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Article

Observer-Dependent Entropy Retrieval and Time-Adaptive Information Recovery in Black Hole Evolution

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Abstract: Background: The black hole information paradox arises from tension between unitary evolution in quantum mechanics and apparent information loss in semiclassical gravity. **Methods:** We develop a relativistic framework in which entropy retrieval is an explicit function of an observer's proper time and trajectory. By defining observer-dependent density matrices and a continuous retrieval law, we derive testable expressions for Rényi entropy and second-order correlation functions. **Results:** Our model predicts measurable deviations in the entanglement structure of Hawking radiation across observer classes and modifies the Ryu–Takayanagi prescription to include frame-dependent surface contributions. **Conclusions:** The information paradox resolves as an observer-dependent phenomenon without requiring nonunitary dynamics or exotic physics. These falsifiable signatures can be probed in black hole analog experiments, offering a new pathway toward empirical tests of quantum gravity.

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1. Introduction

The black hole information paradox remains a central challenge in theoretical physics: unitarity implies information preservation while semiclassical gravity suggests its destruction. Recent work has highlighted observer-dependence in entropic measures [1], yet a concrete retrieval mechanism remains elusive. Existing proposals—including Black Hole Complementarity [2], ER=EPR [5], and the Page curve [3,4]—do not quantify how information becomes accessible to different observers over time. Here, we introduce a relativistic, proper-time-dependent retrieval framework that resolves the paradox as an emergent, observer-dependent phenomenon, and we derive explicit, falsifiable predictions for entanglement signatures in Hawking radiation.

2. Observer-Dependent Entropy in Curved Space-Time

2.1. Classification of Observers

Entropy retrieval depends on the observer's trajectory through spacetime. We consider three key observer classes with distinct information-retrieval dynamics:

Stationary Observer: Positioned at fixed spatial coordinates outside the event horizon ($r > 2M$), this observer detects Hawking radiation as thermal emission with gradually decreasing temperature. The information retrieval rate follows $\gamma(\tau) \propto 1/r$ due to gravitational redshift effects, resulting in slower information acquisition at greater distances from the black hole.

Freely Falling Observer: Crossing the event horizon along geodesic trajectories, this observer experiences no local discontinuity at the horizon but encounters dramatically different information accessibility. Inside the horizon, the observer detects non-thermal corrections to the radiation spectrum that encode correlations with earlier emissions, providing access to information inaccessible to distant observers until much later in the black hole's evolution.

Accelerating Observer: Moving through curved spacetime with proper acceleration a , this observer

experiences Unruh radiation that modifies the perceived entropy. The effective retrieval rate includes contributions from both Hawking and Unruh effects: $\gamma_{\text{eff}}(\tau) = \gamma_{\text{Hawking}}(\tau) + \gamma_{\text{Unruh}}(\tau, a)$. This superposition creates distinctive interference patterns in the correlation functions that serve as experimental signatures of our framework.

2.2. Definition of Observer-Dependent Entropy

We define the observer-dependent entropy as:

$$S_{\text{obs}}(\tau) = -\text{Tr}(\rho_{\text{obs}}(\tau) \log \rho_{\text{obs}}(\tau)). \quad (1)$$

Here, the observer's density matrix transforms under a Lorentz boost:

$$\rho_{\text{obs}} = U(\Lambda) \rho U^\dagger(\Lambda). \quad (2)$$

This formulation implies that different observers reconstruct information at different rates, dependent on their proper time τ and specific trajectory through curved spacetime. The operator $U(\Lambda)$ encodes relativistic effects on quantum information transfer, including time dilation and gravitational redshift near the horizon.

2.3. Proper-Time Evolution of Information Retrieval

Unlike previous models that treat information retrieval as instantaneous, we propose that entropy retrieval follows a dynamical law:

$$\frac{dS_{\text{retrieved}}}{d\tau} = \gamma(\tau) (S_{\text{max}} - S_{\text{retrieved}}) \frac{1 + \tanh(\tau/\tau_{\text{Page}})}{2}. \quad (3)$$

This Equation (3) captures the gradual nature of information recovery, with the hyperbolic tangent providing a smooth transition across the Page time τ_{Page} . The retrieval rate $\gamma(\tau)$ varies between observer classes, reflecting differential access to encoded information.

3. Quantum Information Correlations and Testable Predictions

To validate our model experimentally, we derive expressions for observable correlation functions in Hawking radiation. The Rényi entropy, a generalization of the von Neumann entropy, is particularly useful:

$$I(t) = \frac{1}{n-1} \log \text{Tr}(\rho_A^n). \quad (4)$$

Here, ρ_A is the reduced density matrix of a subsystem and n is the Rényi index.

Second-order correlation functions provide another experimental signature:

$$g^{(2)}(t_1, t_2) = \exp\left[-\frac{|t_2 - t_1|}{\tau_{\text{retrieval}}}\right] \left(1 + \frac{1 + \tanh(t_1/\tau_{\text{Page}})}{2}\right). \quad (5)$$

These correlations exhibit distinctive patterns depending on the observer's trajectory, offering a direct method to test the observer-dependence of entropy retrieval in analog black hole systems [10] such as Bose–Einstein condensates or optical vortices.

Our analysis reveals distinct entropy retrieval patterns between observer classes. For stationary observers, retrieval follows $\gamma(\tau) \propto 1/r$, giving a gradual approach to S_{max} . In contrast, freely-falling observers experience an accelerated retrieval rate after horizon crossing at $\tau = \tau_H$. These differences in information accessibility provide clear experimental signatures for testing our framework.

4. Holographic Connection and Quantum Circuit Simulations

Our observer-dependent retrieval modifies the standard Ryu–Takayanagi prescription. The holographic entanglement entropy becomes:

$$S_{\text{obs}}^{\text{holo}} = \frac{\text{Area}(\gamma_A(\Lambda))}{4 G_N} \sqrt{|g_{00}|}. \quad (6)$$

Here, $\gamma_A(\Lambda)$ is the observer-dependent minimal surface, and $\sqrt{|g_{00}|}$ accounts for observer-based time dilation. This prescription links our framework to AdS/CFT: information retrieval in the bulk corresponds to gradual decoding of quantum data in the boundary. Preliminary tensor-network simulations confirm the emergence of a Page-like curve from observer-dependent vantage points [11].

5. Implications

Our framework has several important implications:

1. It resolves the black hole information paradox by recasting it as an observer-dependent phenomenon rather than a fundamental contradiction.
2. It predicts measurable deviations in Hawking-radiation entanglement structure for different detector motions, enabling experiments in analog systems.
3. It provides a unified framework connecting quantum information theory, semiclassical gravity, and holography without invoking exotic physics.

6. Conclusions and Next Steps

We have presented a relativistic, observer-dependent framework for black hole entropy retrieval that obviates the need for nonunitary dynamics or exotic physics. By tying entropy retrieval explicitly to an observer's proper time and motion, our model reconciles quantum mechanics and general relativity regarding information preservation.

Experimental verification appears feasible with current analog black hole systems. For instance, the Waterloo group's Bose–Einstein condensate horizon emits Hawking-like radiation with detectable quantum correlations [10]. With typical BEC parameters, we estimate $\tau_{\text{retrieval}}$ on the order of 10–100 ms, well within existing coherence times.

Future directions:

- Derive $f(\tau/\tau_{\text{Page}})$ from gravitational path integrals.
- Strengthen the connection to entanglement wedge reconstruction in AdS/CFT.
- Develop more detailed circuit simulations of the retrieval process.
- Design protocols to measure predicted correlation signatures in analog black hole experiments.

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