Series Context

This work presents a three-paper empirical–synthetic sequence addressing the emergence and breakdown of dynamical regularities across astrophysical scales. Paper I establishes regime structure in galaxy rotation data without invoking new physics. Paper II documents early-time structure formation that exceeds standard growth expectations. Paper III provides a unifying physical interpretation, treating regime structure as a consequence of energy-flow constraints rather than model failure.

Epistemic structure: Papers I–II are descriptive and model-agnostic. Paper III is interpretive and physically constrained. No circularity: regimes are defined before EFC; EFC is applied afterward as an organizing framework.

Scope limitation: No claim of model replacement is made. The framework is proposed strictly as an organizing physical interpretation consistent with the reported empirical regime structure.

Energy-Flow Cosmology and Regime-Dependent Structure Formation

Paper III: A Thermodynamic Framework for Galaxy Formation Anomalies

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Abstract

Papers I and II of this series established empirical regime structure in two independent datasets: (I) morphology-dependent rotation curve behavior in 175 SPARC galaxies, and (II) order-of-magnitude galaxy abundance excesses at $z > 6$ in JWST COSMOS-Web data. This third paper introduces Energy-Flow Cosmology (EFC) as a physical framework consistent with both findings. The core mechanism is entropy-gradient-driven energy flow, introduced through the phenomenological decomposition $E_{total} = E_{flow} + E_{latent}$. We show that this framework is consistent with: (i) the three-regime classification (FLOW, TRANSITION, LATENT) observed in galactic dynamics, and (ii) accelerated structure formation in the early universe. The interpretation is offered as an organizing framework, not a replacement for ΛCDM. Testable predictions are provided.

Keywords: regime-dependent validity, entropy gradients, galaxy rotation curves, early structure formation, thermodynamic cosmology

1. Introduction

Persistent tensions between observation and ΛCDM predictions have emerged at both galactic and cosmological scales. Paper I of this series documented that galaxy rotation curve modeling success depends systematically on morphological complexity—a pattern that standard dark matter models do not predict. Paper II documented that massive galaxies at $z > 6$ exceed ΛCDM abundance predictions by factors of 20–1000, with the excess increasing monotonically with redshift.

These anomalies are typically treated as separate problems. This paper proposes they are manifestations of the same underlying physics: regime-dependent structure formation governed by entropy gradients.

1.1 Scope and Claims

This paper claims: A physical framework (EFC) exists that is consistent with the empirical regime structure established in Papers I–II. The framework provides a unified interpretation without requiring separate explanations for galactic and cosmological anomalies.

This paper does not claim: That EFC replaces ΛCDM. That the framework is derived from first principles. That all astrophysical observations are explained. The scope is limited to providing an organizing interpretation for the specific phenomena documented in Papers I–II.

1.2 Epistemic Structure

We maintain strict separation between empirical findings and physical interpretation:

Paper	Type	Content
I	Empirical, model-agnostic	Regime structure in SPARC rotation curves
II	Empirical, model-agnostic	Galaxy abundance excess at $z > 6$
III	Interpretive, constrained	Physical framework consistent with I–II

Table 1: *Epistemic structure. Regimes are defined empirically (I–II) before EFC interpretation (III).*

2. The Energy-Flow Framework

Energy-Flow Cosmology (EFC) treats structure formation as a thermodynamic process driven by entropy gradients. The framework does not modify General Relativity or introduce new particles; it provides an interpretive layer that maps thermodynamic variables to observed dynamical behavior.

2.1 Core Definitions

The local energy-flow potential is defined as:

$$E_f = \rho(1 - S)$$

where ρ is local mass/energy density and $S \in [0,1]$ is normalized entropy. High density with low entropy yields large E_f; high entropy suppresses E_f regardless of density. *This definition is operational rather than fundamental, and serves as a monotonic proxy for the availability of energy for organized flow.*

2.2 Energy Balance Decomposition

For non-equilibrium systems, we introduce a phenomenological decomposition of total energy:

$$E_{total} = E_{flow} + E_{latent}$$

- E_{flow}: Energy participating in smooth entropy-gradient-driven dynamics.
- E_{latent}: Energy stored in non-equilibrium structures (bars, arms, tidal features).

The latent fraction $L = E_{latent}/E_{total}$ determines regime membership. This decomposition is not derived from first principles but serves as an organizing scheme consistent with observed behavior.

2.3 Regime Classification

Three regimes emerge from the L parameter:

Regime	L Range	Physical Interpretation
FLOW	L < 0.25	Near-equilibrium; smooth entropy gradients; simple models valid
TRANSITION	0.25–0.45	Mixed dynamics; developing non-equilibrium features
LATENT	L > 0.45	Non-equilibrium dominated; significant energy in structures

Table 2: *Regime classification based on latent energy fraction.*

The numerical boundaries (0.25, 0.45) are empirically motivated from the SPARC sample and should not be interpreted as universal constants. Independent calibration on other datasets is required.

3. Application to Galactic Dynamics (Paper I)

3.1 Empirical Findings

Paper I analyzed 175 SPARC galaxies and found:

- Three-regime structure: 35% FLOW, 49% TRANSITION, 15% LATENT
- Statistical separation: Mann-Whitney $p < 0.0001$
- Morphology correlation: LSB 100% success → Barred ~4% success
- FIRE alignment: Regime boundaries match simulation cusp-core transitions

3.2 EFC Interpretation

Under EFC, low-surface-brightness galaxies have smooth entropy distributions—energy flows efficiently along gradients, yielding simple rotation curves. Barred galaxies store energy in non-equilibrium structures; this latent energy does not participate in rotation dynamics.

The cusp-core problem is reframed: systems in the FLOW regime develop core-like profiles through thermodynamic relaxation; LATENT systems retain cusps because non-equilibrium storage prevents relaxation. This is not a dark matter physics issue—it is a regime boundary.

4. Application to Early Structure Formation (Paper II)

4.1 Empirical Findings

Paper II analyzed 26,288 COSMOS-Web galaxies and found:

- Abundance excess: 260× at z = 8–9; 920× at z = 10–12
- Monotonic trend: Excess increases systematically with redshift
- Robustness: >20× excess persists under pessimistic systematics

4.2 EFC Interpretation

EFC interprets early-universe entropy gradients as steeper than late-universe gradients. Under the framework, time evolution couples to energy flow—steep gradients drive faster local structure formation. The 'impossible' galaxies are not violations; they are consistent with high-gradient conditions.

The monotonic z-dependence follows directly: as gradients flatten over cosmic time, the acceleration effect diminishes. This explains why the largest excess appears at highest redshift.

5. Cross-Scale Correspondence

The same entropy-gradient principle operates at both galactic (kpc) and cosmological (Gpc) scales:

Gradient	Galactic (Paper I)	Cosmological (Paper II)
Steep	LSB: 100% simple model success	z > 10: 1000× abundance excess
Shallow	Barred: ~4% success	z < 3: ΛCDM valid

Table 3: *Cross-scale correspondence. Same principle, different manifestations.*

6. Testable Predictions

The framework generates specific predictions:

P1: Regime classification replicates on independent samples (LITTLE THINGS, DMS).
P2: Abundance excess continues monotonically to z > 15.
P3: Morphological complexity correlates with regime membership across datasets.
P4: FIRE simulation cusp-core transitions align with EFC regime boundaries.

7. Limitations

Phenomenological: Framework not derived from first principles.
Calibration: Regime boundaries require independent validation.
Scope: Limited to phenomena in Papers I–II. No claim of universal applicability.

8. Conclusions

Given the empirical regime structure established in Papers I–II, Energy-Flow Cosmology provides a consistent physical framework. The phenomenological decomposition $E_{total} = E_{flow} + E_{latent}$ is consistent with both galactic and cosmological anomalies through a single mechanism: entropy-gradient-driven energy flow.

What appear as 'problems' for ΛCDM may be signatures of regime boundaries—places where simple models fail not because they are wrong, but because they are applied outside their domain of validity. The framework is offered as an organizing interpretation, not a replacement for standard cosmology.

Data Availability

All analysis code and supporting documentation are available at https://github.com/supertedai/EFC and https://energyflow-cosmology.com/

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