Chameleons in Cosmology and Astrophysics

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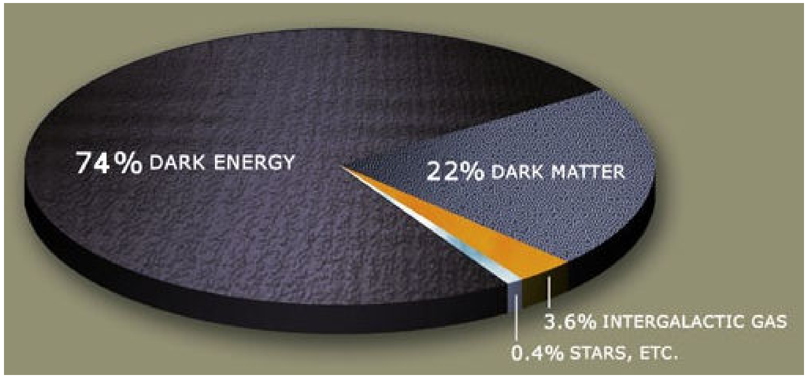
Dark Energy and Light Scalar Fields

- Observations favour a large component of Dark Energy in the universe
  - SNae, CMB, LSS, ISW…



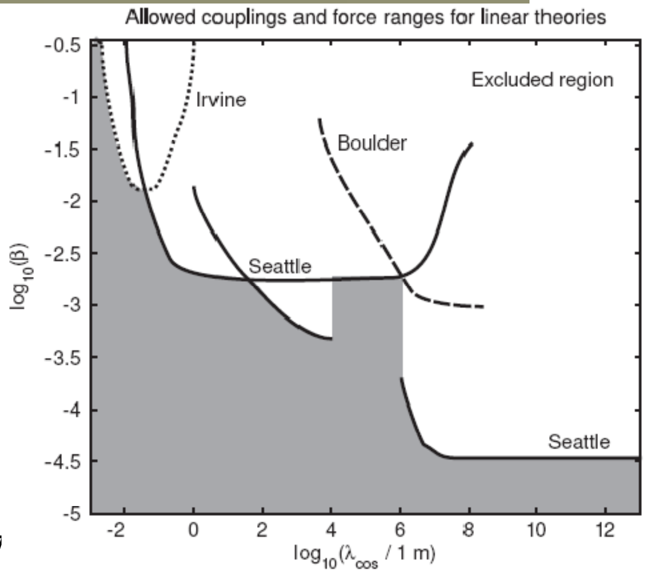
- If caused by the presence of a new scalar field, field must be nearly massless

$$m_\phi(t_0) \sim H_0 \sim 10^{-33} \text{ eV}$$

- But a new light scalar mediates a new force

$$-\Box\phi = m_c^2\phi + \frac{\beta\rho}{M_{pl}}$$

  - Forbid coupling to matter?
  - Non-minimal matter couplings?



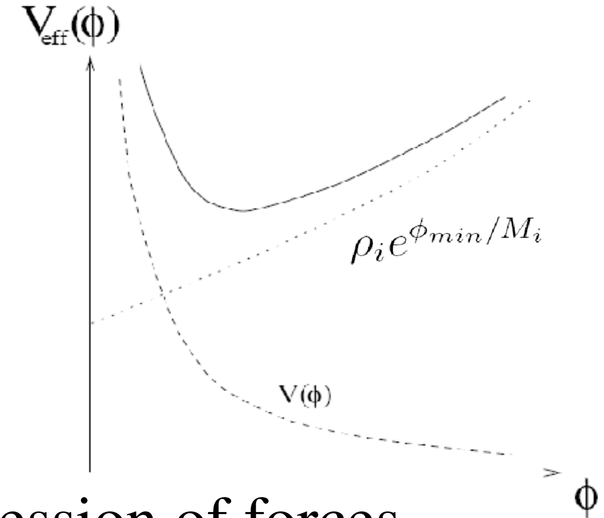
(Mota & Shaw 2007

The Chameleon

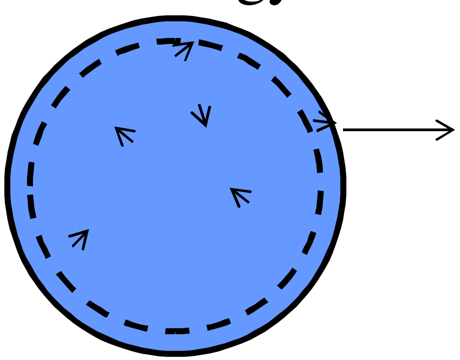
- Scalar with non-minimal couplings to matter

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

$$g_{(i)}^{\mu\nu} = e^{-2\phi/M_i} g^{\mu\nu}$$



- Scalar field moves in an effective potential $V_{eff}(\phi) = V(\phi) + \sum_i \rho_i e^{\phi/M_i},$
- Mass of the field dependant on the local energy density



- Thin shell suppression of forces
  - The chameleon force sourced by a massive body is produced only by a thin shell near the surface

(Khoury & Weltman 2004)

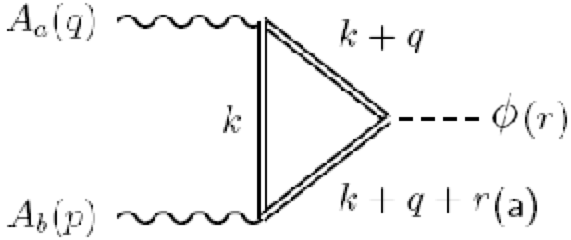
Chameleon Cosmology

- Cosmological chameleon remains in the minimum of the potential (slow roll) as the universe evolves $m \gg H$
- Equation of state
  - early times $\omega \approx 0$ $T \gtrsim 10\text{MeV}$
  - late times $\omega \approx -1$ $T \lesssim 10\text{MeV}$
- The energy scale in the potential may be chosen to be the dark energy scale
- Agrees with observations of the redshift of recombination and BBN if:
  - Chameleon is in minimum by time of BBN
  - Initial chameleon density is $\Omega_\phi^{(i)} \lesssim \frac{1}{6}$

(Brax, van de Bruck, Davis, Khoury & Weltman 2004, Mota & Shaw 2007)

Chameleons Couple to Photons

- A conformally coupled scalar does not necessarily couple to $F_{\mu\nu}F^{\mu\nu}$
- If the theory contains a heavy fermion, there are diagrams



- Integrating out this fermion leads to a chameleon-photon coupling in the low energy effective theory

$$\mathcal{L} \supset \frac{\phi}{4M} F_{\mu\nu}F^{\mu\nu} = \frac{\phi}{2M}(\mathbf{B}^2 - \mathbf{E}^2).$$

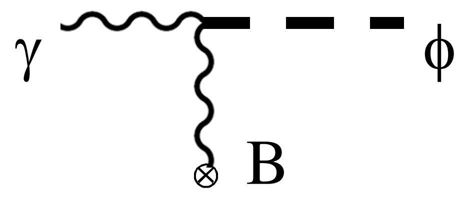
  - strength of coupling model dependent
- The chameleon is an axion-like-particle

(Brax, CB, Davis, Seery & Weltman to appear)

Optics with Chameleons

- Photons propagating in a magnetic field can convert into chameleons

$$\left[\omega^2 + \partial_z^2 + \begin{pmatrix} -m_\phi^2 & \frac{B\omega}{M} & 0 \\ \frac{B\omega}{M} & -\omega_P^2 & 0 \\ 0 & 0 & -\omega_P^2 \end{pmatrix}\right] \begin{pmatrix} \phi \\ A_\perp \\ A_\parallel \end{pmatrix} = 0$$



(Raffelt & Stodolsky 1988)

- Probability of mixing

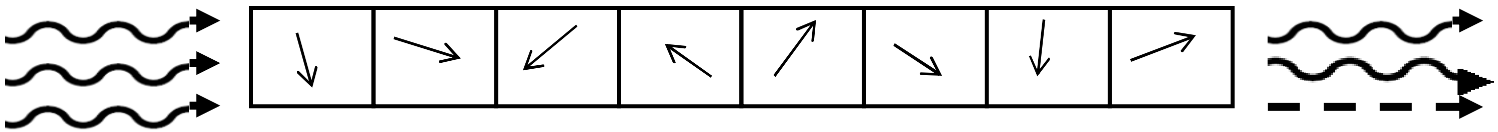
$$P = \sin^2 2\theta \sin^2\left(\frac{\Delta(z)}{\cos 2\theta}\right)$$

$$\Delta(z) = m_{eff}^2 z/4\omega \qquad \tan 2\theta = 2B\omega/M m_{eff}^2 \qquad m^2_{eff} = |m^2_\phi - \omega^2_P|$$

- Can look for effects of this mixing in the laboratory; PVLAS, ALPS, GammeV...
  - So far no ALPs have been seen

Astronomy with Chameleons

- Magnetic fields exist in galaxies and galaxy clusters
  - Disadvantages: Field fluctuates on many different scales
    Fields typically weaker than in the lab
  - Advantages: Fields extend over much greater distances
- Sufficient to use the cell magnetic field model



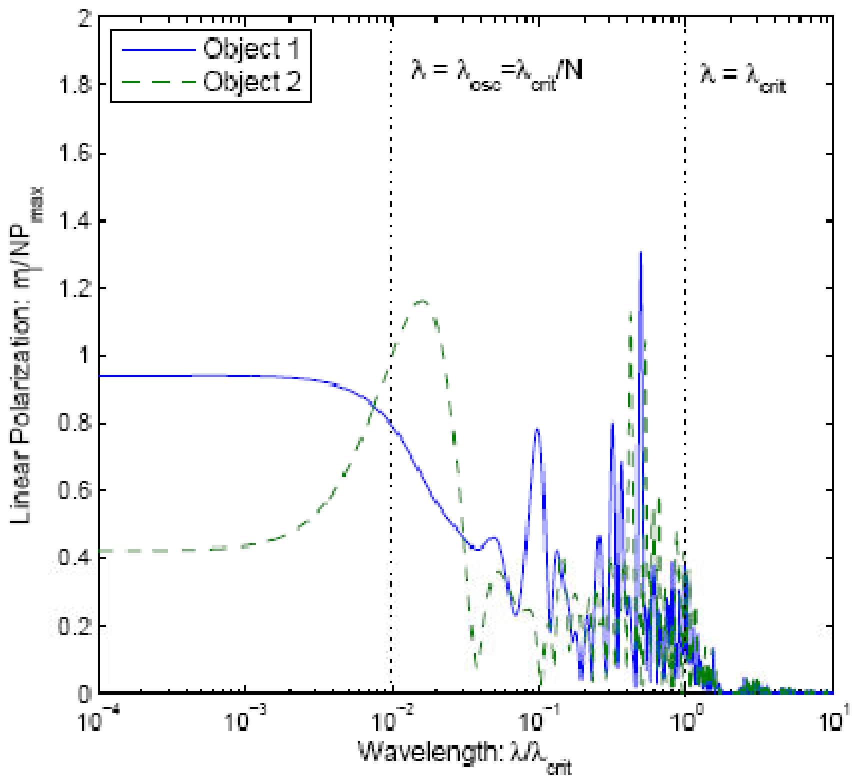
- Photon number is not conserved
  - Now total number of photons + scalars is conserved
- Polarization of light is changed,
  - Scalar mixes with only one component of photon
  - Scalar particles and photons propagate at different speeds

A New Test: Polarization

- Polarizations induced at low frequencies are highly oscillatory functions of frequency
  - Looks like random noise but correlations between frequencies
- Can search for non-trivial correlations in UV observations of stars in the Milky Way from WUPPE (Anderson 1996)
- Using observations of three stars gives best bound on coupling of chameleonic ALPs

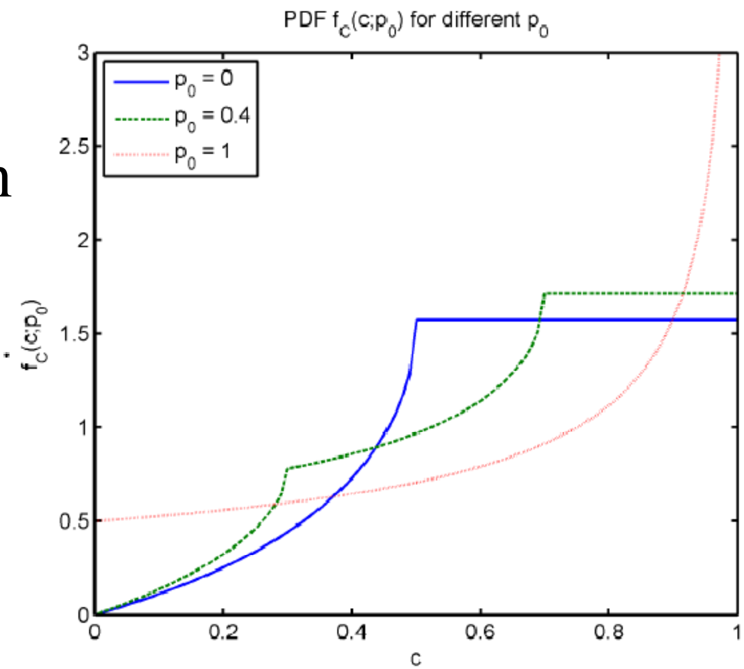
$$M > 1.1 \times 10^9 \text{ GeV}$$

  - Full analysis in progress



A New Test: Luminosity

- At high frequencies mixing in the magnetic fields of galaxy clusters can be very strong
  - Requires $M \lesssim 10^{11}$ GeV $m_\phi \lesssim 10^{-12}$ eV.
  - Distinctive luminosity distribution for standard candles
  - For AGN correlations with low energy luminosities can be used to normalise high energy luminosities

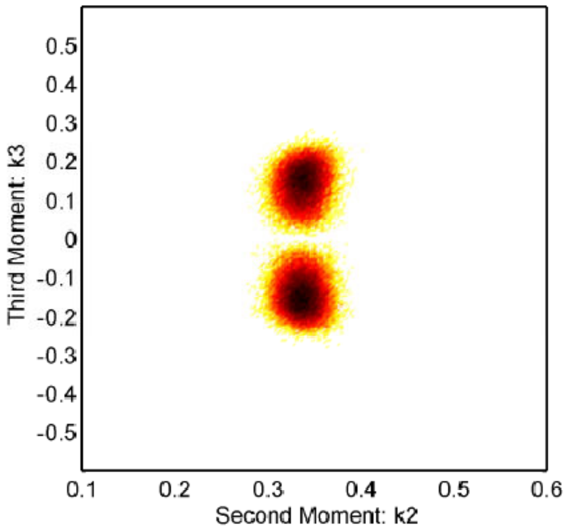


(Steffen et al. 2006, Strateve 2005)

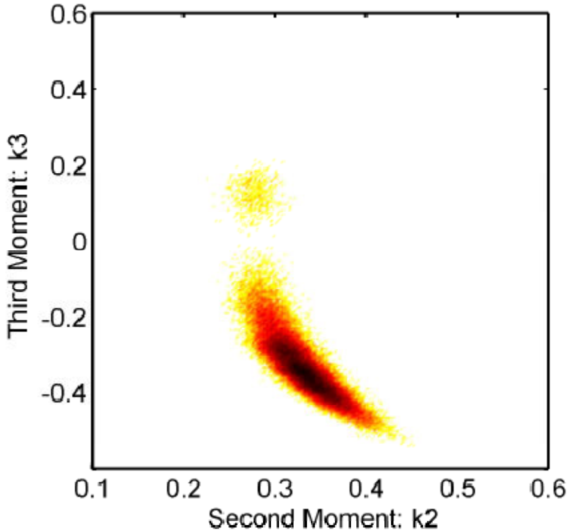
- 203 AGN from COMBO-17, ROSAT and SDSS surveys
  - Likelihood ratio test to compares distribution from photon-scalar mixing with Gaussian scatter
  - $r(p_0 \lesssim 0.5) \approx 25$ $\Rightarrow$ Very strong preference for photon-scalar mixing

A New Test: Luminosity

- Qualitative check - independent of any null hypothesis
  - Construct 10^5 new data sets (with 203 points) by bootstrap resampling with replacement
- Compute statistical moments for data sets k_m
  - k_2 the rms mean, k_3^3/k_2^3 the skew, …



Gaussian Scatter



Chameleon strong mixing

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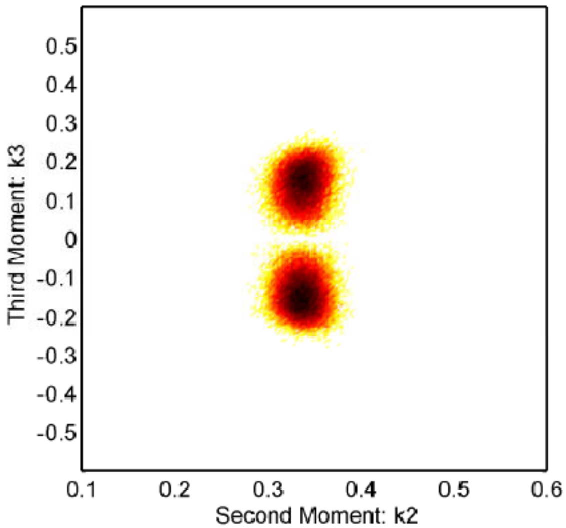

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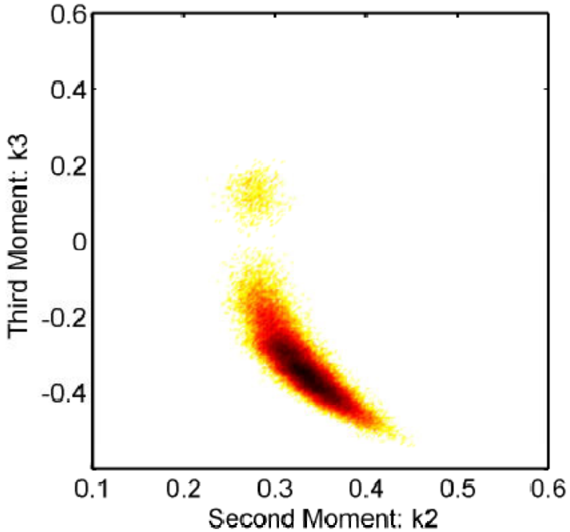

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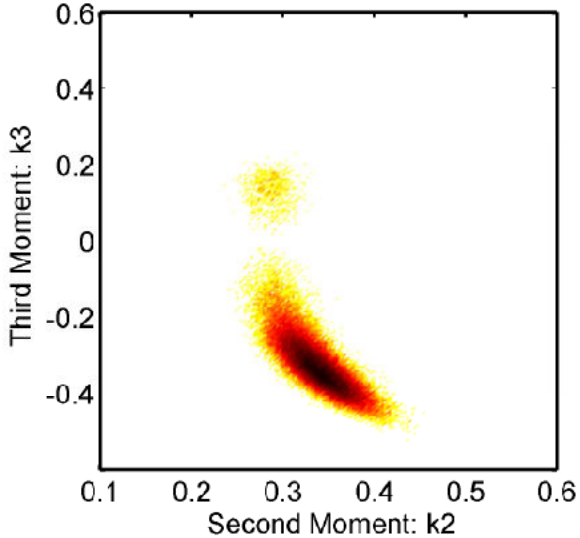

AGN results

Conclusions

- Chameleons are scalar fields with (strong) non-minimal matter couplings
- They have density dependant masses, and so do not give rise to large fifth forces
- At late times in the universe they behave as a dark energy field
- If they couple to photons they affect astronomical observations of polarization and luminosity
- Observations of stars in the Milky Way gives $M > 1.1 \times 10^9\ \mathrm{GeV}$
- Observations of AGN are strongly suggestive of a light scalar with $M \lesssim 10^{11}\ \mathrm{GeV}$