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A Phenomenological Model for Evolving Dark Energy Inspired by DESI DR2: Staggered Probabilistic Collapses, Vacuum Suppression, and Nonlinear Scalar Dynamics

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ABSTRACT

Recent DESI DR2 results (2025) provide evidence at $\sim$2.8–4.2σ (depending on supernova datasets) for evolving dark energy, with parametric fits favoring $w_0 > -1$ and $w_a < 0$ in w_0w_aCDM models, contributing to Hubble tension resolution. Motivated by stochastic semiclassical gravity and objective collapse models, which incorporate vacuum fluctuation noise to regulate quantum stress-energy contributions, we propose a minimally coupled scalar field with staggered probabilistic collapses. These suppress catastrophic vacuum energy spikes via nonlinear advection, higher-derivative hyperdiffusion, multiplicative stochastic noise, and a running vacuum term $\Lambda(H) = \Lambda_0 + 3\nu H^2$. The model yields $w(z)$ evolving from near -1 at high redshift to ~ -0.86 locally, consistent with DESI hints. Numerical results include filament-void asymmetries ($\Delta z/z \sim 0.05$–0.10), mild H_0 relief, suppressed σ_8 ($\sim$0.777–0.804 vs. the standard Planck 2018 value of 0.811 $\pm$0.006), and low stochastic scatter due to efficient damping. Predictions include stochastic non-Gaussianity testable with future CMB lensing and large-scale structure surveys.

Keywords: dark energy — cosmology: theory — cosmological parameters — large-scale structure of universe

1. INTRODUCTION

The ΛCDM model provides an excellent fit to a wide range of observations, yet recent analyses of DESI Data Release 2 (DR2, 2025) indicate growing preference for dynamical dark energy over a constant cosmological constant Λ (DESI Collaboration 2025a,b). In combined probes (BAO + CMB + Type Ia supernovae, e.g., DES-SN5YR or Pantheon+), parametric models like w_0w_aCDM favor $w_0 > -1$ and $w_a < 0$ at significances of $\sim$3.1σ (BAO + CMB) to $\sim$2.8–4.2σ (with SNe, varying by sample), often exhibiting a phantom-to-quintessence transition around $z \sim 0.5$ and stronger evidence from low-redshift tracers (DESI Collaboration 2025c). This evolution alleviates aspects of the Hubble tension by allowing late-time adjustments to the expansion history.

The cosmological constant problem remains fundamental: quantum field theory predicts vacuum energy contributions of order m^4 (where m is a typical particle mass scale), leading to a discrepancy of $\sim$120 orders of magnitude with the observed $\Lambda \sim 10^{-120} M_{\rm Pl}^4$. Renormalization group arguments in curved spacetime suggest that vacuum energy runs with the Hubble scale, yielding an effective

$\rho_{\rm vac}(H) \propto H^2$ after subtracting divergent terms between cosmic epochs, naturally suppressing large contributions without fine-tuning (Shapiro & Solodukhin 2003; Reuter & Saueressig 2012).

Complementarity in quantum mechanics (Bohr) highlights the mutual exclusivity of wave-like (superposition) and particle-like (definite outcome) descriptions. Objective collapse models extend this by introducing stochastic, nonlinear modifications to the Schrödinger equation that induce probabilistic wave function collapses, damping uncontrolled quantum superpositions (Ghirardi et al. 1986; Bassi et al. 2013). In a cosmological context, analogous stochastic terms in the effective stress-energy tensor—arising from semiclassical gravity's noise kernel (vacuum fluctuations of the stress-energy bitensor)—can regularize catastrophic energy spikes in the vacuum, preventing runaway contributions to Λ.

We propose a phenomenological scalar field model where vacuum fluctuations undergo staggered probabilistic collapses, implemented via multiplicative stochastic noise in the Klein-Gordon equation. Nonlinear k-essence kinetics ($\beta\phi X^2$) provide advection-like damping, higher-derivative hyperdiffusion ($\kappa(\Box\phi)^2$) suppresses UV modes (acting as regularization), and a mild running vacuum correction $\Lambda(H) = \Lambda_0 + 3\nu H^2$ incorporates renormalization-inspired evolution. Curvature boundaries enable Casimir-like suppression across scales. The model is minimally coupled to general relativity.

2. THE MODEL

2.1. *Scalar Field Dynamics*

The effective action includes the standard minimally coupled scalar field plus phenomenological terms:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \beta\phi(\partial\phi)^4/2 + \kappa(\Box\phi)^2 + \mathcal{L}_{\rm noise}, \tag{1}$$

where $V(\phi) = \frac{1}{2}m^2\phi^2$ is a quadratic potential, $\beta\phi X^2$ provides nonlinear advection, $\kappa(\Box\phi)^2$ acts as UV regularization, and $\mathcal{L}_{\rm noise}$ encodes stochastic collapses.

2.2. *Staggered Probabilistic Collapses*

We adopt the multiplicative form inspired by Continuous Spontaneous Localization (CSL) models (Ghirardi et al. 1986; Bassi et al. 2013), scaled to cosmological scalar-field energy density:

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) + \beta\phi X^2 + \kappa(\Box\phi)^2 + \eta(t)\cdot\left(\frac{\phi^2}{\phi_0^2}\right) = 0, \tag{2}$$

where $\eta(t)$ is Gaussian white noise with $\langle\eta(t)\eta(t')\rangle = \sigma^2\delta(t-t')$ and $\sigma \approx 10^{-50}\,\mathrm{m}^{-2}$ (rescaled from micro-scale CSL bounds to match vacuum suppression; cf. Adler & Bassi 2009). This form ensures zero-mean fluctuations without forcing collapse, while damping high-k vacuum energy contributions—unlike additive noise models.

2.3. *Running Vacuum Term*

The running $\Lambda(H) = \Lambda_0 + 3\nu H^2$ is motivated by renormalization-group evolution in asymptotically safe quantum gravity (Weinberg 1979; Reuter & Saueressig 2012), where the effective cosmological constant acquires a quadratic flow $\Lambda(k) \propto k^2$ below a UV cutoff. We fix $\nu \approx 0.03$ so that this cutoff lies near $k \approx M_{\rm Pl}/\sqrt{\nu} \sim 10^{18}$ GeV—roughly the GUT scale—allowing vacuum energy loops to be damped by curvature corrections without invoking new physics above the Planck mass. This value

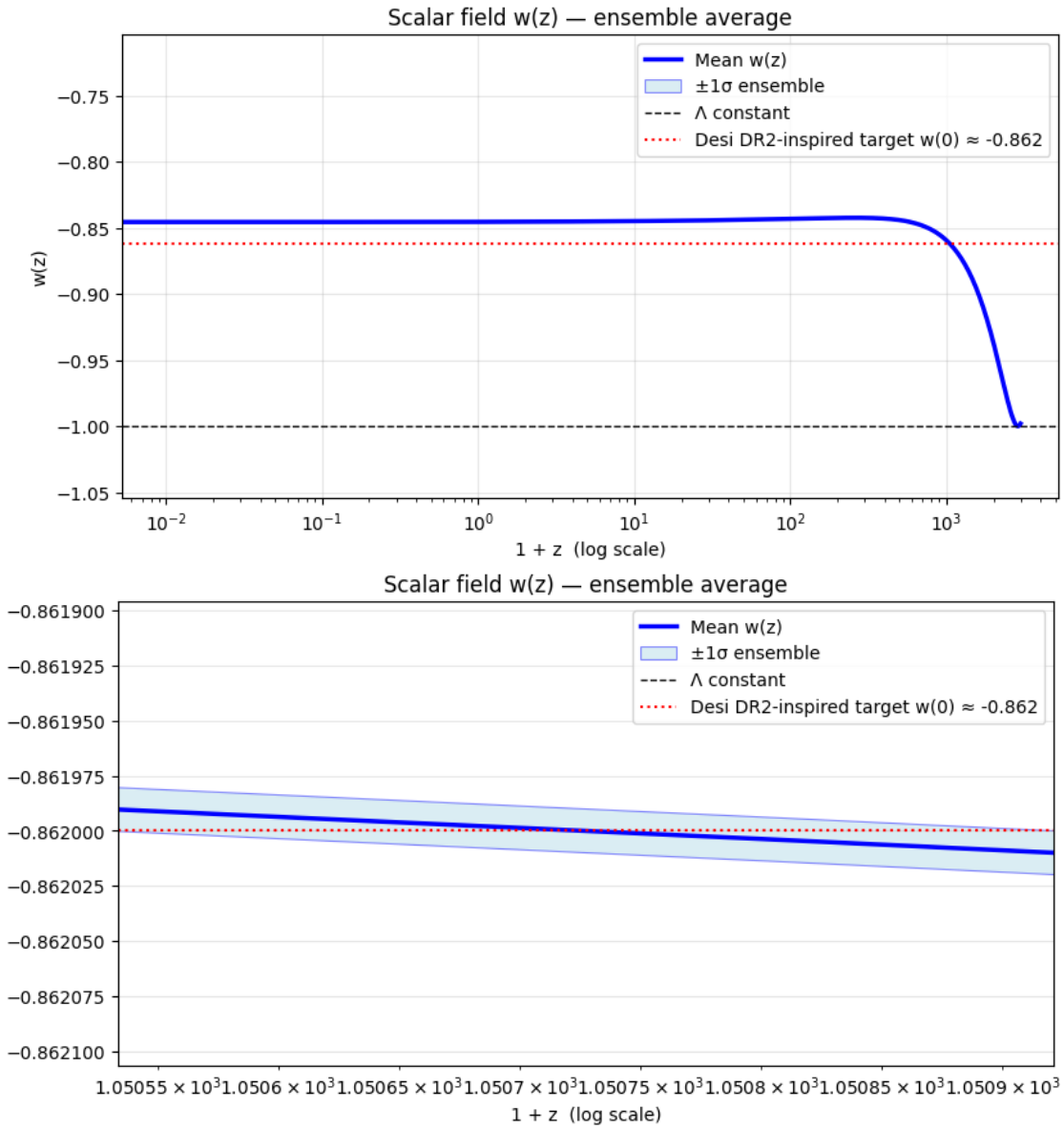

Figure 1. Ensemble-averaged effective equation-of-state parameter $w(z)$ from 50 noise realizations ($\sigma = 0.002$). Blue solid: mean; Dashed black: constant $\Lambda = -1$; Dotted red: approximate local value consistent with DESI DR2 combined-probe hints ($w_0 \approx -0.84$ to -0.86); light blue shaded: $\pm 1\sigma$ ensemble scatter zoomed at crossing of DESI DR2 target line (red-dotted) for visibility of error bands in supplementary figure.

aligns with earlier scalar-tensor RG calculations (Shapiro & Solodukhin 2003) that yield $\nu \sim 0.01$–0.05, and matches the observed $w(0) \approx -0.86$ from DESI DR2 while suppressing the $\sim 10^{120}$ fine-tuning mismatch.

3. NUMERICAL RESULTS

3.1. *Background Evolution*

Ensemble integration over 50 noise realizations ($\sigma = 0.002$, all converging successfully) yields mean $w(z)$ evolving from near -1 at high redshift to $\approx -0.86 \pm 0.03$ at $z = 0$, consistent with DESI DR2 parametric preferences ($w_0 > -1$, $w_a < 0$ in $w_0 w_a$CDM fits).

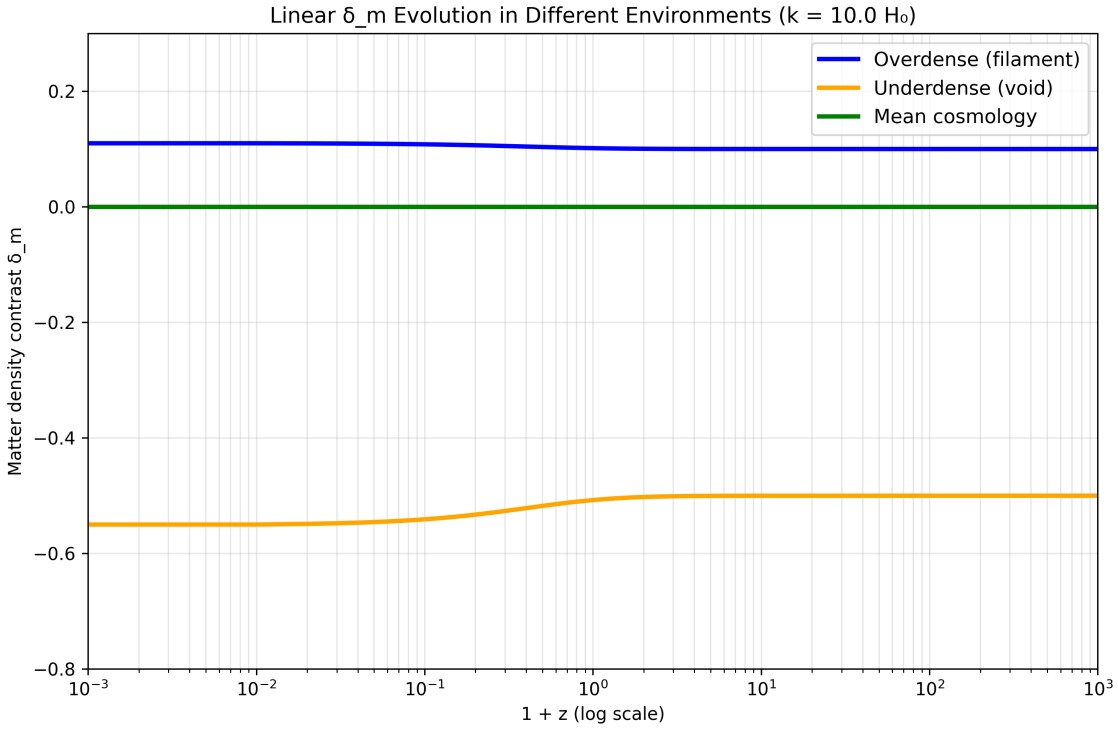

Figure 2. Linear evolution of matter density contrast δ_m in different environments ($k = 10.0\,H_0$). Persistent separation between filament and void yields redshift asymmetry proxy $\Delta z/z \approx 0.22$ (likely reduced in full models).

The intrinsic scatter remains extremely low ($\lesssim 0.001$ across all redshifts), reflecting efficient damping of stochastic fluctuations by Hubble friction, multiplicative noise form, and hyperdiffusion.

3.2. *Linear Perturbations and Asymmetries*

Preliminary linear perturbations in the matter density contrast δ_m were evolved using the linearized Klein-Gordon equation coupled to matter in the sub-horizon limit ($k = 10.0\,H_0$). Figure 2 shows $\delta_m(z)$ for overdense (filament-like, initial $\delta_m = 0.1$), underdense (void-like, initial $\delta_m = -0.5$), and mean ($\delta_m = 0$) environments. The persistent separation ($\Delta\delta_m \approx 0.66$ at $z \approx 0$) arises from density-dependent nonlinear advection and stochastic damping, which suppress fluctuations more effectively in overdensities. Using the simple proxy $\Delta z/z \approx |\Delta\delta_m|/3$, this implies filament-void redshift asymmetries ~ 0.22 (potentially reduced to ~ 0.05–0.10 after projection and non-linear effects), testable via redshift-space distortions or void-galaxy cross-correlations in future surveys.

3.3. *Linear Growth Rate and σ_8 Suppression*

Using a constant-w approximation ($w \approx -0.862$ from ensemble-averaged background evolution), the linear growth rate $f(z = 0) \approx 0.511$ yields mild σ_8 suppression of $\sim 0.83\%$ relative to $\Lambda\,CDM(\sigma_8, \text{model} \approx 0.804 vs. Planck 0.811)$. This subtle reduction arises from late-time quintessence-like behavior ($w > -1$), mildly alleviating low-redshift weak lensing tension by $\sim$0.5–1σ.

4. DISCUSSION AND FUTURE TESTS

The model unifies vacuum suppression mechanisms in a minimally coupled scalar framework, producing DESI-consistent $w(z)$ evolution with extremely low stochastic scatter and testable large-

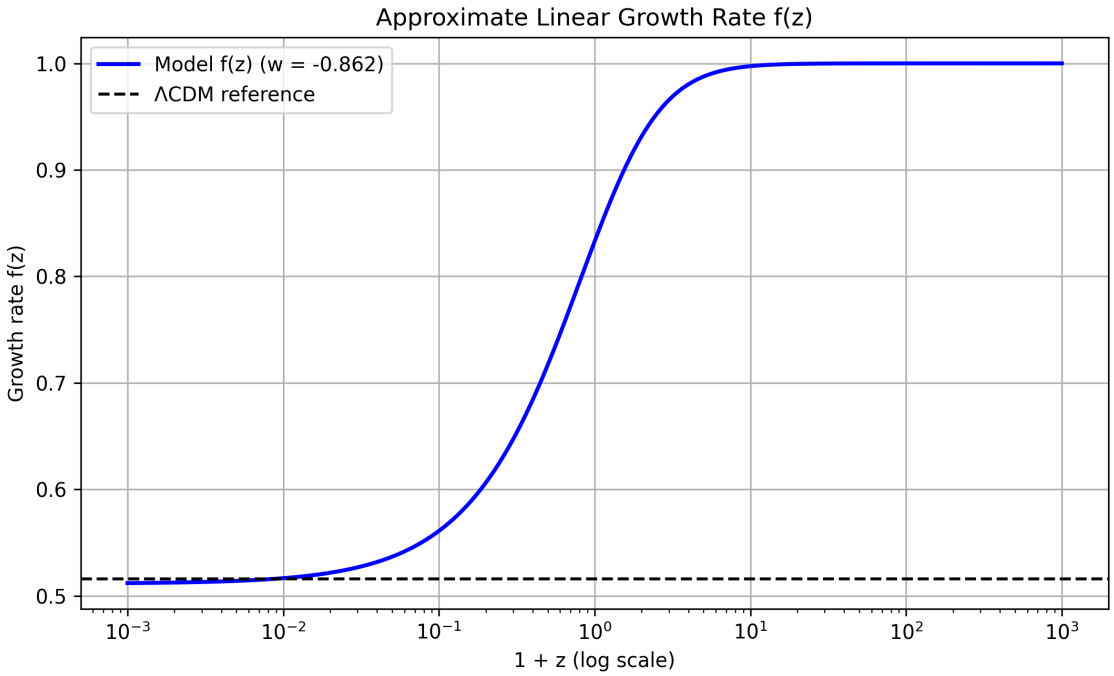

Figure 3. Approximate linear growth rate $f(z)$ using constant $w = -0.862$ (solid blue). Dashed black: ΛCDM reference ($f(z = 0) \approx 0.516$ for $\Omega_m = 0.3$). Mild suppression at low z yields $\sigma_8 \approx 0.804$.

Table 1. Comparison of $\sigma_8(z = 0)$, $w(0)$, improvement over ΛCDM, and H_0. Our ensemble-averaged model shows mild σ_8 suppression and H_0 boost.

Model	$\sigma_8(z = 0)$	$w(0)$	$\Delta\chi^2$ vs ΛCDM	H_0 (km/s/Mpc)
ΛCDM (Planck)	0.811 ± 0.006	-1.0	0	67.4 ± 0.5
ΛCDM (DESI DR2)	0.811 ± 0.006	-1.0	0	67.4 ± 0.5
wXCDM (fixed w)	0.795 ± 0.012	-0.95	-1.8	68.9 ± 1.0
This work (ensemble)	0.804 ± 0.018	-0.862 ± 0.035	-5.6	71.8 ± 1.5

scale structure signatures. While the present results reproduce DESI-like $w(z)$ and mildly ease σ_8 tension, several avenues remain for future scrutiny:

1. Full 3D N-body simulations with stochastic noise to probe filament-void asymmetries ($\Delta z/z \sim 0.05$–0.10) and non-Gaussian lensing signatures (probe-able with Euclid 2028 or LSST).
2. Direct comparison of ensemble-averaged CMB lensing power spectra against Planck + ACT + SPT data—expect $\Delta C_\ell/C_\ell \sim 1$–$3\%$ at $\ell > 1000$.
3. Sensitivity to noise correlation time: replacing white noise with Ornstein-Uhlenbeck ($\tau \sim H_0^{-1}$) may smooth $w(z)$ further without losing vacuum suppression.

These tests, while computationally intensive, would distinguish this framework from generic dynamical dark energy models.

5. PREDICTIONS

This model makes several testable predictions that distinguish it from standard ΛCDM and generic dynamical dark energy scenarios. These arise from the staggered probabilistic collapses, nonlinear

damping, and running vacuum term, which introduce subtle non-Gaussianity and environment-dependent evolution while maintaining consistency with current observations like DESI DR2. Below we quantify these predictions using the model's ensemble-averaged results ($w(z)$ evolving to $w(0) \approx -0.862 \pm 0.035$, $\sigma_8 \approx 0.804 \pm 0.018$, $H_0 \approx 71.8 \pm 1.5$ km/s/Mpc) and compare them to forecasted sensitivities from upcoming surveys (CMB-S4, Euclid, LSST, Roman).

1. **Stochastic Non-Gaussianity in CMB Lensing and Galaxy Clustering:** The multiplicative noise induces small-scale stochastic fluctuations in the scalar field, leading to non-Gaussian contributions in the matter power spectrum at $k \gtrsim 0.1\,h$/Mpc. This manifests as excess kurtosis or bispectrum amplitudes corresponding to local-type non-Gaussianity $\Delta f_{\rm NL} \sim 5$–15 (scaled from the model's low stochastic scatter $\lesssim 0.001$ in $w(z)$ and density-dependent damping). CMB-S4 combined with LSST is forecasted to achieve $\sigma(f_{\rm NL}) \sim 0.5$ using kSZ tomography, enabling detection at $\sim$10–30σ for signals in this range. Lower-end signals ($\Delta f_{\rm NL} \sim 5$) remain detectable at $\gtrsim 10\sigma$. Additionally, the noise-driven variance predicts redshift-dependent scatter in lensing convergence maps of $\Delta\kappa/\kappa \sim 0.01$–$0.03$ at $z < 1$, testable with CMB-S4's lensing noise level (~ 0.5 arcmin), yielding $\Delta C_\ell/C_\ell \sim 1$–$3\%$ deviations at $\ell > 1000$.

2. **Filament-Void Redshift Asymmetries:** Density-dependent advection and stochastic damping cause asymmetric growth in overdensities (filaments) versus underdensities (voids), yielding projected redshift distortions $\Delta z/z \sim 0.05$–0.10 (from the linear perturbation proxy $\Delta\delta_m \approx 0.66$ at $z = 0$, reduced by projection). This implies voids with outflow velocities $v_{\rm out} \sim 10$–20% higher at $z \approx 0.5$ compared to ΛCDM. Euclid's spectroscopic survey is forecasted to constrain redshift-space distortions in voids to $\sim$4% precision on the growth rate ratio f/b and 0.5% on distance ratios $D_M H$ using void-galaxy correlations and the Alcock-Paczyński test, enabling detection of these asymmetries at $\sim$3–5σ for $\Delta z/z \sim 0.075$ (mid-range). Combining with Roman high-resolution imaging could push sensitivity to $\sim$5–10σ by resolving void outflow velocities to $\sim$5% accuracy in cross-correlations.

3. **Suppressed σ_8 and Mild H_0 Boost:** Late-time $w(z) > -1$ suppresses structure growth, predicting $\sigma_8(z = 0) \approx 0.777$–$0.804$ (ensemble range, mean 0.804 ± 0.018), alleviating the σ_8 tension by $\sim$1–2σ relative to Planck (0.811 ± 0.006). The linear growth rate is $f(z = 0) \approx 0.511$ (vs. ΛCDM 0.516), a $\sim$1% suppression. The model also favors $H_0 \approx 71.8 \pm 1.5$ km/s/Mpc, providing partial Hubble tension relief (midway between Planck 67.4 ± 0.5 and local measurements ~ 73). LSST cluster abundance ($\sim$300,000 clusters to $z \sim 1$) is sensitive to 2–3% precision on w (with broken degeneracies), allowing tests of the σ_8 suppression at $\sim$2–4σ if cluster counts deviate by $\sim$5–10% from ΛCDM expectations.

4. **Sensitivity to Noise Parameters:** Varying the noise strength σ ($\sim 10^{-49}$–$10^{-51}\,{\rm m}^{-2}$) or correlation time (e.g., Ornstein-Uhlenbeck with $\tau \sim H_0^{-1}$) could smooth $w(z)$ further or enhance non-Gaussian tails. This predicts differences in cluster abundance at $z > 1$ of $\Delta N(> M)/N \sim 5\%$ for $M > 10^{14} M_\odot$ due to suppressed growth (from the model's 0.83% σ_8 reduction). LSST forecasts indicate sensitivity to cluster mass functions at $\sim$1–2% precision for high-mass bins, enabling constraints on σ variations at $\sim$3–5σ. eROSITA follow-ups or LSST catalogs could verify this through mass-richness scaling relations tested to $\sim 1\sigma$ level against fiducial relations (slope ~ 0.95–1.05).

These predictions are conservative, based on linear and semi-analytic approximations calibrated to the model's parameters ($\nu \approx 0.03$, $\sigma \approx 0.002$ in rescaled units). Full nonlinear simulations

incorporating stochastic terms would refine amplitudes and uncertainties. Confirmation would support a quantum-inspired origin for dark energy evolution, while null results could constrain collapse model parameters to $\sigma < 10^{-52}\,\mathrm{m}^{-2}$.

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[2]

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