Testing parity violation with the CMB

Paolo Natoli
Università di Ferrara

(thanks to Alessandro Gruppuso)

ISSS L'Aquila 24 April 2014

Introduction

- The aim is to use observed properties of CMB pattern to constrain deviations from the Standard Model of Particle Physics. Since the physics that governs the CMB is purely electromagnetic, this implies searching for violations in the photon sector.

- The Maxwell Lagrangian is expected to conserve parity (P symmetry). Models beyond the standard model predict instead P violations that may result in a global violation of the CPT symmetry. [Direct measurements have constrained such theories within the limits allowed by earthily laboratories.]

- Are there any manifestation of Parity violation other than those observed in weak interaction?

CMB and Fundamental Physics

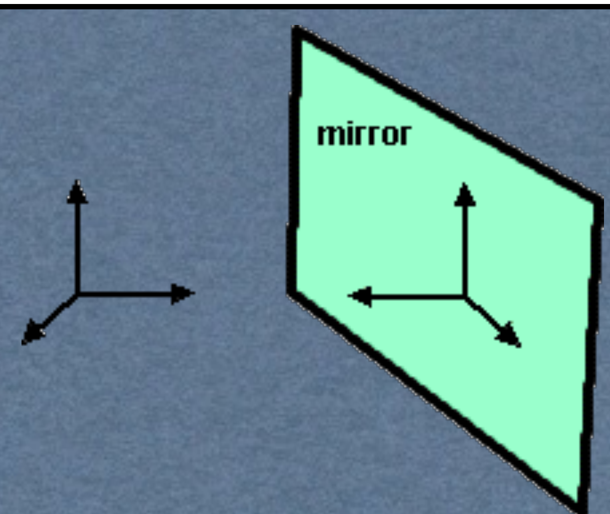
CMB observations provide a new window of investigation, since

- They can probe electromagnetism in the early universe, directly at $z \sim 1100$, and indirectly at much earlier times. These conditions are not obviously identical to present.

- The great majority of CMB photons travel freely 98% of the current horizon distance. No other photon in the universe can propagate that long without interacting. Thus, they provide a unique probe to test in vacuo birefringence and other effects that add up with time.

Parity Symmetry - Basics

It is the transformation that is applied when we look at the world in a mirror. In math it is the flip of sign of one spatial coordinate. In three dimensions it is equivalent to the flips of all the 3 spatial dimensions (note that the flip of signs of 2 axes in 3 dimensions is equivalent to a rotation). The determinant of a Parity transformation is -1 (whereas a Rotation has determinant =1)



$$\begin{cases} x \longrightarrow -x \\ y \longrightarrow -y \\ z \longrightarrow -z \end{cases}$$

If Physics equations are invariant under Parity then we say that Parity is conserved. Specifically Parity is conserved in electromagnetic interactions (as well as in gravity and strong interactions) whereas is broken in weak interactions.

CMB physics is purely electromagnetic! Therefore through CMB anisotropies we can study whether the Lagrangian of the photon is Parity conserved as we expect. This analysis might help in constraining Parity-violating terms that can be introduced within new theories.

Parity Symmetry - Observables

CMB anisotropies are usually expanded in spherical harmonics

spherical harmonics expansion for T anisotropies	Parity	Property
$a_{T,\ell m} = \int d\Omega \, Y^{\star}_{\ell m}(\hat{n}) \, T(\hat{n})$	$\hat{n} \longrightarrow -\hat{n}$	$a_{T,\ell m} \rightarrow (-1)^{\ell} \, a_{T,\ell m}$

behaviour of T coefficients of spherical harmonics under parity symmetry (i.e. even multipoles are invariant under parity whereas odd multipoles acquire a "-1")

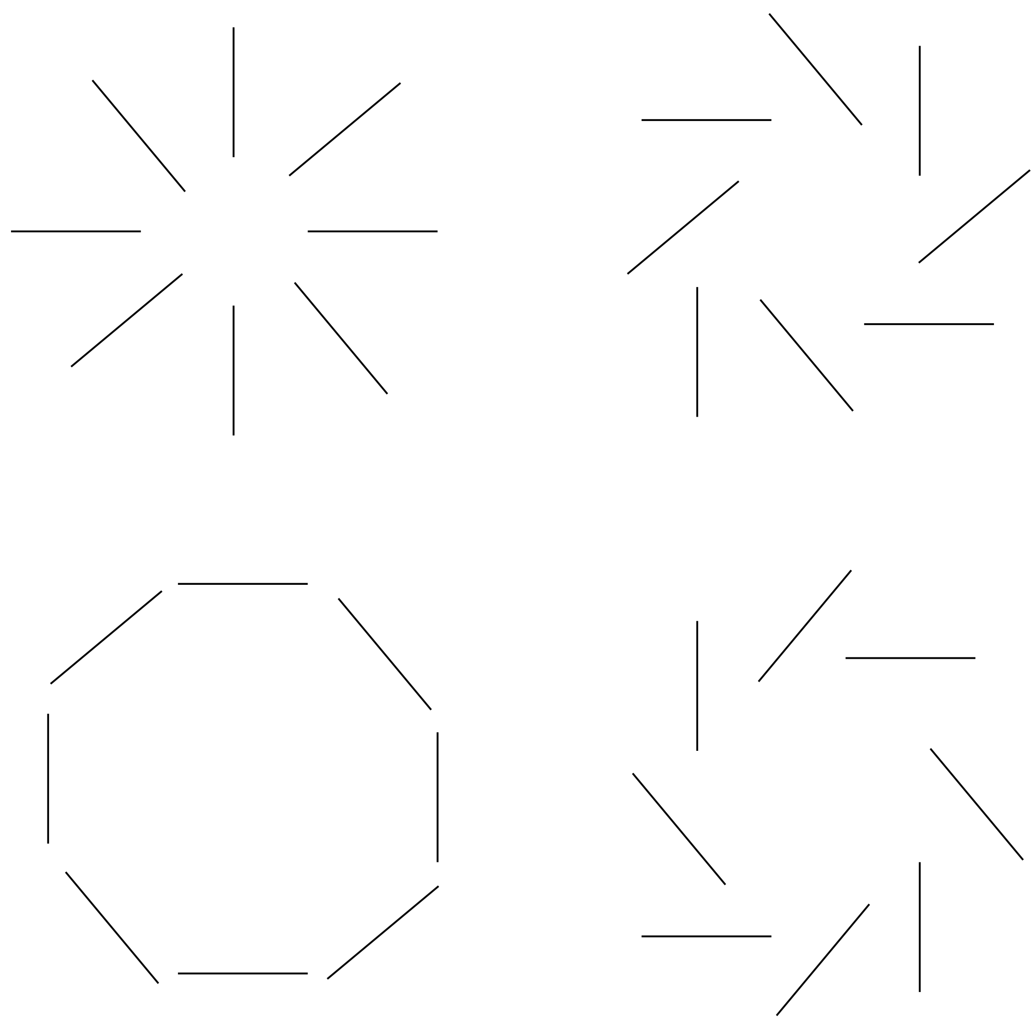
CMB physics does not distinguish between even and odd multipoles.

For example *at low ell* the TT power spectrum is given by the so called Sachs - Wolfe plateau that reads:

$$\boxed{\ell(\ell+1)C_{\ell}^{TT} \sim const}$$

Therefore it is possible to divide each T map in two subsets corresponding to even and odd multipoles, satisfying two different transformation under P symmetry. Estimating the angular power spectrum contained in the two subsets it is possible to study the consistency with P symmetry

E-mode and B-mode



E mode B mode

- Polarization is a spin 2 tensor, can be decomposed in parity even and parity odd component ("E" and "B")
- Gravitational potential (density perturbation, parity even) can generate the E-mode polarization, but not B-modes because CMB physics is electromagnetic (parity conserving)
- **Gravitational waves** can generate both E- and B-modes!

Parity Symmetry - Observables

spherical harmonics expansion for Pol anisotropies	Parity	Property
$a_{\pm 2,\ell m} = \int d\Omega\, Y^{\star}_{\pm 2,\ell m}(\hat{n})(Q(\hat{n}) \pm iU(\hat{n}))$	$\hat{n} \rightarrow -\hat{n}$	$a_{E,\ell m} = (-1)^{\ell} a_{E,\ell m}$ $a_{B,\ell m} = (-1)^{\ell+1} a_{B,\ell m}$

$$a_{E,\ell m} = -(a_{2,\ell m} + a_{-2,\ell m})/2$$
$$a_{B,\ell m} = -(a_{2,\ell m} - a_{-2,\ell m})/2i$$

Similar consideration previously expressed for T can be applied to the E mode and (potentially) to the B mode

Moreover the opposite behavior of B w.r.t. T or E, impose that the cross-correlations <T B> and <E B> have to be null to be consistent with Parity symmetry!

Parity Symmetry - Observables

$$a^{(P)}_{T,\ell m} = (-1)^{\ell} a_{T,\ell m}$$
$$a^{(P)}_{E,\ell m} = (-1)^{\ell} a_{E,\ell m}$$
$$a^{(P)}_{B,\ell m} = (-1)^{\ell+1} a_{B,\ell m}$$

Study of even/odd multipoles
in power spectra for TT, EE, TE and
(potentially) BB

$$C_\ell^{TB} = 0$$
$$C_\ell^{EB} = 0$$

Compatibility with null observation
in power spectra for TB and EB

TT Parity from Planck

- Define: $T^{+}(\boldsymbol{n}) = \dfrac{T(\boldsymbol{n}) + T(-\boldsymbol{n})}{2}; \quad T^{-}(\boldsymbol{n}) = \dfrac{T(\boldsymbol{n}) - T(-\boldsymbol{n})}{2}.$
- These maps have even and odd parity.

$$T^{+}(\boldsymbol{n}) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\boldsymbol{n}) \Gamma^{+}(\ell) \qquad \Gamma^{+}(\ell) = \cos^2(\ell\pi/2)$$

$$\Gamma^{-}(\ell) = \sin^2(\ell\pi/2)$$

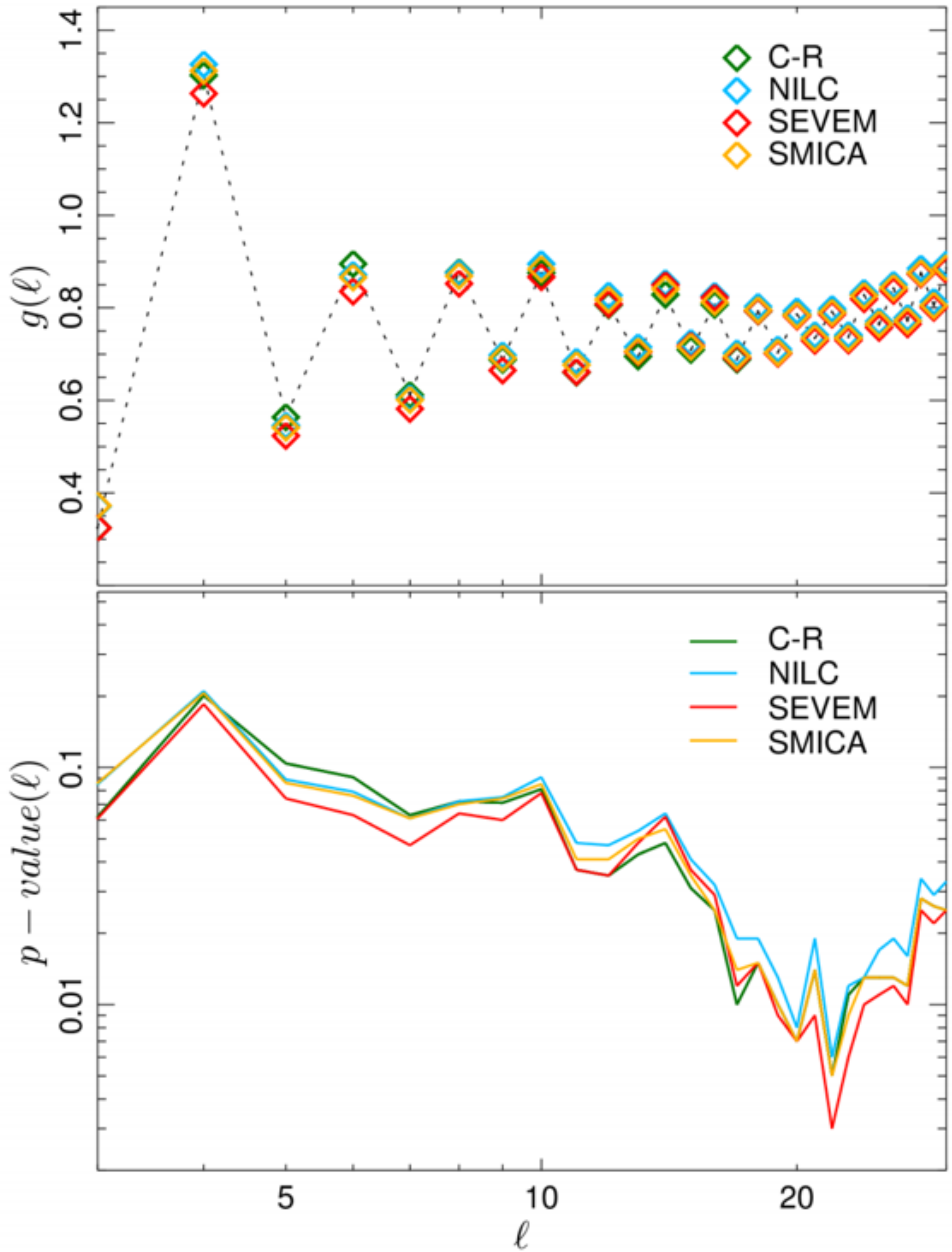
$$T^{-}(\boldsymbol{n}) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\boldsymbol{n}) \Gamma^{-}(\ell)$$

$$P^{+}(\ell) = \sum_{n=2}^{\ell} \Gamma^{+}(n) \frac{n(n+1)}{2\pi} C_n$$

- And then:

$$P^{-}(\ell) = \sum_{n=2}^{\ell} \Gamma^{-}(n) \frac{n(n+1)}{2\pi} C_n$$

$$g(\ell) = \frac{P^{+}(\ell)}{P^{-}(\ell)}.$$



C-R
NILC
SEVEM
SMICA
$g(\ell)$
1.4
1.2
1.0
0.8
0.6
0.4
C-R
NILC
SEVEM
SMICA
$p-value(\ell)$
0.1
0.01
5
10
20
ℓ

Planck polarization forecasts (e.g. 143 GHz channel)

Standard deviation for D [uK^2]

σ_D	WMAP 7 year	Planck
TT	1517.17	1509.21
TE	20.19	9.08
EE	0.65	0.10
BB	0.69	0.04

$$R^X = C_+^X / C_-^X$$

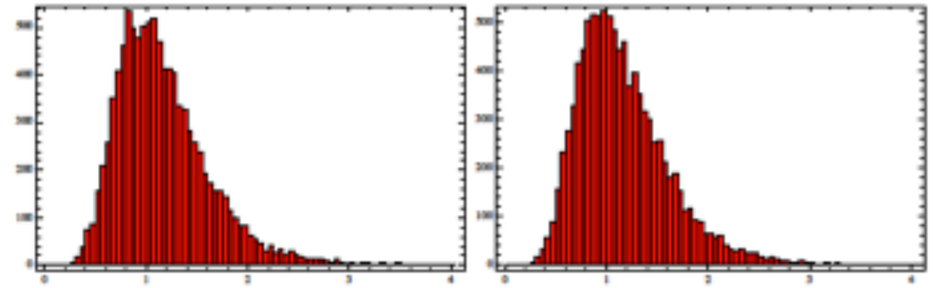
$$D^X = C_+^X - C_-^X$$

Warning: forecast obtained considering just the nominal sensitivity. Systematics are not taken into account

Standard deviation for C [uK^2]

σ_C	WMAP 7 year	Planck
TB	0.95	0.19
EB	0.023	0.001

R on EE



Birefringence - Basics

- In vacuo birefringence is a rotation of the polarization plane of a photon due to non-standard modifications to the Maxwell Lagrangian. It is a powerful probe of new physics beyond the Standard Model and a tracer of P (and therefore CPT) violations.

- CMB polarization arises at two distinct cosmological times: the recombination epoch (z~1100) and the re-ionization era at z~11. When the CMB field is expanded in spherical harmonics, the first signal mostly shows up at high multipoles, since polarization is generated through a causal process and the Hubble horizon at last scattering subtends a degree size angle. The later re-ionization of the cosmic fluid at lower redshift impacts the low ell instead. These two regimes need to be taken into account when probing for cosmological birefringence, since they can be ascribed to different epochs and, hence, physical conditions.

Birefringence - Observables

if such an effect exists then APS of CMB anisotropies get modified as follows:

$$
\begin{aligned}
\langle C_\ell^{TE,obs} \rangle &= \langle C_\ell^{TE} \rangle \cos(2\alpha) \,, \\
\langle C_\ell^{TB,obs} \rangle &= \langle C_\ell^{TE} \rangle \sin(2\alpha) \,, \\
\langle C_\ell^{EE,obs} \rangle &= \langle C_\ell^{EE} \rangle \cos^2(2\alpha) + \langle C_\ell^{BB} \rangle \sin^2(2\alpha) \,, \\
\langle C_\ell^{BB,obs} \rangle &= \langle C_\ell^{BB} \rangle \cos^2(2\alpha) + \langle C_\ell^{EE} \rangle \sin^2(2\alpha) \,, \\
\langle C_\ell^{EB,obs} \rangle &= \frac{1}{2} \left(\langle C_\ell^{EE} \rangle + \langle C_\ell^{BB} \rangle \right) \sin(4\alpha) \,.
\end{aligned}
$$

where alpha is the birefringence angle, "obs" spectra are the ones observed (LHS), whereas the spectra at the RHS are the "primordial" ones, i.e. the spectra that are observed if alpha=0.

these equations are obtained supposing alpha constant. For a generalization see e.g.

Finelli and Galaverni PRD 2009

From these equations it is possible to build estimators for alpha. **Measuring alpha it is then possible to test the fundamental theory of electromagnetism** and constraining the amplitude of the terms that violate CPT symmetries.

alpha is related to the considered modification of Maxwell Lagrangian

$$\Delta \mathcal{L} = -\frac{1}{4} p_\mu \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma} A_\nu \,,$$

Birefringence - Estimators

$$D_{\mathrm{TB},\ell} = C_\ell^{\mathrm{TB,obs}} \cos(2\Delta\alpha) - C_\ell^{\mathrm{TE,obs}} \sin(2\Delta\alpha),$$

$$D_{\mathrm{EB},\ell} = C_\ell^{\mathrm{EB,obs}} - \frac{1}{2}(C_\ell^{\mathrm{BB,obs}} + C_\ell^{\mathrm{EE,obs}}) \sin(4\Delta\alpha).$$

$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{TB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{TB},\ell'},$$

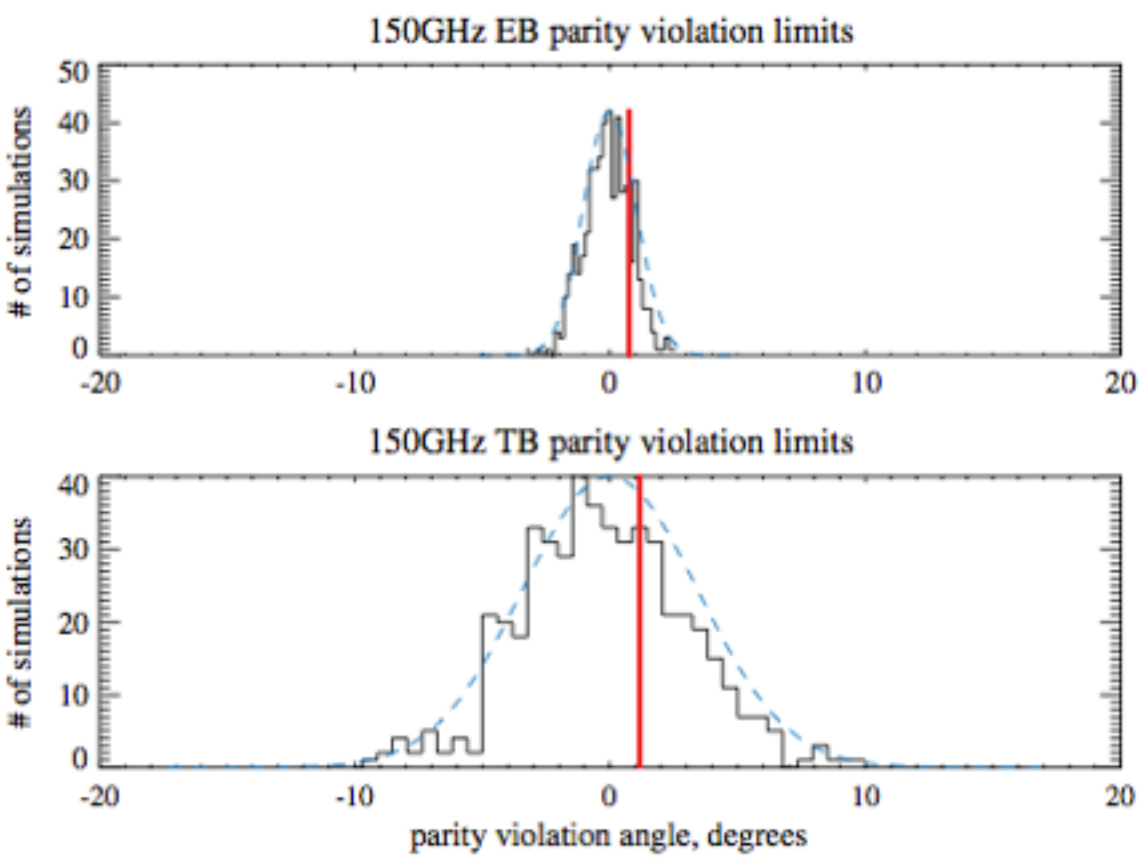
$$\chi^2(\Delta\alpha) = \sum_{\ell\ell'} D_{\mathrm{EB},\ell} M_{\ell\ell'}^{-1} D_{\mathrm{EB},\ell'}.$$

These D estimators have "nice" properties

1. they are linear in C_ell and therefore lead to a naturally unbiased estimators (if the APS estimator is unbiased).
2. the purely signal part drops out (lower variance, specially at low ell)

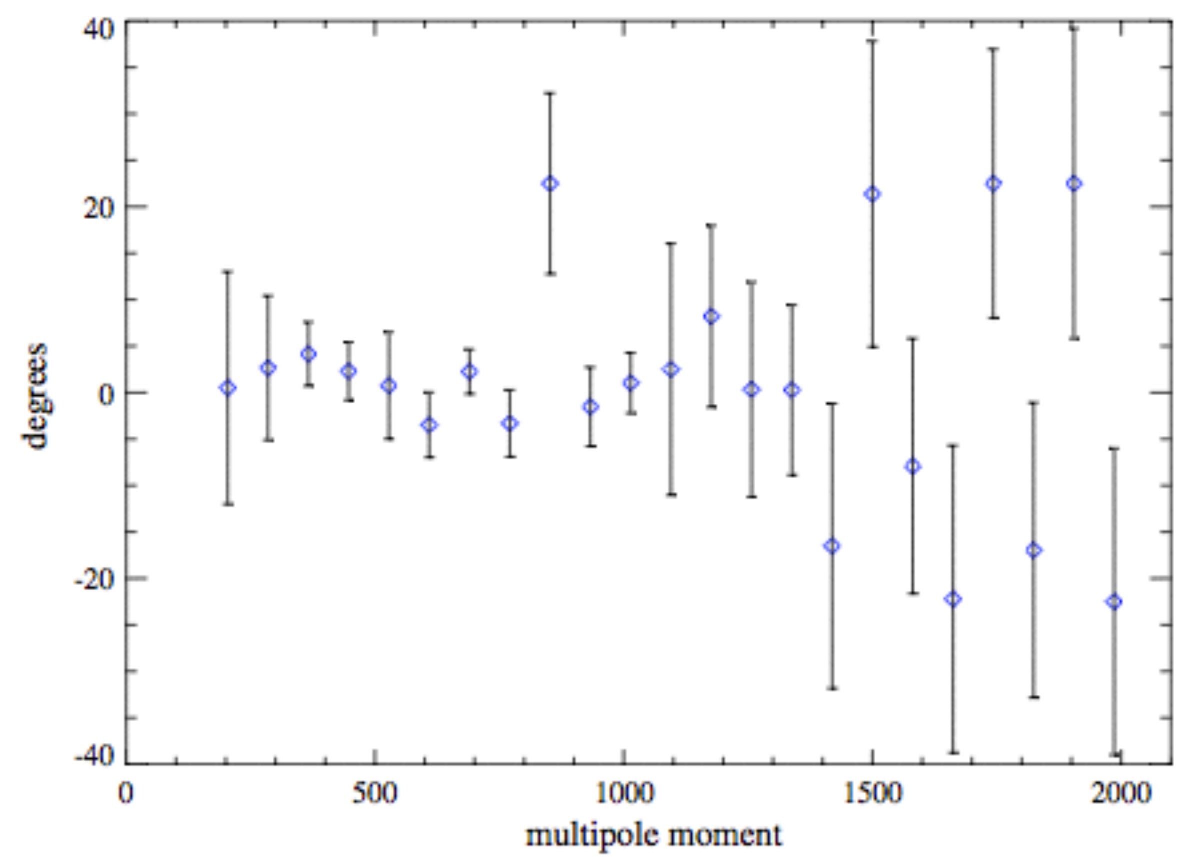
Birefringence - Results

Small Angular scale



QUAD EXPERIMENT

Wu et al. PRL 102 (2009)



alpha = 0.55 +/- 0.82 (statistical) +/- 0.5 (systematic) [deg]

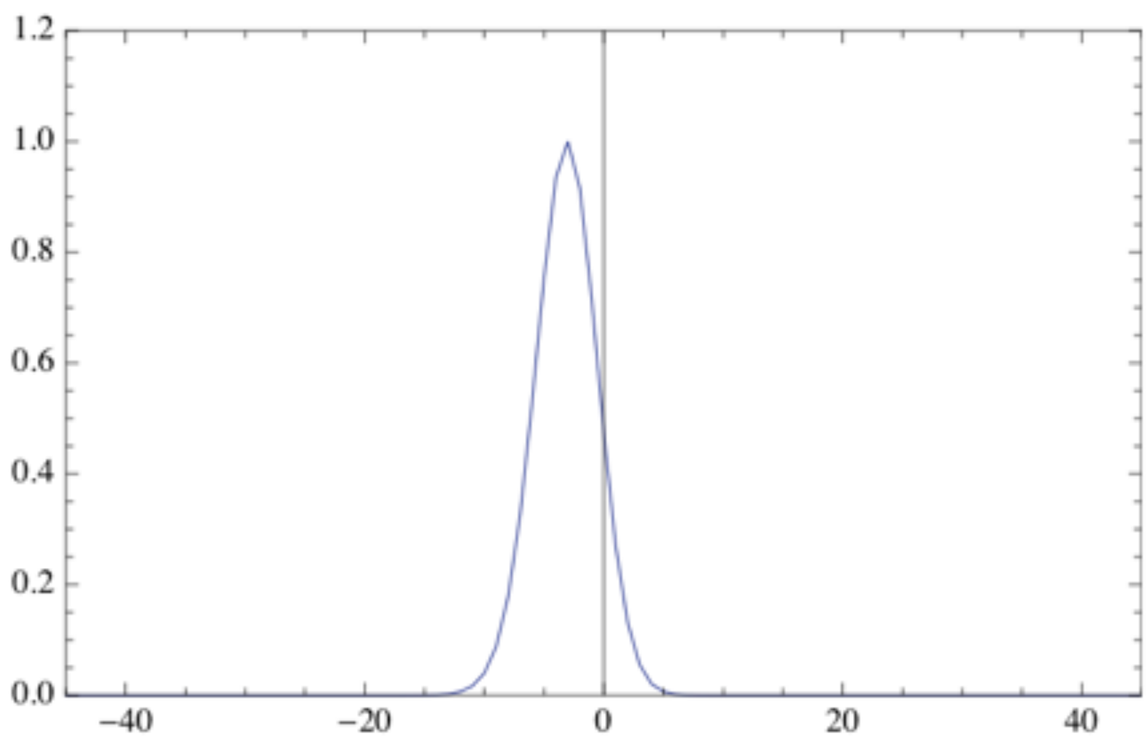
Birefringence - Results

Large Angular scale

WMAP DATA

Gruppuso et al. (2011) JCAP
arXiv:1107.5548

alpha = -3.0 +/- 3.5 [deg] (WMAP 7YR)



using a pixel based likelihood code

Komatsu et al. ApJSS 192 (2011)

alpha = -3.8 +/- 5.2 [deg] (WMAP 7YR)

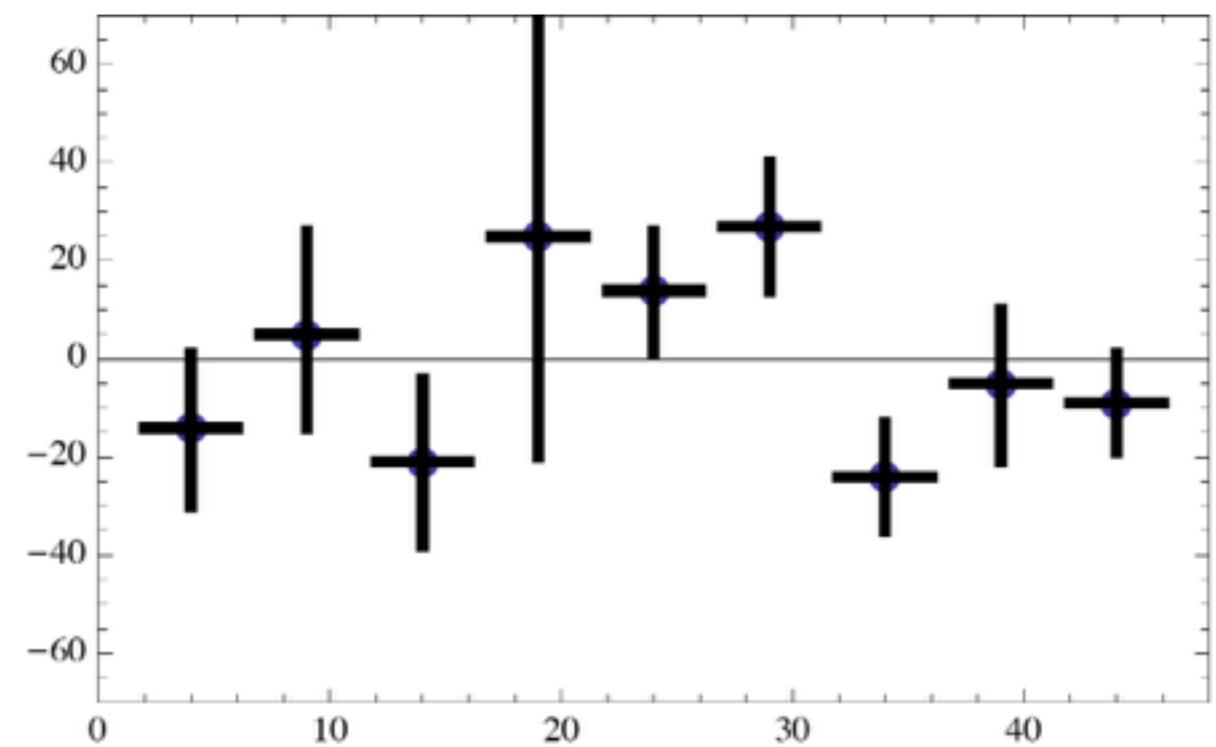
not taking into account a
systematic error of ~1.5 [deg]

Birefringence - Results

Large Angular scale

WMAP EXPERIMENT

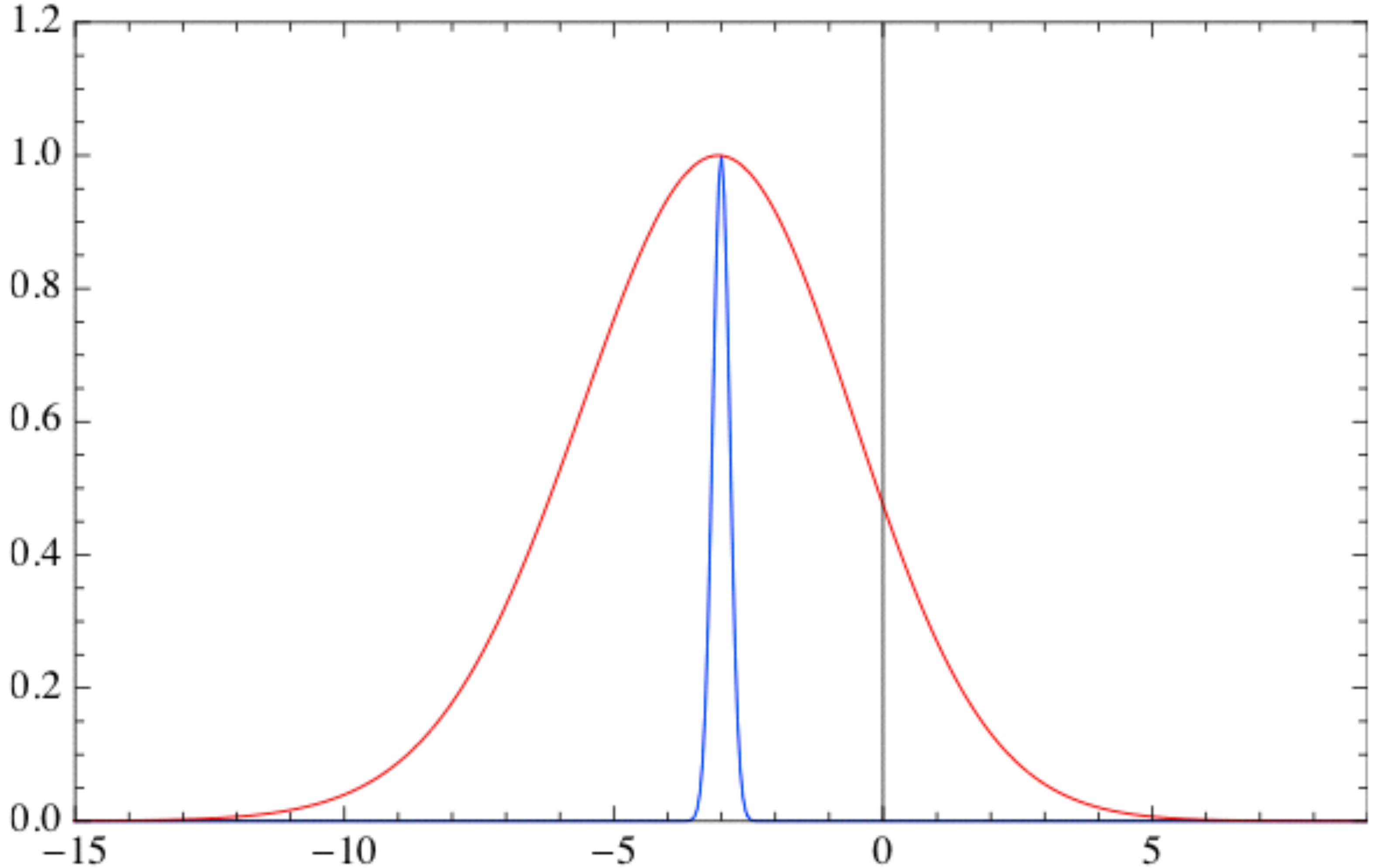
Varying l_min and l_max, the D estimators allow to build the spectrum of the birefringence angle at large angular scale. **This provides a scale dependent information on the birefringence angle.**
For example considering the DTB estimator



Gruppuso et al. (2011) JCAP
arXiv:1107.5548

Birefringence - Forecasts

[low ell]



Planck

Red = WMAP 7 year

Blue = Planck forecast

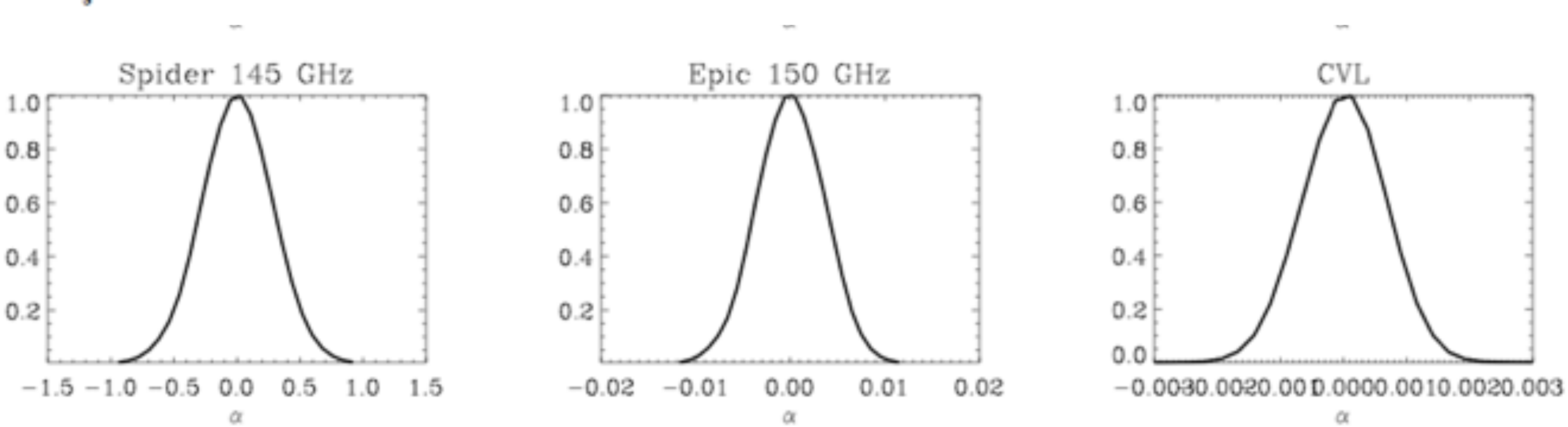
For example considering the joint estimator for the ell range [2,23] Planck should outnumber WMAP by a factor above 16 in terms of standard deviations

Warning: forecast obtained considering just the nominal sensitivity. Systematics are not taken into account

Birefringence - Forecasts

Experiment	Channel	$\sigma(\alpha)$	$\sigma(\xi)$
PLANCK	70	0.64	$6.0 \cdot 10^{-2}$
	100	0.14	$6.5 \cdot 10^{-3}$
	143	0.073	$1.7 \cdot 10^{-3}$
	217	0.10	$1.0 \cdot 10^{-3}$
	100+143+217	-	$8.5 \cdot 10^{-4}$
Spider	145	0.27	$6.1 \cdot 10^{-3}$
EPIC	70	$2.1 \cdot 10^{-3}$	$1.9 \cdot 10^{-4}$
	100	$1.8 \cdot 10^{-3}$	$7.8 \cdot 10^{-5}$
	150	$1.5 \cdot 10^{-3}$	$2.9 \cdot 10^{-5}$
	220	$1.2 \cdot 10^{-3}$	$1.1 \cdot 10^{-5}$
	70+100+150+220	-	$1.0 \cdot 10^{-5}$
CVL	150	$6.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$
	217	$6.1 \cdot 10^{-4}$	$6.1 \cdot 10^{-6}$

Table 3. Expected 1σ error for PLANCK 70, 100, 143, 217 GHz, Spider 145 GHz, EPIC 70, 100, 150, 220 GHz and two ideal CVL experiment at 150 GHz and 217 GHz on α (in degrees) and ξ.



[high ell]

These constraints are obtained performing a MCMC over 8 cosmological parameters, including alpha.

By courtesy of L.Pagano

improvement factors for Planck about 10-20

See paper by G.Gubitosi et al. (2009) JCAP

Conclusions

- Parity and CPT symmetries can be tested with CMB.
- CMB observations are already sensitive enough to provide competitive constraints.
- Stay tuned for Planck!

note

- Thomson scattering. CMB is linearly polarized due to Thomson scattering (photon-charged particles). This happens at recombination epoch (z~1100) and later on when structures begin to form (z~10). These are the two epochs at which CMB gets polarized. However, the universe is expanded enough that density of ionized H is low and the universe is still transparent. Optical depth (tau, i.e., the probability that a given photon scatters once).

- Even though CMB photons are energetically weak, they are important for testing Lorentz and CPT symmetries for two reasons: first, CMB photons are generated during the early universe, when physics at the stake was not obviously identical to present and second, the long journey undertaken by CMB photons may make observable tiny violations to electromagnetic Lagrangian.

- Chern-Simons modification of Maxwell Lagrangian

$$\Delta\mathcal{L} = -\frac{1}{4} p_\mu \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma} A_\nu \ ,$$