2. NISQ Hardware

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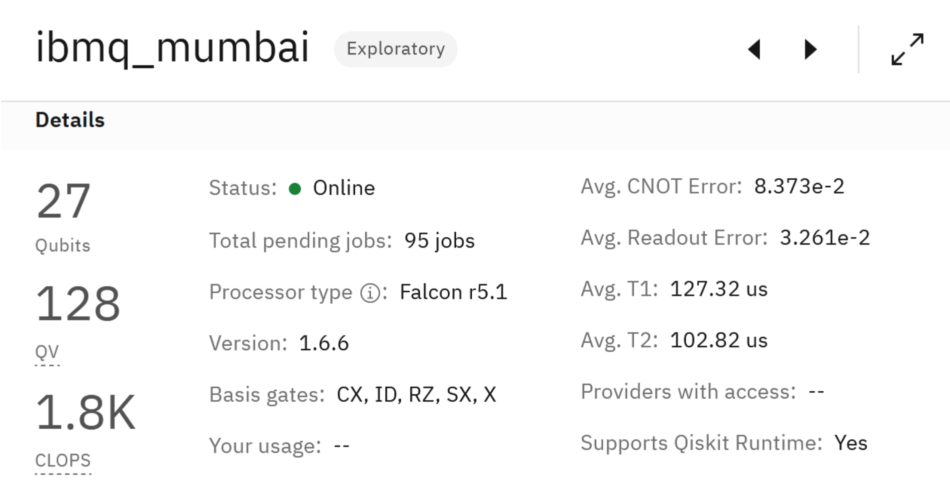
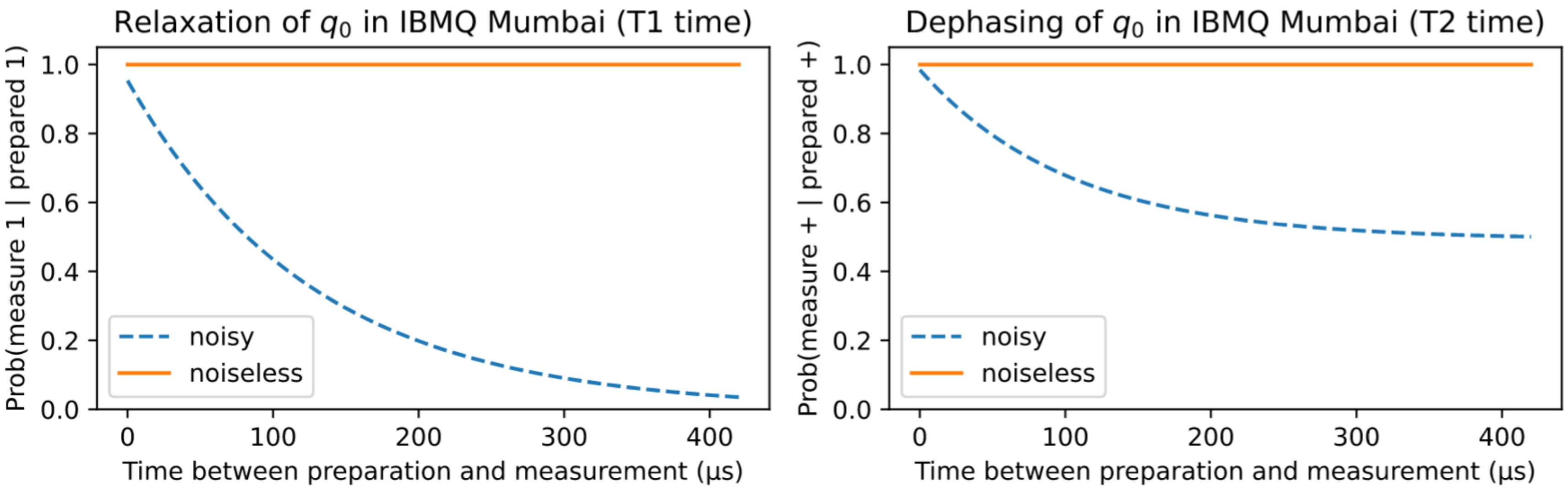
The NISQ Era

NISQ = Noisy Intermediate-Scale Quantum

- **Noisy**: high error rate in computations
- **Intermediate-scale**: few 100s of qubits

Coherence times: Relaxation and Dephasing

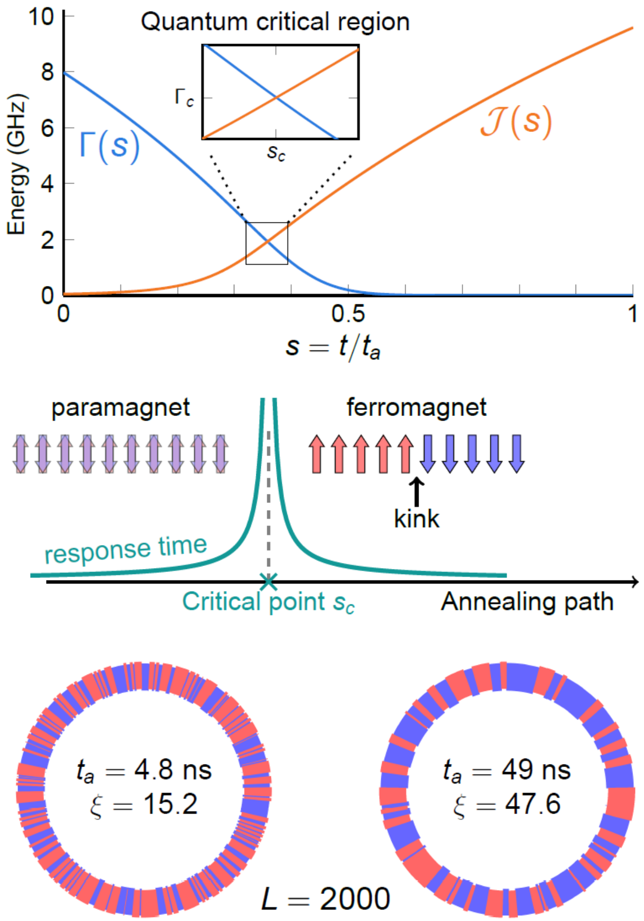


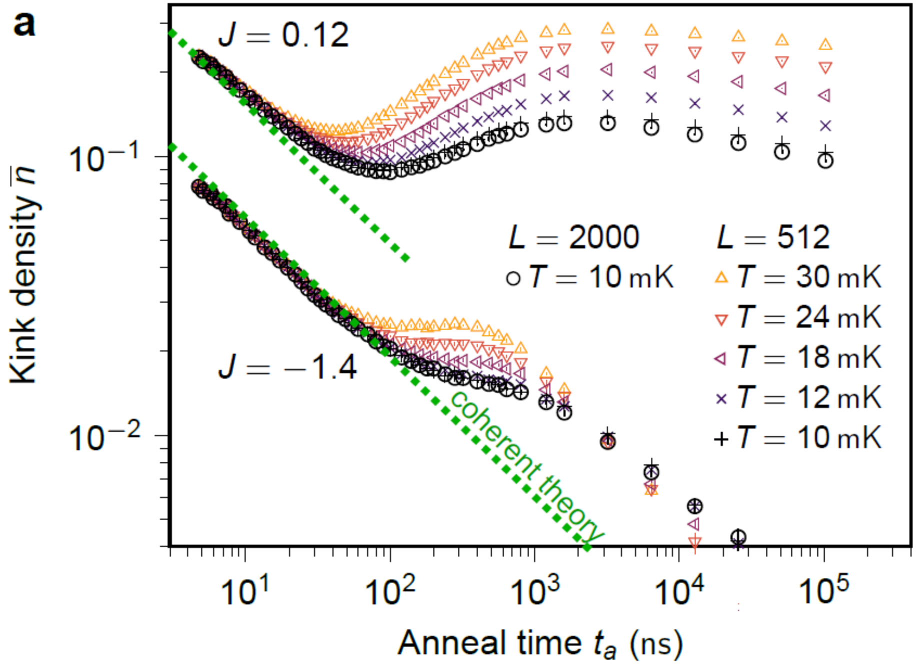


Relaxation and dephasing over 420μs, the approximate time it takes to execute a circuit with 1000 sequential CX gates.

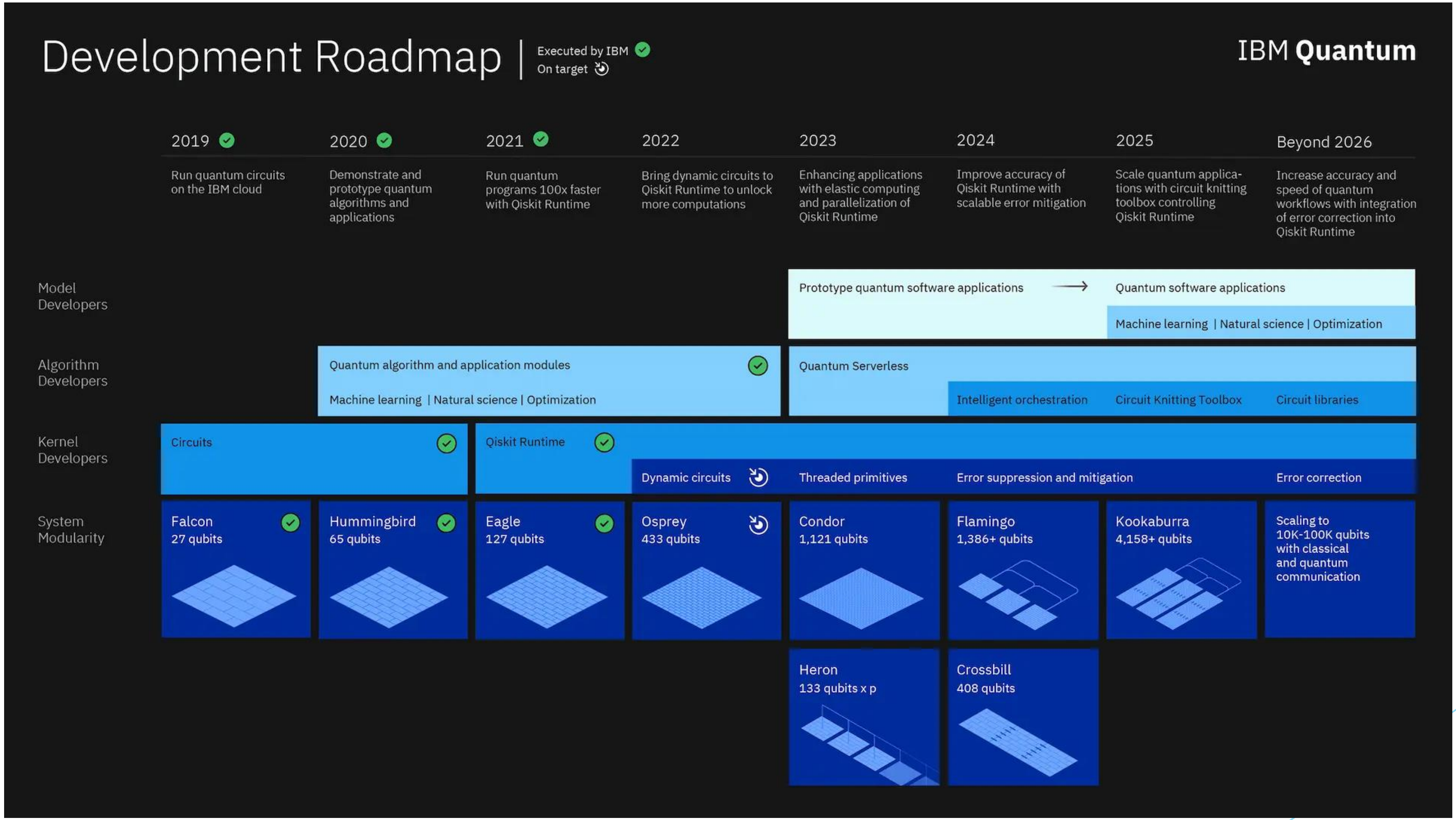
A 2022 paper by D-Wave, benchmarking the coherence times for their superconducting qubits by measuring the density of “kinks” that form in the (anti-)ferromagnetic regime as a function of the annealing time.

https://arxiv.org/abs/2202.05847



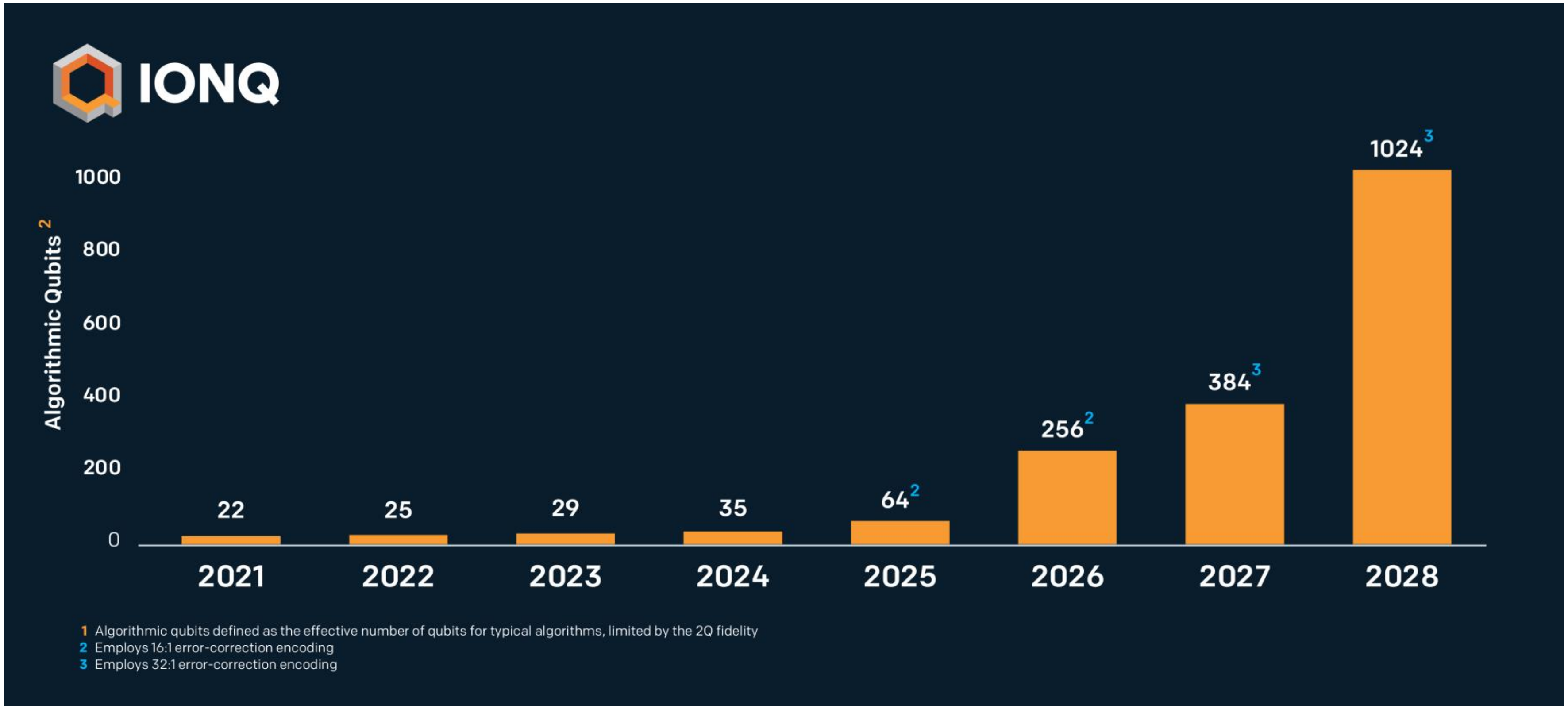


IBM Quantum Roadmap



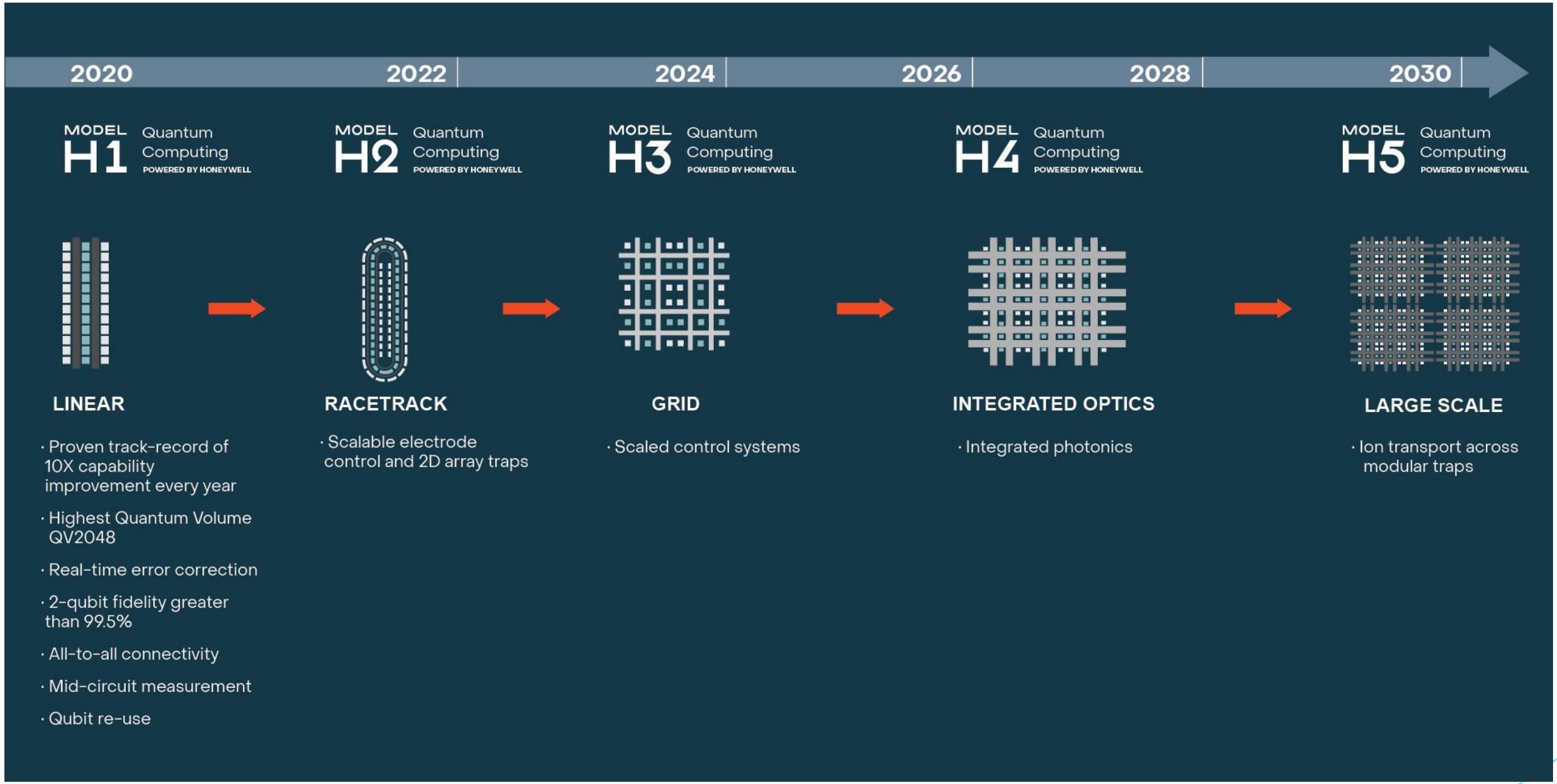
https://research.ibm.com/blog/ibm-quantum-roadmap-2025

IonQ Quantum Roadmap

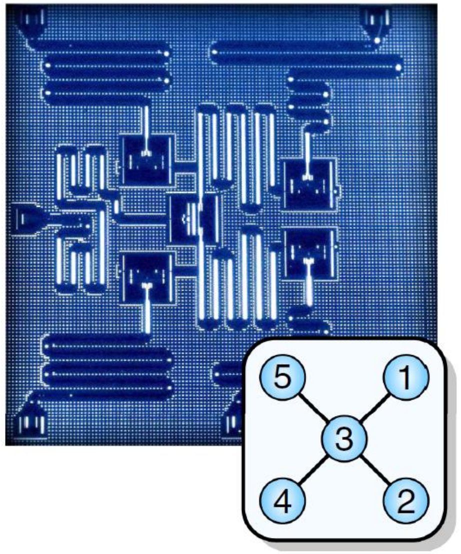


https://ionq.com/posts/december-09-2020-scaling-quantum-computer-roadmap

Quantinuum Roadmap



https://www.quantinuum.com/products/h1



A 2017 paper comparing the noise of 5-qubit superconducting vs ion-trap architectures on some small circuits of interest.

https://arxiv.org/abs/1702.01852

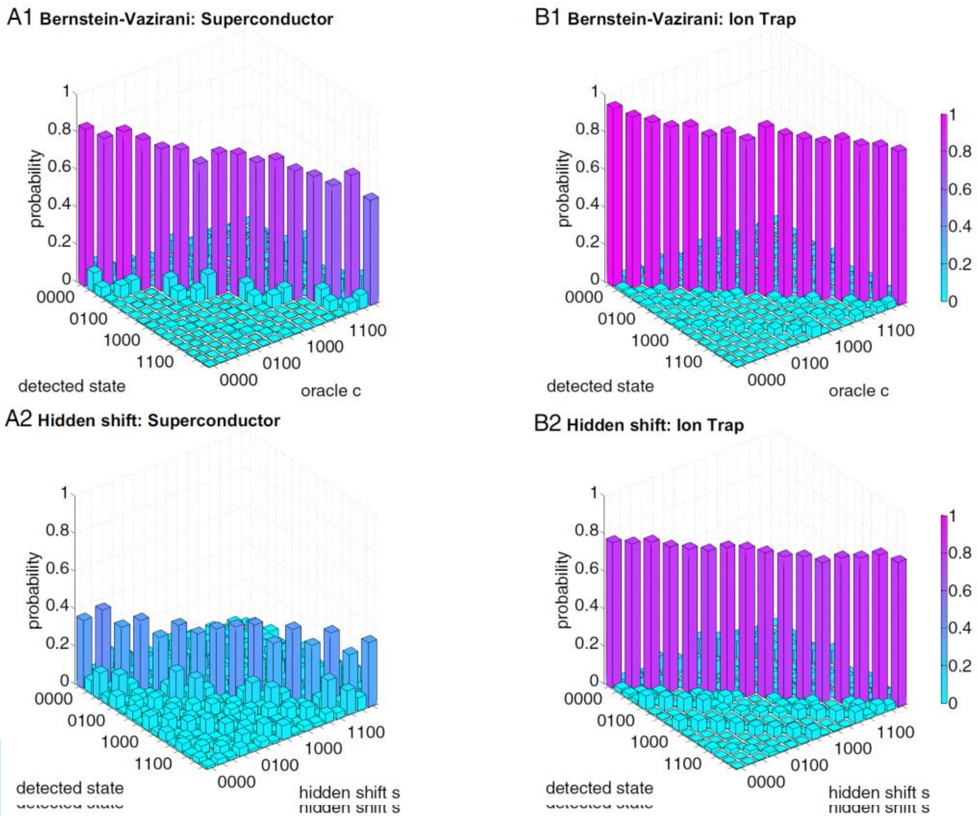
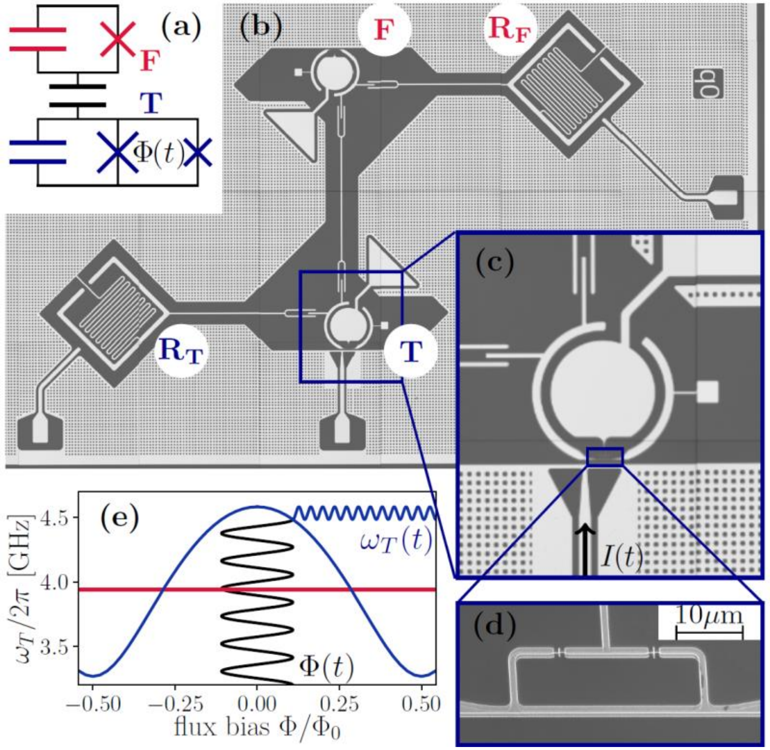


Table 1. Single- and 2-qubit gate counts for the circuits on the superconducting (star-shaped) and the ion-trap (fully connected) system after mapping to the respective hardware using the respective gate libraries

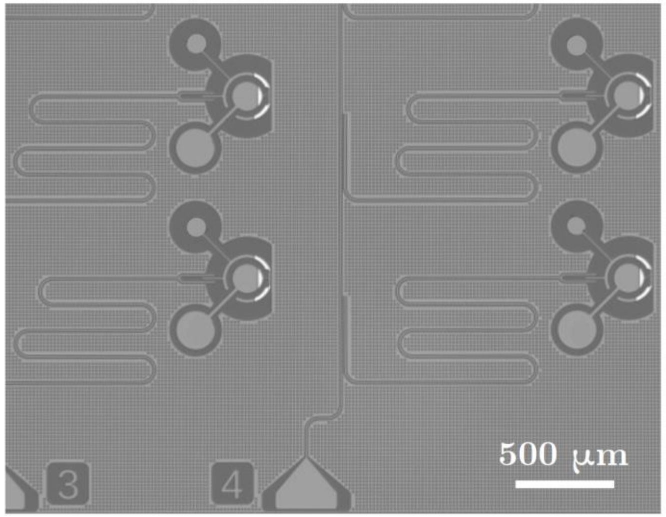
Connectivity	Star		LNN		Full	
Hardware	Superconductor		Superconductor		Ion Trap	
Gate type	1-qubit	2-qubit	1-qubit	2-qubit	1-qubit	2-qubit
Margolus	20	3	20	3	11	3
Toffoli	17	10	9	10	9	5
Bernstein–Vazirani	10	0–4	10	0–10	14–26	0–4
Hidden shift	28–34	10	20–26	4	42–50	4
QFT-3	42	19	11	7	8	3
QFT-5	*	*	35	28	22	10

Three papers showing the evolution of Rigetti hardware in 2017-2019:

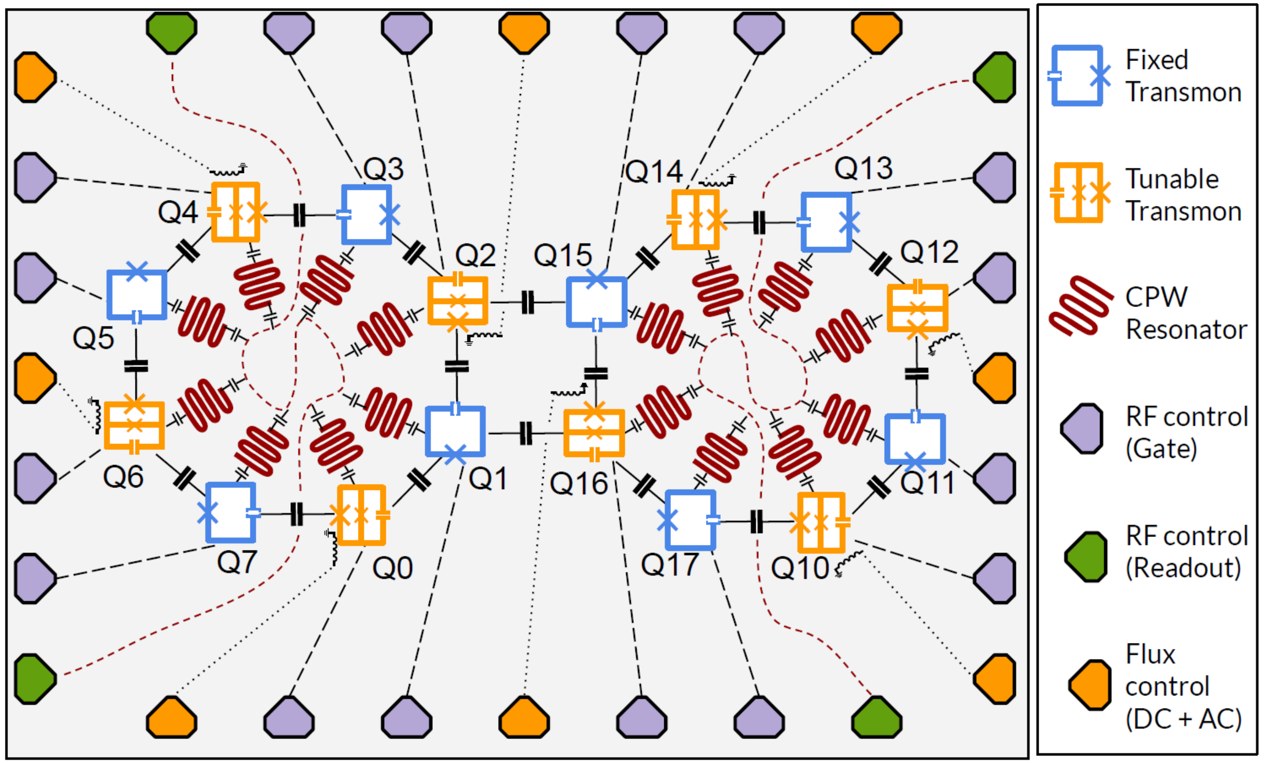
https://arxiv.org/abs/1706.06562
https://arxiv.org/abs/1901.08042
https://arxiv.org/abs/1908.11856



Above: 2 qubits (2016-06).
Below: 4 qubits (2019-01).

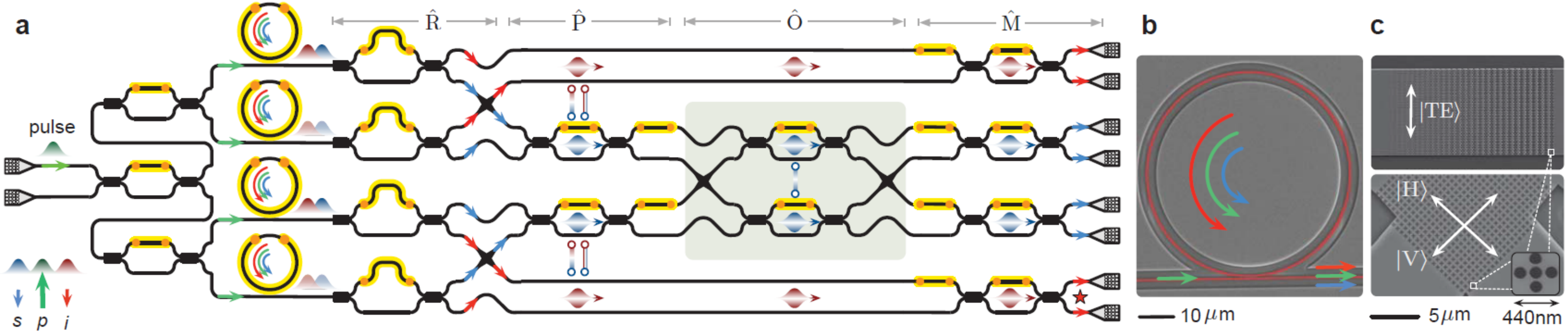


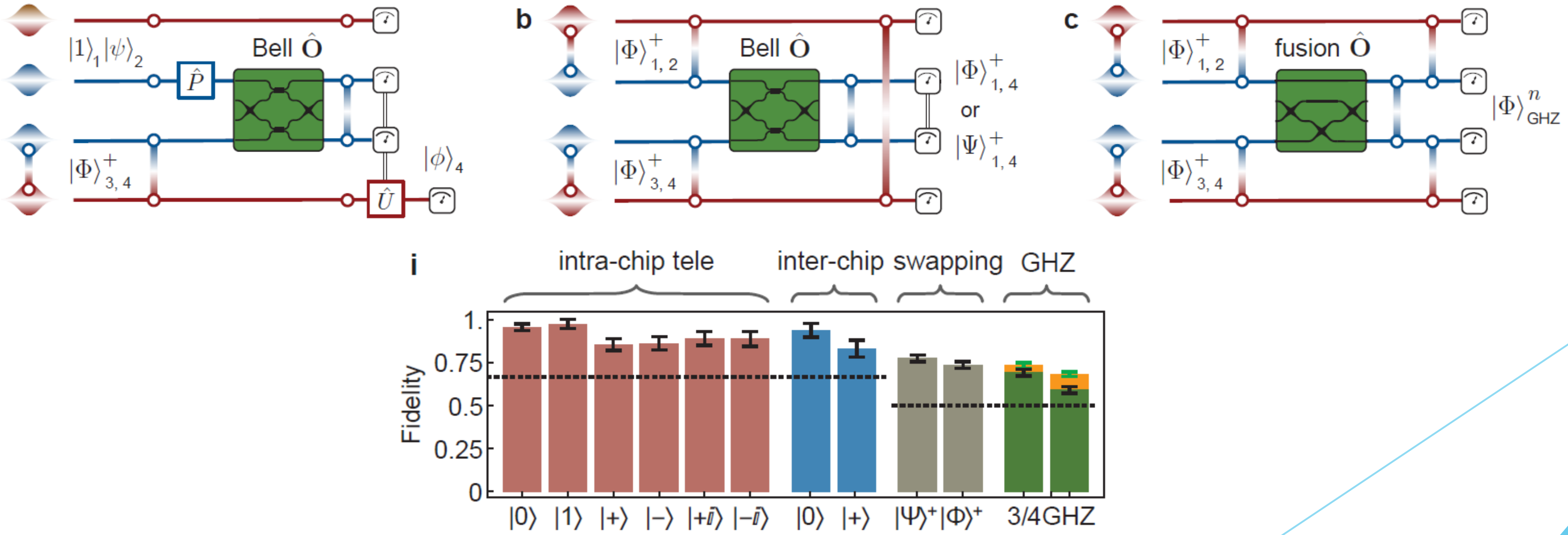
Below: 16 qubits (2019-08)



A paper about on-chip quantum optics in 2019 (4 qubits).

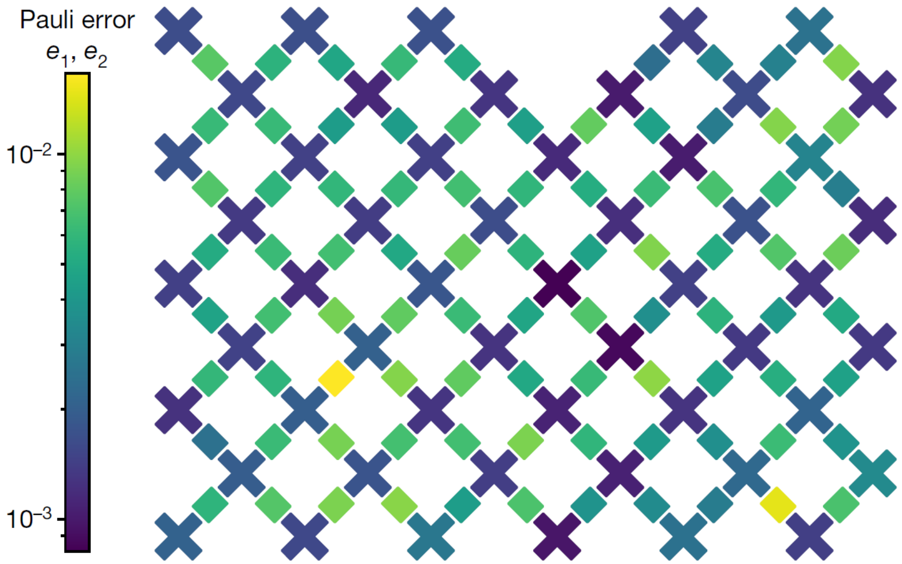
https://arxiv.org/abs/1911.07839





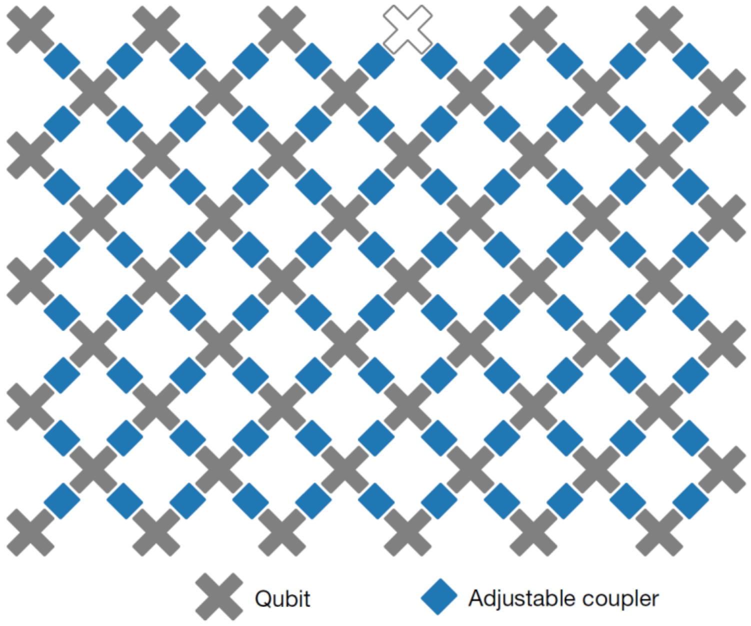
The 2019 Google “quantum supremacy” paper.

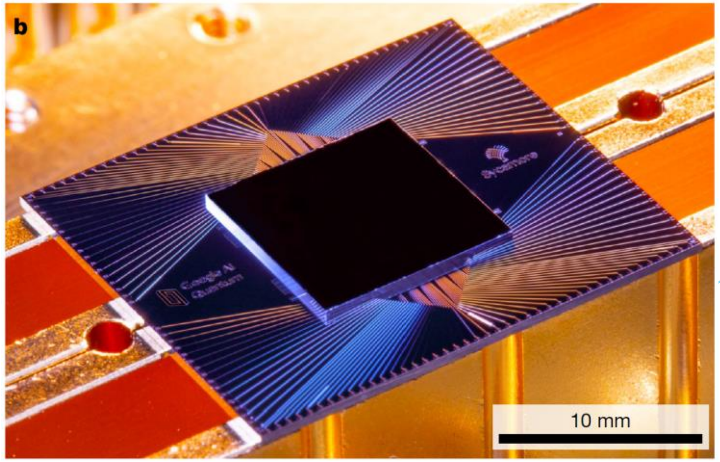
https://www.nature.com/articles/s41586-019-1666-5



Pauli and measurement errors

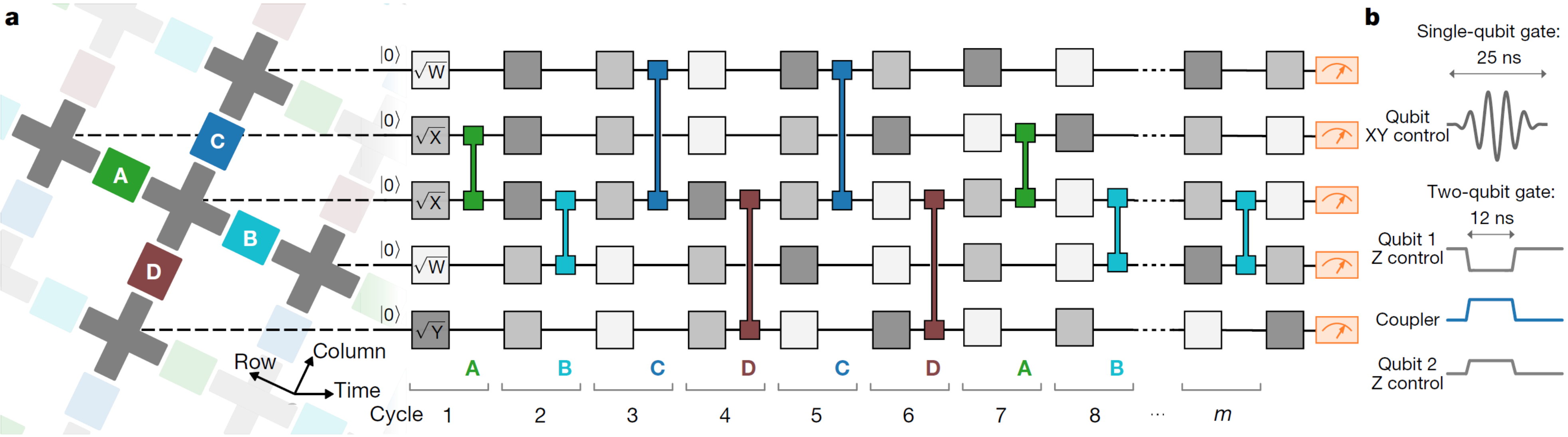
Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%

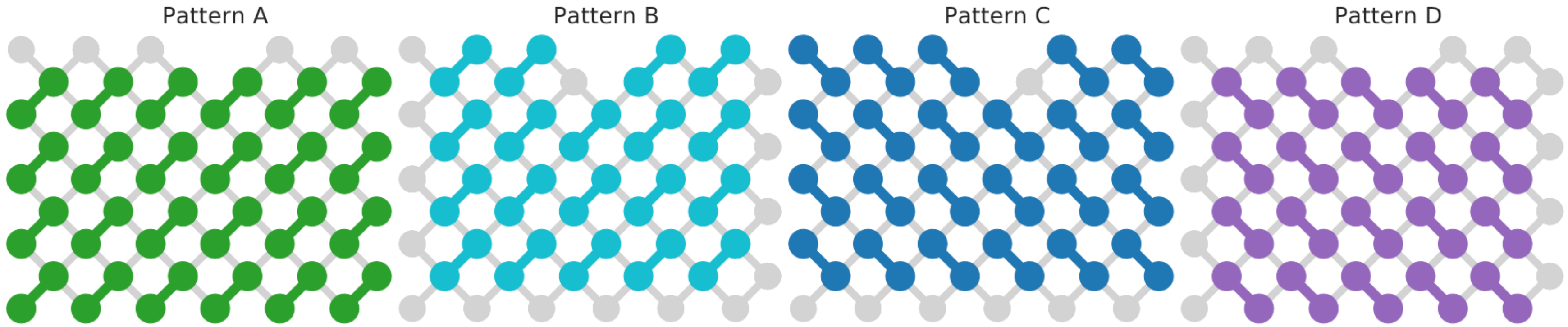




The 2019 Google “quantum supremacy” paper.

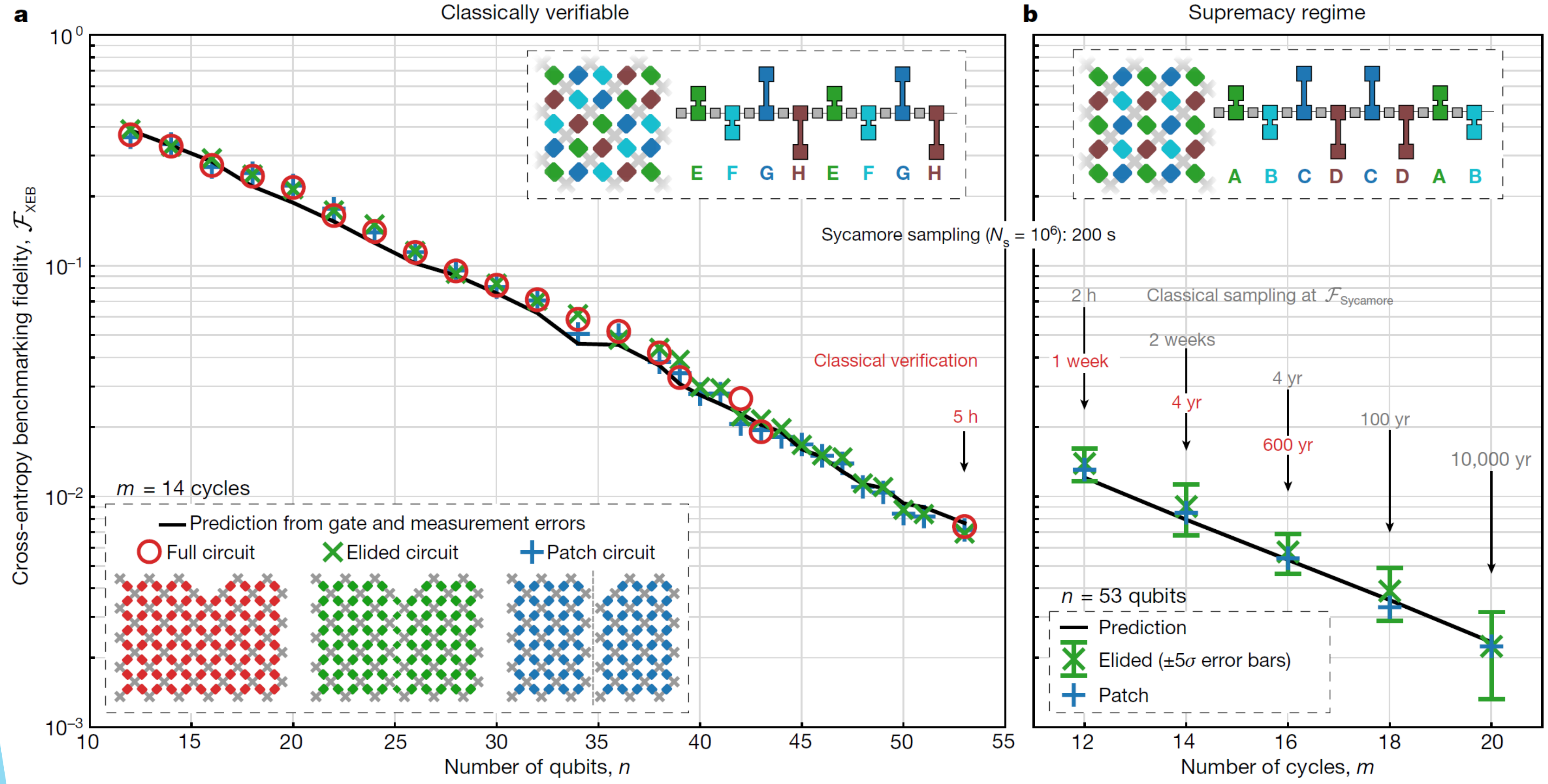
https://www.nature.com/articles/s41586-019-1666-5



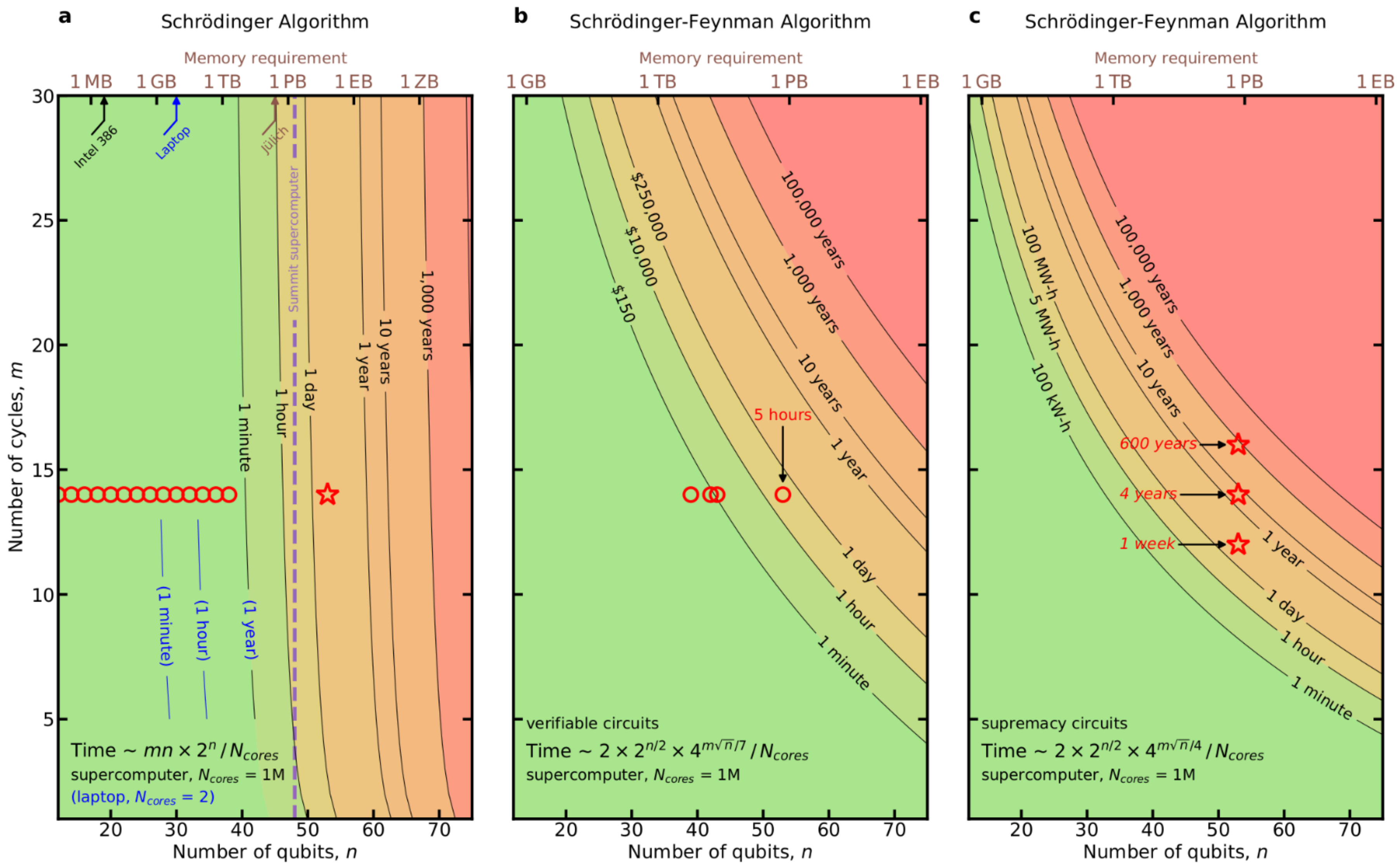


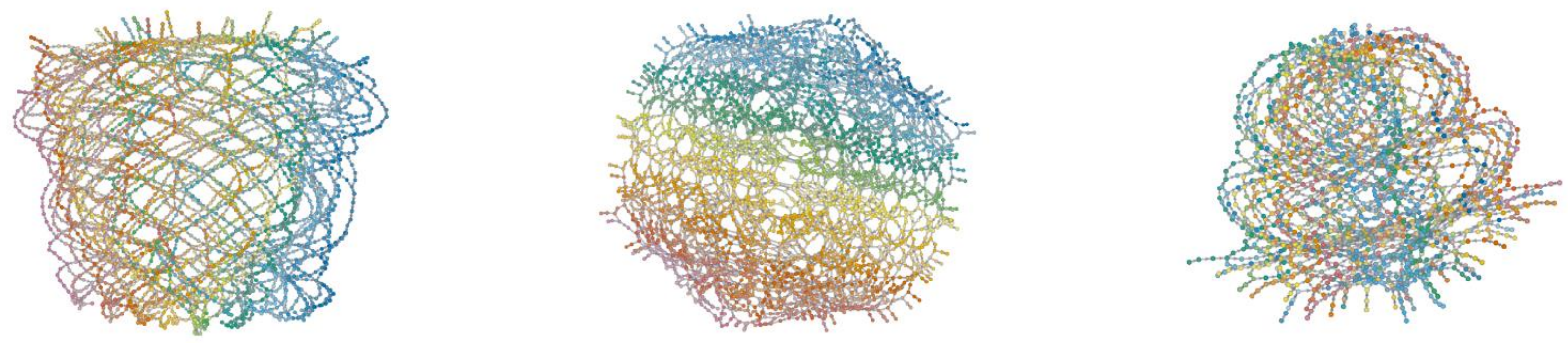
The 2019 Google "quantum supremacy" paper.

https://www.nature.com/articles/s41586-019-1666-5

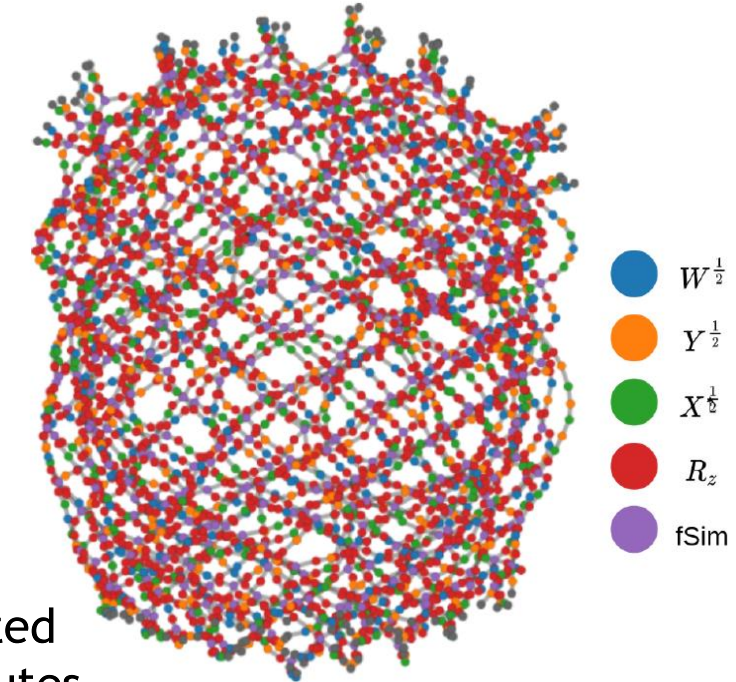


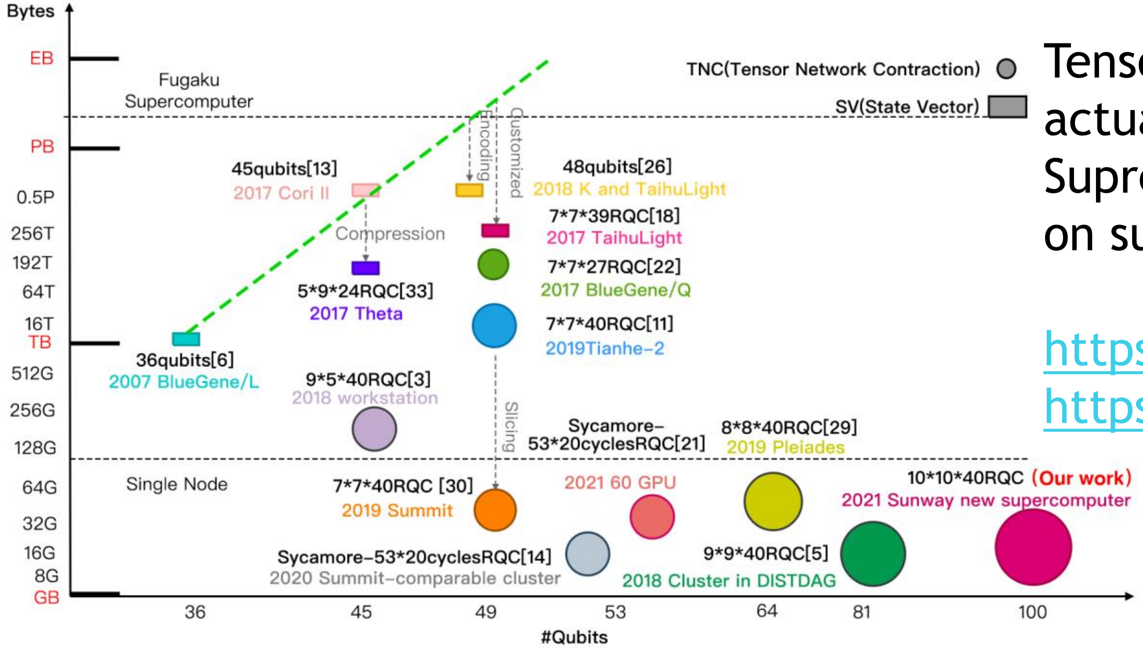
The 2019 Google "quantum supremacy" paper claims that it would take 10k years to simulate their 53-qubits 20-cycle circuits on a supercomputer.





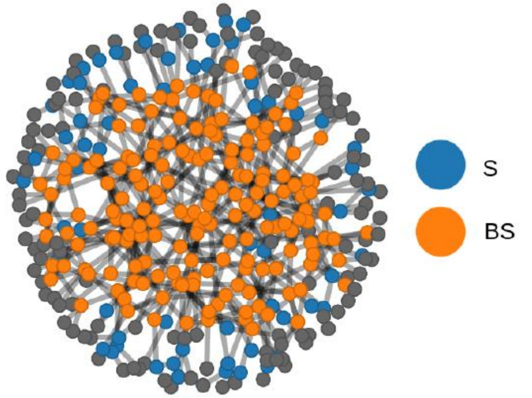
(a) Sycamore (b) 10x10x(1+40+1) (c) Zuchongzhi





Tensor contraction techniques actually allow the Quantum Supremacy circuits to be simulated on supercomputers in a few minutes.

https://arxiv.org/abs/2107.09793
https://arxiv.org/abs/2110.14502



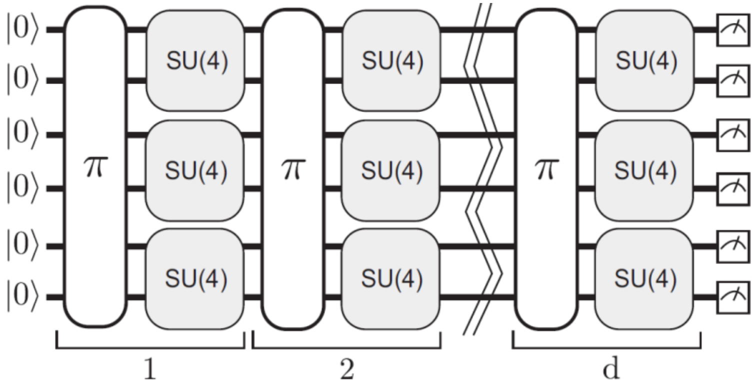
Time needed to sample Sycamore	
our simulation	304 seconds
physical Sycamore [1]	200 seconds
Summit[1]	10,000 years
Summit[25]	2.55 days (estimated)
Ali_Cloud[14]	19.3 days (estimated)
60_GPUs(Pan)[23]	5 days

Circuit	Slices	Max Size	Time (s)
Syc-53-m20	2^{25}	2.7×10^{8}	3.5×10^{1}
Syc-53-m20	0	9.0×10^{15}	1.6×10^{1}
GBS-444-m1	4^{14}	6.7×10^{7}	3.6×10^{2}
GBS-444-m1	0	4.4×10^{12}	1.7×10^{-1}
GBS-666-m1	0	7.9×10^{28}	2.1×10^{14}

IBM uses a metric known as Quantum Volume (QV) to benchmark their quantum computers.

https://arxiv.org/abs/1811.12926

By its definition, the metric appears to grow exponentially: the interesting quantity is $\log_2(QV)$, the size of the largest “square” circuit which generates enough “heavy outputs”.



To define when a model circuit U has been successfully implemented in practice, we use the heavy output generation problem [19]. The ideal output distribution is

$$p_U(x) = |\langle x|U|0\rangle|^2, \qquad (2)$$

where $x \in \{0,1\}^m$ is an observable bit string. Consider the set of output probabilities given by the range of $p_U(x)$ sorted in ascending order $p_0 \leqslant p_1 \cdots \leqslant p_{2^m-1}$. The median of the set of probabilities is $p_{\text{med}} = (p_{2^{(m-1)}} + p_{2^{(m-1)}-1})/2$ and the heavy outputs are

$$H_U = \{x \in \{0,1\}^m \text{ such that } p_U(x) > p_{\text{med}}\}. \qquad (3)$$

The heavy output generation problem is to produce a set of output strings such that more than two-thirds are heavy.

Algorithm 1. Check heavy output generation.

function ISHEAVY$(m, d; n_c \geqslant 100, n_s)$
  $n_h \leftarrow 0$
  for n_c repetitions **do**
    $U \leftarrow$ random model circuit, width m, depth d
    $H_U \leftarrow$ heavy set of U from classical simulation
    $U' \leftarrow$ compiled U for available hardware
    for n_s repetitions **do**
      $x \leftarrow$ outcome of executing U'
      if $x \in H_U$ **then** $n_h \leftarrow n_h + 1$
  return $\frac{n_h - 2\sqrt{n_h(n_s - n_h/n_c)}}{n_c n_s} > \frac{2}{3}$

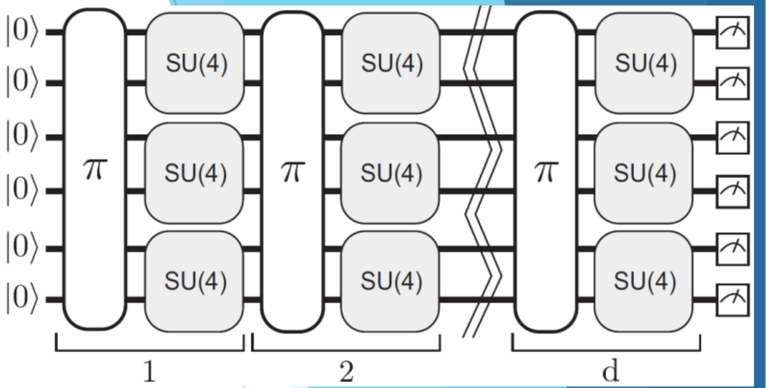
We define the quantum volume V_Q as

$$\log_2 V_Q = \operatorname*{argmax}_m \min(m, d(m))$$

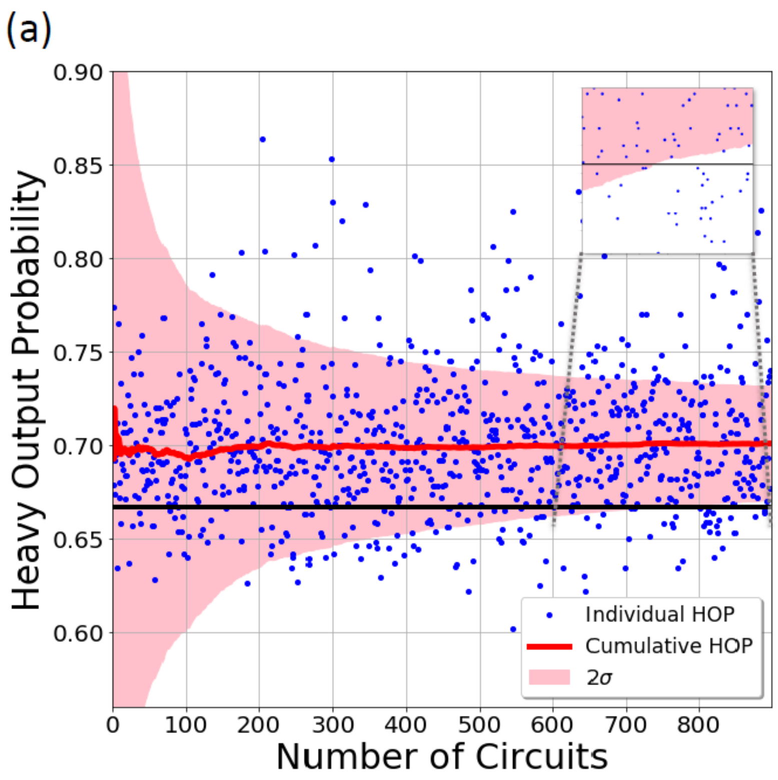
and take this definition going forward.

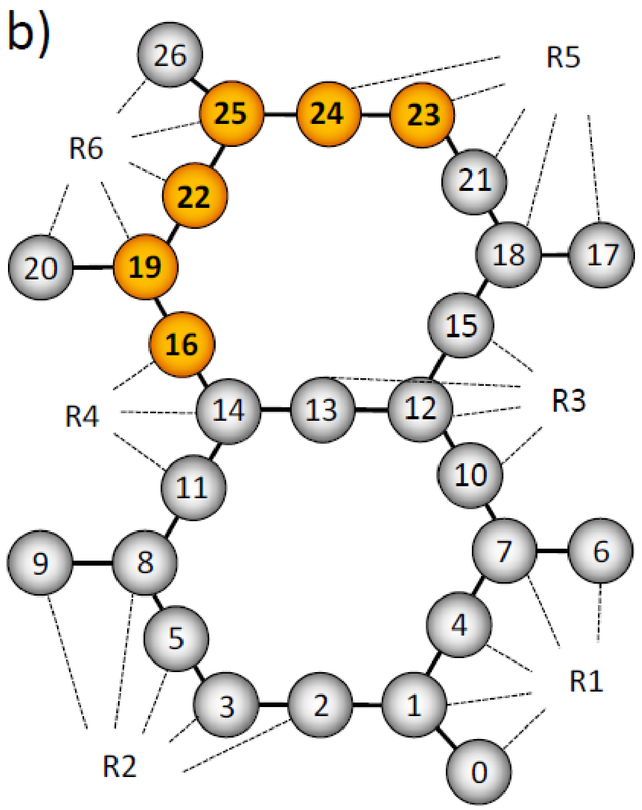
Name		Qubits	QV
ibmq_montreal		27	128
ibmq_mumbai	Exploratory	27	128
ibm_cairo		27	64
ibm_auckland	Exploratory	27	64
ibmq_toronto		27	32
ibmq_guadalupe		16	32
ibm_perth		7	32
ibm_lagos		7	32
ibm_nairobi		7	32
ibmq_jakarta		7	16
ibmq_manila		5	32
ibmq_bogota		5	32
ibmq_santiago		5	32
ibmq_quito		5	16
ibmq_belem		5	16
ibmq_lima		5	8

A 2020 paper verifying QV 64 (i.e. $\mathrm{HOP} > \frac{2}{3}$ on 6 qubits with depth $\mathrm{d} = 6$) to a confidence of 2σ for the 27-qubit device IBMQ Montreal (currently at QV 128).



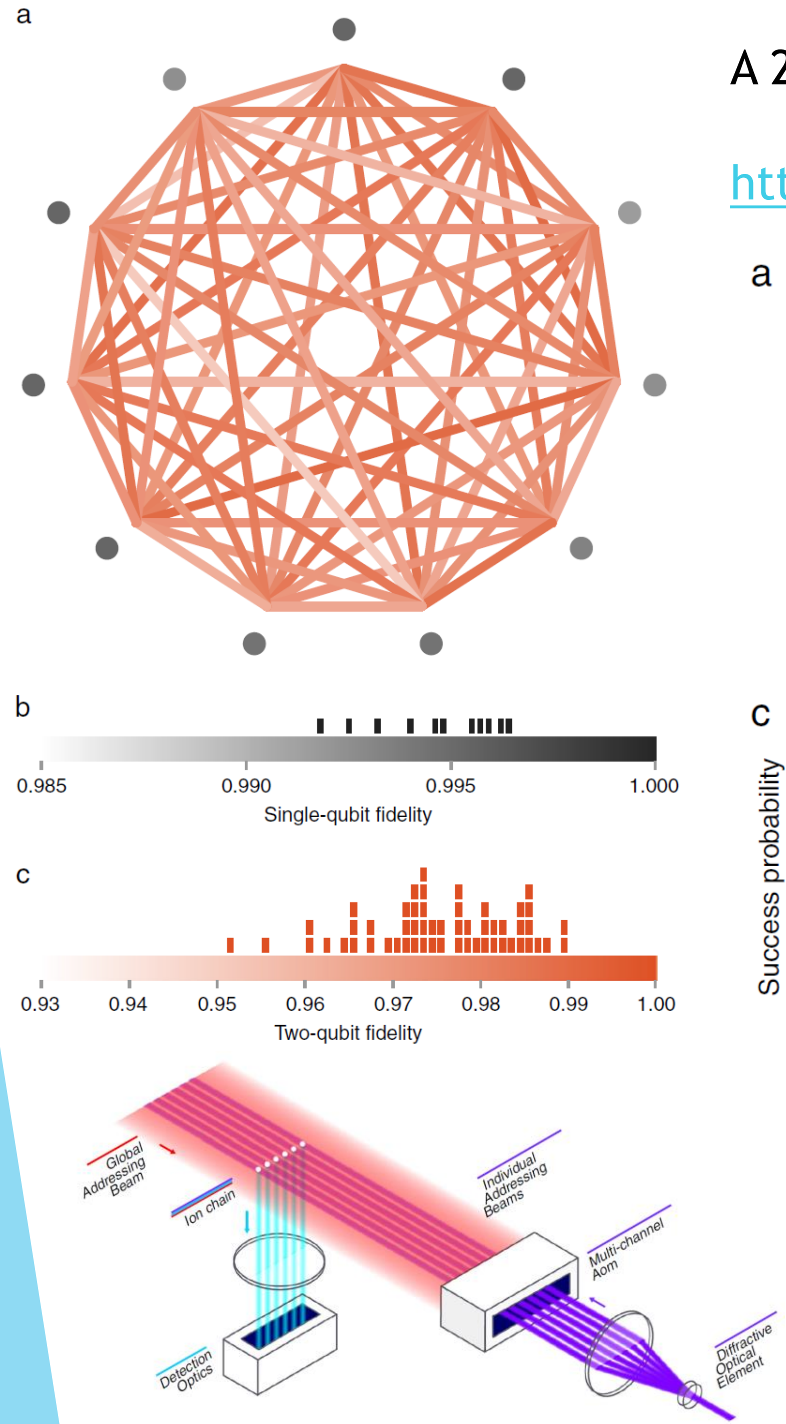
https://arxiv.org/abs/2008.08571

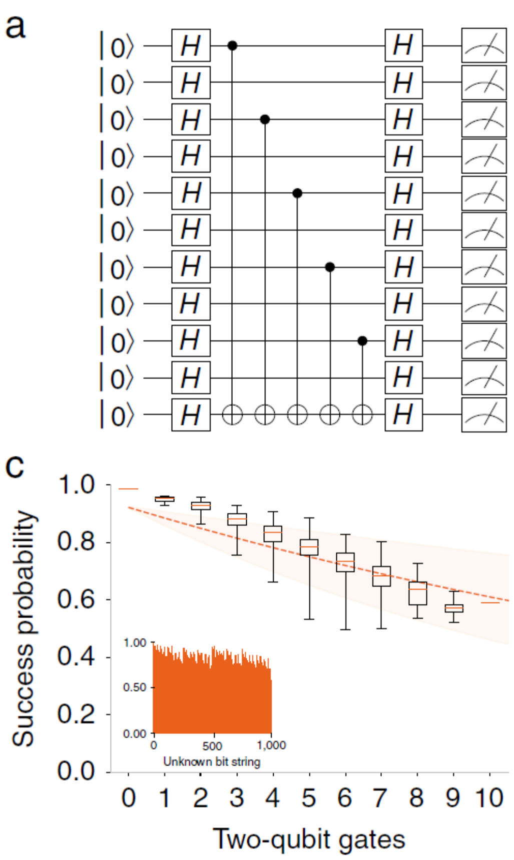




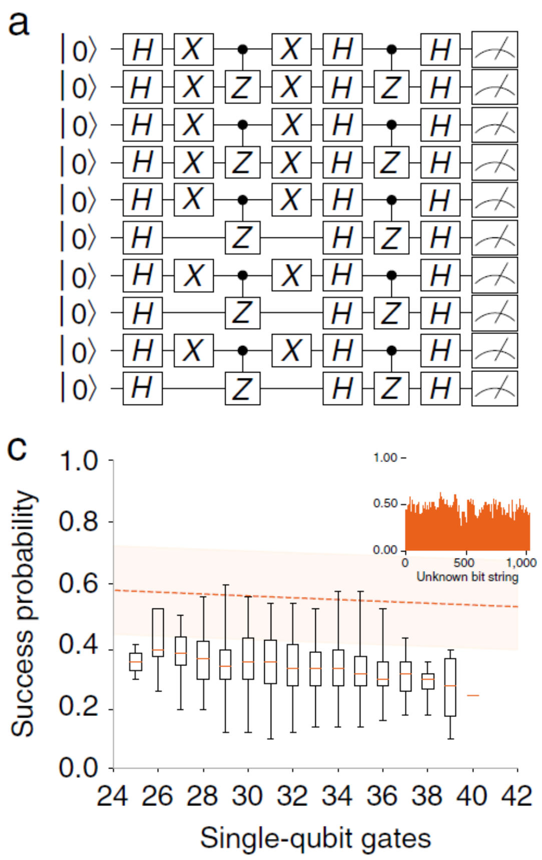
A 2020 IonQ paper benchmarking an 11-qubit ion trap.

https://www.nature.com/articles/s41467-019-13534-2





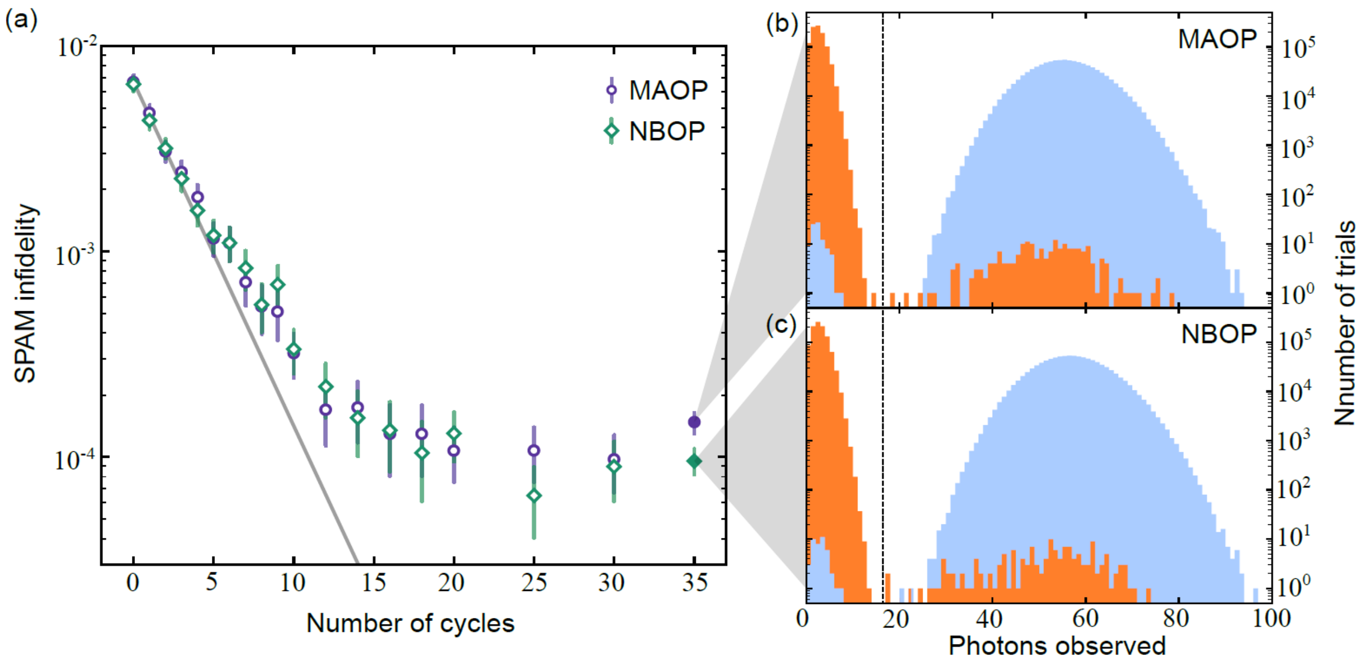
Bernstein-Vazirani



Hidden Shift

A 2022 Quantinuum paper benchmarking State Preparation And Measurement (SPAM) fidelity in their ion trap quantum computers, using two optical pumping techniques (MAOP and NBOP) to reduce state preparation errors to around 0.1%, the approximate threshold for some interesting error correction schemes.

https://arxiv.org/abs/2203.01920

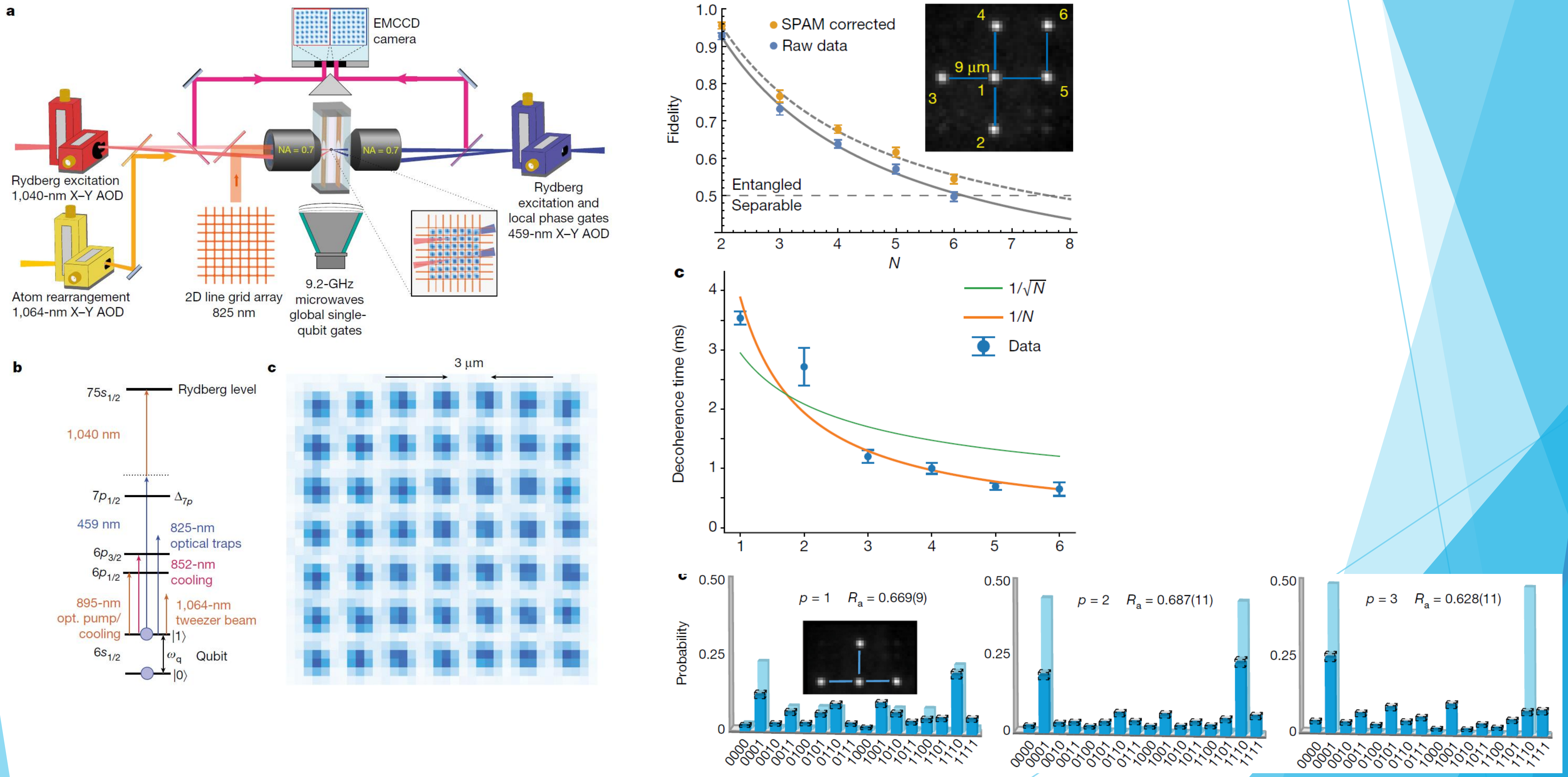


Error Source	Error ($\times10^{-5}$)	
	$\|0\rangle$ State	$\|1\rangle$ State
$\|0\rangle$ state preparation	<9.1	—
$\|0\rangle \to \|1\rangle$ transfer	—	5.4 ± 0.5
Shelving infidelity	~0.1	—
$D_{5/2}$ decay	~1.5	—
Correlated errors	4.0	—
Subtotal (measured)	14.7 ± 2.4	4.2 ± 1.3
Total (measured)	9.6 ± 1.4	

On the right: vertical bar is the threshold separating the |0⟩ and |1⟩ states. Histogram of |0⟩ state preparation in orange, histogram of |1⟩ state preparation in blue.

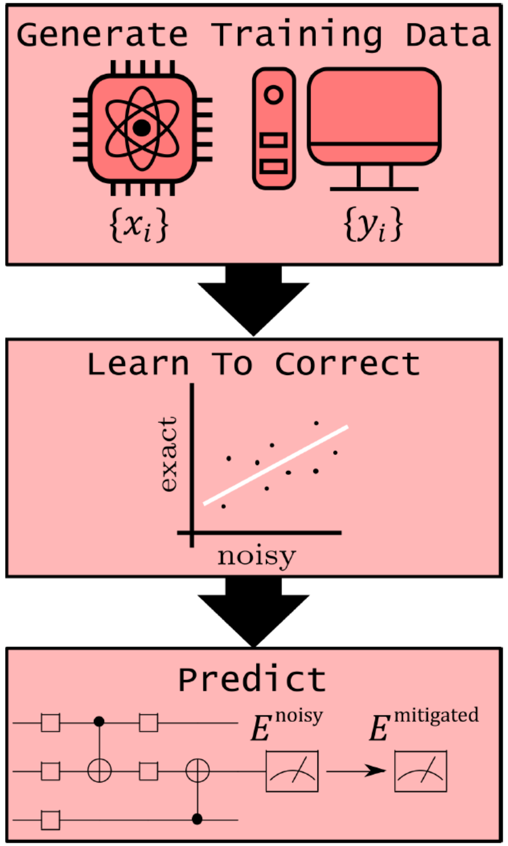
A 2022 paper benchmarking highly entangled GHZ states on 6 qubits in a neutral atom quantum computer.

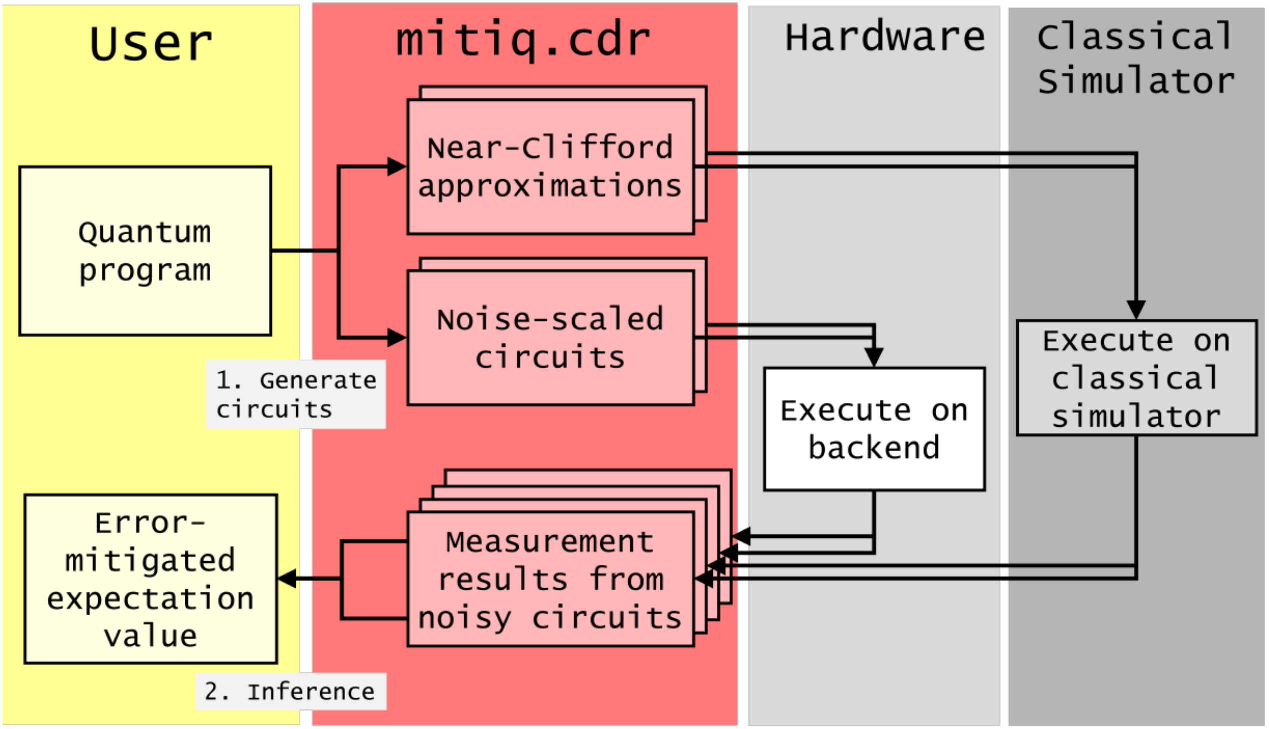
https://www.nature.com/articles/s41586-022-04603-6



2020 paper introducing an error mitigation library for NISQ computations.

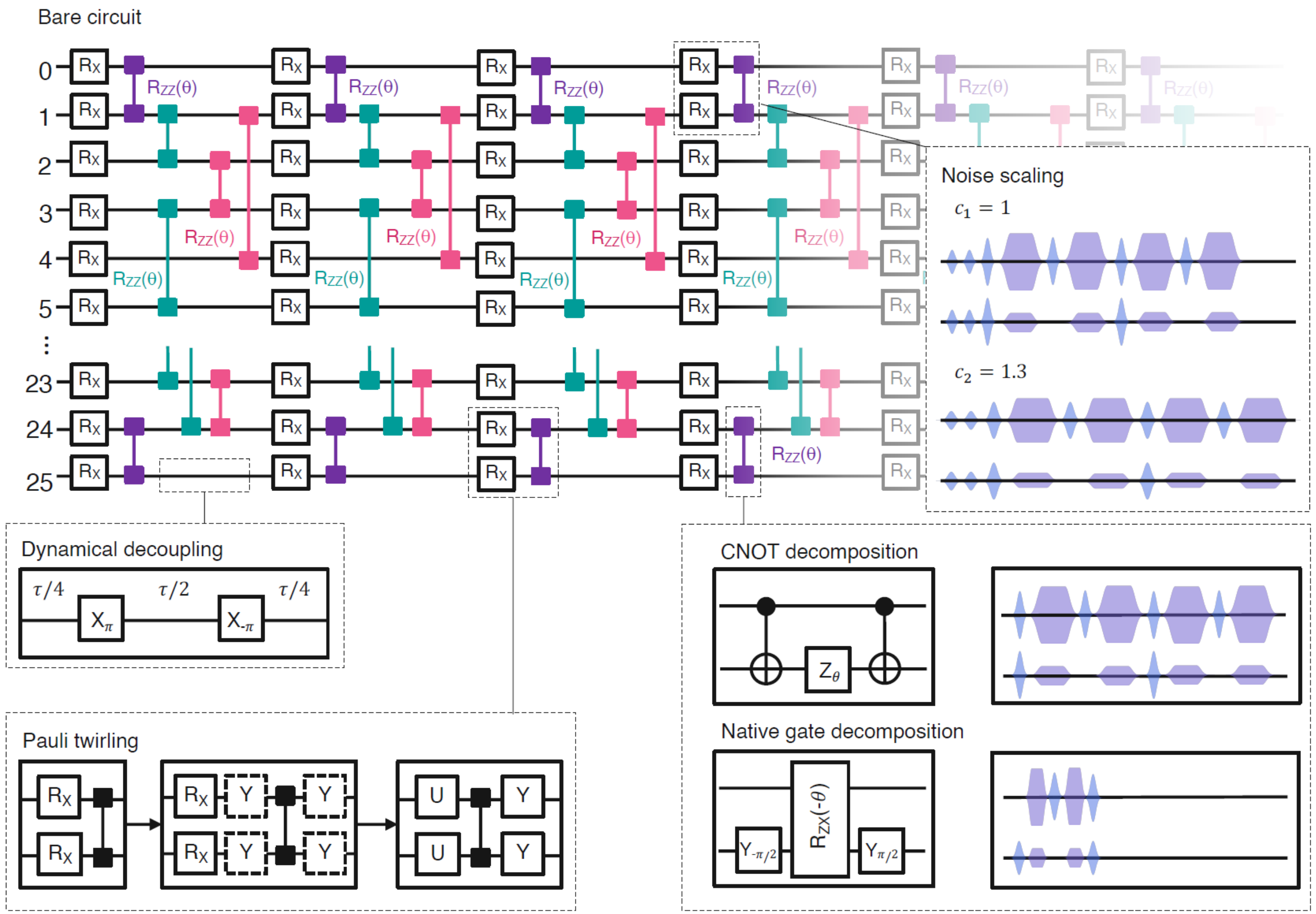
https://arxiv.org/abs/2009.04417



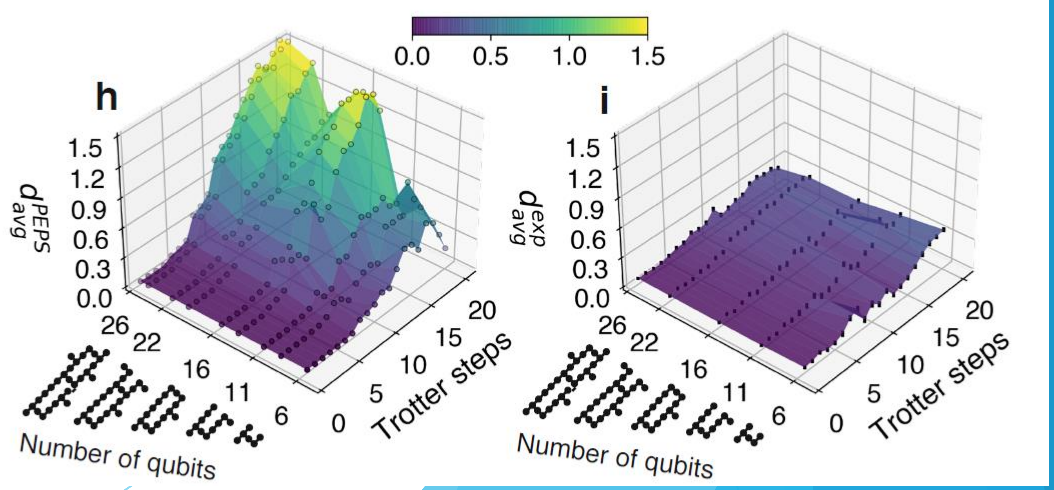


A 2021 error mitigation paper by IBM. Noise scaling is used to extrapolate noise profiles, dynamical decoupling to reduce dephasing, Pauli twirling to average-out coherent errors and native decomposition to reduce the total circuit execution time (and hence the noise).

https://arxiv.org/abs/2108.09197

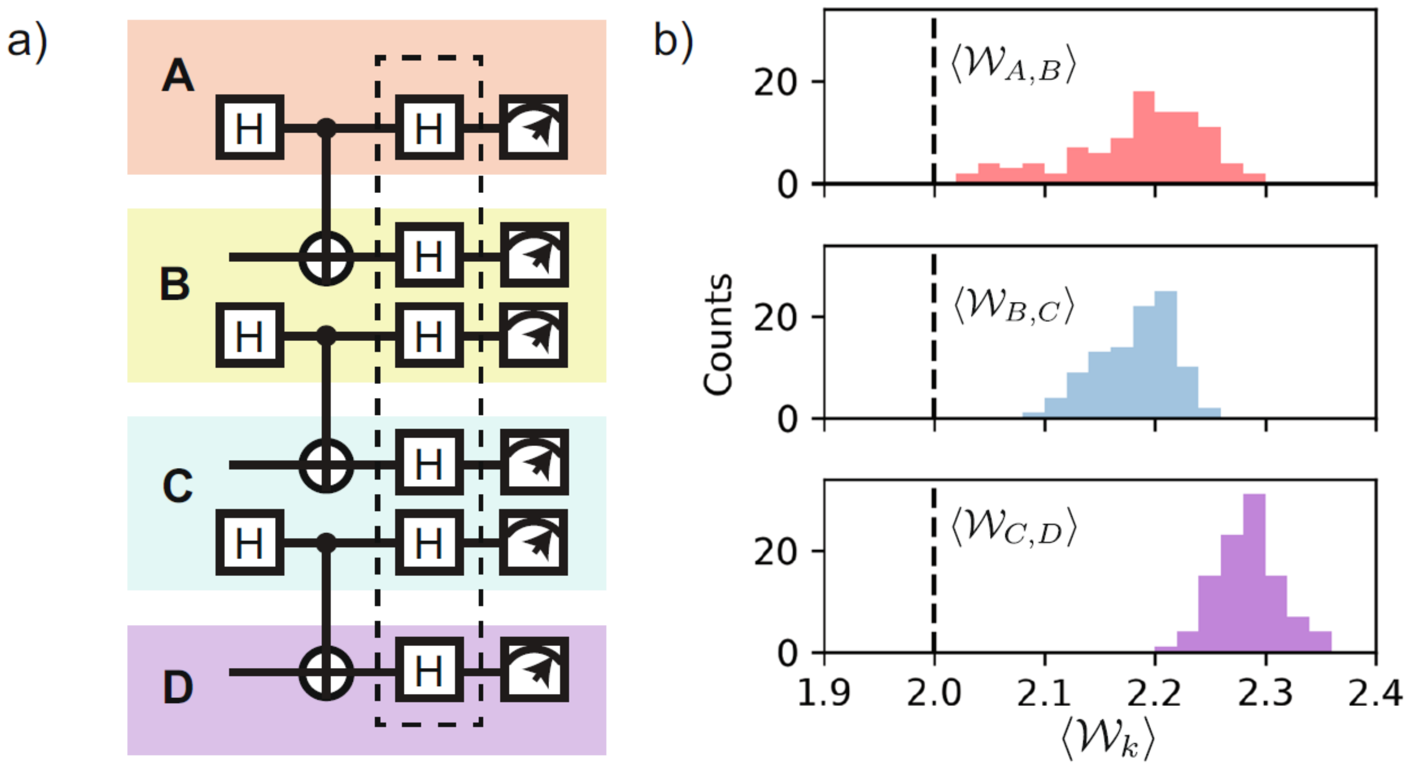


Below: simulation error for quench dynamics of 2D Ising spin lattices, as a function of size and number of simulation steps. Standard technique (left) versus error mitigation (right).

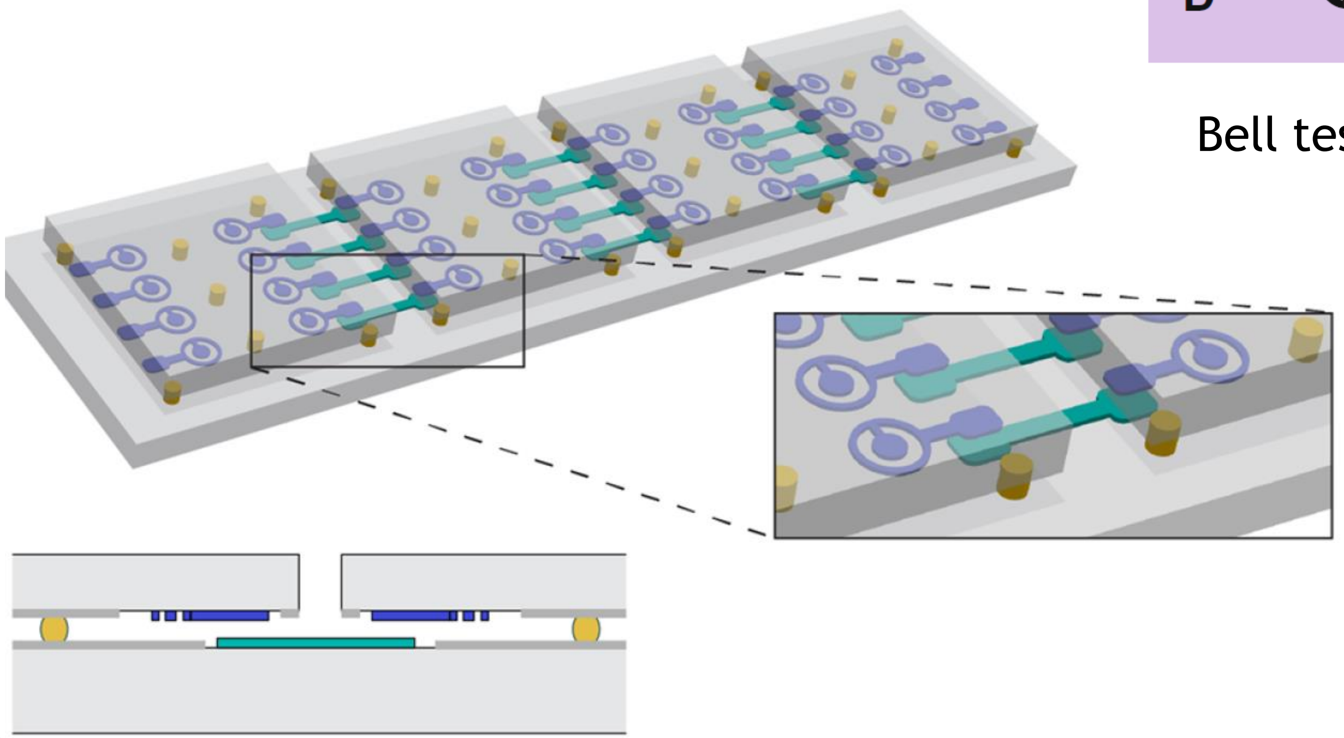


A 2021 Rigetti paper benchmarking entanglement in a multi-chip quantum processor.

https://arxiv.org/abs/2102.13293



Bell test across 4 chips: W above 2 => entanglement.



IBM proposals for multi-chip quantum processors

https://research.ibm.com/blog/ibm-quantum-roadmap-2025