Cosmological Scalars – Theory and Tests

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Cosmological scalars have played a role in cosmology for many years from the early Universe cosmological inflation to the late Universe as dark energy candidates. Here we concentrate on the late Universe, introducing such a class of models. The possibility of detection of light scalar particles in laboratory experiments and underlying constraints are discussed. Finally the possible role they could play in solar physics is introduced.

2nd Training School and General Meeting of the COST Action COSMIC WISPers (CA21106) (COSMICWISPers2024)
10-14 June 2024 and 3-6 September 2024
Istanbul (Turkey)

*Speaker

PoS(COSMICWISPers2024)003

1. Introduction

There are several reasons for considering cosmological scalar fields. One such reason is that they could help explain the mysterious dark energy. Another is that they can modify Einstein gravity but reduce to the usual general relativity in a certain limit, thus testing Einstein relativity in different regimes. If the scalar field couples to matter then it gives rise to an extra, fifth force, which is severely constrained by solar system tests of gravity [1]. Consequently the fifth forces need to be screened by inherent non-linearities in the theory so that they evade solar system tests [2]. Screening mechanisms include chameleon screening [3, 4], the Damour-Polyakov mechanism [5], the K-mouflage [6] and Vainshtein screenings [7]. Here we concentrate on the chameleon and Damour-Polyakov mechanisms. These theories have standard kinetic terms, resulting in the speed of gravitational waves being the same as that of light. They screen whereby the non-linear interactions either cause the mass of the scalar field to depend on the environment, becoming heavy in a dense environment and very light in a sparse environment; the chameleon mechanism, or by the coupling to matter depending on the environment, switching off in dense environments. The latter is the symmetron mechanism [8] and uses the Damour-Polyakov mechanism. Screening fifth forces can be realised in both cases thanks to a new ingredient; one needs the thin shell effect, whereby the scalar field is constant inside a massive body, constant outside and only varies in a thin shell at the surface of the body. The fifth force depends on the gradient of the scalar field; consequently if there is a thin shell the theory evades tests of gravity in the solar system. Such theories allow modified gravity to be tested in the laboratory, cosmologically and astrophysically. In testing these theories one is also testing general relativity and so this class of theories allows GR to be tested in regimes not previously explored.

Here we review a class of scalar-tensor models with the usual quadratic kinetic terms and where the fifth forces are screened either with the chameleon or the Damour-Polyakov mechanism. We will not discuss the K-mouflage and Vainshtein screenings here.

2. Scalar–Tensor Theories

The class of theories we are considering have Lagrangian

$$S = \int d^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}[A^2(\phi)g_{\mu\nu};\psi]\ . \tag{1}$$

with potential $V(\phi)$ and a coupling to matter $A(\phi)$. Note this is written in the Einstein frame, but matter moves in the Jordan frame. In the chameleon case, this reads

$$V(\phi) = \Lambda^4\left(1 + \frac{\Lambda^n}{\phi^n}\right)\ , \qquad A(\phi) = e^{\phi/M} \tag{2}$$

where n is an integer, Λ and M scales specifying the model. This was originally proposed in [3]. In the presence of matter of density $\rho_{\rm m}$, the field does not respond only to the potential $V(\phi)$ but to the "effective potential"

$$V_{\rm eff} = \Lambda^4\left(1 + \frac{\Lambda^n}{\phi^n}\right) + \frac{\phi}{M}\rho_{\rm m}\ , \tag{3}$$

The minimum of the effective potential, and hence the mass of the scalar particle, is density dependent. The particle is massive in a dense environment, evading solar system tests, but almost massless in sparse environments; for instance cosmologically.

For the symmetron model the effective potential is

$$V_{\rm eff}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4 \ . \tag{4}$$

meaning that in regions where the ambient matter density is large, $\rho > \mu^2 M^2$, the effective potential is positive and is minimised when $\phi = 0$ but symmetry can be spontaneously broken in regions with sufficiently small matter density ρ. Thus the coupling to matter 'switches off' in dense environments, but not in sparse ones below a critical density.

One might expect a runaway dilaton to be another model. This has potential and coupling function of

$$V(\phi) = V_0 e^{-\alpha\phi} \ , \qquad A(\phi) = e^{\beta\phi} \tag{5}$$

Whilst the mass derived from the effective potential is density dependent, there is not a thin shell,so the model will not pass solar system tests. Instead one can use the environmentally dependent dilaton model [9] but this will not be discussed further. It should be emphasized that when considering this class of models, it is important to test the thin shell mechanism. This happens when the field inside an objects $\phi_{\rm in}$ and outside $\phi_{\rm out}$ are such that the effective coupling to matter is smaller than the coupling outside

$$\beta_{\rm eff} \equiv \frac{|\phi_{\rm out} - \phi_{\rm in}|}{2m_{\rm Pl}\Phi_N} \leq \beta_{\rm out} \tag{6}$$

where $\beta = m_{\rm Pl}\frac{d\ln A(\phi)}{d\phi}$, $m_{\rm Pl}$ is the reduced Planck scale and Φ_N the Newtonian potential at the surface of the object.

3. Laboratory Tests

Both chameleons and symmetrons can be tested in the laboratory. This, of course, means that general relativity can be tested at scales not previously envisaged. The first such test was torsion balance tests.

Torsion balance experiments have a long history of searching for fifth forces and modifications of gravity. The underlying principle is to have one or more test masses suspended, and to look for deflections of the test masses towards source masses by measuring the torsion in the suspension of the test masses. The current best constraints come from the Eöt-Wash experiment[10], which uses circular disks for the masses. The disks have holes bored into them and are arranged one above the other, so that if there are no modifications to gravity then there is expected to be no net torque between the two plates. Recent constraints on fifth forces are discussed in [1].

Atom interferometry is another technique to measure the external forces acting on a single atom. It functions in a manner somewhat analogous to the classic double slit experiment. The atom's wave function is split into two parts, which are sent along different trajectories and then overlapped again at a later point in time. Any difference in the quantum mechanical phase that is accumulated along the paths results in interference at the end point. The experiment is conducted in a vacuum chamber; a cloud of atoms is injected and subjected to laser light to split the wave packets into two. The paths recombine and the interference pattern detected. The experiment is conducted in the presence of a test mass and any anomalous acceleration is observed. The atoms are such that they are typically unscreened but the test mass heavy enough to be screened. The experiment was originally proposed by[11] and performed by [12–14]. These experiments constrain both chameleons and symmetrons over a wide range of parameter space [14, 15].

Modified gravity models can also be tested with Casimir force experiments. This is the force between two parallel plates, placed in vacuum, due to the quantum fluctuations of the electromagnetic field in the space between the plates. This force scales as d^{-4}, where d is the distance between the plates. Current experiments probe sub-mm and sub-micron distance scales [16, 17]. If fifth forces exist they could also be detected by an experiment searching for Casimir effects. These experiments are particularly sensitive to screening through the thin-shell effect. The chameleon force (per unit area) between two plates scales as [18]

$$\frac{F_{cham}}{A} \approx d^{-\frac{2n}{n+2}} \tag{7}$$

The plates need to be perfectly parallel, an experimental challenge, so it is easier to search for the Casimir effect with a plate and sphere. Usually the proximity force approximation is used to compute the force, Originally this was used for chameleon models [18] as well, but this is less reliable when the underlying theory is non-linear, as is the case for chameleon and symmetron models. A Casimir experiment has been performed using a rotating plate with trenches and a sphere such that the sphere samples the force at two different distances [17]. Whilst the actual configuration is not ideal, one can use this experiment as the basis to make forecasts for future experiments. Detailed forecasts were made for the symmetron model [19]. Two approximations were made; the proximity force approximation whereby each spherical element at the surface of the sphere can be approximated by its tangent plane and the interaction between the sphere and the plate can be obtained as the sum of all the elemental pressures on the tangent planes exerted by the infinitely large plate and the small sphere approximation. In addition, numerics were used and overall forecasts made. A similar analysis was performed for the chameleon model. Here it was found that, due to the non-linearities of the theory, the PFA approximation completely failed, but the small sphere approximation matched the numerical code closely [20]. Our results can be seen in Fig 2. In can also be possible to construct an experiment where a neutral gas, such as xenon, is injected into the vacuum chamber and the Casimir force measured between the case in vacuum and with the neutral gas [21]. In this case the chameleon force switches off in the presence of the neutral gas. This experiment is in progress [22].

4. Atomic Spectra

Due to the coupling between the scalar field and ordinary matter modified gravity theories can give rise to shifts in spectral lines. If the fifth force contribution to the electron's Hamiltonian is δH, the perturbation to the electron's energy levels are given by the classical formula

$$\delta E_n = \langle \psi_n | \delta H | \psi_n \rangle \tag{8}$$

The perturbation to the electron's Hamiltonian is

$$\delta H = m_e A(\phi)\ . \tag{9}$$

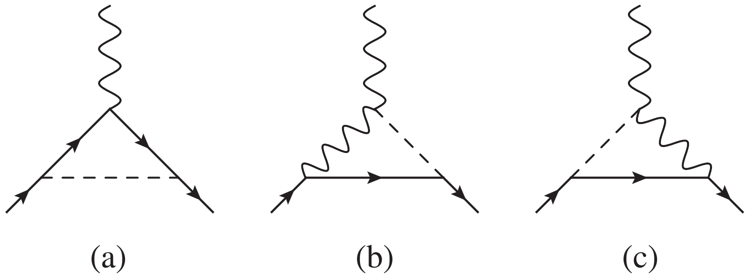

Figure 1: Scalar field (dashed line) contributions at one-loop order to the magnetic moment of the muon. Reproduced from [24].

We can compute the perturbation to the $1s$ and $2s$ energy levels and then compute the shift in the lowest energy spectral line for hydrogen due to modified gravity

$$\delta E_{1s-2s} = A_{,\phi}\, (\phi_{\rm out})^2 \frac{3 m_N m_e}{16\pi a_0}\,, \tag{10}$$

The $1s-2s$ transition of hydrogen has been measured to a high accuracy giving the uncertainty of $\delta E_{1s-2s} = 5.1\times 10^{-10}$ eV, enabling us to constrain the parameters of our modified gravity theories [23]. Before we display the constraints we will first consider muonium, a hydrogen-like system consisting of a single electron orbiting an anti-muon. Since the muon is a fundamental particle this has the advantage over hydrogen. The muon is always unscreened and thus a highly sensitive probe for modified gravity theories. The constraints are displayed in Fig 2 and Fig 3.

Finally we can consider the effect of the modified gravity scalar on the anomalous magnetic moment of the electron and the muon. In both cases there is a classical effect and a quantum effect to take into consideration. For the electron the modified gravity scalar mildly shifts the energy of the electron eigenstates in the Penning trap. For the muon the scalar adds a contribution to the angular velocity vector in the cyclotron. The quantum corrections are given in Fig. 1.

Fermilab measured the anomalous magnetic moment of the muon using a cyclotron. The experimental value of a_μ measured is larger than the standard model prediction, by an amount

$$\delta a_\mu = a_{\mu,\rm exp} - a_{\mu,\rm th} = 2.51\times 10^{-9} \tag{11}$$

A modified gravity scalar field can alleviate the tension if

$$\delta a_\mu \approx \frac{m_\mu}{qB}\frac{1}{\gamma v}\partial_\phi \ln A|\vec{\nabla}\phi| + 2(\partial_\phi \ln A)^2 \left(\frac{m_\mu}{4\pi}\right)^2 I_1\left(\frac{m_0}{m_\mu}\right)\,, \tag{12}$$

where the first and second terms are the classical and quantum corrections to the anomalous spin precession, respectively. This can be computed for both chameleons and symmetrons in order to see if modified gravity can explain the discrepancy, or conversely whether the anomalous magnetic moment of the muon can be used to constrain the theory parameters. There is a region of parameter space for both chameleons and for symmetrons that can account for this discrepancy [25]. Similarly we can use the experimental results for the electron dipole moment, this time using a Penning trap, to constrain modified gravity models [24].

Putting this all together we come up with the following constraints on the modified gravity parameters from laboratory experiments. In the figures we see that both chameleons and symmetrons are now tightly constrained, though there is a region of parameter space left unconstrained.

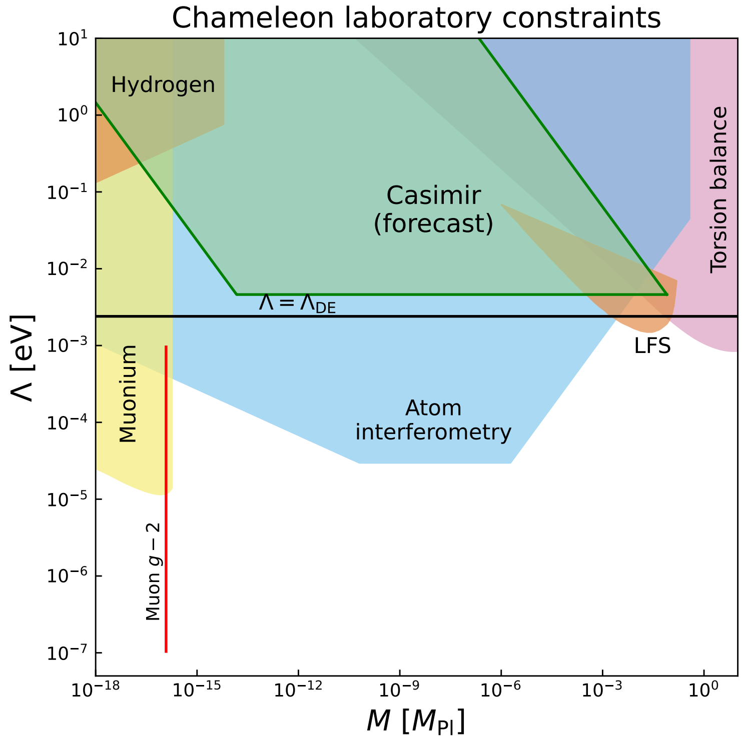

Figure 2: Bounds on chameleon theory parameter space for $n = 1$. The red line indicates chameleon models that alleviate the muon $g - 2$ tension [25]. We see that muonium rules out approximately half of those models.

5. Coupling to Photons

We can also consider the coupling of the scalar particles to photons, either with a direct coupling or a disformal coupling. The direct coupling takes the form

$$\beta_\gamma \frac{\phi}{M_{pl}} F^2, \qquad \beta_\gamma \frac{\phi^2}{M_{pl}^2} F^2 \tag{13}$$

for the chameleon and symmetrons respectively. Indeed Bekenstein showed that the most general coupling of a scalar field to matter is [26]

$$g_{\mu\nu} = A^2(\phi, X) g^E_{\mu\nu} + B^2(\phi, X)\partial_\mu\phi\partial_\nu\phi \tag{14}$$

with the disformal term automatically giving rise to a coupling to photons. Here $g^E_{\mu\nu}$ is the Einstein metric.

The coupling between the scalar and photons can result in the conversion of photons into scalar particles in the presence of a magnetic field, and vice versa. It has been discussed in the laboratory, firstly in relation to the anomalous PVLAS results [27] and as a way to detect chameleons via an 'afterglow' [28] and astrophysically [29]. Some constraints are discussed in [1]. More recently this was used in [30] when considering the direct detection of dark energy with the XENON1T detector. The anomalous results were shown to be explained with a chameleon model by considering just the strong magnetic field in the tachocline. Subsequently the production of chameleons throughout

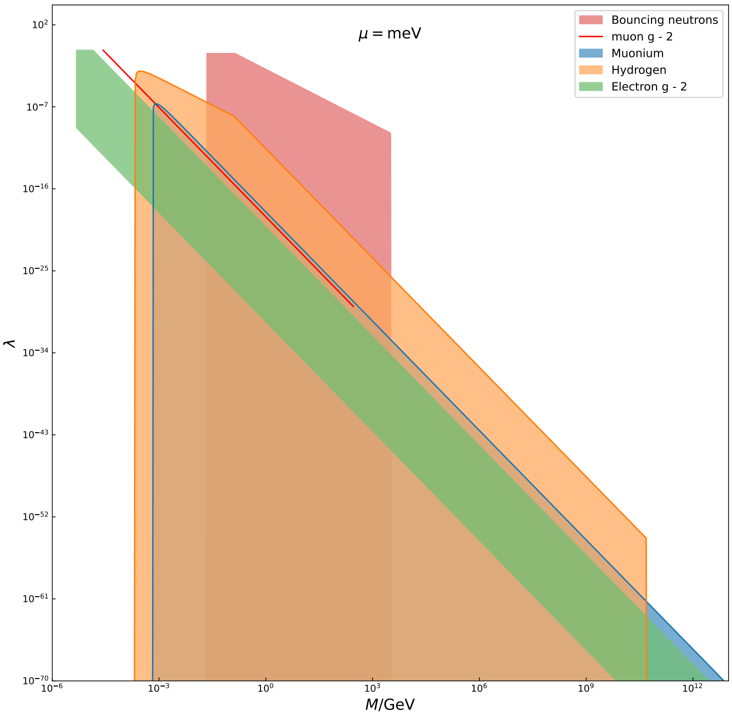

Figure 3: Bounds on symmetron models with mass at the dark energy scale μ = meV. We see that hydrogen is the leading constraint when the proton is unscreened. Meanwhile muonium bounds are comparable to those from electron $g - 2$ experiments [24].

the sun has been computed [31]. This is discussed by Tom O'Shea, these proceedings. The corresponding case of symmetrons has yet to be considered, though this is in progress.

6. Discussion

We have briefly reviewed cosmological scalar particles, in particular the chameleon and symmetron models. Since such scalar particules are very light and of gravitational strength they can modify Einstein gravity, enabling gravity to be tested in environments not previously envisaged. They could be potentially detected in laboratory experiments, giving rise to constraints on the model parameters. Such scalars can also couple to photons resulting in the possibility of potential detection in solar experiments in a similar way to axions. This has been briefly introduced for the chameleon. It is also possible for symmetrons to play a role in solar physics. This is currently in progress.

Acknowledgments

We wish to thank all our collaborators, in particular Ben Elder and Hannah Banks. This work is supported in part by the Science and Technology Facilities Council (STFC) through the STFC consolidated grant ST/T000694/1. This article is based on the work from COST Action COSMIC WISPers CA21106, supported by COST (European Cooperation in Science and Technology).

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