Astrophysical Signatures of Axions

Francesca Day

University of Oxford

Helsinki Institute of Physics
May 2016

1404.7741: J P Conlon & FD
1410.1867: P Alvarez, J P Conlon, FD, M C D Marsh & M Rummel
1506.05334: FD
1605.01043: M Berg, J P Conlon, FD, N Jennings, S Krippendorf, A J Powell & M Rummel

Outline

The Strong CP Problem

- The CP violating term $\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$ is allowed in the QCD Langrangian
- Null measurements of the neutron electric dipole moment constrain $\theta < 10^{-9}$
- Weak interactions transform θ: $\theta \to \theta + \arg \det M$.
- Need very fine tuned cancellations to explain observations.

The Vafa-Witten Theorem

"In parity-conserving vector-like theories such as QCD, parity conservation is not spontaneously broken."

Dynamical parity violating terms have zero vacuum expectation value.
(Vafa and Witten, 1984)

The Peccei-Quinn solution

- Promote θ to a dynamical variable - the QCD axion: $\mathcal{L} \supset (\theta + \frac{\xi a}{f_a}) \frac{g^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$
- The Vafa-Witten theorem guarantees that the *total* θ term is zero in the ground state.
- A potential is generated for the axion such that the total coefficient of $G^{\mu\nu} \tilde{G}_{\mu\nu}$ is zero.

The Peccei-Quinn solution

- The θ term arises from the $U(1)_A$ anomaly of QCD
- To make θ dynamical, we introduce an additional global chiral symmetry $U(1)_{PQ}$, which is spontaneously broken.
- The axion is the Goldstone boson of $U(1)_{PQ}$.
- The QCD chiral anomaly causes non-perturbative explicit breaking of $U(1)_{PQ}$, generating a potential for the axion:

$$V \sim -\cos(\theta + \frac{\xi a}{f_a})$$

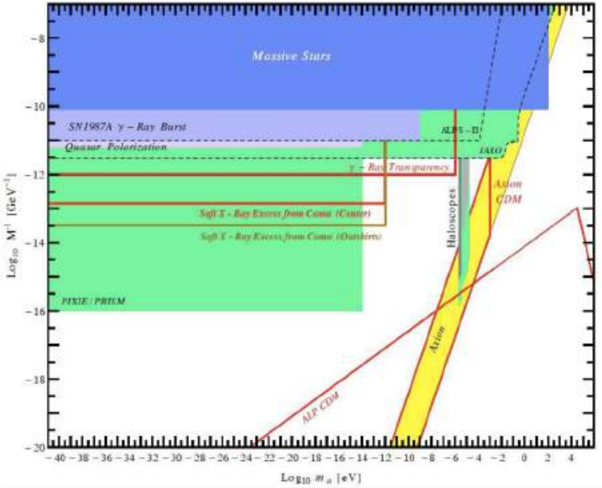
Axions

- Axions arise in extensions of the Standard Model as pseudo-Goldstone bosons of $U(1)_A$ symmetries.
- A generic axion is an ultra-light pseudo-scalar SM singlet.
- We may choose the axion basis such that one is the QCD axion and the rest have no coupling to gluons.
- We explore the phenomenology of the dimension 5 $aF_{\mu\nu}\tilde{F}^{\mu\nu}$ coupling.
- Axions may be observed through their conversion to photons in a background magnetic field.

Motivations

- The Strong CP Problem
- String theory compactificiations typically give rise to many such axion fields, populating many decades in mass.
- Dark matter and dark energy

Limits



Reproduced from Dias *et al* (1403.5760)

Axions

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{a}{M}\mathbf{E}\cdot\mathbf{B}$$

- $\mathcal{L} \supset \frac{a}{M}\mathbf{E}\cdot\mathbf{B}$ leads to axion-photon interconversion in the presence of a background magnetic field.
- Model axion-photon conversion with classical equation of motion from $\mathcal{L}$.
- Assume that the axion wavelength is much shorter than the scale over which its environment changes, allowing us to linearise the equations of motion.

Axion-photon conversion

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma ax} \\ 0 & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - i\partial_z\right) \begin{pmatrix} |\,\gamma_x\rangle \\ |\,\gamma_y\rangle \\ |\,a\rangle \end{pmatrix} = 0$$

- $\Delta_\gamma = \frac{-\omega_{pl}^2}{2\omega}$
- Plasma frequency: $\omega_{pl} = \left(4\pi\alpha\frac{n_e}{m_e}\right)^{\frac{1}{2}}$
- $\Delta_a = \frac{-m_a^2}{\omega}$.
- Here we take $m_a = 0$. This is valid for $m_a \lesssim 10^{-12}\,\mathrm{eV}$.
- Mixing: $\Delta_{\gamma ai} = \frac{B_i}{2M}$

$$P_{a\to\gamma}(L) = |\,\langle 1,0,0|f(L)\rangle\,|^2 + |\,\langle 0,1,0|f(L)\rangle\,|^2$$

Single domain

$$\tan(2\theta) = 10.0 \times 10^{-3} \times \left(\frac{10^{-3}\,\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{B_\perp}{1\,\mu\mathrm{G}}\right)\left(\frac{\omega}{3.5\,\mathrm{keV}}\right)\left(\frac{10^{13}\,\mathrm{GeV}}{M}\right)$$

$$\Delta = 0.015 \times \left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)\left(\frac{3.5\,\mathrm{keV}}{\omega}\right)\left(\frac{L}{1\,\mathrm{kpc}}\right)$$

$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

Small angle approximation

Over a distance R of $R/L \gg 1$ domains, with **B** randomised between each domain, we can approximate:

$$P \simeq 6.9 \times 10^{-7} \left(\frac{L}{1\,\mathrm{kpc}} \frac{R}{30\,\mathrm{kpc}} \right) \left(\frac{B_\perp}{1\,\mu\mathrm{G}} \frac{10^{13}\,\mathrm{GeV}}{M} \right)^2$$

for $\theta, \Delta \ll 1$

In most astrophysical environments with have $\theta \ll 1$ but not always $\Delta \ll 1$.

Axion-photon conversion

- $P_{a\to\gamma} \propto \frac{B_\perp^2}{M^2}$ for $\frac{B_\perp^2}{M^2} \ll 1$
- $P_{a\to\gamma}$ increases with the field coherence length and the total extent of the field.
- High electron densities increase the effective photon mass, suppressing conversion.
- Astrophysical environments lead to the highest conversion probabilities.

Photoelectric absorption

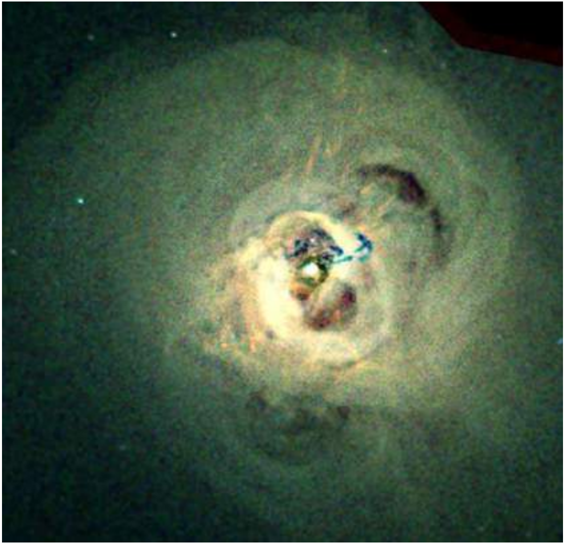
Use density matrix formalism to include photo-electric absorption of photon components:
Damping parameter: $\Gamma = \sigma_{\rm eff}\left(n_{HI} + 2n_{H2}\right)$

$$H = \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma ax} \\ 0 & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - \begin{pmatrix} i\frac{\Gamma}{2} & 0 & 0 \\ 0 & i\frac{\Gamma}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix} = M - iD,$$

$$\rho = \begin{pmatrix} \mid \gamma_x\rangle \\ \mid \gamma_y\rangle \\ \mid a\rangle \end{pmatrix} \otimes \begin{pmatrix} \mid \gamma_x\rangle & \mid \gamma_y\rangle & \mid a\rangle \end{pmatrix}^*$$

$$\rho(z) = e^{-iHz}\rho(0)e^{iH^\dagger z}.$$

Galaxy clusters



Spectral Modulations in NGC1275

We search for axions by studying the X-ray spectrum of the AGN at the centre of the Perseus galaxy cluster.

See also J P Conlon *et al*, 1509.06748; D Wouters and P Brun, 1205.6428; P Brax *et al*, 1505.01020; *The Fermi-LAT Collaboration*, 1603.06978

Photon-Axion Conversion

- Photon to axion conversion can lead to modulations in an initially pure photon spectrum, given by the photon survival probability $P_{\gamma\to\gamma}(E)$.
- At X-ray energies in galaxy clusters, $P_{\gamma\to\gamma}(E)$ is pseudo-sinusoidal in $\frac{1}{E}$.
- Axion induced oscillations in $P_{\gamma\to\gamma}(E)$ would be imprinted on the observed spectrum.
- We seek to constrain M by searching for such oscillations.

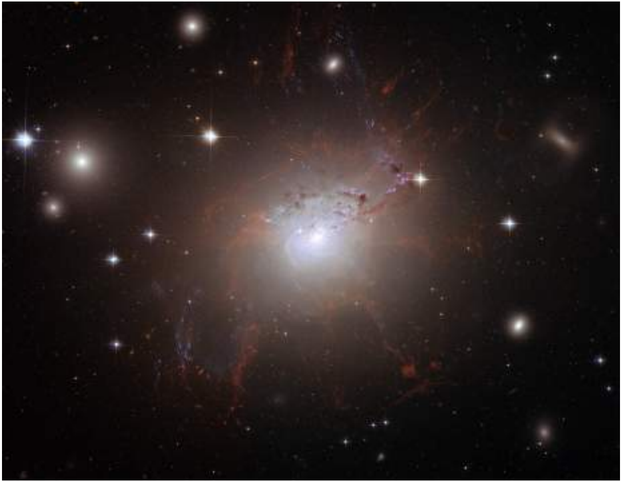
AGN

- Active galactic nuclei (AGN) behind or embedded in galaxy clusters are ideal sources for this search.
- Galaxy clusters are efficient axion-photon mixers.
- Original photon spectrum described by an absorbed power law:

$$F_0(E) = AE^{-\gamma} \times e^{-n_H \sigma(E)}$$

- All photons experience the same magnetic field along the line of sight.
- AGN can provide a large number of counts.

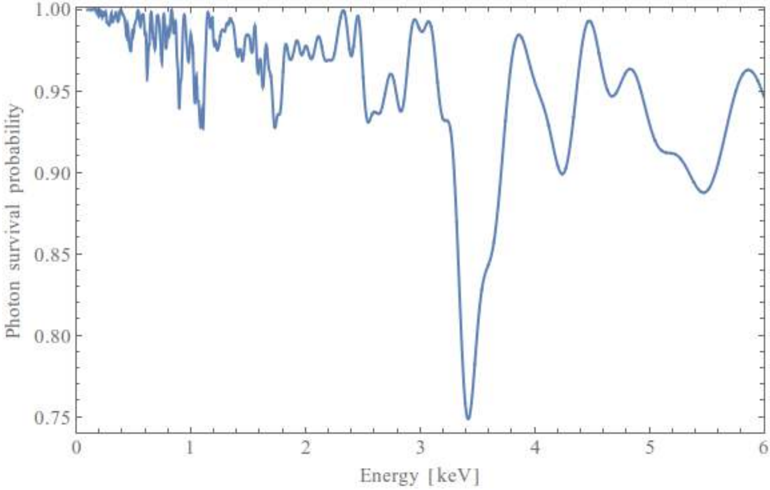
NGC1275



NGC1275

- 1.5 Ms of observation time from the Chandra X-ray telescope, giving over 5×10^5 counts.
- Perseus has a high central magnetic field, estimated at 25 $\mu\mathrm{G}$ (Taylor *et al*, astro-ph/0602622).
- No observational estimates of the coherence length of Perseus' magnetic field - make educated guesses based on other clusters.
- Magnetic field structure along the line of sight to NGC1275 unknown.

Photon survival probability



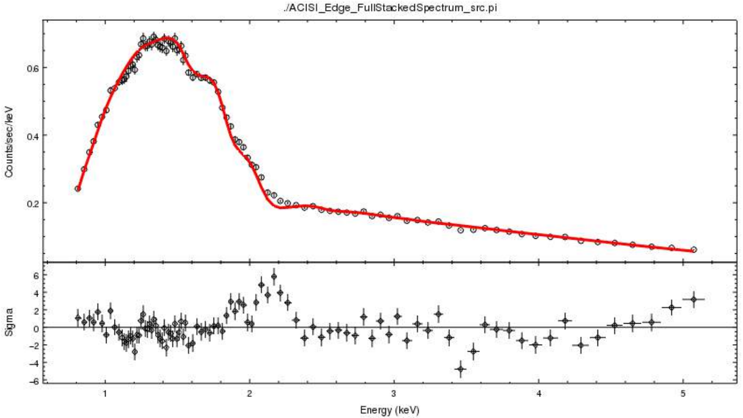
Analysis

- We process the data using *Ciao*, provided by the *Chandra* collaboration.
- Remove time periods polluted by solar flares.
- Subtract background taken from a region near NGC1275.
- The data is effected by pile-up - contamination of the data when the count rate is faster than the read out time.
- We focus on observations where NGC1275 is at the edge of the telescope's field of view.
- This means the point spread function is higher - NGC1275 is spread out over more pixels - so pile-up is reduced.

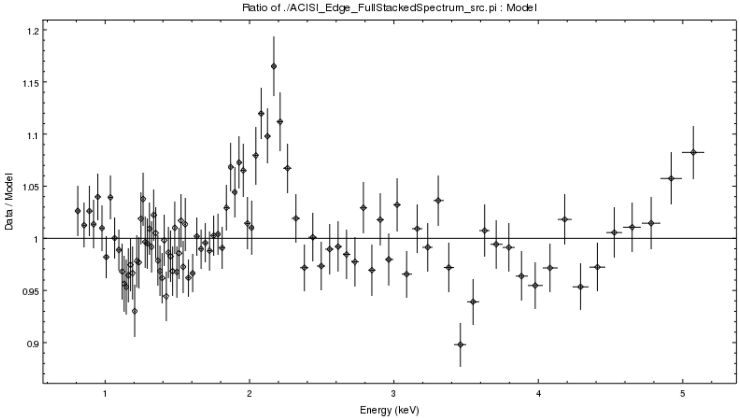
Pile-up

- Energy of two different photon events is summed and recorded as a single photon event.
- Leads to an increased count rate at higher energies compared to the true count rate of the source.
- Low levels of pile-up should not effect localised modulations due to axion-photon oscillations.
- High levels of pile-up would wash out oscillations.

Results


./ACISI_Edge_FullStackedSpectrum_src.pi
Counts/sec/keV
0.6
0.4
0.2
Sigma
6
4
2
0
−2
−4
−6
1
2
3
4
5
Energy (keV)

Results



Ratio of ./ACISI_Edge_FullStackedSpectrum_src.pi : Model
Data / Model
1.2
1.15
1.1
1.05
1
0.95
0.9
1
2
3
4
5
Energy (keV)

Potential Signal

- We see an excess at 2 - 2.2 keV at 6σ local significance and a deficit at 3.4 - 3.5 keV at 5σ local significance.
- These features are also seen in other Chandra observations of NCG1275.
- How do we interpret these features?

Interpretation: Pileup

- The excess at 2 - 2.2 keV coincides with a dip in the effective area of the telescope.
- Pile-up from lower energy photons?
- Due to a low effective area and absorption by neutral hydrogen, there are very few photons below 1.5 keV in the spctrum. It would therefore be difficult for pile-up to create a signal at 2 - 2.2 keV.
- The excess is present in observations with very different amounts of pileup.
- The features remain even when we model pile-up.

Interpretation: Effective Area

- Miscalibration of the effective area?
- The features are present at the same strength in observations from different parts of the detector.
- No unexpected residuals were seen in an analysis of observations of the main part of the Perseus cluster.
- No unexpected residuals were seen in an alaysis of the quasar 3C273, a point source not in or behind a galaxy cluster.

Interpretation: Atomic Line

- Thermal emission line?
- No strong emission lines expected at 2 - 2.2 keV for an ionized gas in this energy range.
- Any strong thermal emission present would also be seen as a strong broad excess extending to lower energies. This is not observed.

Interpretation: Axions

- Localized oscilliatory features consistent with an ALP origin.
- For a central magnetic field $B_0 \sim 25\,\mu\mathrm{G}$, they can be explained by an axion with $M \sim 10^{12}\,\mathrm{GeV}$ and $m_a \lesssim 10^{-12}\,\mathrm{eV}$.
- Further investigation is needed.

Bounds

We can use the absence of larger oscilliatory features in the spectrum to place rough bounds on M. We compare two models for the spectrum:

- Model 0: $F_0(E) = AE^{-\gamma} \times e^{-n_H \sigma(E)}$
- Model 1: $F_1(E, \mathbf{B}) = AE^{-\gamma} \times e^{-n_H \sigma(E)} \times P_{\gamma \to \gamma}(E, \mathbf{B}, M)$.

Our procedure is as follows for each M

1. Randomly generate 100 different magnetic field realisations $\mathbf{B}_i$.
2. For each $\mathbf{B}_i$, compute $P_{\gamma \to \gamma}(E, \mathbf{B}_i, M)$.
3. For each $\mathbf{B}_i$, fit Models 0 and 1 to the spectrum obtained from NGC1275 and compute the reduced χ^2 for each case.
4. If, for any of the 100 $\mathbf{B}_i$, Model 1 produces a better fit (i.e. a lower reduced χ^2) than Model 0, M is not excluded. Otherwise, M is excluded.

Bounds

If we assume:
$B_0 = 25\,\mu\mathrm{G}$, $B \propto n_e^{0.7}$, $l_{\min} = 3.5\,\mathrm{kpc}$:

$$M \gtrsim 7 \times 10^{11}\,\mathrm{GeV}$$

If $B_0 = 15\,\mu\mathrm{G}$ and $l_{\min} = 0.7\,\mathrm{kpc}$:

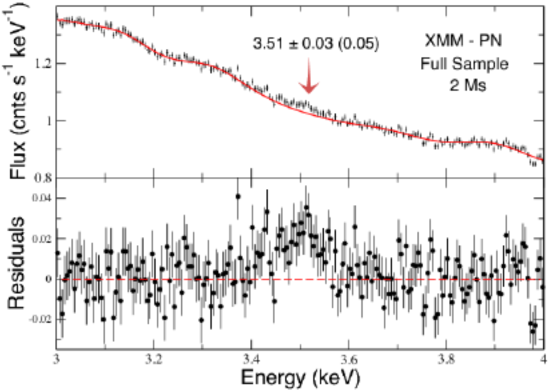
$$M \gtrsim 3 \times 10^{11}\,\mathrm{GeV}$$

NGC1275: Summary

- X-ray observations of NGC1275 are an excellent probe for axions.
- We observe two residuals at 2 - 2.2 keV and 3.4 - 3.5 keV at high local significance. These are consistent with axions with $M \sim 0.2 - 1 \times 10^{12}\,\mathrm{GeV}$.
- More work is needed.

The 3.5 keV line

3.5 keV photon line originally observed in several galaxy clusters and Andromeda (M31) at $4-5\sigma$ (Bulbul *et al* 1402.2301, Boyarsky *et al* 1402.4119).



Observations

- NOT observed in stacked spectra of external galaxies (Malyshev *et al* 1408.3531, Anderson *et al* 1408.4155)
- Observed in the Milky Way centre with the *XMM Newton* X-Ray telescope (Boyarsky *et al* 1408.2503, Jeltema and Profumo 1408.1699)....
- ... but not with the *Chandra* X-Ray telescope (Riemer-Sorensen 1405.7943)
- Possible weak detection in the Draco dwarf galaxy (Jeltama and Profumo 1512.01239, Ruchayskiy *et al* 1512.07217).
- ~~Observations with forthcoming *ASTRO-H* telescope?~~

Morphology

- Signal from the Perseus galaxy cluster is $\sim 8\times$ stronger than for the 72 other clusters
- Half of the Perseus signal is within the central 20 kpc (the cool core), whereas the dark matter density varies over $R_{DM} \simeq 360\,\mathrm{kpc}$
- Signal from Orphiuchus and Centaurus galaxy clusters is also dominated by the cool core
- Morphology of the galactic centre line appears consistent with a spectral line rather than dark matter decay (Carlson *et al* 1411.1758).

Interpretations

Instrumental Line?

- Observed at redshifts 0 - 0.35. An instrumental line would be smeared out by de-redshifting.
- Seen by four different detectors
- Not seen in blank sky data set

Interpretations

Atomic Line?

- No known line at this energy
- Nearby lines would need to exceed expected flux by a factor of ~ 20 to explain the signal
- Observed in the Andromeda galaxy - no hot gas
- Ongoing debate (Jeltema and Profumo 1408.1699 & 1411.1759, Boyarsky *et al* 1408.4388, Bulbul *et al* 1409.4143, Urban *et al* 1411.0050, Tamaru *et al* 1412.1869, Phillips, Sylwester & Sylwester 1506.04619, Gu *et al* 1511.06557, Franse *et al* 1604.01759)

Interpretations

Dark Matter?

- Dark matter decay or annihilation to photons
- Decay scenario predicts that line flux F is proportional to dark matter density ρ_{DM}
- Annihilation predicts $F \propto \rho_{DM}^2$

Dark matter?

- Non-observation in galaxies is inconsistent with observation in galaxy clusters for dark matter decay or annihilation to photons
- Morphology of signal from clusters is inconsistent with direct decay or annihilation of dark matter to photons
- All models with direct dark matter decay to photons are inconsistent with these observations

Dark matter?

- We seek a dark matter model consistent with all the observations.
- Other models based on the signal morphology include excited dark matter (Cline and Frey 1410.7766), where the observed flux depends on the DM velocity dispersion.

$\mathrm{DM} \to a \to \gamma$

$$\mathrm{DM} \to a \to \gamma$$

- Dark matter decays to an axion which mixes with the photon in astrophysical magnetic fields
- The axion to photon conversion probability is much lower in galaxies than in galaxy clusters, primarily due to size.
- Predicted the non-observation of the 3.5 keV line in galaxies.

$\mathrm{DM} \to a \to \gamma$

$$\mathrm{DM} \to a \to \gamma$$

- This model does not predict the nature of the dark matter itself.
- Requires branching ratio to axions $\gg$ branching ratio to photons

Dark matter lifetime

To reproduce observed flux with direct dark matter decay to photons:

$$\tau_{\rm direct} \sim 5 \times 10^{27}\,\rm s$$

For a typical conversion probability $P^{cluster}_{a \to \gamma}$ in galaxy clusters, we require

$$\tau_{\rm axion} \sim 5 \times 10^{27}\,{\rm s} \times P^{cluster}_{a \to \gamma}\big|_{M = 10^{13}\,\rm GeV} \left(\frac{10^{13}\,\rm GeV}{M} \right)^2$$

Predictions

This model was developed to explain the 3.5 keV line signal in galaxy clusters. What does it predict in other systems?

- The Milky Way
- Andromeda
- Other galaxies

Milky Way

- The expected flux from the Milky Way dark matter halo for $DM \to a \to \gamma$ is almost 1000 times lower than for direct decay $DM \to \gamma$.
- Lower conversion probability in the Milky Way than for galaxy clusters.
- The maximal flux in the $DM \to a \to \gamma$ scenario is $\sim 2 \times 10^{-4}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$
- Possible exception of the Milky Way Centre

Andromeda

Andromeda

- Why is the 3.5 keV line flux from Andromeda (M31) not suppressed as in the Milky Way?
- Observational estimates suggest Andromeda's field is significantly larger and more coherent than the Milky Way's (Fletcher *et al* astro-ph/0310258).
- Fletcher *et al* (astro-ph/0310258) found that between 6 and 14 kpc from the centre of M31, the magnetic field is a coherent spiral, with a regular magnetic field strength $B_{reg} \sim 5\,\mu\mathrm{G}$.
- M31 is near edge on (inclination angle $= 77.5^{\circ}$), so axions originating from dark matter decay pass through a large coherent transverse magnetic field on their way to Earth.

Andromeda

Single domain small angle approximation for the conversion probability for a 3.5 keV axion created at the centre of M31 and propagating to Earth:
$B_\perp \sim 5\,\mu\mathrm{G}$
$L \sim R \sim 20\,\mathrm{kpc}$

$$P_{a\to\gamma,M31} \sim 2.3\times10^{-4}\left(\frac{10^{13}\,\mathrm{GeV}}{M}\right)^2$$

Andromeda

- Estimate conversion probabilities two orders of magnitude higher than for the Milky Way.
- In the $DM \rightarrow a \rightarrow \gamma$ scenario the observed signal strength from M31 can be comparable to that from clusters, consistent with the results of Boyarsky et al.
- M31 is an unusually favourable galaxy for observing the 3.5 keV line.

Other Galaxies

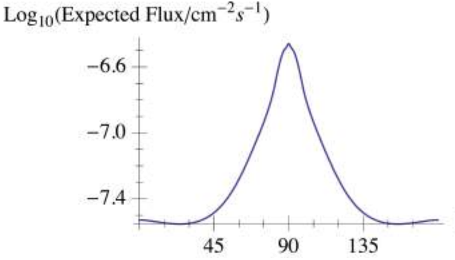
- We predict no 3.5 keV line signal in a generic stacked sample of galaxies, consistent with observations.
- We might be able to observe a signal from a stacked sample of edge-on spiral galaxies or from starburst galaxies.

Face on

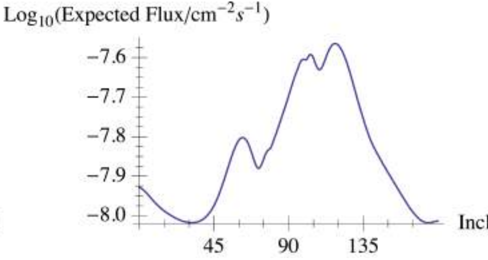
Edge on

Galaxy Inclination

- Simulated observations of an M31-like galaxy 1 Mpc away with a 15' radius field of view (central 4.4 kpc).
- Ratio $\frac{\text{edge}-\text{on flux}}{\text{face}-\text{on flux}}$ ranges from ~ 3 to ~ 10 depending on field configuration.

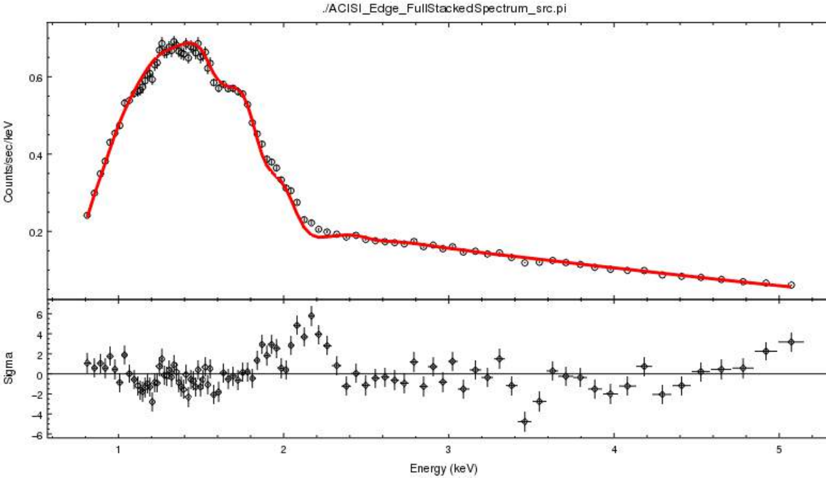


M31-like



Milky Way-like

The 3.5 keV dip



The 3.5 keV dip

- Absorption by dark matter.
- If the magnetic field along the line of sight to the centre of Perseus is fortuitously efficient at mixing 3.5 keV photons and axions, the deficit at 3.5 keV from the AGN and the excess at 3.5 keV from the cluster body could arise from the same physics.

Conclusions

- We use the spectrum of NCG1275 to place leading bounds on the axion-photon coupling.
- We observe residuals in the spectrum at high local significance consistent with the effects of axions.
- The $DM \to a \to \gamma$ scenario reconciles a dark matter explanation for the 3.5 keV line with the non-observation in external galaxies and the line morphology in clusters.