Emergent Spacetime from a Three-Dimensional Elastic Substrate

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Abstract

We propose a framework in which spacetime, gravity, and cosmology arise as emergent phenomena from a condensed elastic phase of a deeper substrate. The substrate is assumed to admit a minimal three-dimensional arena but lacks geometric, causal, or metric structure. Its fundamental degrees of freedom are strand-like objects that are operationally one-dimensional in the sense that they support only a single internal vibrational degree of freedom.

A tachyonic instability drives condensation of these degrees of freedom into a frozen, disordered network of nodes and links. This network constitutes the microscopic spacetime lattice. Geometry emerges as a coarse-grained bookkeeping field describing the elastic response of this lattice to stress, while gravitational dynamics correspond to collective shear modes of the network. Disorder generically localizes or gaps scalar and vector excitations of the network, preventing them from forming long-range, gapless collective modes without fine tuning. By contrast, transverse–traceless shear modes remain structurally robust against disorder, allowing them to dominate the infrared dynamics and reproduce general relativity as an effective universality class.

The Planck scale is reinterpreted as a critical strain threshold beyond which the condensed spacetime phase fails and reverts locally to the substrate. Black holes correspond to regions where tidal strain exceeds this threshold, producing a phase boundary rather than a singularity. Information is preserved through transfer to substrate and interface degrees of freedom. Cosmological features such as inflation, homogeneity, and late-time acceleration arise naturally from global condensation, phase ordering, and residual elastic relaxation.

The framework emphasizes mechanical consistency and minimal assumptions over microscopic completeness, and it identifies concrete directions for numerical, observational, and theoretical tests.

Contents

1 Introduction and Motivation

1.1 Why spacetime should not be fundamental

General relativity describes gravity as the curvature of spacetime rather than as a force acting within spacetime. While extraordinarily successful, this geometric description raises a persistent conceptual tension: spacetime is treated simultaneously as the arena of physics and as a dynamical entity. In contrast, every other known effective theory describes dynamics as occurring *within* a medium or structure.

Multiple independent lines of evidence suggest that spacetime itself may be emergent rather than fundamental. Black hole thermodynamics implies that geometry carries entropy and temperature, properties characteristic of coarse-grained systems rather than fundamental degrees of freedom. Holographic dualities relate bulk geometry to lower-dimensional non-geometric data. Analogue gravity models demonstrate that effective metrics arise generically from collective excitations of condensed matter systems.

Operational realism. General relativity is empirically successful precisely because it treats spacetime geometry as a physically instantiated structure that determines causal relations and signal exchange. Whether this structure is fundamental (ontologically primitive) or emergent from deeper degrees of freedom is a question GR deliberately leaves unanswered; however, the existence of universal gravitational time dilation, redshift, and horizon behavior raises the question of whether the metric field can be 'nothing' in any literal or operational sense. In this work we adopt the conservative stance that, whatever its ultimate ontology, spacetime must be physically realized by some underlying structure. We then explore a minimal physically instantiated substrate framework as one concrete realization of this possibility, reproducing general relativity as its infrared effective description.

Taken together, these considerations motivate the hypothesis that spacetime may be understood as a macroscopic phase of a deeper microscopic system.

1.2 Empirical pressures on spacetime ontology

General relativity provides an extraordinarily successful dynamical description of spacetime geometry, while remaining deliberately noncommittal regarding the ontology of spacetime itself. The metric field is treated as fundamental within the theory, but no account is given of whether spacetime is purely abstract, physically instantiated, or emergent from deeper degrees of freedom.

Nevertheless, several independent empirical features of gravitational physics exert growing pressure on the interpretation of spacetime as a merely abstract arena.

First, gravitational time dilation is universal: all physical clocks, regardless of composition, slow identically in gravitational fields. This universality is difficult to reconcile with a purely relational or bookkeeping interpretation of time and instead suggests that the causal structure itself undergoes physical modification.

Second, proper acceleration is an invariant, physically felt quantity. An observer deviating from geodesic motion experiences internal stress independent of coordinates or reference frames. While general relativity correctly encodes this as non-geodesic motion, the universality of the effect suggests that spacetime possesses a physically instantiated structure capable of supporting invariant dynamical response.

Third, black holes exhibit thermodynamic behavior, including entropy proportional to area and temperature proportional to surface gravity. More recently, observational and theoretical considerations suggest the existence of upper bounds on stable black hole masses under realistic astrophysical conditions. The existence of such absolute limits is naturally interpreted if spacetime possesses finite structural tolerance, rather than being an arbitrarily extensible geometric manifold. A concrete realization of this idea is developed in Sections 7 and 8.

Fourth, the observed dimensionality and internal structure of matter exhibit features that are difficult to motivate if spacetime is treated as a purely abstract stage. The existence of exactly three large spatial dimensions, together with discrete fermion families and internal quantum numbers, is naturally suggestive of underlying structural constraints rather than arbitrary labeling. While these features do not uniquely determine the microphysical nature of spacetime, they are more readily understood if matter and geometry arise from a common physical substrate.

Finally, cosmology presents a striking boundary condition: spacetime itself appears to originate in the early universe. The Big Bang is not merely an event within spacetime, but a transition after which spacetime, causal structure, and metric relations become well-defined, as developed further in Section 9. This strongly suggests that spacetime is not eternal or primitive, but arises through a physical process.

Taken together, these considerations do not invalidate general relativity, nor do they uniquely determine the microphysical nature of spacetime. They do, however, strongly motivate the view that spacetime is physically instantiated and may be emergent from deeper, non-geometric degrees of freedom. The framework developed in this work is intended as one concrete realization of this possibility.

1.3 The failure of point-based microstructure

If spacetime is emergent, its microstructure must be capable of locking into stable extended configurations. A key mechanical observation motivates the present approach:

> *Point-like degrees of freedom cannot lock into a rigid extended structure.*

Points admit no internal extension, no elastic compliance, and no mechanism for collective rigidity. Any attempt to build spacetime from point-like constituents requires additional structure to be imposed by hand.

By contrast, extended objects can interlock, transmit strain, and support collective modes. This immediately suggests that any viable microscopic substrate for spacetime must be extended rather than point-like.

Origin of extended structures. We emphasize that extended strand-like degrees of freedom are not assumed to be fundamental constituents of the substrate. Rather, they arise as the mechanically unavoidable residue of a rapid condensation process acting on initially uncorrelated degrees of freedom. Prior to condensation, these degrees of freedom carry no internal relational extent and may be described as point-like in this limited, pre-geometric sense. During a quench driven by an instability, such unstructured degrees of freedom generically develop extended correlations before freezing. Only these extended correlations are capable of interlocking, transmitting shear, and supporting a rigid emergent phase. The detailed growth dynamics of this process are not required for the arguments that follow; what matters is that extended structures necessarily arise prior to locking, and these structures constitute the effective degrees of freedom of the condensed spacetime phase.

1.4 Dimensional minimality and strand-like degrees of freedom

The observed gravitational sector is remarkably minimal: a single massless spin-2 field with two propagating polarizations and universal coupling. Any microscopic model that naturally reproduces this structure must severely restrict its degrees of freedom.

This motivates a principle of dimensional minimality: the fundamental objects should admit as few internal dynamical modes as possible while remaining extended. Strand-like objects that are operationally one-dimensional satisfy this requirement. They admit internal extension necessary for locking, while supporting only a single relevant internal vibrational degree of freedom.

In this framework, spacetime does not emerge *on top of* the substrate. Rather, it emerges *as* a collective configuration of the substrate itself.

1.5 Why a three-dimensional substrate arena

While the fundamental strands are operationally one-dimensional, the substrate is assumed to admit a minimal three-dimensional arena. This is not a geometric space in the usual sense: it carries no metric, no causal structure, and no notion of distance. It merely provides the capacity for extended configurations and mechanical failure to occur physically rather than abstractly.

This assumption is motivated by physical consistency. Phenomena such as spaghettification, elastic rupture, and strain localization are not meaningful in a purely non-dimensional setting. A three-dimensional arena is the minimal physical assumption that allows such processes to be interpreted mechanically.

Importantly, this three-dimensional substrate is *not* spacetime. Temporal ordering, invariant signal speeds, and causal structure emerge only after condensation, as collective properties of the stable phase.

1.6 The emergence of the "+1" dimension

Time is not introduced as an additional spatial coordinate. Instead, it emerges as the ordering structure associated with stable propagation in the condensed phase. Once the spacetime lattice forms, characteristic signal speeds, causal cones, and relativistic time dilation become well-defined.

In this sense, the "+1" dimension of spacetime is not fundamental but emergent, arising from the collective dynamics of a phase that supports coherent propagation.

1.7 Outline of the paper

This paper develops the framework as follows:

- Section 2 defines the substrate degrees of freedom and their minimal dynamics.
- Section 3 analyzes tachyonic condensation and lattice formation.
- Section 4 derives emergent elasticity and geometric response.
- Section 5 demonstrates the survival of the transverse–traceless gravitational sector.
- Section 6 discusses matter as defects and topological structures.
- Section 7 reinterprets the Planck scale as critical strain.
- Section 8 develops the black hole phase-boundary picture.
- Section 9 outlines cosmological implications.

Throughout, the emphasis is on mechanical plausibility, minimal assumptions, and structural consistency rather than microscopic completion.

2 Substrate Degrees of Freedom and Minimal Dynamics

2.1 Minimal physical assumptions

We begin by specifying the minimal assumptions placed on the underlying substrate. These assumptions are deliberately weak, as the goal is not to fully specify a microscopic theory, but to identify the minimal structure required for spacetime emergence.

The substrate is assumed to:

- admit a three-dimensional arena in which extended configurations can exist,
- lack any pre-existing metric, causal structure, or notion of distance,
- lack any notion of inertial rest or preferred reference frame,
- support extended degrees of freedom capable of mechanical locking.

Crucially, the substrate does *not* possess spacetime structure. Temporal ordering, invariant speeds, and geometry are not assumed but must arise dynamically.

The microscopic origin of the substrate degrees of freedom is not specified at the level of this effective description. A retrodictive pre-geometric consistency analysis outlining one possible grounding for these assumptions is provided in Appendix D; none of the results derived in this work depend on that construction.

Prior to condensation, the substrate supports ubiquitous, rapidly fluctuating degrees of freedom with no stable localization, coherence, or causal ordering. These fluctuations are physically real but exist only as potential excitations, lacking any mechanism for stable propagation or geometric interpretation. The condensation (quench) does not eliminate this activity; instead, it freezes extended correlations out of it, converting unstructured dynamical content into a mechanically rigid, interconnected network capable of supporting coherent modes.

2.2 Pre-locality of the substrate

A common source of confusion in emergent-spacetime models concerns the apparent nonlocality of the underlying substrate. In the present framework, this nonlocality does not reflect superluminal propagation or violation of causality, but rather the absence of geometric structure itself. Locality is a property of spacetime, not a prerequisite for its emergence.

Prior to condensation, the substrate possesses no metric, no notion of spatial separation, and no operational definition of distance or delay. Consequently, substrate interactions are not constrained by geometric locality because no such locality exists. Once the condensed spacetime phase forms, elastic response defines effective distances, invariant propagation speeds, and causal structure, thereby enforcing locality as an emergent constraint rather than a fundamental principle.

2.3 Operationally one-dimensional strand degrees of freedom

The fundamental degrees of freedom are taken to be strand-like objects. These objects need not be mathematically one-dimensional in the sense of zero transverse extent; rather, they are *operationally one-dimensional*. This means that, at the level relevant for long-range dynamics, each strand supports only a single internal vibrational degree of freedom.

We parameterize each strand by an internal coordinate σ labeling its contour and introduce a scalar amplitude field

$$q(\sigma, t), \tag{1}$$

which represents the only dynamically relevant internal excitation.

No transverse oscillation modes are assumed to survive at the substrate level. Any additional internal structure is assumed to be gapped, localized, or dynamically irrelevant for collective behavior. This restriction plays a central role in suppressing unwanted low-energy modes in the emergent phase.

2.4 Why a single internal mode is enforced

The restriction to a single internal mode is not imposed arbitrarily. It follows from the combination of dimensional minimality and the absence of an embedding geometry.

In higher-dimensional extended objects, instabilities may relax through multiple channels, including transverse deformations or rotations. By contrast, a strand-like object without a background metric admits no distinguished transverse directions. In such a setting, the only available local response to instability is variation along the strand itself.

Thus, even if the strand possesses microscopic thickness, its collective dynamics reduce to a single scalar amplitude mode at long wavelengths.

2.5 No static substrate configurations

A natural question arises: why do the strands vibrate at all, rather than remaining static prior to condensation?

The answer is structural. In the absence of a background spacetime, there is:

- no notion of equilibrium configuration,
- no preferred rest state,
- no geometric criterion for stability.

We model this by assuming that the effective potential governing the amplitude field q is unstable at the origin. The simplest such assumption is a tachyonic instability,

$$V(q) = -\frac{1}{2}\mu^2 q^2 + \frac{\lambda}{4} q^4, \tag{2}$$

with $\mu^2 > 0$ and $\lambda > 0$. The configuration $q = 0$ is dynamically unstable, while finite-amplitude configurations are stabilized by nonlinear effects. No relativistic interpretation is implied; the instability is strictly classical and mechanical, analogous to spinodal decomposition or symmetry-breaking quenches in condensed-matter systems.

This does not imply superluminal propagation or exotic causality. The term "tachyonic" is used strictly in the condensed-matter sense of an instability about an unphysical configuration.

2.6 Toy substrate Hamiltonian

To make the discussion concrete, we introduce a schematic Hamiltonian for the substrate degrees of freedom:

$$H_{\text{sub}} = \sum_a \int d\sigma \left[\frac{1}{2}\pi_a^2 + \frac{1}{2}(\partial_\sigma q_a)^2 - \frac{1}{2}\mu^2 q_a^2 + \frac{\lambda}{4} q_a^4 \right] + \sum_{a \neq b} \int d\sigma d\sigma' \, J_{ab}(\sigma, \sigma') q_a(\sigma) q_b(\sigma'). \tag{3}$$

Here:

- a labels strands,
- π_a is the conjugate momentum to q_a,
- J_{ab} encodes interactions between strands.

The precise form of J_{ab} is left unspecified. It may be local or nonlocal in σ, random or structured. The only requirement is that it permits cooperative behavior among strands during condensation.

This Hamiltonian should be understood as a toy model, intended to make the instability and interaction structure explicit rather than to define a complete microscopic theory. This Hamiltonian is intended solely as a qualitative generator of condensation and mode locking, not as a proposed fundamental or unique microscopic theory.

2.7 Collective instability and condensation

The tachyonic term drives exponential growth of amplitude fluctuations. As the amplitudes grow, nonlinear saturation becomes important. Regions of large amplitude effectively “lock” strands together through the interaction term, while regions of smaller amplitude remain flexible.

This separation naturally leads to the formation of:

- high-amplitude, mechanically rigid regions (nodes),
- lower-amplitude, tension-bearing connections (links).

The resulting configuration is a frozen, disordered network. This network constitutes the microscopic spacetime lattice.

Although the condensed spacetime lattice is formed from frozen strand-like degrees of freedom, not all such degrees of freedom need terminate in fully closed or mutually paired configurations. Generic condensation in a disordered extended system permits localized excitations with finite spatial extent whose internal connectivity differs from that of the bulk lattice. Such excitations are neither point-like nor freely propagating substrate modes, but partially bound configurations embedded within the condensed phase. Their finite extent provides a natural mechanical basis for localization, inertia, and stability without introducing additional fundamental fields or violating emergent Lorentz symmetry.

Importantly, the lattice is not imposed externally. It is generated dynamically by the substrate’s own instability and saturation dynamics.

2.8 Universality from non-local pre-geometry

Prior to condensation, the substrate admits no geometric notion of locality, distance, or adjacency. As a result, the instability driving spacetime formation acts globally rather than regionally: there exists no mechanism by which different portions of the substrate could independently select inequivalent macroscopic phases. With a single species of extended degree of freedom and a single dominant quench, the system possesses only one relevant direction in its instability space.

While many microscopic realizations of the condensed network may exist, they are nevertheless expected to flow toward the same infrared universality class. The robustness of the emergent spacetime phase therefore arises not from fine-tuned microstructure, but from the absence of pre-geometric locality itself, which suppresses fragmentation of outcomes prior to condensation.

This same universality mechanism constrains the long-wavelength excitation spectrum of the condensed phase, strongly favoring a unique transverse–traceless shear sector while rendering scalar and vector modes non-propagating at macroscopic scales.

2.9 Emergent ordering and the origin of time

Once a stable network forms, it supports coherent propagation of collective excitations. Only at this stage does it become meaningful to introduce an ordering parameter that functions as time.

Time, in this framework, is not a background dimension but an emergent ordering associated with stable propagation in the condensed phase. Operational time in the condensed phase is defined via Einstein synchronization (radar time) using the emergent massless sector, while the microscopic evolution parameter of the substrate plays no direct observational role. The “+1” dimension of spacetime thus arises from the collective dynamics of the lattice rather than being fundamental.

This perspective also clarifies the interpretation of gravitational time dilation and the behavior of atomic clocks. Atomic clocks do not directly measure spacetime intervals themselves, nor do their internal atomic processes physically “slow down” in a dynamical sense. Rather, an atomic transition provides a stable internal reference process whose completion is counted relative to the surrounding causal structure. In regions of greater spacetime strain, such as deeper gravitational potentials, the condensed lattice undergoes a higher density of microscopic reconfigurations between successive signal exchanges, so that the same atomic process is registered as taking longer when compared against external clocks. Conversely, in regions where spacetime is more weakly strained, fewer underlying reconfigurations occur, and identical atomic processes complete with fewer effective ordering steps. Time dilation therefore reflects changes in the structure of causal ordering supported by the spacetime medium itself, rather than changes in the intrinsic dynamics of matter.

Within this framework, inertial mass is interpreted not as an intrinsic substance but as a measure of the resistance of matter's internal defect structure to reconfiguration as spacetime evolves. The Higgs field sets a universal stiffness scale governing how readily such defect configurations can reorganize, while gravitational strain modifies the local density of spacetime reconfigurations themselves. Operationally, time dilation reflects the combined bookkeeping cost of matter reconfiguration against this stiffness and geometric strain, rather than a change in any underlying microscopic clock rate.

Conceptual lineage. The present framework may be viewed as a physical completion of the operational foundations implicit in general relativity. Einstein defined spacetime geometry through the behavior of idealized rods and clocks, which served as primitive, extended standards for distance and duration without a microscopic account of their constitution. In this sense, rods and clocks functioned as placeholders for an underlying physical structure capable of sustaining extension, deformation, and causal ordering. The elastic substrate proposed here plays an analogous role at a deeper level: it provides a concrete physical mechanism from which rods, clocks, and geometric relations emerge as collective, macroscopic properties. This perspective does not modify general relativity in its domain of validity, but instead addresses the prior question of what physical substrate must exist for Einstein's operational notions of geometry and time to be well-defined at all.

2.10 Scope and limitations

At this stage, no claim is made that the Hamiltonian above is unique or complete. Many microscopic realizations may lead to the same emergent behavior. The emphasis is on identifying a minimal and mechanically consistent route from a non-geometric substrate to an extended, elastic, spacetime-like phase.

In subsequent sections, we show how the elastic response of this lattice leads naturally to emergent geometry and gravitational dynamics in the infrared.

3 Condensation, Lattice Formation, and Coarse-Graining

3.1 From unstable substrate to frozen network

Following the tachyonic instability described in Section 2, the substrate undergoes a rapid amplification of amplitude fluctuations. As nonlinear saturation sets in, the system dynamically separates into regions of distinct mechanical character.

Let $\langle q_a(\sigma)\rangle$ denote the coarse-grained amplitude of strand a along its contour. Regions where

$$|\langle q\rangle| \sim q_0 \equiv \mu/\sqrt{\lambda} \tag{4}$$

form mechanically rigid clusters due to nonlinear self-stabilization. These clusters act as effective nodes. Regions where $|\langle q\rangle$ remains smaller act as deformable connectors between nodes.

This process is analogous to phase separation in condensed matter systems, but here it occurs in a setting without pre-existing geometry. The result is a disordered, frozen network that supports elastic stress.

3.2 Node–edge decomposition

At scales large compared to the microscopic strand spacing, the condensed configuration admits a natural graph-theoretic description. We introduce a set of nodes $\{i\}$ corresponding to locally rigid clusters and a set of edges $\langle ij \rangle$ corresponding to collections of strands that connect nodes i and j.

Each edge is characterized by an effective stiffness k_{ij} and a rest configuration inherited from the frozen substrate. The precise connectivity is disordered and history-dependent, reflecting the non-equilibrium nature of the condensation process.

The key point is that the graph is not imposed by hand; it emerges dynamically as the mechanically stable configuration of the substrate.

3.3 Effective elastic energy

Once the network has frozen, its low-energy excitations are described by small deformations of node positions. Let $\mathbf{x}_i$ denote the coarse-grained position of node i in the emergent description. The leading-order elastic energy takes the schematic form

$$E_{\text{el}} = \frac{1}{2} \sum_{\langle ij \rangle} k_{ij} \left(|\mathbf{x}_i - \mathbf{x}_j| - \ell_{ij} \right)^2 , \tag{5}$$

where ℓ_{ij} is the rest separation associated with edge $\langle ij \rangle$.

Importantly, $\mathbf{x}_i$ should not be interpreted as coordinates in a pre-existing space. They are bookkeeping variables that parameterize the configuration of the condensed network. Geometry emerges only at the level of collective response.

3.4 Continuum limit and coarse-grained fields

At scales much larger than the typical node separation, the discrete network admits a continuum description. We introduce a displacement field $\mathbf{u}(\mathbf{x})$ describing deviations from a reference configuration.

Expanding the elastic energy to leading order in gradients yields

$$E_{\text{el}} \approx \int d^3x \left[\lambda (\nabla \cdot \mathbf{u})^2 + 2\mu \, u_{ij} u^{ij} \right] , \tag{6}$$

where

$$u_{ij} = \frac{1}{2} (\partial_i u_j + \partial_j u_i) \tag{7}$$

is the strain tensor, and λ and μ are effective Lamé coefficients determined by the statistics of k_{ij} and ℓ_{ij}.

This is the standard form of the elastic energy for an isotropic solid, emerging here without assuming any underlying metric structure.

3.5 Emergent geometry as elastic bookkeeping

In the emergent description, the strain tensor plays the role of a metric perturbation. We identify

$$g_{ij} = \delta_{ij} + h_{ij}, \qquad h_{ij} \sim u_{ij}. \tag{8}$$

This identification should be understood operationally: the metric is a bookkeeping device that encodes how distances and angles respond to stress. It does not represent an independently existing geometric field.

Curvature arises from inhomogeneous strain, while flat regions correspond to relaxed configurations of the network.

3.6 Disorder and mode localization

The emergent lattice is intrinsically disordered. The stiffnesses k_{ij} and rest lengths ℓ_{ij} vary throughout the network, reflecting the non-equilibrium condensation history.

Disorder plays a crucial role in shaping the low-energy spectrum. Well-established results from the physics of amorphous solids and random lattices show that disorder tends to localize scalar and vector modes through mechanisms analogous to Anderson localization.

As a result, compressional and rotational modes acquire gaps or become spatially localized, while the transverse–traceless shear sector remains the only structurally stable, extended collective excitation capable of surviving to long wavelengths without fine tuning.

(See Appendix A for a minimal disordered-network mode study illustrating localization and a TT-like shear-dominated subset using simple kinematic proxies.)

3.7 Survival of collective shear modes

By contrast, collective shear modes are robust against disorder. These modes correspond to transverse, traceless distortions of the network that preserve local volume while redistributing stress.

At long wavelengths, these shear modes dominate the spectrum of extended excitations. Their dynamics are governed by an effective wave equation whose form is fixed by symmetry and elasticity:

$$\partial_t^2 h_{ij}^{\mathrm{TT}} - c_T^2 \nabla^2 h_{ij}^{\mathrm{TT}} = 0, \tag{9}$$

where h_{ij}^{TT} denotes the transverse–traceless component of the strain field and c_T is an emergent propagation speed. Here and throughout, "transverse–traceless" refers to the infrared, continuum-effective characterization of these modes; at the microscopic network level they are identified through kinematic proxies rather than exact tensor representations.

This equation anticipates the emergence of a massless spin-2 sector in the infrared.

This robustness of the transverse–traceless sector against disorder provides the structural reason why gravity emerges uniquely as a massless spin–2 interaction in the infrared.

3.8 Emergence of causal structure

Once coherent shear modes propagate, the network acquires a preferred notion of causal ordering. The propagation speed c_T defines an effective light cone, while temporal ordering becomes meaningful only within the condensed phase.

Thus, causality is not fundamental but emergent, arising from the collective dynamics of the elastic network.

Because signal propagation occurs through disorder-averaged collective elastic response rather than along fixed bonds or coherent lattice directions, microscopic orientation and connectivity do not survive coarse-graining, eliminating any preferred directions in the infrared.

Emergence of a unique causal structure. Although the substrate admits no pre-existing notion of time, signal speed, or causal ordering, the condensed phase generically selects a single effective causal structure at long wavelengths. At the microscopic level, multiple proto-propagation channels and local ordering relations may exist within the disordered lattice. However, coarse-graining and disorder suppress all but one coherent, gapless collective mode capable of percolating across the entire network. This surviving mode defines a universal propagation speed and an associated light-cone structure in the infrared. In this sense, the observed uniqueness of relativistic causality is not imposed as a fundamental assumption but emerges as a global stability property of the condensed spacetime phase. Residual violations associated with lattice microstructure are expected to be strongly suppressed by the ratio of the lattice scale to observational scales, placing them well below current experimental bounds.

This mechanism is directly analogous to emergent Lorentz symmetry in condensed-matter systems, where microscopic lattice anisotropies appear as irrelevant operators at the infrared fixed point and are dynamically washed out at long wavelengths.

3.9 Summary

Tachyonic condensation of the substrate produces a frozen, disordered node–edge network. Once condensation occurs, the substrate does not remain as a separate or external arena beneath spacetime; rather, the spacetime phase exhausts the available substrate degrees of freedom, with only localized regions of failure or reactivation appearing where elastic stability is lost. Coarse-graining this network yields an elastic medium whose long-wavelength response is described by strain fields. Disorder suppresses unwanted modes, while robust transverse–traceless shear modes remain extended and gapless.

In the next section, we show how these shear modes reproduce the dynamical content of general relativity in the infrared.

4 Emergent Gravitational Dynamics and the Einstein–Hilbert Limit

4.1 From elastic response to dynamical geometry

In Section 3 we showed that the condensed substrate admits a continuum description as an elastic medium, with transverse–traceless shear modes propagating over a disordered lattice. We now show how this elastic description reproduces the dynamical structure of gravity in the infrared.

The central conceptual move is the following:

> *Gravity is not a fundamental interaction added to spacetime; it is the dynamical response of spacetime itself, viewed as an elastic medium, to stress and strain induced by excitations embedded within it.*

This identification places the theory squarely within the tradition of induced and emergent gravity, while providing a concrete microscopic origin for the elastic degrees of freedom.

4.2 Universal coupling to strain

All excitations that persist in the condensed phase—defects, twist modes, and coherent wave packets—are constructed from the same node–edge network. As a result, they necessarily couple to the same strain field u_{ij}.

This implies a form of universal coupling:

$$\delta S_{\text{matter}} = \frac{1}{2} \int d^4x \, T^{ij} \, h_{ij}, \tag{10}$$

where T^{ij} is the effective stress–energy tensor associated with matter excitations, and h_{ij} is the emergent metric perturbation.

The equivalence principle is therefore not imposed as a postulate; it arises because all physical excitations are made *of* the same medium whose strain defines geometry. At leading order, any excitation whose stability and propagation depend on the elastic response of the same condensed network necessarily couples through the same strain channel. Species-dependent couplings would require additional, independent order parameters or microstructure beyond the minimal substrate assumed here.

4.3 Effective action for the shear sector

To determine the long-wavelength dynamics of the strain field, we integrate out microscopic degrees of freedom below the coarse-graining scale. The resulting effective action for the transverse–traceless sector takes the schematic form

$$S_{\text{eff}}[h^{\text{TT}}] = \int d^4x \left[\frac{1}{2} (\partial_t h_{ij}^{\text{TT}})^2 - \frac{c_T^2}{2} (\partial_k h_{ij}^{\text{TT}})(\partial^k h_{ij}^{\text{TT}}) + \cdots \right], \tag{11}$$

where the ellipsis denotes higher-order derivative and nonlinear terms.

At energies well below the condensation scale, these corrections are strongly suppressed.

4.4 Emergence of diffeomorphism invariance

Although the underlying lattice breaks continuous symmetries explicitly, its long-wavelength response exhibits an approximate redundancy under smooth reparameterizations of the displacement field.

Because all long-lived excitations are constructed from the same condensed medium and propagate through the same elastic response channel, the infrared fixed point necessarily exhibits a single effective causal cone shared by all species.

This redundancy plays the role of emergent diffeomorphism invariance. Infinitesimal transformations of the form

$$h_{ij} \to h_{ij} + \partial_i \xi_j + \partial_j \xi_i \tag{12}$$

leave physical observables invariant at leading order in the infrared.

Crucially, this symmetry is not exact at the microscopic level. It is a collective property of the coarse-grained elastic response, becoming increasingly accurate at large scales.

4.5 Infrared uniqueness of the linearized spin–2 sector (derivation sketch)

At wavelengths large compared to the lattice scale, the surviving extended sector is well described by a symmetric perturbation field $h_{\mu\nu}$ built from the coarse-grained strain degrees of freedom. The transverse–traceless (TT) content identified in Section 3 then corresponds to the propagating part of a massless spin–2 field in the infrared.

A key structural point is that the infrared redundancy $h_{\mu\nu} \to h_{\mu\nu} + \partial_\mu \xi_\nu + \partial_\nu \xi_\mu$ together with locality and a two-derivative expansion strongly constrains the effective action. Up to field redefinitions and an overall normalization, the unique ghost-free quadratic action compatible with this redundancy is the Fierz–Pauli (linearized Einstein) action. Varying this action yields the linearized Einstein equations for $h_{\mu\nu}$, with only two propagating TT polarizations and with sources entering through a conserved $T_{\mu\nu}$.

In this sense, the claim that the long-wavelength gravitational sector lies in the general-relativistic universality class can be sharpened to the statement that the infrared fixed point is governed by the unique massless spin–2 quadratic theory, with nonlinear completion expected once higher-order terms of the elastic response are included.

4.6 Induced Einstein–Hilbert term

Following Sakharov's induced gravity logic, integrating out matter and high-frequency strain fluctuations is expected to generate an effective action for the emergent metric field. The leading generally covariant term in a local derivative expansion is the Einstein–Hilbert action:

$$S_{\text{EH}} = \frac{1}{16\pi G_{\text{eff}}} \int d^4x \sqrt{-g}\, R, \tag{13}$$

where R is the Ricci scalar constructed from the emergent metric $g_{\mu\nu}$.

In the present framework, the effective Newton constant G_{eff} is not fundamental. It is determined by:

- the elastic moduli of the condensed network,
- the density of microscopic degrees of freedom,
- and the cutoff scale at which the continuum description fails.

This reinterpretation demotes the Planck scale from a fundamental input to a derived critical scale of the medium.

4.7 Einstein equations as constitutive relations

Varying the leading effective action with respect to $g_{\mu\nu}$ yields field equations of Einstein form in the regime where higher-derivative and nonlinear corrections are negligible,

$$G_{\mu\nu} = 8\pi G_{\text{eff}} T_{\mu\nu}, \tag{14}$$

which should be understood not as fundamental field equations, but as constitutive relations governing the response of the medium to stress.

In this sense, curvature plays the same role as strain in elasticity: it encodes how the underlying structure responds to applied loads.

4.8 Limitations and regime of validity

The derivation above is valid only within the stable condensed phase. Near regions of extreme strain—such as black holes or the early universe—the continuum elastic description breaks down.

Higher-order corrections, anisotropies, and nonlocal substrate effects become important in these regimes. These deviations are not pathologies but signals that the geometric description is no longer appropriate.

4.9 Summary

The frozen substrate network behaves as an elastic medium whose transverse–traceless shear modes acquire universal coupling to embedded excitations. Coarse-graining and induced dynamics yield an effective Einstein–Hilbert action in the infrared, with Newton's constant emerging as a derived parameter.

We note that standard no-go results concerning emergent massless spin–2 excitations (notably the Weinberg–Witten theorem) rely on assumptions such as exact microscopic Lorentz invariance and the existence of a Lorentz-covariant, conserved stress–energy tensor for the fundamental degrees of freedom. In the present framework, these assumptions need not hold at the substrate level. Lorentz symmetry arises only as an infrared emergent property, and the metric field itself is not a fundamental operator but a collective bookkeeping field of the condensed phase. As a result, the Weinberg–Witten constraints do not apply directly to the emergent gravitational sector described here.

General relativity thus appears not as a fundamental theory, but as the long-wavelength constitutive law of a condensed spacetime medium.

Since general relativity is empirically Lorentz invariant, and TDG recovers general relativity as its infrared universality class, any Lorentz-violating microstructure must be dynamically suppressed at observable scales by the same coarse-graining and universality mechanisms that give rise to general relativity itself; otherwise spacetime would fail to emerge as a coherent macroscopic phase.

In the next section, we examine what happens when this medium is driven beyond its elastic limits, leading to spacetime failure and black-hole formation.

5 Critical Strain, Spacetime Failure, and Black Hole Formation

5.1 Elastic limits of the condensed phase

The emergent geometric description developed in Sections 3 and 4 relies on the existence of a stable condensed phase of the substrate. Like any elastic medium, this phase possesses finite tolerance limits. Beyond a critical strain, the network can no longer support coherent elastic response.

We introduce a dimensionless strain functional

$$\epsilon \sim \frac{\text{local curvature or tidal stress}}{\text{elastic scale}}, \tag{15}$$

and posit the existence of a finite critical value ϵ_{crit} such that

$$\epsilon > \epsilon_{\text{crit}} \quad \Rightarrow \quad \text{loss of condensate stability.} \tag{16}$$

This threshold is not imposed arbitrarily; it is a generic feature of nonlinear elastic systems with finite stiffness.

5.2 Black holes as regions of spacetime failure

In this framework, a black hole is not defined by a singularity of geometry, but by a region where the spacetime condensate fails due to excessive strain.

As matter collapses under its own gravitational self-interaction, the induced strain in the surrounding spacetime lattice increases. When the local strain exceeds ϵ_{crit}, the condensed phase dissolves into the underlying substrate.

We emphasize the following reinterpretation:

> *A black hole is a macroscopic region where spacetime ceases to exist as a geometric phase and reverts to its pre-geometric substrate.*

No curvature singularity forms; instead, the geometric description terminates at a finite strain boundary.

5.3 The event horizon as a phase boundary

The event horizon corresponds to the interface separating the condensed spacetime phase from the substrate-dominated region. It is not a surface beyond which geometry continues in a distorted form, but a boundary at which geometric notions lose operational meaning.

Crossing the event horizon does not represent a catastrophic event from the local substrate perspective. However, from the geometric viewpoint, it marks the point beyond which:

- distances and durations cease to be well-defined,
- causal structure no longer exists in geometric form,
- and elastic response cannot be continued.

The transition need not occur at an infinitesimally sharp surface; it may proceed across a finite-thickness critical zone whose local microphysics can remain smooth for infalling observers while still terminating the applicability of the coarse-grained geometric description.

This resolves the apparent paradox that infalling observers experience nothing locally special at the horizon, while external observers never see objects escape: the geometric description simply no longer applies inside.

5.4 Spaghettification as mechanical strand reactivation

General relativity predicts extreme tidal stretching near black holes, often referred to as spaghettification. In the present framework, this effect acquires a literal mechanical interpretation.

The condensed spacetime lattice consists of strands whose vibrational modes were frozen during condensation. Under extreme tidal strain, these modes are forcibly reactivated. The network fails not abstractly, but because its constituent strands are driven beyond their elastic limits.

> *Spacetime dissolves not because geometry breaks down abstractly, but because the frozen vibrational modes of the underlying strands are forcibly reactivated under extreme tidal strain.*

Matter entering this regime is progressively decoupled into more primitive substrate degrees of freedom before being absorbed into the substrate.

5.5 Persistence of external curvature

A natural concern arises: why does spacetime not immediately recondense once matter crosses the horizon?

The answer lies in boundary conditions. External matter distributions, including accretion disks and surrounding mass, continue to impose boundary strains on the condensate. These external stresses prevent reformation of the condensed phase within the failed region.

The situation is analogous to a membrane held open by sustained external loading. Spacetime fails not due to lack of support, but due to excessive support.

In this picture, rotational phenomena such as frame dragging arise naturally as shear stresses injected into the spacetime lattice near regions of extreme strain, where partial loss of elastic rigidity allows rotational deformation to propagate outward as a geometric twisting of inertial frames.

5.6 Energy bookkeeping and substrate absorption

When spacetime dissolves, energy is not destroyed. Instead, it is redistributed into:

- excitations of the substrate,
- interface degrees of freedom at the phase boundary,
- and entropy production associated with irreversible failure.

This provides a natural sink for energy that would otherwise be problematic in singularity-based descriptions. In the effective geometric description, this transfer appears as dissipation, entropy production, and renormalization of elastic parameters rather than as missing energy. Conservation is preserved at the substrate level even as the geometric description ceases to apply.

5.7 Summary

Black holes are reinterpreted as macroscopic regions of spacetime failure, bounded by phase interfaces where the geometric description ends. Spaghettification reflects mechanical strand reactivation rather than infinite curvature, and energy is conserved through transfer into substrate and interface degrees of freedom.

In the next section, we explore how information and entropy behave at these interfaces and how black hole thermodynamics emerges naturally from this picture.

6 Information, Entropy, and Black Hole Thermodynamics

6.1 Interfaces as entropy carriers

In the preceding section, black holes were identified as regions where the spacetime condensate fails and reverts to the underlying substrate. This failure is not abrupt but occurs across an interface separating the condensed geometric phase from the substrate-dominated region.

Such interfaces generically support a high density of microscopic degrees of freedom. In condensed matter systems, phase boundaries often dominate entropy budgets due to the large number of configurations compatible with boundary constraints. The same logic applies here.

We therefore identify the black hole entropy primarily with interface degrees of freedom localized near the phase boundary.

6.2 Area scaling from interface geometry

The entropy associated with the interface scales with its effective area, not with the volume of the failed region. This follows from the fact that only degrees of freedom residing on or near the interface contribute to the coarse-grained entropy accessible to an external observer.

As a result, the entropy takes the form

$$S_{\mathrm{BH}} \sim \alpha\, A, \tag{17}$$

where A is the area of the interface and α is a constant determined by the microscopic density of interface states.

This reproduces the Bekenstein–Hawking area law without invoking fundamental holographic principles or postulating fundamental Planck-area bits.

6.3 Interpretation of Hawking radiation

In the present framework, Hawking radiation arises from fluctuations and mode conversion near the phase interface. Quantum excitations of the condensate interact with interface degrees of freedom, leading to radiation emitted into the surrounding geometric phase.

From this perspective, Hawking radiation reflects the slow leakage of energy from the interface back into the condensed spacetime, rather than particle creation from a classical horizon.

The temperature associated with this radiation is controlled by the local strain gradient near the interface, which sets the characteristic energy scale of fluctuations.

6.4 Information flow and substrate continuity

A central advantage of the present picture is that the substrate remains dynamically continuous across the phase boundary. While geometric descriptions fail inside the black hole, the underlying degrees of freedom do not.

Information carried by infalling matter is transferred into the substrate and redistributed among substrate and interface degrees of freedom. Over long timescales, this information can be re-encoded into outgoing radiation or released during reconfiguration of the interface.

From the geometric viewpoint, this process appears highly scrambled and effectively irreversible. From the substrate viewpoint, however, the dynamics remain unitary.

6.5 No singular information loss

Because there is no curvature singularity and no fundamental breakdown of the underlying degrees of freedom, the traditional information-loss paradox does not arise. The apparent loss of information reflects the breakdown of the geometric description, not a failure of the underlying dynamics.

The key point can be summarized as follows:

> *Information is not destroyed in black holes; it simply leaves the geometric description and persists in the substrate.*

6.6 Late-time behavior and reconfiguration

As black holes lose mass through radiation or environmental interactions, the external strain imposed on the condensate decreases. When the strain drops below the critical threshold, regions of the failed phase may recondense.

Such recondensation need not be smooth. Rapid rearrangements of interface degrees of freedom may produce burst-like phenomena or deviations from purely thermal radiation. These effects are suppressed at large scales but could become relevant in late-stage evaporation or extreme events.

6.7 Summary

Black hole entropy arises from microscopic degrees of freedom localized at the phase interface between condensed spacetime and the substrate. The area law follows naturally from interface geometry, while Hawking radiation reflects energy exchange between the interface and the surrounding condensate.

Information is preserved at the substrate level, resolving the information-loss problem without invoking singularities, firewalls, or exotic nonlocal mechanisms.

In the next section, we turn to cosmological implications of spacetime condensation, including the origin of the early universe and large-scale structure.

7 Cosmological Implications of Spacetime Condensation

7.1 Cosmology without a pre-existing spacetime

In the present framework, spacetime is not assumed to exist prior to the condensation of the underlying substrate. Cosmology therefore does not describe the evolution of fields *within* spacetime from an initial singularity, but rather the formation and subsequent relaxation of the spacetime condensate itself.

The earliest cosmological epoch corresponds to a regime in which the substrate undergoes a global instability, driving the formation of a macroscopic, connected geometric phase. Conventional notions of distance, time, and causality emerge only after this transition.

7.2 The Big Bang as a condensation transition

The Big Bang is reinterpreted as a condensation event in which the substrate transitions from a non-geometric phase to a metastable spacetime phase. This transition need not be singular or instantaneous; rather, it resembles a rapid but finite phase change occurring throughout the substrate.

Because spacetime does not exist prior to this transition, questions regarding initial conditions at arbitrarily small times lose their conventional meaning. Instead, the relevant initial data concern the state of the substrate and the dynamics governing condensation.

7.3 Origin of homogeneity and isotropy

A key cosmological puzzle is the observed large-scale homogeneity and isotropy of the universe. In standard cosmology, this motivates an inflationary epoch to enforce causal contact across large regions.

In the present framework, homogeneity arises naturally because the substrate is not constrained by geometric locality prior to condensation. During the condensation transition, distant regions of the emergent spacetime may originate from strongly coupled regions of the substrate, allowing equilibration before geometric causality becomes meaningful.

As a result, large-scale uniformity does not require fine-tuned initial conditions or superluminal expansion within spacetime.

7.4 Inflation as rapid phase ordering

Although no fundamental inflaton field is required, the early universe may undergo a period of rapid expansion driven by phase ordering within the newly formed condensate.

As disconnected geometric patches merge and align, effective distances between comoving regions increase rapidly. This produces phenomenology closely resembling inflation, including dilution of inhomogeneities and suppression of anisotropies.

Crucially, this expansion reflects internal reorganization of the condensate rather than accelerated expansion of a pre-existing metric.

7.5 Generation of primordial fluctuations

Small fluctuations in the condensation process inevitably produce variations in local strain, node density, and elastic response. These inhomogeneities become frozen into the spacetime lattice as it stabilizes, seeding the primordial perturbations that later give rise to large-scale structure.

The statistical properties of these fluctuations depend on the condensation dynamics and disorder statistics of the lattice, potentially leading to slight deviations from exact scale invariance.

7.6 Large-scale structure as elastic memory

As the universe evolves, matter and radiation interact with the spacetime lattice, but the lattice itself retains memory of its formation. Residual elastic stresses and variations in network connectivity guide the subsequent clustering of matter.

In this picture, cosmic filaments, voids, and large-scale anisotropies reflect frozen-in stress patterns of the spacetime condensate rather than purely gravitational amplification of initially featureless noise.

7.7 Dark energy as residual relaxation pressure

The late-time acceleration of cosmic expansion is interpreted as a manifestation of incomplete relaxation of the spacetime condensate. Because the condensed phase is metastable, residual strain and misalignment persist at the largest scales.

These residual stresses act as an effective negative pressure, driving accelerated expansion without requiring a fundamental cosmological constant or vacuum energy density.

This interpretation naturally explains why the dark energy density is small, positive, and slowly varying.

7.8 Absence of a fundamental cosmological constant

Because spacetime is emergent, vacuum energy contributions from microscopic degrees of freedom are absorbed into the elastic properties of the condensate rather than gravitating directly.

The cosmological constant problem is therefore reframed as a question of condensate relaxation rather than fine-tuning of vacuum energy.

7.9 Summary

Cosmology emerges naturally from the dynamics of spacetime condensation. The Big Bang corresponds to a phase transition, inflation to rapid phase ordering, large-scale structure to frozen elastic memory, and dark energy to residual relaxation pressure.

No new fundamental fields or ad hoc mechanisms are required. The same degrees of freedom responsible for gravity and black holes also govern the global evolution of the universe.

In the next section, we discuss observational consequences and potential signatures of spacetime condensation.

8 Observational Consequences and Phenomenology

8.1 Principle of phenomenological conservatism

Any viable theory of emergent spacetime must reproduce the empirical successes of general relativity and standard cosmology in all regimes that have been experimentally tested. Deviations are therefore expected to be strongly suppressed in weak-field, low-curvature environments and to become relevant only near the limits of spacetime stability.

The present framework adheres to a principle of phenomenological conservatism: observable deviations from general relativity should arise only in regimes approaching critical strain or involving interface dynamics between condensed spacetime and the underlying substrate.

8.2 Weak-field and solar-system tests

In weak-field regimes, where spacetime strain is far below the critical threshold, the elastic response of the spacetime lattice is linear and well approximated by general relativity.

Consequently, the framework predicts:

- agreement with solar-system tests of gravity,
- correct gravitational lensing,
- standard perihelion precession,
- consistency with binary pulsar timing.

Any measurable deviations in these regimes would falsify the framework.

8.3 Gravitational wave propagation

Gravitational waves correspond to transverse–traceless shear oscillations of the spacetime lattice. In the linear regime, their propagation speed and polarization structure coincide with those predicted by general relativity.

Small deviations may arise due to:

- lattice disorder at very high frequencies,
- weak dispersion near the ultraviolet cutoff of the elastic description,
- interface interactions near compact objects.

Current gravitational-wave observations are consistent with these constraints, but future detectors may probe subtle frequency-dependent effects.

Although the underlying lattice structure breaks continuous symmetries at microscopic scales, any resulting violations of Lorentz invariance are expected to be strongly suppressed in the infrared. Such effects scale with the ratio of the microscopic lattice scale to observational length and time scales, placing them well below current experimental bounds. Observable deviations would therefore be confined to near-critical regimes or to energies approaching the breakdown of the elastic description.

A complete derivation of Lorentz symmetry recovery is deferred. Here we state the expectation that the infrared fixed point exhibits a single effective causal cone shared by all stable emergent excitations constructed from the same medium. Quantitative bounds on residual violations require specifying the microscopic dispersion relations and disorder statistics of the lattice, which we leave for future analytical and numerical investigation.

8.4 Black hole ringdown and echoes

Near black holes, spacetime approaches the critical strain regime. Although early-time ringdown is expected to match general relativity, late-time behavior may reflect the presence of a phase interface rather than a classical horizon.

Potential observational signatures include:

- partial reflectivity of the interface,
- late-time gravitational-wave echoes,
- deviations in quasinormal mode damping.

The absence of such effects would constrain interface reflectivity and dissipation properties rather than directly falsifying the phase-boundary interpretation.

8.5 Upper bounds on curvature

Because spacetime melts at finite critical strain, the framework predicts an upper bound on physically realizable curvature. Classical singularities are replaced by finite regions of non-geometric substrate.

Observationally, this implies:

- bounded tidal forces inside compact objects,
- saturation effects near extreme gravitational fields,
- absence of divergent curvature observables.

Evidence for unbounded curvature would rule out the theory.

8.6 Cosmological observables

In cosmology, the framework predicts:

- near-scale-invariant primordial fluctuations,
- possible small deviations tied to condensation dynamics,
- a dark energy component consistent with slow relaxation.

Precision measurements of the cosmic microwave background and large-scale structure may therefore provide indirect constraints on condensation physics.

8.7 Absence of Planck-scale particles

Unlike many approaches to quantum gravity, the present framework predicts no new elementary particles at the Planck scale. High-energy experiments should therefore observe:

- no direct graviton production,
- no quantum-gravity resonances,
- no violation of effective field theory below spacetime failure.

Any confirmed observation of Planck-scale particle degrees of freedom would strongly disfavor the condensed-spacetime picture.

8.8 Laboratory limitations

Because spacetime failure requires extreme strain rather than high energy density alone, laboratory experiments such as particle colliders are not expected to probe spacetime melting directly.

This explains the persistent absence of quantum-gravity signatures in collider experiments despite enormous energy scales.

8.9 Summary of falsifiability

The framework may be falsified by:

- observation of long-range scalar or vector gravitational modes,
- detection of unbounded curvature singularities,
- direct observation of Planck-scale particles,
- large deviations from general relativity in weak fields.

Conversely, evidence for curvature saturation, interface effects, or near-critical gravitational phenomena would provide support.

In the final section, we synthesize the conceptual implications and outline future directions.

9 Synthesis, Conceptual Implications, and Outlook

9.1 What has been established

This work has developed a coherent framework in which spacetime, gravitation, and cosmology emerge as collective phenomena of a condensed medium rather than as fundamental geometric structures.

The central elements of the framework may be summarized as follows:

- A pre-geometric substrate exists within a three-dimensional arena but lacks metric structure, causal ordering, or lightcones.
- The substrate consists of extended objects that are effectively one-dimensional in their internal dynamics, supporting only a single amplitude-like degree of freedom.
- A dynamical instability drives condensation into a frozen, disordered lattice whose elastic response defines emergent geometry.
- Gravitational dynamics arise as transverse–traceless shear excitations of this lattice, reproducing general relativity as an infrared universality class.
- Matter arises as defects, topological textures, and persistent excitations of the same spacetime medium.
- The Planck regime corresponds to a finite critical strain beyond which spacetime fails as a condensed phase.
- Black holes are interpreted as regions of spacetime breakdown bounded by phase interfaces rather than geometric singularities.
- Cosmological phenomena reflect global condensation, ordering, and relaxation dynamics of the spacetime medium.

Taken together, these elements provide a unified physical picture in which spacetime is emergent, metastable, and subject to mechanical failure.

The goal of this work is not to provide a microscopic ultraviolet completion, but to identify a mechanically consistent universality class capable of reproducing the observed gravitational sector in the infrared.

9.2 What is not claimed

It is equally important to state clearly what is *not* claimed by this framework.

This work does not:

- provide a complete microscopic derivation of the Standard Model,
- offer a closed-form ultraviolet completion,
- prove exact Lorentz invariance at all scales,
- predict new elementary particles accessible at collider energies,
- claim uniqueness among all possible emergent spacetime models.

Instead, the framework identifies a minimal set of structural principles sufficient to reproduce the observed gravitational sector while sharply constraining how spacetime may fail.

9.3 Conceptual implications

Treating spacetime as a condensed phase carries several conceptual implications:

- Geometry becomes an effective bookkeeping device for elastic response rather than a fundamental arena.
- Singularities are reinterpreted as breakdowns of an effective description rather than physical infinities.
- The Planck scale marks the limit of spacetime stability, not the appearance of new geometric degrees of freedom.
- Gravity is understood as a collective phenomenon rather than a force mediated by fundamental point particles.

These shifts do not invalidate general relativity; instead, they clarify its extraordinary success and delineate the regime in which it must eventually fail.

9.4 Relation to existing approaches

The framework developed here shares features with several existing research programs while remaining distinct:

- Like analogue gravity and condensed-matter approaches, gravity emerges from collective dynamics.
- Like string-inspired models, extended objects play a fundamental role, though without assuming higher-dimensional target spaces.
- Like loop-based and graph-based approaches, discrete structures appear, but only as emergent phases rather than fundamental input.

Its distinguishing feature is the combination of dimensional minimality, elastic universality, and a physically motivated failure mechanism for spacetime itself.

9.5 Open problems and future directions

Several key challenges remain and define the future research program:

- Rigorous demonstration of Lorentz symmetry recovery in the infrared, including bounds on residual violations.
- Quantitative modeling of condensation dynamics and elastic parameters.
- Detailed classification of defect excitations and their possible correspondence with observed matter fields.
- Numerical simulations of spacetime melting and interface dynamics.
- Refinement of observational signatures in strong-field and cosmological regimes.

Addressing these questions will require tools from condensed matter physics, numerical modeling, and gravitational phenomenology.

9.6 Final perspective

The guiding intuition of this work is simple but consequential: points cannot lock, but extended structures can. If spacetime is to exist as a stable medium capable of supporting geometry, matter, and gravity, its microscopic constituents must permit locking, shear, and failure.

Within this perspective, gravity is not mysterious but inevitable, and the breakdown of spacetime near black holes is not pathological but physical.

Whether this particular realization survives future scrutiny remains an open question. What appears increasingly difficult to avoid, however, is the conclusion that spacetime itself is not fundamental.

Data and Code Availability

No experimental data were generated or analyzed in this study. The numerical illustrations presented in Appendix A were produced using custom simulation code developed by the author. Source code and scripts sufficient to reproduce the figures are available from the author upon reasonable request.

Author Contributions

The author conceived the framework, developed the theoretical model, performed the numerical illustrations, and wrote the manuscript.

Competing Interests

The author declares no competing financial or non-financial interests.

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Ethics Statement

This work involves no human participants, animals, or sensitive data.

Reproducibility

All results presented in this work are derived analytically or through explicit numerical illustration. No stochastic tuning or undisclosed parameters were used. Qualitative behavior is robust under reasonable variation of simulation parameters, consistent with the universality claims discussed in the main text.

Appendix A: Disordered-network mode study and TT-like classification

This appendix provides a minimal numerical illustration of the qualitative mechanism discussed in the main text: in a disordered elastic network, longitudinal/compressional content tends to be suppressed in the extended long-wavelength sector, while a shear-dominated subset remains robust. The calculation is intentionally simple and is not presented as a definitive derivation; rather, it serves as an explicit sanity-check that the proposed mode-selection logic can arise in an ordinary central-force spring network with disorder. All numerical parameters are chosen for qualitative illustration and robustness rather than empirical matching.

We construct a random three-dimensional node set, connect nodes by a fixed-neighbor heuristic to form a sparse disordered network, and assign spring constants with mild randomness. A small fraction of nodes are pinned to remove rigid translations/rotations. We then compute the lowest normal modes of the corresponding stiffness matrix and evaluate: (i) a participation ratio (PR) as a localization diagnostic (Fig. A1), and (ii) a kinematic longitudinal-versus-transverse measure based on bond-parallel relative motion (Fig. A2). Modes with high shear fraction and low divergence proxy are labeled "TT-like" in the limited sense of being shear-dominated and approximately transverse on the network.

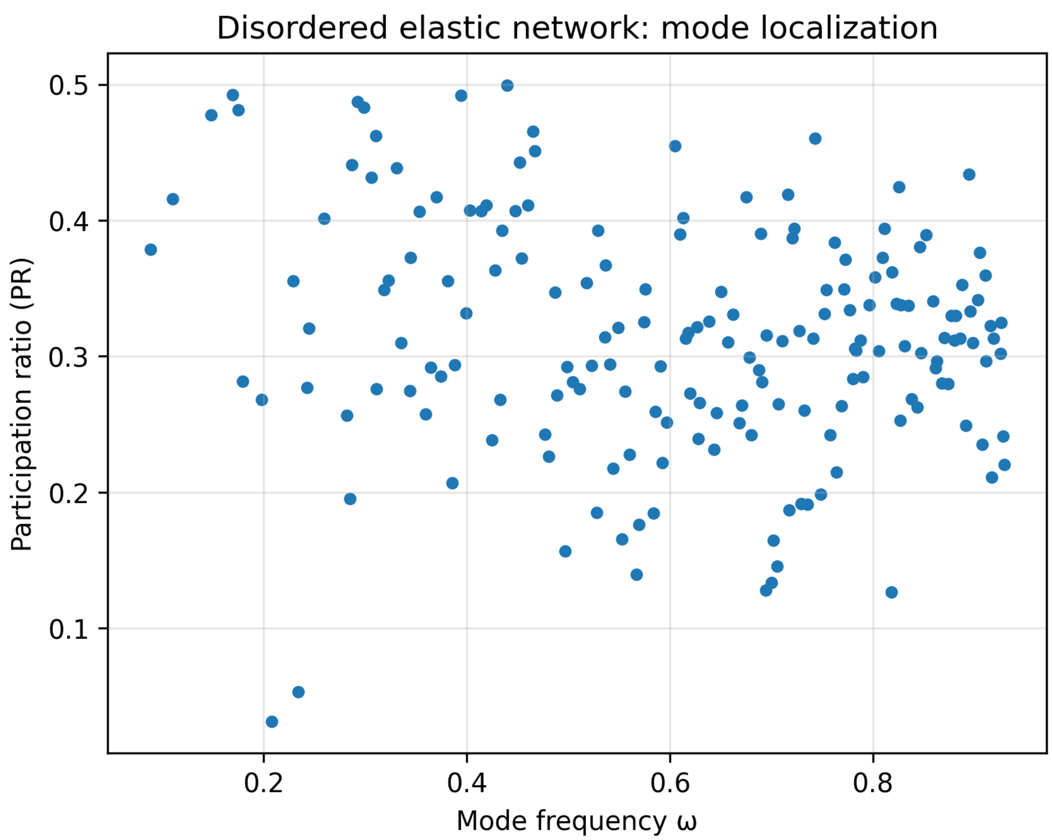

Figure A1: Participation ratio (PR) versus mode frequency ω for a representative disordered elastic network. Low-PR modes are spatially localized, while higher-PR modes are extended across the network. This provides a basic localization diagnostic for the low-lying spectrum.

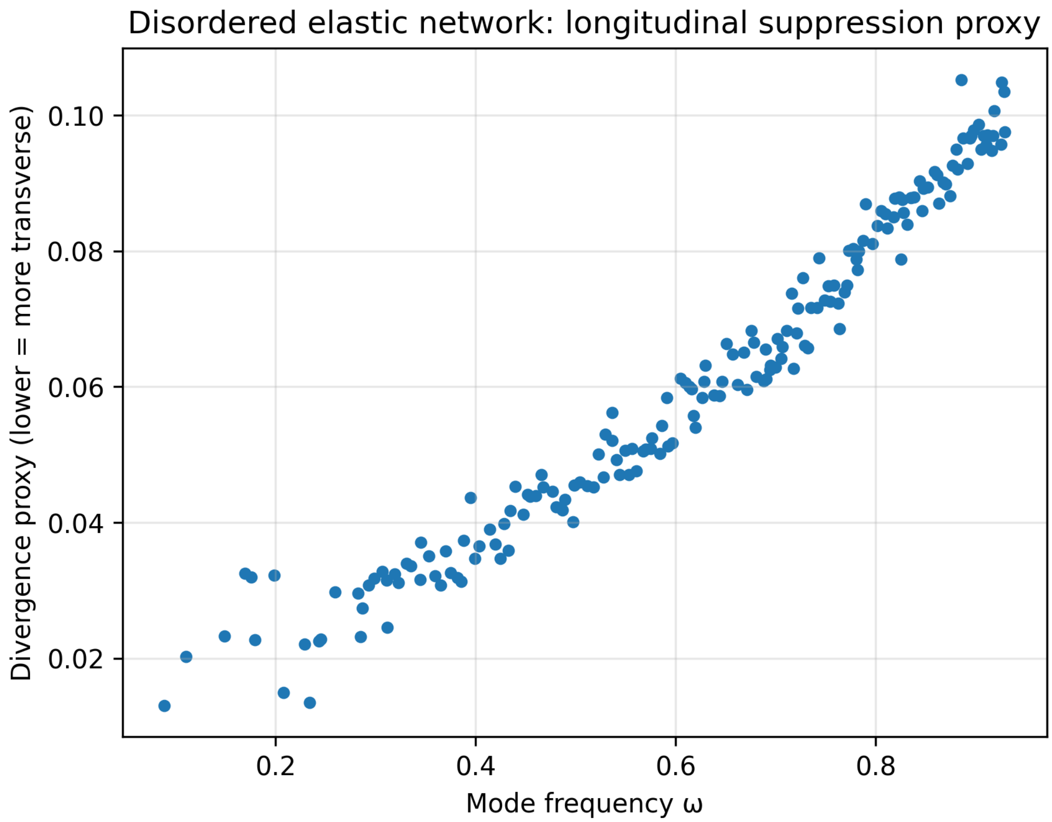

Figure A2: Longitudinal-content proxy ("divergence proxy") versus mode frequency ω. Lower values correspond to increasingly transverse (shear-dominated) relative motion on the bonds. The extended sector clusters toward low divergence, consistent with suppression of compressional content in the long-wavelength regime.

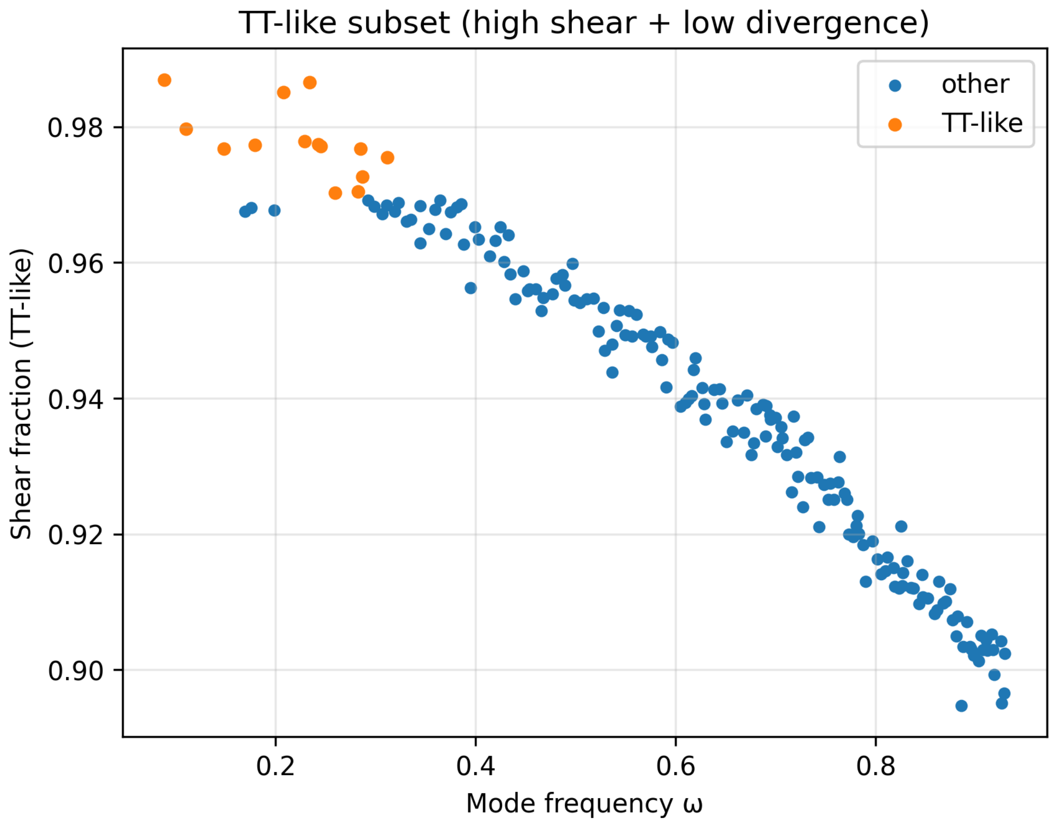

Figure A3: Shear fraction versus mode frequency ω, with a TT-like subset highlighted. "TT-like" here denotes modes that satisfy purely kinematic criteria: high shear fraction together with low divergence proxy. This classification is meant as an illustrative proxy for shear-dominated, approximately transverse extended modes, not as a full continuum TT decomposition. No claim is made that these modes constitute exact transverse–traceless tensor representations in the continuum field-theoretic sense; the designation 'TT-like' is used strictly as a kinematic and structural proxy within a discrete disordered network. No claim is made that the numerical thresholds used here are unique or optimal; they are chosen solely to illustrate qualitative mode separation under disorder.

A representative run (e.g., $N \approx 450$ nodes with sparse connectivity and mild stiffness disorder) typically yields a low-frequency subset of modes that remain extended and shear-dominated by these criteria, while many non-shear modes exhibit stronger localization. The point of this appendix is not numerical precision, but to demonstrate that the qualitative selection logic invoked in the main text can be realized in a concrete disordered elastic-network toy model without fine-tuning. No statistical claims are made regarding universality or scaling exponents; the intent is solely to demonstrate qualitative robustness of shear-dominated extended modes under disorder.

The numerical code used to generate the figures in Appendix A is available upon request or via the associated Zenodo repository.

Appendix B: Physical Interpretation of Spacetime Failure

In this framework, the breakdown of spacetime does not correspond to a geometric singularity but to a physical failure of a condensed phase. This appendix clarifies the mechanical interpretation of that failure.

The spacetime lattice is stabilized by the locking of extended substrate degrees of freedom into a frozen configuration. As long as local strain remains below a critical threshold, elastic response provides an effective geometric description.

When tidal strain exceeds this threshold, locking fails. Nodes lose coherence, elastic response ceases, and the system locally reverts to the underlying substrate phase. Geometry does not continue beyond this point as a meaningful description.

Crucially, spacetime failure is defined relative to surrounding regions where spacetime still exists. External matter and curvature maintain boundary strains that prevent immediate re-condensation. In this sense, black holes are sustained not by interior geometry but by the surrounding mass-energy distribution.

This interpretation replaces the notion of an interior spacetime region with a physically motivated phase boundary, avoiding singularities while preserving consistency with external gravitational phenomena such as lensing and ringdown.

Appendix C: Localized excitations as defect-like matter sectors

This appendix provides a derivation sketch for how "matter-like" degrees of freedom can arise in the present framework without introducing additional fundamental fields. The goal is not to derive the full Standard Model, but to show that the ontology of *localized, stable, finite-extent excitations* is mechanically natural in a frozen disordered strand-network, and that such excitations can carry approximately conserved labels and support particle-like propagation in the infrared.

C1 What is meant by an "excitation" in this framework

Throughout this work, an *excitation* means a persistent departure of the condensed network from its local reference configuration that: (i) has finite spatial support (or an exponentially decaying tail), (ii) is stable or metastable against local relaxation on relevant timescales, and (iii) can propagate as a coherent packet over macroscopic distances in the elastic regime.

In ordinary condensed matter language, these include: localized defects, domain-wall segments, disclination / dislocation-like structures, bound vibrational complexes, and topologically constrained rewirings of the underlying graph. The key point is that these are *configurations of the same medium* whose bulk shear sector defines the emergent metric, so their coupling to the strain channel is universal at leading order.

C2 Finite extent and localization in a disordered frozen network

A disordered frozen network generically supports localized normal-mode content and localized structural rearrangements. Even when the bulk supports a robust, gapless transverse–traceless (TT) shear sector, other degrees of freedom (compressional, rotational, and internal "bond reconfiguration" modes) are typically gapped, pinned, or localized by disorder and by the quenched connectivity constraints. This is the same physical reason amorphous solids can exhibit localized "soft spots" and defect modes while still supporting extended acoustic shear waves.

The "particle-like" character arises when a localized configuration has:

- an internal energy cost E_0 relative to the local relaxed lattice,
- a finite reconfiguration barrier separating it from trivial relaxation,
- and a low-energy manifold of translated configurations through which it can move by successive local rearrangements.

In this case, the defect supports an effective center-of-mass coordinate and moves through the network by a sequence of localized bond-level updates, while remaining embedded within the same condensed phase.

C3 Effective inertia as reconfiguration cost

A standard mechanical route to inertial behavior in a medium is: motion requires reconfiguration. For a localized excitation, changing its position by Δx requires a minimal set of bond updates in a neighborhood of its core. Denote by N_{flip} the number of such local updates required per unit translation and by ΔE_{flip} the typical elastic or configurational energy involved in each update. Then the work required to translate the excitation scales schematically as

$$W(\Delta x) \sim N_{\text{flip}}(\Delta x)\, \Delta E_{\text{flip}}. \tag{18}$$

In the infrared, this generates an effective inertial parameter ("mass") in the coarse-grained dynamics: the excitation resists changes in motion because its translation is not free, but mediated by finite-cost microscopic reconfiguration steps of the condensed network.

This mechanism is compatible with the main text's operational view of time: observers reconstruct time from stable signal exchange in the emergent phase, while microscopic evolution corresponds to a count of underlying reconfiguration events. In this sense, "mass" is the stiffness-weighted difficulty of reconfiguration required to sustain coherent propagation of a localized configuration in the medium.

C4 Approximately conserved labels from topology and connectivity

A persistent excitation can carry discrete labels that are protected (exactly or approximately) by the structure of the condensed phase. The most conservative sources of such labels are:

- **Topological constraints:** invariants associated with the mapping class of the local connectivity pattern, knot/linking data in strand segments, or nontrivial winding relative to the surrounding frozen network.
- **Connectivity class:** discrete adjacency patterns that cannot be removed by a finite sequence of local moves without passing through a high-strain or decondensed intermediate state.
- **Domain structure:** if the condensation admits multiple energetically comparable local orderings, interfaces between them can support stable defect segments with conserved intersection data.

These provide a mechanical basis for why certain excitations behave as distinct "species" rather than continuously deforming into one another.

C5 Coupling to the emergent metric and universality

Because the excitation is embedded in, and constituted by, the same condensed network whose shear strain defines the emergent geometry, its leading coupling to long-wavelength gravitational response is through the same strain channel. In the continuum description, this is captured by the standard minimal coupling structure,

$$\delta S_{\text{exc}} \sim \frac{1}{2} \int d^4x \, T^{\mu\nu}_{\text{exc}} \, h_{\mu\nu}, \tag{19}$$

where $T^{\mu\nu}_{\text{exc}}$ is the effective stress–energy of the localized configuration and $h_{\mu\nu}$ is the emergent metric perturbation (identified with coarse-grained strain as in the main text). Species-dependent long-range gravitational couplings would require additional independent long-range order parameters beyond the minimal substrate assumptions adopted here.

C6 A minimal field-theoretic proxy

A convenient proxy for the center-of-mass dynamics of a stable localized excitation is an effective relativistic point-particle action in the emergent metric,

$$S_{\text{cm}} \approx -m_{\text{eff}} \int d\tau, \tag{20}$$

where τ is the operational proper time defined by the emergent causal structure. This does *not* claim the excitation is fundamentally pointlike; rather, it asserts that at scales large compared to the excitation core size, its motion is well approximated by a worldline with effective inertia m_{eff}.

Corrections to this approximation are expected when: (i) wavelengths approach the core scale, (ii) disorder produces strong pinning or anisotropy, or (iii) the local strain approaches the critical regime where the condensed phase begins to fail.

C7 Remarks on chirality and fermion-like behavior

A well-known challenge for emergent lattice frameworks is reproducing chiral fermions in a strictly local, translationally invariant lattice field theory. The present work does not claim to solve this problem. However, two structural features of the framework weaken the usual "no-go" intuitions at the qualitative level:

- The microscopic structure is *disordered* and non-regular, so standard momentum-space doubling arguments tied to exact lattice symmetries need not apply in their usual form.
- The relevant long-wavelength degrees of freedom are *collective and constraint-driven* (graph elasticity plus defect connectivity), not a fundamental lattice discretization of continuum fermion fields.

A concrete realization of chiral, fermion-like excitations would likely require (i) a defect classification with orientation-sensitive invariants (handedness), (ii) an effective low-energy description with a protected two-state internal structure, and (iii) a mechanism by which one handed sector remains robust while its mirror is gapped, localized, or confined. Establishing any of these conditions requires a dedicated model and is left for future work.

C8 Reconfiguration Transport, Time, and the Roles of Neutrinos and Entanglement

Scope and status. *The following discussion is not required for the recovery of general relativity or cosmological dynamics developed in the main text, but addresses a necessary consistency question concerning how lattice reconfiguration is dynamically transported once spacetime is condensed.*

A necessary but previously implicit element of the framework concerns the mechanism by which lattice reconfiguration is dynamically transported. If massive excitations are interpreted as localized, stabilized defects of the condensed spacetime medium, then their motion and interaction necessarily entail continuous local updating of lattice connectivity. Absent such a mechanism, defect motion would generically induce unphysical accumulation of strain or local tearing of the substrate.

Within the present ontology, mass and inertia are defined as the energetic cost associated with these reconfiguration processes. It follows that reconfiguration itself must be mediated by a distinct dynamical channel: one that propagates changes in lattice state while carrying minimal inertial load and coupling only weakly to static geometric structure.

We therefore note a suggestive correspondence between this required reconfiguration channel and the observed phenomenology of neutrinos. Specifically, neutrinos exhibit the following properties:

- extremely small effective mass,
- weak coupling to localized matter configurations,
- near-luminal propagation,
- copious production in high-strain and rapidly evolving environments (e.g. stellar cores and gravitational collapse).

Within this framework, these features are consistent with interpreting neutrinos not as localized topological defects analogous to massive particles, but as near-threshold collective excitations associated with the propagation of lattice reconfiguration itself. Under this interpretation, neutrinos function as the dynamical carriers of structural updates, enabling smooth transport of defects through the medium without inducing macroscopic lattice failure.

At reconfiguration densities below the threshold for real particle emission, structural updating need not be exported through propagating excitations. Instead, lattice updates remain local, virtual, and continually recycled into the surrounding network. In this regime, reconfiguration is mediated through relational correlations between neighboring degrees of freedom. At the emergent level, this appears as dynamically maintained entanglement: a distributed bookkeeping structure reflecting shared reconfiguration histories rather than exchange of particles or signals.

In the present framework, entanglement plays a dual but unified role. Below the threshold for propagating reconfiguration, required lattice updates cannot be exported through particles or waves and are instead encoded as relational constraints between degrees of freedom. These constraints persist as entanglement while the associated worldlines remain causally separated. When such worldlines later interact or reunite, the same relational structure functions as a reconciliation protocol, enforcing global consistency between their accumulated reconfiguration histories. In this sense, entanglement does not constitute an independent dynamical channel, but a deferred bookkeeping mechanism: it stores incomplete reconfiguration when propagation is unavailable and prescribes how those configurations must be synchronized when causal contact is restored. Time asymmetry and observable update events arise only at this point of reconciliation, while the underlying entanglement itself remains non-local, non-signaling, and relational.

This distinction provides a natural interpretation of gravitational time dilation within the condensed spacetime phase. Atomic processes do not slow intrinsically; rather, clocks embedded in regions of differing strain require different densities of underlying lattice reconfiguration to complete identical internal cycles. Even when individual relational correlations are short-lived and frequently overwritten, their cumulative participation in reconfiguration bookkeeping produces a persistent asymmetry in update density between regions. When clocks are compared via radar-time synchronization, this accumulated relational reconciliation manifests as differential elapsed time, despite locally invariant signal propagation. In this sense, time is not identified with the instantaneous lattice configuration itself, nor with local matter interaction rates, but with the differential reconciliation required to maintain global consistency between distinct reconfiguration histories.

In this sense, neutrinos and entanglement are not competing mechanisms but complementary limits of the same underlying process. Neutrinos dominate reconfiguration transport near criticality, while entanglement encodes distributed, sub-threshold reconfiguration in weak-field regimes. Both serve to maintain global consistency of a discrete, reconfigurable spacetime medium without introducing preferred frames, superluminal signaling, or violations of emergent relativistic causality.

We emphasize that this identification is strictly qualitative. No attempt is made here to derive neutrino flavor structure, chirality, weak interactions, or detailed quantum entanglement dynamics. The purpose of this remark is solely to note that a mechanically consistent spacetime substrate appears to require both propagating and relational channels for reconfiguration bookkeeping, and that known physical phenomena naturally populate these roles.

C9 Summary

This appendix has provided a minimal, mechanically motivated route by which "matter-like" localized excitations can arise as finite-extent, persistent configurations embedded within the condensed spacetime lattice. Their effective inertia emerges as reconfiguration cost, their species labels can arise from topology and connectivity constraints, and their coupling to the gravitational shear sector is universal at leading order because both geometry and excitations are made of the same medium. A full derivation of Standard Model structure is beyond scope, but the framework supplies a coherent ontology in which such a program is not structurally forbidden.

Appendix D: Pre-Geometric Consistency Conditions

This appendix is ontological and retrodictive in character. Its purpose is not to derive the dynamical results of the main text, nor to introduce new empirical claims, but to make explicit the minimal pre-geometric consistency conditions that must hold if spacetime is to emerge as a condensed, elastic phase as assumed in Sections 1–3.

None of the effective gravitational results in the main text depend on the correctness of this appendix. The infrared emergence of Einsteinian dynamics stands independently. This appendix exists to:

- clarify what is (and is not) assumed prior to spacetime,
- prevent the inadvertent importation of geometric or temporal structure into the pre-geometric regime,
- and provide a coherent internal map connecting "nothing," capacity, dimensionality, and condensation.

Throughout this appendix, no spacetime manifold, metric, locality, causal structure, or time parameter is assumed unless explicitly stated.

D1 Absolute Null as an Operational Boundary

We begin by considering *absolute null*: the limit in which there are no degrees of freedom, no relations, no scale, no ordering, and no dimensional structure. This is not introduced as a physical state, but as a candidate boundary condition for a "from-scratch" ontology.

The immediate difficulty is that absolute null cannot be operationally specified. To specify a state is to distinguish it from alternatives; absolute null admits no distinction. Any attempt to characterize it already introduces relational structure. Thus absolute null cannot function as a stable, self-identifying configuration.

We therefore treat absolute null not as a realizable state, but as a *degenerate limit* at which description fails. This failure is not philosophical; it is operational. Absolute null cannot be maintained as a boundary condition once the requirement of distinguishability is imposed.

D2 Instability of Null and the Emergence of Capacity

The inability of absolute null to remain well-defined constitutes its instability. Importantly, this instability is not dynamical and does not unfold in time. It is a logical inconsistency: null cannot remain null once it is required to be definable.

The minimal residue left when absolute null fails is what we call *capacity*. Capacity is not energy, matter, information, or a field. It is the bare admissibility of distinction once perfect absence becomes ill-defined.

Capacity should not be visualized as "empty space." It carries no geometry, no metric, no locality, and no notion of distance. It is simply the condition that differentiation is now possible in principle, even though nothing has yet differentiated.

D3 Nonlocality and the Zero-Dimensional Limit

In the strict null limit, all distinctions collapse. This corresponds to a maximally nonlocal configuration: there is no "here" or "there," no separation, and no relational ordering. Nonlocality in this sense is not superluminal propagation; it is the absence of locality altogether.

Crucially, perfect nonlocality is only coherent in the zero-dimensional limit. Any introduction of dimensional structure immediately permits differentiation and therefore undermines global nonlocal symmetry.

Thus nonlocality is stable only at the null boundary. Once capacity exists, perfect nonlocality becomes unstable.

D4 Dimensional Capacity as the First Structured Outcome

The instability of null produces capacity, but capacity alone is not yet structured. For distinctions to coexist without contradiction, there must exist independent relational channels along which differentiation can occur. We refer to this as *dimensional capacity*.

Dimensional capacity is not geometry. It does not imply distances, angles, or embedding in a manifold. It is the minimal number of independent relational degrees of freedom required for distinctions to persist.

Why fewer than three dimensions fail.

- Zero dimensions correspond to null and support only perfect nonlocality.
- One dimension permits ordering but no extension; it is operational only.
- Two dimensions permit boundaries and interfaces but not volumetric degrees of freedom.

In fewer than three dimensions, relational structure collapses into operational or boundary-only descriptions. No stable, extensible physical degrees of freedom can be realized.

Why more than three dimensions are not physically realized. Additional dimensions beyond three do not introduce new independent physical degrees of freedom unless they support extension, separation, and independent relational variation. Dimensions that are compactified, collapsed, or inaccessible do not function as physical dimensions; they are bookkeeping devices.

Thus three dimensions constitute the minimal and sufficient dimensional capacity for physical realization. This is not asserted as a metaphysical necessity, but as a consistency requirement for stable, extensible structure.

D5 Potential as Structured Capacity

Once dimensional capacity exists, structured difference becomes possible. At this point, *potential* is defined. Potential is capacity with relational structure: the ability for distinctions to vary relative to one another.

A schematic order parameter ϕ may be introduced to label differentiation in configuration space. A potential functional $V(\phi)$ has meaning only after dimensional capacity exists, since variation requires independent channels.

D6 Tachyonic Instability (Pre-Geometric)

If the symmetric configuration of potential is unstable, this is encoded as negative curvature:

$$\left.\frac{d^2V}{d\phi^2}\right|_{\phi=0} < 0. \tag{21}$$

This "tachyonic" condition refers solely to configuration-space instability. It does not imply propagation, speed, or spacetime.

Because locality does not yet exist, this instability is global. The system cannot remain in a maximally symmetric, nonlocal configuration once dimensional capacity permits differentiation.

D7 The Quench and the Big Bang

The instability of nonlocal potential saturates through a *quench*: a configuration-space transition in which nonlocal symmetry is lost and residual correlations are frozen.

This entire sequence—null instability, capacity, dimensional capacity, potential, tachyonic instability, and quench—does not unfold in time. In the absence of time, these distinctions are ontological, not temporal.

From within the emergent spacetime phase, this transition is collectively labeled the "Big Bang." It is not a thermal explosion and not an event occurring at a point in space. It is the global, instantaneous failure of perfect nonlocality and the simultaneous emergence of structured, extensible degrees of freedom.

D8 Residual Structure and Extended Degrees of Freedom

The pre-geometric quench described above eliminates perfect nonlocality but does not return the system to null. Instead, it leaves behind residual correlations that are frozen by the loss of symmetry.

Crucially, these residual structures cannot be point-like. In a three-dimensional dimensional capacity, isolated point-like remnants would admit no internal relational structure and would therefore collapse back toward null. Stability requires that residual distinctions persist across independent relational channels.

As a result, the minimal stable residue of the quench consists of *extended relational structures*: correlations that persist along one or more relational directions without yet defining geometric distance, metric properties, or embedding in a spacetime manifold.

These extended residues are not strings in spacetime, nor objects propagating within a background. Rather, they are pre-geometric carriers of relational persistence—the minimal entities capable of connecting, interlocking, and forming higher-order structures once condensation occurs.

Because they are extended rather than localized, such residues admit connection and recombination. This property is essential: without connectability, no network, lattice, or mechanically rigid phase could later form. The strand-like degrees of freedom assumed in the main text should be understood as descendants of these extended pre-geometric residues after condensation and coarse-graining.

No specific microscopic model is assumed here. The claim is purely ontological: once nonlocal symmetry fails in a three-dimensional dimensional capacity, the surviving degrees of freedom must be extended in order to remain stable and capable of supporting later structure.

D9 Transition to the Main Text

The outcome of the pre-geometric quench is a population of residual, gapped correlations capable of forming extended, mechanically interlocked structures. The main text assumes such structures and analyzes their condensation into a frozen, disordered elastic network whose long-wavelength shear response reproduces general relativity as an infrared universality class.

This appendix supplies one internally consistent ontological pathway into that assumption, without importing spacetime, locality, or time prematurely.

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