Optical circular polarization induced by axion-like particles in blazars

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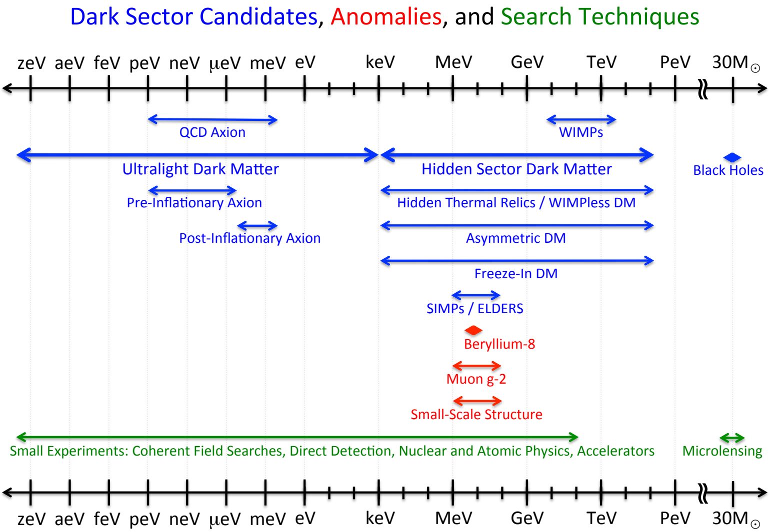
Dark Matter



Credit: Battaglieri et al., 2017

ALP-photon coupling

Effective Lagrangian:

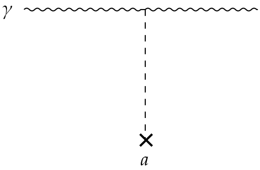
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

Weyl gauge $A_0 = A^0 = 0$:

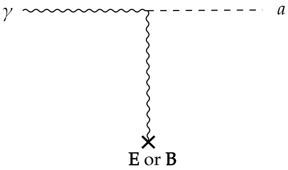
$$\partial_t^2 \boldsymbol{A} + \boldsymbol{\nabla} \times (\boldsymbol{\nabla} \times \boldsymbol{A}) = \boldsymbol{J} + g_{a\gamma\gamma} \partial_t a \boldsymbol{\nabla} \times \boldsymbol{A} - g_{a\gamma\gamma} \boldsymbol{\nabla} a \times \partial_t \boldsymbol{A}$$

$$-\boldsymbol{\nabla} \cdot \partial_t \boldsymbol{A} = \rho - g_{a\gamma\gamma} \boldsymbol{\nabla} a \cdot (\boldsymbol{\nabla} \times \boldsymbol{A})$$

$$\partial_t^2 a - \nabla^2 a + m_a^2 a = -g_{a\gamma\gamma} \partial_t \boldsymbol{A} \cdot (\boldsymbol{\nabla} \times \boldsymbol{A})$$



(a) Birefringence



(b) Conversion

ALP-photon conversion

In the short-wavelength approximation $E \gg m_a$, the equation of motion

$$\left(i\frac{d}{dz} + E + \mathcal{M}\right)\begin{pmatrix} A_x(z) \\ A_y(z) \\ a(z) \end{pmatrix} = 0$$

If the transverse component $\boldsymbol{B}_{\mathrm{T}}$ is set along with the y-axis, the mixing matrix

$$\mathcal{M} = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}$$

$$\Delta_{a\gamma} \equiv \frac{1}{2} g_{a\gamma\gamma} B_{\mathrm{T}}$$

$$\Delta_a \equiv -\frac{m_a^2}{2E},\ \Delta_\perp \approx \Delta_\parallel \approx -\frac{\omega_{\mathrm{pl}}^2}{2E}$$

Stokes parameters

Polarization density matrix

$$\rho(z) = \begin{pmatrix} A_x(z) \\ A_y(z) \\ a(z) \end{pmatrix} \otimes \begin{pmatrix} A_x(z) & A_y(z) & a(z) \end{pmatrix}^*,$$

which obeys the Liouville-Von Neumann equation

$$i\frac{d\rho}{dz} = [\rho, \mathcal{M}].$$

$$\rho_\gamma = \frac{1}{2}\begin{pmatrix} I+Q & U-iV \\ U+iV & I-Q \end{pmatrix}$$

- I: Intensity of photons
- $\Pi_{\rm L} \equiv \frac{\sqrt{Q^2+U^2}}{I}$: Degree of linear polarization
- $\Pi_{\rm C} \equiv \frac{V}{I}$: Degree of circular polarization

Strong-mixing regime

The conversion probability in a constant magnetic field

$$P_{\gamma\to a} = \sin^2(2\theta)\sin^2\left(\frac{\Delta_{\rm osc}\, d}{2}\right)$$

$$\theta = \frac{1}{2}\arctan\left(\frac{2\Delta_{a\gamma}}{\Delta_{\parallel} - \Delta_a}\right)$$

$$\Delta_{\rm osc} = [(\Delta_a - \Delta_{\parallel})^2 + 4\Delta_{a\gamma}^2]^{1/2}$$

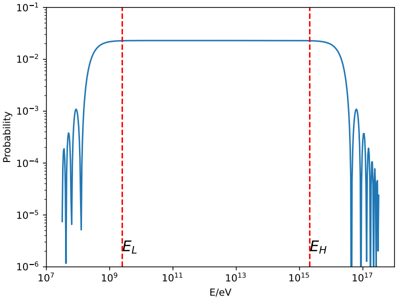
Critical energy of the strong-mixing regime:

$$E_L \equiv \frac{E\,|\Delta_a - \Delta_{\rm pl}|}{2\,\Delta_{a\gamma}}$$

$$E_H \equiv \frac{2\Delta_{a\gamma}}{3.5 E \Delta_{\rm QED}}$$

When $E_L \ll E \ll E_H$, $\theta \simeq \pi/4$, the conversion probability is independent of the energy.

$$P_{\gamma\to a} \simeq \frac{1}{4} g_{a\gamma\gamma}^2\, B_{\rm T}^2\, d^2$$



Weak-mixing regime

Weak-mixing condition

$$|\Delta_{\rm pl}| \gg \Delta_{a\gamma}, \; |\Delta_{\rm pl}| \gg |\Delta_a|.$$

In this regime, the conversion probability turns out to be vanishingly small. And the changes of I, Q, and U are negligible at first leading order.

Circular polarization

$$V(z) = V(z_0)\cos\kappa + \mathcal{V}\sin\kappa,$$
$$\mathcal{V} \equiv Q(z_0)\sin 2\phi + U(z_0)\cos 2\phi,$$
$$\kappa \equiv \frac{\Delta_{a\gamma}^2}{\Delta_{\rm pl} - \Delta_a}(z - z_0)\;.$$

Weak-mixing regime

Single domain:

$$V(z) = V(z_0)\cos\kappa + \mathcal{V}\sin\kappa$$

Multi domains ($|\kappa| \ll 1$):

$$\begin{aligned} V(z) - V(z_0) &\approx \int_{z_0}^{z} \mathcal{V}\frac{\Delta_{a\gamma}^2}{\Delta_{\rm pl} - \Delta_a}\,dz' \\ &= -\frac{m_e g_{a\gamma\gamma}^2 \mathcal{V} E}{8\pi\alpha}\int_{z_0}^{z}\frac{B_T^2(z')}{n_e(z')}\,dz'. \end{aligned}$$

For linearly polarized photons,

$$\mathcal{V} = \Pi_{\rm L}\sin 2(\phi - \psi).$$

ϕ: Magnetic field angle, ψ: Polarization angle

Qualitative understanding

When $P_{\gamma\to a}$ is small,

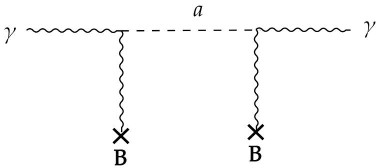
$$\Delta\Pi_{\rm L} = P_{\gamma\to a} \simeq \sin^2(2\theta)\sin^2(\xi/2),\ \ \xi = L/l_{\rm osc}.$$

L: coherent length of magnetic field
$l_{\rm osc}$: oscillation length $\Delta_{\rm osc}^{-1}$
The phase shift of photons induced by ALPs

$$\phi_a \simeq \sin^2(2\theta)(\xi - \sin\xi).$$

Phase difference results in ellipticity

$$V = Q_0 \sin\phi_a \simeq Q_0 \sin^2(2\theta)(\xi - \sin\xi)$$



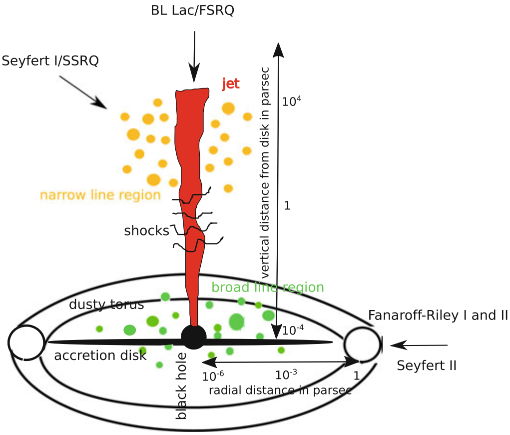
Research target

Requirements

- Large L
- Small $l_{\rm osc} \to$ low n_e
- Detectable

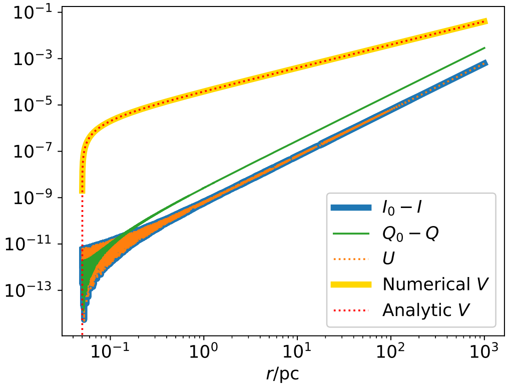
Blazar

- Optical polarization monitoring programs
- $\Pi_{\rm L}$: $10\% \sim 50\%$
- $\Pi_{\rm C}$: no definite detection



Credit: Sigl, 2017

Results



Field model

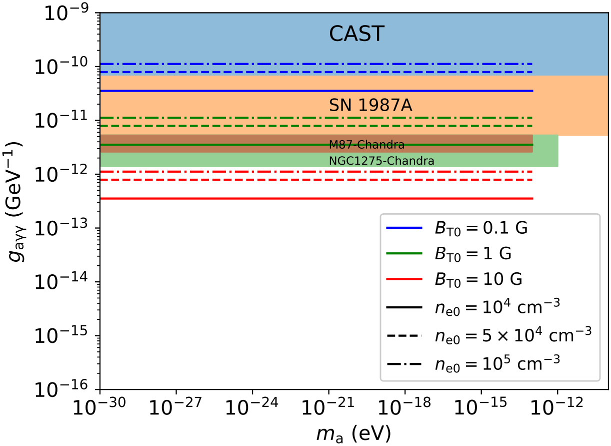
$$B_T^{\text{jet}} = B_{T0}\left(\frac{r}{r_{\text{E}}}\right)^{-1},$$

$$n_e^{\text{jet}} = n_{e0}\left(\frac{r}{r_{\text{E}}}\right)^{-2}$$

- Co-moving frame
- r_{E}: The distance of the emission site from the central black hole

Constraints

Hutsemekers et al., 2010 reported null detection of CP with typical uncertainties $< 0.1\%$ in 21 quasars except for two highly polarized blazars.



Optical CP observation

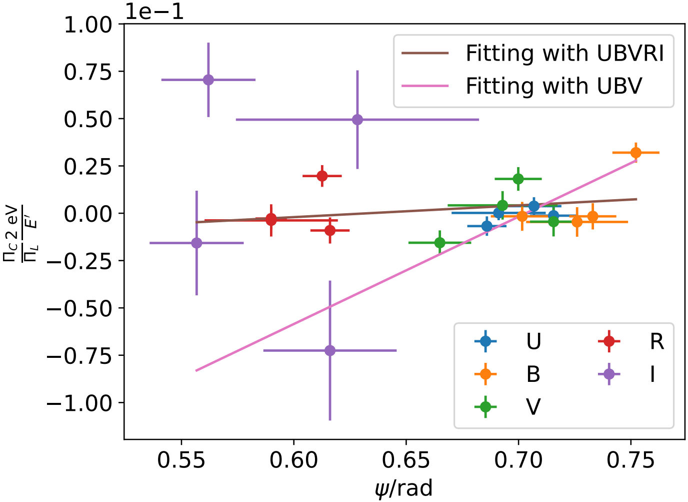
Although the optical CP is rarely observed, there are some observations indicating CP detection.

- Small but significant optical CP in two blazars with uncertainties $< 0.1\%$. (Hutsemekers et al., 2010)
- A marginal detection of the optical CP at 2σ level in V and R bands for 3C 66A. (Tommasi, L. et al., 2001)
- A $3-6\sigma$ detection of CP with large values for 3C 66A. (Takalo and Sillanpaa, 1993)

These possible observations could be interpreted by the ALPs in the context.

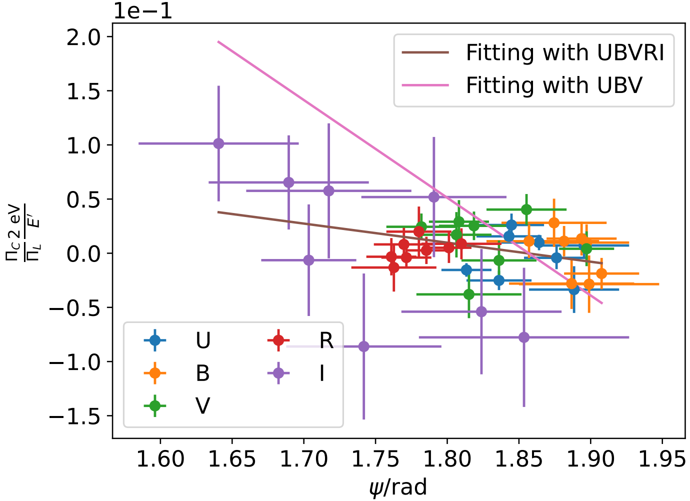
3C 66A

When $\phi - \psi \approx k\pi/2 \;\; (k \in \mathbb{Z})$, $\frac{\Pi_C}{\Pi_L E'} \propto g_{a\gamma\gamma}^2 \psi$

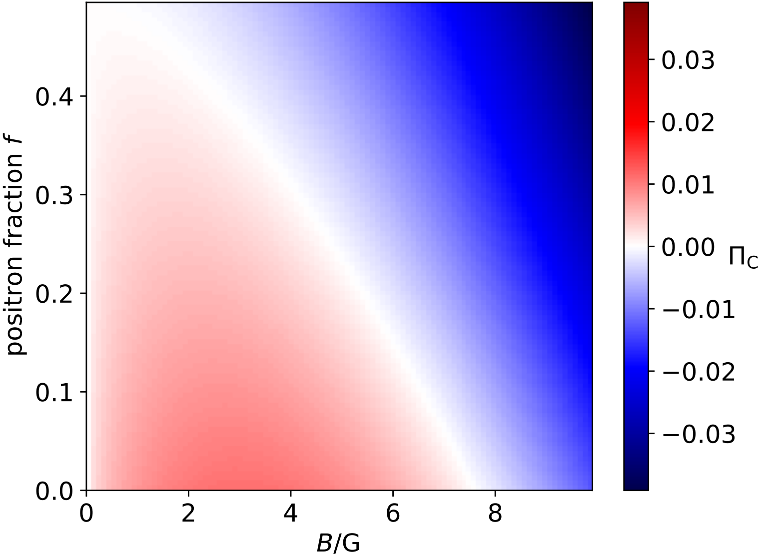


OJ 287

$$g_{a\gamma\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$$



Intrinsic CP



Partially random field

The direction of magnetic field is partially random in each calculation domain

$$\phi = \phi_0 + \alpha\Delta\phi, \quad \Delta\phi \in [-\pi, \pi)$$

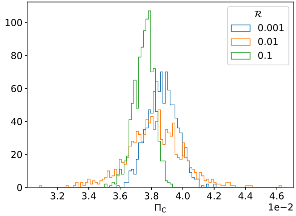
The change of V

Given the approximation that $\alpha \ll 1$ is true,

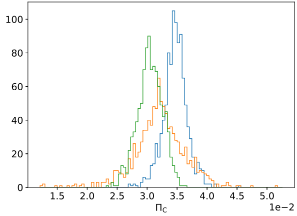
$$\mathcal{V}_{\mathrm{n+1}} \approx \Pi_{\mathrm{L}} \sin 2(\phi_0 - \psi_{\mathrm{n}}) + 2\alpha\Delta\phi_{\mathrm{n}}\Pi_{\mathrm{L}} \cos 2(\phi_0 - \psi_{\mathrm{n}}),$$

- The incremental part: same as the idealized case
- The random part: random walk

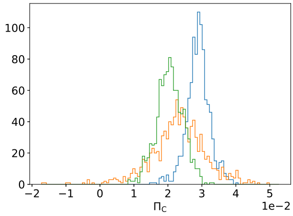
Partially random field



$\alpha = 0.1$



$\alpha = 0.2$

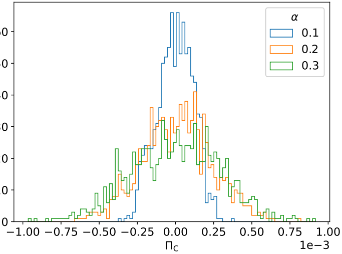


$\alpha = 0.3$

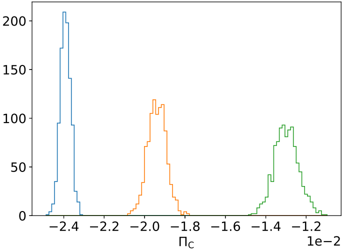
For a more realistic field configuration, the values of CP are smaller than the optimal case, while **its magnitude remains in the same order**.

Structure of the jet

The direction of the transverse magnetic field is spatial dependent.



$\phi_0 : 0 \sim 2\pi$



$\phi_0 : 0 \sim \pi/2$

High-precision measurements can help improve to observe the optical CP. Nevertheless, even in the low-precision cases, it is possible that there are some blazars that can produce observable CP.

Other astrophysical magnetic field

Mixing contribution to CP

$$V \sim \Pi_{\rm L} g_{a\gamma\gamma}^2 B^2 l_{\rm osc} L, \quad l_{\rm osc} = [(\Delta_a - \Delta_{\parallel})^2 + 4\Delta_{a\gamma}^2]^{-1/2}$$

Characteristic quantity

$$f_{\rm CP} \equiv \left(\frac{B}{1\ {\rm G}}\right)^2 \left(\frac{n_{\rm e}}{5\times 10^4\ {\rm cm}^{-3}}\right)^{-1} \left(\frac{L}{1\ {\rm kpc}}\right)$$

Scenarios	B(G)	$n_{\rm e}$(cm^{-3})	L(kpc)	$f_{\rm CP}$
Intra-cluster magnetic field	10^{-6}	10^{-3}	10	5×10^{-4}
Intergalactic magnetic field	10^{-9}	10^{-7}	5×10^{4}	2.5×10^{-2}
Galactic magnetic field	10^{-6}	10^{-1}	10^{-2}	5×10^{-9}

The influence of other astrophysical magnetic fields can be neglected.

Summary

- ALP can induce optical CP in blazar.
- The measurement of CP can place constraints on ALP.
- Some tentative observations of CP indicate the coupling $g_{a\gamma\gamma}$ to be the order of 10^{-11} GeV^{-1}.
- The partial random magnetic fields do not change the magnitude of ALP induced CP.
- High-precision measurements can help observe the optical CP.
- The influence of other astrophysical magnetic fields can be neglected.

Thanks!

References I

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