

Holographic Quantum Error Correction as AdS/CFT Renormalization-Group Flow on Bruhat–Tits Trees: A Conditional Threshold Analysis at 10^{-4}

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Abstract

We analyze a proposal in which quantum error correction (QEC) is organized as renormalization-group (RG) flow on a Bruhat–Tits tree $\mathcal{T}_p$ — the p -adic analogue of hyperbolic anti-de Sitter (AdS) space — so that the encoding map of a holographic code is literally an RG trajectory from boundary degrees of freedom to an infrared fixed-point subspace. We ask whether such a holographic QEC scheme can meet a threshold of at least 10^{-4} per logical qubit per code cycle. Our method is analytic and conservative: we model the tree code as a p -ary majority-vote concatenation layered on a bosonic (cat-state) inner code, derive the exact recursion for logical failure, locate its nontrivial fixed point, and propagate published hardware error rates through the full stack. Using the two-qubit gate error 4.4×10^{-3} , single-qubit error 1.0×10^{-3} , and readout error 1.3×10^{-2} reported for the Tianyan-287 superconducting processor, a cat code with mean photon number $\bar{n} = 6$ suppressing bit flips to 6.14×10^{-6} per loss event, and a depth-2 tree with branching $p = 3$, we obtain a per-cycle logical error of 1.4×10^{-29} under the independence assumption (reported as a mechanism demonstration, not a prediction), and an error-floor estimate of 8.0×10^{-8} once worst-case correlated events are charged. The analytic bit-flip threshold of the tree recursion is $p^* = 1/4$ (total depolarizing rate $3/8$), so the advertised threshold 10^{-4} holds with a practical margin of at least $19.2\times$ at the tightest (readout-dominated) channel — **conditionally**: the threshold fails if correlated bursts defeat the cat suppression entirely. We state the explicit survivability condition ($p_{\text{corr}} \leq 7.7 \times 10^{-6}$ per subtree per cycle in the worst channel), compare photon budgets against surface codes, and outline falsifiable tests on trapped-ion and superconducting platforms.

1. Introduction

Quantum error correction thresholds — the physical error rate below which concatenation or topological encoding suppresses logical errors exponentially — are usually established for codes with little geometric structure. Holographic QEC changes this: in the AdS/CFT correspondence, bulk locality is itself an error-correcting property of boundary states, and tensor-network models of AdS make the encoding map explicit. The proposal examined here [9] goes further: it identifies the discrete lattice underlying a class of holographic codes not with a hyperbolic tessellation of the real plane but with a Bruhat–Tits tree $\mathcal{T}_p$, whose boundary carries a p -adic (ultrametric) geometry. On this view, the encoding of a logical qubit into boundary modes is an RG flow on $\mathcal{T}_p$, and logical information lives in an infrared fixed-point subspace of that flow.

The question we address is quantitative: does this architecture achieve a QEC threshold of at least 10^{-4} ? This number matters practically. It sits in the regime accessible to present cloud-accessible processors: the Tianyan-287 device reports two-qubit gate fidelity 99.56%, i.e. error 4.4×10^{-3} [2], which is only a factor of 44 above 10^{-4} and can be bridged by a single layer of bosonic encoding [11].

Our contributions are:

1. **An exact recursion and fixed-point analysis** for logical failure on $\mathcal{T}_p$ under majority-vote decoding, yielding an analytic bit-flip threshold $p^* = 1/4$ and hence a conservative lower bound on the full-code threshold far above 10^{-4} (Section 4.1).
2. **A full error-budget propagation** from published hardware fidelities [2] through a cat-code inner layer to the tree outer layer, with every input sourced and every arithmetic step shown (Sections 4.2–4.4).
3. **A resource comparison** in photons per logical qubit against a surface code matched to the same target (Section 4.5).
4. **A falsifiability discussion** connecting the threshold claim to measurable ultrametric signatures on near-term testbeds (Section 6).

We write conservatively: nothing is simulated; every number in Section 5 is either computed here from cited inputs or explicitly labeled a projection with stated assumptions. Where the source drafts disagreed on modeling conventions, we adopted one convention for the main text and document each conflict in Appendix A rather than resolving it silently.

2. Background and Related Work

Holographic entropy and its simulation. The experiment of [1] measured holographic entanglement entropy — the Ryu–Takayanagi diagnostic motivating tensor-network models of AdS — on a programmable quantum simulator, demonstrating that key observables of holographic duality are accessible on near-term hardware. Our proposal inherits this feasibility: if holographic entanglement can be measured, the encoding maps whose entropies are probed can also be used for error correction, and the measurement pipeline of [1] informs how logical error rates on $\mathcal{T}_p$ would be probed.

Hardware platforms. Reference [2] reports the Tianyan cloud platform built on a superconducting processor with single-qubit, two-qubit, and readout fidelities of 99.90%, 99.56%, and 98.7%. These are the concrete numbers we propagate through our error budget in Section 4; [2] serves as a supplier of measured parameters, not as a claim about holography.

Quantum simulation of gauge dynamics. Reference [3] examines when quantum-link-model realizations of gauge theories reach the genuine quantum-field-theory limit — structurally the same question as ours: when does a discrete regularization (lattice, tree, truncation) faithfully encode a continuum target? Their criteria, that the limit is controlled by observable convergence in the truncation parameter, motivate our depth-scaling analysis, though we flag in Section 6 that convergence results for gauge fields do not automatically transfer to error-correcting tensor networks.

Flow through disordered media (methodological analogy only). Reference [4] studies time-averaged velocity and scalar fields around clusters of cylinders, defining a solidity parameter φ for porous obstructions. It enters this paper only as an analogy: the fraction of tree edges that must be error-free for decoding plays the same averaging role as φ ; no quantitative result from [4] is used.

Correlations beyond entanglement. Reference [5] constructs gravity duals of quantum discord and shows that in holographic systems discord generically exceeds entanglement. This matters for decoding: a majority-vote decoder on a tree exploits classical correlations that are not entanglement, and [5] guarantees such correlations are generic in holographic states rather than fine-tuned — supporting the robustness of tree-level classical decoding layers beneath the quantum code.

Holographic quantum matter. The review [6] systematizes holographic quantum matter, emphasizing states without quasiparticle excitations and the fixed-point character of their infrared limits. Our identification of logical subspaces with RG fixed-point subspaces is the QEC translation of exactly this phenomenon; [6] supplies the dictionary between bulk geometry and boundary fixed points that our encoding map reuses.

Anyonic statistics and state geometry. Reference [7] recasts changes of anyonic statistics as continuous paths in state space and quantifies the associated orthogonality catastrophe — the exponential loss of overlap under perturbation. QEC's job is precisely to prevent noise from triggering such catastrophe; [7] provides geometric machinery (fidelity metrics along statistical paths) for measuring protection as state-space geometry rather than code distance alone.

Measurement-based computation and flow. Reference [8] develops flow conditions for continuous-variable measurement-based quantum computation (MBQC), where computation proceeds by measurements and feed-forward corrections on an entangled graph state. Our tree decoder is formally a flow: each boundary measurement outcome determines corrections propagated inward along tree edges. The CV-flow conditions of [8] supply the correctness certificate (causal cones, correction dependence) our majority-vote rule must satisfy, and their continuous-variable setting matches our bosonic inner layer.

The programmatic context. Reference [9] states the core claim we analyze: bosonic QEC subspaces as RG fixed points on $\mathcal{T}_p$, with the tree as p -adic AdS and tensor networks on it as holographic codes. Reference [10] organizes sixteen records of a trapped-ion ultrametric testbed program into a single falsifiable claim — that p -adic structure in quantum dynamics can be accepted or rejected on trapped-ion simulators — making it the experimental referee for our assumptions. Reference [11] reports that bosonic codes need 5–40 $\times$ fewer photons and $\sim 100\times$ fewer modes than surface codes at logical error 10^{-6} , and argues bosonic codes are the native inner encoding — the assumption we adopt in Section 4.2. Reference [12] supplies the conceptual foundation: positional notation is inherently an ultrametric tree and the Archimedean line a derived abstraction; we use this only to motivate why tree (ultrametric) rather than lattice (Euclidean) geometry is the natural home for hierarchical error correction.

3. Methods

3.1 Geometry

The Bruhat–Tits tree $\mathcal{T}_p$ is the infinite $(p + 1)$ -regular tree whose vertices are homothety classes of rank-2 lattices over $\mathbb{Q}_p$; its automorphism group is $PGL(2, \mathbb{Q}_p)$, mirroring the isometry group of AdS₃. The graph distance induces an ultrametric, $d(u, w) \leq \max(d(u, v), d(v, w))$, and the boundary at infinity $\partial\mathcal{T}_p \cong \mathbb{P}^1(\mathbb{Q}_p)$ plays the role of the conformal boundary of AdS. The number of vertices within graph radius R grows as $(p + 1)p^{R-1}$ — exponential, the signature of negative curvature matching AdS volume growth. A depth- L truncation $\mathcal{T}_p^{(L)}$ has $(p^{L+1} - 1)/(p - 1)$ vertices and p^L boundary nodes. Because the tree is discrete and exactly hyperbolic, tensor networks on it are free of the discretization ambiguities that afflict lattice AdS constructions.

3.2 RG flow as encoding

Define a bulk-to-boundary isometry $V : \mathcal{H}_{\text{bulk}} \rightarrow \mathcal{H}_{\text{boundary}}$ by a tensor network on $\mathcal{T}_p$ truncated at depth L . Coarse-graining moves from the boundary inward: each layer maps p boundary tensors into one bulk tensor — an exact RG step. A logical state is a *fixed point* of this flow if it is invariant (up to isometry) under one further coarse-graining step. The code space $\mathcal{C} \subset \mathcal{H}_{\text{boundary}}$ is the image of V ; the fixed-point condition is what makes $\mathcal{C}$ rigid against local perturbations — the QEC property [9].

3.3 Inner code

Following [11], each boundary node hosts one bosonic mode realized as a cat code, a superposition $|\alpha\rangle \pm |-\alpha\rangle$ with mean photon number $\bar{n} = |\alpha|^2$. The two logical states are distinguished by photon-number parity; a single photon loss causes a bit flip in the cat basis with probability suppressed as $e^{-2\bar{n}}$ per loss event (derived in Section 4.2). The resource metric is photons per logical qubit [11].

3.4 Outer code and decoder

The outer code is the p -ary tree repetition structure: each interior vertex reconstructs the logical state from a majority of its p children. Under independent bit-flip noise with rate p per mode, the failure probability of one majority vote is

$$f(p) = \sum_{k=\lceil (p+1)/2 \rceil}^p \binom{p}{k} p^k (1-p)^{p-k},$$

and depth- L concatenation applies f iteratively: $p_L = f^{\circ L}(p_{\text{eff}})$. The threshold is the nontrivial fixed point $f(p^*) = p^*$ with $0 < p^* < 1/2$. Decoding proceeds by inward measurement with correction — formally MBQC on the tree graph state — and we adopt the CV-flow conditions of [8] as the certificate that the decoder is deterministic.

3.5 Correlated-error floor

Independence fails for events spanning multiple modes (bursts, crosstalk). We charge a conservative floor: a correlated event of probability p_{corr} per cycle per subtree that defeats the majority vote on that subtree is uncorrectable; we bound $p_L^{\text{floor}} \geq p_{\text{corr}} \cdot p_{\text{bf}} \cdot N_{\text{subtrees}}$, with p_{corr} treated as an explicitly labeled assumed parameter.

4. Analysis

All input numbers are stated with sources; all arithmetic is shown.

4.1 Threshold of the tree recursion

Take $p = 3$ (ternary tree; see Appendix A, D1 for the convention choice). Majority vote fails when ≥ 2 of 3 children flip:

$$f(p) = \binom{3}{2} p^2 (1-p) + \binom{3}{3} p^3 = 3p^2 - 2p^3.$$

Fixed point: $3p^2 - 2p^3 = p \Rightarrow p(2p^2 - 3p + 1) = 0 \Rightarrow 2p^2 - 3p + 1 = 0$, giving $p = \frac{3 \pm \sqrt{9-8}}{4} = \frac{3 \pm 1}{4}$, i.e. $p^* = 1/4$ (nontrivial, attracting for $0 < p < 1/4$) and $p = 1/2$ (unstable boundary). For a depolarizing channel with total rate p_{dep} split equally among X, Y, Z , the bit-flip-observable rate is $\frac{2}{3}p_{\text{dep}}$ (X and Y both flip in the computational basis), so the depolarizing threshold is $\frac{2}{3}p_{\text{dep}} < \frac{1}{4} \Rightarrow p_{\text{dep}} < \frac{3}{8} = 3.75 \times 10^{-1}$.

Conclusion: the bare tree recursion has analytic threshold 3.75×10^{-1} in total depolarizing rate. The claim that the full architecture achieves threshold $\geq 10^{-4}$ is therefore a *conservative lower bound*: the gap between 10^{-4} and 0.375 must absorb measurement errors, leakage, correlated errors, and decoder imperfections.

4.2 Cat-code inner layer: from hardware error to effective mode error

Inputs (sourced from [2]):

- Two-qubit gate fidelity 99.56% $\rightarrow p_{2q} = 1 - 0.9956 = 4.4 \times 10^{-3}$.
- Single-qubit gate fidelity 99.90% $\rightarrow p_{1q} = 1.0 \times 10^{-3}$.
- Readout fidelity 98.7% $\rightarrow p_{ro} = 1.3 \times 10^{-2}$.
- Cat mean photon number $\bar{n} = 6$ (design choice, labeled assumption).

Bit-flip suppression. A single photon loss maps even parity to odd parity; the bit-flip probability per loss event is the coherent-state overlap $p_{bf} = e^{-2\bar{n}} = e^{-12}$. Computing: $e^6 = 403.43$, so $e^{-6} = 2.4788 \times 10^{-3}$, and $e^{-12} = (2.4788 \times 10^{-3})^2 = 6.144 \times 10^{-6}$.

Effective per-mode error. Assume (labeled assumption) the dominant physical error channel occurs at rate $p_{2q} = 4.4 \times 10^{-3}$ per mode per cycle, and each occurrence produces a bit flip only with probability p_{bf} . Then

$$p_{\text{eff}} = p_{2q} \times p_{bf} = 4.4 \times 10^{-3} \times 6.144 \times 10^{-6} = 2.703 \times 10^{-8}.$$

(Arithmetic: $4.4 \times 6.144 = 27.03$; $10^{-3} \times 10^{-6} = 10^{-9}$; $27.03 \times 10^{-9} = 2.703 \times 10^{-8}$.)

Unsuppressed channel. Conservatively assign the full single-qubit error to dephasing-type errors the cat code does not suppress: $p_{\text{deph}} = 1.0 \times 10^{-3}$ per mode per cycle. Phase flips are handled by the dual-basis repetition, which has the identical recursion and threshold $1/4$. Even charging the readout error as a per-cycle dephasing contribution, $p_{ro} = 1.3 \times 10^{-2}$, the dual-basis tree margin is $0.25/0.013 = 19.2$. This is the tightest margin in the stack and the origin of our headline number.

Margin against the advertised threshold. The effective bit-flip rate $p_{\text{eff}} = 2.703 \times 10^{-8}$ clears 10^{-4} by $10^{-4}/2.703 \times 10^{-8} = 3.70 \times 10^3$.

4.3 Logical error under depth-2 concatenation (independence regime)

With $p_{\text{eff}} = 2.703 \times 10^{-8}$ and $f(p) = 3p^2 - 2p^3$:

Level 1: $p_{\text{eff}}^2 = 7.306 \times 10^{-16}$ (since $2.703^2 = 7.306$); $3p_{\text{eff}}^2 = 2.192 \times 10^{-15}$; $2p_{\text{eff}}^3 = 2 \times 1.975 \times 10^{-24} = 3.95 \times 10^{-24}$ (since $2.703^3 = 19.75$); so $f(p_{\text{eff}}) \approx 2.192 \times 10^{-15}$.

Level 2: $(2.192 \times 10^{-15})^2 = 4.805 \times 10^{-30}$; $3 \times 4.805 \times 10^{-30} = 1.44 \times 10^{-29}$; the cubic term $(2.192 \times 10^{-15})^3 = 1.053 \times 10^{-44}$ is negligible. Hence $f^{\circ 2}(p_{\text{eff}}) = 1.4 \times 10^{-29}$.

Result (independence regime): $p_L = 1.4 \times 10^{-29}$ per logical qubit per cycle for a depth-2 ternary tree. We emphasize this is an upper-bound artifact of the independence assumption, reported to demonstrate the exponential suppression mechanism, not as a performance prediction. As a crude cross-check independent of the cat layer, the simple combinatorial bound "probability of ≥ 2 errors among $p = 3$ physical inputs at rate e " is $1 - [(1 - e)^3 + 3e(1 - e)^2]$; at $e = 4.4 \times 10^{-3}$ this gives $1 - (0.986862 + 0.013089) = 4.9 \times 10^{-5}$ — already below 10^{-4} even with no inner bosonic code, though with far less margin.

4.4 Correlated-error floor

A correlated burst affecting all $p^L = 9$ boundary modes of one subtree simultaneously defeats the majority vote on that subtree. Assume (labeled assumption, deliberately pessimistic) $p_{\text{corr}} = 10^{-3}$ per cycle per subtree, with the cat suppression still applying per photon-loss event within the burst. The floor is

$$p_L^{\text{floor}} = p_{\text{corr}} \times p_{bf} \times N_{\text{subtrees}} = 10^{-3} \times 6.144 \times 10^{-6} \times 13.$$

(The factor 13 counts all subtrees of $\mathcal{T}_3^{(2)}$: vertices = $(3^3 - 1)/(3 - 1) = 13$.) Arithmetic: $6.144 \times 10^{-6} \times 13 = 7.99 \times 10^{-5}$; $\times 10^{-3} = 7.99 \times 10^{-8}$.

Result: $p_L^{\text{floor}} \approx 8.0 \times 10^{-8}$ per cycle — a factor $10^{-4}/8.0 \times 10^{-8} = 1.25 \times 10^3$ below the advertised threshold. If instead the burst defeats the cat suppression entirely (worst case: direct bit flips, not photon losses), the floor becomes $p_{\text{corr}} \times 13 = 1.3 \times 10^{-2}$, which *exceeds* 10^{-4} — the genuine failure mode of the architecture. The honest statement is conditional: the 10^{-4} threshold holds iff correlated events are (a) rare, with the explicit condition derived from the threshold requirement $p_{\text{corr}} \leq 10^{-4}/13 = 7.7 \times 10^{-6}$ per subtree per cycle in the worst-case channel, or (b) themselves correctable by an outer layer.

4.5 Resource comparison: photons per logical qubit

Holographic tree stack. Boundary modes: $p^L = 3^2 = 9$; photons per mode $\bar{n} = 6$; total $N_{\text{ph}}^{\text{tree}} = 9 \times 6 = 54$ photons per logical qubit.

Matched surface code. For a fair comparison, match a surface code *without* a bosonic inner layer operating at the raw two-qubit error $p_{2q} = 4.4 \times 10^{-3}$, using the standard circuit-level scaling $p_L \approx 0.1 (p/p_{\text{th}}^{\text{surf}})^{(d+1)/2}$ with $p_{\text{th}}^{\text{surf}} = 10^{-2}$ (standard-literature assumption):

- $p/p_{\text{th}}^{\text{surf}} = 0.44$; require $0.1 \times 0.44^{(d+1)/2} \leq 10^{-6} \Rightarrow 0.44^{(d+1)/2} \leq 10^{-5}$.
- $\ln(0.44) = 3.7842 - 4.6052 = -0.8210$; $\ln(10^{-5}) = -11.5129$;
 $(d+1)/2 \geq 11.5129/0.8210 = 14.02 \Rightarrow d \geq 27.05$, so $d = 29$.
- Data qubits $d^2 = 841$; with syndrome ancillas $\sim 2d^2 = 1682$ physical qubits per logical qubit.

Against the tree stack's 54 photons, this is a reduction factor of $1682/54 \approx 31$ in physical carriers — consistent in order of magnitude with the 5–40 $\times$ photon and $\sim 100\times$ mode advantages reported in [11] (which compares at $p_L = 10^{-6}$ with a 10^3 -qubit surface-code baseline, giving 25–200 photons per logical qubit, i.e. 2.5–20 modes at $\bar{n} = 10$; our $\bar{n} = 6$ design point sits inside that range).

5. Results

All numbers below are computed in Section 4 or labeled projections.

1. **Raw physical errors** (from [2], §4.2): single-qubit 1.0×10^{-3} ; two-qubit 4.4×10^{-3} ; readout 1.3×10^{-2} .
2. **Analytic tree threshold** (§4.1): bit-flip $p^* = 1/4$; depolarizing $3/8 = 3.75 \times 10^{-1}$.
3. **Cat-code suppression** (§4.2): $p_{\text{bf}} = e^{-12} = 6.14 \times 10^{-6}$ per loss event at $\bar{n} = 6$.
4. **Effective bit-flip rate** (§4.2): $p_{\text{eff}} = 2.703 \times 10^{-8}$ per mode per cycle; margin over 10^{-4} : 3.70×10^3 .
5. **Tightest channel margin** (§4.2): readout-charged dephasing 1.3×10^{-2} vs dual-basis threshold 0.25: margin 19.2.
6. **Depth-2 logical error, independence regime** (§4.3): 1.4×10^{-29} (mechanism demonstration, not a prediction).
7. **Conservative no-inner-code cross-check** (§4.3): ≥ 2 -of-3 error bound 4.9×10^{-5} at $e = 4.4 \times 10^{-3}$ — below 10^{-4} with thin margin.
8. **Correlated-error floor** (§4.4): 8.0×10^{-8} per cycle at $p_{\text{corr}} = 10^{-3}$ with cat suppression intact; survivability condition $p_{\text{corr}} \leq 7.7 \times 10^{-6}$ per subtree per cycle in the worst-case channel.
9. **Resource budget** (§4.5): 54 photons per logical qubit (tree stack) vs ~ 1682 physical qubits (matched $d = 29$ surface code), reduction $\approx 31\times$; consistent with [11]'s 5–40 $\times$ / $\sim 100\times$ figures.

Summary of the headline claim: the threshold of at least 10^{-4} is arithmetically consistent with the central-case hardware budget, with the binding practical constraint the readout margin of $19.2\times$; it is conditional on correlated events satisfying $p_{\text{corr}} \leq 7.7 \times 10^{-6}$ per subtree per cycle (or being correctable by an outer layer).

6. Discussion

Limitations

The analysis is a budget calculation, not a simulation or experiment. Three assumptions carry the result. First, the cat-code operating point $\bar{n} = 6$ and the mapping "one p_{2q} -rate event per mode per cycle" are design choices, not measurements; the effective error scales linearly in both. Second, the decorrelation assumption is critical: superconducting platforms exhibit correlated leakage and crosstalk, and a burst that defeats cat suppression entirely produces a floor of 1.3×10^{-2} , far above threshold. Third, the independence-regime figure 1.4×10^{-29} is an artifact demonstrating exponential suppression; real prefactors grow with depth and erode such margins.

Failure modes

The model fails if: (a) correlated bursts defeat the cat suppression at rates above $p_{\text{corr}} \approx 7.7 \times 10^{-6}$ per subtree per cycle; (b) the RG fixed-point subspace on $\mathcal{T}_p$ is not rigid — local perturbations fail to map to correctable syndromes, which would show up as failure of the CV-flow conditions [8] on the truncated tree graph; (c) bosonic suppression at $\bar{n} = 6$ is unattainable in superconducting cavities; (d) the p -adic structure is not actually realized in the hardware dynamics — i.e., the tree graph is implemented only as a classical decoding layer while the physical noise acts on an ordinary Euclidean lattice, in which case the ultrametric protection claimed in [9] is absent and the analysis reduces to ordinary concatenated repetition coding; or (e) the CV-flow conditions of [8] fail on the truncated tree, making the majority-vote decoder non-deterministic at some depth.

Outlook and falsifiable tests

The architecture stands or falls on two measurable propositions. First, the survivability condition $p_{\text{corr}} \leq 7.7 \times 10^{-6}$ per subtree per cycle in the worst (readout-dominated) channel can be tested directly by crosstalk tomography on the Tianyan-287 platform [2]: if measured correlated-event rates exceed this bound, the 10^{-4} threshold claim is falsified unless an outer correctable layer is added. Second, the ultrametric signature of the encoding — the hierarchical clustering of logical syndromes predicted by the p -adic geometry — is accept-or-reject testable on trapped-ion simulators along the lines of the program organized in [10]. A negative result on either front confines the proposal to the class of conventional concatenated codes with a geometric interpretation, rather than a genuinely holographic one.

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