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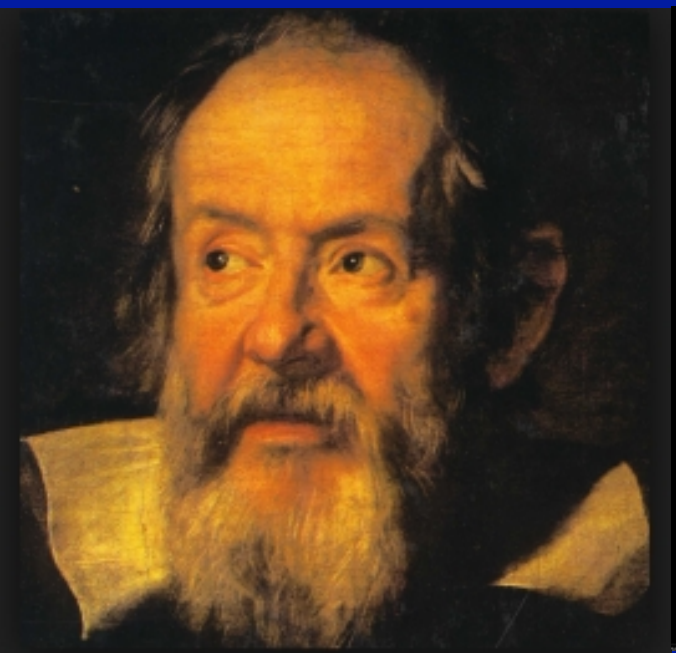
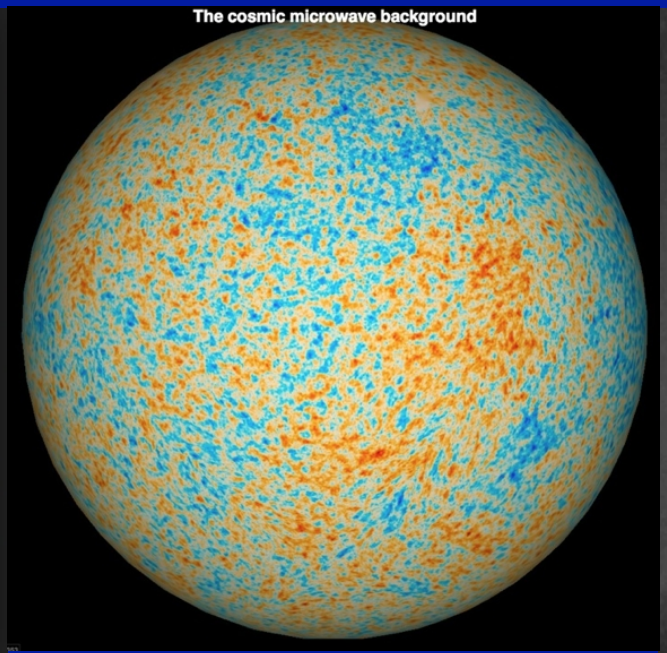
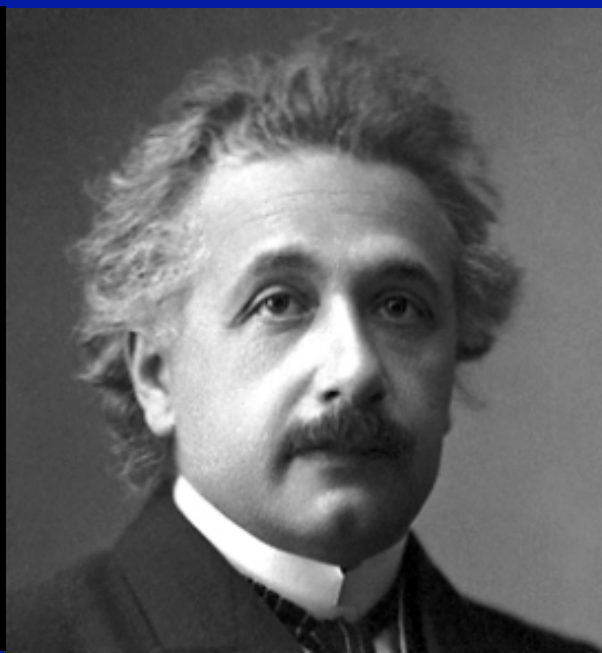
Using ALMA to calibrate the polarization angle at CMB frequencies

Sperello di Serego Alighieri
Osservatorio Astrofisico di Arcetri

in "One Hundred Years of General Relativity", W.-T. Ni ed. (2017), p. I-317, also arXiv:1501.06460v4







Searches for Cosmic Polarization Rotation

CPR is the rotation of the plane of polarization for photons traveling in *vacuum* across the Universe (not Faraday rotation).

We search for CPR for two main reasons:

1. To see if one of the 3 basic informations carried by photons (direction, energy and polarization) is changed while they travel to us.

2. Because eventual violations of fundamental physical principles (Lorentz invariance violation, CPT violation, neutrino number asymmetry, and violation of the Einstein Equivalence Principle) would cause CPR. Therefore our confidence in these principles would increase, if we can put stringent constraints on CPR being zero.

We advise to use the term CPR, not birefringence (rotation, no splitting).

A summary of CPR tests with different methods

Table 1. Measurements of CPR with different methods (in chronological order).

Method	CPR angle ± stat. (± syst.)	Frequency or λ	Distance	Direction	R
RG radio pol.	$\|\alpha\| < 6°$	5 GHz	$0.4 < z < 1.5$	All-sky (uniformity ass.)	12
RG UV pol.	$\|\alpha\| < 10°$	~ 3000 Å rest-frame	$0.5 < z < 2.63$	All-sky (uniformity ass.)	16
RG UV pol.	$\alpha = -1.4° \pm 1.1°$	~ 3000 Å rest-frame	$z = 0.811$	$RA : 176.4°, Dec : 31.6°$	72
RG radio pol.	$\alpha = -0.6° \pm 1.5°$	3.6 cm	$\langle z \rangle = 0.78$	All-sky (uniformity ass.)	14
CMB pol. BOOMERanG	$\alpha = 4.3° \pm 4.1°$	145 GHz	$z \sim 1100$	$RA \sim 82°, Dec \sim 45°$	64
CMB pol. QUAD	$\alpha = -0.64° \pm 0.50° \pm 0.50°$	100–150 GHz	$z \sim 1100$	$RA \sim 82°, Dec \sim 50°$	11
RG UV pol.	$\alpha = -0.8° \pm 2.2°$	~ 1300 Å rest-frame	$\langle z \rangle = 2.80$	All-sky (uniformity ass.)	25
RG UV pol.	$\langle \delta\alpha^2 \rangle \leq (3.7°)^2$	~ 1300 Å rest-frame	$\langle z \rangle = 2.80$	All-sky (stoch. var.)	25
CMB pol. WMAP9	$\alpha = 0.36° \pm 1.24° \pm 1.5°$	23–94 GHz	$z \sim 1100$	All-sky (uniformity ass.)	33
CMB pol. BICEP1	$\alpha = 2.77° \pm 0.86° \pm 1.3°$	100–150 GHz	$z \sim 1100$	$-50° < RA < 50°, -70° < Dec < -45°$	40
CMB pol. POLARBEAR	$\alpha = 1.08° \pm 0.2° \pm 0.5°$	148 GHz	$z \sim 1100$	$RA \sim 70°, 178°, 345°; Dec \sim -45°, 0°, -33°$	3
CMB pol. ACTPol	$\alpha = 1.0° \pm 0.63°$**	146 GHz	$z \sim 1100$	$RA \sim 35°, 150°, 175°, 355°, Dec \sim 50°$	54
CMB pol. B-mode	$\langle \delta\alpha^2 \rangle \leq (1.36°)^2$	95–150 GHz	$z \sim 1100$	Various sky regions	54
CMB pol. Planck	$\alpha = 0.35° \pm 0.05° \pm 0.28°$	30–353 GHz	$z \sim 1100$	All-sky (uniformity ass.)	79

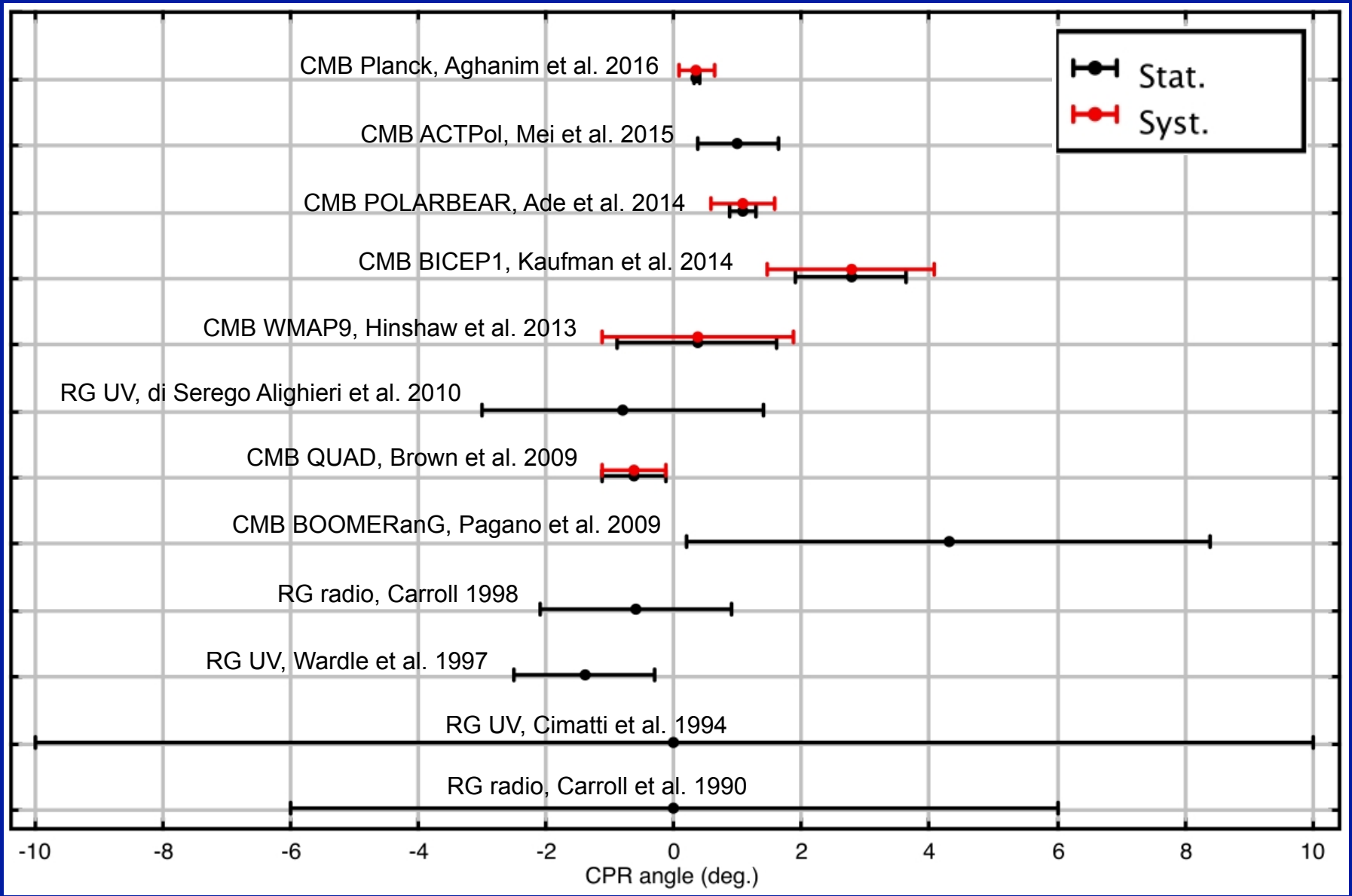
Note: **A systematic error should be added, equal to the unknown difference of the Crab Nebula polarization PA between 146 GHz and 90 GHz.

S. di Serego Alighieri 2016, in "One Hundred Years of General Relativity", ed.W.-T. Ni (World Scientific, Singapore) p. I-317, also arXiv:1501.06460v4

All results are consistent with a null CPR. 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.

A summary of CPR tests with different methods

di Serego Alighieri, arXiv:1501.06460v4



Problems in testing the CPR with the CMB

1. CMB Polarization PA calibration problem

One problem is the calibration of the polarization PA for the **lack of sources with precisely known PA at CMB frequencies**. This introduces a systematic error (related to the offset β of the adopted PA zero point), which is similar (if not bigger) than the statistical measurement error, of the order of 1°. Recently the polarization PA of the Crab Nebula (α Tau) has been measured with an accuracy of 0.2° at 89.2 GHz (Aumont et al. 2010). However most CMB polarization measurements are made at higher frequencies (100 – 150 GHz) and the Crab is not visible from the South Pole. In order to overcome this problem, some CMB polarization experiments have used a TB and EB nulling procedure (Keating et al. 2013). However this procedure actually gives a measurement of α-β and can hardly be used for CPR tests.

Recent measurement by Planck: $\alpha = 0°.35 \pm 0°.05$ (stat.) $\pm 0°.28$ (syst.)
In fact this measurement is likely a measure of the Planck PA offset β.

A rotation of linear polarization produces a coupling between T, E-mode and B-mode polarization of CMB, in particular a leakage of E-modes into B-modes.

$$C_\ell^{TE} = \cos(2\Delta\psi)\tilde{C}_\ell^{TE}$$

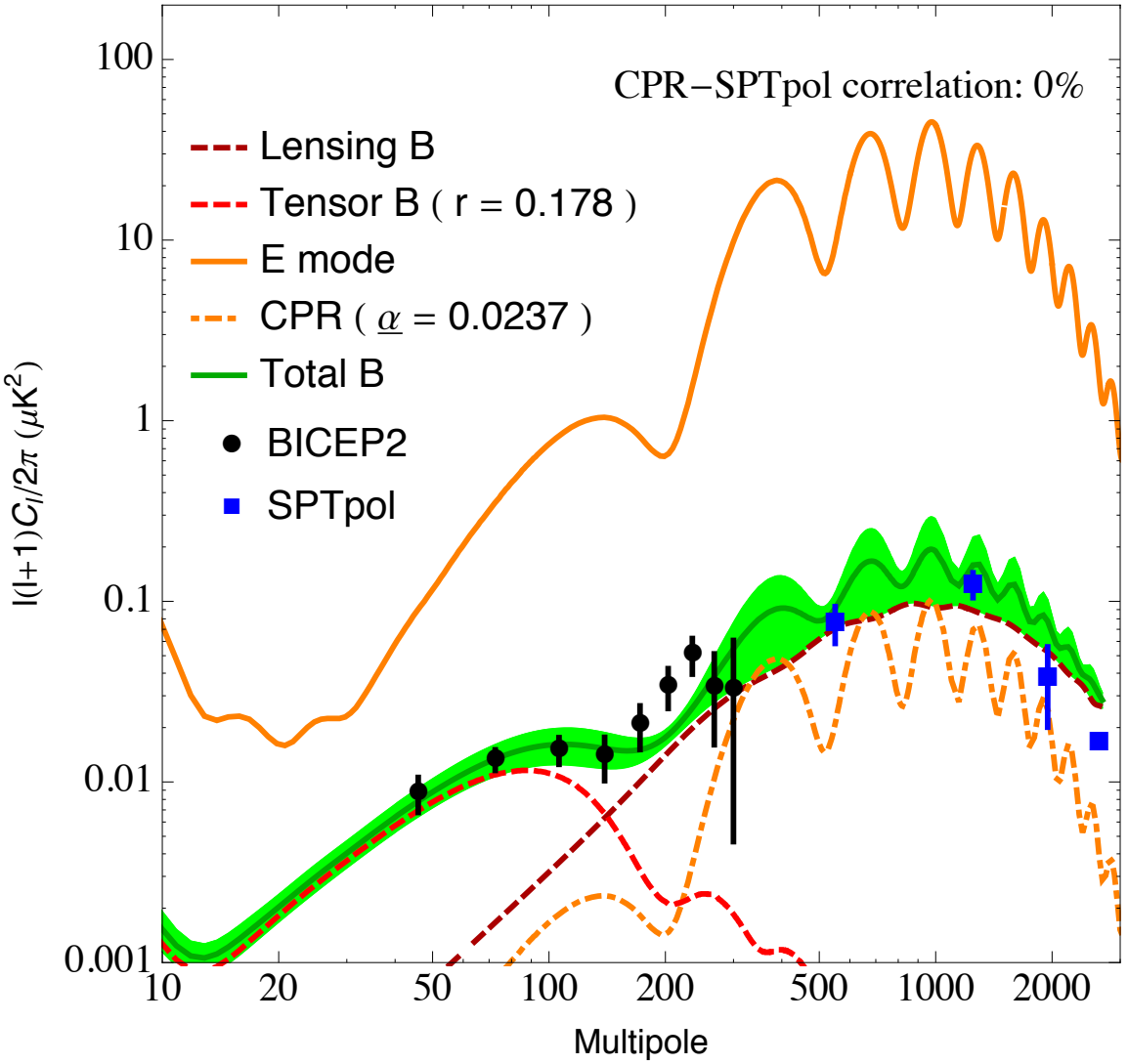
$$C_\ell^{EE} = \sin^2(2\Delta\psi)\tilde{C}_\ell^{BB} + \cos^2(2\Delta\psi)\tilde{C}_\ell^{EE}$$

$$C_\ell^{EB} = \frac{1}{2}\sin(4\Delta\psi)\left(\tilde{C}_\ell^{BB} - \tilde{C}_\ell^{EE}\right)$$

$$C_\ell^{TB} = -\sin(2\Delta\psi)\tilde{C}_\ell^{TE}$$

$$C_\ell^{BB} = \cos^2(2\Delta\psi)\tilde{C}_\ell^{BB} + \sin^2(2\Delta\psi)\tilde{C}_\ell^{EE}$$

A new test of CPR using B-mode polarization of CMB



$\langle \delta\alpha^2 \rangle \leq (0.97°)^2$ Pan et al. (2016) IJMPD, in press, also arXiv:1603.08193

Observations of polarized radio sources with ALMA

In order to provide the CMB experiments with calibration sources for the polarization angle, with Marcella Massardi, Vincenzo Galluzzi and others we have started a programme of polarimetry of southern compact radio sources with ATCA and ALMA at CMB frequencies. A paper with observations with ATCA at frequencies up to 38 GHz has been published (Galluzzi et al. 2017, MNRAS 465, 4085, see also the talk by Vincenzo). Since we need to go to higher frequencies a programme to observe some of these sources with ALMA up to 100 GHz has been started (preliminary results in Vincenzo's talk).

What we need now is to extend this ALMA programme by including higher frequencies (up to about 150 GHz), selecting a few sources which are suitable for the polarization angle calibration, and making sure that the accuracy of the ALMA polarization angle measurement is with a fraction of a degree.

Summary and outlook

1. CPR tests using the CMB and searches for the effects of primordial inflationary gravitational waves on the B-mode polarization of the CMB are currently limited by systematic errors due to the uncertainty on the calibration of the zero point of the polarization angle, which are of the order of 1 degree.

2. In order to solve this problem we have started a programme of polarization angle measurement of compact radio sources with ALMA and ATCA at CMB frequencies, but we need that the accuracy of polation angle measurement with ALMA is within a fraction of a degree.

3. A complementary solution would be a calibration source on a satellite (CalSat, Kaufman et al. 2014) or on balloons. For example POLOCALC (Nati et al. 2017, arXiv:1704.02704) should provide arcsecond accuracy.