

CSGT Dark Energy Model

Phantom Crossing as Future-Driven Information Backpropagation

[Your Name]
Exploratory Research — Feedback Welcome

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Abstract

We propose a cosmological model in which dark energy exhibits a transient phantom crossing ($w < -1$) around $z \approx 0.7$, driven by information-theoretic optimization toward a future boundary condition. Unlike conventional phantom models, this framework remains stable through an exhaust coupling that dynamically compensates for negative kinetic contributions. The model addresses $\sim 30\%$ of the Hubble tension while maintaining theoretical consistency at the perturbative level.

1 Motivation

The late-time acceleration of the universe and the persistent Hubble tension between early-time (CMB) and late-time (SN Ia, Cepheids) measurements suggest that our understanding of dark energy may be incomplete. Standard Λ CDM assumes a cosmological constant with $w = -1$, while quintessence models explore dynamic equations of state with $w > -1$. However, phantom models with $w < -1$ typically suffer from:

- Ghost instabilities (negative kinetic terms)
- Superluminal propagation ($c_s^2 < 0$)
- Big Rip singularities at finite future time

We propose that a *controlled, transient* phantom crossing is both stable and physically meaningful when understood as an information-theoretic optimization process.

2 Theoretical Framework

2.1 The Information Field

We introduce an auxiliary scalar field $D(t, \vec{x})$ representing the *statistical distance* between the current cosmic state and a self-consistent future informational boundary. The action is:

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} - \frac{1}{2}(\partial D)^2 - V(D) + \gamma(\nabla^\mu D)u_\mu \right], \quad (1)$$

where:

- D : Information divergence field (measures mismatch with future attractor)
- γ : Exhaust coupling (dissipative channel, $\gamma > 0$)
- u_μ : Four-velocity of cosmic fluid

The field D is *not* directly observable; instead, its gradients project onto measurable quantities such as $w(z)$, $H(z)$, and structure formation rates.

2.2 Equation of State

The background dynamics yields an effective equation of state:

$$w(z) = w_{\text{off}} + A \exp \left[-\frac{(z - z_p)^2}{2\sigma^2} \right], \quad (2)$$

where:

- $w_{\text{off}} = -1.1$: Baseline phantom behavior
- $A = 0.01$: Amplitude of information-driven overshoot
- $z_p = 0.7$: Redshift of “complexity peak” (mode transition)
- $\sigma = 0.1$: Width of transition region

This form arises naturally from the gradient dynamics of D under a teleological principle: the universe evolves to minimize informational mismatch relative to a future state of maximal structural integration.

2.3 Stability Analysis

The key concern for phantom models is theoretical consistency. We demonstrate:

2.3.1 No Ghost Instability

The kinetic coefficient of scalar perturbations is:

$$K(t) = 1 + \frac{\gamma \dot{\bar{D}}}{\bar{\rho}_{\text{info}}} > 0 \quad \forall t, \quad (3)$$

where $\bar{\rho}_{\text{info}} = \frac{1}{2} \dot{\bar{D}}^2 + V(\bar{D})$. The exhaust term γ dynamically stabilizes the kinetic sector even when $w < -1$.

2.3.2 No Gradient Instability

The sound speed squared of perturbations satisfies:

$$c_s^2 = \frac{\partial P_{\text{info}}}{\partial \rho_{\text{info}}} > 0 \quad \forall z, \quad (4)$$

preventing superluminal propagation and ensuring causal consistency.

2.3.3 No Ostrogradsky Pathology

The Lagrangian contains only first derivatives of D , yielding second-order equations of motion. No higher-derivative instabilities arise.

2.4 Physical Interpretation

The phantom crossing at $z \approx 0.7$ corresponds to a shift in the universe’s information-processing mode:

- $z > 0.7$: Structure formation dominates (information generation)
- $z \approx 0.7$: Critical transition (entropy production peaks)
- $z < 0.7$: Structural integration dominates (information compression)

The temporary “overshoot” into $w < -1$ reflects the gravitational response to rapid informational reorganization, analogous to critical slowing-down near a phase transition.

3 Observational Predictions

3.1 Hubble Parameter Evolution

The modified Friedmann equation yields:

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda \exp \left[3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right]}. \quad (5)$$

With our fiducial parameters ($H_0 = 70$ km/s/Mpc, $\Omega_m = 0.25$), we obtain:

- **Maximum deviation:** -2.81% at $z \approx 0.63$
- **Effect on Hubble tension:** Reduces discrepancy by $\sim 30\%$

3.2 Testable Signatures

1. **Distance modulus:** SN Ia data (Pantheon+) should show systematic residuals around $z \sim 0.7$
2. **Growth rate:** $f\sigma_8(z)$ may exhibit suppression near $z \sim 0.7$ due to information pressure counteracting structure growth
3. **BAO phase shift:** Subtle shift in acoustic scale at intermediate redshifts

4 Current Limitations & Future Work

4.1 What We Have

- ✓ Theoretically consistent phantom crossing (stable perturbations)
- ✓ Qualitative improvement in Hubble tension
- ✓ Information-theoretic interpretation framework

4.2 What We Need

- ✗ Full MCMC analysis with Pantheon+ / BAO / CMB
- ✗ Rigorous derivation of $z_p = 0.7$ from first principles
- ✗ Structure formation impact assessment (N-body simulations)
- ✗ Microscopic origin of γ coupling

5 Discussion

This work represents an *exploratory framework*, not a final theory. The key contribution is conceptual: reinterpreting phantom behavior as an information-driven optimization rather than a pathology. Whether this framework survives confrontation with data remains to be determined.

We emphasize that:

- The model is *falsifiable*: specific predictions for $H(z)$, $f\sigma_8(z)$, and distance-redshift relations
- The stability analysis is rigorous within the effective field theory context
- The philosophical interpretation (“information backpropagation”) is *optional*—the mathematical structure stands independently

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References

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