Quantum Fluctuations and Wavefunction Structure in Black Holes

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Abstract

We propose a novel perspective on the internal structure of black holes by introducing a quantum wavelength relation: $\lambda = 2\ell_p^2/R$, where ℓ_p is the Planck length and R is the characteristic radius of a gravitational region. This inverse relationship suggests that as a black hole shrinks toward Planck-scale dimensions, the corresponding quantum wavelength diverges, implying a breakdown of classical geometric descriptions.

Building on this, we model the black hole not as a singular point, but as a quantum-fluctuating hollow shell, stabilized by intense vacuum fluctuations at its apparent horizon. This perspective offers a potential resolution to the classical singularity and proposes the existence of stable Planck-scale remnants.

Our model aligns conceptually with efforts to reconcile general relativity and quantum mechanics, such as the gravastar and Planck star frameworks, while presenting an original, mathematically concise formulation.

Introduction

General relativity predicts that gravitational collapse leads to a singularity—an infinitely dense point—at the center of a black hole. However, this prediction contradicts the principles of quantum mechanics, which prohibit the existence of physical infinities and demand that spacetime itself must undergo quantum fluctuations at sufficiently small scales.

Recent developments in quantum gravity suggest that black holes may not be true singularities. Instead, models such as the gravastar [1], Planck stars [2], and firewall hypotheses [3] propose that strong quantum effects prevent a central singularity.

Motivated by these ideas, we propose a simplified quantum wavefunction model of the black hole interior. We define a fundamental relationship between the black hole radius R and the quantum fluctuation wavelength λ:

$$\lambda = \frac{2\ell_p^2}{R}$$

This formula connects the Schwarzschild radius $R = 2GM/c^2$ and the Compton wavelength $\lambda_C = \hbar/(Mc)$, yielding an inverse scaling in Planck units.

Theoretical Model

As $R \to \ell_p$, the associated λ increases rapidly, indicating a quantum barrier to further collapse. This introduces a form of quantum pressure that could prevent singularity formation. The model envisions black holes as compact regions surrounded by long-wavelength fluctuations.

Interpretation

Rather than collapsing to a point, the black hole may stabilize into a quantum-fluctuating shell. The increasing wavelength λ at small R suggests localization becomes impossible, acting as a natural regulator of gravitational collapse.

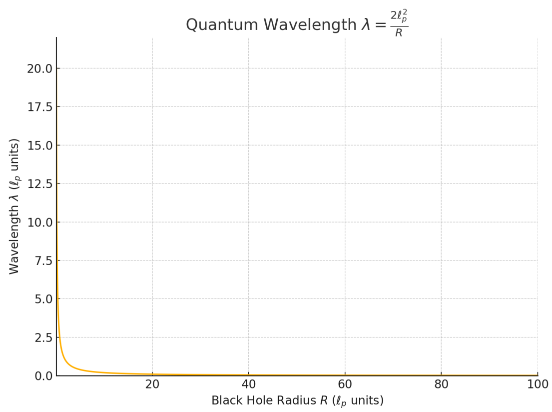

Figure 1: As R decreases, λ increases sharply following $\lambda = 2\ell_p^2/R$.

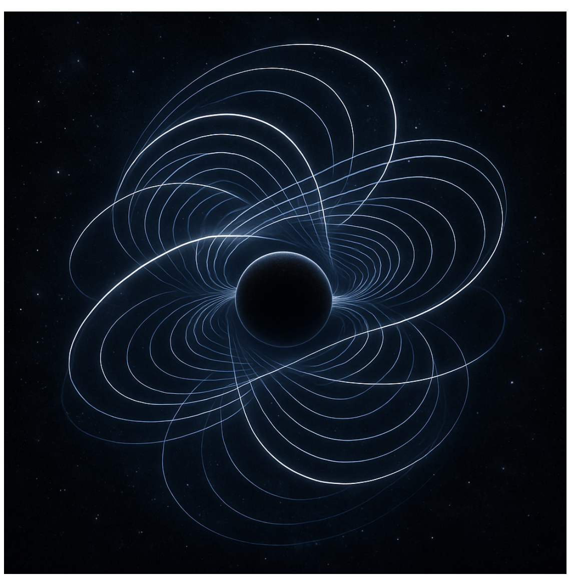

Figure 2: Illustration of a black hole surrounded by expanding quantum wavefunctions.

Comparison with Other Models

While Hawking radiation predicts evaporation, our model implies that as R approaches ℓ_p, increasing quantum fluctuations inhibit further collapse. This aligns qualitatively with ideas involving black hole remnants [4], gravastars, and fuzzballs.

Conclusion

We presented a simplified model where quantum fluctuations characterized by $\lambda = 2\ell_p^2/R$ play a crucial role in halting black hole collapse. This perspective supports the idea of Planck-scale black hole remnants and invites further exploration in quantum gravity frameworks.

References

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