The GammeV search for dark energy coupled to matter and photons

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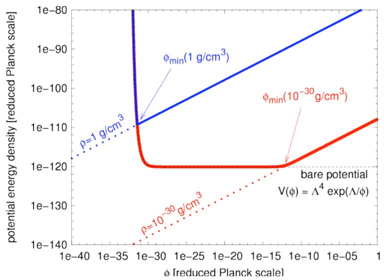
Chameleon dark energy

Quantum corrections to a scalar field dark energy can generate matter couplings, causing the field to violate local fifth force constraints. A chameleon dark energy evades such constraints by acquiring a large mass in high-density regions of the universe, allowing it to escape detection locally. This density-dependence of the mass, known as the chameleon effect, results from the interplay between the matter coupling term and the nonlinear self-interaction of the field.

$$S = \int d^4x \left(-\frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{e^{\beta_\gamma \phi / M_{\rm Pl}}}{4} F^{\mu\nu}F_{\mu\nu} + \mathcal{L}_{\rm m}(e^{2\beta_{\rm m}\phi/M_{\rm Pl}} g_{\mu\nu}, \psi^i_{\rm m}) \right)$$



In a background with fixed matter density and electromagnetic fields, the chameleon dynamics are governed by an effective potential,

$$V_{\rm eff}(\phi) = V(\phi) + e^{\beta_{\rm m}\phi/M_{\rm Pl}}\rho_{\rm m} + \frac{1}{2}e^{\beta_\gamma \phi/M_{\rm Pl}}(\vec{B}^2 - \vec{E}^2)$$

As the density is increased (from the red line to the blue line), the field moves to lower values. The effective mass,

$$m_{\rm eff}^2 = V''_{\rm eff}(\phi_{\rm min}),$$

related to the curvature of the potential at its minimum, is also increased. This is known as the chameleon effect.

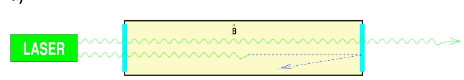
We constrain a chameleon field with self interaction $V(\phi) = \Lambda^4 \exp(\Lambda^n/\phi^n)$, with $\Lambda = \rho_{de}^{1/4}$, which is a model of chameleon dark energy. The theory has three free parameters: the matter coupling β_m, the photon coupling β_γ, and the index n, which controls the rate at which m_{eff} increases with the matter and field densities.

Photon-coupled chameleon fields and the afterglow phenomenon

A photon passing through a magnetic field can oscillate into a chameleon scalar particle. The chameleon particle can be trapped in a chamber of high-density material if its effective mass inside that material is greater than its total energy in the interior of the chamber. Eventually, this trapped chameleon will decay back into a photon, resulting in an "afterglow" of photons that persists after the original light source has been turned off.

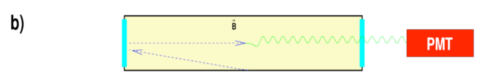
a) Chameleon production: Photons from a laser stream through a chamber with glass windows. Some fraction of them are converted into scalars in the magnetic field. These scalar particles reflect from the walls and windows of the chamber; they are trapped.

a)

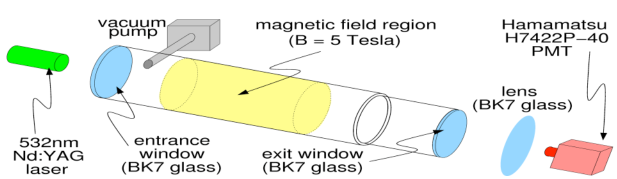


b) Afterglow: The laser is turned off, and the photomultiplier tube (PMT) is switched on. The trapped scalar particles oscillate back into photons in the magnetic field. Some of these photons escape through the chamber windows and are detected by the PMT.

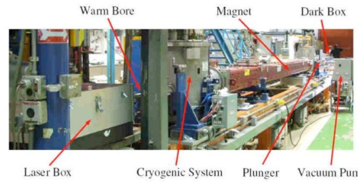
b)

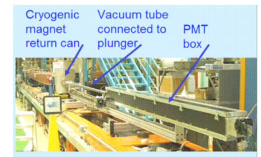


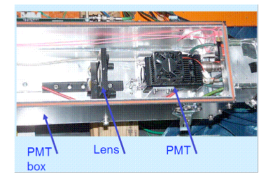
A diagram of the GammeV experiment, designed to search for such an afterglow signtature of chameleons, is shown to the right.



GammeV Apparatus







The GammeV Experiment at Fermilab is the first experiment to constrain photon-coupled chameleons via the afterglow phenomenon. Photons from a frequency-doubled Nd:YAG laser enter the chamber and pass through a region containing a 5 Tesla magnetic field. After the laser is switched off, a PMT is uncovered and used to look for an afterglow of photons emerging from the exit window.

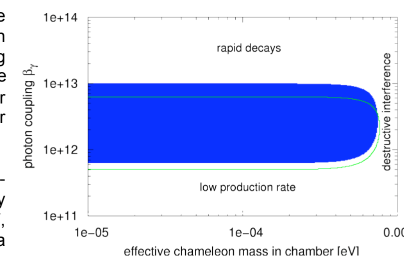
GammeV is sensitive to chameleon particles that are massive enough at the intake of the roughing pump to be reflected [$m_{eff(P=2\times10^{-3}torr)}$ > 2.33 eV], light enough inside the chamber to be produced efficiently through photon oscillation [$m_{eff(P=10^{-7}torr)}$ < 9.8×10^{-4} eV], and with an afterglow rate visible to the PMT (with a dark rate of 100 Hz).

Reference: A. S. Chou, et. al., Phys. Rev. Lett. **102**:030402 (2009)

Experimental constraints (and forecasts) on chameleon dark energy

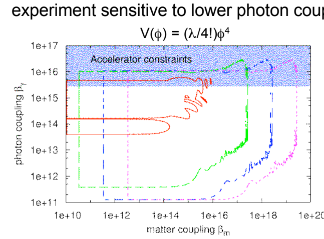
Model-independent constraints on chameleon dark energy are shown in the figure to the right. Assuming that the chameleon reflects from our pump intake, we can constrain its photon coupling β_γ for a range of masses inside the vacuum chamber. We have excluded the region of parameter space shaded in blue for pseudoscalar chameleons, and the region inside the green curve for scalar chameleons.

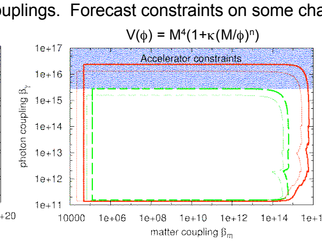
The afterglow signal is suppressed at low couplings by small photon-chameleon conversion probabilities, at high couplings by decay times much less than the 5-15 minutes needed to uncover the PMT, and at high masses by desctrutive interference leading to a suppression in chameleon-photon oscillation.

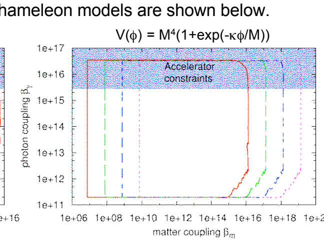


For the chameleon dark energy with $V(\phi) = \Lambda^4\exp(\Lambda^n/\phi^n)$, we are able to exclude the above region in the $m_{eff,chamber}$-β_γ plane for 0 < n < 2/3. This corresponds to matter couplings β_m around 10^{13}.

The ongoing second-generation GammeV chameleon search, GammeV-CHASE, will: (1) improve the pumping system, allowing us to trap chameleons with arbitrarily large values of n and a greater range of matter couplings; (2) reduce the PMT switching time, allowing the detection of rapidly decaying chameleons; (3) control PMT systematics, making the experiment sensitive to lower photon couplings. Forecast constraints on some chameleon models are shown below.







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