SEARCHING FOR AXION-LIKE PARTICLES WITH NGC1275

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My collaborators!

■ This talk is directly based on 1605.01034 (with Marcus Berg, Francesca Day, Nicholas Jennings, Sven Krippendorf, Andrew Powell, Markus Rummel)

■ I also acknowledge much previous collaboration on the physics of ALPs in galaxy clusters, particularly with David Marsh

■ My interest in ALPs arose from understanding the low-energy phenomenology of the Large Volume Scenario, and the desire to connect string theory to experiment.

■ The method described is very similar to previous work by Wouters and Brun 1304.0989 – but they use a much less luminous AGN (data sample less than 1% of that presented here)
Axion-like particles

- Light axion-like particles (ALPs) are one of the most motivated ways to extend the Standard Model.
- They arise generically in string theory – e.g. a light ALP is always present in the Large Volume Scenario.
- Phenomenologically, they are parametrised by the coupling:
  \[ \alpha g_{\alpha \gamma} E.B \equiv \frac{\alpha}{M} E.B \]
- In the presence of a background \( B \) field, the ALP \( \alpha \) and photon \( \gamma \) eigenstates mix, leading to photon-ALP oscillations (cf neutrino oscillations).
How to search for ALPs?

- The basic physics underlying this talk is very simple.
  1. Send photons from A to B
  2. Have a magnetic field in between A and B
  3. Photon-ALP interconversion causes some of these photons to oscillate into ALPs
  4. The photon spectrum on arrival at B will show modulations compared to the source photon spectrum at A.

- In our case, the source A is the central AGN (Active Galactic Nucleus) of the Perseus galaxy cluster and B is the *Chandra* X-ray telescope.
Why X-rays and galaxy clusters?

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

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

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

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

- In magnetic fields leads to photon-ALP oscillations at X-ray energies.
Why X-rays and galaxy clusters?
The Perseus Cluster

- The Perseus galaxy cluster is the brightest X-ray galaxy cluster in the sky, and is located at a redshift of 0.0176.
- It is a cool-core cluster centred around the Seyfert galaxy NGC1275 and its Active Galactic Nucleus.
- The Milky Way column density along the line of sight to Perseus is high, at $n_H = 1.5 \times 10^{21} cm^{-2}$ (implies significant absorption of soft X-rays).
- The Perseus cluster is the subject of enormous observation time with the Chandra X-ray telescope, totalling 1.5 Ms – gives over 500,000 photon counts from the central AGN.
NGC 1275

- NGC1275 is the central galaxy of the Perseus cluster
- At its centre is a very bright AGN, powered by accretion onto the supermassive black hole.
- The brightness of NGC1275 is time-variable (1980 brightness was 20x bigger than in 2001, progressive increase in brightness since 2001)
- AGN is unobscured, shining to us through the Perseus galaxy cluster
AGNs are point sources

- X-ray emission from AGNs comes from extremely small physical region
- We know this because of the time variability observed in AGN: AGN intensities can vary on day timescales, implying emission originates
- Various observations imply X-ray emission comes from innermost region of accretion disc, a few Schwarschild radii of black hole.
- 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)
AGNs: the standard Unified Model

Credit ESA/NASA, AVO project, Paolo Padavani
Photon-ALP Conversion

- Source is NGC1275, destination is Earth: intervening magnetic field is the magnetic field of the Perseus cluster.
- Galaxy clusters are particularly good location for photon-ALP interconversion.
- Magnetic fields extend over approx. 1 Mpc regions, with coherence lengths in 1-10 kpc region.
- Magnetic field strengths are 1 – 10 microGauss.
- Allowed values of photon-ALP coupling $g_{\gamma\gamma}$ can lead to conversion probabilities of order 10 – 50%.
- No detailed knowledge of exact value of Perseus magnetic field; central value should be in range 10 – 25 microGauss.
If ALPs exist, some photons convert to ALPs on passing through a galaxy cluster.

This produces energy-dependent modulations in the observed photon spectrum.

The precise form of these modulations depends on the galaxy luster magnetic field.

AGNs are bright point sources of photons.
Simulated photon survival probability...
...now convolved with detector resolution
The Observations

- NGC1275 observed by Chandra in 2002 and 2004 for 1Ms with ACIS-S and 0.5 Ms in 2009 with ACIS-I.
- In ACIS-S observations, NGC1275 is on-axis, in 2009 observations 300ks with NGC1275 around 4 arcmin off-axis and 200ks with NGC1275 around 8 arcmin off-axis.
- We treat these three sets separately.
- Chandra on-axis point spread function is around 0.5 arcsec diameter on-axis, broadening to around 10 arcsec diameter when source is around 8 arcmin off-axis.
The Observations

- We extract the AGN spectrum and subtract nearby cluster emission for background.
- We then fit the AGN spectrum between 0.8 and 5 keV with an absorbed power law, supplemented if necessary by a soft thermal component.
- We then examine these spectra and look for residuals.
- Counts are grouped so that there are approximately one hundred bins in total.
- Total counts from AGN is
  1. 230000 for 2009 ACIS-I ‘edge’ observations (cleanest dataset)
  2. 242000 for 2009 ACIS-I ‘midway’ observations
  3. 183000 for 2002-4 ACIS-S on-axis observations
Complete extraction for ACIS-I edge

At 2 – 2.2 keV: five data points in a row 3-5 sigma high
At 3.4 – 3.5 sigma: two data points low, 4.5, 2.6 sigma
Possibly a connection to observation of 3.5 keV excess from *diffuse* cluster emission? (Bulbul, Boyarsky)
- Care is needed with pileup as 2 – 2.2 keV region is near a detector feature
- Do features arise from pileup (arrival of multiple photons in a single readout time)?
- We clean the spectrum by removing central regions of highest pile-up.
Cleaned spectrum has same features: excess at 2 – 2.2keV and deficit at 3.4 – 3.5 keV

1. Statistical significance reduces slightly (consistent with reduction in the amount of data)

2. Magnitude of excess remains the same (data/model ratio) – suggesting pile-up is not the origin.
2009 ACIS-I midway data is consistent with clear feature near 2 keV.

Statistical significance reduces with less data (over 50% less once cleaned than for ACIS-I edge data)
2002-4 cleaned ACIS-S observations are all also consistent

Excess at 2 – 2.2 keV and deficit at 3.4 keV
Basic summary of data

- Fits of *Chandra* data on NGC1275 produces two main features
  
  1. Excess at approx. 5-15% level in 2–2.2 keV region
  
  2. Deficit at approx 5-10% level in 3.4–3.5 keV region

- Statistical significance of 2 – 2.2 keV excess is overwhelming (far beyond 5 sigma)

- Statistical significance of 3.4 – 3.5 keV deficit is ‘only’ around 5 sigma

- High statistical significance means think hard about systematic / instrumental effects
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 – can extract in a way that AGN dominates background cluster emission by 15:1 or even 60:1, but O(10%) features survive
- Miscalibration of gain in high-flux regions – but level of flux is very different in the different spectra, and features remain at consistent level.
- Emission line (2 – 2.2 keV) from soft thermal component – no plausible lines in relevant region
- Absorption line (3.4 - 3.5 keV) – no plausible lines, absorption comes from Milky Way, no absorption seen in diffuse cluster spectra
- Fluorescent emission (2 – 2.2 keV) from S Kα line at 2.31 keV – energy too high and line not strong enough
Spectrum from bright quasar 3C273

Extracted in similar way to ACIS-S observations, but no excesses seen
New Physics Interpretations

- ALPs – can explain and generate modulations for $g_{a\gamma\gamma}$ in $1 - 5 \times 10^{-12} GeV^{-1}$ region
- For 3.4 – 3.5 keV deficit, can also consider a dark matter absorption line
  1. Relevant for models of excited dark matter used to explain 3.5 keV cluster emission line
  2. Dark matter column density along line of sight to NGC1275 is higher than almost anywhere else
- Perhaps *Hitomi* observation of Perseus centre will add more useful information
Conclusions

- This dataset is *really, really good*.
- It provides the best current bounds on ALP-photon interactions.
- It also contains a possible signal.
- Statistical significance is enormous – what other systematics are there?
- Immediate next step: what is in *Hitomi* data for AGN? Is there enough to shed further light on these questions?
Fit to complete ACIS-I central observations
No corrections for pileup
Fit for complete ACIS–S observations

No corrections for pileup
Fit for complete ACIS–S observations

No corrections for pileup
Fit to ACIS-S observations incl. central pixels
Pileup modelled with jdpileup