

# Axions in plasmas

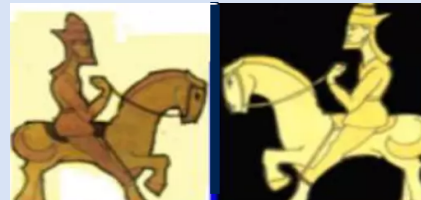
From the lab to astrophysics

**Hugo Terças**

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GoLP/Instituto de Plasmas e Fusão Nuclear

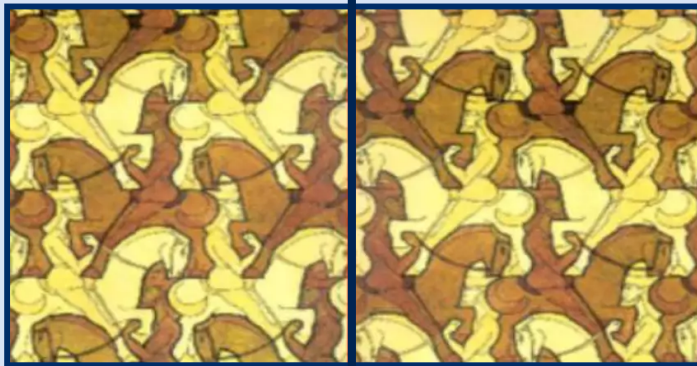
CP-symmetry is the combination of two discrete symmetries

Particle



Anti-particle

Charge conjugation  
(C-symmetry)



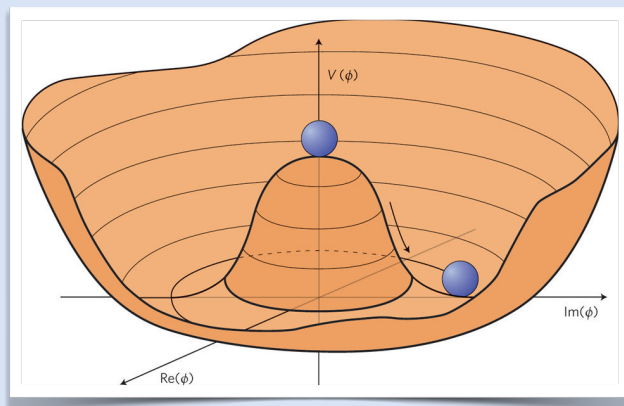
Parity conjugation  
(P-symmetry)







PQ solution to the strong CP-problem: **dynamical** cancelation of  $\theta$





















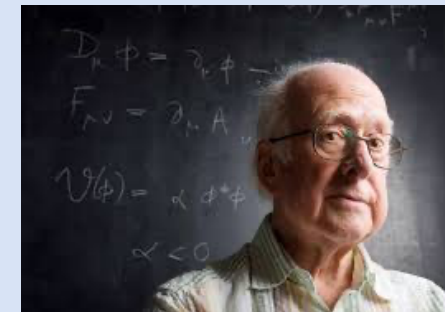
Allow  $\theta$  to swing in a Mexican hat (spontaneous symmetry breaking)

**Axion field  $\varphi$**

$$\mathcal{L}_\theta \rightarrow \mathcal{L}_{\text{PQ}} = \frac{\alpha_s}{8\pi} \left( \theta - \frac{\varphi}{f} \right) G^{\mu\nu a} \tilde{G}_{\mu\nu}^a$$

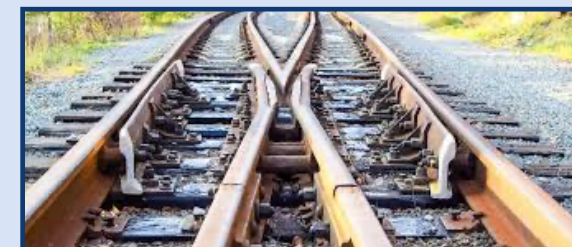
## The Peccei-Quinn solution **extends** the Standard Model

	QUARKS			BOSONS	
	mass: $2.2^*$ charge: $2/3$ spin: $1/2$  up	1,270 $2/3$ $1/2$  charm	173,100 $2/3$ $1/2$  top	0 0 1  gluon	125,180 0 0  Higgs boson
	4.7 $-1/3$ $1/2$  down	96 $-1/3$ $1/2$  strange	4,180 $-1/3$ $1/2$  bottom	0 0 1  photon	
LEPTONS	0.511 $-1$ $1/2$  electron	105.66 $-1$ $1/2$  muon	1,776.8 $-1$ $1/2$  tau	91,188 0 1  Z boson	
	$<0.00000012$ 0 $1/2$  electron neutrino	$<0.00000012$ 0 $1/2$  muon neutrino	$<0.00000012$ 0 $1/2$  tau neutrino	80,379 $+/-1$ 1  W boson	? 0 0  axion



Peter Higgs

Gauge invariance



The Peccei-Quinn Lagrangian **modifies** the electromagnetism

$$\mathcal{L}_{\text{EM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + j_{\mu}A^{\mu} + \underbrace{\frac{g}{4}\varphi F_{\mu\nu}\tilde{F}^{\mu\nu}}_{-g\varphi\mathbf{E}\cdot\mathbf{B}}$$

## Axial Maxwell's equations

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

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

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

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

The Peccei-Quinn Lagrangian **modifies** the electromagnetism

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## Axial Maxwell's equations

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

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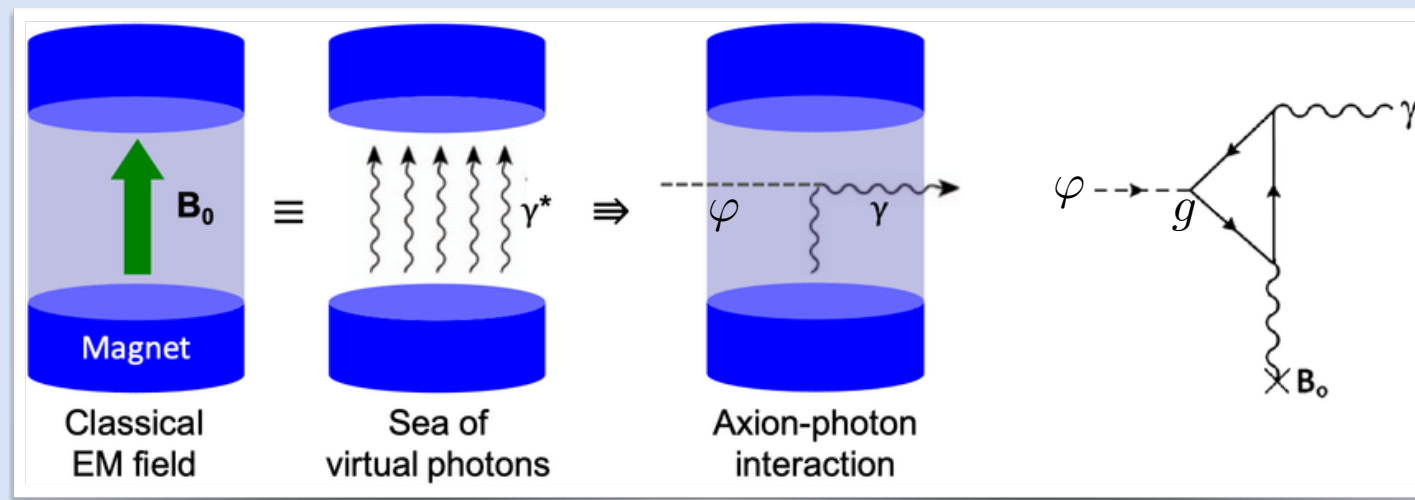
$$\nabla \times (\mathbf{E} + g\varphi\mathbf{B}) = -\frac{\partial}{\partial t}(\mathbf{B} - g\varphi\mathbf{E})$$

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## Klein-Gordon equation

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

Current searches of axions rely on **axion-photon** conversion



Conversion probability

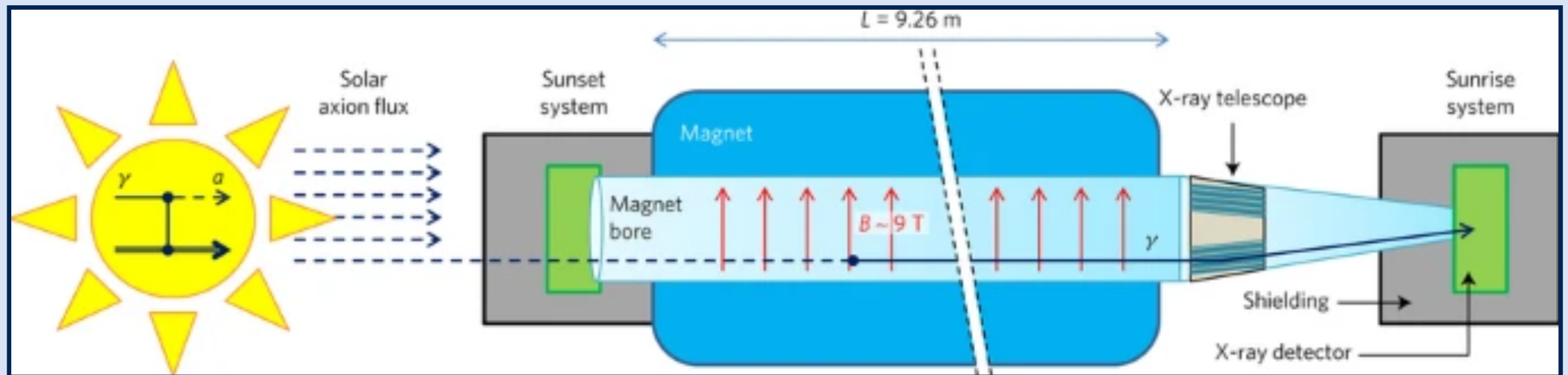
$$P_{\varphi \rightarrow \gamma} \simeq \frac{g^2 B_0^2 L^2}{4} \sim \underline{\underline{10^{-35} - 10^{-32}}}$$

## Passive scheme: CAST (Cern Axion Solar Telescope)



# Axion detection I. Passive schemes

Passive scheme: CAST (Cern Axion Solar Telescope)



Integration time: 2 years!

Predicted flux:  $\frac{d\Phi_\varphi}{dE} \sim 10^{10} \text{ cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$

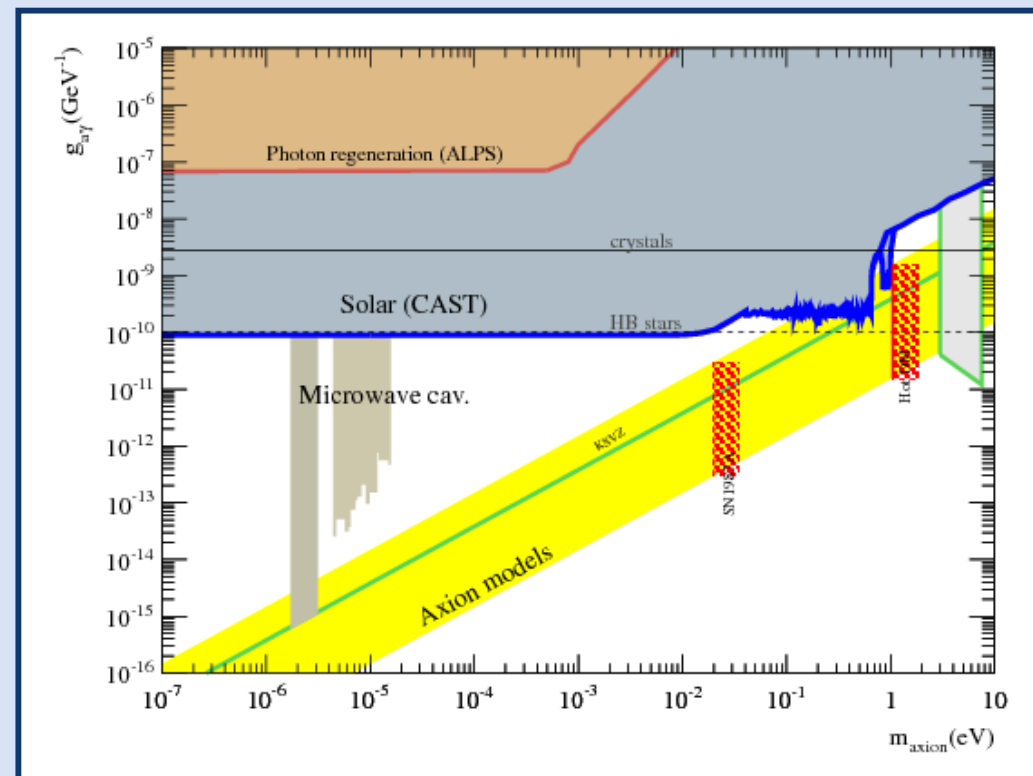
# Axion detection I. Passive schemes

Passive scheme: CAST (Cern Axion Solar Telescope)

No signal to date!

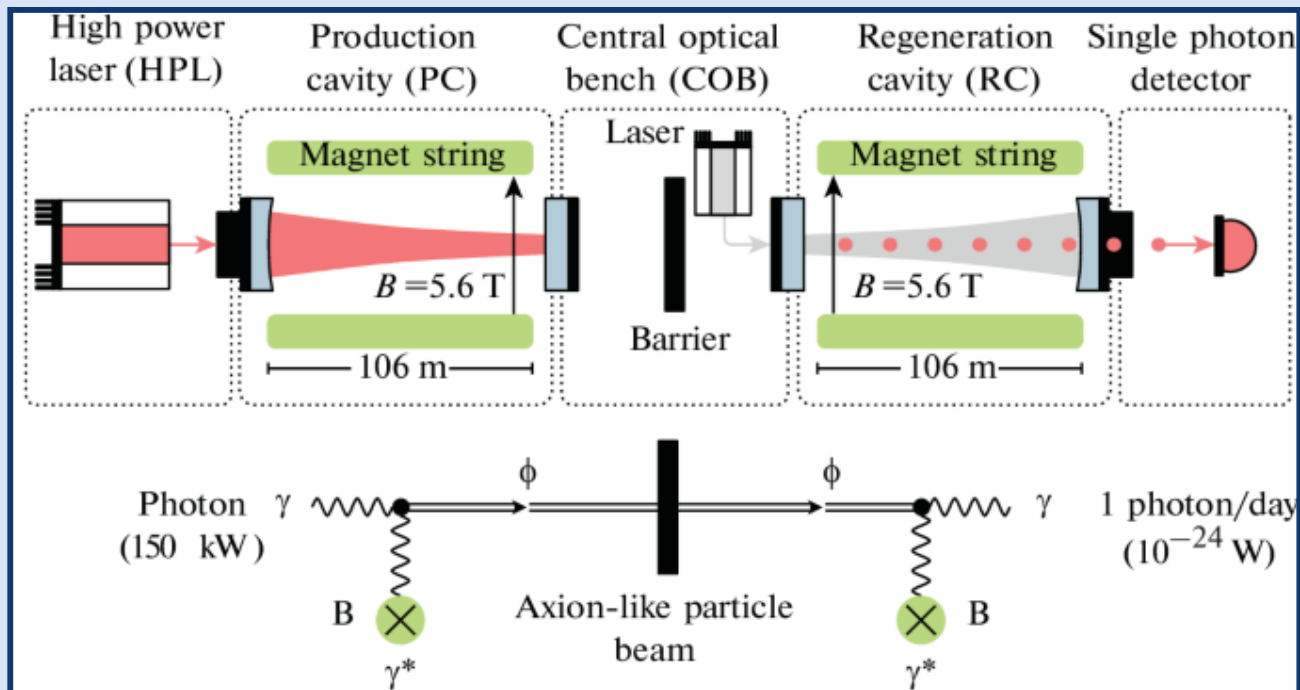
Integration time: 2 years!

Predicted flux:  $\frac{d\Phi_\varphi}{dE} \sim 10^{10} \text{ cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$





## Active scheme: Any Light Particle Search (ALPS) | DESY



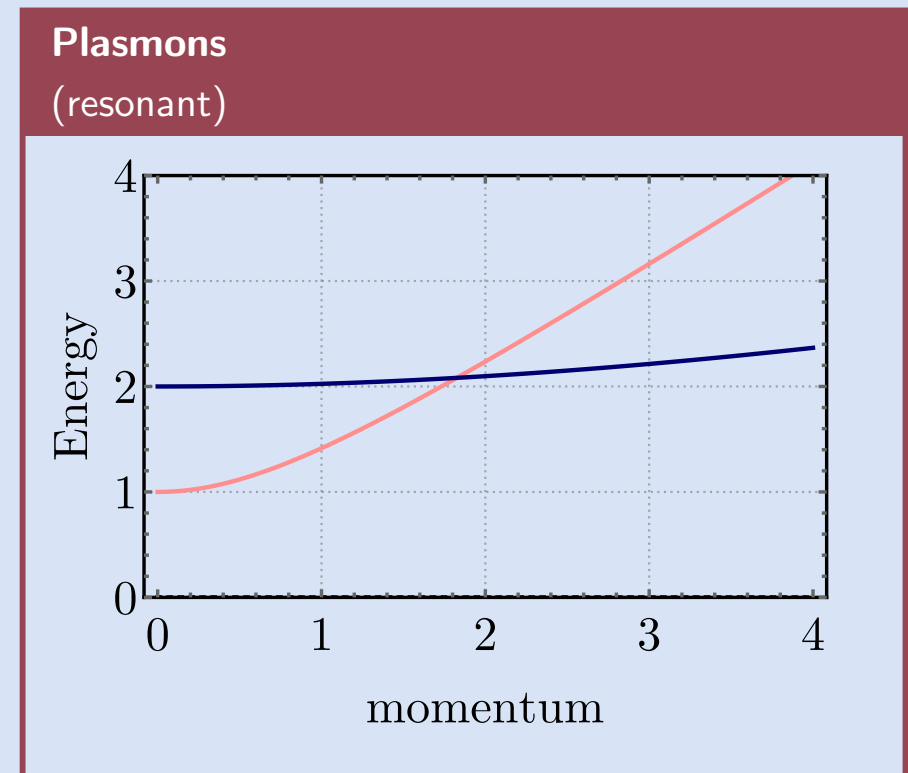
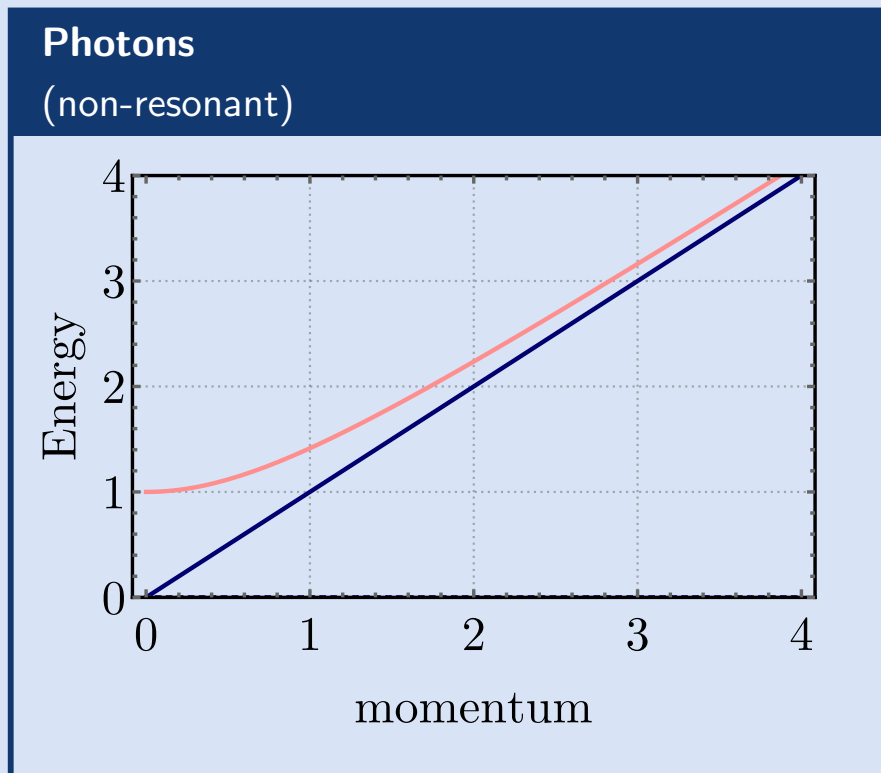
ALPS II

Laser power: 150 kW

Integration time: 15 days

# Axions in plasmas

Why bothering with **plasmon** conversion?



# PART I

## Axions in **homogeneous** plasmas



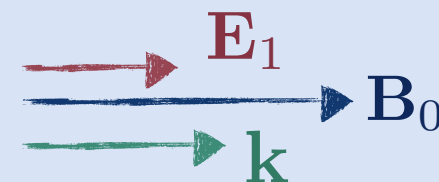
Looking for parallel modes (natural units)

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

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

## Secular equation

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



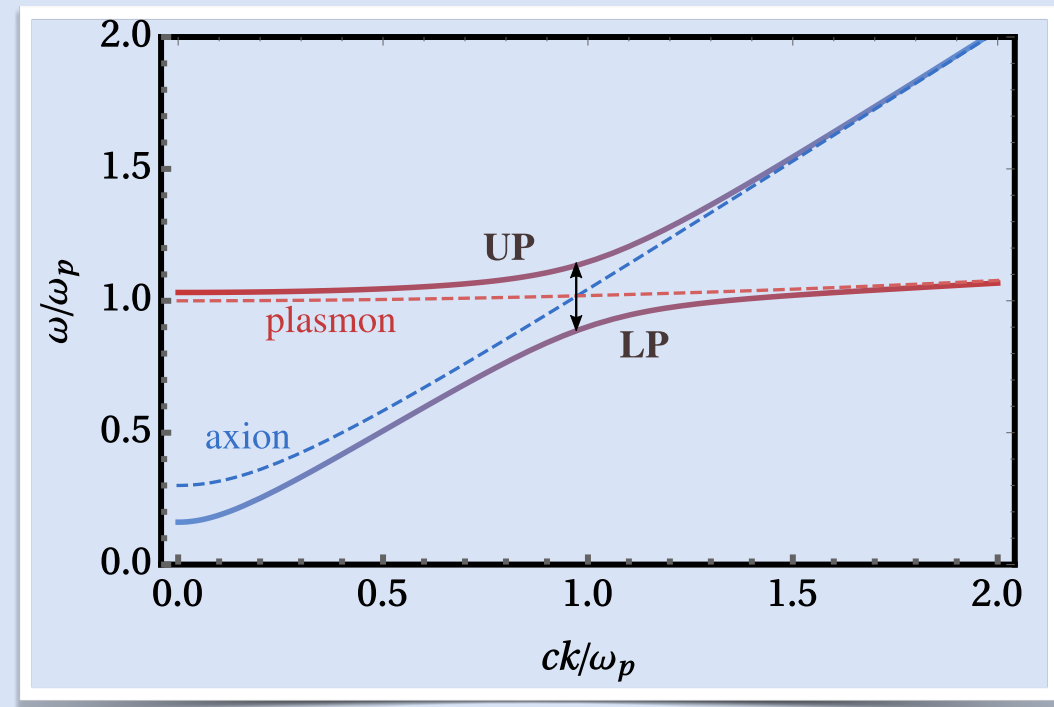
## Rabi frequency

$$\Omega = \sqrt{gB_0\omega_p}$$

# Axions-plasmons polaritons

The dispersion relation contains **two modes**

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



Quantization of the theory: Rotating-wave approximation [RWA]

$$(\omega^2 - \omega_{\text{pl}}^2) \tilde{n} = (\omega - \omega_{\text{pl}}) (\omega + \omega_{\text{pl}}) \tilde{n} \simeq 2\omega_{\text{pl}}(\omega - \omega_{\text{pl}}) \tilde{n}$$

$$(\omega^2 - \omega_{\varphi}^2) \tilde{\varphi} = (\omega - \omega_{\varphi}) (\omega + \omega_{\varphi}) \tilde{\varphi} \simeq 2\omega_{\text{pl}}(\omega - \omega_{\varphi}) \tilde{\varphi}$$

## Inverse Fourier transform

$$\left( i \frac{\partial}{\partial t} - \omega_{\text{pl}} \right) \tilde{n} - ig \frac{B_0}{2\omega_p} kn_0 \tilde{\varphi} = 0,$$

$$\left( i \frac{\partial}{\partial t} - \omega_{\varphi} \right) \tilde{\varphi} + ig \frac{B_0}{k\omega_p} \tilde{n} = 0$$

Creation and annihilation operators for axions and plasmons (canonical quantization)

$$[\hat{c}_k, \hat{c}_q^\dagger] = \delta_{k,q} \quad (\hat{c}_k = \{\hat{a}_k, \hat{b}_k\})$$

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

## Hamiltonian formalism

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

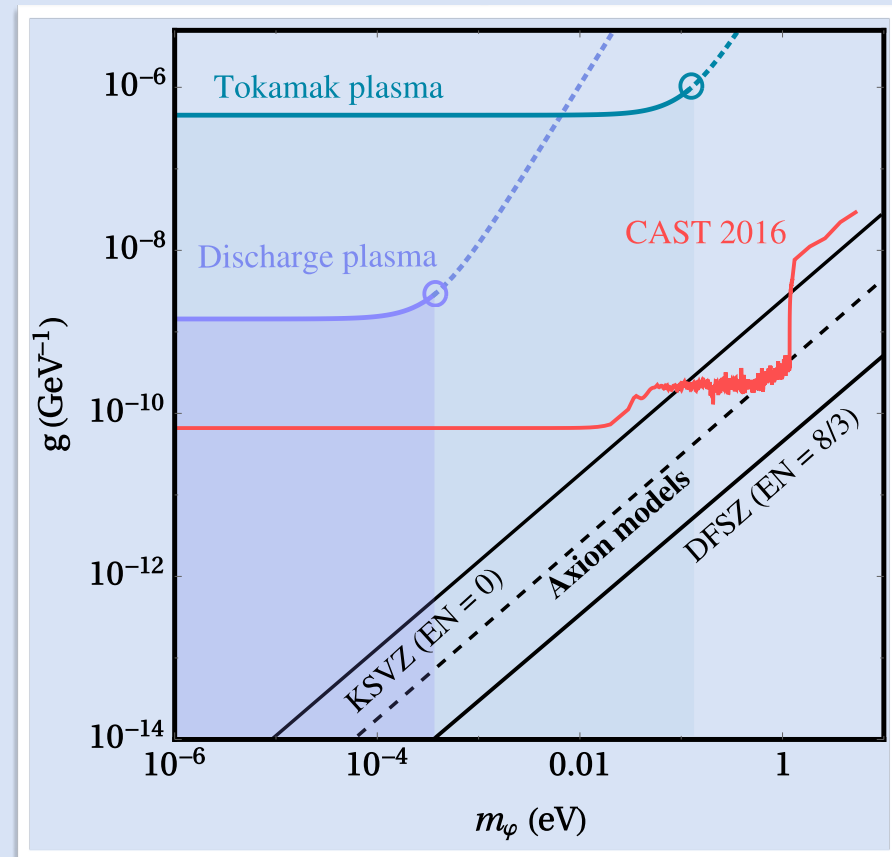


# Strong coupling condition

Strong coupling is achieved for  $\Omega \gg \Gamma_{\varphi \rightarrow pl}$

$$gB_0 \lesssim \omega_p$$

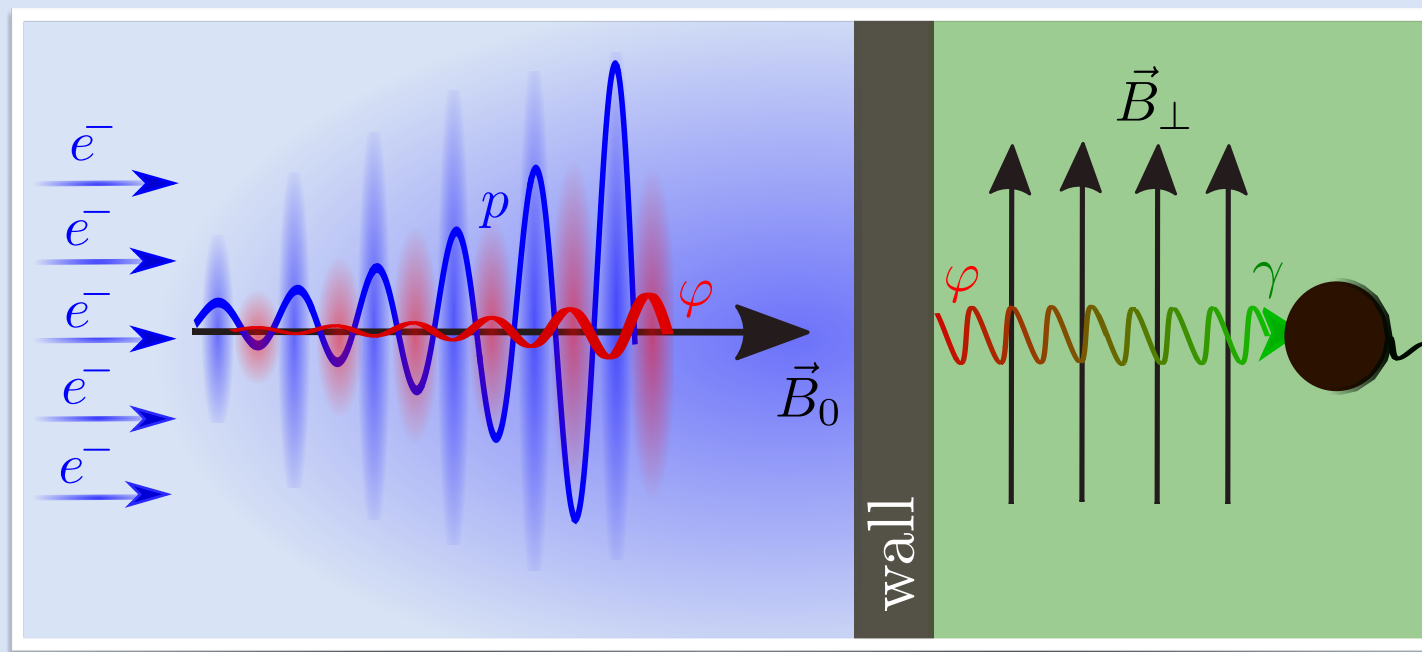
$B_0 = 3 \text{ T}$



HT et al, PRL **120** (2018)

# Active production: beam-plasma

Our idea: an **active search** of axions with plasmas  
(getting inspiration from ALPS)



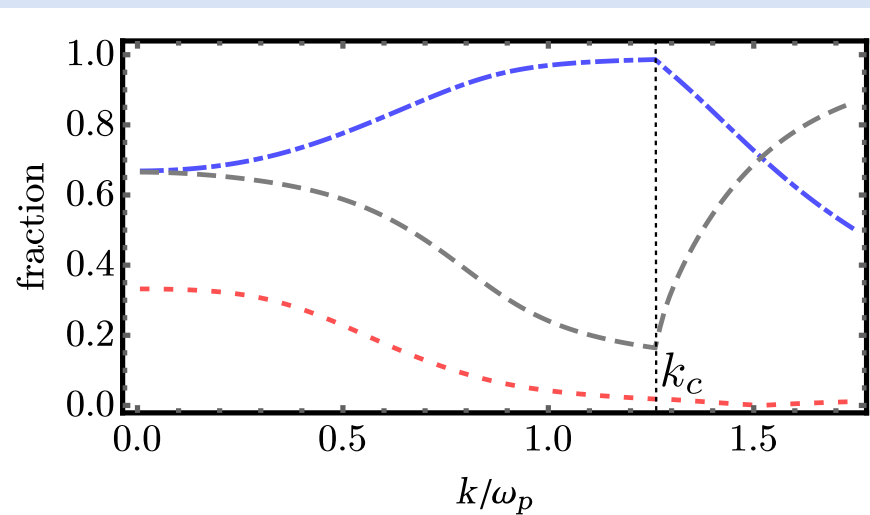
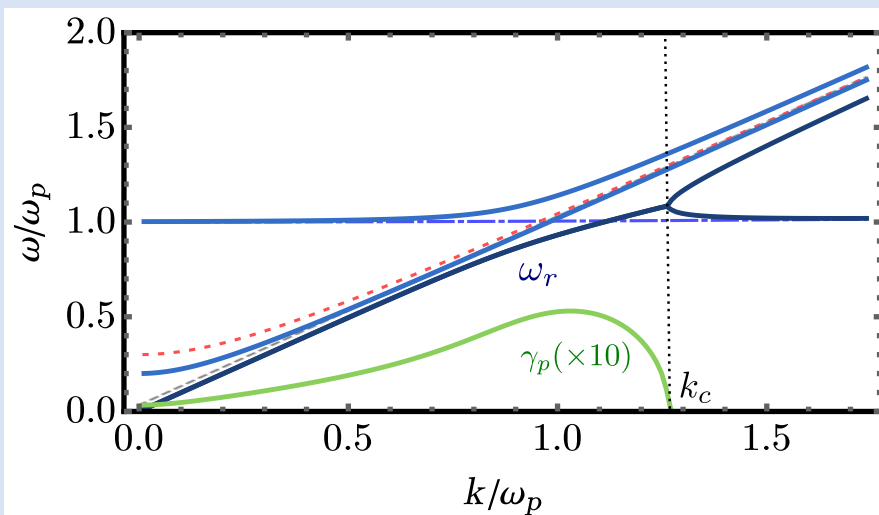
# Dispersion function

We modify the beam-plasma dispersion function with the **axion susceptibility**

$$\epsilon(k, \omega) = 1 - \frac{\omega_p^2}{\omega^2} - \frac{f}{\gamma_0^3} \frac{\omega_p^2}{(\omega - ku_0)^2} \left[ \frac{\Omega^4}{\omega^2(\omega^2 - \omega_\phi^2)} + \frac{f}{\gamma_0^3} \frac{\Omega^4}{(\omega - ku_0)^2(\omega^2 - \omega_\phi^2)} \right]$$

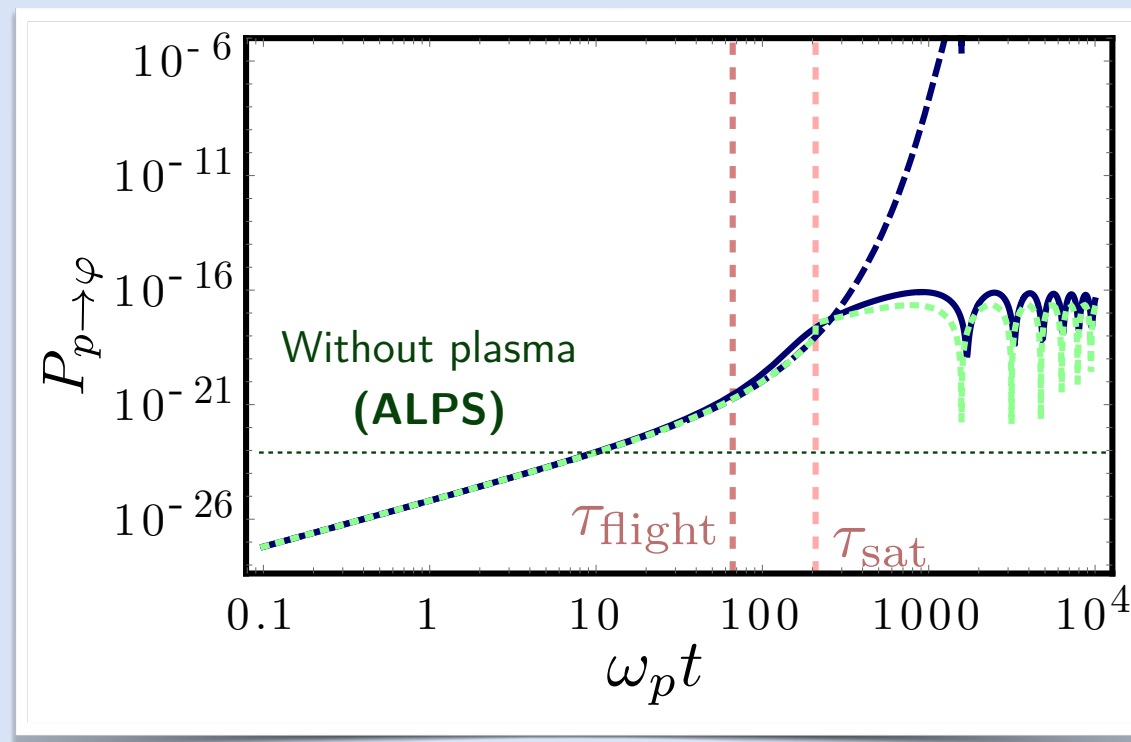
axion-plasma

axion-beam



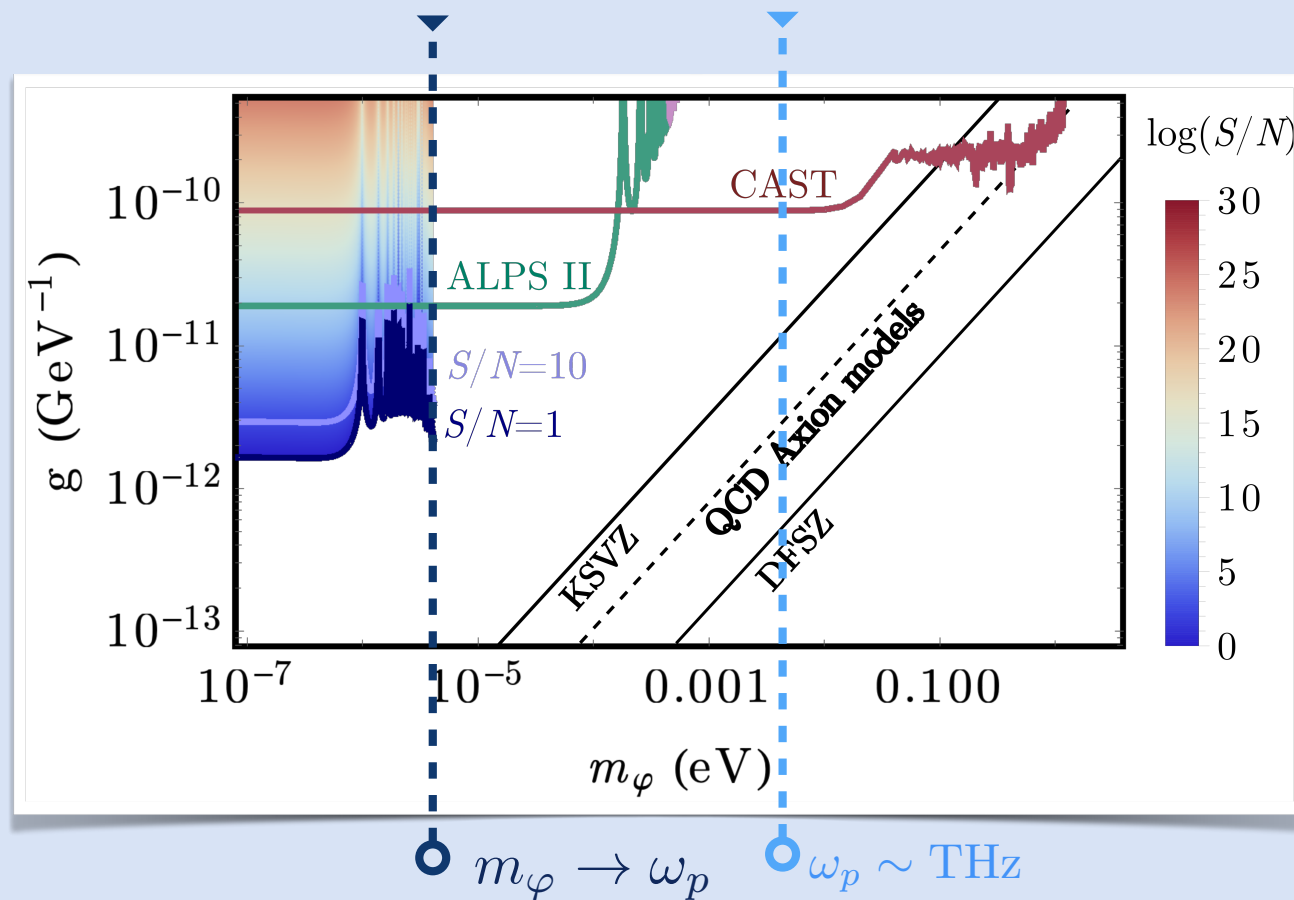
# Active production: beam-plasma

The axion-plasmon conversion probably is much higher



# Beam-plasma sensitivity projection

Projected sensitivity in our “plasma” ALPS scheme



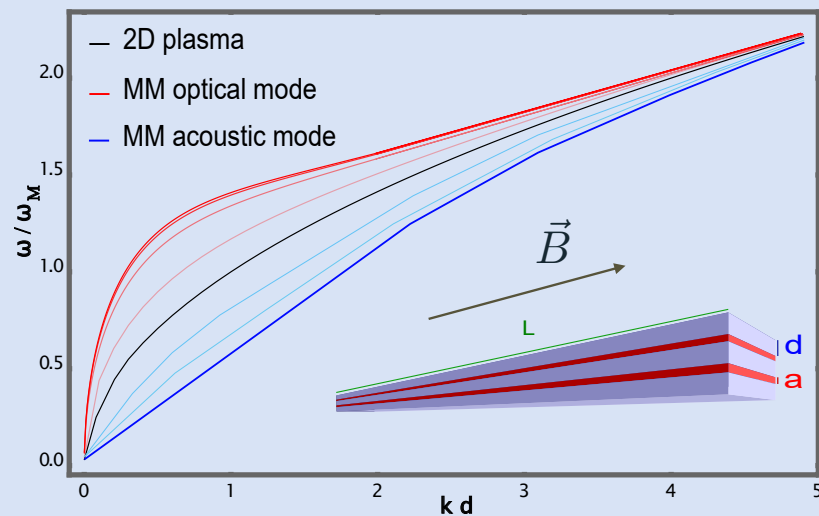
Mendonça et al, PRD  
101 (2020)

# Metamaterials (under construction)

We make use of **metamaterials** (artificial plasmas) to tune the plasmas

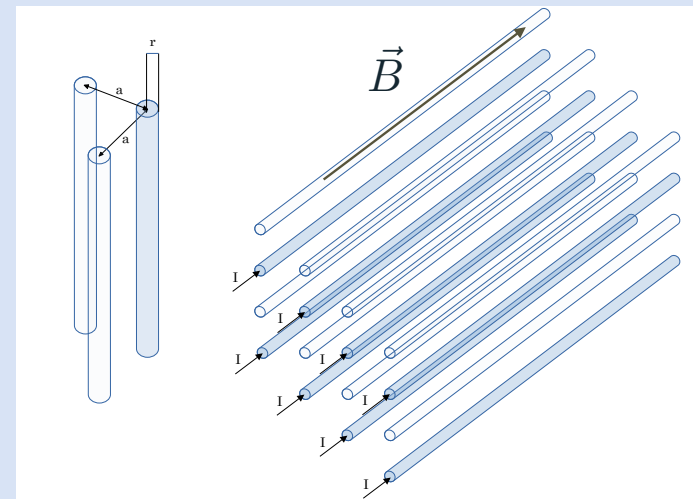
## Stacked

(C. Alfisi | EPJP - accepted)



## Metaplasma

(Under construction)



$$\omega_p = \frac{c}{a} \sqrt{\frac{2\pi}{\ln(a/r)}}$$

(0.1 — 10 THz)

## PART II

# Axions in *inhomogeneous* plasmas

The plasma in the atmosphere of magnetars is **inhomogeneous**

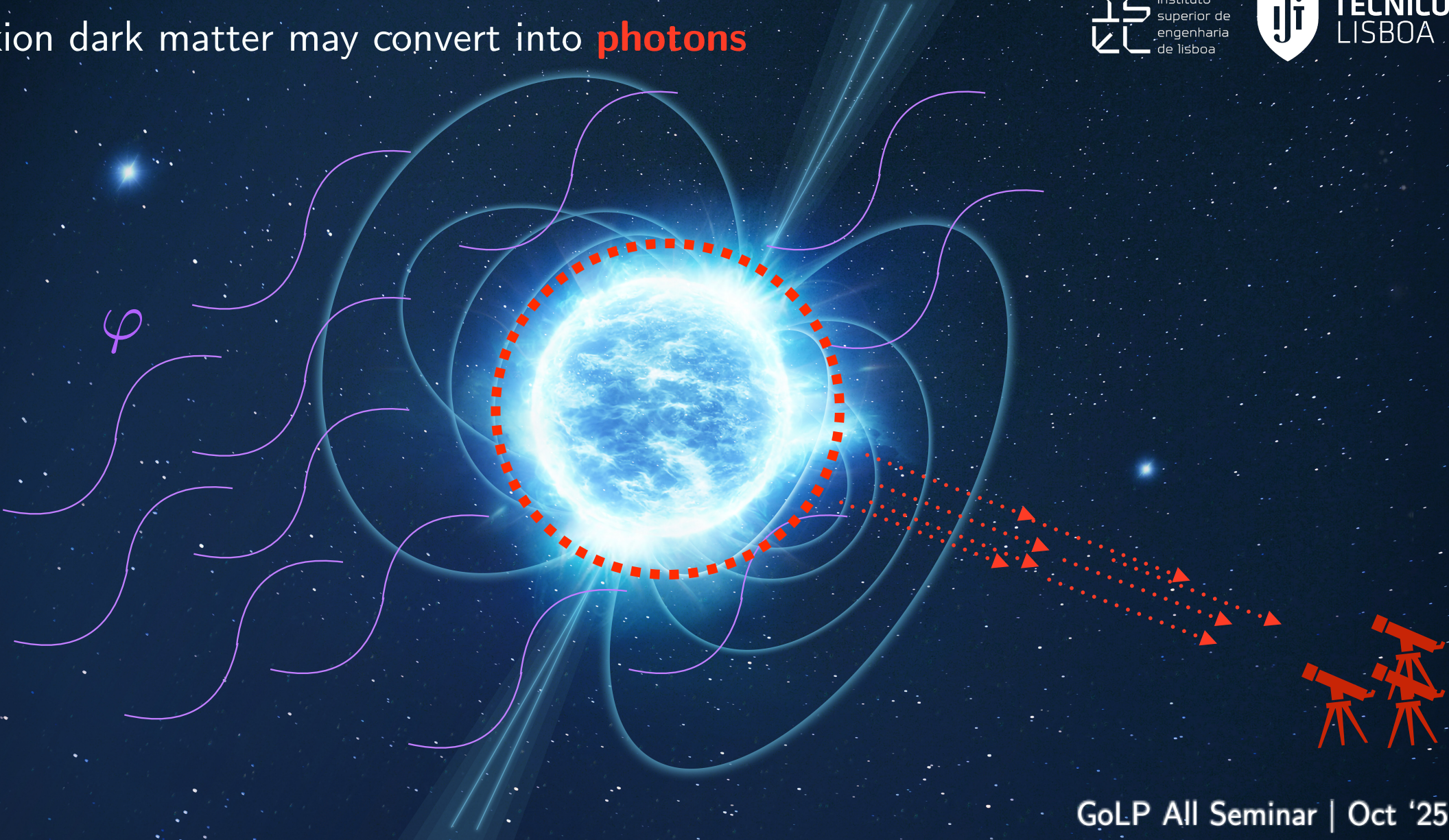
## Goldreich-Julian

$$n(r) = \frac{2\pi B_0}{2\tau} \left(\frac{r_0}{r}\right)^3 f(\theta, \theta_m, \psi)$$

$$B(r) = B_0 \left(\frac{r_0}{r}\right)^3 f(\theta, \theta_m, \psi)$$

$$\rho \mathbf{E} + \frac{1}{c} \mathbf{J} \times \mathbf{B} = 0$$

Axion dark matter may convert into **photons**

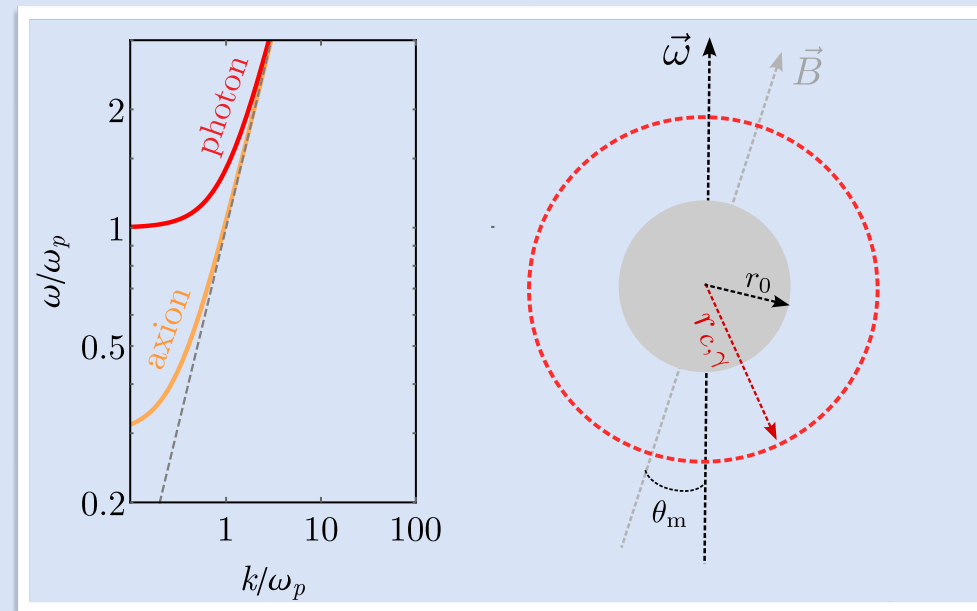


## Adiabatic conversion of axions into photons

$$m_\varphi \simeq \omega_p$$

### Photon conversion radius

$$r_{c,\gamma} = r_0 \left( \frac{\omega_p}{m_\varphi} \right)^{1/3} f^{1/3}$$







# The plasmon case...

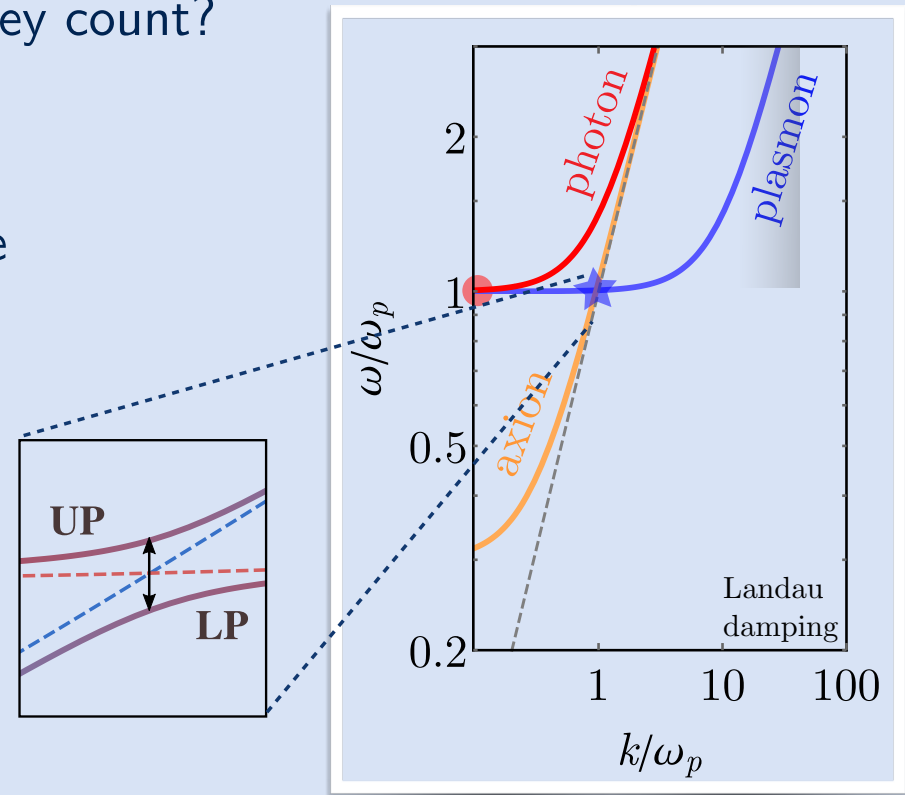
Plasmons (longitudinal photons) do not radiate: do they count?

Investigate **axion-plasmon polaritons** near resonance

$$r = r_c + \xi, \quad k = k_c + \delta$$

## Weber equation

$$\frac{\partial^2 \Psi}{\partial \zeta^2} + \left( \nu + \frac{1}{2} - \frac{\zeta^2}{4} \right) \Psi = 0$$



## Plasmon transmission coefficient

Landau-Zener

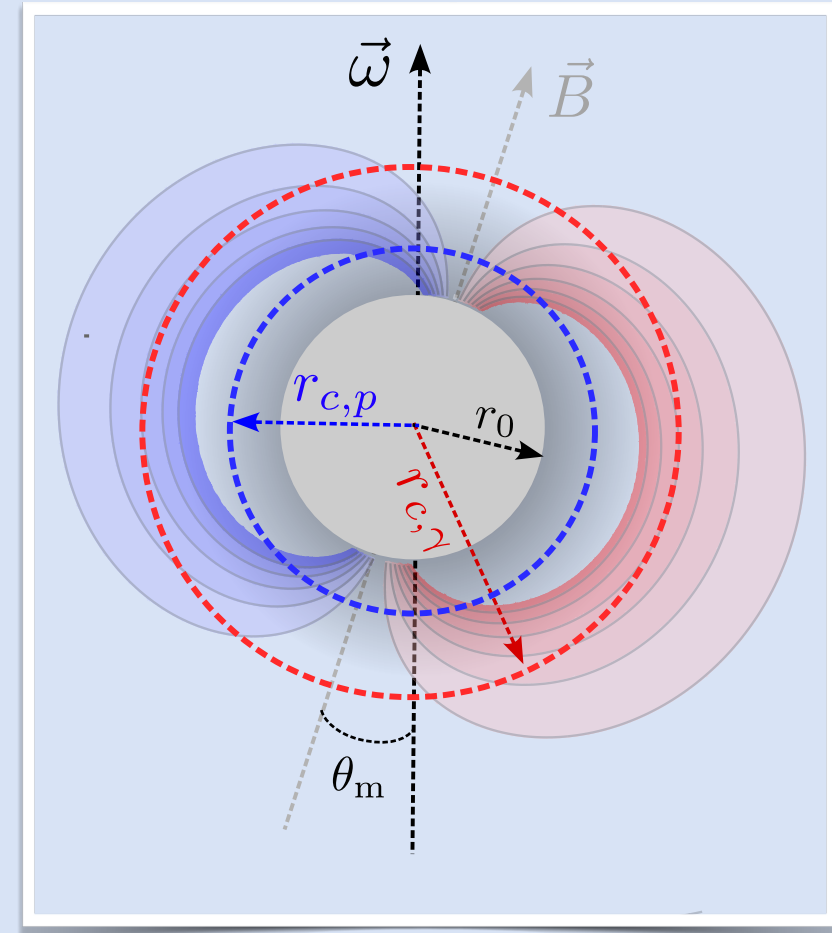
$$T_{\text{plasmon}} = 1 - T_{\text{axion}} = 1 - \exp\left(-\frac{\pi g^2 B_c^2}{2a_\varphi b_e}\right)$$

↓

$$T_{\text{plasmon}} = 1$$

## Plasmon conversion radius

$$r_{c,p} \simeq r_0 \left( \frac{4\omega_p^2 - g^2 B_0^2}{4m_\varphi^2} \right)^{1/6} f^{1/3}$$

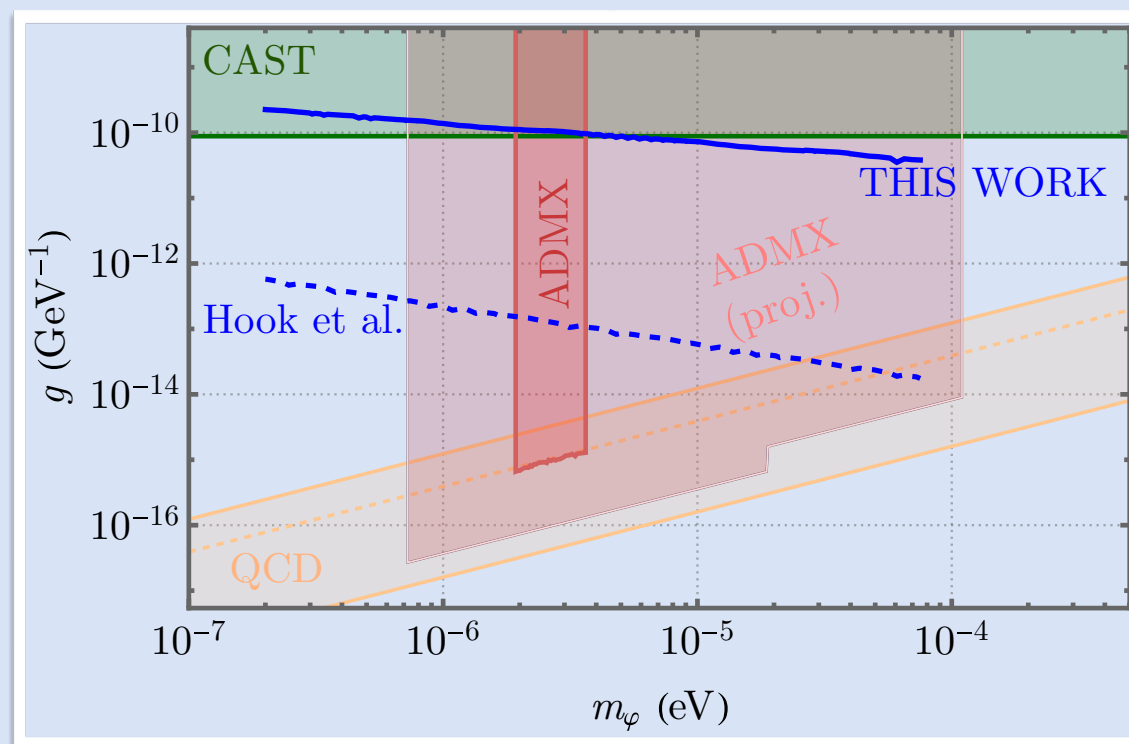


## Corrected power (non-radiative channel)

$$\frac{d\mathcal{P}_\gamma^{(\text{corr})}}{d\Omega} \simeq \frac{d\mathcal{P}_\gamma}{d\Omega} \left[ 1 - \left( 1 - \frac{g^2 B_0^2}{4\omega_p^2} \right)^{1/2} \right]$$

Important sensitivity decrease  
towards  
**EXCLUDED REGIONS**

Terças, Mendonça, Bingham, PRL **135** (2025)



# What could go wrong?

## 1. Strong-field effects

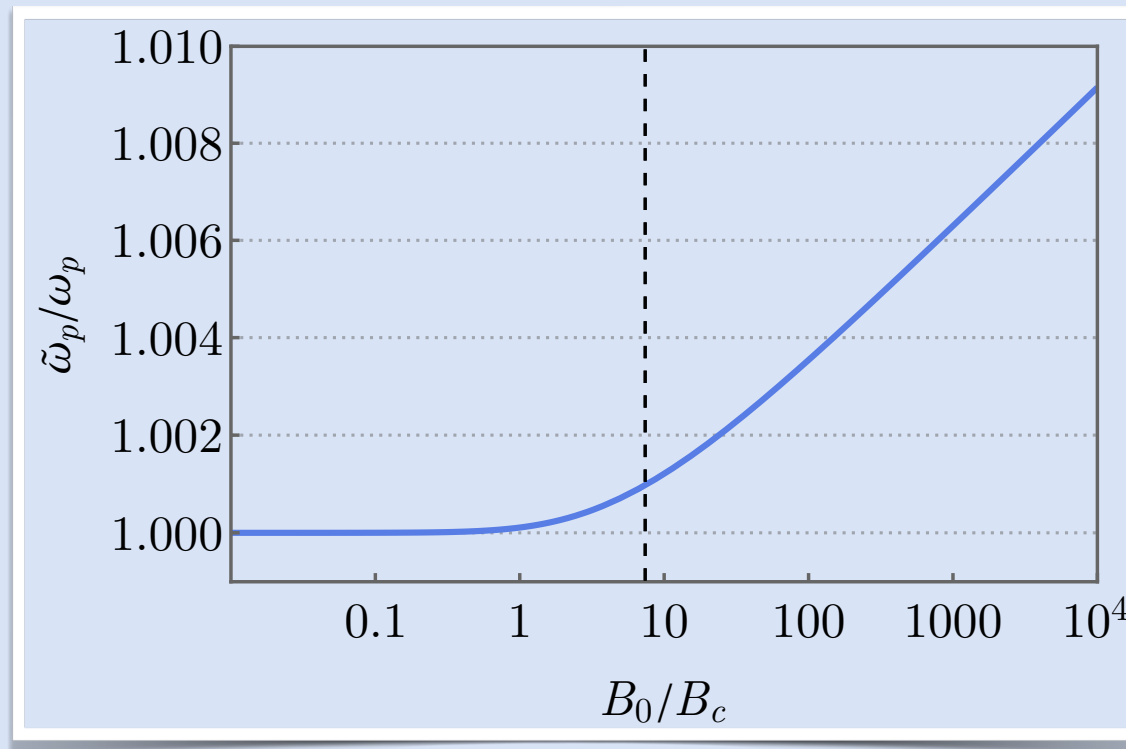
$$\mathcal{L}_{\text{Euler-Heisenberg}} = \beta \left[ \mathcal{F}^2 + \frac{7}{4} \mathcal{G}^2 \right] + \sigma [(\partial_\mu F^{\mu\nu})(\partial_\alpha F_\nu^\alpha) - F_{\mu\nu} \square F^{\mu\nu}]$$

## 2. Electron-positron pair production

$$\text{Im}\Delta\mathcal{L} = \frac{m_e^4}{8\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \left[ \frac{n\pi E}{B} \coth\left(\frac{n\pi B}{E}\right) \right] \exp\left(-\frac{n\pi m_e^2}{|e|E}\right)$$

# Pretty much nothing!

Corrections to the **local plasma frequency** are negligible



# What's next

- Look for active production of axions in “meta-plasmas”
- Understand the axion-electrodynamics controversy

$$\mathcal{L}_{\text{standard}} \sim g\varphi \tilde{F}_{\mu\nu} F^{\mu\nu} \quad \text{vs.} \quad \mathcal{L}_{\text{dual}} \sim g\varphi \left( F_{\mu\nu} \tilde{F}^{\mu\nu} + G_{\mu\nu} \tilde{G}^{\mu\nu} \right)$$

Visinelli, MPL A 28 (2013)

- Investigate EM instabilities with axions (Weibel)
- PIC simulations with axions (HELP NEEDED!)

# Thank you!

(And thank you, Thomas!)

