Strategies to separate foregrounds from the CMB

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Component Separation

Component separation is an inverse problem

$$X = A\,S + N$$

frequencies / # pixels on map → Data

frequencies / # components → Frequency scaling **Mixing Matrix**

components / # pixels on map → Amplitudes of sky components (FGs and CMB)

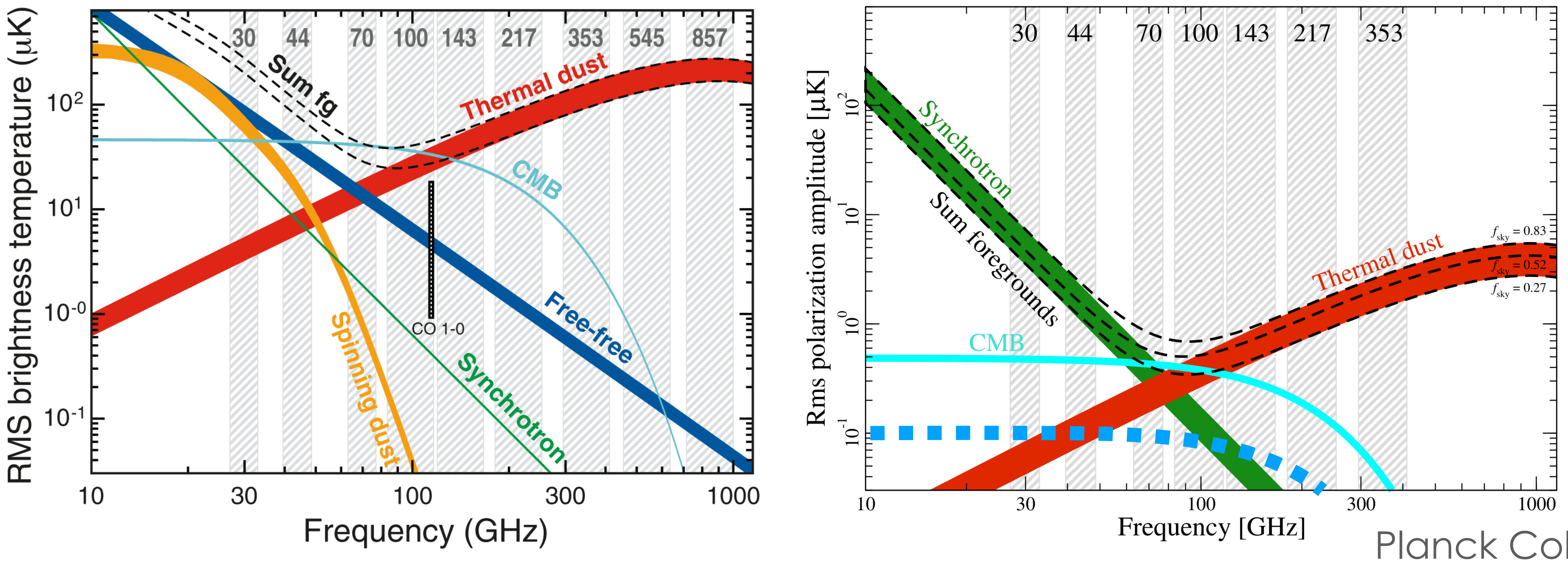
frequencies / # pixels on map → Noise

The goal is to determine the sky components (all of them or only the CMB) given the multifrequency data

Component Separation

The difficulty of component separation depends on several key factors:

- **Foreground-to-signal ratio**: The relative strength of foreground emissions compared to the cosmological signal
- **Foreground complexity**: Spatial variability in spectral energy distributions (SEDs), line-of-sight mixing
- **Instrumental systematics:** interaction between foregrounds and instrument-related effects



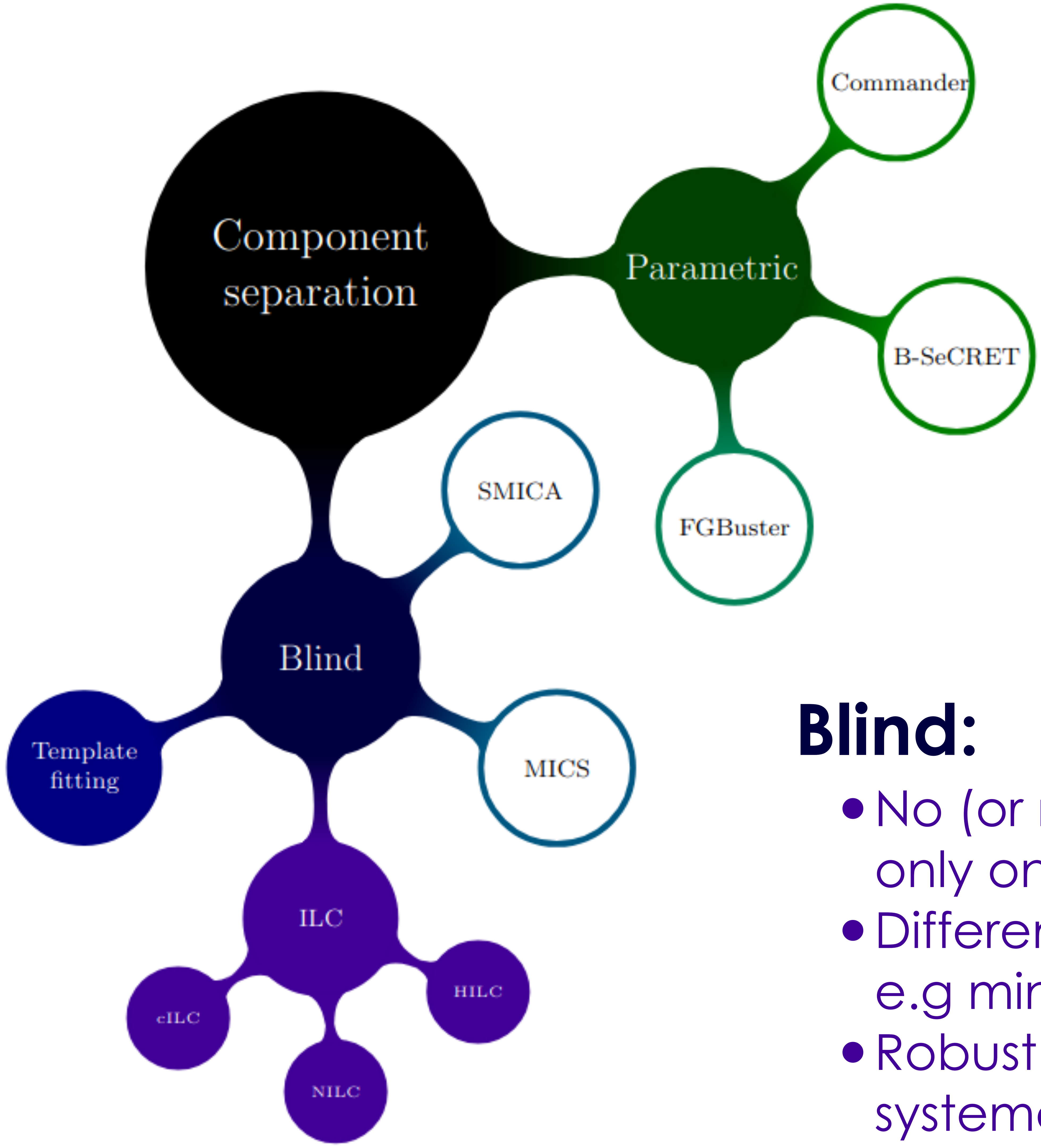
Planck Collaboration

➡ **Total intensity** is easier to separate than **E-mode polarization**, and much easier than **B-modes**, due to the lower foreground contamination

➡ **Smaller angular scales** are less affected by foregrounds and systematics, making separation easier than at large scales.

➡ **Smaller sky patches** are easier to clean than full-sky observations, due to reduced complexity of foreground variation and systematic interactions

Algorithms



Parametric:

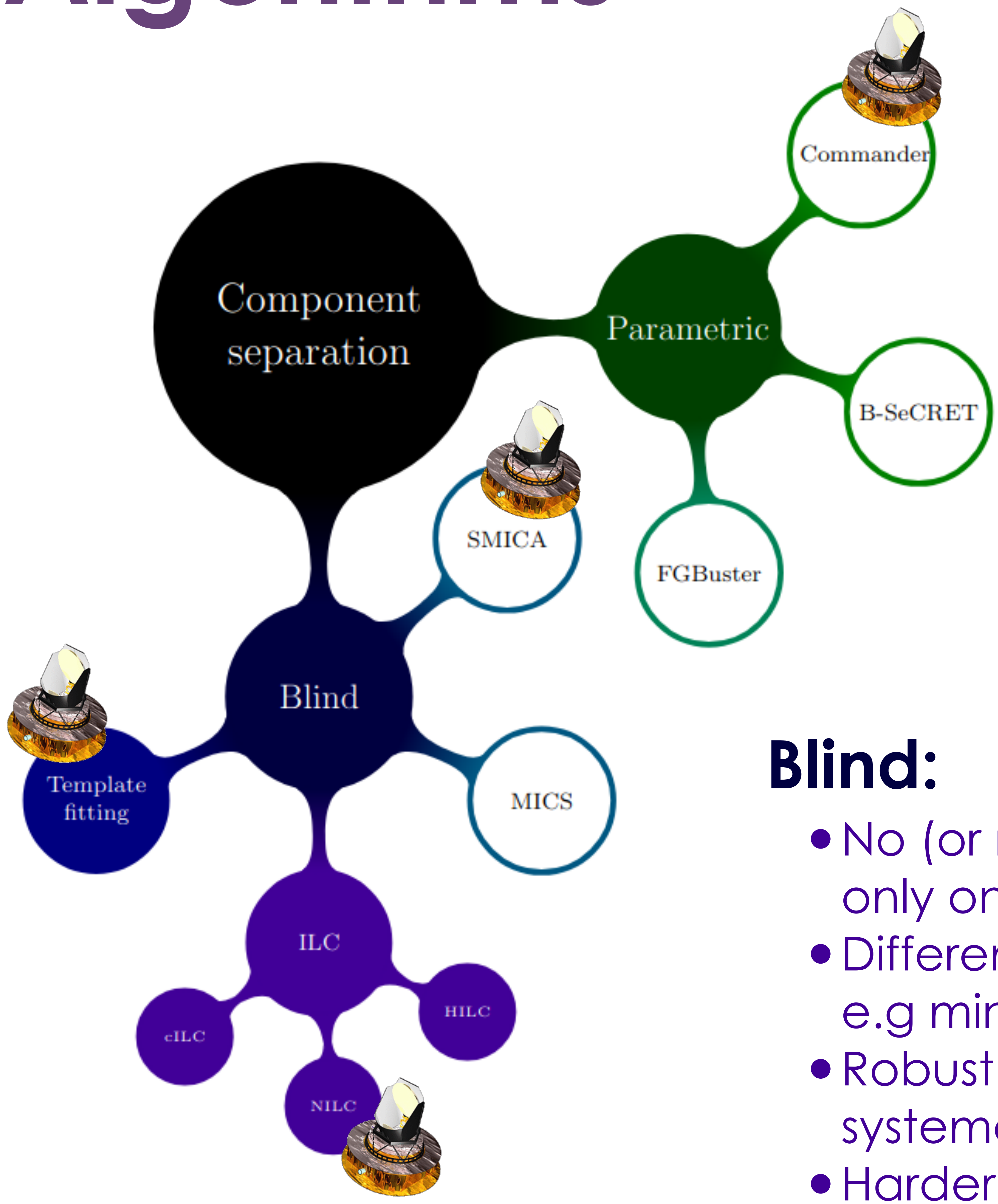
- Assumes a physical model for foreground frequency dependence and fit for the parameters (typically with maximum likelihood estimation) to recover the mixing matrix
- Results are easy to interpret
- Relatively easy to marginalize over additional parameters (e.g. systematic effects)
- Fails if foreground model is incorrect

Blind:

- No (or minimal) assumption on foreground SEDs, only on CMB signal
- Different optimization principles to recover CMB, e.g minimum variance for ILC
- Robust against foreground complexity (and some systematics)
- Harder to interpret

Credits: Clement Leloup

Algorithms



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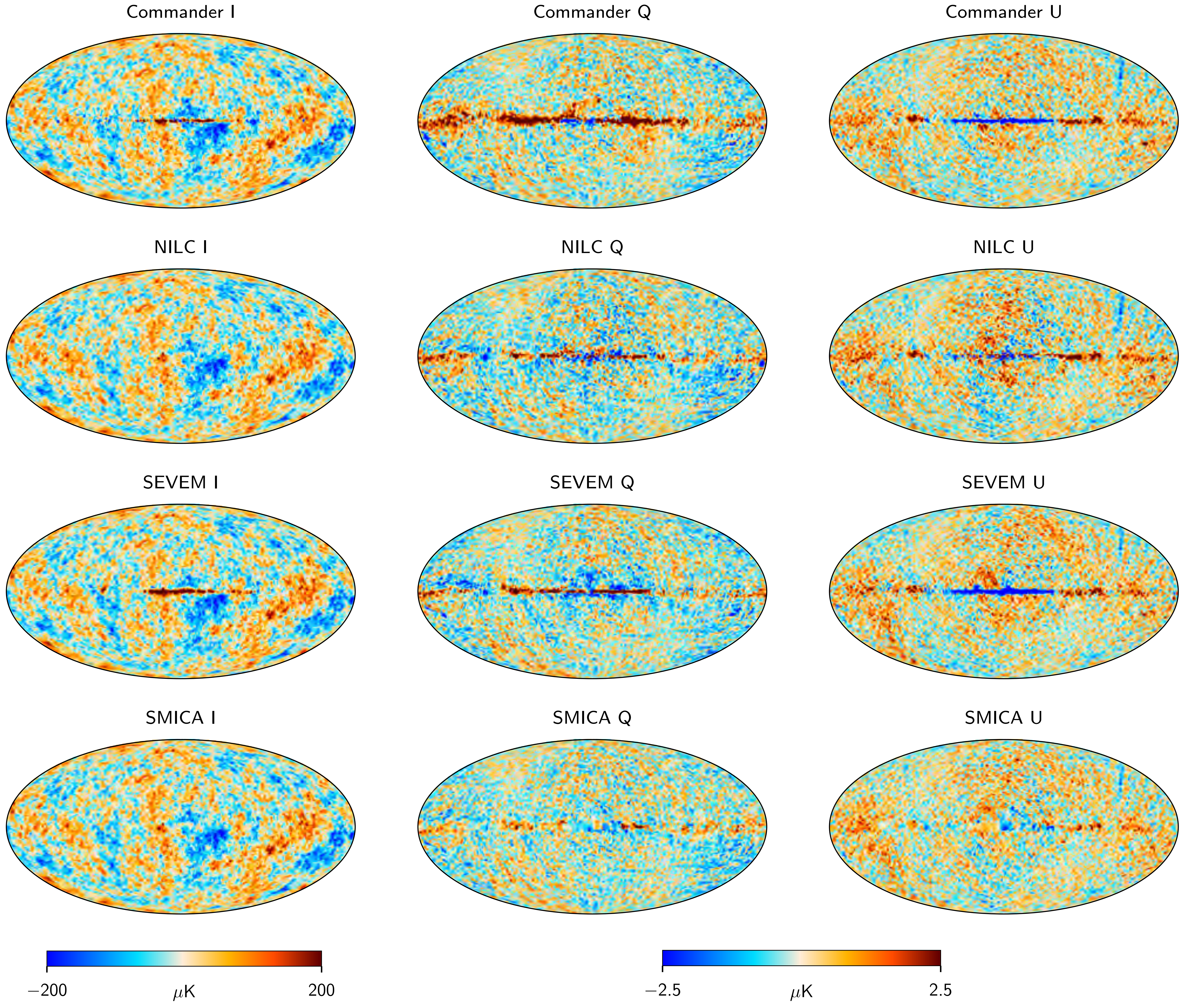
The Planck experience

- The four methods show good consistency in the CMB solution for total intensity
- On Q an *U* maps large scale structures visibile, due to the interplay between instrumental systematic effects and the different component separation methods



Planck 2018 results IV

Cosmology from Planck multi-frequency maps

Cross-C_ℓ likelihood in two different regimes: low and high-ℓ with different treatment of foreground contamination

- $\ell \geq 30$: since foregrounds are less dominant, the inclusion of a dust template at the power spectrum level is enough to prevent biases on cosmological parameters.

- $\ell < 30$: cleaning of foreground emission at map level is needed

  ➡ commander maps in TT

  ➡ template fitting from 30 GHz (synchrotron) and 353 GHz (dust) for EE in PR3

  ➡ commander polarization maps for EE in PR4 (NPIPE)

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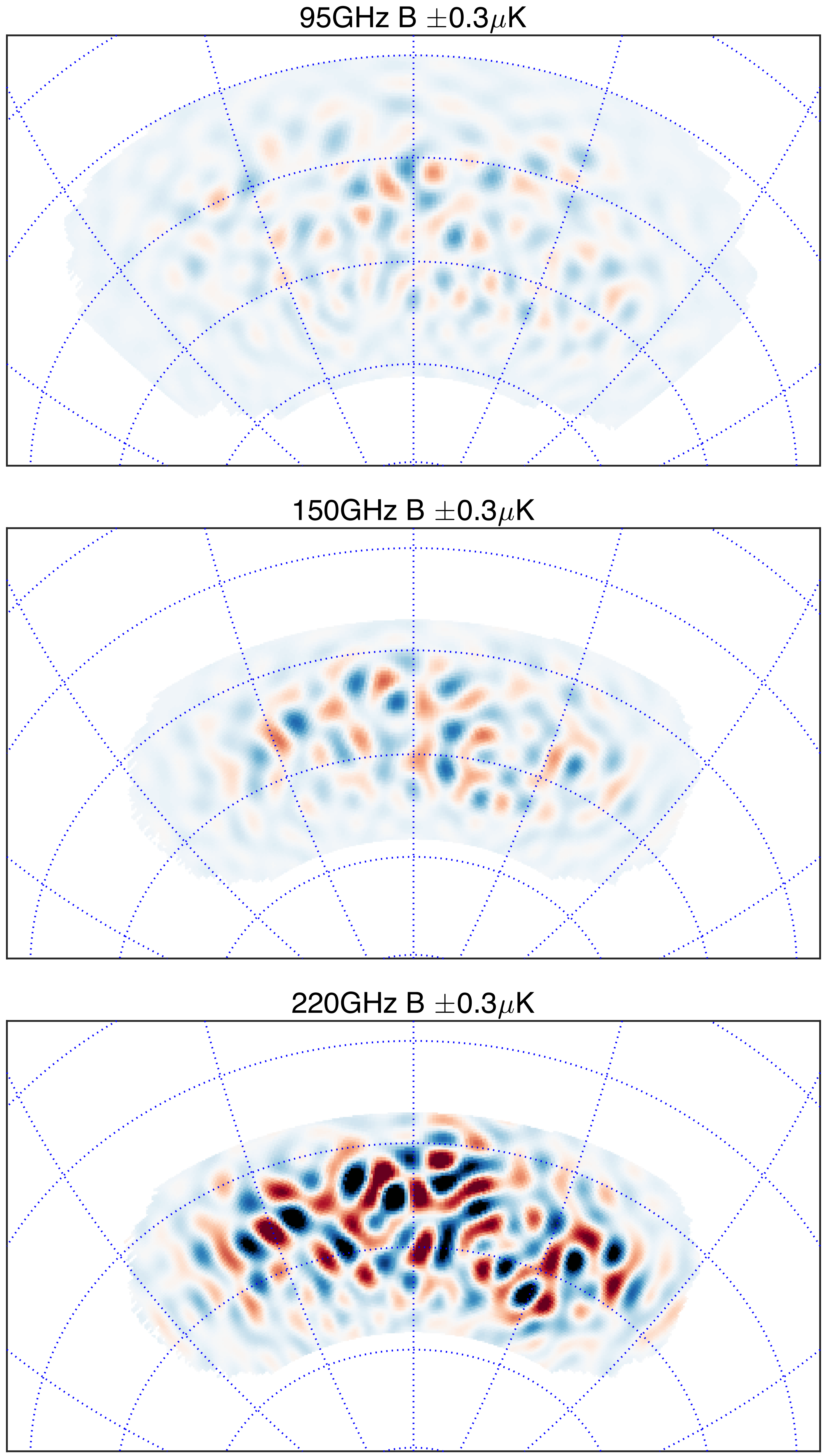
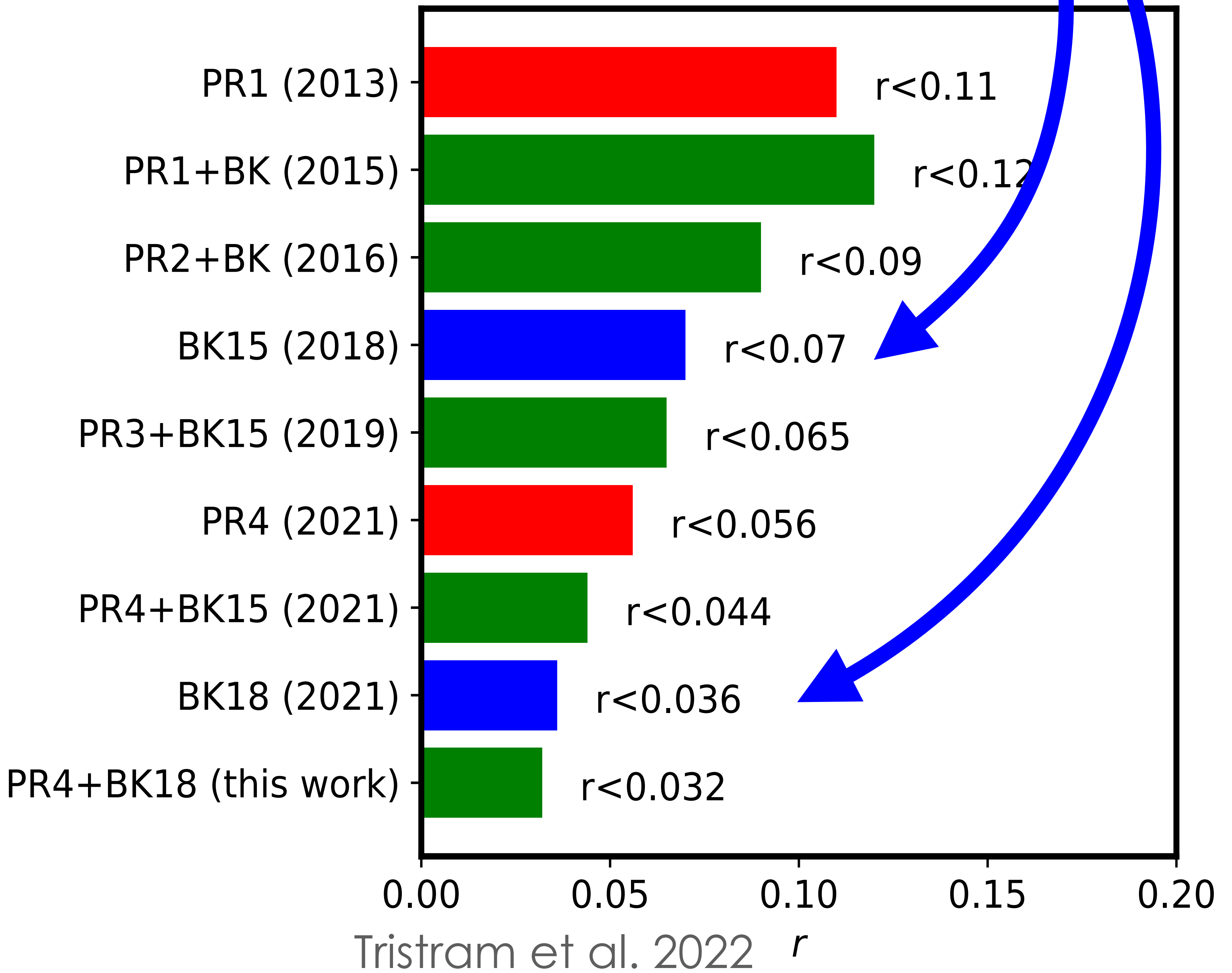
Planck component separated maps have been used in many other studies: lensing reconstructions, isotropy and statistics, compton-y…and to build foreground models used by the entire CMB community

and for B-modes?



BICEP/Keck Collaboration 2021

- The BICEP/*Keck* array has currently reached the highest sensitivity to primordial B-modes
- In their field the B-mode signal is strongly dominated by the thermal dust emission
- But by observing ~1% of the sky (and at the current sensitivity) foreground treatment is still relatively easy, with marginalization over foreground parameters (for both synchrotron and dust) in a cross-C_ℓ likelihood



Tristram et al. 2022

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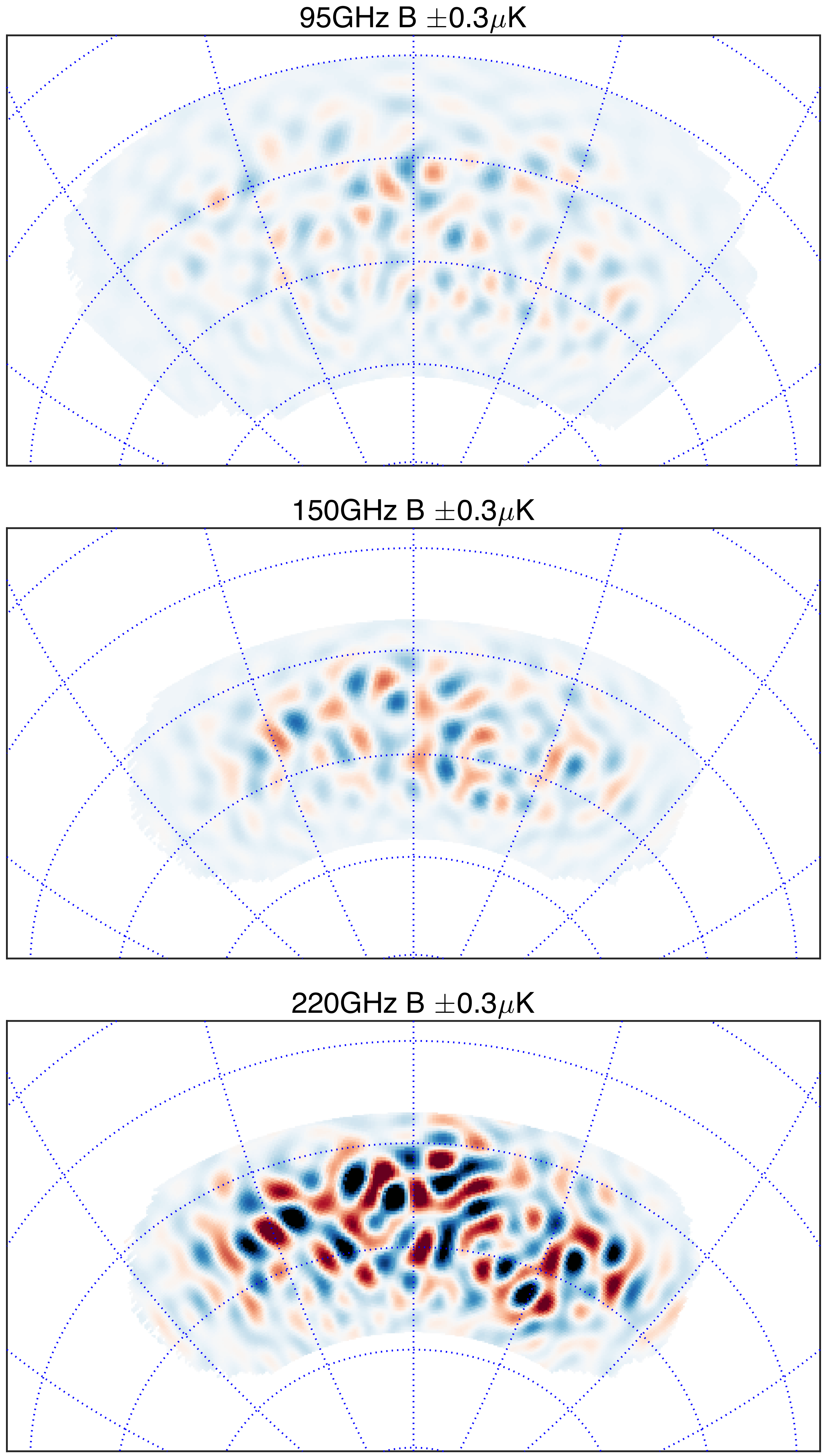

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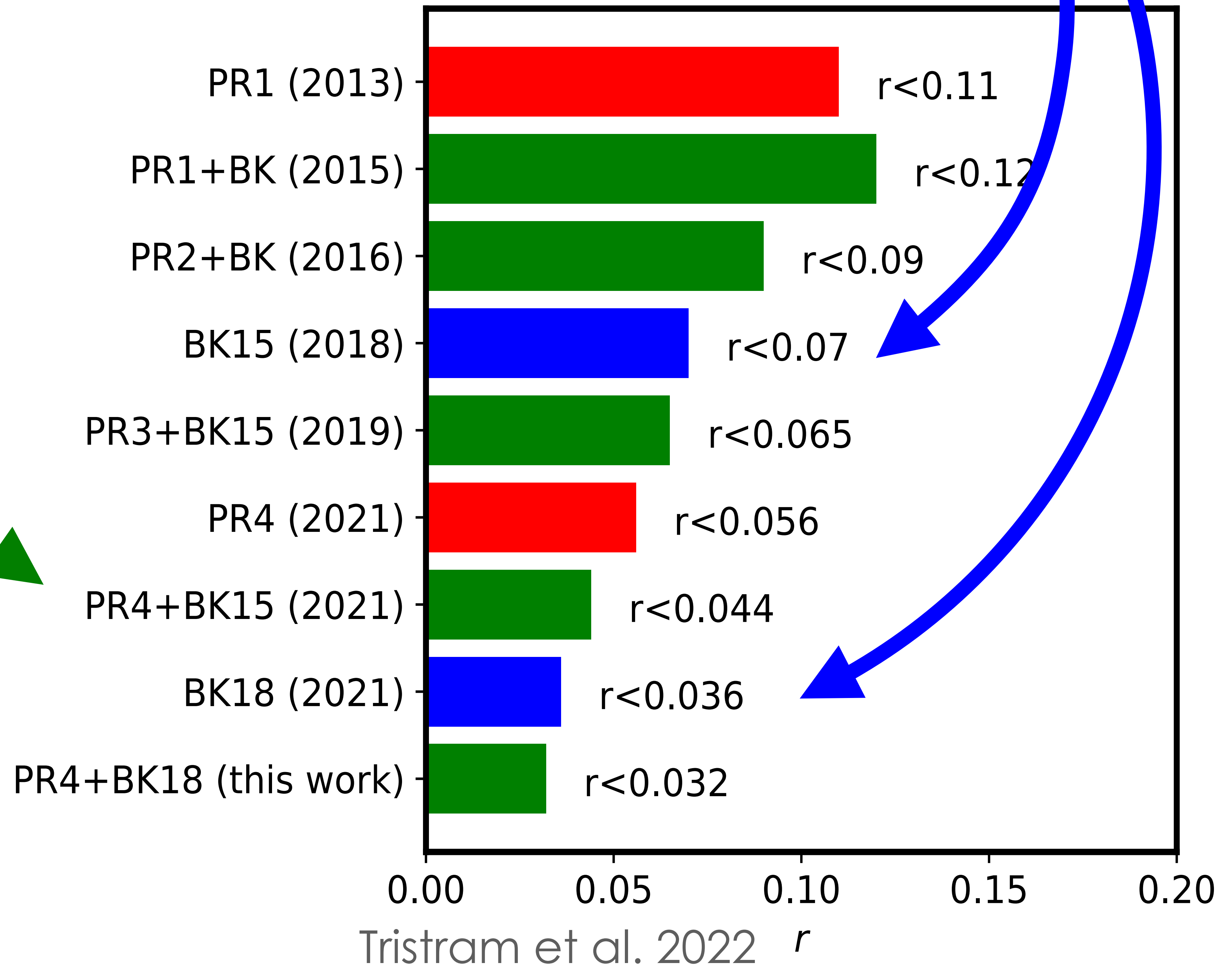
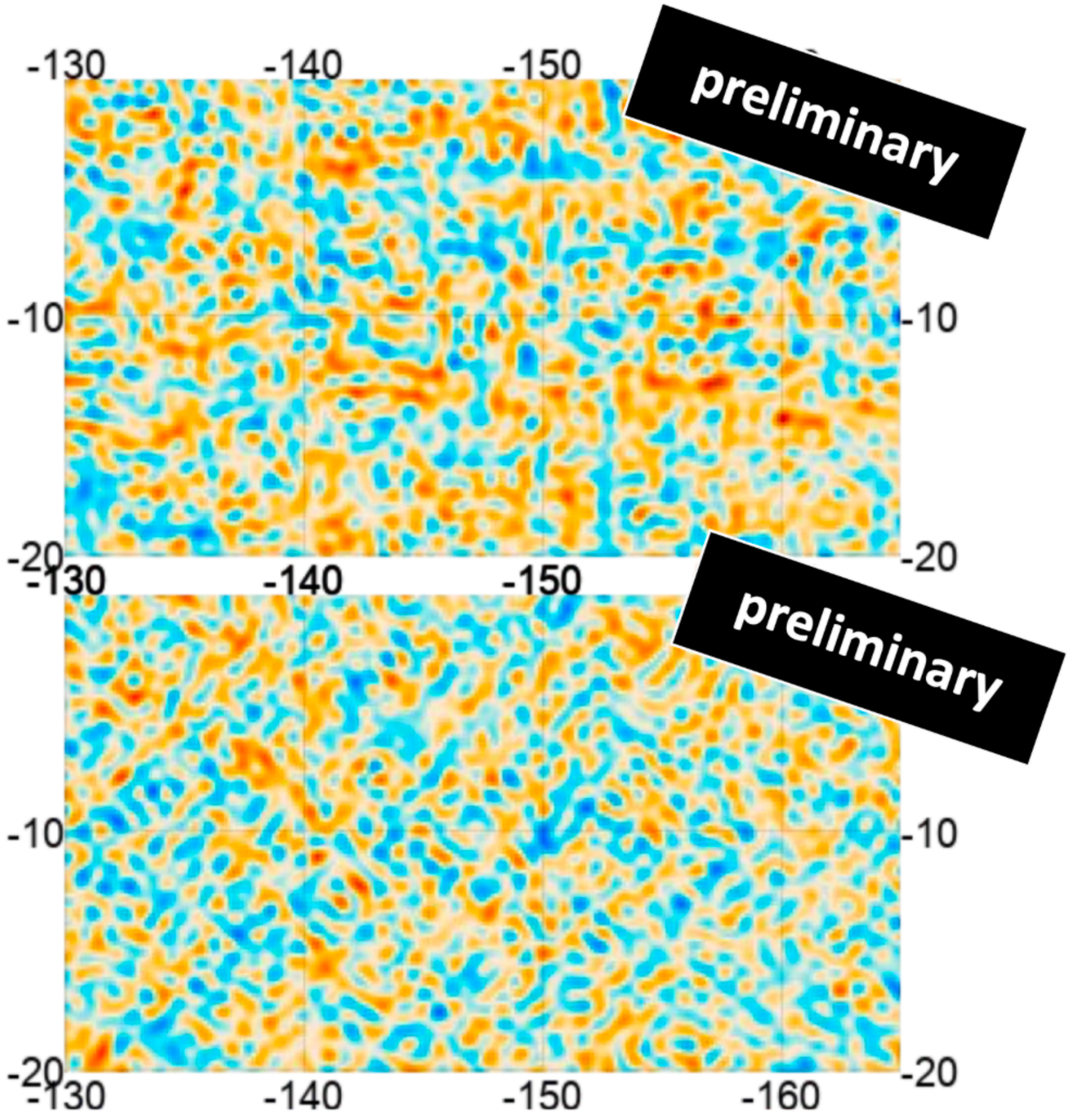
- When Planck polarization full sky data are added to improve the constraints on r, modeling foregrounds at the likelihood level is not accurate anymore and PR4 commander maps are used



Tristram et al. 2022

Component separation strategies for SO-SATs

- Simons Observatory nominal telescopes (3 SATs + 1 LAT) are now all looking at the sky!
- The two middle frequency SATs (95 & 145 GHz) have ended commissioning and are now in initial science observation phase
- The target is $\sigma(r = 0) \lesssim 0.003$ with 5 years of observations on ~10% of the sky from recombination bump



Credits: Simons Observatory Collaboration

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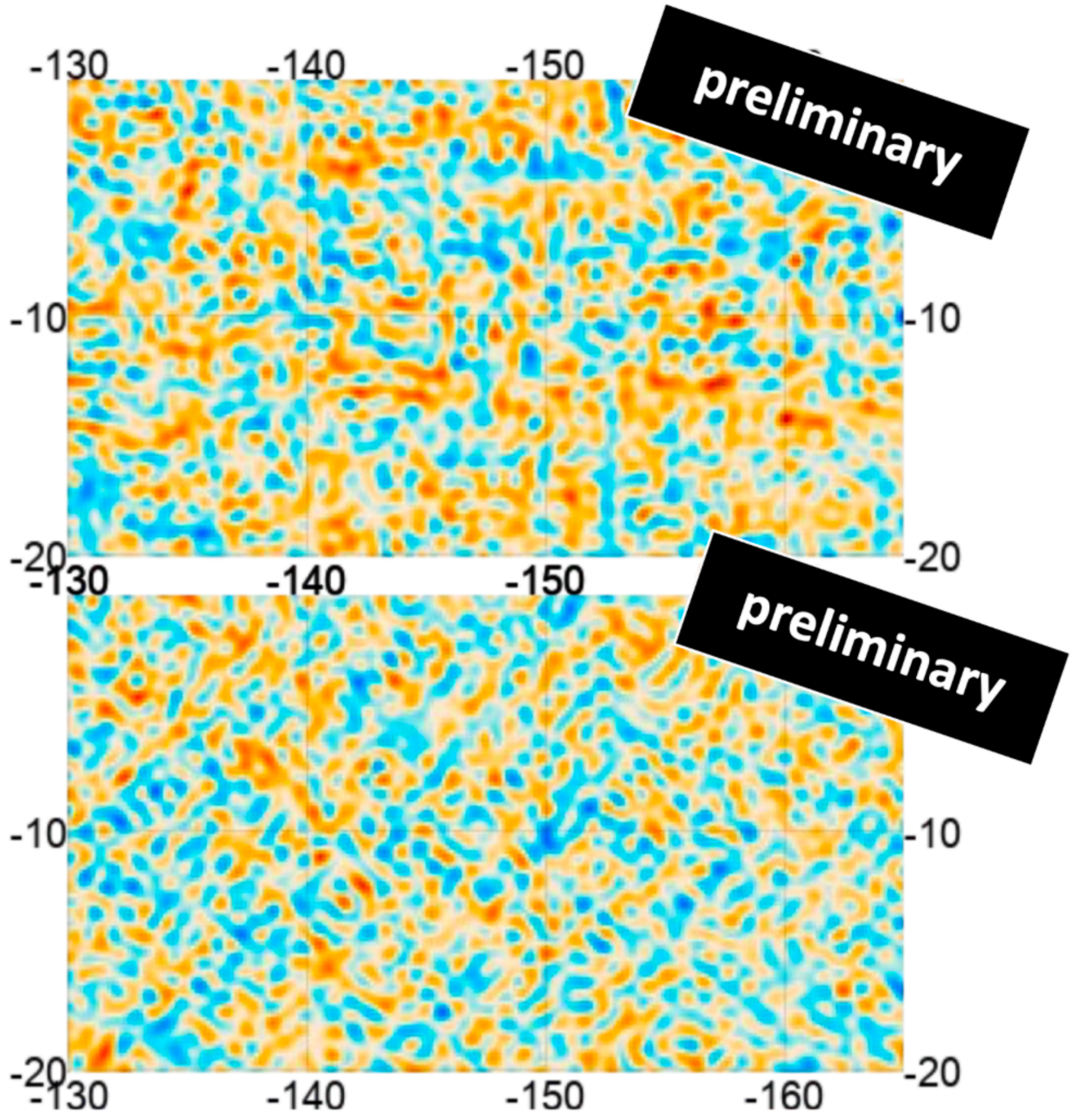
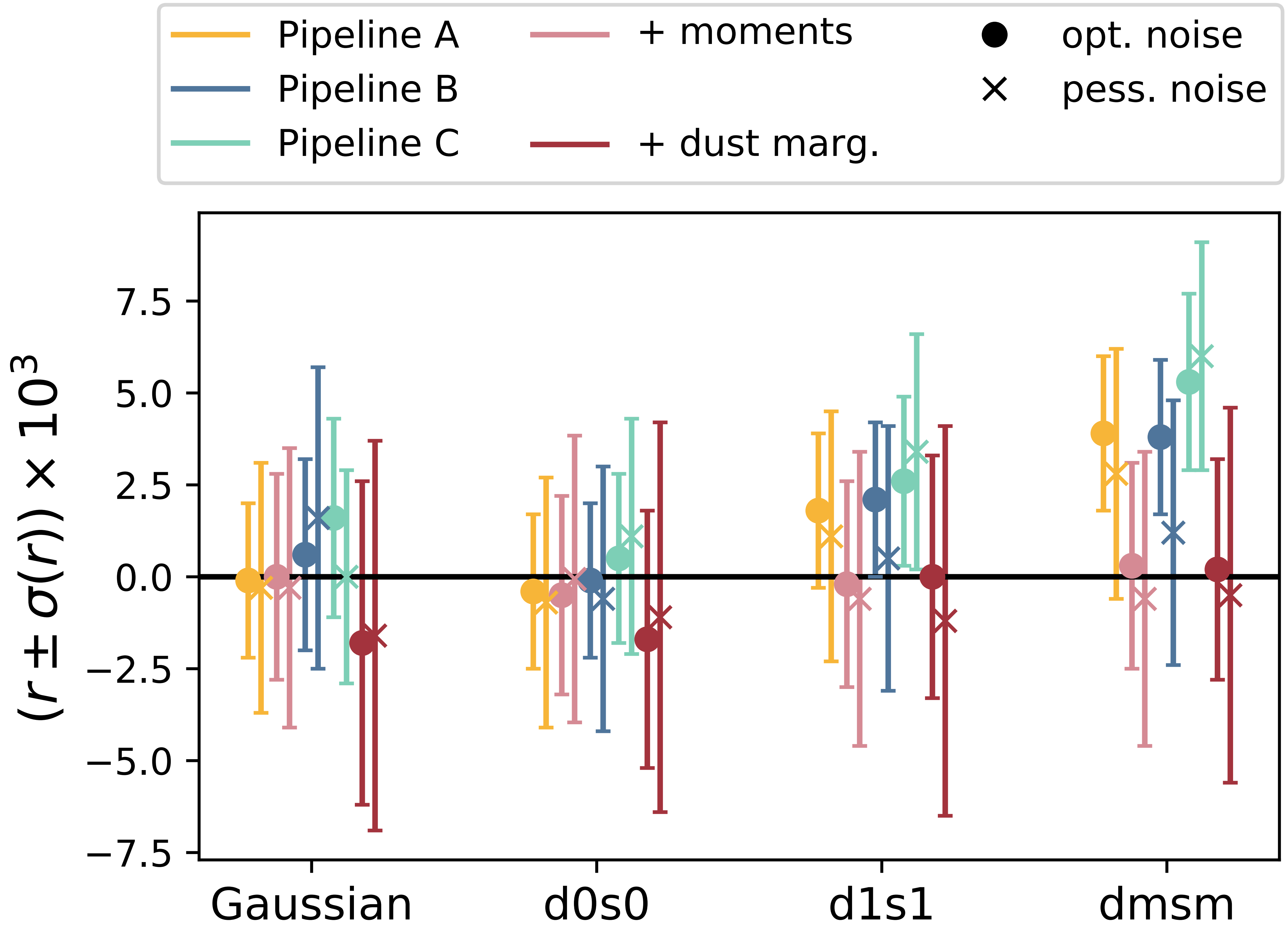


Credits: Simons Observatory Collaboration

- Cross-C_ℓ approach still valid, however on 10% of the sky FG complexity must be taken into account through the inclusion of moment expansion

- Map based approaches (blind and parametric) can lead to biases in the recovery of *r*, marginalization over FG residuals in the likelihood will be needed

- Work in progress to optimize pipelines for real data application: cut sky, frequency dependent filtering, transfer function..



Wolz et al. 2024

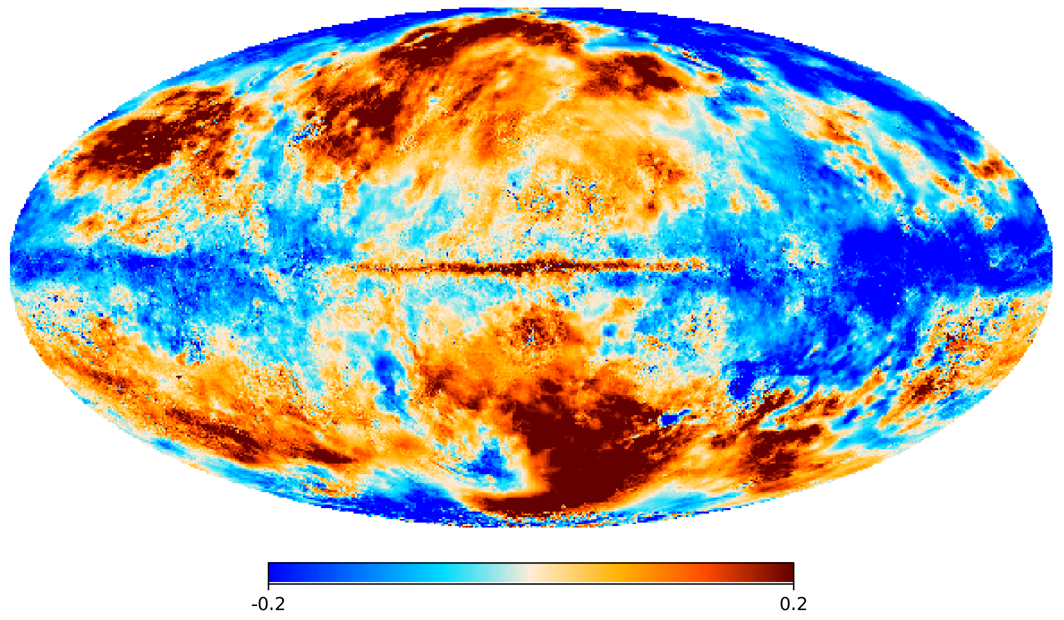
Component separation strategies for LiteBIRD

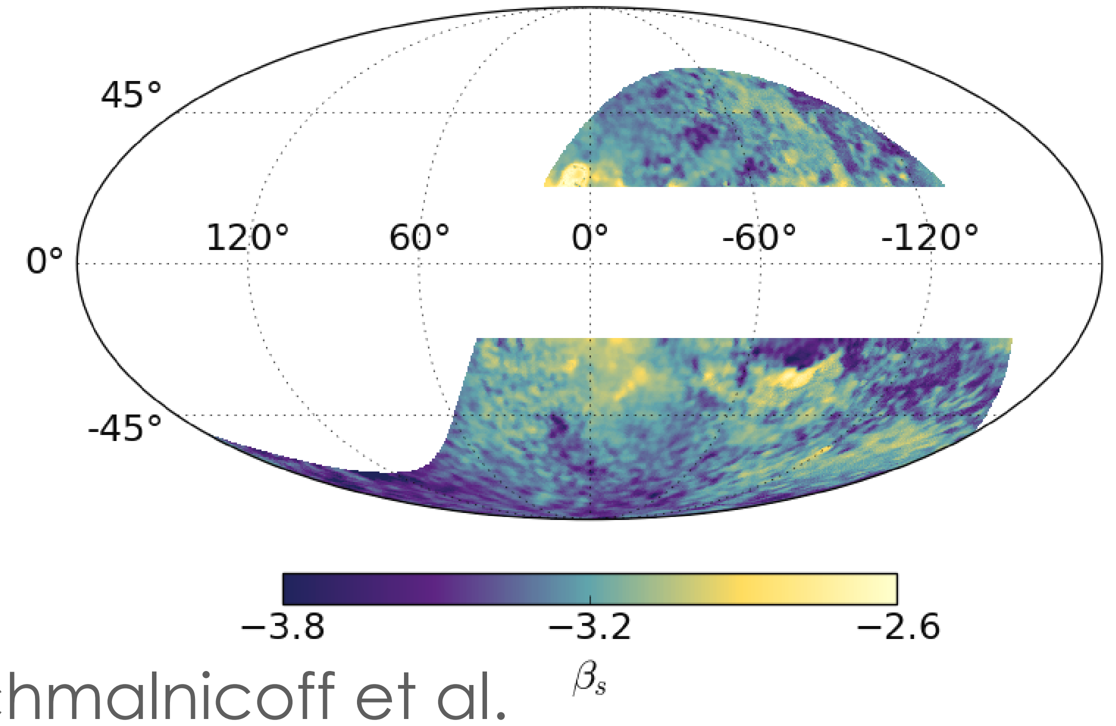
- LiteBIRD will target both the reionization and recombination bumps of primordial B-modes with full sky observations in 15 frequency bands, with target sensitivity $\delta_r(r=0) < 0.001$
- Extremely challenging for component separation: large angular scales, full sky observations, interplay with systematics
- The collaboration is working on the optimization of several component separation methods

Map based algorithms (both blind and parametric) are currently the most advanced ones

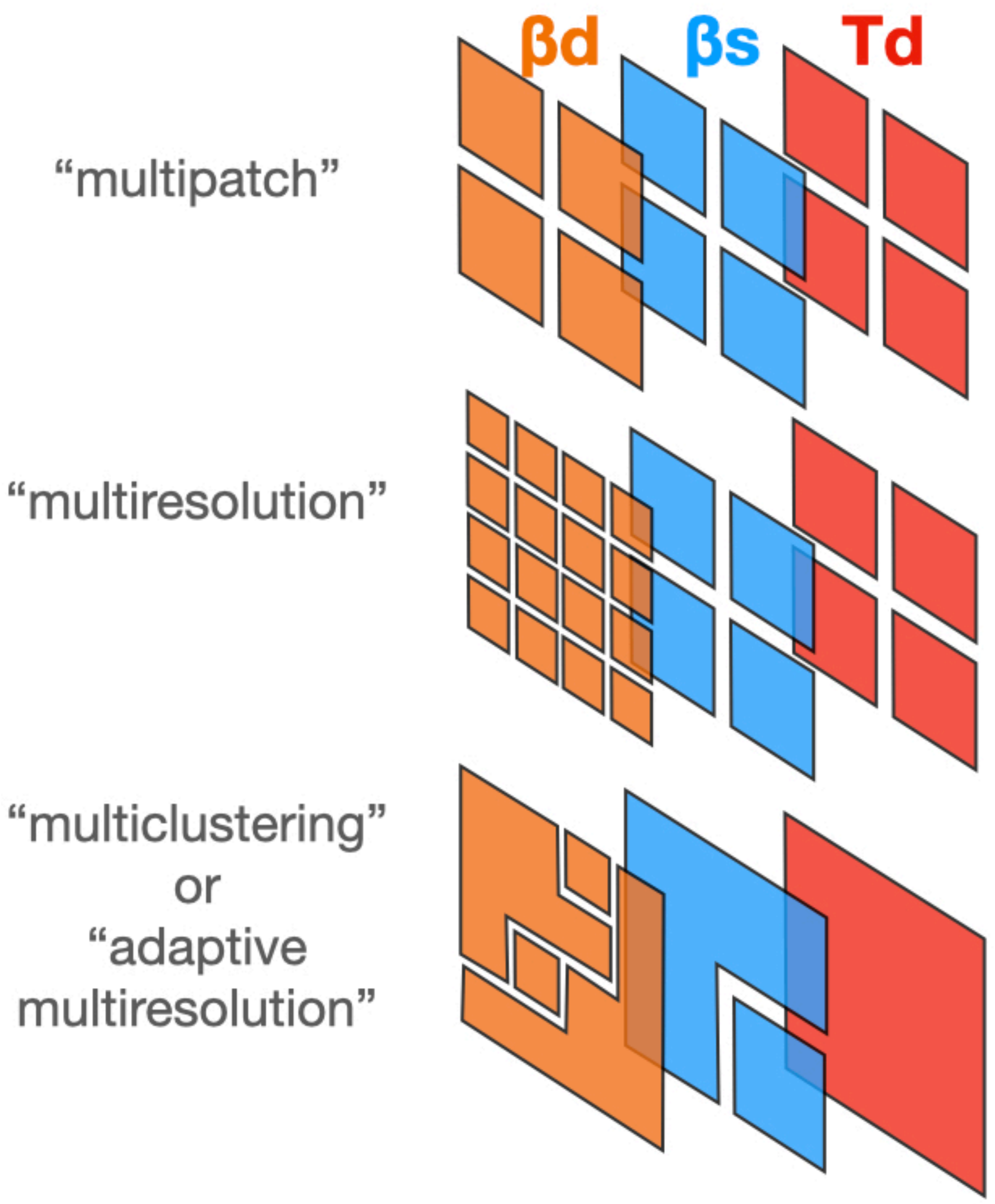
- The major limitation for both approaches is the spatial variation of foreground properties
- Weights to combine maps and recover CMB solution are direction dependent

Planck Collaboration





Krachmalnicoff et al.

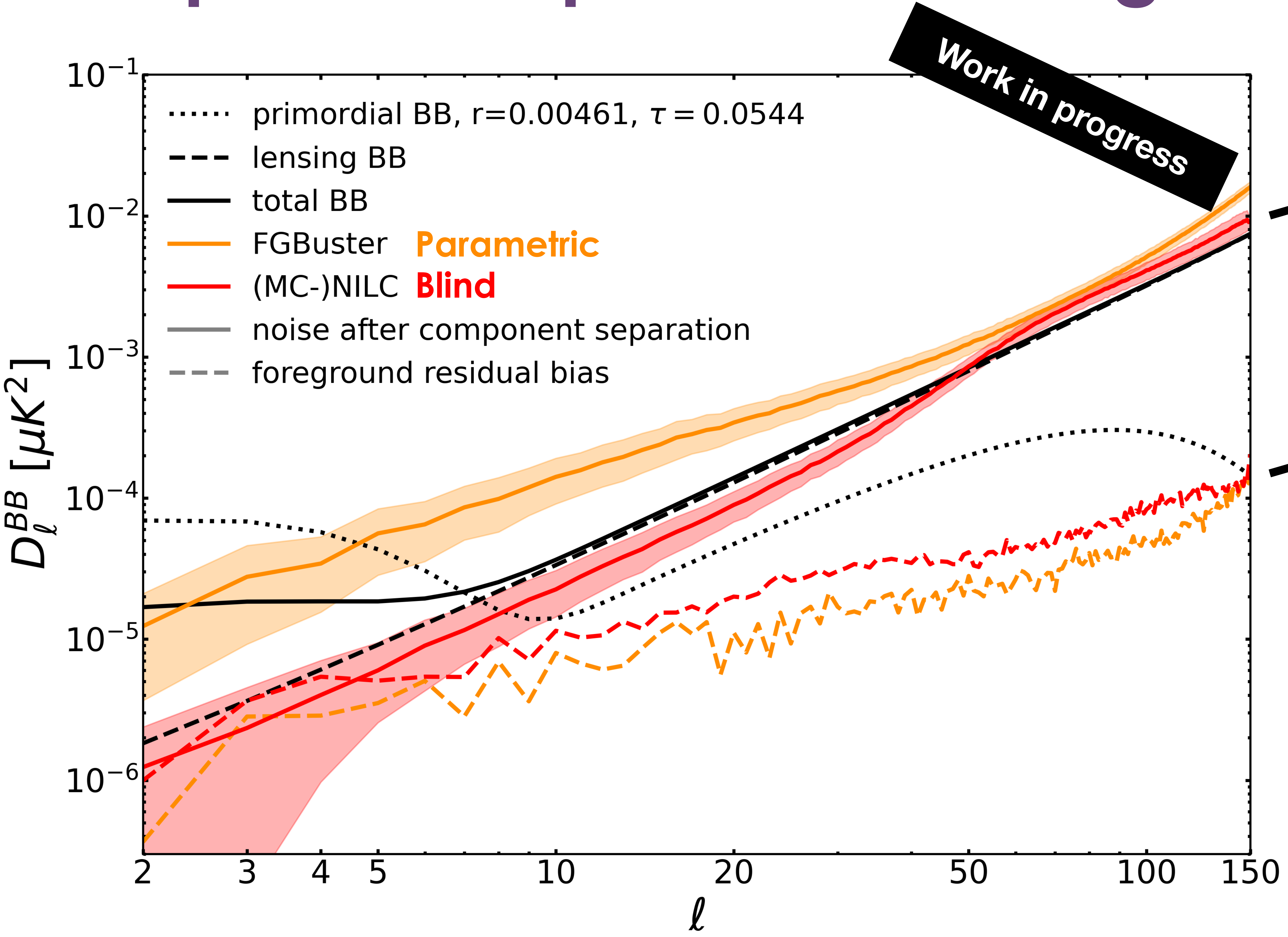


Credits: Josquin Errard

- Weights can be computed independently on different super-pixels on maps
- Trade off to be considered: more patches lead to smaller bias (foreground residuals) on CMB map but higher statistical noise
- Optimal way is to define domains based on physical properties of foregrounds, but:
  - Available data can't be used as prior information (constraints on SED are typically model dependent)
  - domains need to be data driven, and tracer are different depending on component separation algorithm

LiteBIRD Collaboration 2023, Carones et al. 2023

Component separation strategies for LiteBIRD



Statistical noise after component separation leading to larger variance on r posterior

Foreground residuals on CMB map can lead to bias on r posterior

- Component separation algorithms are rapidly evolving, aiming to minimize foreground residuals in cleaned CMB maps.
- In parallel, model-independent and data-driven approaches to construct FG residual templates for marginalization are also being developed.

Credits: Alessandro Carones, Josquin Errard and LiteBIRD collaboration

Conclusions

- Component separation has become a central focus in CMB data analysis over the past two decades.
- Planck demonstrated the value of developing multiple, complementary methods, with great success
- Yet, many key cosmological results still rely on simpler approaches, such as cross-spectra and marginalization over foreground parameters or templates.
- The next major challenge lies in detecting primordial B-modes, especially for full-sky, large-scale experiments like LiteBIRD.
- The field remains highly dynamic and collaborative, with many young researchers driving recent impressive progress.
- Significant room remains for improving how we deal with complex foregrounds and interplay with instrumental systematics.