ALP-Photon Mixing as a Cosmic Magnetometer

Geoff Beck and Sergio Colafrancesco

University of the Witwatersrand, Johannesburg
School of Physics

October 14, 2013
Topics Covered

- Axion-like Particles and Astrophysics
Topics Covered

- Axion-like Particles and Astrophysics
- ALP-Photon Mixing Formalism
Topics Covered

- Axion-like Particles and Astrophysics
- ALP-Photon Mixing Formalism
- Spectral Features
Topics Covered

- Axion-like Particles and Astrophysics
- ALP-Photon Mixing Formalism
- Spectral Features
- Polarisation Effects
Topics Covered

- Axion-like Particles and Astrophysics
- ALP-Photon Mixing Formalism
- Spectral Features
- Polarisation Effects
- Astrophysical Applications
QCD vacuum parameter $\theta$ leads to Neutron electric dipole moments without “fine-tuning”.

Axion-like particles and Astrophysics
Axion-like particles and Astrophysics

- QCD vacuum parameter $\theta$ leads to Neutron electric dipole moments without “fine-tuning”.
- If promoted to a dynamical field associated with a $U(1)$ symmetry $\theta$ can be minimised.
Axion-like particles and Astrophysics

- QCD vacuum parameter $\theta$ leads to Neutron electric dipole moments without "fine-tuning".
- If promoted to a dynamical field associated with a $U(1)$ symmetry $\theta$ can be minimised.
- This Peccei-Quinn $U(1)$ symmetry has a breaking scale leading to pseudo Nambu-Goldstone Bosons called axions.
Axion-like particles and Astrophysics

- QCD vacuum parameter $\theta$ leads to Neutron electric dipole moments without “fine-tuning”.
- If promoted to a dynamical field associated with a $U(1)$ symmetry $\theta$ can be minimised.
- This Peccei-Quinn $U(1)$ symmetry has a breaking scale leading to pseudo Nambu-Goldstone Bosons called axions.
- Axions are pseudo-scalars with a two-photon vertex, this leads to axion-photon mixing.
The Lagrangian for the axion field $a$ takes the form:

$$\mathcal{L} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a - \frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a.$$  (1)
The Lagrangian for the axion field $a$ takes the form:

$$\mathcal{L} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a - \frac{1}{4} g_a \gamma F_{\mu\nu} \tilde{F}^{\mu\nu} a.$$  \hspace{1cm} (1)

With the term $-\frac{1}{4} g_a \gamma F_{\mu\nu} \tilde{F}^{\mu\nu} a$ giving the interaction
Source of Mixing: Cosmic Magnetic fields

- Intra-cluster fields $\rightarrow B \sim \mathcal{O}(\mu G)$ field known by Faraday rotation measures.
- Inter-galactic field $\rightarrow$ Weak field, Upper bounds only (nG).
Axion-like particles and Astrophysics

- **Source of Mixing: Cosmic Magnetic fields**
  - Intra-cluster fields → $B \sim O(\mu G)$ field known by Faraday rotation measures.
  - Inter-galactic field → Weak field, Upper bounds only (nG).
- If mixing occurred in such fields how would it manifest in observation?
  - Reduced EBL absorption (X-ray spectral hardening)?
Axion-like particles and Astrophysics

- Source of Mixing: Cosmic Magnetic fields
  - Intra-cluster fields $\rightarrow B \sim O(\mu G)$ field known by Faraday rotation measures.
  - Inter-galactic field $\rightarrow$ Weak field, Upper bounds only (nG).
- If mixing occurred in such fields how would it manifest in observation?
  - Reduced EBL absorption (X-ray spectral hardening)?
  - Spectral imprints on point-like sources?
Axion-like particles and Astrophysics

- Source of Mixing: Cosmic Magnetic fields
  - Intra-cluster fields → $B \sim O(\mu G)$ field known by Faraday rotation measures.
  - Inter-galactic field → Weak field, Upper bounds only (nG).
- If mixing occurred in such fields how would it manifest in observation?
  - Reduced EBL absorption (X-ray spectral hardening)?
  - Spectral imprints on point-like sources?
  - Polarisation effects?
ALP-Photon Mixing

- Photons have an “effective mass” conferred by plasma effects
ALP-Photon Mixing

- Photons have an “effective mass” conferred by plasma effects
- Neglect Cotton-Mouton (weak fields) and Faraday rotation effects (for high frequency)
ALP-Photon Mixing

- Photons have an “effective mass” conferred by plasma effects
- Neglect Cotton-Mouton (weak fields) and Faraday rotation effects (for high frequency)

\[(\omega + i\partial_z + \mathcal{M}) \begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} = 0 ,\]
ALP-Photon Mixing

- Photons have an “effective mass” conferred by plasma effects
- Neglect Cotton-Mouton (weak fields) and Faraday rotation effects (for high frequency)

\[ (\omega + i \partial_z + M) \begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} = 0, \]

- Photons separated into those polarised parallel and perpendicular to the field (initial choice of axes 2 and 1 respectively). As only those parallel to the field can mix with ALPs.
Introduction
ALP-Photon Mixing Formalism
Spectral Features
Polarisation Effects
Astrophysical Applications
Conclusion
ALP-Photon Mixing Matrix

\[
\mathcal{M} = \begin{pmatrix}
\frac{\omega_{pl}^2}{2\omega} + \Delta \text{CM}_\perp & \Delta R & 0 \\
\Delta R & \frac{\omega_{pl}^2}{2\omega} + \Delta \text{CM}_\parallel & -\frac{1}{2}g_{a\gamma}B_T \\
0 & -\frac{1}{2}g_{a\gamma}B_T & \frac{m_a^2}{2\omega}
\end{pmatrix}.
\]

- \(\omega_{pl}, m_a\rightarrow\) plasma frequency, ALP mass.
- \(\Delta R\) and \(\Delta \text{CM}\) are Faraday and Cotton-Mouton effects.
- \(g_{a\gamma}\rightarrow\) ALP-photon coupling.
- \(B_T\rightarrow\) Transverse magnetic field strength, configured \((0,B_T)\).
Homogenous Fields

- Diagonalise:

\[ P_{\gamma \rightarrow a}(z) = P_{a \rightarrow \gamma}(z) = \frac{\left( \frac{1}{2} g_{a\gamma} B_T z \right)^2}{(\Delta_{osc} z)^2} \sin^2 \left( \frac{\Delta_{osc} z}{2} \right) . \]  

(2)
### Homogenous Fields

- Diagonalise:

\[
P_{\gamma \rightarrow a}(z) = P_{a \rightarrow \gamma}(z) = \frac{\left(\frac{1}{2} g_{a\gamma} B_T z\right)^2}{(\Delta_{osc} z)^2} \sin^2 \left(\frac{\Delta_{osc} z}{2}\right). \tag{2}
\]

\[
\Delta_{osc} = \frac{2\pi}{l_{osc}} = \frac{1}{2\omega} \sqrt{\left(m_a^2 - \omega_{pl}^2\right)^2 + 4\omega^2 g_{a\gamma}^2 B_T^2},
\]

Geoff Beck and Sergio Colafrancesco
ALP-Photon Animation
Turbulent Fields

- Magnetic field characterised by a coherence length $d$. 
Turbulent Fields

- Magnetic field characterised by a coherence length $d$.
- On scales below $d$, the field is homogeneous.
Turbulent Fields

- Magnetic field characterised by a coherence length $d$.
- On scales below $d$, the field is homogeneous.
- On scales above $d$, the transverse Field orientation varies.
Turbulent Fields

- Magnetic field characterised by a coherence length $d$.
- On scales below $d$, the field is homogeneous.
- On scales above $d$, the transverse Field orientation varies.
- Effectively mixes $A_\parallel$ and $A_{\text{perp}}$ between domains, both can then interact with ALPs.
Turbulent Fields

- Magnetic field characterised by a coherence length $d$.
- On scales below $d$, the field is homogeneous.
- On scales above $d$, the transverse Field orientation varies.
- Effectively mixes $A_{\parallel}$ and $A_{\perp}$ between domains, both can then interact with ALPs.
- Can solve analytically inside each domain (by rotating to a basis with only 1 $B_T$ component), continuity applied at the boundaries.
Turbulent Fields II

- Propagation in a turbulent field:

\[ \rho(z + d) = U(d)R(\phi)\rho(z)R^\dagger(\phi)U^\dagger(d). \]

\(U(d)\) is the solution to the propagation equation for a homogeneous field of length \(d\).
Turbulent Fields II

- Propagation in a turbulent field:

\[ \rho(z + d) = U(d)R(\phi)\rho(z)R^\dagger(\phi)U^\dagger(d). \]

- \( U(d) \) is the solution to the propagation equation for a homogeneous field of length \( d \).
- \( R(\phi) \) is a rotation about the z axis, of random angle \( \phi \).
Propagation in a turbulent field:

\[ \rho(z + d) = U(d)R(\phi)\rho(z)R^\dagger(\phi)U^\dagger(d). \]

- \( U(d) \) is the solution to the propagation equation for a homogeneous field of length \( d \).
- \( R(\phi) \) is a rotation about the \( z \) axis, of random angle \( \phi \).
- The solution for \( z + d \) can then be rotated back into the original basis for \( A_1 \) and \( A_2 \) to retrieve polarisation data.
Every set of random angles \( \{\phi_i\} \) represents a different random field configuration.
Every set of random angles \( \{\phi_i\} \) represents a different random field configuration.

Termed a realisation of the field turbulence.
Every set of random angles \( \{\phi_i\} \) represents a different random field configuration.

Termed a realisation of the field turbulence.

In order to obtain meaningful data, we cannot consider any one realisation. We must average over many realisations.
Every set of random angles $\{\phi_i\}$ represents a different random field configuration.

Termed a realisation of the field turbulence.

In order to obtain meaningful data, we cannot consider any one realisation. We must average over many realisations.

This corresponds to a survey type measurement process.
The nature of the probability $P_{\gamma \rightarrow a}$ suggests there should be periodic features.

$$P_{a \rightarrow \gamma} \propto \sin^2 \left( \Delta_{osc} \frac{Z}{2} \right).$$
The nature of the probability $P_{\gamma \rightarrow a}$ suggests there should be periodic features.

$$P_{a \rightarrow \gamma} \propto \sin^2 \left( \Delta_{osc} \frac{Z}{2} \right).$$

We might expect all such features to be obscured by turbulence, as the argument of sin depends on $B_T$. 
The nature of the probability $P_{\gamma \rightarrow a}$ suggests there should be periodic features.

$$P_{a \rightarrow \gamma} \propto \sin^2 \left( \Delta_{osc} \frac{Z}{2} \right).$$

We might expect all such features to be obscured by turbulence, as the argument of sin depends on $B_T$.

In fact we find an energy-dependent threshold

$$\mathcal{O} \left( \frac{\Delta_m^2}{4E^2} \right) \sim \mathcal{O} \left( g_{a\gamma}^2 B_T^2 \right),$$

If $g_{a\gamma}^2 B_T^2$ exceeds this threshold then the spectral features become subject to turbulence.
Spectral Features II

Figure: Left: Photon survival probability for the Inter-galactic field. Right: Photon survival probability for an intra-cluster field.
Figure: Standard Deviation of Photon Survival Probability. Left: Inter-galactic field. Right: Intra-cluster field.
The conversion maxima vary between realisations (amplitude depends on $B_T$), the minima do not.
The conversion maxima vary between realisations (amplitude depends on $B_T$), the minima do not.

These are non-conversion energies are where all photons survive. They also exist identically in every realisation of the field (provided $d$ and plasma density vary insignificantly).
The conversion maxima vary between realisations (amplitude depends on $B_T$), the minima do not.

These are non-conversion energies are where all photons survive. They also exist identically in every realisation of the field (provided $d$ and plasma density vary insignificantly).

They can be analysed analytically,

$$E_n = \frac{\Delta m d}{\sqrt{n^2 \pi^2 - g_{a\gamma} B_T^2 d^2}} \approx \frac{\Delta m d}{n\pi} \quad (n\pi \gg g_{a\gamma} B_T d).$$
The conversion maxima vary between realisations (amplitude depends on $B_T$), the minima do not. These are non-conversion energies are where all photons survive. They also exist identically in every realisation of the field (provided $d$ and plasma density vary insignificantly). They can be analysed analytically,

$$E_n = \frac{\Delta m d}{\sqrt{n^2 \pi^2 - g_{a\gamma}^2 B_T^2 d^2}} \approx \frac{\Delta m d}{n\pi} \left( n\pi \gg g_{a\gamma} B_T d \right).$$

Even in the simplest form they contain information about the domain size and ALP-photon degeneracy.
Turbulence mixes how each polarisation state interacts with the ALPs.
Depolarisation

- Turbulence mixes how each polarisation state interacts with the ALPs.
- Photons polarised parallel to $B_T$ convert into ALPs; but ALPs can convert into either polarisation.
Depolarisation

- Turbulence mixes how each polarisation state interacts with the ALPs.
- Photons polarised parallel to $B_T$ convert into ALPs; but ALPs can convert into either polarisation.
- This means that if one polarisation state is dominant, it will convert into ALPs more often.
Polarisation I

Depolarisation

- Turbulence mixes how each polarisation state interacts with the ALPs.
- Photons polarised parallel to $B_T$ convert into ALPs; but ALPs can convert into either polarisation.
- This means that if one polarisation state is dominant, it will convert into ALPs more often.
- But back-conversion, from ALP to photon, will yield either polarisation state with equal probability.
Depolarisation

- Turbulence mixes how each polarisation state interacts with the ALPs.
- Photons polarised parallel to $B_T$ convert into ALPs; but ALPs can convert into either polarisation.
- This means that if one polarisation state is dominant, it will convert into ALPs more often.
- But back-conversion, from ALP to photon, will yield either polarisation state with equal probability.
- Thusly, the polarisation state populations must tend towards equality.
Figure: Left: Final Photon Polarisation angle inter-galactic field. Right: Final Photon Polarisation angle intra-cluster field.
**Figure:** Left: Photon survival probability for the Inter-galactic field. Right: Photon survival probability for an intra-cluster field.
Similar conversion probabilities yield very different depolarisation magnitudes.
Similar conversion probabilities yield very different depolarisation magnitudes.

The main difference is in the photon-to-photon oscillation length.

\[ l_{osc} = 2\pi \sqrt{\left(\frac{m^2 a - \omega^2}{\omega^2} \right)^2 + 4\omega^2 g^2 a^2 \gamma B^2 T}, \]

Stronger fields and couplings, or less degeneracy, result in shorter \( l_{osc} \) and more depolarisation.
Similar conversion probabilities yield very different depolarisation magnitudes.

The main difference is in the photon-to-photon oscillation length.

As previously argued photon-ALP-photon “flipping” causes depolarisation.
Similar conversion probabilities yield very different depolarisation magnitudes.

The main difference is in the photon-to-photon oscillation length.

As previously argued photon-ALP-photon “flipping” causes depolarisation.

Therefore, the shorter the photon-ALP-photon oscillation length ($l_{osc}$) the more depolarisation occurs.
Similar conversion probabilities yield very different depolarisation magnitudes.

The main difference is in the photon-to-photon oscillation length.

As previously argued photon-ALP-photon “flipping” causes depolarisation.

Therefore, the shorter the photon-ALP-photon oscillation length ($l_{osc}$) the more depolarisation occurs.

$$l_{osc} = \frac{2\pi}{\sqrt{\left(m_a^2 - \omega_{pl}^2\right)^2 + 4\omega^2 g_{a\gamma}^2 B_T^2}}$$
Figure: Depolarisation map for 10 point-sources at 1 GHz (0.3 < z < 3) viewed through the magnetic field of a 1 Mpc diameter galaxy cluster at z = 0.2. Red Arrows: Initial Polarisation, Green Arrows: Final Polarisation. (This neglects Faraday rotations).
Initially unpolarised radiation can also be polarised by ALP mixing.

This requires a favoured field direction (A. Payez et al (2011) [1]). This can be realised as a turbulent field with a weak background field with uniform direction. In strictly turbulent fields, one can observe a slight increase in polarisation $\sim O(1\%)$ in the high-energy limit of ALP-photon mixing.
Initially unpolarised radiation can also be polarised by ALP mixing. This requires a favoured field direction (A. Payez et al (2011) [1]).
Initially unpolarised radiation can also be polarised by ALP mixing.

This requires a favoured field direction (A. Payez et al (2011) [1]).

This can be realised as a turbulent field with a weak background field with uniform direction.
Polarisation

- Initially unpolarised radiation can also be polarised by ALP mixing.
- This requires a favoured field direction (A. Payez et al (2011) [1]).
- This can be realised as a turbulent field with a weak background field with uniform direction.
- In strictly turbulent fields, one can observe a slight increase in polarisation \( \sim \mathcal{O}(1\%) \) in the high-energy limit of ALP-photon mixing.
Now we focus on spectral imprints on point-like sources.
Now we focus on spectral imprints on point-like sources. Using Fermi-LAT data [2] we assume spectra should conform to a power-law. Then we convolve with an ALP-photon spectrum.
Now we focus on spectral imprints on point-like sources. Using Fermi-LAT data [2] we assume spectra should conform to a power-law. Then we convolve with an ALP-photon spectrum. By running many ALP/field parameter combinations we can locate those that are accommodated by the data and its uncertainties.
We chose the AGN NGC1275 in the Perseus cluster and the blazar PKS1830-210 at $z = 2.507$. 

Perseus field: $B_T < 20 \mu G$, domain size $d < 10$ kpc [4].

Inter-galactic field: $B_T < 1$ nG, domain size $d < 10$ Mpc [5].
We chose the AGN NGC1275 in the Perseus cluster and the blazar PKS1830-210 at \( z = 2.507 \). These provide examples using the intra-cluster and inter-galactic type fields respectively.
We chose the AGN NGC1275 in the Perseus cluster and the blazar PKS1830-210 at $z = 2.507$.

These provide examples using the intra-cluster and inter-galactic type fields respectively.

Perseus field: $B_T < 20\mu G$, domain size $d < 10$ kpc [4].
We chose the AGN NGC1275 in the Perseus cluster and the blazar PKS1830-210 at $z = 2.507$.

These provide examples using the intra-cluster and inter-galactic type fields respectively.

- Perseus field: $B_T < 20 \mu G$, domain size $d < 10$ kpc [4].
- Inter-galactic field: $B_T < 1nG$, domain size $d < 10$ Mpc [5].
**Figure:** Left: Perseus Cluster AGN NGC1275 convolved with ALP spectrum. Right: Blazar PKS1830-210 at $z = 2.507$
This “fitting” is achieved by testing which ALP spectra fit within the error bounds of the data.
This “fitting” is achieved by testing which ALP spectra fit within the error bounds of the data.

For PKS1830-210 we noticed we could fit the “tail” of the spectrum to the final points if the initial ones were fitted to a power law.
This “fitting” is achieved by testing which ALP spectra fit within the error bounds of the data.

For PKS1830-210 we noticed we could fit the “tail” of the spectrum to the final points if the initial ones were fitted to a power law.

We are interested in two parameter pairs: $g_{\alpha \gamma}$, $m_a$ and $B_T$, $d$. Characterising the ALP and magnetic field respectively.
This “fitting” is achieved by testing which ALP spectra fit within the error bounds of the data.

For PKS1830-210 we noticed we could fit the “tail” of the spectrum to the final points if the initial ones were fitted to a power law.

We are interested in two parameter pairs: $g_{a\gamma}$, $m_a$ and $B_T$, $d$. Characterising the ALP and magnetic field respectively.

Each time this fitting is performed we vary one pair of parameters while keeping the other fixed.
This “fitting” is achieved by testing which ALP spectra fit within the error bounds of the data.

For PKS1830-210 we noticed we could fit the “tail” of the spectrum to the final points if the initial ones were fitted to a power law.

We are interested in two parameter pairs: $g_{a\gamma}$, $m_a$ and $B_T$, $d$. Characterising the ALP and magnetic field respectively.

Each time this fitting is performed we vary one pair of parameters while keeping the other fixed.

In the first case we are assuming upper bounds for the field data and looking for consequent ALP constraints. In the second case we are doing the reverse.
Figure: Left: Exclusion plot based on Perseus Cluster AGN NGC1275 convolved with ALP spectrum. Right: Blazar PKS1830-210 at $z = 2.507$
Figure: Exclusion Plot with Perseus Cluster AGN NGC1275 in black and Blazar PKS1830-210 at $z = 2.507$ in yellow. $g_{a\gamma}$ normalised so that the CAST limit is $g_{a\gamma} = 2$. 

- Introduction
- ALP-Photon Mixing Formalism
- Spectral Features
- Polarisation Effects
- Astrophysical Applications
- Conclusion
The first exclusion plots demonstrate that couplings close to the CAST limit place strong constraints on the magnetic field configuration.
The first exclusion plots demonstrate that couplings close to the CAST limit place strong constraints on the magnetic field configuration.

The second pair assume the field constraints to be reliable and locate ALP restrictions.
The first exclusion plots demonstrate that couplings close to the CAST limit place strong constraints on the magnetic field configuration.

The second pair assume the field constraints to be reliable and locate ALP restrictions.

Both plots demonstrate “features” which are nothing more than parameter values where a fortuitous circumstance allows much larger field strengths/couplings (as appropriate).
The first exclusion plots demonstrate that couplings close to the CAST limit place strong constraints on the magnetic field configuration.

The second pair assume the field constraints to be reliable and locate ALP restrictions.

Both plots demonstrate "features" which are nothing more than parameter values where a fortuitous circumstance allows much larger field strengths/couplings (as appropriate).

These features occur more at larger ALP masses as this moves oscillations towards data regions with larger uncertainties (or possibly into regions beyond the scope of the data set!).
ALP-photon mixing provides avenues for obtaining astrophysical evidence of ALPs.
In summary

- ALP-photon mixing provides avenues for obtaining astrophysical evidence of ALPs.
- Non-conversion energies constitute ALP spectral features that provide a single-measurement signature of ALP mixing (but require high-precision data to identify).
ALP-photon mixing provides avenues for obtaining astrophysical evidence of ALPs.

Non-conversion energies constitute ALP spectral features that provide a single-measurement signature of ALP mixing (but require high-precision data to identify).

Fermi-LAT data and ALP-mixing provides stronger constraints on cosmic magnetic fields than current Faraday rotation studies (assuming couplings close to CAST).
In summary

- ALP-photon mixing provides avenues for obtaining astrophysical evidence of ALPs.
- Non-conversion energies constitute ALP spectral features that provide a single-measurement signature of ALP mixing (but require high-precision data to identify).
- Fermi-LAT data and ALP-mixing provides stronger constraints on cosmic magnetic fields than current Faraday rotation studies (assuming couplings close to CAST).
- Faraday rotation data excludes a range of couplings (below the CAST limit) for ALPs with masses between 0.001 and 25 neV.
ALP-photon mixing provides avenues for obtaining astrophysical evidence of ALPs.

Non-conversion energies constitute ALP spectral features that provide a single-measurement signature of ALP mixing (but require high-precision data to identify).

Fermi-LAT data and ALP-mixing provides stronger constraints on cosmic magnetic fields than current Faraday rotation studies (assuming couplings close to CAST).

Faraday rotation data excludes a range of couplings (below the CAST limit) for ALPs with masses between 0.001 and 25 neV.

This field has the power to bring together high-energy and radio observation in a multi-frequency synergy.
Thank You For Listening


