Modeling Galactic Foregrounds for Improved CMB B-mode Signal Analysis

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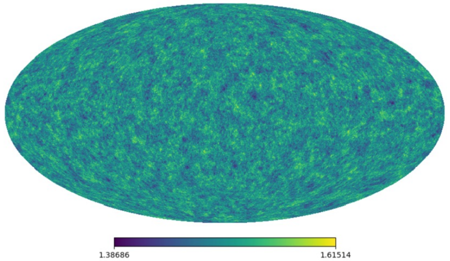
Why CMB?

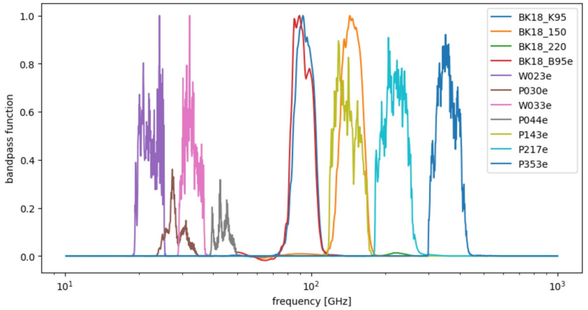
•The Cosmic Microwave Background (CMB) is relic radiation from the early universe, observed ~380,000 years after the Big Bang.
•B-mode polarization in the CMB provides evidence for primordial gravitational waves, supporting cosmic inflation theories.
•Detecting B-modes helps estimate the tensor-to-scalar ratio r, which is crucial for early-universe physics

Foregrounds:

•Major polarized foregrounds: **Synchrotron** (low frequency) and **Thermal Dust Emission** (high frequency).
•These foregrounds obscure faint B-mode signals (~nK level).
•Traditional models assume constant dust parameters (e.g., β_D), but real observations show spatial variability.
•Spatial variation causes **frequency decorrelation**, biasing r.



Simulated Map of Dust Spectral Index β_n demonstrates how dust spectral properties vary across the sky



Instrumental Bandpass Functions centered at different frequencies. This multi-frequency coverage is critical because it allows us to distinguish between the flat spectrum of the CMB and the frequency-dependent foregrounds like thermal dust.

Moments Method – Theory:

Azzoni et al. (2020) introduced a power-spectrum-based formalism that accounts for spatial variations in spectral parameters like β_n.

The total cross-power spectrum between two frequencies ν and ν' can be expanded as: $C_l^{\nu\nu'} = C_l^{0x0} + C_l^{1x1} + C_l^{0x2}$

This expansion is then **propagated into the angular power spectrum**, yielding the following terms:

- Baseline spectrum $C_l^{0x0} = S_\nu(\beta_D) \cdot S_{\nu'}(\beta_D) \cdot C_l^{DD}$
- Curvature corrections due to second-order terms

$$C_l^{0x2} = \sum \frac{1}{2} \cdot \left(S_\nu(\beta_D) \cdot \partial^2 S_{\nu'}(\beta_D) + \partial^2 S_\nu(\beta_D) \cdot S_{\nu'}(\beta_D) \right) \cdot C_l^{DD} \sigma^2$$

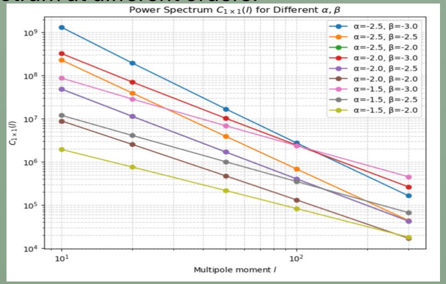
- Correlations of first-order spectral index fluctuations

$$C_l^{1x1} = \sum \partial S_\nu(\beta_D) \cdot \partial S_{\nu'}(\beta_D) \sum_{l_1,l_2} \frac{(2l_1+1)(2l_2+1)}{4\pi} \begin{pmatrix} l & l_1 & l_2 \\ 0 & 0 & 0 \end{pmatrix} C_{l_1}^{DD} \cdot C_{l_2}^{\beta}$$

Here: S_ν *is the average dust spectral energy distribution (SED), modeled as:*

$S_\nu \propto (\frac{\nu}{\nu_0})^{\beta_D} \cdot \frac{B_\nu(T_D)}{B_{\nu'}(T_D)}$,here $B_\nu(T_D)$ being the Planck function and ν_0 the pivot frequency

These components track how spectral variability in dust emission impacts the power spectrum at different orders.



Approximated Power-Law Formula for C_l^{1x1} :

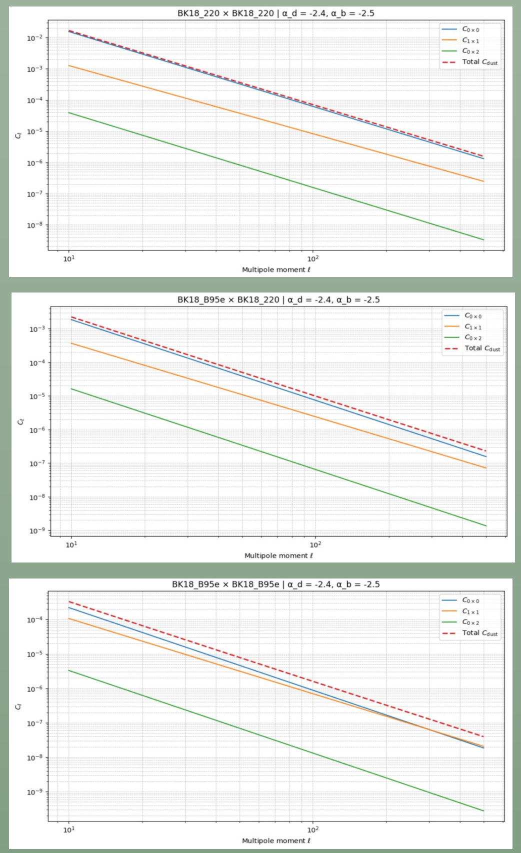
To reduce computation time, we replaced the full Wigner 3j expression with this power-law approximation. The above plot shows the computed values of the moment term C_l^{1x1}, plotted on a log-log scale against l. Each curve exhibits a straight-line trend in log-log space, indicating a clear **power-law behavior**. Thus, making approximations fast enough to use inside MCMC.

$$C_l^{1x1} \approx A_D \left(\frac{l}{l*}\right)^{\gamma_D}$$

Where we approximated expressions as a function of α_β and α_D, then fitting a regression model using polynomial combinations.

•A_D is the amplitude of the moment term at pivot multipole l* (80).
•γ_D is the effective slope of the moment term.

Dust Power Spectrum Decomposition Across BICEP/Keck Bandpasses



These plots show how the total dust spectrum is built from the C_l^{0x0}, C_l^{1x1} and C_l^{0x2} terms for a fixed choice of α_β and α_D, and fitted values of A_D *and* A_β. The 1×1 component speeds up the calculation so that it can be used in a Markov Chain Monte Carlo analysis.

References:

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