Constraints on anisotropic birefringence from Planck data

A.Gruppuso
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Based on:
Gruppuso, Molinari, Natoli and Pagano JCAP 2020
Bortolami, Billi, Gruppuso, Natoli and Pagano JCAP 2022

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DI ASTROFISICA

Cosmic Magnetism in Voids and Filaments
Bologna - 26-01-2023

Outline

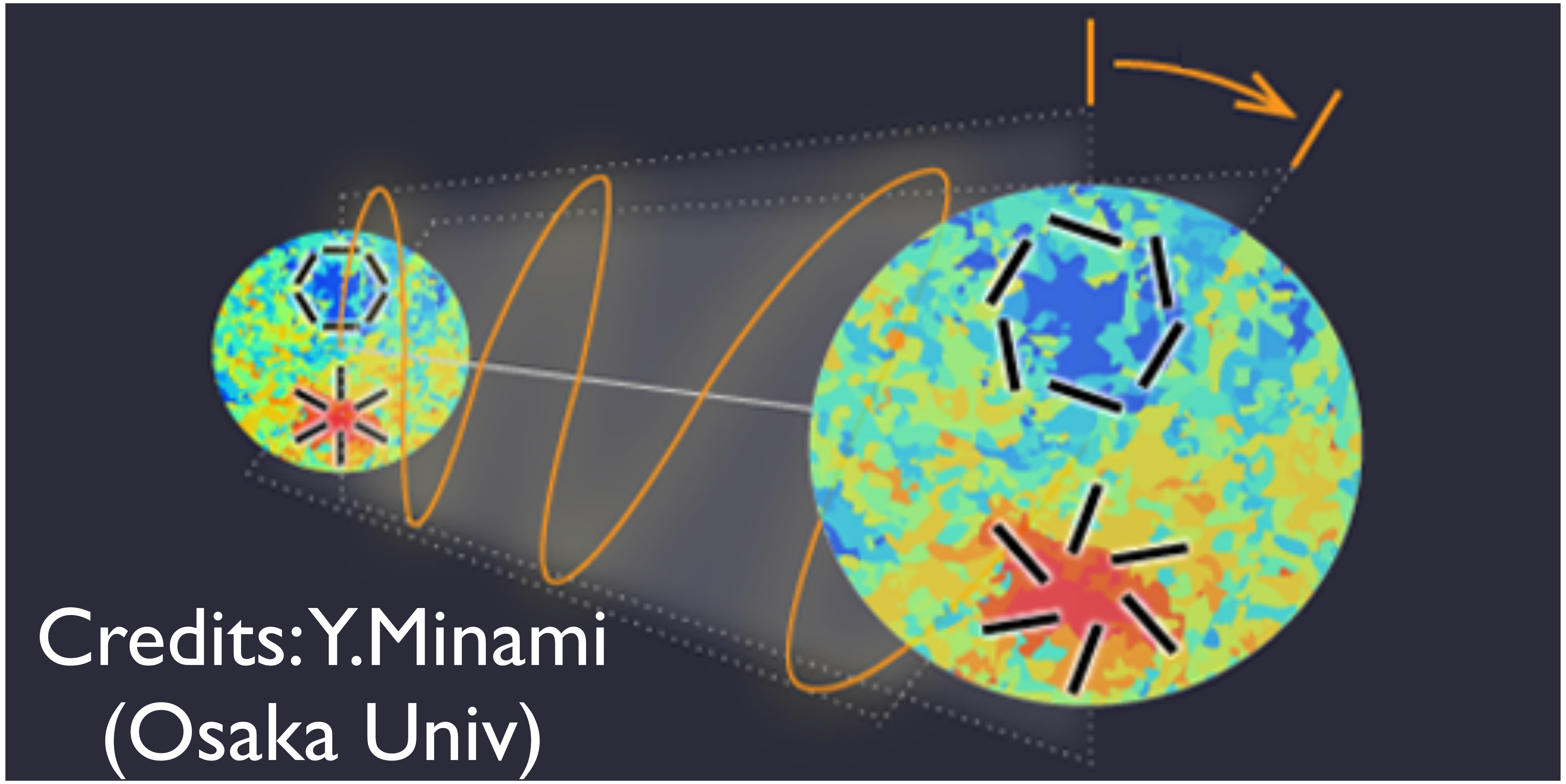
- Introduction
- How to constrain this effect
- Description of the used Planck data
- Constraints on anisotropic birefringence and stochastic primordial magnetic fields
- Conclusions and outlook

Introduction

- What is the **Cosmic Birefringence** effect?
  - It is the rotation of the linear polarisation plane of photons during propagation

$$Q \pm iU \rightarrow e^{\pm 2i\alpha}(Q \pm iU)$$

α is the birefringence angle



We can broadly split the main physical mechanisms that could source the cosmic birefringence in two classes: **parity violating extensions** of standard electromagnetism and **primordial magnetic fields.**

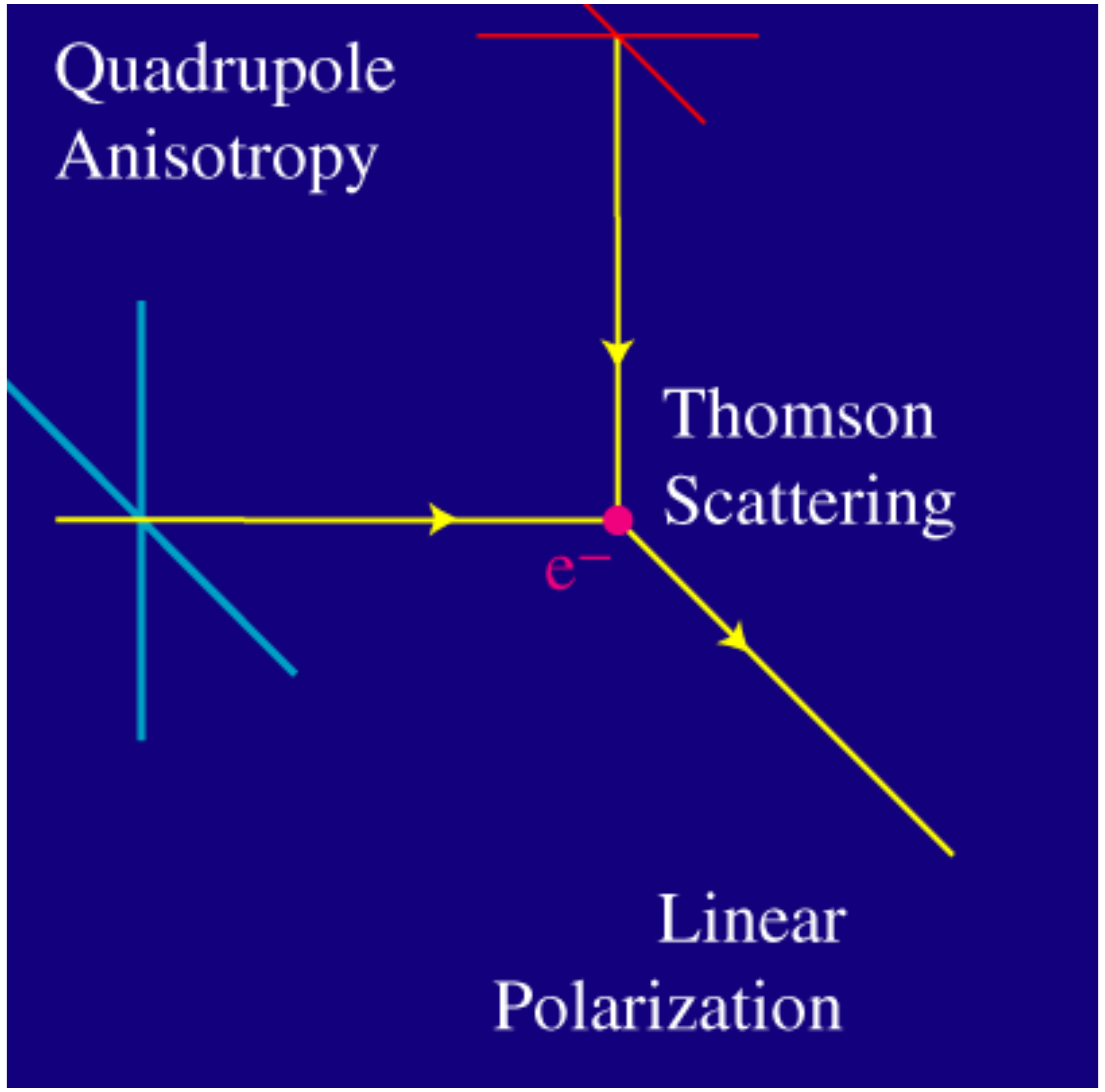
This phenomenon is a tracer of the existence of a medium where photons propagate through.

Introduction

- To probe this effect we need sources of linearly polarised photons
- The CMB appears to be a good/natural candidate to perform this investigation since

1. **CMB is linearly polarised because of Thomson scattering.**
2. **It is the farthest (and oldest) source of linear polarisation. (models where the effect is proportional to the distance traveled by the photons)**

CMB + anisotropic birefringence



How to constrain anisotropic birefringence

$$\alpha = \alpha(\hat{n})$$

It is a function on the sphere

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

which can be characterised with the harmonic spectrum

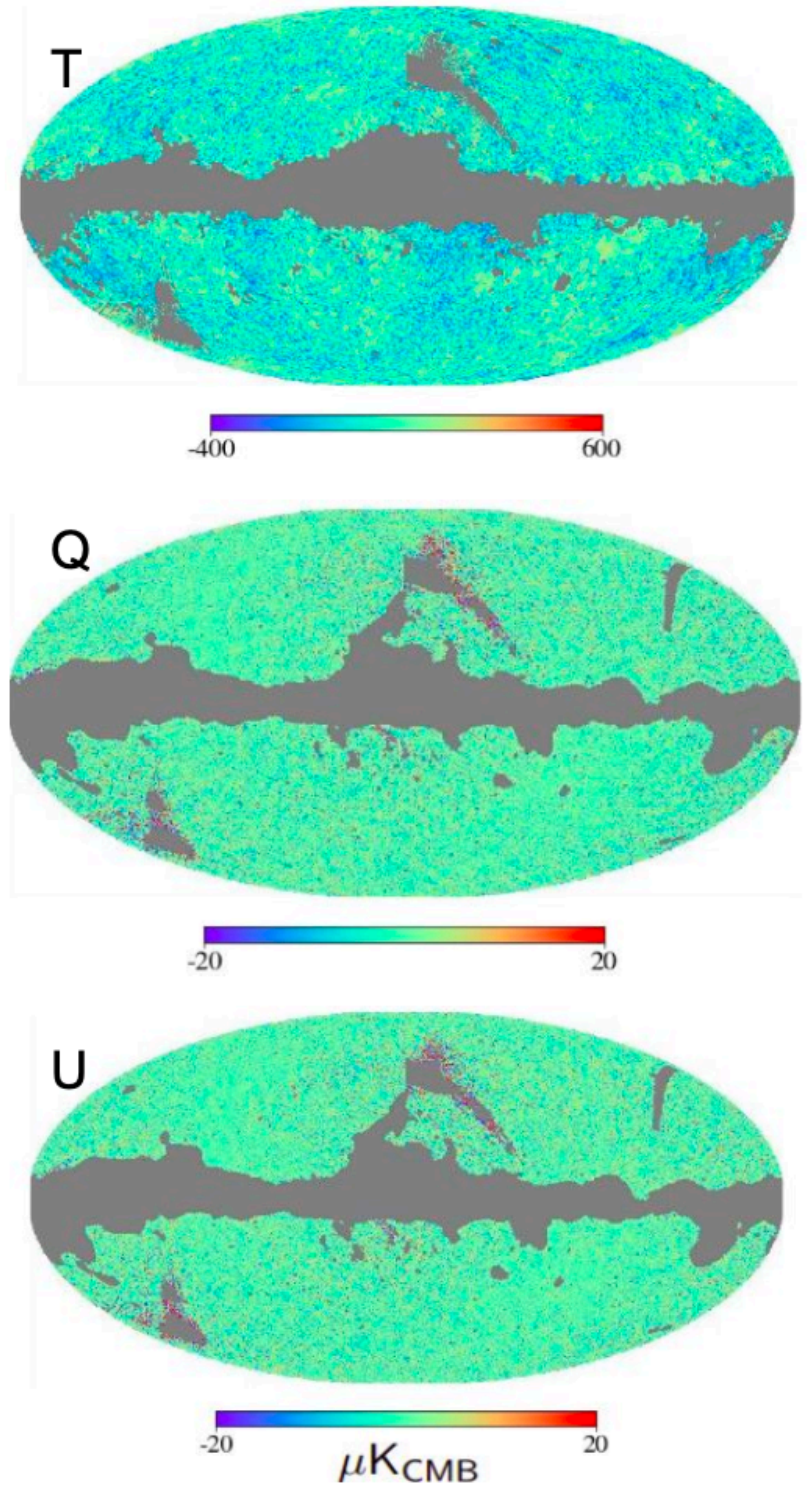
$$C_\ell^{\alpha\alpha} = \frac{1}{2\ell + 1} \sum_m \alpha_{\ell m} \alpha^\star_{\ell m}$$

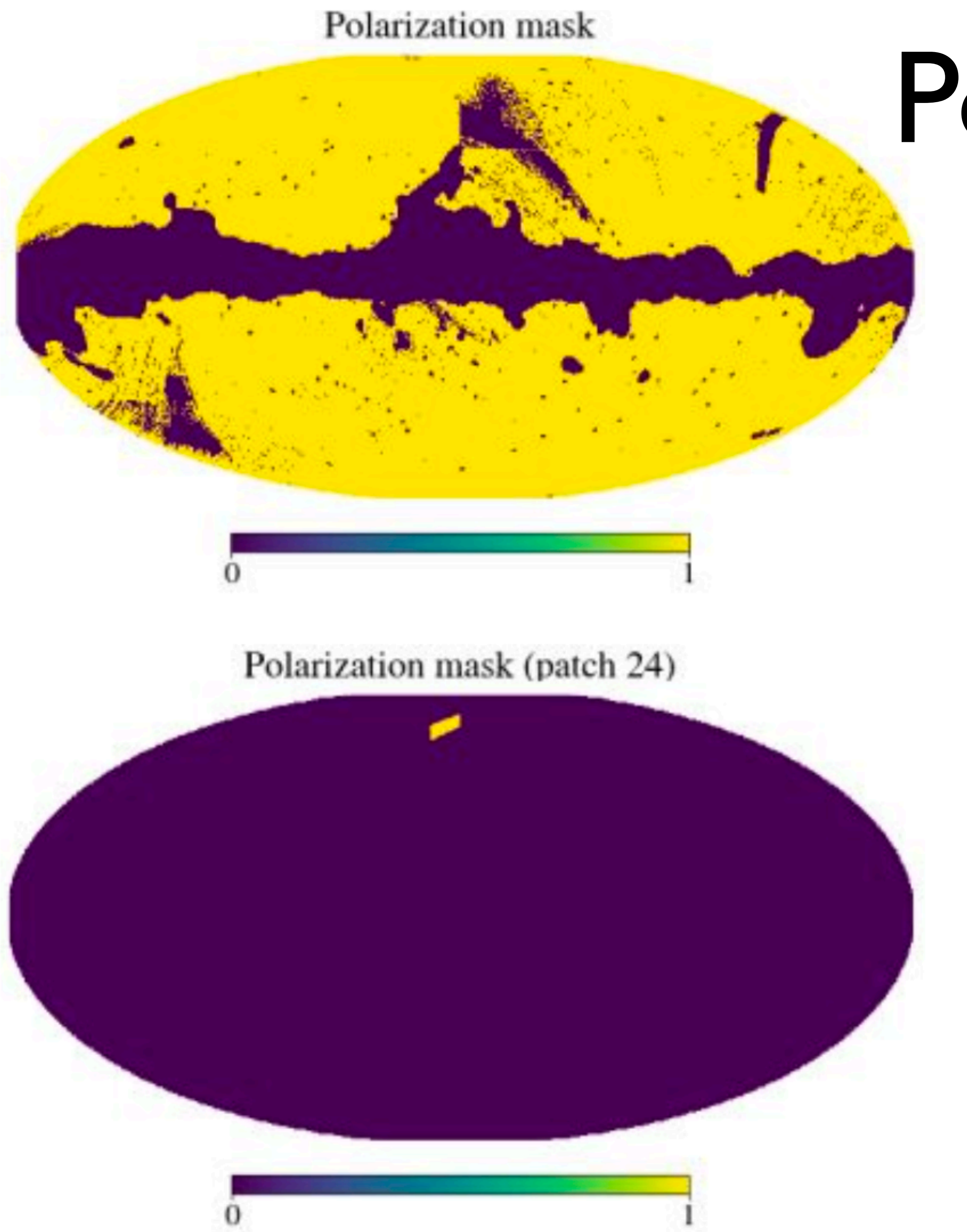
this saturates all the information if $\alpha(\hat{n})$ is a Gaussian field

Note that the isotropic angle is related to the monopole of this expansion

Description of the localisation of the D-est technique

CMB Maps





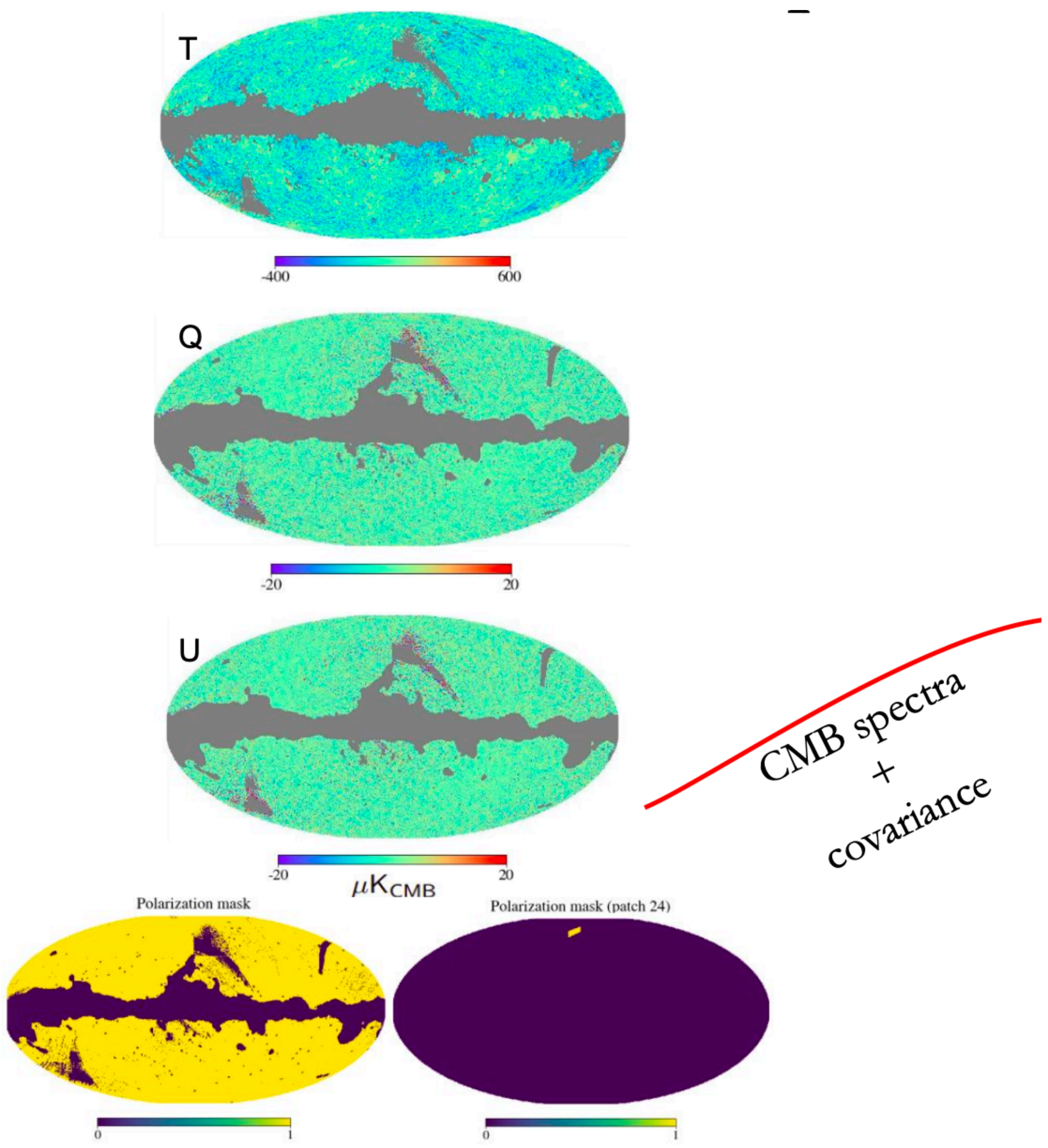
Pol mask

Example of small region considered

Idea: divide the maps in small regions and estimate α in each of these small regions

This will provide a map of angles with a resolution given by the dimension of these small regions

Description of the localisation of the D-est technique



Lue, Wang & Kamionkowski (1999)
Feng, Li, Li & Zhang (2005)

$$C_\ell'^{TT} = C_l^{TT}$$
$$C_\ell'^{EE} = C_\ell^{EE}\cos^2(2\alpha) + C_\ell^{BB}\sin^2(2\alpha)$$
$$C_\ell'^{BB} = C_\ell^{EE}\sin^2(2\alpha) + C_\ell^{BB}\cos^2(2\alpha)$$
$$C_\ell'^{TE} = C_\ell^{TE}\cos(2\alpha)$$
$$C_\ell'^{TB} = C_\ell^{TE}\sin(2\alpha)$$
$$C_\ell'^{EB} = \frac{1}{2}\left(C_l^{EE} - C_\ell^{BB}\right)\sin(4\alpha)$$

Taylor-expanding such equations for small angles we find that:

1. TE, EE and BB depend quadratically on α
2. TB and EB depend <u>linearly</u> on α

TB and EB channels are the most sensitive (and are also sensitive to the sign of alpha) and show an on/off effect

Description of the localisation of the D-est technique

$$D_\ell^{TB,obs} = C_\ell'^{TB}\cos(2\hat\alpha) - C_\ell'^{TE}\sin(2\hat\alpha)\,; \quad (19)$$

$$D_\ell^{EB,obs} = C_\ell'^{EB}\cos(4\hat\alpha) - \frac{1}{2}(C_\ell'^{EE} - C_\ell'^{BB})\sin(4\hat\alpha)\,. \quad (20)$$

where $\hat\alpha$ is the estimate for the birefringence angle α. It is possible to show that on average

$$\langle D_\ell^{TB,obs}\rangle = \langle C_\ell^{TE}\rangle\sin(2(\alpha - \hat\alpha))\,, \quad (21)$$

$$\langle D_\ell^{EB,obs}\rangle = \frac{1}{2}\left(\langle C_\ell^{EE}\rangle - \langle C_\ell^{BB}\rangle\right)\sin(4(\alpha - \hat\alpha))\,. \quad (22)$$

Eqs. (21) and (22) are zero when

$$\hat\alpha = \alpha\,. \quad (23)$$

This suggests that α can be found looking for the angle α that makes null the expectation value of the D-estimators

A.Gruppuso, G.Maggio, D.Molinari, P.Natoli (2016)

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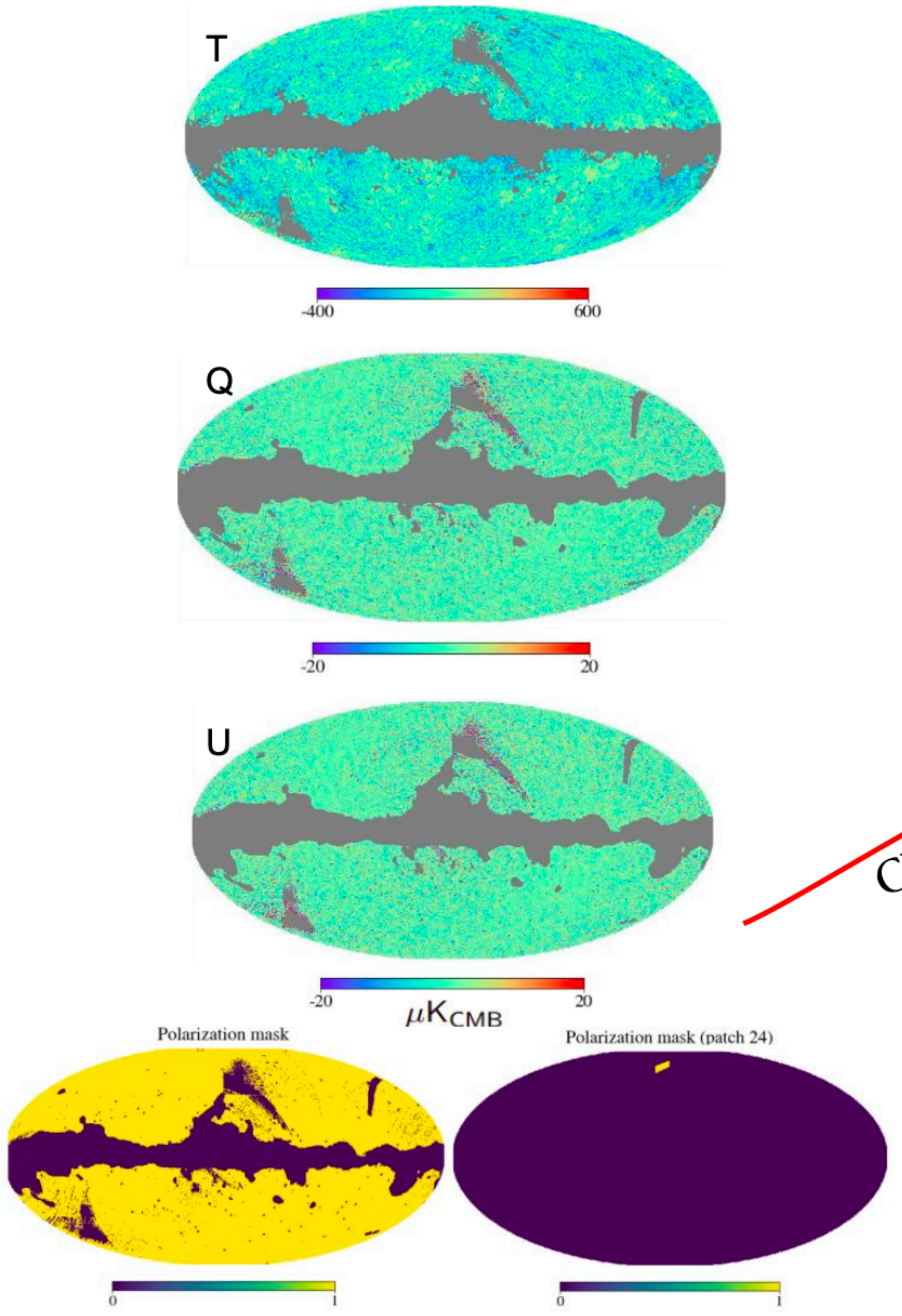
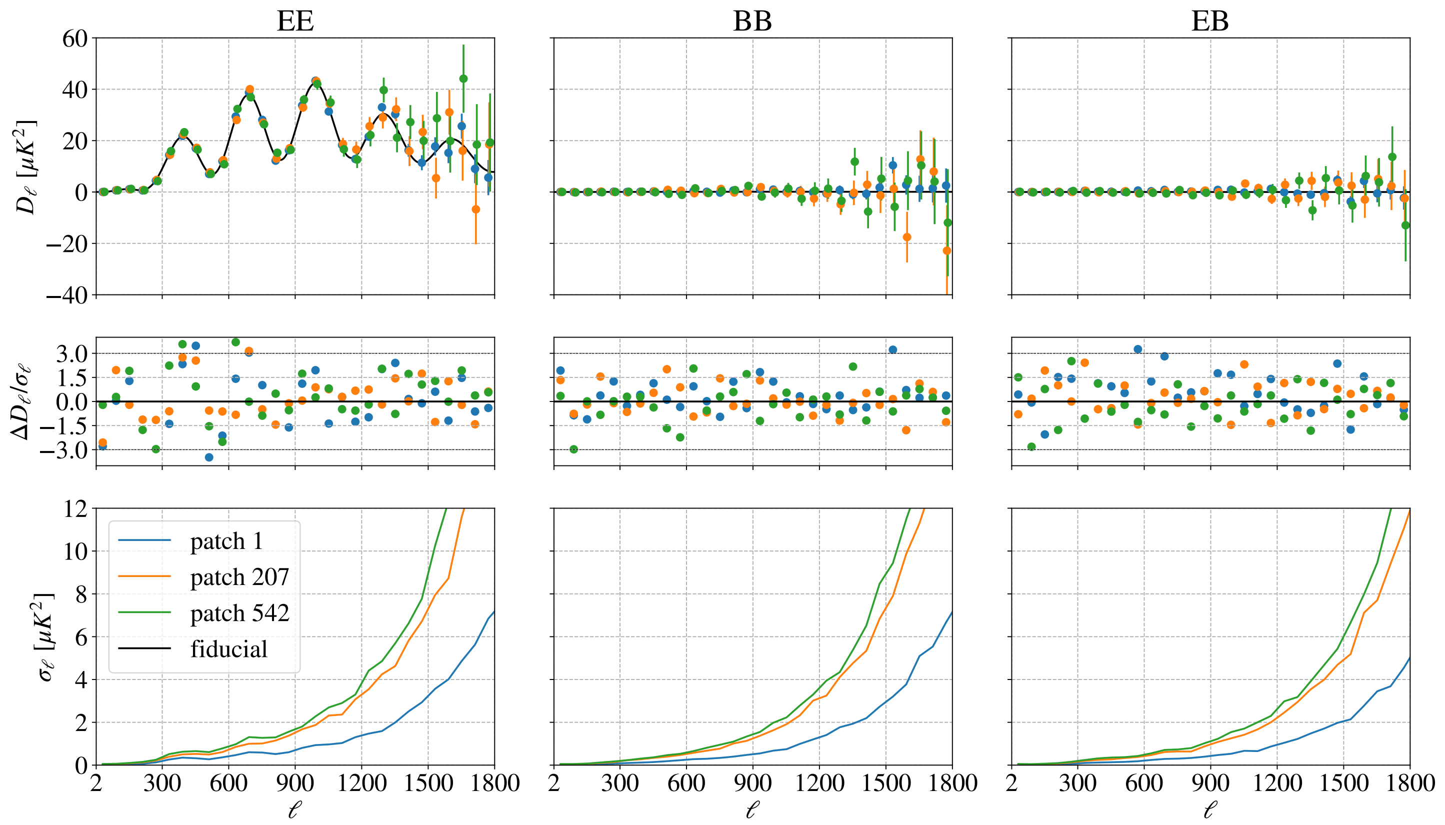
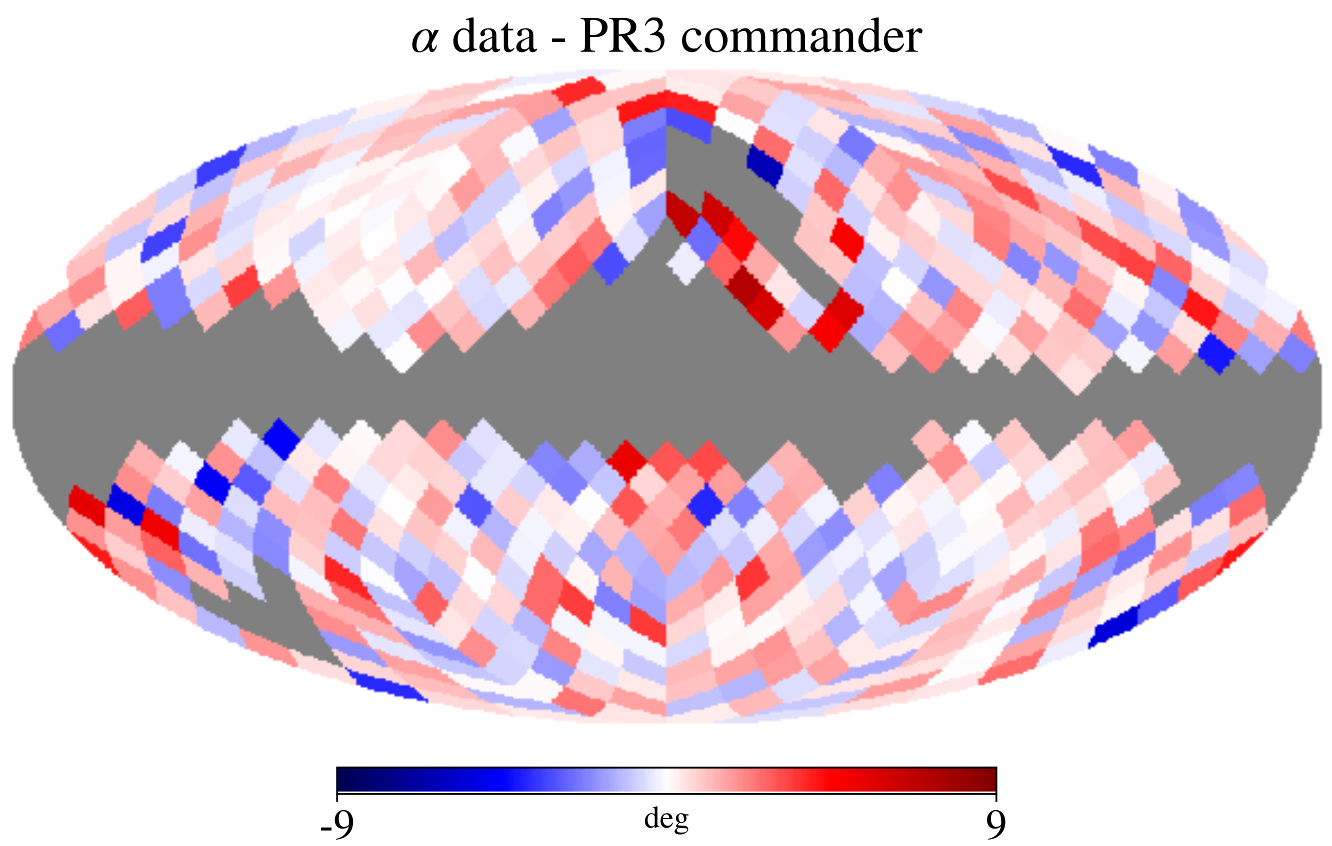


CMB spectra + covariance



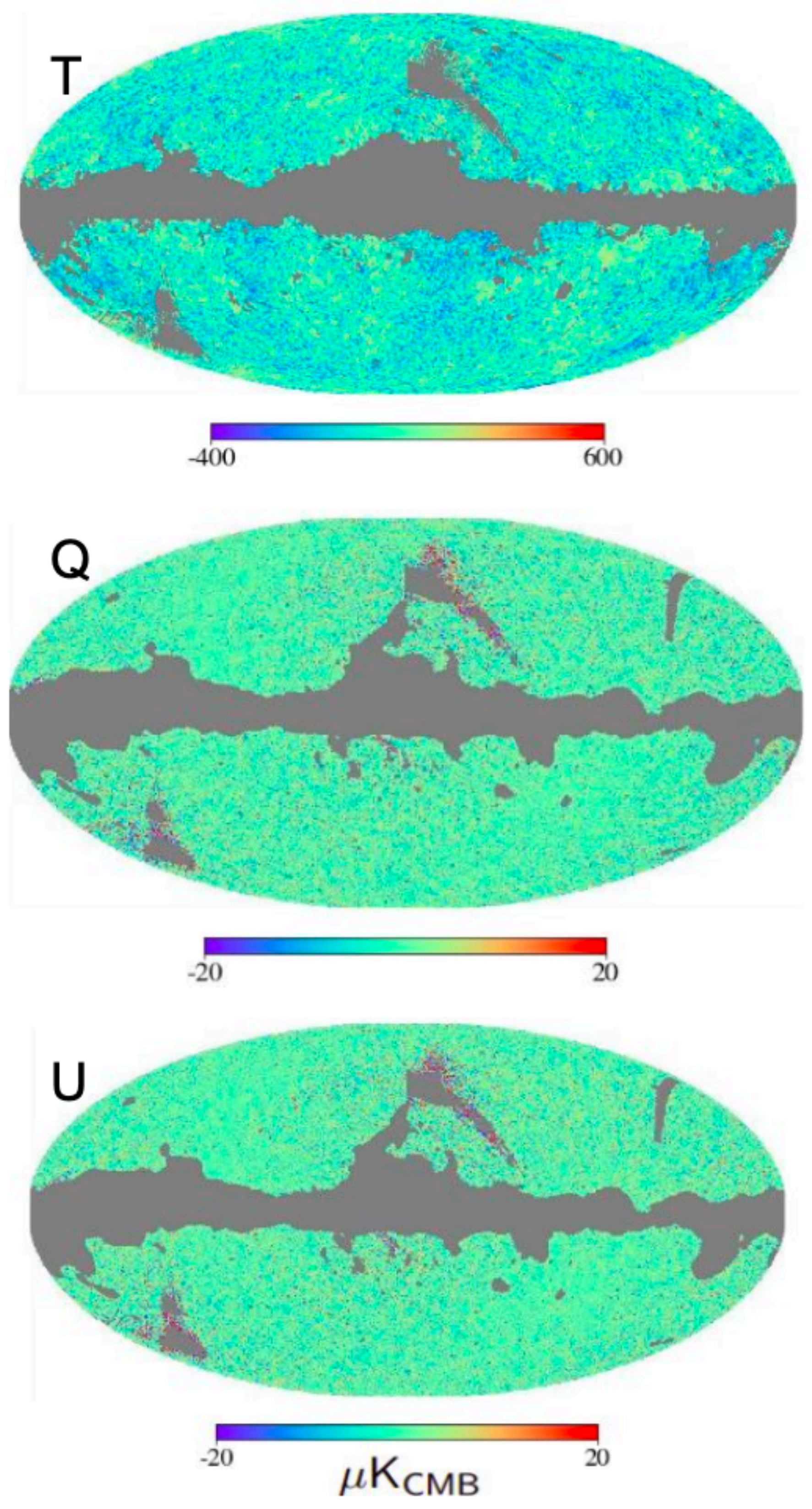
Built the D-estimators

$$\chi^2_Y(\alpha) = \sum_{\ell\ell'} D^Y_\ell \, M^{YY^{-1}}_{\ell\ell'} \, D^Y_{\ell'}$$

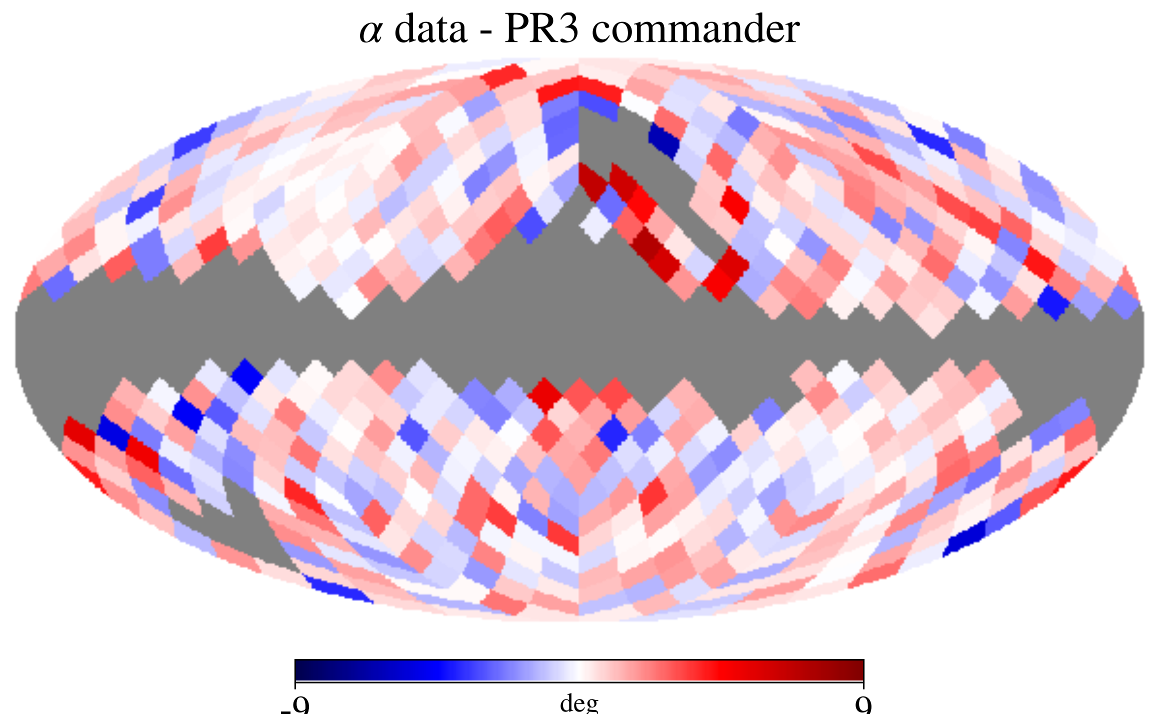


Description of the data set used

Nside=2048



- Planck release PR3;
- Planck release PR4 (aka NPIPE);
- Spectra:
  - computed in cross mode with data splits to reduce systematic effects and noise mismatches
  - Binned with $\Delta\ell$=60 to reduce errors and correlations induced by the cut-sky
- Covariance built with the Namaster code (tested against realistic sims) => $\ell_{min} = 62$
- $\ell_{max} \sim 1500$ (noise and beam)

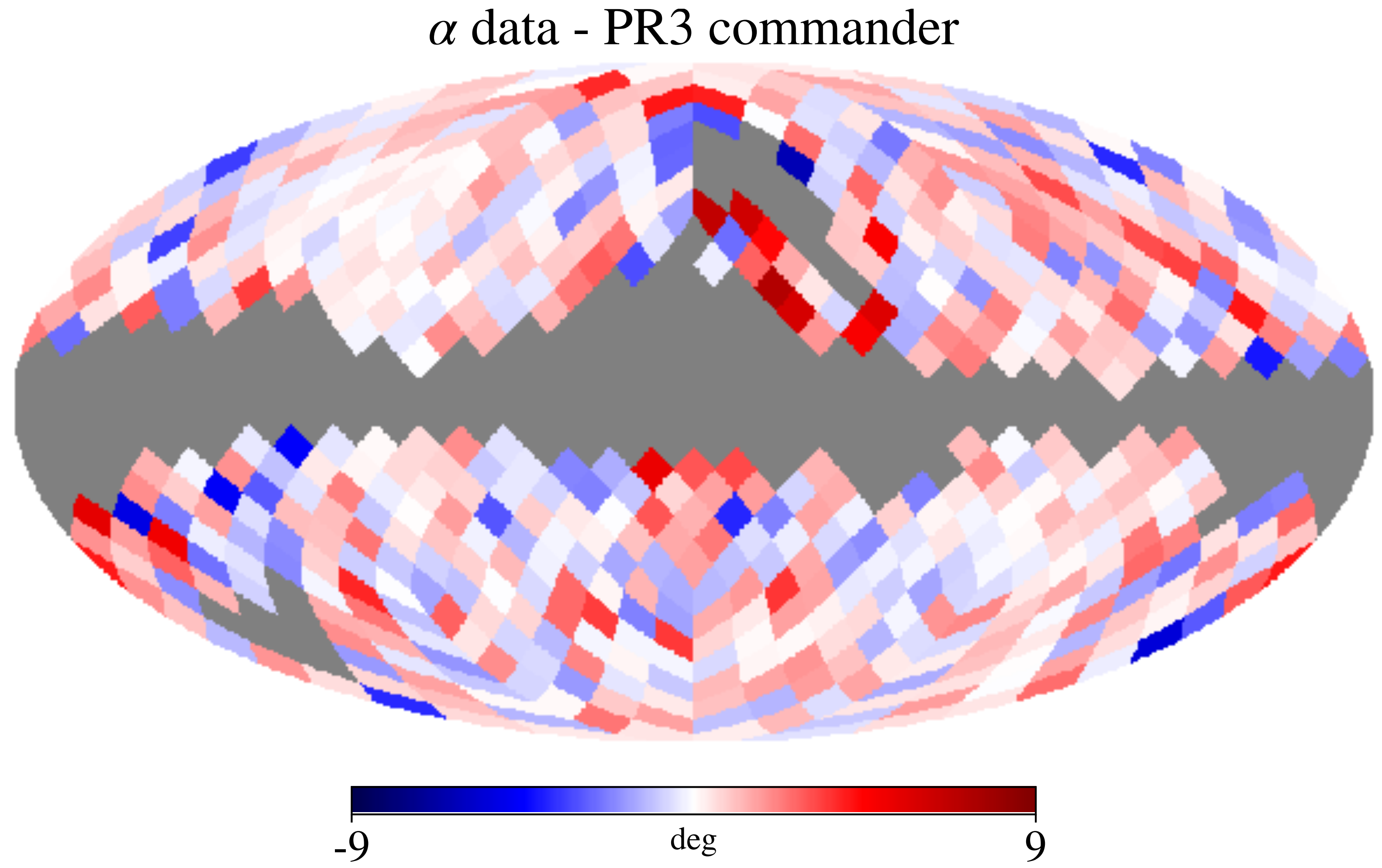


Nside=8

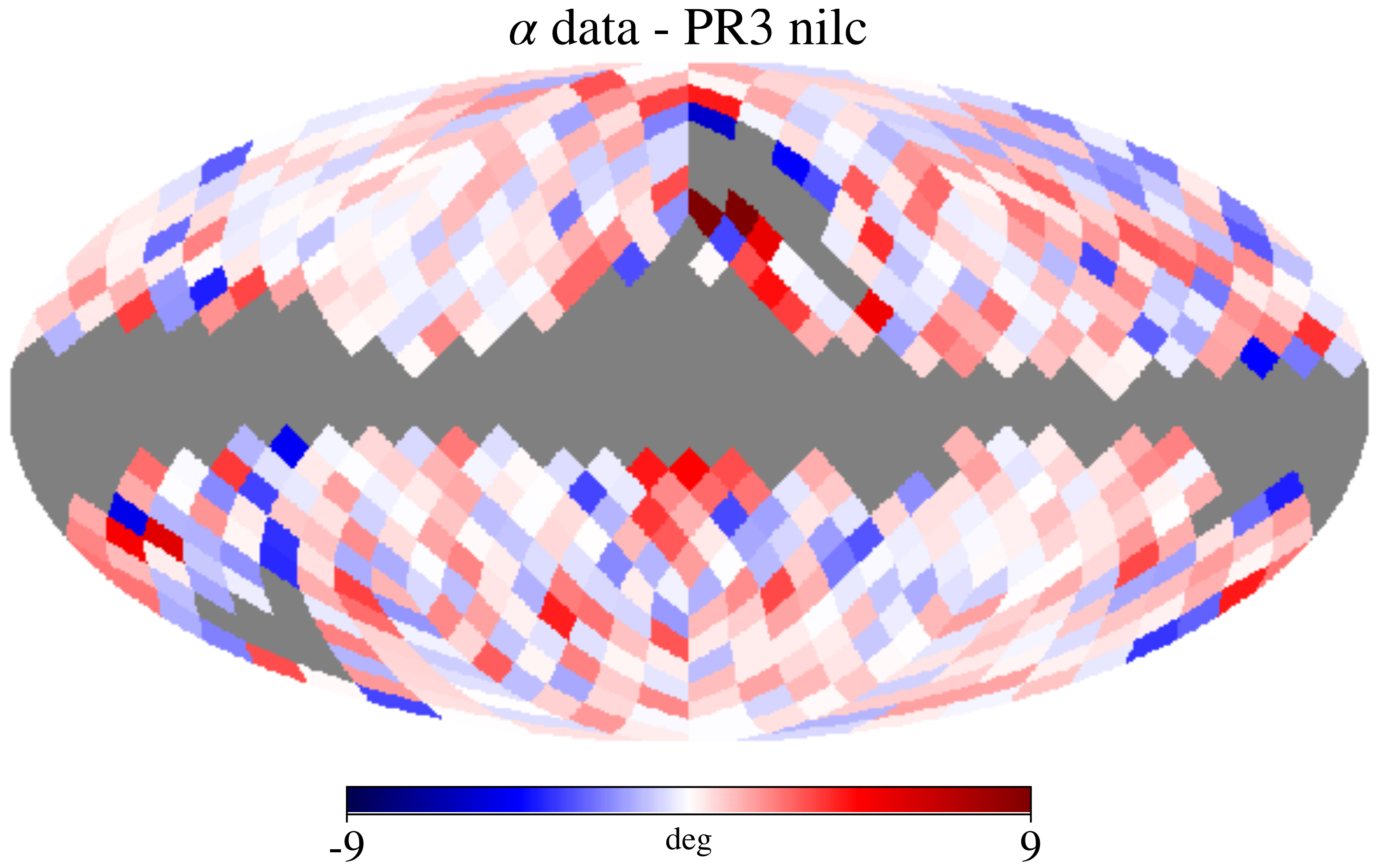
Results

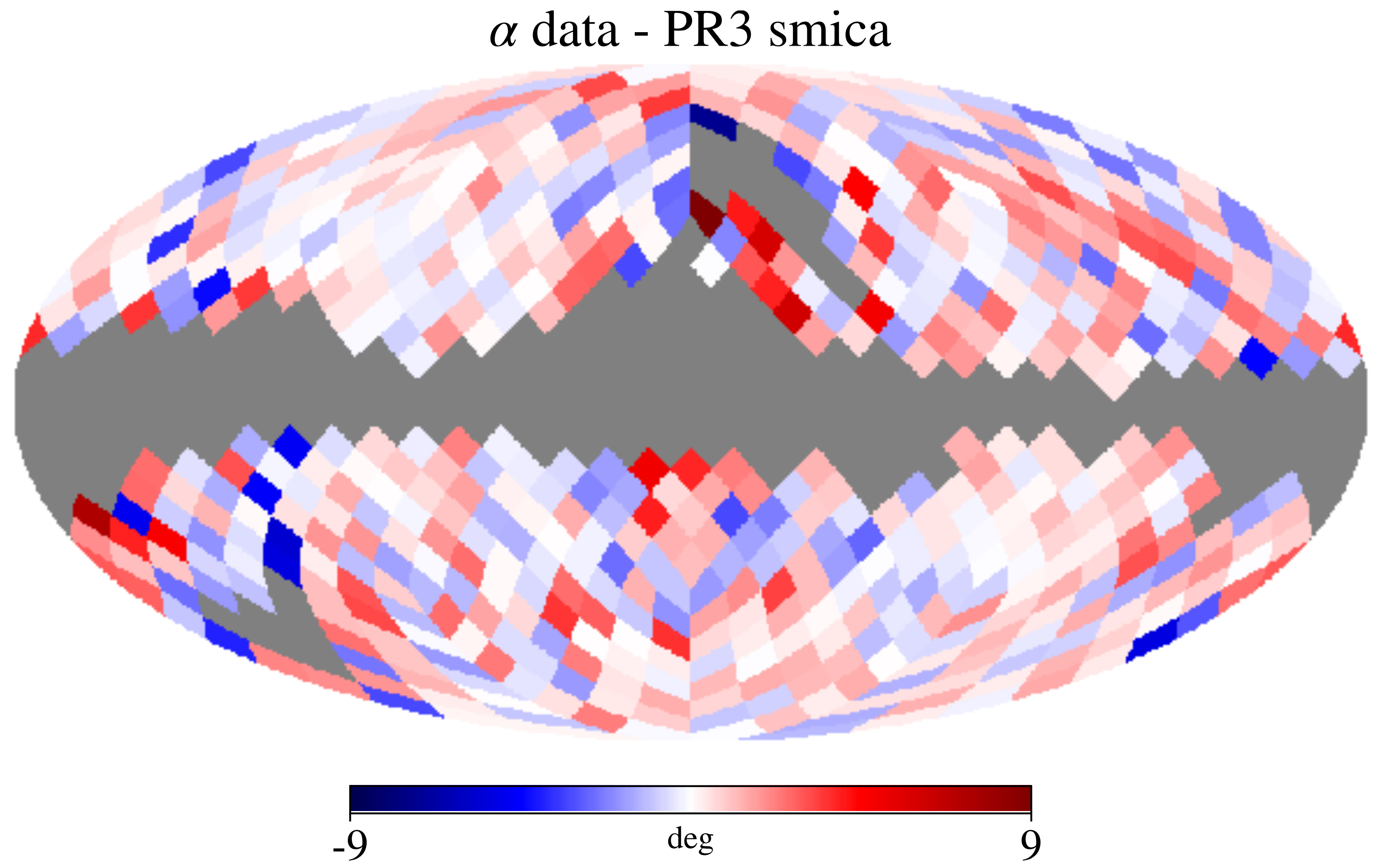
M.Bortolami et al (2022)

Commander

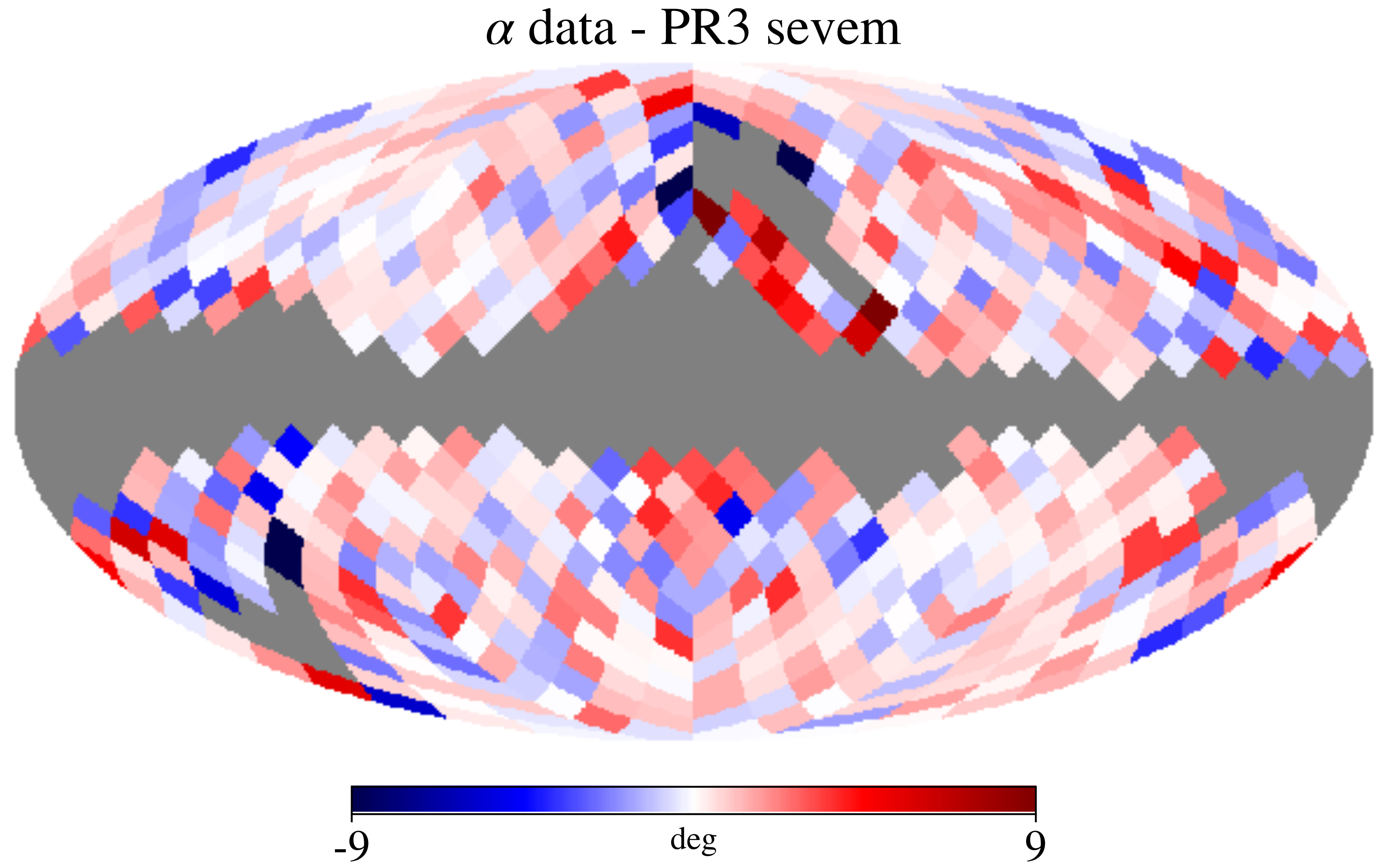


Nilc





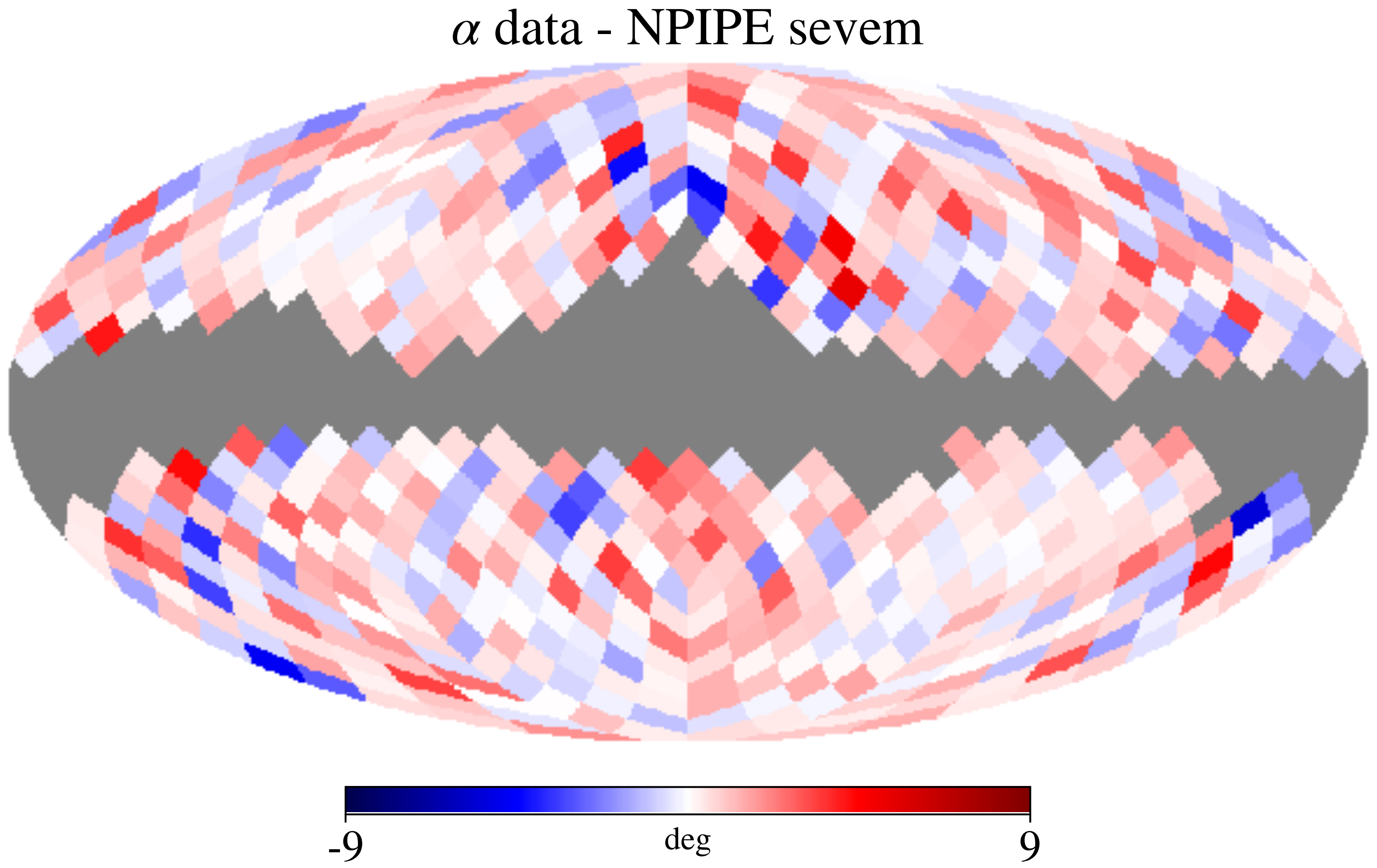
Smica

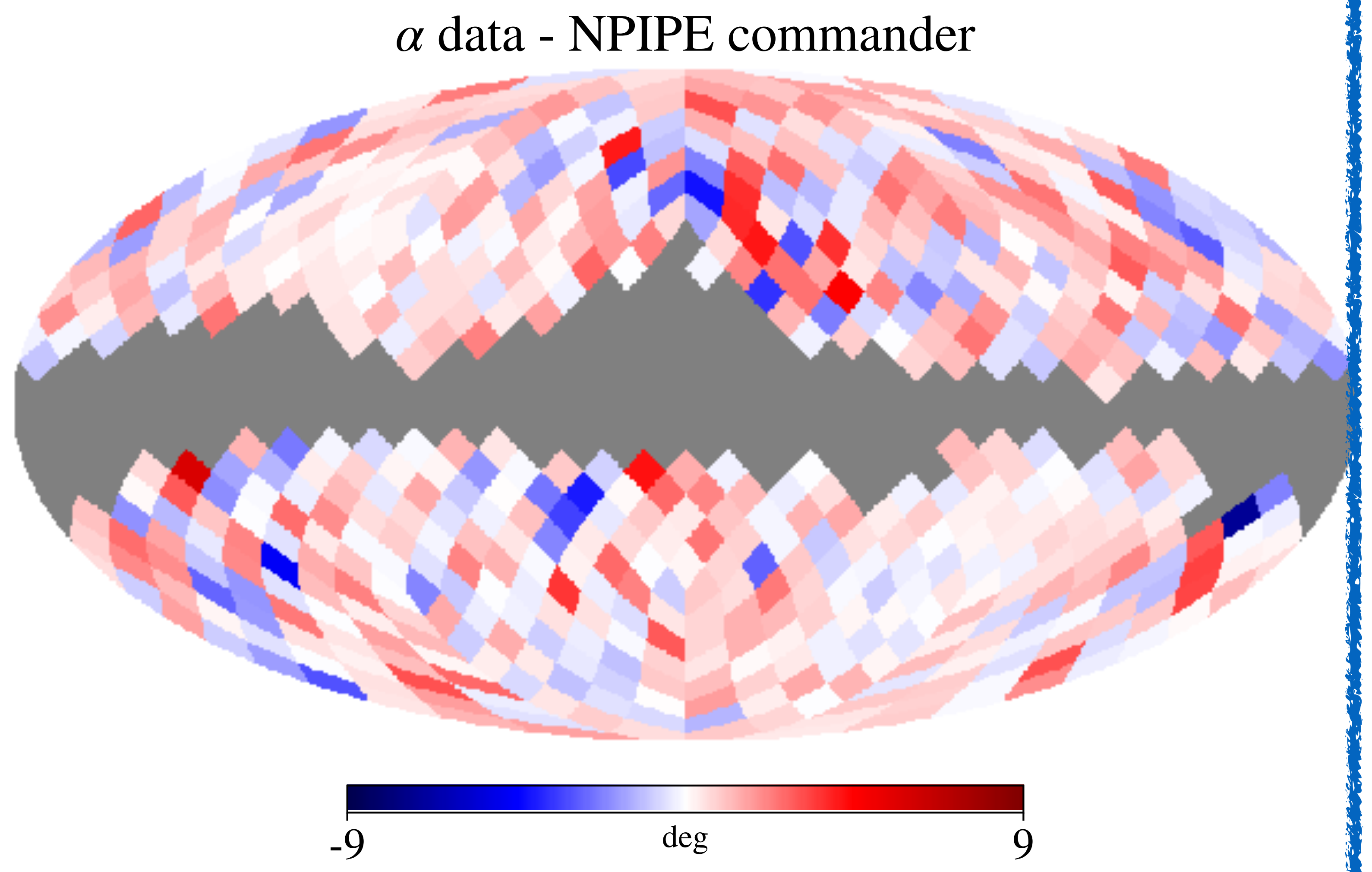


Sevem

PR3

Commander



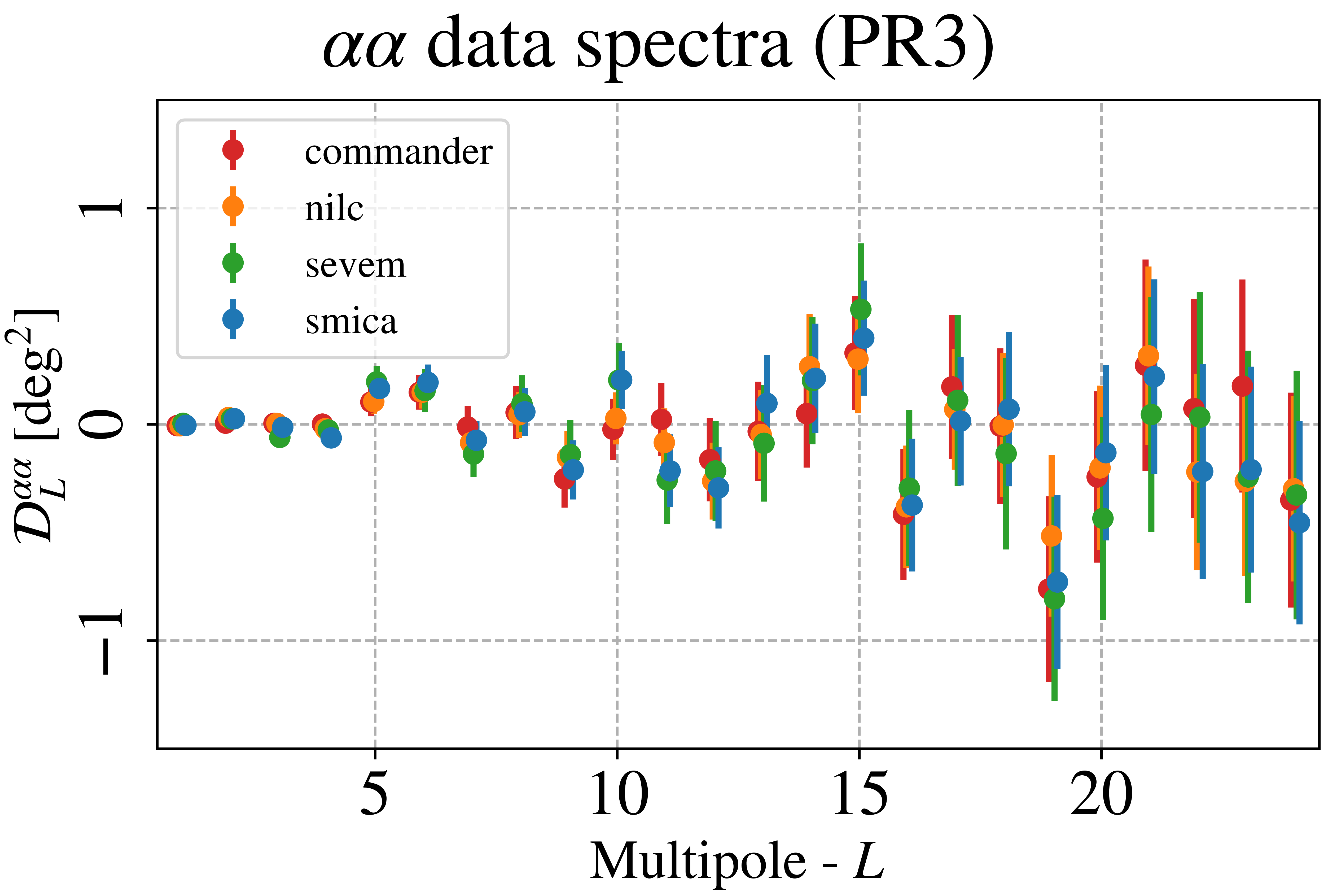


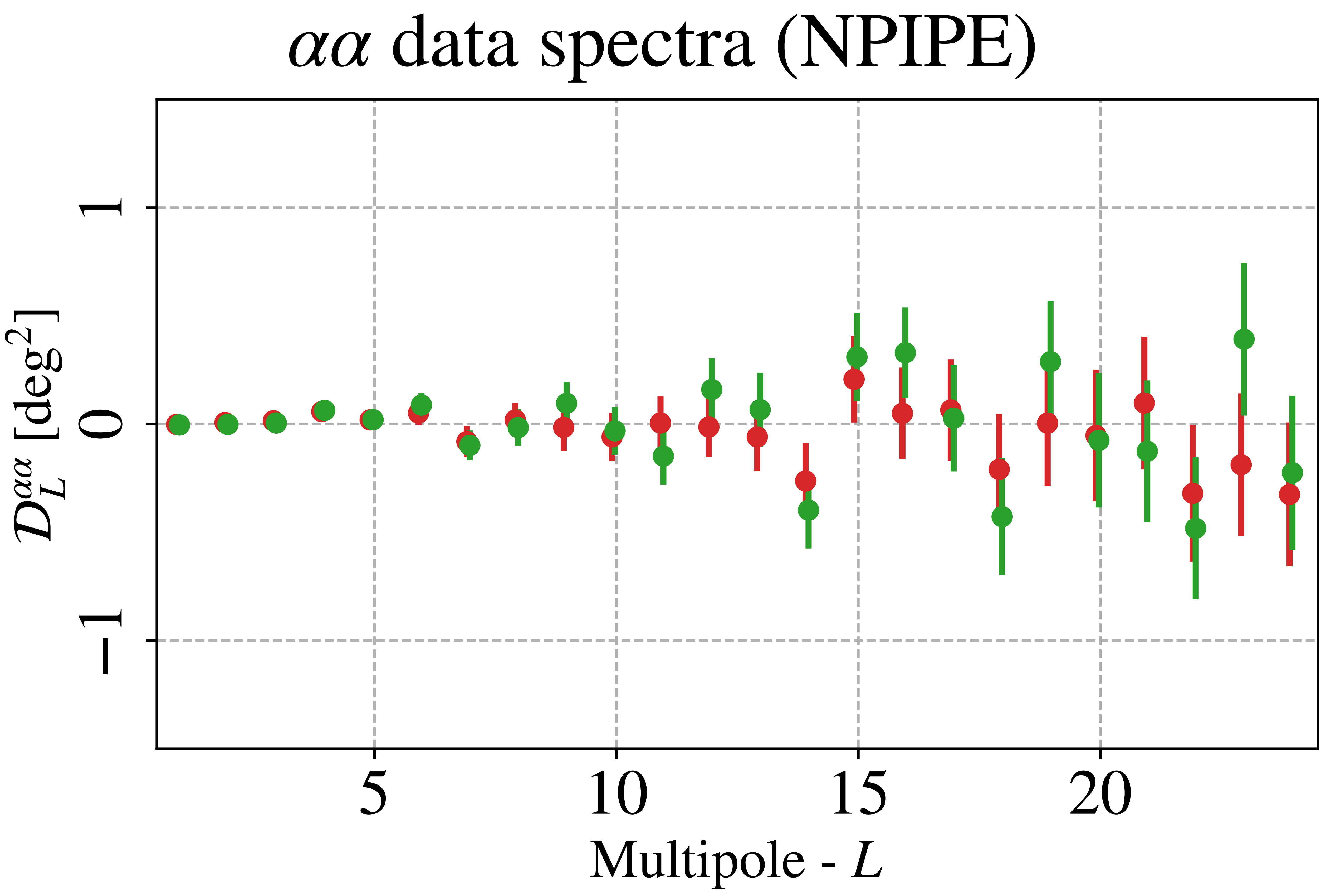
PR4

Sevem

Results

QML method for the APS

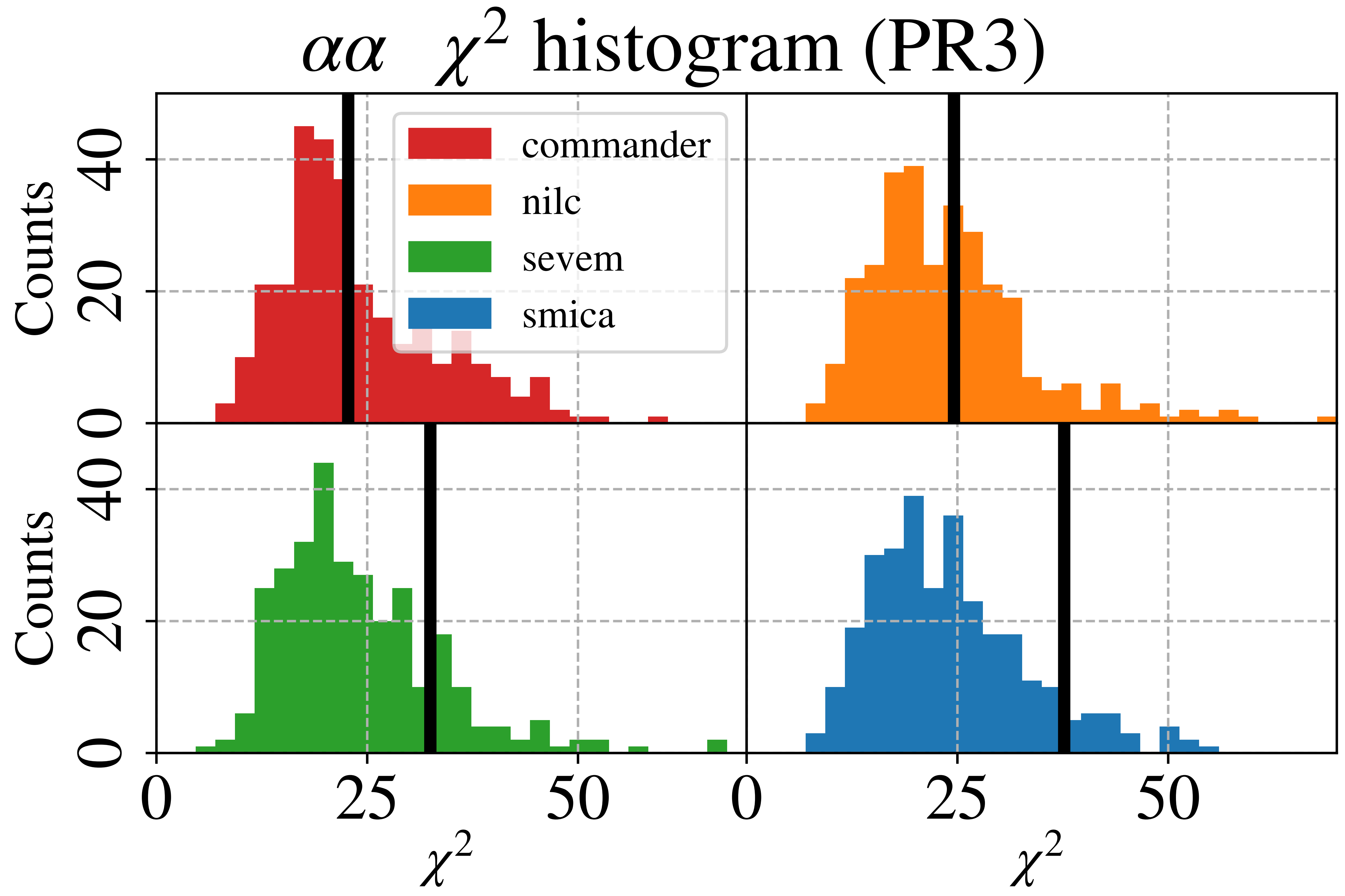


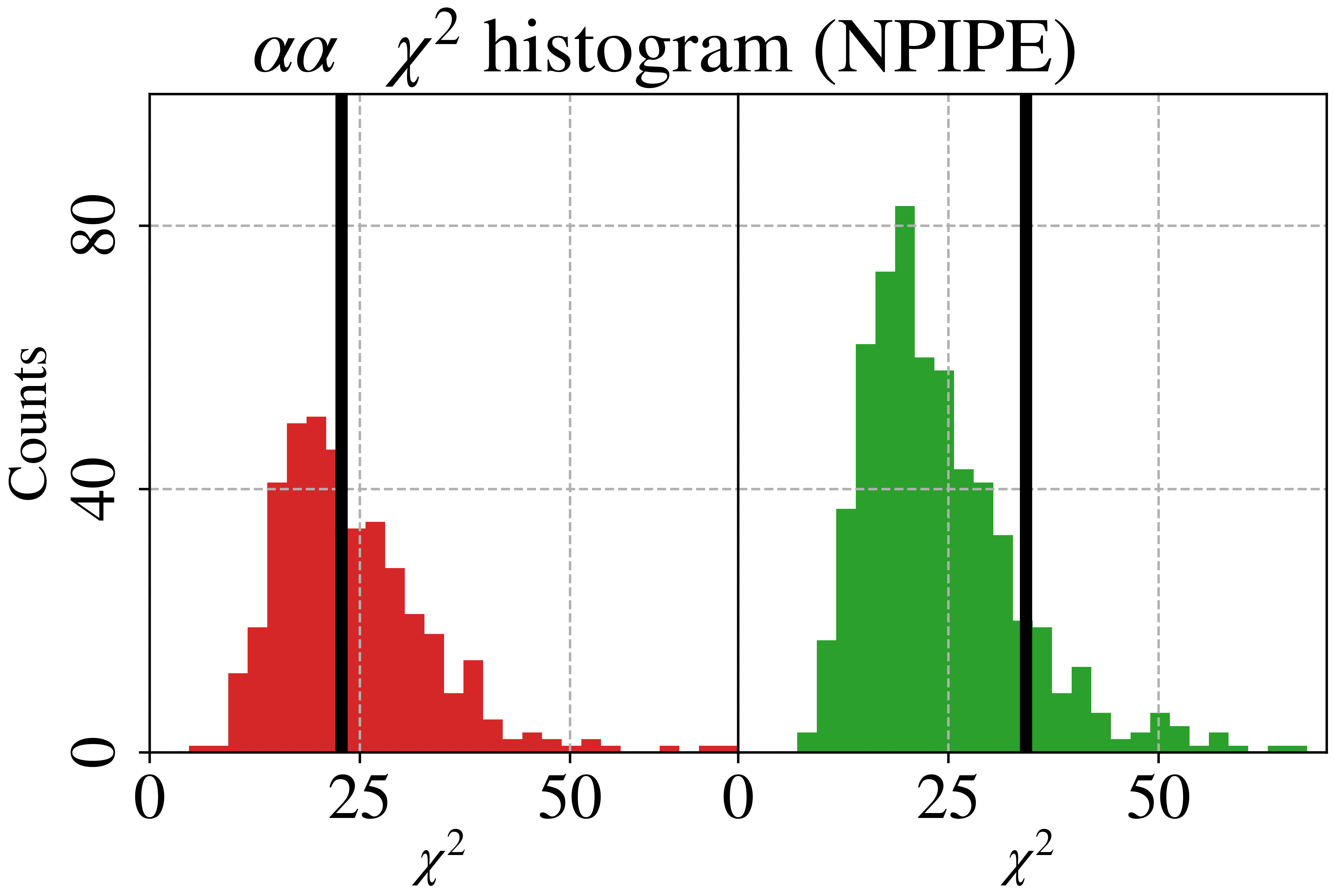


Other cross-spectra have been computed: $\alpha T, \alpha E, \alpha B$

M.Bortolami et al (2022)

Results





$$\chi^2 = \sum_{\ell\ell'} C_\ell^{\alpha\alpha} \langle C_\ell^{\alpha\alpha} C_{\ell'}^{\alpha\alpha} \rangle^{-1} C_{\ell'}^{\alpha\alpha}$$

Very good compatibility with null effect

M.Bortolami et al (2022)

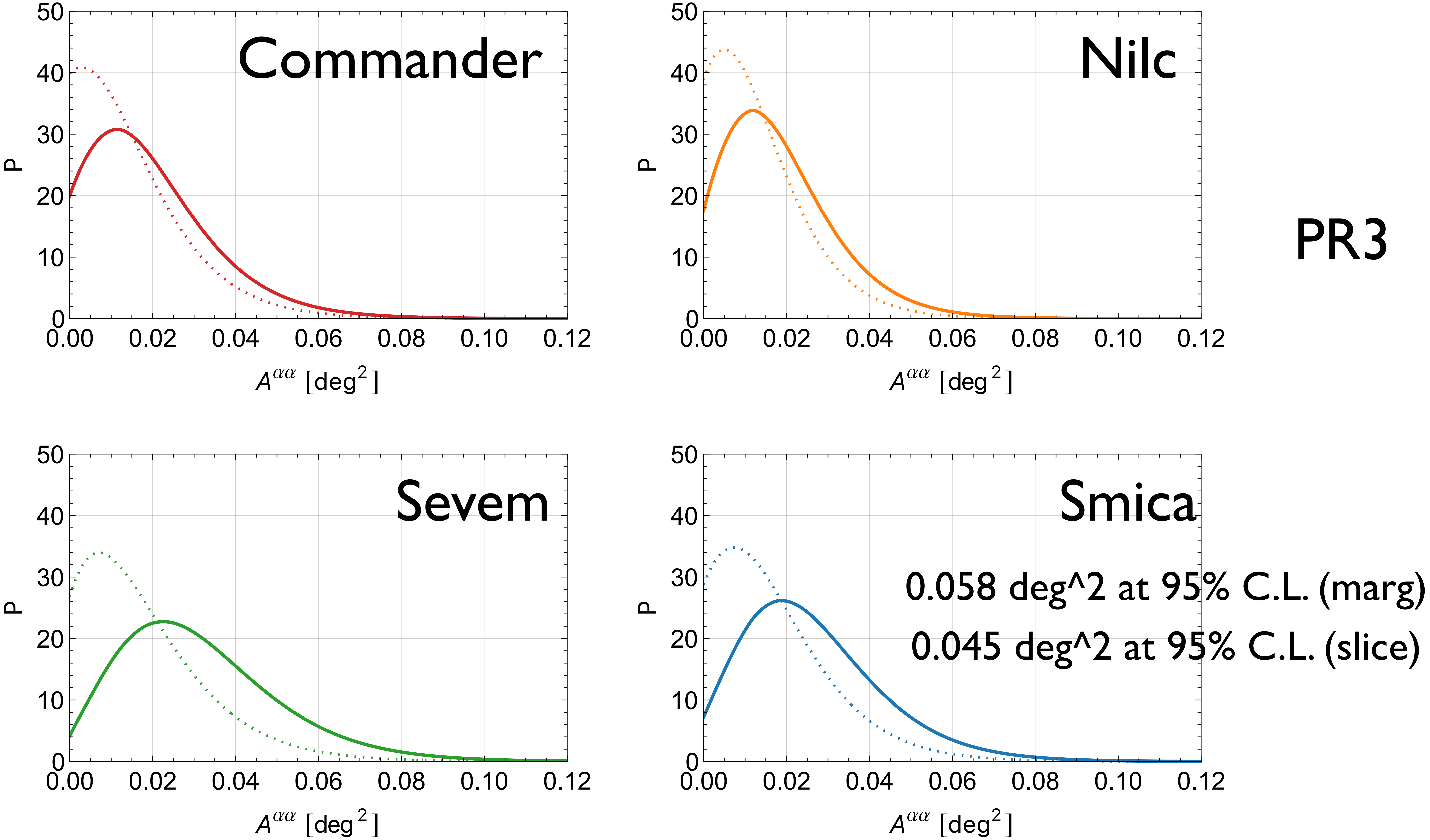
Results

Through a pixel based likelihood in the birefringence maps

Useful parameter

$$A^{\alpha\alpha} \equiv \frac{L(L+1)}{2\pi} C_L^{\alpha\alpha}$$

when the mass of the scalar field is negligible during inflation then the spectrum is scale invariant (at large scales)



PR3

Interpretation in terms of stochastic magnetic fields

De, Pogosian, Vachaspati (2013)

Pogosian (2014)

A PMF present at and just after last scattering would induce a rotation angle along the line-of-sight!
And the simplest inflationary model of magnetogenesis predict a scale invariant PMF which translates in a scale invariant power spectrum of the rotation.
This means that:

$$B_{1Mpc} = 2.1 \times 10^2 \,\text{nG} \left(\frac{\nu}{30\,\text{GHz}} \right)^2 \left(\frac{A^{\alpha\alpha}}{\text{rad}^2} \right)^{1/2}$$

$$B_{1Mpc} < 20.1 \text{ nG}$$

$$B_{1Mpc} < 17.7 \text{ nG}$$

at 95% C.L.

CMB freq ~ 143GHz

Forecasts (a few example)

	$A^{\alpha\alpha}$ [deg]^2 @ 68 % C.L.	B_{1Mpc} [nG]
LiteBIRD	3 x 10^-3	4.5
SO	4 x 10^-4	1.7
CMBS4	2 x 10^-5	0.4

CMB freq ~ 143GHz

Pogosian, Shimon, Mewes, Keating (2019)

Conclusions

- CMB polarisation data can pinpoint new physics beyond the standard model
- Cosmic birefringence is an example of how CMB polarisation can be employed for such investigations (beyond the search for primordial B-modes). This provides a way to estimate PMF.
- Current limits: A ~ 0.033 deg^2 (SPTpol, ACTpol), A ~ 0.045 deg^2 (Planck) [estimated from a different range of multipoles]
- Future CMB data are expected to improve such constraints up to 3 orders of magnitude

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Back-up

How to constrain anisotropic birefringence

Non-exhaustive list

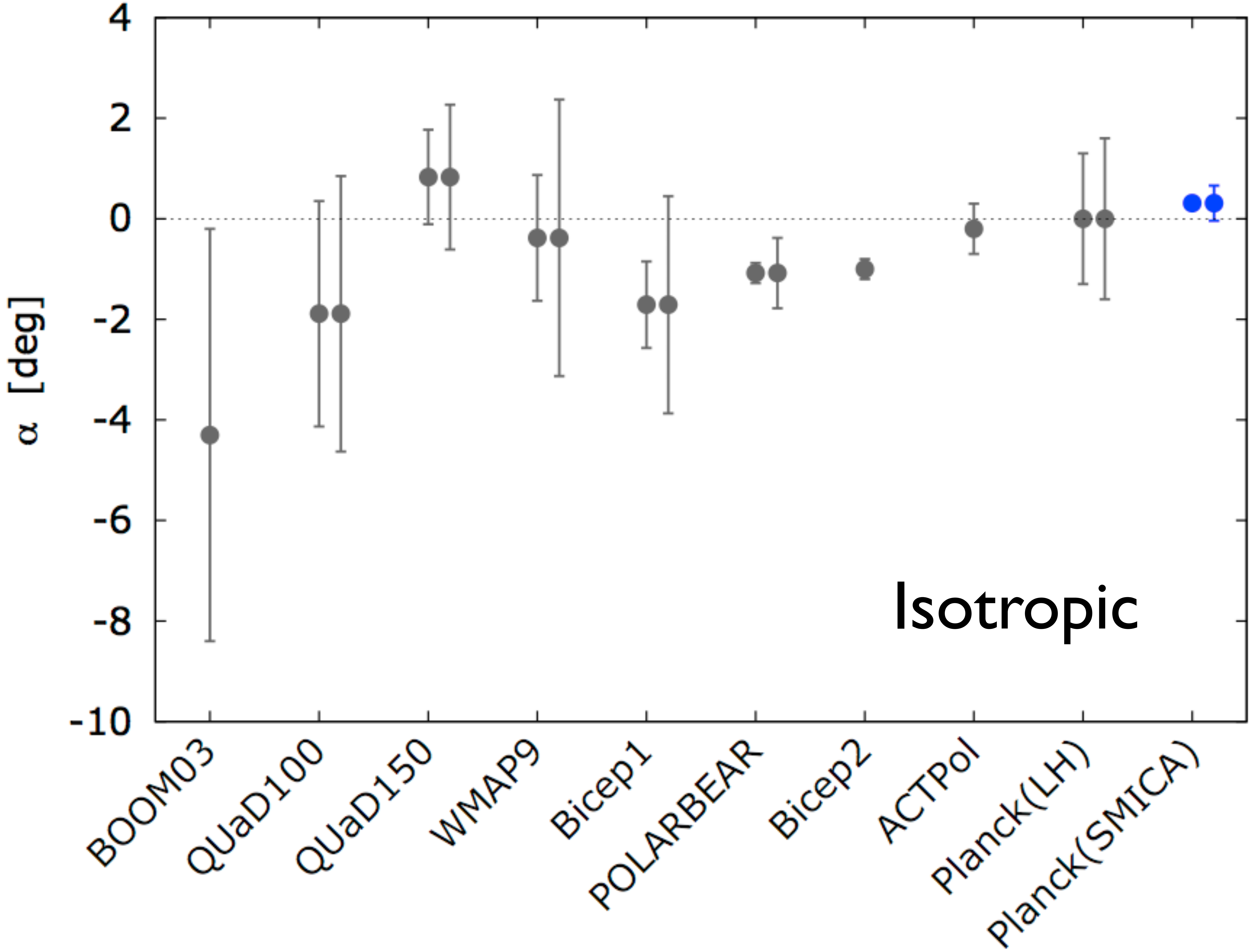
- Mode coupling approach Gluscevic & Kamionkowski (2010)
- Likelihood approach e.g. Zhai, Li, Li, Zhang (2020)
- "Localise" estimators that are employed to extract the isotropic birefringence
  - Stacking approach (pixel based approach) D.Contreras et al (2017)
  - D-estimators (harmonic based approach) A.Gruppuso et al (2020) M.Bortolami et al (2022)

NPIPE

PR4, also known as NPIPE, is a reprocessing of raw LFI and HFI Planck data where a (scale-dependent) reduction of the total uncertainty is obtained due to:

a) addition of data acquired during repointing manoeuvres
b) improved modelling of instrumental noise and systematics

Isotropic birefringence



Planck collaboration, (2016) Astron.Astrophysics 596 A110

Planck collaboration,
Astron.Astrophysics 596 (2016)
A110

- **Planck constraints on α are compatible with 0 within statistical and systematic error budget.** They are dominated by the uncertainty of the Instrumental Polarization Angle (0.3 deg). Statistical uncertainty is at the level of 0.05 deg.

$$\alpha \text{ [deg]} = 0.31 \text{ +/- } 0.05 \text{ (stat) +/- } 0.28 \text{ (sys)}$$

- The found constraints are stable within statistical uncertainties:

1. against two independent methods (D estimators and Stacking maps)
2. against different component separation methods
3. against harmonic scale (multipole)
4. against the details of polarised noise properties (Stacking and Cross-spectra are used right to not to be strongly dependent on that).
5. against beam mismatch (not shown here)

Isotropic

Planck collaboration, (2016) Astron.Astrophysics 596 A110

Isotropic angle

- Planck constraints.

Planck collaboration,
Astron.Astrophysics 596 (2016) A110

  - Isotropic α [deg] = 0.31 +/- 0.05 (stat) +/- 0.28 (sys)

error budget dominated by the uncertainty of the Instrumental Polarization Angle (0.3 deg).

substantially unchanged in 2018

Minami & Komatsu (2020)	α [deg] = 0.35 +/- 0.14	PR3
Diego-Palazuelos et al. (2022)	α [deg] = 0.30 +/- 0.11	PR4
Eskilt & Komatsu (2022)	α [deg] = 0.342 +/- 0.094	Planck+WMAP

Applying a new technique able to break the degeneracy

Introduction

$$Q \pm iU \rightarrow e^{\pm 2i\alpha}(Q \pm iU)$$ α is the birefringence angle

- This might be induced by a Chern-Simons modification of the standard electromagnetism

Carroll, Field & Jackiw (1990)

$$\mathscr{L} = g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\lambda}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \alpha = \frac{\lambda}{2f}\Delta\phi$$

- Faraday rotation, that photons can experience when passing through regions permeated by magnetic fields.

$$\alpha(\hat{n}) \propto \nu^{-2} \int d\vec{l} \cdot \dot{\tau}\vec{B}$$

The linear polarisation plane of photons of course does not change direction if the photons propagate in the vacuo.

e.g. Harari, Hayward & Zaldarriaga (1997)

Component Separation

- Planck employs 4 methods:
  - Commander. It works in pixels domain and use a Bayesian parameter fitting
  - SMICA. It works in harmon domain. Non parametric method (foregrounds are modeled as a small number of templates). The solution is found minimizing the mismatch of the model to the auto and cross power spectra.
  - NILC. Implementation of Internal Linear Comination (ILC) method that works in needlet space (kind of wavelet domain). Variance minimized at each scale.
  - SEVEM. It works in pixel domain and employs a template fitting approach.

Planck collaboration, (2015) "Planck 2015 results. IX. Diffuse component separation: CMB maps". A&A.

Details of the method

Of course the combination must take into account the correlation between the two

$$\chi^2_{TB+EB} = \sum_{\ell,\ell'} \left(D_\ell^{TB,obs}, D_\ell^{EB,obs}\right) \tilde{M}_{\ell\ell'} \left(D_{\ell'}^{TB,obs}, D_{\ell'}^{EB,obs}\right) ,$$

$$\tilde{M}^{-1}_{\ell\ell'} = \begin{bmatrix} \langle D_\ell^{TB,obs} D_{\ell'}^{TB,obs}\rangle & \langle D_\ell^{TB,obs} D_{\ell'}^{EB,obs}\rangle \\ \langle D_\ell^{EB,obs} D_{\ell'}^{TB,obs}\rangle & \langle D_\ell^{EB,obs} D_{\ell'}^{EB,obs}\rangle \end{bmatrix} .$$

$$\begin{aligned}
\langle D_\ell^{TB,obs} D_{\ell'}^{TB,obs}\rangle &= [(C_\ell^T + C_\ell^{nT})(C_\ell^B + C_\ell^{nB}\cos^2(2\alpha) + \\
&\quad + C_\ell^{nE}\sin^2(2\alpha))]\,\delta_{\ell\ell'}\frac{1}{2\ell+1} \\
\langle D_\ell^{EB,obs} D_{\ell'}^{EB,obs}\rangle &= [C_\ell^E C_\ell^B + (C_\ell^E C_\ell^{nB} + C_\ell^B C_\ell^{nE})\cos^2(2\alpha) + \\
&\quad + (C_\ell^B C_\ell^{nB} + C_\ell^E C_\ell^{nE})\sin^2(2\alpha) + \\
&\quad + (C_\ell^{nE} C_\ell^{nB})\cos^2(4\alpha) + \\
&\quad + 2(C_\ell^{nE} C_\ell^{nE} + C_\ell^{nB} C_\ell^{nB})\frac{1}{4}\sin^2(4\alpha)\Big]\,\delta_{\ell\ell'}\frac{1}{2\ell+1} ,
\end{aligned}$$

$$\langle D_\ell^{TB,obs} D_{\ell'}^{EB,obs}\rangle = [C_\ell^{TE}(C_\ell^B + C_\ell^{nB}\cos^2(2\alpha) + C_\ell^{nE}\sin^2(2\alpha))]\,\delta_{\ell\ell'}\frac{1}{2\ell+1} ,$$

$$\langle D_\ell^{EB,obs} D_{\ell'}^{TB,obs}\rangle = \langle D_{\ell'}^{TB,obs} D_\ell^{EB,obs}\rangle .$$

Note also that when $\hat{\alpha} = \alpha$ and the noise in E is ~ noise in B, the dependence on the angle drops out in the covariance. This simplifies the analysis.

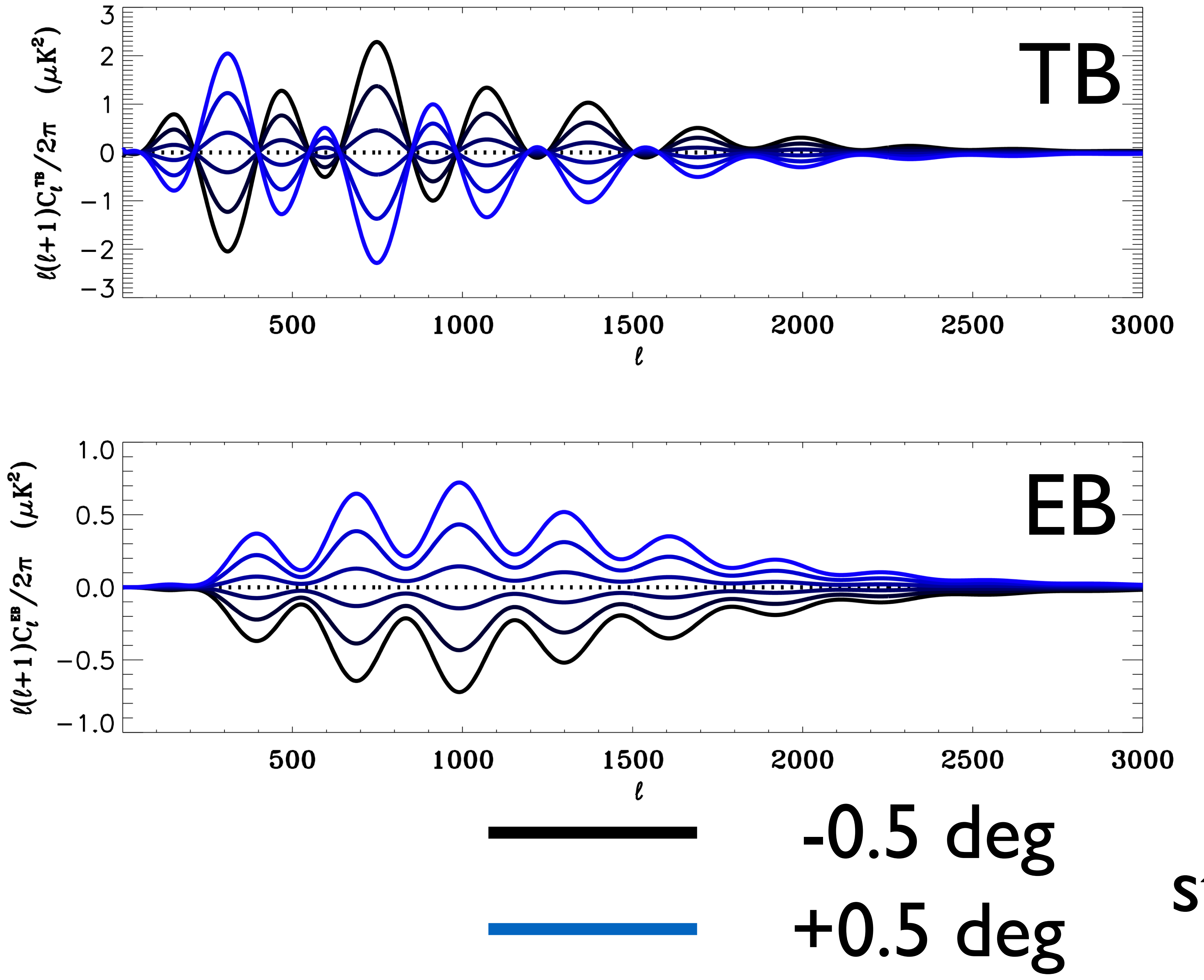
Gruppuso, Maggio, Molinari, Natoli, JCAP (2016)

Impact on CMB spectra

- CB produces a mixing of E and B modes. Its impact on CMB spectra (assuming constant α) is

Lue, Wang & Kamionkoski (1999)
Feng, Li, Li & Zhang (2005)

How the amplitude of the isotropic birefringence effect is related to the value of the angle



few μK^2

< μK^2

step=0.02

Isotropic birefringence

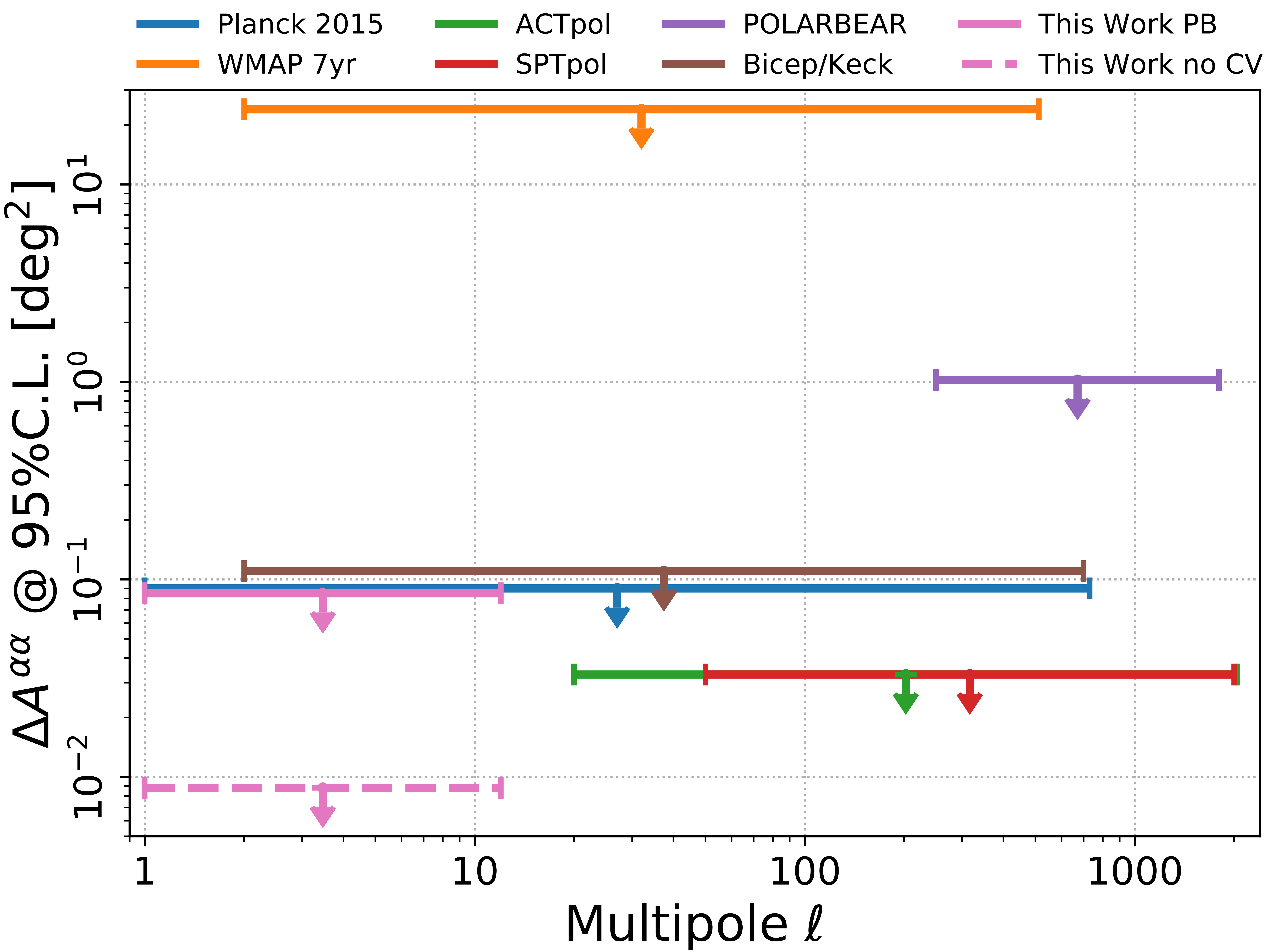
Building the D-estimators

For the Planck Parity paper (2016) we have employed official Planck sims (FFP8.1) to build these D estimators.

FFP8.1 sims (short description).

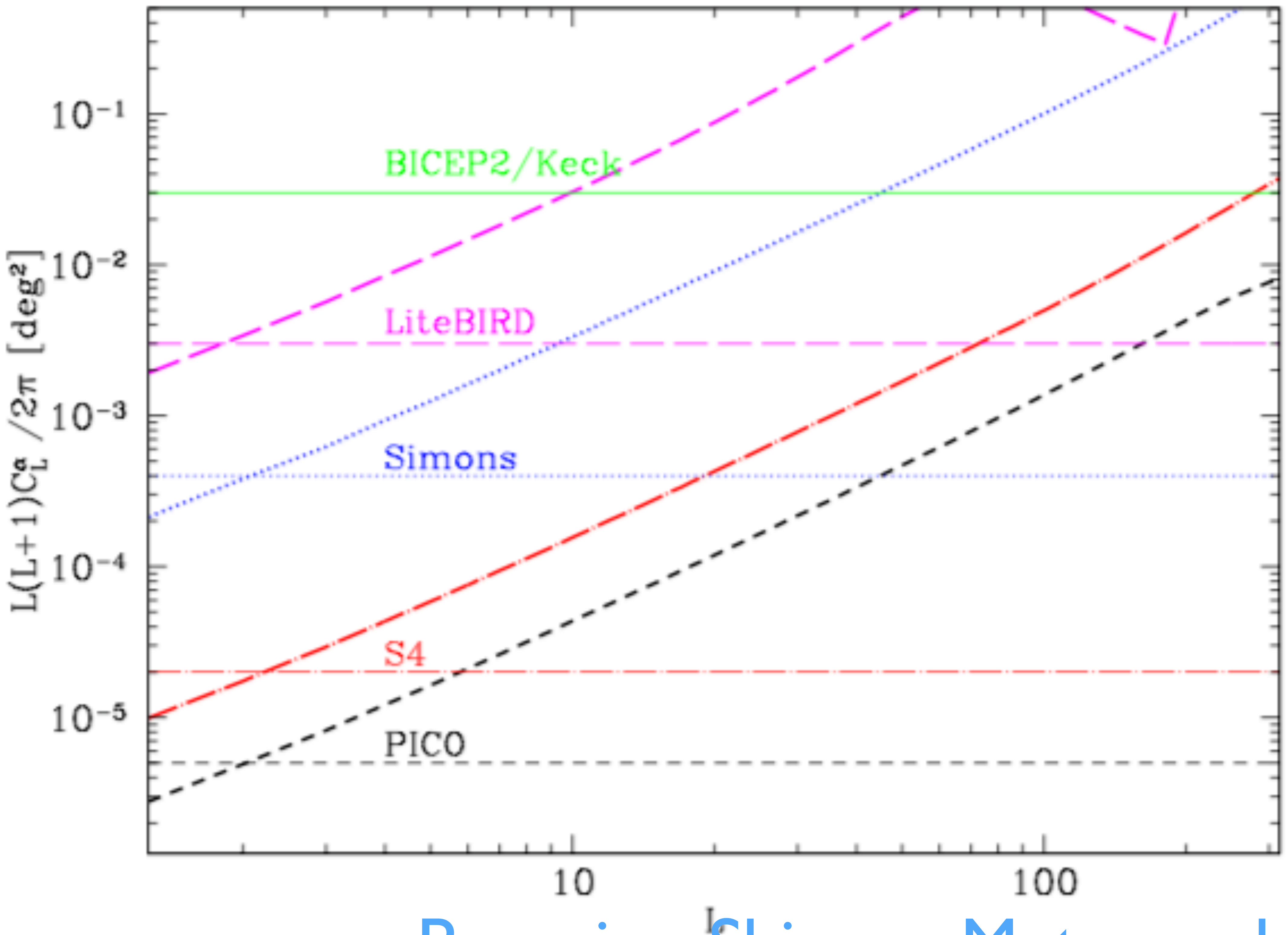
1. "end to end" realistic signal plus noise sims from raw data to channels maps
2. they are processed through the Component Separator Layers (namely Commander, NILC, SEVEM, SMICA). The output CMB maps (w/ corresponding noise description) are what we consider in the estimators
3. they contain residuals of systematic effects (T to P leakage)

D-estimators are based on APS. Therefore we have estimated the spectra from the observed CMB maps and from the FFP8.1 sims.



Gruppuso, Molinari, Natoli and Pagano (2020)

Forecasts



Pogosian, Shimon, Metes and Keating (2019)

FIG. 1. The thick lines show the statistical uncertainty in C_L^α, given by Eq. (21), forecasted for the four experiments considered in this work. These curves assume de-lensing by a fraction f_L given for each experiment in Table II, and account for the effects of beam systematics. The thinner horizontal lines indicate the corresponding expected 68% CL bounds on the amplitude of the scale-invariant rotation spectrum A_α. The thin green solid line shows the current bound on A_α from BICEP2/Keck [46].

Component Separation

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Planck collaboration, (2015) "Planck 2015 results. IX. Diffuse component separation: CMB maps". A&A.

Other observations to test birefringence

S.di Serego Alighieri IJMPD (2015)