

New Astrophysical tests for Axion-like Particles



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Outline



- Axions and Axion-like-particles (ALPs)
- Optics with 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)
- Varying constants: Olive Pospelov model explains observations of varying fine structure constant (Olive & Pospelov 2008)
- 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)
 - Properties depend on the local energy density, leads to ‘thin-shell’ suppression of fifth forces

Optics with ALPs

- Have introduced a new coupling between two photons and an ALP
 - When a photon travels through a magnetic field it can convert into an ALP
- (Raffelt & Stodolsky 1988)

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

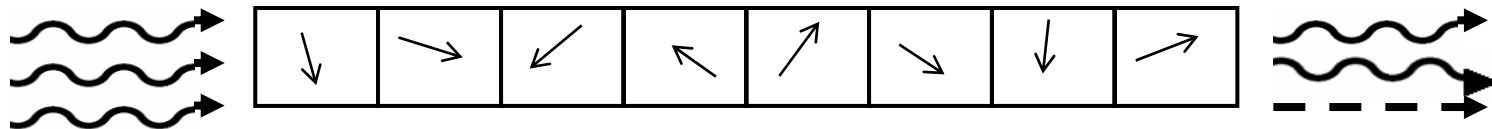
- Probability of mixing $P = \sin^2 2\theta \sin^2 \left(\frac{\Delta(z)}{\cos 2\theta} \right)$

$$\Delta(z) = m_{eff}^2 z / 4\omega \quad \tan 2\theta = 2B\omega / M m_{eff}^2 \quad m_S^{eff} = |m_S^\phi - m_S^b|$$

- 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
- Sufficient to use the cell magnetic field model
 - field has same magnitude in each cell but orientation varies randomly



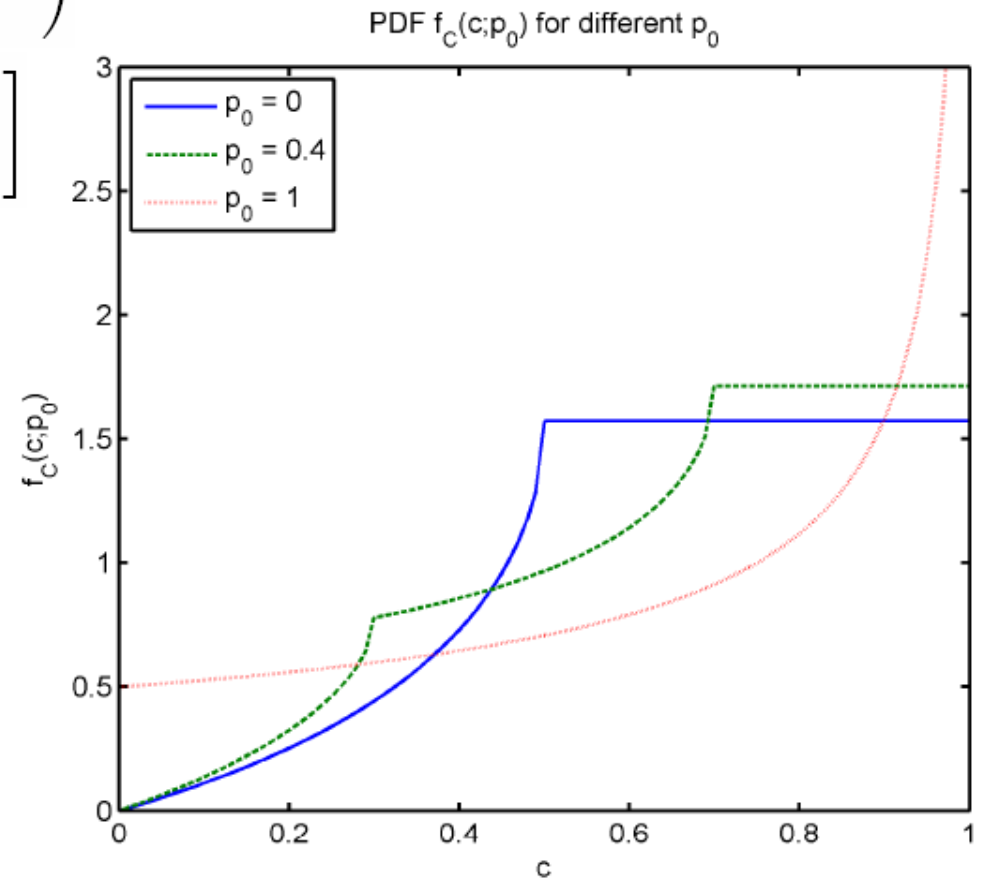
- Strong mixing occurs when $NP \gg 1$ $N\Delta(L) \lesssim \pi/2$
 - Probability of mixing becomes large and frequency independent
 - After passing through a large number of domains the initial flux becomes, on average, equally distributed between A_1, A_2 ϕ
 - The attenuation factor $C = S_0(N)/S_0(0)$

Strong mixing

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

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

$$c_{\pm} = \min(c, (1 \pm p_0)/2)$$



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 low energy flux scatter

- Standard to model the scatter as normally distributed

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

- 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

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

– <u>Against ALPsm</u>	<u>For ALPsm</u>	
$r < -6$	$r > 6$	Strong Evidence
$r < -10$	$r > 10$	Very Strong Evidence

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

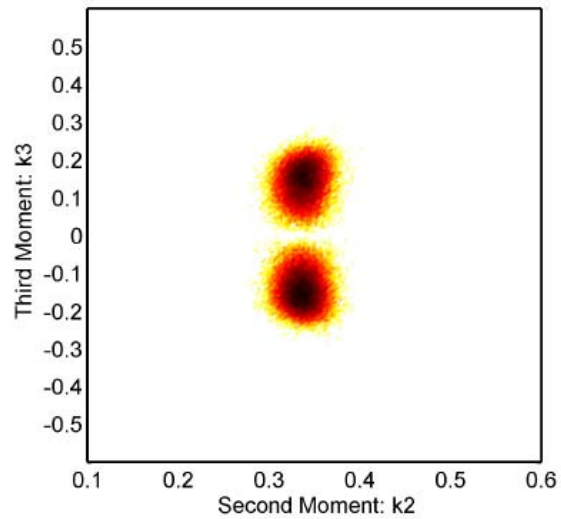
- For model independent constraints we assume $m_\phi^2 \lesssim \omega_P^2$
 $\omega_{\text{pl}} \sim 10^{-12} \text{ eV}$

Active galactic nuclei

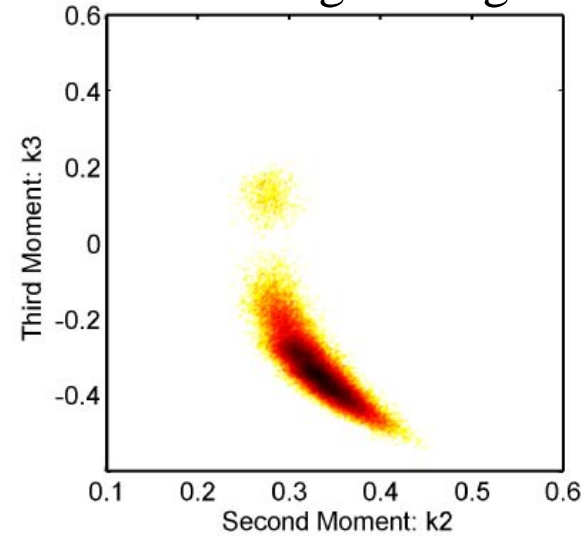
- Luminosity relation between 2 keV x-ray luminosity and 5 eV optical luminosity
 - Observations of 77 AGN from COMBO-17 and ROSAT surveys and 126 objects from the SDSS survey (Steffen et al. 2006, Strateve 2005)
- For the combined data set $r(p_0 \lesssim 0.5) \approx 25$
 - expectation from AGN physics 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/k_2^3 the skew, ...

Active galactic nuclei - Fingerprints

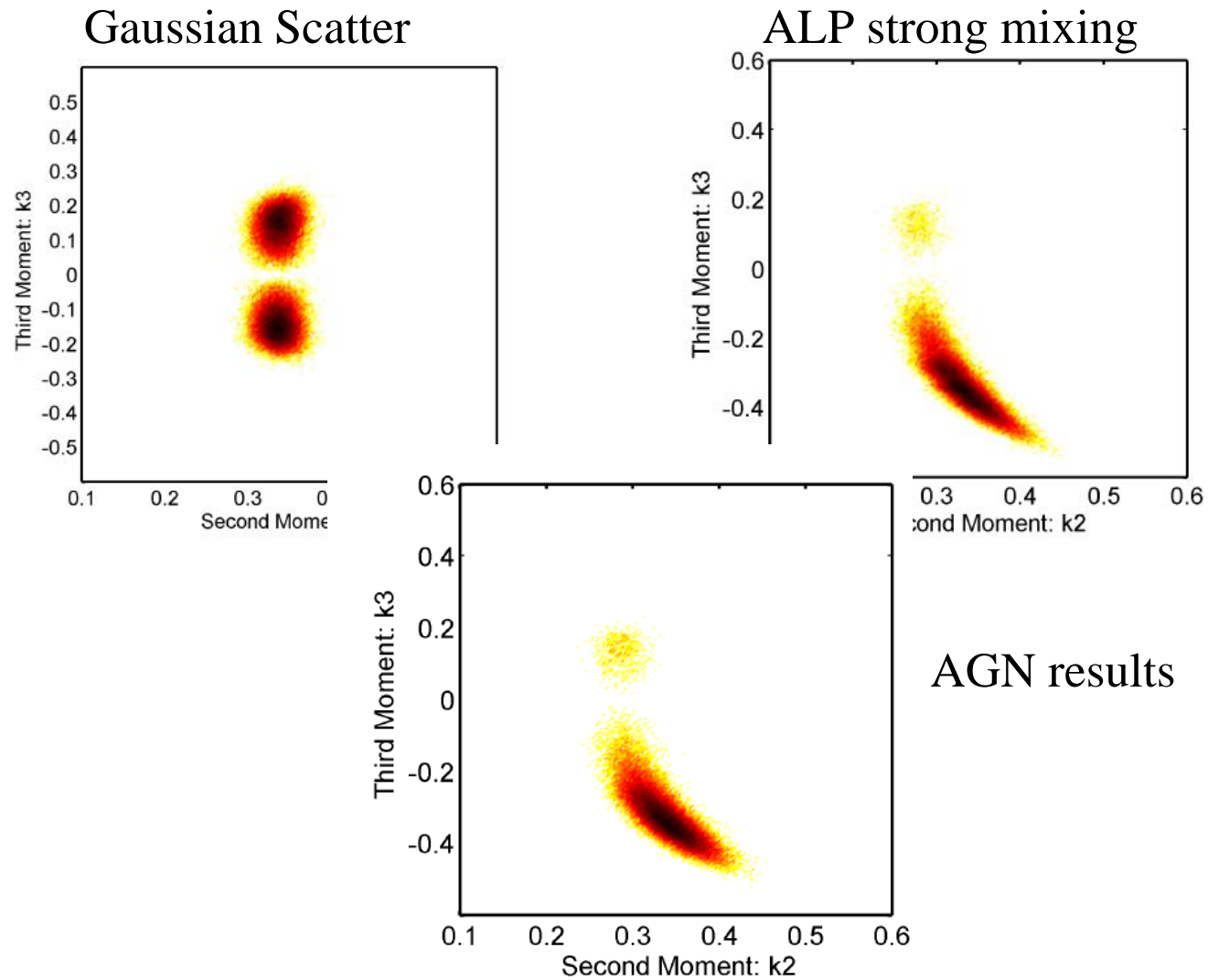
Gaussian Scatter



ALP strong mixing



Active galactic nuclei - Fingerprints



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
- $$M \lesssim 10^{11} \text{ GeV}$$
- $$m_\phi \lesssim 10^{-12} \text{ eV.}$$
- But because we do not understand AGN physics it could still be old physics mimicking new 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 the explanation is non-chameleonic ALPs could potentially be detected by future runs of CAST