Axion-plasmon polaritons in strongly magnetized plasmas: a novel way to probe axions

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Outline

- The axion and the strong CP-violation problem
- The Peccei-Quinn mechanism
- "Axial" electromagnetism
- Excitation of axions with strong lasers
- Axions and Langmuir waves is magnetised plasmas: the axion-polariton

CP-problem

The Lagrangian contains a charge parity-time reversal (CP)- violating term

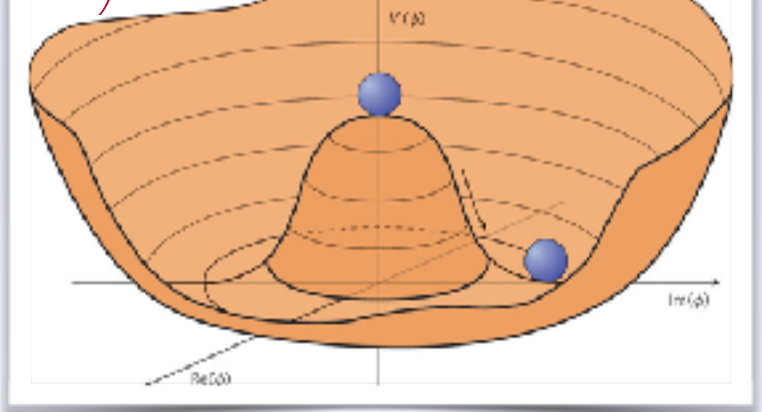
$$\mathcal{L}_\theta = \bar{\theta}\frac{\alpha_s}{8\pi}G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$

$-\pi \leq \bar{\Theta} \leq \pi$: effective parameter after diagonalizing the quark masses

$|\bar{\Theta}| \lesssim 10^{-10}$: imposed by the limits on the **neutron dielectric moment**

Peccei-Quinn mechanism (solving the **strong CP problem**)

$$\mathcal{L} = \left(\bar{\Theta} - \frac{\varphi}{f}\right)\frac{\alpha_s}{8\pi}G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$



Axion coupling with EM sector

Axion two-photon interaction (long story short…)

$$\mathcal{L}_{\text{int}} = \frac{g}{4}\varphi F_{\mu\nu}\tilde{F}^{\mu\nu} = -g\varphi \mathbf{E}\cdot\mathbf{B}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$

"Axial" electromagnetic theory

$$\mathcal{L} = \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \mathcal{L}_\varphi + \mathcal{L}_{\text{int}}$$

$$\mathcal{L}_\varphi = \frac{1}{2}\partial^\mu\varphi^*\partial_\mu\varphi - \frac{1}{2}m_\varphi^2|\varphi|^2$$

Modified Maxwell's equations

Equations of motion $$\partial^\mu \frac{\partial \mathcal{L}}{\partial\left(\partial^\mu A^\nu\right)} = \frac{\partial \mathcal{L}}{\partial A^\nu}$$

Maxwell's equations [1]

$$\nabla \cdot (\mathbf{E} + g\varphi\mathbf{B}) = \rho,$$

$$\nabla \cdot (\mathbf{B} - g\varphi\mathbf{E}) = 0,$$

$$\nabla \times (\mathbf{E} + g\varphi\mathbf{B}) = -\frac{\partial}{\partial t}\left(\mathbf{B} - g\varphi\mathbf{E}\right),$$

$$\nabla \times (\mathbf{B} - g\varphi\mathbf{E}) = \frac{\partial}{\partial t}\left(\mathbf{E} + g\varphi\mathbf{B}\right) + \mathbf{J}_e,$$

Klein-Gordon equation

$$\left(\Box + m_\varphi^2\right) = g\mathbf{E} \cdot \mathbf{B}$$

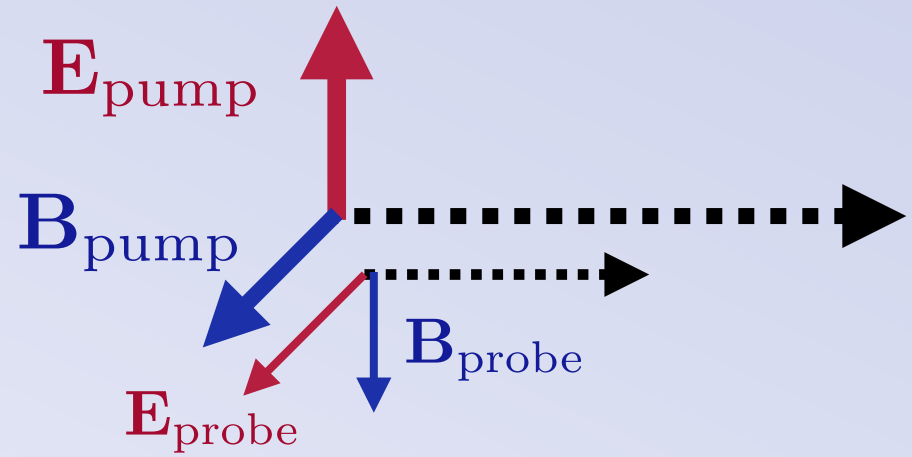
[1] L. Visinelli, Mod. Ph. Lett. A **28** (2013)

Axion excitation by intense lasers

In the absence of sources, axions may be excited with two strong EM fields [1]

$$\Box \mathbf{E} = -g \frac{\partial^2}{\partial t^2} (\varphi \mathbf{B})$$

$$\left(\Box + m_\varphi^2\right) = g \mathbf{E} \cdot \mathbf{B}$$



$$\mathbf{E} = \mathbf{E}_{\text{pump}} + \mathbf{E}_{\text{probe}}$$

$$\mathbf{B} = \mathbf{B}_{\text{pump}} + \mathbf{B}_{\text{probe}}$$

$$\mathbf{E}_j = \tilde{\mathbf{E}}_j e^{i(\mathbf{k}_j \cdot \mathbf{r} - \omega_j t)}$$

$$|\tilde{\mathbf{E}}_{\text{pump}}| \gg |\tilde{\mathbf{E}}_{\text{probe}}|$$

Slowly varying envelopes

$$\frac{\partial \tilde{\mathbf{E}}_j}{\partial z} = ig \frac{\omega_\varphi^2}{2\omega_j} \tilde{\varphi} \tilde{\mathbf{E}}_i e^{i\Delta k z}$$

$$\frac{\partial \tilde{\varphi}}{\partial z} = i \frac{g}{2\omega_\varphi} \tilde{\mathbf{E}}_i^* \tilde{\mathbf{E}}_j e^{-i\Delta k z}$$

$$\omega_\varphi = \omega_{\text{pump}} + \omega_{\text{probe}}$$

$$\Delta k = k_\varphi - (k_{\text{pump}} + k_{\text{probe}})$$

[1] J. T. Mendonça, EPL 79, 21001 (2007)

Axion excitation by intense lasers

In a pump-probe scheme, we can adiabatically eliminate the strong pump, $\frac{\partial \tilde{\mathbf{E}}_{\text{pump}}}{\partial z} \simeq 0$

$$\frac{\partial \tilde{\mathbf{E}}_{\text{probe}}}{\partial z} \simeq i w \tilde{\varphi} e^{i\Delta k z}$$

$$\frac{\partial \tilde{\varphi}}{\partial z} \simeq i w_{\varphi} \tilde{\mathbf{E}}_{\text{pump}} e^{-i\Delta k z}$$

$$w = g \frac{\omega_{\varphi}^2}{2\omega_{\text{probe}}} \tilde{E}_0^*$$

$$w_{\varphi} = \frac{g}{2\omega_{\varphi}} \tilde{E}_0$$

$\omega_{\varphi} = \omega_{\text{pump}} + \omega_{\text{probe}}$

$$\tilde{\varphi}(z) = i \frac{w_{\varphi}}{\Omega} \tilde{E}_{\text{probe}}(0) \sin(\Omega z) e^{-i\Delta k z/2}$$

$\omega_{\varphi} = \omega_{\text{pump}} - \omega_{\text{probe}}$

$$\tilde{\varphi}(z) = i \frac{w_{\varphi}}{\Omega'} \tilde{E}_{\text{probe}}(0) \sinh(\Omega' z) e^{-i\Delta k z/2}$$

What about plasmas?

Photons in relativistic plasmas (SI units for a moment…)

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{a} = \frac{k_p^2}{\gamma}\frac{n}{n_0}\mathbf{u}_\perp$$

$$\nabla^2\phi = \frac{e^2}{\epsilon_0 m_e c^2}(n - n_0)$$

$$\frac{\partial n}{\partial t} + c\nabla\cdot\left(\frac{n\mathbf{u}}{\gamma}\right) = 0$$

$$\mathbf{a} = e\mathbf{A}/m_e c$$

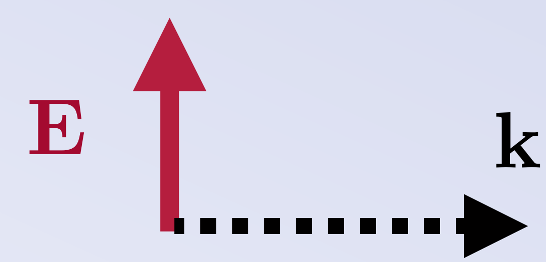
$$\phi = eV/m_e c^2$$

$$\mathbf{u} = \gamma\frac{\mathbf{v}}{c}\,,\quad \gamma = \sqrt{1+u^2}$$

$$k_p = \omega_p/c$$

Plasma frequency

$$\omega_p = \sqrt{e^2 n_0/\epsilon_0 m_e}$$



EM waves

$$\omega^2 = \frac{\omega_p^2}{\langle\gamma_a\rangle} + c^2k^2$$

$$\langle\gamma\rangle = (1 + a_0^2)^{-1/2}$$

Photon mass

$$m_{\text{ph}} = \frac{\hbar\omega_p}{c^2}$$

What about plasmas?

Photons in relativistic plasmas

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Plasma frequency

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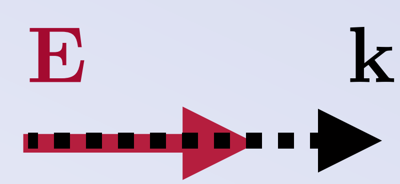
Langmuir waves



$$\omega^2 = \omega_p^2 + S_e^2 k^2$$

$$S_e = \sqrt{3T_e/m_e}$$

Axions in plasmas

"Axial" Maxwell's equations + **plasma fluid equations**

$$\nabla \cdot (\mathbf{E} + g\varphi\mathbf{B}) = \rho,$$

$$\nabla \cdot (\mathbf{B} - g\varphi\mathbf{E}) = 0,$$

$$(\Box + m_\varphi^2) = g\mathbf{E} \cdot \mathbf{B}$$

$$\nabla \times (\mathbf{E} + g\varphi\mathbf{B}) = -\frac{\partial}{\partial t}(\mathbf{B} - g\varphi\mathbf{E}),$$

$$\nabla \times (\mathbf{B} - g\varphi\mathbf{E}) = \frac{\partial}{\partial t}(\mathbf{E} + g\varphi\mathbf{B}) + \mathbf{J}_e,$$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e\mathbf{u}) = 0$$

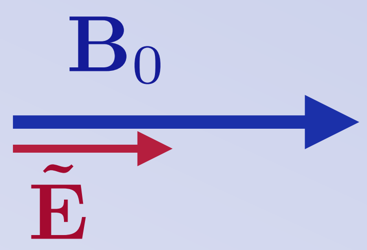
$$m_e\left(\frac{\partial}{\partial t} + \nabla \cdot \mathbf{u}\right)\mathbf{u} = -e(\mathbf{E} + u \times \mathbf{B}) - \frac{\nabla P}{n_e}$$

Axions in plasmas

Electrostatic oscillation in the presence of a **strong magnetic field**

$$\mathbf{J} = -en_e\mathbf{u}$$

$$\rho = -e(n_e - n_0)$$



Linearisation: $\mathbf{E} = \tilde{\mathbf{E}}, \quad n_e = n_0 + \tilde{n}, \quad \varphi = \tilde{\varphi}$

$$\left(\omega^2 - \omega_p^2 - S_e^2 k^2\right)\tilde{n} - ig\frac{eB_0}{m_e}kn_0\tilde{\varphi} = 0,$$

$$\left(\omega^2 - \tilde{m}_\varphi^2 - k^2\right)\tilde{\varphi} + ig\frac{eB_0}{k}\tilde{n} = 0$$

Effective axion mass

$$\tilde{m}_\varphi = \sqrt{m_\varphi^2 + g^2 B_0^2}$$

Axions in plasmas

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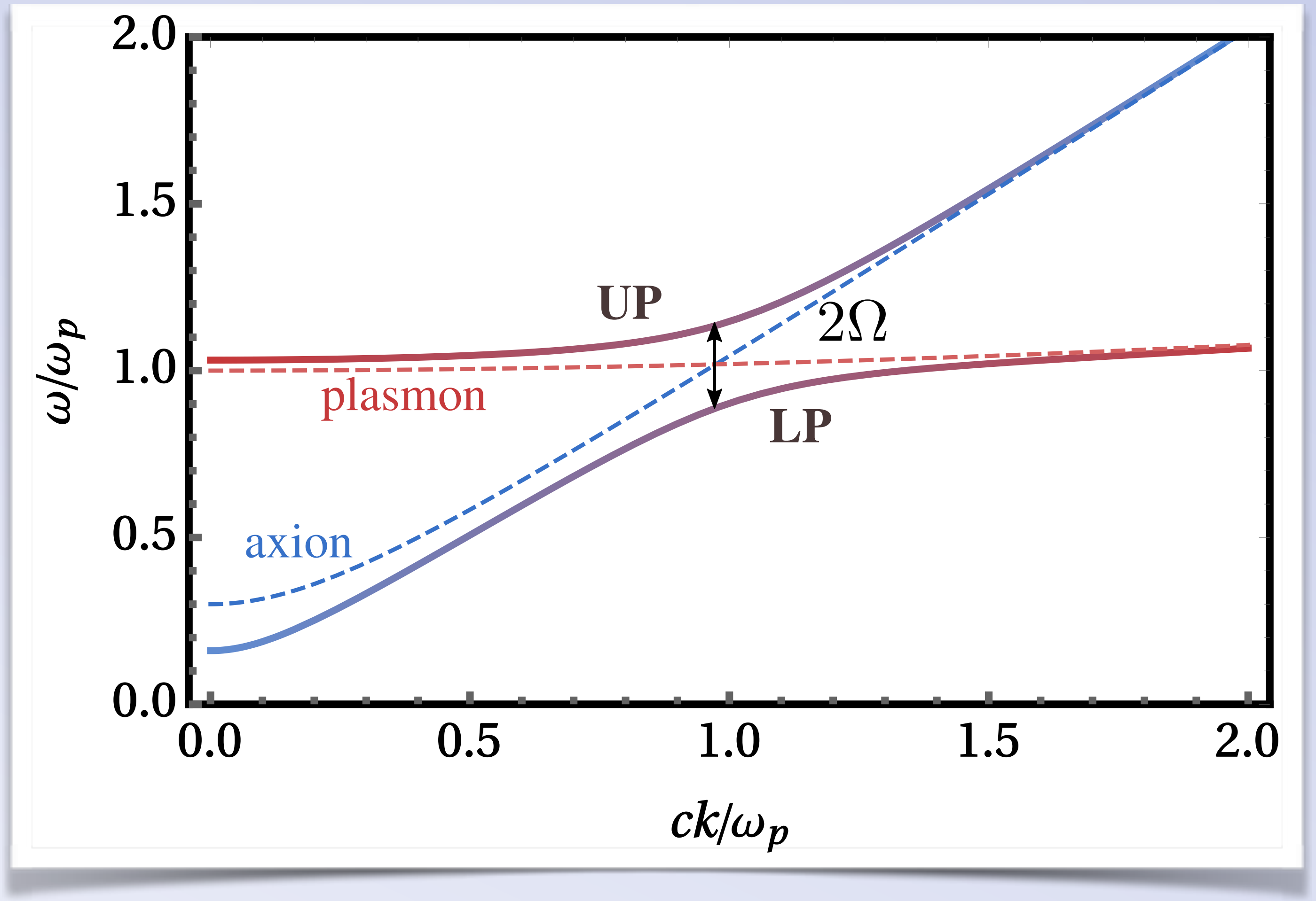


Nontrivial solutions

$$\left(\omega^2 - \omega_{\rm pl}^2\right)\left(\omega^2 - \omega_\varphi^2\right) - \Omega^4 = 0$$

Axion-polaritons

$$\omega_{\rm U,L}^2 = \frac{1}{2}\left(\omega_\varphi^2 + \omega_{\rm pl}^2 \pm \sqrt{\left(\omega_{\rm pl}^2 - \omega_\varphi^2\right)^2 + 4\Omega^4}\right)$$

$$\omega_{\rm pl} = \sqrt{\omega_p^2 + S_e^2 k^2}$$

$$\omega_\varphi = \sqrt{\tilde{m}_\varphi^2 + k^2}$$

Rabi frequency $\Omega = (g^2 n_0 m_e \omega_c^2)^{1/4} = \sqrt{gB_0\omega_p}$

Axion-plasmon polaritons

Let us come back to the secular equations and notice that

$$\left(\omega^2-\omega_{\rm pl}^2\right)\tilde{n}=\left(\omega-\omega_{\rm pl}\right)\left(\omega+\omega_{\rm pl}\right)\tilde{n},$$

$$\left(\omega^2-\omega_{\varphi}^2\right)\tilde{\varphi}=\left(\omega-\omega_{\varphi}\right)\left(\omega+\omega_{\varphi}\right)\tilde{\varphi}.$$

Smallness of the Rabi frequency, $\Omega \ll \omega_p$

Terms $\omega \sim \omega_p$ dominate $\Longrightarrow$ Rotating-wave approximation (RWA)

$$\left(i\frac{\partial}{\partial t}-\omega_{\rm pl}\right)\tilde{n}-ig\frac{eB_0}{2\omega_p m_e}kn_0\tilde{\varphi}=0,$$

$$\left(i\frac{\partial}{\partial t}-\omega_{\varphi}\right)\tilde{\varphi}+ig\frac{eB_0}{2k\omega_p}\tilde{n}=0$$

Axion-plasmon polaritons

Terms $\omega \sim \omega_p$ dominate $\Longrightarrow$ Rotating-wave approximation (RWA)

$$\left(i\frac{\partial}{\partial t} - \omega_{\rm pl}\right)\tilde{n} - ig\frac{eB_0}{2\omega_p m_e}kn_0\tilde{\varphi} = 0,$$

$$\left(i\frac{\partial}{\partial t} - \omega_{\varphi}\right)\tilde{\varphi} + ig\frac{eB_0}{2k\omega_p}\tilde{n} = 0$$

Quantization:

$$\tilde{n}(x) = \sum_k \mathcal{A}_k\left(\hat{a}_k e^{ikx} + \hat{a}_k^\dagger e^{-ikx}\right), \quad \tilde{\varphi}(x) = \sum_k \mathcal{B}_k e^{ikx}\hat{b}_k$$

RWA Hamiltonian

$$\hat{H} = \sum_k \omega_{\rm pl}\hat{a}_k^\dagger \hat{a}_k + \sum_k \omega_\varphi \hat{b}_k^\dagger \hat{b}_k + \Omega\sum_k \hat{a}_k^\dagger \hat{b}_k + \text{h.c.}$$

Axion-plasmon polaritons

RWA Hamiltonian

$$\hat{H} = \sum_k \omega_{\rm pl} \hat{a}_k^\dagger \hat{a}_k + \sum_k \omega_\varphi \hat{b}_k^\dagger \hat{b}_k + \Omega \sum_k \hat{a}_k^\dagger \hat{b}_k + \text{h.c.}$$

Introducing **polariton** operators, $\hat{A}_k = u_k \hat{a}_k - v_k \hat{b}_k, \quad \hat{B}_k = v_k \hat{b}_k + u_k \hat{a}_k$

Diagonalization

$$\hat{H} = \sum_k \tilde{\omega}_L \hat{A}_k^\dagger \hat{A}_k + \sum_k \tilde{\omega}_U \hat{B}_k^\dagger \hat{B}_k$$

Decay rate (Fermi Golden Rule)

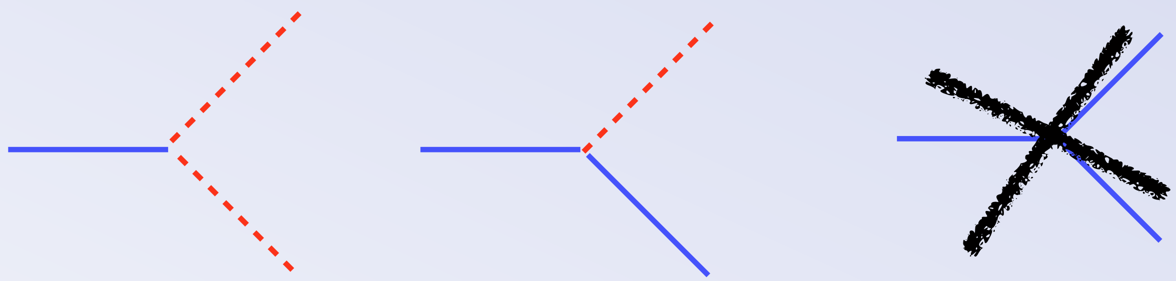
$$\Gamma_{\varphi \to \rm pl} = 2\pi \sum_{k,q} |\mathcal{M}_{k,q}|^2 \delta\left(\omega_\varphi - \omega_{\rm pl}\right)$$

Axions in plasmas: constraints

1. Avoid Landau damping occurring at $k\lambda_D \simeq 1$

$$\omega_p \lesssim c/\lambda_D$$

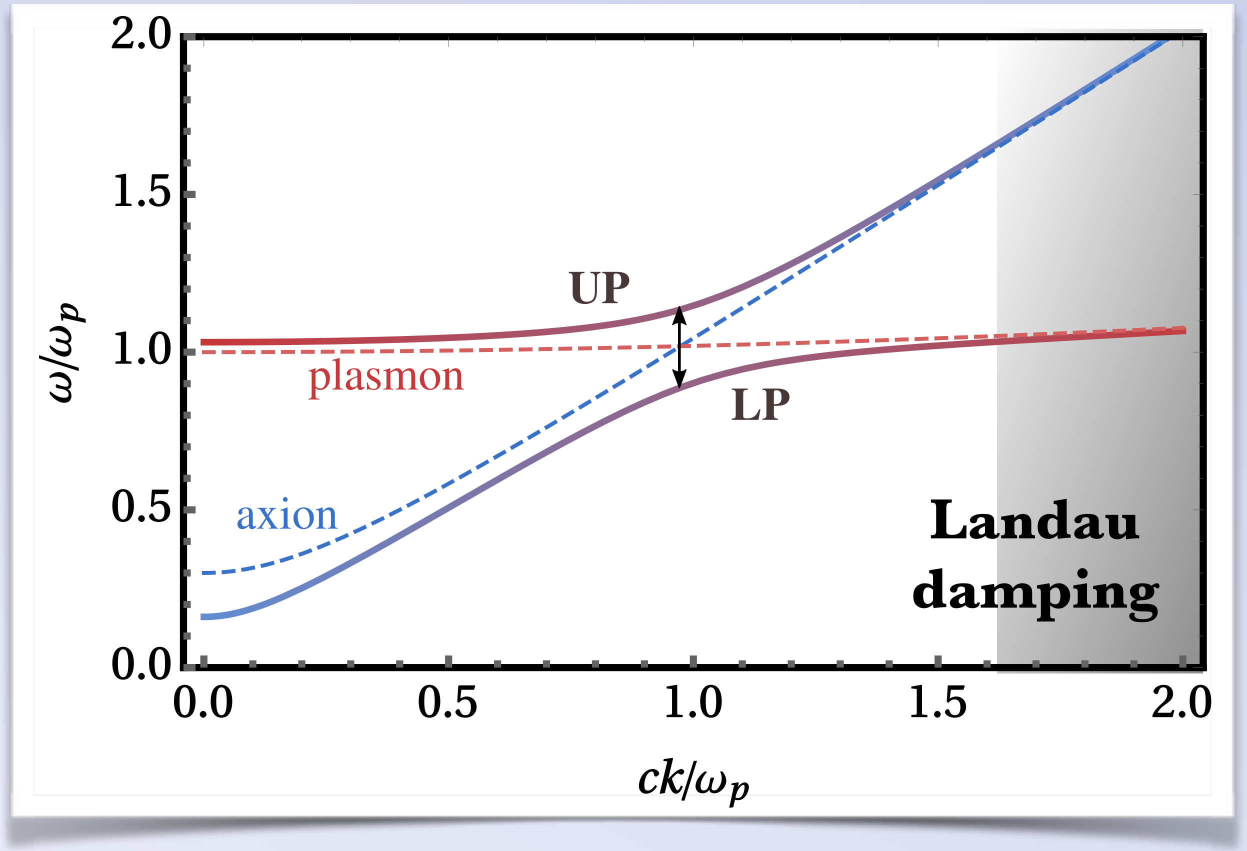
2. Strong coupling occurs for $\Omega > \Gamma_{\text{decay}}$



suppressed near ω_p

$$\mathcal{M}_{k,q} = \Omega \sum_p \langle k|(\hat{a}_p^\dagger \hat{b}_p + \hat{a}_p \hat{b}_p^\dagger)|q\rangle$$

$$\Gamma_{\text{decay}} \simeq \pi \frac{\Omega^2 \left[1 + n_a(\omega_p)\right]}{\sqrt{\omega_p^2 + \tilde{m}_\varphi^2}}$$



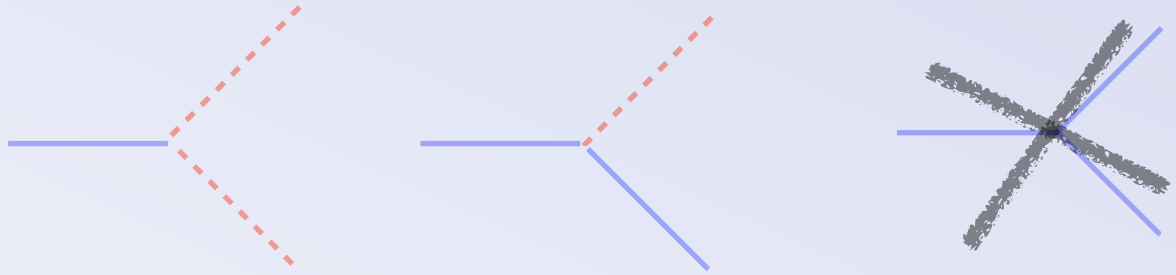
Thermal plasmons: $n_a(x) = (\exp(x/T_p) - 1)^{-1}$

Axions in plasmas: constraints

1. Avoid Landau damping occurring at $k\lambda_D \simeq 1$

$$\omega_p \lesssim c/\lambda_D$$

2. Strong coupling occurs for $\Omega > \Gamma_{\text{decay}}$



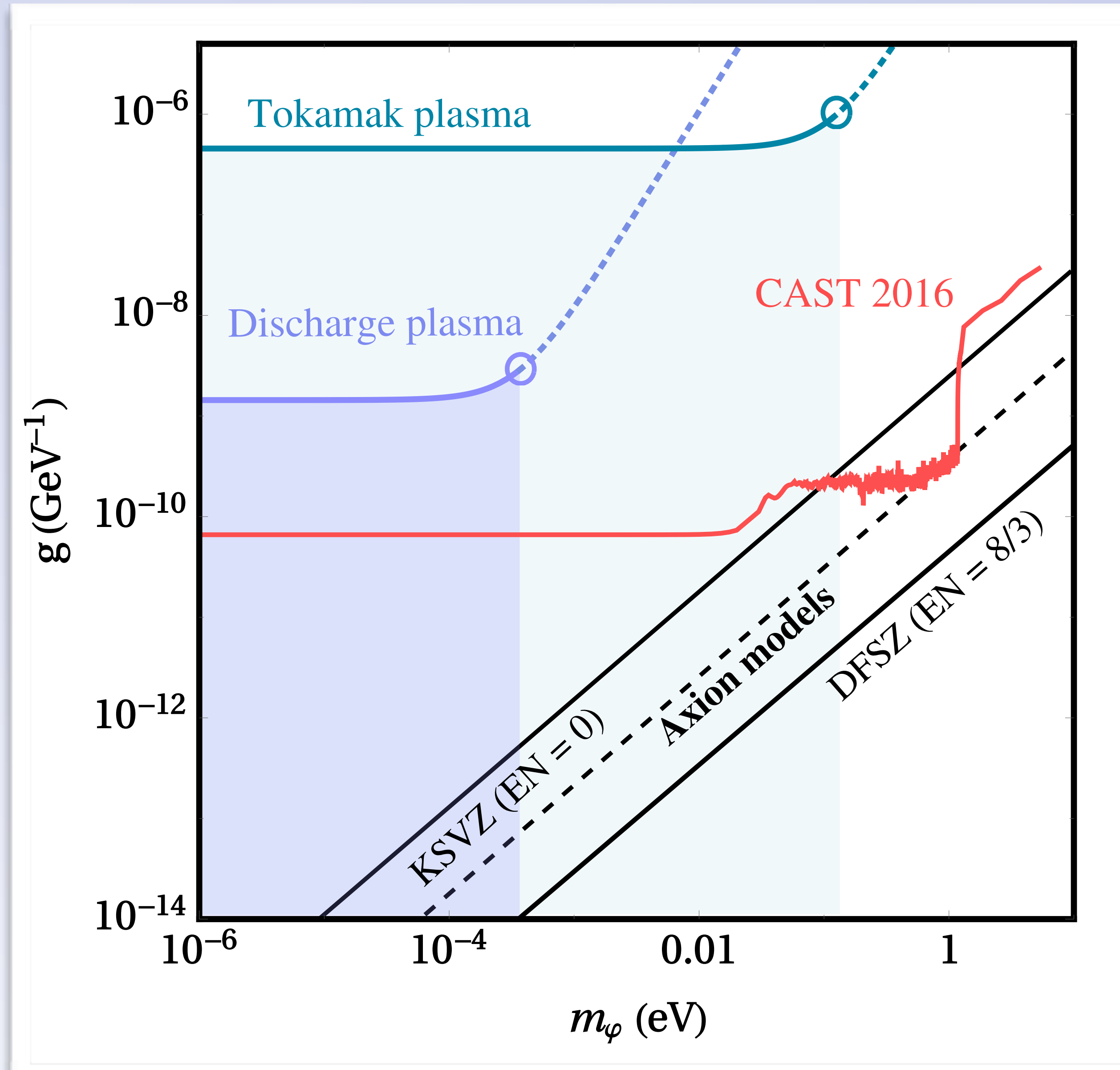
suppressed near ω_p

$$\mathcal{M}_{k,q} = \Omega \sum_p \langle k | (\hat{a}_p^\dagger \hat{b}_p + \hat{a}_p \hat{b}_p^\dagger) | q \rangle$$

Cold plasma approximation $n_a \sim 0$

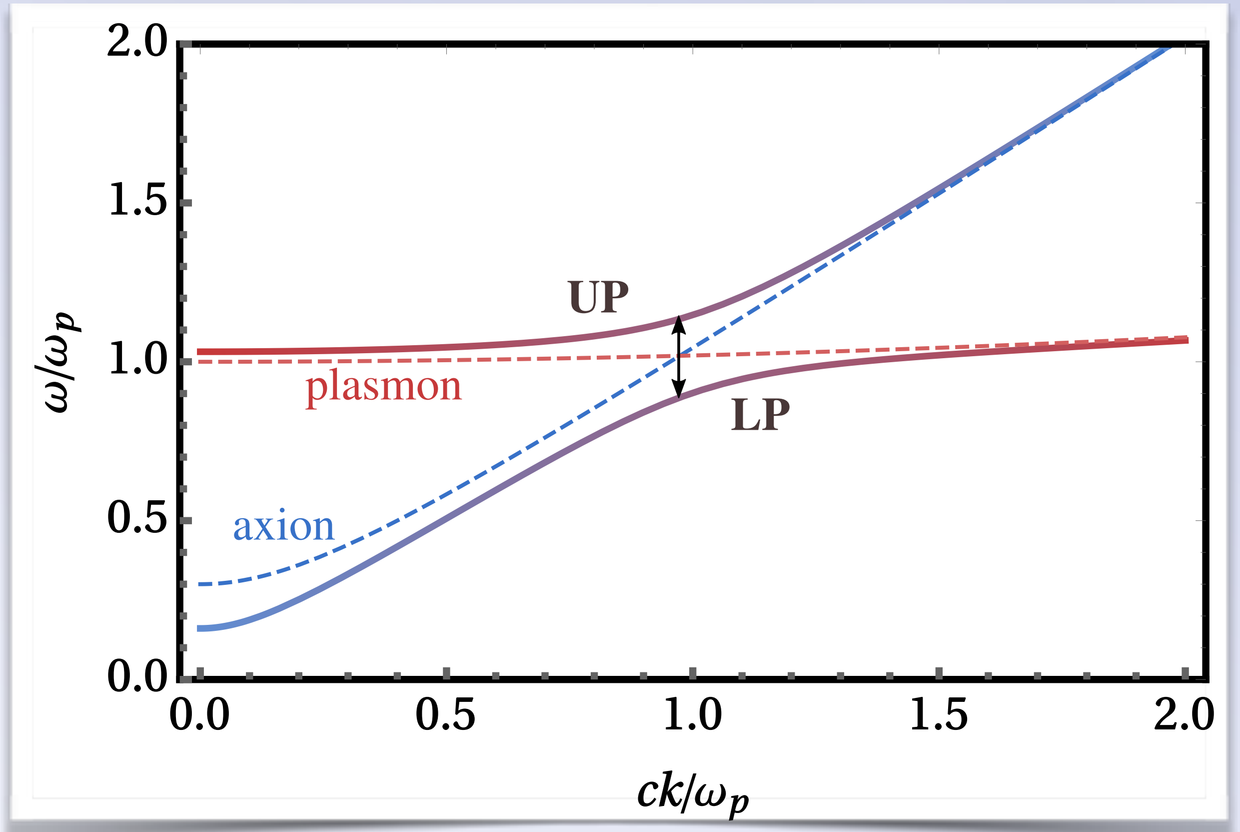
$$\Gamma_{\text{decay}} \simeq \pi \frac{\Omega^2}{\sqrt{\omega_p^2 + \tilde{m}_\varphi^2}}$$

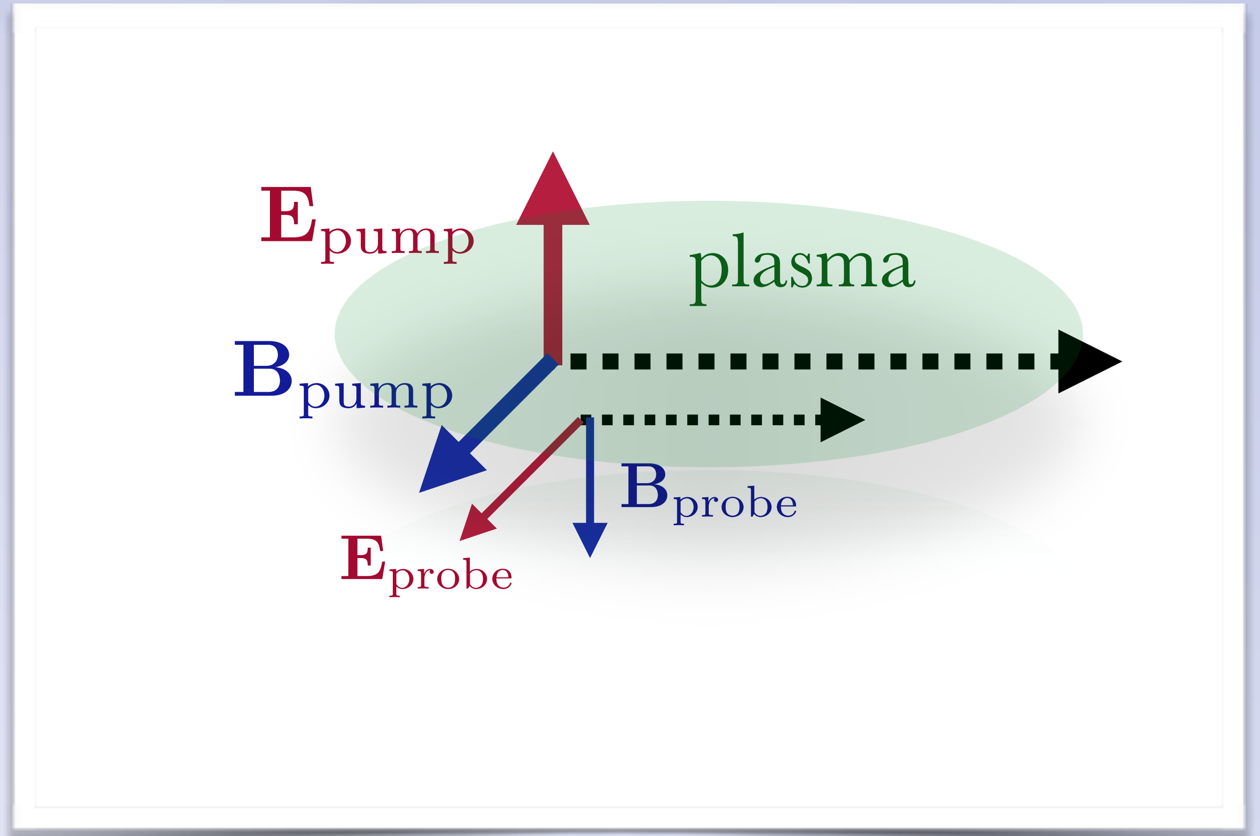
$$\Omega > \Gamma_{\text{decay}}$$



!! Axions couple **strongly** to plasmas in a wide range of non-excluded region !!

Axions in the lab: new experiments





Dilute, cold plasmas exps.

↓ Large frequency sensitivity required

$$\frac{\Omega}{\omega_p} \sim 10^{-8} - 10^{-5}$$

↑ Moderate wavelength sensitivity required

$$\delta\lambda = \frac{2\pi}{\delta k} \sim 1 - 10 \text{ cm}$$

(Langmuir probes)

Laser-plasma exps. (pump-probe)

↓ Large frequency sensitivity required

$$\frac{\Omega}{\omega_p} \sim 10^{-7} - 10^{-4}$$

↑ Wakefield + radiations signals

(Spectroscopy)

Conclusions & future directions

- Axions can be excited with strong magnetic fields
- Plasma (Langmuir) waves hybridise with the axion modes
- Alternative way to probe axions in strong magnetic field experiments
- **Collaboration with Luca Visinelli (see his poster!):** investigate axion-plasma coupling in astrophysics and cosmology
- Investigate phase-space (kinetic) effects
- Include the electron-axion Lagrangian $\mathcal{L} \sim i\bar{\psi}\gamma^5\psi\varphi$

Thank you!