Predictions for a 3.5 keV photon line from dark matter decay to axion like particles

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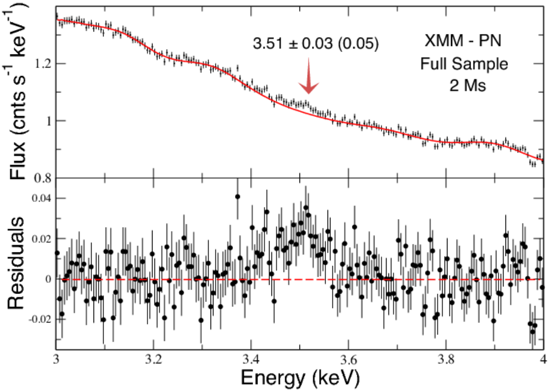
1403.2370: M Cicoli, J P Conlon, M C D Marsh & M Rummel
1404.7741: J P Conlon & FD
1410.1867: P Alvarez, J P Conlon, FD, M C D Marsh & M Rummel

Outline

1. The 3.5 keV line
2. $\mathrm{DM} \to a \to \gamma$
3. Predictions
   - Milky Way
   - Milky Way Centre
   - Andromeda
   - Other Galaxies
4. Conclusions

Observations

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)
- Spectral modelling of the galactic centre region is highly complex - very difficult to draw definitive conclusions from observations.
- Observations with forthcoming *ASTRO-H* telescope?

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, Tamaru *et al* 1412.1869, Urban *et al* 1411.0050)

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 $F \propto \rho_{DM}^2$
- Ruled out at 11.8σ by non-observation in stacked galaxy spectra (Anderson *et al* 1408.4115)
- All models with direct dark matter decay to photons are ruled out by this non-observation.

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).

Dark Matter?

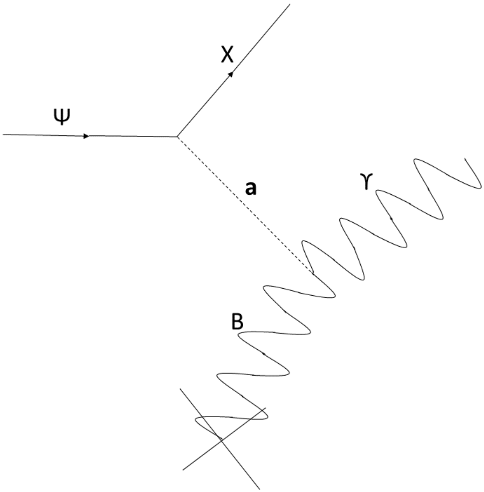
- Non-observation in galaxies is inconsistent with observation in galaxy clusters for dark matter decay or annihilation to photons
- Morphology of signal from clusters is inconsistent with direct decay or annihilation of dark matter to photons
- Our model explains these observations within the dark matter interpretation
- 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.

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

- Axion like particles (ALPs) are very light pseudo-scalars which naturally arise in string theory compactifications.
- ALPs mix with the photon in an external magnetic field through the dimension 5 term $\mathcal{L} \supset \frac{1}{8M} a F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{1}{M} a \mathbf{E} \cdot \mathbf{B}$
- Unlike the QCD axion, ALPs do not in general couple to QCD. Their mass and couplings are, a priori, independent parameters.

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

For example:



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

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

- Dark matter decays to an axion like particle (ALP) 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.
- Scalar DM: $\mathcal{L} \supset \frac{\Phi}{\Lambda}\partial_\mu a \partial^\mu a$
- Fermionic DM: $\mathcal{L} \supset \frac{\partial_\mu a}{\Lambda}\bar{\psi}\gamma^\mu\gamma^5\chi$
- Requires branching ratio to ALPs $\gg$ branching ratio to photons

ALPs

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

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

- $\Delta_\gamma = \frac{-\omega_{pl}^2}{2\omega}$
- 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 $m_a = 0$)
- Mixing: $\Delta_{\gamma ai} = \frac{B_i}{2M}$
- The expected photon flux is set by $\tau_{DM} M^2$

ALPs: Single Domain

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

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

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

ALPs: 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 $\Delta \ll 1$.

ALP to photon conversion

- Conversion probability dominated by magnetic field strength
- $P\left(a \to \gamma\right) \propto \frac{B_\perp^2}{M^2}$
- $P\left(a \to \gamma\right)$ increases with the field coherence length and the total extent of the field.
- Conversion suppressed by high electron densities.
- Obtain conversion probabilities using a discretized simulation of the axion-photon vector propagation

Dark Matter Lifetime

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

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

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

$$\tau_{\mathrm{ALP}} \sim 5 \times 10^{27}\,\mathrm{s} \times P_{a\to\gamma}^{cluster}\Big|_{M=10^{13}\,\mathrm{GeV}} \left(\frac{10^{13}\,\mathrm{GeV}}{M}\right)^2$$

Predictions

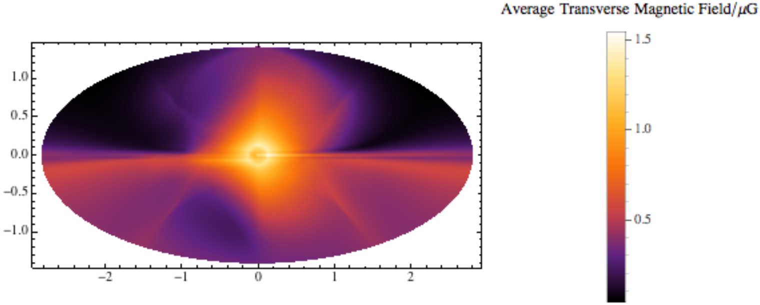
This model was developed to explain the 3.5 keV line signal in galaxy clusters. What does it predict in other systems?

- The Milky Way
- The Milky Way centre
- Andromeda
- Other galaxies

Milky Way Magnetic Field

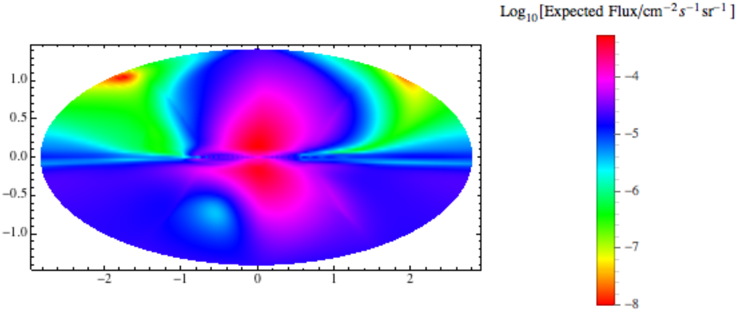
Recent model by Jansson and Farrar (1204.3662) based on 40,000 extragalactic Faraday rotation measures.

Field in central 1 kpc artificially set to zero



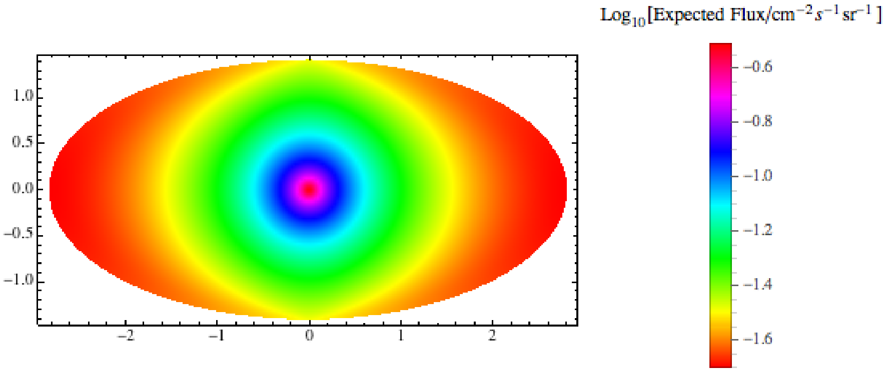
The average regular transverse magnetic field experienced by an ALP on a path starting 20 kpc from the Earth and ending at the Earth.

Expected Flux for $DM \to a \to \gamma$



Taking $P^{cluster}_{a\to\gamma}|_{M=10^{13}\,\mathrm{GeV}} = 10^{-3}$, based on detailed simulation of Coma (Angus *et al* 1312.3947). This may overestimate $P^{cluster}_{a\to\gamma}$, and therefore underestimate τ_{ALP} somewhat.

Expected Flux for $DM \rightarrow \gamma$



Milky Way Results

- 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 $\sim 2 \times 10^{-4}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$
- The corresponding maximum count rate on ASTRO-H's Soft X-ray Spectrometer is $\sim 4 \times 10^{-8}\,\mathrm{s}^{-1}$.
- Detection with ASTRO-H would be impossible, in contrast to the direct decay case.
- Possible exception of the Milky Way Centre

The Milky Way Centre

- Can the observation of the line signal in the Milky Way centre be reproduced with $DM \to a \to \gamma$?
- Estimates of the Milky Way centre magnetic field vary from $\mathcal{O}(10\,\mu\mathrm{G})$ to $\mathcal{O}(1\,\mathrm{mG})$
- An observable signal in the Milky Way centre is possible if $B \sim \mathcal{O}(1\,\mathrm{mG})$.
- Predicted morphology inconsistent with that found by Carlson, Jeltema & Profumo (1411.1758)...
- ... but $DM \to a \to \gamma$ is consistent with no true 3.5 keV line signal from the galactic centre.

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 ALPs 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 ALP created at the centre of M31 and propagating to Earth:

$B_\perp \sim 5\,\mu\mathrm{G}$

$L \sim R \sim 20\,\mathrm{kpc}$

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

Andromeda

- Estimate conversion probabilities two orders of magnitude higher than for the Milky Way.
- In the $DM \to a \to \gamma$ 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

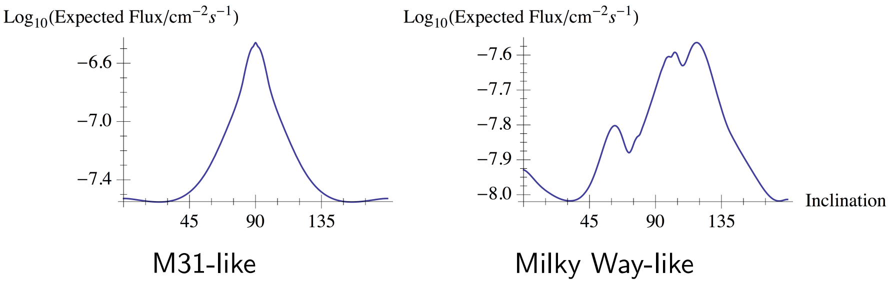
- We predict no 3.5 keV line signal in a generic stacked sample of galaxies, consistent with observations.
- We *might* be able to observe a signal from a stacked sample of edge-on spiral galaxies.

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 $\frac{\text{edge-on flux}}{\text{face-on flux}}$ ranges from ~ 3 to ~ 10 depending on field configuration.



Conclusions

- 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.
- The flux from the Milky Way halo in the $DM \to a \to \gamma$ scenario will be significantly lower than for $DM \to \gamma$.
- The predicted flux from the Milky Way centre is highly uncertain.
- ALP to photon conversion probabilities for M31 are two orders of magnitude larger than in the Milky Way, and are comparable with the conversion probabilities in clusters.
- We predict the 3.5 keV line might be observable in a stacked sample of the central few kpcs of edge-on spiral galaxies.