Including birefringence into time evolution of CMB: current and future constraints

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Based on:
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Outline

1 Planck lensing results

2 Cosmic Birefringence and CMB lensing

3 CMB constraints

4 Summary
1 Planck lensing results

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4 Summary
Planck 2015 measured the lensing amplitude $A_L$

$$C_\ell^{\phi\phi} = A_L \tilde{C}_\ell^{\phi\phi}$$
A non standard $A_L$ may have huge implications for cosmology. It may hint for a deviation from General Relativity.
Planck obtained also the reconstruction of CMB lensing from quadratic estimators

Planck 2015 results. XV. Gravitational lensing

This technique gives a CMB lensing spectrum $1 - \sigma$ away from $\Lambda$CDM

$$A_L = 0.95 \pm 0.04$$
This result show how deviations from standard lensing drive the hint for modifications of gravity.

Planck 2015 results. XIV. Dark energy and modified gravity

The two techniques seem to push in different directions. Is there a way to reconcile the 2 results on $A_L$?
1 Planck lensing results

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4 Summary
Cosmic Birefringence

Cosmic birefringence is the rotation of light’s linear polarization plane through cosmological distances.

Theoretical models departing from the standard $\Lambda$CDM cosmology may drive this rotation.
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- Dark Energy motivated quintessence fields coupled to photons.  
  *Carroll (1998)*

- Axions, possible Dark Matter candidate  
  *Finelli, Galaverni (2009)*

- Quantum Gravity theories  
  *Myers, Pospelov (2003)*
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- Miscalibration of polarimeters
  
  *Pagano et al. (2009)*
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This leads to a leakage of power between CMB spectra.
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\[
\begin{align*}
C_{\ell}^{EE} &= \tilde{C}_{\ell}^{EE} \cos^2 (2\alpha_0) + \tilde{C}_{\ell}^{BB} \sin^2 (2\alpha_0) - \tilde{C}_{\ell}^{EB} \sin (4\alpha_0) \\
C_{\ell}^{BB} &= \tilde{C}_{\ell}^{EE} \sin^2 (2\alpha_0) + \tilde{C}_{\ell}^{BB} \cos^2 (2\alpha_0) + \tilde{C}_{\ell}^{EB} \sin (4\alpha_0) \\
C_{\ell}^{EB} &= \frac{1}{2} \left( \tilde{C}_{\ell}^{EE} - \tilde{C}_{\ell}^{BB} \right) \sin (4\alpha_0) + \tilde{C}_{\ell}^{EB} \left( \cos^2 (2\alpha_0) - \sin^2 (2\alpha_0) \right) \\
C_{\ell}^{TE} &= \tilde{C}_{\ell}^{TE} \cos (2\alpha_0) - \tilde{C}_{\ell}^{TB} \sin (2\alpha_0) \\
C_{\ell}^{TB} &= \tilde{C}_{\ell}^{TE} \sin (2\alpha_0) + \tilde{C}_{\ell}^{TB} \cos (2\alpha_0)
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C^\ell_{EB} & = \frac{1}{2} \left( \tilde{C}^\ell_{EE} - \tilde{C}^\ell_{BB} \right) \sin (4\alpha_0) + \tilde{C}^\ell_{EB} \left( \cos^2 (2\alpha_0) - \sin^2 (2\alpha_0) \right) \\
C^\ell_{TE} & = \tilde{C}^\ell_{TE} \cos (2\alpha_0) - \tilde{C}^\ell_{TB} \sin (2\alpha_0) \\
C^\ell_{TB} & = \tilde{C}^\ell_{TE} \sin (2\alpha_0) + \tilde{C}^\ell_{TB} \cos (2\alpha_0)
\end{align*}
\]

Just a simple example: equations do not include CMB lensing and a constant rotation is assumed.

Full equations can be found in Gubitosi, Martinelli, Pagano (2014)
Cosmic birefringence leads to non vanishing primordial BB, TB and EB spectra. These are not produced in the standard model (BB is produced by lensing and tensor perturbations)
Birefringence produces a leakage from E to B modes, thus can partially mimic the effect of gravitational lensing on CMB spectra.
Lensing and birefringence

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\[
\begin{align*}
D_\ell \left[ \mu K^2 \right] &= 10^0 \quad (\alpha_0 = 0^\circ, \alpha_1 = 0^\circ, A_L = 1) \\
D_\ell \left[ \mu K^2 \right] &= 10^{-1} \quad (\alpha_0 = -2^\circ, \alpha_1 = 0^\circ, A_L = 1) \\
D_\ell \left[ \mu K^2 \right] &= 10^{-2} \quad (\alpha_0 = 0^\circ, \alpha_1 = +2^\circ, A_L = 1) \\
D_\ell \left[ \mu K^2 \right] &= 10^{-3} \quad (\alpha_0 = 0^\circ, \alpha_1 = 0^\circ, A_L = 1.5) \\
D_\ell \left[ \mu K^2 \right] &= 10^{-4} \quad (\alpha_0 = 0^\circ, \alpha_1 = 0^\circ, A_L = 2)
\end{align*}
\]
1. Planck lensing results

2. Cosmic Birefringence and CMB lensing

3. CMB constraints

4. Summary
We used a cosmology including both CMB lensing and cosmic birefringence to fit WMAP and BICEP data.

While still compatible with a vanishing rotation angle, the combination of the two experiments hints for $\alpha \neq 0$. 
The best fit obtained by WMAP+BICEP is used to simulate datasets with Planck and PolarBear sensitivity. We obtained a strong constraint for a non-vanishing birefringence angle.
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Neglecting birefringence

The birefringence cosmology we consider deviates significantly from a standard cosmological model. A standard analysis of a cosmological model containing this effect leads to a bias on the recovered best fit parameters.
Neglecting birefringence \((+A_L)\)

If we fit the same mock dataset including \(A_L\) the bias on parameters is significantly reduced.
Neglecting birefringence ($+A_L$)

If we fit the same mock dataset including $A_L$ the bias on parameters is significantly reduced.

The price to pay is the detection of a non standard lensing amplitude

$$A_L = 1.29 \pm 0.03$$
The real Planck

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The real Planck

No TB and EB spectra were made public by the latest Planck release. Opposite signs of the rotation angle are not distinguished.
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see also Gruppuso et al. arXiv:1509.04157
With Planck data there is also no hint for a $\alpha_0 - A_L$ degeneracy.

It’s likely that stronger constraints are necessary. TB and EB spectra are needed!
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Summary

- Results from CMB spectra and lensing extraction seem to push in different directions.
- Cosmic birefringence has an effect on CMB spectra similar to gravitational lensing.
- Neglecting birefringence in the analysis of CMB data may lead to a false detection of $A_L > 1$.
- Preliminary: TB and EB spectra are crucial to constrain birefringence.
- Upcoming polarization data (ACTpol, PolarBear...) will greatly improve results on this mechanism.
- Can we distinguish cosmological birefringence from miscalibration?
Calibration issues

Cosmic birefringence could also be mimicked by a simple mismatch in the calibration of the axis orientation of polarimeters

Pagano et al. (2009)
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*Pagano et al. (2009)*

As this effect is related to the experimental setup it mixes spectra after their time evolution. Miscalibration brings to a constant, sudden rotation of evolved spectra.

\[
Q = \tilde{Q} \cos 2\beta + \tilde{U} \sin 2\beta \\
U = \tilde{U} \cos 2\beta - \tilde{Q} \sin 2\beta
\]

This rotation acts on spectra after CMB lensing!
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Extremely sensitive BB measurements at low multipoles would be needed to distinguish this from a cosmological effect.
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An example: Planck scale modifications to electrodynamics

In the context of quantum gravity, electrodynamics can be modified at Planck scales

*Gubitosi et al. (2009)*

\[ \mathcal{L} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\xi}{2 E_P} \epsilon^{jkl} F_{0j} \partial_0 F_{kl} \]

Right and left-circularly polarized components of an electromagnetic wave satisfy different dispersion relations

\[ \omega_{\pm} \approx p \left( 1 \pm \frac{\xi}{E_P} p \right) \]

Assuming linear polarization, a wave propagating for a time \( \eta \) will experience a rotation of its polarization plane by an angle

\[ \theta(\eta) = (\omega_- - \omega_+) = \frac{\xi}{E_P} p^2 \eta \]
Accounting for CMB lensing

**Warning:** gravitational lensing affects photons during their evolution. If birefringence is present, $B$ modes and $TB$ and $EB$ cross correlation would have already been generated.

To compute the $C_\ell$ we can obtain the real space correlation functions

\[
\xi_X(\gamma) \equiv \langle T(\hat{n}_1)P(\hat{n}_2) \rangle = \sum_\ell \frac{2\ell + 1}{4\pi} (C_\ell^{TE} - iC_\ell^{TB}) \text{[lensing terms]}
\]

\[
\xi_+(\gamma) \equiv \langle P^*(\hat{n}_1)P(\hat{n}_2) \rangle = \sum_\ell \frac{2\ell + 1}{4\pi} (C_\ell^{EE} + C_\ell^{BB}) \text{[lensing terms]}
\]

\[
\xi_-(\gamma) \equiv \langle P(\hat{n}_1)P(\hat{n}_2) \rangle = \sum_\ell \frac{2\ell + 1}{4\pi} (C_\ell^{EE} - C_\ell^{BB} - 2iC_\ell^{EB}) \text{[lensing terms]}
\]

Full equations can be found in *Gubitosi, Martinelli, Pagano (2014)*