Fractal Physis: Structural Decoherence and the Cosmological Basis of Wavefunction Collapse

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Abstract

We propose a novel structural model of quantum decoherence based on the fractal coherence properties of the Cosmic Microwave Background (CMB). Using wavelet energy scaling on Planck SMICA data, we extract a scale-dependent coherence function $f(\ell)$ and map it to physical space $f(z)$ via a logarithmic transformation. This empirical function is integrated into a modified Schrödinger equation, introducing decoherence as a function of cosmological structure. Simulations of double-slit propagation under this framework reveal coherent-to-incoherent transitions that align with real CMB-derived decoherence boundaries near $\ell \sim 4000$. Our results suggest a cosmologically-grounded, scale-structured foundation for quantum-classical transition, offering a testable alternative to environment-based interpretations of wavefunction collapse.

1 Introduction

Decoherence theory has advanced as the leading explanation for the emergence of classical behavior in quantum systems [1]. Traditionally, this phenomenon is modeled through interactions with environmental degrees of freedom, often treated probabilistically or stochastically. However, these interpretations struggle to define the boundary between quantum and classical behavior objectively and fail to account for cosmological constraints.

Recent observations of the CMB reveal a surprising degree of large-scale coherence, including fractal features and a breakdown of structural alignment beyond multipole moment $\ell \sim 4000$ [2, 3]. This suggests that spacetime itself may carry an inherent coherence structure—one that can influence quantum behavior.

We propose a theory of *Fractal Physis*, in which spacetime coherence is both scale-dependent and structurally encoded in the universe. From this theory, we derive an empirical decoherence function $f(\ell)$ from CMB data, map it to spatial coordinates $f(z)$, and show how it modulates wavefunction evolution in real quantum systems.

This paper outlines the axioms of Fractal Physis, the empirical extraction of $f(\ell)$, and its integration into a structurally-modified Schrödinger equation. We present simulations demonstrating scale-driven wavefunction collapse in a double-slit experiment, guided entirely by cosmological data.

2 Methods

2.1 Data Acquisition

We utilized the Planck 2018 SMICA Cosmic Microwave Background (CMB) temperature and polarization maps available from the Planck Legacy Archive, with a resolution corresponding to a

HEALPix NSIDE of 2048. Polarization E-mode maps were derived from the SMICA Q and U polarization maps using Healpy's spin transformations.

2.2 Synthetic Baseline Generation

For statistical comparison, we generated 500 synthetic Gaussian random CMB simulations using Healpy's `synfast` function with the best-fit ΛCDM power spectra (TT for temperature and EE for polarization).

2.3 Wavelet Energy Decomposition and Fractal Dimension Estimation

We extracted a large set of random patches from the CMB maps (1,000 patches for temperature, 100 patches for polarization), each with a defined angular radius of 10°. Discrete wavelet transforms using Daubechies-4 (db4) wavelets were applied across 10 decomposition levels to each patch. Total wavelet energy at each level was computed, and fractal slopes were estimated via log-log regression of wavelet energy distributions, quantifying the decay of energy across scales. Fractal dimension estimates were derived directly from these slopes.

2.4 Angular Power Spectrum Analysis

Angular power spectra for real and synthetic CMB maps were computed using Healpy routines. The real map spectra were statistically compared against the 95% confidence intervals obtained from the synthetic simulations. Deviations beyond $\ell \approx 4000$ indicated significant non-random structural behavior.

2.5 Residual Analysis and Recursive Band Fitting

We conducted residual analyses by subtracting synthetic baseline spectra from the real spectra to isolate structural deviations. Recursive fitting was applied to these residual bands, characterizing the multipole ranges with significant recursive coherence.

2.6 Low-ℓ Map Reconstruction and Multipole Alignment

Maps were reconstructed for low-ℓ modes to explicitly evaluate large-scale coherence and multipole alignment, focusing on multipoles indicative of recursive structural signatures identified in previous steps.

2.7 Statistical Evaluation

Statistical significance was assessed by calculating p-values representing the fraction of synthetic fractal slopes exceeding the observed slopes from real data. Observed slopes yielding extremely low p-values ($\sim 10^{-5}$ or lower) were considered indicative of statistically significant fractal structures not explained by standard Gaussian random-field models.

2.8 Computational Tools

All analyses, synthetic simulations, wavelet decompositions, power spectrum computations, and statistical evaluations were conducted using Python, with primary packages including Healpy, PyWavelets, NumPy, SciPy, and Matplotlib.

3 Fractal Physis: Structural Axioms

1. **Recursive Coherence:** Spacetime exhibits coherence that repeats across scales in a fractal manner.

2. **Horizon of Decoherence:** A coherence boundary exists near $\ell \sim 4000$, beyond which structure rapidly collapses.

3. **Emergent Classicality:** Classical behavior arises when wavefunction coherence aligns with cosmological coherence zones.

4. **Structure-Driven Decoherence:** Decoherence is not stochastic but driven by scale-local structure encoded in the universe.

4 CMB-Derived Decoherence Function

We extracted the decoherence function $f(\ell)$ by performing wavelet decomposition on Planck SMICA data. Wavelet energy scaling at various multipole bands reveals a distinct coherence pattern. The fractal slope $\alpha(\ell)$, computed via a log-log linear fit of wavelet energies, directly yields $f(\ell)$:

$$\alpha(\ell) = \frac{\log E(\ell)}{\log \ell}, \quad f(\ell) = \frac{\alpha(\ell) - \alpha_{\min}}{\alpha_{\max} - \alpha_{\min}} \tag{1}$$

The resulting $f(\ell)$ clearly indicates a coherence horizon near $\ell \sim 4000$, where the coherence rapidly diminishes.

5 Modified Schrödinger Equation

We incorporate the empirical decoherence function into the Schrödinger equation as a structural damping term:

$$i\hbar \frac{\partial \psi(x,t)}{\partial t} = \left[-\frac{\hbar^2}{2m} \nabla^2 + V(x) \right] \psi(x,t) - i\hbar\gamma \left[1 - f(z) \right] \psi(x,t) \tag{2}$$

Here, γ governs the strength of decoherence, and $f(z)$ spatially modulates decoherence based on cosmological structure.

6 Simulation Results

Simulations of double-slit quantum propagation were conducted using the modified Schrödinger equation with the empirical decoherence function $f(z)$. The simulations clearly demonstrate the transition from coherent interference patterns at lower z, corresponding to large scales (low ℓ), to decoherent (classical) intensity distributions at higher z, corresponding to small scales (high ℓ).

Intensity profiles at selected propagation distances reveal a gradual yet structured transition, aligning precisely with the cosmologically derived coherence function.

7 Discussion and Interpretation

Our results provide compelling evidence that quantum decoherence can be fundamentally structural rather than probabilistic or observer-induced. The alignment between cosmological coherence structures and quantum behavior suggests a deep interconnection between cosmological spacetime structure and quantum mechanics.

This structural decoherence model addresses key conceptual gaps within quantum foundations, particularly regarding the arbitrary nature of quantum-to-classical transitions. It offers a cosmological framework for defining classicality objectively, tied directly to measurable cosmological data.

Future work should focus on experimental validations in quantum optics setups and deeper cosmological investigations to refine the coherence model.

8 Conclusion

We have introduced Fractal Physis as a structural model that integrates cosmological fractal coherence into quantum mechanics, providing a data-driven and objective explanation for wavefunction collapse. Our simulations confirm the viability of this approach, opening new pathways for understanding quantum-classical boundaries and the fundamental structure of spacetime itself.

References

[1] W. H. Zurek, Decoherence, einselection, and the quantum origins of the classical, Rev. Mod. Phys. 75, 715 (2003).

[2] Planck Collaboration, Planck 2018 results. I. Overview and the cosmological legacy of Planck, A&A 641, A1 (2020).

[3] K. Land and J. Magueijo, The axis of evil, Phys. Rev. Lett. 95, 071301 (2005).