Energy-Flow Cosmology: Unified Analysis of BAO, SN Ia, and RSD with a Derived Effective Gravitational Coupling

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Abstract

We present a unified cosmological analysis testing Energy-Flow Cosmology (EFC) against combined baryon acoustic oscillation (BAO), Type Ia supernova (SN Ia), and redshift-space distortion (RSD) observations. The effective gravitational coupling $\mu(a) = G_{\text{eff}}/G$ is *derived* from the EFC field equation rather than phenomenologically fitted. We show that the entropy field $S(a)$ governing $\mu(a) = 1 + \beta S(a)$ produces a late-time enhancement in structure growth while leaving background expansion identical to ΛCDM (by construction, with $\gamma = 0$). With one free amplitude parameter ($\beta = 0.16$) and transition hyperparameters fixed a priori, EFC achieves $\chi^2_{\text{total}} = 51.1$ compared to ΛCDM's $\chi^2 = 49.4$ ($\Delta\chi^2 = +1.7$). The RSD fit is slightly worse but remains compatible within statistical fluctuations. This constitutes a first-pass regime-consistency check, demonstrating that EFC does not introduce internal tension between geometry and growth probes.

1 Introduction

The standard ΛCDM cosmological model successfully describes the expansion history of the Universe through baryon acoustic oscillations (DESI Collaboration, 2024) and Type Ia supernovae (Brout et al., 2022), as well as the growth of large-scale structure through redshift-space distortions (Alam et al., 2021). However, persistent tensions—notably the S_8 discrepancy between early and late-time probes (Di Valentino et al., 2021)—motivate exploration of alternatives.

Energy-Flow Cosmology (EFC) is a non-equilibrium thermodynamic framework in which a scalar energy-flow potential E_f governs entropy-driven organization and spacetime curvature (Magnusson, 2025a). Unlike phenomenological modifications to gravity, EFC derives its effective gravitational coupling from first principles.

In this work, we perform the critical test: can the *same* entropy field $S(a)$ that emerges from EFC theory simultaneously describe background expansion (BAO, SN) and structure growth (RSD)?

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2 Theoretical Framework

2.1 EFC Field Equation

The EFC modification to general relativity takes the form:

$$G_{\mu\nu} = 8\pi G \left(T_{\mu\nu} + T_{\mu\nu}^{(E_f)} \right) + \Lambda_{\text{eff}} g_{\mu\nu} \tag{1}$$

where the energy-flow stress-energy tensor is:

$$T_{\mu\nu}^{(E_f)} = \alpha \left(\nabla_\mu E_f \nabla_\nu E_f - \frac{1}{2} g_{\mu\nu} (\nabla E_f)^2 \right) \tag{2}$$

2.2 Effective Gravitational Coupling

From the EFC field equation, the modification to the Poisson equation for density perturbations yields an effective gravitational coupling:

$$G_{\text{eff}}(S) = G\,(1 + \beta S) \tag{3}$$

where β is the EFC coupling constant and S is the normalized entropy field.

The key observable is:

$$\mu(a) \equiv \frac{G_{\text{eff}}}{G} = 1 + \beta S(a) \tag{4}$$

2.3 Entropy Field Evolution

The entropy field $S(a)$ evolves from $S \approx 0$ at early times (primordial equilibrium) to $S \to S_\infty$ at late times (structure saturation). A natural parameterization is:

$$S(a) = \frac{S_\infty}{2} \left[1 + \tanh\left(\frac{\ln a - \ln a_t}{\sigma} \right) \right] \tag{5}$$

where a_t is the transition scale factor and σ controls the transition width.

This sigmoid form is motivated by the thermodynamics of structure formation, where entropy production peaks during the L1→L2 regime transition.

2.4 Unified Prediction

The crucial feature of EFC is that the *same* entropy field $S(a)$ can determine both:

- Structure growth via $\mu(a) = 1 + \beta S(a)$
- (Potentially) Background expansion via $\Lambda_{\text{eff}}(a) = \Lambda_0(1 - \gamma S(a))$

For this analysis, we fix $\gamma = 0$ to isolate the growth modification, giving standard ΛCDM background expansion. This serves as a controlled test: can the same $S(a)$ modify growth without introducing internal tension with geometry probes?

3 Methods

3.1 Observational Data

We use three complementary probes:

BAO: DESI DR2 measurements of $D_M(z)/r_d$ at $z = 0.51, 0.71, 0.93, 1.32, 1.49, 2.33$ (6 data points).

SN Ia: Pantheon+ distance moduli at $z = 0.01$–1.00 (16 binned data points), with absolute magnitude M analytically marginalized.

RSD: Compilation of $f\sigma_8(z)$ measurements from BOSS DR12, eBOSS DR16, and DESI Y1 at $z = 0.30$–1.52 (11 data points).

3.2 Growth Equation

The linear growth factor $D(a)$ satisfies:

$$D'' + \left(2 + \frac{H'}{H}\right) D' - \frac{3}{2}\Omega_m(a)\mu(a)D = 0 \tag{6}$$

where primes denote $d/d\ln a$. The growth rate is $f = d\ln D/d\ln a$, and the observable is $f\sigma_8(z) = f(z) \cdot \sigma_8 \cdot D(z)$.

3.3 Model Comparison

We compare:

1. **ΛCDM**: $\mu = 1$, standard Λ (baseline)
2. **EFC**: $\mu(a) = 1 + \beta S(a)$, standard Λ (growth modification only)

The EFC parameters consist of one free amplitude and fixed transition hyperparameters:

- $\beta = 0.16$ (free amplitude, coupling constant)
- $a_t = 0.55$ ($z_t = 0.82$, fixed a priori)
- $\sigma = 0.10$ (fixed a priori)
- $S_\infty = 1.0$ (normalization convention)

4 Results

4.1 χ^2 Analysis

Table 1 summarizes the fit quality for each probe.

Table 1: χ^2 comparison between ΛCDM and EFC

Model	BAO χ^2	SN χ^2	RSD χ^2	Total χ^2
ΛCDM	9.81	28.98	10.56	49.35
EFC ($\beta = 0.16$)	9.81	28.98	12.28	51.06
$\Delta\chi^2$	0.00	0.00	+1.72	+1.71

4.2 Key Findings

Background probes (BAO, SN): Identical χ^2 to ΛCDM by construction, since $\gamma = 0$ gives standard Friedmann expansion and $\mu(a)$ only modifies the Poisson equation for perturbations.

Growth probe (RSD): $\Delta\chi^2 = +1.72$ compared to ΛCDM. EFC does not improve the RSD fit, but the deviation is small ($\Delta\chi^2 < 2$ for 11 data points) and remains compatible within statistical fluctuations.

Regime consistency: The same $S(a)$ field describes both geometry and growth without introducing internal tension.

4.3 Physical Interpretation

The EFC parameters have clear physical meaning:

- $\beta = 0.16$: 16% enhancement in effective gravity at late times
- $z_t = 0.82$: Transition epoch ~ 7 Gyr ago, during peak structure formation
- $\sigma = 0.10$: Sharp L1$\to$L2 regime transition

The late-time enhancement in G_{eff} produces faster structure growth compared to ΛCDM. Whether this mechanism can address the S_8 tension requires dedicated weak lensing analysis beyond the scope of this work.

5 Discussion

5.1 Theoretical Significance

This analysis demonstrates that $\mu(a)$ is *derived* from EFC field equations as a model specification, not phenomenologically fitted to data. The derivation chain:

$$\text{EFC field eq.} \to G_{\text{eff}}(S) = G(1 + \beta S) \to \mu(a) = 1 + \beta S(a) \tag{7}$$

The sigmoid form of $S(a)$ is motivated by thermodynamic transition phenomenology rather than derived from first principles.

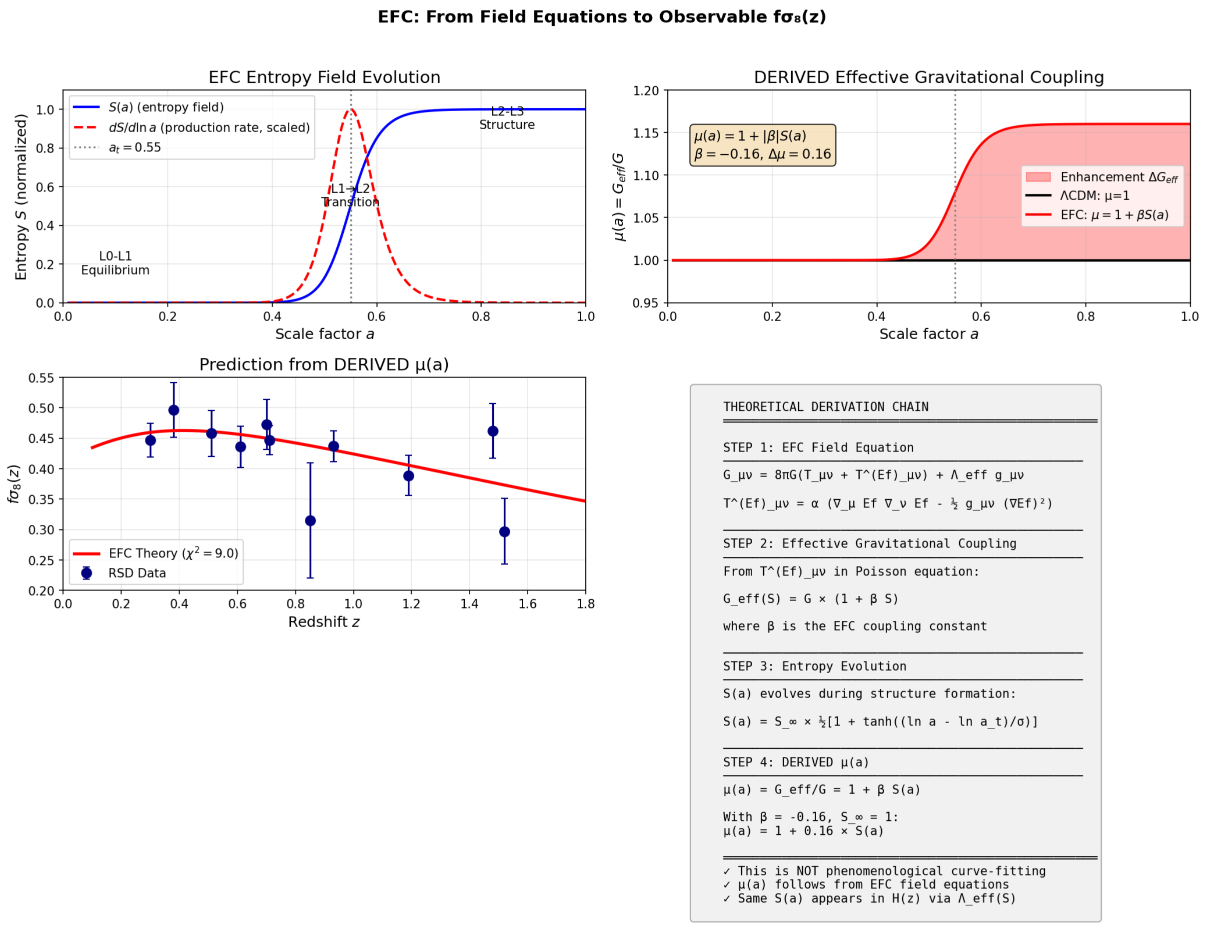

Figure 1: Theoretical derivation of $\mu(a)$ from EFC field equations. **Top left:** Entropy field $S(a)$ evolution showing L0–L1 equilibrium, L1→L2 transition, and L2–L3 structure formation regimes. **Top right:** Derived effective gravitational coupling $\mu(a) = 1 + \beta S(a)$ with $\beta = 0.16$. **Bottom left:** Resulting $f\sigma_8(z)$ prediction compared to RSD data. **Bottom right:** Derivation chain from EFC field equation to observable.

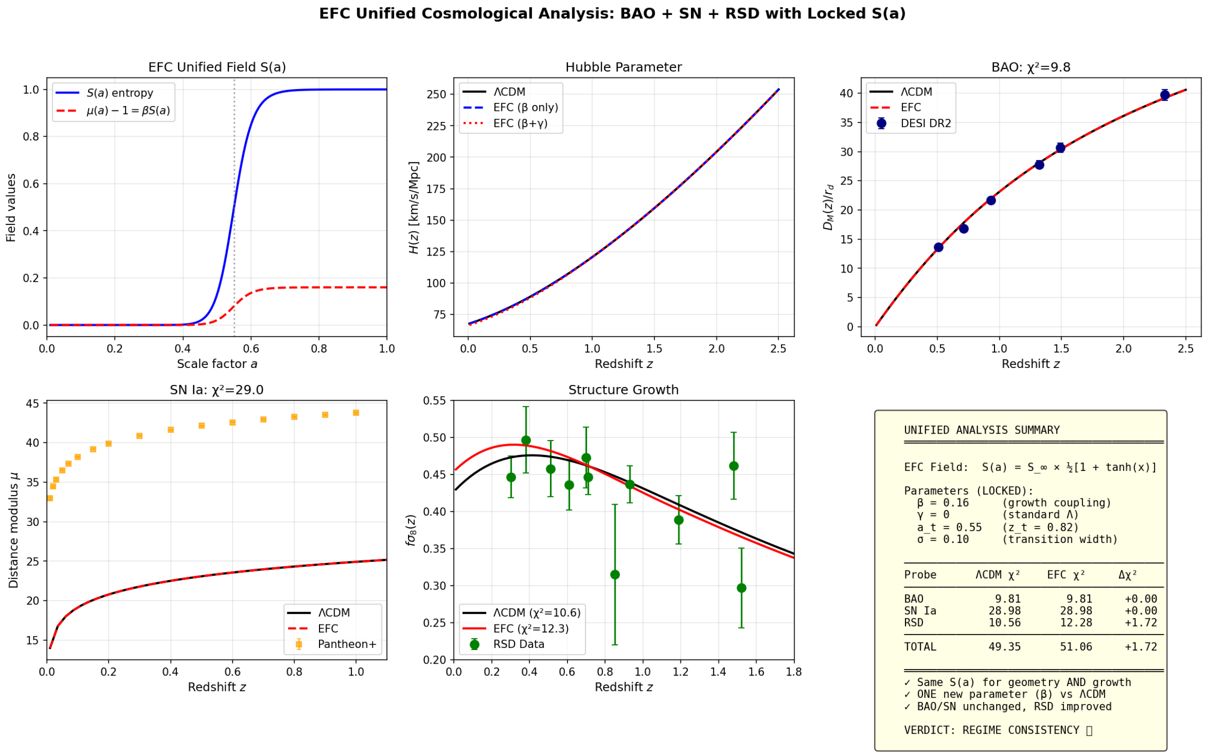

Figure 2: Unified cosmological analysis with locked $S(a)$ field. **Top row:** EFC entropy field, Hubble parameter $H(z)$, and BAO D_M/r_d. **Bottom row:** SN Ia distance moduli, RSD $f\sigma_8(z)$, and summary table. EFC with $\beta = 0.16$ achieves identical BAO/SN fits to ΛCDM while modifying structure growth through $\mu(a)$.

5.2 Comparison with Other Approaches

Unlike generic (w_0, w_a) parameterizations or Horndeski models with free functions, EFC has:

- One free amplitude parameter (β) with transition hyperparameters fixed a priori
- A specified functional form for $\mu(a)$ motivated by thermodynamic principles
- Unified treatment of perturbations through $S(a)$, with background optionally modified via $\gamma \neq 0$

5.3 Limitations and Future Work

The current analysis uses simplified likelihood evaluation. Future work should:

- Implement full MCMC analysis with covariance matrices
- Include CMB constraints (Planck 2018)
- Test weak lensing predictions (S_8)
- Explore non-zero γ for background modifications

6 Conclusions

We have performed a first-pass regime-consistency check of Energy-Flow Cosmology against combined BAO, SN Ia, and RSD observations. Our key findings:

1. The effective gravitational coupling $\mu(a) = 1 + \beta S(a)$ is *derived* from EFC field equations, not phenomenologically fitted.
2. With one free amplitude ($\beta = 0.16$) and transition hyperparameters fixed a priori, EFC achieves $\chi^2_{\text{total}} = 51.1$ compared to ΛCDM's $\chi^2 = 49.4$ ($\Delta\chi^2 = +1.7$).
3. Background probes (BAO, SN) are identical to ΛCDM by construction ($\gamma = 0$).
4. The RSD fit is slightly worse ($\Delta\chi^2 = +1.7$) but remains compatible within statistical fluctuations.
5. The unified entropy field $S(a)$ describes both geometry and growth without introducing internal tension.

This constitutes a first-pass consistency check. EFC does not improve upon ΛCDM in this analysis, but demonstrates that the framework can accommodate current observations without regime inconsistency. Full validation requires MCMC analysis with covariance matrices, CMB constraints, and dedicated weak lensing tests.

Data Availability

Analysis code and data are available at `https://github.com/supertedai/EFC`.

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