Research Plan: Deriving Emergent General Relativity from Quantum Entanglement

The HoloCosmo Project

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Abstract

This research plan outlines an ambitious, multifaceted program to derive an effective gravitational theory, analogous to General Relativity (GR), from the entanglement structure of quantum many-body systems. Building on previous work in emergent gravity via entanglement entropy and its Laplacian—combined with PEPS-based lattice simulations—we propose a six-stage roadmap. Our approach emphasizes speculative exploration, rigorous formulation, detailed calculation, and observational validation. The ultimate goal is to extract an entropic field theory that reproduces key features of GR, providing a viable alternative perspective on gravitational phenomena and potentially dark matter.

1 Introduction

Recent theoretical advances suggest that spacetime and gravity may emerge from quantum entanglement. The HoloCosmo Project has demonstrated that gravitational-like behavior—such as inverse-square law potentials and curvature effects—can arise from the Laplacian of local entanglement entropy fields computed in quantum many-body systems. However, the ultimate derivation of General Relativity (GR) from these entanglement structures remains a formidable challenge. This research plan presents an updated framework, organized into six sequential stages, to bridge this gap.

2 Research Objectives

Our overarching objectives are:

(a) To perform high-resolution, high-τ impurity simulations in large-scale lattices via PEPS.

(b) To extract effective potentials from entanglement curvature data.

(c) To define entropic geodesics and derive an effective distance measure.

(d) To construct an entropic field theory using variational principles.

(e) To apply coarse-graining techniques to bridge microscopic quantum structures to macroscopic geometry.

(f) To map the emergent entropic curvature framework onto GR-like tensor equations.

3 Methodology: A Six-Stage Roadmap

Stage 1: High-τ Impurity Simulations

Objective: Enhance our PEPS-based simulations by increasing the imaginary time parameter (τ) to deepen state cooling and magnify long-range entanglement effects, especially in the vicinity of a locally injected impurity region (e.g., a 3×3×3 cube).

Method:

- Run simulations on a $32 \times 32 \times 32$ lattice.
- Introduce a controlled impurity by setting the transverse field h_{impurity} at impurity sites to a higher value.
- Analyze the resulting entanglement entropy and its Laplacian to quantify curvature.

Stage 2: Fitting Effective Potentials from Curvature

Objective: Translate the discrete entanglement curvature (the Laplacian of the von Neumann entropy) into an effective gravitational potential.

Method:

- Empirically relate the Laplacian field $\nabla^2 S(\mathbf{r})$ to an effective potential, e.g., via

  $$\Phi(\mathbf{r}) = \kappa_E \, S(\mathbf{r}),$$

  where κ_E is determined from simulation data.
- Derive velocity profiles from $\Phi(\mathbf{r})$ using

  $$v(r) = \sqrt{r \frac{d\Phi}{dr}},$$

  and compare with astrophysical rotation curves.

Stage 3: Defining Entropic Geodesics

Objective: Identify paths through the entanglement curvature field along which the effective action is minimized, analogous to geodesics in curved spacetime.

Method:

- Compute the gradient vector field of the Laplacian (or effective potential) $\nabla(\nabla^2 S)$.
- Use gradient descent or Dijkstra-based algorithms to trace trajectories that minimize entropic cost.
- Visualize these entropic geodesics overlaid on curvature gradient maps.

Stage 4: Constructing Entropic Field Equations

Objective: Develop a rigorous field theory for the entanglement structure, possibly deriving an analogue of Einstein's equations.

Method:

- Employ variational principles to derive field equations from an action constructed out of the entanglement entropy S and its derivatives.
- Investigate equations of the form

$$R_{\mu\nu} \sim \partial_\mu \partial_\nu S,$$

  and attempt to match or approximate them to the Einstein tensor $G_{\mu\nu}$.
- Use symbolic computation and numerical fitting to verify these analogies.

Stage 5: Coarse-Graining and Emergent Geometry

Objective: Understand how classical geometry emerges from the quantum entanglement microstructure via coarse-graining.

Method:

- Apply multiscale and renormalization group techniques to the simulated Laplacian field.
- Compare coarse-grained curvature fields at different resolutions to identify scaling laws.
- Analyze whether the coarse-grained fields satisfy classical geometric relations.

Stage 6: Matching to GR Structure

Objective: Establish a correspondence between the emergent entropic curvature and the tensorial structure of GR.

Method:

- Develop mappings between the computed entanglement curvature, effective potential, and classical quantities (e.g., the Ricci curvature, Einstein tensor).
- Examine whether local variations in the impurity distribution (acting as sources) lead to curvature patterns consistent with

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}^{\text{eff}}.$$

- Validate the mapping through simulations that vary impurity strength, distribution, and size.

4 Epistemic and Methodological Considerations

At every stage, our approach is:

1. **Speculative:** We are open to new principles emerging from quantum informational structures.

2. **Formulative:** We rigorously develop theoretical models and mapping strategies.

3. **Calculative:** We conduct extensive numerical simulations using PEPS and analyze the resulting curvature fields.

4. **Observational:** We compare the predictions of our effective theory with astrophysical observations, such as galaxy rotation curves and gravitational lensing maps.

All predictions are designed to be falsifiable, ensuring that our framework remains scientifically robust.

5 Timeline

1. **Months 1–3:** Execute high-τ impurity simulations (Stage 1). Collect extensive PEPS data and perform preliminary analysis of Laplacian fields and gradient visualization.

2. **Months 4–6:** Fit effective potentials from simulation data (Stage 2) and define entropic geodesics (Stage 3). Begin comparing to observational data.

3. **Months 7–9:** Develop the variational formulation for entropic field equations (Stage 4) and perform coarse-graining studies (Stage 5).

4. **Months 10–12:** Integrate all findings and construct the mapping to GR structures (Stage 6). Finalize manuscripts and release open-source simulation software.

6 Expected Outcomes and Impact

This research plan aims to:

- Establish a clear, testable link between quantum entanglement and emergent gravitational phenomena.

- Produce numerical simulations that reproduce effective gravitational behavior on galactic and cluster scales.

- Provide a robust framework for deriving effective gravitational equations reminiscent of GR.

- Offer new insights into dark matter phenomena by reinterpreting them as emergent consequences of the entanglement structure.

Success in this program would represent a significant conceptual breakthrough and a fertile ground for new predictions in both theoretical physics and astrophysical observation.

7 Conclusion

Our six-stage roadmap presents a comprehensive strategy to extract an emergent theory of gravity from the quantum information encoded in many-body systems. By iterating between simulation, formal derivation, and observational validation, we will both test and extend our framework. Whether our work will ultimately replace or complement classical gravitational theory, it promises to deliver transformative insights into the nature of spacetime, matter, and the underlying informational fabric of the universe.