Inverse problem in physics & AI

Geometry reconstruction from entanglement entropy using Transformer Models

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AI and Natural Sciences at KIAS

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Presentation agenda

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The inverse problem

Understanding the challenge in physics.

Duality

Strongly correlated systems and Holography.

AI approaches

Applying AI models to physics.

Results

Data generation and reconstruction performance.

The inverse problem in physics

Uncovering the mathematical theory structure from the phenomena.

What is an inverse problem?

Forward Problem

Given a physical model and parameters, we calculate the observed data. This is typically well-defined and solvable via simulation or equations.

Lagrangian Model → Experimental Data

Inverse Problem

Given the observed data, we attempt to infer the underlying model parameters. This is often "ill-posed," meaning multiple models could explain the same data.

Lagrangian Model ← Experimental Data

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Newton's inverse problem

Observation

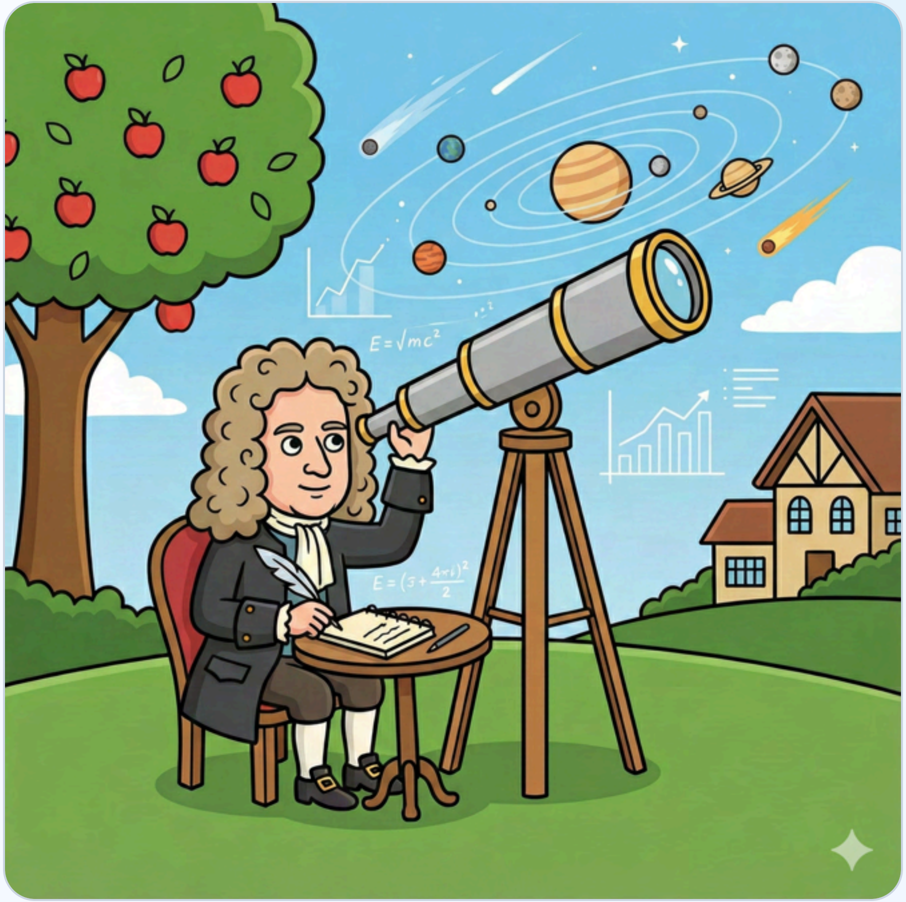
Observation data of planet motion.

Inverse Task

Deducing the invisible Gravitational Potential $\Phi(r)$ that perfectly explains these trajectories.

Prediction

Predicts future planetary motion and reveals fundamental physical laws.



Examples of strongly correlated systems

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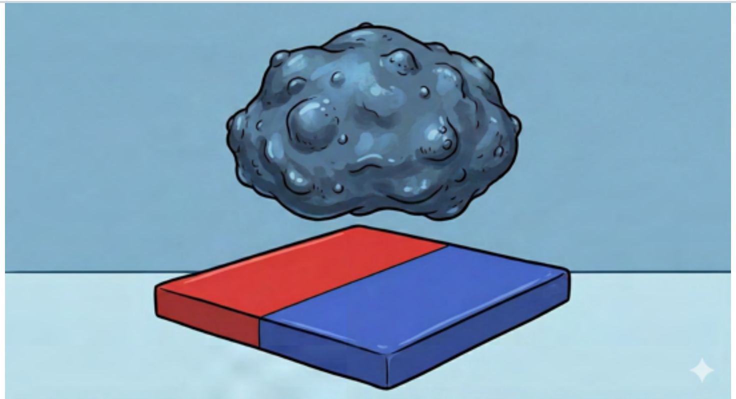
High-Tc Superconductors



Unexplained Phenomena: Conducts electricity with zero resistance at high temperatures. Strong electron correlations defy standard BCS theory explanation.

Quark-Gluon Plasma

The Perfect Fluid: A state of matter with extremely low viscosity created in heavy ion collisions. Dominated by strong nuclear force interactions.

Gauge/Gravity duality

The Holographic Principle

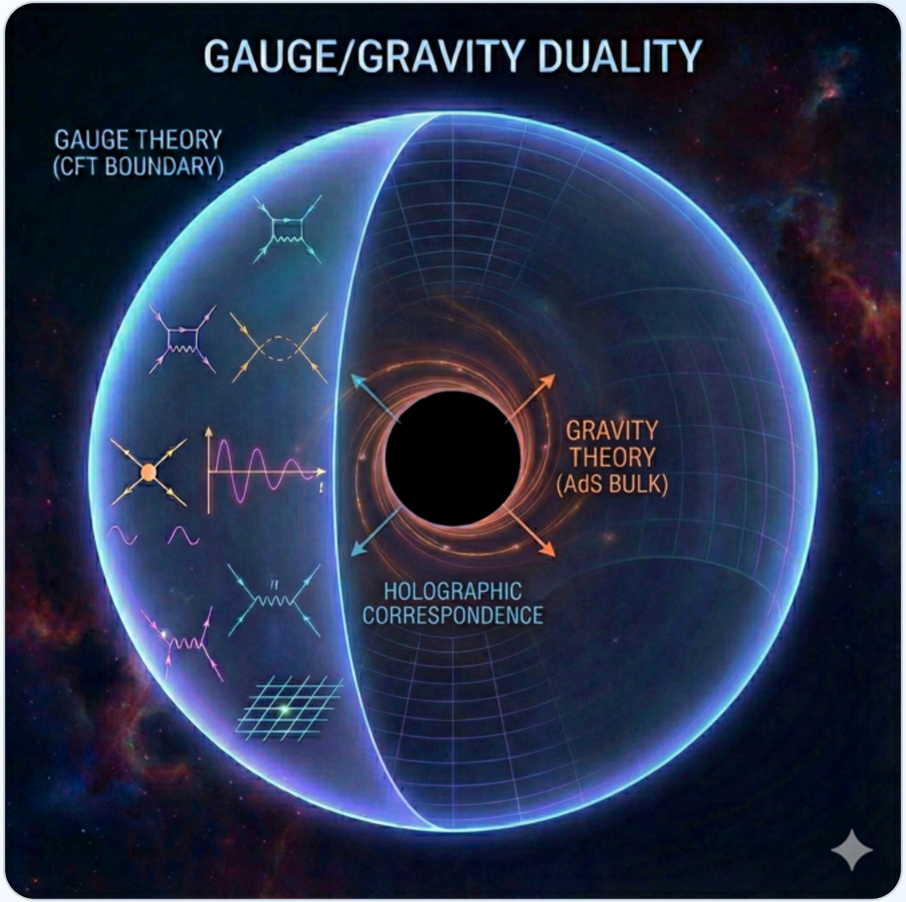
Gauge/Gravity duality

Also known as the **AdS/CFT correspondence**. It proposes a profound mathematical connection between two different worlds:

- **The Boundary (d dims):** A Quantum Field Theory (QFT) where particles interact strongly. Calculations here are difficult.
- **The Bulk ($d+1$ dims):** A Theory of Gravity (Curved Spacetime) in higher dimensions. Physics here is classical and easier to solve.

The Holographic Dictionary

It acts as a translator: transforming impossible "Quantum" problems into solvable "Geometric" problems.



Entanglement entropy

Quantum Connection

A measure of how strongly correlated two parts of a quantum system are. When we divide a system into Region A and Region B, it measures the uncertainty of A when B is hidden.

A Geometric Link

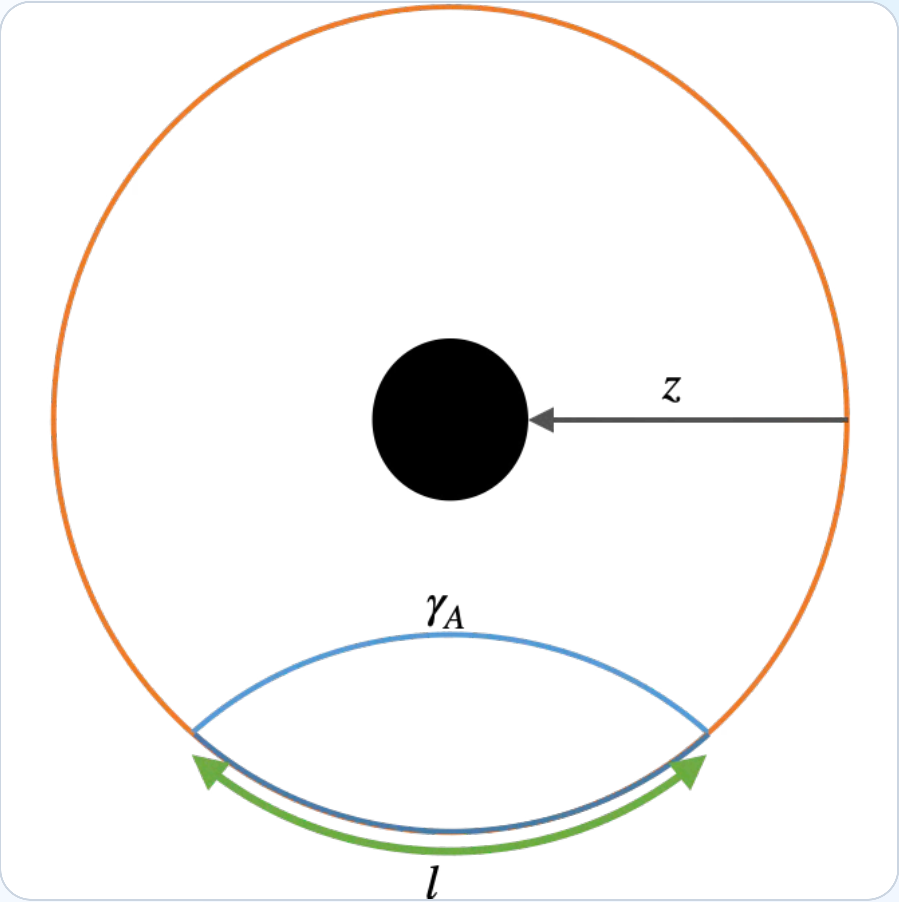
Surprisingly, this abstract quantum quantity has a direct geometric interpretation in the dual gravity theory.

Ryu-Takayanagi formula

The bridge between Quantum Information and Geometry.

$$S_E = \frac{\text{Area}(\gamma_A)}{4G}$$

The entanglement entropy S_E of a region A on the boundary is proportional to the area of the minimal surface γ_A in the bulk gravity theory.



3D AdS black hole

Metric:

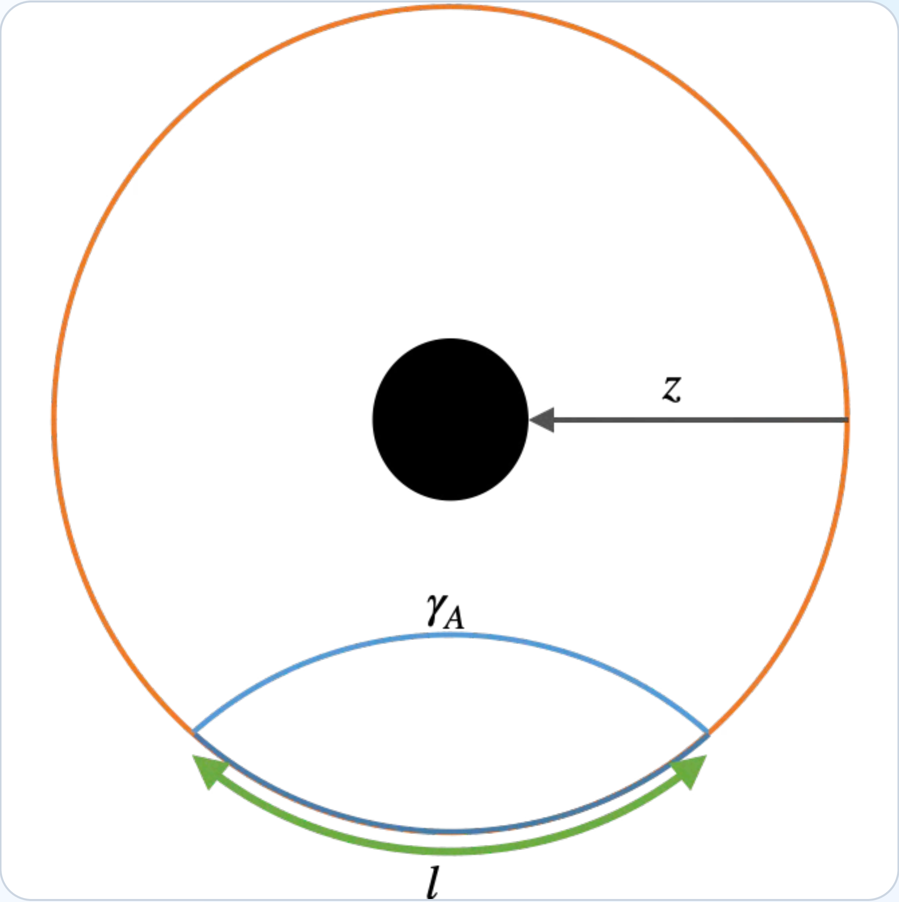
$$ds^2 = \frac{L^2}{z^2}\left(-f(z)dt^2 + \frac{dz^2}{f(z)} + dx^2\right)$$

($z = 0$: boundary, L: AdS radius)

Area Functional:

$$S_E(l) = \frac{L}{4G_N}\int_{-\frac{l}{2}}^{\frac{l}{2}} dx \frac{1}{z}\sqrt{1 + \frac{1}{f(z)}\left(\frac{dz}{dx}\right)^2}$$

(l: boundary size for region A)



Two approaches to inverse problems

1. Deep Learning (PINN)

Physics-Informed Neural Networks

- Directly approximates the solution function.
- Incorporates physical equations (PDEs) into the loss function.
- Optimized for specific boundary conditions.

2. Generative AI

Transformer Models (This Work)

- Learns the probability distribution of solutions.
- Treats physics as a **"Translation"** task (Data ↔ Theory).
- Can generalize to unseen geometries.

Translation vs. duality

NLP Translation

English Sentence → [Transformer] → French Sentence

Maps underlying meaning between two linguistic structures.

Gauge/Gravity Duality

Quantum Field Info → [Transformer] → Geometric Metric

Maps underlying physical reality between two mathematical descriptions.

Generating the dataset

Solving the Data Scarcity Problem.

The data problem

Scarcity of Analytical Models

There are few known gravity theories that accurately describe the experimental results of entanglement entropy.

Solution: Synthetic Data

We generate our own large-scale training datasets using **Gauge/Gravity Duality** to bridge this gap.

Generating data via duality

Step 1: Random Geometries

We generate thousands of random "blackening functions" $f(z)$. These define valid black hole spacetimes.

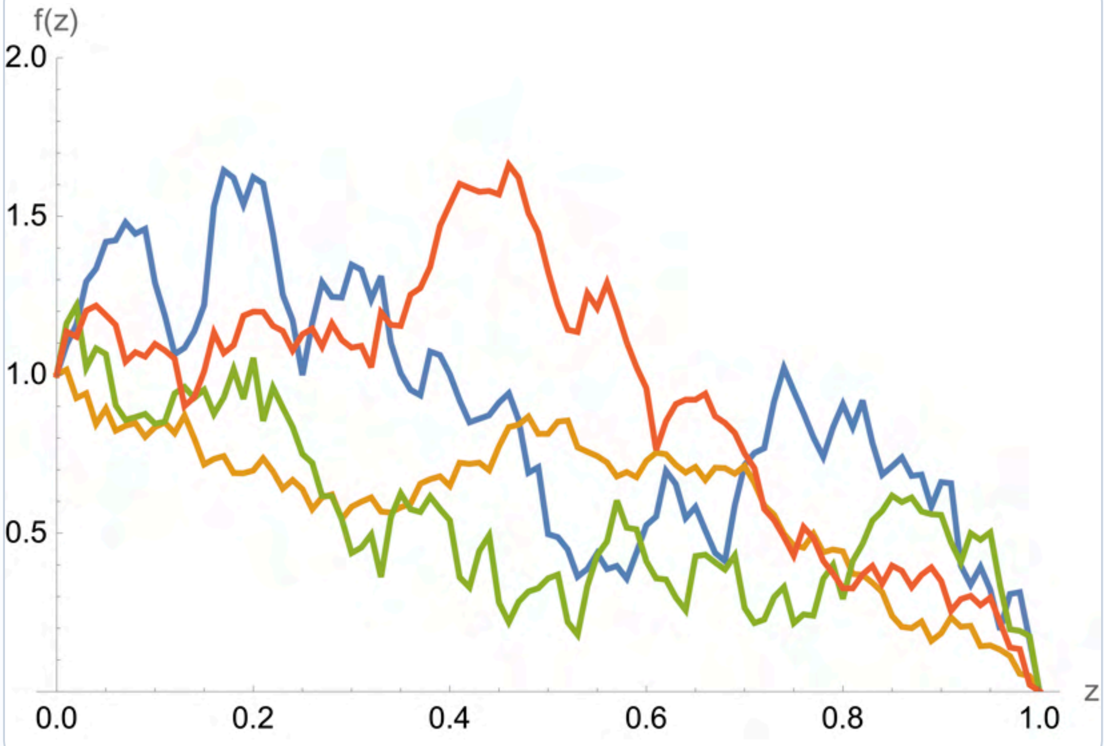
Output : $f(z)$

Step 2: Solve Forward Problem

For each geometry, we use the Ryu-Takayanagi formula to calculate the corresponding Entanglement Entropy $S(\ell)$.

Input : $S(\ell)$

The crucial ingredient: noise



Stochastic White Noise

The paper introduces stochastic noise into the generated blackening functions.

Why? This sharpens the local sensitivity. It forces the Transformer to learn how small changes in entropy relate to specific local changes in geometry, preventing it from just learning a rough average.

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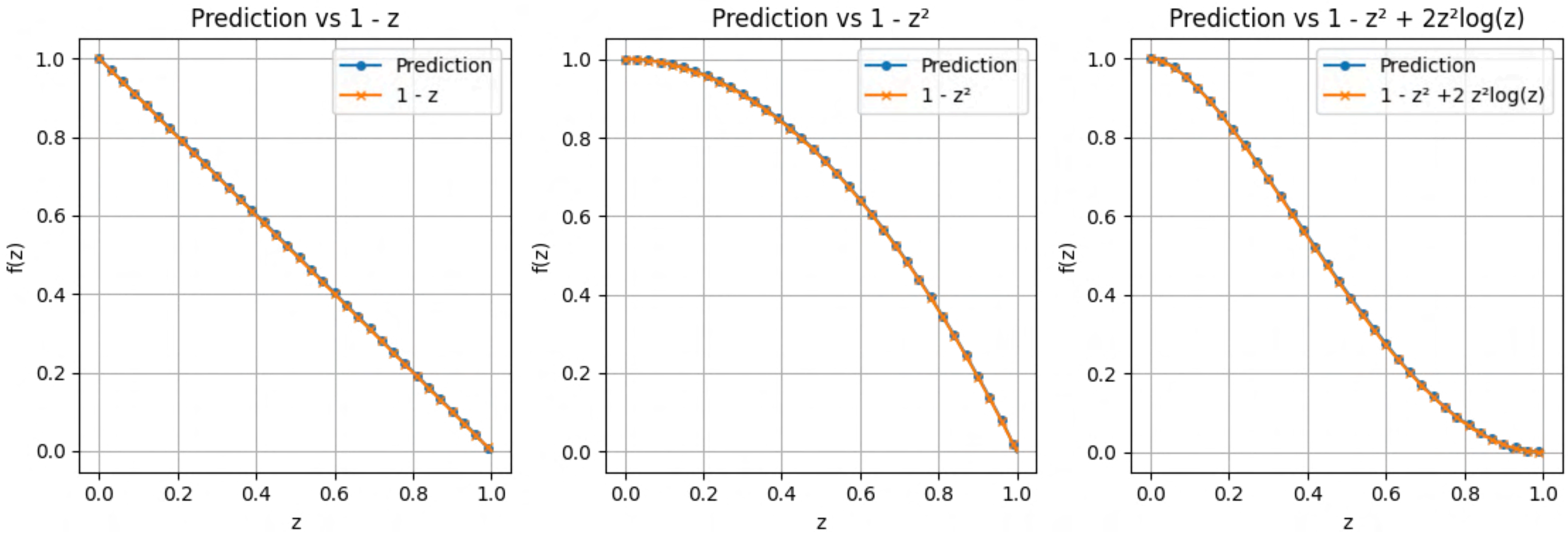
Performance & Results

Can AI reconstruct spacetime?

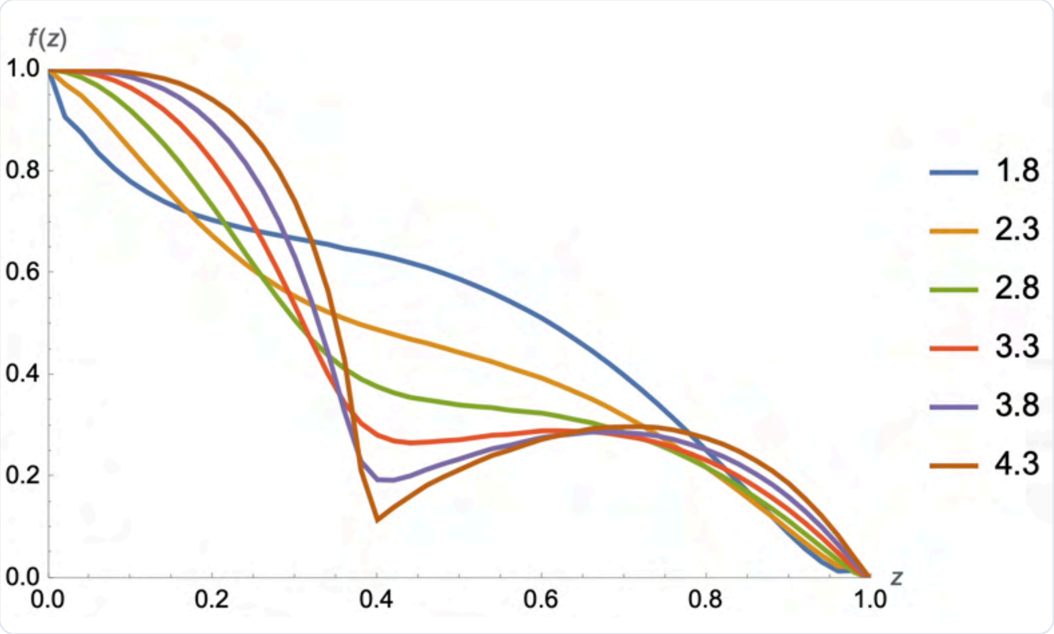
Known dual geometry



Unknown dual geometry results

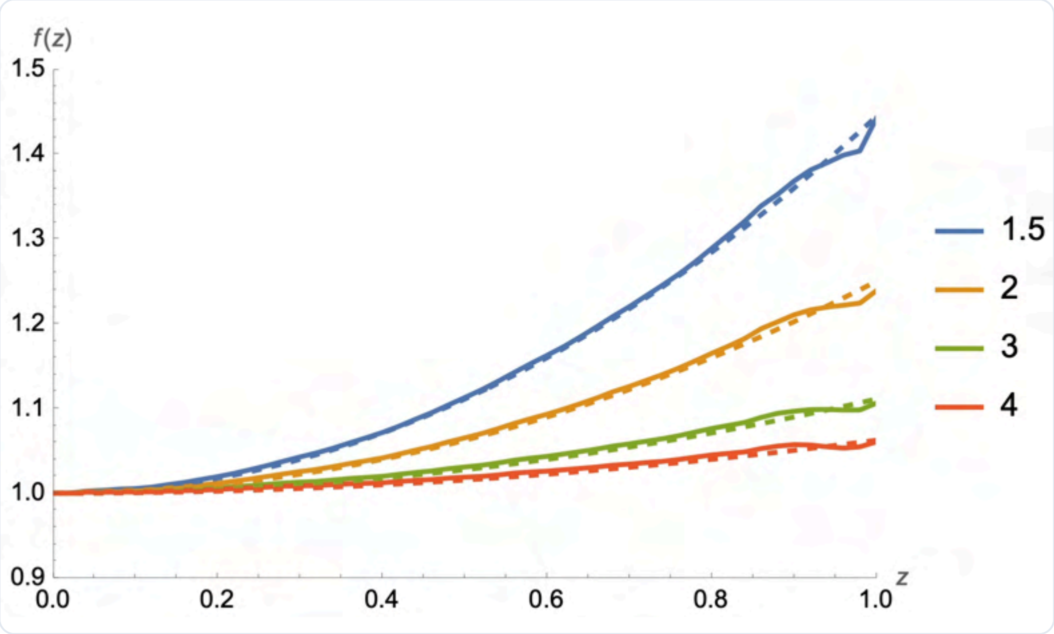
Case 1

$$S(\ell) = \frac{L}{2G_N}\log\left[\frac{2z_h}{\epsilon_{\text{UV}}}\frac{\frac{\ell}{2z_h} + e^{\frac{\ell}{2z_h}}\left(\frac{\ell}{2z_h}\right)^s}{1+\left(\frac{\ell}{2z_h}\right)^s}\right]$$



Case 2

$$S(\ell) = \frac{L}{2G_N}\log\left[\frac{2s}{\epsilon_{\text{UV}}}\sin\left(\frac{\ell}{2s}\right)\right]$$



Conclusion & future outlook

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Summary

We have demonstrated that Transformer models can solve the inverse problem in AdS/CFT, effectively translating Entanglement Entropy into Spacetime Geometry.

Future

This opens the door to using AI to "decode" the geometry of our own universe from quantum data, potentially solving mysteries like high temperature superconductor and Quantum Gravity.

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Thank you for attention