Benchmarking near-term quantum computers via random circuit sampling

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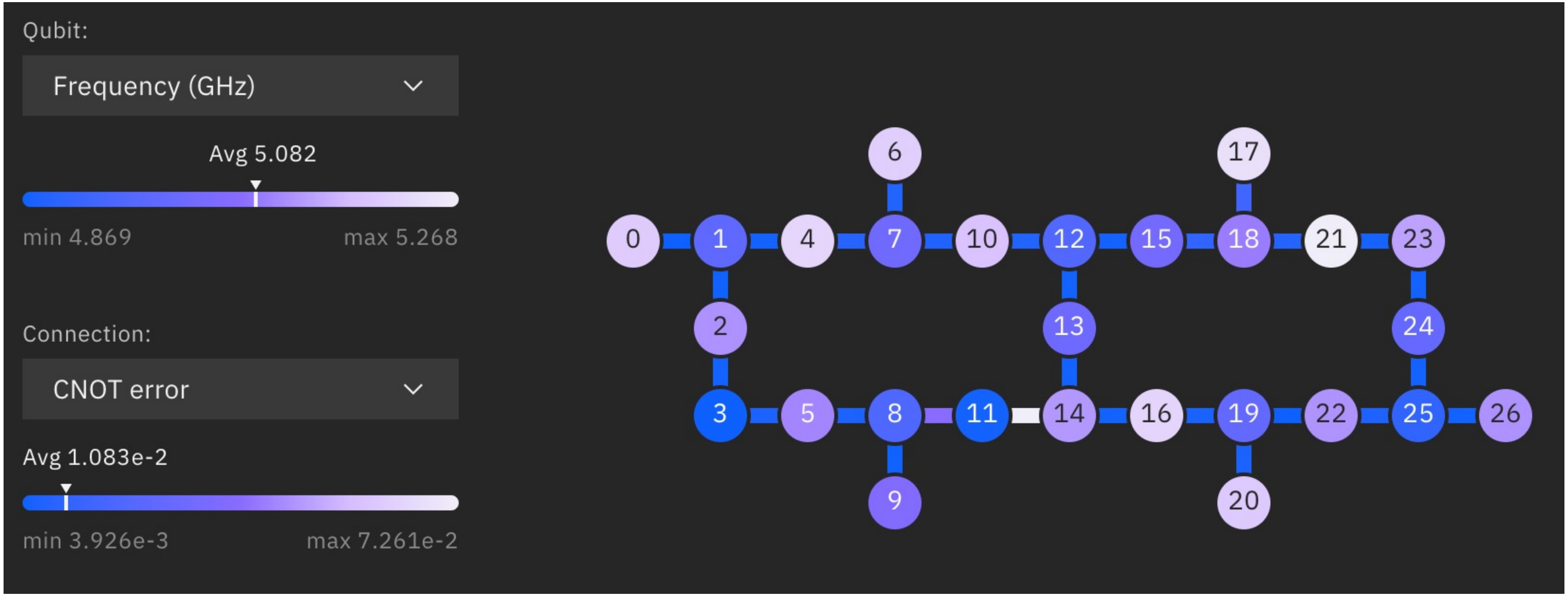
Benchmarking quantum noise

- Learning the quantum noise in a quantum device
- Important because we need to know what the noise look like in order to
  1. further reduce the noise and build better quantum computers
  2. design suitable error correcting codes

- This talk: scalable benchmarking algorithm for non-Clifford gates

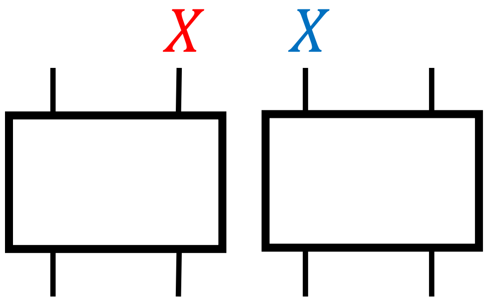
Benchmarking quantum noise



https://quantum-computing.ibm.com/services?services=systems

Challenge: crosstalk and correlated errors

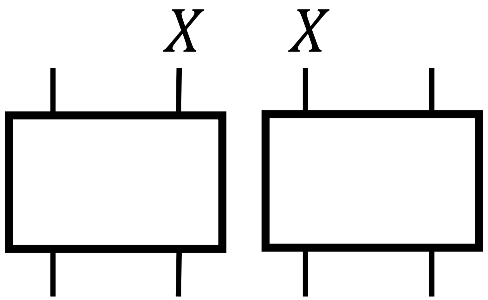
RB: 1%   RB: 1%



X with probability 1%
X with probability 1%

Total error = 2%

RB: 1%   RB: 1%



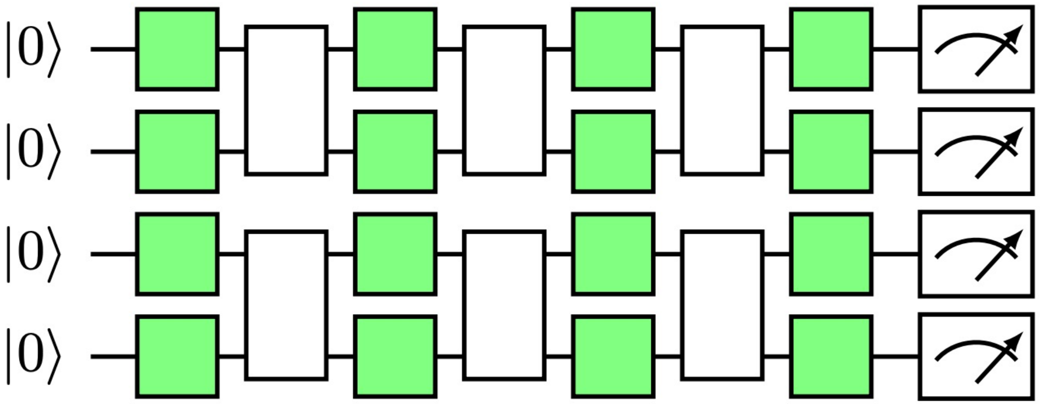
XX with probability 1%

Total error = 1%

Solution: scalable algorithm to estimate the total amount of noise in a layer of gates

Scalable noise benchmarking methods

Cycle benchmarking [Erhard et al'19]



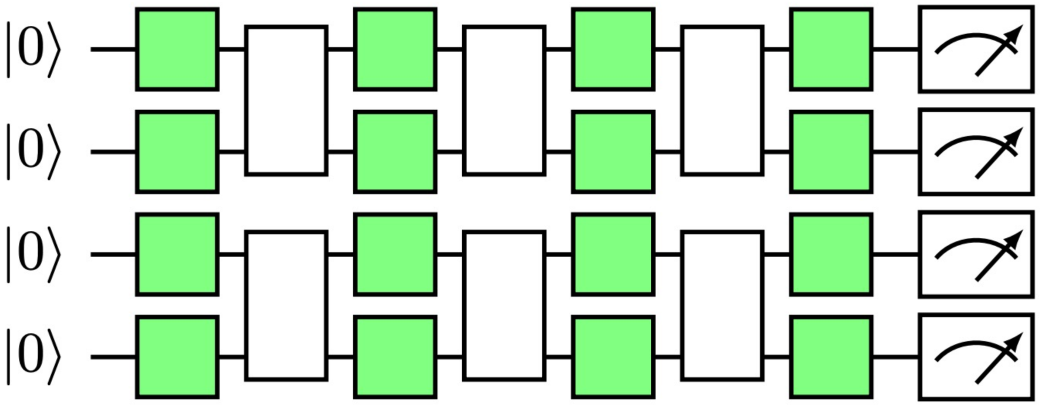
Green: random Pauli gate

Principle: structure of the Clifford and Pauli group
Works for Clifford 2-qubit gates

Challenge: how to do scalable benchmarking of non-Clifford gates?

Scalable noise benchmarking methods

Cycle benchmarking [Erhard et al'19]



Green: random Pauli gate

Principle: structure of the Clifford and Pauli group
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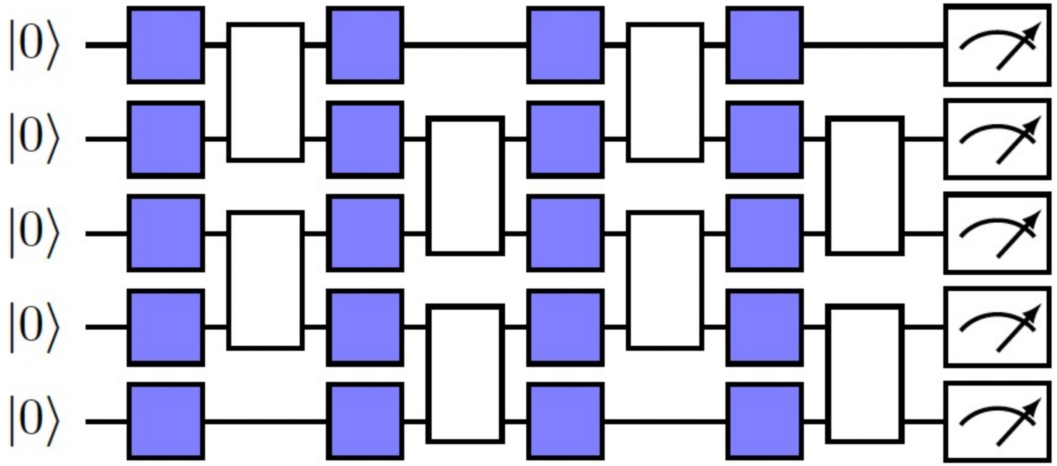
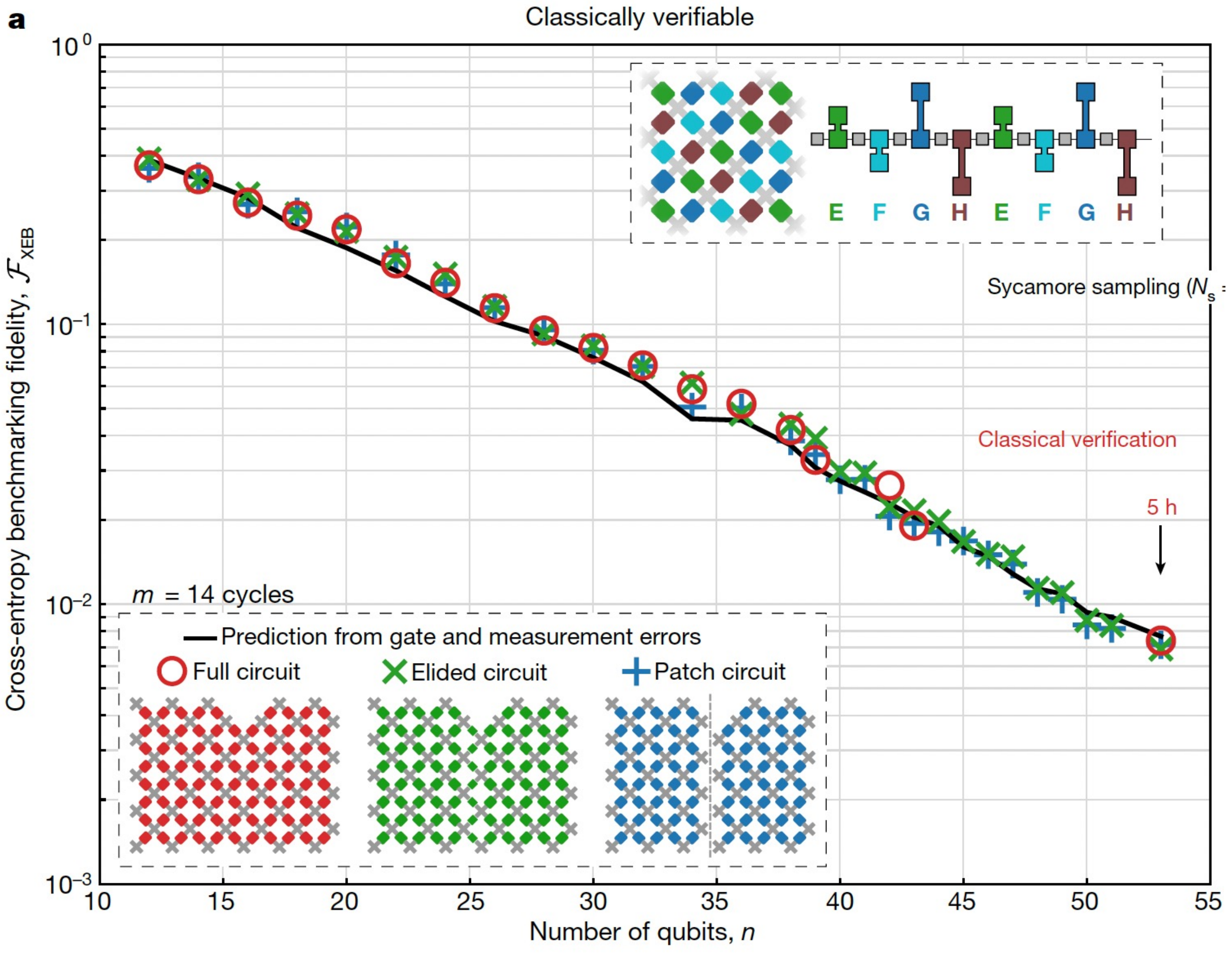
RCS benchmarking [This talk]



Blue: Haar random single qubit gate

Principle: scrambling effect of random quantum circuits
Works for *any* 2-qubit gates

Motivation: Google's quantum supremacy experiment [Arute et al'19]



Linear cross entropy: m measurement samples,

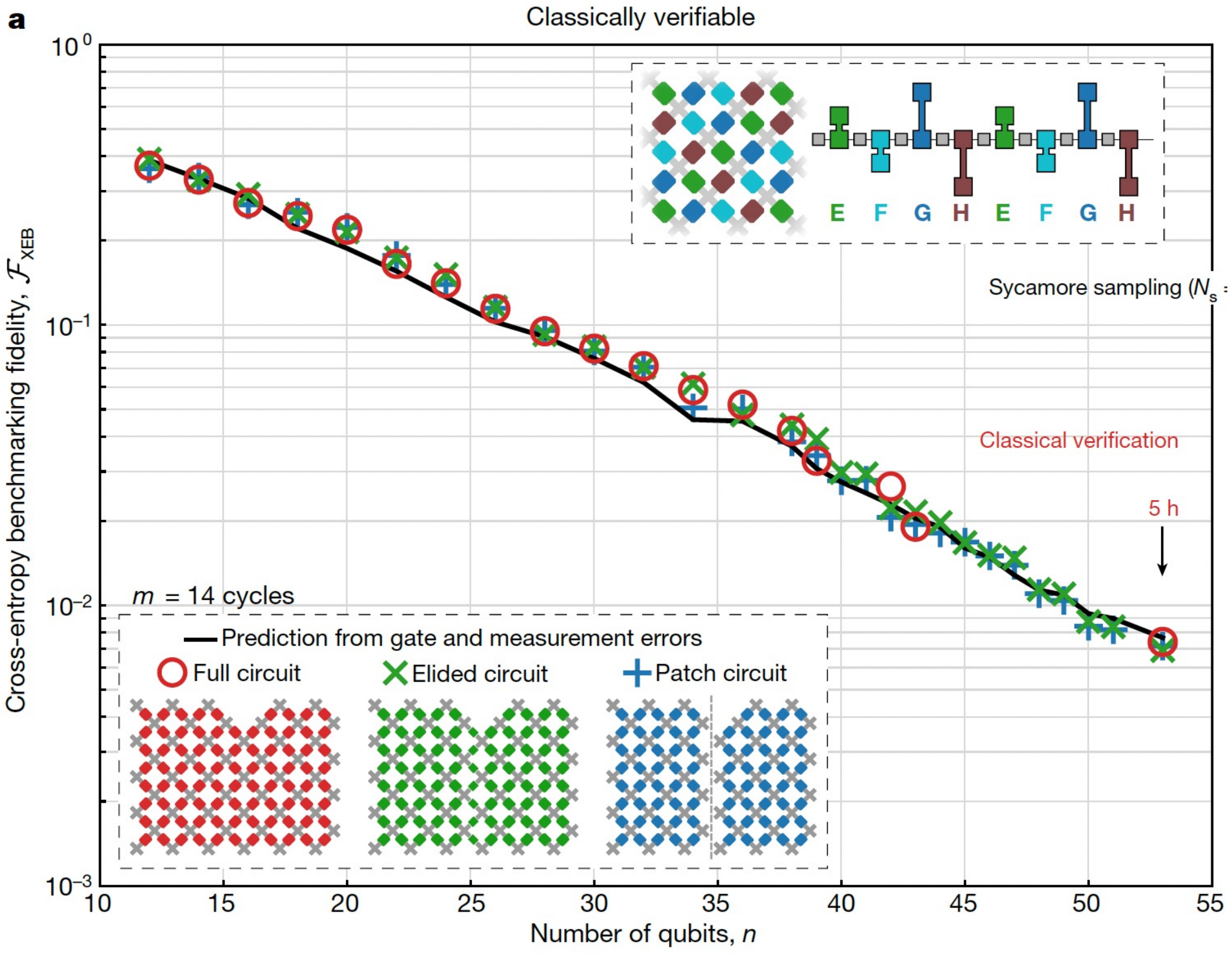
$$XEB = \frac{2^n}{m}\sum_{i=1}^{m} p(x_i) - 1$$

Used as a proxy of the fidelity of their experiment

Claim 1: they have achieved quantum supremacy

Claim 2: the noise in their device was uncorrelated

Motivation: Google's quantum supremacy experiment [Arute et al'19]

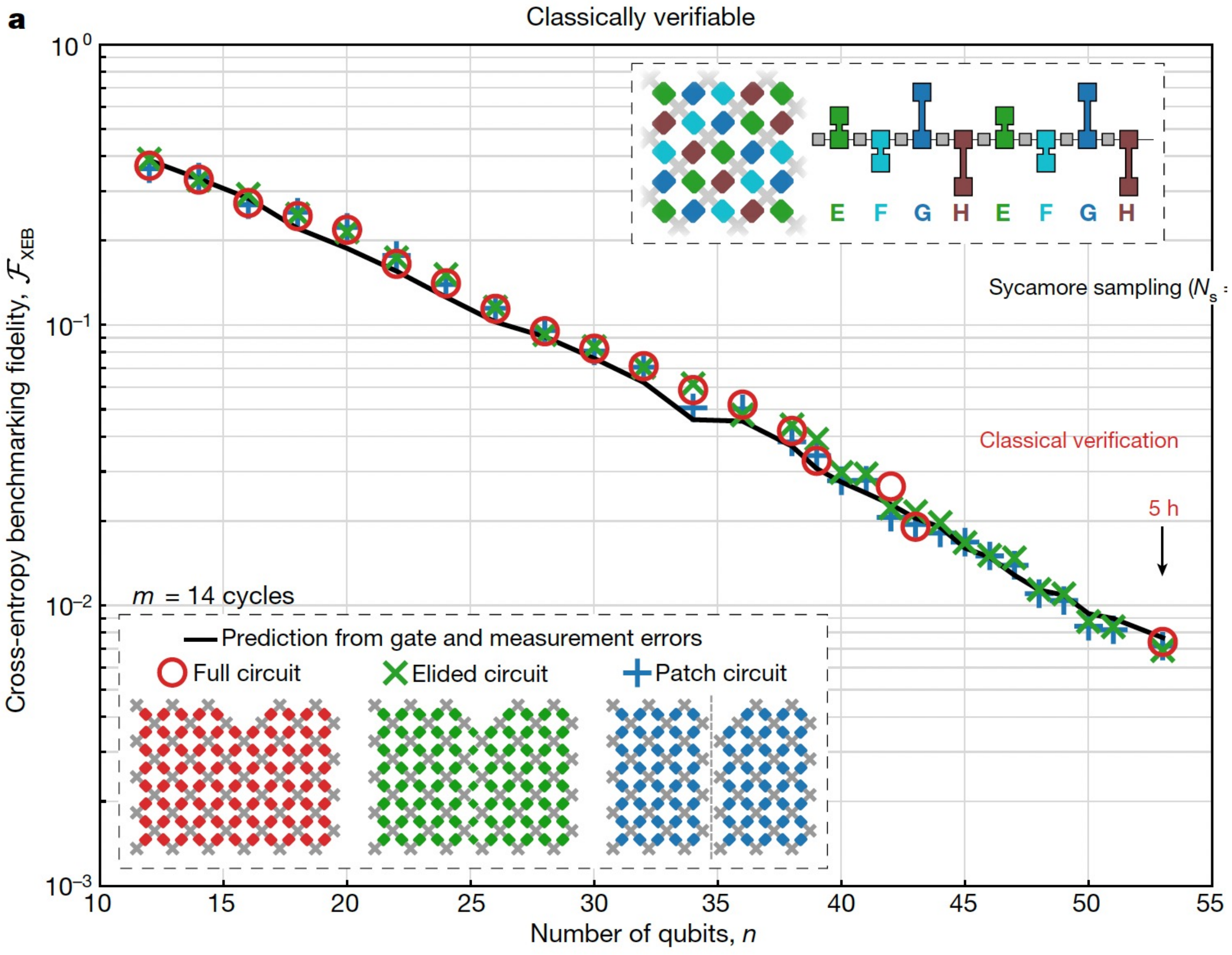


"digital error model" (multiplying individual gate fidelities) $F_{RB} = \prod_{i=1}^{m}(1-e_i)$

For independent events A, B, P(AB)=P(A)P(B)

"Maybe the errors in our device is uncorrelated? In this case, fidelity=P(no error)= ∏P(no error on gate i). Let's plot both XEB and F_{RB}. If they agree with each other, this suggests that the hypothesis (that noise was uncorrelated) is correct, which would be great news!"

Motivation: Google's quantum supremacy experiment [Arute et al'19]



Observation: the linear cross entropy agrees with the "digital error model" (multiplying individual gate fidelities)

Claim: this coincidence indicated that the noise in Google's device is uncorrelated across each 2-qubit gate

Can we understand this observation and claim from the theoretical perspective?

Could this observation be the hint of a scalable noise benchmarking algorithm for non-Clifford gates?

Overview of RCS benchmarking

- Result: $XEB \approx e^{-\lambda d}$, where λ is the total amount of noise in an arbitrary noise model acting on each layer of gates
    - Therefore, λ can be learned by measuring XEB
- Corollary: with correlated noise, XEB would deviate from the digital error model F_{RB}
    - Evidence that supports Google's claim

Theory of RCS benchmarking

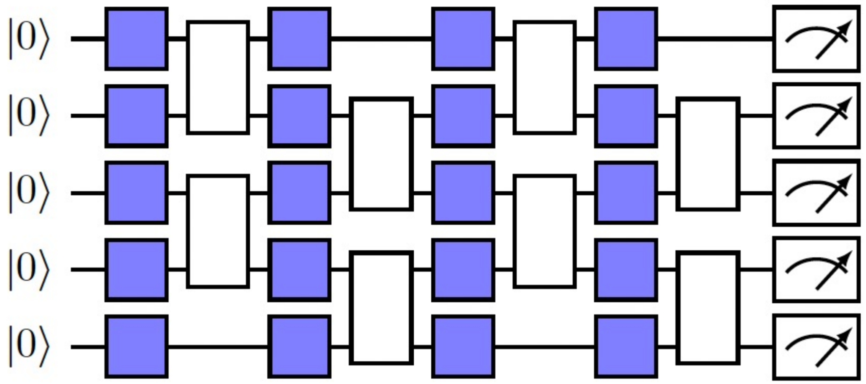
- Consider arbitrary n-qubit Pauli noise channel acting on a layer of 2-qubit gates, $\mathcal{N}(\rho) = \sum_{\alpha\in\{0,1,2,3\}^n} p_\alpha \sigma_\alpha \, \rho \sigma_\alpha$
  - Without loss of generality, as arbitrary noise channel is twirled into a Pauli channel by RCS
- The goal is to estimate total error $\lambda = \sum_{\alpha\neq 0^n} p_\alpha$
  - Effective noise rate
- We show that the average fidelity of random circuits at depth d scales as $\mathbb{E}F \approx e^{-\lambda d}$
- In experiments, estimate average fidelity by measuring XEB → get λ

Exponential decay of average fidelity

- For a random circuit C, the ideal output state is $|\psi\rangle = C|0^n\rangle$
- Experiment implementation of C creates a mixed state ρ
- The fidelity of C is given by $F = \langle\psi|\rho|\psi\rangle$

- Theorem: $\mathbb{E}F \approx e^{-\lambda d}$ when the effective noise rate λ is upper bounded by a small constant
- Proof idea: maps $\mathbb{E}F$ into the partition function of a classical spin model, then bound the partition function

RCS benchmarking



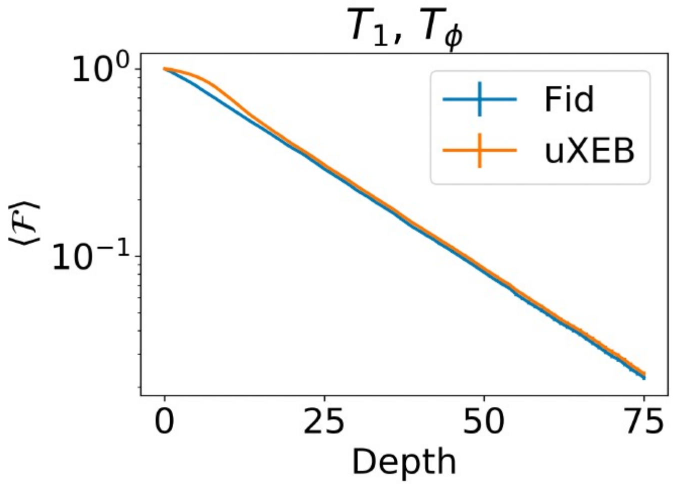
Select a few depths, at each depth, sample a few random circuits

Estimate the fidelity of each circuit via XEB, compute the average $\mathbb{E}F$

Fit exponential decay $\mathbb{E}F = Ae^{-\lambda d}$, obtain λ

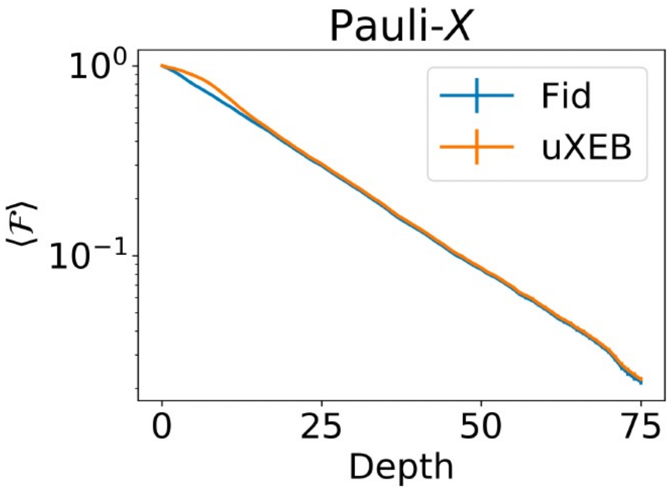
Fidelity estimation via cross entropy

- Why not directly measure fidelity?
- Problem: fidelity is hard to estimate
  - Direct fidelity estimation (DFE) has exponential sample complexity $O(2^n/\varepsilon^2)$ in the worst case
- Intuition from Google’s experiment: for random circuits, linear cross entropy appears to be a sample-efficient estimator of fidelity
  - $O(1/\varepsilon^2)$ samples suffice



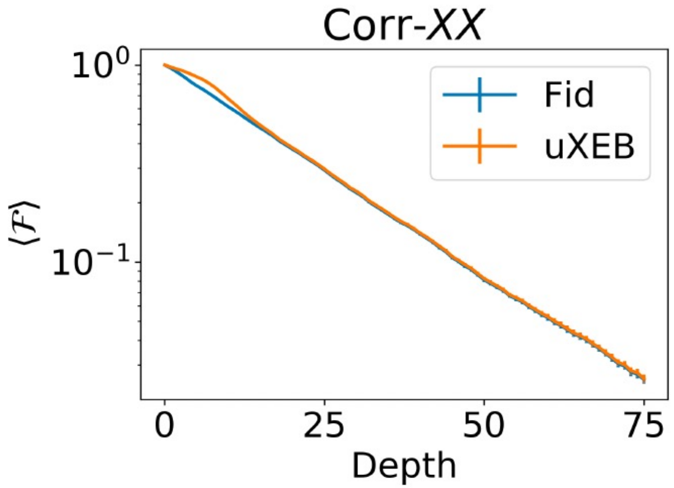
T_1, T_ϕ
10^0
10^{-1}
$\langle \mathcal{F} \rangle$
Fid
uXEB
0
25
50
75
Depth

(a)



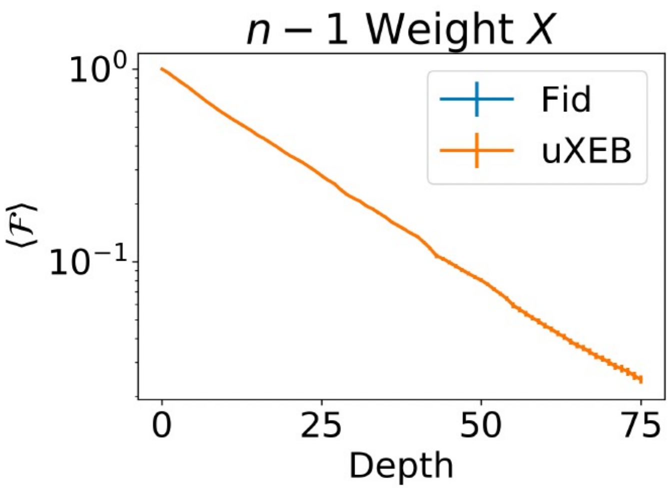
Pauli-X
10^0
10^{-1}
$\langle \mathcal{F} \rangle$
Fid
uXEB
0
25
50
75
Depth

(b)



Corr-XX
10^0
10^{-1}
$\langle \mathcal{F} \rangle$
Fid
uXEB
0
25
50
75
Depth

(c)



$n-1$ Weight X
10^0
10^{-1}
$\langle \mathcal{F} \rangle$
Fid
uXEB
0
25
50
75
Depth

(d)

Fidelity estimation via cross entropy

- Small noise regime: effective noise rate λ is upper bounded by a small constant
  - Error per gate is order $1/n$
- [Dalzell, Hunter-Jones, Brandão'21] Theoretical evidence that cross entropy agrees with fidelity above depth $O(\log n)$
- [Gao et al'21] Argues that cross entropy overestimates fidelity in the large noise regime
  - Error per gate is constant

RCS benchmarking

Select a few depths, at each depth, sample a few random circuits

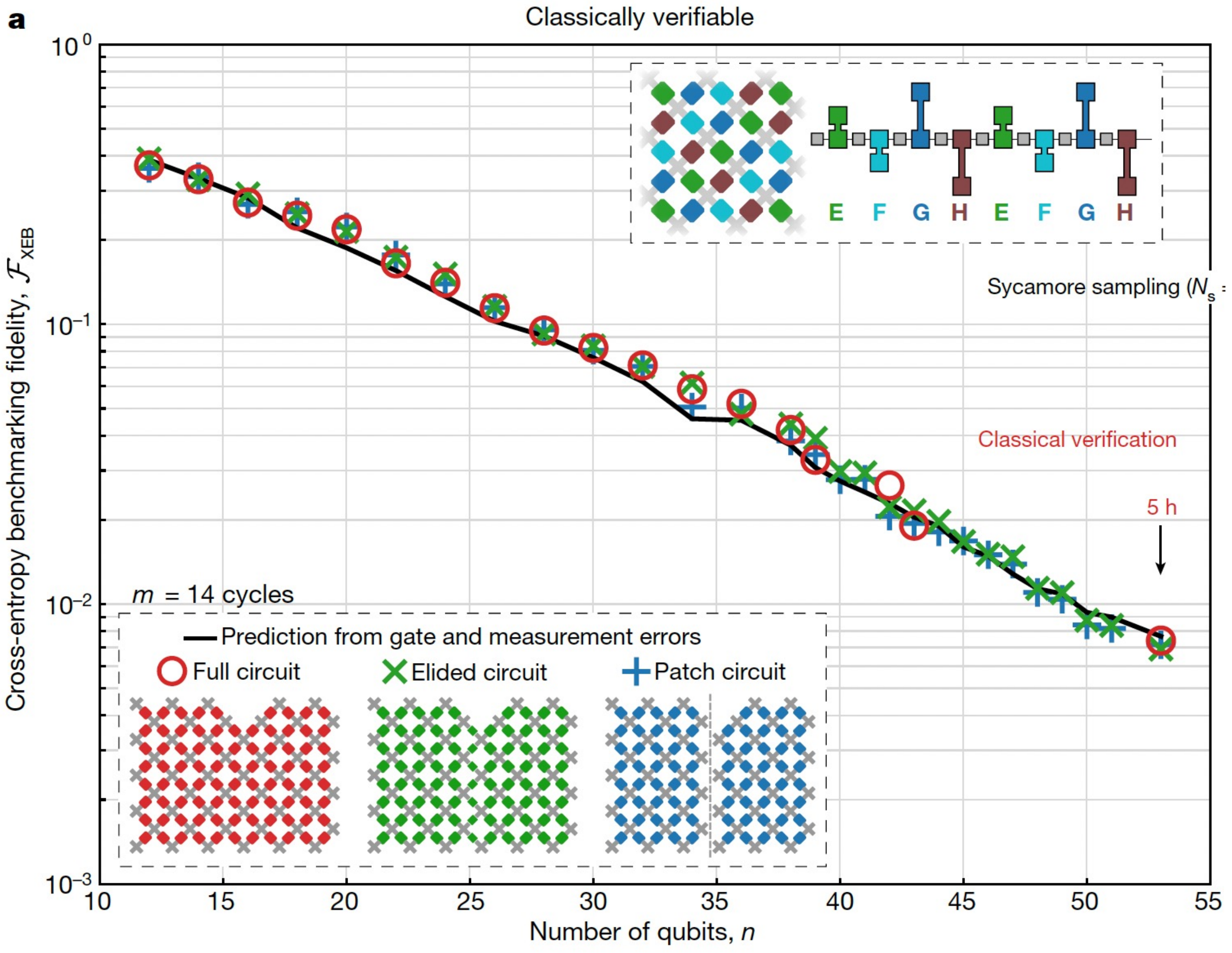
Estimate the fidelity of each circuit via XEB, compute the average $\mathbb{E}F$

←Use linear cross entropy as a proxy for fidelity

Fit exponential decay $\mathbb{E}F = Ae^{-\lambda d}$, obtain λ

λ: the effective noise rate on a layer of arbitrary two-qubit gates

Google's quantum supremacy experiment [Arute et al'19]



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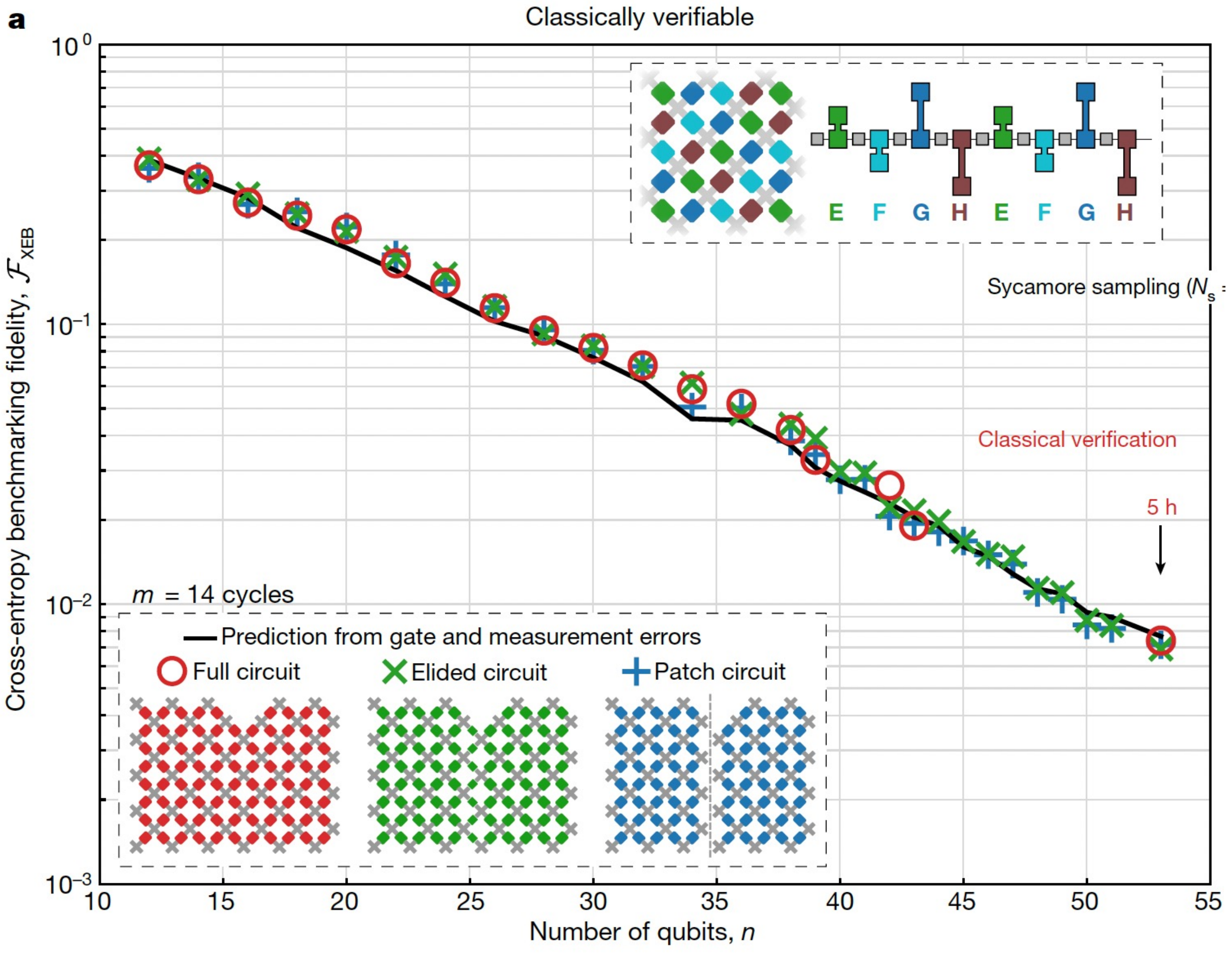

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Correlated errors in fidelity estimation

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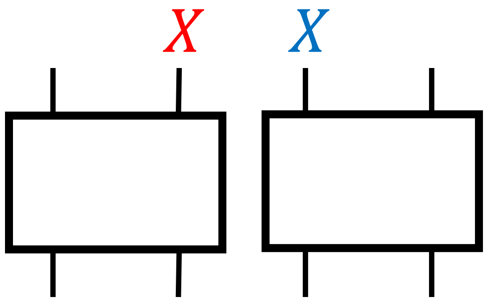
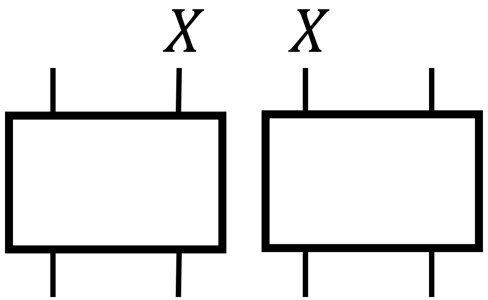


X with probability 1%
X with probability 1%

Total error = 2%

- Contributes 2% to cross entropy and fidelity
- Contributes 2% to F_{RB}

RB: 1%   RB: 1%



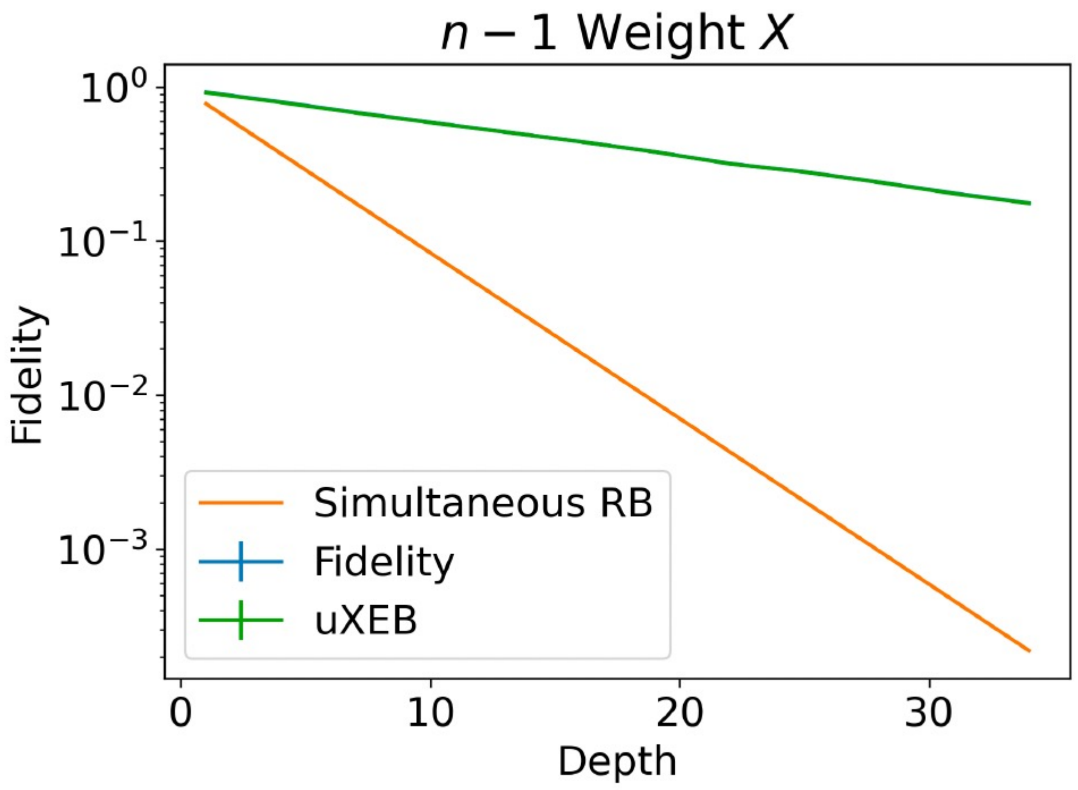
XX with probability 1%

Total error = 1%

- Contributes 1% to cross entropy and fidelity
- Contributes 2% to F_{RB}

F_{RB} overestimates correlated noise

Correlated errors in fidelity estimation



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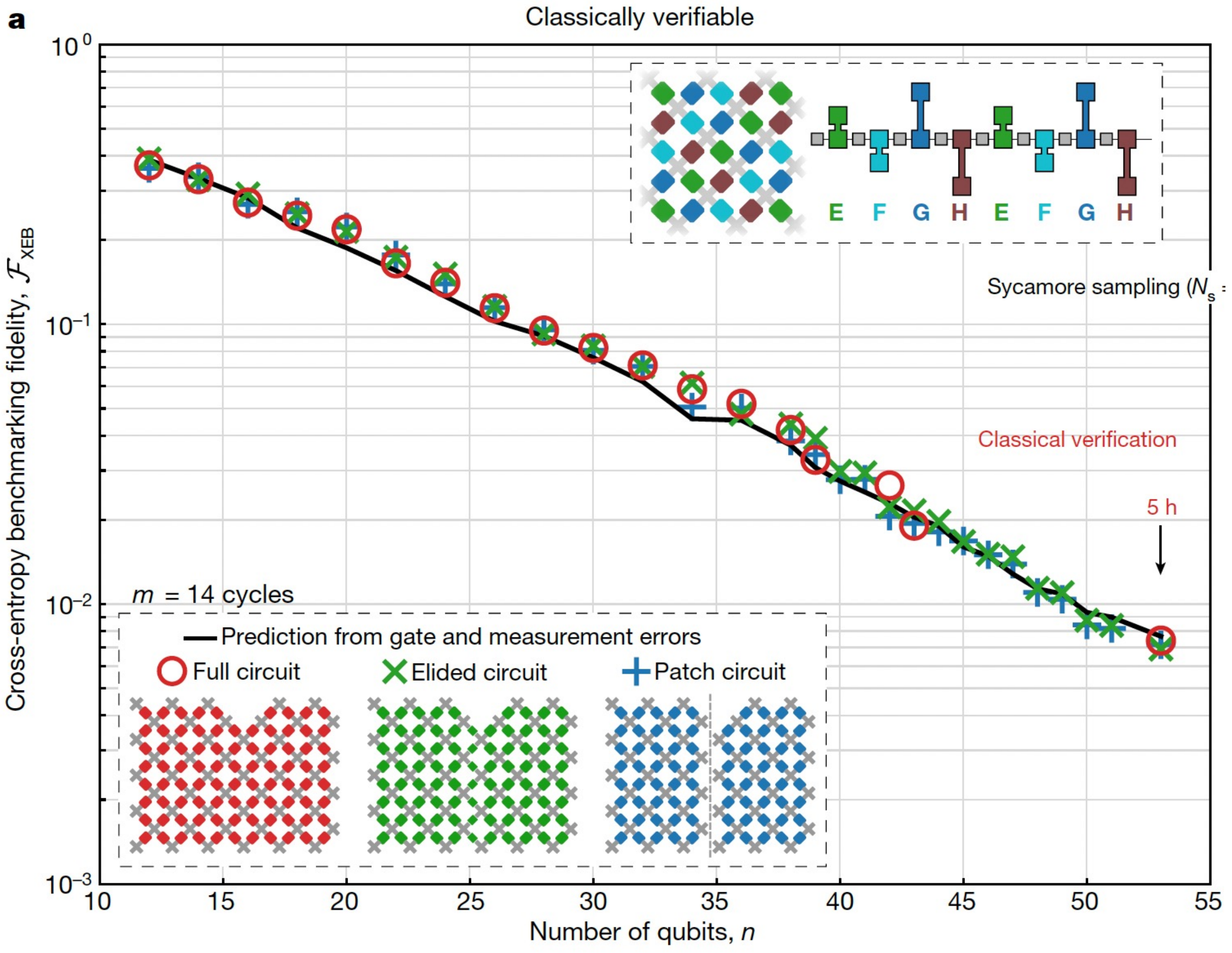

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Conclusion

- We develop an efficient algorithm to estimate the total amount of noise, including all crosstalks, on a layer of arbitrary two-qubit gates
- As an application, our result provides formal evidence to support Google's claim that the coincidence between linear cross entropy and the digital error model indicated that the noise in their device was uncorrelated
  - Good news for fault tolerance

Other applications

- Scott Aaronson's challenge for finding applications for sampling-based quantum supremacy experiments
- Noisy random quantum circuits provide new perspectives for understanding the complexity of ideal random quantum circuits
  - [Bouland, Fefferman, Landau, Liu'21] [Deshpande et al'21]
  - [Gao et al'21]