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Current and Future constraints on Very-Light Axion-Like Particles from X-ray observations of cluster-hosted Active Galaxies

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Abstract. We discuss our recent constraints on the coupling of Very-Light Axion-Like Particles (of masses $<10^{-12}$ eV) to electromagnetism from *Chandra* observations of the cluster-hosted Active Galactic Nuclei (AGN) H1821+643 and NGC1275. In both cases, the inferred high-quality AGN spectra excluded all photon-ALP couplings $g_{a\gamma} > (6.3 - 8.0) \times 10^{-13}$ GeV^{-1} at the 99.7% level, respectively, based on the non-detection of spectral distortions attributed to photon-ALP inter-conversion along the cluster line-of-sight. Finally, we present the prospects of tightening current bounds on such ALPs by up to a factor of 10 with next-generation X-ray observatories such as *Athena*, *AXIS* and *LEM* given their improved spectral and spatial resolution and collecting area compared to current missions.

Key words. Astroparticle Physics – Galaxy clusters – Magnetic fields

1. Overview

Axion-Like Particles (ALPs) are model-independent generalisations of the Quantum Chromodynamics axion, generic predictions of string theories (Conlon , 2006; Svrcek,P. et al. , 2006; Green et al. , 2012; Cicoli et al , 2012) and Dark Matter candidates (Preskill et al , 1983; Abbott et al , 1983; Dine et al. , 1983).

Astronomy provides rich and magnetised environments that probe the interaction of ALPs with electromagnetism as characterised by the coupling strength $g_{a\gamma}$ for a given ALP mass m_a. For a photon beam passing through a magnetised plasma $\mathbf{B}$, the photon-ALP interaction is described by the Lagrangian density:

$$\mathcal{L}_{a\gamma} = g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B} \tag{1}$$

where $\mathbf{E}$ and a are the electric and ALP fields. Equation 1 illustrates that, for a suitable location of parameter space, photon-ALP mixing will take place as photons from a point source traverse a magnetised plasma. For a fixed set of ALP parameters $(m_a, g_{a\gamma})$, this effect will induce energy-dependent distortions, or absorption-like features, in the source spectrum. The presence or absence of such distortions can be used to constrain $g_{a\gamma}$.

Galaxy clusters are the most massive bound objects in the Universe and are perme-

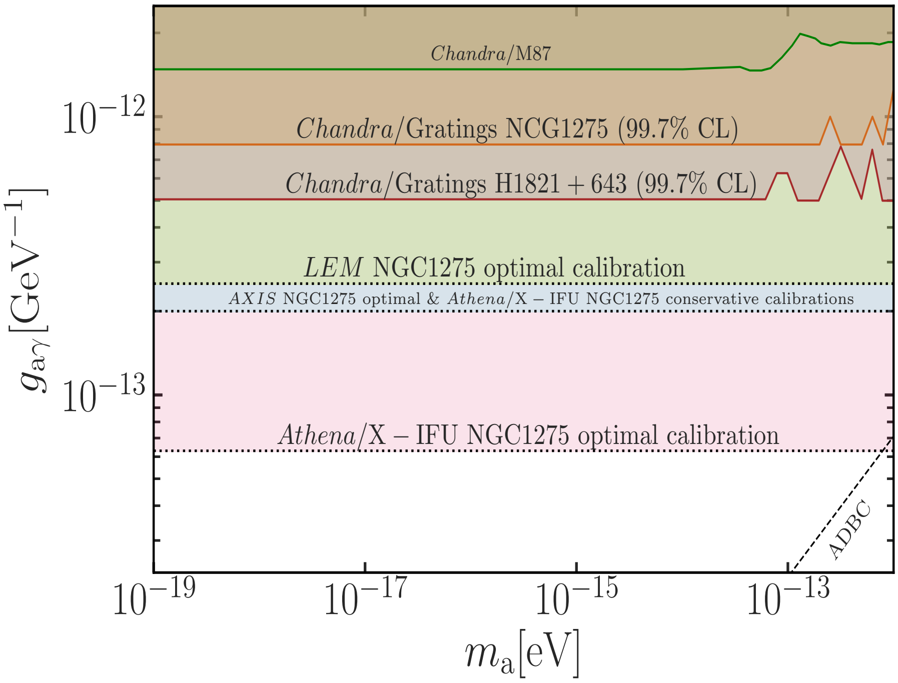

Fig. 1. Constraints on Very-Light ALPs from *Chandra* observations of cluster-hosted AGN. We include projections from the future: *Athena*, *AXIS* and *LEM* X-ray observatories; and the ground-based birefringent cavity for the study of ALP Dark Matter *ADBC*. All results are quoted at the 95% level unless specified (adapted from Sisk-Reynes et al. , 2022b).

ated by the Intracluster Medium (ICM). The ICM is magnetised and turbulent over scales of 100 pc – 10 kpc and can attain attain field strengths up to 10 μG in the cores of the richest (dynamically relaxed) clusters (Govoni et al. , 2004). Some of such cool-core clusters host an Active Galactic Nucleus (AGN) at their Brightest Cluster Galaxy. High-quality spectroscopic observations of cluster-hosted AGN taken with X-ray telescopes can provide a clear view of the intrinsic AGN emission free from ICM contamination (e.g. emission lines), which can be used to constrain ALPs.

2. Current constraints on Very-Light ALPs from cluster-hosted AGNs

The tightest constraints to date on Very-Light ALPs were inferred with a set of deep *Chandra* Transmission Grating observations (570-ks of total exposure) of the very-luminous radio-quiet cluster-hosted quasar H1821+643 (Sisk-Reynes et al. , 2022a). These observations, taken in 2001, disperse the AGN emission across the grating array and enable a high-quality extraction of the AGN spectrum free from photon pile-up and cluster contamination. Sisk-Reynes et al. (2022a) first described the intrinsic AGN emission with an astrophysical model typical of type-1 AGN. This "non-ALP" model, whose free parameters were found by minimising the fit statistic, yielded energy-dependent residuals only below the 2.5% level. To assess whether these remaining spectral distortions could be described by AGN photons undergoing inter-conversion into ALPs along the cluster line-of-sight, the authors first generated a set of photon-ALP mixing curves across a wide range of ALP parameters, (m_a, $g_{a\gamma}$), for 500 possible cell-based realisations of the turbulent cluster magnetic field. Each of these curves was then fitted to the data as a multiplicative term modifying the astrophysical model. After marginalising over all field realisations for a given set of ALP parameters ($m_a, g_{a\gamma}$), the authors computed posteriors on ALPs by comparing the fit statistics of the "non-ALP" and ALP-containing models. At the 99.7% confidence level (99.7% CL), this assessment excluded all photon-ALP coupling values $g_{a\gamma} > 6.3 \times 10^{-13}$ GeV^{-1} for $m_a < 10^{-12}$ eV.

Nevertheless, the ALP constraints inferred from H1821+643 are limited by the assumption of a constant thermal-to-magnetic pressure ratio (β_{pl}) up to the cluster virial radius. However, one would expect bounds on $g_{a\gamma}$ to relax by only up to 0.3 dex with a radially-dependent β_{pl} (Matthews et al. , 2022). Moreover, a more realistic and sophisticated field model could yield tighter constraints on $g_{a\gamma}$ (Carenza et al. , 2022). The previous best constraints on light ALPs had been found by Schallmoser et al. (2021) and Reynolds et al. (2020), where the former employed machine learning to improve on earlier bounds (Conlon et al. , 2017). A high-quality *Chandra* Grating view of the central engine of the Perseus cluster, NGC1275, combined with assumptions about the magnetic field similar to those we made for H1821+643, excluded all photon-ALP coupling values $g_{a\gamma} > 8.0 \times 10^{-13}$ GeV^{-1} for $m_a < 10^{-12}$ eV (Reynolds et al. , 2020).

3. The importance of collecting area and spectral and spatial resolution

Sisk-Reynes et al. (2022b) showed that the next-generation X-ray observatories *Athena* and *AXIS*, with their unprecendented collecting areas and superior spectral and angular resolution, respectively, will further exclude $g_{a\gamma} > (1-4) \times 10^{-13}$ GeV^{-1} (see also Conlon et al. , 2018). These results, shown in Fig. 1, were inferred by simulating observations of NGC1275 with moderate exposure (200-ks) to facilitate comparison with the *Athena*/X-IFU projection found by Conlon et al. (2018). Importantly, in Sisk-Reynes et al. (2022b), the updated *Athena* bounds (Fig. 1) were inferred under a machine learning assessment of detector mis-calibration, given its potential to mimic spectral distortions that could be attributed to photon-ALP inter-conversion. Additionally, Fig. 1 shows the projected bound on Very-Light ALPs we infer from a deep (1-Ms) observation of NGC1275 taken with the next-generation *Line Emission Mapper* observatory (*LEM*, Kraft et al. , 2022, for a target Half Power Diameter of 10″). Clearly, with a high-quality view of the intrinsic AGN emission with an unprecendented spectral resolution (0.9 eV within 0.5-2 keV), as well as with its prominent collecting area, *LEM* will exclude all photon-ALP couplings $g_{a\gamma} > 2.5 \times 10^{-13}$ GeV^{-1} (95% CL) for Very-Light ALPs. Therefore, the *Athena*, *AXIS* and *LEM* projections illustrated in Fig. 1 highlight the exciting prospects of constraining Very-Light ALPs with next-generation X-ray observatories with fundamentally different designs.

4. Conclusions

Bright AGN hosted by rich cool-core galaxy clusters are excellent probes of Very-Light ALPs. Current and next-generation observatories, including the *Chandra*, *Athena*, *AXIS* and *LEM* missions have excluded and will exclude photon-ALP couplings down to $g_{a\gamma} \sim 10^{-13} - 10^{-12}$ GeV^{-1} for ALP masses $<10^{-12}$ eV with high-quality observations of H1821+643 and NGC1275. In future, probing ALPs in this regime may be the *only* plausible observational test of string theories (Halverson et al. , 2019).

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