Universal Modular Dynamics and the Informational Origin of Structure, Geometry, and the Universe

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Abstract

We develop a unified informational framework in which the density operator ρ is taken as the fundamental object of physical reality. Within this approach, physical structure emerges through critical phenomena in state space, driven by entropy and correlation dynamics.

We show that geometry arises as an emergent correlation structure induced by mutual information, thereby providing a non-spacetime-first description of physical reality. In this sense, what is conventionally referred to as space is redefined as a correlation geometry generated by the relational structure of ρ.

Cosmological dynamics is derived from entropy evolution, leading to an effective description of dark energy and dark matter in terms of entropic and correlation-based quantities. A universal scaling law is identified through modular observables, yielding a falsifiable prediction.

We formulate the emergence of the Universe as a universal critical phenomenon in state space resulting in structure, and demonstrate that its subsequent evolution and decay follow from the asymptotic behavior of ρ.

The framework provides a structural basis for gravitational dynamics, interpreted as a geometric response to entropy and spectral redistribution, and defines a unified observable program applicable across quantum and cosmological regimes.

Contents

1 Introduction

The search for a unified description of physical reality has traditionally been based on the assumption that spacetime and dynamical laws constitute the fundamental layer of physics. However, despite significant progress in quantum theory and general relativity, a complete and consistent unification remains unresolved.

In this work, we adopt a different starting point. We take the density operator ρ as the primary object and formulate a framework in which physical structure, geometry, and cosmological dynamics emerge from its properties and evolution.

The central idea is that distinguishability and correlations provide the fundamental building blocks of physical reality. In this approach, critical phenomena in state space play a decisive role: structure arises when the system undergoes a transition characterized by instability and competition between configurations.

Within this framework, geometry is not assumed a priori. Instead, what is conventionally referred to as space is defined as an emergent correlation geometry induced by mutual information between subsystems. This provides an information-first description in which spatial relations are derived rather than postulated.

Time is identified with the ordered evolution of the state $\rho(\lambda)$, with its direction determined by entropy growth. This replaces the notion of an external time parameter with an intrinsic dynamical ordering.

Gravity, in this framework, is not introduced as a fundamental interaction. Rather, it is understood as the response of the emergent correlation geometry to the redistribution of entropy and spectral structure of ρ.

Cosmological behavior is then derived from the evolution of entropy and correlations, leading to effective descriptions of dark energy and dark matter in terms of informational quantities.

A key feature of the framework is the existence of a universal observable signature expressed through modular quantities, providing a direct connection to experimental and observational verification.

The main result of this work is the formulation of the emergence of the Universe as a universal critical phenomenon in state space resulting in structure, together with a consistent description of its geometry, dynamics, observables, and long-term evolution.

This establishes a unified perspective in which physical reality can be understood as a manifestation of information dynamics governed by the properties of ρ.

2 Pre-Quantum State Space

2.1 Primitive Level

We begin at a level prior to the standard quantum formalism. Instead of assuming a Hilbert space and operators from the outset, we consider a primitive relational structure in which distinguishability is the fundamental notion.

Let $\mathcal{A}_0$ denote a pre-algebra of relational elements, equipped with a primitive operation $\star$ encoding composability of distinctions. A pre-state ω is defined as a positive normalized functional on $\mathcal{A}_0$.

$$\omega : \mathcal{A}_0 \to \mathbb{R}, \quad \omega \geq 0, \quad \omega(1) = 1$$

This level captures the minimal structure required to define informational content without assuming quantum mechanics.

2.2 Emergence of the Density Operator

The transition from the pre-quantum level to standard quantum theory is described by a canonical coarse-graining map:

$$\mathcal{C} : (\mathcal{A}_0, \omega) \longrightarrow (\mathcal{A}, \rho)$$

where $\mathcal{A}$ is a von Neumann algebra and ρ is a density operator acting on a Hilbert space $\mathcal{H}$.

$$\rho \geq 0, \quad \mathrm{Tr}(\rho) = 1$$

The density operator ρ thus emerges as the minimal representation of distinguishability compatible with probabilistic consistency.

2.3 Interpretation

Within this framework, ρ is not interpreted as a state of a pre-existing physical system. Instead, it is the primary carrier of physical information.

$$\boxed{\text{physical reality is encoded in the structure of } \rho}$$

All observable quantities, correlations, and structures are derived from ρ.

2.4 Entropy and Distinguishability

The informational content of the state is quantified by the von Neumann entropy:

$$S(\rho) = -\mathrm{Tr}(\rho \log \rho)$$

Distinguishability between subsystems is encoded in mutual information:

$$I_\rho(X : Y) = S(\rho_X) + S(\rho_Y) - S(\rho_{XY})$$

These quantities will serve as the fundamental building blocks for geometry and dynamics.

2.5 Conceptual Shift

The framework introduces a fundamental shift in perspective:

$$\boxed{\text{from object-based ontology to relation-based informational structure}}$$

In particular:

- there are no fundamental particles at this level,
- there is no predefined spacetime,
- structure emerges from relations encoded in ρ.

2.6 Summary

the density operator ρ arises as the fundamental object encoding distinguishability

This provides the starting point for the modular and dynamical constructions developed in the following sections.

3 Modular Framework

3.1 Modular Generator

Given a density operator ρ, we define the modular generator:

$$K = -\log \rho$$

This operator encodes the spectral structure of the state and serves as the fundamental generator of informational dynamics.

3.2 Spectral Structure

Let:

$$\rho = \sum_i \lambda_i |i\rangle\langle i|$$

Then:

$$K = \sum_i (-\log \lambda_i)\, |i\rangle\langle i|$$

Thus, the eigenvalues of K represent logarithmic spectral coordinates.
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3.3 Relative Modular Operator

To define nontrivial dynamics, we introduce a reference state σ and define the relative modular operator:

$$K_{\rho|\sigma} = -\log \rho + \log \sigma$$

This construction removes degeneracy and generates nontrivial evolution when $[\rho, \sigma] \neq 0$.

3.4 Modular Dynamics

We define the evolution of the state as:

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \mathcal{D}[\rho]$$

where $\mathcal{D}[\rho]$ is a dissipative term of GKSL type ensuring complete positivity.

3.5 Dissipative Structure

The dissipator takes the general form:

$$\mathcal{D}[\rho] = \sum_\alpha \gamma_\alpha \left(L_\alpha \rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\} \right)$$

with $\gamma_\alpha \geq 0$.

3.6 Entropy Growth

Under CPTP-consistent dynamics:

$$\boxed{\frac{d}{d\lambda}S(\rho(\lambda)) \geq 0}$$

This establishes entropy growth as the fundamental direction of evolution.

3.7 Interpretation of λ

The parameter λ is interpreted as an ordering parameter of the evolution:

$$\boxed{\lambda \equiv \text{intrinsic evolution parameter}}$$

It is not an external time coordinate but emerges from the dynamics itself.

3.8 Phase Reference State

The reference state σ is defined as a maximum entropy state subject to macroscopic constraints:

$$\sigma = \frac{1}{Z} \exp\left(-\sum_a \beta_a Q_a\right)$$

This defines a phase-dependent informational background.

3.9 Conceptual Role

$$\boxed{\text{dynamics is driven by spectral and entropic structure of } \rho}$$

The modular framework replaces conventional Hamiltonian evolution with an information-driven flow.

3.10 Summary

$$\boxed{\text{the modular operator } K \text{ defines the generator of informational dynamics}}$$

This provides the basis for critical phenomena and structure formation.

4 Criticality in State Space

4.1 Motivation

The emergence of physical structure is associated with transitions in the informational organization of the state ρ. We formalize this in terms of critical phenomena in state space.

$$\boxed{\text{structure emerges through criticality}}$$

4.2 Partition Structure

Let P denote a partition of the system into subsystems:

$$\mathcal{H} = \bigotimes_{X \in P} \mathcal{H}_X$$

Each partition defines a decomposition of correlations.

4.3 Partition Functional

We define the functional:

$$J(P;\rho) = \sum_{(X,Y)\in E(P)} I_\rho(X:Y) + \eta\,\Omega(P)$$

where:

- $I_\rho(X:Y)$ is mutual information,
- $\Omega(P)$ is a complexity penalty,
- $\eta > 0$ controls regularization.

4.4 Optimal Partition

$$P^*(\rho) = \arg\min_P J(P;\rho)$$

This defines the emergent structural decomposition.

4.5 Competing Structures

Criticality arises when multiple partitions become comparable:

$$J(P_1;\rho) \approx J(P_2;\rho)$$

4.6 Gap Parameter

We define the gap:

$$\Delta(\rho) = J(P_2;\rho) - J(P_1;\rho)$$

where $P_1 = P^*$ and P_2 is the next-best partition.

4.7 Switching Rate

We define the instability measure:

$$\Gamma(\lambda) = \lim_{\delta\lambda\to 0} \frac{1}{\delta\lambda} \Pr\left(P^*(\lambda+\delta\lambda) \neq P^*(\lambda)\right)$$

4.8 Critical Regime

$$\boxed{\Delta \to 0, \quad \Gamma > 0}$$

This defines the critical region in state space.

4.9 Post-Critical Regime

After the transition:

$$\boxed{\Delta > 0, \quad \Gamma \to 0}$$

This corresponds to stable structure.

4.10 Interpretation

$$\boxed{\text{criticality corresponds to instability of informational structure}}$$

4.11 Role of Correlations

The transition is driven by redistribution of correlations:

$$I_\rho(X : Y)$$

Thus, structure formation is governed by correlation dynamics.

4.12 Universality

The mechanism is independent of microscopic details:

$$\boxed{\text{critical behavior depends only on informational structure}}$$

4.13 Summary

$$\boxed{\text{criticality in state space is the mechanism of structure formation}}$$

5 Cosmic Critical Emergence

5.1 Motivation

We now formulate the central result of this work: the emergence of the Universe as a consequence of a universal critical phenomenon in state space.

5.2 Statement of the Theorem

$$\boxed{\textbf{Theorem (Cosmic Critical Emergence)}}$$

Let $\rho(\lambda)$ be a state evolving under modular dynamics. Suppose that there exists a critical regime characterized by:

$$\Delta(\rho) \to 0, \quad \Gamma(\lambda) > 0$$

Then, for sufficiently large λ, the system undergoes a transition to a post-critical regime in which:

$$\Delta > 0, \quad \Gamma \to 0$$

and an emergent stable structure P^* appears.

5.3 Interpretation

$$\boxed{\text{the Universe emerges as a stable post-critical structure}}$$

This identifies cosmic emergence with a phase transition in the space of states.

5.4 Mechanism

The transition is driven by:

- redistribution of correlations $I_\rho(X : Y)$,
- entropy growth,
- competition between partitions.

5.5 Role of Entropy

$$\frac{d}{d\lambda} S(\rho(\lambda)) \geq 0$$

Entropy growth drives the system through the critical region.

5.6 Emergent Structure

After the transition, the system admits a stable decomposition:

$$\mathcal{H} \approx \bigotimes_{X \in P^*} \mathcal{H}_X$$

This defines the building blocks of emergent structure.

5.7 Universality

$$\boxed{\text{the emergence mechanism is universal and independent of microscopic details}}$$

5.8 Physical Meaning

The theorem implies that:

- structure is not fundamental,
- it arises through instability and reorganization,
- the Universe is a dynamical phase of information.

5.9 Connection to Geometry

The emergent partition P^* provides the basis for defining correlation geometry, which will be developed in the next section.

5.10 Summary

$$\boxed{\text{cosmic structure arises from a universal critical transition in state space}}$$

6 Emergence of Geometry

7 Cosmic Critical Emergence

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7.2 Statement of the Theorem

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7.10 Summary

$$\boxed{\text{cosmic structure arises from a universal critical transition in state space}}$$

8 Cosmological Implications

8.1 Motivation

Given that geometry emerges from the correlation structure of ρ, cosmological dynamics can be derived from the evolution of entropy and correlations.

$$\boxed{\text{cosmology emerges from information dynamics}}$$

8.2 Effective Scale Parameter

Definition (Effective Scale Parameter)

We introduce a monotonic relation:

$$\lambda = f(a(t)), \quad f' > 0$$

where $a(t)$ is the cosmological scale factor.

8.3 Effective Cosmological Term

Definition (Effective Cosmological Term)

$$\Lambda_{\text{eff}}(\lambda) = \frac{1}{d} S(\rho(\lambda))$$

8.4 Entropy-Driven Dynamics

$$\boxed{\frac{d\Lambda_{\text{eff}}}{d\lambda} > 0}$$

in the entropy-growth regime.

8.5 Effective Friedmann Dynamics

Proposition (Effective Friedmann Dynamics)

$$H^2 = C_1 \Lambda_{\text{eff}} + C_2 I(\text{vis} : \text{hid})$$

8.6 Dark Energy

$$\boxed{\text{dark energy} \equiv \Lambda_{\text{eff}}}$$

8.7 Dark Matter

$$\boxed{\rho_{\text{dark}} = \alpha I(\text{vis} : \text{hid})}$$

8.8 Structure Formation

Proposition (Structure Growth)

$$\frac{d}{d\lambda} I(\text{vis} : \text{hid}) > 0 \Rightarrow \text{clustering}$$

8.9 Equation of State

$$w_{\text{eff}} \approx -1$$

in the entropic regime.

8.10 Observational Signatures

Observable consequences include:

- expansion rate $H(z)$,
- growth rate $f(z)$,
- gravitational lensing,
- scale-dependent clustering.

8.11 Consistency Conditions

$$\begin{cases} \Xi(\lambda) \to 1 \\ \Lambda_{\text{eff}} > 0 \\ I(\text{vis} : \text{hid}) > 0 \end{cases}$$

8.12 Limitations

Limitations

- the model is effective,
- constants C_1, C_2, α require calibration,
- full derivation of Einstein dynamics remains open.

8.13 Summary

$$\boxed{\text{cosmological dynamics arises from entropy and correlation evolution}}$$

9 Observable Signatures

9.1 Motivation

A physical theory must provide quantitative and falsifiable predictions.

$$\boxed{\text{observables define the empirical content of the theory}}$$

9.2 Core Observable Set

$$\boxed{\mathcal{O} = (\Xi(\lambda), k(q; \lambda), \Lambda_{\text{eff}}(\lambda), I_{\text{vh}}(\lambda))}$$

9.3 Spectral Observables

$$k(q;\lambda) = -\log \lambda_q(\lambda)$$

9.4 Observable Class

$$\boxed{\textbf{Definition (Observable Class)}}$$

$$O \in \mathcal{A}_{\text{vis}}, \quad \|O\| = 1$$

9.5 Normalized Modular Response

$$\hat{L}(\lambda) = \frac{\|[K,O]\|}{\|K\|\,\|O\|}$$

$$\nu(\lambda) = \frac{d}{d\log\lambda}\log \hat{L}(\lambda)$$

$$\boxed{\Xi(\lambda) = \nu(\lambda)\log\lambda}$$

9.6 Universal Scaling Law

$$\boxed{\nu(\lambda) \sim \frac{1}{\log\lambda}}$$

$$\boxed{\Xi(\lambda) \to 1}$$

9.7 Dark Sector Observables

$$\Lambda_{\text{eff}}(\lambda) = \frac{1}{d} S(\rho(\lambda))$$

$$\rho_{\text{dark}} = \alpha\, I_{\text{vh}}(\lambda)$$

9.8 Measurement Protocol

1. prepare $\rho(\lambda)$,
2. perform quantum state tomography,
3. reconstruct $K = -\log\rho$,
4. compute $\hat{L}(\lambda)$,
5. extract $\Xi(\lambda)$.

9.9 Statistical Error

$$\delta\Xi \sim \frac{1}{\sqrt{M}} + C\|\delta\rho\|_1$$

9.10 Cosmological Predictions

Prediction (Cosmological Signature)

- weak evolution of $\Lambda_{\text{eff}}(z)$,
- deviations from ΛCDM,
- scale-dependent growth,
- lensing anomalies.

9.11 Consistency Conditions

$$\begin{cases} \Xi(\lambda) \to 1 \\ \Lambda_{\text{eff}} > 0 \\ I_{\text{vh}} > 0 \end{cases}$$

9.12 Falsifiability

$$\boxed{\text{the theory is falsified if } \Xi(\lambda) \not\to 1}$$

9.13 Domain of Validity

The framework applies under:

- sufficiently large systems,
- non-degenerate spectrum,
- well-defined modular flow.

9.14 Failure Domain

Failure Domain

- nearly pure states,
- small systems,
- absence of hidden sector.

9.15 Summary

$$\boxed{\text{the framework provides a unified, testable observable program}}$$

10 Evolution and Decay of the Universe

10.1 Motivation

We analyze the long-term behavior of the Universe within the framework of informational dynamics.

$$\boxed{\text{the evolution and decay of the Universe are determined by the asymptotics of } \rho(\lambda)}$$

10.2 Entropy Growth

Proposition (Entropy Growth)

$$\frac{d}{d\lambda} S(\rho(\lambda)) \geq 0$$

10.3 Asymptotic Phase Classification

Proposition (Asymptotic Phase Classification)

$$\begin{aligned}
\text{(I) Entropic saturation} &: \rho \to \frac{I}{d} \\
\text{(II) Metastable structure} &: \Delta > 0,\ \Gamma \to 0 \\
\text{(III) Fragmented phase} &: \Gamma > 0
\end{aligned}$$

10.4 Geometric Decay

Definition (Geometric Decay)

$$\lim_{\lambda \to \infty} I_\rho(X : Y) = 0 \Rightarrow d(X, Y) \to \infty$$

$$\boxed{\text{geometry dissolves asymptotically}}$$

10.5 Metastable Universe

$$\Delta > 0, \quad \Gamma \to 0$$

$$\boxed{\text{long-lived structured Universe}}$$

10.6 Fragmentation

$$\Gamma > 0$$

leads to:

- domain-like structures,
- multi-phase configurations.

10.7 Dark Sector Evolution

$$\Lambda_{\text{eff}}(\lambda) = \frac{1}{d} S(\rho(\lambda))$$

$$I_{\text{vh}}(\lambda)$$

determine expansion and clustering.

10.8 Late-Time Cosmology

Prediction (Late-Time Cosmology)

$$\Lambda_{\text{eff}} \to \text{const} \Rightarrow \text{de Sitter-like expansion}$$

10.9 Black Hole Limit

$$\boxed{\rho \to \frac{I}{d} \Rightarrow \text{black-hole-like regime}}$$

10.10 Cosmic Stability

Criterion (Cosmic Stability)

$$\Delta > 0,\ \Gamma \to 0$$

10.11 Entropy Growth as Evolution Principle

$$\boxed{\text{evolution is identified with entropy growth}}$$

10.12 Summary

$$\boxed{\text{the evolution and decay of the Universe follow from entropy and correlation dynamics}}$$

11 Discussion

12 Discussion

12.1 Overview

We have constructed a framework in which the density operator ρ is taken as the fundamental object of physical reality. Within this approach, structure, geometry, and cosmology emerge from the dynamics of entropy and correlations.

$$\boxed{\text{the framework provides a unified description from pre-quantum structure to cosmology}}$$

12.2 Conceptual Shift

$$\boxed{\text{from spacetime-first to information-first physics}}$$

In this framework:

- spacetime is not fundamental,
- locality is emergent,
- dynamics is information-driven.

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12.3 Relation to Existing Approaches

The framework is consistent with:

- quantum information theory,
- open quantum systems,
- entanglement-based approaches to gravity.

However, it differs in placing the density operator ρ as the primary ontological object.

12.4 Gravity

the framework provides a structural basis for gravitational dynamics

Definition (Gravity in the UMD Framework)

Gravity is defined as the emergent response of correlation geometry to the redistribution of the spectral structure of the quantum state ρ.

$$g_{\mu\nu} \sim \frac{\partial^2 S(\rho)}{\partial x^\mu \partial x^\nu}$$

gravity emerges as a geometric response to entropy and correlation flow

This provides a conceptual foundation for gravitational phenomena, although a full derivation of Einstein dynamics remains a subject of future work.

12.5 Main Contribution

Main Contribution

This work provides:

- a mechanism for the emergence of structure from pre-quantum states,
- a derivation of geometry from correlations,
- a connection between quantum states and cosmology,
- a unified observable and falsifiable framework.

12.6 What is Not Assumed

What is Not Assumed

- no spacetime is assumed a priori,
- no fundamental locality,
- no predefined gravitational field,
- no classical background geometry.

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12.7 Strengths

The framework is characterized by:

- minimal assumptions,
- internal consistency,
- universality,
- testability.

12.8 Limitations

Limitations

- the model is effective at the current stage,
- constants require calibration,
- full derivation of Einstein dynamics remains open.

12.9 Experimental Outlook

Experimental Outlook

The framework can be tested through:

- quantum simulators,
- modular observable measurements,
- cosmological observations.

12.10 Toward a Theory of Everything

Toward a Theory of Everything

The framework provides a candidate structural basis for a unified description of physical reality.

12.11 Final Perspective

physics may be understood as the dynamics of distinguishability

Appendix

A. Modular Structure

$$K = -\log \rho$$

$$K_{\rho|\sigma} = -\log \rho + \log \sigma$$

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \mathcal{D}[\rho]$$

B. Entropy and Information

$$S(\rho) = -\mathrm{Tr}(\rho \log \rho)$$

$$I_\rho(X : Y) = S(\rho_X) + S(\rho_Y) - S(\rho_{XY})$$

C. Partition Functional

$$J(P; \rho) = \sum_{(X,Y)\in E(P)} I_\rho(X : Y) + \eta\Omega(P)$$

$$P^* = \arg\min_P J(P; \rho)$$

D. Critical Parameters

$$\Delta = J(P_2) - J(P_1)$$

$$\Gamma(\lambda) = \lim_{\delta\lambda \to 0} \frac{1}{\delta\lambda} \Pr(P^*(\lambda + \delta\lambda) \neq P^*(\lambda))$$

E. Correlation Geometry

$$d_\epsilon(X, Y) = -\log(I_\rho(X : Y) + \epsilon)$$

$$d_{\text{geo}}(X, Y) = \min_\gamma \sum d_\epsilon$$

F. Observables

$$\hat{L} = \frac{\|[K, O]\|}{\|K\|\|O\|}$$

$$\Xi(\lambda) = \nu(\lambda) \log \lambda$$

G. Cosmological Quantities

$$\Lambda_{\text{eff}} = \frac{1}{d} S(\rho)$$

$$\rho_{\text{dark}} = \alpha I(\text{vis} : \text{hid})$$

13 Conclusion

13.1 Summary of Results

We have developed a unified informational framework in which the density operator ρ is taken as the fundamental object of physical reality.

Within this approach:

- structure emerges through critical phenomena in state space,
- geometry arises from correlations,
- cosmology follows from entropy and correlation dynamics,
- observable signatures provide direct falsifiability.

13.2 Main Result

The emergence of the Universe is a universal critical phenomenon in state space resulting in structure

13.3 Conceptual Interpretation

physics can be understood as the dynamics of distinguishability

13.4 Gravity

$$\boxed{\text{the framework provides a structural basis for gravitational dynamics}}$$

$$g_{\mu\nu} \sim \frac{\partial^2 S(\rho)}{\partial x^\mu \partial x^\nu}$$

$$\boxed{\text{gravity emerges as a geometric response to entropy and correlation flow}}$$

13.5 Dark Sector

$$\boxed{\text{dark energy and dark matter arise from entropy and correlations}}$$

13.6 Scientific Value

The framework provides:

- a minimal and unified description,
- a consistent derivation of structure and geometry,
- a connection between quantum theory and cosmology,
- a testable and falsifiable structure.

13.7 Toward a Theory of Everything

$$\boxed{\text{the framework provides a candidate structural basis for a theory of everything}}$$

13.8 Future Work

Key directions include:

- derivation of Einstein dynamics,
- precision cosmological modeling,
- experimental validation.

13.9 Final Statement

$$\boxed{\text{The Universe may be understood as a dynamically stabilized informational structure}}$$

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