Searching for Axion-Like-Particles in the Sky

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Scalar Fields

- After Λ, next most simple explanation for accelerated expansion of the universe is a light scalar field
  - (If unknown physics solves the Cosmological Constant problem)
- Naively expect this field to couple to standard model particles
- This should produce observable effects!

Outline

- Axion Like Particles
- Photon-ALP Mixing
  - Effects on Astronomical Observations
- Using the Distribution of Luminosities to Investigate Photon-ALP Mixing
- Conclusions

ALPs and Dark Energy

- Consider scalars and pseudoscalars coupling to photons through the terms

$$(\phi/M)F_{\mu\nu}F^{\mu\nu} \qquad (\phi/M)\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

- Such particles have been proposed as Dark Energy candidates:
  - Coupled Quintessence (Amendola 1999)
  - Chameleon Dark Energy (Khoury, Weltman 2004, Brax, Davis, van de Bruck 2007)
  - Axionic Dark Energy (Carroll 1998, Kim, Nilles 2003)
  - …

ALPs and Dark Energy

- We consider fields with $m_\phi \ll 10^{-12}\,\mathrm{eV}$
- Pseudoscalars: limits from observations of neutrino burst from SN 1987A (Ellis, Olive 1987)

  $10^{11}\ \mathrm{GeV} \lesssim M$
- Scalars: limits from fifth force experiments

  $10^{26}\ \mathrm{GeV} \lesssim M$ (Smullin et al. 2005)
- Chameleons: limits from the structure of starlight polarisation (CB, Davis, Shaw 2008)

  $10^{9}\ \mathrm{GeV} \lesssim M$

Photon-ALP Mixing

- Mixing when photons propagate through background magnetic fields
  - Probability of mixing

$$P_{\gamma\leftrightarrow\phi} = \sin^2 2\theta \sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

$$\Delta = m_{\rm eff}^2 L/4\omega$$

$$\tan 2\theta = 2B\omega/Mm_{\rm eff}^2$$

$$m_{\rm eff}^2 = m_\phi^2 - \omega_{\rm pl}^2 - \epsilon B^2/M^2$$

- Mixing with only one photon polarisation state
  - Also induces polarisation
- Strong Mixing limit:

$$P_{\gamma\leftrightarrow\phi} \approx \sin^2\left(\frac{L_{dom}B}{2M}\right)$$

(Raffelt, Stodolsky 1987)

Astrophysical Photon-ALP Mixing

- Laboratory searches (BRFT, BMV, PVLAS, QSQAR...) so far unsuccessful
- Magnetic fields known to exist in galaxies/galaxy clusters
- These magnetic fields made up of a large number of magnetic domains
  - field in each domain of equal strength but randomly oriented
- ALP mixing changes astrophysical observations
  - Non-conservation of photon number alters luminosity
  - Creation of polarisation

Strong Mixing in Galaxy Clusters

- Galaxy cluster:
  - Magnetic field strength $B \approx 1 - 10\mu\mathrm{G}$
  - Magnetic coherence length $L \sim \mathrm{kpc}$
  - Electron density $n_e \sim 10^{-3}\,\mathrm{cm}^{-3}$
  - Plasma frequency $\omega_{\rm pl} \sim 10^{-12}\,\mathrm{eV}$
  - Typical no. domains traversed $N \approx 100 - 1000$
- Strong mixing if $NP_{\gamma\leftrightarrow\phi} \gg 1$

$$N\Delta \lesssim \pi/2$$

$$\Delta = m_{\rm eff}^2 L/4\omega$$

  - Requires $\omega \gtrsim 0.3 - 3\,\mathrm{keV}$

$$m_\phi \ll 10^{-12}\,\mathrm{eV} \qquad M \lesssim \mathrm{few} \times 10^{11}\,\mathrm{GeV}$$

Effects of Strong Mixing on Luminosity

- After passing through many domains power is, on average, split equally between ALP and two polarisations of the photon
- Average luminosity suppression = 2/3 (Csáki, Kaloper, Terning 2001)
- Difficult to use this to constrain mixing because knowledge of initial luminosities is poor
- Single source:

$$I_{\mathrm{f}}^{(\gamma)}(K_1, K_2, p_0) = \left[1 - (1-p_0)K_1^2 - p_0 K_2^2\right] I^{(\mathrm{tot})}$$

$$K_i \sim U(-1, 1)$$

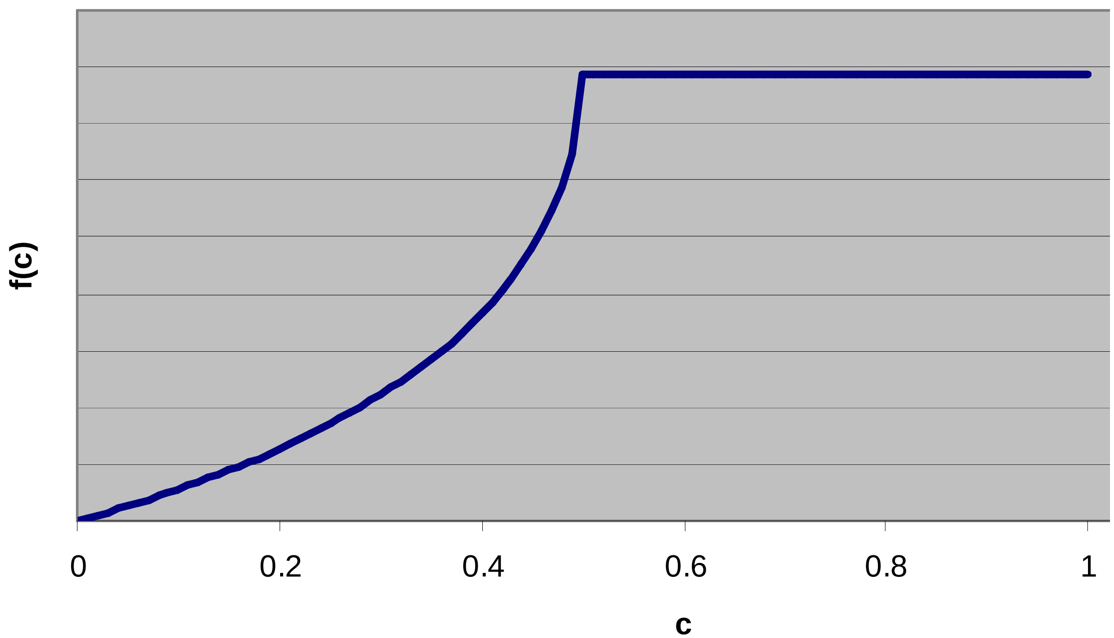
  - If $C \equiv I_{\mathrm{f}}^{(\gamma)}/I^{(\mathrm{tot})}$; averaged over many paths $\bar{C} = 2/3$

Effects of Strong Mixing on Luminosity

- Probability distribution function for C

$$f_C(c;p_0) = \frac{1}{\sqrt{1-p_0^2}}\left[\tan^{-1}\left(\sqrt{a}\left(1-\frac{2c_+}{1+p_0}\right)^{-1/2}\right) - \tan^{-1}\left(\sqrt{a}\left(1-\frac{2c_-}{1-p_0}\right)^{1/2}\right)\right]$$

$$a = (1-p_0)/(1+p_0) \qquad c_\pm = \min(c,(1\pm p_0)/2$$



Luminosity Relations

- Empirically established relations between high frequency luminosity and some feature at lower frequency
  - e.g. peak energy, or luminosity
- Standard relation $$\log_{10} Y_i = a + b \log_{10} X_i + S_i.$$

  High frequency feature (Y_i); Low frequency feature (X_i)

  - If Gaussian noise $S_i = \sigma \delta_i \quad \delta_i \sim N(0,1)$
  - If strong ALP-photon mixing in addition

$$S_i = \sigma \delta_i - \log_{10} C_i + \mu,$$

  - Detection possible if Gaussian component smaller

Luminosity Relations

- Use the likelihood ratio test to compare Gaussian Vs Gaussian + ALP strong mixing

$$L_f(a,b,\sigma,p_0) = \prod_i \frac{1}{\sqrt{2\pi}\sigma} \int_0^1 e^{-\frac{z_i^2}{2\sigma^2}} f_C(c;p_0)\,\mathrm{d}c.$$

$$z_i = \log_{10} Y_i - a - b\log_{10} X_i - h(c;f) \qquad h(c;f) = \log_{10}((1-f)+fc)$$

- Likelihood ratio

$$r_f(p_0) = 2\log\left(\hat{L}_f(p_0)/\hat{L}_0\right)$$

Against ALPsm	For ALPsm	
r<-6	r>6	Strong Evidence
r<-10	r>10	Very Strong Evidence

- For GRB and Blazar relations find |r|<0.75

Active Galactic Nuclei

- Strong correlation between 2 keV X-ray luminosity and optical luminosity (~5eV)
- Use observations of 77 AGN from COMBO-17 and ROSAT surveys (z=0.061-2.54) (Steffen et al. 2006)
- Likelihood ratio
  - r≈14 Assuming initial polarisation $0 < p_0 < 0.4$
  - r>11 Allowing all polarisations

- Is this really a preference for ALPsm? Or just an indication of more structure in the scatter?

Fingerprints

- 10^5 bootstrap resamplings (with replacement) of the data - all samples 77 data points
- Compute the central moments of the data

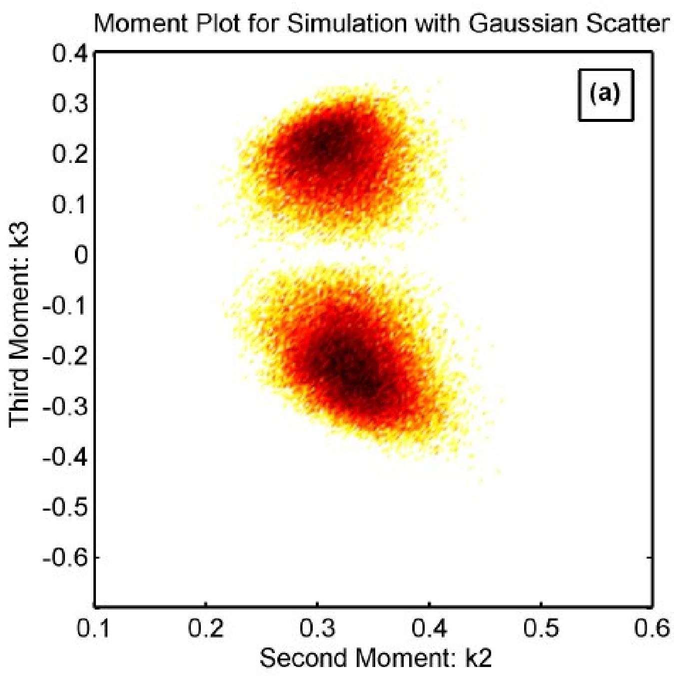
$$k_m(\{s_i\}) = \left(\frac{1}{N_p}\sum_i s_i^{*m}\right)^{\frac{1}{m}}$$

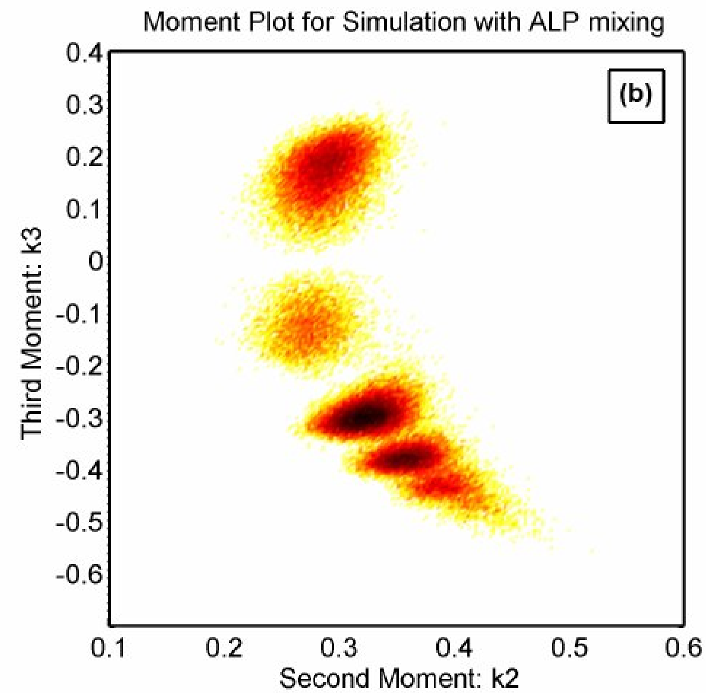
$$D = \langle x_i \equiv \log_{10} X_i, y_i \equiv \log_{10} Y_i \rangle$$

$$s_i^* = y_i^* - (a^* + b^* x_i^*)$$

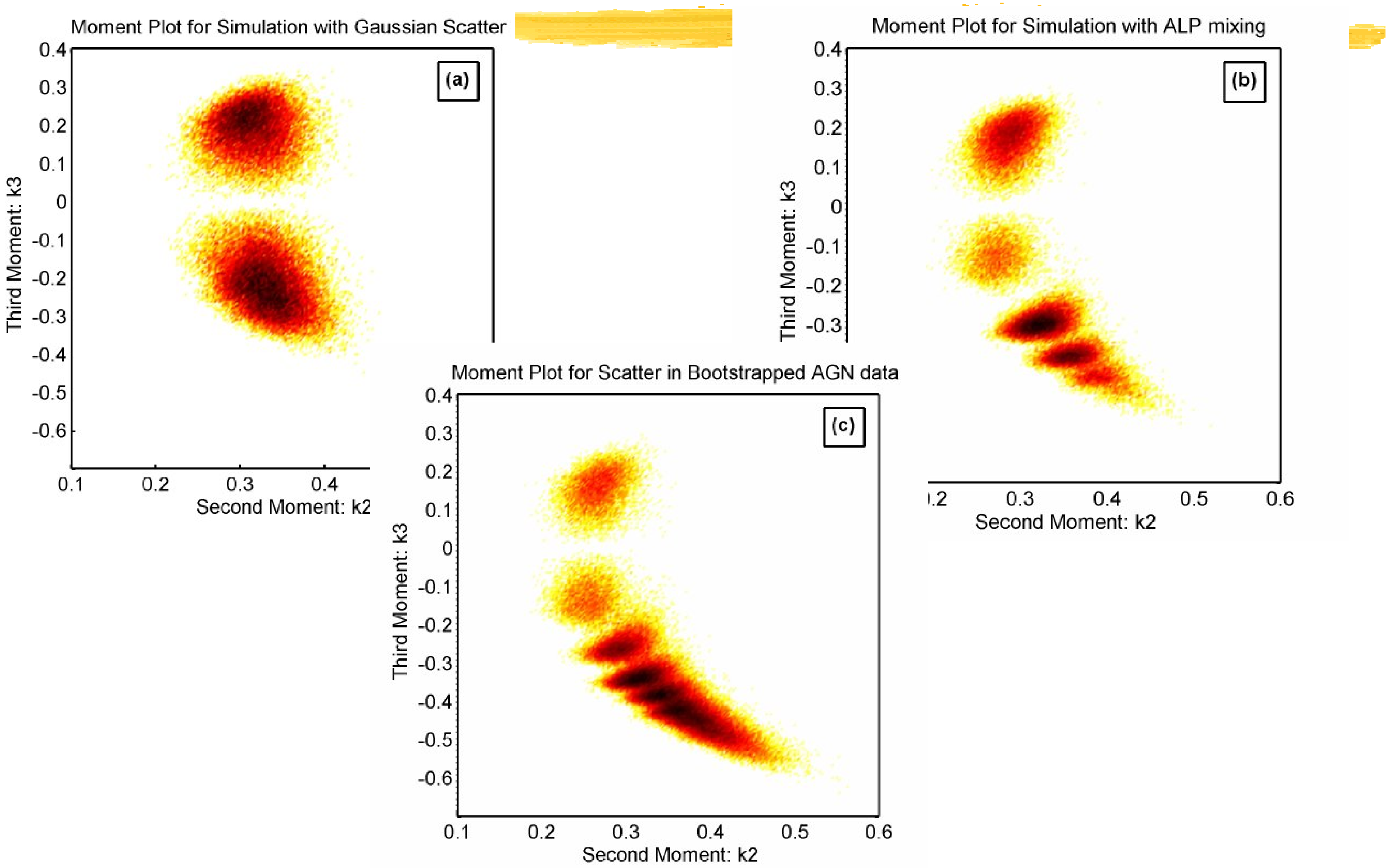
  - k_2 is the standard deviation
  - k_3^3/k_2^3 is the skewness of the data
  - …
- Compare this with simulations of the best fit Gaussian and ALPsm models

Fingerprints





Fingerprints



Conclusions

- If dark energy couples to photons it behaves as an ALP
- ALPs mix with photons in magnetic fields
- Scatter in astrophysical luminosity relations can be used to study this mixing
- Applied to AGN this shows very strong evidence for ALP strong mixing over Gaussian scatter
- Visualisations of the data show strong qualitative similarity to best fit ALP mixing model

Other hints for ALPs

- Ultra-high-energy cosmic rays from BL Lacs
  (Fairbairn, Rashba, Troitsky 2009)
- Anomalously large transparency of the Universe to gamma rays
  (Roncadelli, De Angelis, Mansutti 2009)
- White dwarf cooling
  (Isern, Catalán, García-Berro, Torres 2008)
- Starlight polarisation (chameleons)
  (CB, Davis, Shaw 2008)

GRBs and Blazars

- GRBs: gamma-ray luminosity can be correlated with: spectral lag, variability of light curve, peak energy…
  - 69 GRBs with z=0.17-6.6 (Schaefer 2007)
- Blazars: gamma-ray luminosity correlated with: radio luminosity, near infra-red luminosity
  - 95 EGRET observations, z=0.02-2.5, for radio (Bloom 2007)
  - 16 blazars with z=0.3-1, for IR (Xie, Zhang, Fan 1997)
- All these observations have $|r|<0.75$
  - statistically insignificant preference for ALPsm