Cosmological Inference in the Presence of Finite Propagation Response

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Modern cosmology infers large-scale properties of the universe through the propagation of signals across extreme distances and timescales. These inferences rely on implicit assumptions regarding linearity, locality, scale separability, and memoryless propagation. While such assumptions are well justified in laboratory and astrophysical regimes, their validity over cosmological baselines is rarely interrogated explicitly. In this work we examine whether several persistent cosmological tensions may reflect limitations of inference under finite propagation response rather than the presence of new fundamental components or modifications of gravitational dynamics. We argue that response saturation, coherence loss, and nonlocal propagation effects—common in physical media—can bias distance, growth, and correlation-based observables without violating local physics. This perspective reframes cosmological tensions as potential regime-boundary effects and motivates targeted observational tests.

I. INTRODUCTION

Precision cosmology has entered an era in which multiple independent datasets achieve percent-level accuracy. Paradoxically, this improvement has sharpened rather than resolved several long-standing tensions, including discrepancies in the inferred Hubble constant H_0 [1, 2], tensions in the amplitude of matter fluctuations S_8 [3, 4], and the interpretation of late-time cosmic acceleration [**?** **?**].

Standard responses to these tensions typically involve the introduction of new physical components, early-universe modifications, or extensions of gravitational dynamics. While such approaches are logically consistent, they implicitly assume that the inference machinery itself—particularly the propagation of signals over cosmological distances—remains linear, local, and scale-independent.

In this work we explore an alternative, complementary possibility: that some cosmological tensions arise from the breakdown of idealized propagation assumptions when signals traverse regimes approaching finite response limits. This does not require modification of local physics, nor the introduction of new fundamental fields. Rather, it reflects the finite response properties inherent to all physical systems.

II. IMPLICIT PROPAGATION ASSUMPTIONS IN COSMOLOGY

Cosmological observables are not measured directly; they are inferred through signal propagation. Key assumptions typically include:

- Linearity of signal propagation
- Locality of response
- Scale separability
- Absence of memory or hysteresis effects
- Infinite response bandwidth

These assumptions are excellent approximations in many regimes and are rarely problematic in laboratory or galactic contexts. However, cosmological observations probe distances, timescales, and cumulative interactions far beyond those regimes.

Crucially, these assumptions are methodological rather than fundamental. Their validity must be justified empirically, not assumed a priori.

III. FINITE RESPONSE IN PHYSICAL SYSTEMS

In a wide range of physical systems, effective linear descriptions fail beyond finite excitation or propagation limits. Examples include:

- Optical media exhibiting saturation, dispersion, and coherence loss [5]
- Condensed matter systems with nonlocal and history-dependent response [**?**]
- Hydrodynamic and elastic systems where constitutive relations break down at finite stress

In such systems, the underlying medium remains continuous and well-defined, but effective descriptors cease to be predictive. Importantly, this does not indicate new forces or constituents—only the breakdown of approximation.

There is no fundamental reason to assume cosmological signal propagation is exempt from analogous limitations.

IV. COSMOLOGICAL OBSERVABLES AS PROPAGATING SIGNALS

Key cosmological observables depend on propagation over vast scales:

- Photon propagation in luminosity and angular diameter distances
- Gravitational wave propagation as standard sirens [6]
- Growth of structure inferred from correlation functions
- Weak lensing shear fields [7]

Each of these involves cumulative response effects integrated over cosmic history. If propagation response degrades gradually—through saturation, coherence loss, or nonlocal coupling—then inferred quantities may be biased without violating local dynamics.

This possibility is rarely addressed explicitly in standard analyses.

V. REINTERPRETING MAJOR COSMOLOGICAL TENSIONS

A. The Hubble Tension

The discrepancy between locally inferred values of H_0 and those derived from early-universe observations has proven remarkably robust [8]. Distance ladders and standard candles rely critically on propagation calibration.

Finite response effects that accumulate with distance could systematically bias late-time inference without altering early-universe physics. This possibility does not replace existing explanations but complements them.

B. The S_8 Tension

Weak lensing and large-scale structure analyses infer matter clustering through correlation statistics. These statistics assume linear, scale-independent propagation of perturbations.

Response saturation or nonlocality could suppress apparent clustering amplitude, mimicking reduced growth without modifying underlying gravitational dynamics [9].

C. Cosmic Acceleration

Acceleration is inferred from distance-redshift relationships rather than measured directly. If propagation response changes with scale or history, effective acceleration can emerge without invoking a fundamental cosmological constant [10].

VI. RELATION TO REGIME BOUNDARIES

Finite-response effects are well understood in other domains as regime boundaries rather than fundamental failures. Similar logic applies to cosmology: inference procedures may be extended beyond their regime of guaranteed validity.

This perspective parallels ultraviolet limitations in other areas of physics, where effective descriptions fail gracefully rather than catastrophically.

VII. OBSERVATIONAL CONSEQUENCES AND TESTS

If finite response affects cosmological inference, several observational signatures may arise:

- Differential propagation effects between electromagnetic and gravitational signals
- Hysteresis or history dependence in calibration relations
- Scale-dependent saturation effects rather than parameter shifts
- Redshift-dependent deviations in correlation functions

Future surveys combining multiple messengers and independent distance measures offer promising avenues for testing these ideas.

VIII. DISCUSSION

This work does not propose a new cosmological model, nor does it modify gravitational dynamics. Instead, it interrogates an often-overlooked assumption: that signal propagation remains indefinitely linear and memoryless across cosmological scales.

Reframing cosmological tensions as potential inference-regime effects broadens the space of viable explanations while remaining fully consistent with established physics.

IX. CONCLUSION

Persistent cosmological tensions may reflect the limits of inference under finite propagation response rather than new fundamental components of the universe. Recognizing this possibility motivates both conceptual caution and targeted observational tests. As cosmological precision continues to improve, careful attention to the regime of applicability of inference assumptions will be essential.

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