Searching for Axion-like Particles with Active Galactic Nuclei

Clare Burrage (DESY)

Phys. Rev. Lett. 102 201101 (2009)

With A.C. Davis (Cambridge) and D. Shaw (QMUL)

Outline

- Axion-like-particles (ALPs)
- Astronomy with ALPs
- A new test for ALPs - Luminosity relations
  - Results from Active Galactic Nuclei
- Conclusions

Axions and axion-like-particles

- Axions proposed by Pecci and Quinn (1977) to solve the strong CP problem of QCD
  - Pseudo-scalar particles, (approximate) shift symmetry $\phi \rightarrow \phi + \epsilon$
  - Mass proportional to coupling strength
  - Lagrangian includes
$$\mathcal{L} \supset \frac{\phi}{4M}\epsilon_{\mu\nu\lambda\rho}F^{\mu\nu}F^{\lambda\rho} = -\frac{\phi}{M}\mathbf{E}\cdot\mathbf{B}.$$
- Axion-like-particle (ALP) is a scalar or pseudoscalar particle with a coupling to two photons
- Scalar field couples as
$$\mathcal{L} \supset \frac{\phi}{4M}F_{\mu\nu}F^{\mu\nu} = \frac{\phi}{2M}(\mathbf{B}^2 - \mathbf{E}^2).$$
  - mass and coupling strength are free parameters to be constrained

Motivations and constraints

- ALPs arise in string theory and GUT models (Svrcek & Witten 2006)
- Dark energy: coupled quintessence, axionic dark energy, chameleon dark energy…

  (Amendola 2000, Carroll 1998, Kim, Nilles 2003, Khoury & Weltman 2004)
- Suggested by high energy cosmic rays? See M. Fairbairn's talk

- Current experimental constraints on very light ALPs $m_\phi \lesssim 10^{-12}$ eV.
  - Pseudoscalar ALPs 10^{11} GeV $\lesssim M$ (Hagman et al. 2008)
  - Scalar ALPs 10^{26} GeV $< M$ (Will 1993)
  - Chameleonic ALPs 10^{9} GeV $\lesssim M$ (CB, Davis, Shaw 2009)
    - Mass depends on the local energy density, leads to 'thin-shell' suppression of fifth forces

Optics with ALPs

- A photon travelling through a magnetic field can convert into an ALP (Raffelt & Stodolsky 1988)

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

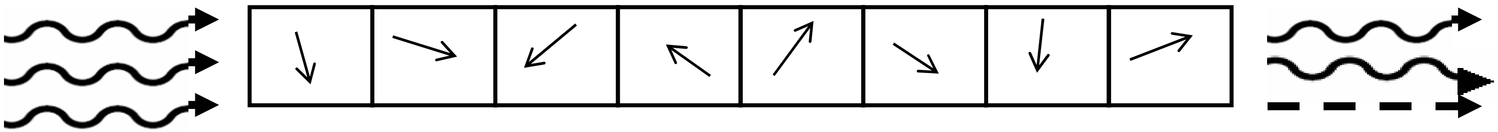
- Probability of mixing $P = \sin^2 2\theta \sin^2\left(\frac{\Delta(z)}{\cos 2\theta}\right)$

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

  - Increases with frequency
  - At large frequencies approaches an upper bound and becomes frequency independent
- So far no detection of ALPs in the laboratory

Astronomy with ALPs

- Can we use astronomy to search for ALPs?
- 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



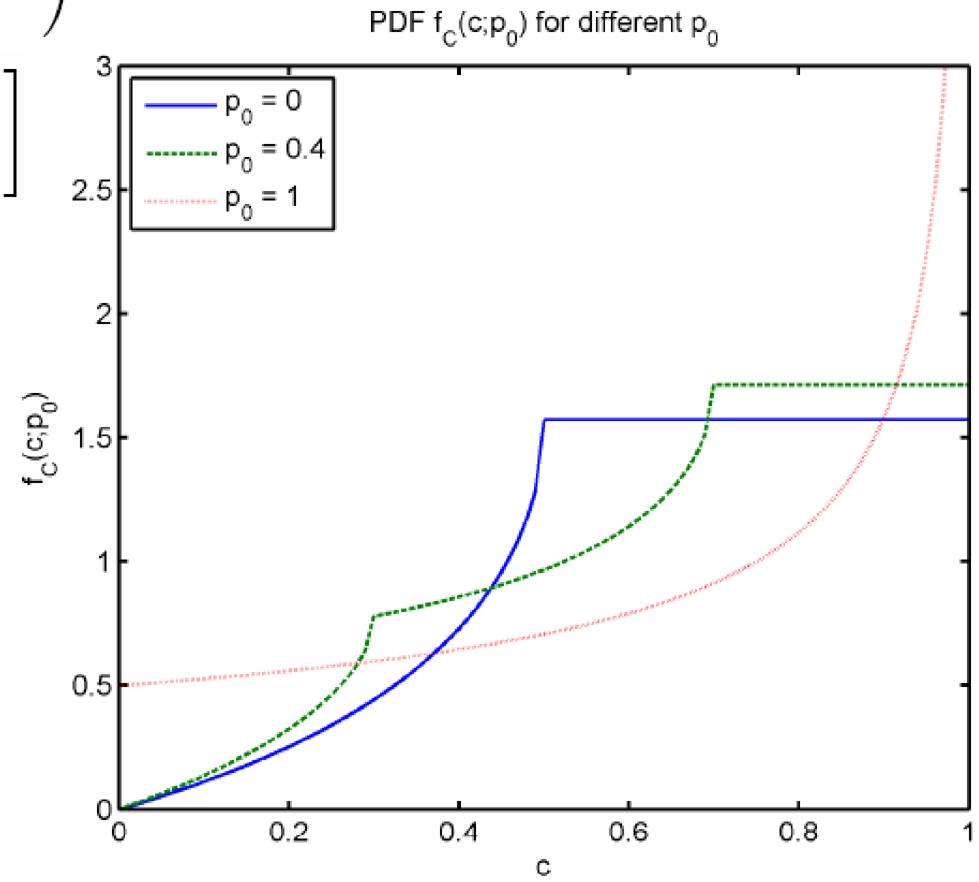
- Strong mixing occurs when $NP \gg 1 \quad N\Delta(L) \lesssim \pi/2$
  - Probability of mixing becomes large and frequency independent
  - After passing through a large number of domains the initial flux becomes, on average, equally distributed between $A_1,\ A_2 \quad \phi$
  - The attenuation factor $C = S_0(N)/S_0(0)$

Strong mixing

$$f_C(c;p_0) = \frac{1}{\sqrt{1-p_0^2}}\left[\tan^{-1}\left(\sqrt{a}\left(1-\frac{2c_+}{1+p_0}\right)^{-1/2}\right) - \tan^{-1}\left(\sqrt{a}\left(1-\frac{2c_1}{1-p_0}\right)^{1/2}\right)\right]$$

$$a = (1+p_0)/(1-p_0)$$

$$c_\pm = \min\left(c, (1\pm p_0)/2\right)$$



A new test for ALPs - Luminosity relations

- Problem: We do not generally know the expected high energy flux from astronomical sources
- For a number of types of object there exist 'luminosity relations' correlating their high and low frequency luminosity
  - At low frequencies light mixes weakly with ALPs, and the luminosity is not altered at leading order
- Relations take the form $\log_{10} Y_i = a + b \log_{10} X_i + S_i$

  High energy flux (Y_i) low energy flux (X_i) scatter (S_i)

  - Standard to model the scatter as normally distributed

    $$S_i = \sigma \delta_i \qquad \delta \sim N(0,1)$$

  - If high frequency light mixes with ALPs $S_i = \sigma \delta_i - \log_{10} C_i$

A new test for ALPs - Luminosity relations

- Compare the two models with the Likelihood ratio test

$$r(p_0) = 2\log\left(\frac{\hat{L}_1(p_0)}{\hat{L}_0}\right)$$

  -

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

- We consider photons propagating through the magnetic fields of galaxy clusters $B \approx 1-10\mu\mathrm{G}$ $L \sim \mathrm{kpc}$ $N \approx 100-1000$
- If $M \lesssim 10^{11}$ GeV strong mixing for x-ray and gamma-ray photons
  - Assume $m_\phi^2 \lesssim \omega_P^2$

$$\omega_{\mathrm{pl}} \sim 10^{-12}\,\mathrm{eV}$$

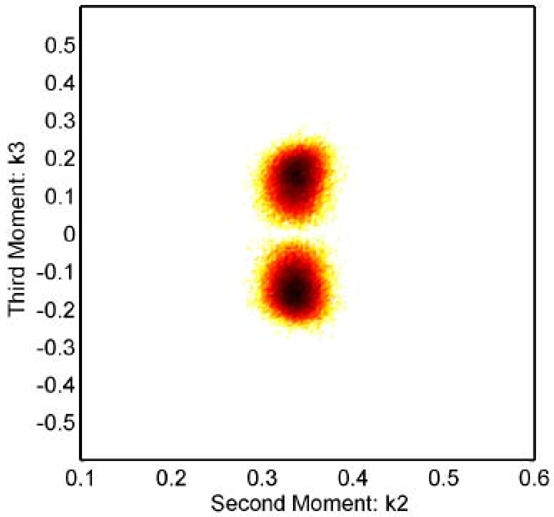
Active galactic nuclei

- Luminosity relation between 2 keV x-ray luminosity and 5 eV optical luminosity
  - Observations of 77 AGN from COMBO-17 and ROSAT surveys and 126 objects from the SDSS survey (Steffen et al. 2006,Strateve 2005)
- For the combined data set $r(p_0 \lesssim 0.5) \approx 25$
  - expectation from AGN physics is $p_0 < 0.1$

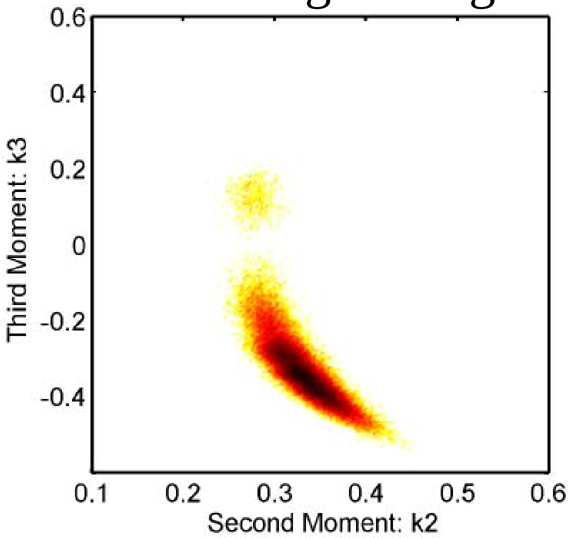
- Qualitative check - independent of any null hypothesis
  - Construct 10^5 new data sets (with 203 points) by bootstrap resampling with replacement
- Compute statistical moments for data sets k_m
  - k_2 the rms mean, k_3^3/k_2^3 the skew, …

Active galactic nuclei - Fingerprints

Gaussian Scatter

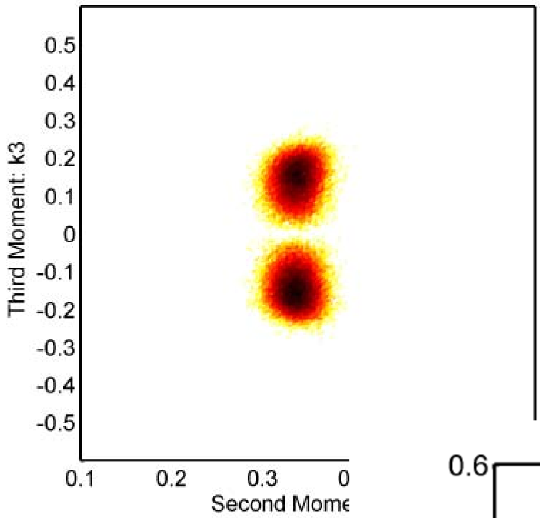


ALP strong mixing

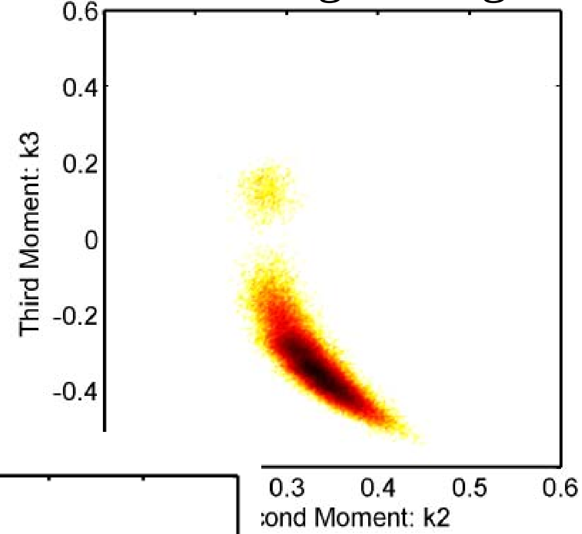


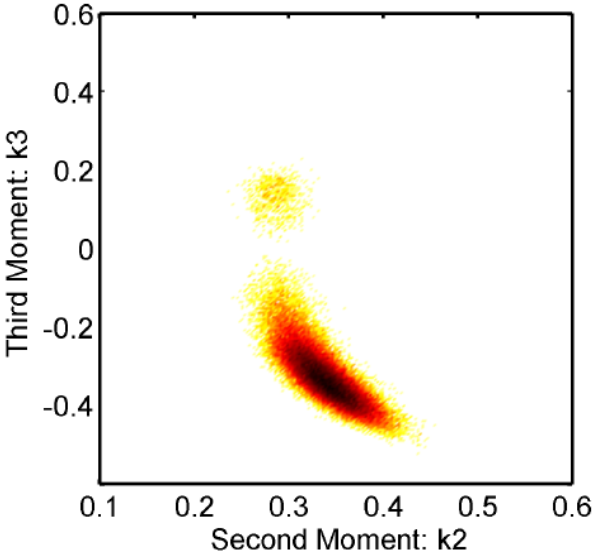
Active galactic nuclei - Fingerprints

Gaussian Scatter



ALP strong mixing





AGN results

Conclusions & future tests

- AGN luminosity relations show very strong evidence for ALP-photon mixing over null hypothesis of Gaussian noise
- There is structure in the scatter which, qualitatively, looks like strong ALP-photon mixing
  - pseudoscalar, or chameleonic field

$$M \lesssim 10^{11}\ \mathrm{GeV}$$

$$m_\phi \lesssim 10^{-12}\ \mathrm{eV}.$$

- Qualitative similarity also exists for higher moments of the distribution
- We do not understand the physics of the luminosity relation - this could be standard physics mimicking ALPs
  - No evidence for correlation between redshift and scatter, so cannot be:
    - evolution effects
    - inaccurate choice of cosmological model

Conclusions & future tests

- Is this effect independent of the objects studied?
  - Luminosity relations also exist currently for GRBs and Blazars
  - Likelihood ratio test gives $r \approx 1.6$
    - either too few data points
    - or too large intrinsic scatter

Schaefer (2007)

Bloom, (2007)

Xie, Zhang, Fan (1997)

- If the explanation is strong mixing expect to also induce a large linear polarization
  - Could be measured with e.g. proposed International X-ray Observatory
- CAST should be sensitive to these couplings in the next decade

Strong mixing

- Strong mixing occurs when $NP \gg 1 \quad N\Delta(L) \lesssim \pi/2$
  - Probability of mixing becomes large and frequency independent
- Mixing between ALP and photons, and between different components of the photon becomes large
  - After passing through a large number of domains the initial flux becomes, on average, equally distributed between $A_1,\ A_2\ \ \phi$
- If photon component fully polarized, initially

$$\mathbf{u}(0) = (\phi(0), A_1(0), A_2(0))^T \qquad |\mathbf{u}(0)| = 1$$

- Finally

$$\mathbf{u}_N = (x, \sqrt{1-x^2}\cos\pi\Theta, \sqrt{1-x^2}\sin\pi\Theta)^T \qquad x, \Theta \sim U(-1,1)$$

  - But in astronomy our sources are partially polarized or unpolarized

Strong mixing

- To describe a partially or unpolarized light beam use the Stokes vector

$$\mathbf{S} \equiv \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} |A_1|^2 + |A_2|^2 \\ |A_1|^2 - |A_2|^2 \\ A_1\bar{A}_2 + \bar{A}_1 A_2 \\ i(A_1\bar{A}_2 - \bar{A}_1 A_2) \end{pmatrix}$$

- Initial photon state

$$\mathbf{S}(0) = \frac{1}{2}(1+p_0)\begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} + \frac{1}{2}(1-p_0)\begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix}$$

- Final photon state

$$\mathbf{S}(N) = \frac{1}{2}(1+p_0)(1-x^2)\begin{pmatrix} 1 \\ \cos 2\theta \\ \sin 2\theta \\ 0 \end{pmatrix} + \frac{1}{2}(1-p_0)(1-y^2)\begin{pmatrix} 1 \\ \cos 2\vartheta \\ \sin 2\vartheta \\ 0 \end{pmatrix}$$

A new test for ALPs - Luminosity relations

- Given data set $\{X_i, Y_i\}$ the likelihood of the models is

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

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

  - $f = 1$ when high frequency light is strongly mixed with ALPs
  - $f = 0$ when high frequency light does not mix with ALPs
- For each model fit for $a,\ b,\ \sigma$ by maximising the likelihood
- Define the ratio

$$r(p_0) = 2\log\left(\frac{\hat{L}_1(p_0)}{\hat{L}_0}\right)$$

  - $\hat{L}$ the model with the most likely parameters

Active galactic nuclei

- Results only weakly dependent on initial polarization,
  - robust to relaxing the universality of p_0
- In the ALP strong mixing model we have taken the probability of mixing $P_{\mathrm{mix}} = 1$ to be universal
  - result robust to different values of P_{mix}
  - Data only constrains $P_{\mathrm{mix}} \geq 0.08$ at 95% confidence
- Have we just chosen a bad null hypothesis?
  - Null hypothesis was chosen because of its simplicity and because for similar relations it is a good fit
  - Do not understand the cause of the luminosity relation for AGN, so we cannot improve the null hypothesis

Discussion

- Qualitative similarity also exists for higher moments of the distribution
- We do not understand the physics of the luminosity relation - this could be standard physics mimicking ALPs
  - No evidence for correlation between redshift and scatter, so cannot be:
    - evolution effects
    - inaccurate choice of cosmological model

- Luminosity relations also exist for GRBs and Blazars
  - Likelihood ratio test gives $r \approx 1.6$
    - either too few data points
    - or too large intrinsic scatter

Schaefer (2007)

Bloom, (2007)

Xie, Zhang, Fan (1997)

Conclusions

- AGN luminosity relations show very strong evidence for ALP-photon mixing over null hypothesis of Gaussian noise
- There is structure in the scatter which, qualitatively, looks like strong ALP-photon mixing
  - pseudoscalar, or chameleonic field

$$M \lesssim 10^{11}\ \mathrm{GeV}$$

$$m_\phi \lesssim 10^{-12}\ \mathrm{eV}.$$

- But because we do not understand AGN physics cannot rule out explanation in terms of old physics
- If the explanation is strong mixing expect to also induce a large linear polarization
  - Could be measured with e.g. proposed International X-ray Observatory
- If we are seeing a pseudoscalar ALP hopefully seen at CAST in the next decade