New particles and forces from chameleon dark energy

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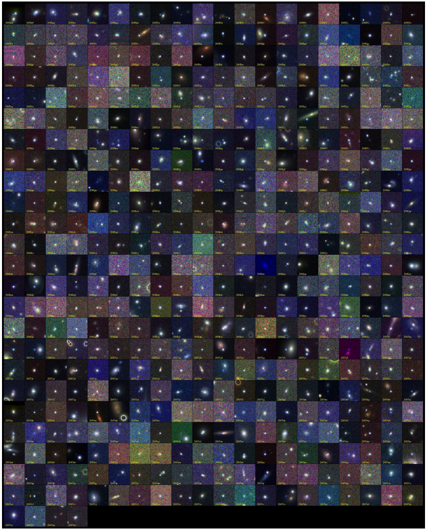
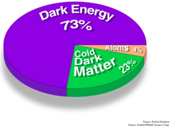
July 20, 2012

Cosmic acceleration: The greatest mystery in cosmology

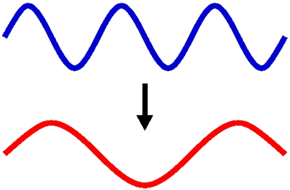




How do we know?

- intrinsic brightness of type Ia supernovae are about the same
- apparent brightness decreases with distance
- farther back in time, supernovae dimmer than expected

Acceleration and supernovae



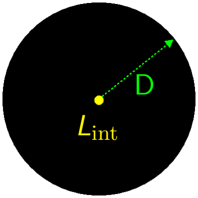
Time variable: red shifting of light

$$z = \frac{\lambda_{\rm final} - \lambda_{\rm initial}}{\lambda_{\rm initial}}$$

Brightness related to distance D:

$$\mathrm{flux} = \frac{L_{\rm int}}{4\pi D^2}$$

$$D = \int \mathrm{expansion\ history}$$



Outline

Types of dark energy

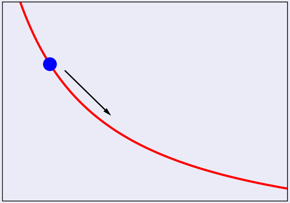
ϕ evolves

ϕ couples

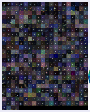
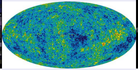
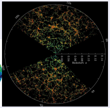
Types of dark energy

ϕ evolves

- $V(\phi)$



- $H(z)$ evolves with ϕ
- Constrain using

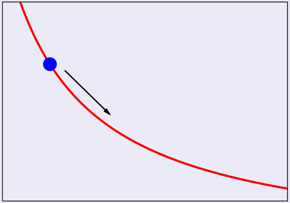




ϕ couples

Types of dark energy

ϕ evolves

- $V(\phi)$



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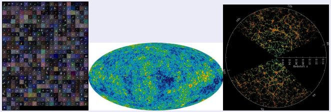
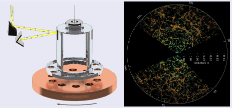
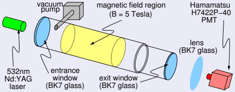


ϕ couples

- New effects:
  - fifth forces
  - new particle
- Screening mechanism
  - chameleon (mass)
  - Vainshtein (kinetic)
- Constrain using:





Chameleon scalar field

Action (in flat spacetime) for a photon-coupled chameleon field:

$$S = \int d^4x \left[-\frac{1}{2}(\partial\phi)^2 - V(\phi) + \mathcal{L}_{\mathrm{mat}}\left(e^{\frac{2\beta_m \phi}{M_{\mathrm{Pl}}}} g_{\mu\nu}\right) - \frac{1}{4} e^{\frac{\beta_\gamma \phi}{M_{\mathrm{Pl}}}} F_{\mu\nu} F^{\mu\nu} \right]$$

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canonical kinetic term

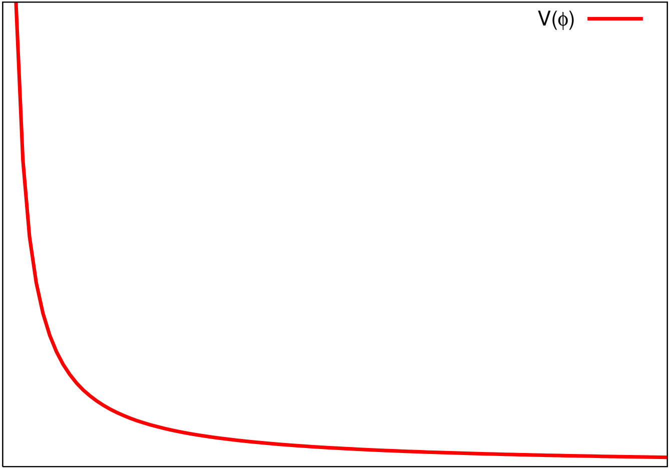
nonlinear $V' \Rightarrow$ nonlinear equations of motion

example: $V(\phi) = M_\Lambda^4 \exp\left(\frac{\kappa\phi^n}{M_\Lambda^n}\right) \approx \kappa M_\Lambda^{4-n}\phi^n + M_\Lambda^4$

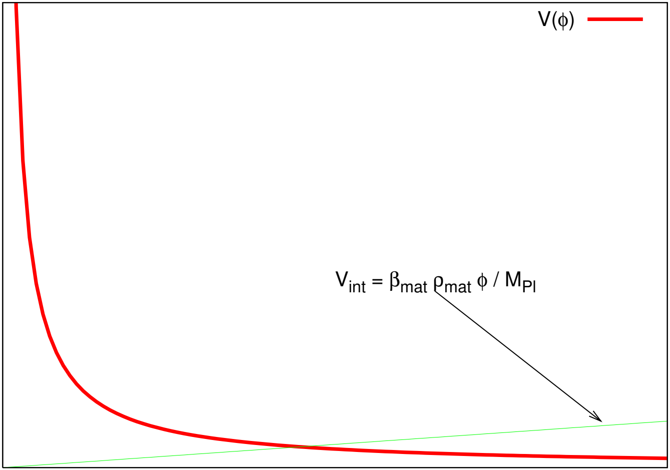
matter coupling: $\mathcal{L}_{\rm int} = -\frac{\beta_m}{M_{\rm Pl}}\phi T^\mu_\mu \approx \frac{\beta_m}{M_{\rm Pl}}\rho_{\rm mat}\phi$ (linear coupling)

photon coupling (leads to scalar-photon oscillation)

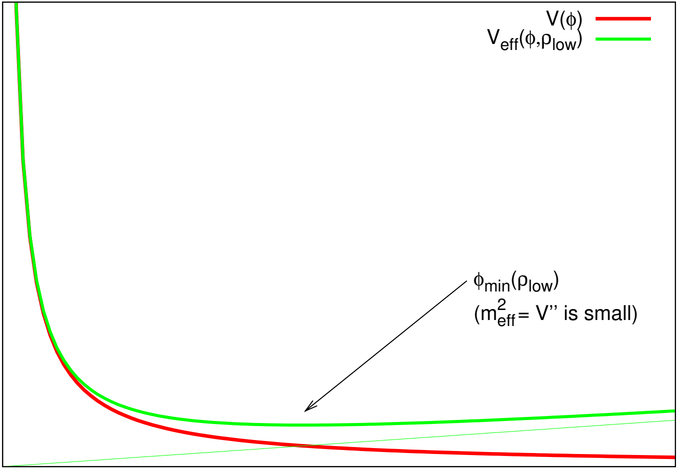
Chameleon effect



Chameleon effect



Chameleon effect



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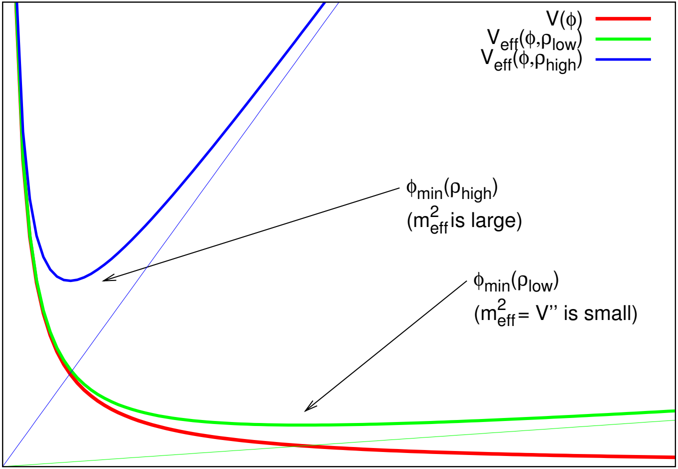
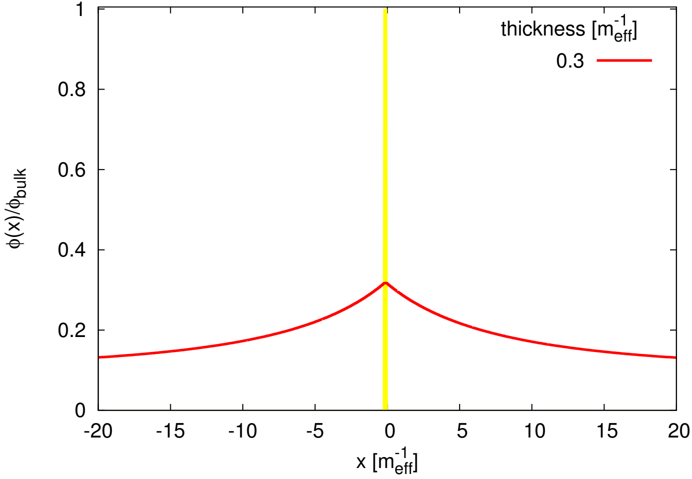


Thin-shell effect



(AU, S. Gubser, J. Khoury 2006)

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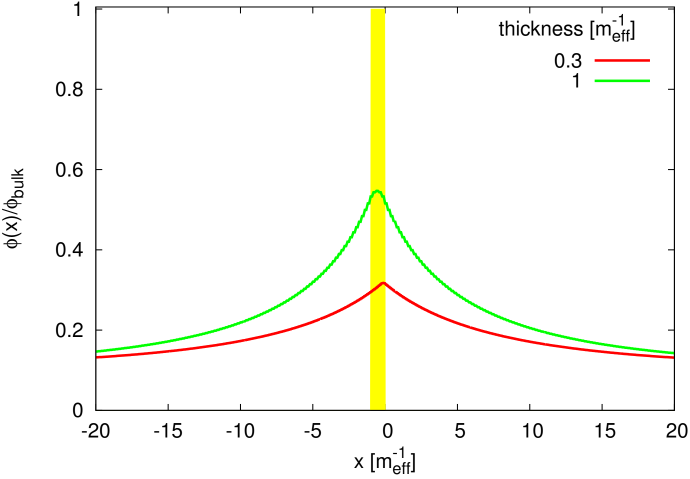

(AU, S. Gubser, J. Khoury 2006)

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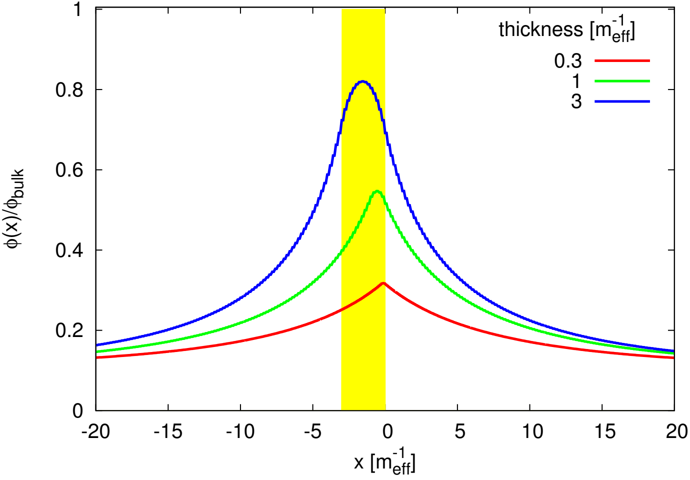

(AU, S. Gubser, J. Khoury 2006)

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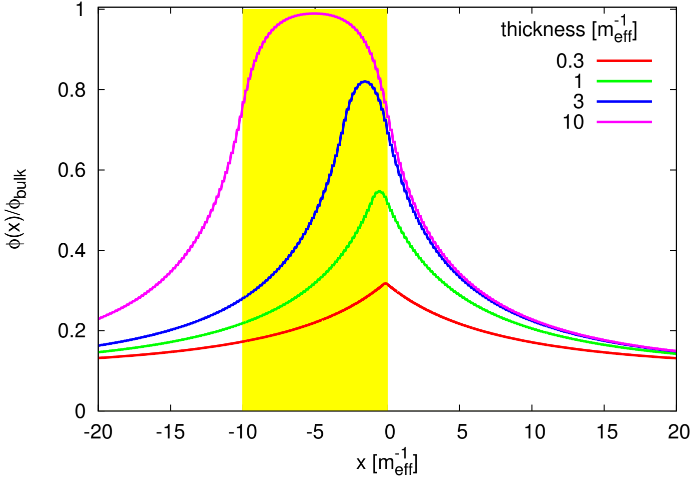

(AU, S. Gubser, J. Khoury 2006)

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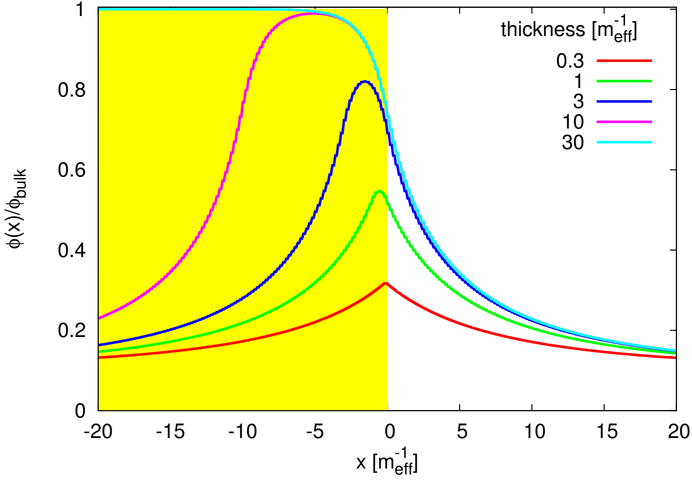
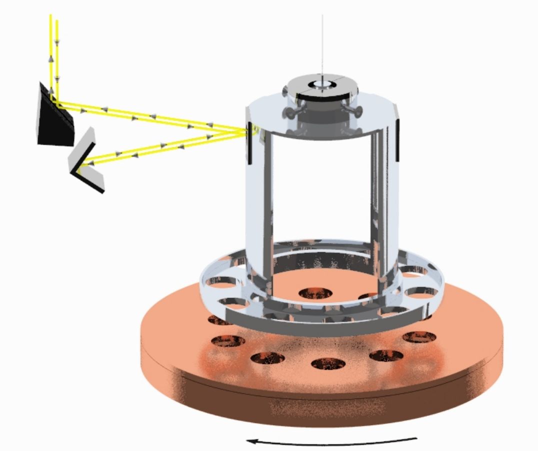
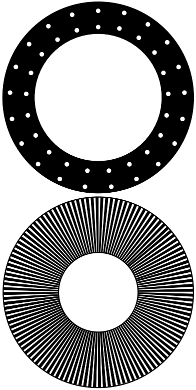


(AU, S. Gubser, J. Khoury 2006)

Fifth-force constraints from a torsion pendulum

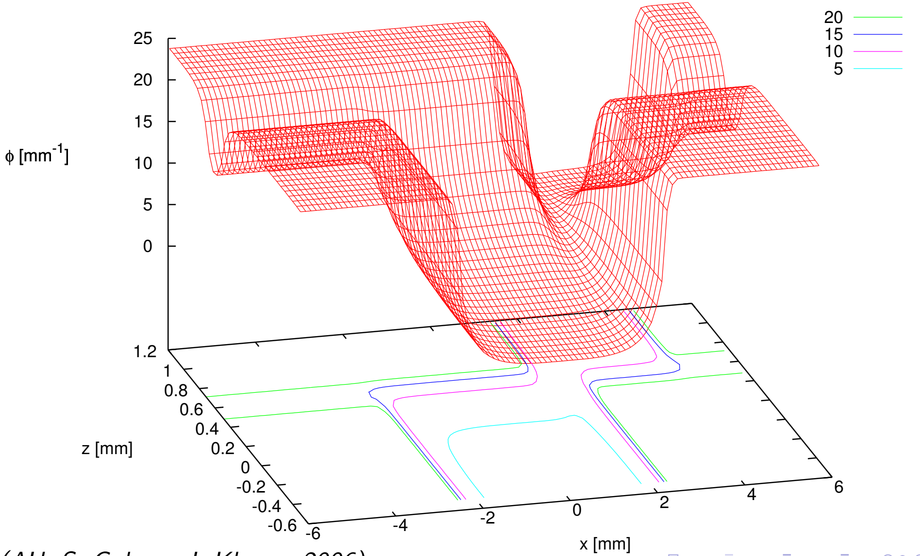
Eöt-Wash Experiment (see talk by Frank Fleischer)





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

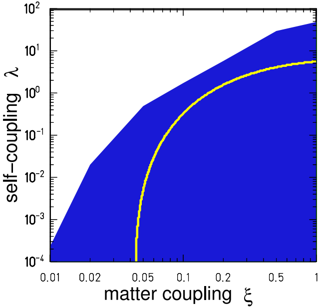
ϕ^4 chameleon field in Eöt-Wash pendulum



(AU, S. Gubser, J. Khoury 2006)

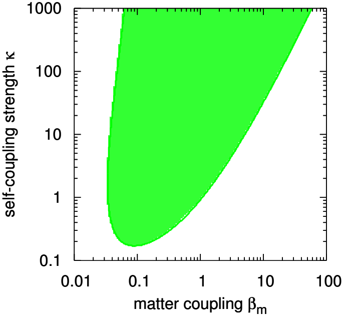
Eöt-Wash constraints

$V(\phi) = \frac{\lambda}{4!}\phi^4 + \text{const.}$



(E. Adelberger, AU, et. al., 2007)

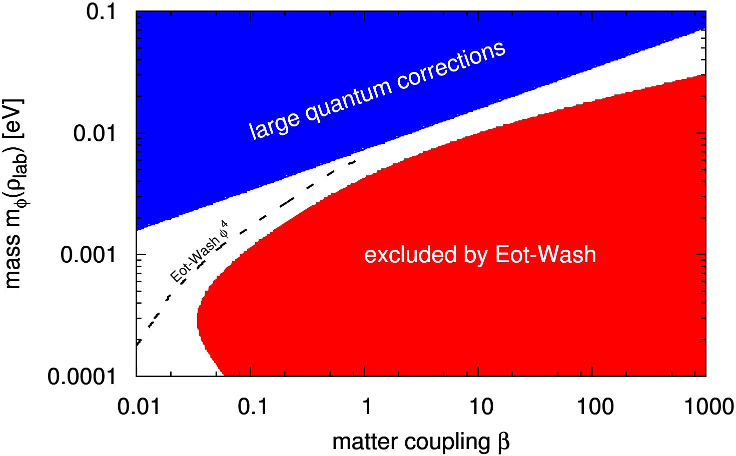
$V(\phi) = \kappa M_\Lambda^5 \phi^{-1} + \text{const.}$



Maximum-mass approximation
(AU, W. Hu, J. Khoury 2012)

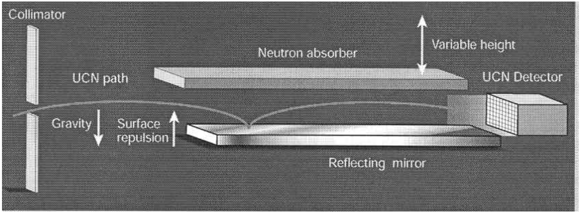
Chameleons with small quantum corrections

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



AU, W. Hu, J. Khoury (2012)

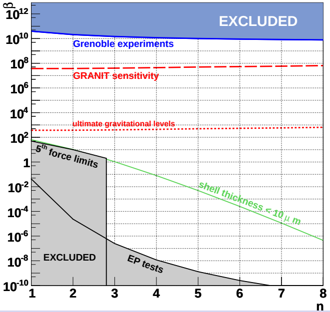
Neutrons in a gravitational field



$$\left(-\frac{\hbar^2}{2m_N}\frac{d^2}{dz^2} + m_N\Psi + \frac{\beta_{\rm m} m_N}{M_{\rm Pl}}\phi\right)|N\rangle = E\,|N\rangle$$

- $\Psi(z) = gz$ is gravitational field
- $\phi(z)$ is chameleon field (nonlinear in z)
- energy levels E of bouncing neutrons quantized ($\Delta E \sim 1$ peV)

(P. Brax and G. Pignol 2011)



Photons coupled to chameleon dark energy

Equations of motion ($\beta\phi \ll M_{\rm Pl}$):

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

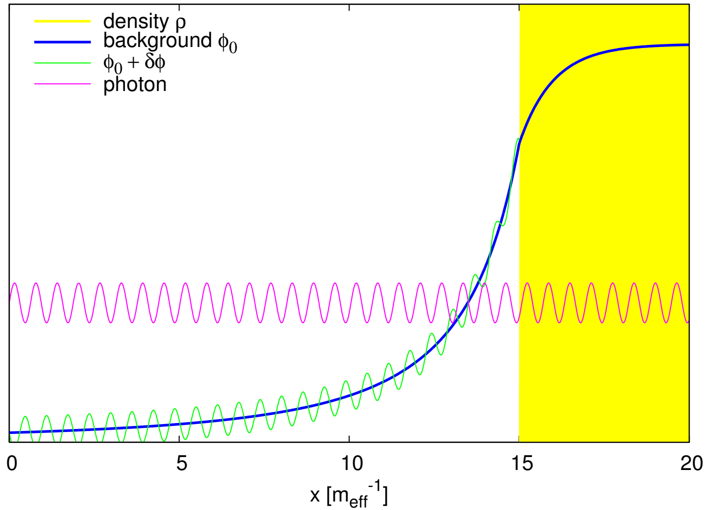
Plane wave perturbations about background ϕ_0 and $\vec{B}_0 = B_0 \hat{x}$ (Raffelt and Stodolsky 1988; AU, Steffen, and Weltman 2010):

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

$\phi \to \gamma$ oscillation in relativistic case:

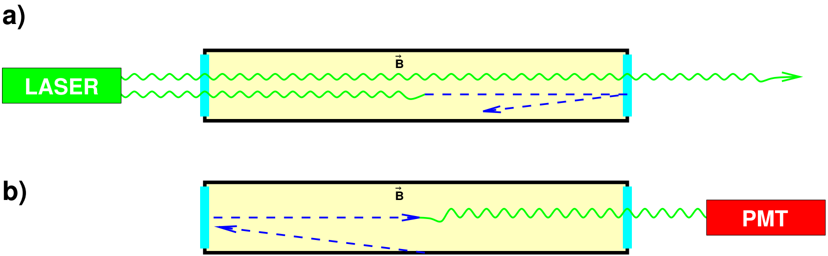
- $\mathcal{P}_{\gamma\leftrightarrow\phi} = \vec{\psi}_\gamma^* \cdot \vec{\psi}_\gamma = \frac{4k^2\beta_\gamma^2 B_0^2}{(\Delta m^2)^2 M_{\rm Pl}^2} \sin^2\left(\frac{\Delta m^2 L}{4k} \right) \left| \hat{k} \times (\hat{x} \times \hat{k}) \right|^2$
- low-mass, $\vec{k} \perp \vec{B}_0$: $\mathcal{P}_{\gamma\leftrightarrow\phi} \approx \frac{\beta_\gamma^2 B_0^2 L^2}{4M_{\rm Pl}^2}$

Window as a quantum measurement device



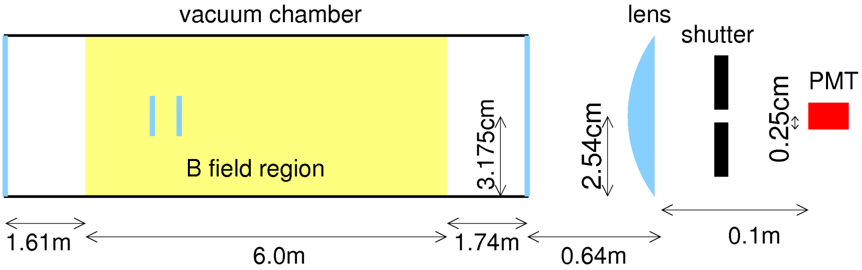
A simple afterglow experiment

(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

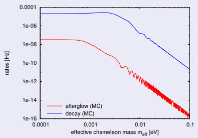
GammeV-CHASE apparatus



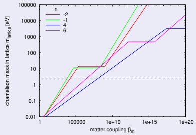
1. Multiple magnetic field runs
2. Partitioning of magnetic field region
3. Modulation of detector
4. Vacuum maintained by ion pump

Chameleons in CHASE: a thorough study

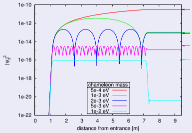
Oscillation



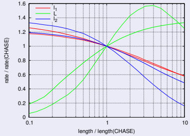
Matter lattice



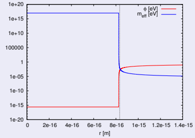
Adiabaticity



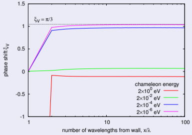
Chamber geom.



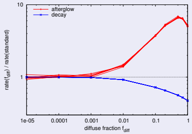
Atom scattering



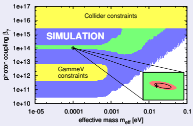
Other potentials



Diffuse ref.

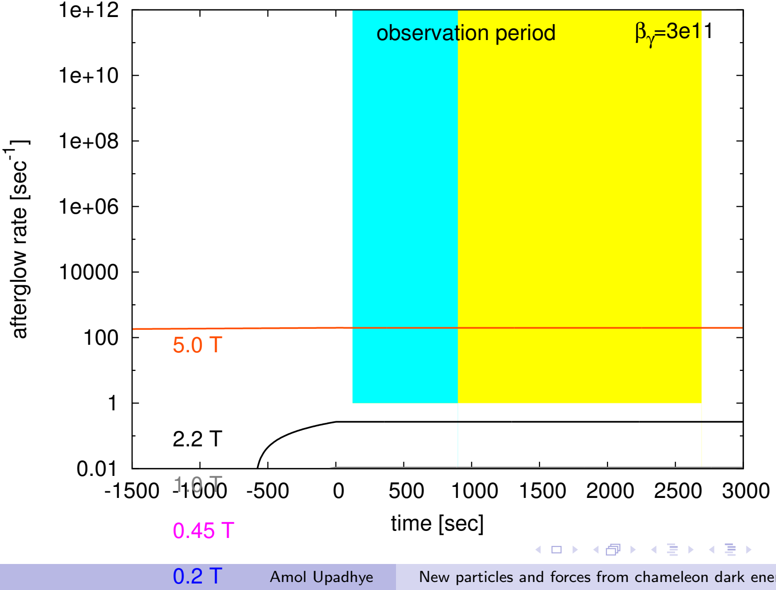


Data analysis

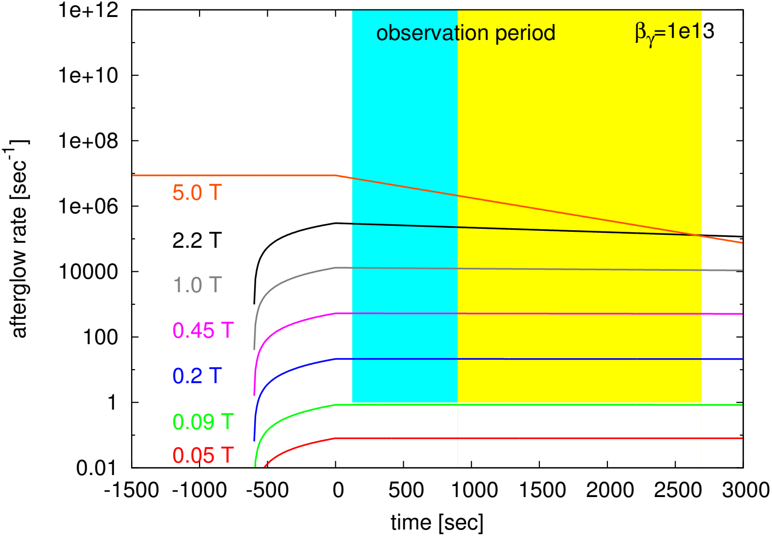


(AU, J. Steffen, A. Chou 2012 [arXiv:1204.5476, PRD accepted])

Expected afterglow signal



Expected afterglow signal



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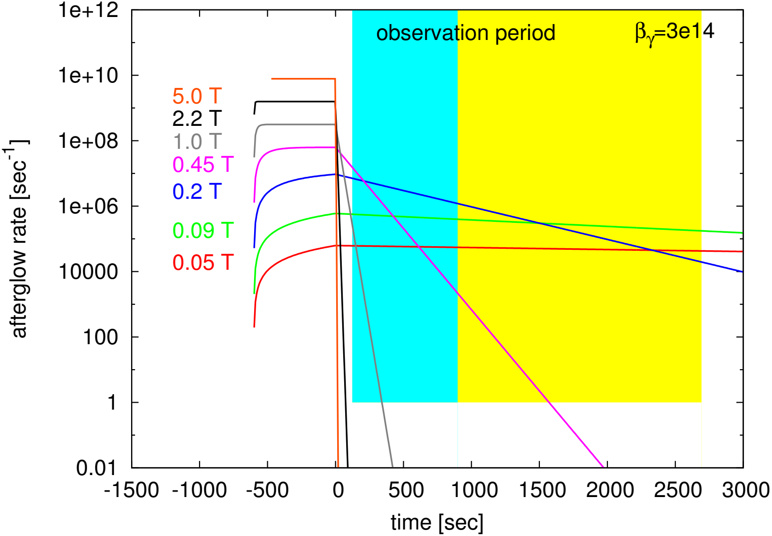

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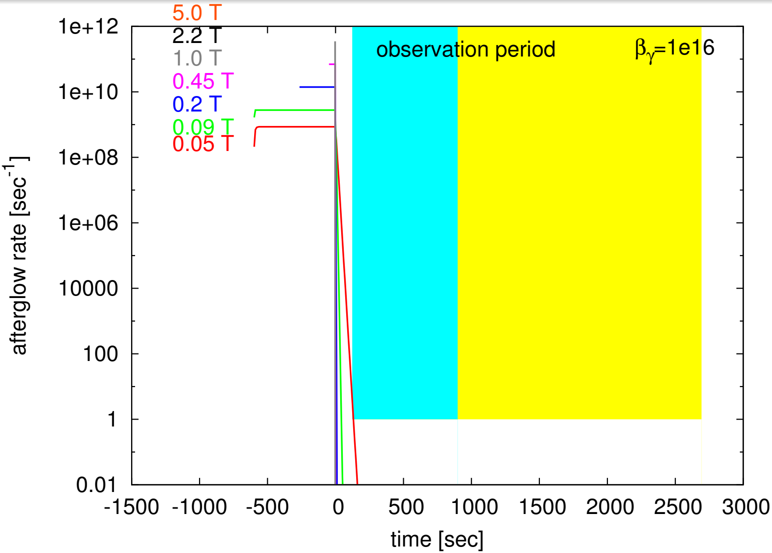
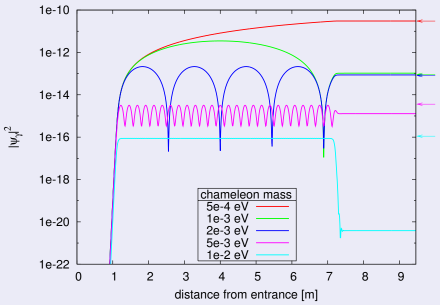


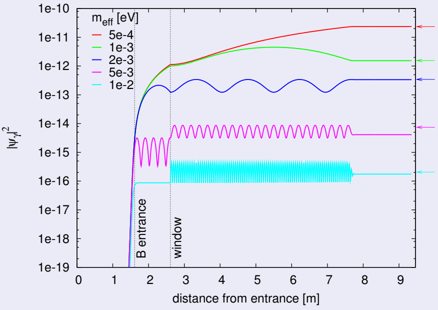
Adiabatic transition suppresses oscillation

- $\vec{B}(z)$ transition distance $\gg$ oscillation length $4\pi E/\Delta m^2$
  $\Rightarrow$ adiabatic transition $\Rightarrow$ no chameleon production
- internal measurement (window) mitigates this effect

No internal measurement

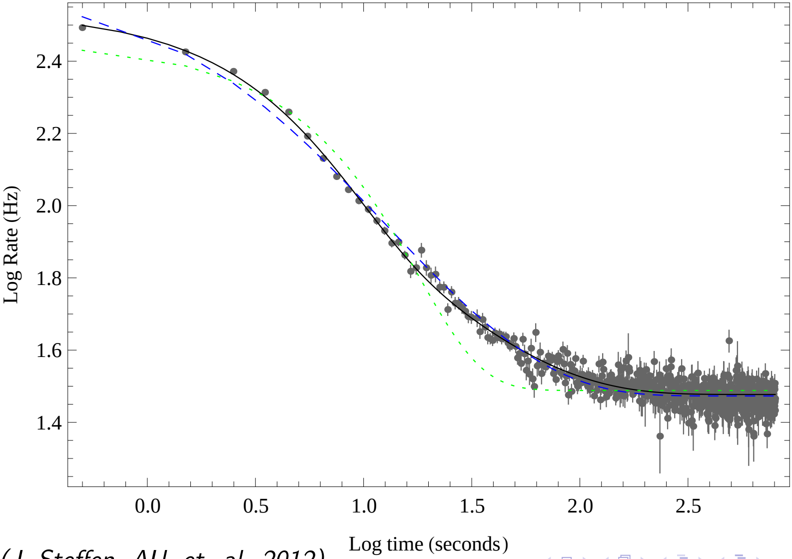


One measurement



(AU, J. Steffen, A. Chou 2012)

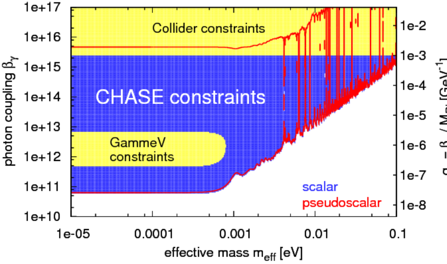
"Orange glow:" a transient systematic photon flux



(J. Steffen, AU, et. al. 2012)

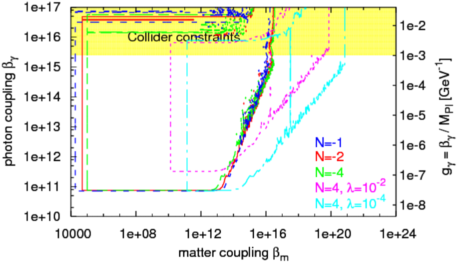
CHASE constraints

Model-independent constraints



Assume $m_{\text{eff}}(\text{wall}) > E$.

Model-dependent constraints



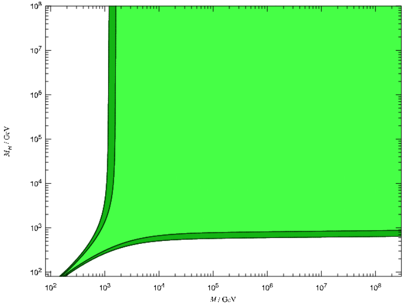
$V(\phi) = M_\Lambda^{4-N}\phi^N + \text{const.}$

- low β_γ: limited by low signal
- low β_m: limited by containment
- high β_m or $m_{\text{eff}}(\text{chamber})$: limited by destructive interference

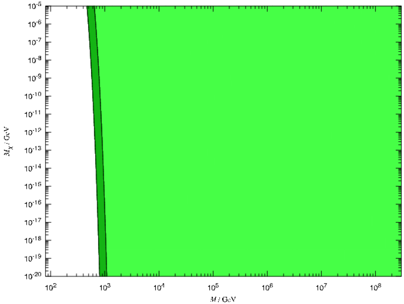
(J. Steffen, AU, et. al. 2010)

Collider constraints

Loop corrections to EW processes require the coupling scale $M_{\rm Pl}/\beta > 1$ TeV. Allowed regions (shown in green):



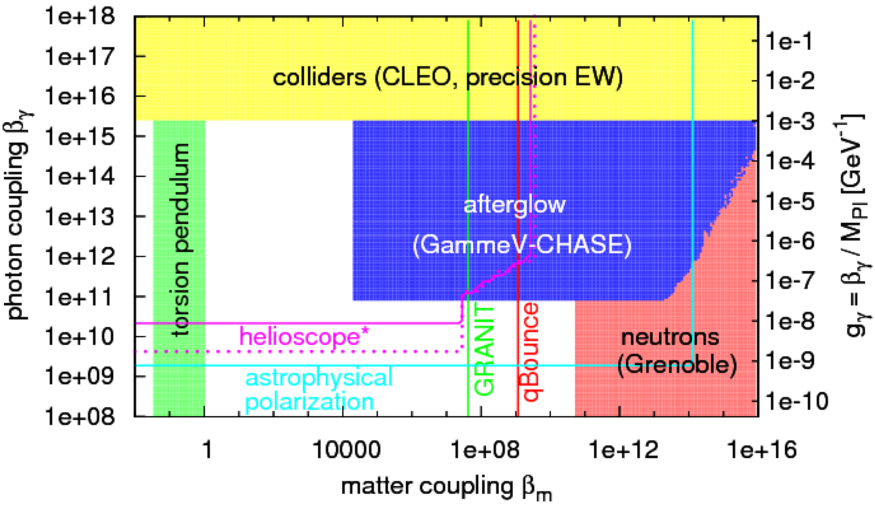
$\beta_{\rm H}^{-1}$ vs. β_γ^{-1}



scalar $m_{\rm eff}$ vs. β_γ^{-1}

(P. Brax, C. Burrage, A.-C. Davis, D. Seery, A. Weltman 2009)

Summary: dark energy with $V(\phi) = M_\Lambda^4 + M_\Lambda^5/\phi$



(AU, J. Steffen, A. Chou 2012) [* see talk by Konstantin Zioutas]

The End.