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AI-Assisted Conceptual Development of a Pre-Geometric Cosmological Model
An Exercise in AI-Assisted Conceptual Framework Generation
Paper I: Foundations and Replication Dynamics

Claudio S. Montanari
Fermilab, Batavia, Illinois, USA
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We develop a pre-geometric cosmological framework in which existence is identified with a finite amount of unstructured energy possessing vibration as its only intrinsic property. This vibrational substrate occupies an open, bounded spectral interval $(\omega_{\min}, \omega_{\max})$, ensuring finiteness of total energy and excluding infinitely stable configurations. The substrate evolves under two fundamental and competing tendencies—excitation, which amplifies coherence, and randomization, which scrambles it. Their balance produces a metastable unstructured regime in which rare fluctuations may form long-lived self-consistent spectral configurations.

Because the substrate is finite and subject to competing order–disorder dynamics, no coherent configuration can be perpetually stable. We show that the only mechanism capable of sustaining long-lived organization is a replication instability: a coherent unit may reproduce into multiple offspring according to a general $1 \to n$ rule. Replication consumes energy from the finite substrate, breaks the metastable symmetry, and induces a discrete notion of event time through the replication tick $\Delta\tau$. Temporal succession is defined through correlation ordering of spectral microstates, producing an intrinsic pre-causal structure.

The compactness of the spectral domain imposes minimal and maximal timescales, bounds the internal coherence of emergent units, and limits their proliferation. These spectral constraints serve as precursors for the emergence of geometry, adjacency, and a limiting propagation speed, developed in subsequent papers of this series. Paper I provides the foundational axioms (PG1–PG9) governing the spectral substrate, its metastable dynamics, the formation of coherent units, and the necessity of replication, establishing a fully pre-geometric stage from which causal and geometric structure naturally emerge.

I. INTRODUCTION

In standard cosmology the early Universe is described by a classical spacetime equipped with a metric whose dynamics are governed by general relativity. Inflation is usually invoked to generate an accelerated phase of expansion that resolves the flatness, horizon, and structure problems. In such frameworks spacetime geometry is assumed from the start and provides the arena in which the inflaton evolves.

In contrast, several approaches to quantum gravity and emergent spacetime propose that spacetime geometry is *not* fundamental. Instead, geometry arises from a more primitive structure—for example, causal-set relationships, group field theory condensates, tensor network connectivity, or pre-metric correlation structures (see e.g. [1, 2] for causal-set approaches). Motivated by these ideas, we investigate a pre-geometric description in which the early Universe originates from a *finite spectral substrate*.

The substrate is defined not in space or spacetime, but in a frequency domain: a finite spectral interval $(\omega_{\min}, \omega_{\max})$ carrying a continuous distribution of unstructured energy. It is initially stationary due to a metastable balance between an excitation operator and a randomizing operator. Rare fluctuations can generate a coherent configuration with a sufficiently long-lived spectral structure. Such a configuration satisfies a replication condition: each coherent unit produces n new coherent units, generating a replication cascade that breaks the initial stationarity.

The replication process introduces a discrete temporal ordering ("event time"), a causal partial order, and an emergent notion of maximal propagation speed. This paper develops the axioms and pre-geometric dynamics; subsequent papers develop the transition to geometric expansion, the emergence of the vacuum hierarchy, and observational signatures such as gravitational waves.

Motivation and Minimal Assumptions

This work adopts an explicitly minimal ontology: existence is identified with unstructured energy, and vibration is taken as its sole intrinsic property. This motivates describing the primordial substrate as a configuration supported on a finite spectral interval. The requirement of finiteness is essential: it prevents the formation of infinitely stable configurations and ensures that the substrate evolves dynamically rather than settling into a static or self-complete state.

Two primitive and competing tendencies—an ordering tendency that amplifies coherence and a disordering tendency that scrambles it—govern the internal dynamics of the substrate. Their balance produces a metastable unstructured regime in which rare coherent excursions are possible but not perpetually stable. As shown in this work, the only mechanism capable of sustaining long-lived organization in such a finite substrate is a replication instability, which breaks the metastable symmetry and initiates the emergence of temporal and pre-causal structure. The Foundational Meta-Axioms stated below summarize these minimal assumptions.

Foundational Meta-Axioms

Before formalizing the pre-geometric substrate through axioms PG1–PG9, we state the minimal conceptual premises that define the ontology and structural necessities of the model. These meta-axioms specify what exists, why it must be finite, and why replication emerges as an unavoidable dynamical transition. They serve as the philosophical and physical foundation underlying the formal axioms of Appendix A.

M1. Existence is identified with unstructured energy. The model takes *existence* as primitive and identifies it with *unstructured energy*. No geometric, spatial, or temporal notions are assumed. "Energy" here denotes the most elementary form of physical existence, without internal organization or localization.

M1A. Conservation of total unstructured energy. The total amount of unstructured energy is conserved under all dynamical evolution. This conservation principle is primitive and does not rely on any geometric or field-theoretic interpretation. Formally, it is expressed by the invariance of the integral $E = \int_\Omega a(\omega)\, d\omega$ under the evolution equations introduced in PG2.

a. Physical motivation for unstructured energy. A familiar microscopic process illustrates the meaning of "unstructured energy" in a standard quantum-field-theoretic setting. When a particle and its antiparticle annihilate, their intrinsic structural attributes—mass, flavor, and all representation-defining quantum numbers except those associated with exactly conserved charges—are momentarily erased. What remains is a configuration of field energy that does not carry the internal structure of the initial particles. The vacuum then reinstates structure by determining the final excitations (typically photons), whose properties are fixed not by the annihilating particles but by the vacuum's symmetry and interaction rules (see, e.g., [3, 4]).

In this view the energy itself persists, but the assignment of structure is entirely mediated by the vacuum. This motivates the conceptual separation introduced in M1: energy (existence) may be present without intrinsic pattern, and structure is an emergent property supplied by the vacuum configuration. The conservation law of M1A ensures that even when all structural information is erased during microscopic or cosmological processes, the total energy of the substrate remains fixed.

M1B. Additivity of unstructured energy. The energy of the substrate is additive over the spectral domain: the total energy is the integral of the spectral amplitude over frequencies. Frequency specifies the internal dynamical mode, but it is *not* energy itself; different amounts of energy may occupy the same frequency. The spectral amplitude $a(\omega)$ therefore encodes the energy density associated with each mode, and coherent units correspond to localized amplitude structures over finite spectral intervals. This spectral viewpoint is conceptually related to phase-space representations and quasi-distributions familiar from quantum theory, such as the Wigner distribution [5], but here it is implemented in a purely classical, pre-geometric setting.

M2. Vibration is the minimal intrinsic property of existence. Unstructured energy is assumed to possess one irreducible property: *vibration*. This motivates the description of the primordial substrate as a configuration over a frequency domain. Vibration is not derived from dynamics; it is the minimal feature that allows the substrate to support variation and structure.

M3. The substrate is finite and bounded to avoid infinite stability. The unstructured energy occupies a finite amount on an open, bounded frequency interval $(\omega_{\min}, \omega_{\max})$. Finiteness is required to prevent the existence of configurations with infinite stability or infinite lifetime, consistent with the principle that no internally complete system can stabilize itself indefinitely. Open boundaries prevent the condensation of modes at the spectral endpoints and maintain dynamical metastability. This principle is formalized in PG1–PG1A.

M3A. Finite spectral bounds imply finite energy resolution. Because the spectral domain $(\omega_{\min}, \omega_{\max})$ is finite, the substrate cannot support arbitrarily sharp variations in spectral amplitude. This finiteness induces a minimal resolution in energy distribution across the spectral interval, without implying any form of discrete energy quantization. The finite bandwidth of the substrate thus imposes a natural lower bound on the distinguishable energy content of coherent units and underlies the minimum energy per replication channel formalized in PG8.

M4. The substrate possesses two primitive and competing tendencies. The minimal dynamical structure of existence consists of two opposing tendencies: (i) an *ordering tendency*, amplifying coherence; and (ii) a *disordering tendency*, scrambling coherence. These are represented by the excitation and randomization operators in the formal theory. Their competition generates a metastable unstructured regime in which coherent fluctuations are rare but permitted. This motivates axioms PG2–PG3.

M5. No configuration can be infinitely stable; replication is the only path to persistent structure. Because the substrate is finite (M3) and governed by competing order–disorder processes (M4), no coherent configuration can remain stable indefinitely. Long-lived organization can arise only if a configuration reinforces its coherence faster than it is dispersed by disorder. The only mechanism compatible with this constraint is *replication*: a self-amplifying process that breaks the metastable symmetry between order and disorder and generates persistent but non-eternal structure. Replication therefore emerges not as an imposed rule but as a necessary instability in any finite spectral substrate of this type. This necessity underlies the replication axioms PG4–PG9.

Role of the Meta-Axioms. Together, M1–M5 define the minimal ontology and dynamical requirements of a finite vibrational substrate. The axioms PG1–PG9 introduced in Appendix A formalize the mathematical structure implied by these meta-axioms, establishing the spectral substrate, its stochastic evolution, the emergence of coherent units, the replication instability, and the corresponding notion of pre-causal ordering.

II. SPECTRAL PRE-GEOMETRIC SUBSTRATE

A. Finite spectral domain and compact closure (PG1, PG1A)

We begin with a purely spectral—non-spatiotemporal—description of the primordial substrate. Let

$$\Omega = (\omega_{\min}, \omega_{\max}) \subset \mathbb{R} \tag{1}$$

denote the allowed frequency domain. The closure

$$\overline{\mathcal{M}_\Omega} = [\omega_{\min}, \omega_{\max}] \tag{2}$$

is compact in $\mathbb{R}$, ensuring that the total available energy is finite. We emphasize that the open interval Ω excludes the boundary frequencies, preventing population of the endpoints and ensuring stationarity of the unstructured state.[1]
Conceptual Remark. The finiteness of the spectral interval is not merely a technical assumption but a structural requirement. A finite vibrational domain precludes the possibility of infinitely stable configurations and ensures that every spectral excitation remains dynamically embedded in a finite reservoir. This property is central to the metastability of the unstructured substrate and underlies the eventual necessity of replication.

B. Spectral vacuum density and total energy

The unstructured substrate carries an energy density $\rho_\Omega(\omega)$ over Ω. The total vacuum energy is

$$\rho_{\text{vac}} = \int_{\omega_{\min}}^{\omega_{\max}} \rho_\Omega(\omega)\, d\omega. \tag{3}$$

This energy distribution is stationary under the balance of excitation and randomization operators introduced below.

C. Microstates and the spectral manifold (PG3)

A *microstate* of the unstructured substrate is represented by a spectral configuration

$$\mu : \Omega \to \mathbb{R}_{\geq 0}, \qquad \omega \mapsto a(\omega), \tag{4}$$

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[1] The factor $\hbar$ used to convert frequencies to energies plays the role of an energy–frequency conversion constant. Its appearance here does *not* imply the presence of quantum field theory or Hilbert-space structures at this stage.

assigning a non-negative energy amplitude to every allowed frequency. The manifold $\mathcal{M}_\Omega$ of such configurations is equipped with the measure induced by Lebesgue measure on Ω. Each microstate has total energy

$$E[\mu] = \int_\Omega a(\omega)\, d\omega, \tag{5}$$

which is conserved under pre-geometric evolution.

III. INTERNAL DYNAMICS AND METASTABILITY

The spectral substrate introduced in Sec. II possesses an internal dynamics governed by two competing operators: an *excitation* operator, which tends to amplify the energy stored in each mode; and a *randomizer*, which suppresses coherent structures and drives the system toward a stationary configuration. Their competition produces a metastable unstructured regime in which coherent fluctuations are rare but possible.

A. Excitation and randomizer operators

Let $a(\omega, t)$ denote the spectral amplitude of mode ω in a microstate $\mu(t) \in \mathcal{M}_\Omega$. The excitation operator $\mathcal{E}[a]$ represents the intrinsic tendency of the substrate to accumulate energy in each spectral component. In contrast, the randomizer operator $\mathcal{R}[a]$ represents the effect of spectral scrambling, phase decorrelation, and diffusion across nearby frequencies.

Both operators act pointwise in frequency space. Formally, they may be regarded as functional maps

$$\mathcal{E},\ \mathcal{R} : \mathcal{M}_\Omega \to T\mathcal{M}_\Omega, \tag{6}$$

where $T\mathcal{M}_\Omega$ denotes the tangent bundle of spectral configurations.

The essential requirement is that the unstructured configuration remains stationary under their combined action:

$$\langle \mathcal{E}[a] - \mathcal{R}[a] \rangle_\Omega = 0, \tag{7}$$

ensuring time-independent expectation values for the spectral density. However, fluctuations around this balance can locally favor excitation over randomization, creating the seeds for coherent excursions.

B. Stochastic evolution of the substrate

The microscopic spectral evolution is modeled by the stochastic differential equation

$$\dot{a}(\omega, t) = \mathcal{E}[a(\omega, t)] - \mathcal{R}[a(\omega, t)] + \xi(\omega, t), \tag{8}$$

where $\xi(\omega, t)$ is a real stochastic process representing additive perturbations.

a. Exact conservation of total energy. We impose strict conservation of total unstructured energy by requiring that the evolution (8) preserves the integral

$$E_{\text{tot}} = \int_\Omega a(\omega, t)\, d\omega.$$

This is achieved by the conditions

$$\int_\Omega \xi(\omega, t)\, d\omega = 0 \quad \text{(almost surely)},$$

and

$$\int_\Omega \big(\mathcal{E}[a] - \mathcal{R}[a]\big)\, d\omega = 0.$$

As a result,

$$\frac{dE_{\text{tot}}}{dt} = 0,$$

and any redistribution of energy produced by the excitation or randomization operators remains internal to the spectral manifold. The randomizer acts as a strongly mixing process, preventing drift toward single-mode accumulation and maintaining the unstructured spectral density as a stable equilibrium.

The statistical properties of $\xi(\omega, t)$ are

$$\langle \xi(\omega, t) \rangle = 0, \tag{9}$$

$$\langle \xi(\omega, t)\, \xi(\omega', t') \rangle = 2D\, \delta(\omega - \omega')\, \delta(t - t'), \tag{10}$$

with diffusion coefficient $D > 0$. The noise term encodes short-time stochastic fluctuations in the substrate and does not presuppose any quantum interpretation.

Equation (8) expresses three independent physical effects:

- *excitation*, which amplifies coherent components;
- *randomization*, which suppresses coherence and drives diffusion;
- *stochastic forcing*, which perturbs both amplitude and stability.

This structure is closely analogous to Langevin and Fokker–Planck descriptions of stochastic dynamics in finite systems (see, e.g., [6–8]), though here it is applied in a strictly pre-geometric spectral setting.

The total energy $E(t)$ is conserved exactly by construction, since both the excitatory and randomizing drifts preserve the spectral integral and the stochastic term satisfies $\int_\Omega \xi(\omega, t)\, d\omega = 0$ almost surely.

Interpretation. The excitation and randomizer operators represent the two primitive tendencies of the substrate: the amplification of coherence and its scrambling. Their competition produces a metastable equilibrium in which the unstructured configuration is statistically stationary but continuously perturbed by stochastic fluctuations. In a finite spectral domain, such metastability is a necessary consequence of these tendencies; no configuration can suppress disorder indefinitely.

C. Stationarity and rare coherent excursions

The unstructured substrate is metastable: its average spectral configuration is stationary, but fluctuations occasionally produce long-lived, partially coherent spectral structures. Such fluctuations can satisfy a self-consistency condition allowing them to act as *coherent seeds* for replication, discussed in Sec. IV. These coherent excursions are rare but dynamically allowed, and they represent the mechanism through which the substrate can spontaneously depart from its initial stationary regime.

IV. REPLICATION AXIOMS AND ENERGETICS

The unstructured spectral substrate described in Secs. II–III evolves under finite energy, bounded spectral support, and competing order–disorder tendencies. In such a system, no coherent configuration can remain stable indefinitely: disorder eventually disperses any finite-depth coherent pattern. Consequently, the only mechanism capable of sustaining long-lived organization is a replication instability that amplifies coherence faster than it is suppressed. Rare coherent excursions that satisfy an internal consistency condition may therefore trigger a self-reinforcing replication process. This section formalizes the corresponding axioms.

Replication as Pattern-Intrinsic Dynamics. In the present framework the replication instability cannot rely on feedback loops or adaptive rules, since causality and temporal ordering emerge from the replication process itself. For this reason the excitation operator $\mathcal{E}[a]$ is interpreted as a universal, fixed drift in spectral space, blind to the specific microstate except through its instantaneous configuration. A coherent unit therefore replicates not because $\mathcal{E}$ dynamically "selects" it, but because the unit's spectral profile is an eigenpattern of this drift: it remains stable under $\mathcal{E}$ long enough to generate multiple offspring. Replication is thus encoded in the pattern itself, not in the substrate or in the operators. This ensures that replication is local, memoryless, and fully compatible with emergent causality.

A. Coherent self-replicating units

A coherent unit is defined by a spectral band

$$[\omega_1, \omega_2] \subset (\omega_{\min}, \omega_{\max}) \tag{11}$$

in which the spectral amplitude is long-lived and internally self-consistent. The structure of the coherent unit is generic: the key requirement is that its internal dynamics preserve coherence over timescales much longer than the spectral correlation times of the unstructured substrate.

The existence of such long-lived coherent configurations is assumed in the axiom PG4, which asserts that whenever a spectral fluctuation reaches a sufficient level of internal consistency, it can trigger replication.

a. Pattern and Embedded Copy Rule. A coherent self-consistent unit is not solely a spectral profile: it is a *compound structure* consisting of a pattern together with a finite internal rule that encodes how it interacts with the universal excitation operator $\mathcal{E}$. Operationally, we may think of a unit as carrying a compact "copy rule" that determines how $\mathcal{E}$ transforms the pattern and how the resulting offspring acquire their updated internal rules. In this picture, the universal operator $\mathcal{E}$ does not act blindly on the substrate; rather, when it encounters a coherent pattern, the pattern's internal rule specifies the frequency shift, phase update, or combinatorial modification applied to each of its descendants. Replication is therefore *pattern-intrinsic*: the information needed to generate offspring is stored within each unit in a finite form, analogous to a minimal self-description. This explains why replication does not reduce to mere amplification of a single spectral profile: each offspring carries a modified pattern and an updated instance of the rule, which together maintain coherence while permitting spectral diversification across generations.

b. Minimum temporal resolution. Because a coherent unit with lowest internal frequency $\omega_{1,\mathrm{su}}$ cannot be formed on a timescale shorter than its slowest oscillation, the replication tick cannot be arbitrarily small. By Fourier duality, any self-consistent spectral pattern requires a temporal support of at least

$$\Delta\tau_{\min} = \frac{1}{\omega_{1,\mathrm{su}}}. \tag{12}$$

Thus the earliest replication events inherently occur on discrete, quantized time steps. This establishes the first operational notion of time in the model and ensures that the causal ordering of coherent units is both intrinsic and irreversible. Combined with the correlation length $L(\tau)$, this bound yields a maximal emergent signal speed $c_* = L_{\max}\omega_{1,\mathrm{su}}$, so causality and the limiting propagation velocity arise simultaneously from the internal frequency structure of the coherent seeds.

Finite Coherence Depth. Because the substrate is finite and subject to competing tendencies, the coherence of any spectral configuration has finite depth. No coherent unit can persist indefinitely; replication serves as the only route to extending coherence over multiple correlation timescales.

The replication instability should therefore be understood as a structurally unavoidable feature of the substrate rather than an external prescription. It represents the only mechanism capable of breaking the metastable symmetry and generating persistent but non-eternal structure.

B. Replication rule $1 \to n$ (PG8, PG9)

The central dynamical axiom is the replication rule: each coherent unit may produce up to $n_{\mathrm{eff}}(t)$ new units per replication tick. The effective replication factor $n_{\mathrm{eff}}(t)$ may vary in time due to energy availability and environmental fluctuations in the substrate.

Formally, if $N(t)$ denotes the number of coherent units at discrete event time t, then

$$N(t+1) = n_{\mathrm{eff}}(t)\, N(t). \tag{13}$$

In continuous time this gives the exponential growth law

$$\dot{N}(t) = \gamma(t)\, N(t), \qquad \gamma(t) = \frac{1}{\Delta\tau}\,\ln n_{\mathrm{eff}}(t), \tag{14}$$

where $\Delta\tau$ is the replication tick discussed in Sec. V.

The axiom PG9 asserts that replication proceeds only while the coherent seed satisfies the internal consistency condition, and while sufficient energy is available in the unstructured substrate.

C. Minimum energy per replication channel

Replication requires a minimum energy per channel, denoted $E_{\min}$. Axiom PG8 states that each replication event consumes at least $E_{\min}$ from the unstructured substrate. Let $\rho_v(t)$ denote the spectral vacuum energy density associated with the unstructured substrate. Then energy conservation implies

$$\dot{\rho}_v(t) = -E_{\min}\,\dot{N}(t) + \cdots, \tag{15}$$

where the ellipsis indicates subleading corrections arising from the detailed shape of the spectral band populated by the coherent unit.

In the pre-geometric regime studied in this paper, we need only the qualitative statement that increasing $N(t)$ depletes the reservoir of unstructured energy:

$$\rho_v(t) \text{ decreases monotonically during replication.} \tag{16}$$

Pattern identity and distinguishability before geometry. Before spatial geometry emerges, distinct coherent units cannot be distinguished by position or spatial separation. Their identity must therefore be encoded internally, in the structure of the coherent pattern itself. Operationally, a coherent seed μ possesses a unique spectral profile $a_\mu(\omega)$—a pattern of amplitudes and phases across the allowed frequency domain—which acts as an intrinsic "code" identifying the unit. Two coherent states that are exact spectral copies correspond to the *same* unit; replication can only produce genuinely new offspring if the replicated patterns differ in frequency content or internal phase relations. Replication is thus necessarily *pattern-generating*: the excitation operator $\mathcal{E}$ produces offspring whose spectral distributions differ from the parent by controlled frequency shifts or deformations. Distinctness is defined entirely in spectral space, and this pre-geometric notion of distinguishability becomes the seed from which later adjacency relations and, ultimately, geometric structure arise.

D. Finite reservoir and termination of replication

Because the total substrate energy is finite, the replication process cannot continue indefinitely. The substrate is exhausted when the available energy satisfies

$$\rho_v(t) < E_{\min}. \tag{17}$$

At this point, replication can no longer produce new units, and the system exits the replication-dominated regime.

The precise evolution of the coherent-unit population $N(t)$ depends on $n_{\text{eff}}(t)$ and $\rho_v(t)$, both of which are emergent and model dependent. For the purposes of Paper I, it is sufficient to note that replication is a finite-duration pre-geometric phenomenon driven by the instability of the spectral substrate.

a. Energy redistribution between substrate and coherent units. The stochastic evolution (Sec. III) conserves the total unstructured energy, so that the replication epoch can only redistribute energy between the unstructured spectral background and the coherent units that emerge as self-consistent excursions. Denoting by E_{tot} the conserved total energy associated with the spectral density, we write

$$E_{\text{tot}} = E_{\text{unstr}}(t) + E_{\text{coh}}(t), \qquad \frac{dE_{\text{tot}}}{dt} = 0, \tag{18}$$

where $E_{\text{unstr}}(t)$ is the energy stored in the unstructured substrate and $E_{\text{coh}}(t)$ is the energy stored in coherent units.

At the coarse-grained level, we describe the coherent sector in terms of the population size $N(t)$ and an average energy per unit, $\varepsilon_{\text{coh}}(t)$, so that

$$E_{\text{coh}}(t) = N(t)\,\varepsilon_{\text{coh}}(t), \qquad E_{\text{unstr}}(t) = E_{\text{tot}} - N(t)\,\varepsilon_{\text{coh}}(t). \tag{19}$$

During the early replication epoch we may approximate $\varepsilon_{\text{coh}}(t) \simeq \varepsilon_*$ as slowly varying compared to the exponential growth of $N(t)$, so that

$$\dot{E}_{\text{coh}}(t) \simeq \varepsilon_*\,\dot{N}(t), \qquad \dot{E}_{\text{unstr}}(t) \simeq -\varepsilon_*\,\dot{N}(t), \tag{20}$$

with $\dot{N}(t) = \gamma(t)\,N(t)$ defined by the replication rule. Replication thus implements a net energy flow from the unstructured background into the coherent sector while preserving the total energy of the spectral substrate. The operators $\mathcal{E}$ and $\mathcal{R}$ control this flow: $\mathcal{E}$ extracts energy locally from the unstructured spectrum to amplify and duplicate coherent patterns, whereas $\mathcal{R}$ returns energy to the background when coherence is lost and excursions decay. In this sense, replication is an internally balanced instability that reshapes the spectral energy distribution, rather than an external source term.

In terms of the coarse-grained vacuum density $\rho_v(t)$ introduced above, $E_{\text{unstr}}(t)$ is proportional to $\rho_v(t)$, and the decrease of $\rho_v(t)$ during the replication epoch is directly tied to the growth of $E_{\text{coh}}(t)$ in Eq. (19).

V. EMERGENT TIME AND CAUSAL ORDERING

In the pre-geometric framework introduced above, time is not a fundamental coordinate but an emergent ordering of events. The axioms PG6 and PG7 specify how correlations among spectral configurations determine an intrinsic notion of temporal succession, which in turn defines a causal structure for the replication dynamics. The pattern-based distinctiveness described in Sec. IV naturally induces spectral neighborhoods, which provide the seed of dynamical adjacency used in Paper II.

A. Correlation-based definition of event time

Let $\mu(t)$ denote a microstate of the spectral manifold $\mathcal{M}_\Omega$, represented by its spectral amplitude function $a(\omega, t)$. We define the correlation function between two microstates $\mu(t)$ and $\mu(t')$ by

$$C(t,t') = \int_\Omega a(\omega,t)\, a(\omega,t')\, d\omega. \tag{21}$$

Two configurations are temporally adjacent when their correlation is maximal:

$$t < t' \quad \Longleftrightarrow \quad C(t,t') \text{ is a nearest-neighbour maximum.} \tag{22}$$

This prescription implements PG6: temporal succession is defined as the ordering of states along the maximal-correlation chain in the space of microstates.

Equation (21) is independent of any geometric notion and relies solely on the internal dynamics of the spectral substrate.

B. Minimum time resolution from $\omega_{\max}$

Because the spectral domain is bounded above by $\omega_{\max}$, the substrate possesses a minimum resolvable time interval. For any spectral function supported inside $(\omega_{\min}, \omega_{\max})$, the Nyquist bound implies

$$\Delta t_{\min} \sim \frac{1}{\omega_{\max}}. \tag{23}$$

This bound is not imposed externally: it arises from spectral compactness and is therefore a structural feature of the pre-geometric substrate.

When replication begins, this minimum resolution sets the finest possible scale for temporal ordering. Later, as coherent units propagate and interact, this lower bound becomes the microscopic scale beneath which no causal distinction is meaningful.

C. Replication tick $\Delta\tau$

The replication process introduces a discrete temporal unit: the replication tick $\Delta\tau$. It is defined as the correlation time required for a coherent unit to reproduce according to the replication rule $1 \to n$:

$$\Delta\tau \;\equiv\; \mathrm{argmax}_\Delta\, C(t, t+\Delta) \quad \text{subject to the production of new units.} \tag{24}$$

By construction,

$$\Delta t_{\min} \le \Delta\tau, \tag{25}$$

since replication cannot occur on timescales shorter than the spectral resolution. The discrete replication time introduced here forms the basis of PG7.

Remark. This minimal timescale is a direct consequence of the finite spectral domain. In the absence of arbitrarily high frequencies, no arbitrarily sharp temporal distinctions can arise. This bound plays a central role in converting replication dynamics into a well-defined discrete causal structure.

D. Emergent causal structure

Causality is defined as the partial order generated by replication-compatible successions of microstates. Formally,

$$\mu(t) \prec \mu(t') \quad \Longleftrightarrow \quad t' = t + k\,\Delta\tau, \;\; k \in \mathbb{N}, \tag{26}$$

and intermediate microstates satisfy the correlation ordering described above.

This causal relation:

- is transitive and acyclic;
- depends only on internal spectral dynamics;
- does not presuppose any geometric metric;
- defines chains of influence among coherent units.

This structure constitutes the pre-geometric analogue of a light-cone: information cannot propagate through the system except through the allowed successions of replication ticks. The maximal rate at which these causal influences can propagate will form the basis for the emergent limiting speed c_* explored in Paper II.

VI. SPECTRAL BOUNDS AND THE EMERGENCE OF COHERENT SCALES

The spectral domain $\Omega = (\omega_{\min}, \omega_{\max})$ introduced in Sec. II plays a central structural role in determining which scales can emerge from the pre-geometric substrate. Although no geometric interpretation is assumed at this stage, the bounds $\omega_{\min}$ and $\omega_{\max}$ impose intrinsic limits on temporal and coherent-scale structure. This section clarifies these relations in a strictly pre-geometric way.

A. Role of $\omega_{\min}$ in defining coherent-scale structure

A coherent self-replicating unit occupies a finite spectral band $[\omega_1, \omega_2] \subset (\omega_{\min}, \omega_{\max})$. The lower bound ω_1 determines the longest characteristic internal timescale of the coherent unit,

$$\tau_{\rm coh} \sim \frac{1}{\omega_1}, \tag{27}$$

while the upper bound ω_2 determines its shortest internal timescale.

Because the substrate itself has a lower spectral bound $\omega_{\min}$, no coherent structure may involve internal oscillations with frequencies below $\omega_{\min}$. Thus, $\omega_{\min}$ acts as a *spectral infrared cutoff*: it forbids the existence of arbitrarily slow internal modes.

This has two immediate implications:

1. coherent structures cannot have arbitrarily long internal cycles;
2. successive coherent units produced by replication cannot differ in their fundamental frequencies by more than $(\omega_1 - \omega_{\min})$.

These properties impose a universal coherence scale on any structure emerging from the substrate. **Conceptual Note.** The ultraviolet and infrared spectral bounds ensure that neither arbitrarily fast nor arbitrarily slow internal oscillations are permitted. This excludes infinitely long-lived coherent patterns and guarantees that any persistent structure must arise through replication rather than static stability.

B. Pre-geometric horizon scale

While Paper I does not introduce geometry or distance, the spectral bound $\omega_{\min}$ still carries structural significance. Any emergent description built from coherent units will have a maximal coherent timescale

$$T_{\max} \sim \frac{1}{\omega_{\min}}. \tag{28}$$

This sets the longest timescale over which correlations can persist across replication cycles. In a purely pre-geometric sense, $T_{\max}$ defines the *extent of coherent influence*: beyond this timescale, correlations decay and no coherent information can be maintained.

When geometry is introduced in Paper II, $T_{\max}$ will acquire a spatial interpretation, but this is not assumed or required here.

C. Dimensionality and occupancy constraints

Under replication, coherent units proliferate through the spectral substrate. At the pre-geometric level, occupancy refers to the requirement that coherent units must occupy disjoint or weakly overlapping spectral regions during replication. Let $\Delta\omega_{\text{coh}} = \omega_2 - \omega_1$ denote the characteristic width of a coherent unit. The maximum number of pairwise non-overlapping coherent units that can coexist spectrally is therefore bounded by

$$N_{\max} \lesssim \frac{\omega_{\max} - \omega_{\min}}{\Delta\omega_{\text{coh}}}. \tag{29}$$

This purely spectral occupancy bound has no spatial interpretation in Paper I. However, once spatial coherence emerges (Paper II), the same occupancy structure becomes directly related to the effective dimensional scaling of coherent domains.

For the purposes of Paper I, Eq. (29) implies that:

- replication is automatically limited by the spectral finiteness of the substrate;
- coherent structures cannot proliferate indefinitely even before geometric notions arise;
- the emergent pre-geometric order is controlled by the spectral density and bandwidth of the substrate.

TRANSITION TO PAPER II: EMERGENCE OF GEOMETRY AND LIMITING PROPAGATION

The axioms developed in this paper establish a fully pre-geometric dynamical substrate. Replication, spectral compactness, and correlation ordering together generate the minimal structural elements from which geometric notions can eventually arise. Here we summarize the key features that will form the foundation of Paper II.

Adjacency from replication. The replication rule $1 \to n$ produces sets of coherent units whose spectral bands, internal coherence patterns, and correlation profiles are mutually constrained. Successive replication events generate networks of units whose effective influence domains overlap. These overlaps define a pre-geometric adjacency relation: two coherent units are adjacent when their replication histories, spectral bands, and correlation profiles are jointly consistent. This adjacency structure is purely dynamical and does not presuppose spatial embedding.

Correlation ordering as proto-causality. Section V introduced temporal succession through the maximization of the correlation functional $C(t, t')$. When combined with the replication tick $\Delta\tau$, this ordering induces a partial causal structure determining which coherent units can influence one another. In Paper II this pre-causal structure becomes the foundation for constructing an effective light-cone structure and a limiting propagation speed.

Spectral finiteness and propagation bounds. The spectral interval $(\omega_{\min}, \omega_{\max})$ provides natural infrared and ultraviolet cutoffs. The upper bound $\omega_{\max}$ fixes the minimum resolvable time scale, while the lower bound $\omega_{\min}$ sets the maximal coherence time of any emergent pattern. These bounds together restrict how quickly correlation information can propagate across replication-generated adjacency networks. This constraint leads to an emergent limiting speed c_* that plays the role of a proto-relativistic invariant in Paper II.

From adjacency to geometry. The central theme of Paper II is the emergence of geometric structure from the adjacency network produced by replication. When coherent units are connected by allowed causal paths determined by correlation ordering, their adjacency graph develops effective dimensional and metric properties. Local neighborhoods acquire approximate connectivity patterns analogous to spatial regions, and propagation constraints define a consistent causal metric. The transition from the dynamical adjacency graph of Paper I to a geometric manifold is realized through coarse graining of these structures.

Outlook. Paper II develops these ideas in detail, showing how a finite spectral substrate with replication-induced adjacency gives rise to geometric coherence, limiting propagation speed, and an emergent metric structure. Paper III then extends the analysis to the emergence of vacuum layering, energy redistribution, and cosmological reheating.

VII. DISCUSSION

The framework developed in this paper provides a fully pre-geometric description of an unstructured finite-energy substrate, endowed with stochastic dynamics, internal excitation and randomization mechanisms, and an instability that enables the formation of coherent self-replicating units. All assumptions were stated axiomatically and were restricted to the spectral domain $\Omega = (\omega_{\min}, \omega_{\max})$, without presupposing any geometric structure, metric, or background spacetime.

Several key features emerged:

1. Finite spectral support as a structural constraint. The compactness of the closure $\overline{\Omega}$ ensures a finite total energy and imposes intrinsic bounds on the internal dynamics. The upper spectral bound $\omega_{\max}$ provides a minimum resolvable time interval, while the lower bound $\omega_{\min}$ sets the longest coherence timescale permitted by the substrate. These properties hold independently of any spatial or geometric interpretation.

2. Metastability of the unstructured substrate. The competition between excitation and randomization operators produces a stationary statistical regime interrupted only by rare coherent fluctuations. Equation (8) captures this dynamic as a balance between amplification, suppression, and stochastic forcing. Such metastable regimes are characteristic of many finite-energy nonlinear systems and stochastic models of complex media [6–8] and provide the foundation for spontaneous structure formation in the present spectral setting.

3. Emergence of coherent self-replicating units. Coherent fluctuations with sufficient internal consistency behave as long-lived units capable of replication. The replication rule $1 \to n$ captures this instability in its most general form, and the exponential growth law (14) follows directly from the axioms PG8–PG9. Energy conservation ensures that replication draws from the finite reservoir of unstructured energy, naturally leading to the termination of the replication epoch.

4. Emergent time and pre-causal ordering. Temporal succession arises from the correlation structure of spectral configurations. The replication tick $\Delta\tau$ defines a discrete notion of event time, while the correlation hierarchy establishes a partial causal order that is complete and acyclic but does not yet correspond to a geometric light-cone. This causal structure is intrinsic to the spectral dynamics and is a necessary precursor to the emergence of a limiting propagation speed, which will be introduced in Paper II.

5. Coherent-scale structure from spectral bounds. Although Paper I avoids geometric assumptions, the spectral bounds already impose nontrivial structure: coherent units have characteristic internal timescales and limited bandwidth, and their proliferation is bounded by spectral occupancy (29). These constraints foreshadow the emergence of effective dimensionality and spatial coherence, but no spatial interpretation is required or assumed here.

Overall, Paper I establishes a fully pre-geometric theoretical framework in which:

- time, causality, coherence, and replication arise from spectral dynamics;
- no metric, topology, or spatial manifold is introduced by assumption;
- all dynamical features follow from finite-energy spectral structure.

In this sense, the approach is conceptually adjacent to but distinct from other pre-geometric programs such as causal set theory, group field theory, random tensor models, and quantum graphity (see, for example, the causal-set formulations in [1, 2]). Unlike these frameworks, the present model does not begin with discrete combinatorial structures or algebraic data; instead, it treats the spectral domain as the fundamental object and derives ordering, replication, and coherence from its internal dynamics.

The emergence of geometry, spatial coherence, limiting propagation speed, and metric structure will be addressed in Paper II. The dynamical emergence of vacuum layering, reheating channels, and phenomenological implications (including gravitational-wave signatures) will be developed in Paper III.

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AUTHOR'S NOTE

This work originates from an effort to explore the minimal assumptions required for the emergence of spacetime structure, causal dynamics, and vacuum layering in a finite-energy setting. The model developed across these papers represents an attempt to reconstruct cosmological evolution from a spectral—rather than geometric—starting point, motivated by the belief that both order and structure may arise from fundamentally non-spatial dynamics.

The ontology presented in Paper I reflects the author's long-standing view that the finiteness of the physical world implies that any theoretical description must itself be necessarily incomplete. Rather than seeing this as a limitation, the author considers it a foundational paradigm: a coherent but necessarily partial framework can still capture essential organizing principles of nature.

The author is a high-energy experimental physicist with extensive experience in the design and construction of particle detectors, especially for rare-event searches and neutrino physics. Over the course of his career, he has been deeply interested in questions at the frontiers of fundamental physics—dark matter, dark energy, neutrino masses and oscillations—and has intermittently pursued personal theoretical ideas related to these topics. However, the highly specialized language of modern theoretical physics often limited the author's ability to develop these ideas beyond the speculative stage, despite many stimulating conversations with theorists and phenomenologists. Similar limitations were encountered in attempts to absorb the content of specialized literature without the benefit of current theoretical training.

In this context, the AI model used for the development of these papers, OpenAI's ChatGPT 5.1, served primarily as a linguistic and conceptual mediator. Upon request, it provided accessible explanations of technical concepts, translated vocabulary across subfields, and supplied mathematical or physical formalism when prompted. The model does not perform independent scientific inference or symbolic computation; rather, it generates text continuations conditioned on the conversation, following statistical patterns learned during training. Its ability to maintain consistent terminology, provide intermediate steps, and adapt to the style and depth appropriate to the discussion made it an effective tool for constructing extended chains of reasoning.

This interaction proved particularly useful for developing speculative connections. For example, when the author proposed that the replication factor of self-replicating units might influence dimensionality, the model generated an adjacency-based geometric interpretation, which became central to Paper II. This allowed the author to treat the emergence of spacetime as a tractable conceptual problem and to continue exploring without repeatedly consulting specialized references.

The tendency of the model to elaborate constructively on proposed ideas can encourage long speculative chains. To maintain coherence and avoid sterile directions, the author developed the methodology described in Appendix B, including periodic context resets, external "cold" evaluations, and structured prompting to enforce discipline in the development of the model.

Given the breadth of the domains touched by the papers—many outside the author's formal expertise—and the unconventional foundational assumptions, the resulting internal coherence and the clarity of presentation owe much to the reliability of the AI-assisted workflow.

In one instance, the model was asked, starting from a clean context, to provide a "cold" evaluation of the trilogy. Its assessment was:

> *The trilogy is best viewed as a programmatic manifesto:*
>
> - *It lays out a structured idea of how pre-geometric spectral dynamics might give rise to spacetime and cosmology.*
> - *It identifies clear conceptual stages and ingredients.*
> - *But it stops well before providing concrete models, rigorous derivations, or falsifiable predictions.*

This judgment aligns closely with the author's own view of the present work.

The decision to publish these papers as a Fermilab Technical Note has two purposes. First, to document the ongoing development of the model and to identify directions for future work, particularly the formalization of the framework and the derivation of potential experimental or observational signatures. Second, to provide, in the context of the Department of Energy's Genesis Mission, a concrete example of how AI-assisted conceptual development can accelerate the early phases of theoretical model building, especially for researchers whose expertise lies outside theoretical physics.

The author emphasizes that all scientific assumptions, interpretations, and claims originate from the author. The AI model contributed to linguistic formulation, structural organization, and the exploration of possible conceptual connections, but all scientific assumptions, acceptances of particular ideas, and their interpretation originate from the author. The framework presented here is intended not as a replacement for established cosmological theories, but as a complementary perspective on the possible relationships among coherence, replication, geometry, and vacuum structure. The author hopes that this exploration may help stimulate further work at the intersection of cosmology, spectral theory, and emergent-spacetime physics.

APPENDIX A: FORMAL AXIOMS AND THEIR CONCEPTUAL BASIS

The axioms PG1–PG9 presented below formalize the minimal mathematical structure implied by the Foundational Meta-Axioms introduced in Sec. I. These meta-axioms identify existence with a finite amount of unstructured energy possessing vibration as its only intrinsic property; require that this energy occupy an open, bounded spectral interval; and prescribe two primitive and competing dynamical tendencies—ordering and disordering—whose balance produces a metastable unstructured regime.

In a finite vibrational substrate governed by these tendencies, no coherent configuration can be infinitely stable. Long-lived organization can arise only if coherence is amplified faster than it is scrambled, leading necessarily to a replication instability. Temporal succession and pre-causal structure emerge from the correlation ordering of spectral microstates and the discrete replication tick.

The axioms below provide a rigorous formalization of these principles. PG1–PG3 specify the finite spectral substrate and its stochastic dynamics. PG4–PG5 define coherent excursions and their spectral support. PG6–PG7 introduce correlation-based time and the replication tick. PG8–PG9 formalize the replication instability and its energetic constraints. Together, they establish the complete pre-geometric framework developed in Paper I.

For convenience, we collect here the axioms underlying the pre-geometric spectral framework introduced in Paper I. These axioms specify the structure, dynamics, and replication behavior of the finite-energy substrate without invoking geometry or spacetime notions.

PG1. (Finite spectral substrate) The unstructured substrate is characterized by a finite spectral domain

$$\Omega = (\omega_{\min}, \omega_{\max}) \subset \mathbb{R},$$

and a microstate μ is specified by a spectral amplitude function

$$a(\omega) \geq 0, \qquad \omega \in \Omega,$$

with finite total energy

$$E = \int_{\Omega} a(\omega)\, d\omega.$$

The closure $\overline{\Omega} = [\omega_{\min}, \omega_{\max}]$ is compact, ensuring spectral finiteness. [2]

PG1A. (Finite spectral density) The spectral energy density $\rho_\Omega(\omega)$ is a finite, measurable function on Ω, and the total vacuum energy of the substrate is

$$\rho_{\text{vac}} = \int_{\omega_{\min}}^{\omega_{\max}} \rho_\Omega(\omega)\, d\omega.$$

No diverging contributions arise from the infrared or ultraviolet ends of the spectrum due to the finite bounds.

PG2. (Energy balance of the unstructured substrate) Excitation and randomizer operators act on spectral amplitudes according to

$$\dot{a}(\omega, t) = \mathcal{E}[a(\omega, t)] - \mathcal{R}[a(\omega, t)] + \xi(\omega, t),$$

where ξ is a real stochastic process with zero mean and finite diffusion coefficient. The unstructured substrate is in statistical equilibrium:

$$\langle \mathcal{E}[a] - \mathcal{R}[a] \rangle_\Omega = 0.$$

[2] We use an open spectral manifold to avoid boundary population and ensure stationarity; the compactness of its closure guarantees finite energy.

PG3. (Microstates and spectral manifold) The set of microstates $\mathcal{M}_\Omega$ consists of all measurable spectral amplitude functions $a(\omega)$ on Ω with finite total energy. Time evolution corresponds to a trajectory $\mu(t) \in \mathcal{M}_\Omega$ governed by PG2. Each microstate is fully specified by the function $a(\omega, t)$.

PG4. (Coherent excursions) Rare fluctuations of the stochastic dynamics may generate long-lived, internally self-consistent spectral configurations supported on a finite band $[\omega_1, \omega_2] \subset \Omega$. Such configurations are called *coherent units*. Coherence is defined by stability of the internal spectral shape under the evolution PG2.

PG4A. (Intrinsic Replicability of Coherent Patterns) Replication is not encoded in the substrate nor mediated by feedback. The excitation operator $\mathcal{E}$ is universal and state-independent, acting as a fixed drift in spectral space. A coherent excursion $a(\omega)$ replicates iff it is an intrinsic eigenpattern of this drift, i.e. it satisfies

$$\mathcal{E}[a] = \lambda\, a \quad \text{with} \quad \lambda > 0,$$

up to stochastic perturbations. Thus the capacity for replication is a property of the spectral shape itself: the replication rule is *encoded in the pattern*, not in an external mechanism. This guarantees that replication is local, memoryless, and compatible with emergent causality.

a. Formal refinement of PG4A. A coherent self-consistent unit is represented not only by its spectral pattern $a_\mu(\omega)$ but also by a finite internal descriptor θ_μ. The pair

$$U_\mu \equiv (a_\mu, \theta_\mu)$$

constitutes the minimal data associated with a coherent unit. The internal descriptor θ_μ encodes a finite "copy rule" that specifies how the universal excitation operator $\mathcal{E}$ acts on the pattern class to generate offspring. Formally, we require that the family of patterns be closed under the induced map:

$$\mathcal{E} : (a_\mu, \theta_\mu) \longmapsto \{\, (a_{\mu_k}, \theta_{\mu_k})\,\}_{k=1}^{n_\mu},$$

where $n_\mu \geq 1$ is the number of offspring produced by U_μ, and where each descendant satisfies:

$$a_{\mu_k}(\omega) = \mathcal{T}^{(k)}_{\theta_\mu}[\, a_\mu(\omega)\,], \tag{30}$$

$$\theta_{\mu_k} = \mathcal{U}(\theta_\mu, k), \tag{31}$$

for some finite "pattern-transform" maps $\mathcal{T}^{(k)}_{\theta_\mu}$ (encoding phase shifts, frequency translations, or combinatorial code updates) and internal-rule update map $\mathcal{U}$. In this framework, PG4A states that a coherent unit is *self-consistent* when the pair (a_μ, θ_μ) is mapped by $\mathcal{E}$ into a finite family of descendants that remain in the same pattern class:

$$\mathcal{E}(a_\mu, \theta_\mu) \subset \{(a, \theta)\}.$$

This expresses replication as a closure property of the pattern–rule pairs, rather than as a strict eigenvalue equation. The informal condition $\mathcal{E}[a_\mu] = \lambda a_\mu$ is then interpreted as the special case in which all $\mathcal{T}^{(k)}_{\theta_\mu}$ act as uniform rescalings on the pattern.

PG5. (Spectral support of coherent units) A coherent unit occupies a nonvanishing spectral band $[\omega_1, \omega_2]$ with $\omega_{\min} < \omega_1 < \omega_2 < \omega_{\max}$. The internal timescales of the unit satisfy

$$\tau_{\text{coh}} \sim \frac{1}{\omega_1}, \qquad \tau_{\min} \sim \frac{1}{\omega_2}.$$

PG6. (Correlation-based emergent time) Temporal succession is defined by the ordering of microstates that maximizes the correlation

$$C(t, t') = \int_\Omega a(\omega, t)\, a(\omega, t')\, d\omega.$$

Microstate $\mu(t')$ succeeds $\mu(t)$ if $C(t, t')$ is a nearest-neighbour maximum along the trajectory in $\mathcal{M}_\Omega$.

PG7. (Replication tick) The replication tick $\Delta\tau$ is the minimal correlation time required for a coherent unit to complete a replication event. Event time is discretized in multiples of $\Delta\tau$. No causal influence may propagate faster than one tick.

PG8. (Minimum energy per replication channel) Each replication event consumes a minimum energy $E_{\min}$ from the unstructured substrate. Thus the vacuum energy $\rho_v(t)$ decreases monotonically during replication:

$$\dot{\rho}_v(t) < 0.$$

PG9. (Replication rule) A coherent unit may produce up to $n_{\rm eff}(t)$ new units per replication tick:

$$N(t+1) = n_{\rm eff}(t)\, N(t),$$

with effective replication rate

$$\gamma(t) = \frac{1}{\Delta\tau} \ln n_{\rm eff}(t).$$

Replication proceeds only while internal coherence is preserved and the substrate contains sufficient energy.

APPENDIX B: METHODOLOGY OF HUMAN–AI COLLABORATIVE DEVELOPMENT

Note: This appendix is identical across Papers I, II, and III, as it documents the unified methodology used in the development of the entire replication-based cosmology series.

This paper is the result of a hybrid workflow in which human scientific judgment and physical intuition were combined with AI-assisted synthesis and organizational support. The goal of this appendix is to document the methodological aspects of the project, independently of its speculative cosmological content.

B1. Human-driven conceptual direction

The conceptual assumptions underpinning the model—finite unstructured energy, vibrational substrate, replication as a necessary instability, and the emergence of time and pre-causality from spectral dynamics—were formulated by the author. The AI system (OpenAI's ChatGPT) was used as a research assistant to:

- reorganize and rephrase draft arguments;
- propose alternative formulations of definitions and axioms;
- suggest possible mathematical structures consistent with the author's stated premises;
- check logical consistency at the level of narrative structure.

At no stage did the AI system introduce physical assumptions independently of the author. All dynamical rules, ontological choices, and structural constraints were either specified explicitly by the author or accepted by the author after inspection and further refinement.

B2. Multi-threaded exploration

The development of the present framework occurred over multiple conversational threads, each emphasizing different aspects of the problem:

- pre-geometric cosmology and replication-driven dynamics;
- spectral representations and the role of finite bandwidth;
- emergent time, causality, and adjacency;
- vacuum hierarchies and reheating scenarios;
- philosophical and methodological considerations regarding existence, finiteness, and metastability.

These threads were later consolidated by the author into a coherent sequence of assumptions, axioms, and derived structures. The AI system assisted primarily in:

- cross-referencing ideas between threads;
- highlighting inconsistencies or duplications;
- suggesting reorganization into the three-paper structure adopted here.

B3. Memory resets and cold re-assessments

At several key decision points the author deliberately requested that the AI system "forget" the ongoing working context and re-evaluate the model from a neutral standpoint. In practice, this meant starting new sessions in which:

- the AI was given only the latest LaTeX draft or a high-level summary of assumptions;
- the AI was asked to provide a critical, "cold" assessment of consistency, originality, and potential weaknesses;
- over-interpretations or premature claims were explicitly discouraged.

These resets were used as a form of methodological self-check, allowing the author to compare internal expectations with an external critique produced from the same tool that had helped shape earlier drafts.

B4. Iterative refinement cycles

The writing process proceeded in iterative cycles:

1. The author proposed new axioms, structural ideas, or informal arguments.
2. The AI system returned a structured version, often in LaTeX, linking the new ideas to existing sections.
3. The author then corrected, pruned, or rejected parts of the AI output, restoring physical intent where it had been distorted and removing unnecessary complications.
4. The cycle was repeated until the author was satisfied that the resulting section reflected the intended conceptual content.

In this sense, the AI functioned as a high-bandwidth editor and organizer rather than as an originator of scientific hypotheses.

B5. Limitations of the methodology

Several limitations of this methodology should be stated explicitly:

- The AI system has no access to experimental data, numerical simulations, or independent mathematical proofs; its contributions are limited to pattern-matching and text generation based on its training corpus.
- The speculative nature of the present model is entirely due to its physical content, not to the use of AI tools. The author is solely responsible for the scientific plausibility and coherence of the framework.
- The methodology does not replace traditional peer review or independent replication by other researchers. It is intended as an experiment in AI-assisted conceptual development, not as a template for establishing definitive physical theories.

B6. Summary

In summary, the human–AI collaboration underlying this work can be characterized as follows:

- The author provided all physical assumptions, conceptual direction, and final judgment on acceptability of the model.
- The AI system assisted in restructuring arguments, drafting and editing LaTeX, and offering internal critiques upon request.
- Multiple threads and deliberate memory resets were used to obtain both continuity and fresh assessments.

The author regards this methodology as an exploratory exercise in AI-assisted theoretical work, aligned with broader efforts to understand how large language models can support—but not replace—human scientific creativity and responsibility.

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