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Searching for Axion-like Particles with Active Galactic Nuclei

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Strong mixing between photons and axion-like particles in the magnetic fields of clusters of galaxies induces a scatter in the observed luminosities of compact sources in the cluster. This is used to construct a new test for axion-like particles; applied to observations of active galactic nuclei it is strongly suggestive of the existence of a light axion-like particle.

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1 Introduction

An Axion-Like Particle (ALP) is any scalar or pseudo-scalar field which couples to the kinetic terms of the photon. The pseudo scalar coupling to photons is identical to that of the axion; $\mathcal{L} \supset \frac{\phi}{4M}\epsilon_{\mu\nu\lambda\rho}F^{\mu\nu}F^{\lambda\rho}$, and a scalar field couples through the Lagrangian term; $\mathcal{L} \supset \frac{\phi}{4M}F_{\mu\nu}F^{\mu\nu}$. The presence of contact interactions between ALPs and photons means that ALPs affect the propagation of photons through a magnetic field. In such an environment a photon can oscillate into an ALP with probability [1]

$$P(z) = \sin^2 2\theta \sin^2\left(\frac{\Delta(z)}{\cos 2\theta}\right). \tag{1}$$

Here z is the distance traveled, $\Delta(z) = m_{eff}^2 z/4\omega$ and $\tan 2\theta = 2B\omega/M m_{eff}^2$. $m_{eff}^2 = |m_\phi^2 - \omega_P^2|$, m_ϕ is the ALP mass, ω_P the plasma frequency of the medium, ω the photon frequency frequency, B the magnetic field strength and M the strength of the photon-ALP coupling.

In these proceedings we describe a new test for ALPs which looks for the effects induced by strong ALP-photon mixing on the luminosity of astronomical objects observed through the magnetic fields of galaxy clusters. Our results apply to ALPs with masses $m_\phi \lesssim 10^{-12}$ eV. The constraints on the couplings of such ALPs are: 10^{11} GeV $\lesssim M$ for pseudo-scalars [2], and 10^{26} GeV $\lesssim M$ for scalars [3]. However a subclass of scalar ALPs known as *chameleonic* [4] ALPs avoid these constraints because their mass depends on the local density, their coupling is required to satisfy 10^9 GeV $\lesssim M$ [5].

2 Astronomy with ALPs

The magnetic fields of galaxy clusters fluctuate on many different scales. However, at the high frequencies we consider in what follows the simple cell magnetic field model can be shown to give the same results for ALP-photon mixing as modeling the variations in the magnetic field with a power spectrum. The cell model of the magnetic field assumes the field is made up of a large number of equally sized magnetic domains. The magnitude of the field strength is the same in each domain but the orientation of the field is randomly chosen.

When the probability of mixing between ALPs and photons is large the system of photons and ALPs can be evolved through a large number of randomly oriented magnetic domains analytically; this is known as the strong mixing limit. If L is the size of a magnetic domain, N the number of domains traversed and $P \equiv P(L)$ is the probability of photon to ALP conversion in one magnetic domain, we say that strong mixing occurs when $NP \gg 1$ and $N\Delta(L) \lesssim \pi/2$. In this limit the probability of mixing is large, and frequency independent. Strong mixing occurs in the magnetic fields of galaxy clusters for x-ray or gamma-ray photons if $M \lesssim 10^{11}$ GeV, assuming $m_\phi \lesssim \omega_P$.[1] Particles with such masses and couplings are allowed by current observations for pseudo-scalar fields and for chameleonic scalars.

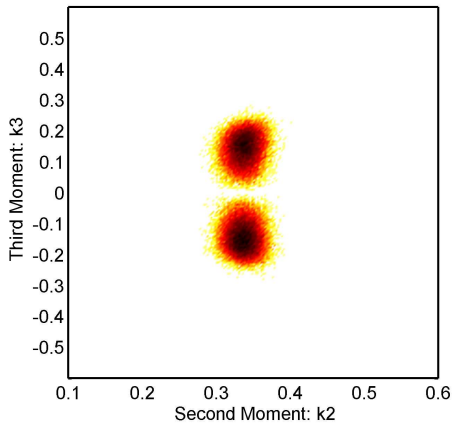

Figure 1: Simulated fingerprint for best fit Gaussian model

As photon number is not conserved photon-ALP mixing will change the apparent luminosity of objects observed through the cluster. We define the attenuation factor to be the ratio of the flux of photons after passing through N domains to the initial flux of photons; $C = I_\gamma(N)/I_\gamma(0)$. Then in the strong mixing limit, assuming no initial flux of ALPs, the mean value for C is $C = 2/3$ [7], and its probability distribution is [8]

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

where $a = (1+p_0)/(1-p_0)$, $c_\pm = \min\,(c, (1 \pm p_0)/2)$ and p_0 is the initial polarization of the photons. This probability distribution has an unusual shape, and is very asymmetric about the mean. In the next Section we show that this can be exploited as a new test for ALPs.

3 Searching for ALPs with luminosity relations

To use the shape of the probability distribution (2) to look for ALPs we would need to know the high energy photon flux for a class of astronomical sources. We do not currently know of any ob-

[1] The strength of the magnetic field is $B \approx 1 - 10$ μG, the size of a magnetic domain is $L \approx 1$ kpc and for a typical source inside the cluster we expect the light observed from that source to have traversed $N \approx 100 - 1000$ magnetic domains [6]. The plasma frequency in the intracluster medium is $\omega_P \approx 10^{-12}$ eV

jects that are standard candles in x- or gamma-rays, however, for certain classes of object there exist *luminosity relations* which correlate the high frequency luminosity of an object with a feature of its low energy spectrum. At low frequencies light mixes weakly with ALPs and hence we assume that low energy observables are not affected by ALPs at leading order. Therefore luminosity relations can be used to normalize the high energy flux, so that the effects of ALPs are observable.
The relations typically take the form

$$\log_{10} Y_i = a + b \log_{10} X_i + S_i, \qquad (3)$$

where Y_i is the high energy luminosity, and X_i is the low energy feature of the spectrum for the i-th object in the survey. S_i represent the scatter in individual measurements, it is standard in astronomy to assume they are normally distributed; $S_i = \sigma\delta_i$ where $\delta \sim N(0,1)$. If the high frequency light mixes strongly with ALPs this will appear as an additional contribution to the scatter $S_i = \sigma\delta_i - \log_{10} C_i$, where the C_i are described by the probability distribution function (2).

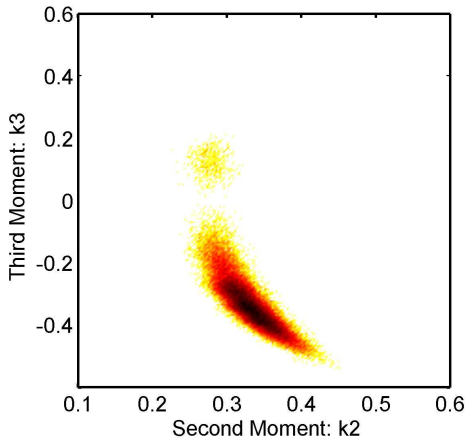

Figure 2: Simulated fingerprint for best fit ALP strong mixing model

For a given data set we use the likelihood ratio test to see if the data prefer strong ALP-photon mixing, or the null hypothesis of Gaussian noise. We find the values of the parameters a, b and σ which maximize the likelihood of each hypothesis given the data, and then compare these two maximum likelihoods with the ratio $r(p_0) = 2\log(\hat{L}_1(p_0)/\hat{L}_0)$, where $\hat{L}_1(p_0)$ is the maximum likelihood allowing for strong ALP-photon mixing and $\hat{L}_0$ is the maximum likelihood for models where the scatter is purely Gaussian. The two hypothesis have the same number of parameters and therefore $r(p_0)$ is equivalent to the Bayesian Information Criterion. Negative $r(p_0)$ is evidence against ALP strong mixing, and positive $r(p_0)$ is evidence for ALP strong mixing. $|r(p_0)| > 6$ is considered strong evidence, $|r(p_0)| > 10$ is considered very strong evidence.

4 Results from active galactic nuclei

To apply the test developed in the previous section we require a class of compact objects within galaxy clusters that emit x-ray or gamma-ray light and for which luminosity relations exist correlating the high energy luminosity with a feature of the low-energy spectrum. Active galactic nuclei (AGN) satisfy these requirements. For AGN a luminosity relation has been established between the 2 keV x-ray luminosity and the 5 eV optical luminosity. We have observations of 77 AGN from the COMBO-17 and ROSAT surveys [9] and 126 objects from the SDSS survey [10].

Applying the likelihood ratio test described in the previous section to these results we find $r(p_0 \lesssim 0.5) \approx 25$, where the expectation from AGN physics is that $p_0 < 0.1$ [11].

As a qualitative check of this result we plot *fingerprints* of the data. To do this we construct 10^5 new data sets, of the same size as the original, by bootstrap re-sampling (with replacement) of the original data set. For each data set we calculate the statistical moments of the

distribution $k_m(s_i) = [(1/N_p)\sum_i s_i^m]^{1/m}$ where $s_i = \log_{10} Y_i - (a + b \log_{10} X_i)$. These moments parametrize the shape of the probability distribution. Fingerprints of the data are then histogram plots of k_i vs. k_j for the resampled data sets. Figures 1 and 2 show example fingerprints for simulated data respectively without and with the effects of strong ALP-photon mixing. Darker regions indicate a higher density of points. Figure 3 shows the same plot for the data obtained from observations of AGN.

Comparing Figures 2 and 3 there is a clear qualitative similarity between the shapes of the predicted and observed distributions. This similarity persists when higher moments of the distribution are plotted.

The astrophysics underlying the luminosity relation for AGN is not known, and we cannot rule out that a combination of standard physical processes in the AGN conspires to mimic the effects of ALP-photon mixing. It can be shown, however, that the scatter in the luminosity relation is not redshift dependent, therefore the observed scatter is not due to evolution effects or an incorrect choice of cosmological model.

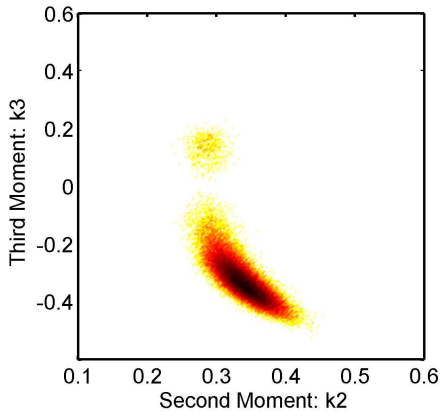

Figure 3: Fingerprint from AGN data

Acknowledgments

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