Chameleon Fields Near and Far

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It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind.
....
And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right,
And all were in the wrong!

So, oft in theologic wars
The disputants, I ween,
Rail on in utter ignorance
Of what each other mean,
And prate about an Elephant
Not one of them has seen! **John Godfrey Saxe (1816 - 1887)**

In this presentation we contemplate the problem of dark energy and advocate for a multi-faceted approach to studying its solution. Indeed it may be that, like the philosophers described above, we too cannot understand the nature of our beast by only touching one side of the problem. In particular we will study chameleon fields as a candidate for driving the observed acceleration of the universe and we will look how to test this theory through a varied approach as advocated here .

1 Introduction

Remarkably, everything we see and experience on all human scales makes up less than 5% of the total matter in the universe. The ingredients of the planets and stars and oceans and cars is tiny compared to the vast amount of the universe that is dark; literally - not observed electromagnetically. At around 70% of the total matter budget, Dark Energy makes up the lion's share of the universe and yet it is the least well understood. What we do believe we know is that Dark Energy drives the universe to expand ever faster with time leaving the universe ultimately a cold and empty place. This observed acceleration, awarded the Nobel Prize in 2011, remarkably is not convincingly explained. Einstein's cosmological constant has survived as the most phenomenologically simple solution while offering even greater puzzles as to why the value it assumes physically is 10^{123} times smaller than expected by theoretical computations of the vacuum energy. Ultimately, what we have here is a fundamentally ultraviolet problem. A problem of high energies and possibly quantum gravity, that plays out cosmologically on the largest scales and appears as an infrared effect. In this presentation we consider an approach that mirrors the problem. In particular, we will study chameleon fields [1, 2] which are a novel and compelling Dark Energy candidate [3, 4]. While, providing an exciting explanation of the observed acceleration of the universe with very testable consequences, these theories lack a full ultraviolet completion. Complementary to the fundamental framework we are working to build, we will also discuss a broad array of tests of this theory at the infrared level, from the laboratory to space tests to astrophysical observations.

2 Chameleon Fields

A cosmological constant is an allowed, if perhaps unnatural solution to the dark energy problem. A more compelling alternative of a scalar field driven acceleration is not without its own challenges. If a scalar field is driving the observed acceleration it would need to be very light $m \sim H_0$ and evolving today. A priori such fields should couple to all forms of matter with gravitational strength and thus cause an as yet unobserved fifth force. In fact these effects should be observable in a broad array of known physics settings, from the early universe through big bang nucleosynthesis, structure formation and in all tests of gravity done today. Thus, we are left with a puzzle as to how a scalar field can both be observable as dark energy and yet not be observed to date in all other experiments and observations.

A solution to this puzzle was presented in [1, 2, 3] with so-called chameleon fields. Chameleon fields couple to all Standard Model particles without violating any known laws or experiments of physics. They are nonetheless testable in ways entirely complementary to the standard observational cosmology techniques, and thus provide a new window into dark energy through an array of possible laboratory and astrophysical tests and space tests of gravity.

It is the self interaction of the scalar field, in conjunction with a matter coupling that gives the scalar field a large effective mass in regions of high matter density [1, 2]. A scalar field that is massive locally mediates a short-range fifth force that is difficult to detect, earning it the name "chameleon field." Furthermore, the massive chameleon field is sourced only by the thin shell of matter on the outer surface of a dense extended object. These nonlinear effects serve to screen fifth forces, making them more difficult to detect in certain environments.

Chameleon dark energy is currently treated as an effective field theory [3, 5] describing new particles and forces that might be seen in upcoming experiments, and whose detection would point the way to a more fundamental theory. The ultraviolet (UV) behavior of such theories and their connection to fundamental physics are not yet understood, although progress is being made [6, 7, 8, 9]. The role of quantum corrections to chameleon fields in the early universe is a hot topic, currently under development [10].

2.1 Chameleon Action

Chameleon fields coupled to matter and photons have an action of the form [3]

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2M_{pl}^2}R - \partial_\mu\phi\partial^\mu\phi - V(\phi)\right) - \frac{e^{\phi/M_\gamma}}{4}F^{\mu\nu}F_{\mu\nu} + S_m(e^{2\phi/M_m^i}g_{\mu\nu}, \psi_m^i)\ , \quad (1)$$

where S_m is the matter action, $V(\phi)$ is the chameleon self interaction and the chameleon field, ϕ can couple differently with coupling β_i, to different matter types ψ_i. Here we will consider a universal coupling to matter defined by $\beta_m = M_{\rm Pl}/M_m$ while allowing for a different coupling to electromagnetism, $\beta_\gamma = M_{\rm Pl}/M_\gamma$, through the electromagnetic field strength tensor $F_{\mu\nu}$.

Crucially, this coupling induces an effective potential

$$V_{\rm eff}(\phi,\vec{x}) = V(\phi) + e^{\beta_m\phi/M_{\rm Pl}}\rho_m(\vec{x}) + e^{\beta_\gamma\phi/M_{\rm Pl}}\rho_\gamma(\vec{x}), \quad (2)$$

where we have defined the effective electromagnetic field density $\rho_\gamma = \frac{1}{2}(|\vec{B}^2 - |\vec{E}|^2)$. An essential insight of chameleon models is noticing that the presence of matter and electromagnetic fields induces a minimum $\phi_{\rm min}$ in $V_{\rm eff}$ where V can be a monotonic function. The dependence of this minimum on the background matter and electromagnetic fields causes the effective mass of the chameleon field to change in response to its environment. In turn we find varied chameleon phenomenology depending on the experimental setup and hence the environment.

We can see explicitly that for an exponential potential, the effective mass of the field ϕ is dependent on the local density of matter and electromagnetic fields,

$$V(\phi) = \Lambda^4 \exp\left(\frac{\Lambda^n}{\phi^n}\right), \quad \phi_{\rm min} \approx \left(\frac{nM_{\rm Pl}\Lambda^{n+4}}{\beta_{\rm m}\rho_m + \beta_\gamma\rho_g}\right)^{\frac{1}{n+1}} \text{ and } m_\phi^2 \approx \frac{(n+1)}{(n\Lambda^{n+4})^{\frac{1}{n+1}}}\left(\beta_m\rho_m + \beta_\gamma\rho_\gamma\right)^{\frac{n+2}{n+1}}$$

where the next to leading order terms are suppressed by factors of $\beta_i\phi/M_{\rm Pl} \ll 1$.

3 Chameleons Near

The chameleon dark energy parameter space is considerably more complicated than that of axions, but constraints can be provided under some assumptions. With the caveat that all matter couplings are the same but not equal to the photon coupling, and the assumption of a specific chameleon potential, $V(\phi) = M_\Lambda^4(1 + M_\Lambda^n/\phi^n)$ in which we set the scale $M_\Lambda = 2.4 \times 10^{-3}$ eV to the observed dark energy density and, for concreteness, $n = 1$, constraints and forecasts are provided by Figure 1. Current constraints (solid regions) and forecasts (curves) are discussed below.

Existing laboratory constraints on chameleon dark energy come from two different types of experiments: fifth force searches, and photon conversion experiments, both of which are shown as shaded regions in Figure 1. Gravitation-strength fifth forces can be measured directly between two macroscopic objects, such as the source and test masses in a torsion pendulum. Currently the shortest-range torsion pendulum constraints on gravitation-strength forces come from the Eöt-Wash experiment [11]. Another type of fifth force experiment uses an ultracold

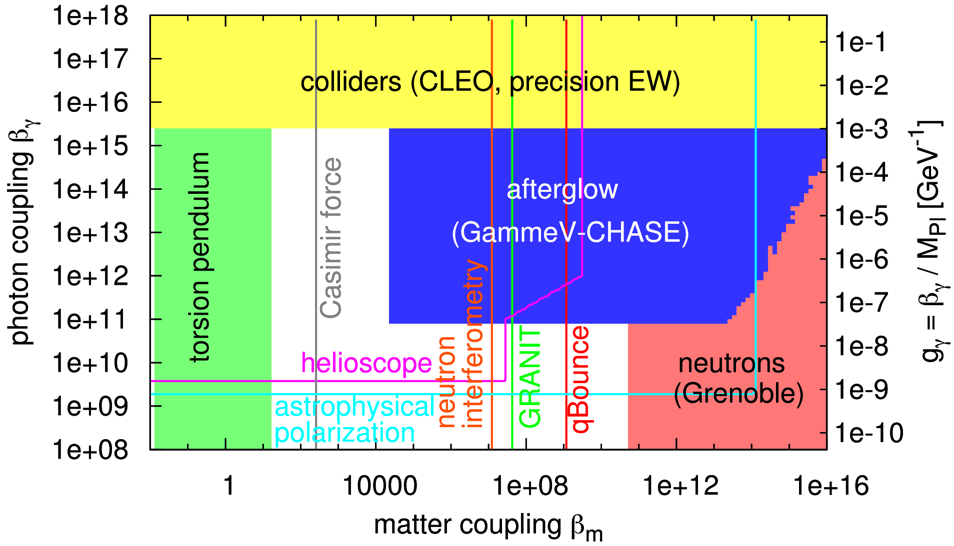

Figure 1: Constraints on the matter and photons couplings for a chameleon dark energy model with $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$. Current constraints are shown as shaded regions, while forecasts are shown as solid lines.

gas of neutrons whose bouncing states in the gravitational field of the Earth are quantized, with energy splittings ~ 1 peV [12]. If the neutrons feel a fifth force from the experimental apparatus comparable to the gravitational force of the Earth, then the energy splittings will be altered. The Grenoble experiment measures these energy splittings at the $\sim 10\%$ level, excluding very strong matter couplings $\beta_m \gtrsim 10^{11}$.

Quantum corrections generate a photon coupling about three orders of magnitude smaller than the matter coupling [13], although classically this coupling is not required. The lowest order chameleon-photon interaction couples the chameleon field to the square of the photon field strength tensor, implying that photons oscillate into chameleon particles in a background electromagnetic field, The resultant chameleon field mass will be environmentally dependent on both the background energy density and the electromagnetic field strength. This allows for a broad array of different tests for these fields on Earth, in space, and through astrophysical observations.

This electromagnetic coupling would allow photons propagating through a magnetic field to oscillate into particles of dark energy, which can then be trapped inside a chamber if the dark energy effective mass becomes large in the chamber walls. An "afterglow experiment" produces dark energy particles through oscillation and then switches off the photon source, allowing the population of trapped dark energy particles to regenerate photons which may emerge from the chamber as an afterglow. Current afterglow constraints from the CHASE experiment exclude photon couplings $10^{11} \lesssim \beta_\gamma \lesssim 10^{16}$ for $\beta_m \gtrsim 10^4$, as shown in Fig. 1 for an inverse-power-law chameleon potential [14, 15, 16]. At yet higher photon couplings the trapped dark energy parti-

Experiment	Type	Couplings excluded
Eöt-Wash	torsion pendulum	$0.01 \lesssim \beta_m \lesssim 10$
Lamoreaux	Casimir	$\beta_m \gtrsim 10^5$ (ϕ^4)
Grenoble	bouncing neutron	$\beta_m \gtrsim 10^{11}$
GRANIT	bouncing neutron	forecast: $\beta_m \gtrsim 10^8$
NIST	neutron interferometry	forecast: $\beta_m \gtrsim 10^7$
CHASE	afterglow	$10^{11} \lesssim \beta_\gamma \lesssim 10^{16}$ subject to $10^4 \lesssim \beta_m \lesssim 10^{13}$,
ADMX	microwave cavity	$m_{\text{eff}} = 1.952$ μeV, $10^9 \lesssim \beta_\gamma \lesssim 10^{15}$
CAST	helioscope	forecast: $\beta_m \lesssim 10^9$, $\beta_\gamma > 10^{10}$

Table 1: Laboratory tests of dark energy. Approximate constraints on chameleon models with potential $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$ and $M_\Lambda = 2.4 \times 10^{-3}$ eV (unless otherwise noted).

cles regenerate photons too quickly for CHASE to detect them. However, collider experiments can exclude such models, by constraining chameleon loop corrections to precision electroweak observables [17].

4 Chameleons Far

Chameleon fields are also testable in space tests of gravity as well as through astrophysical and astronomical effects. In fact several astrophysical puzzles could be explained by chameleons including a matter coupling, *e.g.*, [18]. In particular [18] shows that small galaxies are expected to have a higher peculiar velocity than large ones (independent of the velocity bias) and voids defined by small galaxies would appear larger than those expected by large galaxies. Even comparing the motions of galaxies and clouds in the same environment may reveal the chameleon mechanism at work.

Comparing lensing and dynamical masses of galaxies and clusters can point to a discrepancy as the deflection law for photons that leads to various gravitational lensing effects is the same with or without chameleons. However the acceleration of galaxies, which move at non-relativistic speeds, is altered as the Newtonian potential is different from that in GR: it receives additional contributions from the Chameleon fields. And while the gravitational lensing signature is identical to the signature predicted in general relativity, the Shapiro time delay can be strongly different for a large region of parameter space of chameleon coupling β. A dedicated catalog of gravitational lensing observations and time delay measurements should be able to constrain a wide range of chameleon models. Because photons travel on geodesics defined in the Jordan frame, constraints on the chameleon-matter coupling may be placed, independent of the necessity for a chameleon-photon coupling [20].

The approaches to detecting the effects listed above and distinguishing them from astrophysical sources have been discussed in the literature cited above. One key element to a convincing detection is to be able to compare to a controlled environment where the primary sources of astrophysical uncertainty can be ruled out. Ideal is to be able to compare between a screened and unscreened environment. There are many distinct chameleon signatures observable in the astrophysical arena. We have discussed a few here. For a more extensive discussion - the reader is referred to the recent review [21].

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