Stepwise Emergence of Spacetime Dimensions in the Big Bang Framework

Grigol Keshelava

Healrycore, Tevdore Mgvdeli st. 13, Tbilisi, 0112, Georgia

Email: gagakeshelava@gmail.com

ORCID: 0000-0003-3784-1869

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Abstract

This study proposes a refined hypothesis on the stepwise emergence of spacetime dimensions from a zero-dimensional (0D) singularity within the Big Bang framework, integrating insights from emergent cosmology, quantum gravity, and stochastic dynamics. Building on prior theoretical developments such as loop quantum gravity and matrix theory, the model posits a sequential dimensional activation: 0D (singularity) → one-dimensional (1D; time, enabling causality) → two-dimensional (2D; light, activating electromagnetic fields) → three-dimensional (3D; space, facilitating cosmic expansion). This phenomenological approach offers a novel pathway toward reconciling quantum mechanics and general relativity, circumventing classical singularities through emergent, temperature-dependent transitions governed by effective Lagrangians and stochastic relaxation. By examining the pre-geometric 0D phase, the 1D temporal scaffold, the 2D wave-like behavior of light, and the full 3D spatial regime, the hypothesis provides a comprehensive framework for early-Universe evolution. Its implications extend to black holes, Big Crunch scenarios, and observational tests via cosmic microwave background (CMB), gravitational wave (GW), and Big Bang nucleosynthesis data, challenging unified 4D spacetime paradigms while aligning with holographic dualities and entanglement-based geometries.

Keywords: Big Bang; emergent dimensions

1. Introduction

Standard cosmological models based on general relativity (GR) and the Friedmann–Lemaître–Robertson–Walker (FLRW) metric describe the emergence of a unified four-dimensional (4D) spacetime. However, several approaches to quantum gravity suggest that spacetime may not be fundamental but instead emerges from underlying quantum structures [1, 2]. Recent theoretical developments—including emergent cosmology from matrix theory [3] and stochastic composite gravity [4]—indicate dimensional reduction at high energies, with a full (3+1)D spacetime emerging in the post-Planckian era. This framework is further connected to emergent Standard Model scenarios [5], in which particle physics and spacetime geometry arise concurrently. By incorporating stochastic dynamics, deriving dimensional transitions from effective potentials, and proposing observational tests using cosmic microwave background (CMB), gravitational wave (GW), and Big Bang nucleosynthesis data [6, 7], this refinement aims to address limitations of existing approaches.

2. The singularity as a zero-dimensional (0D) state

The initial singularity of the Universe, associated with the Big Bang, can be conceptualized as a point of infinite density and temperature—a 0D state. It contains all potential configurations of the Universe within a single point, serving as the origin for subsequent dimensional expansion. Minimal formal models of curve singularities support this view, representing states where known physical laws break down and matter and energy are infinitely concentrated [8]. Consequently, the singularity functions as the seed from which the observable Universe emerges. The Friedmann equations, derived from Einstein's GR, describe the evolution of spacetime from such a state [9], providing a framework for understanding early cosmic dynamics.

The Big Bang singularity is conventionally modeled as a 0D point of infinite density, where classical spacetime geometry breaks down into quantum foam [10]. In loop quantum gravity (LQG), this singularity is quantized as a spin network, lacking continuous dimensions [10]. We extend this view by treating the singularity as a pre-geometric phase with zero effective dimensionality (D = 0), governed by quantum information entropy rather than GR. Following the transition to emergent spacetime, the Friedmann equations describe cosmic evolution (1):

$$\left(\frac{a'}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3} \quad (1)$$

where a→0 is avoided through bounce models in stochastic gravity [6].

3. Time as one dimension

Time differs fundamentally from spatial dimensions and is absent at the singularity, where classical concepts of spacetime break down. In physics, time is treated as a one-dimensional (1D) continuum, experienced linearly as past, present, and future, and serves as the essential dimension facilitating change and progression. Each moment represents a snapshot of multidimensional interactions within the Universe, influenced by the initial conditions established at the singularity. Minkowski's formulation of spacetime a century ago provided a framework for understanding the Universe as a 4D entity [2], in which time is intertwined with the three spatial dimensions. The 1D nature of time underpins causality, and the Friedmann equations describe how the Universe evolves along this temporal dimension [9]. A subsequent formalism introduced by Vaccaro provides a framework in which time and space are treated on an equal footing at a fundamental level while preserving their familiar distinctions—such as matter being localized in space but evolving unboundedly in time [11]. Within this framework, a collection of conditional states can represent a human at each clock time as experiencing the present moment, retaining memory of the past, and perceiving the passage of time [12]. As the Universe evolves, it cools and develops structure. In cosmological terms, time is measured from the moment of the Big Bang and precedes the emergence of light and space. All motion in the Universe—including the oscillation of light or the expansion of space—occurs within the temporal dimension. Consequently, time forms the foundational axis upon which all other aspects of the Universe depend. The close relationship between matter motion and time is illustrated by the following formula (2):

$v = S/t$ (speed = distance/time) (2)

In standard Big Bang cosmology, spacetime emerges as a unified 4D continuum at t = 0. Our hypothesis, however, proposes a stepwise emergence in which time precedes the full manifestation of spatial dimensions. This concept is motivated by quantum gravity frameworks such as LQG, where space is quantized into discrete spin networks, representing a breakdown of continuous geometry at the Planck scale, while time can emerge as a relational parameter that facilitates dynamics even in the absence of full space [10]. This allows time to persist through singularities in bounce models, preventing a true t = 0 collapse and enabling a cosmic rebound. Such a separation is not *ad hoc*; it aligns with proposals in which spacetime emerges from quantum entanglement or information, with time functioning as the first "scaffold" dimension [13]. Minkowski spacetime provides a classical foundation; however, in quantum regimes, time and space can be treated on an equal footing at a fundamental level while evolving differently [11].

Initially, time emerges as a 1D continuum, enabling causality in the absence of spatial extension. Motivated by quantum asymmetry [11], we introduce a temperature dependence: at T > T_Pl (i.e., the Planck temperature ~10^{32} K), the effective dimensionality is D = 1 (time-only). The metric in this regime simplifies to $ds^2 = -c^2 dt^2$. The dynamics are described by a relational Schrödinger equation [14] (3):

$$i\hbar\ \partial\psi/\partial t = H\psi \quad (3)$$

where H incorporates quantum fluctuations [15]. Transition to higher dimensionality D occurs via stochastic relaxation (4):

$$\frac{dD}{dt} = -\gamma\left(D - D_{eq}(T)\right) + \xi(t) \quad (4)$$

with $D_{eq}(T) = 1/1 + exp\left((T - T_C)/\Delta T\right), T_C \sim T_{Pl}$ where γ is the relaxation rate and ξ(t) is Gaussian noise representing quantum effects. This formulation is consistent with emergent time scenarios in matrix theory [3].

4. Light as two dimensions (activation of the electromagnetic field)

Photons propagate through 3D space; however, their wavefronts and oscillatory structure can be represented on two-dimensional (2D) manifolds, such as planar wavefronts [16]. Light—understood as electromagnetic radiation—thus serves as a unique messenger capable of probing emergent dimensional structure. Within this hypothesis, treating light as effectively 2D during an early cosmological phase is not contradictory but a logically consistent approximation. When the temperature drops below T_c, a second dimension is activated, permitting electromagnetic wave propagation in an effective (2+1)D regime. In this phase, electromagnetic oscillations exist as wave-like excitations (“pre-photons”) without the full kinematic freedom of three spatial dimensions. Prior to the emergence of fully 3D space, light cannot exhibit complete 3D propagation or interaction, as these require the activation of a third spatial dimension.

De Broglie proposed that all moving particles exhibit wave-like properties [17]. The associated de Broglie wavelength is given by (5):

$$\lambda = h/p \quad (5)$$

This postulate extends wave–particle duality beyond photons to all matter. Because Planck’s constant h is extremely small (6.626×10^{-34} Js), objects with large mass have an associated de Broglie wavelength that is effectively negligible. The CMB, a relic radiation from the early Universe, provides direct insight into conditions shortly after the Big Bang. Analysis of the CMB enables inference of primordial temperature and density fluctuations, offering observational constraints relevant to the proposed dimensional-emergence framework. Visualizing light as a 2D wavefront can further aid understanding of its behavior in different media and clarify the role of electromagnetic radiation in the evolution of the Universe.

When the temperature drops below T_c, a second dimension becomes active, allowing electromagnetic radiation to propagate as a 2D wave. Photons—characterized by the relations E = hf and λ = h/p [17]—can then be described within an effective (2+1)D framework, analogous to reduced-dimensional descriptions used in holographic dualities [18]. In this regime, wave propagation is governed by the 2D wave equation (6):

$$\partial^2\psi/\partial t^2 - c^2\, \partial^2\psi/\partial x^2 = 0 \quad (6)$$

To model dimensional activation, we introduce an effective Lagrangian (7):

$$\mathcal{L} = \int d\tau \left[\frac{1}{2}\left(\frac{dx^u}{d\tau}\right)^2 - m(T) \sum_{i=3}^{D} X^{i2} \quad (7)\right.$$

where m(T) → ∞ at high temperatures suppresses higher-dimensional degrees of freedom [17]. This early 2D electromagnetic phase may leave observable imprints on the CMB, for example through enhanced non-Gaussianity [6].

5. Space as three dimensions

In standard (3+1)D spacetime, electromagnetic waves propagate as fully 3D phenomena, with photons described as massless quanta governed by Maxwell's equations. We propose that, during a brief transitional epoch following the emergence of 1D time but preceding the formation of fully 3D space, light admits an effective 2D description. This interpretation draws on models in which electromagnetism can be consistently formulated in (2+1)D spacetime, such as lower-dimensional effective field theories and analog systems employing temporal modulations to simulate modified light propagation [18]. In this context, plane waves and wavefronts may be visualized and analyzed on 2D manifolds, analogous to ripples on a surface, without requiring a third spatial dimension to exhibit fundamental wave phenomena such as interference and diffraction [16]. This effective 2D phase is consistent with holographic dualities, in which higher-dimensional dynamics, including light-cone structure, are encoded in lower-dimensional theories [18, 19]. In the early Universe, such dimensional reduction may have occurred during the Planck era, when effective dimensionality deviated from asymptotic (3+1)D geometry [20]. The wave–particle duality of light, established by Planck and de Broglie, supports this picture: prior to full spatial expansion, light may have manifested predominantly as a wave-like excitation in a reduced-dimensional substrate, extending into three spatial dimensions as space emerged.

We inhabit a Universe with three spatial dimensions, allowing motion along length, width, and height. As the Universe expanded and cooled, it transitioned into a fully 3D spatial regime, enabling the formation of galaxies and other large-scale structures. The expansion of this 3D space is characterized by Hubble's law (8):

$$v = H_0 D, \quad (8)$$

where v is the recessional velocity of a galaxy, H0 is the Hubble constant, and D is its distance. This relation expresses the approximately linear dependence of recessional velocity on distance in an expanding Universe [21]. This observation reinforces our understanding of the Universe as a 3D spatial expanse. Whitehead argued that both extension (space) and duration (time) are fundamental prerequisites for observation [22]. Physical events require spatial extension and temporal duration, as distinguishing the properties of a location necessarily involves change over time; time thus represents the ordering and flow of events. Because duration is a necessary condition for measurement, it is closely linked to the observable attributes of spatial locations [23]. Within the hypothesis developed here, dimensional emergence proceeds sequentially after the Big Bang: first 1D time, followed by 2D light, and finally 3D space (Figure 1).

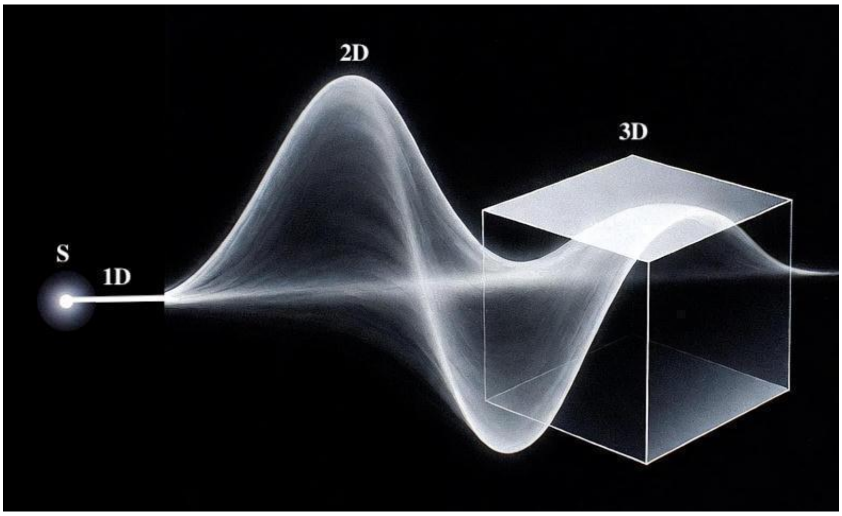

Fig. 1 Schematic sequence of dimensional emergence from the primordial singularity: S, singularity; 1D, one dimension (time); 2D, two dimensions (wave-like light); 3D, three dimensions (space)

Full 3D space emerges at T ~ 10^{28} K, enabling cosmic expansion described by Hubble's law, v = H0D [21]. The spacetime metric then takes the Minkowski form $ds^2 = -c^2 dt^2 + dx^2 + dy^2 + dz^2$. In emergent frameworks such as quantum-information–motivated gravity (QIMG) [7], this transition is attributed to the growth of entanglement entropy. The scale factor a(t) evolves according to an effective potential U(a, D) arising from modified gravity (9):

$$\frac{a'^2}{2} + U(a, D) = -\frac{k}{2} \quad (9)$$

with U minimized at D = 3.

6. Duration of the process

If dimensions emerged as outlined above, this process must have occurred over an extremely short timescale, far beyond direct human intuition. The characteristic timescales associated with electromagnetic phenomena are consistent with this expectation. The oscillation of a light wave is described by its frequency, which is related to the speed of light by the relation c = fλ, where c is the speed of light (approximately 3×10^8 m/s), f is the frequency in hertz, and λ is the wavelength in meters. Consequently, the oscillation frequency of light varies widely depending on wavelength. For visible and higher-frequency radiation, the oscillation period lies in the femtosecond range (10^{-15} s). Even a microsecond therefore encompasses an enormous number of oscillation cycles. Such ultrashort timescales support the idea that dimensional transitions, if governed by quantum and electromagnetic processes, could have occurred rapidly in the early Universe. Within this hypothesis, wave–particle duality becomes physically meaningful only after the emergence of spatial dimensions, when light can propagate and interact in space. Once space forms, the process is no longer temporally bounded in the same sense, as space continues to expand and evolve up to the present epoch.

The stepwise generation of dimensions must occur over an extremely brief interval during the Planck era, the earliest phase of the Universe, spanning from t = 0 to approximately 10^{-43} s (the Planck time). During this epoch, the Universe had a characteristic length scale of the Planck length (about 10^{-35} m) and was dominated by quantum-gravitational effects. This period, often referred to as the quantum gravity era, is expected to unify all fundamental interactions and permits transient departures from classical (3+1)D spacetime, including stepwise dimensional activation. The successive transitions t0 < t1 < t2 are therefore expected to occur extremely rapidly, on timescales comparable to or shorter than the Planck time ($\lesssim 10^{-43}$ s). These durations are vastly shorter than the oscillation periods of electromagnetic radiation, which lie in the femtosecond range. Such rapid transitions are consistent with inflationary and emergent-spacetime scenarios in which effective dimensionality increases sharply at early times. Although the frequency of light is related to its wavelength by c = fλ, in a pre-spatial or pre-geometric phase the relevant dynamics are governed by Planck-scale quantum fluctuations rather than classical electromagnetic waves. Once spatial dimensions emerge, light becomes a propagating degree of freedom exhibiting wave–particle duality within an expanding spacetime, which then continues to evolve up to the present epoch.

Within this framework, all dimensional transitions are confined to the Planck era ($t < 10^{-43}$ s). The effective dimensionality D(t, T) is therefore revised as follows (10):

$$D(t,T) = 3tanh\left(\frac{t-t_0}{\delta t}\right).\frac{1}{1+e^{(T-T_C)/\Delta T}} \quad (10)$$

where $\delta t \sim 10^{-43}$ s provides a smooth transition in time due to quantum effects.

7. Concept

The dimensionality D(t) increases in four discrete stages as time progresses from the initial singularity, with new dimensions “switching on” sequentially in the order 0 → 1 → 2 → 3. We define three transition times (11):

$$t0, t1, t2, with\ t0 < t1 < t2 \quad (11)$$

Before t0, the system has no dimensions to describe dynamics. At t0, the first nontrivial dimension appears, and dynamics begin in 1D time. At t1, a second dimension becomes available, enabling 2D light propagation, and the process continues sequentially. Within this hypothesis of dimensional activation, diffusion provides a clear observable to illustrate the core concept, namely how the scaling of spreading changes as dimensions are added. Diffusion is the process by which particles, energy, or information move from regions of higher concentration to regions of lower concentration due to random motion. In physics, it is typically described by an equation that relates the temporal and spatial evolution of the concentration or field value. The classical diffusion equation is (12):

$$\partial C/\partial t = D\nabla^{2C} \quad (12)$$

where D is the diffusion coefficient, ∇ ^2 is the Laplacian capturing how spatial curvature in C drives the flow, and C represents the concentration or field. In a d-dimensional space, the mean-squared displacement of a random walker typically grows as ⟨x^2⟩ ∝ t (normal diffusion). For a fixed dimension, the relation is ⟨x^2⟩ = 2dDt, where

D is constant for a given medium. In the present toy model with growing dimensionality, we replace the fixed d with a time-dependent effective dimension D(t) and adopt the scaling $\langle x\hat{}2\rangle \propto t\hat{}\{D(t)\}$

Specifically,

$D(t) = 0\ (t \leq t0)$: $\langle x\hat{}2\rangle$ (as no dimensions exist for diffusion)

$D(t) = 1\ (t0 < t \leq t1)$: $\langle x\hat{}2\rangle \propto t$ (corresponding to normal diffusion in a 1D, time-like regime)

$D(t) = 2\ (t1 < t \leq t2)$: $\langle x\hat{}2\rangle \propto\ t\hat{}2$ (representing superdiffusive behavior as light emerges)

$D(t) = 3\ (t > t2)$: $\langle t\hat{}2\rangle \propto t\hat{}3$ (reflecting further amplified spreading in fully 3D space).

In this model, diffusion follows ⟨x^2⟩ ∝ t^{D(t)}, with D(t) defined as a sharp step function (13):

$$D(t) = 0\ for\ t \leq t0, D(t) = 1\ for\ t0 < t \leq t1, D(t) = 2\ for\ t1 < t \leq t2, D(t) = 3\ for\ t > t2. \quad (13)$$

To reconcile this with standard physics while accounting for changing dimensions, the effective dimension is assumed to influence the prefactor and can be integrated over time if D(t) varies (14):

$$\langle x^2\rangle(t) = 2D\int_0^t D(t')dt' \quad (14)$$

The discrete steps can be smoothed using a numerical hyperbolic tangent transition, although the hypothesis emphasizes stepwise jumps (15):

$$D(t) \approx \sum_{k-1}^{3}\frac{1}{2}\left(1 + tanh\ (t - t_{k-1}|\Delta t)\right) \quad (15)$$

where Δt is a small transition width. This approximates the step function while allowing for quantum smoothing in LQG contexts. For the toy diffusion model, the original hypothesis $\langle x^2\rangle \propto t^{d(t)}$ deviates from standard diffusion scaling. In d-dimensional Brownian motion, $\langle r^2\rangle = 2dD$, where D is the diffusion coefficient, and the exponent on t is always 1, with the prefactor scaling with d. In anomalous diffusion, common in early-Universe or fractal models, the exponent α can vary, $\langle r^2\rangle \propto t^\alpha$, with $\alpha > 1$ for superdiffusion. Such behavior has been observed in models of primordial fluctuations during inflation [24].

8. Observational signatures of stepwise dimensional emergence

In 3D space, fundamental elements such as hydrogen or helium exhibit uniform properties across the observable Universe, reflecting the homogeneity enabled by volumetric interactions. Chemical behavior, governed by electromagnetic forces in three dimensions, manifests consistently, underscoring that 3D space constitutes a "complete" framework for matter's structure and behavior. However, time (1D) and light (2D) do not integrate seamlessly with this 3D framework, as evidenced by their anomalous properties.

Time dilation, a well-established prediction of GR, illustrates this mismatch. The proper time τ, experienced in a gravitational field or at relativistic speeds, differs from coordinate time t according to (16):

$$\tau = t\sqrt{1 - \frac{2GM}{rc^2}} \quad (16)$$

where G is the gravitational constant, M is mass, r is radius, and c is the speed of light. This "layering" of time—manifesting as nonuniform temporal flow—suggests that time, as an independently generated dimension, does not perfectly conform to the 3D spatial manifold. If time and space were cogenerated, a uniform temporal progression might be expected; instead, this discrepancy hints at the earlier emergence of time within a dimensional hierarchy.

Similarly, light's wave–particle duality—described by the de Broglie relation $\lambda = h/p$, where h is Planck's constant and p is momentum—reveals its hybrid nature. The wave aspect, propagating as 2D wavefronts, aligns with an earlier dimensional stage, while the particle aspect interacts with 3D matter. This duality implies that light, originating from a 2D regime, retains traces of its origin, thereby resisting full integration into 3D space.

9. Analogies for temperature-dependent dimensional reduction

In theoretical physics, particularly in condensed matter systems and emergent phenomena, several analogies illustrate how temperature variations can influence effective dimensionality or the "dimensional behavior" of a system. These examples provide insightful parallels to the proposed stepwise emergence of dimensions in the early Universe, where high temperatures suppress higher dimensions and cooling activates them sequentially. Below, we explore these analogies, incorporating relevant mathematical formulations for clarity.

1. *Ultrathin Films (e.g., Nickel Films): Temperature-Dependent Dimensional Crossover*

In ultrathin magnetic films, such as nickel, temperature reduction induces a dimensional crossover: at high temperatures, the system behaves as three-dimensional (3D), while at low temperatures, it transitions to two-dimensional (2D) behavior [25, 26]. This is driven by thermal fluctuations affecting the magnetic order parameter exponent [27]. The critical behavior near the transition can be modeled using the Ising model or mean-field approximations, where the effective dimensionality influences the correlation length ξ (17):

$\xi \sim |T - T_c|^{-\nu}$ (17)

with ν being the correlation length exponent, which shifts from ν=0.63 (3D Ising) to ν=1 (2D Ising) as temperature decreases [26]. The crossover temperature T_{cross} marks the point where thermal excitations confine the dynamics to lower dimensions [26].

This analogy mirrors the hypothesis where high T confines the system to lower D (e.g., 1D time), and cooling enables higher-dimensional freedom, akin to stochastic relaxation in Eq. (4):

$$\frac{dD}{dt} = -\gamma \frac{\partial U}{\partial D} + \xi(t)$$

2. *(2+1)D Chern-Simons Gauge Theories: Temperature-Dependent Anomalous Statistics*

In (2+1)-dimensional Chern-Simons gauge theories, which describe particles like anyons in reduced dimensions, the statistics (bosonic/fermionic behavior) become temperature-dependent [28, 29]. At high temperatures, interactions alter the effective particle statistics, effectively modifying the system's dimensional properties through topological order.

The Chern-Simons action is given by (18):

$S = \frac{k}{4\pi} \int A \wedge dA$ (18)

where k is the level parameter, and temperature T introduces thermal effects via the partition function [29] (19):

$Z = \int DA e^{-S/T}$ (19)

High T enhances fluctuations, leading to a regime where effective dimensionality reduces, suppressing higher-degree freedoms [28].

This parallels the 2D light phase in the hypothesis, where electromagnetic fields (similar to Chern-Simons terms) are temperature-suppressed, as in the effective Lagrangian.

3.Scale-Dependent Effective Temperature in Finite and Non-Equilibrium Systems

In statistical physics, effective temperature can be scale-dependent (distance or energy), altering the system's effective dimensions: at high energies (or temperatures), behavior mimics lower D, while at low scales, it approaches higher D [30, 31].

This is captured in renormalization group flows, where the effective dimension D_{eff} evolves with scale μ (20):

$$\beta\left(D = \mu\frac{dD}{d\mu}\right) \quad (20)$$

with temperature entering via thermal corrections [32]. In non-equilibrium systems, effective T_{eff} varies, leading to dimensional reduction at high T [30]. This directly parallels in eq. 10, smoothed by $\delta t \sim 10^{-43} s$, where T drives the transitions.

4.Nonlinear heatwaves: temperature-dependent parameters

In nonlinear heat waves, temperature alters relaxation times and specific heats, effectively changing the propagation's "dimensional" behavior (analogous to optical Kerr effects) [33, 34]. The nonlinear heat equation is (21):

$$\frac{\partial T}{\partial t} = \alpha\nabla^2 T + \beta T^2 \quad (21)$$

where α and β are temperature-dependent coefficients [35]. High T introduces nonlinearities that confine wave dynamics to lower effective dimensions [33]. This resembles the 2D wave equation in the hypothesis (Eq. 6).

These analogies demonstrate that temperature often modulates effective dimensionality in physical systems, offering a robust foundation for extending the stepwise dimensional emergence hypothesis to observable phenomena. They can be further explored through simulations or experiments in condensed matter analogs to test cosmological implications.

10. Stepwise emergence of spacetime: a dynamic dimensional framework reconciling quantum mechanics and GR

The tension between GR and quantum mechanics (QM) is well known. GR describes spacetime as a continuous, malleable fabric warped by mass-energy, while QM introduces discrete, probabilistic fluctuations. At small scales—around the Planck length ($\sim 10^{-35}$ m) [36]—these fluctuations make the direct application of GR equations challenging**.** Instead of imposing QM onto the fixed 4D framework of GR, we allow dimensions to emerge gradually. QM dominates the low-dimensional stages of the proto-Universe, while GR emerges naturally as an effective theory in the fully developed (3+1)D phase. This approach builds on concepts such as the emergence of spacetime from quantum entanglement, where geometry is "woven" from quantum information, and on dynamical dimensionality in cosmology, where the effective dimension increases from approximately 2 near the Planck era to 4 today [13].

The stepwise dimensionality hypothesis provides a novel perspective on quantum gravity: QM establishes the foundational framework, while GR emerges as an achieved, rather than initial, condition.

11. Discussion

The present work offers a phenomenological hypothesis rather than a fully derived dynamical theory. It proposes a simple, integer-valued, discrete sequence of dimensional activation ($0 \rightarrow 1 \rightarrow 2 \rightarrow 3$) that is mathematically natural and consistent with the observed dimensionality of spacetime. The transitions are assumed to occur extremely rapidly ($t \lesssim 10^{-35}$ s), near or within the Planck era ($\sim 10^{-43}$ s), and prior to or during the earliest phases of inflation. At such energies, the effective number of active spatial dimensions need not equal the asymptotic 3+1 geometry that emerges after reheating. Modern inflationary models allow transient departures from 4D spacetime. Accordingly, this hypothesis introduces no conflict with the observational successes of standard cosmology, replacing a single instantaneous or continuous dimensional fixing with two ultra-rapid discrete steps. Several independent lines of research provide indirect support for aspects of this approach:

- Holographic duality demonstrates that higher-dimensional bulk dynamics, including gravitational and light-cone structures, can be encoded exactly in lower-dimensional boundary theories [18, 19] .
- Analog gravity and photonic systems with temporal modulation can simulate effective extra dimensions and altered light propagation [20].
- Entanglement-based geometric reconstructions show that a 3D causal structure can emerge from a 2D substrate [19].

- The 2021 STAR Collaboration observed the Breit–Wheeler process ($\gamma\gamma \rightarrow e^+e^-$) using linearly polarized high-energy photons, providing experimental evidence that photons can generate matter without pre-existing 3D localization, consistent with light having an independent ontological status prior to full 3D space activation [37].

The concept of the Big Crunch—a reverse Big Bang—has been discussed by several physicists and cosmologist [38-40], suggesting that the Universe could eventually collapse back into a singularity. As expansion slows and gravity dominates, contraction may ensue. Within this context, the hypothesis proposes the following sequence for the disappearance of dimensions during a reverse Big Bang. As contraction begins, spatial dimensions would collapse first. Objects would lose their spatial separation, distances would compress, and the Universe would become increasingly dense, ultimately merging all locations into a smaller volume. The behavior of light would also be affected: wavelengths could shift dramatically, producing extreme redshift or blueshift, and in the extreme limit, light may effectively disappear from the diminishing space. As contraction continues toward the singularity, the nature of time itself may alter. The flow of time could slow dramatically or become nonlinear, and conventional distinctions between past, present, and future might collapse, rendering time indistinguishable or nonfunctional as a dimension. In this reverse Big Crunch scenario, the disappearance of dimensions would occur in the reverse order of their emergence: first space, then light, and finally time. Black holes provide valuable analogs for studying singularities, offering insights relevant to the sequential emergence of dimensions. Their singularities resemble those of the Big Bang and Big Crunch, with event horizons where time and space effectively interchange [39].

12. Conclusion: This framework offers a paradigm shift in our understanding of the Universe's dimensional structure. By emphasizing the sequential relationships among singularity, time, light, and space, it opens new avenues for research in theoretical physics, cosmology, and fundamental forces. The hypothesis suggests that time (1D) first emerged from the 0D singularity following the Big Bang, followed by light (2D) and, finally, fully extended space (3D). This perspective may provide novel insights into black holes, the early Universe, and the emergence of physical laws.

13. Limitations: Although this hypothesis provides a novel framework for reconciling quantum mechanics and general relativity through stepwise dimensional emergence, it remains phenomenological and lacks a fully derived dynamical theory. For instance, the stochastic relaxation mechanism (Eq. 4) and effective Lagrangians (Eq. 7) are introduced as approximations, but their microscopic origins from quantum gravity remain speculative.

Additionally, while observational tests via CMB non-Gaussianity and gravitational waves are proposed, these signatures are not unique to this model and could be explained by alternative inflationary scenarios. The temperature-dependent transitions (Eq. 10) are motivated by analogies in condensed matter physics, but direct empirical evidence from Planck-era conditions is currently inaccessible due to technological limitations. Finally, as an interdisciplinary approach drawing from medical perspectives on emergent systems, the model may benefit from further collaboration with theoretical physicists to enhance mathematical rigor. Future work could address these limitations by developing detailed simulations of dimensional activation and comparing predictions with upcoming data from missions like LISA or advanced CMB experiments.

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