Title: Gravity and cosmology of the dilaton at "strong coupling"

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Abstract: A definite prediction of string theory is the existence of a scalar field, the dilaton. The presence of the dilaton generally leads to strong violations of the equivalence principle and thus describe a kind of gravitational force radically different from what we experience. String loop corrections, however, may render phenomenologically acceptable the region of the theory characterized by large values of the dilaton field i.e. the region with a strong tree level-coupling. Interestingly, in this framework, violations of the (weak) equivalence principle should be observed in the next satellite-based generation of experiments. A dilaton running towards infinity can also play the role of coupled dark energy and ease the so-called "cosmic coincidence" problem.

Introduction

The string action at tree-level:

$$S = \frac{M_s^2}{2}\int d^4x\sqrt{-g}\, e^{-\phi}[R + (\nabla\phi)^2 - \frac{M_s^{-2}}{4}F_{\mu\nu}^2 + \ldots]$$

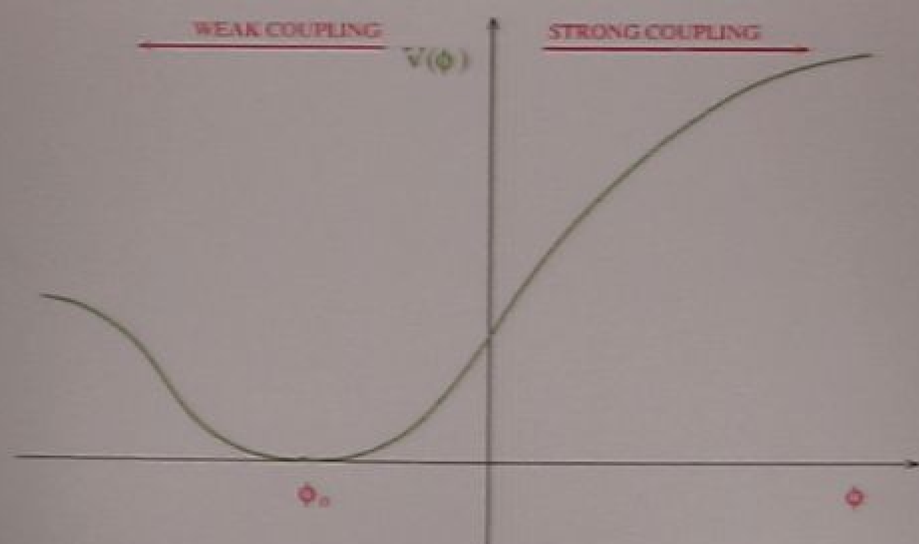
Problems:

- "Constants" are not constant

$$\alpha_{GUT} \simeq e^{\langle\phi_0\rangle} \simeq 0.1 \sim 0.01 \implies \phi_0 \simeq -3$$

- Equivalence principle is violated

Conventional solution: (Taylor-Veneziano)



PHENOMENOLOGY AND COSMOLOGY OF THE DILATON AT "STRONG COUPLING"

Federico Piazza
University of Portsmouth, UK

1 The idea and its theoretical motivations

2 Gravitational phenomenology: E.P. violations
(with T. Damour and G. Veneziano)

3 Late time cosmology: the dilaton as quintessence
(with L. Amendola, M. Gasperini, S. Tsujikawa and G. Veneziano)

4 Conclusions and future developments

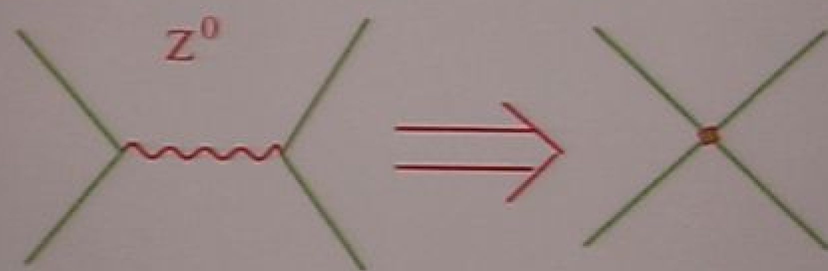
1 Effective Actions

$$i\,S_{\text{eff}}[\varphi_i] = \log \int \mathcal{D}[\psi_i]\, e^{iS[\varphi_i, \psi_i]}$$

Examples:

○ Electro-weak interactions

Integrating over massive $W^{\pm}$ and Z^0 bosons a 4–fermion "Fermi" interaction is produced:



○ Induced Gravity idea (Sakharov, 1967)

$$\mathcal{D}[\psi_i] \cdot \int dV\, \mathcal{L}_m(g_{\mu\nu}, \psi_i) \Longrightarrow$$

$$\Longrightarrow \int dV [\Lambda + R + \mathcal{O}(\partial g^4_{\mu\nu})]$$

A Toy Model (Veneziano, 2001)

QFT with gravity + (rank N_1) gauge fields + $N_{1/2}$ fermions + N_0 scalars. Cut off at Λ.

$$S_0 = \frac{1}{2}\int d^D x\sqrt{-g}\left[\kappa_0^{-2} R - g_0^{-2}\sum_{k=1}^{N_1} F_{\mu\nu}^k F^{k\mu\nu}\right] +$$

$$+\sum_{i=1}^{N_0} S_{\text{scalar}}[\varphi_i] + \sum_{k=1}^{N_{1/2}} S_{\text{fermion}}[\psi_i]$$

$\Longrightarrow$ Integrate over scalars and fermions and obtain $S_{\text{eff}}[g_{\mu\nu}, F_{\mu\nu}]$

$\Longrightarrow$ Integrate over gravity and gauge loops and obtain $\Gamma[g^c_{\mu\nu}, F^c_{\mu\nu}]$ $(N \to \infty)$

$$\kappa_0^{-2} \Longrightarrow \kappa^{-2} \simeq \kappa_0^{-2} + \Lambda^{D-2}\mathcal{O}(N) + \ldots$$

$$g_0^{-2} \Longrightarrow g^{-2} \simeq g_0^{-2} + \Lambda^{D-4}\mathcal{O}(N) + \ldots$$

What does this say about string theory?

$$\Gamma = \frac{M_s^2}{2}\int d^4x\sqrt{-g}\,[B_g(\phi)R +$$
$$- B_\phi(\phi)(\nabla\phi)^2 - M_s^{-2}B_F(\phi)F^2 + \ldots]$$

— Cut off $\Lambda \sim M_s$

— Bare inverse coupling $g_0^{-2} \sim e^{-\phi}$

— Renormalized inverse coupling $g^{-2} \sim B_F(\phi)$

$$B_i(\phi) \underset{\phi\to\infty}{=} C_i + \mathcal{O}(e^{-\phi})$$

The theory allows a "strong coupling" scenario with $\phi \gg 1$!

It's like a "version at infinity" of Damour–Polyakov's least coupling principle :

If all $B_i(\phi)$s have an extremum at some (and the same) ϕ_0, then the theory is OK.

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The value of the dilaton now

Inflation is very efficient in pushing $\phi \to \infty$

Example: slow-roll inflation

$$V(\chi, \phi) \underset{\phi\to\infty}{=} V_0(\chi) + V_1(\chi)e^{-\phi} + \mathcal{O}(e^{-2\phi})$$

V_0 and V_1 have a power-law behaviour:

$$V_0(\chi) \simeq V_1(\chi) \propto \chi^n$$

The inflaton χ rolls down while the dilaton ϕ runs to infinity:

After inflation $\sim$ Now

$$e^{\phi_0} \simeq (\delta_H)^{\frac{-4}{(n+2)}}$$

Density fluctuations on large scales:

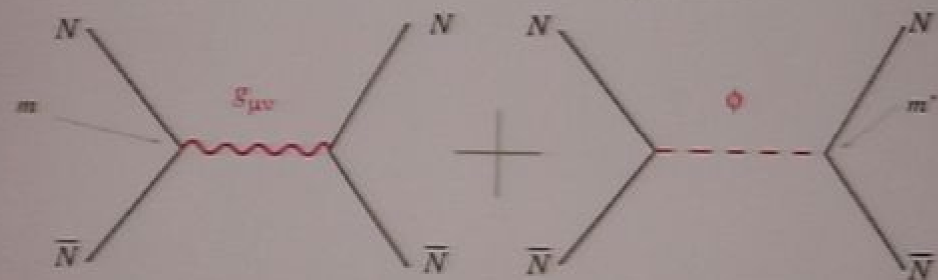
$$\delta_H \equiv \delta\rho/\rho \sim 5 \times 10^{-5}$$

2 Violating E.P. with a scalar field

Go to the "Einstein frame" with a conformal transformation $g_{\mu\nu} \rightarrow g^E_{\mu\nu}$ and define a "canonical" scalar field $\phi \rightarrow \varphi$

$$\mathcal{L} = \frac{\sqrt{-g^E}}{2}\left[\frac{R^E}{8\pi G_*} - \frac{(\nabla\varphi)^2}{4\pi G_*} + m(\varphi)\bar{N}N\right]$$

The scalar field contributes to gravity!



Effective Newton constant between A and B:

$$G_{AB}(\varphi) = G_0\left[1 + \alpha_A(\varphi)\alpha_B(\varphi)\right]$$

$$\alpha_A(\varphi) \equiv \frac{d\ln m_A(\varphi)}{d\varphi}$$

Contributions to the total mass

$$m = m_{QCD} + m_{QED} + m_{quark} + \dots$$

The scalar coupling of the element A:

$$\alpha_A \simeq \alpha_{\rm had} + 0.1 \frac{d\alpha_e}{d\varphi} \left(\frac{E_A}{\mu_A} \right) + \dots ,$$

where

$\alpha_{\rm had} \simeq \dfrac{d \ln \Lambda_{\rm QCD}}{d\phi}$, the same for all elements.

$E = \frac{Z(Z-1)}{(N+Z)^{1/3}}$

$\mu =$ mass of the element in atomic units.

Composition independent effects:

m_{QCD}: Main contribution, its dependence on φ is given by

$$\Lambda_{QCD}(\varphi) \sim M_s B_g^{-1/2}(\varphi) \cdot e^{-B_F(\varphi)/b}$$

$$\alpha_{\text{had}} \equiv \frac{d \log \Lambda_{QCD}}{d\varphi} \simeq 40\, e^{-\phi_0}$$

Solar system bound on composition independent E.P. violations:

(Bertotti et al. 2004)

$$\alpha^2_{\text{had}} = (-1.05 \pm 1.15) \times 10^{-5}$$

While we have . . .

$$\alpha_{\text{had}} \simeq 40 \cdot \delta_H{}^{\frac{4}{n+2}} \overset{n=2}{\simeq} 10^{-4}$$

$$\overset{n=4}{\simeq} 10^{-3}$$

OK with tested composition independent violations of E.P.

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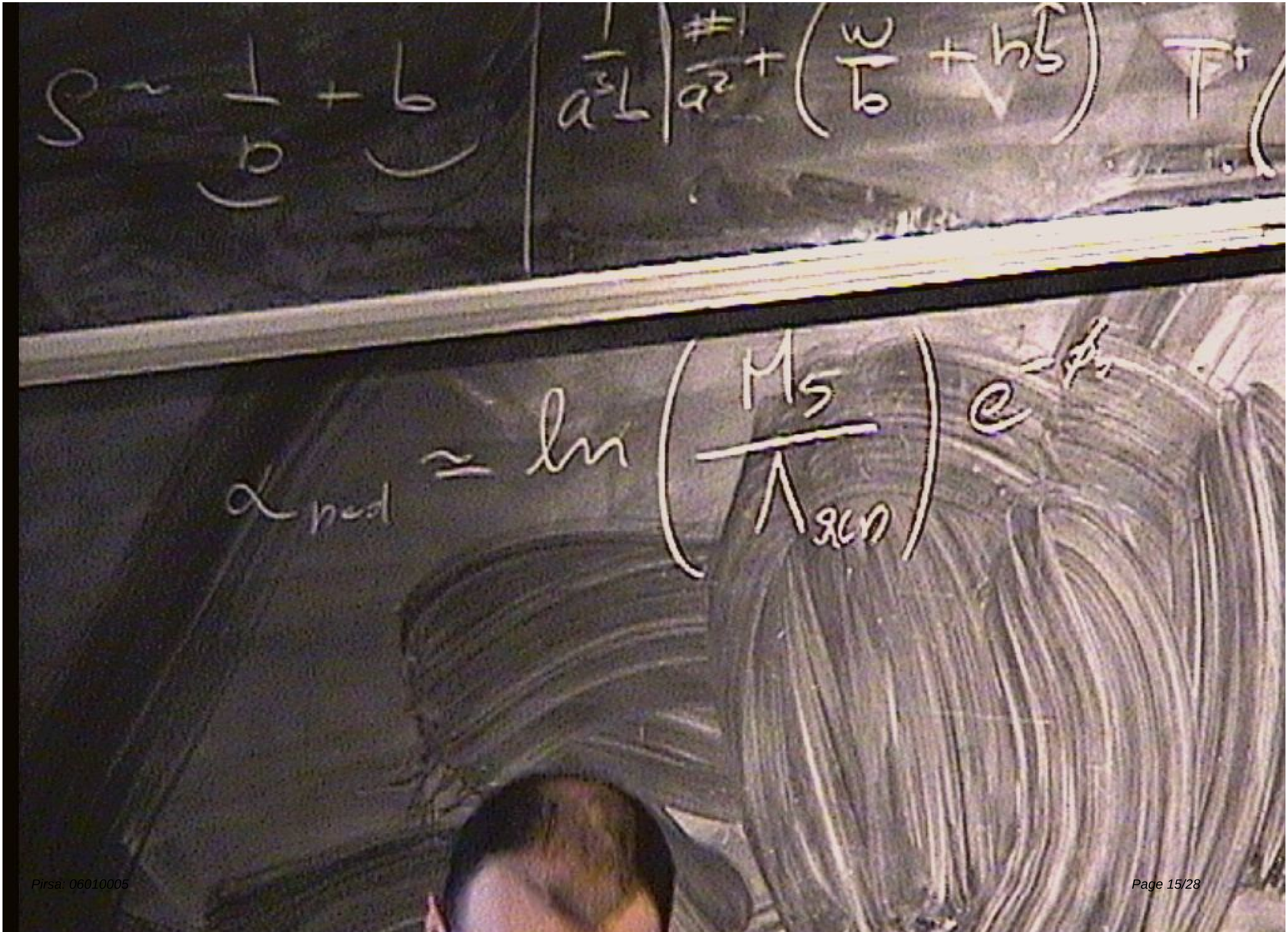
$\alpha_{pert} \simeq \ln\left(\frac{M_s}{\Lambda_{QCD}}\right)$

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Composition dependent effects:

m_{QED}: Varies from neutron to protons: different substances fall in a gravitational field with (slightly) different acceleration:

$$\left(\frac{\Delta a}{a}\right)_{AB} \simeq (\alpha_A - \alpha_B)\alpha_{\text{Earth}} \overset{\text{Cu}-\text{Be}}{\simeq} 10^{-4}\alpha_{\text{had}}^2$$

A much smaller effect but . . .

much better tested! $\left(\frac{\Delta a}{a}\right)_{\text{Cu Be}} \lesssim 10^{-12}$

while we expect . . .

$$\left(\frac{\Delta a}{a}\right) \simeq 10^{-4} \cdot \delta_H{}^{\frac{8}{n+2}} \overset{n=2}{\simeq} 10^{-12}$$

$$\overset{n=4}{\simeq} 10^{-9}$$

The case $n = 2$ is very close to present experimental limits!

MICROSCOPE will explore the level 10^{-15}.

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Coupling variations and E.P. violations:

Variation of the fine-structure constant:

$$\frac{\Delta\alpha_e}{\alpha_e} \simeq \frac{d\ln\alpha_e(\varphi)}{d\varphi}\,\Delta\varphi$$

— $\Delta\varphi$: Cosmological origin: if the dilaton is coupled to vacuum energy we expect, in a Hubble time H_0^{-1}, $\Delta\varphi = \mathcal{O}(1)$

— $d\ln\alpha_e(\varphi)/d\varphi$: "Fundamental" origin, related to E.P. violations!

If the runaway dilaton plays the role of dark energy (with a runaway potential $V \sim e^{-c\varphi}$), then

$$\frac{d\ln\alpha_e}{H_0\,dt} \simeq \pm 3.5\times 10^{-6}\sqrt{1+q_0-3\Omega_m/2}\,\sqrt{10^{12}\frac{\Delta a}{a}}$$

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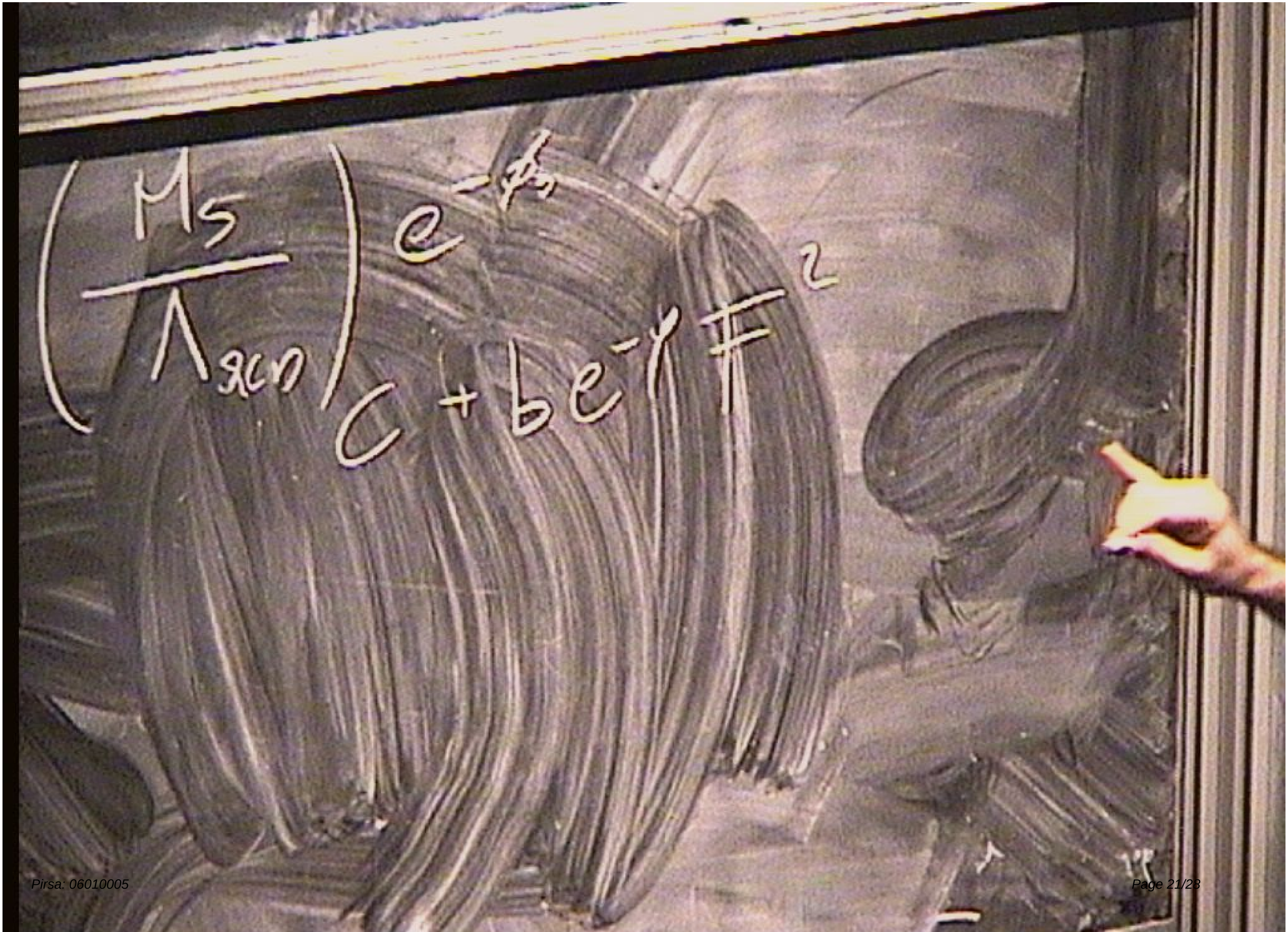
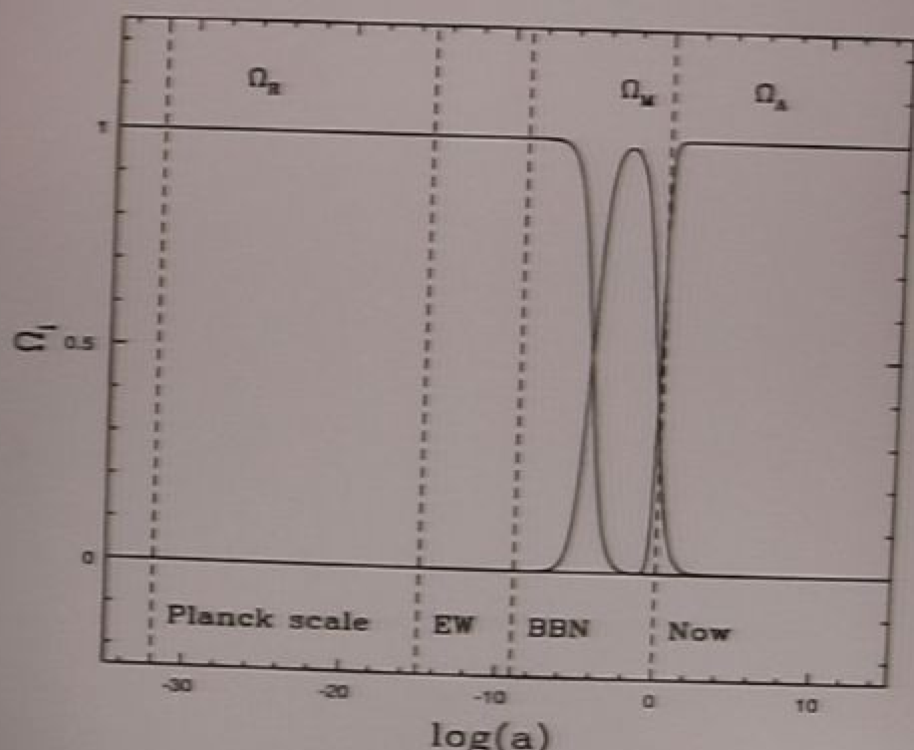

$\left(\frac{M_s}{\Lambda_{gcn}}\right) e$
$c + b e^{-\gamma} F^2$

3 The Acceleration of the Universe:

Why shouldn't it be Λ ?

— It's too small (10^{-3} eV $<$ 10^{19} Gev ...)
— The "coincidence problem"

$$\rho_A \propto a^{-3(1+w_A)}$$



Coupled dark energy allows a late time attractor with:

(e.g. C. Wetterich, 1994; L. Amendola, 1999)

Fixed fraction of critical density Ω_φ

Fixed acceleration $-q$

Conditions for a cosmological Scalar Field:

— a coupling to dark matter $\alpha_d = \mathcal{O}(1)$

— an exponential potential:

$$V(\varphi) = \exp(-c\varphi)$$

or at least (F.P. and S. Tsujikawa, 2004) a Lagrangian of the type

$$(\partial\varphi)^2 g[(\partial\varphi)^2 e^{c\varphi}]$$

Coupled quintessence in string theory at "strong coupling"

$$\Gamma = \frac{M_s^2}{2}\int d^4x\sqrt{-g}\,[B_g(\phi)R + - B_\phi(\phi)(\nabla\phi)^2 - 2M_s^{-2}V(\phi) + \mathcal{L}_d]$$

— $V(\phi)$ of non-perturbative origin, and goes to zero as $\phi \to \infty$ $(\Lambda = 0)$:

$$V(\phi) \underset{\phi\to+\infty}{\sim} e^{-\phi} \sim e^{-c\varphi}$$

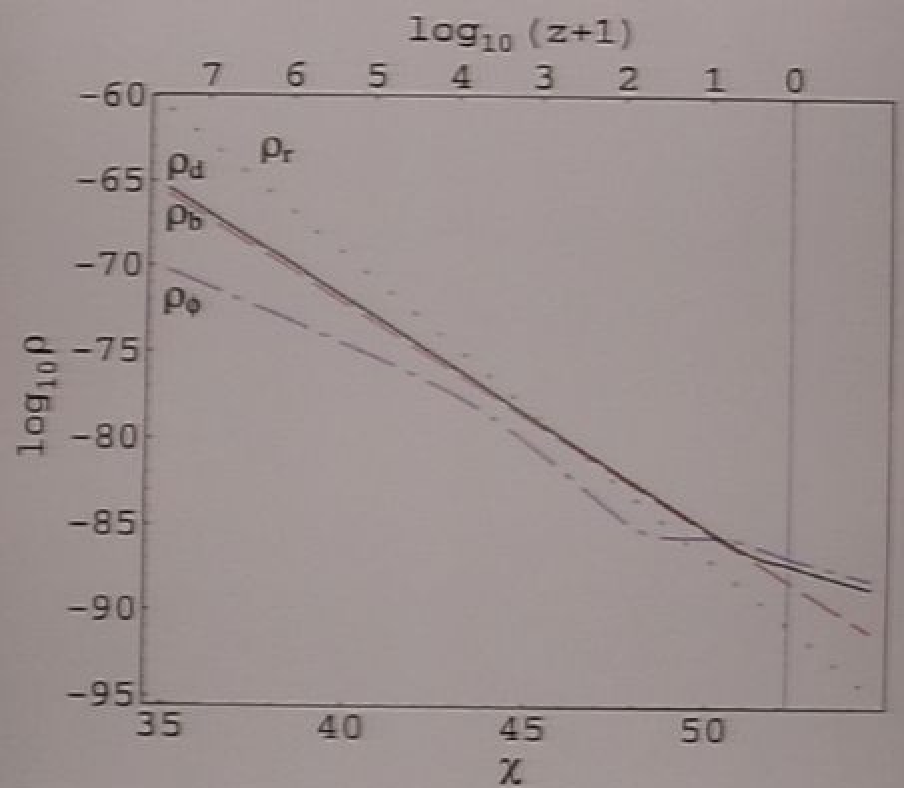
$$c \simeq \sqrt{\frac{2B_g(+\infty)}{B_\phi(+\infty)}}$$

— $\mathcal{L}_d$: Suppose a sector of the theory is still strongly coupled to the dilaton:

$$\alpha_d(\varphi) = \mathcal{O}(1)$$

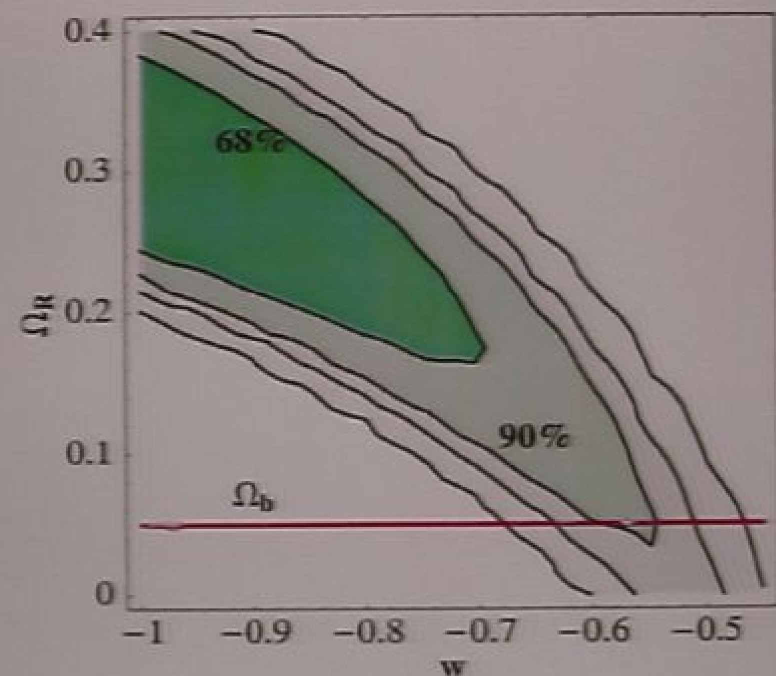
A possible evolution:

normalsize M. Gasperini, F. P. and G. Veneziano, 2002



Coupled dark energy vs phantom matter?

L. Amendola, M. Gasperini, F. P., 2004



Conclusions

— The structure of string-loop corrections allows a "strong coupling" ($\phi \to \infty$) scenario

— No testable composition–independent E. P. violations are expected.

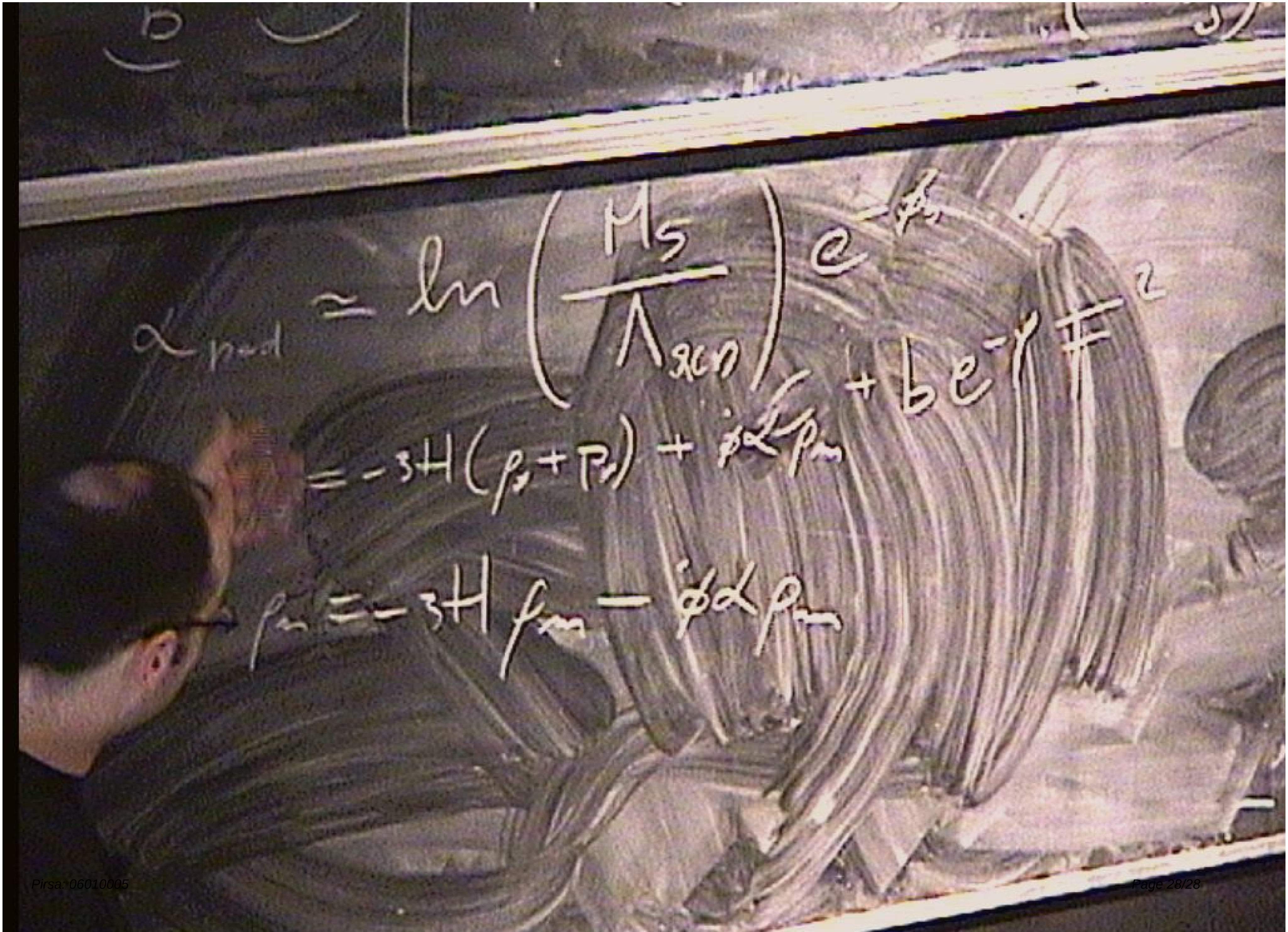
— Composition–dependent E.P. violations are expected in next-to-come experiments

If the dilaton plays the role of (uncoupled) quintessence detectable E.M. coupling variations are expected:

(E.P.) violations and (e^2) variations:

$$\frac{d\ln e^2}{H_0\, dt} \simeq \pm 3.5 \times 10^{-6} \sqrt{1 + q_0 - 3\Omega_m/2}\sqrt{10^{12}\frac{\Delta a}{a}}$$

— In this scenario the dilaton may also play the role of coupled quintessence and that of "ghost condensate" (F. P. and S. Tsujikawa, 2004)


α_pred ≃ ln(M_S / Λ_QCD) e^{-φ} + b e^{-γ} F^2
= -3H(ρ_r + p_r) + φ̇ α ρ_m
ρ̇_m = -3H ρ_m - φ̇ α ρ_m