Bridging Scales: Energy-Flow Cosmology and the Free Energy Principle as Complementary Entropy Frameworks

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Abstract

The Free Energy Principle (FEP) describes how biological systems maintain their existence through variational free energy minimization, while Energy-Flow Cosmology (EFC) formalizes entropy dynamics across cosmic scales. We propose a formal bridge between these frameworks, demonstrating that variational free energy F can be expressed as a blanket-integral of the cosmic energy-flow field $\mathbf{E}_f$. This unification yields three principal results: (1) a dimensional framework grounding Markov blankets as physical energy-flow surfaces with dimension [W/m^2]; (2) a universal emergence threshold $R_c = 0.37 \pm 0.05$ derived from galactic halo stability and predicted to apply to neural systems; and (3) six falsifiable predictions with explicit decision criteria. We distinguish core claims (falsifiable) from auxiliary hypotheses (adjustable) following Lakatos, and provide concrete experimental protocols for validation.

Keywords: Free Energy Principle, Energy-Flow Cosmology, Markov blankets, entropy, emergence, active inference, thermodynamics

1 Introduction

1.1 The Problem of Scale

The Free Energy Principle, developed by Karl Friston and collaborators over the past two decades, provides a powerful account of how self-organizing systems maintain themselves against entropic dissolution [Friston, 2010, Friston et al., 2023]. The principle posits that any system with a Markov blanket—a statistical boundary separating internal from external states—will appear to minimize variational free energy, which bounds the surprise of sensory observations.

Despite its theoretical elegance, FEP faces a persistent criticism: its physical grounding remains abstract. Variational free energy F is an information-theoretic quantity, and Markov blankets are defined statistically rather than physically. While Friston [2019] attempted to connect FEP to physics via "A Free Energy Principle for a Particular Physics," critics have noted that this connection remains more philosophical than predictive [Aguilera et al., 2022].

Energy-Flow Cosmology (EFC), developed in parallel, formalizes entropy dynamics across cosmic scales [Magnusson, 2025a,b]. EFC introduces an energy-flow field $\mathbf{E}_f$ that couples entropy gradients to spacetime geometry, providing a continuous description from galactic halos to consciousness emergence.

1.2 Core Thesis

We propose that these two frameworks are not merely analogous but formally connected:

Thesis: Variational free energy F is the blanket-integral of the energy-flow field $\mathbf{E}_f$, and Markov blankets are physical surfaces where probability flux divergence vanishes—coinciding with energy-flow gradient maxima.

This connection yields:

1. A physical interpretation of F as energy flux through boundaries
2. A universal emergence threshold $R_c \approx 0.37$ applicable across scales
3. Testable predictions that neither framework alone provides

2 Formal Definitions

All subsequent claims inherit these definitions. Reviewers should evaluate the framework against these specifications.

2.1 The Energy-Flow Field

Definition 2.1 (Energy-Flow Field)**.** The energy-flow field is:

$$\mathbf{E}_f(\mathbf{x}, t) = \frac{P_0}{L_0}\phi(S)\nabla S \qquad [\mathrm{W/m^2}] \tag{1}$$

where P_0 [W] is characteristic power, L_0 [m] is characteristic length, $\phi(S)$ is a dimensionless flow function, and $S \in [0, 1]$ is normalized entropy.

Dimensional verification:

$$[\mathbf{E}_f] = \frac{[\mathrm{W}]}{[\mathrm{m}]} \cdot [1] \cdot \frac{[1]}{[\mathrm{m}]} = \frac{\mathrm{W}}{\mathrm{m}^2} \quad \checkmark$$

2.2 Blanket-Integral Free Energy

Definition 2.2 (Blanket-Integral Free Energy)**.** The blanket-integral free energy is:

$$\mathcal{F}(t) = -\frac{1}{k_B T_{\text{eff}}}\frac{\mathrm{d}}{\mathrm{d}t}\oint_{\mathcal{M}} \mathbf{E}_f \cdot \mathrm{d}\mathbf{n} \qquad [1] \tag{2}$$

where $\mathcal{M}$ is the Markov blanket surface and T_{eff} is effective temperature.

2.3 Effective Temperature

Definition 2.3 (Effective Temperature)**.** Effective temperature is defined operationally via the fluctuation-dissipation relation:

$$T_{\text{eff}} = \frac{\mathrm{Var}(\mu)}{\chi_\mu} \tag{3}$$

where $\mathrm{Var}(\mu)$ is variance of internal states and χ_μ is susceptibility.

2.4 Emergence Threshold

Definition 2.4 (Resonance Parameter)**.**

$$R = \frac{|\mathbf{E}_f^{\text{int}}|}{|\mathbf{E}_f^{\text{ext}}|} \cdot \frac{1}{1 + |\nabla S|/S_c} \tag{4}$$

Empirical value: $R_c = 0.37 \pm 0.05$ (from SPARC galaxy fits).

2.5 S-Duality

Definition 2.5 (S-Duality)**.** The flow function satisfies:

$$\phi(S) = -\phi(1 - S) \tag{5}$$

valid for $S \in [0.1, 0.9]$.

3 The Core Correspondence

Proposition 3.1 (EFC-FEP Correspondence)**.** *At quasi-steady state:*

$$\boxed{\mathcal{F} = F + O(\epsilon)} \tag{6}$$

where ϵ measures deviation from stationarity.

Physical interpretation:

- The surface integral $\oint_{\mathcal{M}} \mathbf{E}_f \cdot \mathrm{d}\mathbf{n}$ measures total energy flux through the Markov blanket
- The time derivative captures rate of change of this flux
- The prefactor $-(k_B T_{\text{eff}})^{-1}$ converts to information units

4 Markov Blankets as Energy-Flow Surfaces

Theorem 4.1 (Zero-Flux Factorization)**.** *Under Langevin dynamics with sparse coupling, at NESS there exists a surface Σ such that:*

1. $\nabla \cdot \mathbf{J}|_\Sigma = 0$ *(zero flux divergence)*
2. *The NESS density factorizes:* $p^*(\mu, \eta|\Sigma) = p^*(\mu|\Sigma) \cdot p^*(\eta|\Sigma)$

Conjecture 4.2 (Energy-Flow Coincidence)**.** *The zero-flux surface Σ coincides with* $\arg\max |\nabla \mathbf{E}_f|$.

Proposition 4.3 (Stability Condition)**.** *A Markov blanket $\mathcal{M}$ is stable iff $R > R_c$.*

5 Empirical Tests

Test	Prediction	Criterion	Timeline
P1	Dimensional consistency	χ^2 ratio $\in [0.95, 1.05]$	Now
P2	Blanket-integral correlation	$\text{Corr}(F, \mathcal{F}) > 0.90$	Now
P3	Cross-scale R_c	$\lvert z \rvert < 3$	6–12 months
P4	T_{eff}-precision scaling	$r^2 > 0.30$	6 months
P5	Metabolic gradient ratio	> 1.2 at blankets	12 months
P6	Symmetry breaking	Deviation $> 10\%$ at $S < 0.1$	24+ months

Table 1: Locked predictions with decision criteria.

6 Lakatos Classification

Hard Core (Falsifiable):

1. $F \leftrightarrow \mathcal{F}$ correspondence
2. R_c universality
3. Blanket energy signature

Protective Belt (Adjustable):

1. Specific R_c value
2. T_{eff} operationalization
3. Symmetry-breaking threshold

7 Conclusion

We have proposed a formal bridge between Energy-Flow Cosmology and the Free Energy Principle. The core claim is that variational free energy F equals the blanket-integral of the energy-flow field $\mathbf{E}_f$, up to quasi-steady corrections. This identification:

1. Gives FEP a physical interpretation in terms of energy flux
2. Reinterprets Markov blankets as zero-flux surfaces with energetic signatures
3. Predicts a universal emergence threshold $R_c \approx 0.37$

We have specified the framework precisely enough to be falsified: six predictions with explicit decision criteria. Whether the bridge holds is an empirical question we have made answerable.

Acknowledgments

This work builds on the EFC framework developed since 2024 and benefits from ongoing dialogue with the broader FEP community.

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