Axions and X-ray polarimetry

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Dark Side of the Universe
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Outline

1. Axions
2. Axion searches in X-rays
3. Axion searches in X-ray polarimetry
4. Conclusions

Axions

- Axions are ultra-light particles that exist in many extensions of the Standard Model
- They are pseudo-Nambu Goldstone bosons of global $U(1)$ symmetries.
- Explain null measurements of the neutron electric dipole moment
- String theory compactificiations typically give rise to many axions at a range of masses
- Axions can act as both dark matter and dark energy

Axions

- Axions are theoretically well motivated, but their cosmological abundance and phenomenology depends on many unknown parameters.
- We remain agnostic as to axion cosmology, and seek to constrain the existence of the axion in particle physics.

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

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

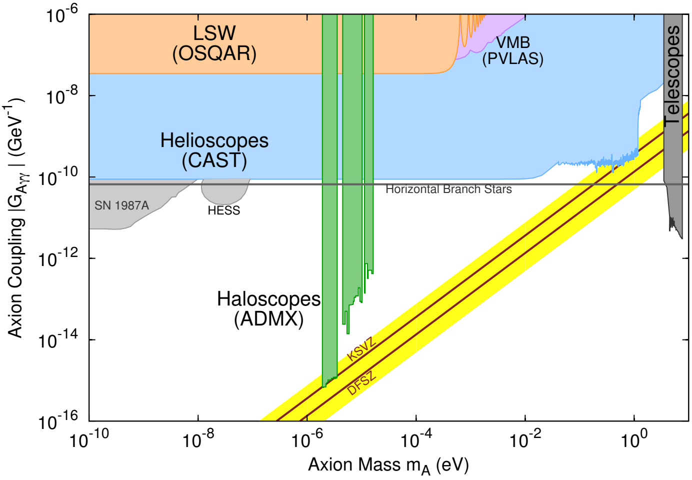
- $\Delta_\gamma = \frac{-\omega_{pl}^2}{2\omega}$
- Plasma frequency: $\omega_{pl} = \left(4\pi\alpha\frac{n_e}{m_e}\right)^{\frac{1}{2}}$
- $\Delta_a = \frac{-m_a^2}{\omega}$.
- Here we take $m_a = 0$. This is valid for $m_a \lesssim 10^{-12}\,\mathrm{eV}$.
- Mixing: $\Delta_{\gamma ai} = \frac{B_i}{2M}$

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

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.

Limits



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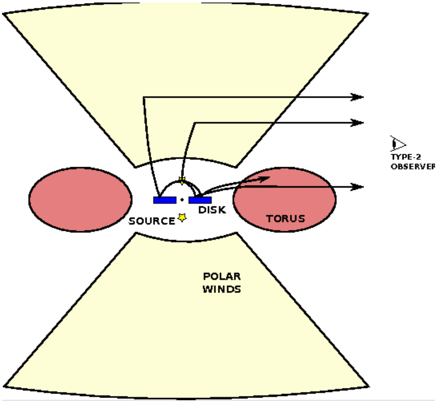
Spectral Modulations

We search for axions by studying the X-ray spectra of point sources in or behind galaxy clusters.

Galaxy clusters

Photon survival probability



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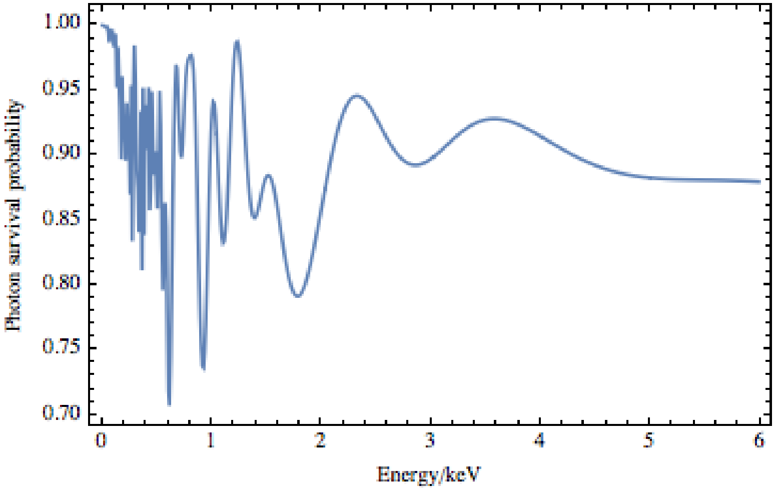
Photon survival probability

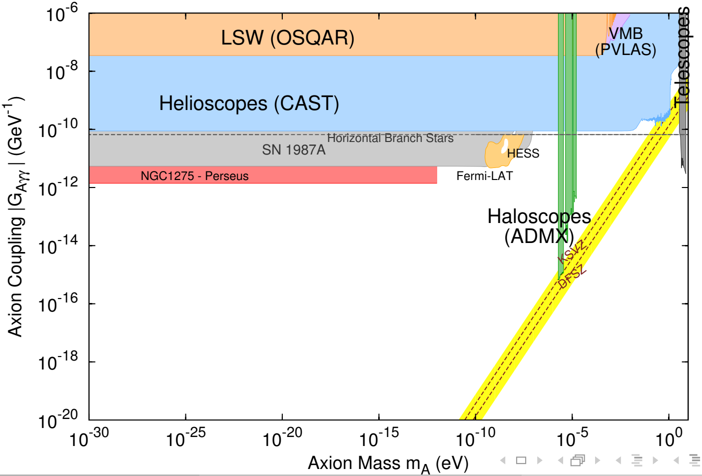


Photon-Axion Conversion

- 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.

Bounds

The leading bounds are from NGC1275 in Perseus, 2E3140 in A1795 and M87 in Virgo: $M \gtrsim 7 \times 10^{11}$ GeV.



Axion-photon conversion

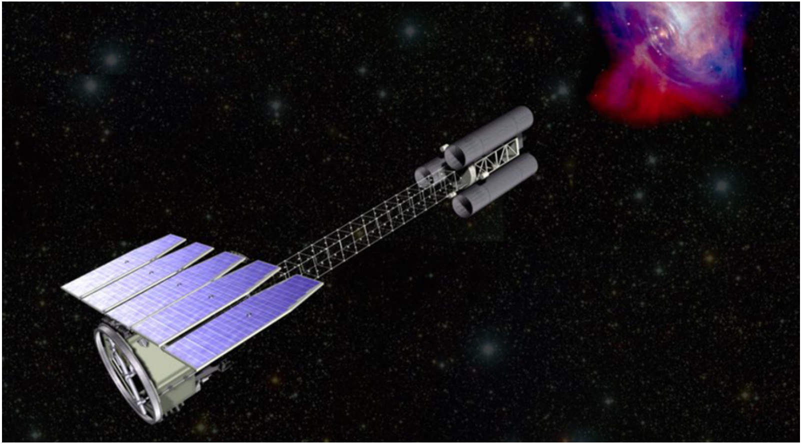
$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma ax} \\ 0 & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - i\partial_z\right) \begin{pmatrix} |\,\gamma_x\rangle \\ |\,\gamma_y\rangle \\ |\,a\rangle \end{pmatrix} = 0$$

Only the photon polarization parallel to the external magnetic field participates in axion-photon conversion.

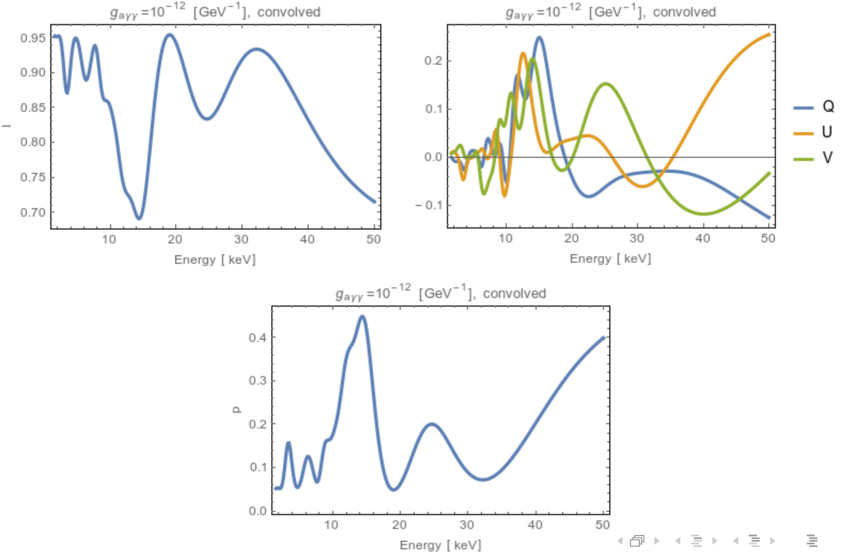
Stokes parameters

Definitions, idea

IXPE



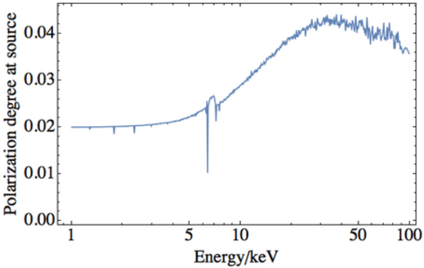
Polarimetry oscillations

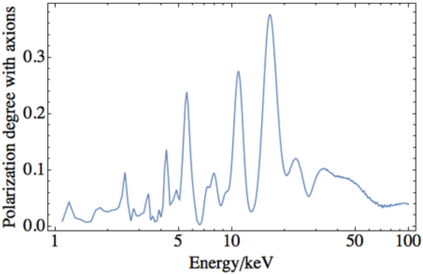


Polarimetry oscillations

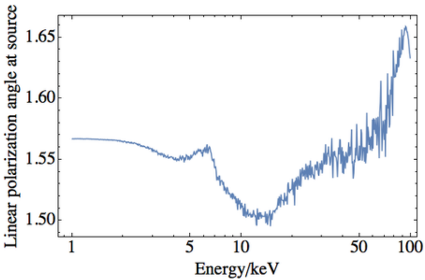
Assuming a featureless intrinsic AGN polarisation, we project constraints of $M \gtrsim 8 \times 10^{11}$ GeV with IXPE.

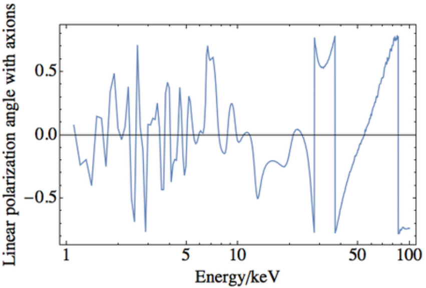
Type I AGN polarization



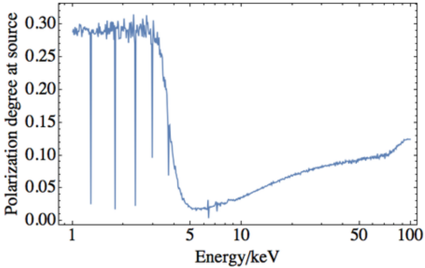


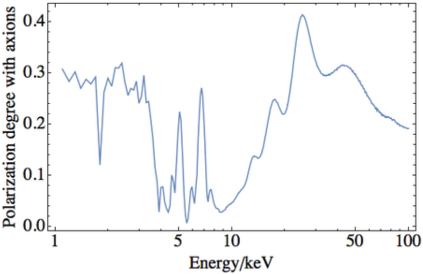
Type I AGN polarization



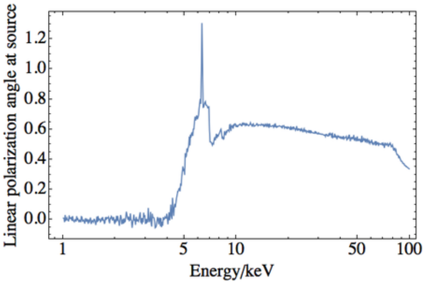


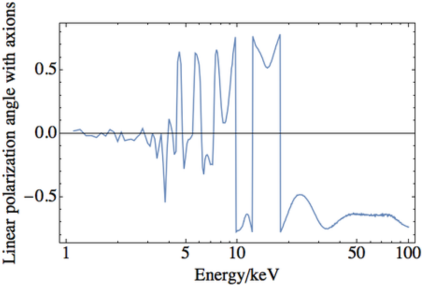
Type II AGN polarization





Type II AGN polarization





Convolution

Axions and AGN polarization

- Axion effects may be clearly present in AGN polarization spectra.
- Competitve bounds on axions may be obtained by studying these spectra.
- Correlation between polarisation and flux anomalies may provide a smoking gun signal for axions.
- Axion effects may effect estimation of AGN parameters

Conclusions

- Axions are a well motivated dark matter candidate.
- Axions and photons interconvert in the presence of a background magnetic field.
- Astrophysical magnetic fields offer powerful opportunities to search for axions.
- Points sources passing through galaxy clusters have the potential to place world leading bounds on the axion photon interaction.

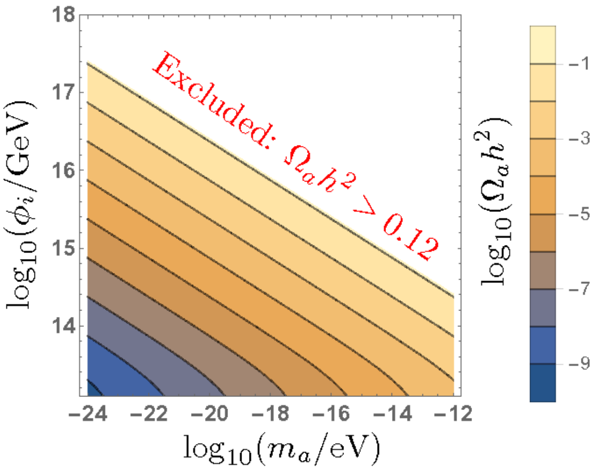
Bounds procedure I

Bounds procedure II

Cosmological Axion Populations

- Vacuum realignment
- Decay of topological defects
- Thermal axions
- Decay of parent particle

Cosmological Axion Populations



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