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Limits on Cosmological Birefringence from the Ultraviolet Polarization of Distant Radio Galaxies

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ABSTRACT

We report on an update of the test on the rotation of the plane of linear polarization for light traveling over cosmological distances, using a comparison between the measured direction of the UV polarization in eight RG at $z > 2$ and the direction predicted by the model of scattering of anisotropic nuclear radiation, which explains the polarization. No rotation is detected within a few degrees for each galaxy and, if the rotation does not depend on direction, then the all–sky–average rotation is constrained to be $\theta = -0.8^o \pm 2.2^o$. We discuss the relevance of this result for constraining cosmological birefringence, when this is caused by the interaction with a cosmological pseudo-scalar field or by the presence of a Cherns-Simons term.

Subject headings: cosmology: miscellaneous — polarization — radio continuum: galaxies

1. Introduction

The possibility that the propagation of light through our universe might suffer from chiral effects, which could rotate the plane of polarization, arises in a variety of important contexts, such as the presence of a cosmological pseudo-scalar condensate, Lorentz invariance violation and charge parity and time (CPT) violation, neutrino number asymmetry, and the Einstein equivalence principle (EEP) violation (see Ni (2008) for a review). The simplest form for modeling cosmological birefringence - a frequency independent rotation of the plane of linear polarization - is described by the interaction of a pseudo-scalar field ϕ with photons through a term (Kolb & Turner 1990; Raffelt 1996):

$$\mathcal{L}_{int} = -\frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \,, \tag{1}$$

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where g_ϕ is the coupling constant, $F^{\mu\nu}$ is the electromagnetic tensor and $\tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$ its dual. ϕ could be a fundamental field or an effective description for cosmological birefringence due to Lorentz violation (Carroll et al. 1989).

Indeed several efforts have been devoted to look for evidence of rotation of the plane of polarization: since we expect tiny effects on the basis of laboratory experiments, cosmological distances are required to have measurable effects and therefore the obvious approach has been to look for rotation in the most distant sources in the universe. What is required for this test is then a polarized distant source, for which the polarization orientation can be predicted: the predicted orientation is then compared with the measured one, looking for a rotation between the two. Radio galaxies (RG) are very good candidates, since these astrophysical objects are often polarized, both at radio and at UV-optical wavelengths, and are found at very high redshifts (Miley & De Breuck 2008). Since the first successful detection of anisotropies in polarization of the cosmic microwave background (CMB) by DASI in 2002 (Kovac et al. 2002), also the CMB polarization pattern has become an important test for cosmological birefringence, which could probe the propagation of light back to the recombination surface, i.e. up to a redshift as high as $z \sim 1100$.

Cosmological birefringence was first constrained from RG observations, since these were the first cosmological sources providing information on polarization. Carroll et al. (1989) have used the fact that the distribution of the difference between the position angle (P.A.) of the radio axis and the P.A. of the E vector of linear radio polarization in distant RG ($0.4 < z < 1.5$) peaks around 90^o to argue that this phenomenon is intrinsic to the source and therefore to put limits ($|\theta| \leq 6.0^o$ at the 95% confidence level) on the rotation of the plane of polarization for radiation traveling over cosmic distances. Later Cimatti et al. (1994) used the perpendicularity between the optical/UV axis and the linear optical/UV polarization of distant RG — this perpendicularity is expected since the polarization and the elongation are due to scattering of anisotropic nuclear radiation — to show that the plane of polarization is not rotated by more than 10^o for every distant RG with a polarization measurement up to $z = 2.63$. The advantage of the test using the optical/UV polarization over that using the radio one is that it is based on a physical prediction of the orientation of the polarization due to scattering, which is lacking in the radio case, and that it does not require a correction for the Faraday rotation, which is considerable in the radio but negligible in the optical/UV.

A few years later Nodland & Ralston (1997) claimed to have found a rotation, independent of the Faraday one, in the radio polarization of distant RG. However several authors (Wardle et al. 1997; Eisenstein & Bunn 1997; Carroll & Field 1997; Loredo 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).

As already said, the observed polarization of the CMB has recently been used to put stringent constraints on cosmological birefringence, which would modify the linear polarization pattern created first by Thomson scattering and then by reionization, and generate correlations between time and magnetic field and between electric and magnetic fields, otherwise zero in a standard cosmological scenario. By using the constant angle approximation - we denote $\bar{\theta}$ the rotation angle in the following - for the integrated rotation of the linear polarization plane along the line of sight (Lue et al. 1999), the observed power spectra are proportional to the power spectra on the last scattering surface through trigonometric functions of $\bar{\theta}$. Several constraints, summarized in Table 1, have been obtained within this approximation (see however Finelli & Galaverni (2009) for the limits of the constant angle approximation).

In this paper we report on an update of the test using the UV polarization of distant RG, because several new polarization information has become available on very distant RG since this test was last performed (Cimatti et al. 1994), and discuss its implications in various contexts. Our paper is organized as follows: after this introduction, we describe the set of observations on UV polarization and the constraints on the rotation angle. We then discuss the implications of this constraints for cosmological birefringence caused by a pseudo-scalar field (playing the role of dark matter or dark energy) and by a Cherns-Simons term respectively in Sections 3 and 4. In Section 5 we conclude.

2. Limits on the rotation of UV linear polarization of radio galaxies at $z > 2$

The birefringence test based on the UV polarization of RG is independent, complementary and placed at a different frequency with respect to those based on the radio polarization of distant RG and on the CMB polarization. The UV polarization test has also some advantages over the other tests. The main advantage over the test based on the radio polarization is that the UV and the CMB tests are based on a clear prediction of the polarization angle, given by the scattering physics, while a clear prediction is lacking for the radio polarization angle, which is only phenomenologically found to peak at about 90^o and 0^o from the radio axis, without a clear understanding of the physics behind it (Clarke et al. 1980). Distant RG observations provide a snapshot integrated up to a much smaller redshifts ($z \simeq$ few) with respect to the CMB one: as it occurs for CMB and SN Ia in probing the expansion history, the combination of CMB and RG may be very useful to constrain the cosmological birefringence. Being based at short wavelengths, the UV test is practically immune from Faraday rotation by intervening magnetic fields along the line of sight, which instead is relevant for radio and - to a smaller extent - for microwave observations (Scannapieco & Ferreira 1997), reminding however that the Faraday rotation can be corrected for, since it depends on frequency, while birefringence does not.

After the first birefringence test based on the UV polarization of distant RG by Cimatti et al. (1994), the test has been repeated by other authors. In particular, the RG 3C 265 at z=0.811 is a suitable source, because its misalignment between the radio and optical/UV axes provides a crucial check of the scattering hypothesis (di Serego Alighieri et al. 1996) and because its bright extensions allow to build up a good polarization map (Tran et al. 1998), in which the perpendicularity of the polarization vectors can be tested for each of the several tens of independent measurements at different locations. Indeed the spectacular polarization pattern of 3C265 has been used by Wardle et al. (1997) to rule out the birefringence claimed by Nodland & Ralston (1997). Since then, several new polarization measurements for distant RG have become available and an update of the birefringence test has become desirable, in particular using the most distant ones, as a complement of the similar test performed using the CMB polarization.

In order to perform the best test now possible with RG, we have selected all RG with $z > 2.0$, with the degree of linear polarization P larger than 5% in the far UV (at ~ 1300 Å, rest frame), and with elongated optical morphology at these wavelengths, since these are the marking characteristics of the presence of scattered nuclear radiation (di Serego Alighieri et al. 1994), and can therefore lead to a safe test of the polarization rotation (di Serego Alighieri et al. 1995). The relevant data are collected from the literature in Table 2. The second-last column of the table lists the difference between the P.A. of the linear UV polarization and the P.A. of the UV axis, which we have measured on the available images in the rest-frame UV, and is shown in Figure 1. According to the scattering model, these two directions should be perpendicular for every object in our sample. The fact that the P.A. difference is close to 90^o for every object, actually compatible with 90^o within the accuracy of the measurements, puts stringent constraints on any possible rotation θ of the polarization plane for light traveling to us from each RG, as listed in the last column of the table. Assuming that the rotation of the polarization plane should be the same in every direction (as is done in the CMB case), we can set the average constraint $\theta = -0.8^o \pm 2.2^o$, as listed in the last row of the table.

3. Constraint on Cosmological Pseudo-Scalar Fields

Upper limits on the linear polarization rotation angle θ can be used to constrain cosmological birefringence caused by the coupling of the electromagnetic field to pseudo-scalar fields, suggested to solve the strong charge and parity (CP) problem (Peccei & Quinn 1977). The existence of light pseudo-scalar particles (Weinberg 1978) is very relevant in cosmology, since these are viable candidate either for dark matter (Kolb & Turner 1990) or for dark energy (Frieman et al. 1995), depending on their (effective) mass. A pseudo-scalar field ϕ is predicted to be coupled to photons as can be read from the Lagrangian of the electromagnetic-ϕ sector:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi) - \frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \tag{2}$$

where $V(\phi)$ is the potential for the pseudo-scalar field. At the lowest order in fluctuations, the photon is coupled to the time derivative of the cosmological value of ϕ, which is governed by the potential. Different time evolutions of ϕ lead to different values for the resulting cosmological birefringence, and therefore in the following two subsections we consider representative cosmological scenarios involving totally different values for the time variation of ϕ [1].

[1]Note that the CMB polarization auto and cross spectra depend on the time variation of ϕ and in many cases the constant angle approximation is a poor description of cosmological birefringence in CMB anisotropies

3.1. Dark Matter Pseudo-scalar Field

We consider as potential in Equation (2):

$$V(\phi) = m^2 f_a^2 \left(1 - \cos\frac{\phi}{f_a}\right) \tag{3}$$

where m is the mass and f_a is the energy scale at which the Peccei-Quinn symmetry is broken. In the dark matter regime the pseudo-scalar field oscillates near the minimum of the potential, therefore $V(\phi) \simeq m^2\phi^2/2$. The evolution of the field as a function of cosmic time t is (Finelli & Galaverni 2009)

$$\begin{aligned} \phi(t) &\simeq \sqrt{\frac{3\Omega_{\rm MAT}}{\pi}}\frac{H_0 M_{\rm pl}}{2ma^{3/2}(t)} \\ &\quad \sin\left[mt\sqrt{1-(1-\Omega_{\rm MAT})\left(\frac{3H_0}{2m}\right)^2}\right] . \end{aligned} \tag{4}$$

where $\Omega_{\rm MAT}$ is the density parameter for ϕ nowadays (which we consider equal to the dark matter one), H_0 is the Hubble constant, $M_{\rm pl}$ is the Planck mass. Averaging through the oscillations, the evolution of the scale factor is given by (Finelli & Galaverni 2009):

$$\begin{aligned} a(t) &\simeq \left(\frac{\Omega_{\rm MAT}}{1-\Omega_{\rm MAT}}\right)^{\frac{1}{3}} \\ &\quad \left[\sinh\left(\frac{3}{2}\sqrt{1-\Omega_{\rm MAT}}H_0 t\right)\right]^{\frac{2}{3}} . \end{aligned} \tag{5}$$

Considering photon propagation in a homogeneous pseudo-scalar background ($\phi = \phi(\eta)$) the Fourier transform of the electromagnetic vector potential in the basis of left and right circular polarized modes in the plane transverse to the direction of propagation in the Coulomb gauge ($\nabla \cdot \mathbf{A} = 0$) is:

$$\tilde{A}''_{\pm}(k,\eta) + \left[k^2 \pm g_\phi \phi' k\right]\tilde{A}_{\pm}(k,\eta) = 0 \, , \tag{6}$$

where $'$ denotes derivative respect to conformal time η ($d\eta = dt/a(t)$, Finelli & Galaverni (2009)). The linear polarization rotation angle is given by:

$$\begin{aligned} \theta_{\rm DM}(z) &= \frac{g_\phi}{2}\left[\phi\left(\eta_0\right) - \phi\left(\eta\right)\right] \\ &= \frac{1}{4}\sqrt{\frac{3\Omega_{\rm MAT}}{\pi}}\frac{g_\phi M_{\rm pl} H_0}{m}\left(\frac{1}{a_0^{3/2}} - \frac{1}{a^{3/2}}\right) \\ &= -\frac{1}{4}\sqrt{\frac{3\Omega_{\rm MAT}}{\pi}}\frac{g_\phi M_{\rm pl} H_0}{m}\left[1-(1+z)^{3/2}\right] . \end{aligned} \tag{7}$$

(Finelli & Galaverni 2009).

Fixed the average redshift ($\bar{z} = 3$), $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $M_{\rm pl} \simeq 1.22 \times 10^{19}$ GeV, and $\Delta\theta < 5.0^o$ we obtain a constraint in the plane $(\log_{10} m\,[\mathrm{eV}]\,,\,\log_{10} g_\phi\,\left[\mathrm{eV}^{-1}\right])$, as from Figure 2, which we superimpose with the one obtained in Finelli & Galaverni (2009).

3.2. Dark Energy pseudo-scalar field

An ultralight pseudo Nambu-Goldstone boson could drive an accelerated expansion of the universe, as proposed by Frieman et al. (1995), by considering a simple shift of the potential in Equation (3):

$$V(\phi) = M^4\,[1 + \cos(\phi/f)] \tag{8}$$

with M and f mass and energy scale for the dark energy case, respectively (note that these numbers and g_ϕ may be quite different from the dark matter case). When ϕ acts as dark energy, it is presently rolling toward the bottom of the potential (located at $\phi = \pi f$) with small velocity: in the future, ϕ will roll around the bottom of the potential and will be another matter component added to cold dark matter (CDM).

The linear polarization angle θ is related to the variation of $\phi(\eta)$:

$$\theta(\eta) = \frac{g_\phi}{2}\,[\phi(\eta_0) - \phi(\eta)]\ . \tag{9}$$

and the evolution of ϕ is determined solving the following system of equations:

$$\begin{cases} \ddot{\phi} + 3H\dot{\phi} - \frac{M^4}{f}\sin\frac{\phi}{f} = 0\,, \\ H^2 = \frac{8\pi}{3M_{\rm pl}^2}\left(\rho_{\rm RAD} + \rho_{\rm MAT} + \rho_\phi\right)\ . \end{cases} \tag{10}$$

We solve it numerically fixed $M = 8.5 \times 10^{-4}$ eV, $f = 0.3 M_{\rm pl}/\sqrt{8\pi}$, $\phi_i/f = 0.25$ and $\dot{\phi}_i = 0$ (Abrahamse et al. 2008): see Figure 3 for the evolution of the critical densities for matter ($\Omega_{\rm MAT}$), dark energy (Ω_ϕ) and for the parameter $w_\phi \equiv p_\phi/\rho_\phi$ of the dark energy equation of state.

Figure 4 shows the variation of ϕ/f as a function of $\ln a/a_0$. In the region probed by high-redshift RG ($\bar{z} = 3$) there is a variation of the pseudo-scalar field the order $\phi/f \sim 1.1$. Therefore Equation (9) can be used to obtain an upper limit on g_ϕ:

$$\begin{aligned} & -5.0 < \theta < 3.4 \\ & \Longrightarrow -2.2 \times 10^{-28}\mathrm{eV}^{-1} < g_\phi < 1.5 \times 10^{-28}\mathrm{eV}^{-1} \end{aligned} \tag{11}$$

Let us also consider a runaway potential like:

$$V(\phi) = V_0 \exp\left(-\lambda\sqrt{8\pi}\frac{\phi}{M_{\rm pl}}\right)\ . \tag{12}$$

The above potential has only $M_{\rm pl}$ as physical scale, differently from the one in Equation (8). The resulting dark energy model is stable for $\lambda < \sqrt{2}$ and has an equation of state $p_\phi = w_\phi \rho_\phi$, with

$w_\phi = -1 + \lambda^2/3$, constant in time (Copeland et al. 1998). The evolution of the scale factor in this cosmological model can therefore be found analytically (Gruppuso & Finelli 2006), as also the evolution of the scalar field. We therefore give the analytical formula for the rotation angle:

$$\begin{aligned}\theta_{\rm DE}(z) &= \frac{g_\phi}{2}\left[\phi\left(\eta_0\right) - \phi\left(\eta\right)\right] \\ &= g_\phi M_{\rm pl}\sqrt{\frac{1+w_\phi}{3}}\frac{1}{-w_\phi}\left[\text{arcsinh}\left(\sqrt{\frac{\Omega_\phi}{1-\Omega_\phi}}\right)\right. \\ &\left. -\text{arcsinh}\left(\sqrt{\frac{\Omega_\phi}{1-\Omega_\phi}}a^{\frac{-3w_\phi}{2}}\right)\right], \end{aligned} \tag{13}$$

where Ω_ϕ is the dark energy fraction at present time. Figure 5 shows the value of $\theta_{\rm DE}(z = 2.80)$ as a function of (Ω_ϕ, w_ϕ). By considering $\theta_{\rm DE}(z = 2.80) \simeq 0.2 g_\phi M_{\rm pl}$ as an representative value, we obtain $|g_\phi| \lesssim \text{few} \times \mathcal{O}(10^{-29})\text{eV}^{-1}$.

4. Constraints on Chern-Simons Theory

We consider the following Lagrangian:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}p_\mu A_\nu \tilde{F}^{\mu\nu} \tag{14}$$

where $p_\mu = (p_0, \mathbf{p})$ is a constant 4-vector and A_ν the vector potential (Carroll et al. 1989).

The corresponding dispersion relation for an electromagnetic-wave $k^\mu = (\omega, \mathbf{k})$ is (Carroll et al. 1989):

$$\omega^2 - k^2 = \pm\left(p_0 k - \omega p \cos\alpha\right)\left[1 - \frac{p^2 \sin^2\alpha}{\omega^2 - k^2}\right]^{-\frac{1}{2}} \tag{15}$$

where α is the angle between $\mathbf{p}$ and $\mathbf{k}$. The angle by which the plane of polarization rotates is half of the difference phase, since p_μ is expected to be small, therefore the dispersion relation can be expanded at first order in p_μ:

$$k = \omega \mp \frac{1}{2}\left(p_0 - p\cos\alpha\right) . \tag{16}$$

For a wave traveling a distance L the linear polarization vector rotates by:

$$\theta = -\frac{1}{2}\left(p_0 - p\cos\alpha\right)L \tag{17}$$

independent of wavelength.

In a ΛCDM universe the evolution of the scale factor in terms of cosmic time is given by Equation (5), therefore the relation between t and redshift is:

$$t = \frac{2}{3H_0\sqrt{1-\Omega_{\rm MAT}}}\text{arcsinh}\left[\sqrt{\frac{1-\Omega_{\rm MAT}}{\Omega_{\rm MAT}}}\left(\frac{1}{1+z}\right)^{\frac{3}{2}}\right] \tag{18}$$

Fixed $L = t$ for the distance traveled by photons, the linear polarization plane from redshift z to nowadays rotates by:

$$\begin{aligned}\theta &= -\frac{1}{2}\left(p_0 - p\cos\alpha\right)t \\ &= -\frac{p_0 - p\cos\alpha}{3H_0\sqrt{1-\Omega_{\rm MAT}}}\left\{\operatorname{arcsinh}\left[\sqrt{\frac{1-\Omega_{\rm MAT}}{\Omega_{\rm MAT}}}\right]\right. \\ &\left. -\operatorname{arcsinh}\left[\sqrt{\frac{1-\Omega_{\rm MAT}}{\Omega_{\rm MAT}}}\left(\frac{1}{1+z}\right)^{\frac{3}{2}}\right]\right\} \qquad (19)\end{aligned}$$

Fixed $\Omega_{\rm MAT} = 0.3$, $H_0 = 100\,h\,{\rm km\,s^{-1}\,Mpc^{-1}} = 2.13\,h\ \times 10^{-33}$ eV and $\bar{z} = 3$:

$$|p_0 - p\cos\alpha| < \theta \times 5.2\,h\ \times 10^{-33}\,{\rm eV} \qquad (20)$$

If $h = 0.72$ and $\theta < 5.0^o$:

$$|p_0 - p\cos\alpha| < 3.2 \times 10^{-34}\,{\rm eV}\,, \qquad (21)$$

which updates the constraint given in Carroll et al. (1989) for a matter-dominated universe to one valid for the present cosmological concordance model.

5. Conclusions

Every single existing measurement of the UV linear polarization in RG at $z > 2$, due to scattering of anisotropic nuclear radiation, excludes that the polarization plane rotates by more than a few degrees while the light travels from the source to us for more than 3/4 of the universe lifetime, confirming previous results at lower redshifts (Cimatti et al. 1994; Wardle et al. 1997). The all-sky-average constraint derived on the rotation of the polarization from the set of observations considered in this paper ($\theta = -0.8^o \pm 2.2^o$) is independent, but consistent with the constraints derived from CMB observations. We have studied the implications of this constraint on physical models of cosmological birefringence, showing how observations at high redshifts as those of RG are complementary to CMB anisotropies, as already occurs for SN Ia and CMB in measuring the expansion history. In the framework of theoretical models associating the cosmological birefringence with the variation of the Newton constant our results increase our confidence in the validity of the EEP, on which all metric theories of gravity are based. An improvement in both quantity and quality of the measurements of the UV linear polarization in RG at high redshift should be possible in the future with the coming generation of giant optical telescopes (Gilmozzi & Spyromilio 2008; Nelson & Sanders 2008; Johns 2008), and would narrow the constraint on θ to a level smaller than what is now possible with RG and CMB.

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REFERENCES

Abrahamse, A., Albrecht, A., Barnard, M. & Bozek, B. 2008, Phys. Rev. D, 77, 103503

Andriamonje, S. et al. [CAST Collaboration] 2007, J. Cosmol. Astropart. Phys., JCAP04(2007)010

Cabella, P., Natoli, P. & Silk, J. 2007, Phys. Rev. D, 76, 123014

Carroll, S. M., Field, G. B. & Jackiw, R. 1989, Phys. Rev. D, 41, 1231

Carroll, S. M. & Field, G. B. 1997, Phys. Rev. Lett., 79, 2394

Carroll, S. M. 1998, Phys. Rev. Lett., 81, 3067

Cimatti, A., di Serego Alighieri, S., Field, G. B. & Fosbury, R. A. E. 1994, ApJ, 422, 562

Cimatti, A., di Serego Alighieri, S., Vernet, J., Cohen, M. H. & Fosbury, R. A. E. 1998, ApJ, 499, L21

Clarke, J. N., Kronberg, P. P. & Simard-Normandin, M. 1980, M.N.R.A.S., 190, 205

Copeland, E. J., Liddle, A. R. & Wands, D. 1998, Phys. Rev. D, 57, 4686

De Breuck, C., van Breugel, W., Stanford, S. A., Röttgering, H., Miley, G. & Stern, D. 2002, AJ, 123, 637

di Serego Alighieri, S., Cimatti, A. & Fosbury, R. A. E. 1994, ApJ, 431, 123

di Serego Alighieri, S., Field, G. B. & Cimatti, A. 1995, ASP Conf. Series, 80, 276

di Serego Alighieri, S., Cimatti, A., Fosbury, R. A. E. & Perez–Fournon, I. 1996, M.N.R.A.S., 279, L57

Eisenstein, D. J. & Bunn, E. F. 1997, Phys. Rev. Lett., 79, 1957

Feng, B., Li, M., Xia, J. Q., Chen, X. & Zhang, X. 2006, Phys. Rev. Lett., 96, 221302

Finelli, F. & Galaverni, M. 2009, Phys. Rev. D, 79, 63002

Frieman, J. A., Hill, C. T., Stebbins, A. & Waga, I. 1995, Phys. Rev. Lett., 75, 2077

Gilmozzi, R. & Spyromilio, J. 2008, Proc. of SPIE, 7012, 701219

Gruppuso, A. & Finelli, F. 2006, Phys. Rev. D, 73, 23512

Johns, M. 2008, Proc. of SPIE, 7012, 70121B

Knopp, G. P. & Chambers, K. C. 1997, ApJS, 109, 367.

Kolb, E. W. & Turner, M. S. 1990, Front. Phys., 69, 1

Komatsu, E. et al. [WMAP Collaboration] 2009, ApJS, 180, 330

Komatsu, E. et al. 2010, arXiv:1001.4538

Kovac, J. M. et al. 2002, Nature, 420, 722

Leahy, J. P. 1997, astro-ph/9704285

Loredo, T. J., Flanagan, E. E. & Wasserman, I. M. 1997, Phys. Rev. D, 56, 7507

Lue, A., Wang, L. M. & Kamionkowski, M. 1999, Phys. Rev. Lett., 83, 1506

Miley, G. & De Breuck, C. 2008, Astron. Astrophys. Rev, 15, 67

Nelson, J. & Sanders, G. H. 2008, Proc. of SPIE, 7012, 70121A

Ni, W. T. 2008, Prog. Theor. Phys. Suppl., 172, 49

Nodland, B. & Ralston, J. P. 1997, Phys. Rev. Lett., 78, 3043

Peccei, R. D. & Quinn, H. R. 1977, Phys. Rev. Lett., 38 1440.

Pentericci, L., Rottgering, H. J. A., Miley, G. K., McCarthy, P., Spinrad, H., van Breugel, W. J. M. & Macchetto, F. 1999, A&A, 341, 329

Raffelt, G. G. 1996, "Stars As Laboratories For Fundamental Physics: The Astrophysics Of Neutrinos, Axions, And Other Weakly Interacting Particles," Chicago, USA: Univ. Pr. 664 p

Scannapieco, E. S. & Ferreira, P. G. 1997, Phys. Rev. D, 56, R7493

Vernet, J., Fosbury, R. A. E., Villar-Martin, M., Cohen, M. H., Cimatti, A., di Serego Alighieri, S. & Goodrich, R. W., 2001, A&A, 366, 7

Tran, H.D., Cohen, M.H., Ogle, P.M., Goodrich, R.W. & di Serego Alighieri, S. 1998, ApJ, 500, 660

Wardle, J. F. C., Perley, R. A. & Cohen, M. H. 1997, Phys. Rev. Lett., 79, 1801

Weinberg, S. 1978, Phys. Rev. Lett., 40, 223

Wu, E. Y. S. et al. [QUaD Collaboration] 2009, Phys. Rev. Lett., 102, 161302

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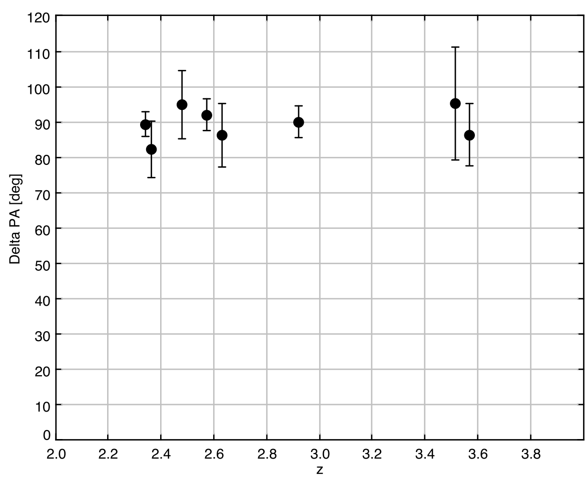

Fig. 1.— Angle between the direction of linear polarization in the UV and the direction of the UV axis for RG at $z > 2$. The angle predicted by the scattering model is 90^o.

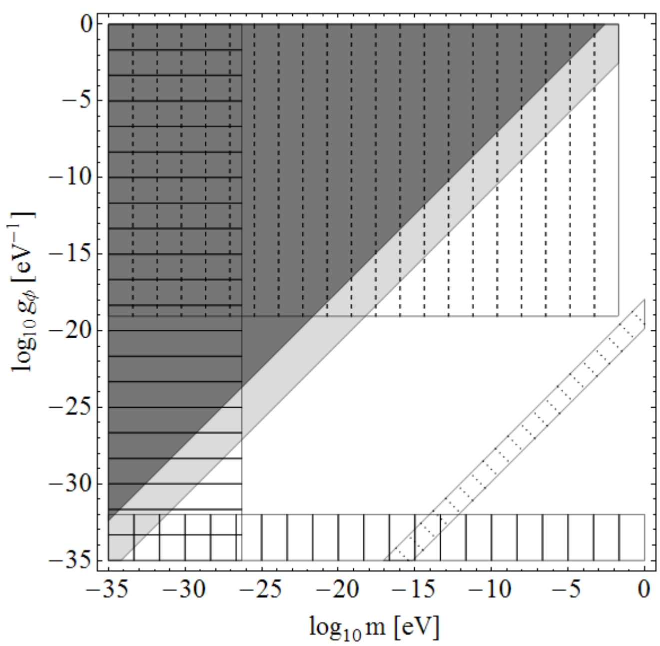

Fig. 2.— Plane ($\log_{10} m$ [eV], $\log_{10} g_\phi$ [eV^{-1}]): region excluded by CAST (Andriamonje et al. 2007) (white with dashed vertical lines), region where $|\theta_{\rm CMB}(\Omega_{\rm MAT} = 0.3, m, g_\phi)| > 10^o$ obtained by the constant angle approximation in Finelli & Galaverni (2009) (light gray region), region where $|\theta_{\rm HzRG}(\Omega_{\rm MAT} = 0.3, m, g_\phi)| > 5.0^o$ (dark gray with dashed vertical lines), $(m,\, g_\phi)$ values expected in main QCD axion models (dotted slanted lines), region where the mass of the pseudo-scalar field is too small in order to explain dark matter ($m < 3H_{\rm eq}$) (white with horizontal lines), and region where PQ symmetry is broken at energies higher than Planck scale ($f_a > M_{\rm pl}$) (white with vertical lines).

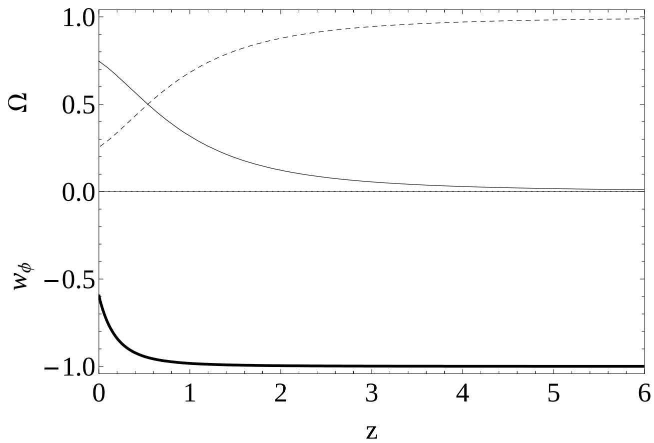

Fig. 3.— Dashed line: $\Omega_{\rm MAT}$, thin continuous line: Ω_ϕ, thick continuous line w_ϕ, in terms of the natural logarithm of the scale factor (from ln $a \simeq -15$ to nowadays ln $a_0 = 0$). Fixed $M = 8.5 \times 10^{-4}$ eV, $f = 0.3 M_{\rm pl}/\sqrt{8\pi}$, $\phi_i/f = 0.25$ and $\dot{\phi}_i = 0$.

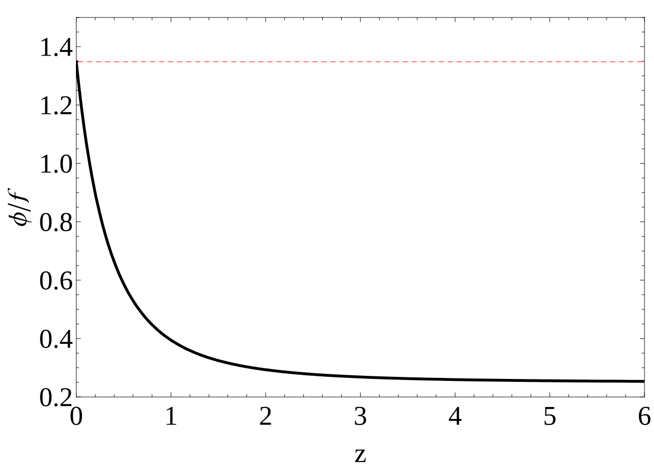

Fig. 4.— Evolution of pseudo Nambu–Goldstone boson field ϕ/f in terms of the natural logarithm of the scale factor from ln $a \simeq -15$ to nowadays ln $a_0 = 0$. Fixed $M = 8.5{\times}10^{-4}$ eV, $f = 0.3 M_{\rm pl}/\sqrt{8\pi}$, $\phi_i/f = 0.25$ and $\dot{\phi}_i = 0$.

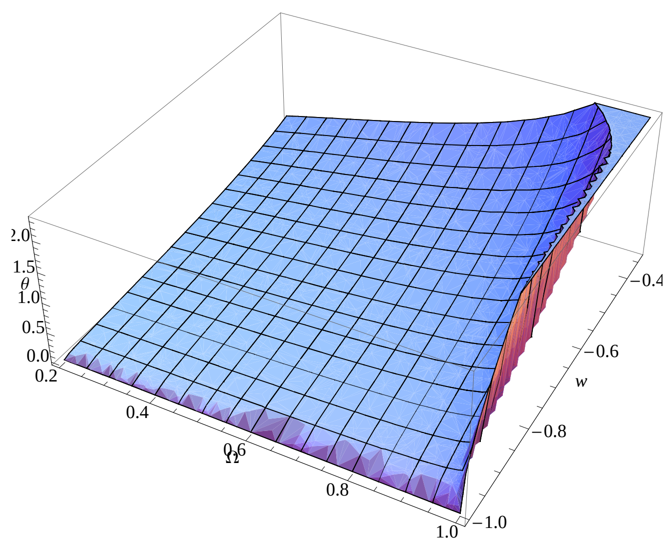

Fig. 5.— Three-dimensional plot of $\theta_{\rm DE}(z = 2.80)$ as a function of (Ω_ϕ, w_ϕ) in the range $\Omega_\phi = [0.2, 1]$ and $w_\phi = [-0.34, -1]$.

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).

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)