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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 ($\sim$2–4σ in combined probes) 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. distant ≈ 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 prevents uniform, catastrophic energy spikes from the naive quantum vacuum ($\sim 10^{120}$ mismatch with observed dark energy), naturally damping via nonlinear advection and hyperdiffusion.

The toy model Lagrangian is

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

yielding the equation of motion

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

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, $w \to$ less negative), while filaments surge—predicting directional asymmetries ($\Delta z/z \sim 0.05$–0.10), filament-vs-void supernova brightening differences, drifting CMB cold spots ($\sim 1^\circ$/Gyr), and a Hubble gradient without new physics beyond quantum principles.

The model is falsifiable with Euclid weak lensing/supernova anisotropies, DESI BAO environmental probes, and future Roman/CMB 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 $\sim$2–4σ in BAO + CMB + SNe combinations. This aligns with the persistent Hubble tension ($\sim 5\sigma$ 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 governed by the Lagrangian in Eq. (1). The nonlinear term $-\phi\partial_x\phi$ captures advection-like flow, while hyperdiffusion $\kappa\partial_x^4\phi$ damps spikes. Casimir suppression arises from curvature boundaries reducing mode density.

The derived equation of motion [Eq. (2)] is a damped, advective Klein-Gordon equation with higher-order diffusion.

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 $\sim$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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