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!

What is the Elephant?

The very early universe questions

- The problem of quantum gravity
- How did the universe make the quantum to classical transition
- Effective field theories as tools for probing early universe physics
- Inflation and its alternatives

The somewhat late universe questions

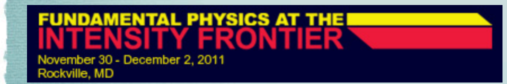
- What is the nature of Dark Energy?
- What is the nature of Dark Matter?
- What role does physics beyond the standard model play in cosmology?

How do we tackle the Elephant?

- Competing theories
- Complementary experiments - high and low energy and intensity
- Complementary observations - cosmology, astrophysics and astronomy
- Use experiment and observation to constrain theory and offer surprises

Many proposed solutions to Dark Energy and Dark Matter involve a BSM new particle.

Cosmology engage with particle physics.



The Intensity Frontier must meet the Cosmic Frontier

Medium risk - huge reward! High Payoff - Low cost

Chameleons

Extensions of Standard Model, higher dimensional theories, string theory have scalar fields generically in them.

- Massless scalar fields are abundant in String and SUGRA theories
- After compactification, moduli appear as scalar fields with kinetic terms but **no potential** i.e.
  - no self interaction terms
  - no mass terms
  - free to move around in moduli space

Moduli couple directly to matter with gravitational strength

- Disrupt Big Bang Nucleosynthesis
- Equivalence Principle violations
- Coupling constants can vary
- Masses of elementary particles can vary

Connect String Theory to Cosmology

Chameleon Dark Energy

astro-ph/0309300 PRL J. Khoury and **A.W**
astro-ph/0309411 PRD J. Khoury and **A.W**
astro-ph/0408415 PRD P.Brax, C v.d Bruck, A. Davis, J. Khoury and **A.W**

Mass of scalar field depends on local matter density

In region of high density → mass is large ⇒ EP viol suppressed

In solar system → density much lower ⇒ fields essentially free

On cosmological scales → density very low ⇒ $m \sim H_0$

Field is a candidate for acceleration of the universe

Approach

Scalar fields can have cosmological effects but **DO NOT** result in EP violations in lab as we live in dense environment

Use EP tests done on earth to **constrain** the parameters of the model (these give largest constraints)

Study the fields **cosmological effects**

Use constraints to make **crucial predictions** for tests in **space** and in the **lab**

Derive new bounds from **purpose built lab tests, astrophysics** and from existing **lab experiments**

Hunt it, constrain it - rule it out or find it!

Ingredients

Reduced Planck Mass

$$M_{Pl} = (8\pi G)^{-1/2}$$

Coupling to photons

Matter Fields

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

$$g = det g_{\mu\nu}$$

$$g_{\mu\nu}^{(i)} = e^{2\beta_i\phi/M_{Pl}}g_{\mu\nu}$$

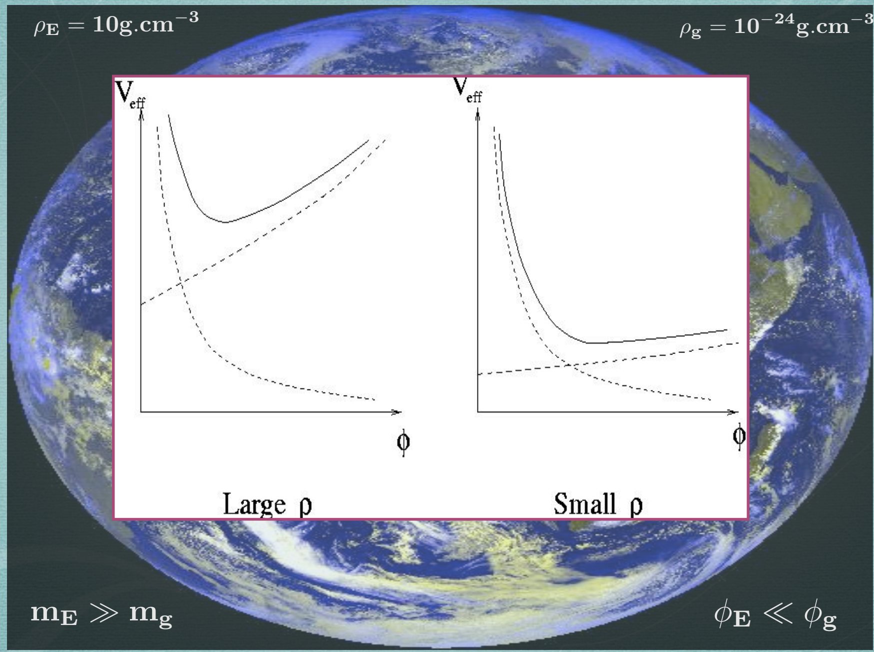
Einstein Frame Metric

Conformally Coupled

Potential is of the runaway form

This field couples to all matter types - and in a different way to regular gravity

Earth


$\rho_E = 10 g.cm^{-3}$
$\rho_g = 10^{-24} g.cm^{-3}$
V_{eff}
ϕ
Large ρ
V_{eff}
ϕ
Small ρ
$m_E \gg m_g$
$\phi_E \ll \phi_g$

Coupling to Photons

Effective potential :

$$V_{\text{eff}}(\phi, \vec{x}) = V(\phi) + \rho_m(\vec{x})e^{\frac{\phi}{M_m}} + \rho_\gamma(\vec{x})e^{\frac{\phi}{M_\gamma}}$$

$$\rho_\gamma \equiv \frac{1}{2}(B^2 - E^2)$$

In the presence of a magnetic field photons convert to chameleons

Chameleon - Photon oscillations can happen in a way very similar to ALPs.

However the interaction with matter is crucially different.

Rather than light shining through the wall - we can build a chameleon jar with an afterglow.

Afterglow Experiments

GammeV

" [Photon]-[dilaton-like chameleon particle] regeneration using a "particle trapped in a jar" technique "   http://gammev.fnal.gov

A. Chou *et. al.* 0806.2438 [hep-ex]
See also - Gies *et. Al.* + Ahlers *et. Al. (DESY)*
Alps at DESY, LIPSS at JLab, OSQAR at CERN, BMV, ADMX

FERMILAB-PUB-08-111-A-CD-E-TD

A search for chameleon particles using a photon regeneration technique

A. S. Chou[1], W. Wester[2], A. Baumbaugh[2], H. R. Gustafson[3], Y. Irizarry-Valle[2], P. O. Mazur[2], J. H. Steffen[2], R. Tomlin[2], A. Upadhye[4], A. Weltman[5,6], X. Yang[2], and J. Yoo[2]
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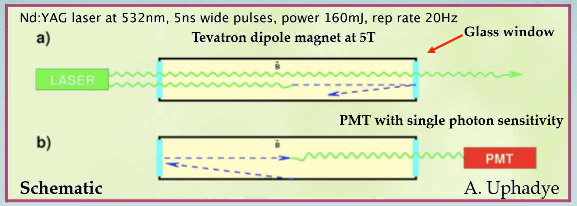
(Dated: February 2, 2009)

We report the first results from the GammeV search for chameleon particles, which may be created via photon-photon interactions within a strong magnetic field. Chameleons are hypothesized scalar fields that could explain the dark energy problem. We implement a novel technique to create and trap the reflective particles within a jar and to detect them later via their afterglow as they slowly convert back into photons. These measurements provide the first experimental constraints on the couplings of chameleons to photons.

PACS numbers: 12.20.Fv, 14.70.Bh, 14.80.Mz, 95.36.+x

GammeV CHASE

http://gammev.fnal.gov

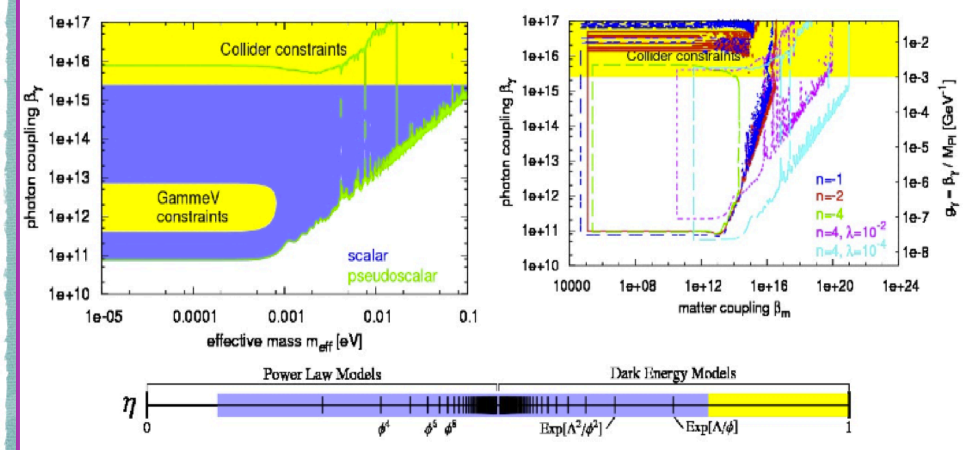


a) Chameleon production phase: photons propagating through a region of magnetic field oscillate into chameleons

- Photons travel through the glass
- Chameleons see the glass as a wall - trapped

b) Afterglow phase: chameleons in chamber gradually decay back into photons and are detected by a PMT

GammeV CHASE Constraints



Chameleons Near

- Experiment to observe the effect - direct detection
- Distinguish clearly from other models
- Constrain the parameters using complementary searches
- Afterglow searches (GammeV, JLab, DESY, etc)
- Helioscope at CAST
- Electroweak at colliders
- Neutrons at Grenoble
- Casimir force experiments
- Torsion pendula experiments
- Space tests of gravity
- Detecting by lightning rod effect - electrostatic analogy

Jones-Smith and Ferrer 2012

Environment with different ambient densities - subtle chameleon effects possible

Chameleons Far

- **Supernova Brightening from Chameleon-Photon Mixing. C. Burrage**
  Effect: photon to chameleon conversion in SN + chameleon-photon mixing in the intergalactic magnetic field
  Result : supernovae brightening + fits observations of std candles and std rulers
- **Detecting Chameleons: The Astronomical Polarization Produced by Chameleon-like Scalar Fields. C. Burrage et. al.**
  Effect : linear and circular polarization
  Result : "a tentative statistical detection of a chameleon-like scalar field from observations of starlight polarization in our galaxy."
- **Active Galactic Nuclei shed light on Axion-like-Particles. C. Burrage et. al.**
  Effect: scatter in luminosity relations of astro objects
  Result : ''we find evidence strongly suggestive of the existence of a very light ALP''

Can also study other objects and systems eg. pulsars, the CMB etc.

...and with Astronomy

- **Searching for chameleon-like scalar fields with the ammonia method. S.A. Levshakov et. al.**
  Goal: probe the dependence of $\mu = \frac{m_e}{m_p}$ on ambient matter density using radio astronomical observations $\frac{\Delta\mu}{\mu} = 2.2 \times 10^{-8}$
- **Searching for spatial variations of alpha^2/mu in the Milky Way. S.A. Levshakov et. al.**
  $$\frac{\Delta\alpha}{\alpha} < 2 \times 10^{-7}$$
- **Equivalence Principle Implications of Modified Gravity Models. L.Hui *et. al.***
  Claims : Small galaxies should accelerate faster than large galaxies.
  Voids defined by small galaxies would appear larger compared to expectations.
  Lensing and dynamical mass estimates should agree for large galaxies but disagree for small ones.
  Stars and diffuse gas in small galaxies should have different velocities, even if they are on the same orbits - effect could be 30% or more - best to look in voids.

Astrophysical Tests of Modified Gravity: the Morphology and Kinematics of Dwarf Galaxies

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ABSTRACT
This paper is the third in a series on tests of gravity using observations of stars and nearby dwarf galaxies. We carry out four distinct tests using published data on the kinematics and morphology of dwarf galaxies, motivated by the theoretical work of Hui et al. (2009) and Jain & Vanderplas (2011). In a wide class of gravity theories a scalar field couples to matter and provides an attractive fifth force. Due to their different self-gravity, stars and gas may respond differently to the scalar force leading to several observable deviations from standard gravity. HI gas, red giant stars and main sequence stars can be displaced relative to each other, and the stellar disk can display warps or asymmetric rotation curves aligned with external potential gradients. To distinguish the effects of modified gravity from standard astrophysical phenomena, we use a control sample of galaxies that are expected to be screened from the fifth force. In all cases we find no significant deviation from the null hypothesis of general relativity. The limits obtained from dwarf galaxies are not yet competitive with the limits from cepheids obtained in our first paper, but can be improved to probe regions of parameter space that are inaccessible using other tests. We discuss how our methodology can be applied to new radio and optical observations of nearby galaxies.

Key words: Modified gravity

Theory Progress

- Derivation from fundamental theory
- Derive the coupling and potential - KKLT type

Hinterbichler, Khoury and Nastase 2011, Nastase and AW 2013, Nastase and AW 2013

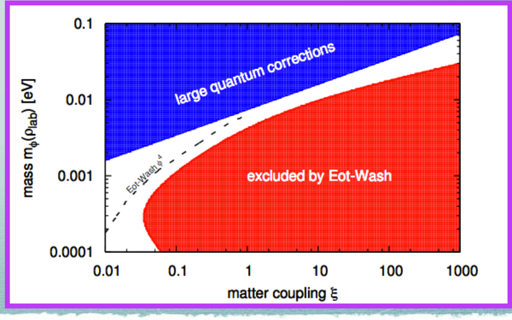
- Quantum Stability of Chameleon Effective field theories

Upadhye, Hu and Khoury 2011

1 loop bounds for

$$\rho_{lab} = 10 g.cm^{-3}$$

Bounds are much weaker on solar system and cosmological scales.



Summary

- Lots of theory motivations to probe this Low Energy frontier
- Need intense beams to probe this low energy frontier
- Existing facilities have not yet been fully exploited + build new!
- Incentive for space tests of gravity
- Great potential for astrophysics probes - complementary
- Chameleons in particular can be probed on land, in space, astrophysics scales and cosmological scales.

Possibility for high impact, major fundamental discoveries at low cost