Title: Testing the equivalence principle in the dark sector

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Abstract:

PROBING THE DARK SECTOR WITH THE EQUIVALENCE PRINCIPLE

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(with Paul Steinhardt)

PI/APC workshop 26.10.05

The dark energy problem: is dark energy dynamical or due to a cosmological constant?

- Why is the cosmological constant so small? (Anthropic explanation? A dynamical explanation?)
- Dynamical dark energy can solve the cosmic coincidence problem (quintessence trackers, *k*-essence)

Measuring the equation of state

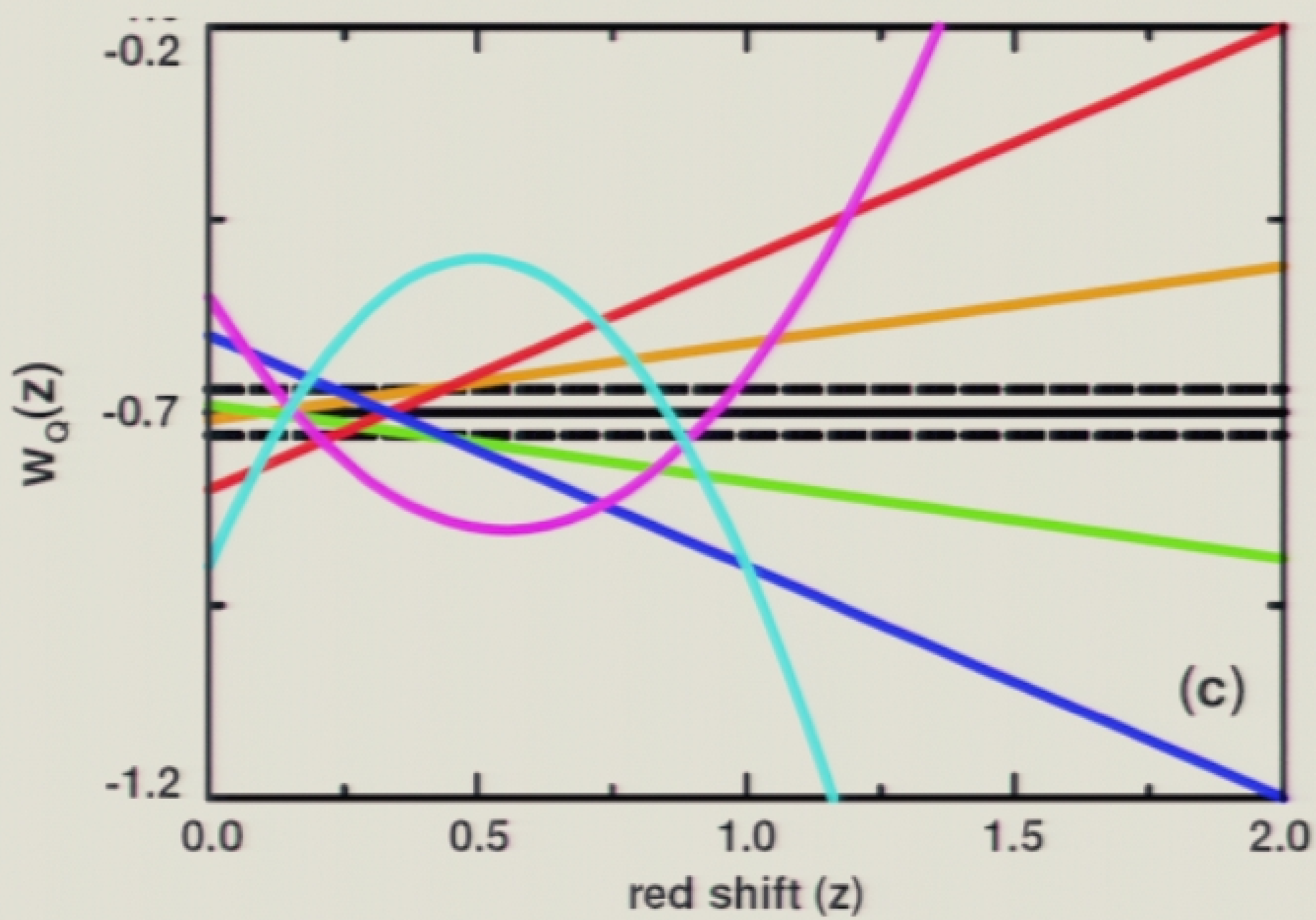
- A detection of $w + 1$ is unambiguous evidence of dynamical dark energy, however
- $w + 1$ is constrained indirectly by supernovae

$$d_L = \frac{1+z}{H_0}(1+\Omega_{\rm m}/\Omega_{\rm Q})^{1/2}\int_1^{1+z}\frac{dx}{x^{3/2}}\left[\frac{\Omega_{\rm m}}{\Omega_{\rm Q}}+\exp\left(3\int_1^x\frac{dy}{y}w_{\rm Q}(y)\right)\right]^{-1/2}$$

and there may be limits to how well it can be measured

- Some models (*e.g.* quintessence trackers) predict w approaching -1 in the late universe

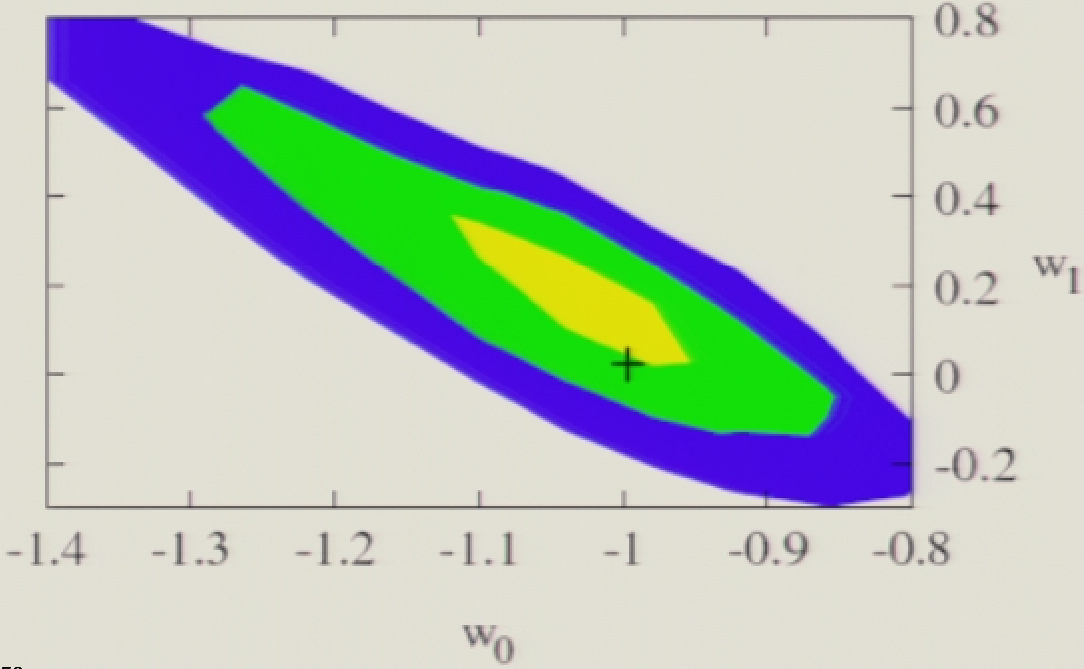
d_L agrees to 1%



(Maor *et al*, 2000)

It may not be possible to *directly* rule out quintessence

- 8 years of WMAP, 2,000+ supernovae, large-scale structure and weak lensing may only give $\Delta w < 0.10$
  and $\Delta dw/dz < 0.18$ (at 1σ).



(Upadhye *et al.*, 2004)

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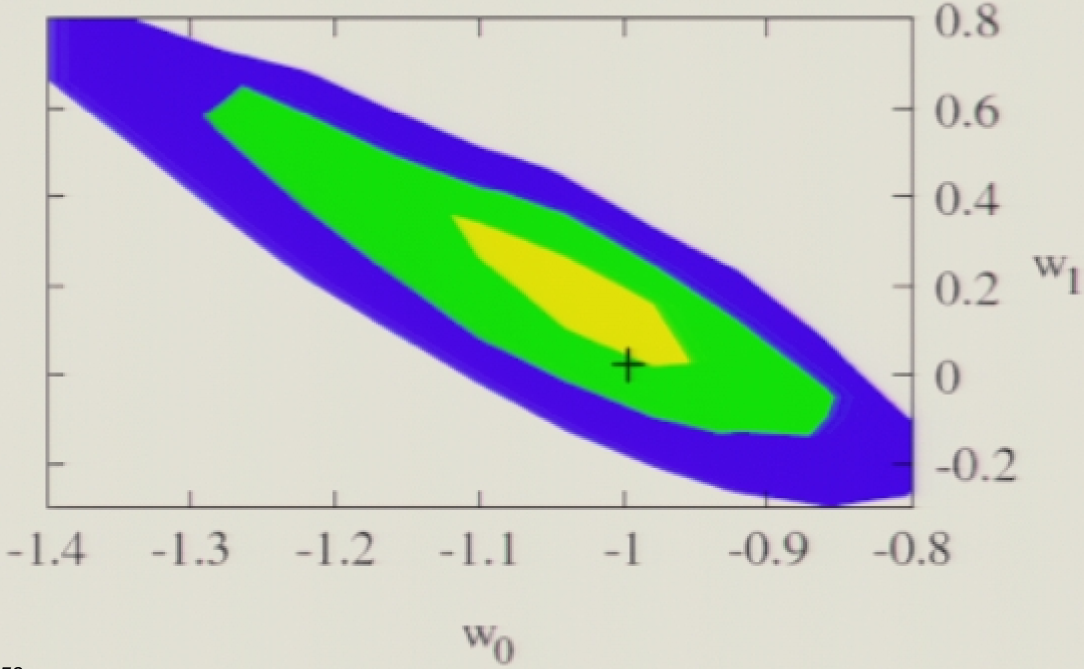


(Upadhye *et al.*, 2004)

Alternative: look for model-dependent signatures of dark energy

1. Dark energy perturbations
2. In this talk: look for equivalence principle violating interactions
   - The minimally coupled quintessence model of dark energy is an idealization
   - Equivalence principle violations are predicted by compactification, string/M theory moduli etc…

What kinds of effects arise?

Violations of:

- the universality of free fall
- variation of fundamental constants
- deviations from general relativity

Universality of free-fall

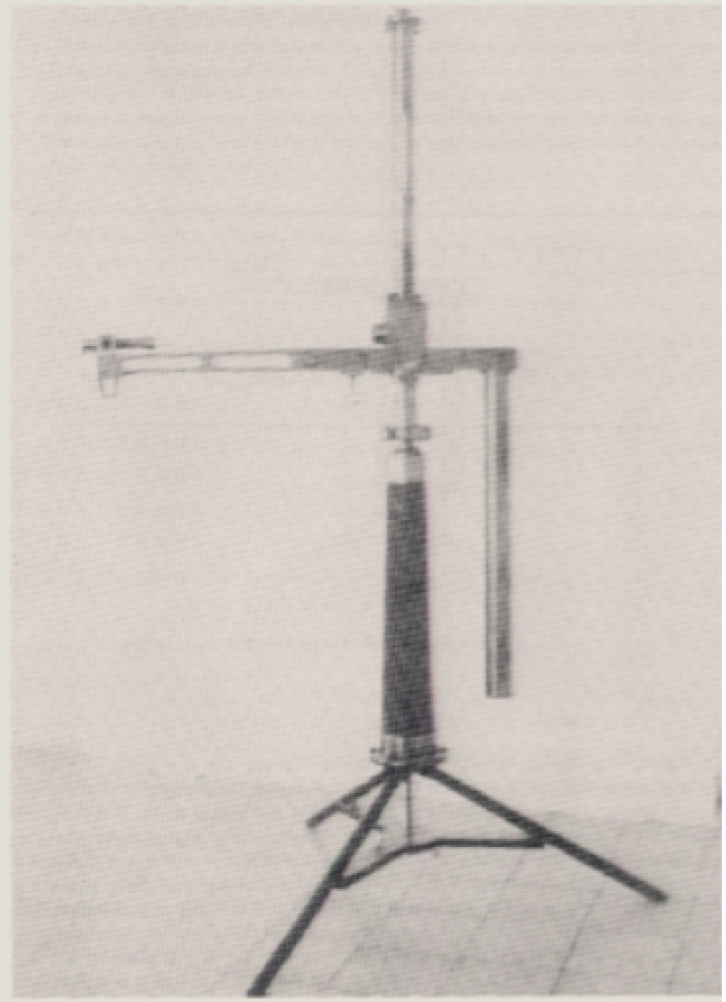
- Test of differential acceleration

$$\eta = 2\frac{|a_1 - a_2|}{|a_1 + a_2|}$$

- Eötvös torsion-balance experiment

  $\eta < 10^{-12}$ (Braginsky & Panov, '72)

  $\eta < 2\times10^{-13}$ (Eöt-Wash)



Eötvös's experiment

Variation of fundamental constants

Fine-structure constant

$\Delta\alpha/\alpha < 10^{-7}$ $d \log \alpha/dz < 8 \times 10^{-7}$ (Oklo, z=0.15)

$d \log \alpha/dz = 9 \times 10^{-6}$ (Keck/HIRES QSO, $z < 4$, 5σ)

$d \log \alpha/dz < 3 \times 10^{-6}$ (VLT/UVES, $z < 2$, 3σ)

Constraints on Newton's constant:

- High-redshift

  $\Delta G/G$ no more than 40% since nucleosynthesis (Accetta, 1990)

- low-redshift

  $d \log G/dz < 10^{-2}$ (stellar physics, pulsars, rangefinding etc…)

SDSS quasar at z=5

Metric tests of gravity

Cassini

Precision tests of general relativity

- Lunar laser rangefinding
- Deflection of distant radio sources by the sun
- Time-delay experiments

Constrains Eddington (or PPN) parameter $\gamma - 1 < 5 \times 10^{-5}$

(related to Brans-Dicke parameter $\omega > 40{,}000$)

$$\gamma = \frac{1+\omega}{2+\omega}$$

The problem: equivalence principle violations are tightly constrained

- Couplings should generically be gravitational strength (*i.e.* suppressed by the Planck constant).
- The generic "prediction" is that $\Delta\alpha/\alpha$, $\Delta G/G$, γ, ω, η are of order unity, which is in conflict with observation.
- Gravity is hard to modify.

Dynamical compactifications violate the EP (at some level)

- Kaluza-Klein theory is a mess (Fierz, 1956)
  - includes variation of the coupling constant of the Kaluza-Klein one-form

$$\frac{1}{2}\int d^4x\sqrt{-h}\left(R_4[h]-(\partial\phi)^2+\tfrac{1}{4}e^{\sqrt{6}\phi}F^2\right)$$

  - couplings of the radion and one-form all throughout the matter sector

Dynamical compactifications violate the EP (at some level)

- The simplest S^1/Z_2 compactification (*i.e.* compactification on an interval) is better.

$$\int d^5x\sqrt{-h}\Big(\tfrac{1}{2}R_4[h]-\tfrac{1}{2}(\partial\phi)^2+e^{-\sqrt{8/3}\phi}\mathcal{L}_0[\Phi_{i,0};e^{-\sqrt{2/3}\phi}h_{\mu\nu}]$$

$$+e^{-\sqrt{8/3}\phi}\mathcal{L}_1[\Phi_{i,1};e^{-\sqrt{2/3}\phi}h_{\mu\nu}]\Big),$$

Matter fields on orbifold planes all couple to the same conformally rescaled metric (this is a *universal* coupling). This is Brans-Dicke theory (but with $\gamma = 1/2$).

Universal couplings generate deviations from general relativity

$$S = \int d^4x\sqrt{-g}\{\tfrac{1}{2}R[g] - \tfrac{1}{2}(\partial\phi)^2 - V(\phi) + e^{4\beta\phi}\mathcal{L}_{\mathrm{NG}}[\Psi_i; e^{2\beta\phi}g_{\mu\nu}]\}$$

Weyl transformation of Brans-Dicke theory with a potential

$$S = \int d^4x\sqrt{-h}\{\psi R - \omega\psi^{-1}(\partial\psi)^2 + 2\psi\lambda(\psi) + \mathcal{L}_{\mathrm{NG}}[\Psi_i; h_{\mu\nu}]\}$$

$$\omega = \frac{1-6\beta^2}{4\beta^2} \approx \frac{1}{1-\gamma}$$

$$\psi = e^{2\beta\varphi}$$

$$G_{\mathrm{eff}} = e^{-2\beta\varphi}(1 + 2\beta^2)$$

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Warped models

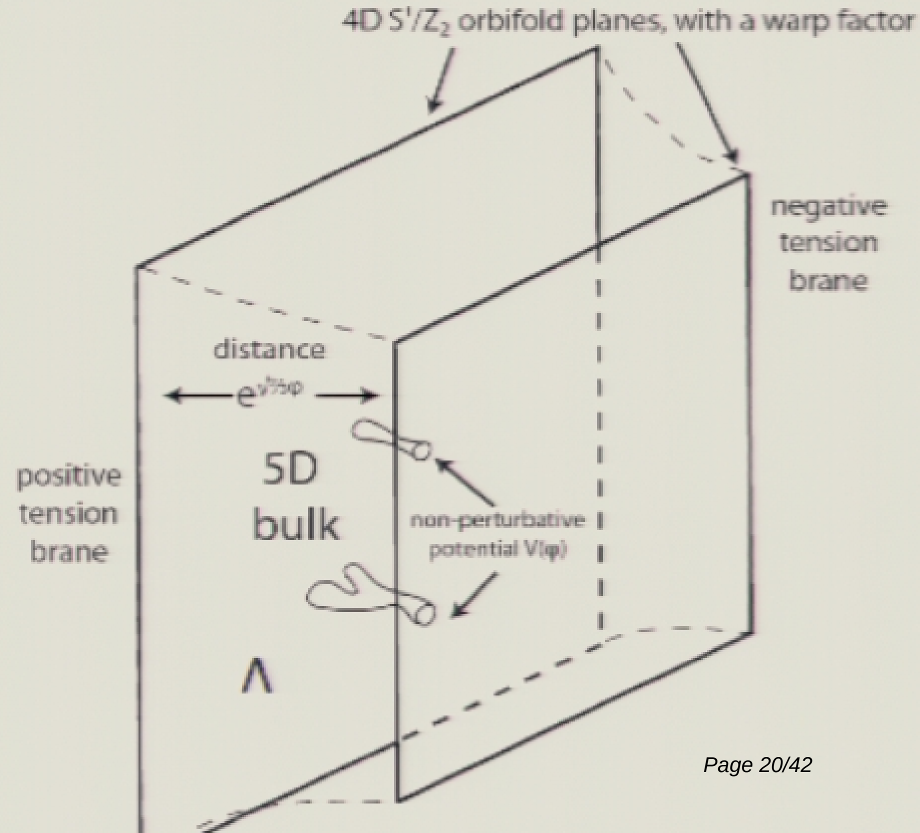
- A *warped* extra dimension

$$ds^2 = \Omega(y)^2 a(t)^2 \eta_{\mu\nu} dx^\mu dx^\nu + (dy)^2$$

where $\Omega(y)$ is the warp factor can improve (or exacerbate) the situation as in the Randall-Sundrum models, heterotic M-theory, etc…

The warp factor

e.g. in RS1 $\gamma = \begin{cases} 1 - \frac{8}{3}\Omega^2 k & \text{+ve tension} \\ -1 + \frac{4}{3}\Omega^2 k & \text{-ve tension} \end{cases}$



(Verlinde 2000, Giddings, Kachru & Polchinski 2002)

4D low-energy effective action of heterotic M-theory (in Brans-Dicke frame)

$$S = \frac{\pi \rho V}{\kappa^2} \int_{\mathcal{M}^4} \sqrt{-h} d^4 x \Big[e^c R - 0 \times e^c (\partial c)^2 - 3\left(1 + \tfrac{1}{3}\xi \alpha_0 e^c\right) \partial_\mu C \partial^\mu \bar{C}$$

$$- \tfrac{3}{8} e^{-c} C C \bar{C} \bar{C} - \frac{3k^2}{4}\left(1 - \tfrac{1}{3}\xi \alpha_0 e^c\right) C C \bar{C} \bar{C}$$

$$- \frac{V}{8\pi\kappa^2}\left(\frac{\kappa}{4\pi}\right)^{2/3} \int_{\mathcal{M}^4} \sqrt{-g}\, d^4 x \left((1 + \xi \alpha_0 e^c) \operatorname{tr}(F^{(1)})^2 + (1 - \xi \alpha_0 e^c) \operatorname{tr}(F^{(2)})^2 \right)$$

(Lukas, Ovrut and Waldram, 1997)

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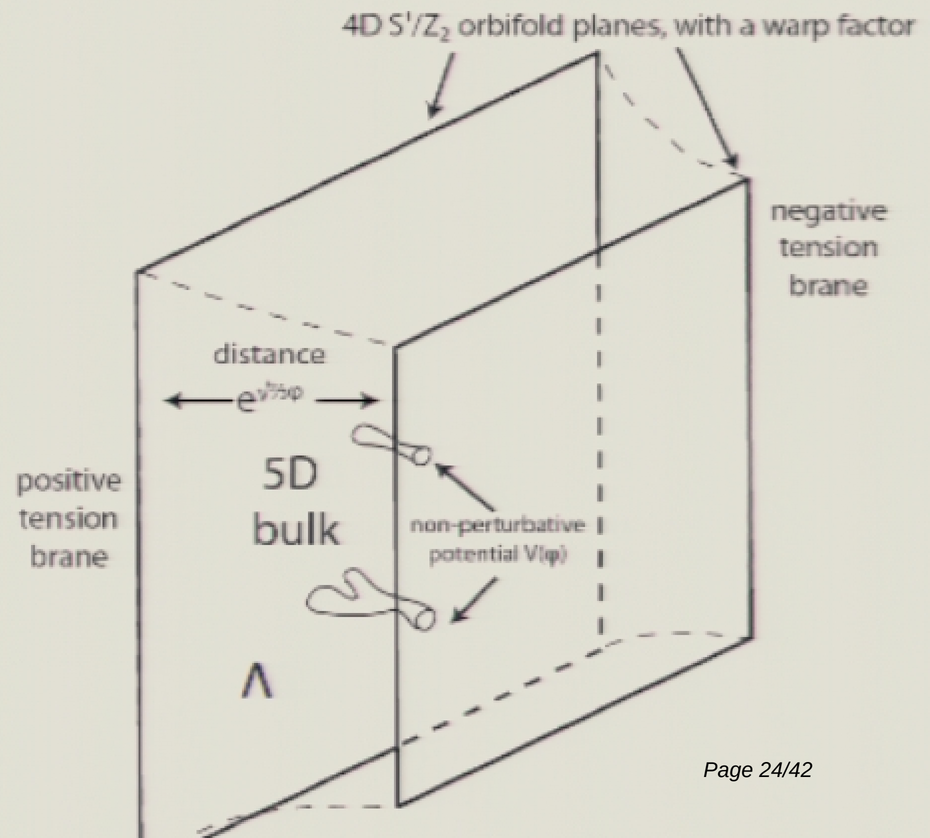

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- Violations of the weak equivalence principle and variation of α are naturally suppressed at higher order (at observational thresholds, depending on the Calabi-Yau manifold)

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- Brans-Dicke parameter is zero, as in the S^1/Z_2 case (*e.g.* $\gamma = 1/2$)

Other models

- Runaway dilaton (Gasperini, Piazza & Veneziano, 2002)
  - Predicts a specific relation between η and ω, and $d \log \alpha / d \log a$ and η.
- Chameleon cosmology (Khoury & Weltman 2003, Brax *et al.* 2002)
  - EP violations heavily suppressed in dense regions

The equivalence principle effects can be related in the context of dark energy

Local and cosmological tests of the EP

- Local tests
  - universality of free fall
  - solar system tests of gravity
  - gravitational redshift experiments

  These tests *directly* measure couplings

- Cosmological tests
  - variation of fundamental constants

  Cosmological tests measure the *combined* couplings and rate of variation of the field

Universal couplings generate deviations from general relativity

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Local and global effects can be related in a dark energy model

$$w+1 = \frac{\dot{\phi}^2}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} = \dot{\phi}^2 / 3H^2\Omega_Q$$

$$= \frac{1}{3\Omega_Q}\left(\frac{d\phi}{d\log a}\right)^2$$

$$= \frac{1}{3\Omega_Q}\frac{1}{1-\gamma}\left(\frac{d\log G}{d\log a}\right)^2$$

since

$$\frac{d\log G}{d\log a} = \sqrt{1-\gamma}\,\frac{d\phi}{d\log a}$$

$$w+1=\frac{1}{3\Omega_Q}\frac{1}{1-\gamma}\left(\frac{d\log G}{d\log a}\right)^2$$

This is a generic relation between three observable parameters. (For a cosmological constant, they are all zero.)

Limits $w + 1$ and γ constrain the evolution of G

$$|H_0^{-1}\dot{G}/G| < 4 \times 10^{-3}$$

Could the equivalence principle be strongly violated for dark matter?

- If dark matter couples to $e^{2\beta\varphi}g_{\mu\nu}$ then there is a φ mediated fifth-force, such that

$$G_{\text{eff}} = G(1 + 2\beta^2).$$

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Coupling to dark matter affects homogeneous evolution

$$\rho_{DM} \propto e^{-\beta\phi} a^{-3}$$

$$\frac{d\rho_X}{d\log a} = -3(1+w_X)$$

$$\beta^2\left(\Omega_{DE}(1+w_{DE}) + \Omega_{DM} w_{DM}\right) = 3w_{DM}^2$$

- Amendola and Quercellini (2003) investigated the effect on CMB and found

  $\beta < 0.09$ (1σ). (But this depends strongly on the fact that they used the power-law potential for quintessence.)

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Likewise,

$$w + 1 = \frac{1}{3\Omega_Q} \frac{C}{\eta} \left(\frac{d \log \alpha}{d \log a} \right)^2 \sim \frac{10^{-3}}{\eta} \left(\frac{\Delta \alpha}{\alpha} \right)^2$$

holds generally for dark energy models. It implies

$$|H_0^{-1} \alpha / \alpha| < 5 \times 10^{-5},$$

which is consistent with but does not improve on other constraints.

Model-dependent couplings to other constants (electron-to-proton mass ratio, QCD scale) are constrained to roughly the same level.

Variation of α

$$\mathcal{L}_{EM} = \frac{1}{16\pi\alpha_0} e^{\lambda\phi} F^2,$$

$$\frac{\dot{\alpha}}{\alpha} = \lambda\dot{\phi} \qquad \frac{\Delta\alpha}{\alpha} = \lambda\Delta\phi$$

generates a composition-dependent fifth force

$$\eta \simeq 10^{-1} \times 10^{-2} \times \lambda^2$$

relative strength

nuclear fraction

difference between two nuclei

(Damour & Polyakov, 1994)

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Conclusions

- It is important to look for dynamical dark energy (equivalently a cosmological scalar field) using other approaches than the equation of state
- Dynamical dark energy is likely to lead to violations of the equivalence principle
- General relations between different kinds of EP violation are satisfied by these models
- Some of the tools of compactification – orbifolds and warped extra dimensions – can be used to suppress deviations from the equivalence principle

Likewise,

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