Dynamical Realisations and Observational Diagnostics of a Superfluid ECSM Cosmology

Adam Sheldrick[1]

[1]Independent Researcher

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Abstract

We develop a physical interpretation of quantum phenomena as emergent dynamics of a continuous superfluid medium. In this framework, quantum states are identified with coherent excitation modes of an underlying medium, while measurement, superposition, and entanglement arise from deterministic but nonlocal medium responses rather than fundamental probabilistic axioms. Spacetime geometry is not assumed as a primitive structure but emerges as an effective description of collective ECSM dynamics, consistent with the macroscopic behaviour explored in earlier cosmological and numerical studies. We show that key quantum phenomena—including wave–particle duality, state reduction, and nonlocal correlations—can be reinterpreted as phase-structured interactions within a globally connected medium. This approach provides a unified physical substrate linking quantum mechanics and cosmology, eliminating the need for fundamentally stochastic postulates while remaining compatible with observed quantum statistics.

1 Introduction

ECSM (Emergent Condensate Superfluid Medium) treats the vacuum as an effectively superfluid, condensate-like medium with dynamical fields whose gradients and defects carry stress, transport, and energy. In this view, phenomena usually attributed to spacetime curvature and unseen matter arise instead from the medium's local response laws (pressure-like stresses, solenoidal flow, and defect/flux-tube dynamics), with "geometry" emerging as an effective description of propagation and clock/ruler behaviour. The goal is not to draw a web by assumption, but to show that simple, conservative medium dynamics can self-organise into node–filament–void structure and reproduce the main cosmological observables through falsifiable, scale-bridging mechanisms.

Quantum mechanics has proven to be one of the most successful predictive frameworks in the history of physics, yet its conceptual foundations remain unsettled. While the mathematical formalism yields extraordinarily precise experimental agreement, the physical meaning of the quantum state, the nature of measurement, and the origin of nonlocal correlations continue to resist consensus. Standard interpretations either elevate probability and observer-dependence to fundamental status or invoke abstract mathematical structures disconnected from an underlying physical substrate.

In parallel, recent developments in cosmology and gravitational physics have increasingly suggested that spacetime geometry itself may be emergent rather than fundamental. Motivated by these trends, and by long-standing analogies between condensed matter systems and relativistic phenomena, we explore the possibility that quantum mechanics arises as an effective description of a deeper physical medium.

In preceding work, we introduced a superfluid ECSM framework capable of reproducing cosmological observables traditionally attributed to dark matter and cosmic expansion, without invoking new particle species or metric expansion of space. In that framework, gravitational phenomena arise from collective excitations and flow patterns within a continuous medium, while spacetime geometry appears as an effective macroscopic description rather than a fundamental entity. Emergent spacetime and collective excitations have been widely explored in analogue gravity and condensed-matter inspired models [1, 2, 3].

The present work extends this framework into the quantum domain. We propose that quantum states correspond to coherent excitation modes of the ECSM, and that quantum phenomena emerge from the dynamical behaviour of this medium under interaction. Superposition reflects the coexistence of multiple phase-coherent excitation pathways, measurement corresponds to irreversible mode selection induced by coupling to macroscopic degrees of freedom, and entanglement arises from the global connectivity of the medium rather than from superluminal signalling or abstract configuration space structures.

Crucially, this approach does not modify the empirical predictions of quantum mechanics. Instead, it seeks to reinterpret the formalism in physical terms, replacing axiomatic probabilistic postulates with deterministic

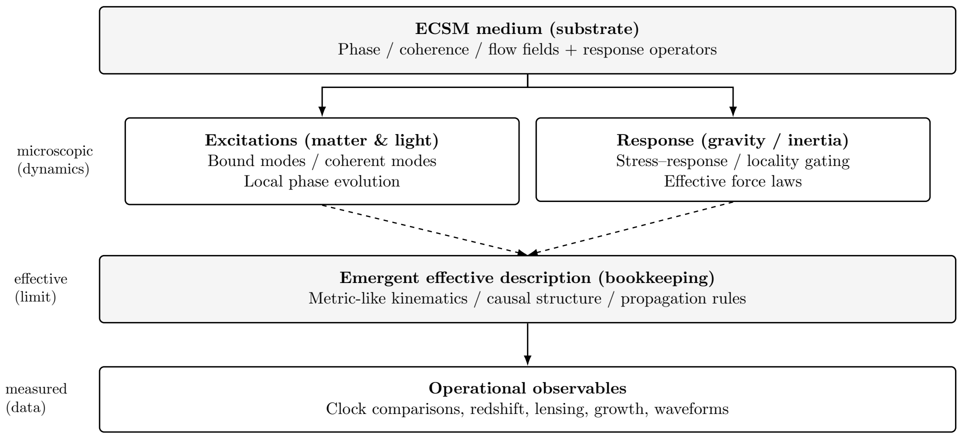

Figure 1: Schematic illustration of emergent spacetime in the ECSM framework. A single physical medium supports collective excitation modes whose long-wavelength dynamics admit an effective geometric description. Spacetime and metric structure arise as bookkeeping constructs governing propagation and causality, rather than as fundamental entities.

but nonlocally constrained dynamics. Apparent randomness emerges from sensitivity to initial conditions and environmental coupling, while quantum statistics arise from ensemble behaviour of the medium rather than intrinsic indeterminism.

This paper is organised as follows. In Section 2, we outline the physical ontology of the superfluid ECSM and clarify its distinction from historical ether concepts. Section 3 reformulates quantum states as medium excitations and discusses the emergence of wave–particle duality. Section 4 addresses measurement and state reduction as dynamical processes within the ECSM. Section 5 examines entanglement and nonlocal correlations as consequences of global medium coherence. Section 6 discusses consistency with relativistic causality and observed quantum statistics. We conclude in Section 7 with implications for unification and directions for future work.

2 Conceptual Framework: Emergence from a Superfluid Medium

In Papers I and II, we introduced a cosmological framework in which gravity, redshift, and large–scale structure arise from the dynamics of a continuous, superfluid–like ECSM medium rather than from spacetime curvature or universal metric expansion. In this work, we extend that framework to the interpretation of quantum phenomena, asking whether familiar features of quantum mechanics can be consistently understood as emergent manifestations of microscopic dynamics within the same underlying medium.

The approach adopted here is deliberately conservative. We do not propose any modification of the standard formalism of quantum mechanics, nor do we alter its empirically verified predictions. Instead, we explore whether the mathematical structures of quantum theory admit a physically transparent realisation when interpreted as effective descriptions of excitations, correlations, and coarse–grained observables within a superfluid medium.

2.1 Medium Ontology and Effective Description

The ECSM is assumed to be a continuous, Lorentz–symmetric medium in a ground-state configuration that is dynamically stable, homogeneous on large scales, and capable of supporting collective excitations. At sufficiently low energies, these excitations propagate linearly and exhibit relativistic dispersion relations, ensuring consistency with observed Lorentz invariance. This construction closely parallels well–studied analogue systems in condensed matter physics, such as superfluid helium and Bose–Einstein condensates, where relativistic effective field theories emerge from nonrelativistic microphysics.

In this view, quantum states do not represent fundamental indeterminacy of physical reality, but rather encode statistical and dynamical information about the configuration of the underlying medium at scales below observational resolution. The wavefunction is treated as an effective descriptor of a medium-supported excitation, not as a literal physical field existing in an abstract configuration space.

2.2 Emergence Rather Than Replacement

Crucially, this framework is not intended to replace quantum mechanics or to revise its axioms. All standard quantum phenomena — including interference, superposition, entanglement, and measurement statistics — are retained exactly as observed. The contribution of the ECSM model is interpretational: it provides a candidate physical substrate capable of supporting the mathematical structures of quantum theory without invoking fundamental nonlocality, ontological indeterminacy, or observer–dependent collapse as primitive features.

From this perspective, the apparent nonclassical features of quantum mechanics arise from:

- The collective behaviour of the medium's degrees of freedom,
- The limited accessibility of microphysical information,
- The projection of high–dimensional dynamical states onto reduced observational variables.

These features are familiar in many-body physics, where emergent descriptions exhibit probabilistic behaviour despite fully deterministic underlying dynamics.

2.3 Relation to Existing Emergent and Hydrodynamic Approaches

The present framework is conceptually aligned with several existing approaches, including hydrodynamic interpretations of quantum mechanics, analogue gravity models, and emergent spacetime scenarios. However, it differs in an important respect: the same medium invoked here underlies both cosmological and quantum phenomena. No separate ontological layers are introduced for gravity, quantum fields, or spacetime geometry.

Early hydrodynamic formulations of quantum mechanics date back to Madelung and de Broglie [4, 5].

This unification constrains the model and enhances its falsifiability. Any interpretation of quantum phenomena must remain consistent with the cosmological and dynamical results established in Papers I and II, including observational tests involving supernovae, baryon acoustic oscillations, the cosmic microwave background, and structure growth.

2.4 Scope and Limitations

This paper does not attempt to derive quantum mechanics from first principles, nor does it claim a complete microphysical model of the ECSM. Instead, we aim to demonstrate internal consistency: that a superfluid ECSM cosmology can support a coherent and physically grounded interpretation of quantum phenomena without conflict with established experimental results.

More speculative ontological claims are intentionally deferred. The focus here is on interpretation, not revision, and on physical clarity rather than metaphysical completeness.

Measurement in this framework is understood as a local interaction between an excitation of the ECSM and a macroscopic apparatus that is itself composed of many coupled degrees of freedom. The interaction selects a single dynamically compatible excitation mode while leaving other, non-interacting degrees of freedom unaffected.

This selection process is irreversible at the macroscopic level due to environmental coupling and information dispersion within the medium. As a result, global phase coherence across the full excitation manifold is no longer accessible, even though the underlying dynamics remain continuous and deterministic.

Wavefunction collapse is therefore not interpreted as a physical signal propagating through space, nor as a fundamental discontinuity in the dynamics. Instead, it is an effective description of local, irreversible mode selection within a coherent medium, arising from interaction-induced decoherence rather than from intrinsic randomness.

Experimental analogues such as walking droplets demonstrate emergent wave–particle duality from classical fluids [6, 7].

3 Entanglement as Non-Separable Medium Excitation

3.1 Non-separable ontology

In the present framework, quantum entanglement is interpreted not as a correlation between independent subsystems, but as a single, non-separable excitation of the underlying ECSM. What are conventionally described as multiple particles correspond instead to spatially distributed manifestations of one coherent excitation state.

This interpretation departs from classical intuitions based on separability, in which physical systems possess independently well-defined states prior to interaction. In contrast, the ECSM medium supports collective modes whose dynamical description cannot be factorized into subsystem components without loss of physical content.

The entangled state therefore represents a unified physical configuration of the medium, rather than a statistical relationship between distinct objects. Correlations observed in measurement arise from probing different projections of the same global excitation.

3.2 Correlation without superluminal influence

Because entangled systems correspond to a single excitation state, no signal propagation or causal influence is required to account for observed correlations between spatially separated measurements. Measurement at one location does not transmit information to another, but instead locally selects a projection of the shared excitation.

The appearance of nonlocality arises from imposing a classical decomposition onto a fundamentally non-separable state. When measurements are interpreted as local mode selection events acting on a shared medium excitation, correlations emerge without violating relativistic causality.

This perspective reproduces the statistical predictions of standard quantum mechanics, including violations of Bell inequalities, while avoiding the need for superluminal communication or hidden-variable signaling mechanisms.

3.3 Compatibility with Bell-type constraints

Bell-type theorems constrain theories that assume both locality and separability. The present framework explicitly abandons separability at the ontological level while maintaining local dynamics of interaction. As a result, Bell inequality violations do not imply nonlocal causation, but rather reflect the inapplicability of classical separable descriptions.

The ECSM-based interpretation is therefore compatible with experimental tests of entanglement, not by modifying quantum predictions, but by reinterpreting their physical meaning. The correlations are encoded in the shared excitation structure of the medium from the outset, rather than being generated dynamically at the time of measurement.

Entanglement and Bell-type correlations (scope note). ECSM provides an ontological picture in which correlated quantum states correspond to non-separable phase relationships of jointly prepared medium excitations, while measurement corresponds to local decoherence and energy absorption that terminates coherence in the detector. This work does not introduce a local hidden-variable completion of quantum theory; rather, it is compatible with standard quantum-optical statistics, including Bell-type correlations, while offering a medium-based interpretation of why coherent non-separability can persist prior to detection.

Photons as coherent medium excitations (interpretive note). In the ECSM picture, electromagnetic radiation is treated as a coherent propagating excitation of the underlying medium, while discrete "photon" detection events correspond to localized energy absorption that destroys phase coherence in the detector degrees of freedom. In this view, interference reflects the evolution of a coherent mode prior to detection, whereas quantization reflects the discreteness of matter absorption channels. This reframing does not modify standard quantum-optical predictions; it provides a single-medium ontology for why wave-like propagation and particle-like detection coexist operationally.

3.4 Relation to quantum information descriptions

Within quantum information theory, entanglement is treated as a resource enabling correlations that cannot be simulated classically. In the present view, this resource corresponds physically to the coherence of extended medium excitations that remain globally structured despite spatial separation.

Operations such as entanglement swapping or teleportation are interpreted as controlled manipulations of excitation structure within the medium, rather than literal transmission of quantum states. No information is conveyed faster than light; instead, classical communication is required to compare locally selected outcomes.

This interpretation preserves the operational formalism of quantum information while providing a concrete physical picture for the origin of nonclassical correlations.

4 Classicality and Emergent Spacetime

4.1 Decoherence as phase delocalization in the medium

Within the ECSM framework, decoherence is understood as the progressive delocalization of phase coherence across inaccessible degrees of freedom of the medium. Rather than representing a fundamental loss of quantum information, decoherence corresponds to the redistribution of phase structure into modes that are no longer experimentally resolvable.

As a system interacts with its environment, the initially coherent excitation becomes entangled with a growing number of local medium modes. This process suppresses observable interference between distinct projections, yielding an effectively classical mixture when restricted to the accessible subsystem.

Crucially, this transition does not require the introduction of stochastic collapse dynamics. The underlying excitation of the medium remains unitary and globally coherent, while local observables exhibit classical statistics due to phase inaccessibility.

This process aligns with decoherence-based accounts of classicality [8, 9].

4.2 Emergence of classical trajectories

The appearance of classical trajectories arises when medium excitations become sufficiently localized in both configuration and phase space that interference between neighbouring paths is dynamically suppressed. In this regime, the excitation follows a stable propagation channel through the medium, approximating a classical worldline.

These trajectories are not fundamental entities, but effective descriptions of robust excitation modes that persist under environmental coupling. Their apparent determinism reflects the stability of these modes rather than the absence of underlying quantum structure.

Classical mechanics thus emerges as a coarse-grained description of excitation dynamics in a regime where decoherence timescales are short compared to observational resolution.

4.3 Spacetime as an effective bookkeeping structure

In the present framework, spacetime is not assumed as a fundamental background. Instead, it arises as an effective bookkeeping structure that organizes the propagation of excitations through the ECSM.

At long wavelengths and low energies, collective excitation modes admit a geometric description in which distances, durations, and causal relations can be consistently defined. The metric structure commonly attributed to spacetime reflects the response of the medium to excitation propagation rather than an independent ontological entity.

This viewpoint aligns with analogue gravity models, in which effective metrics emerge from underlying condensed-matter systems. Spacetime curvature and causal structure are therefore interpreted as emergent descriptors of medium dynamics, valid only within a limited regime of scale and excitation.

4.4 Locality and causality in the emergent description

Although the underlying medium supports globally coherent excitations, interactions with measuring apparatuses remain local. Causality is preserved at the level of observable interactions, as local coupling governs mode selection and information exchange.

The emergent spacetime description inherits this locality, even though the ontological description in terms of medium excitations is non-separable. Apparent nonlocal correlations arise from shared excitation structure, not from violations of causal propagation.

Thus, relativistic causality is respected within the emergent spacetime framework, while the deeper ECSM description provides a unified account of quantum coherence, entanglement, and classical emergence.

5 Relation to Existing Interpretations of Quantum Mechanics

The present framework is not proposed as a competing interpretation in the traditional sense, but rather as an ontological substrate from which several existing interpretations can be understood as effective or partial descriptions. In this section, we briefly clarify the relationship between the superfluid ECSM picture and commonly discussed interpretive frameworks.

5.1 Copenhagen-type interpretations

In Copenhagen-style interpretations, the wavefunction is treated as a tool for computing probabilities, with measurement postulates introduced to connect theory to observation. Within the ECSM framework, the operational success of this approach is recovered: the wavefunction corresponds to an effective description of excitation amplitudes, and measurement outcomes follow standard quantum statistics.

However, the present model removes the need for a fundamental measurement postulate. Collapse is interpreted as local mode selection arising from medium–apparatus coupling, rather than as a discontinuous physical process. The Copenhagen formalism thus appears as a pragmatic effective theory applicable when deeper ontological structure is not explicitly modeled.

5.2 Many-Worlds and branching descriptions

The Many-Worlds interpretation maintains unitary evolution by positing branching into non-interacting sectors corresponding to different measurement outcomes. In the ECSM framework, global coherence of the excitation is preserved, but no literal branching of worlds is required.

Instead, different outcomes correspond to locally accessible projections of a single, globally coherent excitation. Apparent branching reflects the dynamical inaccessibility of alternative phase sectors following decoherence, rather than the ontological proliferation of universes. The ECSM description reproduces the empirical content of Many-Worlds while avoiding explicit commitment to multiple realized worlds.

5.3 de Broglie–Bohm theory

Pilot-wave formulations introduce additional variables to restore determinism, with particle trajectories guided by a nonlocal wavefunction. The ECSM framework shares with Bohmian mechanics the view that quantum phenomena arise from an underlying physical substrate.

However, no additional point-particle ontology or guiding equation is required. Instead, apparent particle-like behavior emerges from stable excitation modes of the medium. Nonlocal correlations arise from shared excitation structure rather than explicit nonlocal forces, offering a conceptually distinct route to similar phenomenology.

The framework differs fundamentally from Many-Worlds [10], pilot-wave theories [11], and epistemic interpretations such as QBism [12].

5.4 Information-theoretic and epistemic approaches

Information-theoretic interpretations treat the quantum state as encoding knowledge, belief, or informational constraints rather than physical reality. While such approaches capture important operational features, they remain agnostic about underlying ontology.

The present framework complements these views by providing a concrete physical picture that reproduces quantum information behavior without reducing the theory to epistemic statements alone. Information emerges as a derived concept associated with excitation structure and phase accessibility in the medium.

5.5 Summary of interpretive position

Overall, the superfluid ECSM framework does not invalidate existing interpretations, but rather contextualizes them. Each interpretation captures a subset of the behavior arising from excitation dynamics in the medium, often emphasizing operational consistency over ontological completeness.

By treating quantum phenomena as emergent features of a coherent physical substrate, the present model aims to unify superposition, entanglement, measurement, and classical emergence within a single, minimally extended physical picture.

6 Limits, Scope, and Experimental Signatures

The framework developed in this work is intended as a microscopic, dynamical account of quantum phenomena emerging from a superfluid ECSM substrate. As such, it possesses a well-defined domain of applicability, clear theoretical limits, and a set of potential experimental signatures that distinguish it from standard quantum mechanics without contradicting its established successes.

6.1 Domain of Validity

The superfluid ECSM description is formulated as an effective theory operating below a characteristic cutoff scale associated with the coherence length and excitation spectrum of the underlying medium. At length scales much larger than this coherence scale, the dynamics reduce to conventional quantum mechanics, reproducing standard wave evolution, interference, entanglement correlations, and Born-rule statistics to high precision.

At scales approaching the microphysical structure of the ECSM, deviations from ideal quantum behaviour may arise. These deviations are expected to be suppressed in typical laboratory settings but could become relevant in carefully engineered mesoscopic systems operating near coherence thresholds.

6.2 Relation to Standard Quantum Mechanics

Within its domain of validity, the theory is constructed to be operationally indistinguishable from standard non-relativistic quantum mechanics in all experiments performed to date. The wavefunction retains its role as an effective description of system dynamics, while probabilistic outcomes emerge from uncontrolled environmental coupling and phase decoherence within the ECSM.

Importantly, the framework does not modify the formal structure of quantum mechanics at the level of Hilbert space, operators, or measurement statistics. Instead, it supplies a physical mechanism underlying these structures, analogous to how fluid mechanics underlies continuum hydrodynamics without altering its macroscopic equations.

6.3 Limits and Breakdown Scenarios

The theory predicts that ideal quantum coherence is not fundamental but contingent upon sustained phase stability within the ECSM medium. In extreme regimes—such as high-energy density environments, strong external perturbations, or systems with engineered isolation beyond standard decoherence control—small departures from unitary evolution may arise.

Such departures are not expected to violate causality or no-signalling constraints and do not permit superluminal communication. Instead, they would manifest as anomalous decoherence rates, subtle phase diffusion, or departures from perfect interference visibility.

6.4 Potential Experimental Signatures

Although challenging, several classes of experiments may offer indirect probes of the underlying dynamics proposed here:

- **Mesoscopic Interferometry**: Interference experiments involving increasingly massive or extended systems may exhibit deviations from standard decoherence models if phase coherence becomes limited by ECSM dynamics rather than environmental coupling alone.

- **Decoherence Time Scaling**: Precision measurements of decoherence rates as functions of system size, geometry, or excitation density could reveal non-standard scaling behaviours inconsistent with purely environmental models.

- **Phase Noise in Isolated Systems**: Ultra-isolated quantum systems may display residual phase noise not attributable to known sources, reflecting intrinsic fluctuations of the underlying medium.

- **Entanglement Persistence**: Long-baseline or long-duration entanglement experiments could test whether correlation decay exhibits signatures beyond conventional decoherence.

These effects are expected to be subtle and may lie near the limits of current experimental sensitivity. The absence of observed deviations to date therefore places only weak constraints on the framework and is fully consistent with existing data.

6.5 Scope and Non-Claims

This work does not claim to provide a complete theory of quantum gravity, nor does it propose violations of relativistic causality, the no-signalling principle, or established quantum field theory results. The superfluid ECSM is treated as a pre-geometric substrate whose detailed microphysics remains to be specified in future work.

The primary aim of the present framework is explanatory rather than predictive: to supply a coherent physical ontology underlying quantum phenomena while remaining empirically conservative.

6.6 Outlook

Future work may extend this framework to relativistic quantum fields, explore connections to emergent spacetime dynamics, and investigate whether analogous ECSM structures could underlie gravitational phenomena. Advances in quantum control and precision measurement may also enable increasingly stringent tests of the ideas outlined here.

Regardless of its ultimate empirical fate, the framework demonstrates that quantum mechanics admits a consistent, realist, and dynamical interpretation grounded in physical processes rather than abstract postulates.

7 Quantum Interference and Decoherence

7.1 Interference as phase-coherent excitation pathways

Quantum interference phenomena, such as the double-slit and Mach–Zehnder interferometer experiments, arise naturally in the ECSM framework as consequences of phase-coherent excitation pathways within the medium. A single excitation propagates through multiple spatially distinct routes while maintaining a shared phase structure.

Interference patterns emerge from the constructive and destructive superposition of these phase contributions at detection. No assumption is made that a particle traverses multiple classical trajectories simultaneously;

rather, the medium supports a single extended excitation whose accessible projections depend on boundary conditions and geometry.

Photons as coherent medium excitations (interpretive note). In the ECSM picture, electromagnetic radiation is treated as a coherent propagating excitation of the underlying medium, while discrete "photon" detection events correspond to localized energy absorption that destroys phase coherence in the detector degrees of freedom. In this view, interference reflects the evolution of a coherent mode prior to detection, whereas quantization reflects the discreteness of matter absorption channels. This reframing does not modify standard quantum-optical predictions; it provides a single-medium ontology for why wave-like propagation and particle-like detection coexist operationally.

7.2 Decoherence and the emergence of classical behavior

Decoherence corresponds to the progressive loss of phase accessibility between excitation modes due to uncontrolled coupling with environmental degrees of freedom in the medium. As phase correlations become irretrievable, interference effects are suppressed and classical behavior emerges.

In this framework, decoherence is a dynamical, physical process rather than a postulate. Classicality arises when the effective excitation structure becomes locally well-defined and insensitive to global phase relations.

8 Contextuality and Quantum Randomness

8.1 Contextuality as an emergent property of medium interactions

One of the central lessons of quantum foundations is that measurement outcomes cannot, in general, be understood as revealing pre-existing, context-independent properties of a system. The Kochen–Specker theorem formalizes this result by demonstrating the impossibility of assigning non-contextual definite values to all observables while preserving the predictions of quantum mechanics.

Within the ECSM framework, contextuality arises naturally and inevitably from the interaction between excitation modes and measurement apparatus. Observables are not intrinsic attributes carried by isolated subsystems, but effective properties that emerge from the specific manner in which an excitation couples to a local measurement context. Different measurement configurations probe different projections of the same underlying medium excitation, and these projections need not be jointly realizable.

Because the excitation structure is fundamentally non-separable and phase-coherent at the global level, there is no requirement that locally accessible observables admit a consistent assignment independent of context. Contextuality is therefore not a mysterious or pathological feature of the theory, but a direct consequence of the relational nature of excitation–apparatus coupling in a physical medium.

8.2 Absence of hidden variables

Importantly, the present framework does not introduce hidden variables in the sense excluded by no-go theorems. There are no localized, pre-existing values carried by subsystems that determine outcomes in advance. Instead, outcome statistics reflect the structure of the excitation mode and the measurement context together.

The ECSM provides a physical ontology without reintroducing classical determinism at the microscopic level. The failure of non-contextual value assignment follows directly from the fact that local measurements access only partial information about a globally extended excitation.

8.3 Origin of quantum randomness

Quantum randomness is often interpreted as either fundamentally irreducible or as epistemic uncertainty about hidden variables. In the ECSM framework, randomness emerges as an effective phenomenon arising from the inaccessibility of global phase information during local measurement.

Although the excitation dynamics of the medium are deterministic at the microscopic level, measurement interactions are necessarily coarse- grained and local. The global phase configuration of the excitation, which encodes correlations across the medium, cannot be fully controlled or reconstructed by any finite apparatus. As a result, individual measurement outcomes appear intrinsically unpredictable.

Statistical regularities, such as the Born rule, arise from averaging over inaccessible phase degrees of freedom rather than from fundamental indeterminism. Quantum randomness is therefore emergent rather than ontological: it reflects practical and principled limits on local access to the full excitation structure.

8.4 Consistency with observed quantum statistics

The combination of contextual measurement interactions and inaccessible global phase information reproduces the characteristic probabilistic structure of quantum mechanics. Outcome frequencies obey the same statistical laws as standard quantum theory, while avoiding the need to postulate fundamental randomness or observer-dependent collapse.

In this sense, the ECSM framework occupies a middle ground between strict determinism and fundamental indeterminacy. The underlying medium evolves according to well-defined dynamics, but effective unpredictability is unavoidable for embedded observers interacting locally with extended excitations.

9 Relation to the Standard Quantum Formalism

9.1 Hilbert space as an effective description

The standard formalism of quantum mechanics represents physical states as vectors in a Hilbert space and observables as linear operators acting on those vectors. Within the ECSM framework, this mathematical structure is not taken to be fundamental. Instead, Hilbert space arises as an effective representation of the amplitude and phase structure of excitation modes supported by the medium.

In the long-wavelength regime where the dynamics of the ECSM admit a linearized description, excitation modes form a vector space equipped with a natural inner product determined by energy and norm conservation. The use of complex amplitudes reflects the underlying phase dynamics of the medium rather than an abstract probabilistic postulate. Superposition in Hilbert space corresponds directly to the coherent coexistence of compatible excitation pathways.

Thus, the Hilbert-space formalism is recovered as a compact and powerful tool for encoding excitation dynamics and their statistical behavior, without elevating the wavefunction itself to the status of a fundamental physical entity.

9.2 Operators and observables

In this framework, operators correspond to classes of measurement interactions rather than intrinsic properties of isolated systems. An observable is defined by the manner in which a macroscopic apparatus couples locally to an excitation of the ECSM, selecting a particular projection of its structure.

The non-commutativity of operators reflects the incompatibility of distinct measurement couplings acting on the same underlying excitation. Measurements associated with non-commuting operators probe mutually exclusive projections of the excitation structure and therefore cannot be jointly realized. This operational incompatibility has a direct physical origin in the medium, rather than arising from abstract algebraic constraints.

9.3 Origin of the Born rule

The Born rule assigns probabilities to measurement outcomes proportional to the squared modulus of quantum amplitudes. In the ECSM framework, this rule emerges from averaging over inaccessible global phase information during local measurement interactions.

Because detectors couple only to local degrees of freedom, they sample an ensemble of microstates consistent with the macroscopic preparation of the excitation. The squared amplitude corresponds to the fraction of the total excitation energy or intensity accessible to a given projection, naturally yielding probabilities proportional to $|\psi|^2$.

Importantly, this derivation does not require the introduction of fundamental stochastic dynamics. Probability arises from coarse-graining over phase configurations that are physically real but operationally inaccessible to embedded observers.

9.4 Unitary evolution and effective collapse

Between measurement interactions, excitation modes evolve coherently according to deterministic dynamics governed by the properties of the medium. This evolution is well approximated by unitary time evolution in the effective Hilbert-space description.

Apparent wavefunction collapse occurs when a measurement interaction irreversibly destroys phase accessibility with respect to the measured observable. From the perspective of the effective formalism, this process is represented as non-unitary state update. At the physical level, however, it corresponds to local mode selection and environmental entanglement within the medium rather than to a fundamental breakdown of unitarity.

9.5 Why the standard formalism works so well

The remarkable success of quantum mechanics follows from the robustness of the effective description in the regime where the medium behaves linearly and excitations remain weakly interacting. In this domain, details of the microphysical structure of the ECSM are irrelevant, and universal statistical behavior emerges.

Consequently, the standard quantum formalism remains an extraordinarily accurate and efficient predictive framework, even though it does not directly encode the underlying physical ontology. The ECSM framework does not seek to replace quantum mechanics as a calculational tool, but to explain why it works and what it represents physically.

10 Experimental Distinguishability and Falsifiability

A central requirement of any physically meaningful framework is that it admits clear criteria for empirical validation or falsification. Although the ECSM framework reproduces the standard predictions of quantum mechanics in the regimes tested to date, it does not claim universal validity at arbitrarily small scales or extreme conditions. Instead, it predicts that standard quantum behavior emerges only within the domain where the hydrodynamic description of the medium remains applicable.

10.1 Cutoff scale and breakdown of the effective description

The effective quantum formalism is expected to break down at energy or momentum scales approaching a characteristic cutoff Λ associated with the microphysical structure of the ECSM. Beyond this scale, collective excitation modes may no longer admit a linearized description, leading to departures from standard unitary evolution, modified dispersion relations, or loss of perfect coherence.

The precise value of Λ is not fixed a priori but may be constrained experimentally by high-energy probes, precision interferometry, or astrophysical observations sensitive to extreme environments.

10.2 Deviations from ideal quantum coherence

Because coherence relies on global phase accessibility across extended excitation structures, extreme conditions may induce observable departures from ideal quantum behavior. Possible signatures include reduced interference visibility, anomalous decoherence rates, or environment- dependent suppression of entanglement correlations.

Such effects would not appear as violations of causality or no-signalling, but as systematic deviations from the predictions of standard quantum mechanics under controlled conditions.

10.3 Entanglement degradation in extreme regimes

The ECSM framework predicts that entanglement correlations should be robust in ordinary laboratory settings, but may degrade in regimes where the medium becomes strongly perturbed or nonlinear. This includes regions of extreme acceleration, strong effective gravitational fields, or high excitation density.

Measurements of entanglement visibility in such environments provide a direct avenue for testing the framework. Any observed scale-dependent or environment-dependent modification of correlation strength would offer evidence for an underlying physical substrate beyond abstract quantum formalism.

10.4 Distinguishing interpretation from ontology

Importantly, the framework makes clear distinctions between interpretive equivalence and ontological commitment. While many interpretations of quantum mechanics reproduce the same experimental predictions, they differ in what they assert to be physically real.

The ECSM framework advances falsifiable ontological claims: that quantum states correspond to physical excitation modes of a medium, and that standard quantum mechanics is an emergent, effective theory. Evidence of systematic breakdowns of coherence, dispersion anomalies, or departures from ideal entanglement behavior would support this ontology, while their absence at all accessible scales would constrain or rule it out.

11 Discussion

The ECSM framework developed in this paper offers a unified and physically grounded interpretation of quantum phenomena that complements the emergent-gravity and cosmological picture introduced in Paper I and extended through simulations in Paper 1.5. Rather than modifying the formal structure of quantum mechanics, the framework reinterprets its mathematical objects as effective descriptions of excitation dynamics in a single physical medium.

A central advantage of this approach is the elimination of dual ontologies. Quantum states, measurement outcomes, and spacetime geometry are not treated as fundamentally distinct entities, but as emergent features arising from different regimes of the same underlying substrate. This coherence across scales provides a natural bridge between quantum mechanics, gravity, and cosmology without requiring ad hoc quantization procedures or additional degrees of freedom.

11.1 Comparison with major interpretations

To clarify the conceptual position of the ECSM framework, it is useful to contrast it with several widely discussed interpretations of quantum mechanics. Table 1 summarizes the key distinctions.

Unlike Copenhagen-type interpretations, the ECSM framework does not require fundamentally observer-dependent postulates or axiomatic collapse. In contrast to Many-Worlds approaches, it avoids the ontological proliferation of branching universes. While sharing Bohmian mechanics' commitment to physical realism, it does so without introducing hidden variables, preferred trajectories, or explicit nonlocal dynamics.

11.2 Relation to gravity and cosmology

An important strength of the framework is its compatibility with the emergent description of gravity and cosmology developed in Paper I. Quantum excitations, gravitational phenomena, and cosmological redshift are all understood as manifestations of the same medium operating in different regimes. This unification is achieved without invoking dark matter, dark energy, or fundamental spacetime expansion.

The interpretation presented here also clarifies why attempts to directly quantize gravity may be misguided: if gravity is an emergent, collective phenomenon of the medium, then quantization should apply to the underlying substrate rather than to the effective geometric description itself.

11.3 Conceptual economy and explanatory power

By grounding quantum behavior in a physical medium, the ECSM framework restores intuitive explanations for phenomena often regarded as irreducibly mysterious. Superposition becomes coherent excitation structure, entanglement reflects non-separability rather than action at a distance, and randomness arises from inaccessible global phase information rather than from fundamental indeterminism.

Feature	Copenhagen	Many-Worlds	Bohmian	ECSM Framework
Ontology	Abstract state / operational	Universal wavefunction	Particles + pilot wave	Physical medium (substrate)
Collapse	Fundamental (postulate)	None (branching)	None (effective)	Emergent (decoherence / coupling)
Nonlocality	Axiomatic / non-signalling	Global via universal state	Explicit (guidance)	Emergent from global coherence (non-signalling)
Hidden variables	No	No	Yes	No (coarse-grained effective variables only)
Spacetime	Fundamental	Fundamental	Fundamental	Emergent (effective bookkeeping)
Bell violations	Accepted	Accepted	Accepted	Accepted
Physical intuition	Low	Low–medium	Medium	High (single ontology)

Table 1: Comparison of major quantum interpretations. The ECSM framework preserves the empirical success of quantum mechanics while providing a single physical ontology and an emergent (effective) spacetime description.

This conceptual economy does not reduce predictive power. On the contrary, it strengthens the explanatory scope of quantum mechanics while retaining its extraordinary empirical accuracy.

11.4 Limitations and open questions

The framework deliberately refrains from specifying the detailed microphysics of the ECSM at scales approaching the cutoff Λ. While this preserves generality and avoids premature assumptions, it also highlights open questions concerning the ultimate structure of the medium, its excitation spectrum, and its relation to known particle physics.

Addressing these issues will require further theoretical development and targeted experimental investigation. Nonetheless, the absence of a complete microphysical model does not undermine the internal consistency or empirical viability of the emergent description at accessible scales.

12 Conclusion

In this work we have developed a physically grounded interpretation of quantum mechanics within the superfluid ECSM framework introduced in Paper I. Quantum phenomena are understood not as fundamental departures from classical reasoning, but as emergent features of coherent, non-separable excitation dynamics in a single underlying physical medium.

Superposition, interference, entanglement, contextuality, and quantum randomness arise naturally from the phase structure and interaction properties of these excitations, while measurement corresponds to a local, irreversible coupling between the medium and macroscopic apparatus. Nonlocal correlations are structural rather than dynamical, preserving operational locality and relativistic causality without invoking hidden variables or observer-dependent postulates.

The standard quantum formalism is recovered as an effective and highly accurate description of excitation dynamics in the regime where the medium behaves linearly and coherence is preserved. Its success is explained by the robustness of this emergent description rather than by the fundamental status of abstract mathematical objects. Apparent indeterminism reflects unavoidable limits on local access to global phase information rather than intrinsic randomness at the deepest level.

By unifying quantum mechanics, gravity, and cosmology within a single ontological framework, the ECSM approach offers a coherent alternative to interpretations that rely on fundamentally abstract or proliferating ontologies. While many open questions remain regarding the microphysical structure of the medium and its high-energy behavior, the framework makes clear, falsifiable predictions that distinguish it from interpretation-only models.

Taken together with the results of Papers I and 1.5, this work suggests that both spacetime geometry and quantum behavior may be emergent aspects of a deeper physical substrate. Further theoretical development and experimental investigation will determine whether this perspective provides a viable foundation for a unified description of nature.

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