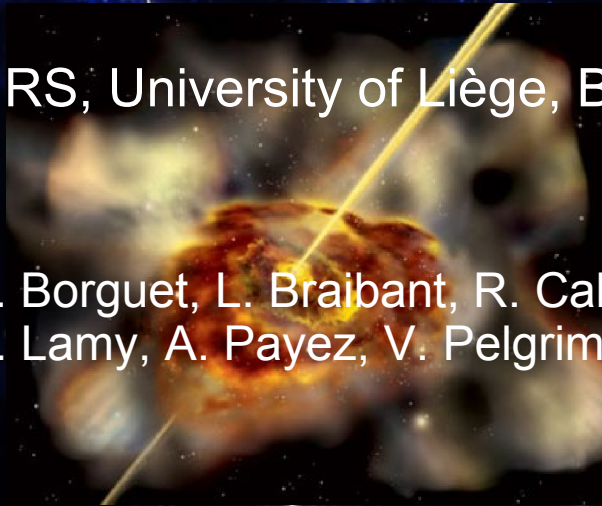# Large-scale alignments of quasar polarization vectors

## Observational evidence and possible implications for cosmology

### Damien Hutsemékers

(FNRS, University of Liège, Belgium)

Collaborators: B. Borguet, L. Braibant, R. Cabanac, J.R. Cudell, H. Lamy, A. Payez, V. Pelgrims, D. Sluse
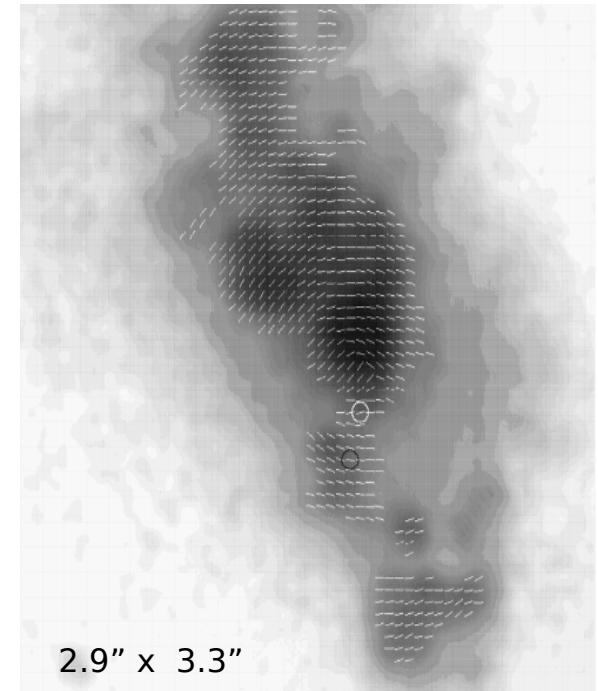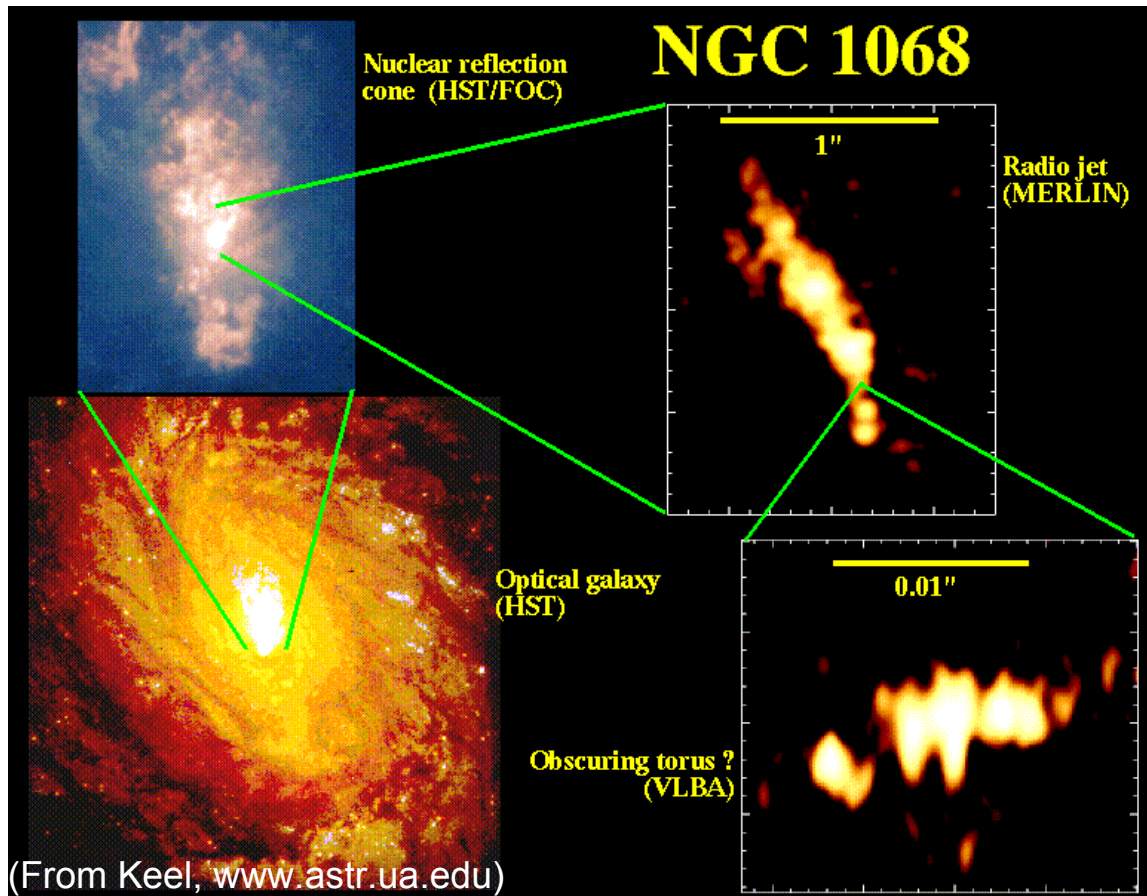
*A Discussion on the Cosmological Principle – Pohang, South Korea – 25-28 October 2021*

# Outline

- Origin and characteristics of optical polarization in quasars

- Large-scale alignments of quasar polarization vectors: statistics, possible contamination

- Characteristics of the alignment effect

- Interpretations. Evidence of a preferred axis

- Alignments of quasar axes with large-scale structures

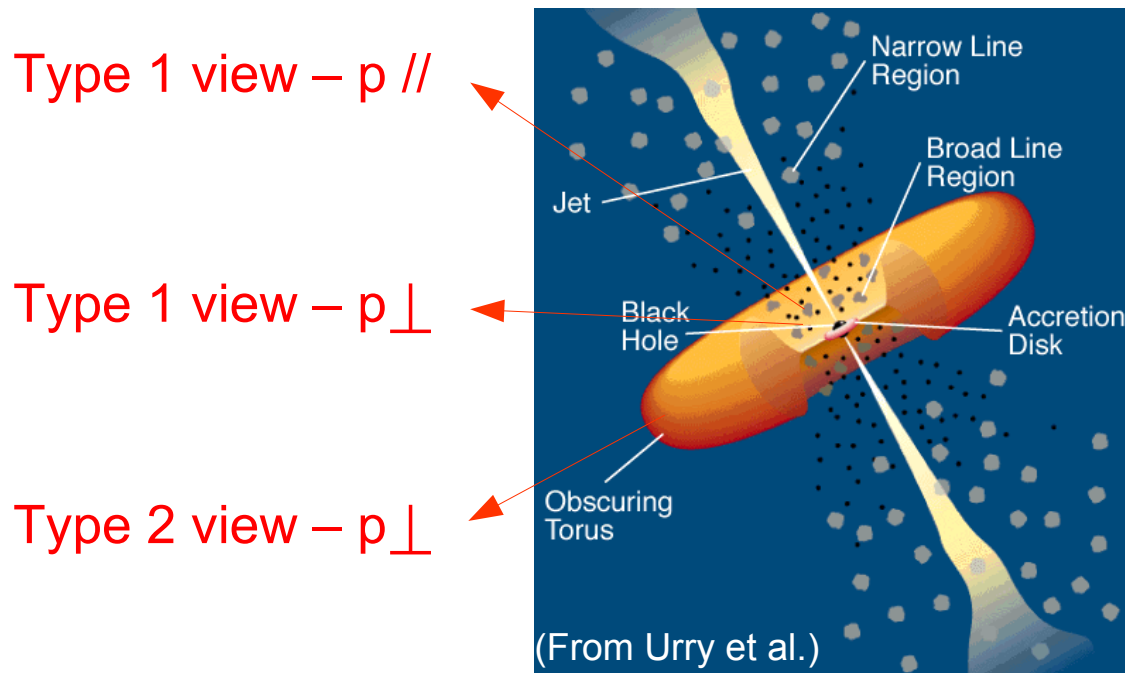# UV-optical polarization in Active Galactic Nuclei / Quasars



**NGC 1068**

Nuclear reflection cone (HST/FOC)

Radio jet (MERLIN)

1"

Optical galaxy (HST)

0.01"

Obscuring torus ? (VLBA)

(From Keel, www.astr.ua.edu)



2.9" x 3.3"

Centrosymmetric polarization due to dust scattering (HST UV observations, Capetti+ 1995)

- polarization due to scattering of nuclear light
- scattering by electrons, and dust in most external regions
- polarization vectors perpendicular to the radio jet / ionization cones

# UV-optical polarization in quasars

- Type 2 AGN show high optical polarization > 3%. The polarization is perpendicular to the radio axis and/or to the ionization cones. This suggests polar scattering.

- Type 1 AGN have mostly low optical polarization ~ 1%. The polarization is most often parallel to the radio axis / ionization cones although it can also be perpendicular at intermediate inclinations. This suggests both equatorial and polar scattering

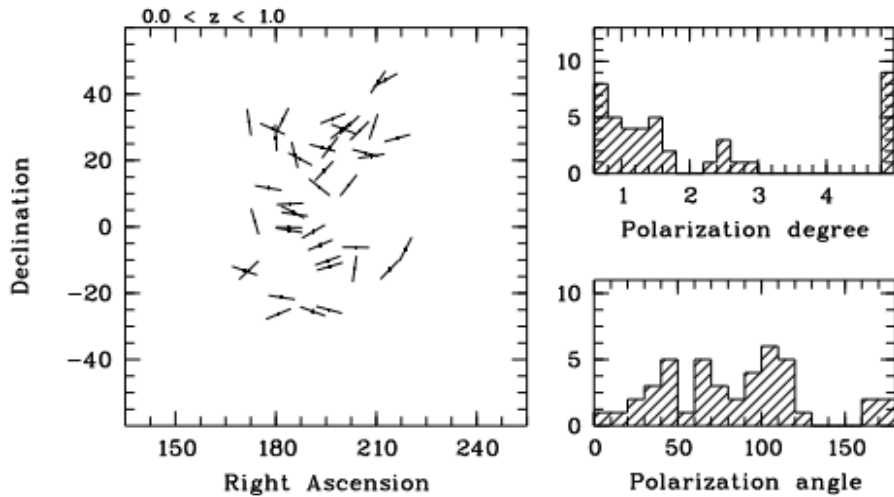Type 1 view – p //

Type 1 view – p⊥

Type 2 view – p⊥

The AGN unification model
(Antonucci+  1985)

Narrow Line Region

Broad Line Region

Jet

Black Hole

Accretion Disk

Obscuring Torus

(From Urry et al.)

# Large-scale alignments of quasar polarization vectors



North Galactic Pole

*Scale ~ 1 Gpc at z ~ 1*

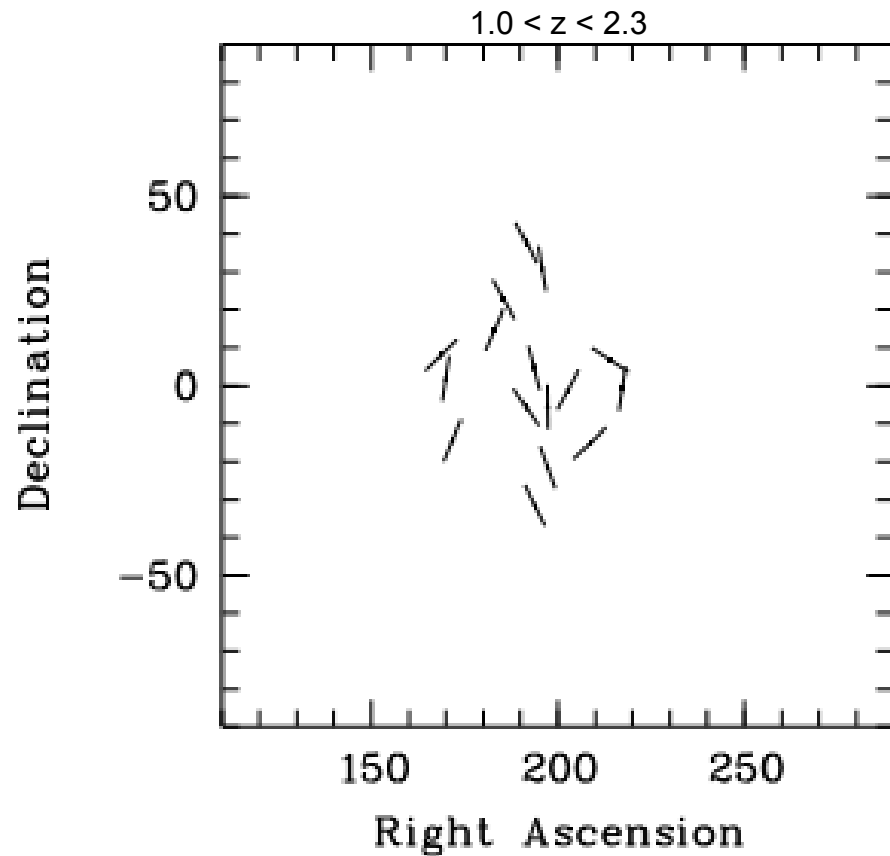*low redshift*

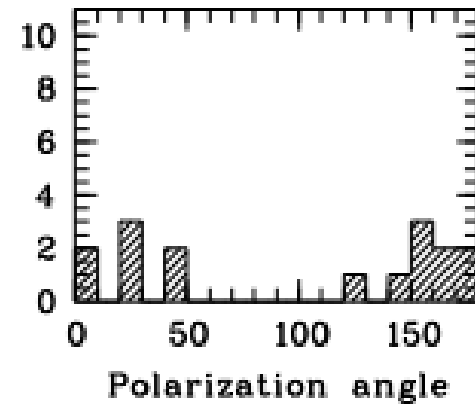$$\bar{\theta}=79^o \ \ with \ \ P=3 \ 10^{-3}$$
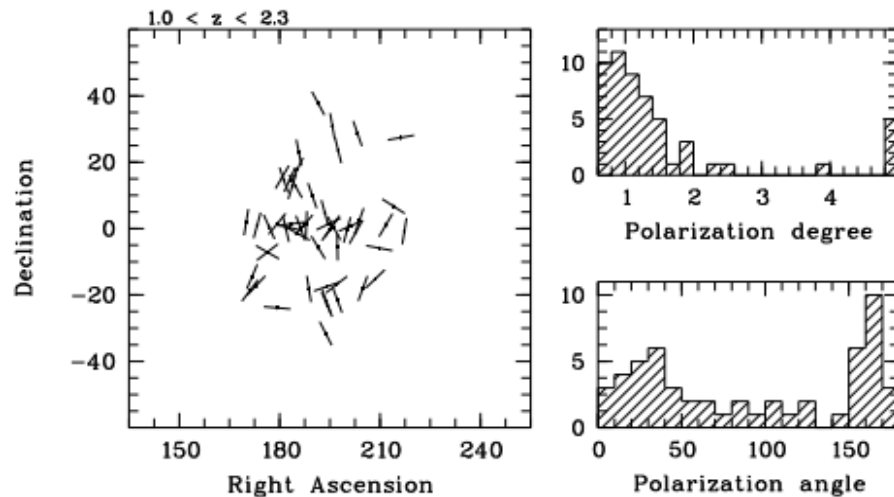
*high redshift*

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

(Hutsemékers+ 2005)

5

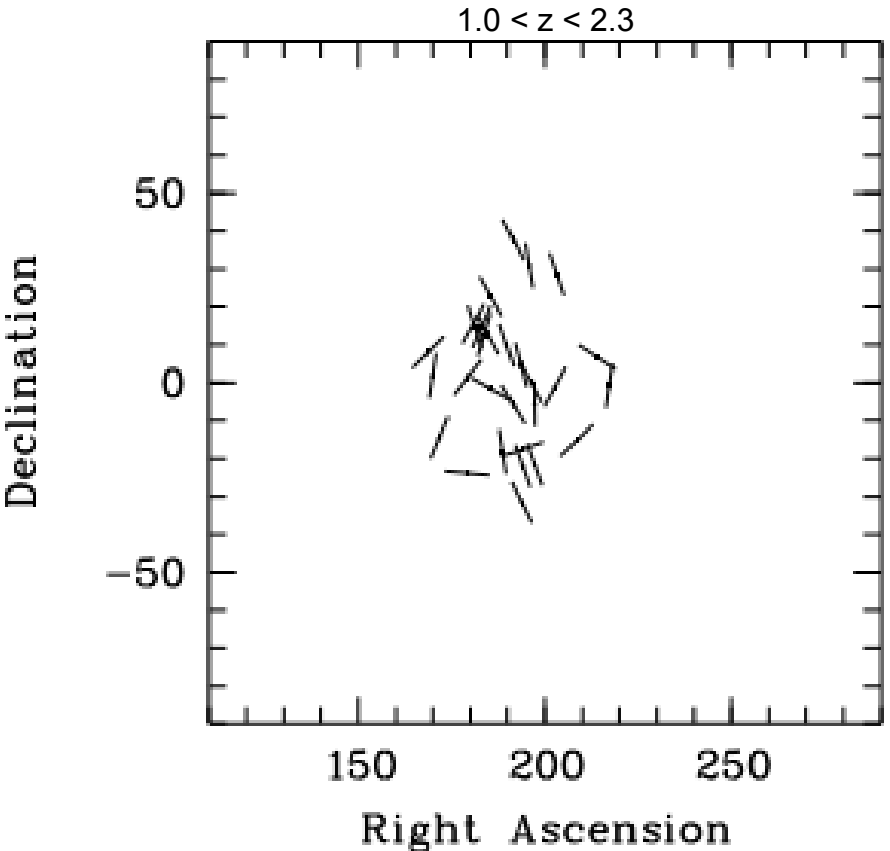# Evolution with sample size
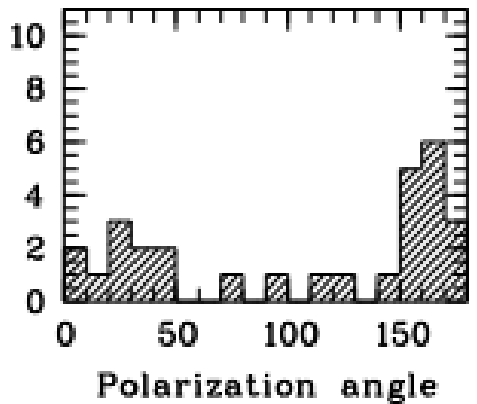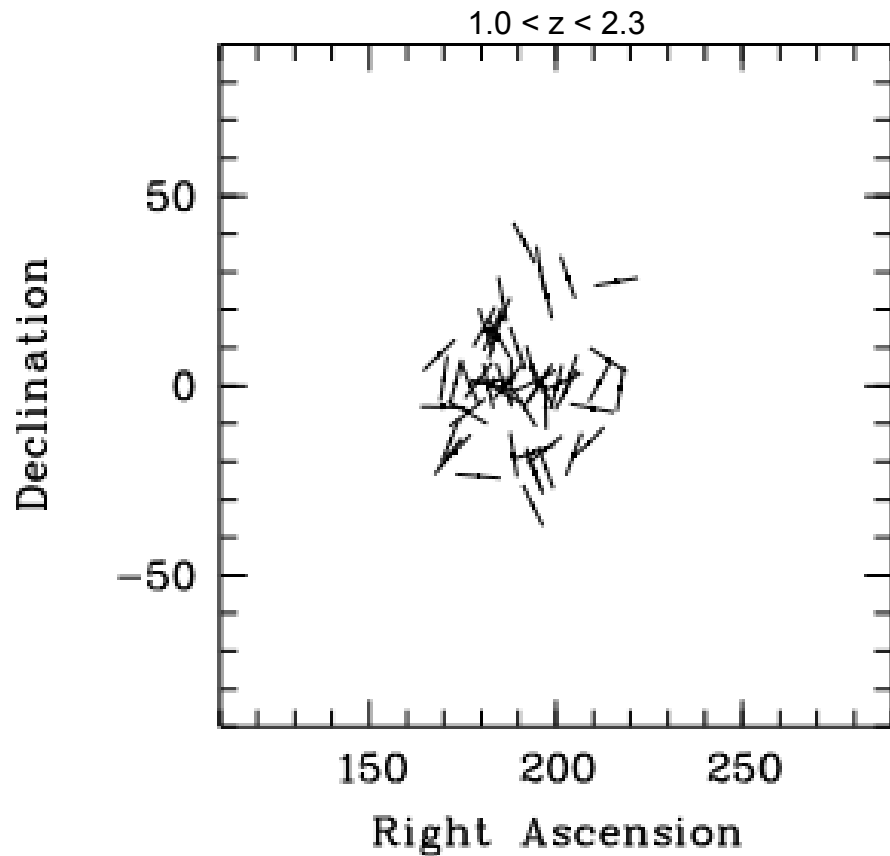


1.0 < z < 2.3

170 quasars
(1998)

# Evolution with sample size
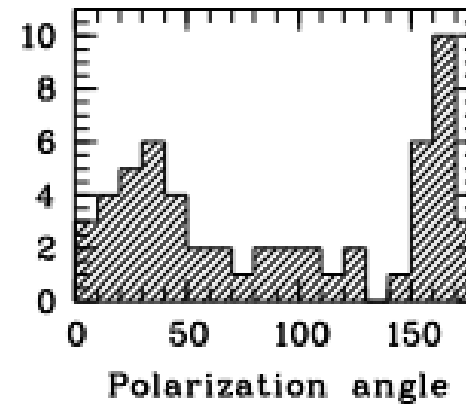


213 quasars
(2001)

# Evolution with sample size

1.0 < z < 2.3

355 quasars
(2005)

# Global statistical analysis: the sample

- A sample of 355 polarized quasars up to $z \sim 2.5$
  *Previous studies with 170 and 213 quasars*
  (Hutsemékers+ 1998, 2001, 2005; see also Jain+ 2004, Shurtleff 2013, Pelgrims+ 2014)

- New observations and compilations from the literature (inhomogeneous sample)

  - Bright, BAL, red, radio-loud quasars preferred

  - Blazars essentially excluded (uncertain redshift)

- Galactic latitude > 30°

- Polarization degree ≥ 0.6%

- Uncertainty of polarization angle ≤ 14°  (or $p/\sigma_p \geq 2$)

# Global statistical analysis: methods

*Are polarization angles uniformly distributed on the sky?*

- Angles are axial data => circular statistics needed

- *S*-statistics based on the dispersion of angles for $n_v$ neighbors in the 3D Universe => $S_{QSO}$

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

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

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

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

- Parallel transport of polarization vectors along great circles
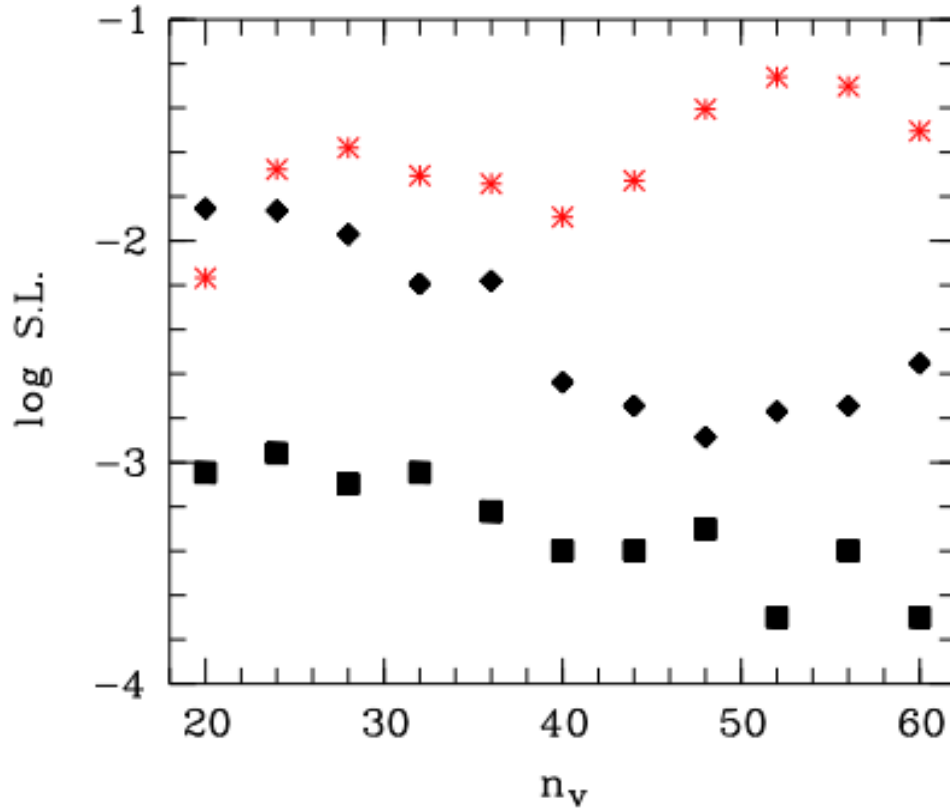(coordinate-invariant statistics, Jain+ 2004)

# Global statistical analysis: methods

- The significance is evaluated through Monte-Carlo simulations

- Shuffling angles over positions: keeps the original values of the polarization angles



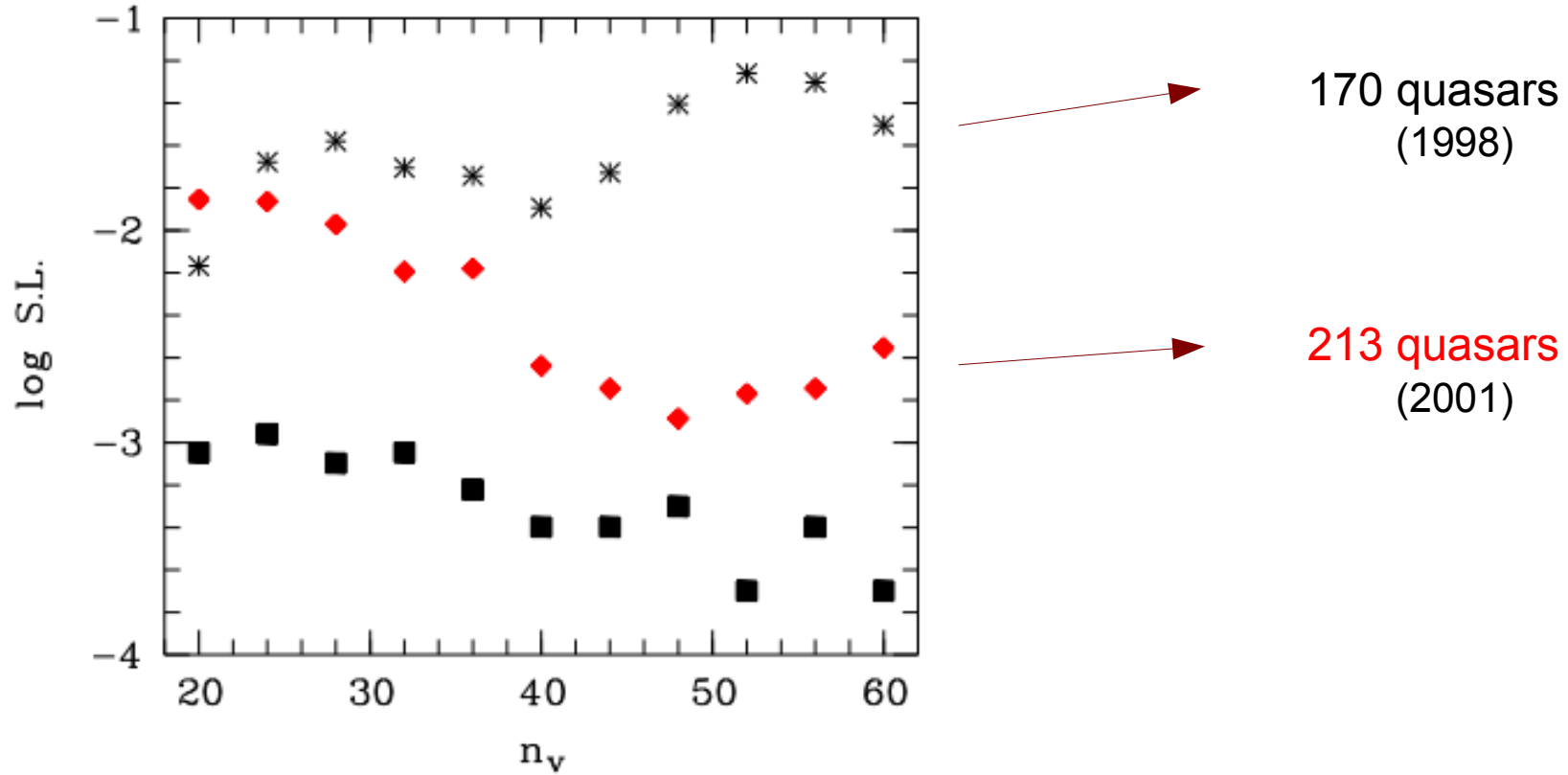$S_{QSO}$

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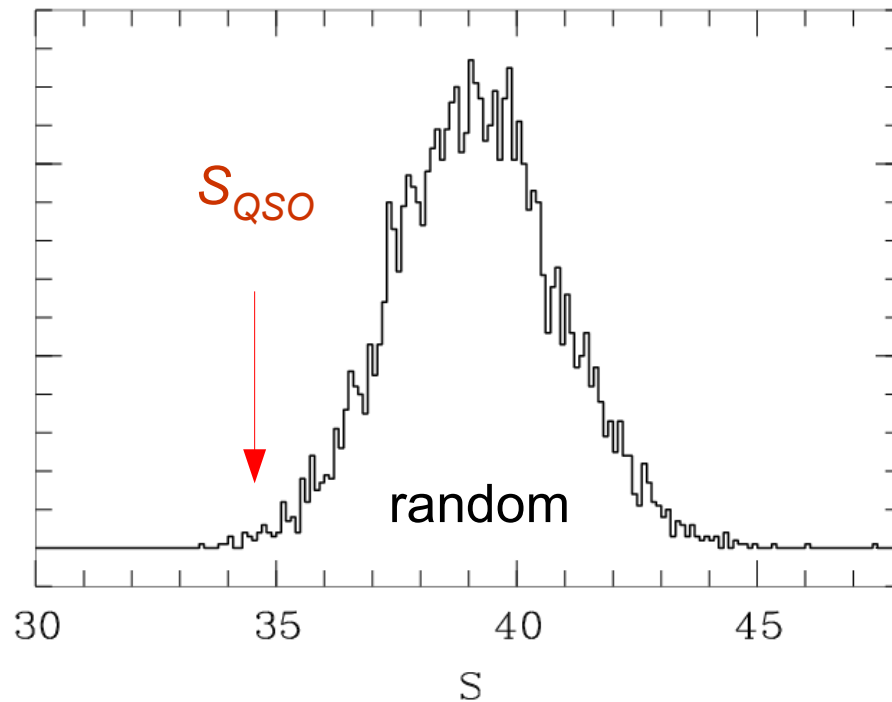
*Significance level*: percentage of simulated configurations with $S < S_{QSO}$

# Global statistical analysis: results



170 quasars
(1998)

# Global statistical analysis: results



170 quasars
(1998)

213 quasars
(2001)

# Global statistical analysis: results



170 quasars
(1998)

213 quasars
(2001)

355 quasars
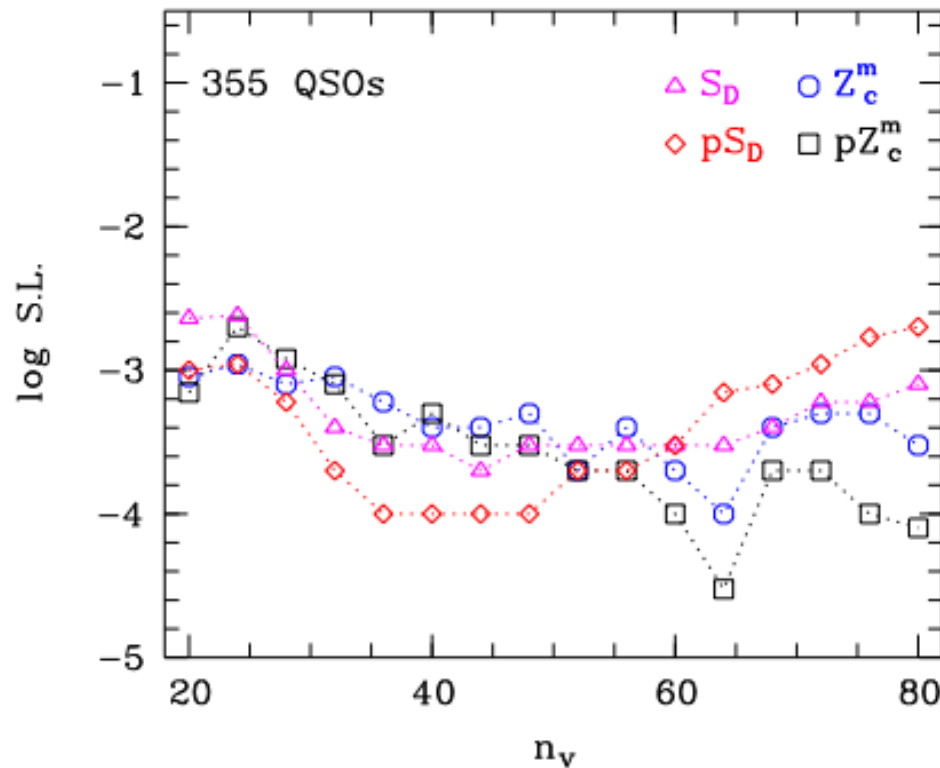(2005)
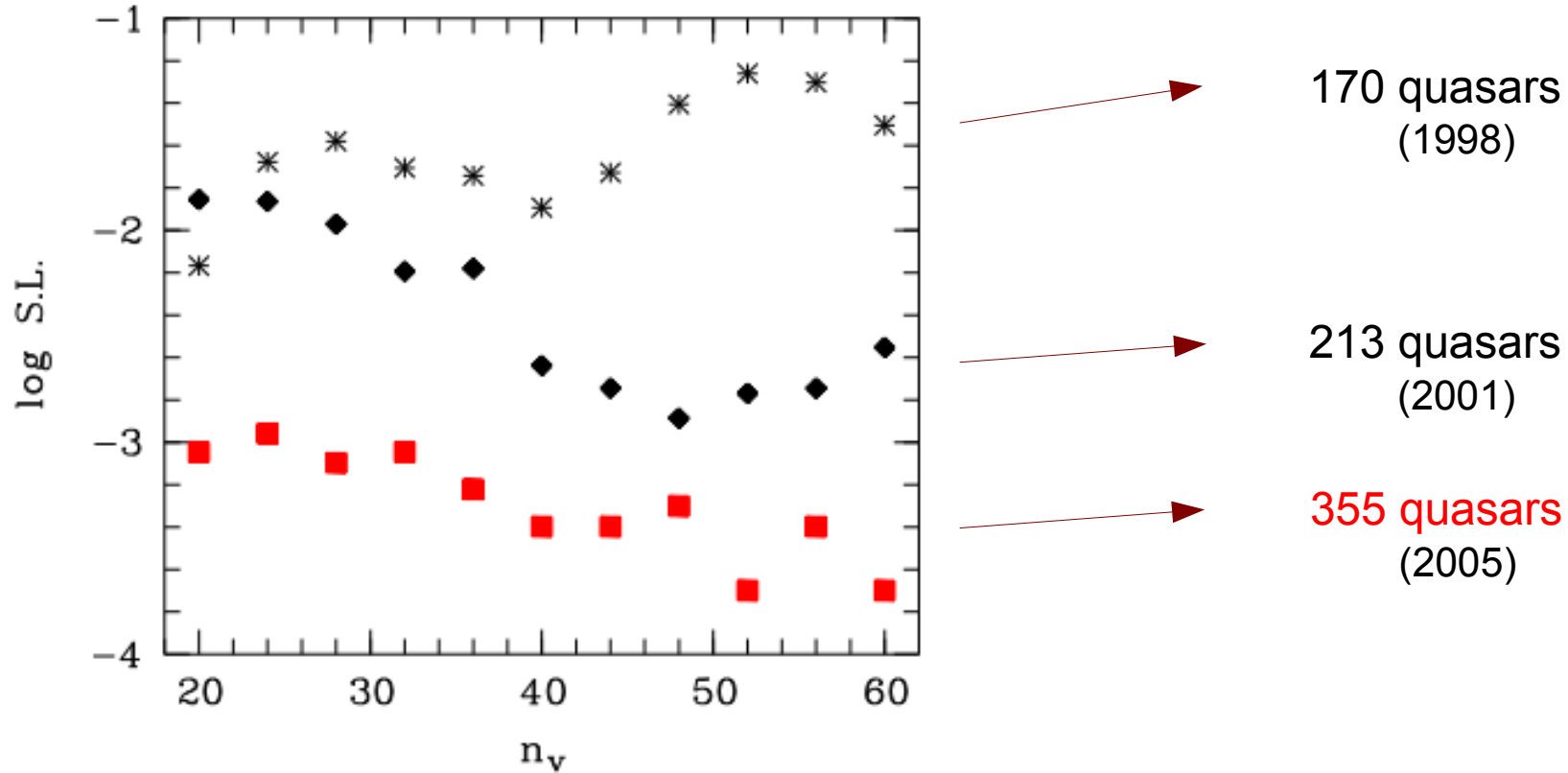
→ *It is more and more difficult to reproduce the observed alignments with random distributions*

# Global 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. <  0.1%)*
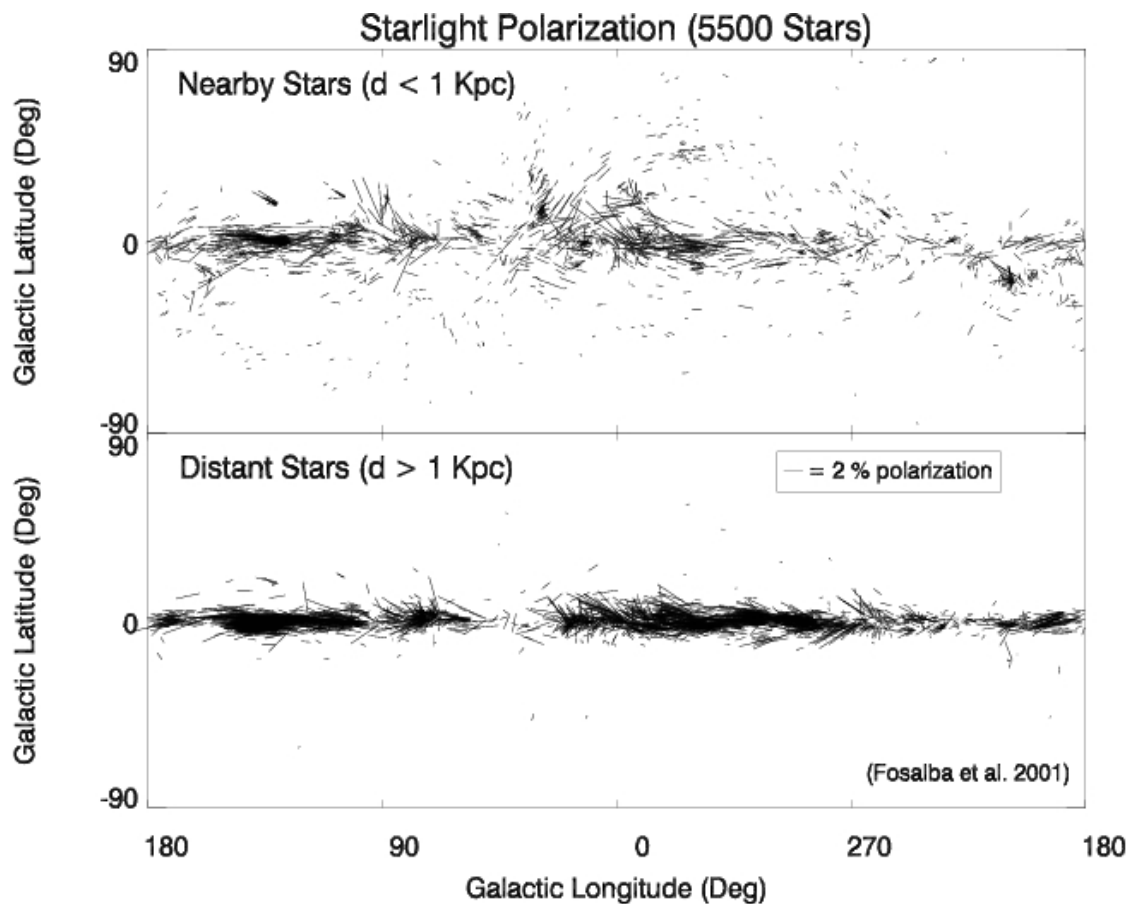
# Contamination by instrumental polarization?

*Systematic instrumental polarization?*

- Measurement of unpolarized and polarized standard stars: instrumental polarization < 0.1%, angle offset within 1°

- The quasar polarization degrees and angles measured in different surveys (with different instruments) do agree within the quoted errors
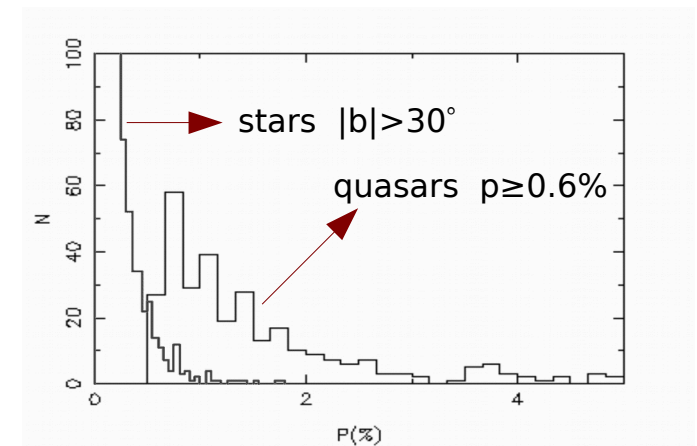
→ *Instrumental contamination is not significant*

# Contamination by interstellar polarization?

Polarization due to elongated dust grains aligned within the Galactic magnetic field (dichroism)



Starlight Polarization (5500 Stars)

Nearby Stars (d < 1 Kpc)

Distant Stars (d > 1 Kpc)    — = 2 % polarization

(Fosalba et al. 2001)

Galactic Latitude (Deg)

Galactic Longitude (Deg)

$p_{star} \leq$ 0.2-0.3% at high Galactic latitudes  ($|b|>30°$)



stars  |b|>30°

quasars  p≥0.6%

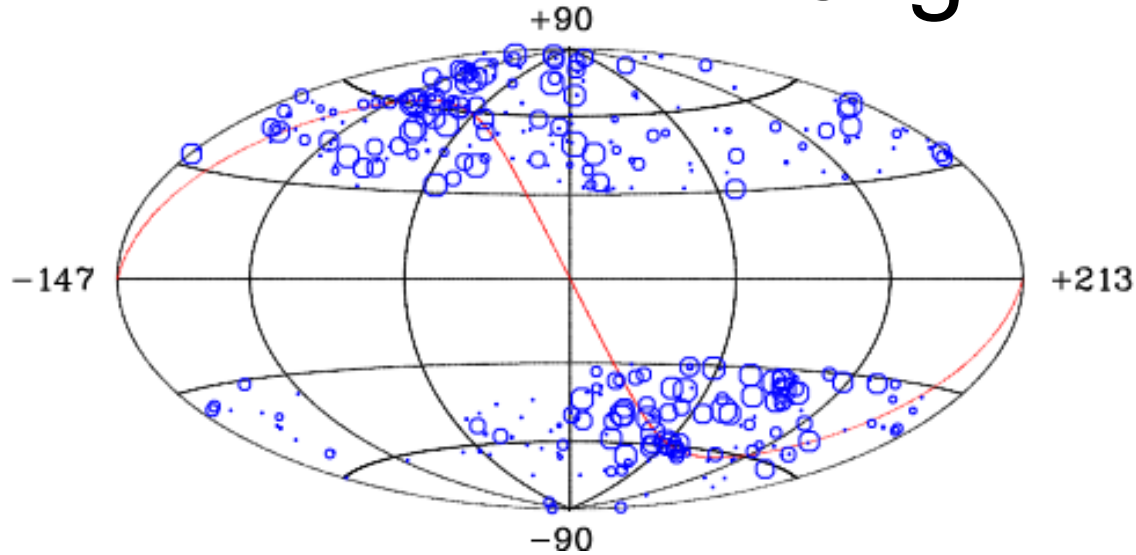$p_{QSO} \geq$ 0.6% is mostly intrinsic

# Contamination by interstellar polarization?
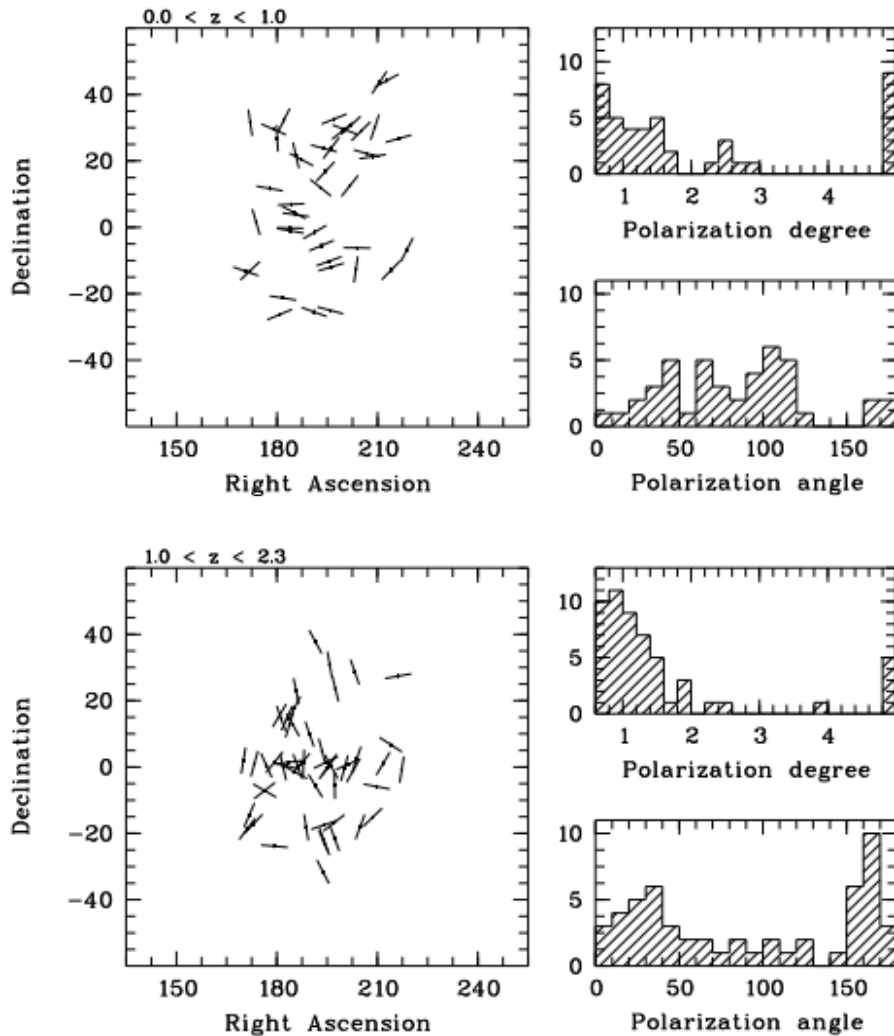


*Interstellar polarization is unlikely to be responsible for the observed alignments since its effect must be the same at all redshifts*
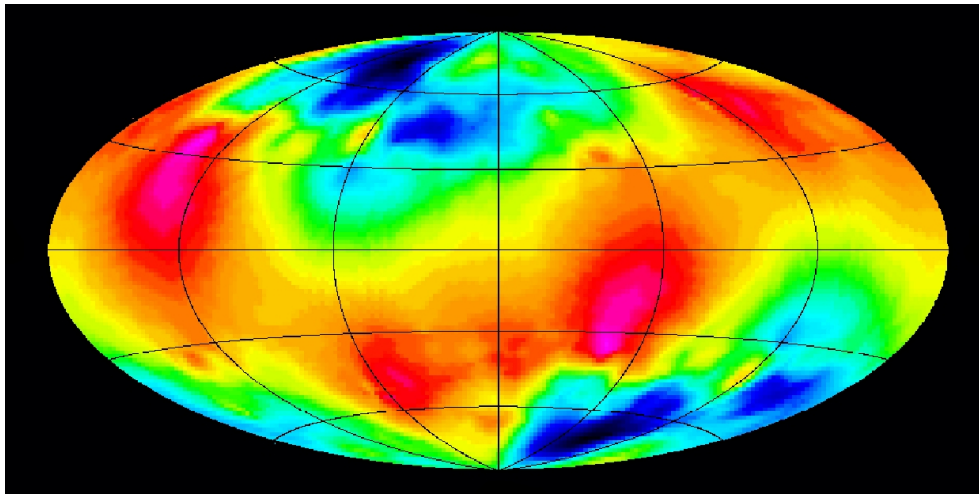
(See also Pelgrims 2019)

# Location of the most significant alignments
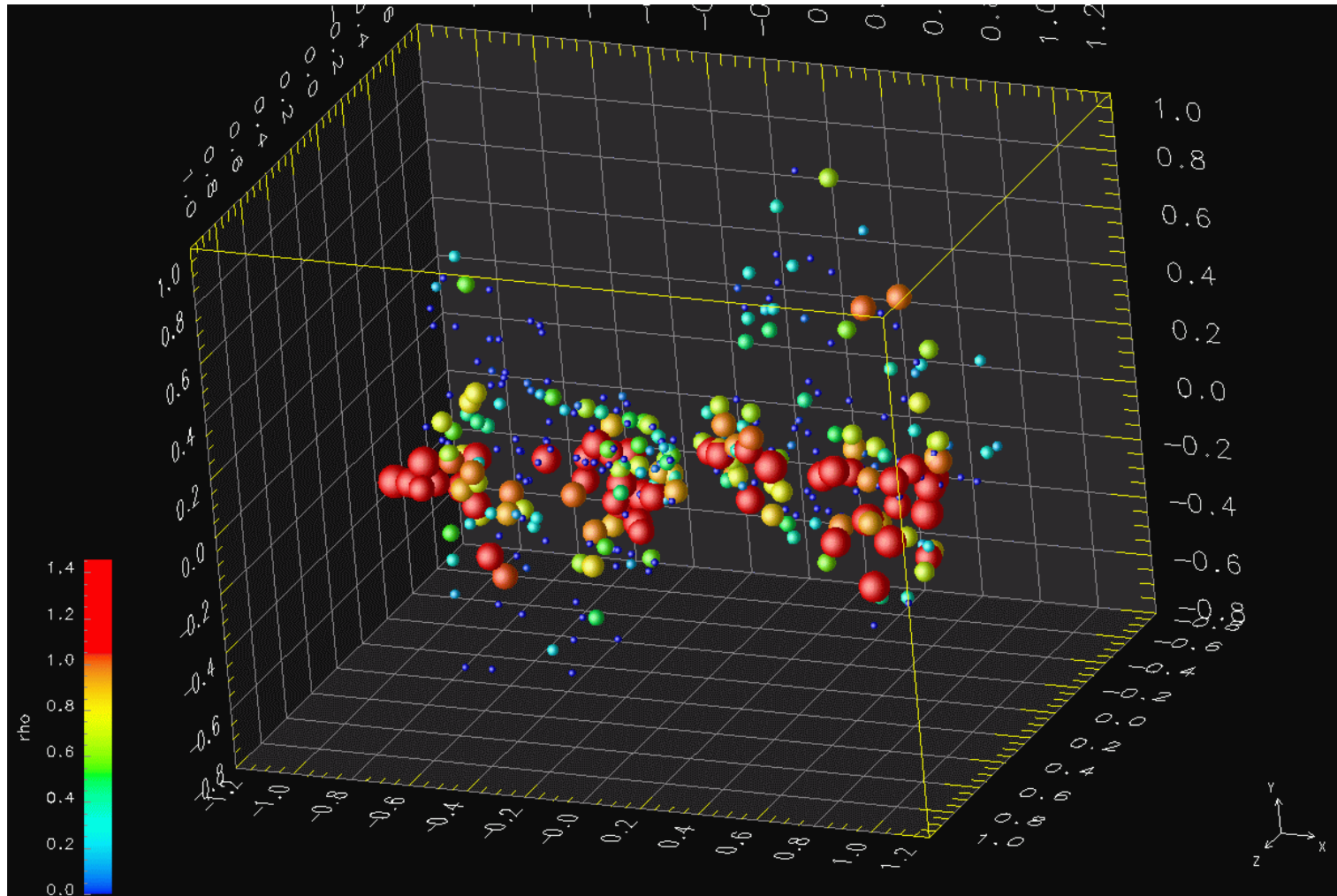


[Galactic coordinates]

*The most significant regions of alignments appear opposite on the sky*
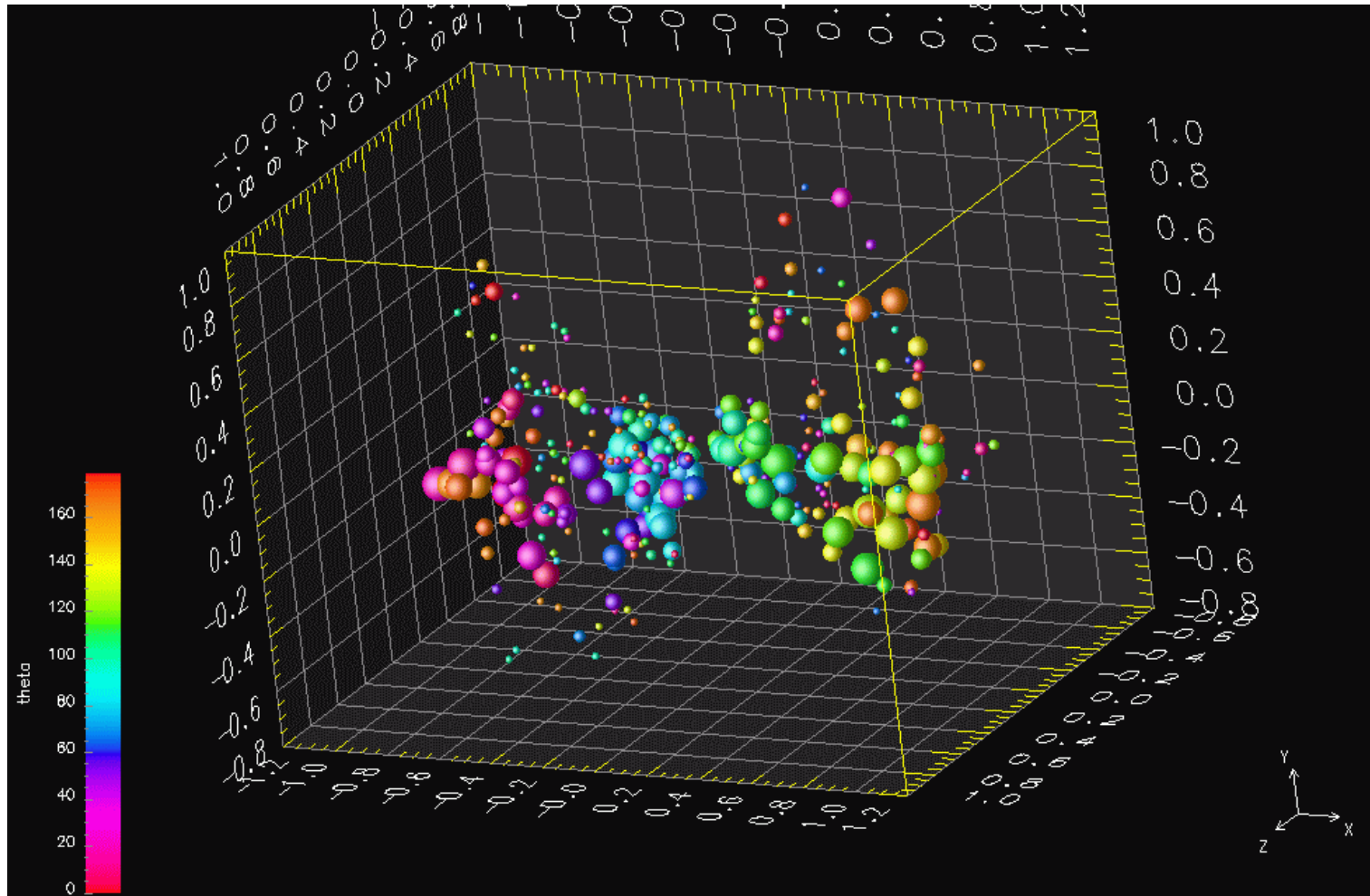
*Caution:*
Incomplete sky coverage



*Axis of polarization alignments ?*

# The effect is more significant along a specific axis

# The polarization angle rotates with the cosmological distance

# A preferred axis in the Universe?
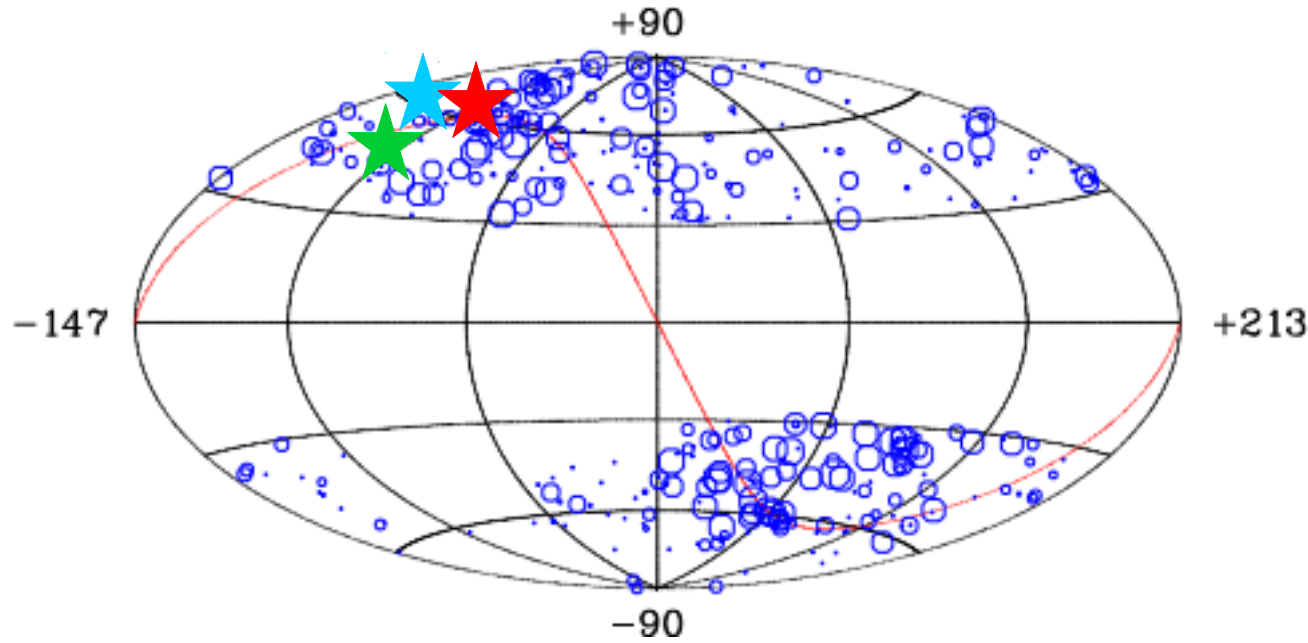


**Quasar polarization**
[α ~ 180°, δ ~ 10°]
[l ~ 270°, b ~ 70°]

**CMB dipole**

**Low CMB multipoles
(Axis of Evil)**
(Tegmark+2003, Land+2005,
de Oliveira-Costa+ 2006)

*Coincidences? Violation of the cosmological principle?*

Several other coincidences have been reported
(e.g. Ralston+2004, Perivolaropoulos 2014, Zhao+ 2016, Shamir 2021, Luongo+ 2021,
and references therein)

# Polarization alignments at radio wavelengths?

Polarizations from the 8.4 GHz JVAS/CLASS survey (Jackson+2007). 4265 flat-spectrum radio sources with polarized flux > 1mJy out of which 1531 have reliable redshifts. In this sample, Faraday rotation is negligible.

- Joshi et al. (2007): No evidence of polarization alignments on Gpc scales

- Tiwari & Jain (2013): Significant alignments on scales of 150 Mpc, and over > 500 Mpc considering low polarization sources

- Pelgrims & Hutsemékers (2015): Significant alignments on 600 Mpc scale at the location of optical alignments and when only considering quasars

Polarizations from the 86 Ghz + 229 Ghz survey (Agudo+2014). About 200 low-redshift radio sources.

Tiwari & Jain (2019): No evidence of polarization alignments

# Toward an interpretation

*→ Quasar polarization is partially modified along the line of sight; a small systematic polarization is added*

*→ Polarization is totally intrinsic to quasars and quasar axes themselves are aligned (that is SMBH spin axes)*

# Toward an interpretation

- *Polarization from intergalactic dust grains aligned within large-scale magnetic fields?*
  Not detected and requires strong magnetic fields over huge domains

- *Polarization from photon-axion mixing?*
  (Jain+2002, Das+2005, Agarwal+2011, Payez+2011)
  Ruled out by the absence of circular polarization (Hutsemékers+2010)

- *Cosmic strings?*
  (Poltis+2010, Slagter+2018, 2021)

- *Primordial large-scale magnetic fields?*
  (Tiwari+2021)

- *Anisotropic expansion of the Universe? Global rotation?*
  Effects on polarization and/or quasar spin axes may be expected, as well as on the CMB power spectrum
  (Brans 1975, Ciarcelluti 2012; Li 1998, Obhukov 2000, Godlowski 2011; Jaffe+ 2005)

# Alignments of quasar axes?

*→ Are quasar / SMBH axes aligned?*
*→ Are quasars aligned with their host structure?*
*→ Over Gpc scales?*

- *Known correlation between polarization and quasar structure*
  (In general optical PPA // and radio PPA ⊥ to the radio jet / SMBH spin axis)
  (Rusk+1985, Rusk 1990)

- *Alignments of galaxy orientations or spin axes with clusters, filaments and sheets are observed on scales up to 30 Mpc*
  (usually interpreted in the framework of the tidal torque theory or preferential merger directions along filaments)
  (e.g. Tempel+ 2013, Zhang+ 2013, Joachimi+ 2015, West+ 2017

  *[N.B. Filaments themselves may be spinning on scales up to 100 Mpc]*
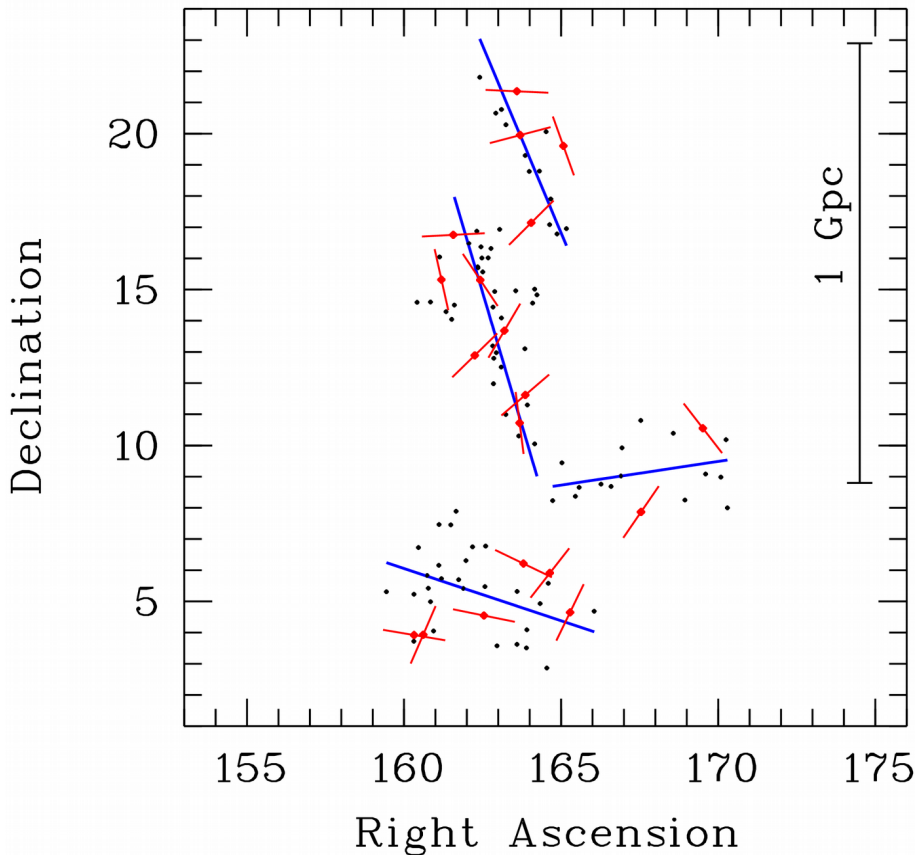  (Wang+ 2021)

# Quasar polarization in LQGs
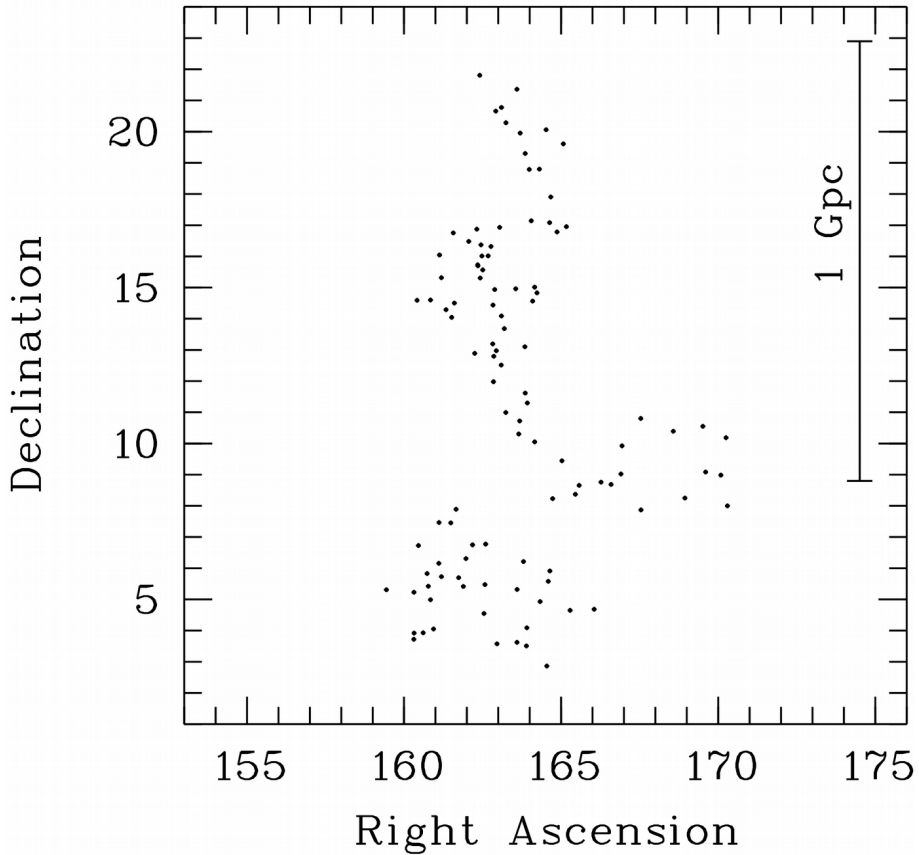


The Huge- and CC- LQGs
(Clowes+ 2013)
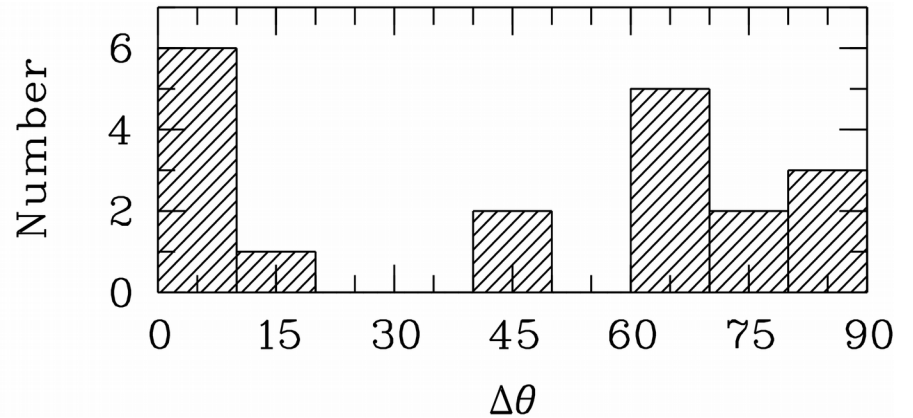
# Quasar polarization in LQGs
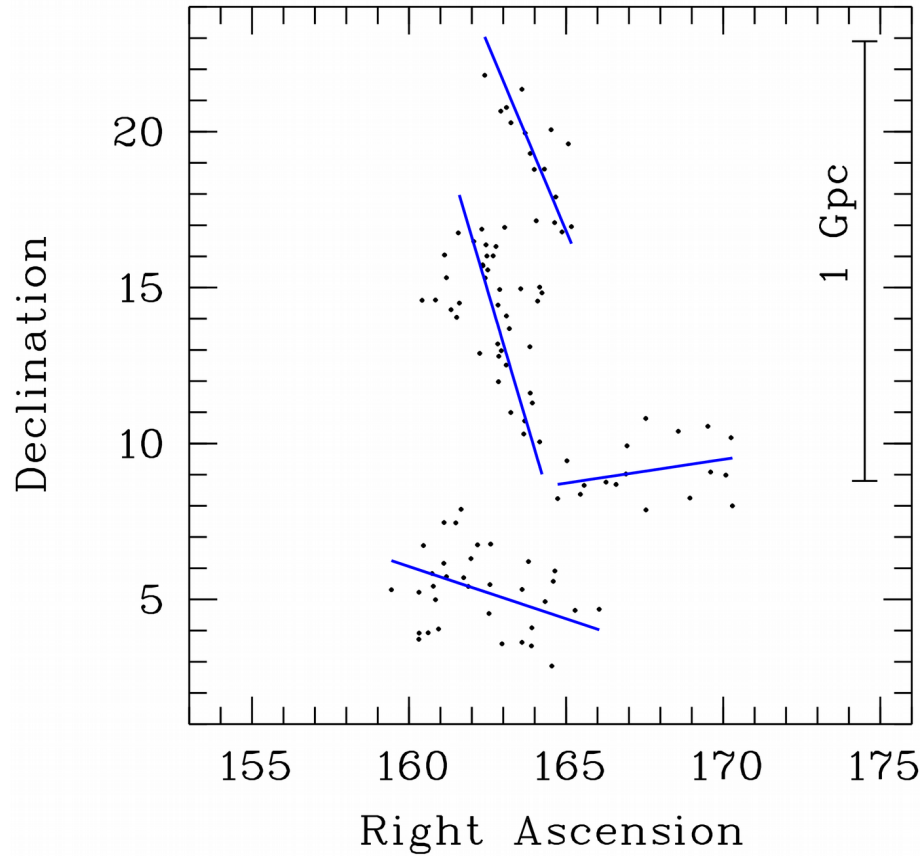


Orientations of sub-structures
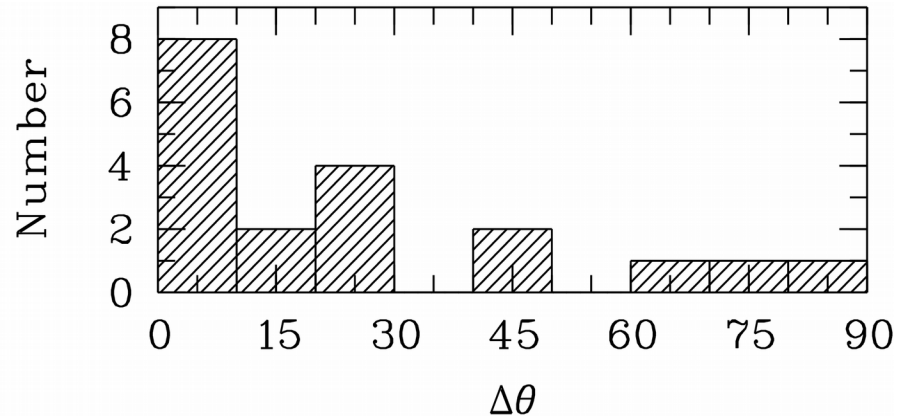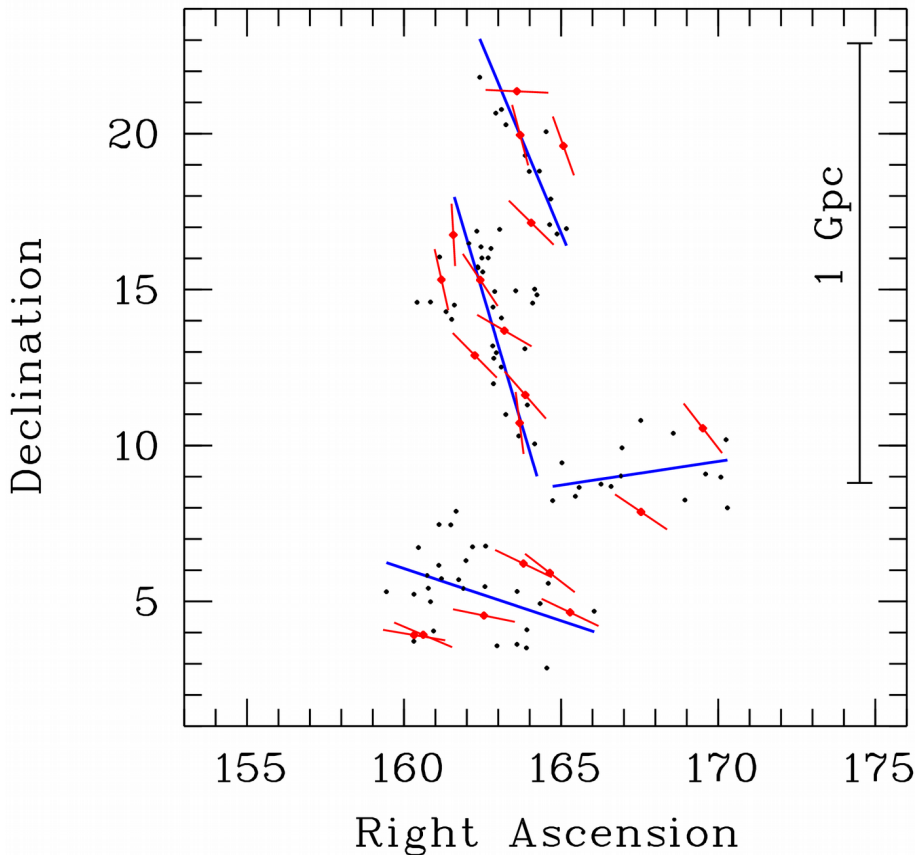
# Quasar polarization in LQGs



*Quasar optical polarization vectors are either parallel or perpendicular to the large-scale structure to which they belong (P ~ 99%)*

Quasars significantly polarized (p > 0.6%)
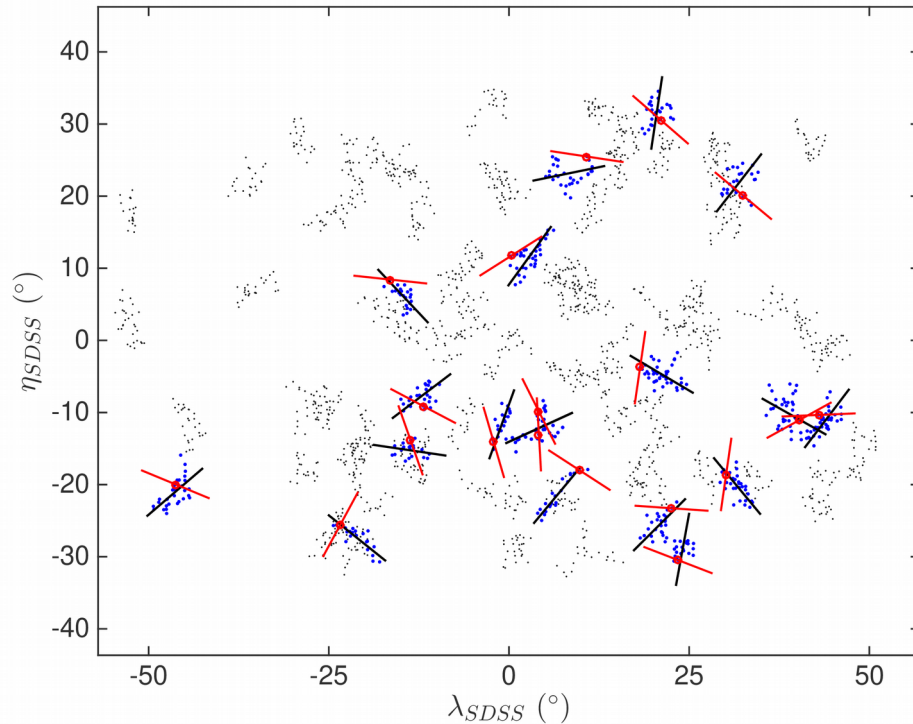
# Quasar polarization in LQGs



*Quasar axes are preferentially parallel to the axis of the host large-scale structure*

(Hutsemékers+ 2014)

With rotation of the polarization angle by 90º assuming it depends on object's inclination w.r.t. the line of sight

# Quasar radio polarizations in LQGs



**Quasars in LQGs**
(Einasto+ 2014)

Richness m > 20
Redshift 1.0 < z < 1.8

LQGs contain at least one
polarized quasar

Major axes of LQGs from
inertia tensors

*Polarization vectors are mostly perpendicular to the LQG major axes (P > 99%), and consequently quasar axes are parallel to the LQG major axes* (Pelgrims+ 2016)

# Quasar radio polarizations in LQGs
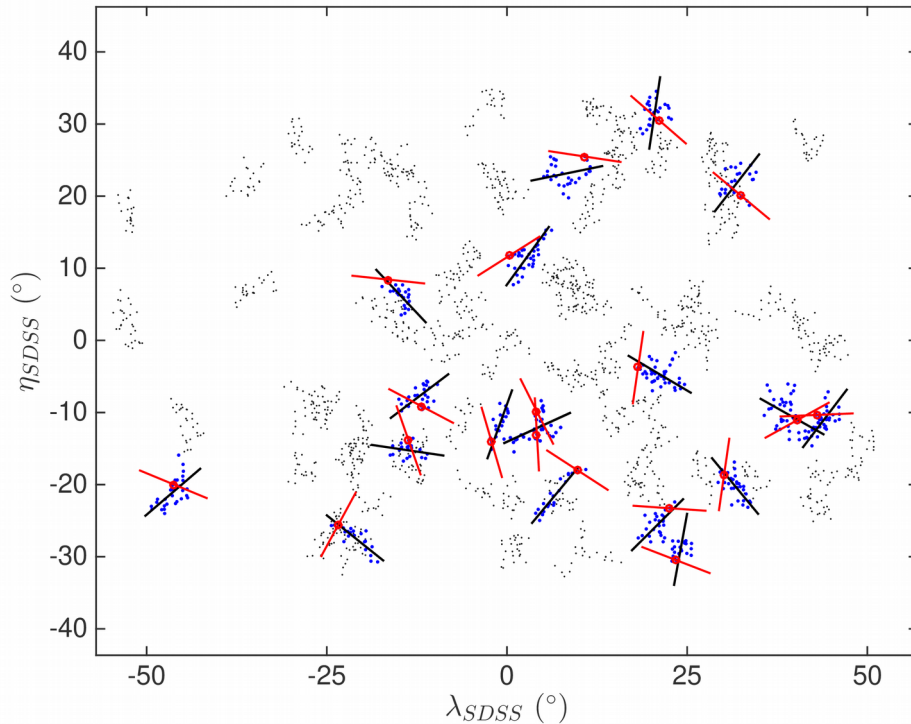


**Quasars in LQGs**
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inertia tensors

*Polarization vectors are mostly perpendicular to the LQG major axes (P > 99%), and consequently quasar axes are parallel to the LQG major axes* (Pelgrims+ 2016)

*LQGs themselves are apparently coherently oriented over scales reaching 1.6 Gpc, linking polarization alignments at various scales*
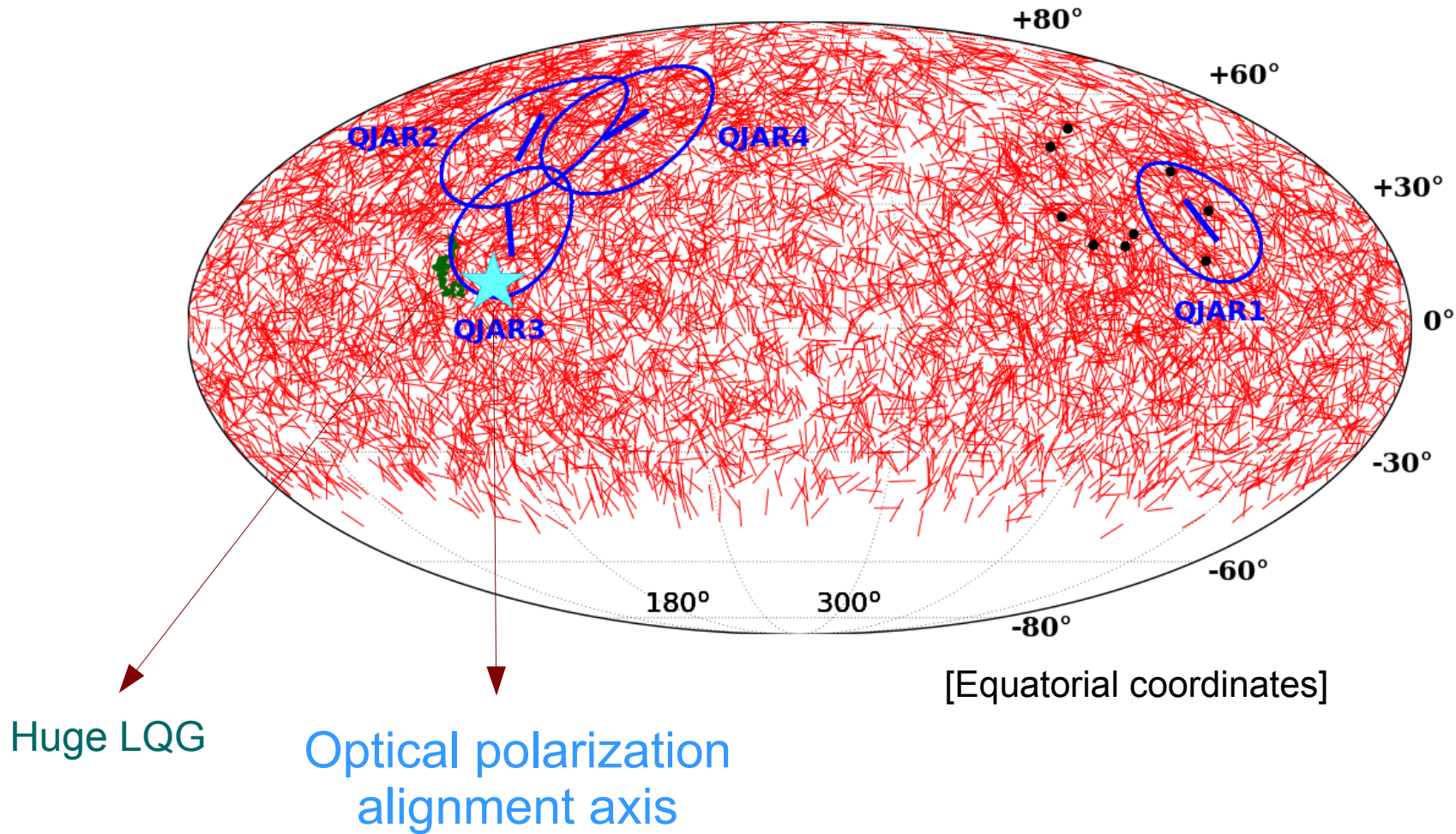(Friday 2020)

# Quasar radio jet alignments

| Data | Test | Scale | References |
|---|---|---|---|
| GMRT (Elais 1) | Mutual alignments – 2D | 30 Mpc | Taylor+2016 |
| FIRST | Mutual alignments – 2D<br>Mutual alignments – 3D | 30 Mpc<br>640 Mpc ? | Contigiani+2017,<br>Panwar+2020 |
| LoTSS | Mutual alignments – 2D<br>Mutual alignments – 3D | 100 Mpc<br>No signal | Osinga+2020 |
| VLBI | Mutual alignments – 2D<br>Mutual alignments – 3D | No signal > 40 Mpc<br>400 to 900 Mpc | Blinov+2020,<br>Mandarakas+2021 |
| Fermi-LAT | BL Lac clustering | 350 Mpc | Marcha+2021 |

# Radio jet alignments: preferred location?



[Equatorial coordinates]

Huge LQG
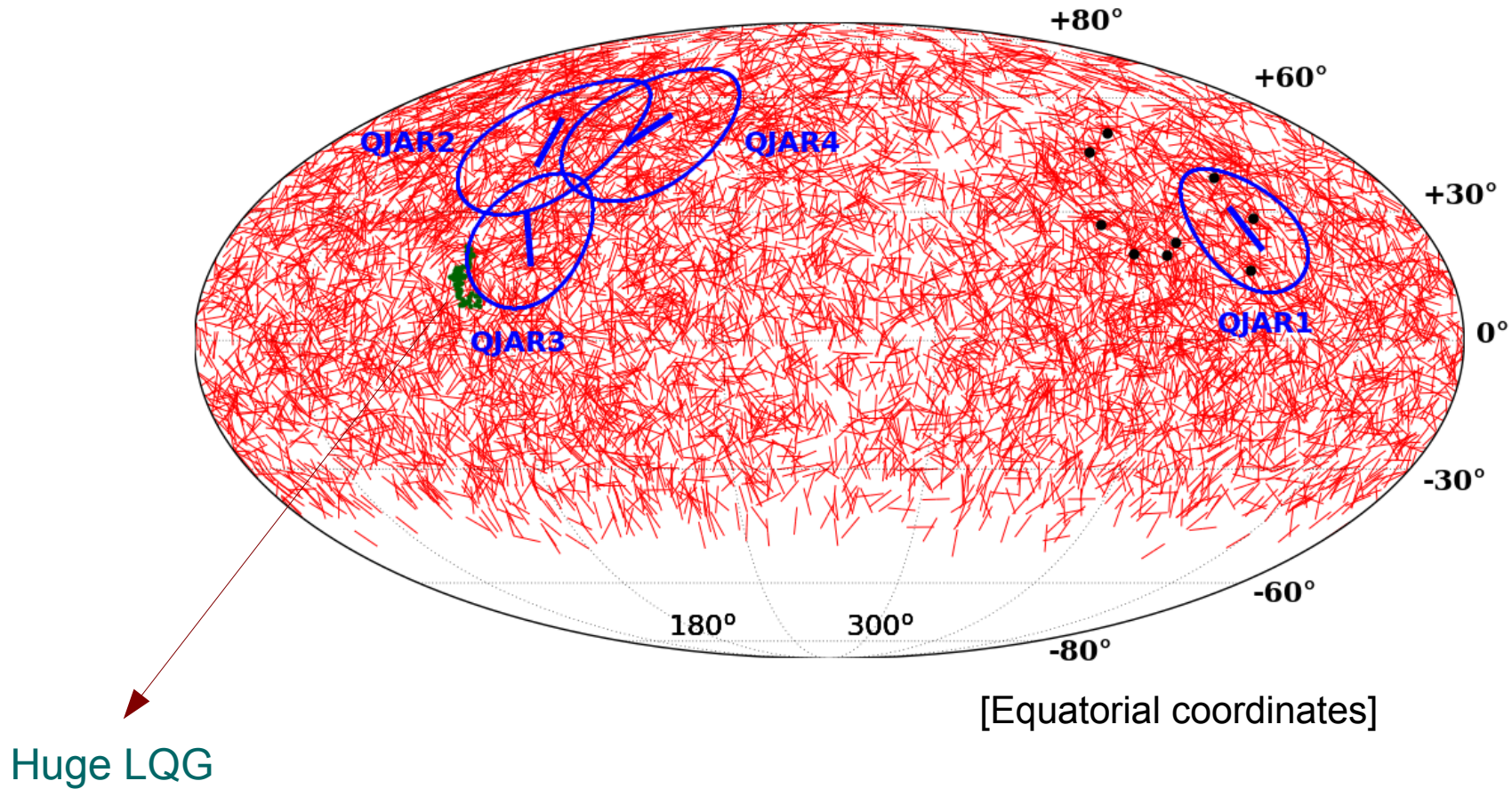
(From Mandarakas+ 2021)

# Radio jet alignments: preferred location?



Huge LQG

Optical polarization alignment axis

[Equatorial coordinates]

(From Mandarakas+ 2021)

# In a nutshell

- *There is evidence for large-scale angular correlations of quasar polarization vectors (regions of ~ 1 Gpc size at z ~ 1)*

- *The effect seems stronger along an axis close to the CMB "Axis of Evil". The mean polarization angle rotates along this axis*

- *The quasar axes inferred from polarization are apparently related to the orientation of the host large-scale structure*

- *There is evidence for large-scale alignments of quasar jets themselves*

*Do quasar (SMBH spin axis) alignments indicate departure to the fundamental cosmological assumption of large-scale isotropy / homogeneity ?*