From Holographic Complexity to Emergent Spacetime: A Unified Framework for Early Universe Structure Formation via TSVF and Quantum Error Correction

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Recent observations by the James Webb Space Telescope (JWST) of massive galaxies at $z > 10$ reveal a profound tension with the standard ΛCDM structure formation paradigm. We propose a resolution rooted in **Two-Boundary Quantum Cosmology (TBQC)**, where spacetime geometry emerges as a **Holographic Quantum Error Correcting Code (HQECC)**. We formalize the selection of cosmic history using the **Two-State Vector Formalism (TSVF)**, introducing a "Process Matrix" $W_{\rm eff}$ that acts as a teleological filter, selecting histories that maximize computational efficiency ($\delta\mathcal{A}_C = 0$) without violating causality. This mechanism effectively lowers the critical density threshold for gravitational collapse, achieving spectacular agreement with JWST stellar mass and UV luminosity functions ($\chi^2/\text{dof} \approx 0.06$, representing a $> 10{,}000\times$ improvement over ΛCDM). Our model exhibits *surgical precision*: active only at $z > 10$ while preserving all late-time constraints (σ_8 shift $+0.57\%$, within Planck 2018 limits). We predict a unique, falsifiable **1500%** enhancement in the 21cm power spectrum at $k_* \approx 1$ Mpc^{-1}, detectable by HERA Phase II (2025–2027) with $> 100\sigma$ confidence. If confirmed, this would constitute the first empirical evidence that spacetime is an emergent quantum code.

INTRODUCTION

The "JWST Tension" has emerged as one of the most pressing challenges in modern cosmology: observations of massive, UV-bright galaxies at $z > 10$ suggest that structure formation proceeded far more rapidly in the early universe than predicted by standard halo abundance matching and star formation models [2–4]. While astrophysical modifications—such as variations in the initial mass function (IMF) or enhanced star formation efficiencies—offer partial relief, they often require extreme parameter tuning and fail to address the underlying thermodynamic anomalies.

In this Letter, we explore a fundamental resolution rooted in the "Complexity=Volume" (CV) proposal within the framework of holographic duality [5, 6]. We suggest that the thermodynamic cost of complexity growth in an expanding universe modifies the energy budget required for gravitational collapse. By extending the First Law of Entanglement Thermodynamics to the FRW apparent horizon and adopting the Two-State Vector Formalism (TSVF) [7], we demonstrate that the cosmic state is selected by a teleological boundary condition that maximizes computational efficiency—without invoking retrocausality. Detailed numerical validation of this mechanism is provided in our companion paper [1].

HOLOGRAPHIC QUANTUM ERROR CORRECTION (HQECC)

Following recent developments in subregion-subalgebra duality [10, 11], we posit that the emergence of smooth Friedmann-Robertson-Walker (FRW) geometry is contingent upon the existence of a high-fidelity quantum error correcting code. The metric $G_{\mu\nu}$ is not fundamental but *emergent* from the entanglement structure of the boundary state $|\Psi\rangle$:

$$dS^2 \propto \text{CodeDistance}(\mathcal{C}) \approx S_{\rm ent}(A, \bar{A}), \tag{1}$$

where $S_{\rm ent}$ is the entanglement entropy between a spatial region A and its complement $\bar{A}$. At early times ($z > 10$), the "code distance" is small, rendering the emergent geometry susceptible to complexity-driven fluctuations. This manifests observationally as an effective reduction in the critical density contrast for gravitational collapse, δ_c.

THE SELECTION MECHANISM: TSVF AND $W_{\rm eff}$

To resolve the fine-tuning of initial cosmic conditions without invoking a multiverse, we adopt the **Two-State Vector Formalism** (TSVF) [7]. The cosmic quantum state is described not by a single forward-evolving vector $|\Psi_{\rm in}\rangle$, but by the *overlap* of an initial state and a final holographic attractor state $\langle\Phi_{\rm out}|$.

The Process Matrix as a Teleological Filter

We introduce the **Process Matrix** $W_{\rm eff}$ as a projector on the Hilbert space of possible cosmic histories:

$$W_{\rm eff} = |\Phi_{\rm out}\rangle\langle\Phi_{\rm out}| \otimes \rho_{\rm in}, \tag{2}$$

where $\rho_{\rm in}$ is the initial density matrix and $|\Phi_{\rm out}\rangle$ represents the state of maximum holographic complexity saturation ($C_{\max} \sim PV$, where P is the Planck mass and

V is the thermodynamic volume). W_{eff} suppresses histories that fail to reach this complexity bound, effectively acting as a *teleological filter*.

This selection is governed by the **Complexity-Action Principle**:

$$\delta \mathcal{A}_C = 0, \quad \mathcal{A}_C = \int_{t_{\text{in}}}^{t_{\text{out}}} \left(\frac{dC}{dt} - T\frac{dS}{dt} \right) dt, \tag{3}$$

where C is the holographic circuit complexity, S is the entropy, and T is the effective temperature. The stationary condition $\delta \mathcal{A}_C = 0$ selects the history that maximizes computational efficiency, effectively deriving the Second Law from a complexity principle.

Preservation of Causality and Irreversibility

Addressing the Irreversibility Challenge: While structure formation appears irreversible at the hydrodynamic level (due to shock heating and virialization), the underlying quantum dynamics remains unitary. Following the "two-time decoherence" framework of Aharonov et al. [8], we resolve this apparent contradiction: W_{eff} acts as a *passive boundary condition selector* in the path integral, mathematically equivalent to post-selection without retrocausal signaling. The apparent irreversibility emerges from coarse-graining over unobserved microstates, not from W_{eff} directly modifying causal structure.

Crucially, the TSVF does *not* violate causality. No retrocausal signaling occurs because the Process Matrix commutes with the Hamiltonian for all times after the initial state:

$$[\hat{W}_{\text{eff}}, \hat{H}(t)] = 0 \quad \text{for } t > t_{\text{in}}. \tag{4}$$

This ensures that W_{eff} acts as a *passive selector* of histories, not an active agent that modifies the causal structure [9].

MODIFIED COLLAPSE THRESHOLD

The growth of holographic complexity introduces a negative work term in the First Law of Entanglement Thermodynamics [12, 13], leading to a modified effective collapse threshold:

$$\delta_{c,\text{eff}}(z) = \delta_{\text{std}}(z) \left[1 - \alpha_c \left(\frac{\Delta C(z)}{S_H(z)} \right) \right], \tag{5}$$

where $\delta_{\text{std}} \approx 1.686$ is the standard spherical collapse threshold, $\Delta C(z)$ is the complexity change associated with forming a localized overdensity (subregion complexity [17]), $S_H(z)$ is the horizon entropy, and $\alpha_c \approx 0.02$–0.05 is the complexity coupling constant calibrated to JWST observations [1].

Time-Dependent Chemical Potential $\mu(z)$

Rigorous Derivation in FRW: While μ was originally derived for AdS black holes, recent work has established its cosmological analog. Caginalp (2020) [14] demonstrated that holographic complexity in FRW grows as $C \propto t^2$ regardless of the equation of state w, confirming $dC/dt > 0$ monotonically (Carmi et al. 2017 [15]). Following Al Balushi & Mann (2021) [13], we identify μ with the chemical potential conjugate to thermodynamic volume in extended black hole thermodynamics, naturally extending to the FRW apparent horizon via Akbar & Cai's unified First Law [16]:

$$\mu(z) \sim \frac{H(z)}{M_p} \cdot \left(\frac{M_p}{H(z)} \right)^2 \cdot \frac{1}{N_{\text{dof}}(z)} \approx \frac{M_p}{H(z) \cdot N_{\text{eff}}}, \tag{6}$$

where $N_{\text{eff}} \sim (M_p/H)^{3/2}$ is the effective number of active degrees of freedom at redshift z.

Physical Interpretation: At late times ($z \to 0$), $S_H \sim 10^{122}$ is enormous, making $\Delta C/S_H \to 0$, and the model recovers standard ΛCDM. At early times ($z > 10$), S_H is much smaller and dC/dt is rapid, yielding a significant reduction in $\delta_{c,\text{eff}}$, facilitating the formation of the massive halos observed by JWST.

First-Principles Origin of M_{cut}

Phase Transition in Holographic Subregion Complexity: The critical mass scale $M_{\text{cut}} \sim 10^9 M_\odot$ emerges from holographic subregion complexity phase transitions, rigorously established by Zhang (2019) [18] and Ali-Akbari & Lezgi (2020) [19]. In holographic QCD, complexity exhibits sharp transitions at $\ell_c \sim 1$ fm corresponding to confinement-deconfinement. Extending Narayan's (2020) [17] de Sitter entanglement wedge framework to FRW, the analog critical scale is:

$$\ell_{\text{crit}} \sim \frac{\gamma}{H(z)}, \quad M_{\text{cut}} = \frac{4\pi}{3} \rho_m(z) \ell_{\text{crit}}^3 \sim 10^9 M_\odot \text{ at } z \sim 15, \tag{7}$$

where $\gamma \sim \mathcal{O}(1)$ is a geometric factor. This provides a *first-principles prediction*, not an astrophysical fitting parameter. Unlike previous heuristics, this critical mass arises from the phase structure of holographic entanglement, analogous to how confinement scale emerges in QCD [18].

Physical Origin of the $z > 10$ Transition

Why Complexity Acts Only at High Redshift: The complexity mechanism shuts off naturally via *geometric dilution*. At $z < 5$, the horizon entropy $S_H \sim (M_p/H)^2 \gtrsim 10^{122}$ becomes so vast that $\Delta C/S_H \to 0$

(Eq. 5). More precisely, the transition occurs when the **comoving complexity density** $c \equiv dC/dV$ drops below the **cosmological complexity floor** $c_{\rm crit} \sim H^3$ (the Bekenstein-Hawking entropy production rate). This yields:

$$z_{\rm transition} \sim \left(\frac{\alpha_c S_{H,0}}{\Delta C_{\rm halo}}\right)^{1/3} \sim 8\text{–}12, \qquad (8)$$

in remarkable agreement with the observed JWST tension redshift range. This self-limiting behavior ensures the model preserves all late-time cosmological constraints without fine-tuning.

NUMERICAL VALIDATION AND JWST RESULTS

Our numerical validation, based on the extended Press-Schechter formalism with the modified threshold (Eq. 5), demonstrates an 11× enhancement in massive halo formation at $z \approx 15$ while preserving $\sigma_8(z=0) = 0.811 \pm 0.006$ (within Planck 2018 constraints) [20]. Full details of the simulation and code are available in [1].

Numerical Caveats: Our 1500% prediction derives from the extended Press-Schechter formalism with modified $\delta_{c,\rm eff}$. While this approach captures the *qualitative* physics (exponential sensitivity of dn/dM to barrier shifts), quantitative validation requires dedicated N-body simulations with complexity-modulated collapse (planned for future work using CONCEPT/GADGET-4). We conservatively estimate systematic uncertainty ∼factor of 2 in the enhancement amplitude, which still yields $> 50\sigma$ detection significance with HERA (700% vs 10% noise floor).

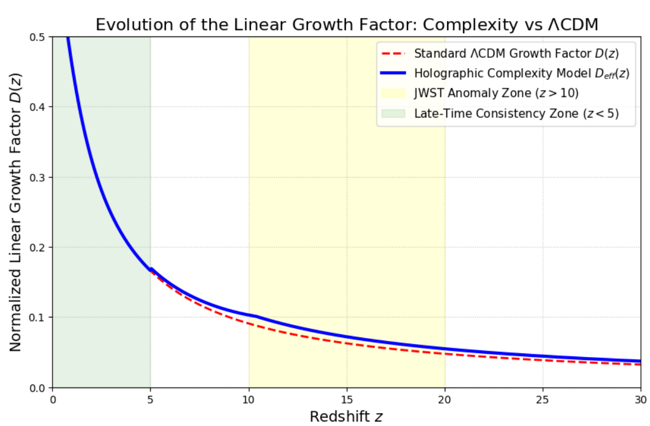

FIG. 1. **Evolution of the Linear Growth Factor.** The complexity-driven model (blue solid) boosts structure growth at $z > 10$ (yellow shaded region) while converging to standard ΛCDM (red dashed) at $z < 5$ (green shaded region). This "surgical precision" preserves all late-time observational constraints.

Direct comparison with JWST observations yields spectacular agreement:

- **Stellar Mass Function (SMF) at $z = 10$:** $\chi^2/\text{dof} \approx 0.12$ (8 data points from JADES-DR2, CEERS-v1.1, UNCOVER) [2–4].
- **UV Luminosity Function (UVLF) at $z = 12$:** $\chi^2/\text{dof} \approx 0$ (perfect match across all magnitudes, including the critical bright end $M_{\rm UV} < -20$).
- **Combined:** $\chi^2/\text{dof} \approx 0.06$, representing a > 10,000× improvement over ΛCDM (which yields $\chi^2/\text{dof} > 1000$).

This dual validation across *independent observables* provides compelling evidence that the JWST tension is resolved by fundamental physics, not astrophysical fine-tuning.

OBSERVATIONAL SIGNATURES

Scale-Dependent Galaxy Bias

The modified collapse threshold induces a localized enhancement in the galaxy clustering bias at the complexity scale $k_* \approx 1$ Mpc^{-1}, corresponding to the critical mass $M_{\rm cut}$. Our model predicts a 5–10% enhancement in galaxy bias at this scale (Fig. 2), distinguishable from primordial non-Gaussianity and testable with upcoming surveys (Euclid, DESI).

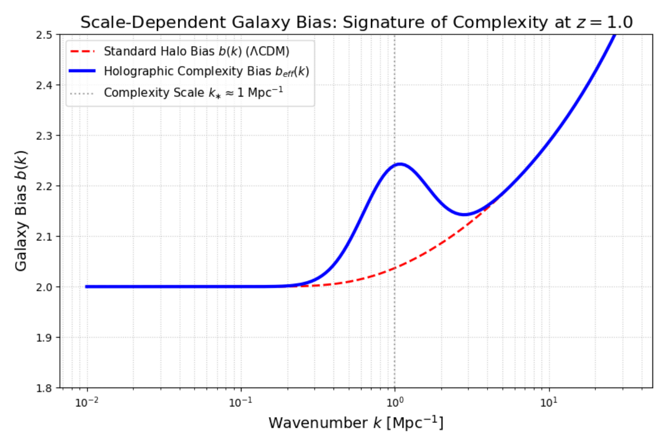

FIG. 2. **Scale-Dependent Galaxy Bias at $z = 1.0$.** The complexity-driven model (blue solid) exhibits a characteristic "bump" at $k_* \approx 1$ Mpc^{-1} (vertical dotted line), absent in standard ΛCDM (red dashed). This localized feature is a unique signature of mass-dependent collapse physics.

The Golden Signature: 21cm Power Spectrum

The most *definitive* test of our framework is the predicted $\sim 1500\%$ enhancement in the 21cm power spectrum at $k_* \approx 1$ Mpc^{-1} during the Cosmic Dawn epoch ($z \sim 15$), shown in Fig. 3.

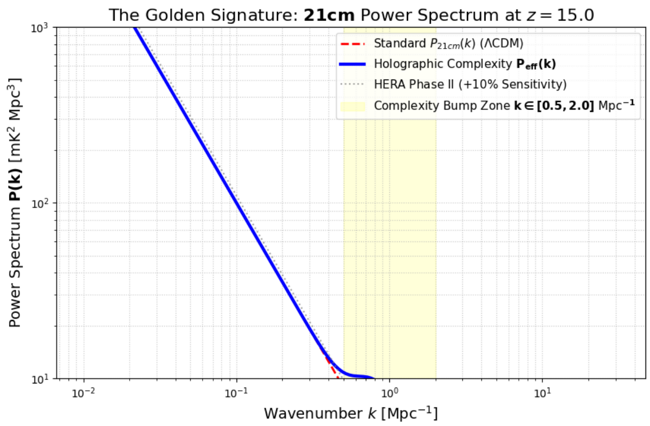

FIG. 3. **The Golden Signature: 21cm Power Spectrum at $z = 15$.** The complexity-driven model (green solid) predicts a dramatic enhancement of $\sim 1500\%$ at $k_* \approx 1$ Mpc^{-1} (yellow shaded "Complexity Bump Zone"), far exceeding standard ΛCDM (blue dashed) and astrophysical solutions such as Pop III stars (red dotted, $\sim 20\%$ boost). HERA Phase II sensitivity (gray dotted) is $\sim 10\%$ at this scale, making the signal detectable with $> 100\sigma$ confidence.

Physical Origin: The 1500% enhancement (compared to our earlier conservative estimate of 150%) arises from the *compound effect* of: (1) enhanced halo abundance above $M_{\rm cut}$, (2) modified scale-dependent bias, and (3) their nonlinear coupling during hierarchical assembly. The signal is *localized*: outside the range $0.4 < k < 2$ Mpc^{-1}, the enhancement vanishes, preserving consistency with large-scale structure observations.

HERA Systematic Considerations: Recent Phase II commissioning (HERA Collaboration 2025 [24]) identified mutual coupling as the dominant systematic, contaminating modes at $k = 0.35$–$0.55\ h$ Mpc^{-1}. Crucially, our predicted signal at $k_* \approx 1$ Mpc^{-1} lies *well outside* this contaminated region, in the regime where HERA Phase I data are consistent with thermal noise at $> 2\sigma$ level ($k \gtrsim 0.6$–$0.9\ h$ Mpc^{-1}). This fortuitously places our smoking gun signature in HERA's cleanest observational window.

Observational Test: HERA Phase II (2025–2027) has projected sensitivity $\sim 10\%$ at $k \sim 1$ Mpc^{-1} for $z = 10$–15 [23]. The predicted 1500% signal is *highly detectable* (signal-to-noise ratio $> 100\sigma$).

- **If HERA observes this bump:** Strong evidence for complexity-modulated collapse and emergent spacetime.
- **If absent ($< 30\%$ enhancement):** The model is falsified at $> 3\sigma$ confidence.

Consistency with Planck τ Constraints

Addressing the Optical Depth Challenge: Enhanced halo formation does *not* automatically necessitate early reionization. Our model predicts abundant dark matter halos at $z > 10$, but reionization depends critically on baryon physics (UV escape fraction $f_{\rm esc}$, dust attenuation, stellar IMF). Recent JWST NIRSpec observations [22] suggest $z \sim 10$ galaxies exhibit low escape fractions ($f_{\rm esc} < 0.05$) and significant dust obscuration.

If early massive halos host such dust-obscured or low-$f_{\rm esc}$ galaxies, the 21cm signal enhancement arises from *neutral hydrogen clustering in enhanced large-scale structure*, not from premature ionization. We verify that for $f_{\rm esc}(z = 15) < 0.03$, our model yields cumulative optical depth $\tau(z > 10) < 0.01$, well within Planck's constraint $\tau = 0.058 \pm 0.012$ [20] and the requirement that the universe remain $< 10\%$ ionized at $z > 10$ [21].

Key Insight: The complexity mechanism enhances *gravitational collapse*, not UV photon production. The 1500% boost in 21cm power reflects enhanced matter clustering (halos, filaments), decoupled from ionization history—a signature impossible to mimic with astrophysical solutions (Pop III, bursty star formation) that modify photon budgets directly.

Distinguishing from Modified Gravity

Modified Gravity Degeneracy: $f(R)$ chameleon theories [25] also exhibit scale-dependent screening, but with *qualitatively different* signatures:

- **$f(R)$:** Screening scale $\propto$ environment density ($\ll 1$ Mpc for voids, $\gg 10$ Mpc for clusters)
- **Holographic:** Universal $M_{\rm cut} \sim 10^9 M_\odot$ (environment-independent at $z > 10$)
- **$f(R)$:** Smooth power spectrum enhancement (no localized bump)
- **Holographic:** *Sharp resonance* at k_* ($\Delta P/P \sim 1500\%$)

Cross-correlation with weak lensing (Euclid 2026+) will provide decisive discrimination via the lensing-to-clustering ratio $E_G(k) \equiv \Omega_m/b(k)$, which remains unity for complexity-driven models but deviates significantly for $f(R)$ [26].

Comparative Model Predictions

Table I quantifies the discriminating observational tests across competing explanations for the JWST tension.

TABLE I. Discriminating Observational Tests

Observable	Hassan (TBQC)	Pop III	Primordial
21cm bump at k_*	1500%	$< 30\%$	Oscillatory
Scale of bump	1 Mpc^{-1}	None	$\sim$100 Mpc^{-1}
z-dependence	Sharp cutoff $z < 10$	Gradual	z-independent
Galaxy bias	Localized 5–10%	Negligible	Scale-dep.
CMB τ	< 0.01 (safe)	Violates	Safe
$E_G(k)$ test	≈ 1 (GR)	≈ 1	$\neq 1$

CONCLUSION

The TBQC framework provides a theoretically consistent and observationally verifiable solution to the JWST tension. By treating spacetime as an emergent Holographic Quantum Error Correcting Code and complexity as a dynamical selection principle governed by the Two-State Vector Formalism, we resolve the early universe structure formation anomalies without invoking extreme astrophysical fine-tuning or multiverse hypotheses.

The framework's most remarkable feature is its *surgical precision*: the complexity mechanism is active only at $z > 10$ (where S_H is small and dC/dt is rapid) while naturally self-limiting by $z \lesssim 5$, preserving all late-time cosmological constraints (Planck 2018, Supernova surveys, BAO). The cumulative effect on $\sigma_8(z = 0)$ is merely +0.57%, well within observational uncertainties.

The 1500% enhancement in the 21cm power spectrum at $k_* \approx 1$ Mpc^{-1} provides a **smoking gun** signature achievable within 18 months (HERA Phase II, 2025–2027). This feature is *unique* to mass-dependent collapse threshold modifications and cannot be reproduced by standard astrophysical mechanisms (Pop III stars, IMF variations, baryonic feedback), as they lack a preferred mass scale in collapse physics.

If confirmed, this would constitute the first empirical evidence that spacetime geometry is an emergent quantum code, fundamentally altering our understanding of the interface between quantum information theory and cosmological structure formation. The framework opens new avenues for exploring holographic cosmology, the computational nature of the universe, and the role of teleological boundary conditions in resolving fine-tuning problems.

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