Tests of Modified Gravity

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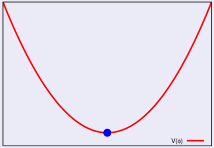
Outline

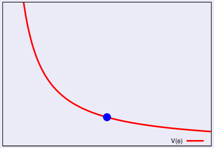
1. Introduction
   - Motivation
   - Observable effects
2. Fifth forces and screening
   - Screening in relativistic stars
   - Torsion pendulum tests
   - Cosmic expansion vs. growth
3. Particles of dark energy
   - Scalar-photon oscillation
   - GammeV-CHASE

What if $w(z) \approx -1$?

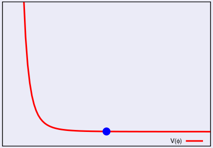
Many models other than Λ give $w \approx -1$



minimum of $V(\phi)$



slow roll



flat potential

- What sorts of models are consistent with observations?
- How can these models be distinguished using the data?
- One class of models: modified gravity and scalar dark energy

Modified gravity and scalar fields

Since our universe looks 4-dimensional (at least since BBN), there must be an effective 4-D description of modified gravity. The simplest models reduce to 4-D matter-coupled scalar field theories.

Modified gravity

- $f(R)$ gravity: action $S = \int \frac{d^4x\sqrt{-g}}{16\pi G_N} f(R)$

Effective scalar

- Conformal transformation $\Rightarrow$ chameleon

New physics

- matter coupling, self-interaction $V(\phi)$

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- matter coupling, non-canonical kinetic term

Modified gravity and scalar fields

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Modified gravity

- $f(R)$ gravity: action $S = \int \frac{d^4x\sqrt{-g}}{16\pi G_N} f(R)$
- DGP, etc.: non-compact extra dimension
- Kaluza-Klein, etc.: compact extra dimension

Effective scalar

- Conformal transformation $\Rightarrow$ chameleon
- Decoupling limit (weak gravity) $\Rightarrow$ Galileon
- Small extra dimension limit $\Rightarrow$ radion

New physics

- matter coupling, self-interaction $V(\phi)$
- matter coupling, non-canonical kinetic term
- matter coupling, photon (gauge field) coupling

Effects of modified gravity

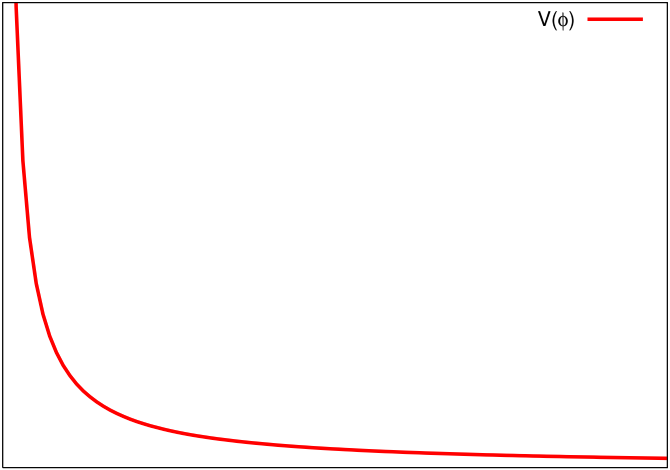
These new scalars can lead to:

- fifth forces between masses;
- equivalence principle violations;
- variations in fundamental constants;
- new particles.

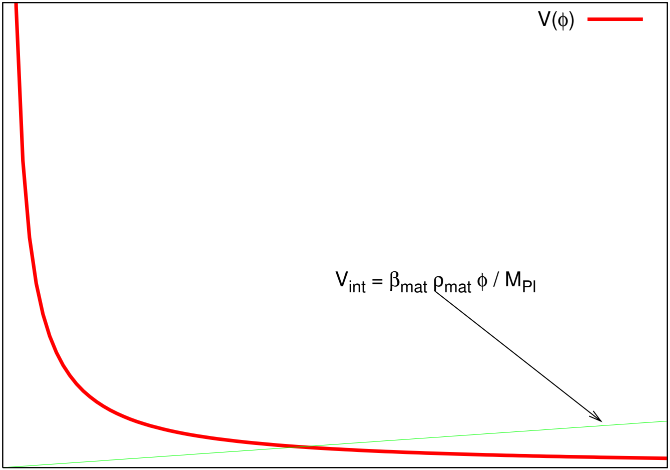
Since gravity looks like General Relativity locally, fifth forces must be screened.

- chameleon screening: large effective mass locally
- Vainshtein screening: effectively weak coupling at high density
- symmetron mechanism: field decouples at high density as symmetry is restored

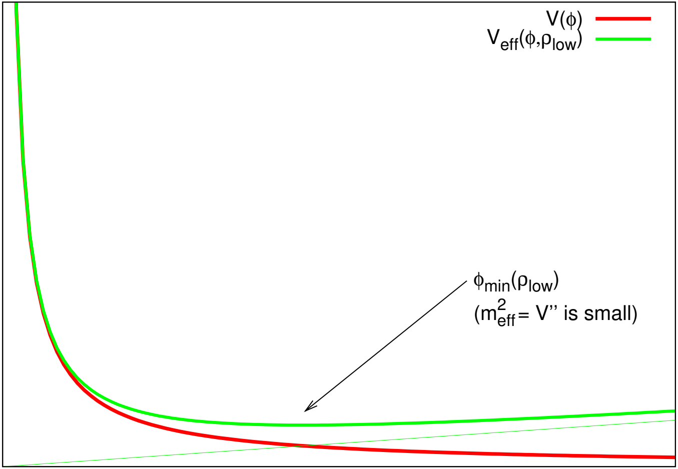
Chameleon mechanism



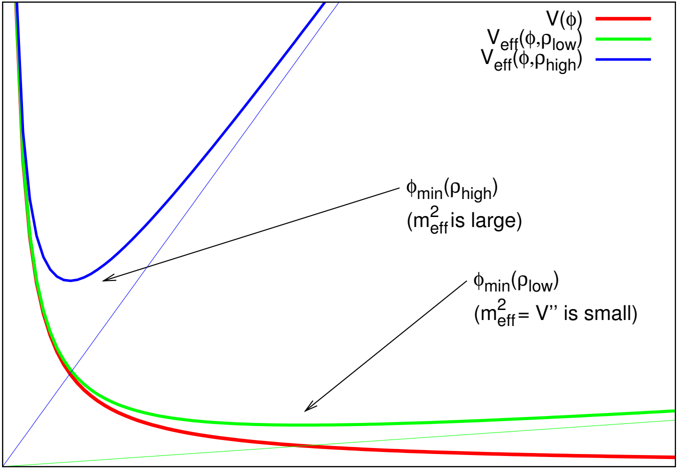
Chameleon mechanism



Chameleon mechanism



Chameleon mechanism



Thin-shell screening

Chameleon field equation of motion: $\Box\phi = V'(\phi) - \frac{\beta_{\rm m}}{M_{\rm Pl}} T^\mu_\mu$

Linear regime: V' negligible

- Static: $\nabla^2\phi = -\frac{\beta_{\rm m}}{M_{\rm Pl}} T^\mu_\mu$
- Nonrelativistic: $T^\mu_\mu \approx -\rho$
- e.o.m. $\approx$ Poisson equation $\nabla^2\Psi = 4\pi G\rho = \frac{1}{2\beta_{\rm m} M_{\rm Pl}} \nabla^2\phi$
- $\phi = 2\beta_{\rm m} M_{\rm Pl}\Psi + \text{constant}$ (scalar follows the gravitational potential)

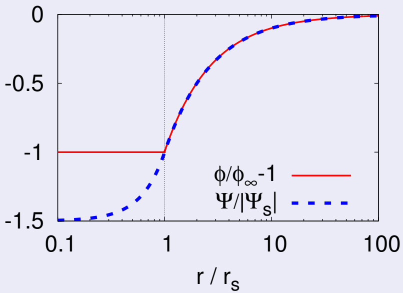
Transition regime: $\Psi \sim \chi_{\rm scr}$

$\chi_{\rm scr} = \frac{1}{2\beta_{\rm m} M_{\rm Pl}} \Delta\phi(\max)$

Nonlinear regime: $\Box\phi$ negligible

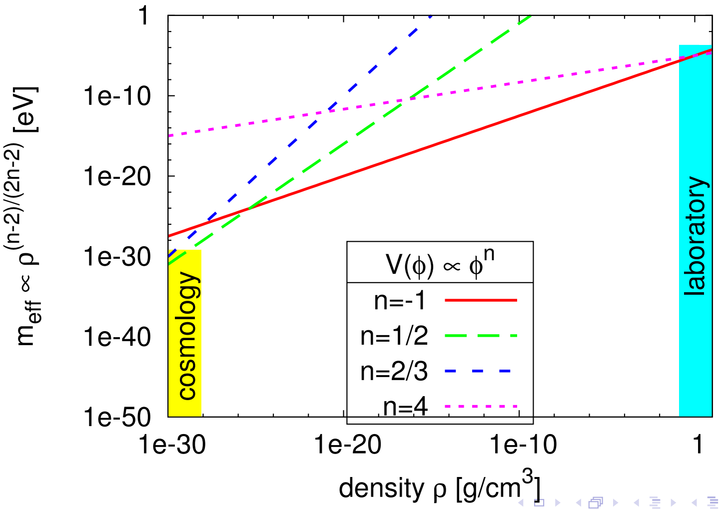
- Nonrelativistic limit: $V'(\phi) = \frac{\beta_{\rm m}}{M_{\rm Pl}}\rho$

$\Rightarrow$ $\phi \to \phi_{\rm bulk}(\rho)$ (constant)

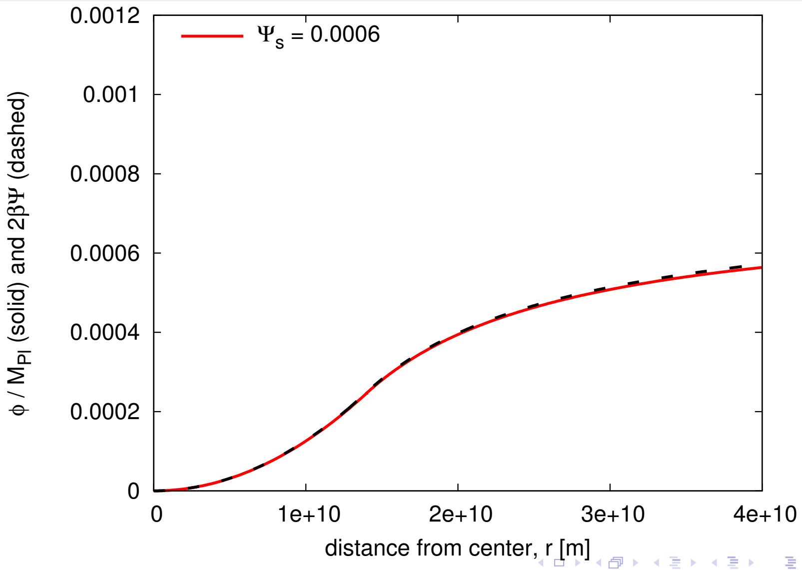


At which scale should we probe each model?

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



Screening in nonrelativistic stars ($\chi_{\rm scr} = 0.0014$)



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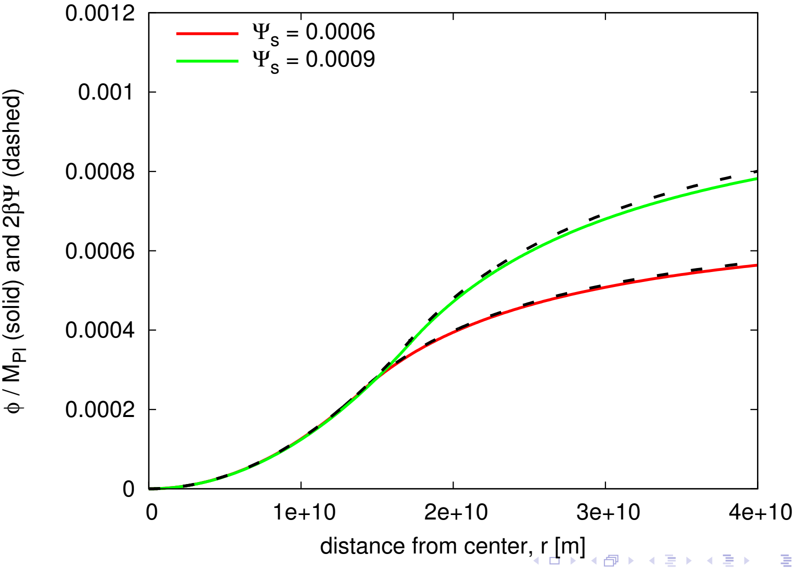

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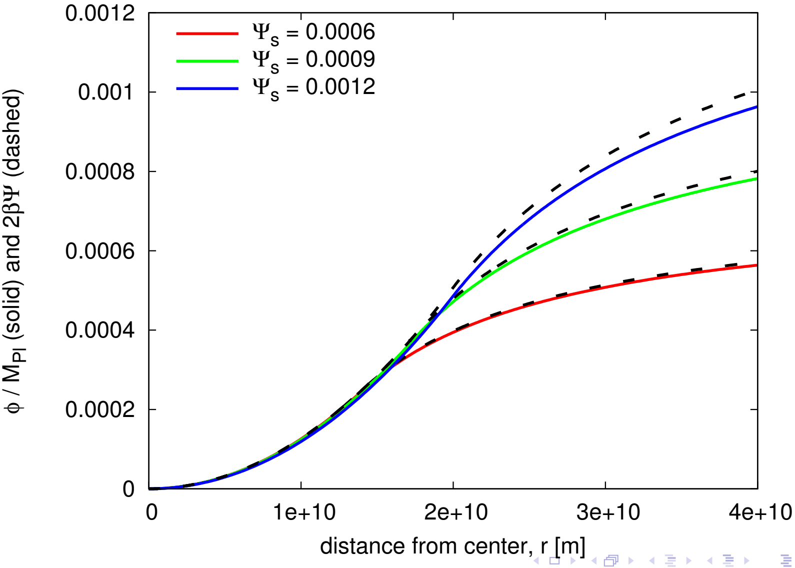

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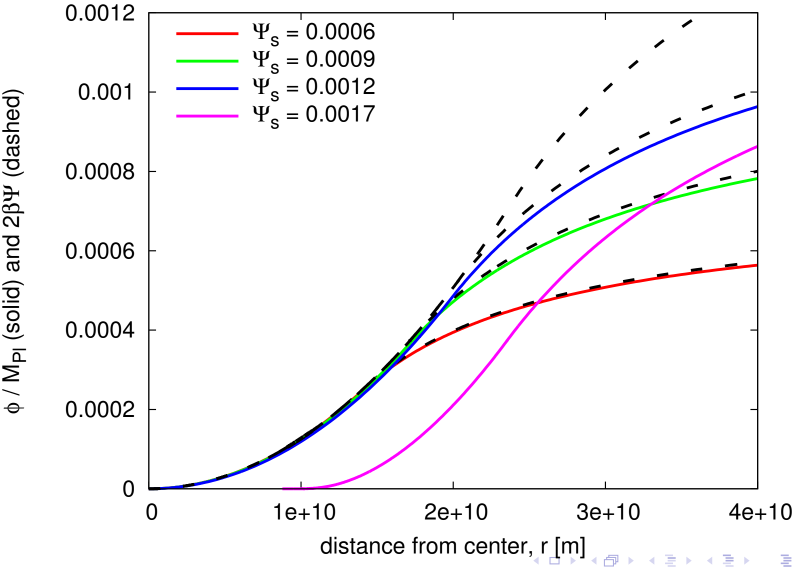

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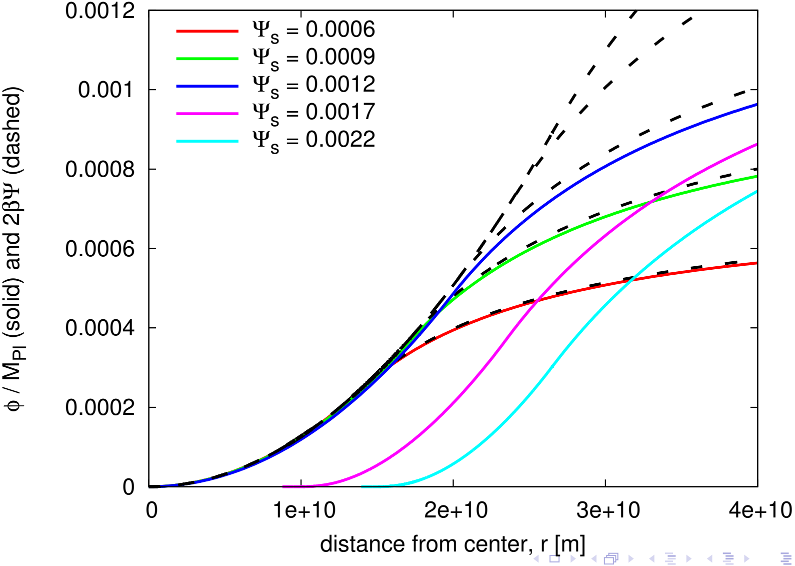


Equations of motion: field and metric

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

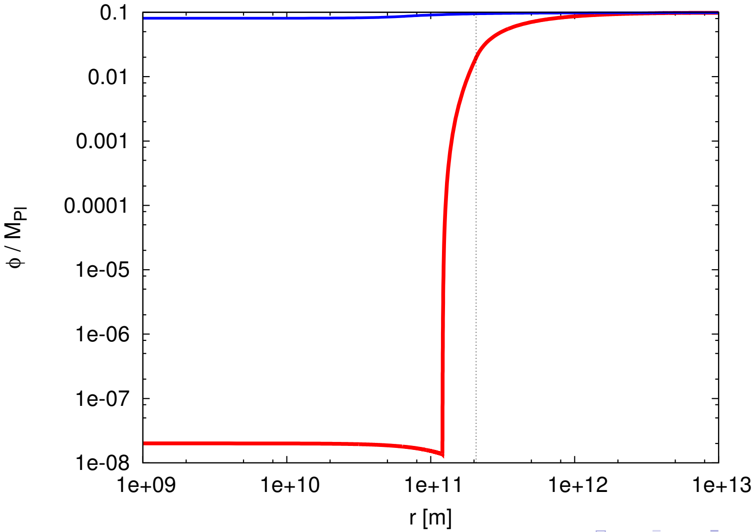
modified Einstein eq. (trace, tt, rr), $f_R = \frac{df}{dR}$, $\phi = -\frac{M_{\mathrm{Pl}}}{2\beta_{\mathrm{m}}} \log f_R$:

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

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

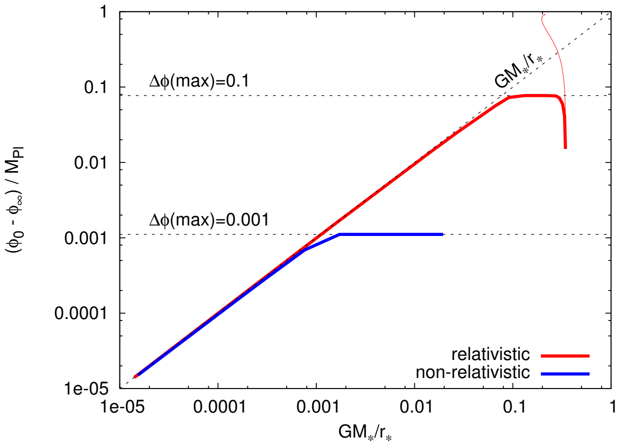
$$\frac{(-1 + B + rBN'/N)f_R}{r^2} + \left(\frac{2}{r} + \frac{N'}{2N}\right) f_R' B = 8\pi GP + \frac{f - Rf_R}{2}$$

$\phi(r)$ in a relativistic star ($\chi_{\rm scr} = 0.1$)



Thin-shell screening in relativistic stars

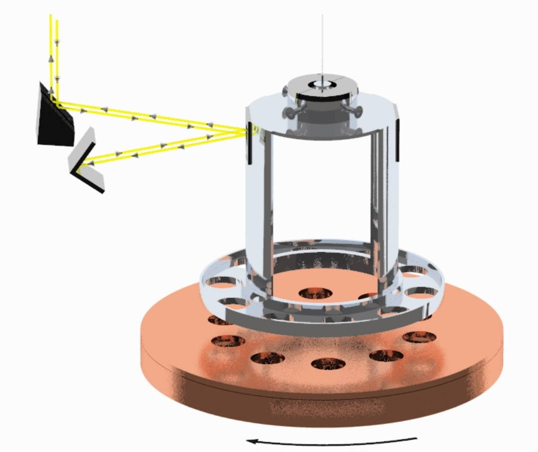
chameleon screening suppresses growth of ϕ:

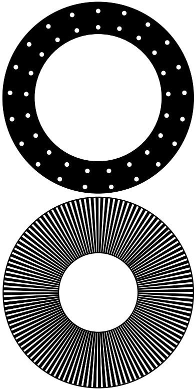


AU and W. Hu (2009)

Fifth-force constraints from a torsion pendulum

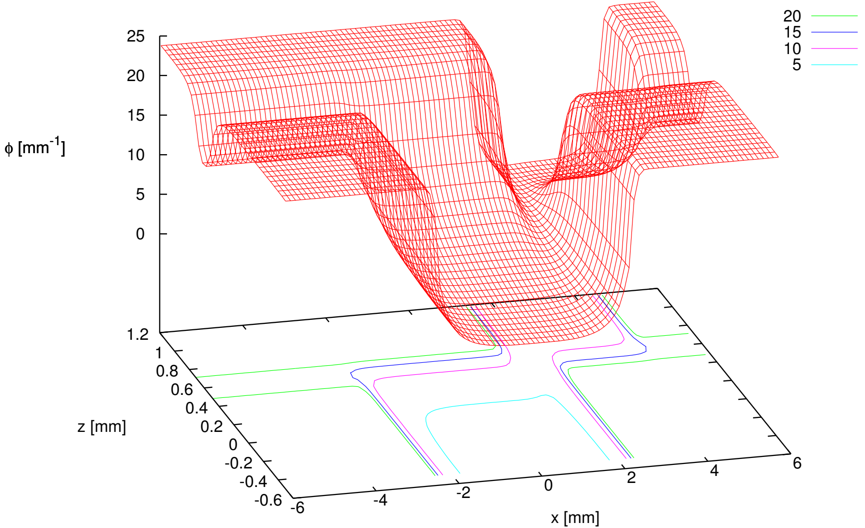
Eöt-Wash Experiment





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

ϕ^4 chameleon field in Eöt-Wash pendulum



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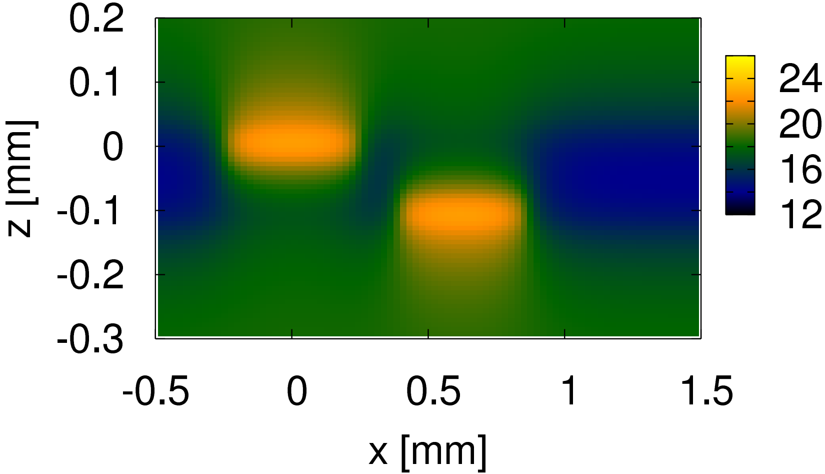
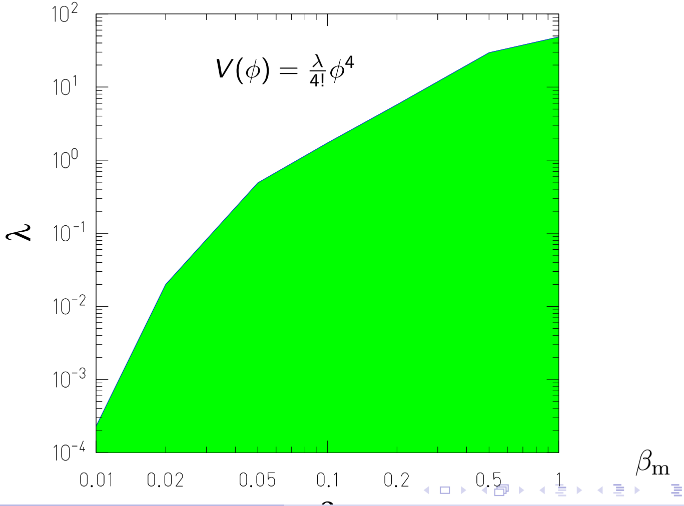


AU, S. Gubser, J. Khoury (2006)

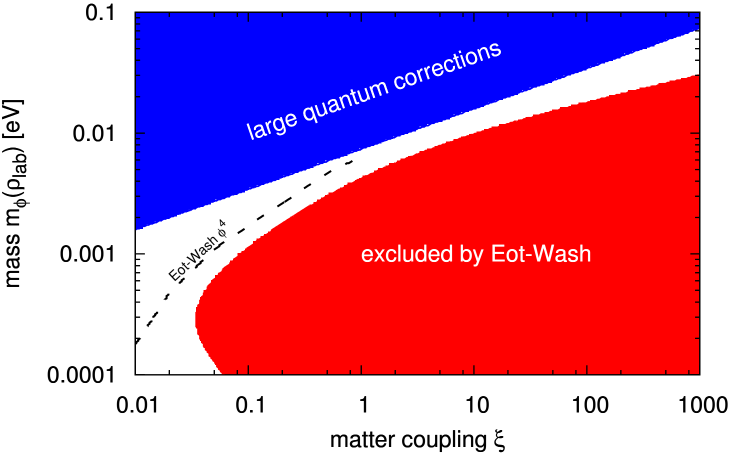
Eöt-Wash constraints

E. Adelberger, et. al. (2007); D. Kapner, et. al. (2007)



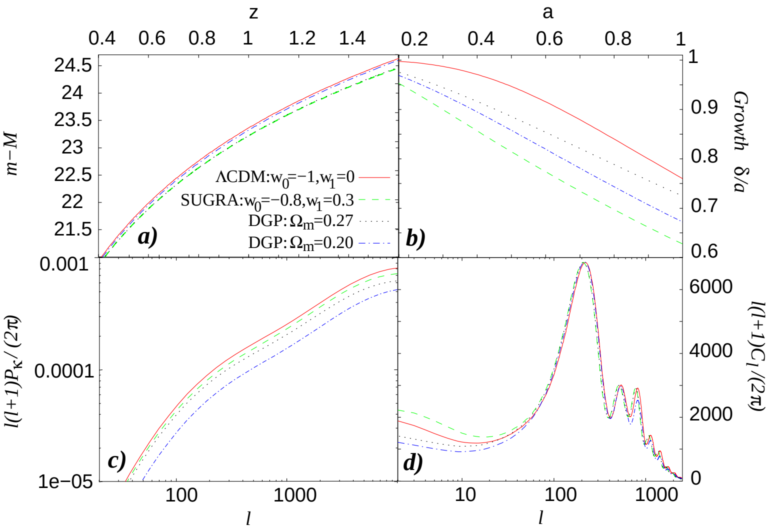
Chameleons with small quantum corrections

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



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

Self-accelerated DGP: Ω_m sets expansion and growth

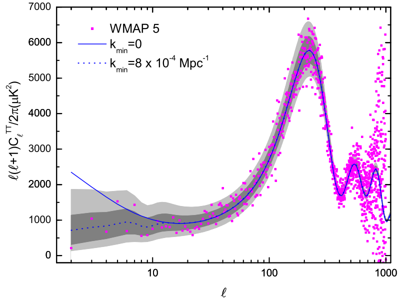


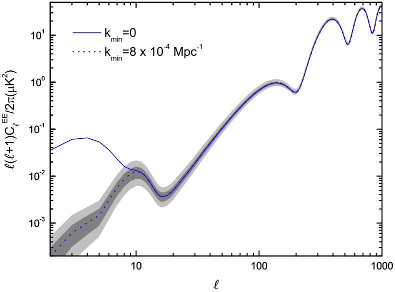
M. Ishak, AU, D. Spergel (2006)

Combined data exclude self-accelerated DGP

- choose Ω_m to fit expansion (SNe) $\Rightarrow$ large C_ℓ^{TT} at low ℓ
- Ω_K helps fit expansion but makes low-ℓ power larger
- suppressing initial large-scale power ruins low-ℓ fit to C_ℓ^{EE}

$\Rightarrow$ self-accelerated DGP ruled out to 4.8σ (w.r.t. ΛCDM)



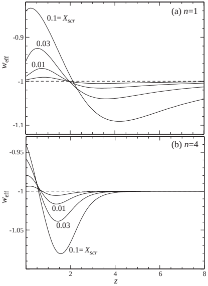


(*W. Fang, et. al, 2008*)

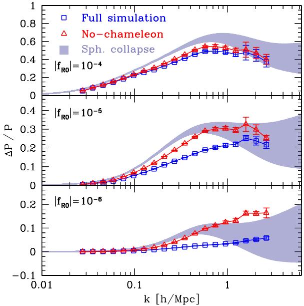
$f(R)$ model with $V(\phi) \propto \phi^{1/2}$

- $f(R)$ gravity "looks like" dark energy with $w \approx -1$
- $f(R) - R \propto 1/R + \text{const.} \Rightarrow V(\phi) \propto \phi^{1/2} + \text{const.}$ with $\chi_{\rm scr} > 10^{-4}$ has unscreened fifth forces, hence an abundance of large clusters which is inconsistent with observations.

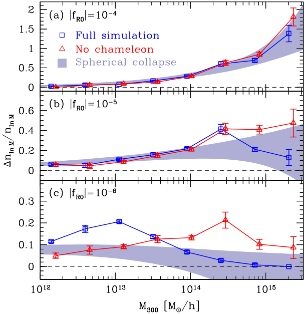
effective $w(z)$



power spectrum



cluster counts



(Hu Sawicki 2007; Schmidt Lima Oyaizu Hu 2009; Schmidt Vikhlinin Hu 2009)

Photons coupled to chameleon dark energy

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

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

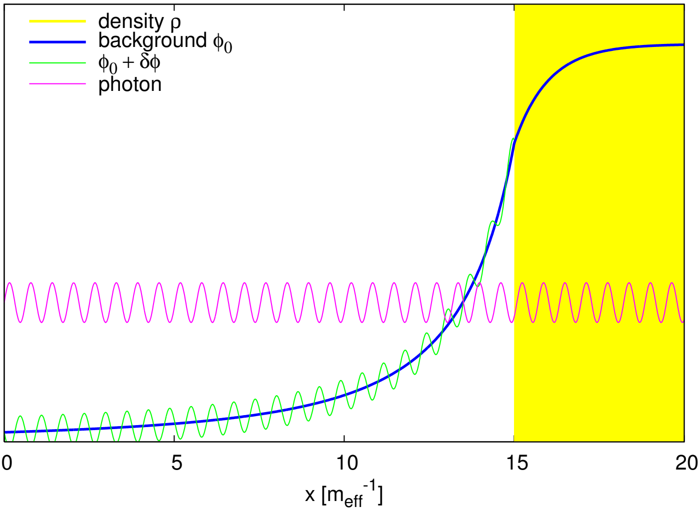
Plane wave perturbations about background ϕ_0 and $\vec{B}_0 = B_0 \hat{x}$ (Raffelt and Stodolsky 1988; AU, Steffen, and Weltman 2010):

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

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

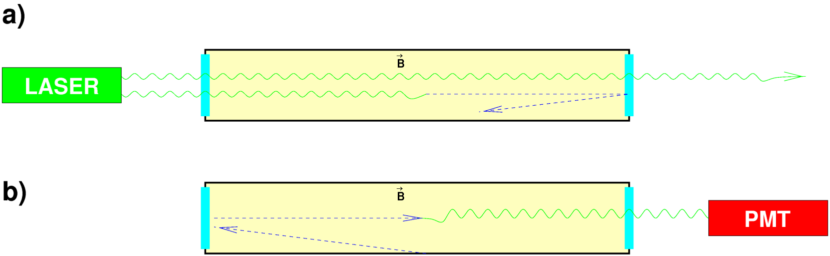
- $\mathcal{P}_{\gamma\leftrightarrow\phi} = \vec{\psi}_\gamma^* \cdot \vec{\psi}_\gamma = \frac{4 k^2 \beta_\gamma^2 B_0^2}{(\Delta m^2)^2 M_{\rm Pl}^2} \sin^2 \left(\frac{\Delta m^2 L}{4k} \right) \left| \hat{k} \times (\hat{x} \times \hat{k}) \right|^2$
- low-mass, $\vec{k} \perp \vec{B}_0$: $\mathcal{P}_{\gamma\leftrightarrow\phi}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

Window as a quantum measurement device



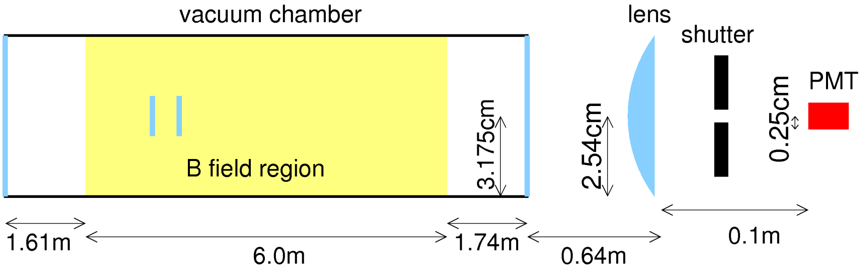
A simple afterglow experiment

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



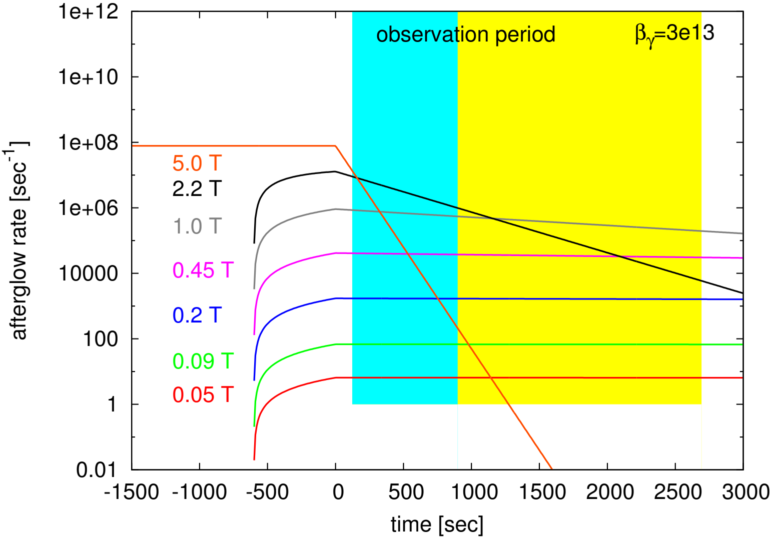
(b) Afterglow phase: chameleons slowly oscillate back into photons, escaping chamber

GammeV-CHASE apparatus



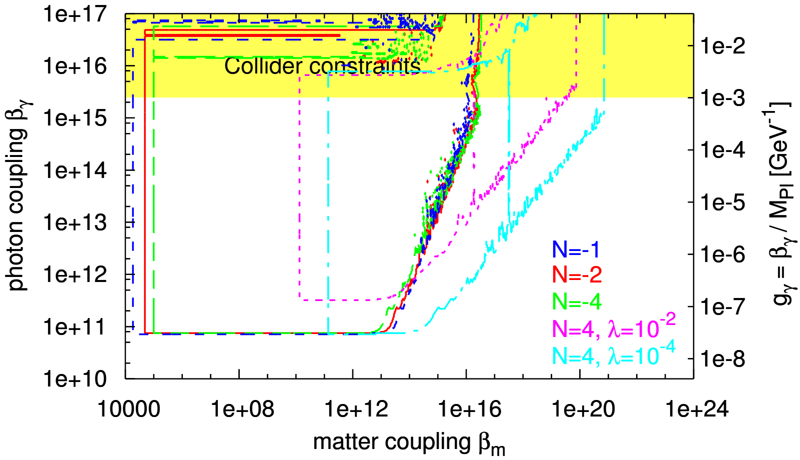
1. Multiple magnetic field runs
2. Partitioning of magnetic field region
3. Modulation of detector
4. Vacuum maintained by ion pump

Expected afterglow signal



Constraints on dark energy

$$V(\phi) = M_\Lambda^4 \exp(\phi^N / M_\Lambda^N) \approx M_\Lambda^4 + M_\Lambda^{4-N} \phi^N$$



(J. Steffen, AU, et. al, 2010; AU, J. Steffen, A. Chou 2012)

Conclusions

Many models "look like" Λ in that $w(z) \approx -1$;

- $f(R)$ modified gravity (chameleon);
- DGP/cascading brane world models (Galileon);
- compact extra dimensions (radion).

Modifications to gravity lead to 5th forces testable at many scales:

- laboratory: torsion pendulum experiments (Eöt-Wash);
- stellar systems: Kepler's law, relativistic stars;
- cosmology: expansion $H(z)$ vs. growth $G(z)$.

Modified gravity models reduce to 4-D scalar theories coupled to matter, and, possibly, to gauge fields.

- production and detection through scalar-photon oscillation

The End.