

# Entropy-First Cosmology: Spacetime as an Emergent Entropic Field

Sean Evans

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## Abstract

We propose a cosmological framework in which spacetime, gravity, and cosmic dynamics emerge from the evolution of a fundamental informational entropy field  $S(t, \vec{x})$ . Unlike models that assume spacetime as primary, we treat entropy as the fundamental substance from which geometric structure arises. We derive an Informational Einstein Equation connecting curvature directly to second covariant derivatives of  $S$ , and show how this framework reduces to Special Relativity, General Relativity, Thermodynamics, and Quantum Mechanics in appropriate limits. The model predicts subtle deviations from  $\Lambda$ CDM, including specific signatures in cosmic expansion and structure formation, offering falsifiable predictions for surveys such as DESI, Euclid, and LSST. We conclude with a roadmap for empirical validation and theoretical refinement.

## 1 Introduction

Modern cosmology is built upon the  $\Lambda$ CDM framework, augmented by inflation to address fine-tuning problems and dark energy to explain late-time acceleration. However, these components are added phenomenologically, lacking fundamental explanation.

We propose an alternative view: spacetime geometry itself emerges dynamically from an underlying entropy field. In this model, entropy gradients and their evolution define curvature and drive cosmic expansion.

This entropy-first approach naturally addresses several outstanding problems:

- **Cosmological Constant Problem:** Vacuum energy does not directly gravitate; only coherent entropy gradients matter.
- **Horizon and Flatness Problems:** Pre-geometric informational connectivity explains early cosmic uniformity without fine-tuning.
- **Dark Energy:** Late-time acceleration arises from residual entropy curvature.

We structure the paper as follows:

- Section 2 defines our axioms and foundational principles.
- Section 3 derives the Informational Einstein Equation.
- Section 4 explains how known physics emerges as limits.
- Sections 5-8 develop cosmological dynamics, observational predictions, and quantum connections.
- Sections 9-12 discuss challenges, comparisons to other theories, and a future research roadmap.

## 2 Axioms and Foundational Principles

1. **Information Precedes Geometry:** Spacetime emerges from a deeper informational substrate.
2. **Curvature from Entropy:** Local curvature is proportional to second covariant derivatives of an entropy field  $S(t, \vec{x})$ .
3. **Dynamics from Entropy Flow:** Cosmic evolution follows the relaxation and stochastic evolution of  $S(t, \vec{x})$ .
4. **Quantum Fluctuations from Entropy Noise:** Planck-scale stochastic fluctuations in  $S$  generate quantum uncertainty.
5. **Minimalism:** No additional fields beyond  $S$  are introduced.

## 3 Physical Interpretation of the Entropy Field $S(t, \vec{x})$

The entropy field  $S(t, \vec{x})$  represents the coarse-grained informational entropy density associated with causal connections in spacetime.

- **Units:** nats per cubic meter ( $\text{nats}/\text{m}^3$ ).
- **Physical Meaning:**  $S$  quantifies the local “causal richness” - the number of accessible microstates or information configurations.
- **Microscopic Picture:** At a fundamental level,  $S$  may encode the density of possible causal graphs or informational links within small spacetime volumes.

This definition unifies concepts from information theory, thermodynamics, and spacetime causal structure, allowing entropy gradients to naturally induce curvature and dynamical evolution.

## 4 Derivation of the Informational Einstein Equation

### 4.1 Entropy Gradients and Spacetime Structure

We begin with the premise that the local informational entropy density  $S(t, \vec{x})$  defines the causal structure of spacetime. Spatial and temporal gradients of  $S$  determine the degree of local curvature.

The key hypothesis is:

*Local curvature is proportional to the second covariant derivatives of the entropy field  $S$ .*

Mathematically, this leads naturally to:

$$G_{\mu\nu} = \kappa \nabla_\mu \nabla_\nu S \tag{1}$$

where:

- $G_{\mu\nu}$  is the Einstein tensor, encoding spacetime curvature,
- $\nabla_\mu$  denotes the covariant derivative associated with the emergent metric  $g_{\mu\nu}$ ,
- $\kappa$  is a coupling constant with appropriate units (discussed below).

### 4.2 Physical Rationale

In standard thermodynamics, forces arise from gradients in entropy. Analogously, in this framework:

- First derivatives  $\nabla_\mu S$  define preferred local directions (information fluxes).
- Second derivatives  $\nabla_\mu \nabla_\nu S$  quantify how these fluxes diverge or converge — naturally giving rise to curvature.

Thus, spacetime curvature is interpreted as the differential resistance of information flow, encoded in the second derivatives of  $S$ .

### 4.3 Dimensional Analysis

We check dimensional consistency of Eq. (1).

- $[G_{\mu\nu}] = (\text{curvature}) = \text{length}^{-2}$ ,
- $[S] = \text{nats}/\text{m}^3$  (entropy density),
- $[\nabla_\mu] = \text{length}^{-1}$ .

Thus:

$$[\nabla_\mu \nabla_\nu S] = \text{length}^{-2} \times \text{entropy density}$$

To match units,  $\kappa$  must have units:

$$[\kappa] = (\text{length})^{-2} \times (\text{entropy density})^{-1}$$

Alternatively,  $\kappa$  can be absorbed into a redefinition of  $S$  if desired, normalizing entropy density appropriately to match curvature scales.

### 4.4 Limiting Behavior

When  $S$  is constant across spacetime:

$$\nabla_\mu \nabla_\nu S = 0 \quad \Rightarrow \quad G_{\mu\nu} = 0$$

thus recovering a Ricci-flat spacetime (Minkowski solution), matching Special Relativity.

When  $S$  varies smoothly, Eq. (1) reduces to an effective sourcing of curvature analogous to the standard Einstein field equations, as shown in later sections.

### 4.5 Remarks

Equation (1) should be viewed as the informational equivalent of the classical Einstein field equations:

- Matter-energy is replaced by entropy curvature.
- Conservation of information replaces conservation of stress-energy.
- Quantum uncertainty emerges from stochastic perturbations to  $S$  at small scales.

This interpretation bridges thermodynamics, information theory, and gravitational dynamics under a unified minimal framework.

## 5 Cosmological Dynamics from the Entropy Field

### 5.1 Application to FRW Metric

We now apply the Informational Einstein Equation to a homogeneous, isotropic spacetime described by the flat Friedmann-Robertson-Walker (FRW) metric:

$$ds^2 = -dt^2 + a(t)^2 (dr^2 + r^2 d\Omega^2) \quad (2)$$

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

Assuming  $S = S(t)$  depends only on cosmic time (homogeneity and isotropy), the covariant derivatives simplify greatly.

Computing the components:

- The 00 component of  $\nabla_\mu \nabla_\nu S$  gives  $\ddot{S}$  (second derivative with respect to time),

- Spatial components introduce factors of  $H\dot{S}$ , where  $H(t) \equiv \dot{a}/a$  is the Hubble parameter.

Thus, the 00 component of Eq. (1) becomes:

$$3 \left( \frac{\dot{a}}{a} \right)^2 = \kappa \ddot{S} \quad (3)$$

analogous to the first Friedmann equation in standard cosmology.  
Similarly, the trace of the spatial components yields:

$$2 \frac{\ddot{a}}{a} + \left( \frac{\dot{a}}{a} \right)^2 = \kappa H \dot{S} \quad (4)$$

analogous to the acceleration equation.

## 5.2 Interpretation

- The cosmic expansion rate is directly driven by the second time derivative of the entropy field  $S(t)$ .
- Positive curvature of  $S(t)$  (positive  $\ddot{S}$ ) drives accelerated expansion.
- Evolution of  $H(t)$  is tied to the relaxation dynamics of the global entropy field.

## 5.3 Simple Solutions: Power-Law Entropy Evolution

Assume:

$$S(t) = S_0 t^\alpha \quad (5)$$

where  $\alpha$  is a constant.

Then:

$$\dot{S}(t) = \alpha S_0 t^{\alpha-1}, \quad \ddot{S}(t) = \alpha(\alpha-1) S_0 t^{\alpha-2}$$

Substituting into Eq. (3):

$$\left( \frac{\dot{a}}{a} \right)^2 = \frac{\kappa}{3} \alpha(\alpha-1) S_0 t^{\alpha-2} \quad (6)$$

Thus:

$$\frac{\dot{a}}{a} = \sqrt{\frac{\kappa}{3} \alpha(\alpha-1) S_0} t^{(\alpha-2)/2} \quad (7)$$

## 5.4 Special Cases

**Case 1:  $\alpha = 2$**  If  $\alpha = 2$ , corresponding to quadratic entropy evolution:

$$\ddot{S} = 2S_0 \quad \Rightarrow \quad \text{constant acceleration of entropy field}$$

Thus:

$$\left( \frac{\dot{a}}{a} \right)^2 = \text{constant} \quad \Rightarrow \quad a(t) \propto e^{Ht}$$

This yields exponential expansion, naturally describing inflationary behavior without invoking an inflaton field.

**Case 2:**  $\alpha < 2$  If  $\alpha < 2$ , expansion is slower than exponential.

For example:

- $\alpha = 1$  yields  $a(t) \sim t^{1/2}$ , characteristic of radiation-dominated expansion.
- $\alpha = 3/2$  yields  $a(t) \sim t^{2/3}$ , matching matter-dominated expansion.

**Case 3: Late-Time Residual Acceleration** If at late times  $\ddot{S}$  relaxes to a small positive value, then  $H(t)$  asymptotically approaches a small constant, leading to late-time accelerated expansion, mimicking dark energy behavior.

## 5.5 Summary of Cosmic Epochs

In this entropy-driven cosmology:

- **Inflation** arises from rapid quadratic growth of  $S(t)$ .
- **Radiation domination** corresponds to slower entropy evolution ( $S(t) \sim t$ ).
- **Matter domination** arises from intermediate power laws ( $S(t) \sim t^{3/2}$ ).
- **Dark energy domination** results from residual positive  $\ddot{S}$  at late times.

Thus, the entire cosmic history emerges naturally from stages of entropy field dynamics.

## 6 Quantum Behavior from Entropy Stochasticity

### 6.1 Stochastic Evolution of the Entropy Field

At small scales, particularly near the Planck length and Planck time, it is natural to expect the entropy field  $S(t, \vec{x})$  to undergo stochastic fluctuations.

We model the late-time evolution of  $S$  as a stochastic differential equation (SDE):

$$dS(t) = \mu(t) dt + \sigma(t) dW(t) \quad (8)$$

where:

- $\mu(t)$  is the deterministic drift term,
- $\sigma(t)$  is the noise amplitude (expected to be Planck-suppressed),
- $dW(t)$  is an increment of a standard Wiener process (Brownian motion).

These stochastic perturbations to  $S$  induce corresponding fluctuations in the emergent metric, leading to quantum-like uncertainty in spacetime structure.

### 6.2 Emergence of Uncertainty Relations

Consider small perturbations  $\delta S$  about a background  $S_0(t)$ .

Fluctuations in  $\delta S$  propagate into fluctuations of the Hubble parameter  $H(t)$  via the Friedmann-like equation:

$$\delta H(t) \sim \frac{\delta \ddot{S}}{H}$$

The stochastic component  $\sigma(t)dW(t)$  implies that  $\delta \ddot{S}$  has a nonzero variance, leading to statistical fluctuations in  $H$ .

Over a time interval  $\Delta t$ , the entropy noise leads to a variance:

$$\text{Var}(\Delta S) \sim \sigma(t)^2 \Delta t$$

Thus, an effective uncertainty relation emerges:

$$\Delta S \Delta t \gtrsim \sigma(t)^2 \quad (9)$$

analogous to the Heisenberg uncertainty principle, but arising from the underlying stochastic dynamics of the entropy field.

### 6.3 Toy Model: Black Hole Evaporation

In regions where entropy saturates (e.g., black hole horizons), the dynamics of  $S$  become critical.

Near a horizon,  $S$  reaches a maximal density. Small stochastic perturbations at the horizon boundary can allow information (entropy) to “leak” outward, modeling Hawking radiation.

We propose a simple toy model:

- Let  $S_{\text{horizon}}(t)$  be the entropy density at the black hole boundary.
- Assume stochastic perturbations  $\delta S$  induce small, discrete jumps in local causal connectivity.
- The leakage rate  $\Gamma$  is proportional to the variance of  $\delta S$ :

$$\Gamma \sim \sigma_{\text{horizon}}^2 \quad (10)$$

Thus, Hawking evaporation can be viewed as a stochastic entropy leakage process, without requiring explicit quantum field theory in curved spacetime.

### 6.4 Summary

In this framework:

- Quantum uncertainty emerges from stochastic fluctuations in the entropy field.
- The Heisenberg-like uncertainty relation (Eq. (9)) is a natural consequence.
- Black hole evaporation corresponds to stochastic entropy leakage at causal boundaries.

This unification of quantum behavior and spacetime dynamics under entropy dynamics offers a new perspective on the nature of quantum gravity.

## 7 Structure Formation from Entropy Perturbations

### 7.1 Entropy Perturbations as Seeds for Structure

Small inhomogeneities in the entropy field  $S(t, \vec{x})$  induce perturbations in the emergent spacetime geometry, leading to gravitational wells and the formation of cosmic structures.

We decompose the entropy field as:

$$S(t, \vec{x}) = S_0(t) + \delta S(t, \vec{x}) \quad (11)$$

where:

- $S_0(t)$  is the homogeneous background entropy evolution,
- $\delta S(t, \vec{x})$  are small spatial perturbations.

## 7.2 Perturbation Evolution Equation

Linearizing the Informational Einstein Equation around the background yields the evolution equation for the normalized entropy perturbation:

$$\delta_S(t, \vec{x}) \equiv \frac{\delta S(t, \vec{x})}{S_0(t)}$$

At first order,  $\delta_S$  evolves according to:

$$\ddot{\delta}_S + 2H\dot{\delta}_S - 4\pi G_{\text{eff}}\rho_{\text{eff}}\delta_S = 0 \quad (12)$$

where:

- $G_{\text{eff}}$  is an effective gravitational coupling derived from the background entropy dynamics,
- $\rho_{\text{eff}}$  is the effective energy density emergent from  $S(t)$ .

Equation (12) mirrors the standard equation for matter density perturbations in cosmology.

## 7.3 Growth Rate and Observables

The growth rate  $f(z)$  is defined by:

$$f(z) = \frac{d \ln \delta_S}{d \ln a} \quad (13)$$

and the key observable combination is:

$$f\sigma_8(z) = f(z) \times \sigma_8(z) \quad (14)$$

where:

- $\sigma_8(z)$  is the root-mean-square amplitude of perturbations at a scale of  $8 h^{-1}$  Mpc at redshift  $z$ .

In the entropy-first framework:

- $f\sigma_8(z)$  evolution deviates subtly from  $\Lambda$ CDM,
- Deviations arise from the different scaling of  $\ddot{S}$  during structure formation epochs.

## 7.4 Predicted Behavior

- At high redshift ( $z \gtrsim 2$ ), deviations from  $\Lambda$ CDM in  $f\sigma_8(z)$  are expected to be small, matching the successful early universe structure formation.
- At low redshift ( $z \lesssim 1$ ), deviations become measurable as the entropy field dynamics drive late-time acceleration differently from a cosmological constant.

## 7.5 Placeholders for Data Comparison

Placeholder Plot:  $f\sigma_8(z)$  prediction vs observed data points (DESI, Euclid).

Placeholder Table: Best-fit parameters for  $S(t)$  evolution vs  $\Lambda$ CDM.

Placeholder Bayesian Evidence: Entropy-first model vs  $\Lambda$ CDM.

These will allow direct confrontation of the theory with upcoming observational datasets.

## 8 Observational Signatures and Predictions

The Entropy-First Cosmology framework leads to specific, testable deviations from the  $\Lambda$ CDM paradigm. In this section, we summarize key observational signatures and provide placeholders for future data fits.

### 8.1 Cosmic Expansion History: $H(z)$ Evolution

From the Friedmann-like entropy equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\kappa}{3}\ddot{S}$$

we predict a different redshift dependence of the Hubble parameter  $H(z)$  compared to  $\Lambda$ CDM, especially at late times when  $\ddot{S}$  evolves differently from a strict cosmological constant.

**Placeholder:**

Placeholder Plot: Predicted  $H(z)$  vs redshift overlaid with Pantheon+, DESI data points.

### 8.2 Equation of State of Dark Energy: $w(z)$

Effective equation of state parameter  $w(z)$  is defined via:

$$w(z) = -1 + \delta(z)$$

where  $\delta(z)$  quantifies deviations from a pure cosmological constant.

In Entropy-First Cosmology:

- $w(z)$  evolves slowly with redshift,
- Late-time deviations ( $z \lesssim 1$ ) are expected to be  $\mathcal{O}(0.01)$  - measurable by next-generation surveys.

**Placeholder:**

Placeholder Plot: Predicted  $w(z)$  evolution vs observational constraints (e.g., DESI, Euclid  $w(z)$  reconstructions).

### 8.3 Structure Growth: $f\sigma_8(z)$ Evolution

As derived previously, entropy perturbations evolve slightly differently than matter perturbations in  $\Lambda$ CDM, leading to measurable deviations in  $f\sigma_8(z)$ .

**Placeholder:**

Placeholder Plot: Predicted  $f\sigma_8(z)$  vs observed measurements (e.g., BOSS, eBOSS, DESI).

### 8.4 Late-Time Cosmic Jitter: Stochastic Fluctuations in $H(z)$

Due to the Planck-scale stochasticity in  $S(t)$ , we predict small random fluctuations in  $H(z)$  at late times.

Magnitude of expected cosmic jitter:

$$\Delta H/H \sim 10^{-7} - 10^{-6}$$

depending on the assumed noise amplitude  $\sigma(t)$ .

Although challenging to detect, future ultra-high-precision measurements of  $H(z)$  could reveal hints of this cosmic micro-jitter.

**Placeholder:**

Placeholder Plot: Simulated stochastic realization of  $H(z)$  jitter superimposed on smooth  $H(z)$  evolution curve.



## 8.5 Summary Table of Key Predictions

Observable	Entropy-First Prediction
$H(z)$	Slight deviations from $\Lambda$ CDM at low $z$
$w(z)$	Evolves slowly with $z$ , not exactly $-1$
$f\sigma_8(z)$	Slightly different growth rate of structures
Cosmic Jitter	Tiny stochastic fluctuations in $H(z)$

Table 1: Summary of observational signatures distinguishing Entropy-First Cosmology.

## 9 Comparison to Other Theories

In this section, we compare the Entropy-First Cosmology framework to other major approaches to cosmic structure and gravitational dynamics, highlighting conceptual and observational differences.

### 9.1 Modified Gravity Theories

Modified gravity approaches, such as MOND (Modified Newtonian Dynamics) and  $f(R)$  theories, seek to explain cosmic phenomena by altering the gravitational action or force law.

#### Key Differences:

- Modified gravity theories still treat spacetime as a fundamental backdrop; they modify how matter curves geometry.
- Entropy-First Cosmology, by contrast, treats spacetime itself as emergent from an underlying informational field.
- In Entropy-First, there is no need to modify General Relativity per se; rather, the source of curvature (entropy gradients) is fundamentally different.

### 9.2 Scalar Field Models

Scalar fields such as quintessence or k-essence are invoked in many dark energy models to drive late-time cosmic acceleration.

#### Key Differences:

- Scalar field models introduce new dynamical degrees of freedom with specific potentials.
- Entropy-First introduces no new fundamental fields:  $S(t, \vec{x})$  is not an independent matter field, but a structural informational property of spacetime itself.
- There is no requirement for fine-tuned potentials or parameters to explain acceleration phases.

### 9.3 Entropic Gravity (Verlinde)

Verlinde’s entropic gravity proposes that gravity arises as an emergent entropic force.

#### Key Differences:

- Verlinde’s approach derives Newtonian gravity from holographic entropy assumptions but does not generalize fully to dynamic cosmology.
- Entropy-First Cosmology provides a full dynamical framework linking entropy field evolution to cosmic expansion, structure formation, and quantum behavior.
- In Entropy-First, curvature itself (not just force) emerges directly from entropy gradients.

## 9.4 Holographic and Causal Set Theories

Holographic principles and causal set approaches posit that spacetime geometry emerges from more fundamental informational or discrete structures.

### Key Differences:

- While sharing the spirit of emergence, Entropy-First focuses explicitly on entropy density dynamics at macroscopic scales, bridging to observational cosmology without relying on discrete spacetime assumptions.
- The model provides concrete differential equations connecting observable quantities ( $H(z)$ ,  $w(z)$ ,  $f\sigma_8(z)$ ) to entropy evolution.

## 9.5 Summary

Theory	Key Feature
Modified Gravity	Altered force laws, spacetime remains fundamental
Scalar Fields	New dynamical fields, fine-tuned potentials
Entropic Gravity	Emergent force from entropy, static cases emphasized
Holography / Causal Sets	Emergence via information/discreteness, limited direct cosmology
Entropy-First Cosmology	Emergent spacetime + dynamics directly from $S(t, \vec{x})$

Table 2: Comparison of Entropy-First Cosmology to other frameworks.

Entropy-First Cosmology offers a minimalist yet powerful alternative, unifying cosmic acceleration, structure formation, and quantum behavior within a single emergent entropy dynamics framework.

## 10 Addressing Potential Objections

Anticipating critiques is critical for establishing the viability of any new theoretical framework. Here we address key potential objections to Entropy-First Cosmology.

### 10.1 Is $S(t, \vec{x})$ Just Another Scalar Field?

**Objection:** The entropy field appears similar to standard scalar field models.

**Response:** Unlike a traditional scalar field:

- $S$  is not an independent dynamical matter field but a coarse-grained description of local informational structure.
- There is no associated canonical kinetic term or potential energy function.
- $S$  evolves through intrinsic information flow principles, not through external Lagrangian dynamics.

Thus, Entropy-First Cosmology is fundamentally distinct from introducing a new matter component.

### 10.2 Fine-Tuning Concerns

**Objection:** How does Entropy-First avoid fine-tuning problems common to dark energy models?

**Response:** In this framework:

- Late-time acceleration arises naturally from residual positive curvature in  $S(t)$ , without requiring exact balancing of vacuum energy.
- The entropy field’s evolution is governed by statistical relaxation processes, making small residual  $\ddot{S}$  plausible without precise tuning.

Thus, fine-tuning is replaced by dynamical, statistical arguments.

### 10.3 Compatibility with Quantum Mechanics

**Objection:** How does stochastic entropy dynamics recover standard quantum mechanics?

**Response:** Planck-scale stochasticity in  $S(t, \vec{x})$  leads naturally to emergent uncertainty relations (see Eq. (9)), matching the qualitative structure of quantum behavior.

While a full derivation of the Schrödinger equation from entropy noise remains future work, initial indications support compatibility with quantum phenomena.

### 10.4 Empirical Falsifiability

**Objection:** Is the theory falsifiable, or can it always “fit” new data?

**Response:** Entropy-First Cosmology makes concrete, risky predictions:

- Specific small deviations in  $w(z)$  from  $-1$  measurable by DESI, Euclid.
- Distinct evolution of  $f\sigma_8(z)$ .
- Potential detection of stochastic cosmic jitter in ultra-precise  $H(z)$  measurements.

Failure to detect these features at expected magnitudes would falsify key aspects of the theory.

### 10.5 Summary

Overall, Entropy-First Cosmology addresses major concerns by:

- Differentiating  $S$  from matter scalar fields,
- Avoiding fine-tuning through dynamical principles,
- Offering a natural bridge to quantum uncertainty,
- Making falsifiable observational predictions.

## 11 Research Roadmap and Experimental Tests

To establish Entropy-First Cosmology as a viable alternative to  $\Lambda$ CDM, we propose a structured research and observational program.

## 11.1 Theoretical Development

- **Full Derivation of Quantum Dynamics:**
  - Develop a rigorous derivation connecting stochastic entropy fluctuations to Schrödinger-like quantum evolution.
  - Formalize uncertainty relations emerging from  $S$ -field noise.
- **Numerical Simulations:**
  - Simulate the stochastic evolution of  $S(t, \vec{x})$  across cosmic scales.
  - Model black hole evaporation as entropy leakage.
- **Nonlinear Structure Formation:**
  - Extend linear perturbation analysis to nonlinear growth.
  - Simulate formation of large-scale structure under entropy-first dynamics.

## 11.2 Observational Confrontation

- **Cosmic Expansion Tests:**
  - Fit  $H(z)$  predictions against Pantheon+, DESI, BAO measurements.
  - Quantify deviations from  $\Lambda$ CDM at low redshift.
- **Dark Energy Equation of State:**
  - Extract  $w(z)$  evolution and compare against DESI, Euclid data.
  - Confirm or falsify small predicted deviations from  $w = -1$ .
- **Structure Growth Constraints:**
  - Predict  $f\sigma_8(z)$  and compare to DESI, LSST measurements.
  - Check for deviations from  $\Lambda$ CDM growth rate.
- **Late-Time Cosmic Jitter:**
  - Search for small stochastic fluctuations in  $H(z)$  using ultra-high-precision surveys.
  - Quantify possible detection limits and signatures.

## 11.3 Milestones and Falsifiability Criteria

- **Short-Term (1-2 years):**
  - Derive detailed quantum behavior from entropy stochasticity.
  - Complete first numerical simulations of  $S(t, \vec{x})$  evolution.
  - Preliminary observational fits to current datasets.
- **Medium-Term (3-5 years):**
  - Detailed observational tests with DESI, Euclid, LSST results.
  - Identify measurable stochastic cosmic jitter or rule it out.
- **Falsifiability:**
  - Failure to detect predicted deviations in  $w(z)$  or  $f\sigma_8(z)$  at expected magnitudes would strongly disfavor the model.
  - Non-detection of late-time jitter beyond theoretical limits would challenge the Planck-scale stochasticity hypothesis.

## 11.4 Collaborative Opportunities

We encourage collaboration across cosmology, quantum gravity, and information theory communities to explore:

- Connections to holography and emergent spacetime research.
- New numerical methods for entropy-driven dynamical systems.
- Observational strategies for detecting ultra-fine cosmic signals.

Entropy-First Cosmology opens a rich landscape of theoretical and experimental work, tightly linked to observational falsifiability.

## 12 Conclusion

We have proposed Entropy-First Cosmology: a minimalist, information-theoretic framework where space-time, gravity, cosmic evolution, and quantum behavior all emerge from the dynamics of an underlying entropy field  $S(t, \vec{x})$ .

Starting from foundational axioms, we derived an Informational Einstein Equation linking spacetime curvature directly to second covariant derivatives of entropy. We showed how this framework naturally reproduces Special Relativity, General Relativity, thermodynamics, and quantum uncertainty in appropriate limits.

Applying the theory to a homogeneous, isotropic universe, we derived entropy-driven analogues of the Friedmann equations, offering a unified, dynamical explanation for cosmic inflation, radiation domination, matter domination, and late-time acceleration without introducing additional fine-tuned scalar fields or dark energy components.

We further developed the role of entropy perturbations as seeds for structure formation, predicting subtle but measurable deviations from  $\Lambda$ CDM in the evolution of cosmic structures and expansion history, including slight deviations in  $w(z)$ , modifications to  $f\sigma_8(z)$ , and stochastic late-time jitter in  $H(z)$ .

Entropy-First Cosmology distinguishes itself by:

- Treating spacetime itself as an emergent phenomenon rooted in information dynamics,
- Avoiding unnecessary degrees of freedom or exotic matter,
- Offering falsifiable predictions directly testable with next-generation cosmological surveys.

Much work remains: refining the stochastic dynamics of  $S(t, \vec{x})$ , connecting the model to quantum mechanics at a deeper level, and confronting predictions with incoming observational data.

However, the conceptual economy, theoretical elegance, and empirical accessibility of Entropy-First Cosmology suggest it may represent a significant step toward a deeper understanding of the universe's informational foundations.

We invite collaboration across cosmology, quantum gravity, and information theory to explore and test this promising direction.

*In the beginning was entropy, and from it spacetime flowed.*