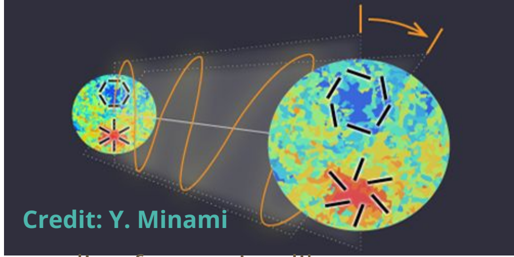
A novel method for joint systematic correction and foreground cleaning and its application to the estimation of cosmic birefringence in Simons Observatory and LiteBIRD.

International Conference on the Physics of the Two Infinities

Baptiste Jost 29/03/2023

Cosmic Birefringence



Cosmic Birefrigence: rotation of polarisation angle of CMB

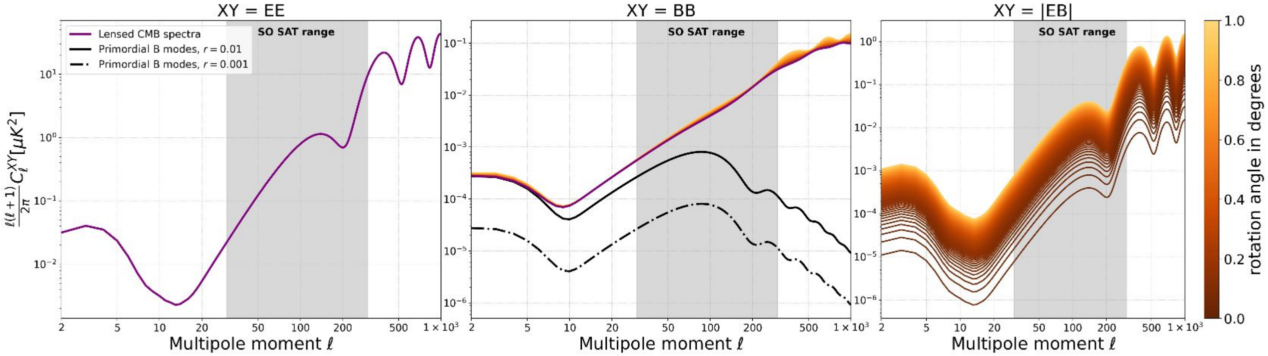
Correlation between E- and B-modes: window into parity violation mechanism, e.g. Chern-Simons coupling from axion-like particles

Focus on **spatially constant** and **time independent** cosmic birefringence: isotropic birefringence β_b

Hints $\beta_b = 0.35° \pm 0.14°$ from Planck data (**Minami et al. 2020** & **Diego-Palazuelos et al. 2022**) based on assumptions about foreground EB correlations for calibration.

My goals:

- How and with what precision can we measure β_b
- Requirements on calibration
- What is the effect on the measurement of r

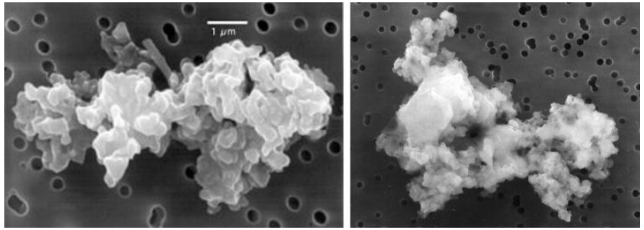


Problem 1: Galactic Foregrounds, Dust & Synchrotron

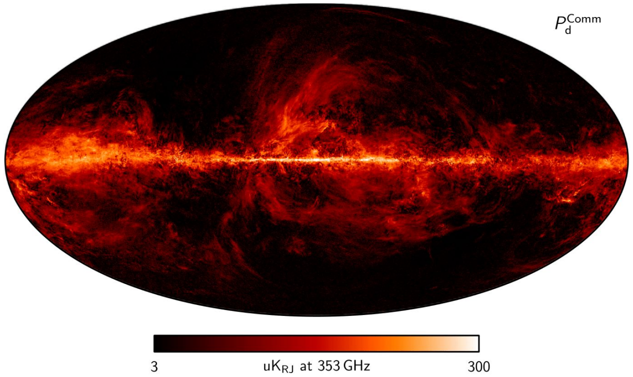
Dust emission: Asymmetric dust grains in the galaxy aligned with magnetic fields.

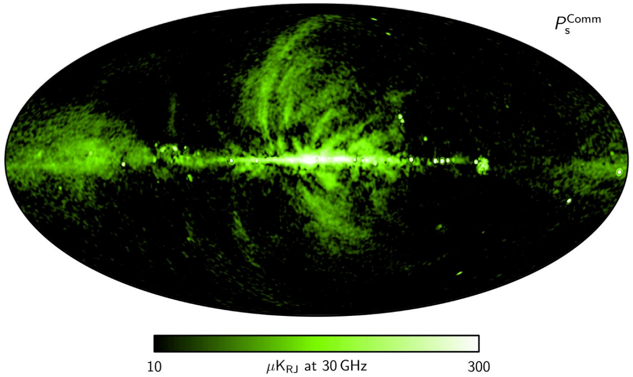
Synchrotron emissions: charged particles accelerated along Galactic magnetic fields.

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



Credit: B. T. Draine





Credit: Planck

Problem 2: Polarisation Angle Miscalibration

Miscalibration of telescope polarisation angle leads to the same effect on the spectra as isotropic birefringence!

Simons Observatory Small Aperture Telescopes (SAT) baseline:

- 3 Small Aperture Telescopes, refractive, 42 cm aperture: for large angular scales
- 6 frequency bands from 27 to 280 GHz.
- Atacama desert: high and dry.
- 30 000 detectors.
- 10% of the sky observed
- Baseline white noise and optimistic 1/f noise from **Ade et al 2018**

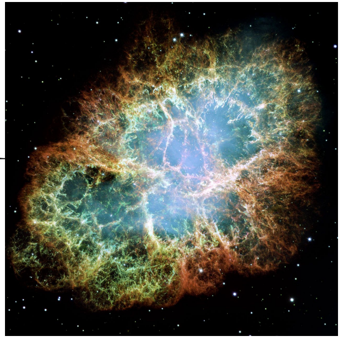
We will use SO SAT specifications for testing thanks to high polarisation sensitivity and promising calibration methods.

Polarisation Angle Calibrations

Several methods are explored for polarisation angle calibration:

- 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**

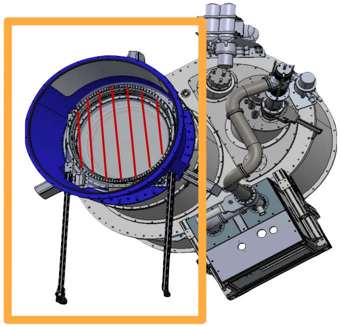
Credit: F. Nati



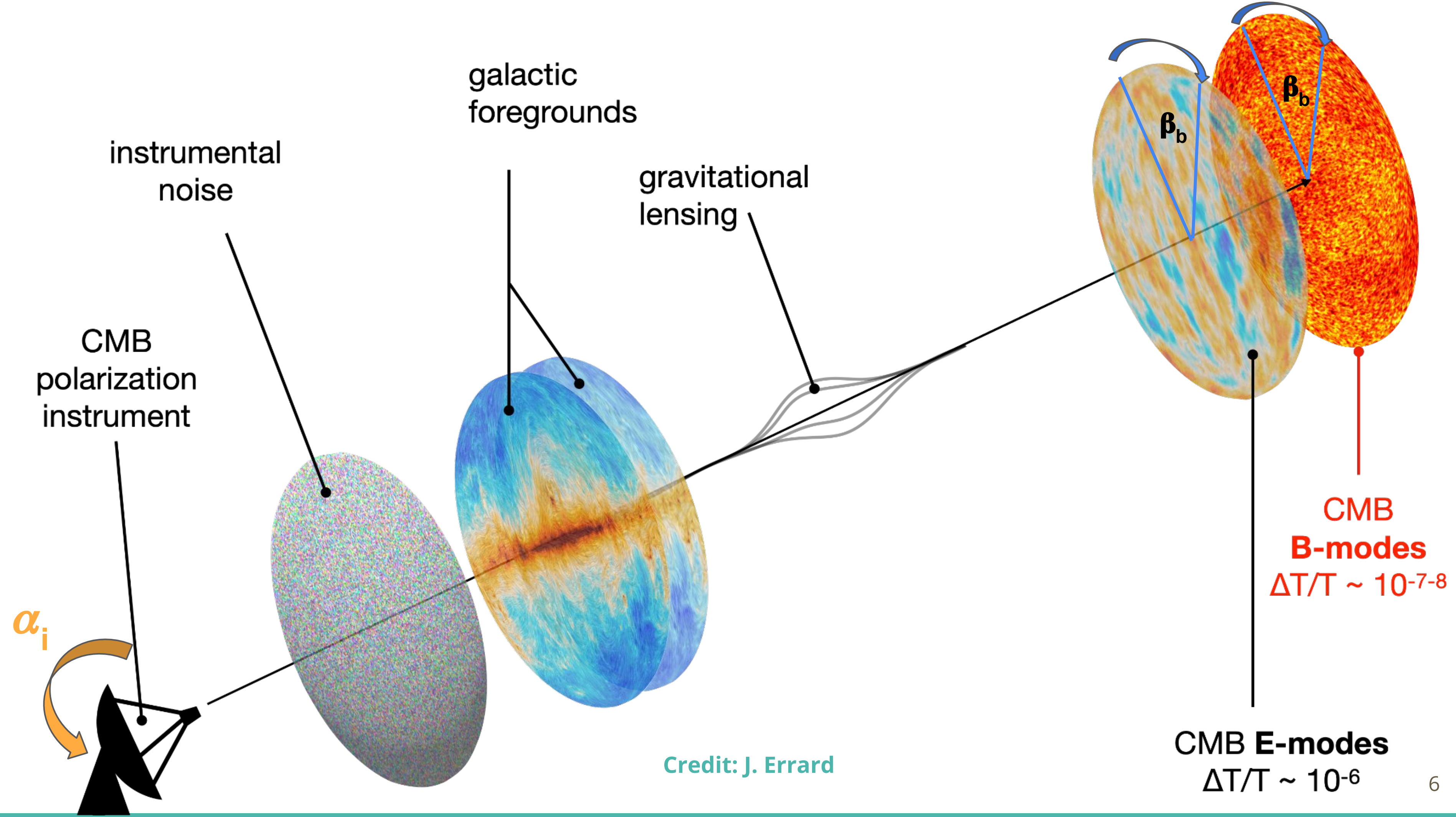
Credit: Nasa/Hubble

Analysis based:

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



Wire grid

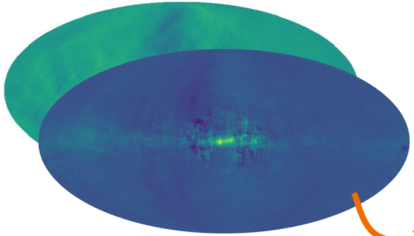


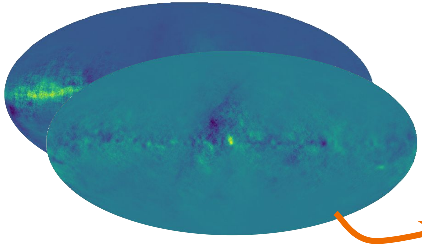
Credit: J. Errard

Map-Based Parametric Component Separation

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

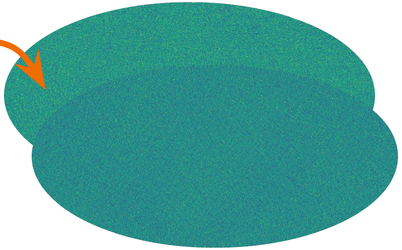
noise





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

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



Input frequency maps

Component maps

Map-Based Parametric Component Separation

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

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, β_d | Synchrotron β_s

The mixing matrix

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.

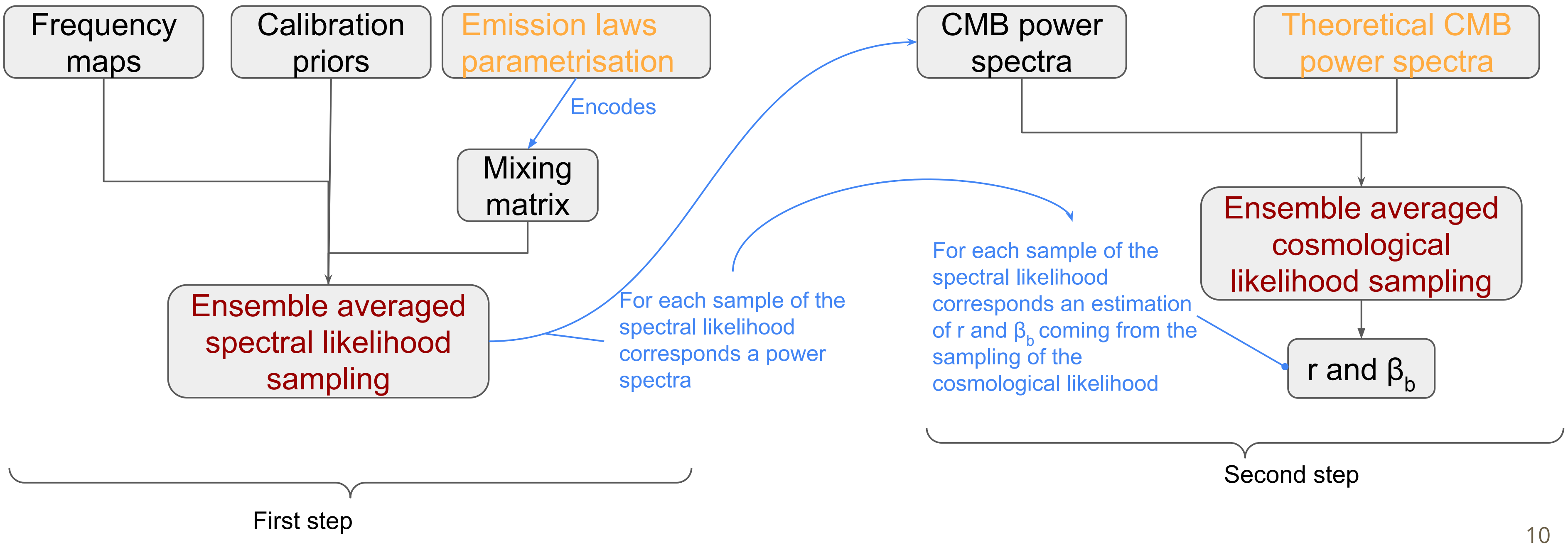
To lift the degeneracy we add priors to the likelihood:

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

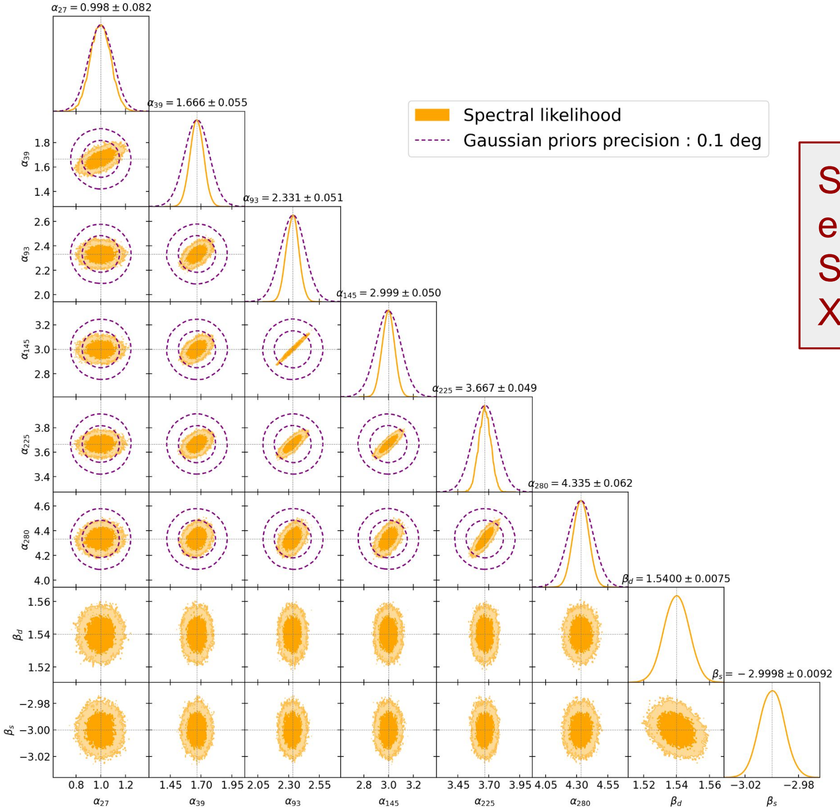
Credit: F. Nati

Pipeline Summary: A 2 Step Analysis

Jost et al. 2212.08007

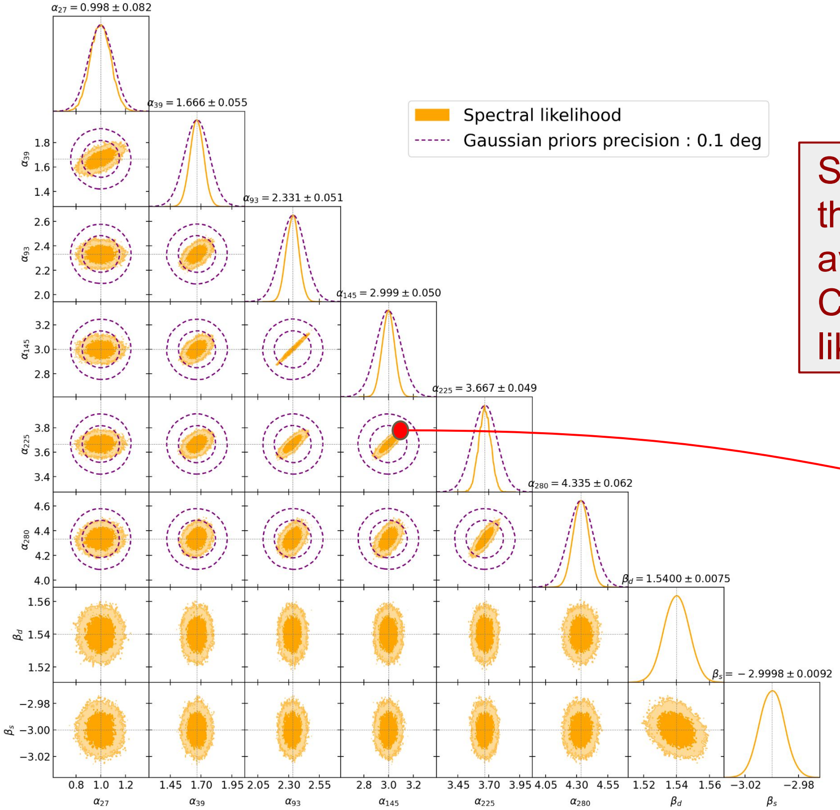


How to Have a Statistically Robust Method ?

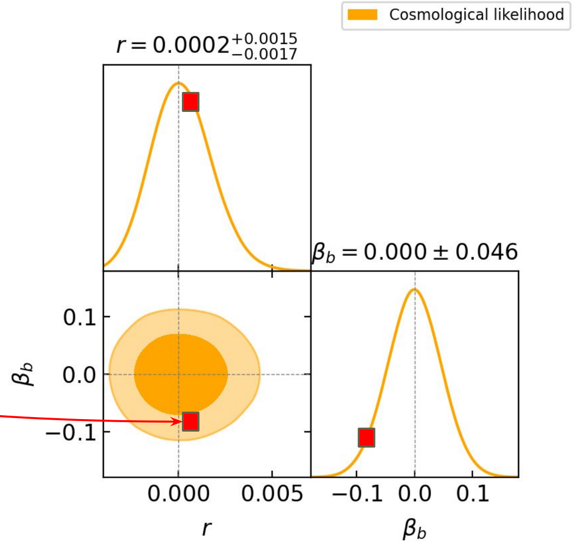


Step 1 : Sampling the ensemble averaged Spectral likelihood $X\{\alpha\}.A\{\beta_{fg}\}$

How to Have a Statistically Robust Method ?



Step 2 : Draw from the ensemble averaged Cosmological likelihood



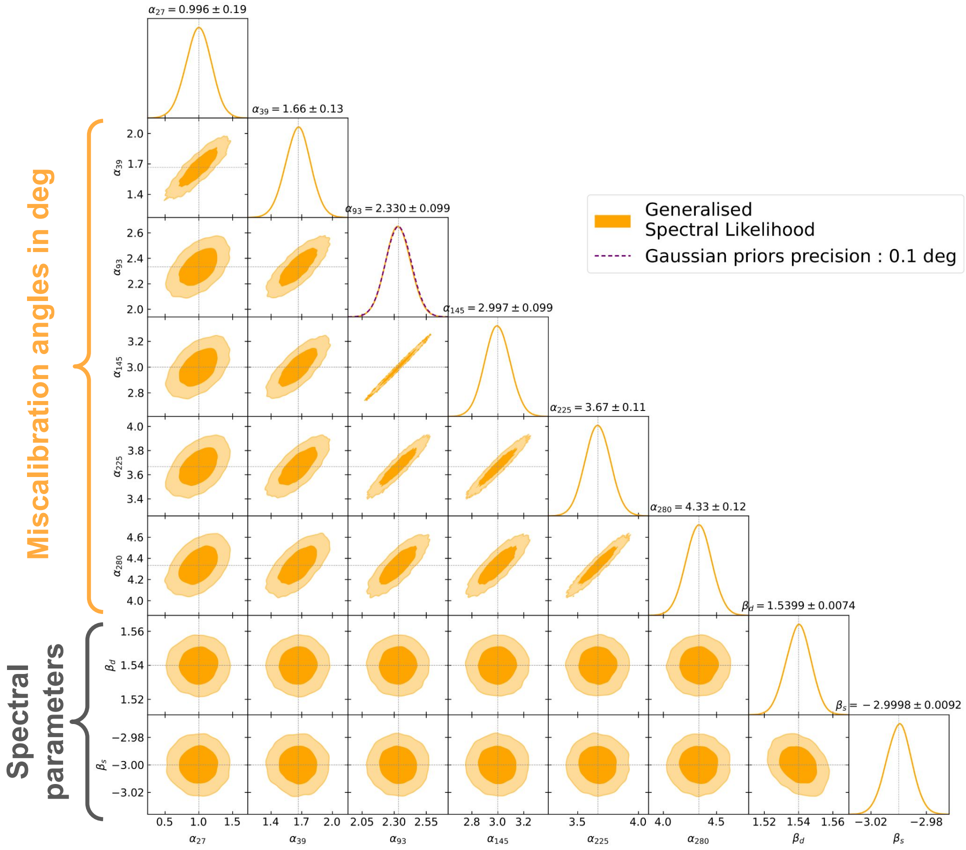
Simple Foregrounds and One Calibration Prior

- 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

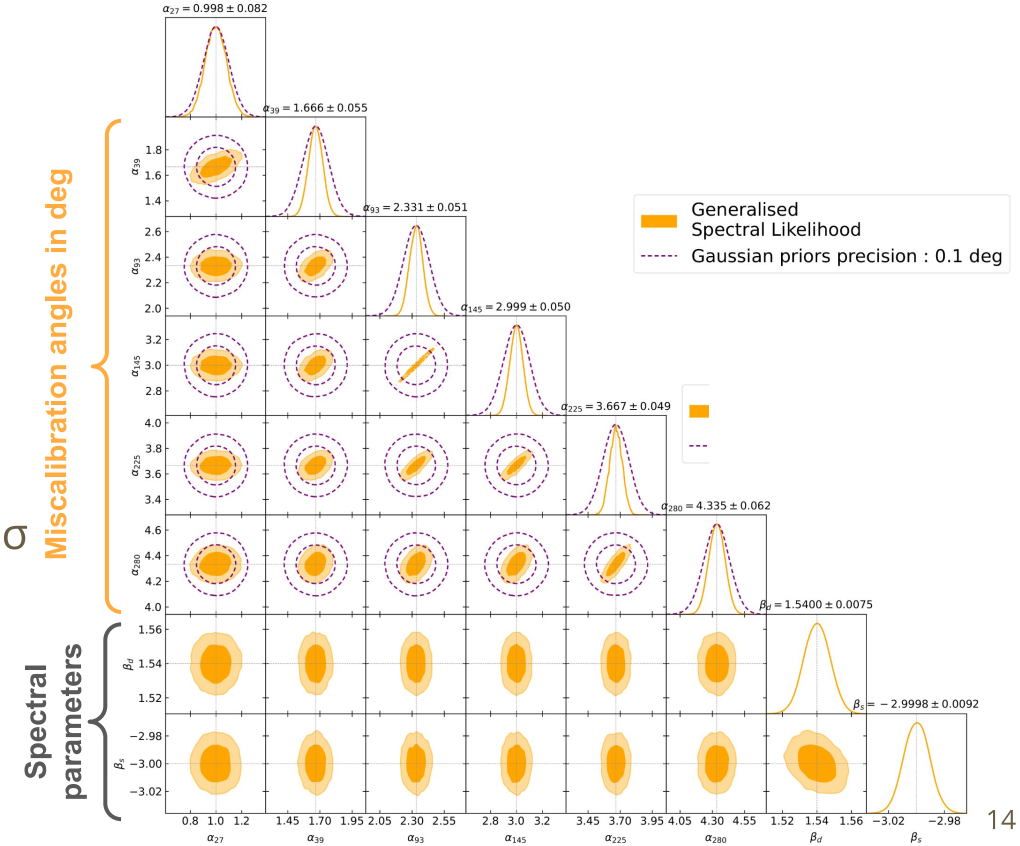


Simple Foregrounds and Six Calibration Priors

- Input CMB: **$r = 0.0$; $\beta_b = 0.0°$**
- 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!



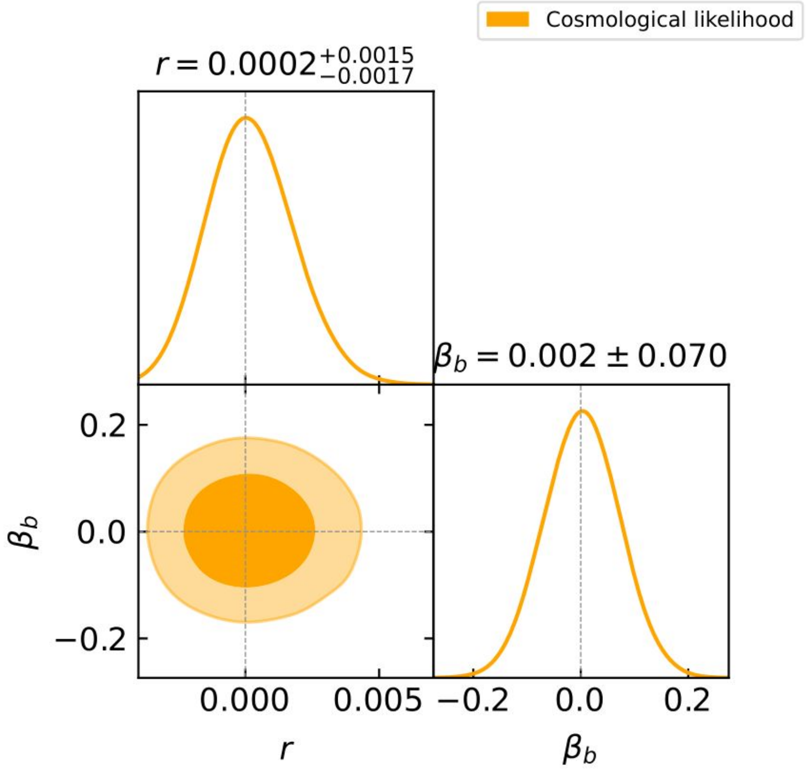
Simple Foregrounds and Six Calibration Priors

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

r and β_b correctly estimated

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

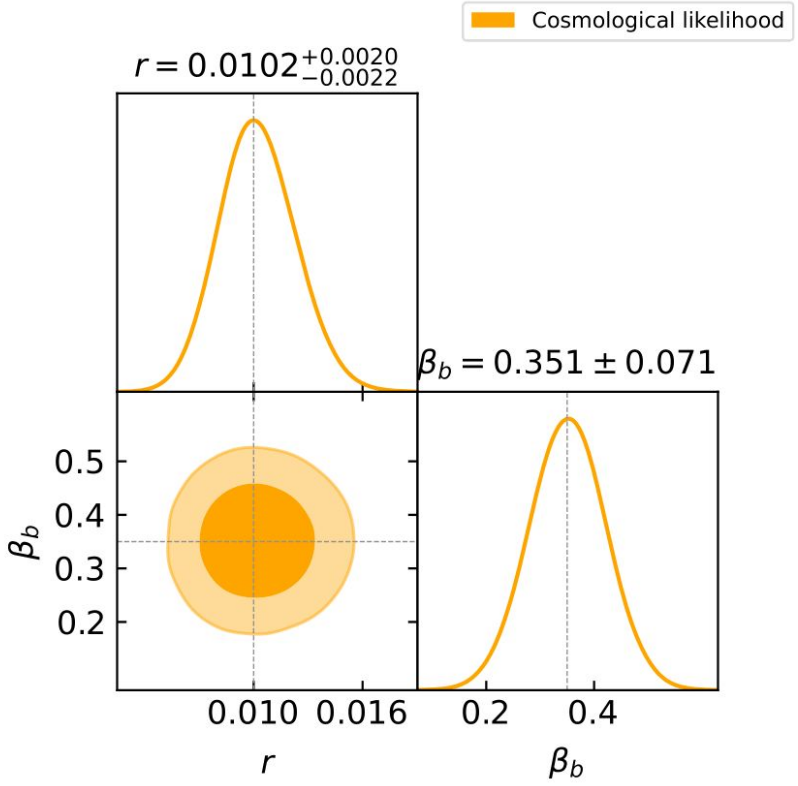
$\sigma(\beta_b)$: improved wrt prior precision!



Simple Foregrounds and Six Calibration Priors

- Simple foregrounds: **d0s0**
- **Prior on all frequency channels**
- **$r = 0.01$, $\beta_b = 0.35°$**

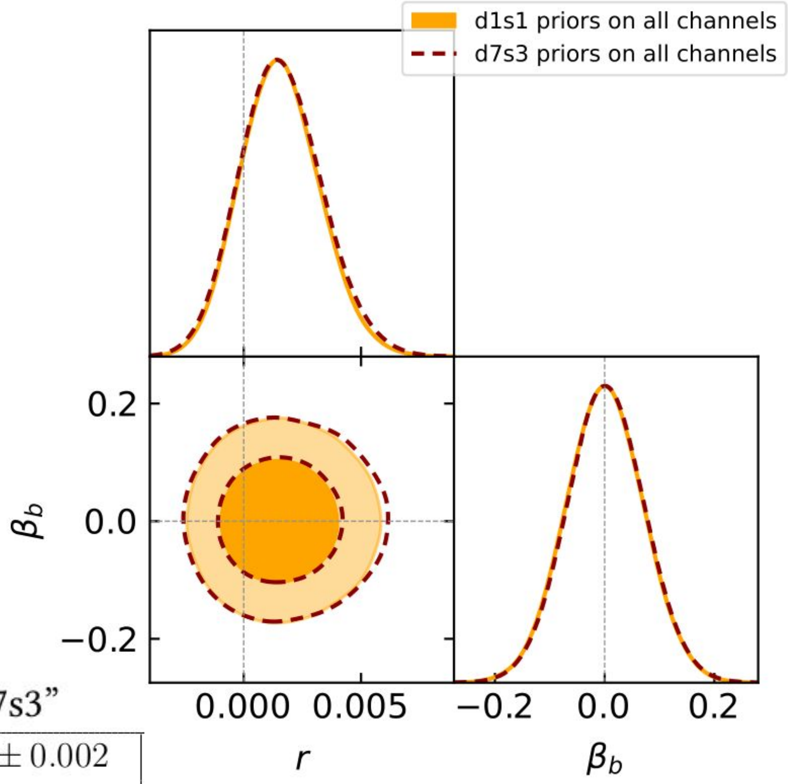
For SO SAT if $\sigma(\alpha_i)$=0.1° ⇒ 5σ detection of β_b = 0.35°



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

Results: Simple Foregrounds and Six Calibration Priors

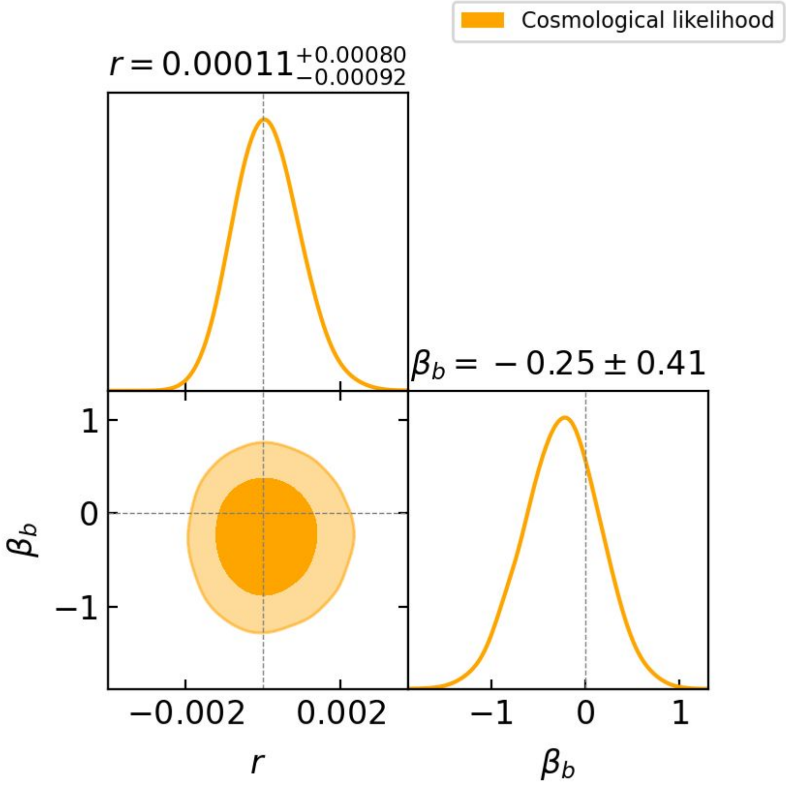
- Simple foregrounds **d0s0**:
  - dust: MBB, isotropic spectral indices
  - synchrotron: power law, isotropic spectral indices
- **Prior on all channels,** $\sigma(\alpha_i) = 1°$
- **Priors randomly biased by N(0,1°)**

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 .



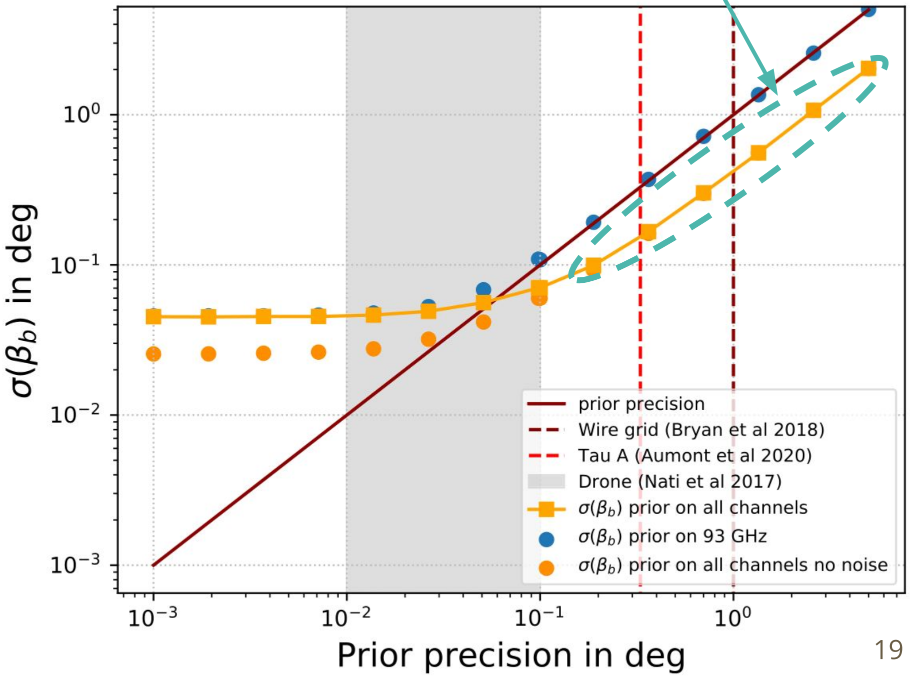
Evolution of Uncertainty wrt Prior Precision

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

We can set calibration requirement.

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

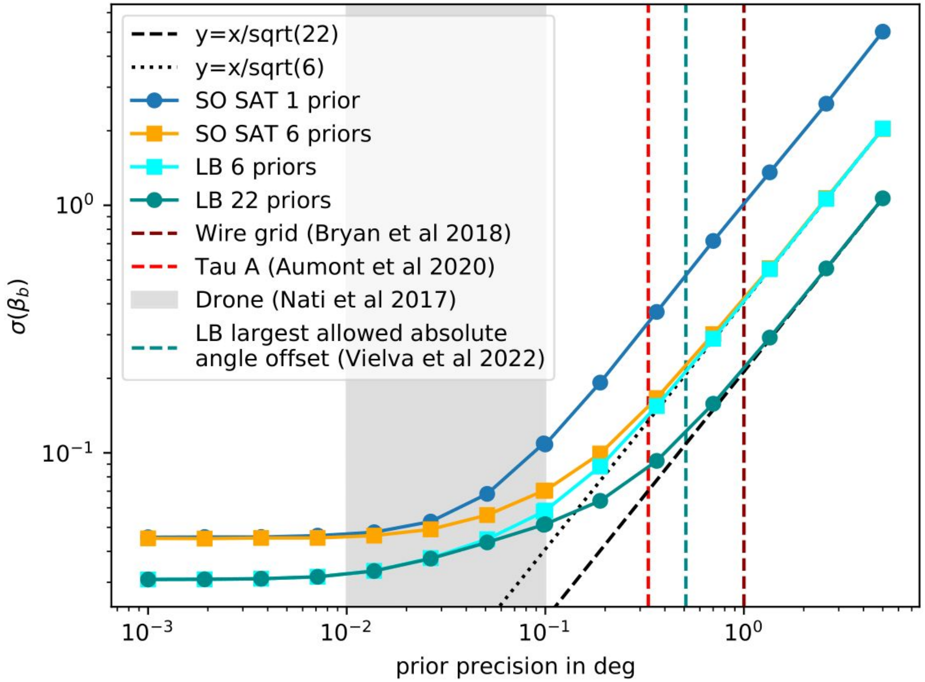
Noise represents ~42% of $\sigma(\beta_b)$ in SO SATs



Results: Evolution of Uncertainty wrt Prior Precision

LiteBIRD space mission:

- Simple Foregrounds: **d0s0**
- 49% sky observed **PTEP 2022**
- Noise levels from **PTEP 2022**
- 22 frequency channels
- l_{min} =2; l_{max}= 125



Conclusion and Future Prospects

- Estimating β_b and α_i doesn't significantly impact r measurements wrt standard parametric component separation
- Birefringence can be efficiently constrained using calibration priors in a multifrequency observation, provided no pathological bias on priors
- We can set requirements on calibration prior precisions :

Prospects:

- Pipeline development:
  - realistic priors from wire grid and drone
  - observation matrices
- Studying the impact of other effects: bandpasses, gain, HWP systematics etc


THANK YOU !
Source : Deborah Kellner

BACKUP SLIDES

Source : Deborah Kellner

Polarisation Power Spectra

primordial B-modes spectrum parameter: **r**

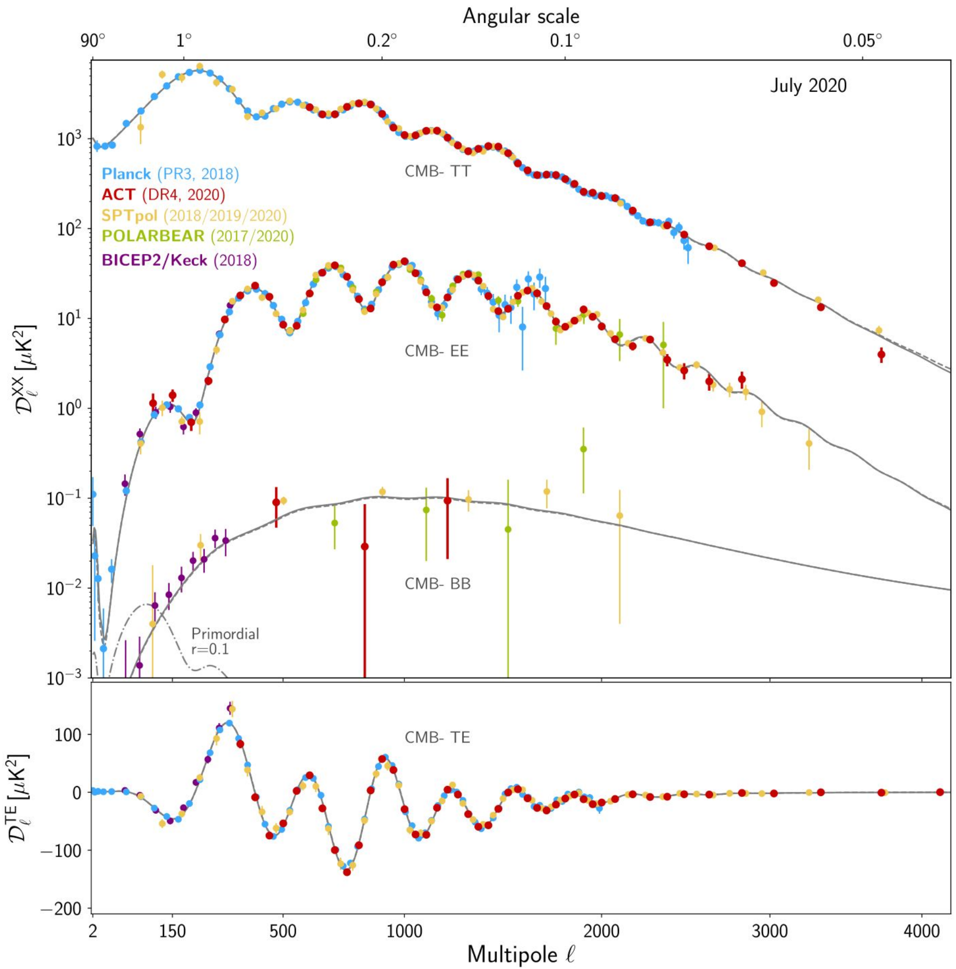
r constraints r < 0.032 (95 C.L.) (Tristram et al. 2021)

E and B modes are also affected by other non-primordial effects:

- Contribution from Sunyaev-Zel'dovich
- Gravitational lensing converts E to B
- **Birefringence**

And contaminants:

- **Instrumental Effects**
- **Galactic Foregrounds**



Credit: ACT

Cosmic Birefringence

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

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

Hints β_b = 0.35°± 0.14° from Planck data (Minami et al. 2020 & Diego-Palazuelos et al. 2022) based on assumptions about foreground EB correlations for calibration.

My goals:

- How and with what precision can we measure β_b
- Requirements on calibration
- What is the effect on the measurement of r

The Cosmological Likelihood

With $\{\beta_{fg}\}$ and $\{\alpha_i\}$ 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

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

Method Validation

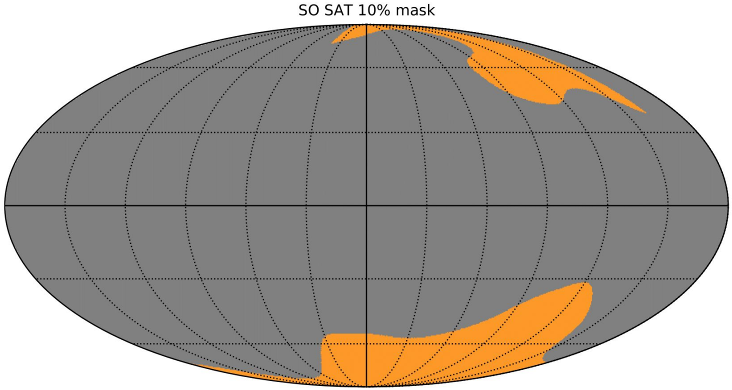
SO SAT characteristics noise, 10% sky coverage, l_{min} = 30, l_{max} =300, 30 000 detectors, first light by the end of the year

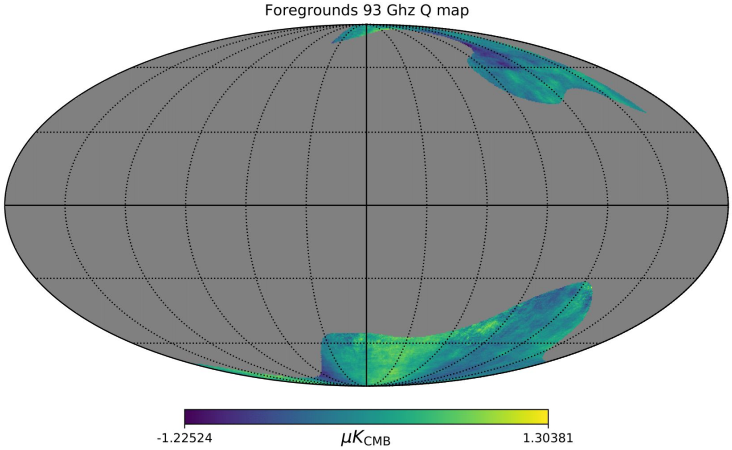
Priors:

- 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, $\beta_b = 0.0°$
- PySM foreground maps with different degrees of complexity (d0s0, d1s1, d7s3 in order of complexity…) (Thorne et al 2016, Zonca et al. 2021)





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)

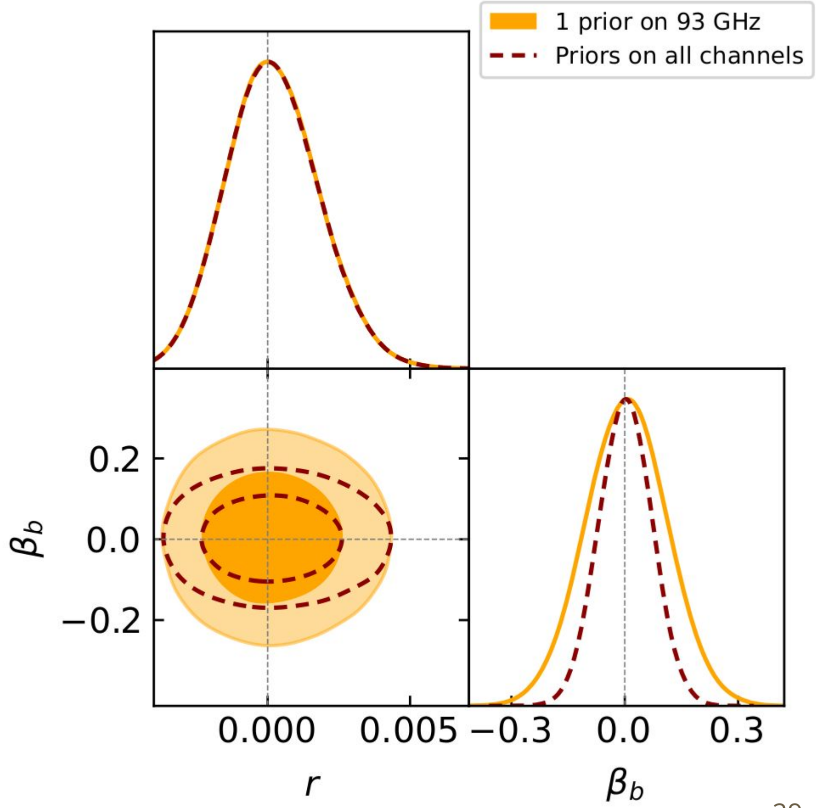
$$Q^{\mathrm{s3}}_{\nu,p} = A^{Q}_{s,p}\left(\frac{\nu}{\nu_0}\right)^{\beta_{s,p}+2+C\ln(\nu/\nu_0)}$$

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

Results: Simple Foregrounds and Six Calibration Priors

- d0s0
- Prior on all frequency channels

σ(β_b): improved wrt prior precision!



Results: Simple Foregrounds and Biased Priors

- Back to simple foregrounds **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