Large-scale alignments of quasar polarisations

A detailed study of the spinless-particle scenario

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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

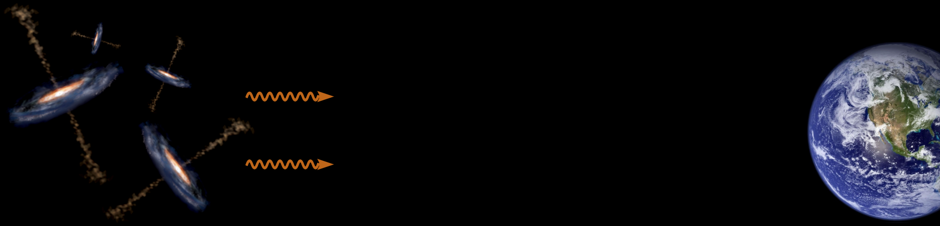
Conclusions

- 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?

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

When we consider the Universe as a whole

Averaging over sufficiently large distances, there is

- no preferred location
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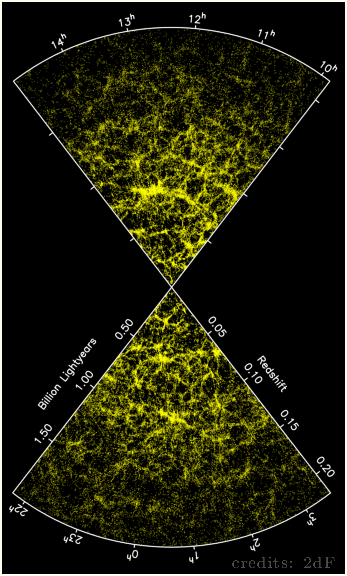
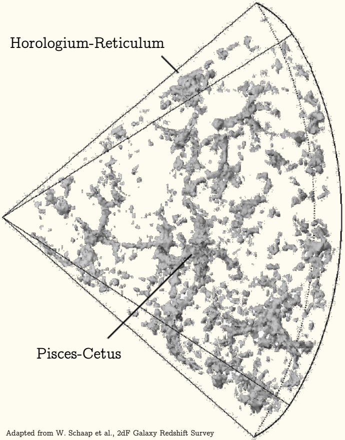


Galaxies as elementary blocks

Galaxies

$\sim$ hundreds of billions of stars
typical scale $\sim 10,000$ parsecs (pc)

...that tend to cluster



Clusters of galaxies

$\sim$ thousands of galaxies

Superclusters of galaxies

$\sim$ dozens/hundreds of clusters

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

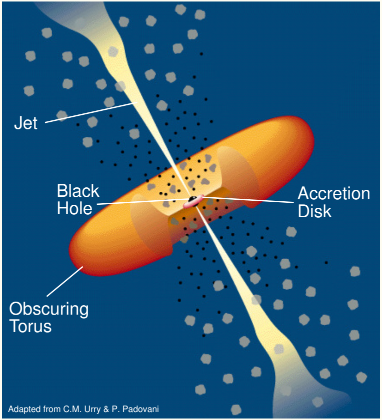
→

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:

$$\text{source of continuum light} \lesssim 1\ \text{pc}$$
$$\updownarrow$$
$$\text{Milky Way} \sim 30{,}000\ \text{pc}$$

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

High-luminosity active galactic nuclei or "quasars"

A valuable tool to study the distant Universe

The alignment effect

[*Hutsemékers* (1998)]

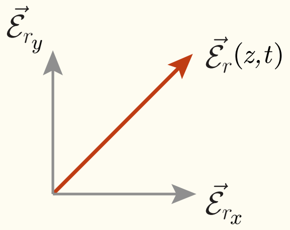
Quasar polarisation vectors (in visible light)

1. tend to be aligned in huge regions of the sky (~ 1 Gpc)
2. this effect depends on their distance.

linear pol.

Stokes parameters

Decomposition in an orthonormal basis



Normalised Stokes parameters

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

Built from intensities

$$\begin{cases} I &= \text{Total intensity} \\ Q &= |\uparrow|^2 - |\rightarrow|^2 \\ U &= |\nearrow|^2 - |\searrow|^2 \\ V &= \text{Circular polarisation} \end{cases}$$

Complete description of polarisation

- polarisation degrees

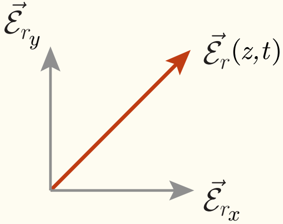
$$p_{\text{lin}} = \sqrt{q^2 + u^2}, \quad p_{\text{circ}} = |v|$$

- polarisation angle

$$\varphi = \frac{1}{2}\text{atan}\left(\frac{u}{q}\right)$$

Stokes parameters

Decomposition in an orthonormal basis



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\end{cases}
$$

Complete description of polarisation

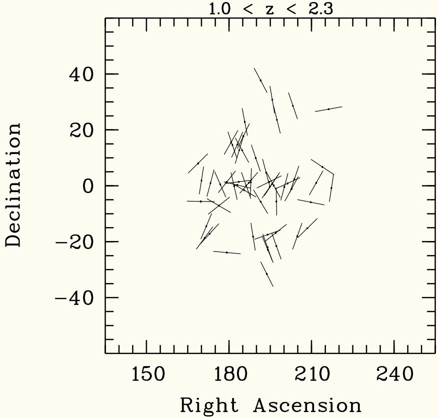
Stokes $\rightarrow$ motivation = unpolarised light (no preferred behaviour)

$$I^2 \geq Q^2 + U^2 + V^2$$

Quasar light is partially polarised

Quasar polarisations are correlated over huge scales

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



$p_{\rm lin} \sim 1\%$

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

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

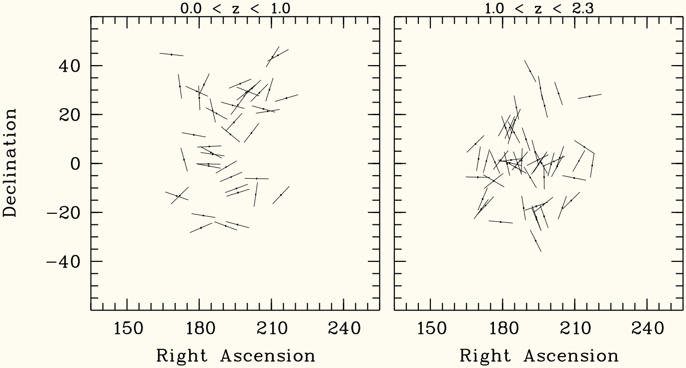
- all types of quasars
- expected polarisation preserved
- high galactic latitudes ($|b| \geq 30°$)
- criterion: good quality ($p_{\rm lin} \geq 0.6\%$, $\Delta\varphi \leq 14°$)

Latest all-sky sample
355 quasars

(1/2 from literature)

Quasar polarisations are correlated over huge scales

[*Hutsemékers, Cabanac, Lamy, Sluse* (2005)]



Non-local effect

Different alignments for regions along the same line of sight

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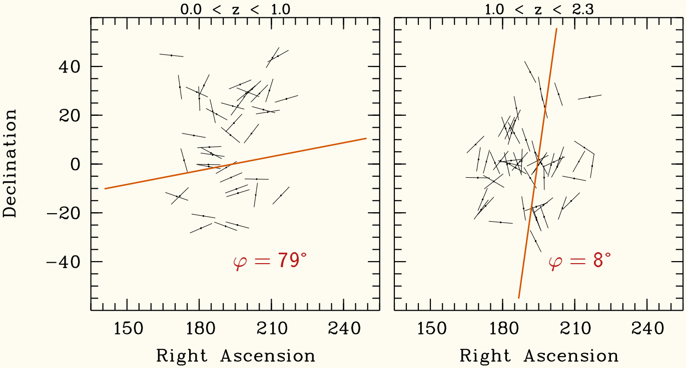

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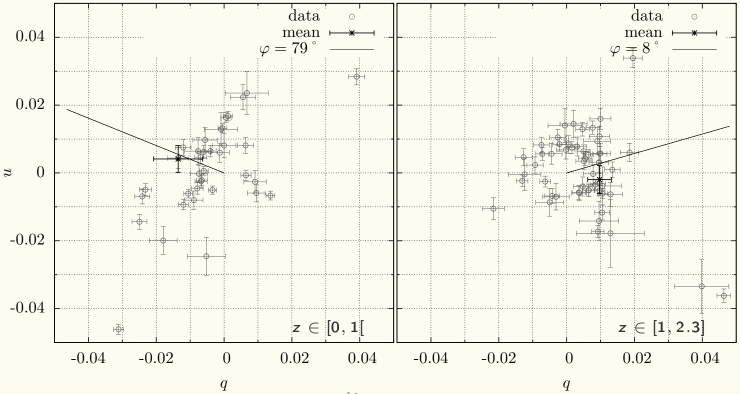
Different alignments for regions along the same line of sight

The effect as seen in a (q, u) linear polarisation space

[Payez, Cudell, Hutsemékers (2011)]



Angular coordinate

$= \operatorname{atan}\left(\frac{u}{q}\right) = 2\varphi$

alignments

$\Updownarrow$

departures from isotropy in (q, u) space

Distance from origin

$= \sqrt{q^2 + u^2} = p_{\text{lin}}$

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 [*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), ϕ: ID Card

- Pseudoscalar particles like π^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 $\nearrow \omega$)

in external transverse magnetic or electric fields, $\gamma \leftrightarrow \phi$ (Primakoff effect for π^0)

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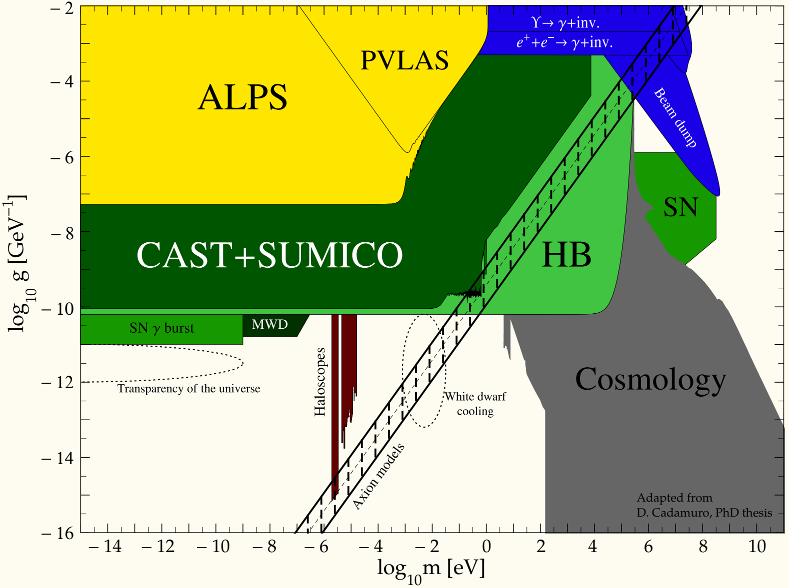
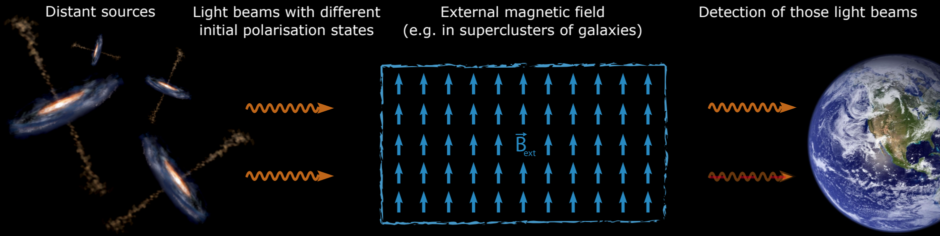
Searching for ALPs using their coupling with light



A step towards a spinless-particle scenario

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



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

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

- Dichroism:
  ⇒ Changes linear polarisation
- Birefringence:
  ⇒ Changes circular polarisation

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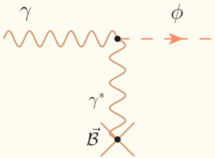

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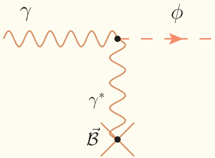

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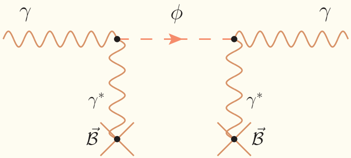
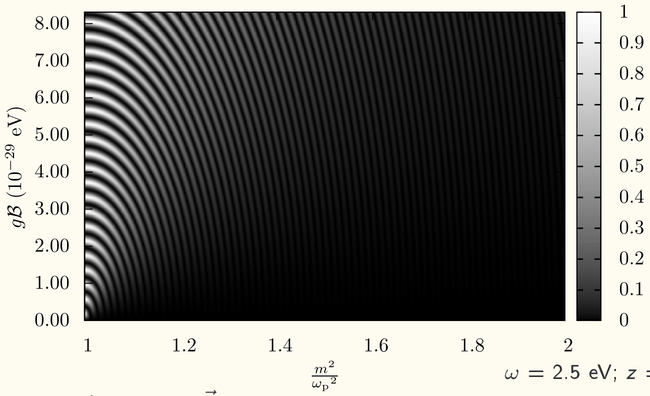


Generating linear polarisation

[*Payez, Cudell, Hutsemékers* (2011)]



$\omega = 2.5$ eV; $z = 10$ Mpc

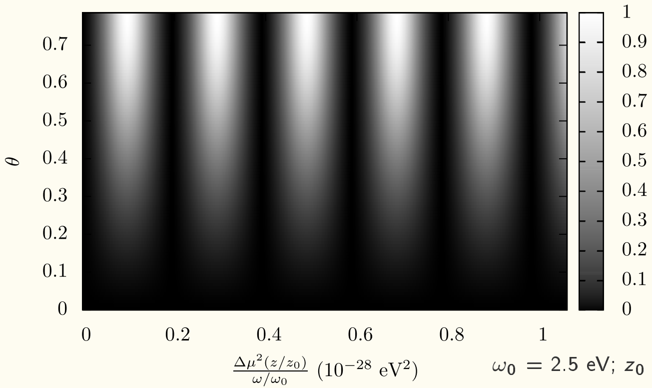
- Just considering one $\vec{\mathcal{B}}$ region
- Light initially unpolarised
- $\omega_p \lesssim 4\ 10^{-14}$ eV, fixed (typical in supercluster)

The mixing can generate **enough linear polarisation** to explain quasar data

A first application: toy model

Generating linear polarisation

[*Payez, Cudell, Hutsemékers* (2011)]



$\omega_0 = 2.5$ eV; $z_0 = 10$ Mpc

Evolution of any Stokes parameter depends only on θ and $\frac{\Delta\mu^2}{\omega} z$

rich phenomenology

Dichroism → alignment

Birefringence → prediction

THE ALIGNMENT EFFECT 2.0

[*Hutsemékers, Borguet, Sluse, Cabanac, Lamy* (2010)]

Quasar polarisation vectors (in visible light)

1. tend to be aligned in huge regions of the sky (~ 1 Gpc)
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$\Big\}$ linear pol.

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

critical for the ALP scenario

..or is it?

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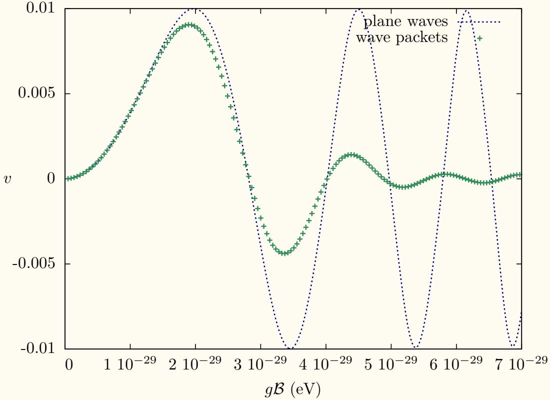
A wave-packet treatment of the mixing

[*Payez, Cudell, Hutsemékers* (2011)]

With relativistic wave packets

$\Rightarrow$ the circular polarisation v generated can be significantly reduced.



- $z = 10$ Mpc;
- $\omega_0 = 2.5$ eV ($\lambda_0 = 500$ 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 $\vec{\mathcal{B}}$ 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

$\Rightarrow$ alignment still possible, as $p_{\mathrm{lin}}(z,\omega) = \sqrt{q^2(z,\omega) + u^2(z,\omega)} \geq 0$

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Not enough to save this kind of explanation
It's all about bandwidths

Measurements were performed in

- White light $\rightarrow$ wave packets OK: no filter, same as before
- Bessell V filter $\rightarrow$ wave packets KO: $\Delta\omega$ not large enough to see sufficient $\searrow$ v

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

Can we reject this scenario?

$\rightarrow$ Focus on V-filter data "$\sim$ quasi-monochromatic"

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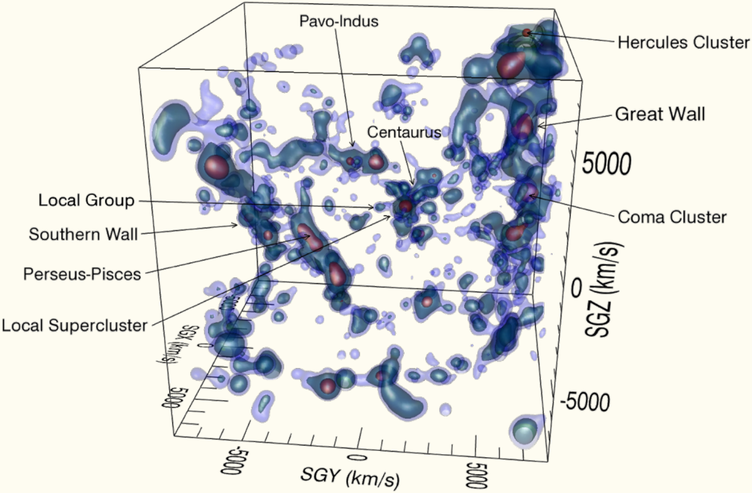
Towards the North Galactic Pole direction

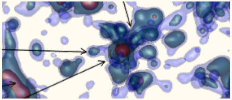
Most observed objects are located in that direction; $z \in [0.4, 2.2]$



[*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
   ≈ 100 kpc random cells with $\approx 2\ \mu$G adding up to ≈ 10 Mpc
2. @ supercluster scale: 5–10 times smaller

Only detection available for local supercluster

$g\mathcal{B}$ 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

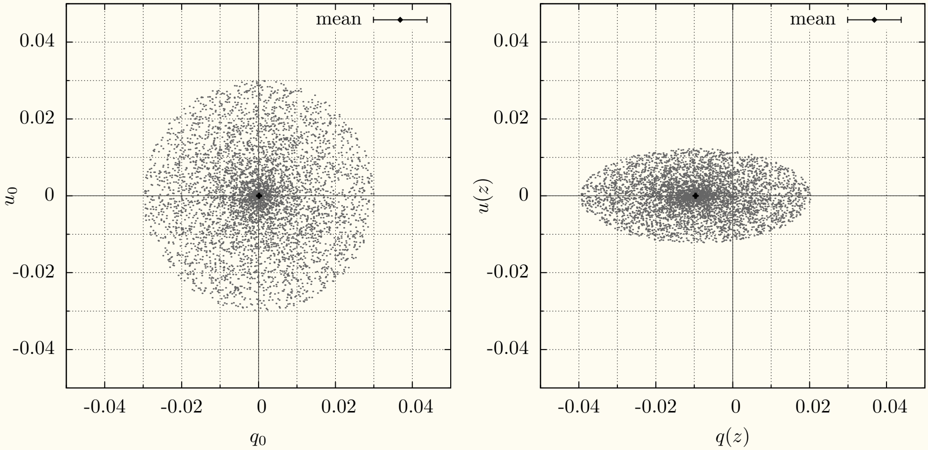
ALP-photon scenario looks dead for real, now

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



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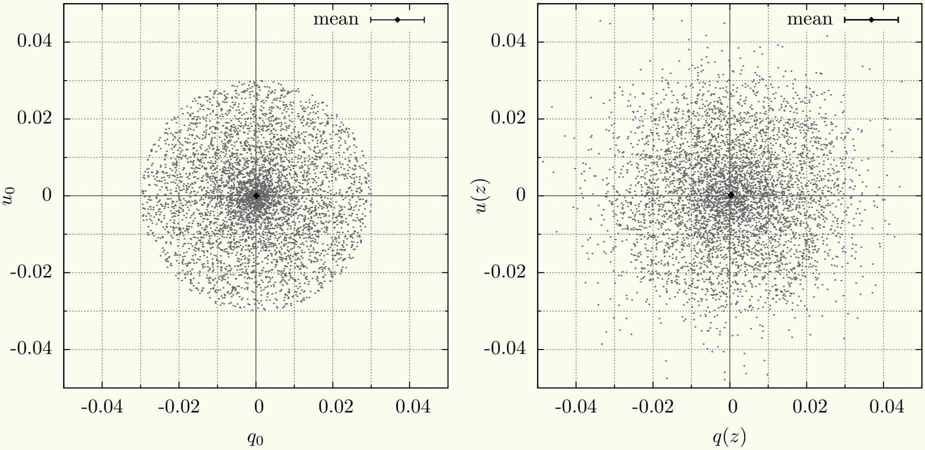

So what?

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

ALPs can be very efficient at producing polarisation

& contradict quasar polarisation data

$\Rightarrow$ New constraints on these elusive particles

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

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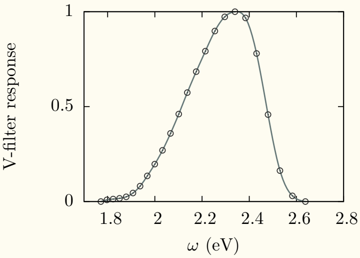
Defining our sample

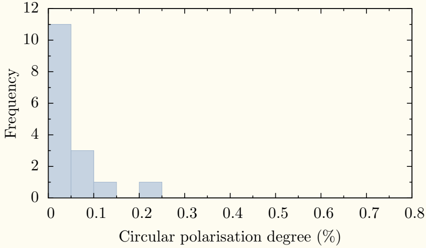
Quasar circular polarisation data in visible light

[*Hutsemékers, Borguet, Sluse, Cabanac, Lamy* (2010)]
Bessell V filter; typical uncertainties $< 0.1\%$



Subsample for our contraints on ALPs

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



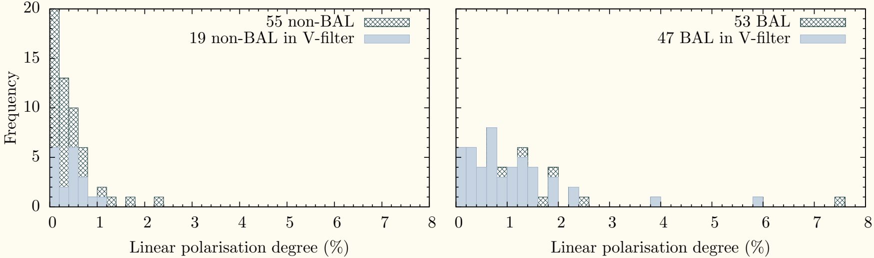
In fact
no evidence for non-vanishing p_{circ} @ 3σ
(except for 2 blazars with $p_{\text{lin}} > 20\%$)

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_{lin}
- only the least polarised classes



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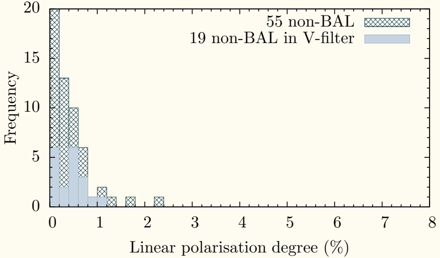


Start with unpolarised light (very conservative, especially for p_{circ})

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

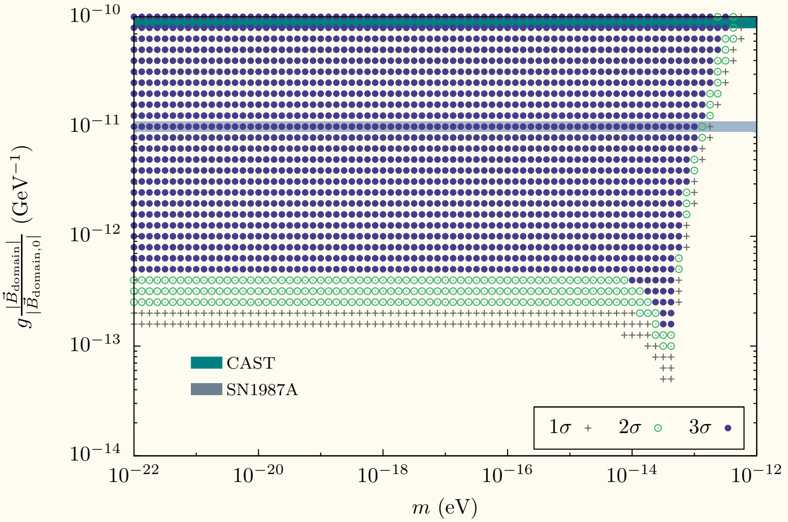
$\stackrel{def}{=} \{$domain sizes, magnetic field directions (3D), electron densities$\}$

New constraints on axion-like particles

Forget about reproducing coherent alignments

[Payez, Cudell, Hutsemékers (2012)]

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



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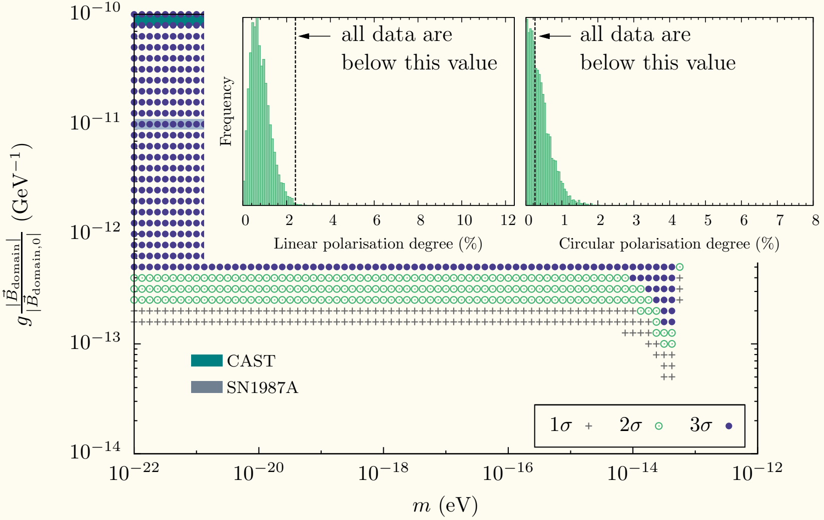

New constraints on axion-like particles

Illustration of distributions corresponding to a 3σ C.L. exclusion; $m = 10^{-20}$ eV

[*Payez, Cudell, Hutsemékers* (2012)]

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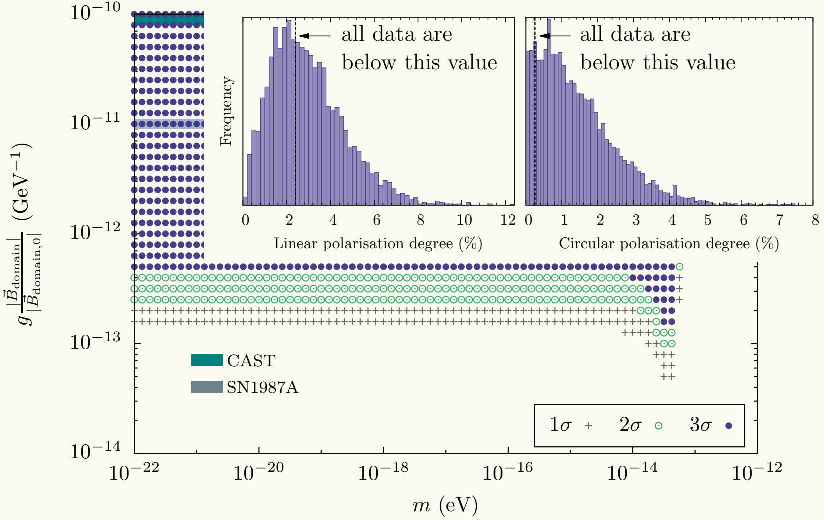

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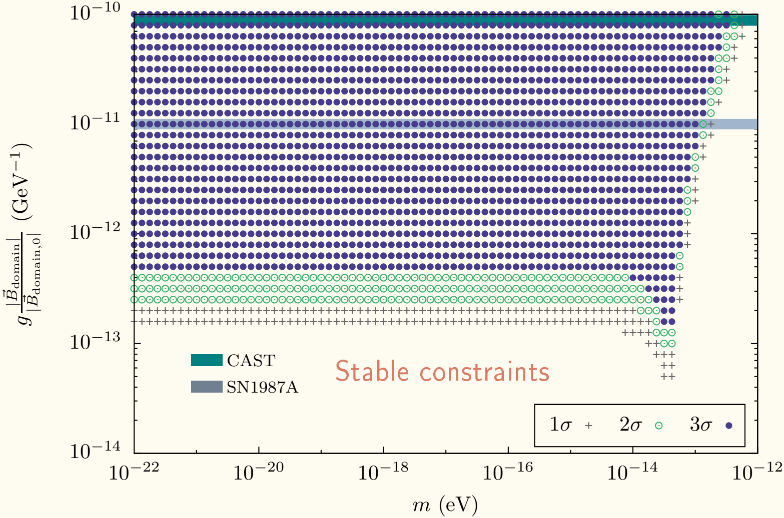
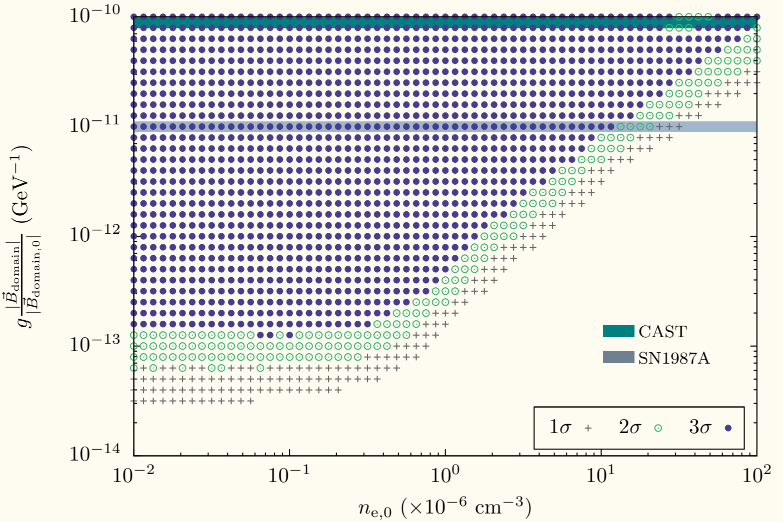
See next edition of the Review of Particle Properties (Particle Data Group)



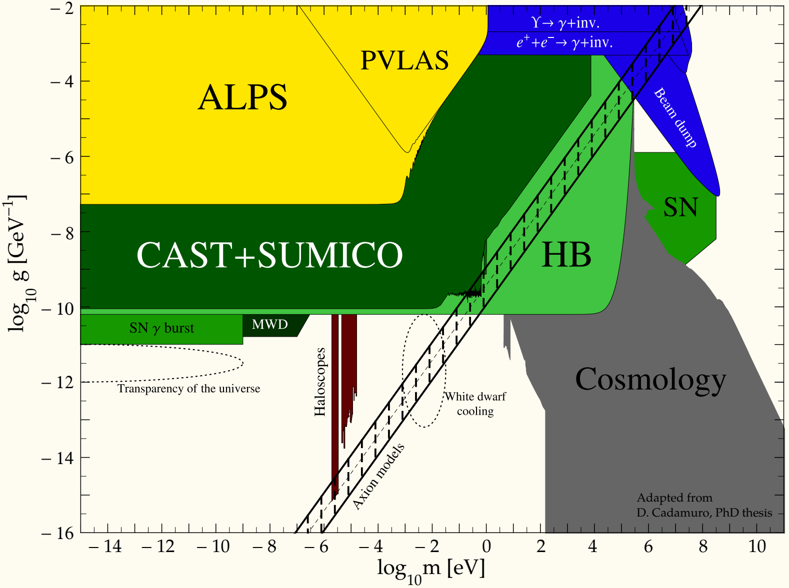
New constraints on axion-like particles

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 $p_{\rm lin}$ and $p_{\rm circ}$

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
  $\rightarrow$ could lead to new constraints or a discovery

Thank you

Evidence for a cosmic sandwich?

With this kind of interpretation:

Large-scale effect $\Leftrightarrow$ Large-scale magnetic field

Simplest way to have different preferred directions:
$\rightarrow$ 2 huge ($\equiv$ all photons pass through) $\vec{\mathcal{B}}$ zones, at $z = 0$ & $z = 1$, can do it.

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

$\Rightarrow$ ALP flux?

Axions and axion-like particles from theory

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];
- $\left\{ \begin{array}{l} \text{Scalars} \\ \text{Pseudoscalars} \end{array} \right\}$ [Super strings/Kaluza-Klein theories];
- ...

Axion-like particles

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

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

$\vec{\mathcal{E}}_r$, $\vec{\mathcal{B}}_r$: 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 $\vec{\mathcal{B}} \neq 0$, $\vec{\mathcal{E}} = 0$

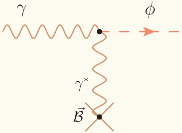
- γ polarised // to $\vec{\mathcal{B}}$ in the case of pseudoscalar ϕ:

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

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

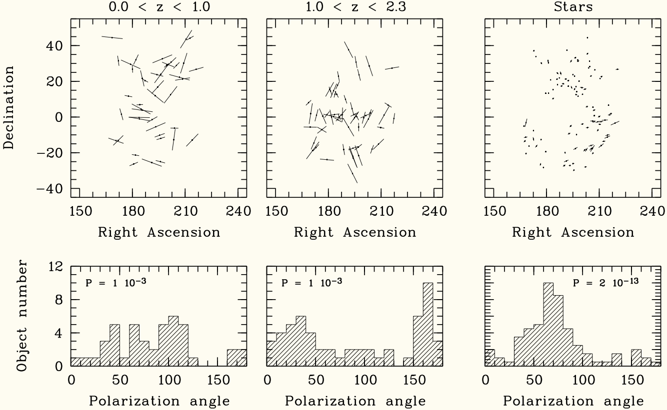
$$\mathcal{L}_{\phi\gamma\gamma,\mathbf{sc}} = \frac{1}{4}\, g\phi F_{\mu\nu}F^{\mu\nu} = \frac{1}{2} g\phi(\vec{B}^2 - \vec{E}^2)$$

and in $(\hat{\vec{B}})^2$ there is $\vec{\mathcal{B}}\cdot\vec{\mathcal{B}}_r$ ($\neq 0$ 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
  $\Rightarrow$ Non-local effect
- Influence of our galaxy?

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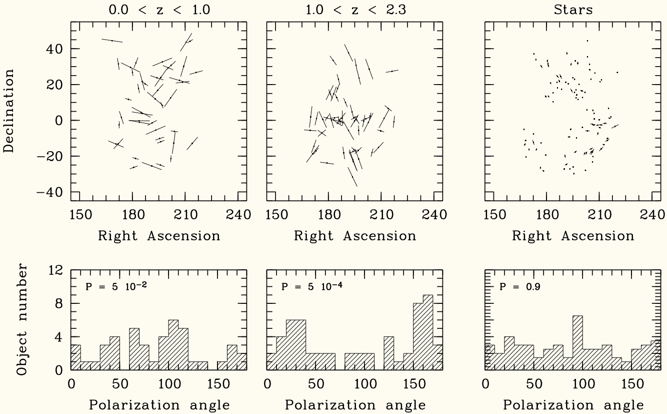
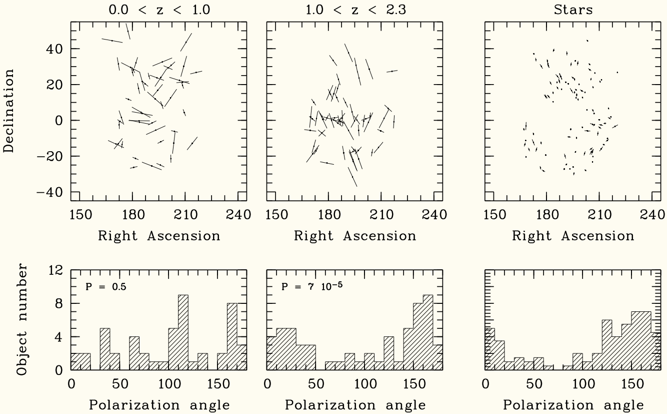


- Different alignments for regions along the same line of sight
  $\Rightarrow$ Non-local effect
- Influence of our galaxy? X

Coherent orientation of quasar polarisation vectors

Showing the influence of dust in our galaxy—after subtraction (extreme case)

[*Payez, Hutsemékers, Cudell* (2010)]



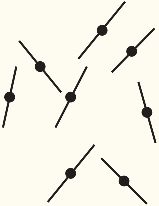
- Different alignments for regions along the same line of sight
  $\Rightarrow$ Non-local effect
- In any case, not possible to suppress the effect in both regions.

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
[*Hutsemékers* (1998)]

n_v: number of nearest neighbours in 3D (free parameter).



$$S = \frac{1}{n_{tot}} \sum_j^{n_{tot}} \vec{v_j} \cdot \left(\sum_i^{n_v} \frac{1}{n_v} \vec{v_i} \right)$$

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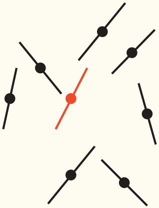

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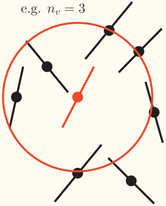

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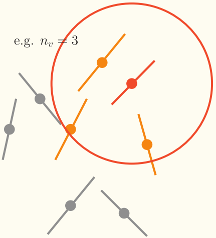

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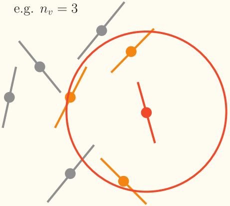

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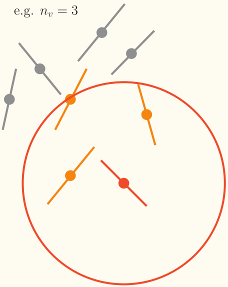

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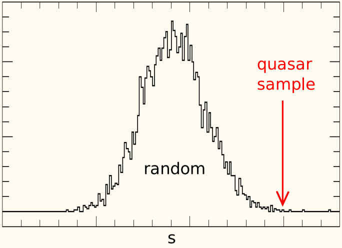
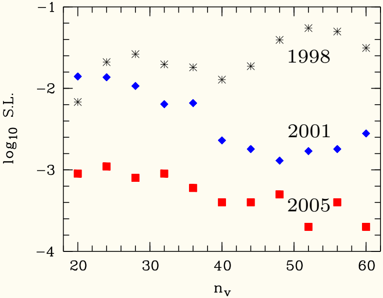
Coherent orientation of quasar polarisation vectors

Quite a puzzling observation—global statistics

Compare with random samples
→ compute S.L.

Keep angles & positions; associate them randomly





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

Harder and harder to produce the observed alignments from random distributions