Polarimetric constraints on axion-like particles
from linear and circular polarisation measurements of quasar light

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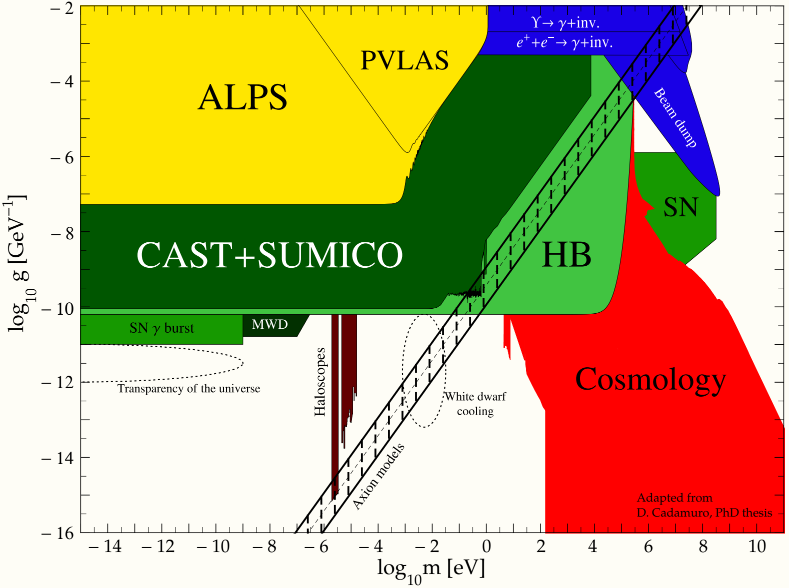
in collaboration with J.R. Cudell and D. Hutsemékers

Interactions Fondamentales en Physique et en Astrophysique
Université de Liège

Searching for ALPs using their coupling with light



Axion-like particles couple to one direction of polarisation

Pseudoscalar ϕ: $\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{4}\, g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g\phi(\vec{E}\cdot\vec{B}) = -g\phi(\vec{\mathcal{E}}_r\cdot\vec{\mathcal{B}}) = -g\phi(\vec{\mathcal{E}}_{r,\parallel}\cdot\vec{\mathcal{B}})$

- Dichroism:
  $\Rightarrow$ Changes linear polarisation
- Birefringence:
  $\Rightarrow$ Changes circular polarisation

[*Sikivie* (1983)], [*Maiani et al* (1986)], [*Raffelt, Stodolsky* (1988)], ...

Remarks:

- any Stokes parameter: evolution $\rightarrow \theta$ and $\frac{\Delta\mu^2}{\omega}z$ (in a given $\vec{\mathcal{B}}$ region)
- averaging over bandwidths $\rightarrow$ reduce circular polarisation (vs. monochromatic)

[*Payez, Cudell, Hutsemékers*, PRD (2011)]

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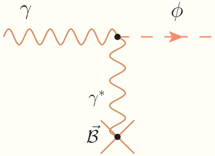

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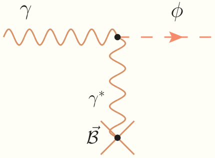

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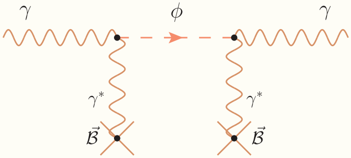

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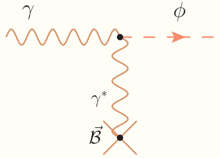

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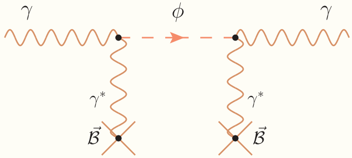

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Polarimetry is a useful tool

The mixing can be very efficient at producing polarisation

& contradict precise quasar polarisation data

⇒ derive constraints

Recent example

→ rotation of UV polarisation angle (↔ quasar morphology)
[*Horns et al.* (2012)], [*di Serego Alighieri et al.* (2010)]

This work

→ consider quasar classes with smallest intrinsic polarisations in visible
⇒ compare amount due to the mixing with observations (p_{lin} and p_{circ})
[*Payez, Cudell, Hutsemékers*, JCAP (2012)]

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Astronomy & Astrophysics

LETTER TO THE EDITOR

Optical circular polarization in quasars★,★★

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ABSTRACT

We present new optical circular polarization measurements with typical uncertainties <0.1% for a sample of 21 quasars. All but two objects have null circular polarization. We use this result to constrain the polarization due to photon-pseudoscalar mixing along the line of sight. We detect significant ($>3\sigma$) circular polarization in two blazars with high linear polarization and discuss the implications of this result for quasar physics. In particular, the recorded polarization degrees may be indicative of magnetic fields as strong as 1 kG or a significant contribution of inverse Compton scattering to the optical continuum.

Key words. quasars: general – polarization

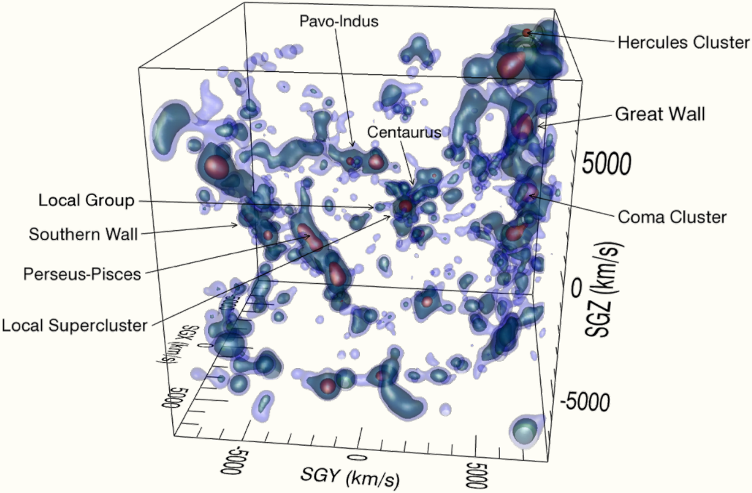
1. Introduction

To interpret the large-scale alignments of quasar optical polarization vectors observed at redshifts $z \sim 1$ (Hutsemékers 1998; Hutsemékers & Lamy 2001; Hutsemékers et al. 2005) polarization induced by photon-pseudoscalar mixing along the line of sight has been invoked (Hutsemékers 1998; Jain et al. 2002). Photon-pseudoscalar mixing generates dichroism and birefringence, the latter transforming linear polarization into circular

telescope equipped with the ESO Faint Object Spectrograph and Camera EFOSC2. Circular polarization was measured using a super-achromatic quarter-wave ($\lambda/4$) retarder plate (QWP), which transforms the circular polarization into linear polarization, and a Wollaston prism, which splits the linearly polarized beam into two orthogonally polarized images of the object (Saviane et al. 2007). The CCD was used in unbinned mode, which corresponds to a scale of 0.157″/pixel on the sky. All

Towards the North Galactic Pole direction

Most observed objects are located in that direction; $z \in [0.4, 2.2]$

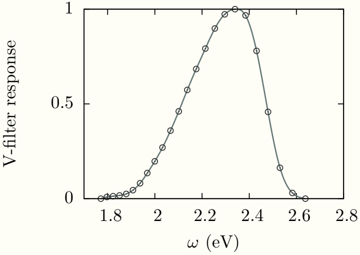


[*Courtois et al.* (2013)]

Defining our sample

Quasar circular polarisation data in visible light

[*Hutsemékers et al.* (2010)]
Bessell V filter; typical uncertainties $< 0.1\%$



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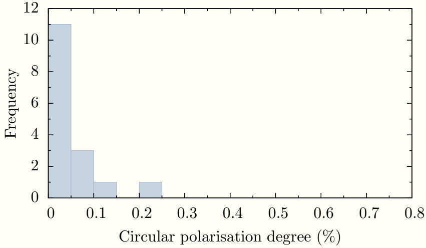
- only V-filter data ("more monochromatic")
- only the least polarised classes



In fact
no evidence for non-vanishing p_{circ} @ 3σ
(except for 2 blazars with $p_{\mathrm{lin}} > 20\%$)

Defining our sample

Linear polarisation data for quasars in that direction (from catalogs)

Subsample for our contraints on ALPs

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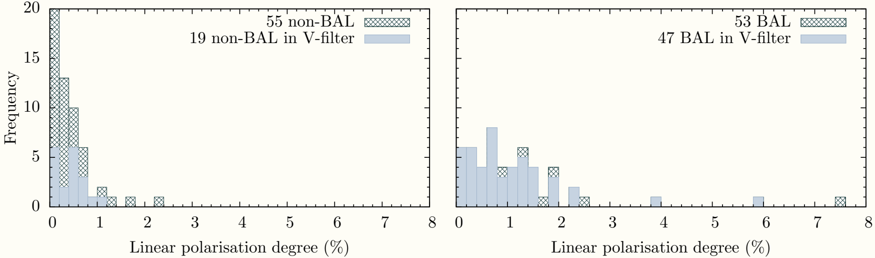

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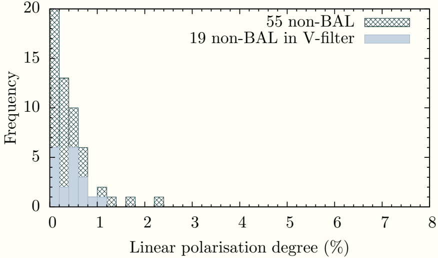
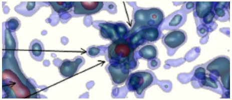


Last relevant magnetic field encountered

Towards center of local supercluster



Magnetic field

Faraday Rotation [*Vallée* (2002, 2011)]:
  Domain structure
  $\approx$ 100 kpc random cells with $\approx 2\ \mu$G adding up to $\approx$ 10 Mpc
NB @ supercluster scale: 5–10 times smaller

Only detection available for local supercluster
$g\mathcal{B}$ always appear together: one can rescale

Electron density

In superclusters, $n_\mathrm{e} \sim 10^{-6}\ \mathrm{cm}^{-3}$; $\omega_\mathrm{p} \propto \sqrt{n_\mathrm{e}}$

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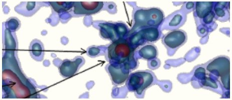

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Conservative method

Start with unpolarised light (very conservative, especially for p_{circ})

For each couple (m, g):

1. Generate random configuration
2. Solve axion-photon mixing $\rightarrow$ polarisation generated
3. Probability to be smaller than the observed one?

$$P = N(p^{\mathrm{obs}} \geq p^{\mathrm{th}})/N_{\mathrm{tot}}$$

4. Repeat and average over many configurations

configuration

$\stackrel{def}{=} \{$domain sizes, magnetic field directions (3D), electron densities$\}$

New constraints on axion-like particles

[*Payez, Cudell, Hutsemékers*, JCAP (2012)]
See next edition of the Review of Particle Properties (Particle Data Group)

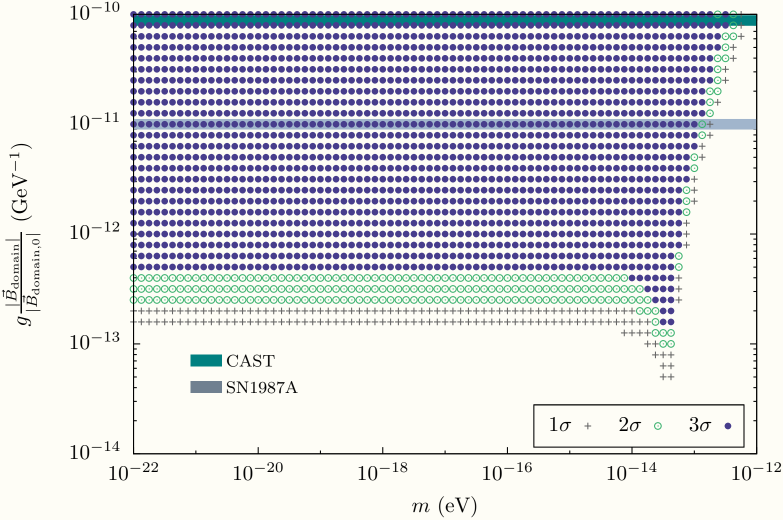

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Illustration of distributions corresponding to a 2σ C.L. exclusion; $m = 10^{-20}$ eV

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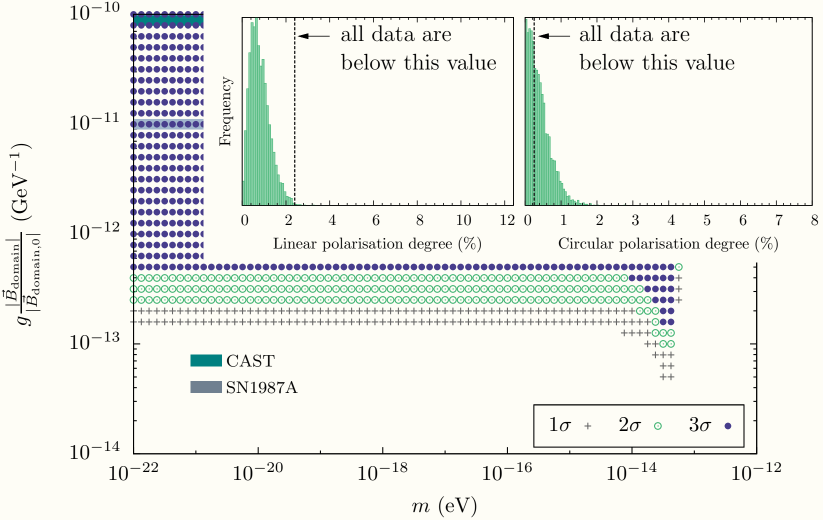

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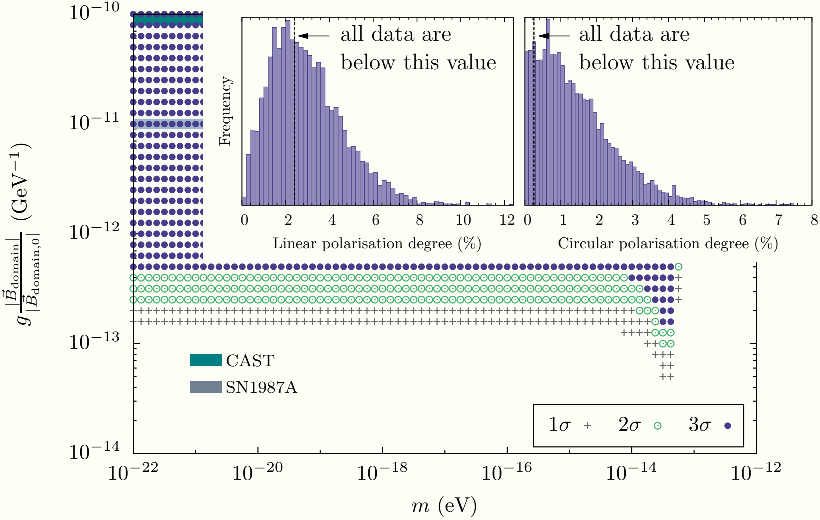

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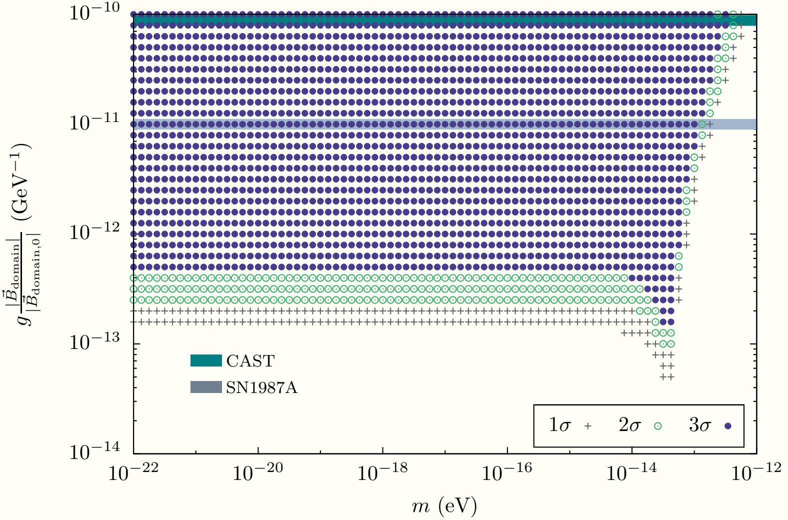
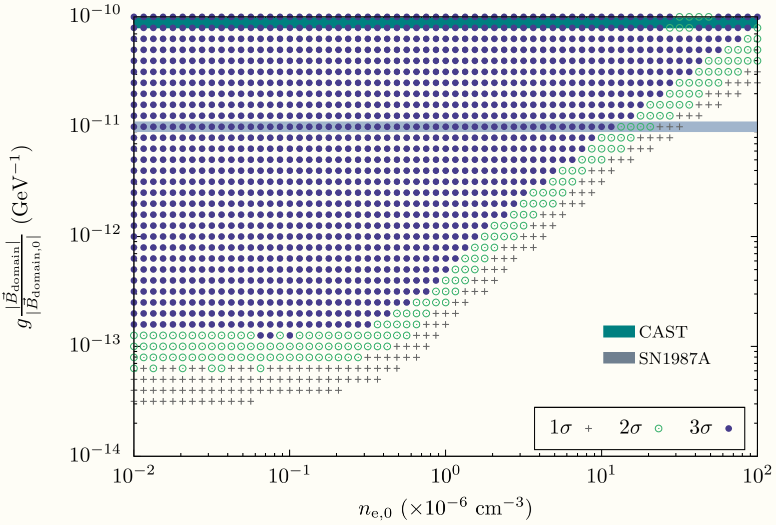


New constraints on axion-like particles

Evolution of the plateau with the average electron density



Summary

- Mixing predicts more polarisation than observed for least polarised quasars
  $\rightarrow$ Improve current bounds on axion-like particles using p_{lin} and p_{circ}
- Conservative method (unpolarised, only inside supercluster)
- Stable constraints

- How well do we know the magnetic field?
  $\rightarrow$ make explicit the dependence on typical magnetic field strength
  and mean electron density

Prospects

- Future: X-ray polarimetry = extremely interesting for astrophysical region
  $\rightarrow$ could lead to new constraints or a discovery

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Quasar circular polarisation data in visible light

[*Hutsemékers et al.* (2010)]

- 21 measurements in white light (compilation)
- 21 measurements using a Bessell V filter; typical uncertainties $< 0.1\%$

$\Rightarrow$ Optical circular polarisation compatible with zero at 3σ for all objects*

*except 3 (1+2) highly linearly polarised blazars ($p_{\rm lin} > 20\%$)

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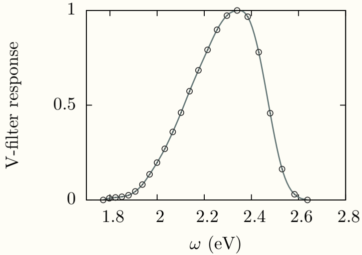
$\Rightarrow$ 18 objects, 16 in the same direction



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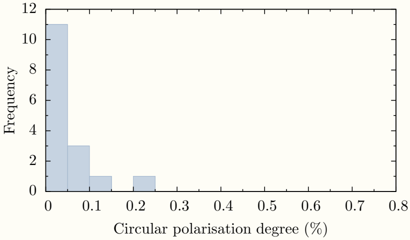
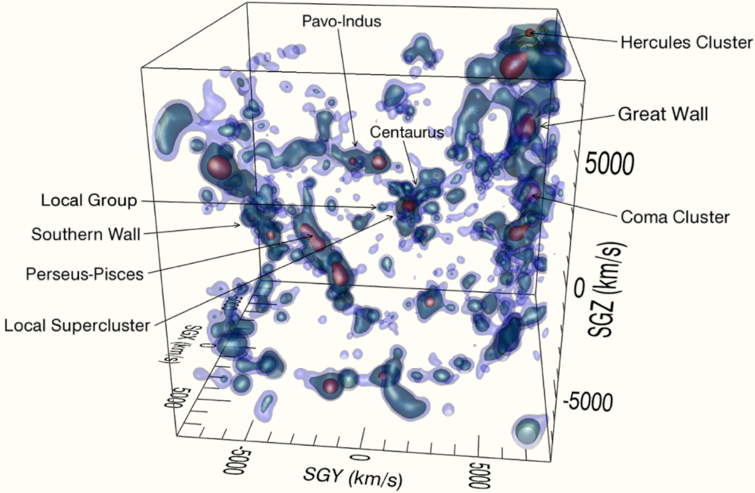


Towards the North Galactic Pole direction
These 16 quasars have $z \in [0.4, 2.2]$



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Linear polarisation data for quasars in that direction (from catalogs)

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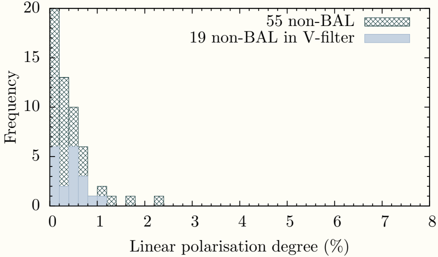

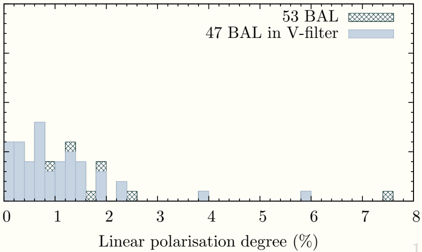

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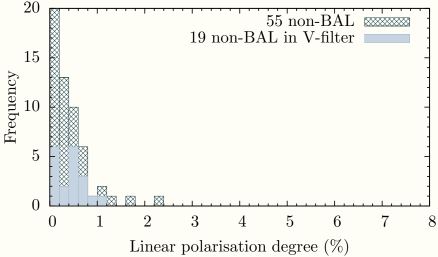

The reason why it can be reduced

Considering:

- fixed-energy solutions
- a single $\vec{\mathcal{B}}$ region.

NB: $\vec{E}_{\perp,\parallel} = i\omega\vec{A}_{\perp,\parallel}$ (temporal gauge)

In the basis $(\vec{e}_\perp, \vec{e}_\parallel)$:

- $A_\perp(z)$ does not feel the interaction (decoupled);
- Equation of motion for $A_\parallel(z)$ and $\phi(z)$:

$$\left[\left(\omega^2 + \frac{\partial^2}{\partial z^2}\right) - \mathcal{M}(\omega)\right]\begin{pmatrix} A_\parallel(z) \\ \phi(z) \end{pmatrix} = 0;$$

$\Rightarrow$ "$C(z)$" & "$D(z)$" = mixtures of $A_\parallel$ and of ϕ, with eigenvalues $\mu_{\mathrm{C,D}}(\omega)$.

$\Rightarrow$ Phase-shift depends on ω, so does circular polarisation

Wave packets = "averaging over ω"

$\Rightarrow \searrow \langle v(z)\rangle_\omega$, as circular polarisation $v(z,\omega)$ can be positive or negative

Axion–photon coupling and Primakoff effect

$\vec{E} = \vec{\mathcal{E}}_r + \vec{\mathcal{E}}, \quad \vec{B} = \vec{\mathcal{B}}_r + \vec{\mathcal{B}};$

$\vec{\mathcal{E}}_r$, $\vec{\mathcal{B}}_r$: orthogonal fields of the radiation
reminder: $\vec{\mathcal{E}}_r$ defines the direction of polarisation

$\vec{\mathcal{E}}$, $\vec{\mathcal{B}}$: possible external transverse fields
for astrophysical applications: usually $\vec{\mathcal{B}} \neq 0$, $\vec{\mathcal{E}} = 0$

- γ polarised // to $\vec{\mathcal{B}}$ in the case of pseudoscalar ϕ:

$$\mathcal{L}_{\phi\gamma\gamma,\mathrm{ps}} = \frac{1}{4}\, g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g\phi(\vec{E}\cdot\vec{B}) = -g\phi(\vec{\mathcal{E}}_r\cdot\vec{\mathcal{B}}) = -g\phi(\vec{\mathcal{E}}_{r,\parallel}\cdot\vec{\mathcal{B}})$$

- γ polarised $\perp$ to $\vec{\mathcal{B}}$ in the case of scalar ϕ:

$$\mathcal{L}_{\phi\gamma\gamma,\mathrm{sc}} = \frac{1}{4}\, g\phi F_{\mu\nu}F^{\mu\nu} = \frac{1}{2} g\phi(\vec{B}^2 - \vec{E}^2)$$

and in $(\vec{B})^2$ there is $\vec{\mathcal{B}}\cdot\vec{\mathcal{B}}_r$ ($\neq 0$ for non-zero coupling)