Is beam chromaticity important for the large-scale B-mode spectra of the SO SATs?

(Paper in prep.)

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Beam chromaticity

- The Simons Observatory (SO) Small Aperture Telescopes (SATs) observe in wide (~25%) frequency bands.

- Beam pattern depends on frequency.

- The band-integrated beam:

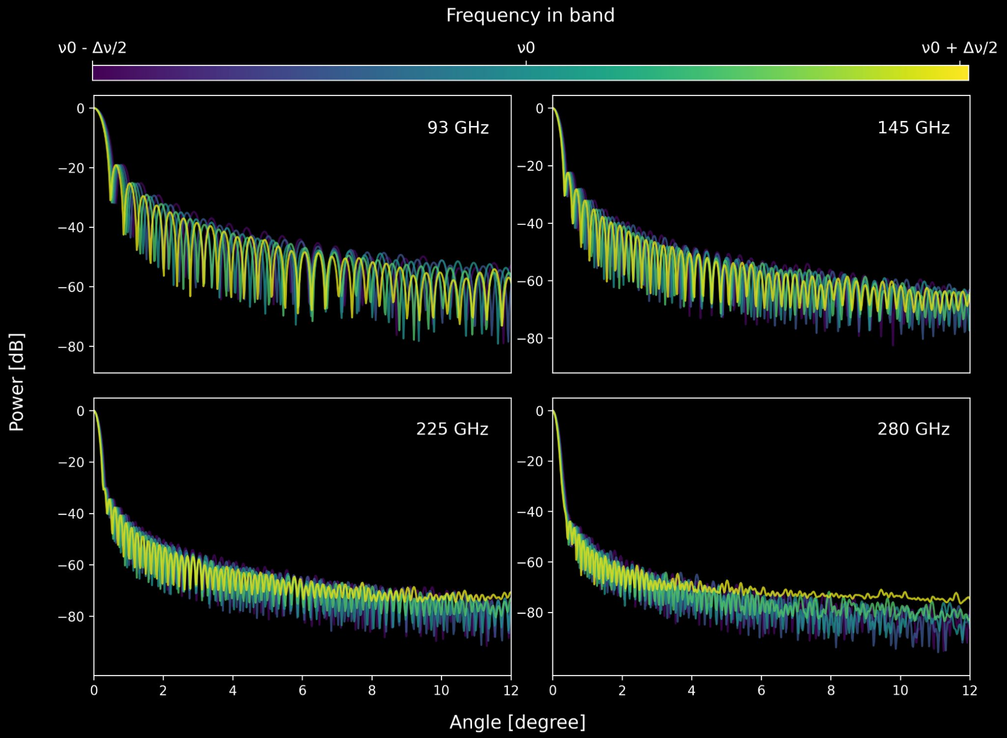
  $B(\theta,\varphi) = \int \tau(\nu) B(\theta,\varphi,\nu) S(\nu) d\nu,$

  $\tau(\nu)$: instrumental bandpass,

  $B(\theta,\varphi,\nu)$: monochromatic beam,

  $S(\nu)$: SED of observed sky component.

Logarithmic profiles of five monochromatic beam maps within each band



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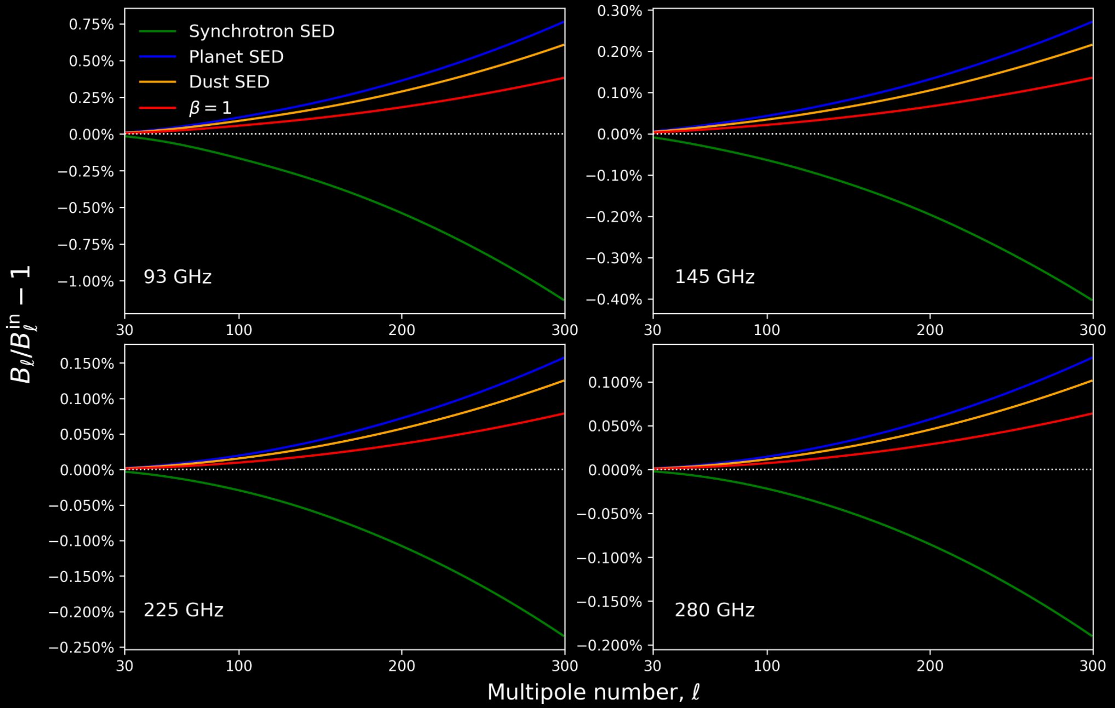
Impact of the observed source SED

- The ratio of the band-integrated beam transfer functions for four chromatic beams after applying frequency-scaling matching the SEDs of Galactic synchrotron (green), planets (blue), dust (orange) and β=1 (red) and the band-averaged beam (white).



Credit: Dachlythra et al. 2023

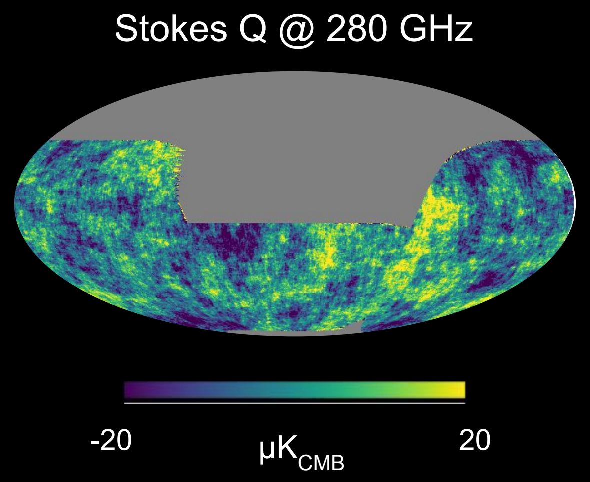
Analysis pipeline (I)

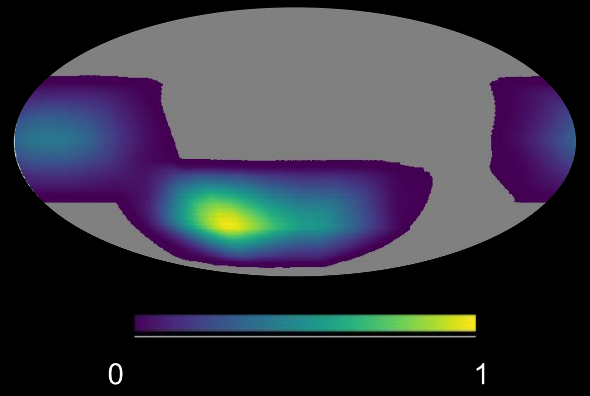
- Inputs:
  - Sky simulations: CMB + Galactic dust + synchrotron (Gaussian or non-Gaussian foreground models).
  - Beam simulations: Generated with `TICRA TOOLS` assuming an idealized version of the SO SAT optics (aperture + lenses + coatings).

- Beam-convolution:
  - `beamconv`: time-domain beam convolution described in Duivenvoorden et al. 2018, 2021.
  - SAT-like scan strategy informed from the nominal observation schedule for 2024.
  - 1 year of simulated scanning in the MF, UHF bands with 50 detector pairs, a Field-of-View of 35°, and sampling rate of 50 Hz.
  - No HWP included.

Analysis pipeline (II)

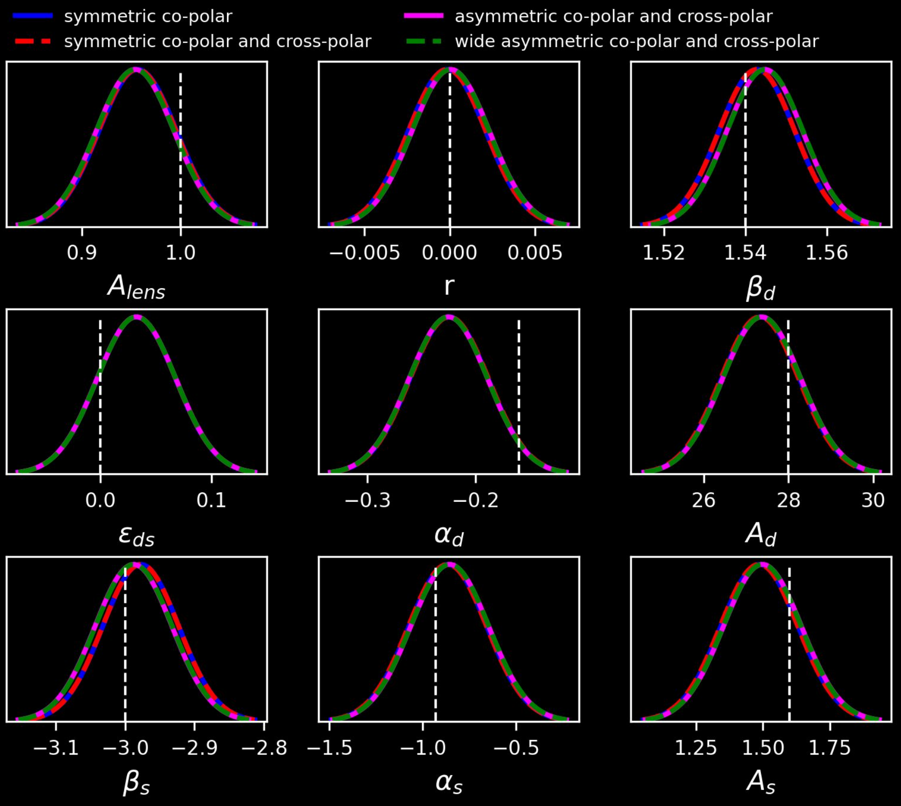
- Power spectra estimation:
  - NaMaster pseudo-C_ℓ estimator described in [Alonso et al. 2019].
  - Mask: apodized version of the `beamconv` hits map (see Figure).
  - B-mode purification.
- Foreground component separation:
  - BBPower [Azzoni et al. 2019, Abitbol et al, 2021, Wolz et al. 2023].
  - Only the low-ℓ B-mode spectra are employed ($30 < \ell < 300$).
  - Best-fit values and uncertainty on: $\{r, A_{lens}, \varepsilon_{ds}, \beta_d, \alpha_d, A_d, \beta_s, \alpha_s, A_s\}$.





Beam non-idealities

- We run beamconv simulations of a single sky realization for the center frequencies of the MF and UHF bands.
- We use four different versions of the simulated beams:
  - Symmetric, co-polar beams.
  - Symmetric beams with cross-polarization.
  - Asymmetric beams with cross-polarization.
  - Asymmetric beams with cross-polarization and wide sidelobes ($\theta_{max} \approx 12°$).
- Asymmetry has the strongest impact.



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Results for beam chromaticity

- We employ five monochromatic beam-convolved simulations of frequencies uniformly spread across the MF and UHF bands (the LF beams are left for future work) and the nominal SO SAT bandpasses shown in Abitbol et al, 2021.

- We estimate the best-fit values for the tensor-to-scalar ratio, lensing amplitude and foreground parameters, averaged over a set of ten different sky realizations and using the covariance from Wolz et al. 2023.

- We compare with the case where the bands are represented only by their center frequency by estimating the difference between the parameters in the achromatic and chromatic beam scenario in terms of each parameter 1σ uncertainty.

Beam chromaticity x Gaussian foregrounds

- The beam chromaticity bias on $\{A_{lens}, r, \varepsilon_{ds}, \beta_d, \alpha_d, A_d, \beta_s, \alpha_s, A_s\}$ is estimated as:

  0.18σ, 0.02σ, 0.17σ, 0.09σ, **0.27σ**, **0.77σ**, 0.24σ, 0.01σ, 0.06σ, respectively.

- The greatest impact is for the dust spatial parameters.

- The r-tensor remains largely unaffected by beam chromaticity.

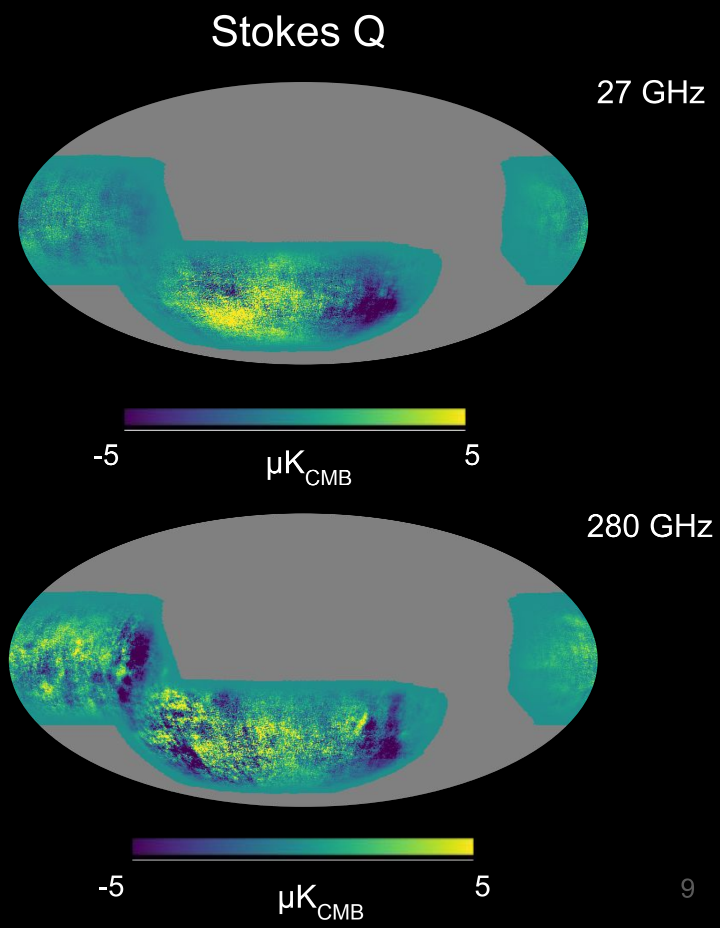
- The bias on all parameters remains well under 1σ.

Beam chromaticity x non-Gaussian foregrounds

- We employ PySM simulations of model 'd0s0' corresponding to a modified black-body and a power-law SED for Galactic dust and synchrotron, respectively.

- The figure shows difference maps of simulations employing Gaussian and non-Gaussian foreground models at 27 GHz and 280 GHz, after masking.

- The beam chromaticity bias on $\{A_{lens}, r, \varepsilon_{ds}, \beta_d, \alpha_d, A_d, \beta_s, \alpha_s, A_s\}$ is estimated as: 0.14σ, 0.01σ, 0.01σ, 0.22σ, **0.47σ**, **0.53σ**, 0.15σ, 0.06σ, 0.02σ, respectively.



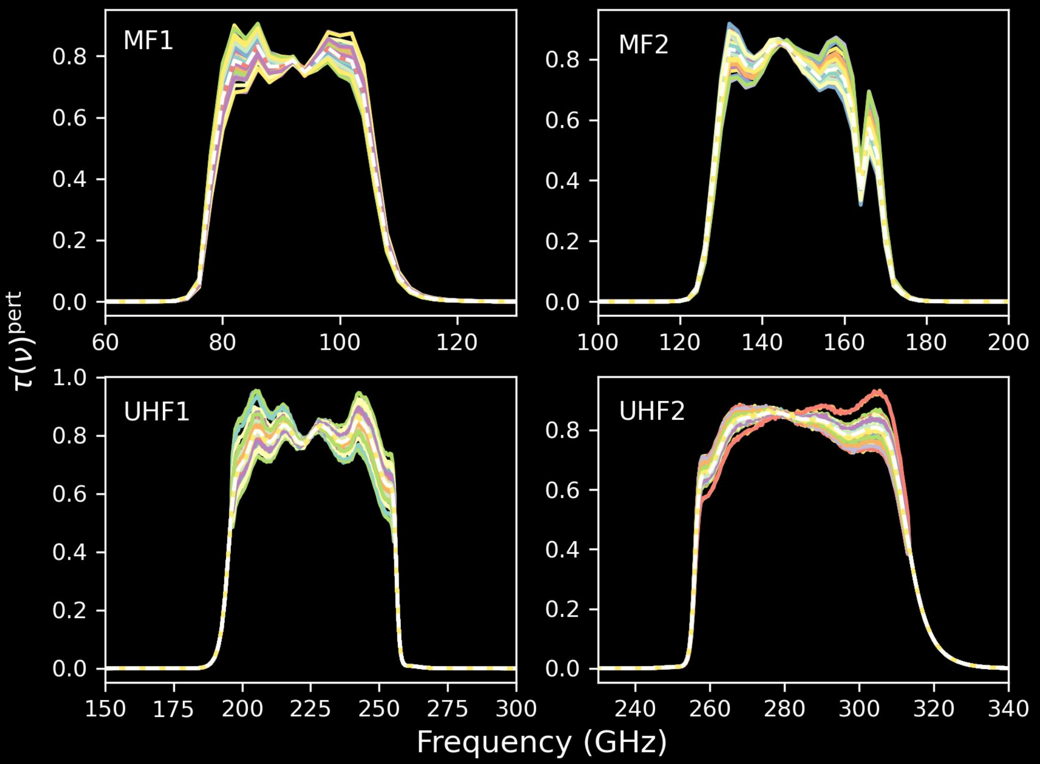
Adding bandpass uncertainty (I)

- The center frequency and gain requirements for the SO SATs have been studied in Abitbol et al, 2021.

- The gain can be expressed as:
  $g = \int A_{eff} \tau(v) B(\theta,\varphi,v) dv$,

  Aeff: effective area of the telescope,
  (v): instrumental bandpass.

- We perturb the nominal bandpasses adding an offset, c(v), and slope, $\beta\tau$:
  $\tau(v)^{pert} = c(v)\tau(v)(v/v_0)^{\beta\tau}$.



Adding bandpass uncertainty (II)

- We now construct ten new bandpass versions for each of the ten sets of `beamconv` maps studied before, assuming both Gaussian and non-Gaussian foregrounds.

- We assess the coupling of beam chromaticity and bandpass uncertainty in terms of the standard deviation of the best-fit values for each parameter, derived from simulations of the same sky realization convolved with the same chromatic beams but varying bandpasses.

- The additional uncertainty on the parameters $\{r, A_{lens}, \varepsilon_{ds}, \beta_d, \alpha_d, A_d, \beta_s, \alpha_s, A_s\}$ is:

  Gaussian foregrounds: 0.07σ, 0.01σ, 0.08σ, 0.08σ, **0.24σ**, **0.4σ**, 0.19σ, 0.02σ, 0.05σ.
  Non-Gaussian foregrounds: 0.08σ, 0.1σ, 0.08σ, 0.02σ, **0.29σ**, **0.38σ**, 0.01σ, 0.005σ, 0.03σ.

Conclusions & future prospects

- The impact of beam chromaticity is mostly pronounced on the dust spatial parameters both when assuming Gaussian and non-Gaussian foregrounds.

- The tensor-to-scalar ratio, r, does not appear to be significantly affected and the bias on all parameters is well under 1σ.

- The coupling of bandpass fluctuations with beam chromaticity results in additional uncertainty that is again most significant for the dust spatial parameters.

- In the future, we plan to add to this work by scaling up the complexity of the beams and foreground models, and study the potential interplay between beam chromaticity and HWP frequency-dependent systematics and most importantly…

Thanks!!

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