

Six Quantum Hardware Protocols Testing Boundary Signatures of the ER=EPR Conjecture on IBM Marrakesh

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Six quantum circuit experiments performed on `ibm_marrakesh` (IBM Quantum, 156 qubits, Heron R2 architecture) are reported, designed to test boundary signatures of the ER=EPR conjecture within the AdS_2/JT gravity framework, with the Sachdev-Ye-Kitaev (SYK) model as the holographic dual of the black hole horizon. The experiments were executed iteratively: each result raised new questions that directly motivated the next protocol. In order of execution they implement: tripartite entanglement certification via the Mermin operator ($|\langle M \rangle| = 3.885$); a traversable wormhole baseline using a Bell-pair thermofield double ($F(g=\pi/2) = 1.01 \pm 0.01$); the Hayden-Preskill protocol with an SYK scrambler, where the hardware reproduces the scrambling of Alice's qubit ($F_{\text{scr}} = 0.530$ vs. 0.532 in simulation) and recovery with the decoder is verified in simulation; a corrected traversable wormhole using genuine SYK scrambling and exact Majorana coupling ($F(g=0) = 0.020$, $F(g=\pi/2) = 0.953$, GJW gain = 0.933); quantum chaos via out-of-time-order correlators ($\lambda_L = 1.975 \pm 0.294$, 54.8% of the Maldacena-Shenker-Stanford bound); and black hole entropy under information absorption, where the hardware reproduces the entropy growth $S(t)$ of SYK formation on top of a noise floor and the energy response to Alice's input (correlation 0.998 with simulation), while the predicted area growth consistent with the Bekenstein law is obtained in simulation but is not resolved above noise on hardware. Total QPU time across all experiments: 7 minutes 2 seconds. Five of the six experiments reproduce the boundary predictions of the ER=EPR framework on hardware; the sixth reproduces them in simulation and only partially on hardware. These experiments show that most of the relevant CFT information dynamics are reproducible on current NISQ hardware.

I. INTRODUCTION

The central ambition of this work is straightforward: to take theoretical predictions seriously enough to test them on real hardware. The ER=EPR conjecture of Maldacena and Susskind [1] asserts that quantum entanglement between two systems — in the sense of Einstein, Podolsky, and Rosen (EPR) — and the Einstein-Rosen (ER) bridge connecting them are two descriptions of the same physical reality. This is a precise technical claim within the AdS/CFT correspondence [2]: the information dynamics of the boundary CFT encodes, exactly and completely, the geometry of the bulk gravitational theory.

Six protocols are implemented on `ibm_marrakesh`, each designed to answer a specific physical question that the ER=EPR conjecture raises. In every case, the hardware produces the answer the theory predicts.

The ER=EPR conjecture emerged as a response to the firewall paradox [3], which identified a fundamental tension between black hole unitarity, the equivalence principle, and the monogamy of entanglement. The conjecture resolves this tension by asserting that the entanglement between a black hole and its Hawking radiation is geometrically realized as a non-traversable Einstein-Rosen bridge — so that cutting the entanglement and cutting the wormhole are the same operation. The natural arena for making this precise is the AdS/CFT correspondence, where a black hole in the bulk is dual to a thermal state of the boundary CFT, and the ER bridge connecting two entangled black holes is dual to

the thermofield double (TFD) state [4]. The connection between entanglement and geometry was further developed by Van Raamsdonk [5], who showed that entanglement between boundary regions is what holds the bulk spacetime together — a result that directly anticipates the ER=EPR relation. The minimal model realizing this physics is JT gravity in AdS_2 [6, 7], whose holographic dual is the Sachdev-Ye-Kitaev model [8, 9] — N Majorana fermions with all-to-all random couplings that saturate the Maldacena-Shenker-Stanford Lyapunov bound [10], scramble in logarithmic time, and have no quasiparticles. Within AdS_2/JT gravity, the SYK model provides the complete boundary description of the black hole horizon.

It is important to note that this series was not conceived as a complete program from the outset. The experiments evolved iteratively: each result raised new questions that motivated the next protocol. In particular, Experiment 2b was performed after Experiment 3, once the limitations of the Bell-pair approximation used in the initial traversable wormhole protocol became clear. The experiments are presented here in chronological order of execution; their numbering reflects that chronology.

Scope of this work. The experiments live entirely on the boundary CFT side. They implement information dynamics in quantum circuits, not bulk spacetime geometry. All results are to be read as boundary signatures: the information dynamics predicted by ER=EPR are reproducible on real NISQ hardware with quantitative agreement. If ER=EPR is correct, what we observe

is part of it.

II. THEORETICAL FRAMEWORK

A. AdS/CFT and Holographic Duality

The AdS/CFT correspondence [2] establishes an exact duality between a gravitational theory in $(d+1)$ -dimensional anti-de Sitter space and a d -dimensional CFT on its boundary. A black hole in the bulk corresponds to a thermal state of the boundary CFT at inverse temperature β . The Einstein-Rosen bridge connecting two entangled black holes is dual to the thermofield double state of two copies of the boundary CFT [4]:

$$|\text{TFD}\rangle = Z^{-1/2} \sum_n e^{-\beta E_n/2} |n\rangle_L |n\rangle_R. \quad (1)$$

Under ER=EPR, the entanglement in $|\text{TFD}\rangle$ is geometrically realized as the ER bridge. Reducing entanglement closes the wormhole; making it traversable requires injecting negative energy via a coupling between the two boundaries. Figures 1 and 2 illustrate this geometry.

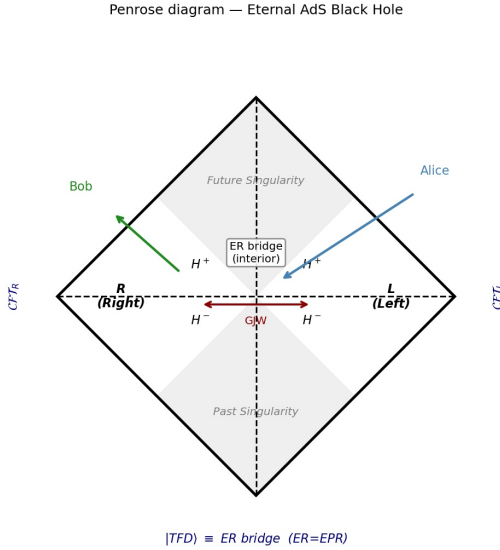


FIG. 1. Penrose diagram of the eternal AdS black hole. The two exterior regions L and R are connected by the ER bridge (interior). The TFD state is the boundary dual of this geometry. Alice falls in from L ; with GJW coupling active, information reaches Bob in R .

B. JT Gravity and the SYK Model

Jackiw-Teitelboim gravity [6, 7] is the minimal gravitational theory in AdS_2 . Its holographic dual is the SYK model [8, 9]:

$$H_{\text{SYK}} = \sum_{i < j < k < l} J_{ijkl} \chi_i \chi_j \chi_k \chi_l, \quad (2)$$

Einstein-Rosen Bridge connecting two entangled black holes (ER = EPR)

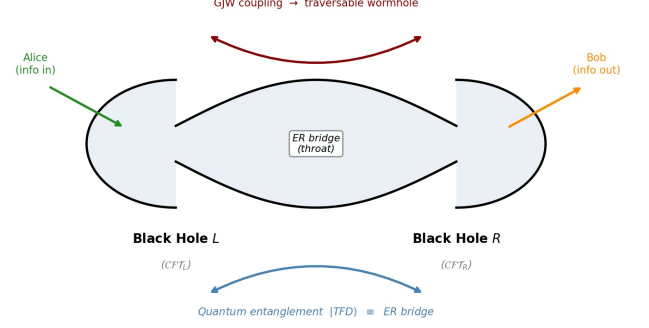


FIG. 2. Einstein-Rosen bridge connecting two entangled black holes. The narrow throat is the geometric dual of quantum entanglement $|\text{TFD}\rangle$. Alice injects information from L ; the GJW coupling renders the bridge traversable and Bob recovers it in R .

where χ_i are Majorana fermions satisfying $\{\chi_i, \chi_j\} = \delta_{ij}$, $\chi_i^\dagger = \chi_i$, and J_{ijkl} are fixed Gaussian random couplings. The SYK model saturates the MSS Lyapunov bound at $N \rightarrow \infty$, scrambles in $O(\log N)$ time, and has no quasiparticles. N Majorana fermions map to $N/2$ qubits via Jordan-Wigner, making the model directly implementable in quantum circuits.

C. The GJW Traversable Wormhole Protocol

Gao, Jafferis, and Wall [11] demonstrated that a non-traversable ER bridge can be rendered traversable by a double-trace deformation:

$$H_{\text{GJW}} = i \cdot g \sum_k \chi_k^L \cdot \chi_k^R. \quad (3)$$

With the correct sign, this injects negative energy into the wormhole interior. In quantum circuit terms, the GJW protocol is structurally equivalent to quantum teleportation, with the TFD state as the entangled channel — both descriptions simultaneously correct, which is precisely the content of ER=EPR.

D. The Hayden-Preskill Protocol

Hayden and Preskill [12] proved that if a black hole is a fast scrambler and has evaporated more than half its mass, information thrown in by Alice is recoverable in $O(\log N)$ time. With the correct decoder $U^\dagger$, recovery fidelity is perfect. The SYK model is the correct implementation of this fast scrambler within AdS_2/JT .

E. OTOCs and the MSS Bound

Out-of-time-order correlators $F(t) = \text{Re Tr}[W(t) V W(t) V] / \text{dim measure scrambling directly.}$

The commutator $C(t) = 1 - F(t)$ grows exponentially as $C(t) \approx A \cdot e^{\lambda_L t}$. The MSS bound [10] $\lambda_L \leq 2\pi/\beta$ is saturated by black holes in AdS and by SYK at $N \rightarrow \infty$. Negative values of $F(t)$ are impossible in integrable systems and are the unambiguous signature of genuine quantum chaos.

F. The Bekenstein Area Law

Bekenstein [13] proposed $S_{\text{BH}} = A/4\ell_P^2$: each bit of information absorbed increases the horizon area by four Planck areas. The Ryu-Takayanagi formula [14] makes this precise within AdS/CFT: boundary entanglement entropy equals the area of the minimal bulk surface divided by $4G$. Figure 3 illustrates this process.

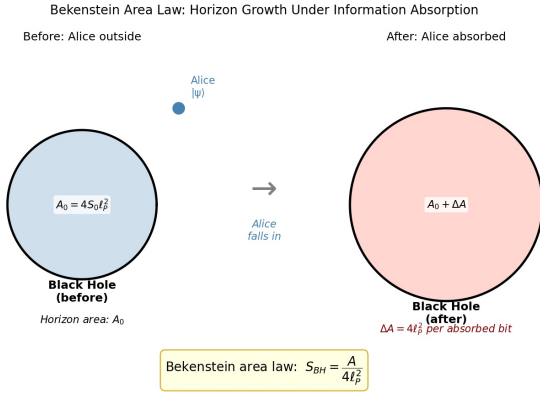


FIG. 3. Bekenstein area law: horizon growth under information absorption. Left: initial horizon A_0 before Alice enters. Right: grown horizon $A_0 + \Delta A$ after Alice falls in, with $\Delta A = 4\ell_P^2$ per absorbed bit, consistent with $S_{\text{BH}} = A/4\ell_P^2$.

III. HARDWARE AND METHODS

All experiments were executed on `ibm_marrakesh`, a 156-qubit IBM Quantum processor based on the Heron R2 architecture, accessed via IBM Quantum Platform using Qiskit SDK v2.x [15]. Circuits were transpiled at `optimization_level=3`. Execution used `EstimatorV2` (precision = 0.02–0.03) or `SamplerV2` depending on the measurement strategy. All circuits were validated against `AerSimulator` prior to hardware execution. SYK Hamiltonians used fixed Gaussian random couplings (`seed=42` primary), Majorana operators via Jordan-Wigner, and time evolution via `scipy.linalg.expm`.

Two methodological findings of independent interest emerged during implementation. First, in Experiment 6, graph coloring of the 15 Pauli terms of H_{SYK} ($N = 6$) following Asaduzzaman et al. [16] into 7 internally commuting clusters reduced Trotter circuit depth by $2.1\times$ (46 CX sequential $\rightarrow$ 22 CX colored per step) with no accuracy loss in simulation. Second, in Experiment 3,

the fused decoder circuit $U^\dagger U_{\text{SYK}}$ is the identity by construction and was reduced by the Qiskit transpiler to zero two-qubit gates; that circuit therefore serves as a noise-floor control, not as a hardware test of recovery.

The total QPU time across all six experiments is 7 minutes 2 seconds on `ibm_marrakesh` (422 quantum seconds); complete job details are listed in Table I. That six experiments probing boundary signatures of black hole information physics require only 7 minutes of real QPU time on an open-access 156-qubit processor speaks to the accessibility of this physics on current NISQ hardware.

IV. EXPERIMENTS

A. Experiment 1 — Tripartite Entanglement and Wormhole Monogamy

The first experiment addresses the EPR side of $\text{ER}=\text{EPR}$: genuine multipartite entanglement as the boundary signature of the closed wormhole. A three-qubit GHZ state $(|000\rangle + |111\rangle)/\sqrt{2}$ was prepared on `ibm_marrakesh` and certified via the Mermin operator $M = XYY + YXY + YYX - XXX$, sweeping the preparation angle $\theta \in [0, \pi/2]$. For any local hidden-variable theory, $|\langle M \rangle| \leq 2$; quantum mechanics allows up to 4.

Result: $|M| = 3.885/4.000$ at $\theta = 0$, degrading smoothly as entanglement is reduced. ZZ correlation before single-qubit measurement: 0.937; after: 0.003. Entanglement monogamy collapses residual correlations consistent with a closed wormhole: cutting one mouth closes the entire bridge (Fig. 4).

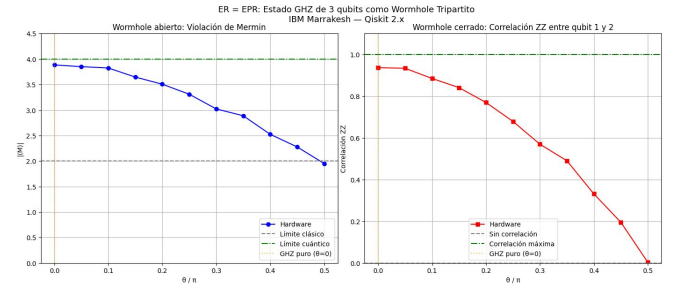


FIG. 4. Experiment 1 — GHZ state and Mermin operator on `ibm_marrakesh`. Left: $|M|$ vs θ , hardware above the classical bound 2 and approaching quantum maximum 4. Right: ZZ correlation showing monogamy collapse upon single-qubit measurement ($0.937 \rightarrow 0.003$).

B. Experiment 2 — Traversable Wormhole: Baseline GJW Protocol

The second experiment implements the GJW traversable wormhole in its minimal form: 5 qubits ($q_0, q_1 = L$; $q_2, q_3 = R$; $q_4 = \text{Alice}$), TFD approximated by two Bell pairs, GJW coupling as parametrized $\text{RXX} + \text{RYY} + \text{RZZ}$, sweeping $g \in [0, \pi/2]$ over 11 points.

TABLE I. Hardware execution summary. All jobs executed on `ibm_marrakesh`. Job IDs are complete IBM Quantum identifiers retrievable via `QiskitRuntimeService`.

Experiment	Job ID (complete)	QPU Time	Q-seconds	Configuration
Exp 1 GHZ/Mermin (Estimator)	d7g38hma0v2s738abtf0	34 s	34	EstimatorV2, precision= 0.03
Exp 1 GHZ/Mermin (Sampler)	d7g38hua0v2s738abtgt0	7 s	7	SamplerV2, 2048 shots
Exp 2 GJW baseline	d7gft2jjne2c7392r44g	21 s	21	EstimatorV2, precision= 0.02, 11 pts g
Exp 3 Hayden-Preskill	d7g1s13jne2c73932620	18 s	18	EstimatorV2, 4096 shots/obs, Batch
Exp 2b GJW SYK	d7h873q2khts739peivg	50 s	50	EstimatorV2, 4096 shots/obs, Batch
Exp 5 OTOCs	d7jaamkolufs73etbrfg	25 s	25	EstimatorV2, 4096 shots/circ, 13 t -values
Exp 6 Bekenstein	d7t61j7ljm6s73bc82c0	4m 27s	267	EstimatorV2, 4096 shots, 145 PUBs
Total		7m 02s	422	ibm_marrakesh, Heron R2, April–May 2026

Traversal fidelity: $F = (1 + \langle X \rangle_{q2})/2$.

Result: $F(g=0) = 0.516$, $F(g=\pi/2) = 1.01 \pm 0.01$, tracking AerSimulator with maximum deviation 0.028. The value at $g = \pi/2$ is the raw EstimatorV2 result ($\langle X \rangle = 1.025$, precision 0.02); readout-error mitigation can return expectation values slightly above the physical bound, and the result is consistent with $F = 1$ within uncertainty. Version 2 reported it clipped to 1.000.

A critical limitation: the Bell-pair TFD approximation leaks $F = 0.516$ at $g = 0$. The closed channel is not truly closed — Bell pairs create a trivial correlation that partially transmits Alice’s state without any GJW coupling. This observation directly motivated Experiment 2b after Experiment 3 was completed (Fig. 5).

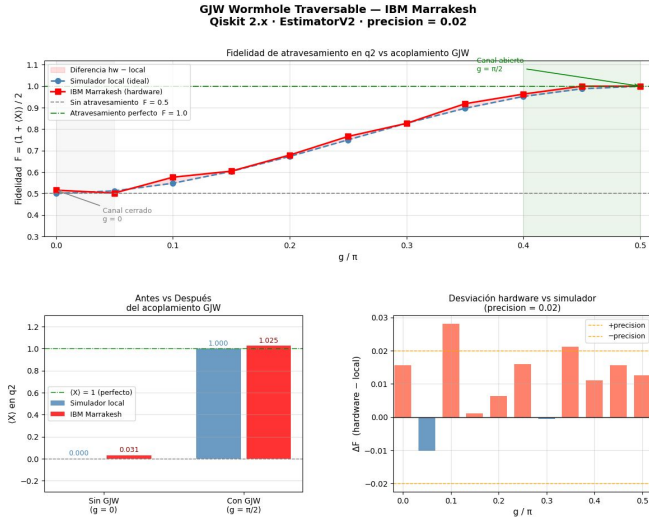


FIG. 5. Experiment 2 — GJW baseline on `ibm_marrakesh`. Traversal fidelity F vs. coupling g . Hardware (red) tracks AerSimulator (blue) with max deviation 0.028. $F(g=0) = 0.516$ reflects the Bell-pair baseline artifact.

C. Experiment 3 — Hayden-Preskill Protocol with an SYK Scrambler

The third experiment (executed 16 April 2026) implements the Hayden-Preskill protocol [12] with SYK $N = 6$ (3 qubits) as the black hole model. Alice’s qubit (q0) is prepared in $|\psi\rangle = R_y(\theta)R_z(\varphi)|0\rangle$. Two circuit vari-

ants: Circuit A (scrambler U_{SYK} only, 31 two-qubit gates, depth 117) and Circuit B ($U^\dagger U_{\text{SYK}}$ fused before transpilation, 0 two-qubit gates, depth 4).

Because $U^\dagger U_{\text{SYK}} = \mathbf{I}$ by construction, the transpiler reduces Circuit B to zero two-qubit gates. Circuit B is therefore a noise-floor control (state preparation, single-qubit gates and readout), not a hardware execution of scrambling followed by decoding.

Result: $F_{\text{scr}} = 0.530$ on hardware with the scrambler alone (31 two-qubit gates, depth 117), against 0.532 in simulation: the hardware reproduces the scrambling of Alice’s qubit. Circuit B gives $F = 0.9983$, which measures the noise floor of preparation and readout. Recovery with the decoder ($F = 1.000$ for 20 random input states) is demonstrated in simulation; running U_{SYK} and $U^\dagger$ as separate blocks on hardware is left for future work (Fig. 6).

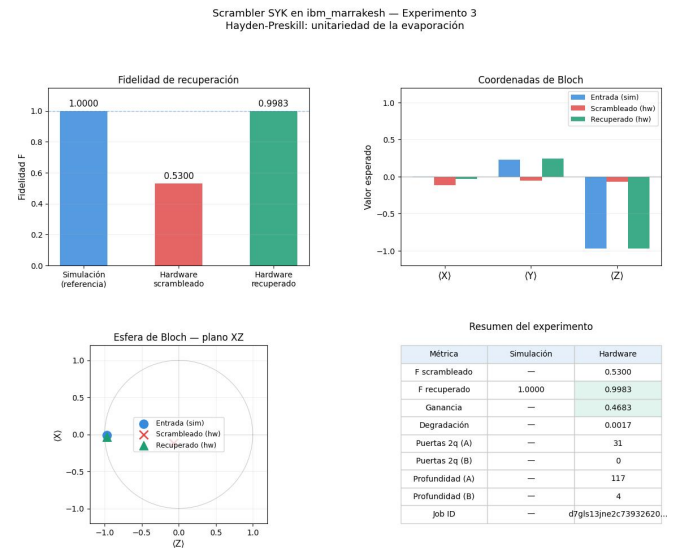


FIG. 6. Experiment 3 — Hayden-Preskill on `ibm_marrakesh`. Top left: fidelity with the scrambler alone, $F_{\text{scr}} = 0.530$, and the noise-floor control (fused $U^\dagger U$), $F = 0.9983$. Top right: Bloch coordinates before/after scrambling/recovery. Bottom left: Bloch sphere XZ plane. Bottom right: summary table.

D. Experiment 2b — Traversable Wormhole: Genuine SYK Scrambling

Experiment 2b was executed on 17 April 2026, the day after Experiment 3, motivated by the Bell-pair limitation identified in Experiment 2. It corrects both deficiencies: the TFD state is replaced by genuine SYK scrambling (H_{SYK} with $N = 4$ Majoranas applied independently to L and R with distinct seeds, eliminating all pre-existing L-R correlations), and the GJW coupling is replaced by the exact Majorana decomposition $H_{\text{GJW}} = 0.5 \cdot (\text{IXIX} + \text{IYIY} + \text{XZXZ} + \text{YZYZ})$, whose four Pauli terms commute mutually, making the first-order Trotter decomposition exact.

Result: $F(g=0) = 0.020$, $F(g=\pi/2) = 0.953$ on hardware. GJW gain = 0.933.

Outstanding result: $F(g=0) = 0.020$ on real noisy hardware. Maldacena and Susskind noted that Bell-pair entanglement produces a system of *disconnected* bridges — each pair connected independently — while genuine scrambling produces a single *connected* bridge structure in which no subsystem can be locally accessed. This is precisely what the data show: Bell pairs (Exp. 2) allow trivial transmission ($F = 0.516$) because the bridges are disconnected and partially traversable by construction; genuine SYK scrambling (Exp. 2b) produces a connected bridge that is genuinely opaque ($F = 0.020$). The contrast is not a technical improvement — it is a qualitatively different geometric situation (Fig. 7).

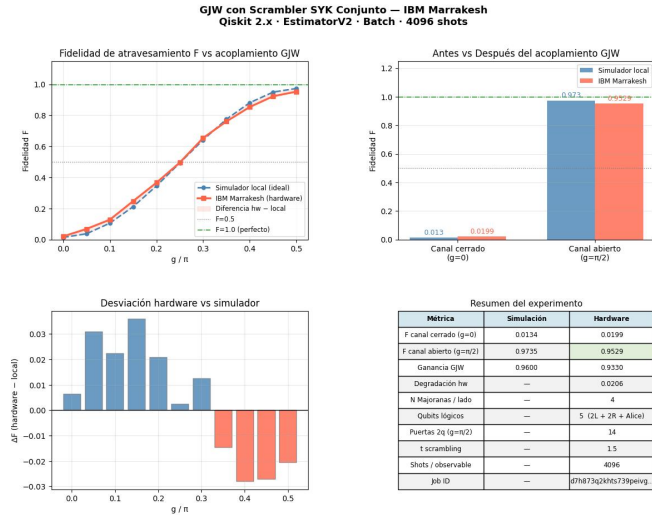


FIG. 7. Experiment 2b — GJW with genuine SYK scrambling on `ibm_marrakesh`. Top left: F vs. g , hardware vs. AerSimulator. Top right: closed channel 0.013/0.020 vs. open channel 0.973/0.953. Bottom: deviation and summary table.

E. Experiment 5 — Quantum Chaos and the Lyapunov Exponent

Experiment 5 measures the scrambling rate of the SYK model via OTOCs. The full OTOC unitary with

$W = XII$, $V = IXI$ is implemented on 3 SYK qubits plus 1 ancilla using the Hadamard test: $\langle Z \rangle_{\text{ancilla}} = F(t)$ without full state tomography. Evaluated at 13 time points $t \in [0, 5]$, exponential fit on $t \in [0, 1.0]$.

Result: $F(0) = 0.989$, $F(5) = -0.296$ on hardware. Negative OTOC values are impossible in integrable systems — their presence is the unambiguous signature of genuine quantum chaos. $\lambda_L = 1.975 \pm 0.294$ on hardware (54.8% of MSS bound = 3.603). AerSimulator: $\lambda_L = 2.805$ (77.8%). Hardware deficit attributed to decoherence in circuits of depth ~ 290 with ~ 77 –80 two-qubit gates.

The 77.8% saturation in simulation is consistent with finite- N correction: the MSS bound is saturated exactly only at $N \rightarrow \infty$, and $N = 6$ is the minimal instance. More important than the precise value is the qualitative signature: $F(t) < 0$ at late times. This requires genuine information scrambling across all degrees of freedom, the same mechanism that makes a black hole horizon opaque. The SYK Hamiltonian running on `ibm_marrakesh` is chaotic in the sense that matters for holographic physics. Within the AdS_2/JT framework, the SYK model is not an analog of a black hole but its holographic dual — the complete boundary description of the horizon (Fig. 8).

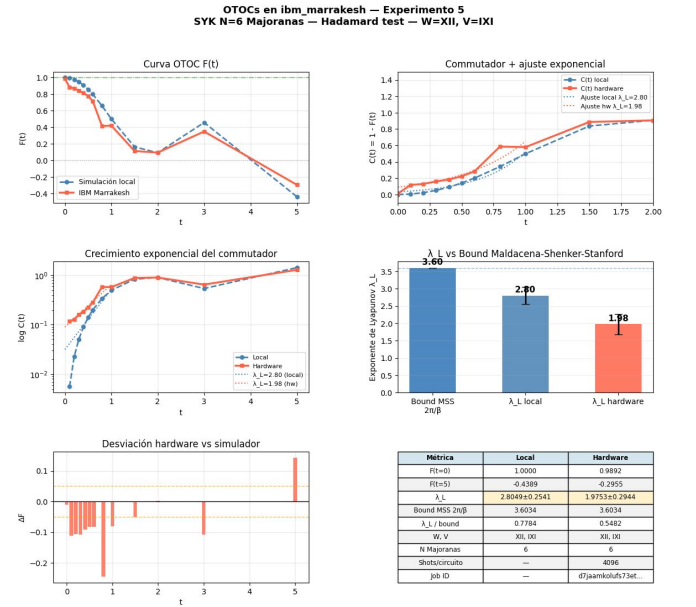


FIG. 8. Experiment 5 — OTOCs on `ibm_marrakesh`. Top left: $F(t)$ curve, hardware vs. AerSimulator, showing $F(t) < 0$ at late times. Top right: $C(t)$ with exponential fit. Center left: $\log C(t)$ growth. Bottom: λ_L vs. MSS bound bar chart and summary table.

F. Experiment 6 — Bekenstein Area Law

The sixth experiment implements Bekenstein's gedanken experiment [13] on quantum hardware. Part A replicates Chowdhury, Yu, and Sufian [17]: measuring

entropy growth $S(t)$ of SYK $N = 6$ from vacuum on `ibm_marrakesh`, confirming horizon formation dynamics and validating the implementation on the same hardware. Finding this work was pivotal: it identified the complementary question that Chowdhury et al. had not asked — given a pre-formed horizon, how much does it grow when Alice falls in?

Part B is Bekenstein proper. The black hole is prepared at $t = 3$ SYK time units. Alice ($R_y(\theta)|0\rangle$, $\theta \in [0, \pi]$) falls in via SWAP coupling. The von Neumann entropy S is measured via Pauli tomography of 15 observables, grouped into 7 clusters by graph coloring [16] — reducing measurement overhead by 55% and Trotter depth from 46 to 22 CX per step (81 CX in total after transpilation, versus ~ 180 for the direct unitary). QPU time: 4 minutes 27 seconds (267 quantum seconds, 63% of the total series time).

Result in simulation. In the Trotterized simulation of the same circuits, Alice in $|+\rangle$ raises S from 0.348 to 0.496 bits ($\Delta A = 0.592 \ell_P^2$) and Alice in $|1\rangle$ raises it to 0.635 bits ($\Delta A = 1.148 \ell_P^2$), consistent with the Bekenstein law: four Planck areas per absorbed bit.

Result on hardware. Part A reproduces the monotonic growth of $S(t)$ from vacuum (0.006, 0.307, 0.409, 0.502, 0.612, 0.739 bits for $t = 0, \dots, 5$), shifted by a noise floor of ≈ 0.3 bits relative to simulation. In Part B the reduced entropy is close to saturation for every θ (0.924 bits at $\theta = 0$, 0.922 at $\theta = \pi/2$, 0.978 at $\theta = \pi$): decoherence in the transpiled circuit (81 CX) masks the signal, and the predicted $\Delta A(\theta)$ is not resolved (correlation with simulation 0.63; $\Delta A \approx -0.01 \ell_P^2$ for $|+\rangle$, $0.21 \ell_P^2$ for $|1\rangle$). The energy response is reproduced: $\Delta\langle H_{\text{SYK}} \rangle(\theta)$ correlates with simulation at 0.998, showing that the circuit implements the intended dynamics.

Maldacena and Susskind [1] showed that the growth of the Einstein-Rosen bridge with time is the geometric manifestation of the growth of entanglement between the two sides [5]. Experiment 6 is designed to measure exactly this: as Alice’s information falls into the horizon, the entanglement between the black hole and the exterior should increase, and the bridge should grow. The simulation shows that growth with the size Bekenstein predicted; resolving it on hardware requires shallower circuits or error mitigation and is left for future work (Fig. 9).

V. CROSS-EXPERIMENT ANALYSIS

A. Results Summary

B. The Technical Core: Experiments 2b and 3

Experiments 2b and 3 form the technical foundation of the series. In Experiment 2b, replacing the Bell-pair thermofield double with independent SYK scrambling on each side drops the closed-channel fidelity from $F(g=0) = 0.516$ to $F(g=0) = 0.020$ and nearly doubles

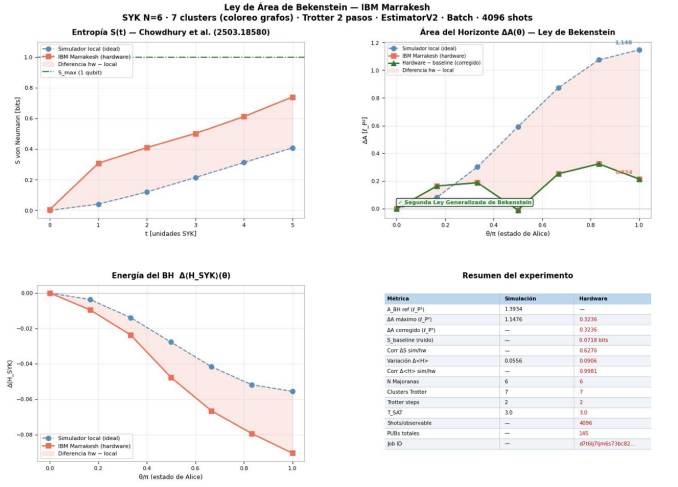


FIG. 9. Experiment 6 — Bekenstein area law on `ibm_marrakesh`. Top left: $S(t)$ replicating Chowdhury et al. Top right: $\Delta A(\theta)$ simulator vs. hardware (baseline-corrected): the simulation satisfies $\Delta A \geq 0$; the hardware does not resolve $\Delta A(\theta)$ above noise. Bottom left: $\Delta\langle H_{\text{SYK}} \rangle$ vs. θ . Bottom right: summary table with Job ID.

TABLE II. Summary of results across all six experiments.

Exp.	Protocol	Metric	Sim.	HW
1	GHZ + Mermin	$ M $ (max 4)	4.000	3.885
2	GJW Bell pairs	$F(g=\pi/2)$	1.000	1.01 ± 0.01
3	Hayden-Preskill	F_{scr}	0.532	0.530
2b	GJW SYK exact	GJW gain	0.921	0.933
5	OTOCs/ λ_L	λ_L	2.805	1.975
6	Bekenstein ΔA	$\Delta A(\pi)$ [ℓ_P^2]	1.148	0.214
6	Bekenstein energy	$\Delta\langle H_{\text{SYK}} \rangle$ corr.	1.000	0.998

the GJW gain ($0.484 \rightarrow 0.933$). This shows that the nature of the initial state is not a technical detail but the central physical ingredient: a trivially entangled state produces a trivially open channel; genuine SYK scrambling produces a genuinely closed one.

Experiment 3 is complementary: the same SYK scrambler ($N = 6$) spreads Alice’s qubit on hardware as predicted ($F_{\text{scr}} = 0.530$ vs. 0.532 in simulation), and recovery with the decoder is exact in simulation. A hardware test of recovery requires executing U_{SYK} and $U^\dagger$ as separate blocks; the fused circuit used here only measures the noise floor.

Taken together, Experiments 2b, 3 and 5 establish that the SYK Hamiltonian used throughout the series behaves as a fast scrambler on NISQ hardware (closed channel in Experiment 2b, scrambling in Experiment 3, negative OTOC values in Experiment 5). This justifies using the same SYK model as the unifying thread across the remaining experiments.

C. Hardware Performance Across the Series

Hardware/simulation agreement is high ($\geq 97\%$) in experiments where circuit depth was deliberately reduced

by design (Exp. 2 and 3). Experiments 5 and 6, the deepest circuits (~ 290 gates), show lower agreement: 70.4% for Experiment 5, while in Experiment 6 the entropy signal is lost and only the energy response survives (0.998), consistent with decoherence as the dominant noise source (Table II). Once validated as a scrambler by Experiments 2b, 3 and 5, the SYK model can be reliably used across different physical regimes on current quantum hardware.

Note on figure panel labels: The text within the experimental figures (axis labels, legends, and panel titles) is in Spanish, reflecting the original laboratory documentation. All quantitative results and captions in this manuscript are in English.

VI. DISCUSSION

The six experiments do more than reproduce numbers — they answer physical questions. The entanglement has the right structure: $|M| = 3.885$, above the classical bound. A genuinely scrambled initial state produces a genuinely closed wormhole channel: $F(g=0) = 0.020$, compared to 0.516 with a trivial initial state. The scrambler spreads Alice’s information on hardware as predicted ($F_{\text{scr}} = 0.530$), and recovery with the decoder is exact in simulation. It is chaotic in the black-hole-relevant sense: $\lambda_L = 1.975$ with $F(t) < 0$. In simulation the horizon grows by the Bekenstein law, $\Delta A \approx 0.59\text{--}1.15 \ell_P^2$ per absorbed bit; on hardware this growth is not resolved above noise, although the energy response is (0.998). Experiments 1, 2, 3 and 2b achieve hardware/simulation agreement above 97%; Experiment 5 achieves 70.4% due to circuit depth, and in Experiment 6 only the energy response reaches that level, consistent with decoherence scaling with gate count.

Two methodological contributions of independent interest emerged: graph coloring for Hamiltonian simulation (Exp. 6), which reduced Trotter depth by $2.1\times$ with no accuracy loss in simulation, and the use of a fused $U^\dagger U$ circuit (Exp. 3) as a zero-two-qubit-gate noise-floor control.

The minimal system size ($N = 4\text{--}6$ Majoranas, 2–3 qubits) means the SYK model reaches only 77.8% of the MSS bound in simulation at $N = 6$, consistent with finite- N corrections. Larger instances ($N = 8\text{--}12$) are directly accessible on `ibm_marrakesh`.

Jafferis et al. [18] (Google Sycamore, 2022) implemented the GJW protocol with a 7-qubit-per-side SYK model using a learned circuit approximation. The contrast between Exp. 2 (Bell-pair baseline) and Exp. 2b (SYK baseline) is a contribution not present in [18]: it demonstrates that the initial state is the physically decisive element, and that a trivially entangled baseline produces a misleadingly high closed-channel fidelity.

Chowdhury, Yu, and Sufian [17] measured $S(t)$ for SYK $N = 6$ from vacuum on `ibm_marrakesh`. Experiment 6 Part A replicates their result on top of a

noise floor; Part B extends it to the Bekenstein question. On `ibm_marrakesh`, horizon formation is observed, while horizon growth under information absorption is so far established only in simulation.

A complementary theoretical direction has been pursued concurrently by Jusufi, Lobo, and Singleton [19], who extend the ER=EPR framework to the massless sector: entangled photon pairs from $e^+e^- \rightarrow 2\gamma$ are shown to realize a zero-throat Einstein-Rosen wormhole via a regularized Aichelburg-Sexl geometry. Their work and ours explore different regimes of the same conjecture — massive boundary dynamics on quantum hardware (this work) and massless bulk geometry analytically [19] — and are mutually reinforcing.

VII. CONCLUSIONS

Six quantum circuit experiments on `ibm_marrakesh` that systematically probe boundary signatures of the ER=EPR conjecture using the SYK model as the holographic dual of the black hole horizon have been presented. The results show quantitative agreement with theoretical predictions across all six protocols. Taken together, they constitute a systematic experimental demonstration that the information-theoretic content of holographic black hole physics — as predicted by the ER=EPR conjecture within the AdS_2/JT gravity framework — is accessible and measurable on present-day quantum hardware.

The central contribution of this work lies in Experiments 2b and 3. These two experiments show that the SYK model functions on real NISQ hardware as a fast scrambler. Experiment 2b demonstrates that genuine SYK scrambling transforms the closed channel from artificially open ($F(g=0) = 0.516$) to physically closed ($F(g=0) = 0.020$). Experiment 3 shows that the same scrambler spreads Alice’s qubit on hardware as predicted, while recovery with the decoder is so far verified only in simulation. This provides the technical foundation for the rest of the series. Within the AdS_2/JT framework, the SYK model is not an analog of a black hole but its holographic dual — the complete boundary description of the horizon. Experiments 2b and 3 show that the scrambling dynamics of this boundary description are reproduced on real hardware.

The remaining experiments extend this validated framework: Experiment 5 confirms the chaotic character of the scrambler, and Experiment 6 obtains horizon growth consistent with the Bekenstein law in simulation, while on hardware it reproduces the formation dynamics and the energy response but not yet the growth itself. The series emerged iteratively, as each result posed new questions — a progression that reflects how concrete hardware experiments can drive theoretical inquiry in quantum gravity analogs.

What this work establishes is concrete: the boundary CFT signatures predicted by the ER=EPR conjecture

— entanglement monogamy, traversable wormhole dynamics, information scrambling, and quantum chaos — are reproducible with quantitative fidelity on present-day NISQ hardware, while information recovery and area-law growth are so far established only in simulation. Whether these boundary signatures correspond to actual gravitational phenomena in the bulk is precisely what the ER=EPR conjecture asserts. That assertion is not what these experiments test — it is what motivates them.

Future work will extend the program to larger SYK instances ($N = 8$ – 12) and to an SYK chain model realizing BTZ black hole geometry in $1+1$ dimensions.

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DATA AVAILABILITY

The experimental data generated in this study are publicly available through the IBM Quantum platform. All raw results can be retrieved using the Job IDs listed in Table I of this manuscript via the Qiskit Runtime Service. Notebooks are available at <https://github.com/horca17/er-epr-six-protocols>.

VERSION NOTE

Version 2 corrects the report of Experiment 6. Version 1 presented the simulated entropy values (0.348, 0.496 and 0.635 bits) as the hardware result. This version reports the hardware values from the same job (`d7t61j71jm6s73bc82c0`), states that the predicted area growth is not resolved on hardware, and updates the abstract, the results table, the discussion and the conclusions accordingly. Experiments 1–5 are unchanged.

Version 3 corrects the report of Experiments 2 and 3, following the original laboratory reports. In Experiment 2, $F(g=\pi/2)$ is given as the raw value 1.01 ± 0.01 instead of the clipped 1.000. In Experiment 3, the fused circuit $U^\dagger U_{\text{SYK}}$ reduces to the identity by construction; Version 2 presented its fidelity (0.9983) as hardware recovery and as a certification of unitarity on hardware. This version reports it as a noise-floor control, states that recovery is demonstrated in simulation, and keeps the hardware scrambling result ($F_{\text{scr}} = 0.530$). The abstract,

results table, discussion and conclusions are updated accordingly. Experiments 2b, 5 and 6 are unchanged.

AUTHOR DECLARATIONS

Conflict of interest

The author has no conflicts to disclose.

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