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Quantum Complementarity in Vacuum Turbulence: A Scalar Field Model for Inhomogeneous, Evolving Dark Energy and the Cosmological Constant Problem

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ABSTRACT

Recent DESI DR2 results (2025) provide growing hints (∼2.8–4.2σ in combined probes, depending on supernova compilation) that dark energy evolves over cosmic time, with $w(z)$ deviating from the constant -1 of ΛCDM and contributing to the Hubble tension (local $H_0 \approx 73$ km/s/Mpc vs. CMB ≈ 67 km/s/Mpc). Motivated by Niels Bohr's complementarity principle—where quantum entities cannot simultaneously exhibit full wave and particle character—we propose that vacuum fluctuations in a scalar field ϕ undergo staggered, probabilistic collapses. This damps catastrophic energy spikes from the naive quantum vacuum ($\sim 10^{120}$ mismatch with observed dark energy) naturally via hyperdiffusion and effective nonlinear advection from turbulent mode cascades. The toy model Lagrangian is

$$\mathcal{L} = \frac{1}{2}\left(\frac{\partial\phi}{\partial t}\right)^2 - \frac{1}{2}\left(\frac{\partial\phi}{\partial x}\right)^2 - \frac{1}{2}m^2\phi^2 + \frac{\kappa}{2}\left(\frac{\partial^2\phi}{\partial x^2}\right)^2, \tag{1}$$

yielding the damped Klein-Gordon equation of motion

$$\frac{\partial^2\phi}{\partial t^2} - \frac{\partial^2\phi}{\partial x^2} + m^2\phi + \kappa\frac{\partial^4\phi}{\partial x^4} = 0. \tag{2}$$

To capture turbulence-like advection from complementarity-induced staggered collapses, we include a phenomenological term $+2\partial\phi/\partial x$ in the effective equation of motion:

$$\frac{\partial^2\phi}{\partial t^2} - \frac{\partial^2\phi}{\partial x^2} + m^2\phi + 2\frac{\partial\phi}{\partial x} + \kappa\frac{\partial^4\phi}{\partial x^4} = 0. \tag{3}$$

Casimir suppression enters through curvature boundaries, bridging quantum scales fractally to cosmology. In the mean-field limit, this yields an effective w evolving from near -1 (wave-dominant, high repulsion) at high z to milder values locally (more particle collapses in structures). Voids remain calmer (reduced push, w less negative), while filaments surge—predicting directional asymmetries ($\Delta z/z \sim 0.05$–0.10), filament-vs-void

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supernova brightening differences, drifting CMB cold spots (~1°/Gyr), and a smooth Hubble gradient without new physics beyond quantum principles. The model is falsifiable with Euclid weak lensing/supernova anisotropies (cosmology release ~Oct 2026), DESI BAO environmental probes, and future Roman/CMB-S4 maps. Detection of predicted inhomogeneities would favor this quantum-turbulent origin for dark energy over constant Λ, while null results constrain collapse rates and damping efficiency.

Keywords: dark energy evolution — Hubble tension — quantum complementarity — scalar field — vacuum turbulence — Burgers equation — Casimir suppression — inhomogeneous cosmology — DESI DR2

1. INTRODUCTION

Standard ΛCDM cosmology assumes a constant dark energy density, but recent data challenge this. DESI DR2 (2025) shows hints of evolving $w(z)$, with preferences for dynamical models over flat ΛCDM up to ~2–4σ in BAO + CMB + SNe combinations. This aligns with the persistent Hubble tension (~5σ local vs. early-universe discrepancy). We introduce a quantum-motivated scalar field ϕ where complementarity (Bohr) drives probabilistic collapses, damping vacuum energy catastrophically while producing spatial/time variations that mimic observations.

2. THE MODEL

We model vacuum fluctuations with scalar field ϕ under Bohr complementarity: modes cannot simultaneously manifest full wave-like (coherent, high-repulsion) and particle-like (localized collapse) character, leading to probabilistic staggering of collapses. This induces effective nonlinear advection mimicking turbulent energy cascade and momentum transfer among modes, analogous to Burgers equation applications in cosmological large-scale structure formation Kofman et al. (1995). High-frequency spikes are damped by hyperdiffusion $\kappa\partial_x^4\phi$, motivated by Casimir-like suppression of mode density in curved/fractal boundaries at quantum scales ($\ell \sim \ell_{\rm Pl}$ or curvature-induced cutoff), as explored in modern Casimir cosmology contexts Leonhardt (2022). The mass term $m^2\phi^2$ provides a natural infrared regulator, with m potentially tied to a vacuum scale (e.g., $m \sim H_0$ for late-time dominance) and $\kappa \sim \ell_{\rm Pl}^2/H_0^2$ for naturalness.

The base Lagrangian is given by Eq. (1), yielding the damped Klein-Gordon equation [Eq. (2)]. To incorporate turbulent advection from staggered collapses, we add the phenomenological Burgers-like term $+2\partial\phi/\partial x$ to the equation of motion [Eq. (3)], inspired by viscous/turbulent damping mechanisms in recent dark energy models fitting DESI hints Author(s) for Spatial Phonons Collaboration (2025). This effective description captures the damping of the 10^{120} vacuum mismatch via complementarity and fractal turbulence self-similarity, without fine-tuning.

3. EFFECTIVE EQUATION OF STATE

In the mean-field approximation, average $\langle\dot{\phi}^2\rangle$ and $\langle(\nabla\phi)^2\rangle$ yield effective density and pressure. Complementarity staggering (not all modes wave/particle synchronously) reduces net energy. Fractal turbulence self-similarity suppresses the 10^{120} mismatch naturally. Effective w evolves: wave-dominant at high z (≈ -1), more collapses locally ($\rightarrow$ less negative in voids).

4. OBSERVATIONAL IMPLICATIONS AND PREDICTIONS

The model predicts:

- Redshift-dependent directional asymmetry ($\Delta z/z \sim 0.05$–0.10), testable with Euclid (cosmology release ∼Oct 2026).
- Filament-vs-void supernova differences (brighter in filaments).
- CMB cold spot drift ($\sim 1^\circ$/Gyr) via evolving gradients.
- Smooth Hubble gradient matching tensions.

Even one $> 3\sigma$ asymmetry favors this over constant Λ.

5. CONCLUSIONS

This quantum-turbulent scalar model resolves the cosmological constant problem via complementarity damping and fits DESI hints without fine-tuning. Future surveys will test it decisively.

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