Co-Designed Architectures for Modular Superconducting Quantum Computers

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INTRODUCTION

Quantum Algorithms
(Shor's, Grover's QAOA, VQE)

Placement/Routing
(Heuristic, SAT, Annealing)

Basis Translation
(KAK, Approx. Decomp)

Connectivity Topologies
(Square-Lattice, Heavy-Hex)

Native Hardware Gates
(CR, fSim, iSwap)

Physical Qubits
(Superconducting, Trapped Ions, Neutral Atoms QCs)

Quantum Co-Design optimizes naturally occurring interactions

- Frequency collisions constrains coupling topologies
- Hamiltonian constrains possible gate types

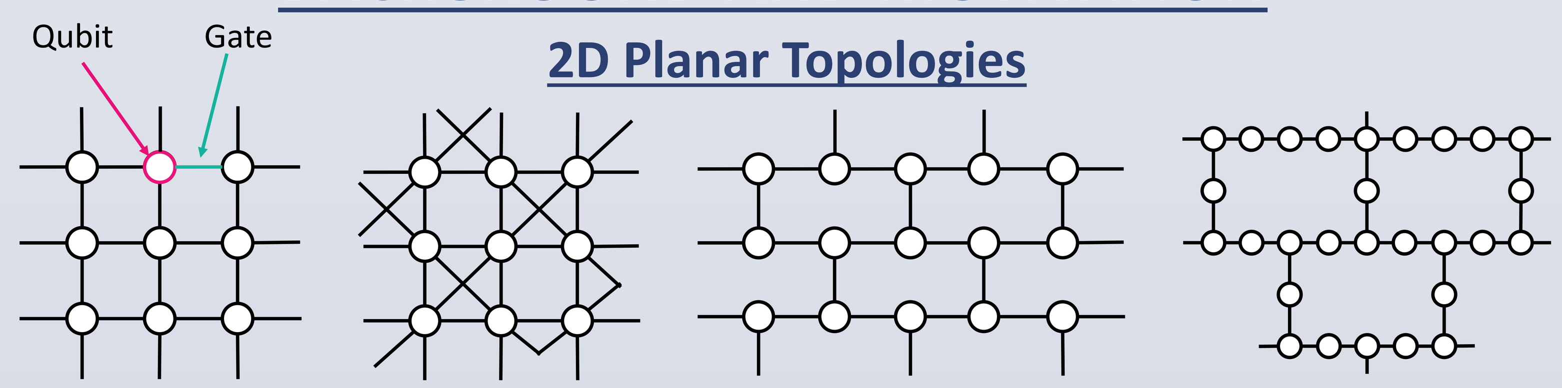
Three-wave SNAIL Modulator Allows for Rich Topologies

- Minimizes qubit frequency crowding
- All-to-all interactions among many qubits
- Implements an efficient continuous iSWAP family
- Flexible parameterization: CNOT, CZ, B, and others possible

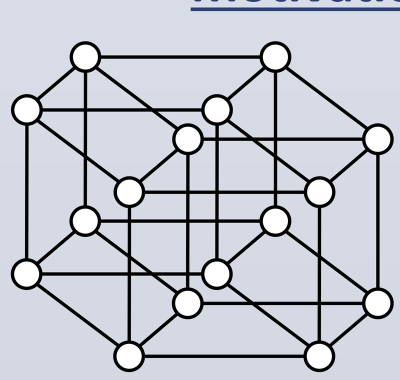
Goal: Find the best topology/gate combination possible

BACKGROUND AND MOTIVATION

2D Planar Topologies



Motivational high performance computing topology



Hypercube:
Low diameter
High connectivity
Difficult Scaling (in 3D)

How to achieve similar characteristics with our modulators?

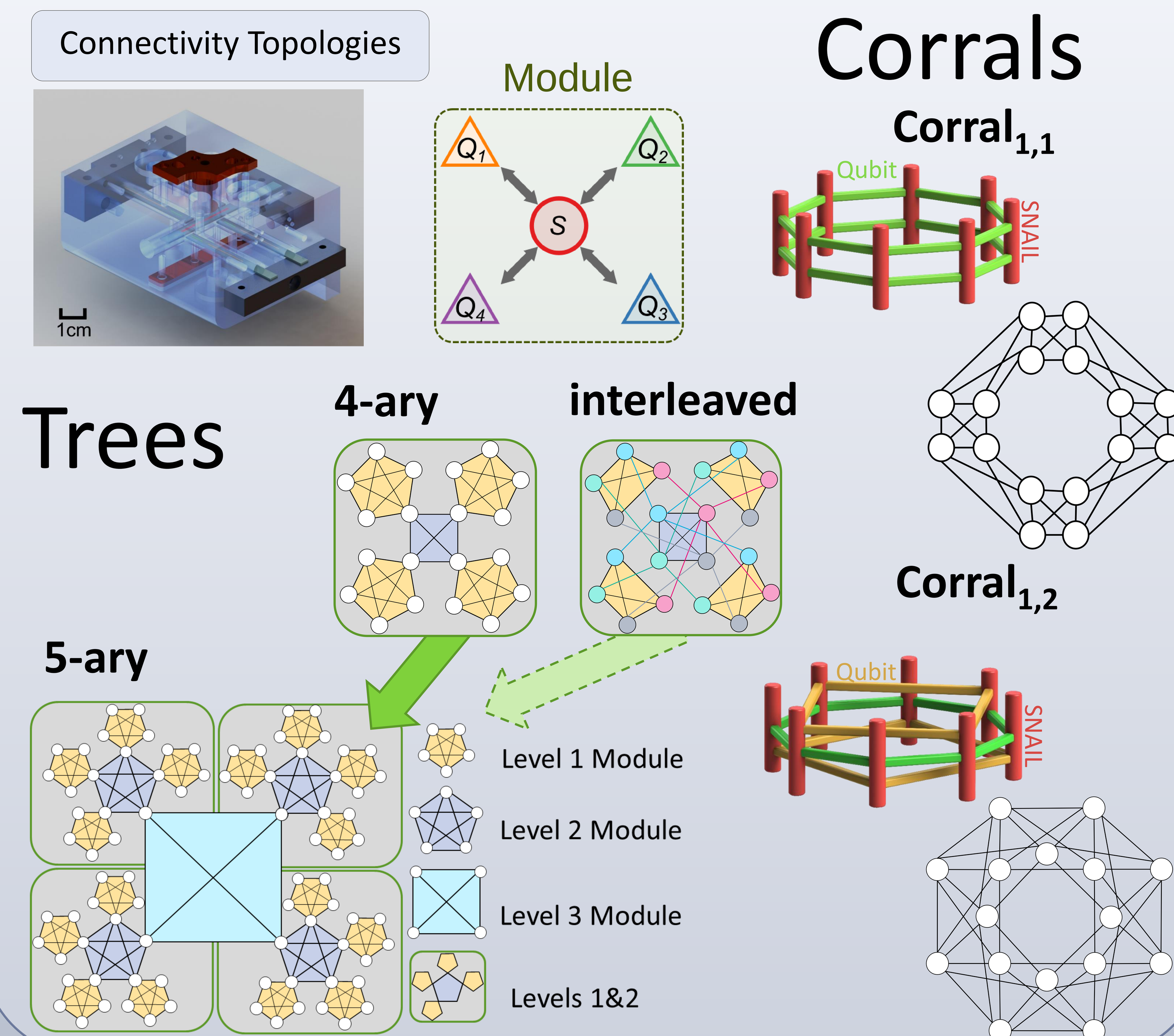
Transpilation Flow

Quantum Circuit → Placement /Routing → Count SWAPs → Basis Translation → Count 2Qs → Transpiled Circuit

Backend: Topology

Backend: Basis Gate

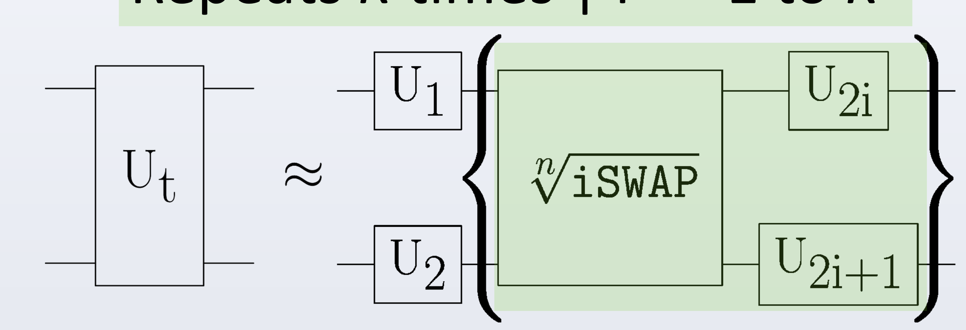
METHODS: Topologies



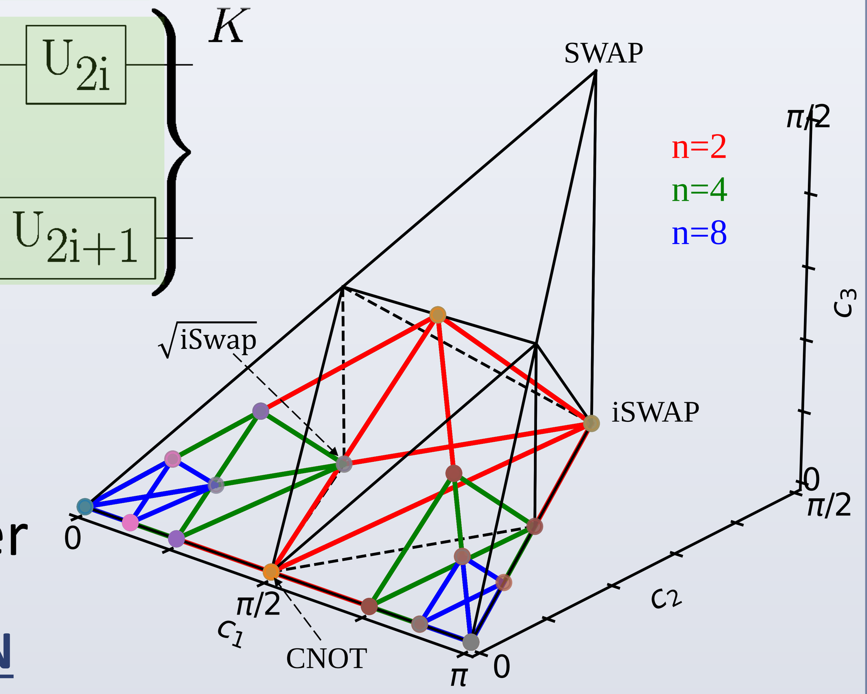
METHODS: Gates

Basis Translation

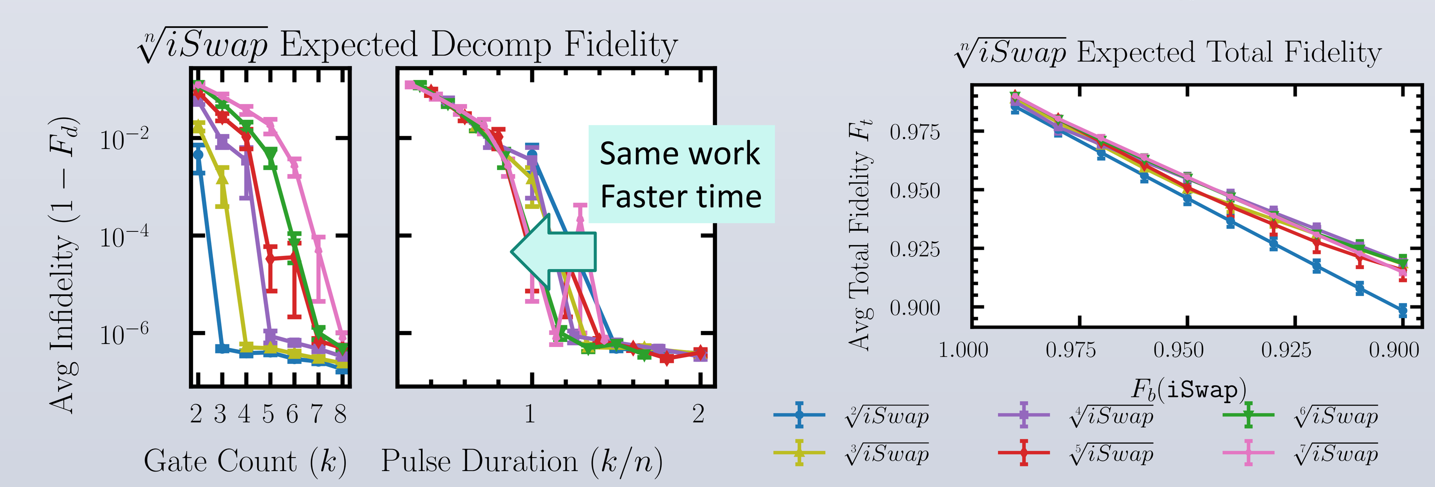
Repeats K times | i → 1 to K



- Coverage for K=2 of $\sqrt[n]{\text{iSWAP}}$ for n ∈ {2,4,8} shown in the Weyl Chamber

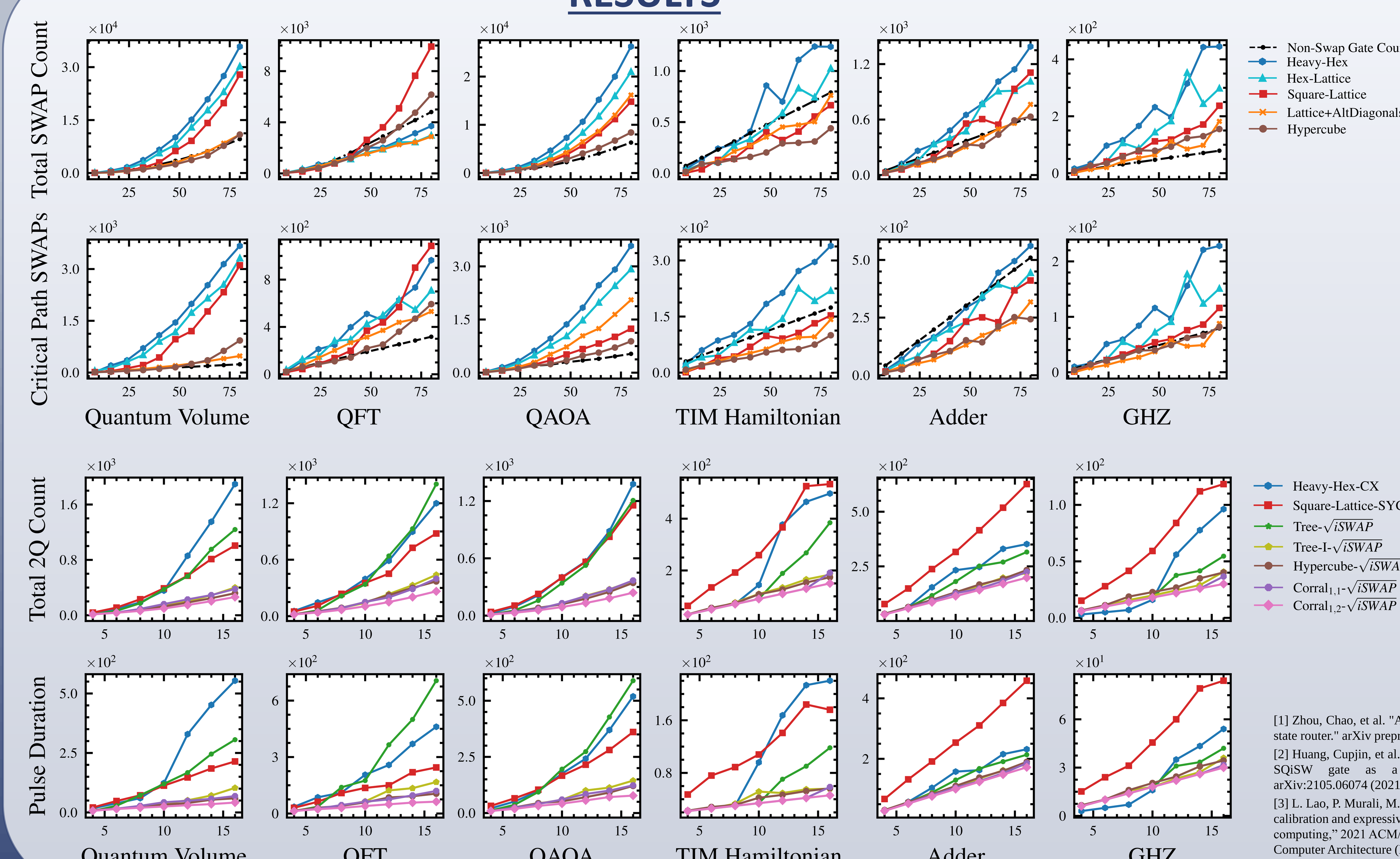


NUMERICAL DECOMPOSITION



$\sqrt[2]{\text{iSwap}}$ decreases infidelity by 51%, $\sqrt[4]{\text{iSwap}}$ by 58% vs iSwap
[Haar sampled 2Q unitaries, 99% iSwap gate fidelity]

RESULTS



CONCLUSIONS

- **Rich topologies are key to data movement and efficient QC**
- **Even smaller 1Q "neighborhoods" can benefit**
  Heavy-Hex is 82% slower (<< fidelity) than Corral_{11}
- **Sparse topologies require more SWAP gates when scaled**
  80Q Heavy-Hex 3X critical path SWAPs vs. Hypercubes
- **Need *scalable, modular* architectures**
- **$\sqrt[n]{\text{iSWAP}}$ gates provide benefits**

References

[1] Zhou, Chao, et al. "A modular quantum computer based on a quantum state router." arXiv preprint arXiv:2109.06848 (2021).

[2] Huang, Cupjin, et al. "Towards ultra-high fidelity quantum operations: SQiSW gate as a native two-qubit gate." arXiv preprint arXiv:2105.06074 (2021).

[3] L. Lao, P. Murali, M. Martonosi, and D. Browne, "Designing calibration and expressivity-efficient instruction sets for quantum computing," 2021 ACM/IEEE 48th Annual International Symposium on Computer Architecture (ISCA), Jun 2021.

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