Searching for ALPs with NGC1275

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Searching for ALPs with NGC1275

- Based on astro-ph/1605.01034 with Marcus Berg, Joseph Conlon, Francesca Day, Sven Krippendorf, Andrew Powell, Markus Rummel.

- Similar analysis by Wouters and Brun (1304.0989) but with a less luminous AGN (Hydra A) than NGC1275 (~1% of data used here).

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

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:

$$\frac{a}{M}\mathbf{E}\cdot\mathbf{B} = a\ g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}$$

- In magnetic fields leads to photon-ALP oscillations.

Current bounds on ALPs

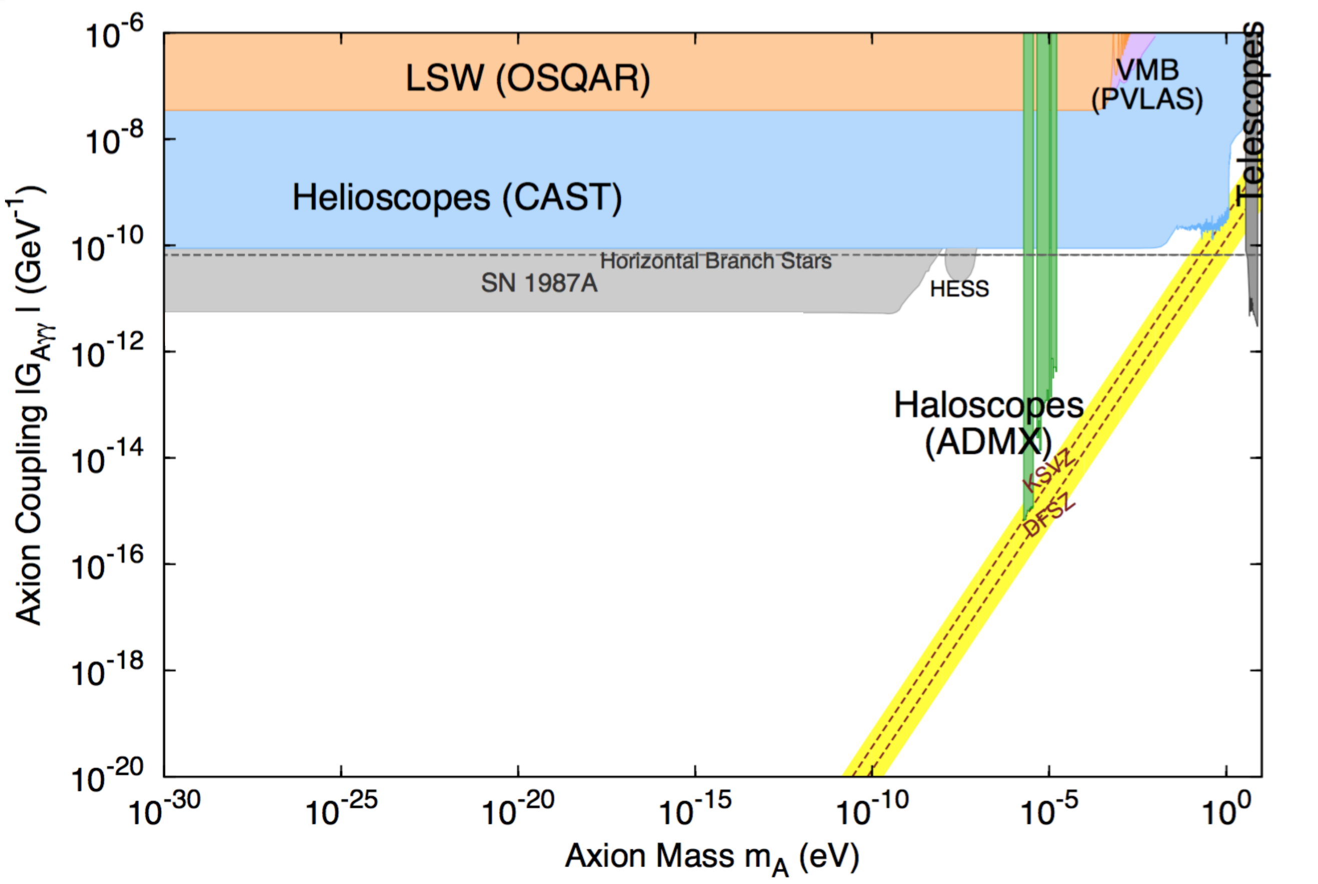


Image credit: Gray Rybka

Photon-ALP oscillations

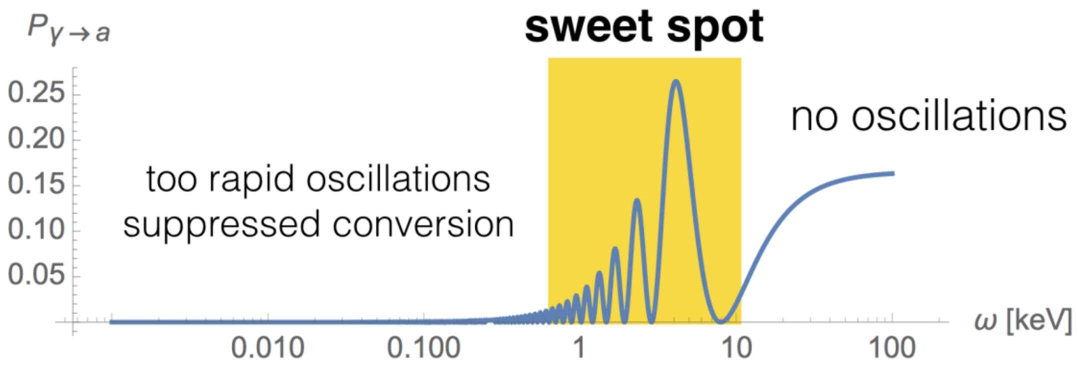
- Probability of photon-ALP conversion (for $m_a \lesssim 10^{-12}\text{eV}$):

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

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

$$\Delta = 0.54\left(\frac{n_e}{10^{-3}\text{cm}^{-3}}\right)\left(\frac{L}{10\text{kpc}}\right)\left(\frac{1\text{ keV}}{\omega}\right)$$

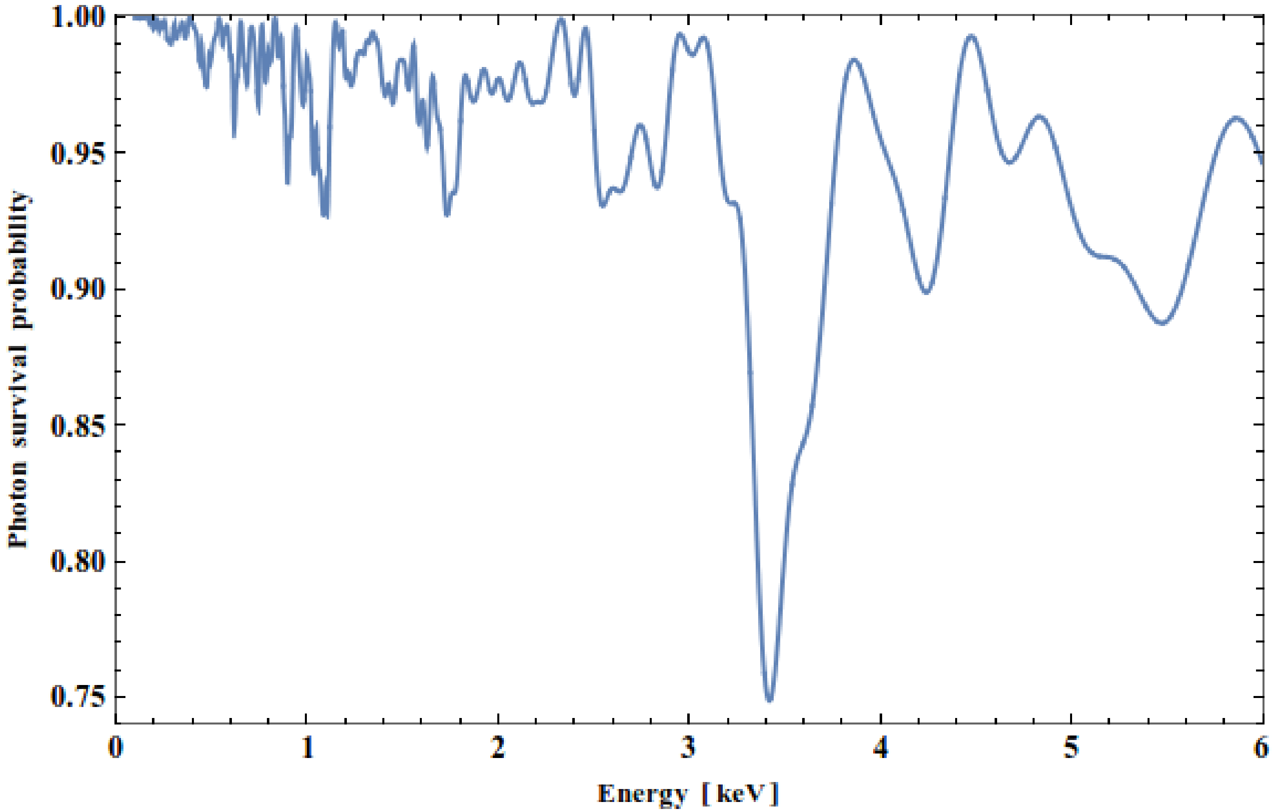
- In magnetic fields leads to photon-ALP oscillations at X-ray energies.



Perseus Cluster

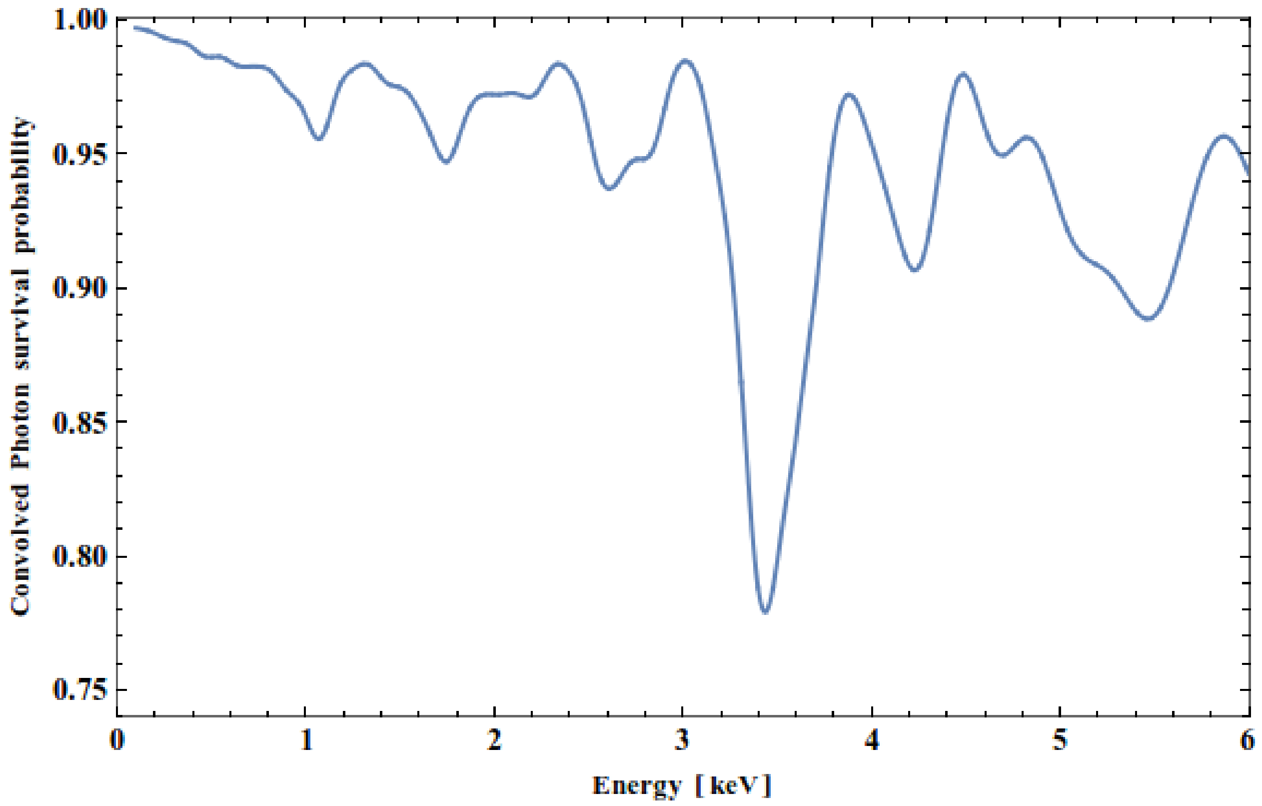
- Magnetic field approx. 1 Mpc across, coherence lengths 1-10 kpc.
- Magnetic field strength estimated at 10-25 μG at the centre [astro-ph/0602622], 1-10 μG across the cluster.
- Maximum value of $g_{a\gamma\gamma}$ consistent with observations could lead to conversion probability of 10-50%.

Photon survival probability in Perseus



100 domains, lengths: 3.5-10 kpc (total: 620kpc), $\mathrm{B}_0 = 15\ \mu\mathrm{G}$

Photon survival probability in Perseus



Convolved with Gaussian FWHM (150 eV)

NGC 1275

- Central galaxy of Perseus, with an AGN unobscured in our direction.

- Basic components to X-ray spectrum are:

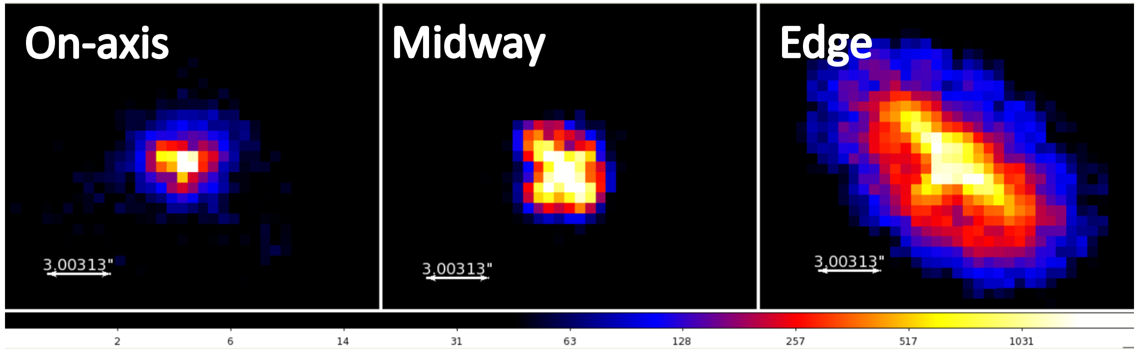
  1. Power-law.

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

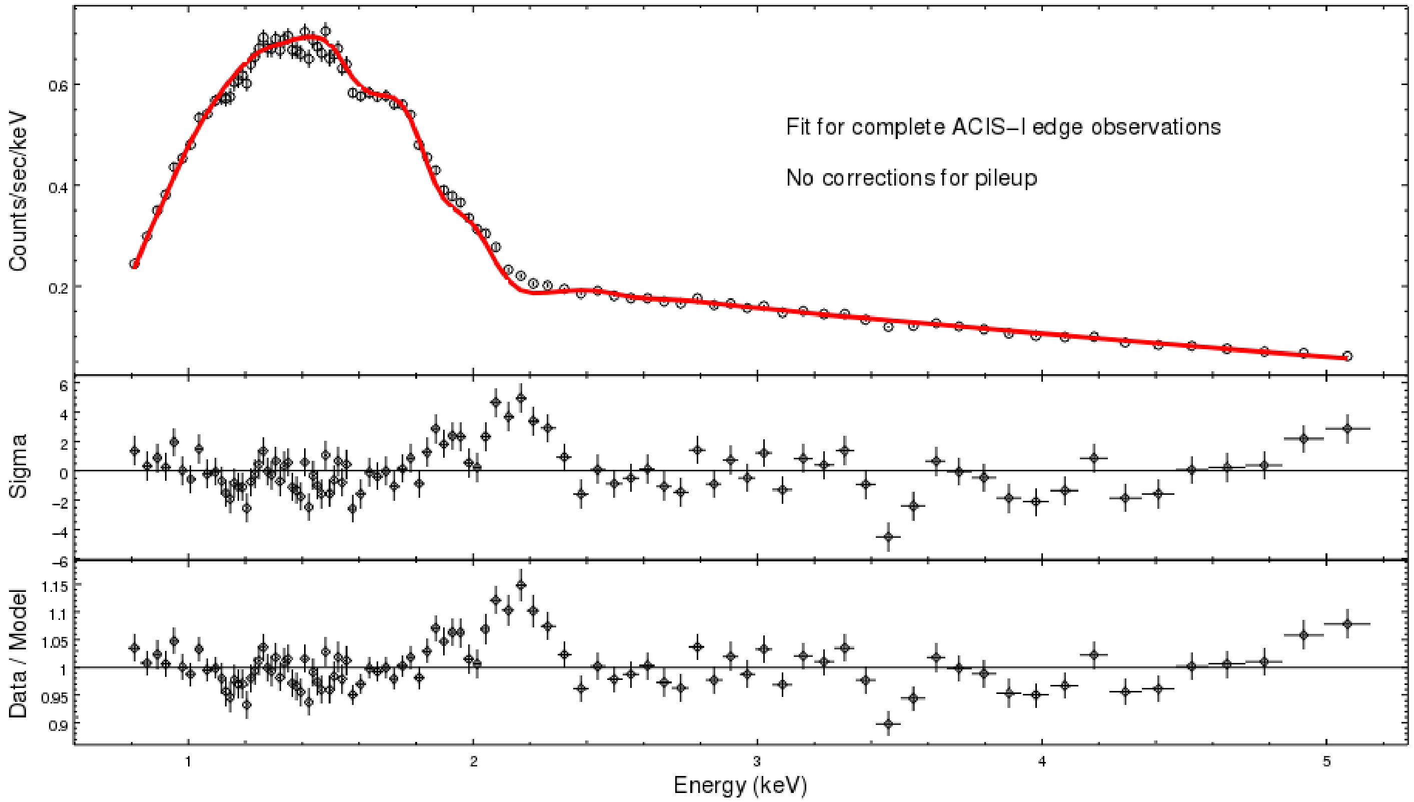
  3. Thermal soft excess (origin not entirely known).

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



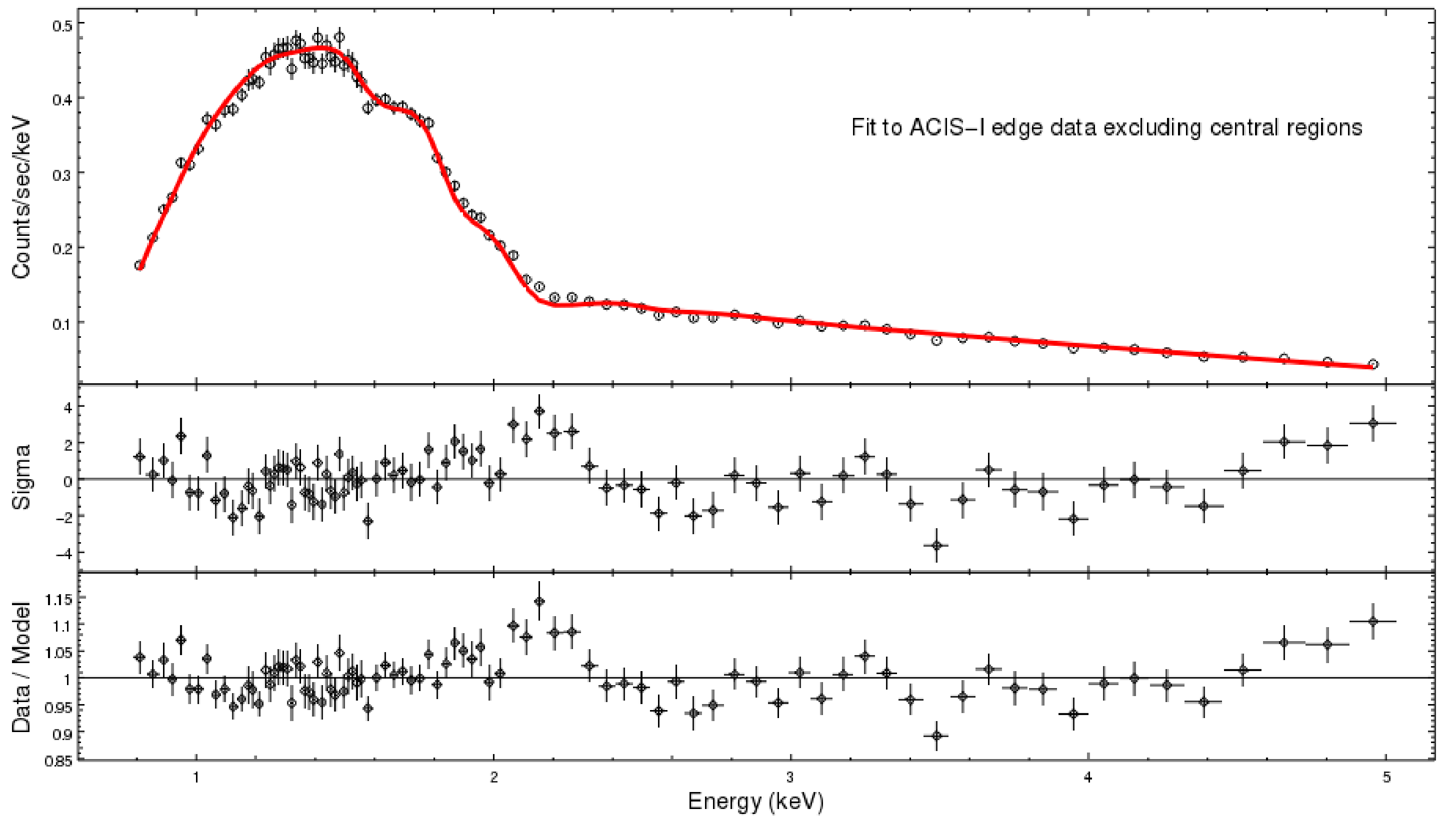
At 2.0–2.2 keV: five data points in a row 3-5 sigma high
At 3.4–3.5 keV: two data points low, 4.5, 2.6 sigma

Pile-up contamination

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

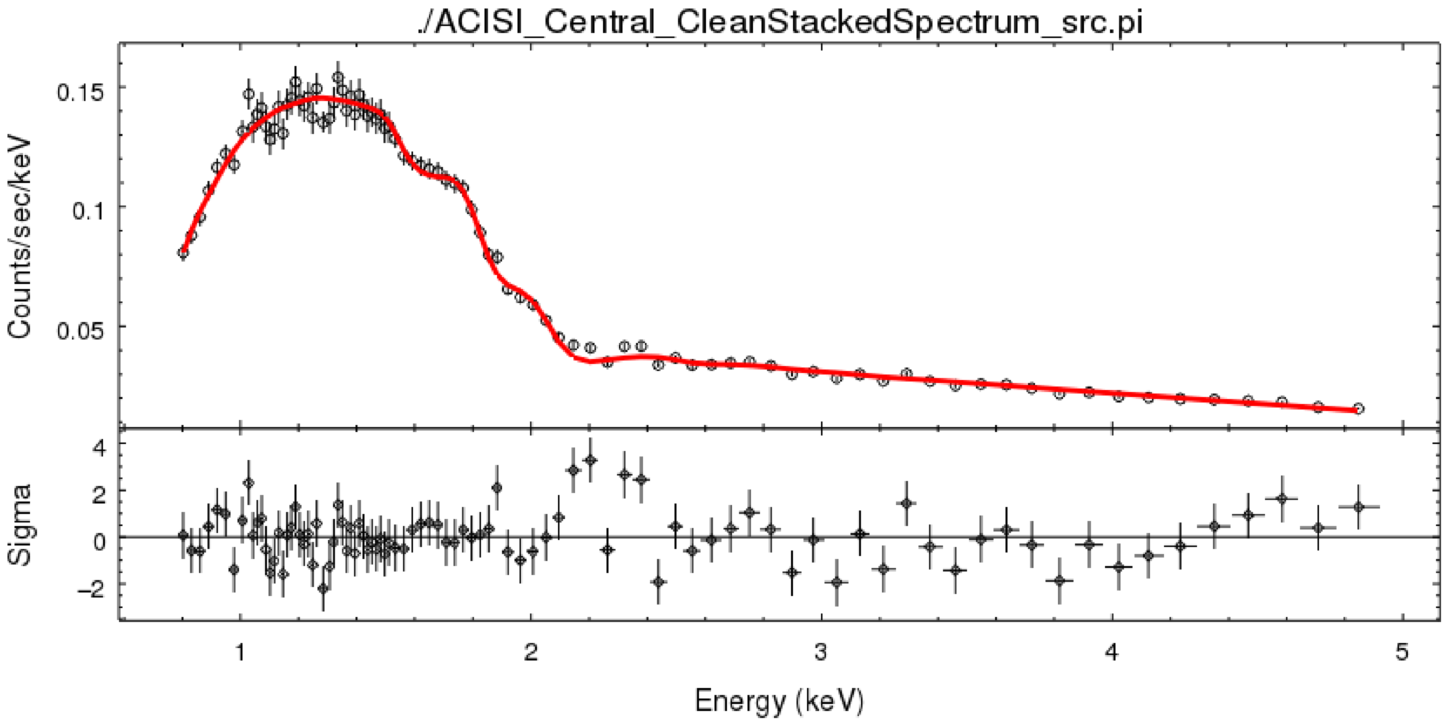
- Two ways to ameliorate this:
  - Discard central pixels with highest flux.
  - Model pile-up effects with `jdpileup` model.

Extraction for ACIS-I edge excluding centre



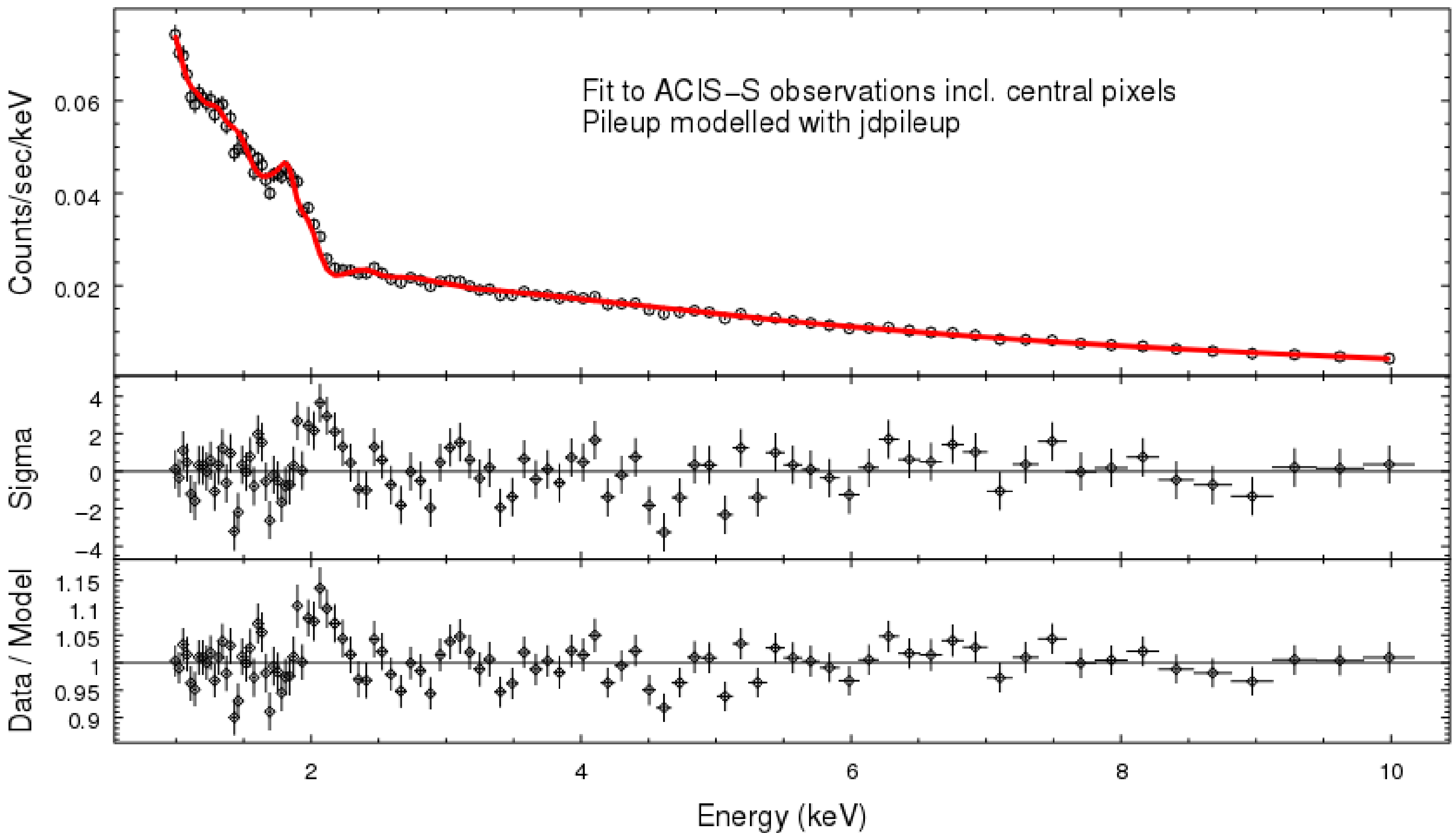
Significance reduced (less data) but ratio the same.

ACIS-I midway excluding centre



Excess remains at 2.2 keV after excluding centre (50% reduction in data).

Extraction for ACIS-S with pileup model



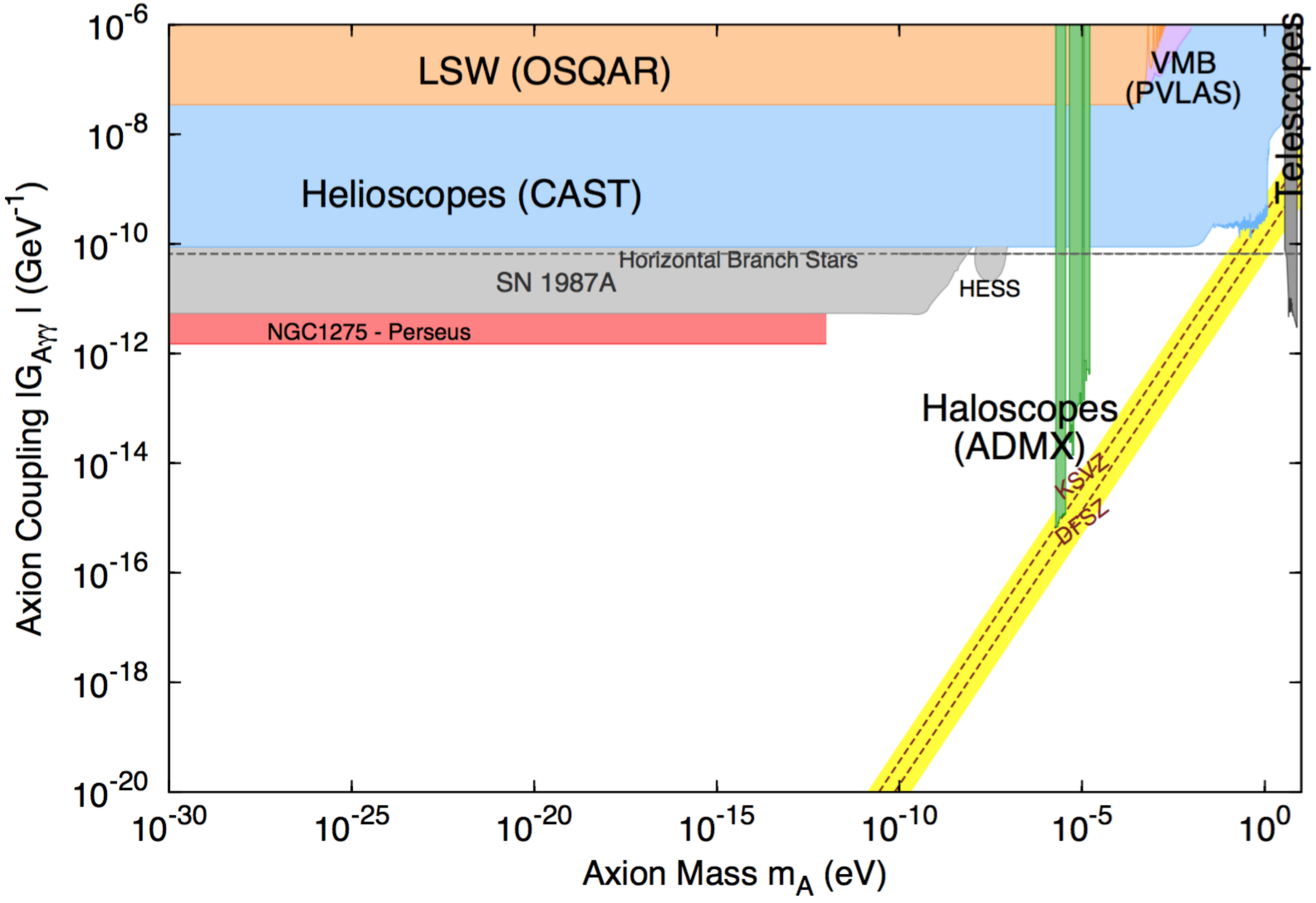
Quick summary of systematics

- 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.

Back to ALPs

- Bounds on $g_{a\gamma\gamma}$ based on lack of $\mathcal{O}(20\%)$ fluctuations.
- Depends on assumptions about Perseus magnetic field.
- $g_{a\gamma\gamma} \lesssim 1.5 - 5.9 \times 10^{-12}\ \mathrm{GeV}^{-1}$ for $m_a \lesssim 10^{-12}\mathrm{eV}$, at 95% confidence.
- What if 2.0-2.2keV excess is caused by ALP-photon oscillations?
  - Would correspond to $g_{a\gamma\gamma} \simeq 1 - 5 \times 10^{-12}\ \mathrm{GeV}^{-1}$.

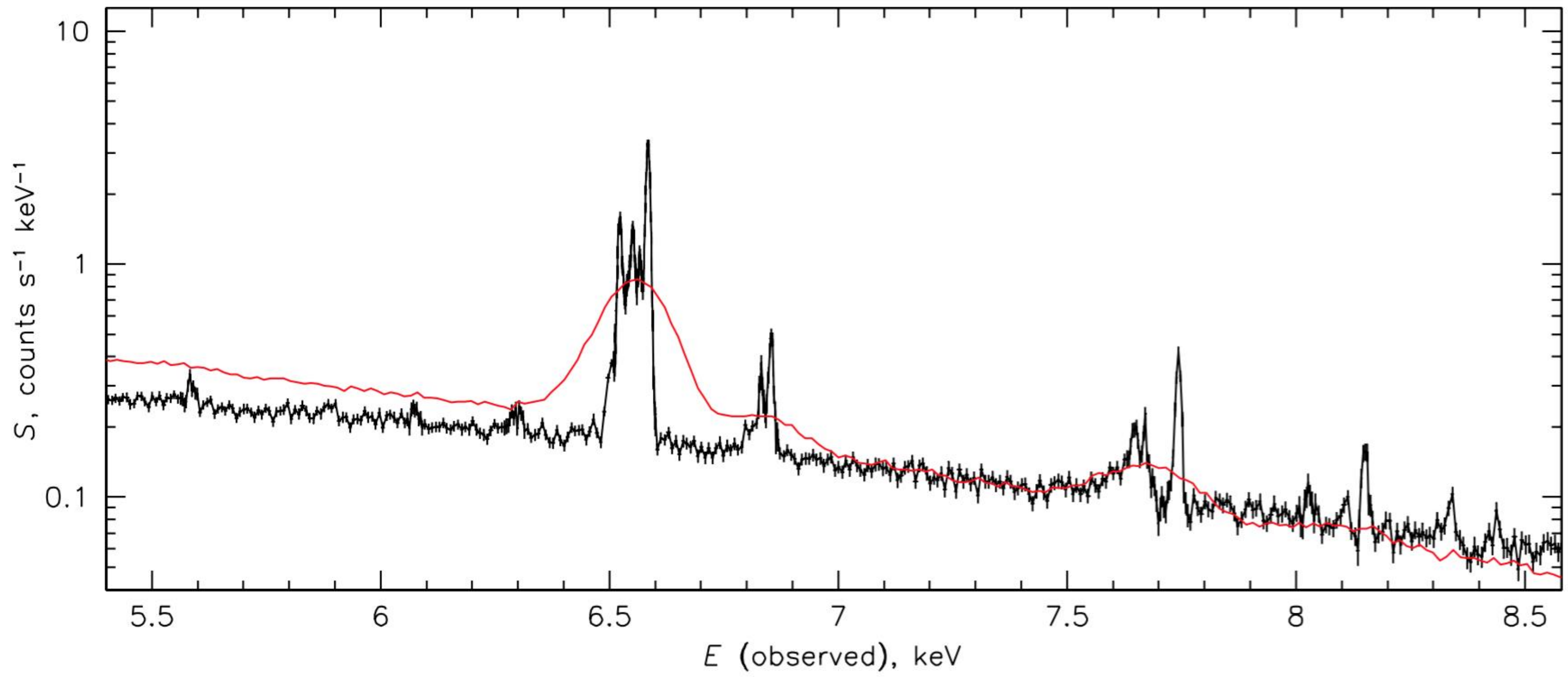
Bounds


LSW (OSQAR)
Helioscopes (CAST)
VMB
(PVLAS)
Telescopes
Horizontal Branch Stars
SN 1987A
HESS
NGC1275 - Perseus
Haloscopes
(ADMX)
KSVZ
DFSZ
Axion Coupling $|G_{A\gamma\gamma}|$ (GeV^{-1})
Axion Mass m_A (eV)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}

Conclusions

- Data set is *very, very* good.
- It provides the best current bounds on ultralight ALP-photon interactions.
- Evidence of spectral modulations: high statistical significance, better understanding of systematics needed.
- Going forward:
  - Comparison with other AGNs.
  - Future observations with *Chandra* could reduce pileup with gratings/shorter readout time.
  - Hitomi… paper out TODAY!

Thanks for listening!



Extended Data Figure 1 | SXS spectrum of the full field overlaid with a CCD spectrum of the same region. The CCD is the Suzaku X-ray imaging spectrometer (XIS) (red line); the difference in the continuum slope is due to differences in the effective areas of the instruments.

doi:10.1038/nature18627

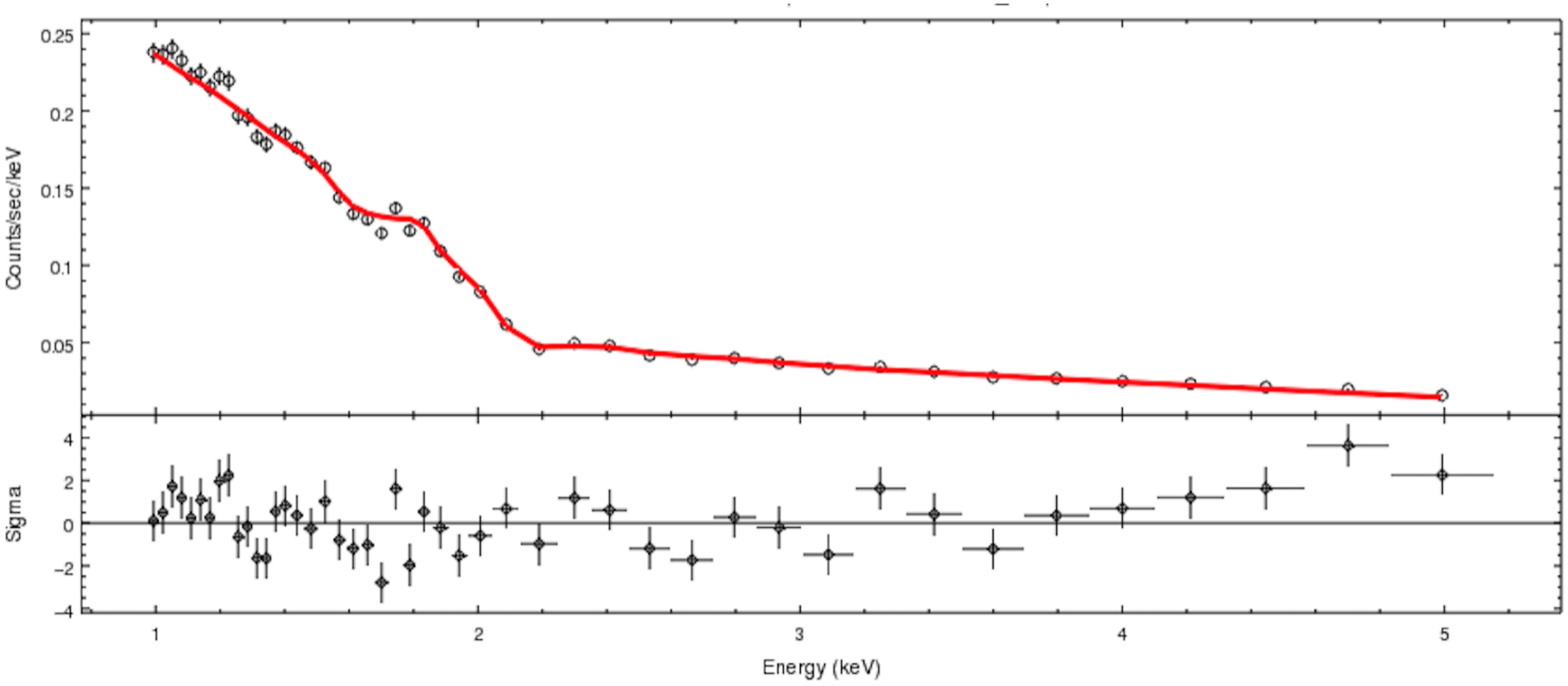
Extra slides – Bounds calculation

- Bounds on $g_{a\gamma\gamma}$ based on lack of $\mathcal{O}(20\%)$ fluctuations.

- Compare 2 models for the spectrum:
  - 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. Fit data to Model 0.
  2. Calculate $P_{\gamma\to\gamma}$ for 50 random magnetic field configurations.
  3. For each mag. field config. generate 10 fake data sets from Model 1.
  4. Fit Model 0 to each of the 500 fake data sets.
  5. If ${\chi_1}^2 < {\chi_0}^2$ for less than 5% of configs, Model 1 excluded at 95% confidence.

Extra slides – 3C 273



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