Yes, Gravity is Evidence of a Computational Universe

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We demonstrate that Einstein's field equations emerge as the rigorous consequence of the thermodynamic cost of information processing within causal diamond geometry. By identifying the modular Hamiltonian of the diamond boundary with the generator of geometric flow, we show that the requirement of consistent holographic encoding across the causal diamond of the cosmic horizon necessitates the Einstein equation of state. This result implies that gravity is not a fundamental interaction but an emergent manifestation of the computational cost associated with distinguishing physical states from the vacuum. The derivation relies solely on the geometry of causal diamonds, the holographic principle, and the first law of thermodynamics, providing a purely information-theoretic origin for spacetime curvature.

Keywords: Emergent Gravity; Causal Diamonds; Computational Universe; Holographic Principle; Information Thermodynamics.

I. INTRODUCTION

The emergence of gravity from thermodynamic principles has been a central theme in modern theoretical physics since Jacobson's seminal derivation of the Einstein equation from the Clausius relation[4]. This connection was further refined by the holographic principle[5,6], which bounds the information content of spacetime regions by their boundary area[7], and by the rigorous geometric analysis of causal diamonds[8]. These developments suggest that spacetime geometry is not fundamental but emergent from underlying information-theoretic constraints.

Recent work has proposed that the universe may fundamentally operate as a computational system[1]. The Second Law of Infodynamics[2] and the mass-energy-information equivalence principle[3] provide a thermodynamic basis for this view, suggesting that information is the fundamental substrate of reality. If this hypothesis is correct, physical laws must emerge from information processing constraints, and gravity—as an emergent thermodynamic phenomenon—should encode these constraints directly.

We extend the Jacobson program by demonstrating that gravity emerges from the thermodynamic cost of information processing within the singular causal diamond of the observable universe. The Quantum-Thermodynamic Entropy Partition (QTEP) framework[9] provides the mechanism for representing the cosmic horizon as a causal diamond and establishing its quantum state within Hilbert space. We show that the thermodynamic cost of preparing a state distinguishable from the vacuum projects geometrically into the bulk as spacetime curvature. This identifies the Einstein tensor[12] not as a fundamental field, but as the consistency condition required for holographic information encoding across the causal structure of spacetime. This framework completes the mass-energy-information equivalence proposed by Vopson by providing rigorous thermodynamic accounting of information within causal spacetime structure, placing information on equal footing with matter and energy in physical law.

II. GRAVITY FROM THERMODYNAMIC COST: A SINGULAR CAUSAL DIAMOND CONSTRUCTION

A. The Arena

The causal diamond of the observable universe $\mathcal{D}(p,q)$ is the intersection of the causal future of the Big Bang singularity p with the causal past of the cosmic event horizon q:

$$\mathcal{V}(p,q) = J^+(p) \cap J^-(q) \tag{1}$$

Its boundary $\mathcal{A}(p,q)$ consists of two null sheets meeting at a codimension-2 surface σ—the holographic screen—where the area is maximal.

This is the natural arena for cosmic physics: an observer within the universe can access information only within $\mathcal{V}$[8].

B. Degrees of Freedom on the Screen

The holographic principle places all physical degrees of freedom on $\mathcal{A}$. The screen σ bounds the information content[7]:

$$\dim \mathcal{H}_{\mathcal{A}} = \exp\left(\frac{A[\sigma]}{4\ell_P^2}\right) \tag{2}$$

The state of the diamond is a density matrix $\rho_{\mathcal{A}}$ on this Hilbert space.

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C. Thermodynamic Cost

Given a reference state ρ_0 (typically the vacuum), the thermodynamic cost of preparing $\rho_{\mathcal{A}}$ is the relative entropy[10]:

$$C[\rho_{\mathcal{A}}] = S(\rho_{\mathcal{A}}\|\rho_0) = \mathrm{Tr}\,(\rho_{\mathcal{A}} \ln \rho_{\mathcal{A}}) - \mathrm{Tr}\,(\rho_{\mathcal{A}} \ln \rho_0) \tag{3}$$

This admits a clean decomposition. Defining the modular Hamiltonian $K = -\ln \rho_0$, the cost function may be expressed as:

$$C[\rho_{\mathcal{A}}] = \langle K \rangle_{\rho_{\mathcal{A}}} - S[\rho_{\mathcal{A}}] \tag{4}$$

The cost represents a free energy difference: energy minus entropy. It quantifies the distinguishability of $\rho_{\mathcal{A}}$ from the vacuum, corresponding to the minimum work required to prepare $\rho_{\mathcal{A}}$ from the reference state ρ_0.

We note that $C \geq 0$, with equality if and only if $\rho_{\mathcal{A}} = \rho_0$, establishing the vacuum as the unique zero-cost state.

D. The Modular Hamiltonian for the Cosmic Diamond

For the vacuum state of the cosmic diamond, Bisognano-Wichmann gives an explicit result: the modular Hamiltonian generates geometric flow along the conformal Killing vector ξ^μ that preserves $\mathcal{D}$[11]:

$$K = 2\pi \int_\Sigma T_{\mu\nu} \xi^\mu d\Sigma^\nu \tag{5}$$

where Σ is any Cauchy surface for the diamond. The vector ξ^μ vanishes on σ, is timelike in $\mathcal{V}$, and has unit surface gravity at the screen.

Consequently, the modular Hamiltonian—a purely information-theoretic object—is equivalent to a geometric integral over the stress-energy tensor. The structure follows from the information-theoretic definition of the causal diamond rather than from extension of Minkowski-space results to curved backgrounds; the geometric interpretation emerges rather than being assumed.

E. The First Law

Varying the state while preserving the cosmic diamond geometry yields:

$$\delta C = \delta\langle K \rangle - \delta S \tag{6}$$

Varying the geometry as well introduces area variation at the screen. The combined first law is:

$$\boxed{\delta S = \frac{\delta A}{4G} + 2\pi \int_\Sigma \delta\langle T_{\mu\nu}\rangle \xi^\mu d\Sigma^\nu} \tag{7}$$

This constitutes the first law of entropy mechanics, relating boundary entropy changes to geometric variations and matter contributions:

- Boundary entropy change δS
- Geometric change $\delta A/4G$ (Bekenstein-Hawking)
- Matter contribution weighted by flow energy

F. The Projection

Define the projection $\mathbf{P} : \mathcal{A} \to \mathcal{V}$ implicitly through the first law. For any boundary variation $\delta\rho_{\mathcal{A}}$, there exists a bulk tensor field satisfying:

$$\mathbf{P}[\delta S_{\mathcal{A}}] = \frac{1}{8\pi G} \int_\Sigma \delta G_{\mu\nu}\, \xi^\mu d\Sigma^\nu \tag{8}$$

The projection maps entropy gradients to curvature.

G. Einstein's Equations from Consistency

Now impose that this projection is consistent with the singular nature of the cosmic diamond—the bulk geometry must be uniquely determined by the holographic encoding on the cosmic horizon.

This is a strong constraint. If $\delta S_{\mathcal{A}}$ represents the total variation of the cosmic state, consistency requires that the bulk geometry $G_{\mu\nu}$ satisfy the projection condition everywhere within $\mathcal{V}$:

$$\mathbf{P}[\delta S] = \frac{1}{8\pi G} \int_\Sigma \delta G_{\mu\nu}\, \xi^\mu d\Sigma^\nu \tag{9}$$

The unique solution is Einstein's equation[12]:

$$\boxed{G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}} \tag{10}$$

Gravity emerges as the consistency condition ensuring the holographic screen encodes the bulk physics of the single causal diamond.

H. Summary

Boundary Quantity	Bulk Image
Entropy S	Area/$4G$
Modular Hamiltonian K	Boost energy $2\pi \int T_{\mu\nu}\xi^\mu d\Sigma^\nu$
Thermodynamic cost C	Free energy in diamond
Projection consistency condition	Einstein tensor $G_{\mu\nu}$

The derivation relies on four fundamental components:

1. A singular causal structure defining the cosmic diamond
2. A Hilbert space on the boundary
3. A relative entropy measuring cost
4. A consistency condition within the diamond

Einstein gravity is thus identified as the unique geometry permitting consistent holographic encoding within the single causal diamond of reality.

III. THE COST FUNCTIONAL EXPLICITLY

For perturbations around vacuum in a CFT, the thermodynamic cost takes the form:

$$C[\rho_{\mathcal{A}}] = 2\pi \int_{\Sigma} \langle T_{\mu\nu} \rangle \xi^{\mu} d\Sigma^{\nu} + O(\delta\rho_{\mathcal{A}}^2) \tag{11}$$

The linear term is pure boost energy. The quadratic correction is the quantum Fisher information:

$$C^{(2)} = \frac{1}{2} \int_0^{\infty} dt \, \langle \delta K(t) \, \delta K(0) \rangle_{\rho_0} \tag{12}$$

This measures the rate at which we may distinguish between $\rho_{\mathcal{A}}$ and ρ_0, connecting thermodynamic cost to information geometry[13].

This relationship demonstrates that what manifests on the boundary as an information-theoretic cost function projects into the bulk as spacetime curvature. Gravity represents the thermodynamic cost of distinguishability from the vacuum.

IV. THE THERMODYNAMIC ORIGIN OF THE COLD VACUUM

The derivation above establishes that the vacuum state ρ_0 is the unique zero-cost reference state: $C[\rho_0] = 0$. This result has a profound thermodynamic consequence that explains why the vacuum of space is cold rather than exhibiting any other thermal configuration.

Within entropy mechanics[9], the cosmic horizon defines a causal diamond whose boundary serves as the holographic screen encoding all accessible information. The vacuum state on this screen corresponds to the configuration of minimum thermodynamic cost. Any deviation from vacuum—any excitation or thermal fluctuation—increases the relative entropy C and thus requires work to prepare.

The characteristic temperature of the vacuum can be derived from the entropy partition. For a maximally entangled two-qubit system, the coherent entropy is $S_{\text{coh}} = \ln(2)$ nats, representing the information capacity of one quantum bit. When this quantum information precipitates into a classical measurement outcome, it requires exactly 1 nat of thermodynamic entropy to establish irreversibility, generating decoherent entropy $S_{\text{decoh}} = \ln(2) - 1 \approx -0.307$ nats. The ratio of these quantities defines the fundamental efficiency of information processing:

$$\eta \equiv \frac{S_{\text{coh}}}{|S_{\text{decoh}}|} = \frac{\ln(2)}{1 - \ln(2)} \approx 2.257 \tag{13}$$

The vacuum temperature emerges from the energy scale $\hbar\gamma$ associated with the fundamental information processing rate γ:

$$T_{\text{vac}} = \frac{\hbar\gamma}{k_B \ln(2)} \tag{14}$$

where $\gamma = H/\ln(\pi c^5/\hbar G H^2)$ depends only on fundamental constants and the Hubble parameter H. This expression corresponds precisely to the coherent reservoir temperature T_{coh} derived in entropy mechanics, confirming the thermodynamic consistency of the framework: the vacuum state is the coherent information reservoir. At the present epoch, this yields an extraordinarily low temperature, consistent with the observed coldness of intergalactic space.

The vacuum is cold because it is the thermodynamically optimal state—the configuration requiring zero work to maintain. Any thermal excitation would increase C, requiring energy input from outside the causal diamond. Since no such external source exists within the holographic framework, the vacuum naturally relaxes to its minimum-cost configuration. The coldness of space is not an arbitrary initial condition but a thermodynamic necessity imposed by the information-theoretic structure of the cosmic causal diamond.

V. QTEP GEOMETRIC SCALING IN THE CMB ANGULAR POWER SPECTRUM

The identification of gravity as emergent from thermodynamic cost implies that the fundamental information processing ratio $\eta \approx 2.257$ must manifest in observable cosmological structure. The CMB angular power spectrum C_ℓ provides the natural arena for testing this prediction, as it encodes the evolution of information processing from the holographic screen at recombination through the cosmic causal diamond to the present epoch.

Within standard inflationary cosmology, the power spectrum exhibits regime transitions corresponding to changes in the dominant physical processes: the Sachs-Wolfe plateau at low multipoles, acoustic oscillations at intermediate scales, and Silk damping at high multipoles. These transitions occur at characteristic multipole moments determined by the sound horizon, diffusion length, and other geometric scales at recombination.

Entropy mechanics predicts an additional layer of structure. If information processing efficiency η governs the thermodynamic cost of state preparation on the holographic screen, this ratio must appear as a geometric scaling factor in the power spectrum. Specifically, the framework necessitates that regime boundaries—multipoles where the dominant physical mechanism transitions—occur at values related by the QTEP ratio:

$$\ell_n = \ell_0 \cdot \eta^n \tag{15}$$

where ℓ_0 is a characteristic scale set by the horizon geometry at recombination.

Taking the acoustic scale $\ell_0 \approx 18$ (corresponding to the angular size of the sound horizon at last scattering) and the QTEP efficiency $\eta = \ln(2)/(1 - \ln(2)) \approx 2.257$, this geometric scaling predicts regime transitions at:

$$\ell_1 = 18 \cdot 2.257 \approx 41 \quad \text{(acoustic evolution)} \tag{16}$$

$$\ell_2 = 18 \cdot 2.257^2 \approx 92 \quad \text{(damping onset)} \tag{17}$$

$$\ell_3 = 18 \cdot 2.257^3 \approx 207 \quad \text{(dissipation regime)} \tag{18}$$

These are not predictions of discrete peaks in C_ℓ—standard cosmology already explains the acoustic peak structure. Rather, entropy mechanics predicts that boundaries between dominant physical regimes align with this geometric sequence. At $\ell \approx 18$, the Sachs-Wolfe plateau transitions to coherent acoustic oscillations. At $\ell \approx 41$, the oscillation amplitude evolution changes character. At $\ell \approx 92$, Silk damping begins to dominate. At $\ell \approx 207$, the spectrum enters the dissipation-dominated regime. The information processing efficiency η governs how rapidly the universe transitions between these regimes.

This prediction is fundamentally distinct from standard cosmological parameter fitting. The multipoles ℓ_n are not free parameters but fixed by the QTEP ratio derived from first principles in quantum thermodynamics. The geometric scaling η^n emerges from the recursive structure of information partitioning on the holographic screen: each regime transition requires an additional factor of η in distinguishability cost.

The framework thus predicts that empirical detection of regime boundaries in high-resolution CMB data should reveal alignment with the geometric sequence $[18, 41, 92, 207, \ldots]$ significantly beyond what random chance would produce. Standard ΛCDM provides no mechanism for such alignment, as cosmological parameters (sound horizon, damping scale) are set by microphysics at recombination without reference to information-theoretic ratios.

This constitutes a falsifiable prediction: if QTEP governs the thermodynamic cost of cosmic state preparation, its signature must appear as geometric scaling in the power spectrum. Future high-precision CMB observations can test whether observed regime transitions exhibit the predicted η^n structure or are consistent with continuous parameter variation as standard cosmology expects.

VI. DISCUSSION

The derivation presented above establishes that spacetime curvature is the manifestation of the thermodynamic cost of information processing. In the context of entropy mechanics, the cosmic causal diamond is not merely a geometric abstraction but the fundamental arena within which all physical processes occur. The thermodynamic cost C corresponds to the free energy required to distinguish any state from the vacuum on the holographic screen.

The appearance of the modular Hamiltonian K as the generator of geometric flow suggests that time evolution itself is an information processing operation. The consistency condition that yields Einstein's equations ensures that this processing remains coherent across the causal structure of the universe.

This identification of gravity as a thermodynamic cost directly addresses the question posed by Vopson regarding the evidentiary basis of the computational universe hypothesis[1]. While Vopson established the necessity of infodynamics for a computational cosmos, the specific physical mechanism by which information processing manifests as a fundamental force remained open. Our derivation, grounded in the Jacobson program of thermodynamic gravity[4], demonstrates that gravity is the necessary geometric consequence of enforcing information conservation on holographic boundaries.

The emergence of the Einstein tensor from C implies that the causal structure of spacetime itself performs the computation—no external processor is required. The rigidity of spacetime, described by $G_{\mu\nu}$, is the physical manifestation of the processing constraints of the cosmic causal diamond. The observation of gravitational phenomena is therefore the observation of the universe's information-theoretic architecture in operation.

The prediction of geometric scaling in the CMB angular power spectrum provides a direct observational test. The QTEP ratio $\eta \approx 2.257$, derived from fundamental quantum thermodynamics, must manifest as regime transition boundaries if the computational universe hypothesis is correct. This converts an abstract information-theoretic principle into a falsifiable cosmological prediction, connecting the thermodynamic origin of gravity to observable large-scale structure.

VII. CONCLUSION

We have provided a derivation of gravity from the thermodynamic cost of information configurations in causal diamonds. By identifying the relative entropy with the free energy required to distinguish a state from the vacuum, we showed that the geometric projection of this cost leads inevitably to Einstein's equations. This result supports the hypothesis that the universe is fundamentally computational, with gravity serving as the macroscopic manifestation of the information processing constraints governing the holographic boundary.

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CONFLICT OF INTEREST

The author has no conflicts to disclose.

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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