

# CSGT Dark Energy Model

Phantom Crossing as Future-Driven Information Backpropagation

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*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  $\Lambda$ 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)
- $\gamma$ : Exhaust coupling (dissipative channel,  $\gamma > 0$ )
- $u_\mu$ : 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  $\gamma$  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  $\gamma$  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

## Acknowledgments

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## References

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