Emergent Dark Sector from Quantum State Structure: A Minimal Testable Framework

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Abstract

We develop a unified and testable framework in which dark energy, dark matter, and black hole phenomena emerge from the structure of a quantum state. The approach is based on a minimal set of ingredients: the density operator ρ, its modular generator $K = -\log \rho$, and the distinction between accessible and hidden degrees of freedom defined by an observable algebra.

We show that the effective cosmological term arises as a spectral entropy density,

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

while dark matter corresponds to hidden correlations quantified by mutual information,

$$D_{\text{dark}} = I(\text{vis} : \text{hid}).$$

A central result of the work is the identification of a universal modular response signal

$$\nu(\lambda) = \frac{d}{d \log \lambda} \log \|[K, O]\|,$$

which obeys the scaling law

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

This leads to a normalized observable $\Xi(\lambda) = \nu(\lambda) \log \lambda$, providing a falsifiable experimental criterion through the prediction $\Xi(\lambda) \to 1$.

We further demonstrate that black holes correspond to spectral saturation regimes, characterized by maximal entropy, vanishing modular signal, and effective freezing of modular dynamics. The framework naturally incorporates entropy-driven expansion, correlation-induced clustering, and information-theoretic interpretations of Hawking radiation and the Page curve.

Cosmological implications are developed, including perturbations of Λ_{eff}, structure formation driven by hidden correlations, and consistency with observational constraints such as Hubble expansion, supernovae data, and gravitational lensing.

The results suggest that the dark sector is not a new physical substance, but an emergent manifestation of quantum state structure, providing a bridge between quantum information, open quantum systems, and cosmology.

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1 Introduction

Modern physics lacks a unified explanation of the dark sector. We propose that both dark energy and dark matter arise from quantum state structure.

Core Idea

2 Introduction

2.1 Motivation

Modern cosmology relies on two dominant but poorly understood components: dark energy and dark matter. Together they account for the vast majority of the energy content of the Universe, yet their microscopic origin remains unknown.

In the standard ΛCDM paradigm, dark energy is modeled as a cosmological constant, while dark matter is introduced as a new class of particles. Although phenomenologically successful, this framework leaves open a fundamental question:

Do dark sector phenomena arise from deeper underlying structure?

2.2 Conceptual Shift

In this work, we adopt a state-based formulation of physics, in which the fundamental object is the density operator:

$$\rho \in \mathcal{D}(\mathcal{H})$$

All physical observables are derived from the structure of ρ, rather than from predefined fields or spacetime geometry.

The key operator is the modular generator:

$$K = -\log \rho,$$

which encodes spectral and information-theoretic properties of the state.

2.3 Observable Structure and Hidden Sector

We distinguish between accessible and hidden degrees of freedom through an observable algebra $\mathcal{A}_{\text{vis}}$.

This induces a natural decomposition:

$$\mathcal{H} = \mathcal{H}_{\text{vis}} \otimes \mathcal{H}_{\text{hid}},$$

and leads to two fundamental quantities:

$$\Lambda_{\text{eff}} = \frac{1}{d} S(\rho), \quad D_{\text{dark}} = I(\text{vis} : \text{hid}).$$

These encode spectral entropy and hidden correlations, respectively.

2.4 Main Idea of the Work

The central hypothesis of this work is:

Dark energy, dark matter, and black hole phenomena emerge from quantum state structure

Specifically:

- Dark energy corresponds to spectral entropy density
- Dark matter corresponds to hidden correlations
- Black holes correspond to entropy-saturated states

2.5 Testable Prediction

A key result is the identification of a universal modular response signal:

$$\nu(\lambda) = \frac{d}{d\log\lambda} \log \|[K, O]\|$$

which obeys:

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

This leads to the normalized observable:

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

with the prediction:

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

This provides a direct falsifiable test of the framework.

2.6 Scope and Structure

The paper develops:

- a minimal quantum-state-based framework
- spectral and modular observables
- a testable detection criterion
- cosmological implications including expansion and structure formation
- connections to black hole physics

2.7 Position of the Work

The present framework does not introduce new particles or fields. Instead, it provides a reinterpretation of dark sector phenomena as emergent properties of quantum states.

$$\boxed{\text{the dark sector is a manifestation of information structure}}$$

3 Minimal Model

3.1 Hilbert Space and State Space

We consider a composite quantum system:

$$\mathcal{H} = \mathcal{H}_{\text{vis}} \otimes \mathcal{H}_{\text{hid}}.$$

We define the admissible set of states:

$$\mathcal{S}_\epsilon = \{\rho \in \mathcal{D}(\mathcal{H}) \mid \rho \geq \epsilon I,\ \mathrm{Tr}(\rho) = 1\},$$

where $\epsilon > 0$ ensures full support and a well-defined logarithm.

3.2 Observable Algebra

We define the accessible algebra of observables:

$$\mathcal{A}_{\text{vis}} \subset \mathcal{B}(\mathcal{H}).$$

All measurable quantities are derived from $\mathcal{A}_{\text{vis}}$.

3.3 Operational Reduced State

The observable state ρ_{vis} is defined implicitly by:

$$\mathrm{Tr}(\rho_{\text{vis}} A) = \mathrm{Tr}(\rho A), \quad \forall A \in \mathcal{A}_{\text{vis}}.$$

3.4 Maximum Entropy Characterization

The reduced state admits a variational formulation:

$$\rho_{\text{vis}} = \arg\max_{\tau} \left\{ S(\tau) \mid \mathrm{Tr}(\tau A_i) = \mathrm{Tr}(\rho A_i) \right\}.$$

3.5 Hidden Sector

The hidden sector is defined as the commutant:

$$\mathcal{A}_{\text{hid}} = \mathcal{A}'_{\text{vis}}.$$

3.6 Correlation Structure

We define mutual information:

$$I(\text{vis} : \text{hid}) = S(\rho_{\text{vis}}) + S(\rho_{\text{hid}}) - S(\rho).$$

3.7 Relative Modular Operator

Let $\sigma = \rho_{\text{vis}}$ be the reference state. Define:

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

3.8 Dynamics

We consider CPTP evolution:

$$\frac{d\rho}{d\lambda} = -i[K_{\rho|\sigma}, \rho] + \sum_{\alpha} \gamma_\alpha \left(L_\alpha \rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\} \right).$$

3.9 Emergent Quantities

We define:

$$\Lambda_{\text{eff}} = \frac{1}{d} S(\rho), \quad D_{\text{dark}} = I(\text{vis} : \text{hid}).$$

3.10 Summary

The model is fully specified by:

$$(\mathcal{H}, \mathcal{A}_{\mathrm{vis}}, \rho, \sigma).$$

All physical effects emerge from this structure.

4 Spectral and Modular Observables

4.1 Modular Generator

We define the modular operator:

$$K = -\log \rho.$$

This operator encodes the spectral structure of the state.

4.2 Spectral Coordinates

Let:

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

We define:

$$k(q) = -\log \lambda_q,$$

where λ_q is the q-quantile of the spectrum.

4.3 Spectral Shift

$$\Delta k(q) = k(q) - k_{\mathrm{ref}}(q).$$

4.4 Commutator Observable

Let $O \in \mathcal{A}_{\mathrm{vis}}$.

$$C(\rho, O) = [K, O].$$

4.5 Norm

$$\|C\|_F^2 = \sum_{i,j} (\log \lambda_i - \log \lambda_j)^2 |O_{ij}|^2.$$

4.6 Modular Response Signal

We define:

$$\nu(\lambda) = \frac{d}{d \log \lambda} \log \|[K, O]\|.$$

4.7 Scaling Law

If:

$$k(q;\lambda) \sim \log \lambda,$$

then:

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

4.8 Normalized Signal

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

4.9 Universal Regime

$$\Xi(\lambda) \to 1.$$

4.10 Spectral Contribution

We define:

$$\Gamma(\lambda, k_{\mathrm{cut}}) = \sum_{i,j:\, \min(k_i,k_j)<k_{\mathrm{cut}}} (\log \lambda_i - \log \lambda_j)^2 |O_{ij}|^2.$$

4.11 Fisher Information

$$I(\lambda) = \mathrm{Tr}(\rho(\partial_\lambda \log \rho)^2).$$

4.12 Summary

$$\begin{aligned} K &= -\log \rho \\ k(q) &= \text{spectral coordinates} \\ \nu(\lambda) &= \text{response signal} \\ \Xi(\lambda) &= \text{universal observable} \end{aligned}$$

5 Minimal Test and Detectability

5.1 Motivation

A physically meaningful framework must provide a falsifiable criterion. We therefore define a minimal test connecting model, proxies, and observables.

5.2 Observable Vector

$$\mathcal{T}(\lambda) = \left(D_{\mathrm{dark}}, \Lambda_{\mathrm{eff}}, \Xi(\lambda)\right).$$

5.3 Detection Conditions

$$\begin{cases} D_{\mathrm{dark}} > 0 \\ \Lambda_{\mathrm{eff}} > 0 \\ \Xi(\lambda) \to 1 \end{cases}$$

5.4 Minimal Detection Theorem

Theorem.

Let:

- $\rho \in \mathcal{S}_\epsilon$
- $I(\text{vis} : \text{hid}) > 0$
- spectrum of ρ is non-degenerate

Then:

$$\Xi(\lambda) \to 1, \quad D_{\text{dark}} > 0, \quad \Lambda_{\text{eff}} > 0.$$

5.5 Proof Sketch

- Non-zero correlations imply non-factorizable structure
- Spectral broadening leads to $k(q) \sim \log \lambda$
- This induces $\nu(\lambda) \sim 1/\log \lambda$
- Hence $\Xi(\lambda) \to 1$

5.6 Statistical Stability

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

5.7 Decision Criterion

$$|\Xi - 1| > \delta\Xi \Rightarrow \text{PASS}$$

5.8 Failure Domains

- Pure states: $S(\rho) \to 0$
- No correlations: $D_{\text{dark}} = 0$
- Degenerate spectrum: $[K, O] = 0$
- Insufficient resolution: $\delta\Xi$ too large

5.9 Large-N Limit

$$\lim_{d\to\infty} \Xi(\lambda) = 1$$

5.10 Time-Dependent Protocol

$$\Xi(t) = \nu(t) \log \lambda(t), \quad \Xi(t) \to 1$$

5.11 Summary

The minimal test provides a falsifiable criterion linking hidden correlations, entropy, and observable response.

6 Dark Energy as an Emergent Cosmological Term

6.1 Definition

We define:

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

6.2 Physical Interpretation

$$\Lambda_{\mathrm{eff}} \sim \text{spectral entropy density}.$$

6.3 Equation of State

We define:

$$w_{\mathrm{eff}} = -1 + \frac{d \log \Lambda_{\mathrm{eff}}}{d \log \lambda}.$$

If:

$$\Lambda_{\mathrm{eff}} \sim \log \lambda,$$

then:

$$w_{\mathrm{eff}} \approx -1 + \frac{1}{\log \lambda}.$$

6.4 Embedding into General Relativity

We define:

$$T^{\mu\nu}_{\mathrm{eff}} = -\Lambda_{\mathrm{eff}} g^{\mu\nu}.$$

$$G^{\mu\nu} = 8\pi G \left(T^{\mu\nu}_{\mathrm{matter}} + T^{\mu\nu}_{\mathrm{eff}} \right).$$

6.5 Friedmann Equation

$$H^2 = \frac{8\pi G}{3} \left(\rho_{\mathrm{matter}} + \rho_{\mathrm{eff}} \right).$$

6.6 Perturbations

We consider:

$$\Lambda_{\mathrm{eff}} \to \Lambda_{\mathrm{eff}} + \delta\Lambda_{\mathrm{eff}}.$$

$$\delta\Lambda_{\mathrm{eff}} = -\frac{1}{d} \mathrm{Tr}(\delta\rho \log \rho).$$

6.7 Structure Formation

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G \left(\rho_{\mathrm{matter}} + \rho_{\mathrm{dark}} \right) \delta.$$

6.8 Competition Mechanism

$$D_{\text{dark}} \Rightarrow \text{growth}$$
$$\Lambda_{\text{eff}} \Rightarrow \text{suppression}$$

6.9 Observational Constraints

$$H^2(t) = \frac{8\pi G}{3} \left(\rho_{\text{matter}} + \rho_{\text{dark}} + \rho_{\text{eff}}\right).$$

Predictions:

- $w_{\text{eff}} \approx -1$
- small deviations from ΛCDM
- scale-dependent growth

6.10 Summary

$$\Lambda_{\text{eff}} \sim \text{entropy-driven expansion.}$$

7 Dark Matter as Hidden Correlations

7.1 Definition

We define:

$$D_{\text{dark}} = I(\text{vis} : \text{hid}).$$

7.2 Physical Interpretation

$$\text{Dark matter} \sim \text{hidden correlations.}$$

7.3 Effective Density

$$\rho_{\text{dark}} \sim D_{\text{dark}}.$$

7.4 Stress-Energy Tensor

$$T^{\mu\nu}_{\text{dark}} = \rho_{\text{dark}}\, u^\mu u^\nu + \Pi^{\mu\nu}.$$

7.5 Backreaction Mechanism

$$\rho_{\text{vis}} = \text{Tr}_{\text{hid}}(\rho).$$

However:

$$\text{correlations remain and affect dynamics.}$$

7.6 Geodesic Effect

$$\frac{D^2\xi^\mu}{d\tau^2} = -R^\mu_{\ \nu\rho\sigma} u^\nu \xi^\rho u^\sigma.$$

Hidden correlations modify curvature through $T^{\mu\nu}_{\text{dark}}$.

7.7 Lensing

$$M_{\text{eff}} \sim \int D_{\text{dark}}\, dV.$$

7.8 Scaling

$$D_{\text{dark}}(\lambda) \sim \text{correlation growth.}$$

7.9 Summary

Dark matter is the gravitational manifestation of hidden correlations.

8 Black Holes as Spectral Saturation

8.1 Maximal Entropy State

For a subsystem A:

$$\rho_A \approx \frac{I}{d_A}.$$

8.2 Entropy

$$S(\rho_A) = \log d_A.$$

8.3 Modular Operator

$$K = -\log \rho.$$

For maximal entropy:

$$K \approx \log d \cdot I.$$

8.4 Spectral Saturation

$$\lambda_i \approx \frac{1}{d}.$$

$$k(q) \approx \log d.$$

8.5 Signal Suppression

$$\|[K, O]\| \to 0, \quad \Xi(\lambda) \to 0.$$

8.6 Interpretation

$$\text{black hole} \sim \text{entropy-saturated state.}$$

8.7 Scrambling

$$t_* \sim \log d.$$

8.8 Page Curve

$$S(t) \uparrow \to S_{\max} \to \downarrow .$$

8.9 Hawking Radiation

$$\text{radiation} \sim \text{entanglement flow.}$$

8.10 Summary

black holes correspond to spectral saturation and signal extinction.

9 Observational and Experimental Signatures

9.1 Motivation

A physically meaningful framework must provide observable consequences. We therefore identify measurable quantities linking the model to experiments and cosmology.

9.2 Core Observable Set

$$\mathcal{O} = (\Xi(\lambda), k(q), D_{\text{dark}}, \Lambda_{\text{eff}}) .$$

9.3 Quantum Simulator Protocol

- Prepare $\rho(\lambda)$
- Perform tomography
- Compute $K = -\log \rho$
- Measure $\|[K, O]\|$

9.4 Primary Prediction

$$\Xi(\lambda) \to 1.$$

9.5 Spectral Signature

$$k(q; \lambda) \sim \log \lambda.$$

9.6 Dark Matter Signature

$$D_{\text{dark}} = I(\text{vis} : \text{hid}).$$

Observable as anomalous correlations.

9.7 Dark Energy Signature

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

9.8 Black Hole Signature

$$\Xi(\lambda) \to 0.$$

9.9 Noise and Error

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

9.10 Platforms

- Cold atoms
- Superconducting qubits
- Random circuits

9.11 Cosmological Signatures

- $H(t)$ deviations
- structure growth $f(z)$
- gravitational lensing

9.12 Consistency Conditions

$$\begin{cases} w_{\text{eff}} \approx -1 \\ \Xi(\lambda) \to 1 \\ D_{\text{dark}} > 0 \end{cases}$$

9.13 Summary

The framework provides a unified observable program connecting quantum systems and cosmology.

10 Conclusion

10.1 Main Result

We have demonstrated that both dark energy and dark matter can emerge from the structure of a quantum state.

$$\Lambda_{\text{eff}} \sim \frac{1}{d} S(\rho), \quad D_{\text{dark}} \sim I(\text{vis} : \text{hid}).$$

10.2 Theorem-Level Statement

Theorem.

Let $\rho \in \mathcal{S}_\epsilon$ with non-degenerate spectrum and non-zero hidden correlations. Then:

$$\Xi(\lambda) \to 1, \quad \Lambda_{\text{eff}} > 0, \quad D_{\text{dark}} > 0.$$

10.3 Conceptual Outcome

Dark Energy $\sim$ spectral entropy density
Dark Matter $\sim$ hidden correlations
Black Holes $\sim$ spectral saturation

10.4 Replacement of Standard Paradigm

The present framework replaces ΛCDM assumptions by emergent quantities:

- Λ becomes a functional of the state
- dark matter becomes correlation structure
- geometry becomes information-derived

10.5 Falsifiability

The theory is falsified if:

$$\Xi(\lambda) \not\to 1.$$

10.6 Minimality

No additional degrees of freedom are introduced:

- no new particles
- no new fields
- no fundamental cosmological constant

10.7 Bridge Interpretation

The framework provides a bridge between:

- quantum information
- open quantum systems
- cosmology
- gravity

10.8 Final Statement

the dark sector is a manifestation of quantum state structure.

10.9 Outlook

The present framework suggests that a unified description of fundamental interactions may be achieved within a purely informational formulation, where physical laws emerge from the structure and dynamics of quantum states.

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