Axion-like Particles and Magnetars

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based on
arXiv:1804.01992 [hep-ph], arXiv:1807.10773 [hep-ph] and arXiv:2101.05302 [hep-ph]

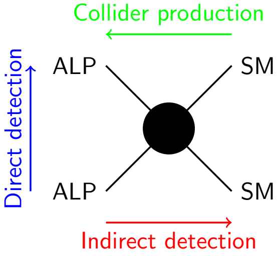
with Huai-Ke Guo, Steven Harris, Elijah Sheridan and Kuver Sinha

Why Axion-like Particles (ALPs)?

- Historical motivation for axions ⇒ Strong CP problem
- UV models ⇒ ALPs ubiquitous in string theory (axiverse)

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 a^2) + \frac{c_1}{f}\partial_\mu a J^\mu - \frac{c_2}{f} a G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{c_3}{f} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$

- IR consequences ⇒ Dark matter



Collider production

ALP

SM

ALP

SM

Direct detection

Indirect detection

$-\frac{g}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g a \boldsymbol{E}\cdot\boldsymbol{B} \Rightarrow$ Photon-ALP mixing in background magnetic field contrary to standard WIMPs

Conversion as ALP Detection Tool

- Strategy for stellar objects like white dwarfs or neutron stars
  1. Photon/ALP production at source Iwamoto (1984)
  2. Photon/ALP propagation from source to sink with photon-ALP conversion in magnetic field during propagation Morris (1986)
  3. Photon spectrum modification at observation point

⇒ "...Given this suppression it is difficult to imagine the occurrence of observable effects." Raffelt, Stodolsky (1988)

  - Radio waves Pshirkov, Popov (2007) & Hook, Kahn, Safdi (2018)
  - Soft X-rays Heyl, Lai (2006) & Perna *et al.* (2012)
  - Hard X-rays JFF, Sinha (2018)

Evolution Equations

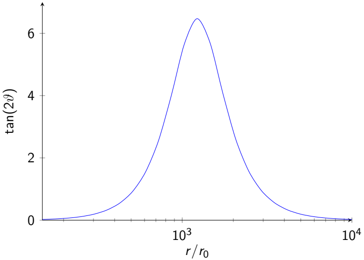
- System of coupled first-order differential equations in the limit where photon wavelength $\ll$ magnetar radius r_0 ($x = r/r_0$)
  - $\Delta_{\|} = \frac{7\alpha}{90\pi} b^2 \omega \sin^2\theta$ and $\Delta_{\perp} = \frac{2\alpha}{45\pi} b^2 \omega \sin^2\theta$ (refractive indices $n_i = 1 + \Delta_i/\omega$ with $b = B/B_c$)
  - $\Delta_a = -\frac{m_a^2}{2\omega}$ and $\Delta_M = \frac{1}{2} g B \sin\theta$

$$i\frac{d}{dx}\begin{pmatrix} a(x) \\ A_{\|}(x) \\ A_{\perp}(x) \end{pmatrix} = M(x) \begin{pmatrix} a(x) \\ A_{\|}(x) \\ A_{\perp}(x) \end{pmatrix}$$

$$M(x) = \begin{pmatrix} \omega r_0 + \Delta_a r_0 & \Delta_M r_0 & 0 \\ \Delta_M r_0 & \omega r_0 + \Delta_{\|} r_0 & 0 \\ 0 & 0 & \omega r_0 + \Delta_{\perp} r_0 \end{pmatrix}$$

- Photon perpendicular mode (X-mode)
  - Decoupling of evolution equation
  - $A_\perp(x) = A_\perp e^{-i\phi_\perp(x)}$ with $I_\perp(x) = |A_\perp(x)|^2 = A_\perp^2$ a constant
- ALP/photon parallel mode (O-mode)
  - Mixing angle $\frac{1}{2}\tan 2\vartheta = M_{12}(x)/[M_{22}(x) - M_{11}(x)]$
  - Dipolar magnetic field $B(x) = B_0/x^3$

$$\omega = 100\,\mathrm{keV}$$
$$B_0 = 20 \times 10^{14}\,\mathrm{G}$$
$$r_0 = 10\,\mathrm{km}$$
$$g = 10^{-15}\,\mathrm{keV}^{-1}$$
$$m_a = 10^{-8}\,\mathrm{keV}$$



$\vartheta \Rightarrow$ Negligible at surface but large at $r_{a\to\gamma} = \left(\frac{7\alpha}{45\pi}\right)^{1/6} \left(\frac{\omega}{m_a}\frac{B_0}{B_c}|\sin\theta|\right)^{1/3} r_0$

Evolution Equations with $M^\dagger = M$

⇒ QM conservation of probability ($\Delta\phi = \phi_a - \phi_\parallel$)

$$i\frac{d\mathbf{a}}{dx} = M(x)\mathbf{a}(x) \qquad \Rightarrow \qquad \frac{d}{dx}[\mathbf{a}^\dagger(x)\mathbf{a}(x)] = 0$$

$$a_1(x) = a(x) = A\cos[\chi(x)]e^{-i\phi_a(x)}$$

$$a_2(x) = A_\parallel(x) = iA\sin[\chi(x)]e^{-i\phi_\parallel(x)}$$

$$\frac{d\chi(x)}{dx} = -\Delta_M r_0 \cos[\Delta\phi(x)]$$

$$\frac{d\Delta\phi(x)}{dx} = (\Delta_a - \Delta_\parallel)r_0 + 2\Delta_M r_0 \cot[2\chi(x)]\sin[\Delta\phi(x)]$$

$$I_a(\chi_0, \Delta\phi_0, x) = A^2\cos^2[\chi(x)|_{\chi(1)=\chi_0,\Delta\phi(1)=\Delta\phi_0}]$$

$$I_\parallel(\chi_0, \Delta\phi_0, x) = A^2\sin^2[\chi(x)|_{\chi(1)=\chi_0,\Delta\phi(1)=\Delta\phi_0}]$$

Photon Polarization

- Averaged intensities
  - $\chi(1) = \chi_0 \Rightarrow$ Mixed initial state
  - Uncorrelated $\phi_a(1)$ and $\phi_{\|}(1) \Rightarrow$ Average over $\Delta\phi_0$

$$\bar{I}_i(\chi_0, x) = \int_0^{2\pi} \frac{d\Delta\phi_0}{2\pi} I_i(\chi_0, \Delta\phi_0, x) \qquad i \in \{a, \|\}$$

- Stokes parameters

$$I(\chi_0, x) = I_\perp + \bar{I}_{\|}(\chi_0, x) \qquad Q(\chi_0, x) = I_\perp - \bar{I}_{\|}(\chi_0, x)$$

- Surface-subtracted Stokes parameters

$$\Delta I(\chi_0, x) = I(\chi_0, x) - I(\chi_0, 1) = \bar{I}_{\|}(\chi_0, x) - A^2 \sin^2(\chi_0)$$
$$\Delta Q(\chi_0, x) = Q(\chi_0, x) - Q(\chi_0, 1) = -\Delta I(\chi_0, x)$$

$\Rightarrow$ All Photon-ALP conversion effects encoded in $R = \frac{\Delta I(\chi_0, x)}{A^2}$

Normalized Surface-subtracted Stokes Parameter

$$\begin{aligned} R(\chi_0, x) &= \cos(2\chi_0) \int_0^{2\pi} \frac{d\Delta\phi_0}{2\pi} \, \frac{1}{2} \left\{ 1 - \frac{\cos\left[2\chi(x)\big|_{\chi(1)=\chi_0, \Delta\phi(1)=\Delta\phi_0} \right]}{\cos(2\chi_0)} \right\} \\ &= P_{a\to\gamma}(x) \cos(2\chi_0) \end{aligned}$$

$$\begin{aligned} I(\chi_0, x) &= A_\perp^2 + \tfrac{1}{2} A^2 \left\{ 1 + \left[2P_{a\to\gamma}(x) - 1 \right] \cos(2\chi_0) \right\} \\ Q(\chi_0, x) &= A_\perp^2 - \tfrac{1}{2} A^2 \left\{ 1 + \left[2P_{a\to\gamma}(x) - 1 \right] \cos(2\chi_0) \right\} \end{aligned}$$

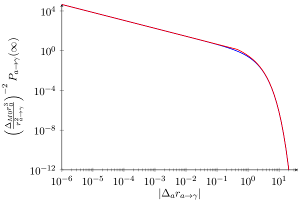
⇒ QM time-dependent perturbation theory

- $|\Delta_a r_{a\to\gamma}| \gtrsim 0.45$

  $$P_{a\to\gamma}(\infty) = \left(\frac{\Delta_{M0} r_0^3}{r_{a\to\gamma}^2} \right)^2 \frac{\pi}{3|\Delta_a r_{a\to\gamma}|} e^{\frac{6\Delta_a r_{a\to\gamma}}{5}}$$

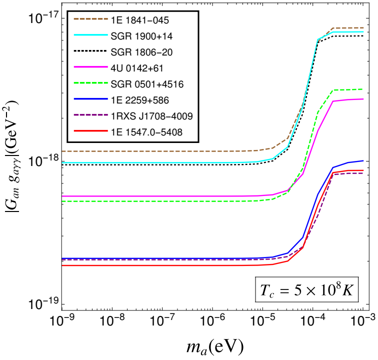
- $|\Delta_a r_{a\to\gamma}| \lesssim 0.45$

  $$P_{a\to\gamma}(\infty) = \left(\frac{\Delta_{M0} r_0^3}{r_{a\to\gamma}^2} \right)^2 \frac{\Gamma\left(\frac{2}{5}\right)^2}{5^{\frac{6}{5}} |\Delta_a r_{a\to\gamma}|^{\frac{4}{5}}}$$



Bounds and Predictions

- Magnetar photon luminosity
  - Observed persistent X-ray emission $L_\gamma \sim 10^{34} - 10^{36}\,\mathrm{erg}\cdot\mathrm{s}^{-1}$ with peaks at $\omega = 1\,\mathrm{keV}$ from magnetar surface thermal emission and $\omega = 100\,\mathrm{keV}$ Beloborodov (2012)
  - ⇒ High core temperature $T \sim 10^9\,\mathrm{K}$ Beloborodov, Li (2017)
  - Most of X-ray thermal emission in photon perpendicular mode (X-mode) Ho, Lai (2003) & Heyl, Lai (2007) & Beloborodov (2012) & Baring (2017)
  - ⇒ $A_\perp$ large and χ_0 small



Future Prospects

- Proposed future mission ⇒ X-ray Polarimetry Probe (XPP)
  - Excellent polarimetric sensitivity in $0.2 - 80\,\mathrm{keV}$ band
  - Follow-up of Imaging X-ray Polarimetry Explorer (IXPE) to be launched in Fall 2021 with polarimetric sensitivity in $2 - 8\,\mathrm{keV}$ band

⇒ Exciting times ahead !!!

Thank you