# Projected bounds on ALPs with *Athena*

**Nicholas Jennings**
**Rudolf Peierls Centre for Theoretical Physics, University of Oxford**

The X-ray Universe 2017
Rome, Italy, 6-9 June 2017

# 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:

$$\mathcal{L} \supset \frac{a}{M} F_{\mu\nu} \widetilde{F^{\mu\nu}} \equiv a \, g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}$$

- In magnetic fields leads to photon-ALP inverconversion.

$$|\gamma(E)\rangle \rightarrow \alpha|\gamma(E)\rangle + \beta|a(E)\rangle$$

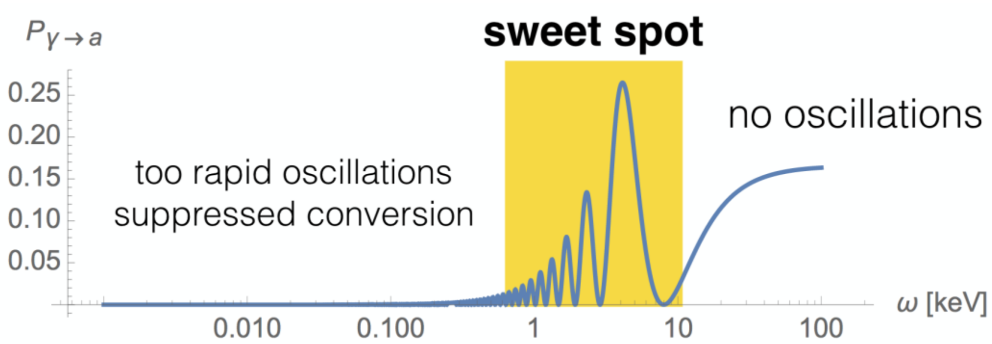
# Photon-ALP oscillations

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

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

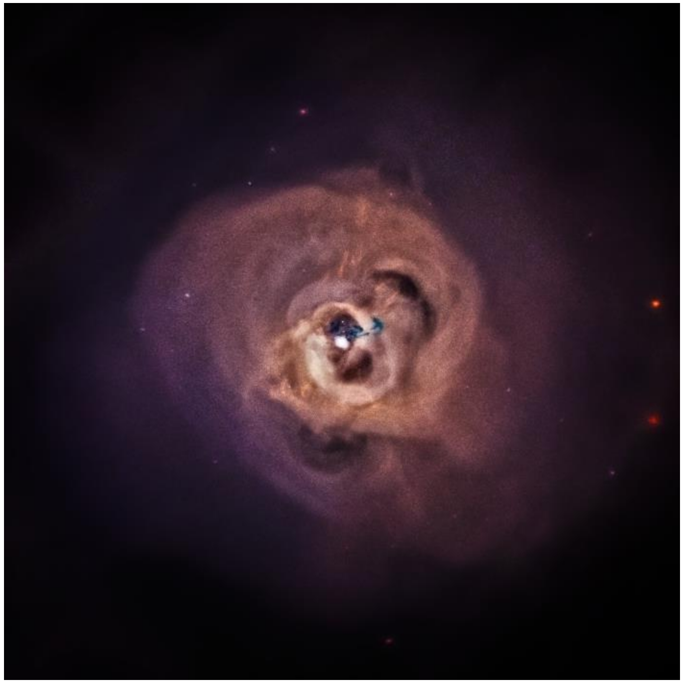
$$\Theta = 0.28\left(\frac{\mathrm{B}_\perp}{1\mu\mathrm{G}}\right)\left(\frac{\omega}{1\ \mathrm{keV}}\right)\left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{10^{11}\mathrm{GeV}}{M}\right) \qquad \Delta = 0.54\left(\frac{n_e}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{L}{10\mathrm{kpc}}\right)\left(\frac{1\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

- In magnetic fields leads to photon-ALP oscillations at X-ray energies.



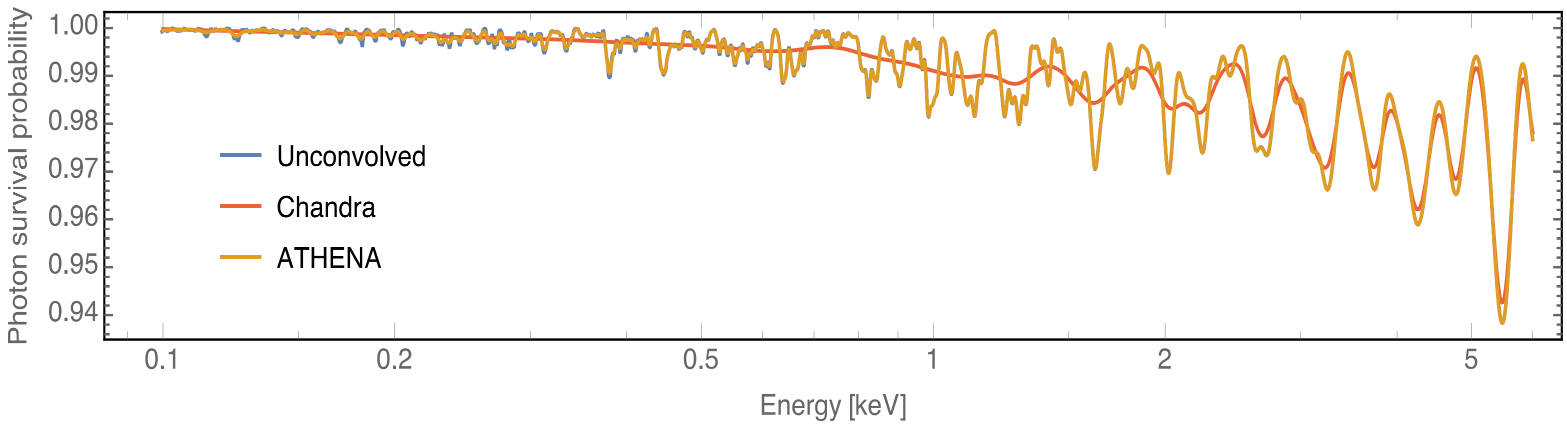
# Perseus Cluster

- Magnetic field approximately 1 Mpc across.
- Coherence lengths 3.5-10 kpc.
- Magnetic field strength estimated at 10-25 $\mu$G at the centre [astro-ph/0602622], and 1-10 $\mu$G across the cluster.
- Very efficient converter of photons to ALPs.



# Photon survival probability in Perseus

$$g_{a\gamma\gamma} = 5 \times\ 10^{-13}\mathrm{GeV}^{-1}$$



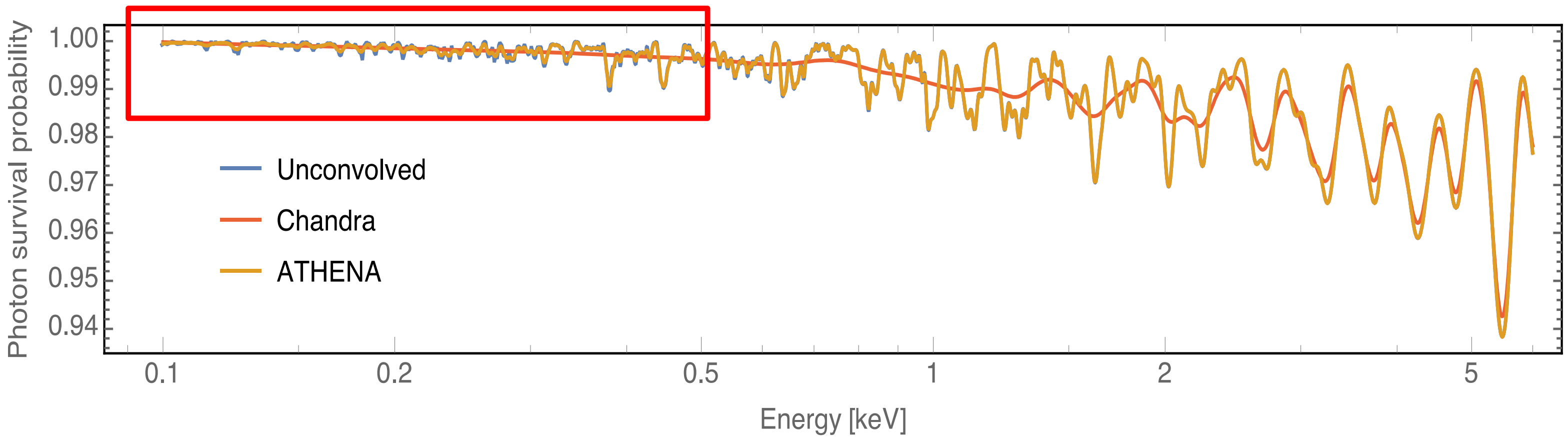

300 domains, lengths: 3.5-10 kpc (total: 1860kpc), $\mathrm{B}_0 = 25\ \mu\mathrm{G}$

Red convolved with 150 eV FWHM Gaussian (*Chandra)*

Orange convolved with 2.5 eV FWHM Gaussian (*Athena)*

# Photon survival probability in Perseus

$$g_{a\gamma\gamma} = 5 \times 10^{-13} \mathrm{GeV}^{-1}$$



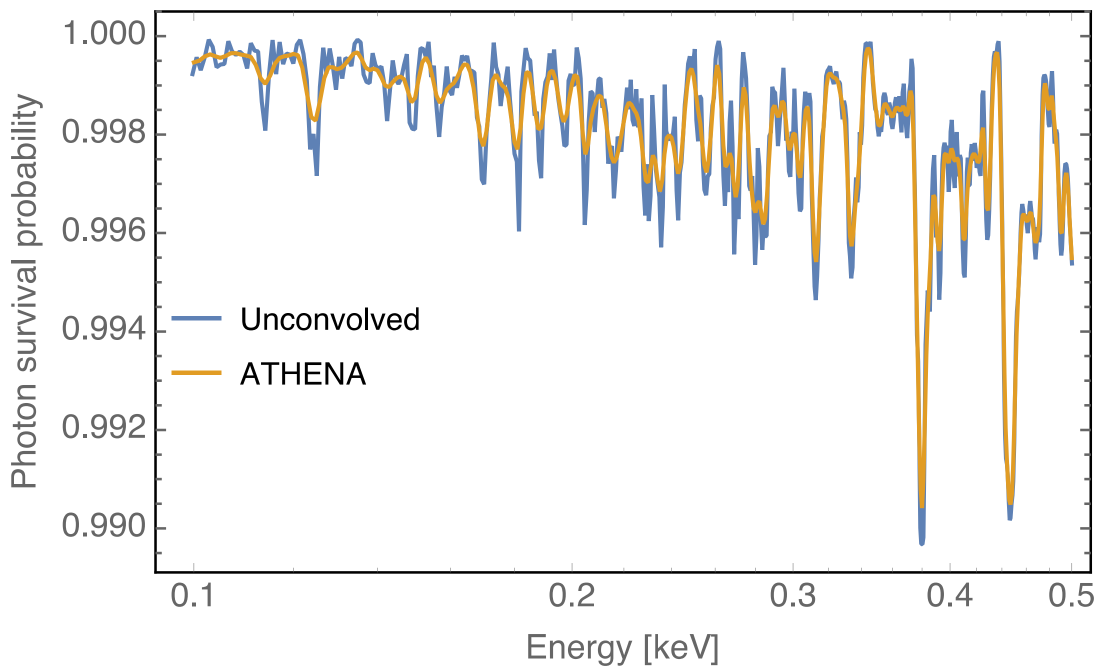

300 domains, lengths: 3.5-10 kpc (total: 1860kpc), $\mathrm{B}_0 = 25\ \mu\mathrm{G}$

Red convolved with 150 eV FWHM Gaussian (*Chandra)*

Orange convolved with 2.5 eV FWHM Gaussian (*Athena)*

# Photon survival probability in Perseus

$$g_{a\gamma\gamma} = 5 \times\ 10^{-13} \mathrm{GeV}^{-1}$$




Blue unconvolved

Orange convolved with 2.5 eV FWHM Gaussian (*Athena)*

# NGC 1275

- 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 K$\alpha$ line at 6.4 keV.
3. Thermal soft excess (origin not entirely known).

# Previous bounds

- Best previous bounds on ALP-photon coupling $g_{a\gamma\gamma}$ for masses $m_a \lesssim 10^{-12}\mathrm{eV}$ from SN1987a:

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

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

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

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

# *Athena* vs. *Chandra*

| | Chandra (ACIS-I detector) | Athena (X-IFU detector) |
|---|---|---|
| Energy range | 0.3-10 keV | 0.2-12 keV |
| Energy resolution | $\sim$150 eV | 2.5 eV below 7 keV |
| Angular resolution | 0.5” | 5” |
| Read-out time | 0.2s (2.8ms single row) | $\sim$10 $\mu$s |
| Effective area | 600 $cm^2$ | 2$m^2$ |

# 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)*` $P_{\gamma\to\gamma}(E, \boldsymbol{B})$
- 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

$$B(r) \propto n_e(r)^{0.7}$$

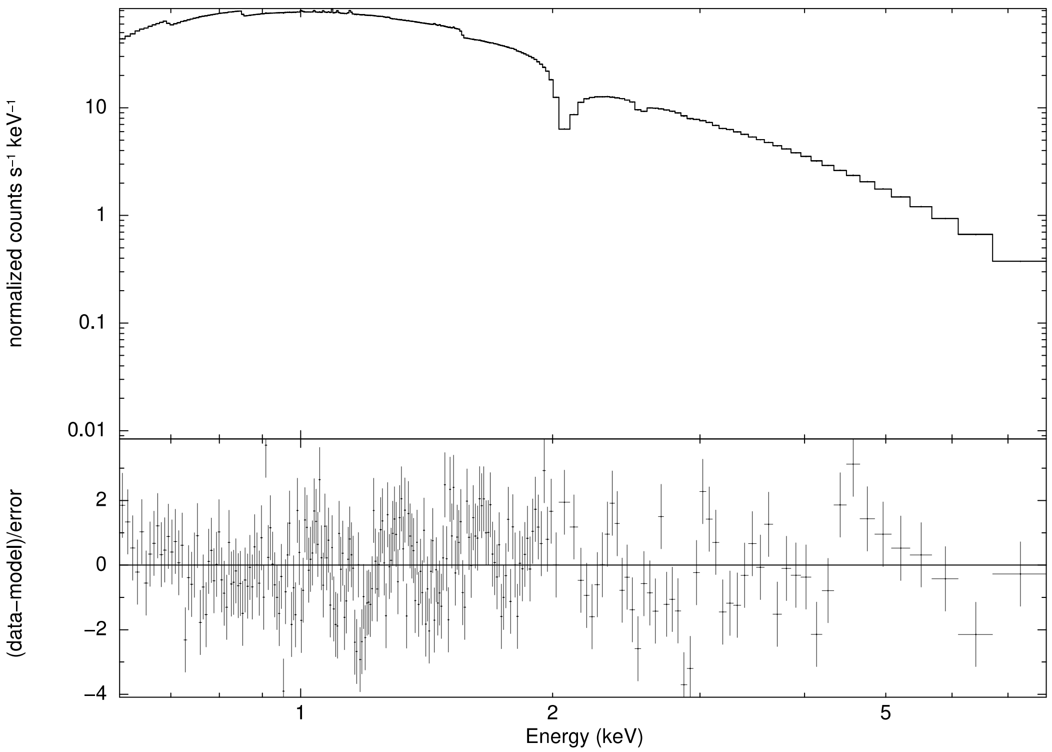
$$n_e(r) = \frac{3.9 \times 10^{-2}}{\left[1 + \left(\frac{r}{80\ \mathrm{kpc}}\right)^2\right]^{1.8}} + \frac{4.05 \times 10^{-3}}{\left[1 + \left(\frac{r}{280\ \mathrm{kpc}}\right)^2\right]^{0.87}}\ \mathrm{cm}^{-3}$$

- 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

$$g_{a\gamma\gamma} = 3 \times 10^{-13}\mathrm{GeV}^{-1}$$



# Bounds calculation

- Generate data from two models:
  - Model 0: $F_0(E) = AE^{-\gamma} \times e^{-n_H \sigma(E)}$
  - Model 1: $F_0(E, \boldsymbol{B}) = AE^{-\gamma} \times e^{-n_H \sigma(E)} \times P_{\gamma \to \gamma}(E, \boldsymbol{B}, M)$

- 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.

# Bounds calculation

- For a 200ks observation of NGC1275, with $B_0 = 25\ \mu$G, at 95% confidence:

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

- For a 10ks observation:

$$g_{a\gamma\gamma} \lesssim 4.5\ \times\ 10^{-13}\ \mathrm{GeV}^{-1}$$

# New bounds

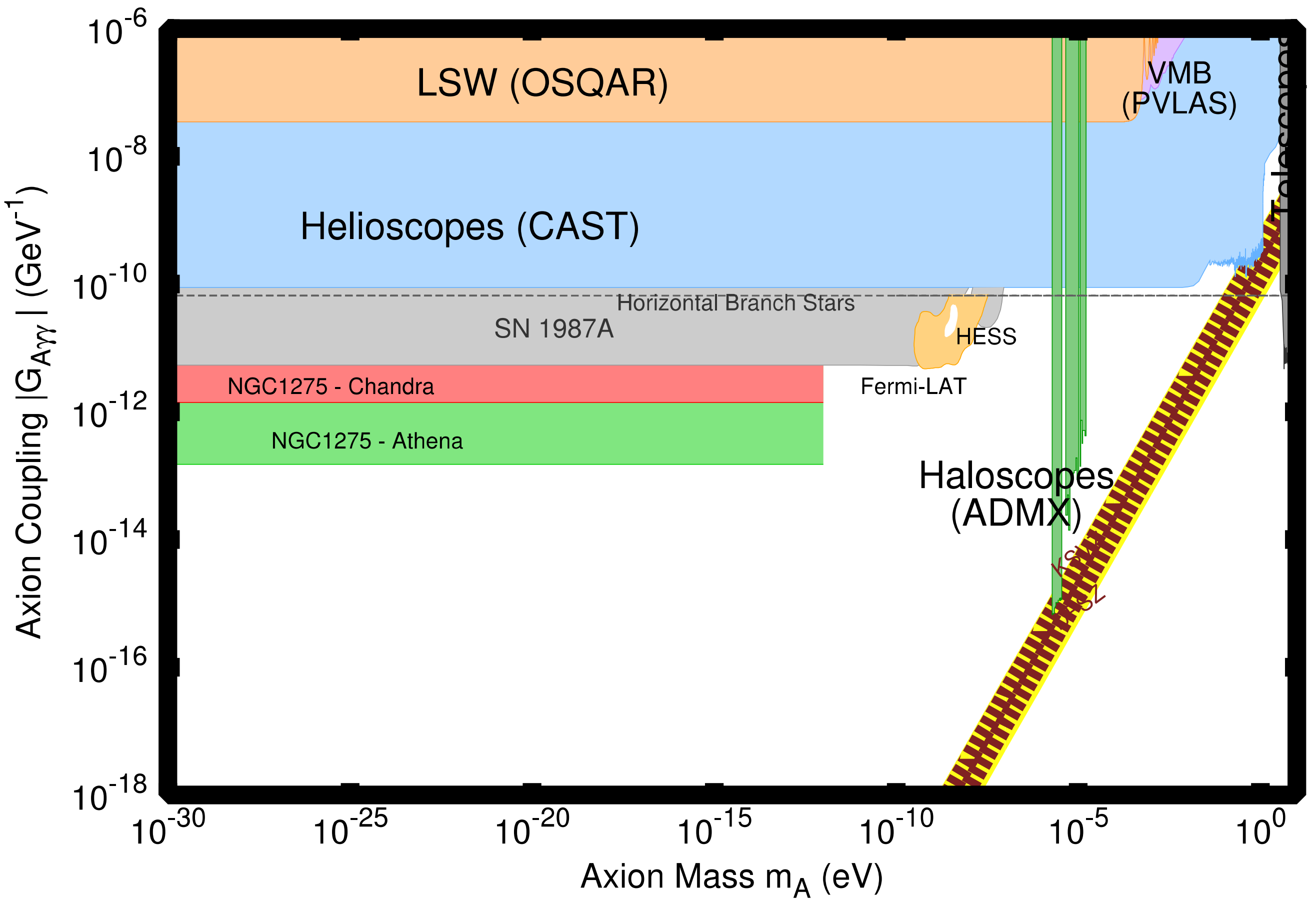



Image credit: Gray Rybka

# Conclusions

- NGC1275 provides an excellent target to constrain ALP-photon interactions.
- Athena stands to greatly improve current bounds on $g_{a\gamma\gamma}$.
- Main uncertainty is Perseus' magnetic field, future telescopes like SKA will hopefully improve our understanding by 2028.

# Extra slides

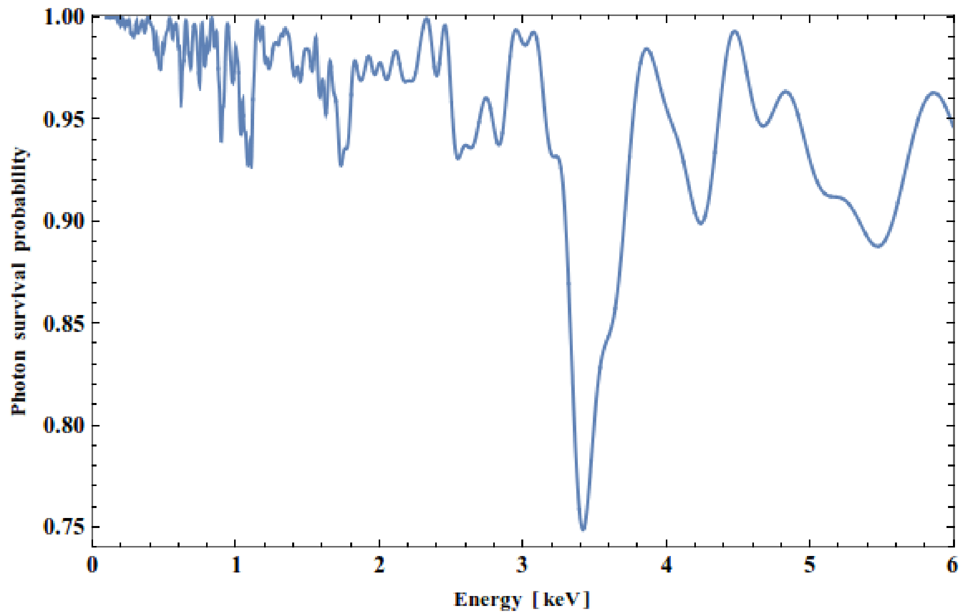
# Projected bounds on ALPs with *Athena*

- Based on methodology by Wouters and Brun (1304.0989).
- Previous paper astro-ph/1605.01034 with M. Berg, J. Conlon, F. Day, S. Krippendorf (Friday talk), A. Powell and M. Rummel.
- 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

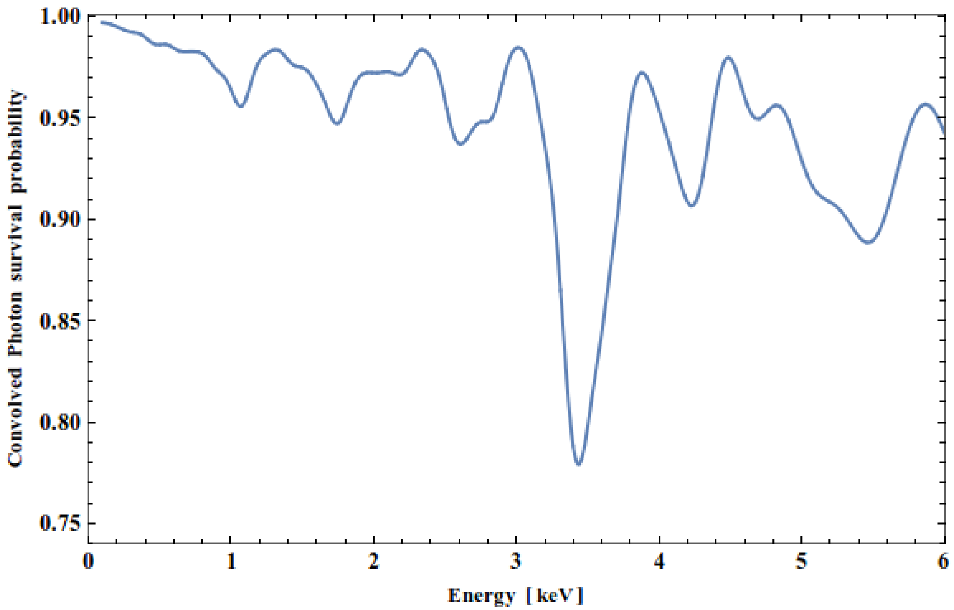
- Most compelling solution to Strong CP problem:
- $\mathcal{L} \supset g\,\theta\,G^{a}_{\mu\nu}G^{a\,\mu\nu}$
- Why is $\theta$ so small ($< 10^{-10}$)?
- U(1) symmetry broken at high scale, creating pseudo-NG boson, the axion.

# Photon survival probability in Perseus




300 domains, lengths: 3.5-10 kpc (total: 1860kpc), $\mathrm{B}_0 = 25\ \mu\mathrm{G}$

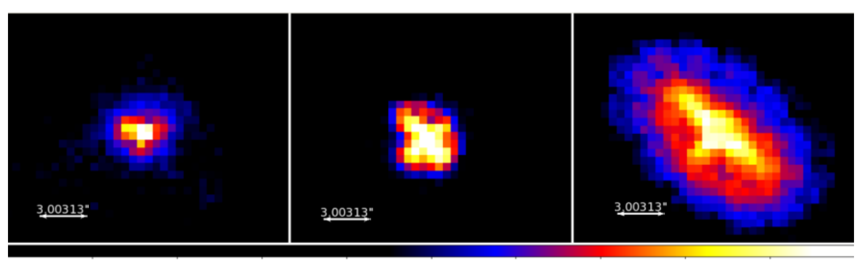
# Photon survival probability in Perseus



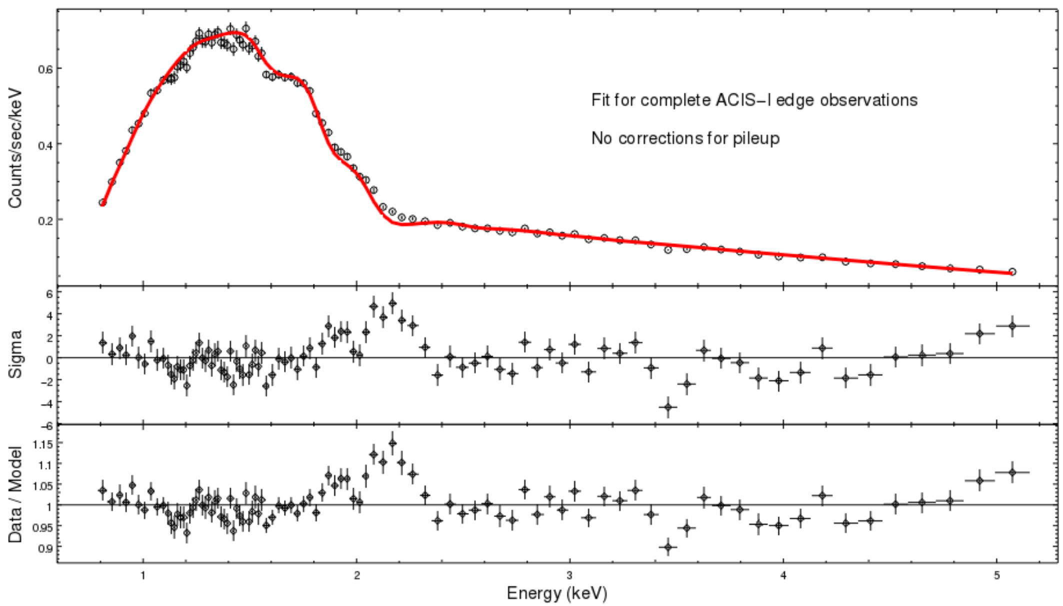

Convolved with Gaussian FWHM (150 eV)

# The data

- Chandra satellite: 1 Ms with ACIS-S in 2002 and 2004, 500 ks with ACIS-I in 2009.
- 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



# Complete extraction for ACIS-I edge

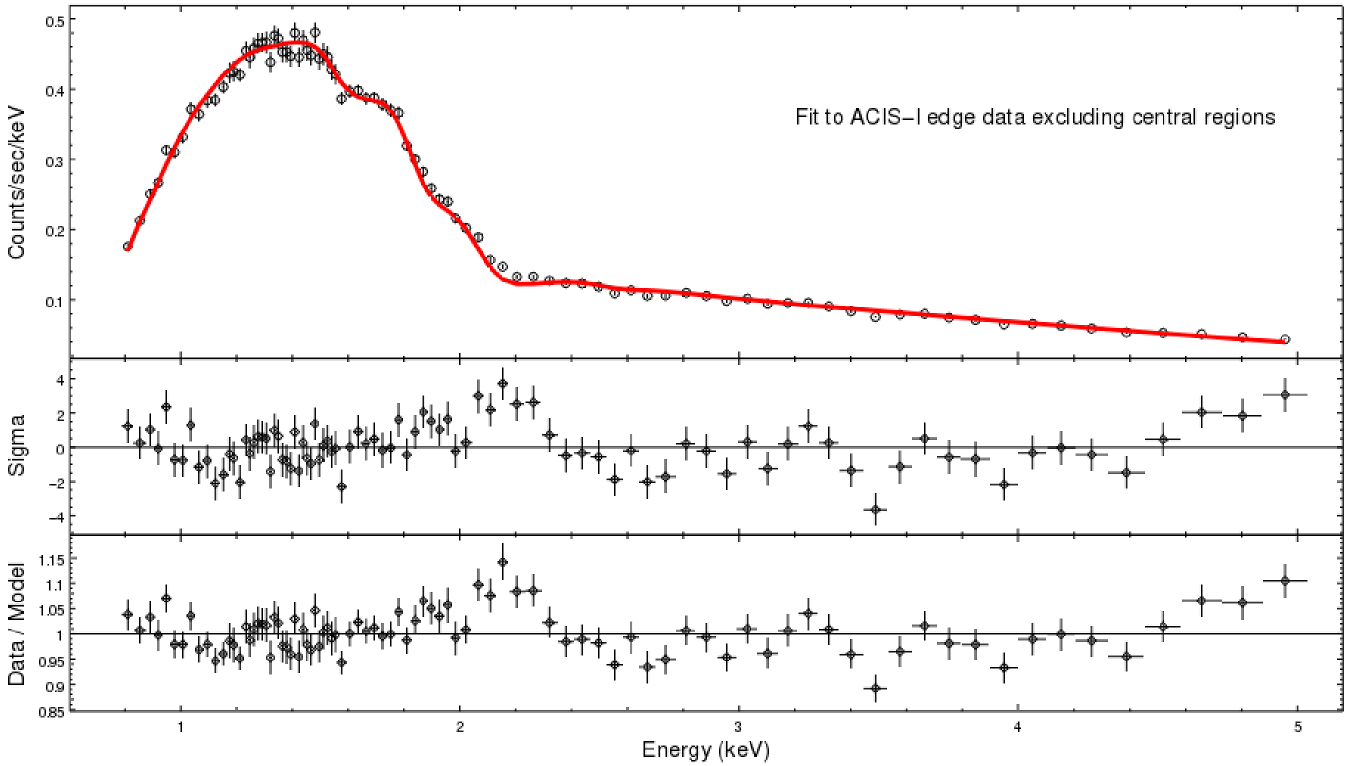



At 2.0–2.2 keV: five data points in a row 3-5 sigma high
At 3.4–3.5 keV: two data points low, 4.5, 2.6 sigma

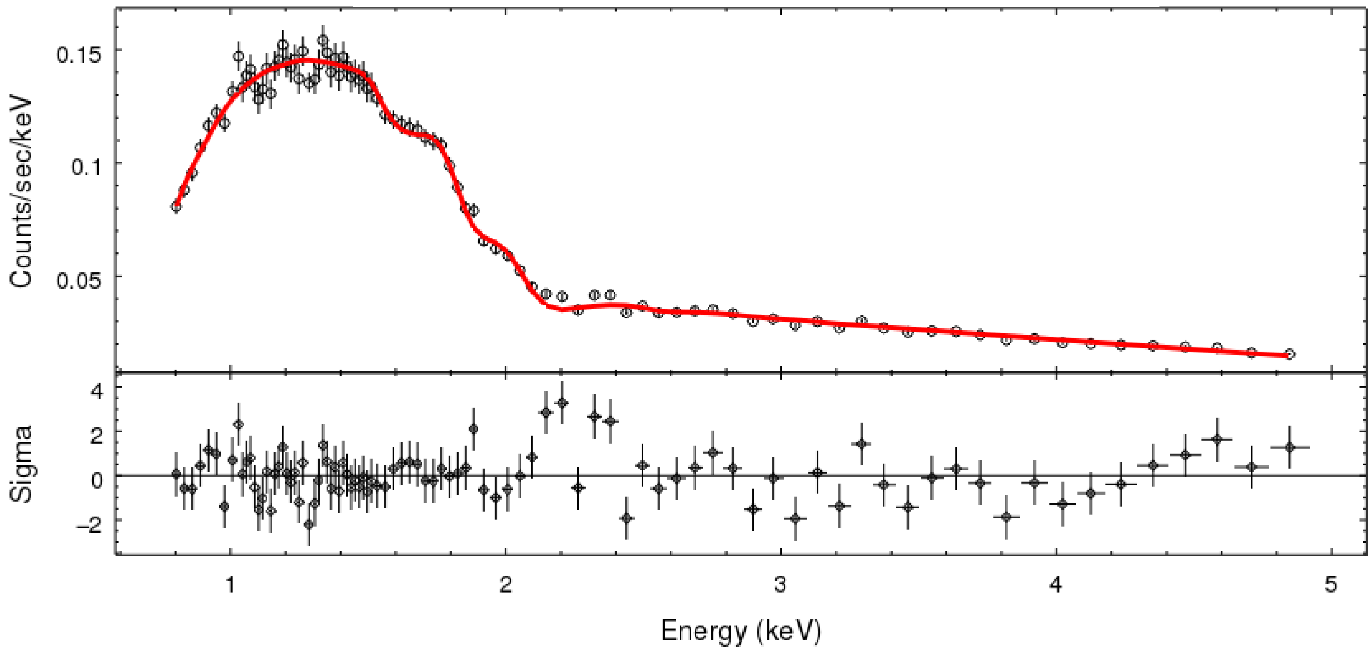
# Pile-up contamination

- 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 `jdpileup` model.

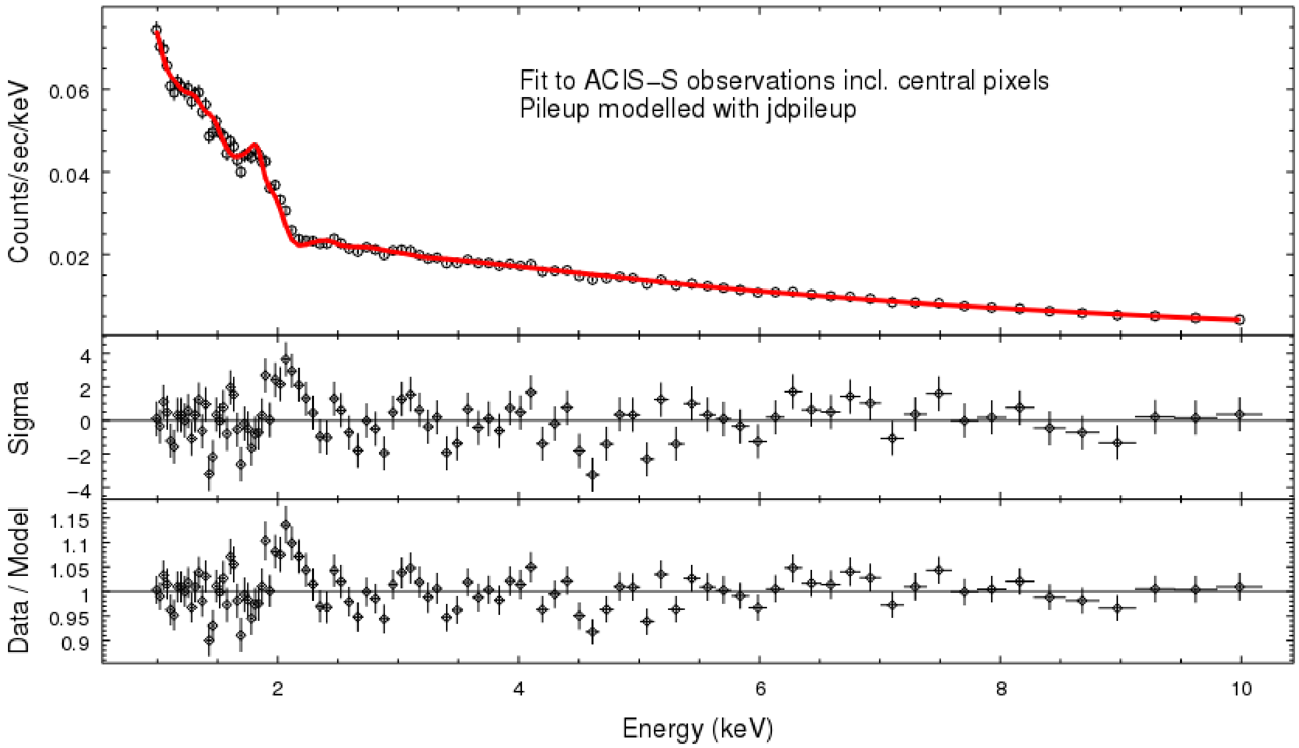
# Extraction for ACIS-I edge excluding centre



# ACIS-I midway excluding centre



# Extraction for ACIS-S with pileup model



# 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

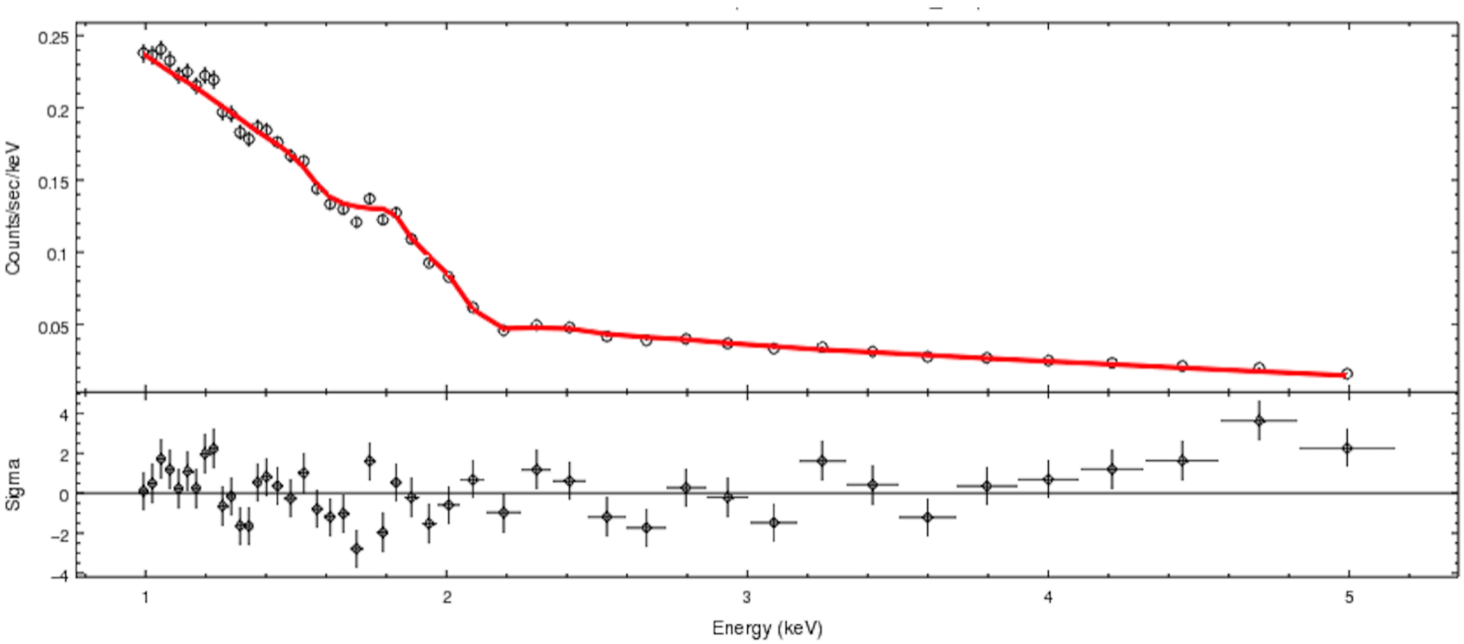
- Analysis of other good point sources recently done in 1704.05256.

- Best sources for constraining ALPs:

2E3140: $g_{a\gamma\gamma} \lesssim 1.5 \times 10^{-12}\ \mathrm{GeV}^{-1}$

NGC3862: $g_{a\gamma\gamma} \lesssim 2.4 \times 10^{-12}\ \mathrm{GeV}^{-1}$

# Extra slides – 3C 273



# 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 K$\alpha$ line at 6.4 keV as expected.
- Atomic lines – none in the right region.