Probing the existence of axions with the polarization of objects at cosmological distances

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The interest of astrophysical observations

Small effects which affect light can accumulate over cosmological distances (Gpc ~ 10^{25} m) and become detectable

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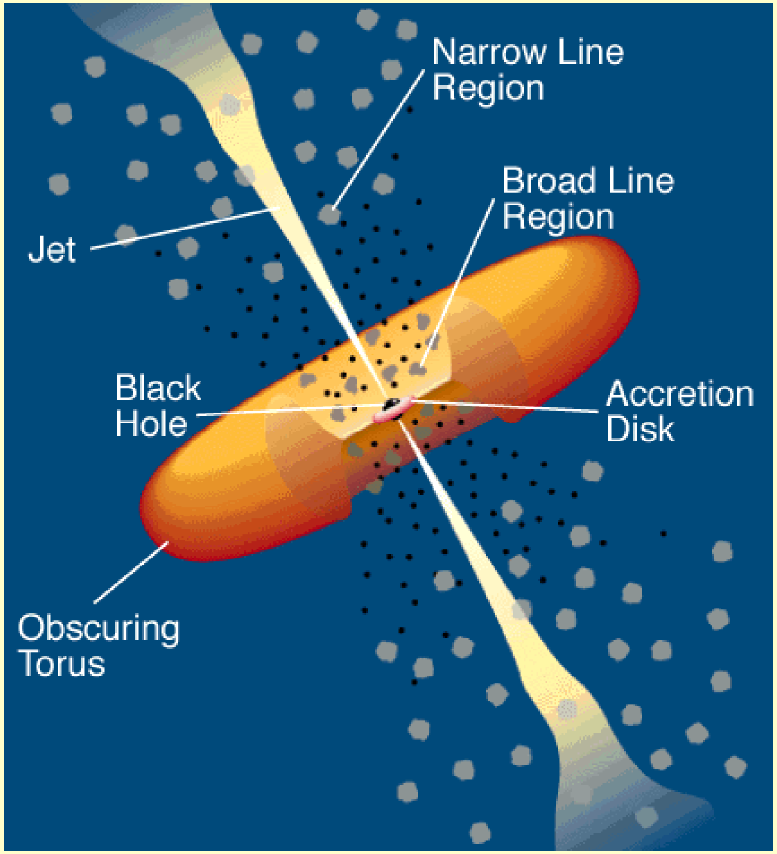
The structure of spacetime or theories of particle physics can be tested and constrained, namely using the polarization of light

Outline

- The polarization of quasars
- Large-scale alignments of quasar polarization vectors? Statistics, possible contaminations
- Characteristics of the alignment effect
- Interpretations. Evidence for photon-axion mixing?
- Searches at radio wavelengths
- Conclusions and future work

The polarization of quasars



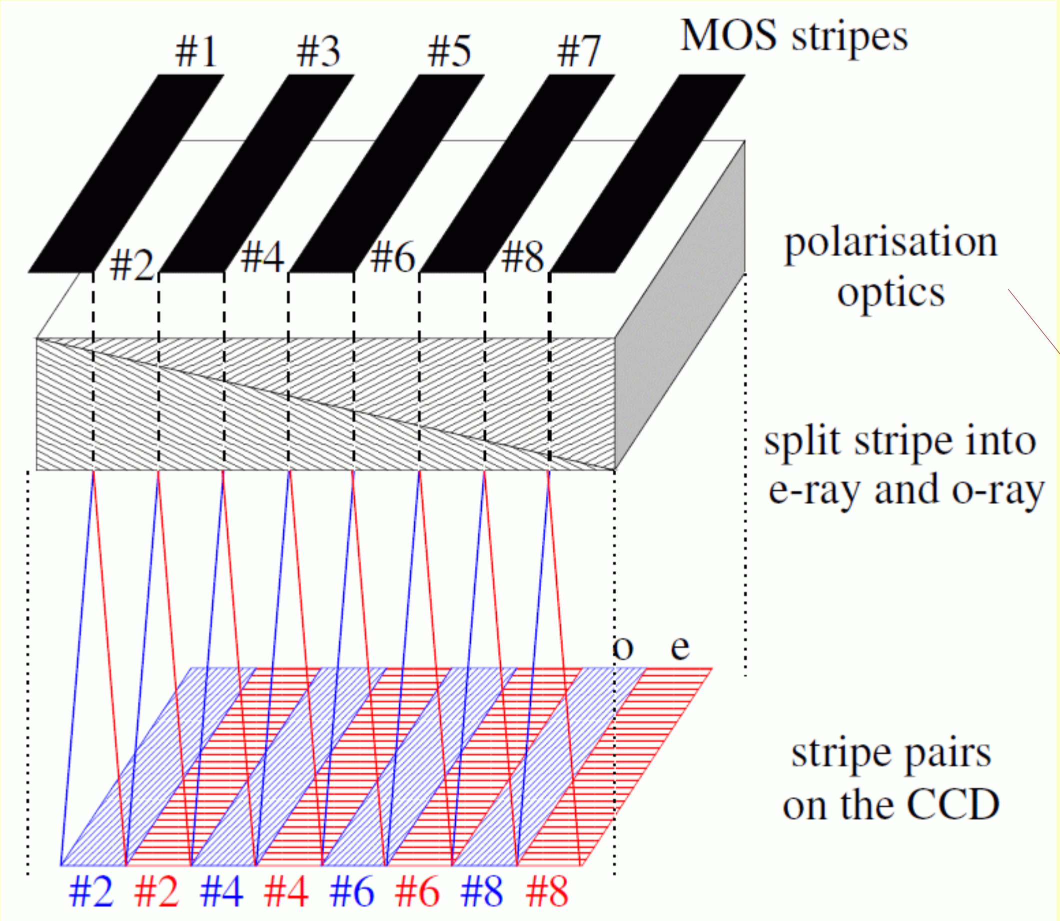
A quasar model (Urry et al)

- Quasars or Active Galactic Nuclei : most luminous objects in the Universe
- Observed at very large distances -> used to probe the Universe
- Unresolved at visible wavelengths
- Linear polarization: indicator of asymmetry

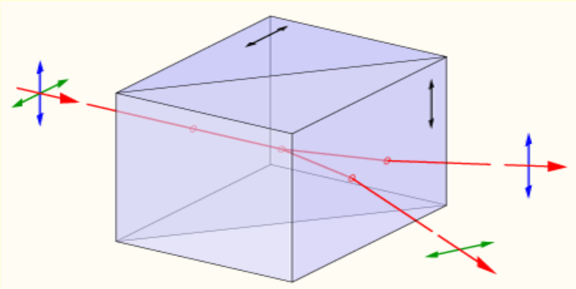
Observations

The ESO 3.6m telescope (La Silla, Chile)

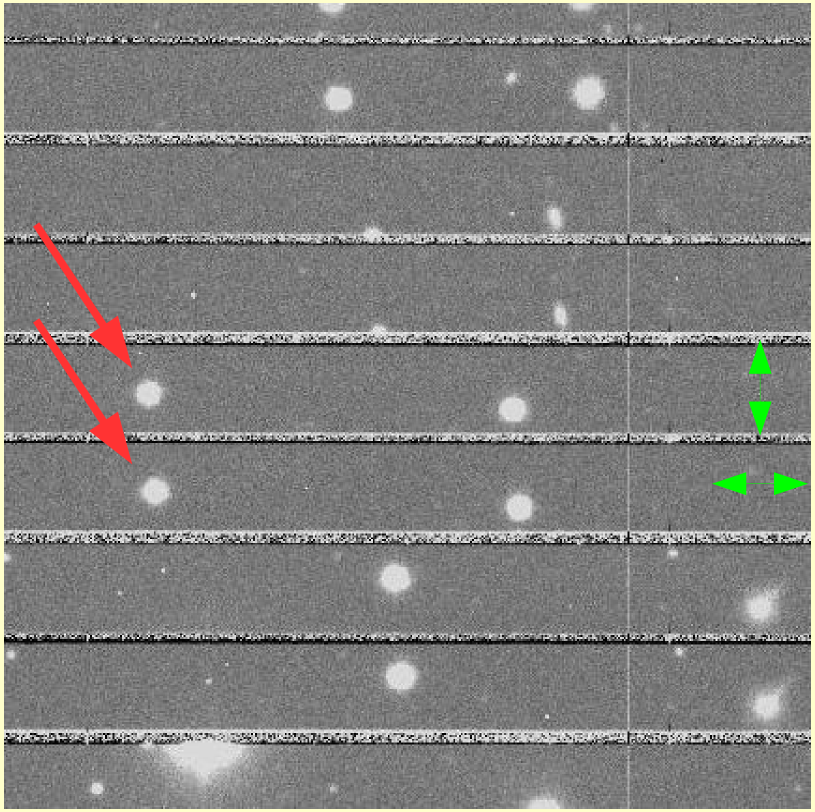
Polarization measurements (1)



Beam splitter:
Wollaston prism



Polarization measurements (2)



$$q = I_{up} - I_{down} / I_{up} + I_{down}$$

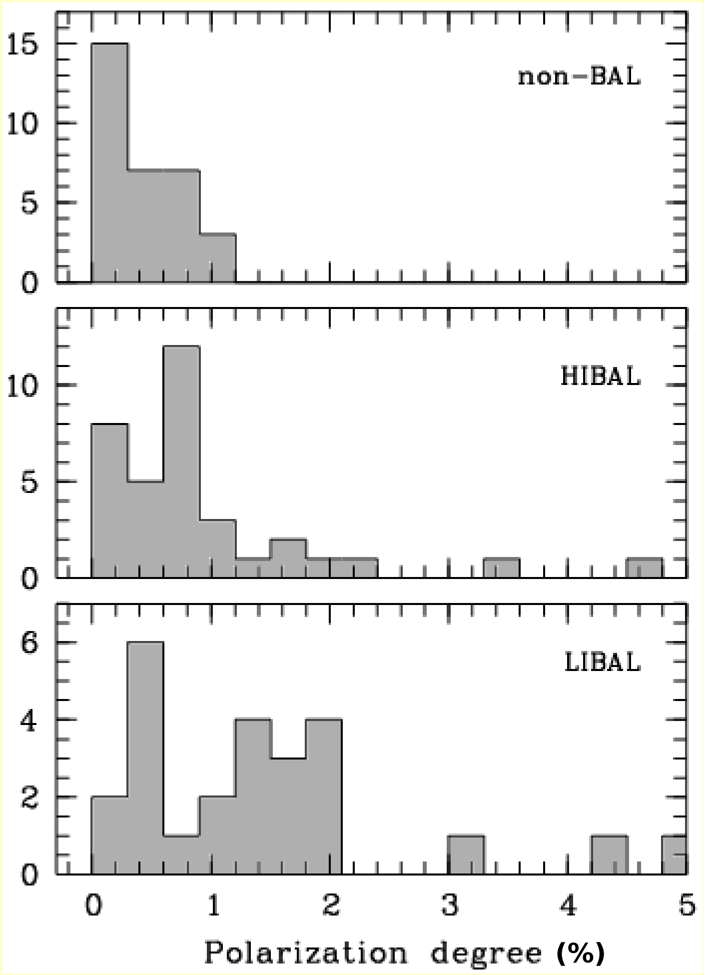
- Measurements of the normalized Stokes *q* and *u* : half-wave plate at 0, 22.5, 45 and 67.5 deg
- Redundancy -> a possible difference of transmission of the *e* and *o* rays is corrected
- Linear optical polarization with 0.15% uncertainty
- Independent of atmospheric variations
- The instrumental polarization is measured to be very small

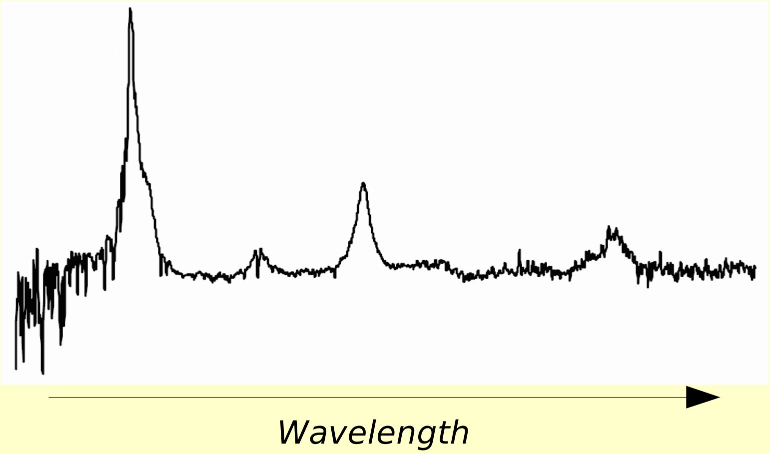
The nature of quasar polarization

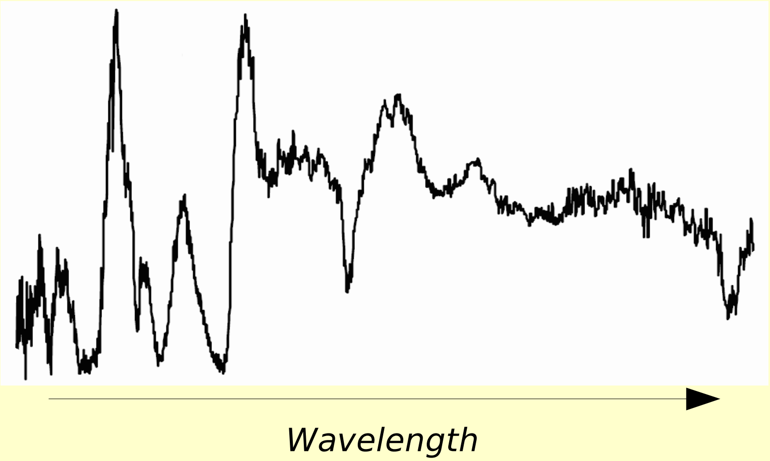
- Most often $p \sim 1 - 2$ %
- Most often due to electron scattering
- Net non-zero polarization indicates departures to spherical symmetry
- The polarization level is related to other characteristics like the presence of broad absorption lines in the quasar spectrum

=> polarization is mainly intrinsic to the quasars

Polarization versus spectrum

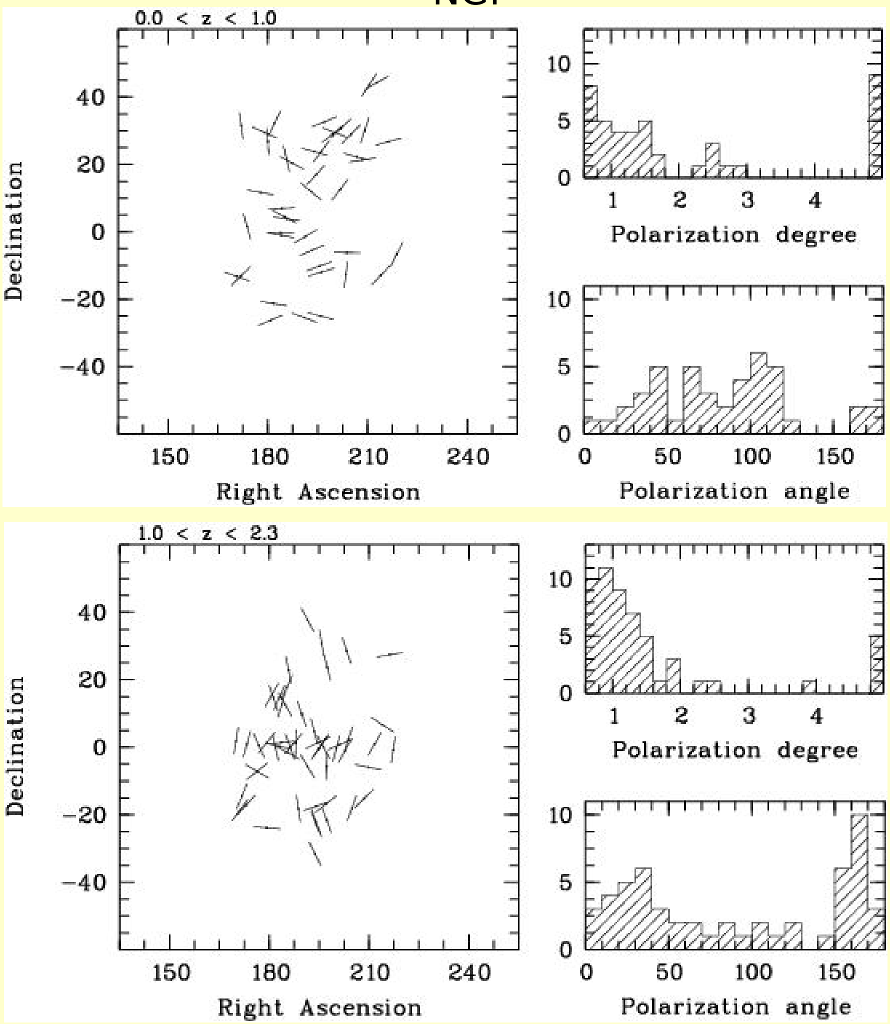






Large-scale alignments of quasar polarization vectors?

NGP



Scale ~ 1 Gpc
at z ~ 1

low redshifts / distances

$\bar{\theta}=79^o$ *with* $P=3\ 10^{-3}$

(circular statistics!)

high redshifts / distances

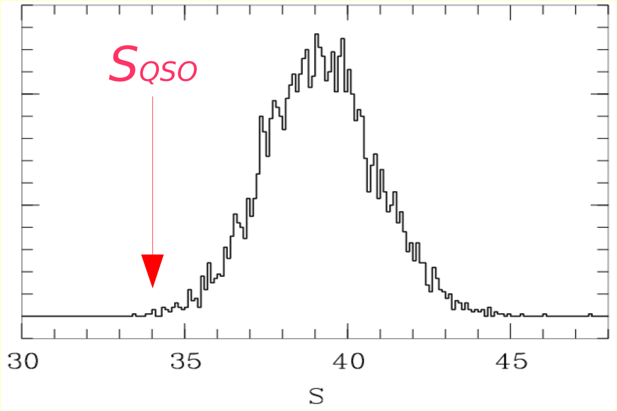
$\bar{\theta}=8^o$ *with* $P=2\ 10^{-3}$

Statistical analysis : the sample

- A sample of 355 polarized quasars up to $z \sim 2.5$
- New observations and compilation from the literature
- Galactic latitude > 30°
- Polarization degree > 0.6%
- Uncertainty of polarization angle < 14°

Statistical analysis : methods

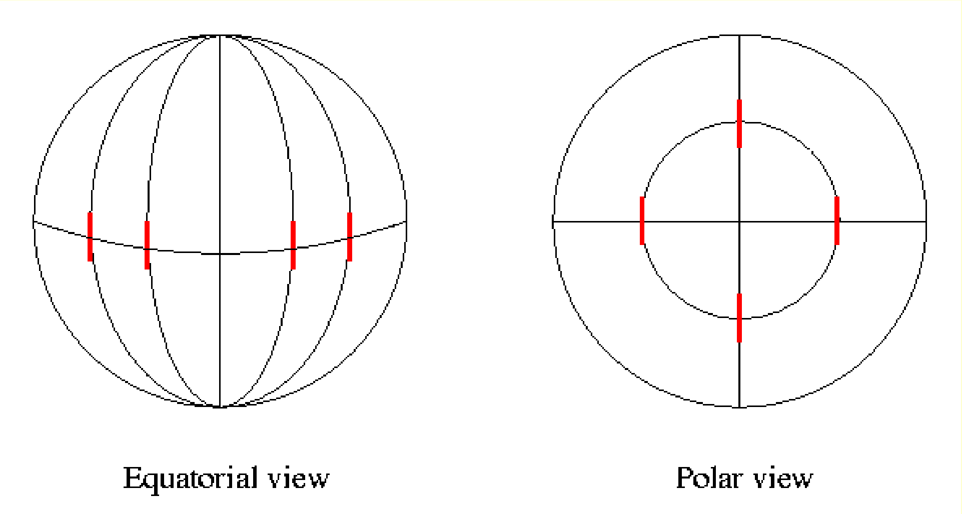
- Are polarization angles uniformly distributed on the sky?
- Statistics based on the dispersion of angles for n_v neighbors in the 3D Universe -> S_{QSO} $\left(S=(1/n)\sum_{i=1}^{n} D_i(n_v)\right)$
- Angles => circular statistics needed (axial data)
- Shuffling angles over positions -> *S distribution*



Significance level : percentage of simulated configurations with $S < S_{QSO}$

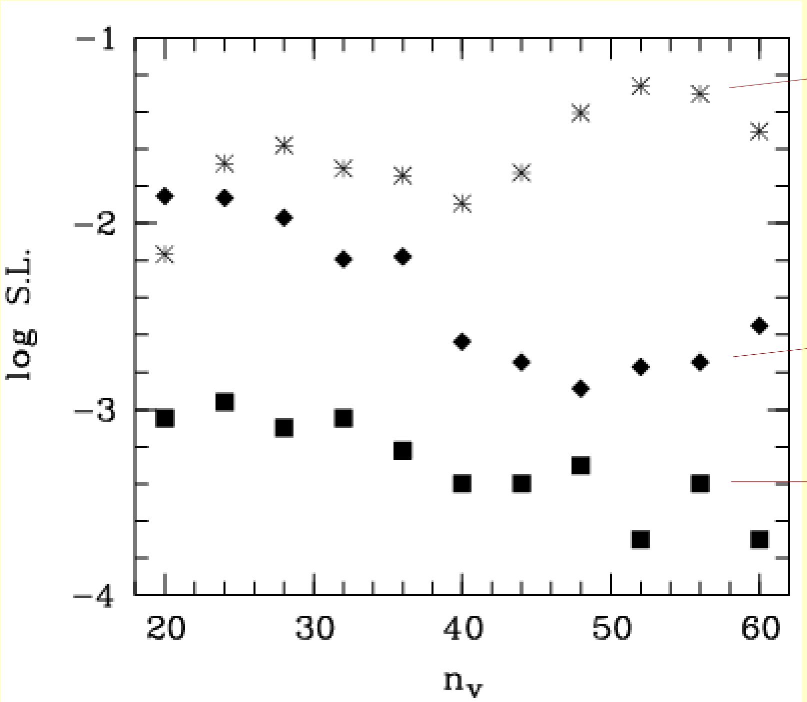
Statistical analysis : methods

- Polarization angles depend on coordinates



=> Statistics with parallel transport (Jain et al 2004)

Statistical analysis : history



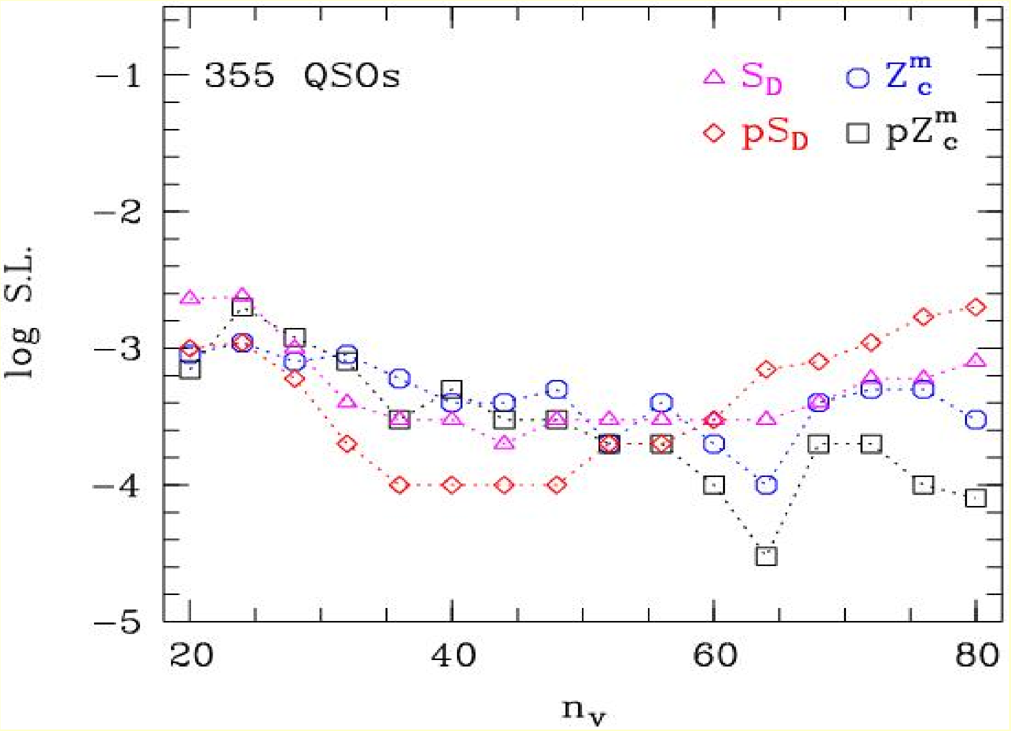
170 quasars (1998)

213 quasars (2001)

355 quasars (2005)

It is more and more difficult to produce the observed alignments from random distributions

Statistical analysis : results

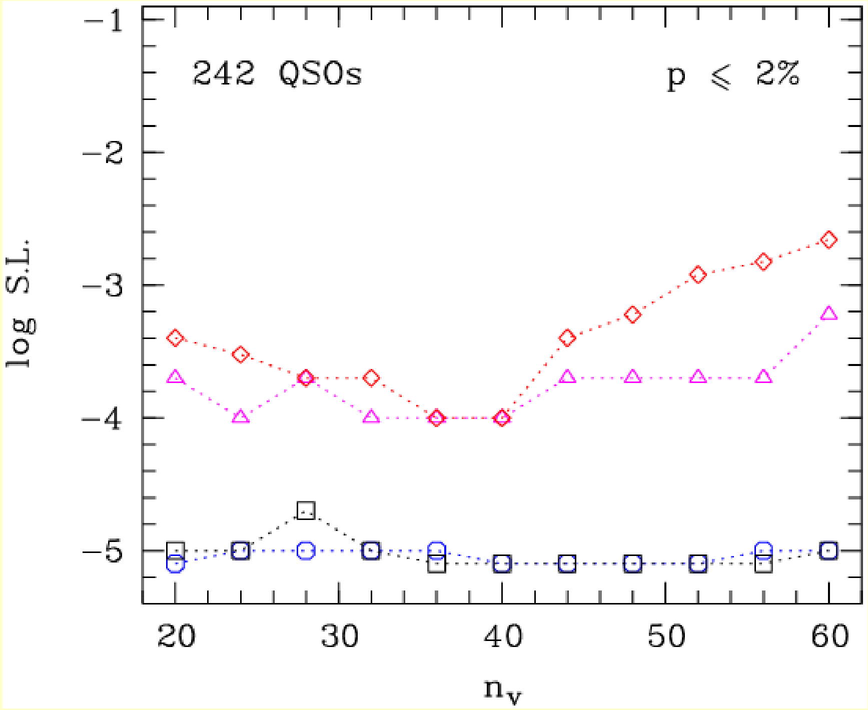


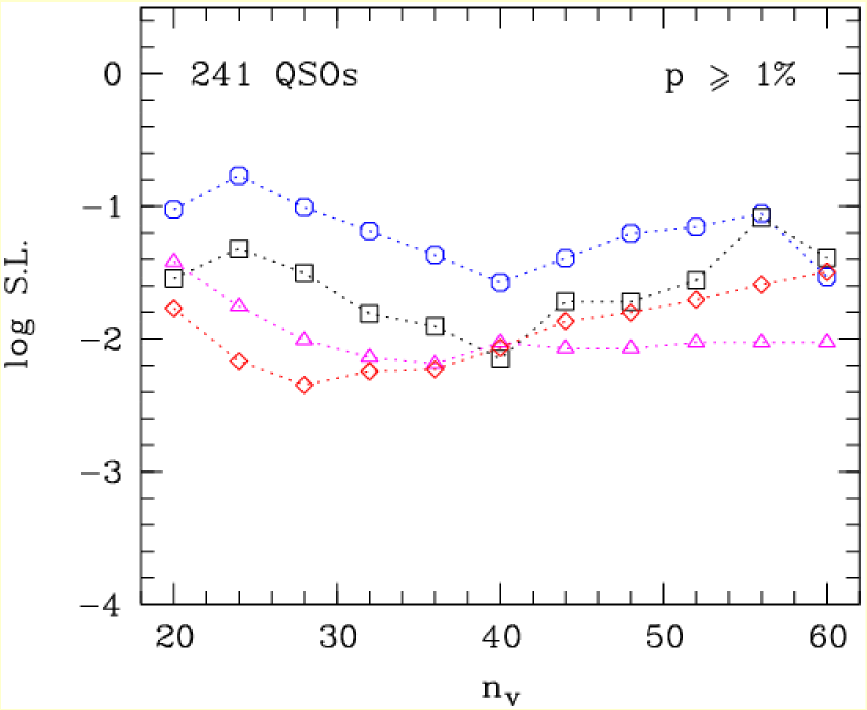
- Two different tests
- With and without parallel transport

Quasar polarization vectors are not randomly oriented over the sky

Statistical analysis : results

Subsamples





Low-p quasars preferentially aligned?
or selection effects?

Systematic contaminations?

Systematic instrumental polarization?

- Unpolarized and polarized standard stars: instrumental polarization < 0.1%, angle offset within 1°
- All quasars observed in different surveys (different instruments) agree within the quoted errors in both polarization degree and angle

➡ *Instrumental contamination is not significant*

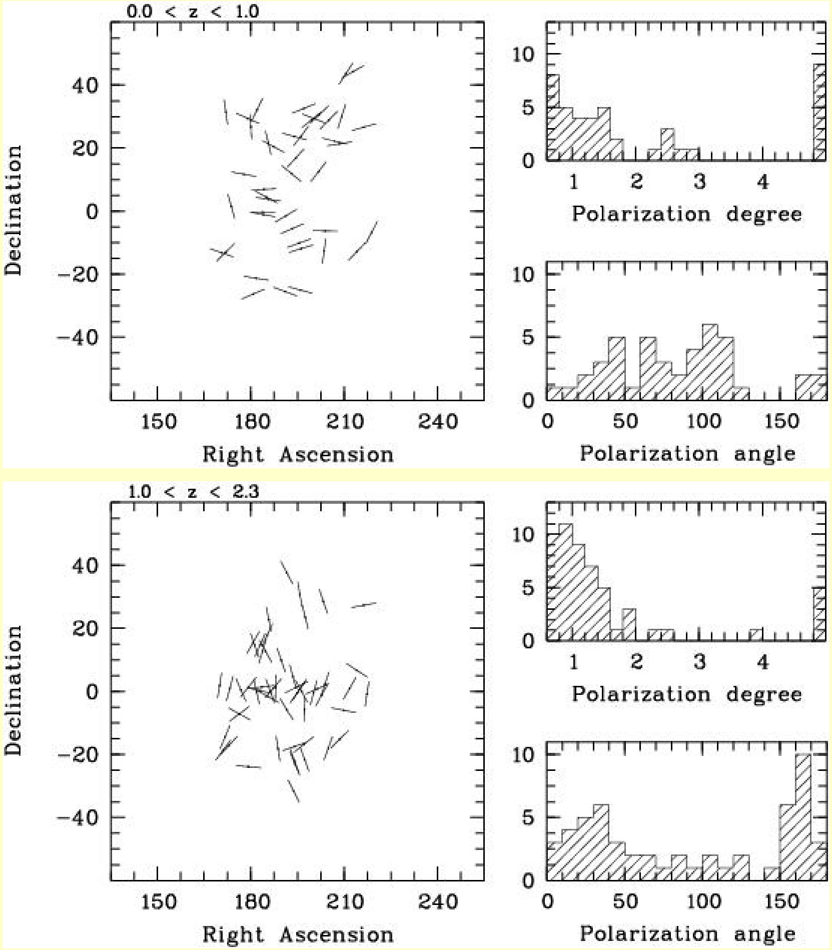
Systematic contaminations?

Elongated interstellar dust grains align within the Galactic magnetic field and polarize the stellar light (dichroism)

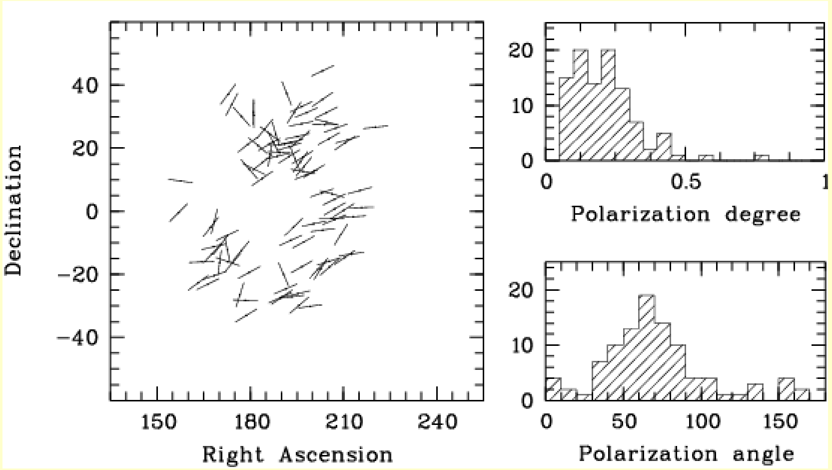
- The polarization is strong in the Galactic Plane => $|b| > 30°$ in the quasar sample
- At high galactic latitudes the interstellar polarization is small compared to $p_{QSO} > 0.6\%$
- Our data are partially corrected using field stars
- No correlation is observed between polarization angles of quasars and angular neighboring stars

Systematic contaminations?

Quasar polarization



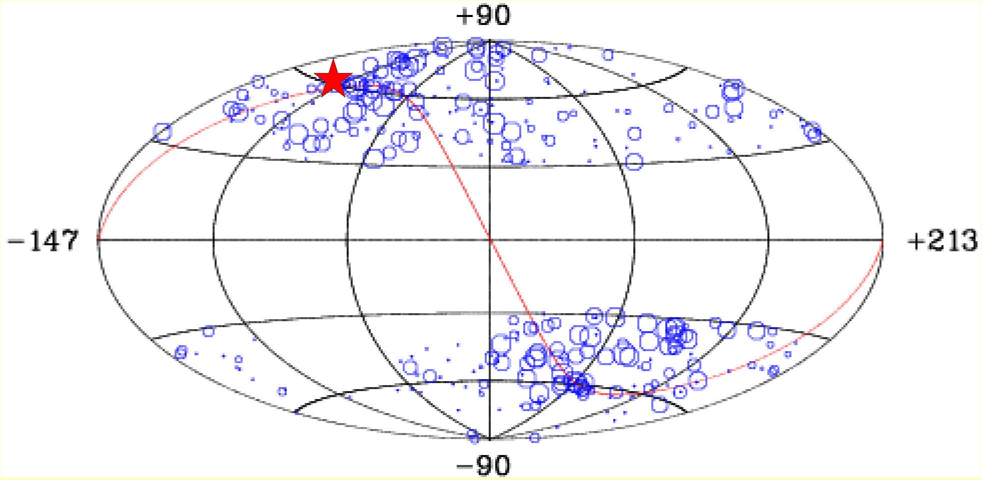
Star polarization



Interstellar polarization is unlikely to be responsible for the observed alignments since its effect must be the same at all redshifts

Location of the most significant alignments

Map of local statistics



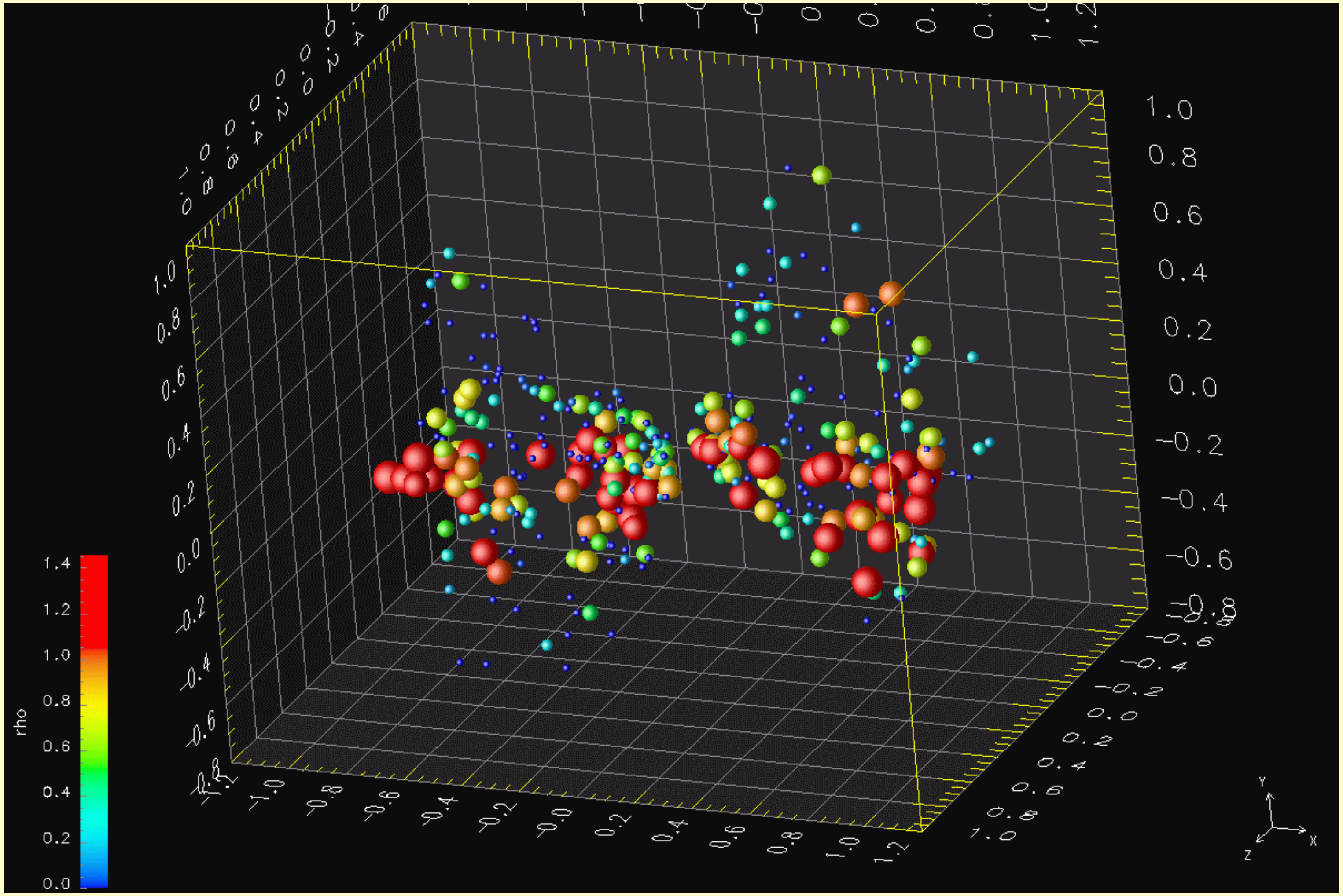
Galactic coordinates

$$S_{QSO} = (1/n)\sum_{i=1}^{n} D_i(n_v)$$

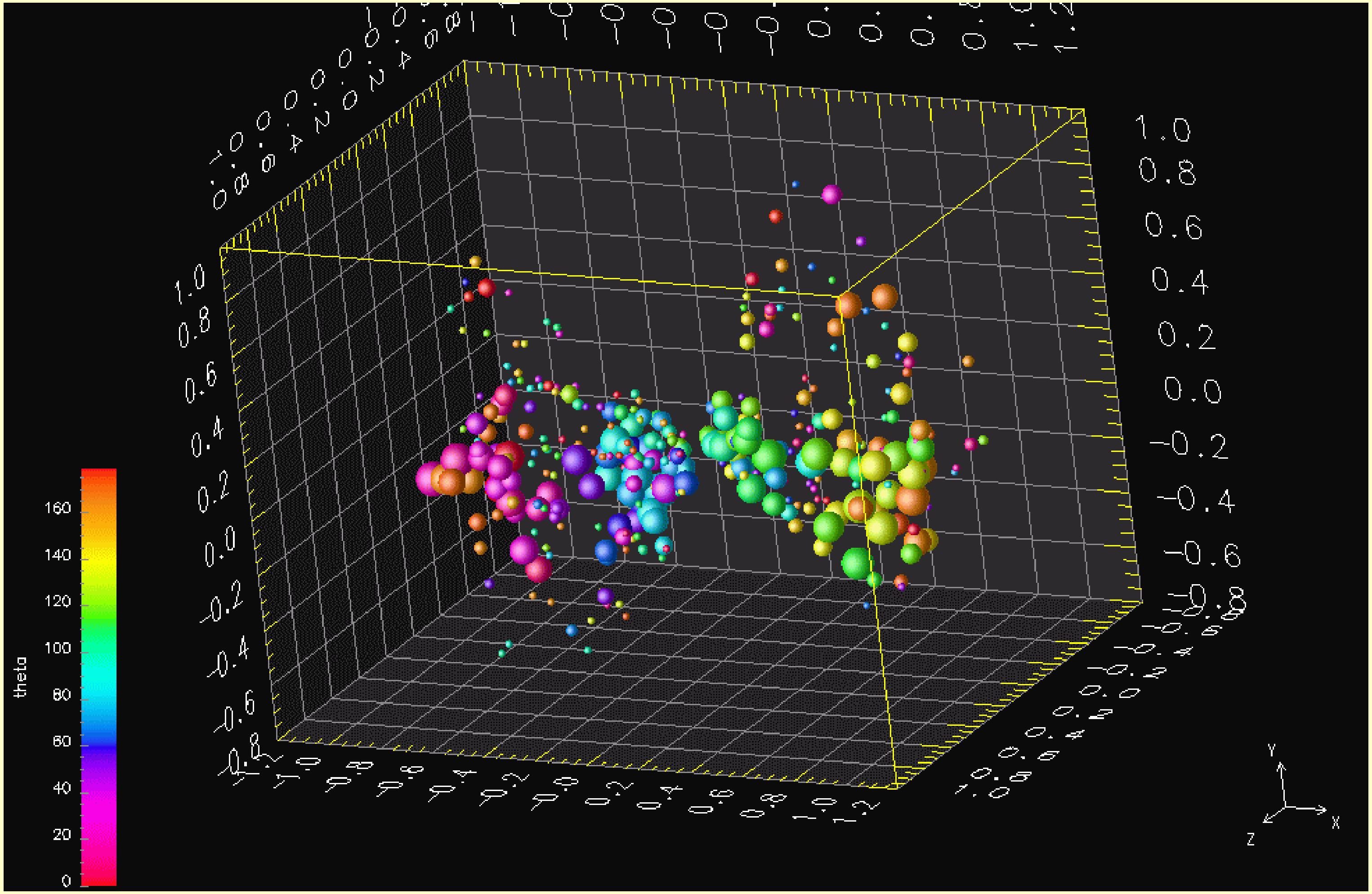
local statistics

The regions previously identified are the most significant (in both the NGP and SGP caps)
They are opposite on the sky in a direction not far from the CMB dipole and the "axis of evil" (Lang et al 2005)

The effect is more significant along an axis NGP -SGP

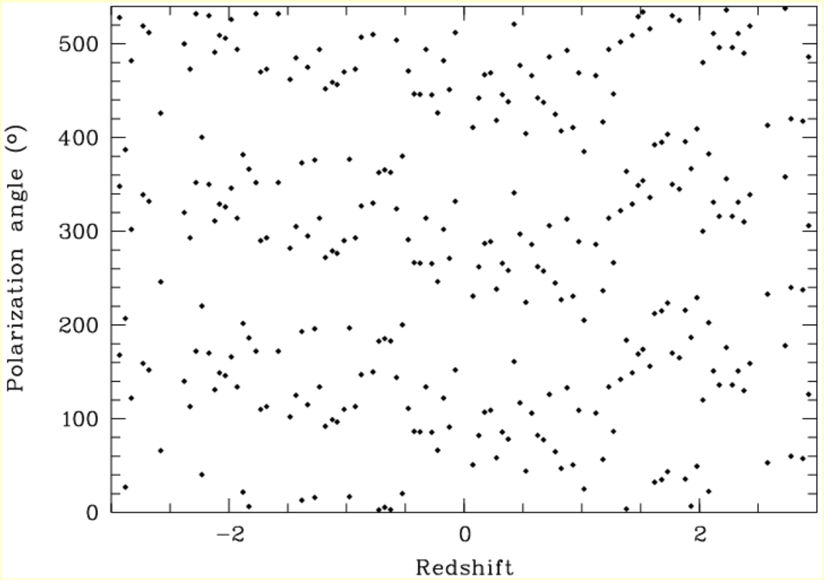


The polarization angle changes with the cosmological distance

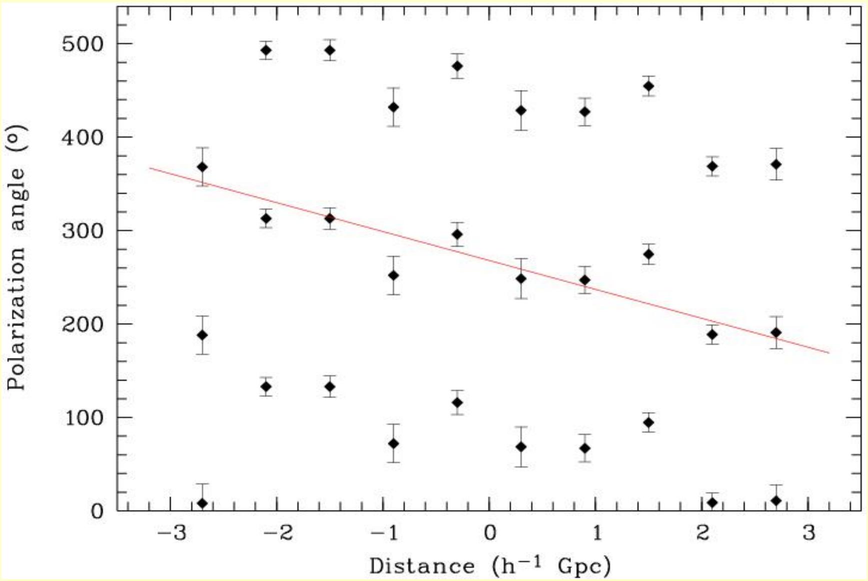


Characteristics of the effect

355 quasars



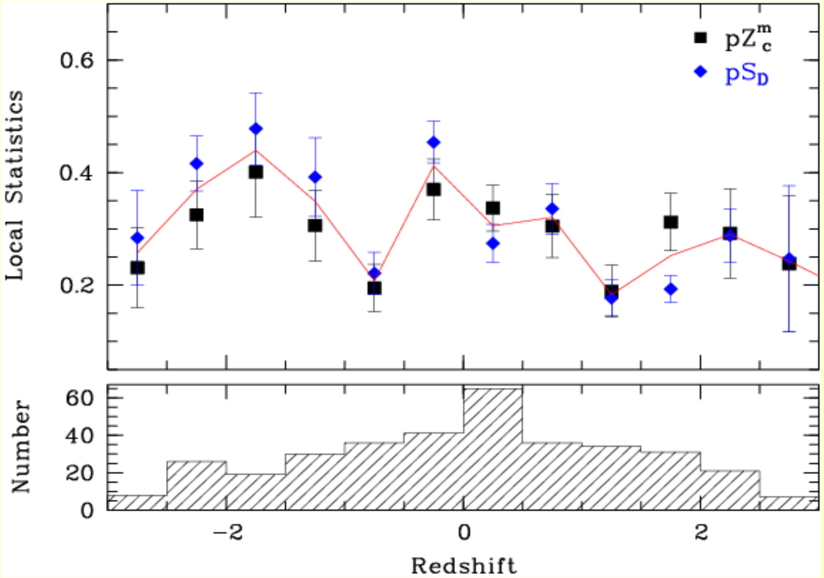
183 quasars along NGP-SGP axis



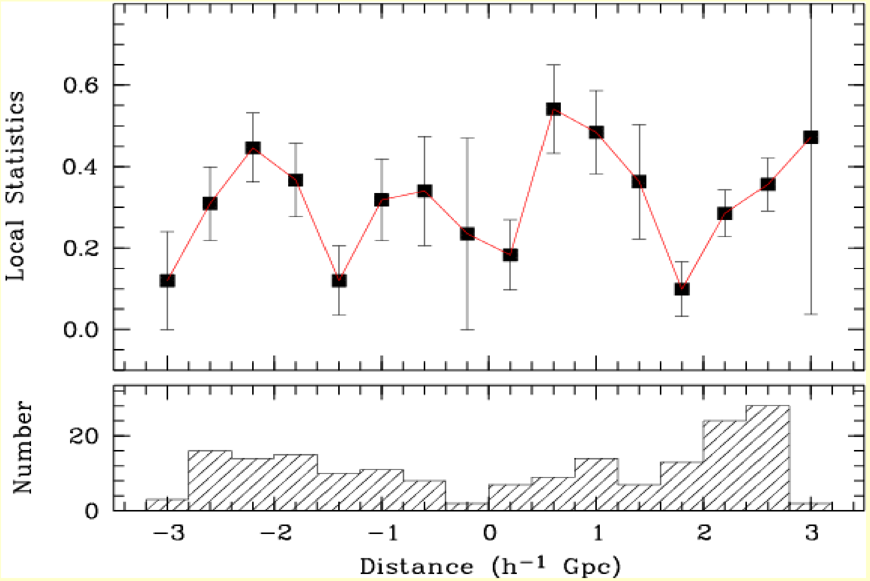
Rotation of the mean polarization angle with redshift or distance (S.L. ~ 10^{-4})

Characteristics of the effect

355 quasars



183 quasars along NGP-SGP axis



Cycles of randomly oriented and aligned polarization vectors?

Towards an interpretation?

- Simple simulations show that random orientations + a small systematic polarization can account for the alignments
- Correlations with quasar spectra are not washed out in the regions of alignments
  => a systematic polarization should remain small

Either polarization is totally intrinsic to quasars and quasars themselves are aligned

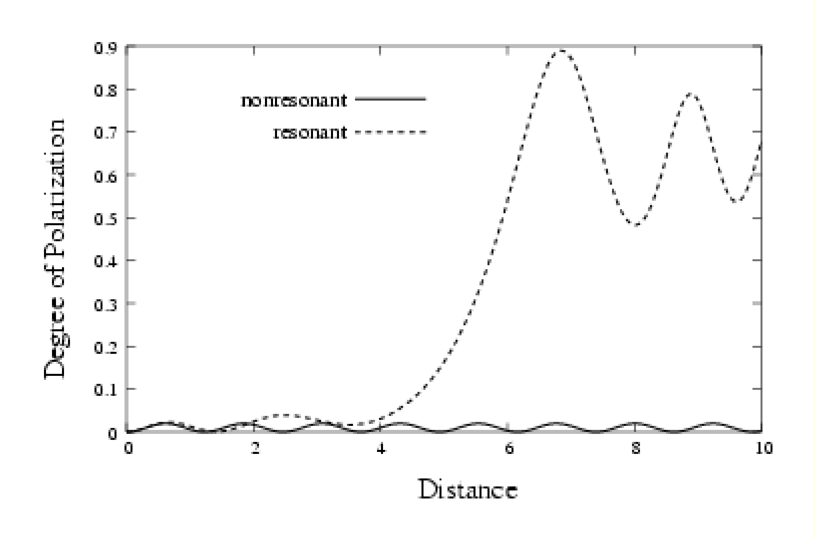
Or their polarization is partially modified along the line of sight (small systematic polarization)

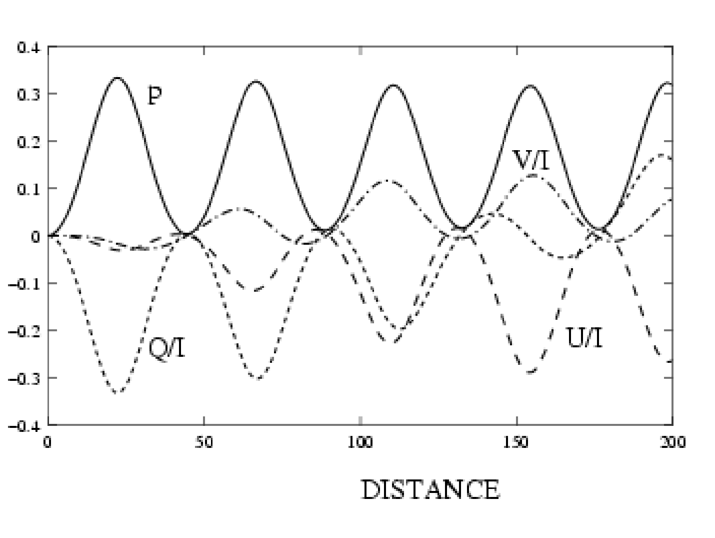
Evidence for photon-axion mixing?

- *Axion-like particles within a magnetic field*
- Photons parallel to an external B decay into axions
  => net linear polarization *p*
- Oscillations of *p* over cosmological distances are predicted (e.g. Gnedin et al. 2005)
  => B < 1 nG coherent over ~ 1 Gpc ?
- A rotation of the polarization angle with distance may also be explained (Das et al. 2005)
  => requires a complex variation of the direction of B with distance

Evidence for photon-axion mixing?

Extensive study by Das et al. 2005:
- resonant mixing (when plasma frequency ~ mass of the field)
- slowly varying magnetic field direction

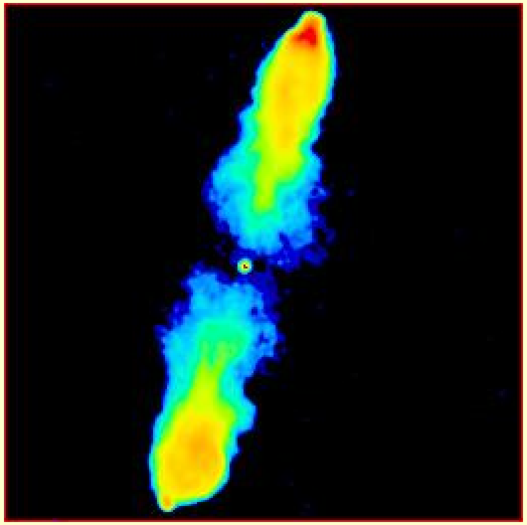


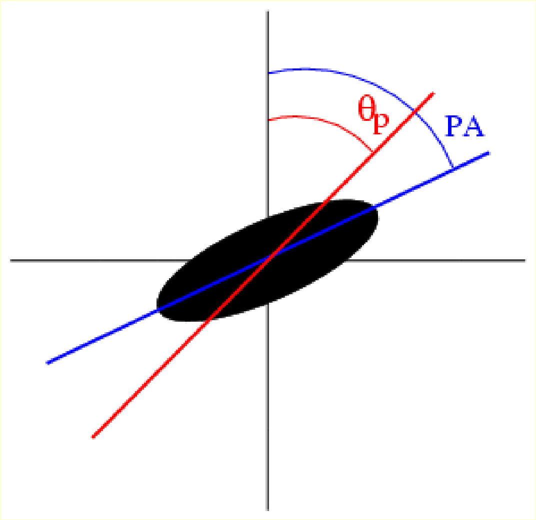


Alternative interpretations

- *Intergalactic dust?*
  But: reddening and polarization expected to increase with redshift (large-scale B also needed); no cycles
- *A global rotation of the Universe?*
  Transfer of angular momentum and rotation of the polarization angle (Obukhov 2000)
- *Structural axes aligned with large-scale magnetic fields?*

Searches at radio wavelengths





Radio-galaxies are resolved at radio wavelengths : PA can be defined and compared to the radio polarization angle corrected for Faraday rotation ($\propto RM\,\lambda^2$) => $\Delta=\theta_p-PA$
Most often $\Delta \sim 90^\circ$ (at redshifts > 0.3)

=> a rotation of the polarization angle is detectable

Searches at radio wavelengths

- Dipole anisotropy of Δ over the sky (Birch 1982, Jain & Ralston 1999). Axis close to the CMB "axis of evil" (Ralston & Jain 2004).
  Redshift dependence (Nodland & Ralston 1997).
- No anisotropy at all (Bietenholz & Kronberg 1986).
  No extra rotation of the polarization angles with redshift => upper limits on extensions to standard theories (Caroll et al. 1990, 1997; Harari & Sikivie 1992)

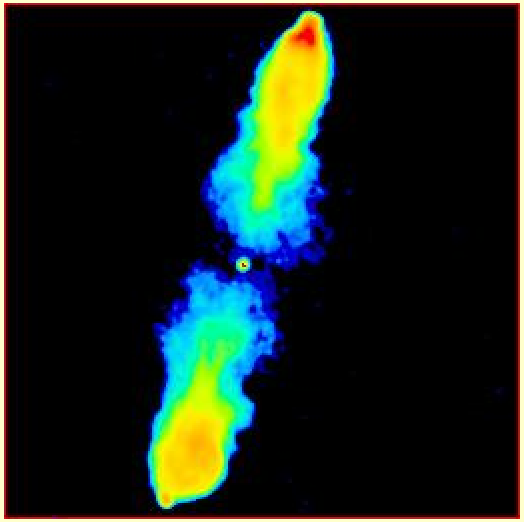
=> Controversial results ?

-> Larger and better sample? Sample at high redshift needed?

Searches at radio wavelengths

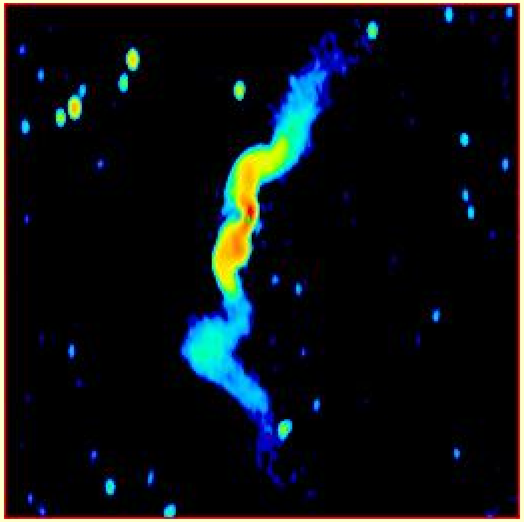
For example: difficulty of accurately defining PA

3C 223



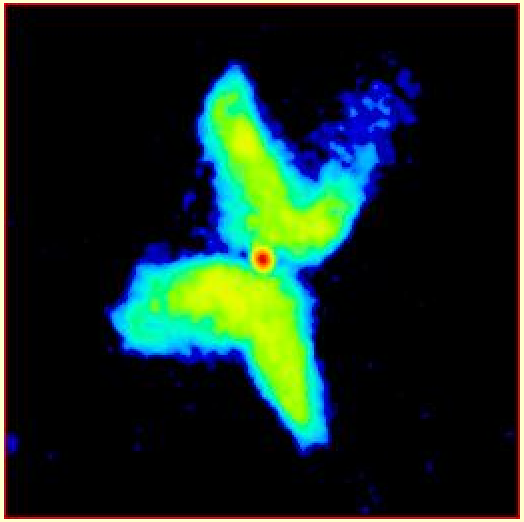
PA=164

3C 31



PA=160

3C 315



PA =10 ?

(Images from Leahy, Bridle & Strom, http://www.jb.man.ac.uk/atlas/)

=> Objective and reproducible criteria are needed
(Bietenholz & Kronberg 1986)

Conclusions and future work

We found large-scale angular correlations of quasar polarization vectors

These alignments are redshift-dependent. They cannot be explained by instrumental contamination

Galactic contamination does not seem to correlate with alignments

A large-scale origin is plausible, either with photon-axion mixing on cosmological scales or intrinsic remnant alignments of quasar axes

Conclusions and future work

Astrophysical observations offer interesting avenues for probing the existence of (light) axions

More observations to further assess the reality of cycles, of the θ-z relation, of a preferential axis

Correlation with quasar structure, with CMB data (WMAP), color dependence of the effect, circular polarization effects, radio studies at high redshifts

More detailed theoretical predictions are also needed to disentangle the various explanations

References

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