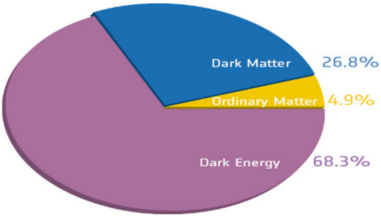
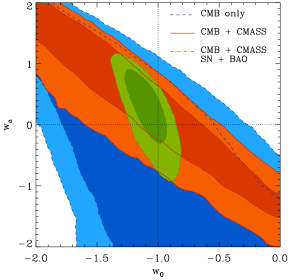
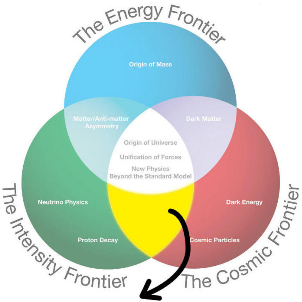
Was Einstein Right? Testing gravity and dark energy in the laboratory

Amol Upadhye
Argonne National Lab
April 25, 2013





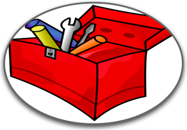
Evolution with time

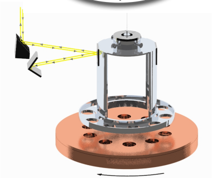


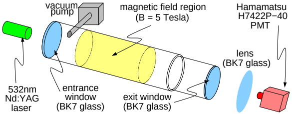
Coupling to known particles

Outline

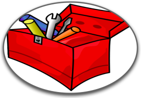
1. Introduction
   - Motivation: DE scale $M_\Lambda = 2.4 \times 10^{-3}$ eV
   - Dark energy: a phenomenological tool box
   - Chameleon screening
2. Fifth forces
   - Quantum-stable chameleons
   - Eöt-Wash constraints and forecasts
   - Symmetrons and Eöt-Wash constraints
3. New particles
   - Production through photon coupling
   - GammeV-CHASE afterglow experiment
   - Upcoming experiments







Coupled dark energy from modified gravity



A phenomenological toolbox:

Modified gravity	**Effective scalar**	**New physics**
4-D modified action: $R \longrightarrow f(R)$	Conformal trans.: $\Rightarrow$ chameleon	matter coupling, effective $m(\rho)$

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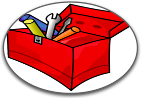

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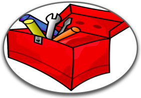

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DGP, etc.: non-compact extra dimension	Decoupling limit (weak gravity) $\Rightarrow$ Galileon	matter coupling, non-canonical kinetic term

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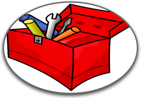

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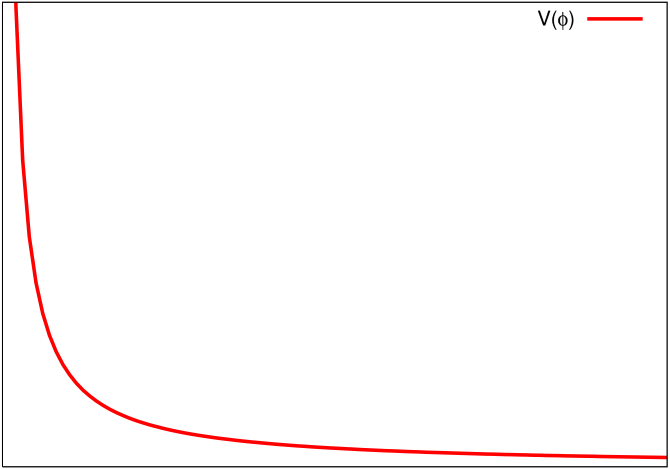
Kaluza-Klein, etc.: compact extra dim.	Small extra dim. $\Rightarrow$ radion	matter coupling, photon coupling

At low energies, dark energy can have a matter coupling, whose fifth force must be screened locally. Dark energy can also have a photon coupling, allowing the production of dark energy particles.

Chameleon mechanism

effective potential: $V_{\rm eff}(\phi,\rho) = V(\phi) + \beta\rho\phi/M_{\rm Pl}$



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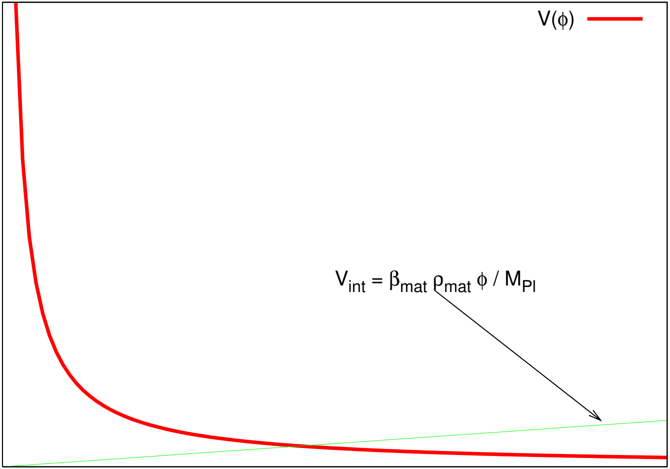

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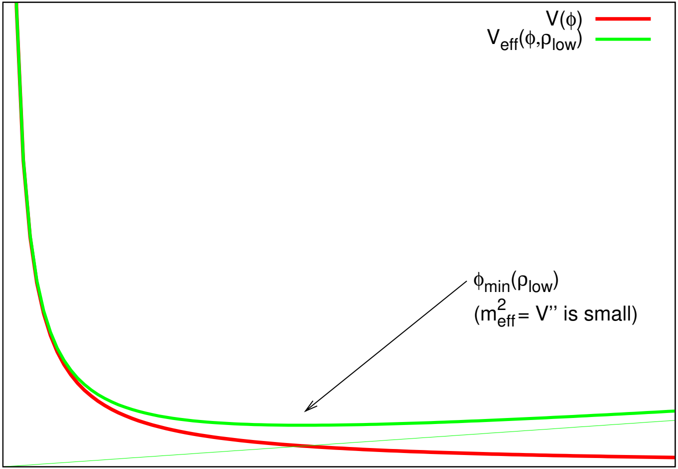

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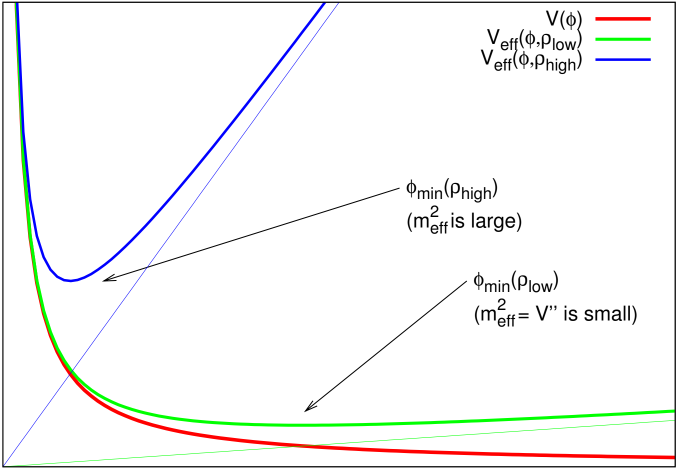
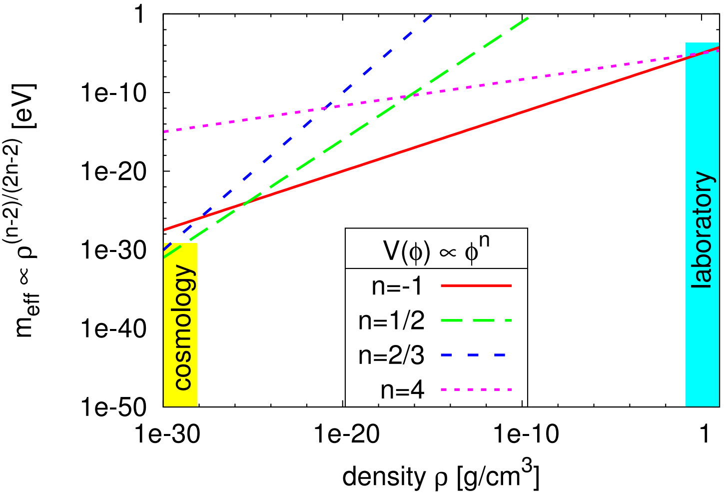


At which scale should we probe each model?

$V(\phi) \propto \phi^n + \text{const.} \Rightarrow m_{\text{eff}} \propto \rho^{\frac{n-2}{2n-2}}$ (use lab for $n \lesssim -\frac{1}{2}$, $n > 2$)

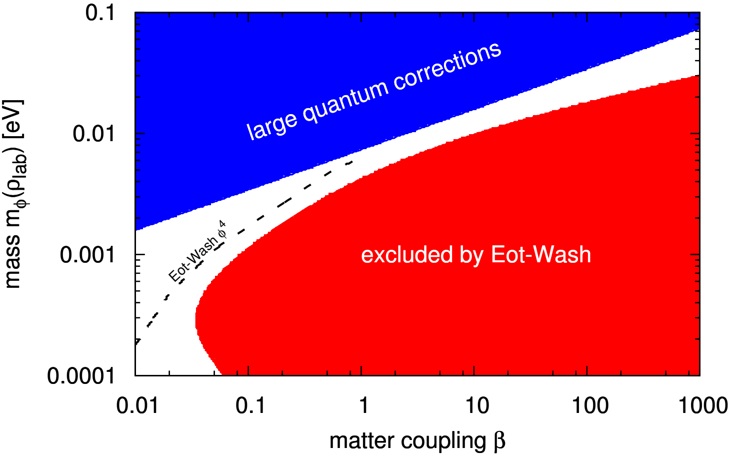


AU, PRD ***86****:102003(2012)[arXiv:1209.0211]*

Laboratory benchmark: "quantum-stable" chameleons

$$\Delta V_{1-\text{loop}}(\phi) = \frac{m_{\text{eff}}(\phi)^4}{64\pi^2} \log\left(\frac{m_{\text{eff}}(\phi)^2}{\mu^2}\right) < V_{\text{tree}}$$

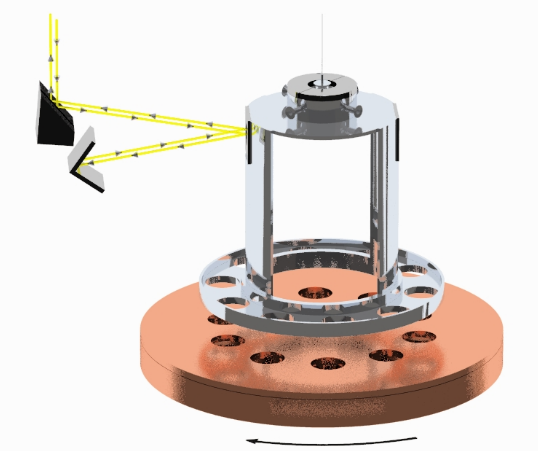
$$\Rightarrow m_{\text{eff}} \leq \left(\frac{48\pi^2\beta^2\rho^2}{M_{\text{Pl}}^2}\right)^{1/6} = 0.0073\left(\frac{\beta\rho}{10\text{g}/\text{cm}^3}\right)^{1/6}\text{eV}$$

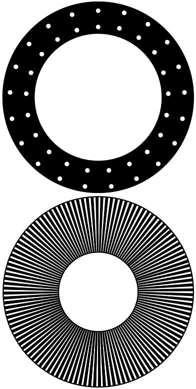


AU, Hu, Khoury, PRL **109***:041301(2012)[arXiv:1204.3906]*

Fifth-force tests using a torsion pendulum

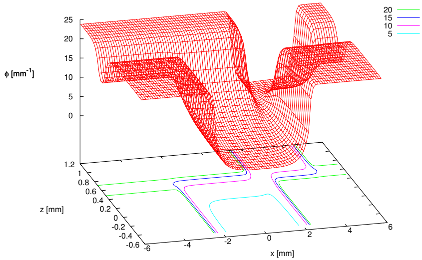
Eöt-Wash Experiment





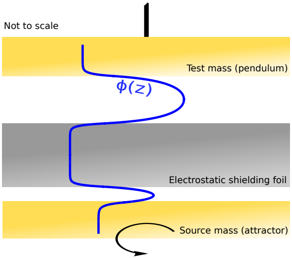
http://www.npl.washington.edu/eotwash

3-D numerical solution:



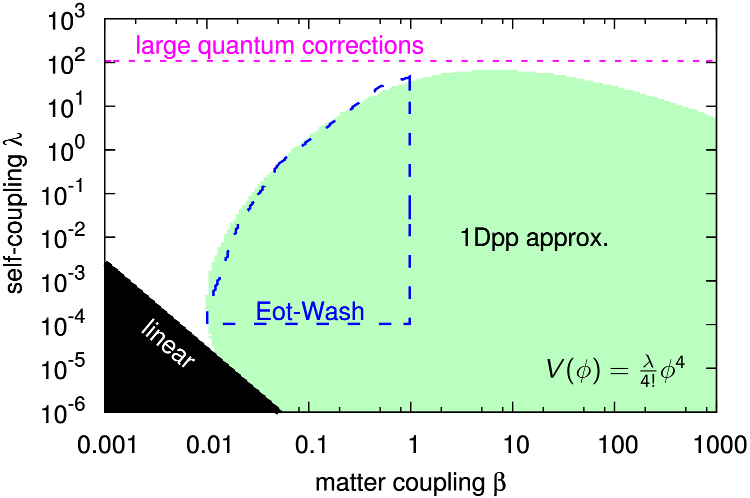
AU, Gubser, Khoury, PRD **74***:104204(2006)[arXiv:hep-ph/0608186]*

1-D plane-parallel approximation



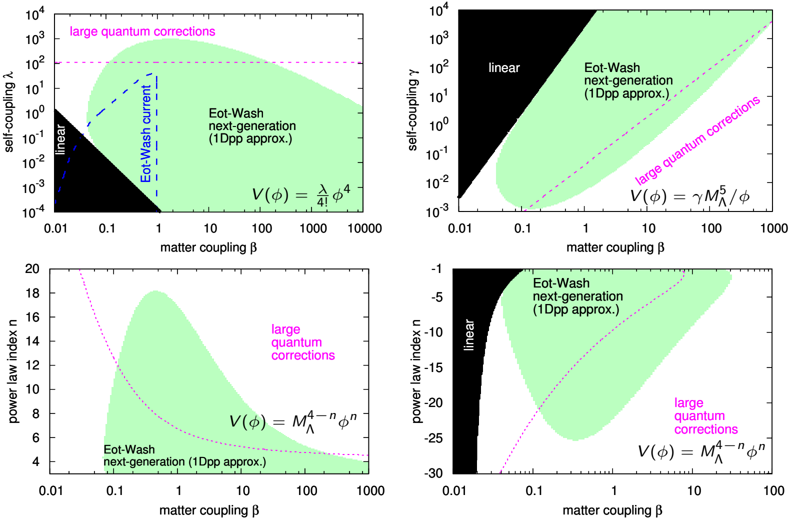
AU, PRD **86***:102003(2012)[arXiv:1209.0211]*

Eöt-Wash constraints on chameleons

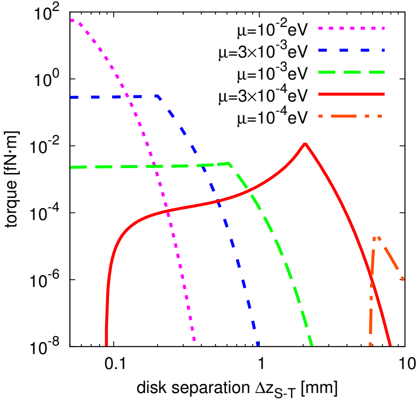


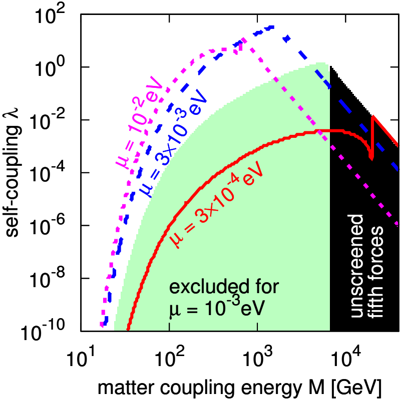
Eöt-Wash: *Adelberger, Heckel, Hoedl, Hoyle, Kapner, AU. PRL* **98** *131104 (2007)*
1Dpp: *AU, PRD* **86** *102003 (2012) [arXiv:1209.0211]*

Next-generation Eöt-Wash: chameleon forecasts



AU, PRD **86***:102003(2012)[arXiv:1209.0211]*



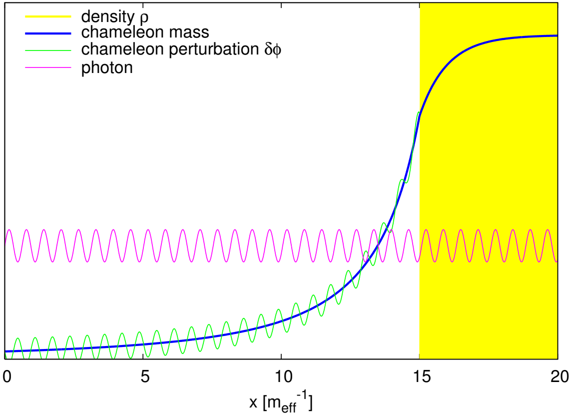


Symmetron effective potential: $V_{\text{eff}} = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4!}\phi^4$
Eöt-Wash probes $\lambda \sim 1$, $\mu \sim 10^{-3}$ eV (dark energy),
$M \sim 1$ TeV (beyond the Standard Model)

AU, PRL **110***:031301(2013)[arXiv:1210.7804]*

Osicillation: Photon coupling term $\frac{\beta_\gamma}{4M_{\mathrm{Pl}}} F_{\mu\nu} F^{\mu\nu} \phi \Rightarrow$ dark energy particles produced from photons in magnetic field

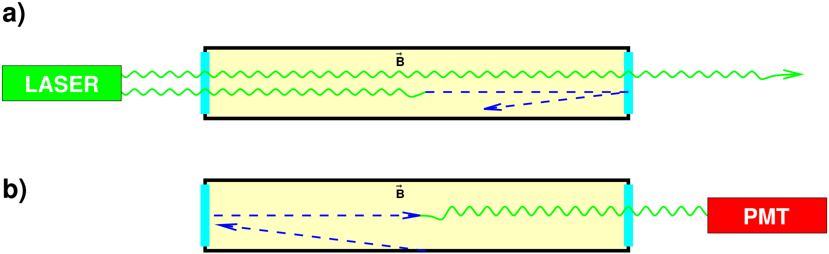
Containment: Dark energy particles reflect from matter. Windows perform quantum measurements.



Afterglow experiments

An afterglow experiment has two phases:

(a) Production phase: photons streamed through $\vec{B}_0$ region; some oscillate into chameleons

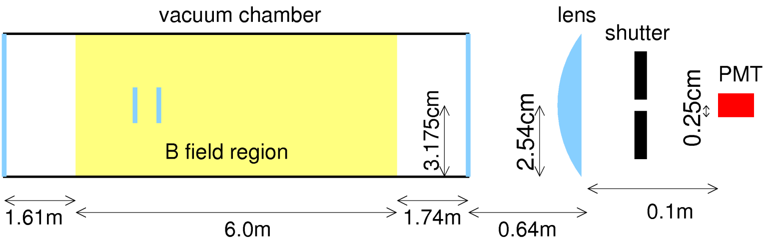


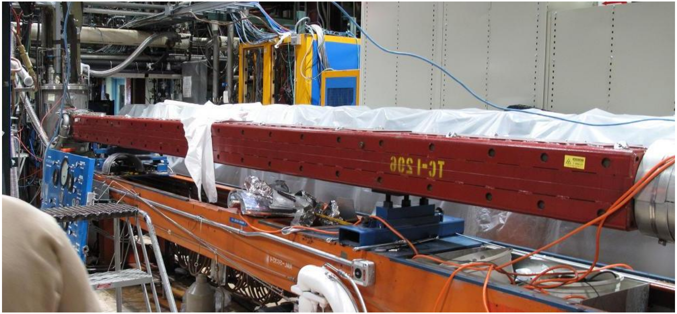
(b) Afterglow phase: chameleons slowly oscillate back into photons, escaping chamber

Systematics: • adiabatic evolution • emission from vacuum materials • diffuse reflection • scattering from atoms • effects of chamber geometry

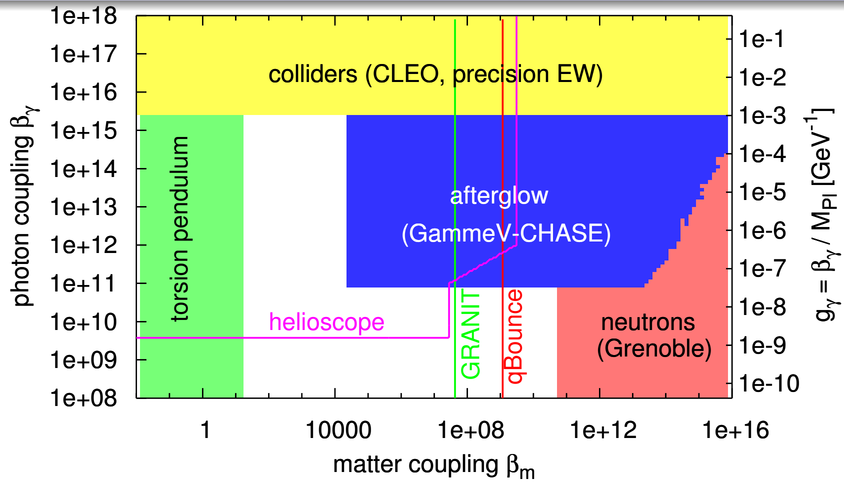
Thorough review: *AU, Steffen, Chou, PRD* **86***:035006(2012)[arXiv:1204.5476]*.

CHASE (CHameleon Afterglow SEarch)





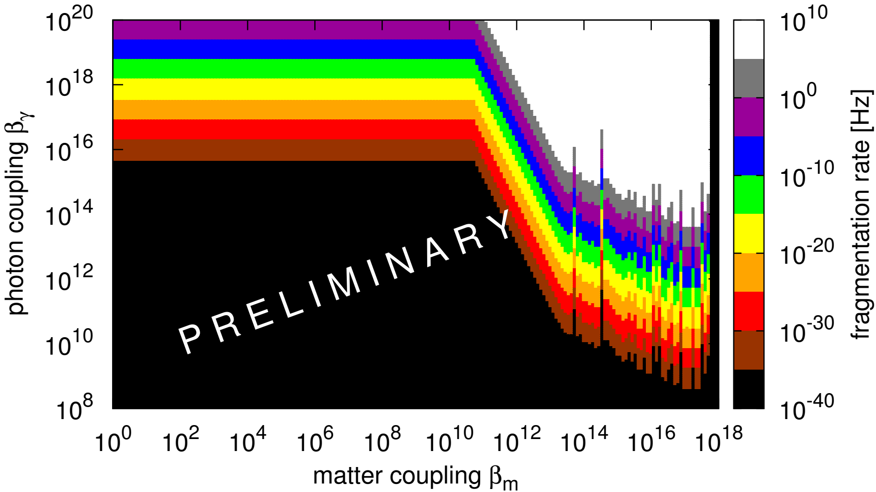
CHASE constraints on $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$



Theory: *AU, Steffen, Chou, PRD* **86***:035006(2012)[arXiv:1204.5476]*,
AU, Steffen, Weltman, PRD **81***:015013(2010)[arXiv:0911.3906]*

Experiment: *Steffen, AU, Baumbaugh, Chou, Mazur, Tomlin, Weltman, Wester, PRL* **105***:261803(2010)[arXiv:1010.0988]*

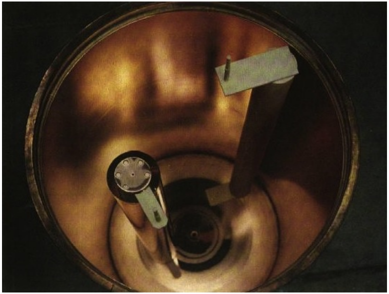
Chameleon fragmentation?



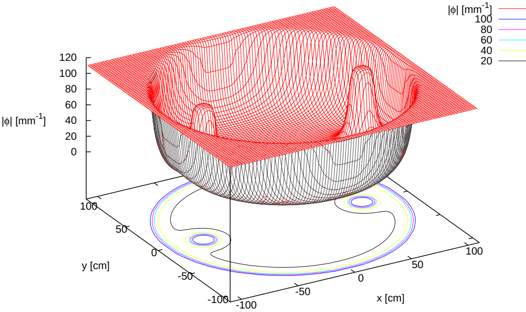
Chameleon particles can interact to produce a greater number of lower-energy chameleon particles.

P. Brax and AU (2013, in prep.)

Cavity afterglow experiments



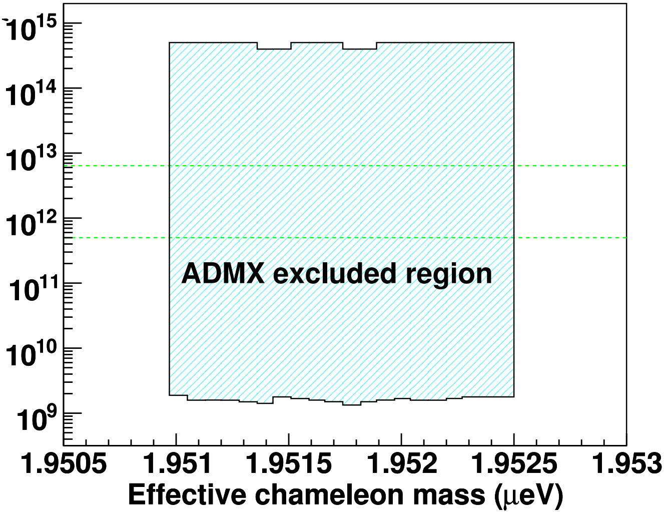
http://www.phys.washington.edu/groups/admx/cavity.html



Procedure:

1. source excites EM mode
2. turn off source; EM modes decay
3. EM modes regenerated from chameleon
4. adjust tuning rods for sensitivity to different mass range

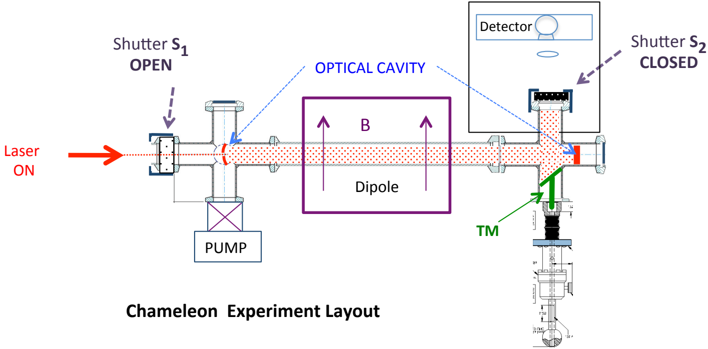
ADMX constraints on photon-coupled chameleons



G. Rybka, M. Hotz, L. Rosenberg, et al., PRL **105** *051801 (2010)*

A Proposed Chameleon Experiment

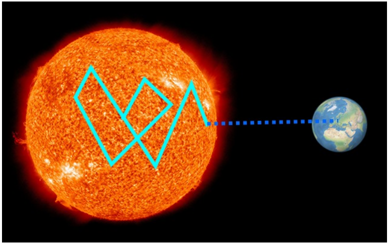
The experiment will use part of the existing LIPSS setup, the dipole, vacuum chamber, and Light Tight Box. New is the optical cavity, the insertable turning mirror TM, and computer controls. The optical cavity will increase the number of photons in the dipole field by a factor between 100 and 1000. Shown here is the configuration where the chameleon gas is being generated. The turning mirror **TM** is withdrawn and Shutter **S_2** is closed, protecting the detector from direct laser light.



Chameleon Experiment Layout

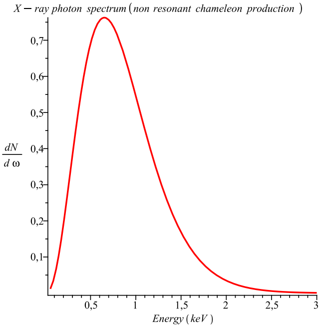
The experiment will use a standard 10 W table top laser. A computer will control proper sequencing of laser on/off, shutter open/closed, and TM insert/withdraw. With the dipole OFF, background decay rates ("after-glow") will be measured. Measurements will be repeated with the dipole field ON. Shown here is the configuration where the chameleon gas is being generated. Decay rates from 200 seconds to 1 second will be covered. Variations between B-field OFF and B-field ON might indicate chameleon generation and decay and would warrant further study.

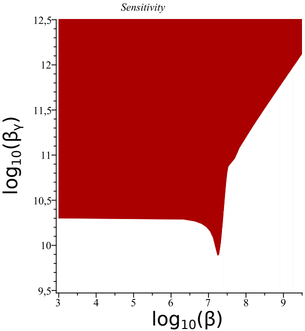
Chameleons from the Sun

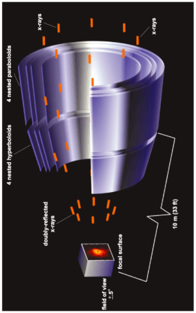


- $\sim$ keV photons oscillate into chameleons inside Sun
- chameleon particles reach Earth
- helioscope magnet regenerates photons for detection

Helioscope forecasts







Solar chameleon spectrum peaked at 600 eV.
Forecast constraints.
P. Brax, A. Lindner, K. Zioutas, PRD **85** *043014 (2012)*

Increase collecting area using an X-ray mirror.
O. K. Baker, A. Lindner, AU, K. Zioutas (2012)

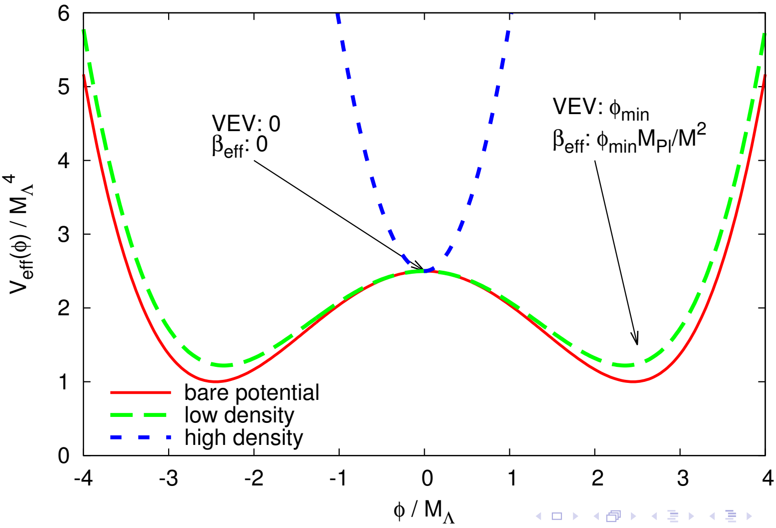
Conclusions

1. The physics responsible for the cosmic acceleration may differ from a cosmological constant by evolving with time or by coupling to known particles. Couplings imply fifth forces.
2. Laboratory and cosmological experiments are complementary; they probe models whose masses scale differently with density.
3. The Eöt-Wash torsion pendulum experiment will be able to exclude chameleon models with gravitation-strength couplings and small quantum corrections.
4. The CHASE afterglow experiment has excluded a range of light photon-coupled dark energy models. Upcoming afterglow and helioscope experiments promise to improve these constraints over the next few years.

EXTRA SLIDES

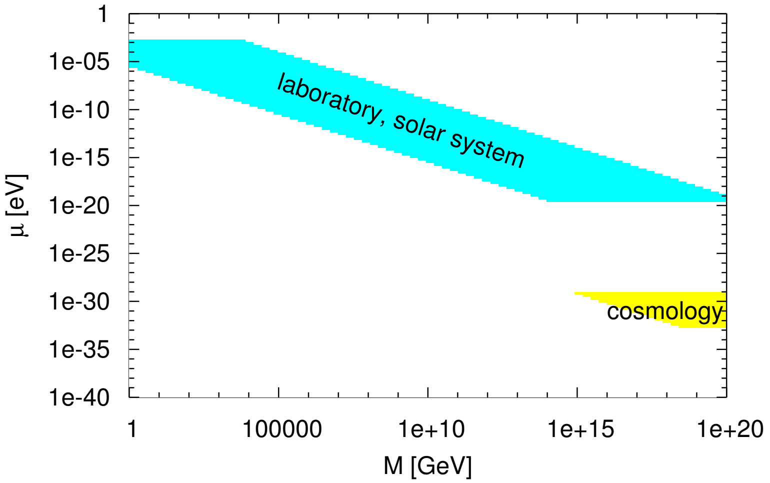
Symmetron mechanism

effective potential: $V_{\text{eff}}(\phi, \rho) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4!}\phi^4$



At which scale should we probe symmetrons?

Fifth forces are predicted for $\rho_{\rm m} > \mu^2 M^2 > \rho_{\rm v}$ at distances $\gtrsim 1/\mu$.



The time-dependent equation of motion is $\Box\phi = V'_{\rm eff}$.

Equations of motion ($V_{\phi\gamma} = \frac{\beta_\gamma}{4M_{\rm Pl}} F^{\mu\nu} F_{\mu\nu}\phi$ with $\beta\phi \ll M_{\rm Pl}$):

- $\partial_\mu \left[\left(1 + \frac{\beta_\gamma \phi}{M_{\rm Pl}} \right) F^{\mu\nu} \right] = 0$
- $\Box\phi = V'(\phi) + \frac{\beta_m}{M_{\rm Pl}} \rho_{\rm mat} + \frac{\beta_\gamma}{4M_{\rm Pl}} F_{\mu\nu} F^{\mu\nu}$

Plane wave perturbations about background ϕ_0 and $\vec{B}_0 = B_0 \hat{x}$ (Raffelt and Stodolsky 1988; AU, Steffen, and Weltman 2010):

- $\left(-\frac{\partial^2}{\partial t^2} - \vec{k}^2 \right) \psi_\phi = m_{\rm eff}^2 \psi_\phi + \frac{\beta_\gamma k B_0}{M_{\rm Pl}} \hat{x} \cdot \vec{\psi}_\gamma$
- $\left(-\frac{\partial^2}{\partial t^2} - \vec{k}^2 \right) \vec{\psi}_\gamma = \omega_{\rm P}^2 \vec{\psi}_\gamma + \frac{\beta_\gamma k B_0}{M_{\rm Pl}} \hat{k} \times (\hat{x} \times \hat{k}) \psi_\phi$

$\phi \rightarrow \gamma$ oscillation (low-mass, $\vec{k} \perp \vec{B}_0$): $\mathcal{P}_{\gamma\leftrightarrow\phi} \approx \frac{\beta_\gamma^2 B_0^2 L^2}{4M_{\rm Pl}^2}$