# Axions and Polarisation of Quasars

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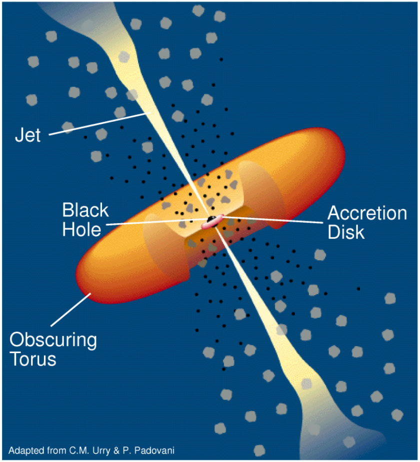
# Quasars and A(ctive) G(alactic) N(uclei): Current Model

## Some Basic Properties of the Objects under Observation



Adapted from C.M. Urry & P. Padovani

- Located at very high redshifts (seldom resolved in V-filter)
- $\sim$ 100 times more luminous than a typical galaxy
- Source of continuum $\leq$ 1 pc

$$\updownarrow$$

Milky Way $\sim$ 30 kpc

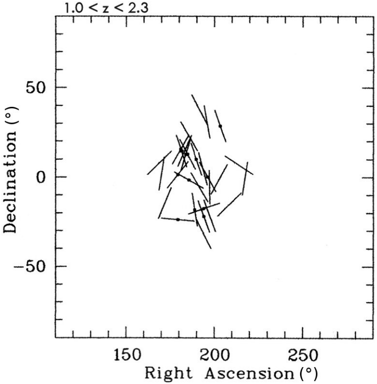
- Emission of polarised light

# 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)

Pol.$\sim$1%

Hutsemékers D. et al (1998, 2001, 2005)

# Coherent Orientation of Quasar Polarisation Vectors

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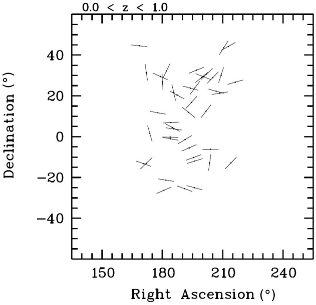
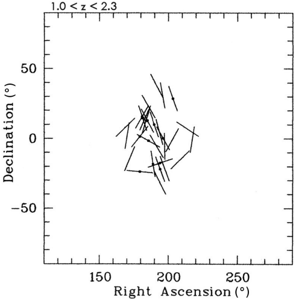




- Different alignments for regions along the same line of sight
  ⇒ Non-local effect

# Looking for a Culprit

## How Axions Come into Play

Two great categories of conceivable explanations for the polarisation alignement:

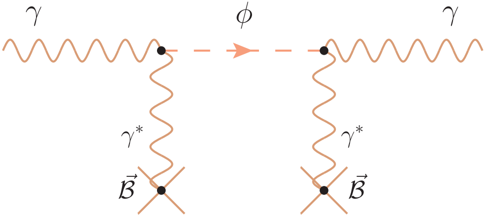
1. Mechanism leading to a global alignment
2. Mechanism affecting light during its propagation
   (NB: addition of a small systematical polarisation ⇒ alignment effect)

**Axions: ID Card**

- Pseudoscalar particles like $\pi^0$
- Strong CP Problem
- Very small mass, interacting very weakly (dark matter candidates)
- Constrain between mass and couplings
- Couple with light

# Axion–Photon Coupling and Primakoff Effect

## Axions'Influence on Light — the way it is done



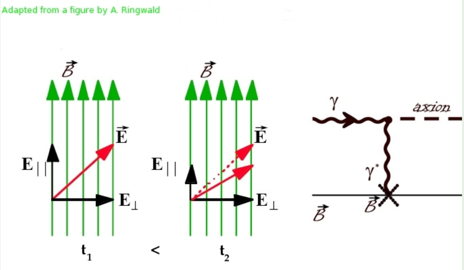
### Primakoff Effect

- Original Effect: for $\pi^0$
- $\gamma\gamma^* \leftrightarrow$ axion
- Pseudoscalars: polarisation // to $\vec{\mathcal{B}}$

# Axion–Photon Coupling and Primakoff Effect

## Axions'Influence on Light — the way it is done

### Dichroism



Adapted from a figure by A. Ringwald

- Selective absorption of one component of the light $\Rightarrow$ appearence of a slight linear polarisation
- Possible rotation of the polarisation plane
- Loss of intensity

# 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, $\phi$

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

(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:

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

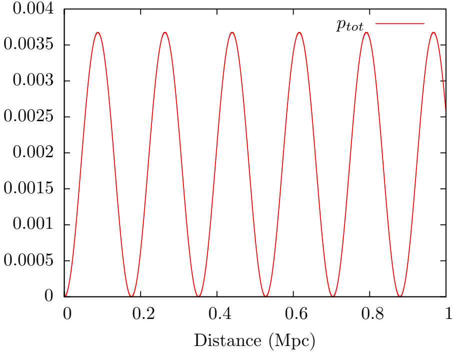
$\omega_p$ (effective mass for photons)

→ Next step: calculate the polarisation.

# Results Considering Plane Waves

## Spontaneous Appearance of Polarisation & Oscillation of Polarisation Degree along $z$

- Additional polarisation (dichroism):



Axion–photon oscillations in $\mathcal{B}$

Parameters

- $\lambda = 500$ nm
- $\mathcal{B} = 0.1\ \mu$G
- $\omega_p \sim 4\ 10^{-14}$ eV

→ typical values.

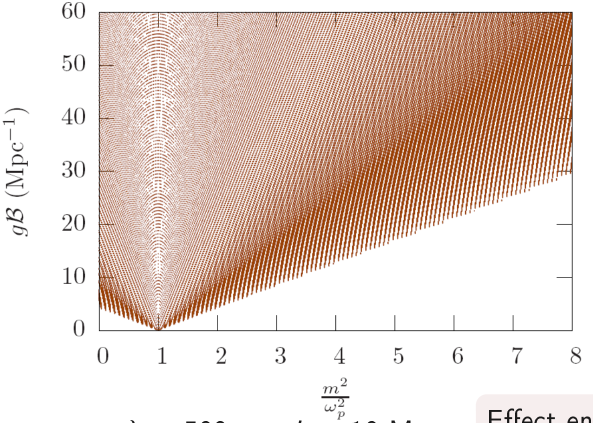
- $g = 7\ 10^{-12}\ \text{GeV}^{-1}$
- $m = 5\ 10^{-14}$ eV

Axions might be able to explain the effects observed concerning quasars

# Results Considering Plane Waves

## Exploration the Parameter Space which Could Explain the Effect

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



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

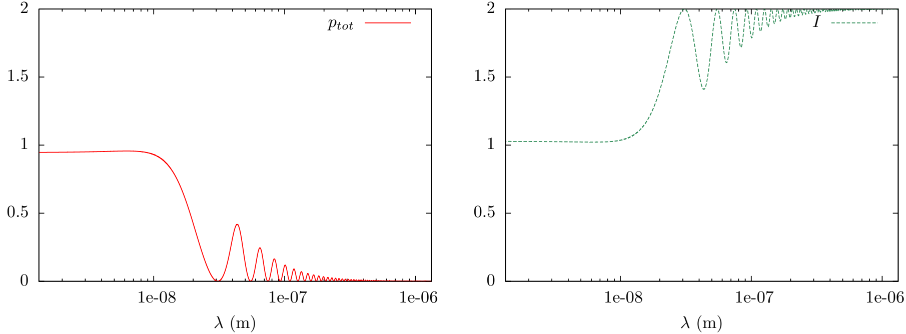
$\lambda$ = 500 nm; $L$ = 10 Mpc

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

# Results Considering Plane Waves

## Spontaneous Appearance of Polarisation & Oscillation of Polarisation Degree with $\lambda$

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 $\lambda_{large} \rightarrow \lambda_{small}$
- Plateau at small $\lambda$ (no oscillations)

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

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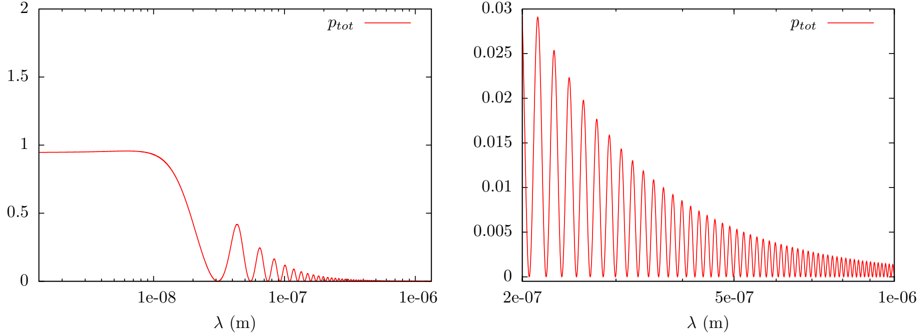

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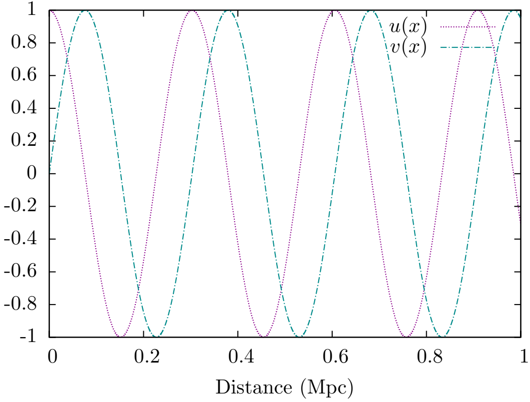
# Results Considering Plane Waves

## Spontaneous Appearance of Polarisation & Birefringence

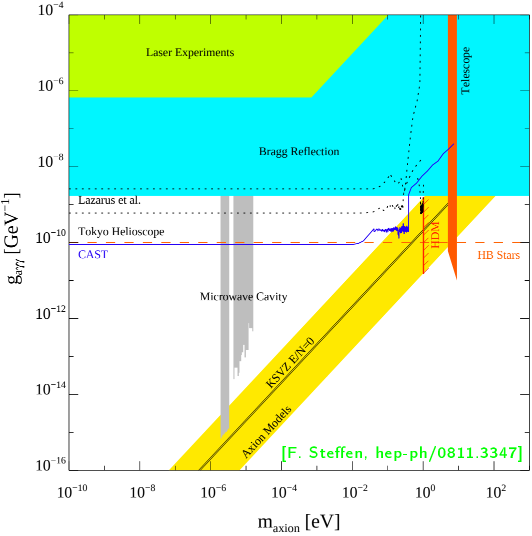


- Case of initially polarised light:
  - $u(x)$ (linear)
  - $v(x)$ (= circular)
- Again: creation of polarisation
- Additional feature: nice (@ low mixing) birefringence effect.

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

# Limits on Axions & Pseudoscalar Particles

## The Need of Axion-Like Particles



[F. Steffen, hep-ph/0811.3347]

- Yellow Band = Axion models
- However, typical estimates of $\mathcal{B}$ require $\omega_p \sim m$ (that can happen somewhere on the way)

$\Rightarrow$ If this is to explain the signal

$\Downarrow$

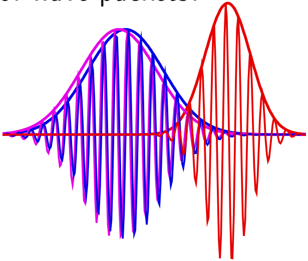
Requires the existence of pseudoscalar particles not predicted by grand unification theories but lighter.

# Working with Relativistic Wave Packets ; Decoherence

## Possible New Effects Concerning the Circular Polarisation, $v$

Consequences of a formalism in terms of wave-packets?

Due to axion–photon mixing, in $\mathcal{B}$:
$E_{\|}$ & $E_{\perp}$ $\rightarrow \neq$ masses ($\neq$ velocities).
$\Rightarrow$ separation & $\neq$ spreading ($k = \sqrt{\omega^2 - m^2}$).



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

$\updownarrow$

While, with plane waves:

Starting with $v(0) = 0$, $v(z) = 0$ if, for example:

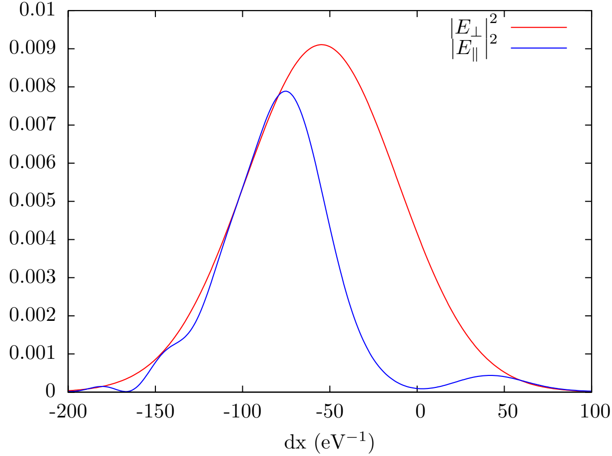
- $\theta_{mix} = 0$ (trivial);
- $u(0) = 0 \Leftrightarrow$ asking $E_{\perp}$ (or $E_{\|}$) $= 0$ (unrealistic).

# 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 ($\sim 2.5$ eV$^{-1}$)
- MPFR library
- Interferences

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



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

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

# Summary

1. Existence of large-scale coherent orientations of quasar polarisation vectors (non-local effect). Very light axions look promising.
2. Axion, some properties: Primakoff effect & dichroism.
3. Study of the axion–photon mixing and results:
   - evolution of polarisation with $z$ and $\lambda$ due to external magnetic fields.
   - parameter space likely to explain the alignment.
4. Discussion about wave packets separation and circular polarisation.

Prospects:

- Compute the effect for $\sim 1\%$ polarised light using wave packets.
- Include redshift effects.
- Consider more realistic magnetic fields (varying, several zones,...).
- Take into account a background axion field. [F. Finelli and M. Galaverni (2008)]
- Test circular polarisation predictions.

# Thanks for your Attention

Any questions?

# Symmetries and Conservation Laws

## Origin of the Axion in QCD

### Lagrangian of Quantum Chromodynamics for the two lighter quarks

$$\mathcal{L}_{QCD}^{fermions} = \bar{u}\left(i\gamma^{\mu}D_{\mu} - m_u\right)u + \bar{d}\left(i\gamma^{\mu}D_{\mu} - m_d\right)d$$

Symmetries: $\mathrm{U}(1)_V$, $\mathrm{U}(1)_A$, $\mathrm{SU}(2)_V$ and $\mathrm{SU}(2)_A$ if $m_u = m_d = 0$.

### Noether's Theorem

"To any continuous symmetry of $\mathcal{L}$ is associated a conserved current."

Approximation of zero-mass quarks ⇒ 8 conserved currents.

# Spontaneous Breaking of Chiral Symmetry

## Origin of the Axion in QCD

However, chiral symmetries $\mathrm{U}(1)_A$ and $\mathrm{SU}(2)_A$ are not symmetries of the vacuum
⇒ Spontaneous symmetry breaking.

### Goldstone's Theorem

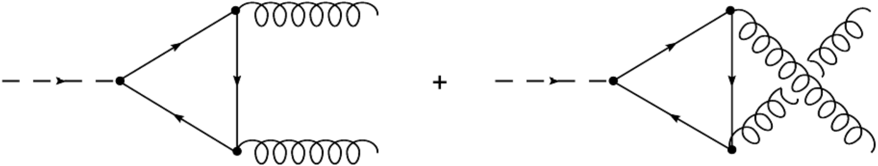
"To each continuous spontaneously broken symmetry
⇒ massless scalar field: Nambu-Goldstone boson."

- Spontaneous Breaking of $\mathrm{SU}(2)_A$ ⇒ 3 pions *V*
- Spontaneous Breaking of $\mathrm{U}(1)_A$ ⇒ *?*

$\mathrm{U}(1)_A$ Problem

# Quantum Corrections: Axial Anomaly

## Origin of the Axion in QCD



- SU(2)$_A$ Still OK
- U(1)$_A$

$$\begin{aligned} \partial_\mu j^{\mu 5} &\propto \epsilon^{\alpha\beta\mu\nu} F^c_{\alpha\beta} F^c_{\mu\nu} \\ &\propto \partial_\mu K^\mu \end{aligned}$$

Additional Term in the Lagrangian: $\mathcal{L} \propto \int \partial_\mu j^{\mu 5} d^4x \neq 0?$

# $|\theta\rangle$ Vacuum and Strong CP Problem

## Origin of the Axion in QCD

**'t Hooft**

QCD (Non-Abelian Theory)
Topological effects prevent the integral to vanish.

**$|\theta\rangle$ vacuum**

$\Rightarrow$ Vacuum one has to consider:
Linear combination of $|n\rangle$ vacua
$= |\theta\rangle$ vacuum

and then, $\mathrm{U}(1)_A$ Problem is solved

Price to pay:

$$\mathcal{L}_\theta \propto \theta F^c_{\mu\nu} \widetilde{F}^{c\mu\nu}$$

CP Violation

**Strong CP Problem (SCPP)**

Experimentally, CP conserved in QCD: $\theta < 10^{-9}$ !

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# Peccei-Quinn Solution and the Axion

## Origin of the Axion in QCD

### Peccei-Quinn Solution to the Strong CP Problem

New continuous symmetry: $U(1)_{PQ}$ whose breaking
⇒ dynamical compensation of the $\theta$ term.

### Weinberg & Wilczek

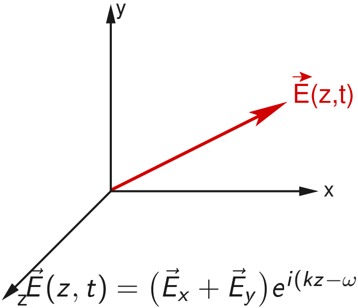
⇒ Pseudo Nambu-Goldstone Boson: Axion.

# 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 $\theta$