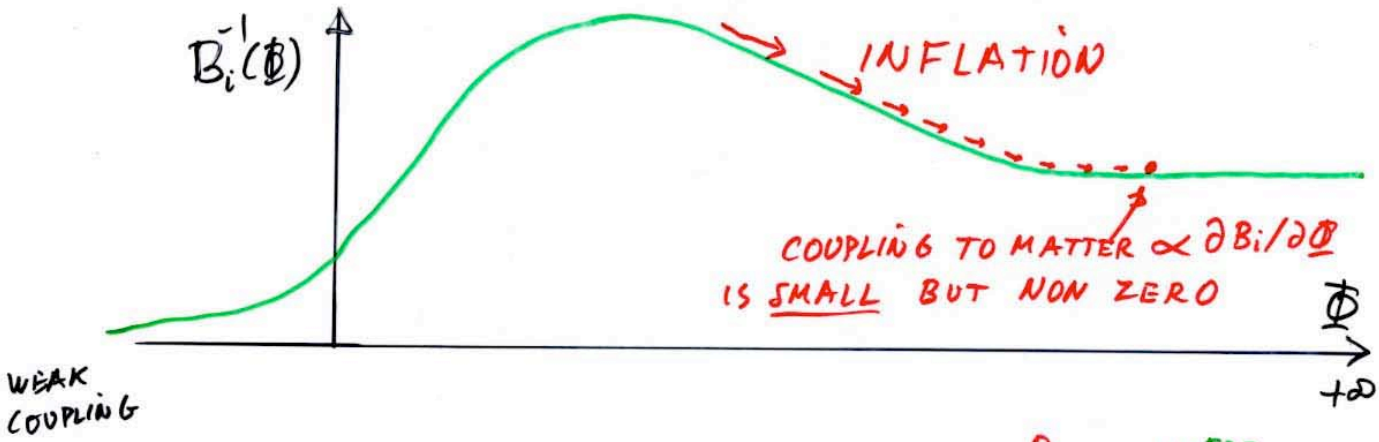
  HOWEVER, ONE THEN NEEDS TO UNDERSTAND WHY THE EFFECTS OF SUCH UNFIXED MODULI HAVE NOT YET BEEN SEEN.

ONE POSSIBLE MECHANISM FOR DOING THIS IS THE

COSMOLOGICAL ATTRACTOR MECHANISM (Damour + Nordtvedt; Damour + Polyakov)

A SIMPLE REALIZATION OF THIS MECHANISM IS TO ASSUME THAT ALL COUPLING FUNCTIONS $B(\Phi)$ OF THE CONSIDERED MODULUS HAVE LIMITS AS $\Phi \longrightarrow +\infty$ ('STRONG COUPLING') (Damour Piazza Veneziano)

ATTRACTOR SCENARIO FOR $\Phi(x)$



RESIDUAL COUPLING $\quad \alpha^2_{had}(\Phi_{end}) \sim 10 \left(\frac{b_F}{b_\lambda c}\right)^2 \left(\frac{\delta\rho}{\rho}\right)^{\frac{8}{n+2}}$ ← FOR INFLATIONARY POTENTIAL $V(\chi) \propto \chi^n$

E.G. IF $n=2 \Rightarrow \alpha^2_{had} \sim 2.5 \left(\frac{b_F}{b_\lambda c}\right)^2 \times 10^{-8}$

PREDICTS CORRELATED EFFECTS

$k \equiv \left(\frac{b_F}{b_\lambda c}\right)^2 \sim O(1)$ BUT COULD BE ~ 0.1 OR LESS

$$\gamma^{PPN} - 1 \simeq -2\,\alpha^2_{had} \sim -5\,k \times 10^{-8}$$

$$\frac{\Delta a}{a} \sim 5 \times 10^{-5}\,\alpha^2_{had} \sim k \times 10^{-12}$$

$$\frac{\dot\alpha_{em}}{\alpha_{em}} \sim \pm\sqrt{1+q_0-\frac{3\Omega_m}{2}}\,\sqrt{10^{12}\frac{\Delta a}{a}}\;10^{-16}\,yr^{-1}$$

→ GIVES AN 'EXISTENCE PROOF' OF EP VIOLATION WHICH IS NATURALLY BELOW THE LEVEL CURRENTLY TESTED:

$$\left(\frac{\Delta a}{a}\right)_{Be-Ti} = (0.3 \pm 1.8) \times 10^{-13}$$

Schlamminger et al. 08

OTHER POSSIBLE MOTIVATION

THE OBSERVATION OF A POSITIVE, NON-VANISHING VACUUM ENERGY

$$\rho_{VAC} \simeq (2.3 \times 10^{-4}\ eV)^4 \sim 10^{-123}\,(m_{Planck})^4$$

IS A CHALLENGE FOR THEORETICAL PHYSICS.

STRING THEORY DOES NOT SEEM TO HELP SOLVING THIS CHALLENGE, BASICALLY BECAUSE (AS USUAL THEORIES) IT CONTAINS A BASIC MASS SCALE: $m_s^{(D=10)}$ (OR $m_P^{(D=11)}$)

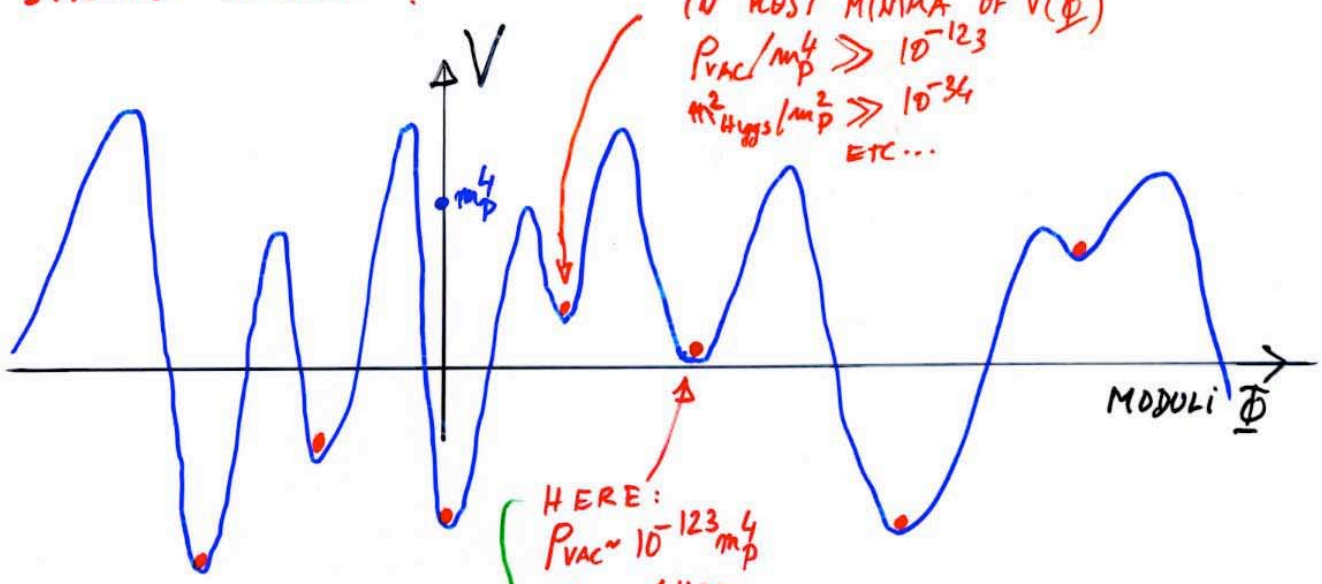
IT HAS BEEN SUGGESTED (Wetterich, ..., Rabinovici '08) THAT THE SOLUTION OF THIS PUZZLE INVOLVES SOME TYPE OF SPONTANEOUS BREAKING OF SCALE INVARIANCE OF SOME UNDERLYING SCALE-INVARIANT THEORY

UNDER SOME ASSUMPTIONS (Wetterich '08) IT SEEMS THAT SUCH A SCENARIO (IF SCALE-INVARIANCE IS RE-ESTABLISHED ONLY WHEN THE 'DILATON' $\varphi \simeq \ln \chi \to \infty$) MIGHT REALIZE THE RUN-AWAY VERSION OF THE COSMOLOGICAL ATTRACTOR SCENARIO.

THIS WOULD RENDER SUCH A SCENARIO COMPATIBLE WITH CURRENT EXPERIMENTS, AND SUGGEST ~~EP~~ AT A LOWER LEVEL.

ANTHROPIC-TYPE ARGUMENTS

- IN STRING THEORY, MANY PEOPLE (Polchinski, Bousso, Susskind, Douglas, Denef, ...) HAVE ARGUED FOR THE EXISTENCE OF A VAST 'LANSCAPE OF STRING VACUA':



HERE:
$\rho_{VAC} \sim 10^{-123} m_p^4$
$\alpha_{em} \sim 1/137$
$m_e/m_p \sim 1/1836$
$m^2_{inflaton}/m_p^2 \sim 10^{-5}$
$m^2_{Higgs}/m_p^2 \sim 10^{-34}$

VERY RARE (BY $\sim 10^{-123} \times 10^{-34} \times \cdots$)

BUT $\exists$ AMONG THE $\gtrsim 10^{500}$ VACUA !

- IF SUCH AN 'ANTHROPIC SELECTION' (OR, SIMPLY, 'BAYESIAN') IS AT WORK, ONE SHOULD EXPECT THAT ONLY THE LIFE-NECESSARY CONSTRAINTS BE SATISFIED. AS I SEE NO REASON WHY THE EXACT EP BE NECESSARY FOR LIFE, ONE SHOULD EXPECT TO HAV SOME VIOLATION OF EP:

$$\frac{\Delta a}{a} \sim \eta_{\text{MAXIMUM TOLERABLE FOR LIFE}} \neq 0$$

IT IS A WELL-POSED, BUT DIFFICULT, QUESTION TO ESTIMATE

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 $\exists$ $\not{EP}$

- THE RECENT OBSERVATION OF $\rho_{VAC} \sim 10^{-123}\, m_{PLANCK}^4$ POSES A CHALLENGE TO PHYSICS WHICH SUGGESTS THAT WE ARE MISSING SOME KEY UNDERSTANDING OF IR GRAVITY. THIS MIGHT PROVIDE ADDITIONAL MOTIVATION FOR $\not{EP}$ (EITHER VIA SOME NAMBU-GOLDSTONE MODE, OR VIA ANTHROPIC ARGUMENTS)

- EVEN WITHIN THE 'MAJORITY VIEW' OF THE 'MODULI STABILIZATION' ISSUE, EP EXPERIMENTS ARE TESTING A KEY ASSUMPTION OF CURRENT STRING MODELS

- $\exists$ NO FIRM PREDICTION FOR LEVEL OF $\not{EP}$, BUT SOME PHENOMENOLOGICAL MODELS SHOW THAT THE VIOLATION COULD NATURALLY BE JUST BELOW THE CURRENTLY TESTED LEVEL

- IN SUCH (DILATON-LIKE) MODELS, THERE $\exists$ CORRELATED MODIFICATIONS OF GRAVITY ($\Delta\alpha/\alpha$, $\gamma_{PPN}-1 \neq 0$, $\dot{\alpha} \neq 0$, $d\alpha/dU \neq 0$, ...) BUT EP TESTS STAND OUT AS OUR DEEPEST PROBE OF NEW PHYSICS WHEN COMPARED TO, E.G., SOLAR SYSTEM, AND CLOCK TESTS ($\dot{\alpha}$ OR $d\alpha/dU$).