Emergence Time Ⅱ : Fermionic Structure Formation and Spiral Dynamics

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Abstract

In the preceding work Emergence Time (Suzuki, 2026), physical time was defined dynamically as the cumulative production of irreversible structure, yielding a strictly monotonic temporal ordering independent of spacetime coordinates.In the present paper, we identify the physical mechanisms that naturally realize such irreversible structure formation. We show that self-gravitating systems subject to intrinsic phase-space constraints generically evolve toward spiral attractors in phase space, providing stable, non-divergent configurations without fine-tuning.We argue that fermionic statistics supply a minimal and universal stabilization mechanism. Through the Pauli exclusion principle and degeneracy pressure, fermionic matter enforces saturation of structural growth while preserving monotonic emergence time. Within this framework, spiral dynamics arise as the natural geometric expression of constrained phase-space evolution.Black hole collapse is reinterpreted as a negative-orientation spiral endpoint, characterized by divergent emergence time in finite proper time, whereas fermionic structures correspond to positive-orientation spiral configurations that remain dynamically accessible.We further propose that cosmological structure formation proceeds through an iterative sequence of phase transitions, each accompanied by effective expansion in phase or information space, followed by spiral stabilization.Together with the emergence-time formulation, these results unify time, matter statistics, spiral geometry, and gravitational collapse within a single dynamical framework, suggesting that cosmic stability follows from minimal statistical and geometric principles rather than from fine-tuned initial conditions.

1. Introduction

In Emergence Time (Suzuki, 2026), physical time was redefined as a dynamical quantity arising from irreversible structure formation rather than as a geometric coordinate of spacetime. By introducing the emergence rate $R(t) \geq 0$ and defining emergence time as $\tau(t) = \int R(t)\, dt$, the arrow of time was shown to follow as a mathematical consequence of structure generation across gravitational and quantum domains. This formulation resolved the long-standing tension between time-reversal symmetric fundamental equations and the observed irreversibility of physical processes.

While the emergence-time framework establishes a consistent and observer-independent temporal ordering, it deliberately leaves open a critical question: what physical mechanisms realize irreversible structure formation in a stable and universal manner? The previous work demonstrated that gravity and quantum measurement necessarily contribute positively to emergence time, but it did not specify why cosmic structure formation avoids generic runaway collapse or why similar geometric motifs—most notably spiral and helical organization—appear ubiquitously across physical scales.

The present paper addresses this missing component by identifying a concrete dynamical realization of emergence time. We focus on the evolution of self-gravitating systems in phase space and show that irreversible attraction combined with intrinsic constraints generically produces spiral attractors. When saturation limits or conserved quantities are present, these spirals close into toroidal manifolds, yielding long-lived and dynamically accessible structures without fine-tuning.

A central claim of this work is that fermionic statistics provide a minimal and universal physical mechanism for such stabilization. The Pauli exclusion principle enforces an upper bound on phase-space occupancy, while degeneracy pressure supplies intrinsic resistance to unlimited compression. Unlike phenomenological feedback prescriptions, these constraints are fundamental and state-independent. As a result, fermionic systems naturally generate non-negative emergence rates while preventing pathological divergence, thereby realizing the requirements imposed by emergence time.

Within this framework, spiral dynamics acquire a precise physical meaning. Spiral structures are not introduced as heuristic metaphors but arise as stable solutions of constrained phase-space evolution. The orientation of these spirals encodes the direction of irreversible progression: positive-orientation spirals correspond to accessible, responsive structures that saturate and stabilize, whereas negative-orientation spirals correspond to terminal configurations in which emergence time diverges. Black hole collapse is reinterpreted accordingly as a negative-orientation spiral endpoint, characterized by infinite emergence time attained within finite proper time.

Finally, we extend this picture to cosmology. Large-scale structure formation is interpreted as an iterative sequence of phase transitions, each accompanied by effective expansion in phase or information space, followed by spiral stabilization. In this view, cosmic expansion and structure formation are complementary aspects of a single dynamical cycle governed by emergence time.

This paper therefore completes the emergence-time program by identifying a physical implementation of irreversible structure formation. Together, Emergence Time and the present work establish a unified framework in which time, matter statistics, geometry, and gravitational collapse emerge from minimal and universal dynamical principles.

2. Phase-Space Dynamics and Spiral Attractors

2.1 General structure of self-gravitating dynamics

Consider a generic self-gravitating many-body system described in phase space by coordinates (x, p). The dynamics are governed by an effective Hamiltonian of the form

$$H = \frac{p^2}{2m} + \Phi(x) + V_{\text{int}}(f),$$

where $\Phi(x)$ is the gravitational potential and V_{int} represents internal constraints arising from collective effects or statistical interactions. Importantly, the explicit form of V_{int} is not specified at this stage; only its role as a non-negligible modification to purely Newtonian collapse is assumed.

Gravitational interaction alone produces nonlinear attraction and generically amplifies inhomogeneities. In phase space, this manifests as trajectories directed toward regions of higher density and curvature. However, in realistic systems, unrestricted collapse is not observed at all scales, indicating the presence of counteracting constraints.

2.2 Linearized dynamics and spiral flow

Near any quasi-stationary configuration, the equations of motion may be linearized. The resulting dynamics generically take the form of a damped or constrained oscillator,

$$\ddot{x} + \gamma \dot{x} + \omega^2 x = 0,$$

where the effective damping term γ encodes irreversible structure formation through phase-space contraction or constraint-induced dissipation.

The solutions to this equation are well known: when $\gamma \neq 0$, trajectories in phase space follow spiral paths toward an attractor. This behavior is not model-dependent but arises generically whenever nonlinear attraction coexists with irreversible constraints. In this sense, spiral flow represents the most elementary geometric expression of irreversible dynamics in phase space.

Crucially, spiral trajectories imply monotonic progression along a preferred direction in phase space, directly corresponding to non-negative emergence rates in the emergence-time framework. The spiral geometry therefore provides a natural realization of irreversible temporal ordering.

2.3 Closure into toroidal manifolds

A spiral trajectory alone does not guarantee long-term stability; without additional structure, it may terminate in singular collapse or dissipative decay. Stability requires the presence of conserved or saturated quantities that prevent unbounded radial contraction in phase space.

When such quantities exist—such as conserved angular momentum, bounded phase-space occupancy, or saturation limits imposed by statistics—radial contraction halts while angular motion persists. The spiral trajectory then closes into a toroidal manifold, forming a stable attractor rather than a terminal point.

This transition from open spiral to closed torus is a direct consequence of constraint-induced saturation. It requires no fine-tuning and follows purely from the coexistence of attraction, irreversibility, and bounded phase-space volume.

2.4 Emergence time and spiral monotonicity

Within the emergence-time formulation, the spiral attractor has a direct interpretation. Radial motion toward the attractor corresponds to structural growth and increasing complexity, while angular motion along the torus represents continued dynamical evolution without further collapse.

The emergence rate $R(t)$ remains non-negative throughout this process, ensuring monotonic growth of emergence time τ. Once the toroidal attractor is reached, $R(t)$ saturates rather than vanishes, reflecting the persistence of structure without runaway divergence.

Thus, spiral and toroidal phase-space geometries provide the minimal dynamical structures required to realize irreversible yet stable evolution consistent with emergence time.

2.5 Orientation and dynamical asymmetry

Spiral trajectories are intrinsically oriented: they possess a handedness corresponding to the direction of irreversible progression. In the absence of symmetry-breaking mechanisms, both orientations are mathematically allowed. However, physical systems frequently exhibit a preferred orientation, indicating the presence of underlying asymmetries.

The origin of this orientation selection is not purely geometric but statistical and dynamical. As will be shown in the following section, fermionic statistics naturally supply such asymmetry by enforcing non-commutative occupancy constraints in phase space. This mechanism selects dynamically stable spiral orientations while suppressing their opposites.

2.6 Summary

Spiral dynamics arise generically in self-gravitating systems with irreversible constraints. When phase-space contraction is balanced by conserved or saturated quantities, these spirals close into toroidal attractors, yielding stable and dynamically accessible structures. This behavior provides the geometric and dynamical foundation for the realization of emergence time.

In the next section, we demonstrate that fermionic statistics supply a minimal and universal physical mechanism for such constraint-induced stabilization, completing the dynamical picture of irreversible structure formation.

3. Fermionic Statistics as a Stabilization Mechanism

3.1 Phase-space constraints from fermionic statistics

Fermionic systems are distinguished by a fundamental statistical constraint: the Pauli exclusion principle forbids multiple particles from occupying the same quantum state. In phase-space terms, this implies an upper bound on the occupation number of any elementary phase-space cell. Unlike phenomenological constraints introduced at the macroscopic level, this bound is intrinsic and independent of environmental conditions.

As a consequence, fermionic systems possess a built-in mechanism that limits phase-space compression. When gravitational attraction drives the system toward higher density, phase-space occupation approaches saturation rather than diverging. This saturation introduces an effective repulsive pressure—degeneracy pressure—that halts further compression without requiring external feedback or fine-tuning.

3.2 Degeneracy pressure and nonlinear balance

The presence of degeneracy pressure fundamentally alters the dynamics of self-gravitating systems. While gravitational interaction promotes collapse, fermionic saturation enforces a nonlinear counterbalance that becomes dominant precisely in regimes of high density and curvature.

From the perspective of phase-space dynamics, this balance manifests as a transition from unbounded radial contraction to constrained motion along surfaces of constant occupancy. The system is therefore prevented from reaching pathological singular configurations under generic conditions, instead stabilizing at finite density.

This balance is not contingent on specific initial conditions or interaction strengths. It arises universally whenever fermionic statistics govern the microscopic degrees of freedom, rendering stabilization a natural consequence rather than an engineered outcome.

3.3 Fermionic realization of spiral attractors

When combined with the spiral dynamics discussed in Section 2, fermionic phase-space constraints yield a particularly robust structure. Gravitational attraction drives trajectories inward along spiral paths, while degeneracy-induced saturation arrests radial motion. Angular motion persists due to conserved quantities, causing the spiral to close into a toroidal attractor.

In this picture, spiral geometry is not imposed externally but emerges from the interplay between attraction and statistical exclusion. Fermionic statistics thus supply the minimal physical ingredients required to convert irreversible collapse into stable, long-lived structure.

Importantly, the resulting dynamics naturally enforce a non-negative emergence rate. Structural growth proceeds until saturation, after which evolution continues without divergence. This behavior directly satisfies the conditions required by the emergence-time framework.

3.4 Orientation selection and fermionic asymmetry

Spiral dynamics admit two orientations corresponding to opposite handedness. In purely classical systems, these orientations are dynamically equivalent. Fermionic systems, however, introduce asymmetry through the non-commutative structure of phase-space occupancy.

Because fermionic states cannot be freely permuted without altering the system's configuration, trajectories that attempt to reverse orientation encounter enhanced phase-space congestion. Such configurations are dynamically suppressed, while orientations compatible with efficient redistribution of occupation remain stable.

As a result, fermionic systems naturally select a preferred spiral orientation. This selection is statistical rather than imposed, emerging from the intrinsic ordering constraints of fermionic matter. The observed uniformity of spiral orientation across scales is therefore consistent with fermionic stabilization rather than requiring external symmetry-breaking fields.

3.5 Black hole formation as a limiting case

Fermionic stabilization does not exclude the formation of black holes. Instead, it delineates the boundary between stable and terminal configurations. When gravitational attraction overwhelms all available phase-space constraints, spiral trajectories fail to close and instead terminate in runaway collapse.

Within the emergence-time framework, such collapse corresponds to negative-orientation spiral endpoints characterized by divergent emergence time attained within finite proper time. Black holes thus represent limiting cases in which stabilization mechanisms are exhausted rather than generic outcomes of gravitational evolution.

This interpretation reconciles the existence of black holes with the predominance of stable structures, situating both phenomena within a unified dynamical hierarchy.

3.6 Summary

Fermionic statistics provide a minimal and universal mechanism for stabilizing irreversible structure formation. Through phase-space occupancy bounds and degeneracy pressure, fermionic systems naturally arrest gravitational collapse while preserving spiral dynamics. Orientation selection arises intrinsically from non-commutative occupancy constraints, and black hole formation emerges as a limiting endpoint rather than a generic fate.

In the following section, we extend this framework to cosmological evolution, interpreting large-scale structure formation as an iterative sequence of phase transitions governed by emergence time.

4. Phase Transitions, Expansion, and Iterative Structure Formation

4.1 Phase transitions as dynamical reorganizations

Phase transitions play a central role in physical systems across all scales. Traditionally, they are described as changes in state variables—such as symmetry breaking or order parameter reconfiguration—often accompanied by macroscopic expansion or contraction. In the present framework, phase transitions acquire a more general interpretation: they correspond to dynamical reorganizations of accessible phase space.

Within the emergence-time formulation, a phase transition is characterized by a sudden increase in the number of physically distinguishable configurations. This increase may occur through spatial expansion, the opening of new momentum-space channels, or the creation of new informational degrees of freedom. In all cases, the defining feature is an increase in the emergence rate $R(t)$, ensuring a forward increment of emergence time.

4.2 Expansion beyond physical volume

Importantly, expansion need not correspond to an increase in physical volume. While cosmological expansion represents a geometric manifestation of this process, similar effects occur in systems whose spatial extent decreases. During structure formation, matter locally contracts, yet the internal configuration space expands as new correlations, modes, and records are generated.

This distinction resolves the apparent tension between expansion and structure formation. Both processes correspond to growth in effective degrees of freedom, albeit in different representations. Expansion in this generalized sense is therefore a necessary condition for irreversible structure formation, not its opposite.

4.3 Spiral stabilization following phase transitions

Following each phase transition, systems undergo a relaxation process governed by the dynamics described in Sections 2 and 3. Newly opened phase-space regions are rapidly explored under nonlinear attraction, leading to spiral trajectories toward stable configurations. Fermionic constraints enforce saturation, converting transient collapse into long-lived structure.

This sequence—phase-space expansion followed by spiral stabilization—constitutes a generic cycle of evolution. Each cycle produces an increment of emergence time and leaves behind a stable structural residue. The universe may therefore be viewed as the cumulative result of repeated phase transitions, each followed by spiral closure into dynamically accessible attractors.

4.4 Iterative cosmological evolution

Applied to cosmology, this framework suggests that large-scale structure formation proceeds through iterative transitions rather than through a single monotonic process. Early-universe phase transitions open vast new configuration spaces, while subsequent gravitational dynamics organize matter into spiral-stabilized structures.

Cosmic expansion and structure formation are thus not competing processes but complementary aspects of a single dynamical sequence. Expansion creates the conditions for new structure, while fermionic stabilization prevents unbounded collapse, allowing complexity to accumulate over cosmic time.

4.5 Emergence time across cycles

Each phase-transition cycle contributes positively to emergence time. The monotonicity of \tau ensures that these cycles define a global temporal ordering independent of coordinate choices. Even when geometric time intervals vary widely between transitions, the cumulative emergence time provides a consistent measure of physical progression.

In this sense, cosmological history is best described not as evolution along a single geometric timeline but as a sequence of emergence events punctuated by stabilization phases. Time flows precisely when new structure becomes physically distinguishable.

4.6 Summary

Phase transitions provide the dynamical triggers that open new regions of phase and information space. Subsequent spiral dynamics, stabilized by fermionic statistics, convert these openings into persistent structures. Iterated across cosmic history, this mechanism yields a universe that expands, structures, and stabilizes repeatedly while maintaining a strictly monotonic emergence time.

In the next section, we discuss the implications of this framework for black hole physics, cosmology, and observational signatures, and contrast it with conventional cold dark matter approaches.

5. Discussion

5.1 Relation to conventional dark matter frameworks

Standard cold dark matter (CDM) models have been remarkably successful at reproducing large-scale cosmological observations. However, at galactic and sub-galactic scales, CDM often requires additional prescriptions—such as baryonic feedback, fine-tuned initial conditions, or phenomenological cutoffs—to prevent excessive central clustering.

Within the emergence-time framework, this difficulty is reinterpreted as a consequence of missing intrinsic stabilization. Classical particle ensembles lack internal phase-space constraints capable of arresting collapse once nonlinear gravitational amplification begins. As a result, stability must be enforced externally through model-dependent mechanisms.

By contrast, fermionic systems incorporate stabilization at the statistical level. Phase-space occupancy bounds and degeneracy pressure arise independently of environmental details and automatically regulate collapse. In this sense, fermionic matter does not replace gravitational dynamics but completes them, providing the minimal additional structure required to realize irreversible yet stable evolution.

5.2 Spiral geometry as a diagnostic feature

A central implication of the present framework is that spiral or helical organization is not incidental but diagnostic. Spiral dynamics emerge whenever irreversible attraction is balanced by intrinsic constraints. Their ubiquity across physical scales—from magnetic field lines and quantum transport to galactic structure—suggests a common underlying mechanism.

In the context of dark matter, the presence of stable cores, smooth central density profiles, and long-lived rotational features may therefore be interpreted as signatures of constrained phase-space evolution rather than as anomalies requiring ad hoc correction. The emergence-time formulation predicts that such features should correlate with indicators of saturation rather than with feedback intensity alone.

5.3 Black holes and structural hierarchy

The framework developed here accommodates black hole formation without elevating it to the generic outcome of gravitational evolution. Black holes arise when all available stabilization mechanisms are exhausted, corresponding to negative-orientation spiral endpoints in phase space.

This interpretation introduces a natural structural hierarchy. Most self-gravitating systems evolve toward stabilized spiral configurations, while a minority reach terminal collapse. Black holes therefore coexist with, rather than dominate, cosmic structure. Their role is to delimit the boundary of dynamical accessibility rather than to define typical behavior.

5.4 Observational and conceptual implications

Although this work is primarily theoretical, it suggests several qualitative avenues for observational discrimination. Systems governed by intrinsic phase-space constraints are expected to exhibit saturation behavior, smooth central profiles, and persistent structural motifs. Deviations from these patterns may signal transitions toward terminal regimes.

Conceptually, the framework reframes cosmic evolution as a sequence of irreversible but regulated processes. Stability is not imposed by special initial conditions but emerges dynamically from minimal statistical principles. Time, structure, and geometry are thus unified through emergence time rather than treated as independent inputs.

5.5 Limitations and scope

The present analysis does not identify a specific fermionic dark matter particle, nor does it claim exclusivity. Instead, it establishes that fermionic statistics constitute a minimal sufficient mechanism for realizing the requirements imposed by emergence time. Alternative mechanisms would need to replicate these properties—intrinsic saturation, orientation selection, and monotonic emergence—without recourse to fine-tuning.

Future work may extend this framework to detailed phenomenological modeling and to explicit confrontation with cosmological data. The present contribution is to clarify the structural logic that any successful implementation must satisfy.

6. Conclusion

In this work, we have extended the emergence-time framework by identifying a concrete physical realization of irreversible structure formation. Building on the dynamical definition of time as cumulative structure production, we have shown that self-gravitating systems with intrinsic phase-space constraints generically evolve toward spiral attractors that stabilize into toroidal configurations.

Fermionic statistics provide a minimal and universal mechanism for such stabilization. Through phase-space occupancy bounds and degeneracy pressure, fermionic matter naturally arrests gravitational collapse while preserving irreversible progression. Spiral dynamics emerge as the geometric expression of this constrained evolution, while black hole formation appears as a limiting terminal case rather than as the generic outcome.

We have further argued that cosmological evolution may be understood as an iterative sequence of phase transitions followed by spiral stabilization, yielding a universe that expands, structures, and stabilizes repeatedly while maintaining a strictly monotonic emergence time. In this unified picture, time, structure, and geometry are not independent ingredients but mutually reinforcing aspects of a single dynamical process.

These results suggest that the large-scale stability of the universe follows from minimal statistical and geometric principles rather than from finely tuned initial conditions. Emergence time provides the organizing variable, fermionic statistics supply intrinsic regulation, and spiral dynamics encode the resulting structure. Together, they form a coherent framework for understanding irreversible cosmic evolution.