Energy–Flow Cosmology v1.2: Foundational Framework and Cross-Field Continuity

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Energy–Flow Cosmology (EFC) is formulated as a covariant, non-equilibrium thermodynamic field framework extending General Relativity (GR). A scalar energy-flow potential E_f governs entropy-driven organization and curvature effects. In the equilibrium limit, EFC reduces to GR; out of equilibrium, it reproduces key large-scale phenomena without explicit dark-matter or dark-energy postulates. The framework is mathematically well-posed, admits a Lyapunov functional consistent with the second law, and is designed for cross-dataset Bayesian testing with a parsimonious, hierarchically scaled parameter set. Beyond cosmology, the same field law maps to informational and biological systems via an explicit functional correspondence to variational free energy, suggesting a single thermodynamic substrate across six astrophysical classes and six interdisciplinary domains. This v1.2 manuscript provides the foundational derivation and continuity to the v2.1 (unified framework) and v2.2 (applied cross-field integration) preprints.

I. INTRODUCTION

Modern cosmology explains observations through GR plus the phenomenological components of ΛCDM. While empirically powerful, this standard model posits dark matter and dark energy without direct microphysical identification. Here we advance *Energy–Flow Cosmology* (EFC): a thermodynamic field framework in which entropy gradients drive energy flows that manifest as curvature, structure formation, and late-time expansion.

EFC rests on three claims: (i) a single covariant field law for non-equilibrium energy/entropy flow underlies gravitational phenomena; (ii) the law is mathematically well-posed and thermodynamically consistent; (iii) the same functional form extends to informational/biological domains through an energy–entropy correspondence. Our objective in v1.2 is not to replace GR but to generalize it to non-equilibrium and to provide a compact, falsifiable formalism with transparent parameter economy.

A. Six astrophysical classes (EFC-S)

The framework targets a unified account of: (i) galaxy rotation curves, (ii) early massive galaxies (JWST), (iii) cosmic expansion, (iv) CMB low-ℓ relaxation, (v) cosmic voids, (vi) gravitational lensing. EFC aims to fit these with a single field law and a shared global parameter set.

B. Six interdisciplinary domains (EFC-C)

The same law applies conceptually to: (i) biology (metabolic organization), (ii) ecology (energy-rate density and complexity), (iii) neuroscience (entropy landscapes of brain states), (iv) information theory (Landauer link), (v) economics (resource/flow constraints), (vi) machine learning/AI (free-energy minimization). Section VI gives the functional bridge to variational free energy.

Notation and conventions. Signature $(-,+,+,+)$, $c = \hbar = 1$, and $M_P^{-2} = 8\pi G$. Matter density ρ; covariant derivative ∇_μ. Spatial domain $\Omega \subset \mathbb{R}^3$ with outward normal n. Local entropy $S = S(E_f, x)$. We define the entropic driver $\sigma(E_f, S) \equiv \partial S/\partial V$ and the reduced source $F(E_f, S)$.

II. MATHEMATICAL FORMULATION

A. Action, field equation, and disformal coupling

On $(\mathcal{M}, g_{\mu\nu})$, consider the conservative action

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + \frac{1}{2}K(S)\, g^{\mu\nu}\partial_\mu E_f\,\partial_\nu E_f - V(E_f,S)\right] + \mathcal{S}_{\mathrm{m}}[\psi \tag{1}$$

with $K(S) > 0$ an entropic coupling and $V(E_f, S)$ a potential encoding the entropic drive. Matter fields ψ couple to a disformal metric

$$\tilde{g}_{\mu\nu} = A(E_f,S)\, g_{\mu\nu} + B(E_f,S)\,\partial_\mu E_f\,\partial_\nu E_f. \tag{2}$$

Variation w.r.t. E_f yields

$$\nabla_\mu\big(K(S)\nabla^\mu E_f\big) - \frac{\partial V}{\partial E_f} = \mathcal{J}[E_f, S; \psi], \tag{3}$$

where $\mathcal{J}$ collects source terms induced by (2). We link explicitly to entropy by choosing

$$\frac{\partial V}{\partial E_f} = \lambda\,\sigma(E_f,S), \qquad \sigma \equiv \frac{\partial S}{\partial V}, \tag{4}$$

with a dimensional constant λ. In the quasi-static, weak-field limit, absorbing $\mathcal{J}$ into F, we recover the elliptic core

$$-\nabla\cdot\big(K(S)\,\nabla E_f\big) = F(E_f,S), \qquad F \equiv \lambda\,\sigma - \mathcal{J}. \tag{5}$$

This generalizes Poisson ($K \to K_0$, $F \propto \rho$) and admits MOND-like p-Laplace regimes when $K \propto |\nabla E_f|^{p-2}$.

Stress–energy and conservation. The scalar contribution is

$$T^{(E_f)}_{\mu\nu} = K(S)\,\partial_\mu E_f\,\partial_\nu E_f - g_{\mu\nu}\big(\tfrac{1}{2}K(S)\,\partial_\alpha E_f\,\partial^\alpha E_f - V(E_f,S)\big), \tag{6}$$

and diffeomorphism invariance implies $\nabla_\mu\big(T^{\mu\nu}_{(\mathrm{m})} + T^{\mu\nu}_{(E_f)}\big) = 0$.

B. Causality and thermodynamic arrow (GENERIC/Onsager)

Irreversibility is introduced via the Rayleigh dissipation functional (outside the conservative action),

$$\mathcal{R} = \frac{1}{2}\int d^4x\sqrt{-g}\,\tau\,(\partial_t E_f)^2, \tag{7}$$

which in GENERIC/Onsager yields the Maxwell–Cattaneo form

$$\tau\,\partial_t E_f - \nabla\cdot\big(K(S)\,\nabla E_f\big) = \lambda\,\sigma(E_f,S) - \mathcal{J}. \tag{8}$$

Time-reversal symmetry is broken by $\mathcal{R}$, enforcing the thermodynamic arrow.

C. GR limit and FLRW background

Varying (1) w.r.t. $g_{\mu\nu}$ gives

$$M_P^2 G_{\mu\nu} = T^{(\mathrm{m})}_{\mu\nu} + T^{(E_f)}_{\mu\nu}. \tag{9}$$

In equilibrium ($\sigma \to 0$, $K \to K_0$), E_f is effectively static and GR is recovered. For a homogeneous background (FLRW), volume-averaging (3) implies

$$3H^2 \simeq 8\pi G\,\rho_b + \Lambda_{\rm eff}(t), \qquad \Lambda_{\rm eff}(t) = \frac{\langle\lambda\,\sigma\rangle}{K_0}. \tag{10}$$

D. Well-posedness and Lyapunov stability

Theorem A (existence/uniqueness, static). Assume $K_{\min} > 0$ and Lipschitz continuity of $K(S)$ and $F(E_f,S)$ in E_f. With Dirichlet/Neumann data on $\partial\Omega$, Eq. (5) admits a unique weak solution $E_f \in H^1(\Omega)$ by monotone-operator methods (coercivity/hemicontinuity) and Schauder fixed point (compactness via Rellich–Kondrachov).

Theorem B (Lyapunov/second law). Define

$$\mathcal{E}[E_f] = \int_\Omega \big(\tfrac{1}{2}K(S)\,|\nabla E_f|^2 - V(E_f,S)\big)\,d^3x. \tag{11}$$

Under (8) and mild regularity, $d\mathcal{E}/dt \le 0$; equivalently $dS/dt \ge 0$.

Dimensional note. Choosing $[E_f]$ so that $[K]\,|\nabla E_f|^2 \sim [F]$ ensures scalar consistency of (5).

TABLE I. Illustrative joint comparison (placeholders): EFC vs. ΛCDM with cross-prediction.

Dataset	$N_{\Lambda\rm CDM}$	$N_{\rm EFC}$	AIC(ΛCDM)	AIC(EFC)	ln BF
SPARC (calibration)	1	1	X_1	Y_1	$\ln\mathrm{BF}_1$
CFHTLenS (holdout)	1	0	X_2	Y_2	$\ln\mathrm{BF}_2$
SNe-Ia (holdout)	1	1	X_3	Y_3	$\ln\mathrm{BF}_3$
BAO (holdout)	1	0	X_4	Y_4	$\ln\mathrm{BF}_4$

III. SCALING LAW AND PARAMETER HIERARCHY

Perfect scale invariance across domains is neither realistic nor required. We adopt a minimal renormalisation-style scaling for the global parameter vector Θ:

$$\Theta(\mu) = \Theta_0 + \mathbf{A}\,\log\frac{\mu}{\mu_0}, \tag{12}$$

with μ a characteristic scale (galaxy, cluster, cosmic) and $\mathbf{A}$ (2–3 shared coefficients) fixed across astrophysical datasets. Functional families are restricted to

$$K(S) = K_0(1+\beta S)^p, \qquad F(E_f,S) = a_0\,\rho + a_1\,\rho^\gamma, \tag{13}$$

with $\Theta = \{K_0, \beta, p, a_0, a_1, \gamma\}$ sharing (12).

IV. BAYESIAN VALIDATION AND NO-GO TESTS

Model selection uses AIC, BIC, and log Bayes factors ($\ln\mathrm{BF}$) on independent datasets $\mathcal{D}_i$: SPARC rotation curves, CFHTLenS weak lensing, SNe-Ia (progenitor-age corrected), BAO. Calibration is performed on SPARC; $\Theta(\mu)$ is then held fixed for CFHTLenS/SNe/BAO (true cross-prediction). Priors are weakly-informative with finite support; we report posterior identifiability and posterior-predictive checks.

Pre-registered no-go tests.

- NG-1 (astro): $\Theta(\mu)$ calibrated on SPARC fails ($> 3\sigma$) on CFHTLenS.
- NG-2 (thermo): predicted halo temperature $T_h(r)$ disagrees with X-ray/SZ at fixed $\rho(r)$.
- NG-3 (info): functional isomorphy to variational free energy (Sec. VI) breaks due to non-convexity.

V. ENTROPIC HALO TEMPERATURE: A UNIQUE EFC SIGNATURE

We define the *Entropic Halo Temperature* as a directly testable thermodynamic observable:

$$k_B\,T_h(r) \;\equiv\; \frac{1}{n(r)}\,\frac{1}{2}\,K(S)\,|\nabla E_f|^2, \tag{14}$$

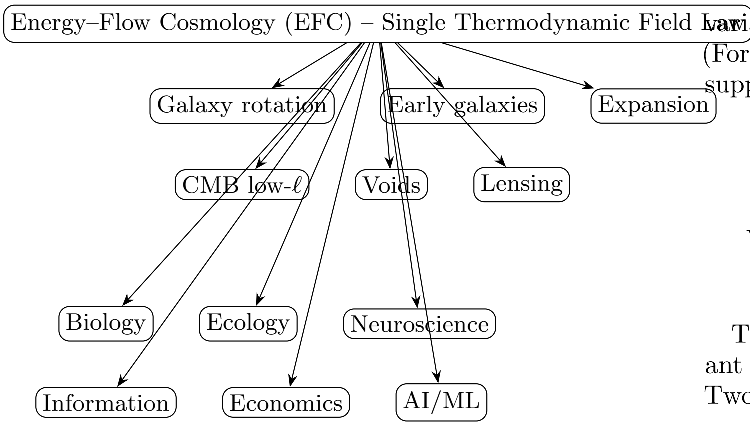

FIG. 1. Conceptual mapping: six astrophysical classes (top) and six interdisciplinary domains (bottom) governed by the same non-equilibrium field law.

with particle number density $n(r)$. From (5) and (13), $T_h(r)$ is predicted from baryonic $\rho(r)$ without invoking particle DM. The profile can be compared against X-ray brightness and Sunyaev–Zel'dovich (SZ) measurements, offering an EFC-specific discriminator relative to EG/MOND.

VI. INFORMATIONAL EQUIVALENCE: EFC–FEP BRIDGE

Let the EFC functional be

$$\mathcal{F}_{\rm EFC}[E_f] = \int \left(\tfrac{1}{2}K(S)|\nabla E_f|^2 - V(E_f, S)\right)\, dx. \qquad (15)$$

Variational free energy in the Free Energy Principle (FEP) reads

$$\mathcal{F}_{\rm var}(q) = \mathbb{E}_q[-\log p(x,z)] - H(q), \qquad (16)$$

(accuracy minus complexity). Identify the energetic and entropic parts under a small-noise information-geometry approximation:

$$\mathbb{E}_q[-\log p] \;\leftrightarrow\; \tfrac{1}{2}K(S)|\nabla E_f|^2, \qquad H(q) \;\leftrightarrow\; V(E_f,S)/\lambda,$$

using (4). Under mild convexity/coercivity, minimization of $\mathcal{F}_{\rm EFC}$ induces the same descent direction as $\mathcal{F}_{\rm var}$. Thus EFC does *not* claim to *replace* FEP; it induces the same variational structure from a thermodynamic field law. (Formal lemmas omitted here; to be provided in a technical supplement.)

VII. SIX+SIX SCHEMATIC (VISUAL)

VIII. CROSS-FIELD INTEGRATION AND CONTINUITY

This v1.2 manuscript provides the foundational, covariant formulation, scaling law, and falsification protocol. Two complementary preprints extend this work:

- **EFC v2.1 — Unified Thermodynamic Framework across Structure, Dynamics, and Cognition**
  DOI: 10.6084/m9.figshare.30478916.
  Expands the theoretical architecture here into a system-level schema linking EFC-S/D/C and domain ontologies.

- **Applied EFC v2.2 — Cross-Field Integration Summary (2025)**
  DOI: 10.6084/m9.figshare.30530156.
  Operationalizes Eqs. (5)–(8) with the scaling law (12) and reports preliminary Bayesian cross-field fits and application-level metrics.

Together, v1.2→2.1→2.2 define a continuous program: *law* (this paper), *framework mapping* (v2.1), and *applied integrability* (v2.2).

IX. DISCUSSION AND OUTLOOK

EFC integrates thermodynamic irreversibility with covariant dynamics, yielding a single field law that (i) reduces to GR at equilibrium, (ii) is mathematically well-posed and Lyapunov stable, and (iii) supports parsimonious, cross-dataset Bayesian validation under a minimal scaling hierarchy. The *Entropic Halo Temperature* provides a distinctive observational signature; the EFC–FEP bridge clarifies cross-field relevance without overclaiming. Immediate priorities include joint fits (SPARC→CFHTLenS/SNe/BAO with fixed $\Theta(\mu)$), quantitative $T_h(r)$ predictions versus X-ray/SZ, and a technical appendix deriving micro-to-meso closures for $K(S)$ and λ.

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