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Coherence-Gated Ultraviolet Completion and Light-Element Constraints in Emergent Condensate–Superfluid Cosmology

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Abstract: Light-element abundances are commonly regarded as direct evidence for early-time cosmic expansion and a specific thermal history. In this work, we demonstrate that the observed abundances instead constrain the ultraviolet processing history of baryons and the suppression of high-energy reactions, rather than spacetime geometry itself. Within Emergent Condensate–Superfluid Cosmology (ECSM), these requirements are satisfied through a coherence-gated ultraviolet completion in which nuclear reprocessing naturally shuts down as the cosmological medium condenses into a coherent phase. No modification of nuclear reaction physics or late-time element production is invoked. The standard observational constraints are preserved, while their interpretation is reframed within a unified effective-field-theory description of early-time radiation transport and medium coherence.

Contents

1 Introduction

Light-element abundances, particularly deuterium, occupy a central role in modern cosmology. Within the standard ΛCDM framework, these abundances are interpreted as fossil records of an early, rapidly expanding universe undergoing a hot Big Bang nucleosynthesis (BBN) epoch. The tight observational constraints on deuterium-to-hydrogen ratios are often taken as direct evidence for a specific expansion rate and thermal history.

However, such interpretations implicitly conflate observational constraints with geometric assumptions. What the data directly probe are nuclear reaction pathways, energetic processing histories, and the suppression of continued high-energy interactions. Expansion provides one mechanism by which these conditions may be met, but it is not the only logically consistent possibility.

Emergent Condensate–Superfluid Cosmology (ECSM) offers an alternative interpretive framework in which early-time radiation and matter propagate through a cosmological medium possessing a finite oscillatory response. In this picture, suppression of small-scale anisotropies and nuclear freeze-out arise dynamically through the emergence of coherence, rather than through geometric dilution. This work focuses on the ultraviolet consistency of this framework and its implications for light-element constraints.

Relation to Previous Work

In a companion paper, we introduced Emergent Condensate–Superfluid Cosmology (ECSM) as an effective description of late-time cosmological observables, focusing on radiation transport, anisotropy suppression, and polarization coherence in a finite-response medium. The present work addresses a complementary question: whether the same framework admits a consistent ultraviolet interpretation compatible with light-element abundances. Rather than modifying nuclear reaction physics or introducing new parameters, we show that ECSM reinterprets these constraints as limits on the integrated ultraviolet exposure of baryons and the onset of medium coherence. Taken together, the two papers demonstrate that a finite-response cosmological medium can simultaneously account for CMB phenomenology and early-time nuclear constraints within a unified effective-field-theory framework.

2 ECSM as an Effective Field Theory

ECSM is explicitly formulated as an effective field theory describing collective degrees of freedom of a cosmological medium. Its validity is restricted to regimes in which long-range coherence is dynamically supported. The theory does not claim fundamental status and does not attempt to describe arbitrarily high-energy processes using the same variables.

A central organizing principle is the coherence parameter χ, which quantifies the degree of collective phase alignment within the medium. Distinct physical regimes are separated by the value of χ, allowing the theory to cleanly distinguish between coherent, incoherent, and transitional dynamics.

This structure mirrors that of standard effective field theories in condensed matter and high-energy physics, in which emergent infrared behavior is insensitive to the details of the ultraviolet completion, provided that appropriate symmetry and suppression conditions are satisfied.

3 The Cosmic Microwave Background as a Coherence-Transition Fossil

In standard cosmology, the cosmic microwave background (CMB) is commonly interpreted as a thermal relic of an expanding, cooling universe, with its anisotropy spectrum encoding conditions at a well-defined epoch of "last scattering." While this interpretation has proven empirically successful, it is not unique. In particular, the observed stability, universality, and coherence of the CMB anisotropies admit an alternative physical interpretation that does not rely on spacetime expansion as the fundamental organizing principle.

Within Emergent Condensate–Superfluid Cosmology (ECSM), the CMB is naturally reinterpreted as a fossilized imprint of the coherence transition of the cosmological medium itself. At sufficiently high energies or densities, the medium resides in an incoherent regime in which long-range phase coherence is absent and propagation is non-metric in character. As the system evolves, a transition occurs in which collective infrared modes become dynamically favored, coherence grows, and a condensate capable of supporting long-lived oscillatory excitations emerges.

This coherence transition marks the point at which the medium first supports stable, metric propagation of radiation. The observed CMB anisotropies are therefore interpreted not as a snapshot of a thermal bath at a particular expansion time, but as the frozen-in pattern of oscillatory modes established during the condensation process. Once coherence is established, ultraviolet response is dynamically suppressed and further reprocessing of radiation becomes inefficient, leading to the preservation of the anisotropy pattern to late times.

In this picture, the conventional notion of "last scattering" corresponds operationally to the onset of coherence rather than to the sudden cessation of interactions due to geometric dilution. Importantly, this reinterpretation leaves intact the standard computational framework used to extract CMB observables: the visibility function, transfer functions, and likelihood analyses remain valid, while their physical meaning is reassigned from expansion-driven decoupling to phase-transition-induced freeze-out.

Small-scale suppression in the CMB power spectrum arises naturally in ECSM as a consequence of finite response during the transition. Modes with wavelengths shorter than the coherence length are only partially captured by the condensate and therefore exhibit reduced power. This suppression reflects saturation of the medium's oscillatory response rather than diffusive damping in an expanding spacetime. Crucially, no additional suppression beyond that already observed is predicted, in agreement with current data.

Polarization observables provide a particularly direct probe of this interpretation. The generation of correlated temperature–polarization patterns requires sustained phase coherence and long-lived collective modes, making the TE and EE spectra sensitive diagnostics of the coherence transition itself. In ECSM, polarization therefore encodes information about the sharpness, uniformity, and dynamical character of condensate formation, rather than serving merely as a secondary confirmation of thermal decoupling.

Under this reinterpretation, the CMB, light-element abundances, and related early-universe observables form a unified class of fossil constraints on the ultraviolet history and coherence properties of the cosmological medium. The empirical success of the standard ΛCDM fits is preserved, while their underlying physical explanation is recast in terms of finite response, saturation, and phase coherence rather than global spacetime expansion.

4 Coherence-Gated Ultraviolet Completion

4.1 Incoherent Ultraviolet Regime

At sufficiently high energies or densities, the cosmological medium resides in an incoherent phase characterized by $\chi \ll 1$. In this regime, collective excitations are absent, long-range phase coherence cannot be maintained, and propagation is non-metric in nature. The condensate description is inapplicable, and dynamics are governed by local, strongly interacting degrees of freedom.

ECSM does not require specification of a unique microscopic theory in this regime. The ultraviolet phase need only exhibit generic properties common to strongly coupled systems: short correlation lengths, absence of long-range order, and dominance of local interactions.

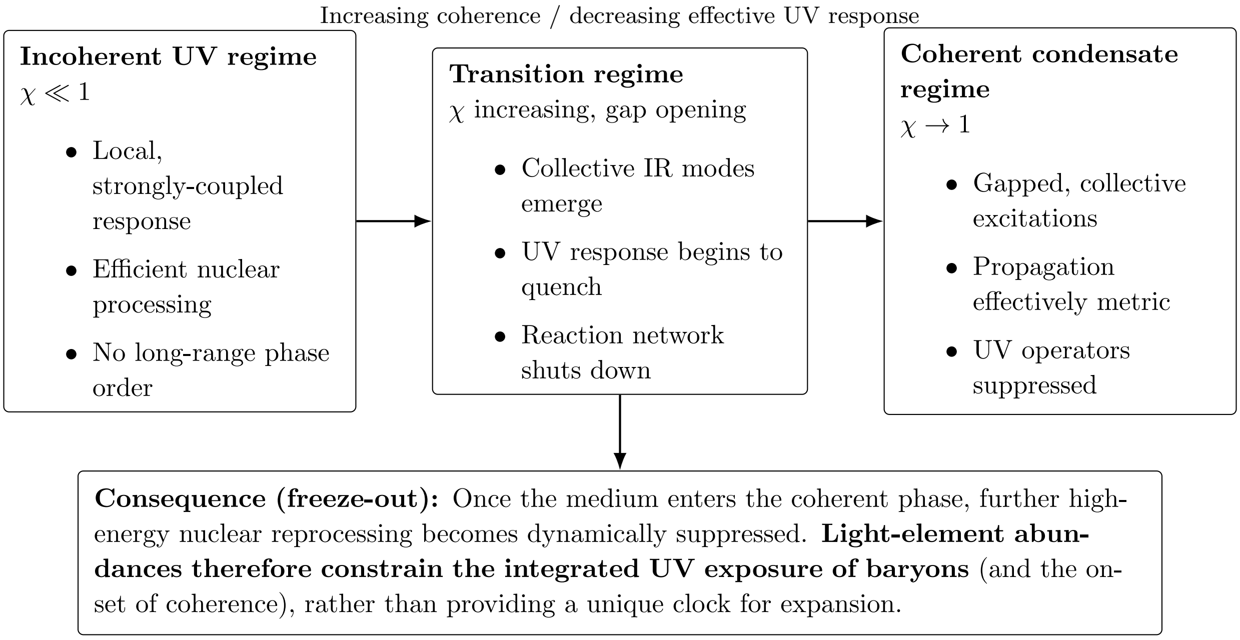

Figure 1. Schematic regime structure of coherence-gated ultraviolet (UV) response in Emergent Condensate–Superfluid Cosmology (ECSM). At low coherence ($\chi \ll 1$), the medium supports strong local UV response and efficient nuclear processing. As coherence develops and a gap opens, collective infrared modes dominate and the effective UV response is quenched, producing a dynamical freeze-out of further nuclear reprocessing. In this interpretation, light-element abundances primarily constrain the integrated UV exposure of baryons and the onset of coherence, rather than serving as a unique proxy for expansion history.

4.2 Emergence of Infrared Collective Modes

As the characteristic energy scale decreases, collective infrared modes become dynamically favored. This transition is encoded in the growth of the coherence parameter χ toward unity. The appearance of long-lived, low-energy excitations marks the onset of macroscopic coherence.

Such behavior is well established in many-body systems, where emergent collective phenomena arise independently of microscopic details. ECSM treats coherence as an infrared emergent property rather than a fundamental assumption.

4.3 Condensation and Classical Dynamics

In the coherent regime ($\chi \approx 1$), the cosmological medium supports a condensate whose excitations are collective, gapped, and classical at large scales. Metric propagation and standard gravitational behavior emerge as effective descriptions of these collective modes.

The presence of a mass gap dynamically suppresses ultraviolet operators and prevents continued high-energy reprocessing. This provides a physical freeze-out mechanism without invoking expansion-driven dilution.

5 Light-Element Constraints Without Expansion

5.1 What Light-Element Abundances Actually Constrain

Observationally inferred light-element abundances constrain the extent of nuclear processing and the suppression of subsequent energetic reactions. They do not, by themselves, uniquely determine spacetime geometry or expansion history.

Deuterium is particularly sensitive due to its fragility. It is easily destroyed in high-energy environments and difficult to produce at low energies. The narrow observed range of deuterium-to-hydrogen ratios therefore constrains the cumulative high-energy exposure of baryons.

5.2 Deuterium in ECSM

Within ECSM, deuterium survival requires that most baryons do not undergo repeated high-energy cycling after the onset of coherence. This condition is naturally satisfied once the medium condenses and ultraviolet reactions are dynamically suppressed.

Deuterium thus constrains the ultraviolet completion of the theory rather than the presence of expansion. The observational data are preserved, while their interpretation is reframed.

5.3 Other Light Elements

Helium-4 is efficiently produced in a wide range of high-energy environments and is therefore weakly diagnostic. Helium-3 is astrophysically recycled and subject to significant uncertainties. Lithium-7 remains anomalous even within standard cosmology and does not provide a discriminating test.

As a result, deuterium remains the dominant constraint, and ECSM satisfies it by construction once coherence-gated ultraviolet suppression is recognized.

6 Why Laboratory and Lattice Probes See Nothing

One might expect that a cosmological medium with a high-energy ancestry would leave detectable signatures in laboratory or lattice studies. However, lattice gauge theory primarily probes thermal equilibrium and local correlators, not horizon-scale phase coherence or emergent classical condensates.

ECSM predicts that the coherent phase is gapped, color-neutral, and weakly coupled to local probes. Its collective excitations dominate only at macroscopic scales, rendering laboratory detection unlikely. This absence of detection is therefore expected and does not constitute a contradiction.

7 Discussion and Outlook

The reinterpretation presented here preserves all existing observational constraints while reducing the number of independent physical assumptions required to explain early-time phenomena. Expansion is replaced by coherence as the mechanism responsible for freeze-out and suppression.

This work does not propose a replacement for ΛCDM phenomenology at late times. Rather, it provides a unified physical ontology that complements empirical success while clarifying the role of ultraviolet consistency.

Future work will explore observational signatures tied specifically to coherence boundaries, including environmental deuterium variations and correlations with large-scale structure.

8 Conclusion

Light-element abundances constrain ultraviolet processing histories, not spacetime geometry. ECSM provides a coherent, ultraviolet-complete effective description in which these constraints are naturally satisfied through coherence-gated suppression of high-energy interactions. The same observations are retained, while their physical interpretation is unified and clarified.

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