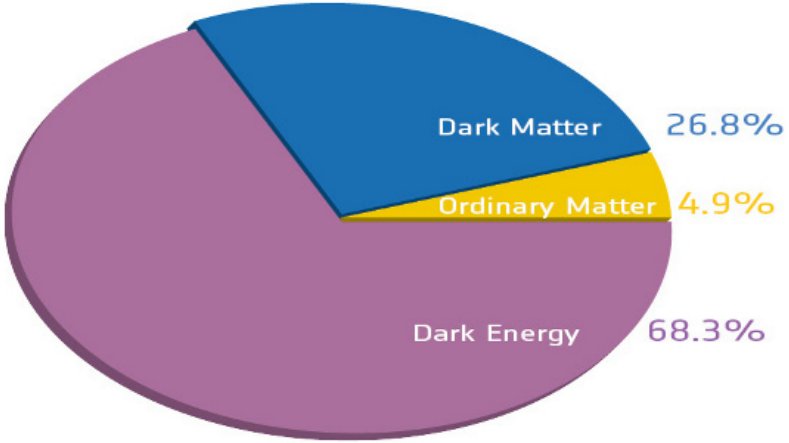
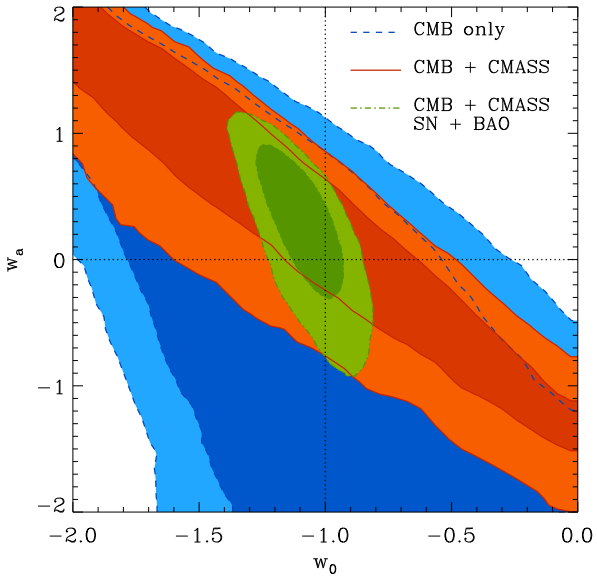
High-intensity searches for dark energy and modified gravity

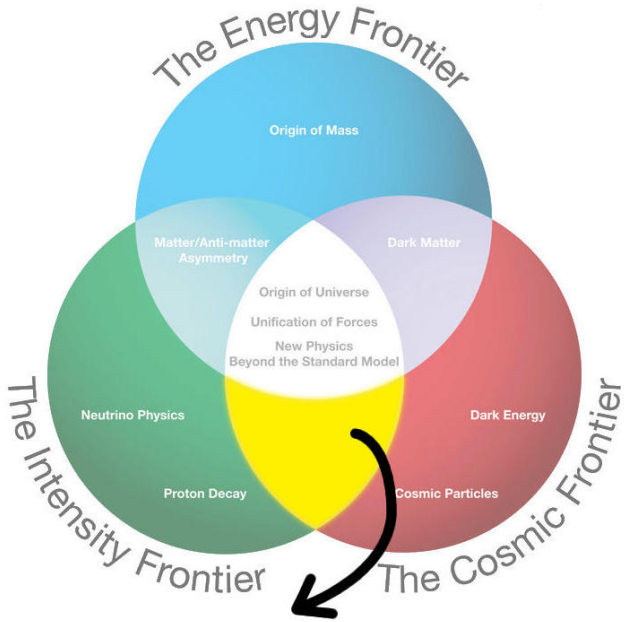
Amol Upadhye
Argonne National Lab
August 2, 2013

Cosmic acceleration





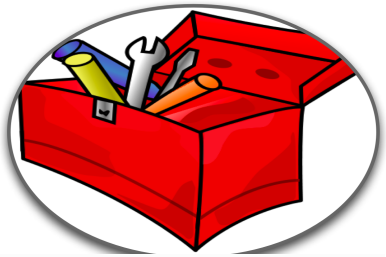
Evolution with time

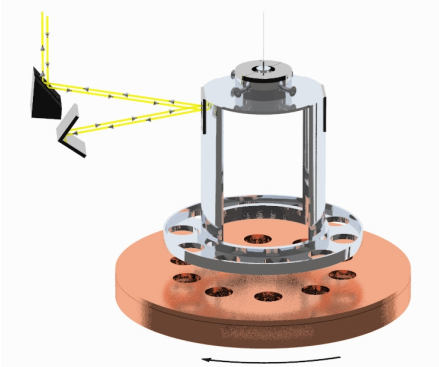


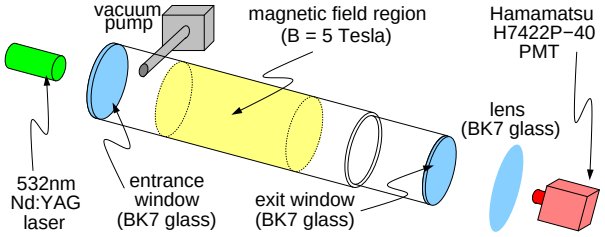
Coupling to known particles

Outline

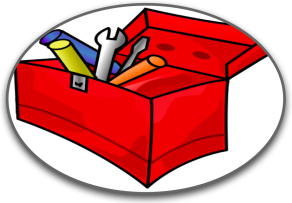
1. Introduction
   - Motivation: DE scale $M_\Lambda = 2.4 \times 10^{-3}$ eV
   - Dark energy: a phenomenological tool box
   - Example: Chameleon screening
2. Fifth forces
   - Quantum-stable chameleons
   - Eöt-Wash constraints and forecasts
   - Neutron experiments
3. New particles
   - Production 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: $R \to f(R)$	Conformal trans.: $\Rightarrow$ chameleon	matter coupling, effective $m(\rho)$

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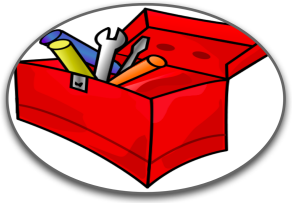

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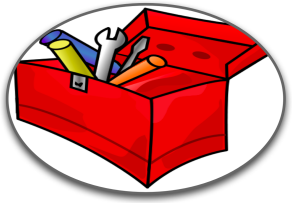

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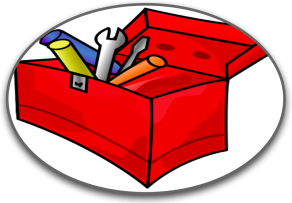

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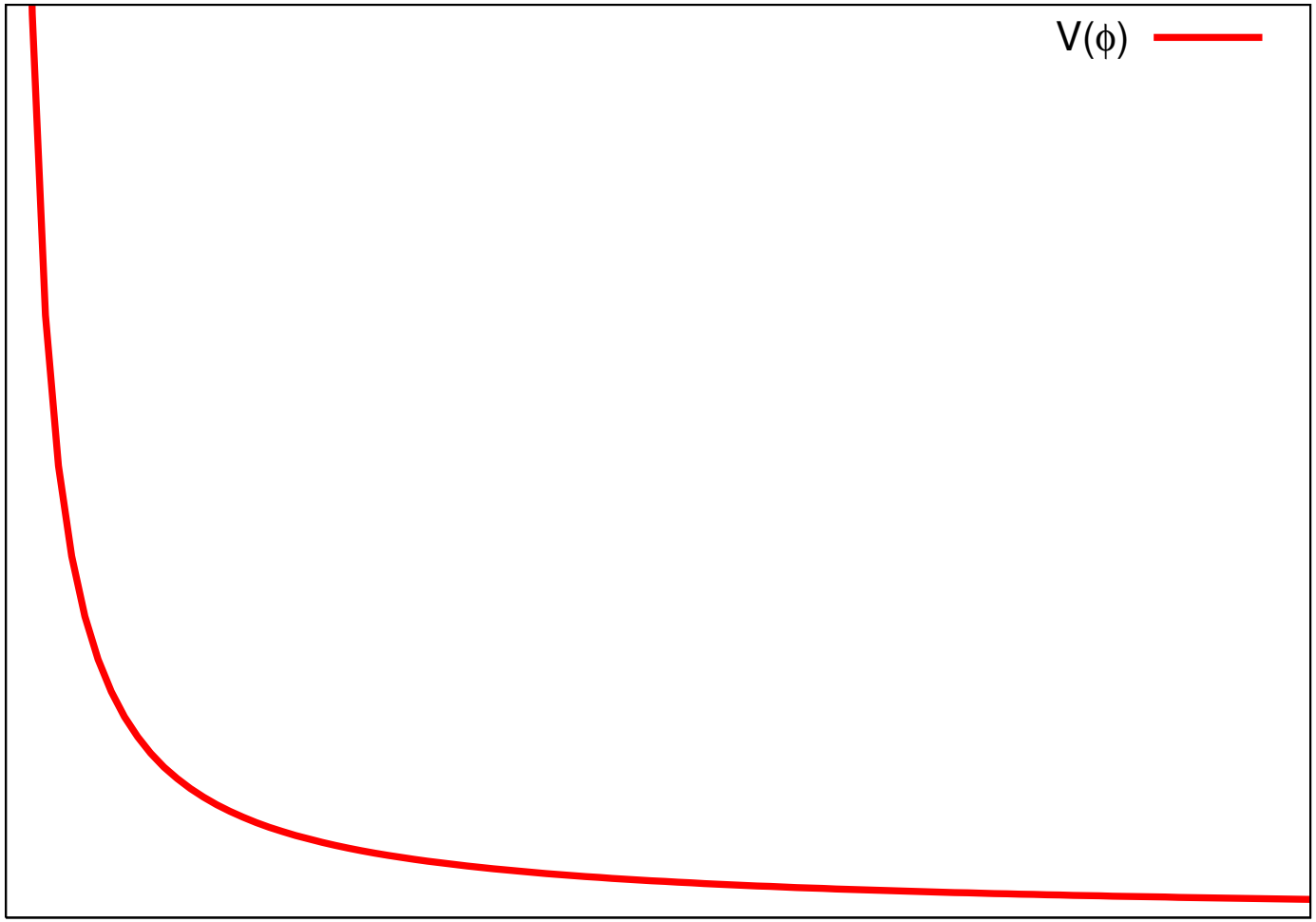
Kaluza-Klein, etc.: compact extra dim.	Small extra dim. $\Rightarrow$ radion	matter coupling, photon coupling

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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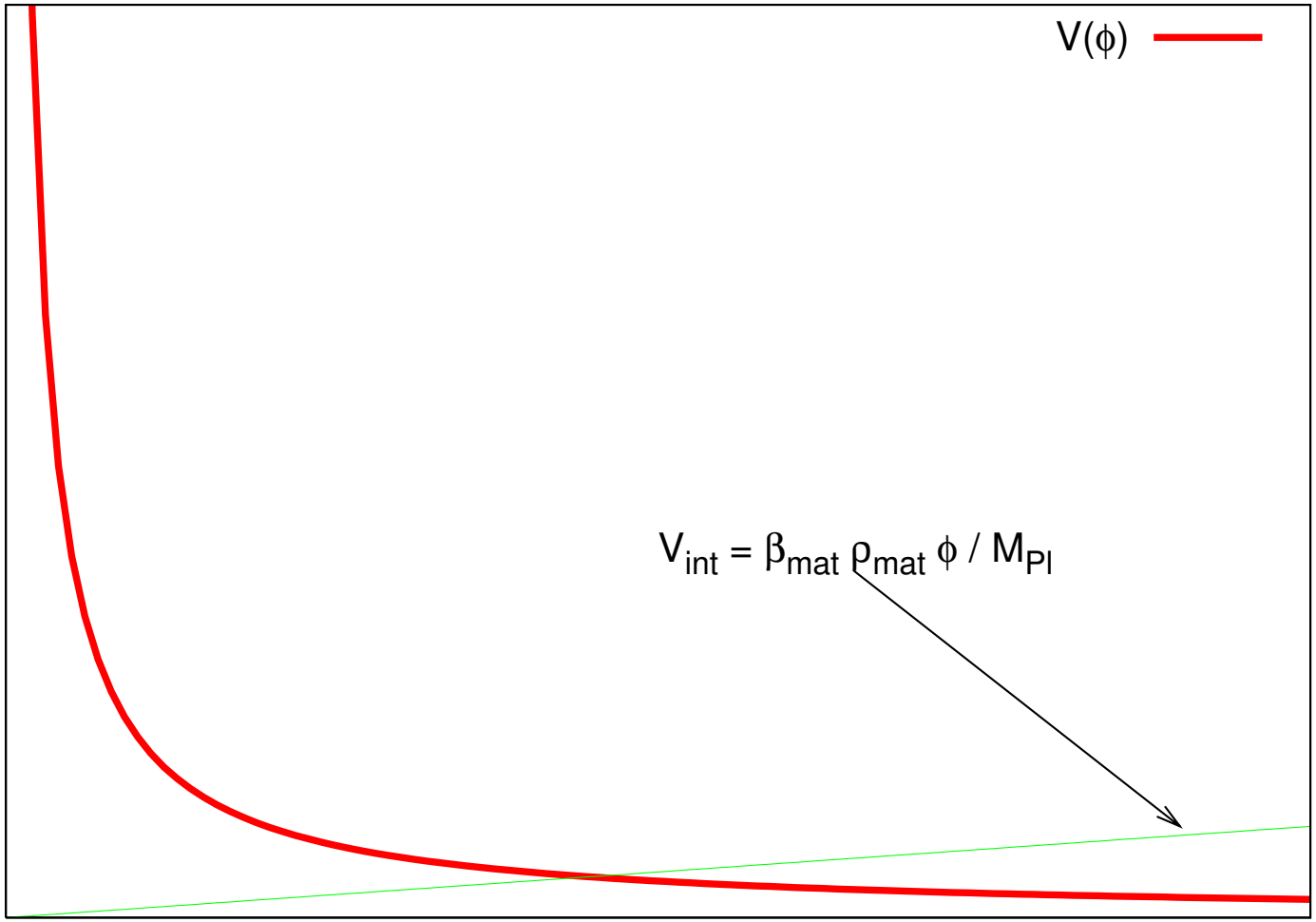

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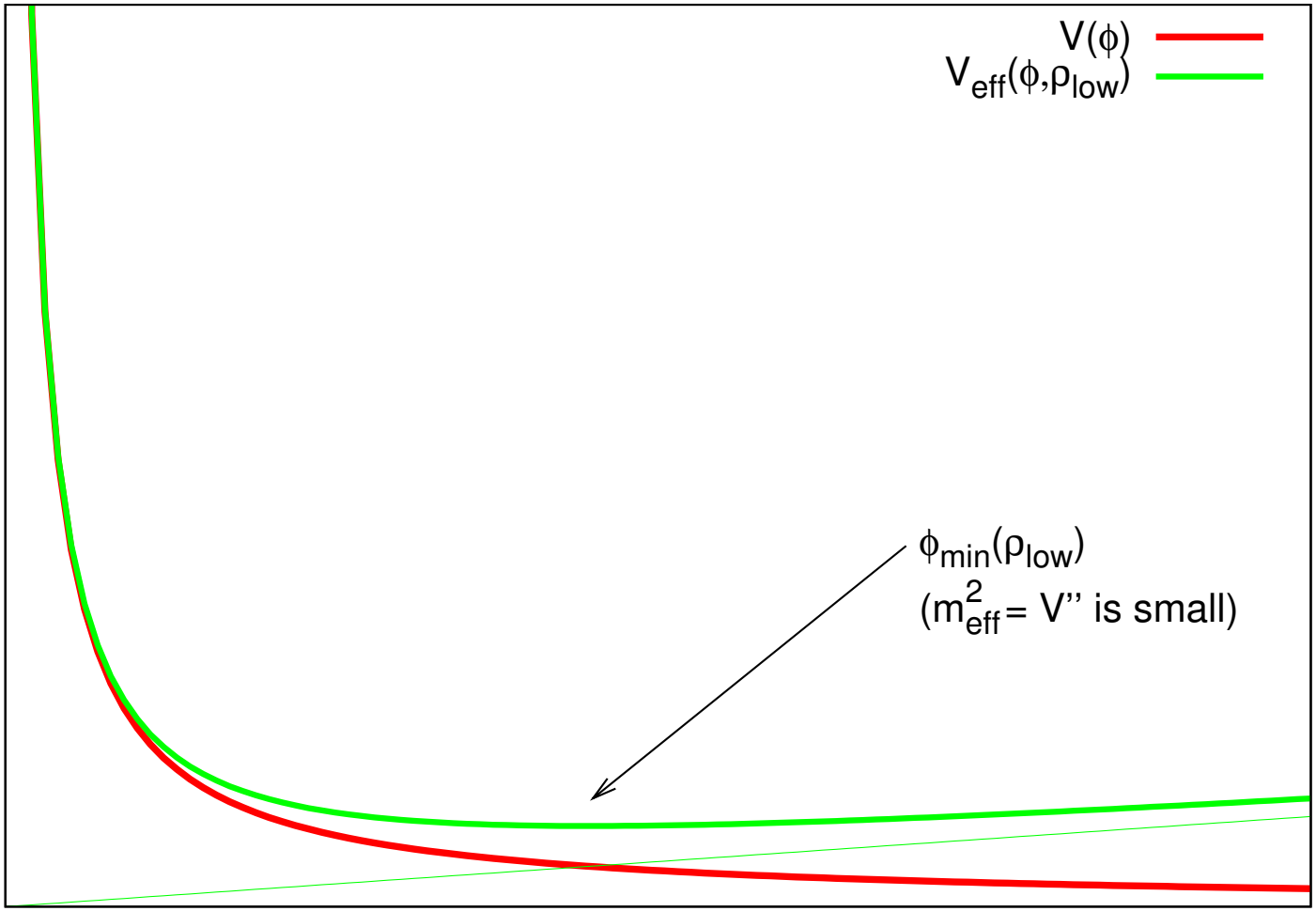

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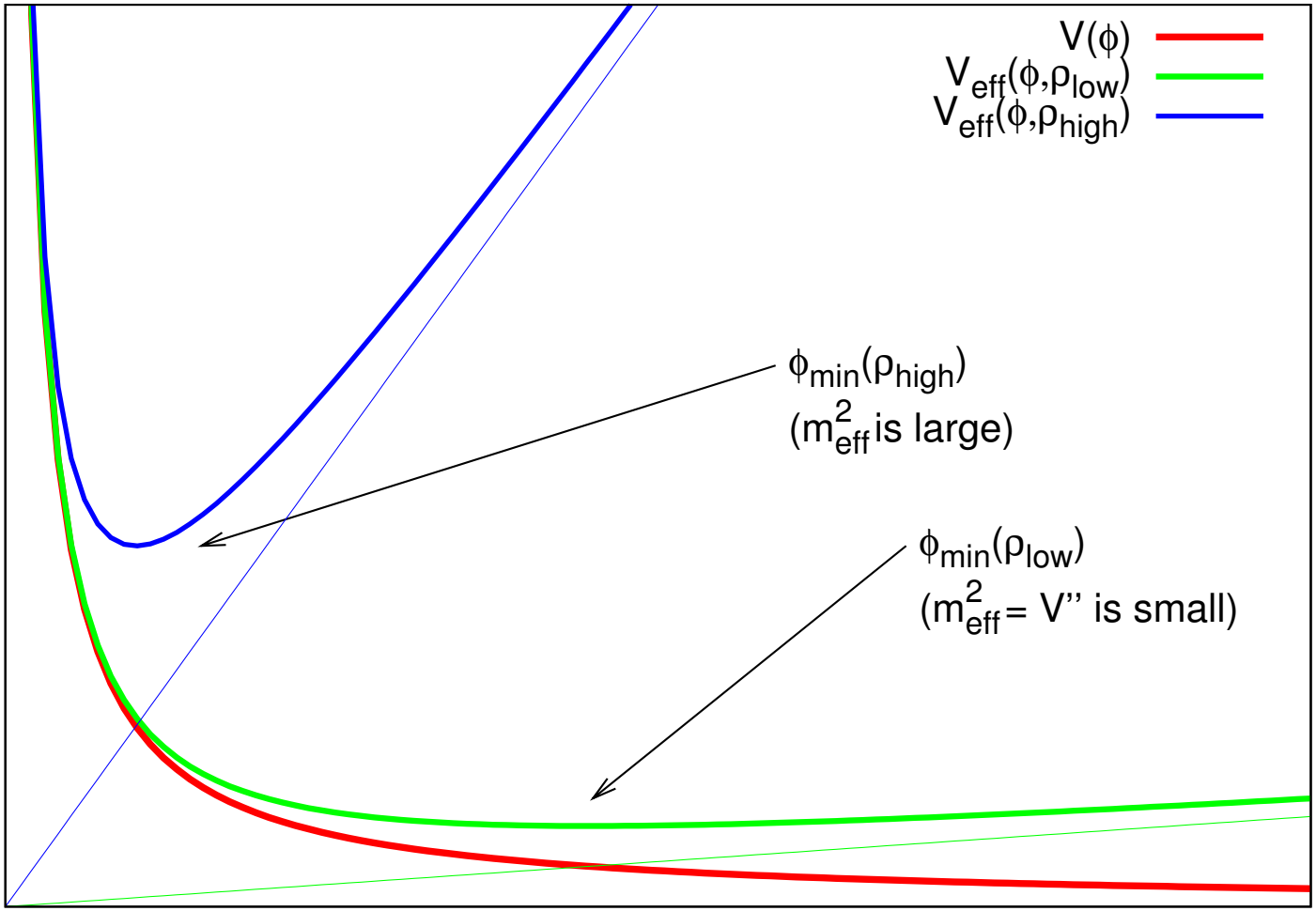
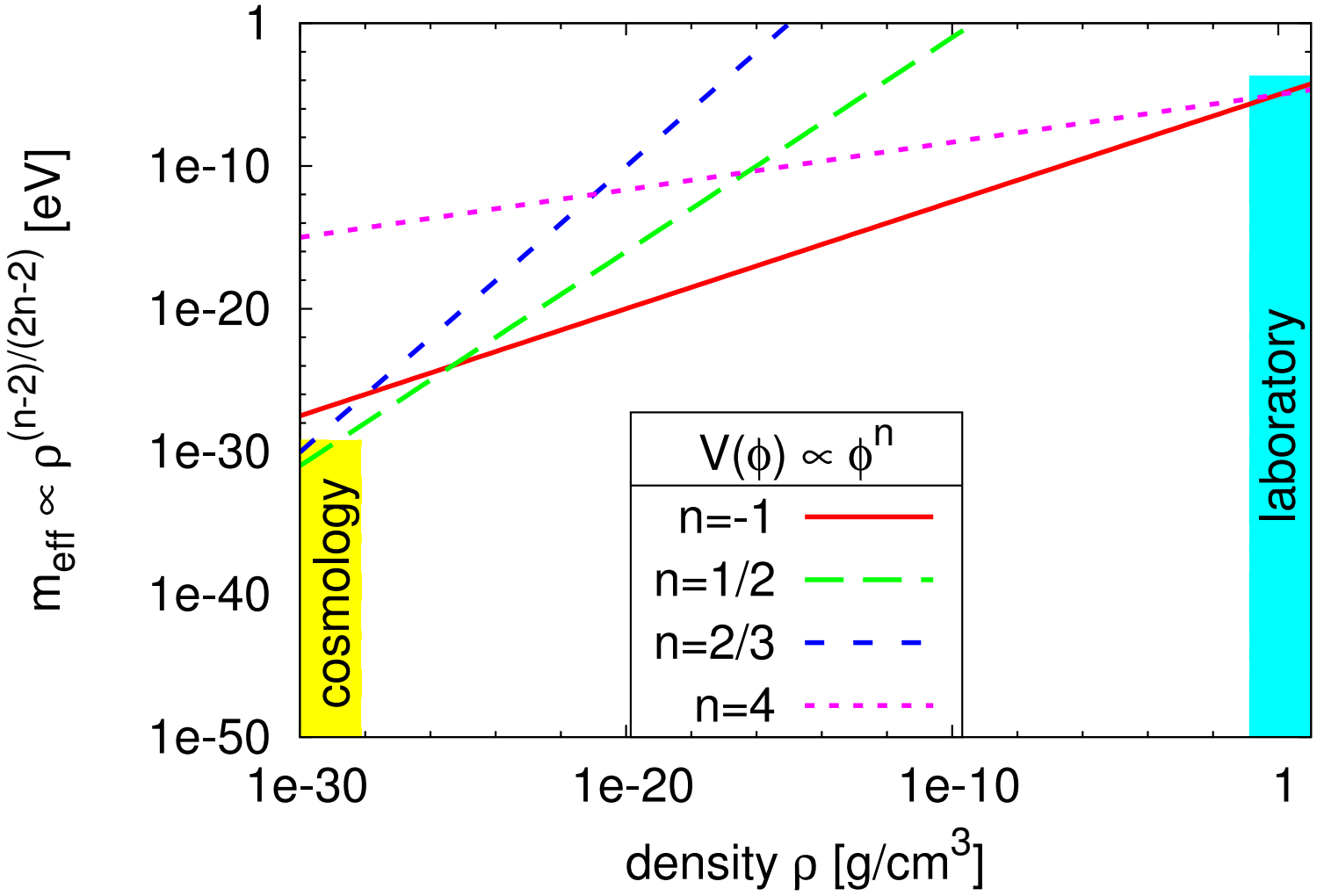


At which scale should we probe each model?

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



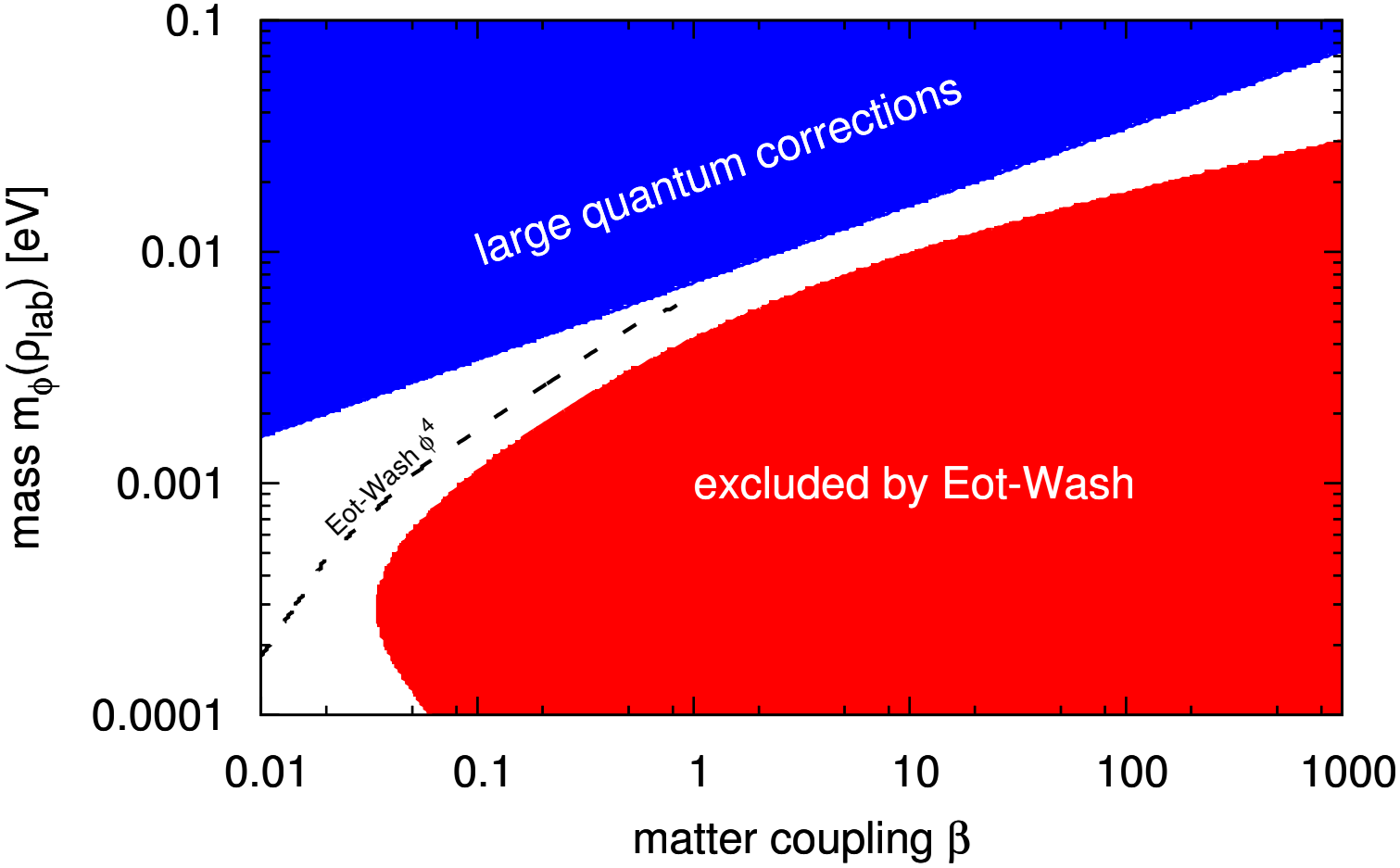
AU, PRD **86***:102003(2012)[arXiv:1209.0211]*

Part II: Fifth forces

Laboratory benchmark: "quantum-stable" chameleons

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

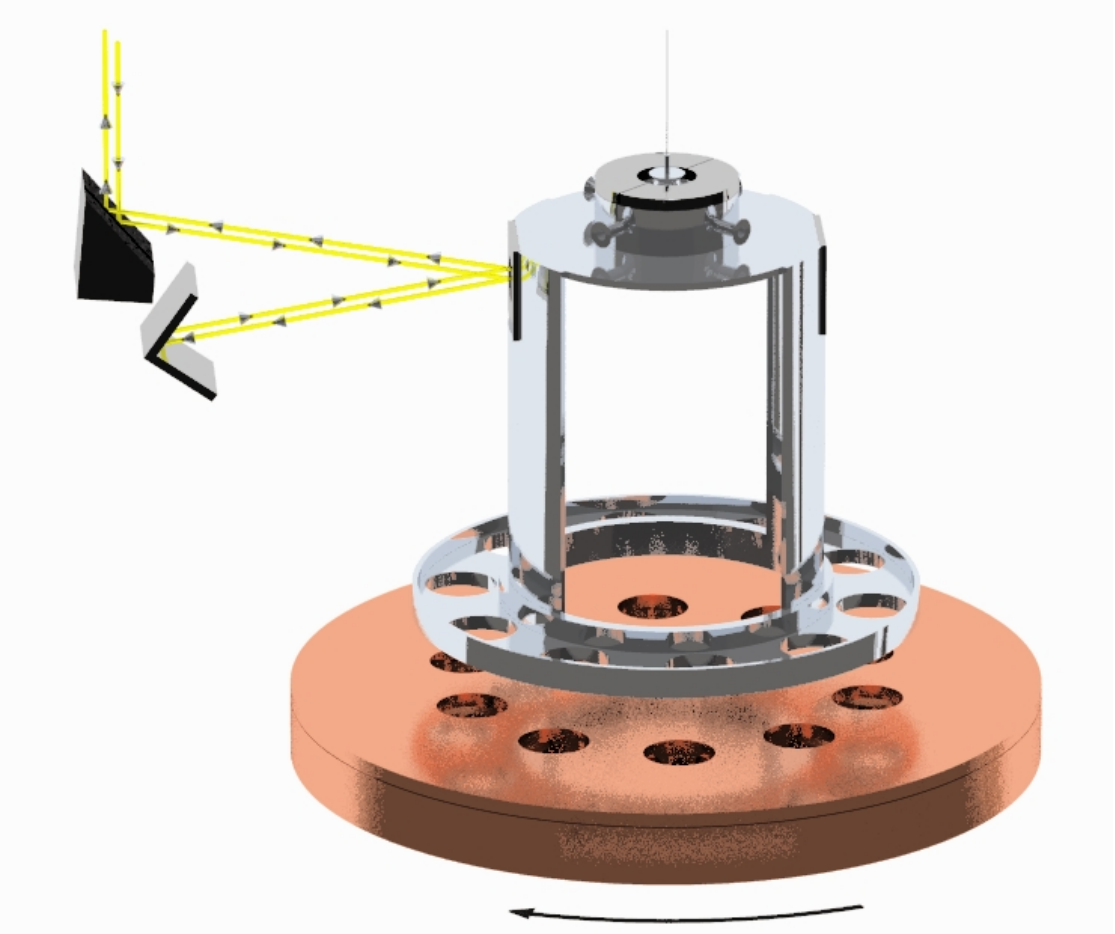
$$\Rightarrow m_{\mathrm{eff}} \leq \left(\frac{48\pi^2\beta^2\rho^2}{M_{\mathrm{Pl}}^2}\right)^{1/6} = 0.0073\left(\frac{\beta\rho}{10\mathrm{g/cm}^3}\right)^{1/6}\mathrm{eV}$$

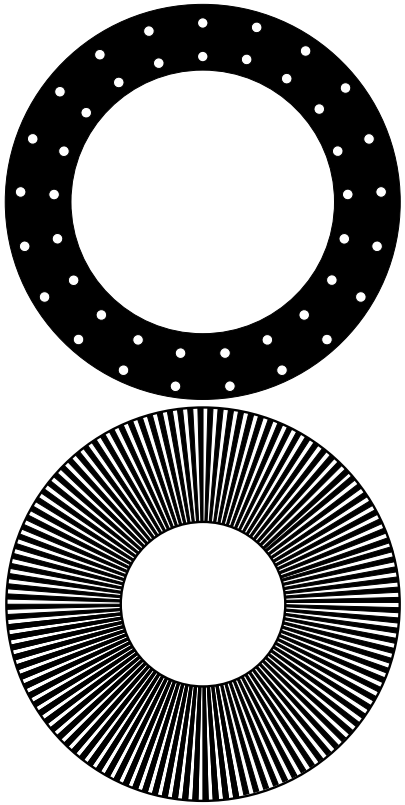


AU, Hu, Khoury, PRL **109***:041301(2012)[arXiv:1204.3906]*

Fifth-force tests using a torsion pendulum

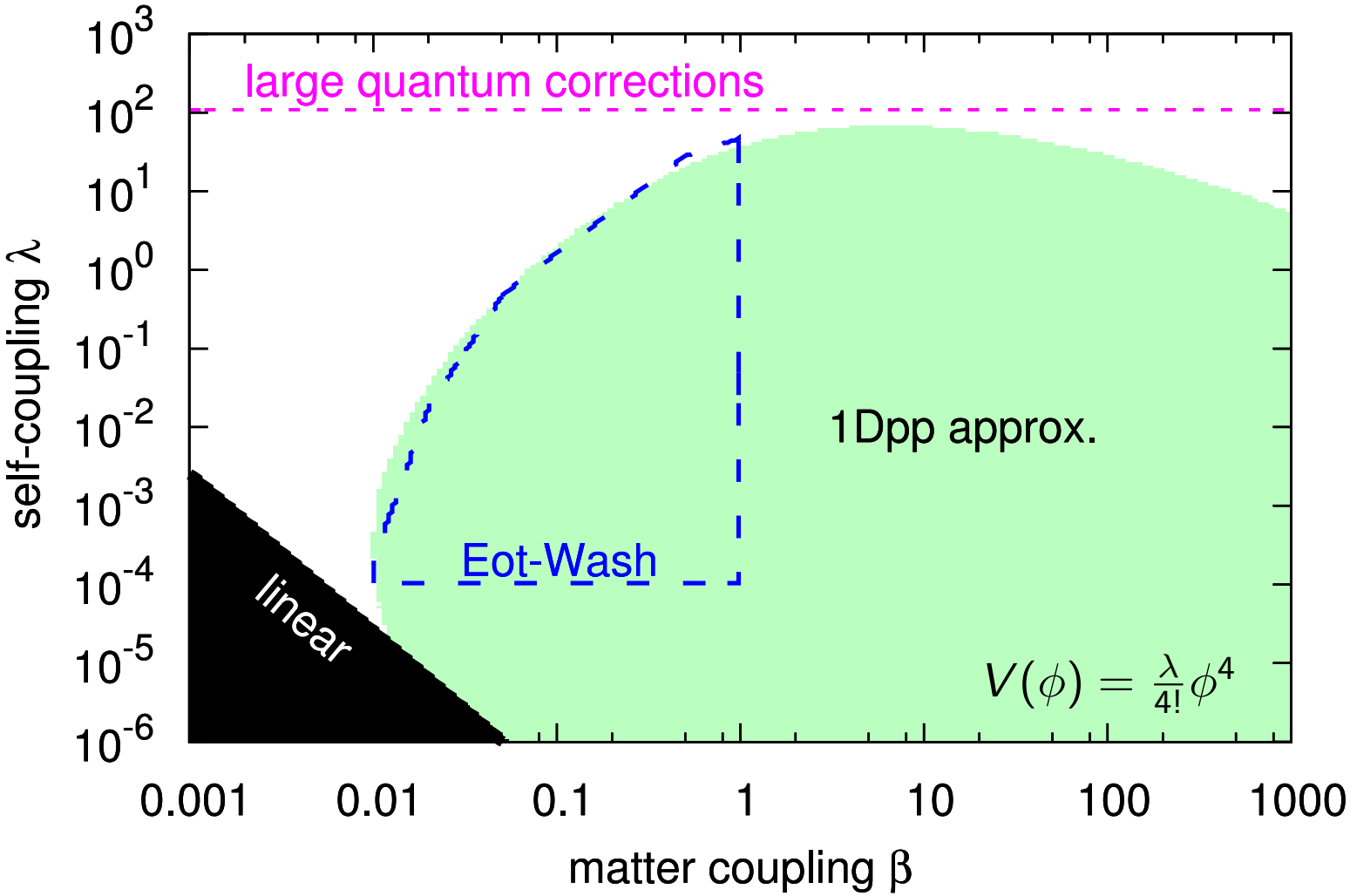
Eöt-Wash Experiment





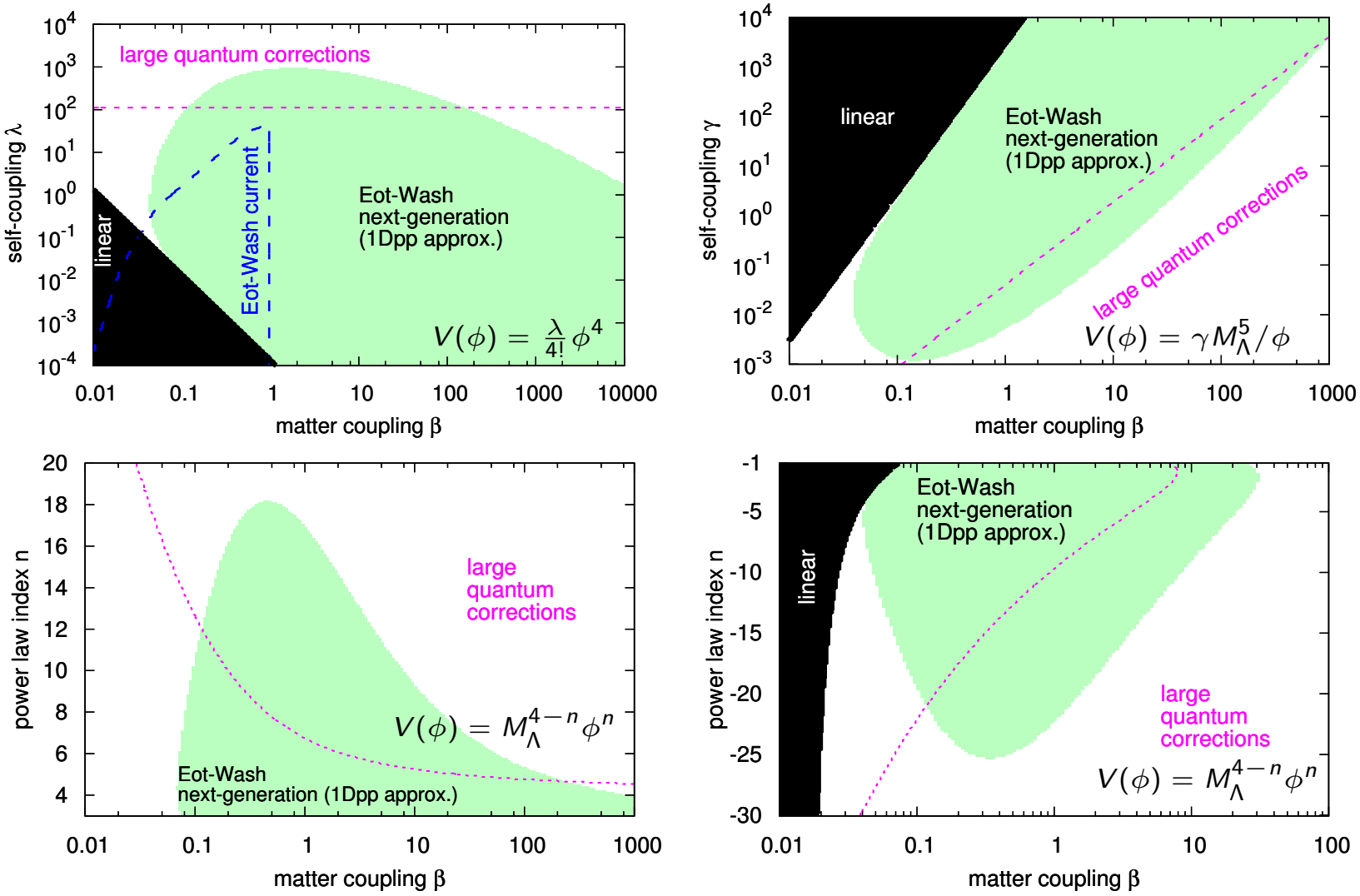
http://www.npl.washington.edu/eotwash

Eöt-Wash constraints on chameleons



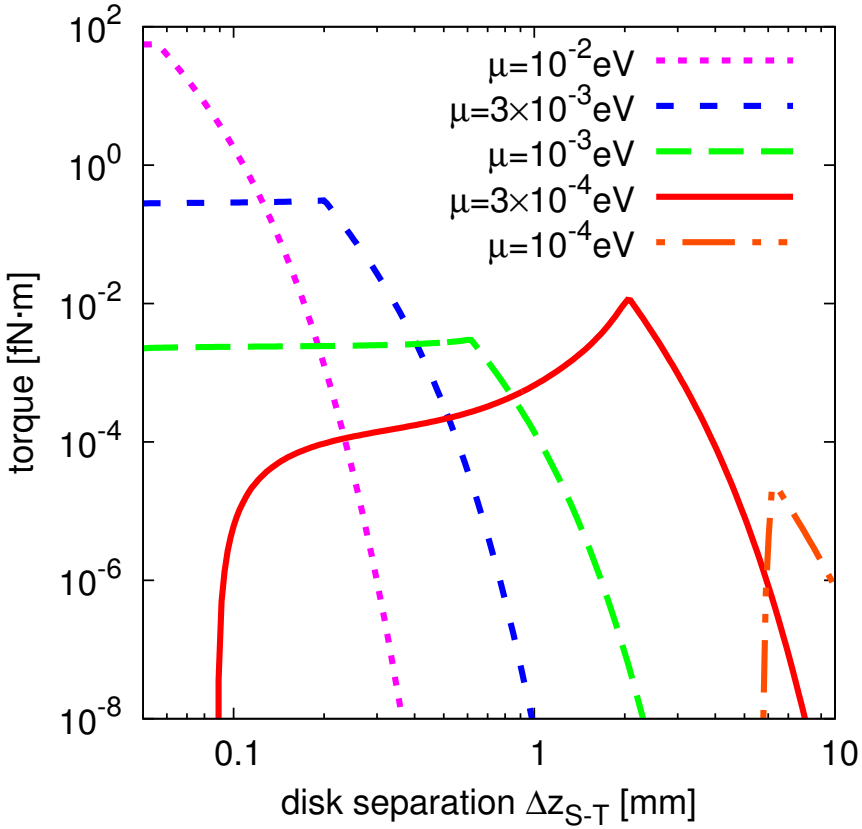
Eöt-Wash: *Adelberger, Heckel, Hoedl, Hoyle, Kapner, AU. PRL* **98** *131104 (2007)*
1Dpp: *AU, PRD* **86** *102003 (2012) [arXiv:1209.0211]*

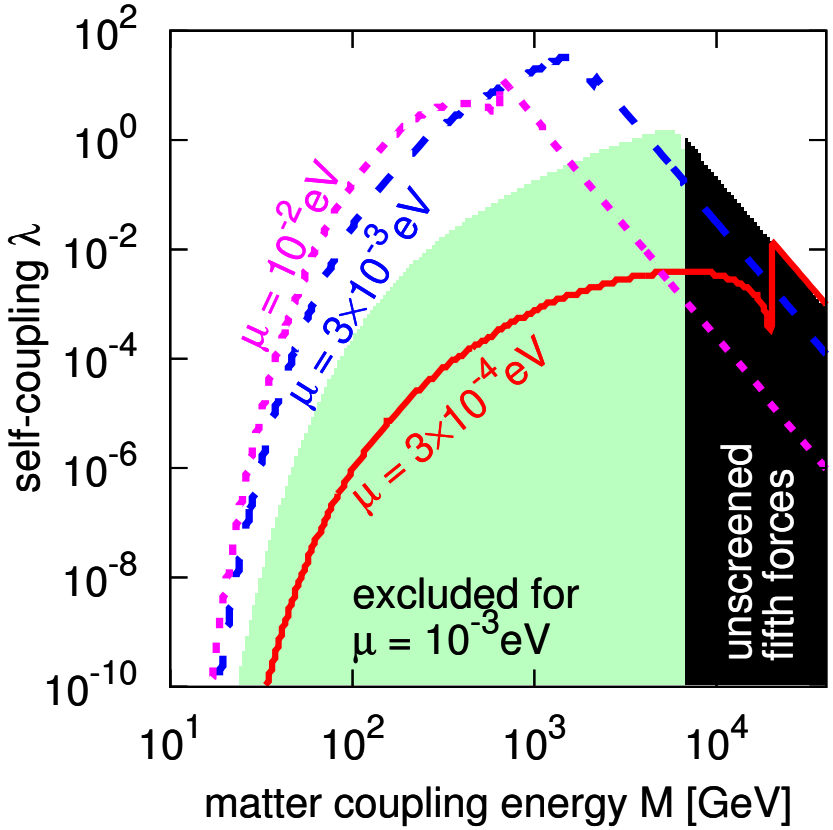
Next-generation Eöt-Wash: chameleon forecasts



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

Estimated (1Dpp) Eöt-Wash constraints on symmetrons





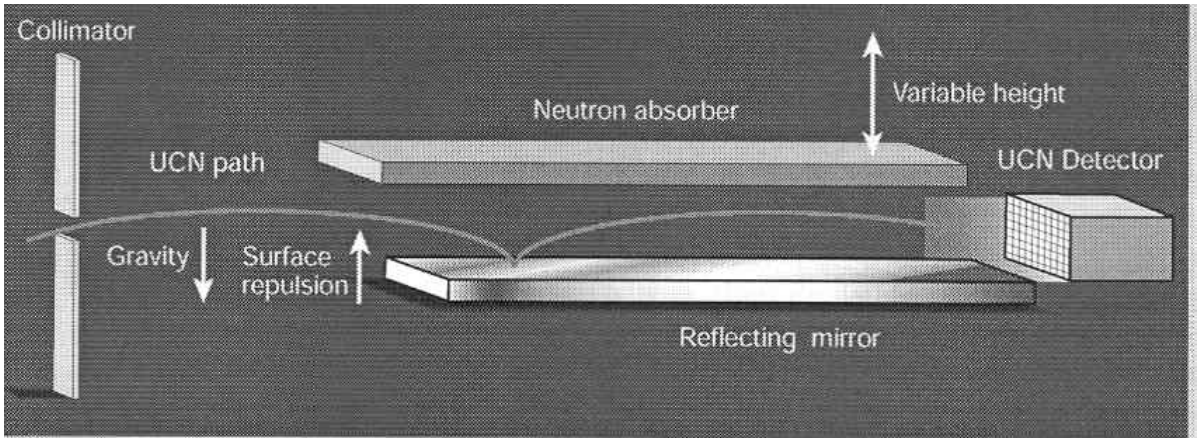
Symmetron effective potential: $V_{\rm eff} = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4!}\phi^4$

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

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

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

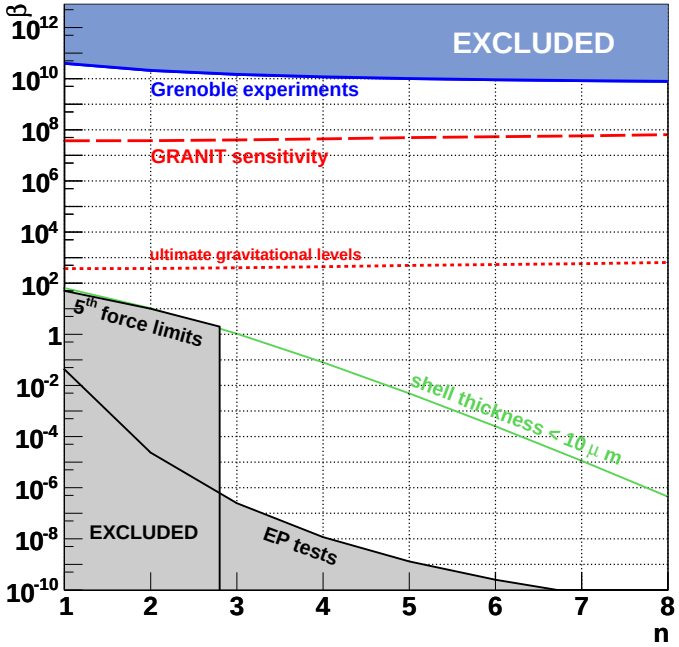
Neutrons in a gravitational field



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

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

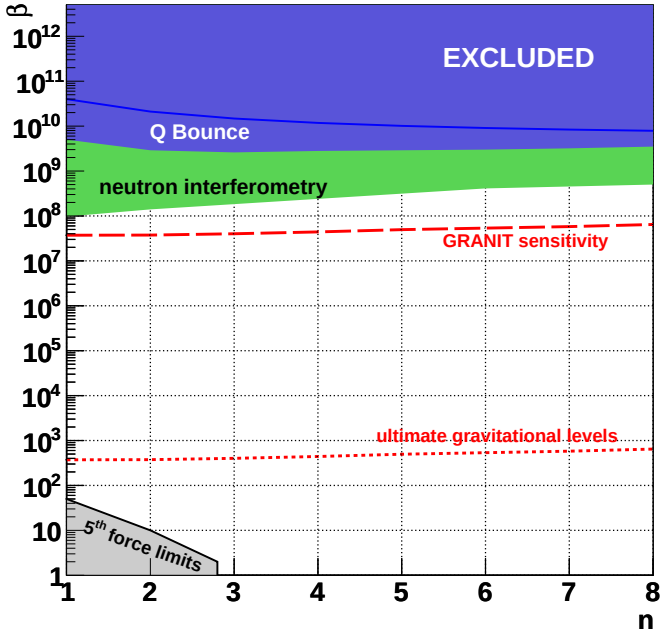
P. Brax and G. Pignol, PRL **107**:*111301(2011)[arXiv:1105.3420]*



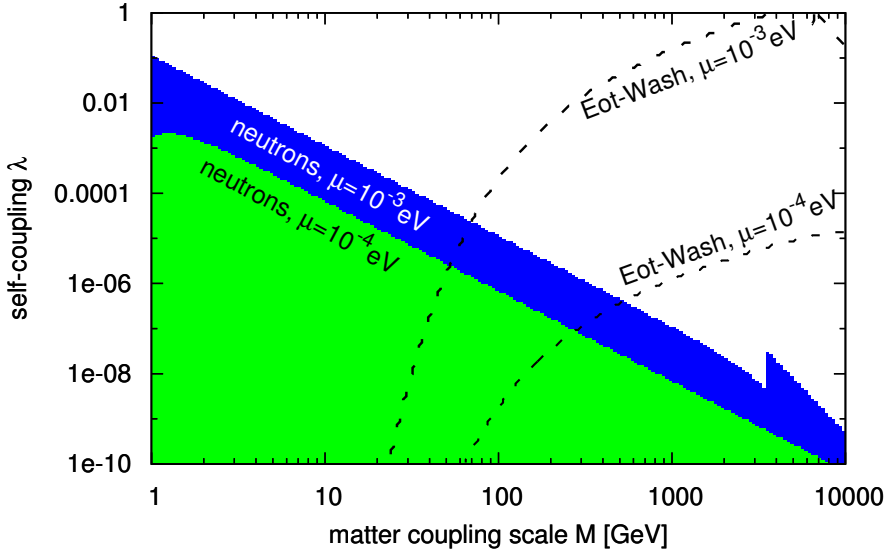
Neutron interferometry

Constraints from neutron interferometry:

- split neutron beam into two
- sent one beam through vacuum chamber with scalar "bubble", other beam through chamber containing phase-neutral gas
- climbing out of scalar potential well slows down beam passing through vacuum chamber ⇒ phase shift



Brax, Pignol, Roulier (2013)
[arXiv:1306.6536]



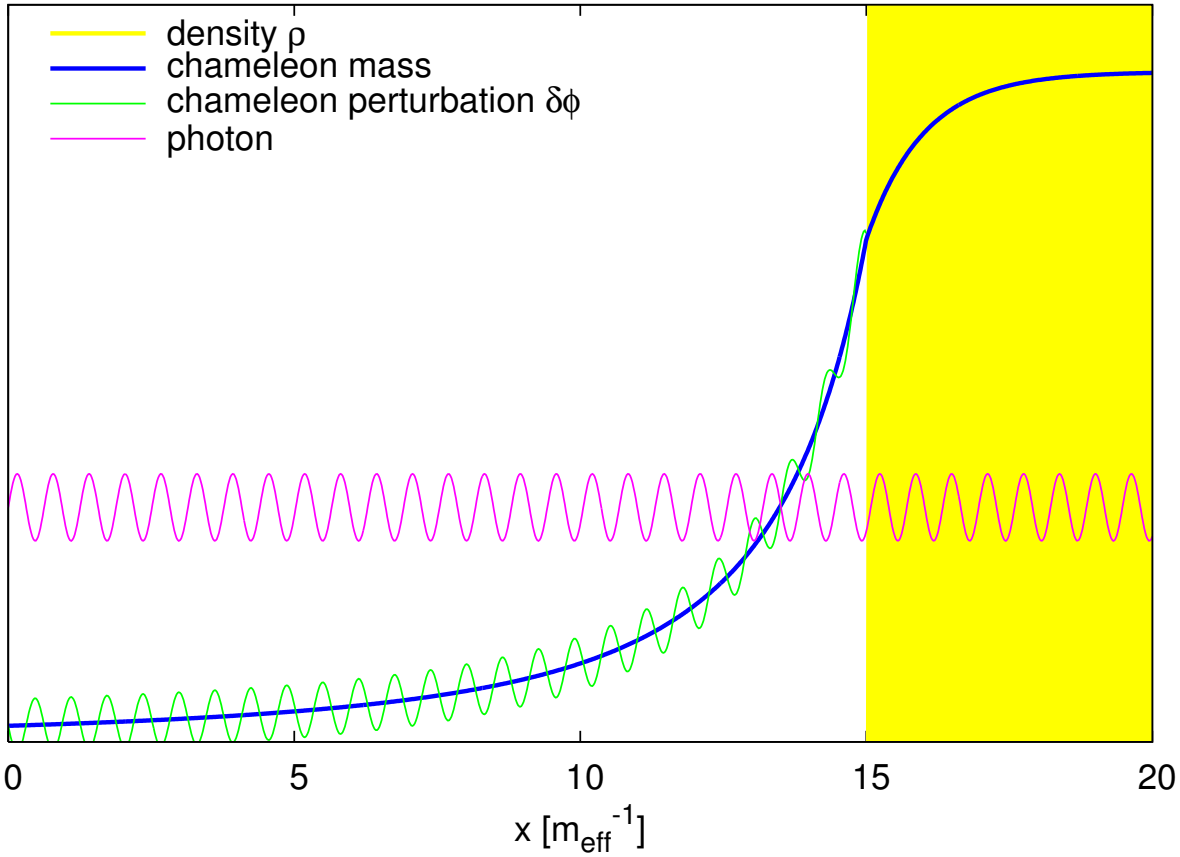
W. M. Snow, AU, et al., NIST proposal

Part III: Dark energy particles

How dark is dark energy? Searches for photon couplings

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.

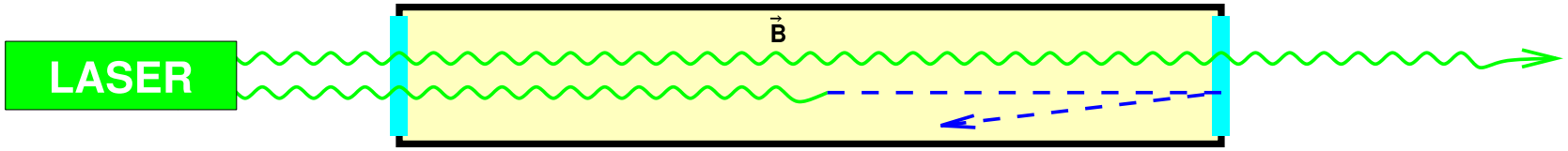


Afterglow experiments

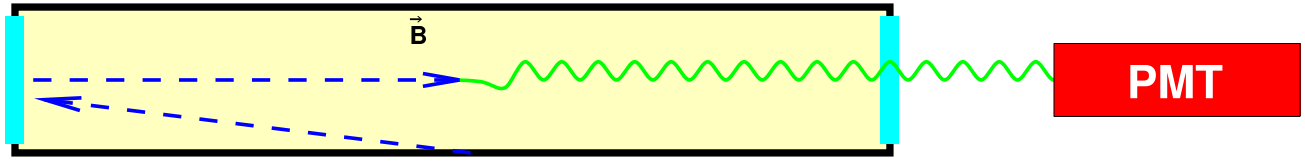
An afterglow experiment has two phases:

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

a)



b)

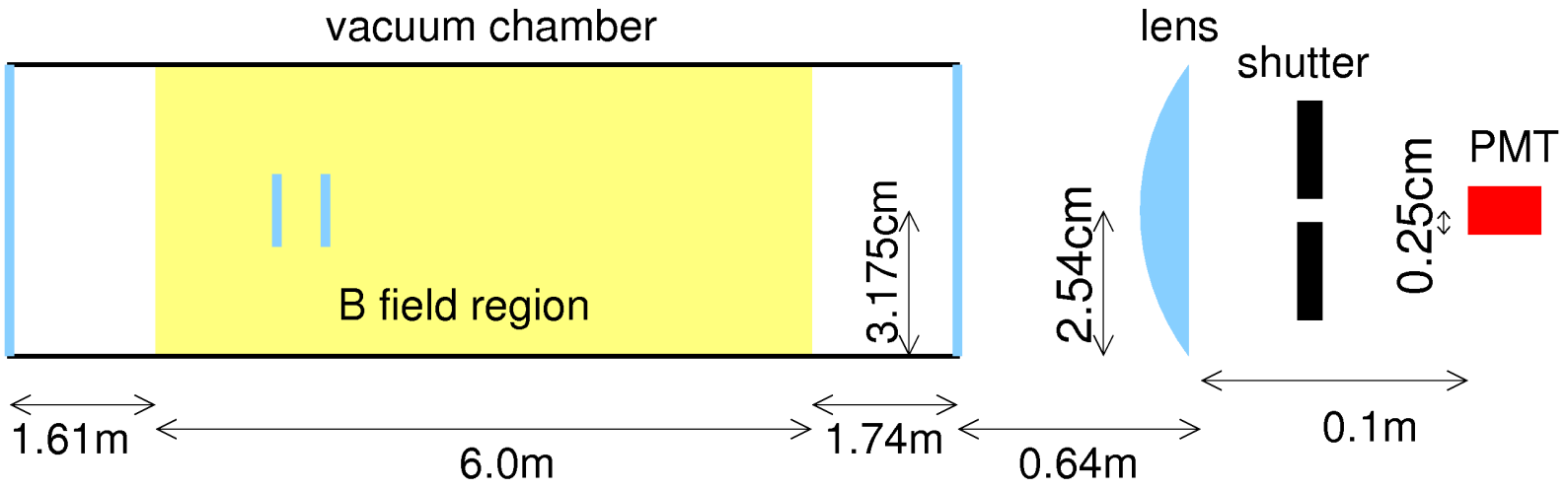


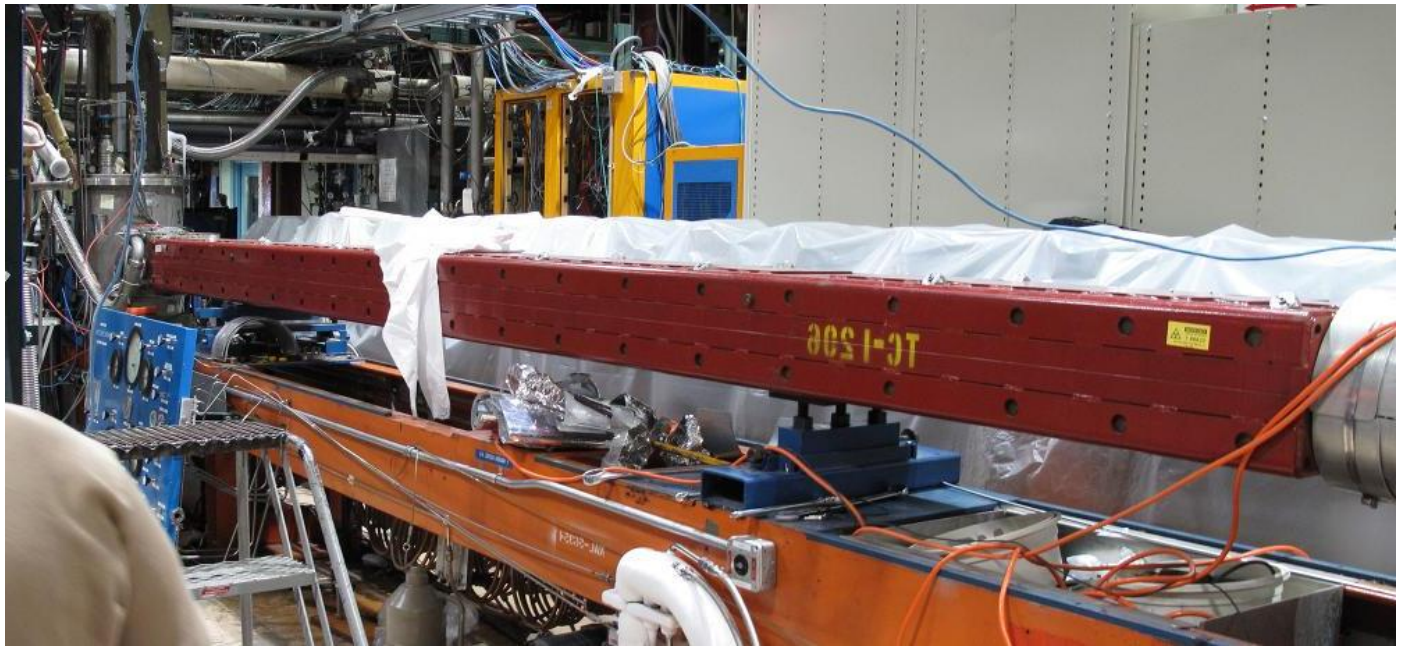
(b) Afterglow phase: chameleons slowly oscillate back into photons, escaping chamber

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

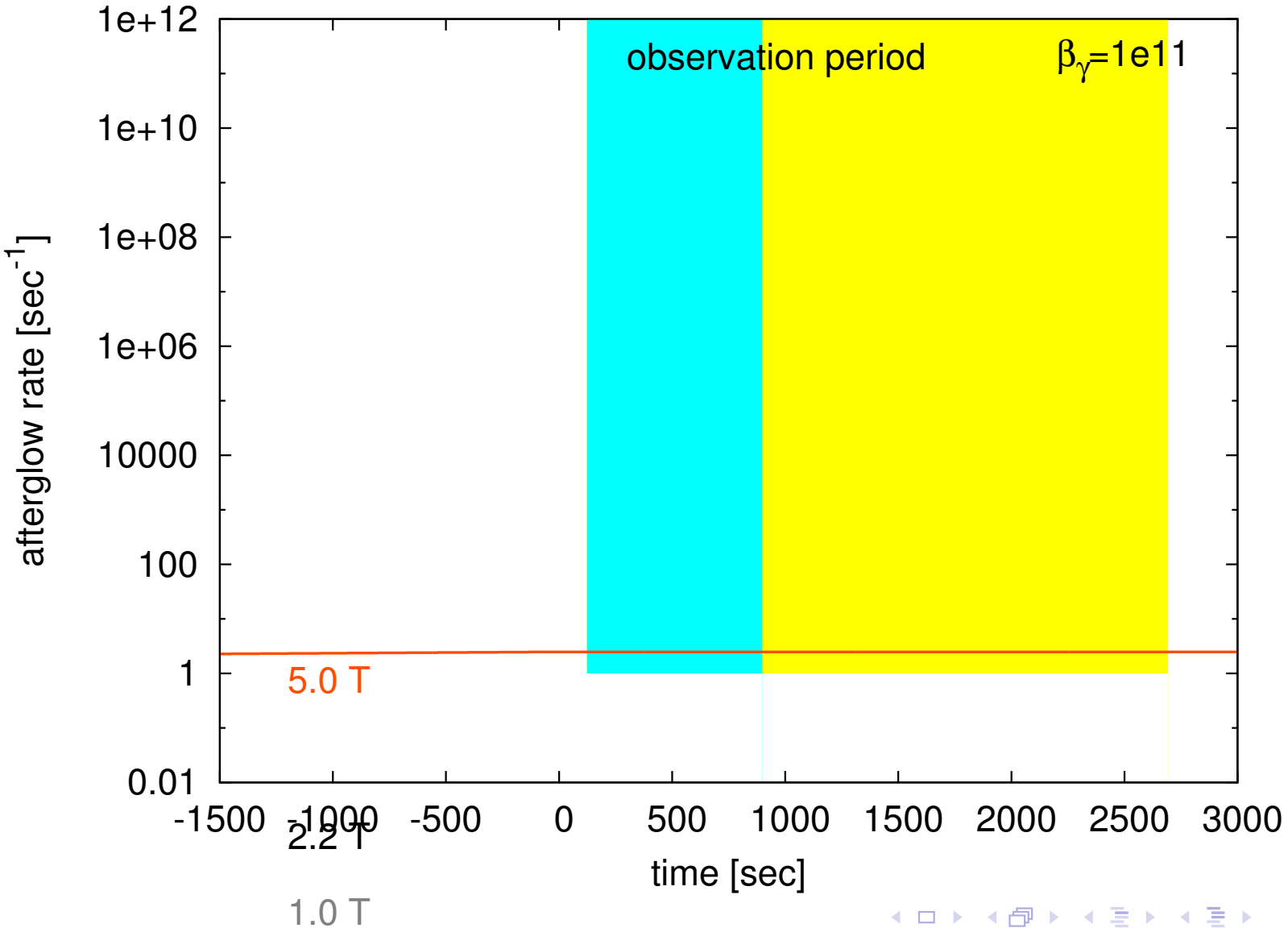
Thorough review: *AU, Steffen, Chou, PRD* **86***:035006(2012)[arXiv:1204.5476]*.

CHASE (CHameleon Afterglow SEarch)





Expected afterglow signal



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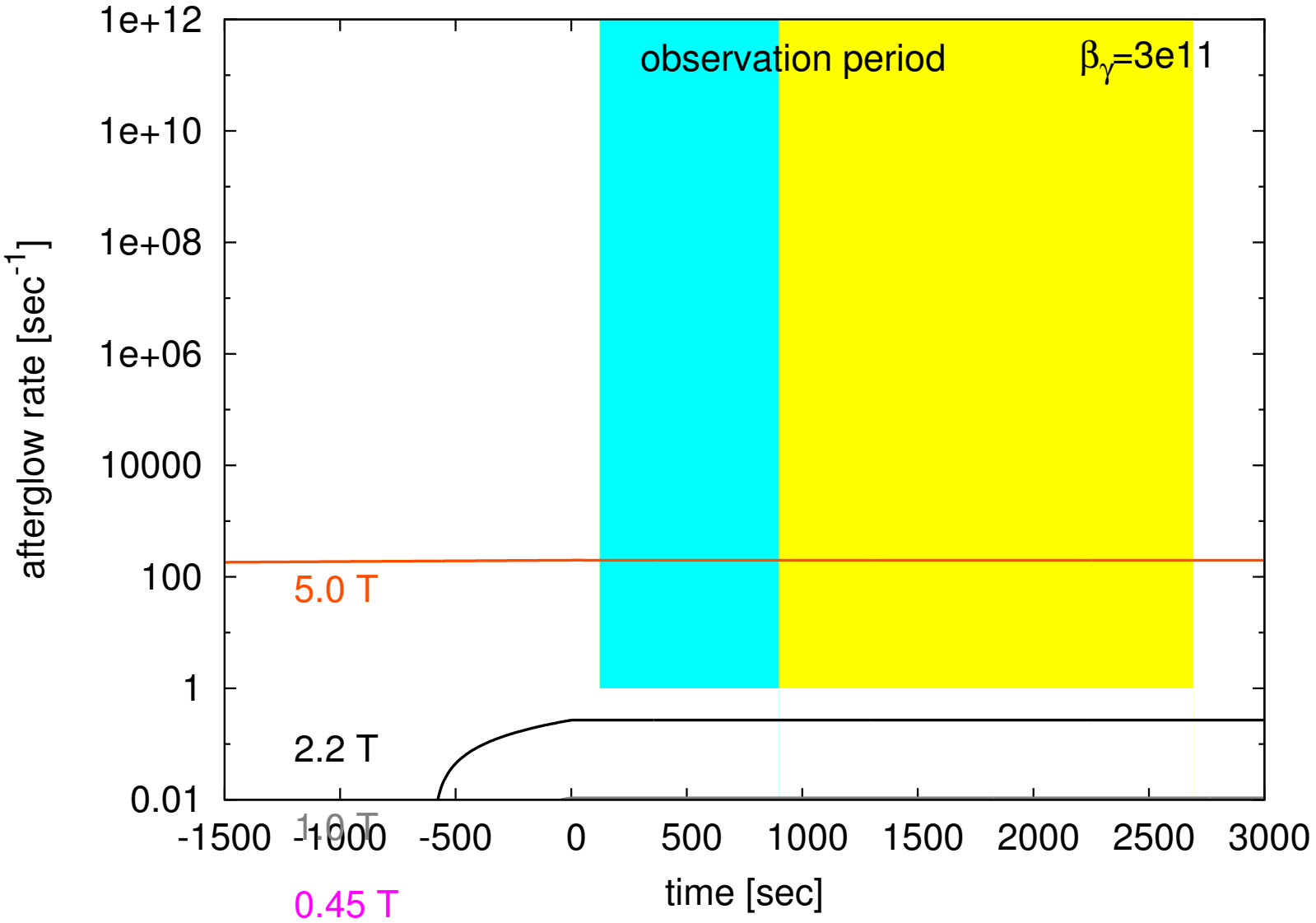

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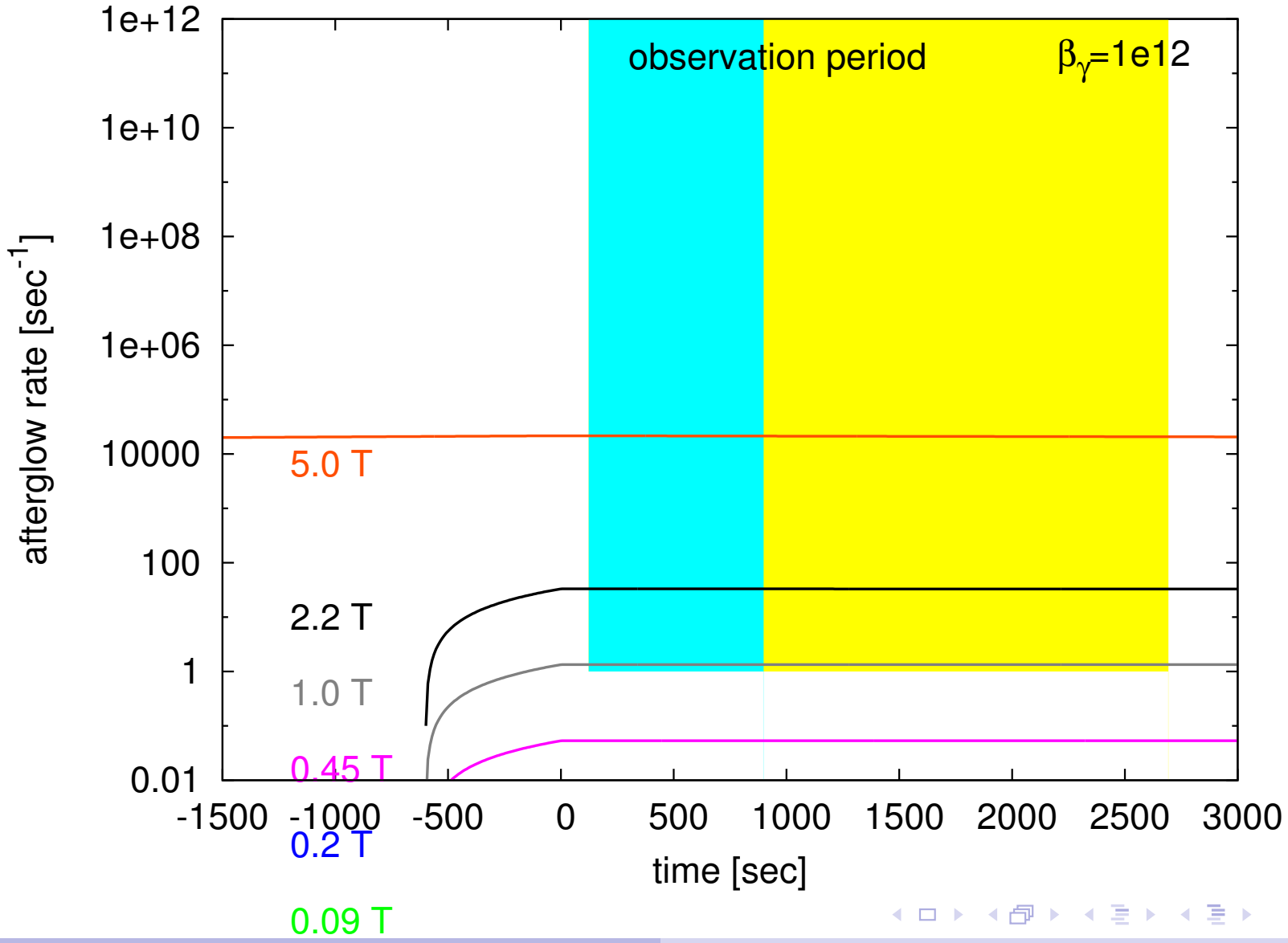

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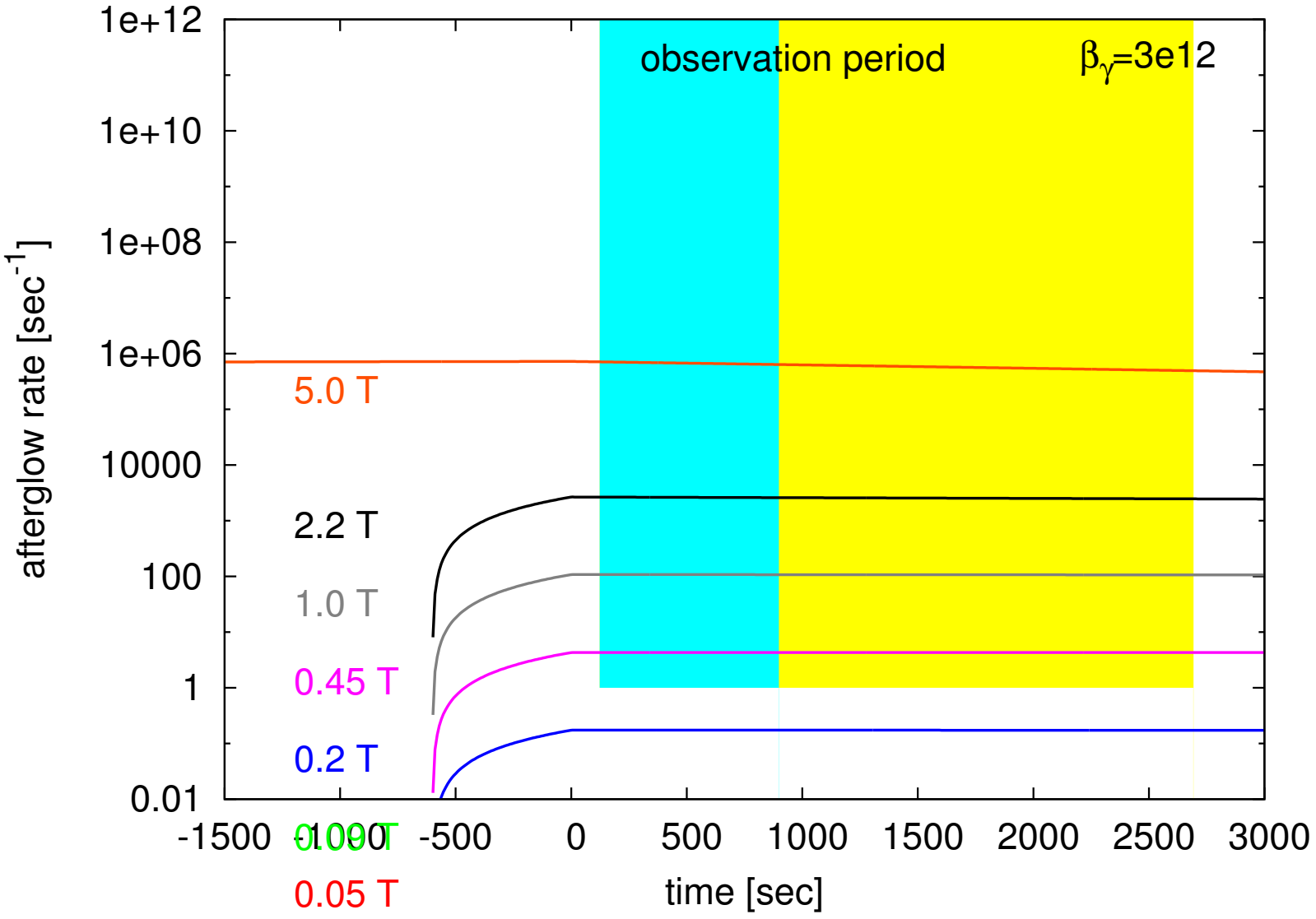

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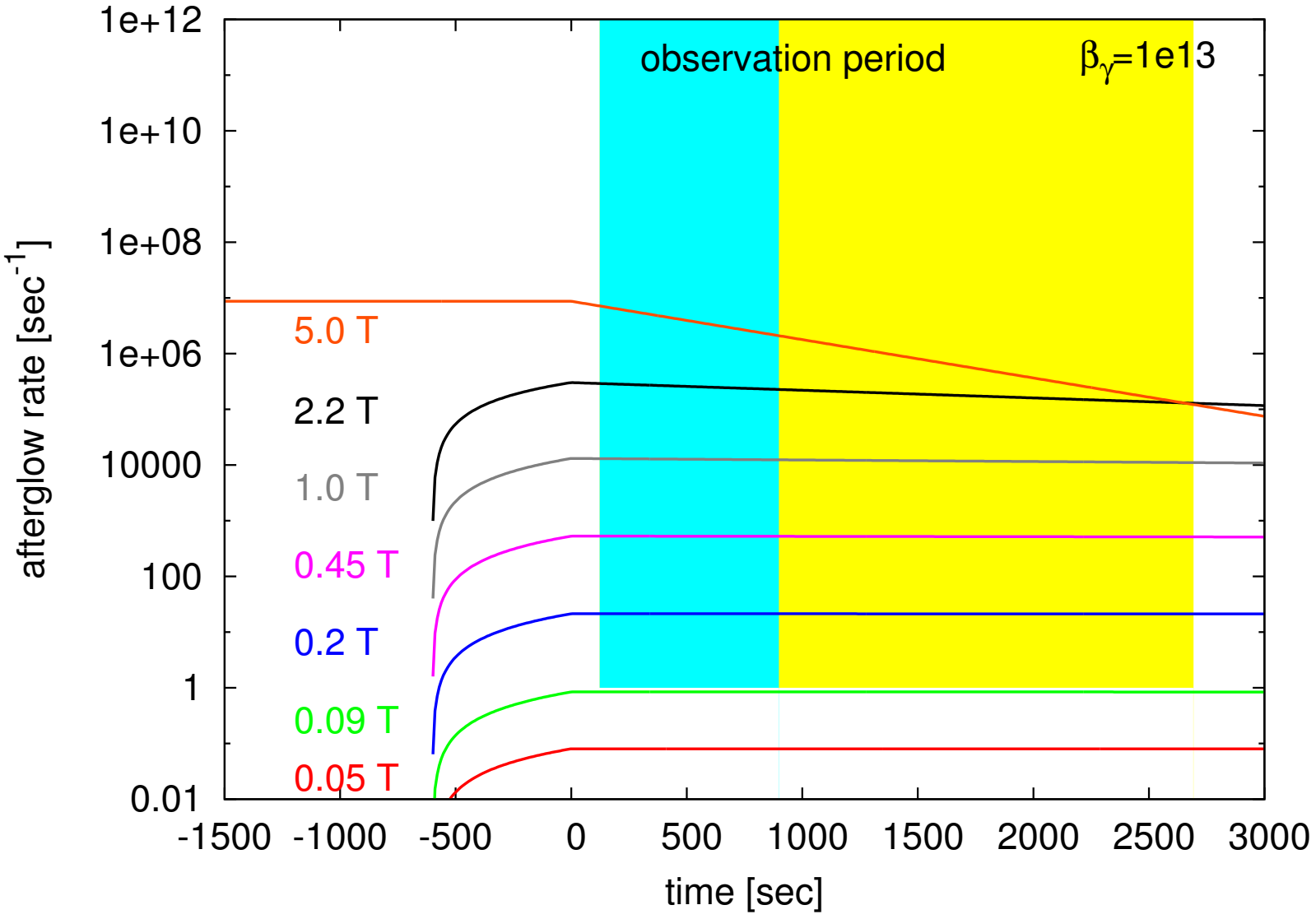

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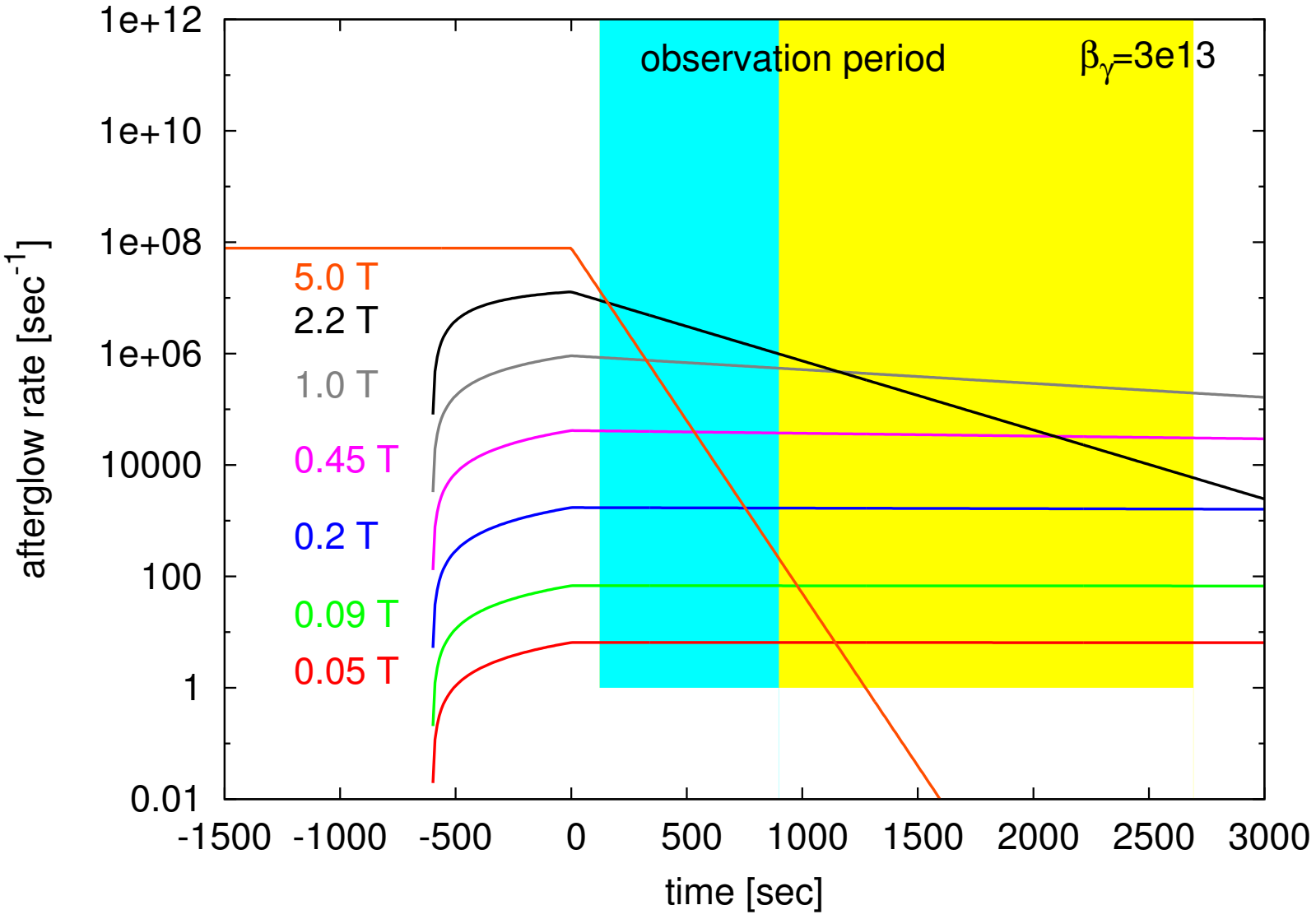

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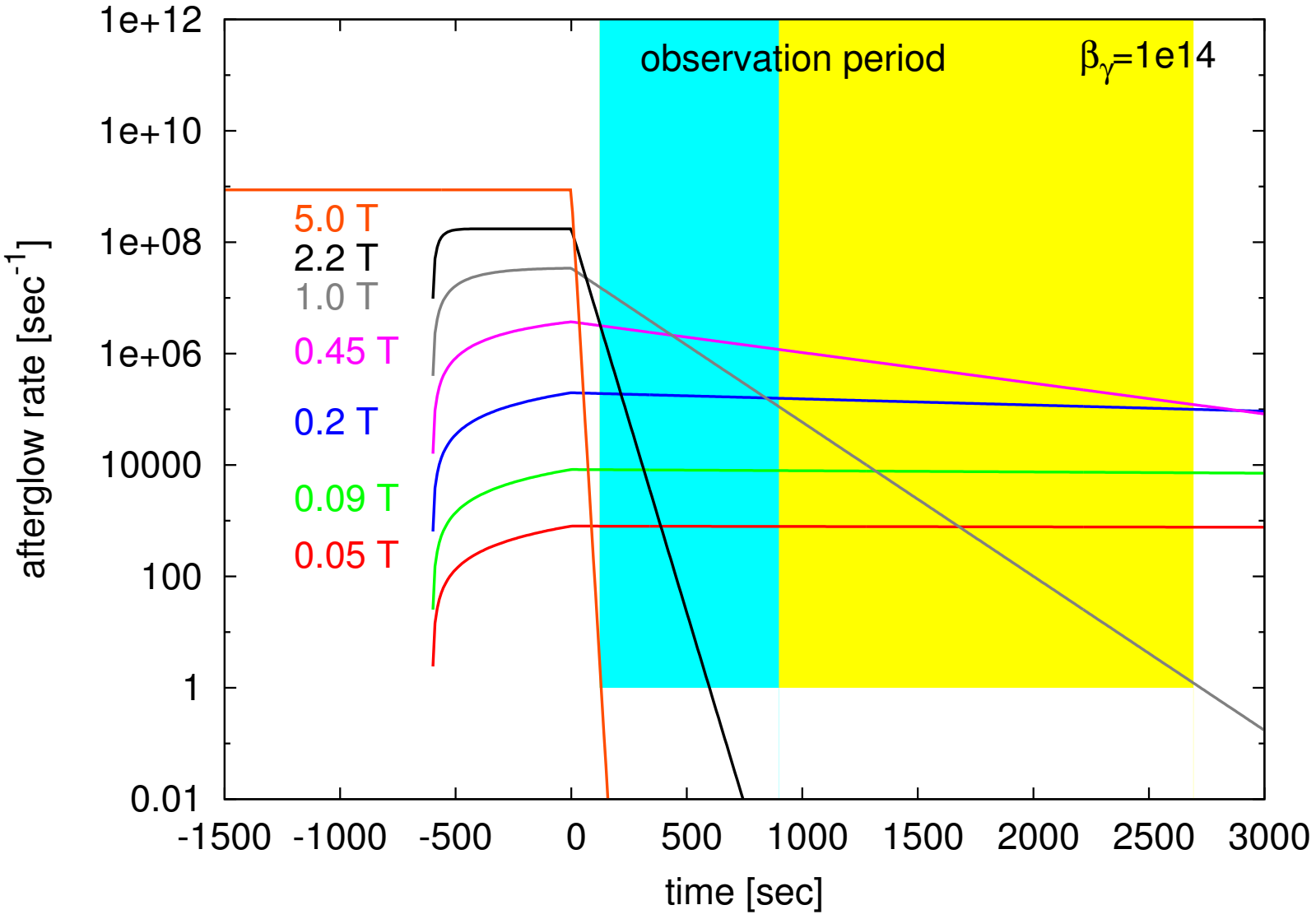

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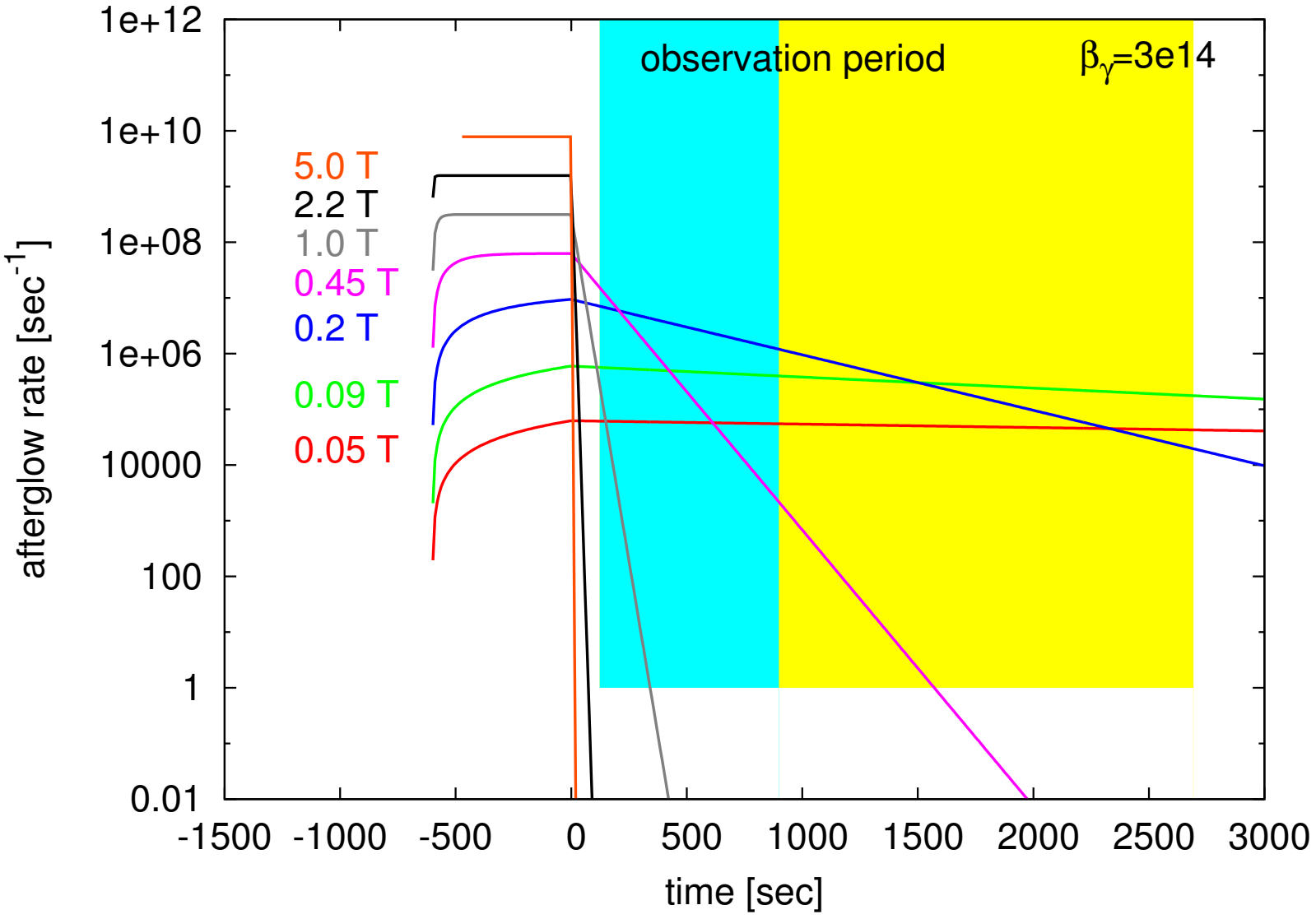
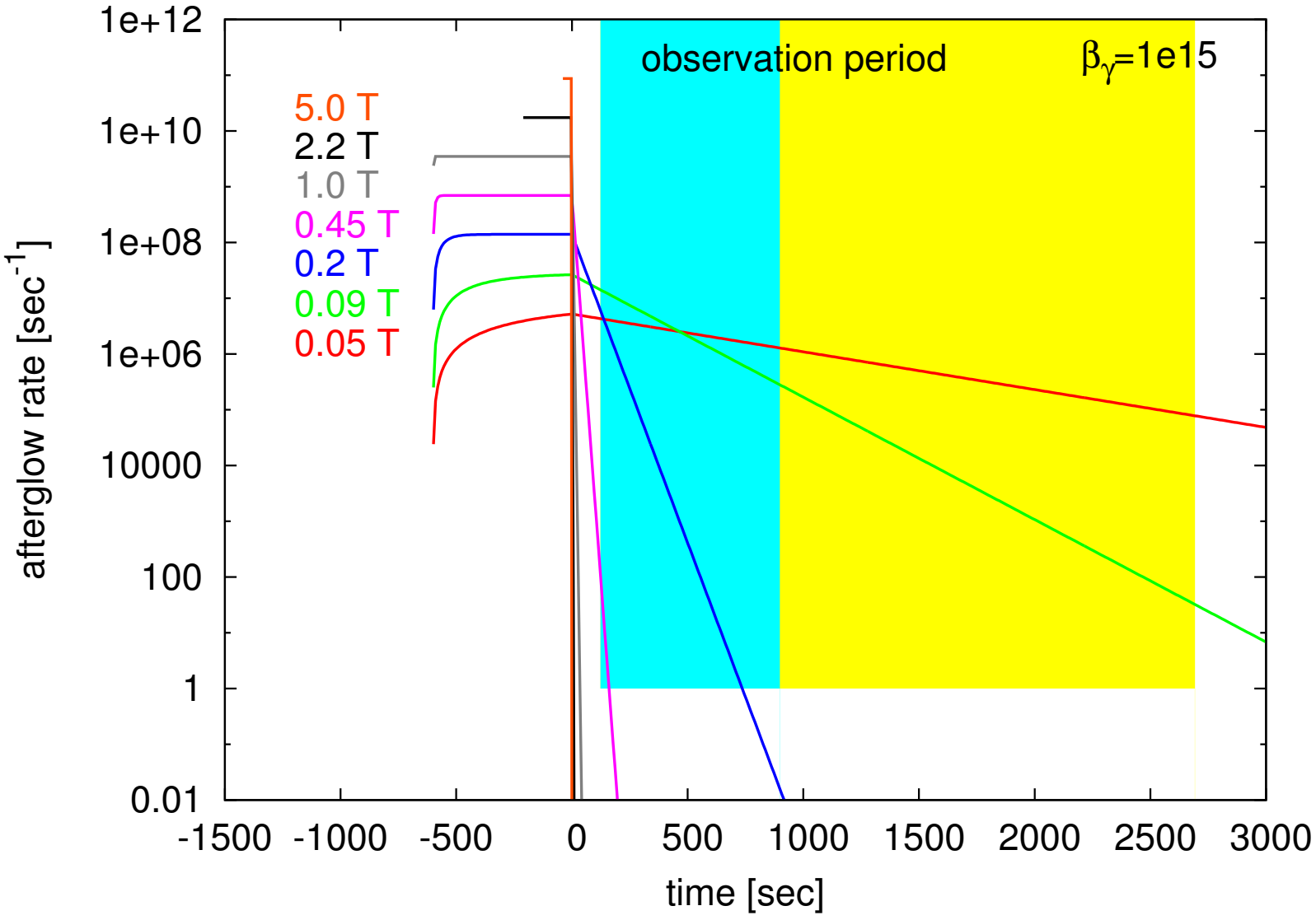
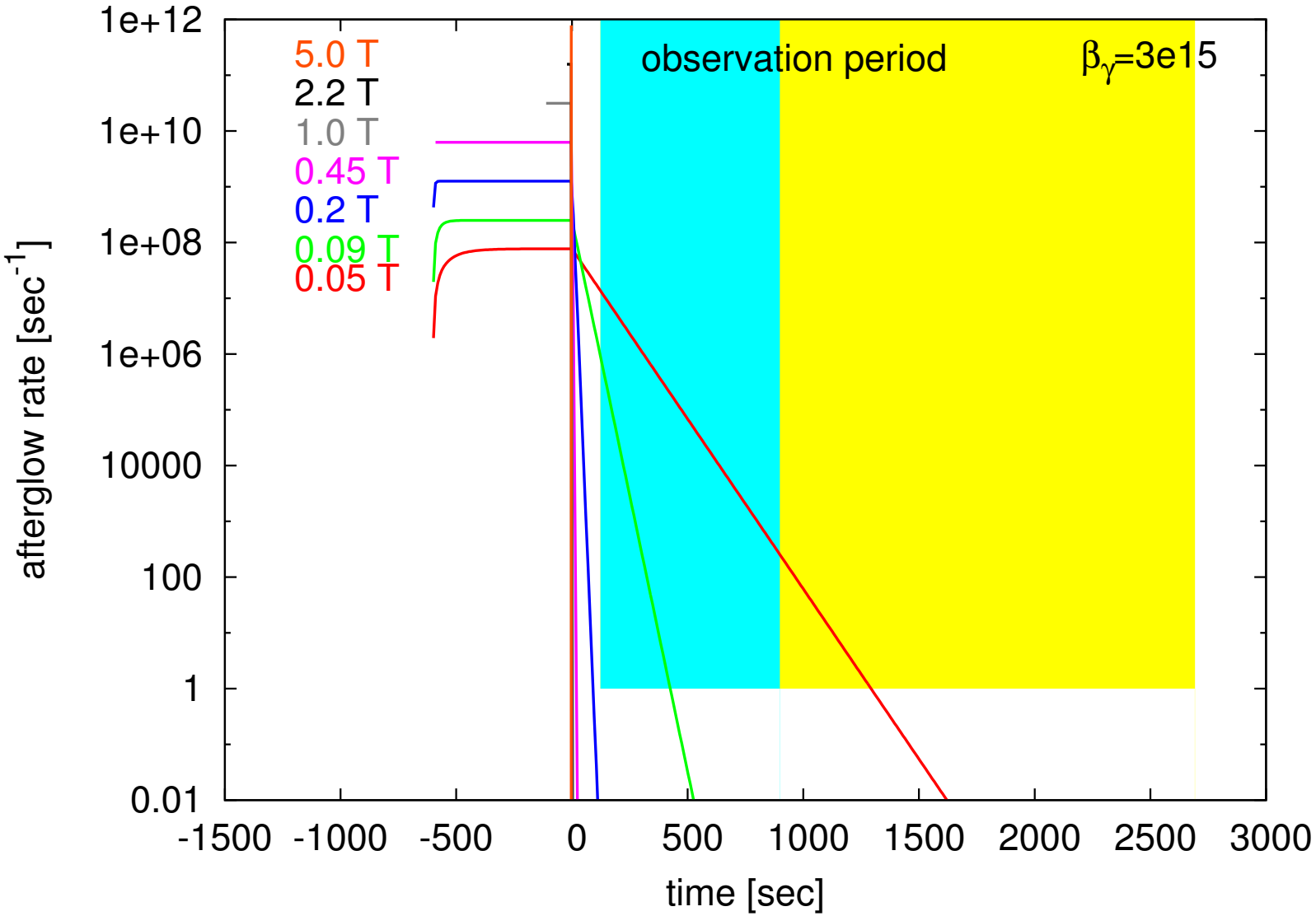


Expected afterglow signal



Expected afterglow signal



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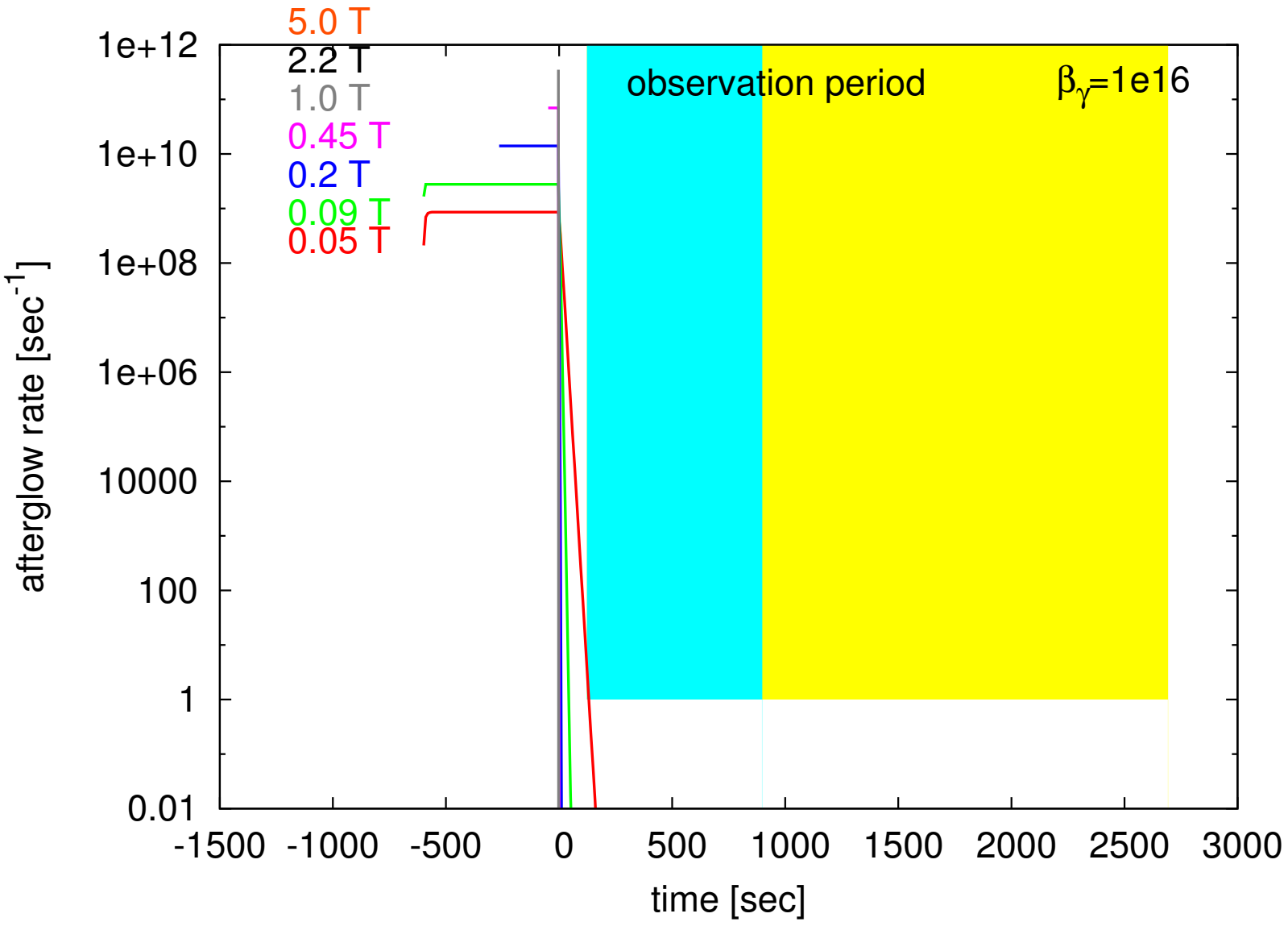
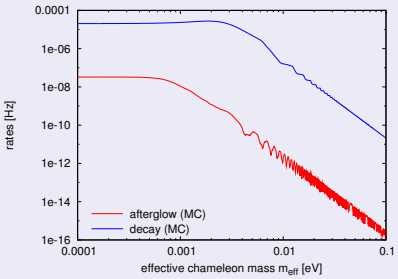
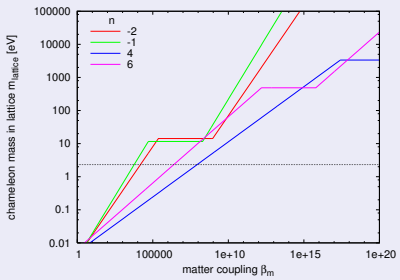


Chameleons in CHASE: a thorough study

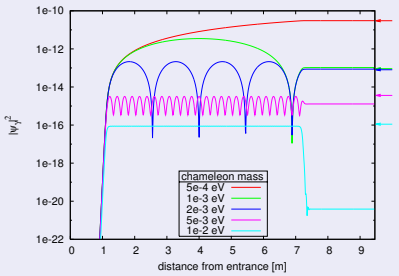
Oscillation



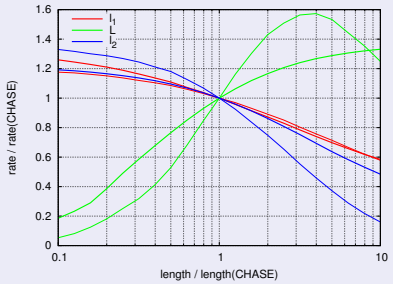
Matter lattice



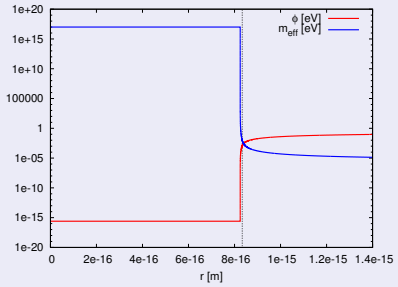
Adiabaticity



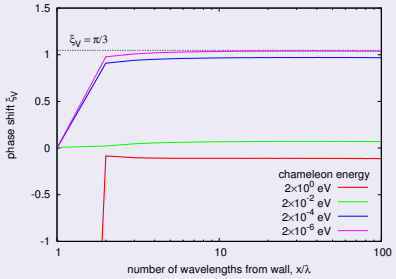
Chamber geom.



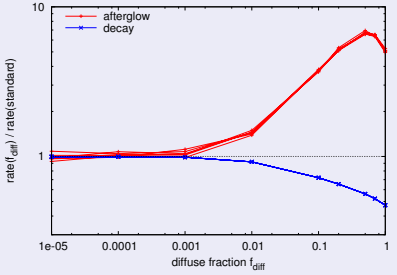
Atom scattering



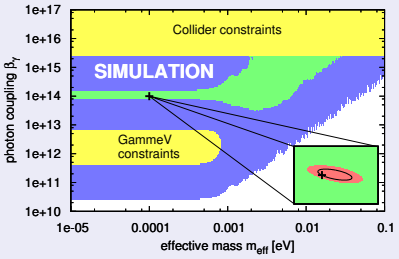
Other potentials



Diffuse ref.



Data analysis

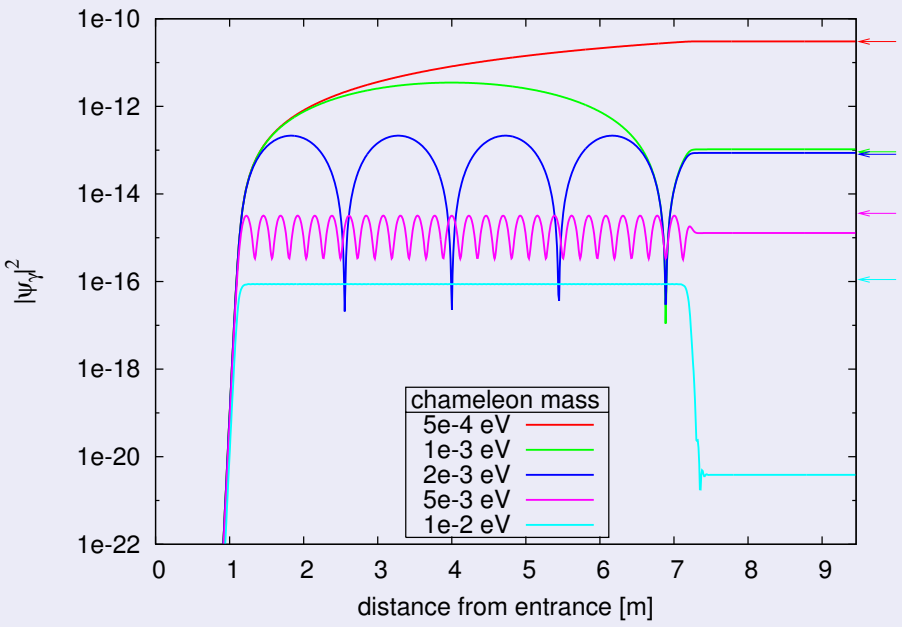


AU, Steffen, Chou, PRD **86***:035006(2012)[arXiv:1204.5476]*.

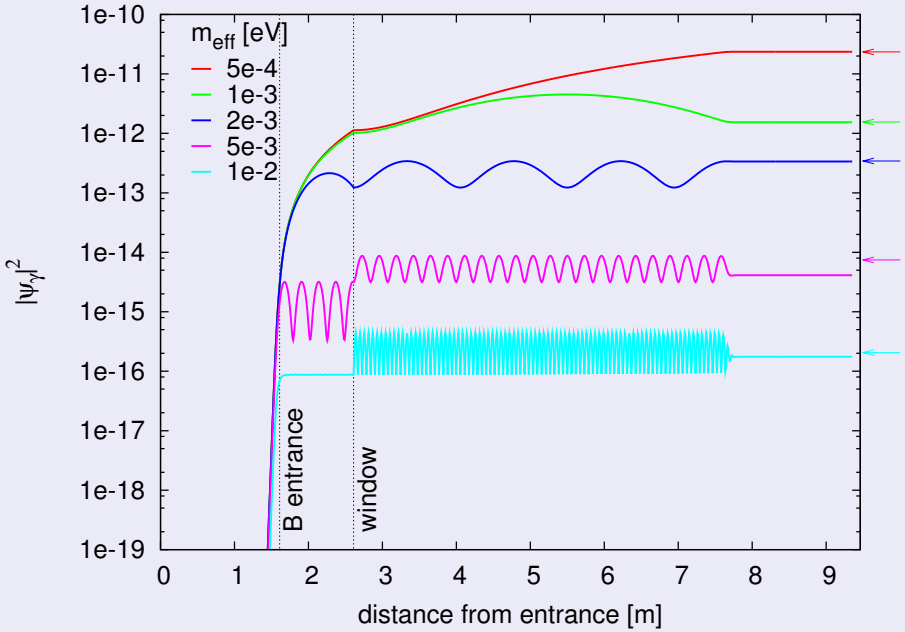
Adiabatic transition suppresses oscillation

- $\vec{B}(z)$ 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

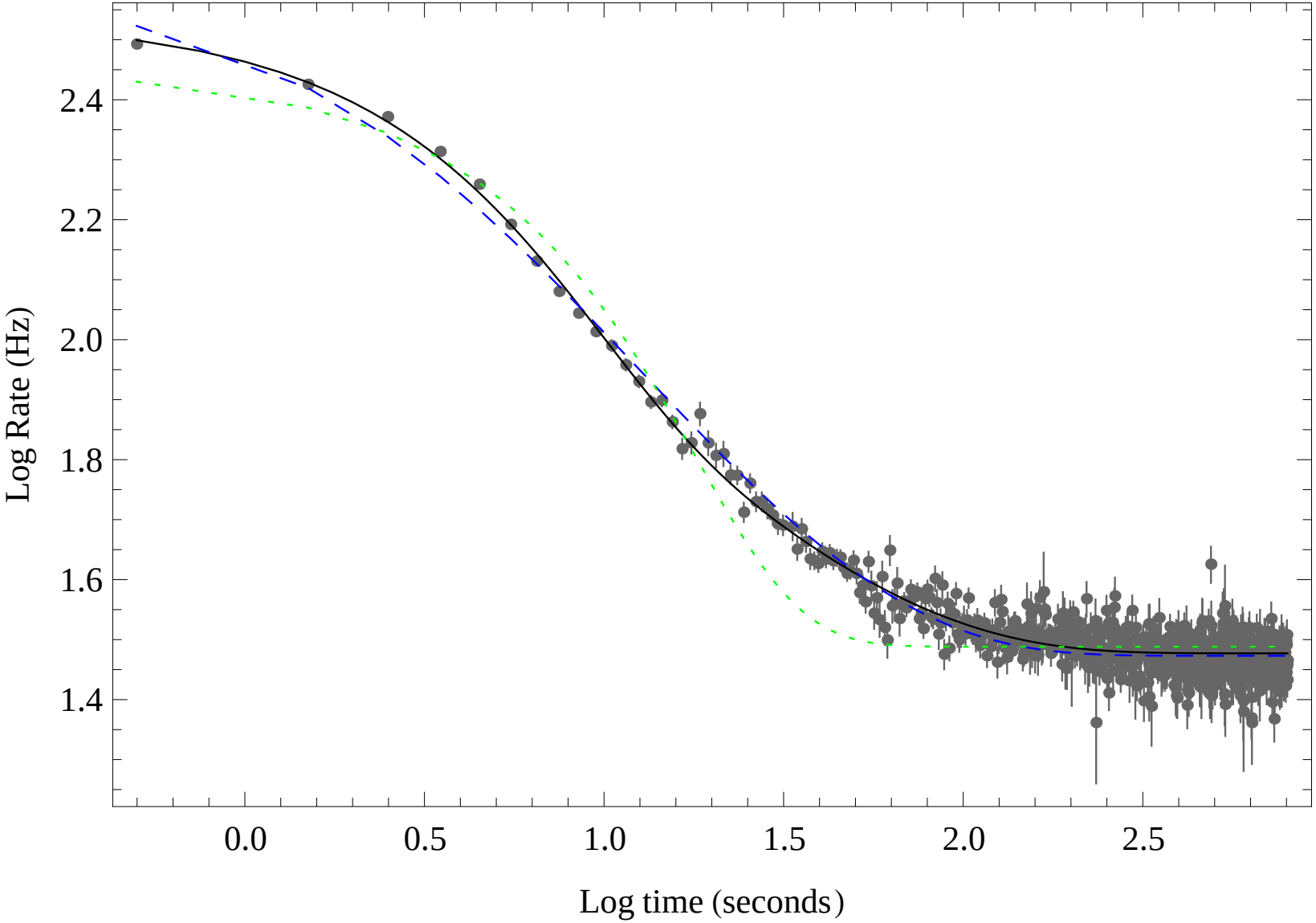


One measurement



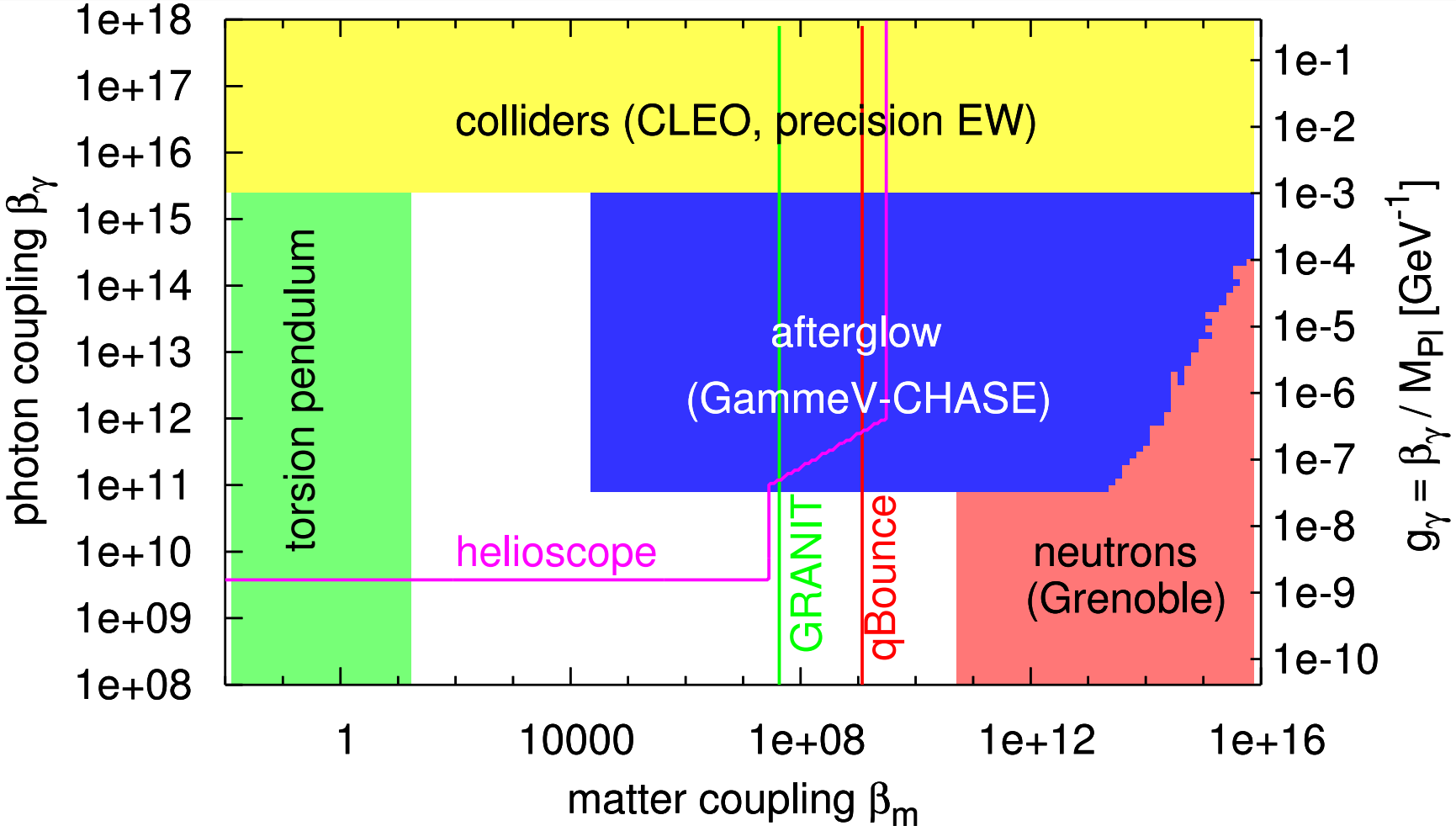
AU, Steffen, Chou, PRD **86***:035006(2012)[arXiv:1204.5476]*.

"Orange glow:" a transient systematic photon flux



Steffen, AU, Baumbaugh, Chou, Tomlin, PRD **86***:012003(2012)[arXiv:1205.6495]*

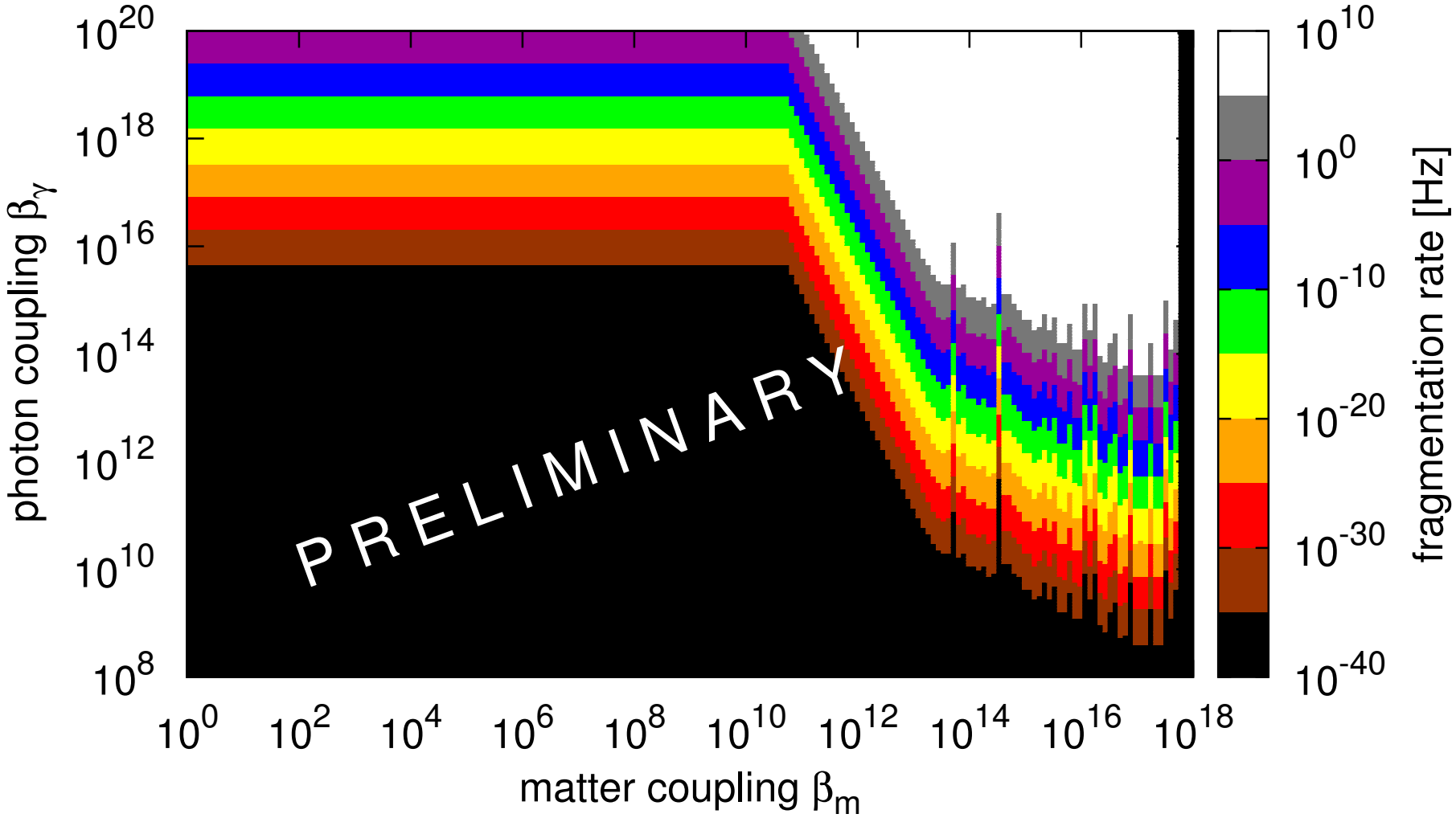
CHASE constraints on $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$



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]*

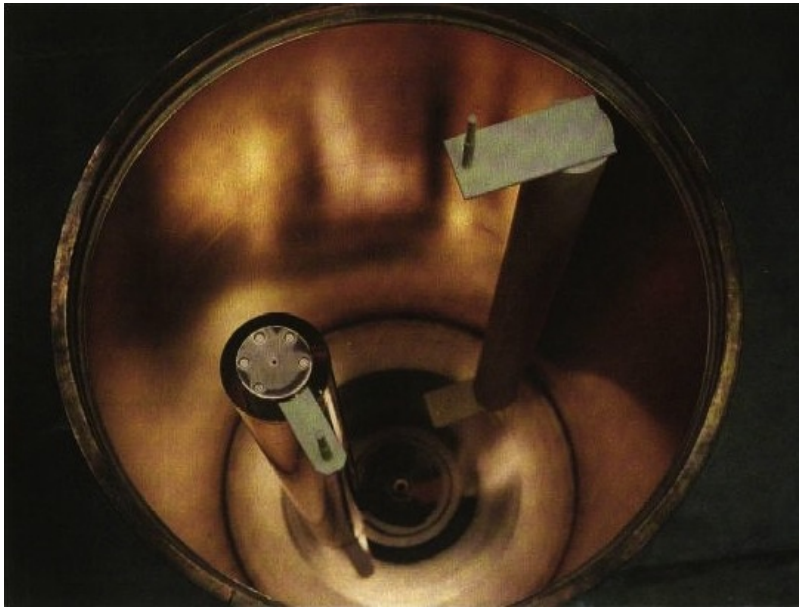
Chameleon fragmentation?



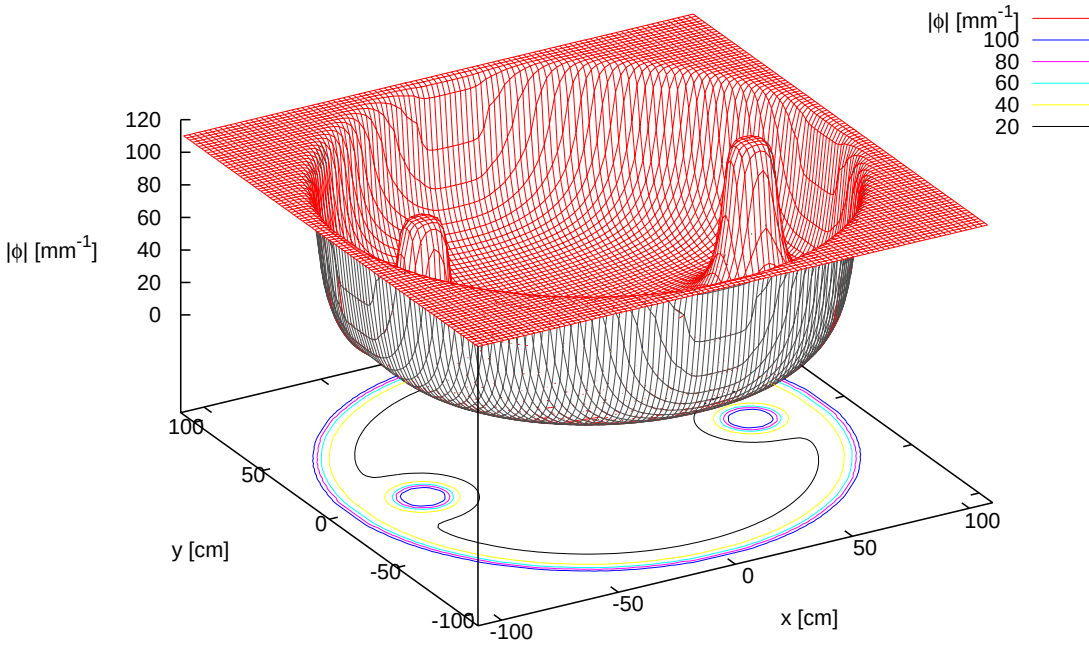
Chameleon particles can interact to produce a greater number of lower-energy chameleon particles.

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

Cavity afterglow experiments



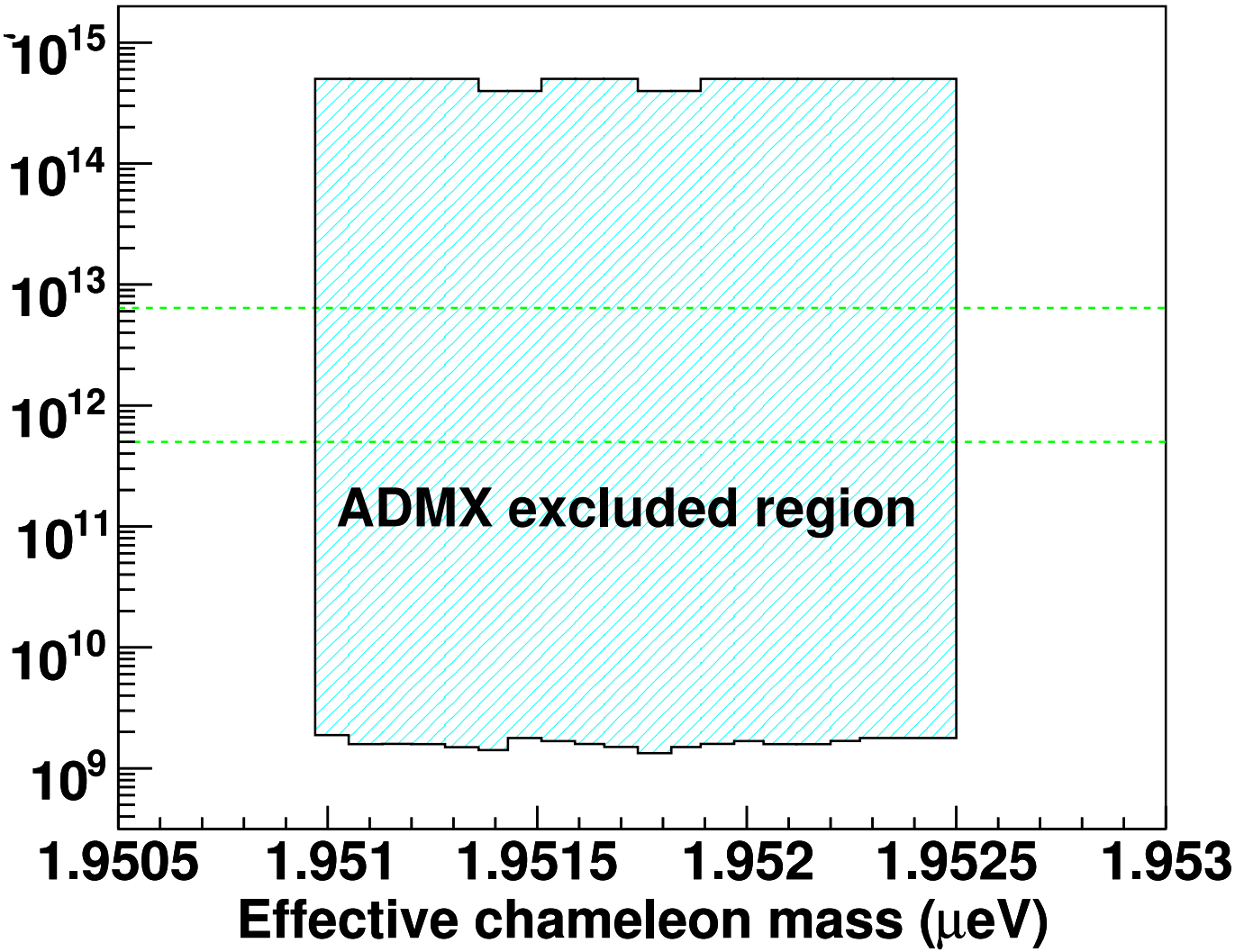
http://www.phys.washington.edu/groups/admx/cavity.html



Procedure:

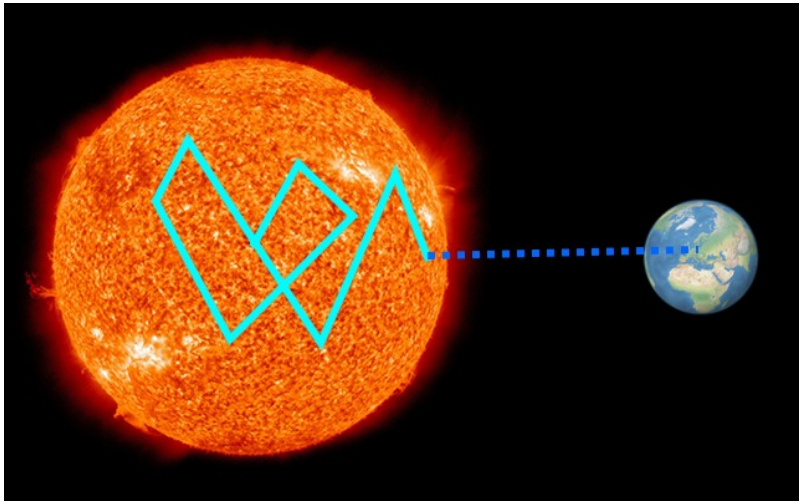
1. source excites EM mode
2. turn off source; EM modes decay
3. EM modes regenerated from chameleon
4. adjust tuning rods for sensitivity to different mass range

ADMX constraints on photon-coupled chameleons



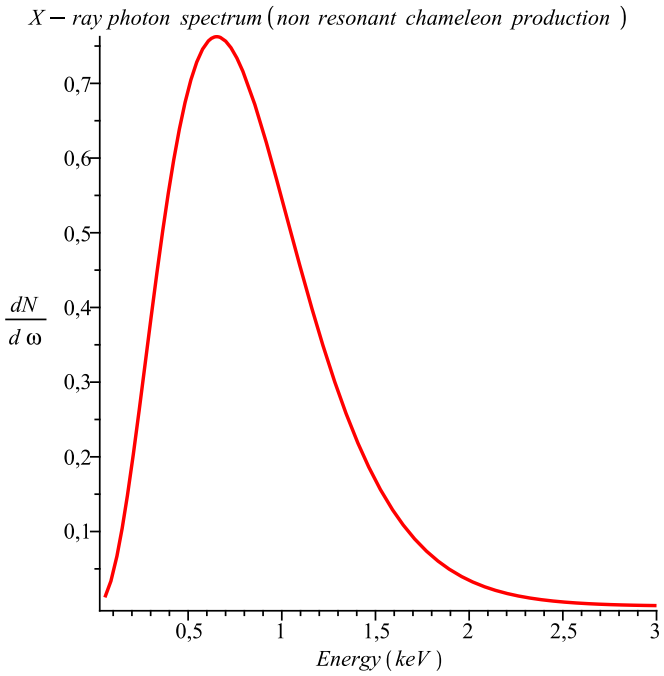
G. Rybka, M. Hotz, L. Rosenberg, et al., PRL **105** *051801 (2010)*

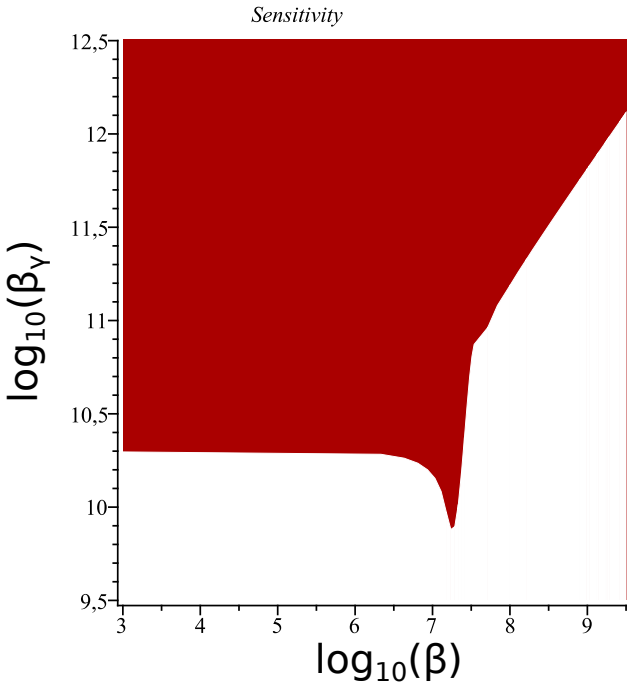
Chameleons from the Sun

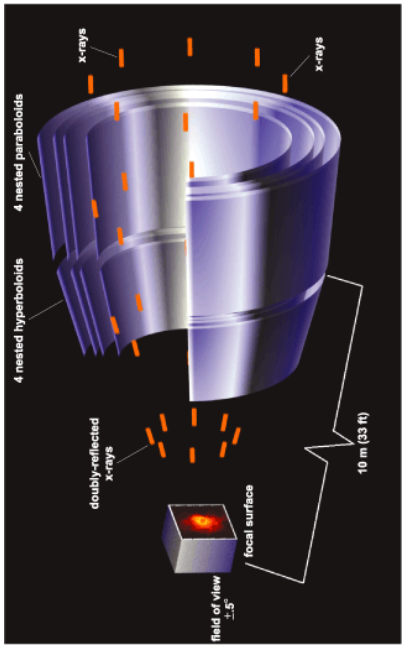


- $\sim$ keV photons oscillate into chameleons inside Sun
- chameleon particles reach Earth
- helioscope magnet regenerates photons for detection

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)

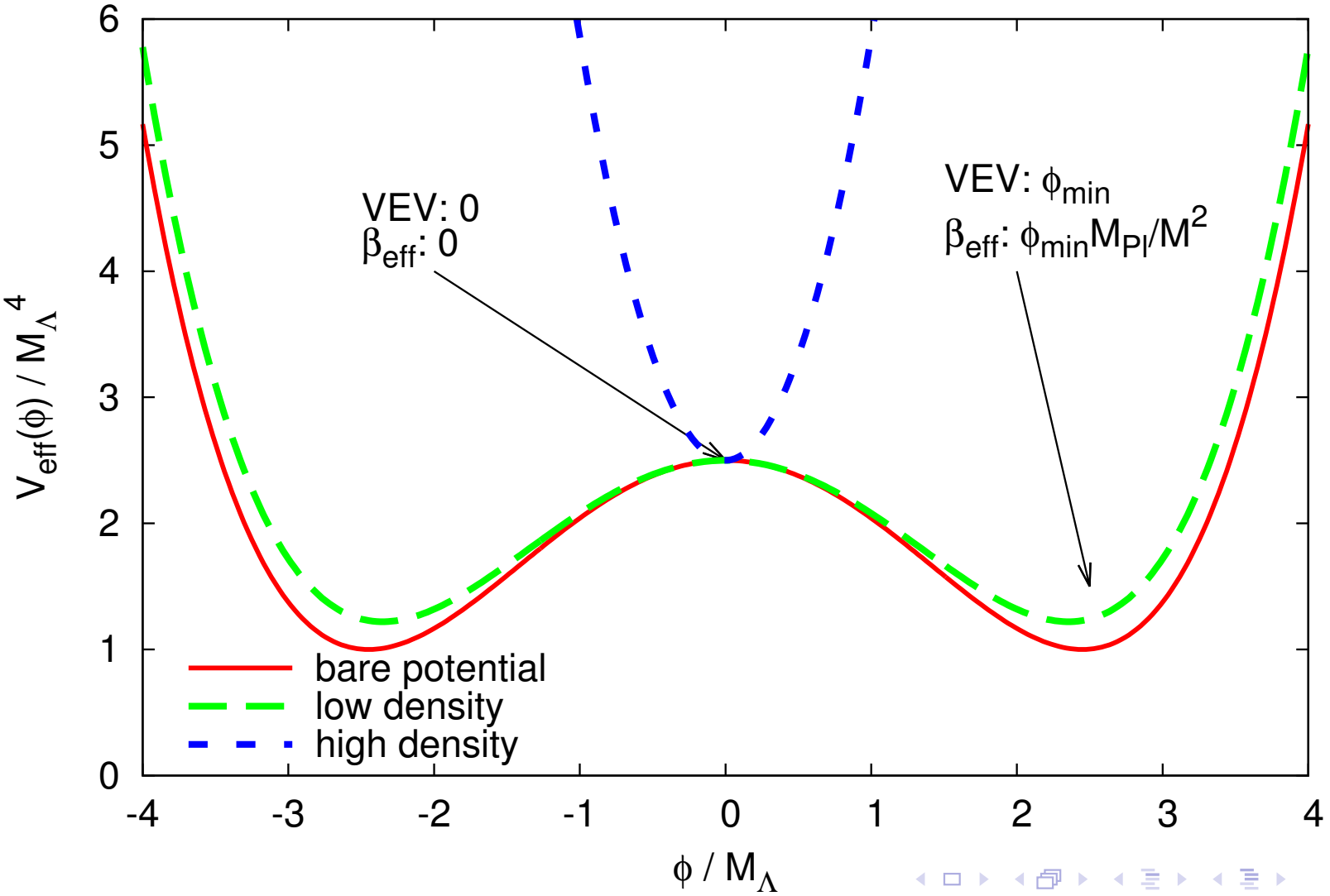
Conclusions

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, as well as symmetron models with TeV-scale couplings. Neutron experiments can exclude chameleons and symmetrons with larger couplings.
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

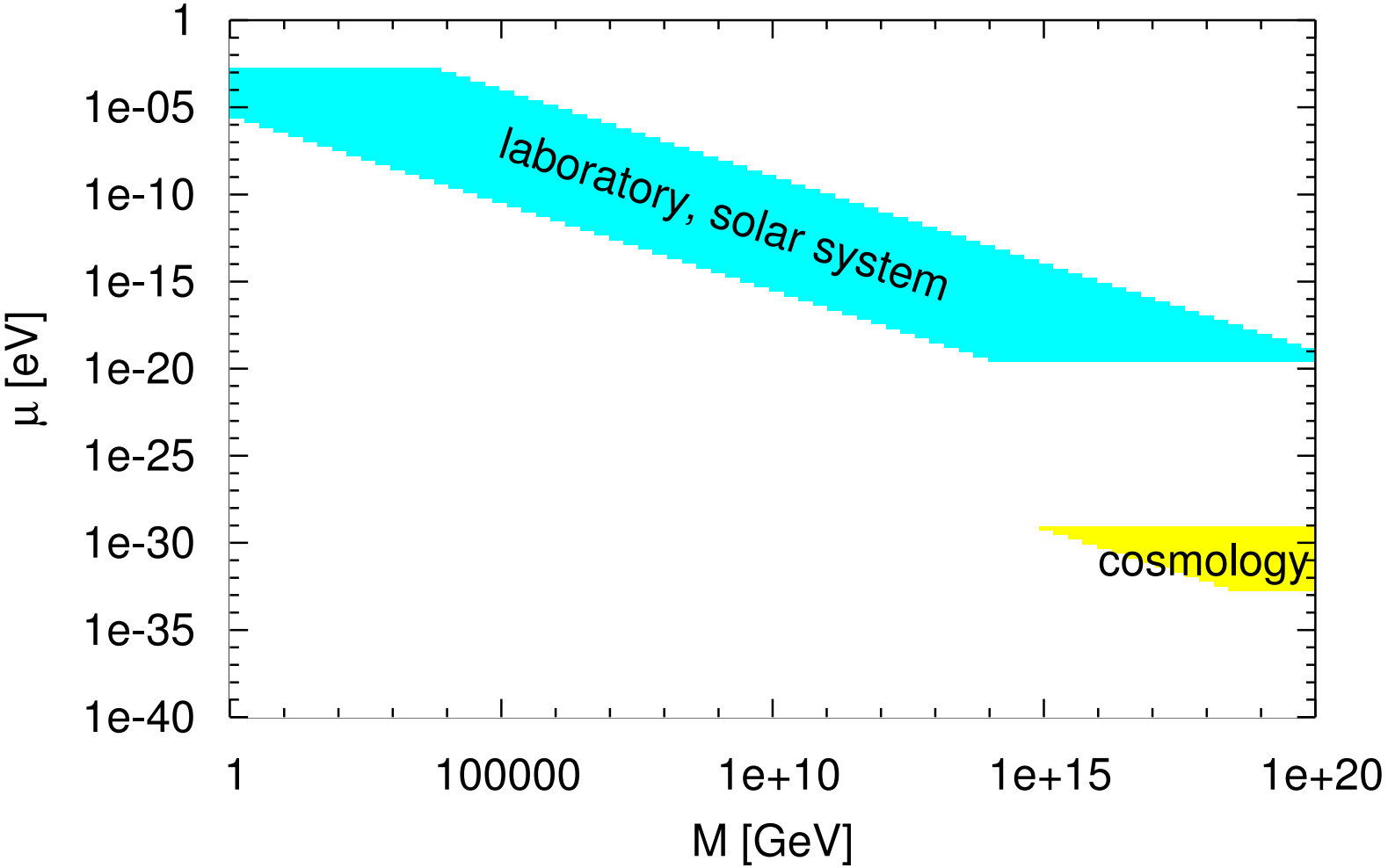
Symmetron mechanism

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



At which scale should we probe symmetrons?

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



Photons coupled to chameleon dark energy

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):

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

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