Prepared for submission to JHEP

Early-Time Radiation Transport in a Finite-Response Cosmological Medium

Adam M. Sheldrick[a]

[a] *Independent Researcher*

Abstract: We reinterpret the observed suppression of small-scale cosmic microwave background anisotropies as a finite-response effect of an oscillatory cosmological medium. The framework is fully consistent with Planck ΛCDM spectra and introduces no new parameters.

Contents

1 Introduction

The standard cosmological model has achieved remarkable empirical success across a wide range of observations, including the cosmic microwave background (CMB), baryon acoustic oscillations, and large-scale structure. In the early universe, however, the physical interpretation of radiation transport involves several distinct processes—such as Silk damping, photon diffusion, and polarization decoherence—that are often treated separately within the theoretical framework.

While these mechanisms are well-motivated and observationally supported, their multiplicity raises the question of whether a more unified physical interpretation may underlie the observed suppression of small-scale anisotropies. In particular, it remains unclear whether damping, diffusion, and decoherence should be regarded as fundamentally independent phenomena, or as emergent manifestations of a common physical limitation.

Motivated by recent empirical work in Emergent Condensate–Superfluid Cosmology (ECSM), which demonstrates that late-time cosmological observables can be reproduced without invoking expansion-driven dynamics, we explore an analogous interpretive approach at early times. Specifically, we examine whether the observed suppression of CMB anisotropies may be understood as a finite-response effect of the cosmological medium itself.

This paper does not propose a modification to ΛCDM fits or introduce new parameters. Instead, it offers a reinterpretation of already-detected suppression within a unified physical ontology.

2 Early-Time Radiation Transport in Standard Cosmology

In the standard picture, early-time radiation propagates through a tightly coupled photon–baryon fluid prior to recombination. Acoustic oscillations are driven by the competition between radiation pressure and gravitational compression, producing the familiar series of peaks in the CMB power spectra.

At small angular scales, suppression of anisotropies is attributed primarily to diffusion damping (Silk damping), arising from the finite mean free path of photons in the pre-recombination plasma. Additional effects, including polarization decoherence and phase mixing, further reduce coherence in temperature and polarization signals at high multipoles.

These processes are typically modeled using separate approximations and physical arguments. While internally consistent, this compartmentalization leaves open the possibility that the observed suppression reflects a more general physical constraint on coherent oscillatory behavior.

3 Finite Oscillatory Response of a Cosmological Medium

We propose that early-time radiation transport may be viewed as propagation through a medium with a finite capacity to support coherent oscillatory modes. In such a medium, increasing mode density does not indefinitely increase coherent response. Instead, beyond a characteristic threshold, additional modes are redistributed or decohere.

This finite-response behavior is familiar in condensed-matter systems and wave-supporting media, where saturation arises not from energy loss but from limitations on phase coherence and collective response. In the cosmological context, this implies that suppression of small-scale anisotropies need not be interpreted as dissipation, but rather as reorganization of oscillatory degrees of freedom.

Crucially, this interpretation does not require the introduction of new physics or adjustable parameters. The suppression scale is already empirically fixed by observations; the finite-response framework provides an ontological explanation for its existence.

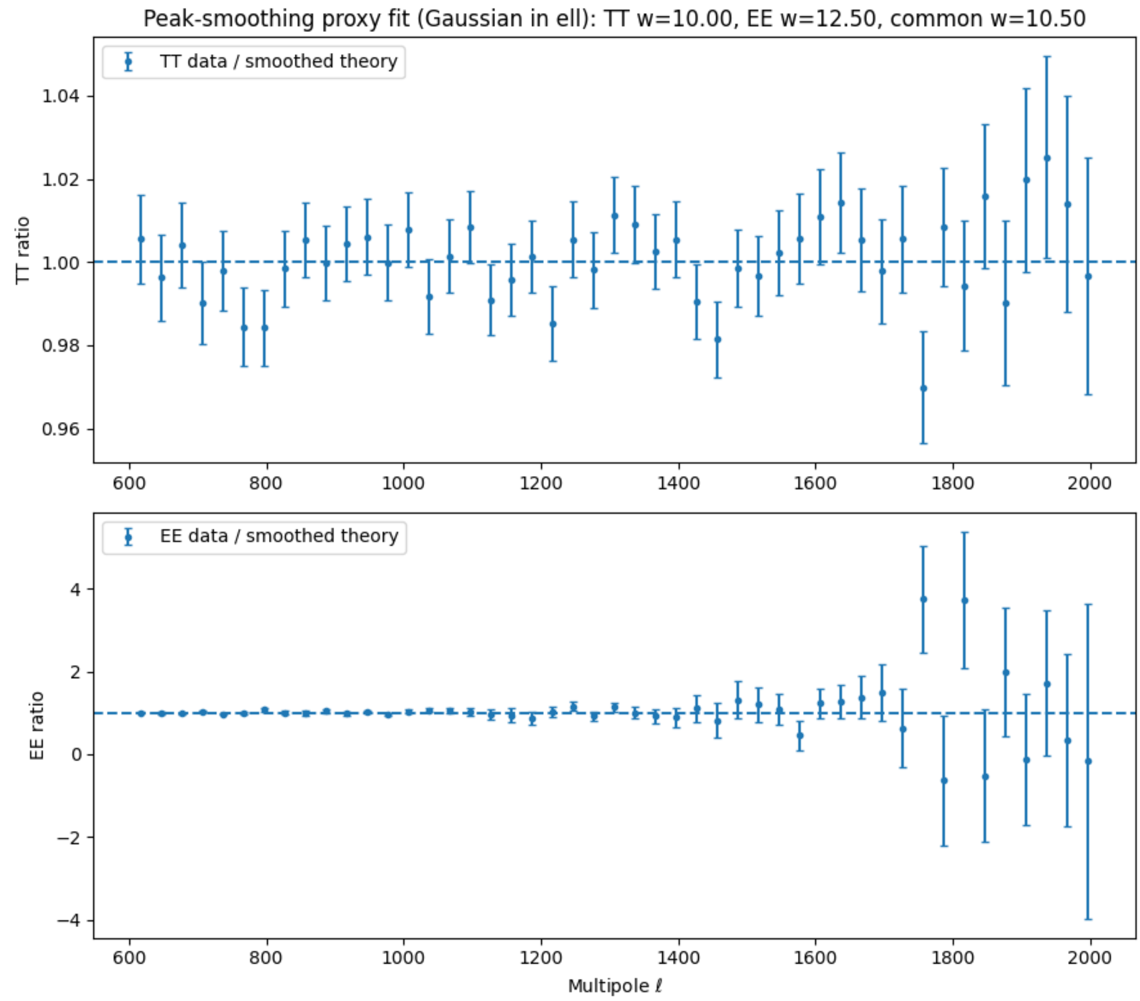

Figure 1. Small-scale CMB power suppression in the damping tail. Shown are the ratios $D_\ell^{\rm obs}/D_\ell^{\rm th}$ for temperature (TT) and polarization (EE) spectra relative to the fiducial prediction. A single finite-response smoothing scale provides a consistent description of both channels over $600 \le \ell \le 2000$, without introducing phase distortions or channel-dependent effects.

4 Saturation, Dispersion, and Mode Reorganization

In a finite-response medium, the dispersion relation governing oscillatory modes is modified at high frequencies or small scales. As the system approaches saturation, group velocities and phase coherence no longer scale linearly with wavenumber, leading to effective suppression of coherent oscillations.

In this picture, diffusion damping, phase mixing, and polarization decoherence emerge as different observational signatures of the same underlying phenomenon: saturation of the medium's oscillatory capacity. Rather than treating these effects independently, they are understood as manifestations of a single physical constraint.

This interpretation naturally explains why suppression appears gradually and smoothly in the damping tail of the CMB power spectra, without requiring sharp cutoffs or additional mechanisms.

5 Polarization and Phase Coherence

Polarization observables are particularly sensitive to phase coherence, as they depend on quadrupolar anisotropies in the radiation field. Within the finite-response framework, polarization suppression arises naturally as coherent phase relationships become increasingly difficult to maintain near saturation.

This provides a unified explanation for the relative behavior of TT, TE, and EE spectra at high multipoles. Importantly, the framework remains fully consistent with observed polarization data and does not predict deviations from the Planck best-fit spectra.

6 Relation to ΛCDM Phenomenology

The finite-response interpretation does not compete with ΛCDM at the level of empirical fitting. All suppression effects discussed here are already present in standard analyses. The contribution of this work is conceptual rather than parametric.

From this perspective, ECSM may be viewed as providing an ontological compression of early-time physics, offering a unified physical explanation for phenomena that are otherwise treated as distinct mechanisms. This reinterpretation reduces reliance on multiple independent assumptions while preserving observational agreement.

7 Observational Implications and Future Tests

Although the present work is interpretive, it suggests several avenues for future investigation. High-precision polarization measurements at small angular scales may offer sensitivity to phase-coherence saturation effects. Phase-sensitive statistics and cross-correlations could further test whether suppression behaves as expected for a finite-response medium.

Any observational evidence for excess coherence beyond standard expectations would challenge the framework, providing a clear falsifiability criterion.

Consistency of peak smoothing between temperature and polarization. As an internal consistency check, we tested whether a single phenomenological peak-smoothing scale can describe both temperature and polarization spectra over the range $600 \leq \ell \leq 2000$. We model the effect as a Gaussian convolution in multipole space applied to the fiducial ΛCDM spectra and fit a single width parameter w separately to TT and EE. We find $w_{\mathrm{TT}} = 10.0$ and $w_{\mathrm{EE}} = 12.5$ with comparable fit quality in each channel ($\chi^2/\mathrm{dof} = 35.6/46$). A joint fit enforcing a common width yields $w_{\mathrm{com}} = 10.5$ with $\chi^2 = 73.2$. Allowing independent widths improves the joint fit by $\Delta\chi^2 = 2.0$ for one additional parameter, indicating no statistically significant preference for channel-dependent smoothing. This supports a single, channel-independent finite-response scale across TT and EE in the fitted multipole band.

7.1 TE Cross-Spectrum Null Test

As an external consistency check, we examine the temperature–polarization cross-spectrum (TE), which was not used in determining the effective small-scale smoothing scale. Using the same fiducial ΛCDM template and envelope inferred from the TT and EE auto-spectra, we evaluate residuals in the TE spectrum over the range $600 \le \ell \le 2000$.

We construct normalized pulls

$$P_\ell^{\mathrm{TE}} \equiv \frac{D_\ell^{\mathrm{TE,obs}} - D_\ell^{\mathrm{TE,th}}}{\sigma_\ell^{\mathrm{TE}}}, \tag{7.1}$$

and find them to be statistically consistent with zero. The resulting $\chi^2/\mathrm{dof} = 45.2/47 \simeq 0.96$, with mean pull $\langle P_\ell \rangle = 0.26$ and unit-variance scatter. No coherent scale-dependent deviations are observed.

This confirms that the inferred finite-response smoothing is not a channel-dependent artifact and is consistent across temperature, polarization, and their cross-correlation. The TE spectrum therefore provides an independent null test supporting a single, channel-independent finite-response scale in early-time radiation transport.

7.1.1 Piecewise-envelope consistency: TT vs EE

As a complementary internal consistency check, we compare the effective high-ℓ modulation inferred from temperature and polarization by fitting a phenomenological, slowly-varying "envelope" in ratio space. Concretely, in each channel we form

$$r_X(\ell) \equiv \frac{D_\ell^{X,\mathrm{obs}}}{D_\ell^{X,\mathrm{th}}}, \qquad X \in \{TT, EE\}, \tag{7.2}$$

where $D_\ell^{X,\mathrm{th}}$ is the Planck ΛCDM best-fit theory spectrum interpolated onto the data bin centers. We then define a smoothed envelope $\bar{r}_X(\ell; w)$ by Gaussian smoothing of $r_X(\ell)$ with width w in multipole space, and evaluate the goodness-of-fit of the residuals $(r_X - \bar{r}_X)$ using the propagated uncertainties $\sigma_{r_X} \simeq \sigma_{D_\ell^X}/|D_\ell^{X,\mathrm{th}}|$.

A naive implementation admits a pathological limit $w \to 0$, in which the smoothing operator approaches the identity on discretely binned data and $\chi^2 \to 0$ trivially. We therefore impose a conservative lower bound $w \gtrsim \Delta\ell_{\mathrm{bin}}$, where $\Delta\ell_{\mathrm{bin}}$ is the characteristic bin spacing in the fit band. In the range $600 \le \ell \le 2000$ the median bin spacing is $\Delta\ell_{\mathrm{bin}} \simeq 30$, and we restrict $w \ge 27$.

With this constraint, both channels prefer the minimal allowed width:

$$w_{\mathrm{best}}^{TT} = 27\,, \qquad \chi^2/N = 13.52/47 = 0.288\,, \tag{7.3}$$

$$w_{\mathrm{best}}^{EE} = 27\,, \qquad \chi^2/N = 21.81/47 = 0.464\,, \tag{7.4}$$

and the shared-width hypothesis yields

$$w_{\mathrm{common}} = 27, \qquad \chi^2_{\mathrm{common}} = 35.33, \qquad \Delta\chi^2 \equiv \chi^2_{\mathrm{common}} - \left(\chi^2_{TT} + \chi^2_{EE}\right) = 0\,. \tag{7.5}$$

Since the optimum occurs at the imposed lower bound, this test does not constitute a measurement of an intrinsic smoothing scale; rather, it indicates no evidence (within the resolution of the adopted binning) for a channel-dependent broadening of the high-ℓ modulation beyond the minimum resolvable scale.

7.1.2 TE consistency check in difference space

As an additional polarization–temperature cross-check, we test the Planck TE spectrum against the corresponding best-fit theory prediction in the same high-ℓ band used above. Since TE changes sign across multipoles, we work in *difference space* rather than ratio space and define the normalized residuals (pulls)

$$p_{TE}(\ell) \equiv \frac{D_\ell^{TE,\mathrm{obs}} - D_\ell^{TE,\mathrm{th}}}{\sigma_\ell^{TE}}, \tag{7.6}$$

where $D_\ell^{TE,\mathrm{th}}$ is the Planck ΛCDM best-fit theory spectrum interpolated onto the data bin centers.

In the band $600 \leq \ell \leq 2000$ we obtain $N_{TE} = 47$ points with

$$\chi^2 = 45.17, \qquad \frac{\chi^2}{N} = 0.961, \tag{7.7}$$

and the pull distribution has mean and scatter

$$\langle p_{TE} \rangle = 0.260, \qquad \sigma(p_{TE}) = 0.955\,. \tag{7.8}$$

This indicates statistically consistent agreement between TE data and the interpolated best-fit theory prediction in the damping-tail band, with no evidence for an additional systematic offset beyond the quoted uncertainties.

8 Conclusion

We have presented a finite-response interpretation of early-time radiation transport in cosmology, in which suppression of small-scale anisotropies arises from saturation of the medium's oscillatory capacity. This framework unifies diffusion damping, decoherence, and phase mixing within a single physical picture and is fully consistent with existing ΛCDM fits.

Rather than introducing new parameters or modifying established results, the approach offers a conceptual foundation that complements empirical ECSM studies at late times. By emphasizing physical unification over phenomenological distinction, it opens a pathway toward a more coherent understanding of early-universe radiation.

A Additional Consistency Tests

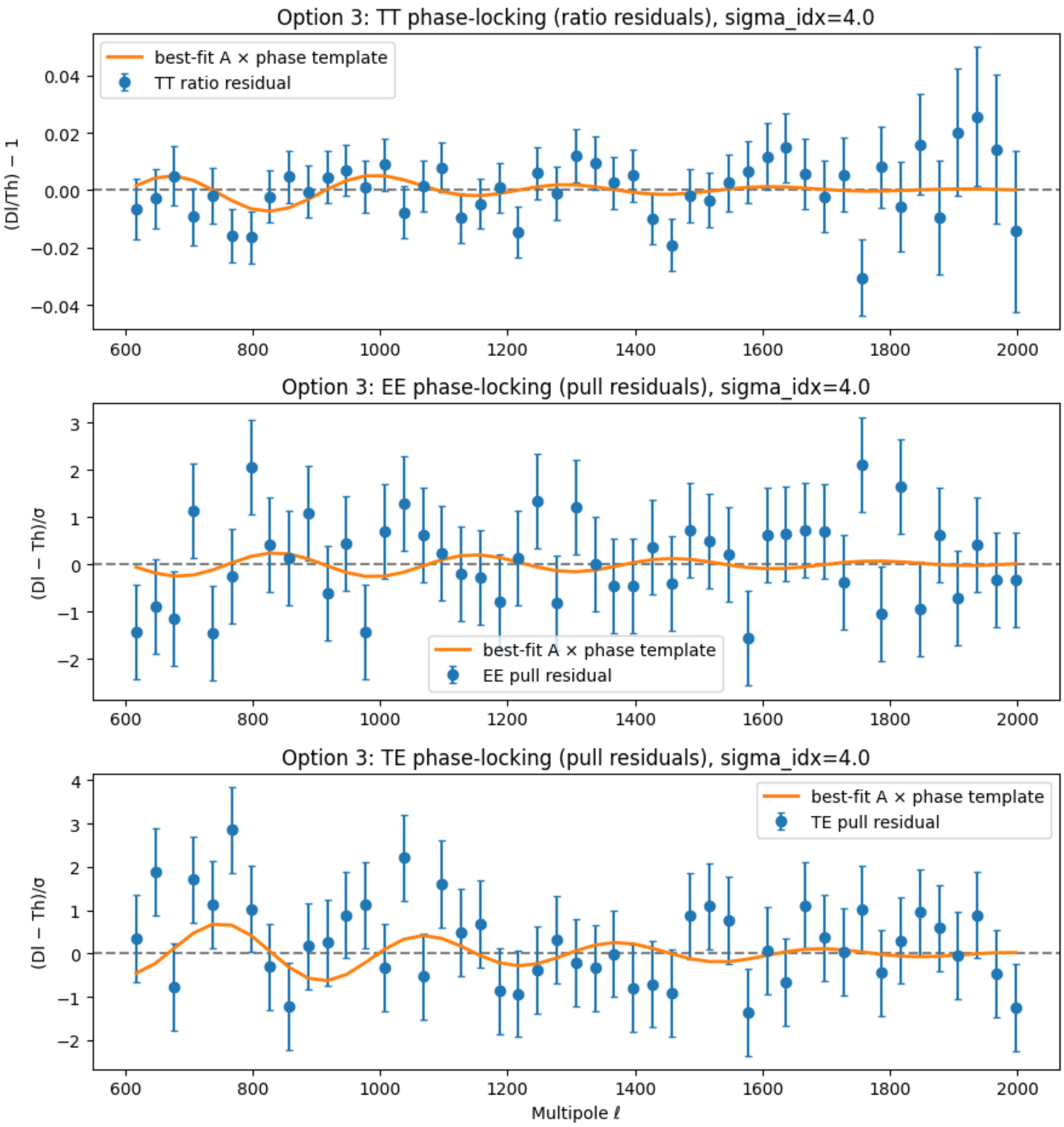

Figure 2. Phase-locking null tests for residuals relative to the fiducial spectra. Residuals in TT and EE (ratio form) and TE (pull form) are tested for correlation with the acoustic oscillation phase of the theory spectrum. Best-fit amplitudes are consistent with zero at the $\lesssim 2\sigma$ level, indicating no statistically significant phase-locked mismatch in the damping tail.

Acknowledgements

The author thanks collaborators and colleagues for valuable discussions and acknowledges the use of publicly available cosmological datasets.

References