

Constraints on axion-like particles from active galactic nuclei seen through galaxy clusters

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Constraints on axion like particles from active galactic nuclei seen through galaxy clusters – Supplementary Information

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1 Supplementary Methods

Assessing residual bias caused from the smooth absorption curve fitting. The photon survival probability, $P_{\gamma\gamma}$, averaged over 32 AGN-cluster pairs, shows noticeable deviations from the assumed smooth model. To further investigate this effect, we examine the difference between the individual averaged $P_{\gamma\gamma}$ curves (black curves) and the adopted smooth model (red curve), as shown in the left panel of Figure 1. While the distribution of these residuals has a mean of zero and a standard deviation of approximately 2%, it exhibits a non-negligible skewness, which can introduce a bias in the estimation of ALP parameters. To quantify this bias, we will compare the parameters of the injected and recovered ALP signals.

We built a model for the stacked AGN spectrum, where systematic uncertainties dominate. This model is based on a log-parabola best-fit of the 4FGL *Fermi*/LAT spectral points of NGC 1275, using spectral bins of fixed logarithmic width. To assess how sensitive the fit is to residual deviations from a smooth model, we analyzed two cases: (i) Broad spectral bins with relatively large systematic uncertainties (three bins per decade of energy, i.e., $E_{\max,i}/E_{\min,i} = 3$, with 3% systematics), mimicking the 4FGL *Fermi*/LAT-like spectral bins. (ii) Narrower spectral bins with lower systematic uncertainties (ten bins per decade of energy, i.e., $E_{\max,i}/E_{\min,i} = 1.1$, with 1% systematics), representing the spectral resolution achievable by future γ -ray missions. The right panel of Figure 1 shows the stacked spectrum for the narrow-bin case (blue points).

We then generated 10^3 independent realizations of $P_{\gamma\gamma}$ curves, averaged over 32 objects (black curves) and modified the toy model spectrum accordingly. All black curves have the same ALP parameters, chosen to match those in Figure 2 (Main Text). A typical realization of the stacked spectrum modified by photon-ALP conversion is shown in Figure 1 as red points.

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Each modified spectrum is now fitted with the smooth curve Eq. 2 (Main Text) following the procedure described in the main text by scanning over the (p_0, E_c) parameter space. The fractional residuals between the red points and the best-fit smooth model are displayed in the bottom-right panel of Figure 1.

Figure 2 shows the χ^2 difference as a function of (p_0, E_c) between the log-parabola baseline model and its modification by a smooth photon-ALP conversion function Eq. 2 (Main Text). Figure shows $\Delta\chi^2$ values averaged over 10^3 realizations. The left panel corresponds to the case of narrow energy bins, while the right panel shows results for broader, 4FGL *Fermi*/*LAT*-like spectral bins. The green diamond in both panels represents the expected (p_0, E_c) values from the smooth photon-ALP conversion model (i.e., the parameters of the red curve in Figure 2 (Main Text)). The magenta cross denotes the best-fit (p_0, E_c) values averaged over realizations. The color bar corresponds to the 1σ confidence level. Notably, in the case of narrow bins with low systematic uncertainties, the ALP signal is recovered with high significance, and the color bar thus represents $\Delta\chi^2 + 2336$.

Figure 2 further demonstrates that the bias in estimating (p_0, E_c) can reach approximately 10% for broad spectral bins but remains within the 1σ confidence contour, defined by the quality of the data and the errors on p_0 and E_c due to the final number of AGN/cluster pairs. Since (p_0, E_c) can serve as proxies for (m_a, g_a) (see, e.g., Figure 1 (Extended Data)), we conclude that a similar $\sim 10\%$ bias can be expected for these parameters as well. Furthermore, for large spectral bins, the skewness of the distribution is significantly greater than that shown in Figure 1 due to finite sampling effects, as observed in the left panel of Figure 2.

Finally, while the smooth photon-ALP conversion model does not capture the rapid fluctuations in the $P_{\gamma\gamma}$ conversion probability (as evident from the residuals in the bottom-right panel of Figure 1 for the narrow-bin spectrum), it accurately reproduces the overall spectral shape of the absorption feature. This allows us to recover the (p_0, E_c) parameters and, consequently, the (m_a, g_a) parameters, as shown in the right panel of Figure 2 – well within the error bars induced by the finite number of AGN-cluster pairs, confirming the robustness of the method.

Consistency checks. To further elaborate on the validity of the proposed approach and to verify its self-consistency and statistical reliability, we artificially added to the data the ALP-induced suppression and then tried to detect it, using our procedure. This has been done for several values of $(m_a, g_{a\gamma})$ within the excluded region (the solid green contour in Figure 5 (Extended Data)). Namely, using the `ALPPRO` code^{1,2}, we generated $3 \cdot 10^5$ random photon-to-ALP conversion probability curves for several ALP parameters.

We then randomly drew 32 conversion curves, binned them (i.e. averaged over spectrum bin width) to match *Fermi*/*LAT* spectral binning, and convolved them with the AGN spectra. The procedure was repeated, creating 10^4 independent samples of 32 AGNs spectra, each “containing” the ALP-induced signal with the same parameters $(m_a, g_{a\gamma})$.

We applied our detection procedure (assuming the nominal level of *Fermi*/*LAT* systematics) to each sample to determine the frequency of falsely excluding the ALP. Figure 3 (left panel) shows

the resulting distributions of $\Delta\chi^2$ values. We found that for all selected trial points, more than 99% of the $\Delta\chi^2$ values are below 6.2 (see q_{99} values in the legend).

The validation procedure shows that, if a signal were present, it would be excluded in fewer than 1% of all realizations.

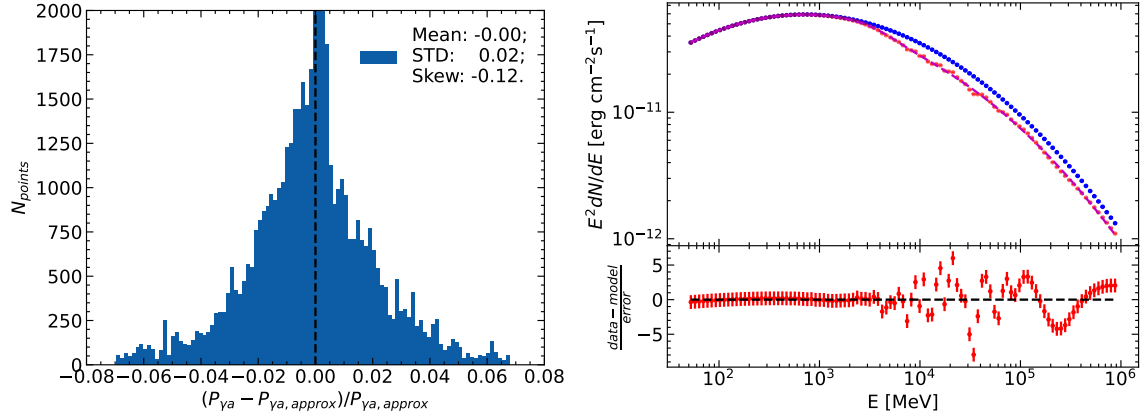
The right panel of Figure 3 illustrates the “exclusion plot” based on our sample modified by the photon-to-ALP conversion for an ALP with parameters $m_a = 3 \text{ neV}$, $g_{a\gamma} = 4 \times 10^{-12} \text{ GeV}^{-1}$ (i.e., a randomly drawn realization from the red curve in the left panel). These ALP parameters are indicated with a white star. The green contours are identical to the exclusion contours in Figure 5 (Extended Data). Notably, the ALP with the corresponding parameters is no longer excluded and, moreover, it creates an “island” in the parameter space similar to that seen in the real data when purely statistical uncertainties are considered.

Sensitivity to the assumed distance of the lines of sight from the cluster center. In our study, we specifically selected AGN/galaxy cluster pairs where the line of sight to the AGN intersects the cluster at a distance smaller than $R_{\text{max}} = 500 \text{ kpc}$. Here, we examine the sensitivity of our results to the choice of this parameter. Several competing effects influence the derived limits when the R_{max} parameter is varied. A smaller R_{max} results in a reduced number of selected AGN/galaxy cluster pairs, which not only decreases the statistical power of the data but also increases the uncertainties in the p_0 and E_c parameters due to the smaller sample size, as illustrated in Figure 4 (Extended Data). Both of these factors can lead to weaker constraints. On the other hand, since the magnetic field strength is higher closer to the cluster center, one may expect an overall increase in p_0 , potentially improving the constraints.

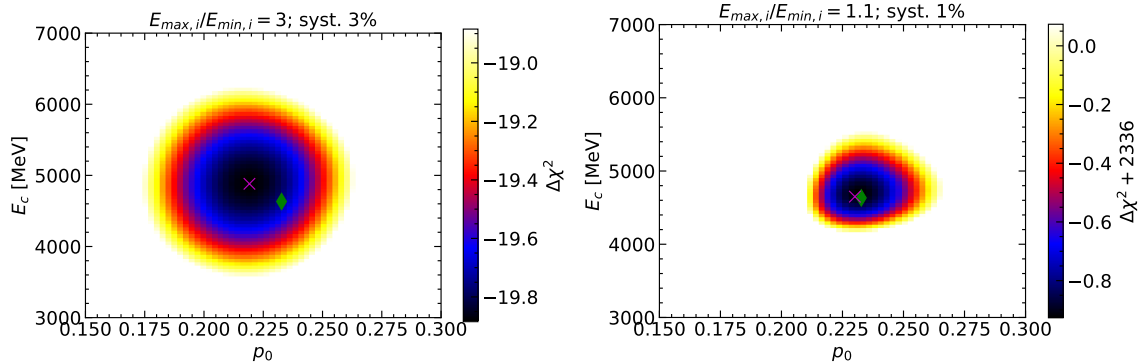
Figure 4 highlights the relative significance of the effects discussed above. It presents the map of $\Delta\chi^2$ in the absence of systematic uncertainties, analogous to Figure 5 (Extended Data). The white contours are 2σ upper limits (i.e., $\Delta\chi^2 = 6.2$).

While the constraints weaken for $R_{\text{max}} \leq 200 \text{ kpc}$, the derived limits remain consistent and largely independent of its exact choice for larger values. This confirms that the presented upper limits are robust and not predominantly influenced by AGNs whose lines of sight pass at large distances from cluster centers. Finally, we note that the significance of the marginally detected ALP with the parameters $(m_a, g_{a\gamma}) = (1 \text{ neV}, 2 \times 10^{-12} \text{ GeV}^{-1})$ (orange dashed region in Figure 5 (Extended Data)) reduces to $\lesssim 1.6\sigma$ for $R_{\text{max}} < 500 \text{ kpc}$.

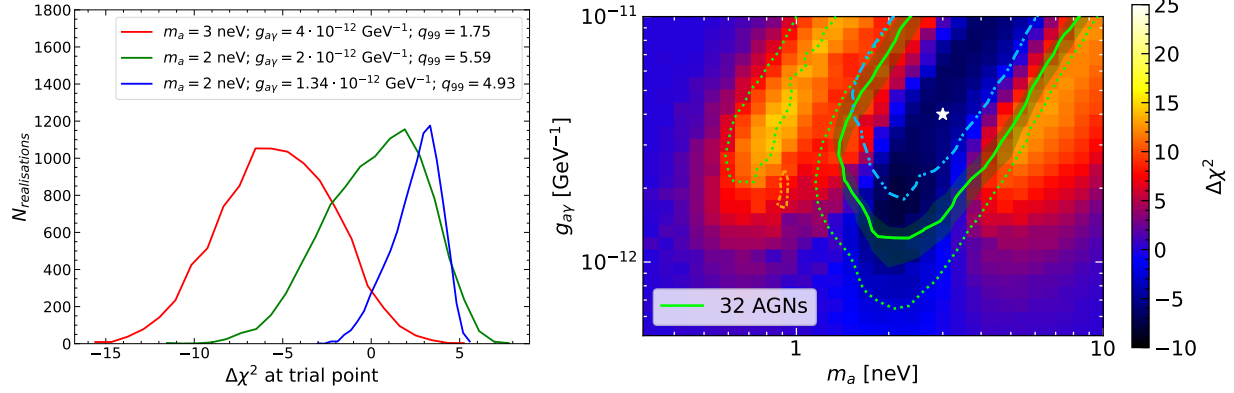
1. Matthews, J. H., Reynolds, C. S., Marsh, M. C. D., Sisk-Reynés, J. & Rodman, P. E. How do magnetic field models affect astrophysical limits on light axion-like particles? An X-ray case study with NGC 1275. *Astrophys. J.* **930**, 90 (2022).
2. Matthews, J. alpro: Axion-Like PROpagation <https://doi.org/10.5281/zenodo.6137185> (2022).



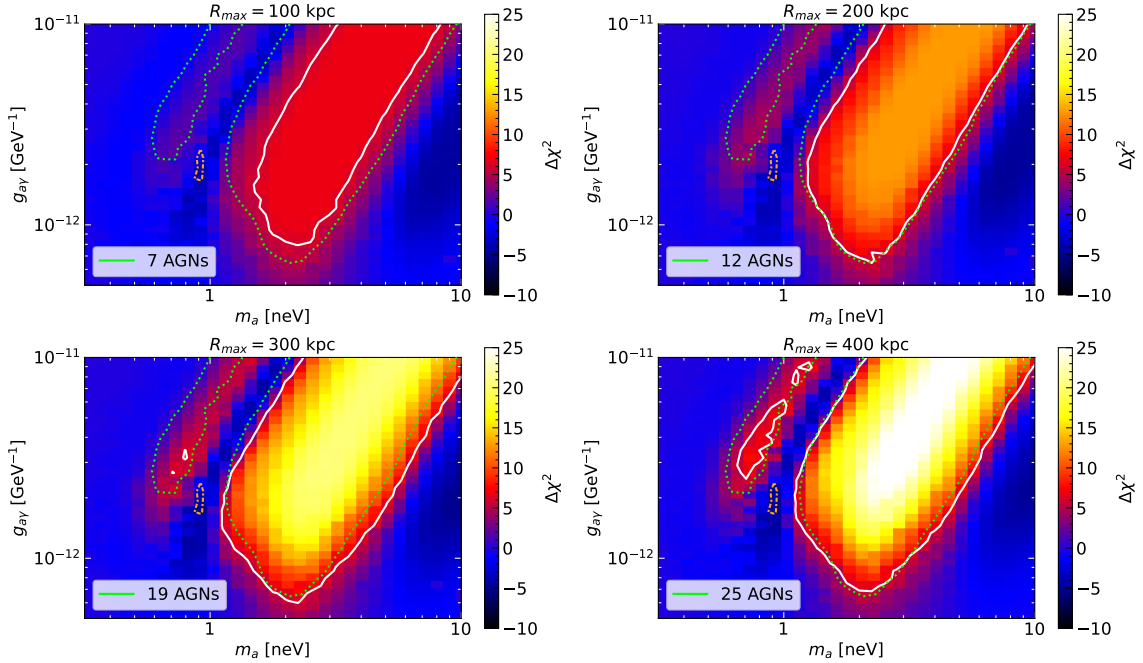
Supplementary Figure 1: **Structure of residuals between smooth and realistic absorption models.** *Left panel:* Fractional residuals of the $P_{\gamma a}$ conversion probability (black curves in Figure 2 (Main Text)) relative to the smooth function used for its modeling (red curve in Figure 2 (Main Text)) **based on 100 independent realizations of 32 galaxy-cluster pairs**. The data show the skewness of the distribution. *Right panel:* An example of a systematics-dominated spectrum mimicking the stacked spectrum of 32 AGNs, assuming narrow energy bins (10 bins per decade of energy, 1% systematics, **shown with 1σ errorbars**). Blue points represent the simulated spectrum based on a log-parabola model, while red points show this spectrum further modified by a randomly drawn $P_{\gamma\gamma}$ conversion probability curve. The lower sub-panel displays the fractional residuals of the red points relative to the best-fit smooth step-like photon-ALP conversion model. Both panels use ALP parameters $(m_a, g_a) = (3 \text{ neV}, 2 \times 10^{-12} \text{ GeV}^{-1})$.



Supplementary Figure 2: **Residual bias in recovered parameters caused by smooth model fitting.** Difference between the expected (green diamond) and recovered (magenta cross, averaged over 10^3 realizations) values of (p_0, E_c) , compared to the 1σ contours that account for uncertainties due to the finite number of AGN-cluster pairs. Colors indicate the average χ^2 difference between the log-parabola baseline model and the same model modified by a smooth photon-ALP conversion function Eq. 2 (Main Text). *Left panel:* Broad spectral bins (3 bins per decade) with 3% systematics. The bias in recovered parameters is $\lesssim 10\%$ and remains within the inferred 1σ confidence range. *Right panel:* Narrow spectral bins (10 bins per decade) with 1% systematics. This case corresponds to a strong detection of the injected signal, so $\Delta\chi^2$ offset by 2336 is shown. Although the confidence contours are smaller, the recovered parameters remain well within 1σ of the expected values.



Supplementary Figure 3: **Consistency checks: adding ALP to the data.** *Left panel:* Distribution of χ^2 values for several ALP masses and coupling constants computed using random ALP absorption curves convolved with the data. The values of $\Delta\chi^2$ in Figure 5 (Extended Data) for the parameters corresponding to the red, green, and blue curves were 19.2, 10.9, and 6.4, respectively. *Right panel:* A typical realization of the simulated exclusion plane for an ALP with parameters $m_a = 3$ neV and $g_{a\gamma} = 4 \times 10^{-12}$ GeV $^{-1}$, marked by a white star. The green contours are identical to those shown in Figure 5 (Extended Data). For both panels, the nominal level of *Fermi/LAT* systematics was considered.



Supplementary Figure 4: **Impact of adopted R_{max} on $\Delta\chi^2$ and ALP exclusion regions.** The heatmaps show the change in χ^2 between the baseline and ALP models for different values of the assumed maximum distance, R_{max} , between the cluster center and the AGN line of sight. The adopted values of R_{max} are shown on top of each plot. The white solid line indicates a worsening of $\Delta\chi^2$ by 6.2, corresponding to the 2σ exclusion region. The bottom-left corner of each panel displays the number of AGN/cluster pairs used in that case. The green dotted contours mark the exclusion region for $R_{\text{max}} = 500$ kpc, which corresponds to the same line in Figure 5 (Extended Data). See Section **Sensitivity to the assumed distance of the lines of sight from the cluster center** for further details.