Shared Structural Features in Emergent Gravity Approaches

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Abstract

A wide range of contemporary approaches to emergent gravity treat classical spacetime geometry not as a fundamental structure but as an effective description that becomes valid only within particular physical regimes. This family of approaches includes thermodynamic formulations of gravity, entanglement-based and holographic constructions, and pre-geometric frameworks in which spacetime arises from fundamentally non-spatial degrees of freedom. Although these programs differ substantially in their microscopic assumptions, mathematical tools, and motivating principles, they nevertheless exhibit a set of strikingly similar structural commitments concerning the status, scope, and breakdown of spacetime geometry.

In this work, we develop a detailed comparative synthesis of these approaches, focusing on the shared features that recur across them rather than on their technical differences. We argue that, taken together, these features support a unified interpretive perspective in which classical spacetime geometry functions as a stable macroscopic regime that arises only under specific conditions, remains robust against microscopic variation within those conditions, and ceases to be applicable outside them. This perspective closely parallels the role played by macroscopic phases in other areas of physics, where collective descriptions emerge from underlying degrees of freedom and are meaningful only within restricted regions of parameter space.

The aim of this paper is not to propose a new model of emergent gravity or to privilege one existing framework over others. Instead, it seeks to make explicit a structural perspective that is already implicit across several influential research programs. By articulating this shared structure in a model-agnostic way, the analysis clarifies points of convergence within emergent gravity research, highlights the conceptual unity underlying diverse approaches, and provides a coherent framework for understanding how spacetime geometry can emerge as an effective description without being fundamental.

1 Introduction

The possibility that classical spacetime geometry is not a fundamental constituent of physical reality but an emergent, effective description has become an increasingly prominent theme in contemporary research on quantum gravity [1–3]. This idea represents a significant departure from the traditional view, inherited from general relativity, in which spacetime provides the basic arena in which physical processes unfold. Instead, a growing body of work suggests that spacetime itself may arise only under appropriate physical conditions from more primitive, non-geometric degrees of freedom.

This shift in perspective is motivated by a range of considerations. On the one hand, attempts to quantize gravity using conventional methods encounter deep conceptual and technical difficulties, many of which appear to stem from treating spacetime geometry as fundamental at all scales [4,5]. On the other hand, insights from black hole thermodynamics and quantum information theory have suggested that macroscopic geometric behavior may reflect collective phenomena rather than microscopic structure [6, 7]. Together, these developments have encouraged the exploration of frameworks in which spacetime is understood as emergent rather than fundamental.

Over the past several decades, this idea has been developed within a number of distinct research programs. Among the most influential are thermodynamic approaches to gravity, which reinterpret the Einstein field equations as equations of state arising from underlying microscopic degrees of freedom [1–3]; entanglement-based and holographic approaches, which relate geometric structure to patterns of quantum entanglement [8–11]; and pre-geometric approaches, such as group field theory and loop quantum gravity, in which spacetime is constructed from fundamentally non-spatial constituents [4, 12, 13].

These programs differ widely in their technical implementations and in the kinds of microscopic entities they posit. Thermodynamic approaches typically remain agnostic about the detailed nature of spacetime microstates, focusing instead on general statistical and thermodynamic principles [1–3]. Entanglement-based approaches often rely on specific quantum field-theoretic or holographic settings, where entanglement measures can be related to geometric quantities [8–11]. Pre-geometric approaches introduce explicit microscopic building blocks, such as combinatorial, algebraic, or network-like structures, from which spacetime geometry is recovered only in suitable limits [4,12,13].

Despite these differences, a common pattern emerges when one examines how spacetime geometry is treated across these approaches. In each case, general relativity is regarded not as a universally valid description but as an effective theory that applies only within a restricted regime [1, 14]. Spacetime geometry is associated with large-scale, coarse-grained behavior and is expected to lose its applicability under extreme conditions, such as at very small length scales, high energies, or strong curvature [14]. The breakdown of geometry is not treated as a failure of the theory but as an indication that the effective description has reached the limits of its domain of validity.

The purpose of this paper is to examine this shared structural pattern in detail and to articulate its implications in a model-agnostic way. Rather than advancing a new proposal for the microscopic origin of spacetime, the analysis focuses on the conceptual commitments that recur across several influential emergent gravity programs. By making these commitments explicit, we aim to clarify the sense in which classical spacetime geometry can be understood as a stable macroscopic regime analogous to a phase in other areas of physics [15–17].

This interpretive perspective does not require that all emergent gravity approaches adopt identical mechanisms or mathematical structures. Nor does it imply that the emergence of spacetime must occur in the same way in every framework. Instead, it highlights a common structural view: that spacetime geometry is contingent, regime-dependent, and emergent from underlying degrees of freedom whose detailed nature may vary from one approach to another.

The paper is organized as follows. In Section II, we review thermodynamic, entanglement-based, and pre-geometric approaches to emergent gravity, emphasizing how each treats the status of spacetime geometry. Section III examines the notion of regime dependence and stability, drawing out parallels with macroscopic phases in other physical systems. Section IV develops a unified structural interpretation that captures the shared features of these approaches. Section V addresses why explicit phase-theoretic language has largely remained implicit in the literature, despite the prevalence of phase-like behavior. Section VI clarifies the scope and limits of the present analysis, emphasizing what it does and does not claim. Finally, Section VII summarizes the main conclusions and discusses potential implications for future research.

2 Emergent Gravity Programs

The term "emergent gravity" encompasses a broad class of approaches that share a common departure from traditional formulations of general relativity. Rather than treating spacetime geometry as a fundamental structure defined at all scales, these approaches seek to explain gravitational dynamics and geometric behavior as arising from more primitive degrees of freedom. Although the specific nature of these degrees of freedom varies widely across different frameworks, emergent gravity programs tend to converge on a common methodological stance: classical spacetime is recovered only in certain limits, and its validity is restricted to particular physical regimes [1, 14].

This section reviews three influential strands within emergent gravity research: thermodynamic approaches, entanglement-based approaches, and pre-geometric approaches. The aim is not to provide an exhaustive survey of the technical literature, but rather to highlight how each strand treats the status, scope, and breakdown of spacetime geometry. By focusing on these structural features, we prepare the ground for a comparative analysis that brings their shared commitments into sharper relief.

2.1 Thermodynamic Approaches to Gravity

Thermodynamic approaches to gravity are among the earliest and most conceptually striking attempts to reinterpret gravitational dynamics as emergent phenomena. The central insight motivating these approaches is the observation that gravitational systems exhibit thermodynamic behavior, most notably in the context of black hole physics [6, 7]. The discovery that black holes possess entropy proportional to the area of their horizons and radiate thermally suggested a deep connection between geometry, entropy, and microscopic degrees of freedom.

Building on these insights, seminal work demonstrated that the Einstein field equations can be derived from thermodynamic considerations applied to local causal horizons [1]. In this framework, spacetime geometry is treated analogously to a macroscopic thermodynamic variable, while the underlying microscopic degrees of freedom remain unspecified. The Einstein equations appear not as fundamental laws but as equations of state characterizing the collective behavior of these degrees of freedom [1–3].

A key feature of thermodynamic approaches is their explicit emphasis on coarse graining. The geometric description of spacetime emerges only after averaging over microscopic details, much as temperature and pressure emerge in conventional thermodynamics. This averaging process renders the resulting description insensitive to the precise nature of the microstates, focusing instead on macroscopic quantities that characterize equilibrium or near-equilibrium configurations [2, 3].

Crucially, the thermodynamic perspective also delineates clear limits to the applicability of geometric descriptions. Thermodynamic relations are meaningful only within certain regimes, such as near equilibrium or at scales large compared to microscopic correlations. When these conditions are violated, the thermodynamic description breaks down, and with it the geometric interpretation of spacetime [14]. This breakdown is not treated as a failure of the theory but as an indication that the effective description has reached the boundaries of its domain of validity.

Later developments expanded the thermodynamic approach by exploring the role of entropy gradients, entropic forces, and holographic equipartition in generating gravitational dynamics [3, 18]. While these formulations differ in their details and assumptions, they retain the core idea that spacetime geometry and gravitational behavior arise from collective, statistical properties of underlying degrees of freedom. Across these variants, general relativity is consistently framed as an emergent, macroscopic description rather than a fundamental starting point.

2.2 Entanglement-Based and Holographic Approaches

Entanglement-based approaches to emergent gravity shift the focus from thermodynamic variables to quantum correlations. These approaches are motivated by the growing recognition that entanglement plays a central role in structuring quantum many-body systems and may likewise underlie the emergence of spacetime geometry [8, 19]. In this view, geometric relations reflect patterns of entanglement among underlying quantum degrees of freedom, rather than preexisting spatial structure.

This perspective has been developed most explicitly within holographic frameworks, where precise mathematical relationships can be established between entanglement measures in a quantum field theory and geometric quantities in a higher-dimensional spacetime [9–11]. Results linking entanglement entropy to minimal surfaces in the bulk provided some of the earliest concrete evidence that spacetime geometry might be encoded in quantum correlations [20].

Beyond specific holographic constructions, entanglement-based approaches emphasize more general principles. Spacetime connectivity, dimensionality, and curvature are understood as emergent features that arise when entanglement satisfies certain structural conditions, such as sufficient connectivity across scales or particular patterns of correlation [8, 19, 21]. When these conditions are absent, the geometric description ceases to be meaningful.

As with thermodynamic approaches, entanglement-based frameworks treat spacetime geometry as a collective, long-wavelength description. The microscopic details of the underlying quantum system are largely irrelevant to the emergent geometry, provided that the relevant entanglement structure is present. This insensitivity to microscopic detail is a hallmark of emergent behavior and reinforces the interpretation of spacetime as an effective macroscopic regime.

Importantly, entanglement-based approaches also anticipate the breakdown of geometry. Changes in entanglement structure, such as disentanglement or fragmentation, are associated with geometric transitions or the loss of spacetime connectivity [8, 22]. These breakdowns highlight the contingent nature of spacetime and underscore its dependence on underlying quantum correlations.

2.3 Pre-Geometric Approaches

Pre-geometric approaches to emergent gravity pursue the idea of spacetime emergence in a more literal sense, beginning from microscopic degrees of freedom that are not themselves spatial or geometric. Frameworks such as group field theory and loop quantum gravity exemplify this strategy by constructing spacetime from combinatorial, algebraic, or network-like elements that carry no direct geometric interpretation at the fundamental level [4, 5, 12, 13].

In these approaches, spacetime geometry emerges only through collective behavior in large ensembles of microscopic constituents. Techniques such as coarse graining, renormalization, and mean-field approximations play a central role in recovering effective geometric descriptions [12, 13]. Classical spacetime typically appears only in specific phases or condensate-like regimes, where many microscopic degrees of freedom act coherently.

The recovery of general relativity in pre-geometric approaches is therefore explicitly regime dependent. Outside the appropriate collective states, geometric notions such as distance, curvature, and dimensionality lose their meaning. This feature is not regarded as a defect but as a reflection of the fundamentally non-geometric nature of the underlying degrees of freedom [14].

Pre-geometric frameworks often provide the most explicit realizations of spacetime emergence, since they construct geometry from the ground up rather than reinterpreting existing geometric laws. At the same time, their technical complexity and model dependence make it challenging to extract general conclusions that apply across different formulations. Nevertheless, their structural treatment of spacetime aligns closely with that of thermodynamic and entanglement-based approaches.

Taken together, these three strands illustrate how diverse emergent gravity programs converge on a common view of spacetime geometry. Although they differ in their microscopic assumptions and technical tools, all treat geometry as an effective description that arises only under specific conditions and ceases to apply outside a restricted regime. This convergence provides the foundation for the unified structural interpretation developed in subsequent sections.

3 Regime Dependence and Stability

A defining feature shared across emergent gravity approaches is the explicit restriction of classical spacetime geometry to particular physical regimes. In contrast to the traditional view, where spacetime provides a universal backdrop applicable at all scales, emergent gravity programs consistently treat geometric descriptions as contingent, approximate, and domain-limited [1, 14]. Understanding how these regimes are defined, stabilized, and ultimately broken is therefore essential to clarifying the conceptual unity underlying otherwise diverse frameworks.

This section examines the notions of regime dependence and stability as they appear across thermodynamic, entanglement-based, and pre-geometric approaches. By analyzing how geometric descriptions arise, persist, and fail within each context, we show that spacetime geometry functions as a robust collective description only under specific conditions. These features closely parallel the behavior of macroscopic phases in other areas of physics, where emergent descriptions are meaningful only within restricted regions of parameter space [15–17].

3.1 Regime Dependence of Geometric Descriptions

In emergent gravity frameworks, the applicability of spacetime geometry is tied to the satisfaction of certain physical conditions. These conditions vary in their precise formulation across different approaches, but they typically involve scale separation, coarse graining, and the presence of collective behavior among underlying degrees of freedom.

In this respect, spacetime geometry itself can be understood as playing the structural role of an order parameter across emergent gravity approaches. The spacetime metric is well-defined only within regimes where underlying degrees of freedom organize collectively in a manner that supports a geometric description, remains stable and largely insensitive to microscopic details within those regimes, and loses its physical meaning when those organizing conditions fail. This role does not require that the metric be fundamental, nor that it be derived from a unique microscopic mechanism. Rather, it reflects the fact that geometric structure functions as a collective indicator of regime: its presence signals an ordered, geometric phase, while its breakdown marks a transition to non-geometric behavior where alternative descriptions become necessary.

In thermodynamic approaches, the regime of validity is associated with near-equilibrium conditions and large-scale averaging. Geometric variables such as curvature emerge as effective quantities only when microscopic fluctuations are sufficiently suppressed. Away from equilibrium, the thermodynamic relations underpinning the Einstein equations no longer hold, and the geometric description loses its operational meaning [1–3].

Entanglement-based approaches define geometric regimes in terms of the structure and distribution of quantum correlations. Spacetime geometry emerges when entanglement satisfies particular connectivity and scaling properties, allowing for a smooth, continuous description. When these conditions fail, such as in highly disentangled or fragmented states, geometric notions become ill-defined or cease to apply altogether [8, 19, 22].

Pre-geometric approaches characterize regimes through collective states of fundamentally non-geometric constituents. Classical spacetime appears only when a large number of microscopic elements organize coherently, often in condensate-like configurations. Outside these regimes, the underlying degrees of freedom do not support geometric interpretation, and concepts such as distance or dimensionality have no direct meaning [12, 13].

Across all three strands, the emergence of geometry depends not merely on the presence of underlying degrees of freedom, but on their organization into specific collective configurations.

Geometry is therefore not an automatic consequence of microscopic structure but a contingent feature that arises only when certain regime-defining conditions are met.

3.2 Stability and Robustness of Spacetime Geometry

Once a geometric regime is established, emergent gravity approaches generally attribute a high degree of stability and robustness to the resulting spacetime description. This stability is essential for explaining the empirical success of general relativity across a wide range of physical contexts.

In thermodynamic frameworks, stability arises from the insensitivity of macroscopic variables to microscopic details. Just as temperature remains well-defined despite microscopic fluctuations, geometric quantities retain their meaning across a broad class of underlying microstates [2,3]. This robustness allows spacetime geometry to serve as a reliable effective description over large scales.

Entanglement-based approaches similarly emphasize robustness. Provided that entanglement patterns maintain certain structural features, the emergent geometry remains stable even as microscopic degrees of freedom evolve. Small perturbations in entanglement do not typically disrupt the large-scale geometric description, mirroring the resilience of macroscopic phases to local disturbances [19, 21].

Pre-geometric frameworks attribute stability to the collective coherence of large ensembles of microscopic constituents. Once a condensate or ordered state is formed, geometric properties emerge that are largely insensitive to individual microscopic variations. This collective stability underwrites the persistence of spacetime geometry as an effective description [12, 13].

The stability of geometric regimes explains why classical spacetime appears universal and enduring within its domain of applicability. At the same time, it underscores that this universality is emergent rather than fundamental, resting on the maintenance of underlying conditions that may fail under extreme circumstances.

3.3 Breakdown and Loss of Geometric Meaning

Equally important to the emergence and stability of spacetime geometry is its anticipated breakdown. Emergent gravity approaches consistently predict that geometric descriptions cease to be valid beyond certain limits, such as at very high energies, small length scales, or strong curvature.

In thermodynamic approaches, breakdown occurs when systems are driven far from equilibrium, invalidating the assumptions required to derive geometric relations. In such regimes, entropy production, large fluctuations, or nonlocal effects may dominate, rendering the geometric description inapplicable [14].

Entanglement-based frameworks associate breakdown with changes in the structure of quantum correlations. Disentanglement, fragmentation, or topological changes in entanglement networks can lead to the loss of spacetime connectivity or continuity. Geometry, in this view, is not destroyed but simply ceases to be an appropriate description [8, 22].

Pre-geometric approaches anticipate breakdown when collective states dissolve or fail to form. Near phase transitions or outside condensate regimes, the microscopic degrees of freedom no longer support geometric interpretation. The loss of geometry is thus a natural and expected feature of the underlying theory [12, 13].

The breakdown of spacetime geometry across these approaches is not regarded as pathological. Rather, it reflects the limited scope of effective descriptions and signals the need to revert to more fundamental, non-geometric variables.

3.4 Parallels with Macroscopic Phases in Physics

The regime dependence, stability, and breakdown of spacetime geometry bear a strong resemblance to the behavior of macroscopic phases in condensed matter and statistical physics. Phases are characterized by collective order, robustness to microscopic variation, and well-defined domains of applicability. Outside these domains, phase descriptions lose meaning or undergo transitions [15–17, 23–25].

In this light, classical spacetime geometry can be understood as a macroscopic regime characterized by collective organization among underlying degrees of freedom. Its stability reflects the robustness of this organization, while its breakdown signals transitions to qualitatively different regimes where geometric language no longer applies.

This analogy does not require that spacetime behave exactly like familiar material phases, nor does it imply specific microscopic mechanisms. Instead, it highlights a shared structural role: spacetime geometry functions as an effective, collective description that is meaningful only under particular conditions.

Recognizing this structural parallel provides a unifying lens through which diverse emergent gravity approaches can be interpreted. It sets the stage for the more explicit synthesis developed in the next section, where we articulate a common interpretive framework that captures these shared features without committing to a specific microscopic model.

4 Shared Structural Interpretation

The preceding sections have shown that thermodynamic, entanglement-based, and pre-geometric approaches to emergent gravity, despite their technical and methodological differences, converge on a strikingly similar treatment of spacetime geometry. In each case, geometry is not posited as a fundamental constituent of reality, but emerges as a stable, large-scale description that is valid only within specific physical regimes [1, 14]. This convergence suggests the presence of a shared structural interpretation that transcends individual models and formalisms.

Rather than advancing a new proposal for the microscopic origin of spacetime, this section articulates that interpretation explicitly. The focus is on clarifying common conceptual commitments that already guide a wide range of emergent gravity research, and on providing a coherent framework for understanding how spacetime geometry functions across these approaches.

4.1 Geometry as an Effective Collective Description

Across emergent gravity programs, spacetime geometry consistently appears as a description of collective behavior rather than as a fundamental structure. Geometric variables such as the metric, curvature, and causal structure do not directly correspond to microscopic degrees of freedom. Instead, they summarize large-scale features of underlying systems in much the same way that macroscopic variables summarize the behavior of many-body systems [15–17].

This effective character is reflected in the fact that geometric descriptions are insensitive to many microscopic details. Different microscopic configurations can give rise to the same geometric behavior, provided they share the relevant collective properties. This universality mirrors the behavior of macroscopic descriptions in other areas of physics, where a wide range of microstates correspond to the same effective phase.

The treatment of geometry as a collective description also explains why general relativity is so successful within its domain of applicability. Its equations capture stable, large-scale behavior that emerges reliably from diverse underlying configurations. At the same time, this perspective clarifies why attempts to extend general relativity to all scales encounter difficulties: the theory is not intended to describe microscopic structure directly [4, 5].

4.2 Regime Dependence and Conditional Applicability

A central element of the shared structural interpretation is the conditional applicability of spacetime geometry. In emergent gravity approaches, geometric descriptions are meaningful only when certain conditions are satisfied. These conditions may involve scale separation, coherence, entanglement structure, or collective organization, depending on the framework [1, 8, 12].

Importantly, these conditions are not merely technical assumptions introduced for calculational convenience. They play a constitutive role in defining when geometric language is appropriate. Outside the relevant regimes, geometric quantities lose their operational meaning, and alternative, non-geometric variables must be employed.

This regime dependence distinguishes emergent gravity approaches from views in which spacetime is treated as a universal backdrop. It also provides a natural explanation for the expected breakdown of geometry in extreme situations, such as near singularities or at very small length scales [14].

4.3 Stability, Universality, and Insensitivity to Microphysics

Another shared feature of emergent gravity approaches is the emphasis on stability and universality. Once a geometric regime is established, its large-scale behavior is robust against microscopic variation. This robustness is essential for the empirical adequacy of general relativity and for the apparent universality of spacetime structure across diverse physical contexts.

The insensitivity of geometry to microphysical details allows different emergent gravity models to recover similar large-scale behavior despite differing radically at the microscopic level [2, 3, 15].

This universality is a hallmark of emergent phenomena and supports the interpretation of spacetime geometry as a macroscopic description that transcends specific microphysical realizations.

Stability also plays a key role in distinguishing geometric regimes from transient or unstable configurations. Only when underlying degrees of freedom organize in sufficiently coherent and persistent ways does a geometric description become applicable. This requirement helps explain why spacetime geometry appears as a dominant organizing structure in familiar physical regimes.

4.4 Breakdown, Transitions, and the Limits of Geometry

The shared structural interpretation also accounts for the anticipated breakdown of spacetime geometry. Emergent gravity approaches consistently predict that geometric descriptions fail outside their domains of applicability. Rather than signaling inconsistency or incompleteness, such failures are treated as natural consequences of the effective character of geometry [14].

Transitions between geometric and non-geometric regimes may be abrupt or gradual, depending on the underlying framework. In some cases, these transitions resemble phase transitions, where qualitative changes in collective behavior lead to new effective descriptions [15–17,24,25]. In others, the breakdown of geometry may occur more smoothly, as collective coherence is gradually lost.

Regardless of the details, the possibility of breakdown underscores that spacetime geometry is not a universal feature of physical reality. Its applicability depends on the maintenance of specific conditions that may not hold universally.

4.5 Toward a Unified Structural Perspective

Taken together, these features define a unified structural perspective on emergent gravity. Spacetime geometry functions as an effective, collective description that is valid only within particular regimes, stabilized by collective organization, and expected to break down outside its domain of applicability. This perspective is shared, at least implicitly, across a wide range of emergent gravity programs.

Articulating this shared structure does not resolve outstanding technical challenges in quantum gravity, nor does it identify a unique microscopic origin of spacetime. Instead, it clarifies the conceptual landscape in which such challenges are addressed. By recognizing the common structural commitments that underlie diverse approaches, researchers can better situate their work within a broader context and identify points of genuine disagreement or convergence.

The next section addresses an important question raised by this synthesis: if such a shared structural perspective is already present across emergent gravity research, why has it remained largely implicit? Understanding the reasons for this reticence sheds light on the development of the field and helps explain the diversity of language and emphasis found in the literature.

5 Why Phase-Theoretic Language Has Remained Implicit

The analysis developed in the preceding sections raises a natural question. If a phase-like structural interpretation of spacetime is shared, at least implicitly, across a wide range of emergent gravity approaches, why has this perspective rarely been articulated explicitly in the literature? Addressing this question is important not only for situating the present synthesis but also for understanding how conceptual frameworks evolve within active research programs.

The relative absence of explicit phase-theoretic language does not reflect a lack of relevance or applicability. Instead, it can be traced to a combination of methodological priorities, historical developments, and pragmatic constraints that shape how ideas are formulated and communicated within different communities.

5.1 Model-Specific Objectives and Local Conceptual Economies

Much of the work in emergent gravity is driven by the development and analysis of specific models. In thermodynamic, entanglement-based, and pre-geometric frameworks alike, researchers typically focus on demonstrating that a given microscopic construction reproduces known gravitational behavior under appropriate conditions. The conceptual language employed is therefore closely tied to the technical tools and aims of each approach.

Within such contexts, introducing broad, model-agnostic interpretive frameworks often offers little immediate payoff. Phase-theoretic language, while useful for comparative synthesis, may not contribute directly to solving concrete technical problems. As a result, it tends to remain implicit, embedded in assumptions about regime dependence, stability, and breakdown rather than elevated to an explicit organizing principle.

This tendency is reinforced by the local conceptual economies of individual research programs. Each framework develops its own preferred metaphors, formalisms, and explanatory strategies, which are optimized for internal coherence rather than cross-program comparison. Phase-like behavior may be acknowledged within a specific model without being abstracted into a general interpretive claim.

5.2 Caution Regarding Overgeneralization

Another factor contributing to the implicit status of phase-theoretic interpretations is a well-founded caution against overgeneralization. Emergent gravity encompasses a diverse array of approaches, many of which differ substantially in their microscopic assumptions. Explicitly characterizing spacetime as a phase across all such approaches risks being perceived as imposing a uniform ontology where none has been established.

To avoid this risk, researchers often prefer to frame their results in more narrowly defined terms. They emphasize the recovery of geometry within specific limits or regimes without committing to broader claims about the general status of spacetime. Phase-theoretic language, which naturally invites cross-domain comparison, may therefore be avoided in favor of more conservative descriptions.

This caution is particularly pronounced in pre-geometric approaches, where the precise relationship between microscopic structures and emergent geometry remains an active area of investigation. In such settings, explicit phase language may appear premature until the relevant mechanisms are better understood.

5.3 Disciplinary Boundaries and Language Choices

The language of phases and collective behavior originates primarily in condensed matter physics and statistical mechanics. While these concepts have increasingly influenced research in quantum gravity, they have not always been integrated seamlessly into its conceptual vocabulary. Disciplinary boundaries can therefore shape which interpretive frameworks are foregrounded and which remain implicit.

In thermodynamic approaches, phase-like behavior is often discussed using the language of equilibrium, entropy, and equations of state rather than explicit phase terminology. In entanglement-based approaches, geometric emergence is framed in terms of information-theoretic quantities, even when the underlying structure exhibits clear parallels with macroscopic phases. Pre-geometric approaches sometimes invoke condensate behavior, but typically within the confines of specific models rather than as a general interpretive stance.

These language choices reflect both historical trajectories and practical considerations. Researchers adopt terminology that resonates with their immediate audiences and disciplinary backgrounds, even when alternative vocabularies might capture broader structural similarities.

5.4 Implicit Consensus and Conceptual Saturation

Finally, the implicit status of phase-theoretic interpretations may reflect a form of conceptual saturation within the field. As certain assumptions become widely shared, they cease to be articulated explicitly. The contingent, regime-dependent nature of spacetime geometry may now be taken for granted within emergent gravity research, reducing the perceived need to foreground it as a distinct interpretive claim.

In such cases, making implicit assumptions explicit can appear redundant or uninformative, particularly to specialists already familiar with the underlying ideas. Nevertheless, explicit articulation can play an important role in clarifying conceptual foundations, facilitating cross-program comparison, and communicating shared perspectives to broader audiences.

The present synthesis aims to serve this clarificatory function. By drawing attention to a structural interpretation that is already doing conceptual work across multiple frameworks, it seeks not to revise existing approaches but to illuminate their common ground.

6 Scope, Limits, and Non-Claims

The synthesis developed in this paper is intentionally limited in scope. Its aim is not to advance a new theory of quantum gravity, propose a specific microscopic model, or resolve outstanding technical problems in the unification of general relativity and quantum mechanics. Instead, it seeks to clarify a set of structural commitments that recur across several influential emergent gravity programs. This section makes explicit what the present analysis does and does not claim, in order to prevent misinterpretation and to situate its contribution appropriately within the broader literature.

6.1 No Claim of Microscopic Unification

First, this work does not claim that there exists a single microscopic theory underlying all emergent gravity approaches. The thermodynamic, entanglement-based, and pre-geometric frameworks surveyed here posit fundamentally different kinds of microscopic degrees of freedom, ranging from unspecified statistical microstates to quantum fields, networks, or algebraic structures. The present synthesis does not attempt to reconcile these differences or to privilege one class of microphysical entities over others.

The shared structural interpretation articulated in this paper operates at a higher level of abstraction. It concerns the role played by spacetime geometry as an effective description, rather than the detailed mechanisms by which such descriptions arise. Any convergence identified here should therefore be understood as conceptual rather than ontological at the microscopic level.

6.2 No Resolution of Technical Open Problems

Second, the analysis does not resolve open technical questions in emergent gravity or quantum gravity more broadly. Issues such as the precise recovery of Einstein dynamics, the treatment of singularities, the emergence of Lorentz invariance, and the formulation of testable predictions remain active areas of research within individual frameworks.

By focusing on shared structural features, this paper abstracts away from many of these technical challenges. Doing so allows for a clearer comparison of conceptual commitments, but it necessarily leaves unresolved the detailed questions that motivate much of the technical literature. The present contribution should therefore be seen as complementary to, rather than substitutive for, ongoing model-specific work.

6.3 No Claim of Universality Across All Approaches

Third, the synthesis does not claim that all approaches to quantum gravity or modifications of general relativity adopt the structural perspective described here. The analysis is restricted to a subset of research programs commonly grouped under the heading of emergent gravity. Other approaches may treat spacetime geometry differently or may not share the same assumptions about regime dependence, stability, and breakdown.

Even within emergent gravity, there may be important exceptions or alternative formulations that do not fit neatly into the picture presented here. The identification of shared structural features should therefore be understood as a tendency rather than a universal rule.

6.4 Clarificatory Rather Than Revisionary Intent

A central aim of this paper is clarification rather than revision. The structural interpretation articulated here is not introduced as a new hypothesis about the nature of spacetime, but as a way of making explicit assumptions that already play a role in existing work. In this sense, the contribution is interpretive and organizational rather than foundational.

By drawing attention to common structural commitments, the synthesis may help to clarify points of agreement and disagreement across different approaches, facilitate communication between research communities, and provide a more coherent conceptual framework for situating future developments. It does not, however, seek to redefine the goals or methods of emergent gravity research.

6.5 Limits of the Phase Analogy

Although the paper highlights parallels between spacetime geometry and macroscopic phases in other areas of physics, this analogy has limits. Spacetime is not a material medium, and its emergence may differ in important respects from familiar phase transitions in condensed matter systems. The analogy is intended to illuminate structural similarities rather than to suggest direct physical equivalence.

Recognizing these limits is essential for avoiding overextension of the phase-theoretic perspective. The value of the analogy lies in its ability to clarify regime dependence, stability, and breakdown, not in mapping all features of material phases onto spacetime.

7 Conclusion

This paper has examined a range of influential emergent gravity approaches with the aim of identifying structural features that recur across otherwise distinct frameworks. By comparing thermodynamic, entanglement-based, and pre-geometric programs, we have shown that these approaches converge on a common treatment of spacetime geometry as an effective, regime-dependent description rather than a fundamental constituent of physical reality.

Across these frameworks, classical spacetime geometry arises only under specific physical conditions, exhibits stability and robustness within those regimes, and is expected to lose its applicability outside them. These shared commitments are reflected in the treatment of general relativity as a large-scale, coarse-grained description that captures collective behavior while remaining insensitive to many microscopic details. Although the mechanisms by which geometry emerges differ substantially from one approach to another, the structural role assigned to spacetime is remarkably consistent.

By articulating this shared structure explicitly, the present synthesis clarifies points of convergence within emergent gravity research that are often obscured by differences in language, formalism, and emphasis. The analysis does not propose a new microscopic model or resolve outstanding technical challenges. Instead, it provides an interpretive framework that helps situate diverse approaches within a coherent conceptual landscape.

Understanding spacetime geometry as a collective, macroscopic regime highlights both its explanatory power and its limitations. It explains the empirical success of general relativity within familiar domains while naturally accommodating the expectation that geometric descriptions will break down under extreme conditions. This perspective also underscores the importance of identifying the conditions under which spacetime emerges and the ways in which those conditions may fail.

The synthesis offered here is intended as a clarificatory contribution rather than a revisionary one. By making explicit assumptions that are already implicit across several emergent gravity programs, it aims to facilitate communication between research communities and to provide a clearer basis for evaluating similarities and differences among competing approaches. Future work may build on this perspective by exploring its implications within specific models or by examining how it interfaces with other approaches to quantum gravity.

More broadly, the analysis suggests that progress in understanding the quantum nature of spacetime may depend as much on clarifying shared conceptual commitments as on developing new technical tools. Recognizing the effective, regime-dependent character of spacetime geometry provides a unifying lens through which diverse lines of research can be viewed, and may help guide the search for a deeper understanding of the conditions under which spacetime itself emerges.

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