Particles and forces from chameleon dark energy

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Chameleon dark energy is a matter-coupled scalar field which hides its fifth forces locally by becoming massive. We estimate torsion pendulum constraints on the residual fifth forces due to models with gravitation-strength couplings. Experiments such as Eötvös are on the verge of ruling out “quantum-stable” chameleon models, in which quantum corrections to the chameleon field and mass remain small. We also consider photon-coupled chameleons, which can be tested by afterglow experiments such as CHASE.

1 Introduction

The accelerating expansion of the universe is well-supported by the data [1, 2, 3], but its cause is the greatest mystery in modern cosmology. Dynamical alternatives to a “cosmological constant” density $\rho_{\Lambda} \approx 10^{-120} M_{P}^{4}$ explain the smallness of $\rho_{\Lambda}$ by fields tunneling among local minima of their potential [4, 5], or by a slow decrease of the vacuum energy known as “degravitation” [6, 7]. At low energies, the simplest of these models reduce to effective “dark energy” scalar fields which may evolve with time or couple to known particles. Matter-coupled scalars mediate fifth forces which must be screened at high densities in order to evade local constraints [8]. The three best-understood screened dark energy models are: chameleons, which acquire large effective masses [9, 10, 11]; symmetrons, which decouple from matter through a symmetry-restoring phase transition [12, 13]; and Galileons, in which a non-canonical kinetic energy term reduces the effective matter coupling [14]. We will discuss “quantum-stable” chameleon models, in which the one-loop Coleman-Weinberg corrections to the field and mass remain small [15].

On the experimental front, the dark energy scales $M_{\Lambda} = \rho_{\Lambda}^{1/4} \sim 10^{-3} \text{ eV}$ and $1/M_{\Lambda} \sim 100 \mu \text{m}$ are readily accessible in the laboratory [16]. We demonstrate that the Eötvös torsion pendulum experiment [17] is on the verge of excluding quantum-stable chameleons with gravitation-strength matter couplings. A coupling between dark energy and electromagnetism would imply that dark energy particles could be produced through photon oscillation in a magnetic field. We show that such particles can be trapped by afterglow experiments including CHASE [18, 19, 20]. This paper is organized as follows. Section 2 discusses chameleon fifth forces and quantum stability. Oscillation and afterglow constraints are covered in Sec. 3.

2 Fifth forces

We begin with a scalar field coupled to the trace of the matter stress tensor $-T_{\mu}^{\mu} \approx \rho$, and possibly to the electromagnetic field strength tensor $F_{\mu\nu}^{\mu\nu}$, with effective potential $V_{\text{eff}}(\phi) = V(\phi) - \beta_{m} T_{\mu}^{\mu} \phi/M_{P} + \beta_{\gamma} F_{\mu\nu}^{\mu\nu} \phi/(4 M_{P})$. The self-interaction $V(\phi)$ can be approximated as a constant plus a power law when specific examples are necessary [11]. In this section we assume a static system with $\beta_{\gamma} = 0$, reducing the equation of motion $\Box \phi = V_{\text{eff}}(\phi)$ to $\nabla^{2} \phi =$
$V'(\phi) + \beta_m \rho / M_{\text{Pl}}$. Inside a constant-density bulk the spatial derivatives vanish, so $\phi$ takes its bulk value $\phi_B$ defined by $V'(\phi_B) = -\beta_m \rho / M_{\text{Pl}}$. With $-V', V'', -V''' > 0$, an increase in $\rho$ implies a lower $\phi_B$, hence a larger effective mass $m_{\text{eff}}(\phi) \equiv V''(\phi)^{1/2}$ (the “chameleon effect”).

One-loop quantum corrections $\Delta V_{\text{1-loop}}(\phi) = m_{\text{eff}}^4/(64\pi^2) \log(m_{\text{eff}}^2/\mu^2)$ modify the self-interaction $V(\phi)$, altering $\phi_B$, $m_{\text{eff}}$, and the predicted fifth force. In "quantum-stable" chameleon models, these corrections remain small inside laboratory fifth force experiments [15]. Neglecting the logarithm in $\Delta V_{\text{1-loop}}$, the quantum stability condition is $m_{\text{eff}} < 0.0073(\beta_m \rho/10 ~\text{g cm}^{-3}) ~\text{eV}$. Models with large quantum corrections in a laboratory experiment with $\rho = 10 ~\text{g cm}^{-3}$ are shaded in the upper left hand corner of Fig. 1 (Left). The shaded region in the lower right approximates the constraints of Eöt-Wash [17], leaving a small allowed region near $\beta_m \sim 1$.

These allowed models near $\beta_m \sim 1$ can be excluded by the next-generation Eöt-Wash experiment, which will be several times more sensitive to chameleon fifth forces than the current apparatus [21]. Using a one-dimensional plane-parallel (1Dpp) calculation which approximates the geometry locally as an exactly-solvable one-dimensional configuration, Refs. [22, 23] estimate fifth forces and constraints. Figure 1 shows that the next-generation Eöt-Wash experiment will substantially improve upon current constraints [24] and will exclude a large range of quantum-stable chameleon models.

3 New particles

Next we consider nonzero $\beta_\gamma$. The equation of motion $\Box \phi = V_{\text{eff}}'(\phi)$ and the modified Maxwell equations $\partial\mu\nu\equiv[1+\beta_\gamma \phi/M_{\text{Pl}}]F_{\mu\nu}=0$ couple the scalar and electromagnetic fields such that, in a background magnetic field $B_0$, a photon may oscillate into a chameleon particle. The oscillation amplitude is proportional to $\beta_\gamma$ and $B_0$. For $m_{\text{eff}}^2 \ll 4\pi\omega/L$, where $\omega$ is the photon energy and $L$ is the length of the magnetic field region, the amplitude is also proportional to $L$.

If the magnetic region is bounded by dense walls inside which $m_{\text{eff}} > \omega$, then by energy conservation the chameleon particles will be trapped inside the magnetic region. An afterglow experiment streams photons through a dense-walled vacuum chamber enclosing a magnetic field in order to build up a population of trapped chameleon particles. After the photon source is
Figure 2: Constraints on photon-coupled chameleon dark energy. (Left): Model-independent CHASE constraints. (Right): Combined constraints for $V(\phi) = M_\Lambda^4 (1 + M_\Lambda / \phi)$. Constraints from colliders [25] and neutrons [26] as well as forecasts for helioscopes [27, 28] are shown.

turned off, these chameleons regenerate photons which may emerge as a detectable afterglow. A thorough study of the design and analysis of afterglow experiments is given in [20]. Monte Carlo simulations are used to compute the rate at which the trapped chameleon population decreases, and the rate at which detectable afterglow photons are regenerated. Glass windows inside the magnetic field chamber, used by CHASE to lessen the effects of destructive interference at large $m_{eff}$, are shown to mitigate the adiabatic suppression of photon-chameleon oscillation. Systematic effects, such as transient glows emitted by vacuum materials in CHASE [29], are also considered. Model-independent CHASE constraints are shown in Fig. 2 (Left), while Fig. 2 (Right) compares CHASE constraints on inverse power-law chameleon dark energy to the Eötvös analysis of Sec. 2 as well as constraints from colliders and ultracold neutrons.

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