Solar Chameleons

Collaboration with A. Lindner and
K. Zioutas

“Patras 2011” workshop
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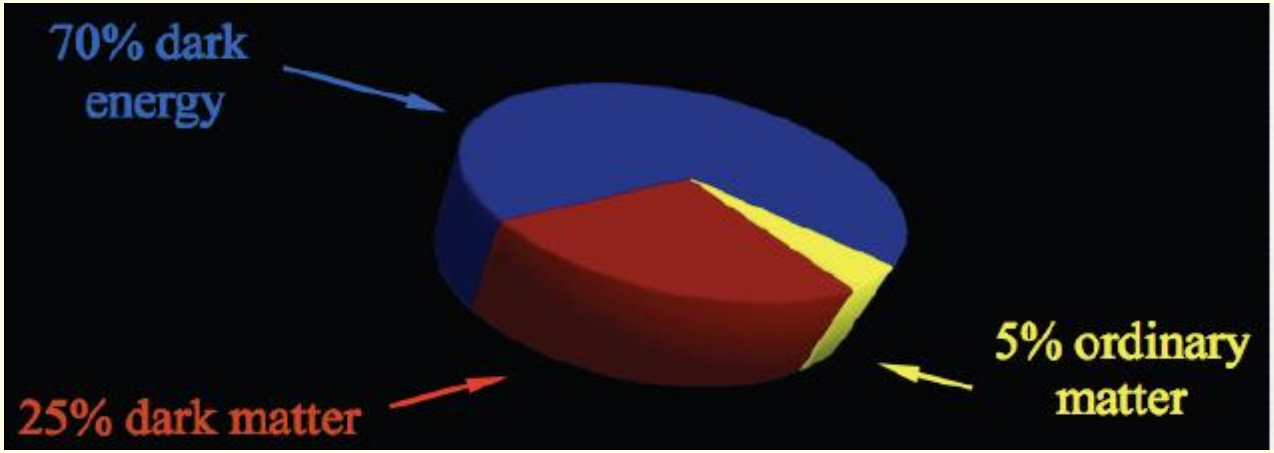
Outline

1-Dark Energy and Chameleons.

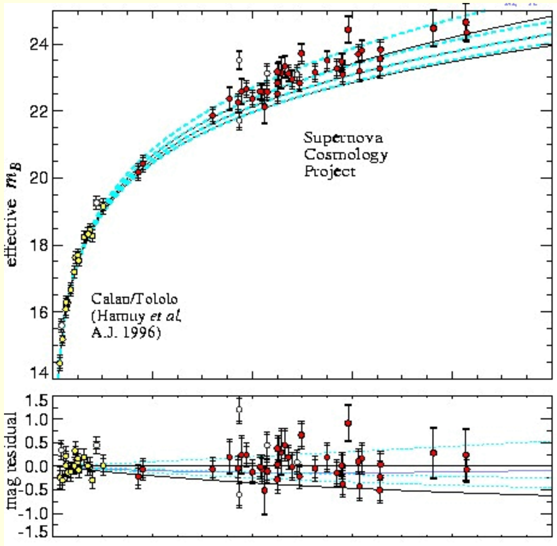
2-Solar Chameleons.

The Big Puzzle



Evidence: The Hubble Diagram

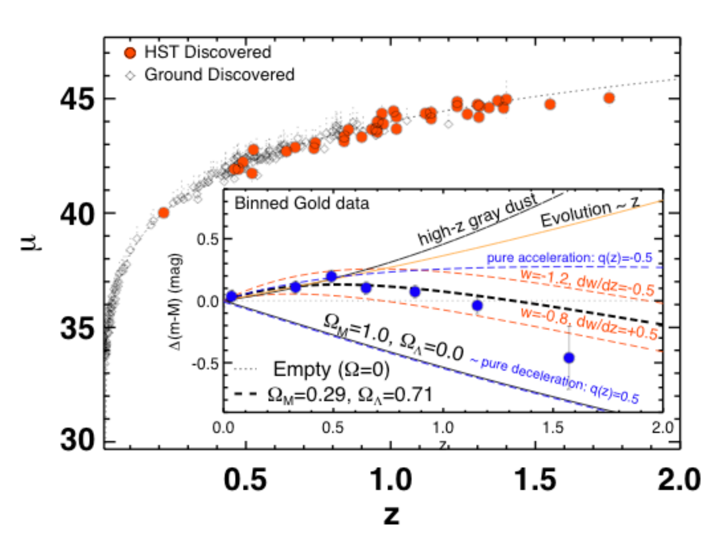
The explosion of high red-shift SN Ia (standard candles):



$$q_0 \equiv -\frac{a_0 \ddot{a}_0}{(\dot{a}_0)^2} \simeq -0.67 \pm 0.25$$

Within General Relativity, link to matter and dark energy

$$q_0 = -\Omega_\Lambda + \frac{1}{2}\Omega_m \sim -0.67$$



Dark Energy must exist!

The Cosmic Microwave Background

Fluctuations of the CMB temperature across the sky lead to acoustic peaks and troughs, snapshot of the plasma oscillations at the last scattering

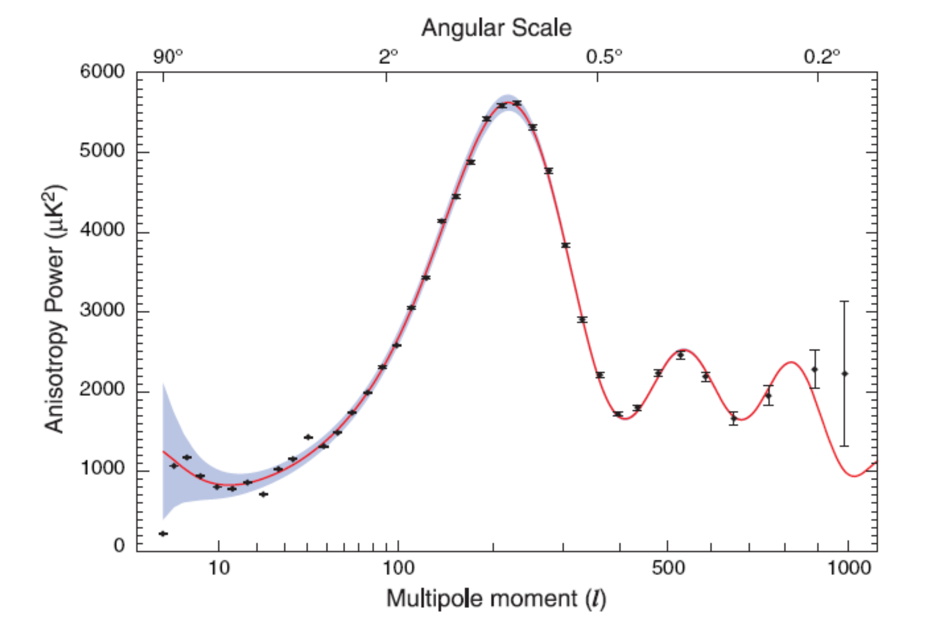
The position of the first peak:

$$l_1 \approx \frac{220}{\sqrt{\Omega_\Lambda + \Omega_m}}$$

The universe is spatially flat

$$\Omega_\Lambda + \Omega_m = 1$$

$$\Omega_\Lambda = \frac{2}{3}\left(\frac{1}{2} - q_0\right) \sim 0.78$$



WMAP data

Dark Energy Really?

In fact we are not absolutely certain that the acceleration of the universe is due to dark energy. On the contrary, the acceleration of the expansion of the universe may be interpreted in four different ways:

1) The acceleration is entirely due to the presence of a constant vacuum energy (cosmological constant).

$$\frac{1}{16\pi G_N}\int d^4x\sqrt{-g}(R-2\Lambda)$$

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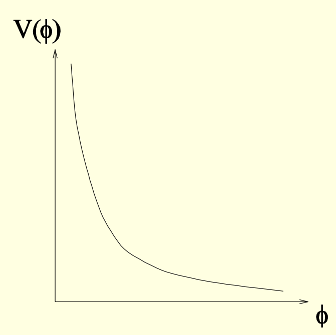
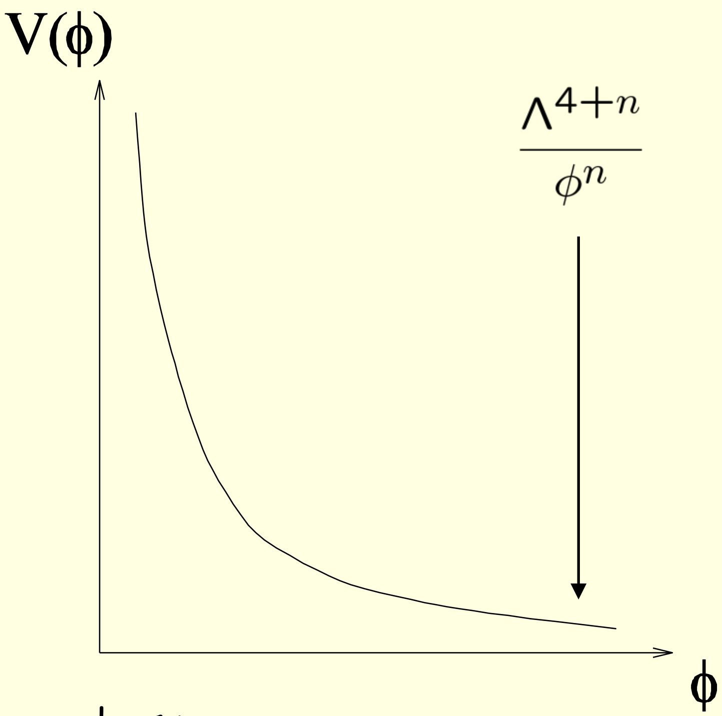
2) The acceleration results from the existence of a new type of matter: dark energy.

$$S = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}(R - \mathcal{L}_{DE})$$



Dark Energy

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + V(\phi)$$



Field rolling down a runaway potential, reaching large values now
(typically Planck scale)

How Flat?

Energy density and pressure:

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi), \;\; p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$w = \frac{p}{\rho}$$

$m \gg H_0$	very fast roll	$w \approx 1$	
$m \ll H_0$	slow roll	$w \approx -1$	cosmological constant
$\boxed{m \approx H_0}$	gentle roll	$w \neq -1$	dark energy

$$H_0 \approx 10^{-42}\text{GeV}$$

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3) What is seen as acceleration is in fact a misinterpretation of data and really we must face a modification of gravity at large enough scales.

$$S = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}h(R, R_{\mu\nu}, R_{\mu\nu\rho\sigma})$$

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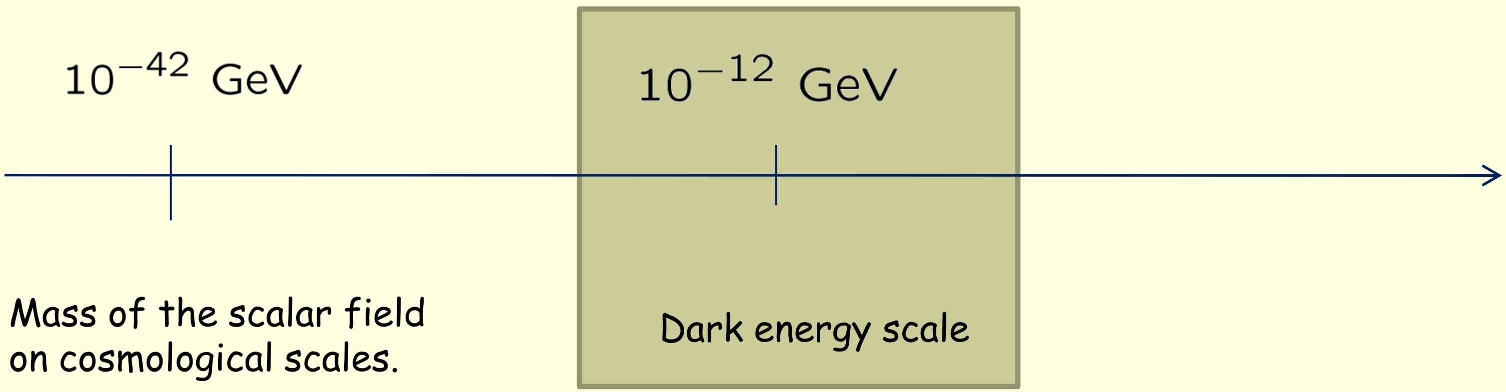
2) The acceleration results from the existence of a new type of matter: dark energy.

3) What is seen as acceleration is in fact a misinterpretation of data and really we must face a modification of gravity at large enough scales.

4) There is no real acceleration. We just live in a void surrounded by more matter. No copernican principle stands.

$$ds^2 = -dt^2 + \frac{R'^2(r,t)}{1-k(r)r^2}dr^2 + R^2(r,t)d\Omega^2$$

New Scales in Physics



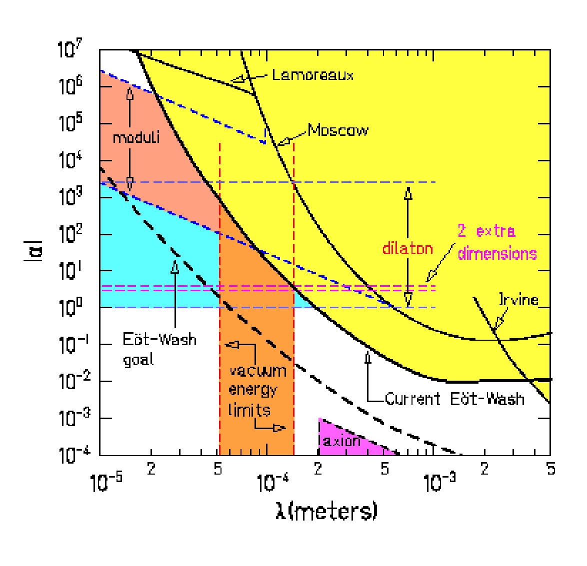
The dark energy scale is tantalizingly close to the neutrino mass scale and the scale at which gravity has been tested…

- Deviations from Newton's law are parametrised by:

$$\phi_N = -\frac{G_N}{r}(1 + 2\beta_\phi^2 e^{-r/\lambda})$$

For fields of zero mass or the order of the Hubble rate now, the tightest constraint on β comes from the Cassini probe measuring the Shapiro effect (time delay):

$$\beta_\phi^2 \leq 1.210^{-5}$$



Three known mechanisms can accomodate usual gravity locally with deviations on larger scales:

i) The Vainshtein mechanism in the case of DGP gravity (and similar models like the Galileon). In this case, gravity is like GR locally, like a scalar-tensor theory at larger scales (and 5d at very large scales).

ii) The chameleon mechanism for scalar-tensor theories and f(R) models. Gravity is locally like GR, deviates from GR at intermediate distances and is like GR far away.

iii)The Damour-Polyakov mechanism (dilaton at strong coupling) or symmetron. Gravity is like GR locally and modified at all scales further away.

Chameleons

Chameleon field: field with a matter dependent mass

A way to reconcile gravity tests and cosmology:

Nearly massless field on cosmological scales

Massive field in the laboratory

Chameleon Lagrangian

Effective field theories with gravity and scalars:

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{16\pi G_N}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) + \mathcal{L}_m(\psi_m, A^2(\phi)g_{\mu\nu})\right)$$

$$\beta_\phi = m_{\mathrm{Pl}}\frac{d\ln A}{d\phi}$$

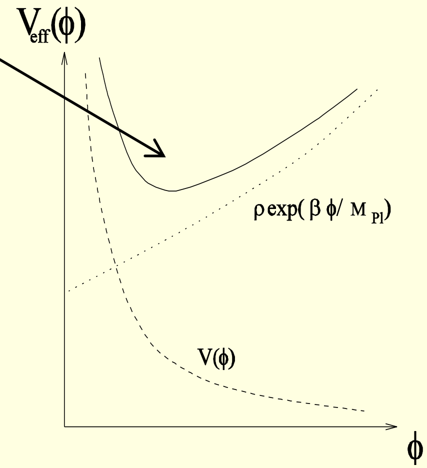
Scalars differ from axions inasmuch as they can couple to matter with non-derivative interactions. All the physics is captured by the function $A(\phi)$.

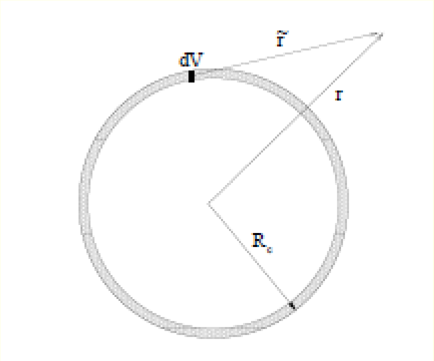
The effect of the environment

When coupled to matter, scalar fields have a matter dependent effective potential

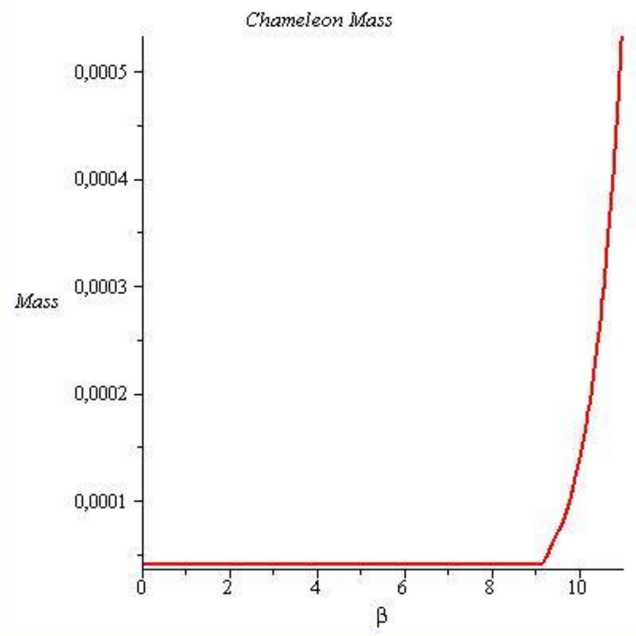
$$V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)$$

Environment dependent minimum





The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.



Vacuum mass in eV

Chameleons adapt their mass to the vacuum. The mass in a cylinder is determined by a resonance of the order 1/R for low values of the coupling. For larger values, the mass depends on the coupling.

$\beta \leq 10^{11}$

ILL constraints on neutronic energy levels in the terrestrial gravitational field

$p_{\text{vacuum}} = 10^{-8}\text{mbar}$

Coupling to Photons

$$L_{\text{eff}} = \frac{1}{M_\gamma}\phi F_{ab}F^{ab}$$

$$\beta_\phi = \frac{m_{\text{Pl}}}{M_{\text{matter}}}$$

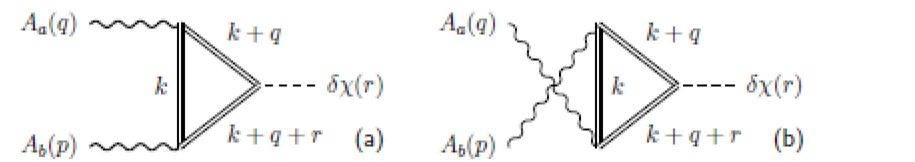


Figure 1. Diagrams contributing to the leading interaction between dark energy and the electroweak gauge bosons, which determine an effective operator acting on $A_a(q)A_b(p)\chi(r)$. Note that the momentum carried by χ is taken to flow into the diagram. Double lines represent a species of heavy fermion charged under $SU(2)\times U(1)$.

When the coupling to matter is universal, and heavy fermions are integrated out, a photon coupling is induced. Other contributions from conformal anomaly.

Chameleons Coupled to Photons

- The chameleon mixes with the polarisation orthogonal to the magnetic field and oscillations occur. Mixing happens when the chameleon is not tachyonic:

$$k^2(\omega) = \omega^2 - (m^2 - \frac{B^2}{M_\gamma^2} - \omega_{\mathrm{Pl}}^2)(\frac{\cos\theta + 1}{2\cos\theta})$$

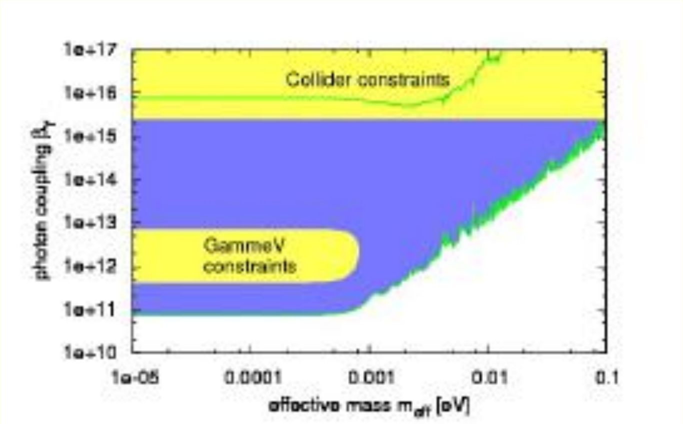
- The mixing angle between chameleons and photons is:

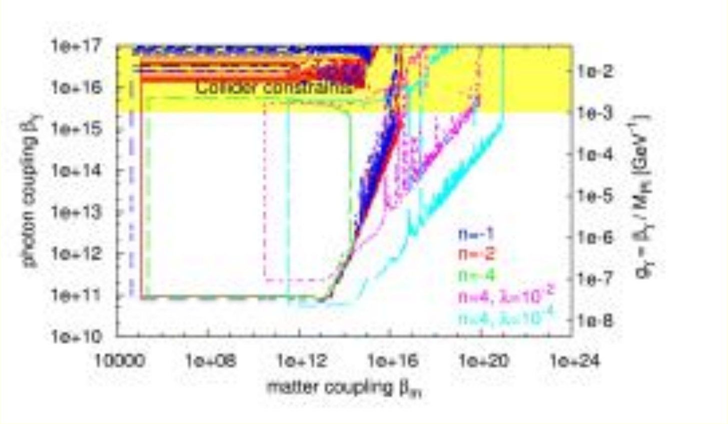
$$\tan 2\theta = \frac{2\omega B}{M_\gamma(m^2 - \frac{B^2}{M_\gamma^2} - \omega_{\mathrm{Pl}}^2)}$$

- The transition probability is:

$$P_{\text{chameleon}} = \sin^2\theta \sin^2(\frac{\Delta}{\cos 2\theta})$$

$$\Delta = \frac{(m^2 - \frac{B^2}{M_\gamma^2} - \omega_{\mathrm{Pl}}^2)L}{4\omega}$$

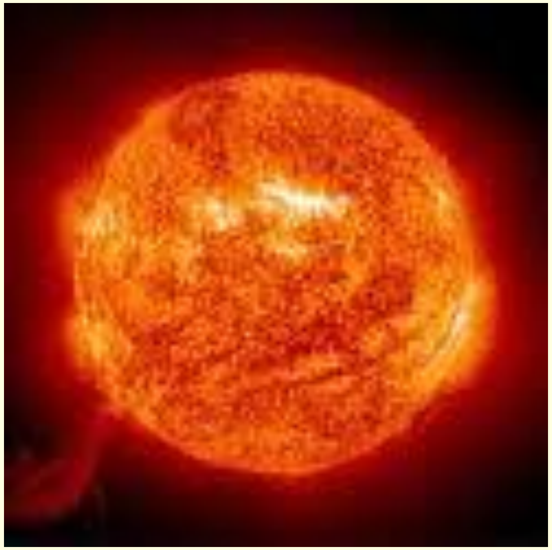




Photon coupling bounded by afterglow experiment (Chase-Fermilab)

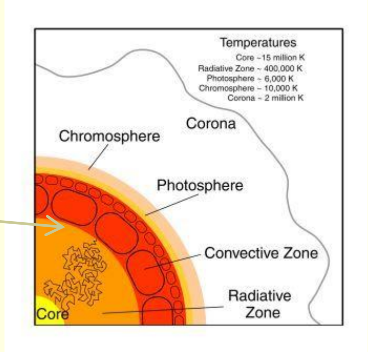
$$\beta_\gamma \leq 10^{11}$$

Solar Chameleons



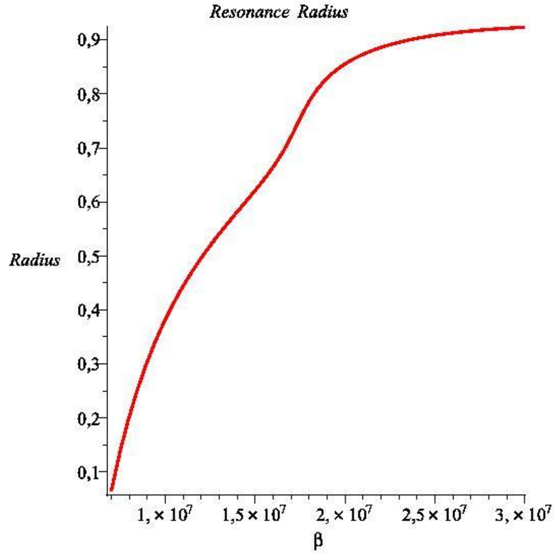
Chameleons can be produced in the tachocline region at a radius 0.7 Rs. The magnetic field is 20-50 T. The mean free path is about 0.3 cm. The photons have a temperature of 200 eV and the photon flux is $n_\gamma \sim 10^{21} s^{-1} cm^{-2}$. These thermal photons create chameleons.

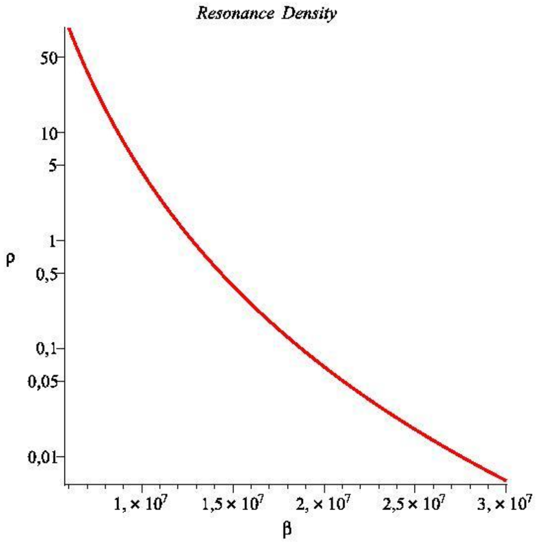
tachocline



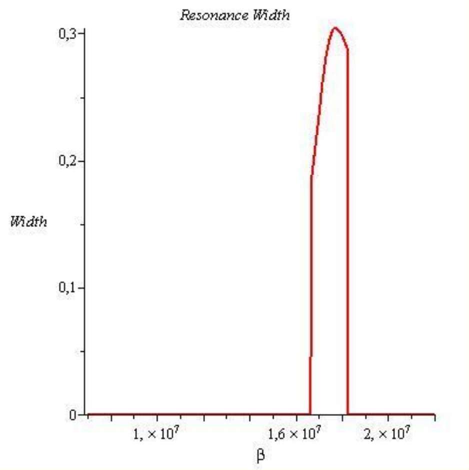
Most chameleons escape the sun, a tiny fraction are back-converted to photons in the outer sun (the photosphere) over magnetic regions of about 10-100 km where the magnetic field is up to 0.2 T. The photons perform a random walk and lose their directionality. Some are also produced at altitude in a weaker magnetic field around 1 Gauss but over large magnetic regions such that BL=10000 T.m .

There are two types of production in the sun: resonant and non-resonant





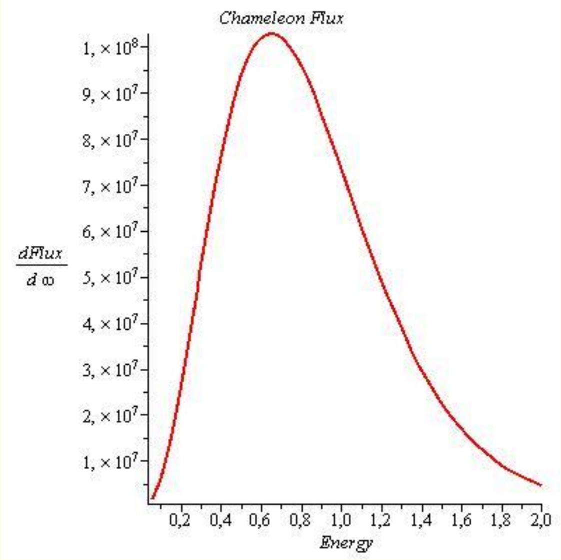
A resonance occurs when the mass of the chameleon becomes equal to the plasma frequency. A resonance is only possible for a very narrow range of matter coupling. The resonance width is typically very narrow.



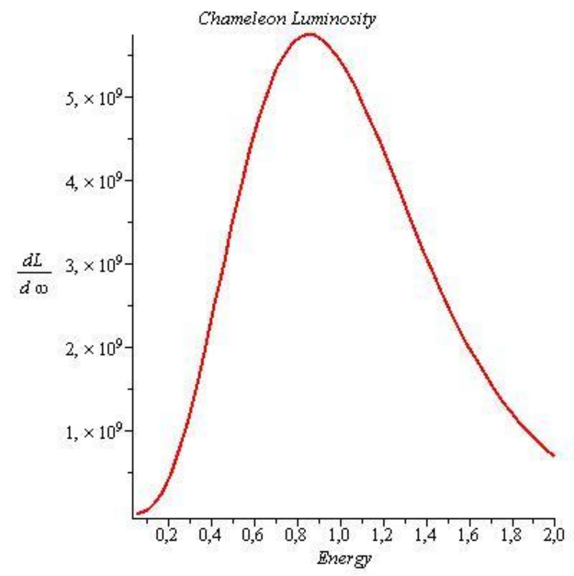
The resonance width in cm as a function of the matter coupling when the production region is a narrow shell of width 0.01 Rs above the tachocline with a magnetic field of 30T

Non-resonant production takes places over all the magnetic regions in the sun.

Chameleons leaving the sun must not exceed the solar luminosity, too much energy loss. Being in the keV range, they go through the atmosphere and even metal.

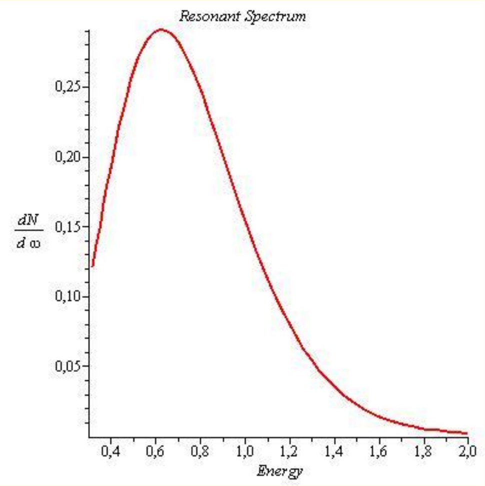


Flux reaching the earth.

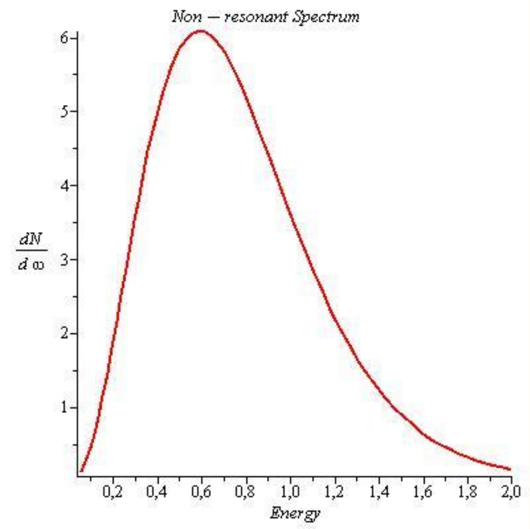


Chameleon luminosity leaving the sun amounting to 6 Gerg/s.cm2

The spectrum of back-converted photons in the CAST pipe (vacuum)

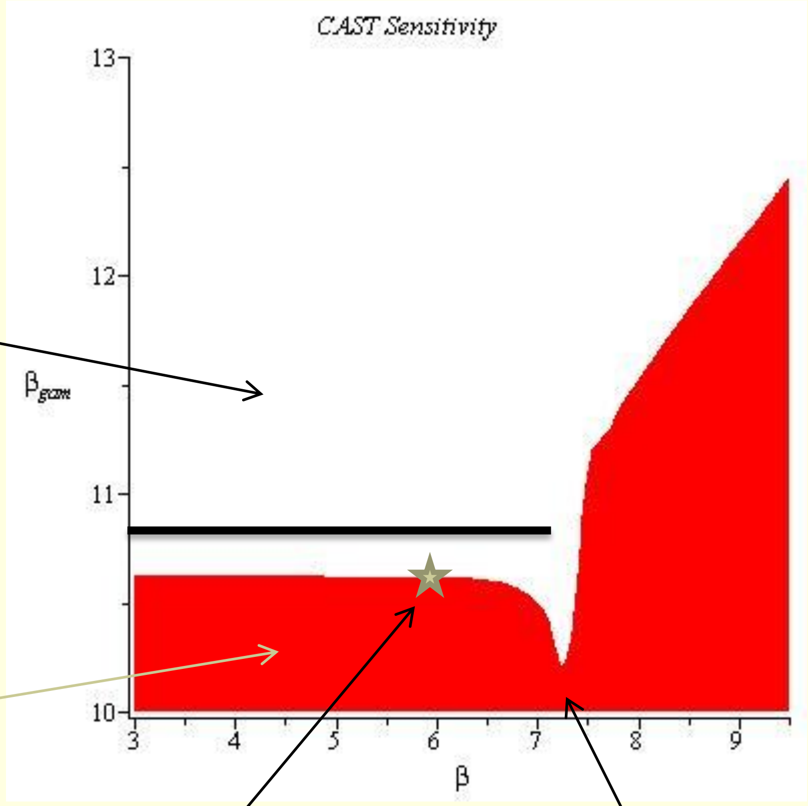


For a matter coupling leading to a resonance.



When there is no resonance.

Too much energy loss in the sun.



For given matter and photon couplings, the sensitivity plot for CAST with a noise of 4 counts per hour, 200 hours of observation, and vacuum in the pipe, at the 2-sigma level.

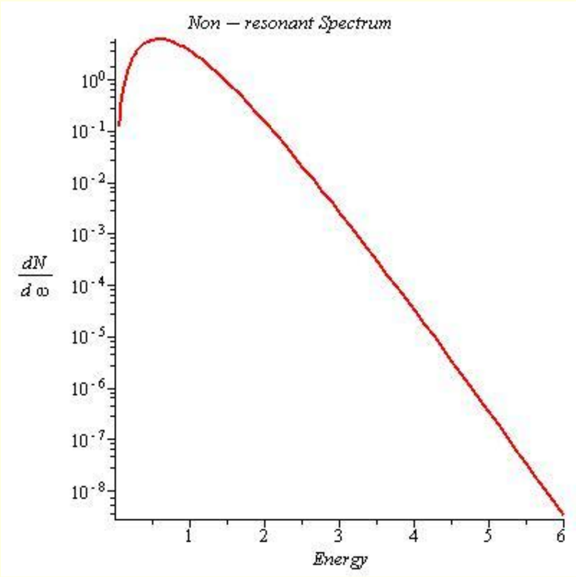
Production in a shell of 0.01 Rs with a magnetic field of 30T

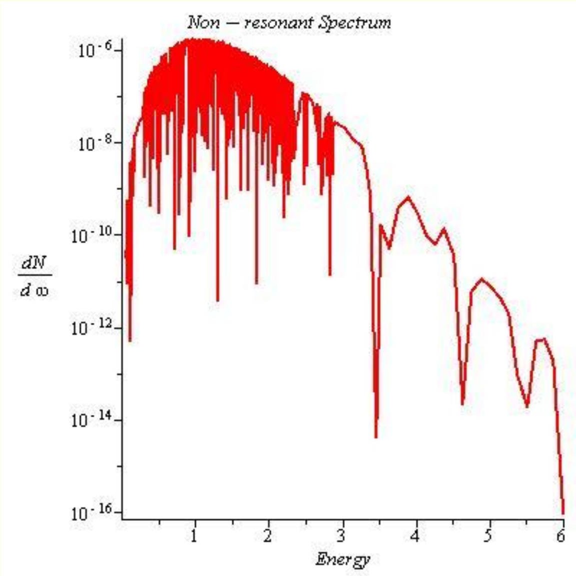
Below the CAST sensitivity.

Benchmark point

Resonance effect.

If not vacuum, the spectrum of back-converted photons shows characteristic oscillations.

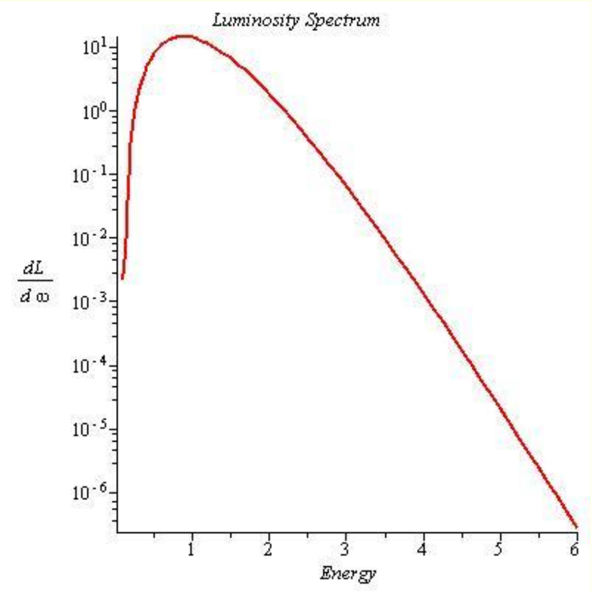




The benchmark spectrum with vacuum in the pipe

With a pressure of 10 mbar

We are also interested in the photons back-converted from chameleons in the outer sun, photosphere and above.

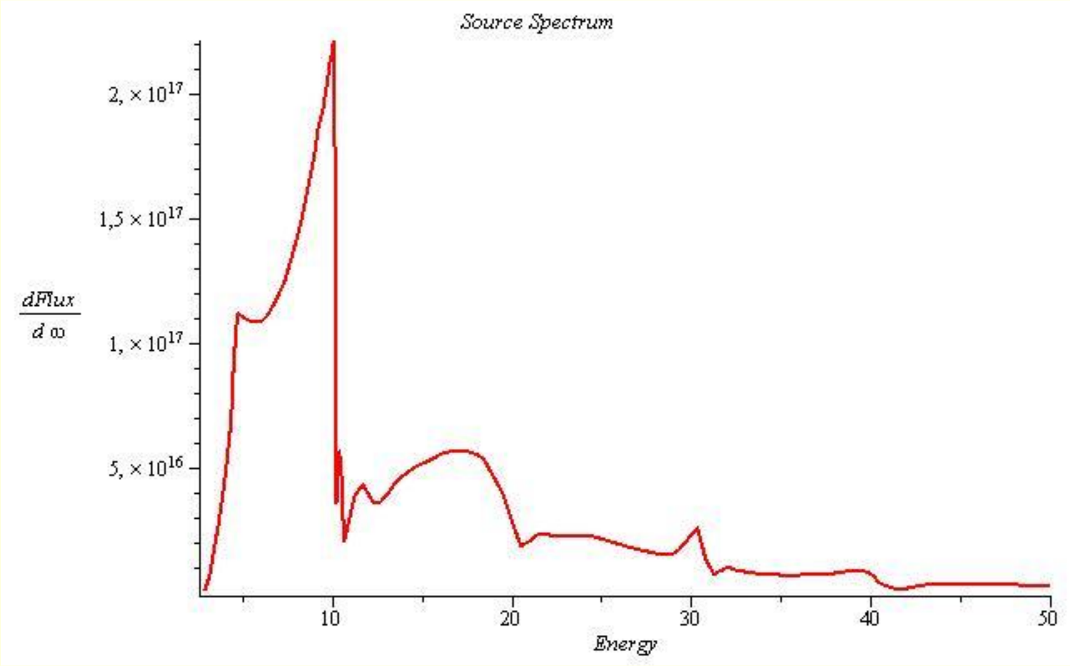


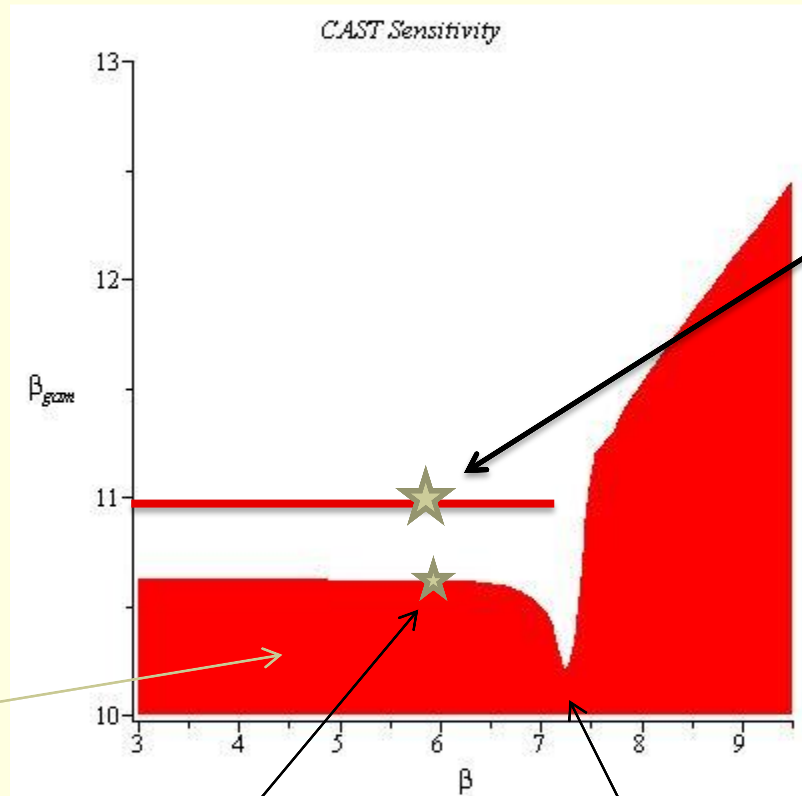
Globally the outer sun has a magnetic field of 1 G and magnetic regions of size 100000 km. This leads to a soft X-ray spectrum compatible with the quiet sun measurements.

Chameleons could be the source of a very interesting photon spectrum above 1 keV. Could reproduce the solar spectrum of the quiet sun. Needs more investigation!

A new experiment

Intrinsic solar uncertainties could be overcome with lab experiment mimicking the sun:a chameleon-through-wall experiment using a powerful X-ray source in a CAST pipe. Chameleons would be created, go through a wall and then regenerate X-rays on the other side.





Chase limit and 2-sigma limit for a chameleon through wall experiment after 700 hours of observation.

For given matter and photon couplings, the sensitivity plot for CAST with a noise of 4 counts per hour, 200 hours of observation, and vacuum in the pipe, at the 2-sigma level.

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Below the CAST sensitivity.

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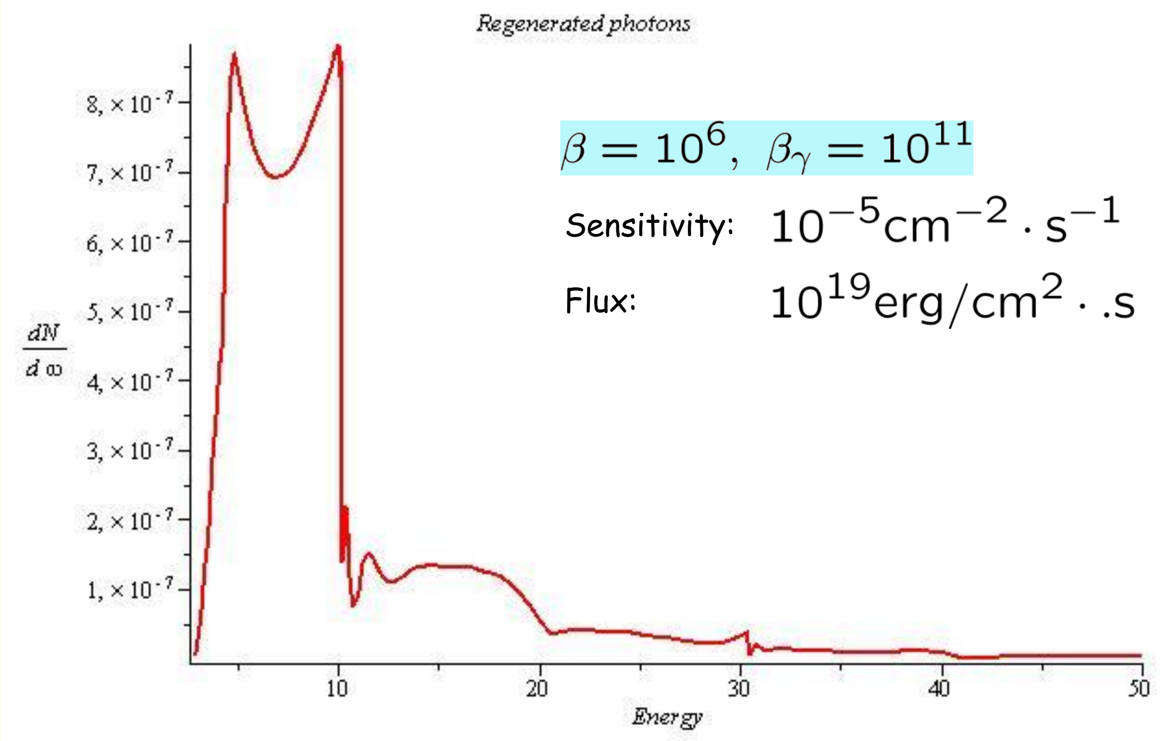

The 2-sigma spectrum with a better luminosity by a factor of 10 after 700 hours of observations.

The CAST bounds depend on the production zone in the sun. If chameleons were detected, this would be a way of probing magnetic fields in the sun. With reasonable assumptions on the magnetic fields in the sun, CAST can probe a region of parameters not probed by Chase.

Independently of any solar model, a chameleon-through-wall experiment in the X-ray band would probe chameleons in a different energy regime from optical cavity experiments.

Conclusions

- Most chameleons escape the sun and could regenerate photons in the CAST pipes.
- The quiet sun luminosity in the soft X-ray region could be generated by the back-converted photons produced from chameleons in the outer sun.
- Regenerated photons detectable with X-ray chameleon-through-wall experiment.