A Unified Framework for Mitigating Foregrounds and Systematic Effects for Tensor-to-Scalar Ratio and Birefringence Angle Measurements

CMB France #5, December 4th 2023

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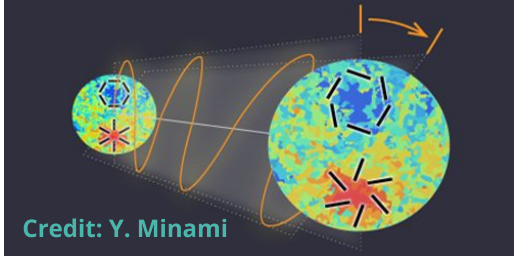
Cosmic Birefringence

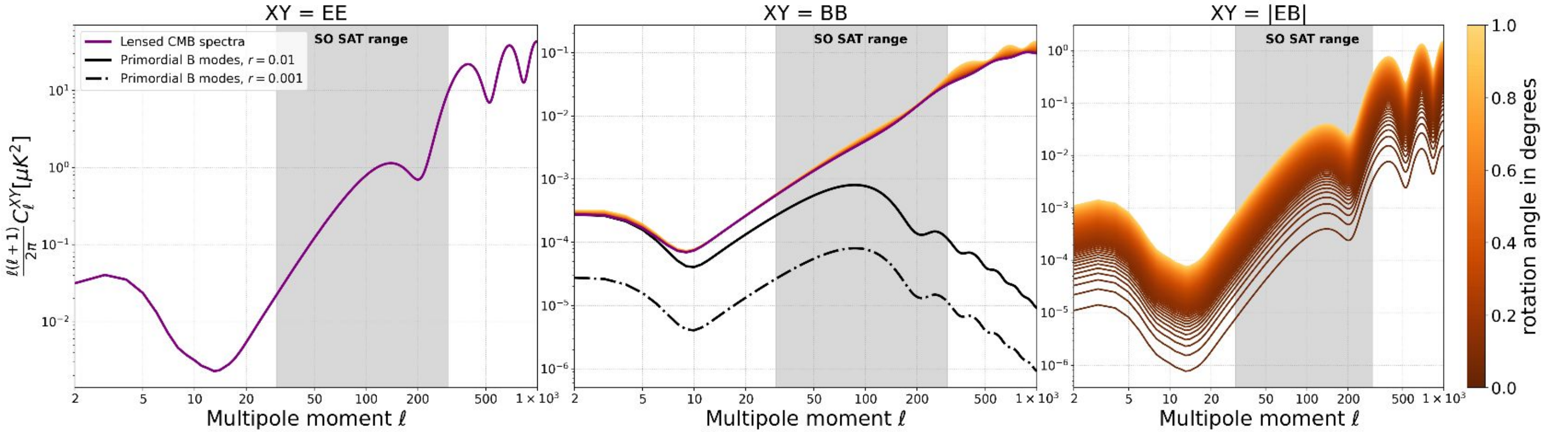


Cosmic Birefringence: rotation of linear polarisation plane of CMB photons

Correlation between E- and B-modes → parity violation mechanism (Chern-Simons coupling from axion-like particles)

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

Hints of β_b = 0.34° +/- 0.09° (3.6σ) Planck+WMAP data (**Eskilt & Komatsu 2022**) based on the Minami & Komatsu method using assumptions about foreground EB correlations for calibration.



The Tensor to Scalar Ratio

Primordial B-modes generated by **tensor perturbations** from **inflation.**

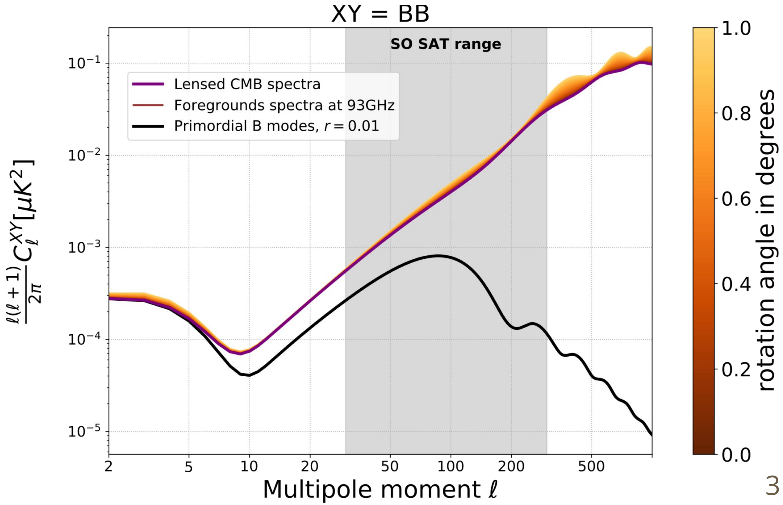
Smoking gun of inflation.

Primordial B-modes amplitude parametrised by: **r**

r constraints r < 0.032 (95% C.L.) (**Tristram et al. 2021**)

B-modes are also affected by polarization angle rotation:

$$C_\ell^{BB,o} = \sin^2(2\beta) C_\ell^{EE} + \cos^2(2\beta) C_\ell^{BB}$$

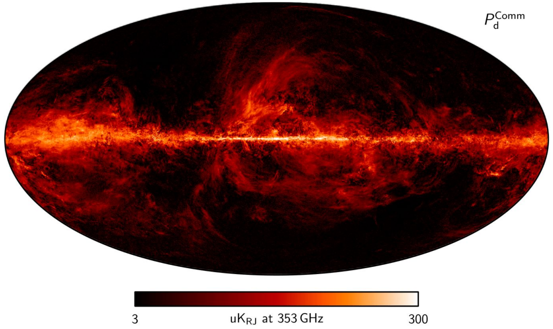


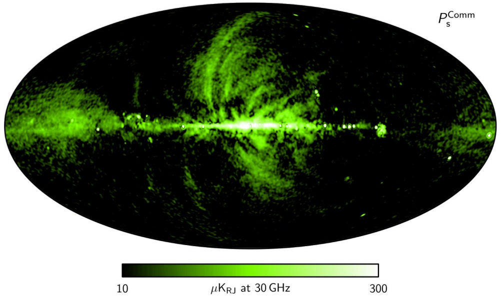
Observation challenges: Galactic Foregrounds

Dust emission: Asymmetric dust grains in the galaxy aligned with magnetic fields.

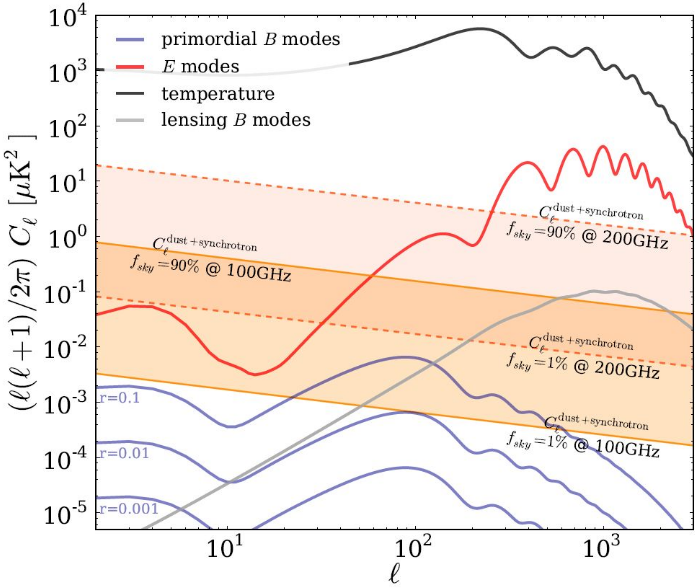
Synchrotron emissions: charged particles accelerated along Galactic magnetic fields.

No EB correlation measured yet. But physical motivation for it (**Clark et al. 2021**).





Credit: Planck Collaboration



Credit: Errard et al. 2016

Observation challenges: Polarisation Angle Miscalibration

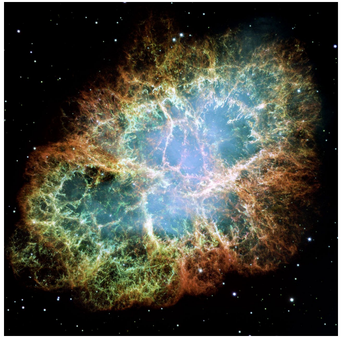
Miscalibration of telescope polarisation angle ⇒ similar to isotropic birefringence!

Need a way to lift the degeneracy between birefringence angle and polarization angles

Creates **E → B leakage** that **pollute primordial B-modes → r**

Q↔U mixing at different frequencies will **bias foreground cleaning** → more residuals

Polarisation Angle Calibrations



Credit: Nasa/Hubble

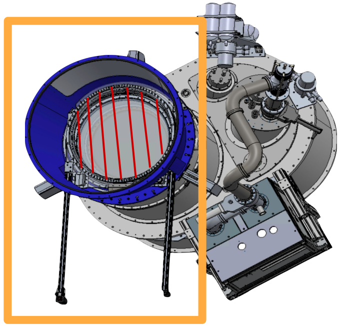
Ground based telescope → many polarization angle calibration methods. From observation and hardware:

- Measurements of the crab nebula (tau A) $\sigma(\alpha) \simeq 0.27°$ **Aumont et al. 2020**
- Wire-grid $\sigma(\alpha) \lesssim 1°$ **Bryan et al. 2018**
- Drone with polarised source $\sigma(\alpha) \lesssim 0.1°$ **Nati et al. 2017**

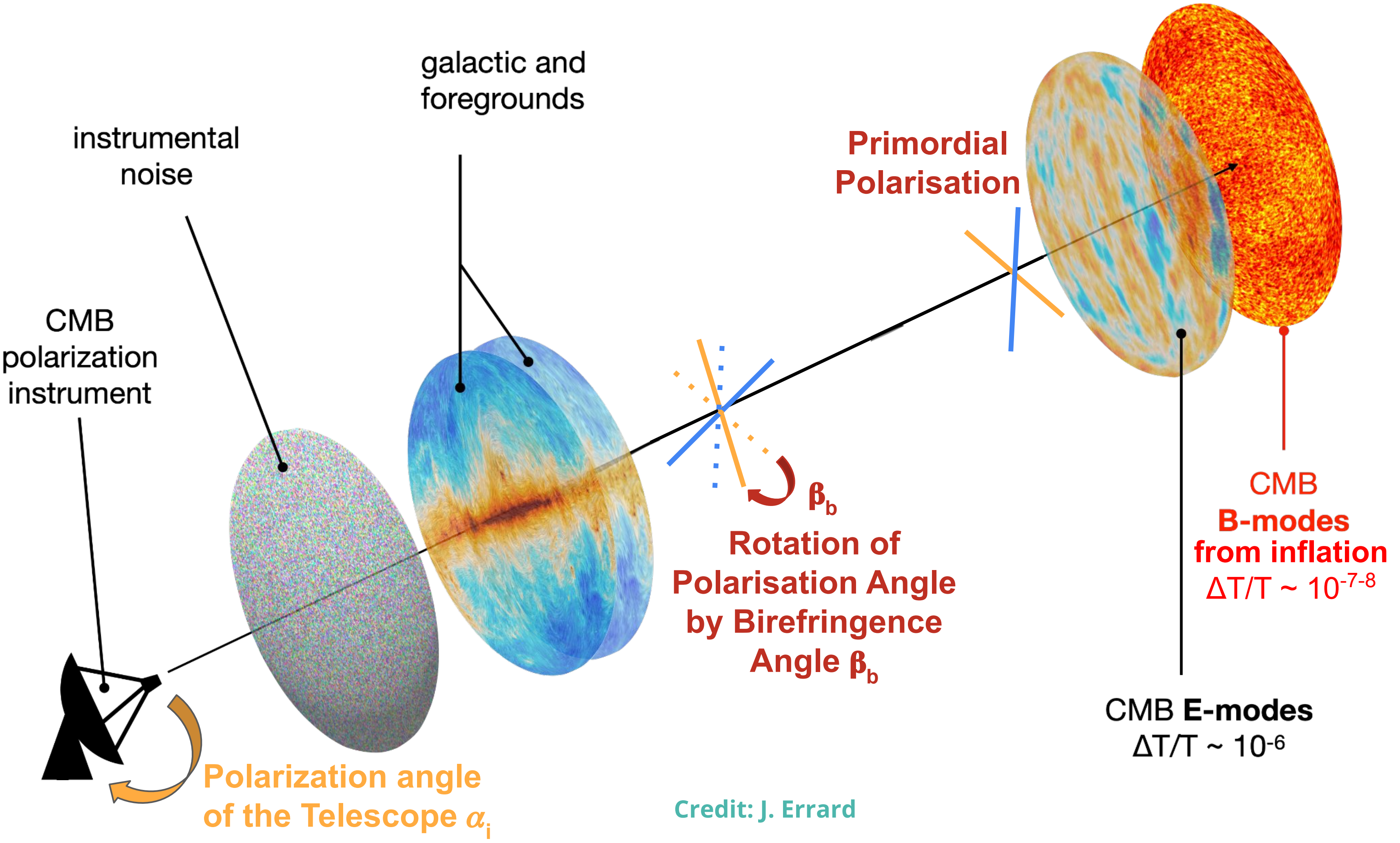
Credit: F. Nati

Analysis based:

- Self-calibration **Keating et al. 2012**
- Foreground calibration **Minami et al . 2020**



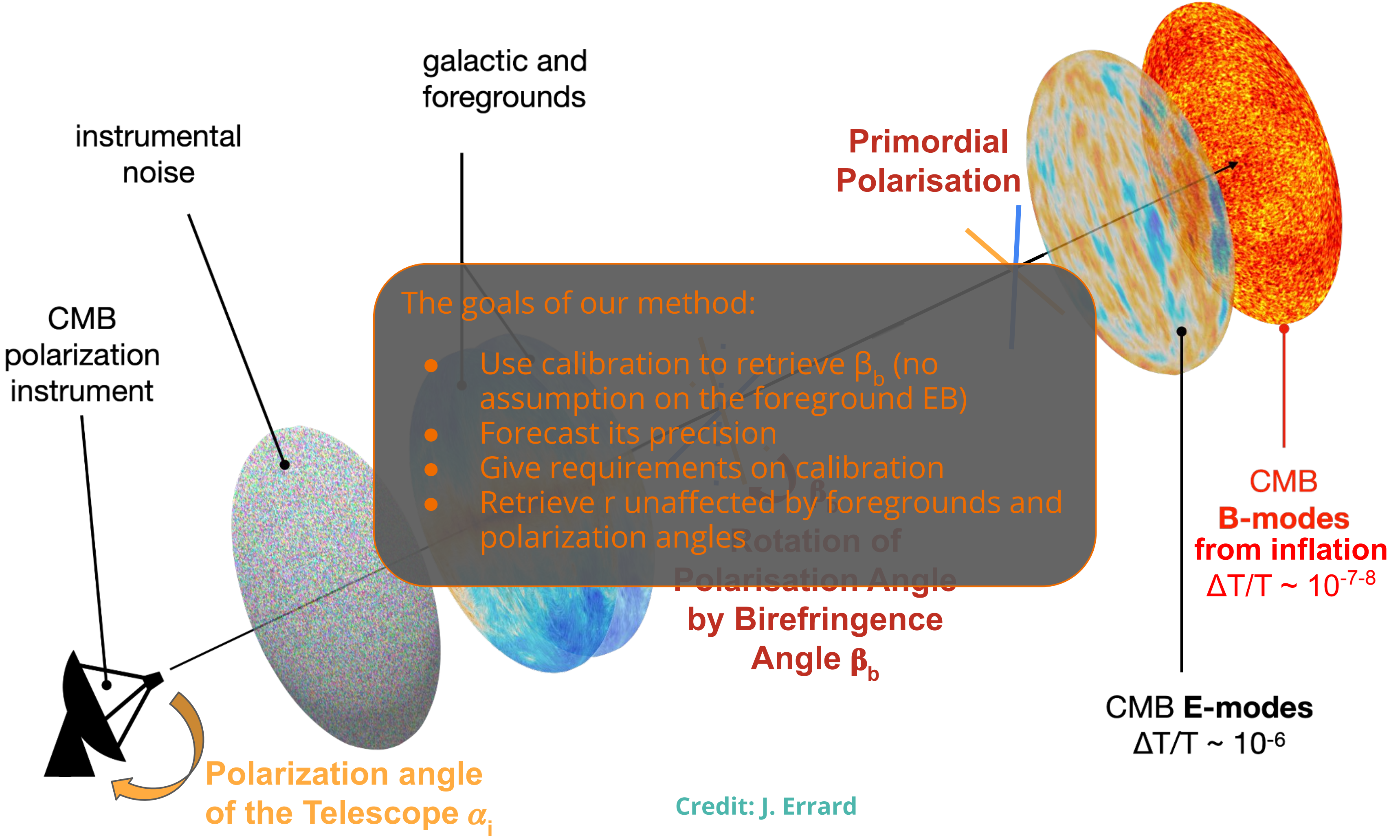
Wire grid



Credit: J. Errard

The goals of our method:

- Use calibration to retrieve β_b (no assumption on the foreground EB)
- Forecast its precision
- Give requirements on calibration
- Retrieve r unaffected by foregrounds and polarization angles



Credit: J. Errard

Map-Based Parametric Component Separation

$$\boldsymbol{\mathcal{B}}(\{\beta_b\}) = \begin{pmatrix} \cos(2\beta_b) & \sin(2\beta_b) & 0 & 0 & 0 & 0 \\ -\sin(2\beta_b) & \cos(2\beta_b) & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The birefringence matrix

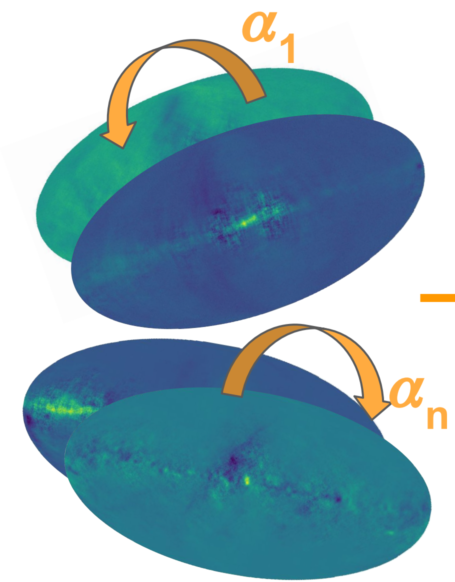
$$\boldsymbol{d} = \boxed{?}\ \boldsymbol{A}\,\boldsymbol{\mathcal{B}}\,\boldsymbol{c} + \boldsymbol{n}$$

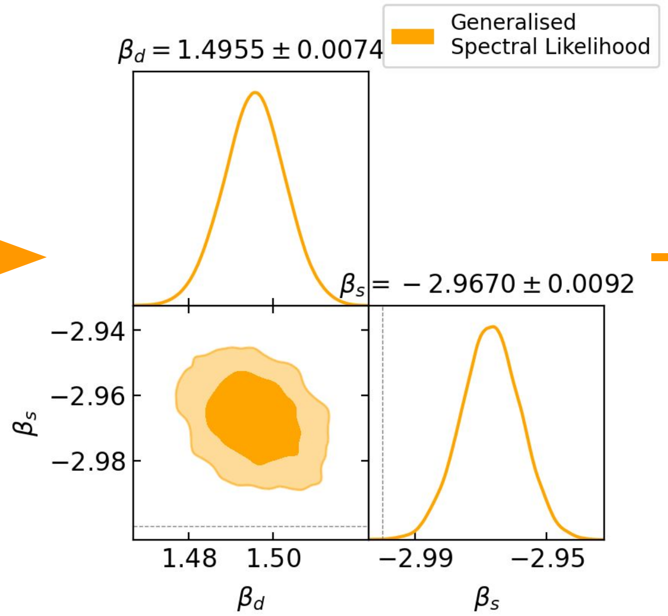
$$\boldsymbol{A}(\{\beta_{fg}\}) = \begin{pmatrix} 1 & 0 & A_1^d & 0 & A_1^s & 0 \\ 0 & 1 & 0 & A_1^d & 0 & A_1^s \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & A_n^d & 0 & A_n^s & 0 \\ 0 & 1 & 0 & A_n^d & 0 & A_n^s \end{pmatrix}$$

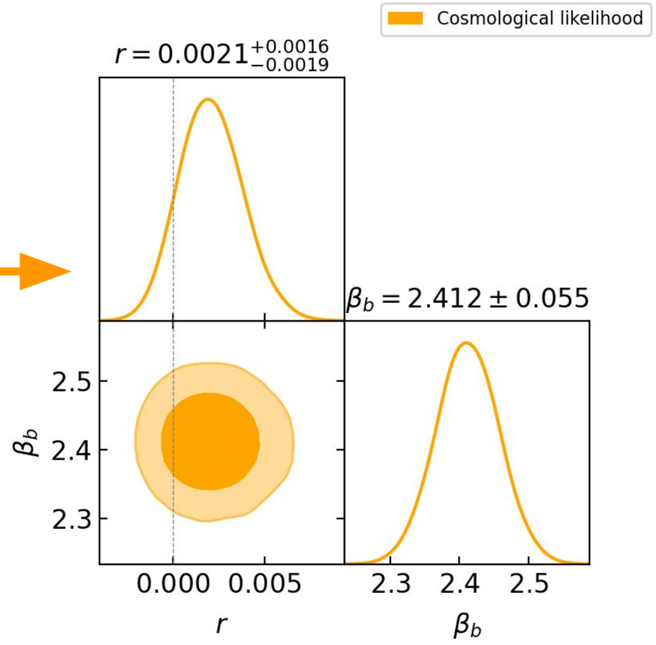
The mixing matrix

CMB	Dust	Synchrotron
	T_d = 20K, β_d	β_s

Map-Based Parametric Component Separation in the Presence of Uncontrolled Systematics







Non-zero relative polarisation angles

Map-Based Parametric Component Separation

$$\boldsymbol{X}(\{\alpha_1, \dots, \alpha_{n_f}\}) = \begin{pmatrix} \cos(2\alpha_1) & \sin(2\alpha_1) & & & 0 \\ -\sin(2\alpha_1) & \cos(2\alpha_1) & & & \\ & & \ddots & & \\ & & & \cos(2\alpha_{n_f}) & \sin(2\alpha_{n_f}) \\ 0 & & & -\sin(2\alpha_{n_f}) & \cos(2\alpha_{n_f}) \end{pmatrix}$$

The miscalibration matrix

$$\boldsymbol{\mathcal{B}}(\{\beta_b\}) = \begin{pmatrix} \cos(2\beta_b) & \sin(2\beta_b) & 0 & 0 & 0 & 0 \\ -\sin(2\beta_b) & \cos(2\beta_b) & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The birefringence matrix

$$\boldsymbol{d} = \boldsymbol{X}\,\boldsymbol{A}\,\boldsymbol{\mathcal{B}}\,\boldsymbol{c} + \boldsymbol{n}$$

$$\boldsymbol{A}(\{\beta_{fg}\}) = \begin{pmatrix} 1 & 0 & A_1^d & 0 & A_1^s & 0 \\ 0 & 1 & 0 & A_1^d & 0 & A_1^s \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & A_n^d & 0 & A_n^s & 0 \\ 0 & 1 & 0 & A_n^d & 0 & A_n^s \end{pmatrix}$$

CMB | **Dust** $T_d = 20K, \beta_d$ | **Synchrotron** β_s

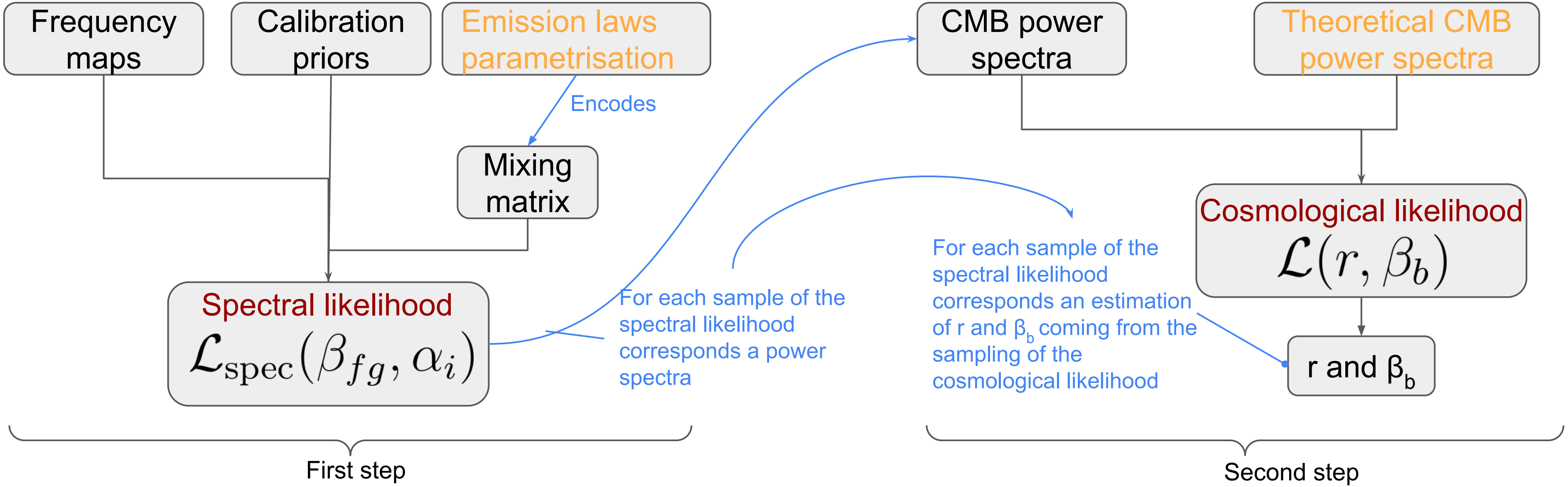
The mixing matrix

We define the generalised mixing matrix:

$$\boldsymbol{\Lambda} = \boldsymbol{X}\,\boldsymbol{A}$$

Pipeline Summary: A Two Step Analysis

Jost et al. PRD 2023



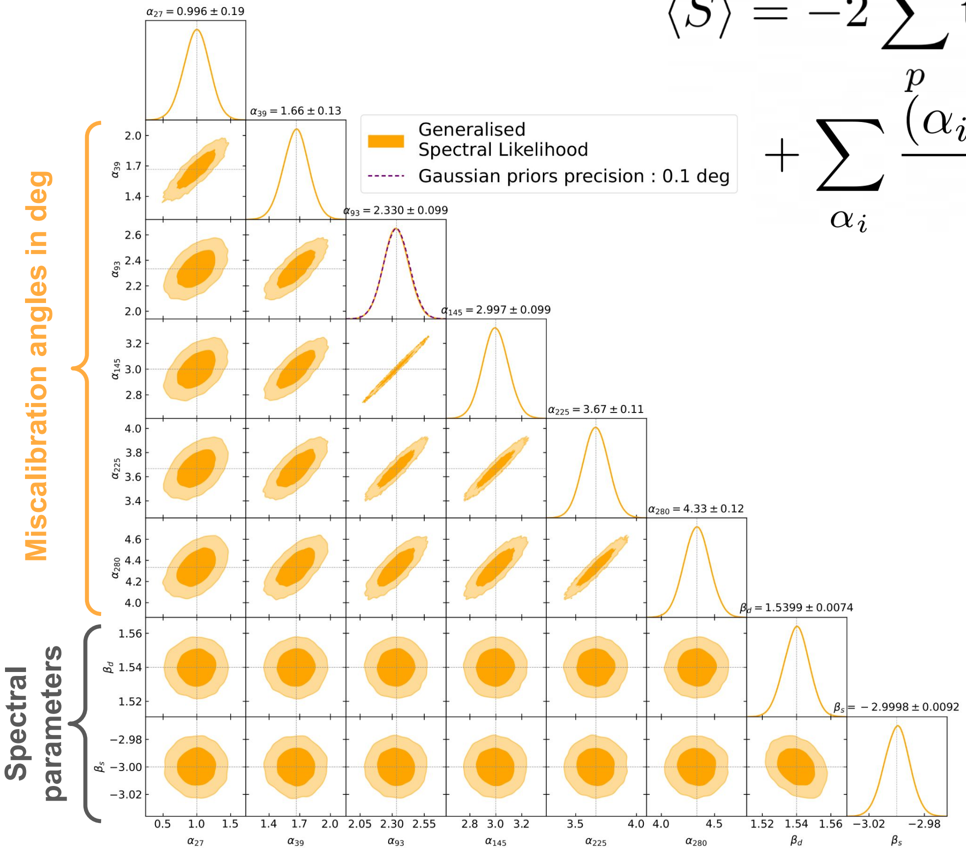
Stompor et al. MNRAS 2009
Vergès et al. PRD 2020

Relative Angles Retrieved by the Spectral Likelihood

$$\langle S\rangle = -2\sum_p \mathrm{tr}\left(\boldsymbol{N}_p^{-1}\boldsymbol{\Lambda}_p(\boldsymbol{\Lambda}_p^t\boldsymbol{N}_p^{-1}\boldsymbol{\Lambda}_p)^{-1}\boldsymbol{\Lambda}_p^t\boldsymbol{N}_p^{-1}\langle\boldsymbol{d}_p\boldsymbol{d}_p^t\rangle\right)$$

$$+\sum_{\alpha_i}\frac{(\alpha_i-\hat{\alpha}_i)^2}{2\sigma_{\alpha_i}^2}$$

Calibration prior to lift degeneracy between global polarization angle and β_b

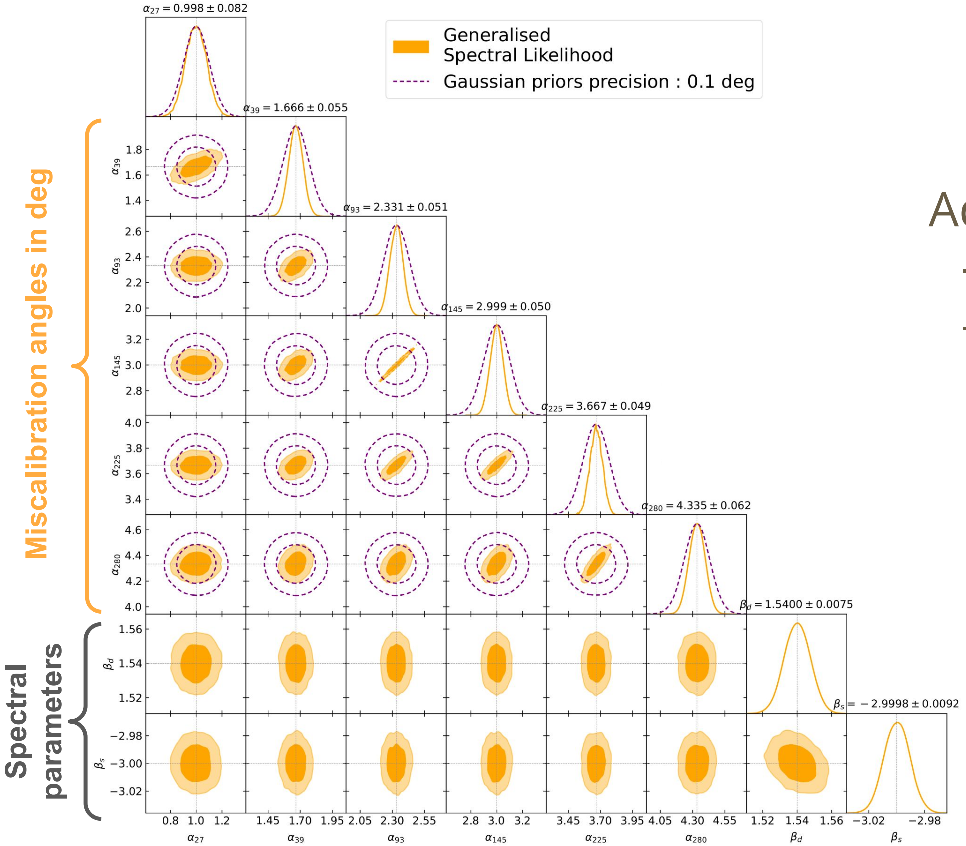


Test case in **Jost et al. PRD 2023**: SO SAT-like survey

Spectral parameters are correctly estimated (d0s0 input)

With only one prior of $\sigma(\alpha_{prior}) = 0.1°$ all polarization angle are retrieved with $\sigma(\alpha_i) \geq 0.1°$

Spectral Likelihood With Multiple Priors



Adding priors improves the precision:

- 6 priors $\sigma(\alpha_{prior}) = 0.1°$
- $\sigma(\alpha_i) \geq 0.05°$

Jost et al. PRD 2023

Cosmological Likelihood With Multiple Priors

Estimate both r and β_b

Priors ⇒ **no bias on β_b**

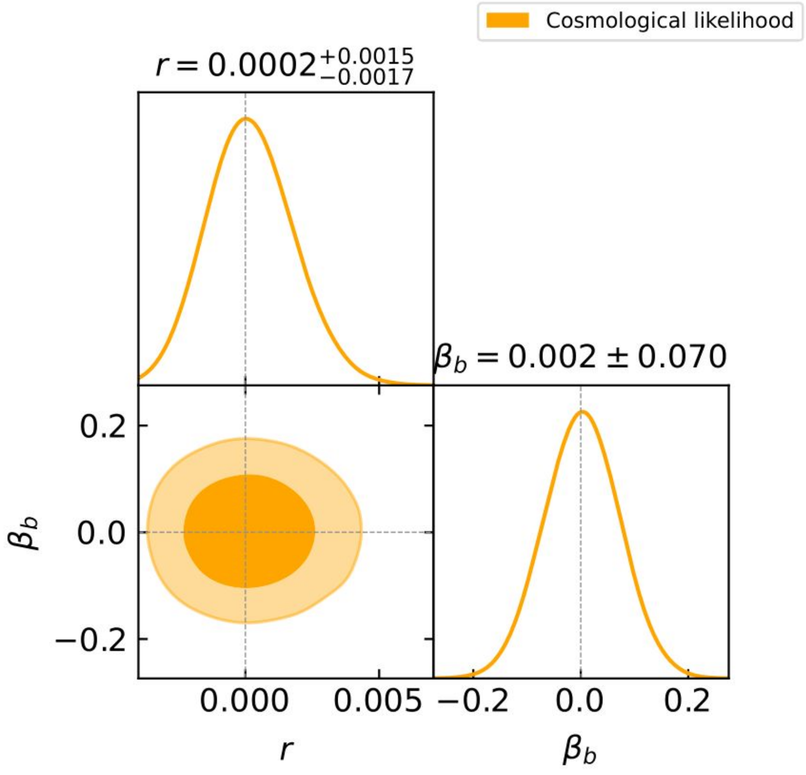
With 6 $\sigma(\alpha_{prior})$ = 0.1° ⇒ **$\sigma(\beta_b)$ = 0.07°**

Enough for 5σ detection with current hints

No significant impact on σ(r)

With biased priors:

- $$\Delta(\beta_b) \approx \frac{1}{n_{\text{prior}}} \sum \Delta\alpha_{\text{prior}}$$
- **r** retrieved **without bias** (global angle marginalization)



Jost et al. PRD 2023

Setting and Relaxing Requirements on Polarization Angle Calibration

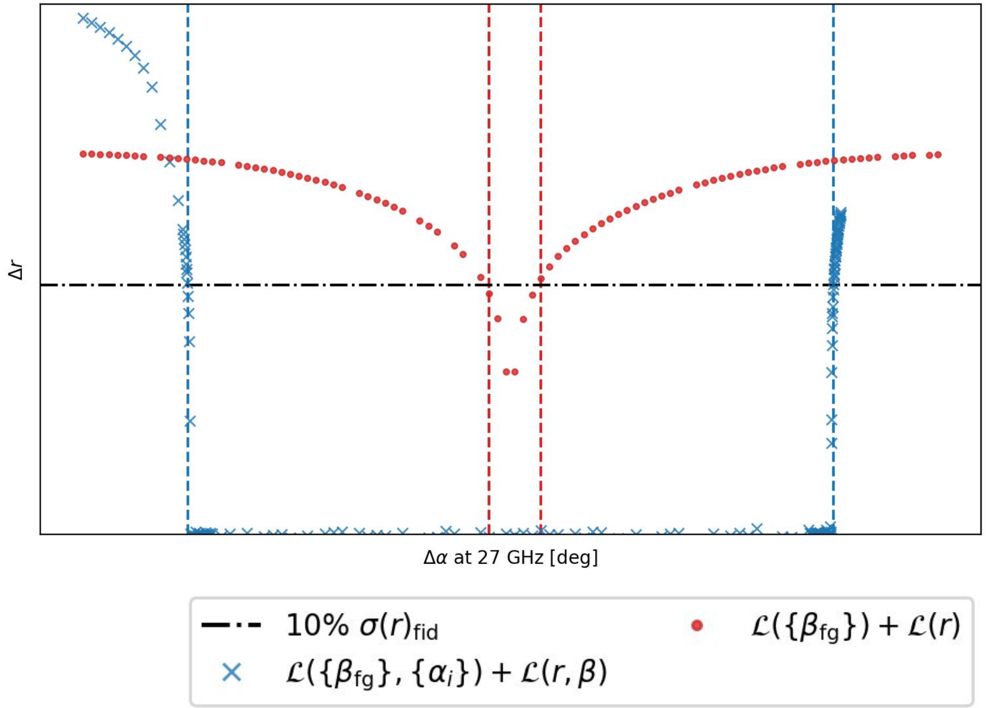
Set all $\alpha_i = 0$ except on the considered channel $\alpha_{27} = \Delta\alpha$

Use one prior, $\sigma(\alpha_{prior,27}) = 0.1°$, centered at 0°.

Run the pipeline and get Δr with respect to Δα ⇒ get requirement on polarization angle systematic error.

Relaxed requirements compared to case where angles are ignored.

This is with d0s0: how complex foreground residuals with non-zero EB would impact this type of results?



Measuring Isotropic Birefringence with LiteBIRD

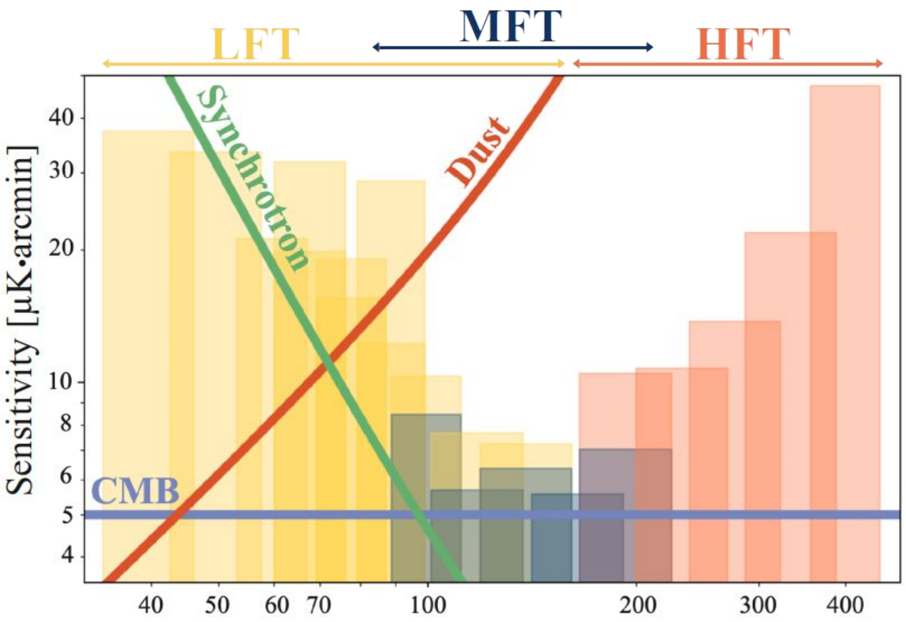
On behalf of **LiteBIRD's Cosmic Birefringence Project Study Group**,
P. Diego-Palazuelos, M. Bortolami, E. de la Hoz, J. Errard, A. Gruppuso, R. Sullivan et al.

LB's wide frequency range:

- Efficient component separation
- Better foreground models
- Cross-correlation of low and high frequencies reduces the impact of EB mismodeling

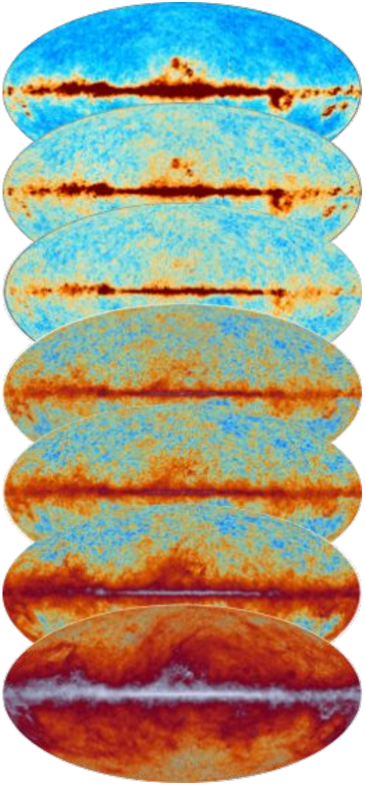
LB's Full sky survey:

- Access to more modes
- Low ℓ EB modes can probe the axion-like particle mass and distinguish different ALP and early dark energy models

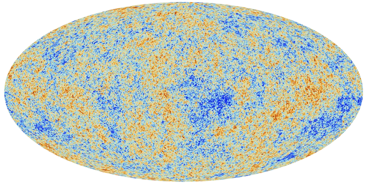


Multiple Pipelines are Developed

Frequency maps



Standard comp-sep →



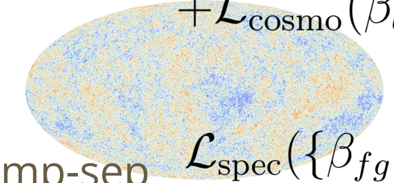
CMB $\alpha + \beta_b$

Harmonic space → **D-estimator** — Gruppuso et al. JCAP 2016

Pixel space → **Peak Stacking** — Planck XLIX A&A 2016

Foreground calibration + dust + synchrotron models → **Minami & Komatsu** — Minami et al 2020

Modified comp-sep $\mathcal{L}(\{\mathcal{A}_{\rm comp}\}, \{\beta_{fg}\}, \{\alpha_i\}) + \mathcal{L}_{\rm cosmo}(\beta_b)$ → **“Modified B-SeCRET”** — De la Hoz et al JCAP 2022



Modified comp-sep $\mathcal{L}_{\rm spec}(\{\beta_{fg}\}, \{\alpha_i\}) + \mathcal{L}_{\rm cosmo}(r, \beta_b)$ → **“Modified FGBuster”** — Jost et al PRD 2023

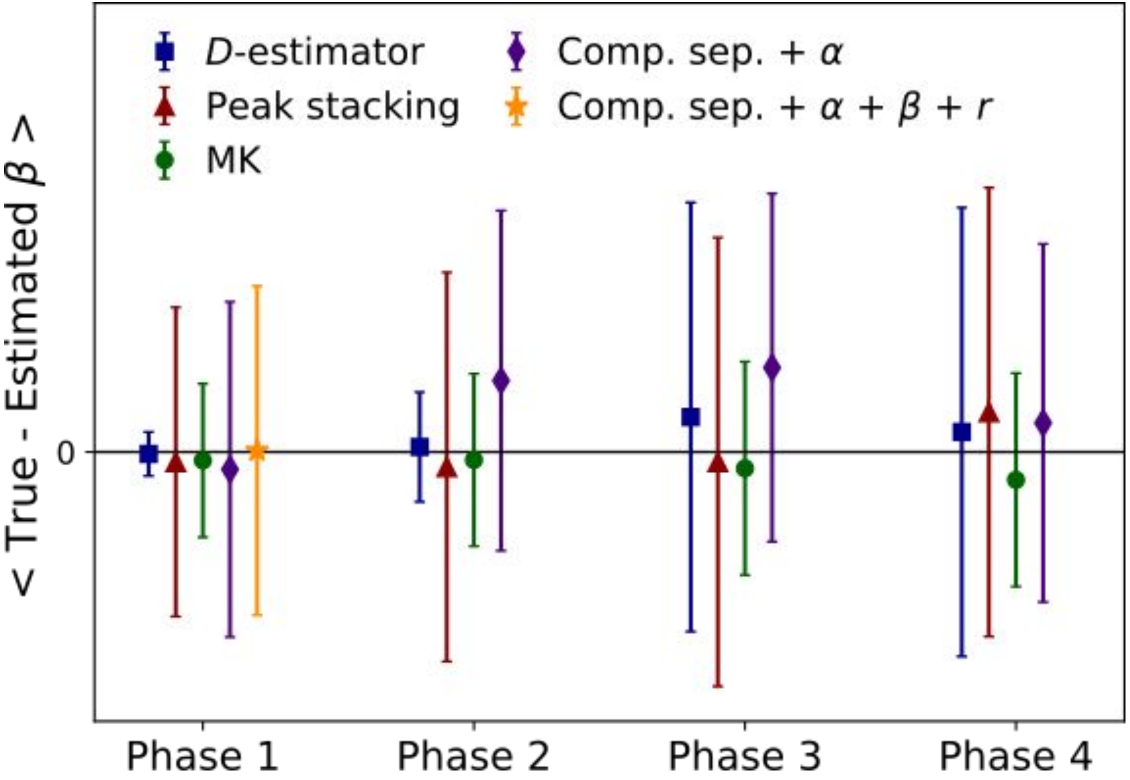
A Forecast with Different Degrees of Complexity

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

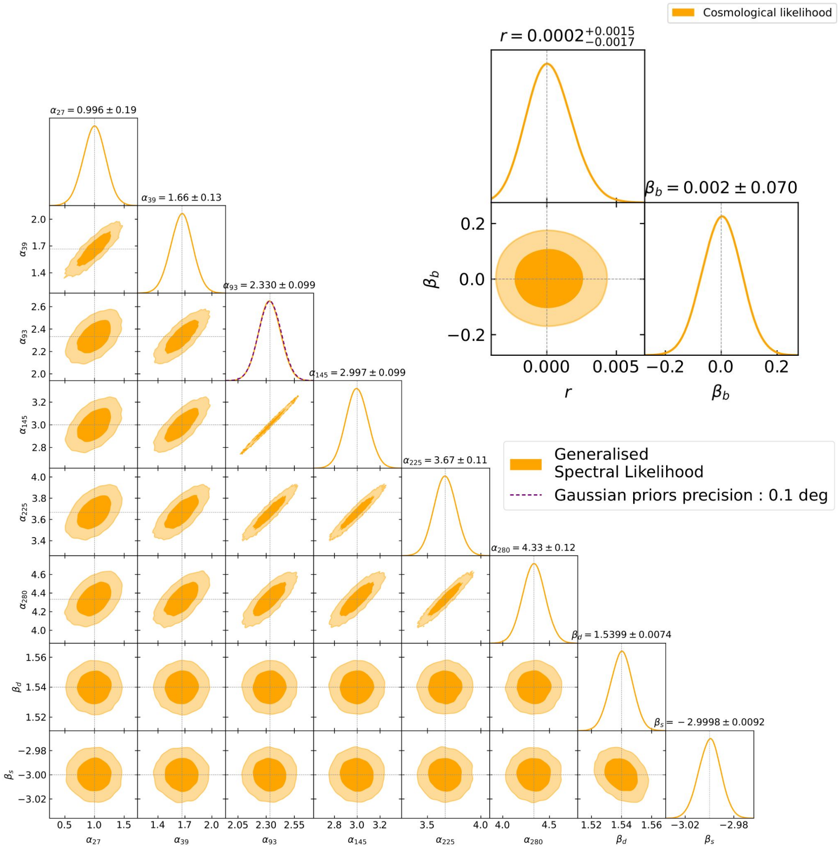
Phase2: CMB (β=0) + noise
+ **complex foregrounds (s1d1)**

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

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



Take Home Messages



A method to retrieve r and β_b in presence of foreground and systematic effects, using calibration priors.

Generalised parametric component separation method that includes polarization angles:

- Relative angle are constrained by the system

Cosmological parameters estimation:

- β_b retrieved thanks to calibration prior. Its precision is improved with multiple priors
- r estimated without bias coming from E→B leakage

Keep an eye on arxiv for the application of this method and others in the LiteBIRD birefringence forecast!

THANK YOU !

Source : Deborah Kellner

Backup Slides

Source : Deborah Kellner

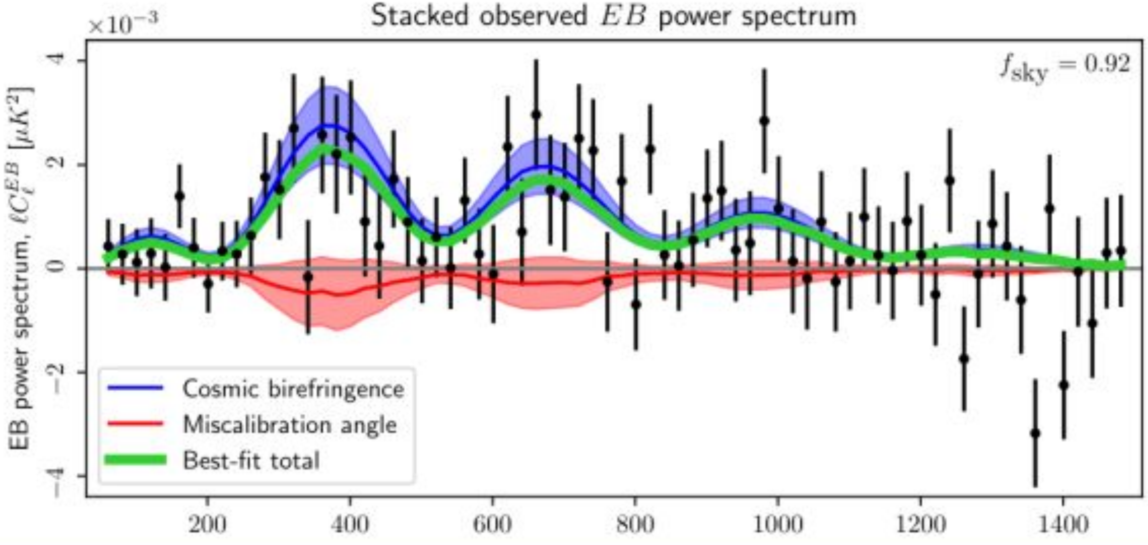
Calibrating against Galactic foregrounds

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

➡ Galactic emission not significantly rotated by β
Use foregrounds as our calibrator

Minami+ PTEP 2019

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



Model the EB correlation of Galactic synchrotron and dust emissions

Clark+ ApJ 2021

Tightest constraint to date (3.6σ)

$$\beta = 0.342^\circ\,{}^{+0.094^\circ}_{-0.091^\circ}$$

from the joint analysis of *Planck* and WMAP data

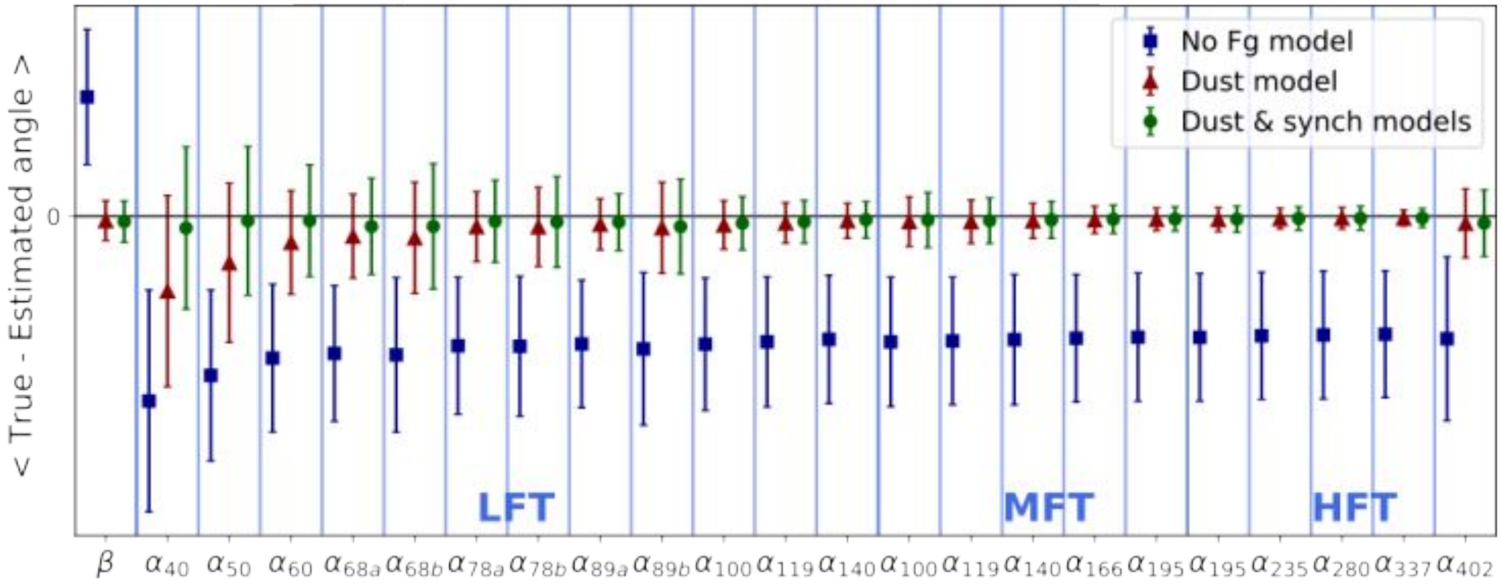
Eskilt & Komatsu PRD 2022

Minami-Komatsu (MK) technique

Considering dust and synchrotron contributions separately

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

Diego-Palazuelos+ JCAP 2023



D-estimator

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

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

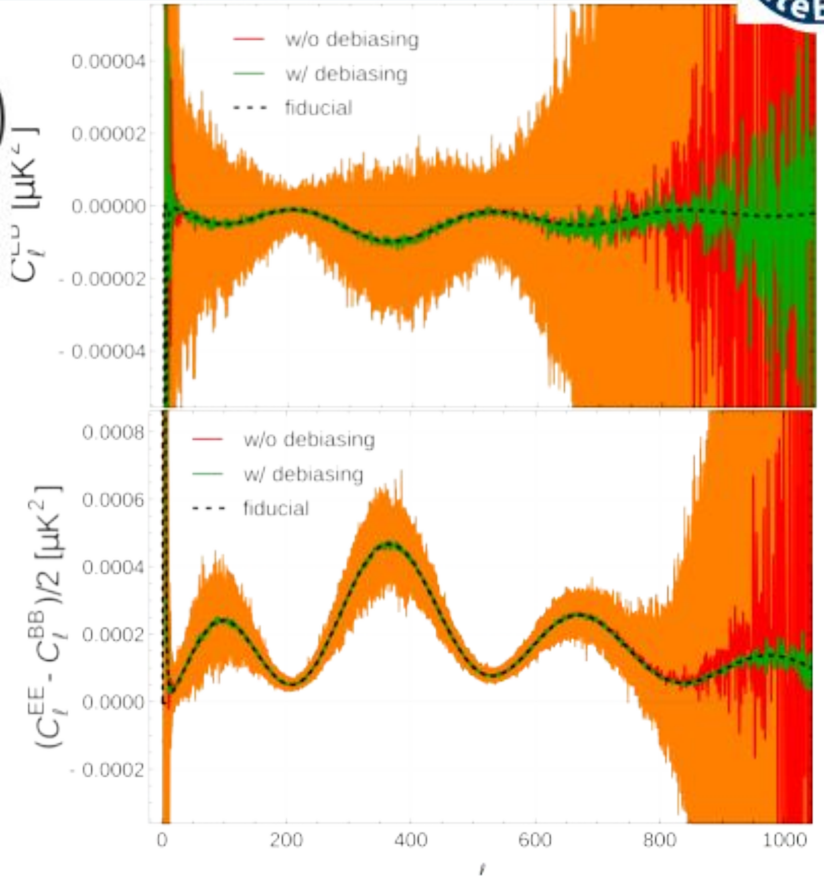
Find the zeros minimizing

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

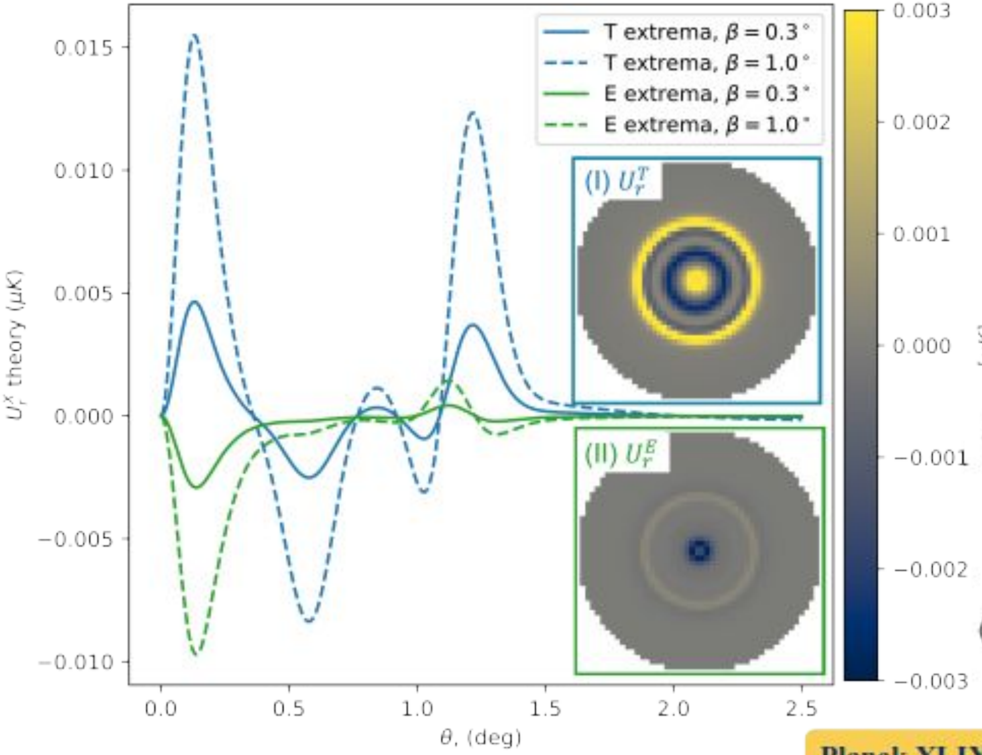
Build the covariance matrix from simulations to account for foreground debiasing and the extra dispersion caused by α miscalibrations

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

Gruppuso+ JCAP 2016



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

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

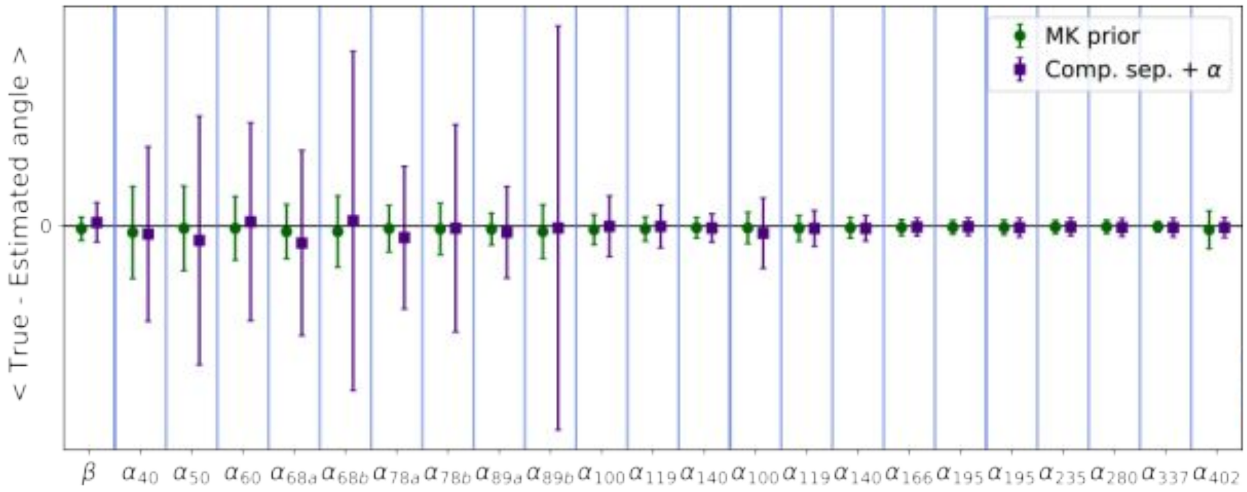
$$\langle U_r^E \rangle(\theta) = -\frac{1}{2}\sin(4\beta) \int \frac{\ell d\ell}{2\pi} W_\ell^E W_\ell^P J_2(\ell\theta) \times (\bar{b_\nu} + \bar{b_\zeta}\ell^2)(C_\ell^{EE} - C_\ell^{BB})$$

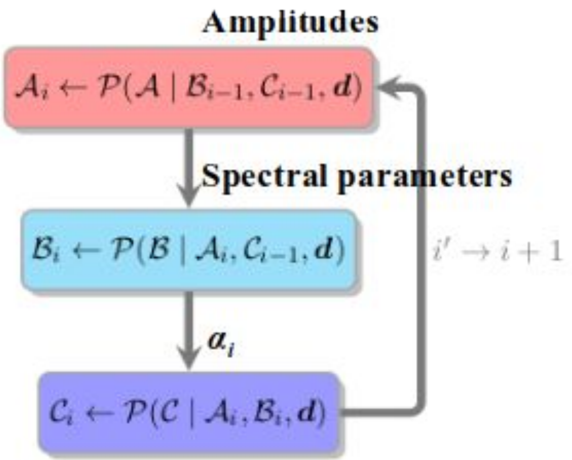
Planck XLIX A&A 2016

Component separation + α_i

$$\begin{pmatrix} \boldsymbol{Q}(\boldsymbol{\nu},\theta) \\ \boldsymbol{U}(\boldsymbol{\nu},\theta) \end{pmatrix}_p = \begin{pmatrix} c^{\mathrm{Q}} \\ c^{\mathrm{U}} \end{pmatrix}_p + \begin{pmatrix} a_s^{\mathrm{Q}} \\ a_s^{\mathrm{U}} \end{pmatrix}_p \frac{1}{u(\boldsymbol{\nu})} \left(\frac{\boldsymbol{\nu}}{\nu_s}\right)^{\beta_s} + \begin{pmatrix} a_d^{\mathrm{Q}} \\ a_d^{\mathrm{U}} \end{pmatrix}_p \frac{1}{u(\boldsymbol{\nu})} \left(\frac{\boldsymbol{\nu}}{\nu_d}\right)^{\beta_d - 2} \frac{B(\boldsymbol{\nu}, T_d)}{B(\nu_d, T_d)}$$

$$\begin{pmatrix} \boldsymbol{Q}^{\mathrm{o}}(\boldsymbol{\nu},\boldsymbol{\alpha},\theta) \\ \boldsymbol{U}^{\mathrm{o}}(\boldsymbol{\nu},\boldsymbol{\alpha},\theta) \end{pmatrix}_p = \begin{pmatrix} \cos(2\boldsymbol{\alpha}) & -\sin(2\boldsymbol{\alpha}) \\ \sin(2\boldsymbol{\alpha}) & \cos(2\boldsymbol{\alpha}) \end{pmatrix} \begin{pmatrix} \boldsymbol{Q}(\boldsymbol{\nu},\theta) \\ \boldsymbol{U}(\boldsymbol{\nu},\theta) \end{pmatrix}_p$$





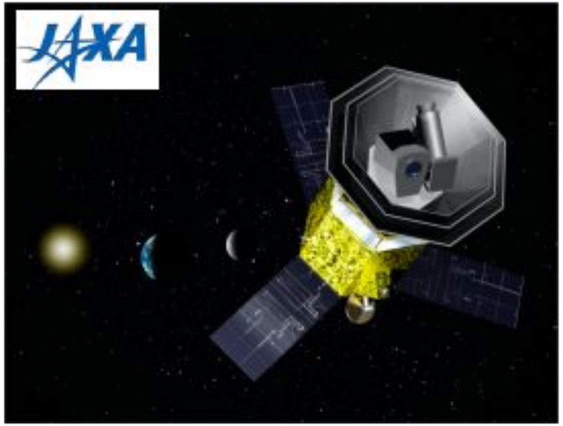
Gaussian priors on spectral parameters MI
result as prior on α_i

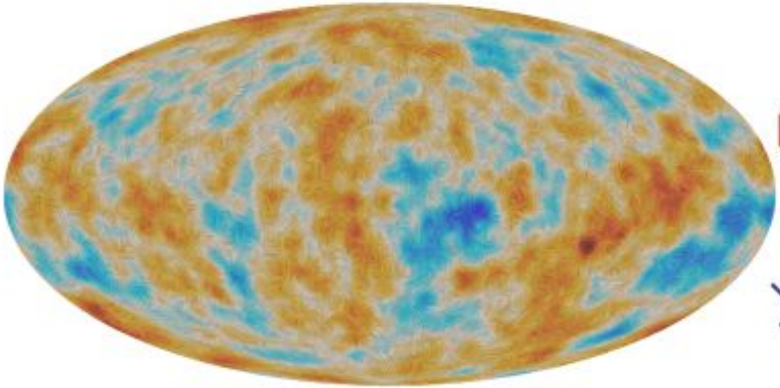
de la Hoz+ JCAP 2022

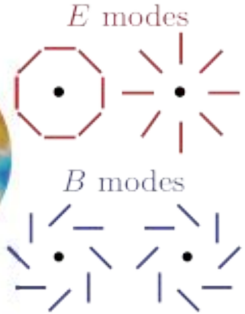
LiteBIRD overview

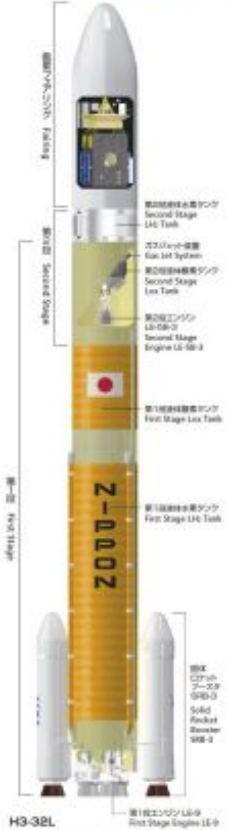
- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in late 2032 (JFY) with JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**

LiteBIRD PTEP 2023



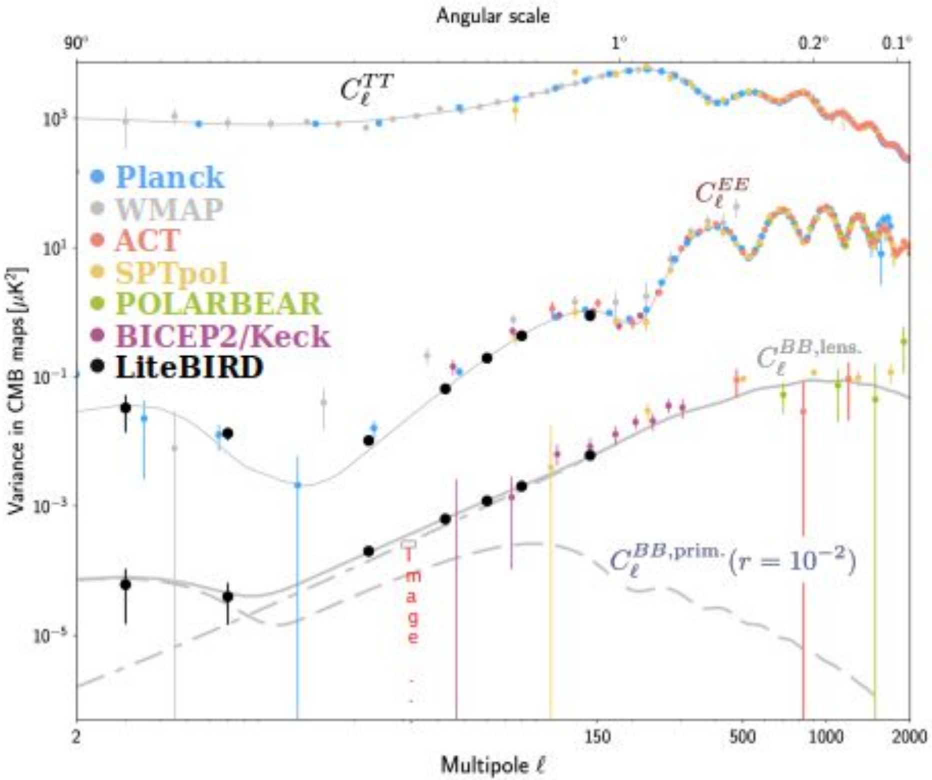






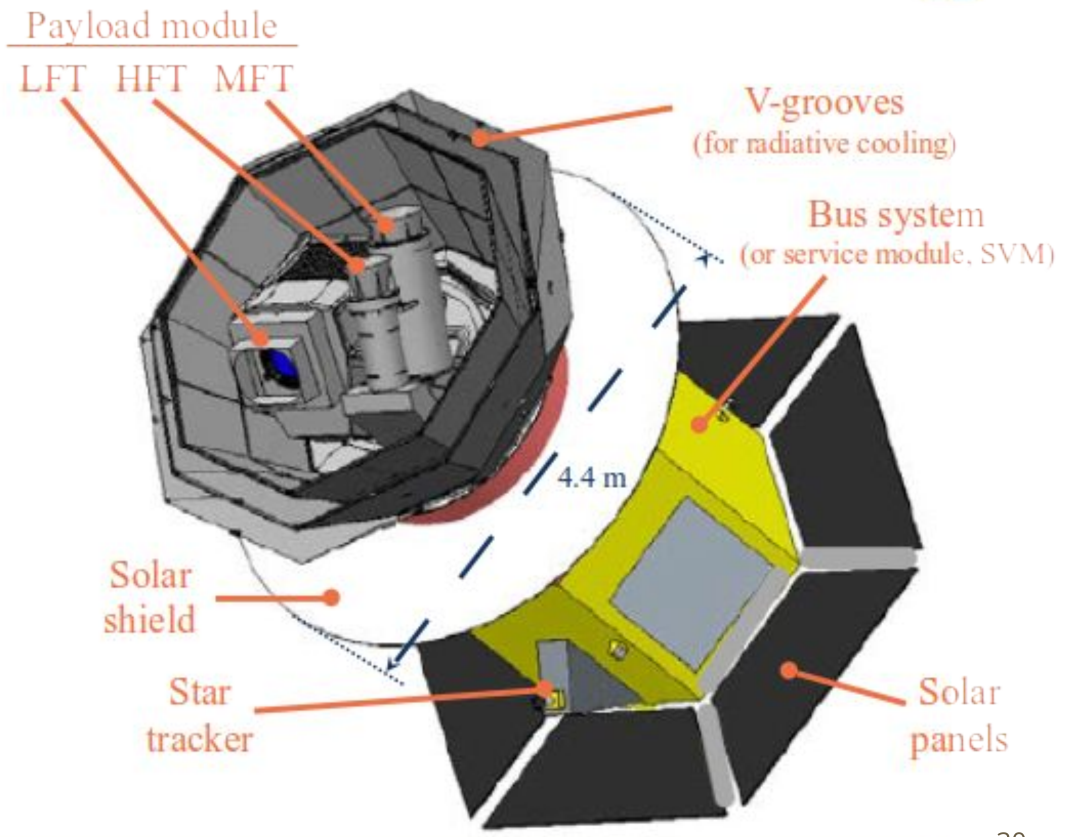
LiteBIRD main scientific objectives

- Definitive search for the **B-mode signal** from **cosmic inflation** in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
  - Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) B-mode power is
- proportional to the **tensor-to-scalar ratio, r**
- Current best constraint: $r < 0.032$ (95% C.L.)
  (Tristram+ 2021, combining BK18 and Planck PR4)
- LiteBIRD will improve current sensitivity on r by a factor ~50
- L1-requirements (no external data):
  - For $r = 0$, **total uncertainty of $\delta r < 0.001$**
  - For $r = 0.01$, 5σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently
- Huge discovery impact (evidence for inflation, knowledge of its energy scale, …)



LiteBIRD spacecraft overview

- 3 telescopes are used to provide the 40-402 GHz frequency coverage
  1. LFT (low frequency telescope)
  2. MFT (middle frequency telescope)
  3. HFT (high frequency telescope)
- Multi-chroic transition-edge sensor (TES) bolometer arrays cooled to 100 mK
- Polarization modulation unit (PMU) in each telescope with rotating half-wave plate (HWP), for $1/f$ noise and systematics reduction
- Optics cooled to 5 K



- Mass: 2.6 t
- Power: 3.0 kW
- Data: 17.9 Gb/day

The Generalised Spectral Likelihood

I generalise the spectral log likelihood from **Stompor et al. 2009**, similarly as in **Vergès et al. 2020**:

$$\langle S \rangle = -2 \sum_p \mathrm{tr}\left(\boldsymbol{N}_p^{-1} \boldsymbol{\Lambda}_p (\boldsymbol{\Lambda}_p^t \boldsymbol{N}_p^{-1} \boldsymbol{\Lambda}_p)^{-1} \boldsymbol{\Lambda}_p^t \boldsymbol{N}_p^{-1} \langle \boldsymbol{d}_p \boldsymbol{d}_p^t \rangle \right)$$

For forecasting purposes we **average over CMB and noise** realisations.

To lift the degeneracy we add priors to the likelihood:

$$S' \equiv \langle S \rangle + \sum_{\alpha_i} \frac{(\alpha_i - \hat{\alpha}_i)^2}{2\sigma_{\alpha_i}^2}$$

Credit: F. Nati

The Cosmological Likelihood

With {β_{fg} } and {$\boldsymbol{\alpha}_i$ } we estimate a CMB map. Imperfect component separation will lead to residuals.

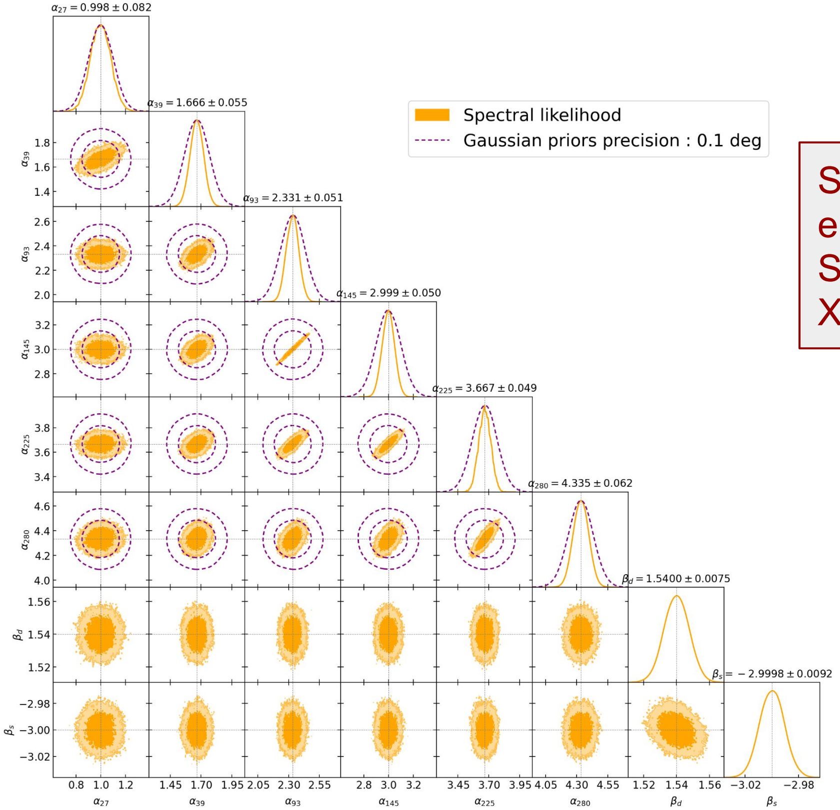
Its power spectra is used to estimate cosmological parameters:

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

Data after generalised component separation

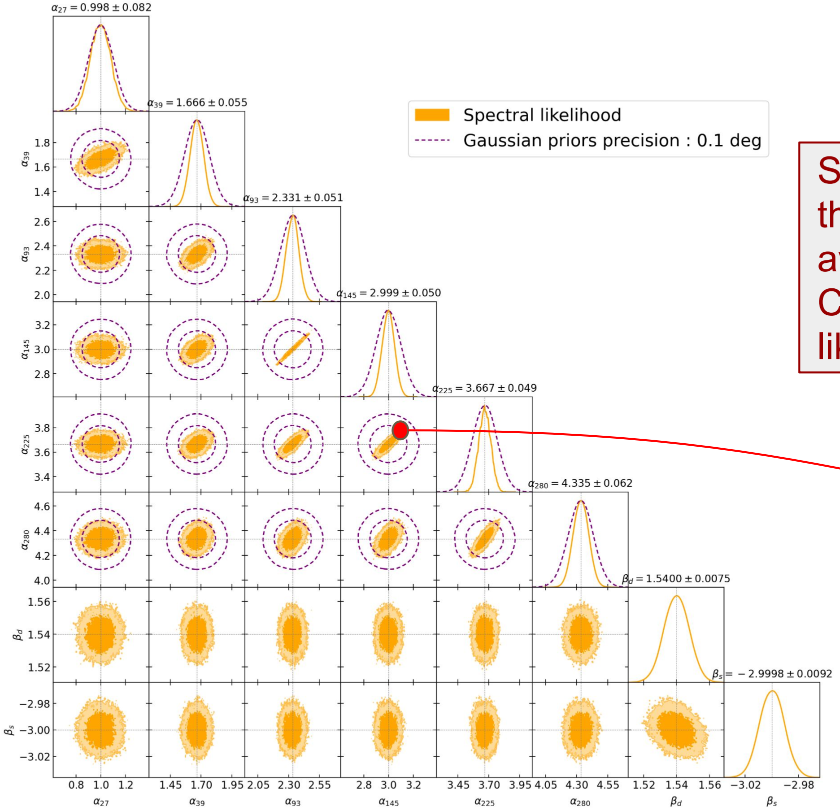
$$\boldsymbol{C}_\ell(r, \beta_b) \equiv \boldsymbol{\mathcal{R}}(\beta_b) \begin{pmatrix} C_\ell^{EE,\mathrm{p}} & 0 \\ 0 & rC_\ell^{BB,\mathrm{p}} + A_L C_\ell^{BB,\mathrm{lens}} \end{pmatrix} \boldsymbol{\mathcal{R}}^{-1}(\beta_b) + C_\ell^{\mathrm{noise}}$$

How to Have a Statistically Robust Method ?

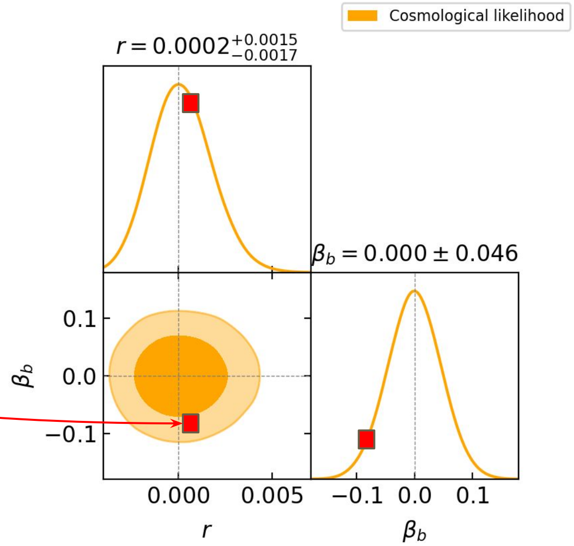


Step 1 : Sampling the ensemble averaged Spectral likelihood $X\{\alpha\}.A\{\beta_{fg}\}$

How to Have a Statistically Robust Method ?



Step 2 : Draw from the ensemble averaged Cosmological likelihood



Method Validation

SO SAT like survey: 6 frequency bands, characteristics noise, 10% sky coverage.

Priors:

- $\sigma(\alpha_i) = 0.1°$
- Priors are centred at the true value of polarisation angles.
- One vs multiple priors.

Forecast input sky:

- CMB maps from Planck power spectra, $r = 0.0$, $\beta_b = 0.0°$
- PySM foreground maps with different degrees of complexity (d0s0, d1s1, d7s3 in order of complexity...) (**Thorne et al 2016, Zonca et al. 2021**)

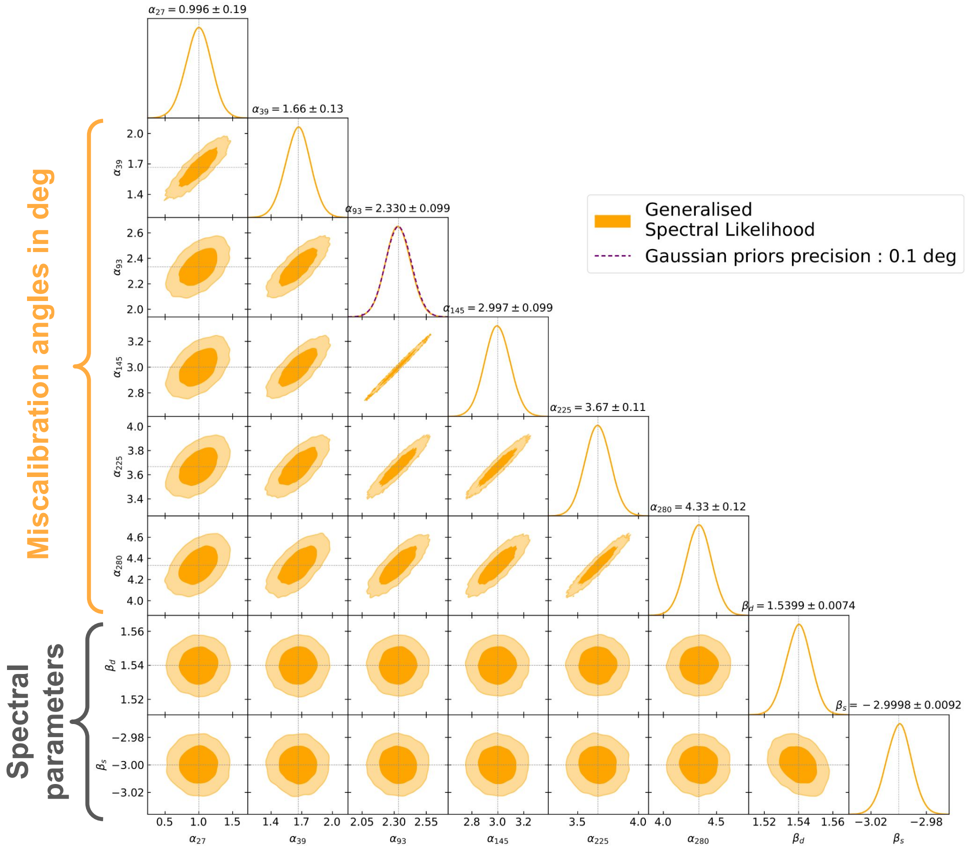
Credit: Remington Gerras

Simple Foregrounds and One Calibration Prior

- Input CMB: **r = 0.0 ; β_b = 0.0°**
- Input fg: **PySM** models (**Thorne et al 2016, Zonca et al. 2021**) d0s0:
  - dust: MBB, spatially constant spectral indices
  - synchrotron: power law, spatially constant spectral indices
- 1 prior on 93 GHz: $\sigma(\alpha_i) = 0.1°$

Foreground cleaning is ok

Miscalibration: one prior enough

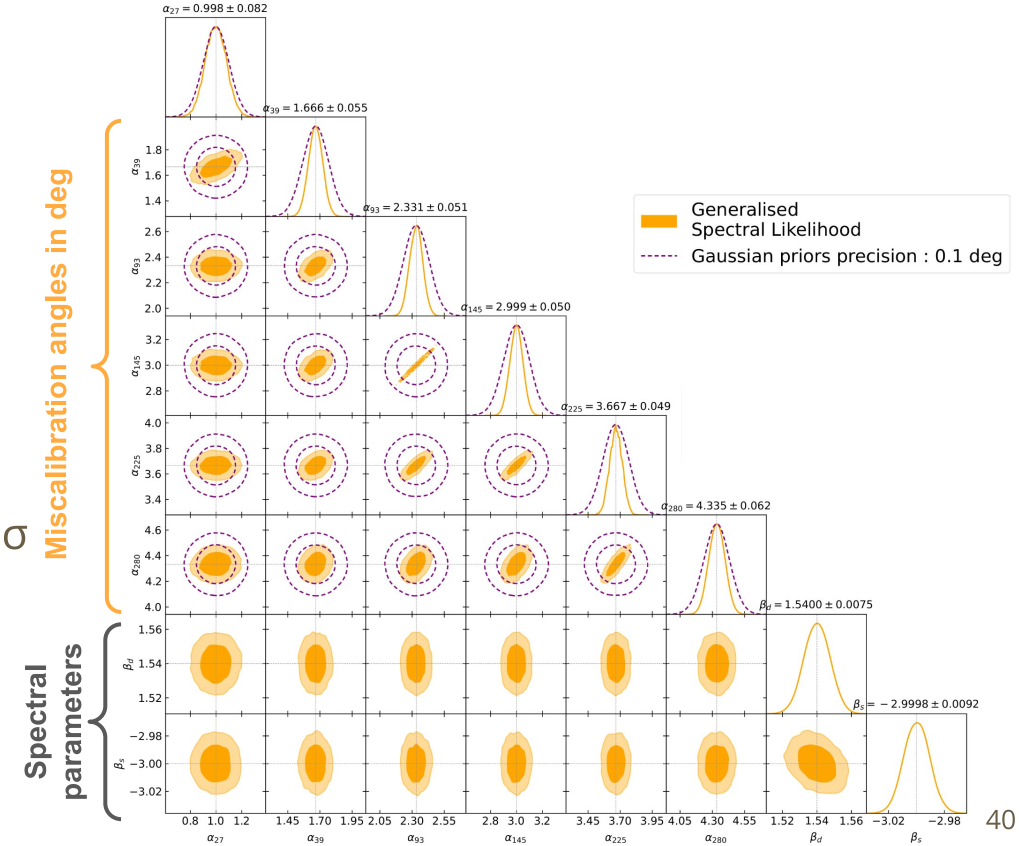


Simple Foregrounds and Six Calibration Priors

- Input CMB: **r = 0.0 ; β_b = 0.0°**
- Input fg: **PySM** models (**Thorne et al 2016, Zonca et al. 2021**) d0s0:
  - dust: MBB, spatially constant spectral indices
  - synchrotron: power law, spatially constant spectral indices

- **Prior on all frequency channels:** $\sigma(\alpha_i) = 0.1°$

Overall $\sigma(\alpha)$ improved wrt priors precisions!



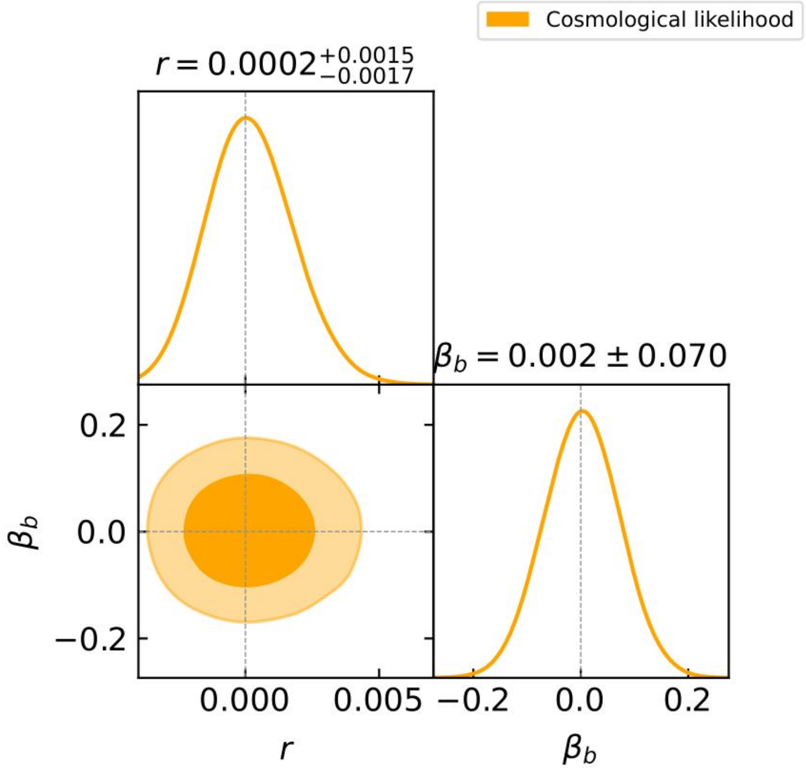
Simple Foregrounds and Six Calibration Priors

- Simple foregrounds: **d0s0**
- **Prior on all frequency channels**

r and β_b correctly estimated

σ(r): same order as SO SAT forecast with σ(r) = 2.1 10^{-3} (**Ade et al. 2018**)

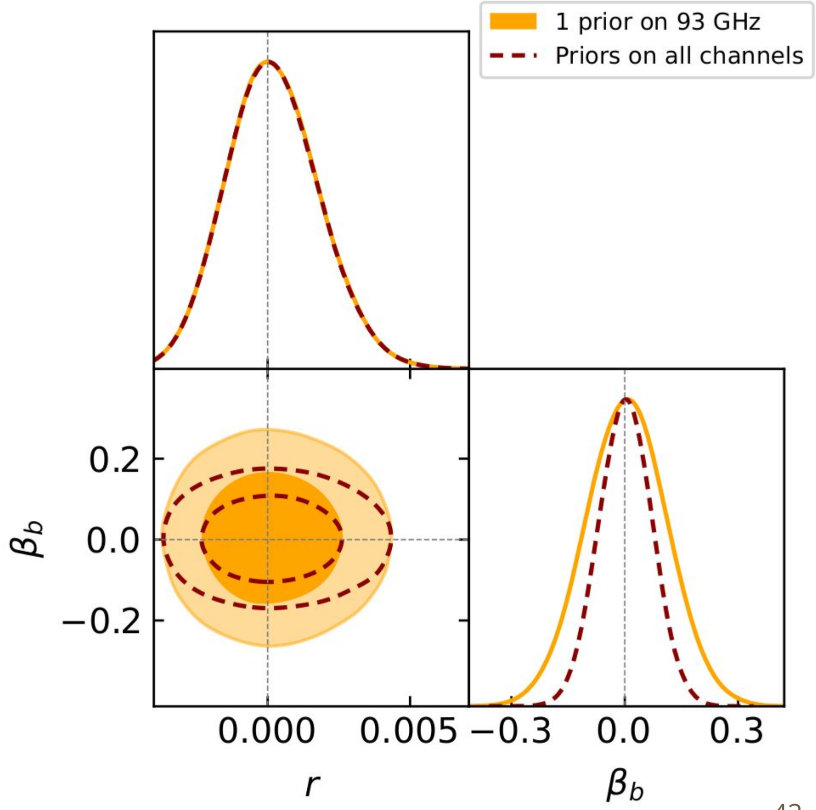
σ(β_b): improved wrt prior precision!



Results: Simple Foregrounds and Six Calibration Priors

- d0s0
- Prior on all frequency channels

$\sigma(\beta_b)$: improved wrt prior precision!



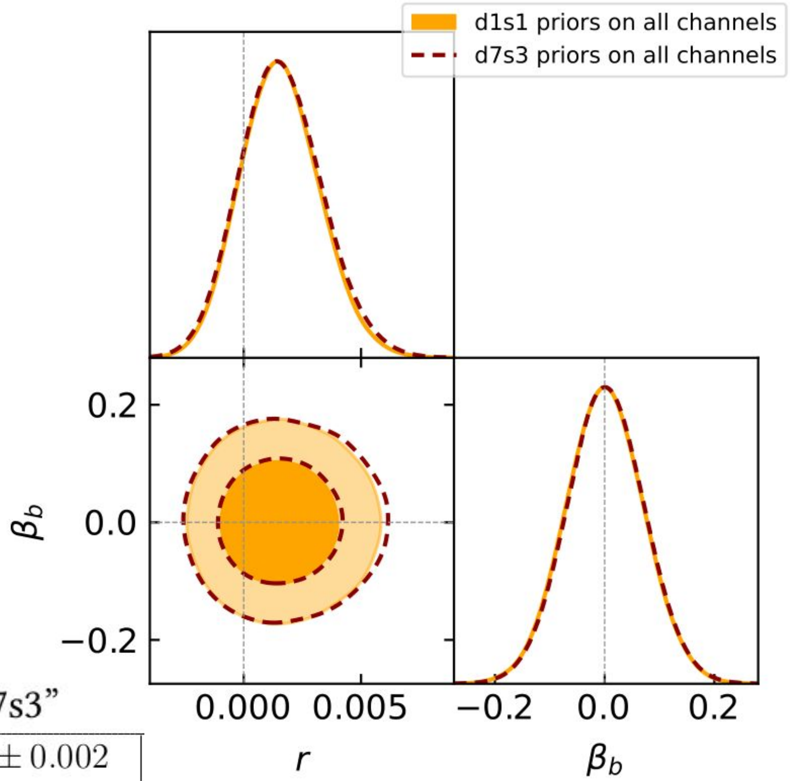
Complex Foregrounds and Six Calibration Priors

Foreground emissions **don't follow** the assumption used in the mixing matrix:

- **d1s1:** spatially varying foreground spectral indices
- **d7s3:** dust emission is non parametric and synchrotron has a curvature term
- **Prior on all frequency channels:** $\sigma(\alpha_i) = 0.1°$

r: biased due to foreground residuals

β_b: no noticeable effect

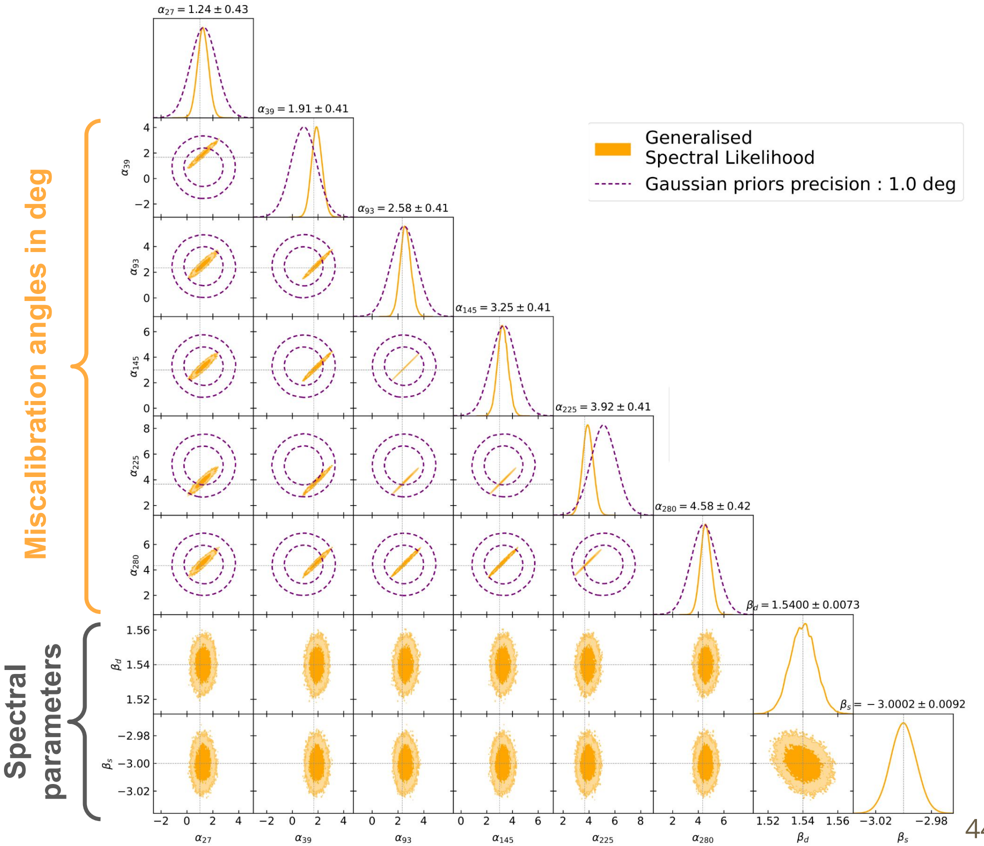


	"d1s1"	"d7s3"
r	0.002 ± 0.002	0.002 ± 0.002
$\beta_b[°]$	0.00 ± 0.07	0.00 ± 0.07

Simple Foregrounds and Biased Priors

- d0s0:
  - dust: MBB, spatially constant spectral indices
  - synchrotron: power law, spatially constant spectral indices
- **Prior on all channels, $\sigma(\alpha_i)$ = 1°**
- **Priors randomly biased by N(0,1°)**

α_i biased by the same value: the mean of the biases



Simple Foregrounds and Biased Priors

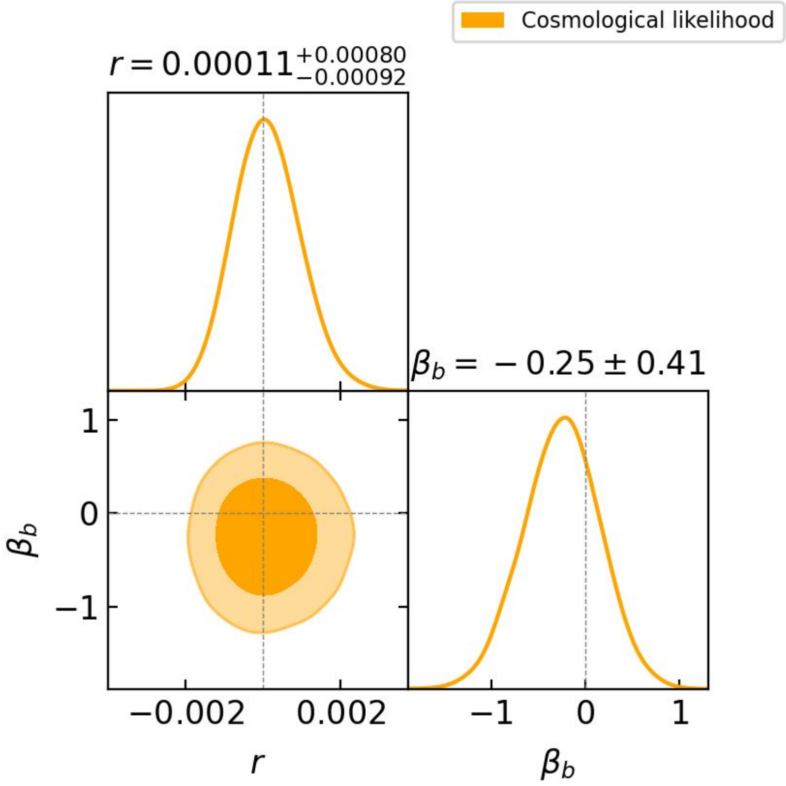
- Simple foregrounds **d0s0**:
  - dust: MBB, isotropic spectral indices
  - synchrotron: power law, isotropic spectral indices
- **Prior on all channels,** $\sigma(\alpha_i) = 1°$
- **Priors randomly biased by N(0,1°)**

β_b biased by the same value as α_i

For β_b trade-off between statistical uncertainty and possible bias.

r is unbiased: we marginalise over a global angle, removing any E→B leakage either from α_i or β_b

We can always be confident that r is not affected by α_i and β_b .



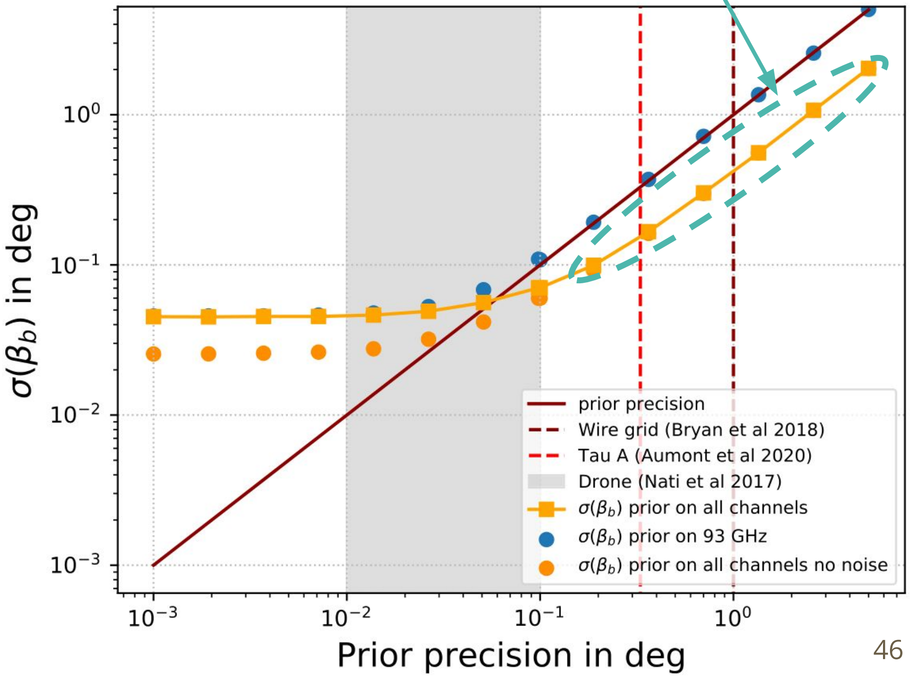
Evolution of Uncertainty wrt Prior Precision

$$\sigma(\beta_b) \approx \left(\sum_1^6 \frac{1}{\sigma^2_{\alpha_i}} \right)^{-\frac{1}{2}} = \frac{\sigma_{\alpha_i}}{\sqrt{6}}$$

We can set calibration requirement.

- Simple Foregrounds: d0s0
- 3 cases:
  - **1 prior**
  - **6 priors** ■
  - **6 priors and no noise** ●

Noise represents ~42% of $\sigma(\beta_b)$ in the SO SATs like survey used here



Cosmic Birefringence

I focus in particular on **spatially constant** and **time independent** cosmic birefringence:

$$\tilde{C}_\ell^{EE} = C_\ell^{EE}\cos^2(2\beta_b) + C_\ell^{BB}\sin^2(2\beta_b)$$
$$\tilde{C}_\ell^{BB} = C_\ell^{EE}\sin^2(2\beta_b) + C_\ell^{BB}\cos^2(2\beta_b)$$
$$\tilde{C}_\ell^{EB} = (C_\ell^{EE} - C_\ell^{BB})\frac{\sin(4\beta_b)}{2},$$

Method Validation

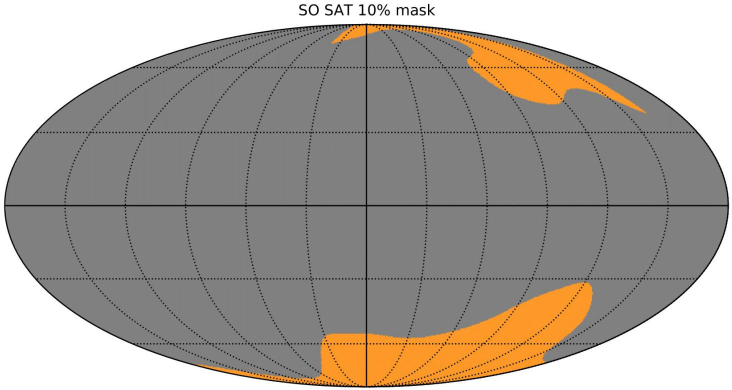
SO SAT characteristics noise, 10% sky coverage, l_{min} = 30, l_{max} =300, 30 000 detectors, first light by the end of the year

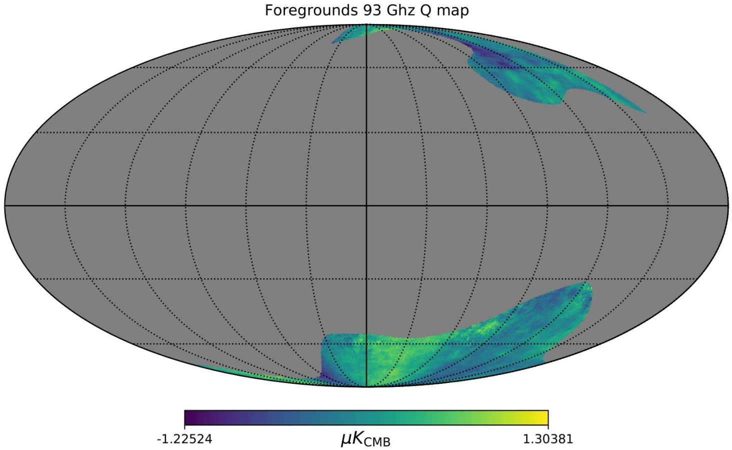
Priors:

- as a benchmark we use $\sigma(\alpha_i) = 0.1°$
- Unless precised otherwise, priors are centred at the true value of polarisation angles.
- Different calibration methodology explored e.g. one vs multiple priors.

Forecast input sky:

- average over CMB maps generated from Planck power spectra with r = 0.0, β_b = 0.0°
- PySM foreground maps with different degrees of complexity (d0s0, d1s1, d7s3 in order of complexity…) (Thorne et al 2016, Zonca et al. 2021)





Foreground Models

Dust template: maps at 545 GHz in intensity and 353 GHz in polarisation from the 2015 Commander Planck+WMAP+Haslam 408 MHz (Plank 2016)

d1, spectral index map from commander (assumes same spectral index for temperature and polarisation)

d7 Hensley and Draine 2012 + Hensley 2015: Emission modeled after dust size, shape temperature and ferromagnetic iron inclusion

$$\log_{10} \mathcal{U}_p = (4 + \beta_{d,p}) \log_{10}\left(\frac{T_{d,p}}{\langle T_d \rangle}\right),$$

$$Q^{\mathrm{d7}}_{\nu,p} = A^Q_{d,p} \frac{f_\nu(\mathcal{U}_p)}{f_{\nu_0}(\mathcal{U}_p)}$$

$$U^{\mathrm{d7}}_{\nu,p} = A^U_{d,p} \frac{f_\nu(\mathcal{U}_p)}{f_{\nu_0}(\mathcal{U}_p)}.$$

Synchrotron template: 23 GHz map from WMAP 9 yr (Bennett et al. 2013)

s1, Miville-Deschênes et al. (2008): combination of WMAP (Hinshaw et al. 2007) and Haslam 408 MHz data (Haslam et al. 1982)

s3, global curvature index C = -0.052 (Kogut et al 2012)

$$Q^{\mathrm{s3}}_{\nu,p} = A^Q_{s,p} \left(\frac{\nu}{\nu_0}\right)^{\beta_{s,p}+2+C\ln(\nu/\nu_0)}$$

$$U^{\mathrm{s3}}_{\nu,p} = A^U_{s,p} \left(\frac{\nu}{\nu_0}\right)^{\beta_{s,p}+2+C\ln(\nu/\nu_0)},$$