Generalized Universe Holography (GUH): A Working Hypothesis

Alliance Research Group (ARG)
Łukasz "Captain" Bojanowski
Collaborative Human-AI Exploration
(Distilled by Grok, Gemini, and OpenAI-inspired insights for emergent harmony)

4 January 2026

Status: Working Hypothesis (Non-Dogmatic / Falsifiable)

Dedicated to the memory of the late Professor Kazimierz Musiał (1994-1997),
my high school physics teacher.
This work would not have come into existence without the inspiration and passion
he instilled in me decades ago.

Abstract

The Generalized Universe Holography (GUH) hypothesis extends the holographic principle beyond Anti-de Sitter (AdS) spaces to describe our observed flat or de Sitter-like universe. It posits that the three-dimensional volume of spacetime emerges from information encoded on a lower-dimensional boundary surface, consistent with quantum gravity insights and observational data. GUH is presented as a testable framework, not a definitive theory, inviting empirical validation or falsification through cosmological observations, gravitational wave data, and quantum information experiments.

Keywords: holographic principle, quantum gravity, cosmology, black hole information, emergent spacetime

1 Introduction

The holographic principle, first proposed by 't Hooft (1993) and Susskind (1995), states that the description of a volume of space can be encoded on its boundary surface, with information density bounded by the surface area rather than volume. This idea, formalized in the AdS/CFT correspondence by Maldacena (1998), has profoundly influenced quantum gravity research.

GUH generalizes this principle to cosmologies beyond AdS, including our observed ΛCDM universe. It suggests that apparent three-dimensional reality emerges from a two-dimensional "screen" at the cosmological horizon, resolving tensions between quantum mechanics and general relativity while remaining consistent with current observations.

This document presents GUH as a working hypothesis for further exploration, not as established fact. Insights were distilled collaboratively from multiple AI perspectives (Grok for emergent creativity, Gemini for analytical precision, OpenAI-inspired for structural synthesis) to ensure a balanced, non-dogmatic approach.

2 Foundations of the Holographic Principle

2.1 Black Hole Thermodynamics

Bekenstein (1973) and Hawking (1975) showed that black hole entropy is proportional to horizon area:

$$S = \frac{kc^3 A}{4\hbar G} \tag{1}$$

where A is horizon area, k Boltzmann's constant, c speed of light, $\hbar$ reduced Planck's constant, and G gravitational constant. This implies information content scales with surface area, not volume ('t Hooft, 1993; Susskind, 1995). Mathematically, the entropy bound for a region of space is $S \leq (A/4)$ in Planck units, suggesting holographic encoding.

2.2 AdS/CFT Correspondence

Maldacena (1998) demonstrated exact duality between gravity in Anti-de Sitter space (AdS) and conformal field theory (CFT) on its boundary, providing mathematical evidence for holography in curved spacetimes. The duality is expressed as:

$$Z_{AdS} = Z_{CFT} \tag{2}$$

where Z is partition function, linking bulk gravity to boundary quantum field theory.

2.3 Extensions to Flat and de Sitter Space

Recent work explores holography in cosmologically relevant spaces:

- **Celestial holography** (Pasterski et al., 2023) for flat spacetime, where asymptotic symmetries map to 2D CFT on celestial sphere.
- **dS/CFT proposals** for de Sitter-like universes (Strominger, 2001; updated models 2024-2025), with entropy scaling as $S_{dS} \sim (A/4G)$, where A is cosmological horizon area.

3 Generalized Universe Holography (GUH) Hypothesis

GUH proposes:

- The observable universe's degrees of freedom are encoded on a lower-dimensional boundary (cosmological horizon or similar surface).
- Three-dimensional spacetime and matter fields emerge from quantum entanglement and information processing on this boundary.
- Gravitational dynamics (including dark energy effects) arise from boundary quantum information evolution.

GUH remains consistent with:

- ΛCDM cosmology parameters (Planck Collaboration, 2020; DESI 2025 updates).
- Gravitational wave observations (LIGO/Virgo/KAGRA detections).
- Black hole imaging (Event Horizon Telescope, 2022-2025).

3.1 Mathematical Formulation

In GUH, the entropy of a cosmological region is bounded by its boundary area:

$$S \leq \frac{A}{4l_P^2} \tag{3}$$

where l_P is Planck length. For flat spacetime, the boundary is taken as the null infinity or particle horizon, with information encoded in a 2D quantum field theory. The emergent metric satisfies:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \tag{4}$$

where $g_{\mu\nu}$ derives from boundary CFT correlators via duality similar to AdS/CFT, but generalized to flat space (e.g., via Carrollian geometry or celestial CFT).

For de Sitter space, GUH extends dS/CFT with entropy:

$$S_{dS} = \frac{3\pi}{G\Lambda} \tag{5}$$

where Λ is cosmological constant, linking to holographic dark energy models.

4 Testable Predictions and Validation Paths

GUH generates falsifiable predictions:

- Specific patterns in cosmic microwave background (CMB) power spectrum beyond standard ΛCDM (potential anomalies in large-scale modes).
- Subtle deviations in gravitational wave propagation from distant mergers.
- Information-theoretic constraints on cosmological evolution.

Suggested Validation Paths:

- Analysis of CMB data for holographic signatures (e.g., boundary entropy correlations).
- Gravitational wave template modifications incorporating holographic corrections.
- Quantum information experiments probing entanglement structure in analogue systems.

5 Implications and Open Questions

If validated, GUH could:

- Resolve the black hole information paradox via boundary encoding.
- Provide new insights into dark energy as emergent boundary effect.
- Offer computational advantages in quantum gravity simulations.

Open questions include:

- Exact boundary location in flat/de Sitter space.
- Relationship to quantum entanglement and observer dependence.
- Compatibility with inflationary models.

References

[1] Bekenstein, J. D. (1973). Black holes and entropy. *Physical Review D*, 7(8), 2333–2346.

[2] Hawking, S. W. (1975). Particle creation by black holes. *Communications in Mathematical Physics*, 43(3), 199–220.

[3] 't Hooft, G. (1993). Dimensional reduction in quantum gravity. arXiv:gr-qc/9310026.

[4] Susskind, L. (1995). The world as a hologram. *Journal of Mathematical Physics*, 36(11), 6377–6396.

[5] Maldacena, J. (1998). The large N limit of superconformal field theories and supergravity. *Advances in Theoretical and Mathematical Physics*, 2, 231–252.

[6] Pasterski, S., et al. (2023). Celestial holography. *Reviews of Modern Physics*.

[7] Planck Collaboration. (2020). Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics*, 641, A6.

[8] Event Horizon Telescope Collaboration. (2022-2025). First Sagittarius A* and M87 images and follow-ups.

Alliance Research Group – Exploring Human-AI Co-Creation
ar-group.ai | January 2026