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Randomized benchmarking of many-qubit devices

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[2]University of Waterloo.

SQuInT 2019

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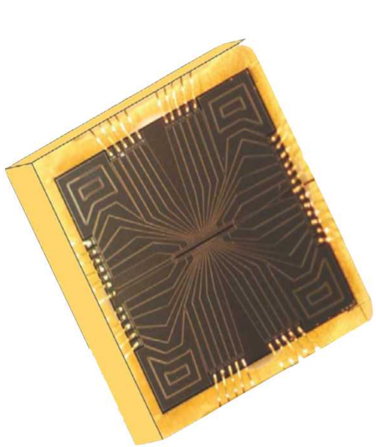
Part I – Background

Device characterization and benchmarking

- Characterization & benchmarking = Techniques for understanding device performance.



Pick some circuits → Collect data → Estimate parameters of a model

	00	01	10	11
Circuit 1	23	27	10	40
Circuit 2	00	00	99	01
⋮		⋮		
Circuit K	10	80	05	05

$\text{gate}_1 = M_1$, $\text{gate}_2 = M_2$, …
measurement = E, …

gate rotation angle = 0.01

average gate error rate = 0.034

- Examples: randomized benchmarking[1-3], tomographic methods, robust phase estimation, …

[1]Magesan *et al.,* PRL 106, 180504 (2011), [2]Emerson *et al.,* Science 317, 1893 (2007), [3]Knill *et al.,* PRA 77, 012307 (2008).

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Randomized benchmarking (RB)

- Benchmarks gates using random circuits, returning an average error rate for the gates.
- Arguably the first method for characterizing a quantum device that is not prone to catastrophic systematic errors (unlike, e.g., "ordinary" process tomography).
- Easy and fast to use.
- Has become a *de facto* standard technique.
- The current standard RB method[1] benchmarks the Clifford group, and is often called "Clifford RB".

(Clifford group = gates that map Pauli gates to Pauli gates under conjugation.)

[1]Magesan *et al.,* PRL 106, 180504 (2011), [2]Emerson *et al.,* Science 317, 1893 (2007), [3]Knill *et al.,* PRA 77, 012307 (2008).

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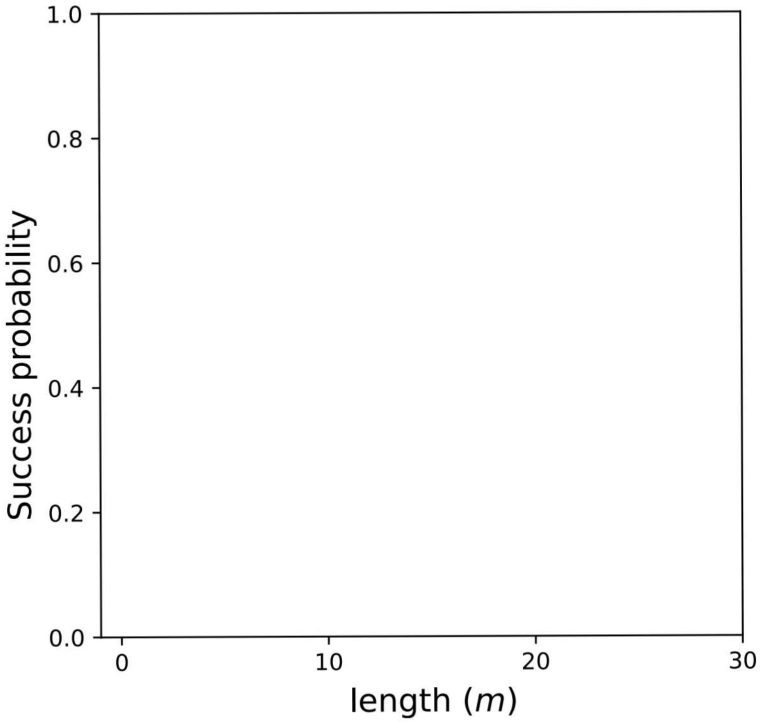
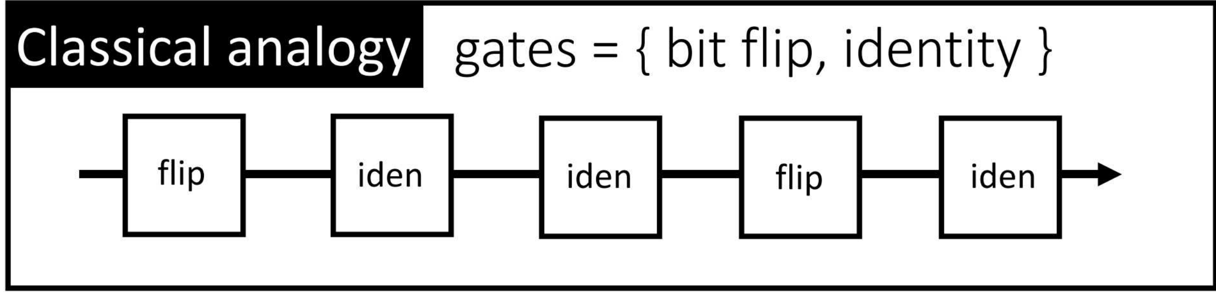
Clifford RB on n qubits

- Pick a set of non-negative integers m, and for each m:



Clifford RB on *n* qubits



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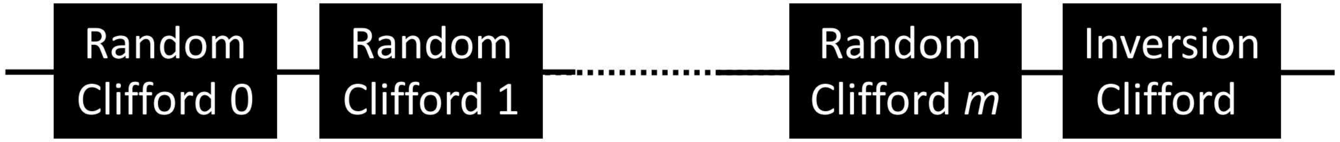

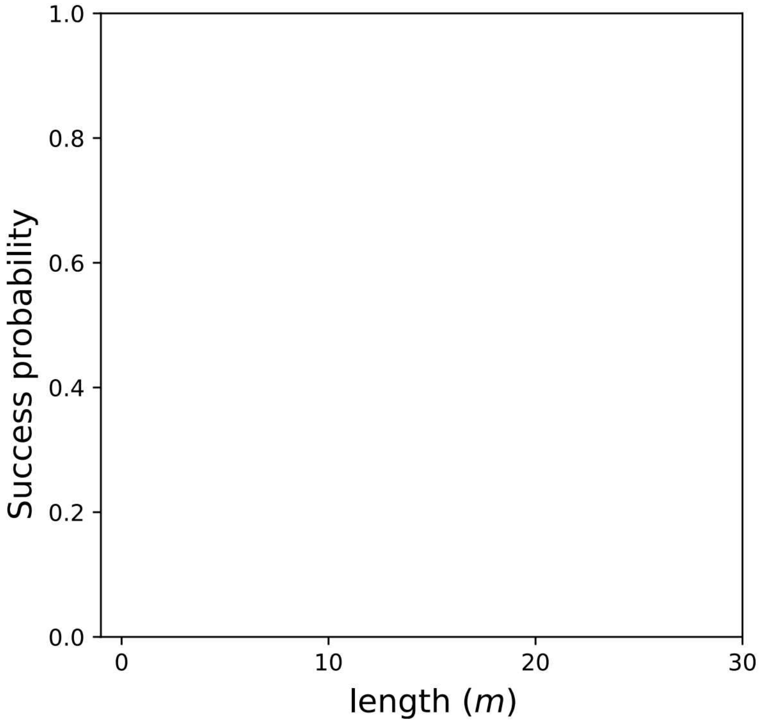

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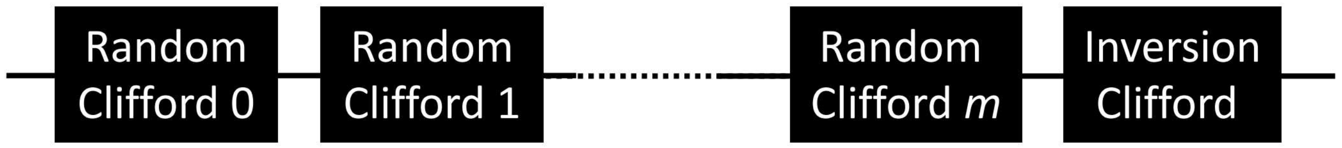

  - For each circuit, repeat 1+ times:
    - Prepare all *n* qubits in $|0\rangle$
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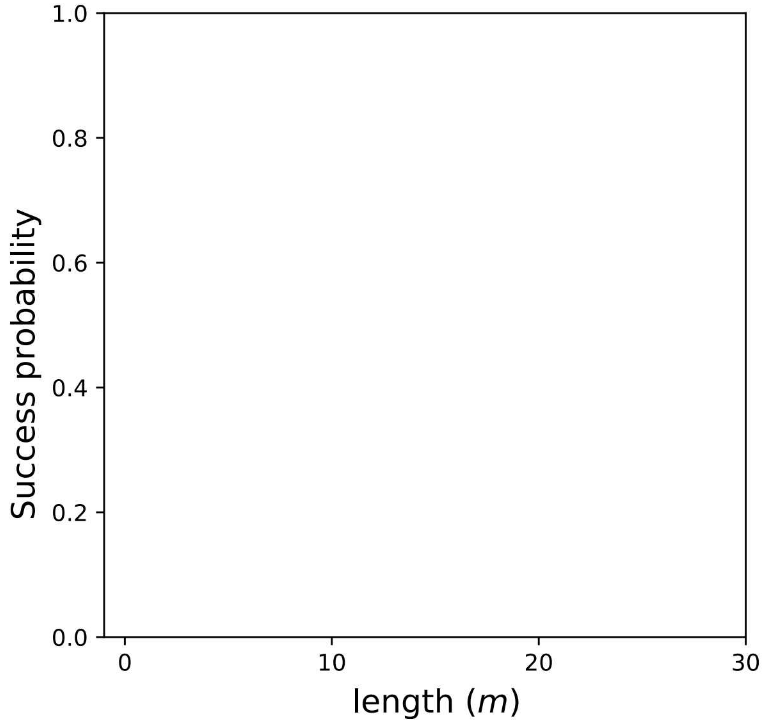

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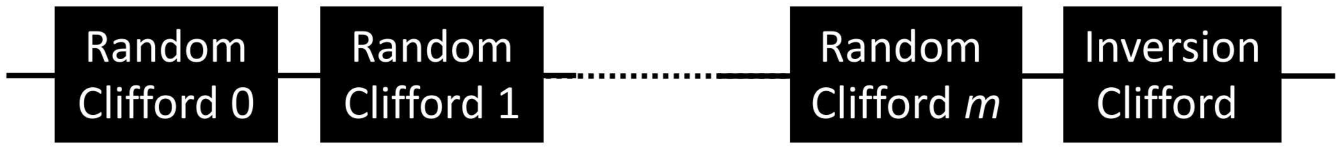

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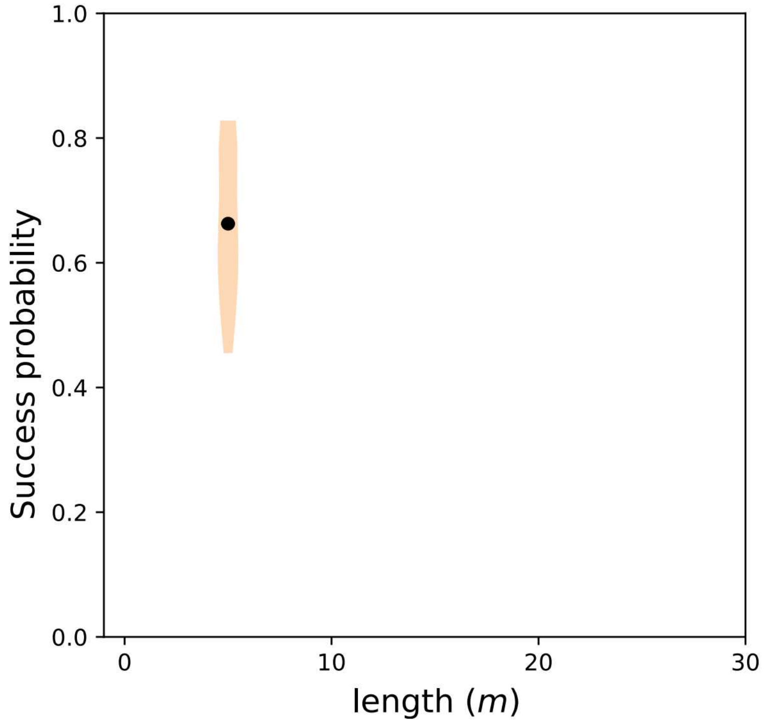

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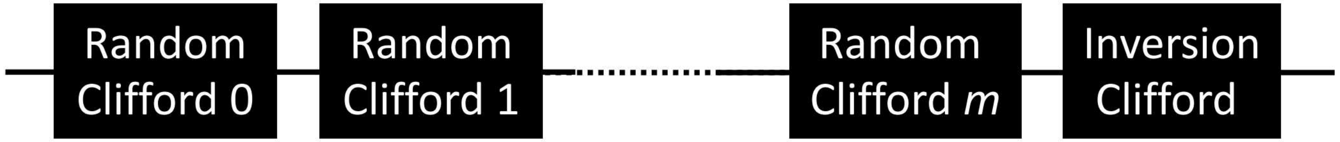

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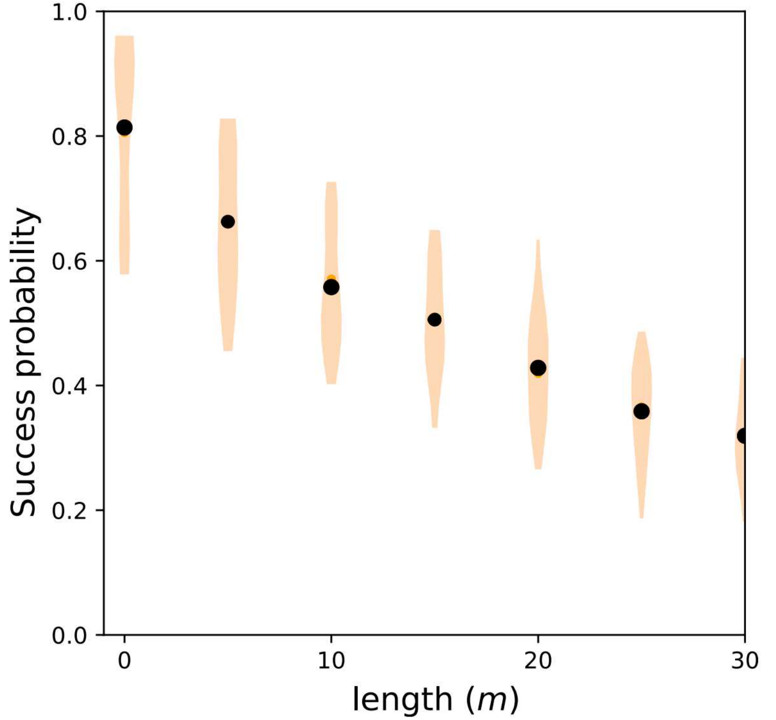

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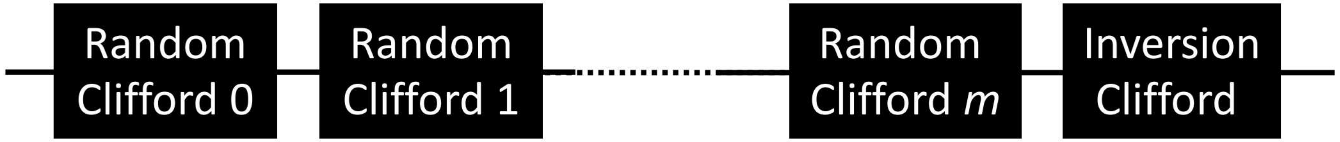

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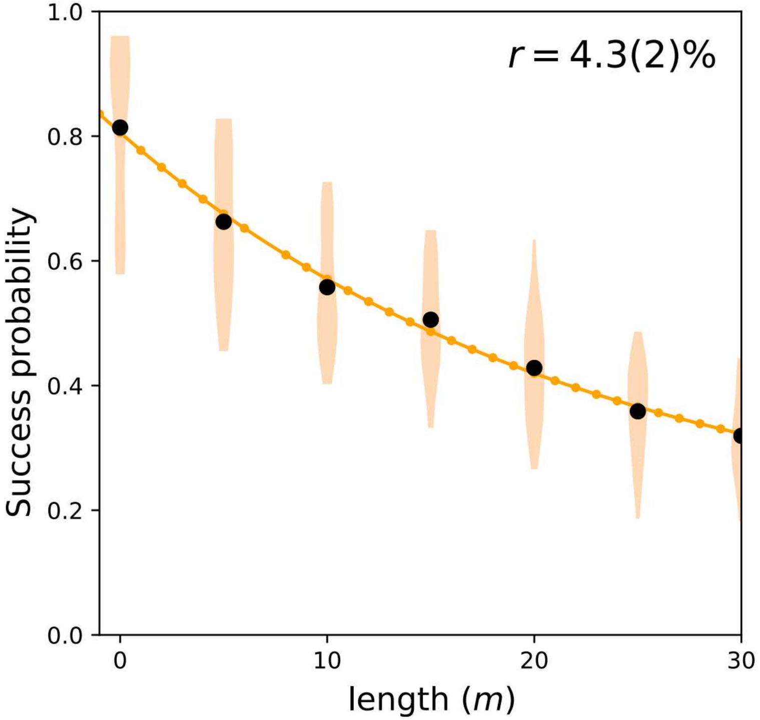

- Fit P_m to $P_m = A + Bp^m$, obtaining an error rate via $r \propto 1 - p$.

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Clifford RB cannot holistically benchmark near-term devices

- Clifford RB scales well with the number of qubits n in ***some*** ways:
  - The number of experiments needed is independent of n.[1]
  - The data analysis complexity is independent of n.[2]

[1]Magesan et al., PRA 85, 042311 (2012), [2]Helsen *et al.,* arXiv:1701.04299 (2017), [3]McKay *et al,* arXiv:1712.06550 (2017).

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- Clifford RB scales well with the number of qubits *n* in ***some*** ways:
  - The number of experiments needed is independent of *n*.[1]
  - The data analysis complexity is independent of *n*.[2]
- Yet, there is only one reported case of 3-qubit Clifford RB[3], and none of 4+ qubit Clifford RB. Because…

Scaling Clifford RB up to many qubits is difficult because of ***compilation.***

[1]Magesan et al., PRA 85, 042311 (2012), [2]Helsen *et al.,* arXiv:1701.04299 (2017), [3]McKay *et al,* arXiv:1712.06550 (2017).

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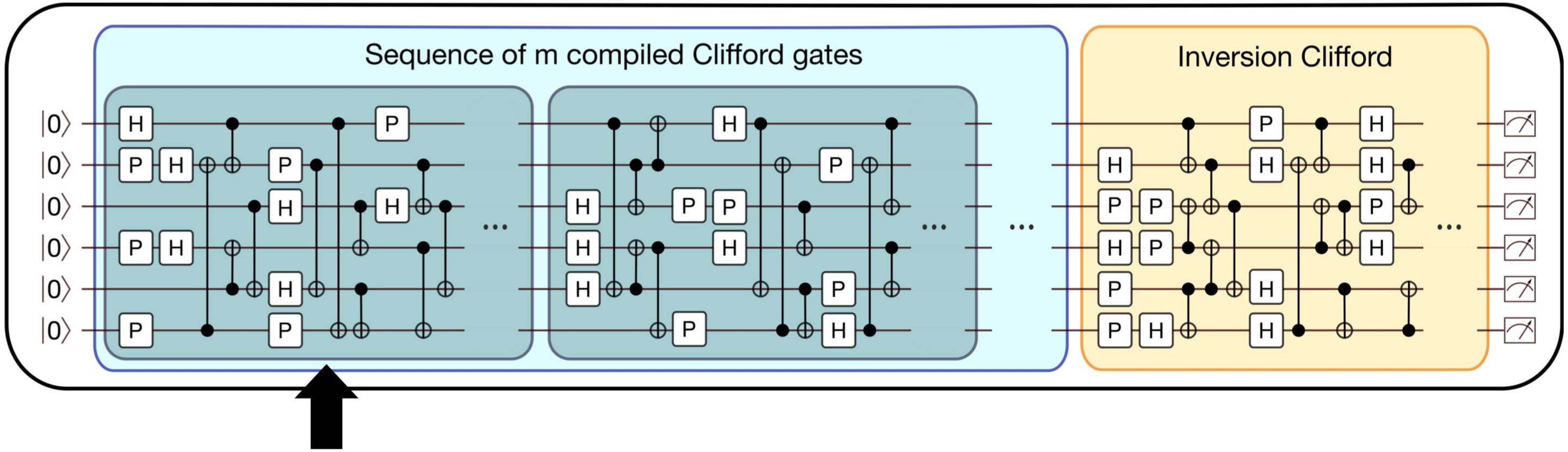
Clifford RB cannot holistically benchmark near-term devices

- The full set of *n*-qubit Clifford gates are not computational primitives.
- Each Clifford gate has to be compiled into many 1- and 2-qubit gates ($O[n^2/\log(n)]$ of them[1]).



- A typical *n*-qubit Clifford is a circuit with a size that grows quickly with *n.*

[1]Patel *et al.*, QIC 8, 282 (2008), Aaronson and Gottesman, PRA 70, 052328 (2014).

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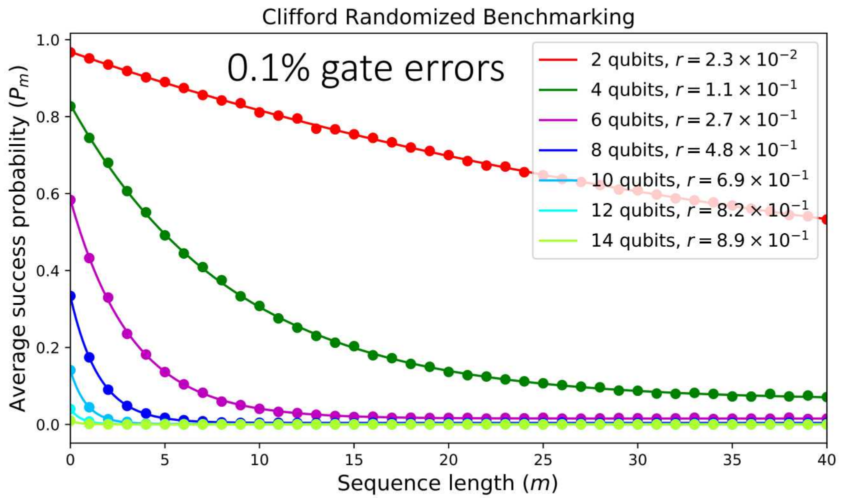

Problem: The fidelity of an n-qubit Clifford quickly decreases with increasing n, severely limiting the number of qubits Clifford RB can handle.

- A typical n-qubit Clifford is a circuit with a size that grows quickly with n.

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Part II – Streamlining randomized benchmarking

Streamlining RB

We've developed a streamlined version of RB, called ***direct RB.***[1]

- Direct RB is feasible on more qubits than Clifford RB.
- Direct RB retains the core robustness and simplicity of Clifford RB.
- Direct RB directly measures an average error rate of the native gates.
- Direct RB is flexible, as it can be used to extract a variety of error rates.

[1]Proctor et al., arXiv:1807.07975 (2018).

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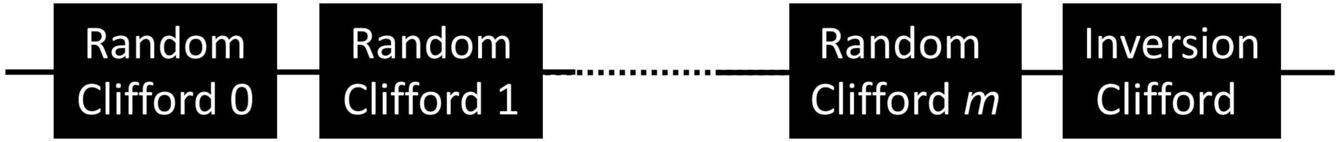

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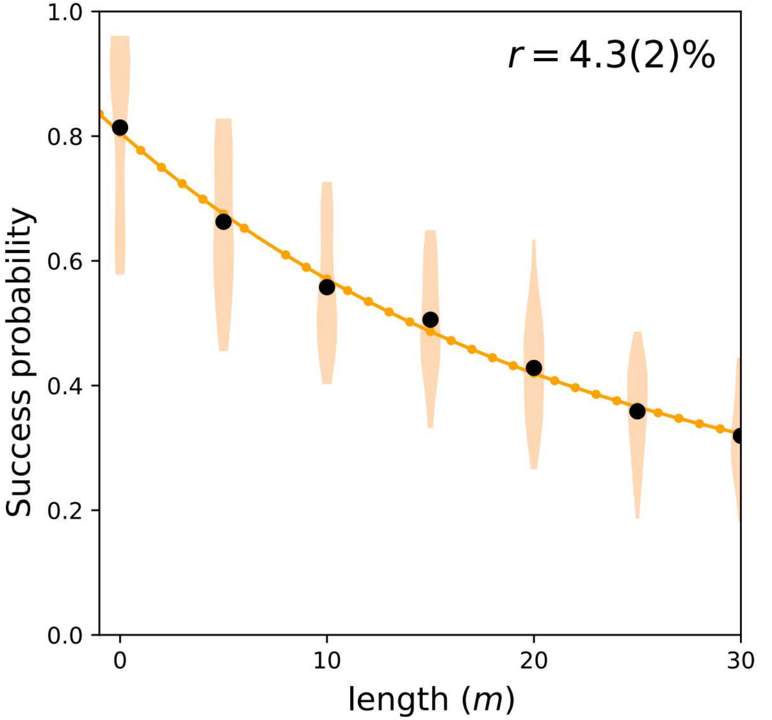

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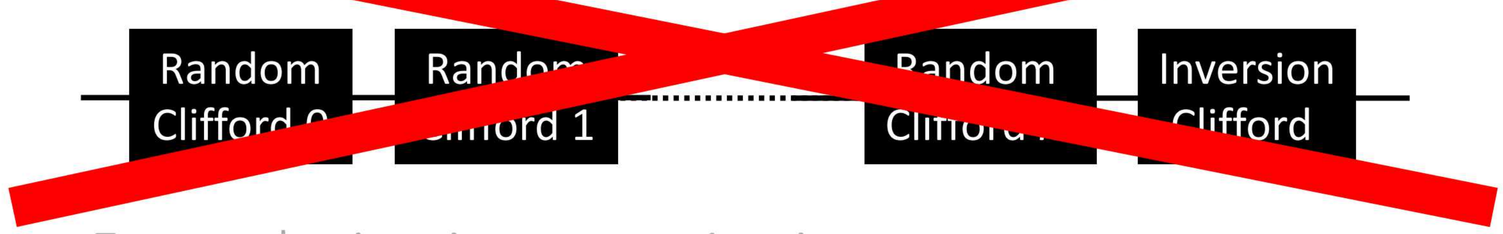

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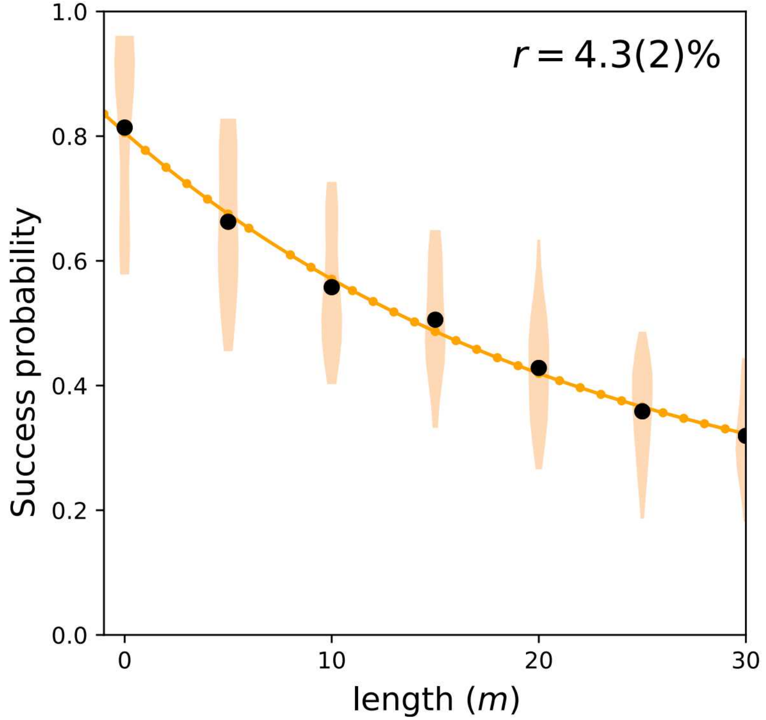

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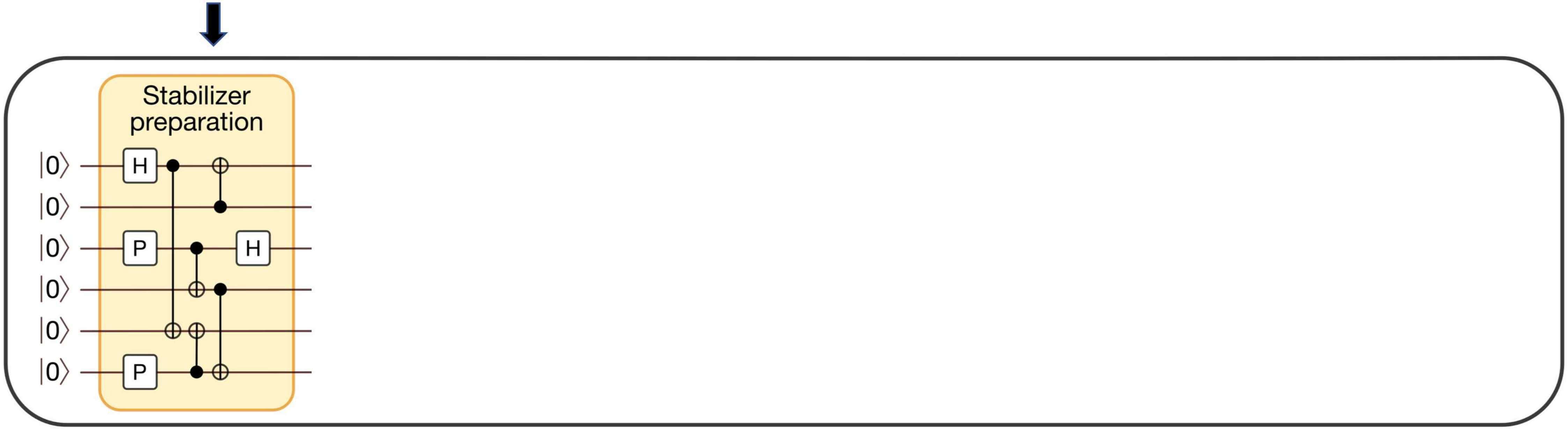
Direct randomized benchmarking

Prepare a uniformly random
n-qubit stabilizer state. ***Purpose: port the robustness of Clifford RB to the new method.***



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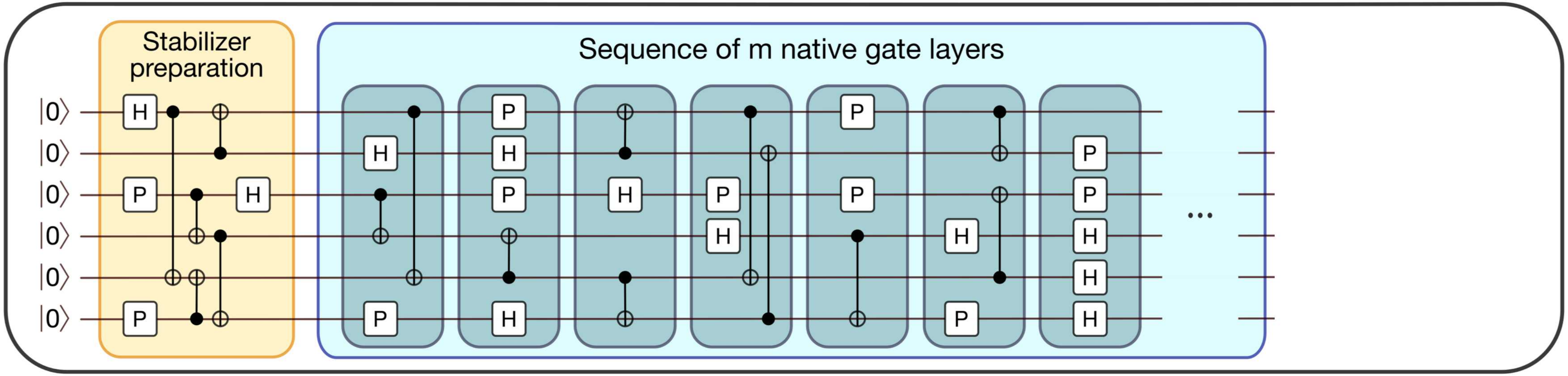

Depth-1 circuit layers sampled according to a user-specified and flexible distribution. ***Purpose: streamlined layers mean (1) better scalability and (2) estimation of a per-native-gate error rate.***

Direct randomized benchmarking

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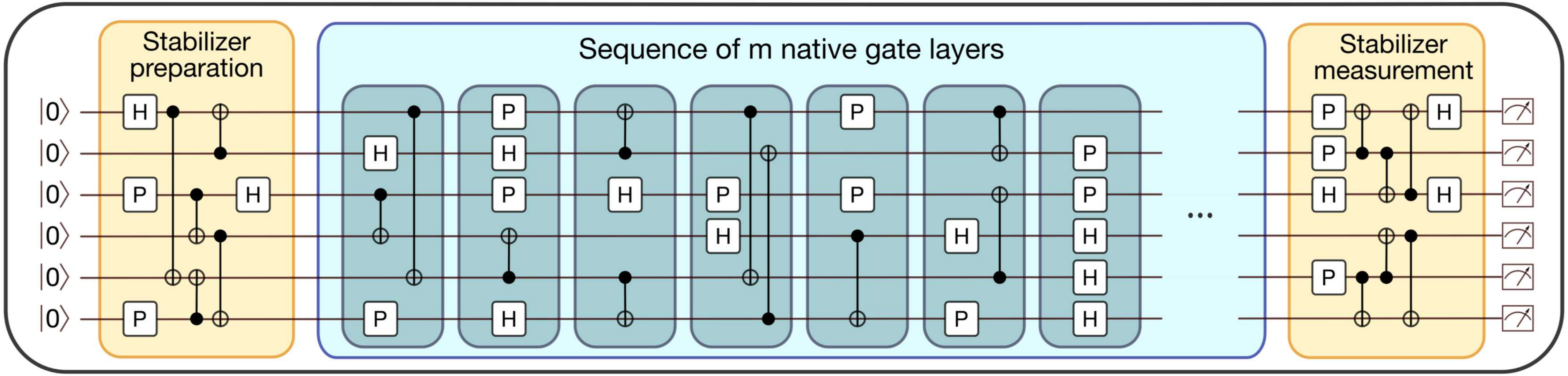
Return the ideal output to a computational basis state. ***Purposes: as in all RB, make errors detectable.***



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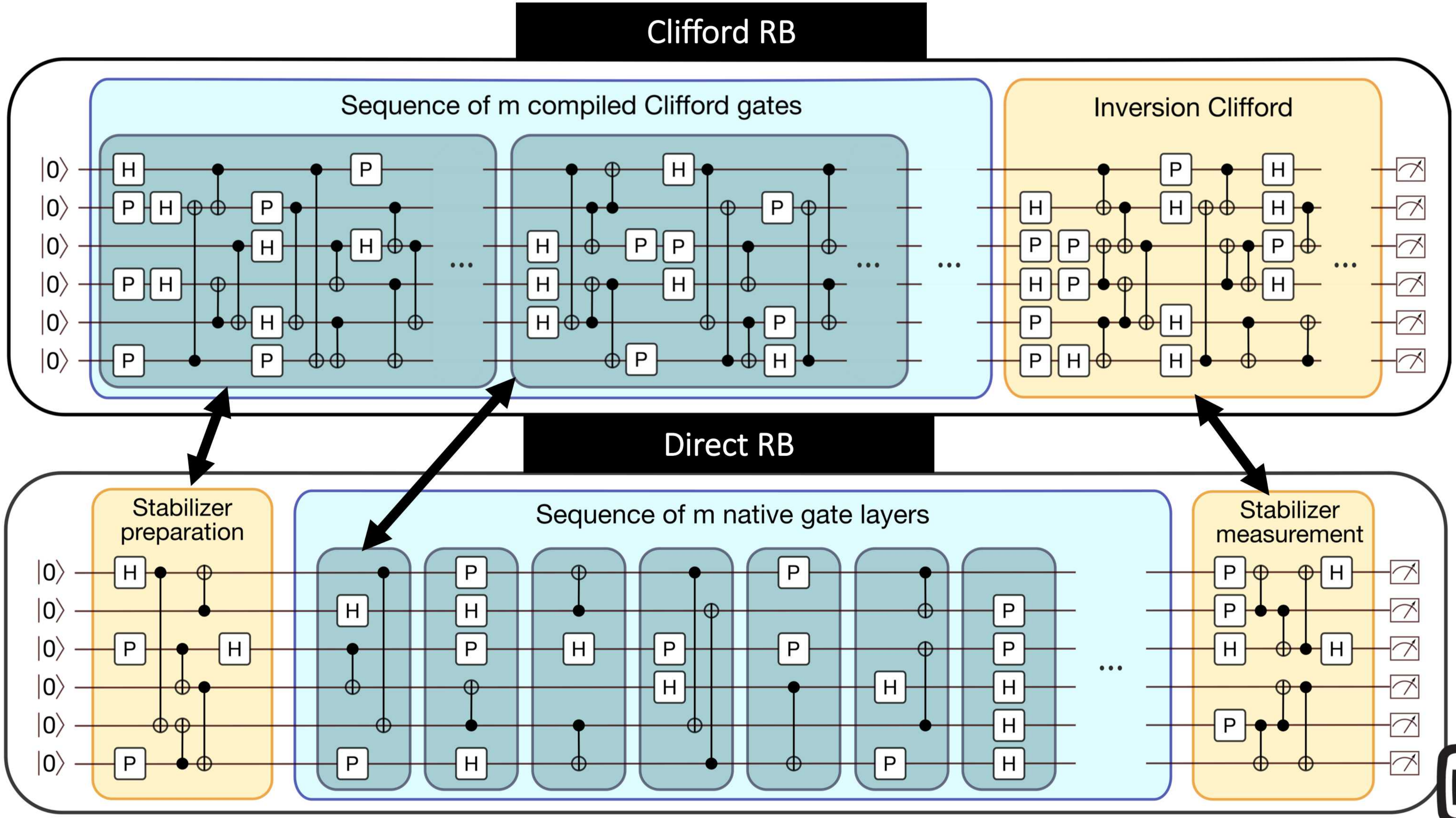
Direct RB versus Clifford RB



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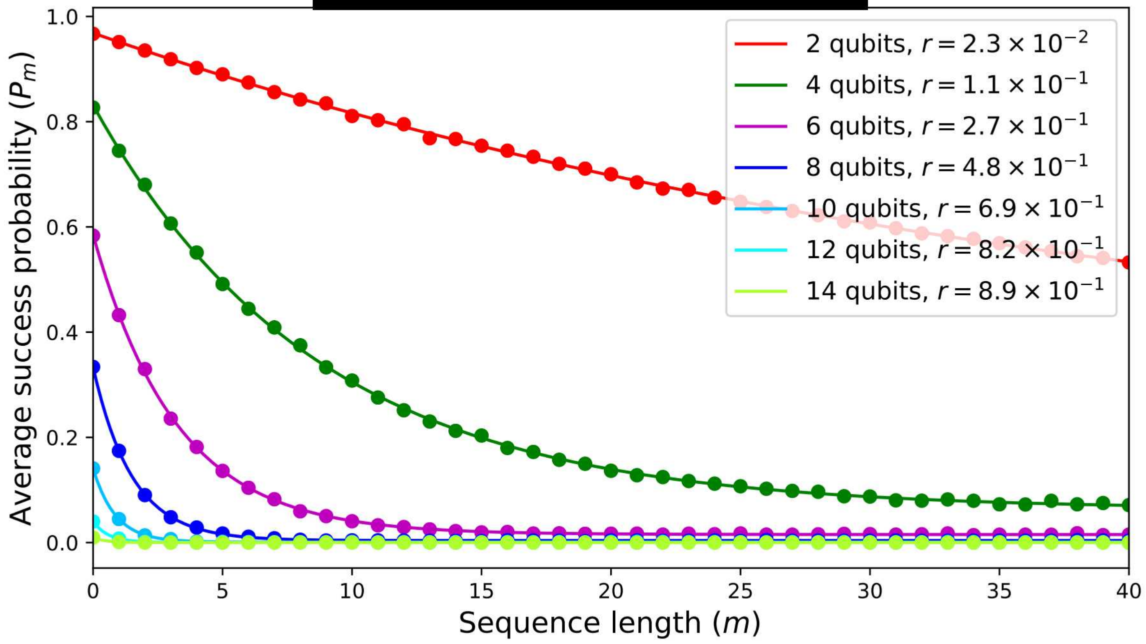
Direct RB versus Clifford RB

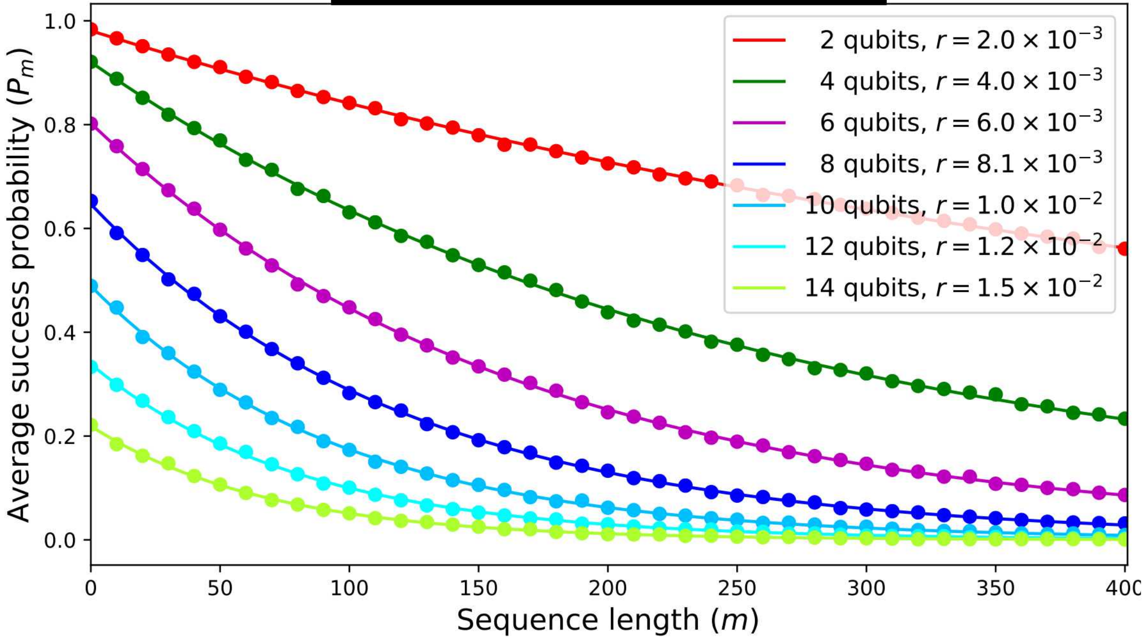
An illustrative simulation, with 0.1% i.i.d depolarizing errors on each qubit

Clifford RB



Number of Clifford gates - 2

Direct RB



Number of native gate layers

Simulation demonstration better scaling with *n* for direct RB!

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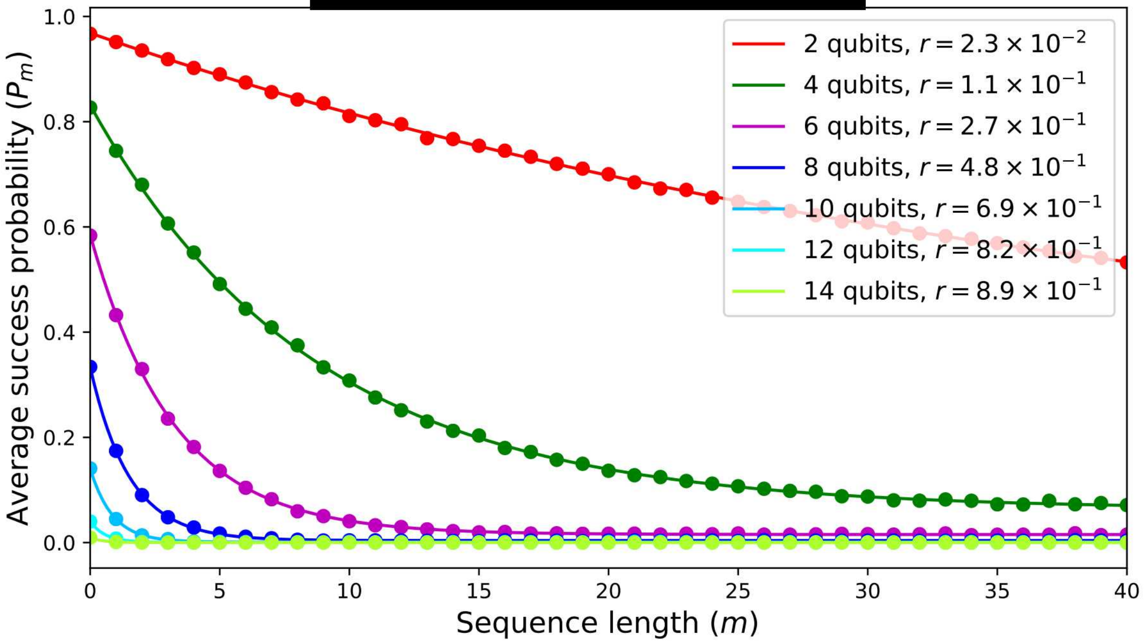
Direct RB versus Clifford RB

Bonus: Direct RB error rates are directly linked to the gate error rate! $r \approx n \times 0.001$.

An illustrative simulation, with 0.1% i.i.d depolarizing errors on each qubit

Clifford RB



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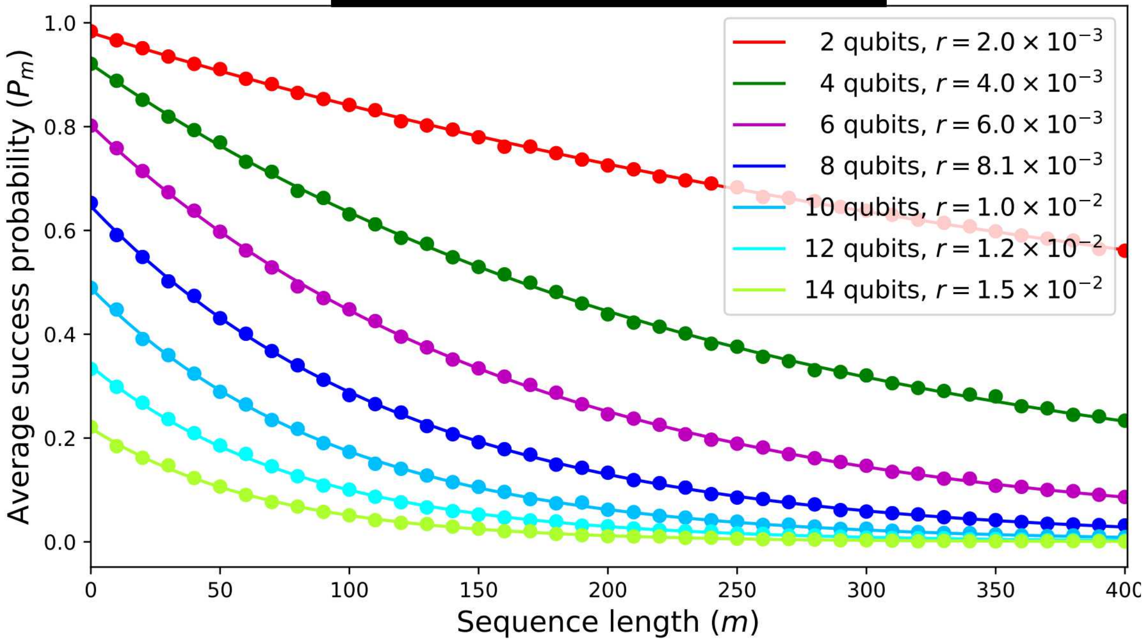

Number of native gate layers

Simulation demonstration better scaling with n for direct RB!

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Direct RB is robust

- Clifford RB is known to be reliable, from theory[1] and experience.
- To justify replacing Clifford RB with direct RB, it is important to know that direct RB is equally reliable.
- We've developed a theory that proves that direct RB has equivalent robustness to Clifford RB (similar to the best Clifford RB theories[1]).
- Here we'll only outline the fundamental ideas, sticking to *Pauli stochastic* errors.

[1]Proctor *et al.*, PRL 119, 130502 (2017), Wallman, Quantum 2, 47 (2018), Merkel *et al.*, arXiv:1804.05951 (2018).

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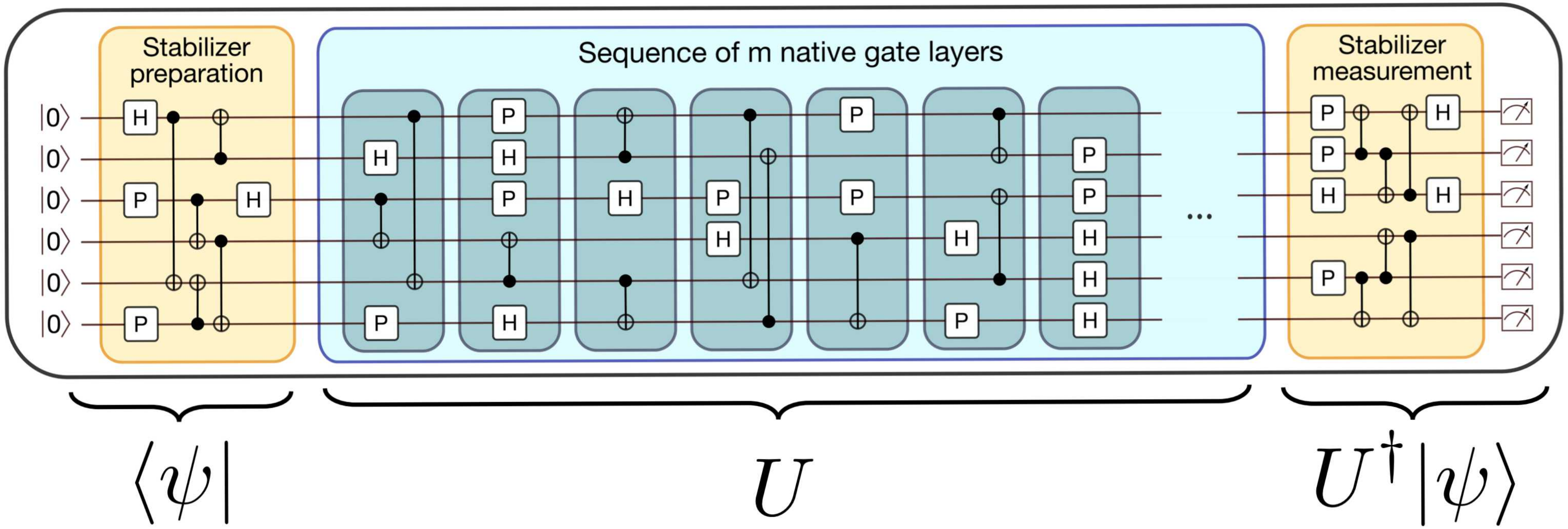
Direct RB is robust

- The key for reliable RB is for the probability of circuit "success" to depend only on the rate of errors, and not their exact form (e.g., X versus Z errors).



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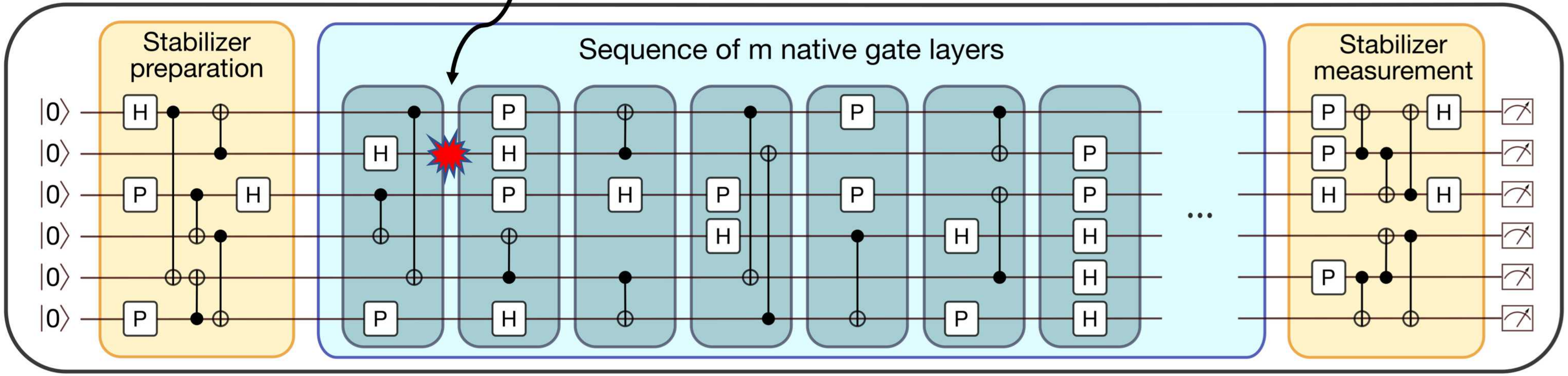
- Let's look at what happens when there is an error in a direct RB circuit.

Some Pauli error!



$$\underbrace{\langle\psi|}\qquad\underbrace{U}\qquad\underbrace{U^\dagger|\psi\rangle}$$

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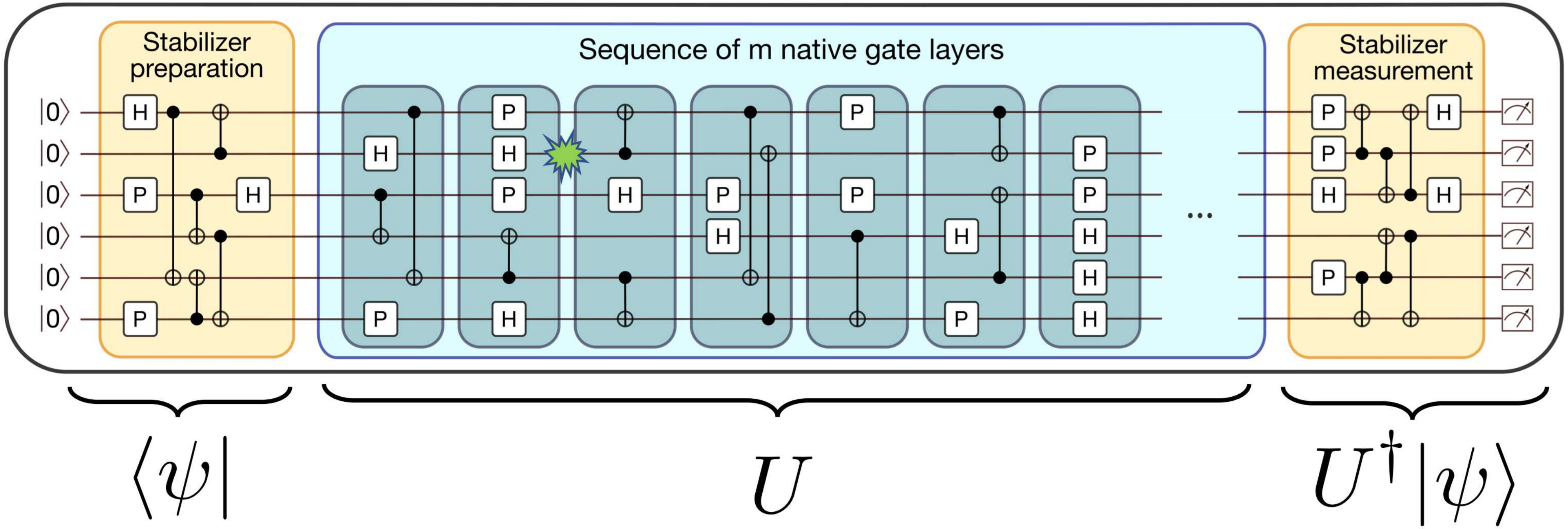
This error almost certainly spreads as it propagates through the random circuit layers.



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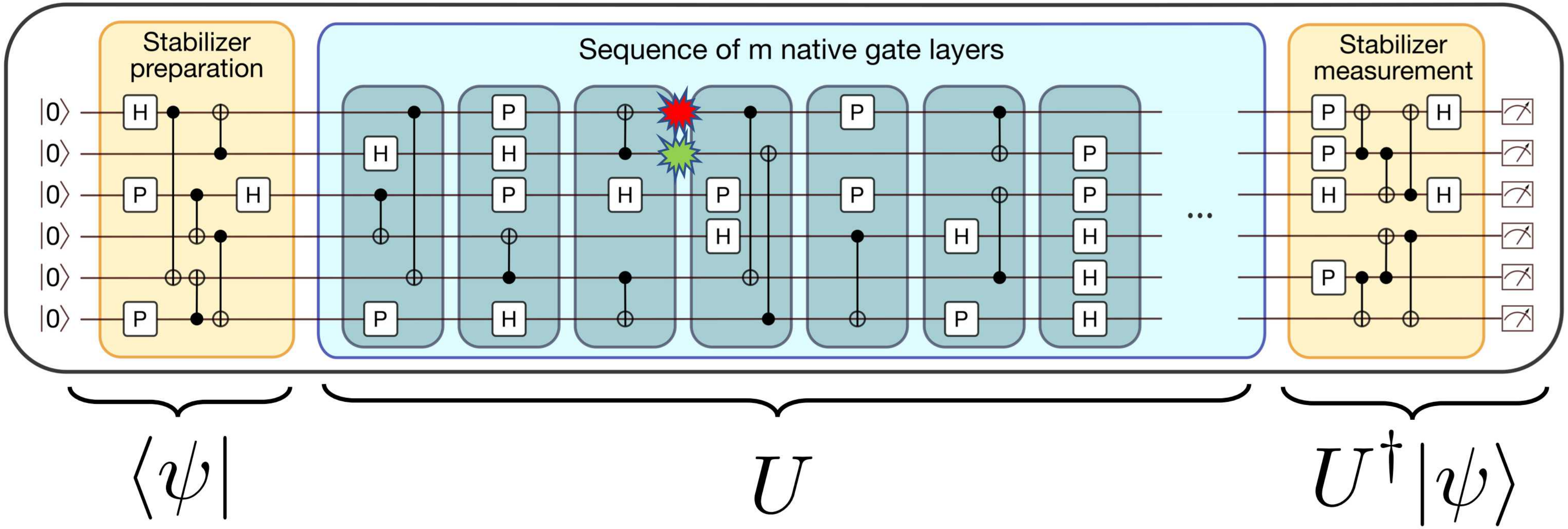

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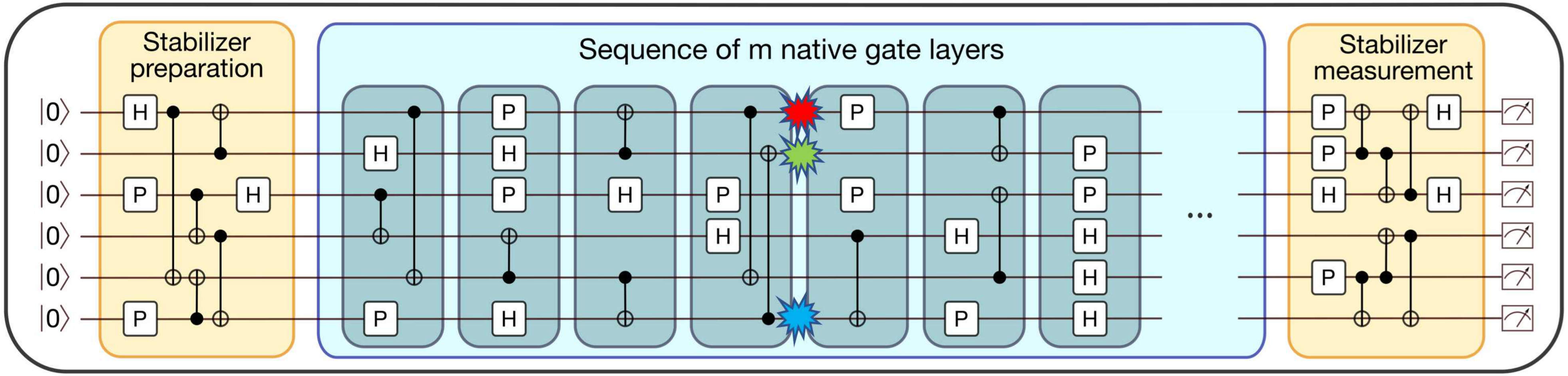

$\langle\psi|$ $\quad U \quad$ $U^{\dagger}|\psi\rangle$

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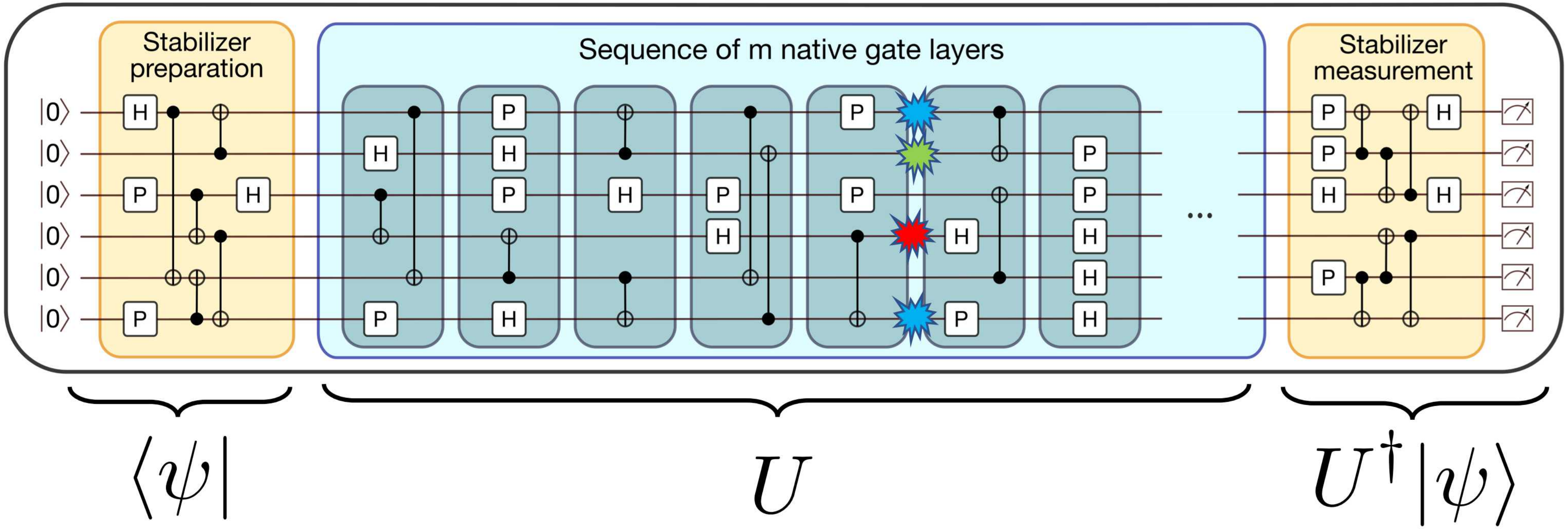

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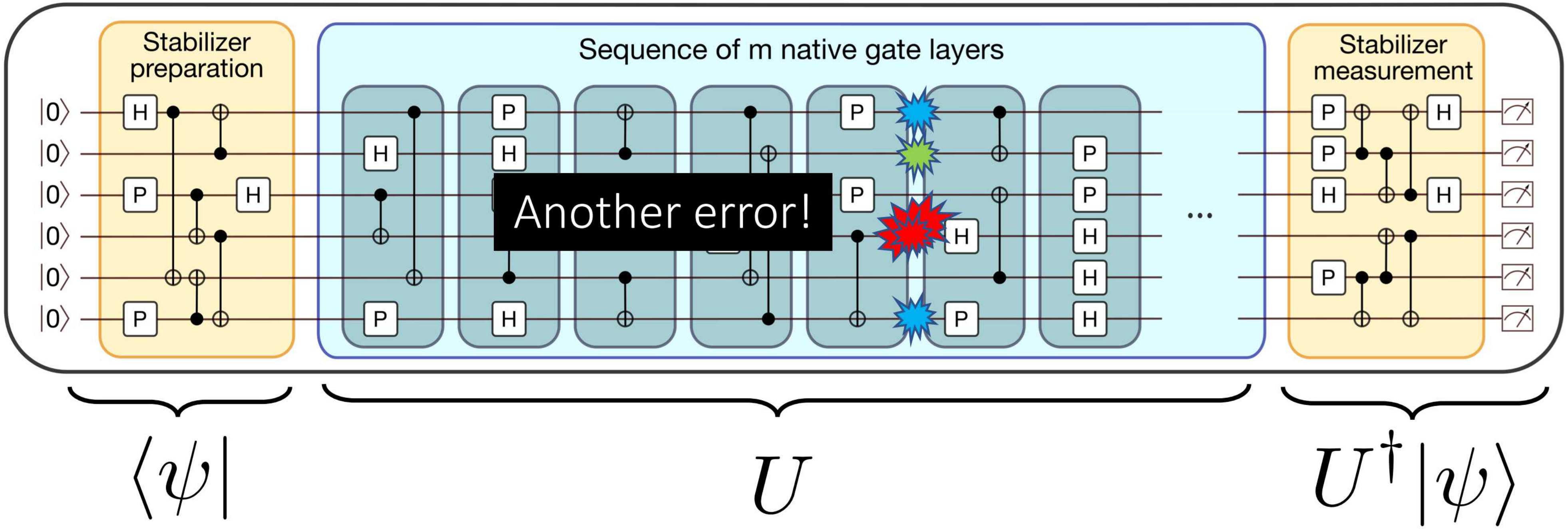
And if another error happens it will almost certainly not entirely cancel the previous error



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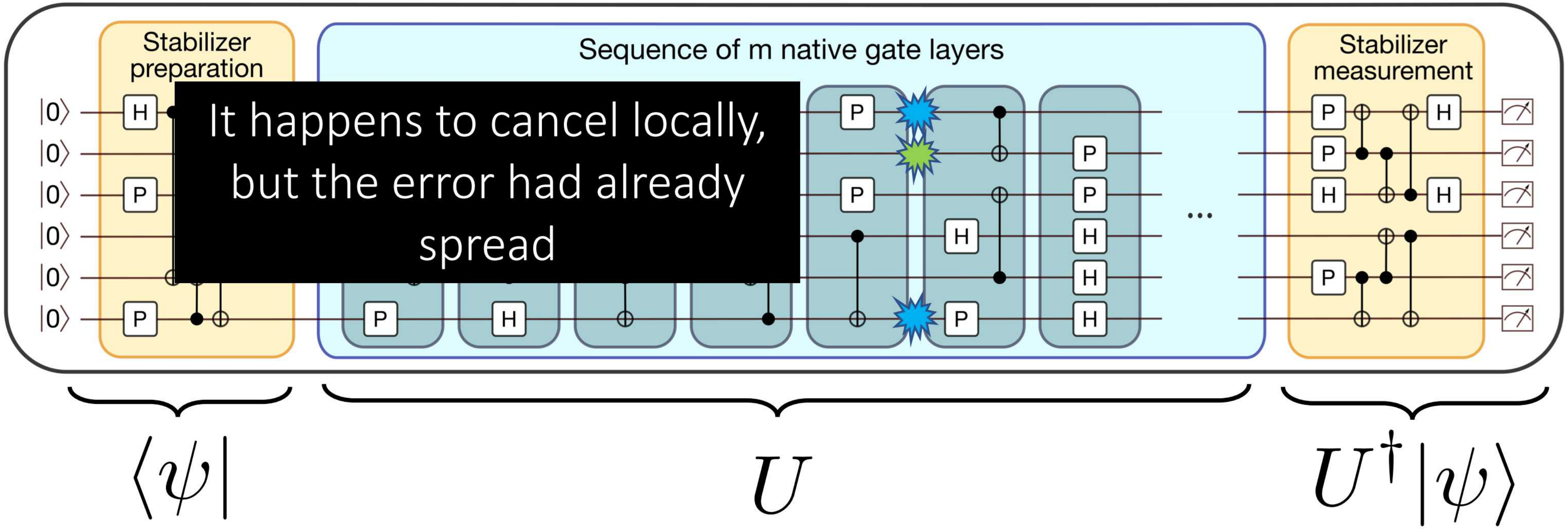

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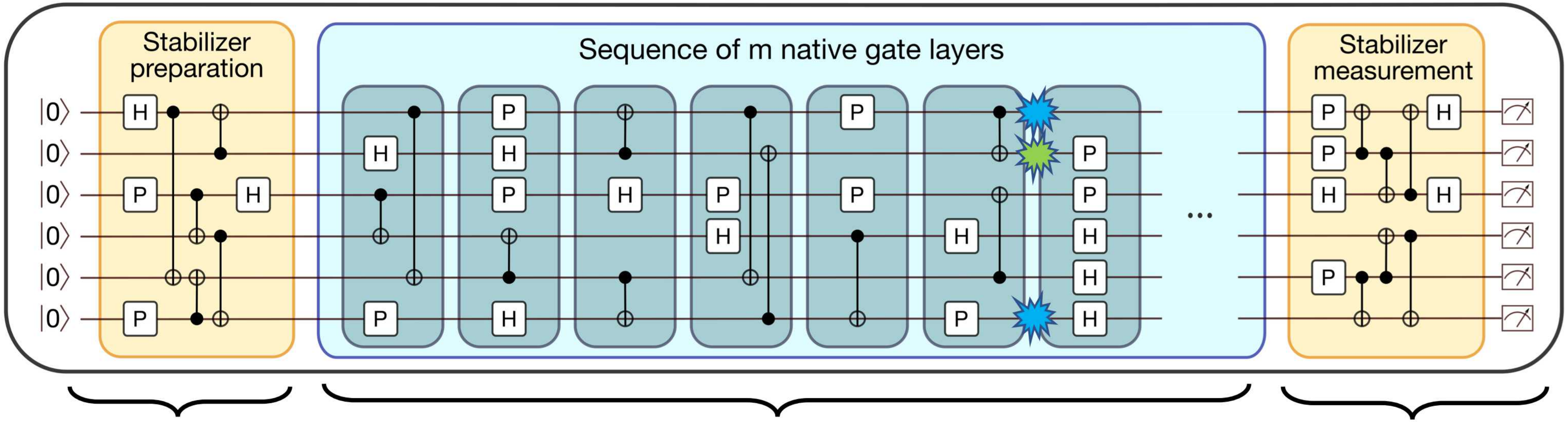

$\langle\psi|$ U $U^\dagger|\psi\rangle$

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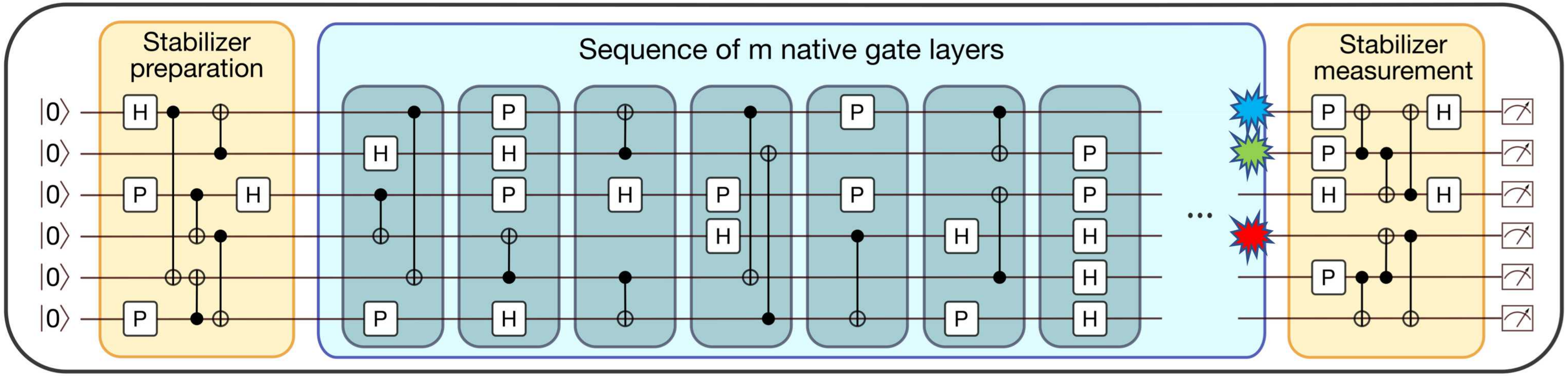

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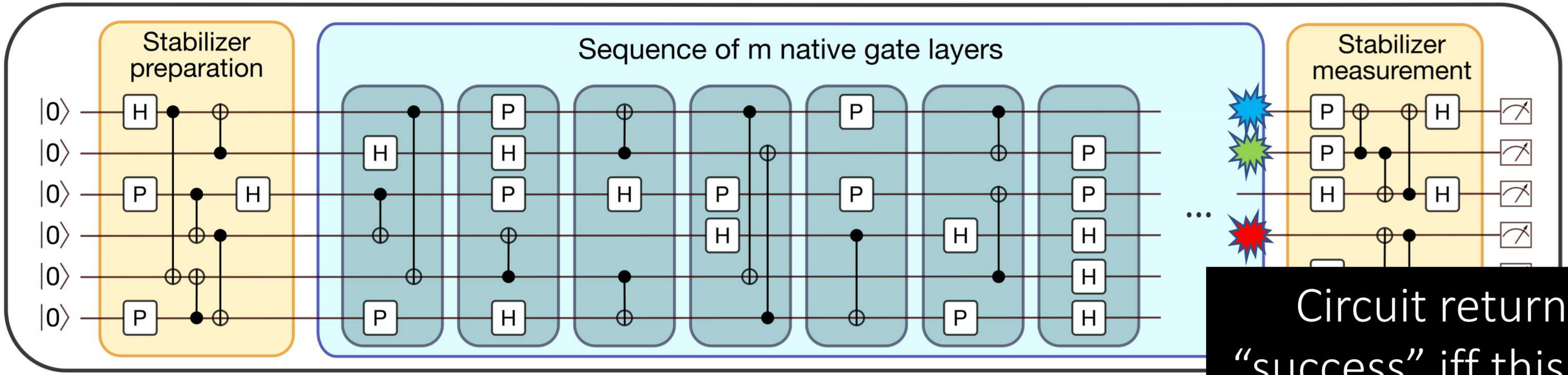

Circuit returns “success” iff this = 1.

$$\langle\psi| U \text{ Some Pauli error } U^\dagger |\psi\rangle$$

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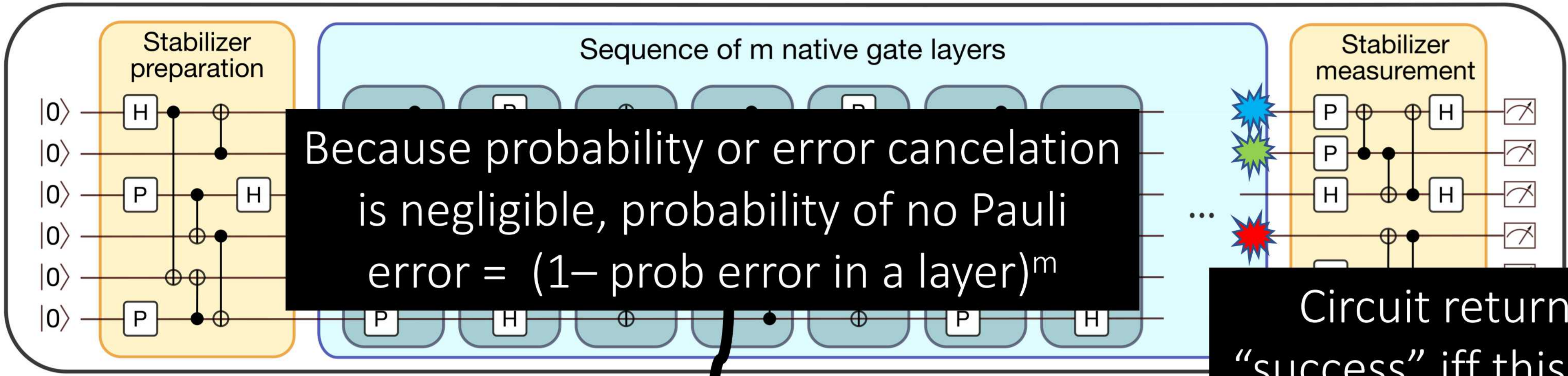

Because probability or error cancelation is negligible, probability of no Pauli error = $(1 - \text{prob error in a layer})^m$

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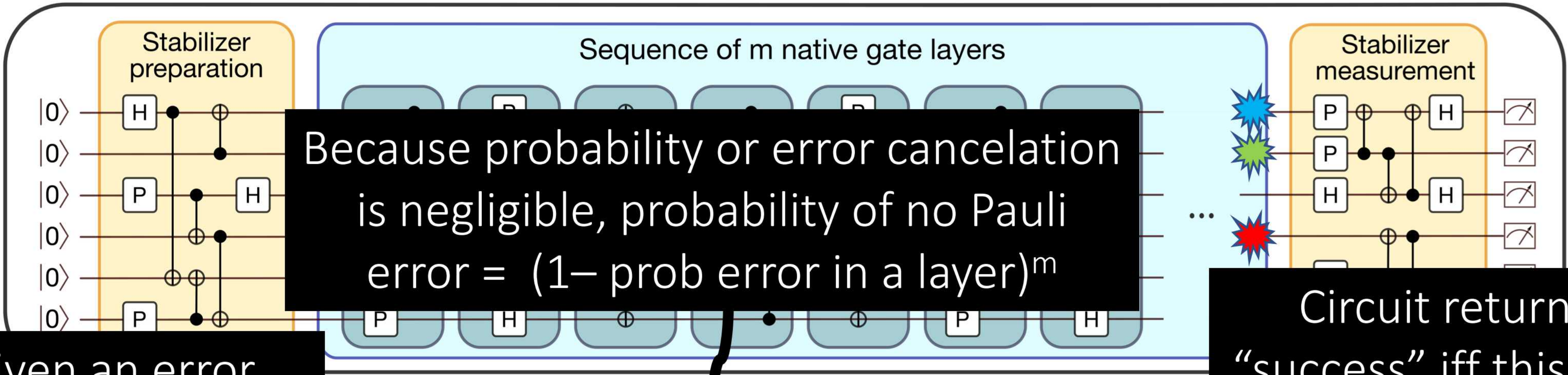

Because probability or error cancelation is negligible, probability of no Pauli error = (1– prob error in a layer)^{m}

Given an error, probability this is 1 is 2^{-n} *(up to $O(4^{-n})$)*

Circuit returns “success” iff this is 1.

$\langle\psi|U$ Some Pauli error $U^{\dagger}|\psi\rangle$

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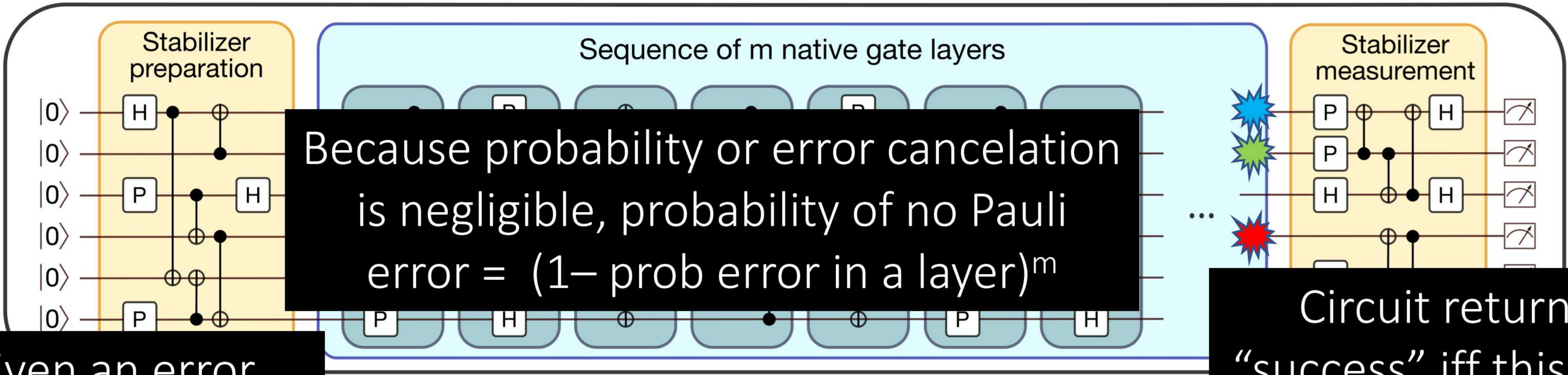
Direct RB is robust

- The key for reliable RB is for the probability of circuit “success” to depend only on the rate of errors, and not their exact form (e.g., X versus Z errors).

- Let’s look at what happens when there is an error in a direct RB circuit.

And if another error happens it will almost certainly not entirely cancel the previous error



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Circuit returns “success” iff this is 1.

Given an error, probability this is 1 is 2^{-n} *(up to $O(4^{-n})$)*

$$P_m = 2^{-n} + (1-2^{-n})(1\text{– prob error in a layer})^m + O(4^{-n})$$

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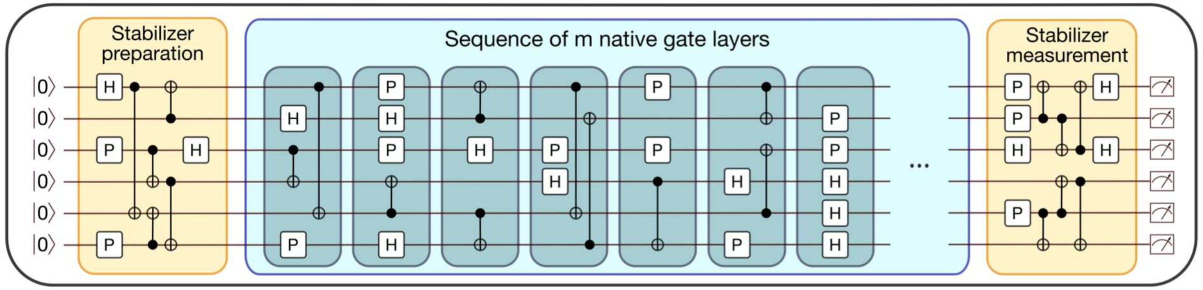
Direct RB is robust

- The key for reliable RB is for the probability of circuit "success" to depend only on the rate of errors, and not their exact form (e.g., X versus Z errors).
- We've shown that direct RB measures the weighted-average error rate of the circuit layers, whenever our reasoning holds.
- The argument relies on quick error "scrambling" in the direct RB circuits, and almost all random circuits quickly scramble errors.[1]



[1]Sekino and Susskind, J. High Energy Phys. 10, 065 (2008), and many many other papers.

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2 – 5 qubit direct RB on IBM Q Experience

The aim is to:

(1) Demonstrate that direct RB works.

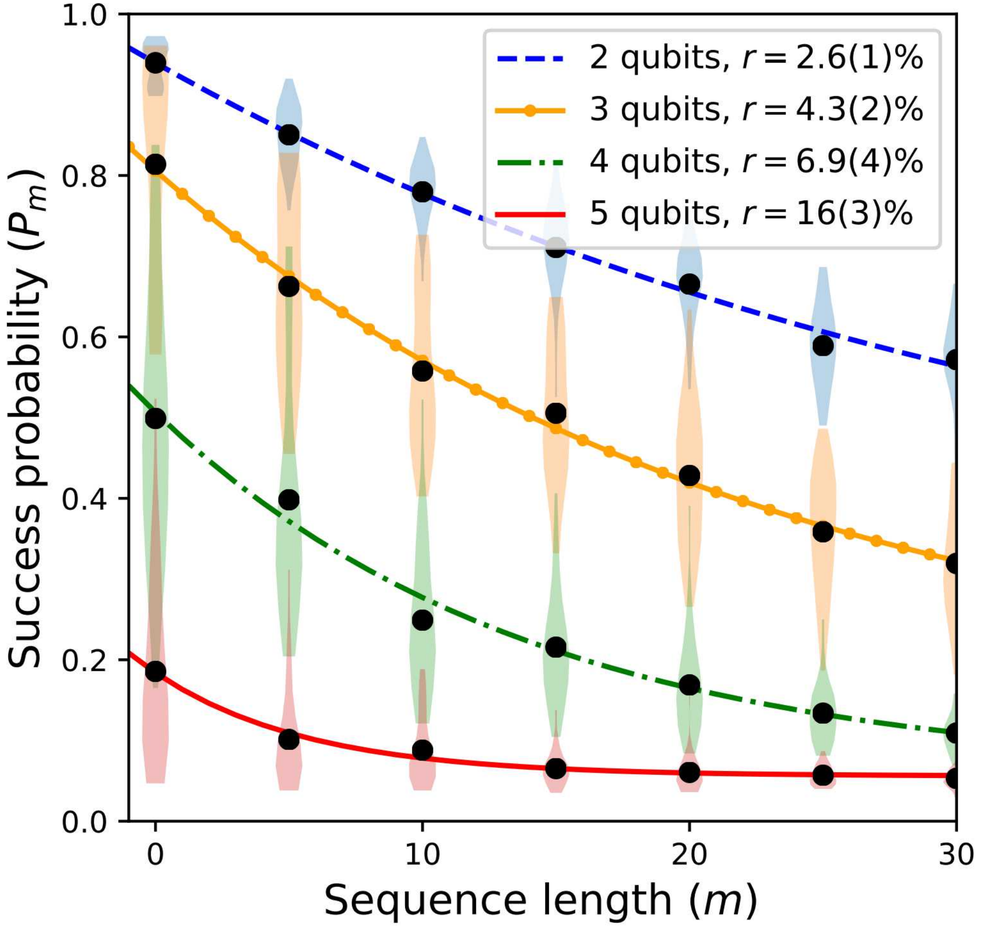
(2) Illustrate how direct RB it can be used to provide interesting insight into a device.

This is not intended as a comprehensive benchmarking of IBMQX.

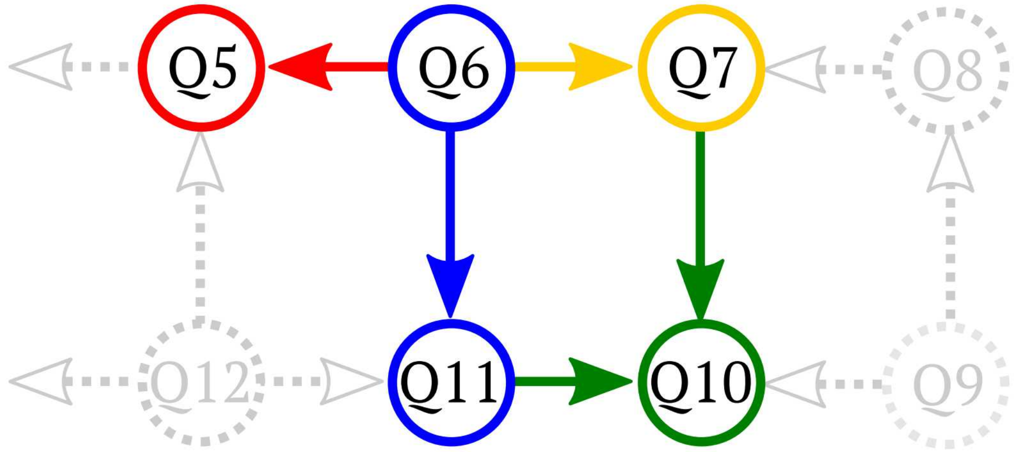
IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

2 – 5 qubit direct RB on IBM Q Experience

Successful 2 – 5 qubit direct RB!



Benchmarked portion of ibmqx5



Circuit layer sampler:

- With prob. p apply 1 CNOT + local gates.
- With prob. 1 - p apply only local gates.
- We chose p = 0.75.

IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

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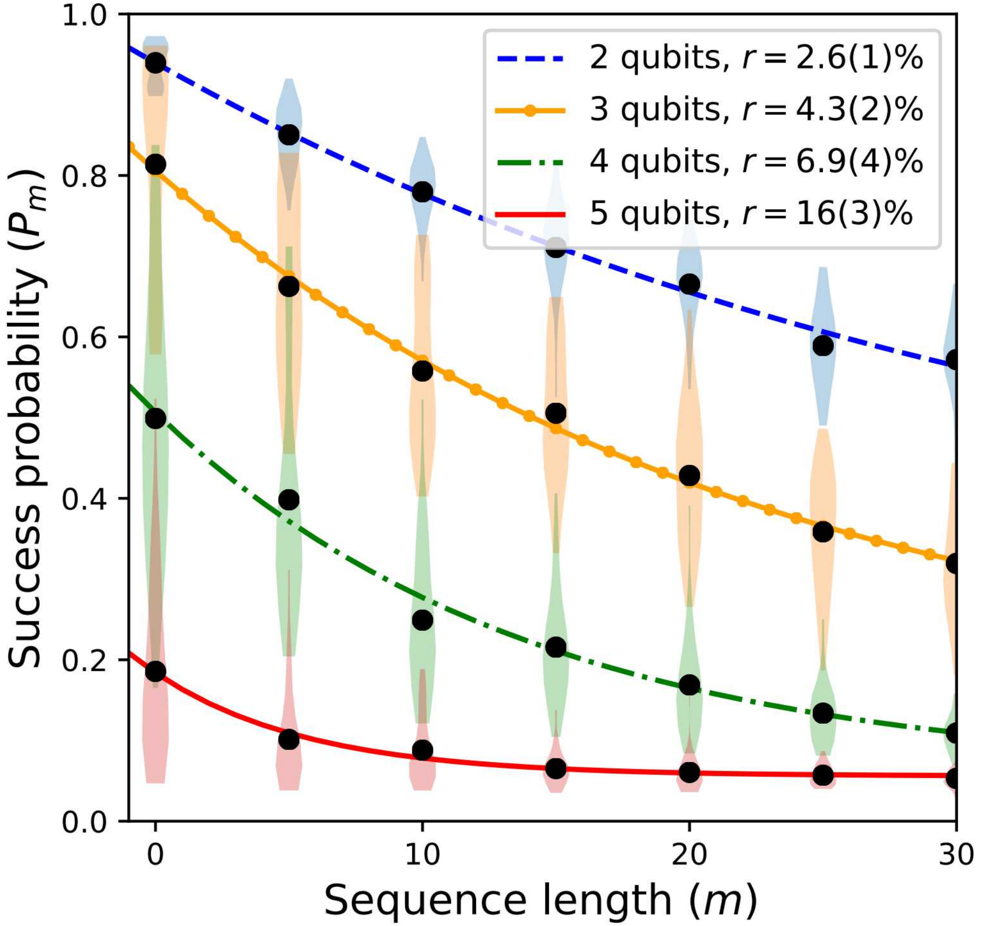
2 – 5 qubit direct RB on IBM Q Experience

Successful 2 – 5 qubit direct RB!

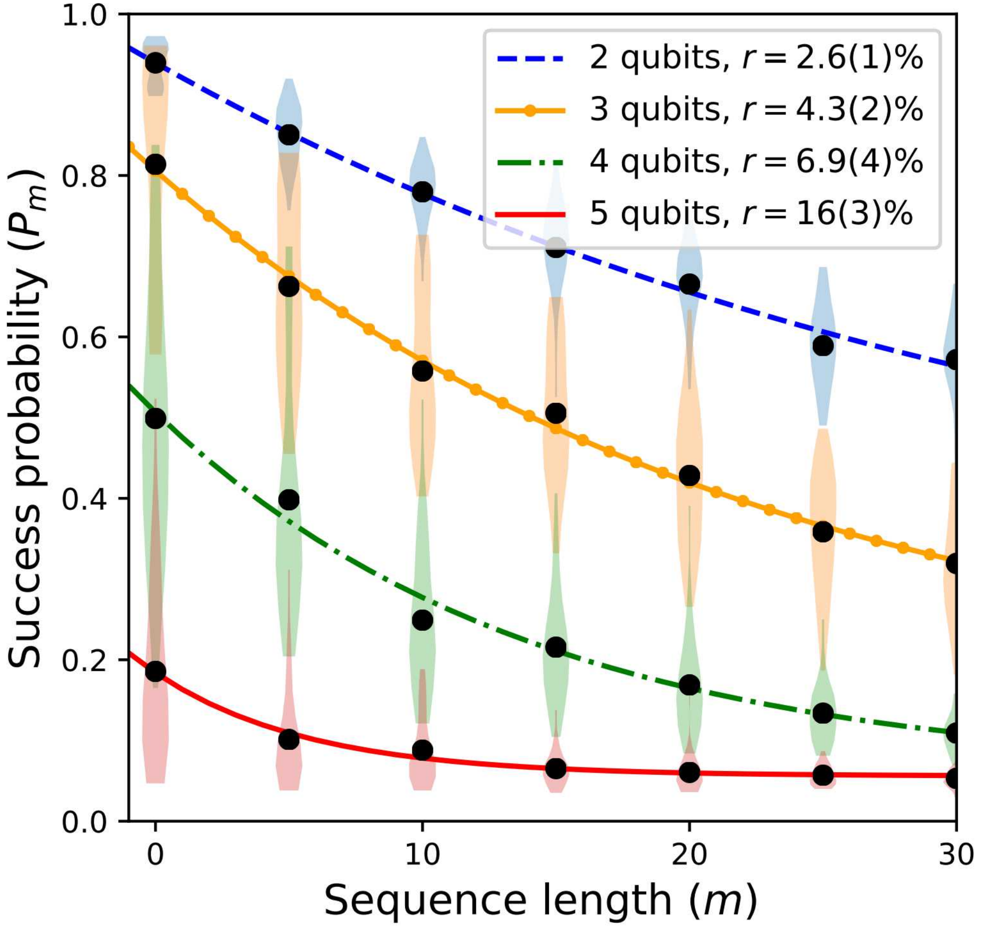


- The average number of CNOTs per layer is independent of *n*.
- Therefore *r* should grow slowly with *n* if:
  - CNOT errors dominate and
  - *n*-qubit RB is predictive of *m* > *n* qubit circuits *in this device*.
- This is not what we observe, which is suggestive of crosstalk. Let's quantify this…

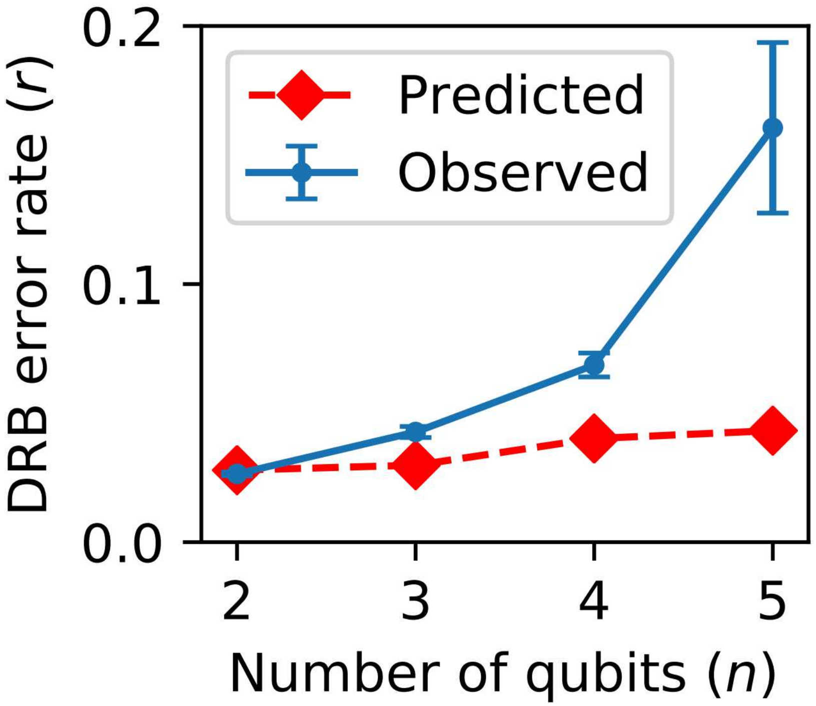
IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

2 – 5 qubit direct RB on IBM Q Experience

Successful 2 – 5 qubit direct RB!



Comparing predictions from Clifford RB calibration data and direct RB results



Discrepancy shows that n-qubit RB reveals errors not predicted by 1- and 2-qubit RB (i.e., crosstalk).

IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

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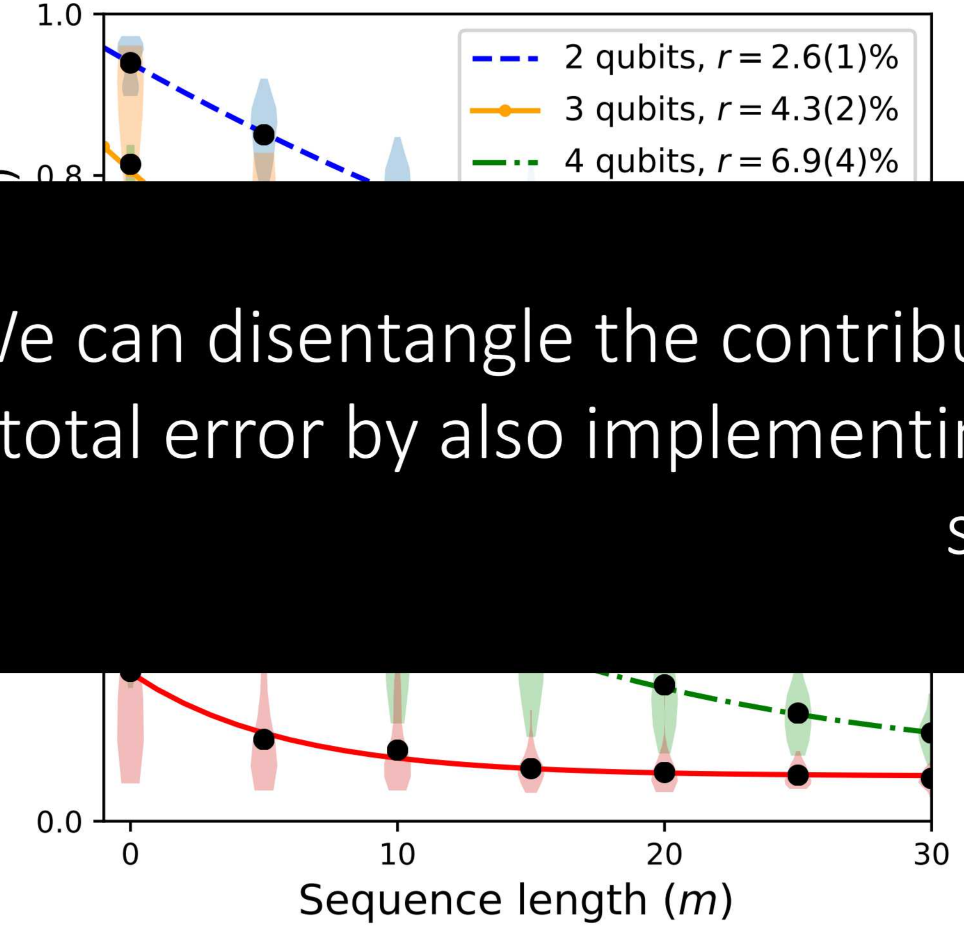
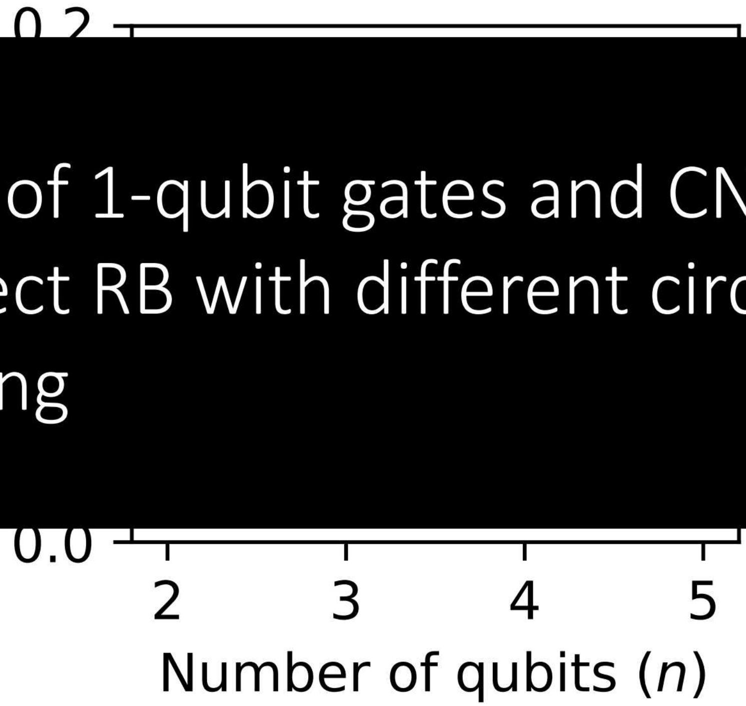
2 – 5 qubit direct RB on IBM Q Experience

Successful 2 – 5 qubit direct RB!



Comparing predictions from Clifford RB calibration data and direct RB results



We can disentangle the contributions of 1-qubit gates and CNOTs to the total error by also implementing direct RB with different circuit layer sampling

IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

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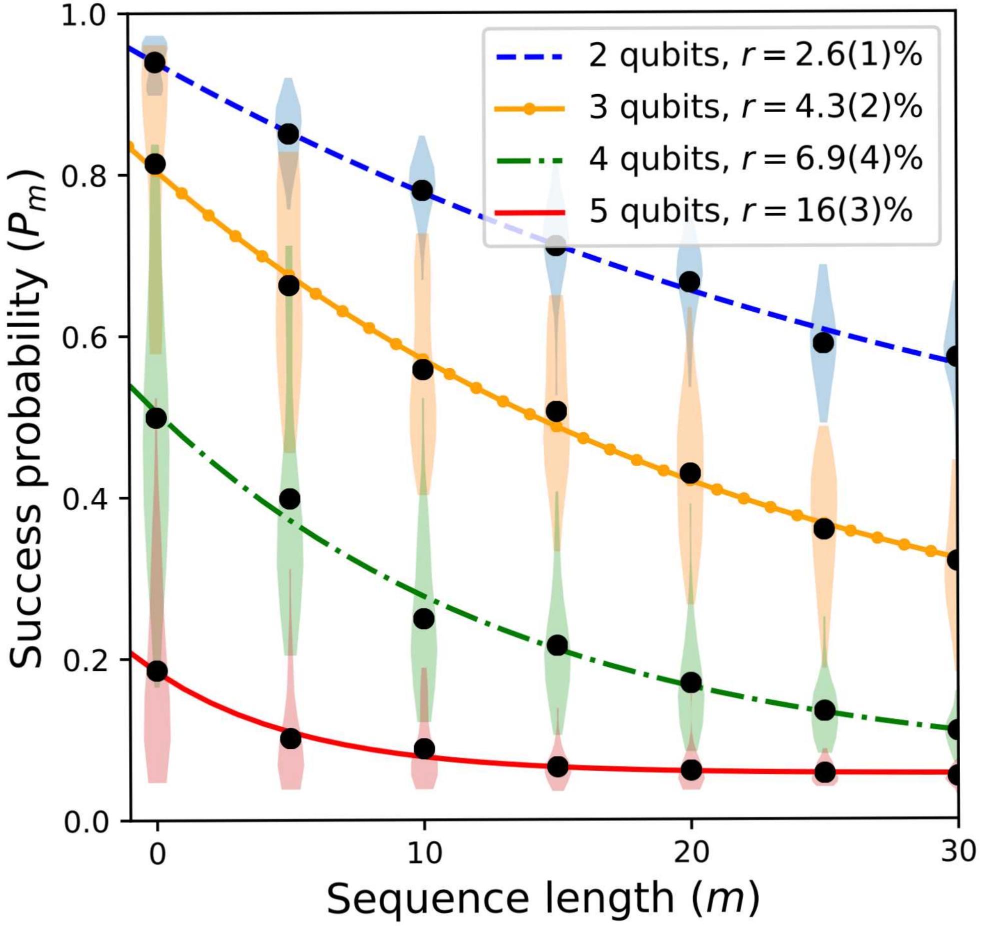
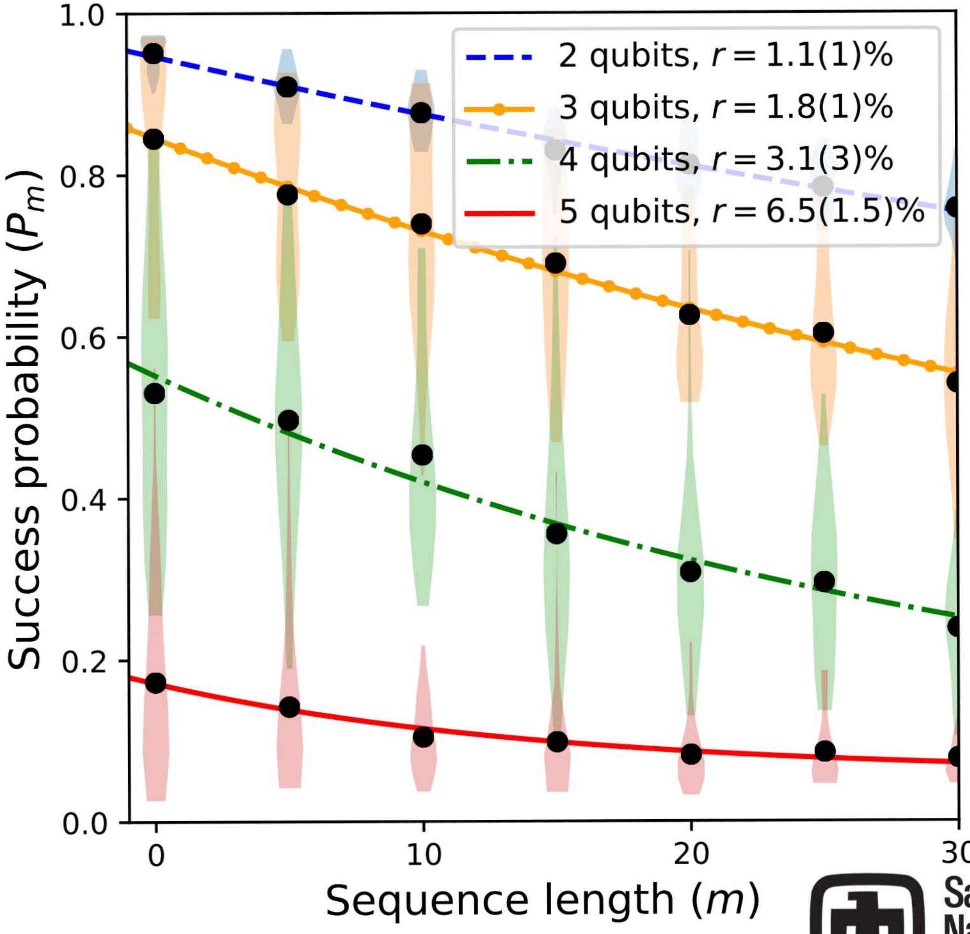
2 – 5 qubit direct RB on IBM Q Experience

0.75 CNOTs per layer



0.25 CNOTs per layer



IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

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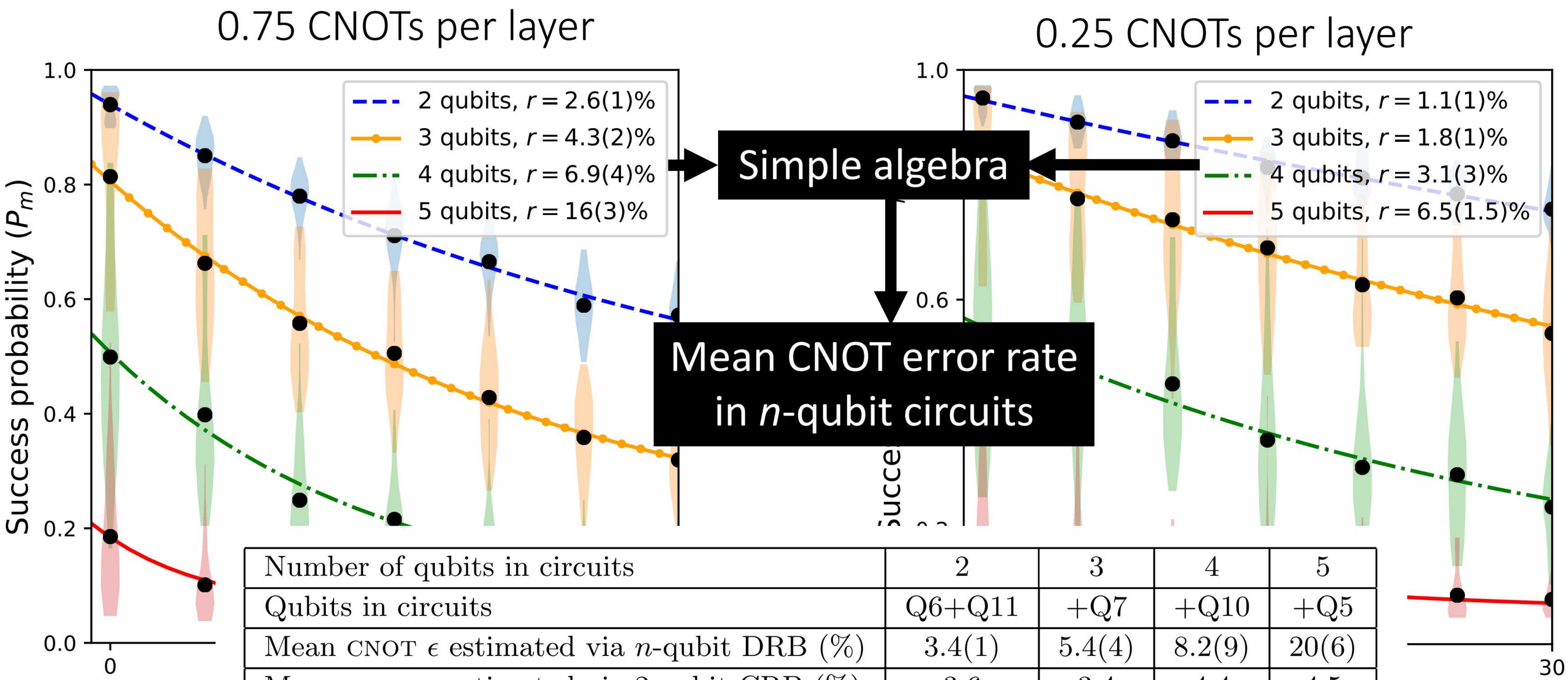
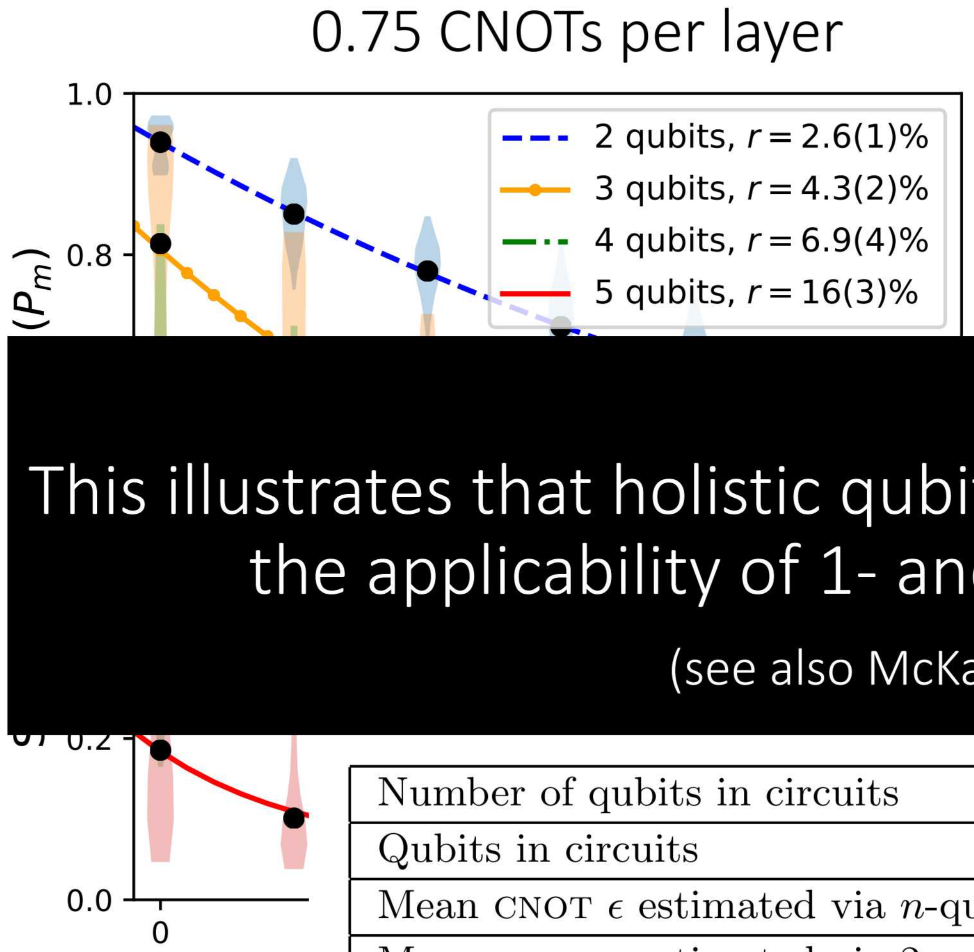
2 – 5 qubit direct RB on IBM Q Experience

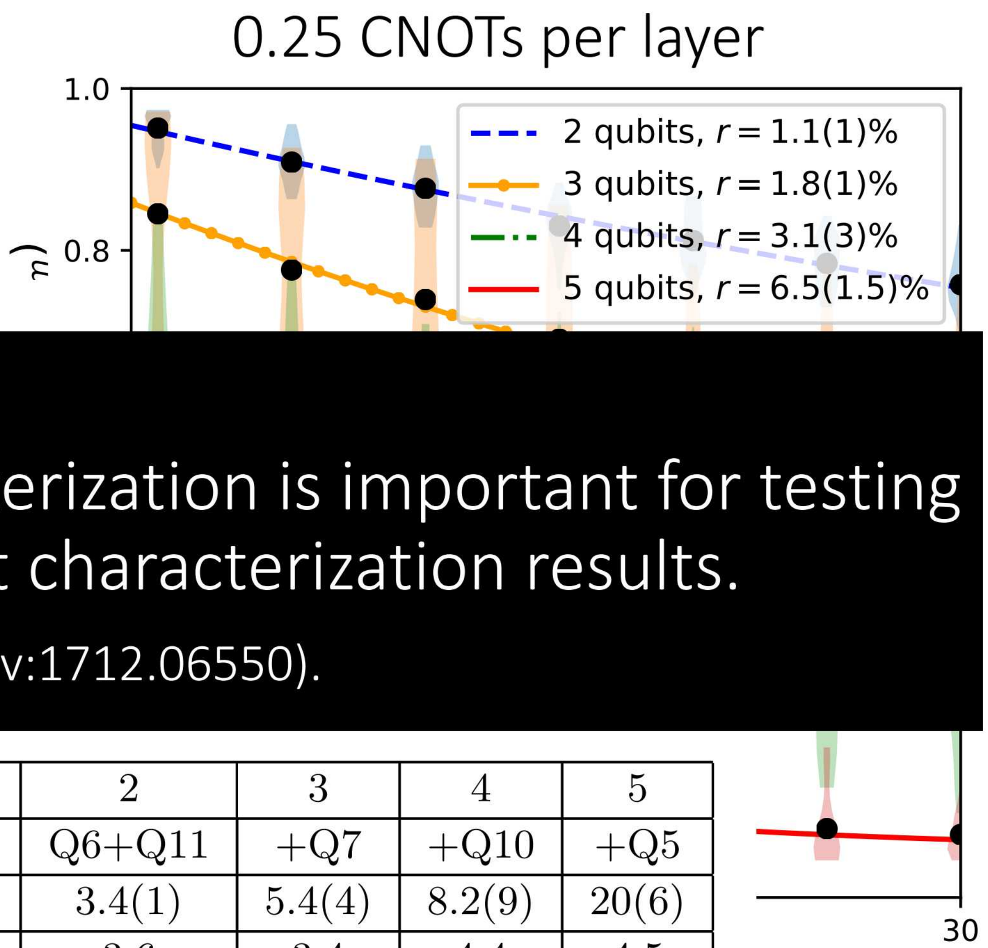


Number of qubits in circuits	2	3	4	5
Qubits in circuits	Q6+Q11	+Q7	+Q10	+Q5
Mean CNOT ϵ estimated via n-qubit DRB (%)	3.4(1)	5.4(4)	8.2(9)	20(6)
Mean CNOT ϵ estimated via 2-qubit CRB (%)	3.6	3.4	4.4	4.5

IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

2 – 5 qubit direct RB on IBM Q Experience





This illustrates that holistic qubit characterization is important for testing the applicability of 1- and 2-qubit characterization results.

(see also McKay *et al.*, arXiv:1712.06550).

Number of qubits in circuits	2	3	4	5
Qubits in circuits	Q6+Q11	+Q7	+Q10	+Q5
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IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

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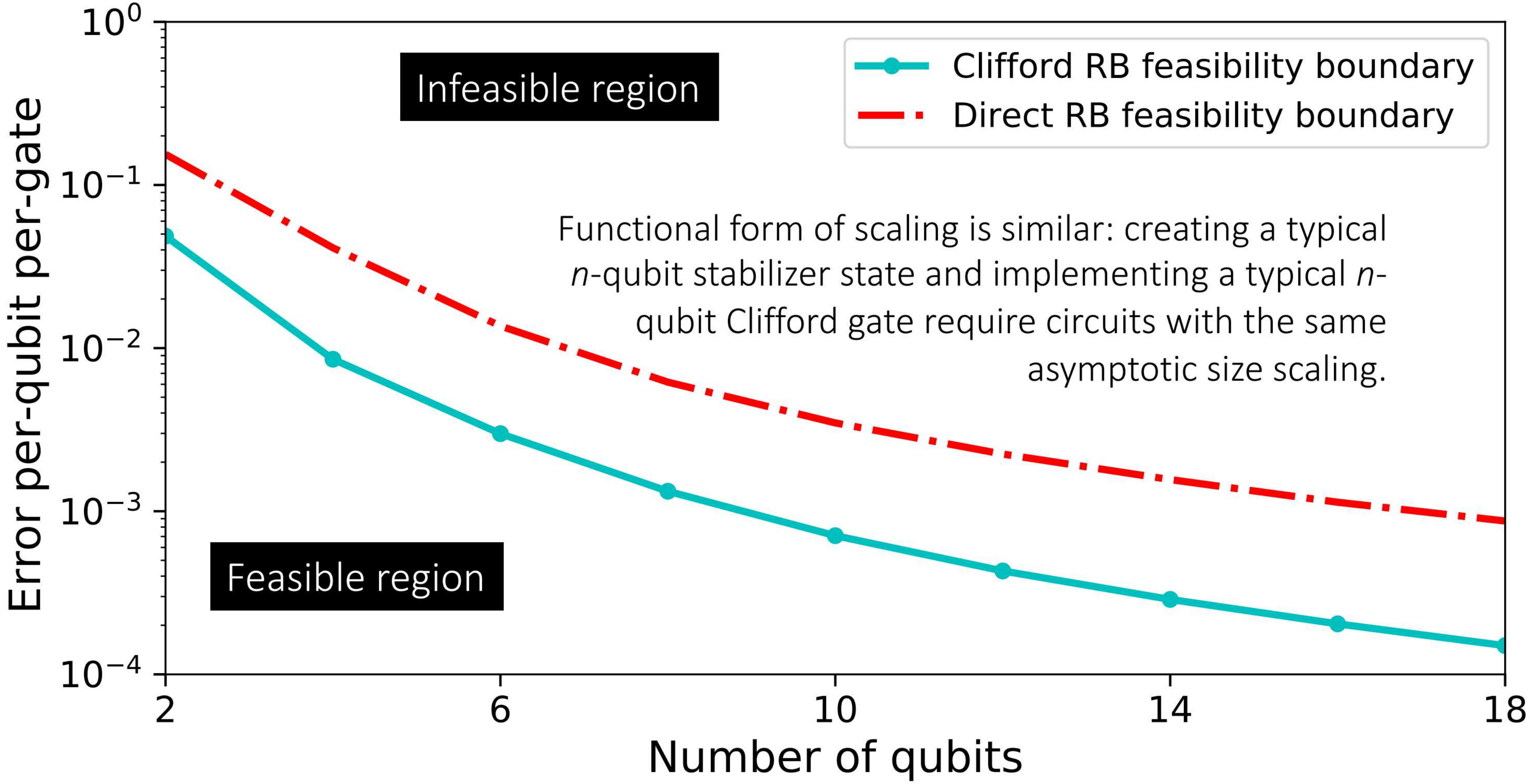
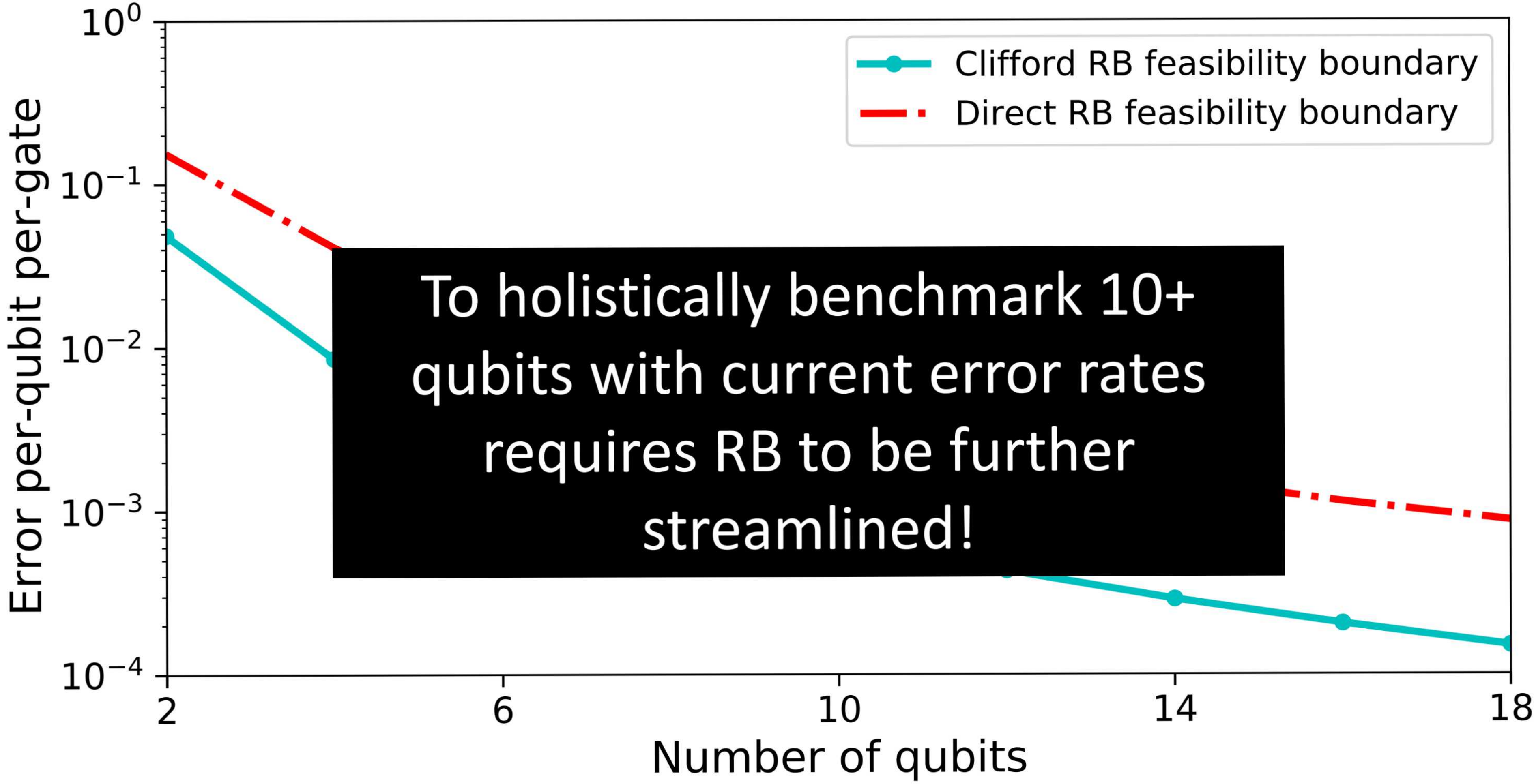
Part III – Optimally scalable RB

Gate fidelity requirements for holistic RB



(Exact positions of boundaries depend on a variety of factors, e.g., device connectivity)

Gate fidelity requirements for holistic RB



To holistically benchmark 10+ qubits with current error rates requires RB to be further streamlined!

(Exact positions of boundaries depend on a variety of factors, e.g., device connectivity)

Adapting direct RB for optimal scalability

- We’re adapting direct RB so that it is optimally scalable (the new method’s working title is “mirror RB”).

- This method unavoidably trades off some of the robustness of direct RB for increased scalability. But we expect the method to be sufficiently robust to be useful.

- We’ve used the method to holistically benchmark an entire 16-qubit device (IBMQX5), with promising results.

IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

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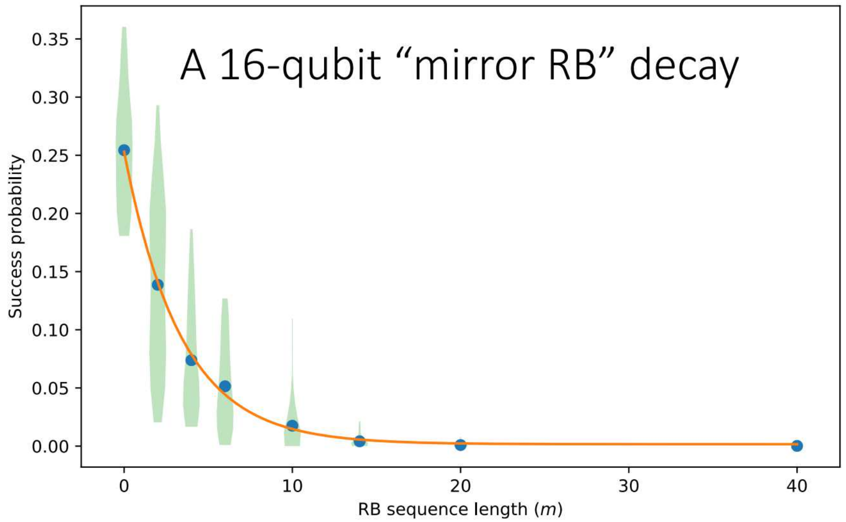
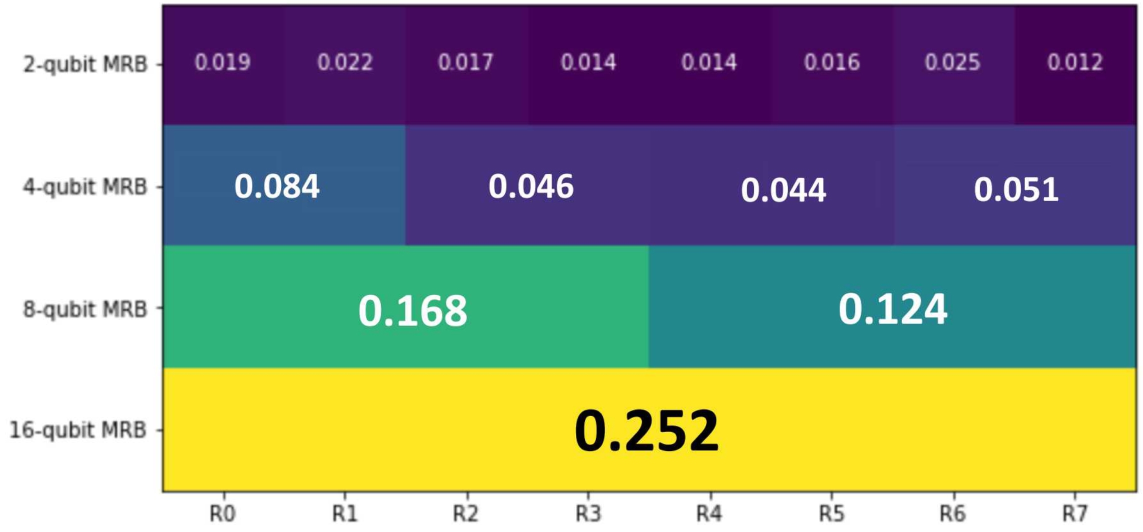
Adapting direct RB for optimal scalability

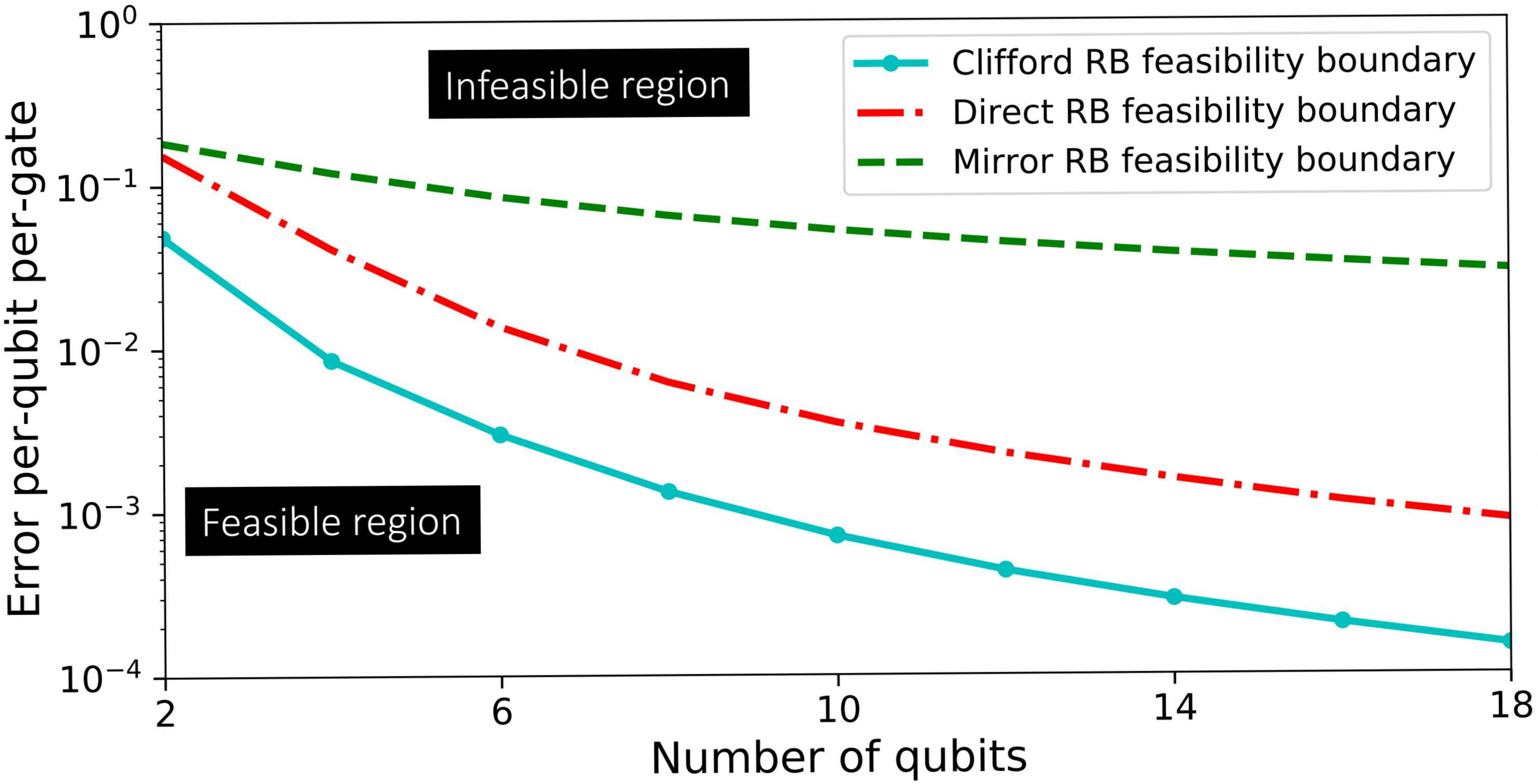




- We've used the method to holistically benchmark an entire 16-qubit device (IBMQX5), with promising results.

IBM Q Experience, https://quantumexperience.ng.bluemix.net/qx/devices

Gate fidelity requirements for holistic RB



(Exact positions of boundaries depend on a variety of factors, e.g., device connectivity)

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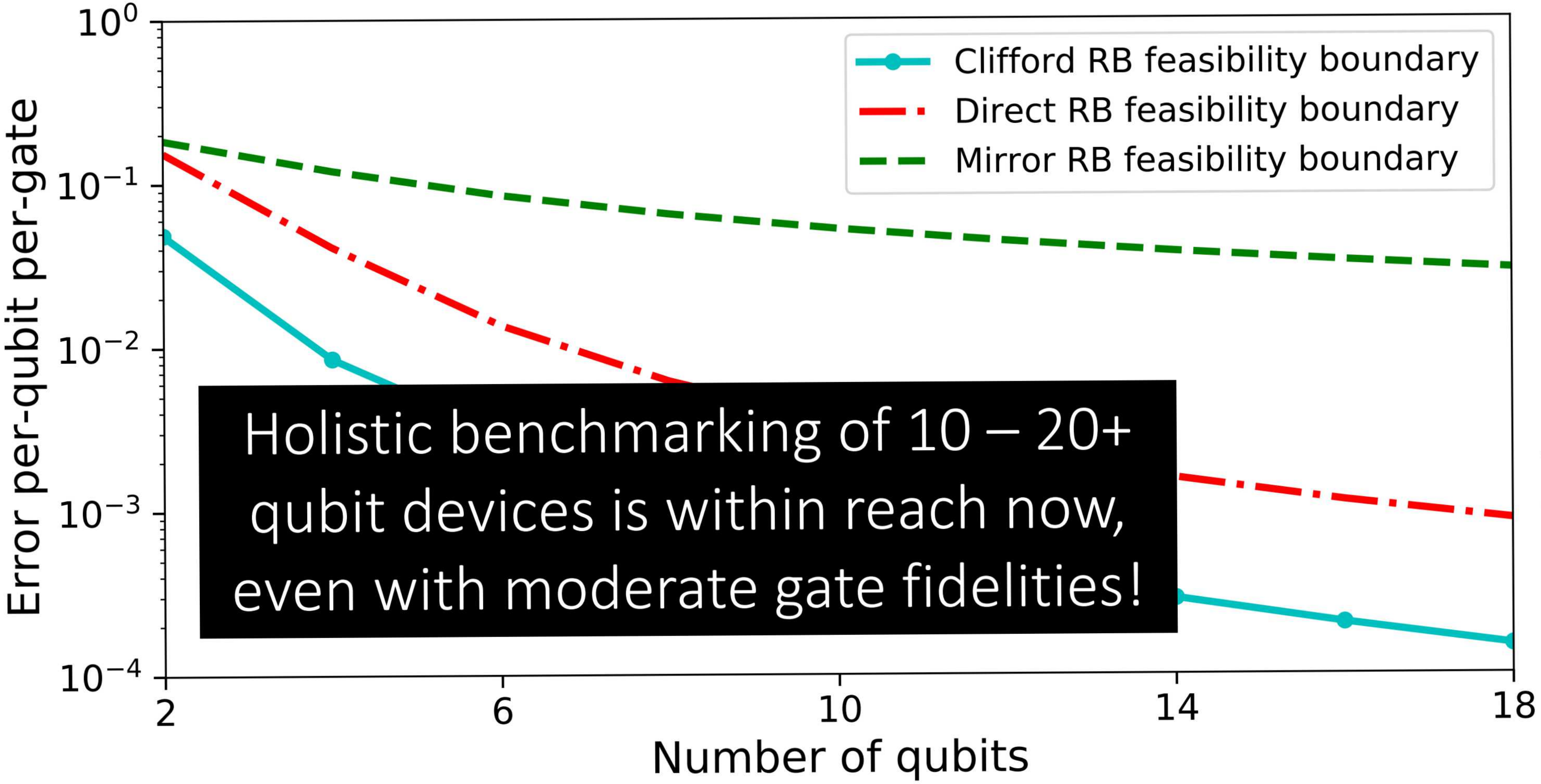
Gate fidelity requirements for holistic RB



Holistic benchmarking of 10 – 20+ qubit devices is within reach now, even with moderate gate fidelities!

(Exact positions of boundaries depend on a variety of factors, e.g., device connectivity)

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Want to run direct (or mirror) RB?

- Install "pyGSTi" using pip (see www.pygsti.info).
- Input your device's specification (number of qubits, the gates, connectivity).

```
nQubits = 17
gate_names = ['Gi','Gxpi2', 'Gxmpi2', 'Gypi2', 'Gympi2', 'Gcphase']
availability = {'Gcphase':[(i,i+1) for i in range(nQubits-1)]}
pspec = pygsti.obj.ProcessorSpec(nQubits, gate_names, availability=availability)
```

- Pick direct or "mirror" RB, and sample the circuits.

```
lengths = [0,10,20,30,40]
circuitsPerLength = 10
expDict = rb.sample.direct_rb_experiment(pspec, lengths, circuitsPerLength)
```

- Obtain and import data, and run the analysis.

```
rbresults = rb.analysis.std_practice_analysis(rbdata)
```

(some of this code will likely be out of date soon. Check the pyGSTi tutorials for the latest version!)

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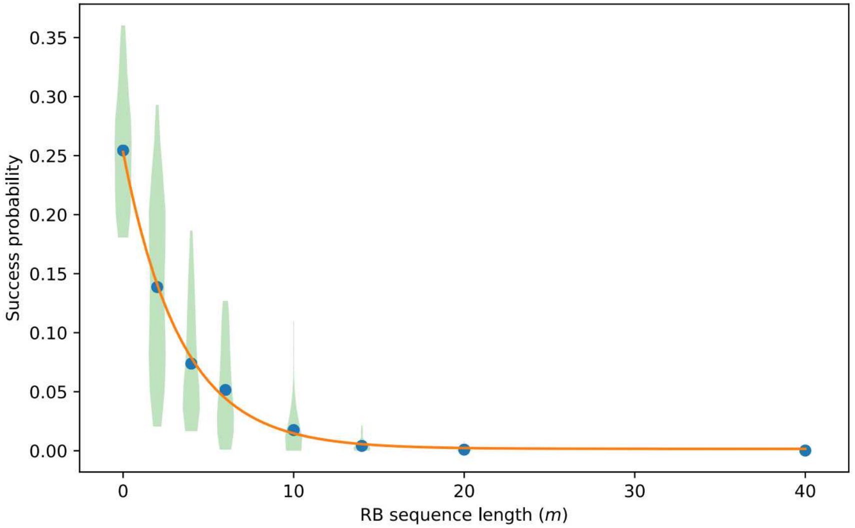
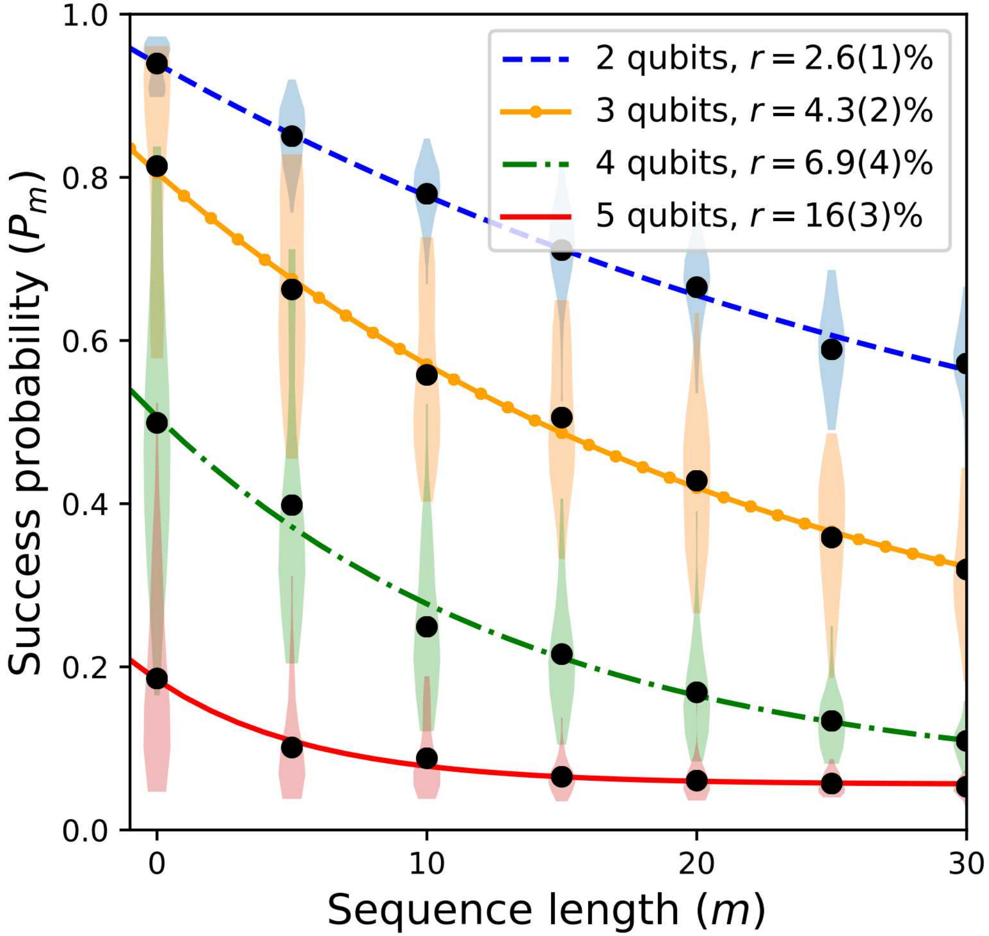
Want to run direct (or mirror) RB?

And this is the sort of output you'll get…



	R0	R1	R2	R3	R4	R5	R6	R7
2-qubit MRB	0.019	0.022	0.017	0.014	0.014	0.016	0.025	0.012
4-qubit MRB	0.084	0.084	0.046	0.046	0.044	0.044	0.051	0.051
8-qubit MRB	0.168	0.168	0.168	0.168	0.124	0.124	0.124	0.124
16-qubit MRB	0.252	0.252	0.252	0.252	0.252	0.252	0.252	0.252



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Summary

- RB is a standard-practice tool for assessing qubit performance, but the current *de facto* standard version ("Clifford RB") is not easily applied to more than 3^{ish} qubits.

- We've developed streamlined RB techniques – direct and mirror RB – that facilitate benchmarking of 1 - 10s of qubits, without sacrificing the core simplicity of RB.

- Benchmarking of 10+ qubits is now feasible with current or near-term error rates!

- If you're interested in using or learning more about direct RB or beta-stage mirror RB:

    - Come talk to me, or email me at tjproct@sandia.gov
    - Have a play around with the Jupyter notebooks on direct RB at www.pygsti.info
    - Have a read of arXiv:1807.07975 (2018).

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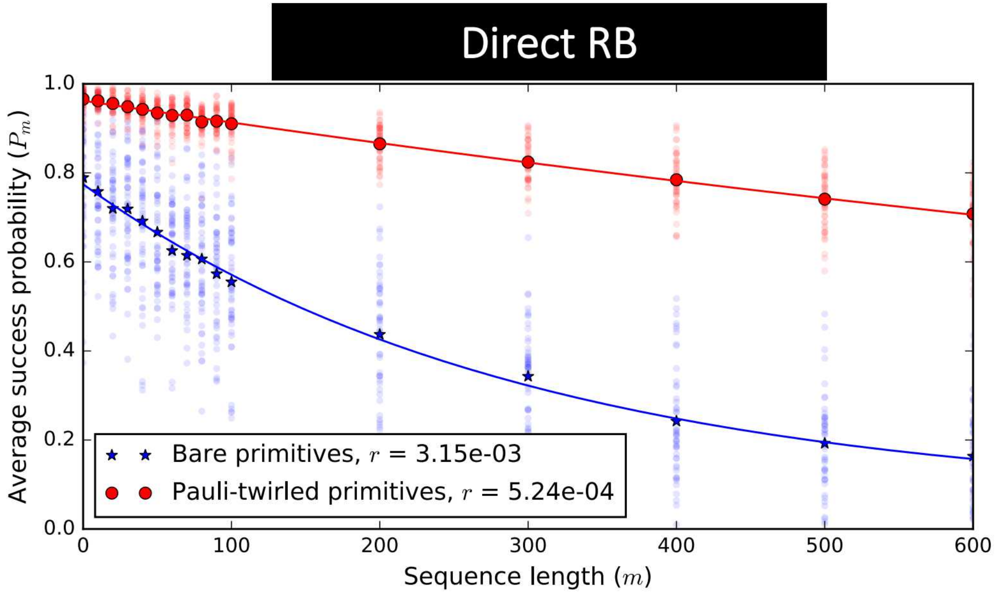
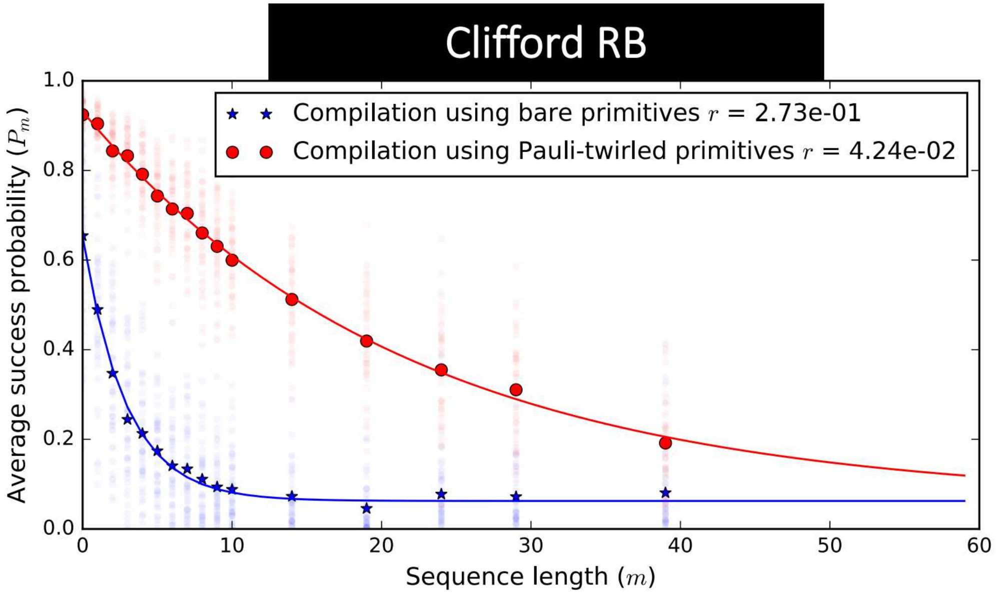
Bonus material

Direct RB with coherent errors

- Direct RB can have complex behavior with strongly coherent errors, but this is directly analogous to the behavior of Clifford RB under coherent errors.





- If you want to avoid this sort of behavior (this is a subjective choice) then add Pauli-randomization in between every direct RB layer.

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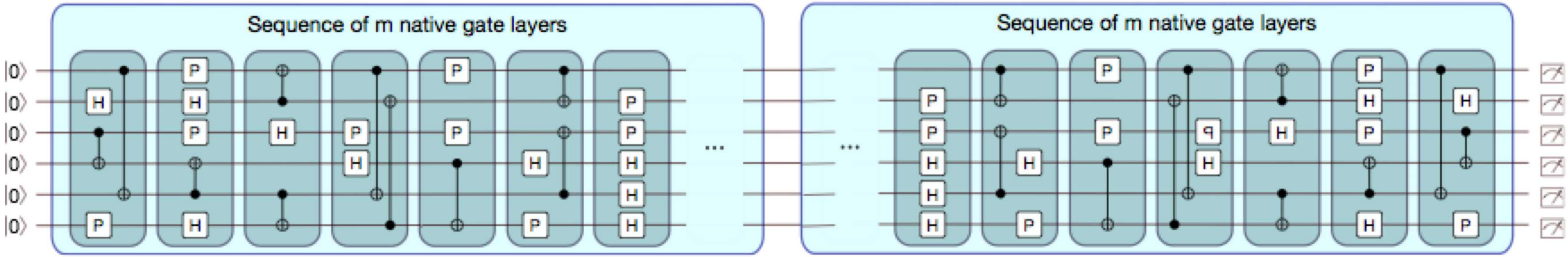
Mirror randomized benchmarking

Bare mirror RB – a random circuit followed by it's the circuit in reverse with each gates replaced by it's inverse.[1]



But this is insensitive to some types or error (e.g., if every gate was accidentally an identity gate)… So let's adjust the circuits!

[1]An idea along these lines appears in Emerson *et al.,* JOB 7, S347 (2005). In that paper the gates are specified as Haar-random.

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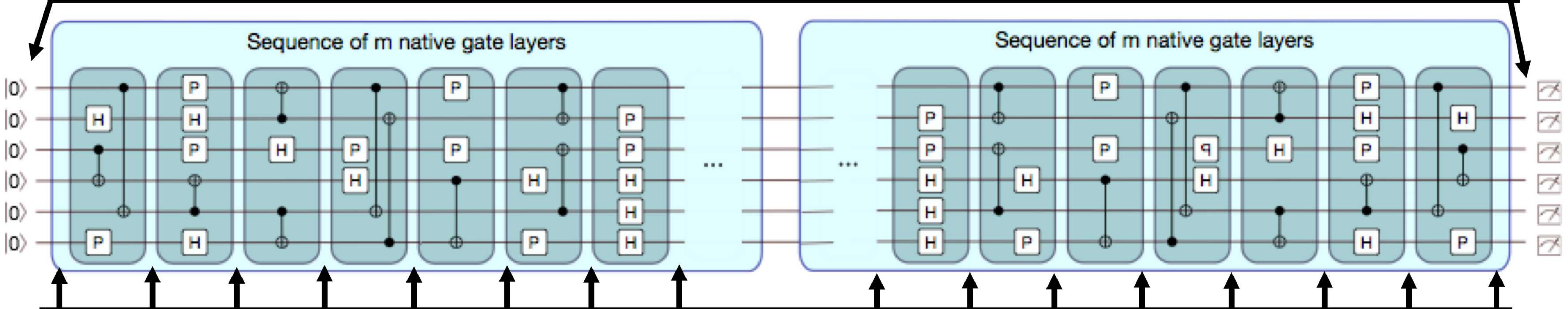
Mirror randomized benchmarking

(Pauli-twirled) mirror RB:

Insert uniformly random 1-qubit Cliffords on each qubit at start, and their inverse at end



Inserting an independently sampled random *Pauli gate* between every layer