Horizon-Enabled Expansion Framework (HEEF): A Conservation-Respecting Effective-Description Framework for Horizon-Mediated Accessibility Reconfiguration in Early-Universe Cosmology

Abstract

The Horizon-Enabled Expansion Framework (HEEF) is a conceptual framework—explicitly not a fundamental theory—developed to reorganize and rigorously stress-test effective interpretations of early-universe cosmology. It targets long-standing puzzles, including the origin of extremely low initial entropy, large-scale homogeneity and isotropy, and the inflation-like phase of rapid early expansion, without introducing new fields, modifying known dynamical laws, or violating standard conservation principles. HEEF operates at the level of effective description, focusing on how causal boundary conditions determine which quantum degrees of freedom are dynamically accessible within a given region and therefore contribute to the region's interior effective dynamics. The framework proposes that an early regime may exist in which spacetime geometry is present but the degrees of freedom permitted to participate in local effective evolution are severely restricted, yielding low entropy and suppressed gravitational backreaction. When such a constrained description can no longer remain self-consistent under coarse-graining, an abrupt redefinition of causal boundary conditions—termed a Horizon Reconfiguration Event (HRE)—becomes necessary to establish a stable interior effective description. An HRE reorganizes which degrees of freedom contribute to the interior effective stress–energy tensor that sources spacetime evolution through the standard Einstein and Friedmann equations. In principle, such reorganization may, under specific and currently unidentified conditions, include transient, effective, and approximately conserved contributions with an approximately vacuum-like equation of state capable of sourcing accelerated expansion at the level of homogeneous background dynamics. However, explicit stress tests demonstrate that horizon reconfiguration alone does not generically produce vacuum-like behavior under conservative assumptions, indicating that inflation-like expansion—where it arises—must depend on additional structure beyond boundary reconfiguration itself. Following any such transient phase, the framework recovers standard cosmological evolution, including radiation and matter domination, conventional entropy growth, and an emergent thermodynamic arrow of time. HEEF does not specify a microphysical trigger for horizon reconfiguration, nor does it

introduce new quantitative predictions beyond those already encompassed by standard cosmology. Its purpose is to provide a disciplined reframing lens, precise bookkeeping rules, and explicit failure modes that clarify which features of early-universe phenomenology can—and cannot—be coherently interpreted as consequences of horizon-mediated changes in state accessibility.

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1. Introduction

Modern cosmology provides an extraordinarily successful quantitative description of the universe using General Relativity, quantum field theory, and the ΛCDM model. Observations of the cosmic microwave background, large-scale structure, and primordial nucleosynthesis are well accounted for within this framework. Inflationary cosmology, in particular, supplies an effective description capable of explaining large-scale homogeneity and isotropy, near-flatness, and the origin of primordial perturbations. These empirical successes establish inflation as a central component of the standard cosmological model, even as questions remain regarding its deeper physical interpretation and microphysical origin.

Despite this success, conceptual questions persist concerning how early-universe expansion is interpreted. Inflation is commonly modeled through scalar-field dynamics, yet a wide landscape of inflationary scenarios exists, many of which differ substantially in their assumed degrees of freedom, potential structures, and microphysical motivations while remaining observationally viable. In parallel, foundational puzzles—such as the horizon problem, the emergence of large-scale uniformity, and the origin of the thermodynamic arrow of time—are often discussed in language that blends dynamical mechanisms with effective descriptions and bookkeeping conventions. This blending can obscure which features reflect underlying physical dynamics and which arise from changes in description, coarse-graining, or boundary conditions. These issues do not undermine standard cosmology, but they motivate a disciplined separation between assumptions, derived consequences, and interpretive framing.

The Horizon-Enabled Expansion Framework (HEEF) is introduced as a conceptual framework for organizing and stress-testing an alternative effective interpretation of inflation-like behavior. Rather than proposing new dynamics, HEEF asks whether certain features commonly attributed to inflation can arise as consequences of changes in causal boundary conditions—understood here as a re-partitioning of dynamically accessible degrees of freedom, rather than the motion of a physical boundary or any violation of causality. In this view, accelerated expansion is not treated as a fundamental driver, but as a geometric response to a reorganization of the effective stress–energy tensor that sources spacetime evolution through the standard Einstein and Friedmann equations.

A central guiding principle of HEEF is that horizons are causal boundaries that regulate interaction, correlation, and dynamical participation, rather than sources of energy, agency, or information creation. When causal boundary conditions change—through what the framework terms a Horizon Reconfiguration Event (HRE)—the system–environment partition relevant to a local effective description must be redefined. This redefinition alters which degrees of freedom contribute to the interior effective stress–energy tensor, and spacetime geometry responds according to its standard dynamics. All energy–momentum accounting is handled through this re-partitioning of participation within an effective description; no creation, destruction, or transfer of energy across horizons is assumed. Inflation-like expansion, where it occurs, is interpreted as a transient geometric relaxation toward configurations compatible with the post-reconfiguration effective description, rather than as the action of a new field or force.

HEEF is intentionally limited in scope. It does not introduce new equations of motion, nor does it seek to replace ΛCDM, General Relativity, or quantum mechanics. The framework is designed to fail decisively if it collapses into metaphor, requires hidden violations of conservation laws, or remains observationally indistinguishable from inflation while offering no mechanism-level explanatory gain. Explicit stress tests performed under conservative assumptions indicate that horizon reconfiguration alone does not generically reproduce vacuum-like expansion, underscoring that the framework remains incomplete. Identifying the additional structure or conditions required for inflation-like behavior to emerge is therefore a central open problem, not a settled result.

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2. Framework Status and Scope

The Horizon-Enabled Expansion Framework is a conceptual framework, not a fundamental theory and not a phenomenological replacement for ΛCDM or inflationary cosmology. It introduces no new particles, fields, symmetries, or equations of motion. Its purpose is to provide a disciplined lens for organizing, stress-testing, and clarifying effective interpretations of early-universe expansion that remain compatible with General Relativity, quantum mechanics, and standard conservation laws.

HEEF operates explicitly at the level of effective description. It focuses on how physical systems are partitioned, coarse-grained, and modeled within a given causal structure, and on how changes in that structure alter which degrees of freedom contribute to the effective stress–energy tensor sourcing spacetime evolution. The framework does not posit new dynamics; it constrains how existing dynamics are represented and sourced when causal boundary conditions reconfigure, without introducing new evolution equations beyond those already present in semiclassical gravity and cosmology.

A central constraint is that bookkeeping must not be mistaken for dynamics. Changes in accessibility are treated as changes in which degrees of freedom contribute to a local effective description, not as creation or destruction of states, energy, or information. Horizons are therefore understood as regulators of participation and correlation, not as agents that inject energy, generate forces, or drive expansion. Any formulation of HEEF that requires violations of energy–momentum conservation, superluminal signaling, or departures from standard quantum mechanics is invalid by construction.

The scope of the framework is intentionally narrow. HEEF does not attempt to derive a complete perturbation spectrum, fix cosmological parameters, or supply a microphysical account of horizon reconfiguration. Instead, it focuses on enforcing clear distinctions between accessibility and thermalization, local and global entropy, and boundary conditions versus forces; identifying where inflation-like behavior may admit an alternative effective interpretation without contradicting established physics; and articulating explicit failure modes that constrain admissible extensions. HEEF earns relevance only insofar as it sharpens questions, exposes hidden assumptions, and survives aggressive internal consistency checks.

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3. Core Concepts

3.1 Horizons

Within HEEF, a horizon is defined operationally as a causal boundary that limits interaction, correlation, and dynamical influence between degrees of freedom. Horizons are not observational artifacts, coordinate conventions, or epistemic limitations; they are features of causal structure that determine which physical processes can mutually influence one another.

A horizon regulates participation in local effective dynamics, not existence. Degrees of freedom outside a causal horizon may exist in a global description, but they are dynamically inaccessible to a given region and therefore do not contribute directly to that region's interior effective evolution, except through boundary bookkeeping such as traced-out sectors, renormalized contributions, or entropy accounting. Horizons do not inject energy, generate forces, or act as agents; they define boundary conditions under which local effective descriptions are constructed.

3.2 Accessibility

Accessibility refers to the set of degrees of freedom that are dynamically available within a given causal structure. It is a statement about participation in evolution, not about the total set of mathematically definable states. A state is accessible if the degrees of freedom encoding it can participate in interactions, correlations, and causal influence within the region's effective dynamics, given constraints from geometry, causality, energy conditions, and quantum structure.

Accessibility is distinct from both energy content and thermalization. Thermalization redistributes energy among degrees of freedom that are already accessible; accessibility reconfiguration changes which degrees of freedom belong to the interior effective description at all. Conflating these processes leads to incorrect inferences about entropy, expansion, and gravitational backreaction. HEEF maintains this distinction strictly.

3.3 Constraint Layers

HEEF models effective physical description as governed by a set of constraint layers rather than by a hierarchy of dynamical causes. These layers represent regimes of limitation—such as spacetime geometry, causality, locality, conservation laws, quantum structure, and horizon boundaries—that jointly determine which degrees of freedom contribute to a region's interior effective description.

When these constraints admit a mutually consistent coarse-grained description, evolution appears smooth and classical at macroscopic scales. When no single coarse-grained description can simultaneously satisfy the relevant constraints—typically in regimes of extreme curvature, coupling, or boundary sensitivity—the effective system–environment partition becomes non-robust under variation of the domain. In such regimes, causal boundary conditions must be redefined to establish a self-consistent interior effective description. Constraint layers are conceptual tools, not physical strata; they delimit admissible effective descriptions under given conditions.

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4. Horizon Reconfiguration Events

A Horizon Reconfiguration Event (HRE) is an effective-level transition in which existing causal boundary conditions can no longer support a self-consistent local effective description, forcing an abrupt re-partitioning of dynamically accessible and inaccessible degrees of freedom. An HRE does not violate causality, conservation laws, or quantum mechanics. It is a change in boundary conditions, not an injection of energy.

During an HRE, the system–environment partition underlying the effective description reorganizes discontinuously. Degrees of freedom that were previously dynamically inaccessible may enter the interior effective description defined by the new causal boundary, altering the set of contributions to the effective stress–energy tensor governing interior evolution. From within that region, the transition may correspond to a hot, dense effective initial condition, even though no states or energy are created globally. HEEF treats the HRE as a bookkeeping reconfiguration required to establish a stable and self-consistent interior effective description. Its physical consequences arise from how standard gravitational dynamics respond to the reorganized effective stress–energy, not from new forces, fields, or interactions.

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5. Stability of Interior Effective Descriptions

An interior effective description of a causal domain is considered stable when the physically relevant content of that description is robust under legitimate variations in how the description is constructed. Stability does not require uniqueness of the effective description; it requires that physically meaningful predictions remain approximately invariant under changes to partitioning, coarse-graining, and renormalization procedures used to define it. Stability is therefore a property of the effective description, not of the underlying global state or fundamental dynamics.

A stable effective description must remain robust under variations including small adjustments to the horizon location or shape at fixed causal structure, variations in coarse-graining scale such as cutoffs or smoothing windows, and variations in traced-out sector definitions consistent with the same causal partition. For stability, physically relevant quantities—including the renormalized stress–energy tensor $\langle T_{\mu\nu} \rangle$, the effective equation of state, and the resulting geometric evolution—must exhibit limited sensitivity to these variations. When fractional changes become order unity, the description depends strongly on arbitrary bookkeeping choices and ceases to function as a predictive semiclassical interior theory.

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6. Postulates

Postulate 1 (State Accessibility) asserts that physical evolution within any causal region is governed not by the total set of possible states that exist, but by the subset of states that are dynamically accessible. States beyond a causal horizon may exist globally, but they do not contribute directly to the region's interior effective physics except through boundary bookkeeping.

Postulate 2 (Horizon Reconfiguration) asserts that changes in accessibility occur only through reconfiguration of causal boundary conditions. When no coarse-grained interior description can jointly satisfy relevant constraint layers, a new horizon-defined partition becomes necessary to reassign degrees of freedom into dynamically accessible and inaccessible sets, without creating or destroying states, energy, or information.

Postulate 3 (Geometric Response to Accessibility Change) asserts that when a causal domain's boundary reconfigures, the set of degrees of freedom contributing to the interior effective stress–energy tensor changes, and spacetime geometry responds through the standard Einstein and Friedmann equations. For a finite interval, the reorganized effective description may, under specific and currently unidentified conditions, include transient, effective, and approximately conserved contributions with an approximately vacuum-like equation of state sufficient to source accelerated expansion at the level of homogeneous background dynamics. The conditions under which such behavior emerges, persists, and decays are not assumed to be generic; identifying accessibility evolution profiles and constraint configurations that yield $w \approx -1$ constitutes a central open problem. Conservative stress tests indicate that horizon reconfiguration alone does not generically produce vacuum-like behavior.

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7. The Trigger Mechanism and Its Operational Status

7.1 Provisional Operational Trigger Criterion

HEEF does not treat horizon reconfiguration as a dynamical instability, force, or entropy-driven process. The proposed trigger is instead the loss of robustness of the interior semiclassical effective description under legitimate partition variations. Operationally, an HRE is permitted when order-unity partition sensitivity arises in the renormalized stress–energy tensor that sources semiclassical geometry, under infinitesimal variations of horizon-consistent partitioning, coarse-graining, and renormalization prescriptions while holding the global quantum state and underlying dynamics fixed. In this regime, semiclassical closure fails in the sense that gravitational backreaction becomes dependent on arbitrary bookkeeping choices, and the interior description ceases to be predictive.

7.2 Status of the Trigger Mechanism (Provisional)

Within HEEF, order-unity partition sensitivity constitutes the sole operational trigger proposed for permitting an HRE. The trigger classes introduced in the following subsection are not independent physical mechanisms nor distinct dynamical causes of horizon reconfiguration. They are phenomenological regimes in which the same underlying failure of effective-description robustness may arise under different physical circumstances. The trigger taxonomy is therefore provisional. Validation of any class requires demonstrating that it produces the partition sensitivity specified above in a realistic semiclassical regime, prior to singularity formation or quantum-gravity breakdown. Trigger classes that cannot be shown to reduce to the operational criterion must be eliminated as redundant, unphysical, or purely interpretive.

At present, no trigger class has been supported by a worked example establishing order-unity partition sensitivity under conservative assumptions. The taxonomy should accordingly be read as an organizational framework for identifying and testing possible failure modes of semiclassical descriptions, not as a demonstrated mechanism for horizon reconfiguration. The framework's current scientific burden is therefore not to elaborate additional trigger narratives, but to produce at least one explicit semiclassical construction in which the operational trigger occurs.

7.3 Phenomenological Regimes for the Emergence of Partition Sensitivity

The taxonomy distinguishes several candidate regimes in which partition sensitivity might arise. These regimes are not asserted as independent triggers and may collapse into one another upon analysis. One regime concerns internal geometric inconsistency: the Einstein equations sourced by the currently accessible sector do not admit semiclassically stable closure under horizon-consistent coarse-graining, such that legitimate partition choices yield mutually incompatible $\langle T_{\mu\nu} \rangle$ and therefore incompatible backreaction. A second candidate regime concerns cross-domain constraint misalignment in gravitationally coupled settings, where distinct regions can be consistently described locally but fail to admit a single global semiclassical description whose sourcing remains robust to partition variations. A third candidate concerns accessibility saturation, in which the accessible sector approaches its maximal entropy state given constraints and the interior description becomes increasingly sensitive to how near-boundary degrees of freedom are traced out and renormalized. A fourth candidate concerns horizon-definition ambiguity in strongly dynamical settings, where multiple inequivalent horizon candidates might exist and partition choices become non-robust; however, this regime is particularly likely to reduce to the general partition sensitivity criterion and may represent no physics beyond description failure. In all cases, admissibility is conditional on demonstration that the operational partition-sensitivity threshold is met.

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8. Stress Tests and Failure Registration

HEEF is designed to fail decisively under explicit diagnostic tests. The framework explicitly forbids category errors such as treating entropy as causal agency, treating horizons as dynamical drivers, or treating bookkeeping changes as sources of new dynamics. In particular, conservative numerical stress tests of toy implementations indicate that horizon reconfiguration alone does not generically yield an effective vacuum-like equation of state in the accessibility sector; instead, the accessibility contribution tends to behave radiation-like, with effective w near 1/3 under stable evolution. This negative result does not falsify the framework as a conceptual lens, but it decisively constrains what the framework may claim: inflation-like behavior cannot be treated as a generic consequence of horizon reconfiguration without additional structure. Any future realization must specify what additional constraints, boundary behavior, or microphysical conditions are responsible for producing slow evolution of effective energy density and approximately vacuum-like behavior.

This failure is not treated as a setback to be patched by ad hoc terms. It is registered as a delimiting result: the selection principle and partition logic may be internally consistent while still failing to produce inflation-like expansion. Accordingly, HEEF’s present value lies in clarifying which intuitive stories fail under conservation-respecting bookkeeping, and in structuring the search for the conditions under which inflation-like behavior could arise without introducing new fields.

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9. Relationship to Standard Cosmology and Observational Content

HEEF is not presented as a competitor to ΛCDM or inflationary cosmology, but as a disciplined interpretive framework for exploring whether some features commonly attributed to inflation admit an alternative effective-description interpretation rooted in horizon-mediated accessibility changes. The framework is observationally relevant only if it can eventually establish a nontrivial predictive wedge—either by mapping to inflationary observables in a constrained way that differs from generic inflation, or by predicting deviations in correlators, non-Gaussianities, reheating signatures, or large-scale anomalies that can distinguish one HRE-trigger regime from another. At present, HEEF does not provide such quantitative predictions. The framework therefore adopts the conservative position that its primary near-term scientific output is not new fits to data, but a sharpened account of what must be demonstrated for a horizon-based accessibility model to become explanatory rather than merely interpretive.

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10. Discussion and Current Debts

The central conceptual contribution of HEEF is the strict separation between causal structure, state accessibility, and effective dynamical description, and the insistence that horizons regulate participation rather than act as energetic or informational agents. The framework's central operational proposal is that horizon reconfiguration is permitted when semiclassical closure fails due to order-unity partition sensitivity in the renormalized stress–energy tensor, rendering the interior description non-predictive. This proposal is conservative in the sense that it introduces no new dynamics and treats reconfiguration as a demand of description consistency rather than a physical force.

The framework's central debts are equally explicit. No microphysical trigger has been provided. No realistic semiclassical worked example has demonstrated the operational trigger prior to the onset of quantum-gravity dominance. No quantitative mapping to perturbation spectra or reheating has been established. In addition, the trigger taxonomy remains provisional until reducibility questions among its regimes are resolved. These limitations are not treated as future-work boilerplate; they define the current boundary between the framework's legitimate claims and its speculative ambitions.

Appendix A. Effective Pressure and Equation of State (Bookkeeping Scaffold)

This appendix defines a formal bookkeeping scaffold for characterizing effective pressure and equation-of-state behavior associated with accessibility contributions. It does not assert that such contributions generically exhibit slow evolution or vacuum-like behavior. Conservative stress tests indicate that accessibility sectors tend to behave radiation-like rather than vacuum-like under stable evolution. Accordingly, this appendix specifies how vacuum-like behavior would appear if realized, not evidence that it is generically realized.

One may write a generalized continuity relation for an effective accessibility contribution,

$$\dot{\rho}_\alpha + 3H(\rho_\alpha + p_\alpha) = Q_\alpha,$$

where Q_α encodes effective exchange associated with re-partitioning of degrees of freedom across the causal boundary. For the special case where $Q_\alpha \approx 0$ over the interval of interest, an effective equation-of-state parameter may be defined by

$$w_\alpha \equiv \frac{p_\alpha}{\rho_\alpha} = -1 - \frac{1}{3}\frac{d \ln \rho_\alpha}{d \ln a}.$$

If ρ_α varies slowly with respect to expansion, then $w_\alpha \approx -1$, yielding inflation-like accelerated expansion at the level of homogeneous background dynamics. Within HEEF, this is a conditional bookkeeping statement: it identifies the behavior required of the effective stress–energy contribution if accelerated expansion is to occur without new fields, but does not claim that such behavior arises generically from horizon reconfiguration alone.

Appendix B. Provisional Trigger Criterion (Operational Threshold)

A Horizon Reconfiguration Event is permitted when the interior effective description ceases to be self-consistent under coarse-graining, in the sense that physically relevant observables become non-robust to small variations in the horizon-defined partition. Let $\langle T_{\mu\nu} \rangle_{\mathcal{D}}$ denote the renormalized stress–energy tensor sourcing semiclassical evolution in a causal domain $\mathcal{D}$. An HRE is permitted when, for fixed global quantum state and fixed underlying dynamics,

$$\left| \frac{\delta \langle T_{\mu\nu} \rangle_{\mathcal{D}}}{\langle T_{\mu\nu} \rangle_{\mathcal{D}}} \right| \gtrsim \mathcal{O}(1),$$

under infinitesimal variations of horizon-consistent partitioning, coarse-graining prescriptions, and renormalization choices consistent with the same causal structure. This condition signals failure of semiclassical closure: predictions for backreaction depend on bookkeeping choices rather than remaining parametrically stable. The trigger does not represent energy creation, breakdown of General Relativity or quantum mechanics, or dynamical action exerted by the horizon; it represents loss of robustness of the interior effective description.

Appendix C. Glossary (Brief)

Horizon-Enabled Expansion Framework (HEEF): A conceptual framework for organizing and stress-testing whether horizon-mediated changes in dynamical accessibility can coherently underlie early-universe phenomenology without introducing new fields or dynamics.

Horizon Reconfiguration Event (HRE): An abrupt redefinition of causal boundary conditions required when no stable interior effective description remains robust under legitimate partition variations.

Accessibility: The subset of degrees of freedom that can participate in interior effective evolution given causal structure and constraints; distinct from thermalization and energy content.

Partition sensitivity: Dependence of renormalized interior quantities—especially ⟨Tμν⟩\langle T_{\mu\nu}\rangle⟨Tμν⟩—on legitimate variations of horizon-consistent system–environment partitioning and coarse-graining.