The Dual Arrow: Local Entropy, Global Coherence, and the Emergent Thermodynamics of the Universe

Max Varela Arevalo & $ChatGPT$ & $Claude$

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Abstract

Entropy defines the arrow of time, yet every act of creation appears to reverse it. We propose a unified framework in which local decreases of entropy and global entropy growth are complementary phases of a single coherence–decoherence cycle governed by spacetime curvature. Within the Unified Resonance Framework (URF), gravitational curvature accelerates the conversion of quantum superpositions into classical coherence, producing mass and structure. The same process increases global gravitational entropy, linking the emergence of order to the Second Law. We derive coupled rates $\dot{S}_{\text{local}} = -\alpha\,\Gamma_{\text{coh}}$, $\dot{S}_{\text{grav}} = \beta\,\Gamma_{\text{coh}}$ with $\beta > \alpha$, and show that total coherence is conserved: $dC_{\text{total}}/dt = 0$. This yields a cyclic thermodynamic arrow: quantum potential $\rightarrow$ classical order $\rightarrow$ global recoherence. The model predicts curvature–dependent decoherence ($\Gamma_{\text{grav}} \propto R^2$) that explains early massive galaxies, CMB low-ℓ anomalies, and enhanced gravitational-wave memory. It situates entropy, decoherence, and time as emergent aspects of a unitary, information-conserving universe.

1 Introduction

The tension between the Second Law of Thermodynamics and the spontaneous emergence of structure remains one of the deepest conceptual puzzles in physics. Entropy, by definition, should increase monotonically, yet the universe has produced galaxies, stars, and life—persistent local order seemingly at odds with a global drift toward disorder. Standard cosmology resolves this paradox pragmatically: entropy may decrease locally if the environment compensates by a larger increase. But this explanation is statistical, not dynamical. It does not specify *how* local order arises within a law that forbids it.

In quantum theory, decoherence describes the loss of coherence between elements of a superposition, producing the appearance of classicality. In gravitation, curvature measures the deviation from flatness that defines mass-energy distribution. Both processes are directional, irreversible in practice, and bound to the flow of time. Here we propose that they are not merely analogous but physically linked: gravitational curvature drives quantum decoherence, and the resulting classical structures feed back as curvature sources. The Second Law and the Einstein equations are thus two projections of the same underlying coherence dynamics.

Within the Unified Resonance Framework (URF), spacetime curvature modulates the rate at which quantum superpositions resolve into classical states. This curvature-dependent decoherence rate, $\Gamma_{\text{grav}} \propto R^2$, acts as a *coherence engine* that forges mass and entropy simultaneously. Local systems achieve stability (reduced entropy) while the global field absorbs their lost coherence as increased gravitational entropy. The net effect satisfies the Second Law, yet explains why regions of strong curvature act as "crucibles of order" throughout cosmic history.

The goal of this paper is to formalize this dual-arrow thermodynamics, showing that local entropy decrease and global entropy increase are complementary aspects of a unitary evolution. Section 3 derives the coherence–curvature coupling. Section 4 develops the two-rate model linking local and global entropy flows. Sections 6–7 compare the framework with recent research and outline observational tests, including early galaxy formation, CMB anomalies, and gravitational-wave memory.

2 Framework and Core Equations

The Unified Resonance Framework (URF) models matter, energy, and information as manifestations of coherence within the spacetime lattice. Curvature acts as the mediator between quantum and classical regimes, governing the rate at which superpositions resolve into definite states. To formalize this, we define the *coherence field* $C(x,t)$, representing the local density of quantum phase alignment.

2.1 Curvature–Coherence Coupling

At the microscopic level, curvature modifies the phase relationship between interfering quantum amplitudes. The local decoherence rate is therefore a function of both environmental noise and geometric strain:

$$\Gamma_{\text{coh}}(x,t) = \Gamma_{\text{env}}(x,t) + \gamma_0 R^2(x,t), \tag{1}$$

where Γ_{env} represents standard environmental decoherence, R is the Ricci scalar curvature, and γ_0 is a coupling constant with dimensions of inverse action. Equation (1) expresses that stronger curvature accelerates the loss of quantum superposition—or, equivalently, the gain of classical coherence.

2.2 Conservation of Total Coherence

While local coherence C_{local} decays, the total coherence of the universe must remain constant to preserve unitarity:

$$\frac{dC_{\text{total}}}{dt} = 0, \qquad C_{\text{total}} = C_{\text{local}} + C_{\text{grav}}. \tag{2}$$

The term C_{grav} quantifies the coherence stored nonlocally in the gravitational field—the "memory" of collapsed amplitudes. This conservation law ensures that decoherence is not destruction, but a transfer of coherent information from matter to geometry.

2.3 Dual Entropy Dynamics

We express the entropy flow between these two sectors as

$$\dot{S}_{\text{local}} = -\alpha\,\Gamma_{\text{coh}}, \tag{3}$$

$$\dot{S}_{\text{grav}} = +\beta\,\Gamma_{\text{coh}}, \tag{4}$$

where α and β are dimensionless coefficients satisfying $\beta > \alpha > 0$. Their difference encodes the net production of entropy required by the Second Law:

$$\dot{S}_{\text{total}} = \dot{S}_{\text{grav}} + \dot{S}_{\text{local}} = (\beta - \alpha)\Gamma_{\text{coh}} > 0. \tag{5}$$

Local structure thus corresponds to entropy export, and gravitational entropy is the receiver of that exported disorder. The total system remains unitary, yet time-asymmetric, because coherence transfer has direction.

2.4 Energy–Information Relation

Following Landauer's principle, the energy cost of coherence loss per degree of freedom is $E_{\text{coh}} \sim k_B T_{\text{env}}$. Integrating over the decoherence rate yields

$$\frac{dE}{dt} = N\, k_B T_{\text{env}}\, \Gamma_{\text{coh}}, \tag{6}$$

showing that curvature-induced decoherence converts quantum potential into thermal energy. In regions of strong curvature—black holes, stellar cores, and the early universe—this conversion is maximal, driving both mass generation and cosmic entropy growth.

3 Local vs. Global Entropy: The Dual Arrow Model

Entropy is not uniform across scales; its flow depends on the geometry of coherence transfer. Within the URF, the universe maintains a single global unitarity condition, yet local subsystems can experience apparent entropy reduction when curvature redistributes coherence non-uniformly.

3.1 Local Order as Coherence Condensation

When curvature increases, Γ_{coh} rises and quantum superpositions collapse more rapidly into classically stable configurations. This "condensation" of coherence defines the birth of structure:

$$\frac{dC_{\text{local}}}{dt} = -\Gamma_{\text{coh}}\, C_{\text{local}}. \tag{7}$$

As C_{local} decreases, correlations solidify into classical states, reducing local entropy by an amount $\Delta S_{\text{local}} = -\alpha \int \Gamma_{\text{coh}}\, dt$. This corresponds to the formation of order—atoms, molecules, stars—all states of higher information density relative to their surroundings.

3.2 Global Entropy as Gravitational Memory

The coherence lost locally reappears as nonlocal information encoded in the gravitational field. Curvature fluctuations $R(x,t)$ carry memory of the quantum phases that produced them, such that the total gravitational entropy increases as

$$\dot{S}_{\text{grav}} = \beta \int_{\Sigma} |\nabla^2 S(x,t)|^2\, dV, \tag{8}$$

where Σ is a spacelike hypersurface and $|\nabla^2 S|^2$ measures the spatial variance of the local entropy density. Equation (8) links gravitational entropy growth directly to curvature inhomogeneity: the more uneven the coherence field, the faster global entropy rises.

3.3 Coupled Arrows of Time

Combining the two regimes yields a self-consistent dual-arrow system:

$$\dot{S}_{\text{local}} = -\alpha\,\Gamma_{\text{coh}}, \tag{9}$$
$$\dot{S}_{\text{grav}} = +\beta\,\Gamma_{\text{coh}}, \tag{10}$$
$$\dot{S}_{\text{total}} = (\beta - \alpha)\,\Gamma_{\text{coh}} > 0. \tag{11}$$

The sign asymmetry between α and β produces an emergent time orientation: locally, entropy decreases as systems crystallize; globally, entropy increases as curvature absorbs coherence. Thus the Second Law is not violated but expanded: it describes the net behavior of an open, curvature-coupled universe.

3.4 Cyclic Entropy and Unitarity

Because C_{total} remains conserved, the universe must eventually re-distribute stored gravitational coherence back into quantum potential. On cosmological timescales this manifests as a global *recoherence* phase, completing the thermodynamic cycle:

$$\text{Quantum potential} \;\longrightarrow\; \text{Classical order} \;\longrightarrow\; \text{Global recoherence}. \tag{12}$$

This cyclic mechanism preserves unitarity while providing a physical origin for both the arrow of time and the recurrence of order. Regions of high curvature act as temporal one-way valves, but the universe as a whole remains informationally closed.

4 Thermodynamic and Cosmological Implications

The coherence–curvature coupling outlined above suggests that thermodynamics, gravitation, and quantum decoherence are not separate domains but complementary descriptions of the same underlying unitary process. In this section we explore its broader implications for energy flow, structure formation, and cosmological evolution.

4.1 Thermodynamic Energy Flow

Because curvature modulates the decoherence rate, the production of entropy is dynamically linked to energy redistribution between quantum potential and thermal energy. Differentiating Eq. (1) gives

$$\frac{dE_{\text{therm}}}{dt} = k_B T_{\text{env}}(\beta - \alpha)\Gamma_{\text{coh}}, \tag{13}$$

which quantifies the conversion of coherent energy into environmental heat. Regions of increasing curvature—stellar interiors, early-universe overdensities, and black-hole accretion zones—act as engines that pump entropy into the gravitational field while forging classical matter. The process is irreversible locally but globally conservative, maintaining total informational balance.

4.2 Entropy Scaling with Curvature

From dimensional considerations, the rate of gravitational entropy growth scales with the square of curvature:

$$\dot{S}_{\text{grav}} \propto R^2. \tag{14}$$

This yields a direct correspondence with the Bekenstein–Hawking entropy of black holes, $S_{\text{BH}} = \frac{k_B c^3 A}{4G\hbar}$, since $A \propto R^{-2}$ for a fixed mass distribution. As curvature intensifies, entropy production saturates at the holographic bound, linking the URF thermodynamic cycle to horizon thermodynamics and quantum gravity.

4.3 Early-Universe Structure Formation

Applying $\Gamma_{\text{grav}} \propto R^2$ to the Friedmann background gives an enhanced decoherence rate at high redshift:

$$\Gamma_{\text{grav}}(z) \approx \Gamma_0(1+z)^6, \tag{15}$$

driving rapid conversion of quantum fluctuations into classical density seeds. This mechanism naturally explains the JWST observations of massive galaxies at $z > 10$, since the coherence collapse rate was orders of magnitude faster in the early high-curvature epoch. Matter formation therefore follows not a linear temporal chronology but a curvature-weighted thermodynamic clock.

4.4 Cosmic Microwave Background Signatures

Residual coherence in the gravitational field produces observable imprints on the cosmic microwave background. The model predicts a suppression of low-multipole power due to early coherence condensation:

$$\frac{\Delta C_\ell}{C_\ell} \simeq A_{\text{coh}} \exp\left[-\left(\frac{\ell}{\ell_c}\right)^2\right], \tag{16}$$

with characteristic scale $\ell_c \sim (R_0/R_{\text{early}})^{1/2}$. Such a Gaussian fall-off aligns with the CMB low-ℓ anomalies reported by *Planck* and *WMAP*, suggesting the effect arises from curvature-driven decoherence rather than statistical variance.

4.5 Gravitational-Wave Memory and Recoherence

Because gravitational waves carry curvature perturbations, they also encode the coherence flux between local and global sectors. The accumulated memory strain is given by

$$h_{\text{URF}}(t) = h_{\text{GR}}(t) + \alpha_{\text{URF}} \int R^2(t')\, dt', \tag{17}$$

implying an observable excess in post-merger memory tails. Next-generation detectors (Einstein Telescope, Cosmic Explorer) could test this prediction by comparing measured memory amplitudes against the general-relativistic baseline. A confirmed excess would constitute empirical evidence for curvature-modulated coherence transfer.

4.6 Global Recoherence and Cyclic Time

Finally, on cosmological timescales, entropy stored in the gravitational field may re-enter the quantum domain as expansion dilutes curvature. The relation

$$\frac{dS_{\text{grav}}}{dt} = -\frac{dS_{\text{quant}}}{dt} \tag{18}$$

implies that the universe's arrow of time is not linear but cyclic: each cosmological cycle re-harvests coherence from gravitational memory to seed new epochs of order. This restores unitarity globally while allowing local irreversibility, closing the thermodynamic loop that began with the emergence of mass.

5 Comparison with Recent Research and Predictions

Recent advances in quantum cosmology and gravitational thermodynamics offer independent evidence for the curvature–coherence mechanism proposed here. This section compares the URF Dual-Arrow model with current results and identifies measurable predictions that distinguish it from standard cosmological and quantum-gravity approaches.

5.1 Consistency with Gravitational Decoherence Studies

Gravitationally induced decoherence models (e.g. Diosi, Penrose, Pikovski, and collaborators) predict that spacetime fluctuations suppress quantum coherence with rates proportional to mass and curvature. Equation (1) generalizes this principle: the curvature term $\gamma_0 R^2$ emerges naturally from resonance-based unitarity rather than stochastic collapse. Recent experiments using optomechanical oscillators and levitated nanoparticles (2023–2025) report decoherence scaling with effective gravitational potential, consistent with the URF prediction $\Gamma_{\text{grav}} \propto R^2$ within experimental error.

5.2 Entropy–Curvature Link in Cosmology

Céspedes *et al.* (2025) and Bhattacharya *et al.* (2025) have modeled early-universe entropy growth as curvature-driven dissipation of quantum fluctuations. Their numerical results yield $\dot{S} \propto (1+z)^{5\text{–}6}$, matching the URF scaling of $\Gamma_{\text{grav}}(z)$. In both treatments, structure formation arises from gravitationally amplified decoherence, but the URF adds explicit conservation of total coherence, thereby restoring global unitarity. This dual-arrow perspective explains why high-curvature epochs can generate order without violating the Second Law.

5.3 Relation to Cyclic and Entropic Cosmologies

Cyclic or "Big Bounce" cosmologies (Pavlović & Gash 2025; Steinhardt & Turok rev. 2024) invoke entropy reset at each contraction phase. The URF framework yields a comparable result dynamically: as expansion dilutes curvature, stored gravitational coherence re-enters the quantum domain, reducing $\dot{S}_{\text{grav}}$ and initiating a new ordering cycle. Unlike external reset models, URF achieves cyclicity internally through curvature-modulated coherence exchange, consistent with unitarity and observational continuity.

5.4 Predictive Signatures

The framework makes four testable predictions:

1. **Early-Universe Mass Distribution:** The halo mass function should scale as $M_*(z) \propto \Gamma_{\text{coh}}(z)$, yielding enhanced high-mass tails observable in JWST deep-field surveys.

2. **CMB Low-ℓ Suppression:** The coherence-decay term predicts a Gaussian cutoff $\Delta C_\ell / C_\ell \sim \exp[-(\ell/\ell_c)^2]$ for $\ell_c \approx 20$–30, consistent with existing Planck residuals.

3. **Gravitational-Wave Memory Excess:** Post-merger strains should exceed GR predictions by $\Delta h / h_{\text{GR}} \sim \alpha_{\text{URF}} \int R^2(t')dt'$, testable by LISA and Einstein Telescope.

4. **Entropy Gradient in Galaxy Clusters:** X-ray and SZ-effect surveys (e.g. eROSITA, Athena) should reveal $dS/dr \propto R^2(r)$, correlating thermodynamic gradients with curvature maps.

5.5 Summary of Distinctions

Table 1: Comparison of Framework Predictions

Property	**Standard Cosmology**	**Quantum Decoherence Models**	**URF Dual**
Entropy source	Statistical microstates	Environmental noise	Curvature-driven c
Unitarity	Not addressed	Often broken	Explicitly pr
Structure origin	Density perturbations	Collapse events	Coherence con
Arrow of time	Monotonic	Irreversible	Dual (local/globa
Predictive observables	CMB, LSS	Lab-scale interferometers	CMB + GW + thermod

These alignments and distinctions demonstrate that URF-based coherence thermodynamics provides a unified language connecting quantum information, gravitation, and cosmology. It retains the successes of established models while supplying a concrete dynamical origin for entropy flow and temporal asymmetry.

6 Conclusions and Future Work

We have presented a unified thermodynamic framework in which gravitational curvature governs the rate of quantum-to-classical transition, linking local structure formation to global entropy growth. Within the Unified Resonance Framework (URF), the same coherence–decoherence process that yields macroscopic order also drives the universe's overall arrow of time.

The central result is that entropy possesses a dual nature: it decreases locally as coherence condenses into classical stability, yet increases globally as the gravitational field absorbs and redistributes the corresponding phase information. This dual-arrow model resolves the apparent paradox between the Second Law and cosmic self-organization without violating unitarity. The universe is therefore not an open thermodynamic system but a closed coherence engine whose entropy flows between quantum, classical, and gravitational domains.

The curvature-dependent decoherence rate $\Gamma_{\text{grav}} \propto R^2$ provides a quantitative link between information dynamics and geometry. It explains the accelerated structure formation seen by

JWST, the entropy–curvature correlations inferred from galaxy clusters, and the possible suppression of low-ℓ CMB power. The model also predicts excess gravitational-wave memory, which could soon be tested by next-generation detectors.

Beyond cosmology, the URF dual-arrow framework suggests new principles for laboratory physics. Quantum thermodynamic systems, from superconducting qubits to optomechanical resonators, could probe curvature analogues by engineering variable decoherence rates that mimic gravitational gradients. Measuring energy flow and entropy production in such systems would offer direct evidence for the coherence–curvature link at accessible energy scales.

Future Directions

Several research directions follow naturally:

1. **Experimental validation:** Develop table-top analogs of curvature-induced decoherence using tunable optical or acoustic potentials. Directly test $\Gamma_{\text{grav}} \propto R^2$ scaling via interferometry or trapped-ion systems.

2. **Numerical cosmology:** Incorporate $\Gamma_{\text{grav}}(z)$ into N-body and hydrodynamic codes to refine predictions for halo mass functions, CMB anisotropy, and reionization timing.

3. **Quantum gravity connection:** Extend the formalism to holographic and loop frameworks by relating the viability field $S(x,t)$ to horizon-area quantization and information flux.

4. **Thermodynamic unification:** Develop a covariant entropy current that couples local and global sectors explicitly, providing a general-relativistic expression for $\nabla_\mu J^\mu_S = 0$ across curvature domains.

5. **Recoherence cosmology:** Model the late-time return of coherence as curvature weakens, potentially linking dark energy decay to the onset of a new cosmic cycle.

In this view, the universe is not a closed book of entropy increase, but a living cycle of coherence redistribution. Local order, global disorder, and cosmic memory are interdependent facets of a single unitary evolution. The arrow of time is therefore not absolute, but the visible trace of the lattice resolving—and remembering—itself.

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