Projected bounds on ALPs with Athena

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Axion-Like Particles

- Light pseudo-scalars arising from the breaking of a U(1) symmetry at a high scale.

- Well motivated from string theory: always arise in the Large Volume Scenario.

- ALPs couple to electromagnetism via the Lagrangian term:

\[ \mathcal{L} \supset \frac{a}{M} F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv a g_{\gamma\gamma} E \cdot B \]

- In magnetic fields leads to photon-ALP inverconversion.

\[ |\gamma(E)\rangle \to \alpha |\gamma(E)\rangle + \beta |a(E)\rangle \]
Photon-ALP oscillations

• Probability of photon-ALP conversion (for $m_a \lesssim 10^{-12} \text{eV}$):

$$P_{\gamma \rightarrow a} = \frac{1}{2} \frac{\Theta^2}{1 + \Theta^2} \sin^2 \left( \Delta \sqrt{1 + \Theta^2} \right)$$

$$\Theta = 0.28 \left( \frac{B_\perp}{1 \mu \text{G}} \right) \left( \frac{\omega}{1 \text{keV}} \right) \left( \frac{10^{-3} \text{cm}^{-3}}{n_e} \right) \left( \frac{10^{11} \text{GeV}}{M} \right) \quad \Delta = 0.54 \left( \frac{n_e}{10^{-3} \text{cm}^{-3}} \right) \left( \frac{L}{10 \text{kpc}} \right) \left( \frac{1 \text{keV}}{\omega} \right)$$

• In magnetic fields leads to photon-ALP oscillations at X-ray energies.
• Magnetic field approximately 1 Mpc across.

• Coherence lengths 3.5-10 kpc.

• Magnetic field strength estimated at 10-25 \( \mu G \) at the centre \([\text{astro-ph/0602622}]\), and 1-10 \( \mu G \) across the cluster.

• Very efficient converter of photons to ALPs.
Photon survival probability in Perseus

\[ g_{\gamma\gamma} = 5 \times 10^{-13} \text{GeV}^{-1} \]

300 domains, lengths: 3.5-10 kpc (total: 1860 kpc), \( B_0 = 25 \, \mu \text{G} \)

- Red convolved with 150 eV FWHM Gaussian (Chandra)
- Orange convolved with 2.5 eV FWHM Gaussian (Athena)
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Blue unconvolved

Orange convolved with 2.5 eV FWHM Gaussian (Athena)
• Central galaxy of Perseus, with an AGN unobscured in our direction.

• Basic components to X-ray spectrum are:

  1. Power-law.

  2. Reflection spectrum (incident photons illuminate accretion disc, resulting in fluorescent emission) – in practice manifest as neutral Fe Kα line at 6.4 keV.

  3. Thermal soft excess (origin not entirely known).
Best previous bounds on ALP-photon coupling $g_{a\gamma\gamma}$ for masses $m_a \lesssim 10^{-12}\text{eV}$ from SN1987a:

$$g_{a\gamma\gamma} \lesssim 5 \times 10^{-12}\text{GeV}^{-1}$$

From *Chandra* observations of NGC1275, in astro-ph/1605.01034 we constrained (see S. Krippendorf talk):

$$g_{a\gamma\gamma} \lesssim 1.5 \times 10^{-12}\text{GeV}^{-1}$$

Based on methodology by Wouters and Brun (1304.0989).
# Athena vs. Chandra

<table>
<thead>
<tr>
<th></th>
<th>Chandra (ACIS-I detector)</th>
<th>Athena (X-IFU detector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>0.3-10 keV</td>
<td>0.2-12 keV</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>~150 eV</td>
<td>2.5 eV below 7 keV</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.5’’</td>
<td>5’’</td>
</tr>
<tr>
<td>Read-out time</td>
<td>0.2s (2.8ms single row)</td>
<td>~10 μs</td>
</tr>
<tr>
<td>Effective area</td>
<td>600 cm²</td>
<td>2m²</td>
</tr>
</tbody>
</table>
Simulating using SIXTE

- Simulation of X-ray TELEscopes software.
- End-to-end simulator for X-IFU on Athena.
- Methodology: Create 2 Xspec models:
  - Model 0: zwabs*(powerlaw + bapec)
  - Model 1: zwabs*(powerlaw + bapec)* $P_{\gamma \rightarrow \gamma}(E,B)$
- Parameters based on Chandra and Hitomi observations.
- Simulate X-IFU response using xifupipeline.
- Fit both sets of data to Model 0, compare
Magnetic Field Model

\[ B(r) \propto n_e(r)^{0.7} \]

\[ n_e(r) = \frac{3.9 \times 10^{-2}}{1 + \left(\frac{r}{80 \text{ kpc}}\right)^2}^{1.8} + \frac{4.05 \times 10^{-3}}{1 + \left(\frac{r}{280 \text{ kpc}}\right)^2}^{0.87} \text{ cm}^{-3} \]

- Domain lengths drawn randomly from a Pareto distribution between 3.5 kpc and 10 kpc.

- Power spectrum index \( n = 2.8 \) based on analysis of cool-core cluster A2199 done in 1201.4119.
Simulated spectrum

200 ks observation with ALP modulations

\[ g_{\alpha\gamma\gamma} = 3 \times 10^{-13} \text{GeV}^{-1} \]
• Generate data from two models:
  – Model 0: \( F_0(E) = AE^{-\gamma} \times e^{-n_H \sigma(E)} \)
  – Model 1: \( F_0(E, B) = AE^{-\gamma} \times e^{-n_H \sigma(E)} \times P_{\gamma \to \gamma}(E, B, M) \)

• Procedure:
  1. Calculate \( P_{\gamma \to \gamma} \) for 50 random magnetic field configurations.
  2. For each mag. field config. generate 10 fake data sets from Model 1.
  3. Fit Model 0 to each of the 500 fake data sets.
  4. Generate 100 fake data sets from Model 0, and fit.
  5. If \( \chi_1^2 < \max(\chi_0^2, 1) \) for less than 5% of configs, Model 1 excluded at 95% confidence.
• For a 200ks observation of NGC1275, with $B_0 = 25 \mu G$, at 95% confidence:

$$g_{\gamma\gamma} \lesssim 1.5 \times 10^{-13} \text{ GeV}^{-1}$$

• For a 10ks observation:

$$g_{\gamma\gamma} \lesssim 4.5 \times 10^{-13} \text{ GeV}^{-1}$$
New bounds

Image credit: Gray Rybka
Conclusions

• NGC1275 provides an excellent target to constrain ALP-photon interactions.

• Athena stands to greatly improve current bounds on $g_{\gamma\gamma}$.

• Main uncertainty is Perseus’ magnetic field, future telescopes like SKA will hopefully improve our understanding by 2028.
Projected bounds on ALPs with *Athena*

- Based on methodology by Wouters and Brun (1304.0989).


- More recently M. Marsh et al (1703.07354) looking at M87.

- Fermi-LAT analysis of NGC1275 (1603.06978) and H.E.S.S. (PKS 2155-304, 1311.3148).
Introduction to axions

• Most compelling solution to Strong CP problem:

\[ \mathcal{L} \supset g \theta G_{\mu\nu}^a G^{a\mu\nu} \]

• Why is \( \theta \) so small (< \( 10^{-10} \) )?

• \( U(1) \) symmetry broken at high scale, creating pseudo-NG boson, the axion.
300 domains, lengths: 3.5-10 kpc (total: 1860kpc), B_0 = 25 \mu G
Photon survival probability in Perseus

Convolved with Gaussian FWHM (150 eV)

• We subtract source spectrum from nearby cluster emission background and fit spectrum with absorbed power-law.

• Total counts:
  – 230000 for 2009 ACIS-I ‘edge-of-chip’ observations
  – 242000 for 2009 ACIS-I ‘midway’ observations
  – 183000 for 2002-4 ACIS-S on-axis observations
At 2.0–2.2 keV: five data points in a row 3-5 sigma high
At 3.4–3.5 keV: two data points low, 4.5, 2.6 sigma
Pile-up contamination

• If two or more photons arrive during the detector read-out time (3.1s), they are registered as one photon.

• Two ways to ameliorate this:
  – Discard central pixels with highest flux.
  – Model pile-up effects with \texttt{jdpileup} model.
Extraction for ACIS-I edge excluding centre
ACIS-I midway excluding centre
Extraction for ACIS-S with pileup model

Fit to ACIS–S observations incl. central pixels
Pileup modelled with \texttt{jpileup}
Features

• Excess at 2-2.2 keV:
  – Overwhelming statistical significance, however at an effective area edge.
  – No numerical package was able to model this excess directly.

• Dip at 3.5 keV:
  – Significant at 4-sigma.
  – Possible connection to 3.5 keV line (Bulbul 14, Boyarsky 14).
  – See 1608.01684 for an analysis of the consistency of this result with other 3.5 keV analyses.
Other Point Sources

- Analysis of other good point sources recently done in 1704.05256.

- Best sources for constraining ALPs:
  
  \[
  \begin{align*}
  \text{2E3140:} & \quad g_{\alpha\gamma\gamma} \lesssim 1.5 \times 10^{-12} \text{ GeV}^{-1} \\
  \text{NGC3862:} & \quad g_{\alpha\gamma\gamma} \lesssim 2.4 \times 10^{-12} \text{ GeV}^{-1}
  \end{align*}
  \]
Extra slides – 3C 273

[Graph showing data on counts per second vs. energy (keV), with error bars indicating sigma values.]
Quick summary of systematics

• Pileup – but magnitude of excess is the same across different spectra on different instruments with widely differing levels of pileup.

• Effective area miscalibration – but excess is not present in the background spectra.

• Missubtraction of cluster background – O(10%) features survive for SNR of up to 60:1.

• Miscalibration of gain in high-flux regions – but feature consistent at varying levels of flux. Also Fe Kα line at 6.4 keV as expected.

• Atomic lines – none in the right region.