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Demonstrating Scalable Benchmarking of Universal Gate Sets

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Scalable Randomized Benchmarking

Many-qubit errors such as crosstalk are not apparent in low-width circuits

Randomized Benchmarking (RB) [1] and Random Circuit Sampling (RCS) [2] characterize average gate performance

- Large gate overhead (RB)
- High computational cost for universal gate sets (RB, RCS)

Circuit mirroring [3]: Flexible technique for designing scalable benchmarks

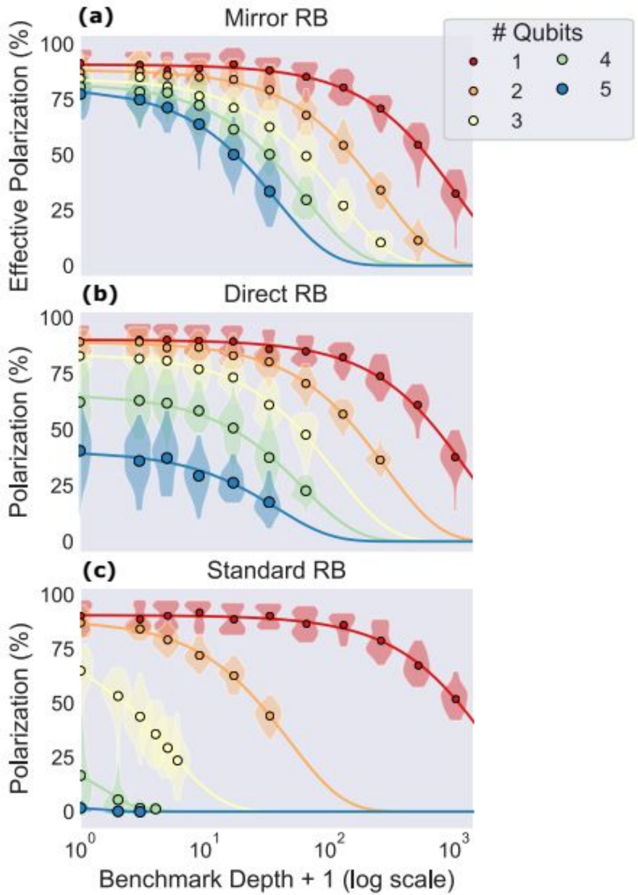


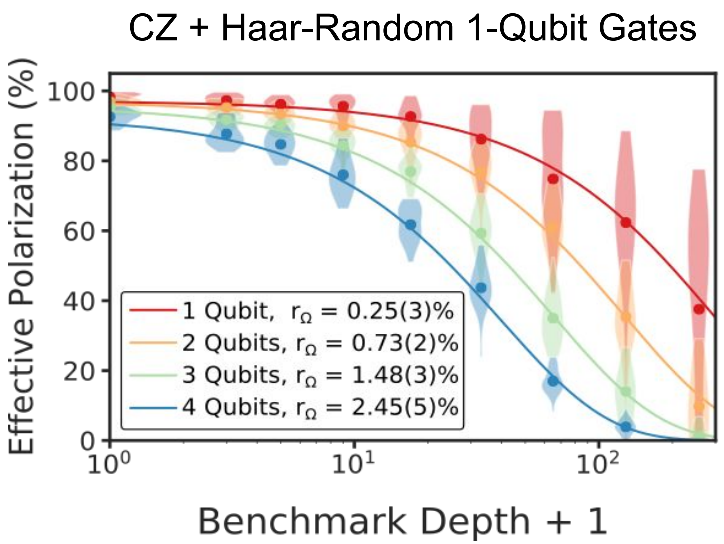
Figure: T. Proctor et al. arXiv:2112.09853

[1] E.Magesan et al., Phys. Rev. Lett. 106, 180504 (2011).
[2] Y. Liu et al. (2021), arXiv:2105.05232
[3] T. Proctor et al. (2022) Nat. Phys. 18,75-79

Scalable RB of Universal Gate Sets

We apply circuit mirroring to construct a scalable RB protocol for universal gate sets with

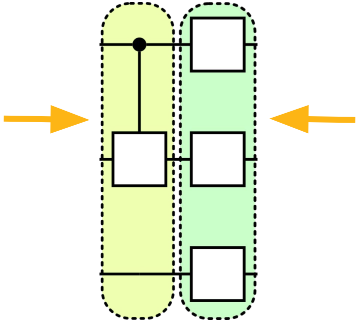
- Flexible gate set (two qubit gates can be any controlled Pauli axis rotations)
- Minimal gate overhead
- Low computational cost to construct circuits
- Efficiently computable circuit result



Structure of Mirror RB

MRB measures the **average error rate r_Ω** of circuit layers from a distribution Ω(L)

random 2-qubit gate layer, fixed average gate density



1-qubit gates sampled from 2-design

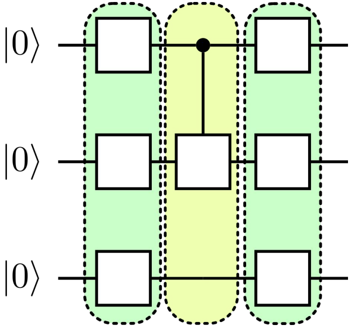
Run circuits with many depths with layers sampled from Ω(L)

The average **effective polarization** (measure of success) of MRB circuits decays exponentially in depth, at a rate determined by **r_Ω**

$$\bar{S}_d = Ap^d \qquad r_\Omega = \frac{4^n - 1}{4^n}(1-p)$$

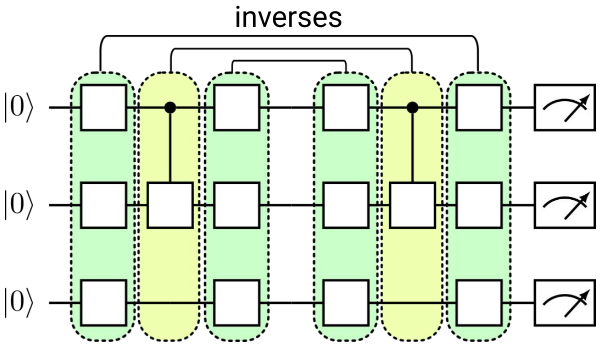
Non-Clifford Mirror Circuit Construction

1. Sample initial random 1-qubit gate layer and circuit layers from Ω(L)



Output not efficiently computable classically

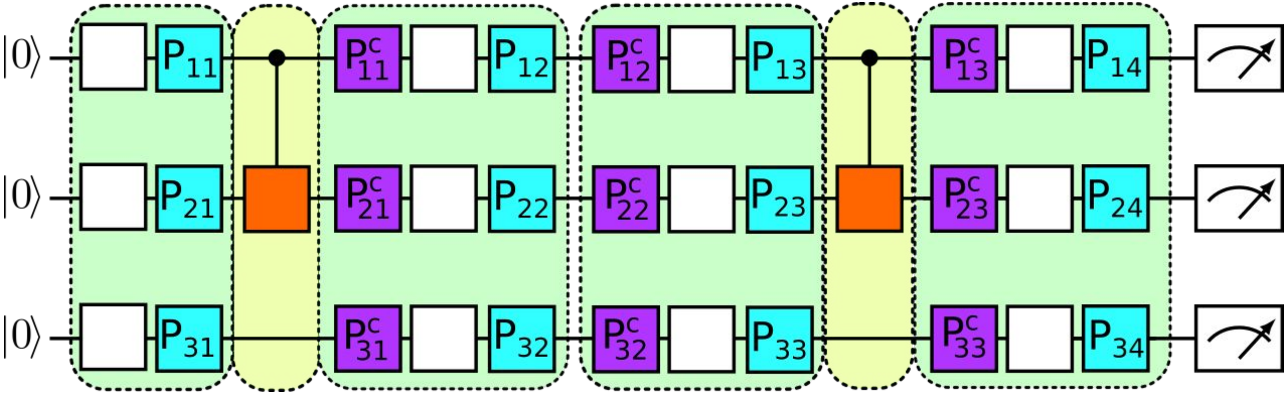
2. Append (layer-by-layer) inverse



susceptible to coherent cancellation of error

3. Randomized compiling:

- Insert random Paulis after 1-qubit gate layers
- Insert "corrections" before 1-qubit gate layers that cancel the action of the random Paulis
- Circuit ideal output is a definite bit string



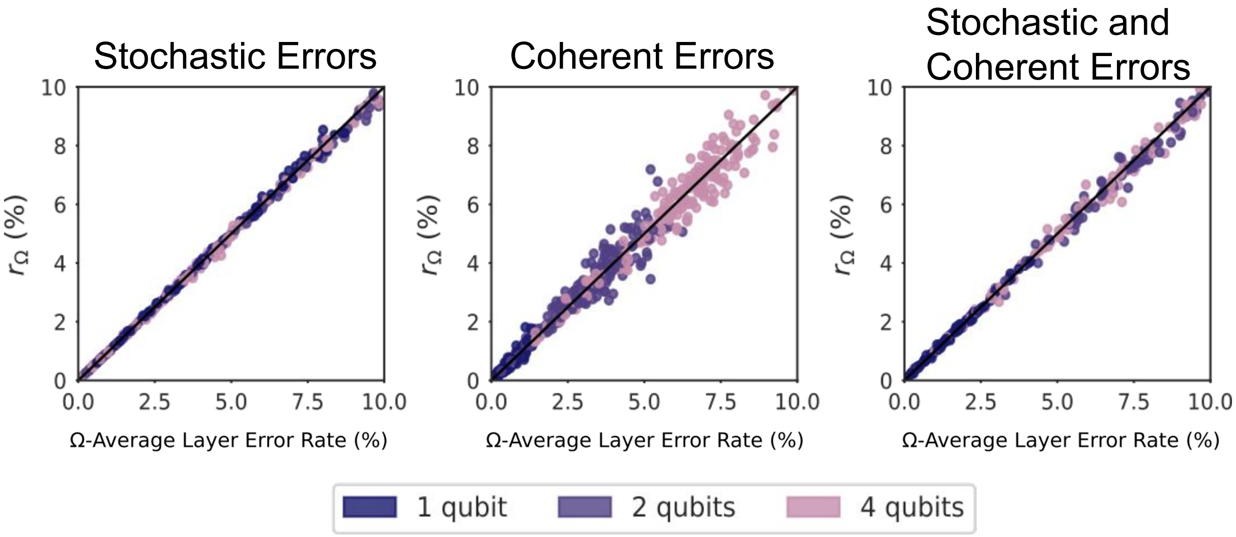
Sensitivity of Non-Clifford MRB

Only Clifford 2-qubit gates: Gate error twirled into Pauli noise when 1-qubit gate noise is gate-independent

- Special case of randomized compiling as defined by Wallman and Emerson [4]

With Non-Clifford Two-Qubit Gates: Gate error not perfectly twirled

- r_Ω typically approximates average layer infidelity closely for combination of stochastic and coherent errors
- Our circuit structure is insensitive to some coherent errors

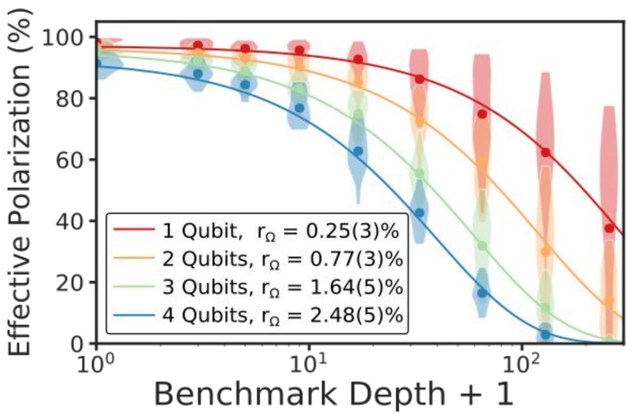


[4] J. Wallman and J. Emerson, Phys. Rev. A 94, 052325 (2016).

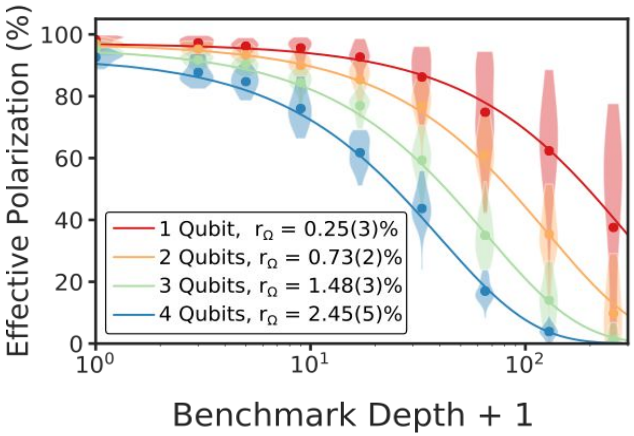
Demonstrating MRB with Universal Gate Sets

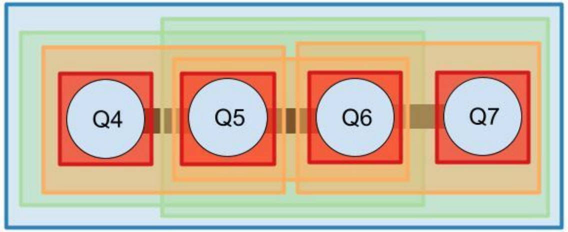
MRB on 4 linearly-connected superconducting qubits (Advanced Quantum Testbed at LBNL)

CS, CS† + Haar-Random 1-Qubit Gates



CZ + Haar-Random 1-Qubit Gates

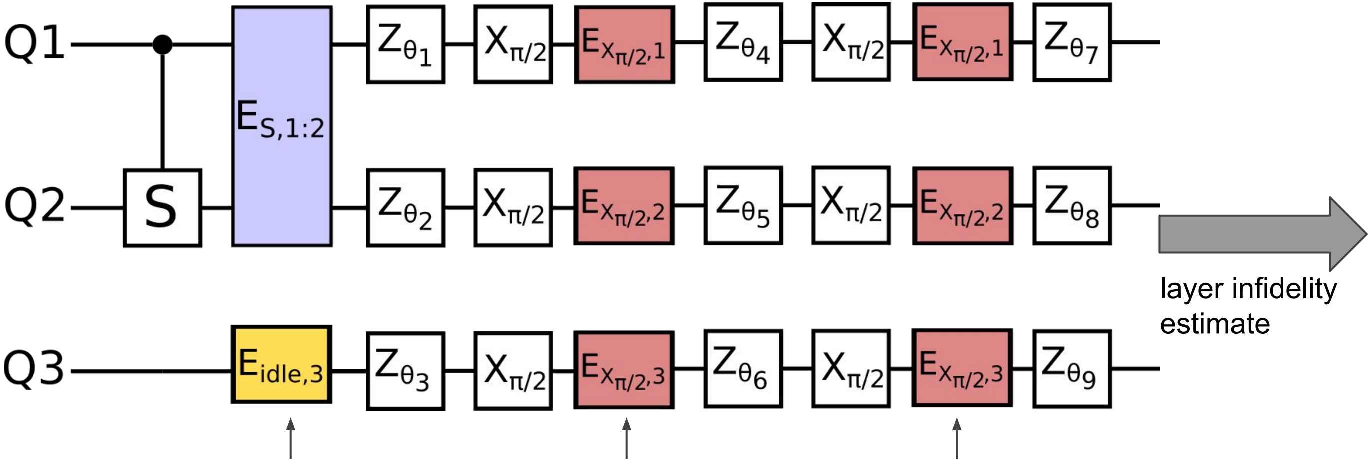




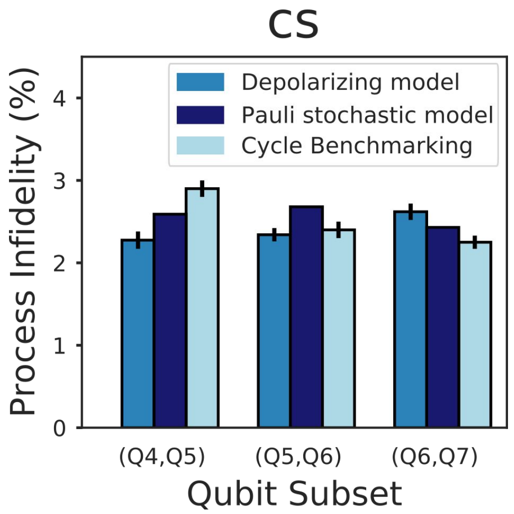
- Effective polarization decays exponentially
- CS, CS† gate set has slightly higher average error than CZ (cross-validated with Cycle Benchmarking)

Experimental Validation of Non-Clifford MRB

Fit a model to MRB data assigning an error channel to each gate



depolarizing or **Pauli stochastic** error channels



Layer infidelity estimates consistent with cycle benchmarking

Many Qubit MRB Captures Crosstalk Error

Predict n>2 qubit MRB error rate from 1- and 2-qubit MRB error rates using

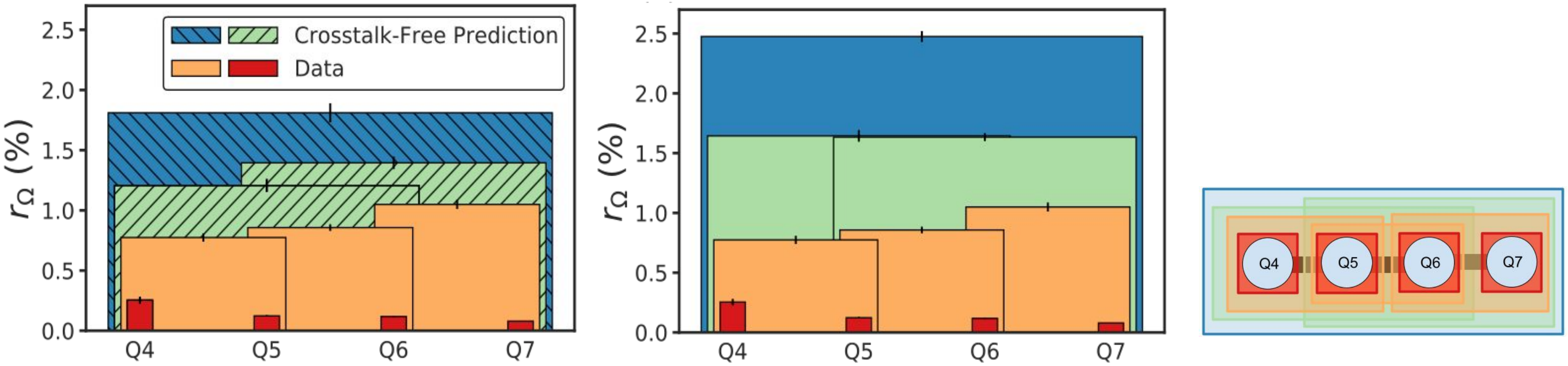
$$r_{\Omega} \approx \sum_{\mathsf{L} \in \mathbb{L}} \Omega(\mathsf{L}) \epsilon_{\mathsf{L}}$$

Assuming no crosstalk:

$$\epsilon_{\mathsf{L}} = 1 - \prod_{\mathsf{g} \in \mathsf{L}} (1 - \epsilon_{\mathsf{g}})$$

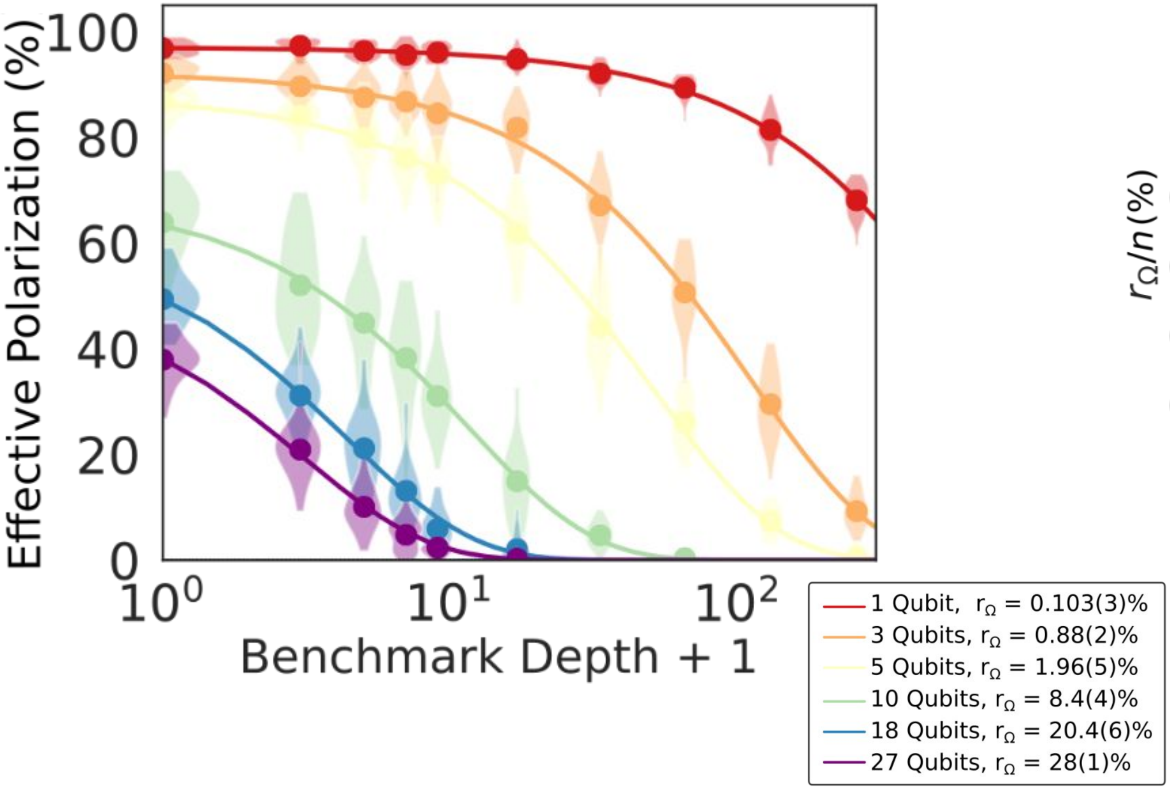
$\mathbb{L}$: layer set
Ω : layer sampling distribution
ϵ_{L} : infidelity of layer L
ϵ_{g} : infidelity of gate g

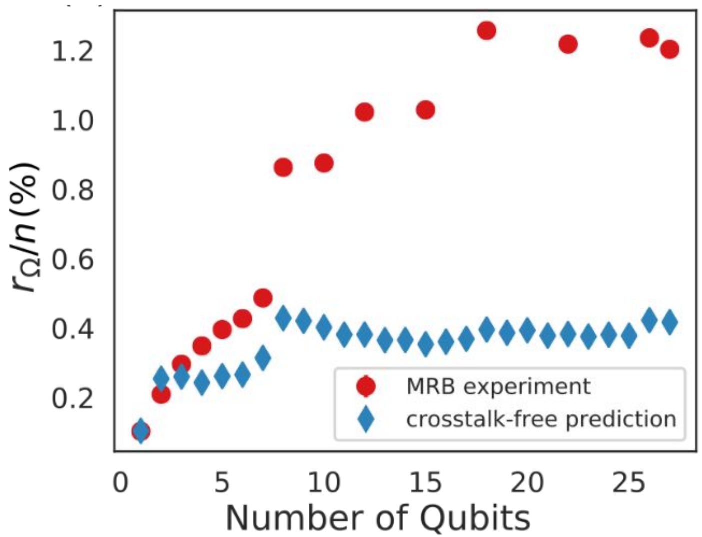
MRB with CS, $\mathsf{CS}^{\dagger}$ and Haar-random 1-qubit gates



Non-Clifford MRB is Highly Scalable

Mirror RB of a universal gate set on 27 superconducting qubits (IBMQ Montreal)





Many-qubit MRB reveals finite-radius crosstalk error.

Summary

Non-Clifford Mirror RB is a highly-scalable benchmarking technique for average performance

- Has low gate overhead
- Has low classical computational cost
- Can extract information on many-qubit error

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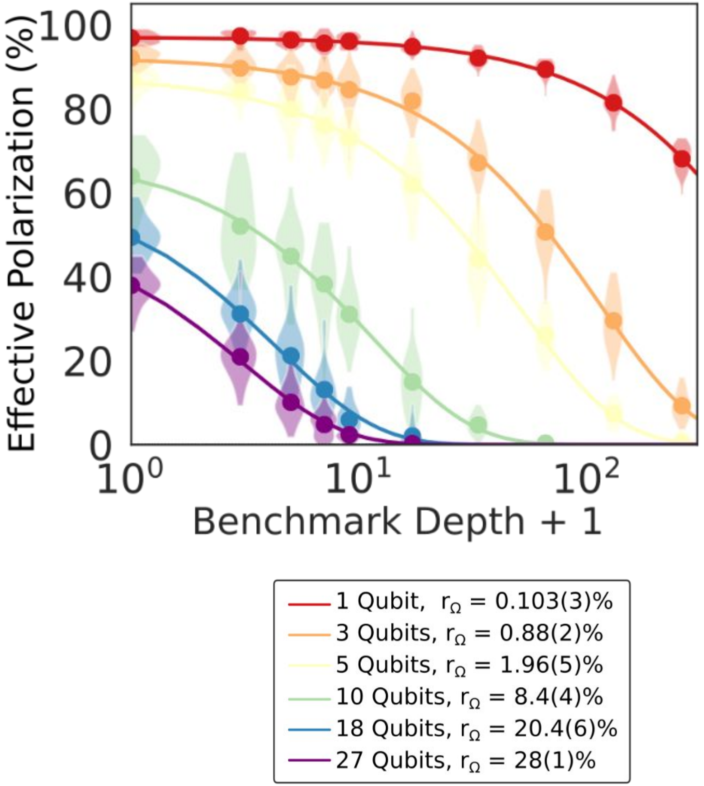
arXiv: Coming Soon



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