Cosmic Polarization Rotation: 
an Astrophysical Test of Fundamental Physics

Sperello di Serego Alighieri  
INAF - Osservatorio Astrofisico di Arcetri  
Largo E. Fermi, 5, 50125 Firenze, Italy  
sperello@arcetri.astro.it

Received 20 January 2015  
Revised 23 January 2015

Possible violations of fundamental physical principles, e.g. the Einstein Equivalence Principle on which all metric theories of gravity are based, including General Relativity, would lead to a rotation of the plane of polarization for linearly polarized radiation traveling over cosmological distances, the so-called cosmic polarization rotation (CPR). We review here the astrophysical tests which have been carried out so far to check if CPR exists. These are using the radio and ultraviolet polarization of radio galaxies and the polarization of the cosmic microwave background (both E-mode and B-mode). These tests so far have been negative, leading to upper limits of the order of one degree on any CPR angle, thereby increasing our confidence in those physical principles, including General Relativity. We also discuss future prospects in detecting CPR or improving the constraints on it.

Keywords: Equivalence principle; general relativity; polarization; radio galaxies; cosmic background radiation.

PACS numbers: 04.20.Cv, 04.80.Cc, 95.30.Gv, 98.54.Gr.

1. Introduction

Linear polarization is a simple phenomenon by which a single photon is able to transmit across the universe the information about the orientation of a plane. The question which we discuss in this review is whether the orientation of the plane of linear polarization, the so-called position angle (PA), is conserved for electromagnetic radiation travelling long distances, i.e. if there is any cosmic polarization rotation (CPR). Clearly, if the CPR angle $\alpha$ is not zero, symmetry must be broken at some level, since $\alpha$ must be either positive or negative, for a counter-clockwise or clockwise rotation. This immediately suggests that CPR should be connected with the violation of fundamental physical principles. Indeed it is linked also to a possible violation of the Einstein equivalence principle (EEP), which is the foundation of any

\footnote{We adopt the IAU convention for PA: it increases counter-clockwise facing the source, from North through East.}
metric theory of gravity, including general relativity (GR), for which we celebrate the Centennial this year.

The fundamental principles whose violation would imply CPR are briefly discussed in Section 2. For most of them the CPR angle would be independent of wavelength. However the violation of some principles would imply a wavelength dependent CPR, not to be confused with the Faraday rotation, which is a well-known effect for radiation passing through a plasma with a magnetic field. CPR, if it exists, would occur in vacuum. CPR has sometimes been inappropriately called ”cosmological birefringence”. However we follow here the advice of Ref. 60, since birefringence is only appropriate for a medium whose index of refraction depends on the direction of polarization of the incident light beam, which is then split in two. The phenomenon we are considering here is pure rotation of the polarization, without any splitting.

Testing for CPR is simple in principle: it requires a distant source of linearly polarized radiation, for which the orientation \( P_{\text{em}} \) of the polarization at the emission can be established. Then CPR is tested by comparing the observed orientation \( P_{\text{obs}} \) with \( P_{\text{em}} \):

\[
\alpha = P_{\text{obs}} - P_{\text{em}}
\]

In practice it is not easy to know a priori the orientation of the polarization for a distant source: in this respect the fact that scattered radiation is polarized perpendicularly to the plane containing the incident and scattered rays has been of great help, applied both to radio galaxies (see section 4) and to the cosmic background radiation (CMB, see section 5). For those cases in which CPR depends on wavelength, one can also test CPR simply searching for variation of \( P_A \) with the wavelength of the radiation, even without knowing \( P_{\text{em}} \). In this paper we will review the astrophysical methods which have been used to test CPR, we list the results of these tests, discuss the advantages and disadvantages of the various methods, and suggest future prospects for these tests.

2. Impact of Cosmic Polarization Rotation on fundamental physics

This possibility of CPR arises in a variety of important contexts, like the presence of a cosmological pseudo-scalar condensate, Lorentz invariance violation and CPT violation, neutrino number asymmetry, the Einstein Equivalence Principle (EEP) violation. In particular the connection of the latter with CPR is relevant for this GR Centennial year, since all metric theories of gravity, including GR are based on the EEP. Since the Weak Equivalence Principle (WEP) is tested to a much higher accuracy than the EEP, Ref. 68 conjectured that any consistent Lorentz-invariant theory of gravity which obeys the WEP would necessarily also obey the EEP. If this were true, the EEP would tested to the same accuracy as the WEP, increasing our experimental confidence in GR. However Refs. 57, 58 found a unique counter
example to Schiff’s conjecture: a pseudoscalar field which would lead to a violation of the EEP, while obeying the WEP. Such field would produce a CPR. Therefore testing for the CPR is important for our confidence in GR. For the other theoretical impacts of CPR we refer the reader to Refs. 59, 60, 62.

3. Constraints from the radio polarization of radio galaxies
Already in his seminal paper about the unique counter-example to Schiff’s conjecture giving rise to CPR, Ref. 57 suggested that observations of polarized astrophysical sources could give constraints on the CPR. However, only in 1990 the polarization at radio wavelengths of radio galaxies and quasars was used for the first astrophysical test of CPR. Ref. 12 used the fact that extended radio sources, in particular the more strongly polarized ones, tend to have their plane of integrated radio polarization, corrected for Faraday rotation, usually perpendicular and occasionally parallel to the radio source axis, to put a limit of $6^\circ$ at the 95% confidence level to any rotation of the plane of polarization for the radiation coming from these sources in the redshift interval $0.4 < z < 1.5$.

Reanalyzing the same data, Ref. 63 claimed to have found a rotation of the plane of polarization, independent of the Faraday one, and correlated with the angular positions and distances to the sources. Such rotation would be as much as 3.0 rad for the most distant sources. However, several authors have independently and convincingly rejected this claim, both for problems with the statistical methods and by showing that the claimed rotation is not observed for the optical/UV polarization of 2 radio galaxies (see below) and for the radio polarization of several newly observed radio galaxies and quasars.

In fact, the analysis of Ref. 62 is important also because it introduces a significant improvement to the radio polarization method for the CPR test. The problem with the radio polarization method is the difficulty in estimating the direction of the polarization at the emission. Since the radio emission in radio galaxies and quasars is due to synchrotron radiation, the alignment of its polarization with the radio axis implies an alignment of the magnetic field, which is not obvious per se. In fact theory and magnetohydrodynamics simulations foresee that the projected magnetic field should be perpendicular to strong gradients in the total radio intensity. For example, for a jet of relativistic electrons the magnetic field should be perpendicular to the local jet direction at the edges of the jet and parallel to it where the jet intensity changes. On the other hand such alignments are much less clear for the integrated polarization, because of bends in the jets and because intensity gradients can have any direction in the radio lobes, which emit a large fraction of the polarized radiation in many sources. In fact it is well known that the peaks at $90^\circ$ and $0^\circ$ in the distribution of the angle between the direction of the radio polarization and

\[^b\text{Ref. 6 had earlier claimed a substantial anisotropy in the angle between the direction of the radio axis and the direction of linear radio polarization in a sample of high-luminosity classical double radio sources, but used it to infer a rotation of the Universe, not to test for CPR.}\]
Sperello di Serego Alighieri

that of the radio axis are very broad and the alignments hold only statistically, but
not necessarily for individual sources (see e.g. fig. 1 of Ref. [12]). More stringent
tests can be carried out using high angular resolution data on radio polarization
and the local magnetic field’s alignment for individual sources,[22] although to our
knowledge only once,[48] this method has been used to put quantitative limits on the
polarization rotation. For example, Ref. [14] using the data on the 10 radio galaxies
of Ref. [48], obtains an average constraint on any CPR angle of \( \alpha = -0.6^\circ \pm 1.5^\circ \) at
the mean redshift \( \langle z \rangle = 0.78 \). However the preprint by Ref. [48] remained unpublished
and does not explain convincingly how the angle between the direction of the local
intensity gradient and that of the polarization is derived. For example, for 3C9, the
source with the best accuracy, Ref. [48] refers to Ref. [47], who however do not give
any measurements of local gradients.

4. Constraints from the ultraviolet polarization of radio galaxies

Another method to test for CPR has used the perpendicularity between the direction
of the elongated structure in the ultraviolet (UV) and the direction of linear UV
polarization in distant powerful radio galaxies. The test was first performed by Refs.
[17][24], who obtained that any rotation of the plane of linear polarization for a dozen
radio galaxies at \( 0.5 \leq z \leq 2.63 \) is smaller than \( 10^\circ \).

Although this UV test has sometimes been confused with the one at radio wave-
lengths, probably because they both use radio galaxies polarization, it is a com-
pletely different and independent test, which hinges on the well established unifica-
tion scheme for powerful radio-loud AGN. This scheme foresees that powerful radio
sources do not emit isotropically, but their strong UV radiation is emitted in two
opposite cones, because the bright nucleus is surrounded by an obscuring torus: if
our line of sight is within the cones, we see a quasar, otherwise we see a radio galaxy.
Therefore powerful radio galaxies have a quasar in their nuclei, which can only be
seen as light scattered by the interstellar medium of the galaxy. Often, particularly
in the UV, this scattered light dominates the extended radiation from radio galaxies,
which then appear elongated in the direction of the cones and strongly polarized in the
perpendicular direction.[23] The axis of the UV elongation must be perpendicular
to the direction of linear polarization, because of the scattering mechanism which
produces the polarization. Therefore in this case it is possible to accurately predict
the direction of polarization at the emission and compare it with the observed one.
This method of measuring the polarization rotation can be applied to any single
case of distant radio galaxy, which is strongly polarized in the UV, allowing inde-
pendent CPR tests in many different directions. Another advantage of this method
is that it does not require any correction for Faraday rotation, which is large at
radio wavelengths, but negligible in the UV.

\(^c\)When a distant radio galaxy (\( z > 0.7 \)) is observed at optical wavelengths (\( \lambda_{\text{obs.}} \sim 5000\)Å), these
correspond to the UV in the rest frame (\( \lambda_{\text{em.}} \leq 3000\)Å).
The method can be applied also to the polarization which is measured locally at any position in the elongated structures around radio galaxies, and which has to be perpendicular to the vector joining the observed position with the nucleus. From the polarization map in the V-band (∼3000 Å rest-frame) of 3C 265, a radio galaxy at z=0.811, the mean deviation of the 53 polarization vectors plotted in the map from the perpendicular to a line joining each to the nucleus is $-1.4^\circ \pm 1.1^\circ$. However, more distant radio galaxies are so faint that only the integrated polarization can be measured, even with the largest current telescopes: strict perpendicularity is expected also in this case, if the extended emission is dominated by the scattered radiation, as is the case in the UV for the strongly polarized radio galaxies.

Recently the available data on all radio galaxies with redshift larger than 2 and with the measured degree of linear polarization larger than 5% in the UV (at ∼1300 Å) have been re-examined, and no rotation within a few degrees in the polarization for any of these 8 radio galaxies has been found. In addition, assuming that the CPR angle should be the same in every direction, an average constraint on this rotation $<\alpha> = -0.8^\circ \pm 2.2^\circ (1\sigma)$ at the mean redshift $\langle z \rangle = 2.80$ has been obtained. The same data have been used by Ref. to set a CPR constraint in case of a non-uniform polarization rotation, i.e. a rotation which is not the same in every direction: in this case the variance of any rotation must be $\langle \alpha^2 \rangle \leq (3.7^\circ)^2$.

The CPR test using the UV polarization has advantages over the other tests at radio or CMB wavelengths, if CPR effects grow with photon energy (the contrary of Faraday rotation), as in a formalism where Lorentz invariance is violated but CPT is conserved.

### 5. Constraints from the polarization of the Cosmic Background Radiation

A more recent method to test for the existence of CPR is the one that uses the CMB polarization, which is induced by the last Thomson scattering of decoupling photons at $z \sim 1100$, resulting in a correlation between temperature gradients and polarization. CMB photons are strongly linearly polarized, since they result from scattering. However the high uniformity of CMB produces a very effective averaging of the polarization in any direction. It is only at the CMB temperature disuniformities that the polarization does not average out completely and residual polarization perpendicular to the temperature gradients is expected. Therefore also for the CMB polarization it is possible to precisely predict the polarization direction at the emission and to test for any CPR. After the first detection of CMB polarization anisotropies by DASI, there have been several CPR tests using the CMB E-mode polarization pattern.

Unfortunately, the scientists working on the CMB polarization have adopted for the polarization angle a convention which is opposite to the IAU one, used for decades by all other astrophysicists and enforced by the IAU for the CMB polarimetrists, following a software for the data pixelization on a sphere.
larization angle increases clockwise, instead of counter-clockwise, facing the source, this produces an inversion of the U Stokes parameter, corresponding to a change of PA sign. Obviously, these different conventions have to be taken into account, when comparing data obtained with the different methods used for CPR searches. As mentioned in the Introduction, all PA in this work are given in the IAU convention. Independently of the adopted convention, a problem of CMB polarimetry is the calibration of the position angle, which is not easy at CMB frequencies. Although different methods are used, like the a-priori knowledge of the detector’s orientation, the use of calibration sources both near the experiment on the ground and on the sky, the current calibration accuracy is of the order of one degree, producing a non-negligible systematic error $\beta$ on the measured PA. In order to alleviate the PA calibration problem, Ref. 42 have suggested a self-calibration technique consisting in minimizing EB and TB power spectra with respect to PA offset. Unfortunately such a calibration technique would eliminate not just the PA calibration offset $\beta$, but $\alpha - \beta$, where $\alpha$ is the uniform CPR angle, if it exists. Therefore no independent information on the uniform CPR angle can be obtained, if this calibration technique is adopted, like with the BICEP2 and POLARBEAR experiments.

In the following we summarize the most recent and accurate CPR measurements obtained using the CMB polarization. The BOOMERanG collaboration, revisiting the limit set from their 2003 flight, find a CPR angle $\alpha = 4.3^\circ \pm 4.1^\circ$ (68% CL), assuming uniformity over the whole sky.\footnote{EB and TB are the cross-correlation power spectra between E- and B-modes and between temperature and B-mode, respectively.} The QUaD collaboration finds $\alpha = -0.64^\circ \pm 0.50^\circ$ (stat.) $\pm 0.50^\circ$ (syst.) (68% CL)\footnote{EB and TB are the cross-correlation power spectra between E- and B-modes and between temperature and B-mode, respectively.} while using three years of BICEP1 data one gets $\alpha = 2.77^\circ \pm 0.86^\circ$ (stat.) $\pm 1.3^\circ$ (syst.) (68% CL)\footnote{EB and TB are the cross-correlation power spectra between E- and B-modes and between temperature and B-mode, respectively.} Combining 9 years of WMAP data and assuming uniformity, a limit to CPR angle $\alpha = 0.36^\circ \pm 1.24^\circ$ (stat.) $\pm 1.5^\circ$ (syst.) (68% CL) has been set, or $-3.53^\circ < \alpha < 4.25^\circ$ (95% CL), adding in quadrature statistical and systematic errors.\footnote{EB and TB are the cross-correlation power spectra between E- and B-modes and between temperature and B-mode, respectively.} Recently the Atacama Cosmology Telescope Polarimeter (ACTPol) team\textsuperscript{56} have used their first 3 months of observations to measure the CMB polarization over 4 sky regions near the celestial equator. They do not give an explicit value for the CPR, also because they have used the EB and TB power minimization technique of Ref. 42. However it is possible to derive a value of the CPR from their data, since they have measured a PA of $150.9^\circ \pm 0.6^\circ$ for Crab Nebula (Tau A, a polarization standard source), using the EB and TB nulling procedure (Hasselfield, priv. comm.). The most precise fiducial measurement at CMB frequencies of the Crab Nebula polarization angle is a PA of $149.9^\circ \pm 0.2^\circ$ at 89.2 GHz.\footnote{EB and TB are the cross-correlation power spectra between E- and B-modes and between temperature and B-mode, respectively.} If we assume that the Crab Nebula polarization PA would not change between 89.2 and 146 GHz (see e.g. the discussion in Section 6 of Ref.\textsuperscript{6}), then the average CPR angle over the ACTPol equatorial regions would be the difference between the above values $\alpha = 1.0^\circ \pm 0.63^\circ$, however the above assumption leaves room for some systematic error. We could instead use the data of Ref.\textsuperscript{56} in a different way: since the PA offset angle which they obtain from the
EB minimization technique is $-0.2^\circ \pm 0.5^\circ$, i.e. consistent with zero, Ref. [54] suggest that their optical modeling procedure should be free of systematic errors at the $0.5^\circ$ level or better. If this were true, then $\alpha = 0.22^\circ \pm 0.32^\circ \pm 0.5^\circ$. In summary, for the ACTPol result we prefer the assumption on the constancy of the Crab Nebula polarization angle between 89.2 and 146 GHz, also because this can be tested a posteriori and an eventual correction applied.

In summary, although some have claimed to have detected a rotation, the CMB polarization data appear well consistent with a null CPR. In principle the CMB polarization pattern can be used to test CPR in specific directions. However, because of the extremely small anisotropies in the CMB temperature and polarization, these tests have so far used averages over relatively large regions of sky, assuming uniformity.

Recently [26] have suggested the possibility of setting constraints on the CPR also using measurements of the B-mode polarization of the CMB, because of the coupling from E-mode to B-mode polarization that any such rotation would produce. This possibility is presently limited by the relatively large systematic errors on the polarization angle still affecting current data. The result is that from the South Pole Telescope polarimeter (SPTpol), POLARBEAR and BICEP2 B-mode polarization data it is only possible to set constraints on the fluctuations $\langle \delta \alpha^2 \rangle \leq (1.56^\circ)^2$ of the CPR, not on its mean value. Ref. [54] have similarly obtained an upper limit on the CPR fluctuations $\langle \delta \alpha^2 \rangle \leq (1.68^\circ)^2$ from the ACTPol B-mode data of Ref. [56]. The last row of Table 1 reports the combined constraint on the CPR fluctuations obtained from all the B-mode data mentioned above.

6. Other constraints

Observations of nearby polarized galactic objects could contribute to the CPR test, in particular for those cases where polarization measurements can be made with high accuracy and at very high frequencies (useful if CPR effects grow with photon energy). Pulsars and supernova remnants emit polarized radiation in a very broad frequency range. For example, hard X-ray polarization observations of the Crab Nebula [22] have been used to set a limit to CPR angle $\alpha = -1^\circ \pm 11^\circ$. However this limit is not particularly stringent, both because of the low accuracy of the X-ray polarization measurement, and because of the limited distance to the source. Future more precise X-ray polarization experiments, such as POLARIX [19], could much improve the situation.

Gamma-ray bursts (GRB) are very distant sources which emit polarized radiation both in the optical afterglow [20, 23] and in the prompt gamma-ray emission [31, 38]. Nevertheless they cannot be used for CPR searches, since the orientation of the polarization at the emission is unknown. However they can be used to test for birefringence effects, i.e. an energy-dependent rotation of the polarization angle, such as those produced by Lorentz invariance violation [50] since the detection of linear polarization in a gamma-ray band excludes a significant rotation of the polarization
within that energy band. Ref. 31 was able to put an upper limit to the dimensionless parameter $\xi$ of this birefringence effect of $\xi < 1 \times 10^{-16}$ from the gamma-ray polarization of a GRB at $z=2.74$. Using the same data for testing the Lorentz symmetry and the Equivalence principle Refs. 45, 61 obtain a birefringence constraint of about $10^{-38}$.

For an issue related to CPR, Ref. 34 provides evidence that the directions of linear polarization at optical wavelengths for a sample of 355 quasars ($0 \leq z \leq 2.4$) are non-uniformly distributed, being systematically different near the North and South Galactic Poles, particularly in some redshift ranges. Such behaviour could not be caused by uniform CPR, since a rotation of randomly distributed directions of polarization could produce the observed alignments only with a very contrived distribution of rotations as a function of distance and position in the sky. Moreover the claim by Ref. 34 has not been confirmed by the radio polarization directions on a much larger sample of 4290 flat-spectrum radio sources, and Ref. 35 recently suggested that the alignments could be due to an alignment of quasar’s spin axis to the structures to which they belong. The possibility that the quasar’s polarization alignments could be due to the mixing of photons with axion-like particles is excluded by the absence of circular polarization.

The rotation of the plane of linear polarization can be seen as different propagation speeds for right and left circularly-polarized photons ($\Delta c/c$). The sharpness of the pulses of pulsars in all Stokes parameters can be used to set limits corresponding to $\Delta c/c \leq 10^{-17}$. Similarly the very short duration of gamma ray bursts (GRB) gives limits of the order of $\Delta c/c \leq 10^{-21}$. However the lack of linear polarization rotation discussed in the previous sections can be used to set much tighter limits ($\Delta c/c \leq 10^{-32}$).

In a complementary way to the astrophysical tests described in the previous sections, also laboratory experiments can be used to search for CPR. These are outside the scope of this review and have not obtained significant constraints. For example the PVLAS (Polarizzazione del Vuoto con LASer) collaboration has found a polarization rotation in the presence of a transverse magnetic field, but later refuted this claim, attributing the rotation to an instrumental artifact. The null result is consistent with the measurement of Ref. 15.

7. Discussion

Table 1 summarizes the most important limits set on the CPR angle with the various methods examined in the previous sections. Only the best and most recent results obtained with each method are listed. For uniformity, all the results for the CPR angle are listed at the 68% CL (1$\sigma$), except for the first one, which is at the 95% CL, as given in the original Ref. 12. In general all the results are consistent with

$\xi \equiv (n_0)^3$, where $n_0$ is the time component of the Myers-Pospelov four-vector $n_\alpha$, in a reference frame where $n_\alpha = (n_0, 0, 0, 0)$.2, 32, 55
each other and with a null CPR. Even the CMB measurement by BICEP1, which apparently shows a non-zero rotation at the 2σ level, cannot be taken as a firm CPR detection, since it has not been confirmed by other more accurate measurements.

In practice all CPR test methods have reached so far an accuracy of the order of 1° and 3σ upper limits to any rotation of a few degrees. It has been however useful to use different methods since they are complementary in many ways. They cover different wavelength ranges, and, although most CPR effects are wavelength independent, the methods at shorter wavelength have an advantage, if CPR effects grow with photon energy. They also reach different distances, and the CMB method is unbeatable in this respect. However the relative difference in light travel time between \( z = 3 \) and \( z = 1100 \) is only 16%. The radio polarization method, when it uses the integrated polarization, has the disadvantage of not relying on a firm prediction of the polarization orientation at the source, which the other methods have. In addition, the radio method requires correction for Faraday rotation. All methods can potentially test for a rotation which is not uniform in all directions, although this possibility has not yet been exploited by the CMB method, which also cannot see how an eventual rotation would depend on the distance. Ref. [28] have recently examined the dependence of CPR on the wavelength and on the distance of the source, and found none, which is not surprising for a null (so far) CPR: in practice they cannot improve the limit already set on the birefringence parameter \( \xi \) in Ref. [31] (see Section 6).

8. Outlook

In the future improvements can be expected for all methods, e.g. by better targeted high resolution radio polarization measurements of radio galaxies and quasars, by more accurate UV polarization measurements of radio galaxies with the coming generation of giant optical telescopes, and by future CMB polarimeters such as PLANCK and BICEP3. Indeed the Planck satellite is expected to have a very low statistical error (\( \sim 0.06° \)) for CPR measurements, about a factor of 10 better than previous experiments. Unfortunately, although Planck has completed its observations more than a year ago, its results on CPR have not yet been released. In any case, in order to exploit the much improved measurement accuracy of Planck, it will be necessary to reduce accordingly also the systematic error in the calibration of the polarization angle, which at the moment is of the order of 1° for CMB polarization experiments. The best prospects to achieve this improvement are likely to be more precise measurements of the polarization angle of celestial sources at CMB frequencies, e.g. with the Australia Telescope Compact Array and with ALMA and a calibration source on a satellite.

Acknowledgments

We would like to thank Matthew Hasselfield, Matteo Galaverni, and Wei-Tou Ni for useful discussions.
Table 1. Measurements of CPR with different methods (in chronological order).

| Method              | CPR angle ± stat. (± syst.) | Frequency or $\lambda$ | Distance | Direction | Ref. |
|---------------------|-----------------------------|-------------------------|----------|-----------|------|
| RG radio pol.       | $|\alpha| < 6^o$             | 5 GHz                   | 0.4 < $z$ < 1.5 | all-sky (uniformity ass.) | 12   |
| RG UV pol.          | $|\alpha| < 10^o$            | $\sim$ 3000 Å rest-frame | 0.5 < $z$ < 2.63 | all-sky (uniformity ass.) | 16,17|
| RG UV pol.          | $\alpha = -1.4^o \pm 1.1^o$ | $\sim$ 3000 Å rest-frame | $z = 0.81$ | RA : 176.40, Dec : 31.60 | 72   |
| RG radio pol.       | $\alpha = -0.6^o \pm 1.5^o$ | 3.6 cm                  | $\langle z \rangle = 0.78$ | all-sky (uniformity ass.) | 14   |
| CMB pol. BOOMERanG | $\alpha = 4.3^o \pm 4.1^o$ | 145 GHz                 | $z \sim 1100$ | RA ~ 82°, Dec ~ 45° | 64   |
| CMB pol. QUAD       | $\alpha = -0.64^o \pm 0.50^o \pm 0.50^o$ | 100-150 GHz | $z \sim 1100$ | RA ~ 82°, Dec ~ 50° | 11   |
| RG UV pol.          | $\alpha = -0.8^o \pm 2.2^o$ | $\sim$ 1300 Å rest-frame | $\langle z \rangle = 2.80$ | all-sky (uniformity ass.) | 25   |
| RG UV pol.          | $\langle \delta \alpha^2 \rangle \leq (3.7^o)^2$ | $\sim$ 1300 Å rest-frame | $\langle z \rangle = 2.80$ | all-sky (stoch. var.) | 25,59|
| CMB pol. WMAP9      | $\alpha = 0.36^o \pm 1.24^o \pm 1.5^o$ | 23-94 GHz | $z \sim 1100$ | all-sky (uniformity ass.) | 33   |
| CMB pol. BICEP1     | $\alpha = 2.77^o \pm 0.86^o \pm 1.3^o$ | 100-150 GHz | $z \sim 1100$ | $-50^o < RA < 50^o, -70^o < Dec < -45^o$ | 33   |
| CMB pol. ACTPol     | $\alpha = 1.0^o \pm 0.63^o$ | 146 GHz | $z \sim 1100$ | RA ~ 35°, 150°, 175°, 355°, Dec ~ 50° | 33,56|
| CMB pol. B-mode     | $\langle \delta \alpha^2 \rangle \leq (1.36^o)^2$ | 95-150 GHz | $z \sim 1100$ | Various sky regions | 23   |

Note: *A systematic error should be added, equal to the unknown difference of the Crab Nebula polarization PA between 146 and 89.2 GHz.
References
1. Ade, P.A.R. et al. (2014a, Planck Collaboration), A&A, 571, A16
2. Ade, P.A.R. et al. (2014b, BICEP2 Collaboration), Phys. Rev. Lett., 112, 241101
3. Ade, P.A.R. et al. (2014c, POLARBEAR Collaboration), ApJ, 794, 171
4. Ahmed, Z. et al. (2014), Proc. SPIE, Vol. 9153, 1
5. Antonucci, R. (1993), Ann. Rev. Astron. Astrophys., 31, 473
6. Aumont, J. et al. (2010), A&A, 514, A70
7. Begelman, M.C., Blandford, R.D., and Rees, M.J. (1984), Rev. Mod. Phys., 56, 255
8. Bernstein, R.A. et al. (2014), Proc. SPIE, Vol. 9145, 91451C
9. Birch, P. (1982), Nature, 298, 451
10. Bridle, A.H. and Perley, R.A. (1984), Ann. Rev. Astron. Astrophys., 22, 319
11. Brown, M.L. et al. (2009), ApJ, 705, 978
12. Carroll, S. M., Field, G. B., and Jackiw, R. (1990), Phys. Rev. D, 41, 1231
13. Carroll, S. M. and Field, G. B. (1997), Phys. Rev. Lett., 79, 2394
14. Carroll, S. M. (1998), Phys. Rev. Lett., 81, 3067
15. Chen, S.-J, Mei, H.-H and Ni, W.-T. (2007) Mod. Phys. Lett. A, 22, 2815
16. Cimatti, A., di Serego Alighieri, S., Fosbury, R.A.E., Salvati, M., and Duncan, T. (1993), MNRAS, 264, 421
17. Cimatti, A., di Serego Alighieri, S., Field, G. B., and Fosbury, R. A. E. (1994), ApJ, 422, 562
18. Clarke, J. N., Kronberg, P. P., and Simard-Normandin, M. (1980), MNRAS, 190, 205
19. Costa, E. et al. (2010), Exp. Astron., 28, 137
20. Covino, S. et al. (1999), A&A, 348, L1
21. de Zeeuw, T., Tamai, R., and Liske, J. (2014), The Messenger, 158, 3
22. Dean, A.J. et al. (2008), Science, 321, 1183
23. di Serego Alighieri, S., Cimatti, A., and Fosbury, R. A. E. (1994), ApJ, 431, 123
24. di Serego Alighieri, S., Field, G. B., and Cimatti, A. (1995), ASP Conf. Series, 80, 276
25. di Serego Alighieri, S., Filoci, F., and Galaverni, M. (2010), ApJ, 715, 33
26. di Serego Alighieri, S., Ni, W.-T., and Pan, W.-P. (2014), ApJ, 792,35
27. Eisenstein, D. J. and Bunn, E. F. (1997), Phys. Rev. Lett., 79, 1957
28. Galaverni, M., Gubitosi, G., Paci, F., and Filoci, F. (2014), submitted to JCAP, arXiv:1411.0287
29. Goldhaber, M. and Trimble, V. (1996), J. Astrophys. Astr., 17, 17
30. Gorski, K.M. et al. (2005) ApJ, 622, 759
31. G"otz, D. et al. (2014), MNRAS, 444, 2776
32. Gubitosi, G. et al. (2009), JCAP 0908, 021
33. Hinshaw, G. et al. (WMAP Collaboration) (2013), ApJS, 208, 19
34. Hutsemekers, D., Cabanac, R., Lamy, H., and Sluse, D. (2005), A&A, 441, 915
35. Hutsemekers, D., Braibant, L., Pelgrims, V., and Sluse, D. (2005), A&A, 572, A18
36. IAU Commission 40 (1974), Transactions of the IAU, Vol. XVb, p. 166
37. Joshi, S.A., Battye, R.A., Brown, I.W.A. Brown, Jackson, N., Muxlow, T.W.B., and Wilkinson, P.N. (2007), MNRAS, 380, 162
38. Kalemci, E. et al. (2007), ApJS, 169, 75
39. Kamionkowski, M. (2010), Phys. Rev. D, 82, 047302
40. Kaufman, J.P. et al. (BICEP1 Collaboration) (2014), Phys. Rev. D, 89, 062006
41. Kaufman, J.P., Keating, B.G., and Johnson, B.R. (2015), submitted, arXiv:1409.8242
42. Keating, B.G., Shimom., M., and Yadav, A.P.S. (2013), ApJL, 762, L23
43. Kostelecký, V.A. and Mewes, M. (2001), Phys. Rev. Lett., 87, 251304
44. Kostelecký, V.A. and Mewes, M. (2002), Phys. Rev. D, 66, 056005
45. Kostelecký, V.A. and Mewes, M. (2013), Phys. Rev. Lett., 110, 201601
46. Kovac, J. M. et al. (2002), Nature, 420, 722
47. Kronberg, P. P., Dyer, C. C., and Röser, H.-J. (1996), ApJ, 472, 115
48. Leahy, J. P. (1997), astro-ph/9704285
49. Lepora, N. F. (1998), arXiv:gr-qc/9812077
50. Liberati, S. and Maccione, L. (2009), Annu. Rev. Nucl. Part. Sci., 59, 245
51. Loredo, T. J., Flanagan, E. E., and Wasserman, I. M. (1997), Phys. Rev. D, 56, 7507
52. Maccione, L., Liberati, S., Celotti, A., Kirk, J. G., and Ubertini, P. (2008), Phys. Rev. D, 78, 103003
53. Massardi, M. et al. (2013), MNRAS, 436, 2915
54. Mei, H.-H., Ni, W.-T., Pan, W.-P., Xu, L., and di Serego Alighieri, S. (2014), submitted to ApJ, arXiv:1412.8569
55. Myers, R. C. and Pospelov, M. (2003), Phys. Rev. Lett., 90, 211601
56. Naess, S. et al. (2014), JCAP, 10, 007
57. Ni, W.-T. (1973), A Nonmetric Theory of Gravity, Montana State University, http://astrod.wikispaces.com/
58. Ni, W.-T. (1977), Phys. Rev. Lett., 38, 301
59. Ni, W.-T. (2008), Prog. Theor. Phys. Suppl., 172, 49
60. Ni, W.-T. (2010), Rep. Prog. Phys., 73, 056901
61. Ni, W.-T. (2014), submitted to Phys. Lett. A, arXiv:1411.0460
62. Ni, W.-T. (2015), Equivalence principles, spacetime structure and the cosmic connection, to be published as Chapter 5 of One Hundred Years of General Relativity: from Genesis and Empirical Foundations to Gravitational Waves, Cosmology and Quantum Gravity, W.-T. Ni, ed., World Scientific, Singapore
63. Nodland, B. and Ralston, J. P. (1997), Phys. Rev. Lett., 78, 3043
64. Pagano, L. et al. (2009), Phys. Rev. D, 80, 043522
65. Payez, A., Cudell, J. R., and Hutsemékers, D. (2011), Phys. Rev. D, 84, 085029
66. Saikia, D. J. and Salter, C. J. (1988), Ann. Rev. Astron. Astrophys., 26, 93
67. Sanders, G. H. (2013), Jour. Astrophys and Astron., 34, 81
68. Schiff, L. I. (1960), Am. J. Phys., 28, 340
69. Testi, L. and Walsh, J. (2013), The Messenger, 152, 2
70. Tran, H. D., Cohen, M. H., Ogle, P. M., Goodrich, R. W., and di Serego Alighieri, S. (1998), ApJ, 500, 660
71. Vernet, J., Fosbury, R. A. E., Villar-Martin, M., Cohen, M. H., Cimatti, A., di Serego Alighieri, S., and Goodrich, R. W. (2001), A& A, 366, 7
72. Wardle, J. F. C., Perley, R. A., and Cohen, M. H. (1997), Phys. Rev. Lett., 79, 1801
73. Wiersema, K. et al. (2014), Nature, 509, 201
74. Xia, J.-Q., Li, H., Wang, X., and Zhang, X. (2008), A& A, 483, 715
75. Xia, J.-Q., Li, H. and Zhang, X. (2010), Phys. Lett. B, 687, 129
76. Zavattini, E. et al. (2006), Phys. Rev. Lett., 96, 110406
77. Zavattini, E. et al. (2007), Phys. Rev. D, 77, 032006