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Photon-Axion Conversion and Magnetic Field Configuration

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1. Introduction

- **Photon - Axion Conversion**

It is well known that the axions can converted into photons and vice versa in the presence of background magnetic fields.

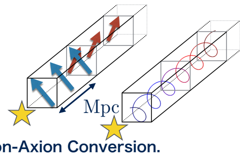
- **Cosmological Magnetic Field**

$10^{-15}\,\mathrm{G} \lesssim$ Strength of Inter Galactic Magnetic Field $\lesssim 1\,\mathrm{nG}$

Astrophysical Origin :
Ejection from Galaxy … galactic wind, AGN jet etc.

v.s.

Primordial Origin :
Inflationary Generation
… Magnetic field can have nonzero helicity.



➡ **We study configuration dependence of Photon-Axion Conversion.**

2. Photon-Axion Conversion

$$S = \int d^4x\left[-\frac{1}{2}(\partial_\mu a\,\partial^\mu a + m_a^2 a^2) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g_{a\gamma\gamma}\,aF_{\mu\nu}\tilde{F}^{\mu\nu}\right]$$

- **Klein-Gordon eq.**

$$(\Box - m_a^2)\,a = -g_{a\gamma\gamma}\,B_T\,\omega\,A_\parallel$$

- **Maxwell eq.**

$$\Box A_\parallel = -g_{a\gamma\gamma}\,B_T\,\omega\,a$$
$$\Box A_\perp = 0$$

Axion can mix with the only component **parallel** to background magnetic field.

- **Conversion Probability**

➡ $$P = \left(\frac{2\Delta_M}{\Delta_{osc}}\right)^2 \sin^2\left(\frac{\Delta_{osc}}{2}z\right)$$

Axion Intensity : $I_a(z) = P \times I(z_0)$
Photon Intensity : $I(z) = [1-P]\times I(z_0)$

$$\Delta_a = \frac{m_a^2}{2\omega} \quad \Delta_p = \frac{\omega_p^2}{2\omega} \quad \Delta_M = -\frac{1}{2}g_{a\gamma\gamma}B_T \quad \Delta_{osc} = \sqrt{(\Delta_a - \Delta_p)^2 + (2\Delta_M)^2}$$

mass term, mixing term

3. Astrophysical Configuration

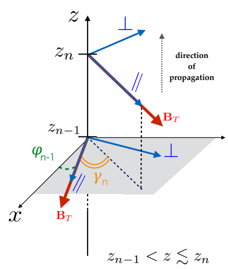
- **Domain Network**

Within each domain, the direction of magnetic field is constant, but between domains its direction randomly changes.

$$\rho(z) \equiv \begin{pmatrix} a(z)\\ A_\parallel(z)\\ A_\perp(z)\end{pmatrix} \otimes \left(a^*(z)\ A_\parallel^*(z)\ A_\perp^*(z)\right) = \frac{1}{2}\begin{pmatrix} 2I_a & K-iL & M-iN\\ K+iL & I+Q & U-iV\\ M+iN & U+iV & I-Q\end{pmatrix}$$

Stokes Parameters

$$\rho(z) = T(z,z_0)\rho(z_0)T^\dagger(z,z_0) \quad T(z_0,z_0)=1, \quad T^\dagger T = 1$$



$z_{n-1} < z \lesssim z_n$

random variable: $0 \lesssim \varphi_n \lesssim 2\pi$

In the limit $n = z/s \to \infty$, the conversion probability saturates so that on average one third of all photons converts to axions.

Grossman *et al.* Phys.Lett.**B543**, 23(2002)

➡ $I_a \to \frac{1}{3}, \ I \to \frac{2}{3}$

Domain Numbers $n = z/s \to \infty$

We can find the same limit for other quadratic quantity.

$$Q = U = V = K = L = M = N = 0$$

$$I^2 = Q^2+U^2+V^2 \quad \Pi_L = \frac{\sqrt{Q^2+U^2}}{I} \quad \Pi_C = \frac{|V|}{I}$$

Linear Polarization, Circular Polarization

- **Mean-Square Values of Polarization**

$\rho^2(z)$ obeys the same equation as $\rho(z)$.

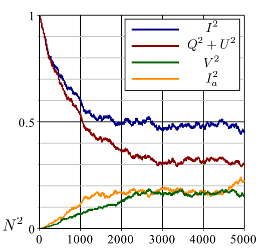
$$\rho^2(z) = T(z,z_0)\rho^2(z_0)T^\dagger(z,z_0)$$

This implies the corresponding components of $\rho^2(z)$ have the same limit as $\rho(z)$.

$$\tilde{I}_a \equiv I_a^2 + \frac{K^2+L^2+M^2+N^2}{4} = \frac{1}{3}$$

$$\tilde{I} \equiv \frac{I^2+Q^2+U^2+V^2}{2} + \frac{K^2+L^2+M^2+N^2}{4} = \frac{2}{3}$$

Assuming equipartition for $I_a^2, Q^2, U^2, V^2, K^2, L^2, M^2, N^2$



➡ $I_a^2 = \frac{1}{6}, \ I^2 = \frac{1}{2}, \ Q^2 = \frac{1}{6}, \ U^2 = \frac{1}{6}, \ V^2 = \frac{1}{6}$

➡ $\Pi_L = \sqrt{\frac{Q^2+U^2}{I^2}} = 0.816 \quad \Pi_C = \sqrt{\frac{V^2}{I^2}} = 0.577$

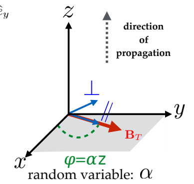
4. Helical Configuration

- **Magnetic Field Helicity**

$$H \equiv \frac{1}{V}\int_V \boldsymbol{A}\cdot\boldsymbol{B}\,d^3x \qquad \bar{\boldsymbol{B}}_T = B_T\cos(\alpha z)\,\hat{e}_x + B_T\sin(\alpha z)\,\hat{e}_y$$

Wang & Lai, JCAP06(2016)006 — their random variable: $0 \lesssim \varphi_n \lesssim 2\pi$

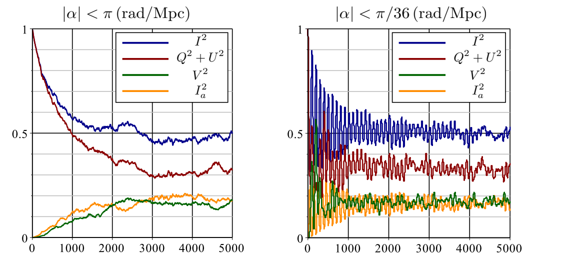
$$i\frac{d}{dz}\begin{pmatrix} a(z)\\ A_\parallel(z)\\ A_\perp(z)\end{pmatrix} = \begin{pmatrix} \Delta_a & \Delta_M & 0\\ \Delta_M & 0 & i\alpha\\ 0 & -i\alpha & 0\end{pmatrix}\begin{pmatrix} a(z)\\ A_\parallel(z)\\ A_\perp(z)\end{pmatrix}$$



- **Mean-Square Values of Polarization**

Left Panel :
Quite similar behavior to astrophysical configuration.

Right Panel :
Convergence to the same asymptotic values via damped oscillating behavior.
In case of α=0, mean-square values oscillate characterized by conversion parameters Δ.
After many domains, change of magnetic configuration is accumulated and ends up with the same asymptotic values.



5. Constraint for Physical Quantity

- **Observation of GRBs**

The measurement of polarization says that the circular polarization of GRBs is less than 1%.
Since the photon-axion conversion can produce the circular polarization, we can constrain the conversion parameters Δ so as not to contradict observation.

Mixing Term :

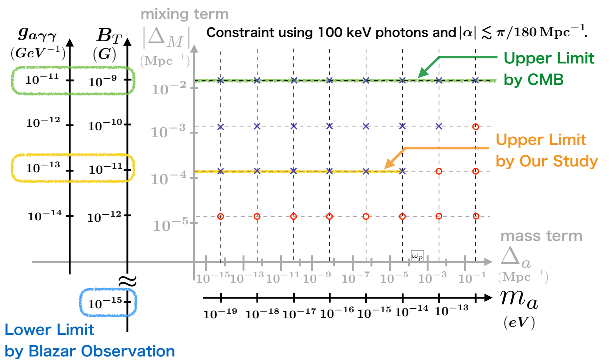
$$\Delta_M \equiv -\frac{1}{2}g_{a\gamma\gamma}B_T = -1.5\times10^{-2}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\mathrm{GeV}^{-1}}\right)\left(\frac{B_T}{\mathrm{nG}}\right)\mathrm{Mpc}^{-1}$$

Mass Term :

$$\Delta_a \equiv \frac{m_a^2}{2\omega} = 7.8\times10^{23}\left(\frac{m_a}{1\mathrm{eV}}\right)^2\left(\frac{100\,\mathrm{keV}}{\omega}\right)\mathrm{Mpc}^{-1}$$

$$\Delta_p \equiv \frac{\omega_p^2}{2\omega} = 1.1\times10^{-4}\left(\frac{100\,\mathrm{keV}}{\omega}\right)\left(\frac{n_e}{10^{-7}\,\mathrm{cm}^{-3}}\right)\mathrm{Mpc}^{-1}, \quad \omega_p^2 \equiv e^2\frac{n_e}{m_e}$$

For the parameters corresponding to the boundary between allowed and excluded regions, we found the mean-square values do not reach the asymptotic values.
Rather, the transient regime is relevant.



6. Conclusion

- We analytically obtained asymptotic values of the variance of photon polarization in astrophysical magnetic field configuration.
- It turned out that the asymptotic behavior does not depend on the magnetic field configuration. However, when helicity is small, we showed numerically that the oscillation appears in the early phase of evolution.
- We also applied our results to the astrophysical situation. Since the constraints for physical quantity depends on magnetic field configuration, it may be possible to restrict configuration by combing with other axion or magnetic field observations.