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Cosmological Birefringence:
an astrophysical test of fundamental physics

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The relevance of cosmological birefringence

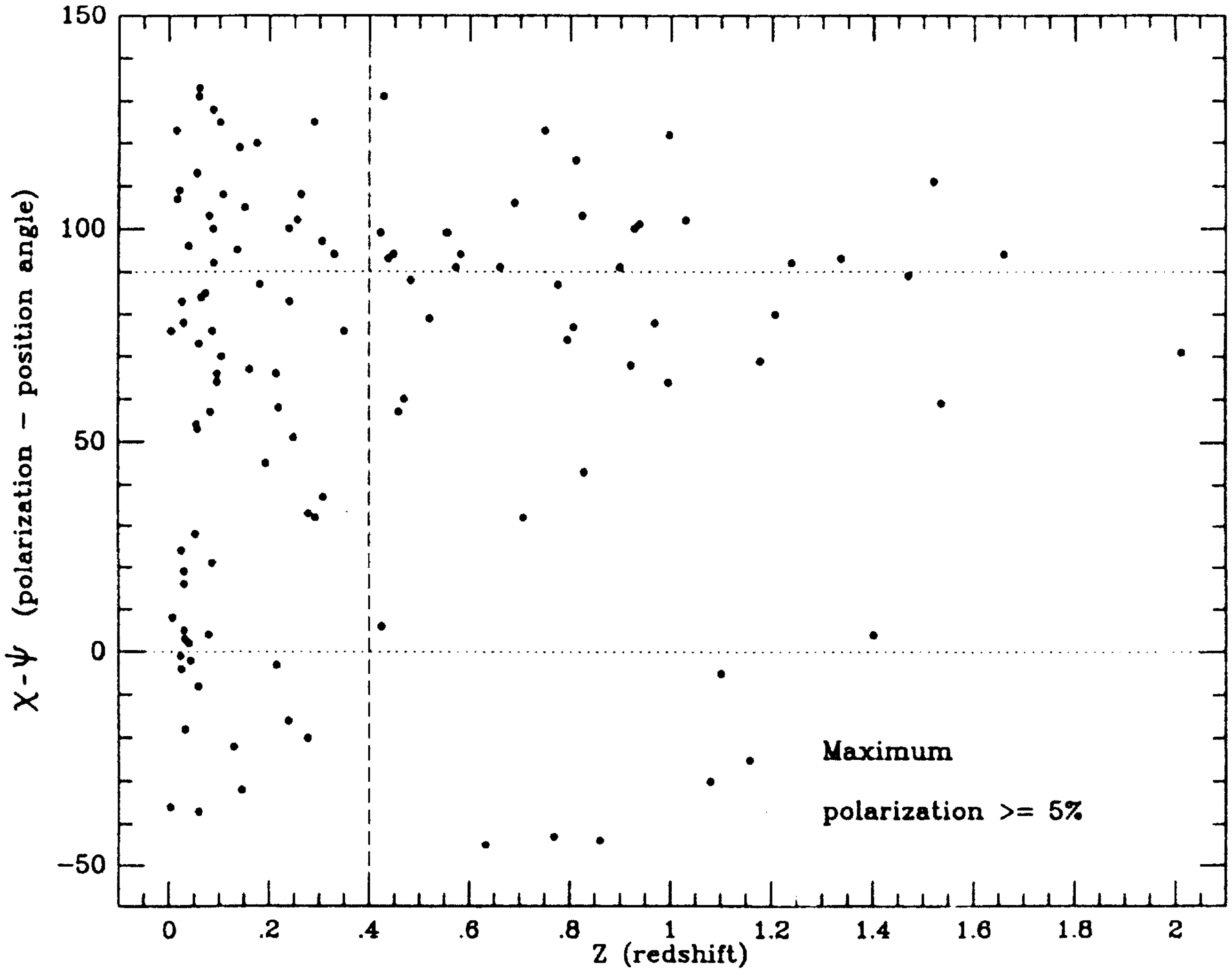
Cosmological birefringence or, better, optical activity, i.e. a frequency independent rotation of the plane of linear polarization for light traveling long distance trough the universe, might arise for:

1. The presence of a cosmological pseudoscalar condensate;
2. Lorentz invariance violation;
3. CPT violation;
4. Neutrino number asymmetry;
5. EEP violation.

See Ni 2008, 2010 for a review.

Birefringence test with the radio polarization of distant RG

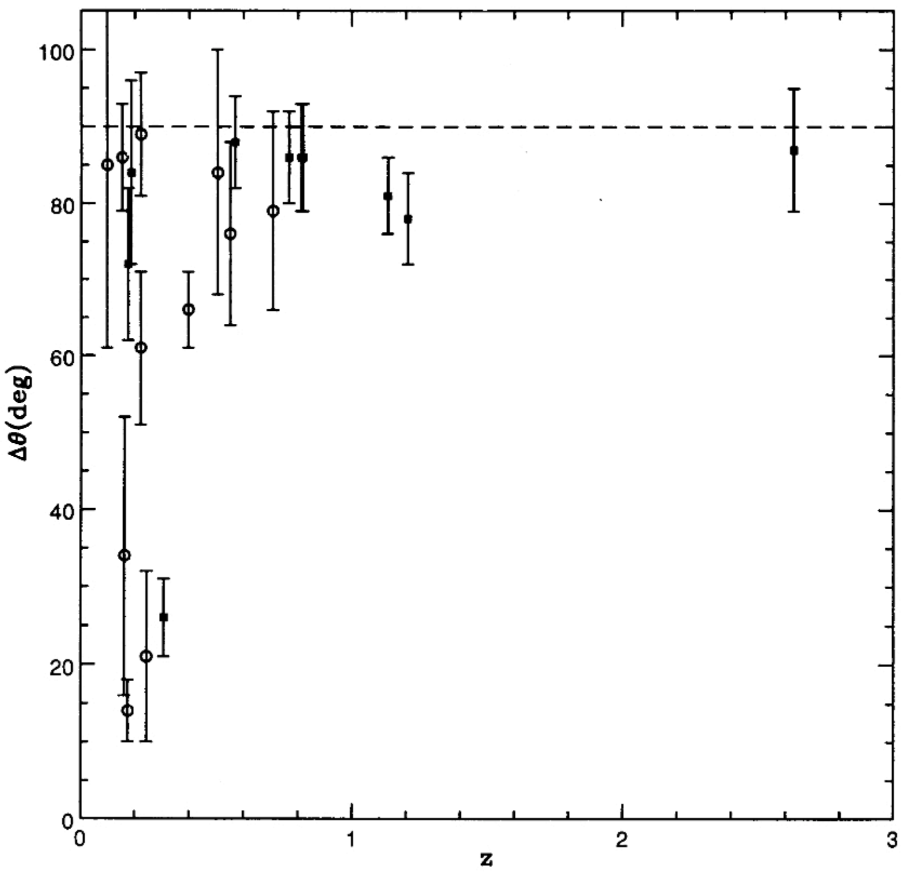
Carroll, Field & Jackiw (1990) have looked at the difference between the PA (χ) of the radio polarization, corrected for Faraday rotation ($\theta(\lambda) = \alpha\lambda^2 + \chi$), and the PA ($\psi$) of the radio axis of RG with $0.4<z<2$ and $P>5\%$ and find a peak in the distribution at 90° (and a smaller one at 0°). From the width of the distribution they conclude that any rotation of the polarization must be smaller than 6.0° at the 95% confidence level.



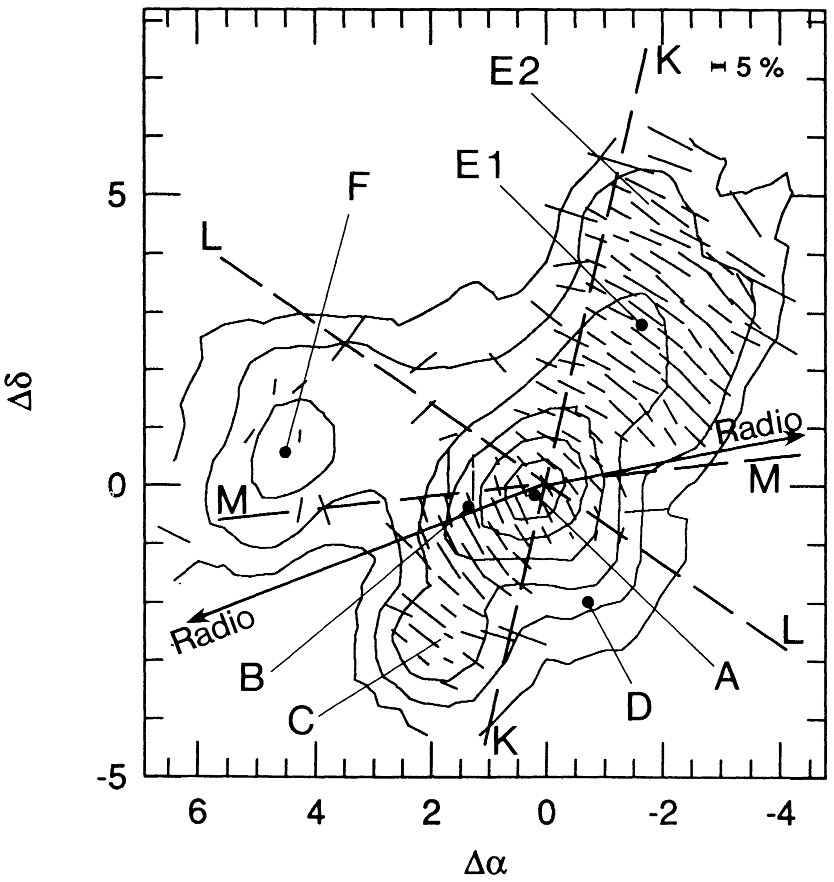
Birefringence test with the optical/UV polarization of distant RG

Cimatti, di Serego Alighieri, Field & Fosbury (1994) have used the perpendicularity between the optical/UV axis and the direction of the plane of optical/UV polarization to show that this plane is not rotated by more than 10° for every distant RG with a polarization measurement, up to z=2.63. This perpendicularity is strictly expected, since the elongation and the polarization are due to scattering of anisotropic nuclear radiation. The advantages of the optical/UV test over the radio one are:

1. It does not require correction for Faraday rotation.
2. It is based on a strict physical predition of the polarization orientation due to scattering.
3. It holds for every single distant RG, not just statistically.



Scattering of anisotropic optical/UV nuclear radiation in powerful radio galaxies



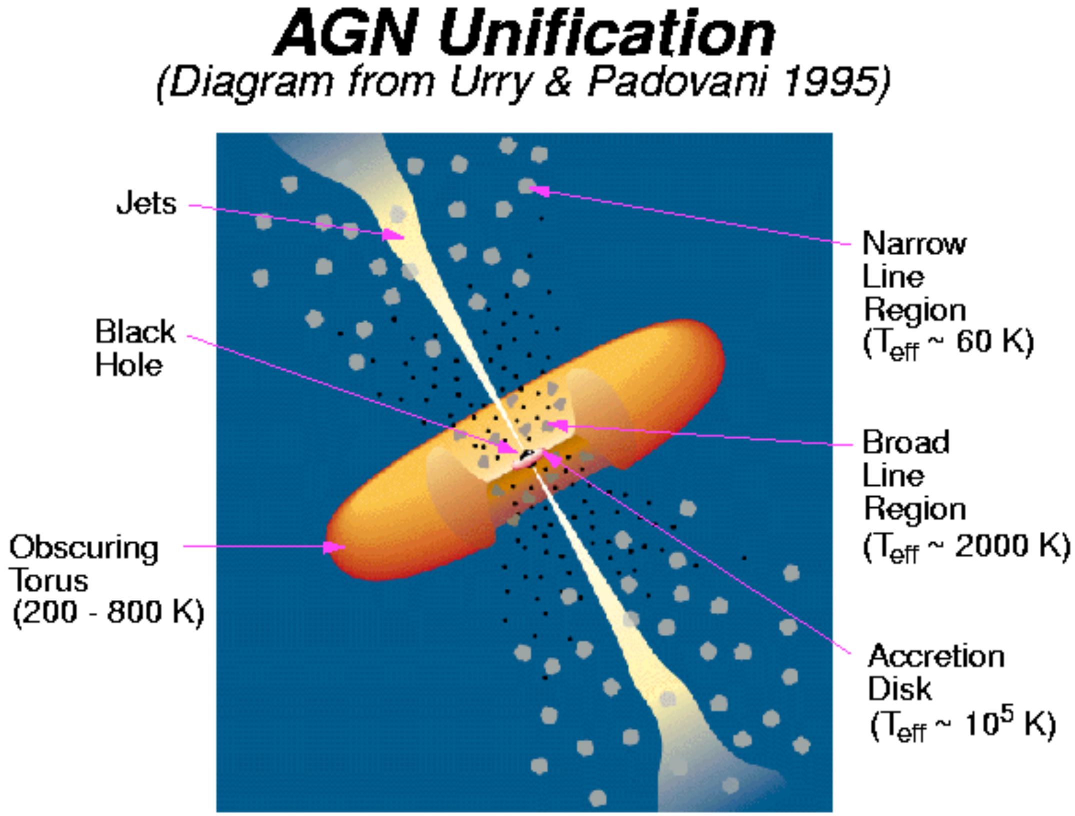
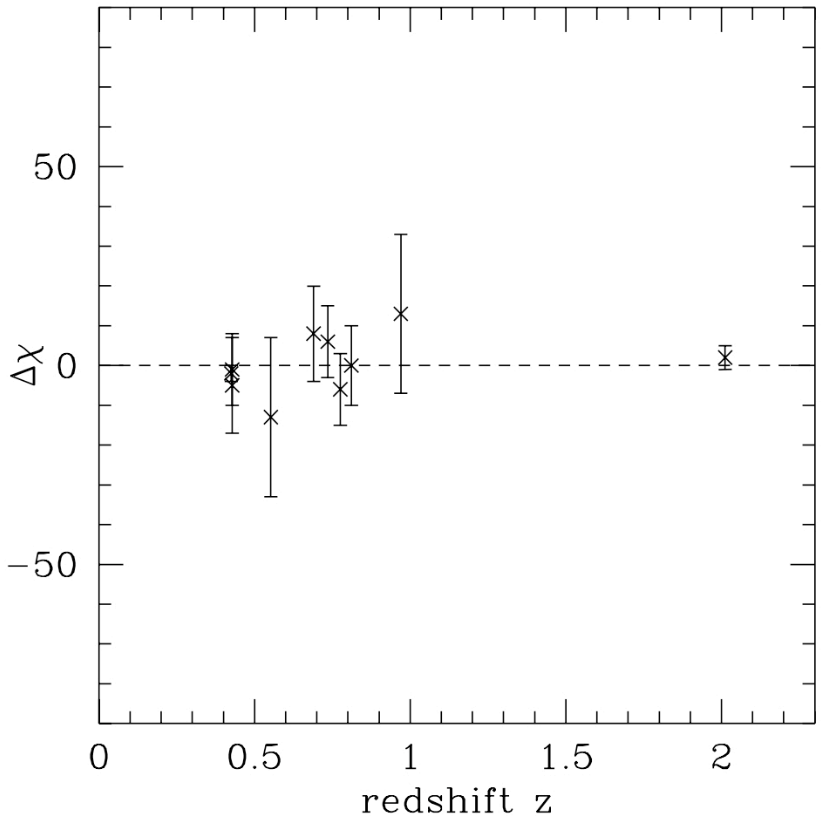


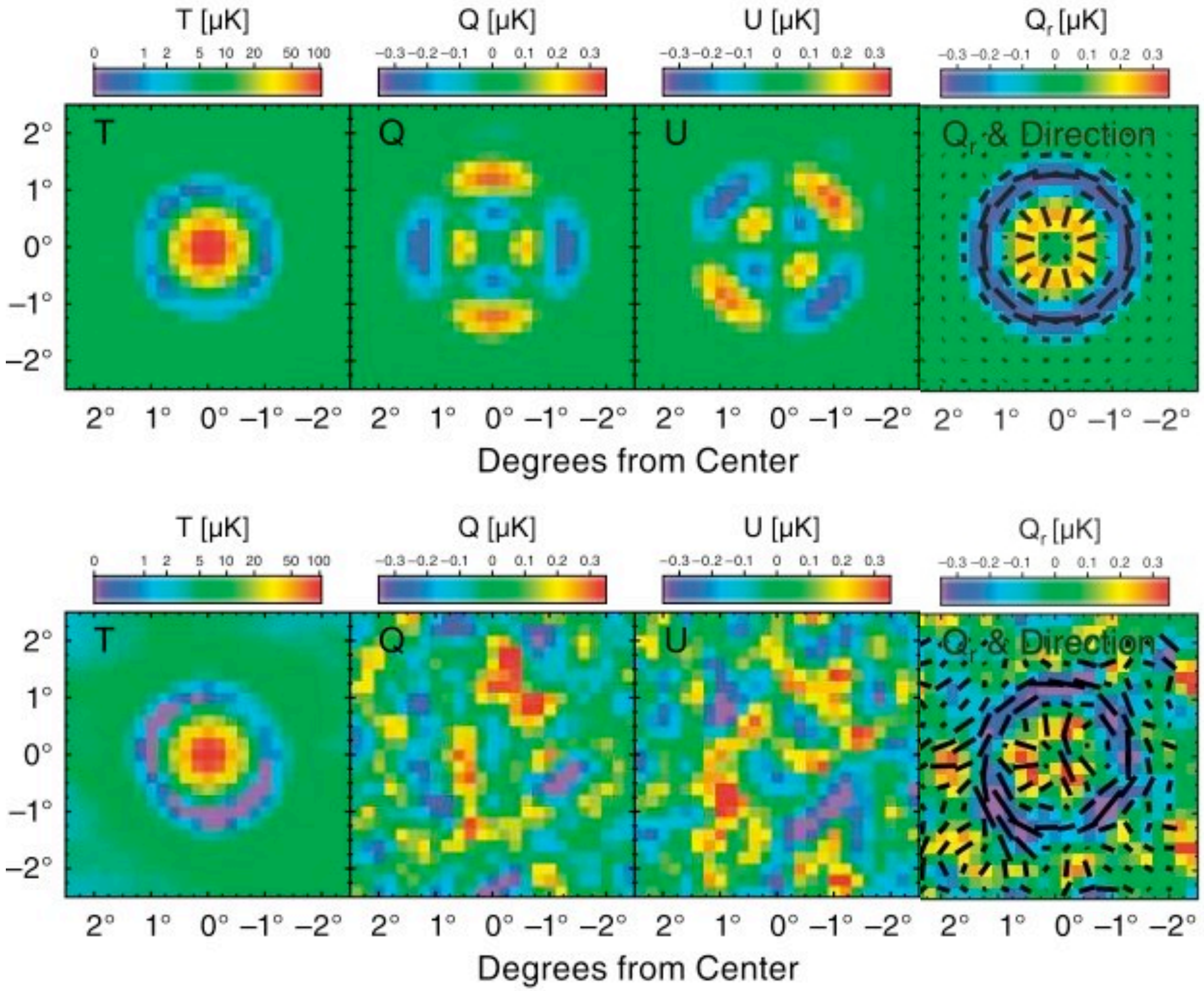
Image Polarimetry of 3C 265 by Cohen et al. 1996
V band, at z=0.811 λ~3000Å

Difficulties for the radio birefringence test on RG

Nodland & Ralston (1997), re-examining the data on the radio polarization of RG used by Carroll, Field & Jackiw (1990), claimed to have found a systematic rotation of the plane of polarization, independent of the Faraday one, and correlated with the angular position and with the distance of the RG.
However several authors (Wardle et al. 1997, Eisenstein & Bunn 1997, Carroll & Field 1997, Laredo et al. 1997) have independently and convincingly argued against this claim, and additional unpublished data (Leahy 1997) on the lack of rotation for the radio polarization of distant RG have been reported (Carroll 1998).



Birefringence test based on the CMB



WMAP7 data (Komatsu et al. 2010) on CMB temperature and polarization.
Top panel: model for a temperature hot spot.
Bottom panel: coadded WMAP7 data for temperature hot spots.

Birefringence limits from CMB polarization

Table 1. Constraints on Linear Polarization Rotation $\bar{\theta}$ in the Constant Angle Approximation.

Data Set	$\bar{\theta}$ (2σ) (deg)	Reference
WMAP3 and Boomerang (B03)	$-13.7 < \bar{\theta} < 1.9$	1
WMAP3	$-8.5 < \bar{\theta} < 3.5$	2
WMAP5	$-5.9 < \bar{\theta} < 2.4$	3
QUaD	$-1.2 < \bar{\theta} < 3.9$	4
WMAP7	$-5.0 < \bar{\theta} < 2.8$	5

References. — (1) Feng et al. (2006); (2) Cabella et al. (2007); (3) Komatsu et al. (2009); (4) Wu et al. (2009); (5) Komatsu et al. (2010).

An update on the birefringence test with the UV polarization of distant RG

Since our first test based on the optical/UV polarization of distant RG in 1994, several new polarization data have become available. Therefore we have made an update of the test (di Serego Alighieri, Finelli & Galaverni 2010, ApJ 715, 33).

We have taken all the RG with z>2, P>5% in the UV (λ~1300Å), and elongated UV morphology, and measured the difference between the PA of the linear UV polarization and the PA of the UV axis.

Table 2. Linear Far UV Scattering Polarization in Distant RG.

RG Name	RA. (deg)	Dec. (deg)	z	P (%)	Pol. P.A. (deg)	UV P.A. (deg)	ΔP.A. (deg)	θ (1σ) (deg)
MRC 0211-122	33.5726	-11.9793	2.34	19.3±1.15[a]	25.0±1.8	116±3[b]	89.0±3.5	$-4.5 < \theta < 2.5$
4C -00.54	213.3131	-0.3830	2.363	8.9±1.1[c]	86±6	4±5[b]	82±8	$-16 < \theta < 0$
4C 23.56a	316.8111	23.5289	2.482	15.3±2.0[c]	178.6±3.6	84±9[d]	94.6±9.7	$-5.1 < \theta < 14.3$
TXS 0828+193	127.7226	19.2210	2.572	10.1±1.0[a]	121.6±3.4	30±3[b]	91.6±4.5	$-2.9 < \theta < 6.1$
MRC 2025-218	306.9974	-21.6825	2.63	8.3±2.3[e]	93.0±8.0	7±5[b]	86±9	$-13 < \theta < 5$
TXS 0943-242	146.3866	-24.4804	2.923	6.6±0.9[a]	149.7±3.9	60±2[b]	89.7± 4.4	$-4.7 < \theta < 4.1$
TXS 0119+130	20.4280	13.3494	3.516	7.0±1.0[f]	0±15	85±5[g]	95±16	$-11 < \theta < 21$
TXS 1243+036	191.4098	3.3890	3.570	11.3±3.9[a]	38.0±8.3	132±3[b]	86.0±8.8	$-12.8 < \theta < 4.8$
Mean			2.80				89.2±2.2	$-3.0 < \theta < 1.4$

Note. — The last row shows the mean for all RG.

[a] Vernet et al. (2001)

[b] Pentericci et al. (1999)

[c] Cimatti et al. (1998)

[d] Knopp & Chambers (1997)

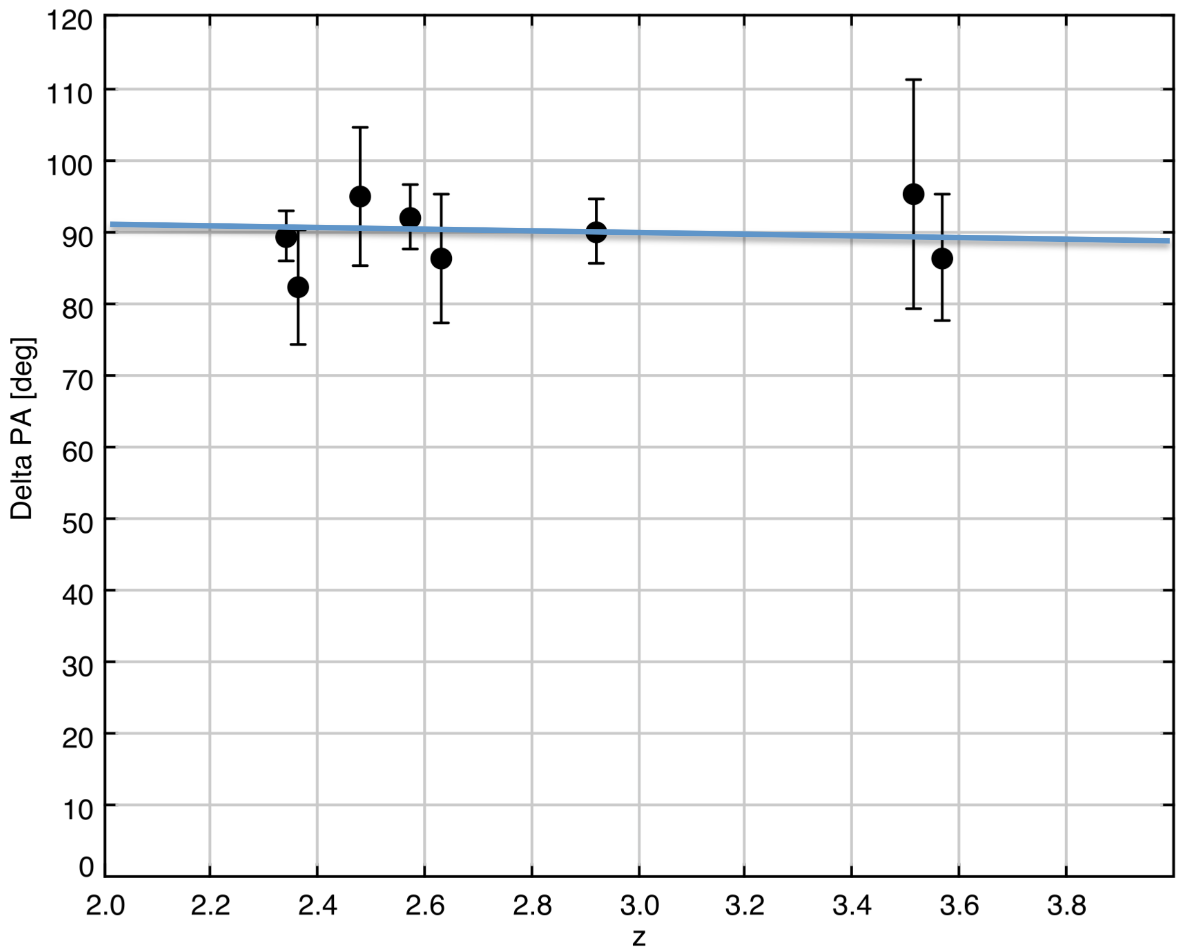
[e] Cimatti et al. (1994)

[f] C. De Breuck (2009, private communication)

[g] De Breuck et al. (2002)

An update on the birefringence test with the UV polarization of distant RG

Assuming that the rotation of the polarization plane should be the same in every direction, we can set the average constraint on the rotation:
$\theta = -0^{\circ}.8 \pm 2^{\circ}.2$



A test of the Einstein Equivalence Principle (EEP)

The equivalence principle equates a gravitational field and a uniformly accelerated frame (inertial mass = gravitational mass). It comes in three forms:

1. The weak equivalence principle (WEP, or Galilean EP) states the equivalence as far as the motion of free falling bodies is concerned.
2. The EEP extends the equivalence to all experiments involving non-gravitational forces; all metric theories of gravity are based on the EEP.
3. The strong equivalence principle (SEP) extends the equivalence also to gravitational experiments.

The WEP is tested to an accuracy of $\sim 10^{-13}$ by Eötvös type (torsion balance) experiments, while the EEP is tested to an accuracy of only $\sim 10^{-4}$ by gravitational redshift experiments.

In 1960 Schiff has conjectured that any complete, self-consistent theory of gravity, which obeys the WEP, would necessarily obey the EEP.

However Ni (1977) has found a unique counterexample to Schiff's conjecture: a pseudoscalar field φ that couples to electromagnetism in a Lagrangian of the form:

$$L = -1/(16\pi)\ \varphi\ e^{\mu\nu\rho\sigma}\ F_{\mu\nu}\ F_{\rho\sigma}$$

leading to a violation of the EEP, while obeying the WEP.

Carroll & Field (1991) have shown that, if such coupling were significant in a cosmological context, then the plane of polarization of light coming from very distant objects would be rotated during its journey across a considerable fraction of the size of the Universe.

If we could show that such a rotation is not observed, we would conclude that the EEP is not violated in this unique fashion.

Other applications of the Birefringence test

As we have seen, upper limits on the rotation of the polarization plane can be used to constrain cosmological birefringence caused by the coupling of the electromagnetic field to pseudo-scalar fields, therefore to put limits on the existence of light pseudo-scalar particles.
Such particles are viable candidates either for the dark matter (Kold & Turner 1990) or for the dark energy (Frieman et al. 1995), depending on their mass. Please see ApJ 715, 33 for details.
The current situation is that the cosmological birefringence tests cannot at the moment set useful constraints on the nature of dark matter or dark energy.

Further developments of the birefringence test with the UV pol. of RG

Very recently Kamionkowski (2010) has used our data to set limits on a rotation of the plane of polarization, which depends on the direction in the sky $\alpha(\theta,\varphi)$ with a spherical-harmonic variation and a stochastic variation. In the latter case the constraint is $\langle\alpha^2\rangle^{1/2} \leq 3.7°$. This non-uniform rotation is foreseen by some quintessence models (e.g. Li & Zhang 2010) and by some dark-matter models (Gardner 2008).

Also, Kostelecky & Mewes (2001, 2002) have developed a formalism in which CPT is conserved, but Lorentz invariance is violated, and birefringence effects grow with photon energy. In this case our test based on UV photon is more suitable than those at longer wavelengths.