Modified theories of gravity and mechanisms of mass screening

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Dark Energy in a nutshell

Chameleon

Symmetron

Vainshtein

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- Friedmann equation

$$3H^2 = \rho$$

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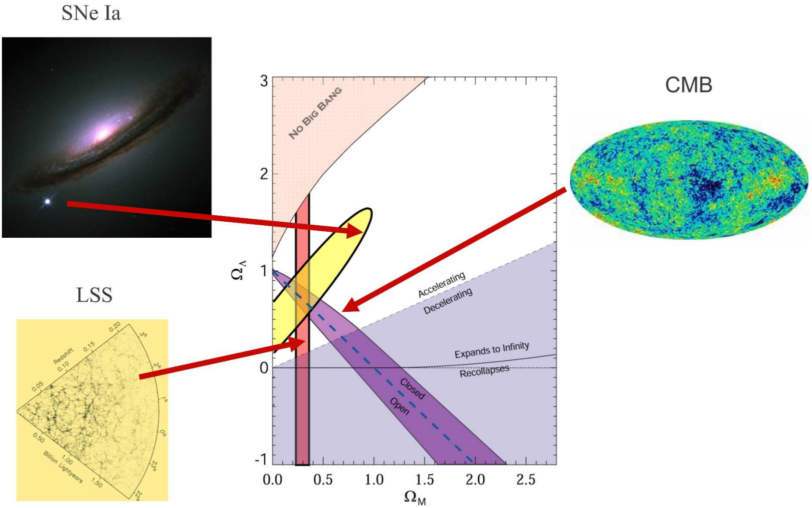
$$3H^2 = \rho + \Lambda$$

$$\Omega_{DE} = 0.72 \pm 0.015, \qquad -1.11 < w_{DE} = P/\rho < -0.86$$



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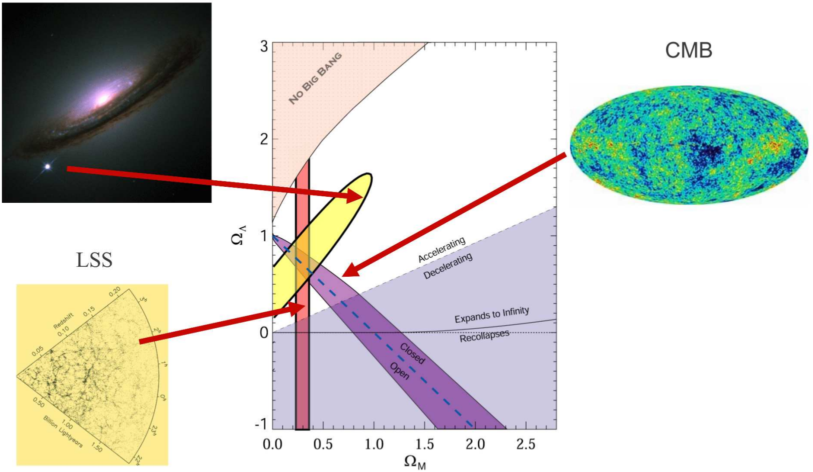

⇒ **The Universe is accelerating**

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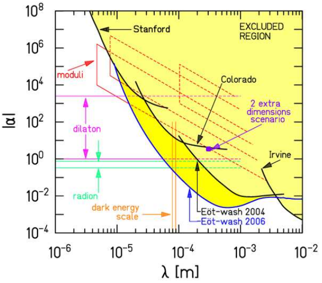
Local bounds

- Laboratory Bounds

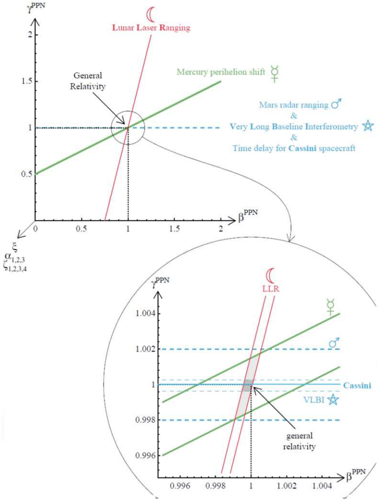
$$V(r) = -G\frac{m_1 m_2}{r}\left[1 + \alpha \exp^{-r/\lambda}\right]$$



$$g_{00} = -1 + 2\frac{GM}{rc^2} - 2\beta^{\text{PPN}}\left(\frac{GM}{rc^2}\right)^2 + \cdots$$

$$g_{ij} = \delta_{ij}\left[1 + 2\gamma^{\text{PPN}}\frac{GM}{rc^2} + \cdots\right]$$

- Solar System Bounds



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- **How to modify the theory of gravity?**
  Weinberg's theorem: A Lorentz-invariant theory of a massless spin-two field must be equivalent to GR in the low-energy limit.
  Low-energy modifications of gravity therefore necessarily involve introducing new degrees of freedom, such as a scalar.
  Giving the graviton a small mass width turns out to introduce a scalar.
  Theories that invoke a Lorentz violating massive graviton also involve a scalar.

Three ways to hide

$$\mathscr{L} = -\frac{1}{2} Z^{\mu\nu}(\phi)\partial_\mu\phi\partial_\nu\phi - V(\phi) + A(\phi)T$$

- The scalar field is weakly coupled to matter
  - Quintessence
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$$S = \int d^4x \sqrt{-g} \left(R - \frac{1}{2}(\partial\phi)^2 - V(\phi) \right) + S_m[\psi_m; A^2(\phi) g_{\mu\nu}]$$

- Equation of motion
- Dynamics governed by effective potential:

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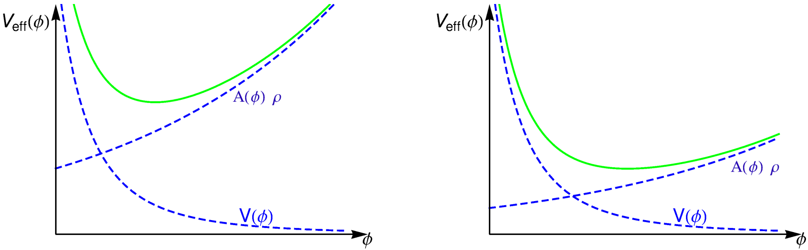
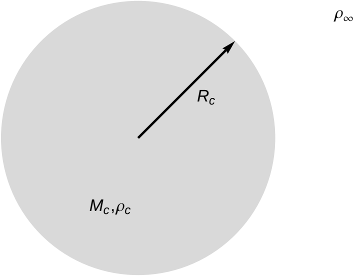


Large ρ Small ρ

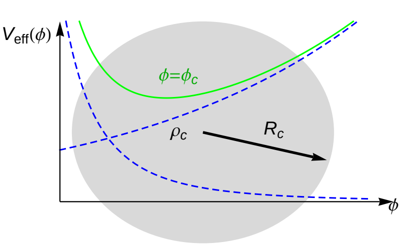
Solution for a compact object

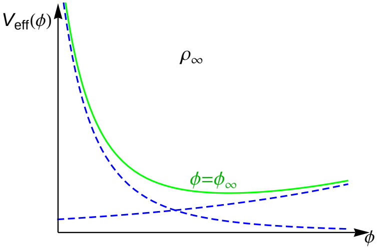


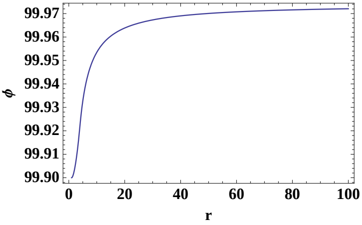
$$\frac{\mathrm{d}^2\phi}{\mathrm{d}r^2} + \frac{2}{r}\frac{\mathrm{d}\phi}{\mathrm{d}r} = V_{,\phi} + A(\phi)\rho(r)$$

The boundary conditions specify that the solution be nonsingular at the origin: $\dfrac{\mathrm{d}\phi}{\mathrm{d}r} = 0$ at $r = 0$

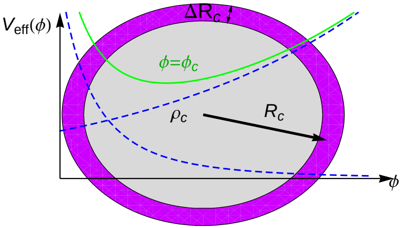
And that the force on a test particle vanishes at infinity: $\phi \to \phi_\infty$ as $r \to \infty$

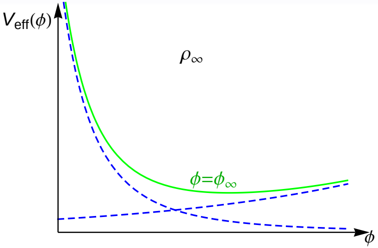


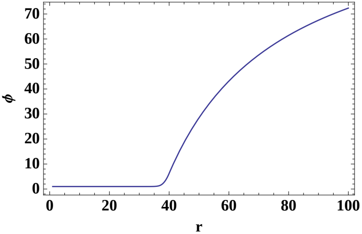




$$\phi(r) \approx -\left(\frac{\beta}{4\pi M_{pl}}\right)\frac{M_c e^{-m_\infty(r-R_c)}}{r}+\phi_\infty$$







$$\phi(r) \approx -\left(\frac{\beta}{4\pi M_{pl}}\right)\left(3\frac{\Delta R_c}{R_c}\right)\frac{M_c e^{-m_\infty(r-R_c)}}{r} + \phi_\infty$$

- Field reaches effective minimum almost everywhere in the body
- All field variations confined to small region near body surface
- This region is called a thin-shell $\dfrac{\Delta R_c}{R_c} \ll 1$

Fifth Force on Body with Thin-Shell

A test mass M_1 in a static chameleon field ϕ experiences a force $\vec{F}_\phi$

$$\frac{\vec{F}_\phi}{M_1} = -\frac{\beta}{M_{pl}}\vec{\nabla}\phi$$

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$$\Rightarrow \quad F_{12} = \frac{G_N m_1 m_2}{r^2}\left(1 + \alpha e^{-mr}\right)$$

- deviations from Newton's law are given by $\alpha = 6\beta^2\frac{\Delta R_c}{R_c}$

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  for large objects (sun, earth, moon) , Newton's potential is large and a thin shell is always present

  $\Rightarrow$ Planetary motion unaffected by the chameleon field

- Example (Earth)

  Modeled as a sphere of radius $R_c = 6000\ Km$ and density $\rho_c = 10 g/cm^3$.

  Far away the matter density is approximately that of baryonic gas and dark matter: $\rho_\infty = 10^{-24} g/cm^3$

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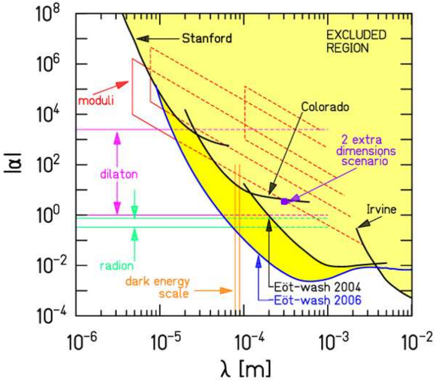
Gravity Test



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$$\alpha = 10^{-8}$$

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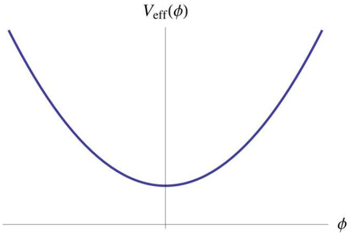
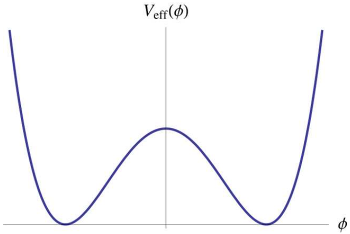


Large density



Low density

Coupling to matter $\simeq \frac{\phi^2}{M^2}\rho$

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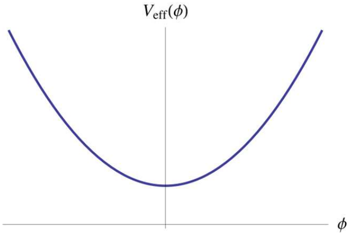

Large density Low density

$$\text{Coupling to matter} \simeq \frac{\phi^2}{M^2}\rho$$

$$\text{Fluctuations } (\delta\phi) \text{ around the local background } (\phi_0) \simeq \frac{\phi_0}{M^2}\delta\phi\rho$$

Conclusion

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- Weaknesses
  - Singularity problem ?
  - We do not solve the cosmological constant problem:

$$m_\phi < 10^{-33}\text{eV}$$

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$$L = -\frac{1}{2} Z^{\mu\nu}(\phi)\partial_\mu \phi \partial_\nu \phi - V(\phi) + A(\phi) T$$

- At low energy $Z_{\mu\nu} \approx g_{\mu\nu}$
- At high energy $Z_{\mu\nu} \gg 1$
- The field is strongly coupled to itself and becomes weakly coupled to external sources

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$$\frac{\phi}{M_{pl}}T = \frac{\hat{\phi}}{\sqrt{Z}M_{pl}}T \ll 1$$

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Vainshtein

$$L = -\frac{1}{2}Z^{\mu\nu}(\phi)\partial_\mu\phi\partial_\nu\phi - V(\phi) + A(\phi)T$$
$$= -\frac{1}{2}Z^{\mu\nu}(\phi)\partial_\mu\phi\partial_\nu\phi + \frac{\phi}{M_{pl}}T$$

$$Z_{\mu\nu} \approx g_{\mu\nu} + \frac{1}{\Lambda^3}\partial_\mu\partial_\nu\phi + \frac{1}{\Lambda^6}\left(\partial_\mu\partial_\nu\phi\right)^2 + \cdots$$

- At low energy $Z_{\mu\nu} \approx g_{\mu\nu}$
- At high energy $Z_{\mu\nu} \gg 1$

$$-\frac{1}{2}Z^{\mu\nu}(\phi)\partial_\mu\phi\partial_\nu\phi = -\frac{1}{2}\left(\partial\hat{\phi}\right)^2, \qquad \hat{\phi} = \frac{\phi}{\sqrt{Z}}$$

$$\frac{\phi}{M_{pl}}T = \frac{\hat{\phi}}{\sqrt{Z}M_{pl}}T \ll 1$$

- The field is strongly coupled to itself and becomes weakly coupled to external sources

DGP

- Dvali, Gabadadze, Porrati (2000).
- The 3-brane is embedded in a Minkowski bulk spacetime with infinitely large 5^{th} extra dimensions:
- Boundary effective action (Luty,Porrati,Rattazzi: 2003)
  - ADM decomposition $(g_{\mu\nu}, N, N_\mu)$
  - $G_{MN} = \eta_{MN} + h_{MN}$
  - We focus on the scalar mode (ϕ)

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Decoupling limit

$$L_\phi = -3(\partial\phi)^2 - \frac{1}{\Lambda^3}\Box\phi(\partial\phi)^2 + 2\frac{\phi}{M_{pl}}T$$

- The effective action is local
- The equation of motion remain second order in derivative
- The equations of motion are invariant under shift and Galilean global transformations $\phi \to \phi + c + v_\mu x^\mu$

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$\Rightarrow$ Galileon models

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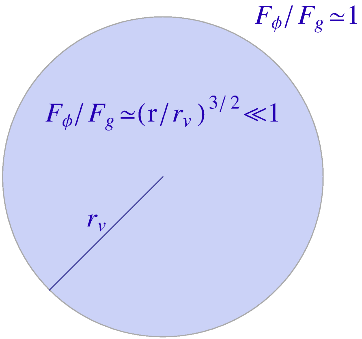

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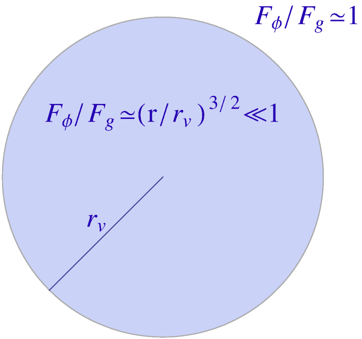

$\Rightarrow$ The fifth force is suppressed locally

Conclusion

- Three ways to hide the additional degrees of freedom
  - Chameleon
  - Symmetron
  - Vainshtein
- Nontrivial interactions between the scalar field and matter allowed
- Candidate for dark energy
- Bounds from laboratories, solar system and astrophysical experiments are exponentially relaxed
- The best model is the cosmological constant

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