Isotropic Cosmic Birefringence

co-leads: Alessandro Gruppuso & J.E.

Josquin Errard, May 13, 2024

Introduction

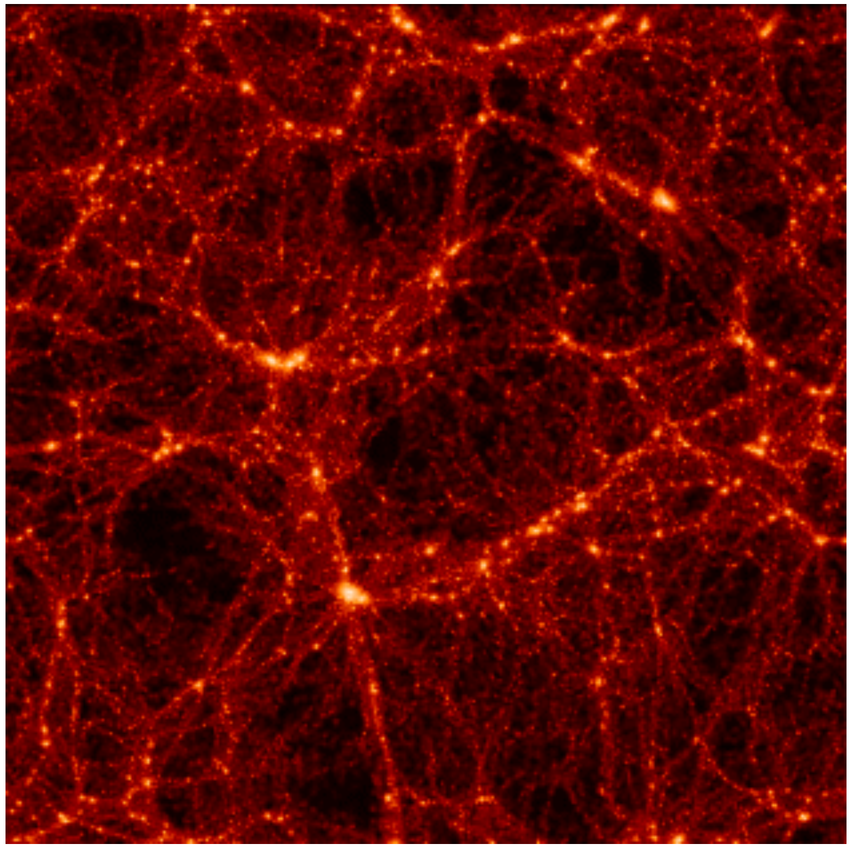
The Universe is

- Homogeneous (translation symmetry)
- Isotropic (rotational symmetry)

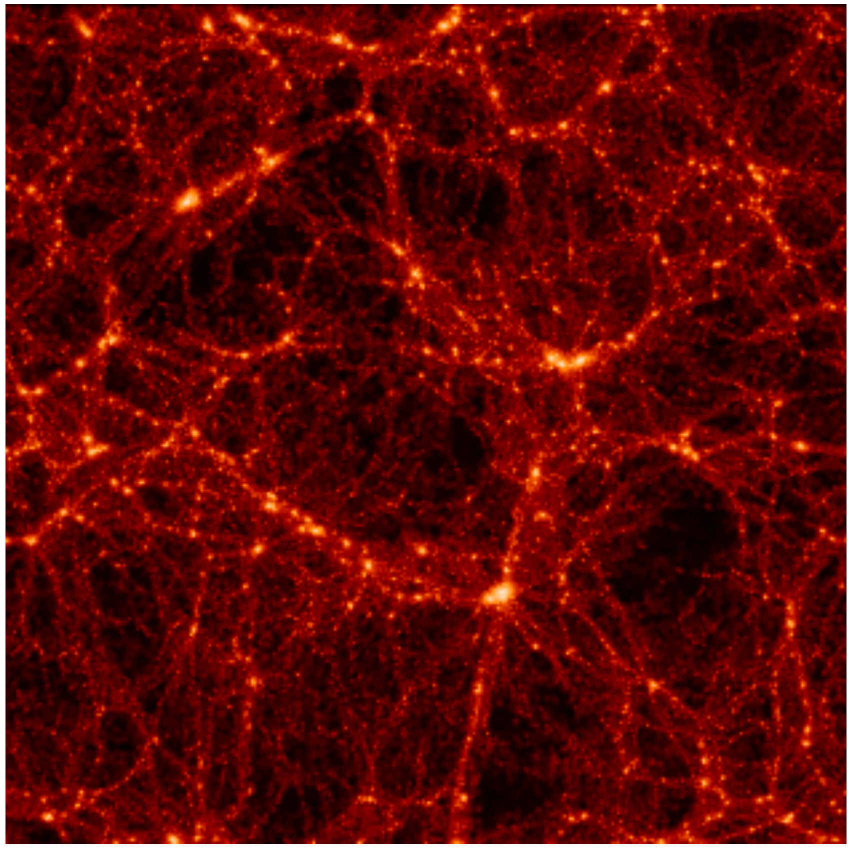
Introduction

The Universe is
- Homogeneous (translation symmetry)
- Isotropic (rotational symmetry)

what about reflection symmetry?



vs.



Introduction

Parity-violating extensions of the standard electromagnetism due to the coupling between photon and a (pseudo-)scalar field, as for instance an **axion**, can be modeled with a **Chern-Simons term** [Carroll+ 1989]:

Chern-Simons term

$$\mathcal{L} \supset -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Parity-violating
pseudo-scalar field

Introduction

Parity-violating extensions of the standard electromagnetism due to the coupling between photon and a (pseudo-)scalar field, as for instance an **axion**, can be modeled with a **Chern-Simons term** [Carroll+ 1989]:

Chern-Simons term

$$\mathcal{L} \supset -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Parity-violating pseudo-scalar field

This term makes the phase velocities of right- and left-handed polarisation states of photons different, leading to a rotation of the linear polarisation direction.

Introduction

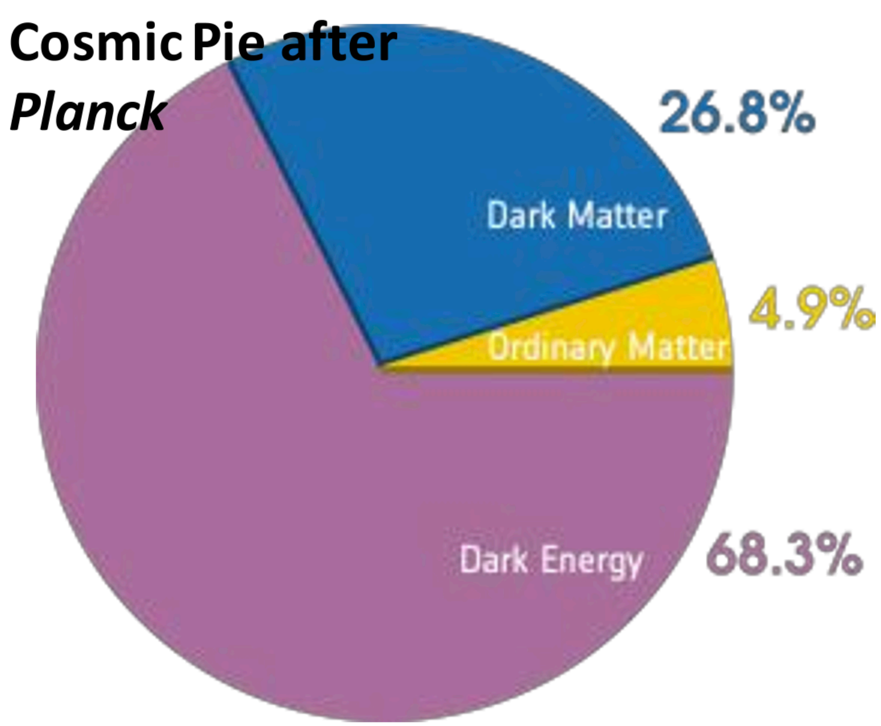
Parity-violating extensions of the standard electromagnetism due to the coupling between photon and a (pseudo-)scalar field, as for instance an **axion**, can be modeled with a **Chern-Simons term** [Carroll+ 1989]:

Chern-Simons term

$$\mathcal{L} \supset -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Parity-violating pseudo-scalar field

This term makes the phase velocities of right- and left-handed polarisation states of photons different, leading to a rotation of the linear polarisation direction.



Such a rotation is expected to be null in the standard Maxwellian electromagnetism, so detecting a non-zero angle different from zero would probe the existence of a **new cosmological scalar field ϕ, possibly acting as dark matter or dark energy** [Marsh+ 2015, Ferreira+ 2020].

Introduction

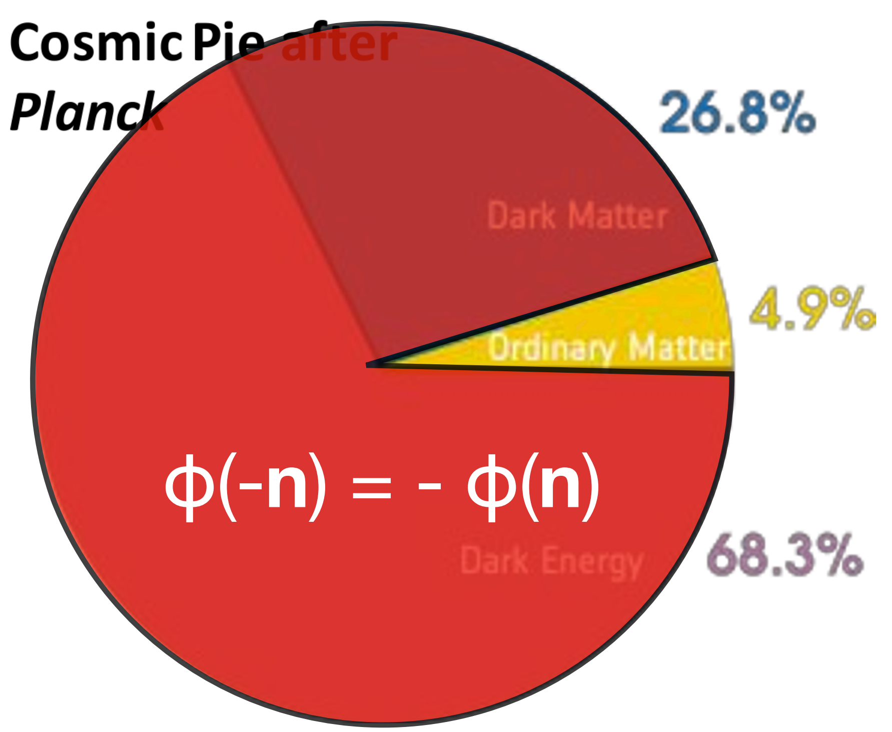
Parity-violating extensions of the standard electromagnetism due to the coupling between photon and a (pseudo-)scalar field, as for instance an **axion**, can be modeled with a **Chern-Simons term** [Carroll+ 1989]:

Chern-Simons term

$$\mathcal{L} \supset -\frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4} g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Parity-violating pseudo-scalar field

This term makes the phase velocities of right- and left-handed polarisation states of photons different, leading to a rotation of the linear polarisation direction.

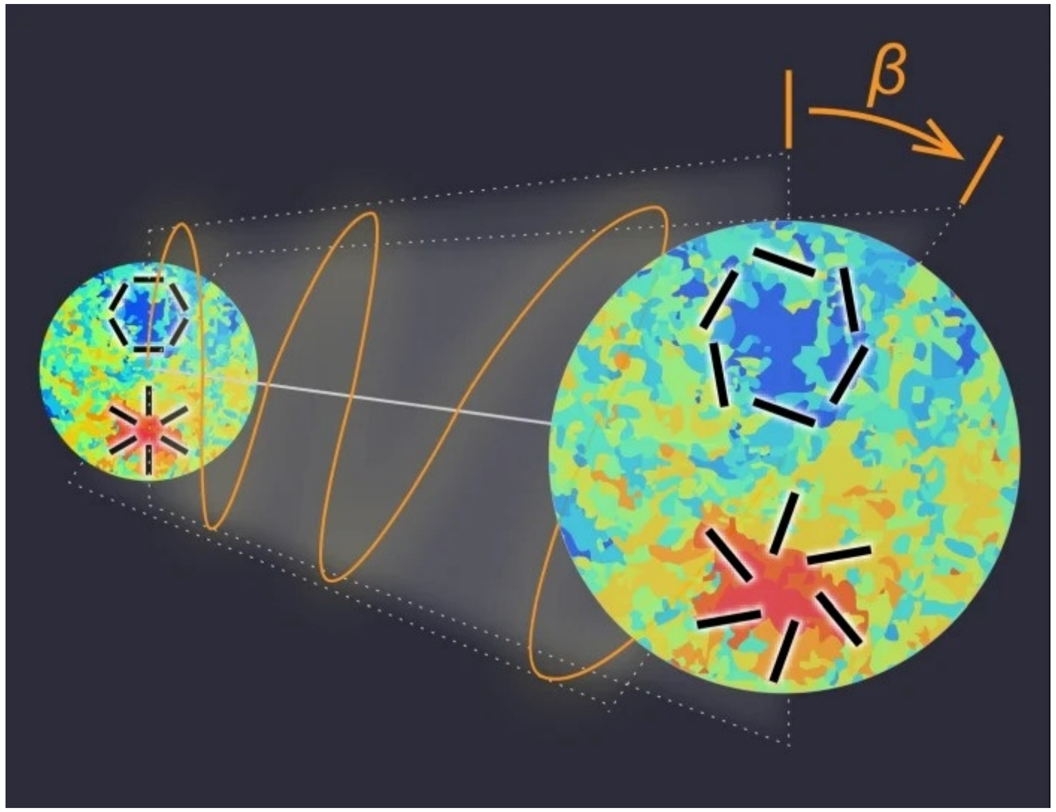


Such a rotation is expected to be null in the standard Maxwellian electromagnetism, so detecting a non-zero angle different from zero would probe the existence of a **new cosmological scalar field ϕ, possibly acting as dark matter or dark energy** [Marsh+ 2015, Ferreira+ 2020].

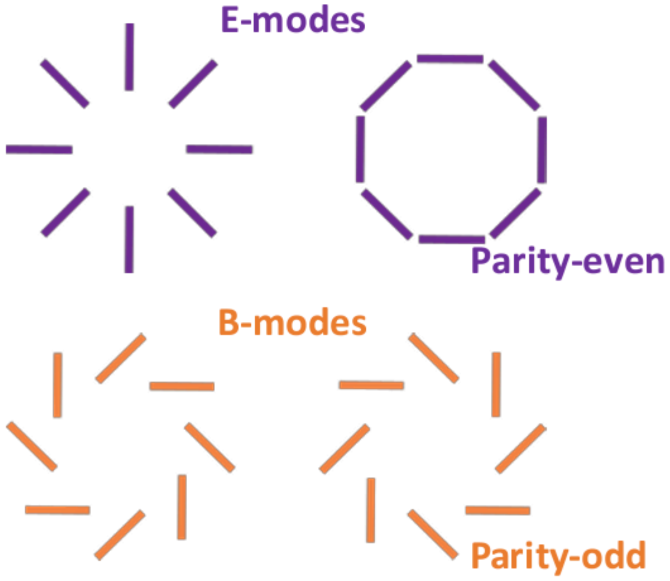
Introduction

$$\beta = \frac{1}{2} g_{\phi\gamma} \int \frac{\partial \phi}{\partial t} dt$$

The effect accumulates over the distance!
[Harari+ 1992,Li+ 2008, Pospelov+ 2008]

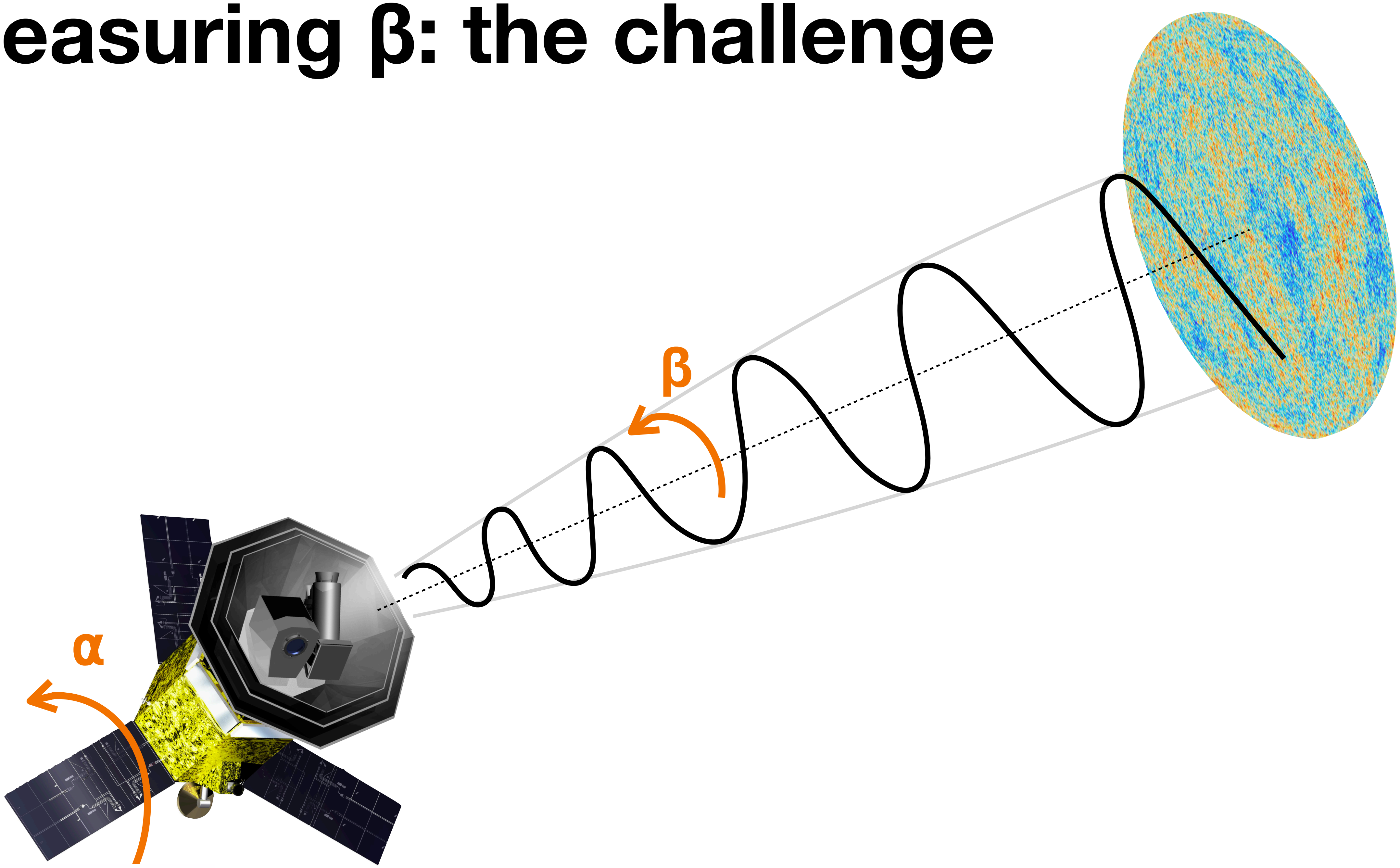


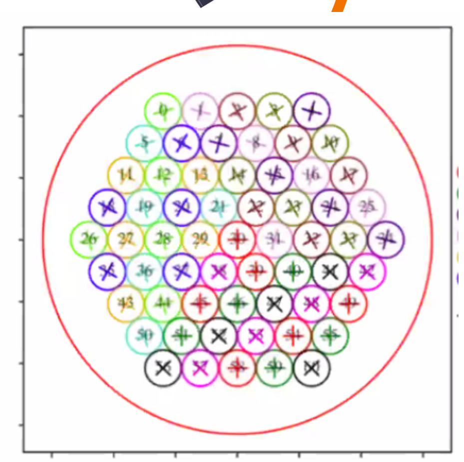
CMB polarisation is naturally sensitive to this effect



$$\begin{pmatrix} E^{\rm o}_{\ell m} \\ B^{\rm o}_{\ell m} \end{pmatrix} = \begin{pmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{pmatrix} \begin{pmatrix} E^{\rm cmb}_{\ell m} \\ B^{\rm cmb}_{\ell m} \end{pmatrix}$$

Measuring β: the challenge





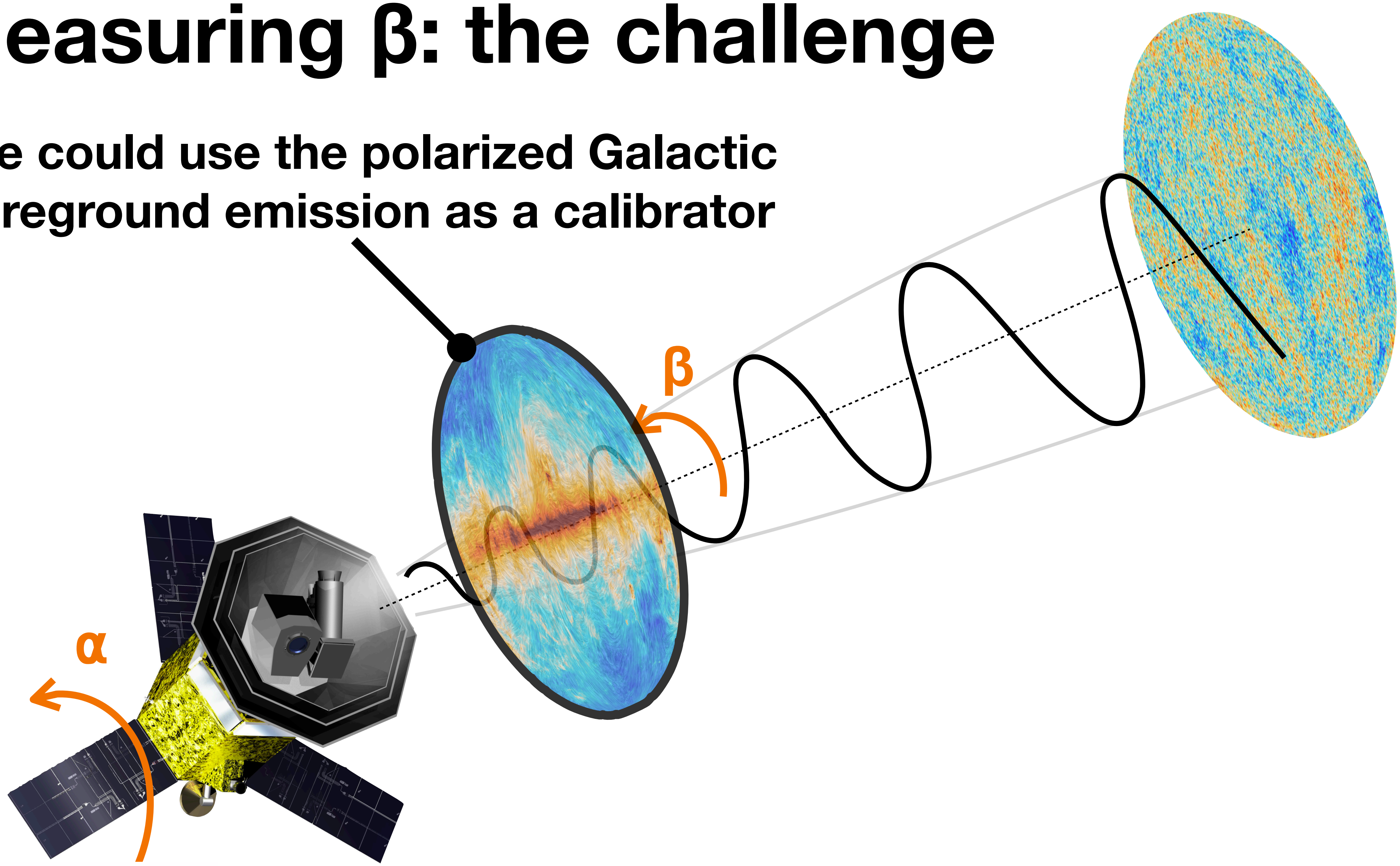
impossibility to distinguish between a genuine cosmic birefringence effect and a rotation of the detectors orientation with respect to the sky coordinates

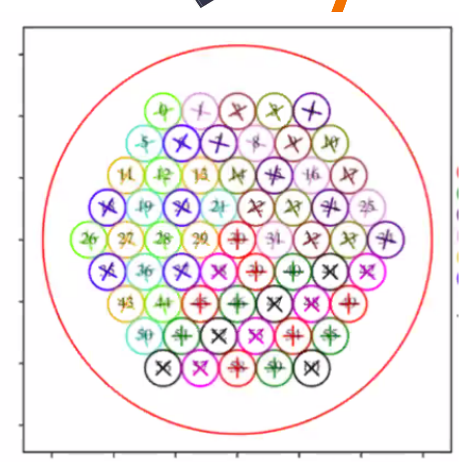
➤ we could a priori only measure/constrain the **sum α+β**

see Sophie’s talk from this morning

Measuring β: the challenge

We could use the polarized Galactic foreground emission as a calibrator





impossibility to distinguish between a genuine cosmic birefringence effect and a rotation of the detectors orientation with respect to the sky coordinates

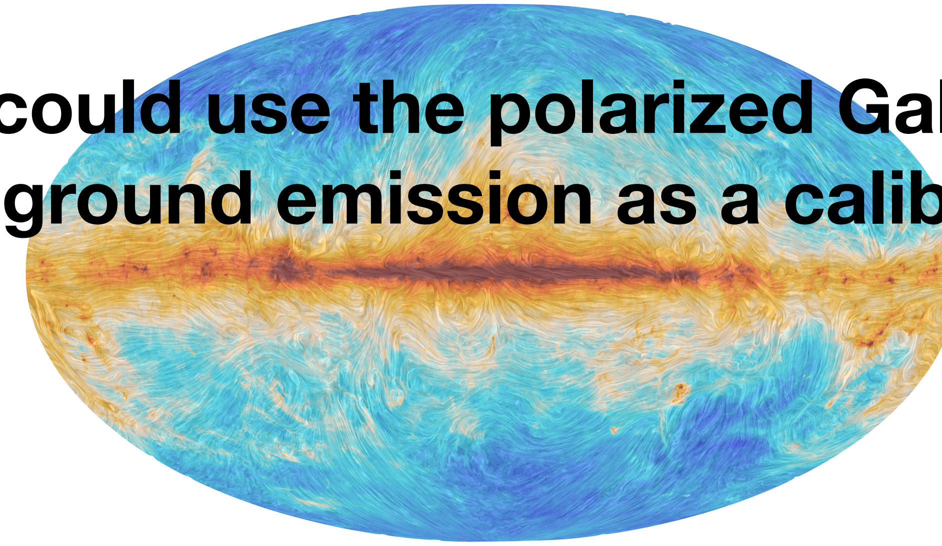
➤ we could a priori only measure/constrain the **sum α+β**

see Sophie's talk from this morning

Introduction

Minami et al 2019, PTEP, 083E02
Minami 2020, PTEP, 063E01
Minami, Komatsu 2020, PTEP, 103E02

We could use the polarized Galactic foreground emission as a calibrator



Observed signal is a rotation of the intrinsic CMB and Galactic foreground emissions

$$\begin{pmatrix} E^{\rm o}_{\ell m} \\ B^{\rm o}_{\ell m} \end{pmatrix} = \begin{pmatrix} \cos(2\alpha) & -\sin(2\alpha) \\ \sin(2\alpha) & \cos(2\alpha) \end{pmatrix} \begin{pmatrix} E^{\rm fg}_{\ell m} \\ B^{\rm fg}_{\ell m} \end{pmatrix} + \begin{pmatrix} \cos(2\alpha+2\beta) & -\sin(2\alpha+2\beta) \\ \sin(2\alpha+2\beta) & \cos(2\alpha+2\beta) \end{pmatrix} \begin{pmatrix} E^{\rm cmb}_{\ell m} \\ B^{\rm cmb}_{\ell m} \end{pmatrix}$$

so the observed EB is

Experimental constraints ***Planck*** **Collaboration XI. 2020, A&A, 641, A11**

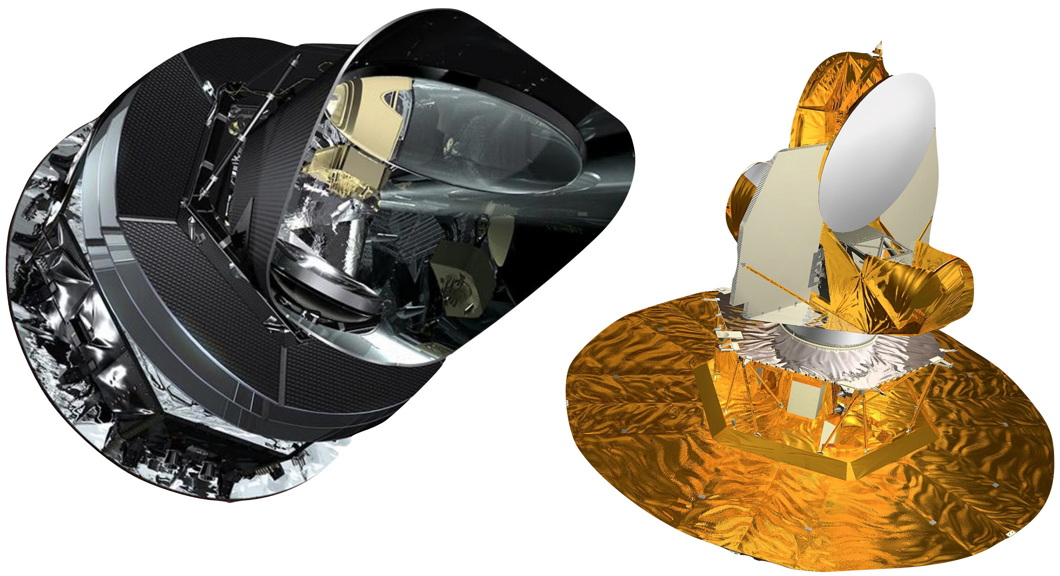
$$C_\ell^{EB,{\rm o}} = \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,{\rm o}} - C_\ell^{BB,{\rm o}}\right) + \frac{1}{\cos(4\alpha)} C_\ell^{EB,{\rm fg}} + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,{\rm cmb}} - C_\ell^{BB,{\rm cmb}}\right)$$

≈ 0?

Build a Gaussian likelihood to simultaneously determine both angles

$$-2\ln\mathcal{L} = \sum_{b=1}^{N_{\rm bins}} \left(\mathbf{A}\bar{C}^{\rm o}_b - \mathbf{B}\bar{C}^{\rm cmb}_b\right)^T \mathbf{M}_b^{-1} \left(\mathbf{A}\bar{C}^{\rm o}_b - \mathbf{B}\bar{C}^{\rm cmb}_b\right) + \sum_{b=1}^{N_{\rm bins}} \ln|\mathbf{M}_b|$$

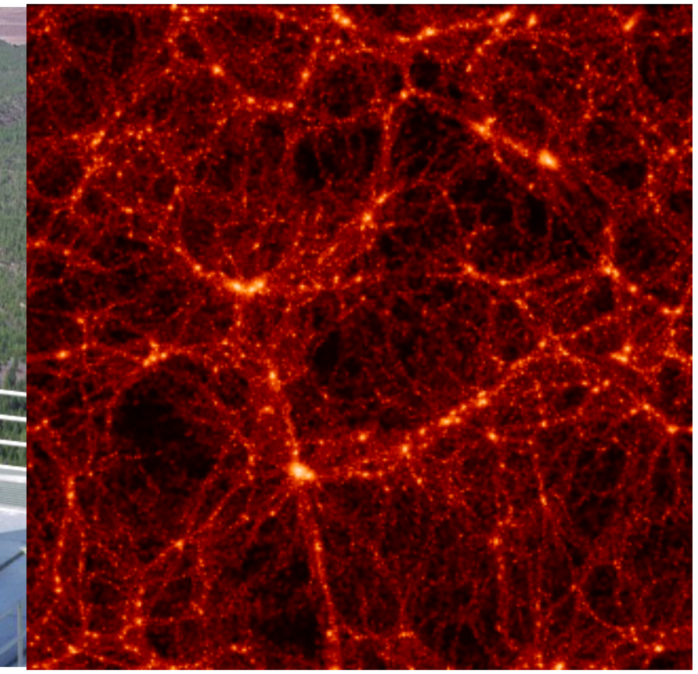
Current constraints



Minami & Komatsu, 2020, PRL, **β= 0.35 ± 0.14 deg (2.4σ)** for nearly full-sky
Diego-Palazuelos et al, 2022, PRL, **β = 0.30 ± 0.11 deg (2.7σ)** for nearly full-sky data
Eskilt & Komatsu, 2022, PRL, **β=0.33 ± 0.10 deg (3.3σ)** for nearly full-sky data

- The impact of the known instrumental systematics seems to be negligible;
- Systematic uncertainty due to the modeling of foreground EB?
- No evidence for frequency dependence of β
    - if confirmed as cosmological, it would have **profound implications for fundamental physics behind dark matter and energy!**

Current constraints from galaxy surveys



Measurement of Parity-Odd Modes in the Large-Scale 4-Point Correlation Function of SDSS BOSS DR12 CMASS and LOWZ Galaxies

Jiamin Hou,[1,2⋆] Zachary Slepian,[1,3†] & Robert N. Cahn[3]
[1] *Department of Astronomy, University of Florida, Gainesville, FL 32611, USA*
[2] *Max-Planck-Institut für Extraterrestische Physik, Postfach 1312, Giessenbachstr., 85748 Garching, Germany*
[3] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

7.1σ evidence for parity violation

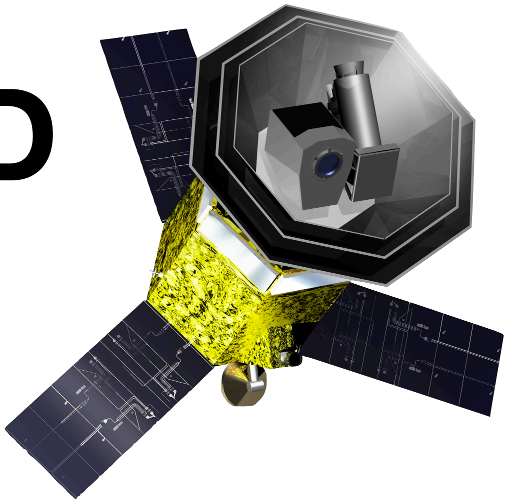
Probing Parity-Violation with the Four-Point Correlation Function of BOSS Galaxies

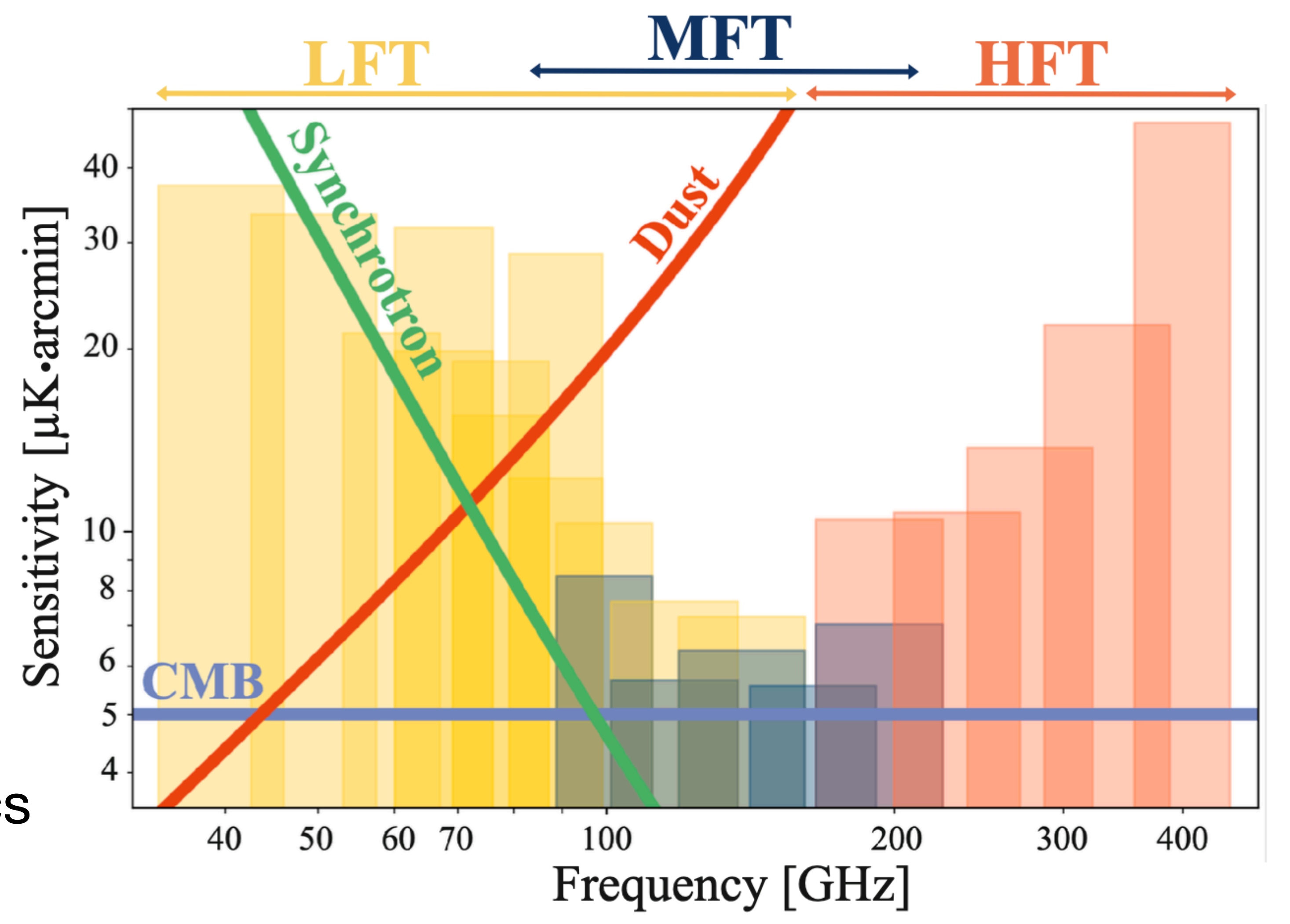
Oliver H.E. Philcox[1,2,*]
[1] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08540, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, 1 Einstein Drive, Princeton, NJ 08540, USA*

2.9σ evidence for parity violation

➔ 1.9σ after updating the covariance matrix

LiteBIRD





Precision measurement of EB

Unprecedented sensitivity
High control of instrumental systematics

Wide frequency range

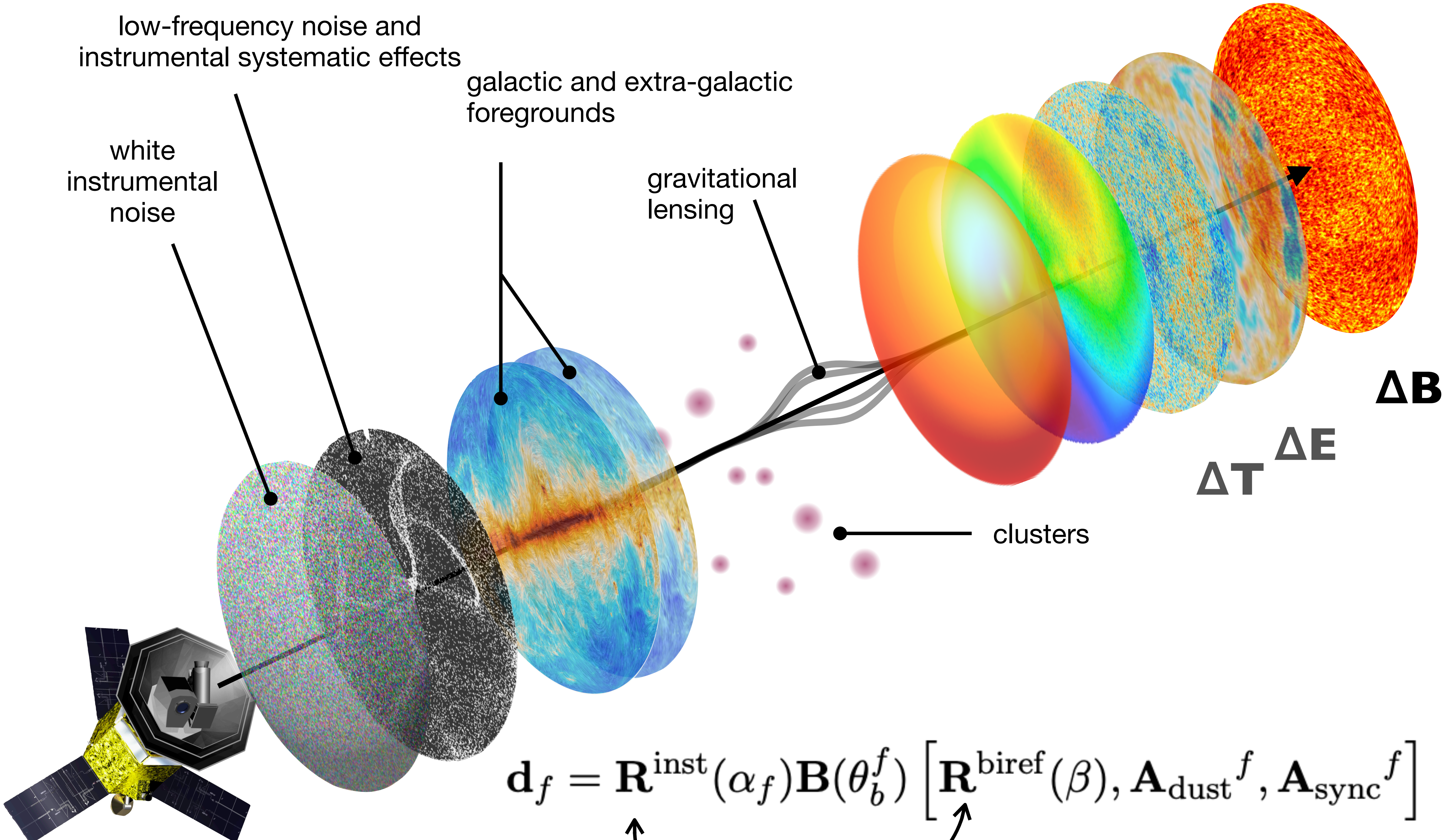
- high-level characterization of astrophysical contaminants
- efficient component separation

Full-sky coverage

- EB around the reionization peak probes the axions mass and can distinguish between different axion models and early dark energy models

High signal-to-noise detections of β are possible with > 20 arcmin resolutions

LiteBIRD: forecast



$$\mathbf{d}_f = \mathbf{R}^{\text{inst}}(\alpha_f)\mathbf{B}(\theta_b^f)\left[\mathbf{R}^{\text{biref}}(\beta), \mathbf{A}_{\text{dust}}{}^f, \mathbf{A}_{\text{sync}}{}^f\right]\begin{bmatrix}\mathbf{s}_{\text{CMB}}\\ \mathbf{s}_{\text{dust}}\\ \mathbf{s}_{\text{sync}}\end{bmatrix} + \mathbf{n}_f$$

$$\mathbf{R}^{\mathbf{x}}(\gamma) \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(2\gamma) & \sin(2\gamma) \\ 0 & -\sin(2\gamma) & \cos(2\gamma) \end{pmatrix}$$

LiteBIRD: forecast

A forecast with different degrees of complexity (4 x 100 simulations)

Phase1: CMB (β=0) + noise + simple foregrounds (s0d0)

Phase2: CMB (β=0) + noise + complex foregrounds (s1d1)

Phase3: CMB (β=0) + noise + complex foregrounds (s1d1) + systematics (α≠0)

Phase4: CMB (β≠0) + noise + complex foregrounds (s1d1) + systematics (α≠0)

sky signal frequency scaling:

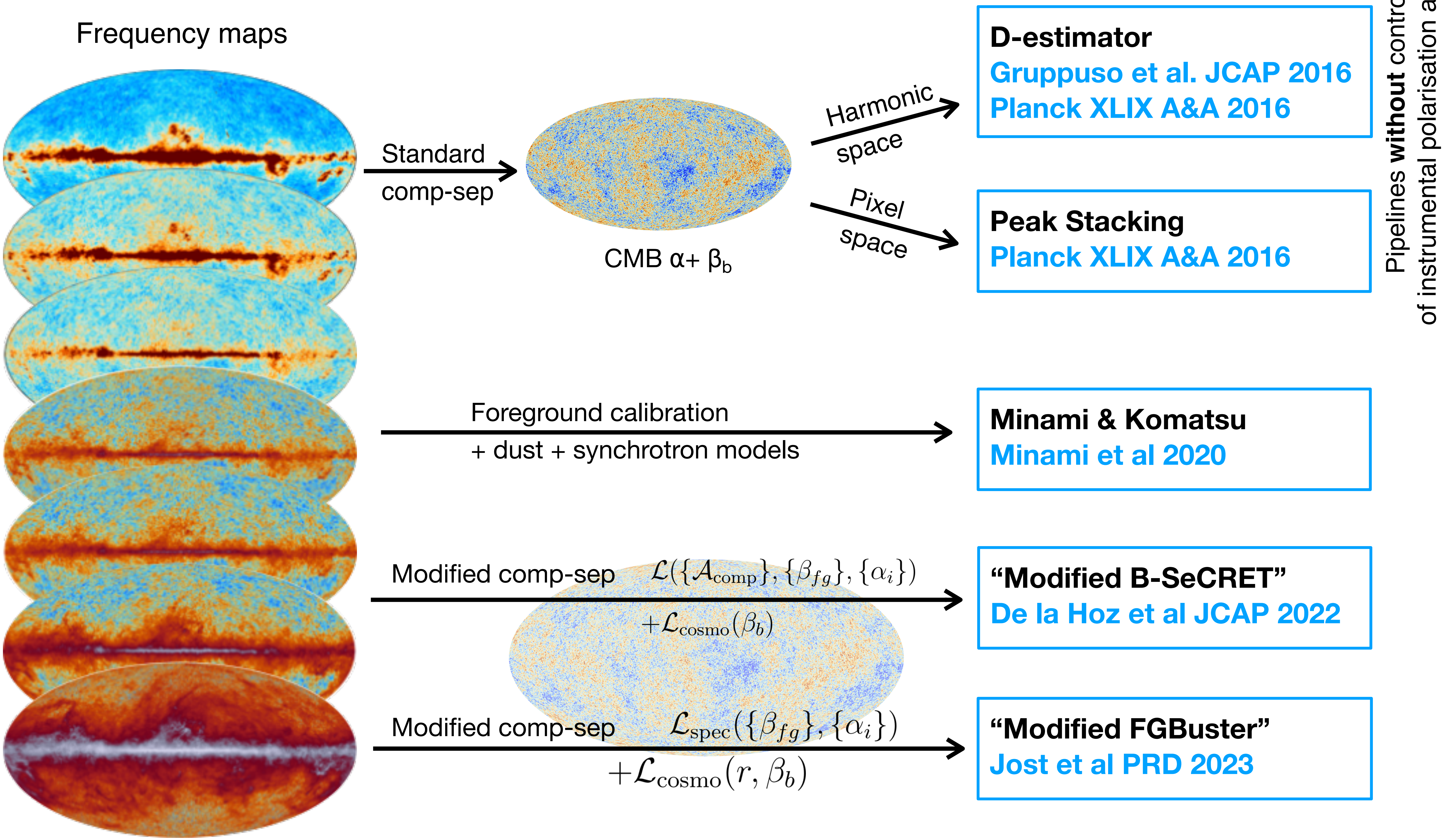
$$\mathbf{A}_{\rm cmb}(\nu, \nu_0) = 1$$

$$\mathbf{A}_{\rm dust}(\nu, \nu_0, \beta_d, T_d) \propto \left(\frac{\nu}{\nu_0}\right)^{\beta_d} B_\nu\left(T_d\right)$$

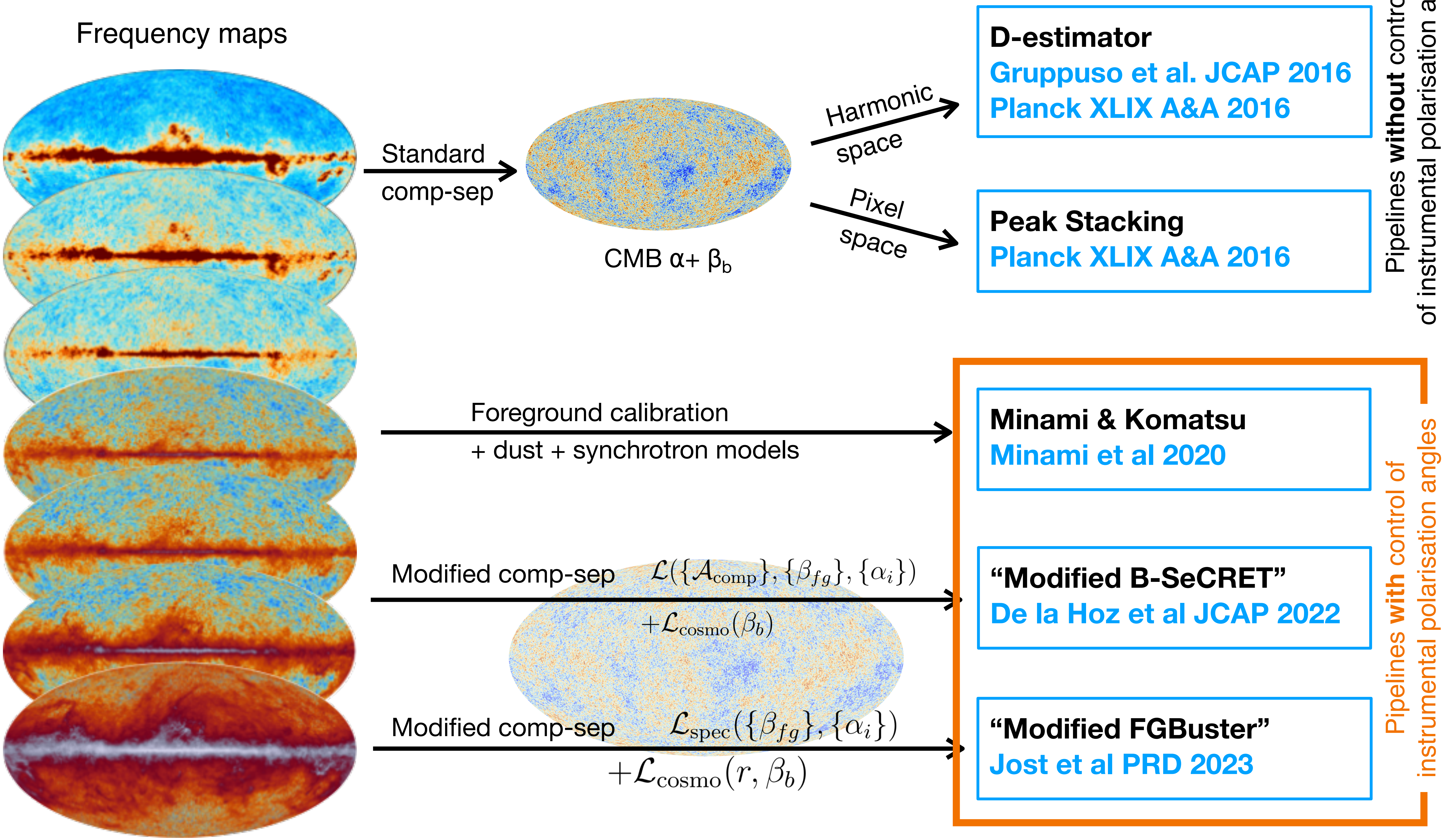
$$\mathbf{A}_{\rm sync}(\nu, \nu_0, \beta_s) \propto \left(\frac{\nu}{\nu_0}\right)^{\beta_s+2}$$

Phase	α [deg]	β [deg]	β_d, T_d, β_s
1	0	0.0	constant
2	0	0.0	varying
3	random	0.0	varying
4	random	0.3	varying

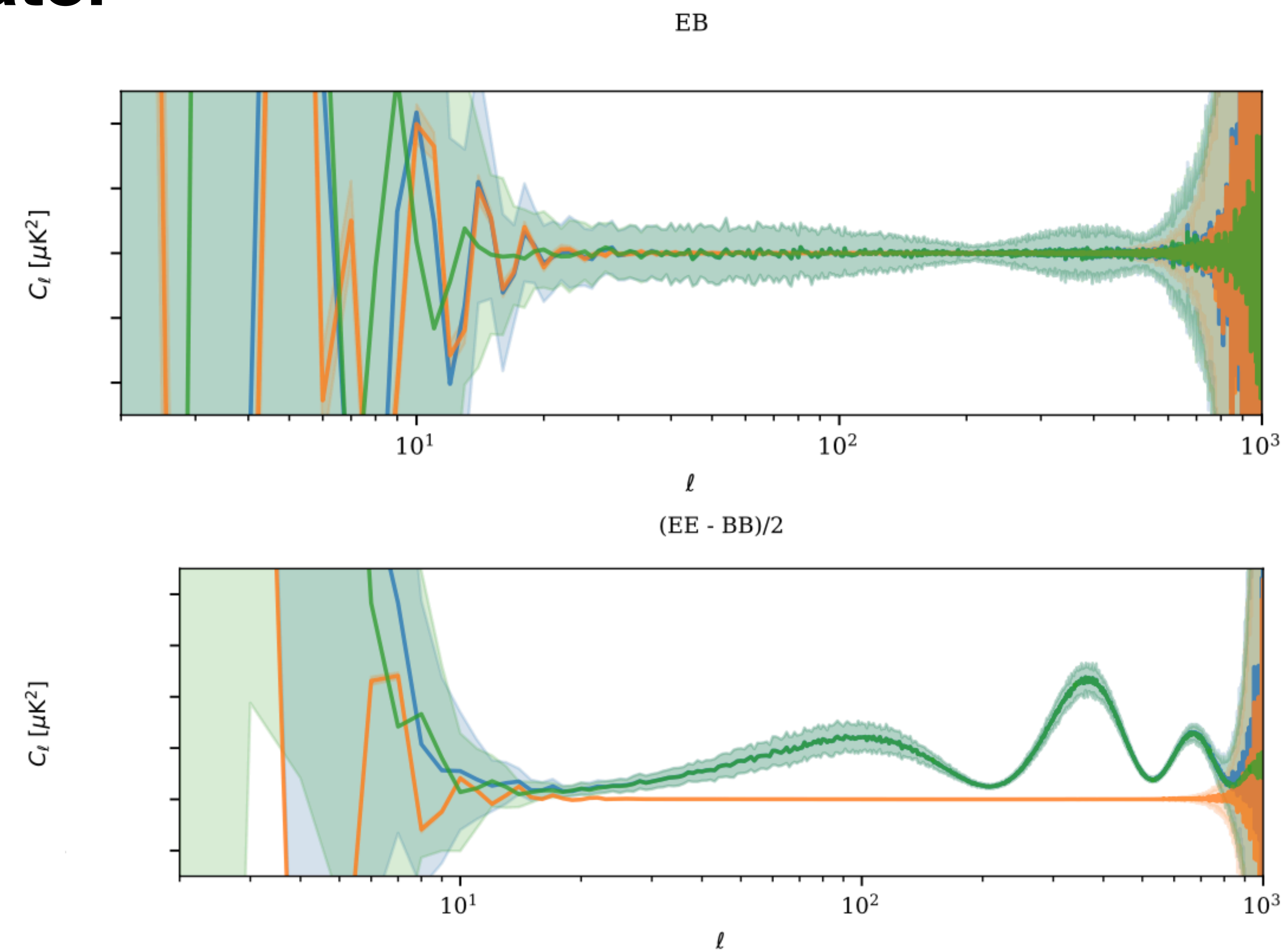
Multiple Pipelines



Multiple Pipelines



D-estimator



$$D_\ell(\hat{\beta}) = C_\ell^{EB,\mathrm{o}} - \frac{1}{2}\tan(4\hat{\beta})\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)$$

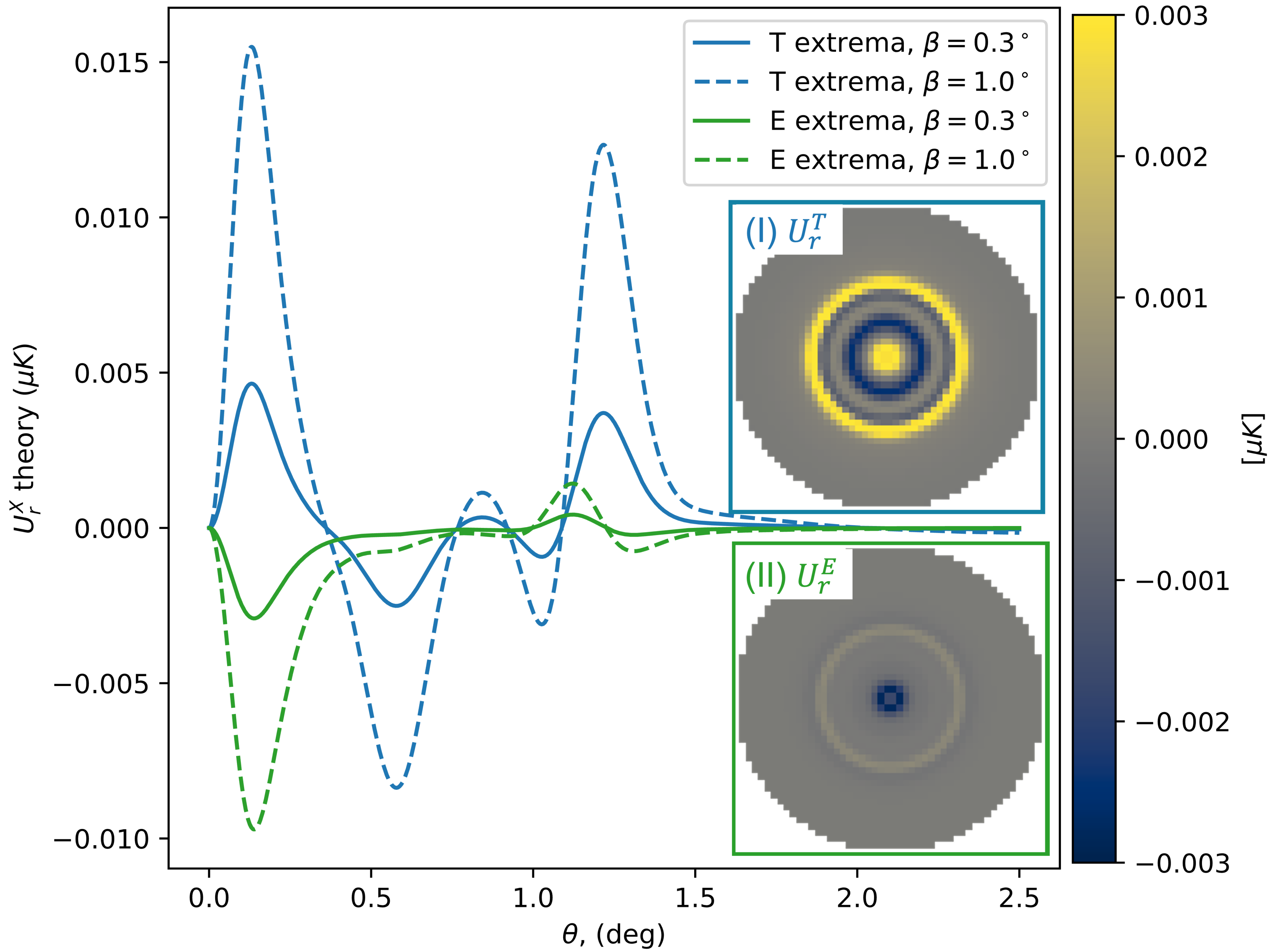
$$\langle D_\ell(\hat{\beta} = \beta)\rangle = 0$$

$$\chi^2(\hat{\beta}) = \sum_{\ell\ell'} D_\ell(\hat{\beta}) M_{\ell\ell'}^{-1} D_{\ell'}(\hat{\beta})$$

Build the covariance matrix from simulations to account for foreground debiasing and the extra dispersion caused by α miscalibrations

$$M_{\ell\ell'} = \langle D_\ell D_{\ell'}\rangle$$

Stacking of peaks



Find local extrema in T and E anisotropies

Transform the Stokes parameters and stack peaks

$$Q_r(\theta) = -Q(\theta)\cos(2\phi) - U(\theta)\sin(2\phi)$$
$$U_r(\theta) = \quad Q(\theta)\sin(2\phi) - U(\theta)\cos(2\phi)$$

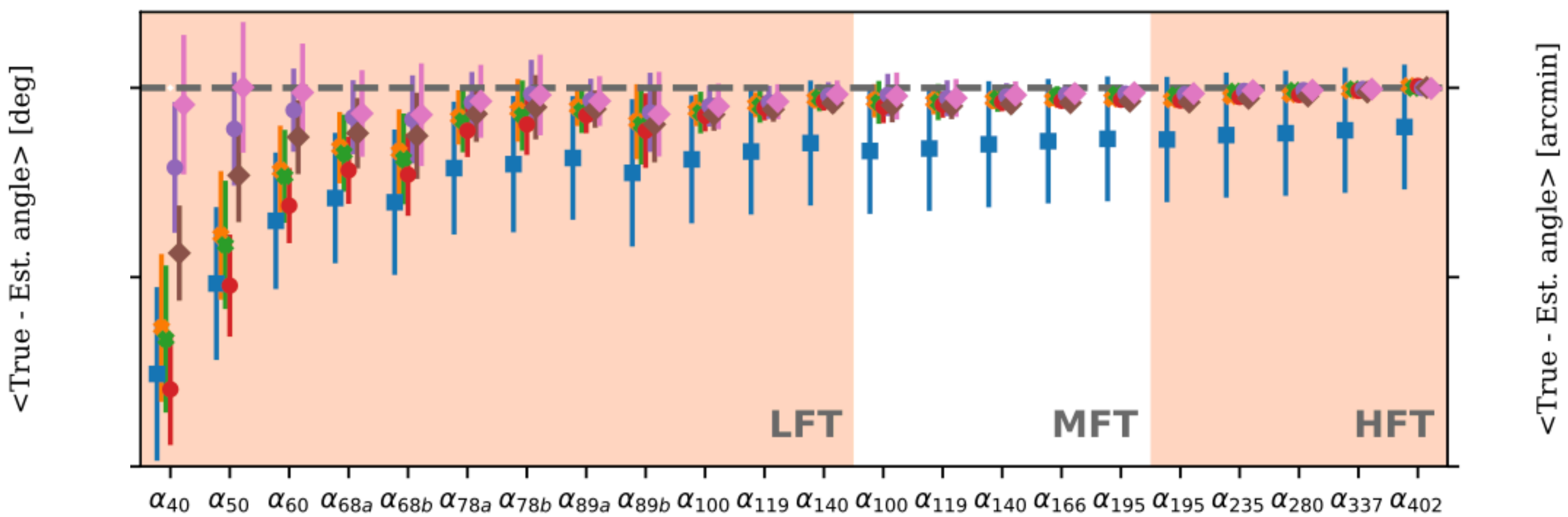
Radial profile around peaks is sensitive to β

$$\langle U_r^T\rangle(\theta) = -\sin(2\beta)\int \frac{\ell d\ell}{2\pi} W_\ell^T W_\ell^P J_2(\ell\theta) \times (\bar{b_\nu} + \bar{b_\zeta}\ell^2) C_\ell^{TE}$$

$$\langle U_r^E\rangle(\theta) = -\frac{1}{2}\sin(4\beta)\int \frac{\ell d\ell}{2\pi} W_\ell^E W_\ell^P J_2(\ell\theta) \times (\bar{b_\nu} + \bar{b_\zeta}\ell^2)(C_\ell^{EE} - C_\ell^{BB})$$

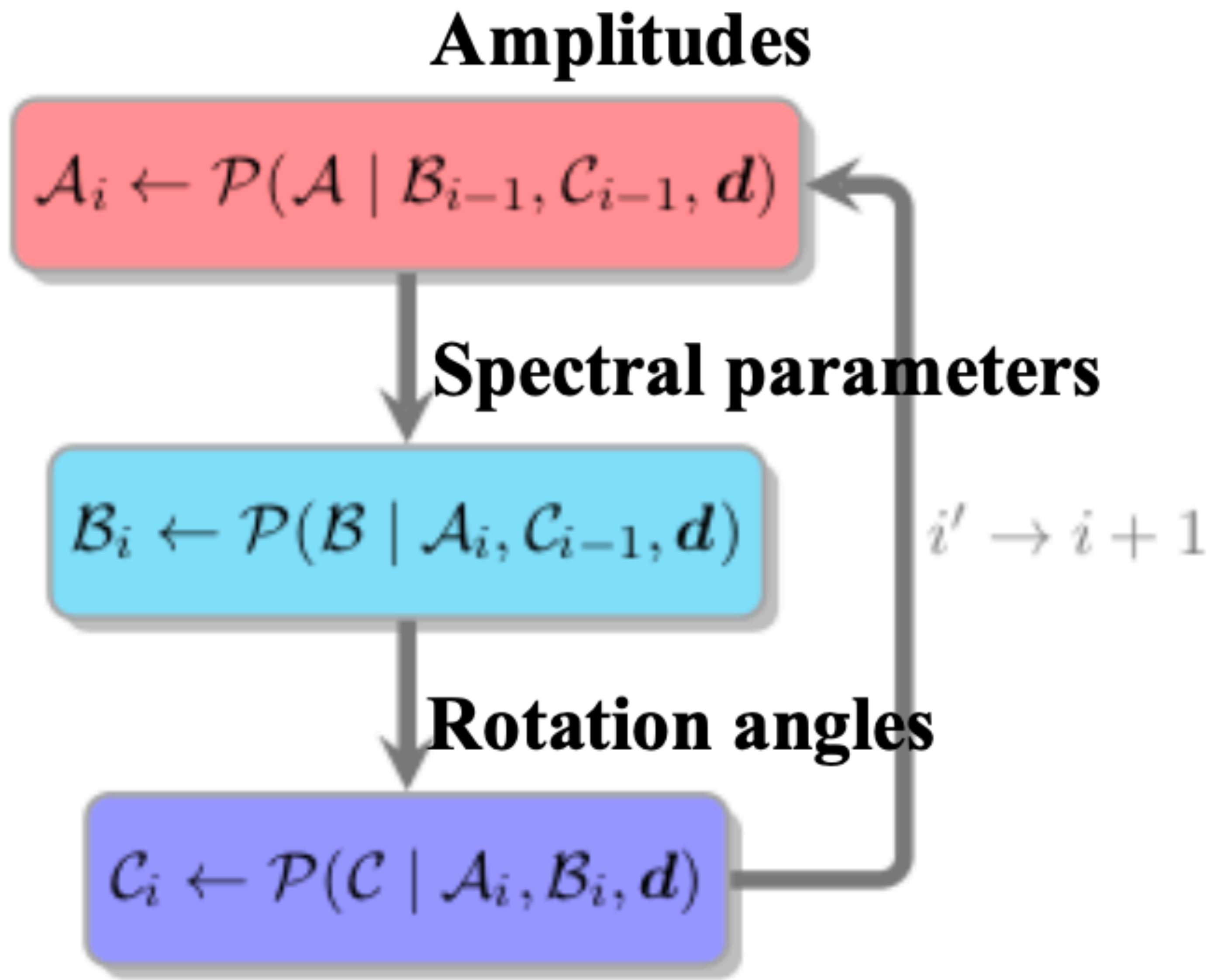
Minami-Komatsu technique

$$C_\ell^{EB,\mathrm{o}} = \frac{1}{2}\tan(4\alpha)\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\mathrm{cmb}} - C_\ell^{BB,\mathrm{cmb}}\right)$$
$$+ \frac{1}{\cos(4\alpha)}\left(C_\ell^{EB,\mathrm{s}} + C_\ell^{EB,\mathrm{d}} + C_\ell^{E_\mathrm{s}B_\mathrm{d}} + C_\ell^{E_\mathrm{d}B_\mathrm{s}}\right)$$



"Modified B-SeCRET"

Component separation + α + β



Gaussian priors on spectral parameters

MK result as prior on rotation angles

"Modified FGBuster"

Component separation + α + β + r

Instrument miscalibration **Spectral parameters** **Birefringence**

$$\boldsymbol{d} = \underbrace{\boldsymbol{X}\,\boldsymbol{A}}_{\boldsymbol{\Lambda}}\underbrace{\boldsymbol{\mathcal{B}}\,\boldsymbol{c}}_{\boldsymbol{s}} + \boldsymbol{n}$$

Generalized spectral likelihood

$$\langle S \rangle = -2 \sum \mathrm{tr}\left(\boldsymbol{N}_p^{-1}\boldsymbol{\Lambda}_p(\boldsymbol{\Lambda}_p^t\boldsymbol{N}_p^{-1}\boldsymbol{\Lambda}_p)^{-1}\boldsymbol{\Lambda}_p^t\boldsymbol{N}_p^{-1}\langle \boldsymbol{d}_p\boldsymbol{d}_p^t\rangle\right) + \sum_{\alpha_i}\frac{(\alpha_i - \hat{\alpha}_i)^2}{2\sigma_{\alpha_i}^2}$$

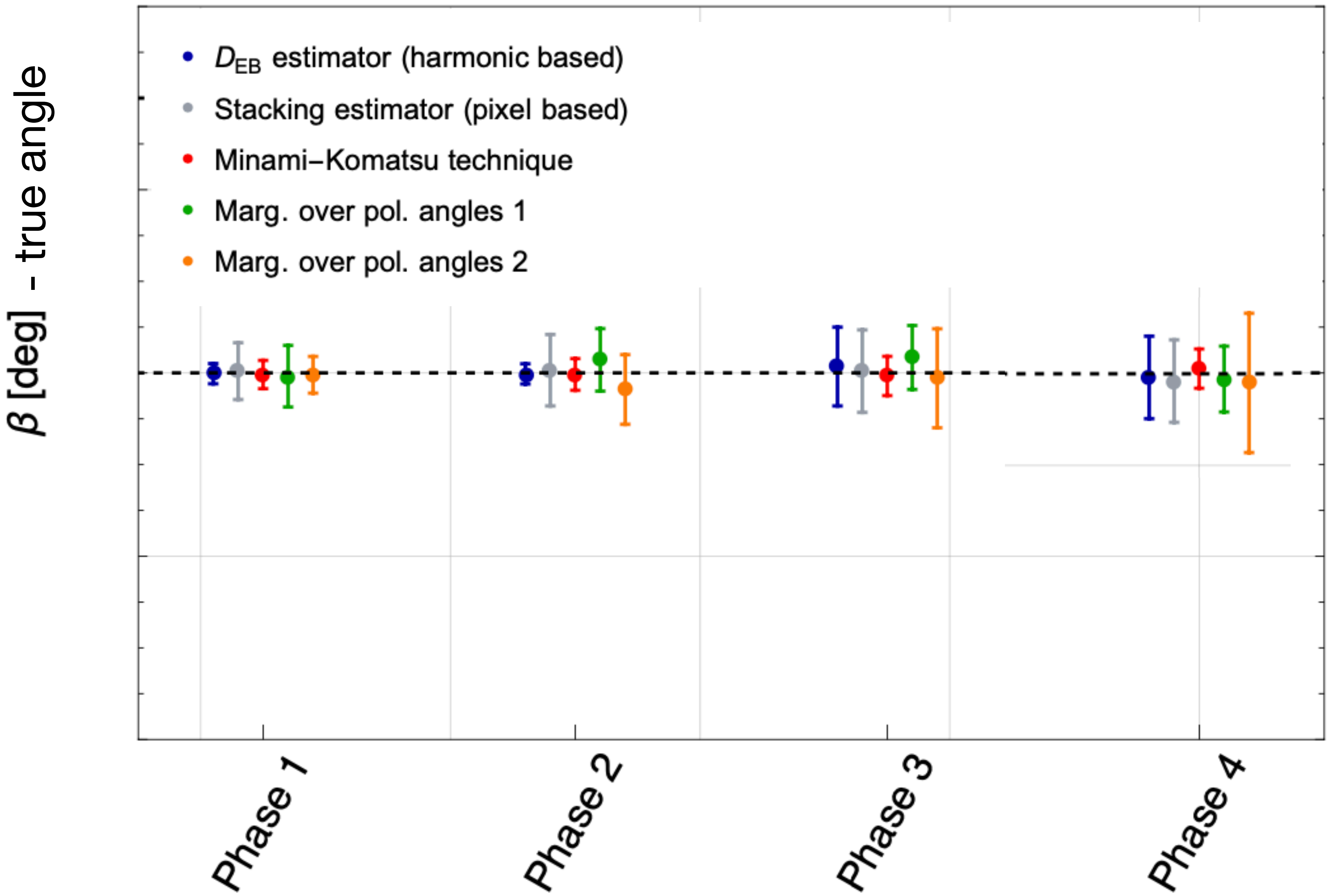
Cosmological likelihood **Output of spectral likelihood**

$$\langle S^{cos}\rangle = f_{sky}\sum_{\ell=\ell_{min}}^{\ell_{max}}\frac{(2\ell+1)}{2}\left(Tr(\boldsymbol{C}_\ell^{-1}\boldsymbol{E}_\ell) + \ln(\det(\boldsymbol{C}_\ell))\right)$$

$$\boldsymbol{\mathcal{C}}_\ell(r,\beta_b) \equiv \boldsymbol{\mathcal{R}}(\beta_b)\begin{pmatrix} C_\ell^{EE,\mathrm{p}} & 0 \\ 0 & rC_\ell^{BB,\mathrm{p}} + A_L C_\ell^{BB,\mathrm{lens}}\end{pmatrix}\boldsymbol{\mathcal{R}}^{-1}(\beta_b) + C_\ell^{\mathrm{noise}}$$

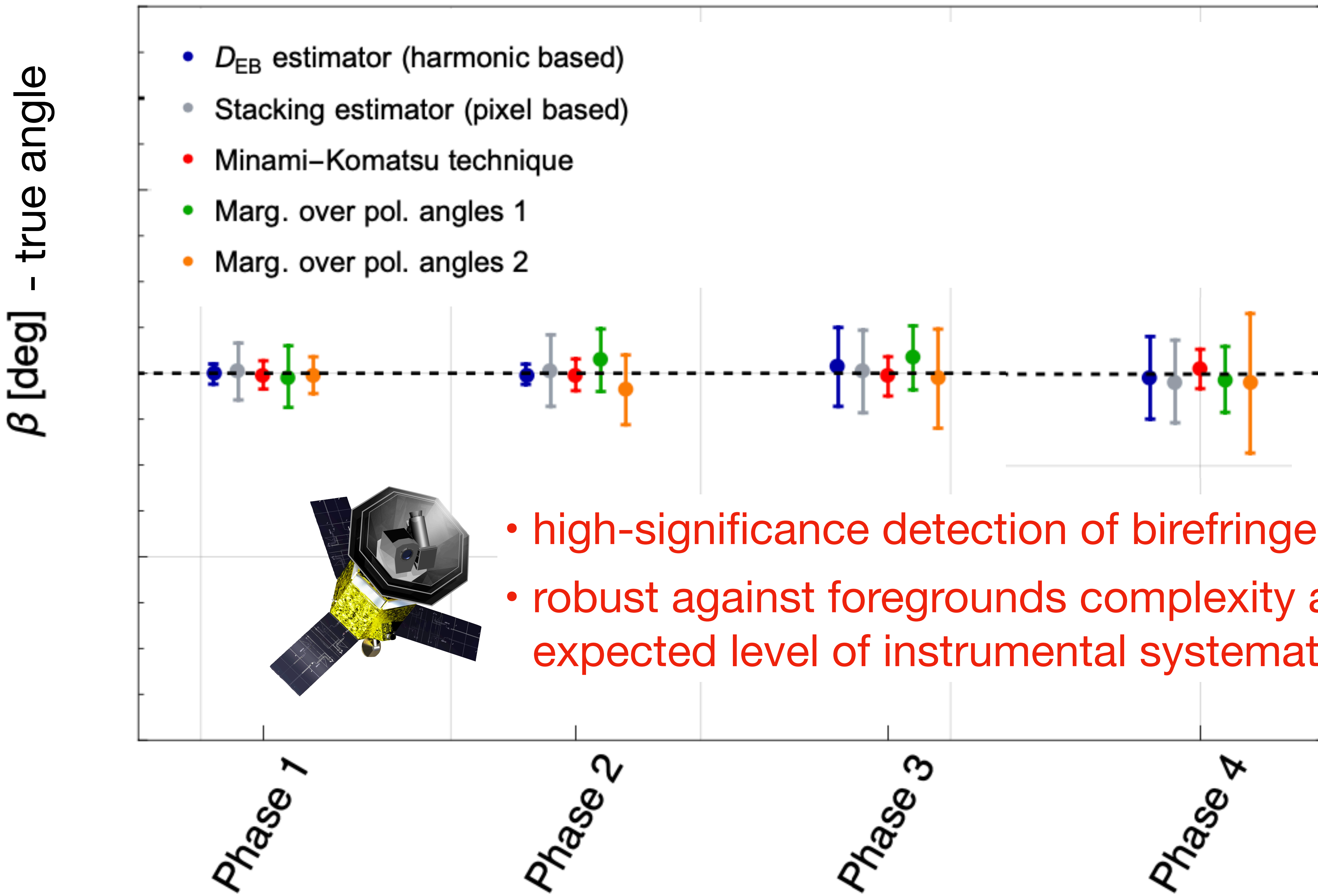
External calibration priors from an artificial or astrophysical calibration source on some frequency channels

comparison among the pipelines



complexity of the simulations ⟶

comparison among the pipelines



- high-significance detection of birefringence
- robust against foregrounds complexity and expected level of instrumental systematics

complexity of the simulations ⟶

Conclusions

- LiteBIRD provides the perfect venue to confirm the current hints of $\beta \approx 0.3$ found in Planck and WMAP data.

- we are developing different complementary analysis pipelines that will allow for a β measurement that is robust against both instrumental systematics and Galactic foregrounds

- analysis pipelines have successfully overcome the different levels of complexity in the simulations
  $\longrightarrow$ we should continue exploring more complex foregrounds and additional sources of systematics

- keep an eye on the arXiv for the full forecast soon!