Observing the String Axiverse

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Young Theorists' Forum, 2016

1404.7741: J P Conlon & FD
1410.1867: P Alvarez, J P Conlon, FD, M C D Marsh & M Rummel
1506.05334: FD

Outline

The String Axiverse

- String theory compactificiations typically give rise to many moduli and axion fields, populating many decades in mass.
- Axions are ultra-light pseudo-Nambu-Goldstone bosons of global $U(1)_A$ symmetries.
- Axions are singlets under the SM gauge group, with weak effective interactions to the SM suppressed by the symmetry breaking scale M.
- We may choose the axion basis such that one is the QCD axion and the rest have no coupling to gluons.

Axion production

Axions may be produced in the early universe by:

- Misalignment production (dark matter and dark energy)
- Decay of moduli (dark radiation)

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.
- For low mass axions ($m_a \lesssim 10^{-10}\,\mathrm{eV}$), $M > 2 \times 10^{11}\,\mathrm{GeV}$ from SN1987a (Brockway, Carlson and Raffelt astro-ph/9605197).
- 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 $m_a = 0$)
- 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.

Semi-analytic formula

For $P_{a\to\gamma} \ll 1$:

$$P_{a\to\gamma}(L) = \sum_{i=x,y} \left| \int_0^L dz e^{i\varphi(z)} \Delta_{\gamma ai}(z) \right|^2 , \qquad (1)$$

where,

$$\varphi(z) = \int_0^z dz' \Delta_\gamma(z') = -\frac{1}{\omega} \int_0^z dz' \omega_{pl}^2(z') . \qquad (2)$$

- $\Delta_\gamma(z) \propto n_e$
- Electron density rotates the probability amplitudes $\langle 1,0,0|f(L)\rangle$ and $\langle 0,1,0|f(L)\rangle$ in the complex plane as L increases, suppressing the efficacy of the magnetic field in increasing the conversion probability over increasing distances.

Photoelectric absorption

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

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

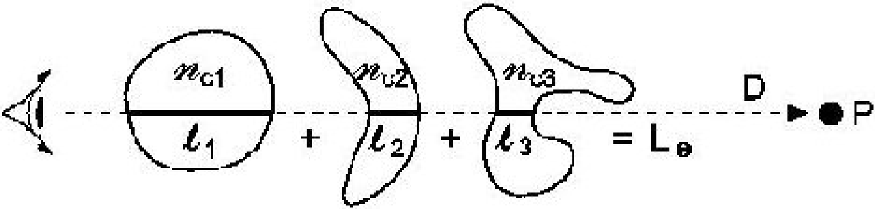
$$\rho = \begin{pmatrix} \mid \gamma_x\rangle \\ \mid \gamma_y\rangle \\ \mid a\rangle \end{pmatrix} \otimes \begin{pmatrix} \mid \gamma_x\rangle & \mid \gamma_y\rangle & \mid a\rangle \end{pmatrix}^*$$

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

Electron density

- Smooth electron density models used in previous work on axion-photon conversion.
- This approximates the *volume averaged* electron density.
- Astrophysical electron densities may exist in high density clouds with much lower inter-cloud electron density.
- Characterized by the filling factor f, the fraction of a line of sight occupied by clouds.

Electron density



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Do we predict the wrong conversion probability using the volume averaged distribution?

Electron density

The electron density rotates $A(L) = \langle 1,0,0|f(L)\rangle$ in the complex plane.

$$P_{a\to\gamma}(L) = \left| \int_0^L dz e^{i\varphi(z)} \frac{B_x(z)}{2M} \right|^2 , \tag{3}$$

where,

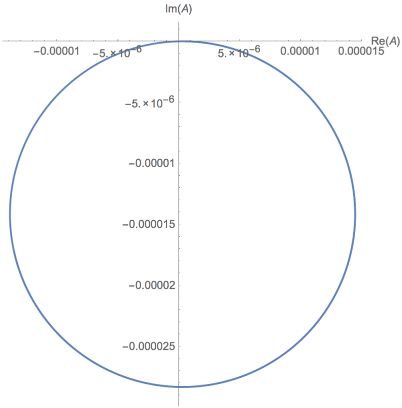
$$\varphi(z) = \int_0^z dz' \Delta_\gamma(z') = -\frac{1}{\omega} \int_0^z dz' \omega_{pl}^2(z') , \tag{4}$$

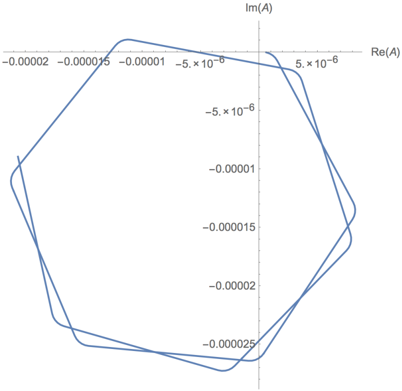
with

$$\omega_{pl}^2 = 4\pi\alpha \frac{n_e}{m_e} . \tag{5}$$

- The angle of turn in the complex plane is given by $\varphi(z)$, which is linear in $n_e(z)$.
- Whether this turning happens continuously or in steps does not significantly effect $P_{a\to\gamma}$.

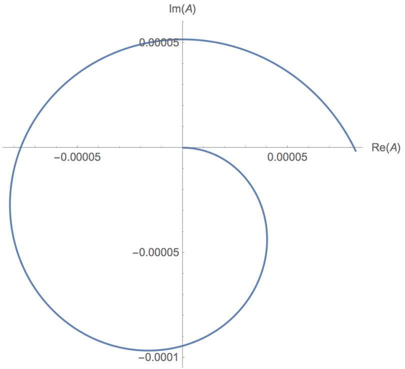
Electron density

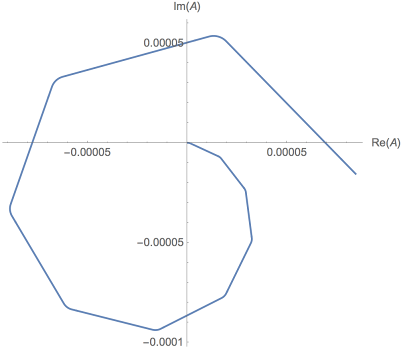




$A(L) = \int_0^L dz e^{i\varphi(z)} \Delta_{\gamma ai}(z)$ for $L = 0 - 1\,\mathrm{kpc}$. $B_\perp = 1\,\mu\mathrm{G}$, $\overline{n}_e = 0.05\mathrm{cm}^{-3}$, $d_c = 10\,\mathrm{pc}$, $f = 0.1$, $M = 10^{13}\,\mathrm{GeV}$ and $\omega = 500\,\mathrm{eV}$. LHS: volume averaged, $P_{a\to\gamma}^{\mathrm{average}} = 4.9 \times 10^{-10}$ RHS: clouds, with an intercloud electron density of $10^{-7}\,\mathrm{cm}^{-3}$, $P_{a\to\gamma}^{\mathrm{clouds}} = 5.2 \times 10^{-10}$.

Electron density



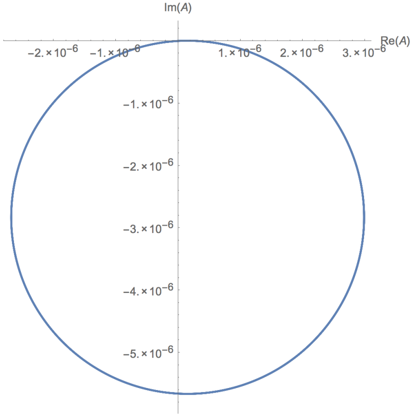


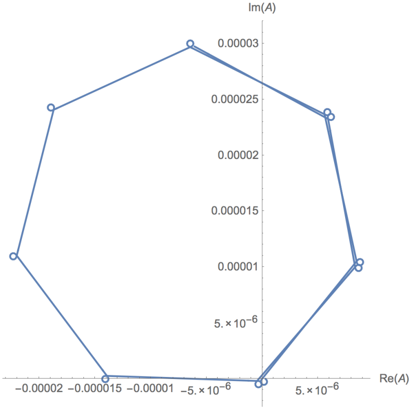
$A(L) = \int_0^L dz e^{i\varphi(z)} \Delta_{\gamma a i}(z)$ for $L = 0 - 1\,\mathrm{kpc}$. $B_\perp = \mathrm{e}^{\frac{z}{0.5\,\mathrm{kpc}}}\,\mu\mathrm{G}$, $\overline{n}_e = 0.02\mathrm{e}^{\frac{z}{1\,\mathrm{kpc}}}\,\mathrm{cm}^{-3}$, $d_c = 10\,\mathrm{pc}$, $f = 0.1$, $M = 10^{13}\,\mathrm{GeV}$ and $\omega = 500\,\mathrm{eV}$. LHS: volume averaged, $P^{\mathrm{average}}_{a\to\gamma} = 6.8 \times 10^{-9}$ RHS: clouds, with an intercloud electron density of $10^{-7}\,\mathrm{cm}^{-3}$, $P^{\mathrm{clouds}}_{a\to\gamma} = 7.3 \times 10^{-9}$.

Electron density

- $e^{i\varphi(z)}$ is also *periodic* in $n_e(z)$
- What happens if $\varphi(z)$ changes by $\gtrsim 2\pi$ within a single cloud?
- This regime is reached for high electron densities, low filling factors and/or low axion energies.
- In this regime, the overall *large scale* turning of A in the complex plane is decreased by the organisation of n_e into clouds.
- The significant ($\gtrsim 2\pi$) turning within a cloud essentially gives us a 'free lunch' - the volume averaged electron density is increased, but there is no contribution to the net large scale turning.

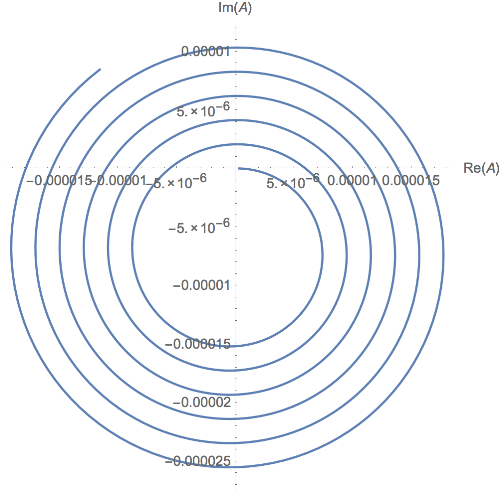
Electron density





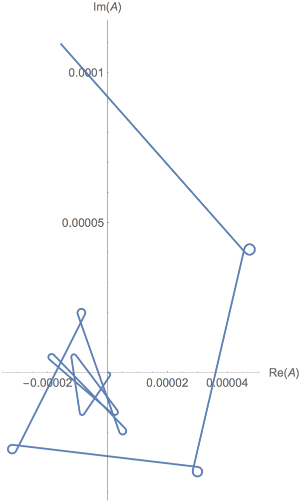
As before with $\omega = 100\,\mathrm{eV}$ rather than $\omega = 500\,\mathrm{eV}$. For the volume averaged case, $P_{a\to\gamma}^{\mathrm{average}} = 3.0 \times 10^{-11}$. With clouds, $P_{a\to\gamma}^{\mathrm{clouds}} = 9.2 \times 10^{-10}$.

Electron density



Volume averaged, $P^{\text{average}}_{a\to\gamma} = 2.1 \times 10^{-10}$

Electron density



Cloud Structure, $P_{a\to\gamma}^{\text{clouds}} = 1.2 \times 10^{-8}$

Electron density

We therefore see that the condition for the cloud structure of the WIM to be significant is:

Change in $\varphi(z)$ within an electron cloud $\gtrsim 2\pi$

$$\delta = 1.1 \times 10^{-2} \left(\frac{n_c}{10^{-2}\,\mathrm{cm}^{-3}} \right) \left(\frac{\mathrm{keV}}{\omega} \right) \left(\frac{\mathrm{cloud\,size}}{10\,\mathrm{pc}} \right) \gtrsim 2\pi$$

Electron Density

$$\delta = 1.1 \times 10^{-2} \left(\frac{n_c}{10^{-2}\,\mathrm{cm}^{-3}} \right) \left(\frac{\mathrm{keV}}{\omega} \right) \left(\frac{\mathrm{cloud\,size}}{10\,\mathrm{pc}} \right)$$

- If $\delta >> 2\pi$, the probability amplitude follows a discrete random walk in the complex plane.
- For a 2D discrete random walk with average step length l, the root mean square displacement after N steps is $l\sqrt{N}$
- Assume the magnetic field coherence length is greater than the distance between clouds
- Assuming the small angle approximation holds between clouds, we obtain:

$$P_{a\to\gamma} = \frac{L_c}{f} \frac{LB^2}{4M^2}$$

- This is independent of the magnetic field coherence length.

Dark radiation

Dark radiation axions arise from decay of heavier particles:

- In the early universe, giving a Cosmic Axion Background today
- At late times, for example dark matter decays

A Cosmic Axion Background

- A primordial CAB is a natural prediction of string inflation.
- Reheating is driven by the decay of moduli, which have a significant branching ratio to axions
- The resultant CAB spectrum is quasi-thermal and today redshifted to soft X-ray central energies.
- The CAB contributes to ΔN_{eff}.

Galaxy clusters

- We might detect a CAB as an excess of soft X-ray photons in environments with strong magnetic fields.
- Galaxy clusters host $1 - 10\,\mu\mathrm{G}$ fields over Mpc distances.
- There is a long standing excess in the soft X-ray ($E \lesssim 400\,\mathrm{eV}$) flux observed from galaxy clusters, above the predicted thermal emission from the intra-cluster medium.

See 1312.3947 (Angus, Conlon, Marsh, Powell and Witkowski)

The Milky Way

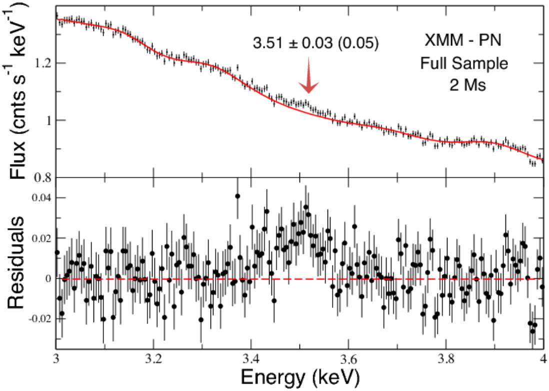
- Could we observe a diffuse flux from axion-photon conversion in the Milky Way?
- At soft X-ray energies, we find that $P_{a \to \gamma}$ is three orders of magnitude lower in the Milky Way than in galaxy clusters.
- Therefore a CAB would not be observable by its passage through the Milky Way.

Starburst galaxies

- Starburst galaxies host strong magnetic fields of up to $\mathcal{O}\,(100\,\mu\mathrm{G})$.
- The electron density is correspondingly higher at $\mathcal{O}\,(100 - 1000\,\mathrm{cm}^{-3})$.
- $\delta \gg 1$, so we must take into account the cloud structure of the electron density.
- Using the random walk approximation, we obtain a conversion probability comparable to that in galaxy clusters.

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).



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.

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

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

- 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.

Axiverse intepretations

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

- This model does not predict the nature of the dark matter itself.
- Requires branching ratio to axions $\gg$ branching ratio to photons
- Moduli dark matter: $\mathcal{L} \supset \frac{\Phi}{\Lambda}\partial_\mu a \partial^\mu a$
- Axion dark matter: $\mathcal{L} \supset \lambda \sin\left(\frac{a_1}{M}\right)\partial_\mu a \partial^\mu a$ (?)

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

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

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
- 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 $\sim 2 \times 10^{-4}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$
- 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

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:
$B_{\perp} \sim 5\,\mu\mathrm{G}$
$L \sim R \sim 20\,\mathrm{kpc}$

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

Andromeda

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

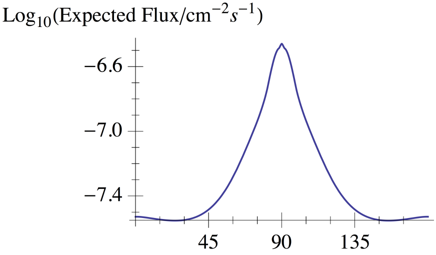
- We predict no 3.5 keV line signal in a generic stacked sample of galaxies, consistent with observations.
- We *might* be able to observe a signal from a stacked sample of edge-on spiral galaxies or from starburst galaxies.

Face on

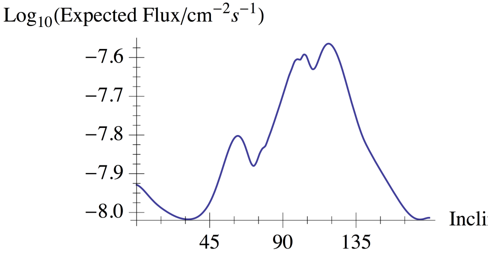
Edge on

Galaxy Inclination

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



M31-like



Milky Way-like

Conclusions

- Axions may be observed through axion-photon conversion in astrophysical magnetic fields.
- I have derived a condition for when the cloud structure of a galaxy's electron density is relevant for axion-photon conversion:

$$\delta = 1.1 \times 10^{-2} \left(\frac{n_c}{10^{-2}\,\mathrm{cm}^{-3}}\right) \left(\frac{\mathrm{keV}}{\omega}\right) \left(\frac{\mathrm{cloud\,size}}{10\,\mathrm{pc}}\right) \gtrsim 2\pi$$

- The signal from axion-photon conversion in the Milky Way is unobservable.
- In addition to galaxy clusters, starburst galaxies may be good observational targets for axion-photon conversion. In this environment, the cloud structure of the electron density is crucial.

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.
- We predict the 3.5 keV line might be observable in a stacked sample of the central few kpcs of edge-on spiral galaxies or in starburst galaxies.