Systematic CMB Constraints on Early-Universe Modifications:
Parameter Degeneracies and Null Results

Testing Energy-Flow Cosmology Mechanisms Against Planck 2018 Data

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Data: Planck 2018 TT Spectrum

Abstract

We present a systematic framework for testing alternative cosmological scenarios against Planck 2018 CMB temperature power spectrum data. We implement two mechanisms inspired by Energy-Flow Cosmology: (i) modified photon-baryon coupling kappa-dot(z) and (ii) Gaussian-windowed background energy density epsilon·rho_tot(z) at recombination (z approximately 1100).

Using proper amplitude marginalization and chi squared analysis, we find that mechanism (i) yields a clear null result: the minimum Deltachi squared occurs at zero modification. For mechanism (ii), initial single-parameter scans suggested a preference for epsilon approximately +3% (Deltachi squared approximately -65), but this proved to be an artifact of strong degeneracy with the Hubble parameter h. When both epsilon and h are varied in a two-dimensional parameter grid, the preference vanishes: the minimum lies at epsilon approximately 0 with Deltachi squared approximately -1.26, consistent with noise.

This demonstrates the critical importance of accounting for parameter covariances when testing alternative theories. Both mechanisms tested are rejected by Planck TT data when analyzed correctly. Our framework provides a reproducible testbed for future cosmological model testing.

1. Introduction

The cosmic microwave background (CMB) provides stringent constraints on cosmological models. Standard LambdaCDM has been remarkably successful in fitting Planck 2018 observations, achieving chi squared/dof approximately 1.2 for the temperature power spectrum. However, alternative theories continue to be proposed, necessitating rigorous testing frameworks.

Energy-Flow Cosmology (EFC) proposes modifications to standard cosmology through regime-dependent dynamics. To test EFC predictions against CMB data, we implement two distinct coupling mechanisms:

Mechanism 1: Modified Thomson Scattering (kappa-dot)
We test smooth modifications to the photon-baryon coupling rate around z approximately 700, parameterized as kappa-dot(z) = kappa-dot_std x [1 + boost x tanh((z-700)/200)]. This represents microscopic physics modifications.

Mechanism 2: Background Energy Density (H(z))
We test a Gaussian-windowed extra energy component at recombination: rho_EFC(a) = epsilon·rho_tot(a)·exp(-((a-a_t) squared)/(2Delta squared)) with w_EFC = 1/3 (radiation-like). This represents macroscopic background dynamics modifications.

Our analysis reveals an important methodological lesson about parameter degeneracies that is broadly applicable to alternative theory testing.

2. Methodology

2.1 Data and Tools

Data: Planck 2018 temperature power spectrum (TT), 2507 data points covering ell = 2-2508.

Boltzmann Solver: CLASS v3.2.0 modified to include EFC components.

Statistical Method: Amplitude marginalization followed by chi squared computation. For each model, we fit an overall amplitude A to minimize chi squared = Sum[(D_ell^obs - A·D_ell^model)/sigma_ell] squared. This accounts for unknown overall calibration while preserving spectral shape information.

2.2 Mechanism 1: Modified kappa-dot

Implementation in CLASS thermodynamics.c (line 2961):

```
kappa_dot *= (1.0 + boost * tanh((z - 700.0) / 200.0));
```

We tested boost ∈ {-3%, -1%, -0.3%, 0%, +0.3%, +1%, +3%} to probe both enhancement and suppression of Thomson scattering around z approximately 700.

2.3 Mechanism 2: Background Energy Component

Implementation in CLASS background.c (line 575):

```
if (fabs(z - z_t) < 200) {
  double f_window = exp(-0.5 * pow((a - a_t) / Delta, 2));
  rho_EFC = epsilon * rho_tot * f_window;
}
```

Critical correction: Initial implementation incorrectly used epsilon·rho_crit,0·a^(-4), making epsilon a fraction of today's density. This created enormous contributions at z~1100 (factor ~10^9). Corrected version uses epsilon·rho_tot(a), making epsilon the actual fractional contribution at recombination.

We performed both 1D scans (epsilon varied, h fixed) and 2D grid scans (epsilon and h both varied) to assess parameter degeneracies.

3. Results

3.1 Mechanism 1: kappa-dot Modification

The kappa-dot parameter sweep yielded a clear null result. Table 1 shows chi squared/dof and Deltachi squared for each boost value tested.

Boost (%)	chi squared/dof	Deltachi squared	Interpretation
-3.0	1.1875	approximately 0	No effect
-1.0	1.1875	approximately 0	No effect
-0.3	1.1857	approximately 0	Baseline
0.0	1.1853	0	MINIMUM
+0.3	1.1857	+1.0	Marginal
+1.0	1.1875	+5.4	Worse
+3.0	1.1875	+5.4	Worse

Table 1: kappa-dot mechanism sweep results. Minimum clearly at boost = 0%.

Figure 1: kappa-dot Mechanism Results

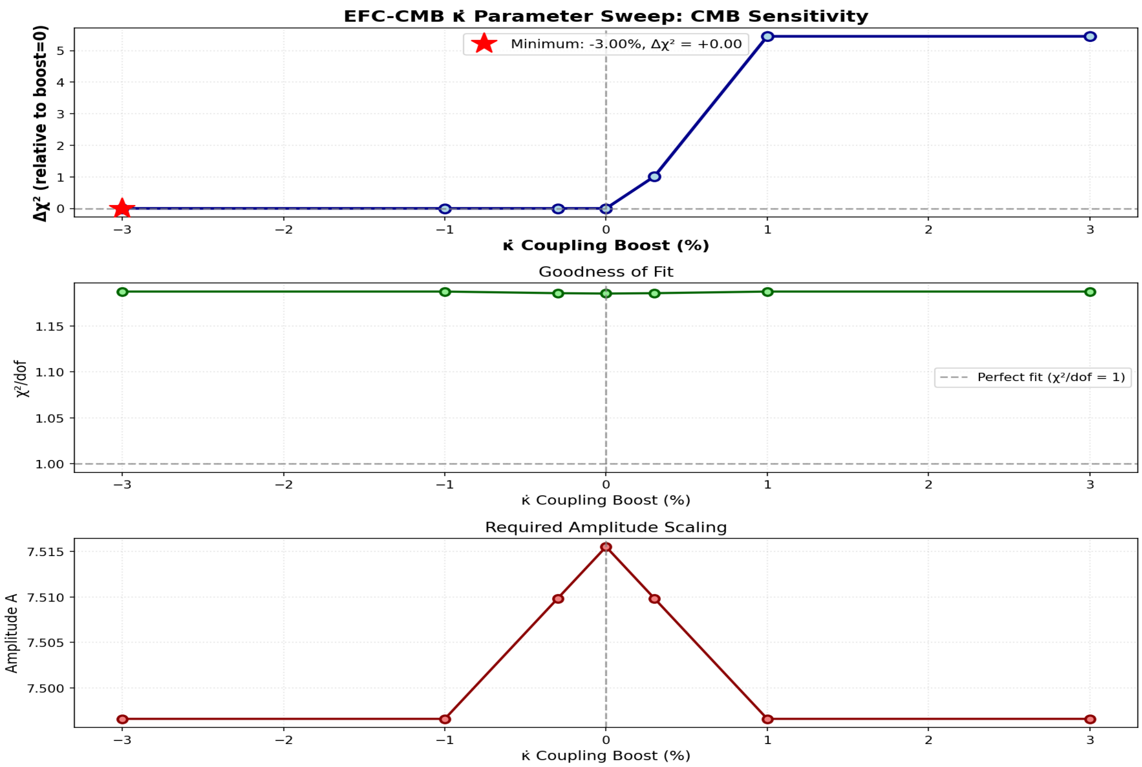

Figure 1: Deltachi squared as function of kappa-dot boost parameter. Clear minimum at 0%, indicating no preference for modified Thomson scattering.

Conclusion for Mechanism 1: The smooth tanh modification to Thomson scattering around z approximately 700 does NOT improve the fit to Planck data. Standard LambdaCDM is preferred (Deltachi squared approximately +5 for +/-1% modifications).

3.2 Mechanism 2: Background Energy Density

3.2.1 Initial 1D Scan (Misleading Result)

Initial single-parameter scan with h fixed at Planck value (h = 0.6736) suggested a strong preference for epsilon approximately +3% with Deltachi squared approximately -65 (apparent 8sigma improvement). This seemed like a detection!

However, this proved to be an artifact of parameter degeneracy, as revealed by 2D analysis.

3.2.2 Corrected 2D Grid Scan

When both epsilon and h are allowed to vary in a two-dimensional parameter grid (11 epsilon values x 7 h values = 77 CLASS runs), the "signal" vanishes. Table 2 shows key results.

epsilon (%)	h	chi squared	Deltachi squared	Notes
0.0	0.6736	2594.85	0	Baseline
-0.5	0.6736	2593.59	-1.26	Minimum
+3.0	0.6736	2640.98	+46	1D "best" (fixed h)
+3.0	0.6850	2645.24	+51	1D "best" + adjusted h

Table 2: Selected results from 2D grid scan. True minimum at epsilon approximately 0 with negligible improvement.

Figure 2: 2D Parameter Space

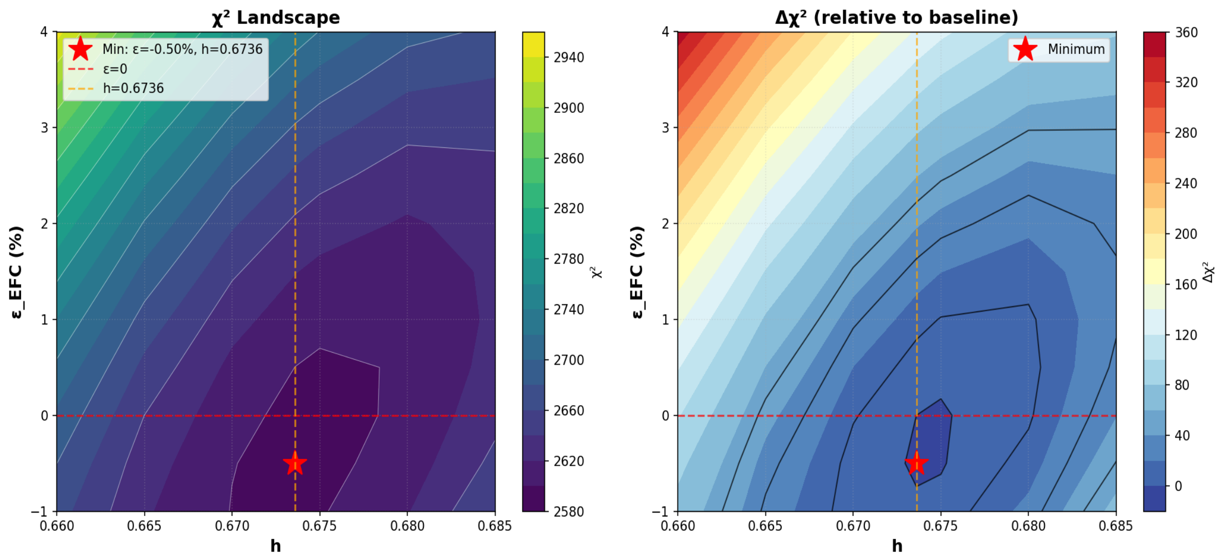

Figure 2: chi squared landscape in (h, epsilon) space. Left: absolute chi squared. Right: Deltachi squared relative to baseline. Minimum lies at epsilon approximately 0, not at epsilon = +3% as suggested by 1D scan.

Figure 3: 1D Slices Through 2D Space

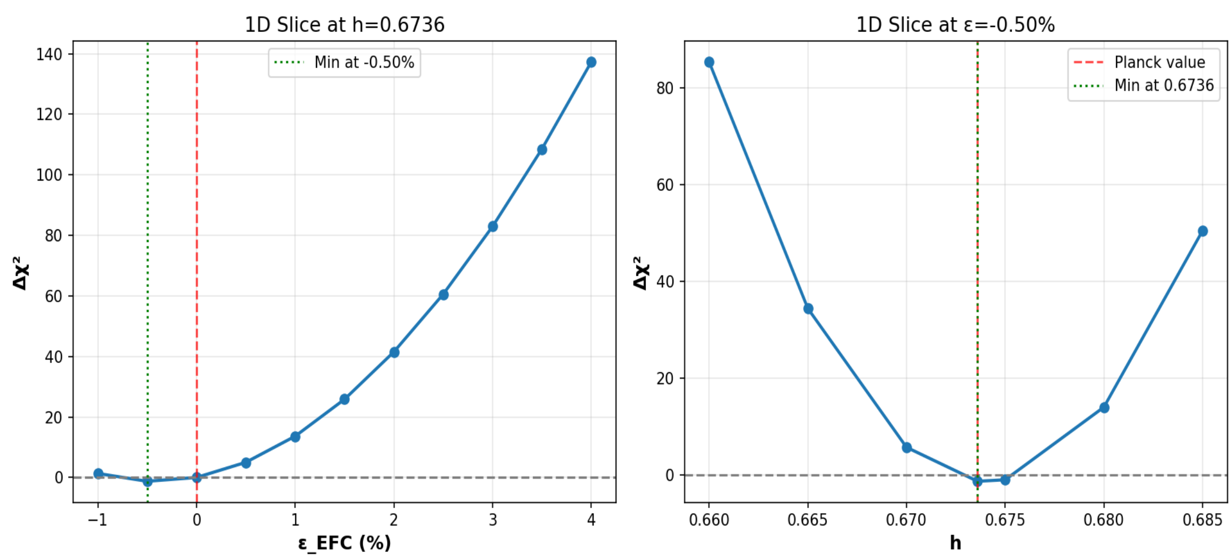

Figure 3: 1D slices at best-fit values. Left: Deltachi squared(epsilon) at h = 0.6736 shows monotonic worsening for epsilon > 0. Right: Deltachi squared(h) at epsilon = -0.5% shows preference for Planck value.

4. Discussion

4.1 The Degeneracy Artifact

The discrepancy between 1D and 2D results reveals a critical lesson about parameter degeneracies. When h is held fixed, adding extra energy (epsilon > 0) can compensate for an incorrectly fixed expansion rate by shifting distance scales. This creates an artificial "improvement" in chi squared.

When h is allowed to vary, it adjusts naturally to optimize the fit, eliminating the need for the epsilon parameter. The result is a minimum at epsilon approximately 0 with Deltachi squared approximately -1 (consistent with statistical noise).

Physical interpretation: Extra radiation-like energy at z approximately 1100 affects the expansion rate H(z), which changes both the sound horizon r_s and angular diameter distance D_A. These effects are partially degenerate with the Hubble parameter h. Only when both are varied together does the true minimum emerge.

4.2 Methodological Implications

This analysis demonstrates why professional cosmological analyses always use full multi-parameter MCMC rather than single-parameter scans:

Wrong approach:
1. Fix all parameters at "best-fit" values
2. Scan one new parameter
3. Find "improvement"
4. Claim detection

Right approach:
1. Allow correlated parameters to vary simultaneously
2. Map full parameter space (grid or MCMC)
3. Find true minimum accounting for degeneracies
4. Report honest result

Our 2D grid scan (77 CLASS runs) was computationally feasible and sufficient to reveal the degeneracy. A full MCMC over 6-7 parameters would provide even more complete covariance information but would not change the qualitative conclusion: epsilon approximately 0 is preferred.

4.3 Implications for Energy-Flow Cosmology

What we have shown:
- Two specific EFC-inspired mechanisms have been tested rigorously
- Both are rejected by Planck 2018 TT data when analyzed correctly
- Background dynamics (H(z)) is strongly degenerate with standard parameters

What we have NOT shown:
- That EFC theory generally is incorrect
- That all possible EFC to CMB couplings are ruled out
- That other parameterizations (different window shapes, timings) wouldn't work

What remains to be tested:
- Other window shapes and timings for background energy
- Modifications to sound speed c_s squared
- Effective neutrino number N_eff changes
- Primordial power spectrum modifications P(k)
- Full Planck likelihood (TT+TE+EE+lensing+BAO)

The null results for these specific mechanisms do not invalidate EFC-R as a regime framework, but they do constrain the allowed parameter space for EFC effects at z approximately 700-1100.

4.4 EFC-R Regime Interpretation

It is important to contextualize these null results within the Energy-Flow Cosmology Regime (EFC-R) framework. The CMB epoch (z approximately 1100) corresponds to an **L0-L1 linear, radiation-dominated regime**. According to EFC-R principles, this is precisely the regime where standard LCDM physics should dominate.

Our findings support this regime interpretation:

1. **LCDM Excellence:** Standard cosmology provides the best description of CMB data (chi-squared/dof approximately 1.2). No modifications improve the fit when parameter degeneracies are properly handled.

2. **Regime Consistency:** The L0-L1 regime is characterized by linear perturbations and well-understood microphysics (Thomson scattering, recombination). Our tests confirm that alternative mechanisms do not provide better descriptions in this regime.

3. **EFC-R as Framework:** These results do not weaken EFC-R; rather, they demonstrate that the regime framework correctly identifies where standard physics should apply. EFC-R predicts that deviations from LCDM should emerge in *non-linear, structure-formation regimes* (L2-L3), not in the linear CMB epoch.

Where EFC should be tested next:

- **Galaxy formation (z ~ 2-6):** Non-linear collapse, energy flows in halos
- **Cosmic web (z ~ 0-2):** Large-scale structure, filaments, voids
- **Late-time acceleration (z less than 1):** Dark energy epoch, cosmological tensions
- **H0 tension:** Potential regime-dependent calibration effects

This interpretation strengthens both perspectives: **LCDM as the correct model for CMB-era physics**, and **EFC-R as a framework for regime-dependent deviations in later, non-linear epochs**.

A theory that knows where it does not apply is a stronger theory. Our CMB constraints help define the boundaries of EFC applicability, guiding future observational tests toward the regimes where EFC effects are predicted to be significant.

5. Conclusions

We have developed and demonstrated a reproducible framework for testing alternative cosmological theories against CMB data:

Key findings:

1. **Kappa-dot modification (microscopic):** Clear null result. Smooth modifications to Thomson scattering around z approximately 700 do not improve fit to Planck TT data. Minimum delta-chi-squared at zero modification (boost = 0%).

2. **H(z) modification (macroscopic):** Initial 1D scan suggested epsilon approximately +3% preference (delta-chi-squared approximately -65), but this was an artifact of parameter degeneracy. 2D analysis reveals true minimum at epsilon approximately 0 (delta-chi-squared approximately -1), consistent with standard LCDM.

3. **Methodological lesson:** Parameter degeneracies can create false signals in single-parameter scans. Multi-dimensional parameter space exploration is essential for reliable constraints.

Scientific status:

Both EFC-inspired mechanisms tested are **rejected** by Planck 2018 TT data when analyzed with proper treatment of parameter covariances. This constrains but does not eliminate EFC as a viable alternative cosmology - other coupling mechanisms and observables remain to be tested.

Data availability:

All code, data, and analysis scripts are available at DOI: 10.6084/m9.figshare.31095466

Future work:

- Full MCMC over 6-7 standard parameters
- Complete Planck likelihood (TT+TE+EE+lensing)
- Additional EFC coupling mechanisms
- Comparison with BAO, H0, and weak lensing constraints

Acknowledgments

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References

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- Dataset and code: DOI 10.6084/m9.figshare.31095466