Chameleon scalar fields and the GammeV Experiment

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Fermilab Munch

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Outline

- Background and motivation
- Chameleon phenomenology
- Constraints (lab and astrophysical)
- Chameleon afterglow and the GammeV Experiment
- Conclusions

Background: PVLAS

- Rotation in polarization direction of photons passing through a region of high magnetic field
- Could be explained by photon coupling to light scalar/pseudoscalar particle
- Recent PVLAS data: effect not reproduced

Background: Cosmology

- Accelerating cosmic expansion could be caused by light scalar field
- Scalar field must be heavy on solar system and laboratory scales to avoid fifth force constraints
- Chameleon mechanism: use scalar coupling to fermions/photons to increase mass in high-density regions

Phenomenology: action

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2M_{\rm Pl}} R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{e^{2g_\gamma\phi/M_{\rm Pl}}}{4} F_{\mu\nu}F^{\mu\nu} \right) + S_m(e^{2g_m\phi/M_{\rm Pl}}, \psi_m)$$

typical matter coupling: $m(\phi) = m_0 e^{g_m\phi/M_{\rm Pl}}$

chameleon potentials:

- power law $V(\phi) = \frac{\xi}{N!}\phi^N$
- exponential $V(\phi) = \Lambda^4 \exp\left(\frac{\Lambda^n}{\phi^n}\right)$

Chameleon mechanism

Effective potential:

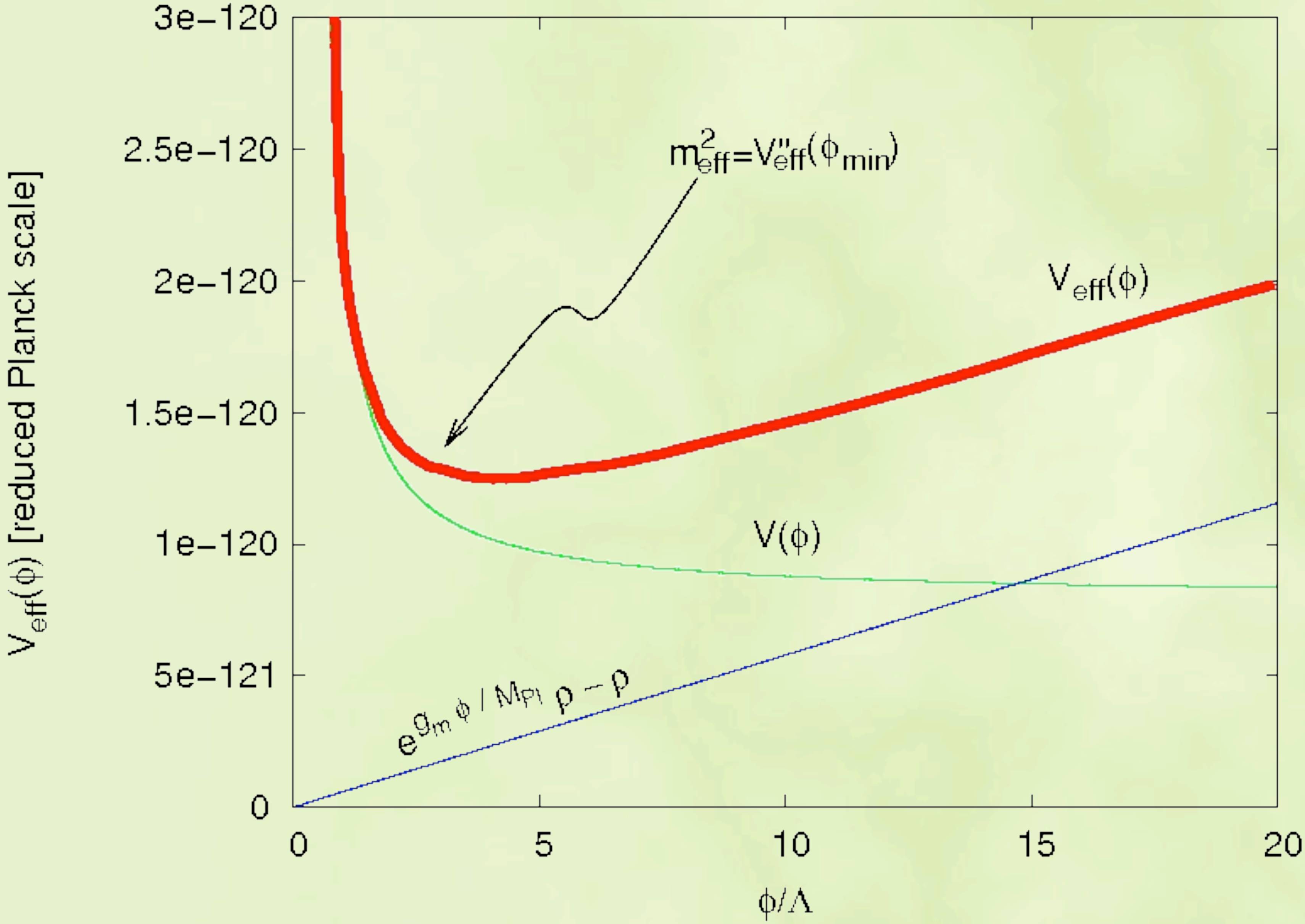
$$V_{\rm eff}(\phi,\vec{x}) \quad = \quad V(\phi) + e^{g_m\phi/M_{\rm Pl}}\rho_m(\vec{x}) + e^{g_\gamma\phi/M_{\rm Pl}}\rho_\gamma(\vec{x})$$

$$\rho_\gamma \equiv \frac{1}{2}(B^2 - E^2)$$

Effective mass:

$$m_{\rm eff}^2 = \left.\frac{\partial^2 V_{\rm eff}}{\partial\phi^2}\right|_{\phi=\phi_{\rm min}}$$

Chameleon mechanism



Chameleon mechanism

Power law potential:

$$m_{\rm eff} = \left[\frac{(N-2)!}{\xi}\left(\frac{(N-1)g_m}{M_{\rm Pl}}\right)^{N-1}\right]^{\frac{1}{2N-4}} \times \left(\rho_m + \frac{g_\gamma}{g_m}\rho_\gamma\right)^{\frac{N-2}{2N-2}}$$

Exponential potential:

$$m_{\rm eff} = \left(\frac{(n+1)^{n+1} g_m^{n+2}}{n M_{\rm Pl}^{n+2}\Lambda^{n+4}}\right)^{\frac{1}{2n+2}} \left(\rho_m + \frac{g_\gamma}{g_m}\rho_\gamma\right)^{\frac{n+2}{2n+2}}$$

Chameleon mechanism

Power law potential:

$m_{\rm eff}$ $\sim \rho^{\beta}$ (with $0<\beta<{}^{1}/_{2}$)

Exponential potential:

$$m_{\rm eff} = \left(\frac{(n+1)^{n+1} g_m^{n+2}}{n M_{\rm Pl}^{n+2} \Lambda^{n+4}}\right)^{\frac{1}{2n+2}} \left(\rho_m + \frac{g_\gamma}{g_m}\rho_\gamma\right)^{\frac{n+2}{2n+2}}$$

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Exponential potential:

$m_{\rm eff}$ ~ ρ^β (with $^1/_2 < \beta < 1$)

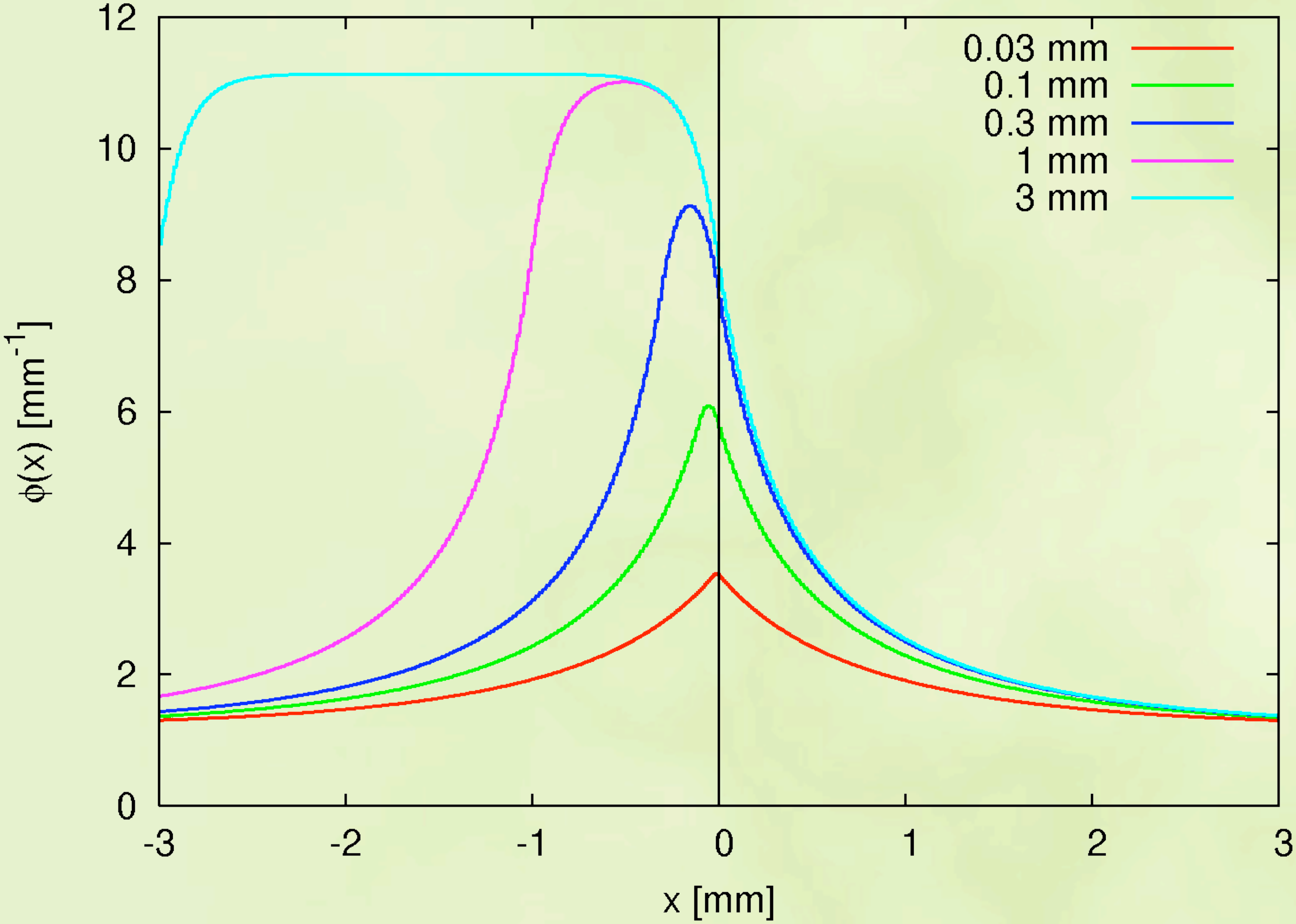
Thin shell effect

$$\frac{\partial V_{\text{eff}}}{\partial \phi} = \frac{\xi}{(N-1)!}\phi^{N-1} - \frac{g_m}{M_{\text{Pl}}} e^{-g_m \phi / M_{\text{Pl}}} \rho_m$$

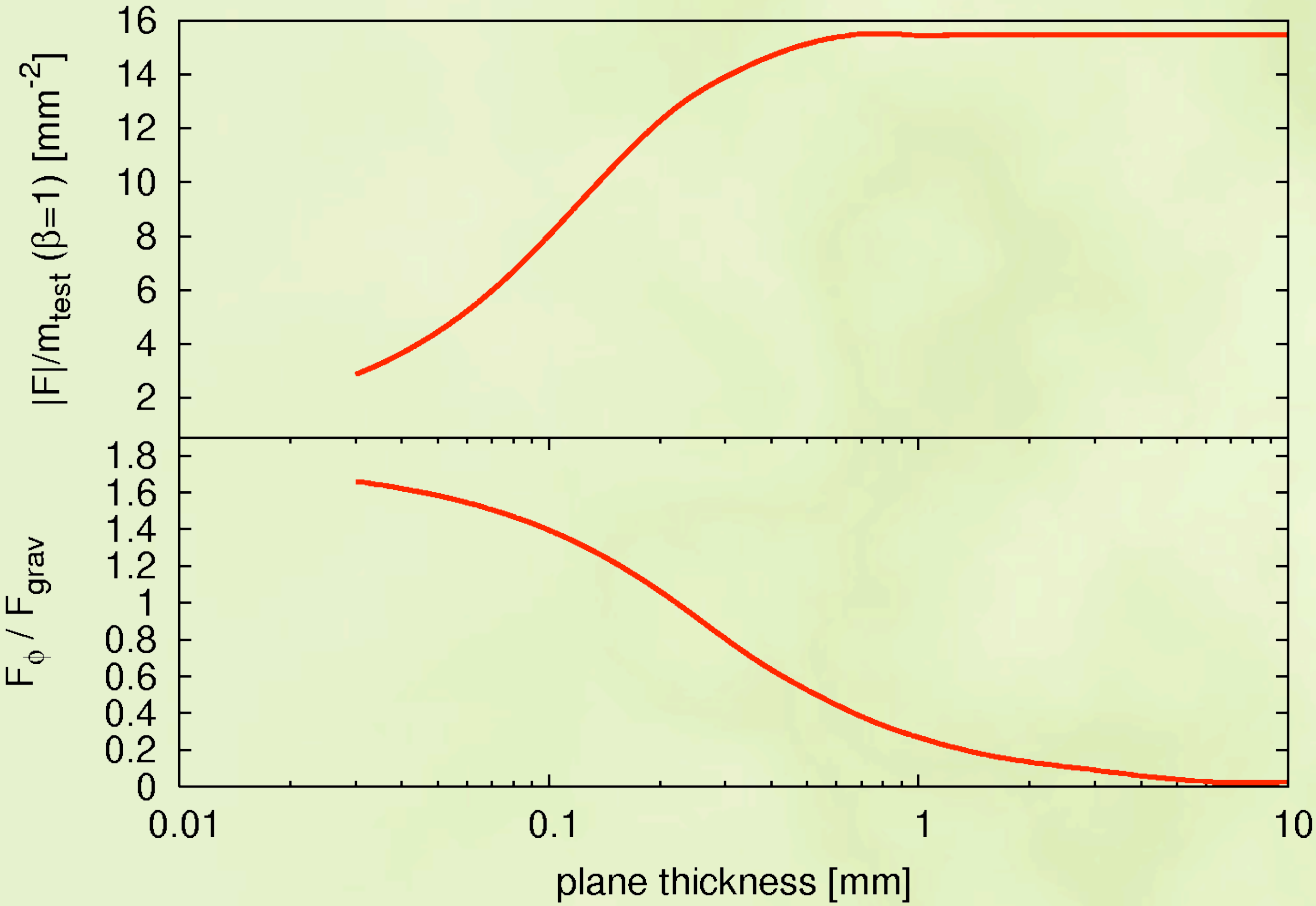
$$\Rightarrow \phi_{\min} \approx \left(\frac{(N-1)! g_m \rho_m}{M_{\text{Pl}} \xi} \right)^{\frac{1}{N-1}}$$

- matter coupling $g_m \neq 0$ implies a minimum energy in bulk matter
- ϕ_{min} attained for objects of size $R >> m_{eff}^{-1}$
- field outside large object couples only to thin outer shell of size ~ m_{eff}^{-1}

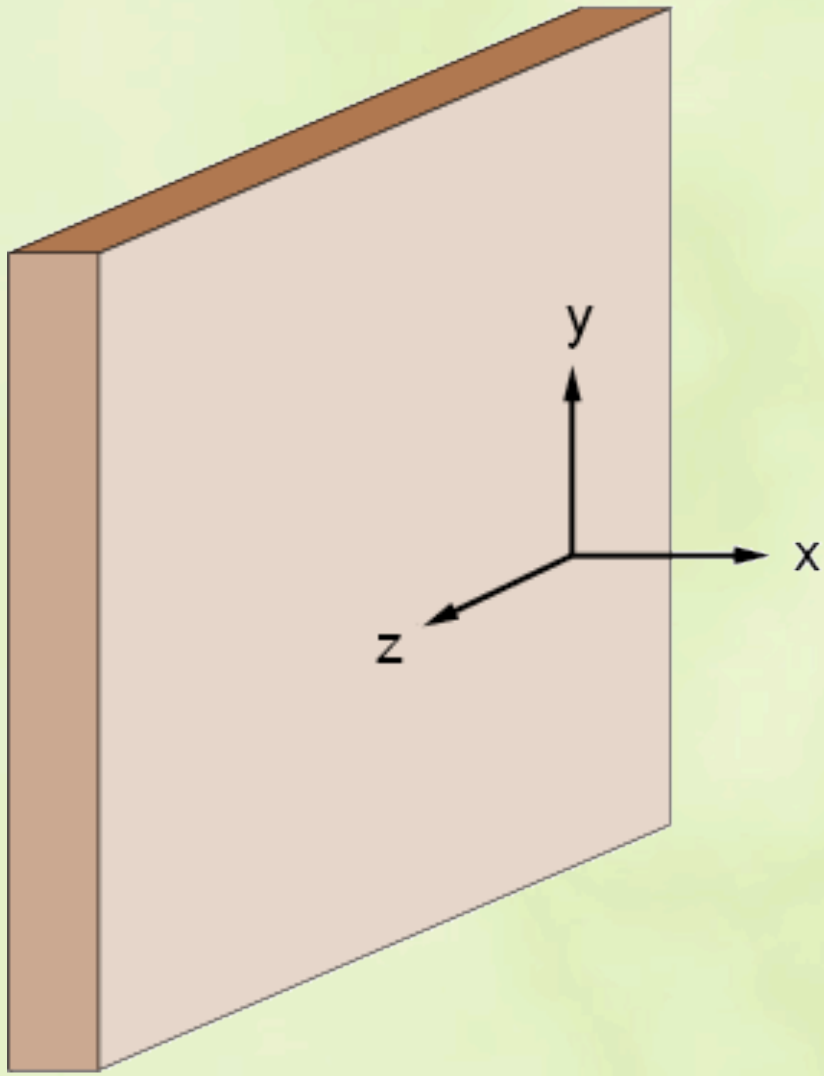
Thin shell effect



Thin shell effect



Fifth force



Fifth force

Power law chameleon:

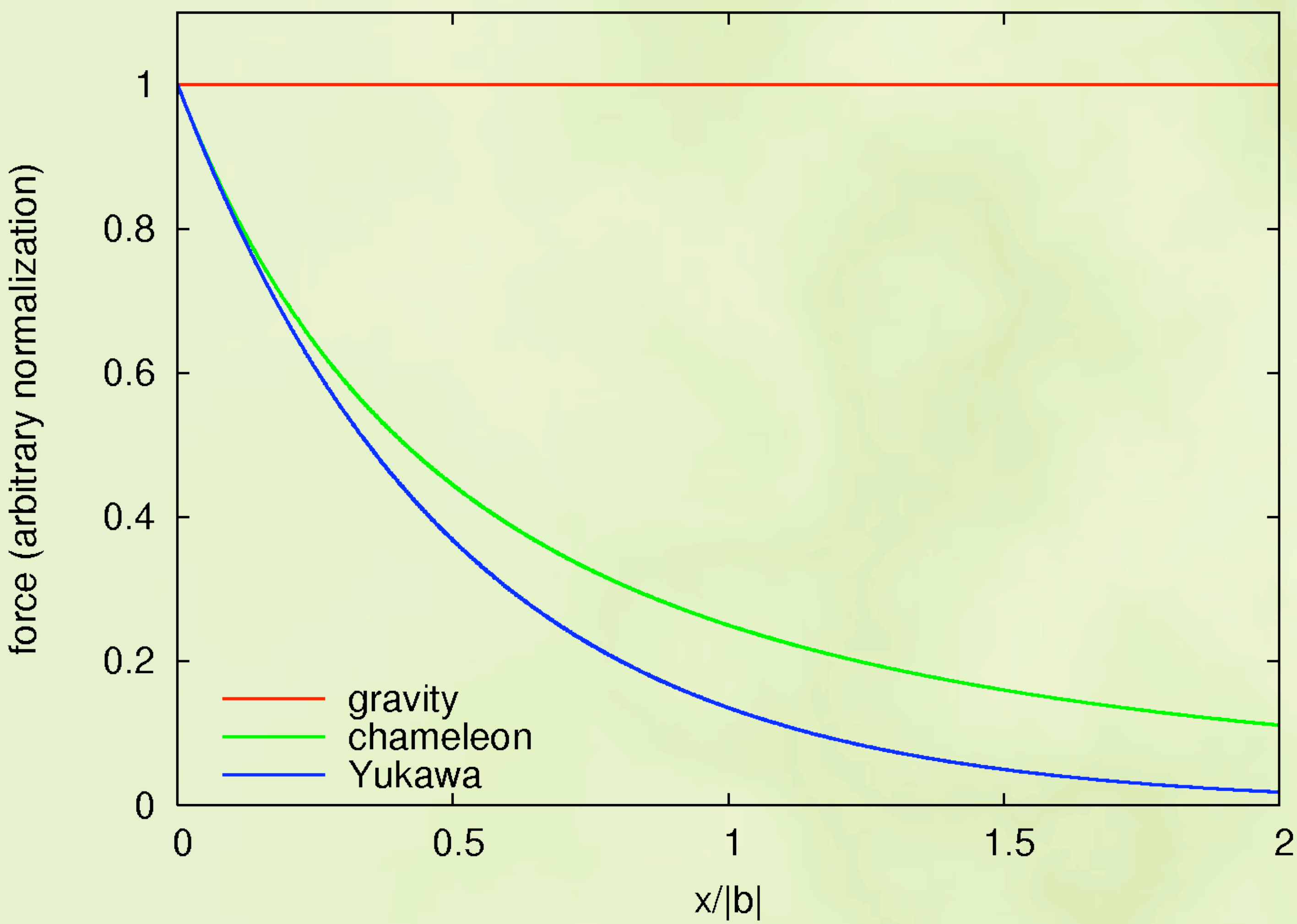
$$\phi(x) = \left(\frac{2N!}{\xi(N-2)^2}\right)^{\frac{1}{N-2}} \frac{1}{(x+b)^{\frac{2}{N-2}}}$$

$$F_{test} = -\frac{2}{N-2}\left(\frac{2N!}{\xi(N-2)^2}\right)^{\frac{1}{N-2}} \frac{g_m m_{test}}{(x+b)^{\frac{N}{N-2}}}$$

Exponential chameleon ($\phi \gg \Lambda \Rightarrow V(\phi) \approx \Lambda^4 \left(1 + \frac{\Lambda^n}{\phi^n}\right)$):

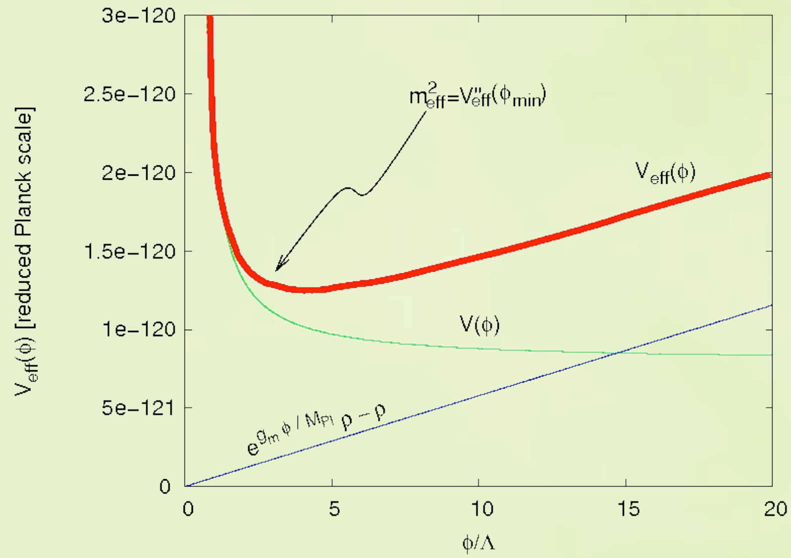
$$\phi(x) = \left(\frac{1}{2}(n+2)^2\Lambda^{4+n}\right)^{\frac{1}{n+2}} (x+b)^{\frac{2}{n+2}}$$

Fifth force



force (arbitrary normalization)
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
x/|b|
gravity
chameleon
Yukawa

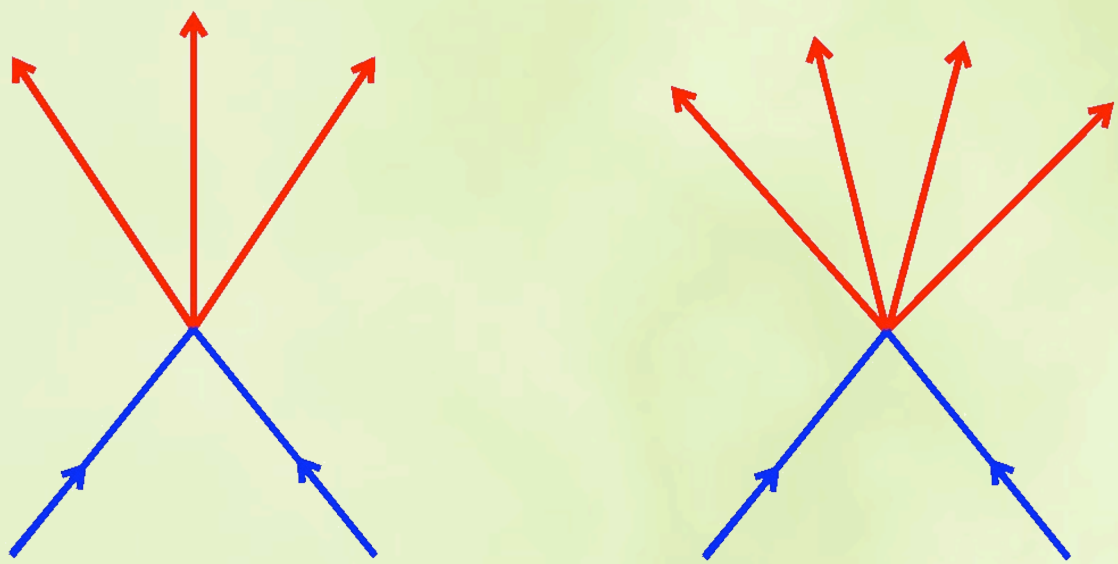
Chameleon fragmentation



$$\phi_{\min} = \left(\frac{n M_{\rm Pl} \Lambda^{4+n}}{g_m \rho_m + g_\gamma \rho_\gamma} \right)^{\frac{1}{n+1}}$$

$$\left. \frac{\partial^m V_{\rm eff}}{\partial \phi^m} \right|_{\phi = \phi_{\min}} = \frac{(-1)^m (n+m-1)! \Lambda^{4+n}}{(n-1)! \phi_{\min}^{n+m}}$$

Chameleon fragmentation



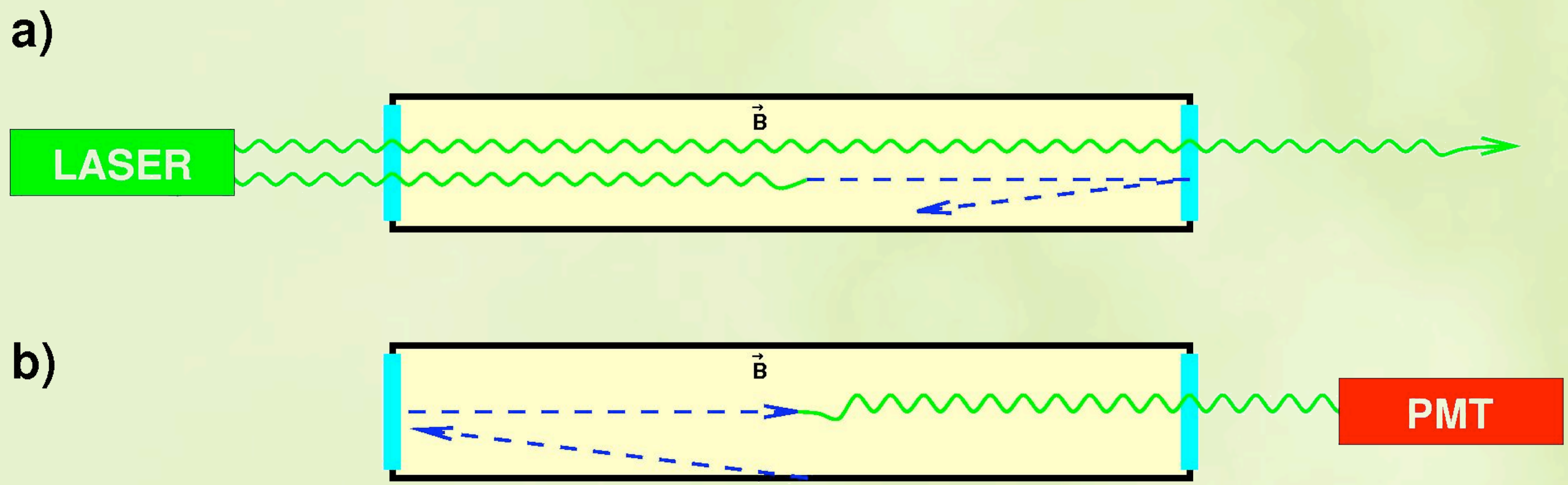
$$\sigma_{\mathrm{frag},m} \sim \left(\frac{\partial^m V_{\mathrm{eff}}(\phi_{\mathrm{min}})}{\partial \phi^m} \right)^2 E_{\mathrm{CM}}^{2(m-5)} \sim \left(\frac{E_{\mathrm{CM}}}{\phi_{\mathrm{min}}} \right)^{2m}$$

so $E_{\mathrm{CM}} > \phi_{\mathrm{min}} \Rightarrow$ fragmentation!

Experimental constraints

- Laboratory: chameleon Compton wavelength $m_{eff}^{-1} < 10\ \mu m$ at laboratory densities $\rho \sim 1\ g/cm^3$ ($m_{eff} > 0.01$ eV)
- Solar cooling: $m_{eff}(\rho) >> T_{sun}(\rho)$ in order to avoid energy loss by chameleon emission

The GammeV Experiment

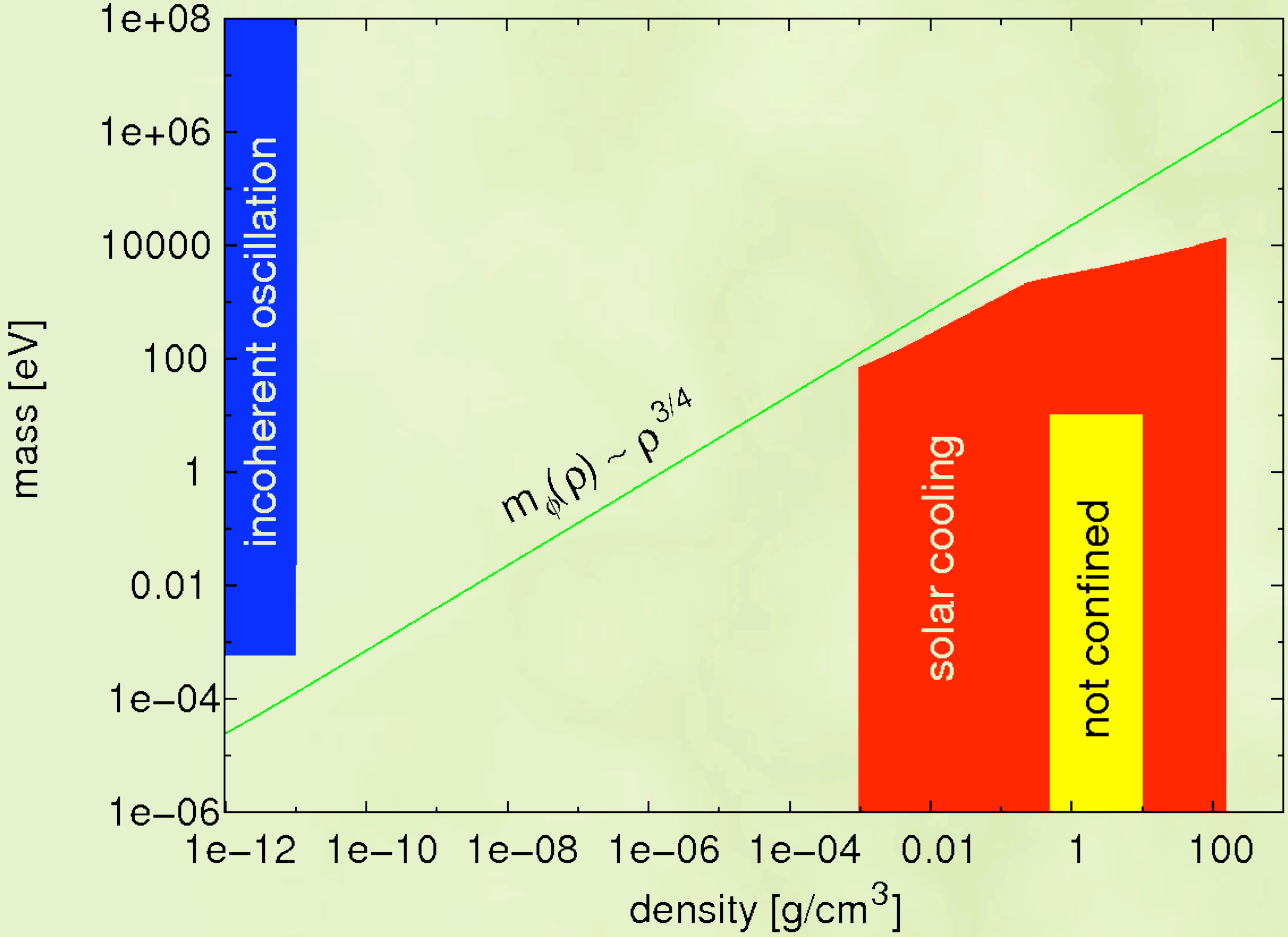


a) Chameleon production phase: photons propagating through region of magnetic field oscillate into chameleons
b) Afterglow phase: chameleons in chamber gradually decay back to photons and are detected

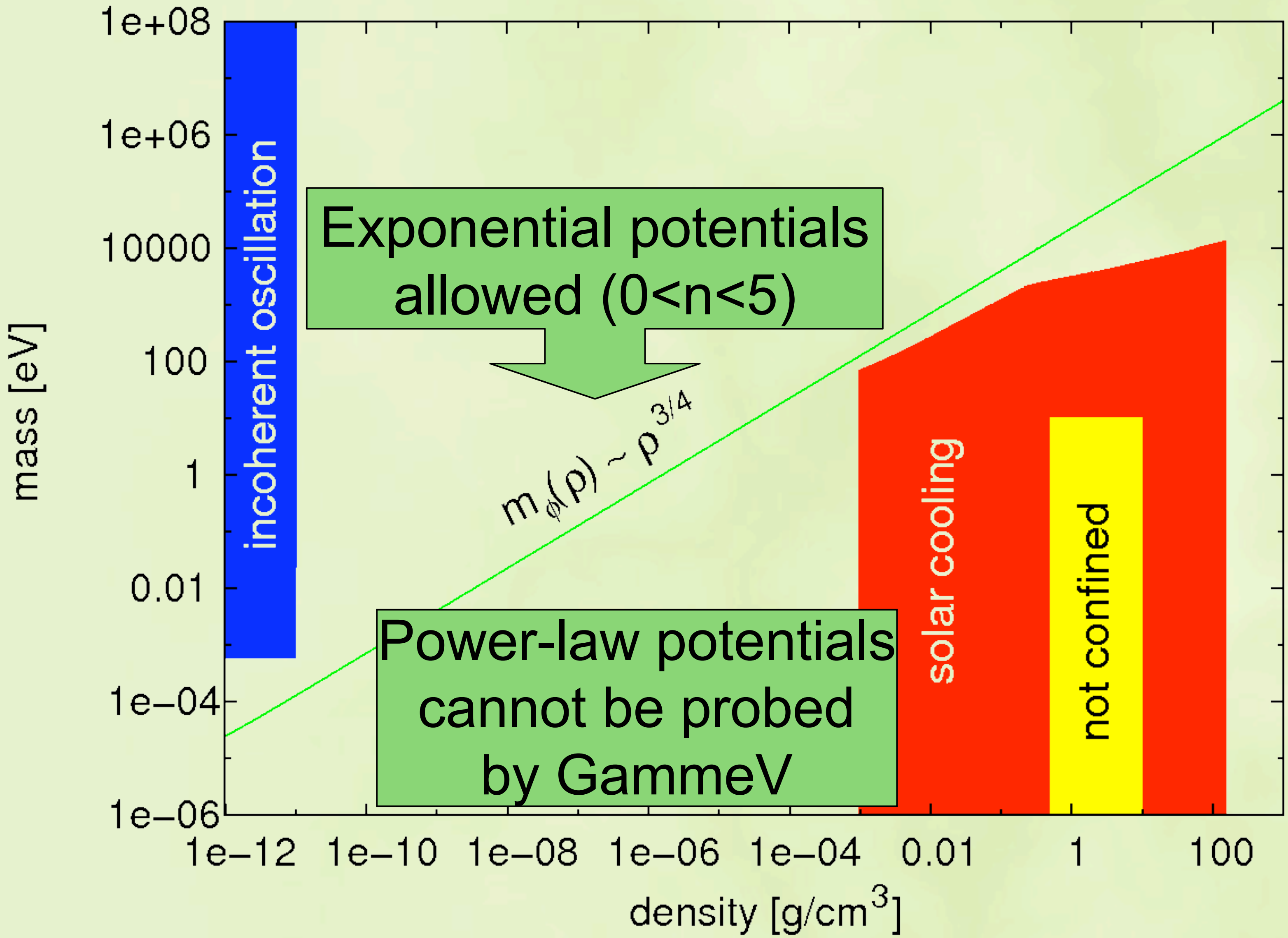
The GammeV Experiment

- Coherent chameleon-photon oscillations: $m_{eff} << 10^{-3}$ eV inside chamber
- Containment: $m_{eff} >> 1$ eV in walls and windows of chamber ($\rho \sim 1$ g/cm^3) in order for chameleons to be contained

Requirements for detectability



Requirements for detectability



Chameleon production

- Initial state (entrance window):

$$|\psi(0)\rangle = |\gamma\rangle$$

- Photon oscillation into chameleon:

$$|\psi(z)\rangle = \mathcal{M}_{\text{osc}}(z)\,|\psi(0)\rangle = \kappa z\,|\phi\rangle + |\gamma\rangle$$

(where $\kappa = \frac{B g_\gamma}{2 M_{\text{Pl}}}$, $\mathcal{M}_{\text{osc}}(\Delta z) = \begin{pmatrix} 1 & -\kappa\Delta z \\ \kappa\Delta z & 1 \end{pmatrix}$)

- Measurement at exit window:

$$\mathcal{P}_{\gamma\to\phi} = \left|\langle\phi|\,\psi(L)\rangle\right|^2 = \frac{B^2 L^2 g_\gamma^2}{4 M_{\text{Pl}}^2}$$

Afterglow

- Laser turned off
- Chameleon momentum isotropized after multiple bounces
- Measurement at window (z=0): photon escapes, chameleon is reflected
- Photon regeneration amplitude:

$$\langle \gamma | \psi(L) \rangle = \kappa \lambda$$

geometric factor

Afterglow

- Production phase: $-\tau_{\rm prod} < t < 0$
- Afterglow phase: $0 < t$
- Number of chameleons:

$$\frac{dN_\phi}{dt} = f_\gamma P_{\gamma\to\phi}\Theta(-t) - \frac{N_\phi}{\tau_{\rm decay}}$$

where $f_\gamma \sim 10^{19}\ \text{photons/sec}$

$$\tau_{\rm decay} = \frac{L}{\kappa^2\lambda^2} = \frac{4M_{\rm Pl}^2 L}{\lambda^2 B^2 g_\gamma^2}$$

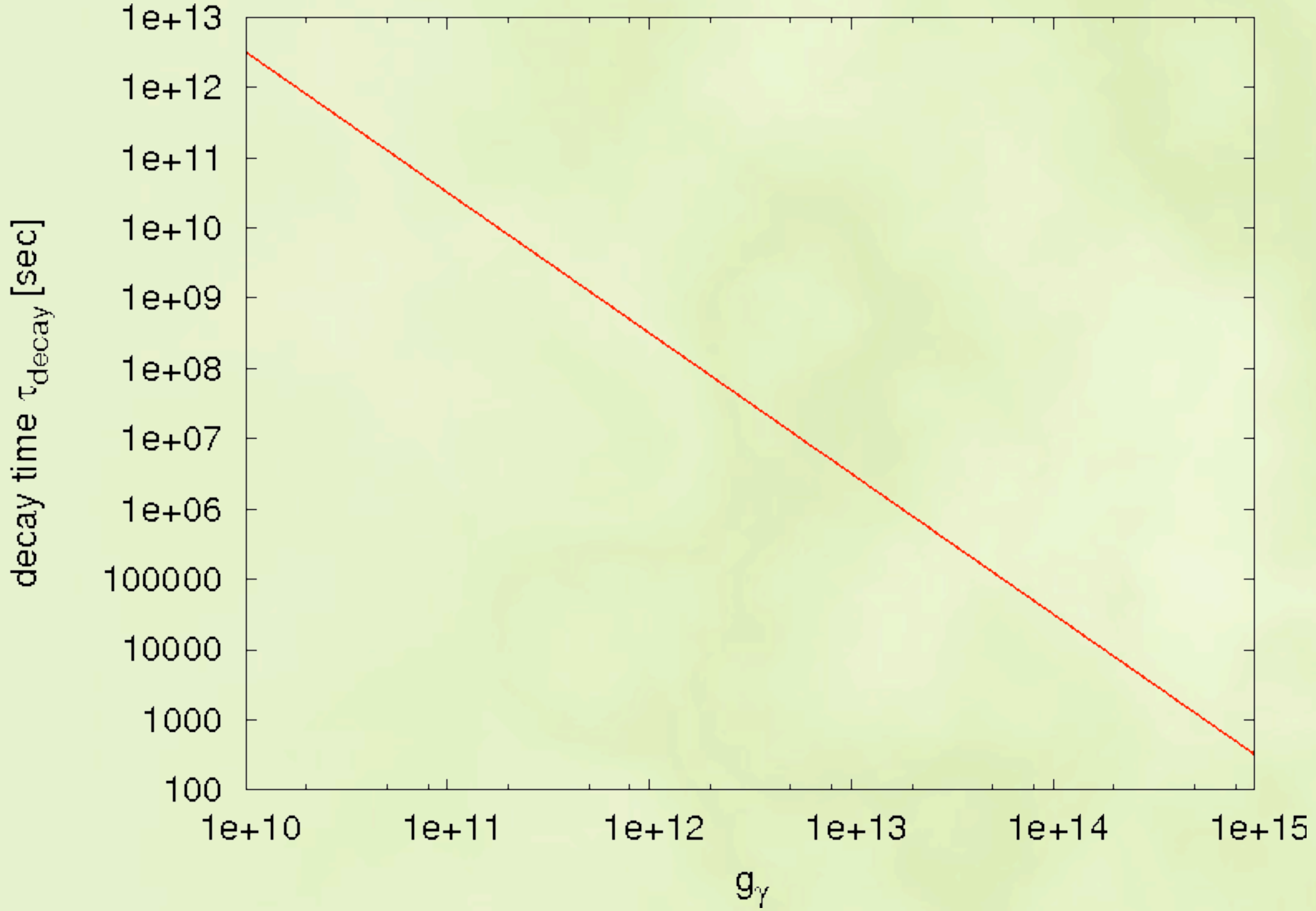
Afterglow

$$N_\phi(t) = \begin{cases} \tau_{\text{decay}} f_\gamma \mathcal{P}_{\gamma\to\phi} \left(1 - \exp\left(-\frac{\tau_{\text{prod}}+t}{\tau_{\text{decay}}}\right)\right) \\ \qquad \text{for } t \leq 0, \\ N_\phi(0) \exp\left(-\frac{t}{\tau_{\text{decay}}}\right) \\ \qquad \text{for } t > 0 \end{cases}$$

Afterglow signal:

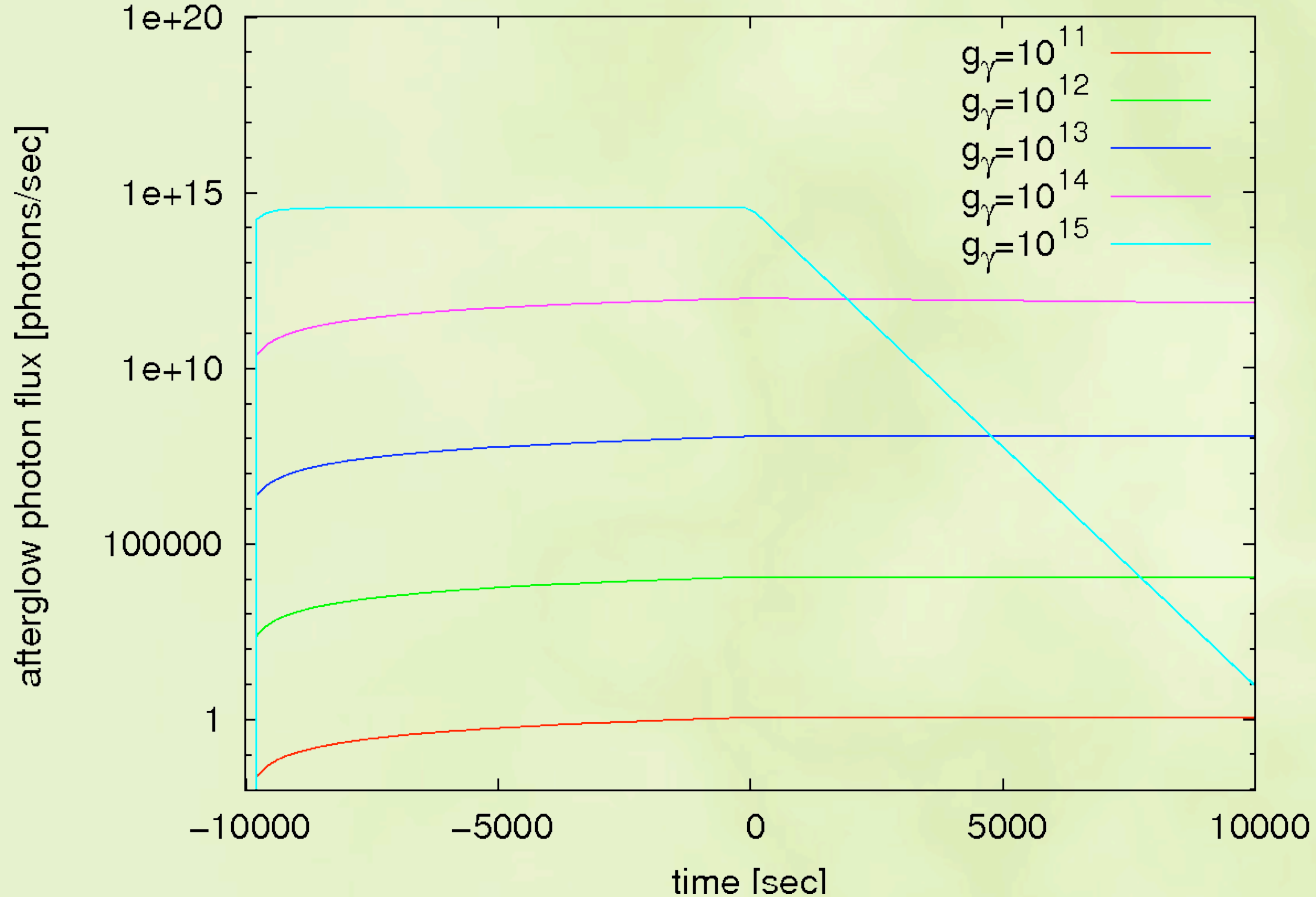
$$f_{\text{afterglow}} = \frac{N_\phi(t)}{\tau_{\text{decay}}} = \frac{N_\phi(0)}{\tau_{\text{decay}}} \exp\left(-\frac{t}{\tau_{\text{decay}}}\right)$$

Decay time

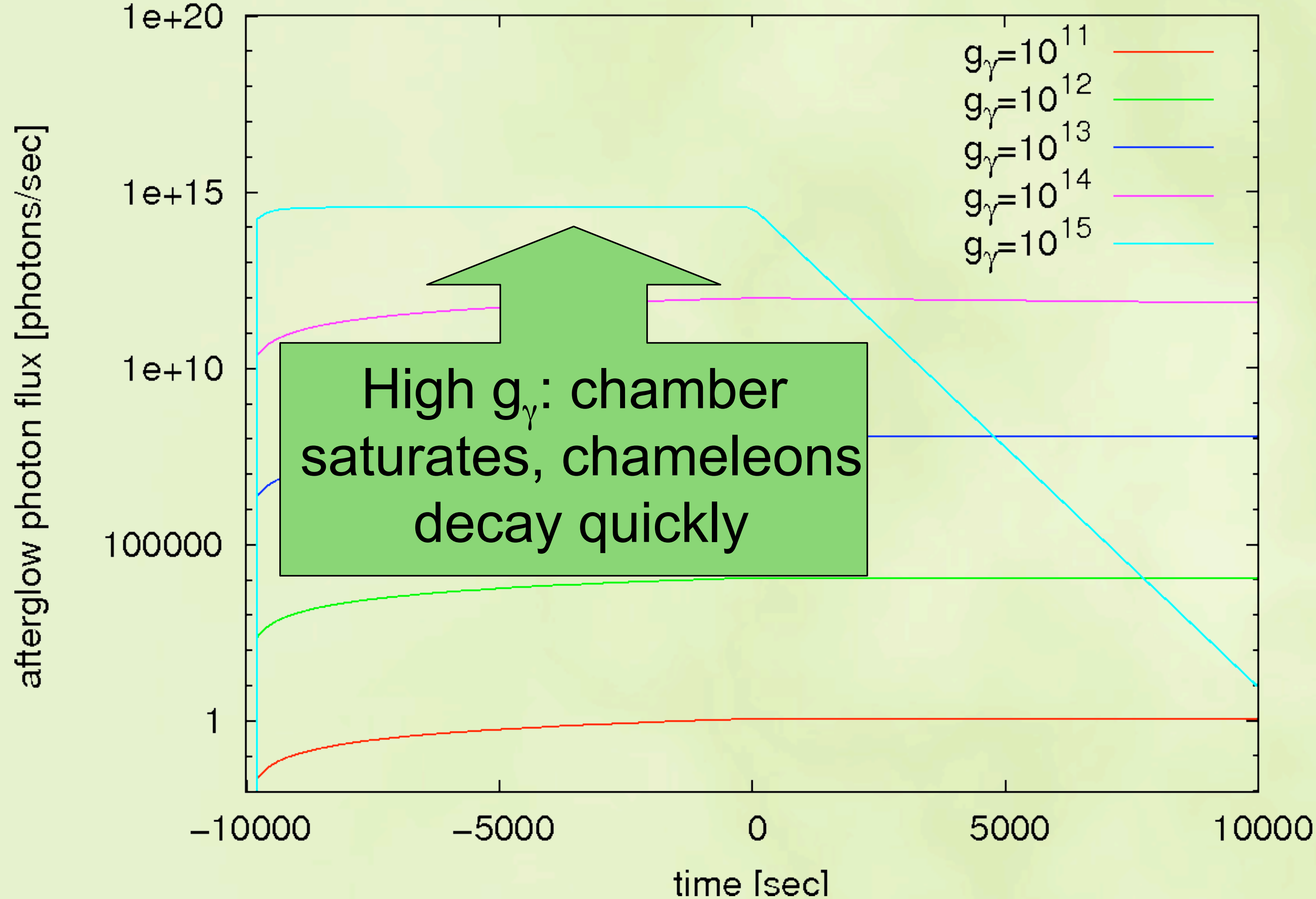


1e+13
1e+12
1e+11
1e+10
1e+09
1e+08
1e+07
1e+06
100000
10000
1000
100
decay time τ_{decay} [sec]
1e+10
1e+11
1e+12
1e+13
1e+14
1e+15
g_γ

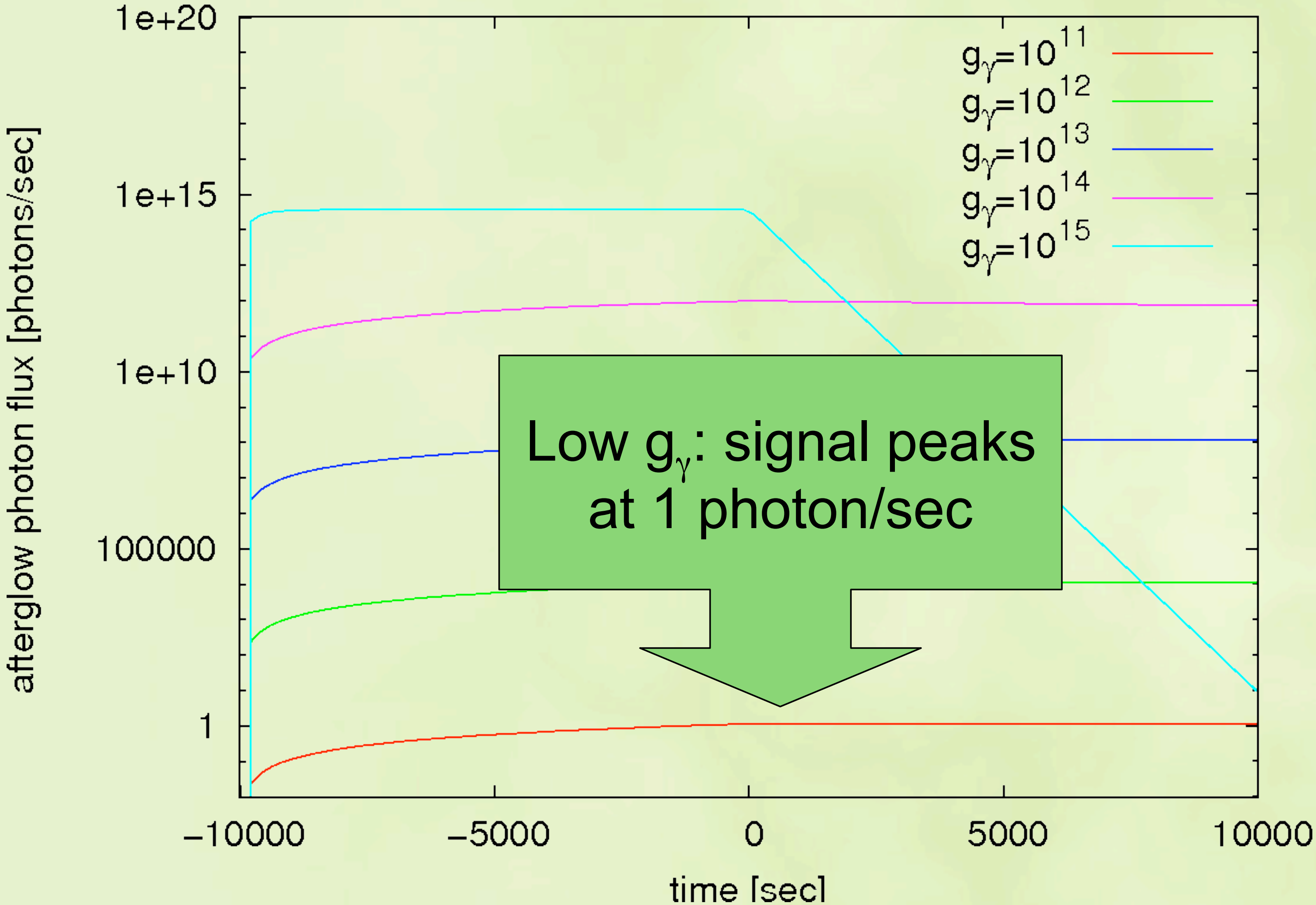
Afterglow signal dNϕ/dt



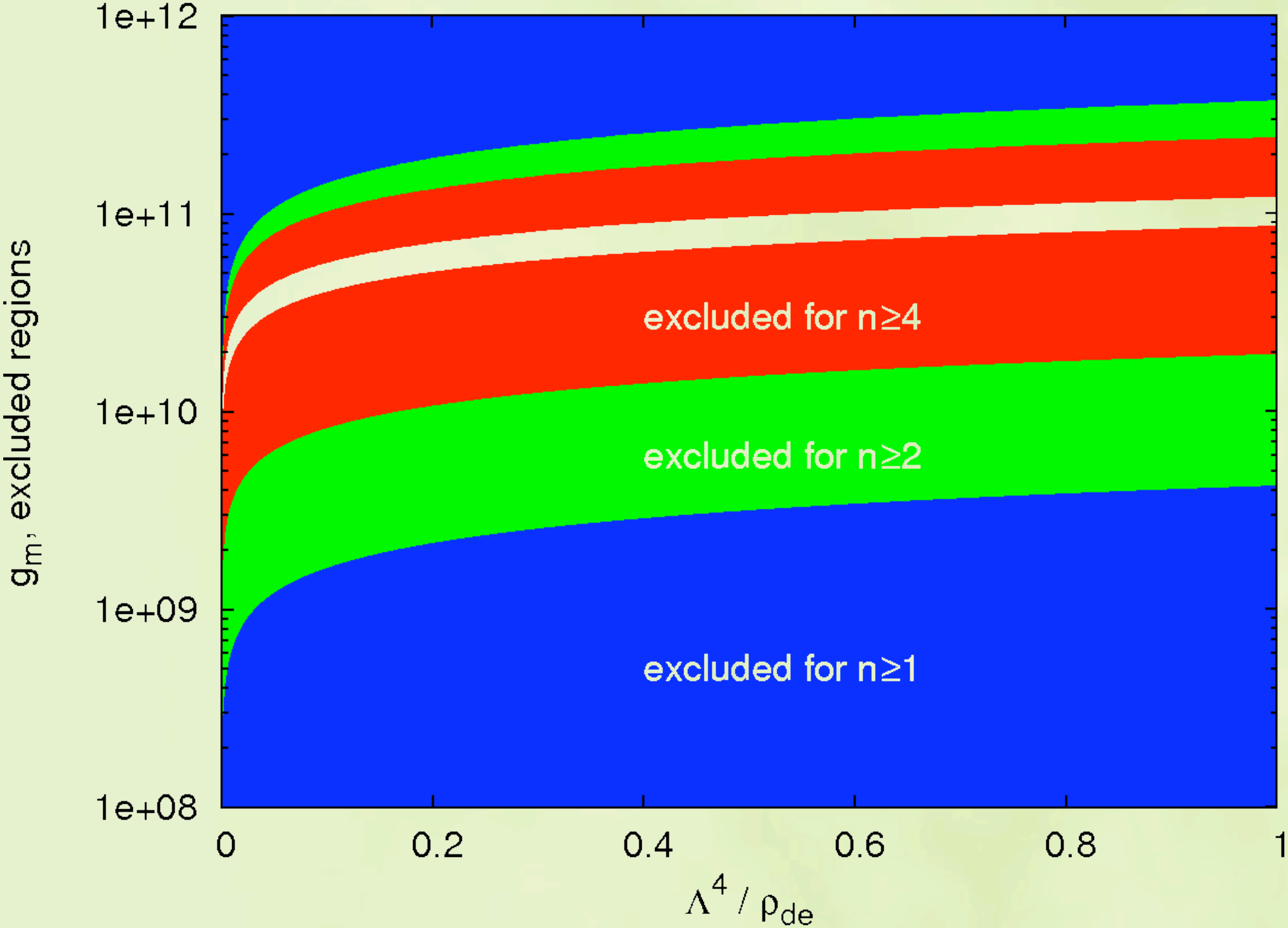
Afterglow signal dNϕ/dt



Afterglow signal dNϕ/dt



Constraining the parameters



Complications

- In all cosmologically interesting cases, τ_{decay} >> 1 day, and any observed signal will be constant.
- Other types of interactions allow smaller decay times:
    1. decay to other particles
    2. fragmentation

Decay to other particles

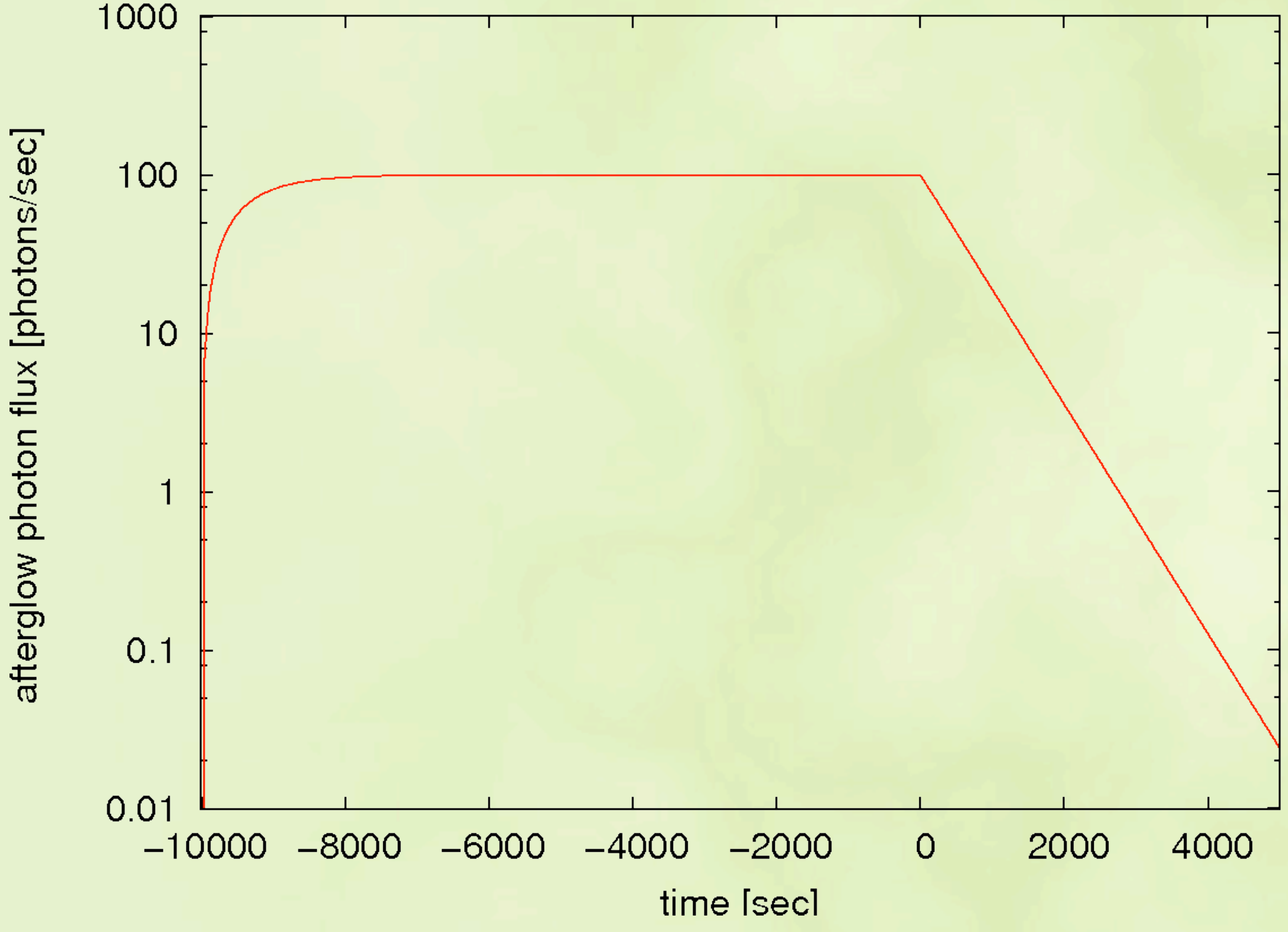
Assume that chameleons can decay to other particles not detectable by GammeV, with decay time τ_{other}.

$$\frac{dN_\phi}{dt} = f_\gamma P_{\gamma\to\phi}\Theta(-t) - \frac{N_\phi}{\tau_{\rm decay}} - \frac{N_\phi}{\tau_{\rm other}}$$

This alternative decay channel can speed up the decay of the afterglow signal:

$$f_{\rm afterglow} = \frac{N_\phi(0)}{\tau_{\rm decay}} \exp\left(-\frac{t}{\tau_{\rm decay} + \tau_{\rm other}}\right)$$

Decay to other particles



Fragmentation

- Fragmentation causes chameleons with detectable energies (E ~ 1 eV) to split into undetectable, lower-energy chameleons.
- Exponential potential: fragmentation cross section diverges if $E_{CM} > \phi_{min}$
- In GammeV, $E_{CM} \sim 1$ eV.
- For detectable chameleons, $\phi_{min} < 0.1$ eV.
- Assume σ_{frag} remains finite. Fragmentation can change the afterglow time scale.

Fragmentation

Fragmentation turns two chameleon particles into many chameleons. Thus the rate at which the number N_ϕ of detectable chameleons decreases should be given by:

$$\frac{dN_\phi}{dt} = f_\gamma P_{\gamma\to\phi}\Theta(-t) - \frac{N_\phi}{\tau_{\rm decay}} - \frac{N_\phi^2}{\tau_{\rm frag}}$$

Fragmentation

Production phase ($-\tau_{prod} < t < 0$):

$$N_\phi(t) = \frac{\tau_{\rm frag} f_\gamma \mathcal{P}_{\gamma\to\phi} \sinh\left(\frac{a(t+\tau_{\rm prod})}{\tau_{\rm frag}}\right)}{a\cosh\left(\frac{a(t+\tau_{\rm prod})}{\tau_{\rm frag}}\right) + b\sinh\left(\frac{a(t+\tau_{\rm prod})}{\tau_{\rm frag}}\right)}$$

where

$$a = \sqrt{\left(\frac{\tau_{\rm frag}}{2\tau_{\rm decay}}\right)^2 + \tau_{\rm frag} f_\gamma \mathcal{P}_{\gamma\to\phi}}, \qquad b = \frac{\tau_{\rm frag}}{2\tau_{\rm decay}}$$

Afterglow phase ($0 < t$):

$$N_\phi(t) = \frac{2bN_\phi(0)\exp(-t/\tau_{\rm decay})}{2b + N_\phi(0) - N_\phi(0)\exp(-t/\tau_{\rm decay})}$$

Fragmentation

In the limit where fragmentation is much quicker than decay, N_ϕ is given by

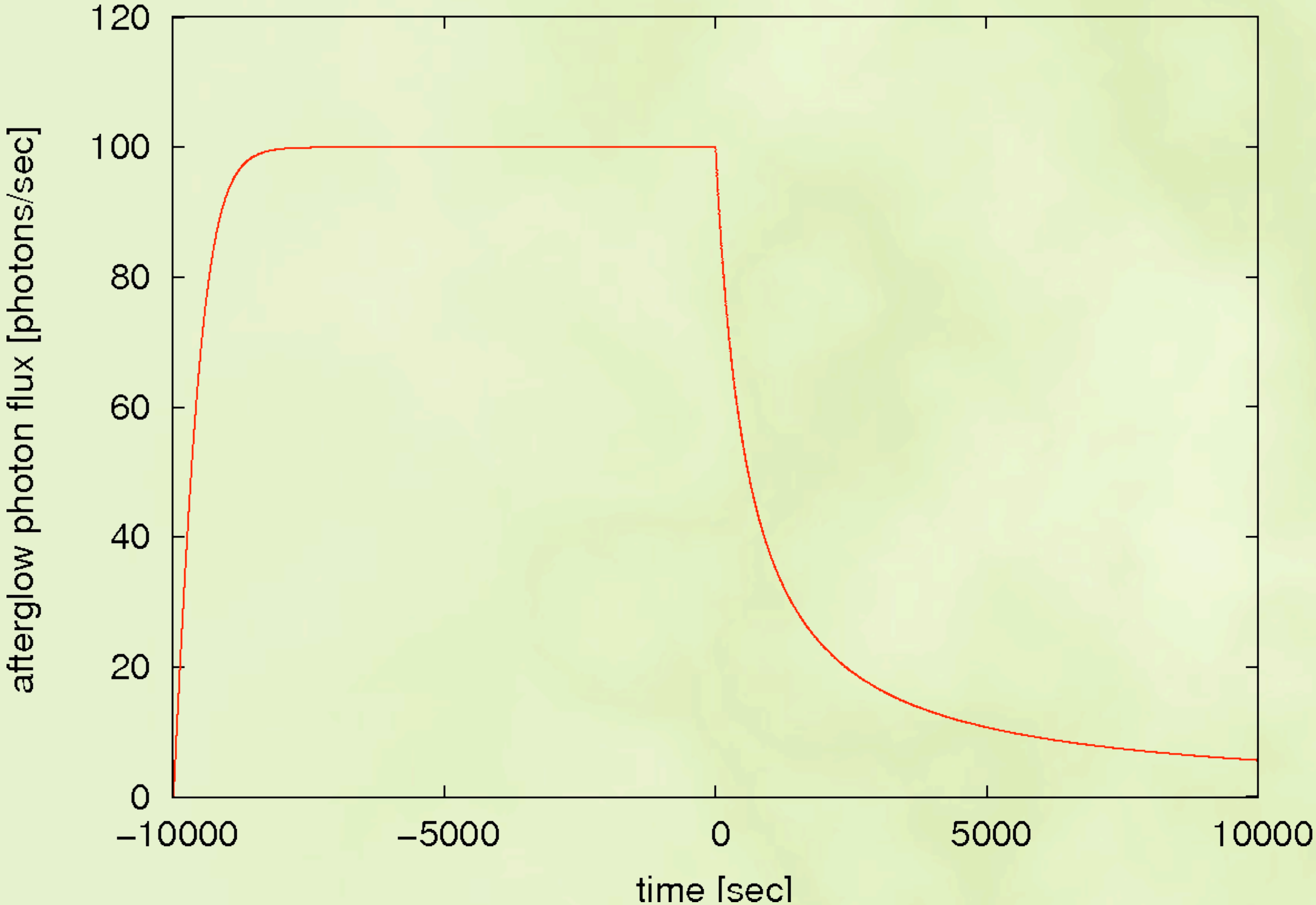
$$N_\phi(t) \approx \frac{N_\phi(0)}{1 + t/\tau_{\rm half}}$$

where τ_{half} is the time required for the initial number of chameleons $N_\phi(0)$ to be halved.

The afterglow signal is:

$$f_{\rm afterglow}(t) \approx \frac{N_\phi(0)/\tau_{\rm decay}}{1 + t/\tau_{\rm half}}$$

Fragmentation



Conclusions

- Chameleons, self-interacting matter-coupled scalar fields, are candidates for the dark energy.
- GammeV is an experiment searching for afterglow, a unique signature of photon-coupled chameleon particles.
- GammeV can probe cosmologically interesting chameleon theories.
- Data analysis is under way!