Chameleon Fields: Awaiting Surprises for Tests of Gravity in Space

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astro-ph/0309300, astro-ph/0309411

Motivation

- Massless scalar fields are abundant in String and SUGRA theories
- Massless fields generally couple directly to matter with gravitational strength
    - Unacceptably large Equivalence Principle violations
    - Coupling constants can vary
    - Masses of elementary particles can vary

Light scalar field + Gravitational strength coupling

Theory disagrees with Experiment

Solutions?

- Use string loop effects to dynamically suppress couplings of fields to matter “Least Coupling Principle”- Damour & Polyakov hep-th/9401069, gr-qc/9411069

- Suppress couplings with an approximate global symmetry - Carroll astro-ph/9806099

- Field acquires mass due to some mechanism

Observations

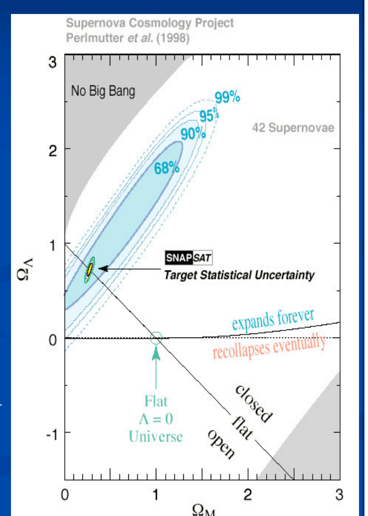
•Accelerated expansion of the Universe

Dark Energy, $P < 0$

□ Still possible

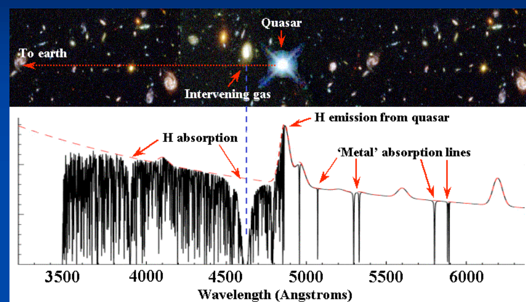
or

Quintessence □ Need very light scalar field



More Observations

Webb et. Al.



•Absorption lines in QSO spectra imply variation in fine structure constant

•Observations suggest existence of scalar fields evolving on cosmological time scales

Idea

$\boxed{\text{Mass of scalar field depends on local matter density}}$

In region of high density → mass is large → EP viol supressed

In solar system → density much lower → fields essentially free

On cosmological scales → density very low → $m \sim H_0$

→ Field may be a candidate for acc of universe

Approach

- Scalar fields can have cosmological effects but DO NOT result in EP violations in lab as we live in dense environment (This is the bomb!)
- Use experiments done on earth to constrain the parameters of the model (These give largest constraints)
- Use these constraints to make crucial predictions for tests in space (This is the fallout!)
- Could this field have cosmological effects?

Ingredients

Reduced Planck Mass

$$M_{Pl} = (8\pi G)^{-1/2}$$

Matter Fields

$$S = \int d^4x\sqrt{-g}\left\{\frac{M_{Pl}^2}{2}\mathcal{R} - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right\} - \int d^4x\mathcal{L}_m(\psi_m^{(i)}, g_{\mu\nu}^{(i)})$$

$$g = det g_{\mu\nu}$$

Einstein Frame Metric

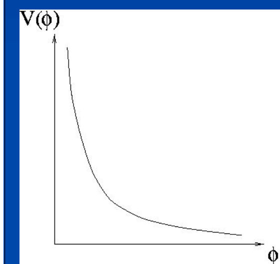
$$g_{\mu\nu}^{(i)} = e^{2\beta_i\phi/M_{Pl}} g_{\mu\nu}$$

Conformally Coupled

Potential is of the runaway form

Potential

Runaway Potential



$$\lim_{\phi\to\infty} V = 0\,, \qquad \lim_{\phi\to\infty} \frac{V_{,\phi}}{V} = 0\,, \qquad \lim_{\phi\to\infty} \frac{V_{,\phi\phi}}{V_{,\phi}} = 0\ldots$$

$$\lim_{\phi\to 0} V = \infty\,, \qquad \lim_{\phi\to 0} \frac{V_{,\phi}}{V} = \infty\,, \qquad \lim_{\phi\to 0} \frac{V_{,\phi\phi}}{V_{,\phi}} = \infty\ldots$$

e.g. $V(\phi) = M^{4+n}\phi^{-n}$

Effective Potential

Energy density in the i^{th} form of matter

Equation of motion : $\nabla^2\phi = V_{,\phi} + \sum_i \frac{\beta_i}{M_{Pl}}\rho_i e^{\beta_i\phi/M_{Pl}}$

Dynamics governed by Effective potential : $V_{eff}(\phi) \equiv V(\phi) + \sum_i \rho_i e^{\beta_i\phi/M_{Pl}}$

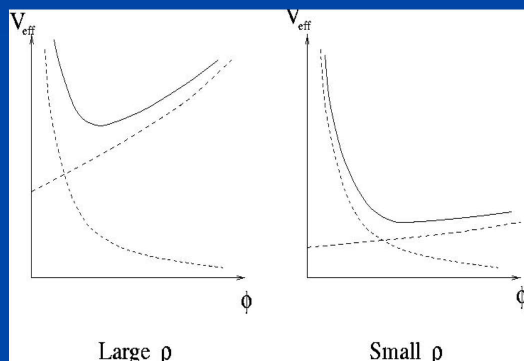
$$\boxed{V_{eff}(\phi) = V(\phi) + \rho e^{\beta\phi/M_{Pl}}}$$

Effective Potential

$\phi_C \ll \phi_\infty$ $m_C \gg m_\infty$

$r \ll R_C$

$\phi \approx \phi_C$



$r \gg R_C$

$\phi \approx \phi_\infty$

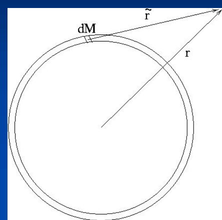
Compact Object

Assumptions :
- Static
- Spherical Symmetry R_c
- Homogeneous density ρ_c

Equation of motion :
$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} = V_{,\phi} + \frac{\beta}{M_{Pl}}\rho(r)e^{\beta\phi/M_{Pl}}$$

Boundary conditions :
$$\frac{d\phi}{dr} = 0 \qquad \text{at} \quad r = 0$$
$$\phi \to \phi_\infty \qquad \text{as} \quad r \to \infty$$

Exterior Solution



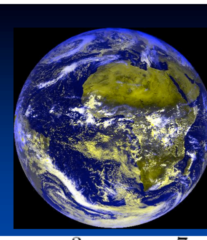
Thin shell condition

$$\phi(r) \approx -\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_c}{R_c}\right)\frac{M_c e^{-m_\infty r}}{r} + \phi_\infty \qquad \text{if} \quad \frac{\Delta R_c}{R_c} \ll 1\,,$$

Solution:

$$\phi(r) \approx -\left(\frac{\beta}{4\pi M_{Pl}}\right)\frac{M_c e^{-m_\infty r}}{r} + \phi_\infty \qquad \text{if} \quad \frac{\Delta R_c}{R_c} > 1\,;$$

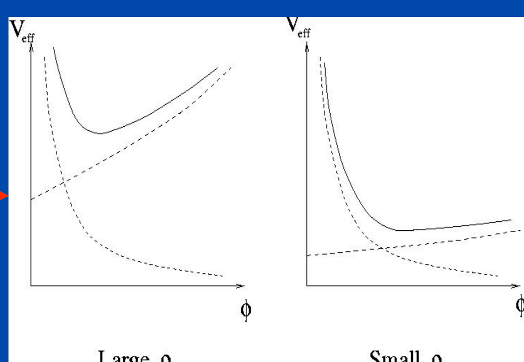
Earth



$R_E = 6 \times 10^{18} cm$

$\rho_E = 10 g/cm^3 = 10^{18} eV^4$

$\rho_\infty = 10^{-24} g/cm^3 = 10^{-7} eV^4$



Thin Shell Condition

$$\frac{\Delta R_c}{R_c} = \frac{\phi_c - \phi_\infty}{6\beta M_{Pl}\Phi_c}$$

Newtonian Potential

$$\frac{\Delta R_C}{R_C} \ll 1$$

Object displays thin shell effect

Both earth and atmosphere display thin shell effect

$$\frac{\Delta R_E}{R_E} < 10^{-7}$$

Fifth Force on Earth

5th Force: $\vec{F}_\phi = -\frac{\beta}{M_{Pl}} M \vec{\nabla}\phi$

Range of interaction

Potential : $V(r) = -2\beta_1\beta_2 \frac{M_1 M_2}{8\pi M_{Pl}^2} \frac{e^{-r/R_{vac}}}{r}$

Strength of interaction

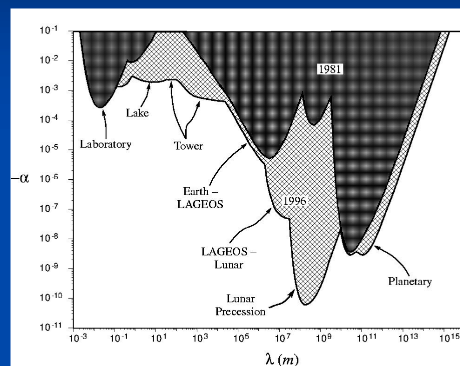
Separation betw particles

Thin shell

$$\beta_{eff} = \frac{\Delta R_C}{R_C}\beta$$

Fifth Force Searches

$$V(r) = -\alpha \frac{M_1 M_2}{8\pi M_{Pl}^2} \frac{e^{-r/\lambda}}{r}$$



□ ~ □$_{1eff}$ □$_{2eff}$

□ ~ R_{vac}

Constraints on Model Parameters

$$\frac{\Delta R_E}{R_E} < 10^{-7} \quad + \quad V(\phi) = M^{4+n}\phi^{-n}$$

$$\longrightarrow \quad M \le 10^{-3} eV \approx (1mm)^{-1}$$

Coincides with Energy scale of Dark Energy

$$m_{atm}^{-1} \le 1mm \qquad m_{atm} \ge 10^{-3} eV$$

$$m_G^{-1} \le 10^4 AU \quad \Rightarrow \quad m_G \ge 10^{-21} eV$$

$$m_0^{-1} \le 10^3 pc \qquad m_0 \ge 10^{-23} eV$$

Predictions for tests in Space

New Feature !! → Different behaviour in space

Tests for universality of Free Fall $$\eta \equiv 2\frac{|a_1 - a_2|}{a_1 + a_2}$$

Current Limit on earth Eöt-Wash $\eta < 10^{-13}$

We predict → $$\beta^2 \cdot 10^{-19} < \eta < \beta^2 \cdot 10^{-11}$$

Near- future experiments in space :

STEP	$\eta \sim 10^{-18}$
GG	$\eta \sim 10^{-17}$
MICROSCOPE	$\eta \sim 10^{-15}$

SEE Capsule

No thin shell supression

→ $10^{-15} < \Delta R_E/R_E < 10^{-7}$

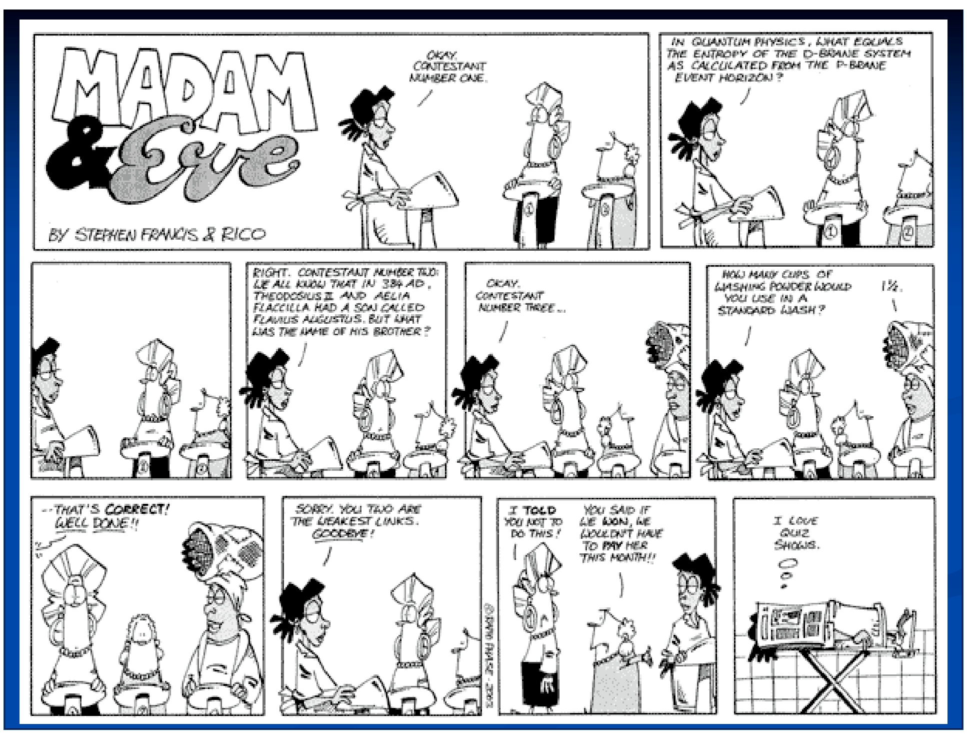
$$|\vec{F}| = \frac{GM_1M_2}{r^2}(1 + 2\beta_1\beta_2)$$

→ Corrections of O(1) to Newton's Constant

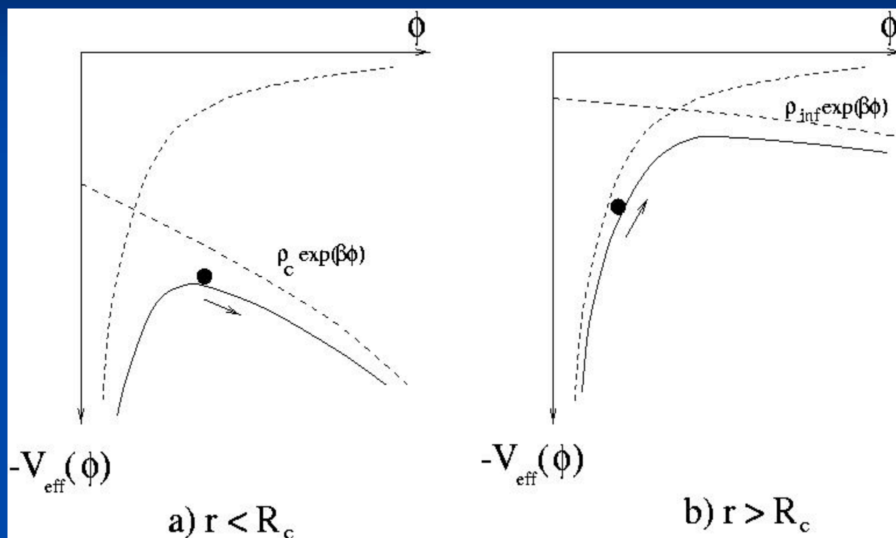
Take Aways

Chameleon fields are nice because

- No EP violations on earth
- Make predictions for experiments in space
- Interesting cosmological consequences



Inverted Potential



Vacuum Chamber

Model as empty spherical chamber of radius R_v

Results :

- Within the chamber $\phi \sim \phi_v$ where ϕ_v satisfies

$$m_v^2 = \frac{d^2V}{d\phi^2} = R_v^{-2}$$

- ϕ_v varies slowly throughout the chamber, with

$$\frac{d\phi}{dr} \leq \frac{\phi_v}{R_v}$$

- Outside the chamber the solution tends to ϕ_{atm} within m_{atm}^{-1} from the walls