Detecting Chameleon Fields with Casimir Force Experiments

"dark energy on your desk top"

Douglas Shaw
DAMTP, Cambridge

In collaboration with
Ph. Brax, C. van de Bruck,
A-C Davies and D. F. Mota

Chameleon Fields??

- Chameleon fields are:
  - scalar fields ϕ
  - which couple to matter M
  - and have self-interactions $V(\phi)$

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2\kappa_4^2}R - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right) + S_m(e^{\phi/M}g_{\mu\nu}, \psi_m),$$

$$\Box\phi = V_{,\phi} + \frac{\rho}{M}$$

J. Khoury and A. Weltman, PRL 93 (2004)

Chameleon Fields Adapt

- A chameleon field has mass:

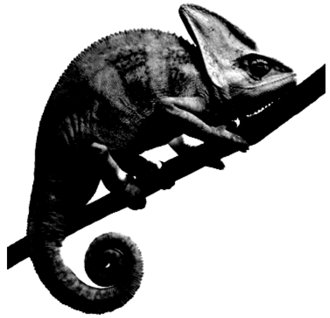
$$m_\phi = \sqrt{V_{,\phi\phi}(\phi)}$$

- This is not constant but grows with the ambient density of matter.
- This requires:

$$V_{,\phi}(\phi) < 0 \qquad V_{,\phi\phi}(\phi) > 0, \qquad V_{,\phi\phi\phi} < 0$$

- The stronger the matter coupling, the faster they adapt and the better they hide.

The Dark Chameleon



- Cosmologically chameleon fields have equation of state:

$$w \approx -1 + \frac{27\Omega_m^2}{\Omega_\phi}\left(\frac{H}{m_\phi}\right)^2\left(\frac{M_{\rm Pl}}{M}\right)^2$$

  - where $M_{\rm Pl} = \sqrt{1/8\pi G}$
  - and generally they must obey $H^2 \ll m_\phi^2$
  - so if $\Omega_\phi \approx 0.73, \quad M \lesssim M_{\rm Pl}$

- They could be dark energy

Ph. Brax et al., PRD 70 (2004)

Dark Energy

- For dark energy:

$$V(\phi) = \Lambda_c^4 f(\phi/\Lambda)$$

  - where

$$\Lambda_c = (2.4 \pm 0.1) \times 10^{-3}\,\mathrm{eV}$$

  - and cosmologically today $f = 1$
  - and $f'(1), f''(1) \sim \mathcal{O}(1)$
- For example:

$$V = \Lambda_c^4 \exp(\Lambda/\phi)^n$$

  - simplest case would be when $\Lambda \approx \Lambda_c$

Playing with Dark Energy

- Dark energy is difficult to probe experimentally:
  - so far its effects have only been detected on astrophysical scales...
  - and there's only one Universe, and we don't have much control over it!
- But chameleonic dark energy would be different:
  - It could be detected in the laboratory, under controlled conditions.
  - One could actually play with dark energy on your desk top!

Detecting Chameleon Fields

- Chameleon fields mediate a new force that can be as large as:

$$2\beta^2 \equiv \left(\frac{M}{M_{\rm Pl}}\right)^2$$

  the strength of gravity.
- Might think that experiments limit

$$\beta^2 \ll 1$$

- But this is not the case.
  - Chameleons evade experimental constraints because the test masses develop thin-shells.

Thin Shells

- The chameleon field evolves in the effective potential:

$$V_{\mathrm{eff},\,\phi} = V_{,\phi}(\phi) + \frac{\rho}{M}$$

  - Outside a body:

$$\rho = \rho_b \text{ and } V_{\mathrm{eff},\,\phi} = 0 \text{ for } \phi = \phi_b$$

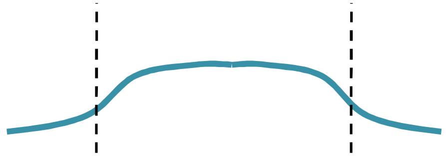
  - And inside the body:

$$\rho = \rho_c \gg \rho_b \text{ and } V_{\mathrm{eff},\,\phi} = 0 \text{ for } \phi = \phi_c$$

  - And importantly:

$$m_c = m_\phi(\phi_c) \gg m_b = m_\phi(\phi_b)$$

No Thin Shells



- There are then two possibilities:
- If the body is small then

$$V(\phi(r=0) - V(\phi_b) \ll V(\phi_c) - V(\phi_b)$$

  - The chameleonic force between two such bodies with masses M_1 and M_2 is:

$$F_\phi = 2\beta^2(1+m_b r)e^{-m_b r}\frac{GM_1M_2}{r^2}$$

  - It looks just like a standard Yukawa force.
- Such bodies do not have thin-shells

Thin Shells

- If the body is large enough then

$$V(\phi(r=0)) - V(\phi_b) \approx V(\phi_c) - V(\phi_b)$$

  - at large distances:

$$F_\phi = (1 + m_b r)e^{-m_b r}\frac{C(V, R_1, R_2)}{r^2}$$

  - C is independent of β, M_1 and M_2. It depends only on the potential, V, and the radii of the bodies.

- These bodies have thin-shells
  - most of the change in ϕ occurs in a thin region near the surface of the body.
  - the chameleonic force is composition independent.

More Thin Shells

- If the chameleon is dark energy and

$$\Lambda \approx \Lambda_c \qquad M \lesssim M_{\rm Pl}$$

  - then test masses used in gravity tests generally have thin-shells.

- This why the chameleon can hide but also makes it difficult to detect.

Detecting Chameleons

- Force between two nearby thin-shelled bodies depends on the distance of separation between their surfaces:

$$\frac{F_\phi}{A} \sim \Lambda_c^4 g(\Lambda_d d)$$

  - where $\Lambda_d = \Lambda_c^2/\Lambda$

- If $\Lambda \approx \Lambda_c$ then you might think that ISL test could see this....

D. F. Mota and DJS, PRL 97 (2006)

Detecting Chameleons

- ISL tests only provide bounds on

$$M \sim M_{\rm Pl}$$

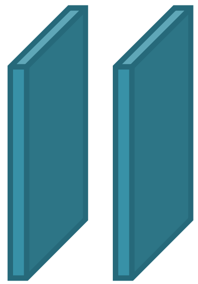
- If $M \lesssim 10^{16}\mathrm{GeV}$ then the electrostatic shield acts as a chameleon shield.
- Chameleon force looks very similar to the Casimir force:

$$\frac{F_\phi}{A} \propto d^{-p} \qquad \frac{F_{\rm cas}}{A} \propto \frac{\pi^2}{240 d^4}$$

D. F. Mota and DJS, PRD 75 (2007)

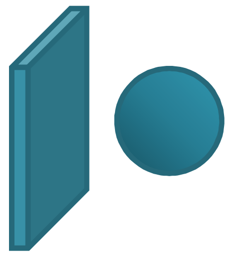
Casimir Force Experiments

- Measure force between
  - Two parallel plates
    - Difficult to keep plates parallel
    -



R. S. Decca et al., PRD 75 (2007)

  - A plate and a sphere
    - Harder to calculate analytically.



S. K. Lamoreaux, PRL 78 (1997)

- No physical shield is used.
  - Electrostatic forces calibrated for by controlling electric potential between plates.

Chameleons & Casimir

- We consider two potentials:
  - $V = V_1 = \Lambda_c^4(1 + \Lambda^n/\phi^n)$
  - $V = V_2 = \Lambda_c^4 \exp(\Lambda/\phi)^n$
  - If $\Lambda \approx \Lambda_c$ and n = -4 or n = -6 with $V = V_1$ is strongly ruled out.

- More generally we find that currently:

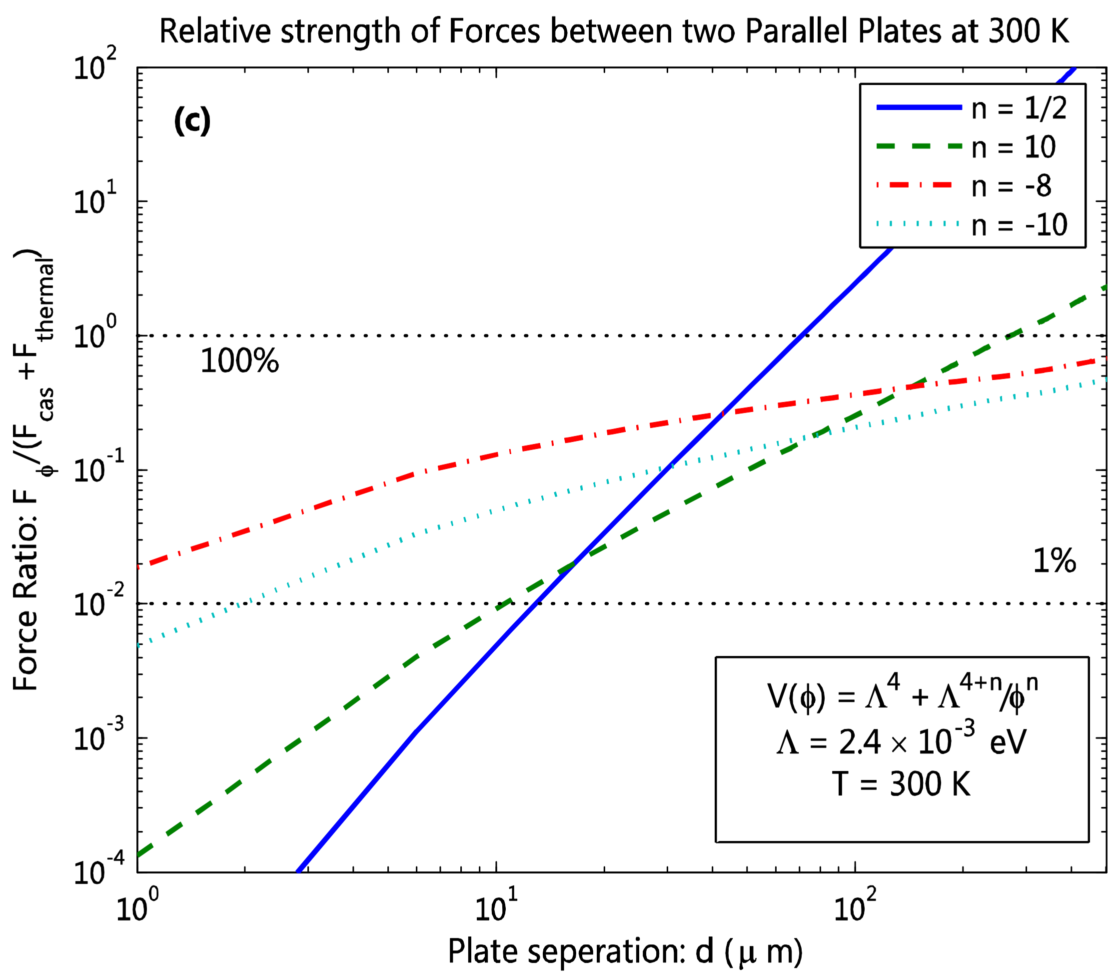
$$\Lambda \lesssim (10 - 100)\Lambda_c$$

What the future holds

- Currently the Casimir force has been detected to 1% accuracy at $d \approx 1\,\mu\mathrm{m}$
- How far does this need to improve to detect dark energy chameleons??
- Must remember thermal contribution:

$$\frac{\bar{F}_{\mathrm{thermal}}}{A} \equiv \frac{\zeta(3) k_B T}{4\pi d^3}$$

What the future holds



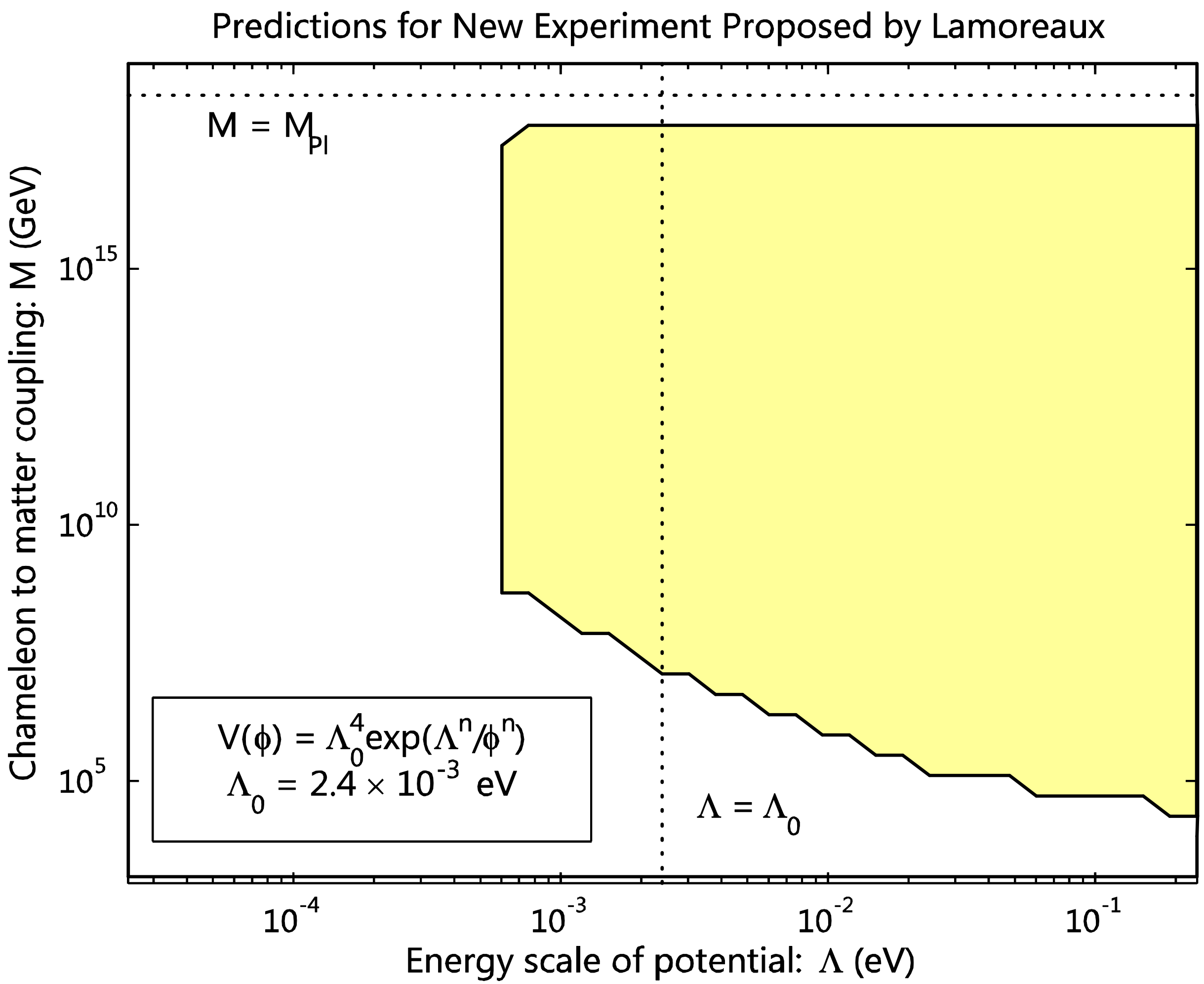
New experiments

- Two new experiments currently under construction have real prospect of detecting chameleons.

- Los Alamos experiment
  - Sphere and plate
  - Could detect chameleon force if $n \approx 1$ without a detailed knowledge of the thermal force.

S.K. Lamoreaux

New Experiments

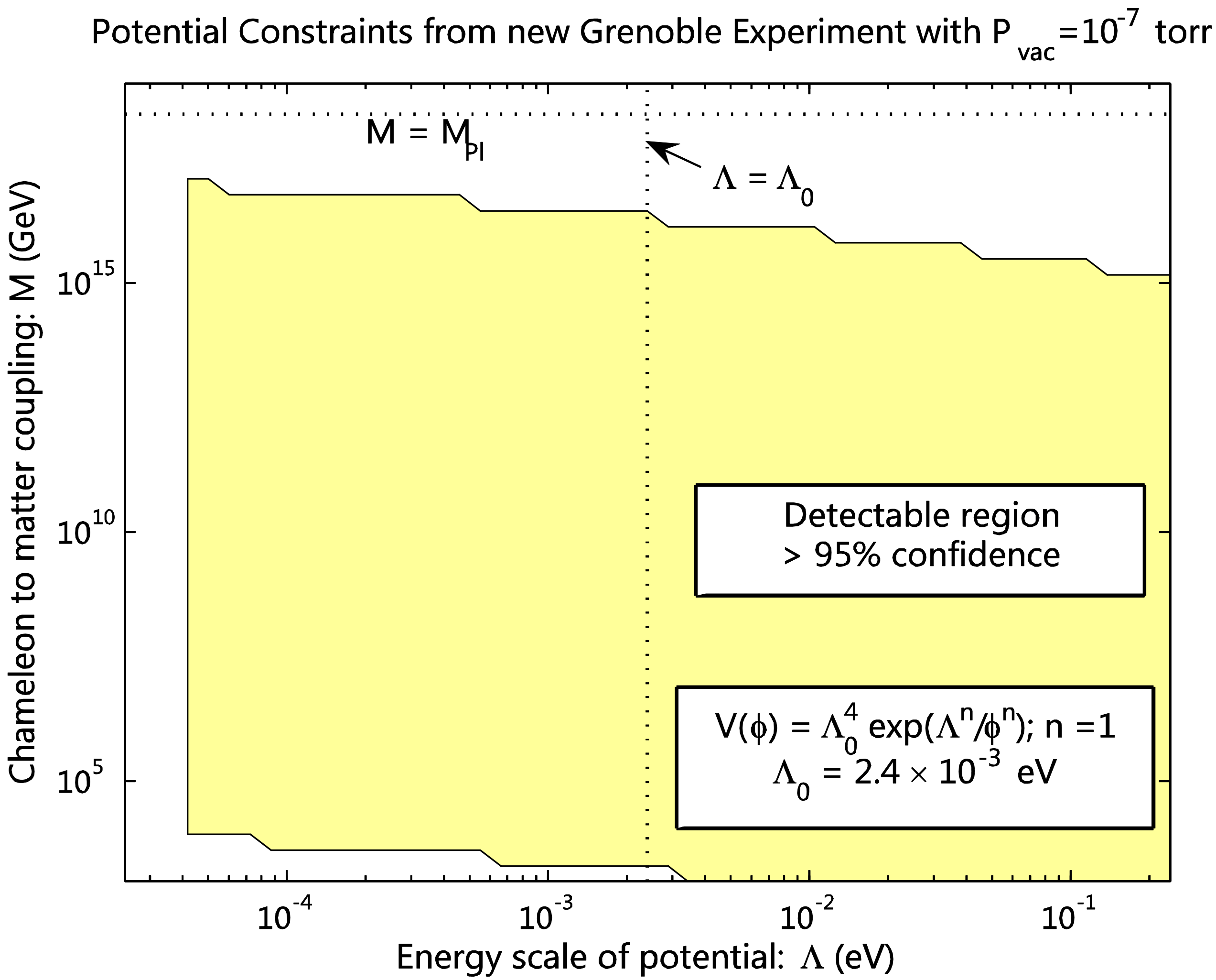


New Experiments

- If the thermal background can be modelled to 1% then new experiment at Grenoble could detect virtually all chameleon fields.
  - Uses parallel plates
  - Enhanced accuracy due to ability to keep plates parallel to a very high precision.

A. Lambrecht et al., CQG 22 (2005)

New Experiments



Chameleons??

- Next generation of Casimir force measurement experiments have the precision to detect almost all chameleon dark energy models with

$$M \lesssim 10^{16}\text{GeV}$$

- Generally a good model for the thermal Casimir force is required although some models can be detected without it.

Conclusions

- Chameleonic dark energy models can e probed in the laboratory.
- Casimir force measurements are best suited to testing for chameleons.
- If chameleons exist, next generation of Casimir force test should detect them.
- If they do not then chameleonic dark energy is all but ruled out.