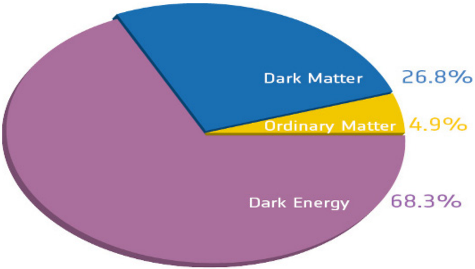
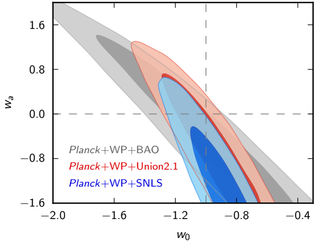
# Modified gravity from the laboratory to the stars

Amol Upadhye
IEU, Ewha University

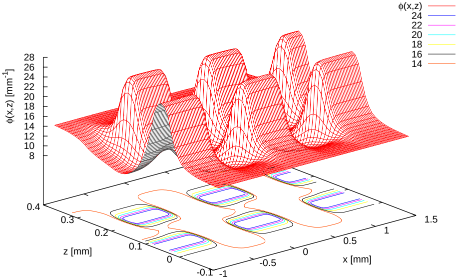
February 20, 2014

# Cosmic acceleration




Time-variation

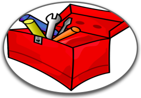



Couplings to known particles

# Outline

1. Introduction: Coupled dark energy from modified gravity
2. Fifth forces from matter couplings
   - "Quantum-stable" chameleon dark energy
   - Laboratory searches
   - Modified gravity in stars
3. How dark is dark energy? Searches for photon couplings
   - Scalar-photon oscillation
   - Afterglow experiments
   - Dark energy from the Sun

# Coupled dark energy from modified gravity



A phenomenological toolbox:

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

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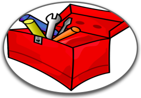

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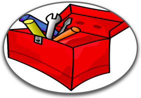

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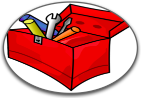
# Coupled dark energy from modified gravity



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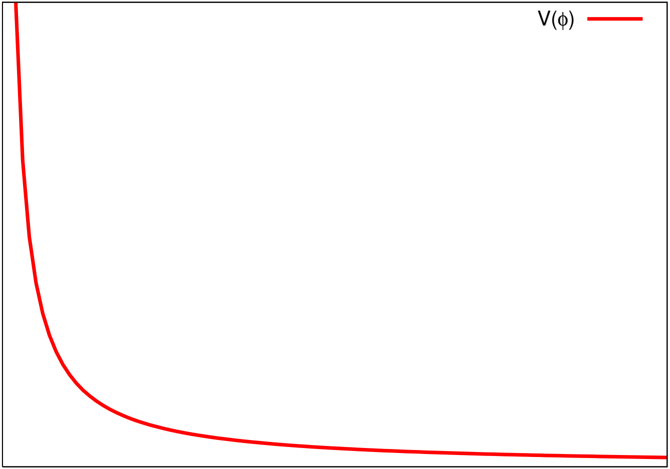
| Kaluza-Klein, etc.: compact extra dim. | Small extra dim. $\Rightarrow$ radion | matter coupling, photon coupling |

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



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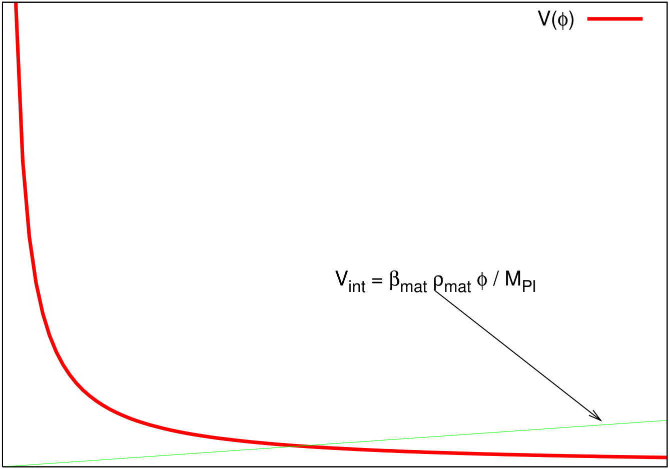

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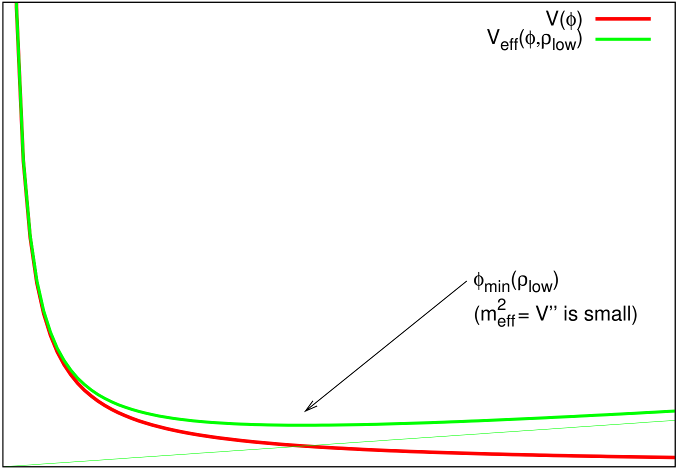

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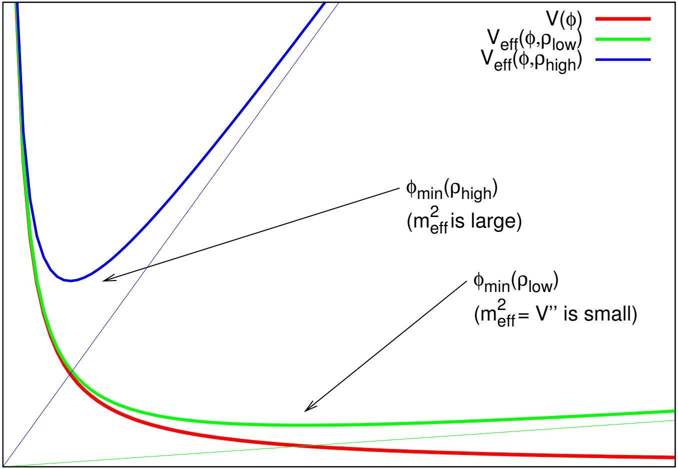
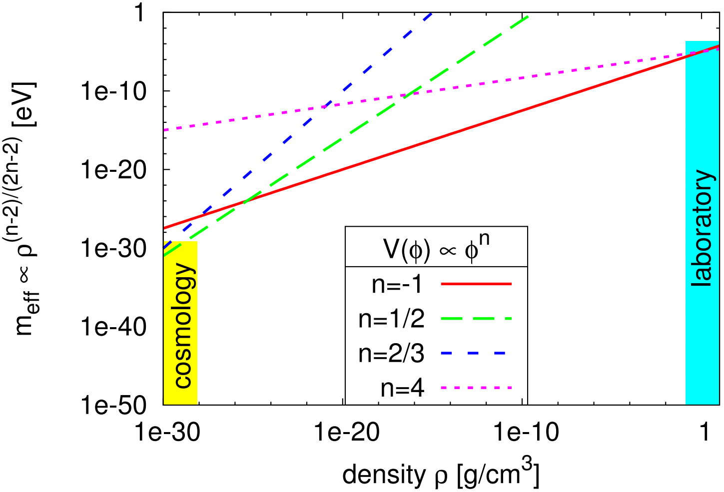


# At which scale should we probe each model?

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

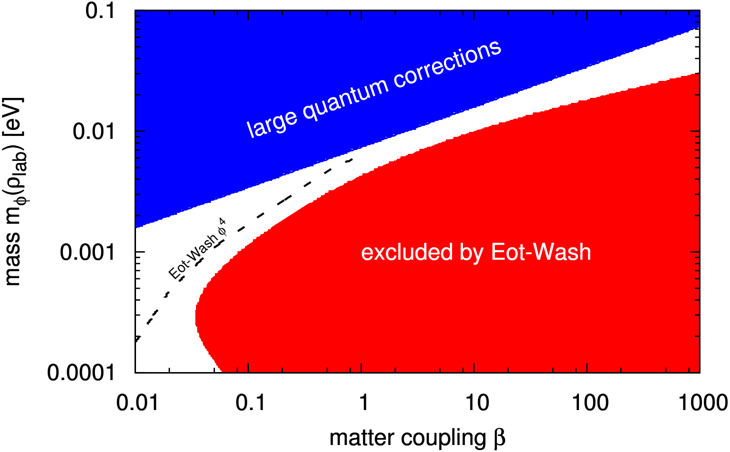



*AU, PRD* **86***:102003(2012)[arXiv:1209.0211].*

# Laboratory benchmark: "quantum-stable" chameleons

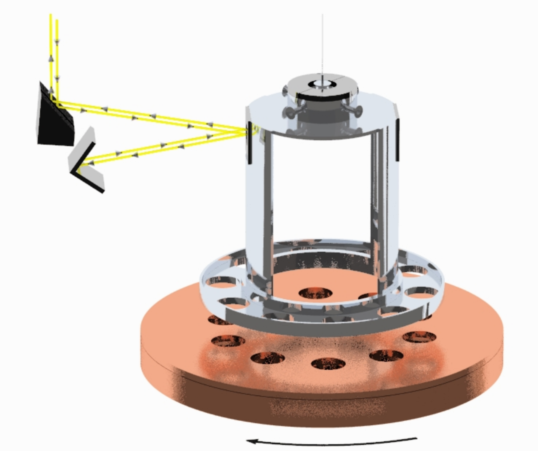
$$\Delta V_{1-\mathrm{loop}}(\phi) = \frac{m_{\mathrm{eff}}(\phi)^4}{64\pi^2} \log\left(\frac{m_{\mathrm{eff}}(\phi)^2}{\mu^2}\right) < V_{\mathrm{tree}}$$

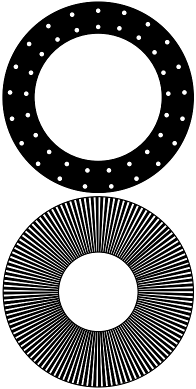
$$\Rightarrow m_{\mathrm{eff}} \leq \left(\frac{48\pi^2\beta^2\rho^2}{M_{\mathrm{Pl}}^2}\right)^{1/6} = 0.0073\left(\frac{\beta\rho}{10\mathrm{g/cm}^3}\right)^{1/6}\mathrm{eV}$$




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

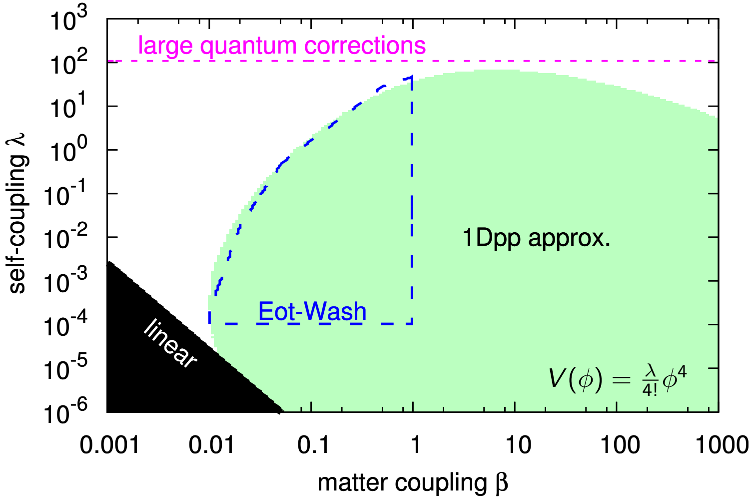
Eöt-Wash Experiment





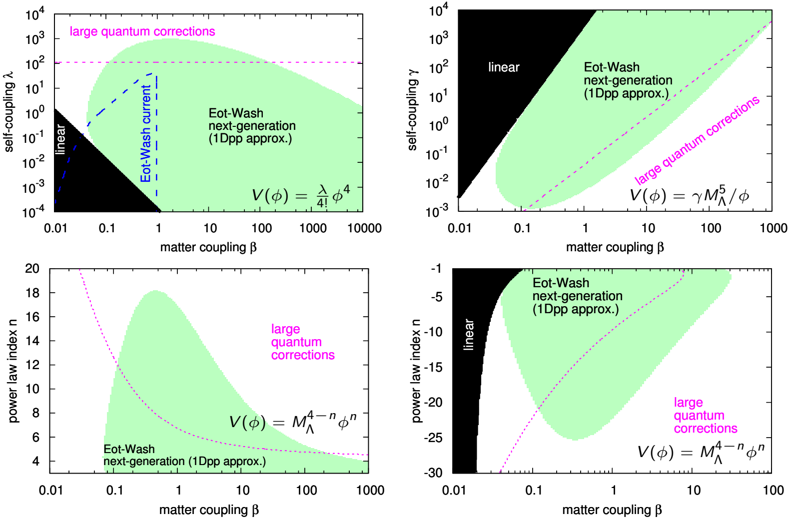
http://www.npl.washington.edu/eotwash

# Eöt-Wash constraints on chameleons



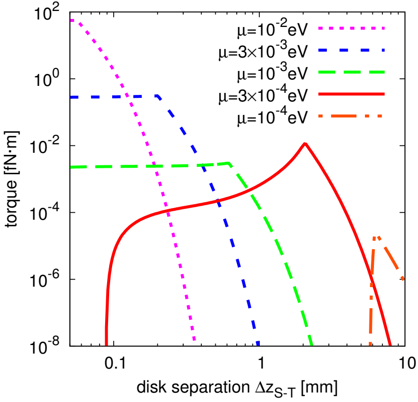

Eöt-Wash: *Adelberger, Heckel, Hoedl, Hoyle, Kapner, AU. PRL* **98** *131104 (2007)*
1Dpp: *AU, PRD* **86** *102003 (2012) [arXiv:1209.0211]*

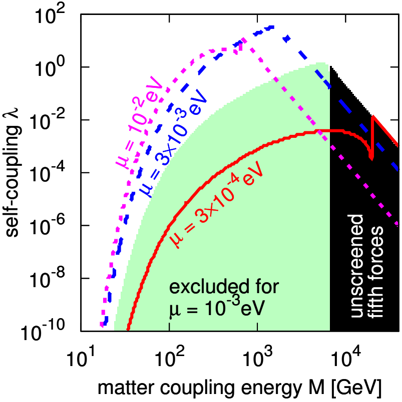
# Next-generation Eöt-Wash: chameleon forecasts




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

# Estimated (1Dpp) Eöt-Wash constraints on symmetrons



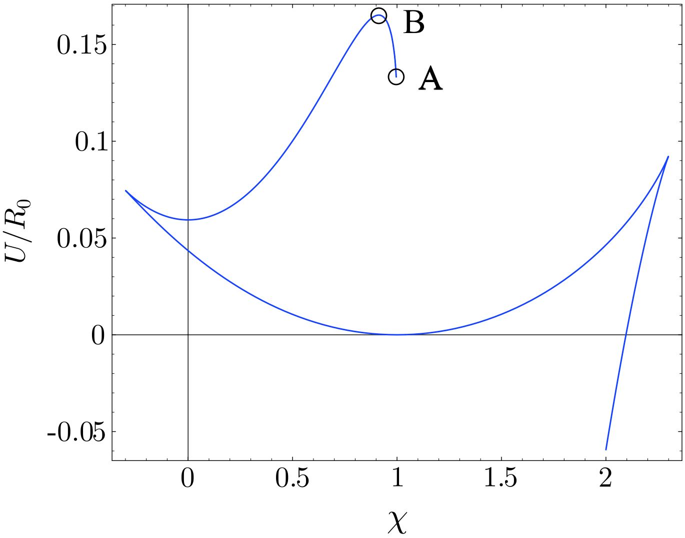

Symmetron effective potential: $V_{\text{eff}} = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4!}\phi^4$

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].*

# Does screening work at all in relativistic stars?




*Kobayashi and Maeda, PRD* **78***:064019(2008)[arXiv:0807.2503].*

# Chameleon screening in stars: equations of motion

metric: $ds^2 = -N(r)dt^2 + \frac{dr^2}{B(r)} + r^2(d\theta^2 + sin^2\theta\, d\varphi^2)$

hydrostatic equilibrium: $P'(r) = -\frac{N'}{2N}(\rho + P)$

equation of state: $\rho(r) = \mathrm{constant}\ (1\mathrm{g}/\mathrm{cm}^3)$

modified Einstein eq. (trace, $tt$, $rr$), $f_R = \frac{df}{dR}$, $\phi = -\frac{M_{\mathrm{Pl}}}{2\beta_{\mathrm{m}}} \log f_R$:

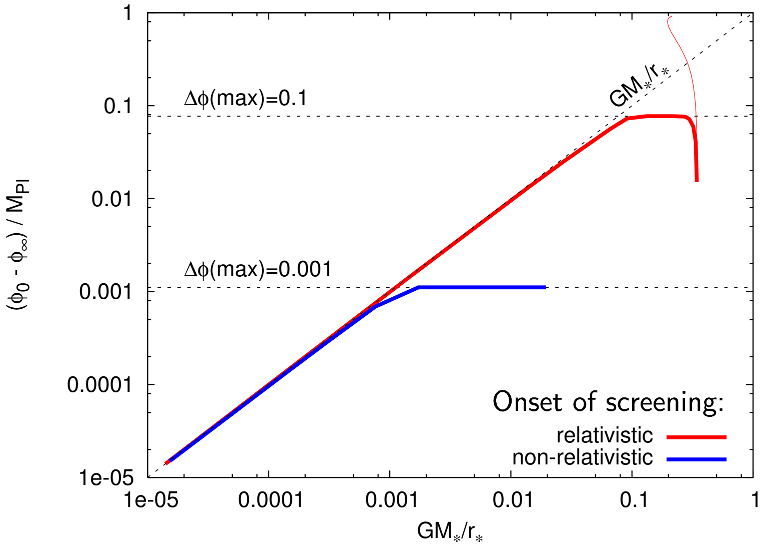
$$\left[f_R'' + \left(\frac{2}{r} + \frac{N'}{2N} + \frac{B'}{2B}\right) f_R'\right] B = \frac{dV}{df_R} - \frac{8\pi G}{3}(\rho - 3P)$$

$$\frac{(-1 + B + rB')f_R}{r^2} + \left[f_R'' + \left(\frac{2}{r} + \frac{B'}{2B}\right) f_R'\right] B = -8\pi G\rho + \frac{f - Rf_R}{2}$$

$$\frac{(-1 + B + rBN'/N)f_R}{r^2} + \left(\frac{2}{r} + \frac{N'}{2N}\right) f_R' B = 8\pi GP + \frac{f - Rf_R}{2}$$

*AU and Hu, PRD* ***80****:064002(2009)[arXiv:0905.4055].*

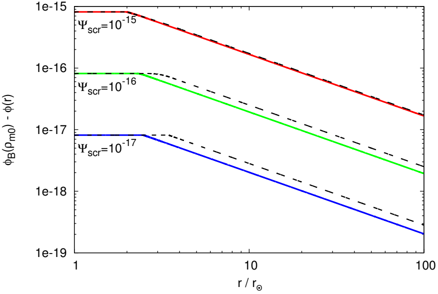
# Chameleon screening in relativistic stars



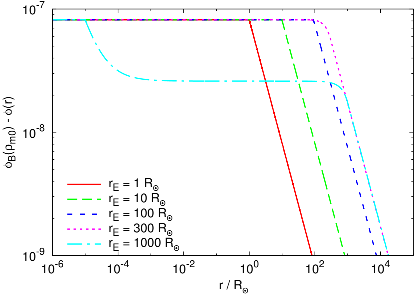

*AU and Hu, PRD* **80***:064002(2009)[arXiv:0905.4055].*

Screening implies that the scalar charge associated with an object is not conserved. An oscillating or expanding star can emit scalar monopole radiation.

Variable stars

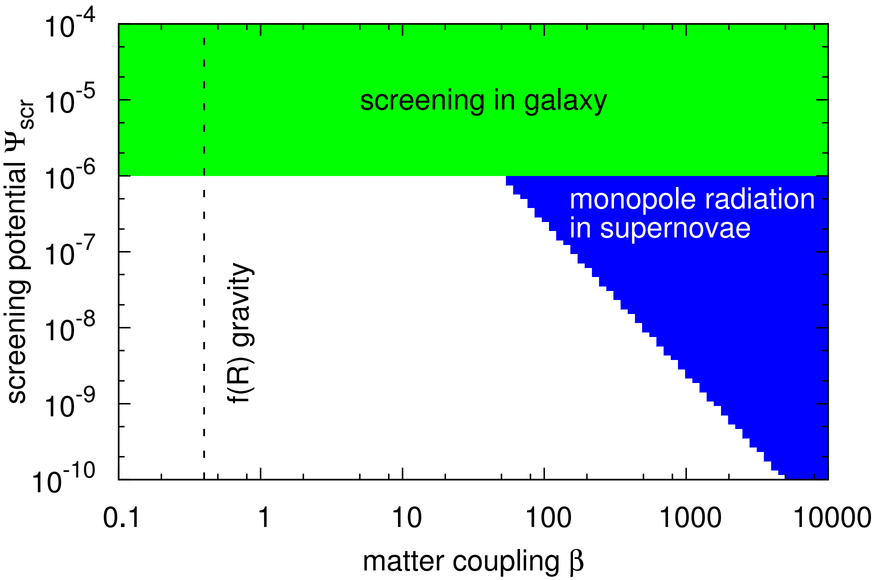



Supernovae




*AU and Steffen, arXiv:1306.6113*

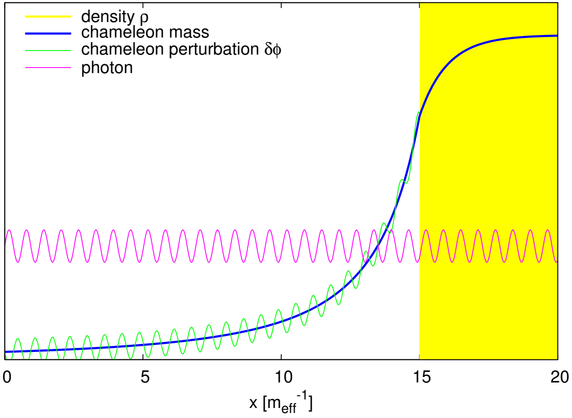
# Estimated constraints from monopole radiation




*AU and Steffen, arXiv:1306.6113*

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

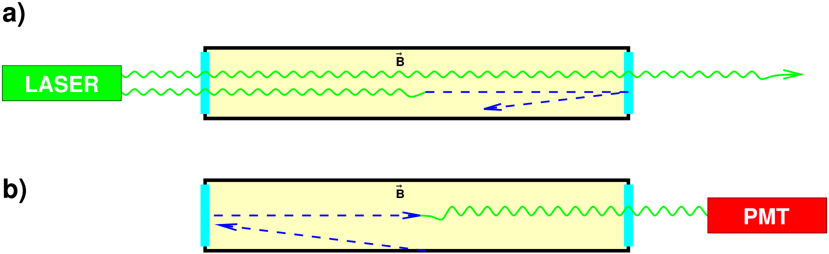
Containment: Dark energy particles reflect from matter. Windows perform quantum measurements.



# Afterglow experiments

An afterglow experiment has two phases:

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

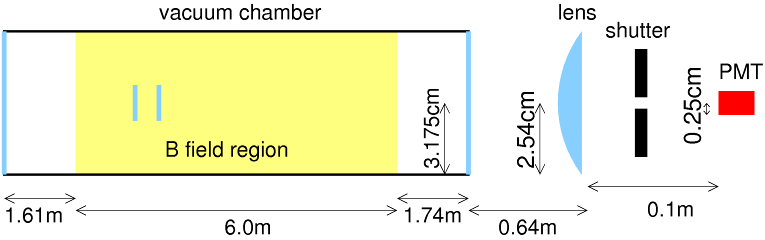


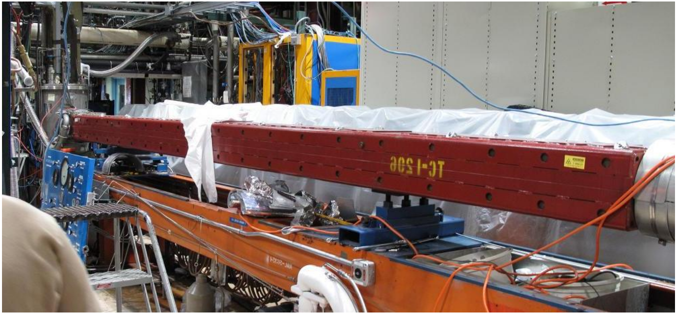

(b) Afterglow phase: chameleons slowly oscillate back into photons, escaping chamber

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

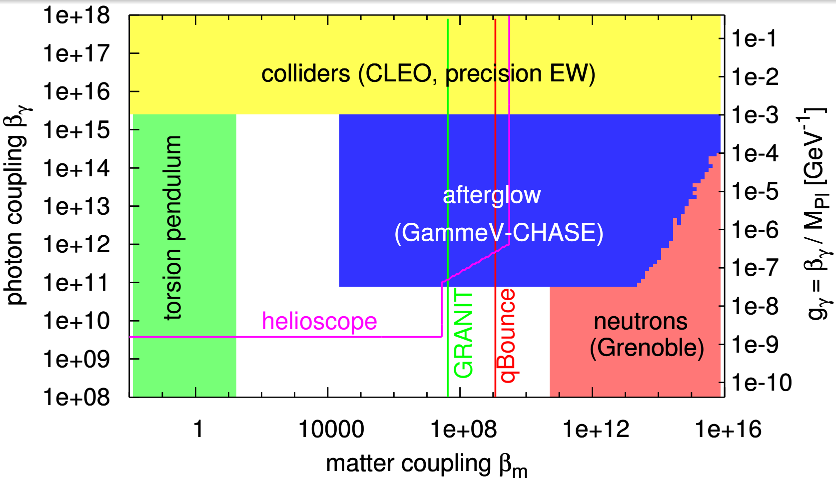
Thorough review: *AU, Steffen, Chou, PRD* **86***:035006(2012)[arXiv:1204.5476]*..

# CHASE (CHameleon Afterglow SEarch)



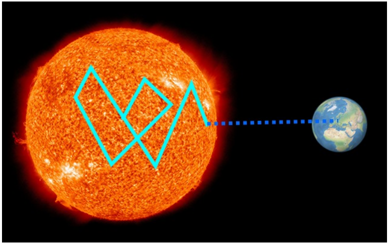
# CHASE constraints on $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$




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

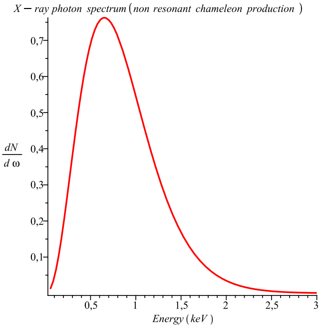
Experiment: *Steffen, AU, Baumbaugh, Chou, Mazur, Tomlin, Weltman, Wester, PRL* **105***:261803(2010)[arXiv:1010.0988].*

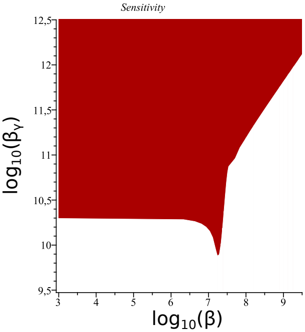
# Chameleons from the Sun

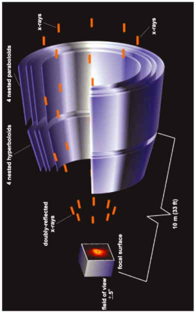


- $\sim$ keV photons oscillate into chameleons inside Sun
- chameleon particles reach Earth
- helioscope magnet regenerates photons for detection

# 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 can be tested in the laboratory and stars as well as in the universe.
2. Modifications to gravity lead to couplings to Standard Model particles.
3. Laboratory torsion pendulum experiments will soon rule out "quantum-stable" chameleon models and an interesting class of symmetron models.
4. $f(R)$ gravity is consistent with relativistic and variable stars.
5. Afterglow experiments have placed bounds on the coupling between dark energy and photons.
6. Dark energy candidate particles from the Sun could be detected by a helioscope such as CAST at CERN.