

# 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 ( $\sim 2\text{--}4\sigma$  in combined probes) that dark energy evolves over cosmic time, with  $w(z)$  deviating from the constant  $-1$  of  $\Lambda$ CDM and contributing to the Hubble tension (local  $H_0 \approx 73$  km/s/Mpc vs. distant  $\approx 67$  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  $\phi$  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

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

yielding the equation of motion

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

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,  $w \rightarrow$  less negative), while filaments surge—predicting directional asymmetries ( $\Delta z/z \sim 0.05\text{--}0.10$ ), filament-vs-void supernova brightening differences, drifting CMB cold spots ( $\sim 1^\circ/\text{Gyr}$ ), 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  $\Lambda$ , 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  $\Lambda$ CDM 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  $\Lambda$ CDM up to  $\sim 2\text{--}4\sigma$  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  $\phi$  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  $\phi$  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 sup-

presses the  $10^{120}$  mismatch naturally. Effective  $w$  evolves: wave-dominant at high  $z$  ( $\approx -1$ ), more collapses locally ( $\rightarrow$  less negative in voids).

## 4. OBSERVATIONAL IMPLICATIONS AND PREDICTIONS

The model predicts:

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

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

## 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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