Polarization angle miscalibration in CMB B-mode experiments

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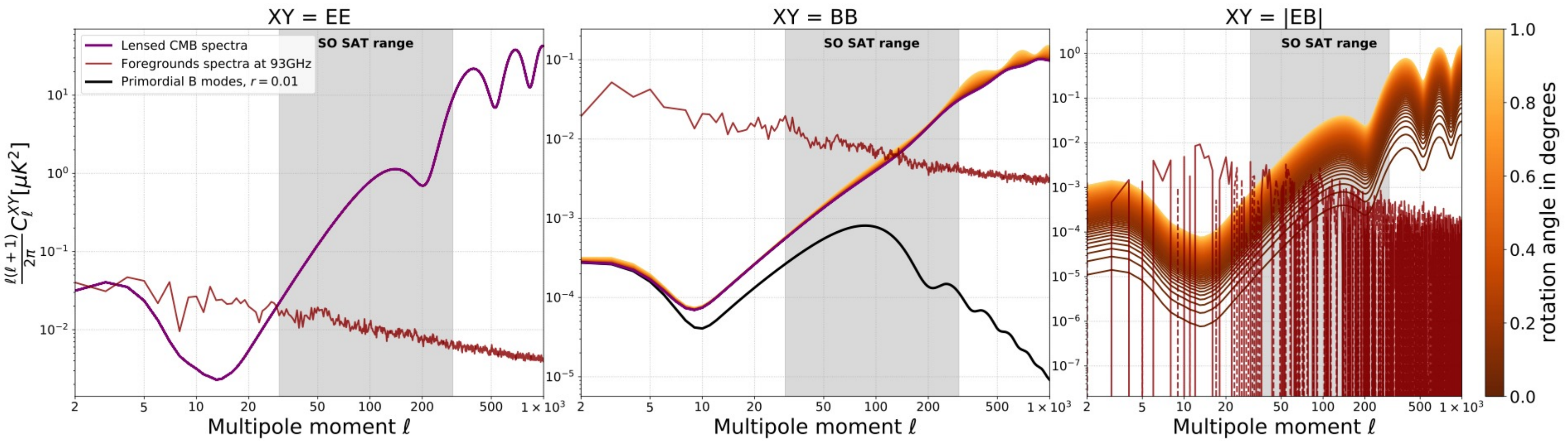
Credits

- Mostly based on a paper by Jost, Errard, Stompor (2023)
- As well as earlier papers by
  - Vergès et al (2021),
  - Stompor, Errard, Poletti (2016)
  - Stompor, Leach, Stivoli, Baccigalupi (2009)
- And on-going work by Baptiste Jost, Arianna Rizzieri, Magdy Morshed, Clément Leloup, Carlo Baccigulupi …

Polarization miscalibration effects on CMB:



- Converting EE into BB;
- Generating spurious EB (and TB) cross-correlations;

- Essentially identical to the isotropic birefringence effects (assuming pixel-independent miscalibration) :
  - Affecting our ability to detect it;
  - Potentially biasing detection of the primordial B-mode signal → self-calibration (Keating et al (2022))

Foregrounds

- Need for multi-frequency maps each in principle with its specific miscalibration angle
    - Need to calibrate all of them
        - Self-calibration problematic
        - Lab calibration
        - Astrophysical sources
- Need for a component separation/foreground cleaning procedure to separate/remove the foregrounds from the CMB signal …
    - Either define requirements which do not affect our sience goals (Vielva et al (2022))
    - Or somehow correct for the miscalibration as part of the procedure.

Component separation – basics (1)

- Data model:

noise

$$\mathbf{d} = \mathbf{A}\,\mathbf{s} + \mathbf{n}$$

Multi-frequency data

Mixing matrix

Component maps

- Q and U Stokes parameters are mixed the same way …
- Q and U Stokes parameters are mixed separately …

- Mixing matrix **A** may be pixel-dependent …
- Noise term **n** is a Gaussian random variable with zero mean and covariance **N** (assumed to be diagonal hereafter for simplicity).

Component separation – basics (2)

- Parametric component separation: $\mathbf{A} \,=\, \mathbf{A}(\{\beta\})$

1. Estimation of the mixing matrix: (…., Stompor et al 2009, ….)

$$\mathcal{S}_{spec}(\{\beta\}) \,=\, \mathbf{d}^t\,\mathbf{N}^{-1}\,\mathbf{A}\,(\mathbf{A}^t\,\mathbf{N}^{-1}\,\mathbf{A})^{-1}\,\mathbf{A}^t\,\mathbf{N}^{-1}\,\mathbf{d}$$

2. Estimation of the component maps

$$\hat{\mathbf{s}} = (\mathbf{A}^t\,\mathbf{N}^{-1}\,\mathbf{A})^{-1}\,\mathbf{A}^t\,\mathbf{N}^{-1}\,\mathbf{d}$$

Including miscalibration

- Data model: $$\mathbf{d} \;=\; \mathbf{R}(\{\alpha\})\,\mathbf{A}\,\mathbf{s} \;+\; \mathbf{n}$$

$$\mathbf{R}(\{\alpha\}) \;=\; \left[\begin{array}{cccc} \mathbf{R}(\alpha_0) & 0 & \dots & 0 \\ 0 & \mathbf{R}(\alpha_0) & \dots & 0 \\ \vdots & \ddots & \vdots & 0 \\ 0 & \dots & 0 & \mathbf{R}(\alpha_{n_f-1}) \end{array}\right]$$

$$\mathbf{R}(\alpha_i) \;=\; \left[\begin{array}{cc} \cos 2\alpha_i & \sin 2\alpha_i \\ -\sin 2\alpha_i & \cos 2\alpha_i \end{array}\right]$$

- Solve generalized foreground component separation problem:

$$\mathbf{A}(\{\beta\}) \longrightarrow \hat{\mathbf{A}}(\{\alpha,\beta\}) \;=\; \mathbf{R}(\{\alpha\})\,\mathbf{A}(\{\beta\})$$

Degeneracies …

We have

$$\begin{aligned}\mathbf{d} \;&=\; \mathbf{R}(\{\alpha\})\,\mathbf{A}\,\mathbf{s} \,+\, \mathbf{n} \\ &=\; \mathbf{R}(\{\alpha-\bar{\alpha}\})\,\mathbf{A}\,\hat{\mathbf{R}}(\bar{\alpha})\,\mathbf{s} \,+\, \mathbf{n}\end{aligned}$$

as both Q and U Stokes parameters scale the same for all the components

Any common miscalibration of all single frequency maps is equivalent to miscalibrating all components maps by the same angle.

So we can not ever constrain the overall, common miscalibration of all the single frequency maps or the estimated component maps without further assumptions …

Concerning the properties of at least one of the components, i.e., its EB correlations …

Or with help of some prior knowledge, i.e., a constraint on a miscalibration angle of at least one of the frquency maps

The procedure

- Use generalized data model
- Fit for all the parameters with help of priors if necessary (generalized parametric component separation)
- Estimate component maps, including CMB
- Fit cosmological model to the CMB map (neglecting potential presence of the residual foregrounds) and derive constraints on cosmological parameters
  - tensor-to-scalar ratio and birefringence angle
  - nested MCMC sampling to marginalize over all other parameters

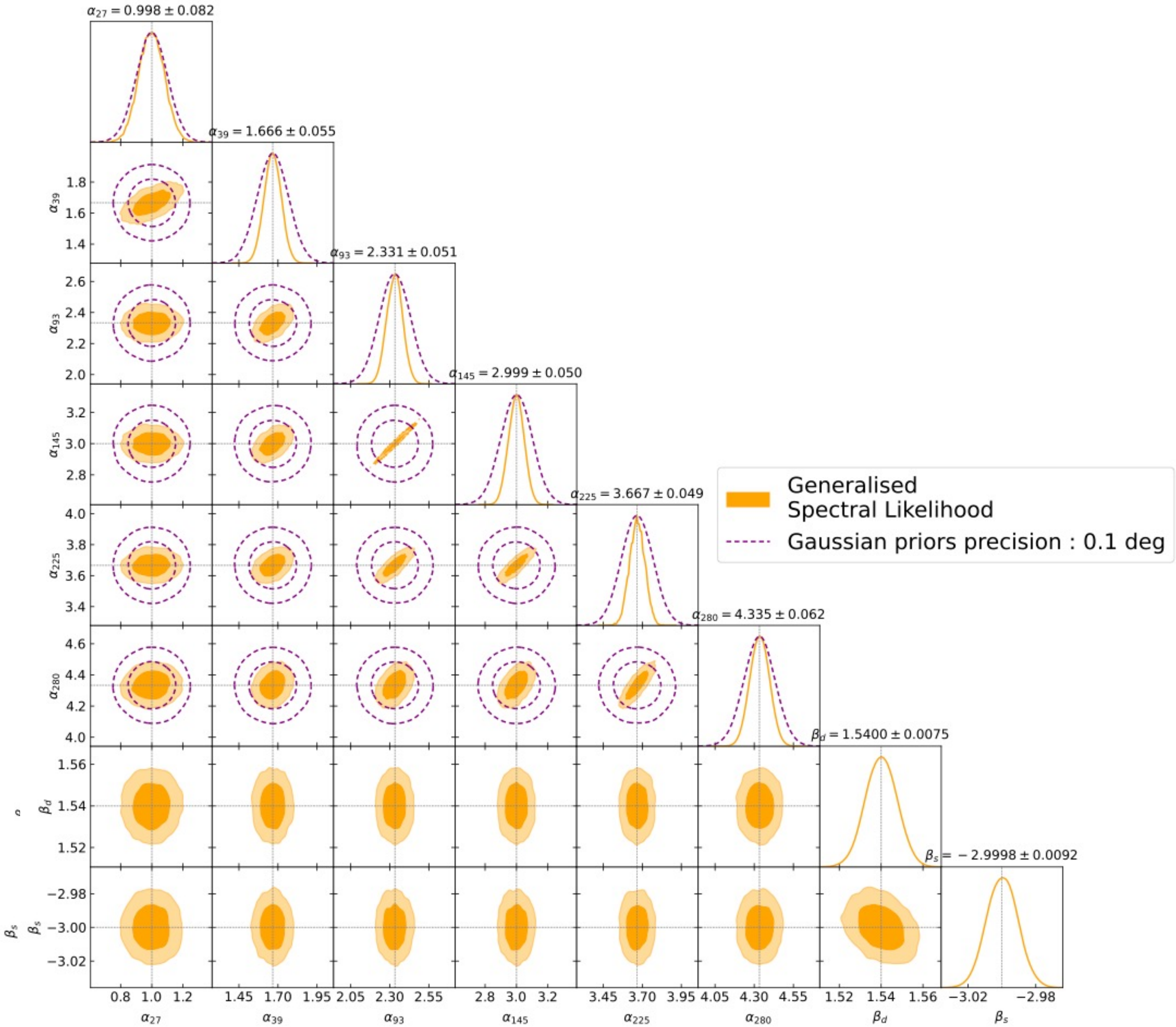
Study cases

- Simulations (based on PySM)
  d0s0 - parametric pixel-indepedent foreground model
  d1s1 – parametric pixel-dependent foreground model
  d7s3 – non-parametric pixel-dependent foreground model

- Analysis:
  parametric model for foregrounds with pixel-independent parameters

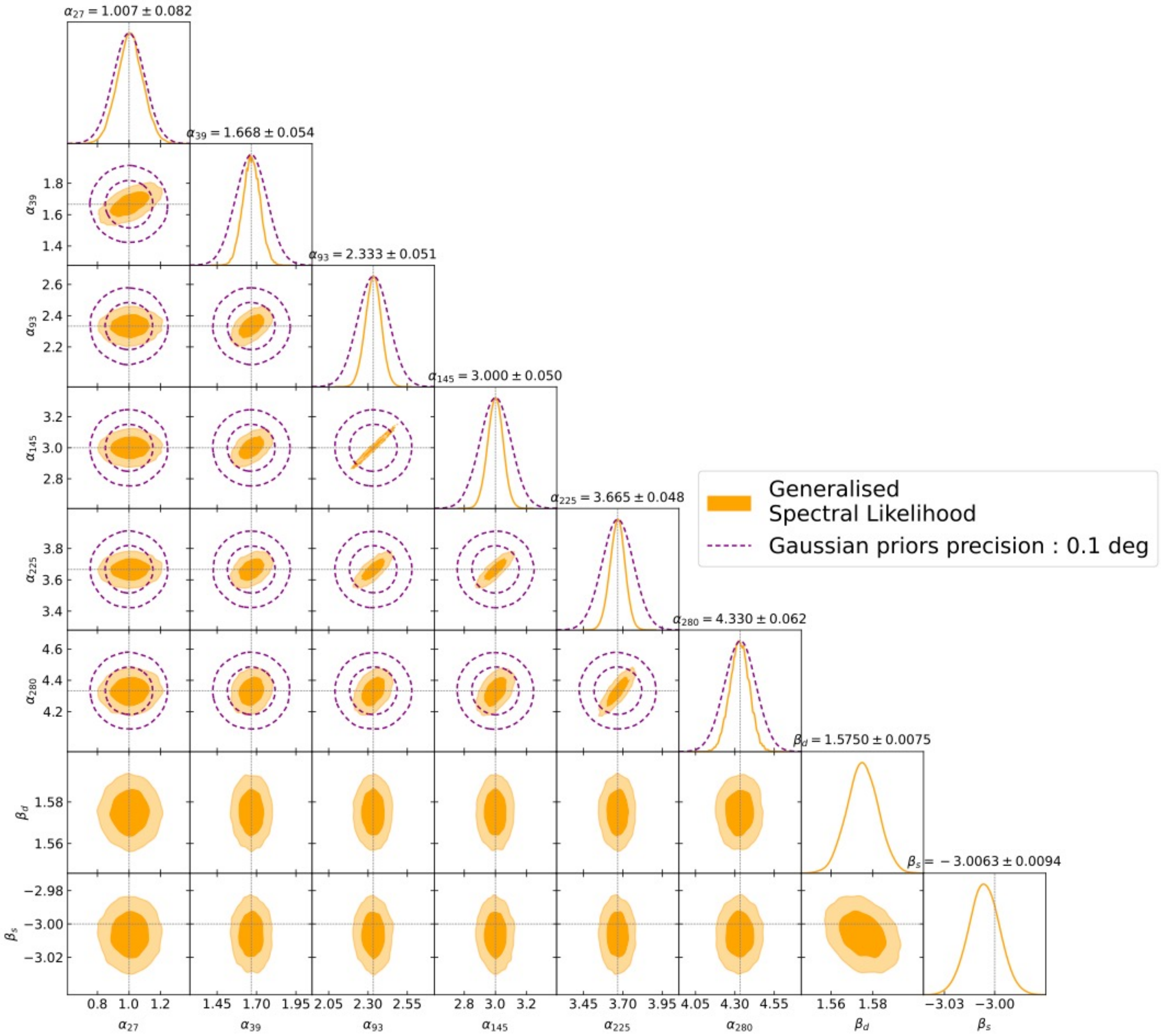
- Experiment:
  Simons Observatory Small Aperture Telescopes (nominal set up)
  6 Frequencies: 27, 39, 93, 145, 225, 280 GHz
  and nominal noise levels.

PySM d0s0:



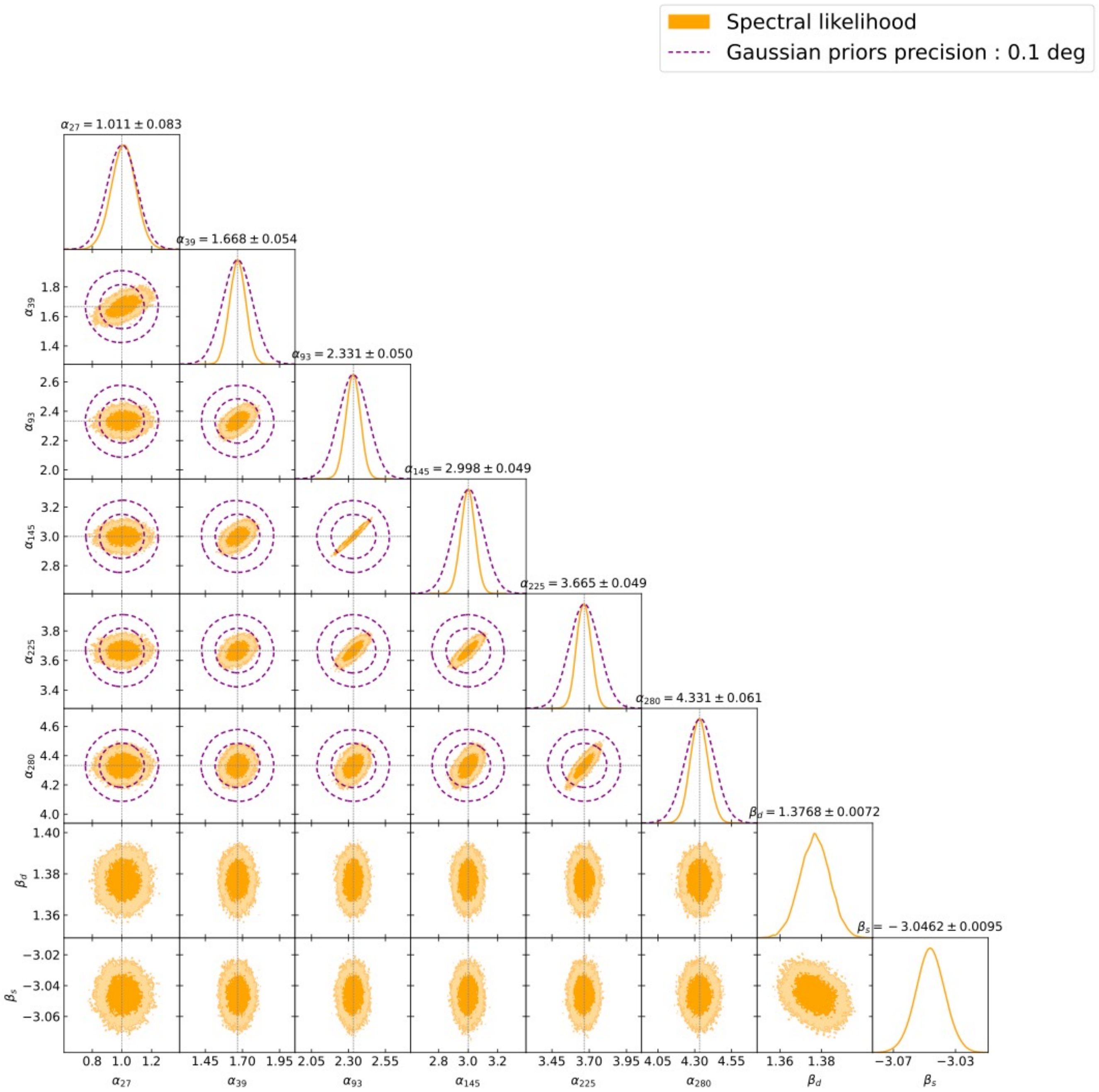
$\alpha_{27} = 0.998 \pm 0.082$
$\alpha_{39} = 1.666 \pm 0.055$
$\alpha_{93} = 2.331 \pm 0.051$
$\alpha_{145} = 2.999 \pm 0.050$
$\alpha_{225} = 3.667 \pm 0.049$
$\alpha_{280} = 4.335 \pm 0.062$
$\beta_d = 1.5400 \pm 0.0075$
$\beta_s = -2.9998 \pm 0.0092$
Generalised Spectral Likelihood
Gaussian priors precision : 0.1 deg
α_{27}
α_{39}
α_{93}
α_{145}
α_{225}
α_{280}
β_d
β_s

PySM d1s1:



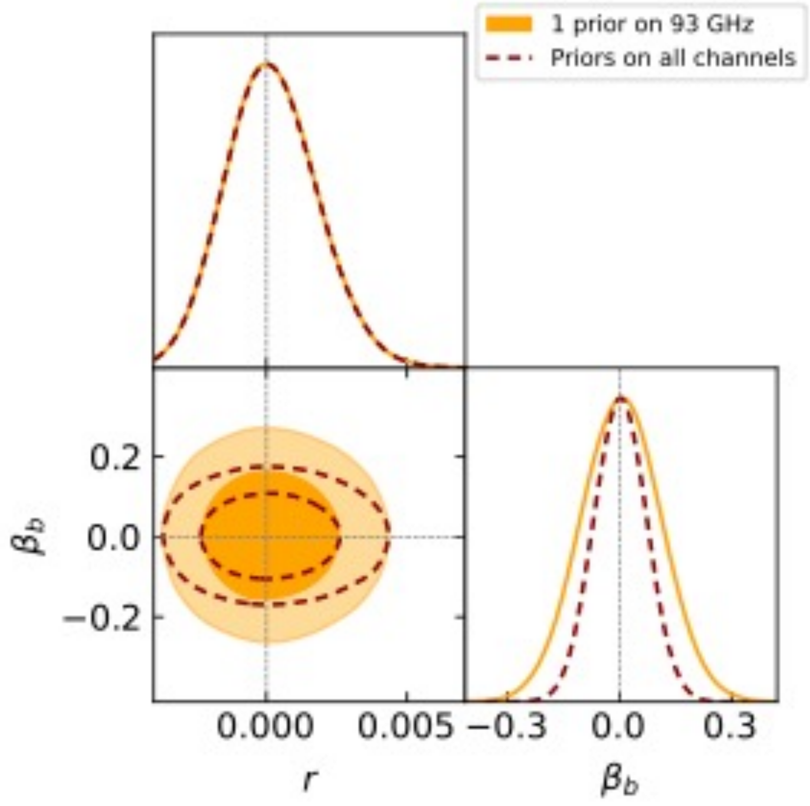
$\alpha_{27} = 1.007 \pm 0.082$
$\alpha_{39} = 1.668 \pm 0.054$
$\alpha_{93} = 2.333 \pm 0.051$
$\alpha_{145} = 3.000 \pm 0.050$
$\alpha_{225} = 3.665 \pm 0.048$
$\alpha_{280} = 4.330 \pm 0.062$
$\beta_d = 1.5750 \pm 0.0075$
$\beta_s = -3.0063 \pm 0.0094$
Generalised Spectral Likelihood
Gaussian priors precision : 0.1 deg
α_{27}
α_{39}
α_{93}
α_{145}
α_{225}
α_{280}
β_d
β_s

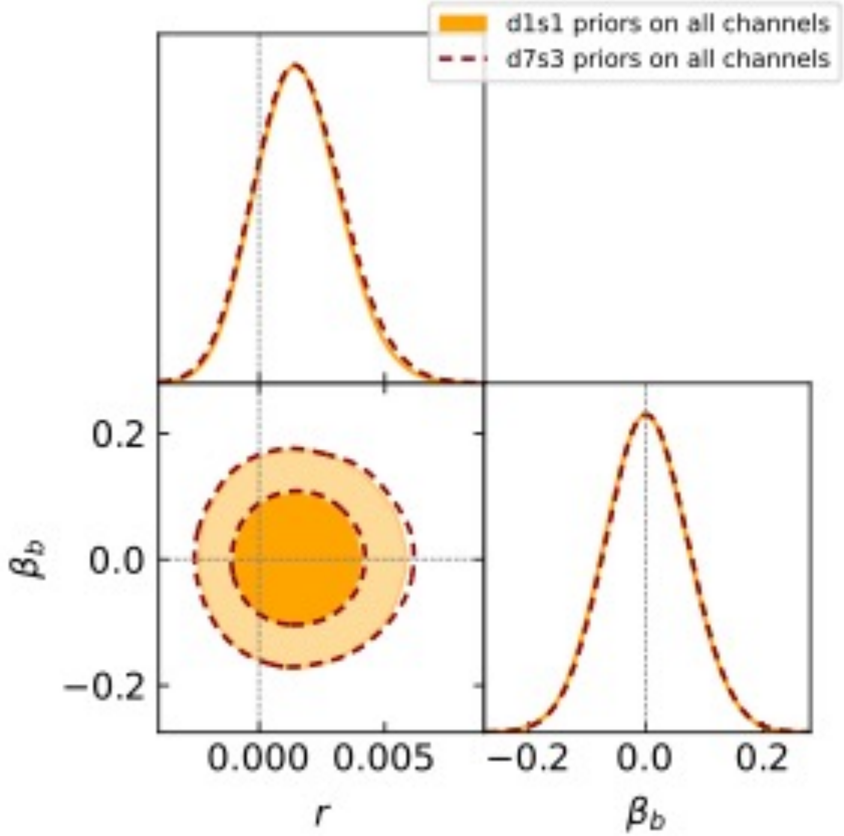
PySM d3s7:



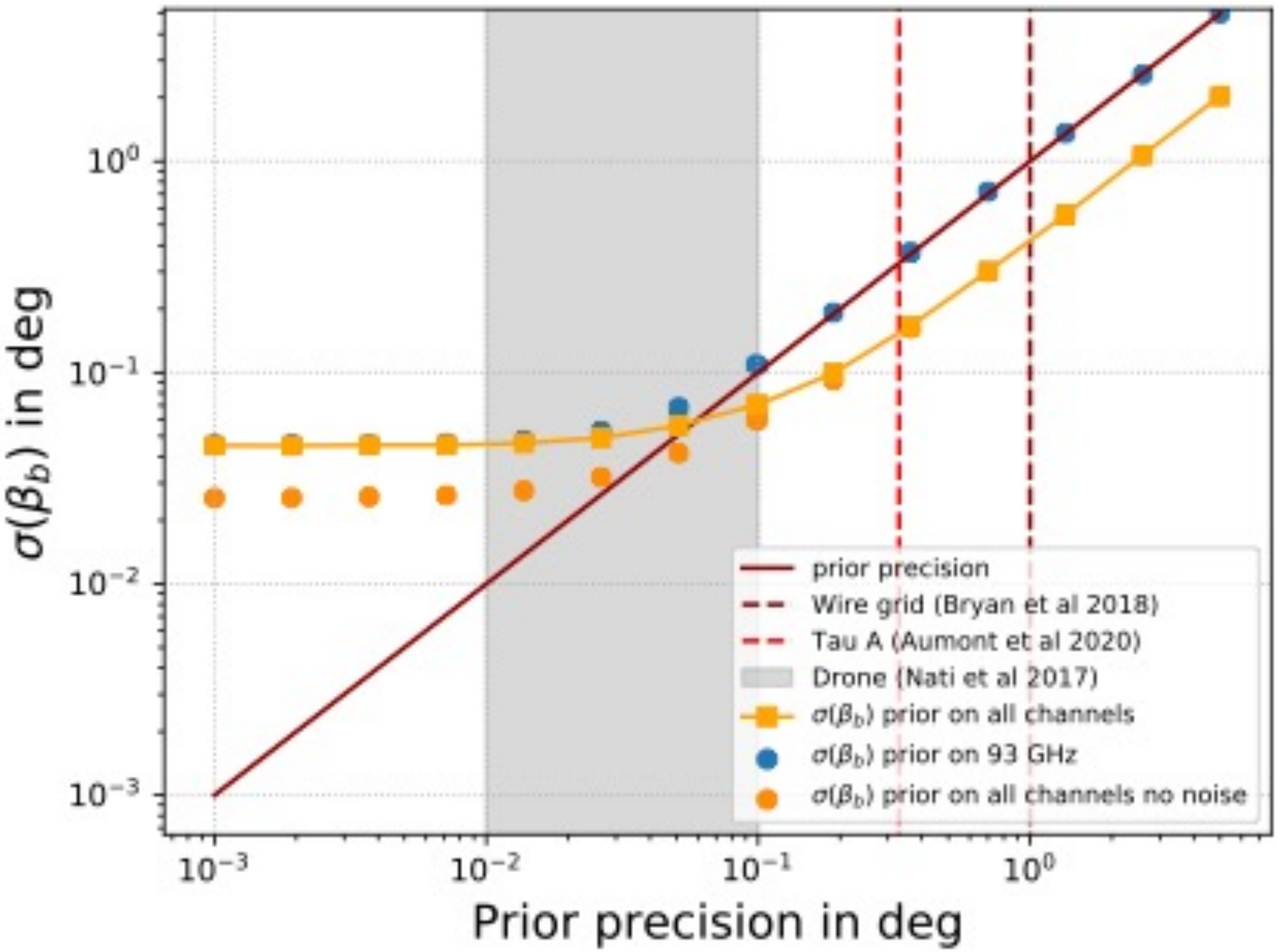
Spectral likelihood
Gaussian priors precision : 0.1 deg
$\alpha_{27} = 1.011 \pm 0.083$
$\alpha_{39} = 1.668 \pm 0.054$
$\alpha_{93} = 2.331 \pm 0.050$
$\alpha_{145} = 2.998 \pm 0.049$
$\alpha_{225} = 3.665 \pm 0.049$
$\alpha_{280} = 4.331 \pm 0.061$
$\beta_d = 1.3768 \pm 0.0072$
$\beta_s = -3.0462 \pm 0.0095$
α_{27}
α_{39}
α_{93}
α_{145}
α_{225}
α_{280}
β_d
β_s

Constraints on cosmological parameters





Cosmic birefringence



Conclusions …

- If not corrected-for miscalibration of the polarization angles of single frequency channels will bias our estimation of the cosmological parameters.
- We can constrain the relative miscalibration angles internally on the component separation steps.
- The global angle needs to be constrained either by making assumptions about the properties of the recovered signals or calibration prior.
- The lack of the latter does not prevent us from deriving constraints on the tensor-to-scalar ratio parameters.
- The birefringence angle constraint is then set by the prior (before cosmic/sampling variance kicks-in).

… and comments

- Other systematic effects need to be included and may affect these conclusions.
- A single miscalibration pixel-indepoendent angle per map is oversimplification.
- Non-parametric approaches (SMICA-type) can be as good in correcting for the relative angles.