Large-scale alignments of quasar polarisations
A detailed study of the spinless-particle scenario

Alexandre Payez

in collaboration with Jean-René Cudell and Damien Hutsemékers
based on [arXiv:1308.6608]
Outline

Motivation
- Astrophysical context
- An unexpected observation (quasars and polarisation)

Mixing with axion-like particles
- The mechanism
- Possible issues?
- Constraints

Conclusions
- Summary
- Some prospects
Getting started

This work
all about light with puzzling properties from far-away sources

What are the scales involved?
Why is this a problem?
What does the observable Universe look like?
The current framework and the largest structures

When we consider the Universe as a whole

Averaging over sufficiently large distances, there is

- no preferred location
- no preferred direction

Galaxy surveys (2dF, SDSS)
Superclusters of galaxies, filamentary structure
What does the observable Universe look like?
The current framework and the largest structures

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Galaxy surveys (2dF, SDSS)
Superclusters of galaxies, filamentary structure
Galaxies as elementary blocks

Galaxies

\[ \sim \text{hundreds of billions of stars} \]

\[ \sim 10,000 \text{ parsecs (pc)} \]
...that tend to cluster

Clusters of galaxies
∼ thousands of galaxies

Superclusters of galaxies
∼ dozens/hundreds of clusters

Adapted from W. Schaap et al., 2dF Galaxy Redshift Survey
Astrophysical information derived from light
Various properties, complementary indications

Most of what we know and observe in astrophysics comes in the form of light

Properties
- intensity
- frequency
- polarisation

Information obtained about
- the source itself
- the medium encountered

Bright sources are therefore very interesting
Quasars and active galactic nuclei

- Among the most distant objects observed
- Found at the center of active galaxies
- Compact objects:
  
  \[
  \text{source of continuum light} \leq 1 \text{ pc}
  \]
  
  Milky Way \( \sim 30,000 \text{ pc} \)

- Up to \( \sim 10^4 \) times more luminous than a whole galaxy
- Non-spherical morphology
  → emission of polarised light

High-luminosity active galactic nuclei or “quasars”

A valuable tool to study the distant Universe

Adapted from C.M. Urry & P. Padovani
Quasar polarisation vectors (in visible light)

1. tend to be aligned in huge regions of the sky ($\sim 1$ Gpc)
2. this effect depends on their distance.
Stokes parameters

Decomposition in an orthonormal basis

\[ \vec{E}_{r,y}(z,t) \]

\[ \vec{E}_{r,x}(x) \]

Built from intensities

\[
\begin{cases}
  I &= \text{Total intensity} \\
  Q &= |\uparrow|^2 - |\rightarrow|^2 \\
  U &= |\leftarrow|^2 - |\downarrow|^2 \\
  V &= \text{Circular polarisation}
\end{cases}
\]

Complete description of polarisation

- polarisation degrees
  \[ p_{\text{lin}} = \sqrt{q^2 + u^2}, \quad p_{\text{circ}} = |v| \]
- polarisation angle
  \[ \varphi = \frac{1}{2} \arctan \left( \frac{u}{q} \right) \]
Stokes parameters

Decomposition in an orthonormal basis

\[ \vec{E}_r(z,t) = \left( \vec{E}_{rx}, \vec{E}_{ry} \right) \]

Built from intensities

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Complete description of polarisation

Stokes \rightarrow motivation = \text{unpolarised light (no preferred behaviour)}

\[ I^2 \geq Q^2 + U^2 + V^2 \]

Quasar light is partially polarised
Quasar polarisations are correlated over huge scales

Various statistical tests give $P_{\text{random}}$ from $3 \times 10^{-5}$ to $2 \times 10^{-3}$

see also [Jain, Narain, Sarala (2004)]

- all types of quasars
- expected polarisation preserved
- high galactic latitudes ($|b| \geq 30^\circ$)
- criterion: good quality ($p_{\text{lin}} \geq 0.6\%, \Delta \varphi \leq 14^\circ$)

Latest all-sky sample 355 quasars (1/2 from literature)
Quasar polarisations are correlated over huge scales

\[ \phi = 0.79 \]

[Hetsemékers, Cabanac, Lamy, Sluse (2005)]

**Non-local effect**

Different alignments for regions along the same line of sight
Quasar polarisations are correlated over huge scales

\[ \phi = 79^\circ \]

\[ \phi = 8^\circ \]

Non-local effect
Different alignments for regions along the same line of sight
The effect as seen in a \((q, u)\) linear polarisation space

\[
\begin{align*}
q &\in [0, 1] \\
u &\in [-1, 1]
\end{align*}
\]

Angular coordinate

\[
\alpha = \tan \left( \frac{u}{q} \right) = 2\varphi
\]

Distance from origin

\[
\rho_{\text{lin}} = \sqrt{q^2 + u^2}
\]

Alignments

\(
\uparrow \downarrow
\)

Departures from isotropy in \((q, u)\) space

\[\text{[Payez, Cudell, Hutsemékers (2011)]}\]
Looking for an explanation
How spinless particles enter the game

1. Mechanism leading to an alignment of quasar axes in each region? 
   but no effect in radio waves \cite{Joshi, Battye, Browne, et al. (2007)}?

2. Mechanism affecting light during its propagation? 
   NB: addition of a small systematic polarisation \(\Rightarrow\) alignment effect

Axion-like particles (ALPs), \(\phi\): ID Card

- Pseudoscalar particles like \(\pi^0\) (also scalar)
- Generic prediction of theories beyond the Standard Model
- Goldstone bosons (global \(U(1)\) broken @ high scale \(f_a\))
- Very (very) small mass, interacting very (very) weakly
- Effective coupling with light (gets stronger with \(\gamma^\omega\))

in external transverse magnetic or electric fields, \(\gamma \leftrightarrow \phi\) (Primakoff effect for \(\pi^0\))
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Searching for ALPs using their coupling with light

Adapted from D. Cadamuro, PhD thesis
A step towards a spinless-particle scenario

Photons can mix with axion-like particles in faint but extended magnetic fields on the way from distant sources.

Detection of those light beams

External magnetic field (e.g. in superclusters of galaxies)

Light beams with different initial polarisation states

Distant sources

[Jain et al. (2002)], [Das et al. (2004)], [Piotrovich et al. (2008)], [Payez et al. & Hutsemékers et al. (2008)], ...

How would this lead to an alignment tendency?
Axion-like particles couple to one direction of polarisation

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

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

- **Dichroism:**
  - Changes linear polarisation

- **Birefringence:**
  - Changes circular polarisation
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- **Dichroism:**
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A first application: toy model
Generating linear polarisation

Just considering one $\vec{B}$ region

Light initially unpolarised

$\omega_p \lesssim 4 \times 10^{-14}$ eV, fixed (typical in supercluster)

The mixing can generate enough linear polarisation to explain quasar data

$\omega = 2.5$ eV; $z = 10$ Mpc
A first application: toy model
Generating linear polarisation

Generating linear polarisation

\[ \frac{\Delta \mu^2(z/z_0)}{\omega/\omega_0} (10^{-28} \text{ eV}^2) \]

\( \omega_0 = 2.5 \text{ eV}; z_0 = 10 \text{ Mpc} \)

Evolution of any Stokes parameter depends only on \( \theta \) and \( \frac{\Delta \mu^2}{\omega} z \)

rich phenomenology

Dichroism \( \rightarrow \) alignment
Birefringence \( \rightarrow \) prediction
THE ALIGNMENT EFFECT 2.0

[Horsemékers, Borguet, Sluse, Cabanac, Lamy (2010)]

Quasar polarisation vectors (in visible light)

1. tend to be aligned in huge regions of the sky ($\sim 1$ Gpc)

2. this effect depends on their distance.

3. update: no evidence for circular polarisation (typical uncertainty $< 0.1\%$)

.. or is it?
The Alignment Effect 2.0

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A wave-packet treatment of the mixing

[Payez, Cudell, Hutsemékers (2011)]

With relativistic wave packets

⇒ the circular polarisation \( v \) generated can be significantly reduced.

![Graph showing wave packets and plane waves comparison]

- \( z = 10 \text{ Mpc}; \)
- \( \omega_0 = 2.5 \text{ eV} \)
  \((\lambda_0 = 500 \text{ nm});\)
- \( u(0) = 0.01.\)

Most unfavourable case.

While with plane waves, the circular polarisation can be as large as the linear one.
The reason why it can be reduced
Frequency dependence of the effect

Considering:

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

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 $\phi(z)$:

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

⇒ “$C(z)$” & “$D(z)$” = mixtures of $A_{\parallel}$ and of $\phi$, with eigenvalues $\mu_{C,D}(\omega)$.

⇒ Phase-shift depends on $\omega$, so does circular polarisation

Wave packets = “averaging over $\omega$”

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

⇒ alignment still possible, as $p_{\text{lin}}(z,\omega) = \sqrt{q^2(z,\omega) + u^2(z,\omega)} \geq 0$
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$\Rightarrow$ Phase-shift depends on $\omega$, so does circular polarisation

Wave packets = “averaging over $\omega$”

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

$\Rightarrow$ alignment still possible, as $p_{\mathrm{lin}}(z, \omega) = \sqrt{q^2(z, \omega) + u^2(z, \omega)} \geq 0$
Not enough to save this kind of explanation
It’s all about bandwidths

Measurements were performed in

- White light → wave packets OK: no filter, same as before
- Bessell V filter → wave packets KO: $\Delta \omega$ not large enough to see sufficient \( \updownarrow \nu \)

If axions were at work, given the “narrow bandwidth” of the V filter, circular polarisation should have been observed.

Can we reject this scenario?

→ Focus on V-filter data “~ quasi-monochromatic”
Not enough to save this kind of explanation
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Can we reject this scenario?
$\rightarrow$ Focus on V-filter data “~ quasi-monochromatic”
Towards the North Galactic Pole direction
Most observed objects are located in that direction; $z \in [0.4, 2.2]$

[Courtois et al. (2013)]
Different scenarios for the magnetic field

Towards center of the local supercluster

Magnetic field in the plane of the local supercluster

Rotation Measures [Vallée (2002)]

1. Domain structure
   \( \approx 100 \text{ kpc} \) random cells with \( \approx 2 \mu \text{G} \) adding up to \( \approx 10 \text{ Mpc} \)

2. @ supercluster scale: 5–10 times smaller

Only detection available for local supercluster

\( gB \) always appear together: one can rescale

This field is important

\( \Rightarrow \) very large field strength given coherence length & essentially the latest
Different scenarios for the magnetic field

ALP-photon scenario looks dead for real, now

1 zone creates an alignment but fails for circular polarisation;

100 zones might pass the circular polarisation test
but fails for the alignment (lack of common preferred direction).

+ background field (∼10 times weaker): still no alignment.
if we try to recover an alignment: too much circular polarisation
Different scenarios for the magnetic field in our supercluster.
Different scenarios for the magnetic field in our supercluster
So what?

Can the most popular scenario indeed explain alignments of quasar polarisation?

**Our answer**

very unlikely given present data, constraints, estimations of magnetic fields

**In general, there is either**

- too much circular polarisation;
- too much linear polarisation;
- no alignment
New constraints on axion-like particles
Forget about reproducing coherent alignments

ALPs can be very efficient at producing polarisation
& contradict quasar polarisation data

⇒ New constraints on these elusive particles

consider quasar classes with smallest intrinsic polarisations in visible
⇒ compare amount due to the mixing with observations ($p_{\text{lin}}$ and $p_{\text{circ}}$)
New constraints on axion-like particles
Forget about reproducing coherent alignments

ALPs can be very efficient at producing polarisation & contradict quasar polarisation data

⇒ New constraints on these elusive particles

consider quasar classes with smallest intrinsic polarisations in visible ⇒ compare amount due to the mixing with observations ($p_{\text{lin}}$ and $p_{\text{circ}}$)
Defining our sample

Quasar circular polarisation data in visible light

[Hutsemékers, Bourget, Sluse, Cabanac, Lamy (2010)]

Bessel V filter; typical uncertainties < 0.1%

Subsample for our contraints on ALPs

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

In fact

no evidence for non-vanishing $p_{\text{circ}} \oplus 3\sigma$
(except for 2 blazars with $p_{\text{lin}} > 20\%$)
Defining our sample

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

- Filter not as crucial for $\rho_{\text{lin}}$
- Only the least polarised classes
Defining our sample

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

Subsample for our contraints on ALPs

- Filter not as crucial for $p_{\text{lin}}$
- only the least polarised classes
New constraints on axion-like particles
Forget about reproducing coherent alignments

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

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?

$$P = \frac{N(p_{\text{obs}} \geq p_{\text{th}})}{N_{\text{tot}}}$$

4. Repeat and average over many configurations

configuration

$\overset{\text{def}}{=} \{\text{domain sizes, magnetic field directions (3D), electron densities}\}$
New constraints on axion-like particles
Forget about reproducing coherent alignments

[Payez, Cudell, Hutsemékers (2012)]

See next edition of the Review of Particle Properties (Particle Data Group)
New constraints on axion-like particles

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

See next edition of the Review of Particle Properties (Particle Data Group)

| $g/|\vec{B}_{\text{domain,0}}| \ (\text{GeV}^{-1})$ | Linear polarisation degree (%) | Circular polarisation degree (%) |
|-----------------------------------------------|---------------------------------|---------------------------------|
| $10^{-10}$                                   |                                 |                                 |
| $10^{-11}$                                   |                                 |                                 |
| $10^{-12}$                                   |                                 |                                 |
| $10^{-13}$                                   |                                 |                                 |
| $10^{-14}$                                   |                                 |                                 |
| $10^{-15}$                                   |                                 |                                 |

CAST
SN1987A

1σ + 2σ ○ 3σ ●

[Payez, Cudell, Hutsemékers (2012)]
New constraints on axion-like particles
Illustration of distributions corresponding to a $3\sigma$ C.L. exclusion; $m = 10^{-20}$ eV

See next edition of the Review of Particle Properties (Particle Data Group)
New constraints on axion-like particles

See next edition of the Review of Particle Properties (Particle Data Group)

Stable constraints

[Payez, Cudell, Hutsemékers (2012)]
New constraints on axion-like particles
Evolution of the plateau with the average electron density

[Payez (2013)]
Searching for ALPs using their coupling with light.
Summary

- Existence of large-scale correlations in quasar polarisation data
- Most popular scenario: mixing with axion-like particles
- Dichroism would explain data but birefringence spoils it
- A wave-packet treatment recovers partially the mechanism but quasi-monochromatic measurements contradict the predictions
- Last magnetic field region: confirms that the mechanism is excluded
- Improve current bounds on axion-like particles using $p_{\text{lin}}$ and $p_{\text{circ}}$
Some prospects

Alignment effect

- Coherent orientations in polarisation from type-II quasars?
- A new statistical approach [Cudell, Pelgrims (work in progress)]

Axion-like particles

- Future: X-ray polarimetry = extremely interesting for astrophysical region → could lead to new constraints or a discovery
Thank you
Evidence for a cosmic sandwich?

With this kind of interpretation:

\[
\text{Large-scale effect} \Leftrightarrow \text{Large-scale magnetic field}
\]

Simplest way to have different preferred directions:

→ 2 huge \((\equiv \text{all photons pass through})\) \(\vec{B}\) zones, at \(z = 0\) & \(z = 1\), can do it.

...but there might have been other ways to deal with axion-like particles.

⇒ ALP flux?
In particle physics, **spinless particles** = the simplest case one can think of. Simpler than spinor (e.g. electrons) or vector (e.g. photons).

Examples:
- **Axions** [solve problem in QCD];
- **Chameleons** [$f(R)$ theories];
- \{ **Scalars**, **Pseudoscalars** \} [Super strings/Kaluza-Klein theories];
- ... 

Axion-like particles: generic feature of extensions of the Standard Model.

**This kind of particles**
- From the theoretical point of view: very well motivated;
- From the experimental point of view: yet to be observed.
Axion–photon coupling and Primakoff effect
Axions’ influence on light—difference between scalars and pseudoscalars

\[ \vec{E} = \vec{E}_r + \vec{E}, \quad \vec{B} = \vec{B}_r + \vec{B}; \]

\[ \vec{E}_r, \vec{B}_r: \text{ orthogonal fields of the radiation} \]

reminder: \( \vec{E}_r \) defines the direction of polarisation

\( \vec{E}, \vec{B} \): possible external transverse fields

for astrophysical applications: usually \( \vec{B} \neq 0, \vec{E} = 0 \)

- \( \gamma \) polarised // to \( \vec{B} \) in the case of pseudoscalar \( \phi \):

\[ \mathcal{L}_{\phi\gamma\gamma, \text{ps}} = \frac{1}{4} g \phi F_{\mu\nu} \tilde{F}^{\mu\nu} = -g \phi (\vec{E} \cdot \vec{B}) = -g \phi (\vec{E}_r \cdot \vec{B}) = -g \phi (\vec{E}_r,\parallel \cdot \vec{B}) \]

- \( \gamma \) polarised \( \perp \) to \( \vec{B} \) in the case of scalar \( \phi \):

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

and in \( (\hat{\vec{B}})^2 \) there is \( \vec{B} \cdot \vec{B}_r \) (\( \neq 0 \) for non-zero coupling)
Coherent orientation of quasar polarisation vectors
Showing the influence of dust in our galaxy—before subtraction

[Payez, Hutsemékers, Cudell (2010)]

- Different alignments for regions along the same line of sight
  ⇒ Non-local effect
- Influence of our galaxy?
Coherent orientation of quasar polarisation vectors

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- Different alignments for regions along the same line of sight
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Coherent orientation of quasar polarisation vectors
Showing the influence of dust in our galaxy—after subtraction (extreme case)

Payez, Hutsemékers, Cudell (2010)

- Different alignments for regions along the same line of sight ⇒ Non-local effect
- In any case, not possible to suppress the effect in both regions.
Coherent orientation of quasar polarisation vectors
Quite a puzzling observation—global statistics

Significance Level:
S.L. = Probability(no correlations between angles and positions in the full sample)

Global statistics, an example

\[ n_v : \text{number of nearest neighbours in 3D (free parameter)}. \]

\[
s = \frac{1}{n_{tot}} \sum_{j} n_{tot} \vec{v}_j \cdot \left( \sum_{i} \frac{1}{n_v} \vec{v}_i \right)
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[Hutsemékers (1998)]
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Coherent orientation of quasar polarisation vectors

Quite a puzzling observation—global statistics

Compare with random samples

→ compute S.L.

Keep angles & positions; associate them randomly

Harder and harder to produce the observed alignments from random distributions

170 quasars (1998)
213 quasars (2001)
355 quasars (2005)