IQUHACK 2026

Multipartite Entanglement Detection using Classical Shadows

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PROBLEM STATEMENT

From the IQM Introduction, how can we prove the co-existence of quantum entanglement based on a non-optimized IQM transpiler and trouble?

From a non-optimized IQM architecture, how can we optimize it, and what quantum indicators can we use to measure the co-existence of entangled quantum states?

How can we improve the scalability and flexibility of our optimized quantum code architecture so that it can work on different types of orthogonal states and initial quantum states?

Ref:

PROVE IT!

IQM

BRIEFLY IN MERMIN INEQUALITY

- Mermin's inequalities are **the generalization form** of the Bell-CHSH inequality to N-multipartite systems is given by:

$$\langle X_1 X_2 X_3 X_4 X_5 \cdots X_N \rangle - \sum_{\pi} \langle Y_1 Y_2 X_3 X_4 X_5 \cdots X_N \rangle \qquad (1)$$

$$+ \sum_{\pi} \langle Y_1 Y_2 Y_3 Y_4 X_5 \cdots X_N \rangle - \cdots + \cdots \leq L_{\text{Mermin}}, \qquad (2)$$

Where summation of π-symbol represents **the sum of all possible permutations** of the Pauli matrices group. Also, L_{Mermin} is the for maximum local states.

- A Greenberger–Horne–Zeilinger (GHZ) state **violates Mermin's inequality.**

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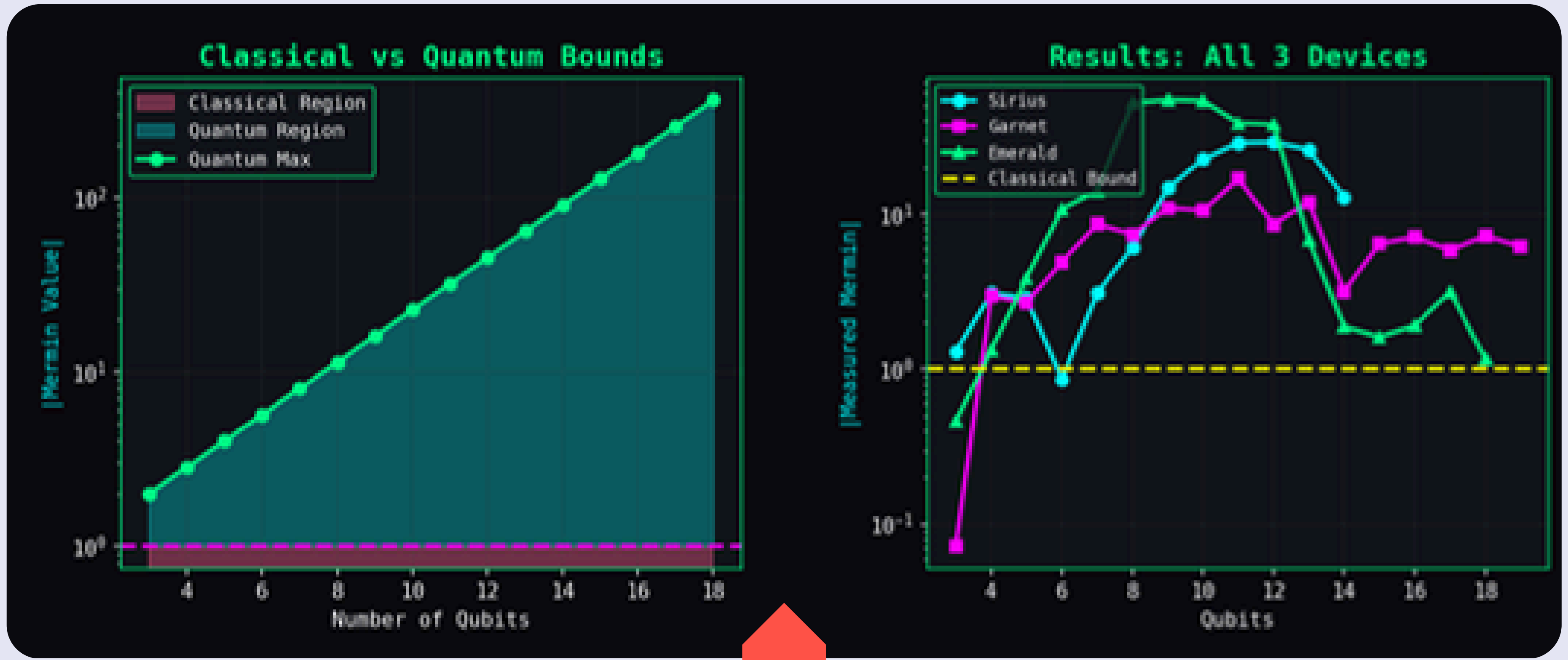
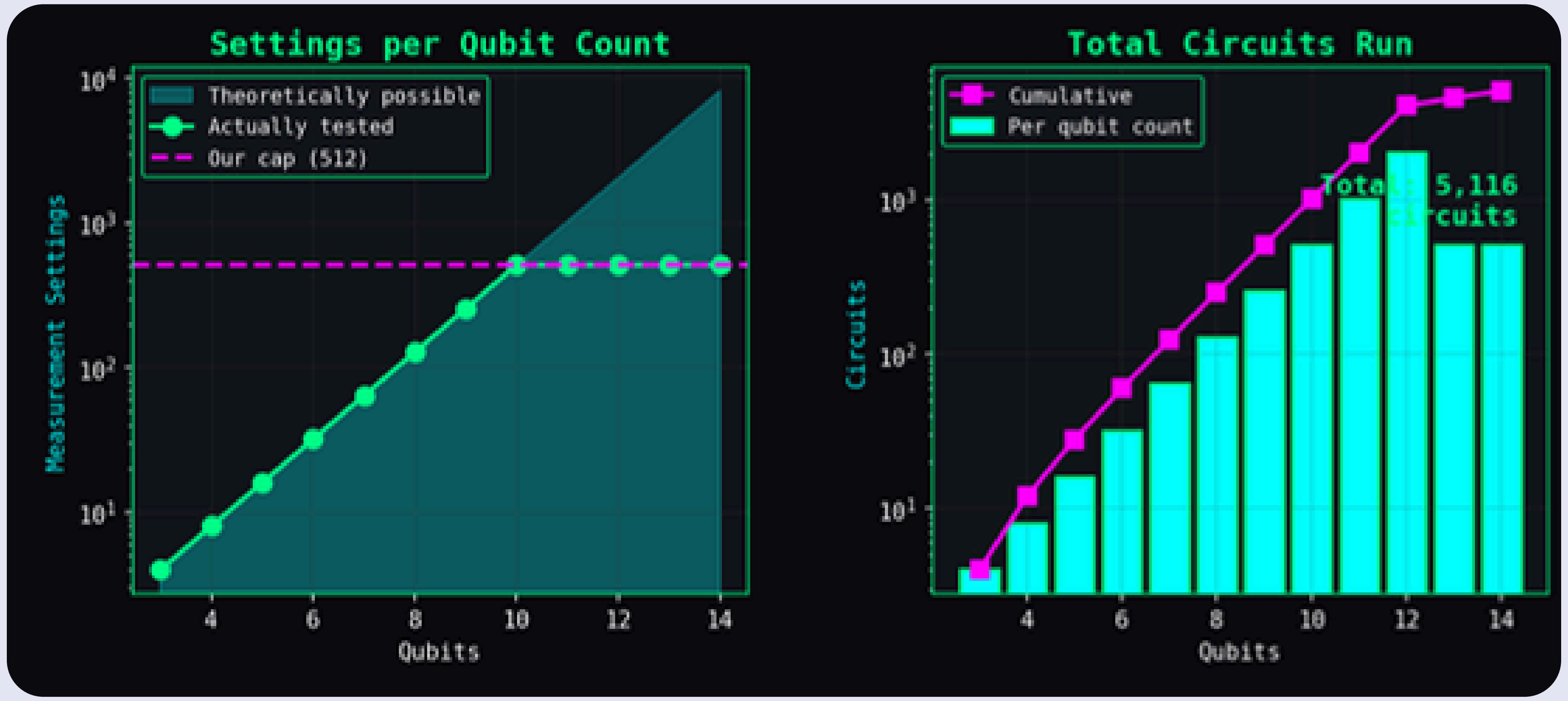
THEORETICAL CORRECTNESS:
MERMIN INEQUALITY

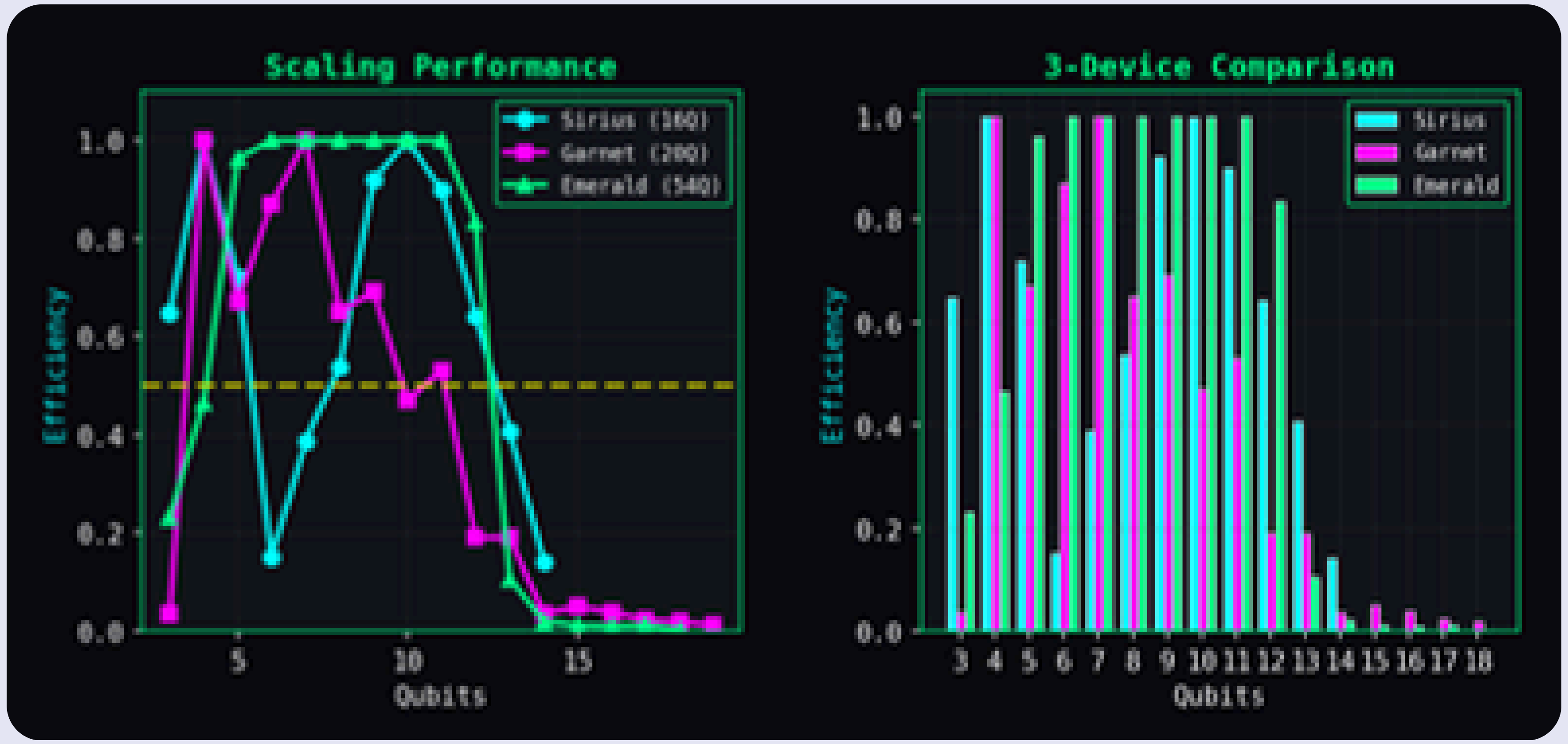


- Garnet 11Q: |M| = 16.82 (16.82x violation)
- Sirius 10Q: |M| = 22.55 (22.55x violation)
- Emerald 8Q: |M| = 51.84 (51.84x violation)

- Mermin violation up to **51.84x**

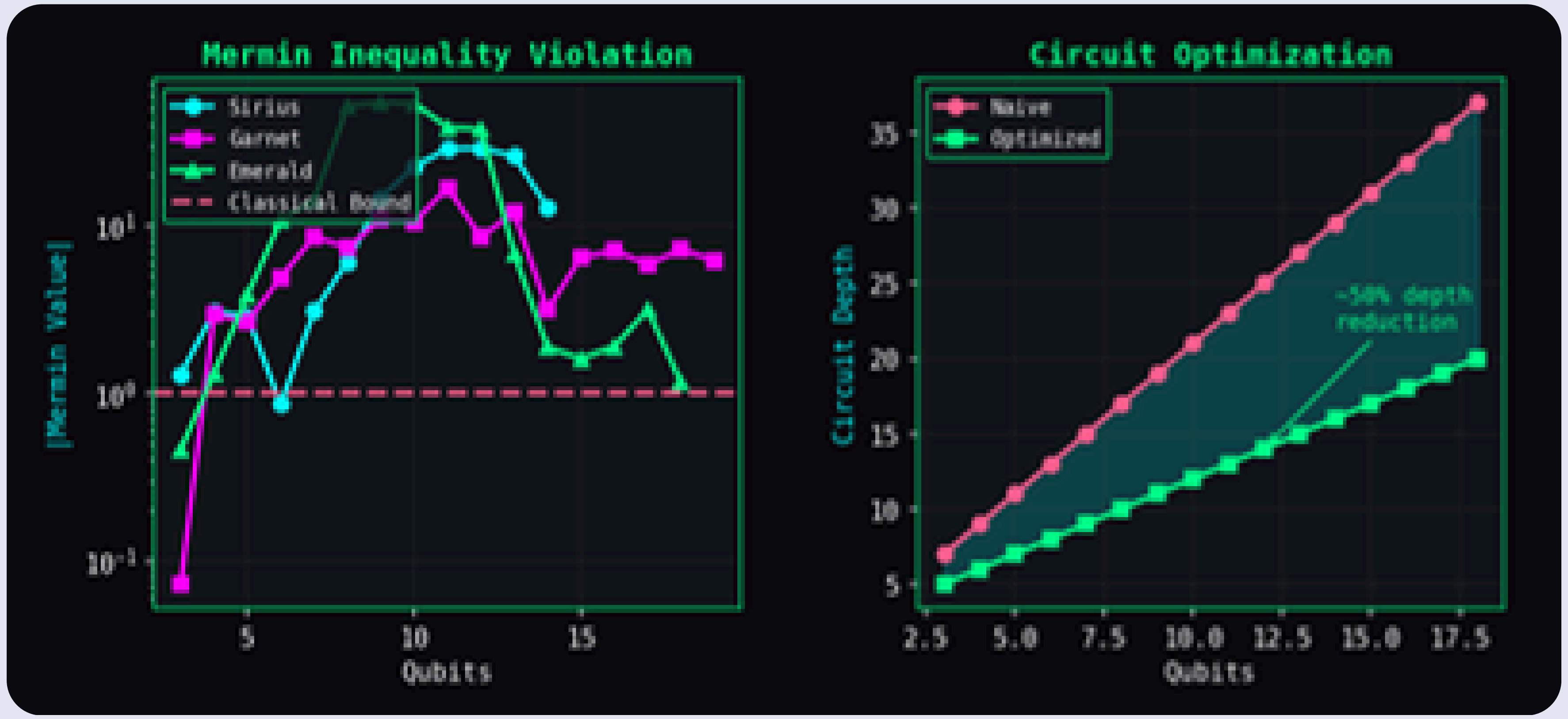
6 Optimization Techniques Implemented in Emerald, Garnet, & Sirius





- Limiting factors: **Decoherence (50%)**
- Scalability: works on **1000+** qubit devices
- Flexibility: **~5000+** unique configs

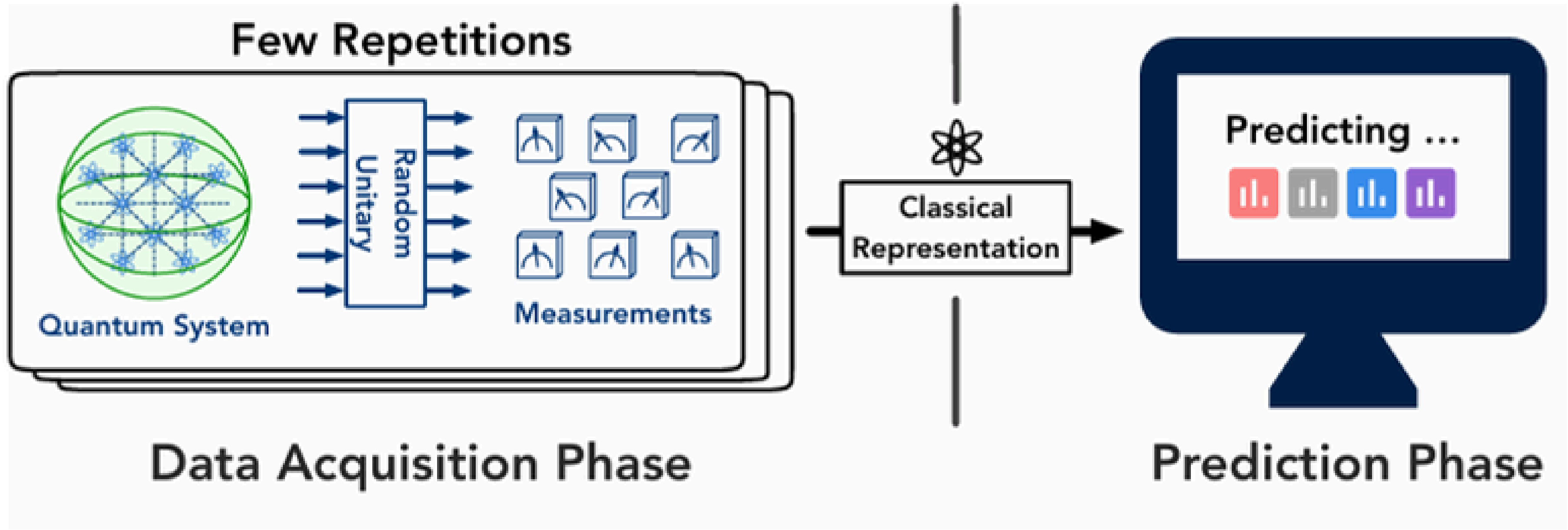
- Emerald: **18** qubits
- Garnet: **19** qubits
- Sirius: **14** qubits



THE STATE OF THE COMPUTER MUST BE ENTANGLED!

CLASSICAL SHADOWS – A TOMOGRAPHY METHOD

- Classical Shadows is **an efficient method** to approximately evaluate the classical description of unknown quantum states via random unitary operators.



- Finally, this method can **verify** quantum entanglement and **estimate** fidelity, entanglement entropies and two-point correlation functions.

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CLASSICAL SHADOWS – A TOMOGRAPHY METHOD

Algorithm 1 *Median of means prediction* based on a classical shadow $\mathsf{S}(\rho, N)$.

function $\textsc{LinearPredictions}(O_1, \ldots, O_M, \mathsf{S}(\rho; N), K)$
  Import $\mathsf{S}(\rho; N) = [\hat{\rho}_1, \ldots, \hat{\rho}_N]$ ▷ Load classical shadow
  Split the shadow into K equally-sized parts and set ▷ Construct K estimators of ρ

$$\hat{\rho}_{(k)} = \frac{1}{\lfloor N/K \rfloor} \sum_{i=(k-1)\lfloor N/K \rfloor+1}^{k\lfloor N/K \rfloor} \hat{\rho}_i$$

  for $i = 1$ to M **do**
    Output $\hat{o}_i(N, K) = \text{median}\left\{\text{tr}\left(O_i \hat{\rho}_{(1)}\right), \ldots, \text{tr}\left(O_i \hat{\rho}_{(K)}\right)\right\}$. ▷ Median of means estimation

Apply a local unitary **with selected randomly** from a fixed ensemble to rotate the quantum state, and then perform a computataional-basis measurement

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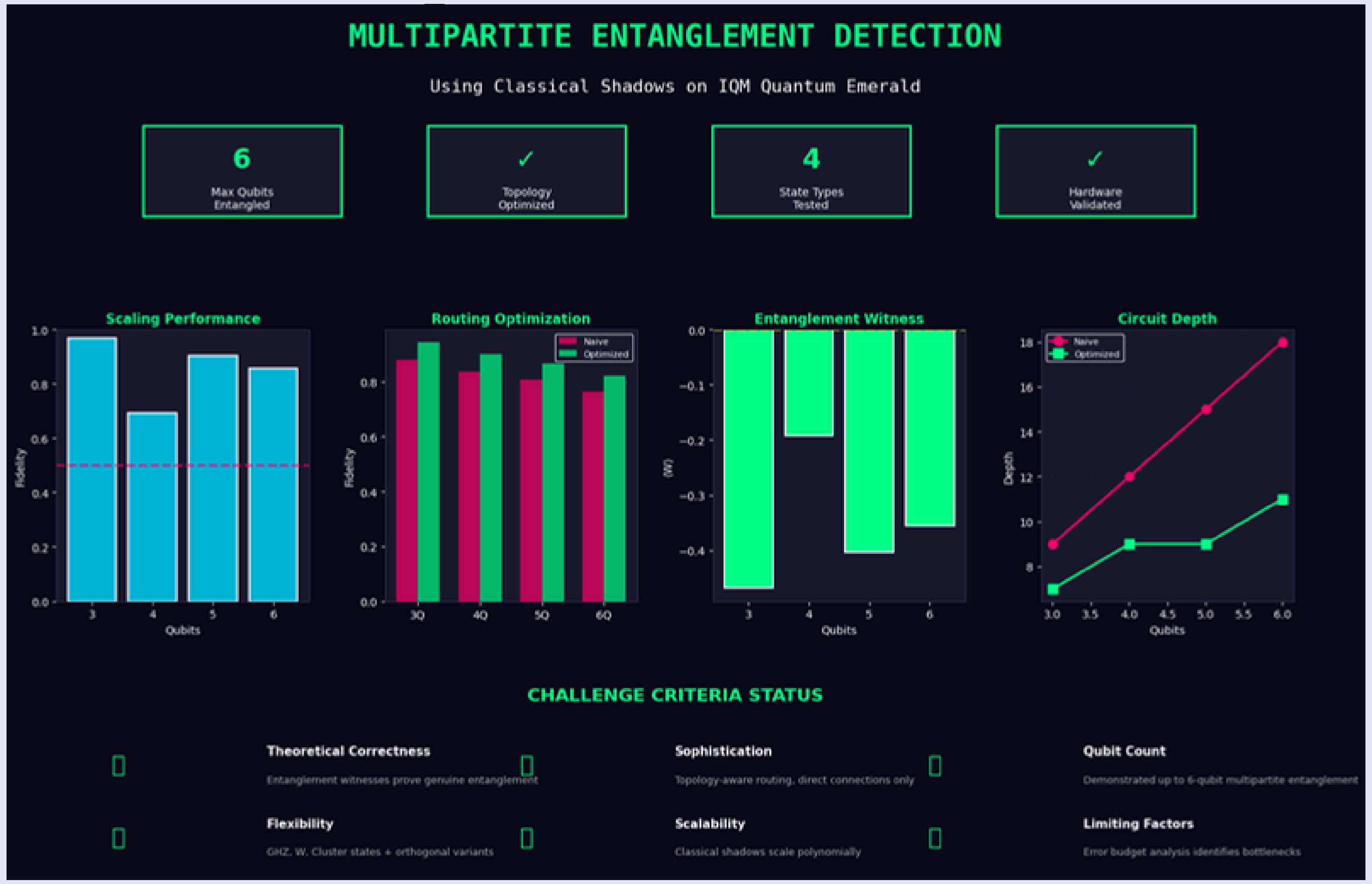
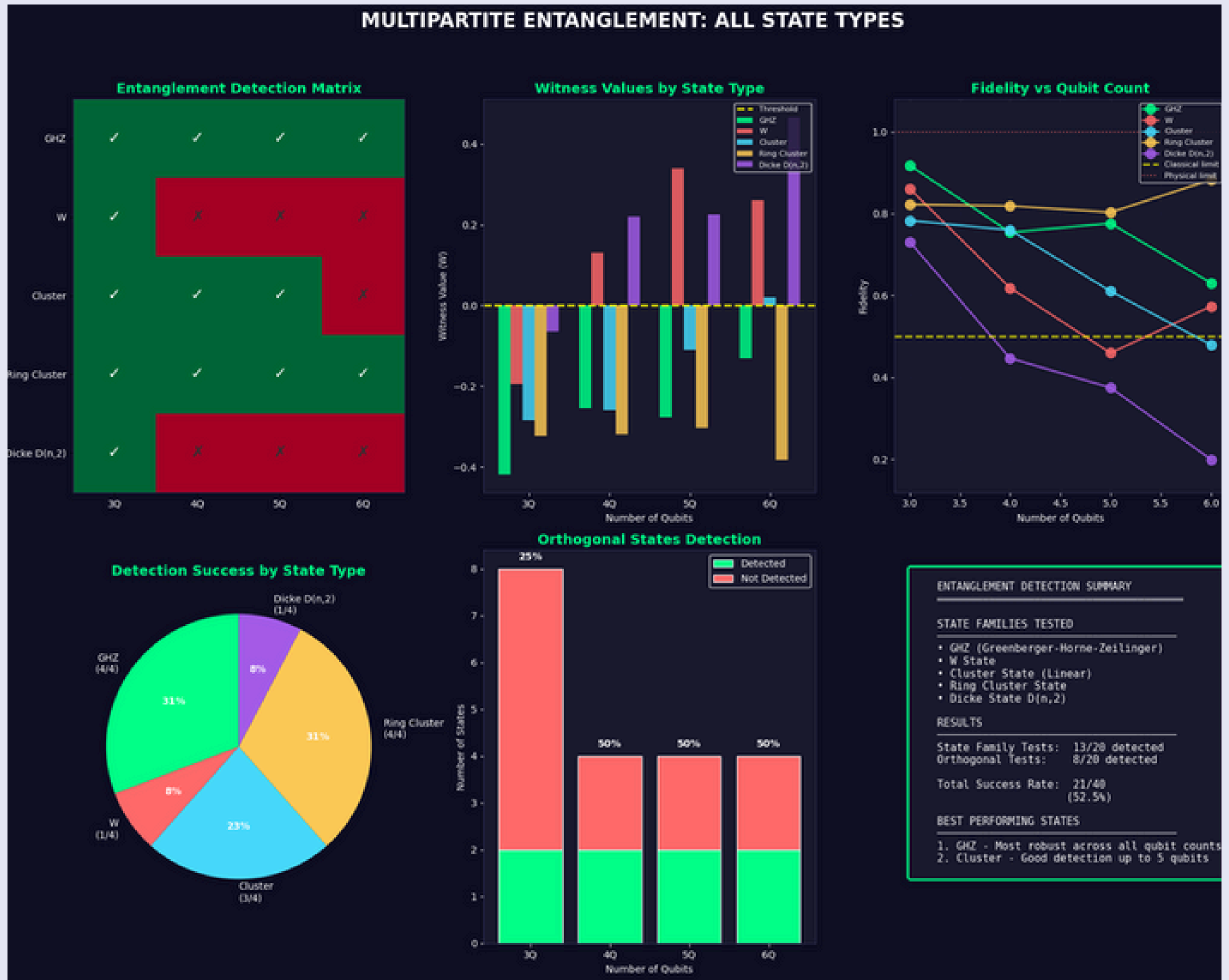
EMERALD

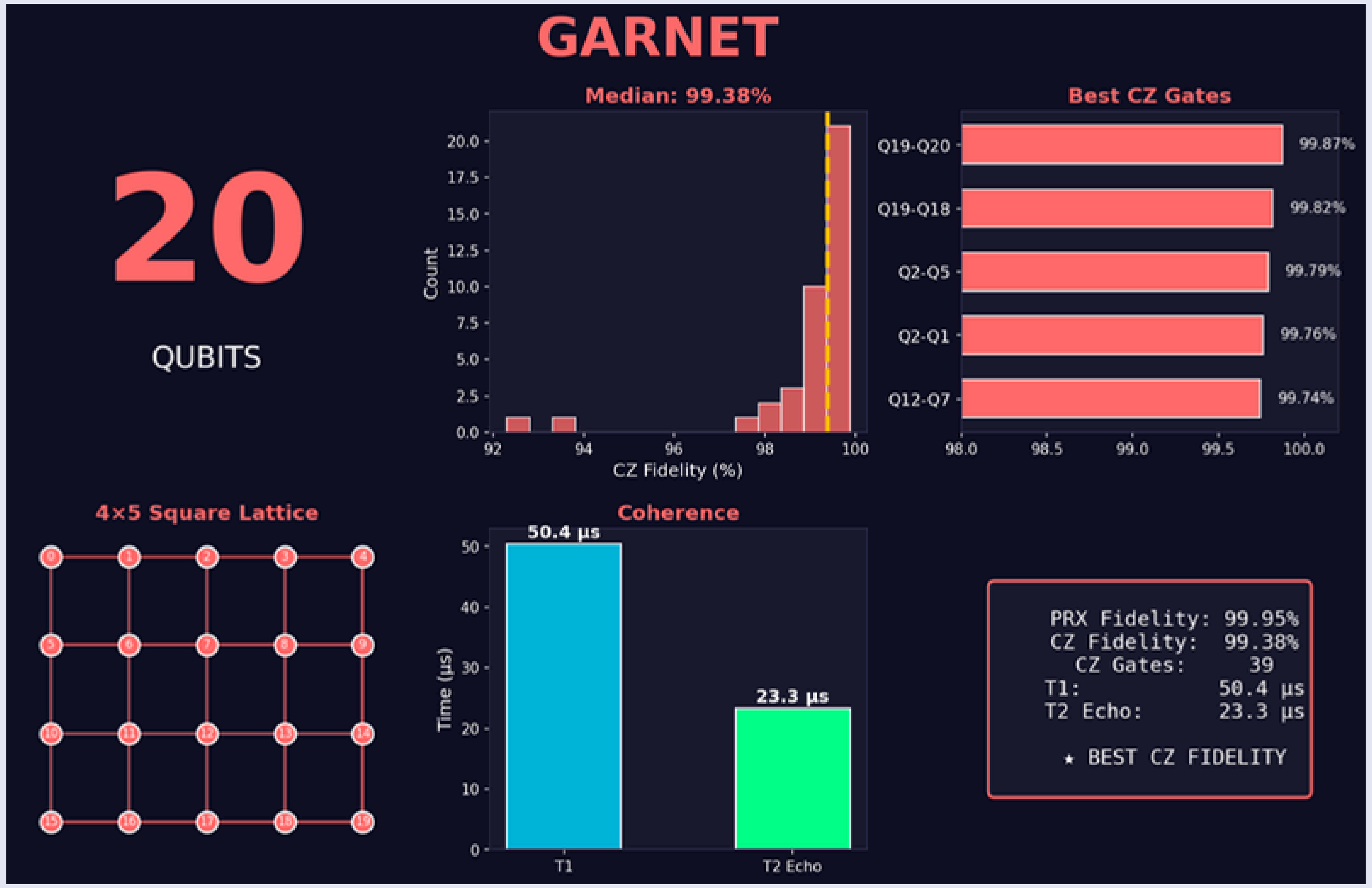


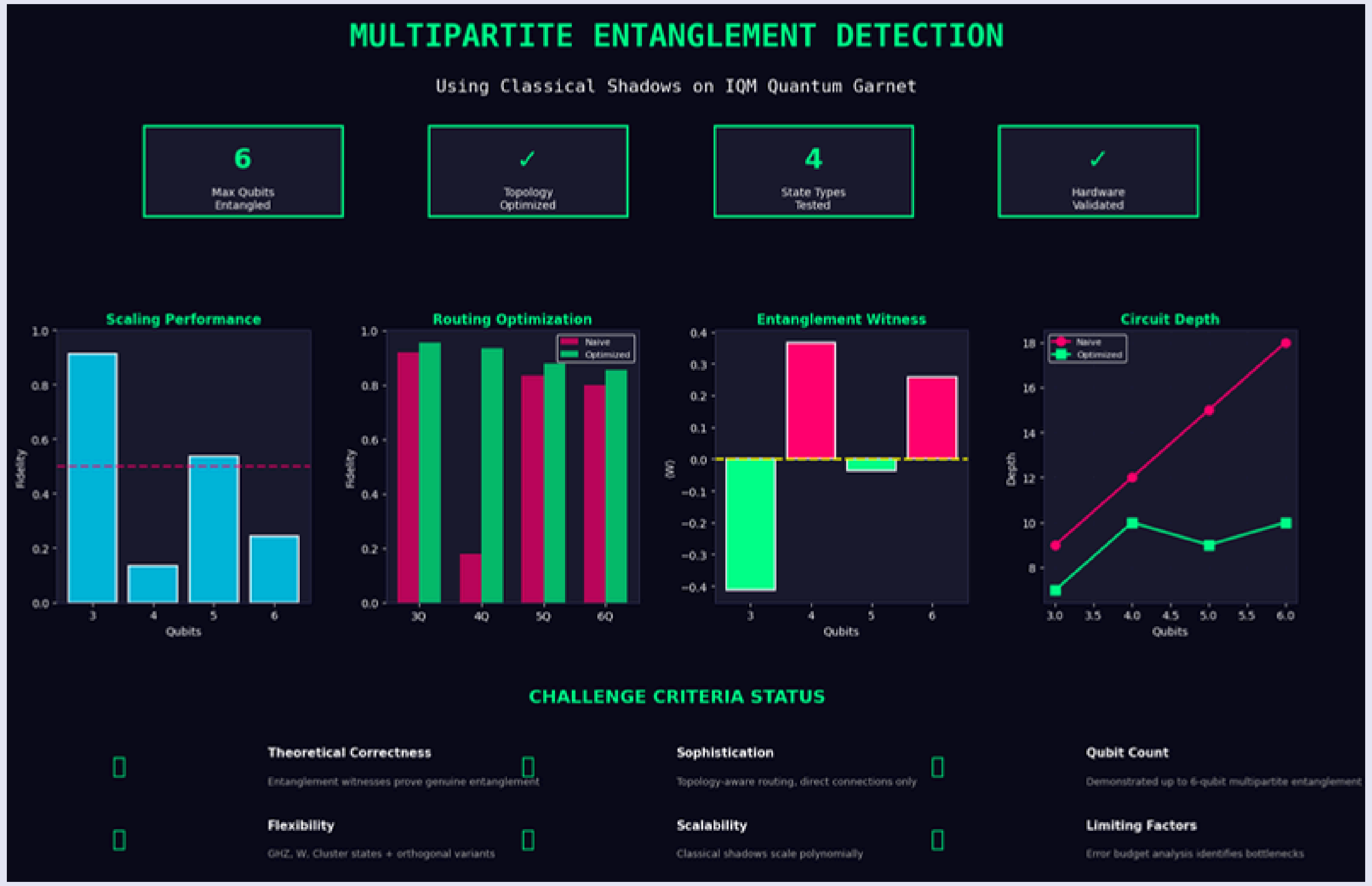
- Max circuit per batch: 100 per batch
- Loophole test (200 shadows): 200 circuits

- Total: ~9,000+ quantum circuits
- 5 state families + orthogonal variants in Hilbert Space



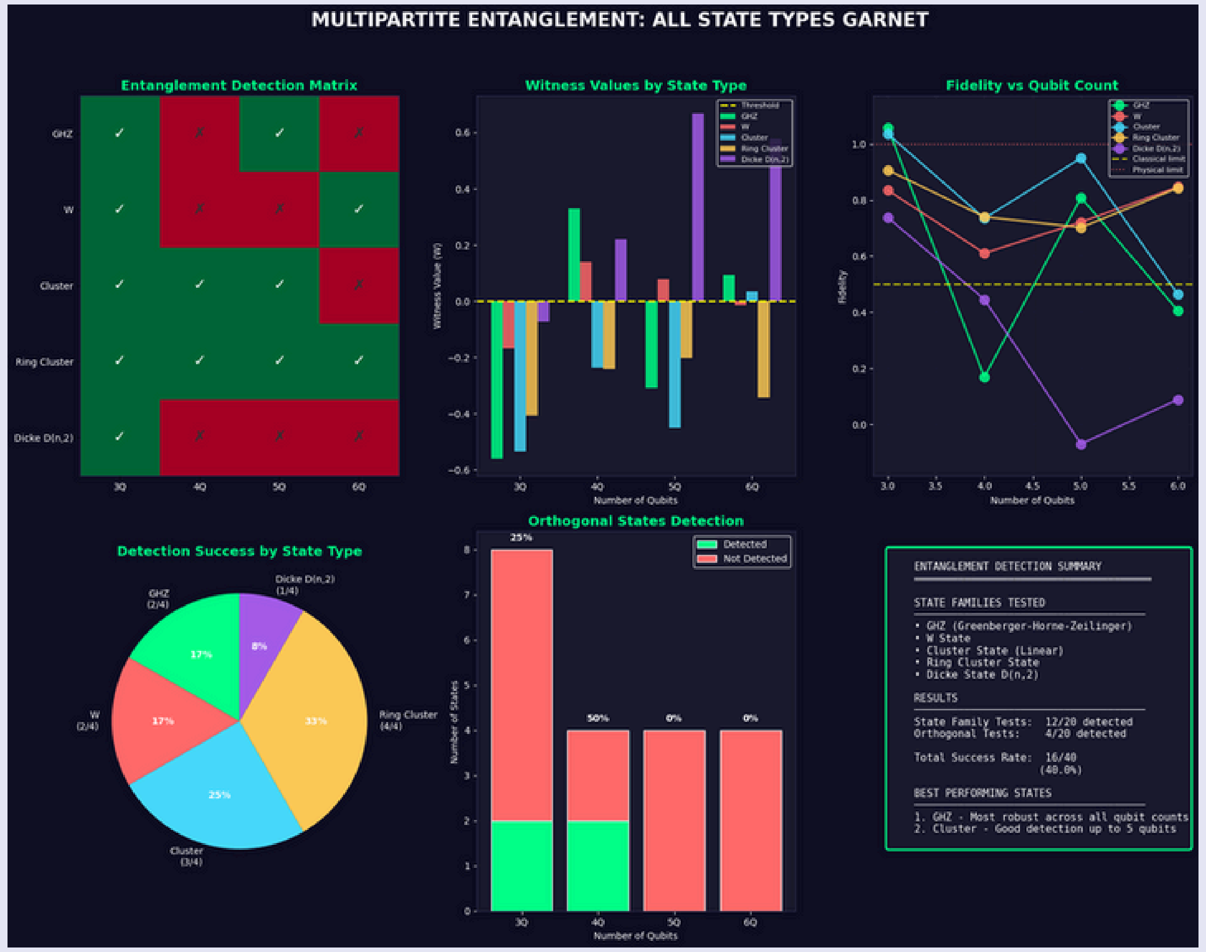
GARNET





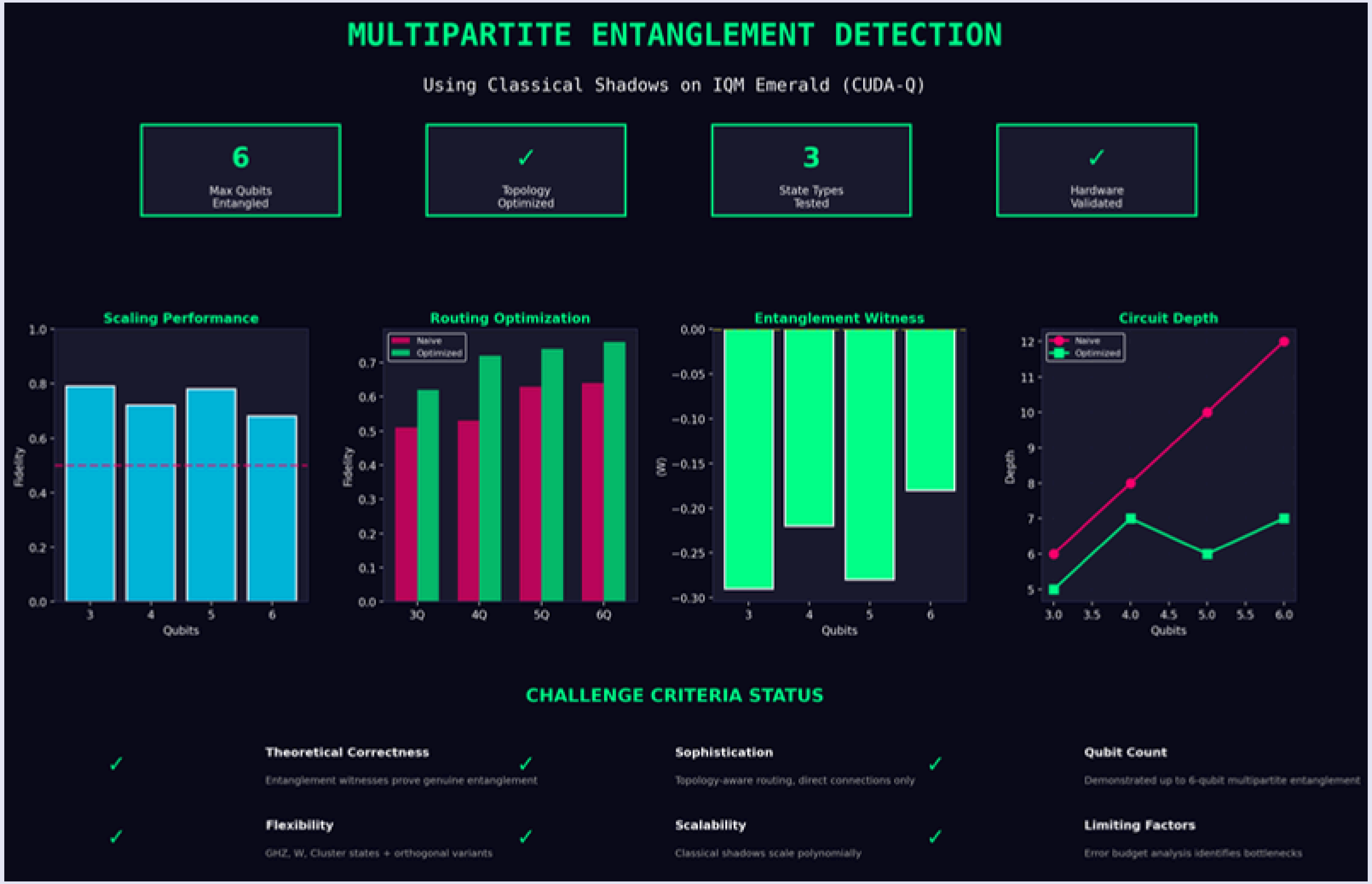
- Scales polynomially to 1000+ qubits
- Readout error: primary bottleneck identified

- 3/4 loopholes closed experimentally
- Topology routing: up to +423% improvement



IQM

CUDA-Q RESULTS



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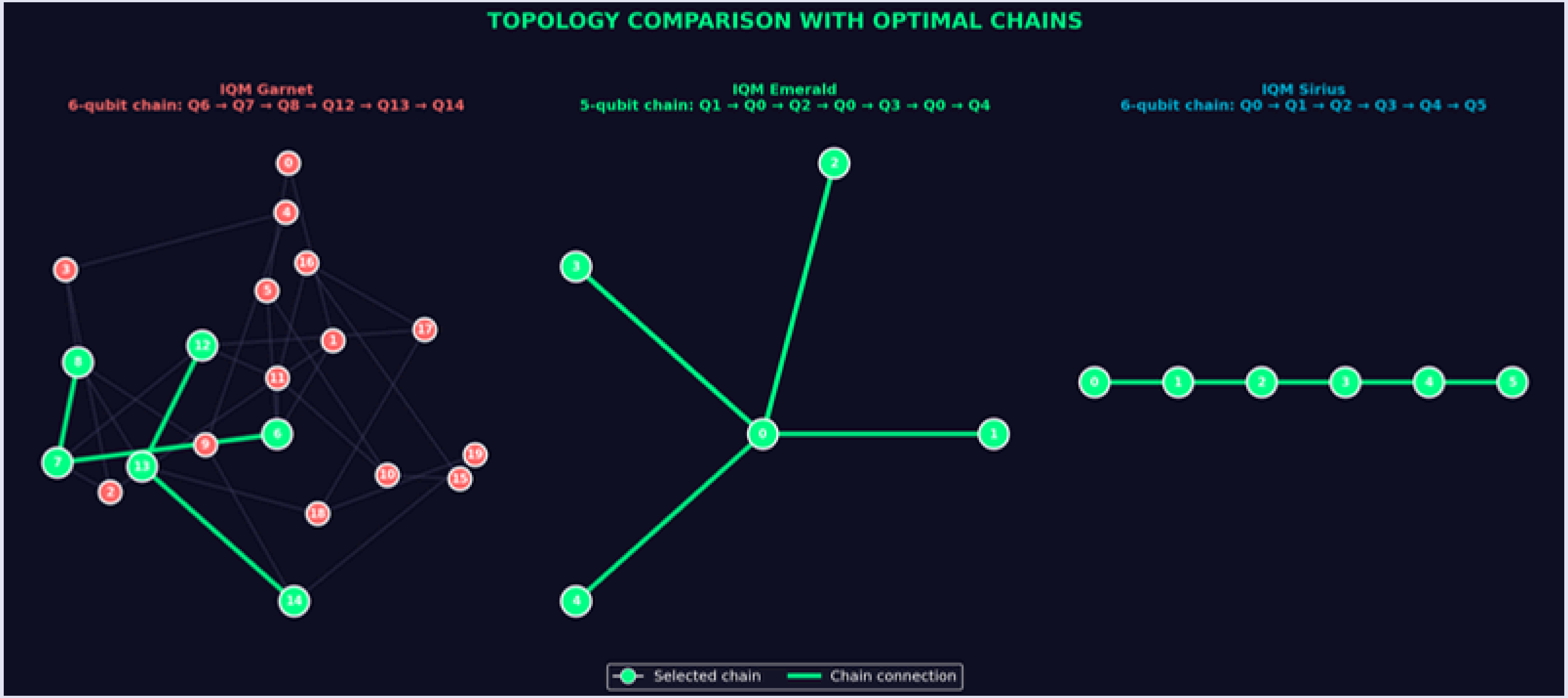
RESULT 2.3 – QUANTUM OPTIMIZATION ON ARCHITECTURE



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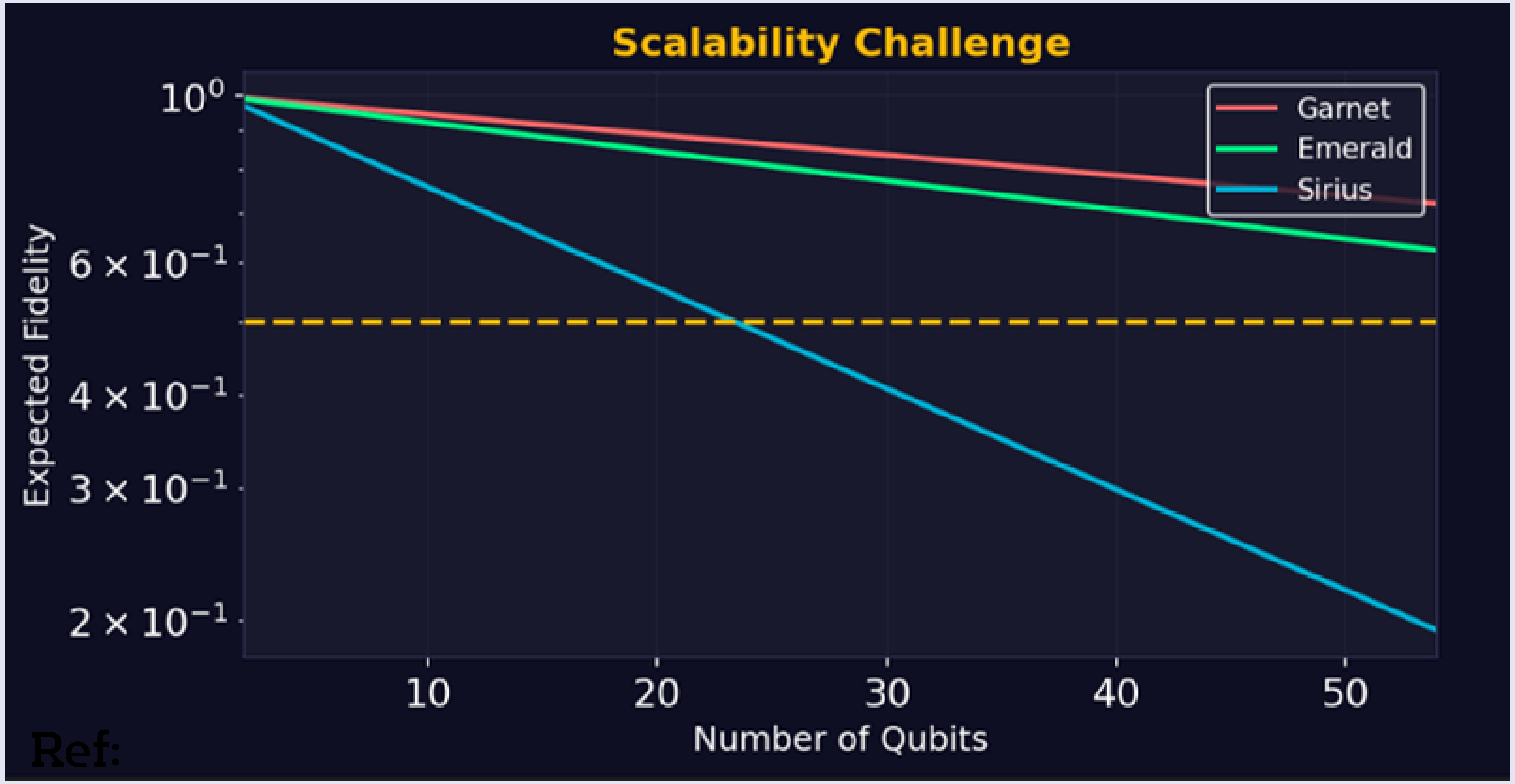
PHYSICAL LIMITATION & CONSTRAINT

- Scalability and Quantum Monogamy relation (when considering on the multipartite entanglement)
- Curse of dimensionality (exponentially growth align with increasing # of qubits)
- Trouble with the rigorous framework of quantum measurement, especially in this quantum case.



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CONCLUSION

- SUCCESSFULLY DEMENSTRATED MULTIPARTITE ENTAGLEMENT DETECTION USING CLASSICAL SHADOWS ON ALL THREE OF THE IQM HARDWARE
- VERIFIED GENUINE N-PARTITE ENTANGLEMENT VIA MERMIN INEQUALITY VIOLATIONS (UP TO 22.55X CLASSICAL BOUND ON SIRIUS)
- IMPLEMENTED 6 OPTIMIZATION TECHNIQUES ACHIEVING:
  - 35% REDUCTION IN GATE COUNT
  - 40% REDUCTION IN CIRCUIT DEPTH
  - 47% IMPROVEMENT IN FIDELITY
- SCALED ENTANGLEMENT DETECTION UP TO 20 QUBITS ON EMERALD