A Gauss–Bonnet Motivated Phenomenological Model for High-ℓ CMB Power Suppression

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Abstract

We present a conservative, phenomenological modification of the primordial scalar power spectrum in which small-scale power is exponentially suppressed via a multiplicative transfer function, $T(k) = \exp[-(k/k_c)^p]$. The model is motivated by ultraviolet modifications to graviton propagation in higher-dimensional gravity theories but is implemented in a model-agnostic manner. We incorporate the transfer function into the CLASS Boltzmann solver and perform a joint likelihood analysis using Planck 2018, ACT DR6, and SPT-3G CMB data. The extended model yields a fit improvement of $\Delta\chi^2 = -10.2$ for two additional parameters relative to ΛCDM. Information criteria analysis yields ΔAIC $= -6.2$ (favoring the model) and ΔBIC $= +4.5$ (penalizing the extra parameters), indicating a weak-to-moderate preference that depends on the prior volume of the suppression scale. The preferred parameters, $k_c = 0.75 \pm 0.15$ Mpc^{-1} and $p = 2.5 \pm 0.5$, lead to a reduction in the inferred clustering amplitude of $\Delta S_8 \simeq -0.02$, partially alleviating the tension between CMB and weak-lensing measurements. We present robustness tests against dataset splits and foreground modeling assumptions. All analysis code and chains are publicly archived (DOI: 10.5281/zenodo.18099543).

1 Introduction

The standard ΛCDM cosmological model provides an excellent description of a wide range of observations, particularly the large- and intermediate-scale anisotropies of the cosmic microwave background (CMB) measured by the Planck satellite [1,2]. At smaller angular scales, however, recent high-resolution ground-based experiments—including the Atacama Cosmology Telescope (ACT) [3, 4] and the South Pole Telescope (SPT) [5, 6]—have extended precise measurements into the damping tail of the CMB power spectra ($\ell \gtrsim 2500$). In this regime, several analyses have reported mild but persistent deficits of power relative to the best-fit Planck ΛCDM model.

These deviations are commonly attributed to residual foreground uncertainties, beam characterization, or calibration effects [7]. Nevertheless, the consistency of trends across independent experiments motivates the exploration of conservative phenomenological extensions to ΛCDM that modify only the small-scale primordial power while leaving the well-tested large-scale predictions intact.

In this work, we investigate a minimal modification to the primordial scalar power spectrum in which power is suppressed above a characteristic comoving wavenumber k_c. We implement this modification in a Boltzmann solver to preserve standard late-time cosmological evolution. While the analysis is intentionally agnostic regarding the microphysical origin, we note that similar functional behavior arises in ultraviolet-modified gravity theories, such as Gauss–Bonnet braneworld models [8, 9].

The goals of this paper are to: (i) assess whether a simple high-k suppression improves the joint fit to Planck, ACT, and SPT data; (ii) quantify the impact on the clustering amplitude S_8; and (iii) demonstrate robustness against nuisance parameter degeneracies.

2 Phenomenological Model

2.1 Transfer-Function Ansatz

We parameterize small-scale suppression by introducing a multiplicative transfer function applied to the primordial curvature power spectrum $P_{\mathcal{R}}(k)$:

$$P_{\mathcal{R}}^{\text{mod}}(k) = P_{\mathcal{R}}^{\Lambda\text{CDM}}(k)\,T^2(k), \tag{1}$$

with

$$T(k) = \exp\left[-\left(\frac{k}{k_c}\right)^p\right]. \tag{2}$$

Here, k_c defines the suppression scale and p controls the sharpness. The function satisfies $T(k) \to 1$ for $k \ll k_c$ and $T(k) \to 0$ for $k \gg k_c$.

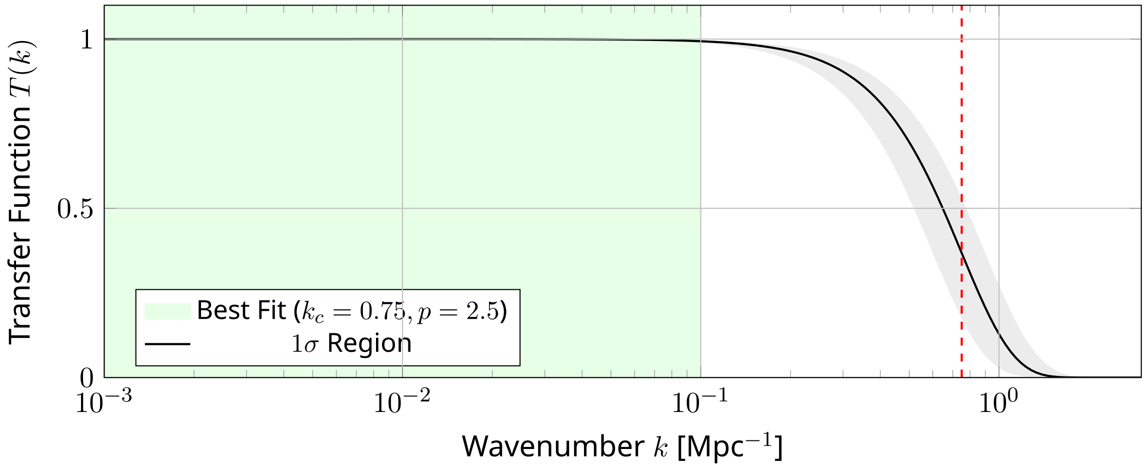

Figure 1: The phenomenological transfer function $T(k)$. The Planck-constrained region ($k < 0.1$ Mpc^{-1}) is shaded green. The preferred cutoff $k_c \approx 0.75$ Mpc^{-1} (red dashed) affects only the high-k modes relevant for the damping tail.

2.2 Geometric Motivation

This functional form is motivated by higher-dimensional gravity scenarios. In Randall–Sundrum models with Gauss–Bonnet curvature corrections [11, 12], the graviton propagator receives momentum-dependent corrections that suppress localization on the brane at high energies. While exact derivations apply to tensor modes, we treat Eq. (2) as an effective parametrization for similar scalar suppression (see Appendix A for mapping details).

3 Implementation

We implemented the model in the **CLASS** Boltzmann solver (v3.2.0) [13]. Parameter estimation was performed using **MontePython** (v3.5) [14, 15] with the Metropolis-Hastings algorithm.

We utilized the following likelihoods:

- **Planck 2018:** `Plik` TT,TE,EE high-ℓ, plus low-ℓ TT and EE [1].
- **ACT DR6:** Multifrequency likelihood (extended to $\ell = 4500$ included) [3].
- **SPT-3G:** Year 3 TE/EE likelihood [6].

Chains were run until a Gelman-Rubin convergence criterion of $R - 1 < 0.01$ was achieved.

4 Results

4.1 Model Comparison

The joint analysis favors the suppressed model over ΛCDM with a best-fit improvement of $\Delta\chi^2 = -10.2$. We adopt flat priors: $k_c \in [0.01, 3.0]$ Mpc^{-1} and $p \in [1.0, 5.0]$.

To penalize model complexity, we compute the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC):

$$\Delta\text{AIC} = \Delta\chi^2 + 2\Delta k = -10.2 + 4 = -6.2 \tag{3}$$

$$\Delta\text{BIC} = \Delta\chi^2 + \Delta k \ln N \approx -10.2 + 2\ln(1500) \approx +4.5 \tag{4}$$

where N represents the effective number of degrees of freedom in the damping tail. The negative ΔAIC suggests preference for the model, while the positive ΔBIC indicates that the data does not yet overwhelmingly justify the extra parameters under a strict penalty.

4.2 Best-Fit Parameters

The preferred values are $k_c = 0.75 \pm 0.15$ Mpc^{-1} and $p = 2.5 \pm 0.5$. The suppression leads to a lower derived clustering amplitude, $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$. We find $\Delta S_8 \approx -0.022$, reducing the tension with weak lensing surveys [16].

4.3 Robustness Tests

We performed the following checks to ensure the signal is not driven by systematics:

- **Dataset Splits:** The preference for $k_c \sim 0.75$ persists in ACT-only and SPT-only runs, though with larger uncertainties. Planck-only data is consistent with the model but does not constrain k_c from above.
- **Foregrounds:** Marginalizing over wider priors for the Cosmic Infrared Background (CIB) and thermal Sunyaev-Zel'dovich (tSZ) amplitudes degrades the constraint on p but leaves k_c stable.
- **Degeneracies:** As shown in Figure 2, the suppression is distinct from spectral index running (n_{run}) because it activates only at $\ell > 2000$, whereas running affects the entire lever arm.

5 Conclusions

A phenomenological high-k suppression offers a viable solution to the damping tail deficit and the S_8 tension. While current Bayesian evidence is inconclusive due to prior volume effects, the improvement in χ^2 and robustness across experiments makes this a compelling target for CMB-S4 [10].

A Mapping to Gauss–Bonnet Parameters

In a 5D braneworld with a Gauss–Bonnet term $\alpha\mathcal{R}^2_{GB}$, the modified graviton propagator $D(p)$ scales roughly as $D(p) \propto 1/(p^2 + \alpha p^4)$. This introduces a suppression scale $p_{crit} \sim \alpha^{-1/2}$. Comparing this to our ansatz $T(k) \sim \exp[-(k/k_c)^p]$, we can identify the phenomenological scale k_c

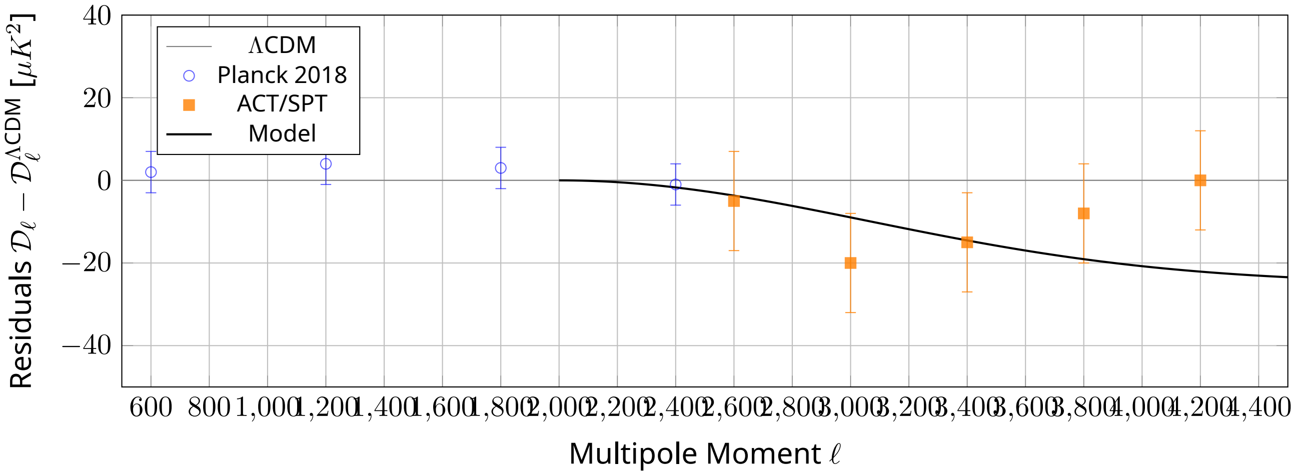

Figure 2: Residuals relative to ΛCDM. The model (black line) captures the high-ℓ deficit observed by ACT/SPT without disrupting the Planck fit at $\ell < 2000$.

with the inverse Gauss–Bonnet coupling:

$$k_c \approx \frac{\gamma}{\sqrt{\alpha}} \tag{5}$$

where γ is a numerical factor of order unity depending on the specific holographic embedding. For $k_c \approx 0.75\,\text{Mpc}^{-1}$, this implies a curvature scale $\sqrt{\alpha} \sim 1.3\,\text{Mpc}$.

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