Title: Production of Solar Scalars

Speakers: Anne Davis

Collection/Series: 50 Years of Horndeski Gravity: Exploring Modified Gravity

Subject: Cosmology, Strong Gravity, Mathematical physics

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Abstract:

I will first introduce screened modified gravity theories and then discuss the chameleon mechanism. Light scalars can be produced from the sun and detected on earth. I will discuss the production of chameleons, including novel production channels, and discuss potential detection in helioscopes.

Production of Solar Chameleons

T. O'Shea, ACD, M. Giannotti , S. Vagnozzi, L. Visinelli, J. Vogel

Anne-Christine Davis, 50 Years of Horndeski Theory

Outline

Introduction

Modified Gravity

Screened Modified Gravity;

Chameleons

Direct Detection — S Vagnozzi, L. Visinelli, P. Brax, ACD, J. Sakstein; PRD 104 (2021) 6, 063023 2103.15834

Solar Production —

New Channels — T. O"Shea, ACD, M. Giannotti, S. Vagnozzi,, L. Visinelli, J. Vogel; 2406.01691

It's an honour to be invited to speak at the 50 years of Horndeski Theory and to acknowledge the ground-breaking work of Professor Horndeski.

Thank you Gregory

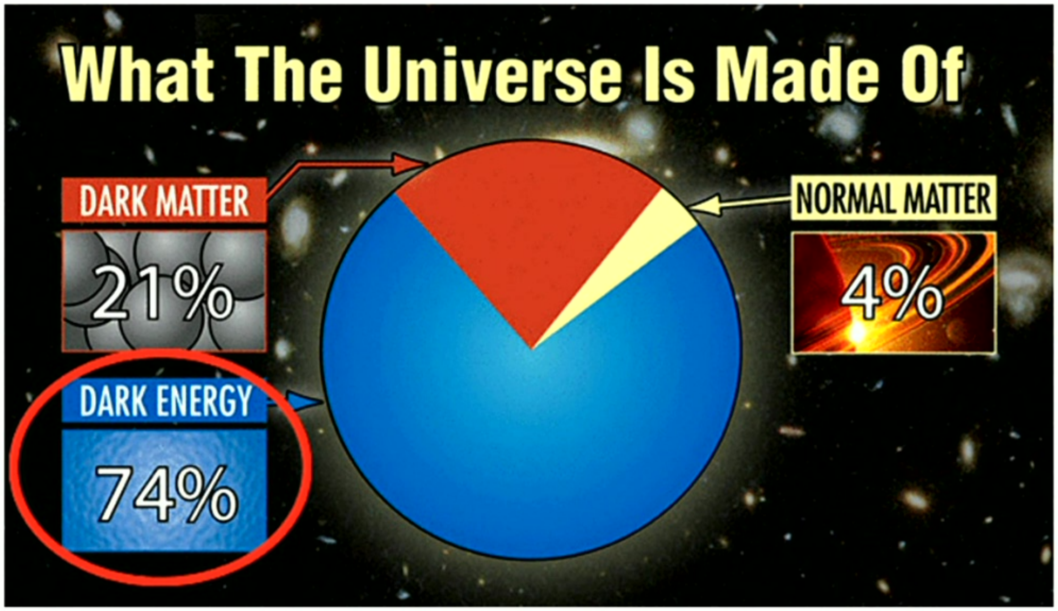
- **Why Modified Gravity?**

There are several reasons to investigate modified gravity theories. These are theories which modify Einstein theory, but reduce to Einstein relativity in certain limits

Modified Gravity could account for the observed accelerated expansion of the Universe today.

Modified Gravity allows one to test General Relativity in new regimes one hadn't originally thought of.

Dark Energy



The Universe is undergoing accelerated expansion today.

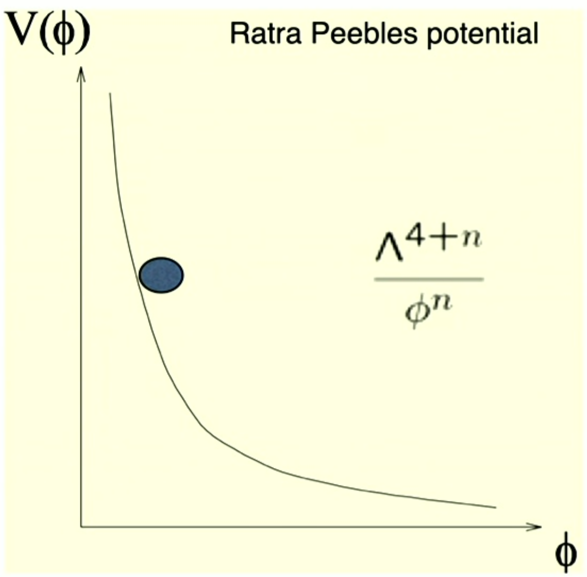
It could be a cosmological constant

$$\Lambda \approx (H_0 M_{pl})^2 \approx (meV)^4$$

or the dynamics of a light scalar field

$$m_\phi < H_0 \approx 10^{-33} eV$$

If coupled to gravity this will give rise to a fifth force, unless screened



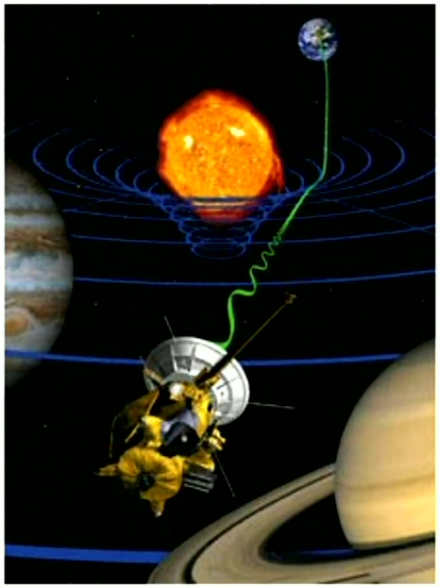
Deviations from Newton's Laws parametrised by

$$\Phi_N = -G_N/r(1 + 2\beta^2 e^{-r/\lambda})$$

tightest constraint from Cassini

$$\beta^2 \le 4 \cdot 10^{-5}$$

Fifth Force must be screened



Two general classes of theories

1) Chameleon type screening. Can be tested in the lab, in the solar system, astrophysics and cosmology. Does not affect speed of gravitational waves, so no test from LIGO/VIRGO or eLISA

2) Vainshtein screening. For example Galileons, Horndeski, massive gravity, k-mouflage. Vainshtein radius is very large, so no laboratory tests, but astrophysical and cosmological tests. Some models give speed of gravitational waves to be different from that of photons, so severely constrained by pulsar constraints and by LIGO/VIRGO and will be even more constrained by eLISA

The Chameleon Mechanism

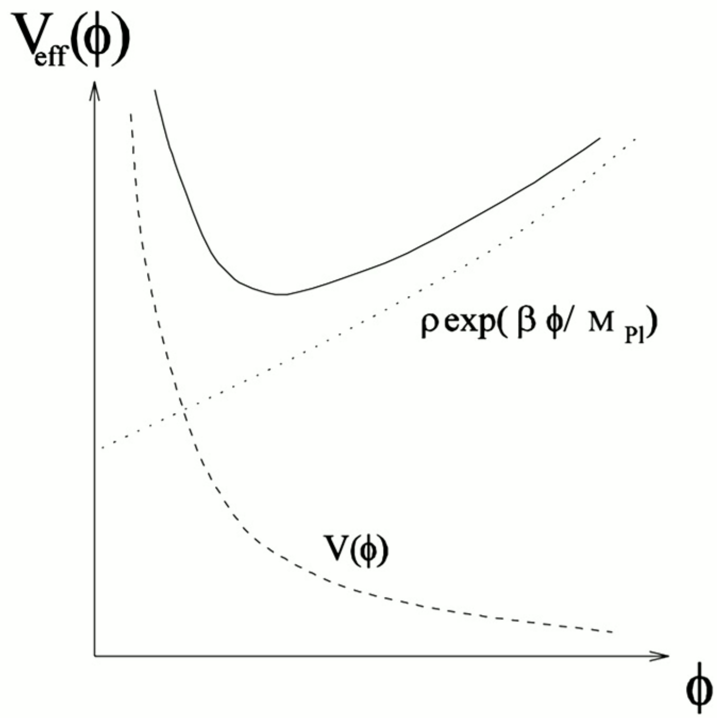
consider the action

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

gives the effective potential

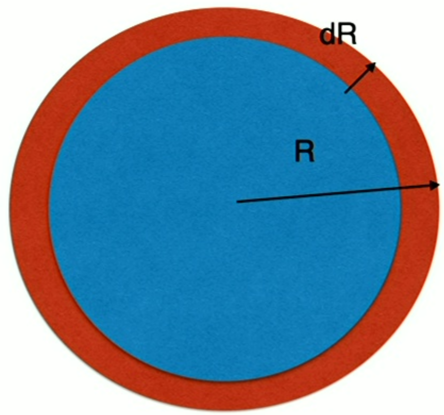
$$V_{\text{eff}}(\phi) = V(\phi) - (A(\phi) - 1)T$$

There is an environmental effect: when coupled to matter the potential depends on the ambient matter density as well



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

To screen fifth forces in the solar system one needs the thin shell effect.



The fifth force is proportional to the size of the thin shell where the field varies

$$F_\phi \approx \frac{\Delta R}{R\Phi_N}$$

Symmetrons

Khoury&Hinterbichler, 1001.4525

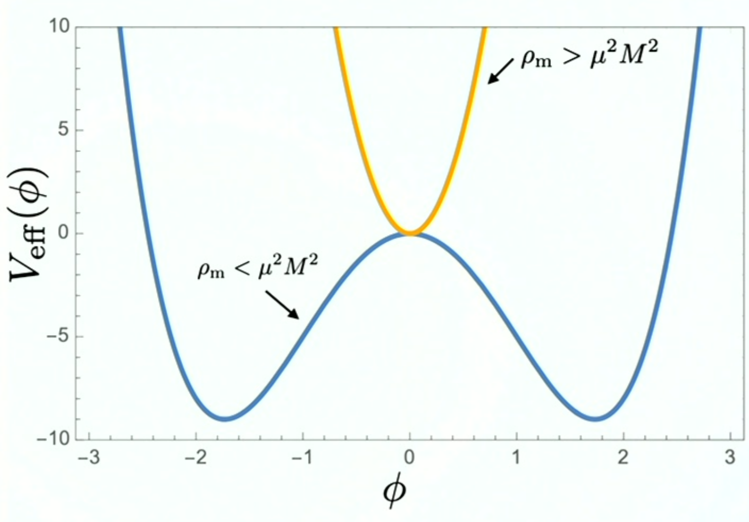
This has potential

$$V(\phi) = V_0 + \frac{\lambda}{4}\phi^4 - \frac{\mu^2}{2}\phi^2$$

and coupling function

$$A(\phi) = 1 + \frac{\beta_\star}{2\phi_\star m_{\rm Pl}}\phi^2$$

In a dense environment the field is at the origin whilst in a sparser one the field is at the minimum of the potential with the transition happening at density ρ_*



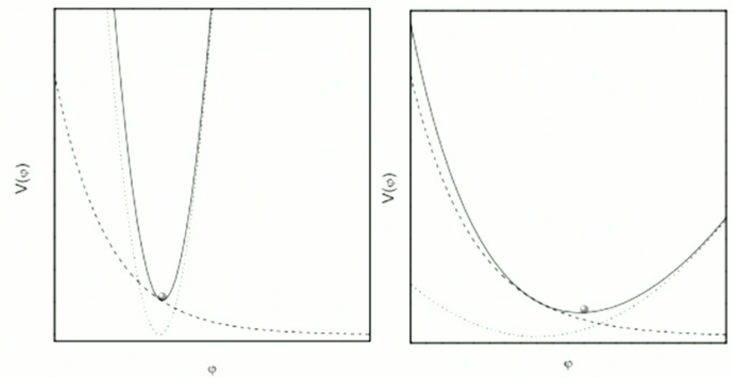
Environmentally Dependent Dilaton

$$V(\phi) = V_0 e^{-\alpha\phi}$$

Where the potential is derived from string theory in the strong coupling limit. We chose the coupling to matter to be

$$A(\phi) = 1 + \frac{A_2}{2}(\phi - \phi_\star)^2$$

This keeps the scalar in the strong coupling regime as the Universe evolves. See Brax et al 1005.3735 for full details of the cosmological behaviour, local constraints and linear perturbation theory



The most general coupling of the scalar field to matter in scalar-tensor gravity is due to Bekenstein

$$g_{\mu\nu} = A^2(\phi) g^E_{\mu\nu} + B^2(\phi, X)\partial_\mu\phi\partial_\nu\phi$$

$$A(\phi) = e^{\beta\phi/m_{\rm Pl}} \qquad B(\phi, X) = \frac{1}{M^4}$$

A is the conformal and B the disformal coupling

There are strict constraints on the chameleon parameters, even with screening. For the conformal coupling these come from a variety of experiments on a range of scales. Constraints on the disformal coupling come from collider constraints

The disformal coupling adds the term $\frac{1}{M_\gamma^4}(\partial_\mu\phi)(\partial_\nu\phi)T^{\mu\nu}_\gamma$ to the action

and coupling to photons $\frac{\beta_\gamma}{M_{\rm Pl}}\phi\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$ This is a coupling to two photons

We originally considered production of chameleons in the strong magnetic field in the tachycline of the sun, motivated by the XENON1T results. This was because we assumed the chameleon would be too heavy in the core of the sun to be produced.

Can we detect (screened) DE in DM direct detection experiments?

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Direct detection of dark energy: The XENON1T excess and future prospects

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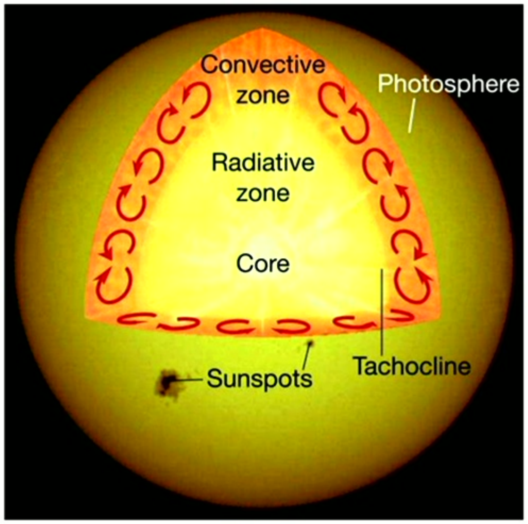
Direct detection of dark energy

Production

$$\mathcal{L}_{\phi\gamma} \supset \underbrace{-\beta_\gamma \frac{\phi}{M_{\rm Pl}} F_{\mu\nu}F^{\mu\nu}}_{\text{(anomalous)}} + \underbrace{\frac{T^{\mu\nu}_\gamma \partial_\mu\phi\partial_\nu\phi}{M_\gamma^4}}_{\text{disformal}}$$

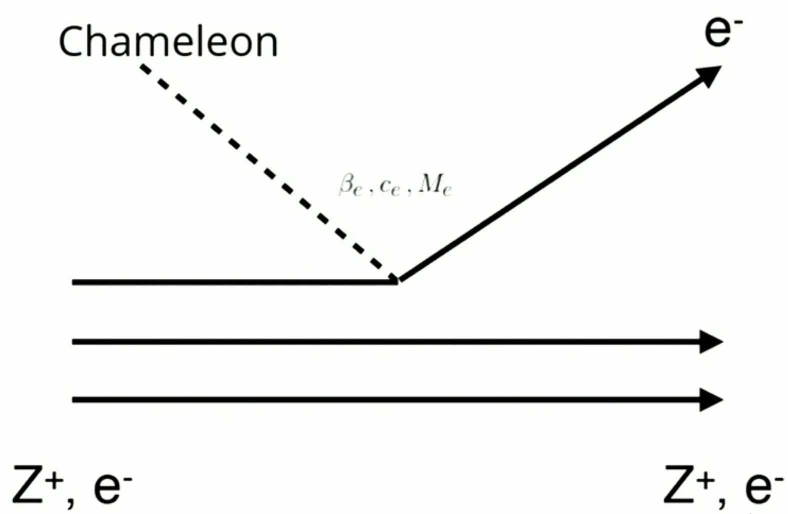
Production in strong magnetic fields of the tachocline



Detection

$$\mathcal{L}_{\phi i} \supset \underbrace{\beta_i \frac{\phi T_i}{M_{\rm Pl}}}_{\text{conformal}} - \underbrace{c_i \frac{\partial^\mu\phi\partial_\mu\phi}{M^4}}_{\text{kinetic-conformal}} T_i + \underbrace{\frac{T_i^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}{M_i^4}}_{\text{disformal}}$$

Analogous to photoelectric and axioelectric effects



The flux of chameleons on earth is given by

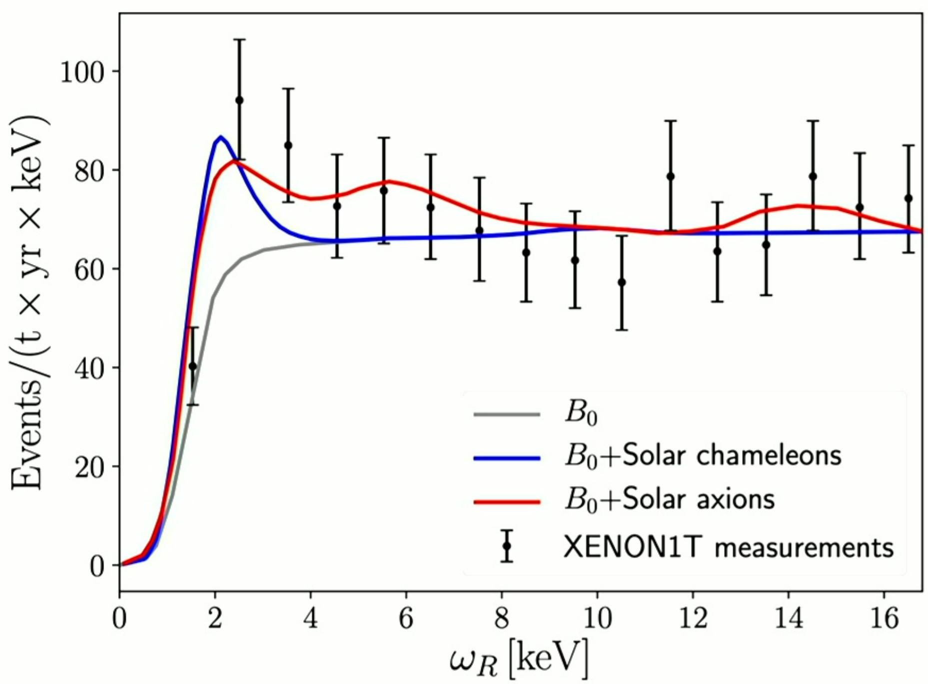
$$\frac{\mathrm{d}\Phi_{\mathrm{Earth}}}{\mathrm{d}\omega} = \frac{\pi R_\odot^2}{4\pi d_\odot^2}\frac{\mathrm{d}\Phi}{\mathrm{d}\omega}$$

The flux is computed by evaluating the Feynman diagram for the interactions between the chameleon and matter. In practice the disformal coupling dominates. The production is dominated by that in the magnetic field of the tachocline

The dominant cross-section is $$\sigma_{\phi e,disf} = \frac{m_e^2\omega^4}{8\pi^2 M_e^8}$$

Detection of solar chameleons on Earth

$$\frac{\mathrm{d}R_0(\omega)}{\mathrm{d}\omega} = N_{\mathrm{Xe}} \frac{\mathrm{d}\Phi_{\mathrm{Earth}}}{\mathrm{d}\omega} \sigma_{\phi e} \,,$$



Parameters

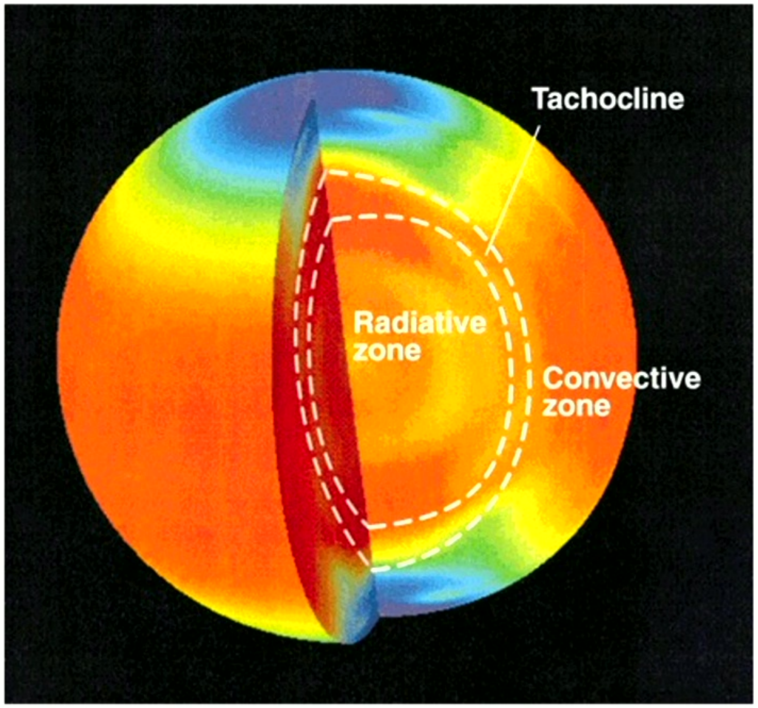
$\beta_e = 10^2$

$M_e = 10^{3.7} keV$

$\beta_\gamma = 10^{10}$

$M_\gamma = 1000 TeV$

The Sun



Previous work considered production of scalars in the tachycline where the B field is 50T. In our work we consider production in all regions of the sun, taking into account the density dependent mass of the chameleon. In the radiative zone the magnetic field is $3 \times 10^3 T$

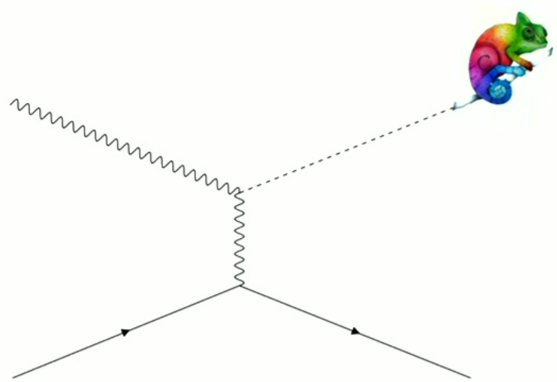
Hence we consider the bulk magnetic field with production of chameleons via the Primakoff effect. We consider Primakoff production in the electric field of the electrons and ions and the role of longitudinal production of scalars.

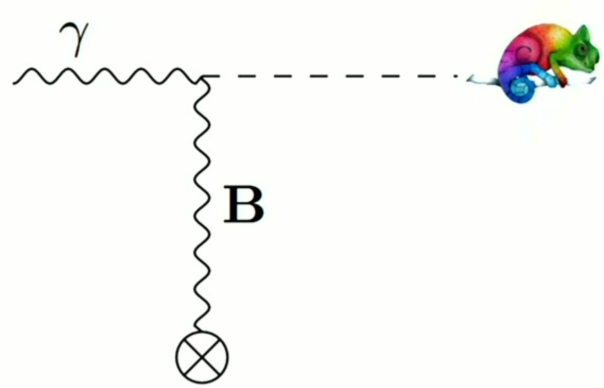
We used thermal field theory techniques to evaluate the Feynman diagrams. Since the coupling is

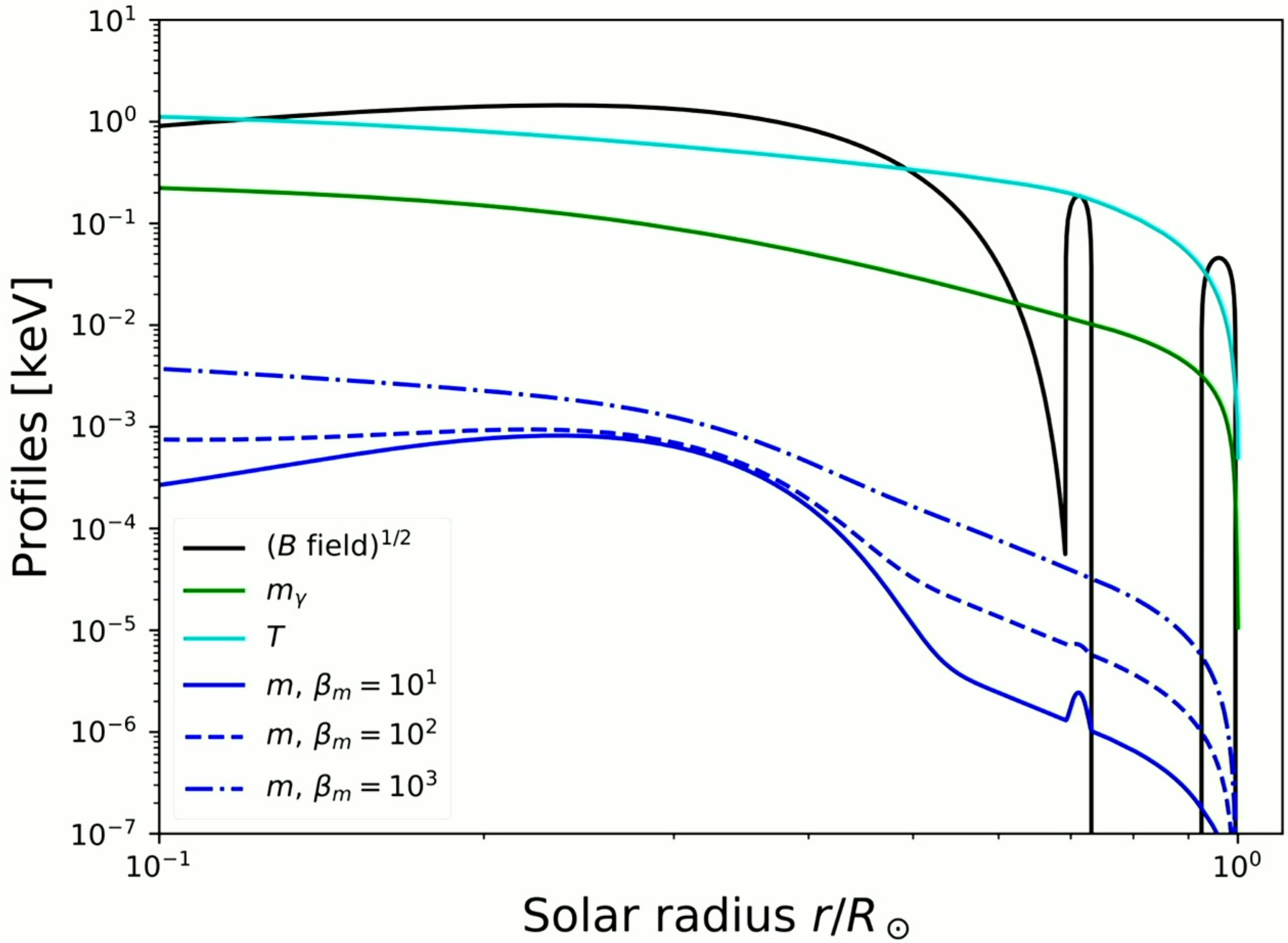
$$\phi F_{\mu\nu} F^{\mu\nu} \propto \phi(B^2 - E^2)$$

The B field gives the scalar photon coupling whilst the E field gives the scalar coupling with the photon and plasmon. This gives rise to TT, TL and LL modes unlike the case for axions where TL are forbidden. We used a model for the solar magnetic field and considered the three sections of the core, the tachycline and the outer region.

Solar Production







10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Profiles [keV]
$(B \text{ field})^{1/2}$
m_γ
T
$m,\ \beta_m = 10^1$
$m,\ \beta_m = 10^2$
$m,\ \beta_m = 10^3$
10^{-1}
10^0
Solar radius $r/R_\odot$

With the B-field model we can calculate the chameleon flux as a function of parameters.

$$\beta_\gamma \quad \beta_m \;\; n \quad \Lambda = \Lambda_{DE}$$

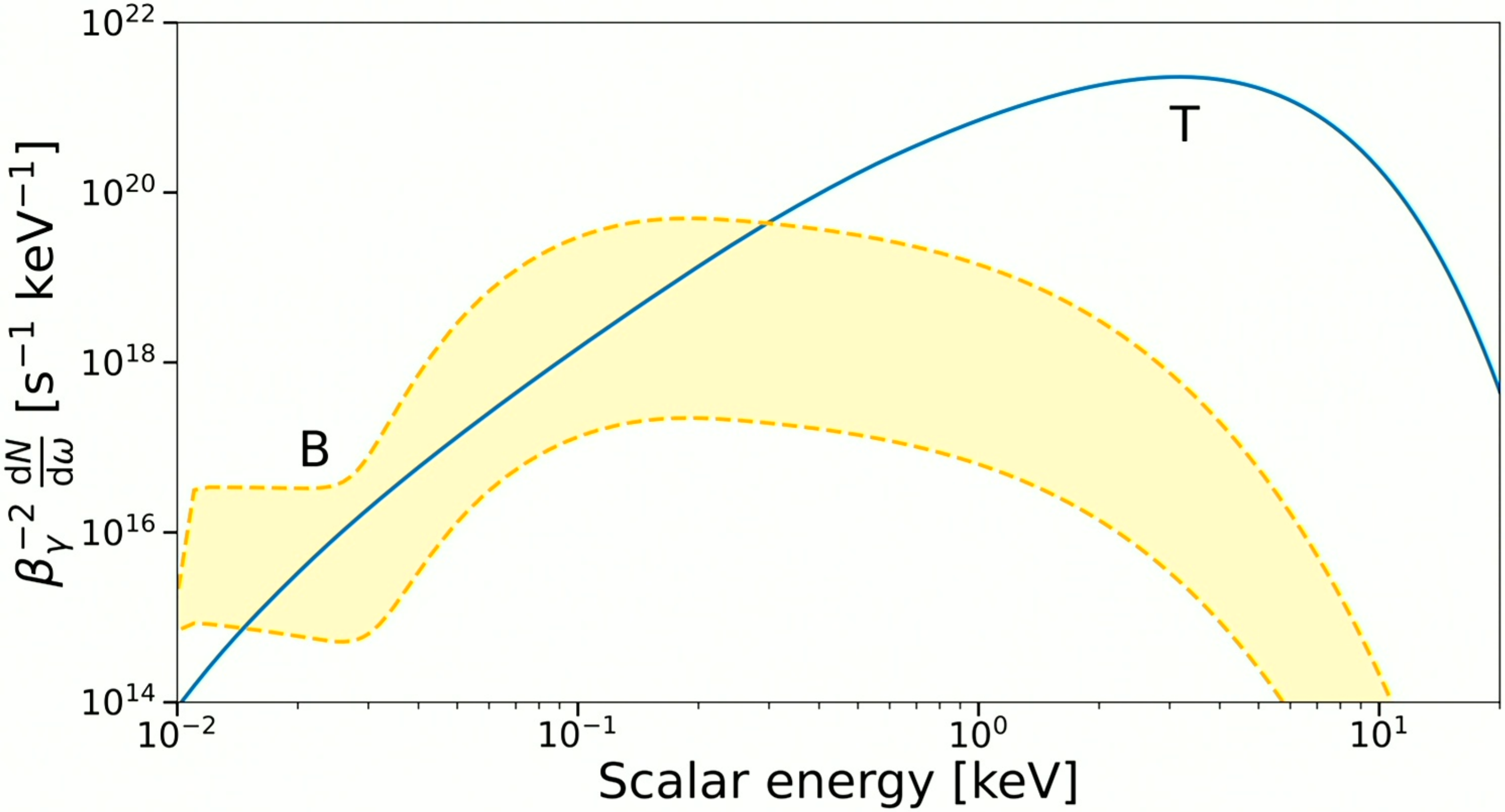
we find the that for the allowed range of values of couplings the effective mass is less than the plasma frequency.

$$m_{eff} << \omega_p$$

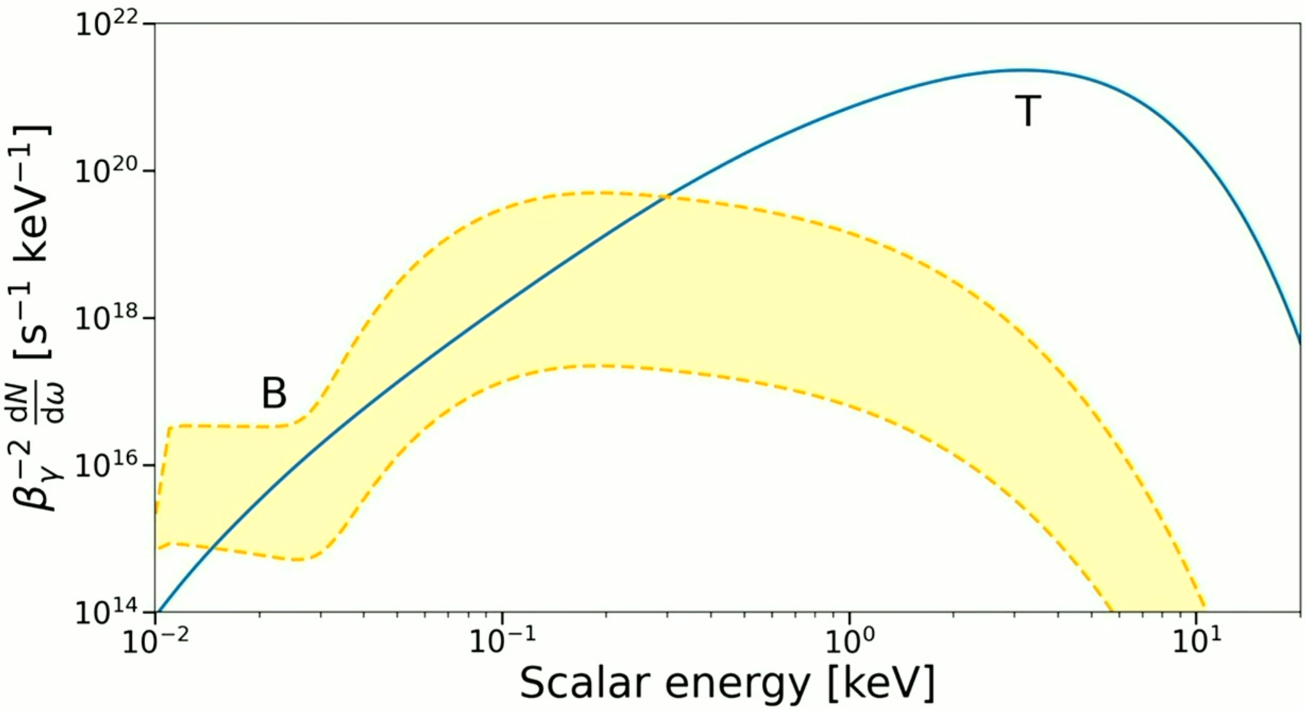
For the magnetic field production we find

and for charged particle production we need to consider the E field which gives

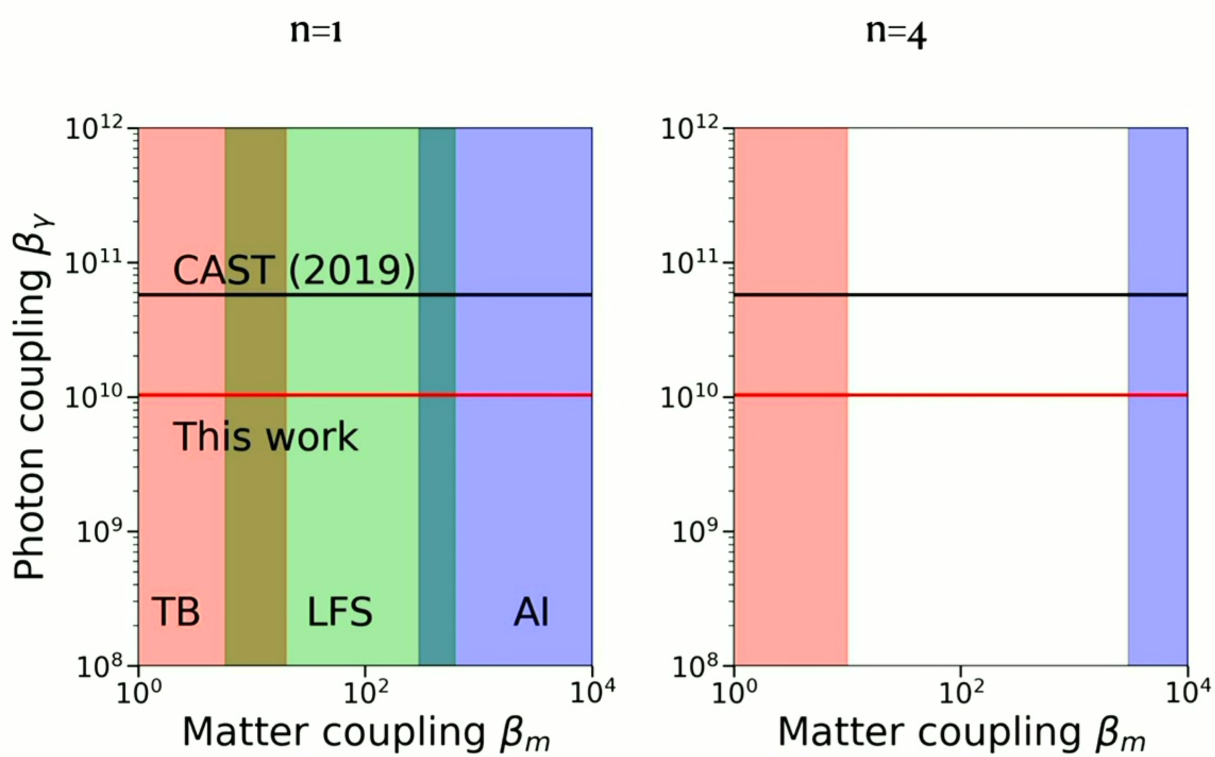
Magnetic Field Production

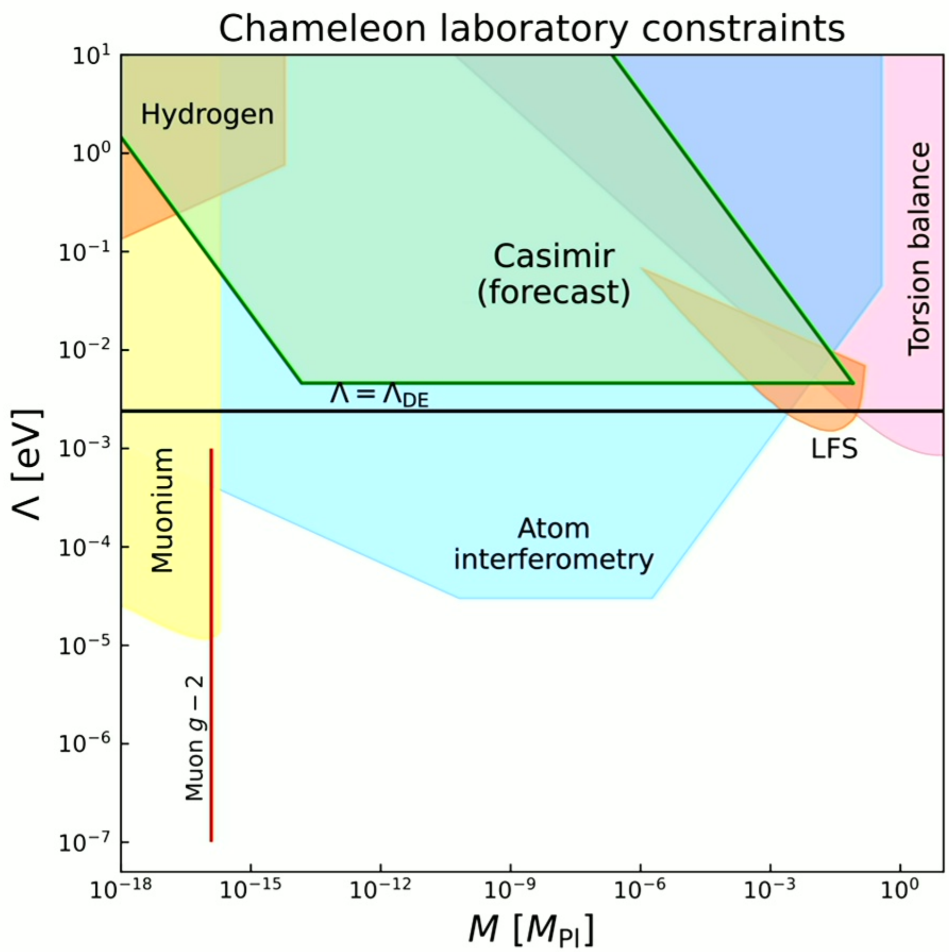


Charged Particle Production



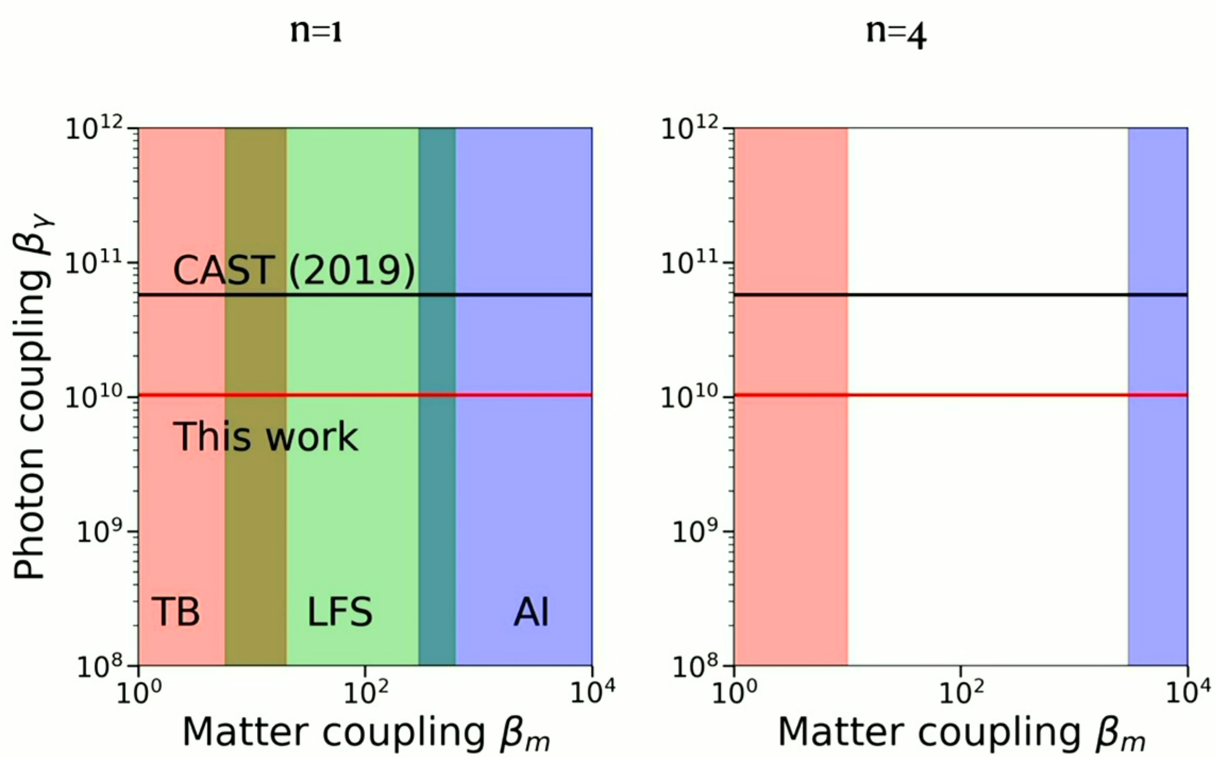
Solar Energy Loss Bounds





Chameleon laboratory constraints
Hydrogen
Casimir
(forecast)
Torsion balance
$\Lambda = \Lambda_{DE}$
LFS
Muonium
Atom
interferometry
Muon $g-2$
Λ [eV]
M [M_{Pl}]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}

Solar Energy Loss Bounds



Our techniques are general and can be applied to other light scalars, eg symmetron, dilaton.

We can make predictions for the next generation of helioscopes, eg IAXO. With our updated solar production model we can compute the IAXO sensitivity and probe beyond the solar energy loss bound; in progress

Scalars have clear differences with axions (pseudo scalars) in the polarisation of B field and the channels allowed. We will compute the clear differences for IAXO detection

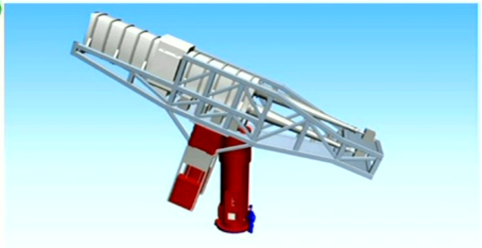
What about other modified gravity theories? We would need.

$$m_{eff} << \omega_p$$

Fine for symmetron but coupling is $\phi^2 F_{\mu\nu} F^{\mu\nu}$

other modified gravity scalars?

Future Detection



- Helioscopes sensitive to chameleons
  - back-conversion to photons in external B-field
- Difference in polarisation to axions
  - axion => polarisation along B
  - scalar => polarisation perpendicular to B
- Difference in spectrum at low ω due to plasmon contribution

40

The most general coupling of the scalar field to matter in scalar-tensor gravity is due to Bekenstein

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Solar Production