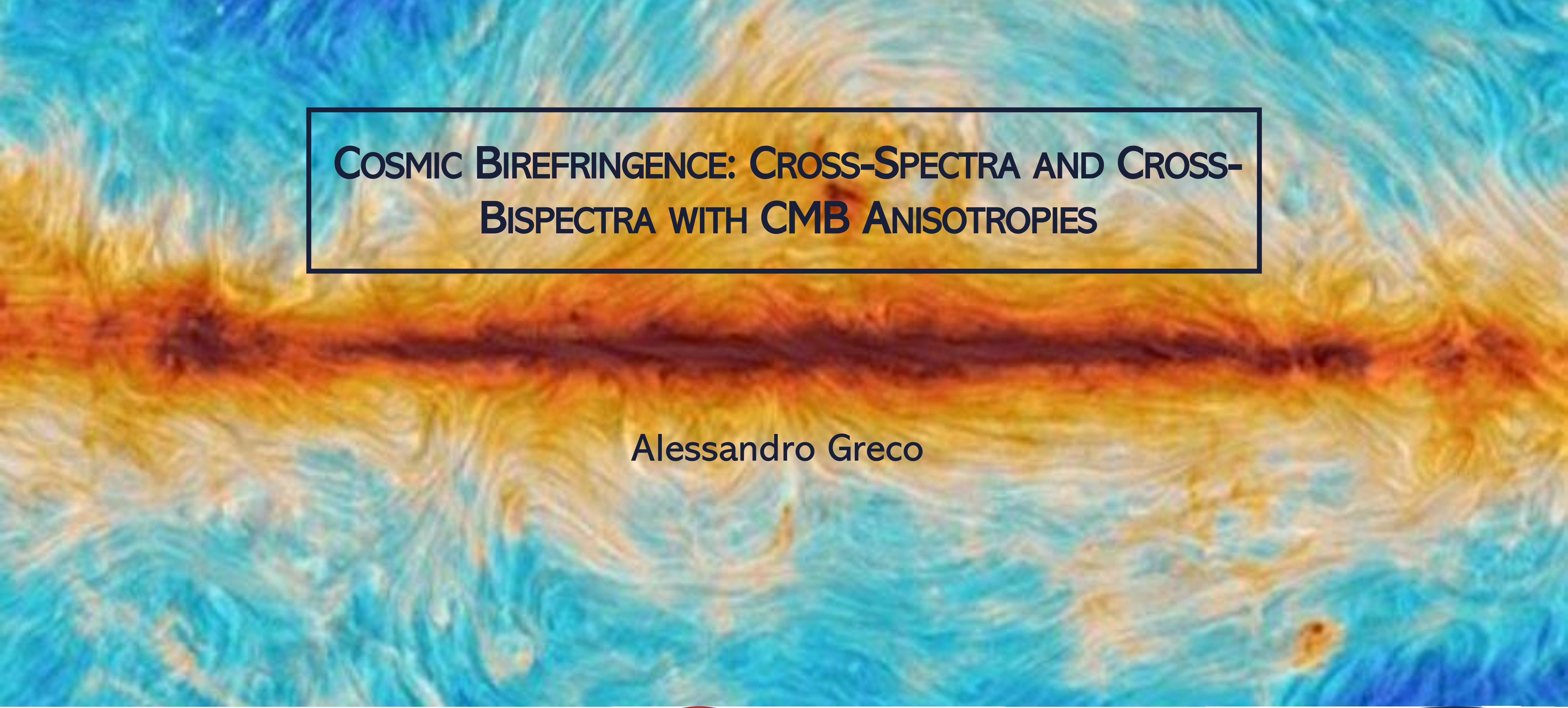

Cosmic Birefringence: Cross-Spectra and Cross-Bispectra with CMB Anisotropies

Alessandro Greco

Cosmology from Home

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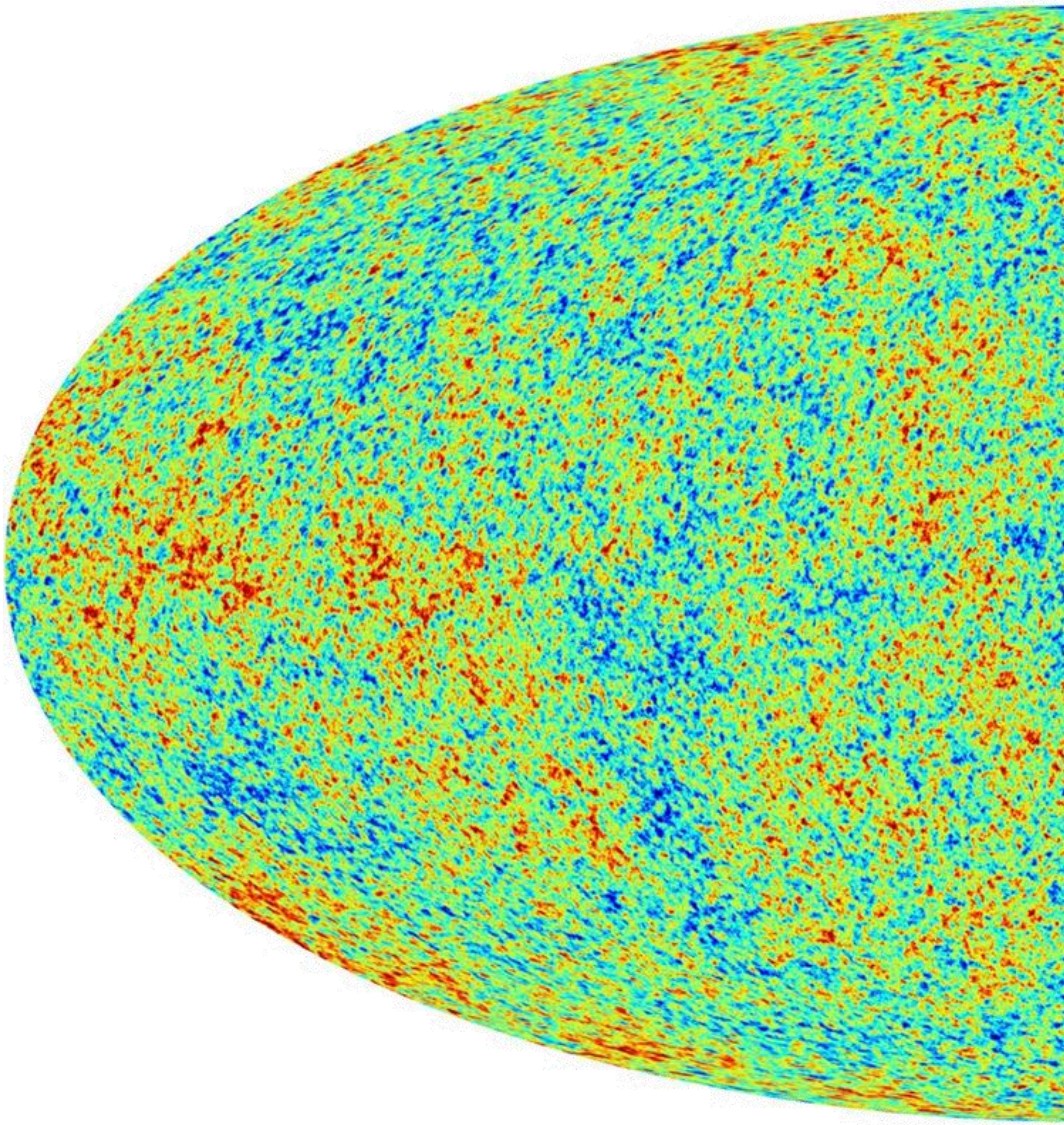
Università degli Studi di Padova

INFN

INTRODUCTION

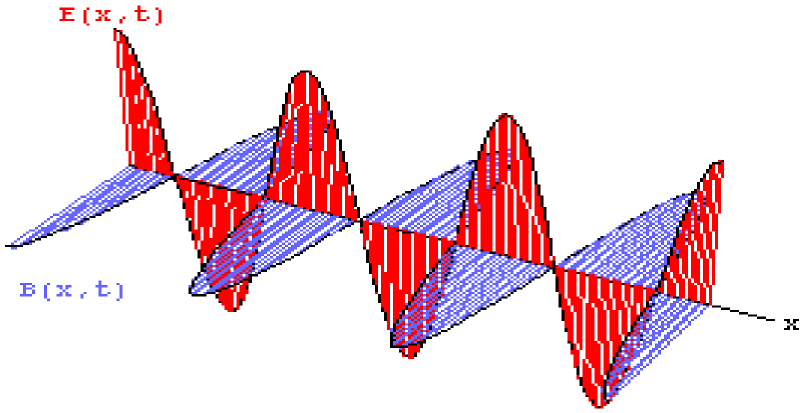
- The Cosmic Microwave Background (CMB) is electromagnetic radiation which is remnant from an early stage of the Universe.
- CMB is polarized at the level of a few μK in E-modes and B-modes. CMB polarization arise naturally from Thomson scattering, and in particular the B-modes are generated by gravitational lensing of E-modes and by gravitational waves produced during inflation.
- B-modes and E-modes polarizations are uncorrelated, since any cross-correlation between them would be parity-violating. In analogy with electrostatics, they transform in the opposite way under spatial inversion.
- CMB can be seen as a very efficient natural «laboratory» for investigating deviations from the standard Maxwell theory.



Modified Electromagnetism

Maxwell Electromagnetic Theory

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$



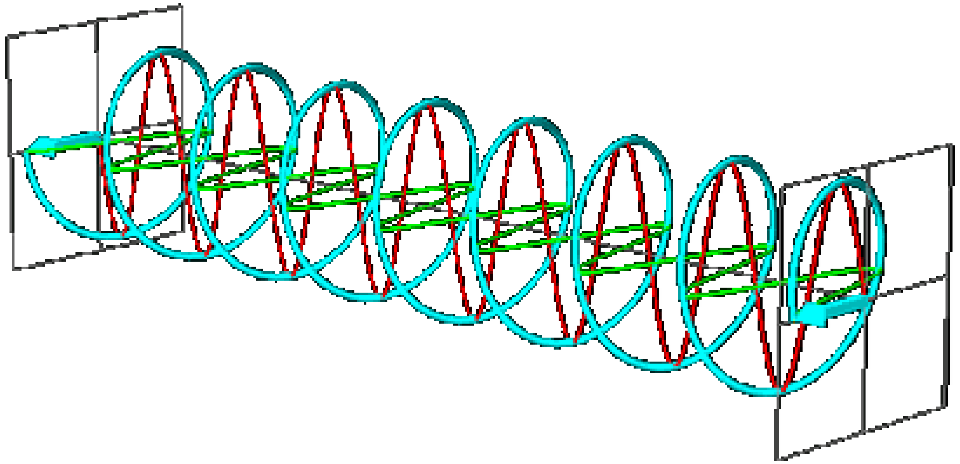
$$F_{\mu\nu} \equiv \nabla_\mu A_\nu - \nabla_\nu A_\mu$$

Maxwell Field Tensor

Chern-Simons Modification of Electromagnetism

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + h(\chi)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Carroll+1990

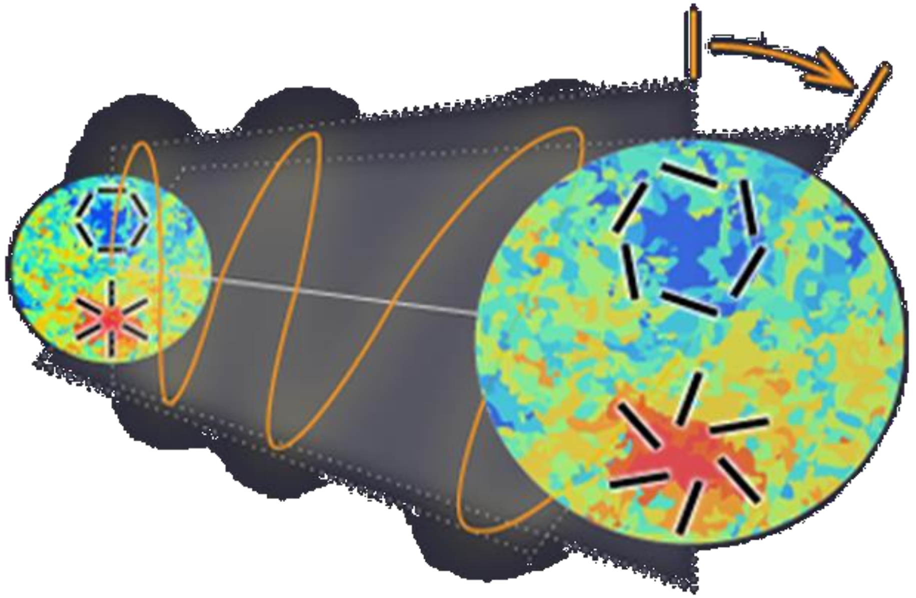


$$\tilde{F}^{\mu\nu} \equiv \epsilon^{\mu\nu\varrho\sigma}F_{\varrho\sigma}/2$$

Hodge Dual Tensor

A phenomenological consequence of the extra coupling $h(\chi)$ between photons and a new field χ is **birefringence**, i.e. the in-vacuo rotation of the polarization plane during the electromagnetic waves' propagation. Komatsu2022

Cosmic Birefringence



χ_{ini} $\longrightarrow$ χ_{fin}

LSS at Recombination — Today on Earth

The birefringence angle is related to the field χ via

$$\alpha = 2[h(\chi_{\text{fin}}) - h(\chi_{\text{ini}})]$$

Li+2008

The linear polarization of CMB radiation is described by the following combination of Stokes parameters:

$$[Q \pm iU](\hat{n}) = \sum_{\ell m} a_{\ell m}^{\pm 2} \, {}_{\pm 2}Y_{\ell m}\,(\hat{n})$$

that behaves as a spin-2 field. The Chern-Simons modifications of Maxwell theory induces a rotation of the polarization plane by an angle α, the **birefringence angle**, so that the Stokes parameters are rotated too:

$$[Q \pm iU] \longrightarrow [Q \pm iU]e^{\pm 2i\alpha}$$

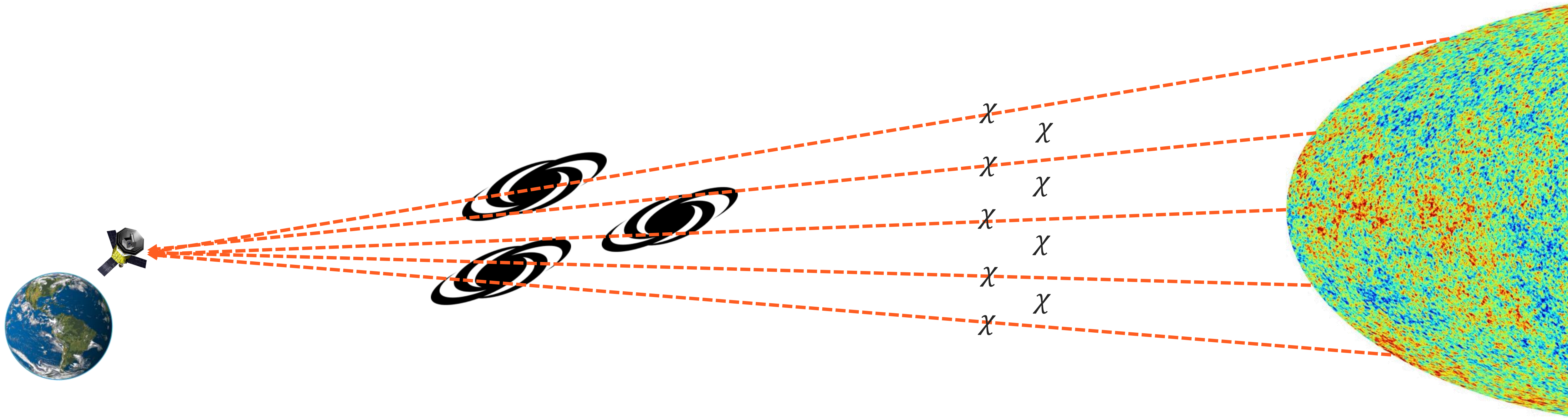
Liu+2006

Investigating **Cosmic Birefringence** (CB) can help us in unveiling the nature of the field χ, which could be e.g.:

- early dark energy in the form of a Nambu-Goldstone boson; Capparelli+2020
- dark matter in form of an ultra-light **axion**. Liu+2017

The Birefringence Mechanism

Observation | Gravitational Lensing | Cosmic Birefringence | Emission



$$[Q \pm iU](\hat{n} + \vec{\nabla}_{\hat{n}}\Phi)e^{\pm 2i\alpha(\hat{n})} \longleftarrow [Q \pm iU](\hat{n})e^{\pm 2i\alpha(\hat{n})} \longleftarrow [Q \pm iU](\hat{n})$$

0 → 1000

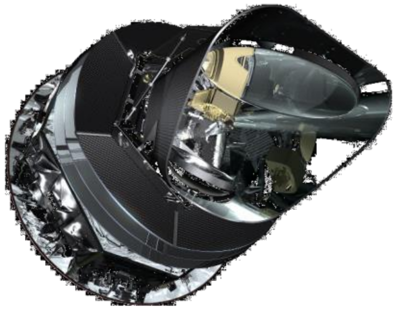
Redshift z

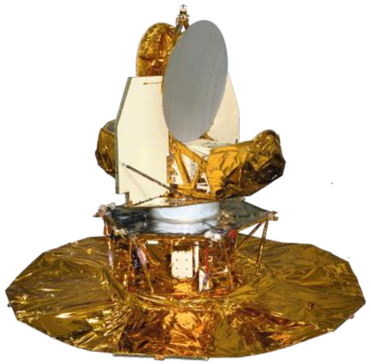
Observational Constraints on Isotropic CB

Cosmic birefringence impacts on the CMB observations producing a mixing of E and B polarization modes which is otherwise null in the standard scenario. | Lue+1999

ΛCDM		+ Cosmic Birefringence
C_ℓ^{TT}	→	C_ℓ^{TT}
C_ℓ^{EE}	→	$C_\ell^{EE}\cos(2\alpha_0)^2 + C_\ell^{BB}\sin(2\alpha_0)^2$
C_ℓ^{TE}	→	$C_\ell^{TE}\cos(2\alpha_0)$
C_ℓ^{BB}	→	$C_\ell^{BB}\cos(2\alpha_0)^2 + C_\ell^{EE}\sin(2\alpha_0)^2$
$0 = \{ C_\ell^{TB}$	→	$C_\ell^{TE}\sin(2\alpha_0)$
C_ℓ^{EB}	→	$\frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\alpha_0)$

If the rotation angle is isotropic in sky, $\alpha(\hat{n}) = \alpha_0$, then we talk about **isotropic birefringence**, which is currently constrained by measurements of CMB polarized data.





Minami+2020	Diego-Palazuelos+2022	Eskilt+2022
PR3 [68% C. L.]	**PR4** [68% C. L.]	***Planck* + WMAP** [68% C. L.]
$\alpha_0 = (0.35 \pm 0.14)^\circ$	$\alpha_0 = (0.30 \pm 0.11)^\circ$	$\alpha_0 = 0.342^{\circ\,+0.094^\circ}_{\;\;-0.091^\circ}$

$\alpha_0 = 0$ excluded at $(99.2 - 99.987)\%$ C. L. !

Anisotropic Birefringence

- Inhomegeneites $\delta\chi$ of the field χ at the last scattering surface (LSS) can induce anisotropies $\delta\alpha$ in the angle α.

- It is possible to expand the **anisotropic cosmic birefringence** angle on the sky.

- In literature, the angular power spectra involving the anisotropic CB and its cross-correlation with CMB have been computed, and it is constrained by observations.

$$\chi = \chi_0 + \delta\chi \longrightarrow \alpha = \alpha_0 + \delta\alpha(\hat{n})$$

$$\delta\alpha(\hat{n}) = \sum_{\ell m} \alpha_{\ell m} Y_{\ell m}(\hat{n})$$

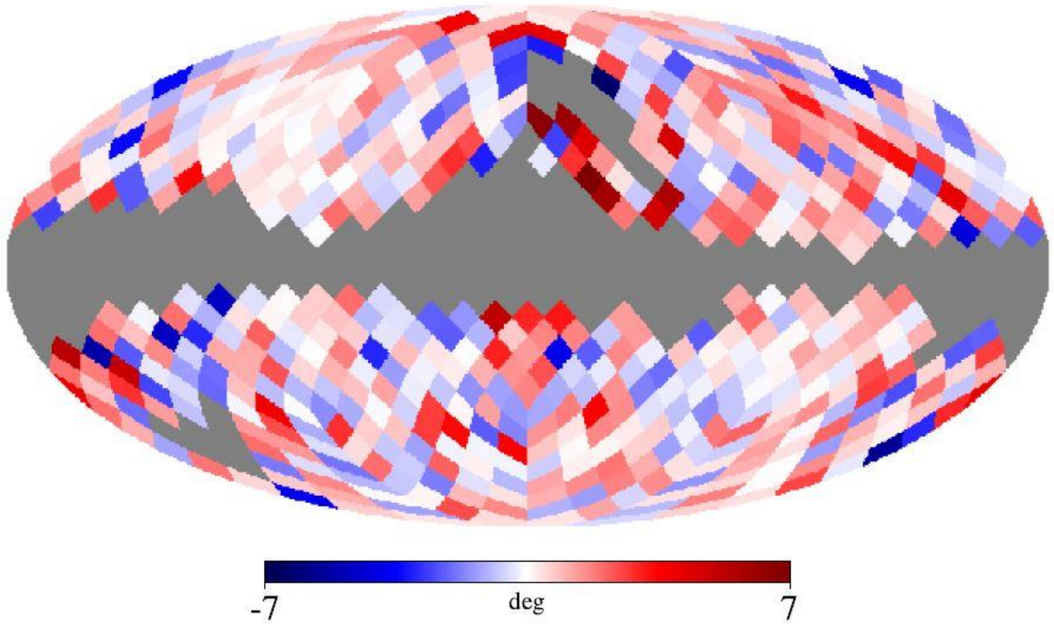
Gruppuso+2020

Planck PR3 (68% C.L.)

$$\begin{cases} \frac{\ell(\ell+1)C_\ell^{\alpha\alpha}}{2\pi} < 0.104\ \mathrm{deg}^2 \\ \frac{\ell(\ell+1)C_\ell^{\alpha T}}{2\pi} = 1.50^{+2.41}_{-4.10}\ \mu\mathrm{K}\cdot\mathrm{deg} \end{cases}$$

Other observational constraints are provided e.g. by ACTPol and SPTpol

Namikawa+2020
Bianchini+2020



CB angle maps from PR3 for the `Commander` component separation method. Bortolami+2022

BIREFRINGENT CROSS-BISPECTRA

In JCAP 03 (2022) 050, we have computed the three-point cross-correlation functions of anisotropic cosmic birefringence, also called **angular bispectra** in the harmonic space, with the "observed" CMB fields.

OBSERVED —means→ accounting for weak gravitational lensing and eventual birefringence effects.

$$\langle \alpha_{\ell_1 m_1} a^X_{\ell_2 m_2} a^Z_{\ell_3 m_3} \rangle = B^{\alpha XZ}_{\ell_1 \ell_2 \ell_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \qquad X, Z = \alpha, T, E, B$$

We have found that these bispectra can be seen as new cosmological observables that:

- Are $\neq 0$ even if the fields involved are Gaussian;
- Are $\neq 0$ even if $\delta\alpha$ is uncorrelated with CMB maps;
- Encode signatures of parity-violation;
- Provide a new observable to test cosmic birefringence and an additional consistency check for present constraints and for specific models.

→ **HOW IS THAT POSSIBLE?**

$$B^{\alpha TE}_{\ell_1 \ell_2 \ell_3} \quad B^{\alpha TB}_{\ell_1 \ell_2 \ell_3} \quad B^{\alpha EE}_{\ell_1 \ell_2 \ell_3} \quad B^{\alpha EB}_{\ell_1 \ell_2 \ell_3} \quad B^{\alpha BB}_{\ell_1 \ell_2 \ell_3}$$

ΛCDM + **Cosmic Birefringence**

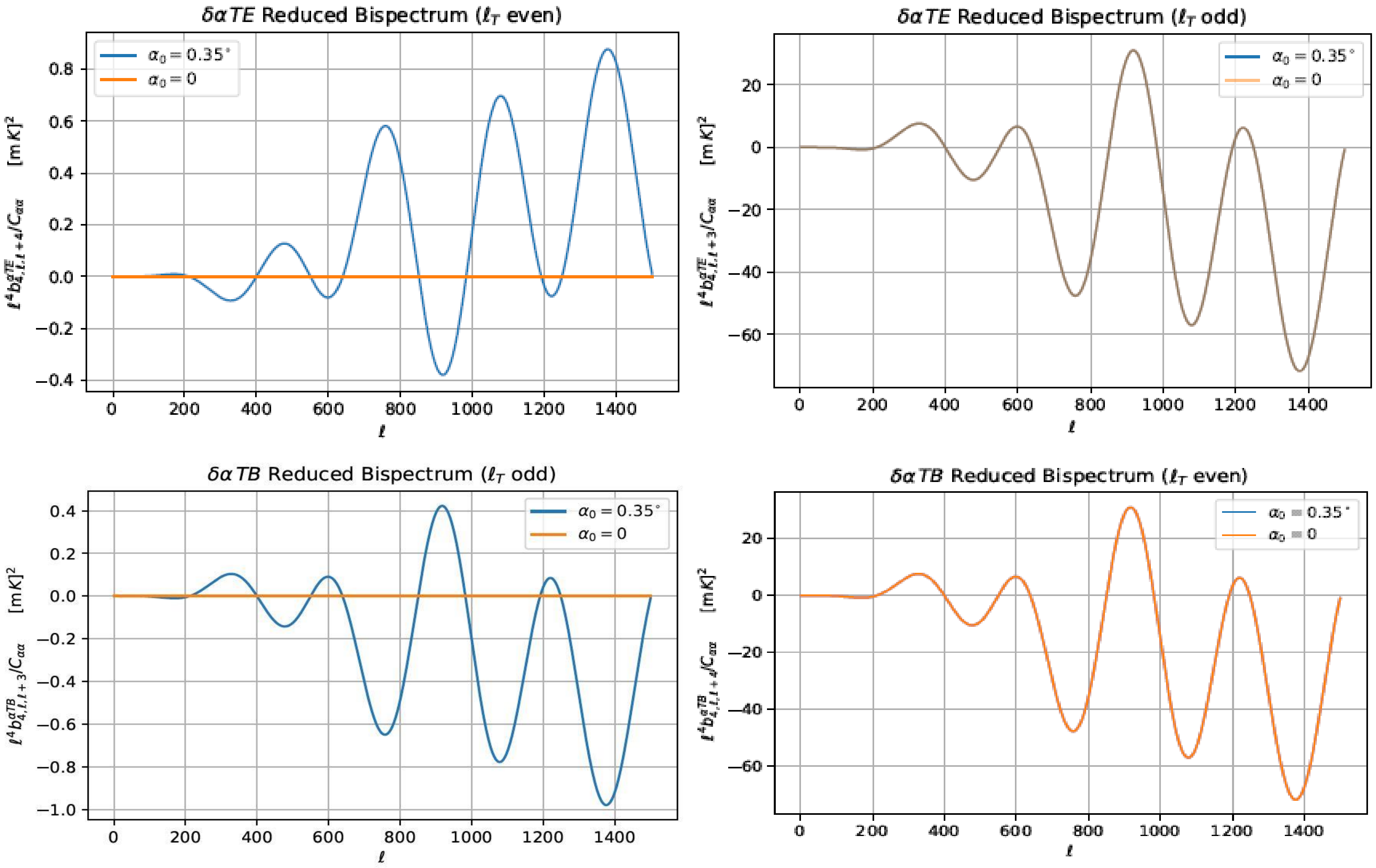
$$\begin{pmatrix} a_{E,\ell m} \\ a_{E,Bm} \end{pmatrix} \longrightarrow \sum_{s=\pm 2} \frac{e^{is\alpha_0}}{2} \sum_{LM} \int \mathrm{d}^2\hat{n} \; {}_sY^*_{\ell m}(\hat{n}) \; {}_sY_{LM}(\hat{n}) \begin{pmatrix} 1 & is/2 \\ -is/2 & 1 \end{pmatrix} \begin{pmatrix} a_{E,\ell m} \\ a_{E,Bm} \end{pmatrix} e^{is\delta\alpha(\hat{n})}$$

| Greco+2022

BIREFRINGENT CROSS-BISPECTRA

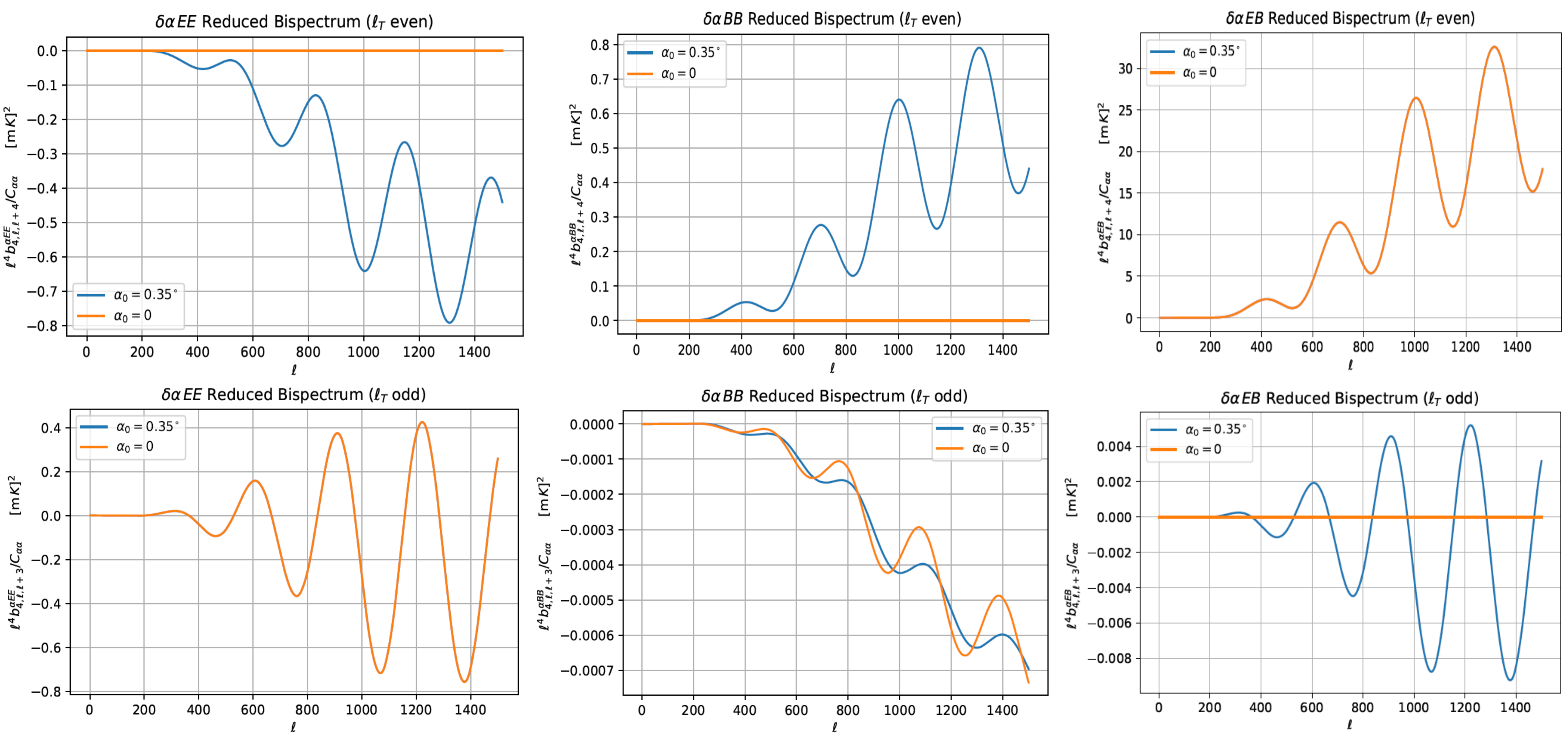
We have assumed that:

- $\delta\alpha$ is uncorrelated with the unrotated CMB fields;
- the underlying inflationary model is such that C_ℓ^{TB} and C_ℓ^{EB} are zero;
- the unrotated anisotropy fields of CMB and $\delta\alpha$ are all Gaussian random fields;
- CB spectrum is scale-invariant.



We have obtained these plots with **CLASS** by accounting for lensing effects and no tensor modes.

Birefringent Cross-Bispectra



Estimation of the SNR

We have numerically performed a **Fisher forecast** to estimate signal-to-noise ratio (SNR) of our bispectra in a regime of purely anisotropic birefringence (i.e. $\alpha_0 = 0$) for a **LiteBIRD-like experiment** ($f_{sky} = 0.7$; $\ell_{max} = 200$):

$$\mathrm{F}_{XYZ} = \sum_{\ell_1 \leq \ell_2 \leq \ell_3} \sum_{ij} B^i_{\ell_1\ell_2\ell_3} \left[\mathrm{Cov}\left(\widehat{B^i_{\ell_1\ell_2\ell_3}}, \widehat{B^j_{\ell_1\ell_2\ell_3}}\right)\right]^{-1} B^j_{\ell_1\ell_2\ell_3}$$

$$\mathrm{SNR}_{XYZ} = 1/\sqrt{\mathrm{F}^{-1}_{XYZ}}$$

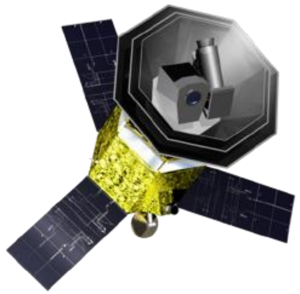
where i, j label all the possible permutations of a fixed triplet of the X, Y, Z fields, and:

$$\mathrm{Cov}\left(\widehat{B^i_{\ell_1\ell_2\ell_3}}, \widehat{B^j_{\ell_1\ell_2\ell_3}}\right) \equiv \left\langle \widehat{B^i_{\ell_1\ell_2\ell_3}} \widehat{B^j_{\ell_1\ell_2\ell_3}} \right\rangle - \left\langle \widehat{B^i_{\ell_1\ell_2\ell_3}} \right\rangle \left\langle \widehat{B^j_{\ell_1\ell_2\ell_3}} \right\rangle$$

Covariance Matrix Element

$$\widehat{B^{XYZ}_{\ell_1\ell_2\ell_3}} \equiv \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} a^X_{\ell_1 m_1} a^Y_{\ell_2 m_2} a^Z_{\ell_3 m_3}$$

Unbiased Estimator for the Observed Angular Averaged Bispectrum



beam width $= 30'$
noise power $= 4.5\ \mu\mathrm{K} \cdot \mathrm{arcmin}$

Bispectrum	**SNR** [for $\ell(\ell+1)C_\ell^{\alpha\alpha}/2\pi = 0.1\ \mathrm{deg}^2$]
$\delta\alpha\ TE$	0.0661
$\delta\alpha\ TB$	4.0635
$\delta\alpha\ EE$	0.0543
$\delta\alpha\ BB$	0.0004
$\delta\alpha\ EB$	7.5658

Conclusions and Future Prospects

We have considered a well-motivated parity-violating extension of electromagnetism which induces the phenomenon of cosmic birefringence, and we have computed the cross-bispectra of the anisotropic angle with CMB maps:

- we have obtained non-vanishing birefringent bispectra even under some restricting assumptions (Gaussianity, no two-point cross-correlation, parity-conserving inflation);
- we have estimated the SNR of our bispectra for an idealized LiteBIRD-like experiment (where foregrounds have been neglected) and we have found that we can look at $B^{\alpha TB}_{\ell_1\ell_2\ell_3}$ and $B^{\alpha EB}_{\ell_1\ell_2\ell_3}$ as really promising new cosmological observables;
- a natural development of our work should be to repeat our analysis by relaxing some of the phenomenological assumptions that we used in this research (e.g. scale-invariant $C^{\alpha\alpha}_{\ell}$), and/or making forecasts for other future CMB experiments.

Thank you for your attention!