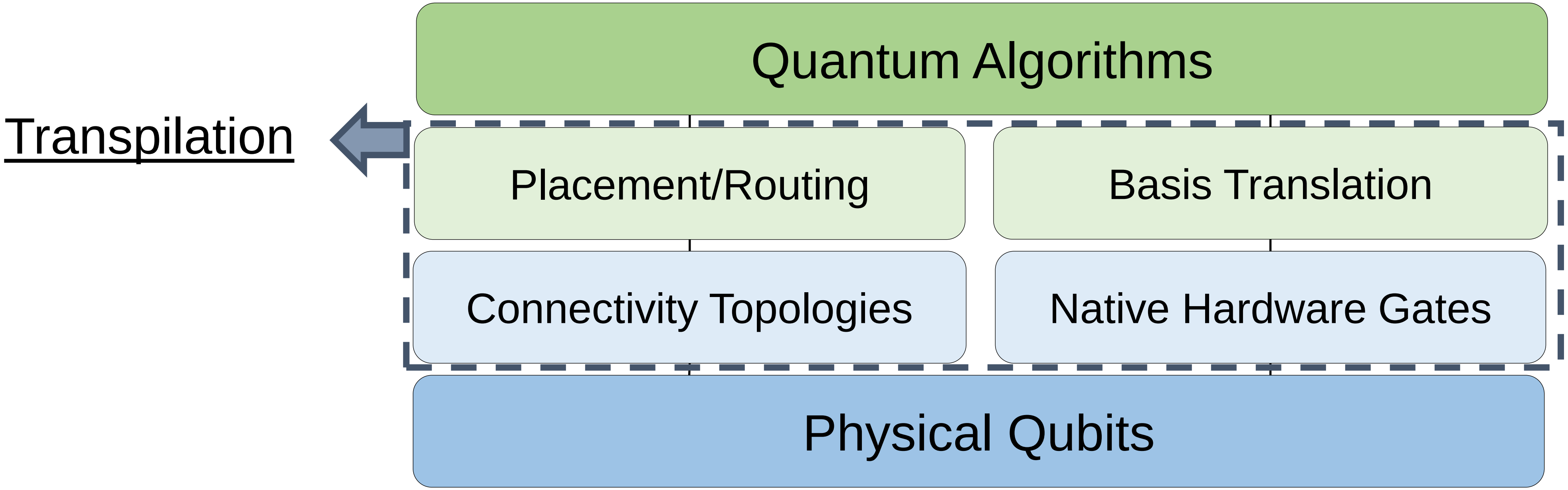
Using Quantum Hardware Speed Limits to Improve Basis Gate Selection

Evan McKinney[†],
C. Zhou[§], M. Xia[§], M. Hatridge[§], A.K. Jones[†]

[†]Department of Electrical and Computer Engineering, University of Pittsburgh
[§]Department of Physics and Astronomy, University of Pittsburgh

ISCA 2023

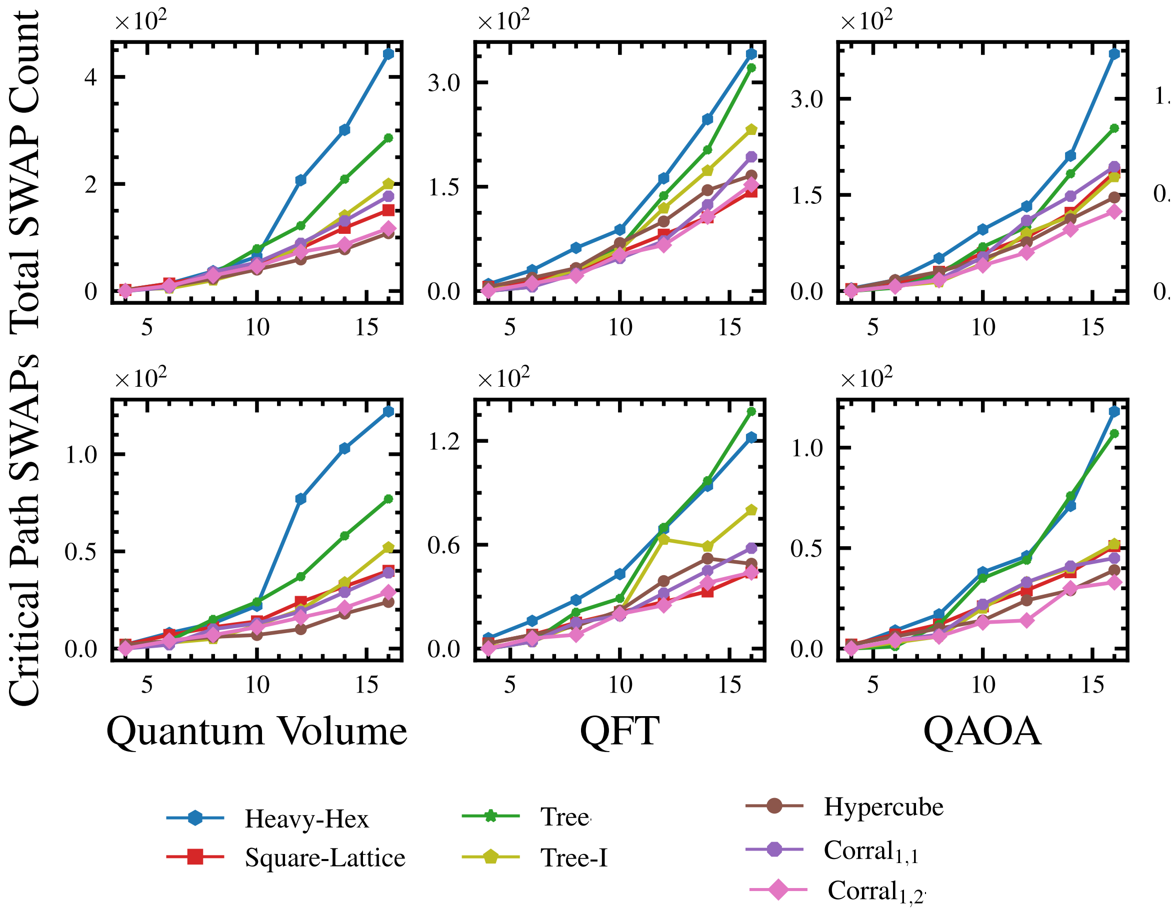
Quantum computer co-design



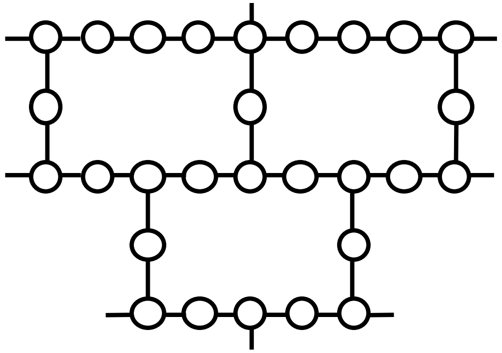
- Physics constrains possible topologies and basis gates
- Prioritize improving qubit and gate fidelities

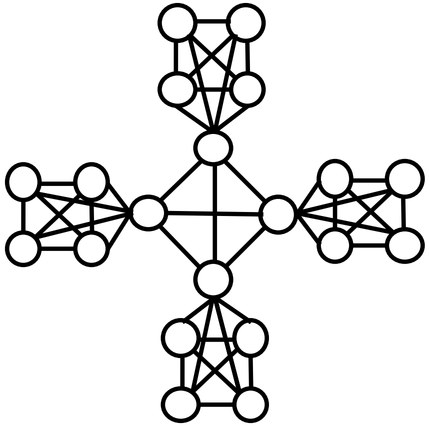
What we've done

- Transpile circuits to Hatlab connectivity
- Co-design study topology networks



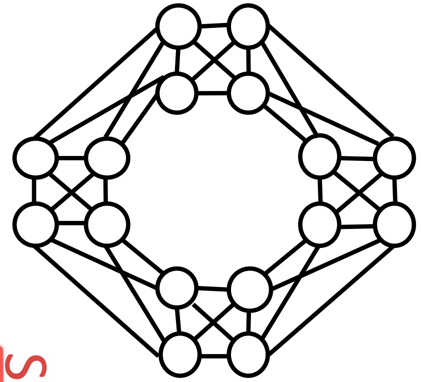
(a) Heavy-Hex, 28-qubits

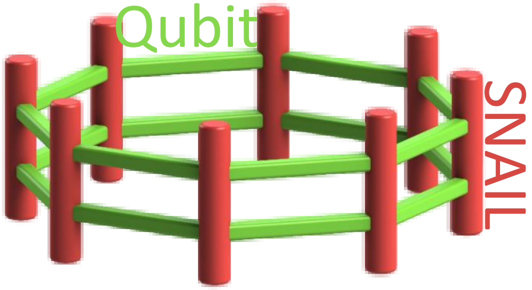




(b) Tree, 20-qubits

(c) Corral, 16-qubits





(d) Corral realization via SNAILS

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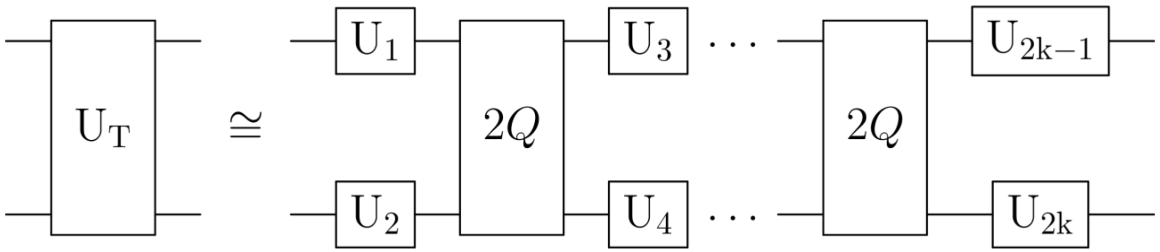
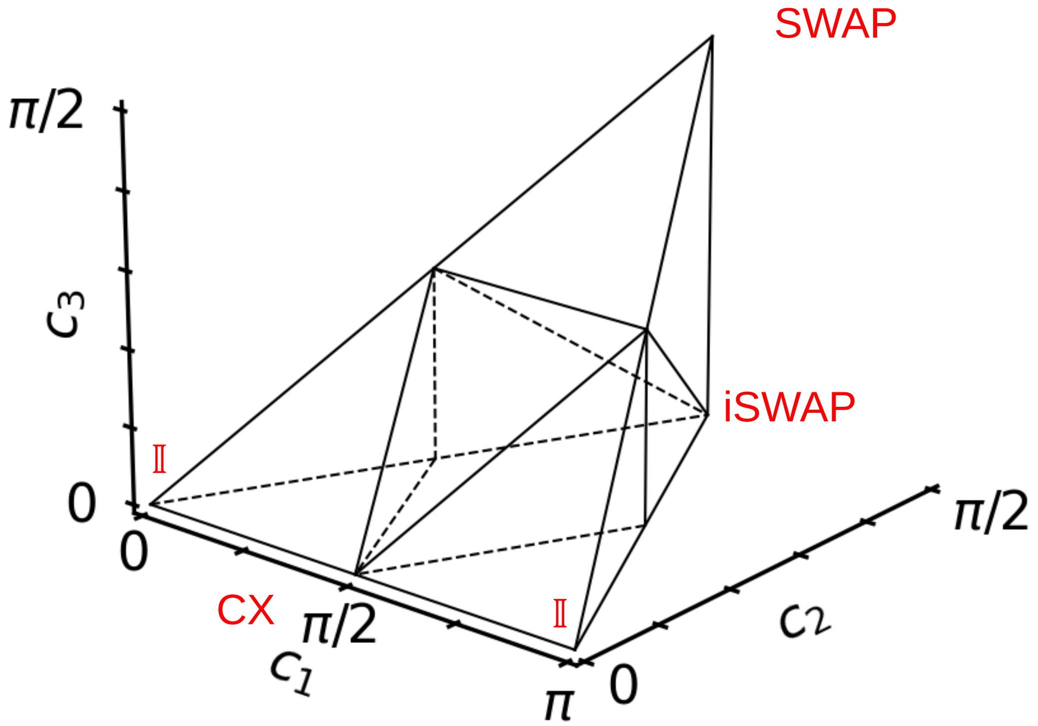
Two-qubit basis gates

- Decompose all algorithm gates into new basis using repeated applications



- An optimal basis gate *reduces overall duration*
  - Powerful gates need less applications
  - Fidelity limited by decoherence in time

- Weyl Chamber visualizes the set of all 2Q gates



Y. Makhlin, **Quantum Info. Process. 1**, (2002)

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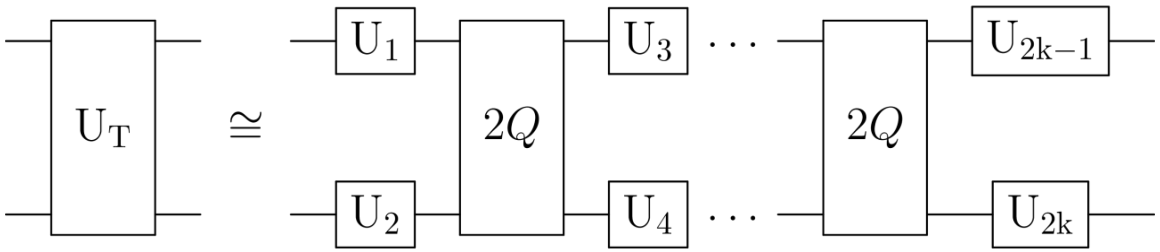

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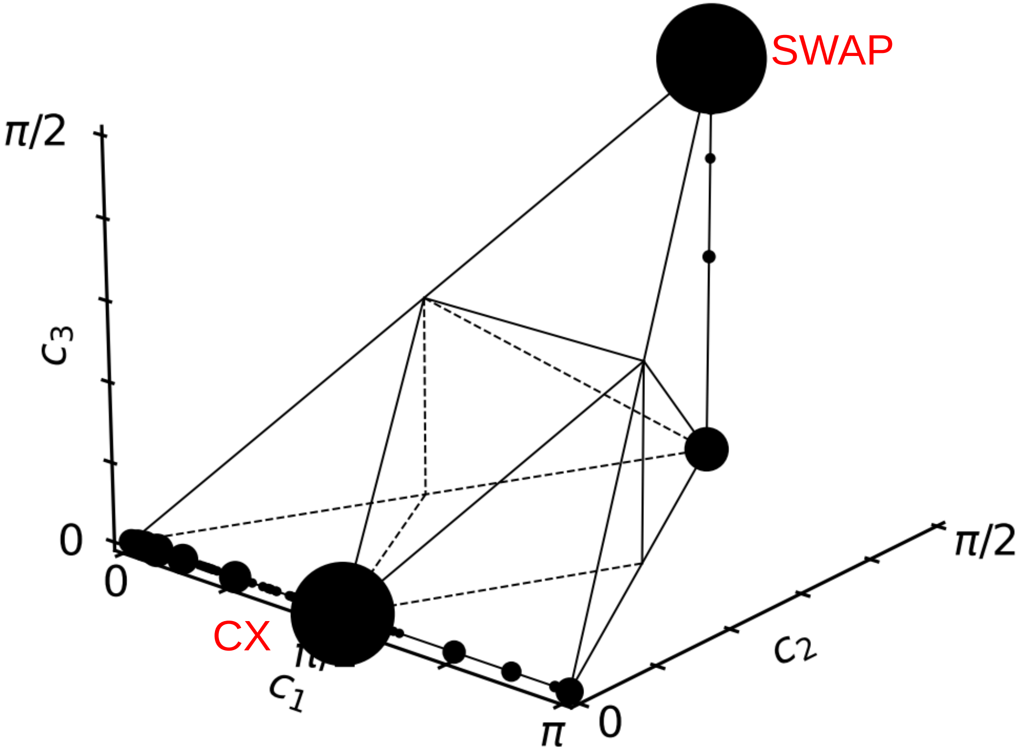

- NISQ algorithms dominated by CX and SWAP gates

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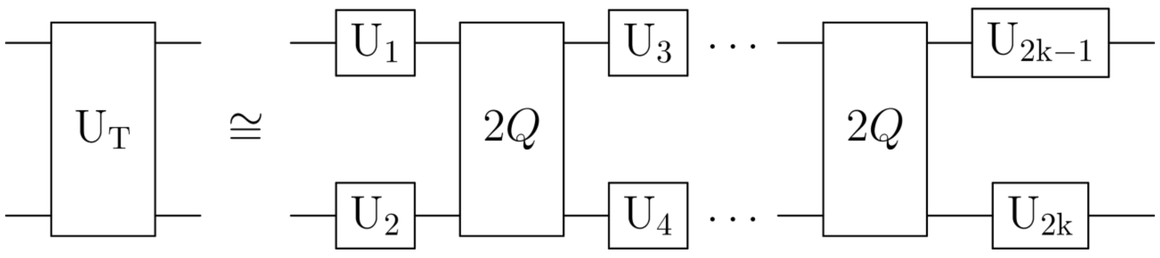

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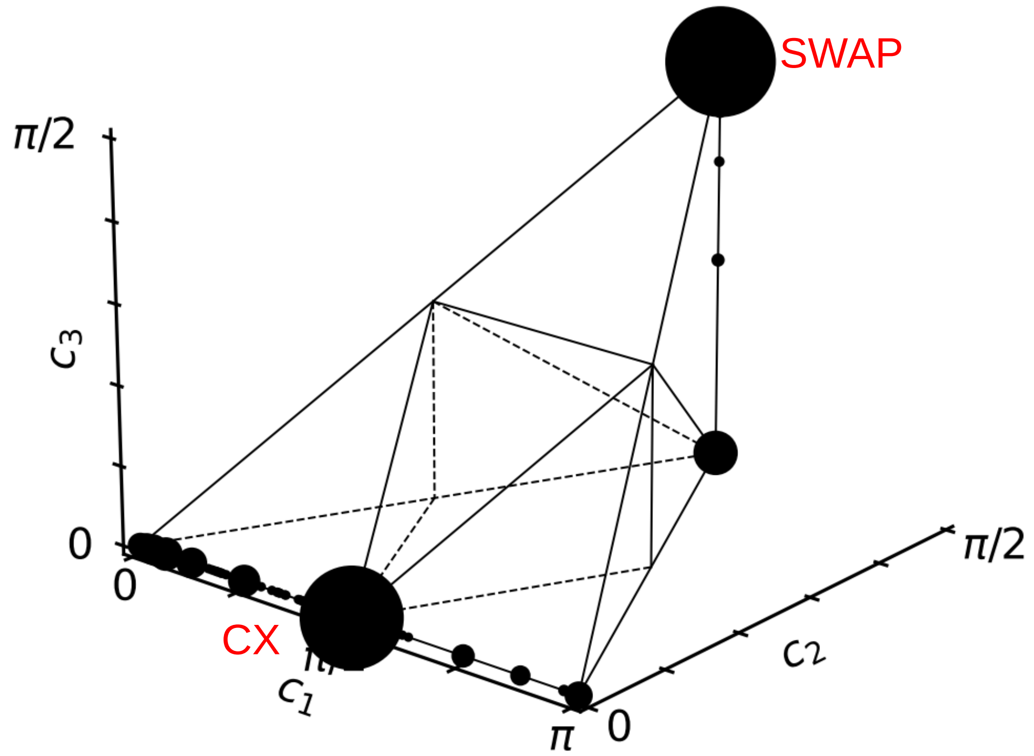

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- **Goal: Use both decomposition efficiency and hardware latency = overall duration**

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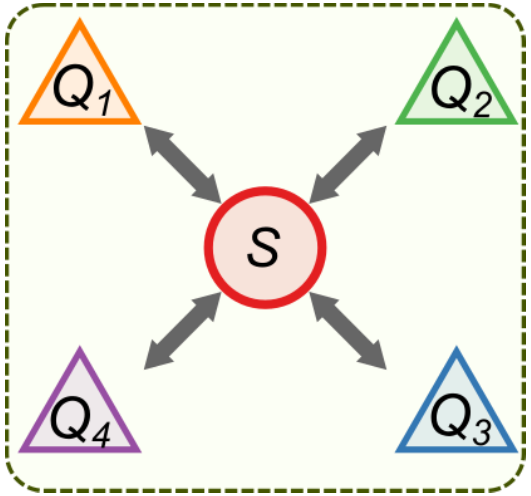
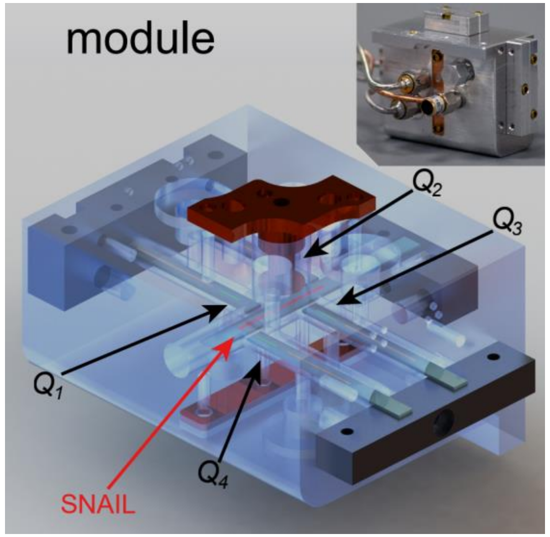
Conversion/Gain candidate basis gates

Four qubit SNAIL-based quantum module





- **Engineerable interactions yields a basis gate design-space**

$$\hat{H} = g_c(e^{i\phi_c} a^\dagger b + e^{-i\phi_c} a b^\dagger) + g_g(e^{i\phi_g} ab + e^{-i\phi_g} a^\dagger b^\dagger)$$

Xia, et al. **APS March Meeting** (2023)
Zhou, et al. **npj Quantum Inf 9**, 54 (2023).

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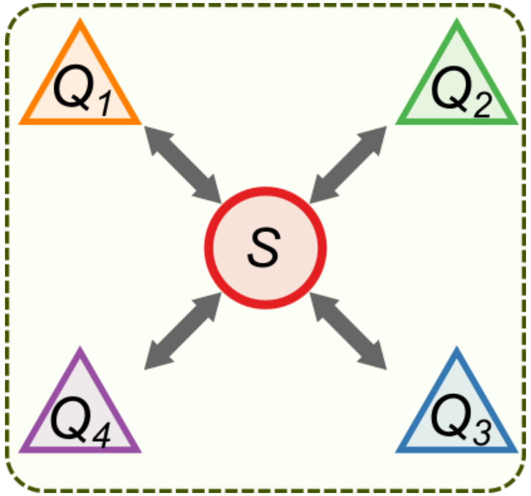

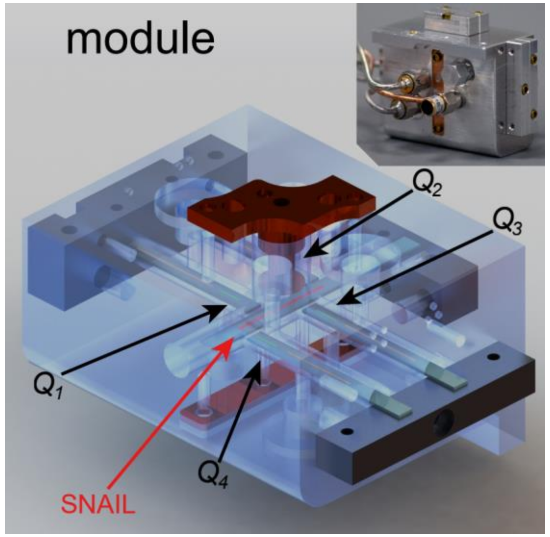

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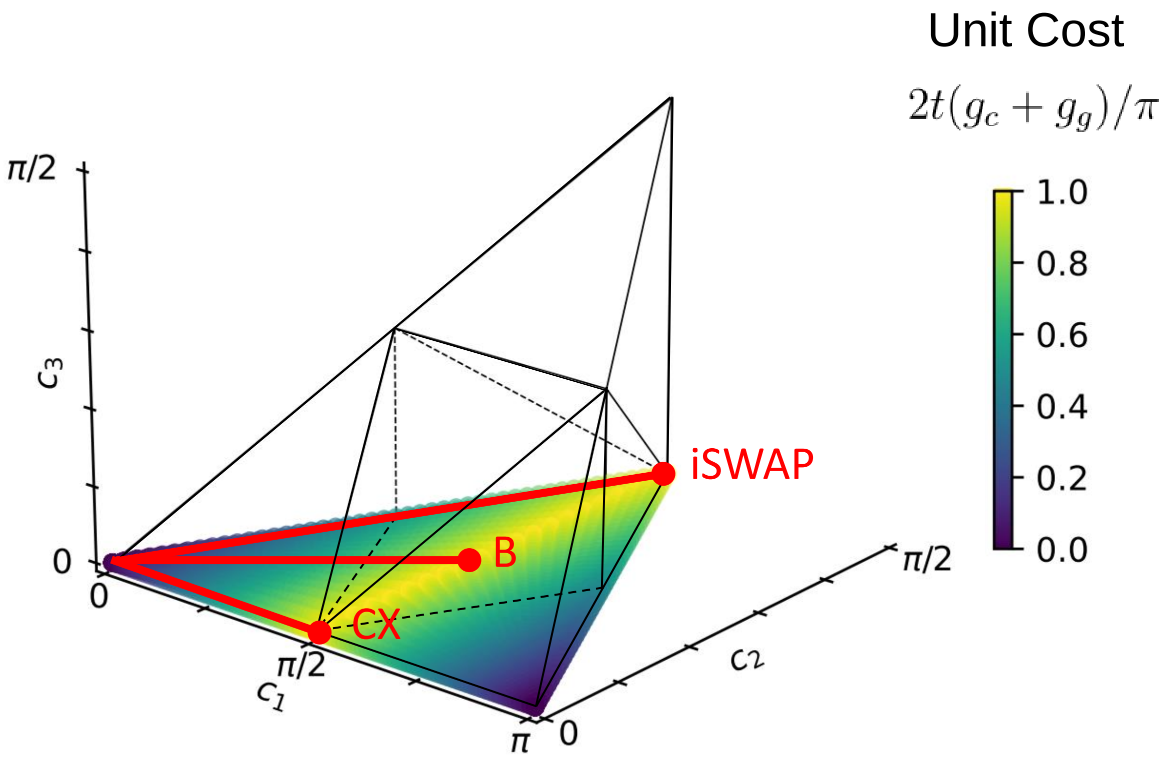

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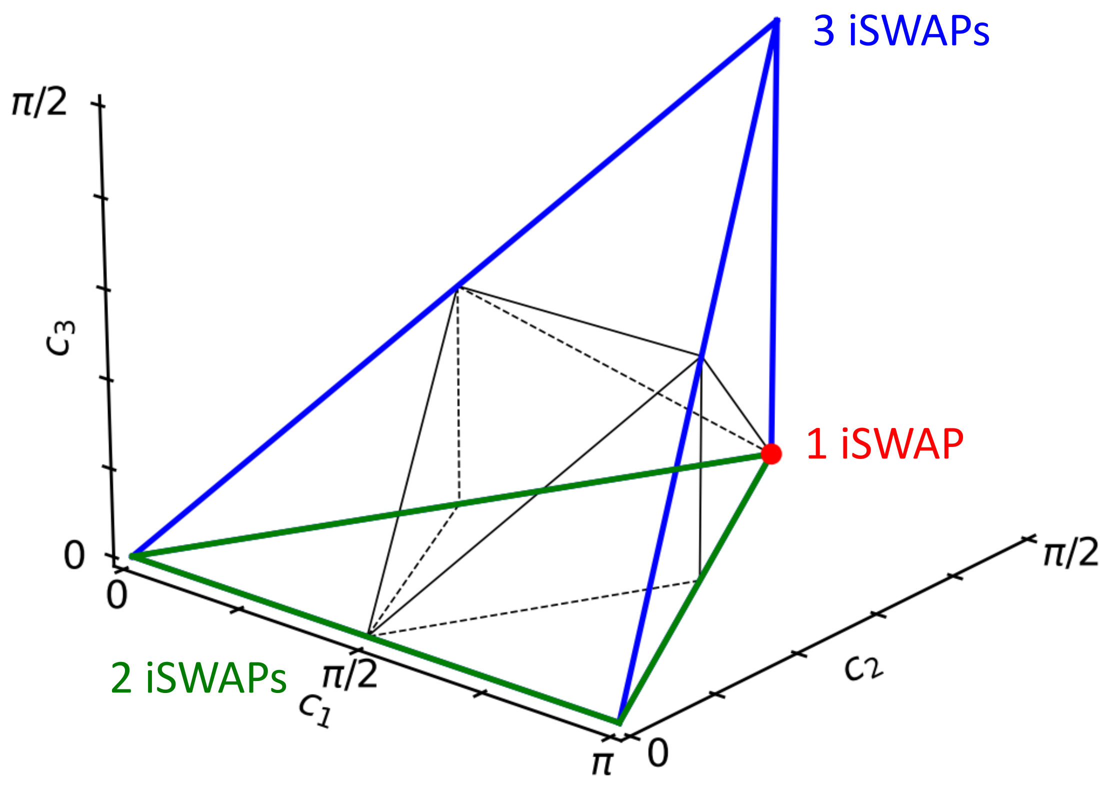
Basis coverage volumes

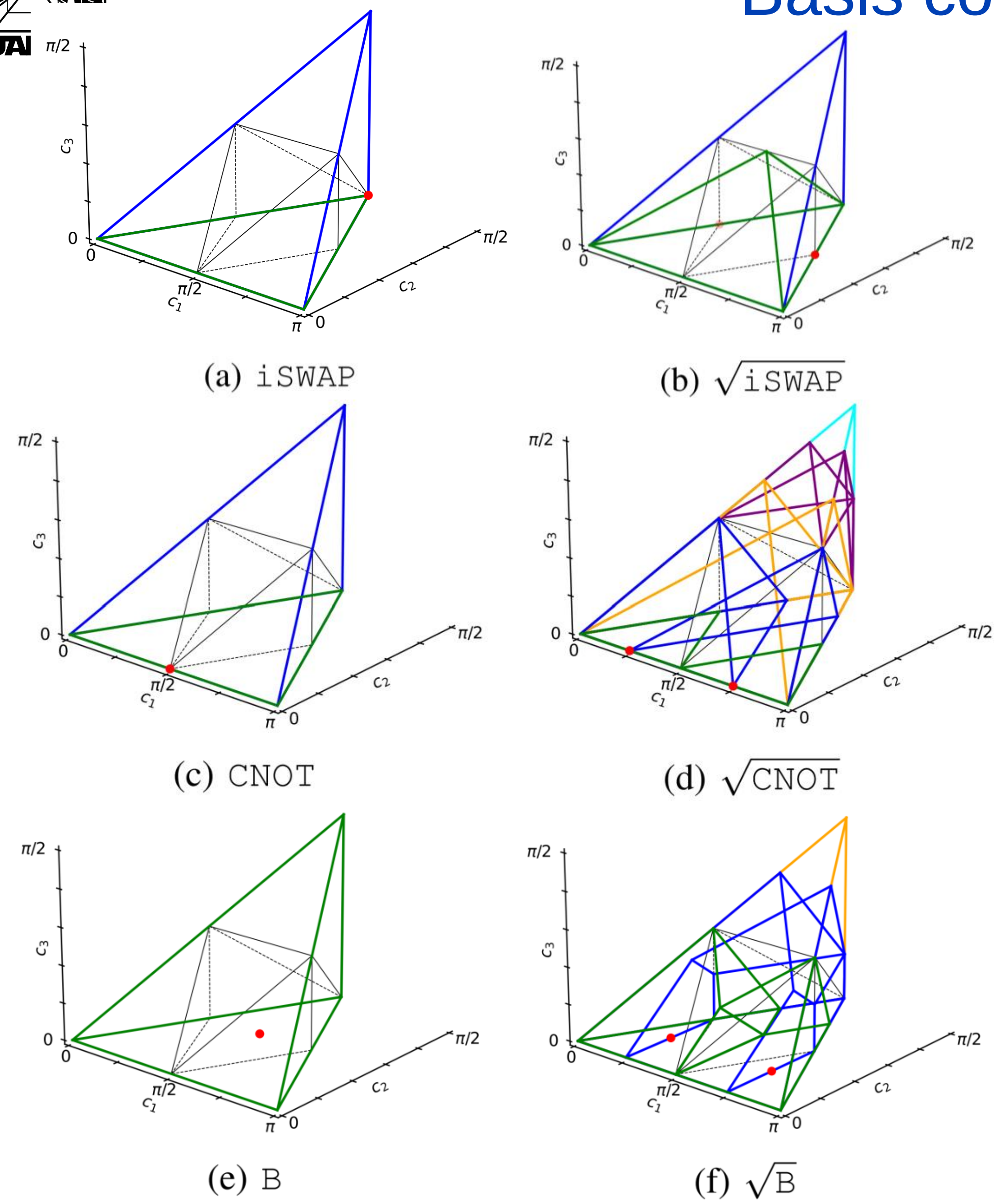


- **Monodromy polytopes** finds minimum gate applications for any 2Q target gate
- A single gate is locally equivalent to itself
- SWAP is the most expensive target

Target\Basis	iSWAP
CNOT	2.0
SWAP	3.0
Haar	3.0

Peterson, et al. ***Quantum* 4** (2020): 247

Basis coverage volumes



(a) iSWAP (b) $\sqrt{\text{iSWAP}}$ (c) CNOT (d) $\sqrt{\text{CNOT}}$ (e) B (f) $\sqrt{\text{B}}$

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Decomposition *gate count* costs

Target\Basis	iSWAP	$\sqrt{\text{iSWAP}}$	CX	$\sqrt{\text{CX}}$	B	$\sqrt{\text{B}}$
CNOT	2.0	2.0	1.0	2.0	2.0	2.0
SWAP	3.0	3.0	3.0	6.0	2.0	4.0
Haar	3.0	2.2	3.0	3.5	2.0	3.1

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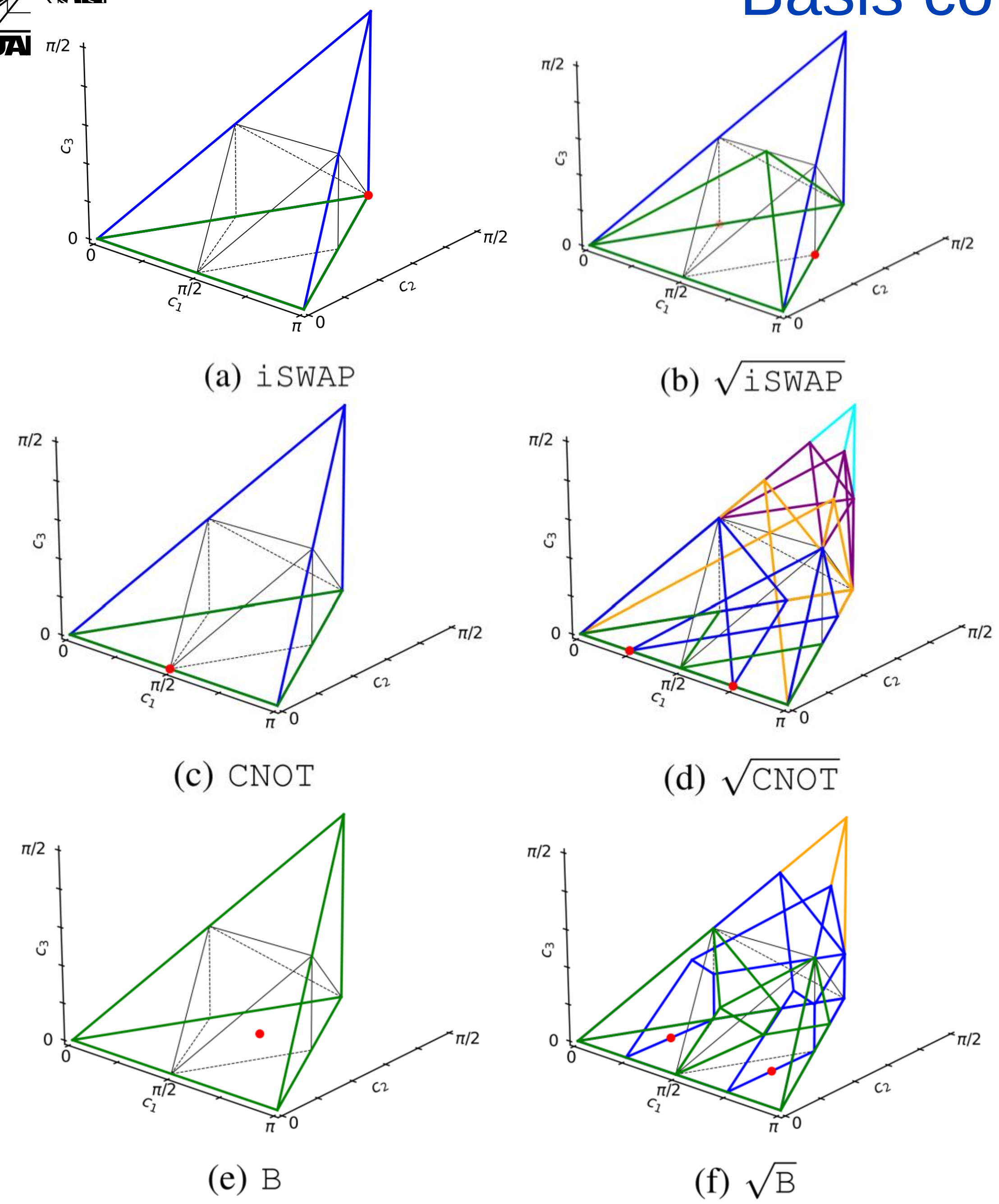

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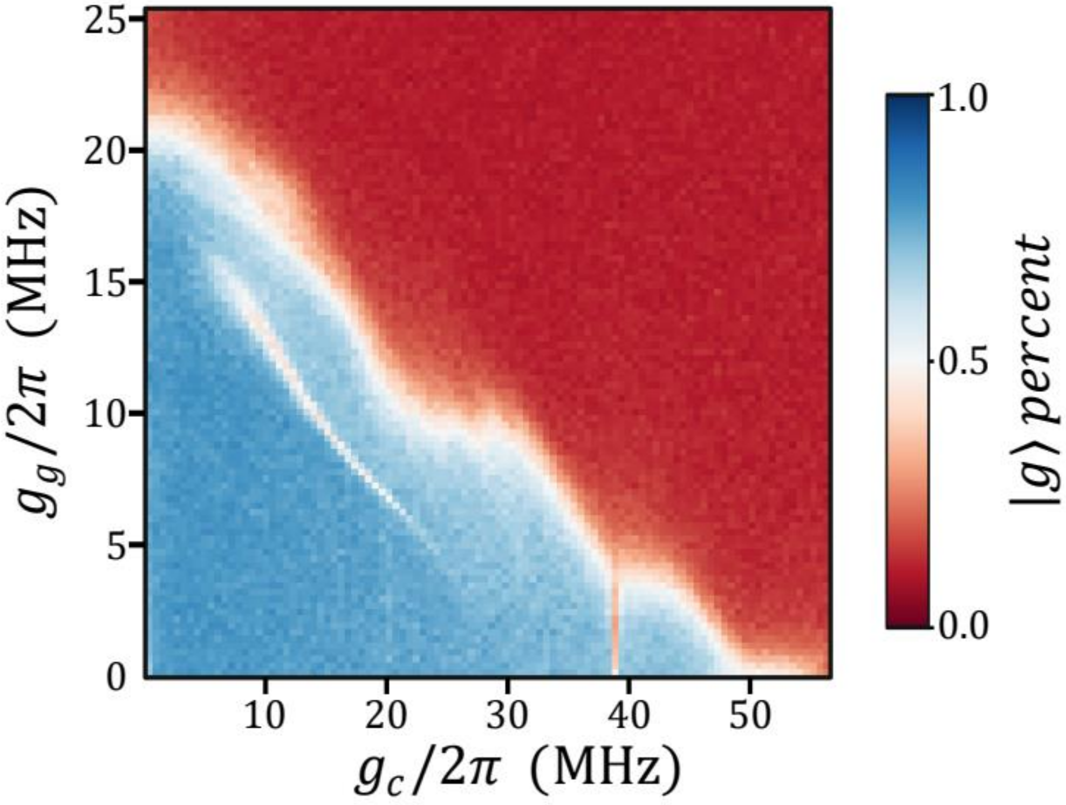
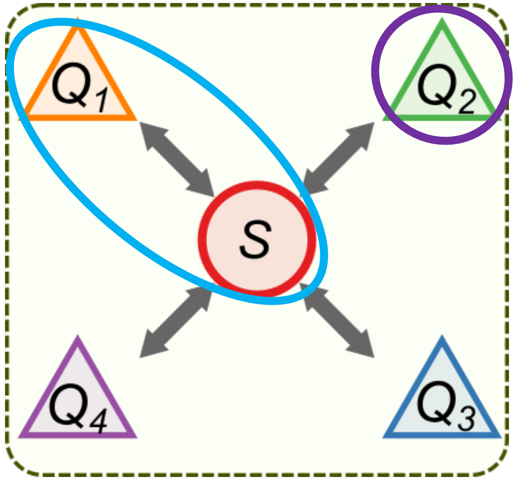
Hardware speed limits



Limitation of SNAIL when driving both gain and conversion

Module



Drives applied between SNAIL and qubit

Measure second qubit to witness SNAIL breakpoint

Zhou, et al. **npj Quantum Inf 9**, 54 (2023).

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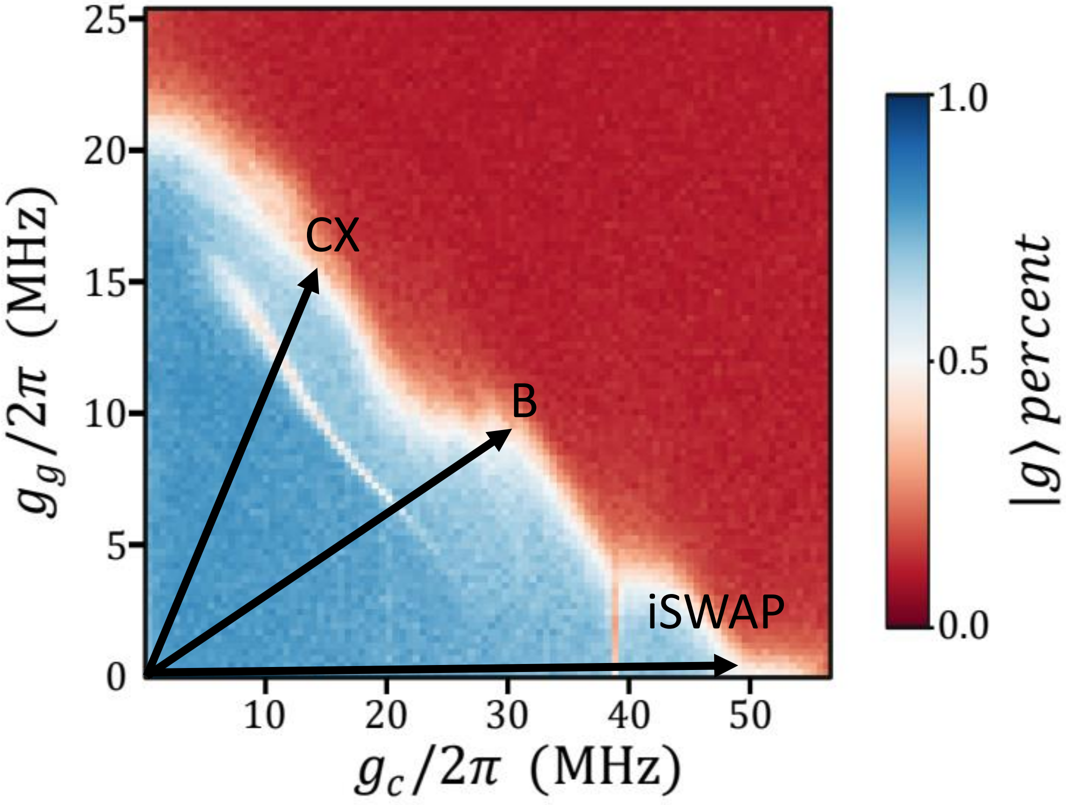

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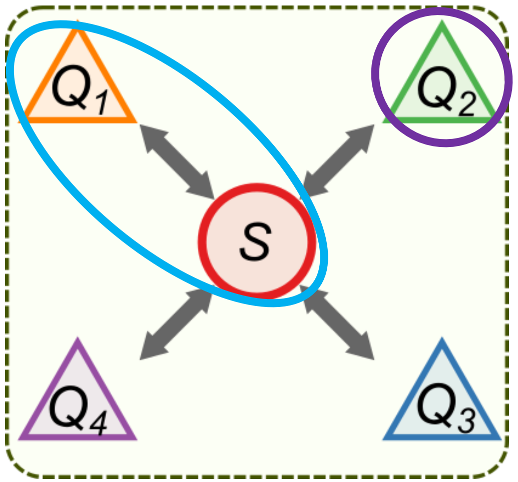

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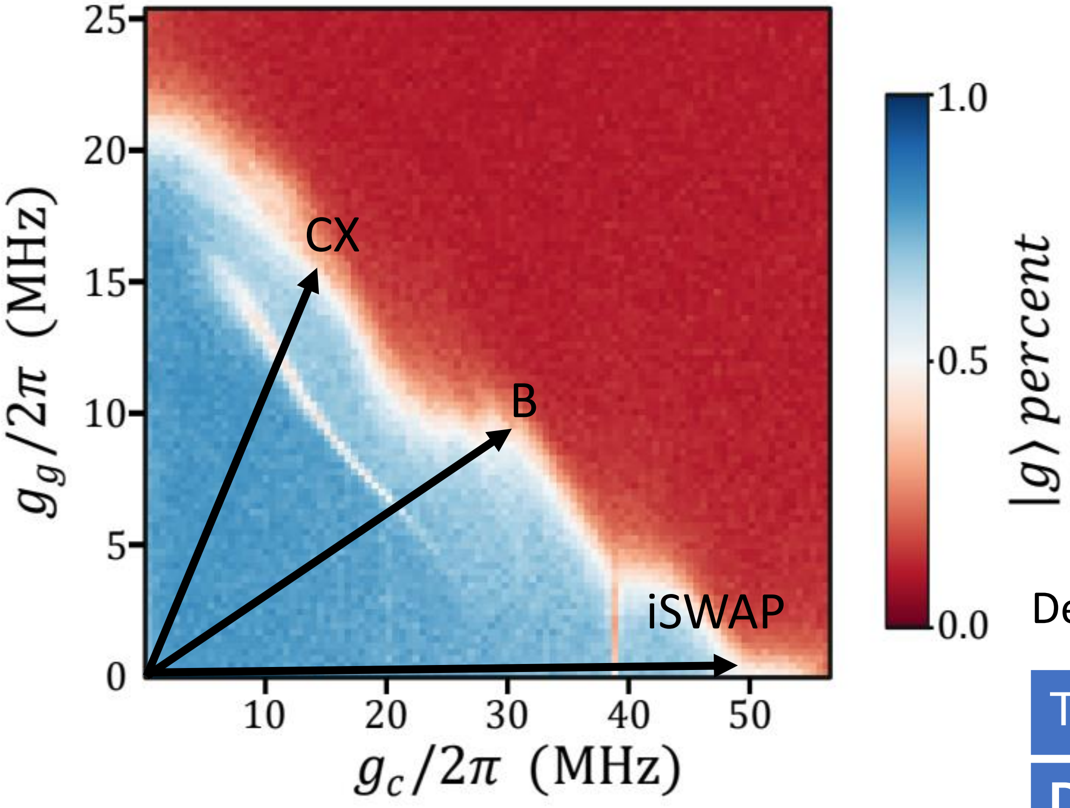

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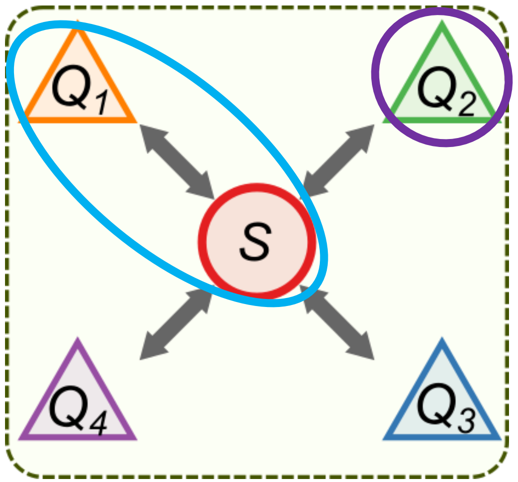

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Target\Basis	iSWAP	$\sqrt{\text{iSWAP}}$	CX	$\sqrt{\text{CX}}$	B	$\sqrt{\text{B}}$
Duration	**1.0**	**0.5**	**1.8**	**0.9**	**1.4**	**0.7**
CNOT	2.0	1.0	1.8	1.8	2.8	1.4
SWAP	3.0	1.5	5.4	5.4	2.8	2.8
Haar	3.0	1.1	5.4	3.2	2.8	2.2

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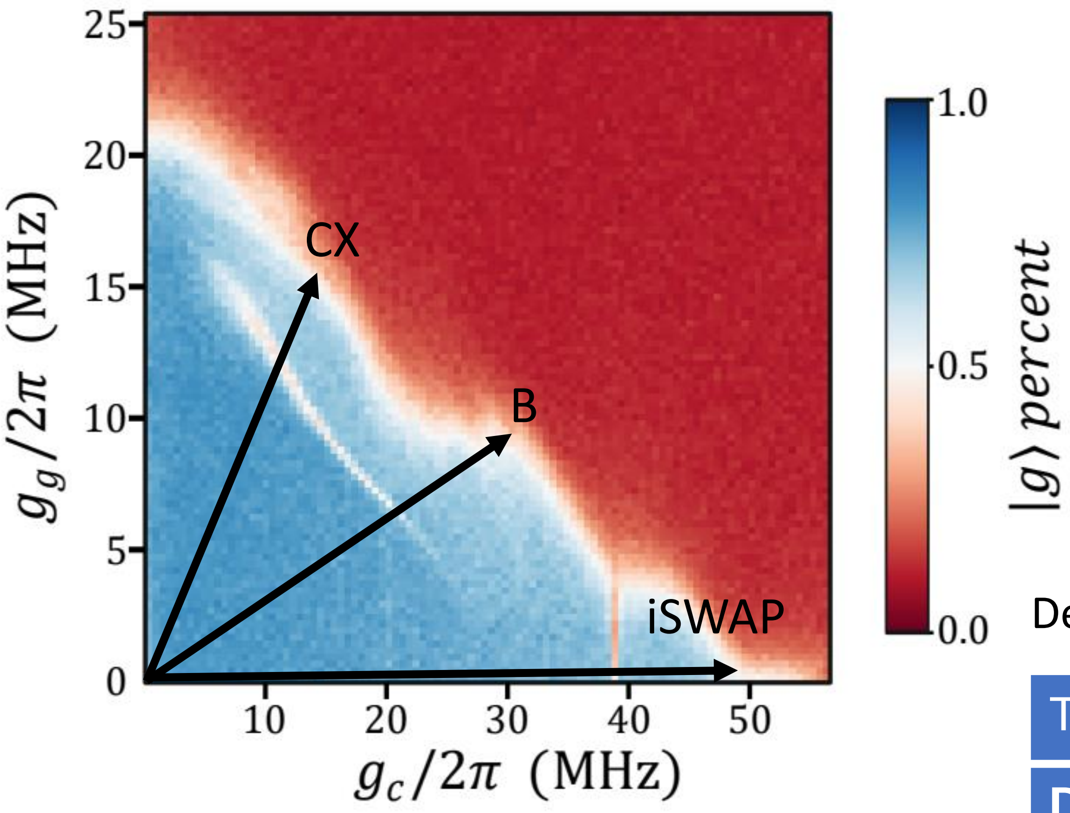

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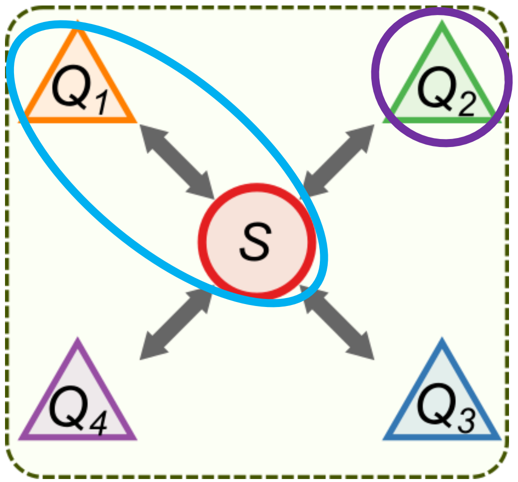

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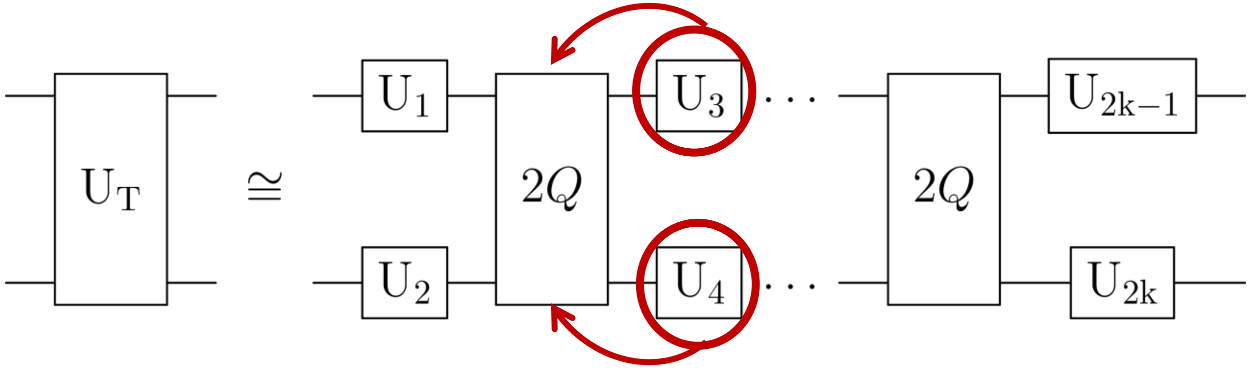
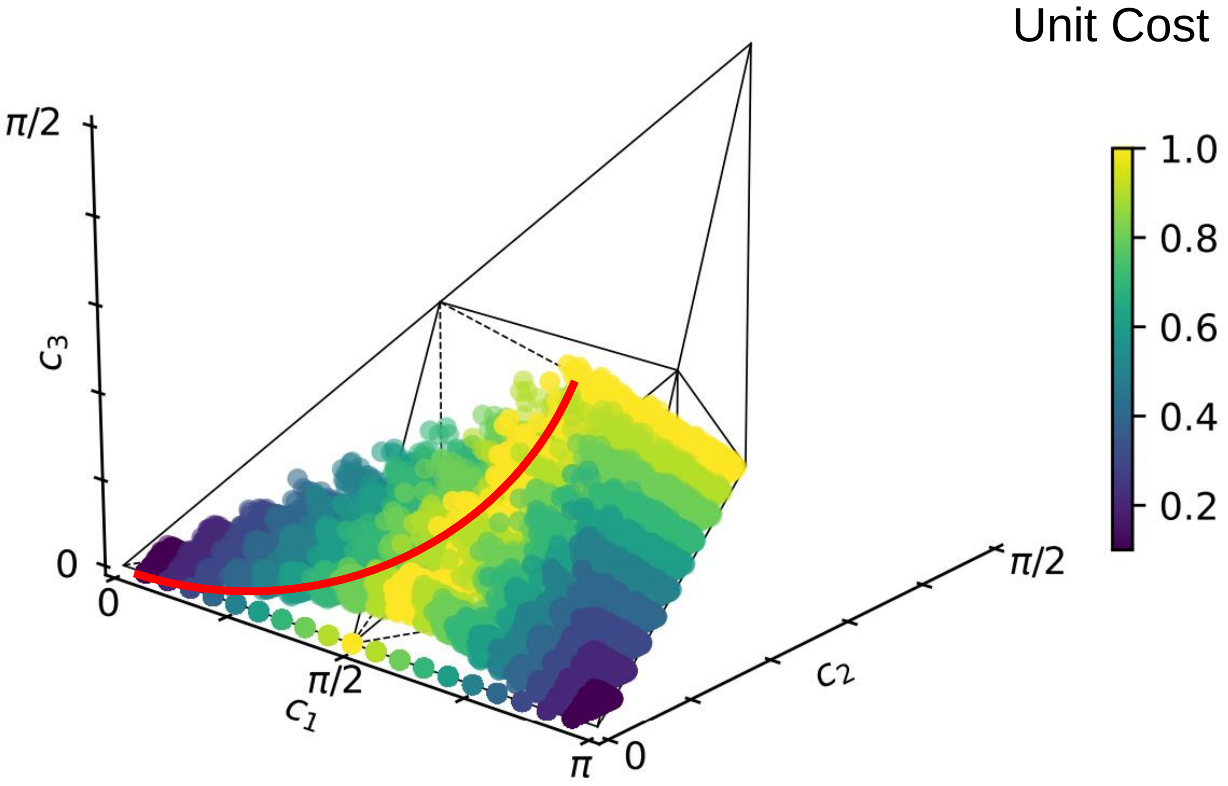
Extended candidate basis gates



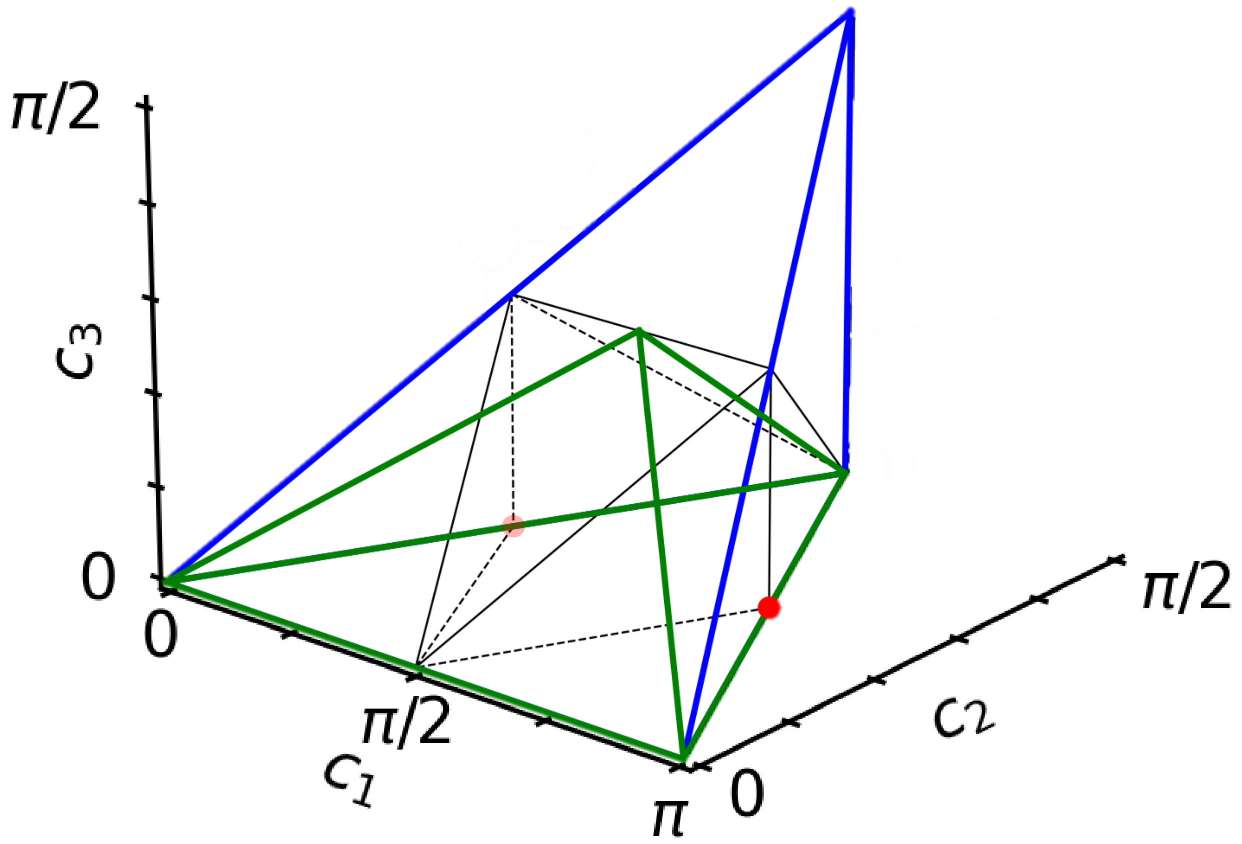
- **Drive qubits independently from the SNAIL in discrete time steps equivalent to basis gate duration**

$$\hat{H} = g_c(e^{i\phi_c}a^\dagger b + e^{-i\phi_c}ab^\dagger) + g_g(e^{i\phi_g}ab + e^{-i\phi_g}a^\dagger b^\dagger)$$
$$+\epsilon_1(t)(a + a^\dagger) + \epsilon_2(t)(b + b^\dagger)$$



- Parallel-Drive “steers” to previously inaccessible regions

Extended basis coverage volumes



Watts, et al. ***Physical Review A* 91.6** (2015): 062306

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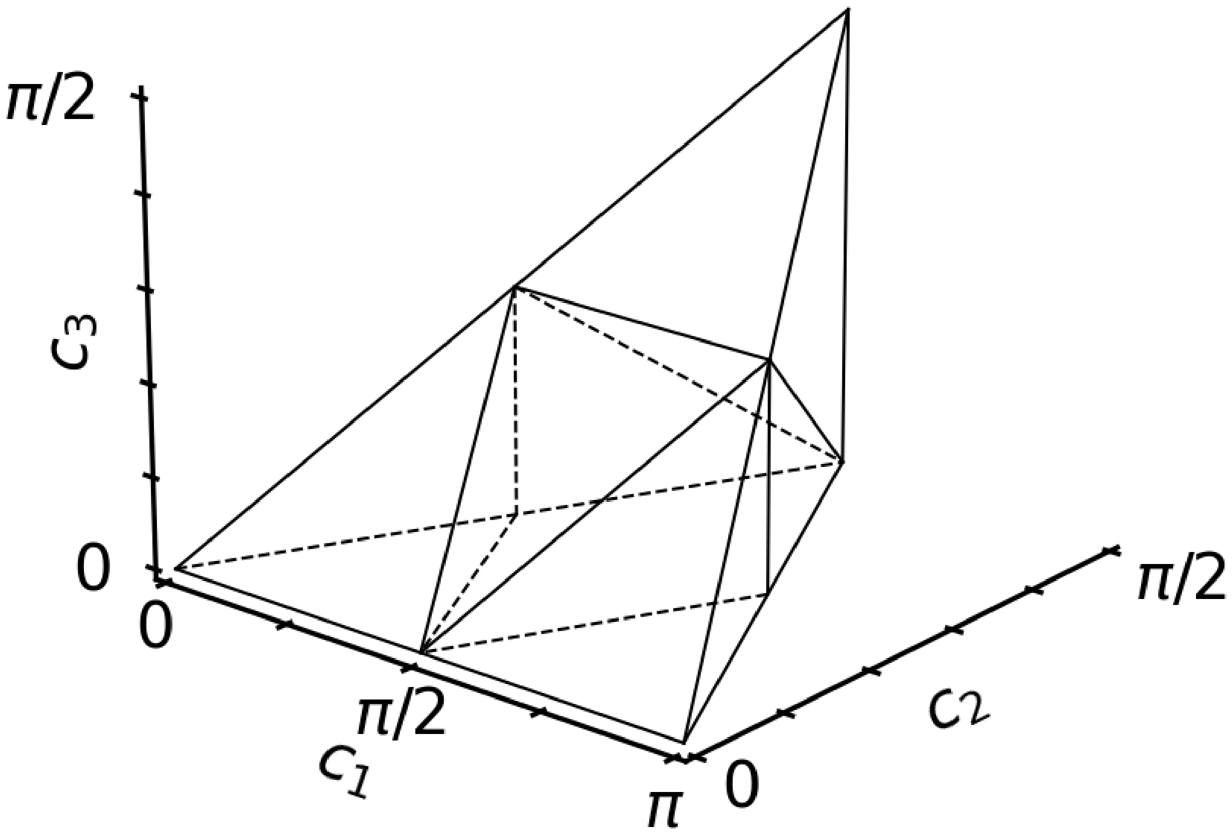

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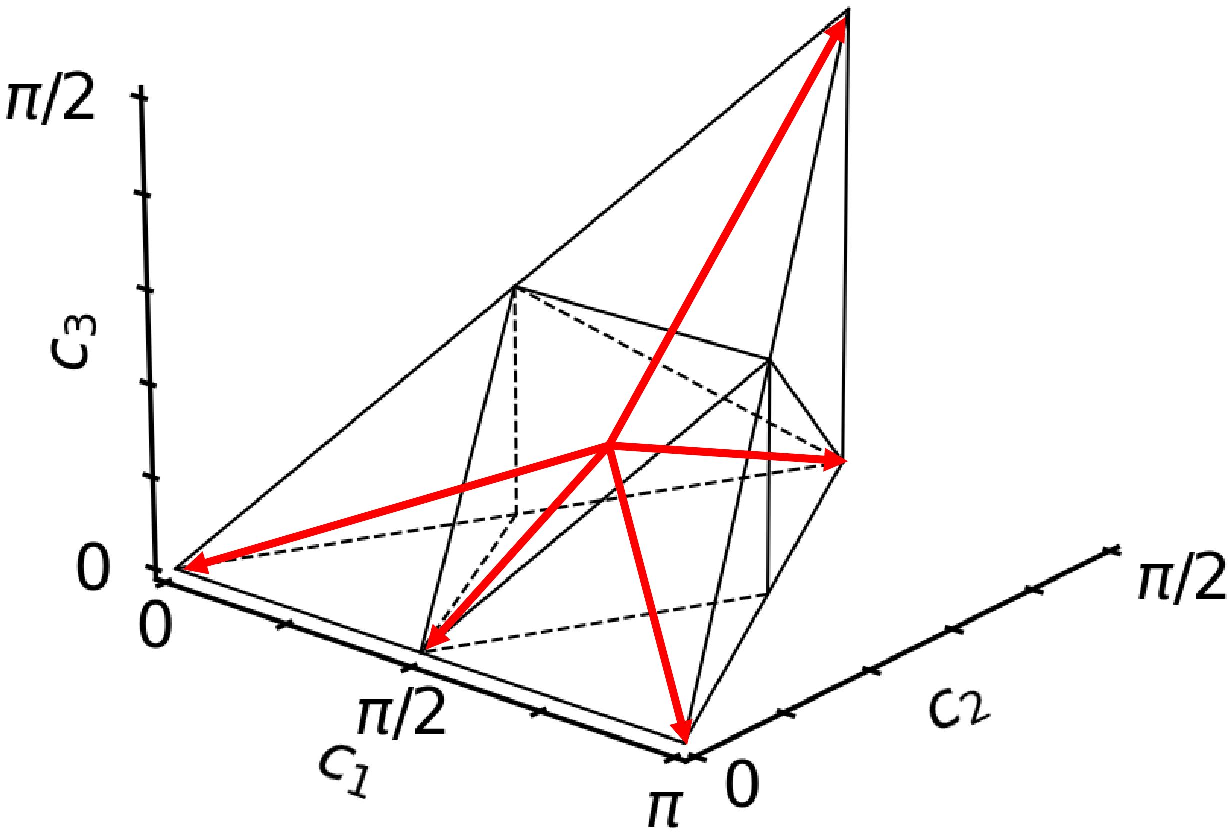

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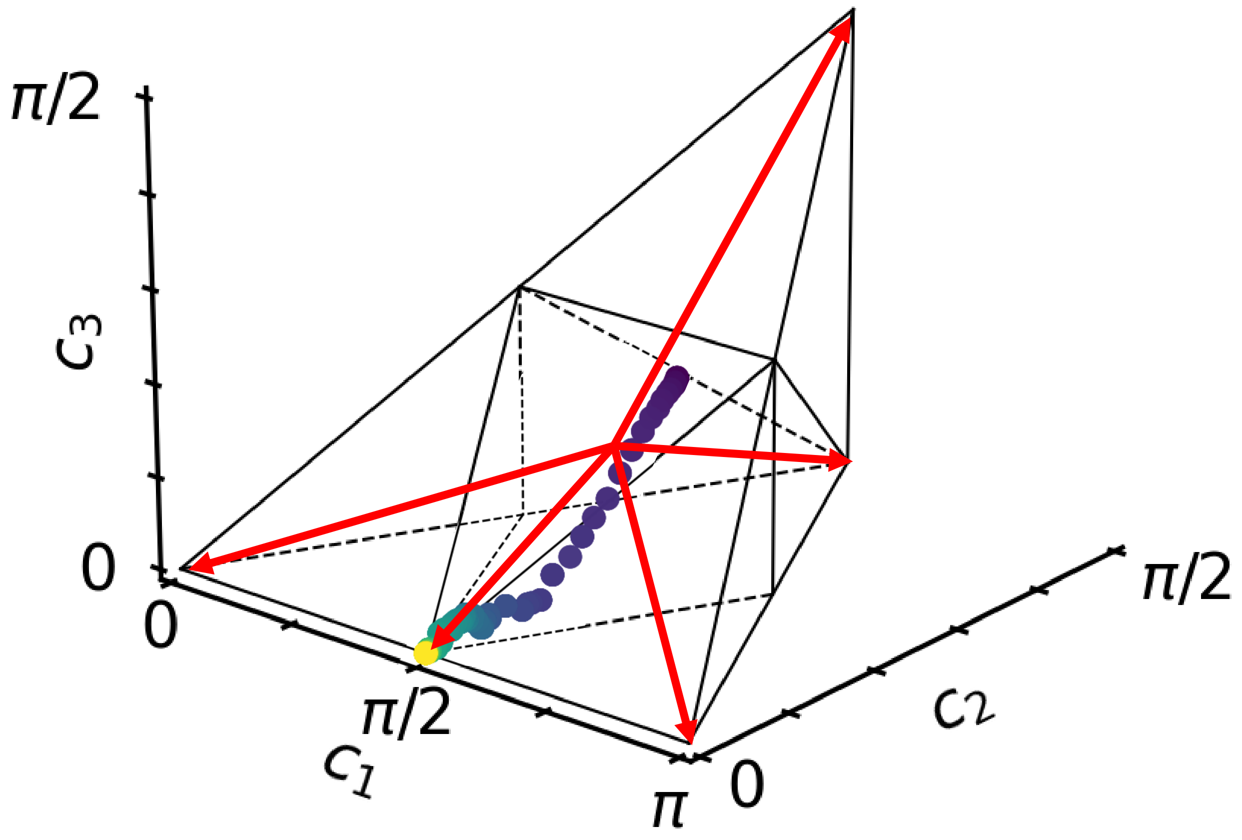
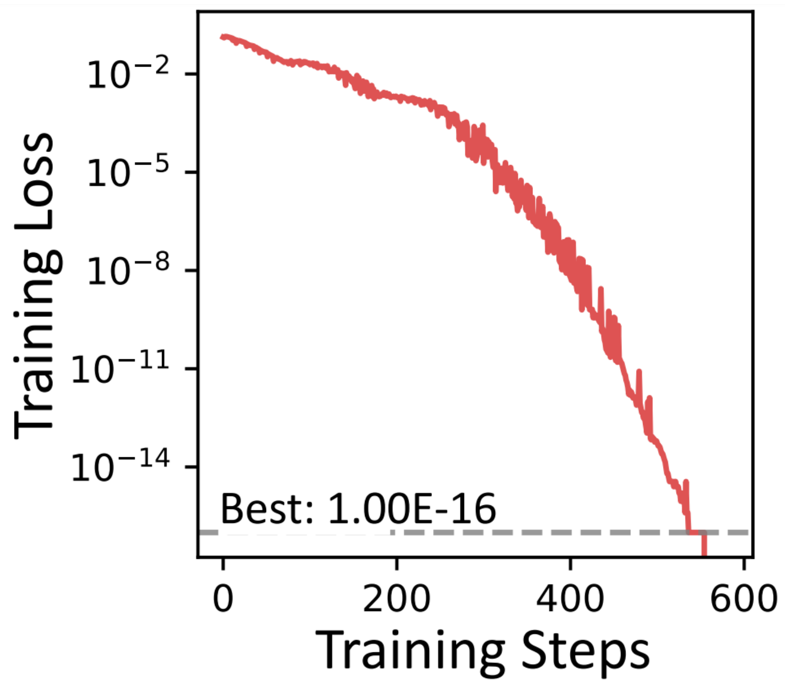


- Nelder-Mead optimization over Makhlin invariants functional



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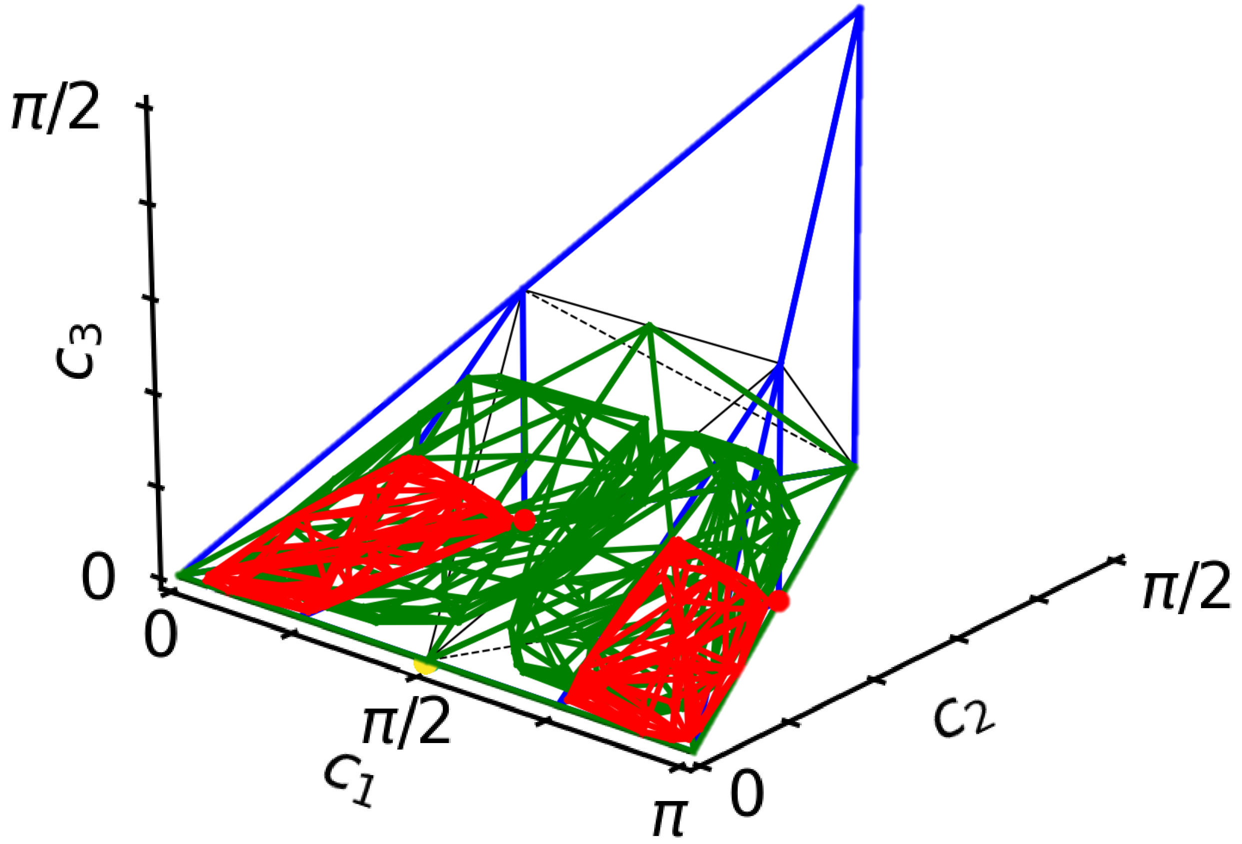

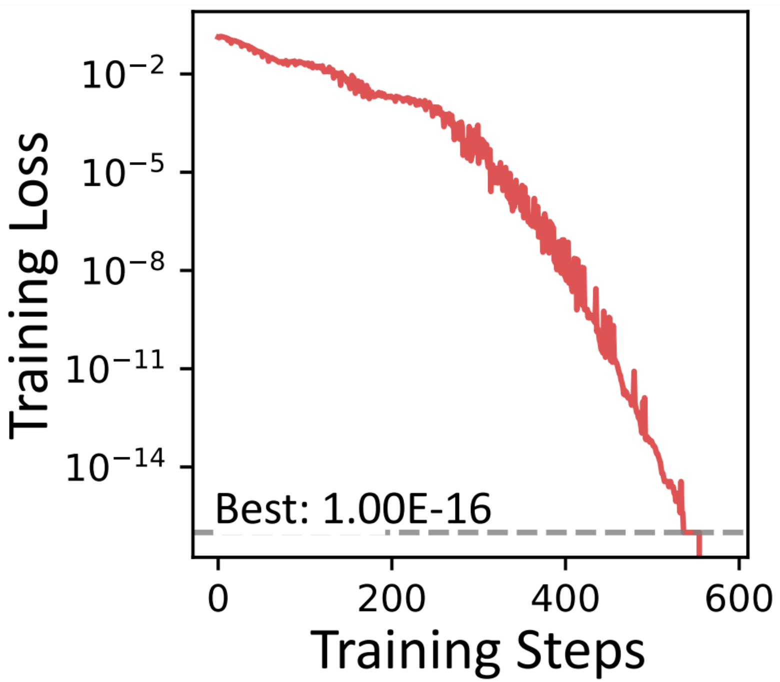

- Single gates have non-zero volume!

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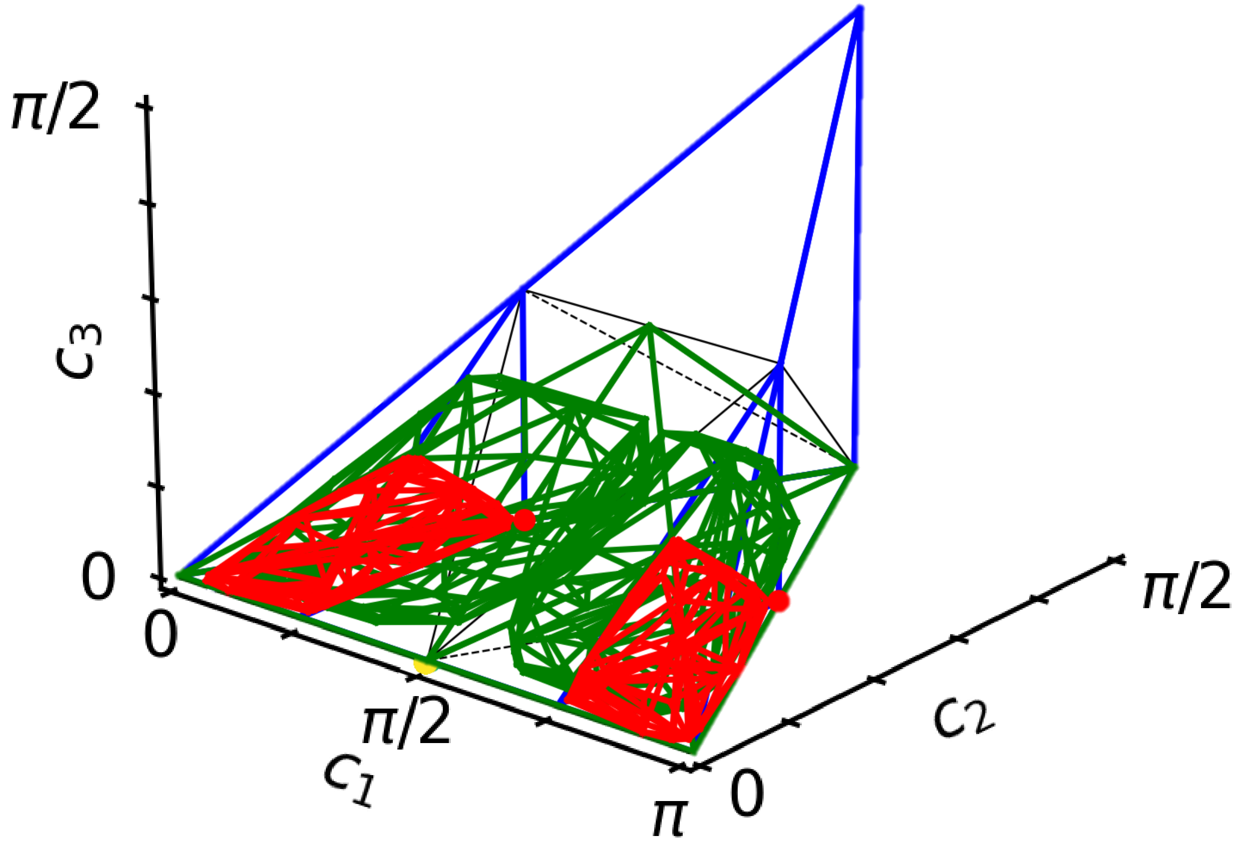

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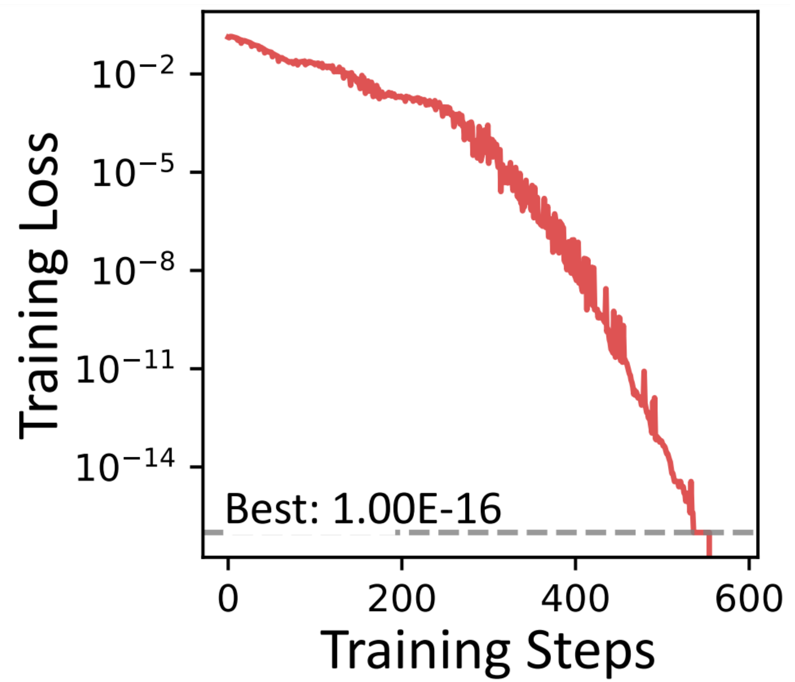

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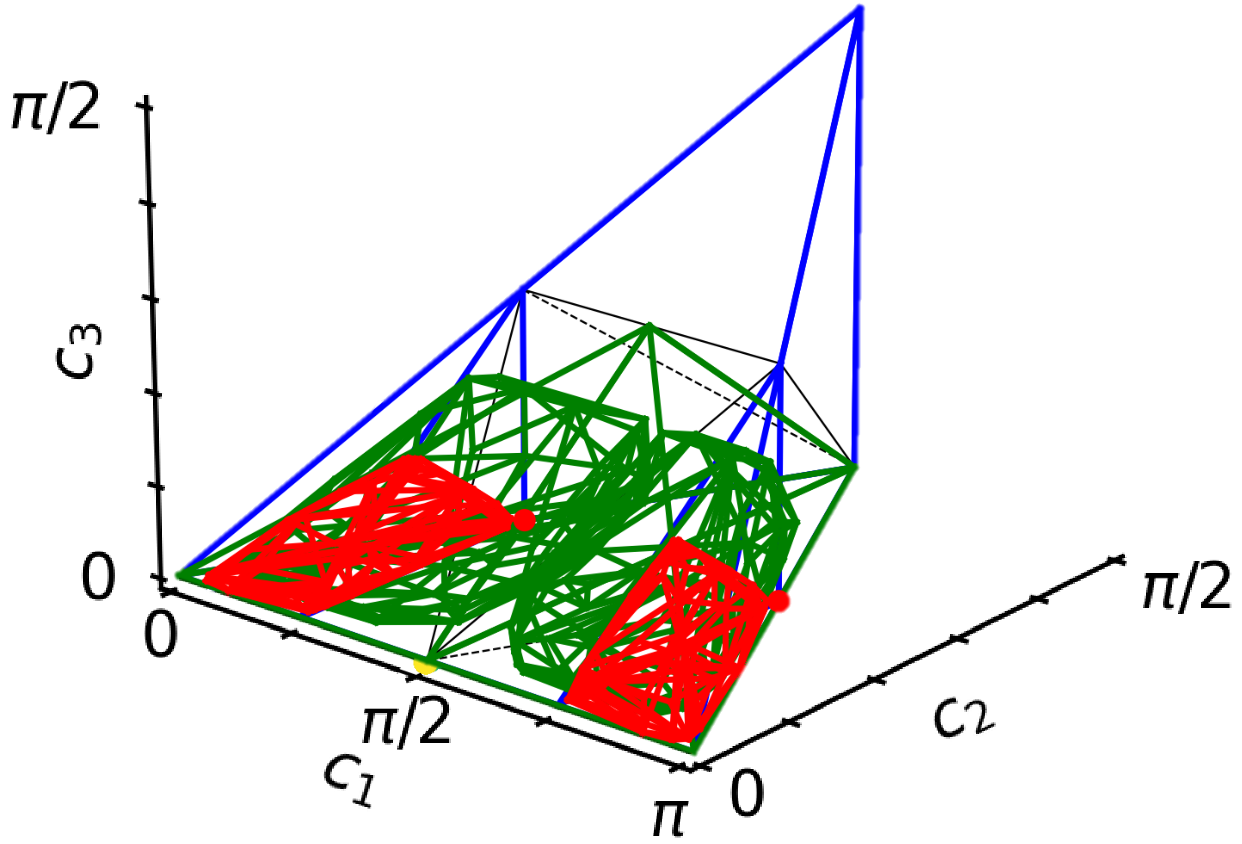

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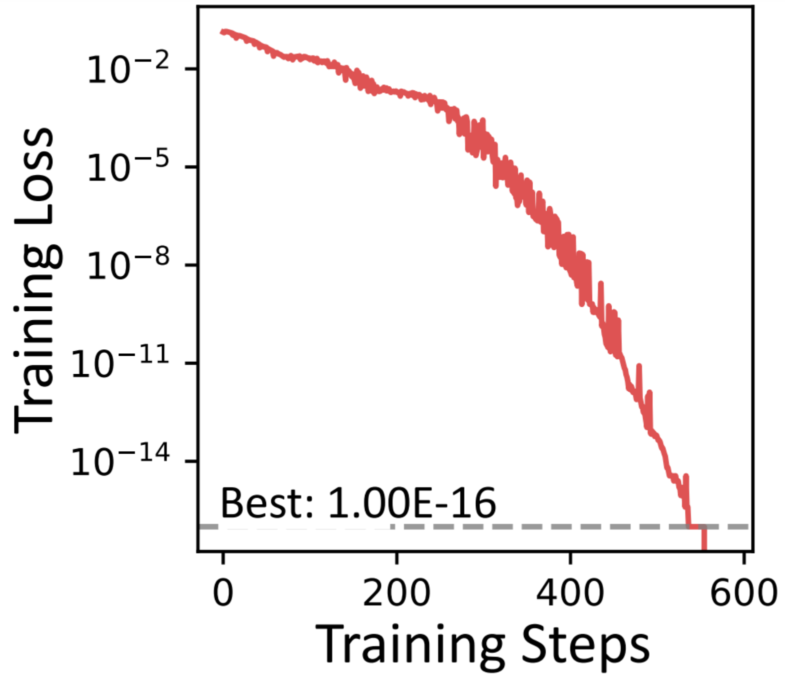

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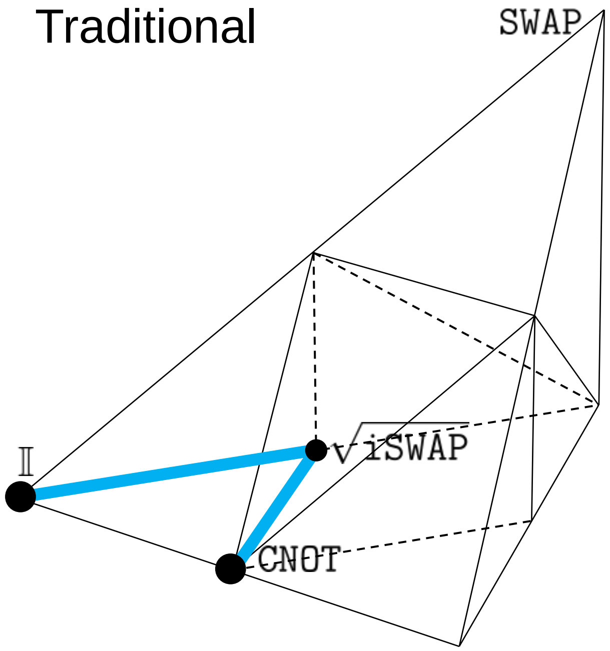
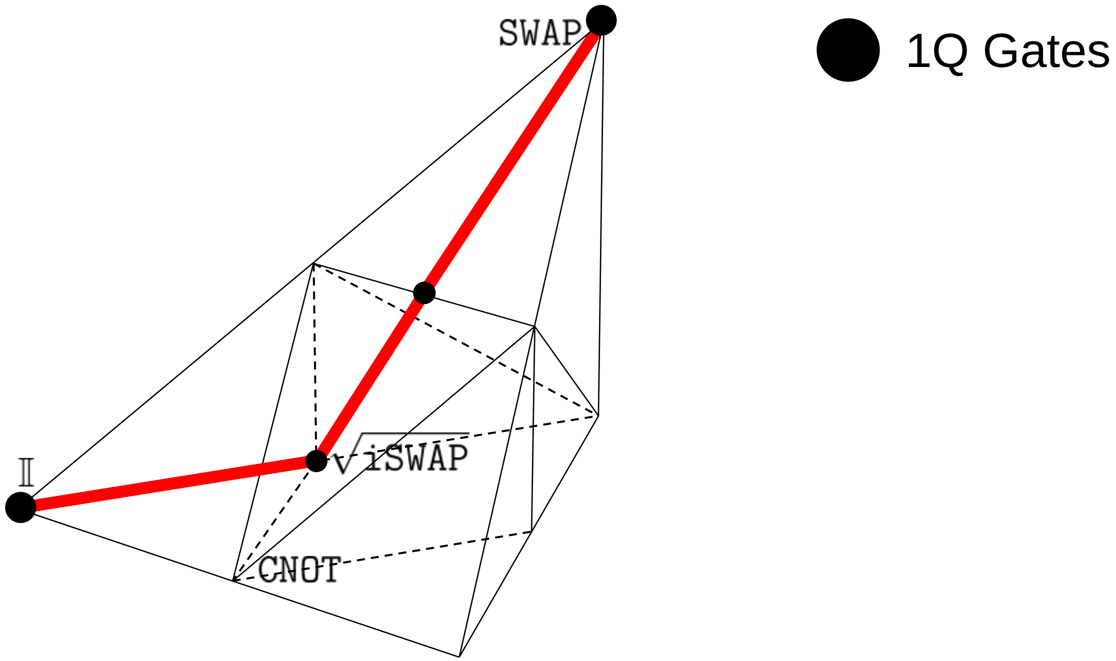
Cartan trajectories for √iSWAP

Traditional





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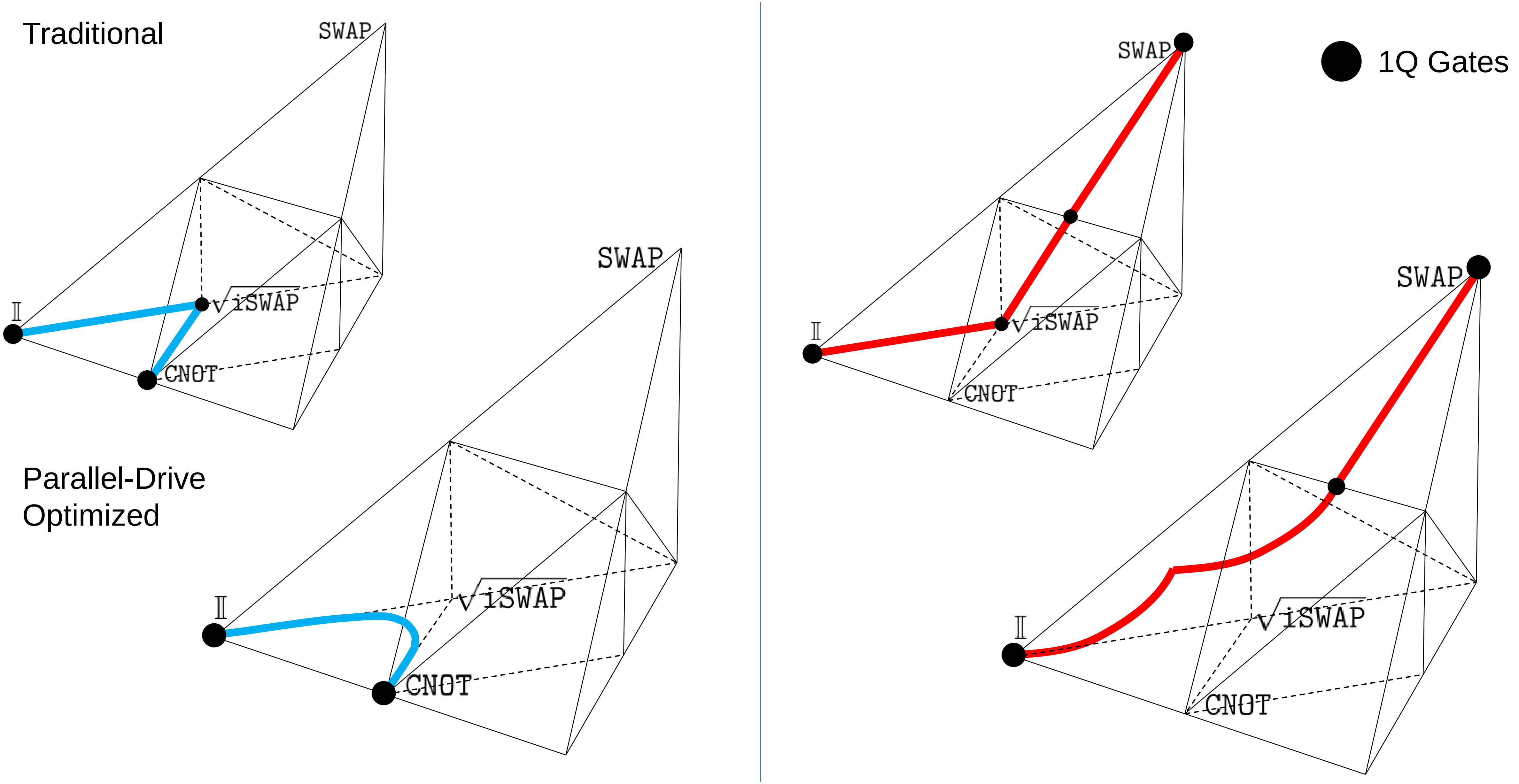
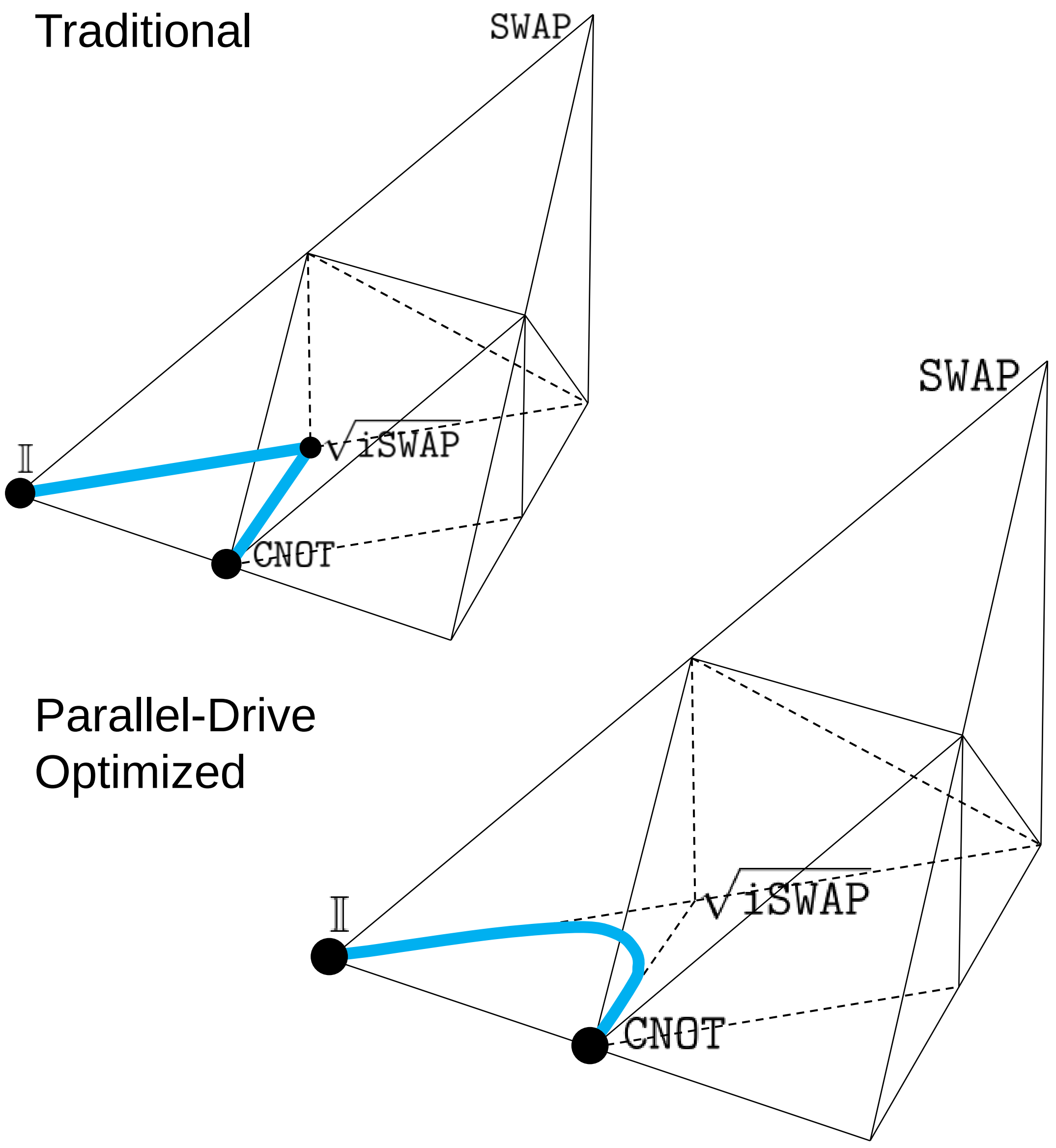
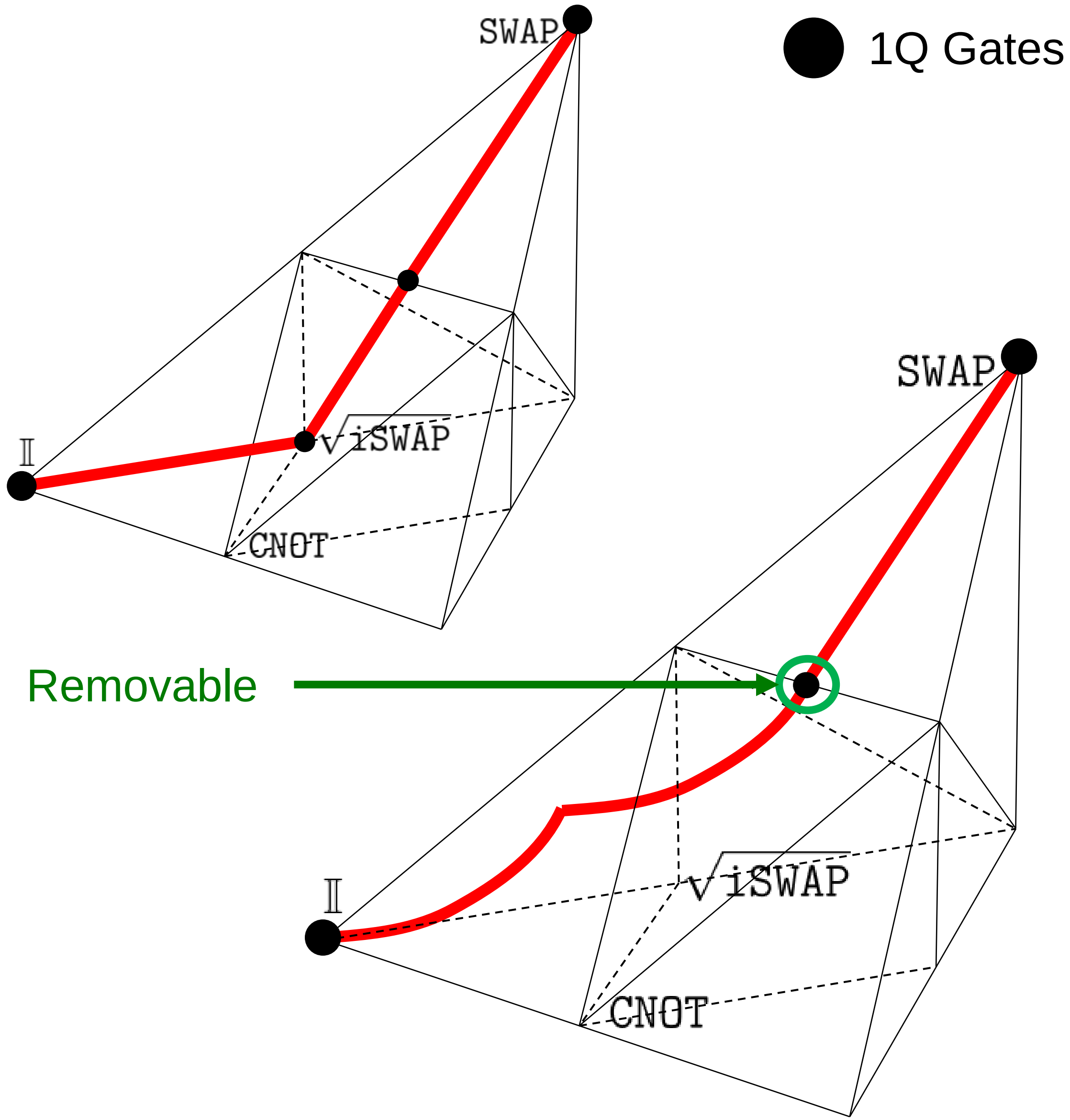


Cartan trajectories for $\sqrt{iSWAP}$





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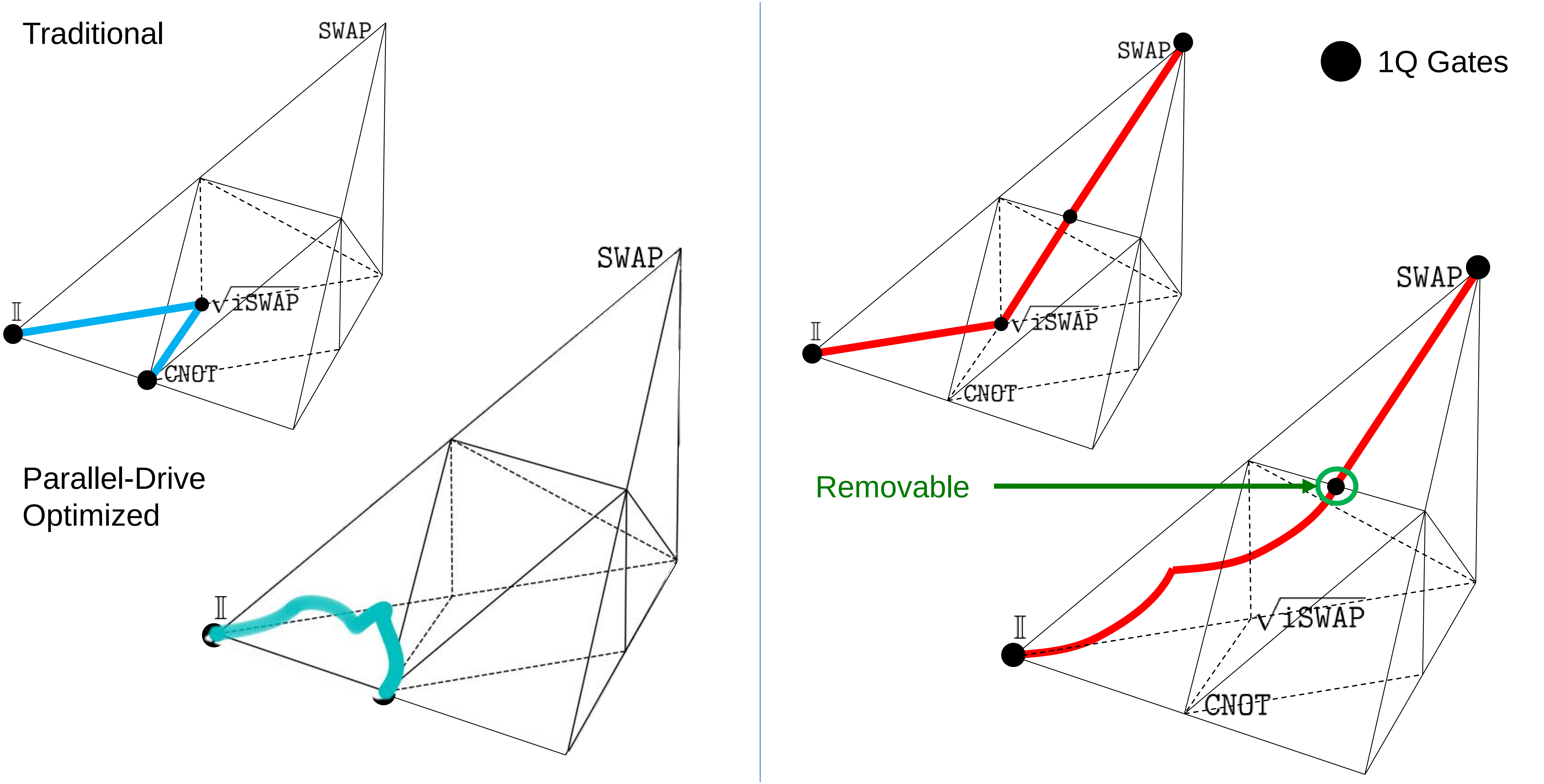

Conclusion

1. Decrease circuit duration by 17.84% over NISQ benchmarks!
2. Improve fidelity using $\sqrt{\text{iSWAP}}$ basis by 10.5% for random gates
3. Next steps, hardware realization

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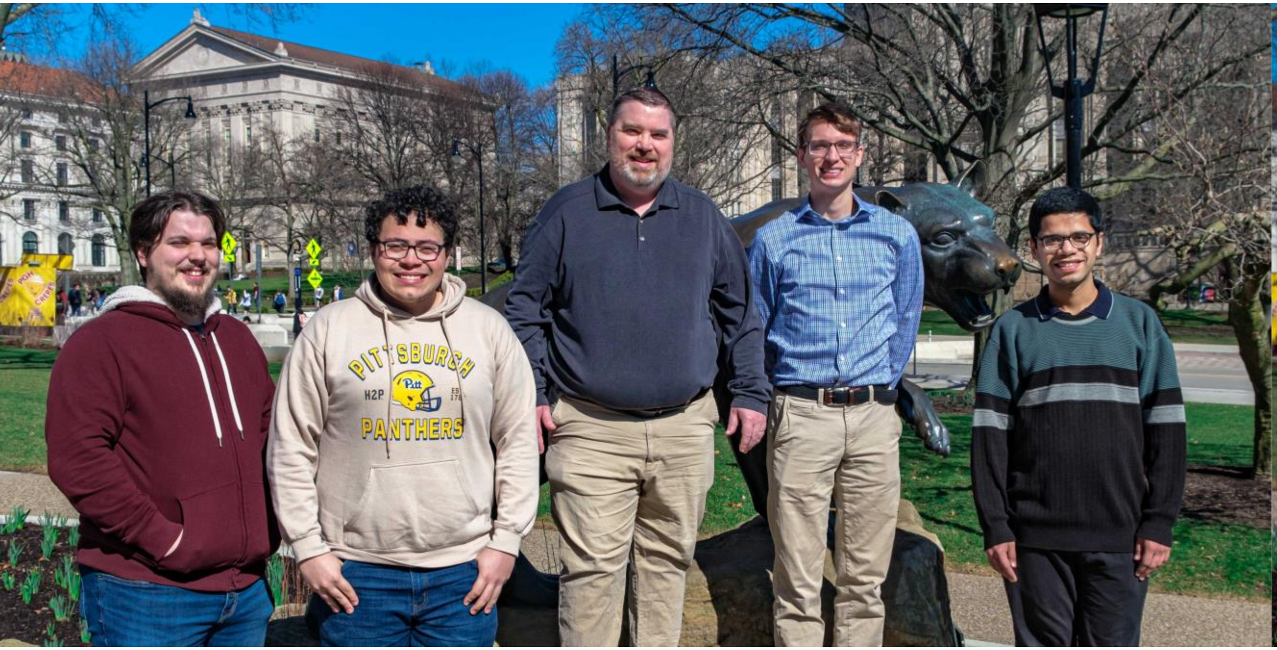

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