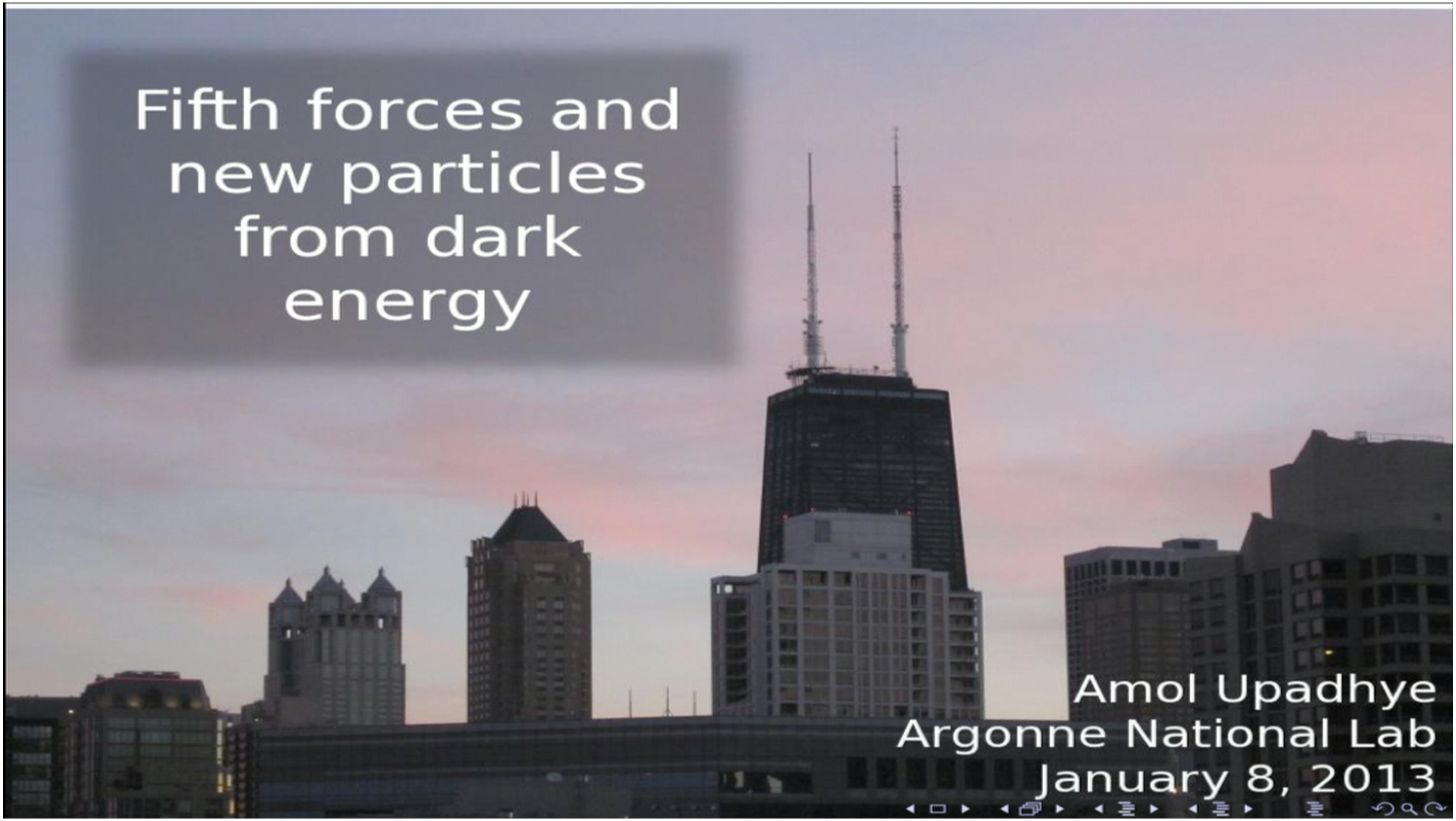
Title: Fifth forces and new particles from dark energy

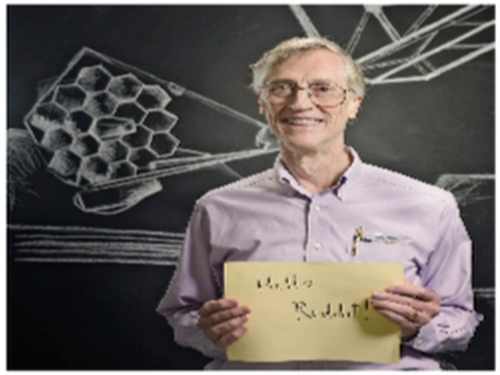
Date: Jan 08, 2013 11:00 AM

URL: http://www.pirsa.org/13010023

Abstract: Dark energy coupled to Standard Model fermions and gauge bosons gives rise to fifth forces and new particles, which are readily accessible to experiments from laboratory to cosmological scales. I will discuss chameleon and symmetron models, whose fifth forces are screened locally through large effective masses and symmetry-restoring phase transitions, respectively. Fifth force experiments such as the Eot-Wash torsion balance will test chameleons with small quantum corrections and gravitation-strength fifth forces, as well as symmetrons with coupling energies just beyond the Standard Model scale. A dark energy coupling to electromagnetism would imply that photons passing through a magnetic field will oscillate into particles of dark energy, a phenomenon studied by afterglow experiments such as CHASE. After constraining dark energy using laboratory experiments, I proceed to astrophysical probes. Particles of a photon-coupled dark energy could be produced in the Sun and detected in magnetic helioscopes such as CAST, while fifth forces may alter the dynamics of variable stars and the growth of large-scale structure.


Fifth forces and new particles from dark energy
Amol Upadhye
Argonne National Lab
January 8, 2013

Motivation: John Mather on Reddit



[–] VelvetEuler 21 points 7 hours ago

Are you optimistic that the James Webb Space Telescope will help uncover the nature of Dark Matter/Dark Energy that permeates the Universe?

permalink

[–] johnmather [S] 43 points 6 hours ago

Actually, JWST can only observe the effects of dark matter and dark energy. But to uncover their nature, we need lab experiments, or maybe a comprehensive theory of everything. Both are hard, but worth the effort.

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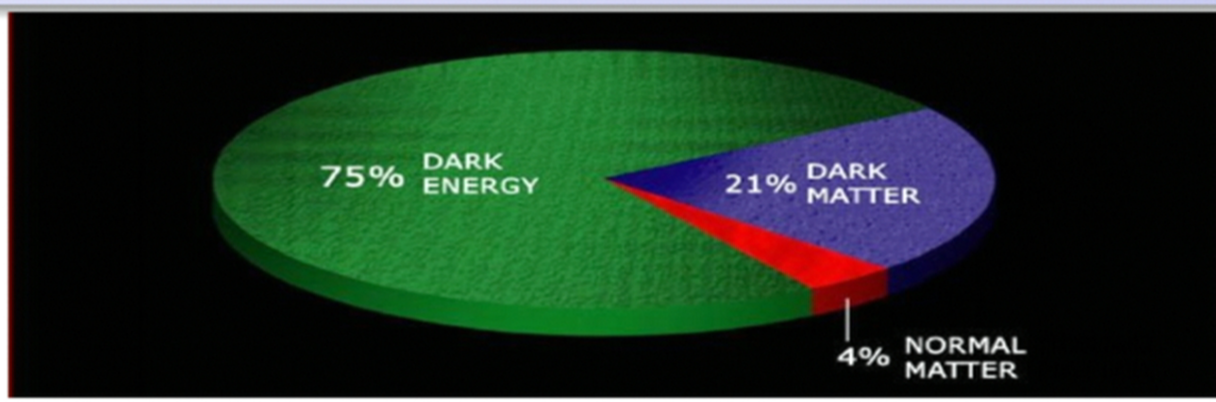
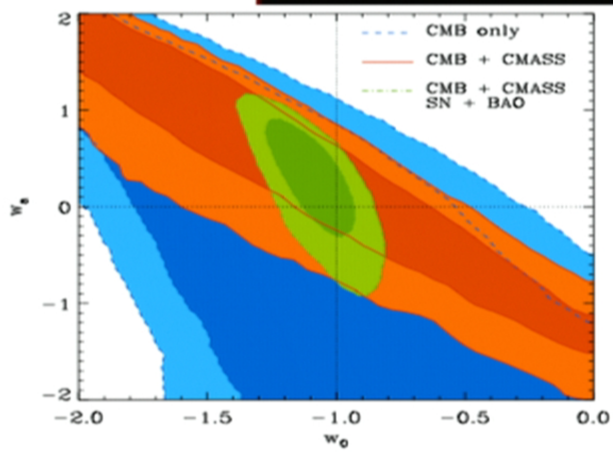
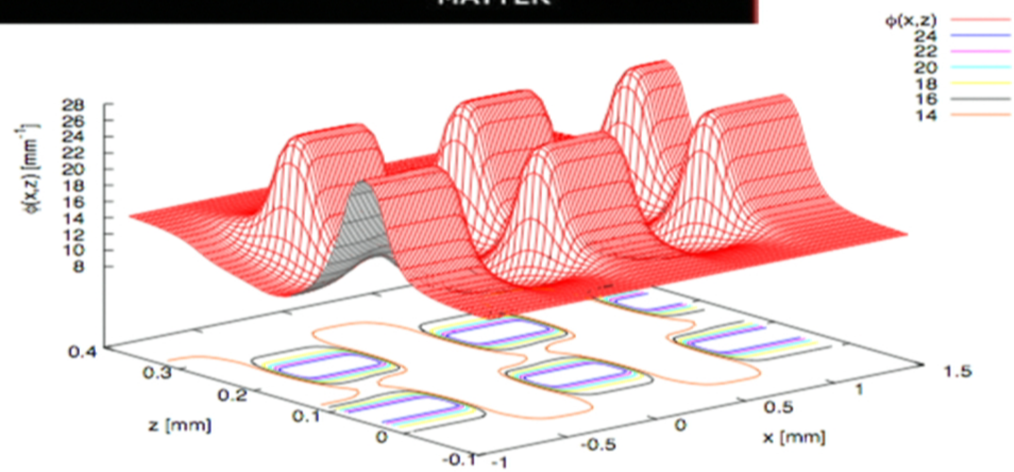
Motivation: What if the dark energy density is constant?





Time-variation



Couplings to known particles

Motivation: Effective dark energy from modified gravity

Modified gravity	**Effective scalar**	**New physics**
Modified action: $f(R)$, symmetric curvature coupling	Conformal trans.: $\Rightarrow$ chameleon, symmetron	matter coupling, effective mass $m_{\text{eff}}(\rho)$

Motivation: Effective dark energy from modified gravity

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Kaluza-Klein, etc.: compact extra dimension	Small extra dimension limit $\Rightarrow$ radion	matter coupling, photon coupling (gauge field)
DGP, etc.: non-compact extra dimension	Decoupling limit (weak gravity) $\Rightarrow$ Galileon	matter coupling, non-canonical kinetic term

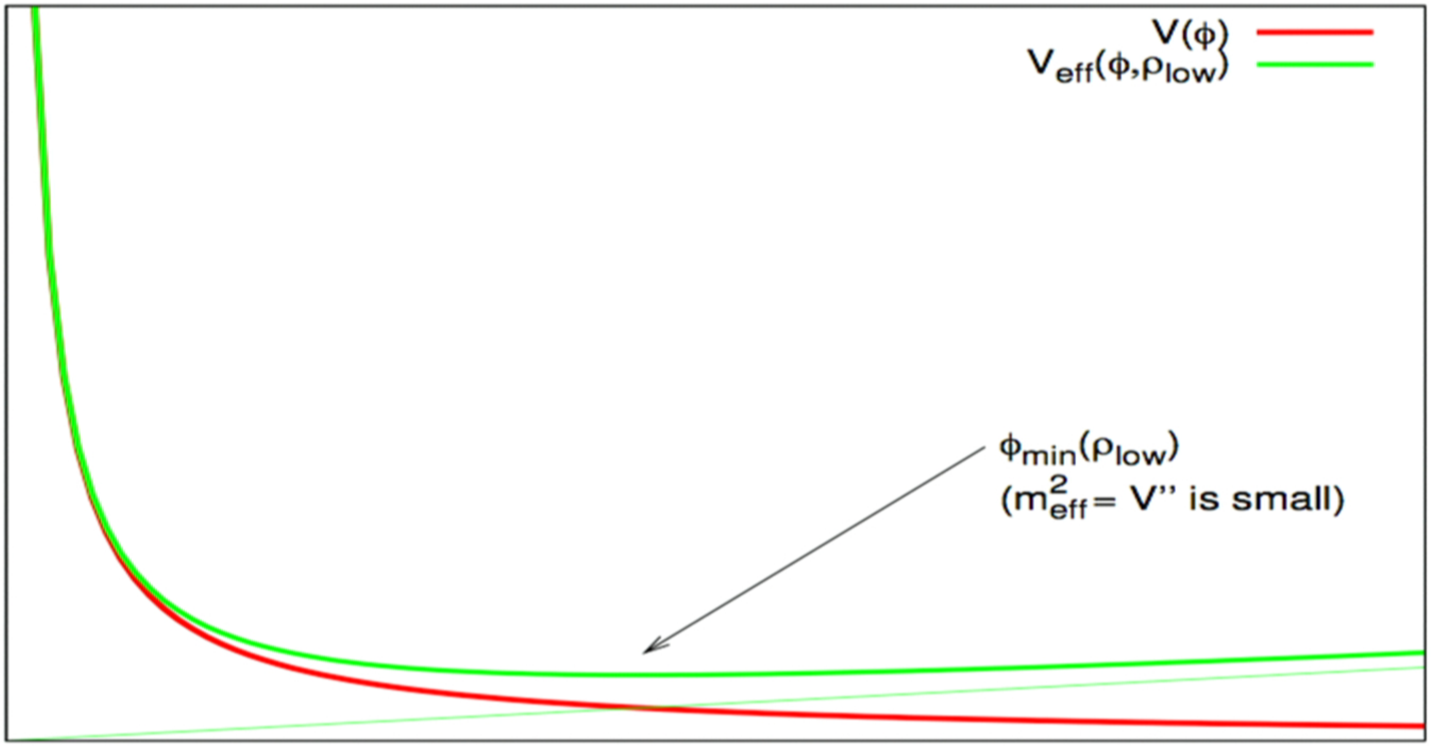
At low energies, dark energy can have a matter coupling, whose fifth force must be screened locally. Dark energy may have a photon coupling allowing the production of dark energy particles.

Outline

1. Screened fifth forces and laboratory experiments
   - Chameleon dark energy: Fifth forces and quantum stability
   - Experimental constraints on chameleon dark energy
   - Symmetron dark energy: Fifth forces and constraints
2. How dark is dark energy? Photon-dark energy oscillation
   - Chameleon particles and oscillation
   - CHASE chameleon afterglow experiment
   - ADMX search for chameleon dark energy
3. Fifth forces and new particles in astrophysical systems
   - Dark energy particles from the Sun
   - Screened fifth forces in stars
   - Fifth forces and the growth of large-scale cosmic structure

Chameleon mechanism

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



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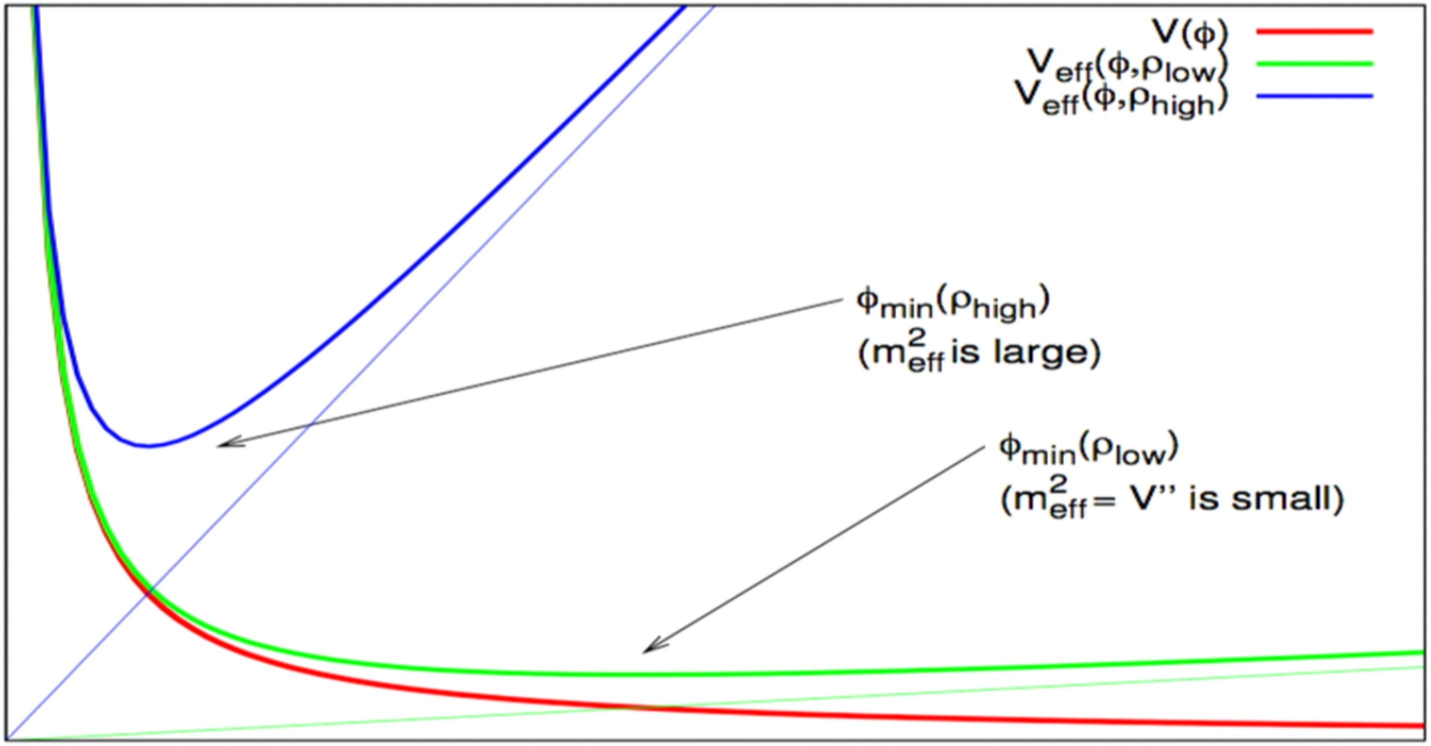


Chameleon thin-shell screening

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

Linear regime: V' negligible

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

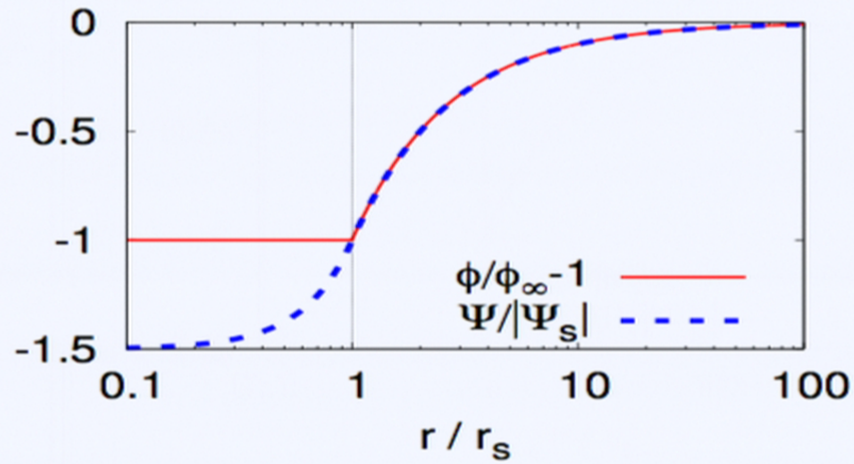
Transition regime: $\Psi \sim \chi_{scr}$

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

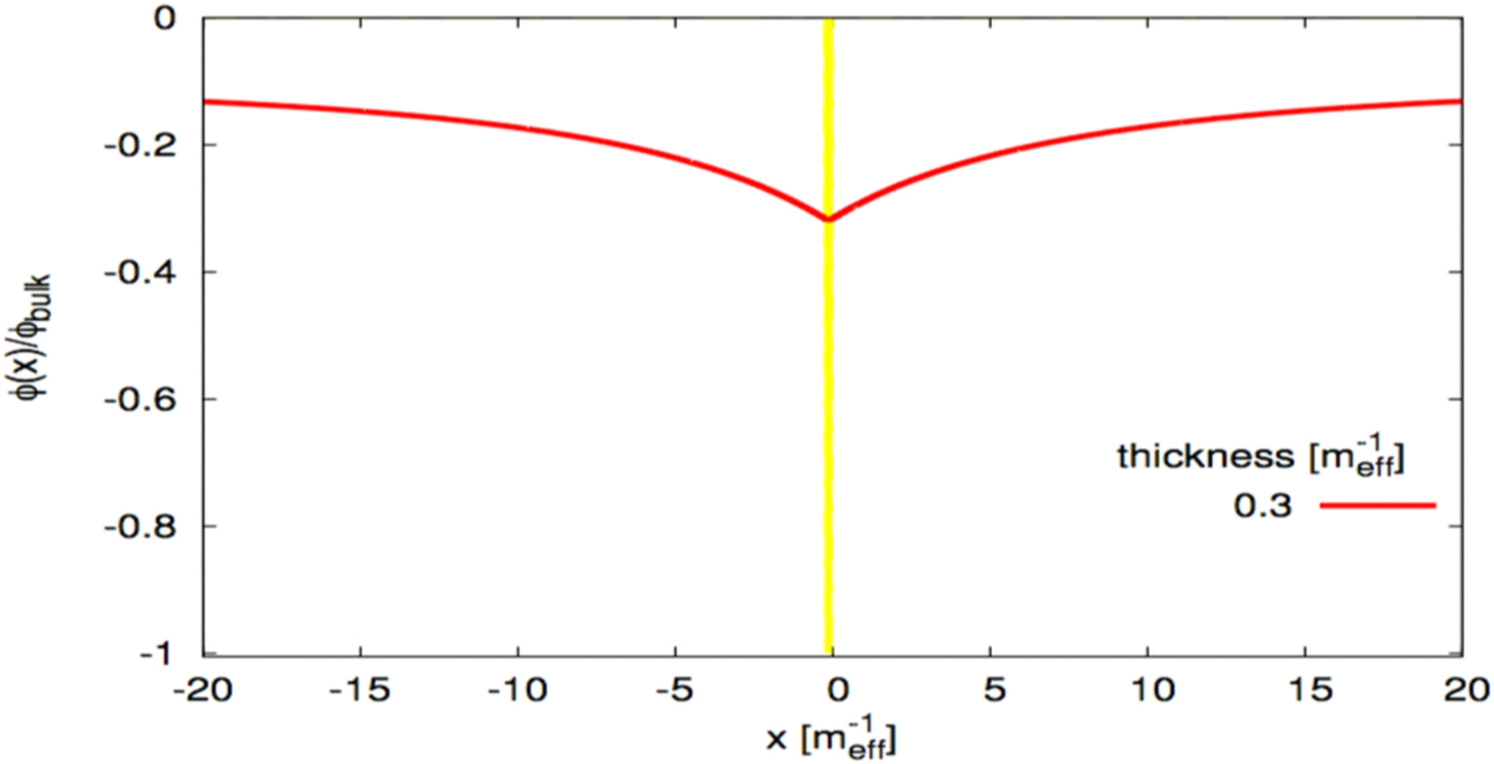
Nonlinear regime: $\Box\phi$ negligible

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

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

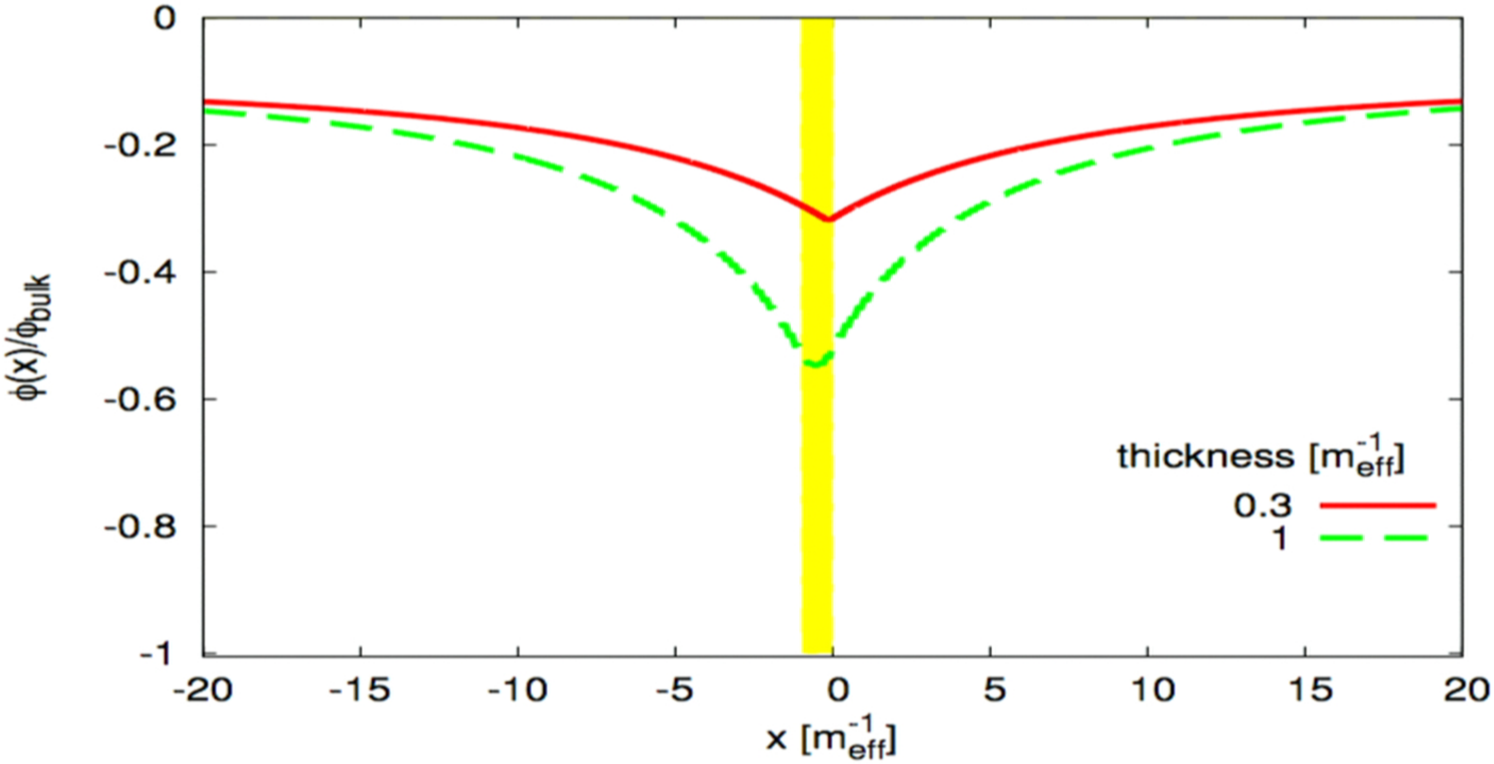


Thin-shell effect



AU, S. Gubser, J. Khoury, PRD **74** *104204 (2006)*

Thin-shell effect



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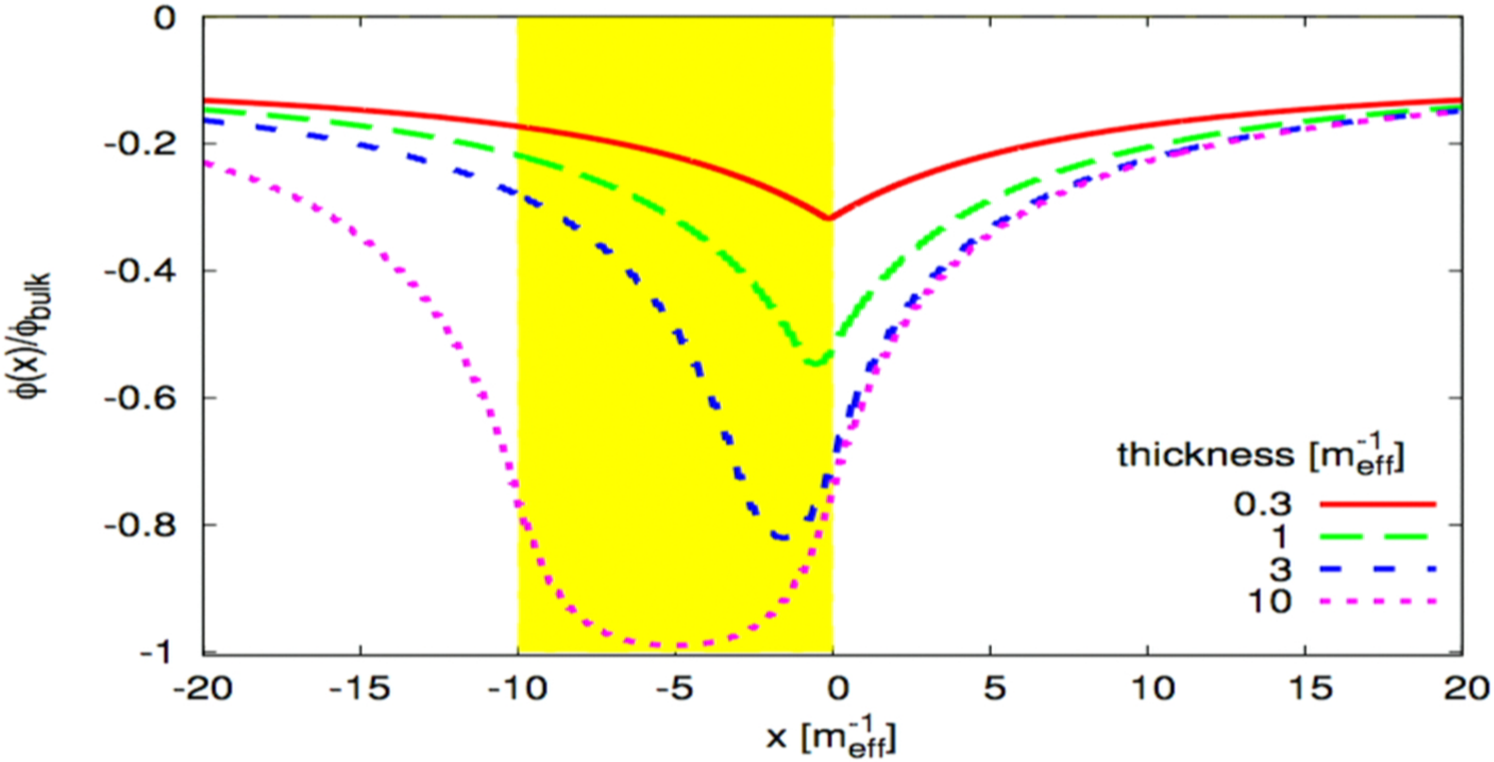

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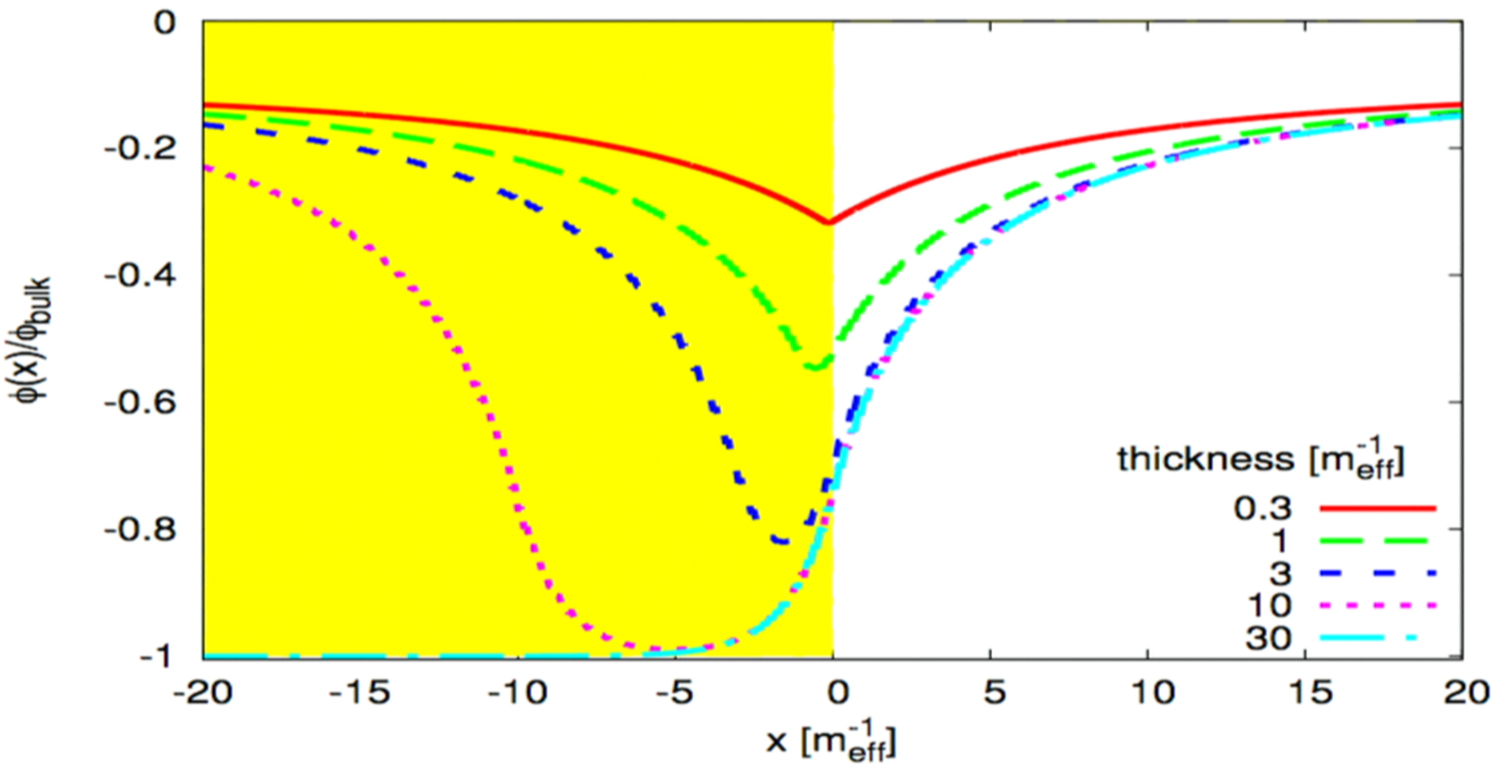
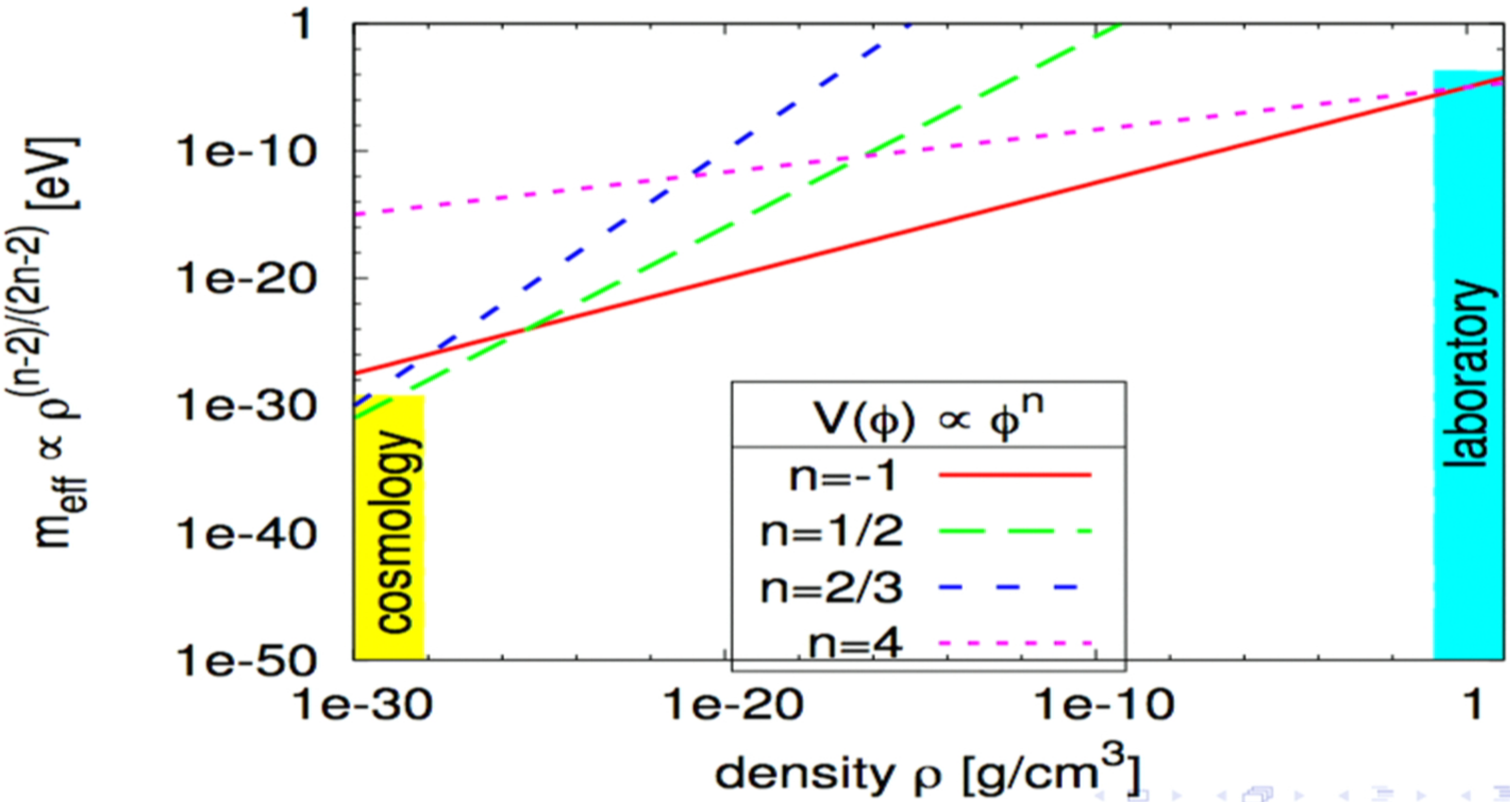


AU, S. Gubser, J. Khoury, PRD **74** *104204 (2006)*

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 $n \lesssim -\frac{1}{2}$, $n > 2$)



Chameleons with small quantum corrections

One-loop Coleman-Weinberg correction to the potential:

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

Neglect the log term, and require that the corrections to V' and V'' (that is, to ϕ_{bulk} and m_{eff}) be less than the tree level values:

$$\frac{1}{\rho}\frac{d^2 m_{\mathrm{eff}}^6}{d\rho},\ \left|\frac{d^2 m_{\mathrm{eff}}^6}{d\rho^2}\right| \leq \frac{96\pi^2\beta^2}{M_{\mathrm{Pl}}^2} \Rightarrow m_{\mathrm{eff}} \leq \left(\frac{48\pi^2\beta^2\rho^2}{M_{\mathrm{Pl}}^2}\right)^{1/6}$$

Possible objections:

1. Failure of naturalness or perturbation theory?
2. Aren't chameleons already tuned? (mass, matter coupling)
3. There is no reason for nature to be nice to us!

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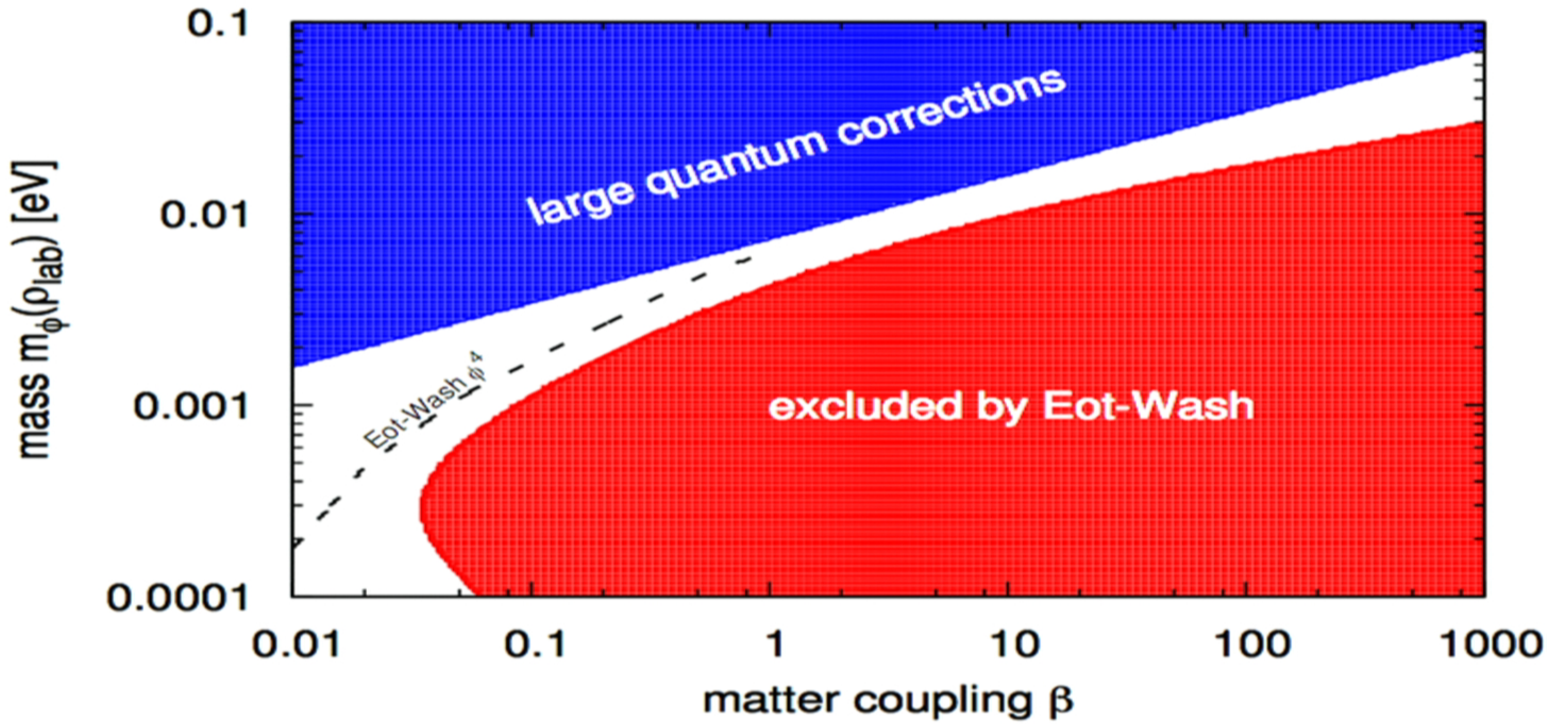
Bounds on "quantum-stable" chameleons

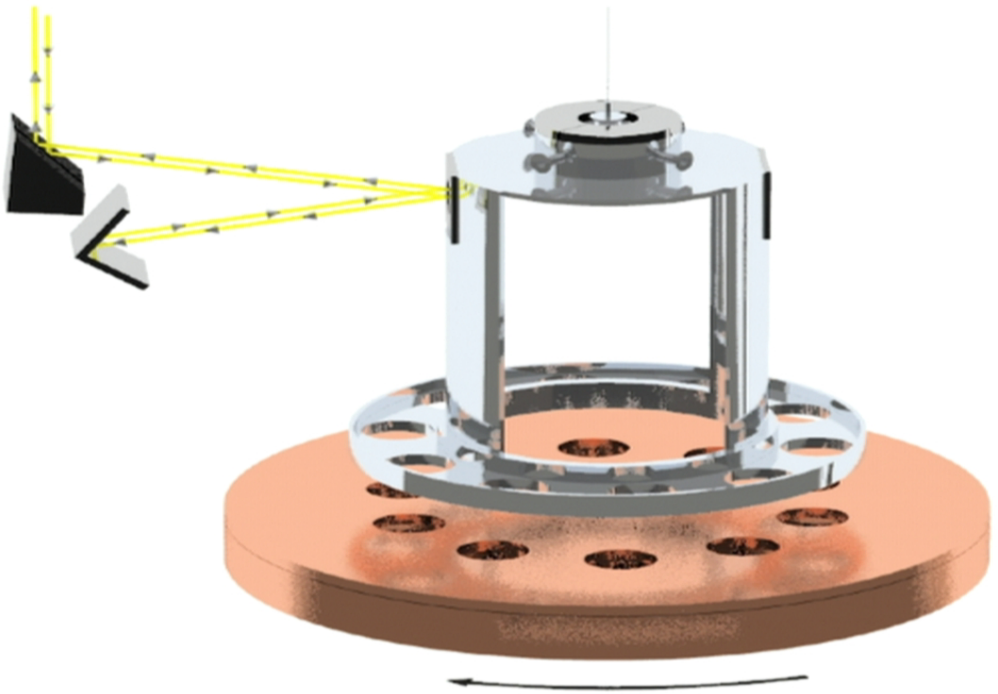
$$m_{\rm eff} \leq \left(\frac{48\pi^2\beta^2\rho^2}{M_{\rm Pl}^2}\right)^{1/6} = 0.0073\left(\frac{\beta\rho}{10{\rm g/cm^3}}\right)^{1/6}{\rm eV}$$

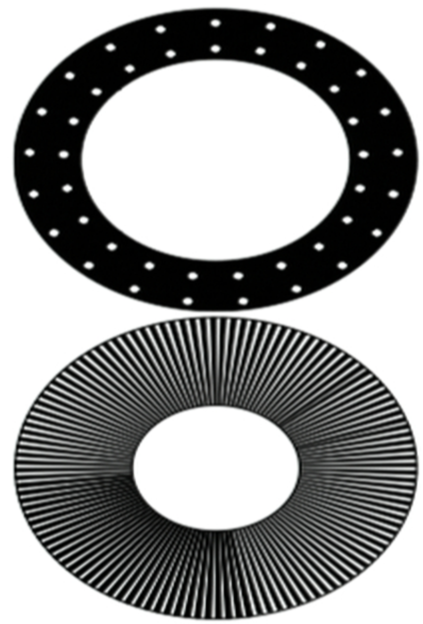


AU, W. Hu, J. Khoury. PRL **109** *041301 (2012)*

Fifth-force constraints from a torsion pendulum

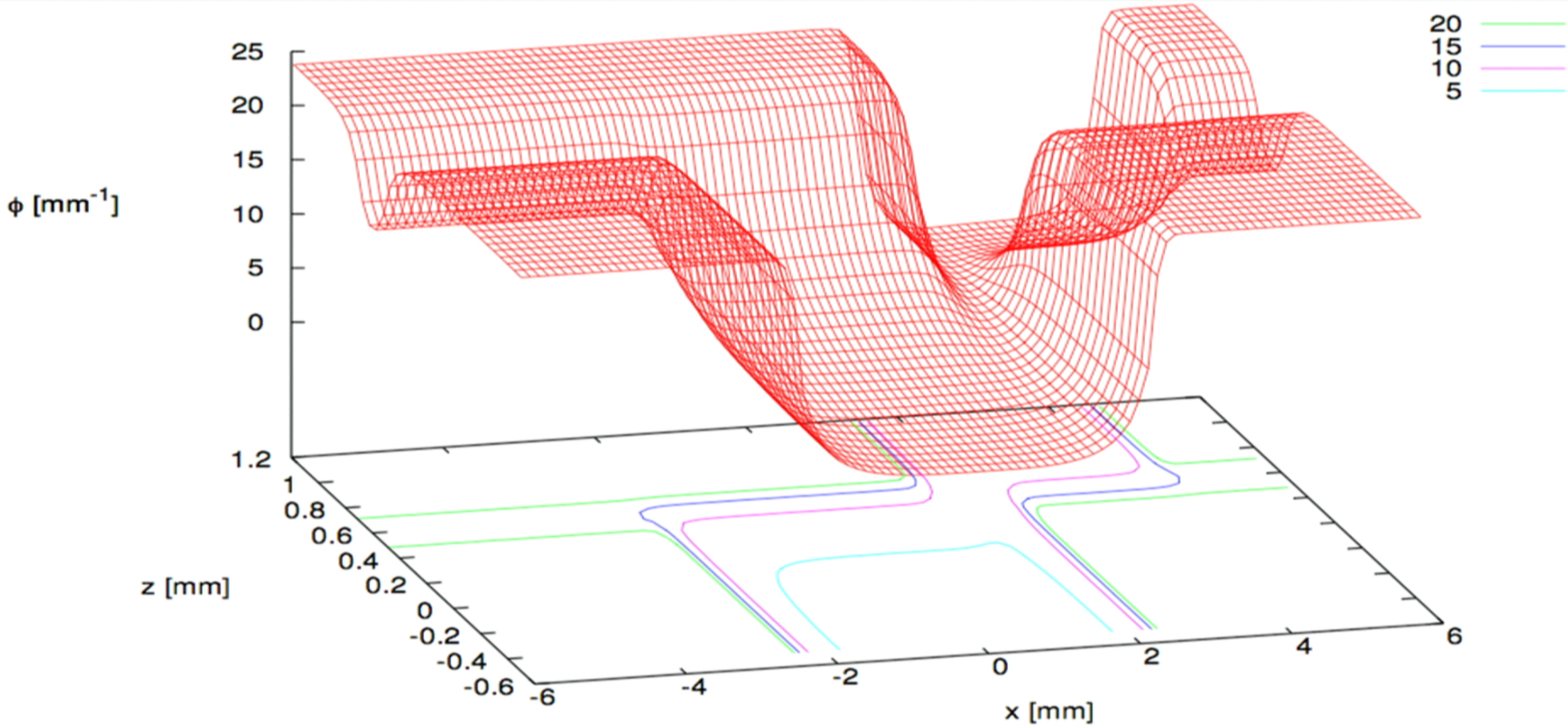
Eöt-Wash Experiment





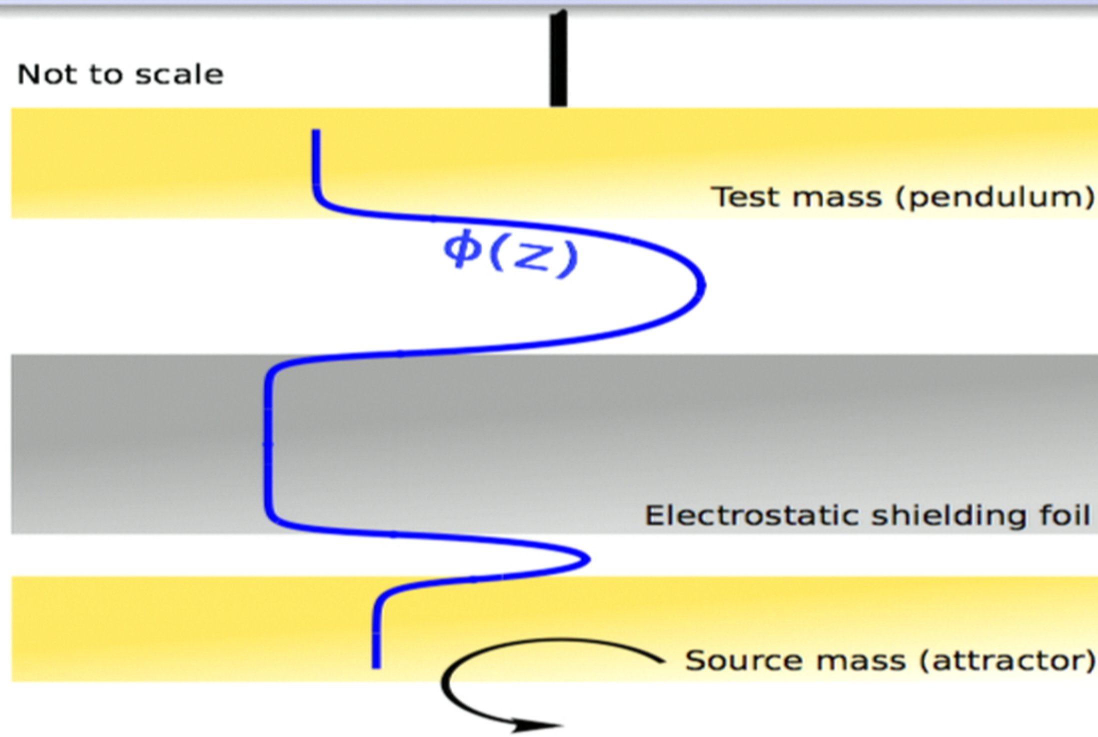
http://www.npl.washington.edu/eotwash

ϕ^4 chameleon field in Eöt-Wash pendulum



AU, S. Gubser, J. Khoury, PRD **74** *104204 (2006)*

1-D plane-parallel approximation to Eöt-Wash constraints



1Dpp Approximation: Approximate the surface field in a torsion pendulum using the exact one-dimensional planar solution.
AU, PRD **86** *102003 (2012)*

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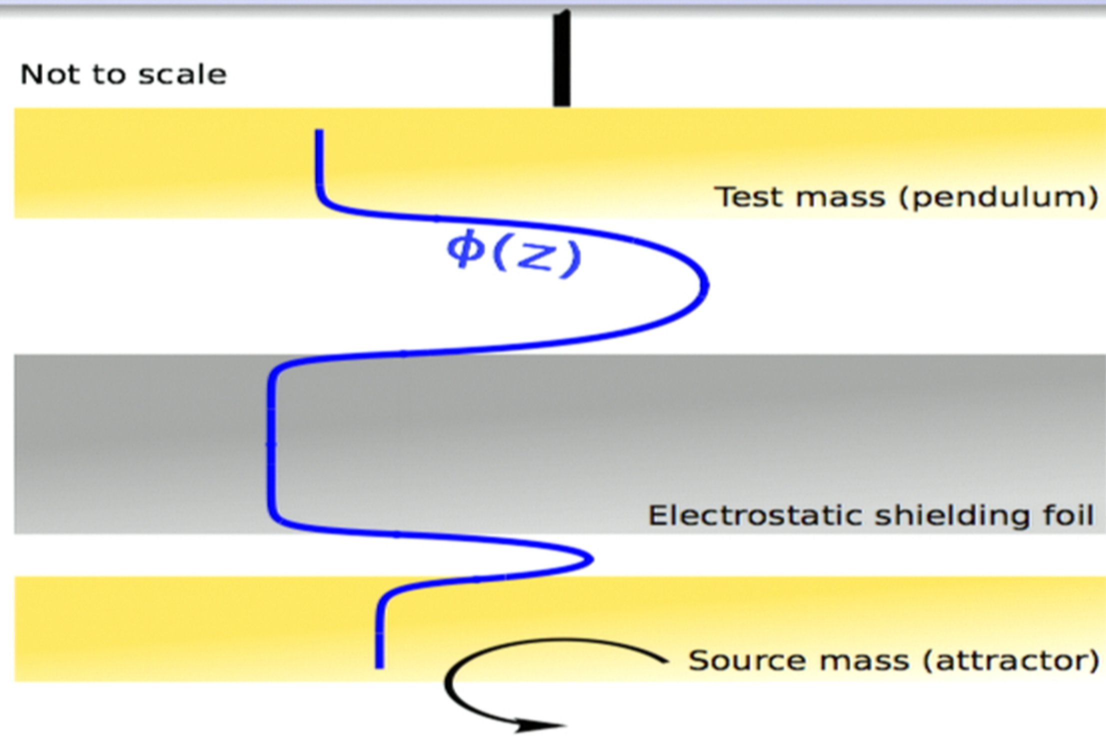

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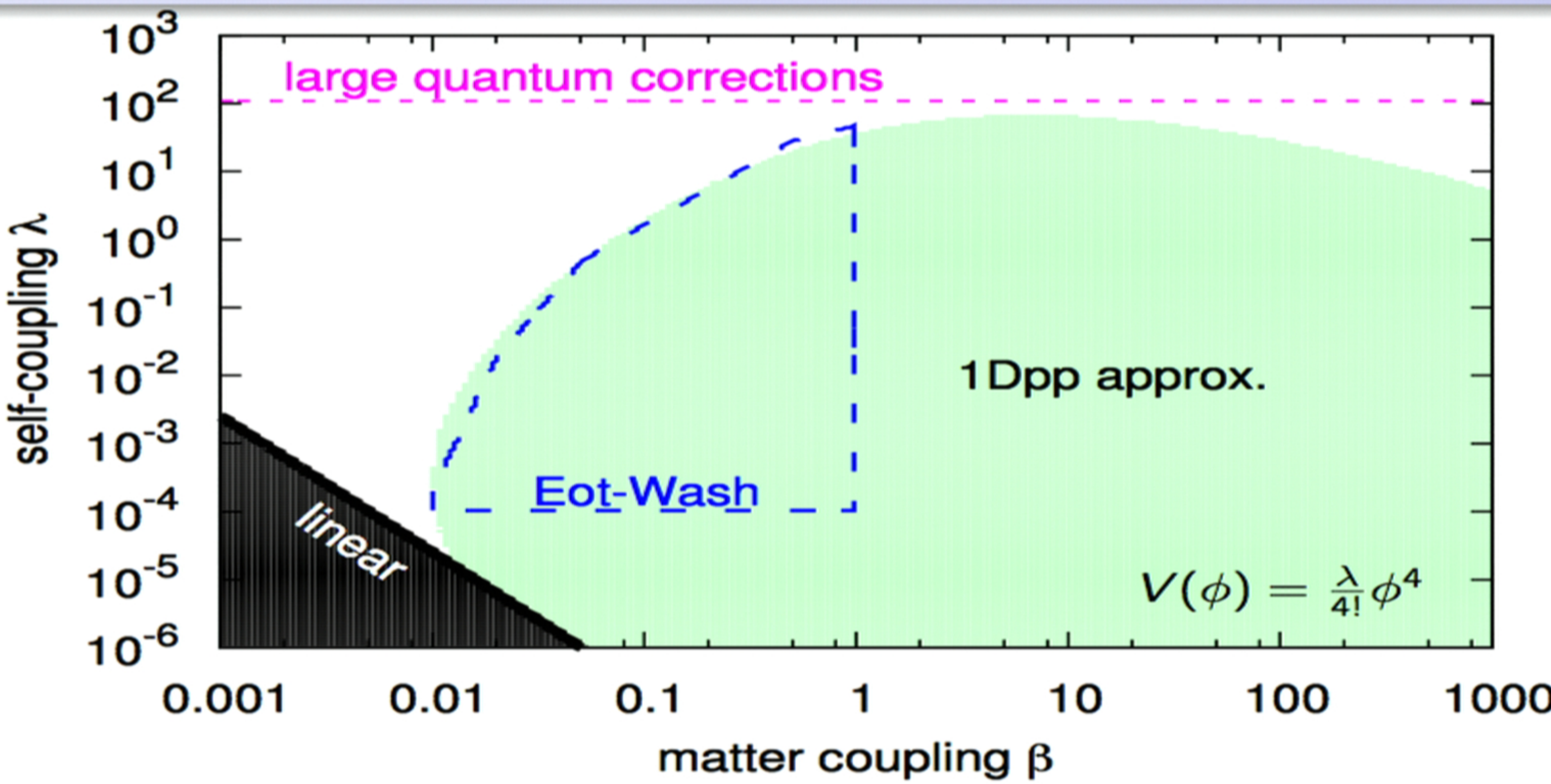
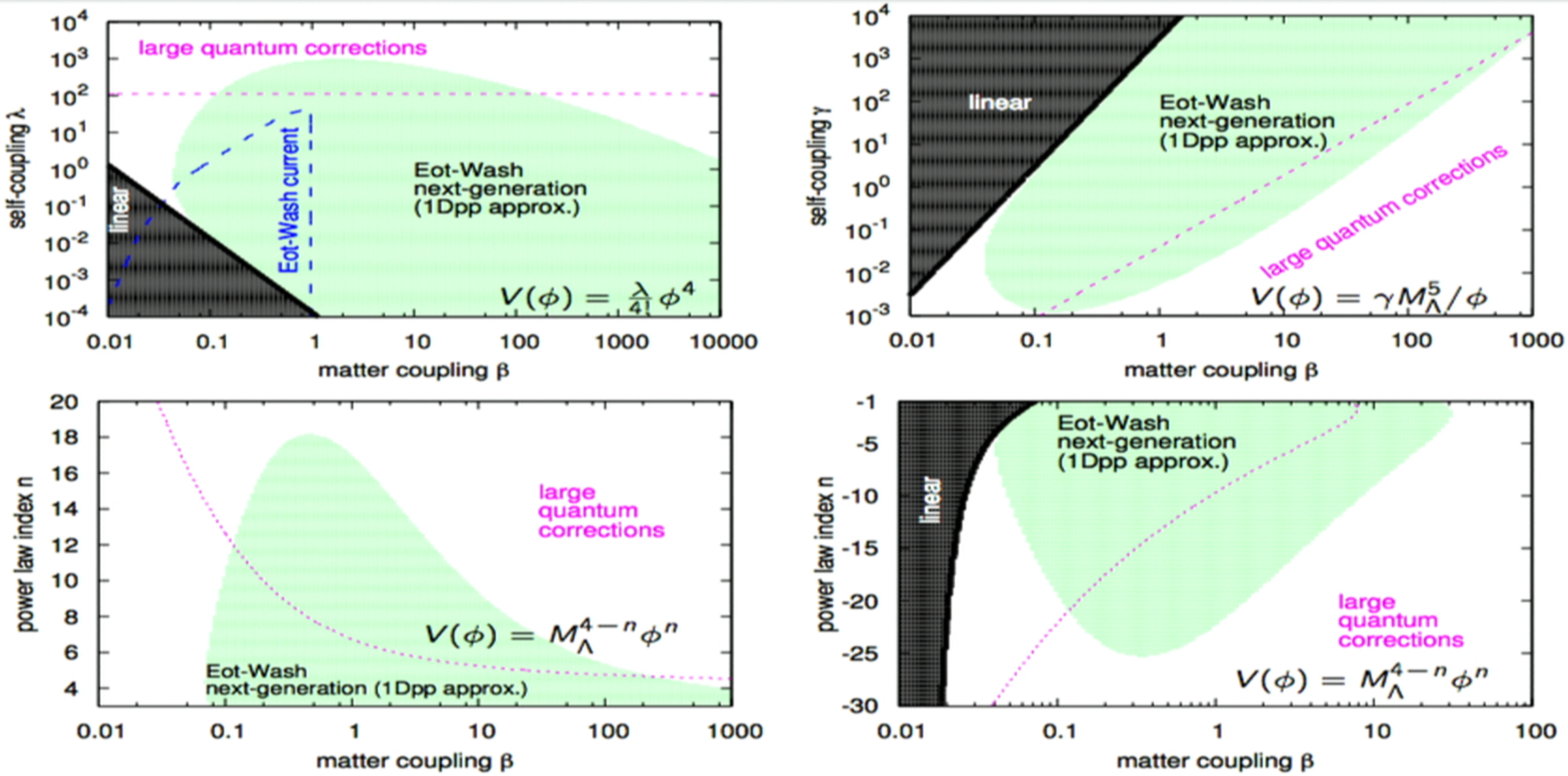
AU, PRD **86** *102003 (2012)*

Eöt-Wash constraints on chameleons



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

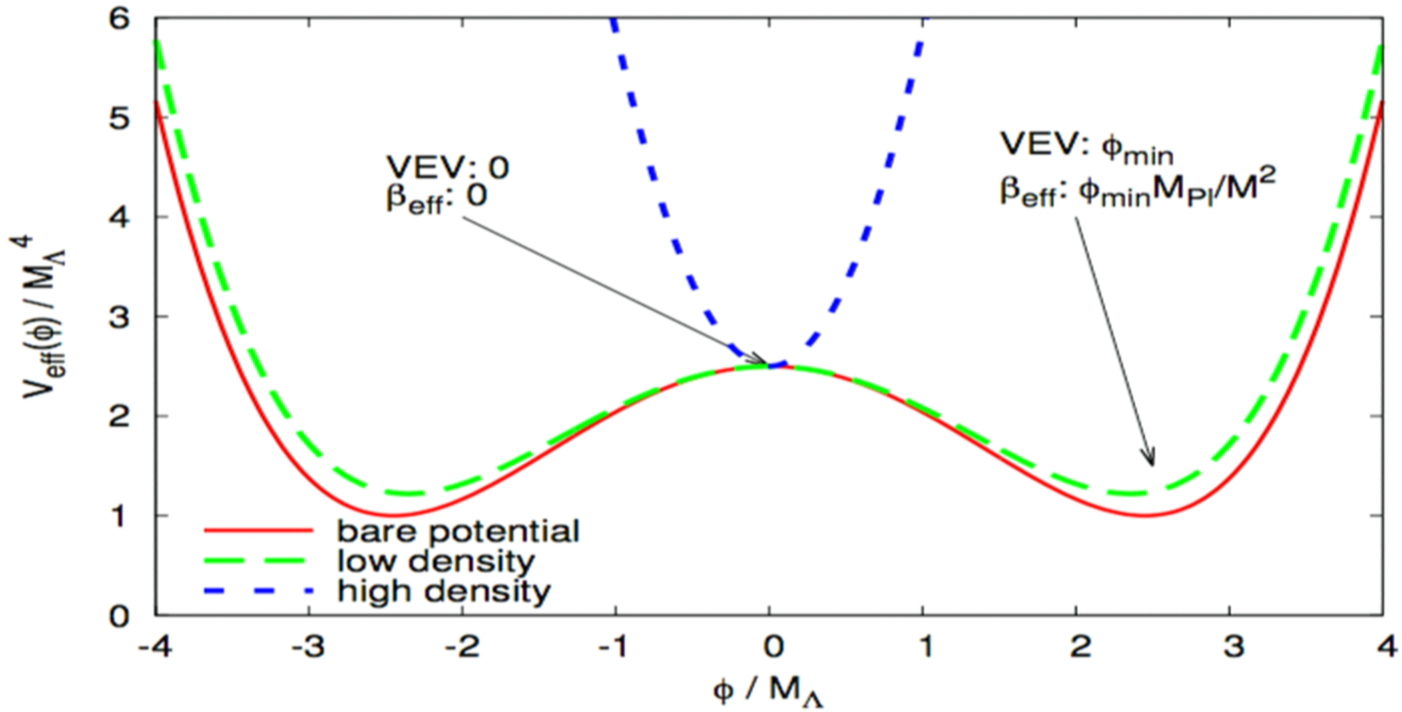
Next-generation Eöt-Wash: chameleon forecasts



AU, PRD **86** *102003 (2012)*

Symmetron mechanism

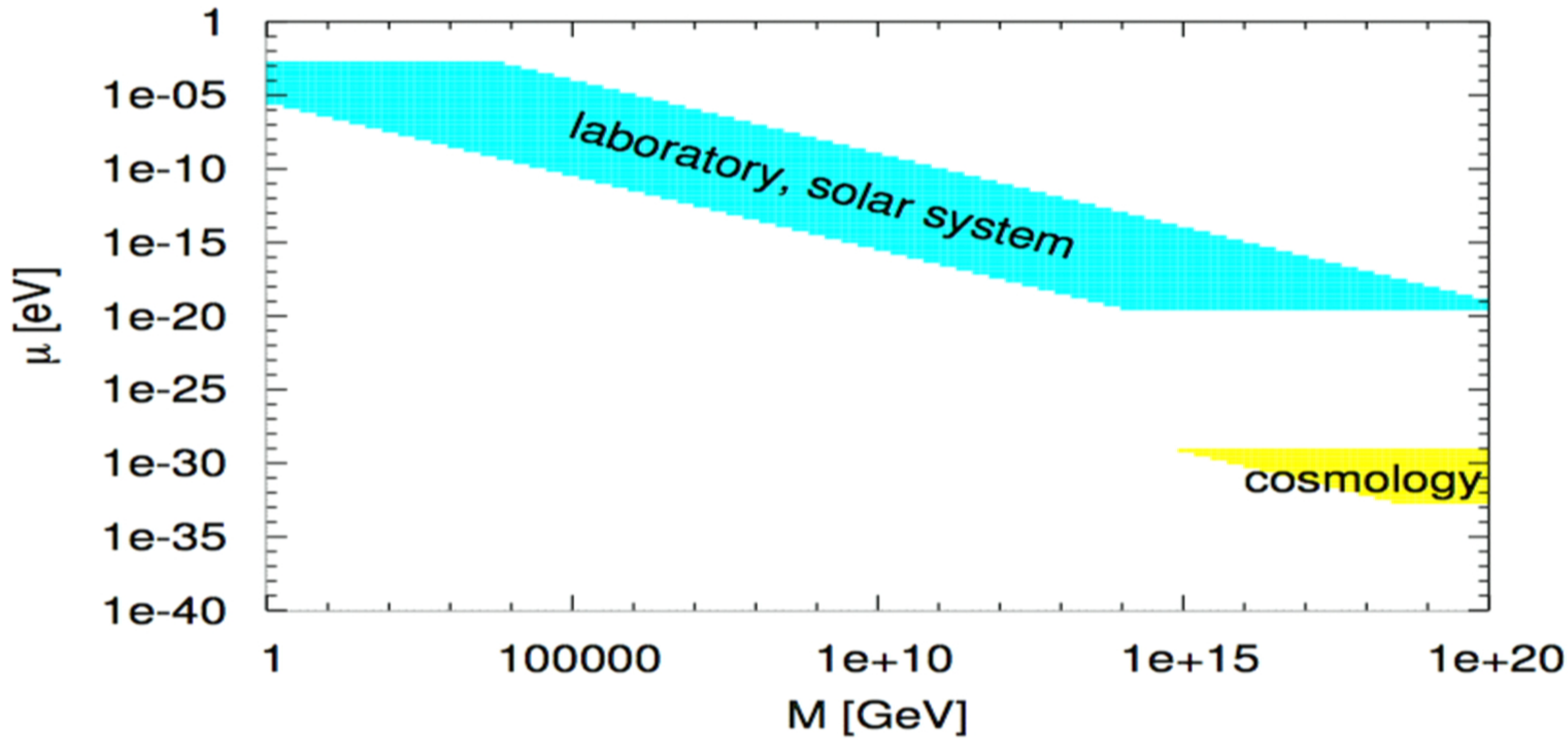
effective potential: $V_{\rm eff}(\phi,\rho) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4!}\phi^4$



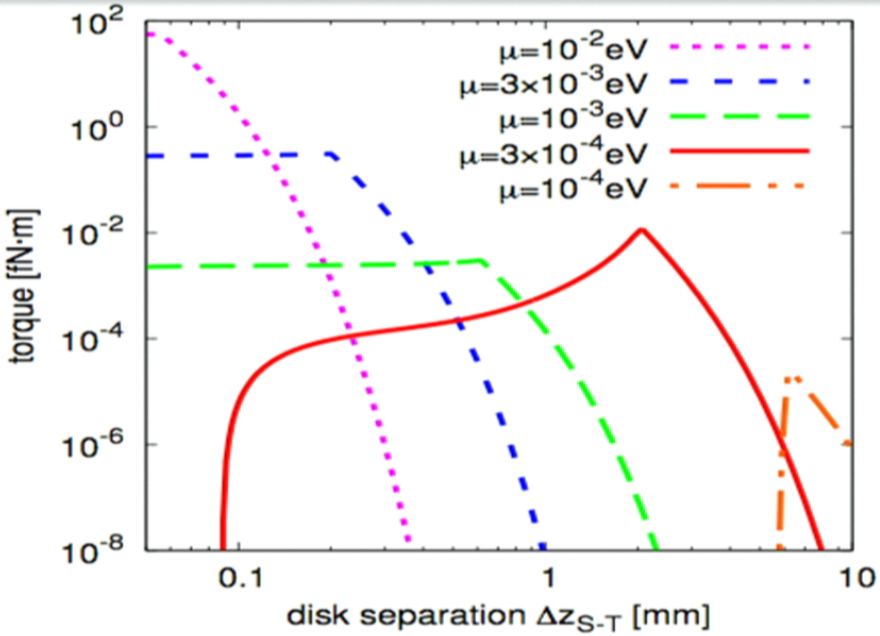
Olive and Pospelov, PRD **77** *043524 (2007);*
Hinterbichler and Khoury, PRL **104** *231301 (2010)*

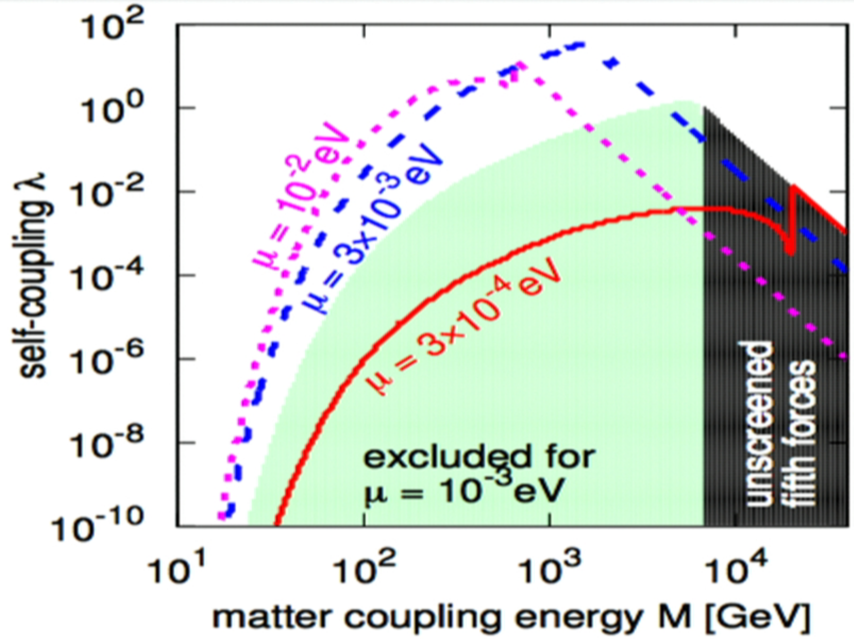
At which scale should we probe symmetrons?

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



Estimated (1Dpp) Eöt-Wash constraints on symmetrons



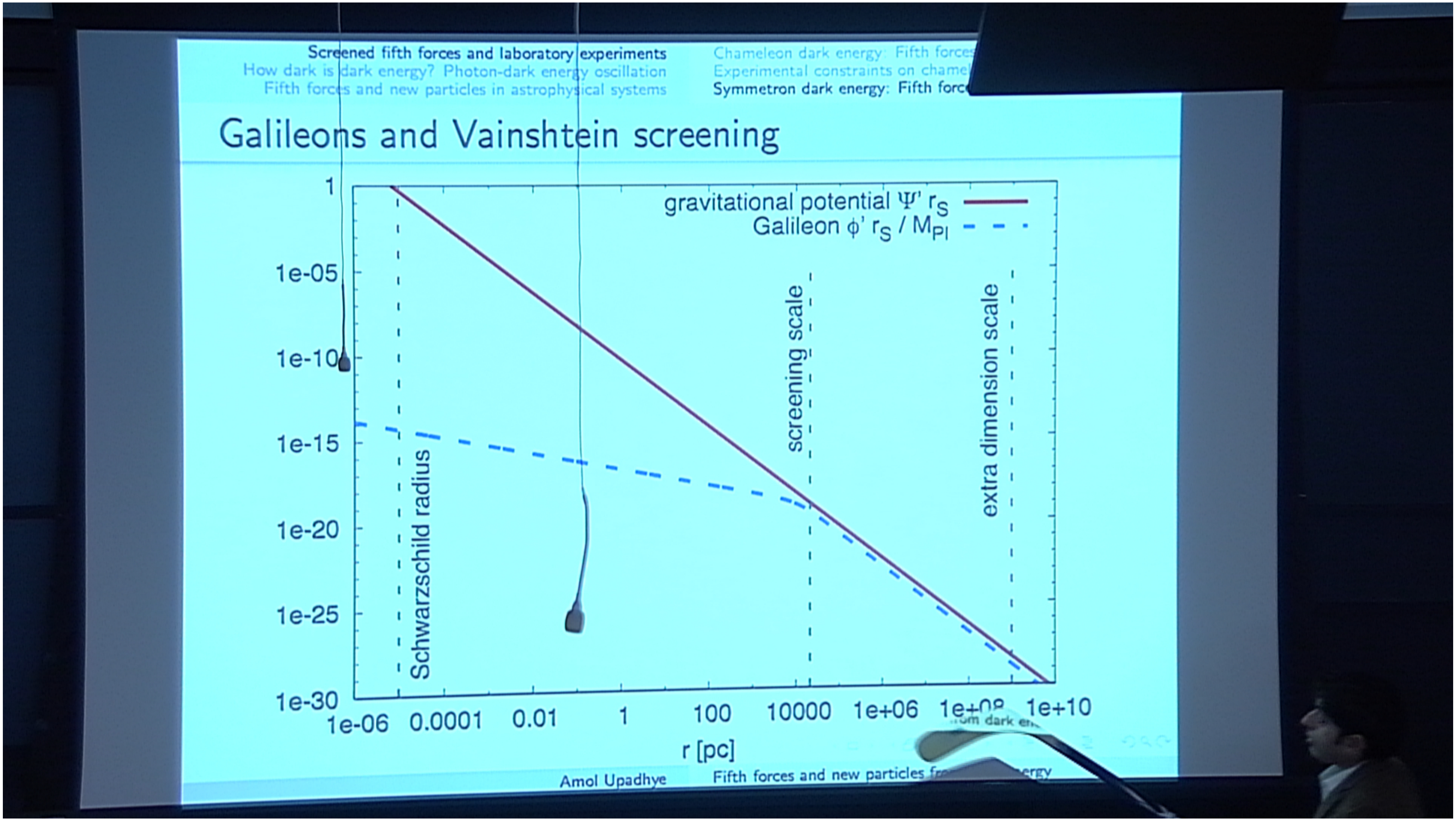


Symmetron effective potential: $V_{\rm eff} = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4!}\phi^4$

Eöt-Wash probes $\lambda \sim 1$, $\mu \sim 10^{-3}$ eV (dark energy),

$M \sim 1$ TeV (beyond the Standard Model)

AU, arXiv:1210.7804 (to appear in PRL, 2013)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gravitational potential Ψ' r_S
Galileon ϕ' r_S / M_Pl
Schwarzschild radius
screening scale
extra dimension scale
1
1e-05
1e-10
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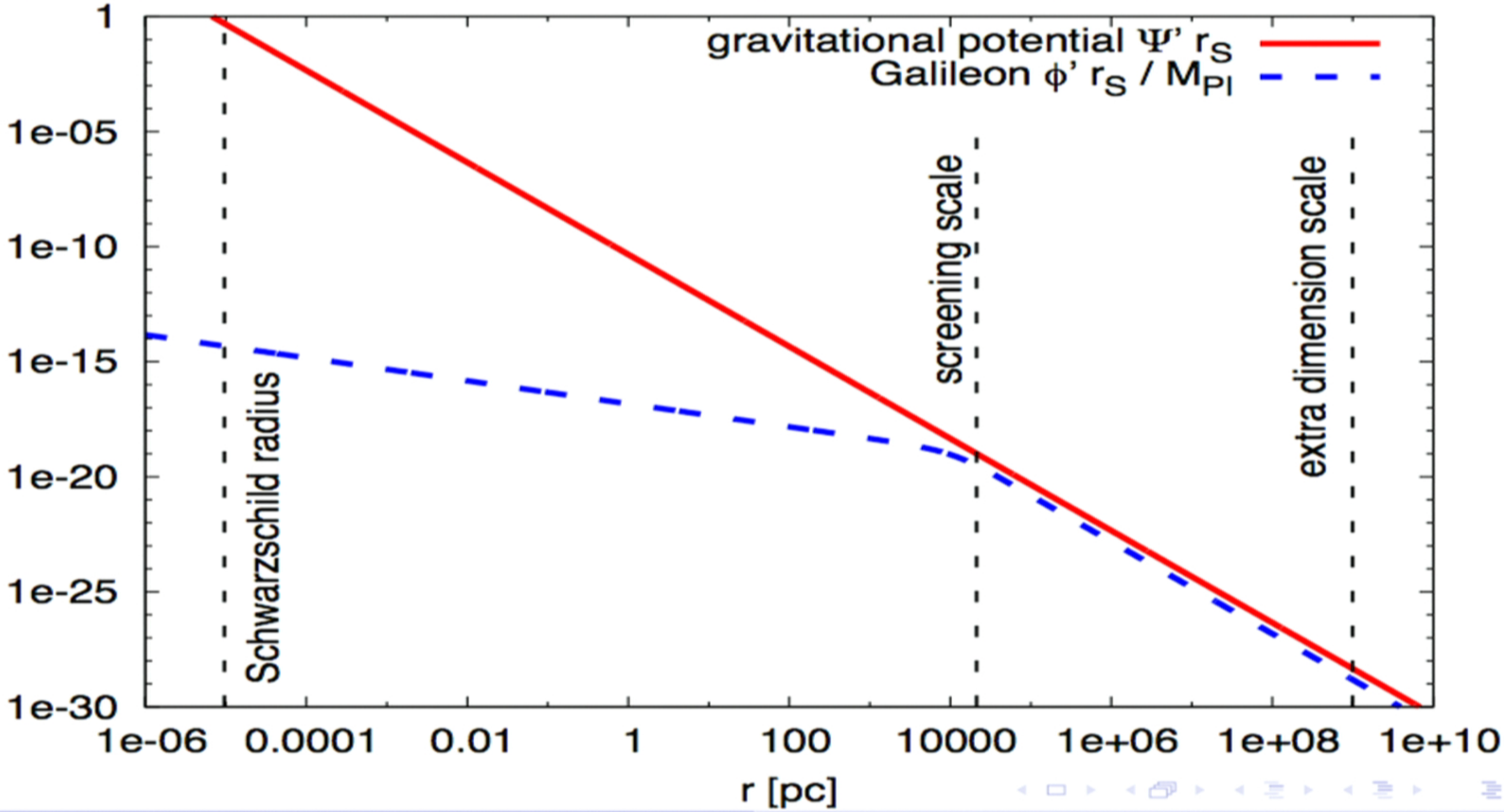


Part II:
How dark is dark energy? Photon-dark energy oscillation

Photons coupled to chameleon dark energy

Next, look at the time-dependent equation of motion, $\Box\phi = V'_{\rm eff}$.

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

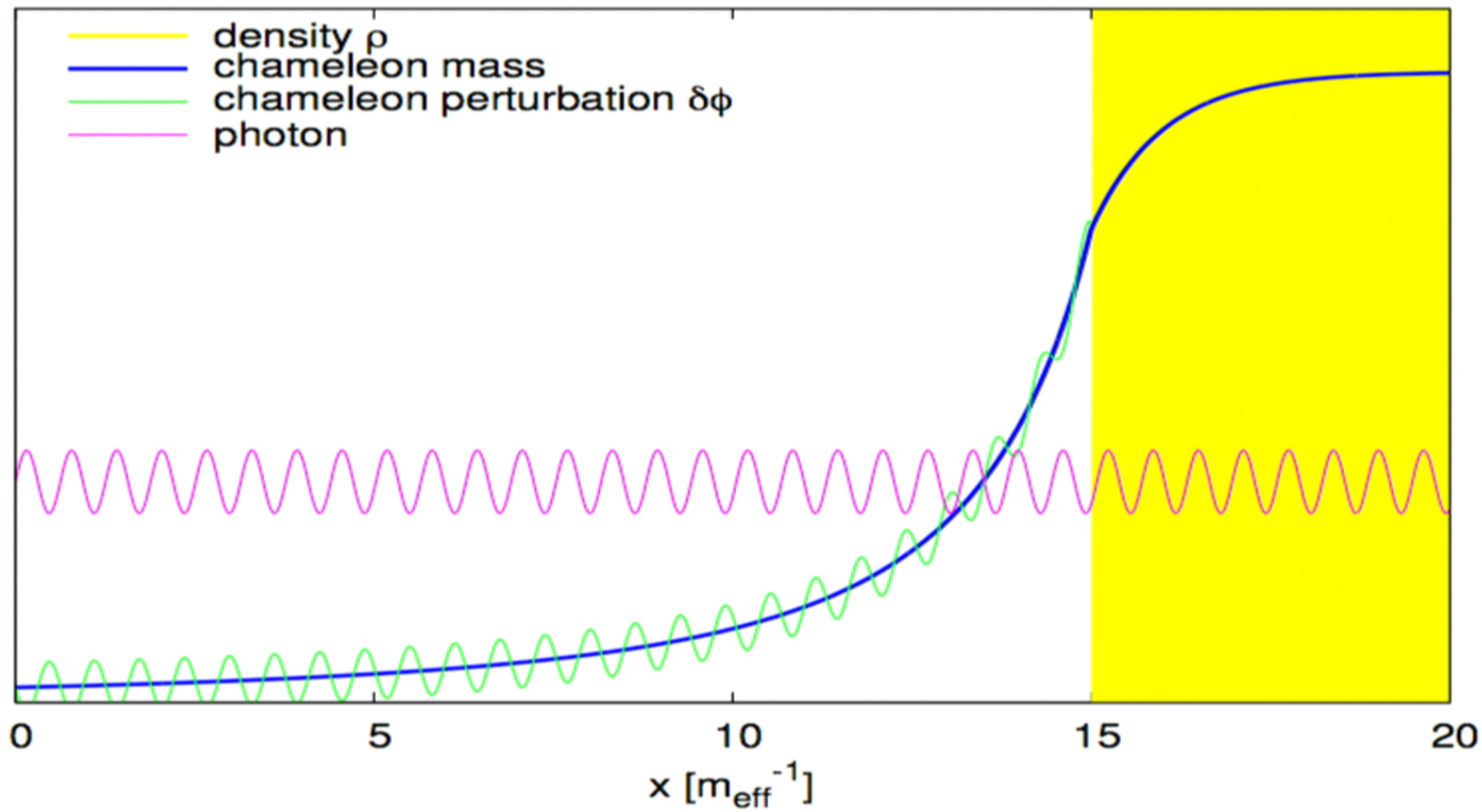
- $\partial_\mu \left[\left(1 + \frac{\beta_\gamma \phi}{M_{\rm Pl}}\right) F^{\mu\nu} \right] = 0$
- $\Box\phi = V'(\phi) + \frac{\beta_m}{M_{\rm Pl}}\rho_{\rm mat} + \frac{\beta_\gamma}{4M_{\rm Pl}} F_{\mu\nu}F^{\mu\nu}$

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

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

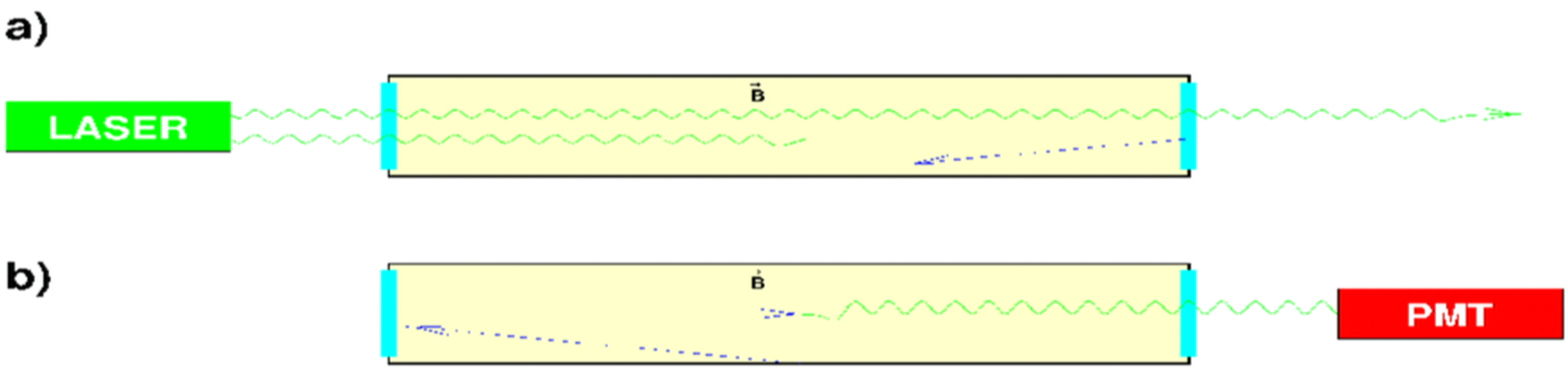
$\phi \to \gamma$ oscillation (low-mass, $\vec{k} \perp \vec{B}_0$): $\mathcal{P}_{\gamma\leftrightarrow\phi} \approx \frac{\beta_\gamma^2 B_0^2 L^2}{4M_{\rm Pl}^2}$

Window as a quantum measurement device



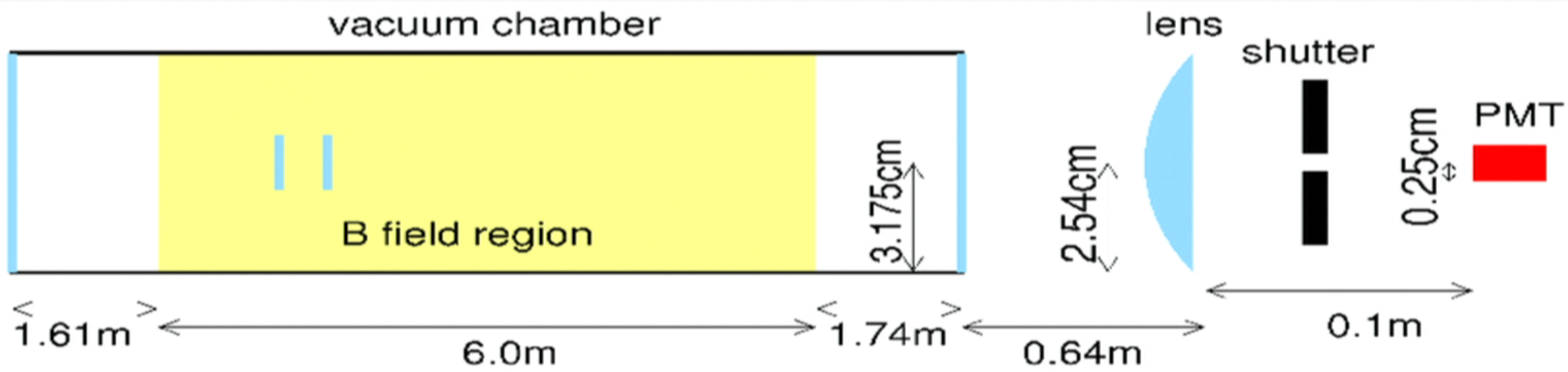
A simple afterglow experiment

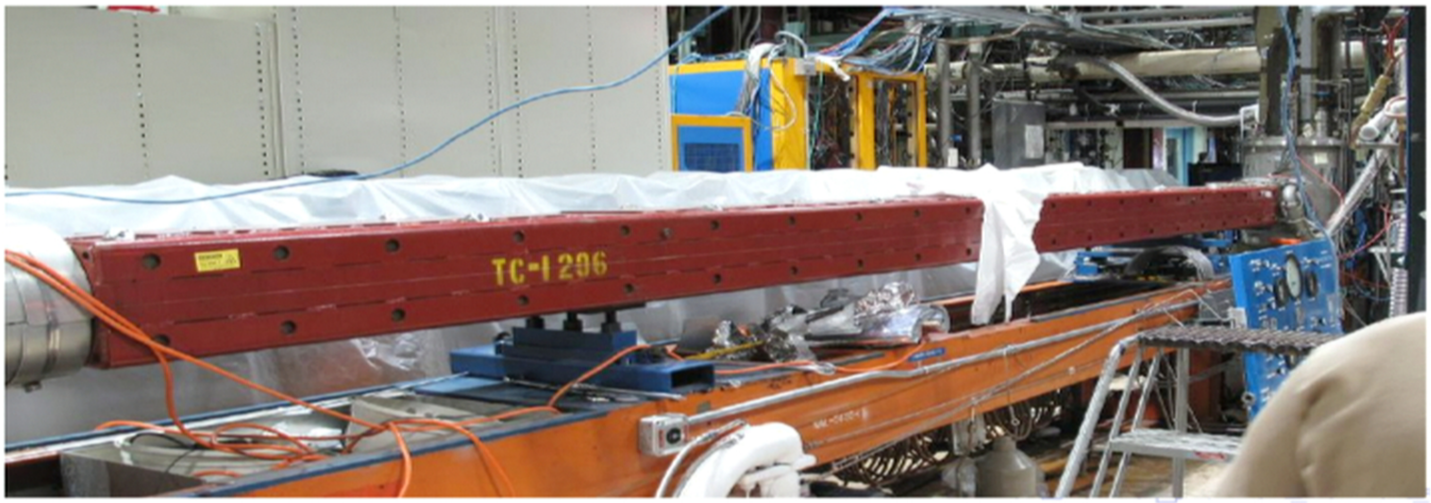
(a) Production phase: photons streamed through $\vec{B}_0$ region; some oscillate into chameleons



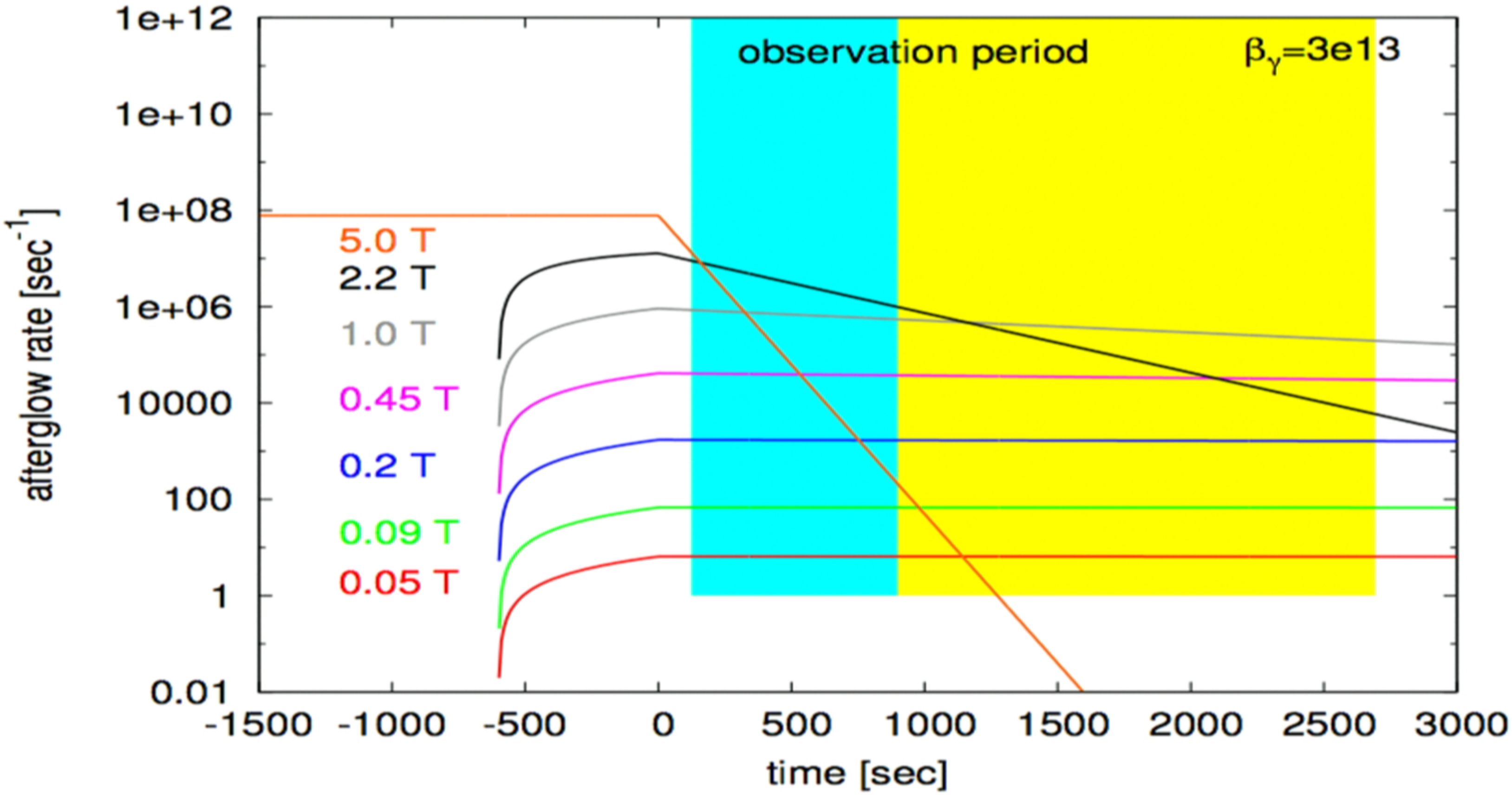
(b) Afterglow phase: chameleons slowly oscillate back into photons, escaping chamber

CHASE (CHameleon Afterglow SEarch)





Predicted afterglow signal in CHASE



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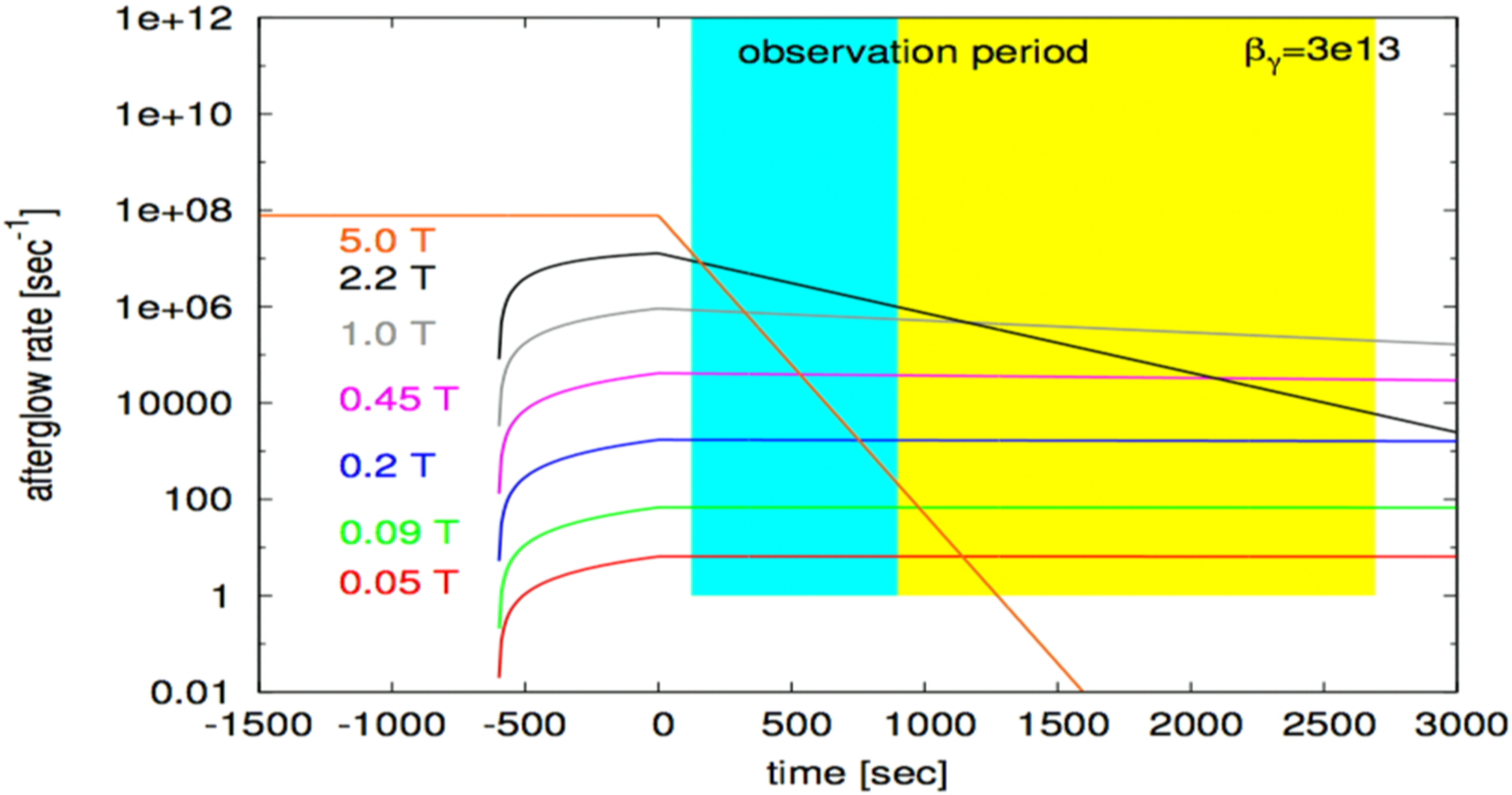
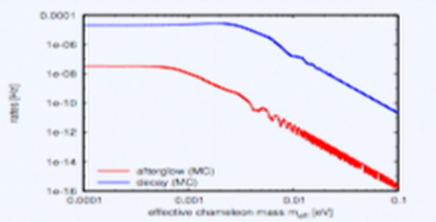
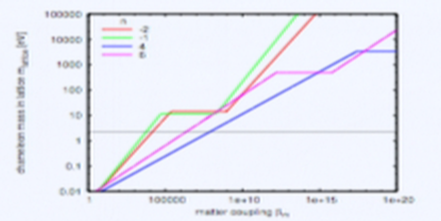


Chameleons in CHASE: a thorough study

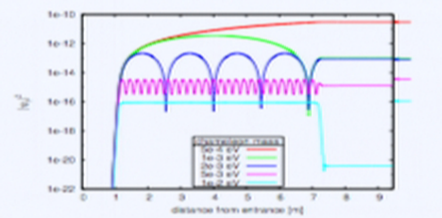
Oscillation



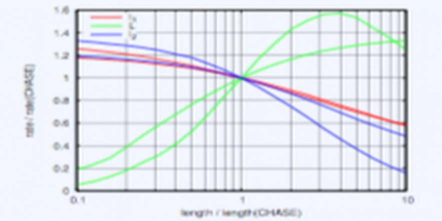
Matter lattice



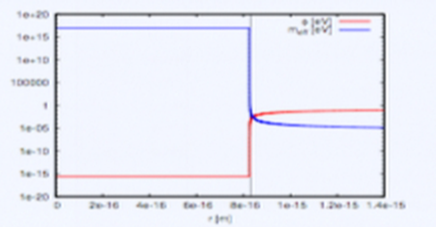
Adiabaticity



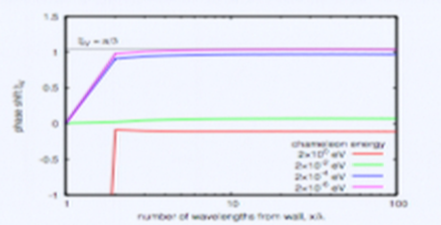
Chamber geom.



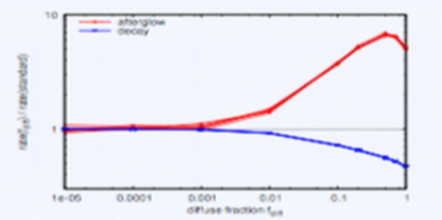
Atom scattering



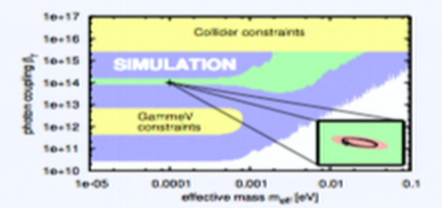
Other potentials



Diffuse ref.



Data analysis

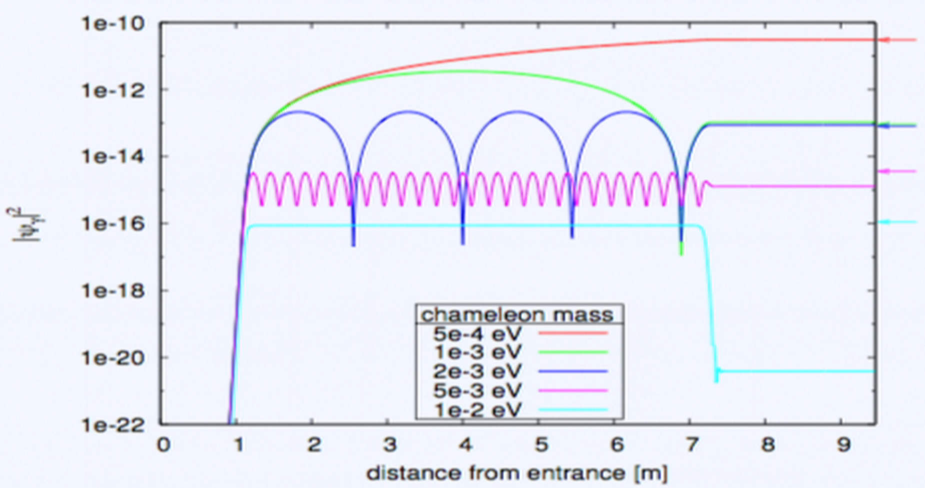


AU, J. Steffen, A. Chou, PRD **86** *035006 (2012)*

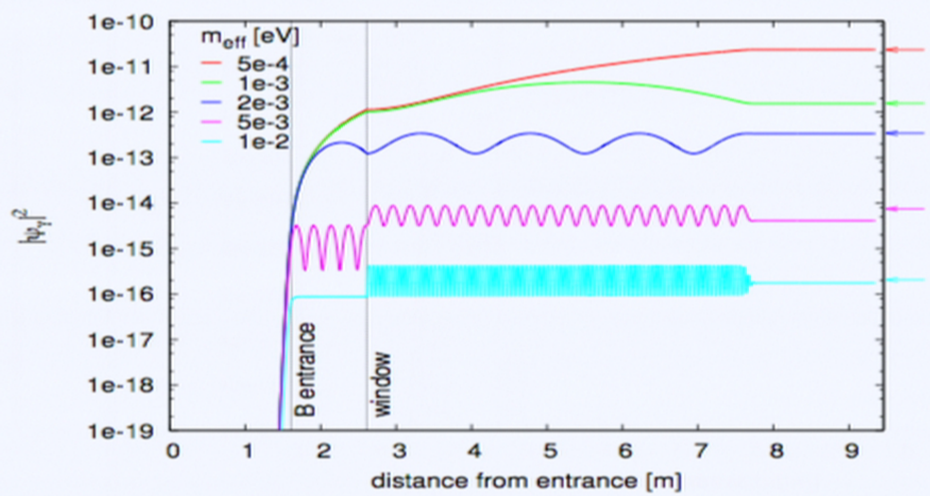
Adiabatic transition suppresses oscillation

- $\vec{B}(z)$ 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

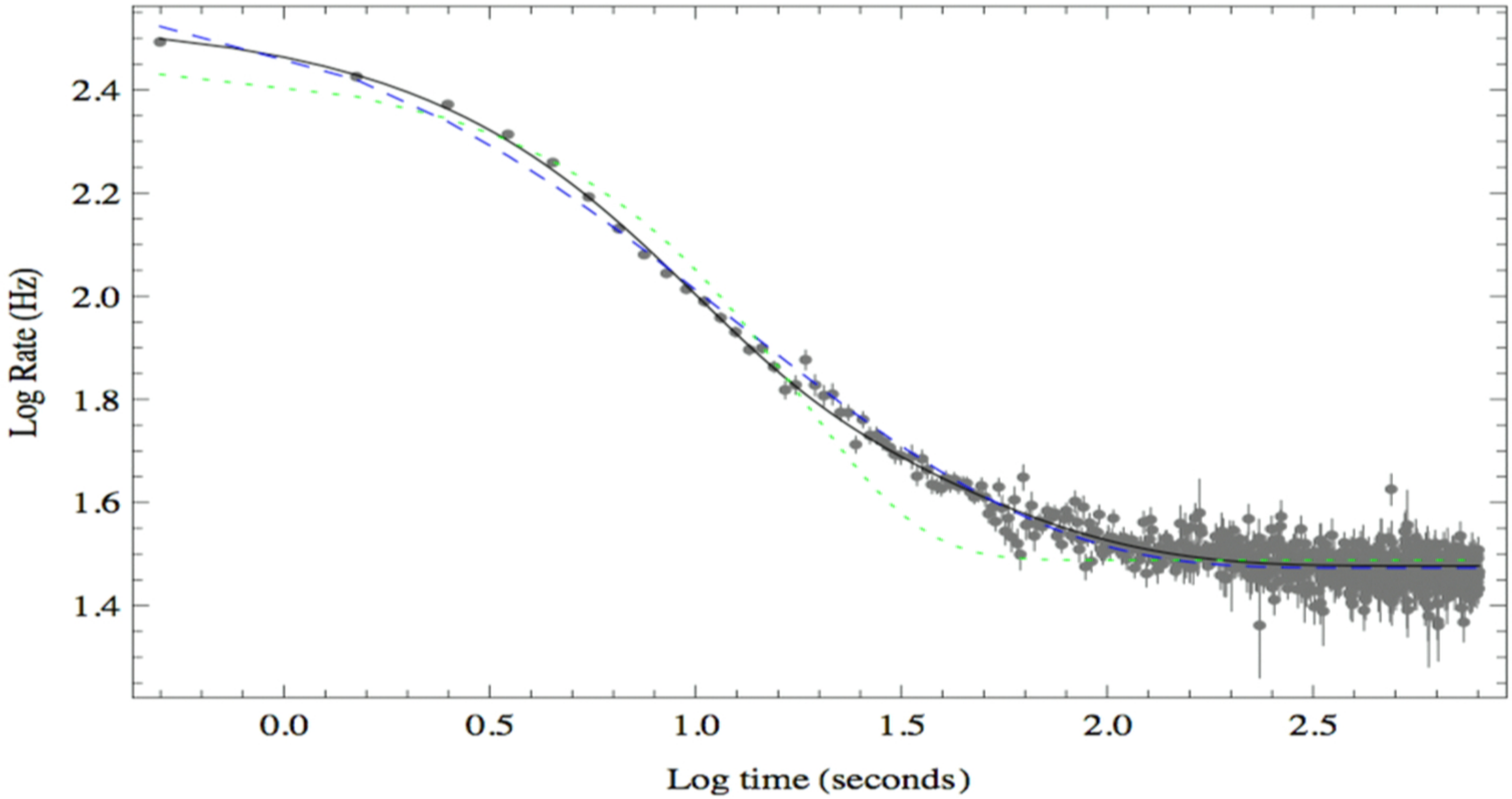


One measurement



AU, J. Steffen, A. Chou, PRD **86** *035006 (2012)*

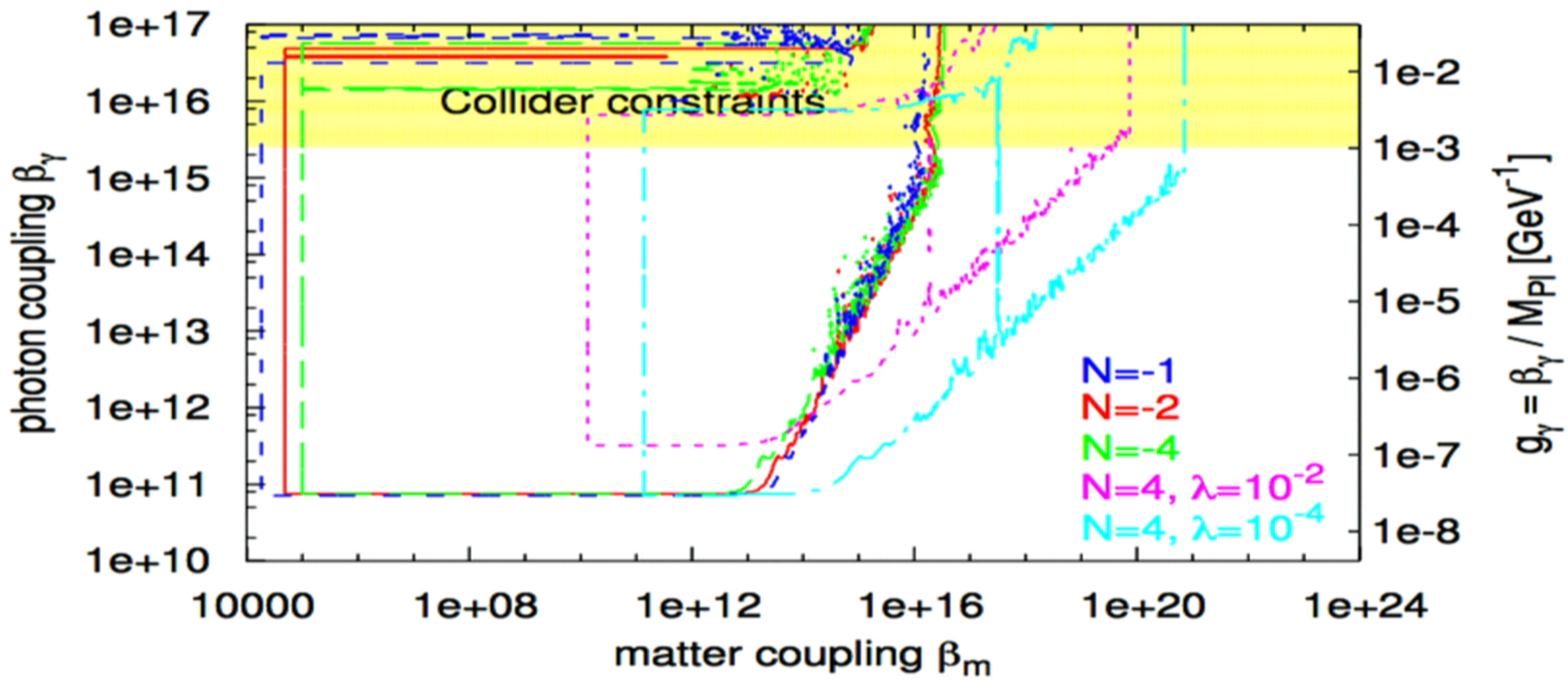
"Orange glow:" a transient systematic photon flux



J. Steffen, AU, et al. PRD **86** *012003 (2012)*

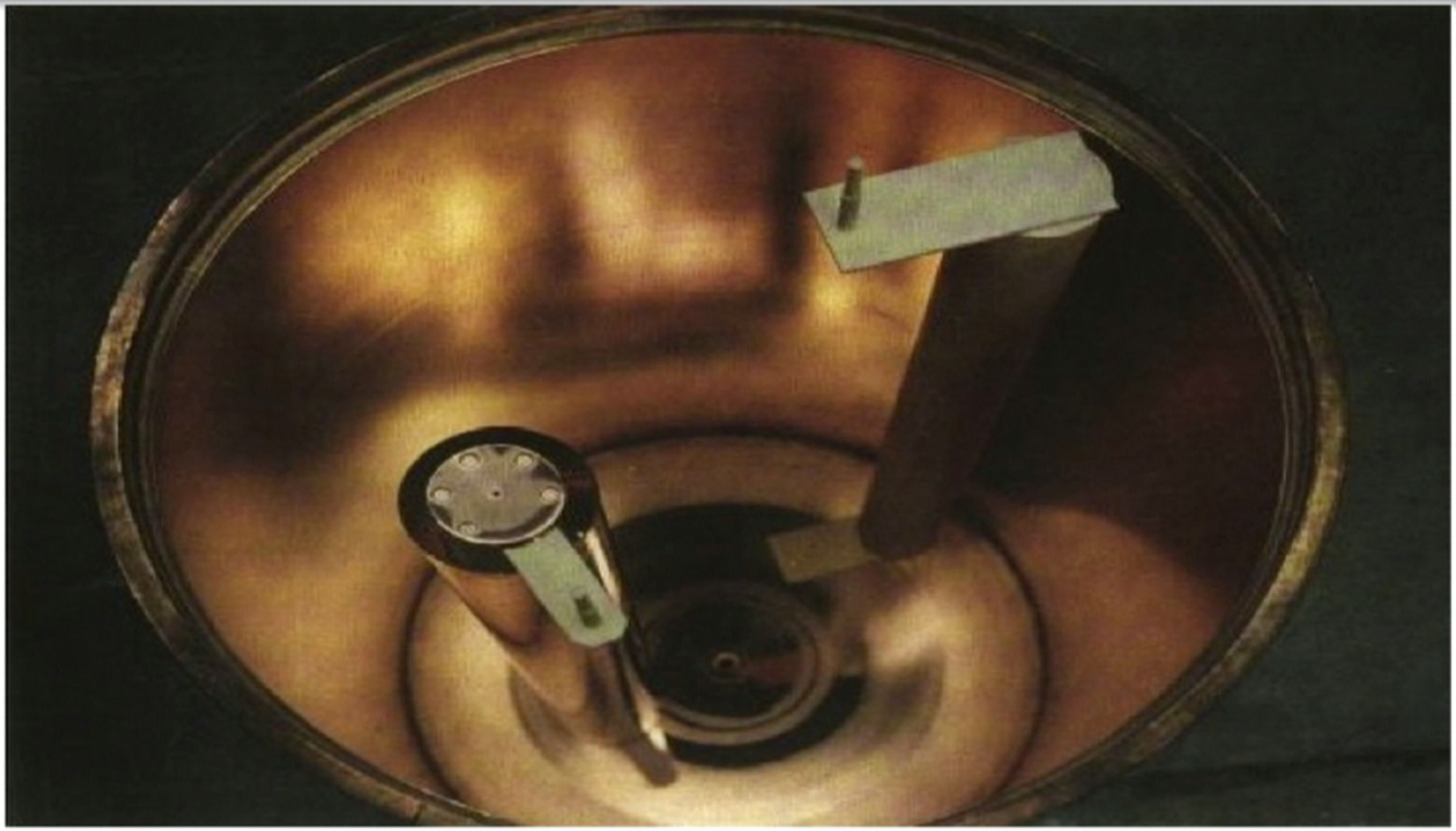
CHASE constraints on chameleon dark energy

$$V_{\rm eff} = M_\Lambda^4 + M_\Lambda^{4-N}\phi^N + \beta_{\rm m}\rho\phi/M_{\rm Pl} + \beta_\gamma F^{\mu\nu}F_{\mu\nu}\phi/(4M_{\rm Pl})$$



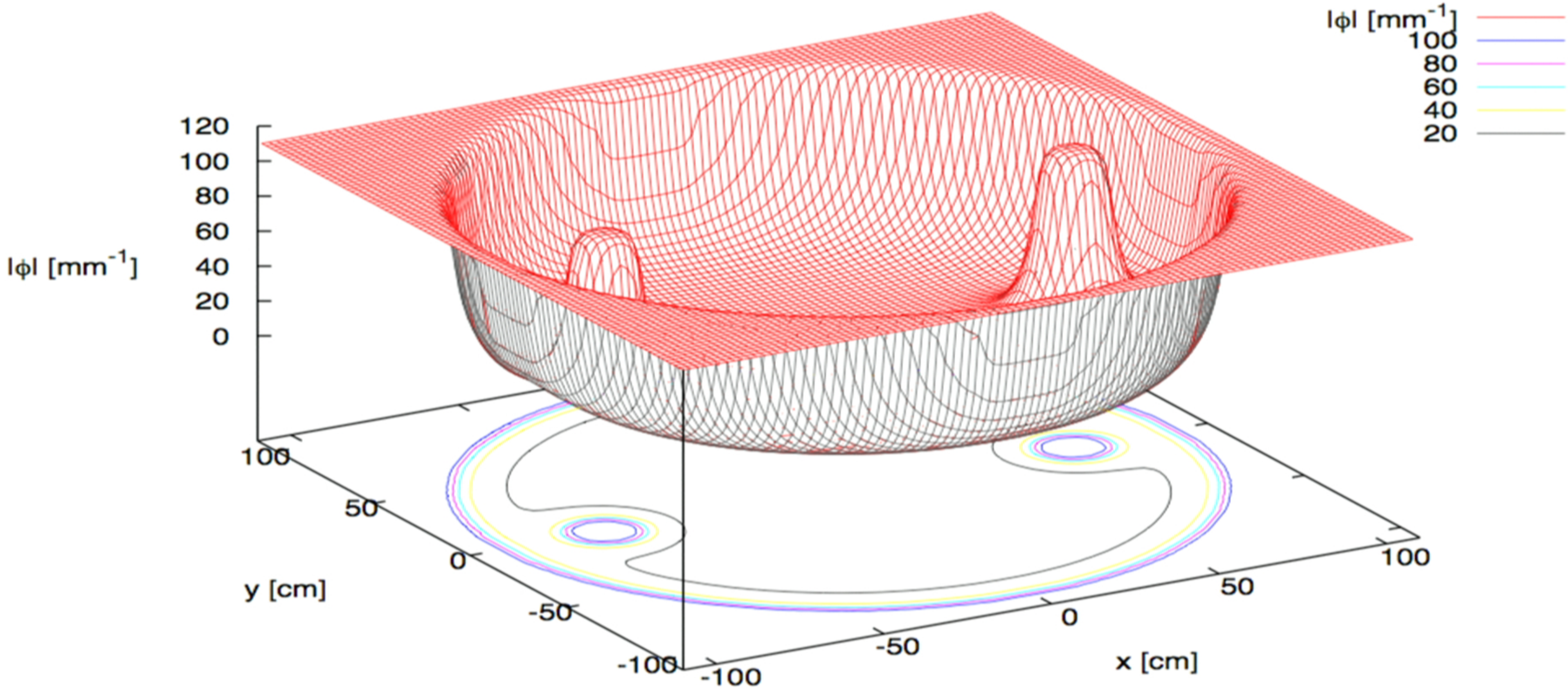
J. Steffen, AU, et al., PRL **105** *261803 (2010); AU, J. Steffen, A. Weltman, PRD* **81** *015013 (2010); AU, J. Steffen, A. Chou, PRD* **86** *035006 (2012)*

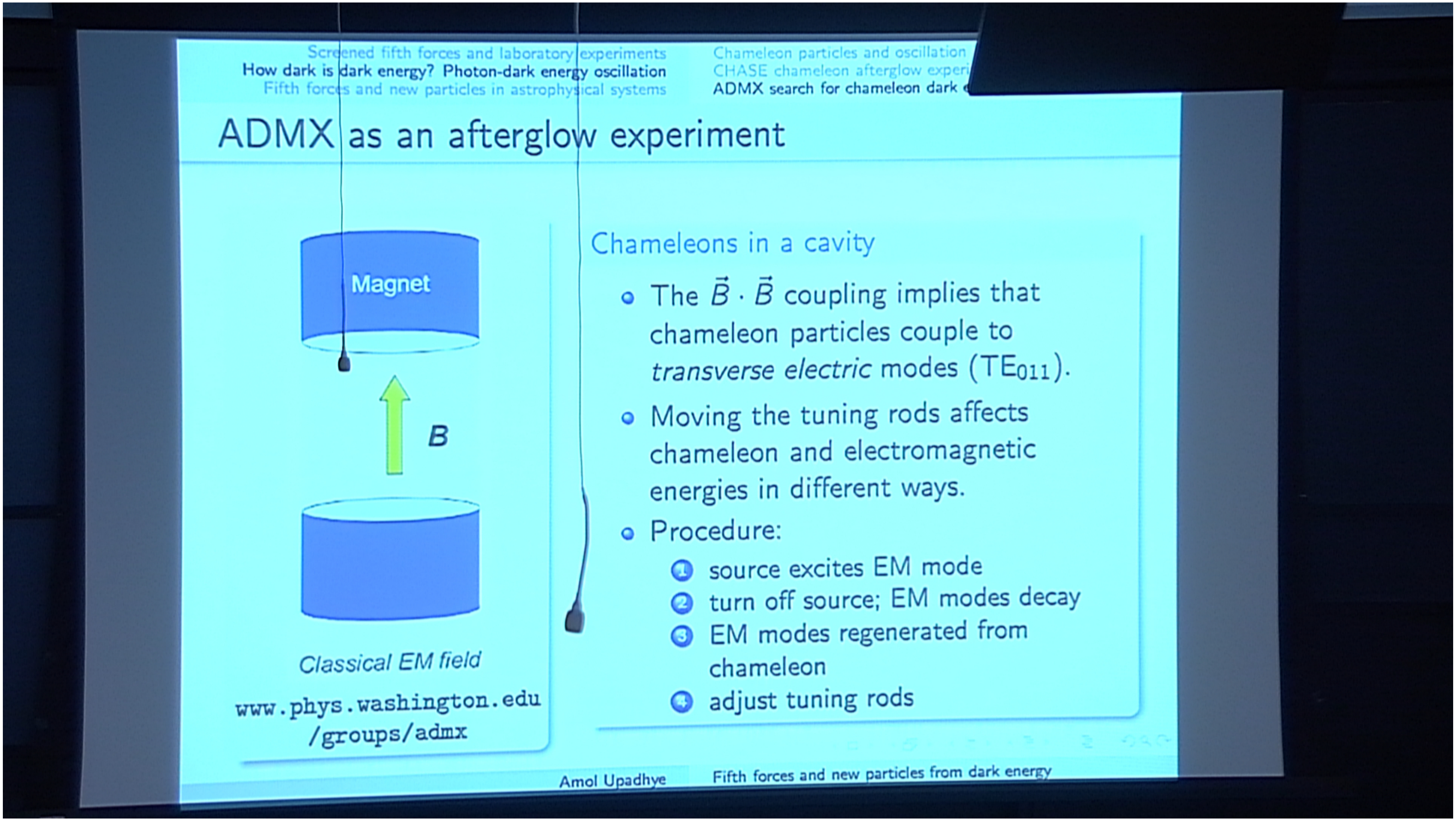
ADMX microwave cavity



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

Chameleon field profile




Screened fifth forces and laboratory experiments
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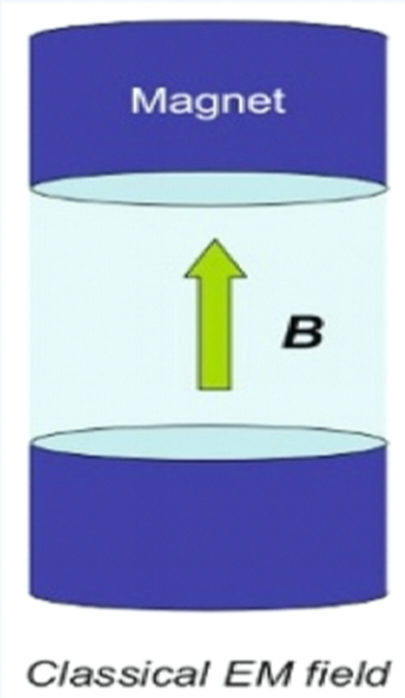
Chameleon particles and oscillation
CHASE chameleon afterglow experi
ADMX search for chameleon dark
ADMX as an afterglow experiment
Magnet
B
Classical EM field
www.phys.washington.edu
/groups/admx
Chameleons in a cavity
The $\vec{B} \cdot \vec{B}$ coupling implies that chameleon particles couple to *transverse electric* modes (TE_{011}).
Moving the tuning rods affects chameleon and electromagnetic energies in different ways.
Procedure:
1 source excites EM mode
2 turn off source; EM modes decay
3 EM modes regenerated from chameleon
4 adjust tuning rods
Amol Upadhye
Fifth forces and new particles from dark energy

ADMX as an afterglow experiment



www.phys.washington.edu/groups/admx

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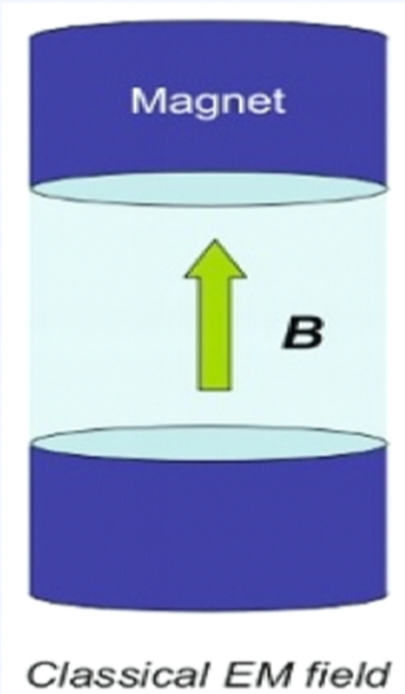

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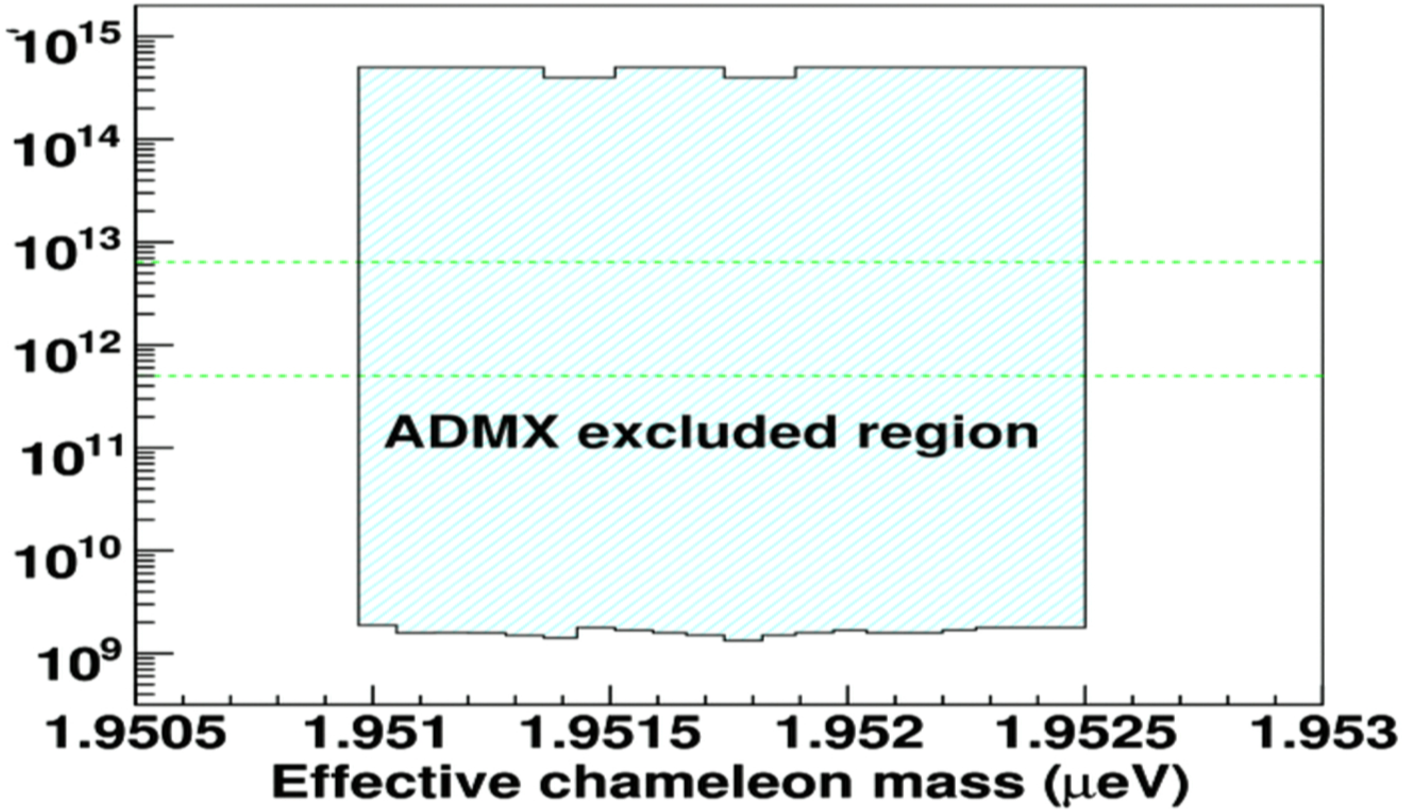
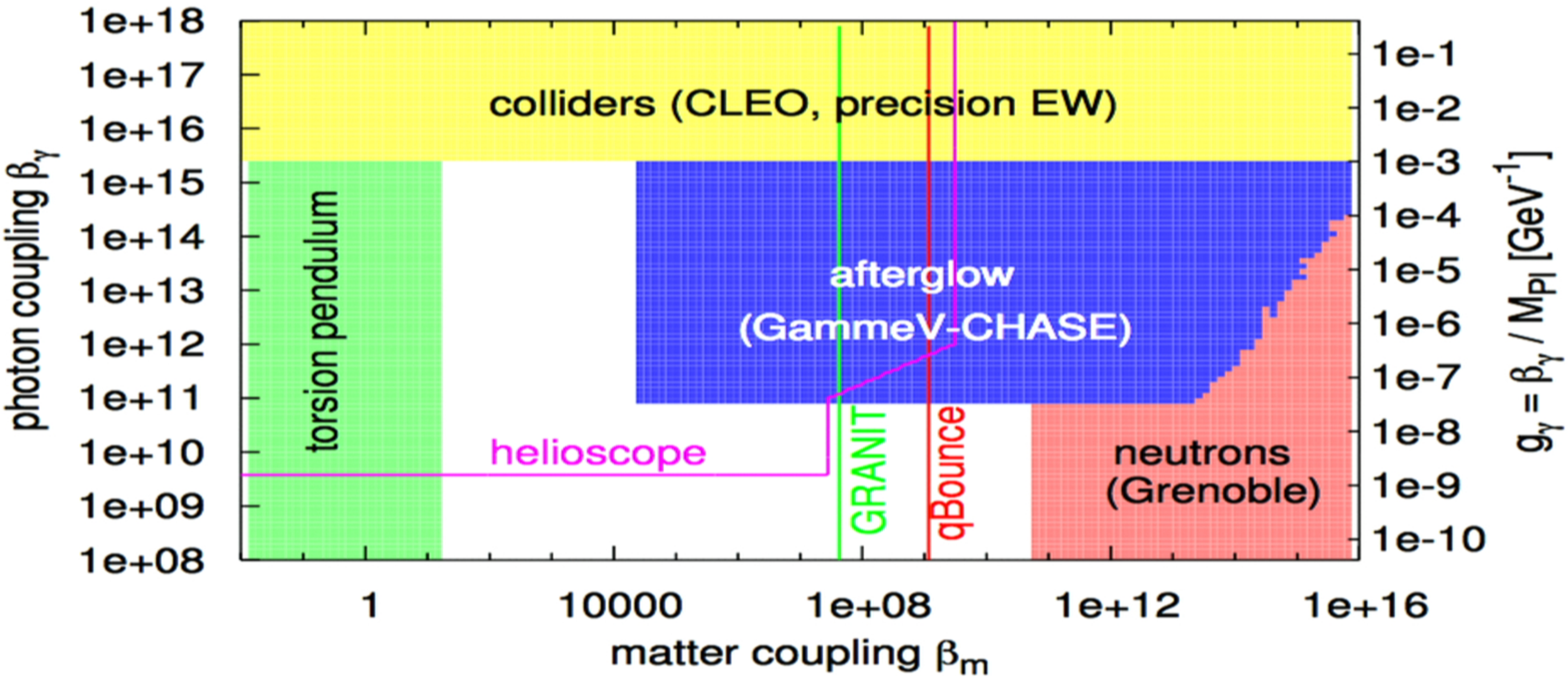
ADMX constraints on photon-coupled chameleons



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

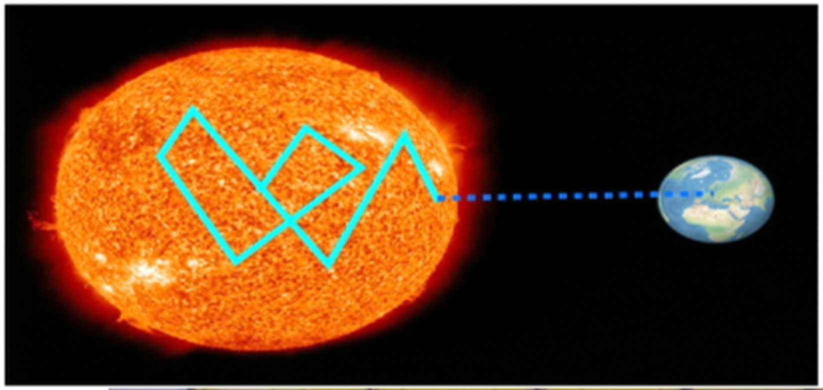
Laboratory constraints on chameleons: $V(\phi) = M_\Lambda^5/\phi$



AU, J. Steffen, A. Chou, PRD **86** *035006 (2012)*

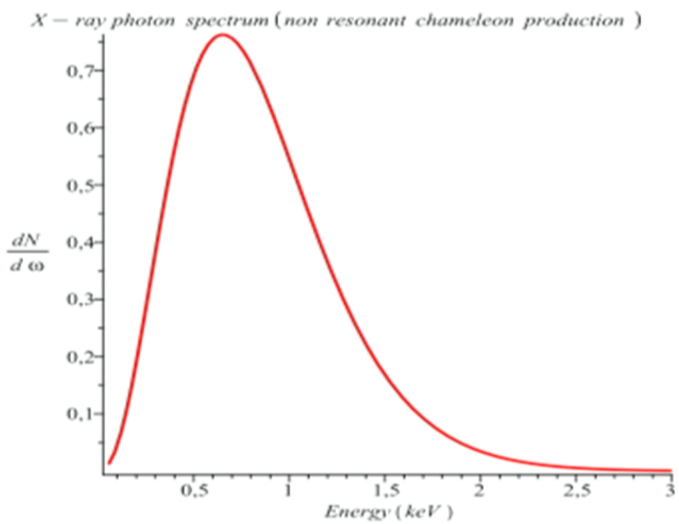
Part III:
Fifth forces and new particles in astrophysical systems

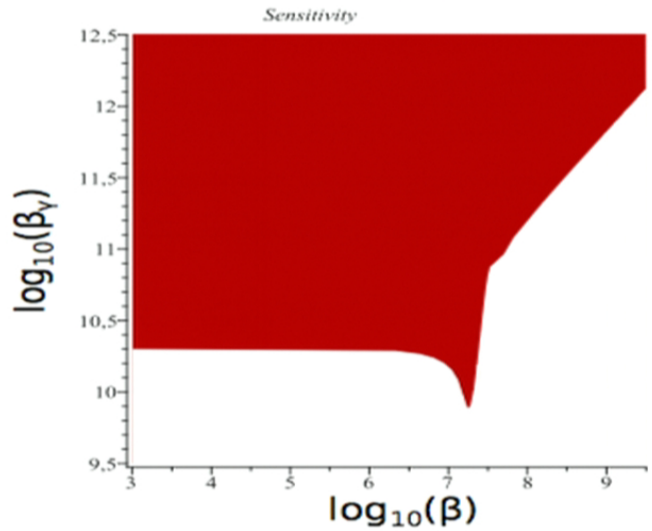
Chameleons from the Sun

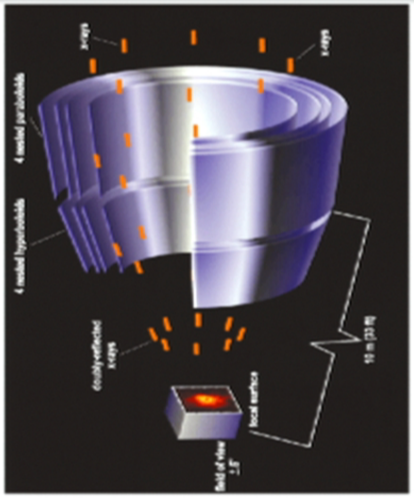


- $\sim$ keV photons oscillate into chameleons inside Sun
- chameleon particles reach Earth
- helioscope magnet regenerates photons for detection

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)

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

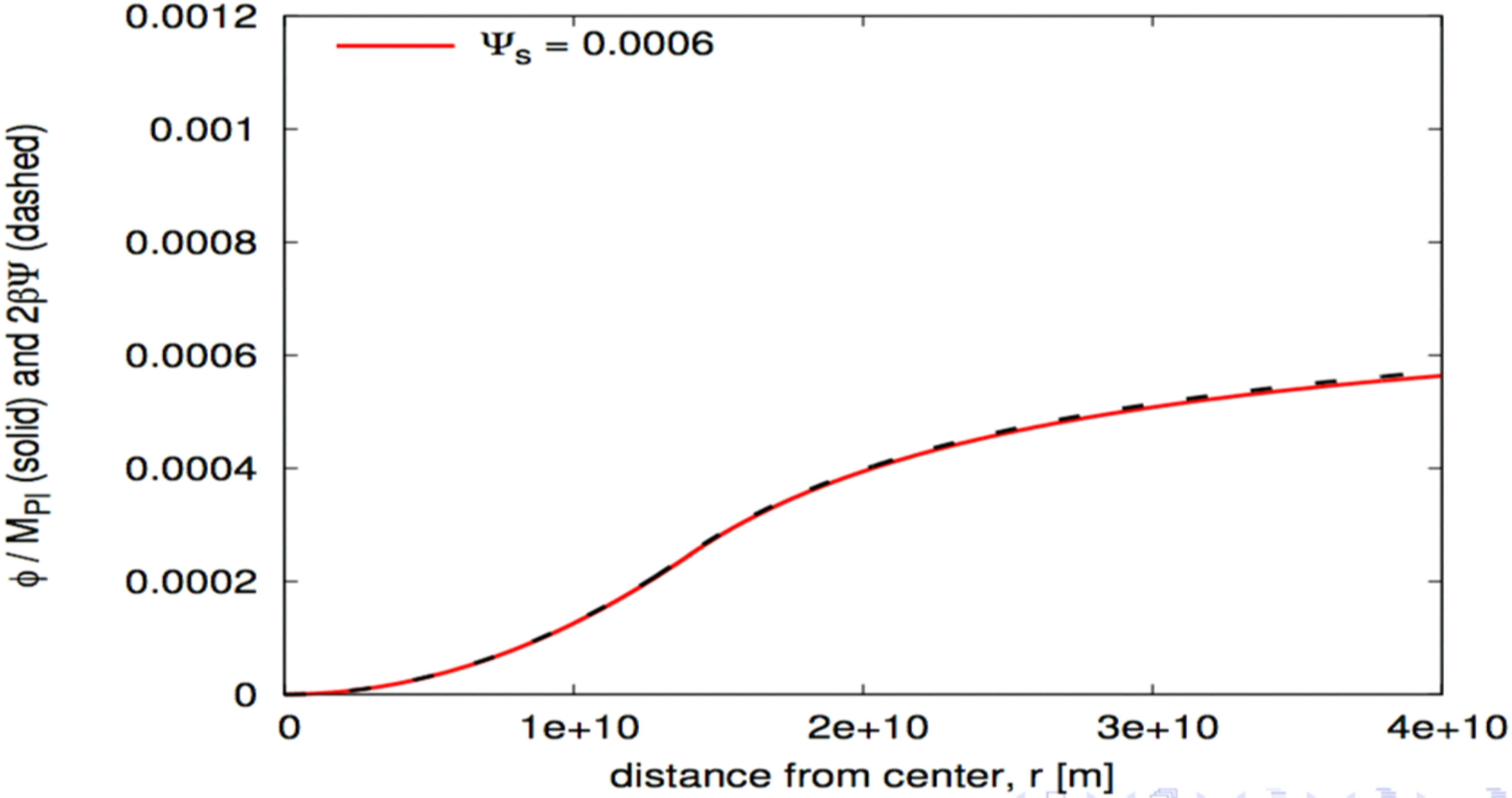
modified Einstein eq. (trace, tt, rr), $f_R = \frac{df}{dR}$, $\phi = -\frac{M_{\rm Pl}}{2\beta_{\rm m}} \log f_R$:

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

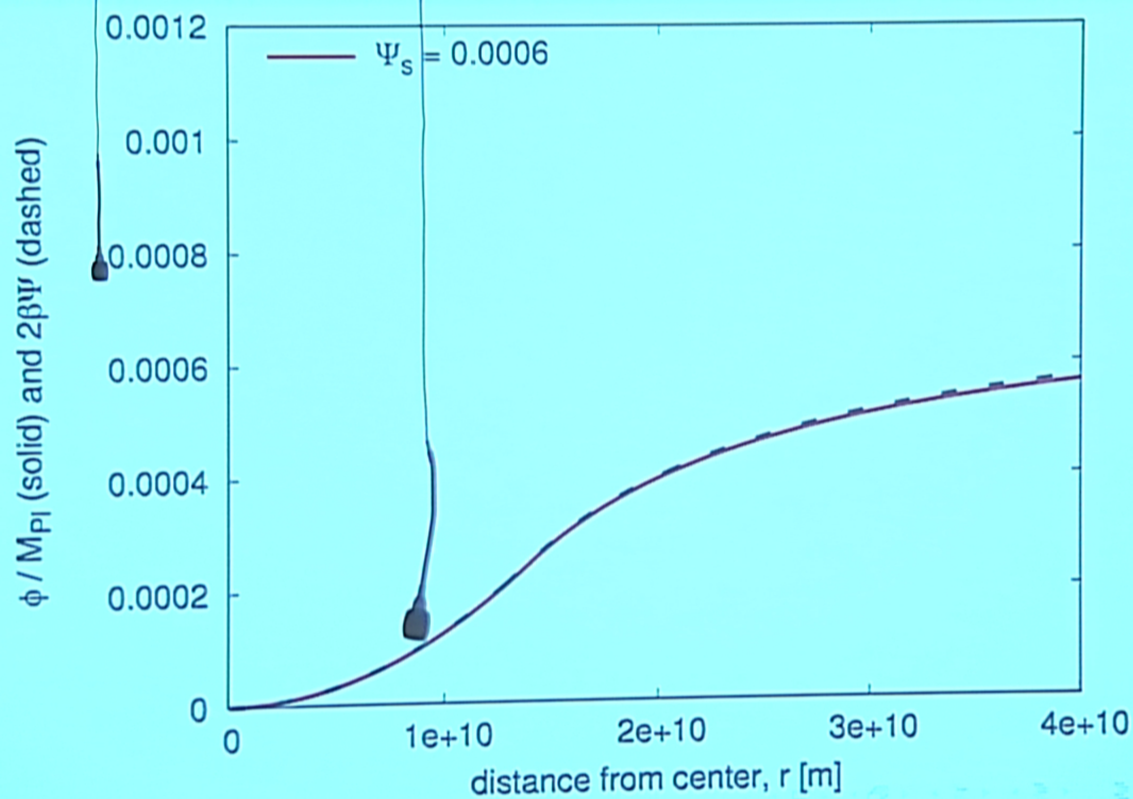
$$\frac{(-1 + B + rB')f_R}{r^2} + \left[f_R'' + \left(\frac{2}{r} + \frac{B'}{2B}\right) f_R'\right] B = -8\pi G\rho + \frac{f - Rf_R}{2}$$

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

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



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



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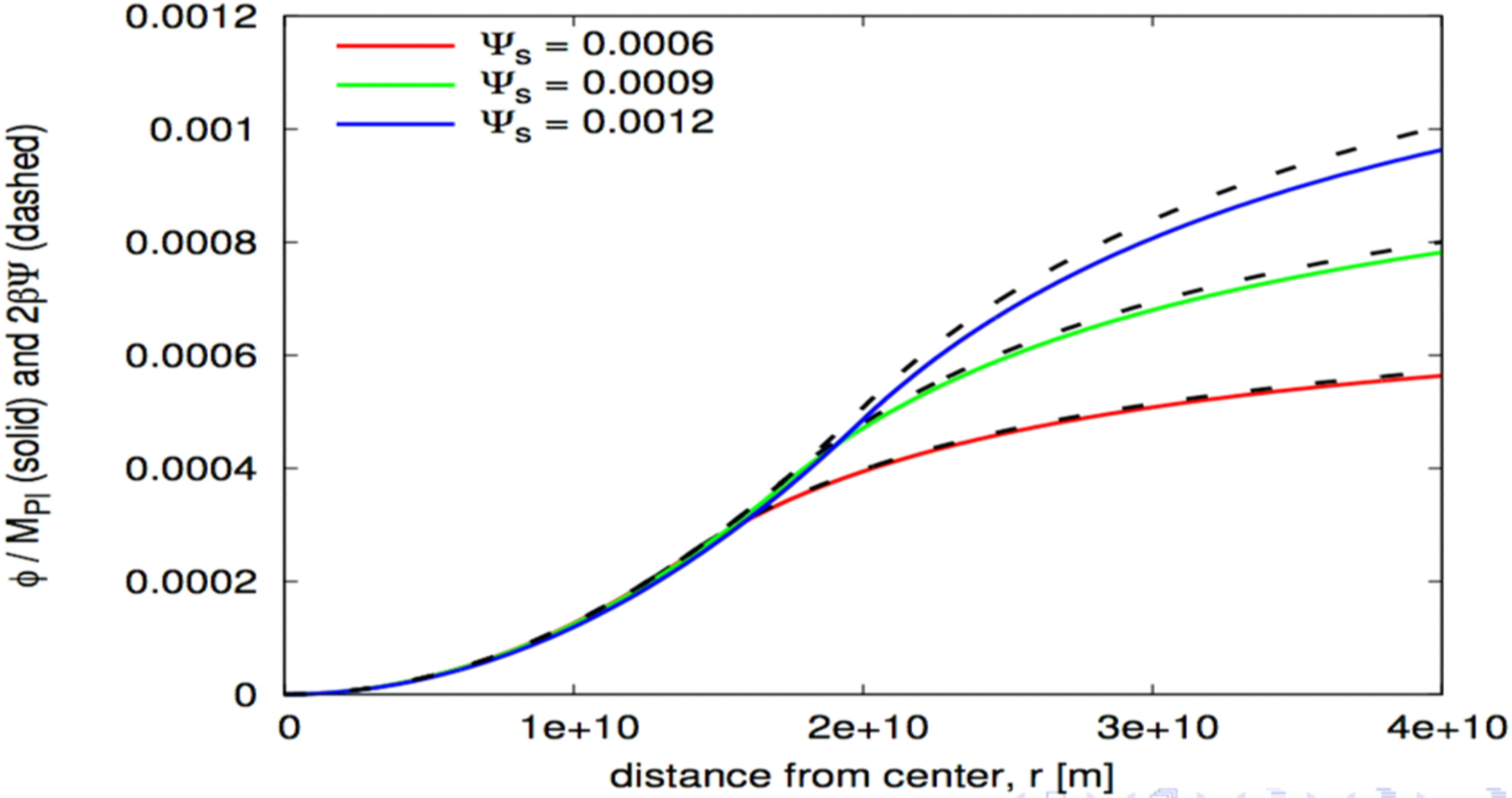

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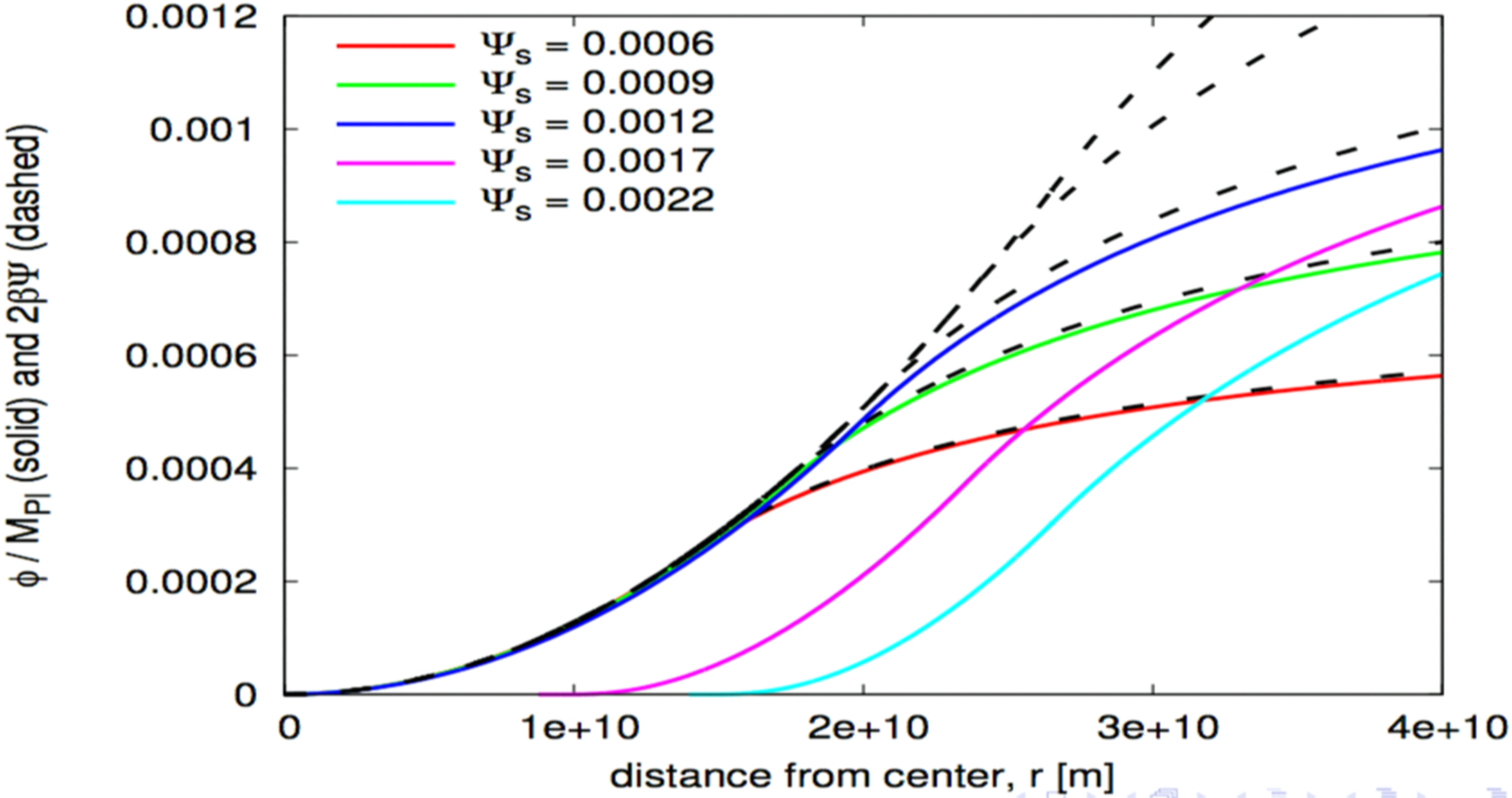
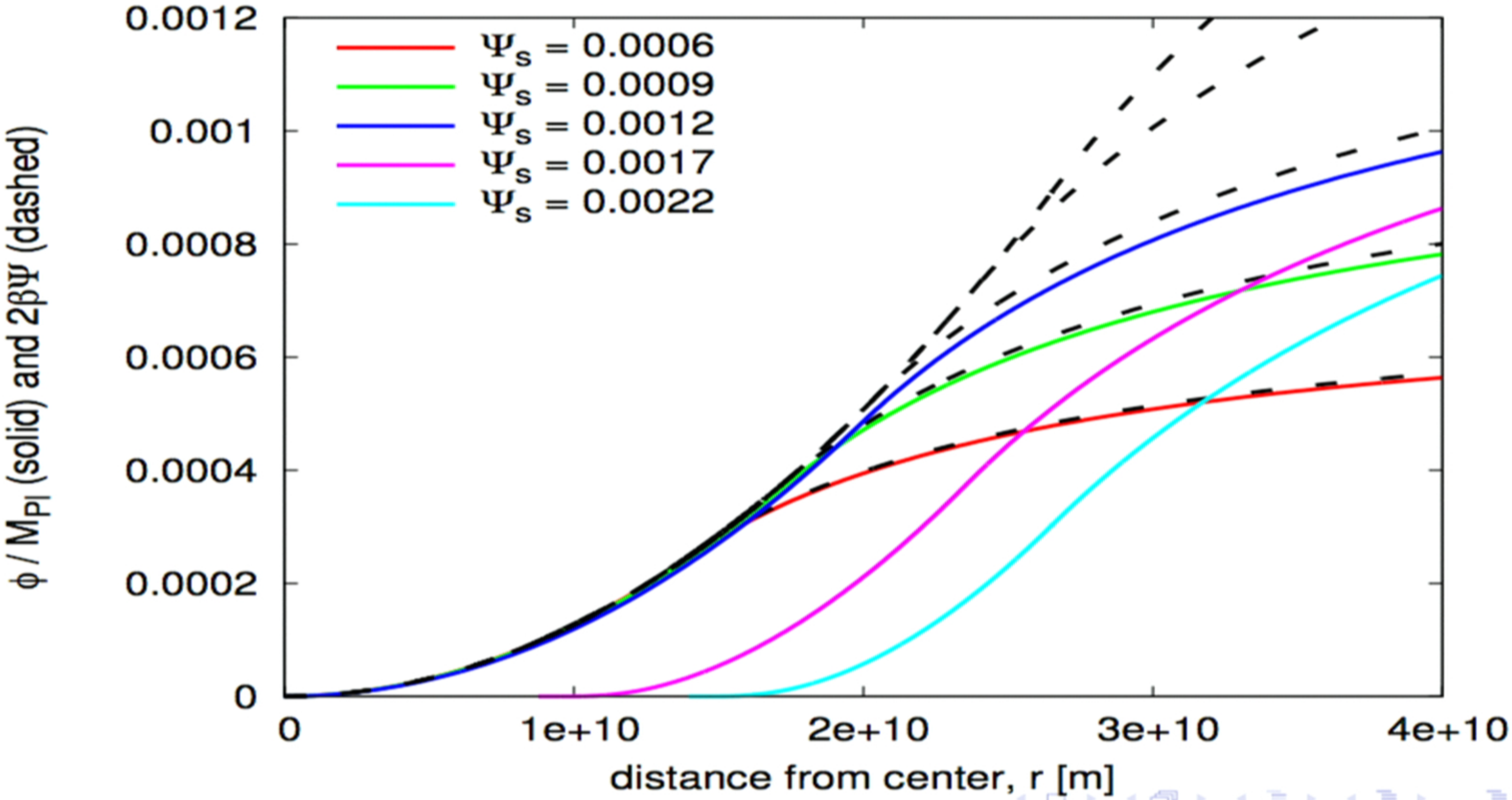
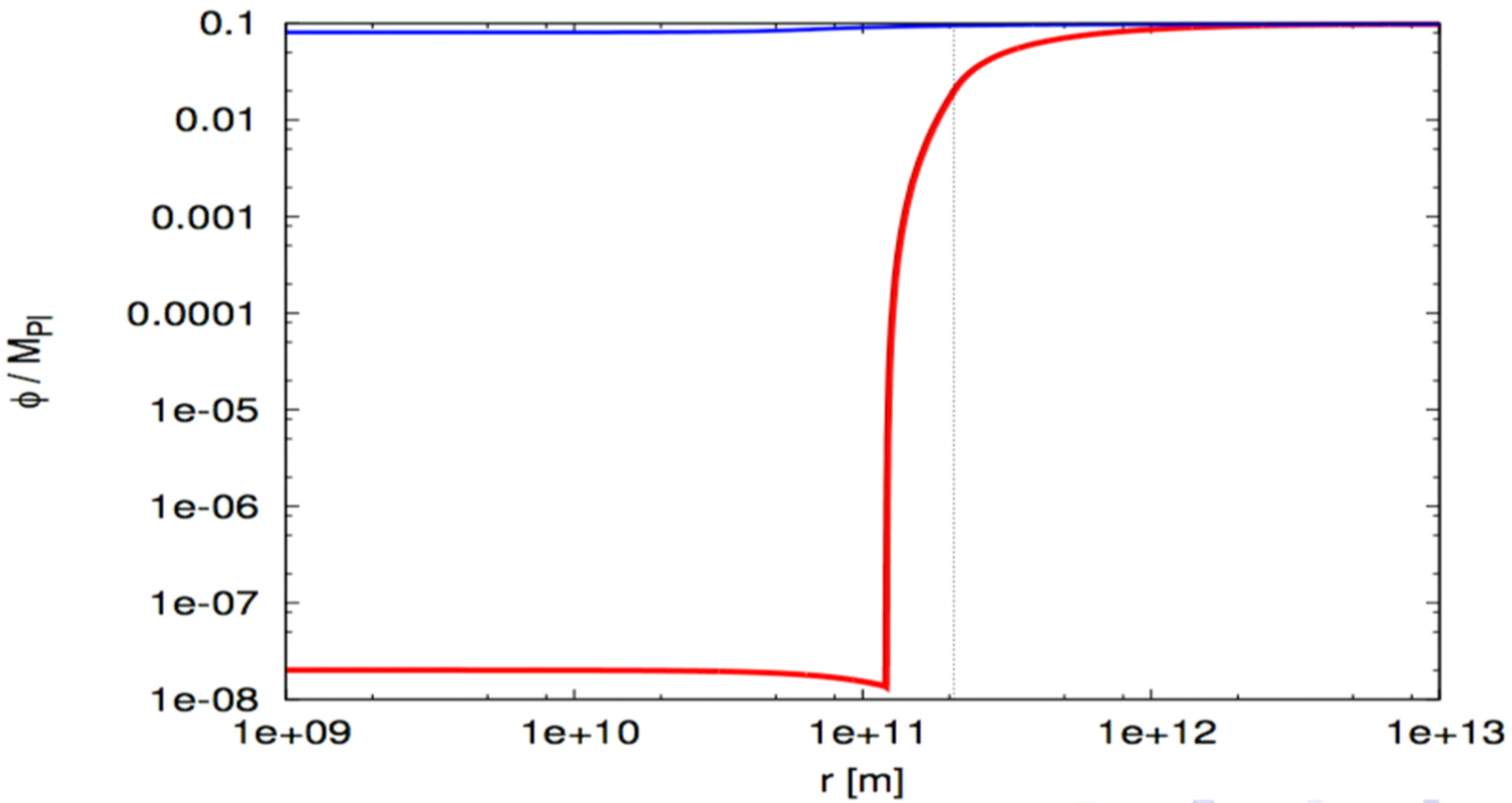


Screening in stars ($\chi_{\mathrm{scr}} = 0.0014$)

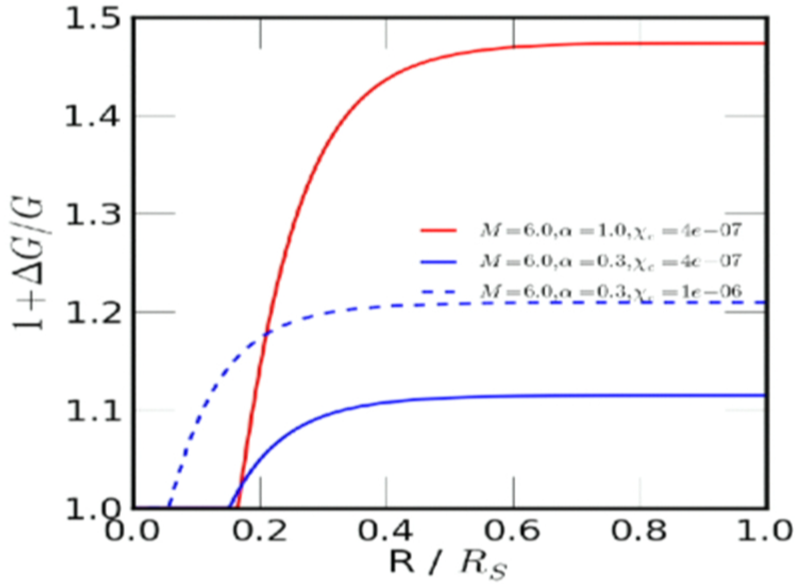


$\phi(r)$ in a relativistic star ($\chi_{\rm scr} = 0.1$)

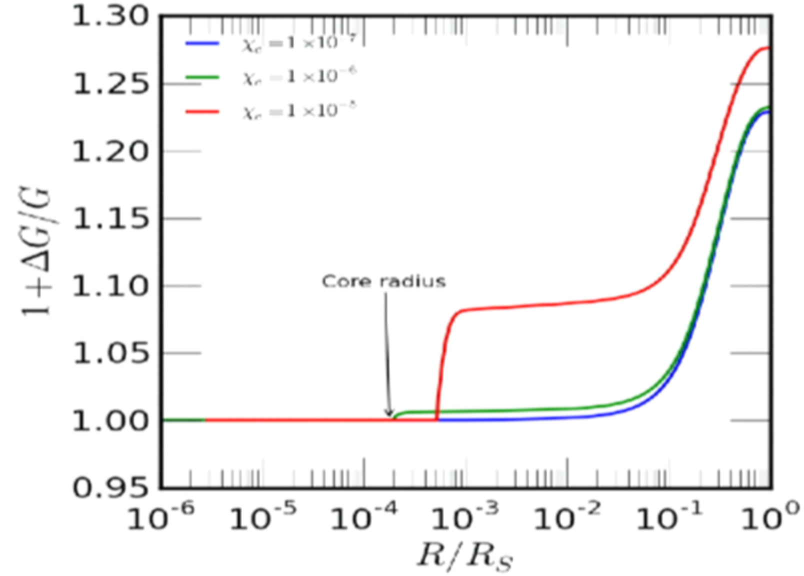


Chameleon fifth forces and unscreened stars

Cepheid variables
(location-dependent screening)



Tip of Red Giant Branch stars
(self-screening)



Fifth forces in unscreened galaxies affect Cepheid variables, but not TRGB stars. Observations require $\chi_{\rm scr} \lesssim 10^{-6}$.

B. Jain, V. Vikram, J. Sakstein, arXiv:1204.6044 (2012)

Chameleon fifth forces and unscreened stars

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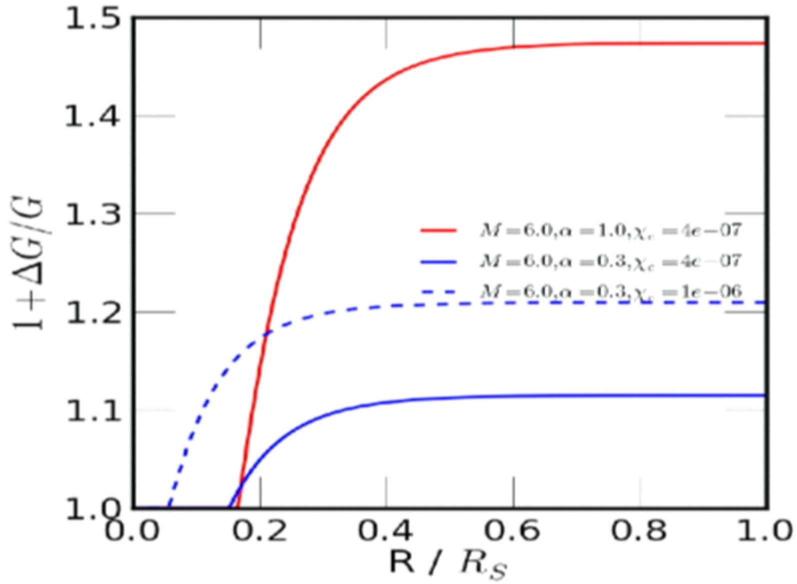

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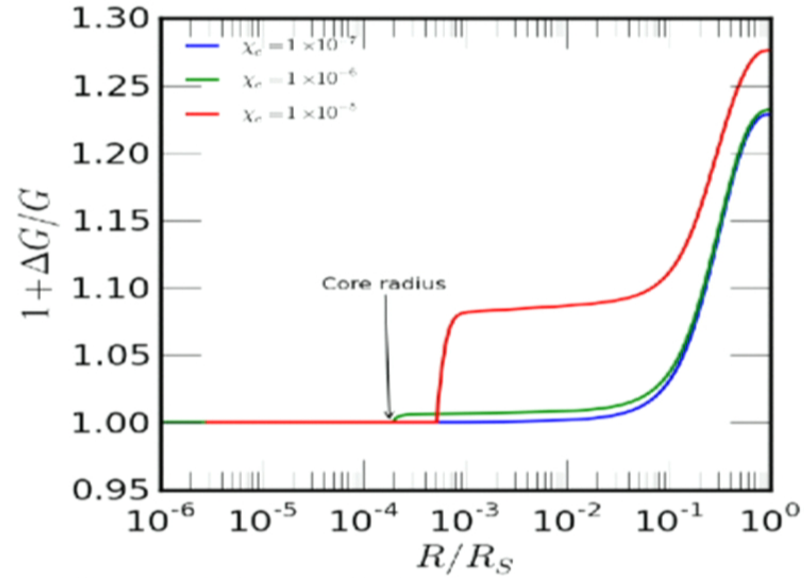

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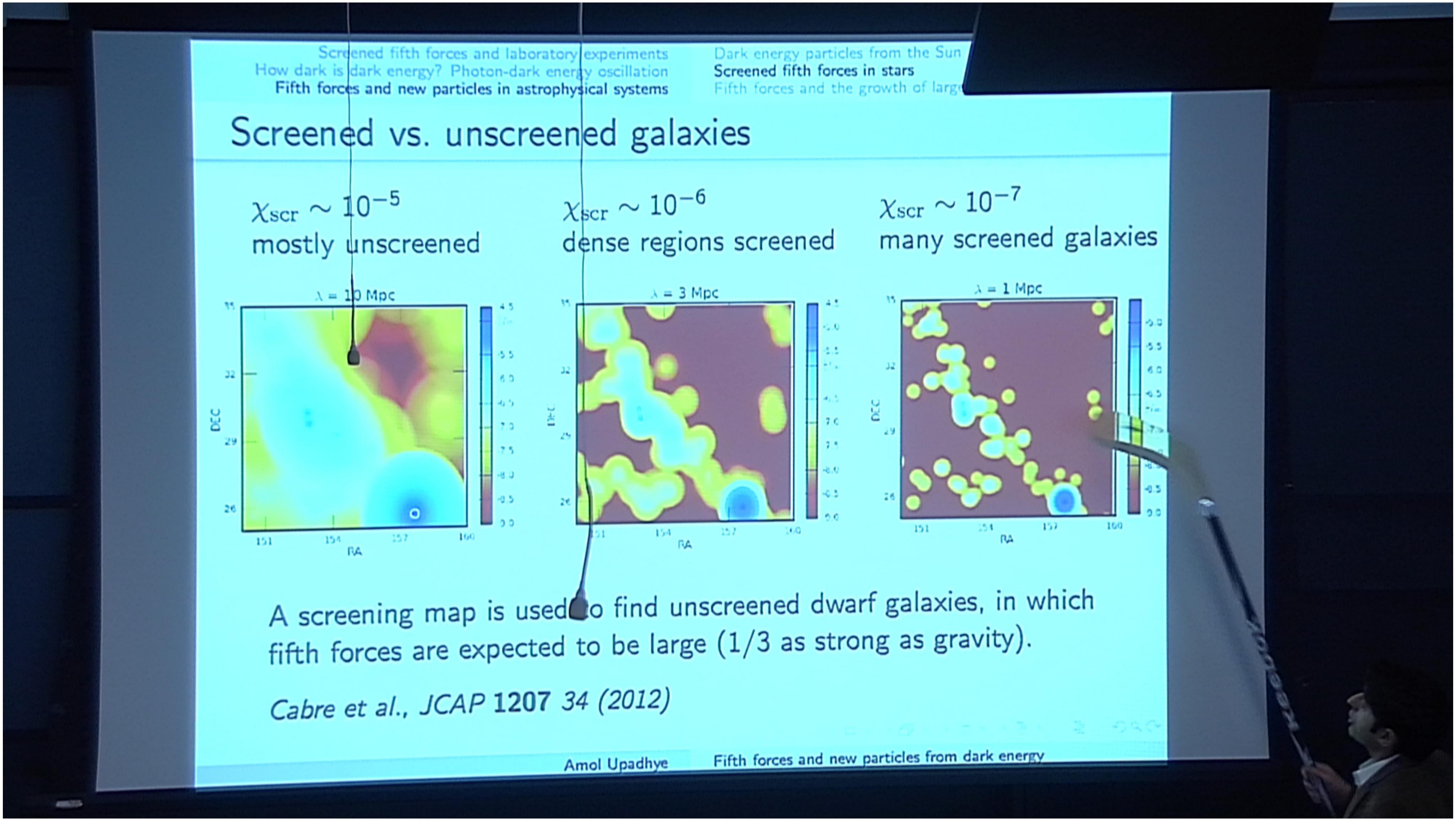
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Screened vs. unscreened galaxies
$\chi_{scr} \sim 10^{-5}$
mostly unscreened
$\chi_{scr} \sim 10^{-6}$
dense regions screened
$\chi_{scr} \sim 10^{-7}$
many screened galaxies
λ = 10 Mpc
λ = 3 Mpc
λ = 1 Mpc
DEC
RA
A screening map is used to find unscreened dwarf galaxies, in which fifth forces are expected to be large (1/3 as strong as gravity).
Cabre et al., JCAP 1207 34 (2012)
Amol Upadhye
Fifth forces and new particles from dark energy

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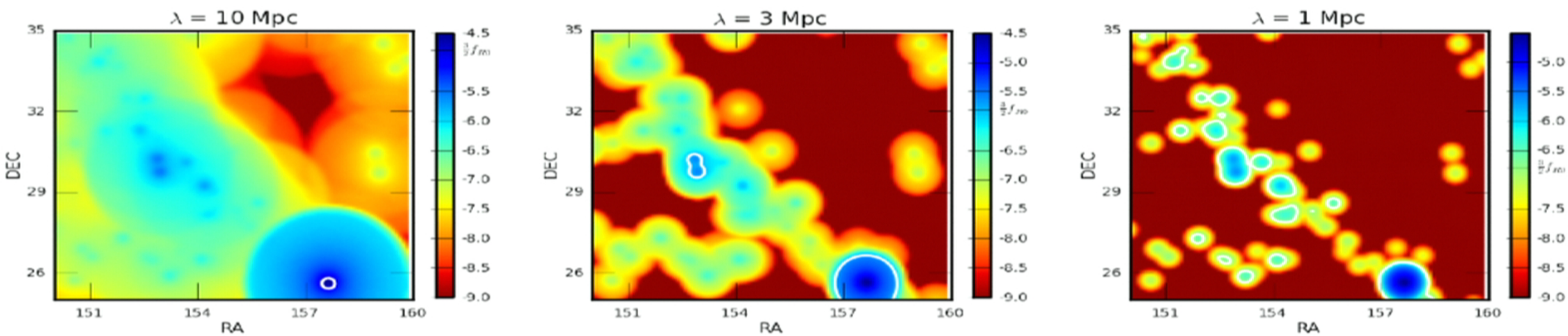

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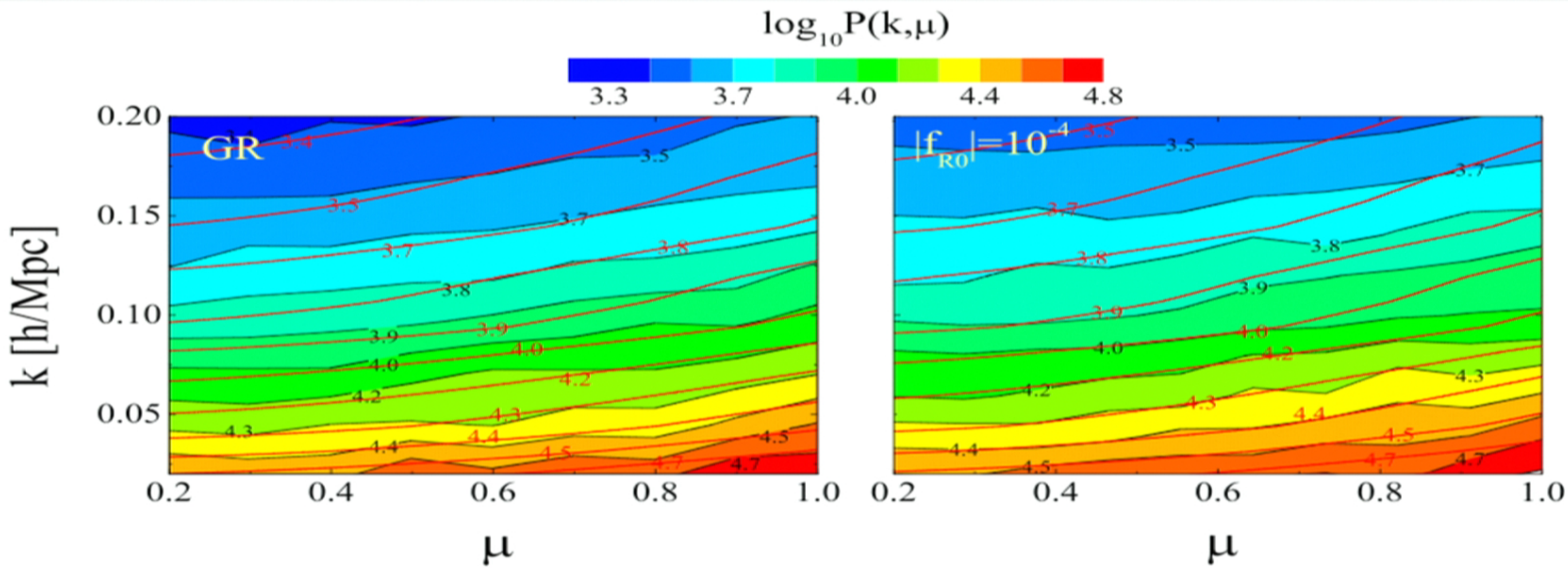
Cabre et al., JCAP **1207** *34 (2012)*

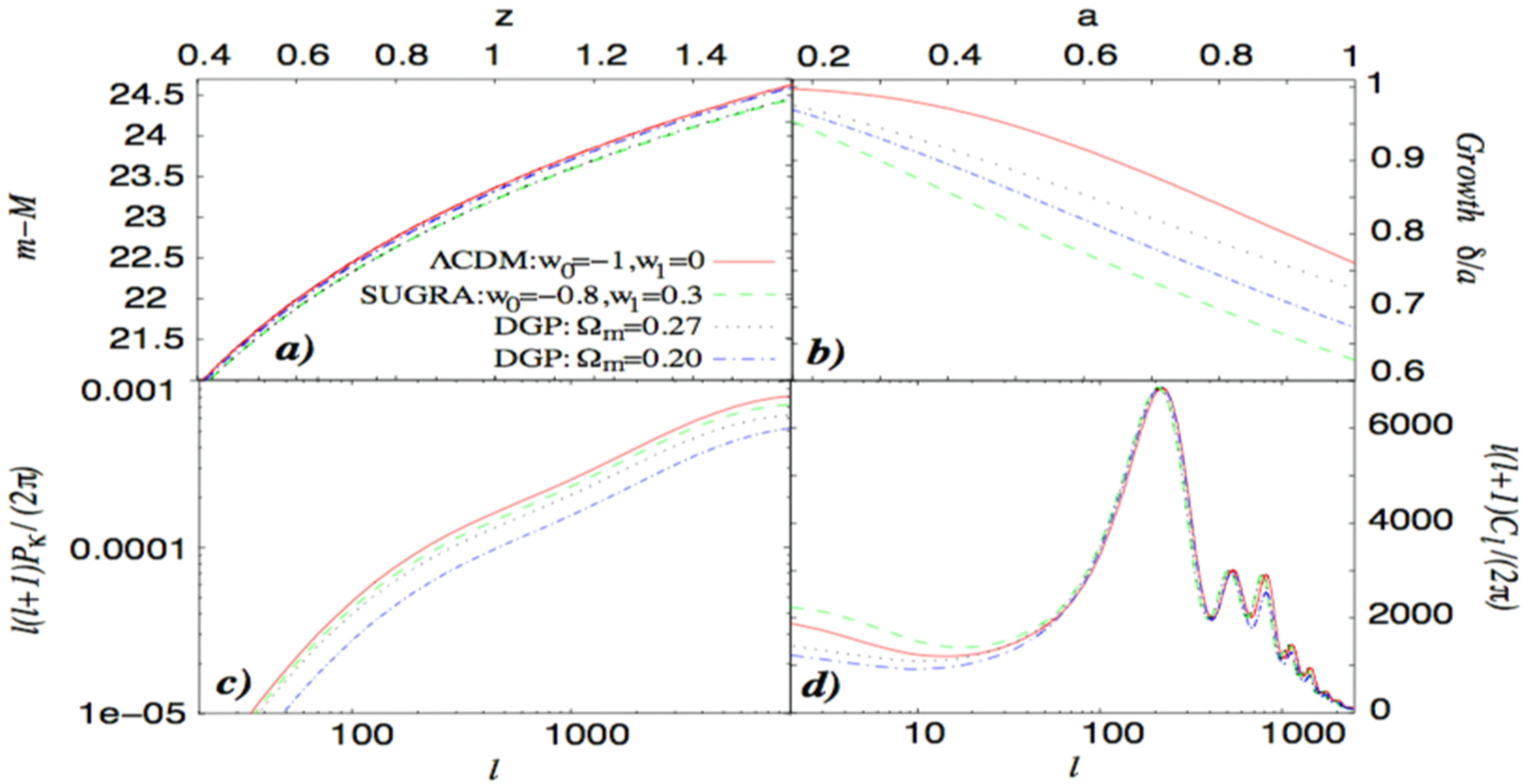
Fifth forces and galaxy velocities



Fifth forces cause galaxies to fall faster towards matter overdensities. In red shift space, matter appears more strongly clustered along the line of sight $\mu = 1$ (red-shift space distortions).

E. Jennings, et al., arXiv:1205.2698, to appear in MNRAS (2012)

Self-accelerated DGP: Ω_m sets expansion and growth

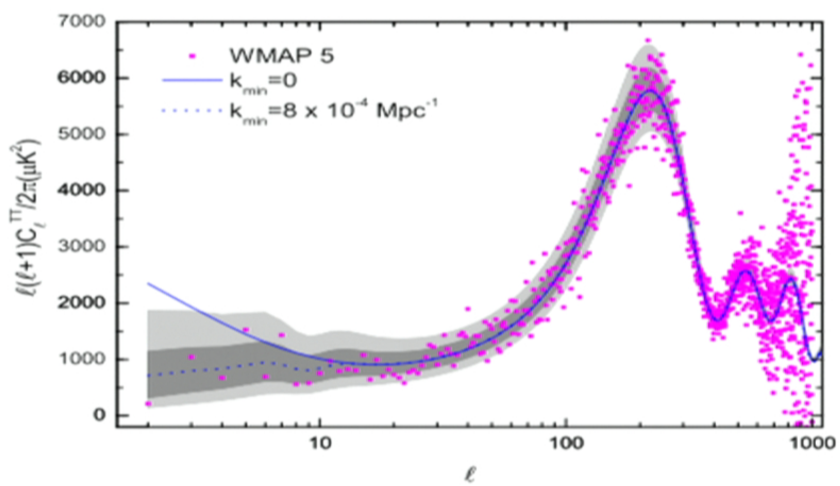


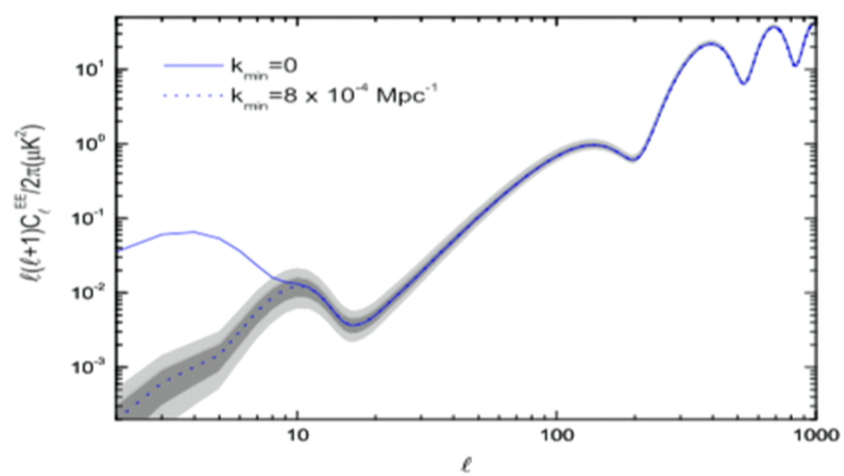
M. Ishak, AU, D. Spergel, PRD **74** 043513 (2006)

Combined data exclude self-accelerated DGP

- choose Ω_m to fit SNe, large-ℓ CMB $\Rightarrow$ 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)



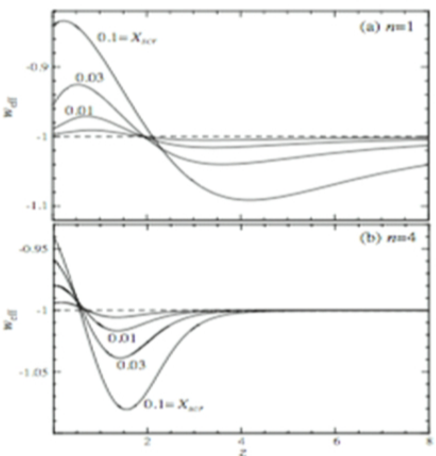


W. Fang, et al., PRD **78** *103509 (2008)*

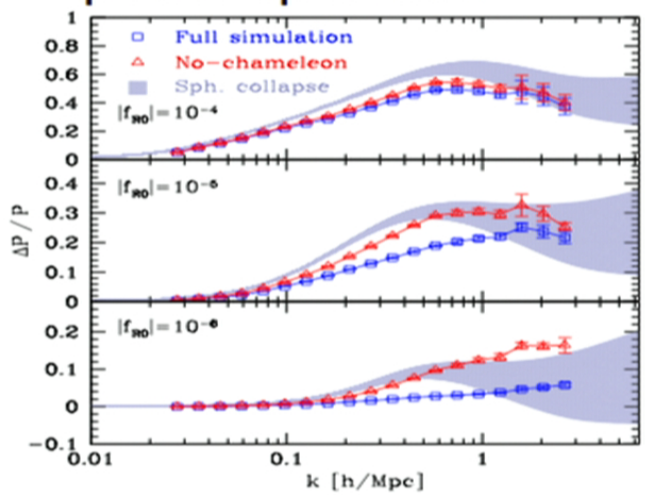
Cluster counts and $f(R)$/chameleon models

- $f(R)$ 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.

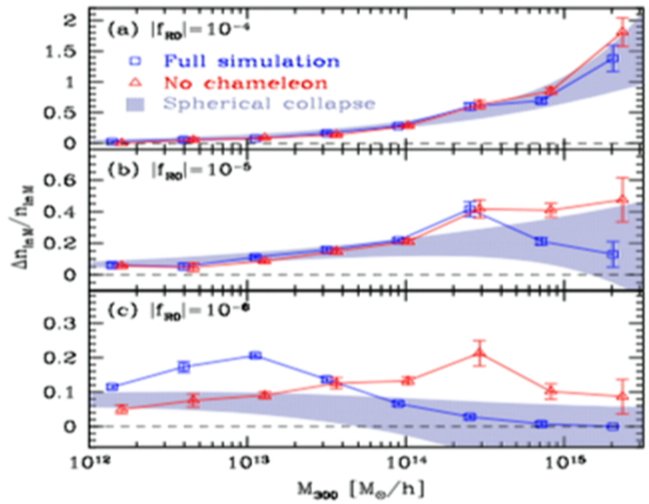
effective $w(z)$



power spectrum



cluster counts



Hu, Sawicki. PRD **76** *064004 (2007); Schmidt, Lima, Oyaizu, Hu. PRD* **79** *083518 (2009); Schmidt, Vikhlinin, Hu. PRD* **80** *083505 (2009)*

Conclusions

1. Dark energy could couple to matter with gravitation strength, as long as the resulting fifth force is screened locally.
2. Modern torsion pendulum experiments such as Eöt-Wash can probe the dark energy scale $\sim 10^{-3}$ eV $\sim (0.1\ \mathrm{mm})^{-1}$, allowing several interesting dark energy models to be tested.
   - quantum-stable chameleons with $\beta \sim 1$
   - symmetrons with $M \sim 1$ TeV, $\mu \sim 10^{-3}$ eV, $\lambda \lesssim 1$
3. Particles of dark energy can be produced through photon couplings. Such particles may be probed using afterglow experiments (CHASE), microwave cavity experiments (ADMX), and helioscopes (CAST).
4. Chameleon dark energy in a different regime can be tested by searching for unscreened stars in nearby galaxies, or by looking for fifth force enhancements to the growth of large-scale cosmological structure.