Large-scale alignments of quasar polarization vectors :

Evidence at cosmological scales for very light pseudoscalar particles mixing with photons?

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Outline

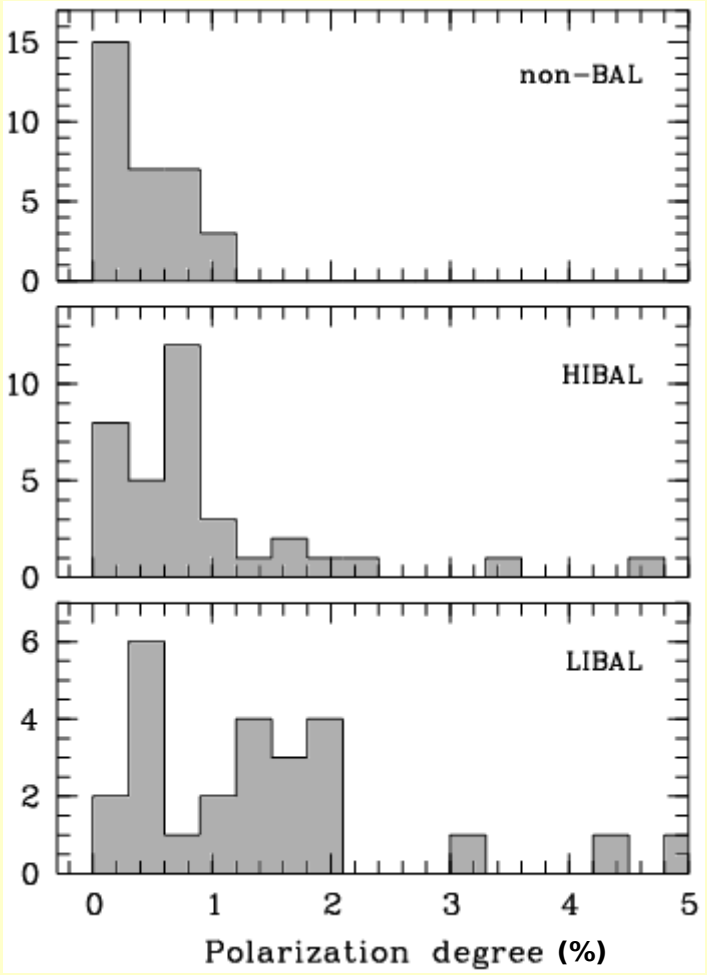
- The nature of quasar polarization
- Large-scale alignments of quasar polarization vectors? Statistics, possible contaminations
- Characteristics of the alignment effect
- Interpretations. Evidence for photon-axion mixing?
- Conclusions

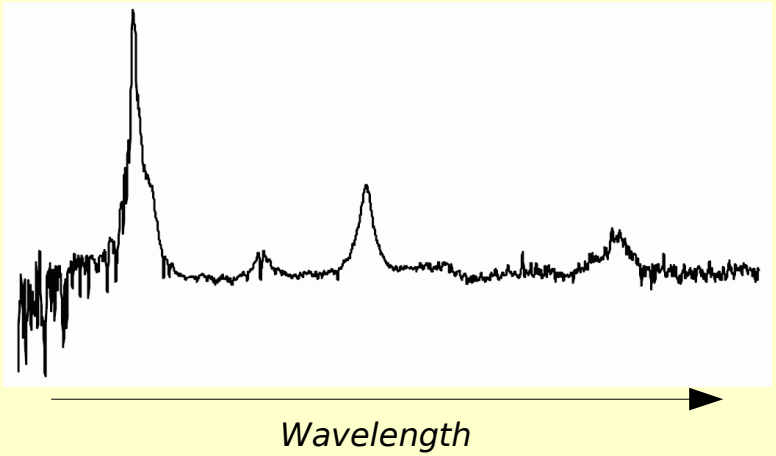
Quasar optical linear polarization

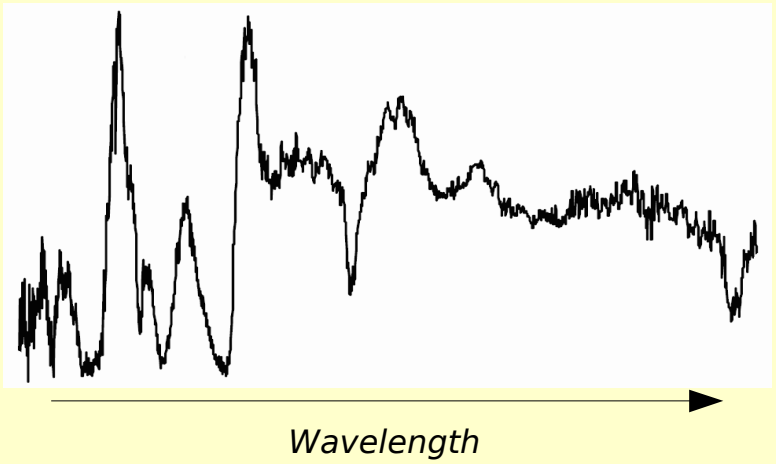
- Most often $p \sim 1 - 2\%$ (but a few have $p > 3\%$)
- Most often θ is constant with wavelength (B to R)
- Most often due to dust or electron scattering
- Net non-zero polarization indicates departures to spherical symmetry
- The polarization level is related to other characteristics like the presence of broad emission or broad absorption lines in the quasar spectrum

=> polarization is mainly intrinsic to the quasars

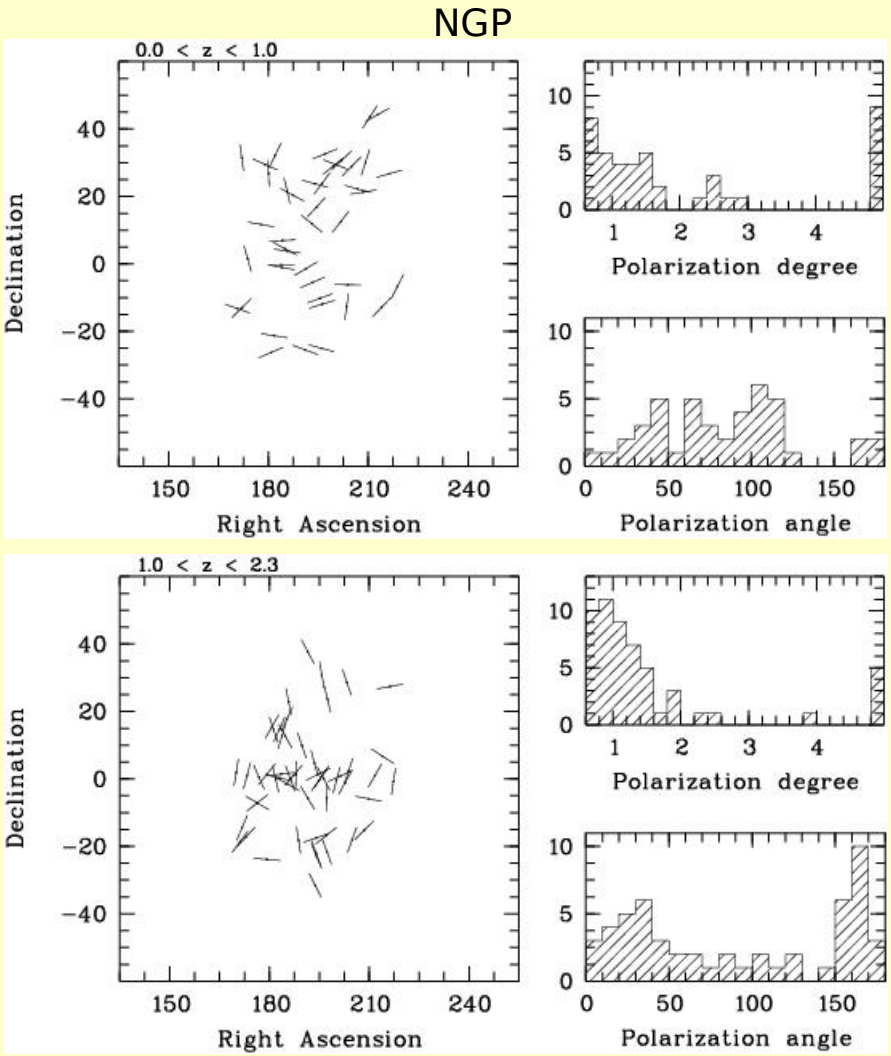
Polarization versus spectrum







Large-scale alignments of quasar polarization vectors?



Scale ~ 1 Gpc
at z ~ 1

low redshifts / distances

→ $\bar{\theta}=79^o \;\; (P=3\ 10^{-3})$

(circular statistics!)

high redshifts / distances

→ $\bar{\theta}=8^o \;\; (P=2\ 10^{-3})$

Statistical analysis : the sample

- A sample of 355 polarized quasars up to $z \sim 2.5$ (previous studies with 170 and 213 quasars)
- New observations and compilations from the literature (inhomogeneous sample)
  - Bright, BAL, red, radio-loud quasars preferred
  - Blazars essentially excluded (unsecured z)
- Galactic latitude > 30°
- Polarization degree $\geq$ 0.6%
- Uncertainty of polarization angle $\leq$ 14°

Statistical analysis : methods

- Are polarization angles uniformly distributed on the sky?
- Angles are axial data => circular statistics needed
- *S*-statistics is based on the dispersion of angles for n_v neighbors in the 3D Universe -> S_{QSO}

$$S=(1/n)\sum_{i=1}^{n} D_i(n_v) \quad where \quad D_i = minimum \ \ of \ \ d(\theta)=90-(1/n_v)\sum_{k=1}^{n_v}\left|90-\left|\theta_k-\theta\right|\right|$$

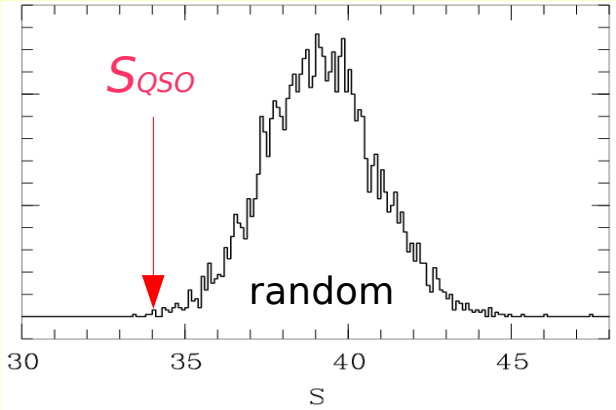
- *Z*-statistics compares QSO polarization vectors to the mean resultant vector of the n_v neighbors -> Z_{QSO}

$$D_{i,j}(n_v)=\boldsymbol{y_i}.\boldsymbol{Y_j} \quad where \quad \boldsymbol{y_i}=(cos2\theta_i, sin2\theta_i) \quad \boldsymbol{Y_j}=1/n_v(\sum_{k=1}^{n_v} cos2\theta_k, \sum_{k=1}^{n_v} sin2\theta_k)$$

$$D_{i,j=1,n} \ \ ordered \ \Rightarrow \ rank\, r_i \ \Rightarrow \ Z_i=\frac{r_i-(n+1)/2}{\sqrt{(n/12)}} \ \Rightarrow \ Z=(1/n)\sum_{i=1}^{n} Z_i(n_v)$$

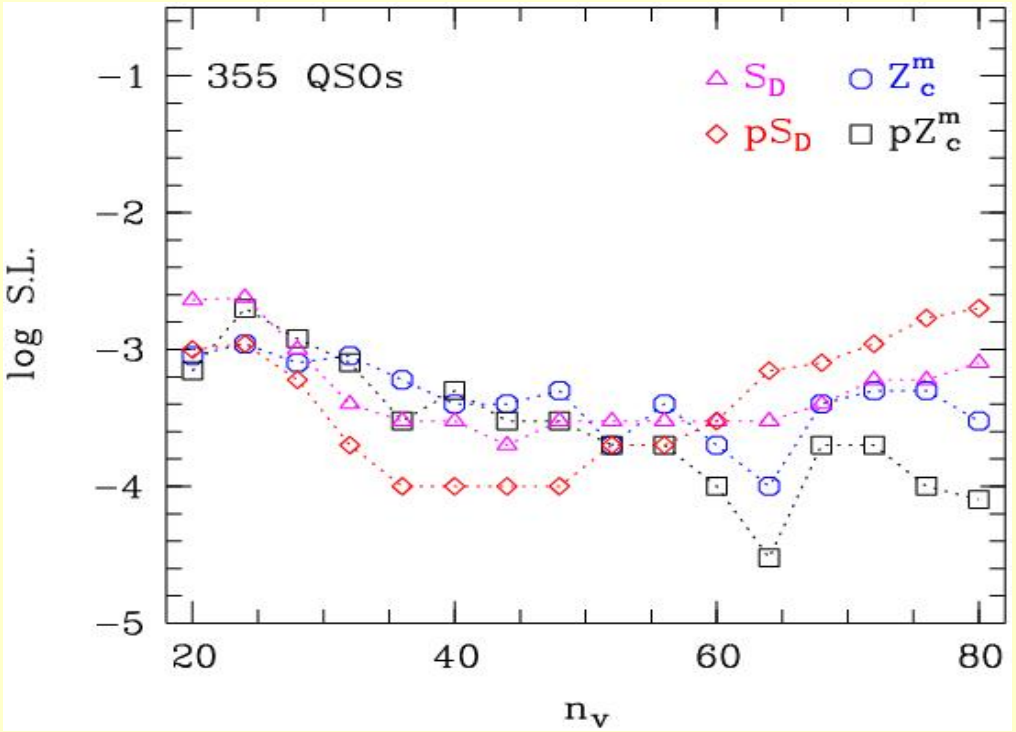
Statistical analysis : methods

- The significance is evaluated through Monte-Carlo simulations
- Shuffling angles over positions: *S (or Z) distribution* (keeps the original values of the polarization angles)



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

Statistical analysis : results



- Two different tests (*S* and *Z*)
- With and without parallel transport

Quasar polarization vectors are not randomly oriented over the sky

Systematic contaminations?

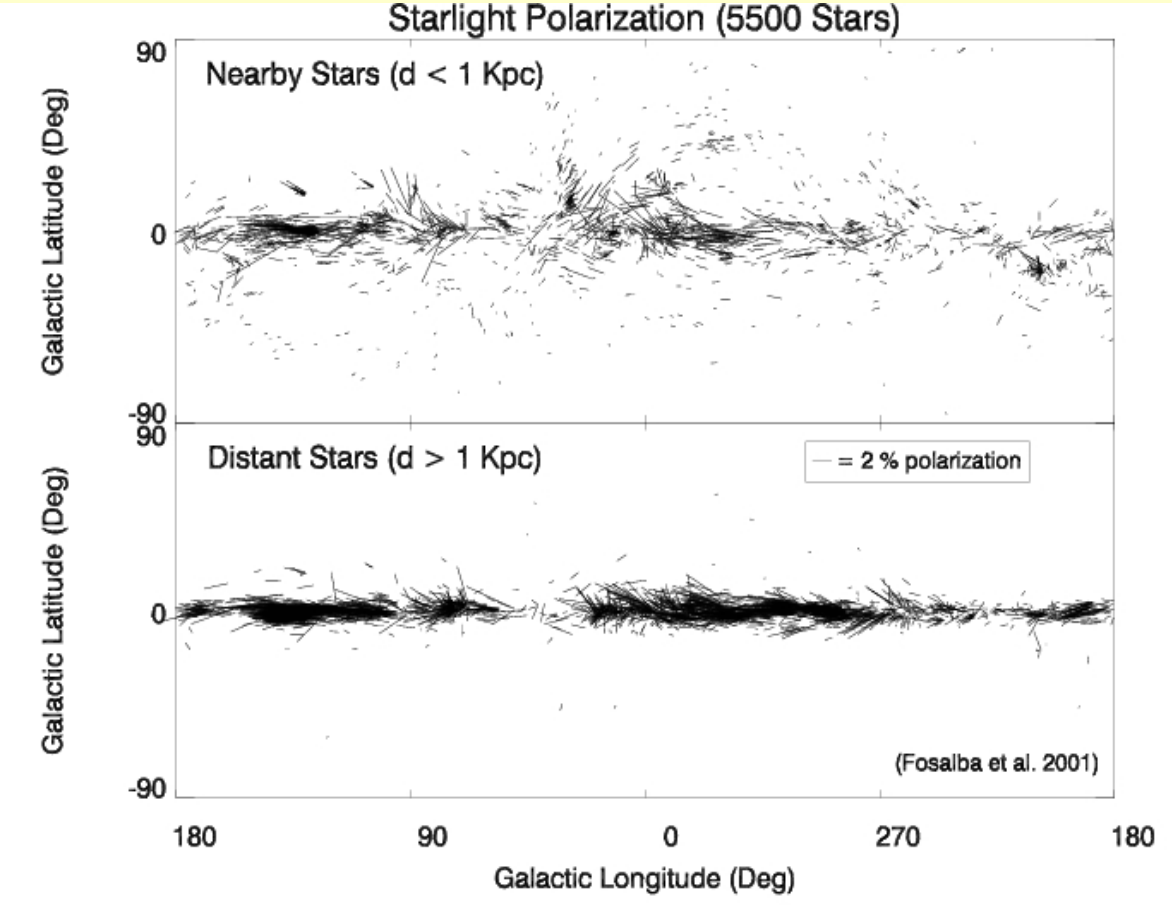
Systematic instrumental polarization?

- Measurement of 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

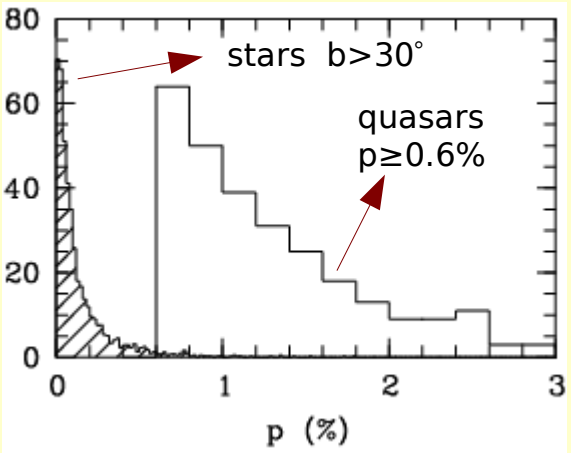
➡ *Instrumental contamination is not significant*

Interstellar polarization (ISP)

Stellar polarization due to elongated dust grains (dichroism) aligned within the galactic magnetic field

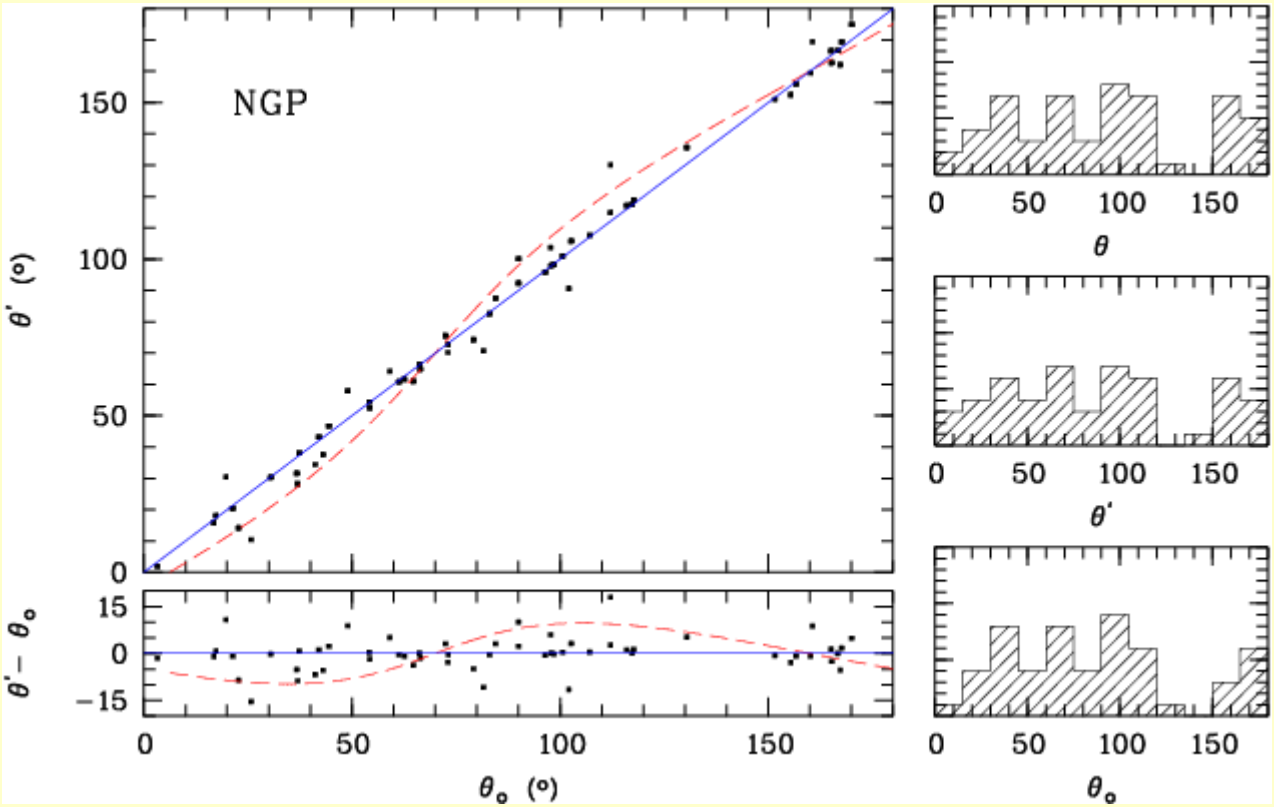


- $p_{star} \leq$ 0.2-0.3% at high galactic latitudes (b>30˚)



- $p_{QSO} \geq$ 0.6% is mostly intrinsic

Effect on quasar polarization angles

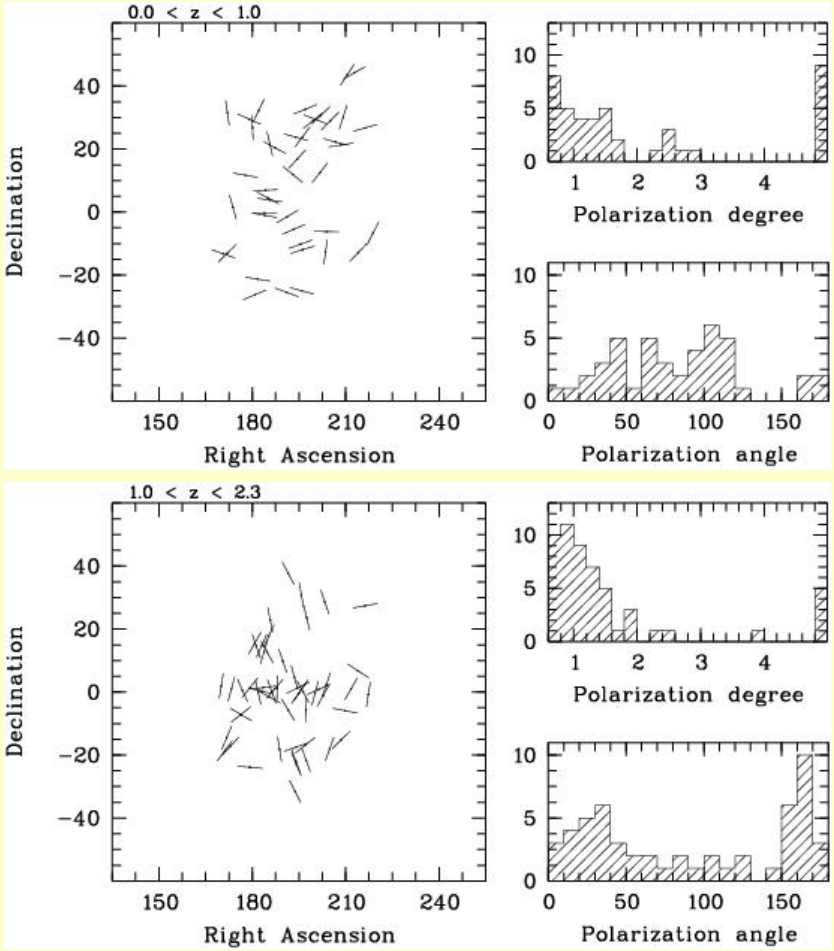


Quasars with
$p \geq 0.6\%$ only

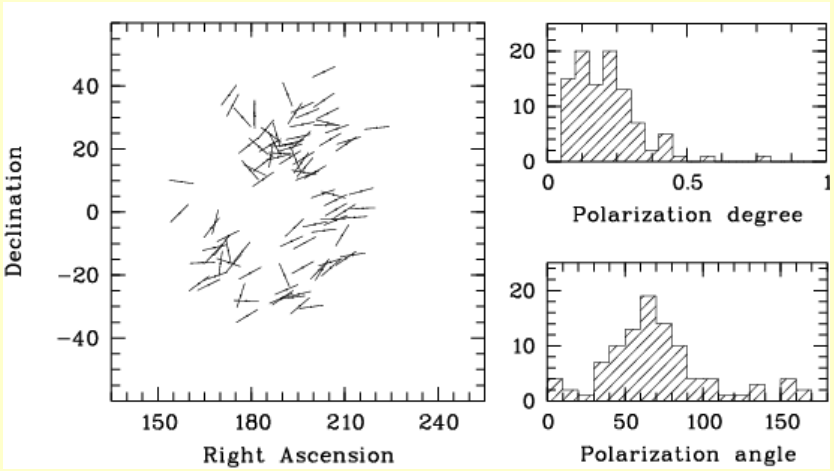
Correction frame by frame using the field star polarization: the interstellar polarization does not significantly contaminate the quasar polarization angles

Systematic ISP contamination?

Quasar polarization

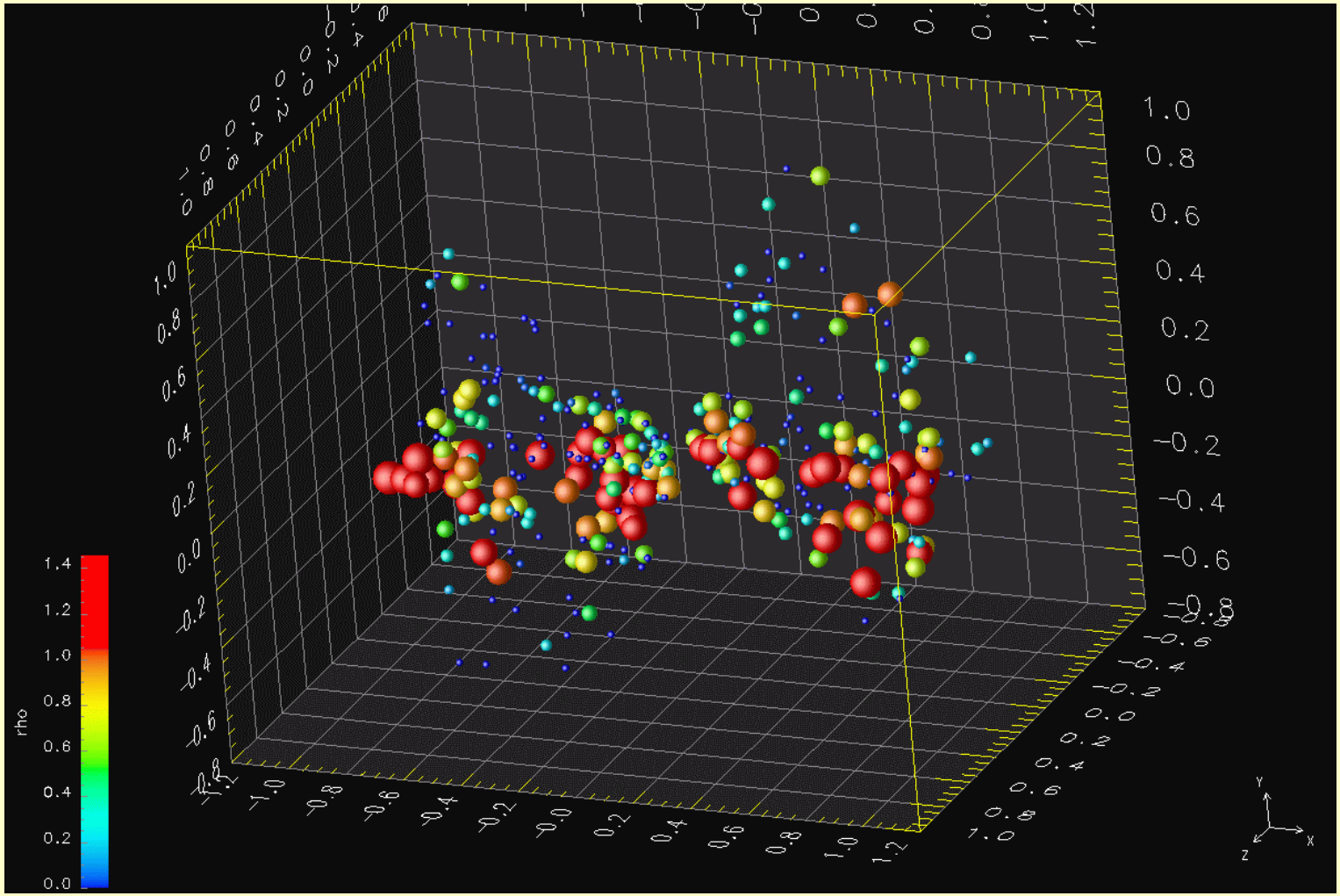


Star polarization



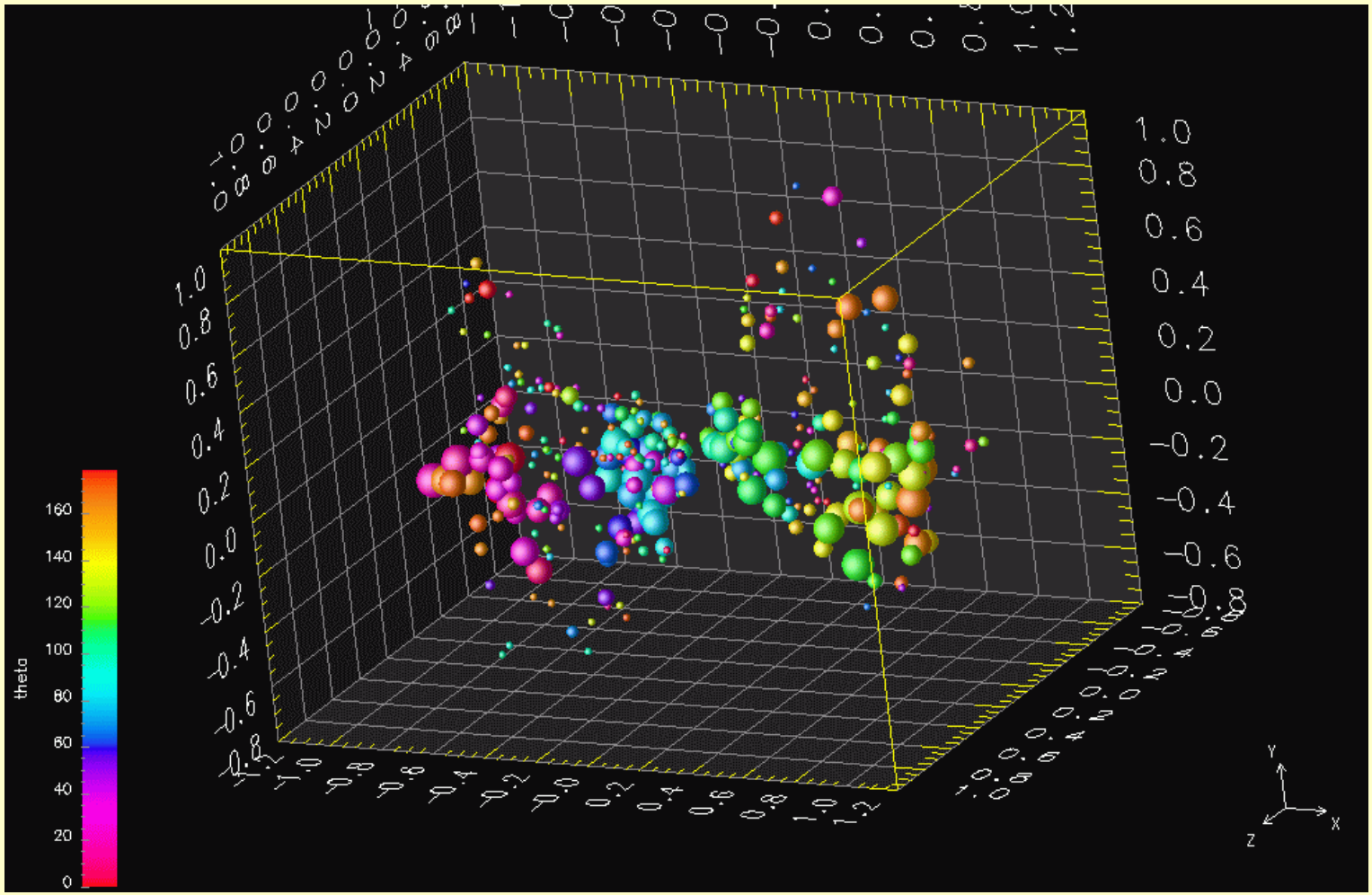
Interstellar polarization is unlikely to be responsible for the observed alignments since its effect must be the same at all redshifts

The effect is more significant along an axis NGP -SGP



Size and color ~ local statistics

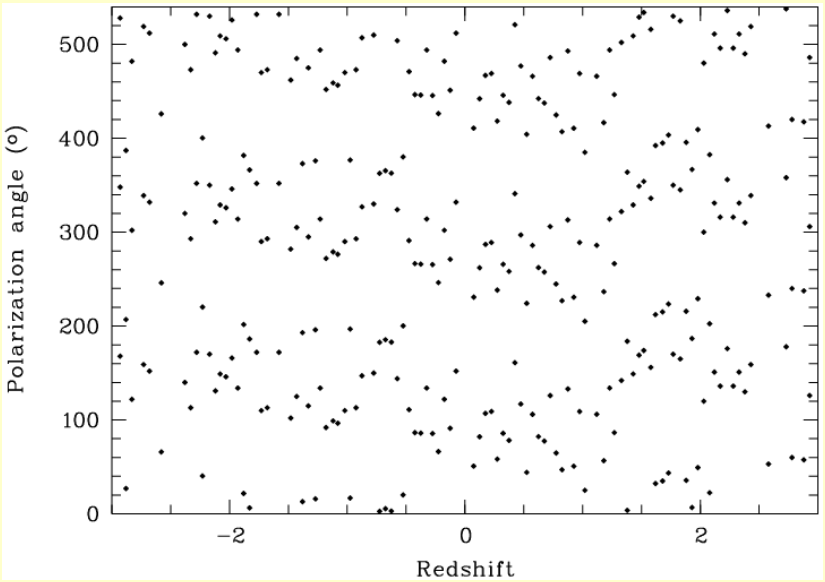
The polarization angle changes with the cosmological distance



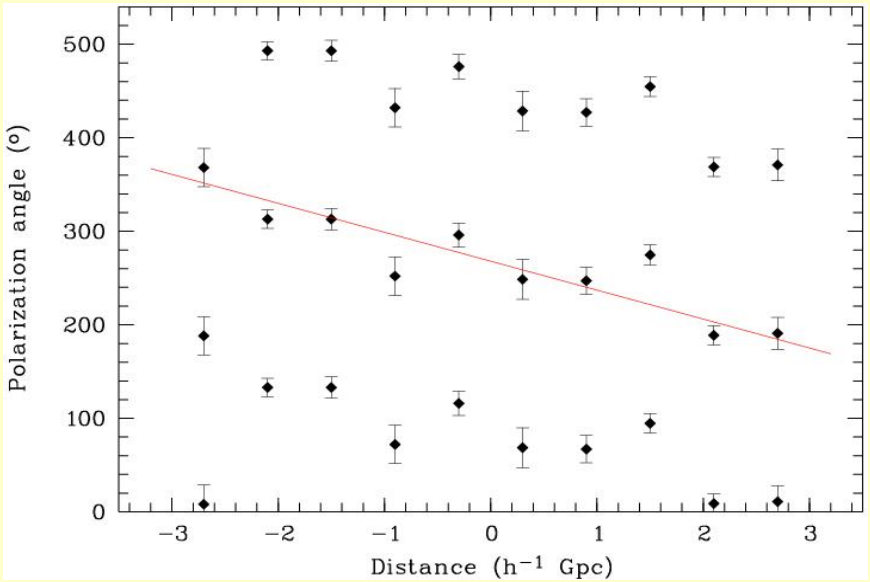
Size ~ local statistics --- Color ~ value of the polarization angle

Rotation with redshift?

355 quasars



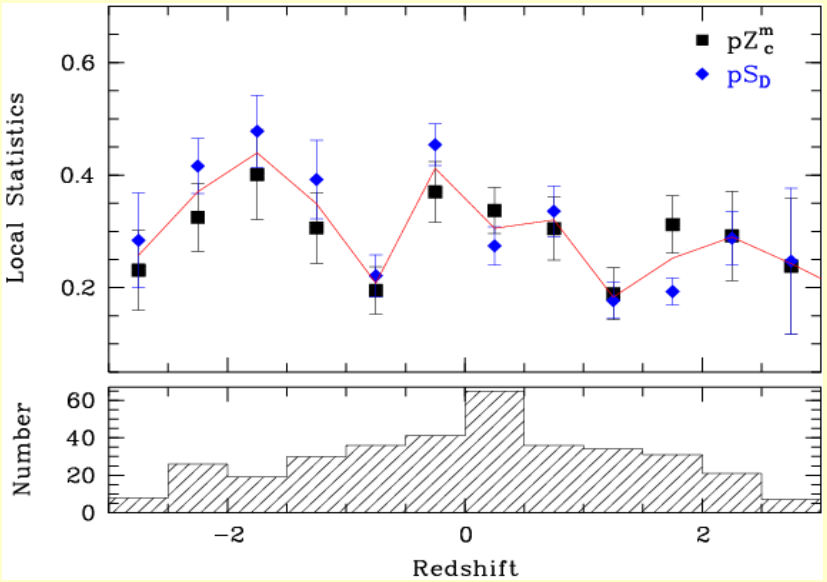
183 quasars along NGP-SGP axis



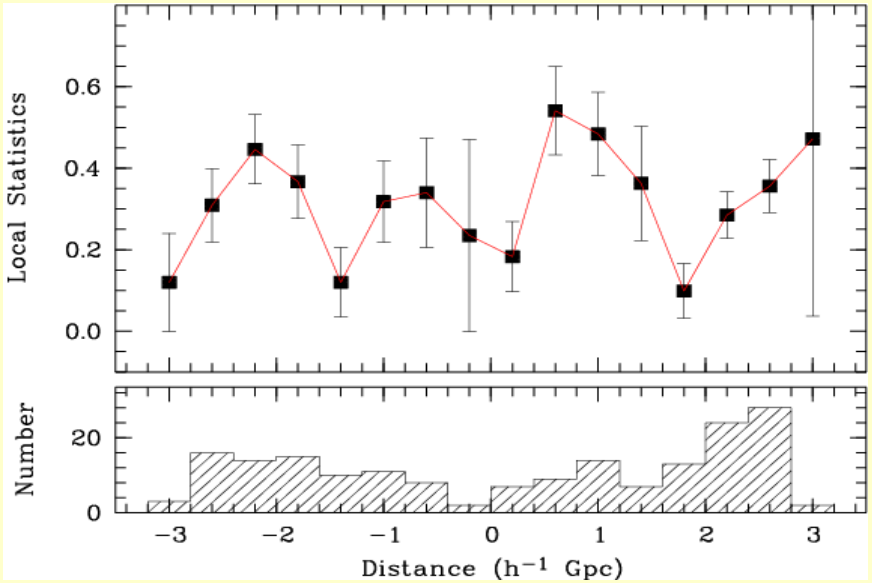
Rotation of the mean polarization angle with redshift or distance (S.L. ~ 10^{-4})

Characteristics of the effect

355 quasars



183 quasars along NGP-SGP axis



Cycles of randomly oriented and aligned polarization vectors?

Towards an interpretation

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)

- 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

Structural alignments?

- Known correlations between optical polarization and VLBI structure of compact radio-sources (Rusk 1990)
  => quasars themselves could be aligned
- Galaxy/galaxy, galaxy/cluster, cluster/cluster and cluster/super-cluster alignments have been reported up to $z \sim 1$ (e.g. West 1991, 1994, Plionis 2004).
  But: on much smaller spatial scales ($\leq$ 50 Mpc)
- Mechanisms acting at 1 Gpc scales?
  - Cosmic rotation? Transfer of angular momentum and rotation of the polarization angle (Obukhov 2000)
  - Axes aligned with large-scale magnetic fields? (e.g. Battaner & Lesch 2000)

Intergalactic dust?

- *Intergalactic dust grains aligned within large-scale (~1 Gpc) magnetic fields => small additional polarization*
- But: dust is not detected in the diffuse IGM (and only marginal evidence in galaxy clusters)

  [Recent search for intracluster dust by Muller et al. (2008): <*Av*> = 0.004 +/- 0.010 => p_V < 0.09 % at 3 σ]
- Assuming dust grains comparable to the grains in the Galaxy (and $p / A_v \propto B^2 / n_H$), the IGM magnetic field should be equal to or stronger than current upper limits in order to align them
- A succession of huge domains would be needed to explain the rotation with redshift

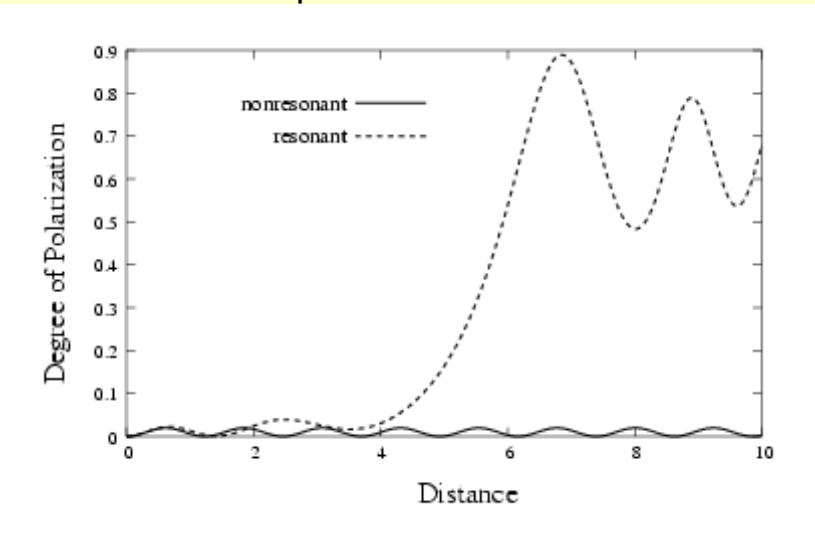
Photon-pseudoscalar mixing?

- Light-mass pseudoscalars (e.g. axions) are predicted by many theories beyond the Standard Model (candidates for dark matter and/or dark energy)
- Photons with polarization parallel to an external magnetic field B decay into pseudoscalars
  => net linear polarization p
- Oscillations of p over cosmological distances are predicted (e.g. Gnedin et al. 2005, 2007);
  needs $B < 1$ nG coherent over ~ 1 Gpc
- A rotation of the polarization angle with distance may also appear (Das et al. 2005) assuming a variation of the direction of B with distance

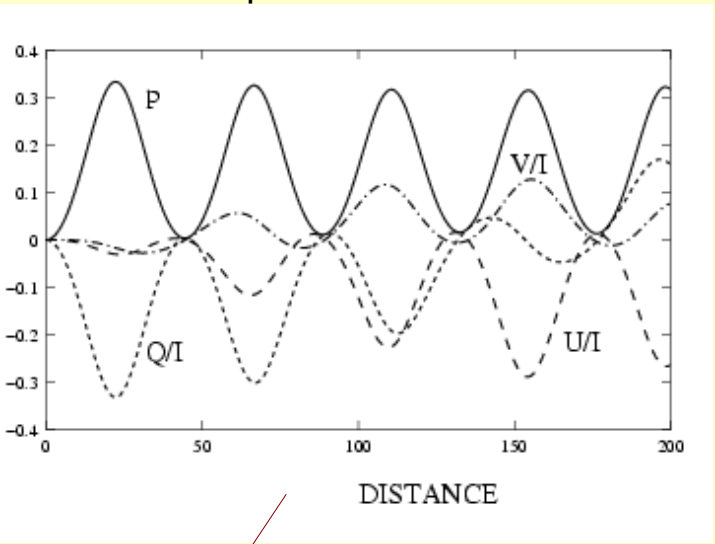
Evidence for photon-axion mixing?

Extensive studies by Das et al. 2005, Payez et al. 2008:
- resonant mixing (when plasma frequency ~ mass of the field)
- slowly varying magnetic field direction

Unpolarized source



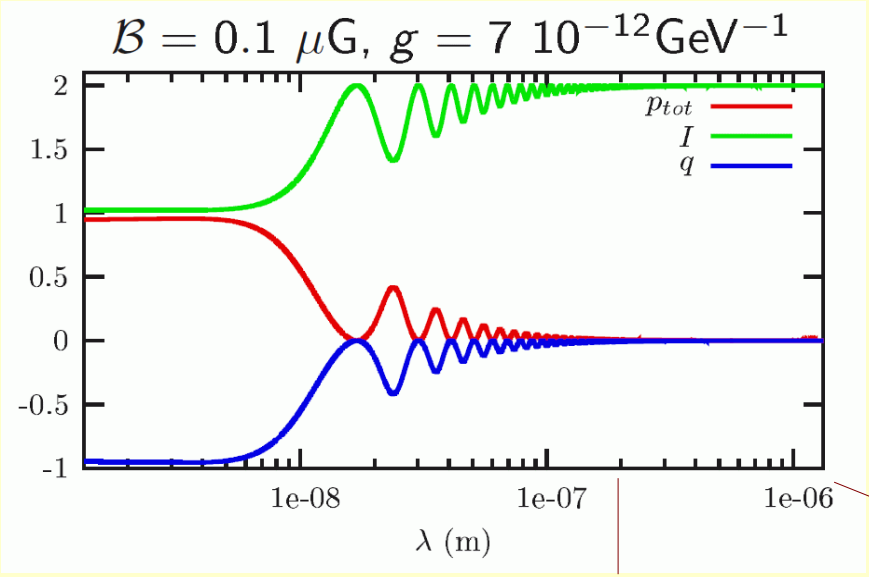
Unpolarized source



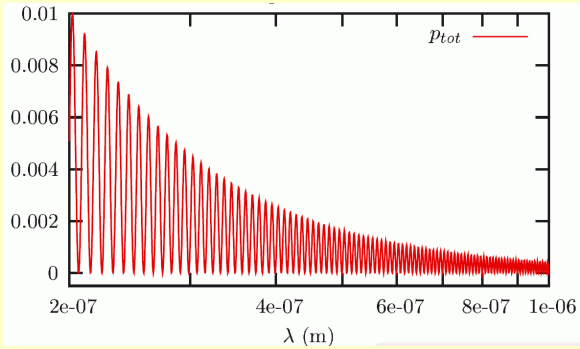
Circular polarization generated

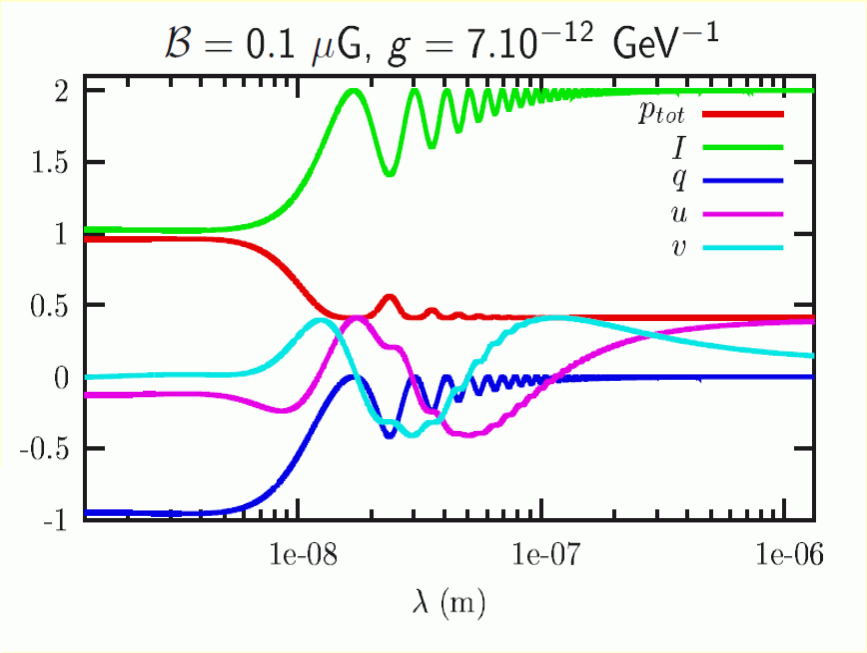
Evidence for photon-axion mixing?

Wavelength dependence



Unpolarized source





Polarized source

No effect expected at radio wavelengths in agreement with observations by Joshi et al. (2007)

Conclusions

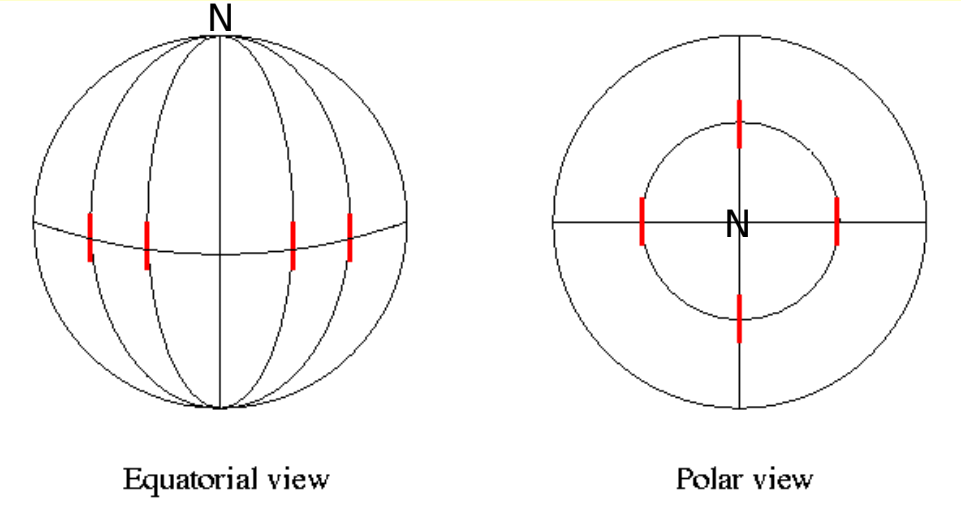
- *Evidence for large-scale angular correlations of quasar polarization vectors (in regions of ~ 1 Gpc size at z ~ 1)*
- *The mean polarization angle changes with redshift*
- *The effect is statistically significant (> 99.9%) in a sample of 355 quasars*
- *Instrumental and interstellar polarization cannot produce a redshift dependent effect*
- *A large-scale origin might be due to a modification of the quasar polarization along the line of sight (photon-pseudoscalar conversion?)*
- *The regions of alignments might be among the largest structures in the Universe and indicate departures to the fundamental cosmological assumption of large-scale isotropy*

References

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- Das et al. 2005, JCAP 06, 002
- Fosalba et al. 2002, ApJ 564, 762
- Gnedin et al. 2005, astro-ph/0509437
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- Lang et al. 2005, PRL 95, 071301
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- Ralston & Jain 2004, Int.J.Mod.Phys. 13, 1857
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Statistical analysis : methods

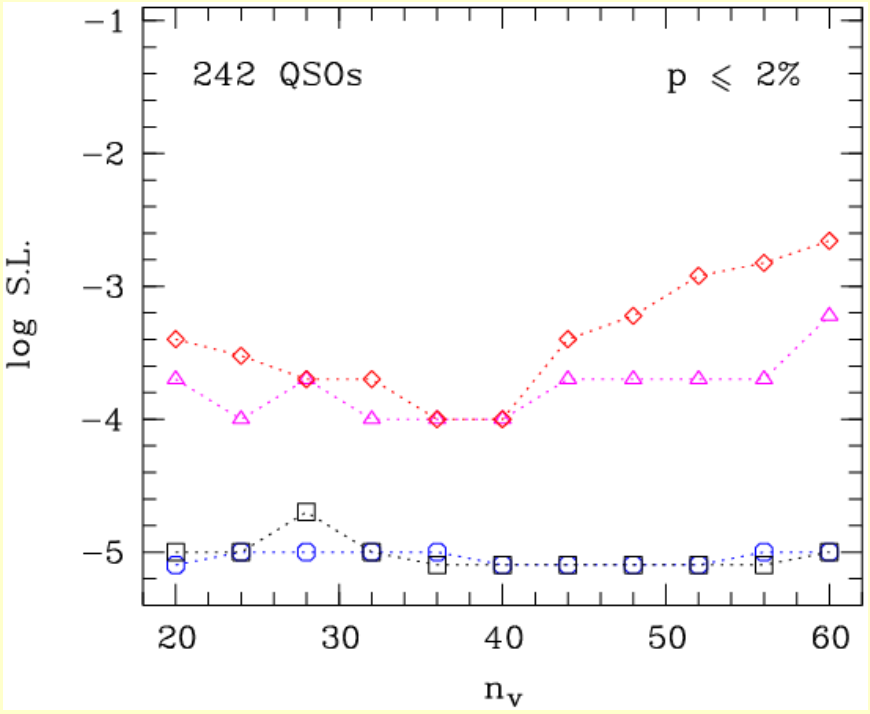
- Polarization angles depend on coordinates

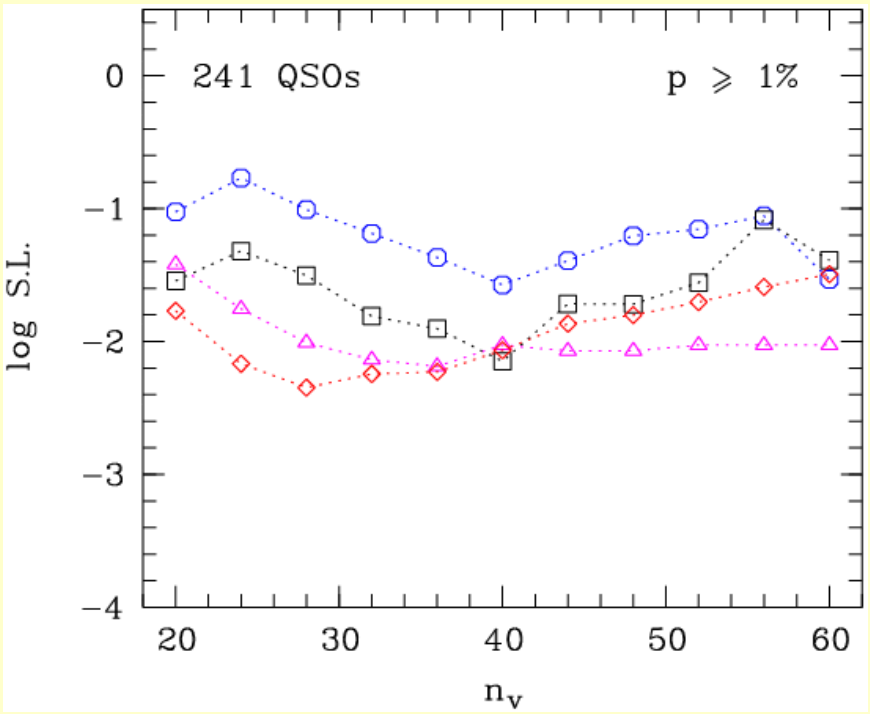


=> Statistics with parallel transport along great circles (Jain et al 2004)

Statistical analysis : results (4)

Subsamples

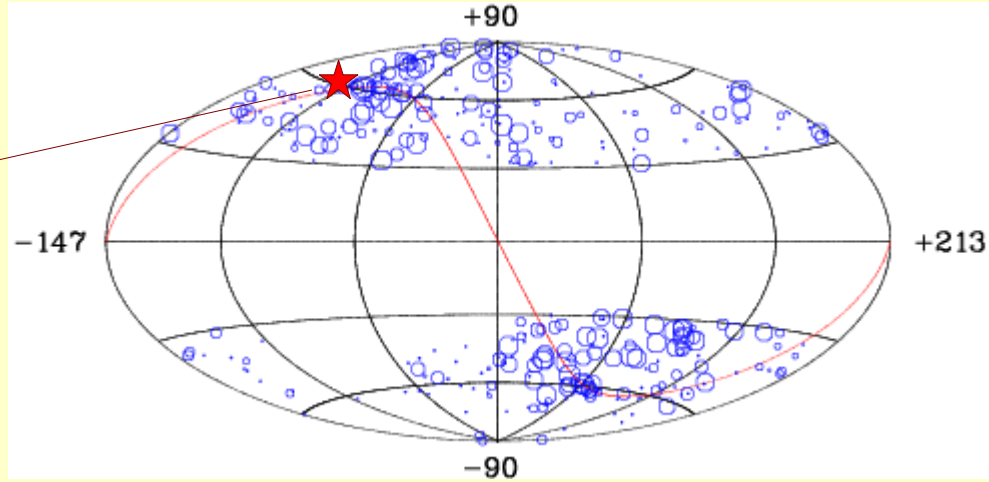




Low-p quasars preferentially aligned?
or selection effects?

Related to a preferred axis in the CMB?

Direction of the preferred axis in the CMB



Galactic coordinates

The identified axis is not far from the so-called "axis of evil"
(the axes associated with the dipole, the quadrupole and the octopole CMB moments are found to be aligned, e.g. Lang et al 2005, Ralston & Jain 2004)