Predictions for a 3.55 keV photon line from dark matter decay to axions in the Milky Way

Francesca Day

University of Oxford

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Introduction

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- Sharp peak in the cool core region of Perseus
- Morphology inconsistent with direct decay of dark matter to photons

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- $P(a \to \gamma) \propto B_{\perp}^{2}$
- Fits the observed morphology of the 3.55 keV flux

ALPs

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

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

- $\Delta_\gamma = \frac{-\omega_{pl}^2}{2\omega}$
- 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: $\Delta_{\gamma ai} = \frac{B_i}{2M}$

ALPs: Small Angle Approximation

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

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

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- We use a full discretized simulation for propogation in the Milky Way.

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  We will assume this is typical of galaxy clusters.
- Therefore to reproduce the observed flux with $DM \rightarrow a \rightarrow \gamma$ we require:

$$\tau_{\rm ALP} \sim 5 \times 10^{24}\,{\rm s} \left(\frac{10^{13}\,{\rm GeV}}{M} \right)^2$$

Milky Way Dark Matter Halo

What does $DM \to a \to \gamma$ predict in the Milky Way?

NFW Profile:

$$\rho_{NFW}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2},$$

where $r_s = 20\,\mathrm{kpc}$ and $\rho_{NFW}(R_\odot) = 0.4\,\mathrm{GeV cm}^{-3}$
(Parameters from Fermi-LAT collaboration, 1305.5597)

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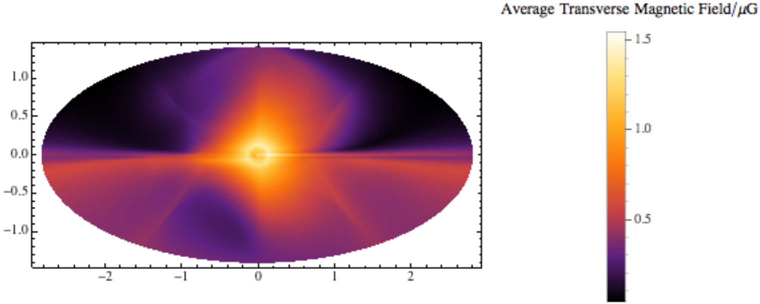
- Typical field strengths $B \sim O(1\,\mu\mathrm{G})$ in the disc
- Contains regular and random components.
- The random field has a coherence length of less than 100 pc, and so does not contribute significantly to $a \to \gamma$ conversion.
- Regular component, composed of disc, halo and X fields, has structure on the scale of the Milky Way.

Milky Way Magnetic Field



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

ALPs: Photoelectric Absorption

In the Milky Way, photoelectric absorption can be significant.
Damping parameter: $\Gamma = \sigma_{\rm eff} \left(n_{HI} + 2n_{H2} \right)$

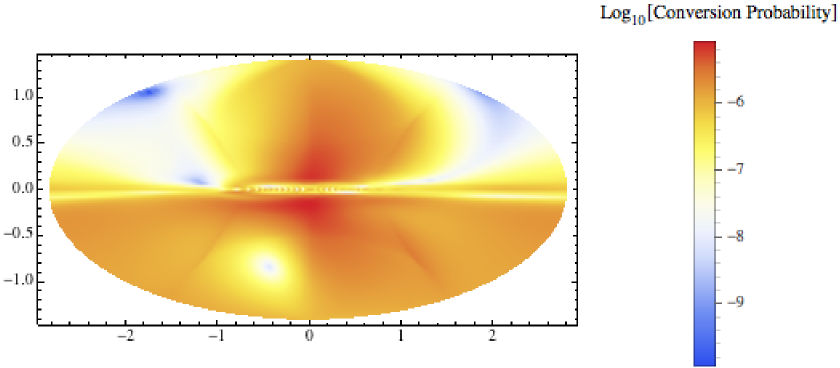
$$H = \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma ax} \\ 0 & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - \begin{pmatrix} i\frac{\Gamma}{2} & 0 & 0 \\ 0 & i\frac{\Gamma}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix} = M - iD,$$

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

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

For $\omega = 3.55\,\mathrm{keV}$, we find the effect is negligible.

$P(a \to \gamma)$ in the Milky Way



The ALP to photon conversion probability for an ALP with $M = 10^{13}\,\mathrm{GeV}$ starting at 30 kpc from the Earth and propagating to Earth.

Expected Photon Flux from Milky Way Halo

For direct decay $DM \to \gamma$:

$$F = \frac{1}{\tau_{\rm direct}} \frac{1}{4\pi} \int_{r=0}^{\infty} \frac{\rho_{DM}\left(r, \theta, \phi\right)}{m_{DM}} dr \, \mathrm{sr}^{-1},$$

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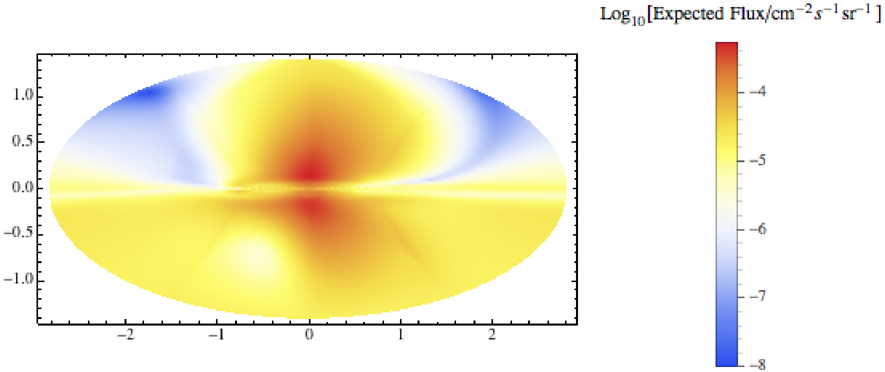
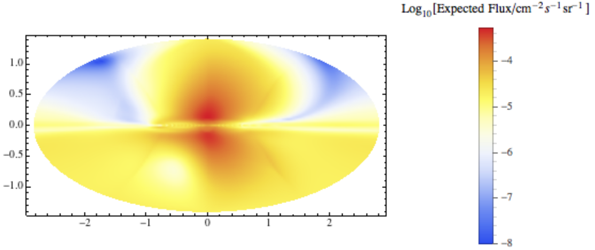
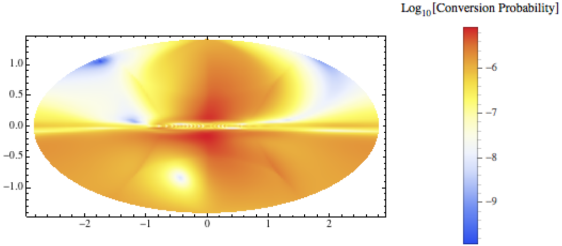
- Evaluate the integral as a sum for the first 30 spherical shells.
- For ALPs produced greater than 30 kpc from the Earth, we take $P\left(r > 30\,\mathrm{kpc}, \theta, \phi\right) = P\left(30\,\mathrm{kpc}, \theta, \phi\right)$ and integrate ρ_{DM} from $r = 30\,\mathrm{kpc}$ to $r = \infty$ numerically.

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



Expected Flux for $DM \to a \to \gamma$ and $P(a \to \gamma)$





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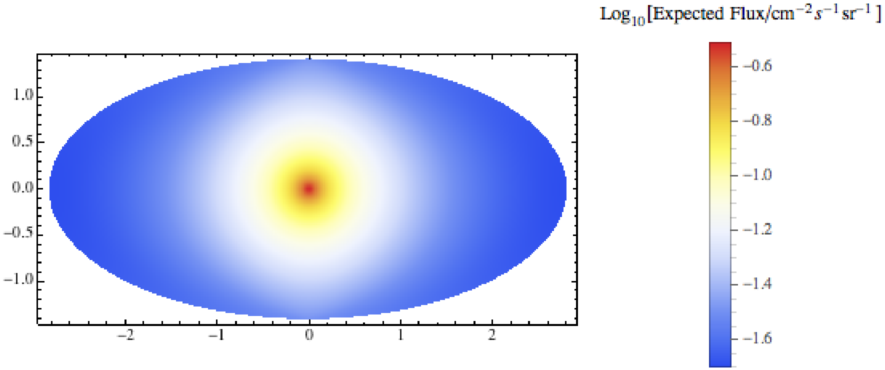

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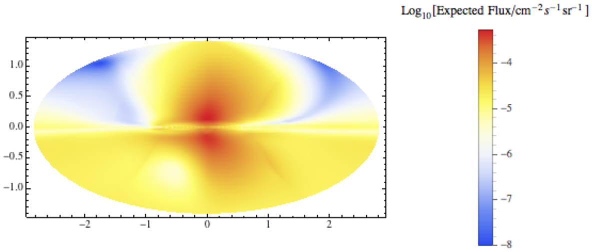

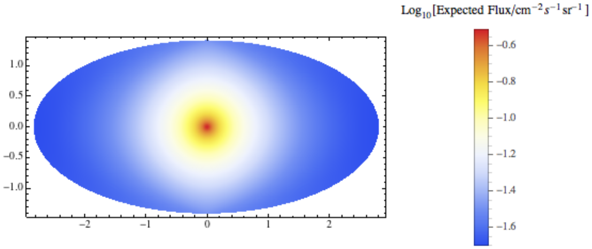

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- The corresponding maximum count rate on ASTRO-H's Soft X-ray Spectrometer is $\sim 4 \times 10^{-8}\,\mathrm{s}^{-1}$.
- Detection with ASTRO-H would be impossible, in contrast to the direct decay case.

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- The vertical scale height is at least 1 kpc.
- 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.

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Single domain small angle approximation for the conversion probability for a 3.55 keV ALP created at the centre of M31 and propagating to Earth:

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Single domain small angle approximation for the conversion probability for a 3.55 keV ALP created at the centre of M31 and propagating to Earth:
$B_\perp \sim 5\,\mu\mathrm{G}$
$L \sim R \sim 20\,\mathrm{kpc}$

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

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Andromeda

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- 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 3.55 keV line.

Conclusions

1. The flux from the Milky Way halo in the $DM \rightarrow a \rightarrow \gamma$ scenario will be significantly lower than for the case of direct dark matter decay to photons, and will be unobservable with ASTRO-H.

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Conclusions

1. The flux from the Milky Way halo in the $DM \rightarrow a \rightarrow \gamma$ scenario will be significantly lower than for the case of direct dark matter decay to photons, and will be unobservable with ASTRO-H.
2. 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.
3. A non-observation of the 3.55 keV line from the Milky Way with ASTRO-H will not rule out a dark matter origin of the signal.

ALPs: Single Domain

$$\tan(2\theta) = 5.0 \times 10^{-3} \times \left(\frac{10^{-3}\,\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{B_\perp}{1\,\mu\mathrm{G}}\right)\left(\frac{\omega}{3.55\,\mathrm{keV}}\right)\left(\frac{10^{13}\,\mathrm{GeV}}{M}\right)$$

$$\Delta = 0.015 \times \left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)\left(\frac{3.55\,\mathrm{keV}}{\omega}\right)\left(\frac{L}{1\,\mathrm{kpc}}\right).$$

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

- $P(a \to \gamma) \propto \frac{B_\perp^2}{M^2}$
- For small conversion probabilities, $P(a \to \gamma)$ increases with the domain size L.
- Conversion suppressed by high electron densities.

Milky Way Electron Density

- Gomez and Cox (2001) model, sum of thick and thin disk components
- Thick disk component:

$$n_{\rm thick} = 1.77\times10^{-2}\,{\rm cm}^{-3}\times\frac{{\rm sech}^2\left(\frac{\rho}{15.4\,{\rm kpc}}\right)}{{\rm sech}^2\left(\frac{R_\odot}{15.4\,{\rm kpc}}\right)}{\rm sech}^2\left(\frac{z}{1.10\,{\rm kpc}}\right)$$

- Thin disk component:

$$n_{\rm thin} = 1.07\times10^{-2}\,{\rm cm}^{-3}\times\frac{{\rm sech}^2\left(\frac{\rho}{3.6\,{\rm kpc}}\right)}{{\rm sech}^2\left(\frac{R_\odot}{3.6\,{\rm kpc}}\right)}{\rm sech}^2\left(\frac{z}{0.04\,{\rm kpc}}\right)$$

- Minimum n_e of $10^{-7}\,{\rm cm}^{-3}$

Photo-electric absorption

- Scattering cross sections in Morrison and McCammon (1983), given as an effective cross section per hydrogen atom: $\Gamma = \sigma_{\mathrm{eff}} \left(n_{HI} + 2 n_{H2} \right)$
- For a 3.55 keV photon, $\sigma_{\mathrm{eff}} \sim 10^{-23}\,\mathrm{cm}^2$.
- Neutral hydrogen distributions from Misiriotis et al (2006):

$$n_{HI} = \begin{cases} 0.32\,\mathrm{cm}^{-3} \exp\left(-\frac{\rho}{18.24\,\mathrm{kpc}} - \frac{|z|}{0.52\,\mathrm{kpc}} \right), & \text{if } \rho \geq 2.75\,\mathrm{kpc} \\ 0, & \text{otherwise} \end{cases}$$

$$n_{H2} = 4.06\,\mathrm{cm}^{-3} \exp\left(-\frac{\rho}{2.57\,\mathrm{kpc}} - \frac{|z|}{0.08\,\mathrm{kpc}} \right).$$

Simulation

- Discretize the field:

$$\rho_k = e^{-iH_k \delta z} \rho_{k-1} e^{iH_k^\dagger \delta z}$$

- Simulate the propagation of ALPs created at 1 kpc, 2 kpc, ... and 30 kpc from the Earth. Magnetic field has structure on the scale of the whole Milky Way - must simulate each path seperately.
- Assume ALPs created over 30 kpc from the Earth propagate without conversion up to this point.
- 20000 points in the sky, 4000 domains for each path