How Dark Is Dark Energy? The GammeV-CHASE Search for Couplings between Light and Chameleon Dark Energy

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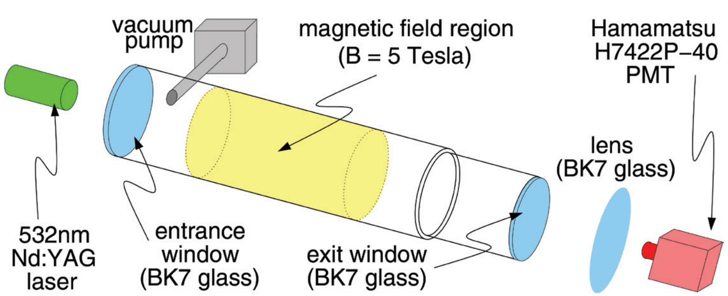
Over the past decade, evidence has continued to mount for an astonishing astrophysical phenomenon known as the cosmic acceleration. The universe appears to be expanding increasingly rapidly; distant objects are receding faster and faster. If the universe consisted entirely of ordinary matter, and if gravity were well-described by Einstein's General Relativity, then the expansion of the universe would slow down due to attractive gravitational forces. Thus, the cosmic acceleration demands a significant change to one of our two most fundamental theories. Either General Relativity breaks down on cosmological scales, or a new type of particle must be added to the Standard Model of particle physics, the quantum theory describing all known particles. Since particle physicists have known for some time that General Relativity cannot be incorporated directly into a quantum theory such as the Standard Model, the cosmic acceleration may give some insight into a more fundamental theory unifying gravity and quantum mechanics.

The simplest theoretical modification that could explain the acceleration is the "cosmological constant," a constant vacuum energy density, which Einstein noted could be added to the equations of General Relativity. The contribution of Standard Model fields to the cosmological constant is approximately 120 orders of magnitude greater than its observed value. One might imagine an as-yet-unknown symmetry that would cancel the Standard Model contribution. However, a theory in which this contribution is cancelled to precisely 120 decimal places, leaving an energy density that just happens to be very close to the observed matter density today, would be quite bizarre. Furthermore, a cosmological constant gives no clues about quantum gravity.

These mysteries have spurred cosmologists to search for deviations from a simple cosmological constant. One type of deviation allows the energy density responsible for the cosmic acceleration to vary with time, resulting in an expansion history that differs from cosmological constant models. Another type of deviation involves couplings between known particles and a "dark energy" field associated with the vacuum energy. (Some simple modifications to General Relativistic gravity may also be recast as matter-coupled dark energy with standard gravity.) The simplest coupled dark energy theories consistent with current observations are "chameleon" theories, which "hide" fifth forces and variations in fundamental constants by becoming massive in high-density regions of the universe. Since massive fields give rise to very short-range forces, chameleon dark energies are notoriously difficult to detect.

Fig.1. The apparatus used in the GammeV experiment. During the production stage, the photomulitplier tube (PMT) is covered and the laser switched on. Photons convert into chameleon particles, building up a chameleon population. During the afterglow stage, the laser is switched off and the PMT uncovered in order to search for an afterglow of regenerated photons.



The GammeV and GammeV-CHASE experiments [1-4] are "afterglow" experiments specifically designed to search for photon couplings to chameleon dark energy. A chameleon coupling to electromagnetism would allow a photon to convert to a chameleon particle, and vice versa, in the presence of electric or magnetic fields, much as axions may be produced from photons. Consider a vacuum chamber with glass windows through which a beam of photons is streamed, as in Fig. 1. Some of the photons will convert to chameleon particles in the strong magnetic field inside the chamber. As a chameleon particle approaches a high-density barrier such as a chamber wall or window, its mass increases sharply. Sufficiently close to the wall, the chameleon mass will equal the total energy, and energy conservation will prevent the particle from approaching any closer to the wall. Thus, the chameleon particle will bounce. The chameleon is trapped inside the chamber by the chameleon mechanism, the very mechanism that allowed it to evade other laboratory constraints. Once the photon source is switched off, the chameleon particles which remain trapped in the chamber will gradually convert back into photons, emitting an "afterglow" of light.

As the successor to the GammeV experiment, GammeV-CHASE has

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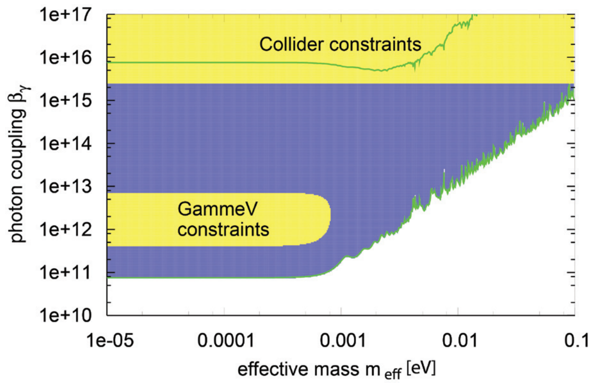

Fig. 2. GammeV-CHASE constraints. Previously excluded are shown in yellow. New GammeV-CHASE constraints are shown in solid blue for scalar chameleons and a green line for pseudoscalar chameleons.

searched for an afterglow over a large range of magnetic fields and time scales. By modulating the photon detector with a shutter, we are able to monitor background noise in real time, increasing the time resolution. Improvements to the vacuum system have decreased the gas pressure inside the chamber by two orders of magnitude, allowing us to probe a much greater range of models. Finally, glass partitions within the magnetic field region facilitate the production of higher-mass chameleons, so that constraints now extend to the dark energy mass scale M_{de} = 2.3 meV. As shown in Fig. 2, GammeV-CHASE excludes many orders of magnitude in the mass-coupling parameter space, bridging the gap between constraints from GammeV and colliders. These constraints can be applied to specific dark energy models such as the power law models in Fig.3, none of which was probed by the original GammeV. First results from GammeV-CHASE have been accepted for publication [4].

Further analysis, including studies of systematic effects in afterglow experiments and the application of GammeV-CHASE constraints to a greater range of dark energy models, continues at LANL and at Fermilab. Future afterglow experiments could potentially improve constraints considerably through a series of incremental improvements such as: a better understanding and control of background photon sources, a higher magnetic field, a more powerful laser, increased detector sensitivity, and additional passes of the photon beam through the chamber. Laboratory experiments such as GammeV-CHASE promise to considerably extend our knowledge of chameleon dark energy in the coming years.

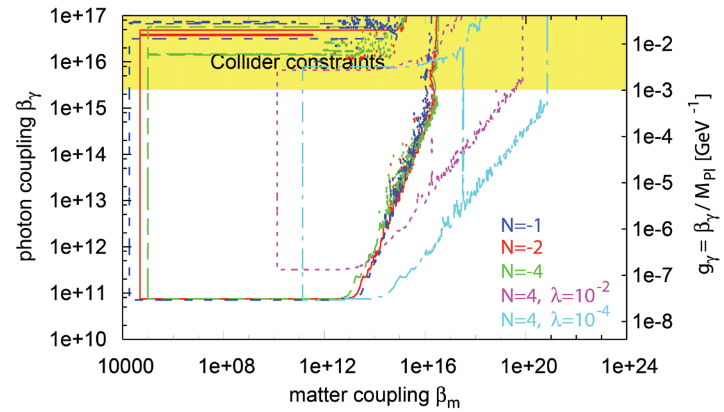

Fig. 3. GammeV-CHASE constraints on power-law dark energy models, $V(\varphi)$ = constant+ $g\varphi^N$. For N not equal to 4, $g = M_{de}^{4-N}$ is defined in terms of the dark energy scale $M_{de} = \rho_{de}^{1/4}$ = 2.3×10^{-3} eV; for N = 4 we define $g = \lambda/4!$ in the usual way.

[1] Chou, A.S., et al., *Phys Rev Lett* **102,** 030402 (2006).
[2] Steffen, J.H. and A. Upadhye, *Mod Phys Lett A* **24,** 2053 (2009).
[3] Upadhye, A., et al., *Phys Rev D* **81,** 015013 (2010).
[4] Steffen, J.H., et al., *Phys Rev Lett* (accepted), arXiv:1010.0988 (2010).

Funding Acknowledgments
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