Large-scale alignments of quasar polarization vectors

Observational evidence and possible implications for cosmology and fundamental physics

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ESO Santiago - March 5, 2014

Collaborators

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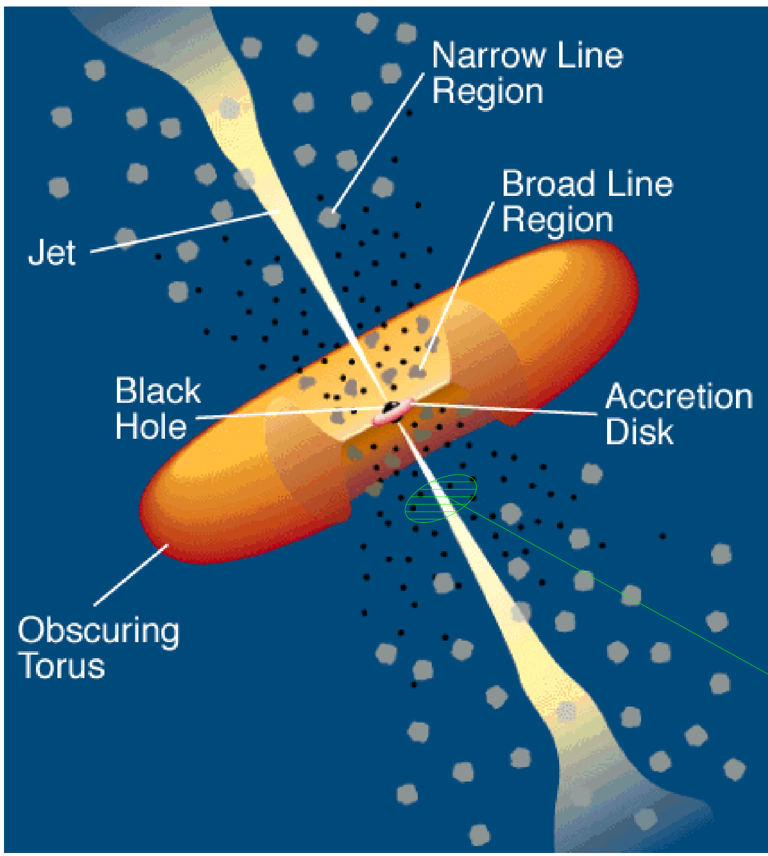
Based on

- Hutsemékers 1998, A&A 332, 410
- Hutsemékers and Lamy 2001, A&A 367, 381
- Sluse et al. 2005, A&A 433, 757
- Hutsemékers et al. 2005, A&A 441, 915
- Hutsemékers et al. 2010, A&A 520, L7
- Payez et al. 2011, PhRvD 84, 085029
- Payez et al. 2012, JCAP 07, 041

Outline

- Polarization : motivation, definition, measurement
- The nature of the polarization of quasars
- Large-scale alignments of quasar polarization vectors? Statistics, possible contaminations
- Characteristics of the alignment effect
- Evidence for photon-axion mixing?
- Evidence for an anisotropic Universe?
- Conclusions and future work

The polarization of quasars : motivation



A quasar model
(Urry & Padovani 1995)

- Quasars : very luminous objects observed at very large distances => used to probe the Universe
- Unresolved at visible wavelengths
- Linear polarization: indicator of asymmetry

Electron scattering "mirror"

The interest of polarization observations for fundamental physics

Tiny effects which affect light can accumulate over cosmological distances (1 Gpc ~ 10^{25} m) and become detectable

The structure of space-time or theories of particle physics can be tested and constrained, in particular using the polarization of light

Polarization : definitions

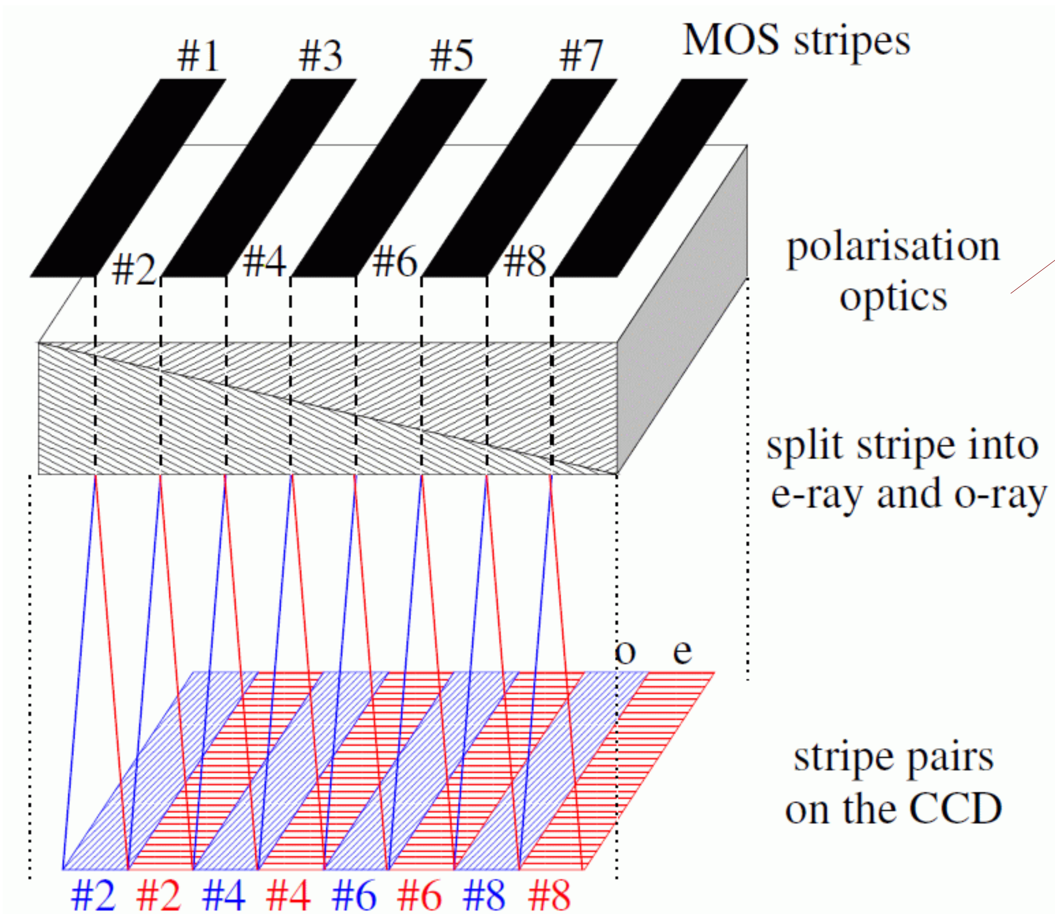
- The polarization of a plane wave $\boldsymbol{E} = \boldsymbol{E_0}\ e^{i(kz-\omega t)}$ can be described by the Stokes parameters

$$I = E_{\parallel}\tilde{E}_{\parallel} + E_{\perp}\tilde{E}_{\perp} \qquad Q = E_{\parallel}\tilde{E}_{\parallel} - E_{\perp}\tilde{E}_{\perp}$$

$$U = E_{\parallel}\tilde{E}_{\perp} + E_{\perp}\tilde{E}_{\parallel} \qquad V = i(E_{\parallel}\tilde{E}_{\perp} - E_{\perp}\tilde{E}_{\parallel})$$

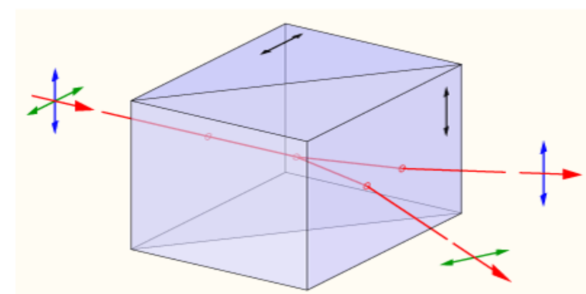
  - Normalized parameters $q = Q/I \quad u = U/I$
  - Linear polarization degree $p = \sqrt{(q^2+u^2)}$
  - Polarization angle $\theta = \frac{1}{2}\arctan(u/q)$
  - Circular polarization degree $p_c = |V|/I$

Polarization measurements

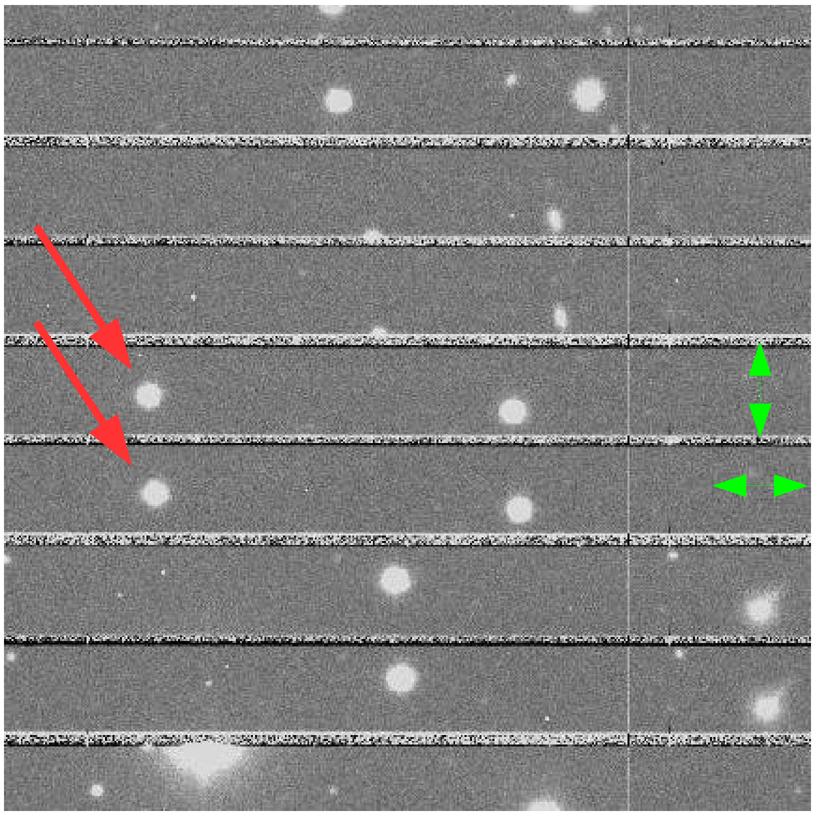


Beam splitter :

Half-wave plate
+
Wollaston prism



Polarization measurements



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

- Measurements of the optical normalized Stokes *q* and *u* : half-wave plate at 0˚, 22.5˚, 45˚ and 67.5˚; V filter used (~ 550nm)
- Redundancy => a difference of transmission for the *e* and *o* rays is corrected
- Linear optical polarization measured with 0.15% uncertainty
- Independent of atmospheric variations

Polarization measurements

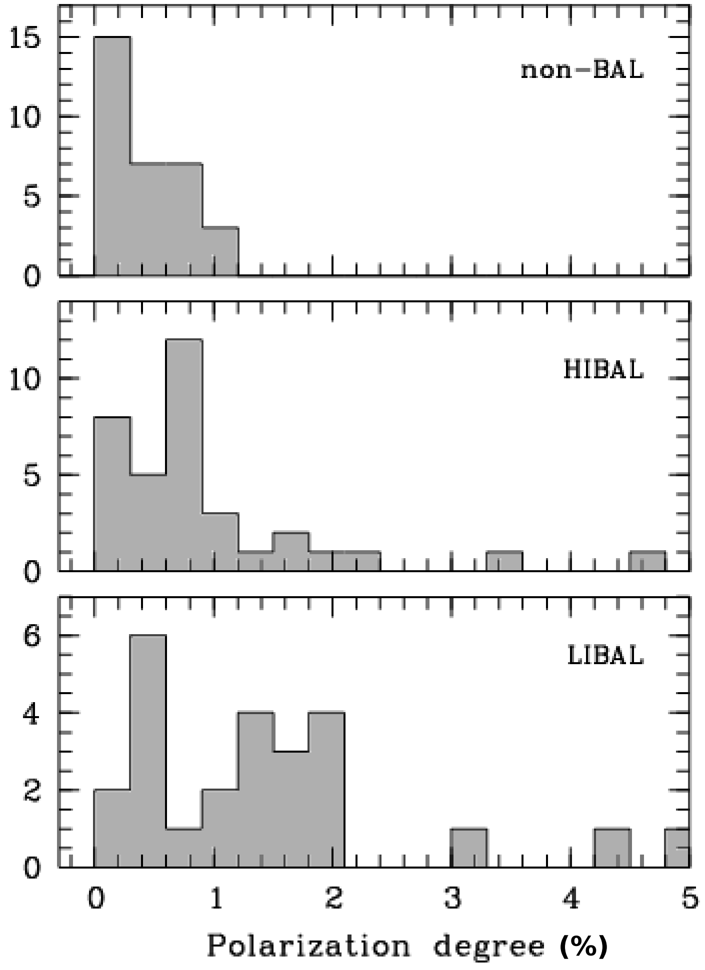
- Measurements of polarized standard stars : fix the reference polarization angle and give the accuracy of the procedure (~ 1°)
- Measurements of unpolarized standard stars : the instrumental polarization is small < 0.1%
- Measurements of stars and galaxies in the same field => small but systematic residual polarization <q> ~ <u> ~ 0.1% the average can be used to correct the quasar polarization
- Polarization degrees are biased at low p/σ_p => correction needed

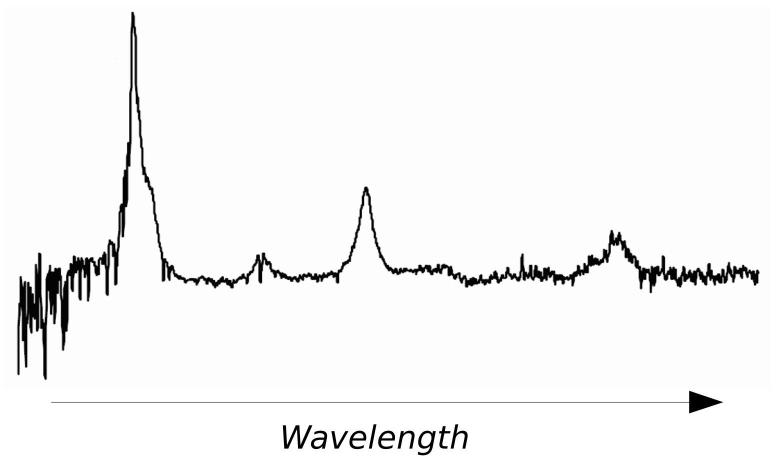
The nature of quasar polarization

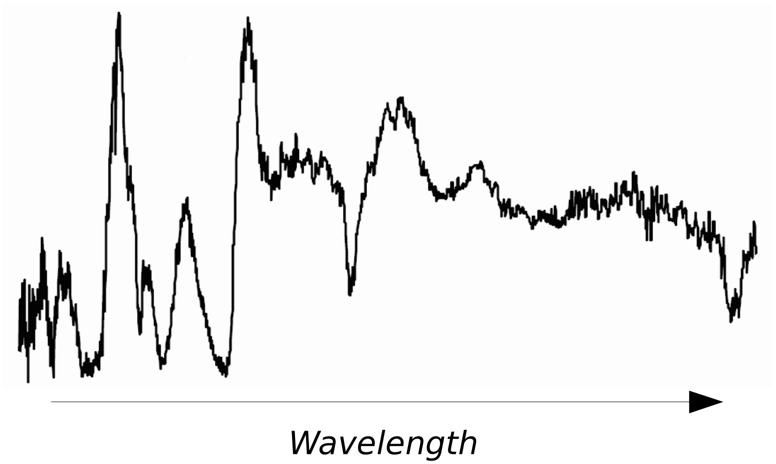
- Most often $p \sim 1 – 2\%$ (a few have $p > 3\%$)
- Most often θ is only slowly changing with wavelength
- Most often due to electron scattering
- Net non-zero polarization indicates departure to spherical symmetry
- The polarization degree depends on the quasar type, in particular the presence of broad absorption lines in the quasar spectrum

=> *polarization is mainly intrinsic to the quasars*

Polarization versus spectrum

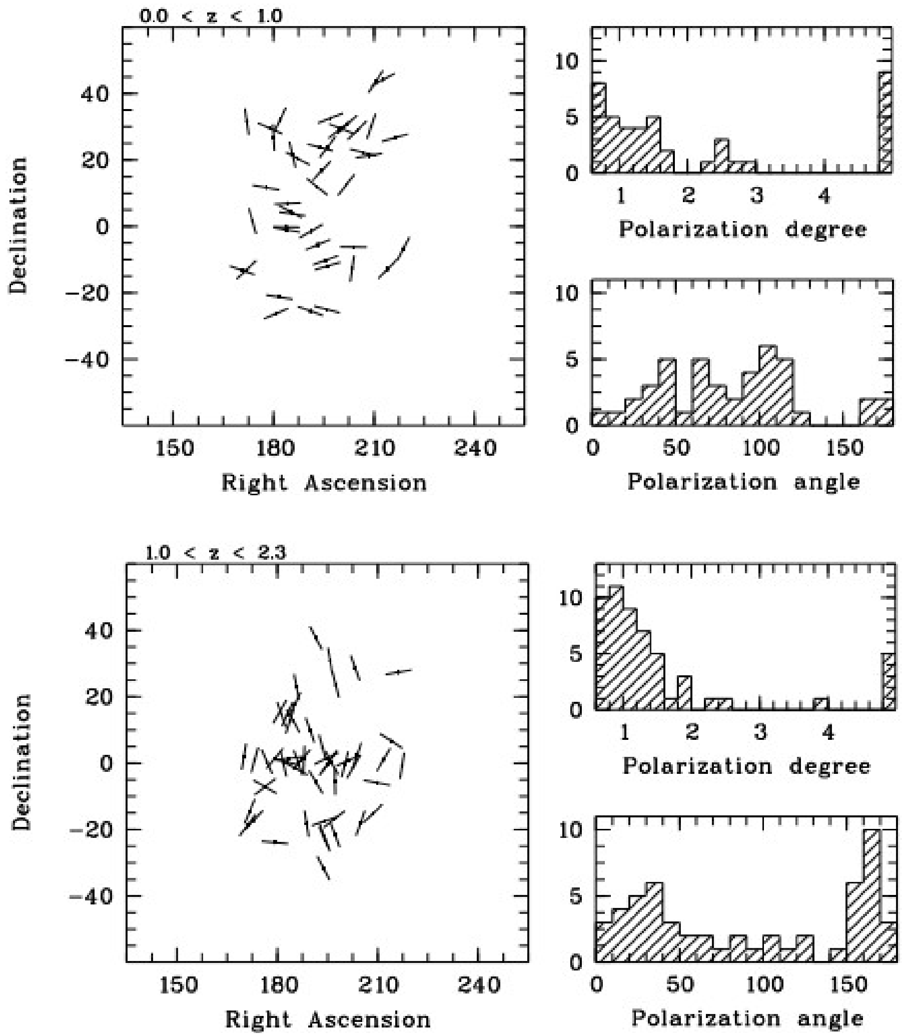






Large-scale alignments of quasar polarization vectors?

NGP



Scale ~ 1 Gpc at z ~ 1

low redshifts

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

(circular statistics!)

high redshifts

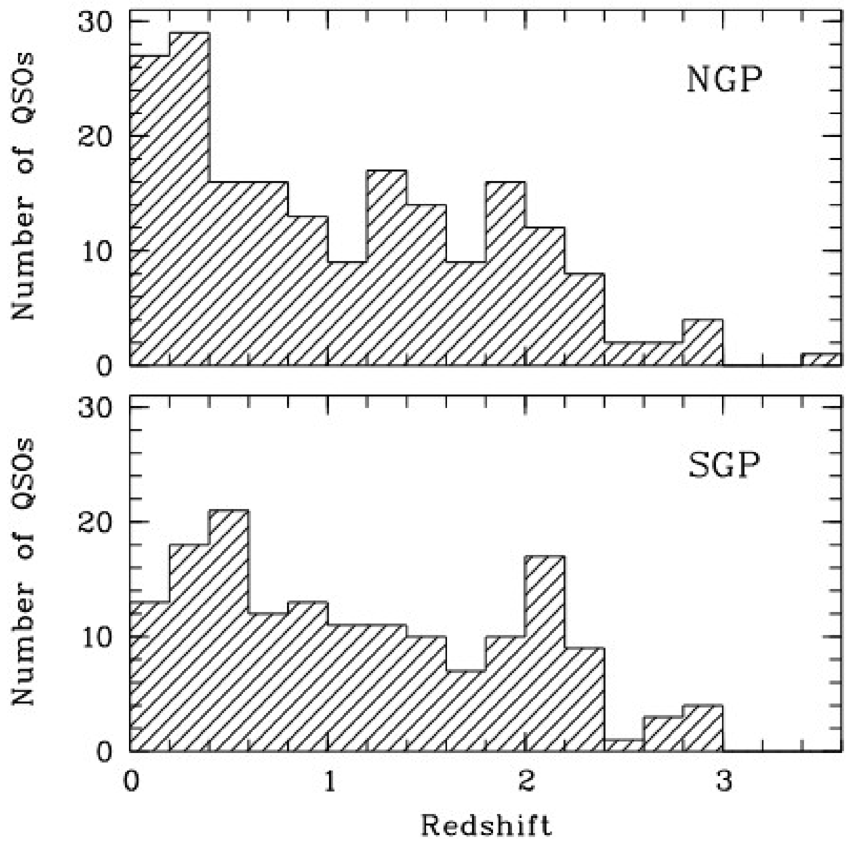
$\bar{\theta}=8^o$ *with* $P=2\ 10^{-3}$

Statistical analysis : the sample

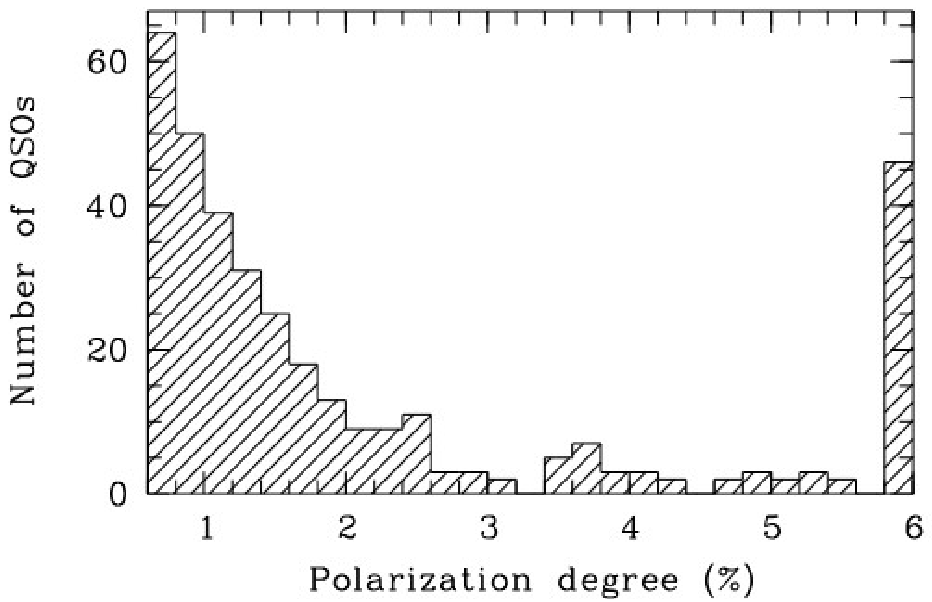
- A sample of 355 polarized quasars up to $z \sim 2.5$ (previous studies with 170 and 213 quasars)
- New observations and compilations from the literature (=> inhomogeneous sample)
  - Bright, BAL, red, radio-loud quasars preferred
  - Blazars essentially excluded (unsecured *z*)
- Galactic latitude > 30°
- Polarization degree ≥ 0.6%
- Uncertainty of polarization angle ≤ 14° (or $p/\sigma_p \geq 2$)

Statistical analysis : the sample

Distribution of redshifts and polarization degrees

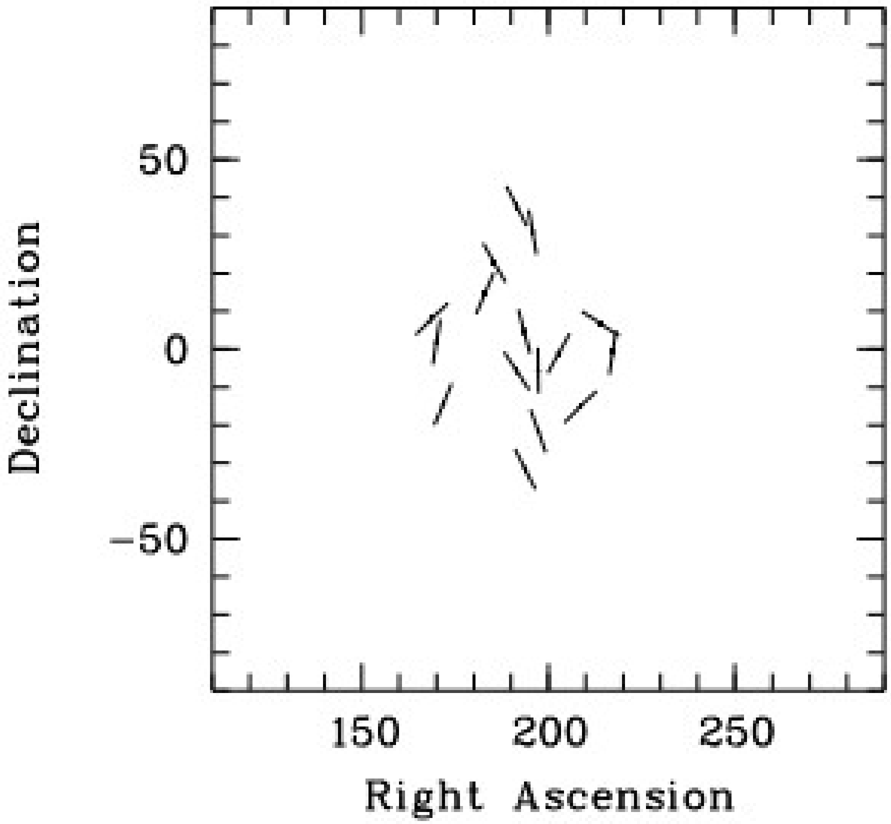


355 QSOs



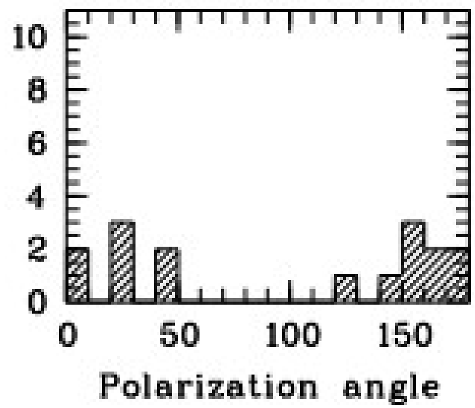
Evolution with sample size

$1.0 < z < 2.3$



170 quasars

(1998)



Evolution with sample size

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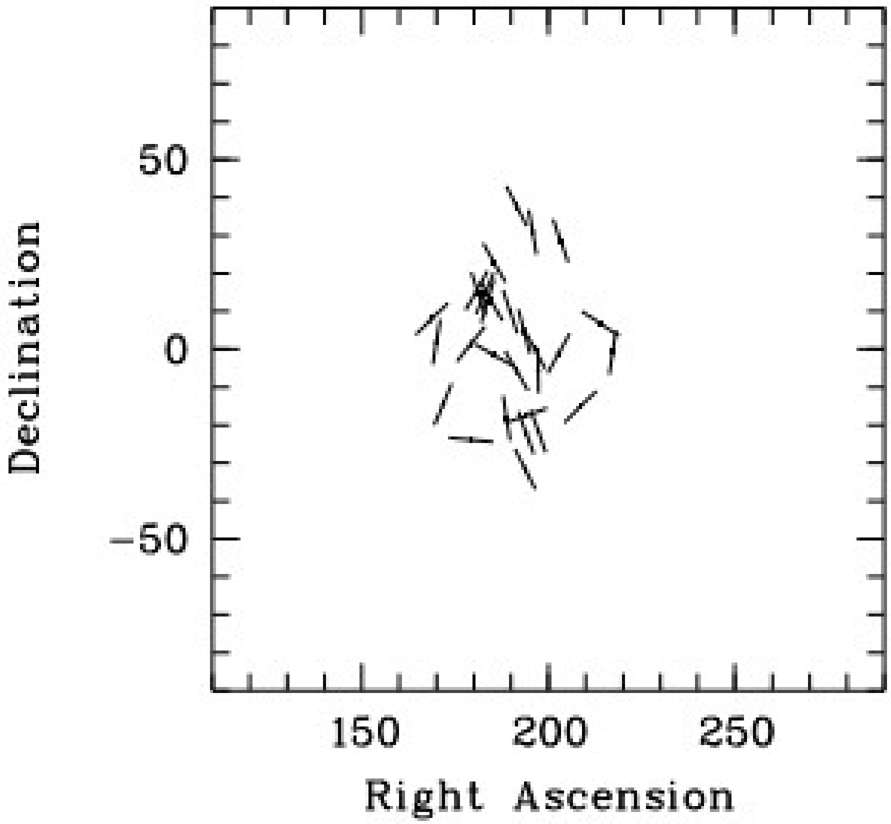
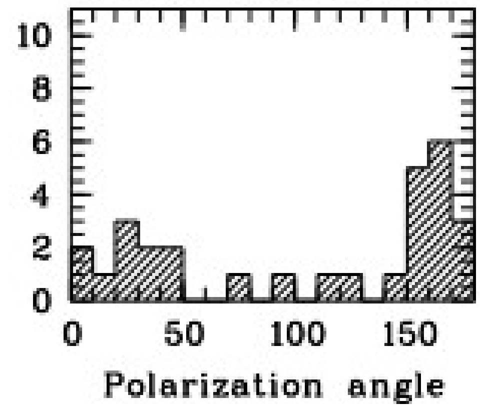
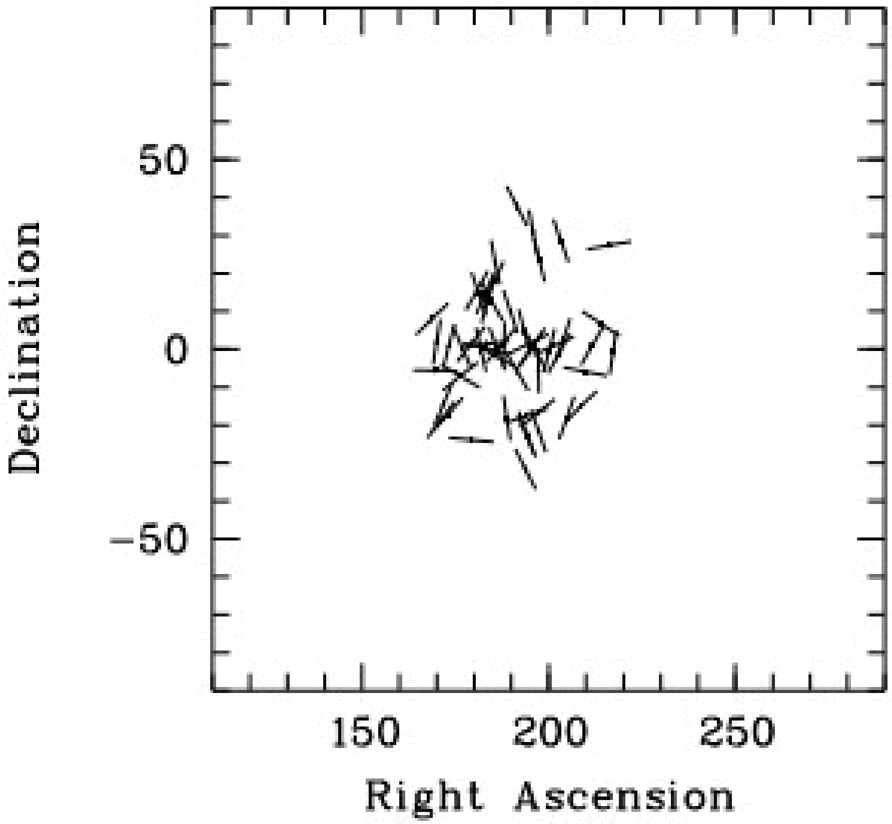


213 quasars
(2001)



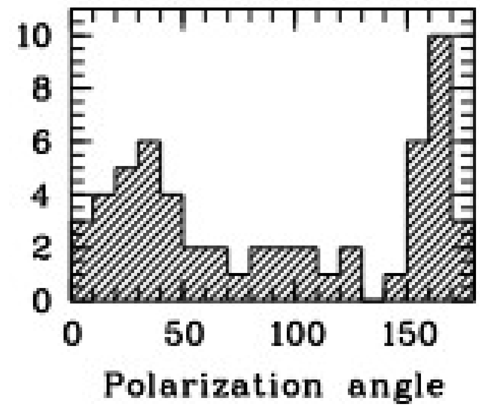
Evolution with sample size

1.0 < z < 2.3



355 quasars

(2005)



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}

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

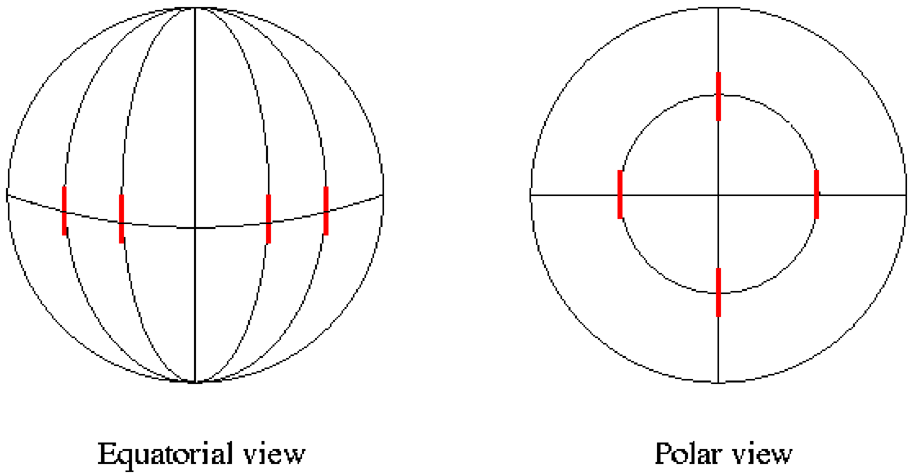
- *Z*-statistics compares QSO polarization vectors to the mean resultant vector of the n_v neighbors => Z_{QSO}

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

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

Statistical analysis : methods

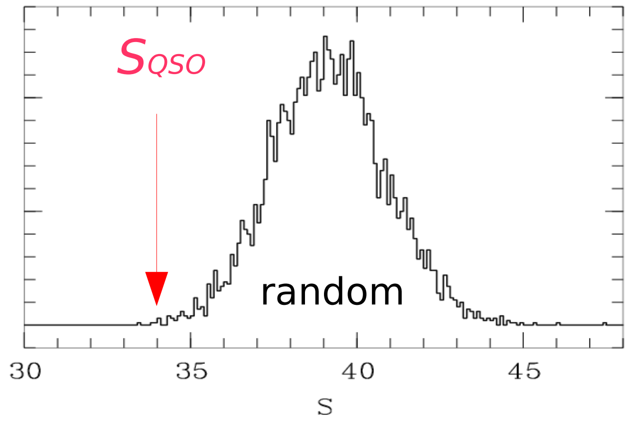
- Polarization angles depend on coordinate systems



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

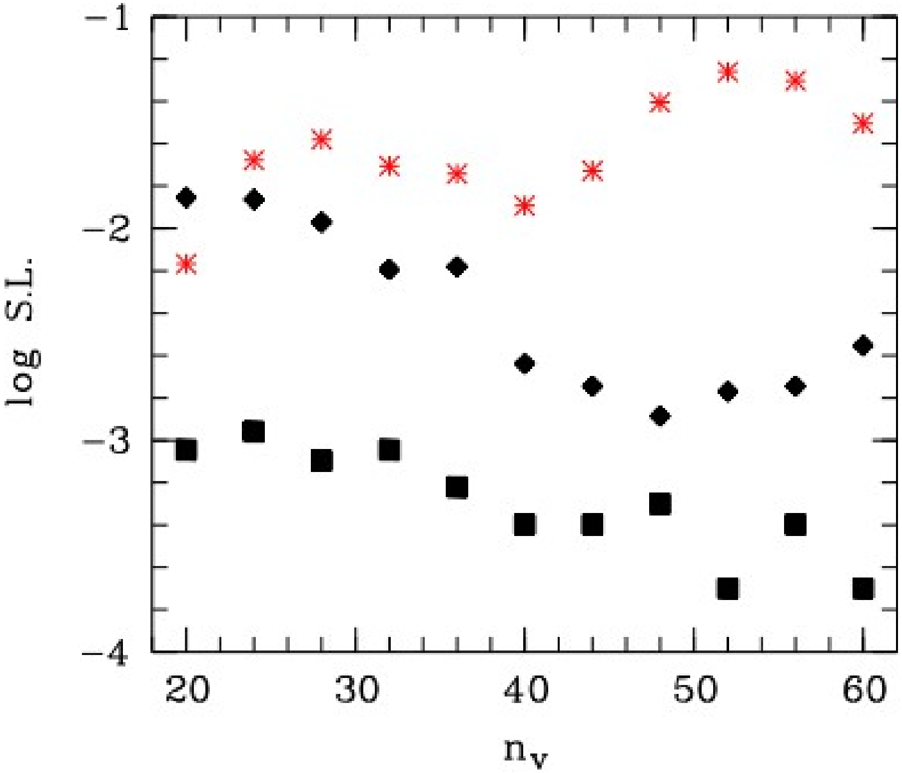
Statistical analysis : methods

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



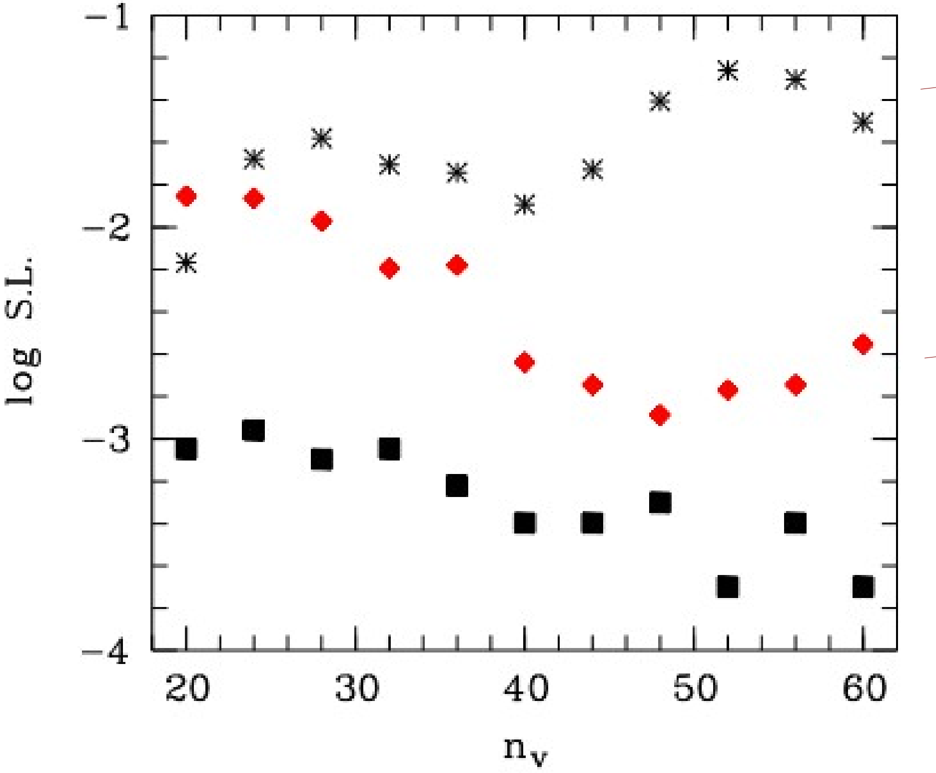
Significance level : percentage of simulated configurations with $S < S_{QSO}$

Statistical analysis : results



170 quasars
(1998)

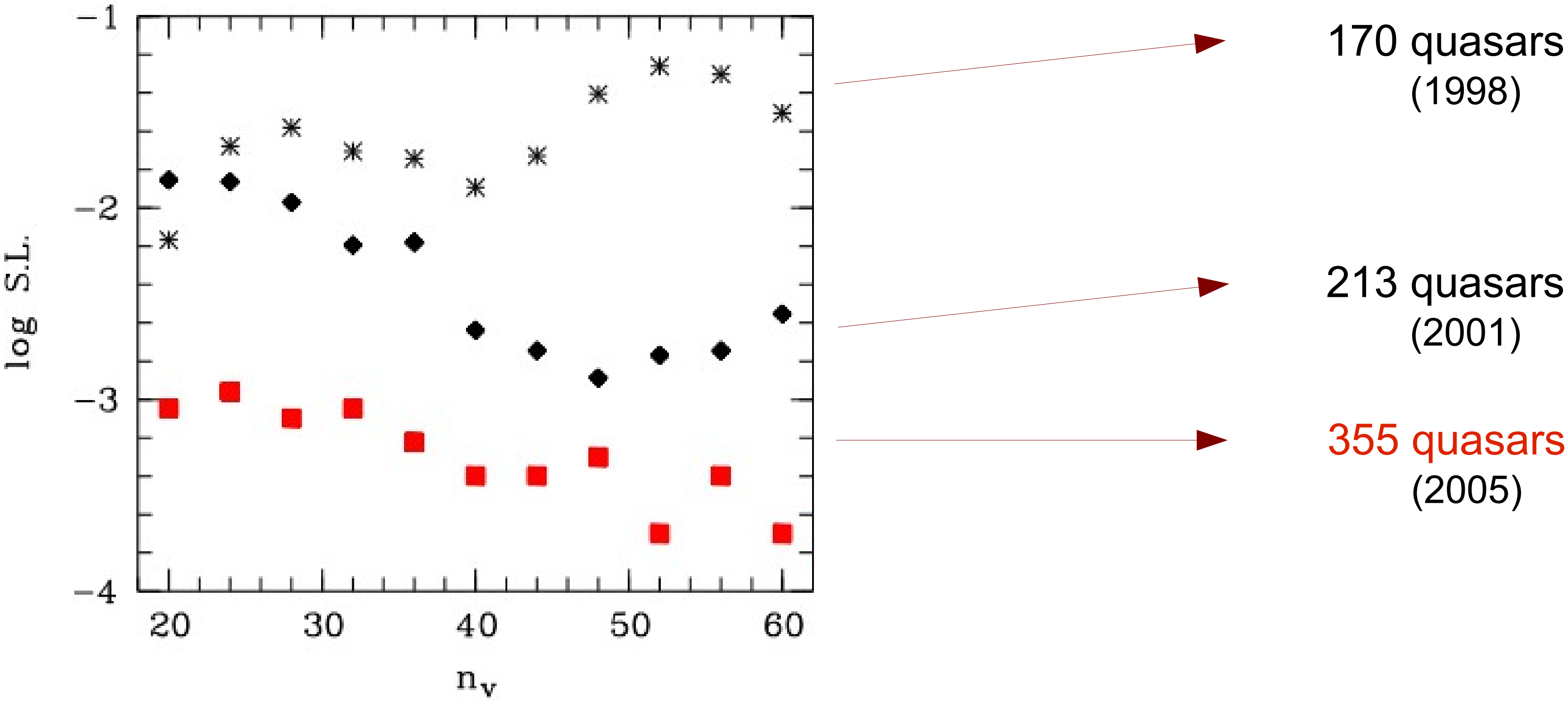
Statistical analysis : results



170 quasars
(1998)

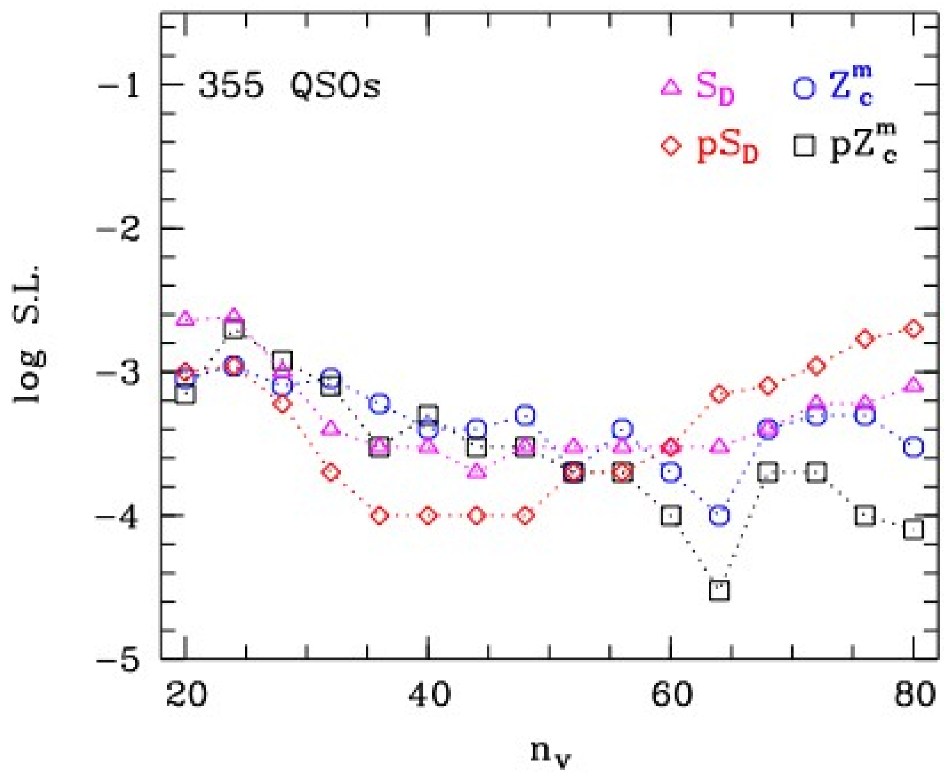
213 quasars
(2001)

Statistical analysis : results



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

Statistical analysis : results

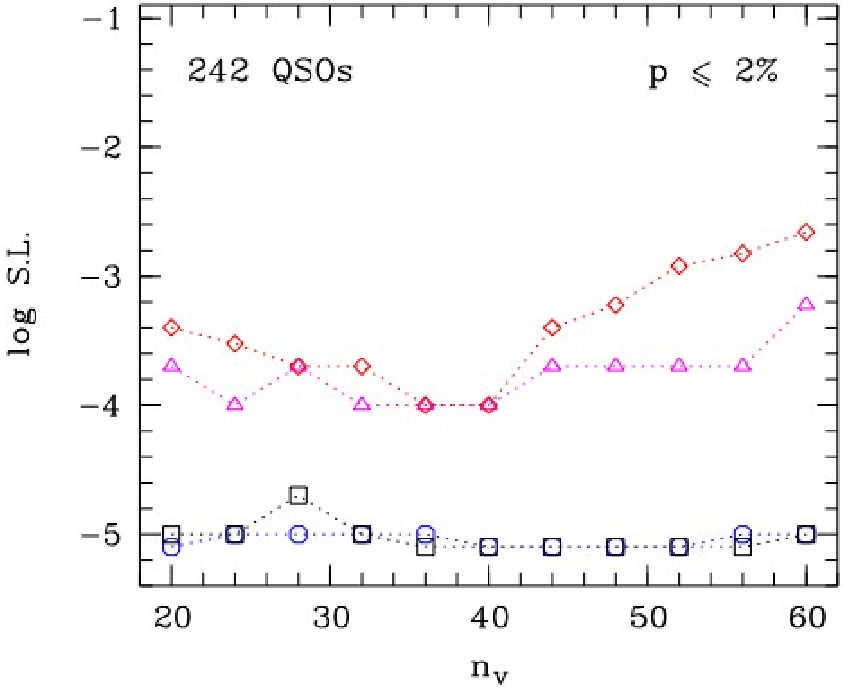


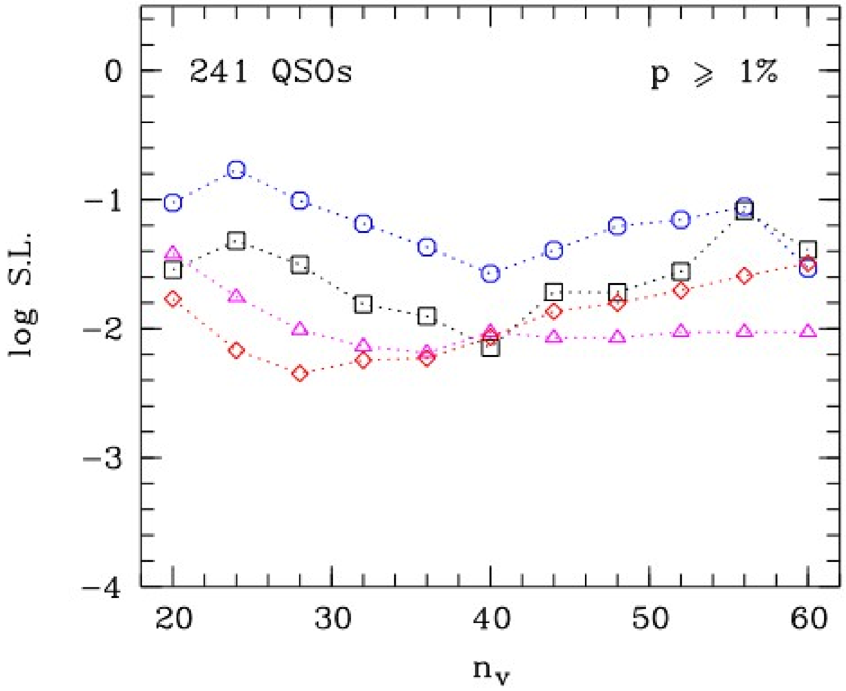
- Two different tests (*S* and *Z*)
- With and without parallel transport

Quasar polarization vectors are not randomly oriented over the sky (S.L. < 10^{-3})

Statistical analysis : results

Subsamples





➡ *Low-p quasars preferentially aligned*

Instrumental polarization?

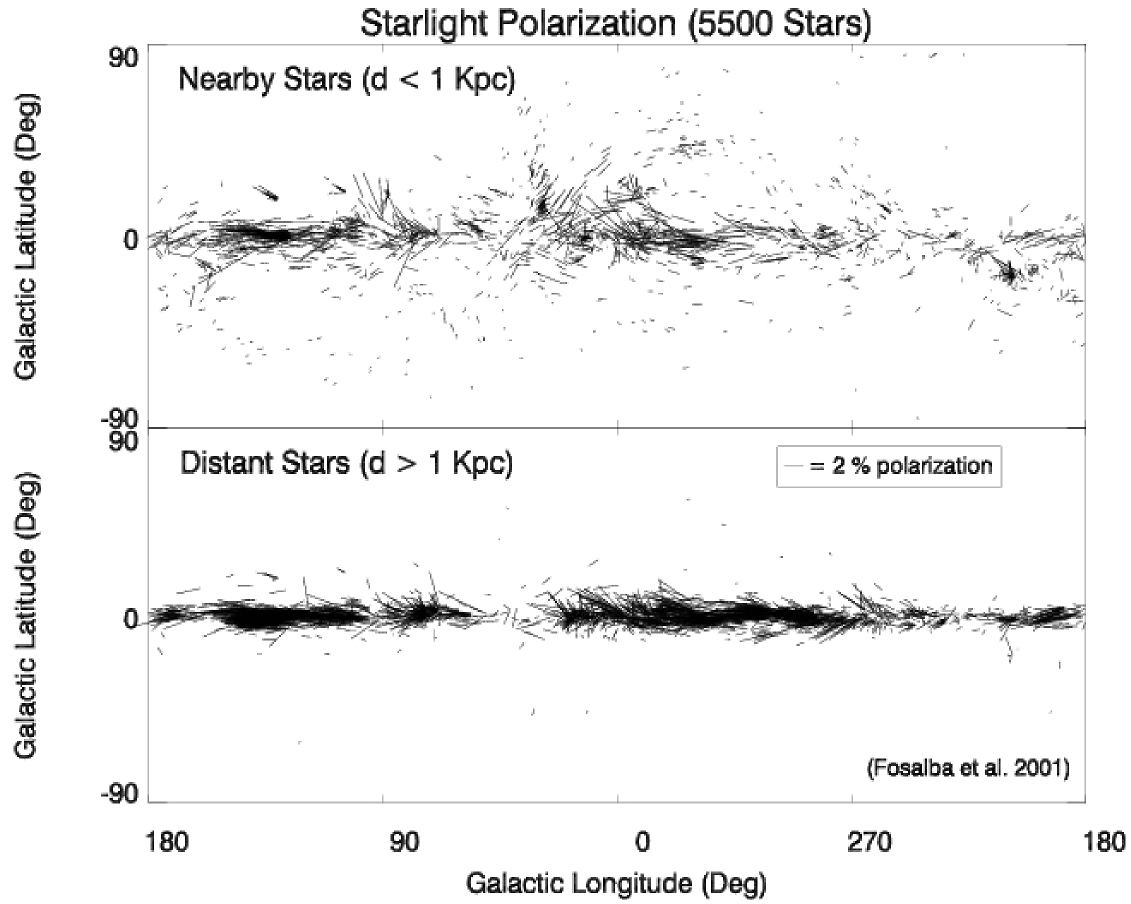
Systematic instrumental polarization?

- 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

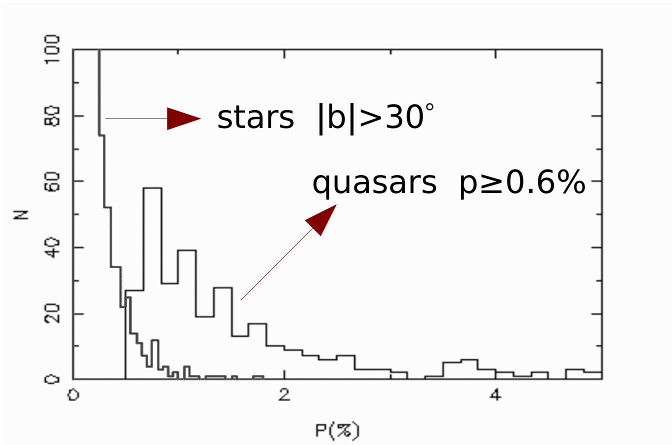
⇒ *Instrumental contamination is not significant*

Interstellar polarization

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˚)

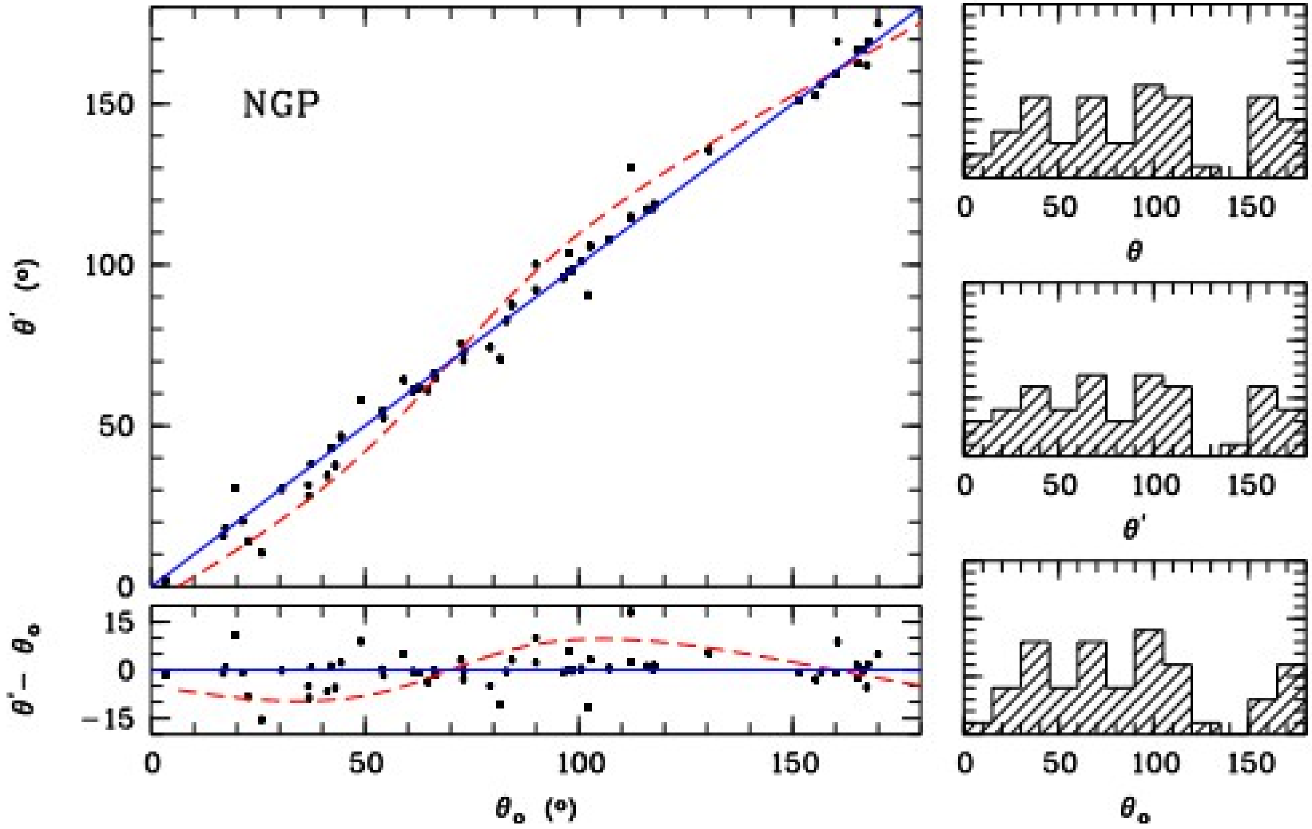


– $p_{QSO} \geq$ 0.6% is mostly intrinsic

Contamination by interstellar polarization is minimized

- 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 $p_{QSO} \geq 0.6\%$
- Our data are partially corrected using field stars
- No correlation is observed between polarization angles of quasars and angular neighboring stars

The effect of a systematic polarization



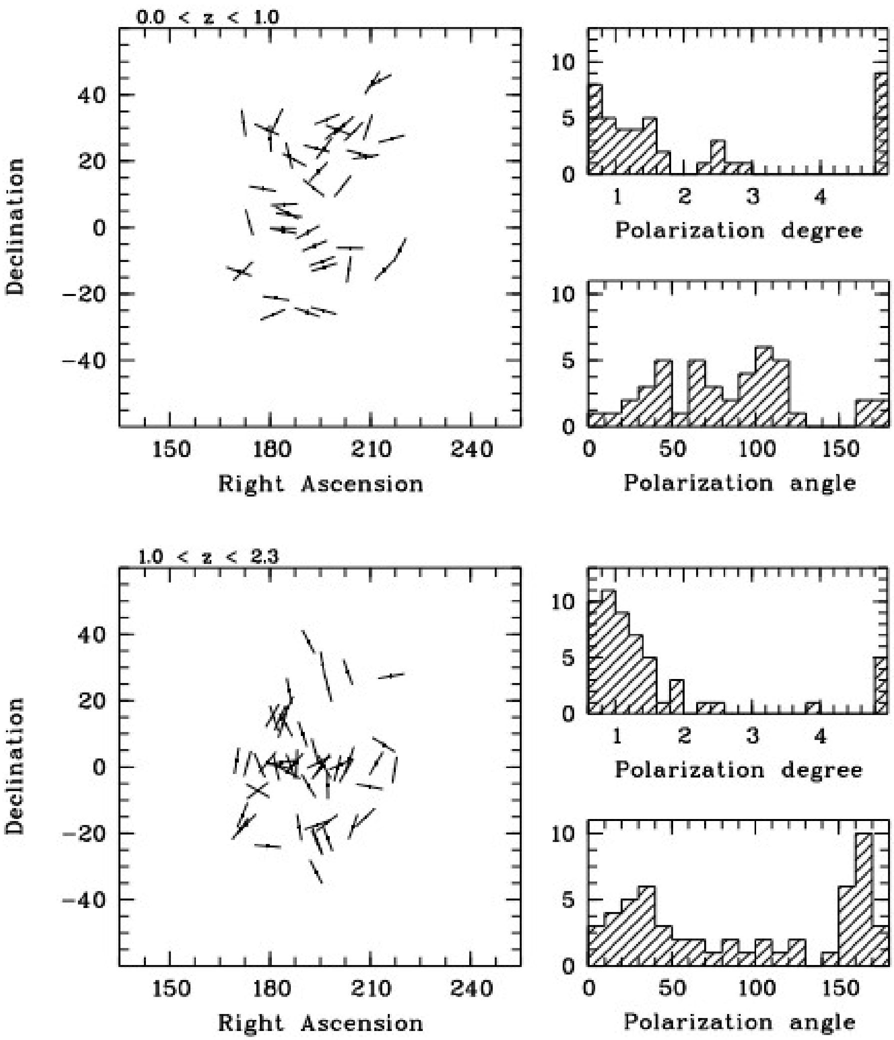
Quasars with
$p \geq 0.6\%$ only

Correction frame by frame using the field star polarization:

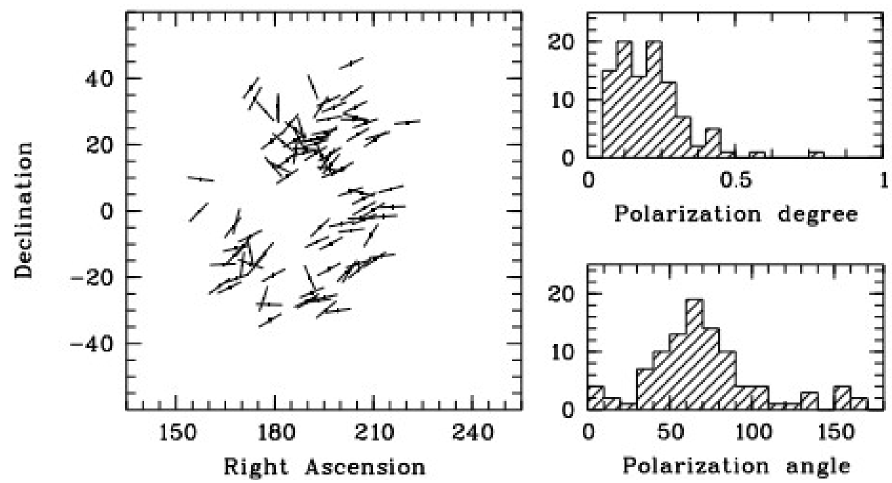
the interstellar polarization does not significantly contaminate the quasar polarization angles

Systematic contaminations?

Quasar polarization



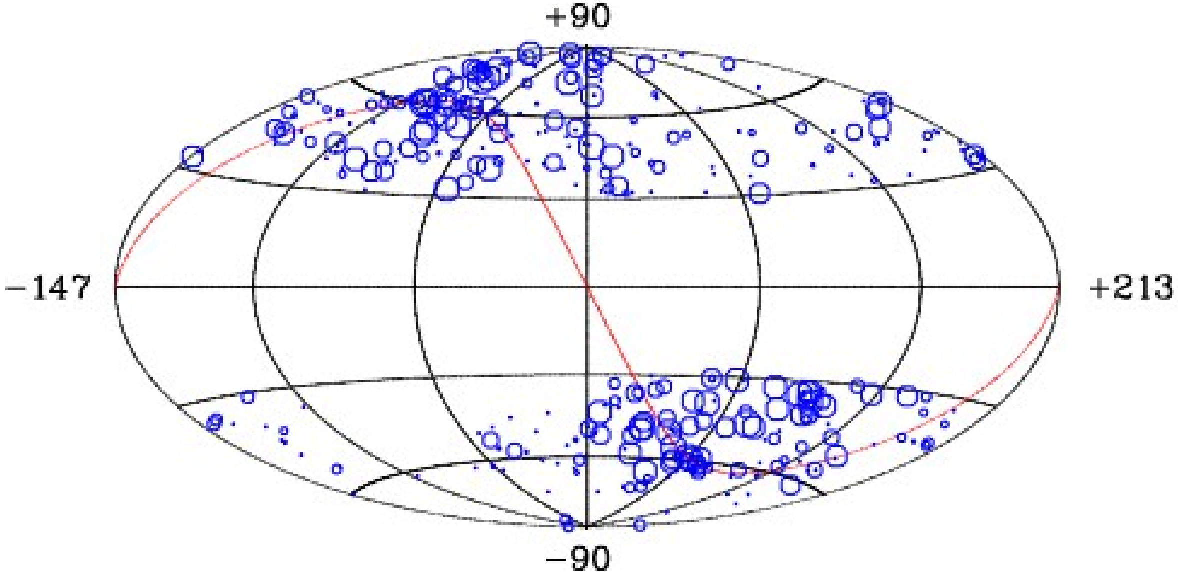
Star polarization



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



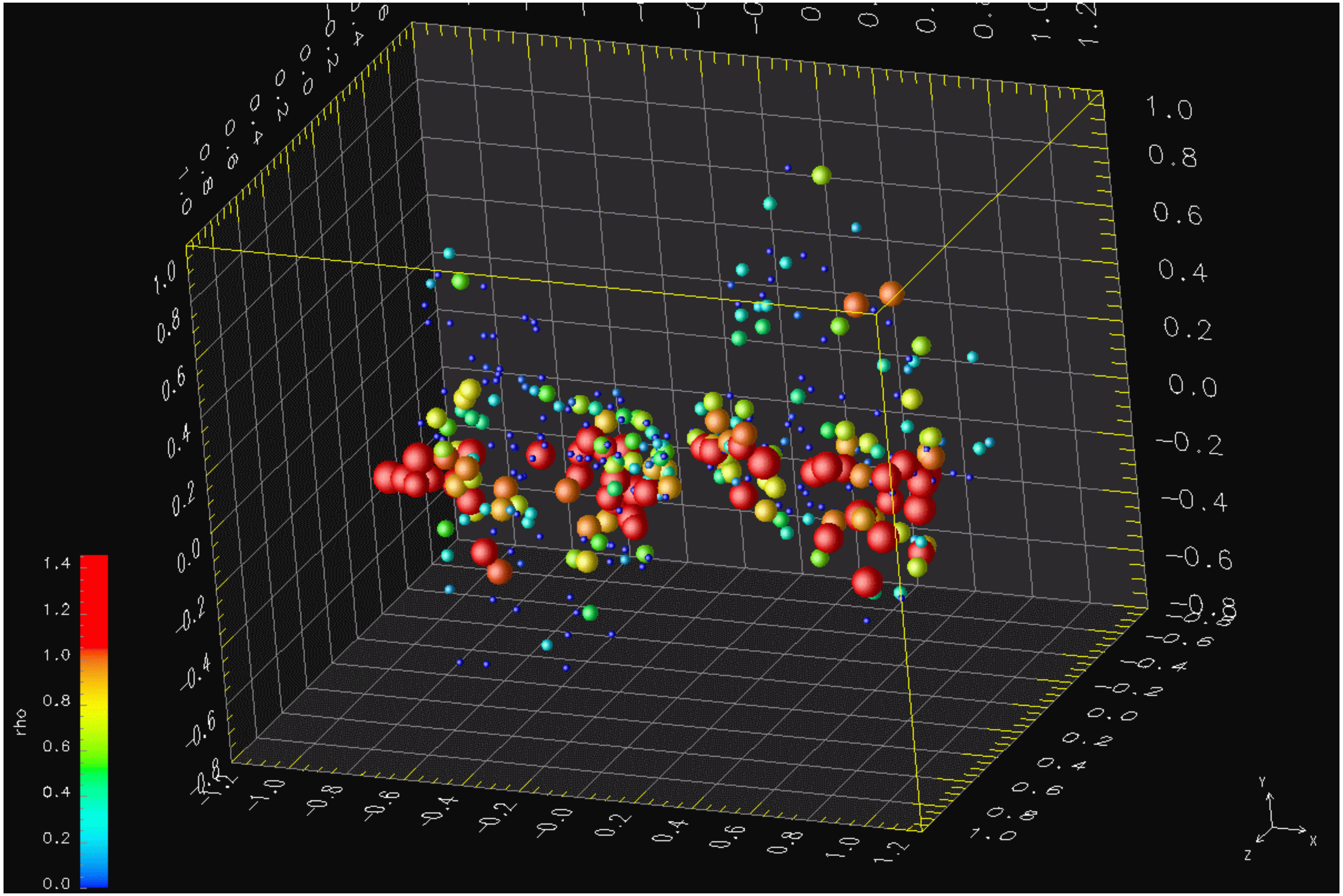
Galactic coordinates

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

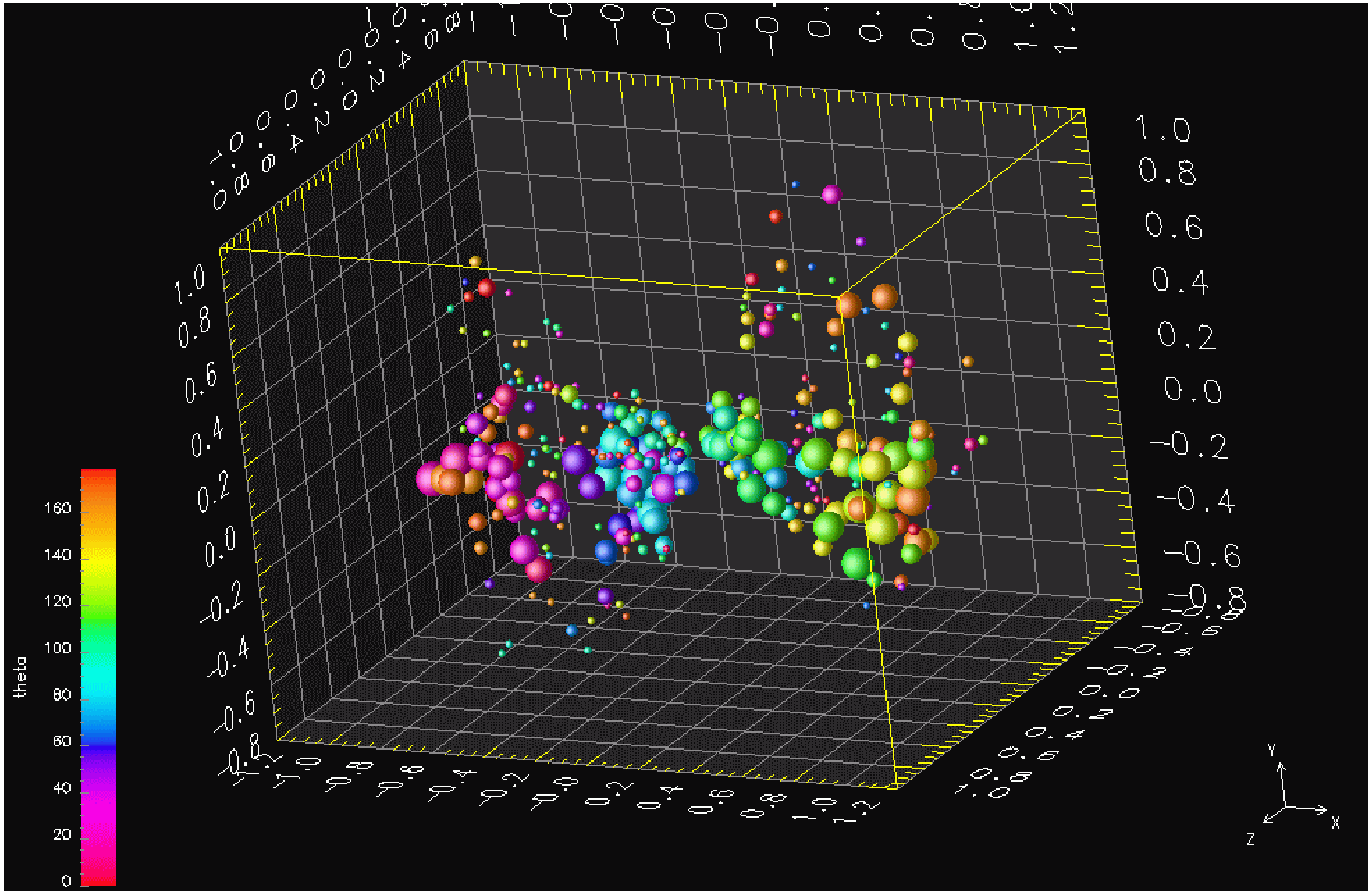
local statistics

The regions previously identified are the most significant (in both the NGP and SGP caps). They appear opposite on the sky

The effect is more significant along an axis NGP -SGP

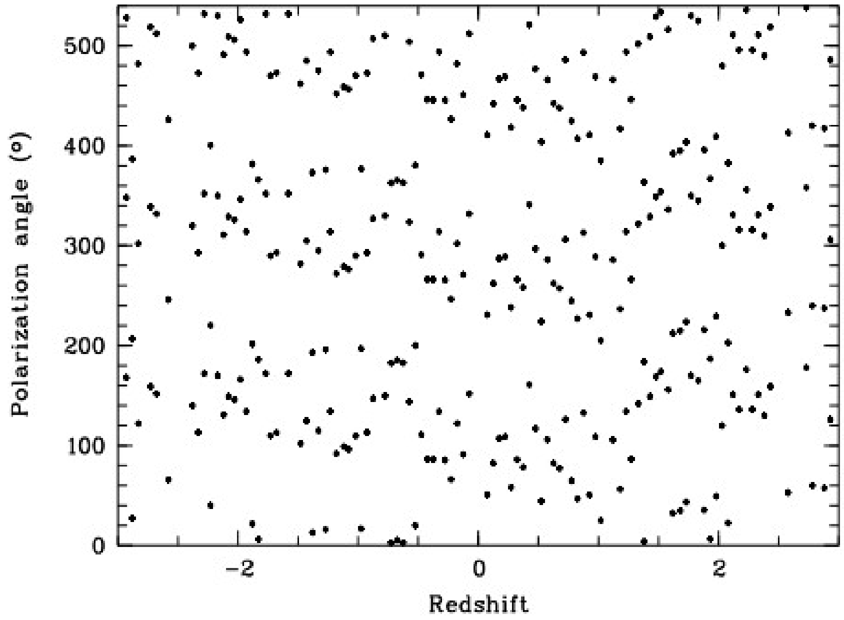


The polarization angle changes with the cosmological distance

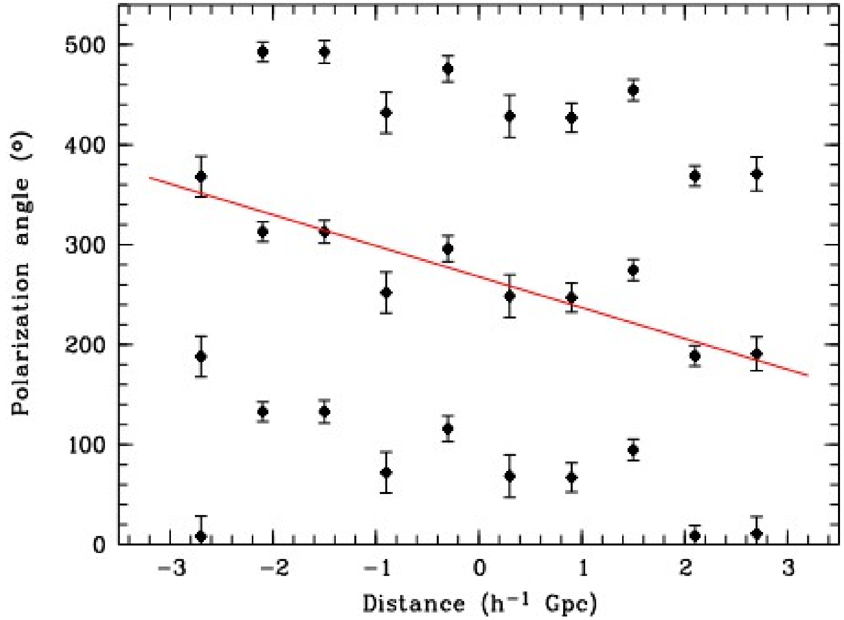


Alignments versus redshift

355 quasars



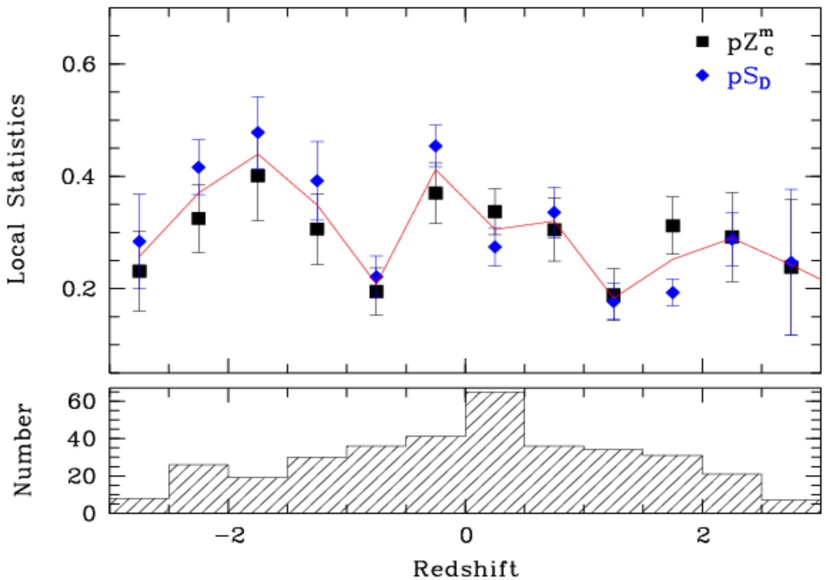
183 quasars along NGP-SGP axis



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

Alternance of aligned and random polarizations?

355 quasars



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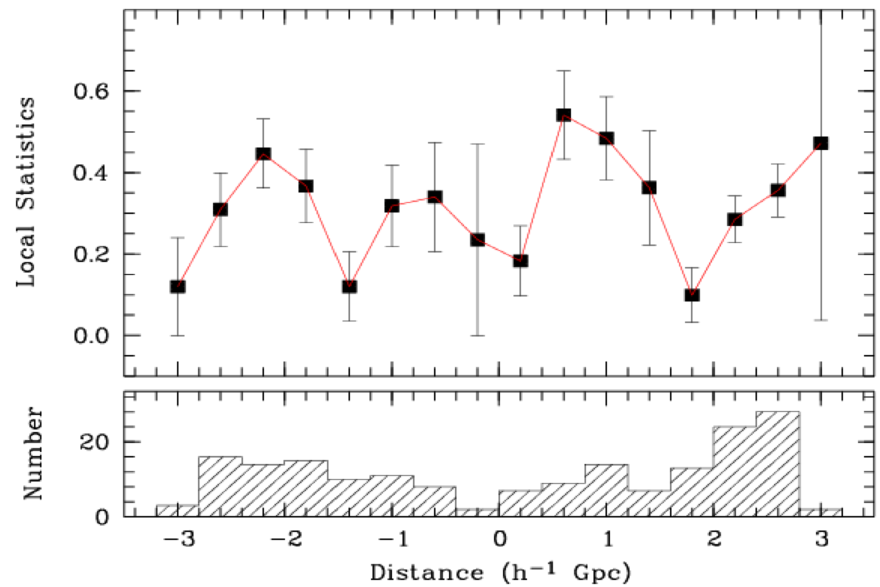


Summary

- *Evidence for large-scale angular correlations of quasar polarization vectors (in regions of ~ 1 Gpc size at z ~ 1)*
- *The effect is statistically significant (> 99.9%) in a sample of 355 quasars*
- *The mean polarization angle changes with redshift*
- *Instrumental and interstellar polarization cannot produce a redshift dependent effect*

What happens at radio wavelengths?

- Joshi et al. 2007 analyzed a sample from the 8.4 GHz JVAS/CLASS survey
- 4290 sources with polarized flux density > 1 mJy out of which 1273 with measured redshift
- Faraday rotation apparently not significant

=> *No evidence for polarization alignments*

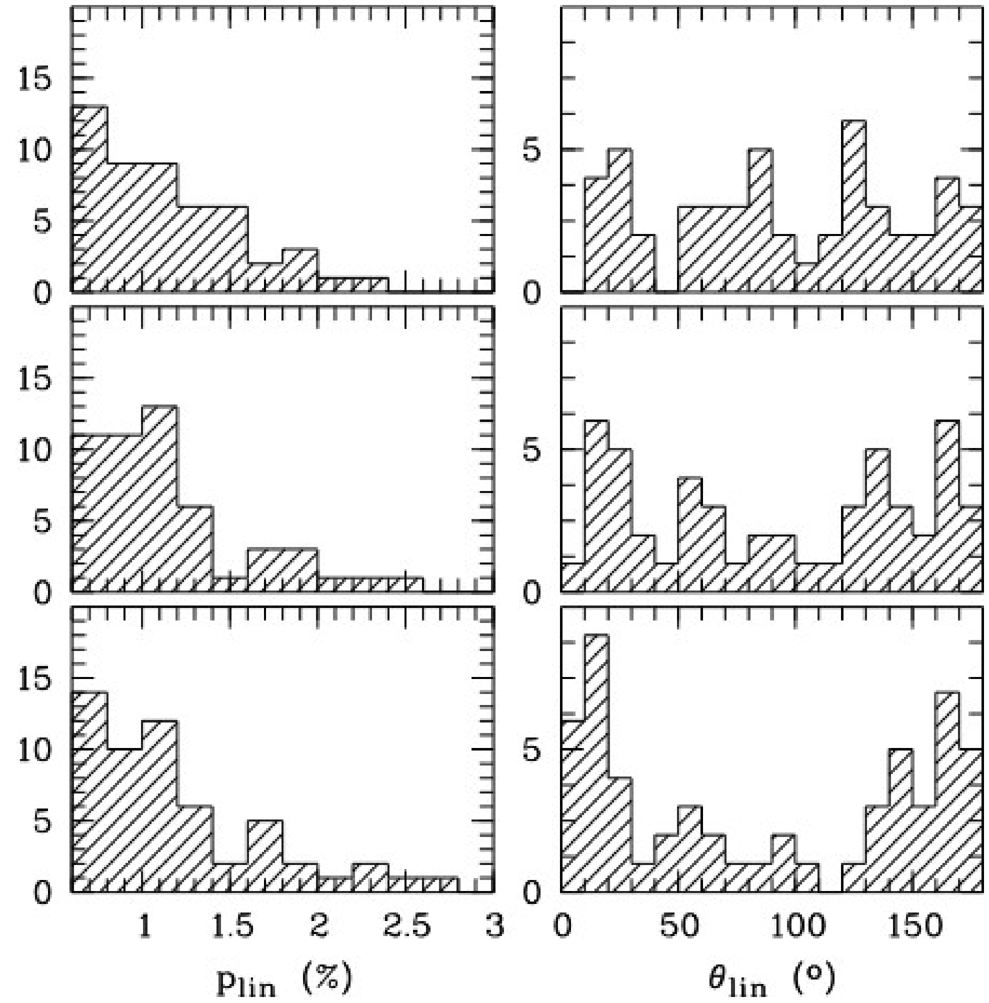
- But, Tiwari & Jain 2013 found significant alignments at scales of 150 Mpc and > 500 Mpc

=> *Controversial results*

Towards an interpretation?

- Simple simulations show that random orientations + a small systematic polarization (~0.5%) can account for the alignments

The effect of adding a systematic Δp_{lin}



Δp_{lin} = 0.00%

Δp_{lin} = 0.25%

Δp_{lin} = 0.50%

Towards an interpretation?

- Simple simulations show that random orientations + a small systematic polarization (~0.5%) can account for the alignments
- Correlations with quasar spectra are not washed out in the regions of alignments => the systematic polarization should remain small (< 2%)

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=> Quasar polarization is partially modified along the line of sight: a small systematic polarization is added

=> Or polarization is totally intrinsic to quasars and quasars themselves are aligned

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)

  (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 the polarization efficiency: $p/A_V \propto B^2/n_H$, the IGM magnetic field should be stronger or equal to current upper limits in order to align them
- A succession of huge domains would be needed to explain the rotation with redshift

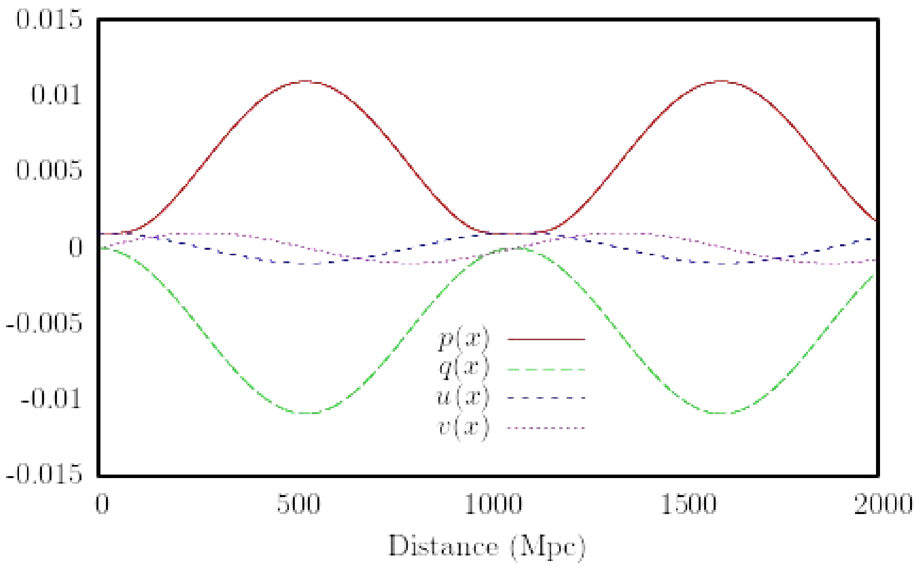
Evidence for photon-axion mixing?

- *Light-mass pseudoscalars (e.g. axions and axion-like particles) are predicted by many theories beyond the Standard Model (and are a candidate for dark matter)*
- Photons parallel to an external magnetic field *B* decay into axions => net linear polarization *p*
- Oscillations of *p* over cosmological distances are predicted (e.g. Gnedin et al. 2005, 2006)
  => *B* < 1 nG coherent over ~ 1 Gpc ?
- A rotation of the polarization angle with distance can be explained (Das et al. 2005) but requires regular variation of the direction of *B* with distance

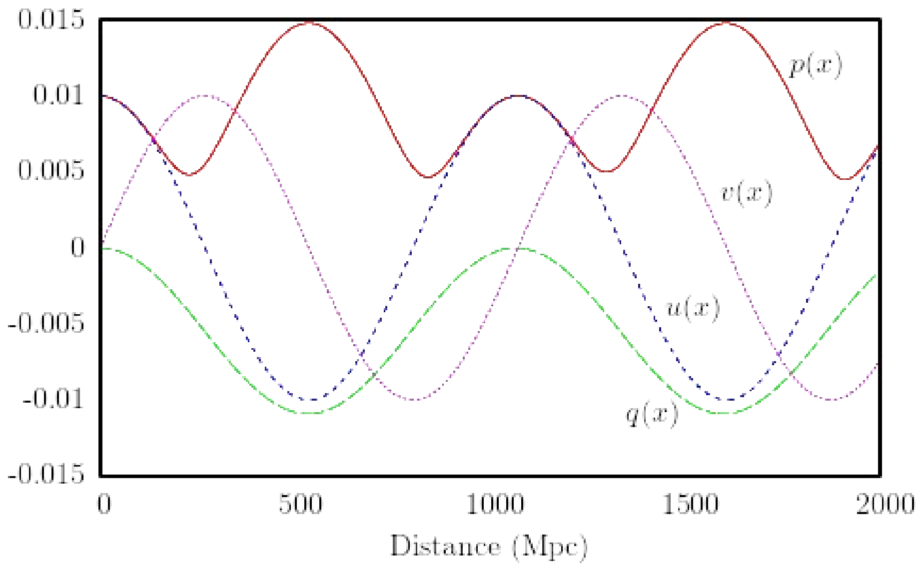
Evidence for photon-axion mixing?

Extensive studies by Das et al. 2005, Payez et al. 2008
(parameters B,g,ω_p,m fine-tuned)

Initial source polarization u=0.001



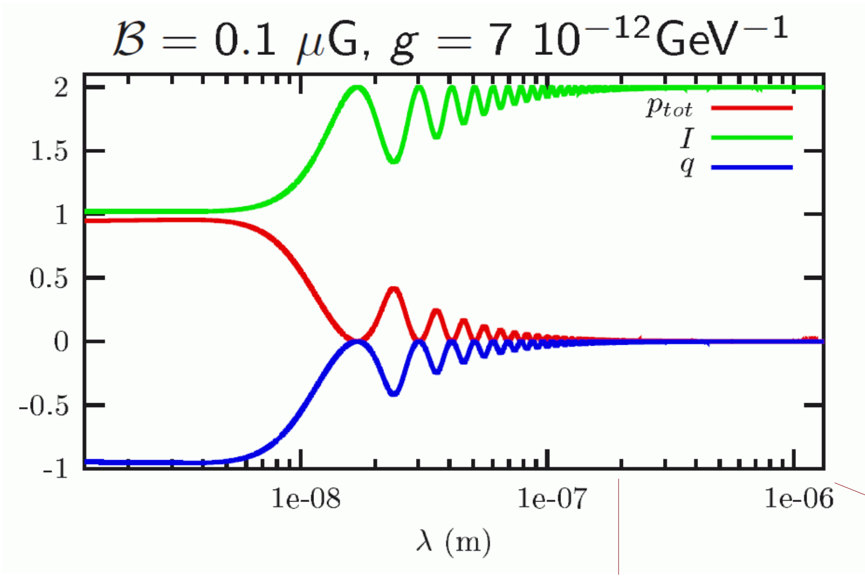
Initial source polarization u=0.01



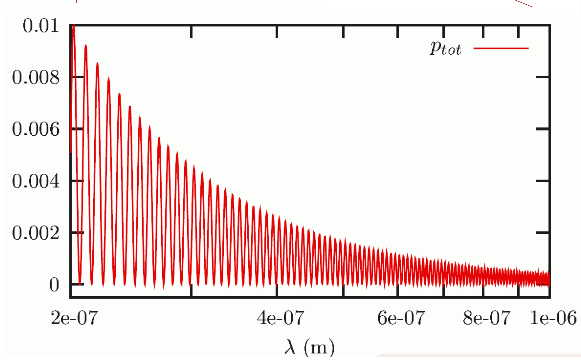
➡ A small additional linear polarization oscillating with the distance is created.
Circular polarization is also generated

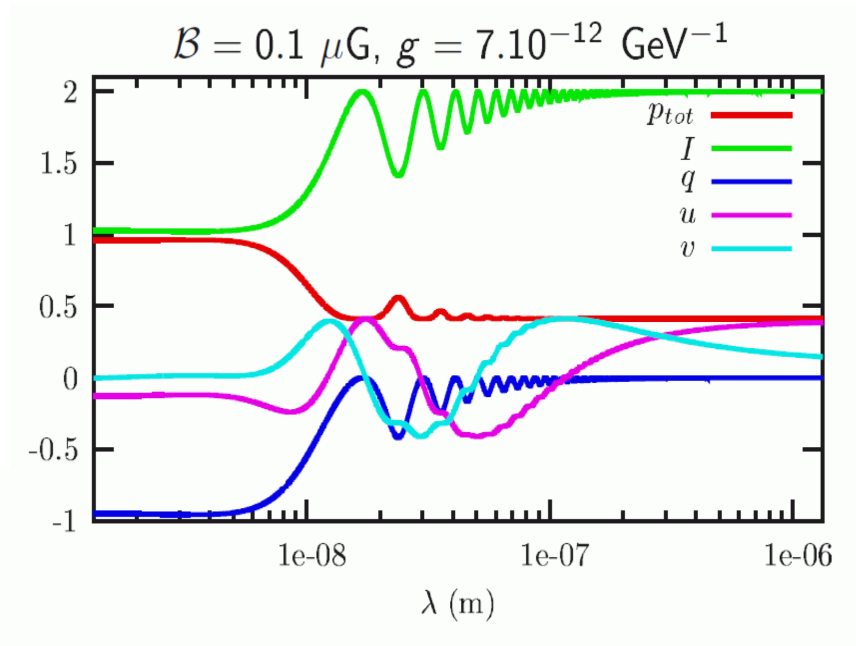
Evidence for photon-axion mixing?

Wavelength dependence



Unpolarized source





Polarized source

No effect expected at radio wavelengths in agreement with the analysis of Joshi et al. (2007)

Circular polarization

- Circular polarization p_{circ} ~ Δp_{lin} ~ 0.5% expected under a wide variety of plausible situations (B,ω_p,...) and for a band-width corresponding to the V filter
- We accurately measured p_{circ} in the V filter for 21 quasars with aligned linear polarizations (EFOSC2 + λ/4 plate)
- We derived a stringent upper limit $p_{circ} < 0.05\%$

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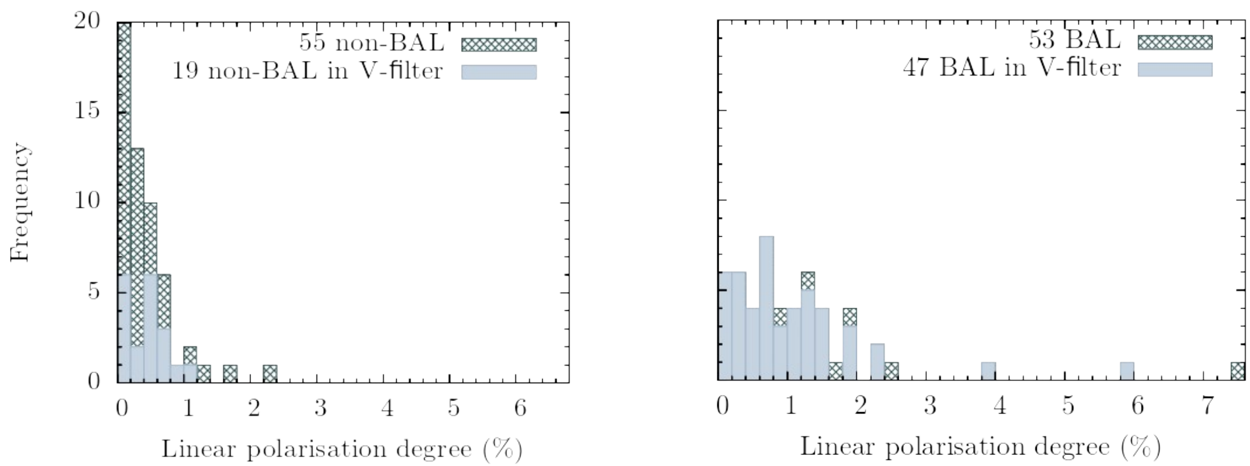
- Circular polarization $p_{circ} \sim \Delta p_{lin} \sim 0.5\%$ expected under a wide variety of plausible situations (B,ω_p,...) and for a band-width corresponding to the V filter
- We accurately measured p_{circ} in the V filter for 21 quasars with aligned linear polarizations (EFOSC2 + λ/4 plate)
- We derived a stringent upper limit $p_{circ} < 0.05\%$

This rules out the photon-axion mixing at the origin of the observed alignements

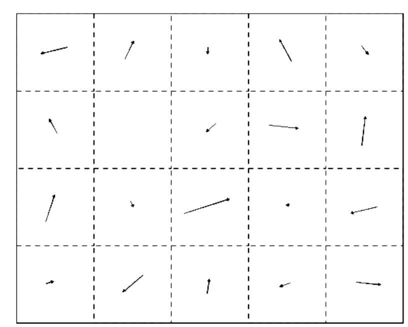
Constraints on photon-axion mixing

- We allow p_{circ} < 0.05% and p_{lin} < 2% (higher values would wash out the differences observed between BAL and non-BAL quasars)



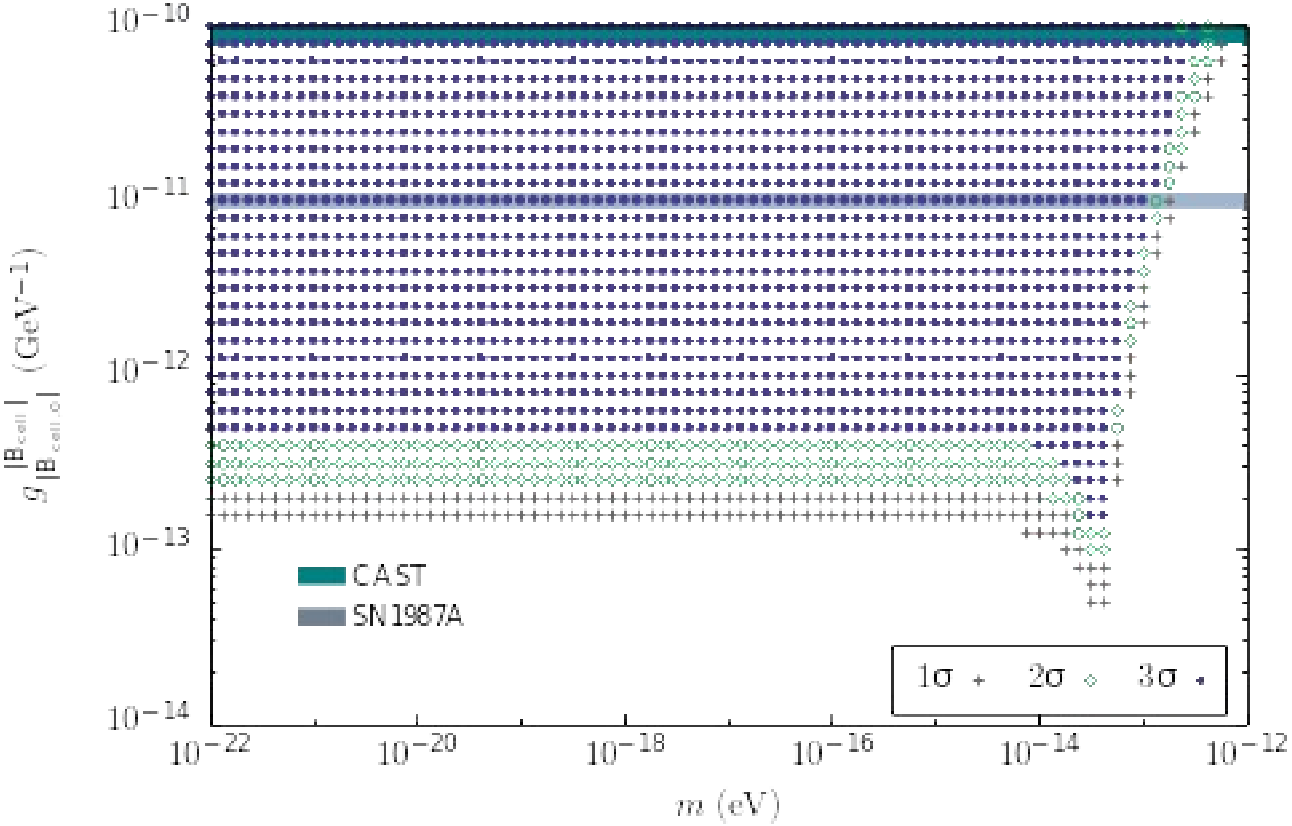
In the direction of Virgo

- We consider quasars in the direction of Virgo. The last relevant *B* is the local Supercluster one, modeled as a patchy field with 100 kpc cells and a random *B* of 2 μG, over 10 Mpc (Vallée 2011)



Constraints on photon-axion mixing

Exclusion plot



Provide much stronger limits than CAST and SN1987A robust against plausible variations of the parameters

(=> included in PDG Review of Particle Physics)

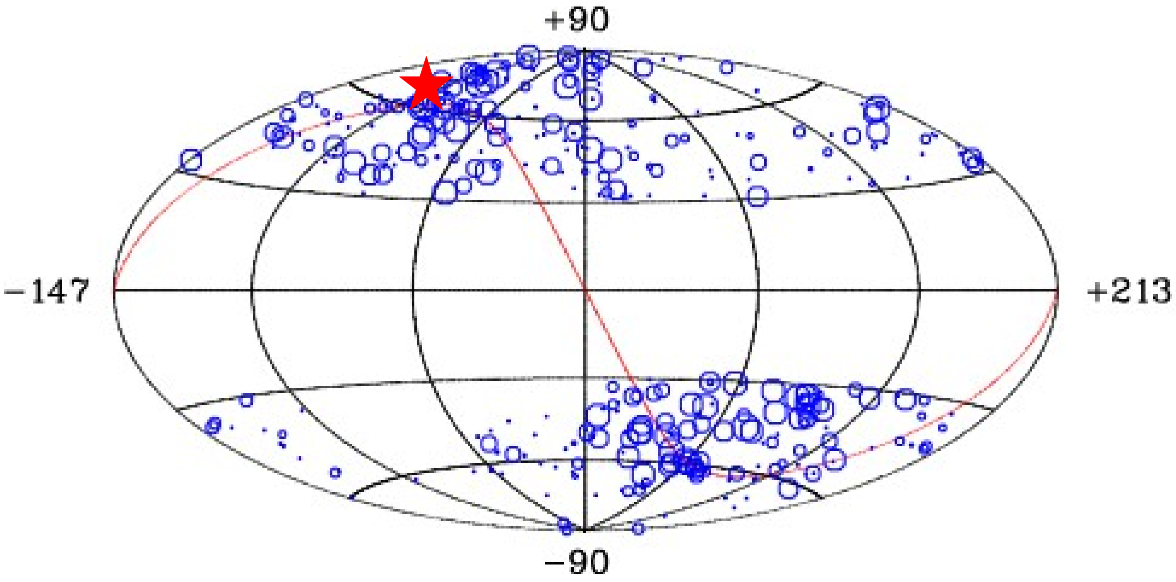
Alignments : alternative interpretations

Anisotropic expansion of the Universe? Global rotation?

Effects on polarization are expected
(Brans 1975, Ciarcelluti 2012, Obhukov 2000)

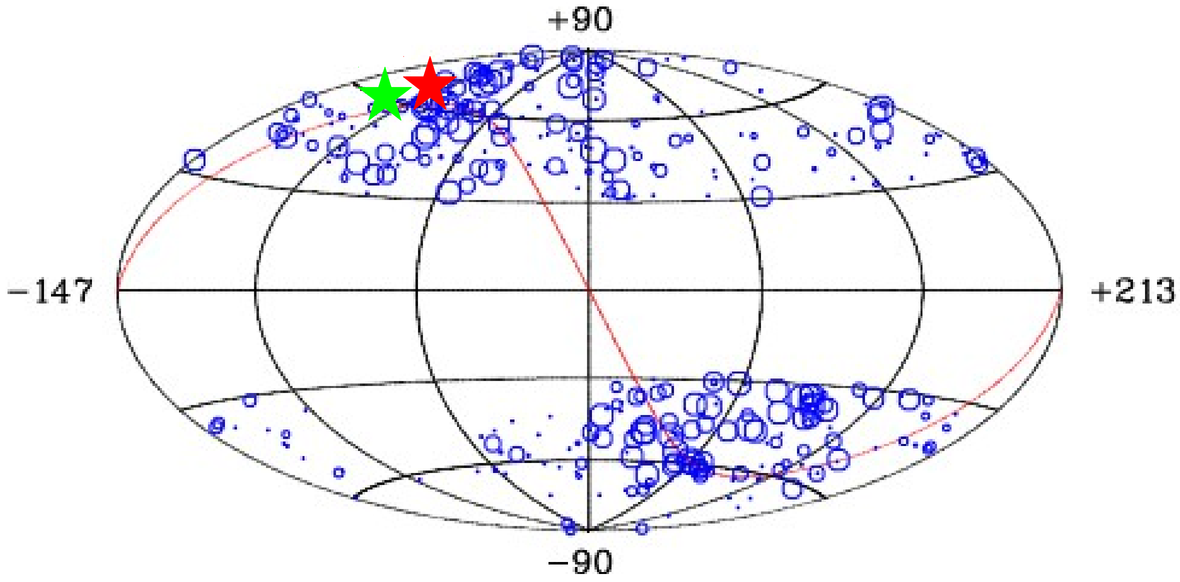
=> A preferred direction / axis is expected

A preferred axis in the Universe?



Quasar polarizations

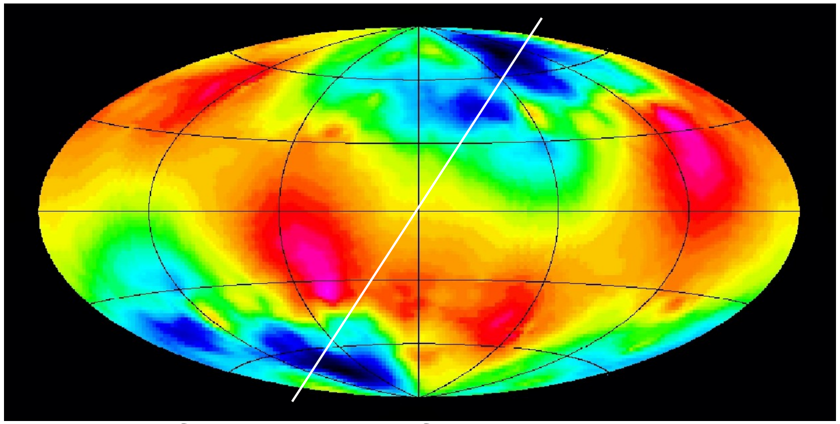
A preferred axis in the Universe?



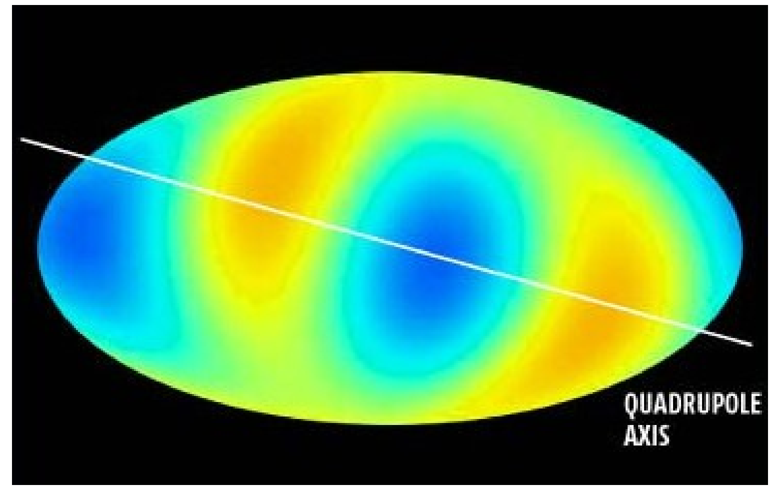
Quasar polarizations

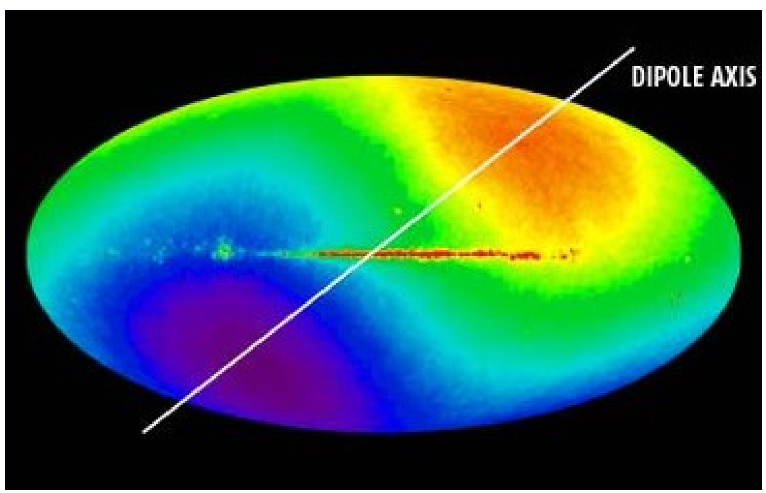
Low multipoles in the CMB
(Axis of Evil)
[Oliveira-Costa & Tegmark 2006]

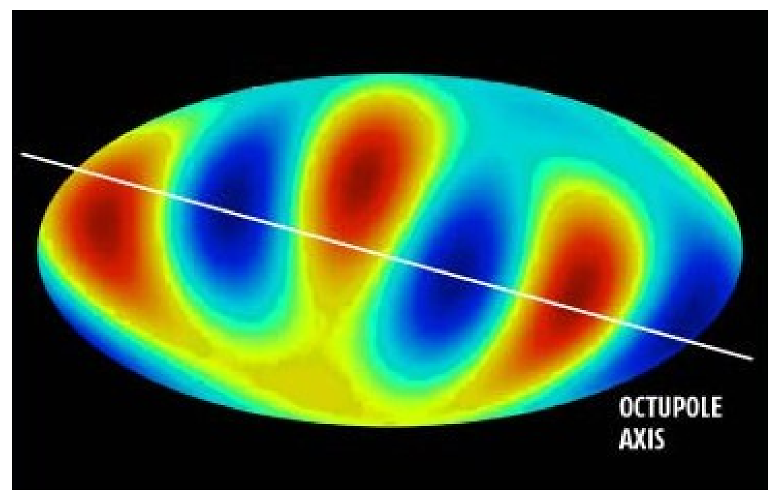
Polarization axis vs the “axis of evil”



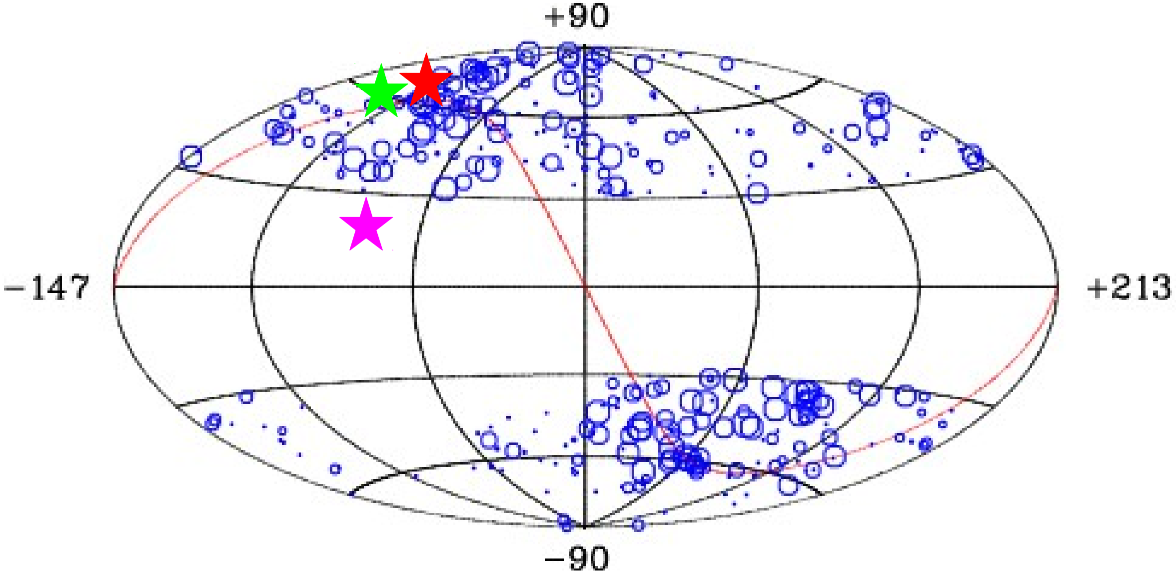
Axis of most significant alignments







A preferred axis in the Universe?



Quasar polarizations

Low multipoles in the CMB
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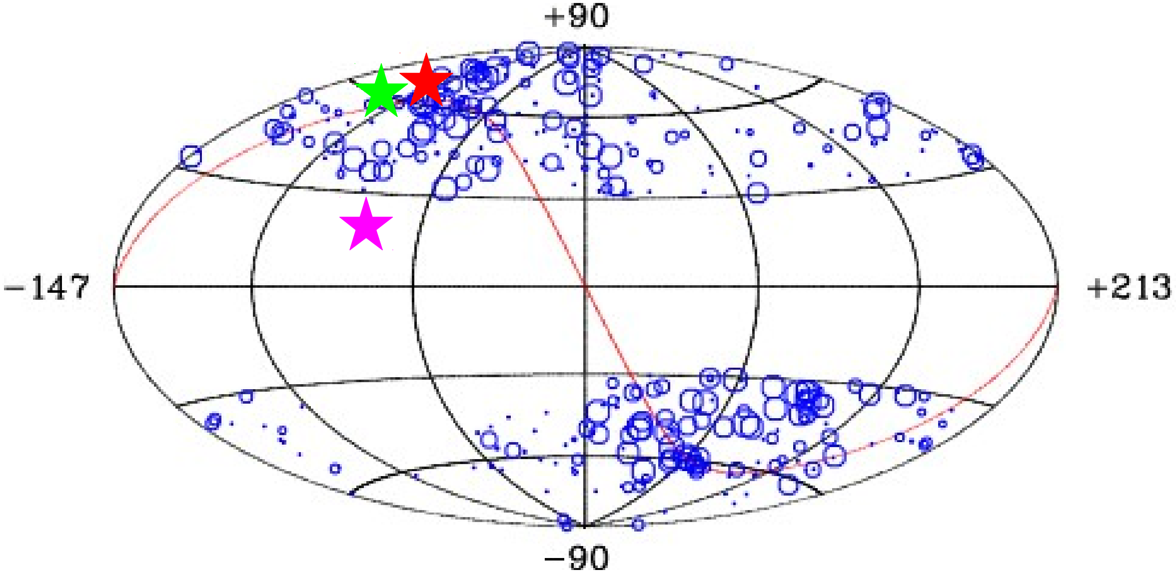
[Oliveira-Costa & Tegmark 2006]

Maximum expansion rate
from Union2 SN
[Antoniou & Perivolaropoulos 2012]

The axes are consistent within the -large- uncertainties

A preferred axis in the Universe?



Quasar polarizations

Low multipoles in the CMB
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Coincidences? Large statistical fluctuation?
Violation of the cosmological principle?

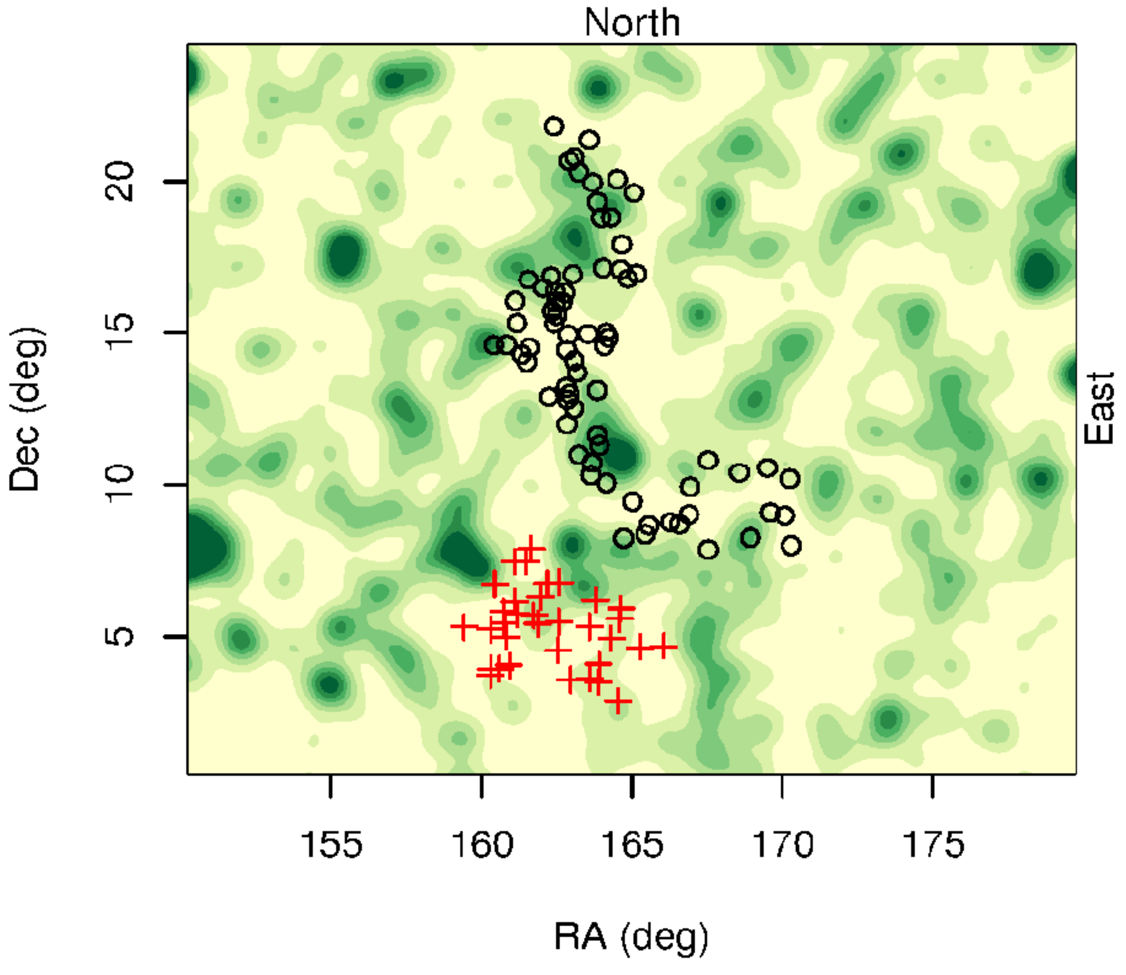
Alignments : alternative interpretations

Quasar themselves are aligned?

- Known correlation between optical polarization and VLBI structure of compact radio-sources (Rusk 1990)
- Alignment of galaxy orientations or spins in filaments and sheets are observed and explained in the framework of the tidal torque theory
  (Tempel & Libeskind 2013, Zhang et al. 2013)

Are quasars aligned with their host structure? at Gpc scales?

Polarization of a large quasar structure



[From Clowes et al. 2013]

Largest quasar structure
z ~1.3; ~ 500 Mpc;
73 quasars from SDSS DR7)

Close to the region of strongest polarization alignments with roughly the same PA

(l,b) = (-125,60)
=> close to the "cosmic axis"

Conclusions

- *Evidence for large-scale angular correlations of quasar polarization vectors (in regions of ~ 1 Gpc size at z ~ 1)*
- *The effect seems stronger along an axis close to the CMB "Axis of Evil"*
- *A large-scale origin might be due to a modification of the quasar polarization along the line of sight and/or assuming intrinsic remnant alignments of quasar axes*
- *Quasar polarization alignments might indicate departures to the fundamental cosmological assumption of large-scale isotropy*

Conclusions

- *Evidence for large-scale angular correlations of quasar polarization vectors (in regions of ~ 1 Gpc size at z ~ 1)*
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- *Quasar polarization alignments might indicate departures to the fundamental cosmological assumption of large-scale isotropy*

=> OR a complex contamination of the data set ?

Future work

- *Polarimetry is time consuming: with 0.5h per quasar, doubling the sample requires 50 nights (> 4m-class telescope)*
- *Polarimetry of the ~ 80 quasars of the large Clowes et al. structure can be done*
- *Infrared / sub-mm polarization : free of interstellar polarization and Faraday rotation uncertainties*
- *Radio polarization alignment controversy : clarification needed*
- *Search for large-scale correlations in Planck CMB polarization*
- *Investigate more quantitatively the effect of anisotropic expansion on polarization*

Thank You

References

- Antoniou & Perivolaropoulos 2012, JCAP 12, 012
- Clowes et al. 2013, MNRAS 429, 2910
- Das et al. 2005, JCAP 06, 002 (+ hep-ph/0410006)
- de Oliveira-Costa & Tegmark 2006, PhRvD 74, 023005
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- Hutsemékers et al. 2005, A&A 441, 915
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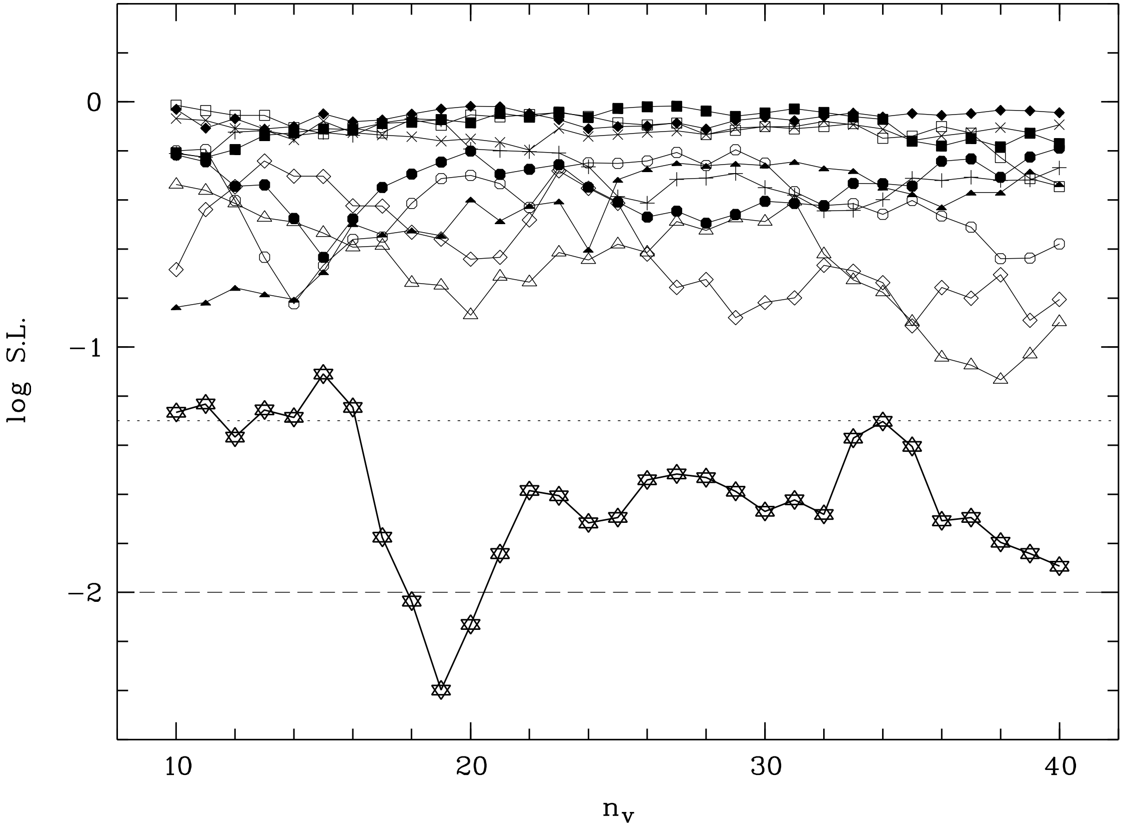
- Rusk 1990, JRASC 84, 199
- Sluse et al. 2005, A&A 433, 757
- Tempel & Libeskind 2013, ApJL 775, L42
- Tiwari & Jain 2014, IJMPD 22, 1350089
- Urry & Padovani 1995, PASP 107, 803
- Zhang et al. 2013, ApJ 779, 160

Additional Material

Statistical analysis : results (1)

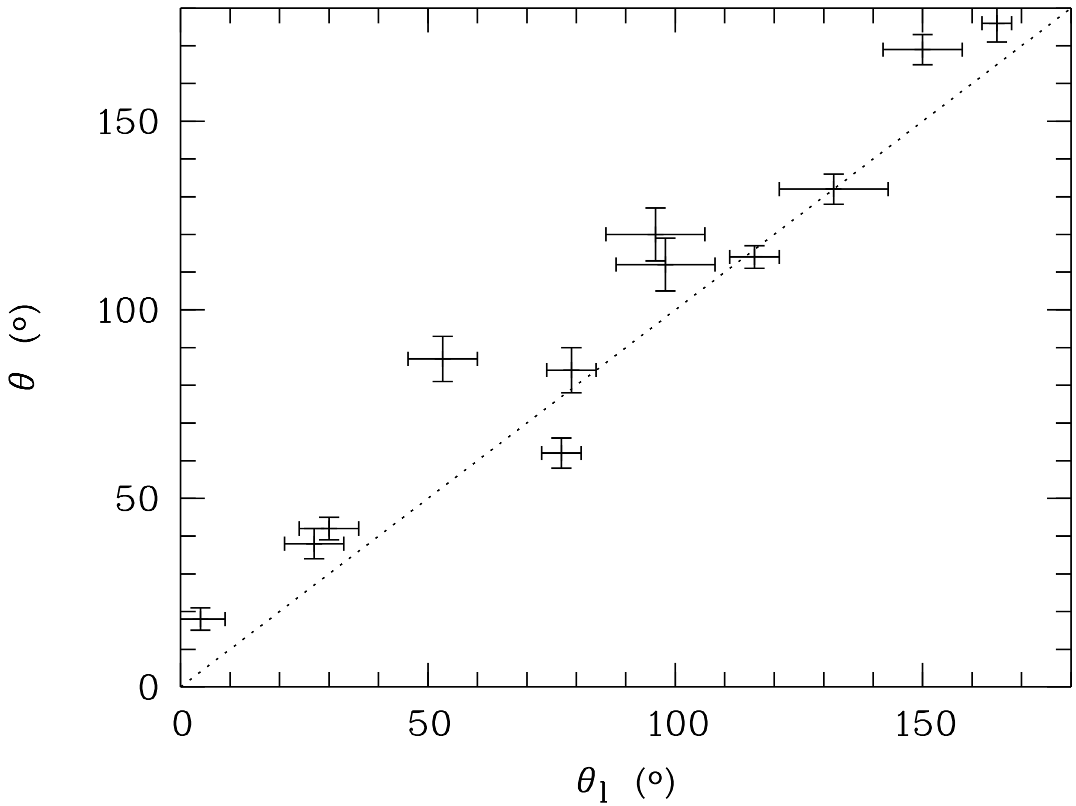


10 first random samples

170 quasars sample (1998)

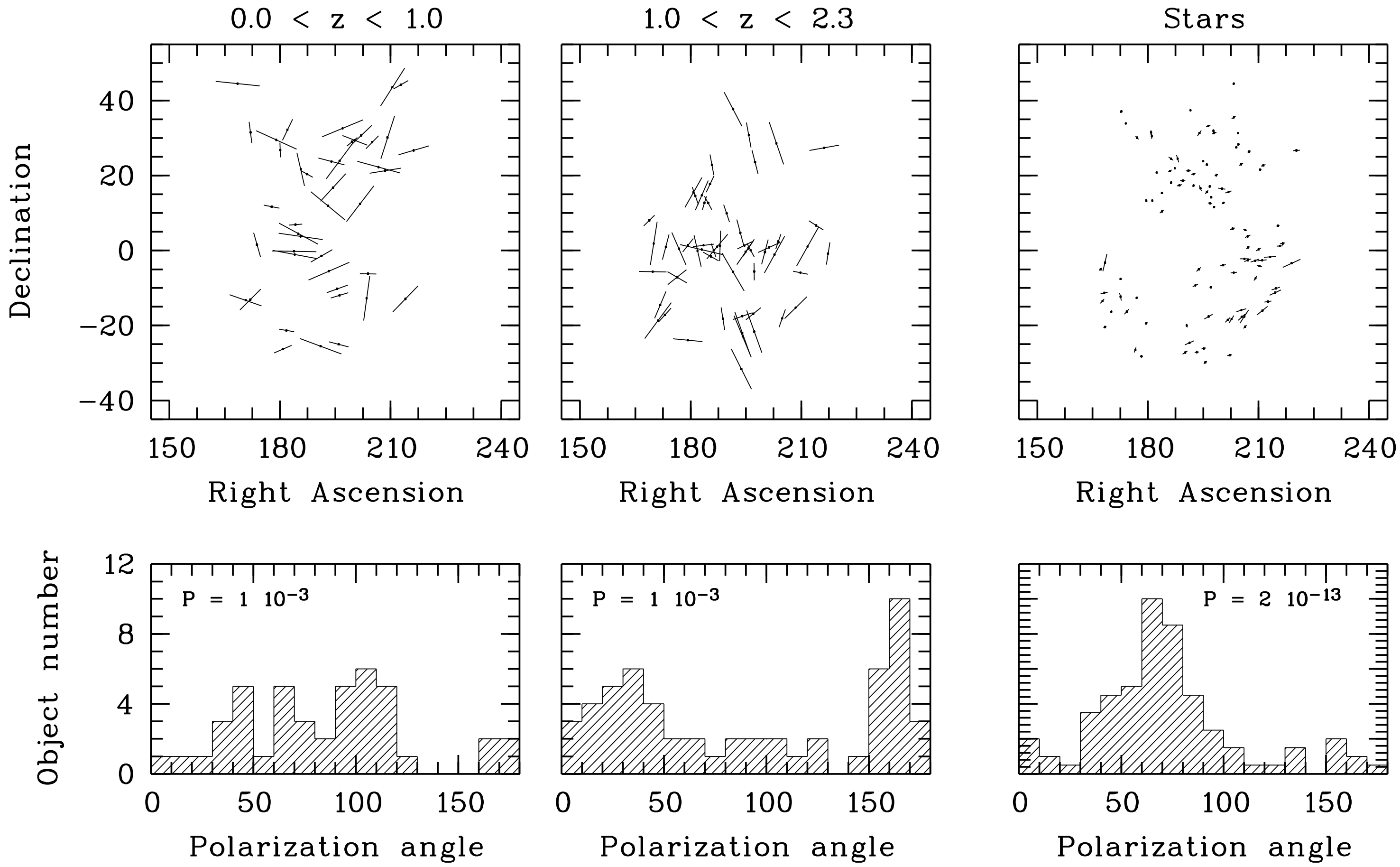
Instrumental polarization?

Quasar polarization angles : EFOSC2 versus other instruments



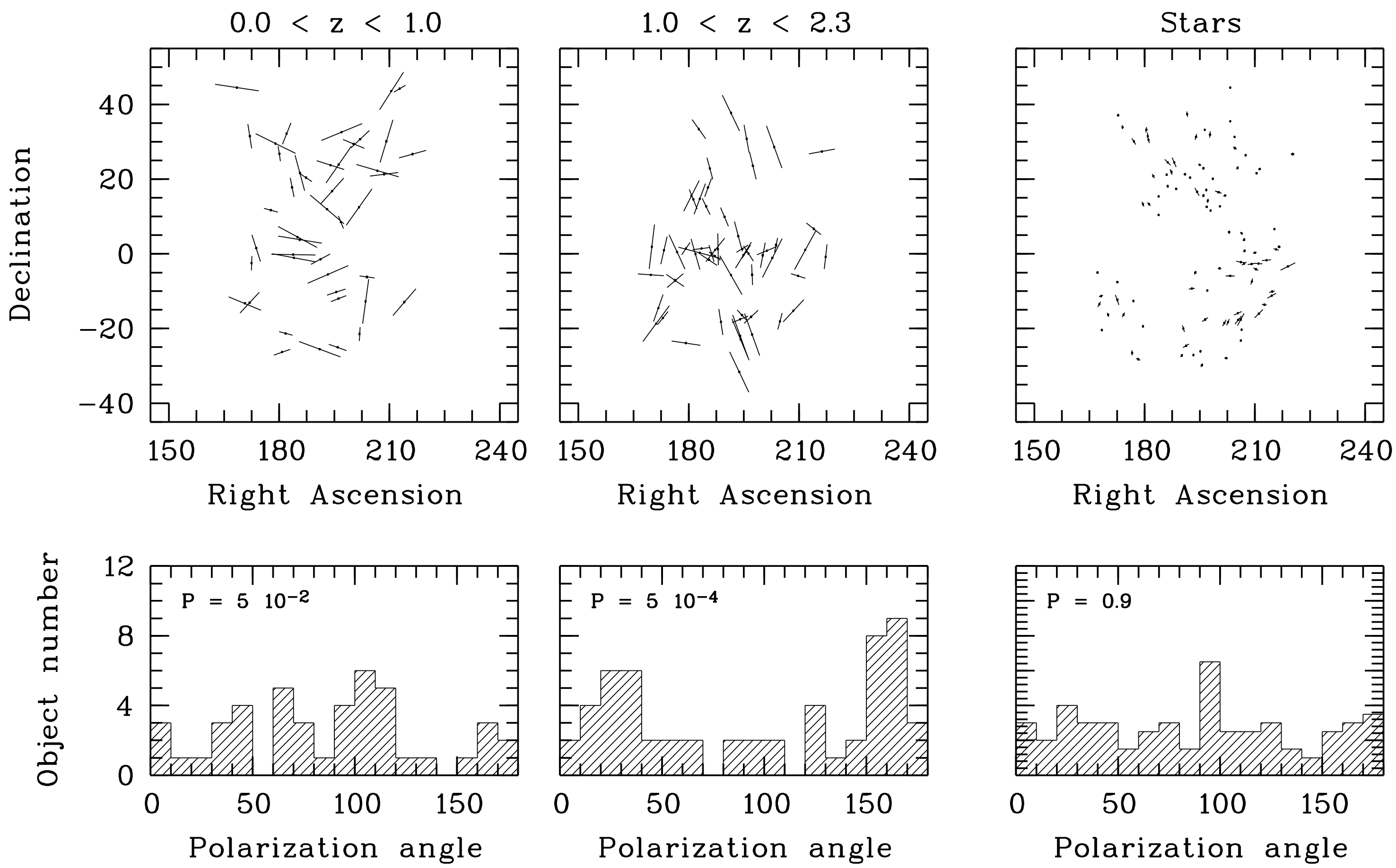
Good agreement given that different filters were used (white light versus V filter) and that some quasars may be variable

Simulations of interstellar polarization correction



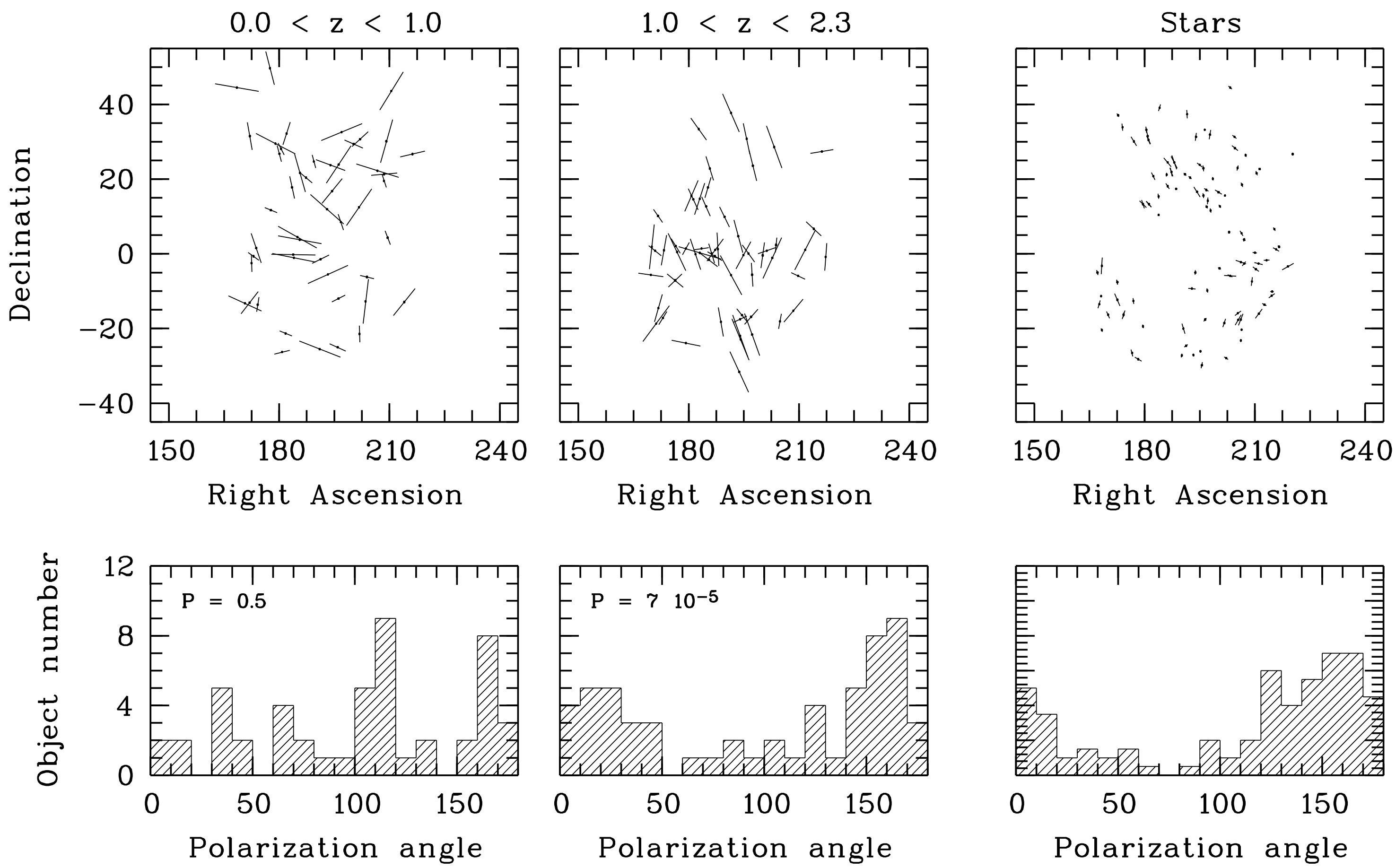
No correction

Simulations of interstellar polarization correction



Correction

Simulations of interstellar polarization correction



Over-corrected