Axion-like particles and polarisation of quasars

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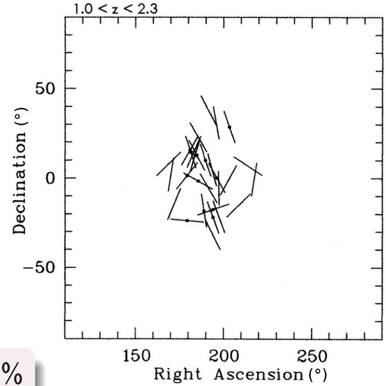
Coherent orientation of quasar polarisation vectors

Quite a puzzling observation —our starting point

Quasar polarisation vectors (in visible light):

→ tend to be aligned in some regions of the sky ($\sim$ 1000 Mpc)



Statistics:
$P_{\text{random}} = 10^{-4}$

Latest Sample
355 quasars

(1/2 from literature)

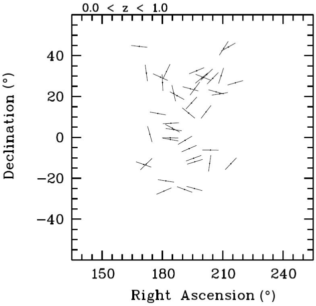
Linear pol.$\sim$1%

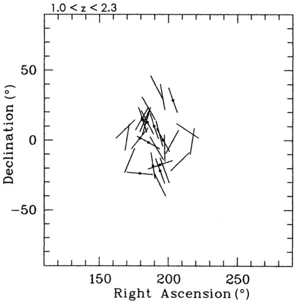
[D. Hutsemékers* *et al* (1998, 2001, 2005)]

*results presented @ the 2nd Patras Workshop

Coherent orientation of quasar polarisation vectors

Quite a puzzling observation —our starting point





- Different alignments for regions along the same line of sight
  $\Rightarrow$ Non-local effect

Looking for an explanation
How axions come into play

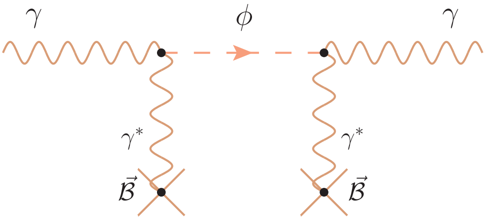
1. Mechanism leading to a global alignment?
2. Mechanism affecting light during its propagation?
   (NB: addition of a small systematical polarisation $\Rightarrow$ alignment effect)

Axion-like particles (ALPs): ID Card

- Pseudoscalar particles like π^0
- Very small mass, interacting very weakly
- Couple with light

Axion–photon coupling and primakoff effect

Axions'influence on light —the way it is done



Primakoff effect

- Original effect: for π^0
- $\gamma\gamma^* \leftrightarrow$ axion
- Pseudoscalars: polarisation // to $\vec{\mathcal{B}}$
- Add small polarisation: Dichroism
- Photons interacting with $\vec{\mathcal{B}} \longrightarrow$ acquire a mass

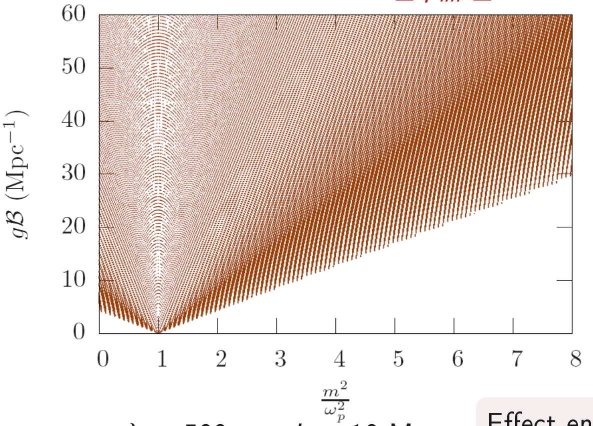
A far from exhaustive list of references:

[P. Sikivie (1983)], [G. Raffelt and L. Stodolsky (1988)], ..., [S. Das *et al* (2005)], ...

Results considering plane waves

Exploration of the parameter space which could explain the effect

Parameters such that $0.005 \leq p_{lin} \leq 0.02$



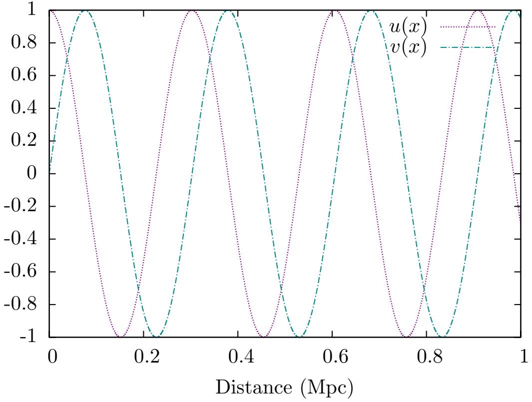
$\lambda = 500$ nm; $L = 10$ Mpc

- Just considering one $\mathcal{B}$ region
- Light initially unpolarised
- $g\mathcal{B}$, always together
- x-axis: only m varies ($\omega_p \lesssim 4\ 10^{-14}$ eV for clusters, super-clusters)

Effect enhanced when $m \approx \omega_p$: resonance $\Rightarrow$ Amplitude of $p_{lin} \gg$

Results considering plane waves

Spontaneous appearance of polarisation & birefringence



- Case of initially polarised light:
  - $u(x)$ (linear);
  - $v(x)$ (= circular).
- Again: creation/modification of polarisation.

Generic feature of that kind of mixing:
v can be as large as the linear polarisation.

$m = 4.5\ 10^{-14}$ eV
$\mathcal{B} = 0.1\ \mu$G
$g = 7\ 10^{-12}$ GeV^{-1}

Results considering plane waves

The circular polarisation, v

Describing light with plane waves:

Starting with $v(0) = 0$, $v(x)$ will be kept small if, for example:

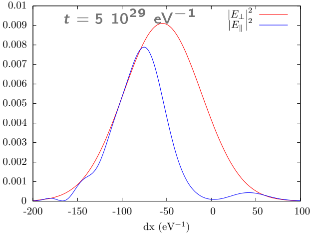
- No mixing (trivial);
- Light polarised perpendicular or parallel to $\vec{\mathcal{B}}$ (unrealistic).

Working with relativistic wave packets

Possible new effects concerning the circular polarisation, v —decoherence

Consequences of a formalism in terms of wave-packets?

Due to axion–photon mixing, in $\mathcal{B}$:
$\neq$ polarisations $\longrightarrow$ $\neq$ masses ($\neq$ velocities).
$\Rightarrow$ separation & $\neq$ spreading.

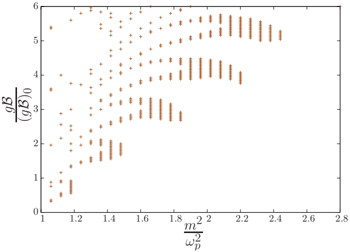


If such an effect occur, v ($\propto E_\parallel E_\perp^*$) could actually be quite small.

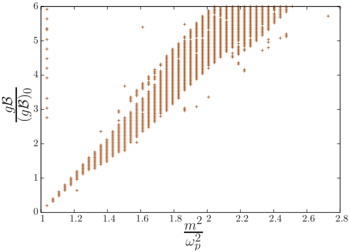
Working with relativistic wave packets

What wave packets can do —compared to plane waves

Plane Waves

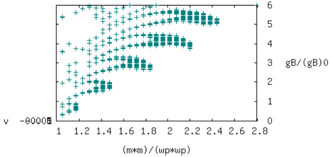


Wave-Packets

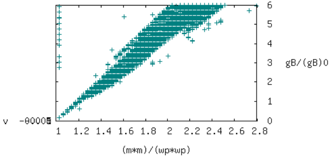


linear pol.

(constraint)



circular† pol.



†in the worst-case scenario for the circular polarisation: $|\vec{E}_{\perp,0}| = |\vec{E}_{\parallel,0}|$; here, $u(0) = 0.01$

Working with relativistic wave packets

Plasma frequency in voids —possible unwanted effect

If ω_p (n_e) is too large in voids $\Rightarrow$ Wave-packets will spread too much.
If so, behaviour reduced to the one of plane waves.

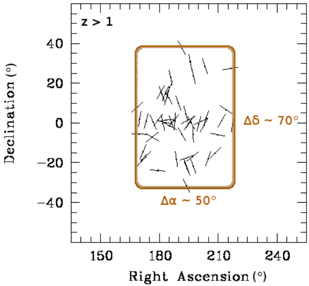
Some comments

- ω_p: poorly estimated (& needs $|\vec{\mathcal{B}}|$), might be small (lower bound?)
- Do we really have to consider ω_p when using wave packets?

The question of the magnetic field needed

The price to pay for having a large-scale effect —something to keep in mind

Different large-scale alignment in two zones
$\Leftrightarrow$ coherent large-scale magnetic field between them.



$t_L(z=1, \Omega_\Lambda=0.8, \Omega_M=0.2) \simeq 2.5$ Gpc

To explain the data with $z > 1$:
a coherent B over huge regions
may be needed (of size ~ 1 Gpc^2?).

Summary

1. Existence of large-scale coherent orientations of quasar polarisation vectors (non-local effect). Very light axion-like particles look promising.
2. Possible to create linear polarisation thanks to axion–photon mixing.
3. Discussion about wave packets separation and circular polarisation. [paper in preparation]
4. The question of $\vec{\mathcal{B}}$ and ω_p: key parameters.

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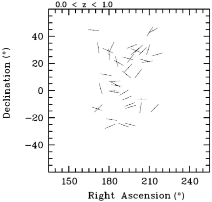

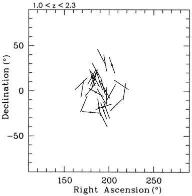

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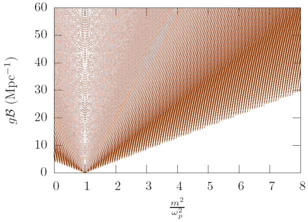

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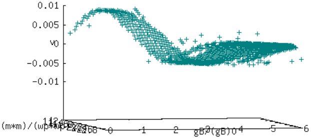

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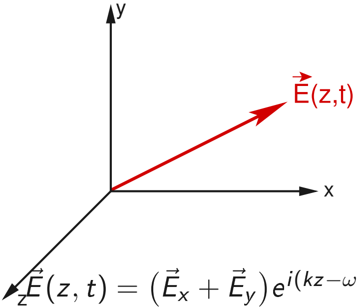
Characterisation of the polarisation

Stokes parameters and related quantities

Stokes Parameters

$$\begin{cases} I & : \text{Intensity} \\ Q & : \text{Linear Polarisation} \\ U & : \text{Linear Polarisation} \\ V & : \text{Circular Polarisation} \end{cases}$$



$$\vec{E}(z,t) = \left(\vec{E}_x + \vec{E}_y\right) e^{i(kz-\omega t)}$$

Having introduced

$$q = \frac{Q}{I}, \quad u = \frac{U}{I} \quad \text{and } v = \frac{V}{I},$$

in astrophysics, one uses often

- the degree of linear polarisation $p_{lin} = \sqrt{q^2 + u^2}$
- the polarisation angle θ

Obtaining the equations of motion

some ref.: Raffelt G. & Stodolsky L. (1988), Das S. et al. (2005)

Modified Maxwell's equations

$$\begin{aligned} \vec{\nabla}\cdot\vec{E} &= g\vec{\nabla}\phi\cdot\vec{B}+\rho; \\ -\frac{\partial\vec{E}}{\partial t}+\vec{\nabla}\times\vec{B} &= g\left(\vec{E}\times\vec{\nabla}\phi-\vec{B}\,\frac{\partial\phi}{\partial t}\right)+\vec{j}; \end{aligned}$$

$$\begin{aligned} \vec{\nabla}\times\vec{E}+\frac{\partial\vec{B}}{\partial t} &= 0; \\ \vec{\nabla}\cdot\vec{B} &= 0. \end{aligned}$$

Equation of motion for the axion field, ϕ

$$\frac{\partial^2\phi}{\partial t^2}-\nabla^2\phi+m^2\phi=-g\vec{E}\cdot\vec{B}.$$

(Heaviside-Lorentz convention)

Some approximations

Simplification of the system of coupled equations and resolution

Let us suppose:

- large distance from quasars: $\rho, \vec{j} \approx 0$
- $\vec{B} = \vec{\mathcal{B}} + \vec{B}_r; \qquad \mathcal{B} \gg B_r, E_r$
- non-linear terms can be dropped ($\mathcal{O}(g^2)$)

Combining Maxwell's equations, rewrite the equations of motion:

$$\begin{cases} \frac{\partial^2 \vec{E}}{\partial t^2} - \nabla^2 \vec{E} + \omega_p^2 \vec{E} = g \vec{\mathcal{B}} \frac{\partial^2 \phi}{\partial t^2} \\ \frac{\partial^2 \phi}{\partial t^2} - \nabla^2 \phi + m^2 \phi = -g \vec{E} \cdot \vec{\mathcal{B}} \end{cases}$$

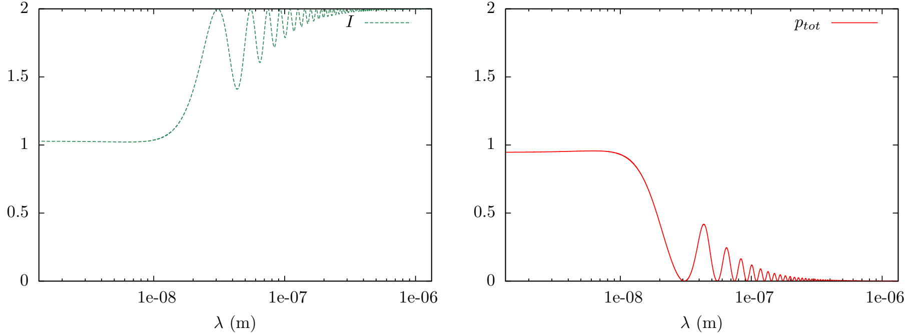
ω_p (effective mass for photons)

→ Next step: calculate the polarisation.

Results considering plane waves

Spontaneous appearance of polarisation & oscillation of polarisation degree with λ

Status of the polarisation when light exits a zone of $\mathcal{B}$ ($L = 10$ Mpc)

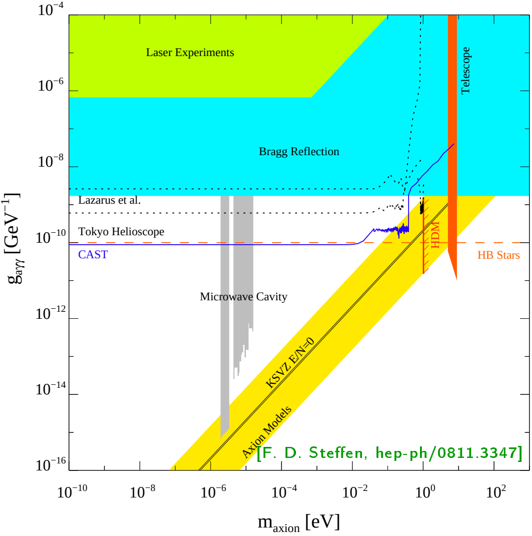


- Case of initially unpolarised light
- Oscillations of increasing amplitude from $\lambda_{large} \longrightarrow \lambda_{small}$

$m = 4.5\ 10^{-14}$ eV
$\mathcal{B} = 0.1\ \mu$G
$g = 7\ 10^{-12}$ GeV^{-1}

Limits on axions & similar pseudoscalar particles

The need of axion-like particles



[F. D. Steffen, hep-ph/0811.3347]

- Yellow Band = Axion models
- However, typical estimates of $\mathcal{B}$ require $\omega_p \sim m$

$\Rightarrow$ If this is to explain the signal

$\Downarrow$

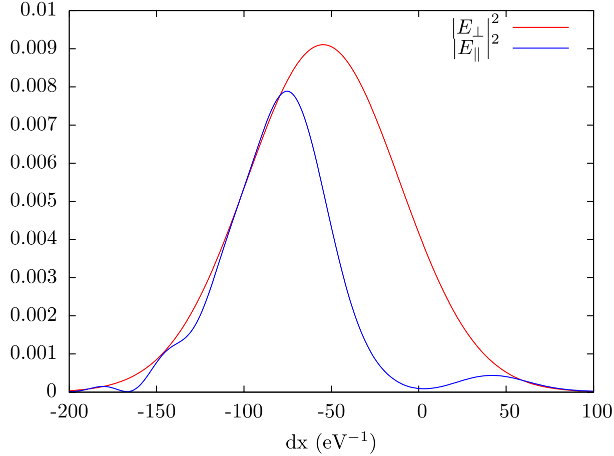
Requires the existence of pseudoscalar particles not predicted by grand unification theories but lighter.

Working with relativistic wave packets ; decoherence

Separation of wave packets —preliminary result

- $E_\perp(t=0) = E_\parallel(t=0)$ (100% polarised)
- $\lambda_0 = 500$ nm (~ 2.5 eV^{-1})
- Interferences

$t = 5\ 10^{29}$ eV^{-1}



Close to resonance (mixing angle $\sim \frac{\pi}{8}$):

$m = 3.8\ 10^{-14}$ eV

Quasars and A(ctive) G(alactic) N(uclei): current model

Some basic properties of the objects under observation