Tachyonic Quenched Spacetime

Jerad Happe

haje1983@gmail.com

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Abstract

Tachyonic Quenched Spacetime (TQS) proposes that classical spacetime arises as a condensed, elastic phase of an underlying discrete relational substrate, following a pre-geometric tachyonic instability and global quench. Here, "tachyonic" refers solely to a negative-curvature instability in configuration space prior to the emergence of locality, time, or propagation, and does not imply superluminal dynamics or the existence of faster-than-light particles.

Starting from minimal ontological assumptions—absolute null as an operational boundary, the emergence of relational capacity, and finite-dimensional resolution—this framework argues that perfect nonlocality is unstable once differentiation becomes admissible. The resulting quench freezes residual correlations into extended relational structures, which subsequently interlock to form a disordered, elastic network. In the long-wavelength limit, the shear response of this network reproduces Einsteinian gravity as an infrared universality class, while resolving classical singularities through finite reconfiguration capacity.

Within the condensed phase, physical processes are interpreted as lattice reconfiguration dynamics. Time emerges as reconciliation accounting between distinct reconfiguration histories rather than as a fundamental parameter. Photons are identified with propagating chains of incremental bond updates that transport energy and momentum without persistent defects, while neutrinos arise as minimal stabilized defects exporting irreducible reconfiguration mismatch near criticality. Quantum entanglement corresponds to deferred relational bookkeeping prior to causal contact, and smooth worldline reunions follow from amortized reconciliation rather than instantaneous collapse.

The framework further identifies a necessary microscopic resolution scale set by reconciliation locality, admitting neither arbitrarily small nor arbitrarily large relational elements. This naturally yields a finite lattice scale without imposing a cutoff by hand. Disorder at the microscopic level emerges as a structural consequence of capacity resolution, suppressing preferred frames while permitting curvature, wave propagation, and defect motion.

TQS does not attempt a full derivation of the Standard Model. However, it identifies ontological slots for matter-like secondary defects, electromagnetic interactions as organized bond-update dynamics, and weak and strong interactions as threshold and confinement phenomena of the same substrate. The result is a mechanically coherent pathway from pre-geometric null to emergent spacetime, gravity, and quantum phenomena, without introducing additional background structures, preferred frames, or violations of emergent relativistic causality.

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1 Introduction and Motivation

1.1 Why spacetime should not be fundamental

General relativity and quantum field theory have each achieved remarkable success in probing spacetime across disparate regimes. Quantum field theory, in particular, has demonstrated extraordinary predictive power by describing matter and interactions as fields whose excitations give rise to observed particles and forces. Yet the introduction of any field—whether defined on spacetime or treated as intrinsic to it—implicitly presupposes a substrate capable of supporting phase, correlation, and dynamical propagation. In this sense, quantum field theory already points toward spacetime as something physically operative rather than purely geometric. The framework developed here suggests that the apparent tension between general relativity and quantum field theory may arise not from mutual inconsistency, but from the absence of an explicit account of spacetime as a condensed, reconfigurable medium—within which geometric elasticity and quantum excitations emerge as complementary limits. Seen in this light, spacetime becomes less a fundamental mystery and more a physical substrate whose observable properties depend on scale, strain, and mode of excitation.

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 string-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 pre-geometric degrees of freedom that possess no intrinsic locality, geometry, or internal relational extent. Prior to condensation, such degrees of freedom are not point-like objects in space, but capacity-bearing relational elements for which notions of size, separation, and correlation are not yet defined.

During a quench driven by instability, these pre-geometric elements generically develop extended relational correlations before freezing. Only correlations with finite relational extent can persist once dimensional capacity is resolved; purely localized remnants are unstable and collapse back toward null configuration. As a result, extended structures necessarily arise prior to locking. These extended correlations alone 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 relational structure is an unavoidable prerequisite for the existence of a condensed spacetime medium.

A more detailed ontological discussion of why purely localized pre-geometric remnants are unstable, and why extended relational structure is unavoidable once dimensional capacity is resolved, is provided in Appendix B.

1.4 Dimensional minimality and string-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. string-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 strings 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 and minimal dynamics.
- Section 3 derives condensation and elastic emergence.
- Section 4 shows how the shear sector reproduces general relativity.
- Sections 5 and 6 analyze spacetime failure and black-hole thermodynamics.
- Section 7 develops cosmological implications.

- Section 8 constructs matter and interaction sectors.
- Section 9 develops gauge transport and electromagnetism.
- Section 10 examines observational consequences.

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 B; 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 string degrees of freedom

The fundamental degrees of freedom are taken to be string-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 string supports only a single internal vibrational degree of freedom.

We parameterize each string 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 string-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 string itself.

Thus, even if the string 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 strings 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:

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

Here:

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

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 strings 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" strings 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 string-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.

The foregoing operational interpretation of time has a sharp empirical test: gravitational time dilation is universal. Any substrate account must reproduce not only dilation itself, but its strict composition-independence.

Physical enforcement of gravitational time dilation. General Relativity predicts gravitational time dilation as an invariant effect: all clocks, atoms, and physical processes exhibit identical dilation when compared across differing gravitational potentials, independent of their internal composition or construction. Crucially, this invariance implies that local microscopic dynamics do not themselves slow or malfunction. Spectral lines, decay rates, and internal atomic transitions remain locally unchanged within their own frames.

If spacetime were merely an abstract geometric structure without physical content, gravitational time dilation would have to arise from direct changes in local matter dynamics. Such a mechanism would generically introduce composition-dependent effects or preferred responses: clocks based on electronic transitions, nuclear decays, or mechanical oscillations would be expected to dilate by different amounts under identical gravitational conditions. No such dependence is observed.

The universality of gravitational time dilation therefore implies that the effect is enforced not by local matter, but by spacetime itself. Geometry may encode the relational structure of dilation, but it cannot enforce invariance without a physical carrier. The observed composition-independence instead indicates a substrate-level constraint acting as a universal bottleneck for all information-processing events. In this sense, if General Relativity is correct and gravitational time dilation is truly invariant, spacetime cannot be "nothing": it must function as a physical medium that constrains all processes equally without altering their internal dynamics.

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 string 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 string 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 strings 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 TQS 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 derived in Sections 3 and 4 relies on the existence of a stable condensed phase of the substrate. We now examine what occurs when this elastic description is driven beyond its regime of validity. 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 string 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 strings 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 strings are driven beyond their elastic limits.

> *Spacetime dissolves not because geometry breaks down abstractly, but because the frozen vibrational modes of the underlying strings 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 string 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

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

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.

8 Localized excitations as defect-like matter sectors

This section 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 string-network, and that such excitations can carry approximately conserved labels and support particle-like propagation in the infrared.

8.1 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.

8.2 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.

8.3 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 consistent with the operational interpretation of time developed above: observers infer time through stable signal exchange in the emergent phase, whereas microscopic evolution corresponds to a count of elementary reconfiguration events. Within this picture, mass is not a fundamental substance but a measure of stiffness-weighted reconfiguration cost: the inertial burden associated with maintaining coherent propagation of a localized configuration in the condensed medium.

8.4 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 string 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.

8.5 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 necessarily proceeds through that same strain channel. In the continuum description this appears as 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 $T^{\mu\nu}_{\text{exc}}$ denotes the effective stress–energy of the localized configuration and $h_{\mu\nu}$ represents the coarse-grained metric perturbation arising from elastic strain of the substrate.

Species-dependent long-range gravitational couplings would require additional independent long-range order parameters beyond those present in the minimal condensed network. In their absence, universality of gravitational coupling follows directly from the shared strain channel.

8.6 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,

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

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 $m_{\rm eff}$.

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.

8.7 Sketch of weak-sector structure

We emphasize that the following discussion is qualitative and structural in character. It is not intended as a microscopic derivation of fermionic field theory, but as an ontological account of why chiral, fermion-like behavior is naturally selected in a discrete, disordered, reconfigurable spacetime substrate.

The weak interaction plays a qualitatively different role from the other long-range interactions: rather than merely redistributing stress or curvature, it changes defect identity. In Standard Model language, weak processes alter flavor and charge through $SU(2)_L$ currents; in the present framework such processes correspond to local reassignments of topological bookkeeping within the condensed spacetime substrate.

A persistent challenge for emergent lattice frameworks is the appearance of chirality. In regularly ordered or crystalline lattices, local torsional deformations are generically shared symmetrically across the network and can be continuously unwound, making the selection of a preferred handedness difficult. By contrast, the condensed spacetime substrate assumed in TQS is intrinsically disordered and elastically connected through local touch–points rather than rigid, globally aligned bonds. In such a medium, local gradients in reconfiguration cost can stabilize orientation–sensitive configurations that are not globally mirrored.

Within this context, fermion-like excitations are modeled as topologically locked defects characterized by both a direction of motion and an internal torsional orientation of the surrounding lattice. Chirality reflects the relative orientation of this torsion with respect to the defect's worldline: two inequivalent locking configurations are possible, analogous to left- and right-handed twist. Identity-changing processes require a local rewiring of defect connectivity that must close consistently into the ambient lattice without leaving unreconciled torsion or inducing bond failure. In a discrete, reconfigurable medium, this constraint generically selects one locking orientation as dynamically admissible, while the opposite orientation fails to stabilize as a propagating excitation.

In this sense, the chiral structure of the weak interaction is not introduced as an independent postulate, but reflects the fact that only one torsional orientation supports mechanically consistent identity-reassignment vertices in the condensed lattice. At the effective field-theoretic level, this bias toward a single locking orientation is naturally represented by a vector–axial ($V - A$) current structure: the vector component encodes ordinary defect transport, while the axial component encodes sensitivity to internal torsion. The empirical suppression of right-handed weak couplings then appears as the statement that the corresponding torsional configuration has vanishing overlap with any admissible reconfiguration channel.

The short range and effective mass of the weak gauge bosons admit a similar interpretation. Massless gauge modes in TQS (photons and, in the infrared limit, gravitons) correspond to coherent phase waves of bond reconfiguration for which no persistent defect or localized strain core is transported. By contrast, a weak gauge boson must mediate a local change in defect identity, requiring a temporarily locked region of high-cost reconfiguration to accompany the interaction. The resulting excitation is therefore a localized packet of strained lattice connectivity with finite inertial cost and limited propagation range. In effective field theory language this appears as a massive, short-range gauge boson; in TQS it is the mechanical consequence of transporting a bounded region of locked reconfiguration through an elastic but disordered medium.

These remarks are strictly qualitative and do not constitute a derivation of the Standard Model weak sector. Their purpose is to indicate that chiral couplings, vector–axial current structure, and massive weak gauge bosons can be interpreted as structural features of identity-changing reconfiguration in a discrete, reconfigurable spacetime substrate, rather than as independent, axiomatically imposed ingredients.

The qualitative picture developed above can be restated more compactly in terms of defect reclassification and export channels, which we now summarize.

8.8 Fermion-like behavior, exclusion, and charge

A persistent challenge for emergent lattice frameworks is reproducing fermion-like behavior, in particular the Pauli exclusion principle, without introducing it as a fundamental postulate. The present work does not claim a microscopic derivation of fermionic statistics. However, the TQS ontology provides a natural structural context in which exclusion emerges as a necessary consistency condition of lattice reconciliation.

Primary topological defects generate extended strain gradients in the condensed spacetime substrate. To maintain lattice connectivity and finite reconciliation cost, these gradients must be regulated. This generically necessitates the formation of stable, low-mass secondary defects (electron-like excitations) that act as strain buffers, redistributing and limiting the gradient imposed by the primary defect.

Crucially, these secondary defects are not independent, freely duplicable entities. Each represents a distinct unit of reconfiguration bookkeeping: a locally stabilized pattern that resolves a specific portion of the surrounding strain field. Two such defects occupying identical relational states would correspond to redundant bookkeeping entries, rendering the lattice unable to distinguish or reconcile their update histories. Such a configuration is structurally ill-defined and therefore forbidden.

In this sense, Pauli exclusion arises not as a repulsive force or imposed quantum rule, but as a prohibition against duplicate reconciliation records within the same relational slot. Only one secondary defect may occupy a given effective state because only one distinct strain-buffering role can be assigned to that state without ambiguity. Exclusion is thus a bookkeeping constraint required for coherent lattice updating, not an additional dynamical interaction.

Metastability of secondary defects. Secondary (electron-like) defects arise as local strain-buffering configurations in response to primary excitations, but their persistence does not require continuous sourcing from the original defect. Once formed, they constitute locally self-consistent reconfiguration states of the condensed substrate. Their removal would require a coordinated relaxation of the surrounding lattice that exceeds the local reconciliation threshold and is therefore energetically suppressed.

In an unbounded three-dimensional medium, localized topological defects admit no lower-dimensional escape channel. Relaxation requires either annihilation with an oppositely oriented defect or a coherent, large-scale reconfiguration of the ambient network. Free electron-like defects are thus metastable excitations of the spacetime substrate, stabilized not by ongoing forcing but by the absence of any locally admissible decay pathway.

Interpretation of the electron cloud. Within the present framework, the electron "cloud" is not interpreted as a particle orbiting a nucleus nor as a fundamental probability wave in empty space. Instead, it represents the spatial region over which a secondary defect can migrate while performing its strain-buffering role. Because the strain field generated by a primary defect is distributed and directionally degenerate, no single localization of the secondary defect is energetically preferred. The electron-like excitation therefore occupies a connected volume of eligible lattice configurations, moving freely within that region to redistribute reconfiguration load.

The spatial extent and structure of the electron cloud reflect the geometry of least-cost strain accommodation rather than a dynamical trajectory. Regions of higher electron density correspond to configurations where buffering is most effective, while nodes and exclusion zones arise from lattice symmetry, boundary conditions, and the presence of other buffering defects. Pauli exclusion follows immediately: two secondary defects cannot occupy the same cloud configuration because they would attempt to perform identical buffering roles, rendering reconciliation bookkeeping ill-defined.

Chemical bonding then admits a simple interpretation. When two primary defects approach, sharing a distributed buffering region is energetically cheaper than maintaining separate strain buffers. Electron clouds therefore merge, distort, or reorganize to minimize total reconciliation cost, producing the observed structure of molecular bonds without invoking additional forces or ad hoc rules.

Interpretation of charge and electron number. Within this framework, electric charge is not treated as a fundamental source quantity, but as an emergent diagnostic of lattice reconfiguration. The number of electron-like secondary defects associated with a given primary defect is determined by the minimum buffering capacity required to stabilize its strain field while preserving lattice coherence. Electron number therefore measures how much strain buffering is required, not how much charge exists.

Observed electric charge reflects the residual reconfiguration imbalance after this buffering is established. It functions as a macroscopic bookkeeping parameter encoding how the lattice organizes and distributes reconciliation work, rather than as the microscopic cause of interaction. The discreteness of charge and the exclusion of identical electron states follow jointly from the requirement that reconciliation records remain unique, finite, and locally resolvable.

8.9 Bosonic substrate and emergent fermionic matter.

Within the present framework, the condensed spacetime substrate is naturally described in terms of bosonic relational degrees of freedom that support coherent phase dynamics and collective modes. Such bosonic structure is required for condensation, long-range coherence, and the existence of massless propagating excitations. Fermionic matter does not appear as a fundamental constituent added to this substrate. Instead, fermionic behavior emerges when persistent strain or reconciliation constraints force bosonic phase degrees of freedom into topologically constrained configurations characterized by discrete phase-winding numbers, which admit only a finite set of orientation-sensitive states. These locked configurations are stabilized by reconciliation locality and strain regulation, leading naturally to exclusion, two-valued internal structure, and defect-like persistence. In this sense, fermions arise as topologically protected excitations of an underlying bosonic relational network rather than as independent microscopic primitives.

8.10 Reconfiguration Transport, Time, and the Roles of Photons, Neutrinos, Entanglement and Interaction Channels

Reconfiguration transport requirement. If massive excitations are interpreted as localized, stabilized topological defects of the condensed spacetime lattice, then their motion and interaction necessarily entail continuous local updating of lattice connectivity. Absent mechanisms capable of exporting or resolving these updates, defect motion would require indefinite localization of strain, implying either unbounded curvature or permanent bond failure. Such behavior would be incompatible with the observed long-term stability of spacetime and with the assumption of a finite, elastic, reconfigurable substrate.

Within the present ontology, mass and inertia are defined as the energetic cost associated with these reconfiguration processes. It follows that lattice reconfiguration itself must be mediated through multiple dynamical regimes, distinguished by the density and urgency of required updates.

Three regimes of reconfiguration transport. Once spacetime is condensed, lattice reconfiguration proceeds through three complementary mechanisms:

- **Relational buffering (entanglement):** At sub-threshold reconfiguration densities, required updates cannot be finalized locally without introducing unnecessary strain. Instead, they are stored as distributed relational constraints between degrees of freedom. At the emergent level, this appears as dynamically maintained quantum entanglement: a non-signaling bookkeeping structure encoding unresolved reconfiguration debt while worldlines remain causally separated.

- **Incremental finalization (photons):** When reconfiguration demand exceeds relational buffering capacity but remains below defect-creation thresholds, updates are finalized incrementally through propagating bond reconfiguration events identified phenomenologically as photons. Photon propagation does not correspond to the transport of a localized object through the lattice. Rather, it consists of a sequential chain of locally finalized bond updates.

  The energy budget resides in the state change itself: each update releases locally stored lattice stress and triggers the next eligible bond. Energy is conserved because it is released and re-stored at each step in the sequence, rather than being carried through space by a persistent material entity. In standard notation, the momentum associated with a photon reflects the rate at which reconciliation energy E is finalized per unit propagation speed c, yielding the familiar relation $p = E/c$ without invoking a traveling massive object.

  In this sense, a photon has no rest mass because no enduring topological defect traverses the medium. However, when a reconfiguration sequence terminates on a stabilized defect (such as an atom or macroscopic body), the final bond update cannot be passed further. The associated reconciliation stress is transferred to the defect as a change in its motion. Radiation pressure and momentum transfer thus arise as the mechanical consequence of terminating a massless reconfiguration cascade on a massive topological defect.

- **Forced defect export (neutrinos):** In near-critical regimes where neither relational buffering nor photon-mediated finalization is sufficient, unresolved lattice mismatch must be stabilized and exported as a persistent topological defect. Neutrinos are interpreted within this framework as minimal, weakly coupled defects generated when lattice update thresholds are exceeded. Their small but nonzero mass reflects the irreducible cost of defect stabilization, while their weak coupling indicates limited geometric participation in the condensed lattice. Neutrino emission thus represents forced finalization of reconfiguration debt rather than incremental reconciliation.

Entanglement as deferred reconciliation. Entanglement plays a dual but unified role within this framework. While worldlines remain causally separated, entanglement encodes unresolved reconfiguration as relational constraints without enforcing final state agreement. When such worldlines later interact or reunite, the same relational structure prescribes how accumulated histories must be synchronized. In this sense, entanglement is not an independent dynamical channel, but a deferred reconciliation protocol that becomes operative precisely when propagation channels re-engage.

Time as reconciliation accounting. Within the condensed spacetime phase, time is not identified with the instantaneous lattice configuration nor with local matter interaction rates. Instead, elapsed time corresponds to the cumulative reconciliation required to maintain global consistency between distinct reconfiguration histories. Atomic processes do not slow intrinsically; rather, clocks embedded in regions of differing strain require different densities of underlying lattice updates to complete identical internal cycles.

Whenever an atom emits a photon, the emission event is itself a finalized lattice update. The frequency of the emitted photon encodes the reconciliation cost of the corresponding transition. When Observer A receives photons emitted by clocks or processes in a region occupied by Observer B, A does not access B's configuration directly. A samples B's reconciliation history as encoded in the arriving photon stream and compares it to the local update density of A's own region.

If B occupies a region of higher strain or stronger gravitational potential, more underlying lattice updates are required to complete the same internal cycle. The photons emitted by B therefore encode a higher reconciliation cost per cycle but are received by A at a lower frequency relative to A's own clocks. To A, B's processes appear slowed. This is not an illusion but a direct manifestation of differing reconciliation densities when histories are compared via exchanged photons.

The effect is symmetric. Each observer samples the other through photons whose frequencies encode the source-region reconciliation density, and each evaluates those records against a distinct local cost basis. There is no global clock and no preferred frame, only exchanged reconciliation records.

Reconciliation does not occur instantaneously at reunion. Instead, photon-mediated bond updating progressively integrates accumulated histories as causal contact increases. Because reconciliation has been amortized throughout the evolution, no observable discontinuity or "snap" is produced upon worldline reunion. The smoothness of observed reunions is therefore a structural consequence of distributed reconciliation.

Photon propagation and interference. The same ontology provides a natural interpretation of interference phenomena such as the double-slit experiment. In a reconfigurable lattice, a photon is a distributed sequence of bond reconfigurations exploring all causally available update paths. When multiple apertures are present, the lattice admits multiple compatible reconfiguration pathways around the obstruction. These pathways propagate concurrently and recombine downstream, where the local pattern of allowed and disallowed updates reproduces the observed interference structure.

Detection corresponds to terminating the reconfiguration cascade on a persistent defect in the detector medium. At that point, the lattice can no longer sustain a distributed update, and unresolved reconfiguration must be finalized as a single localized outcome. The apparent "collapse" of a delocalized description is therefore reinterpreted as forced settlement of a distributed reconfiguration process, not as a change in ontological category.

Unified interpretation. Entanglement, photons, and neutrinos are not competing mechanisms but distinct operational limits of a single reconfiguration process. Entanglement stores unresolved updates below threshold, photons incrementally finalize reconfiguration while mediating force and momentum transfer, and neutrinos stabilize and export irreducible mismatch near criticality. Together, these mechanisms maintain global consistency of a discrete, reconfigurable spacetime substrate without introducing preferred frames, superluminal signaling, or violations of emergent relativistic causality.

Photons as structured information carriers. The ability of light to transmit coherent spatial information—such as phase, polarization, interference structure, and focus—precludes an interpretation of photons as purely ballistic, featureless particles propagating through an empty geometric background. Within the TQS framework, photon propagation is understood as a sequence of locally finalized lattice-reconciliation events, whose collective structure encodes relational constraints imposed along the propagation path. Visual information is therefore not carried by particle impacts alone, but by the distributed pattern of allowed and disallowed substrate updates. Observation corresponds to the termination and comparison of these structured update sequences, implying that spacetime functions as an active, high-fidelity information-transmitting medium rather than a passive arena.

Polarization as evidence of substrate structure. The existence of polarization provides a particularly direct indication that electromagnetic propagation does not occur in a featureless void. Polarization distinguishes between transverse modes that differ only by orientation, a distinction that would be meaningless in the absence of internal relational structure. Within the present framework, polarization labels which transverse reconfiguration channels of the spacetime substrate are being excited by a propagating update sequence. Although the substrate remains statistically isotropic at macroscopic scales, local relational anisotropies arising from bond connectivity and strain alignment permit orientation-dependent propagation. Polarizing media therefore act not by blocking particles, but by selectively admitting reconfiguration pathways compatible with their own internal relational alignment. In this sense, polarization reflects an intrinsic property of the spacetime medium itself rather than an abstract attribute imposed on propagation through empty geometry.

Strong and weak interactions. The preceding discussion establishes that a mechanically consistent, reconfigurable spacetime substrate generically requires multiple reconfiguration channels, distinguished by their locality, reversibility, and threshold behavior. While the present work does not attempt to derive the full structure of the Standard Model, it is nevertheless instructive to note that two additional classes of reconfiguration behavior appear to be structurally unavoidable within the same ontology.

First, the existence of composite, tightly bound defects (such as atomic nuclei) requires a mechanism by which local relational connectivity becomes nonlinearly locked once a critical bond-saturation threshold is exceeded. Absent such a mechanism, extended defects would generically fragment under ambient lattice strain or shear, preventing the formation of stable, localized composite structures. This suggests a natural ontological role for an interaction characterized by confinement, nonlinearity, and increasing restoring cost under separation. In the present framework, these features are consistent with interpreting the strong interaction as a connectivity locking regime of the lattice: a constraint on allowable reconfiguration pathways once bond saturation is reached, rather than a long-range propagating force.

Second, a reconfigurable substrate that supports persistent defects must also admit rare but decisive processes in which defect identity itself is altered. Certain forms of reconfiguration cannot be accomplished through incremental bond updating or elastic relaxation alone; they require topology-changing transitions in which relational bookkeeping is irreversibly reassigned. Such transitions are necessarily weakly coupled, short-ranged, and probabilistic, as they correspond to discrete updates of defect structure rather than continuous deformation. Within this ontology, these features align naturally with the phenomenology of the weak interaction, which may be interpreted as the channel through which irreversible topological reconfiguration of defects is permitted, accompanied by the export of reconciliation mismatch through neutrinos as discussed above.

In this sense, the strong and weak interactions need not be introduced as independent fundamental forces acting on an otherwise inert spacetime background. Rather, they occupy distinct operational limits of the same underlying reconfiguration dynamics already required for photons, entanglement, neutrinos, and gravity. The strong interaction corresponds to the saturation and locking of relational connectivity, while the weak interaction corresponds to discrete topology-changing reconciliation events. Both emerge as structural necessities of a finite, elastic, and dynamically reconfigurable spacetime substrate, even though their detailed quantitative dynamics lie beyond the scope of the present work.

Limitations. This discussion is strictly qualitative. No attempt is made here to derive detailed quantum dynamics, neutrino flavor structure, or interaction cross-sections. The purpose is solely to note that a mechanically consistent spacetime substrate appears to require relational, incremental, and defect-based channels for reconfiguration transport, and that known physical phenomena naturally populate these roles.

8.11 Color Confinement and the Strong Interaction

Scope and status. The present work does not attempt a derivation of quantum chromodynamics or the full non-Abelian gauge structure of the strong interaction. The purpose of this section is instead ontological: to identify the structural role occupied by color degrees of freedom within the TQS framework and to explain, at a mechanical level, why confinement-like behavior is generically required once localized defects enter a regime of saturated reconfiguration.

Strong interaction as internal reconfiguration saturation. In TQS, long-range interactions are mediated by propagating reconfiguration channels (photons) or exported defect modes (neutrinos). The strong interaction corresponds to a qualitatively distinct regime in which neither incremental finalization nor defect export is available. Instead, unresolved reconfiguration must be accommodated entirely within a tightly localized composite structure.

This occurs when the local reconciliation demand associated with a defect exceeds the capacity of photon-mediated updates, but where export of a new defect would violate conservation or stability constraints. In this regime, reconfiguration cannot be released outward and must instead circulate internally. The strong interaction is thus identified as the saturation limit of local reconfiguration, in which strain is trapped and redistributed within a composite defect rather than propagated away.

Color as internal reconciliation routing. Within a three-dimensional condensed substrate, internal reconfiguration circulation admits a minimal number of independent, non-collapsing routing channels. Fewer than three channels fail to support volumetric closure and collapse under shear; more than three introduce redundant routing that is energetically unstable. As a result, stable internal circulation generically organizes into three independent channels.

These channels correspond phenomenologically to color degrees of freedom. Color is therefore not interpreted as a spatial direction, particle label, or additional field, but as an internal bookkeeping structure that tracks how unresolved reconfiguration is routed within a confined composite defect. Individual color charges cannot be isolated because doing so would require breaking the closed circulation of reconciliation, inducing lattice failure. This provides a mechanical origin for confinement.

Quarks as partial, directionally biased defects. Within this picture, quark-like excitations are not free particles but partial, orientation-dependent strain defects whose reconfiguration load occupies a specific internal routing channel. Composite hadrons correspond to closed, color-neutral configurations in which internal circulation is complete. Attempts to separate quark constituents do not liberate isolated color charges; instead, they increase the length and tension of internal reconfiguration pathways, raising the energetic cost until new defect pairs are created.

Gluons as re-routing operations. Reconfiguration transfers between internal routing channels are mediated by localized update operations that modify how strain is distributed among the channels. These operations correspond to gluon-like excitations. Because such re-routing changes the internal bookkeeping itself, gluons necessarily interact with one another, reflecting the non-Abelian character of the effective description. In TQS terms, this behavior arises from the self-coupling of internal reconfiguration routing rather than from an imposed gauge symmetry.

Relation to standard descriptions. The emergence of three internal routing channels provides an ontological substrate for the observed SU(3) color structure of the strong interaction without assuming it as a fundamental input. No claim is made that this section derives the quantitative content of QCD. Rather, the argument establishes that once a discrete, elastic spacetime substrate supports localized defects operating beyond the photon-mediated regime, confinement and threefold internal routing are mechanically unavoidable.

Interpretive summary. In TQS, the strong interaction is not a separate force layered atop spacetime, but the inevitable behavior of reconfiguration when local strain saturation precludes both propagation and export. Color degrees of freedom label internal reconciliation routes within confined defects, and confinement reflects the impossibility of maintaining coherent, open-ended routing in a finite, locally reconcilable lattice. This placement completes the ontological map of known interaction channels without extending the formal claim surface of the present work.

Weak interaction and flavor change. Within the TQS framework, the weak interaction is interpreted not as a long-range force or a binding interaction, but as a mechanism for defect reclassification under conditions where internal structure can no longer be maintained consistently. Unlike electromagnetic interactions, which redistribute reconfiguration incrementally, or strong interactions, which confine unresolved reconfiguration internally, the weak interaction governs transitions between distinct defect classes.

In this ontology, flavor labels correspond to discrete internal configurations of a localized defect that encode how reconfiguration is routed, stored, and released. Under sufficiently high reconfiguration stress, certain internal configurations become unstable and must reorganize into alternative, admissible forms. Such transitions require the emission or absorption of a weakly coupled export channel to preserve global reconciliation consistency.

Neutrinos naturally occupy this role. As minimal, weakly interacting defects, they carry away the bookkeeping difference associated with a change in internal defect structure. Flavor-changing processes therefore correspond to forced reclassification events in which a defect transitions between nearby internal configurations while exporting the reconciliation mismatch through neutrino emission.

This interpretation accounts qualitatively for the defining features of the weak interaction: its short range, its association with neutrinos, its violation of certain internal symmetries, and its role in particle transmutation rather than force mediation. No detailed model of weak gauge structure is assumed here; the purpose of this remark is solely to identify the ontological function served by weak processes within a discrete, reconfigurable spacetime substrate.

9 Electromagnetism as Reconfiguration Dynamics

Scope and status. Earlier sections on reconfiguration transport treat photons phenomenologically as propagating chains of bond reconfiguration events that carry energy and momentum without transporting persistent defects. Appendix B sketches how a minimal $U(1)$ gauge sector can be realized directly on lattice bonds. The purpose of this section is to synthesize those elements into a single operational picture of electromagnetism in TQS and to show how the Lorentz force law arises from reconfiguration dynamics in a discrete, elastic substrate. No new empirical claims are made; the discussion is architectural and interpretive.

9.1 Lattice gauge structure and photon channel

We represent the condensed spacetime substrate by a graph $G = (V, E)$, with nodes $x \in V$ and bonds $(x, y) \in E$ linking neighboring sites. Following Appendix B2, each oriented bond (x, y) carries a phase variable

$$U_{xy} = e^{i\theta_{xy}} \in U(1), \qquad U_{yx} = U_{xy}^{-1}, \tag{21}$$

encoding a reversible reconfiguration angle between neighboring sites. Local redundancy in the choice of reference phase at each node,

$$\theta_{xy} \;\mapsto\; \theta_{xy} + \alpha_x - \alpha_y, \tag{22}$$

is interpreted as a $U(1)$ gauge symmetry: only gauge-invariant combinations of bond phases correspond to distinct physical states.

Given U_{xy} on bonds, the oriented product around an elementary plaquette p,

$$U_p = \prod_{(x,y)\in p} U_{xy} = e^{i\Phi_p}, \tag{23}$$

defines a gauge-invariant phase Φ_p that measures the net reconfiguration curvature associated with that loop. In the continuum limit, the collection $\{\Phi_p\}$ encodes the field strength $F_{\mu\nu}$; spatial plaquettes correspond to magnetic flux.

Time variation of θ_{xy} defines a discrete electric field E_{xy} on bonds. A minimal gauge-sector Hamiltonian takes the schematic form

$$H_{U(1)} \;\sim\; \sum_p \kappa_p\big(1 - \cos\Phi_p\big) \;+\; \frac{1}{2}\sum_{(x,y)} E_{xy}^2, \tag{24}$$

which reduces in the weak-field, long-wavelength limit to a Maxwell-like quadratic form

$$H_{U(1)} \;\approx\; \frac{1}{2}\int d^3x\,\big(\mathbf{E}^2 + \mathbf{B}^2\big). \tag{25}$$

Here **E** and **B** arise as continuum descriptions of bond-wise reconfiguration gradients and plaquette-wise reconfiguration curvature, respectively.

Within this structure, photons correspond to coherent, transverse normal modes of the coupled (θ_{xy}, E_{xy}) system: they are propagating waves of bond reconfiguration that transport reconciliation energy at finite speed c without carrying persistent topological defects. This realizes the photon channel of the reconfiguration transport framework in explicit gauge-theoretic form.

9.2 Charges as defect-induced Gauss law imbalance

Massive excitations in TQS are modeled as persistent topological defects of the condensed lattice. In the present language, an electrically charged defect at node x is characterized by a localized mismatch in the bond-phase and electric-field configuration such that a discrete Gauss law is violated:

$$\sum_{y\sim x} E_{xy} = q_x, \tag{26}$$

where $y \sim x$ denotes neighbors of x and q_x is the effective charge. Physically, $q_x \neq 0$ signals that local reconfiguration demands cannot be fully neutralized by bond updates alone; a persistent defect remains that sources ongoing reconfiguration dynamics.

In this picture, electric charge is not a fundamental label attached to a point-like object. It is a measure of the persistent reconfiguration imbalance imposed by a defect on its surrounding bonds. The familiar Coulomb field emerges as the configuration of θ_{xy} and E_{xy} that minimizes the reconfiguration cost subject to this discrete Gauss constraint.

9.3 Electric force as reconciliation gradient

The TQS ontology identifies mass and inertia with the energetic cost of lattice reconfiguration. A defect experiences a force when reconciliation impulses transmitted along its attached bonds fail to cancel. In the continuum description, this imbalance is captured by the gradient of stored reconfiguration energy $U(\mathbf{x})$.

For a charge q in an electric field $\mathbf{E}$, the local reconfiguration cost decreases fastest along $-\mathbf{E}$. The defect is therefore driven in the direction of decreasing cost, yielding

$$\mathbf{F}_E = -\nabla U = q\,\mathbf{E}. \tag{27}$$

In TQS terms, the electric force is the net reconciliation impulse on a defect due to spatial variation in unresolved bond-update demand. A static electric field is a biased eligibility landscape for reconfiguration; charged defects move down that bias.

9.4 Magnetism as necessary circulation of update flow

When a charged defect moves with velocity $\mathbf{v}$ through the lattice, it drags its Gauss-law imbalance along its worldline. Because reconfiguration signals propagate at finite speed c through the photon channel, the surrounding field cannot adjust instantaneously to the defect's new position. Regions ahead of the defect and regions in its wake experience different reconciliation demands, and the bond-update flow develops circulation around the path of motion.

This circulating component of the reconfiguration flow is the magnetic field $\mathbf{B}$ in continuum language. It is not an independent substance, but the curl of the bond-update pattern required to maintain reconciliation consistency for moving defects in a finite-speed, discrete medium.

Two structural facts follow:

- Stationary charges generate electric fields but no circulation; their reconfiguration imprint is purely gradient-like.
- Moving charges generate both gradients and circulation: a charge that traverses the lattice at velocity $\mathbf{v}$ necessarily induces a curl in the update flow, whose strength is proportional to $|\mathbf{v}|$ and to the existing field configuration.

Requiring that different inertial observers assign compatible reconfiguration histories to the same process then forces the electric and magnetic sectors to mix under frame changes. A configuration that is purely electric in the rest frame of a charge appears as a combination of electric and magnetic fields in a frame where the charge is moving. Magnetism is thus not optional; it is the minimal structural response of a reconfigurable substrate that carries photon-like update waves at finite speed while preserving frame-independent reconciliation bookkeeping.

9.5 Lorentz force as transverse reconciliation impulse

In the TQS ontology, the total force on a charged defect is the net reconciliation impulse transmitted through its attached bonds. The electric contribution drives motion along the gradient of reconfiguration cost, $\mathbf{F}_E = q\,\mathbf{E}$. The magnetic contribution arises because a moving charge interacts anisotropically with the circulating update flow it both sources and traverses.

Qualitatively, the lattice must satisfy three constraints:

- No magnetic force on a stationary charge: $\mathbf{F}_B = 0$ if $\mathbf{v} = 0$.
- No work done by a purely magnetic field: the magnetic contribution is orthogonal to $\mathbf{v}$.

- Linear response at low velocities: $\mathbf{F}_B$ is proportional to q and to $\mathbf{v}$.

The unique vector structure satisfying these constraints and consistent with the curl-based definition of $\mathbf{B}$ is a force of the form

$$\mathbf{F}_B = q\,\mathbf{v} \times \mathbf{B}, \tag{28}$$

so that the total force becomes

$$\boxed{\mathbf{F} = q\big(\mathbf{E} + \mathbf{v} \times \mathbf{B}\big)}. \tag{29}$$

In TQS terms, the $\mathbf{v} \times \mathbf{B}$ term encodes the transverse reconciliation impulse on a moving defect due to its passage through a circulating bond-update field. The direction of the force is set by the orientation of that circulation relative to the defect's motion; its magnitude is set by the product of the charge q, the speed $|\mathbf{v}|$, and the local circulation strength $|\mathbf{B}|$.

9.6 Relation to reconfiguration transport and outlook toward the Standard Model

Earlier sections on reconfiguration transport characterized photons, neutrinos, and entanglement as three complementary regimes of lattice reconfiguration transport: relational buffering, incremental finalization, and forced defect export. The present section refines the photon channel by exhibiting an explicit $U(1)$ gauge structure on lattice bonds and by showing how electric and magnetic fields arise as gradient and circulation components of the same underlying bond-update dynamics.

Within this picture:

- Entanglement encodes unresolved reconfiguration below the threshold for propagating updates.
- Photon modes are coherent bond-update waves that transport and gradually settle this debt when causal contact is restored.
- Charged defects appear as persistent Gauss-law imbalances that source long-range reconfiguration patterns interpreted as electromagnetic fields.
- The Lorentz force law expresses the net reconciliation impulse on such defects due to both gradients and circulation of the bond-update field.

Electromagnetism in TQS is therefore not an additional structure imposed on spacetime, but the organized, gauge-redundant limit of a particular reconfiguration channel of the same discrete substrate that supports gravity and massive defects. A quantitative derivation of full Standard Model charge assignments, non-Abelian sectors, and fermionic excitation spectra would require extending this construction to richer internal symmetries and defect classes. That task lies beyond the scope of the present work, but the architecture outlined here indicates where such structures would live and how they would inherit their dynamics from the underlying lattice.

9.7 Distinct Substrate Responses: Gravity and Electromagnetism

Although both gravity and electromagnetism arise within the same condensed spacetime substrate, they correspond to fundamentally different response channels of the medium. Conflating them obscures the structural economy of the framework.

Electromagnetism corresponds to a *directional bias in bond-phase reconfiguration*. A charged defect imposes an orientation-sensitive strain on the surrounding lattice, producing preferred update directions. Photons represent coherent phase transport of this directional reconfiguration. Electromagnetic interactions therefore depend on the presence and sign of charge and act only on defects carrying the appropriate coupling. In this sense, electromagnetism is a selective interaction mediated by bond-orientation structure.

Gravity, by contrast, does not require directional bond bias or phase orientation. It corresponds to the *collective shear response* of the condensed lattice to energy density. Any localized excitation—charged or neutral, fermionic or bosonic—modifies the reconciliation cost of nearby reconfiguration. This modification appears at long wavelengths as curvature of effective geodesics. Importantly, no preferred bond direction is required for gravitational response; gravity reflects the elastic deformation of the substrate as a whole rather than reorientation of specific bonds.

This distinction explains several observed features:

- Gravity couples universally to energy-momentum because all excitations contribute to local reconciliation cost.
- Electromagnetism couples selectively because only defects carrying bond-phase asymmetry generate directional bias.
- Gravitational propagation in the infrared limit corresponds to long-wavelength shear modes of the medium, whereas electromagnetic propagation corresponds to phase-coherent bond reconfiguration.

Thus gravity is not the macroscopic limit of electromagnetism, nor is electromagnetism a microscopic fragment of gravity. They are distinct mechanical responses of the same underlying substrate: one elastic and geometry-defining, the other phase-transport and orientation-defining.

9.8 Interpretation of the Fine-Structure Constant

Having identified electric charge as persistent reconfiguration imbalance, we now ask whether the strength of that imbalance is itself structurally constrained.

The dimensionless fine-structure constant,

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c},$$

controls the strength of electromagnetic coupling in the Standard Model. Its numerical value,

$$\alpha^{-1} \approx 137,$$

has long resisted derivation from deeper principles.

Within the present framework, α acquires a structural interpretation. Electromagnetic interactions correspond to orientation-sensitive reconfiguration of bond phases in the condensed spacetime substrate. Stabilizing a minimal charge defect therefore requires a finite fraction of the locally available reconfiguration bandwidth.

We may thus interpret α as the dimensionless ratio between:

- the reconciliation cost required to stabilize a unit charge defect, and
- the total local reconfiguration capacity of the substrate.

In this view, α measures the fraction of available electromagnetic reconfiguration bandwidth consumed by a minimal charge excitation.

This interpretation naturally aligns with the well-known relativistic saturation condition $Z\alpha \sim 1$, which marks the onset of instability in high-Z atomic systems. As nuclear charge increases, the cumulative electromagnetic strain demand scales proportionally to $Z\alpha$. When this demand approaches unity, the required reconciliation cost saturates the available local bandwidth, and the bound-state structure becomes unstable.

In conventional quantum electrodynamics, this appears as a breakdown of the Dirac spectrum at large Z. In the present framework, it is interpreted as a mechanical saturation of substrate reconfiguration capacity.

No claim is made here to derive the numerical value of α. Rather, the constant is reinterpreted as a structural parameter of the quenched spacetime medium. Determining whether specific microscopic connectivity statistics yield $\alpha^{-1} \sim 10^2$ is left to future work involving an explicit lattice Hamiltonian.

10 Observational Consequences and Phenomenology

10.1 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.

10.2 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.

Agreement in these regimes is a non-negotiable requirement; significant deviations would falsify the framework.

10.3 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.

10.4 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.

10.5 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.

10.6 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.

10.7 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.

10.8 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.

10.9 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.

11 Synthesis, Conceptual Implications, and Outlook

11.1 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.

11.2 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.

11.3 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.

11.4 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.

11.5 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.

Scope, contestability, and empirical leverage. The absence of generic low-energy deviations in the present framework should be understood as a consequence of its starting assumptions rather than a limitation of ambition. If spacetime functions as a condensed, elastic substrate, then its infrared behavior is necessarily governed by the same universal constraints that underwrite general relativity and standard quantum phenomenology.

Empirical leverage is therefore expected not where spacetime behaves smoothly, but where it is forced into regimes of extreme strain, rapid reconfiguration, or topological stress. Black hole ringdowns, high-curvature gravitational wave events, and the transport of quantum coherence through dynamically curved backgrounds provide natural arenas in which such effects may manifest. The extent to which additional signatures arise will depend on the detailed realization of the microscopic dynamics, which lies beyond the scope of the present work.

11.6 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.

Where conventional approaches seek to quantize gravity, the present framework may instead be viewed as "general relativitizing" quantum phenomena—treating quanta not as fundamental objects placed upon spacetime, but as emergent bookkeeping structures required to preserve relativistic consistency within a discrete, reconfigurable substrate. In this view, the extended microscopic structures often informally referred to as "strings" are not auxiliary ingredients nor effective stand-ins, but the minimal residual structures that persist once spacetime condenses out of a pre-geometric quench. They represent the irreducible connective elements through which the substrate maintains coherence, elasticity, and finite reconciliation capacity. Geometry, fields, and particles are not layered atop these structures; they are different large-scale descriptions of how this underlying fabric bears strain, transmits excitation, and holds itself together.

In this sense, what unites general relativity and quantum field theory is not abstraction, but tension: a physical thread from which both curvature and quanta are woven.

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.

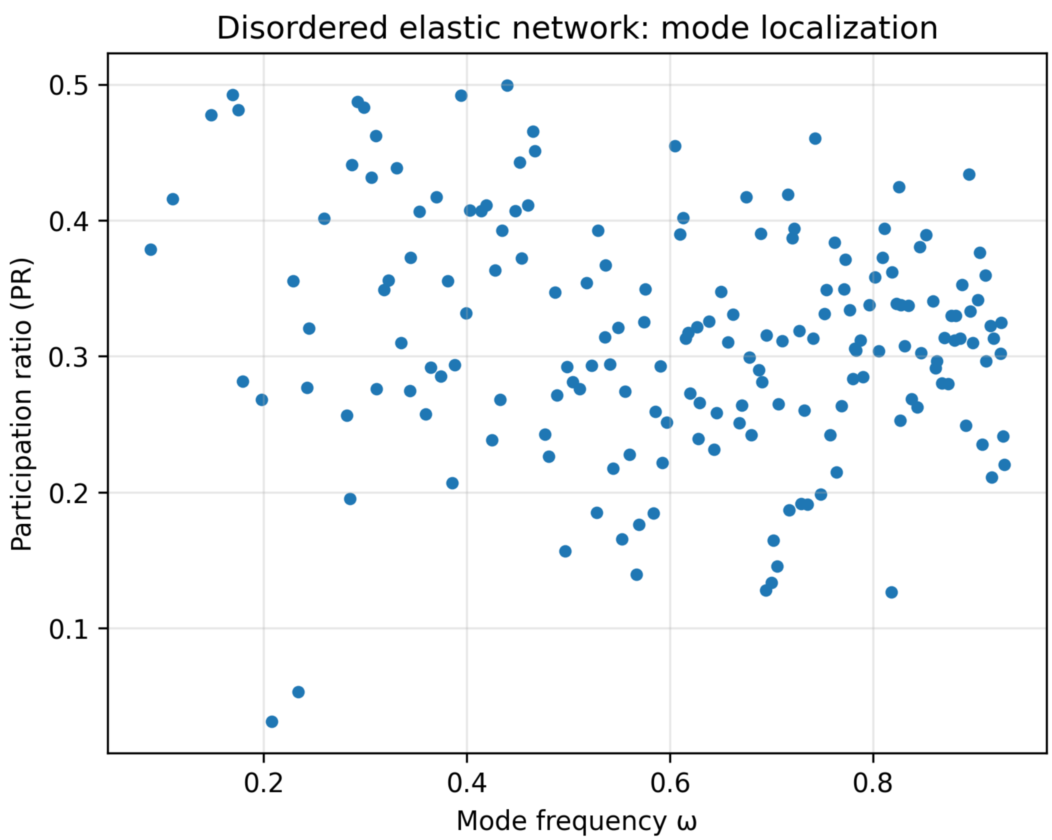

Figure A1: Participation ratio (PR) versus mode frequency ω for a representative disordered elastic network. Low-PR modes are spatially localized, while higher-PR modes are extended across the network. This provides a basic localization diagnostic for the low-lying spectrum.

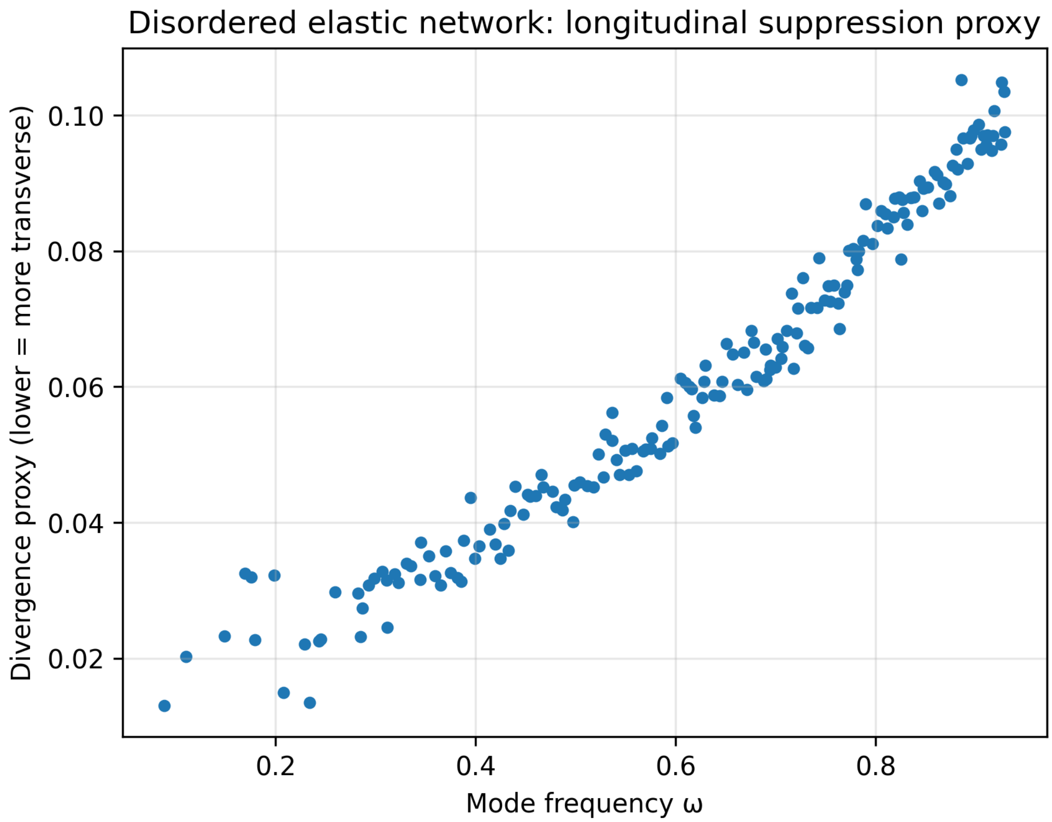

Figure A2: Longitudinal-content proxy ("divergence proxy") versus mode frequency ω. Lower values correspond to increasingly transverse (shear-dominated) relative motion on the bonds. The extended sector clusters toward low divergence, consistent with suppression of compressional content in the long-wavelength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

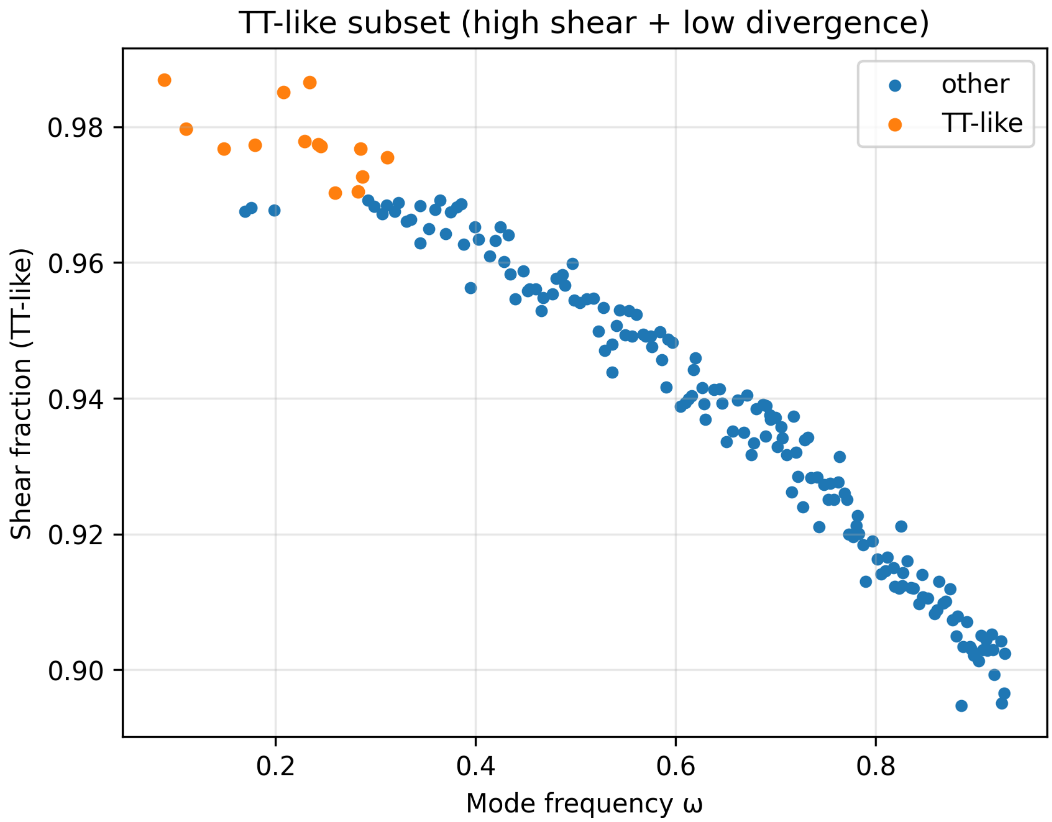

Figure A3: Shear fraction versus mode frequency ω, with a TT-like subset highlighted. "TT-like" here denotes modes that satisfy purely kinematic criteria: high shear fraction together with low divergence proxy. This classification is meant as an illustrative proxy for shear-dominated, approximately transverse 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: 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.

B1 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.

B2 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.

B3 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.

B4 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.

Disorder as a structural consequence of capacity. The resolution of null capacity into an extended three-dimensional arena does not generically produce a crystalline or regularly ordered lattice. A perfectly ordered grid would require the prior selection of preferred directions, orientations, or basis vectors, none of which are available at the null or capacity stage. Once relational degrees of freedom exist, local reconfiguration paths admit continuous angular variation, and bond formation proceeds without global alignment constraints. The resulting spacetime substrate is therefore disordered at the microscopic level while remaining statistically isotropic and homogeneous at large scales. This disordered connectivity is not a defect but a requirement: it prevents global rigidity, suppresses preferred frames, and permits elastic accommodation of curvature, wave propagation, and defect motion without tearing. In this sense, spacetime does not remain coherent because it is rigidly ordered, but because no larger-scale ordered structure can survive reconciliation without failure.

B5 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.

B6 Tachyonic Instability (Pre-Geometric)

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

$$\left.\frac{d^2V}{d\phi^2}\right|_{\phi=0} < 0. \tag{30}$$

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.

B7 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.

B8 Residual Structure and Extended Degrees of Freedom

The microscopic disorder implied by unconstrained dimensional capacity plays a central role in determining which residual structures can survive the pre-geometric quench. 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 relational 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 string-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.

B9 Minimal relational scale and resolution of capacity

In the preceding discussion, null was characterized as the absence of definable relational structure, and the emergence of spacetime as the resolution of capacity arising from that indefiniteness. Once capacity resolves into a finite-dimensional arena, however, reconciliation locality imposes strict constraints on how relational structure may persist.

Within a condensed spacetime phase, all reconfiguration must be locally reconcilable. Relational updates that span multiple update neighborhoods introduce incompatible reconciliation demands and therefore cannot remain coherent. As a result, extended relational elements that exceed a minimal local scale are dynamically unstable and are fragmented by the lattice itself. Such fragmentation is not driven by energetic weakness but by the logical incompatibility of sustaining nonlocal reconciliation in a discrete, reconfigurable medium.

Conversely, further subdivision of relational structure below a certain scale destroys definability entirely. Below this threshold, connectivity collapses back into null reconfiguration, and no stable relational bookkeeping is possible. The spacetime lattice therefore admits neither arbitrarily small nor arbitrarily large relational elements.

The characteristic microscopic scale of the lattice thus arises as a necessary consequence of reconciliation locality rather than as an imposed cutoff or material parameter. Relational elements persist not because they are strong, but because nothing smaller can exist and nothing larger can survive. In this sense, the Planck scale is identified as the minimal stable resolution of relational capacity in a finite-dimensional, dynamically reconfigurable spacetime substrate.

B10 Transition to the Main Text

The finite relational scale discussed above supplies the microscopic cutoff implicitly assumed in the elastic analysis of 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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