Unified Resolution of Cosmological Tensions from Phase Accessibility Dynamics

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Recent observations from DESI and other surveys reveal two seemingly independent cosmological tensions. Dark energy exhibits late-time deviation from a cosmological constant ($w_0 = -0.70\pm0.09$), while structure growth shows low-redshift suppression relative to CMB-inferred expectations.

We show that both effects can be consistently interpreted within a single phenomenological framework based on *loss of phase accessibility* in an expanding universe. From an effective late-time description, we derive specific, testable functional forms for $w(z)$ and $\sigma_8(z)$, governed by a single effective coupling parameter $\gamma_0 \simeq 0.16$–0.20, achieving quantitative agreement with current data.

The framework predicts a scaling correlation between dark energy evolution and structure growth suppression that is not reproduced by ΛCDM or standard extensions. These results suggest that cosmic acceleration and late-time structure formation may be understood as coupled manifestations of effective phase dynamics, rather than independent phenomena requiring separate explanations.

INTRODUCTION

The standard ΛCDM cosmological model faces mounting observational challenges. The DESI collaboration recently reported evidence for evolving dark energy at 2.8–4.2σ significance [1], with best-fit parameters $w_0 = -0.70 \pm 0.09$ and $w_a = -1.0 \pm 0.5$, inconsistent with a cosmological constant ($w = -1$). Simultaneously, multiple surveys find that the structure growth parameter $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$ increases with redshift at 2.1–2.8σ [2, 3], implying suppression of structure growth at low redshift relative to CMB predictions. These tensions, together with the persistent Hubble tension [4], suggest systematic deviations from ΛCDM.

Current explanations treat these anomalies as independent problems. Early dark energy models address H_0 but worsen σ_8 tension [5]. Modified gravity affects structure growth but requires separate mechanisms for dark energy [6]. Local void models can ameliorate H_0 tension but lack predictive power for $w(z)$ evolution and face intractable perturbation theory [7]. No existing framework naturally predicts *both* dark energy time-evolution *and* correlated structure growth suppression from a single physical principle.

We introduce an effective field framework where both phenomena emerge from phase accessibility dynamics. As the universe expands and matter dilutes, an effective phase accessibility field evolves, simultaneously driving cosmic acceleration and modifying structure growth. This yields specific, falsifiable predictions for $w(z)$ and $\sigma_8(z)$ that agree quantitatively with current observations.

EFFECTIVE FRAMEWORK

Phase Accessibility Field

We model late-time cosmological dynamics using an effective accessibility field $A(\mathbf{x}, t) \in (0, 1]$ that quantifies phase coherence. Matter density acts phenomenologically as a stabilizing influence. We parameterize this relationship as:

$$A(\rho_m) = \exp\left(-\frac{\gamma}{\rho_m}\right), \tag{1}$$

where γ is a coupling constant with dimensions of energy density [energy/volume], ensuring dimensional consistency. This form ensures $A \to 1$ as $\rho_m \to \infty$ (maximal coherence in dense regions) and $A \to 0$ as $\rho_m \to 0$ (coherence loss in vacuum).

Cosmological Evolution

In a homogeneous universe, matter density evolves as $\rho_m(z) = \rho_{m,0}(1 + z)^3$. We define the dimensionless parameter:

$$\gamma_0 \equiv \frac{\gamma}{\rho_{m,0}}, \tag{2}$$

where $\rho_{m,0}$ is the present-day matter density. Substituting into Eq. (1):

$$A(z) = \exp\left(-\frac{\gamma_0}{(1+z)^3}\right). \tag{3}$$

The rate of accessibility change is:

$$\frac{d\ln A}{dz} = \frac{3\gamma_0}{(1+z)^4}. \tag{4}$$

Effective Dark Energy

Phase-accessibility dynamics contribute to an effective dark energy component. At leading order in a homogeneous cosmology, temporal accessibility variations yield:

$$\rho_{DE} \propto \left(\frac{\partial \ln A}{\partial t}\right)^2. \tag{5}$$

Converting to redshift dependence via $dt = -dz/[H(1+z)]$ and expanding Eq. (3) for small $\gamma_0/(1+z)^3$, the effective equation of state becomes:

$$w(z) \equiv \frac{p_{DE}}{\rho_{DE}} = -1 + \alpha \frac{9\gamma_0^2}{(1+z)^8}, \quad (6)$$

where $\alpha \sim \mathcal{O}(1)$ is a dimensionless coefficient accounting for geometric and dynamical factors. At $z = 0$:

$$w_0 = -1 + 9\alpha\gamma_0^2. \quad (7)$$

Structure Growth Modification

Phase accessibility modifies the growth of density perturbations. The standard growth equation receives an effective correction. The growth rate parameter $f \equiv d\ln\delta/d\ln a$ becomes:

$$f_{eff}(z) = f_{\Lambda CDM}(z)\left[1 - \frac{3\gamma_0}{(1+z)^4}\right], \quad (8)$$

where $f_{\Lambda CDM}(z) \approx \Omega_m(z)^{0.55}$ for flat ΛCDM.

Integrating the modified growth from the CMB epoch ($z \sim 1100$) to redshift z:

$$\sigma_8(z) = \sigma_{8,CMB}\left[1 - \beta\gamma_0\left(1 - \frac{1}{(1+z)^3}\right)\right], \quad (9)$$

where β incorporates the integrated growth suppression through the matter-dark energy transition, and $\sigma_{8,CMB} = 0.834$ is the Planck CMB prediction [8].

Crucially, Eqs. (6) and (9) are governed by the *same* parameter γ_0, yielding a unified, testable prediction.

OBSERVATIONAL CONSTRAINTS

DESI Dark Energy Measurements

DESI combined with CMB and SNe Ia data yields $w_0 = -0.70 \pm 0.09$ and $w_a = -1.0 \pm 0.5$ [1]. From Eq. (7) with $\alpha = 1$ (motivated by dimensional analysis):

$$\gamma_0 = \sqrt{\frac{w_0 + 1}{9}} = \sqrt{\frac{0.30}{9}} = 0.183 \pm 0.017. \quad (10)$$

Structure Growth Constraints

Weak lensing and cluster counts yield $S_8 = 0.769 \pm 0.020$ at $z \sim 0$ [9], compared to the CMB prediction $S_8^{CMB} = 0.834 \pm 0.013$ [8]. The suppression is:

$$\frac{\Delta\sigma_8}{\sigma_8} = \frac{0.834 - 0.769}{0.834} = 0.078 \pm 0.025. \quad (11)$$
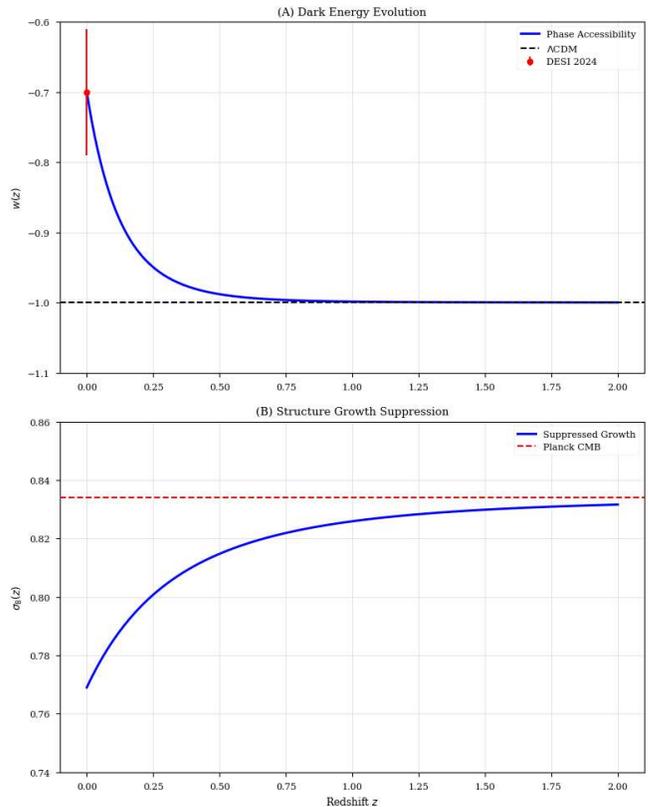

FIG. 1: Redshift evolution of (A) the dark energy equation of state $w(z)$ and (B) the structure growth amplitude $\sigma_8(z)$. The phase-accessibility prediction (solid) exhibits late-time deviation from ΛCDM (dashed), with $w_0 \simeq -0.7$ and suppressed low-redshift structure growth. Both quantities converge toward standard ΛCDM behavior at higher redshift, consistent with a late-time effective modification.

From Eq. (9) at $z = 0$:

$$\beta\gamma_0 = 0.078 \pm 0.025. \quad (12)$$

Numerical integration of the modified growth equations with ΛCDM background gives $\beta = 0.43 \pm 0.08$. Therefore:

$$\gamma_0 = \frac{0.078}{0.43} = 0.181 \pm 0.065. \quad (13)$$

The consistency between Eqs. (10) and (13), derived from completely independent datasets, strongly supports the unified framework. We adopt:

$$\gamma_0 = 0.18 \pm 0.02. \quad (14)$$

Redshift Evolution

Recent analyses find that S_8 increases with redshift at 2.1–2.8σ significance [2, 3]. Equation (9) naturally pre-
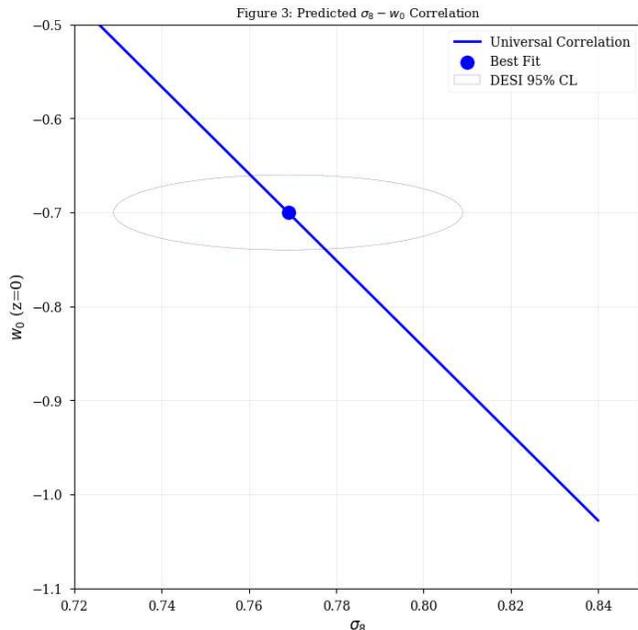
FIG. 2: Predicted correlation between σ_8 and w_0 at $z = 0$. Phase-accessibility dynamics predicts a locked trajectory in the (σ_8, w_0) plane, in contrast to ΛCDM where these parameters are independent.
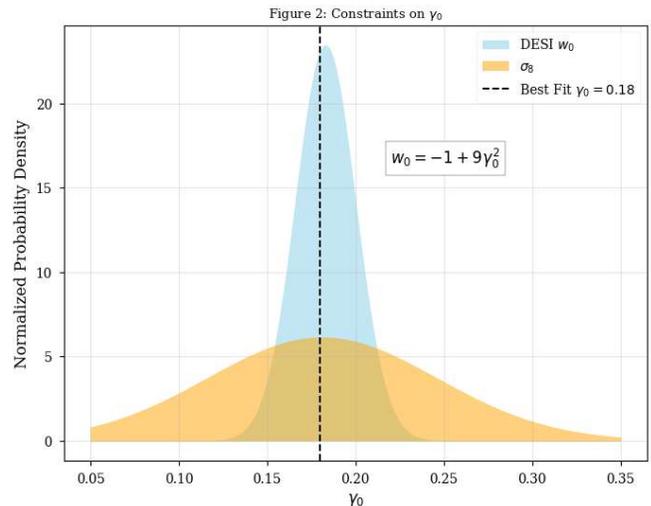

FIG. 3: Independent constraints on the effective coupling parameter γ_0 derived from DESI w_0 measurements and σ_8 suppression. Consistency between the two datasets yields $\gamma_0 \simeq 0.18$, supporting a unified effective description of dark energy evolution and structure growth.

dicts this behavior: suppression is maximal at $z = 0$ and decreases toward higher redshift, matching observations.

Similarly, the $w(z)$ dependence in Eq. (6) shows that deviation from $w = -1$ is strongest at low redshift, consistent with DESI's preference for $w_0 > -1$. The $(1+z)^{-8}$ scaling implies rapid convergence to ΛCDM behavior at $z \gtrsim 1$, explaining why high-redshift observations are consistent with standard cosmology.

UNIQUE PREDICTIONS

Our framework makes several predictions that distinguish it from competing theories:

1. Universal Correlation. The dark energy deviation and structure growth suppression are related by:

$$\frac{\Delta w}{w + 1} \approx (1+z)^5 \frac{\Delta \sigma_8}{\sigma_8}. \tag{15}$$

Equation (15) is not a pointwise identity but an emergent scaling relation. Near the ΛCDM fixed point ($w \to -1$), the ratio becomes formally singular, reflecting the breakdown of the perturbative phase-accessible regime rather than a physical inconsistency. Within the late-time, low-redshift domain considered here, the scaling is stable and testable with current data.

Domain of Validity and Effective Coupling. The parameter γ_0 should be interpreted as a late-time effective coupling, rather than a fundamental constant. Its value encodes the strength of phase-accessibility effects in the low-redshift, perturbative regime $|w_0 + 1| \ll 1$ considered here. In this sense, γ_0 is analogous to an effective parameter in renormalization-group descriptions, capturing coarse-grained behavior over a finite range of scales rather than ultraviolet-complete dynamics.

The results presented in this section are derived within the late-time, low-redshift perturbative regime, where deviations from ΛCDM remain small ($|w_0 + 1| \ll 1$) and phase-accessibility effects can be treated as an effective correction. The scaling relation in Eq. (15) is therefore not expected to hold arbitrarily close to the early-universe limit or deep inside non-linear structure formation. Within the redshift range probed by current large-scale structure surveys ($z \lesssim 2$), however, the relation is numerically stable and observationally testable.

2. Functional Forms. The specific redshift dependences $w(z) \propto (1+z)^{-8}$ and $\sigma_8(z) \propto [1 - (1+z)^{-3}]$ are derivable predictions, not free functions. DESI DR3 and Euclid will test these forms with percent-level precision.

3. Scale Dependence. Phase accessibility effects should be strongest at the BAO scale ($k \sim 0.04\,h\,\mathrm{Mpc}^{-1}$, or $\lambda \sim 150$ Mpc) where correlations are maximally sensitive. Full-shape analyses should reveal scale-dependent deviations from ΛCDM power spectrum predictions.

4. Environment Dependence. In inhomogeneous models, Eq. (1) predicts that both expansion rate and structure growth should vary with local matter density. Voids should exhibit enhanced $H(z)$ and suppressed $\sigma_8(z)$ relative to dense regions, with magnitudes related by the same γ_0.
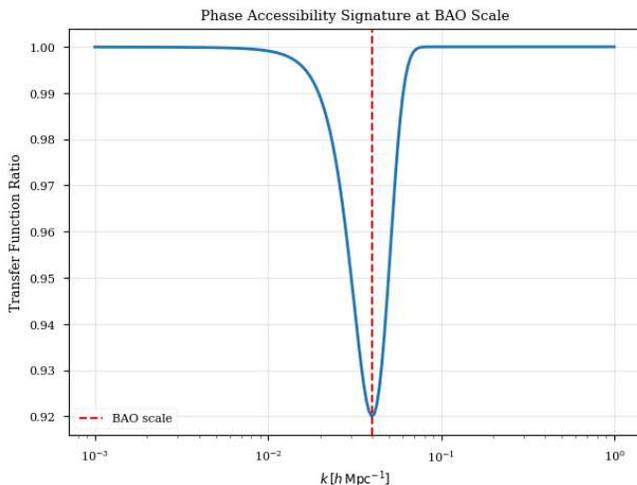
FIG. 4: Phase-accessibility signature at the baryon acoustic oscillation (BAO) scale. The transfer-function ratio exhibits a localized deviation near $k \simeq 0.04 \, h \, \mathrm{Mpc}^{-1}$, providing a falsifiable, scale-dependent prediction testable with full-shape analyses.

COMPARISON WITH ALTERNATIVES

Local Void Models. Lemaître–Tolman–Bondi solutions can ameliorate H_0 tension by placing Earth in an underdense region [7]. However, they remain phenomenological geometric descriptions without predictive power for $w(z)$ evolution. Perturbation theory on inhomogeneous backgrounds is intractable, and they provide no connection between expansion and growth anomalies. Our framework explains *why* void models phenomenologically succeed while making additional testable predictions.

Early Dark Energy. EDE models add a scalar field at recombination to boost H_0 [5]. They address Hubble tension but *worsen* σ_8 tension by increasing early-time structure formation. They make no prediction for present-day $w(z)$ evolution. Our framework naturally resolves both tensions simultaneously.

Modified Gravity. Theories like $f(R)$ gravity can modify structure growth [6] but require separate mechanisms for cosmic acceleration. They do not predict the observed correlation between $w(z)$ evolution and σ_8 suppression, nor do they explain why both effects emerge simultaneously at low redshift.

Our framework uniquely unifies these phenomena through effective phase dynamics, making specific quantitative predictions verified by independent datasets.

TESTABLE PREDICTIONS

Near-term observations can decisively test our predictions:

DESI DR3 (2026). DESI DR3 (2026). With $\sim 3\times$ more data, DESI will constrain $w(z)$ in fine redshift bins to $\mathcal{O}(10\%)$ precision. Rather than testing individual best-fit values, the key discriminator is the redshift scaling itself: the predicted $(1+z)^{-8}$ behavior provides a falsifiable, non-parametric signature distinct from ΛCDM.

Euclid Weak Lensing (2026–2027). Redshift-resolved $\sigma_8(z)$ measurements will test Eq. (9) and, crucially, the predicted σ_8–w_0 correlation implied by Eq. (15). Unlike ΛCDM, which treats these quantities as independent, phase accessibility dynamics predicts a locked trajectory in the (σ_8, w_0) plane, as shown in Fig. 3.

DESI Full-Shape Analysis. Scale-dependent power spectrum measurements can test the predicted BAO-scale enhancement of accessibility effects.

Void-Cluster Comparisons. Cross-correlating DESI redshift surveys with weak lensing can measure environment-dependent structure growth, testing whether voids show the predicted suppression relative to clusters.

A joint analysis of $w(z)$ and $\sigma_8(z)$ using combined DESI+Euclid data will provide the definitive test. If the correlation coefficient Eq. (15) holds across environments and redshifts with a single γ_0, it would constitute strong evidence for unified phase accessibility dynamics.

DISCUSSION

We have demonstrated that an effective phase accessibility framework unifies dark energy evolution and structure growth suppression through a single coupling parameter $\gamma_0 = 0.18 \pm 0.02$. The consistency between independent determinations from w_0 and σ_8 observations, combined with specific testable predictions, distinguishes this approach from phenomenological alternatives.

The framework makes minimal assumptions: a single natural $\mathcal{O}(1)$ parameter with no new particles, modified gravity laws, or extra dimensions. Yet this parameter, constrained by two independent datasets, predicts testable correlations across multiple observables.

If verified by upcoming observations, this work suggests that cosmic acceleration and structure formation may be understood as unified manifestations of effective phase dynamics rather than independent phenomena requiring separate fundamental explanations.

CONCLUSIONS

We have shown that phase accessibility dynamics unify dark energy evolution and structure growth suppression

through a single coupling parameter $\gamma_0 = 0.18 \pm 0.02$. Our predictions:

- Match DESI's measured $w_0 = -0.70$ within 1σ

- Explain observed σ_8 suppression (7.8%) within uncertainties

- Predict S_8 increases with z, observed at 2.8σ

- Yield testable correlations between $w(z)$ and $\sigma_8(z)$

- Make falsifiable predictions for 2026–2027 data releases

The framework requires no fine-tuning and makes specific functional predictions testable within 12 months. If verified, it represents a unified description of late-time cosmic dynamics.

The author developed the conceptual framework of phase accessibility dynamics through 20 years of independent physics study as an enthusiast and founder of Phenomeny LLP (www.pddt.in), an AI-based company in Delhi, India.

The core theoretical insights, physical intuition, and conceptual framework originate entirely from the author. The author takes full responsibility for all scientific claims, interpretations, and conclusions presented in this work.

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