Large-scale alignments of quasar polarization vectors :

Observational evidence and possible implications for cosmology and fundamental physics

Damien Hutsemékers

(University of Liège, Belgium)

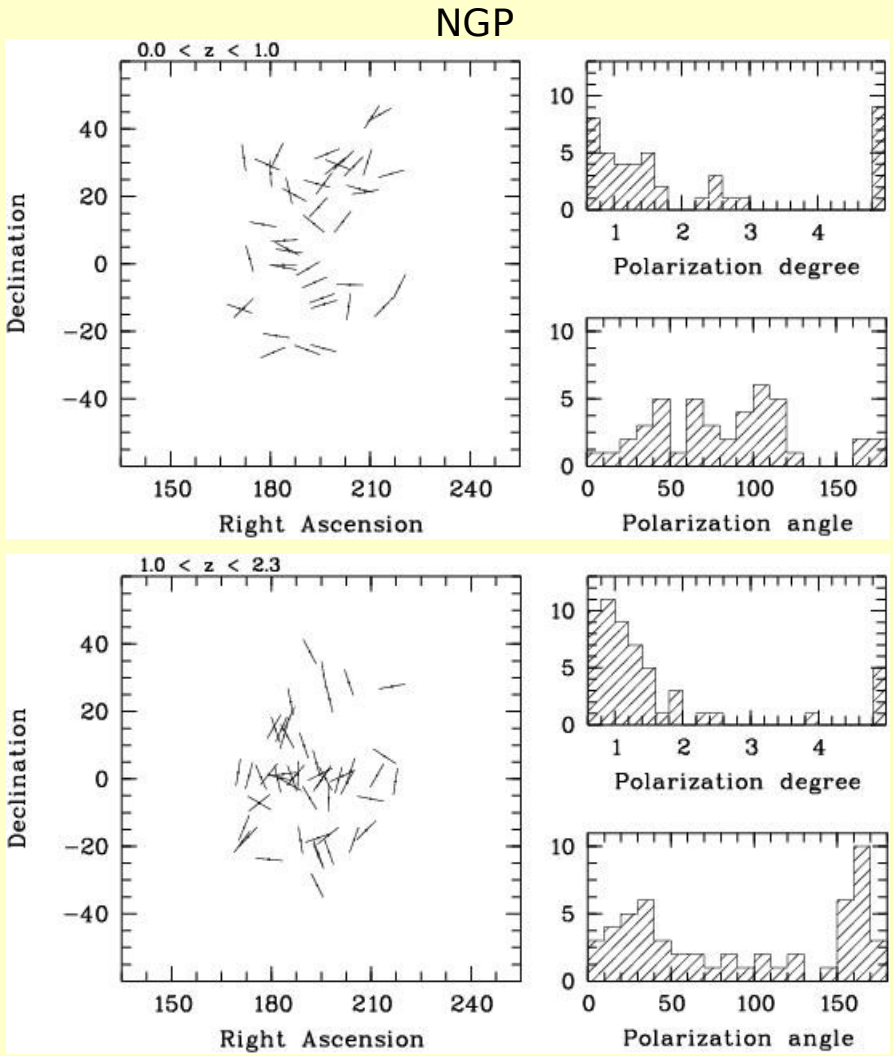
in collaboration with
R. Cabanac, H. Lamy, D. Sluse

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

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}

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

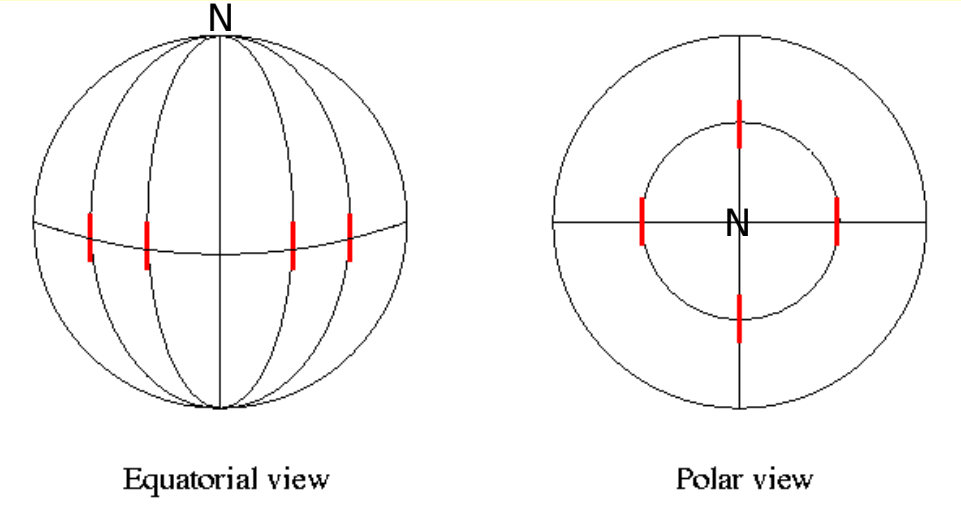
- *Z*-statistics compares QSO polarization vectors to the mean resultant vector of the n_v neighbors -> Z_{QSO}

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

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

Statistical analysis : methods

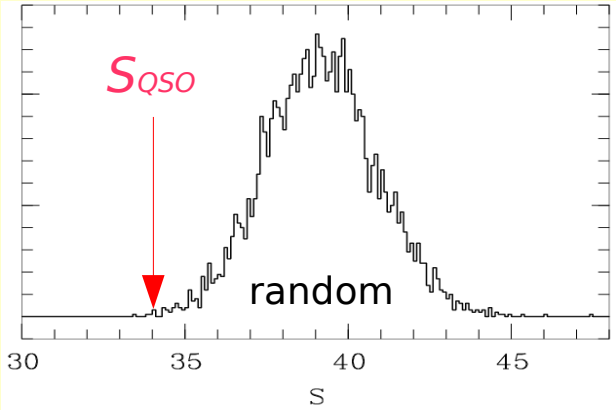
- Polarization angles depend on coordinates



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

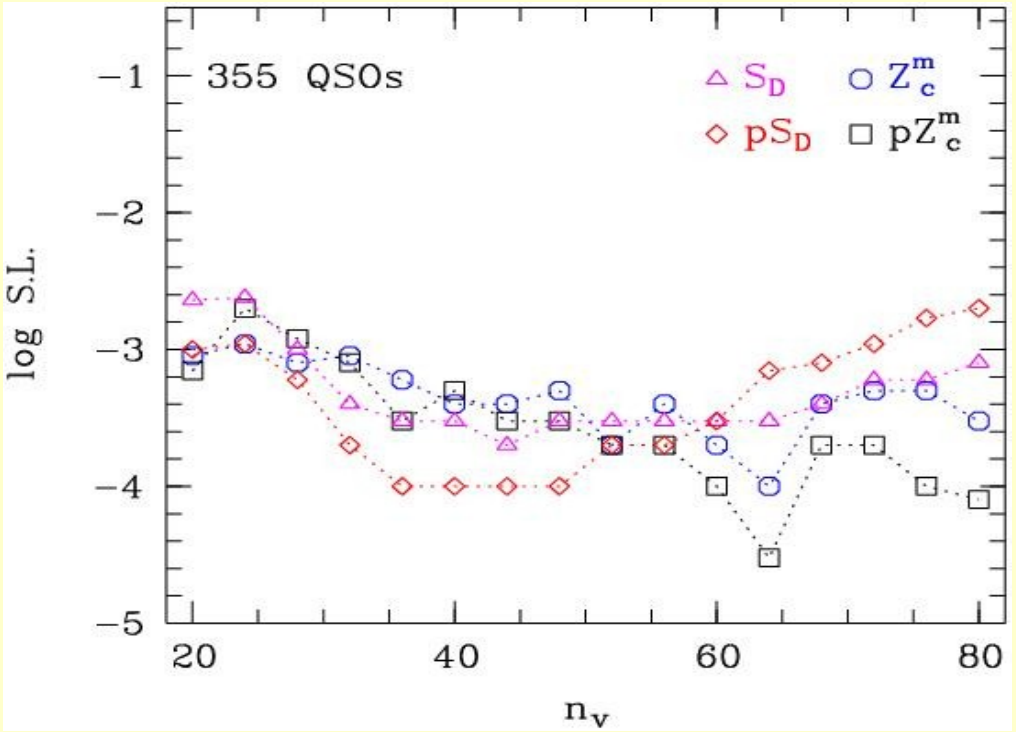
Statistical analysis : methods

- 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?

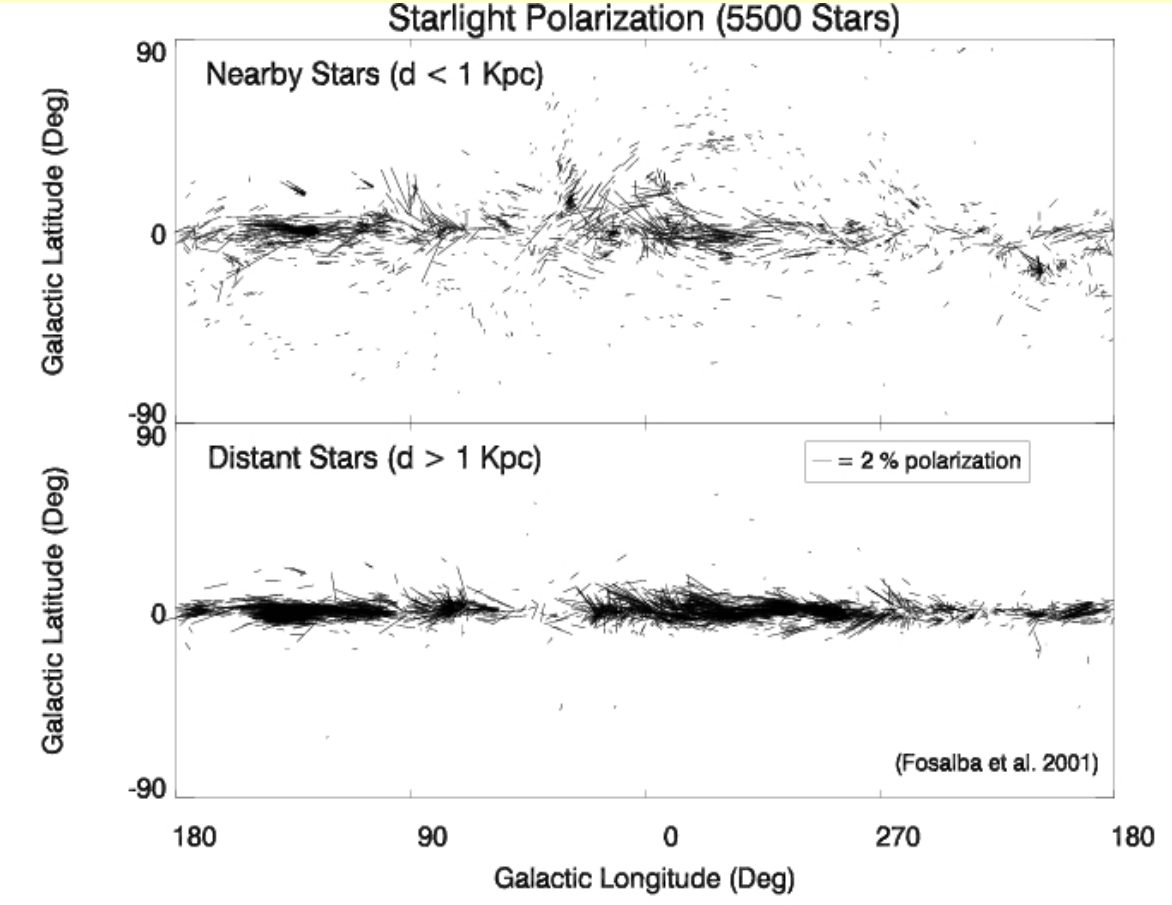
Systematic instrumental polarization?

- 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

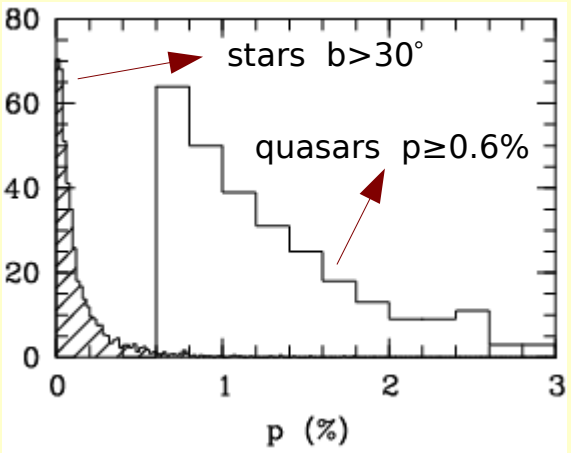
➡ *Instrumental contamination is not significant*

Interstellar polarization (ISP)

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



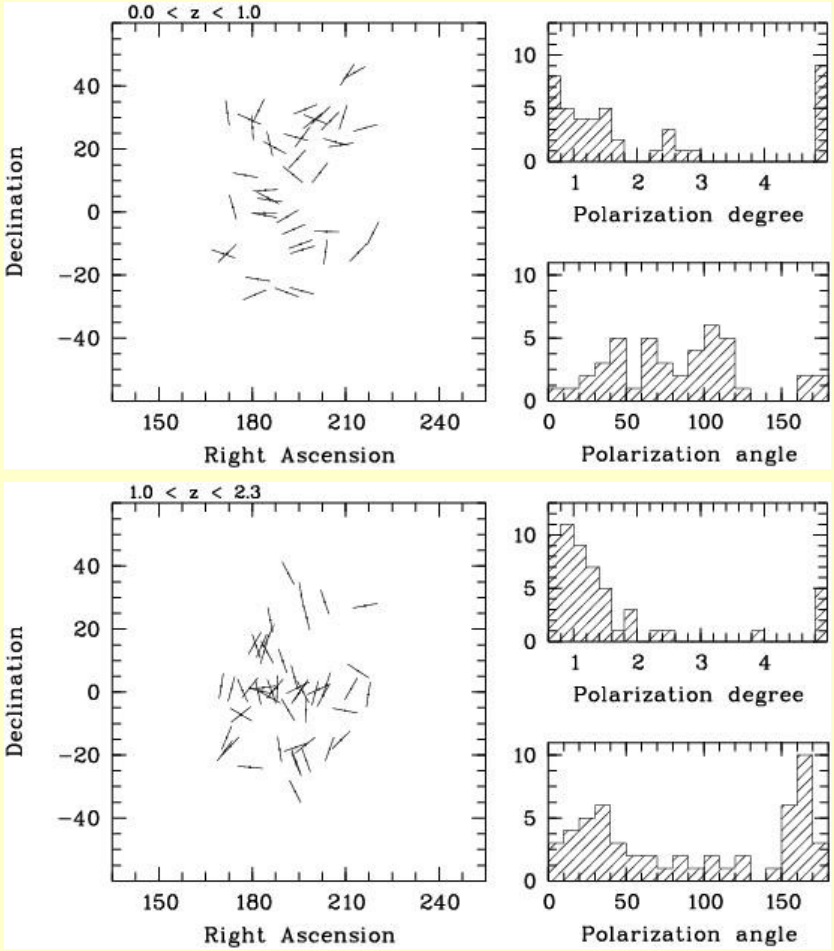
- $p_{star} \leq$ 0.2-0.3% at high galactic latitudes (b>30˚)



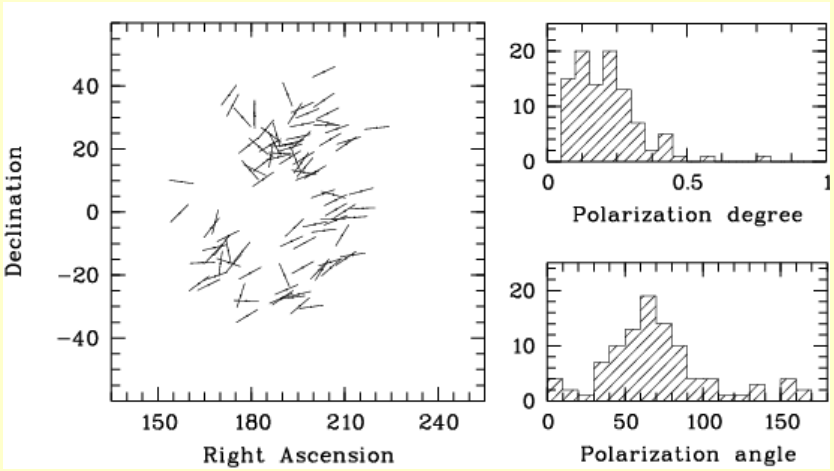
- $p_{QSO} \geq$ 0.6% is mostly intrinsic

Systematic ISP contamination?

Quasar polarization

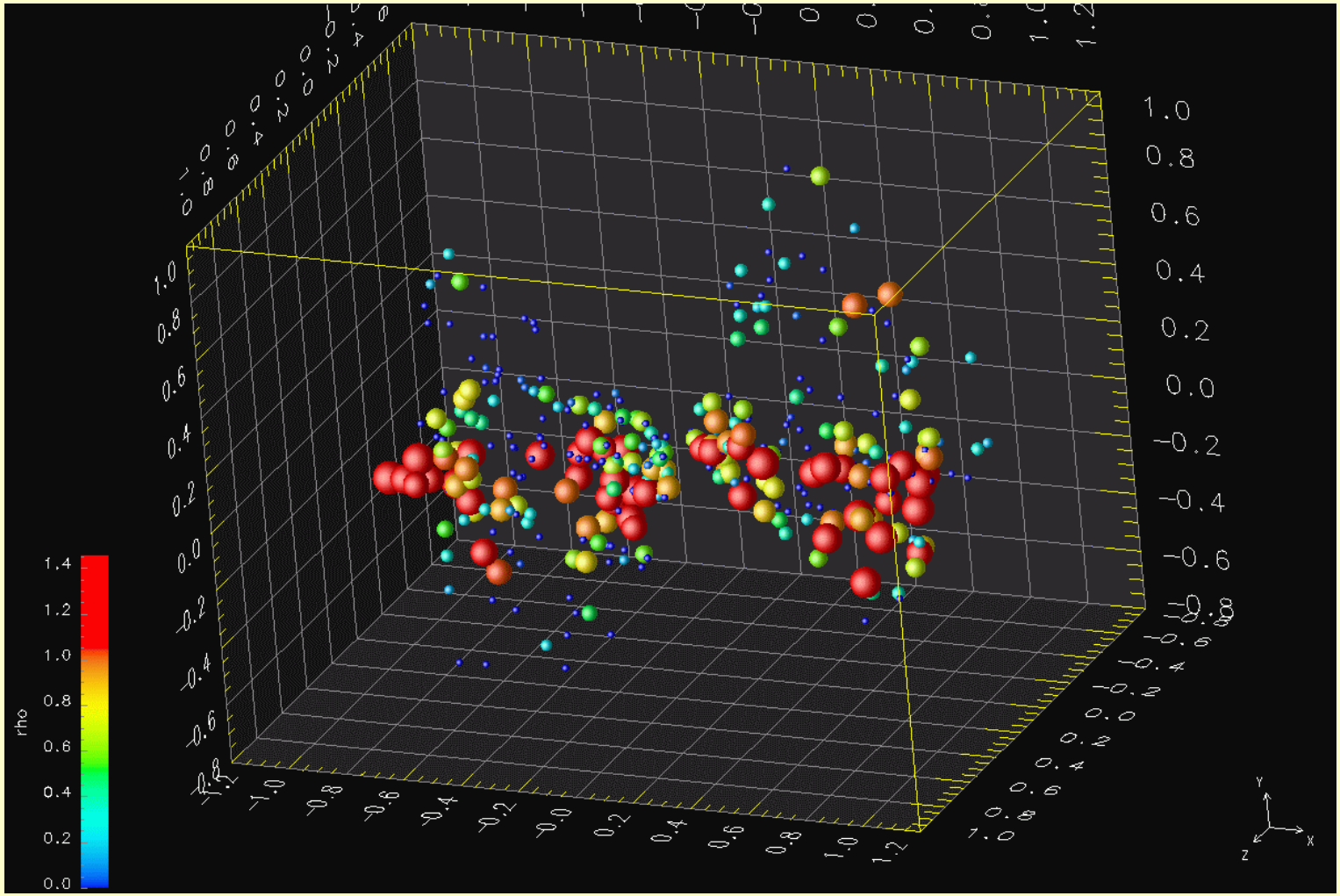


Star polarization



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

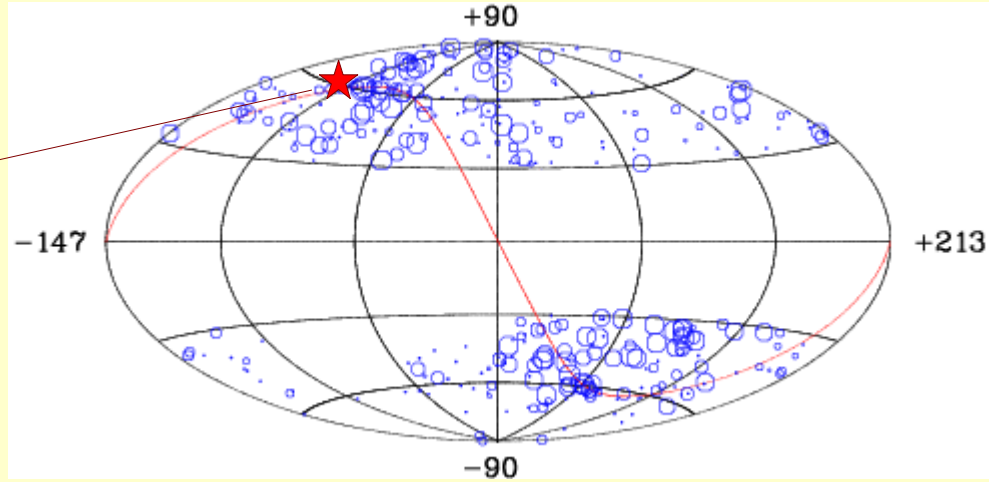
The effect is more significant along an axis NGP -SGP



Size and color ~ local statistics

Related to a preferred axis in the CMB?

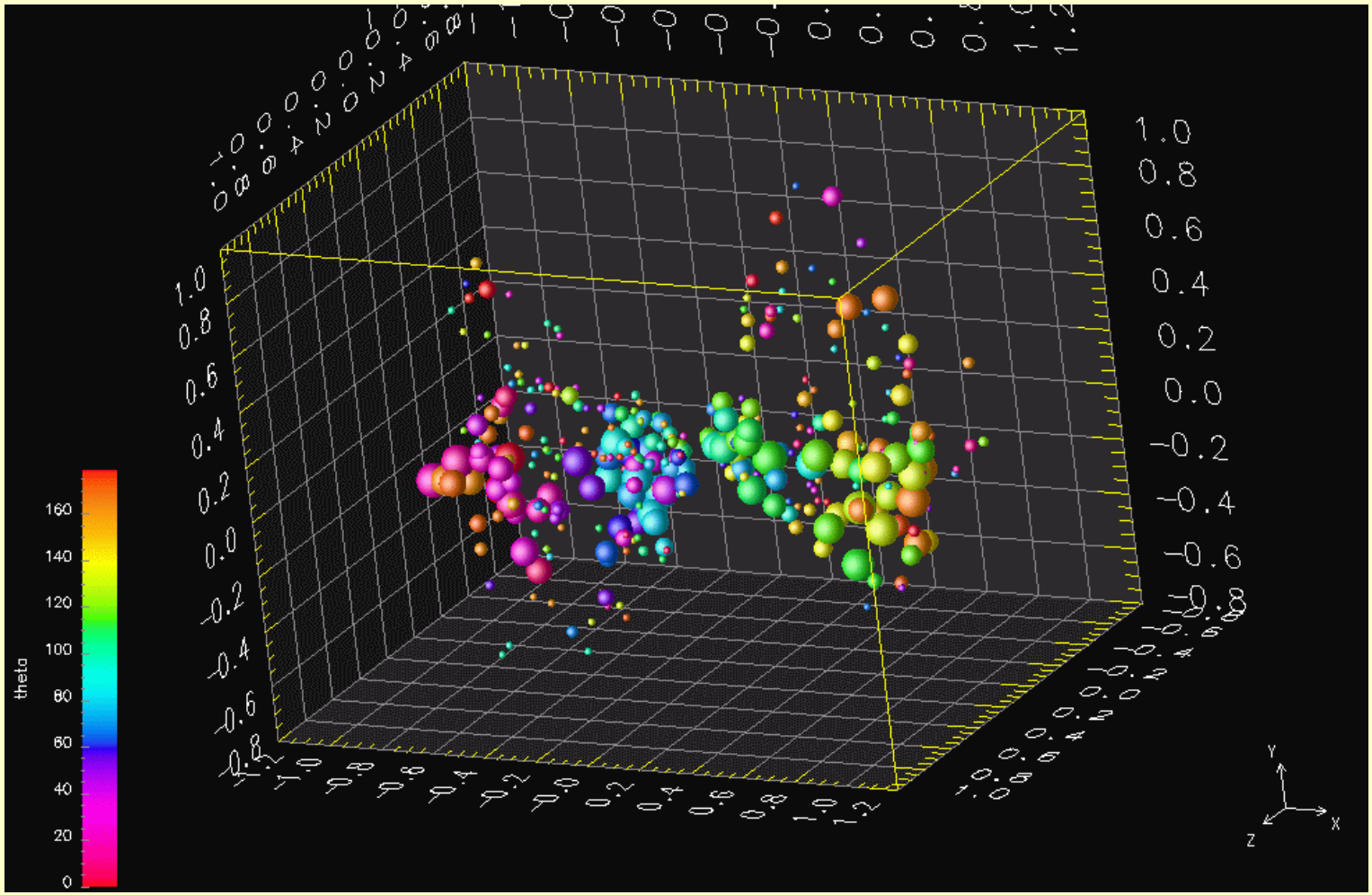
Direction of the preferred axis in the CMB



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)

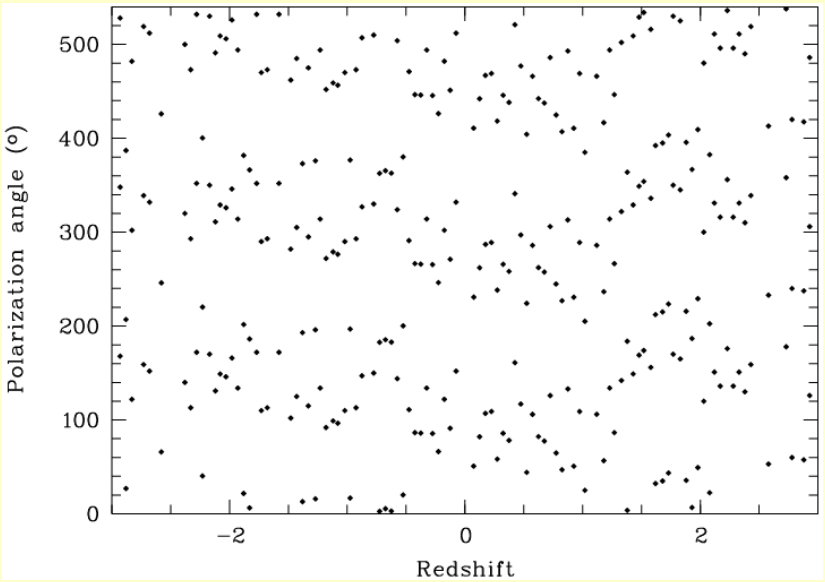
The polarization angle changes with the cosmological distance



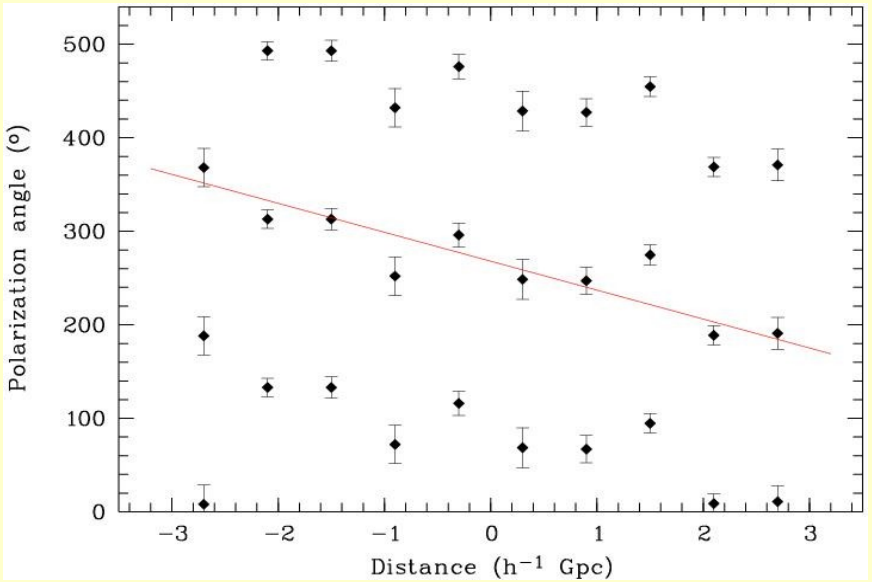
Size ~ local statistics --- Color ~ value of the polarization angle

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})

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)
- 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

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*
- *The effect seems stronger along an axis close to the CMB dipole and the "axis of evil"*
- *A large-scale origin might be due to a modification of the quasar polarization along the line of sight (photon-pseudoscalar conversion? large-scale rotation? anisotropic expansion?) and/or assuming intrinsic remnant alignments of quasar axes*
- *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

- Battaner & Lesch 2000, An. Fisica 95, 213
- Das et al. 2005, JCAP 06, 002
- Fosalba et al. 2002, ApJ 564, 762
- Gnedin et al. 2005, astro-ph/0509437
- Gnedin et al. 2007, MNRAS 374, 276
- Hutsemékers 1998, A&A 332, 410
- Hutsemékers & Lamy 2001, A&A 367, 381
- Hutsemékers et al. 2005, A&A 441, 915
- Jain et al. 2004, MNRAS 347, 394
- Lang et al. 2005, PRL 95, 071301
- Obukhov 2000, astro-ph/0008106
- Plionis 2004, IAU Coll. 195, 19
- Ralston & Jain 2004, Int.J.Mod.Phys. 13, 1857
- Rusk 1990, JRASC 84, 199
- West 1991, ApJ 379, 19
- West 1994, MNRAS 268, 79