Data Analysis - Do We Have All The Necessary Tools?

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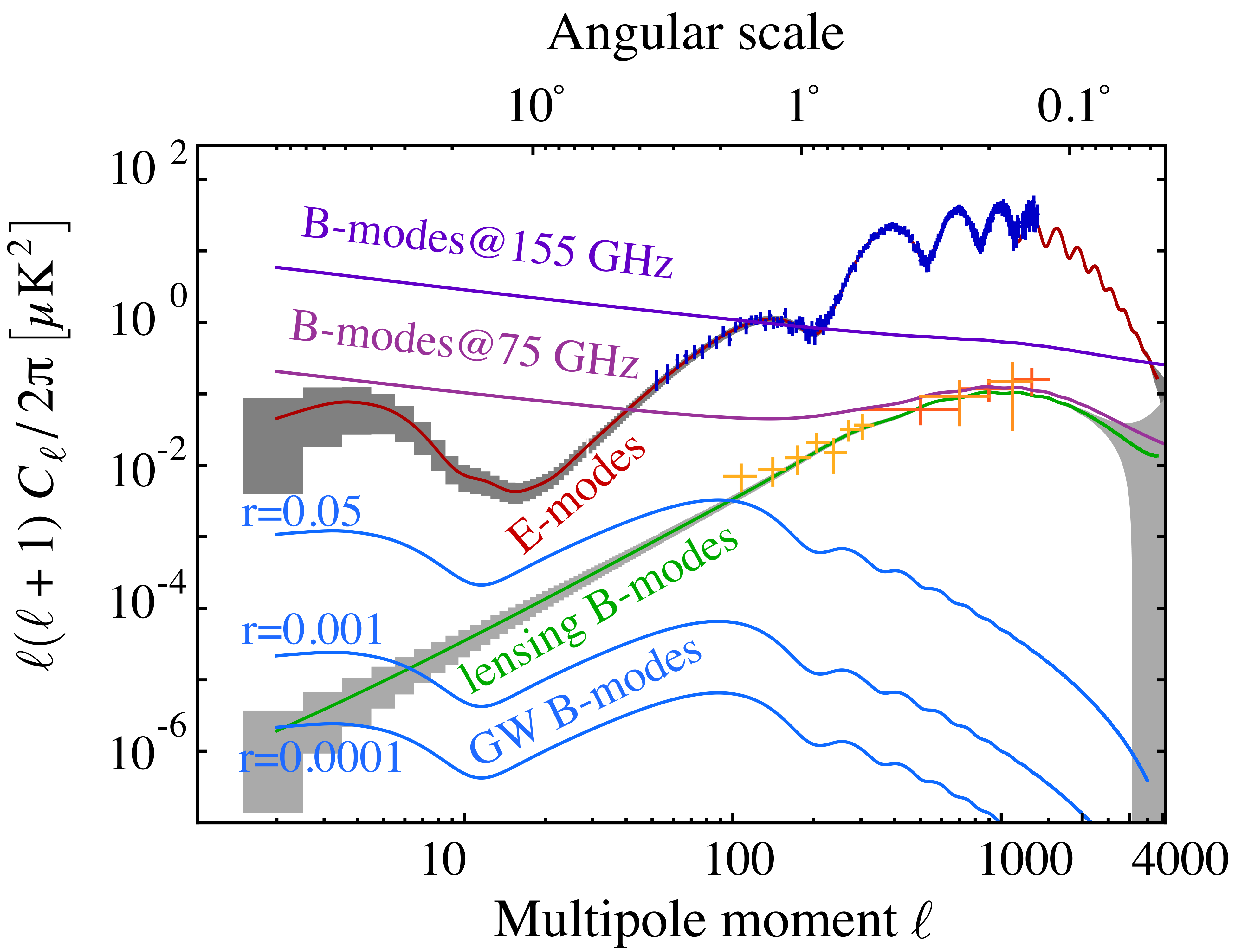
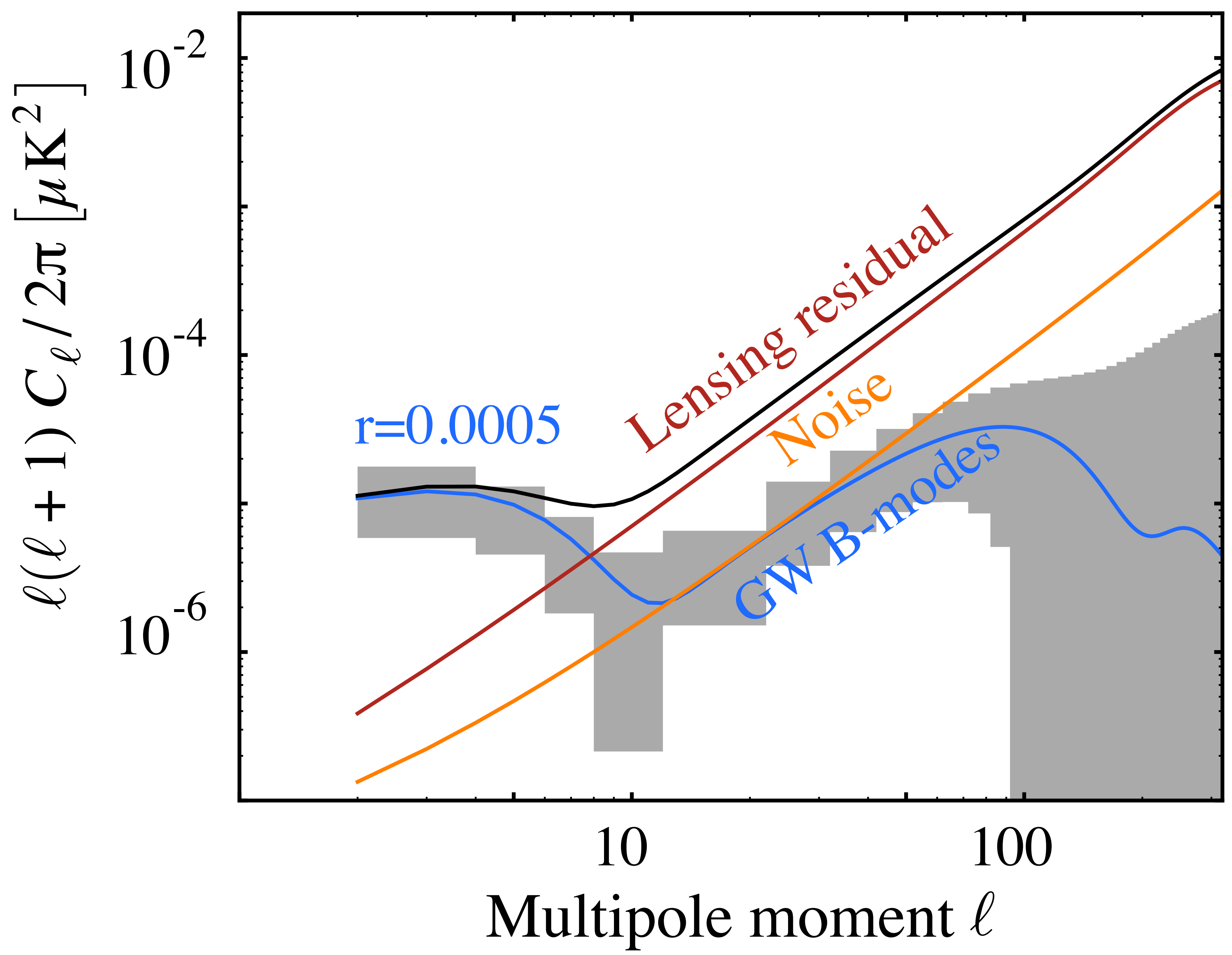
Ever more stringent requirements



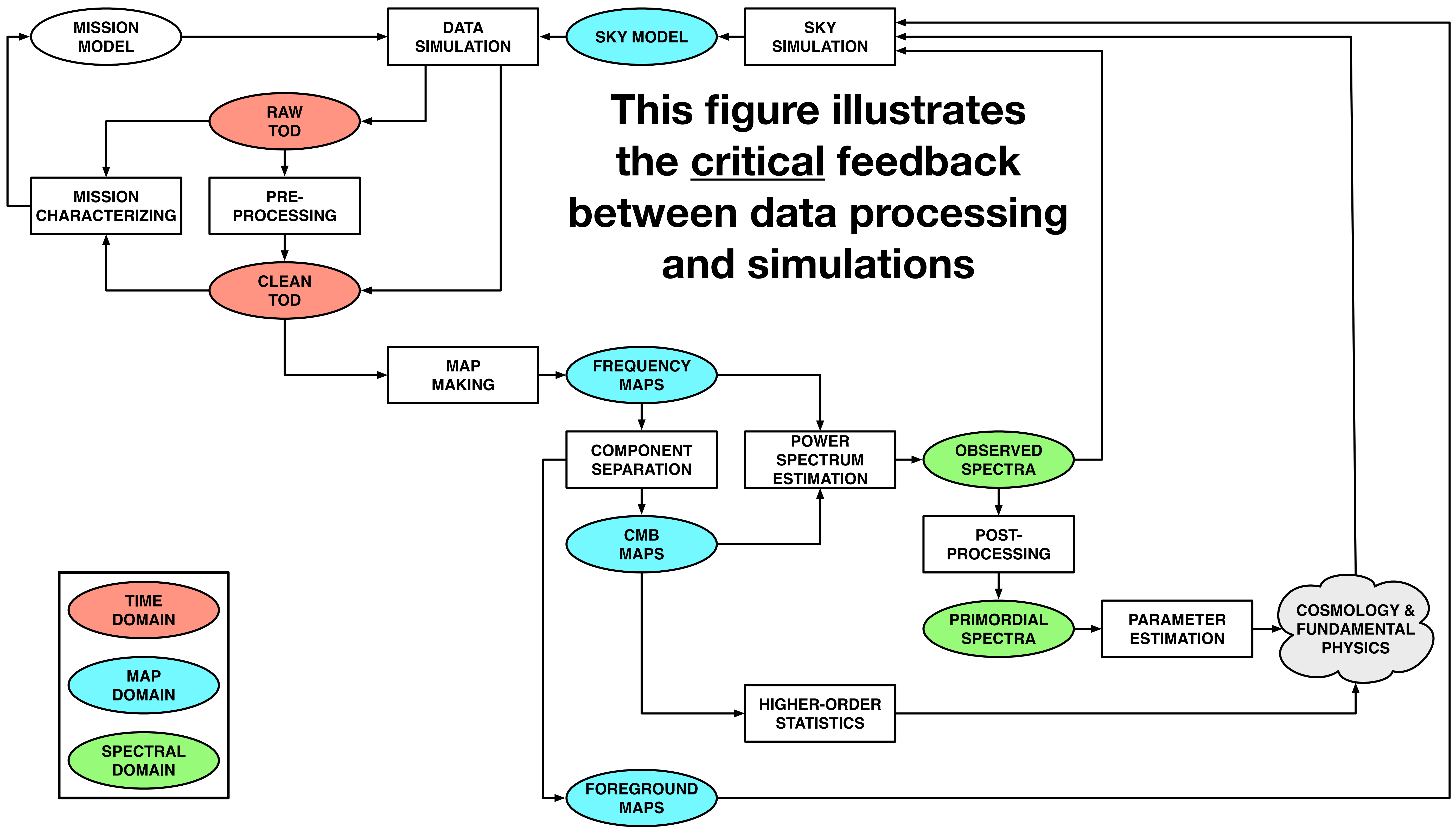


Figures from PICO mission study report arXiv:1902.10541

- Systematics suppression
- Characterization of uncertainty, propagation of errors
- Sky model (component separation) accuracy

End-to-end simulations

- As we dig deeper, systematics cannot be mitigated and suppressed in vacuum
- Only way to assess the efficacy of the mitigation strategies is to run end-to-end simulations
- Simulation capability **must** be developed **with** the mitigation modules
- Developing and maintaining the E2E simulation capability should be part of the data processing effort



This figure illustrates the <u>critical</u> feedback between data processing and simulations

Figure from P. Natoli et al: *"Exploring cosmic origins with CORE: mitigation of systematic effects"* arXiv:1707.04224

Tightly-coupled analysis

- Coming from Planck, the trend is towards global fitting
- Allows error propagation and maximal signal-to-noise
- Planck 2018 -> SRoll2 -> NPIPE -> BeyondPlanck/SRoll3
- The challenge is to find an economical way to capture the systematics in the data, then propagating the uncertainties down to the final, component separated CMB map or even the cosmological parameters behind it

Planck 2018 analysis

- Extension of the destriping principle allows fitting for bandpass mismatch, gain fluctuations and noise offsets in a single step

- The Planck scan strategy left certain large scale polarization modes degenerate with the systematic templates

- Uncertainties were captured with simulations but the destriping framework could have been used to derive the full pixel-pixel covariance.

Time-ordered data

$$\vec{d} = \mathrm{P}\vec{m} + \mathrm{F}\vec{a} + \vec{n}$$

Instrumental, unmitigated noise

Static sky signal

Systematics, noise offsets, time-dependent sky signal

Columns of *F*

- Each panel is a visualization of one detector time-ordered data
- horizontal axis is the pointing period
- vertical axis is the spacecraft spin phase
- Some of the templates are further split into stationary periods

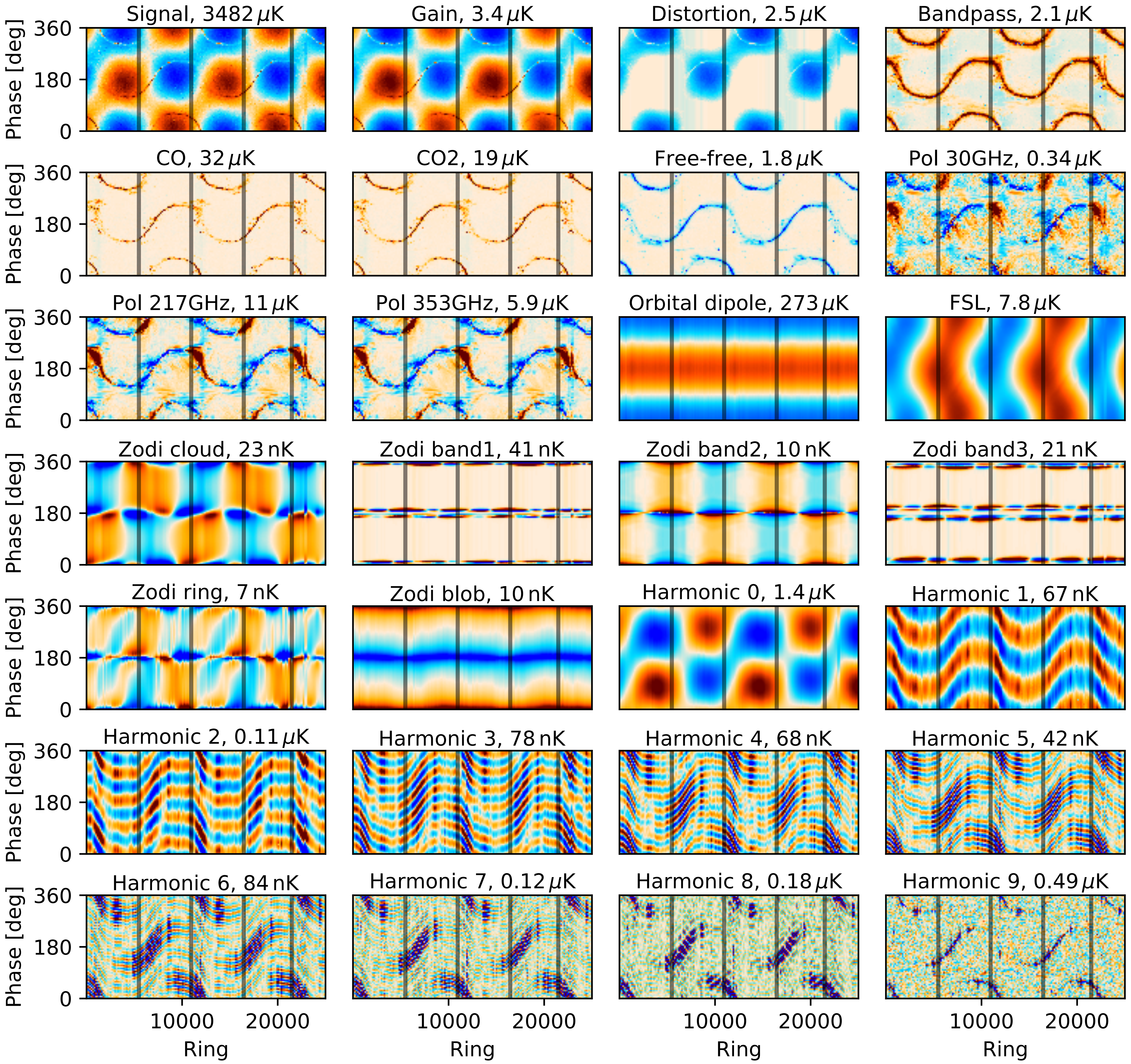


Figure from Planck Collaboration (2020) (in preparation)

BeyondPlanck

- Planck LFI 2018 calibration was deeply dependent on the full sky model

- Iterations between data processing, mapmaking and component separation were slow, allowing for only a few iterations

- The BeyondPlanck project combines flagging, calibration, mapmaking and component separation into a single Gibbs sampler with full propagation of uncertainties

- First release expected this year

- Current LFI-focused project is being followed up with a proposal to include HFI data and extend the analysis with HFI-specific systematics

$$
\begin{array}{lcl}
s^{i+1} & \leftarrow & P(s|f^i, \beta^i, g^i, d, \ldots) \\
f^{i+1} & \leftarrow & P(f|s^{i+1}, \beta^i, g^i, d, \ldots) \\
\beta^{i+1} & \leftarrow & P(\beta|s^{i+1}, f^{i+1}, g^i, d, \ldots) \\
g^{i+1} & \leftarrow & P(g|s^{i+1}, \beta^{i+1}, f^{i+1}, d, \ldots) \\
 & \vdots &
\end{array}
$$

https://beyondplanck.science/

De-projection is alternative to error propagation

- The BICEP/Keck analysis projects out modes compromised by systematics
- Resulting maps are biased but the bias is quantifiable and accounted for in further analysis
- De-projection replaces the need for systematic error propagation with the careful measurement of the pipeline transfer function.
- Biased map-making presents unique challenges to component separation

List of relevant systematics

- **Beam/pointing mismatch**
- Far sidelobe pick-up
- **Gain fluctuations**
- Time-dependent signals (Zodiacal light, variable sources, Doppler shift)
- **Bandpass mismatch**
- Cross-talk
- ADC and detector nonlinearity
- Pointing errors
- Errors in polarization angle and efficiency
- Frequency-dependent beam
- Electromagnetic interference
- **Half-wave plate systematics**

Conclusions

- Future analysis is likely much more tightly-coupled
- Extensive, representative simulations will be needed to tell if we are ready to process the next generation experiments
- An economic basis to capture the systematics will require exquisite understanding of the experiment
- To answer the title question: We don’t have the tools yet, but we know how to make them.