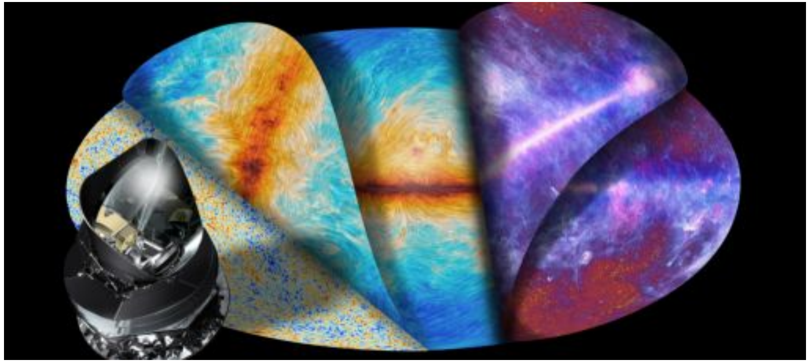
# A new method for constraining cosmic birefringence *in the presence of foregrounds and instrumental effects in the Simons Observatory*



Baptiste Jost (APC, CPB)

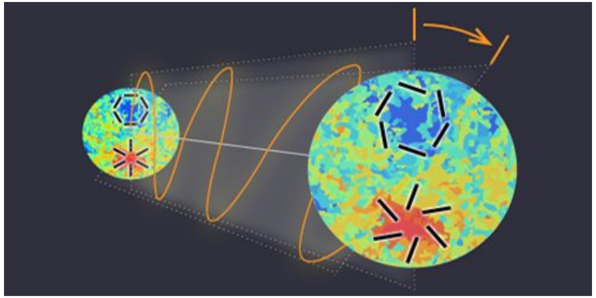
Radek Stompor (CPB), Josquin Errard (APC)

**From Planck to the Future of CMB**

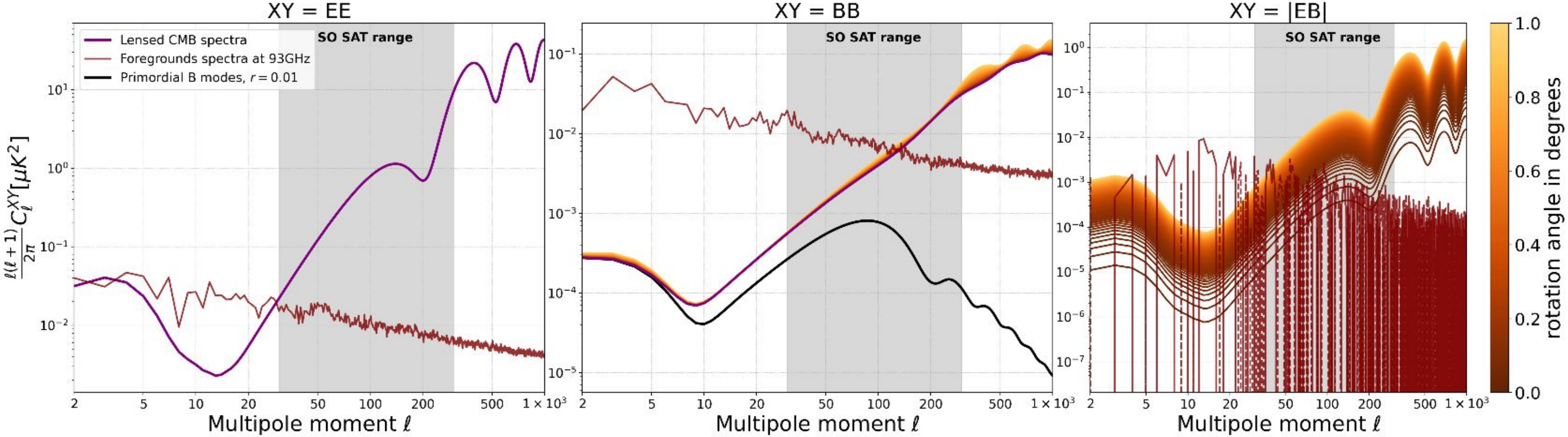
May 24th, 2022

# Cosmic birefringence

- Standard cosmology conserves parity ⇒ EB=0
- Birefringence generates non-zero EB
- Generally: parity violating interactions such as Chern-Simons effect
- Could be a hint of photon/axion interaction



Credit: Minami / Keck

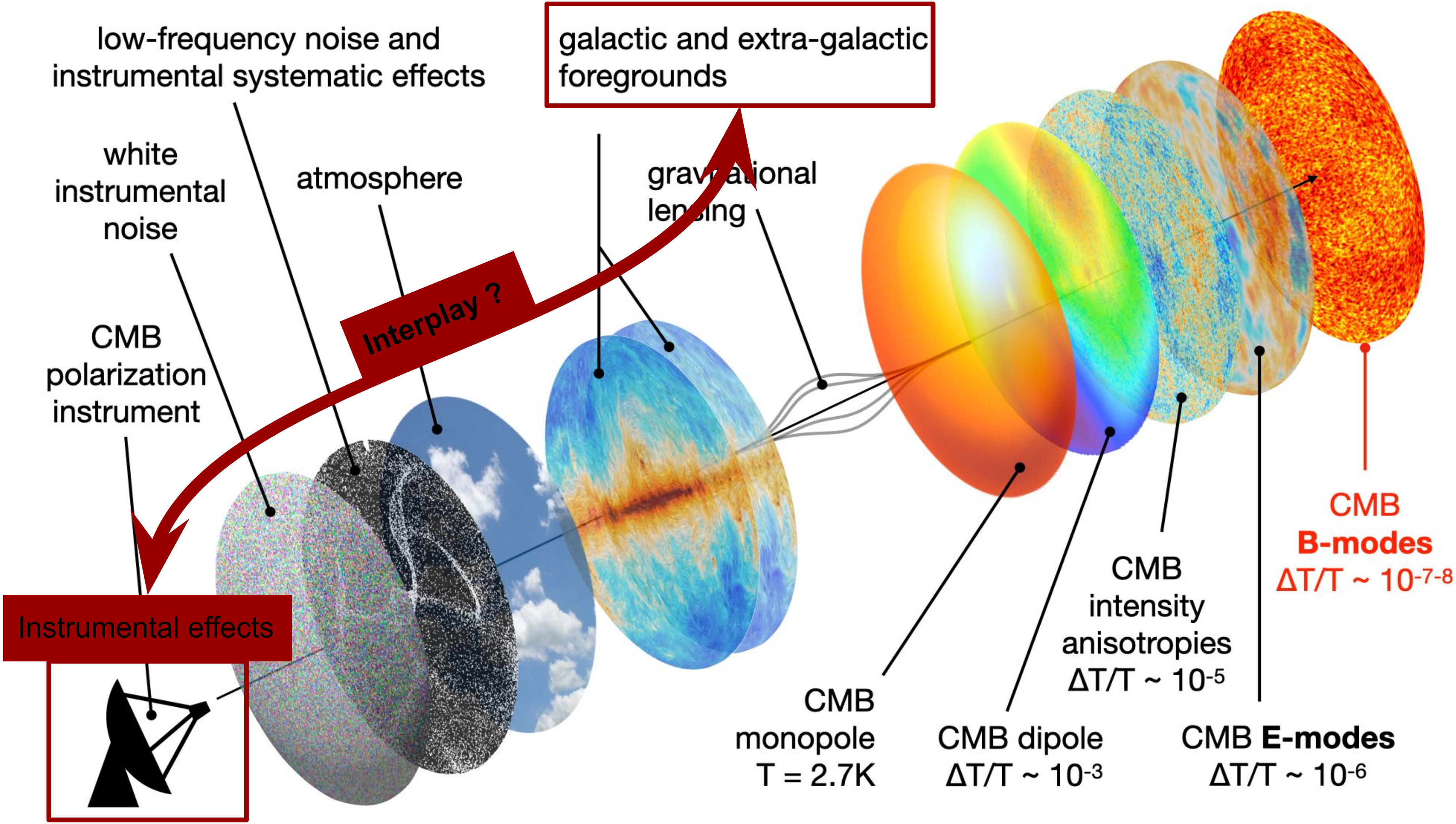



# The Simons Observatory Small aperture telescopes (SAT)

- **3 Small Aperture Telescopes (SAT) :**
  - large angular scale
  - main scientific goal : large scales BB
  - 42 cm aperture
  - 6 frequency bands (30 - 280 GHz)
  - 30,000 dichroic TES
  - 10% of the sky observed splitted in 2 patches

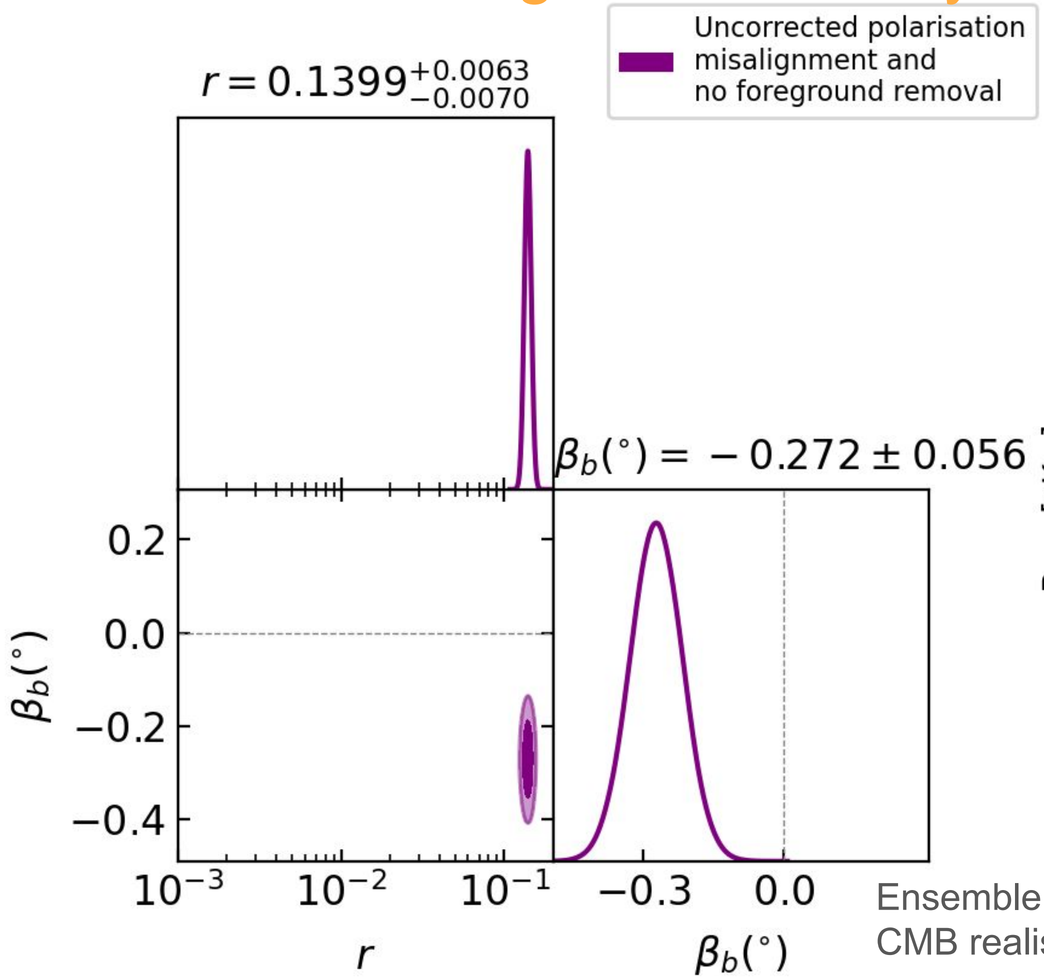
**Baseline white noise, optimistic 1/f from Ade et al 2018:**

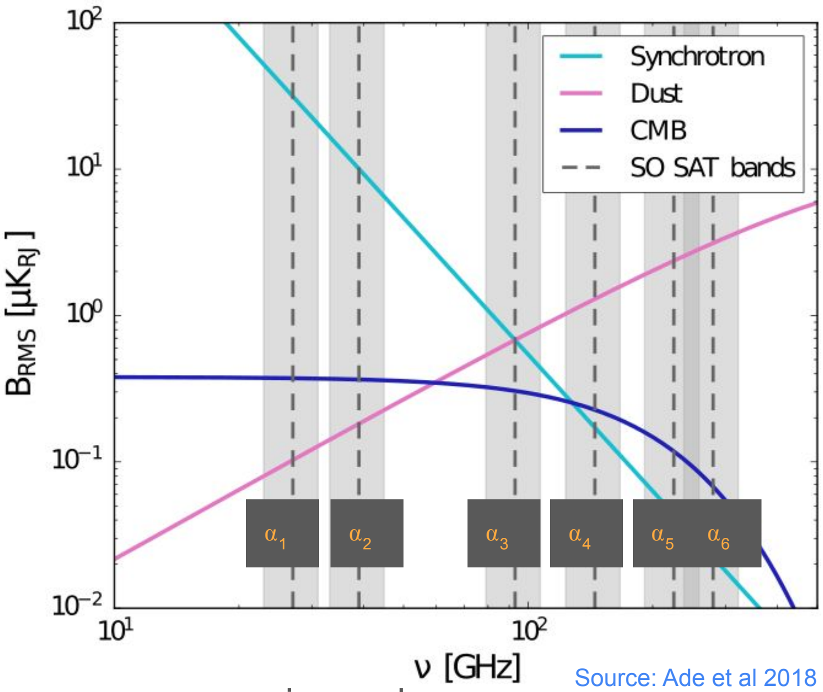
| Frequency channel [GHz] | 27 | 39 | 93 | 145 | 225 | 280 |
|---|---|---|---|---|---|---|
| sensitivity [$\mu$K-arcmin] | 21 | 13 | 3.4 | 4.3 | 8.6 | 22 |
| $\ell_{knee}$ | 15 | 15 | 25 | 25 | 35 | 40 |
| FWHM [arcmin] | 91 | 63 | 30 | 17 | 11 | 9 |




Source : Josquin Errard

# The effects of foregrounds and systematics on r and $\beta_b$




Source: Ade et al 2018

Ensemble average over noise and CMB realisation

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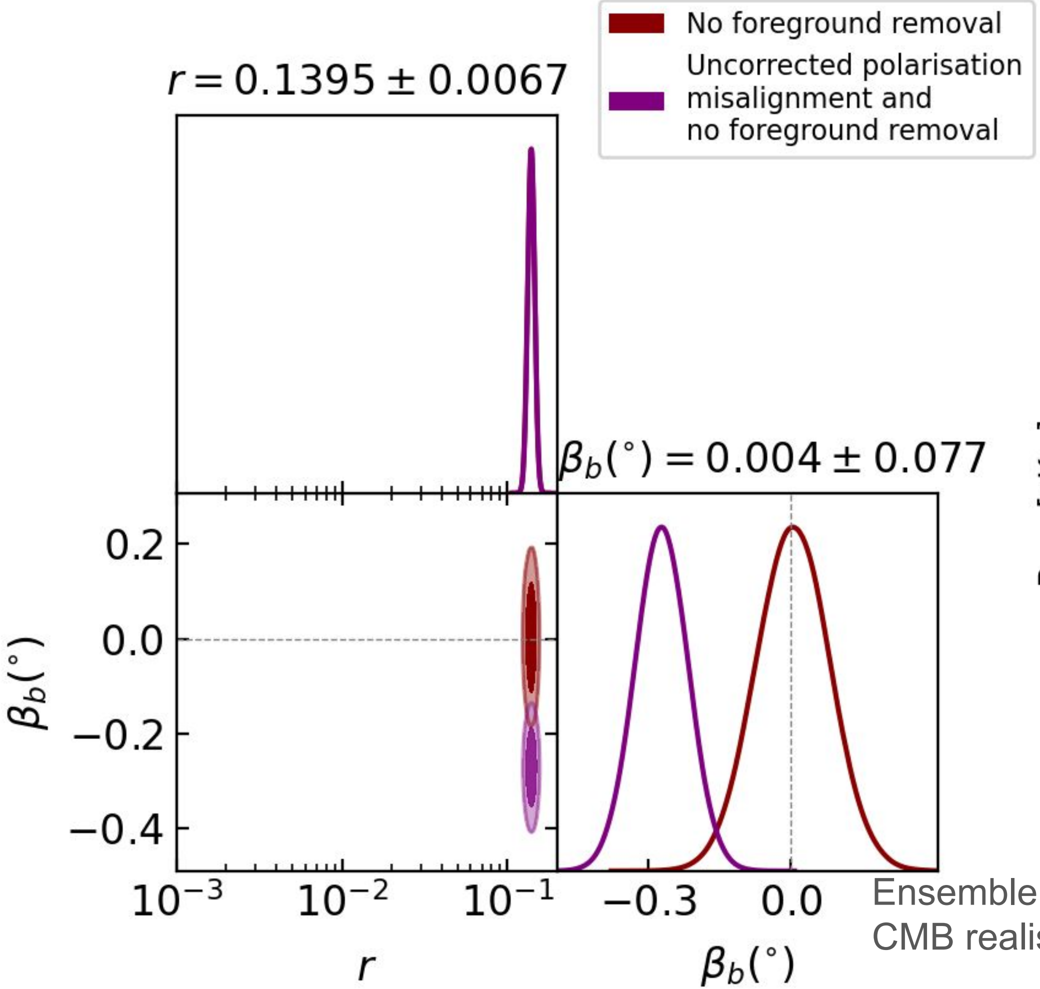


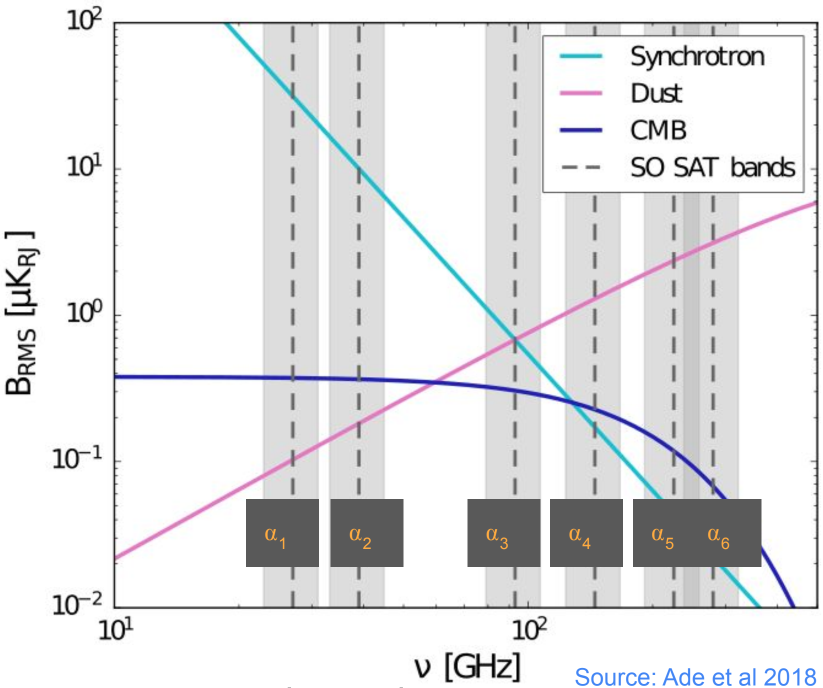


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Ensemble average over noise and CMB realisation

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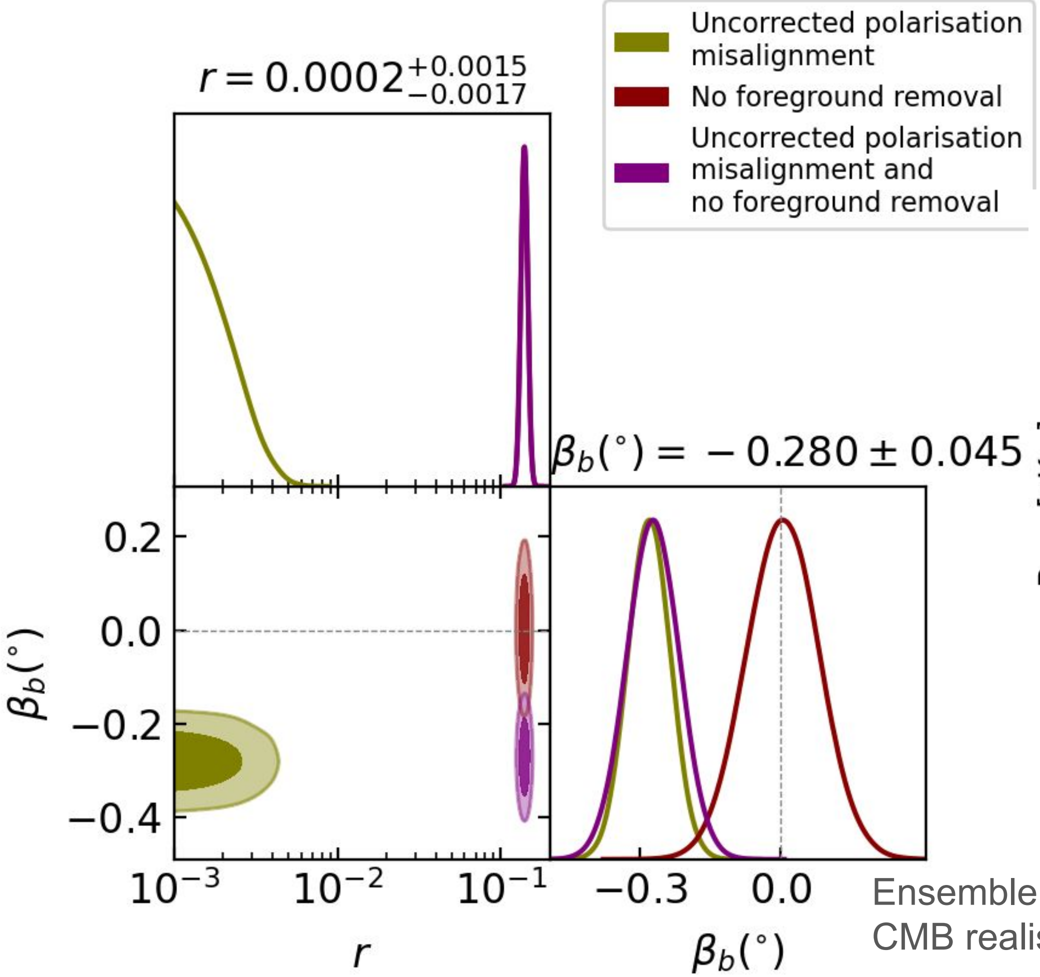


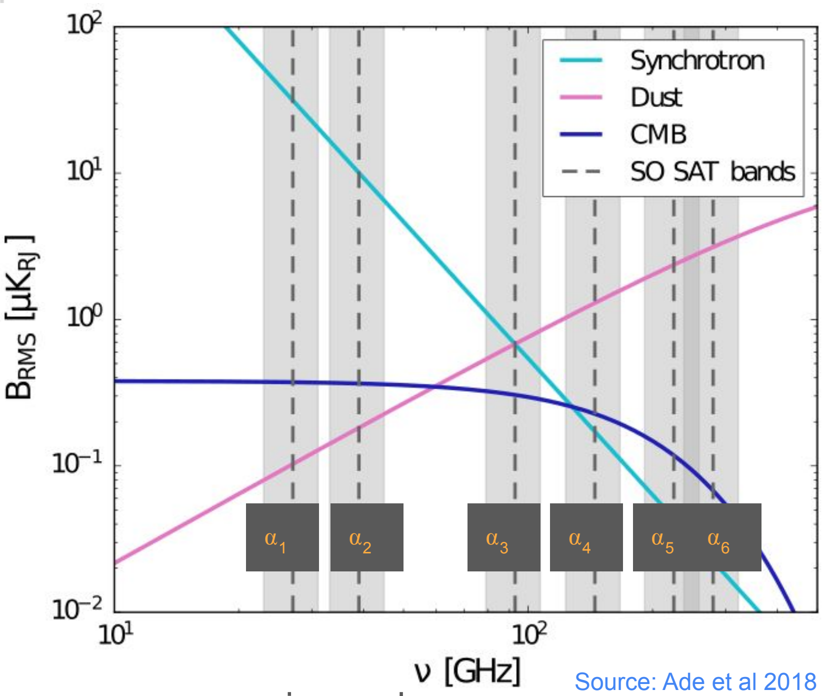


Ensemble average over noise and CMB realisation

Source: Ade et al 2018

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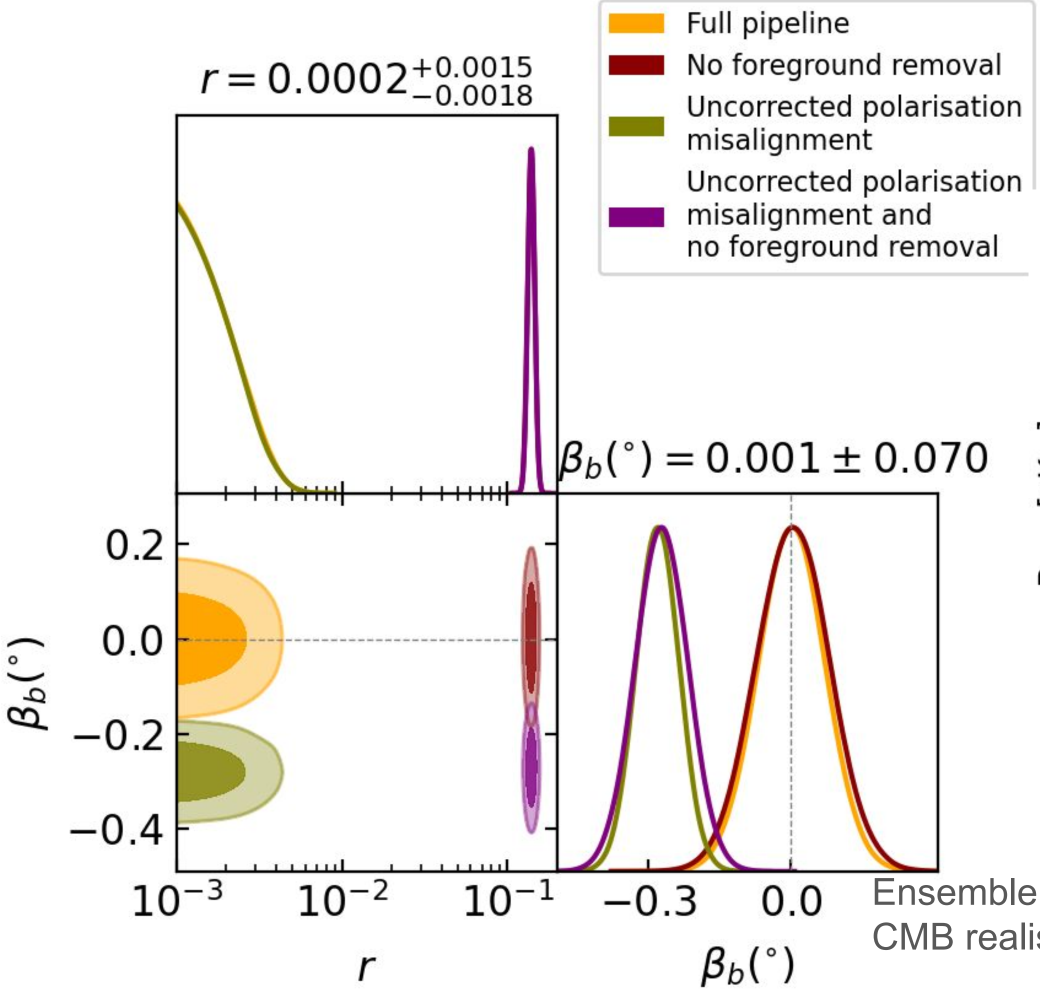
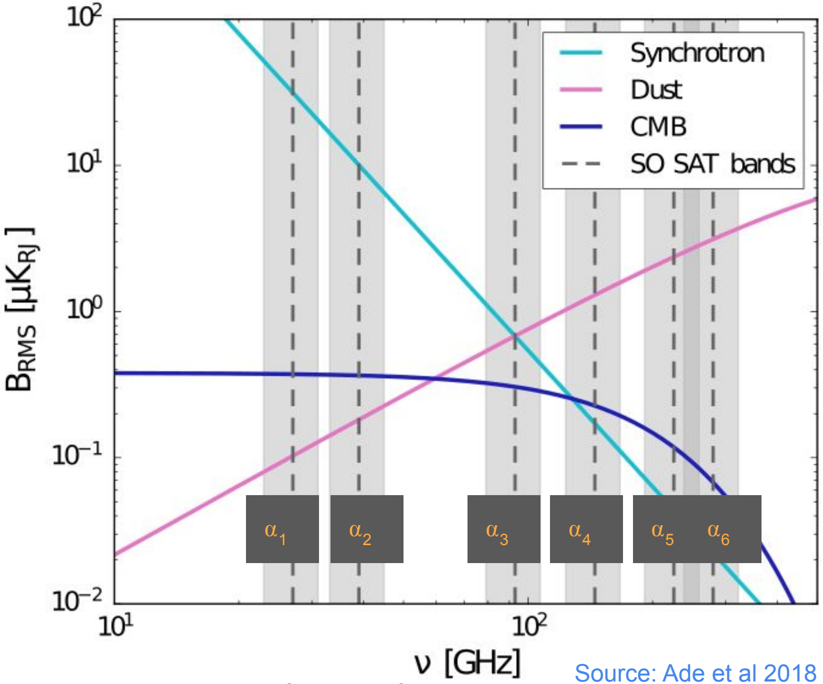


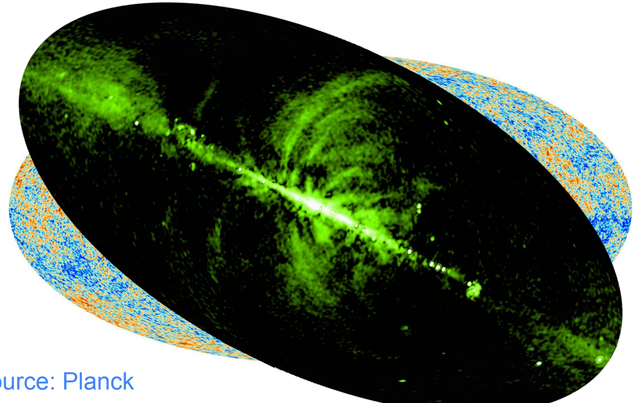




Ensemble average over noise and CMB realisation

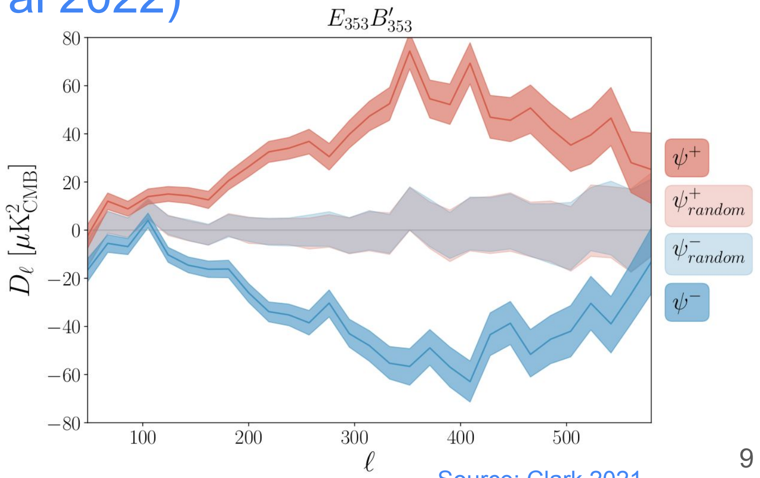
Source: Ade et al 2018

# The polarisation angle of the telescope problem

- Miscalibration of the polarisation angle of the telescope degenerate with birefringence angle
- Self calibration (Keating et al 2012) destroys isotropic birefringence signal
- Lift the degeneracy : Minami, Komatsu 2020 uses foregrounds
- Vanishing EB correlations are assumed to fit for miscalibration
- Hint of non-zero birefringence angle β=0.35 ± 0.14° from Planck data (Minami, Komatsu 2020, Diego-Palazuelos et al 2022)
- Clark et al 2021: non-zero foregrounds EB



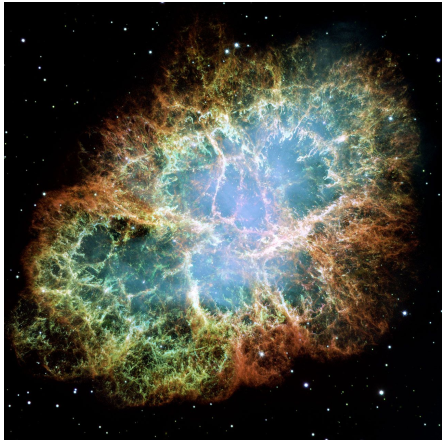
Source: Planck




Source: Clark 2021

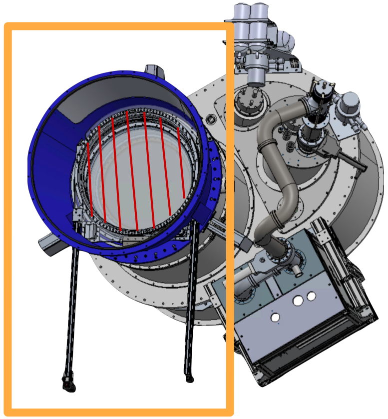
# Foreground cleaning and instrumental effects

- We investigate a method which is agnostic wrt foregrounds EB and uses calibration priors to lift degeneracy in the component separation step.
  - Tau A measurements $\sigma(\alpha) \simeq 0.27°$ (Aumont et al 2020)
  - Wire grid on top of the window $\sigma(\alpha) \simeq 1°$ (Bryan et al 2018)
  - Drone $0.01° \lesssim \sigma(\alpha) \lesssim 0.1°$(Nati et al 2017, Gabriele Coppi's talk this morning)
- Frequency dependence of signals
  - Propagation of prior informations



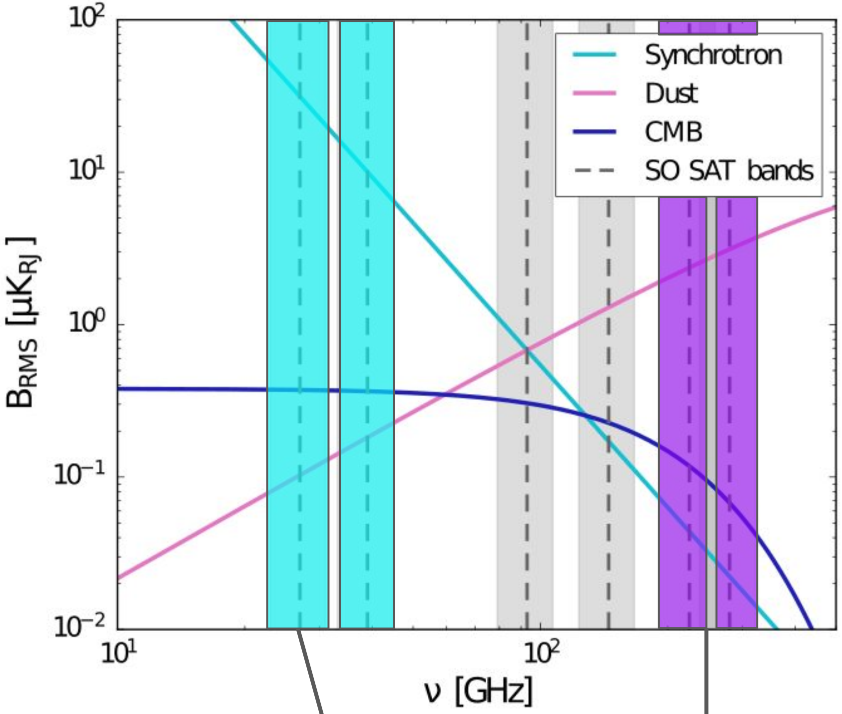
Source: Nasa/Hubble

Source: Nati 2017



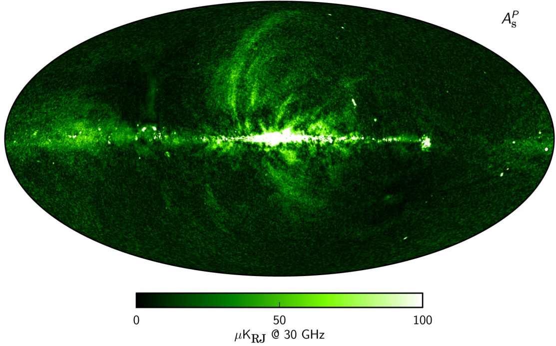
Wire grid

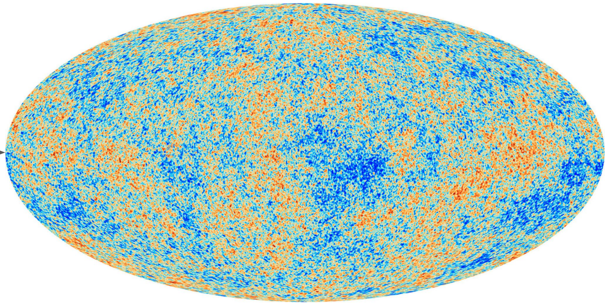
# Component separation

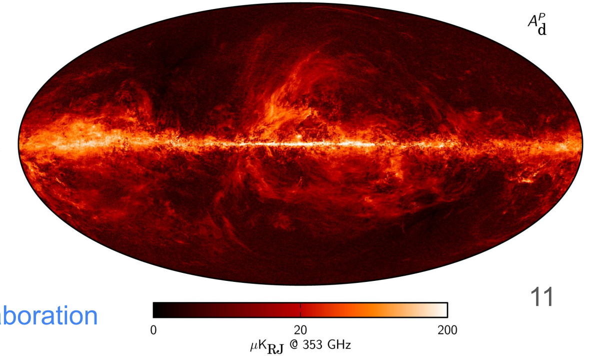



**synchrotron characterisation**

**dust characterisation**

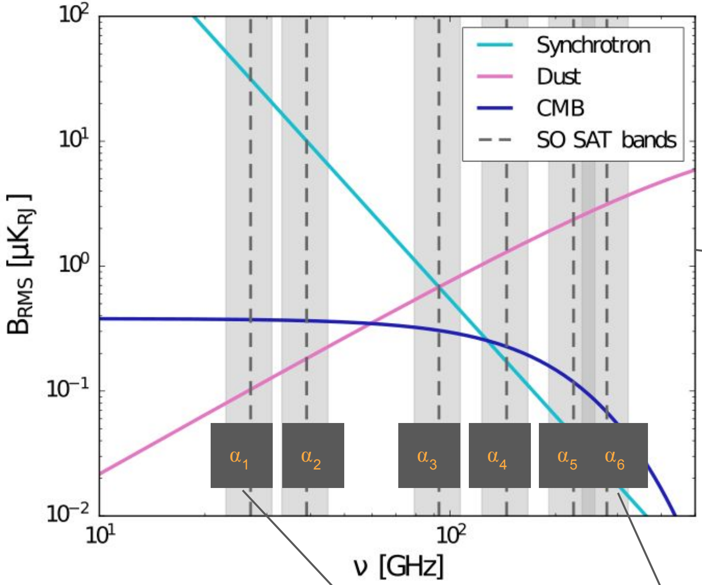





Source : 1808.07445; Planck collaboration

# A new data model for generalised parametric component separation




$$d_p = X(\{\alpha_1, ..., \alpha_n\}).A_p(\{\beta_{fg}\}).B(\{\beta_b\}).s_p + n_p$$

Miscalibration matrix

Mixing matrix

Birefringence matrix

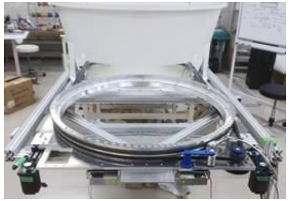
# Prior on spectral likelihood

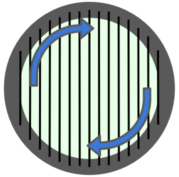
We add calibration priors to the spectral likelihood from Stompor et al 2016 averaged of CMB and noise realisations to lift degeneracies :

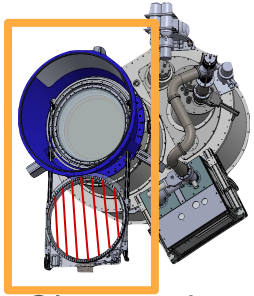
$$\langle \mathcal{S}_{spec} \rangle = -\mathrm{tr} \sum_{p} \left\{ (\mathbf{N}_p^{-1} - \mathbf{P}_p) \left( \hat{\mathbf{d}}_p \hat{\mathbf{d}}_p^t + \mathbf{N}_p \right) \right\}.$$

$$\mathcal{S}' = \mathcal{S} + \sum_{\alpha_i} \frac{1}{2\sigma_{\alpha_i}^2} (\alpha_i - \tilde{\alpha}_i)^2$$

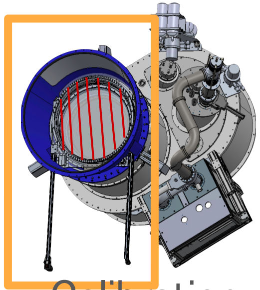
- Astrophysics free calibration methods
- Sparse wire grid : 1 deg precision requirement (Bryan et al 2018)
- Drone : 0.01°≲ σ(α) ≲ 0.1° precision (Nati et al 2017)



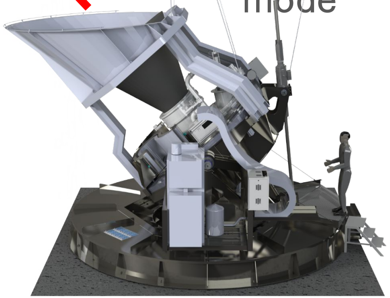




Observation mode

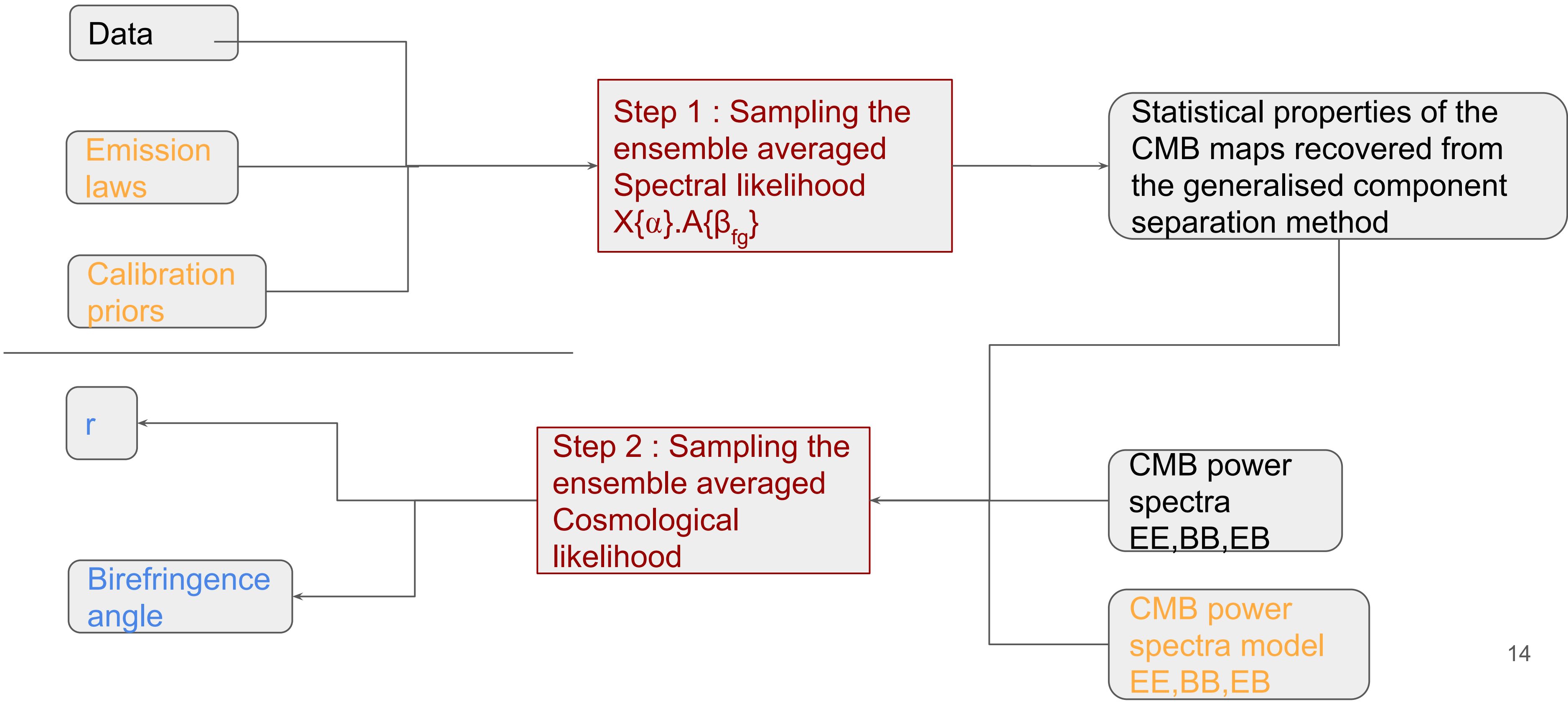


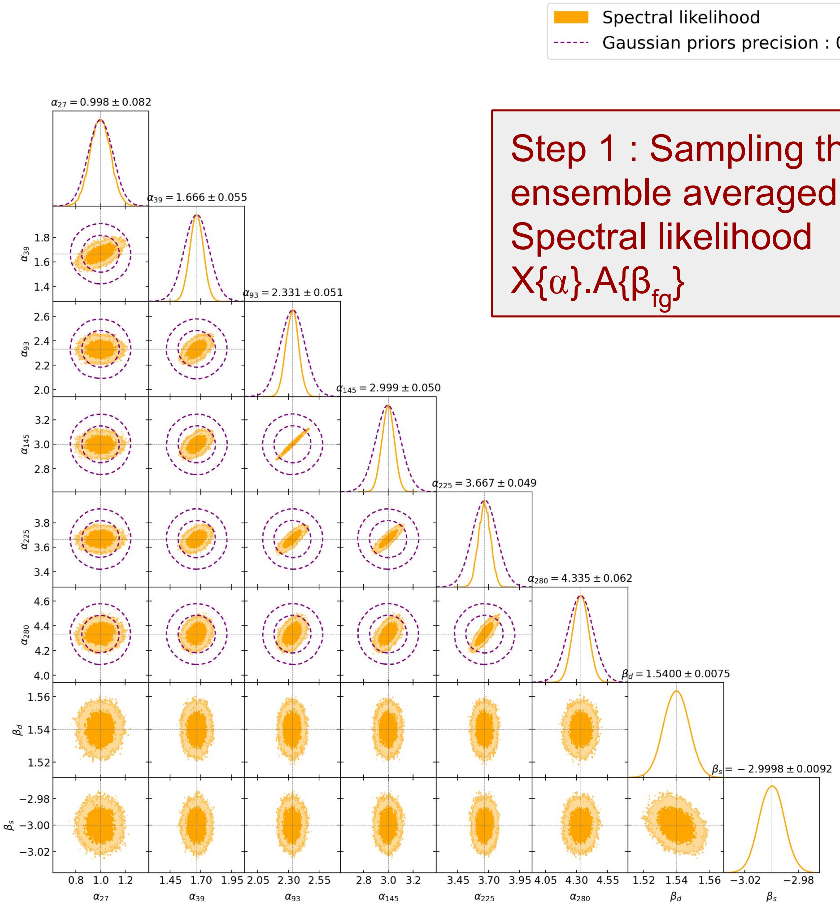
Calibration mode



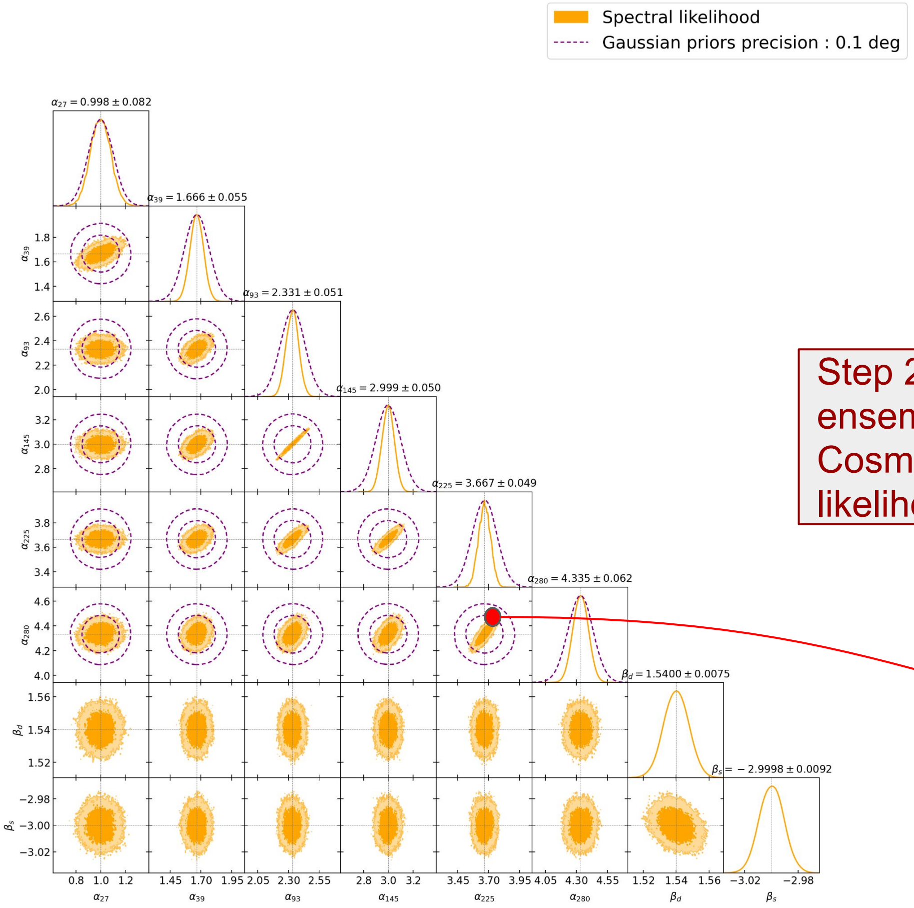
# Pipeline summary : 2 steps analysis

Jost et al (2022) in prep

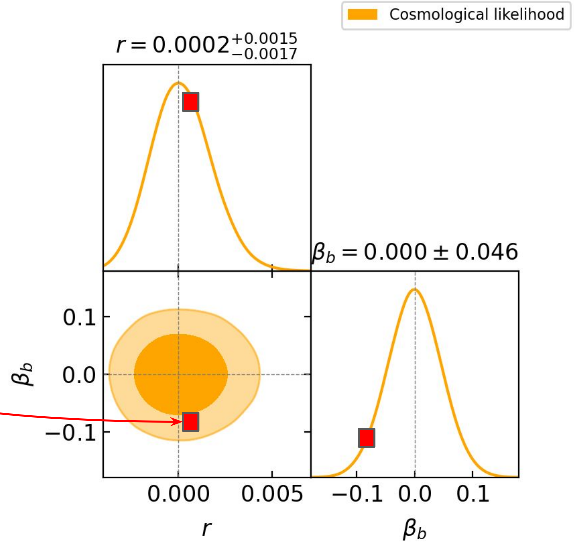




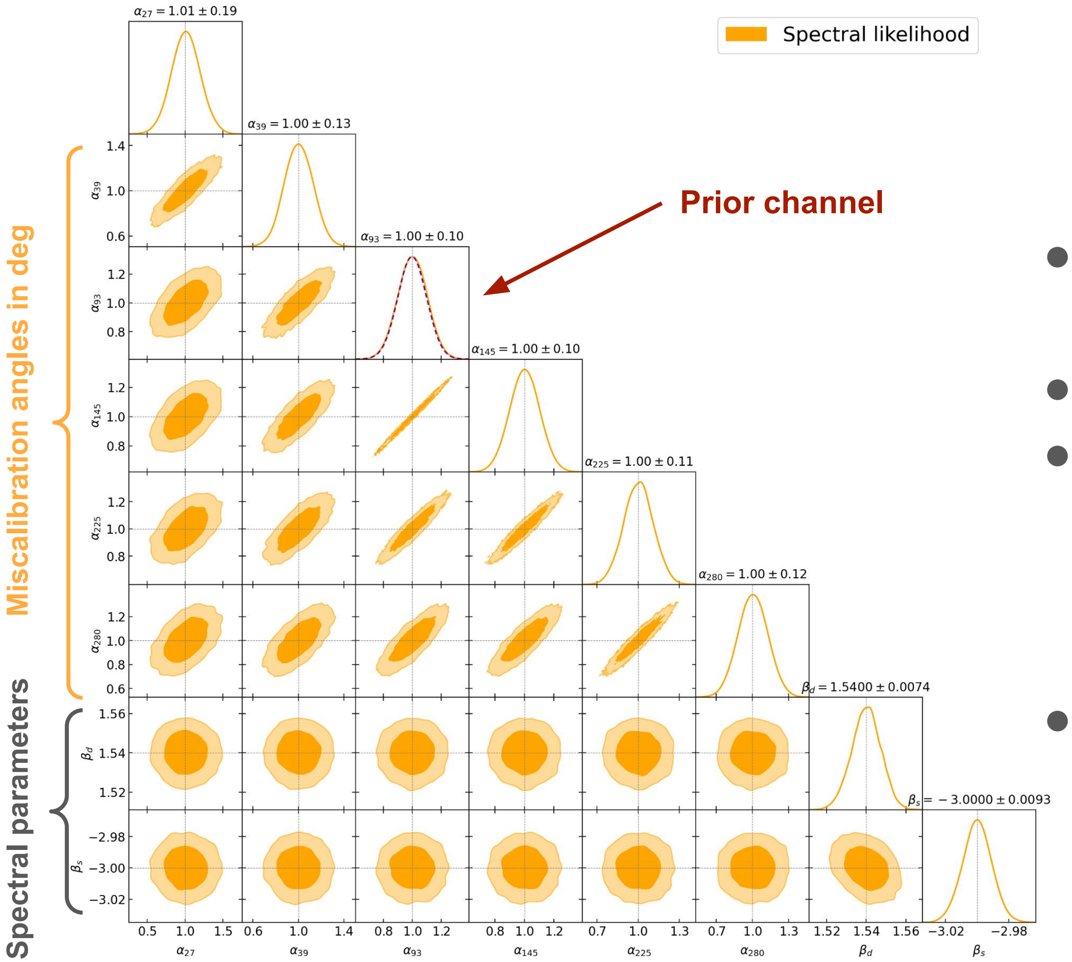

Step 1 : Sampling the ensemble averaged Spectral likelihood $X\{\alpha\}.A\{\beta_{fg}\}$




Step 2 : Sampling the ensemble averaged Cosmological likelihood



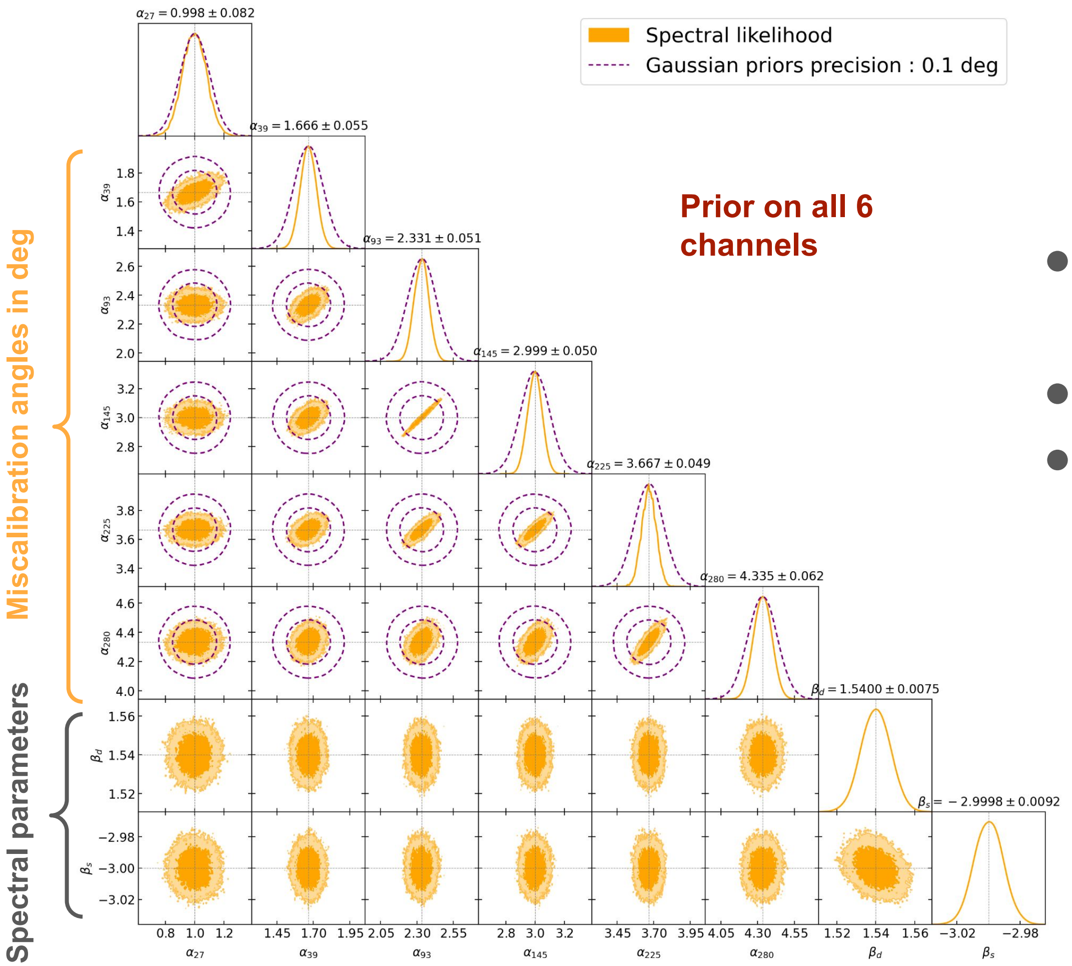
# Forecast case study : SO SAT 0.1 deg prior on 93 GHz




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

- True sky model : d0s0 pysm model Zonca et al 2021
- **Baseline white noise,**
- Taking advantage of the foregrounds to constrain miscalibration angles : only one prior needed
- Only one prior needed but adding more is better and more robust

# Forecast case study : SO SAT 0.1 deg prior on all channels

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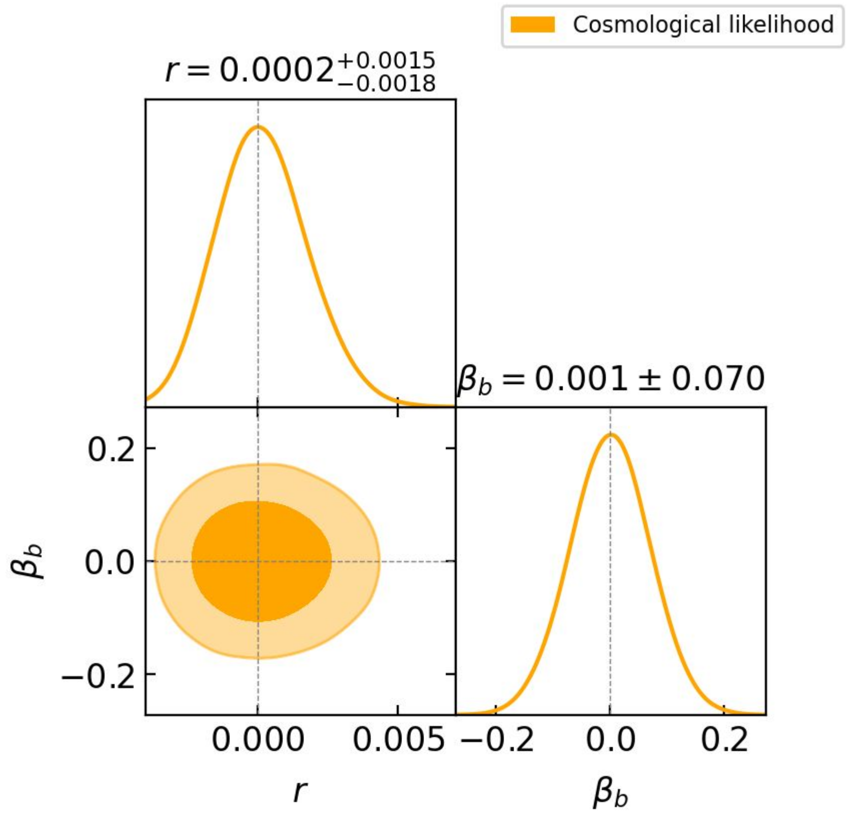
# Results : SO SAT 0.1 deg prior on all channels

Step 2 : Sampling the ensemble averaged Cosmological likelihood




- True sky model : d0s0 pysm model Zonca et al 2021
- **input parameters :**
  - **r = 0.0**
  - **$\beta_b$ = 0.0°**

**Baseline white noise, optimistic 1/f from Ade et al 2018:**

| Frequency channel [GHz] | 27 | 39 | 93 | 145 | 225 | 280 |
|---|---|---|---|---|---|---|
| sensitivity [$\mu$K-arcmin] | 21 | 13 | 3.4 | 4.3 | 8.6 | 22 |
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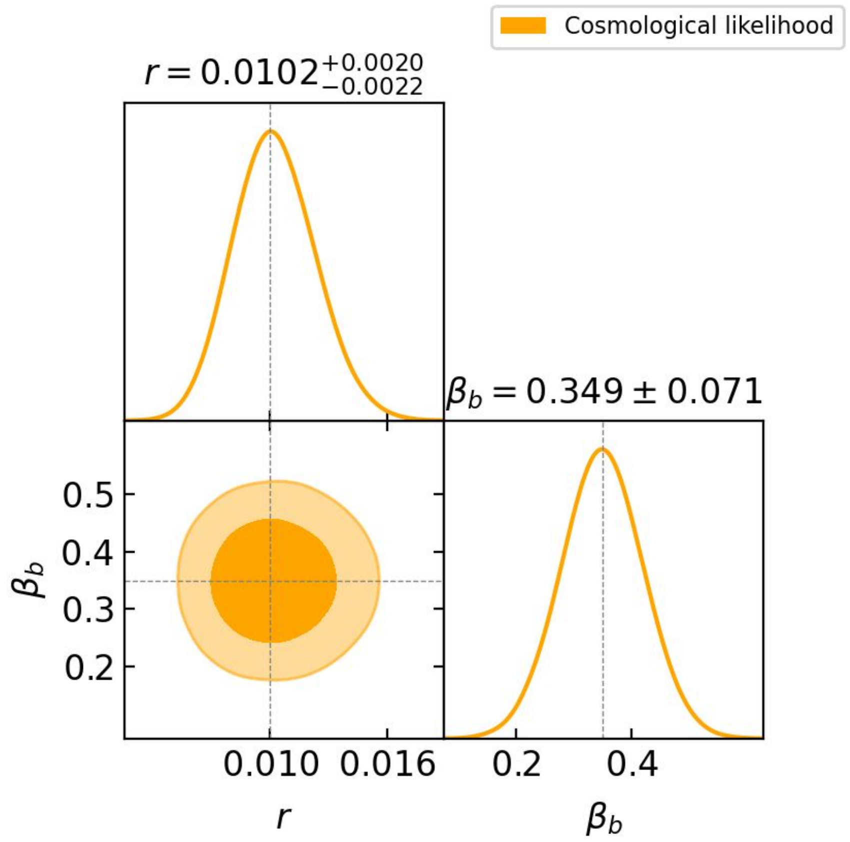


- True sky model : d0s0 pysm model Zonca et al 2021
- **input parameters :**
  - **r = 0.01**
  - **$\beta_b$ = 0.35° (Minami & Komatsu 2020)**
- **~ 5 sigma**

**Noise and beam specifications from Ade et al 2018:**

| Frequency channel [GHz] | 27 | 39 | 93 | 145 | 225 | 280 |
|---|---|---|---|---|---|---|
| sensitivity [$\mu$K-arcmin] | 21 | 13 | 3.4 | 4.3 | 8.6 | 22 |
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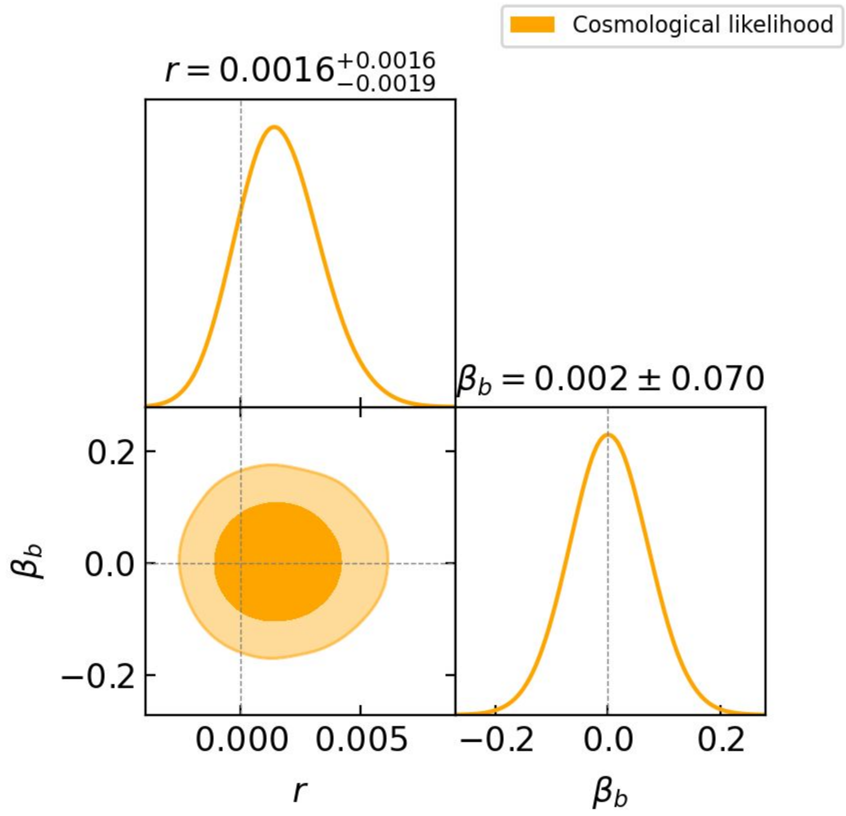


- True sky model : **d7s3** pysm model Zonca et al 2021
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| Frequency channel [GHz] | 27 | 39 | 93 | 145 | 225 | 280 |
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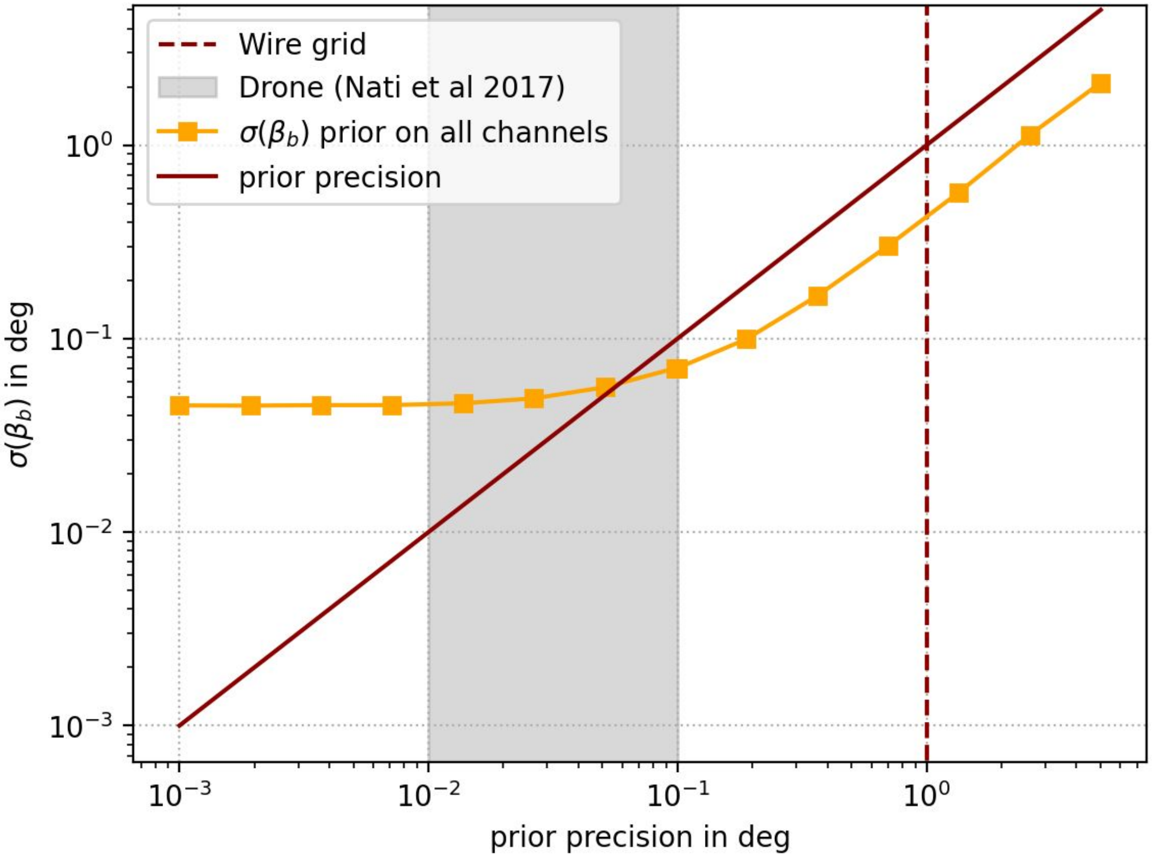
# Results : Evolution of precision wrt prior precision

We are able to set requirements for future calibration missions




- True sky model : d0s0 pysm model Zonca et al 2021
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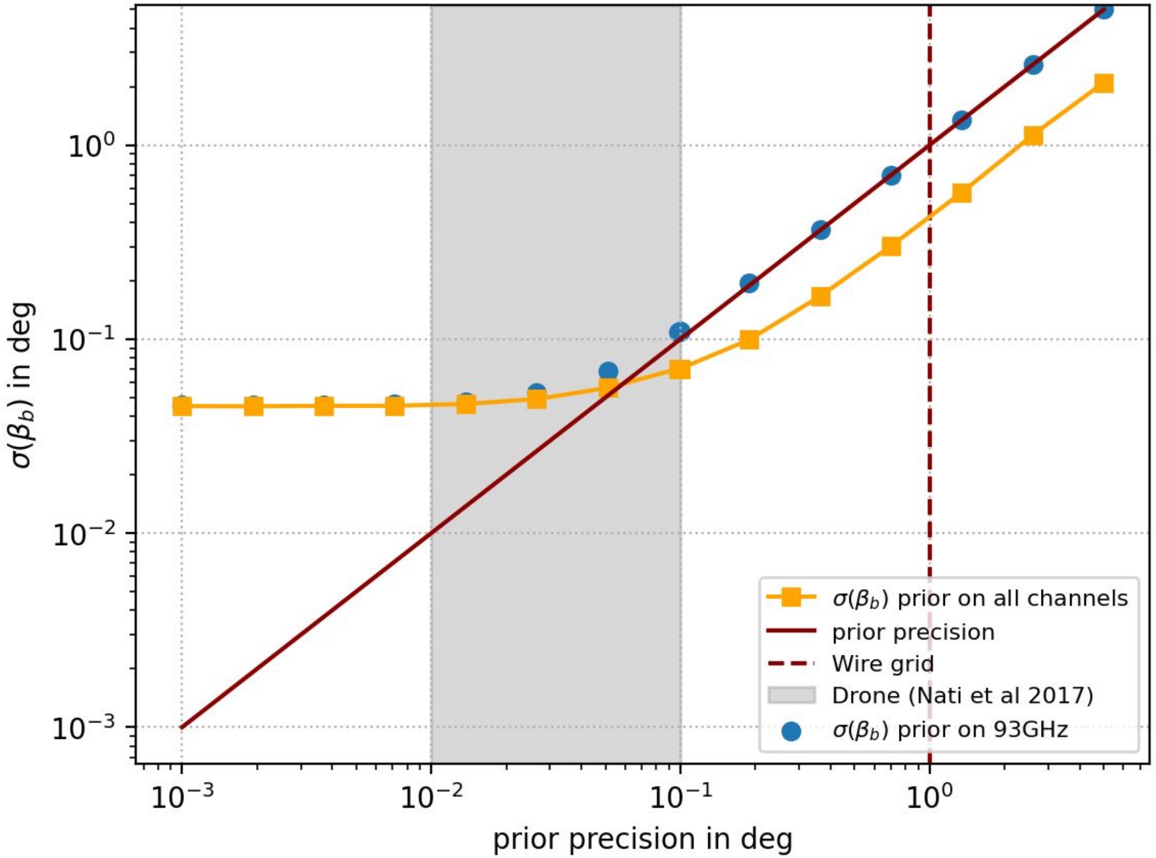


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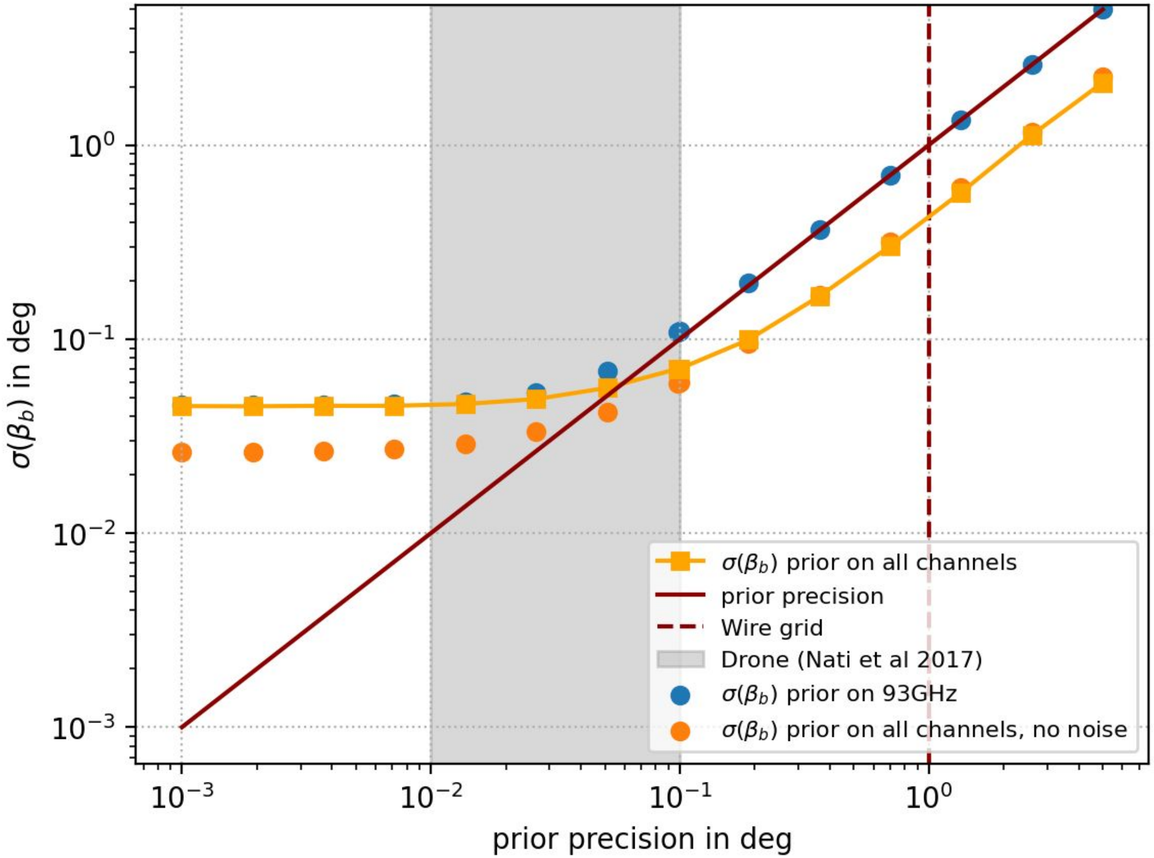


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# Perspectives

$$X(\{\alpha_1, ..., \alpha_n\}) = \begin{pmatrix} cos(2\alpha_1) & sin( & & 0 \\ -sin(2\alpha_1) & cos( & & \\ & & & \\ & & \alpha_n) & sin(2\alpha_n) \\ 0 & & 2\alpha_n) & cos(2\alpha_n) \end{pmatrix}$$


à la Vergès et al 2020

**Systematic** matrix

$$d_p = X(\{\alpha_1, ..., \alpha_n\}).A_p(\{\beta_{fg}\}).B(\{\beta_b\}).s_p + n_p$$

Source: Kyohei Yamada

# Perspectives

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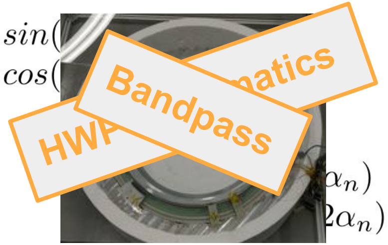


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# Perspectives

$$X(\{\alpha_1, ..., \alpha_n\}) = \begin{pmatrix} cos(2\alpha_1) & sin( \cdots & & 0 \\ -sin(2\alpha_1) & & & \\ & & & \\ & & \alpha_n) & sin(2\alpha_n) \\ 0 & & 2\alpha_n) & cos(2\alpha_n) \end{pmatrix}$$

Polarisation efficiency

HWP

...tics

**Systematic** matrix

$$d_p = X(\{\alpha_1, ..., \alpha_n\}).A_p(\{\beta_{fg}\}).B(\{\beta_b\}).s_p + n_p$$

# Perspectives

$$X(\{\alpha_1, ..., \alpha_n\}) = \begin{pmatrix} cos(2\alpha_1) & sin(\dots & & 0 \\ -sin(2\alpha_1) & \dots & & \\ & & & \\ & & \dots\alpha_n) & sin(2\alpha_n) \\ 0 & & \dots 2\alpha_n) & cos(2\alpha_n) \end{pmatrix}$$

Polari…

…tics

**And many more …**

**Systematic** matrix

$$d_p = X(\{\alpha_1, ..., \alpha_n\}).A_p(\{\beta_{fg}\}).B(\{\beta_b\}).s_p + n_p$$

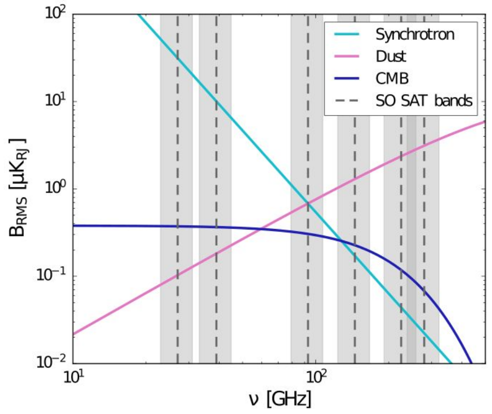
# Conclusion :

- I developed a new method based on parametric component separation that estimates the impact of foregrounds and systematic on the precision of r and $\beta_b$ in multi-frequency CMB experiments assuming for now the simplest (constant over the sky) parametrisation of foreground parameters.
- General and versatile framework :
  - other systematic such as HWP
  - other experiments CMB-S4 / LiteBIRD

# THANK YOU !

Source : Deborah Kellner

# Parametric component separation




- We assume frequency scaling of sky components
- Only spectral parameters to fit

$$d_p = A_p(\{\beta_{fg}\}).s_p + n_p$$

Data vector

$$d_p = \begin{pmatrix} Q_1 \\ U_1 \\ \vdots \\ Q_n \\ U_n \end{pmatrix}_p$$

Mixing matrix

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

Sky signal

$$s_p = \begin{pmatrix} Q^{CMB} \\ U^{CMB} \\ Q^d \\ U^d \\ Q^s \\ U^s \end{pmatrix}$$

# Example : The polarisation angle of the telescope, new data model

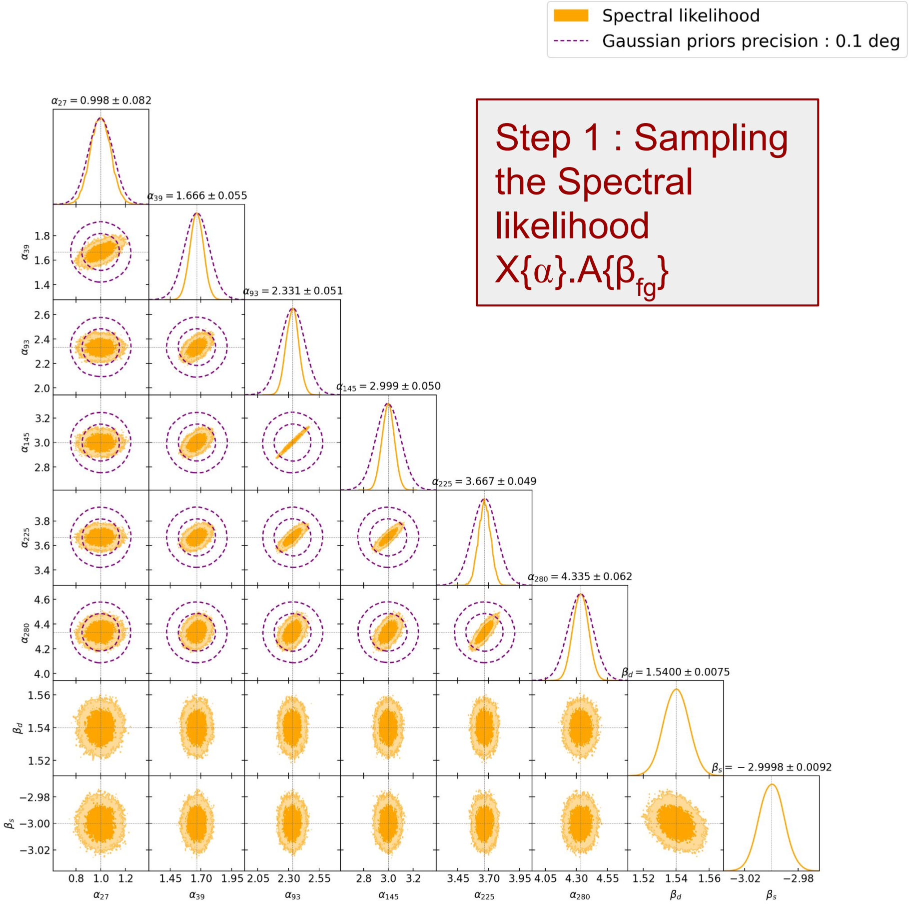
$$X(\{\alpha_1, ..., \alpha_n\}) = \begin{pmatrix} cos(2\alpha_1) & sin(2\alpha_1) & & & 0 \\ -sin(2\alpha_1) & cos(2\alpha_1) & & & \\ & & \ddots & & \\ & & & cos(2\alpha_n) & sin(2\alpha_n) \\ 0 & & & -sin(2\alpha_n) & cos(2\alpha_n) \end{pmatrix}$$

Miscalibration matrix

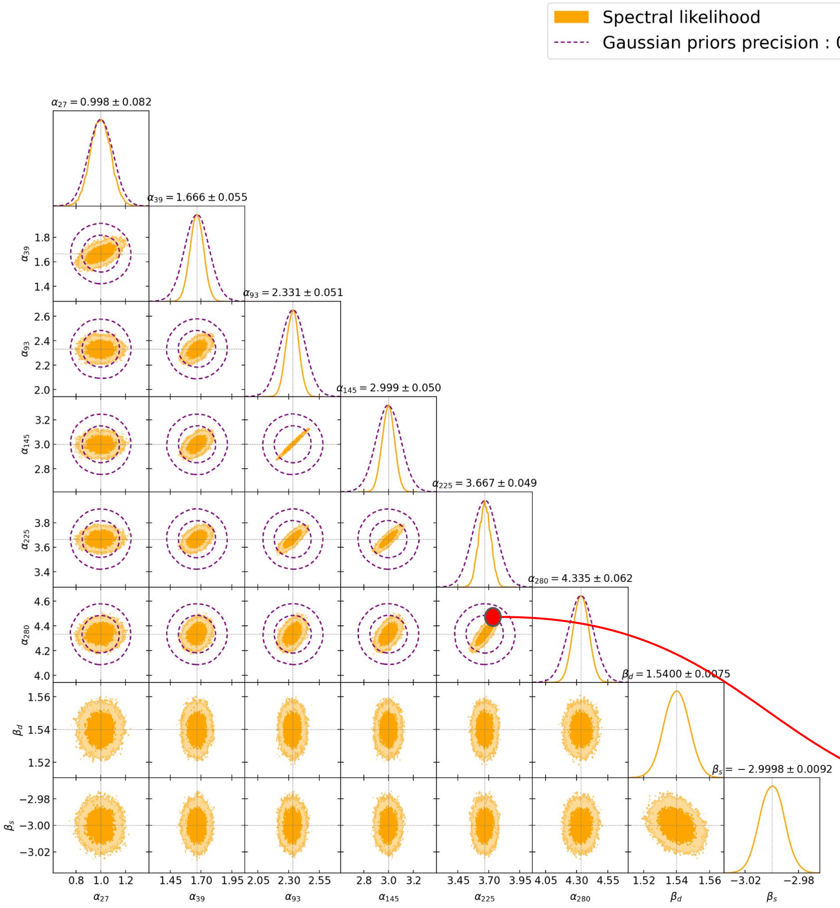
$$d_p = X(\{\alpha_1, ..., \alpha_n\}).A_p(\{\beta_{fg}\}).B(\{\beta_b\}).s_p + n_p$$

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

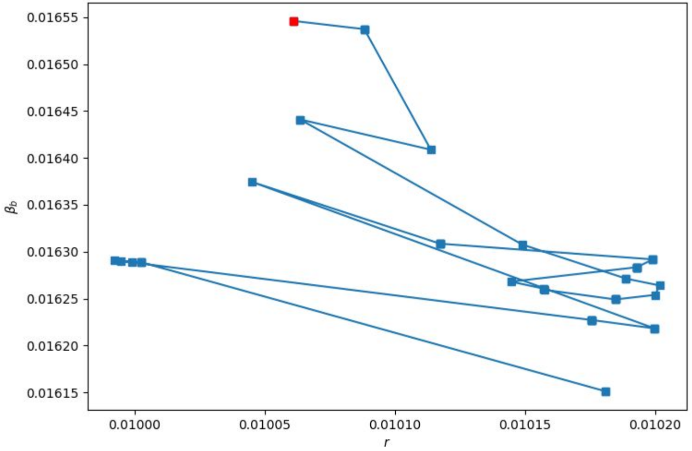
Birefringence matrix

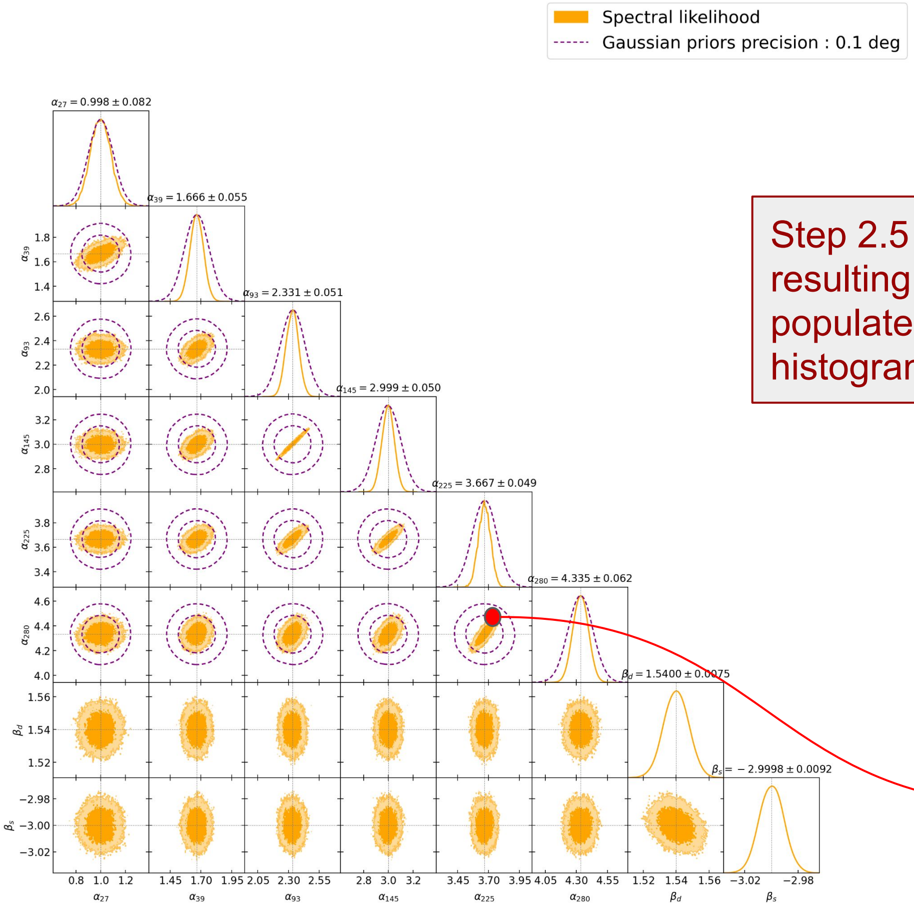



Step 1 : Sampling the Spectral likelihood $X\{\alpha\}.A\{\beta_{fg}\}$




Step 2 : For each sample of the spectral likelihood : sample the Cosmological likelihood






Step 2.5 : The resulting point populates the final histogram of r and $\boldsymbol{\beta_b}$