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Technische Universität München

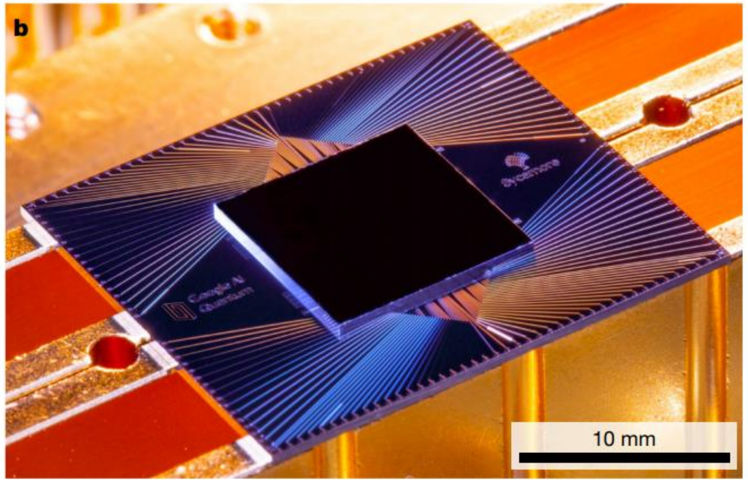
Martinis et al.: Quantum supremacy using a programmable superconducting processor (23.10.2019)

19.05.2020

Philipp Krüger

Outline

- Basic Concepts
  - Qubit Gates
  - Transmon
  - Dispersive Readout
  - Coupling
- Sycamore Chip
- Cross Entropy Benchmarking
- Gate Benchmarking
- Demonstration of Quantum Supremacy
- Discussion



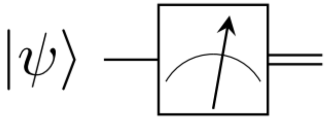
Martinis et al., 10.1038/s41586-019-1666-5 (2019)

Qubit vs Bit

Classical Bit: 0, 1

Quantum bit „qubit“: normalized superposition of 0 and 1 described as

$$|\psi\rangle := \alpha\,|0\rangle + \beta\,|1\rangle = \begin{pmatrix}\alpha \\ \beta\end{pmatrix}; \quad |\alpha|^2 + |\beta|^2 = 1.$$



$$\begin{cases} 0 & \text{with probability } |\alpha|^2 \\ 1 & \text{with probability } |\beta|^2 \end{cases}$$

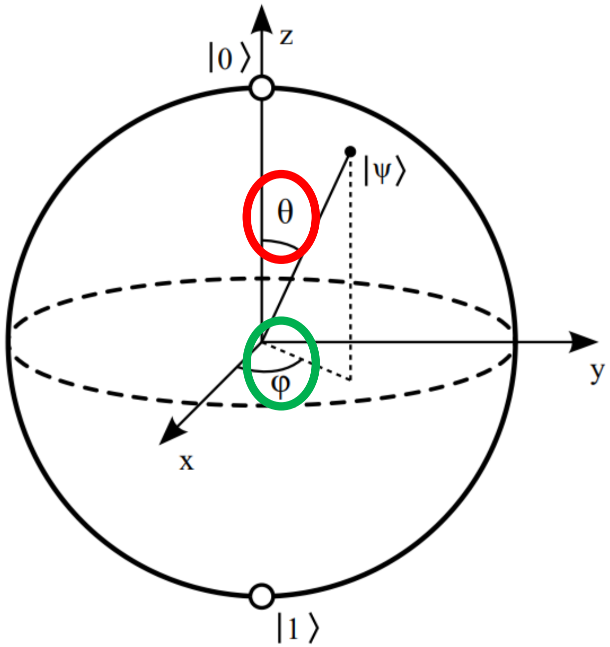
Bloch sphere representation:

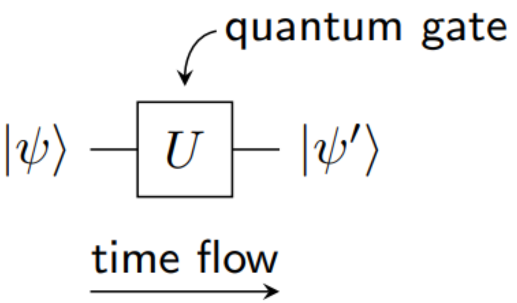
Amplitude ~ Population

$$\alpha = \mathrm{e}^{i\gamma}\cos\frac{\theta}{2},$$

$$\beta = \mathrm{e}^{i(\gamma+\varphi)}\sin\frac{\theta}{2}$$

Phase ~ Coherence

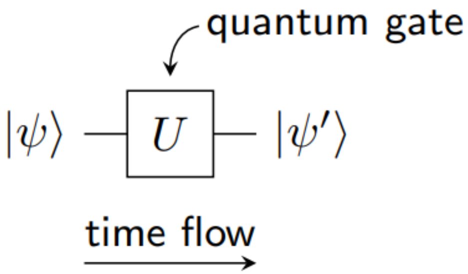


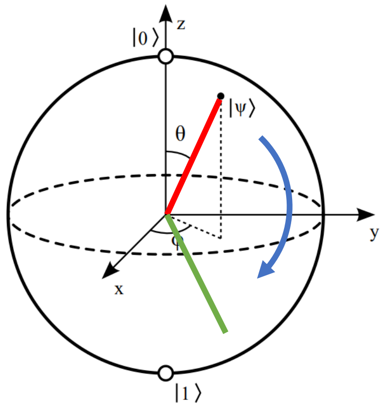


$$|\psi'\rangle = U|\psi\rangle = \begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix}\alpha \\ \beta\end{pmatrix} = \begin{pmatrix} a\alpha + b\beta \\ c\alpha + d\beta \end{pmatrix}$$

Nielsen, Chuang: Quantum Computation and Quantum Information (2010)

NOT-Gate $|0\rangle \leftrightarrow |1\rangle$



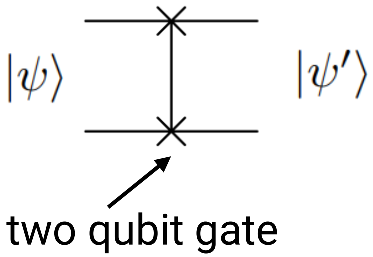


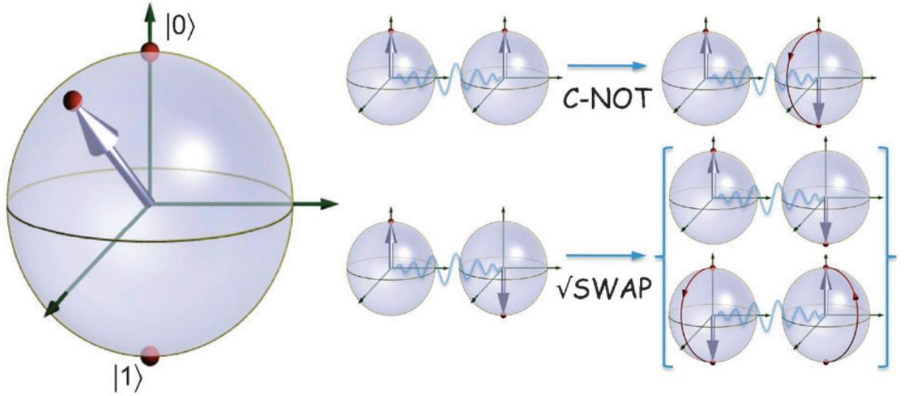
$$X \equiv \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$X|0\rangle = \left(\begin{smallmatrix} 0 & 1 \\ 1 & 0 \end{smallmatrix}\right)\left(\begin{smallmatrix} 1 \\ 0 \end{smallmatrix}\right) = \left(\begin{smallmatrix} 0 \\ 1 \end{smallmatrix}\right) = |1\rangle$$

iSWAP gate

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$$



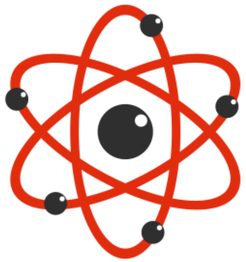


$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \alpha_{00} \\ \alpha_{01} \\ \alpha_{10} \\ \alpha_{11} \end{pmatrix} = \begin{pmatrix} \alpha_{00} \\ i\alpha_{10} \\ i\alpha_{01} \\ \alpha_{11} \end{pmatrix}$$

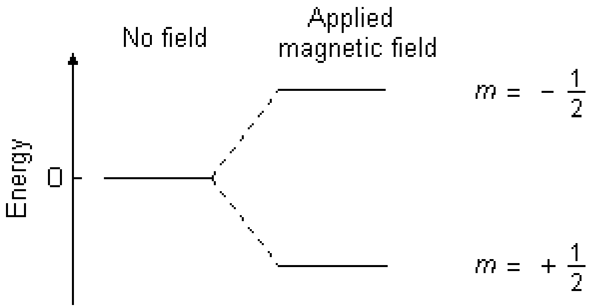
Nielsen, Chuang, Quantum Computation and Quantum Information (2010)

Qubit Realisation

Atom: hard to handle, no design flexibility



Energy levels for a nucleus with spin quantum number 1/2



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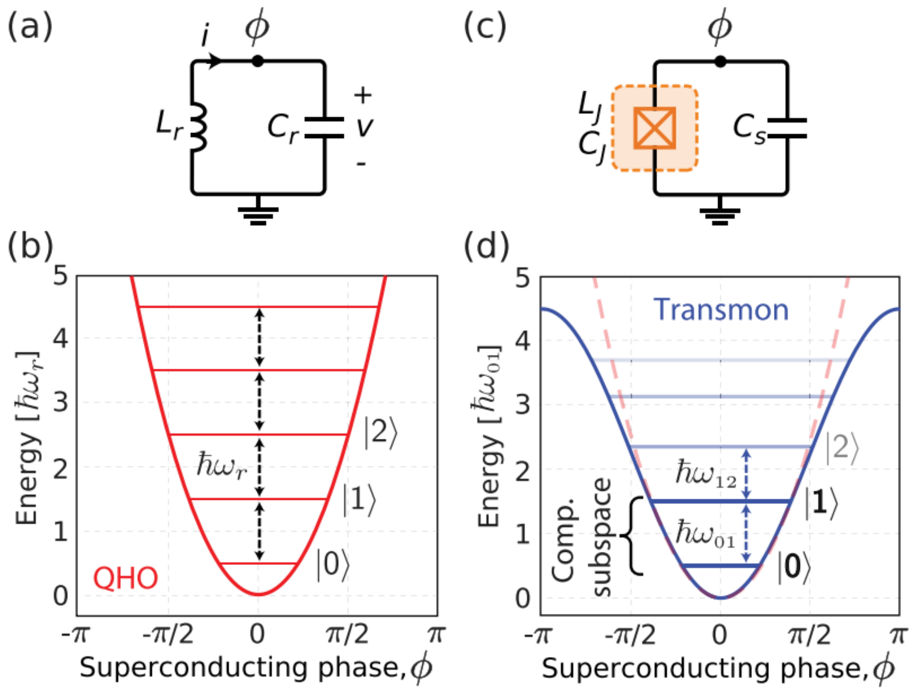
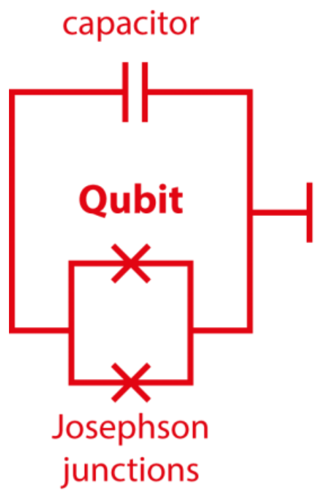
Engineered Circuit: easier to maintain, tunable parameters



Krantz et al., 10.1063/1.5089550 (2019)

What is a Transmon?



Potential

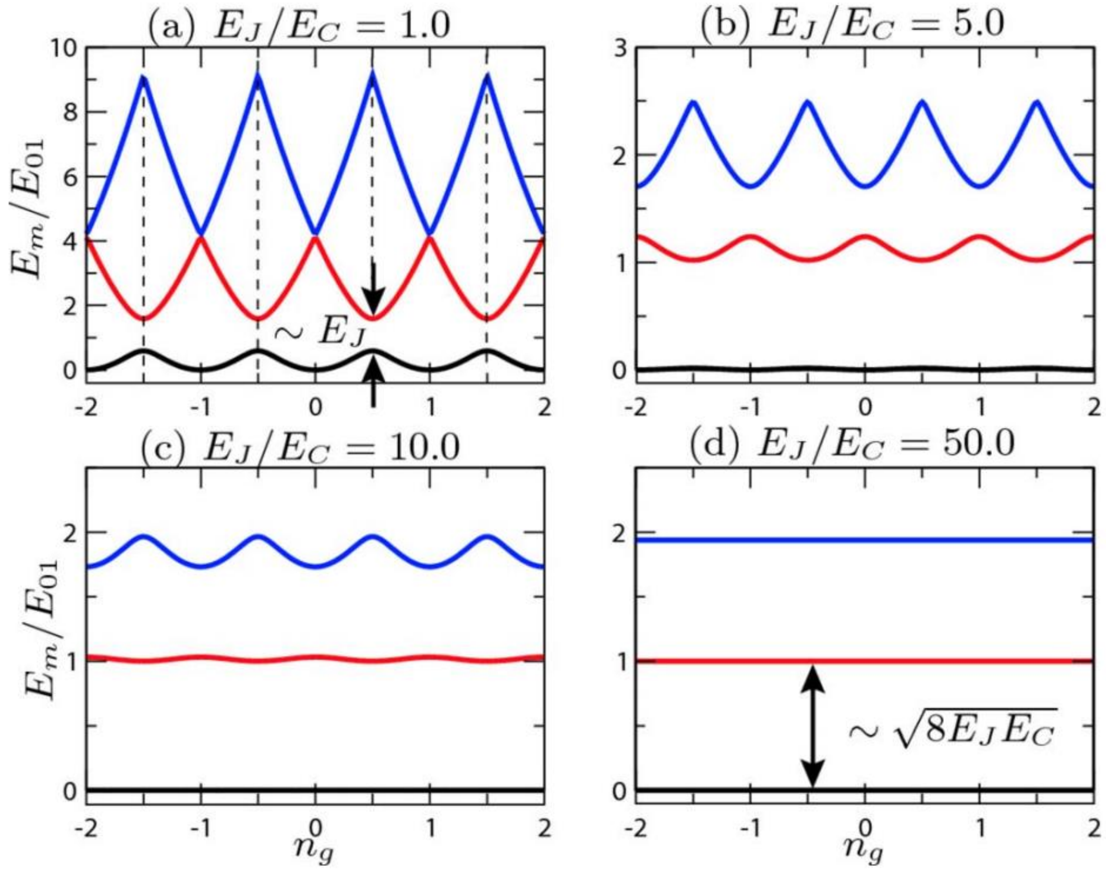
$$\underbrace{E_C = e^2/2C_\Sigma}$$

Kinetic

$$\int_0^t V(t)I(t)dt = \underbrace{\frac{\hbar}{2e}\int I_c \sin\phi \, d\phi}$$

$$\mathcal{H} = 4E_C\,(n - n_g)^2 - E_J \cos\delta$$

- JJ for nonlinear Hamiltonian
- Optimize Harmonicity vs charge offset impact



Schoelkopf et al., 10.1103/76.042319 (2007)

Dispersive Readout

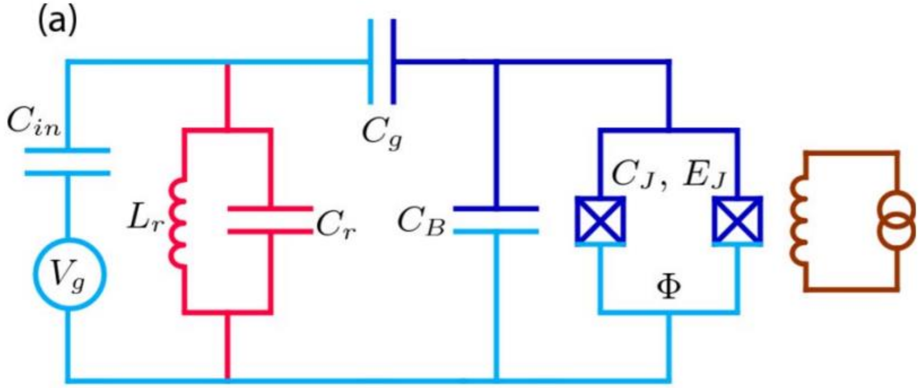
$$\hat{H}_{JC} = \underbrace{\hbar\omega_q\hat{\sigma}^+\hat{\sigma}^-}_{\text{Transmon}} + \underbrace{\hbar\omega_r\hat{a}^\dagger\hat{a}}_{\text{Resonator}} + \underbrace{\hbar g(\hat{a}^\dagger\hat{\sigma}^- + \hat{\sigma}^+\hat{a})}_{\text{Interaction}}$$

(a) Assume strong detuning ➔ AC Stark Shift
(b) Schrieffer-Wolf-Transformation
(c) Neglect higher order terms

$$\hat{H}^{(2)} = \hbar(\underbrace{\omega_r + \frac{g^2}{\delta}\hat{\sigma}_z}_{\text{AC Stark Shift}})\hat{a}^\dagger\hat{a} + \frac{\hbar}{2}\underbrace{(\omega_q + \frac{g^2}{\delta})}_{\text{Lamb Shift}}\hat{\sigma}_z$$

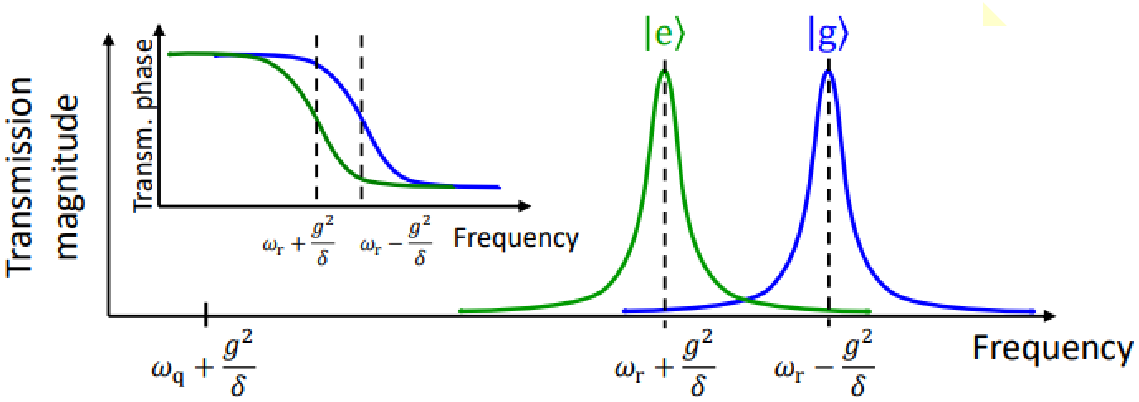
$\delta = \omega_r - \omega_q$ Detuning

(a)



Schoelkopf et al., 10.1103/76.042319 (2007)

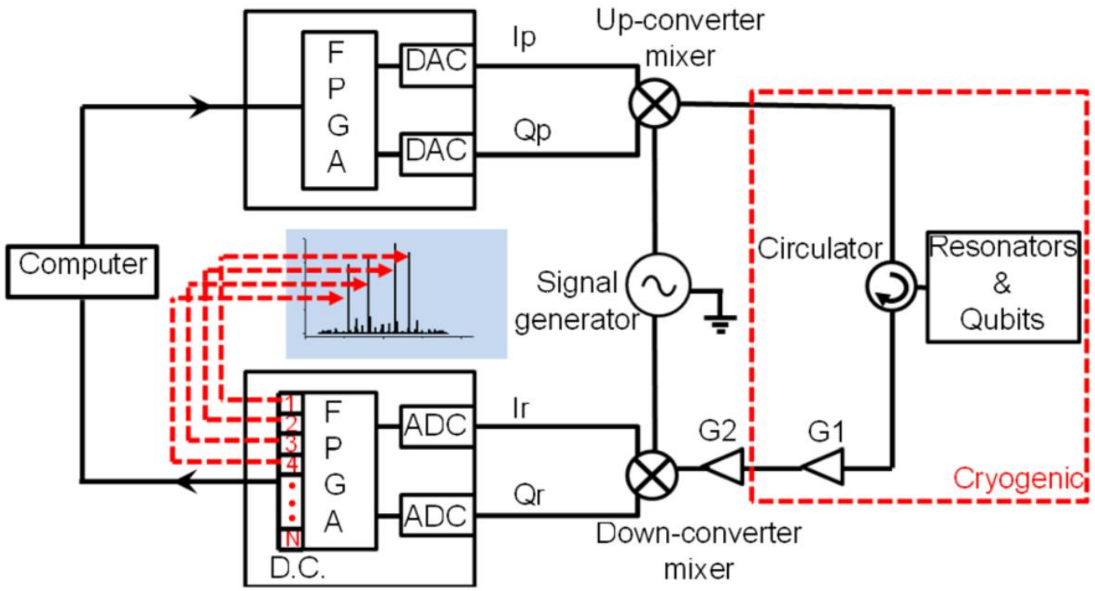
(b)



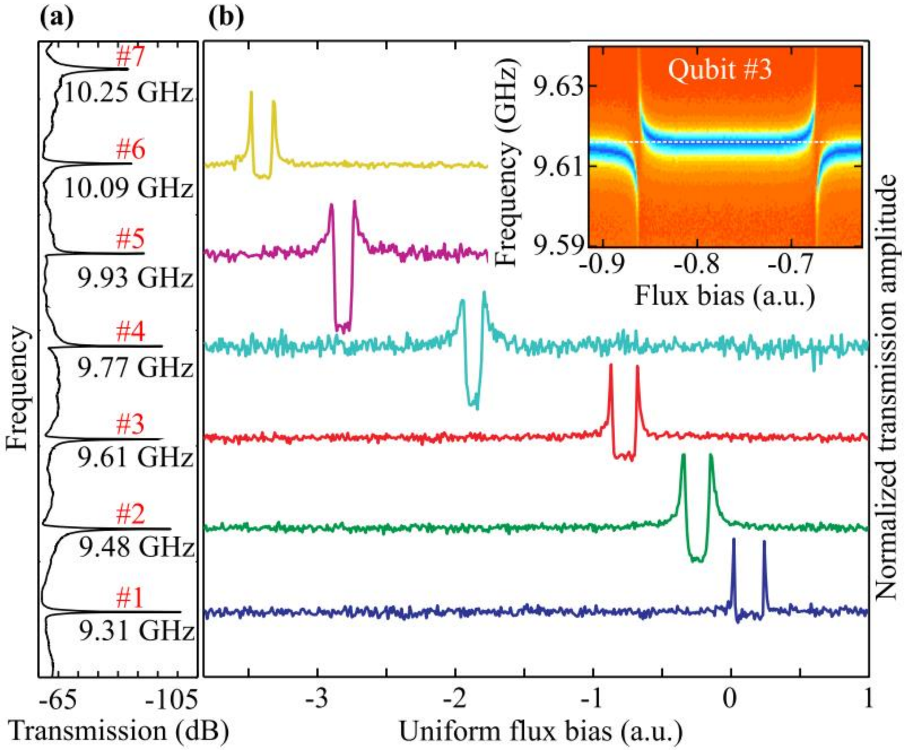
Gross et al., Appl. Superc. Lecture (2005)

Multiplexed dispersive readout

Inject multiple microwave tones that minimize transition probability
→ readout resonators at different frequencies

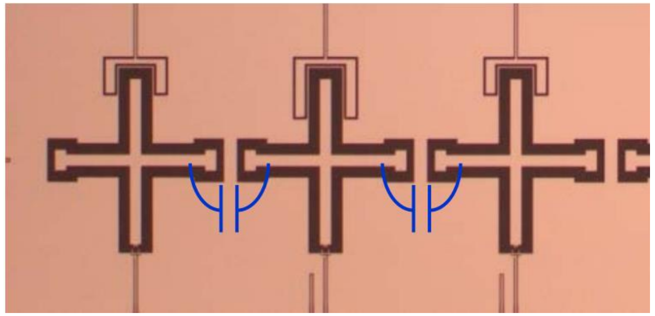


Chen et al., 10.1063/1.4764940 (2012)

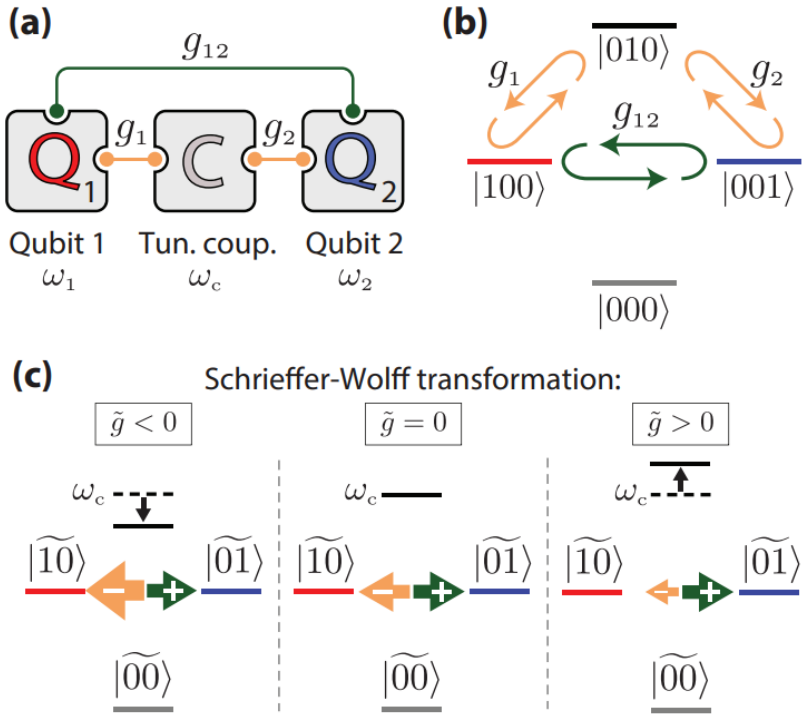


Jerger et al., 10.1063/1.4739454 (2012)

Tunable Couplers



Martinis, Design of a Superc. Qu. Comp. Lecture (2014)



Yan et al., arXiv:1803.09813 (2018)

$$H = \sum_{j=1,2} \frac{1}{2}\omega_j \sigma_j^z + \frac{1}{2}\omega_c \sigma_c^z + \sum_{j=1,2} g_j \left(\sigma_j^+ \sigma_c^- + \sigma_j^- \sigma_c^+\right) + g_{12}\left(\sigma_1^+ \sigma_2^- + \sigma_2^- \sigma_1^+\right), \quad (1)$$

$\Downarrow$ Interaction picture + strongly detuned regime

$$\widetilde{H} = \sum_{j=1,2} \frac{1}{2}\widetilde{\omega}_j \sigma_j^z + \underbrace{\left[\frac{g_1 g_2}{\Delta} + g_{12}\right]\left(\sigma_1^+ \sigma_2^- + \sigma_2^- \sigma_1^+\right)}_{\text{Effective Qubit coupling}}, \quad (2)$$

$$\Delta_j \equiv \omega_j - \omega_c < 0,$$

$$\widetilde{\omega}_j = \omega_j + \frac{g_j^2}{\Delta_j} \quad \text{Lamb-shifted qubit frequency}$$

What is Quantum Supremacy?

"[…] demonstrating that a programmable quantum device can solve a problem that no classical computer can feasibly solve."

Preskill, arXiv:1203.5813 (2012)

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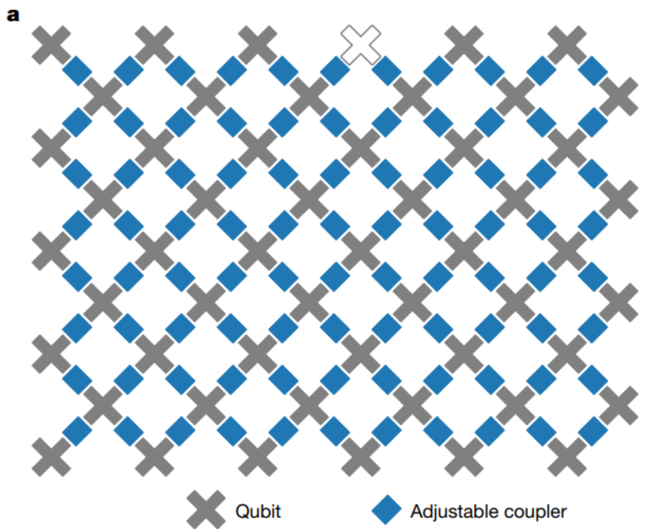
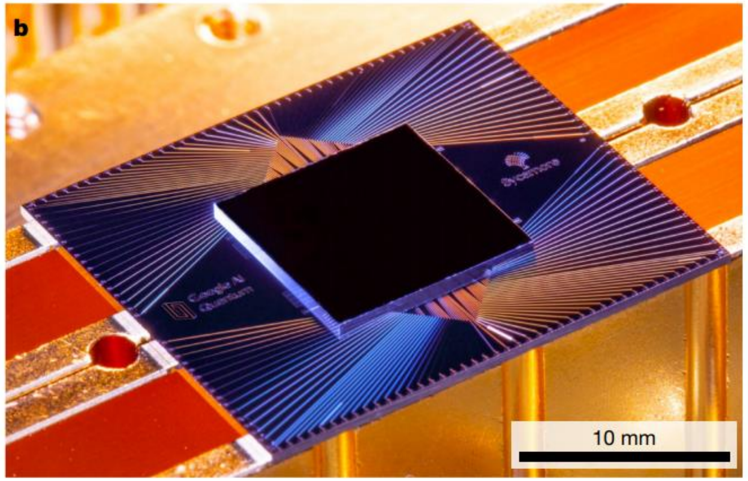
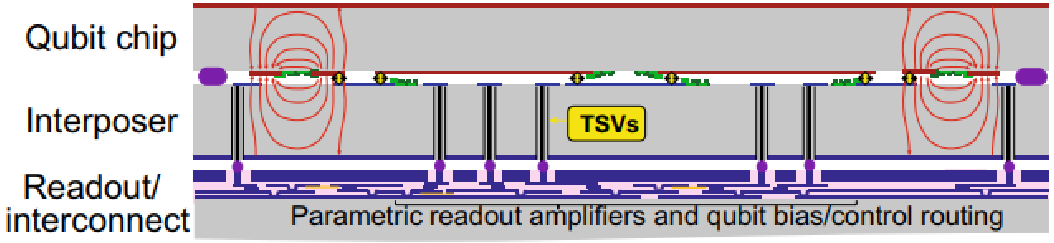
Sycamore Chip Layout





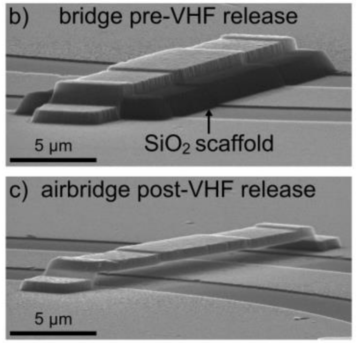
Martinis et al., 10.1038/s41586-019-1666-5 (2019)

Crosstalk Interposer using Indium bump bonding



Rosenberg et al., 10.1038/s41534-017-0044-0 (2017)

Low loss Aluminum Air Bridges



Dunsworth et al. 10.1063/1.5014033 (2017)

Cross Entropy Benchmarking (XEB)

Sampled bitstrings, {0000101, 1011100, …}.

➔ speckled intensity pattern

➔ some bitstrings are much more likely than others.

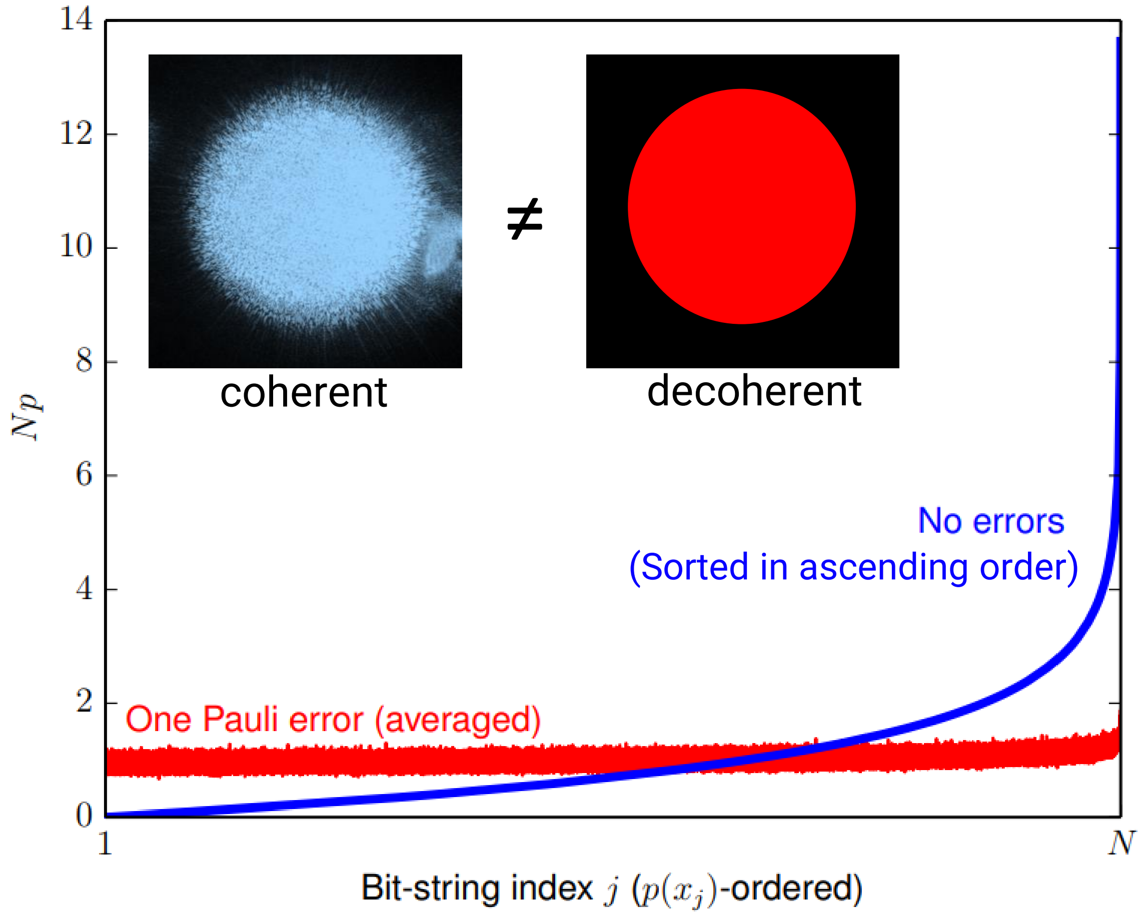
$$\mathcal{F}_{\mathrm{XEB}} = 2^n \langle P(x_i) \rangle_i - 1$$

$P(x_i)$ probability of bitstring x_i

$\{x_i\}$ measured bitstrings

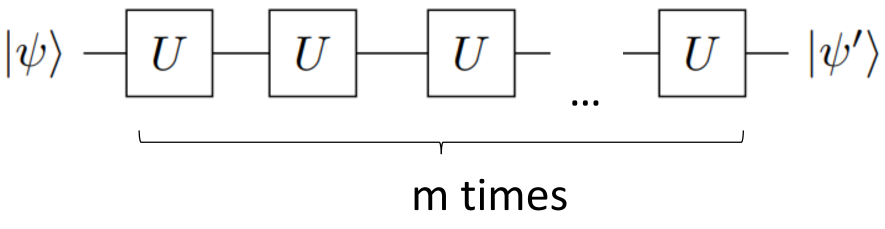
Martinis et al., 10.1038/s41586-019-1666-5 (2019)

Porter Thomas Distribution



Boixo et al., arXiv:1608.00263 (2017)

Pauli Gate Error



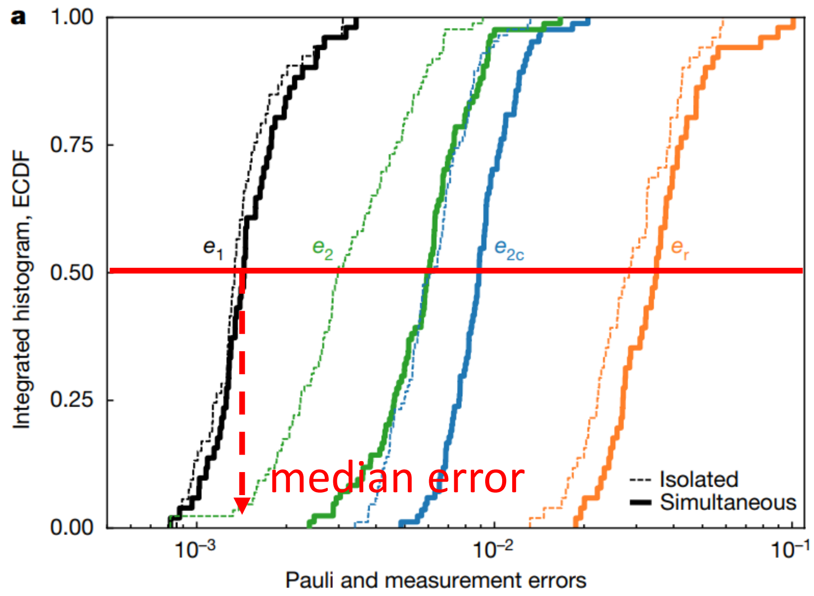
Fit the model

$$\mathcal{F}_{XEB} = \left(1 - e_1/(1 - 1/D^2)\right)^m$$

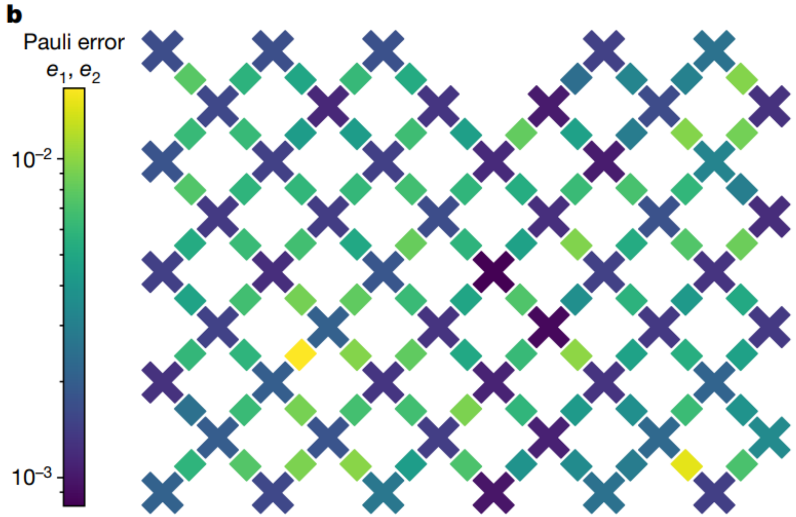
e_1 Pauli error probability

$D = 2^n$ Hilbert space dimension, n states

m Number of gates



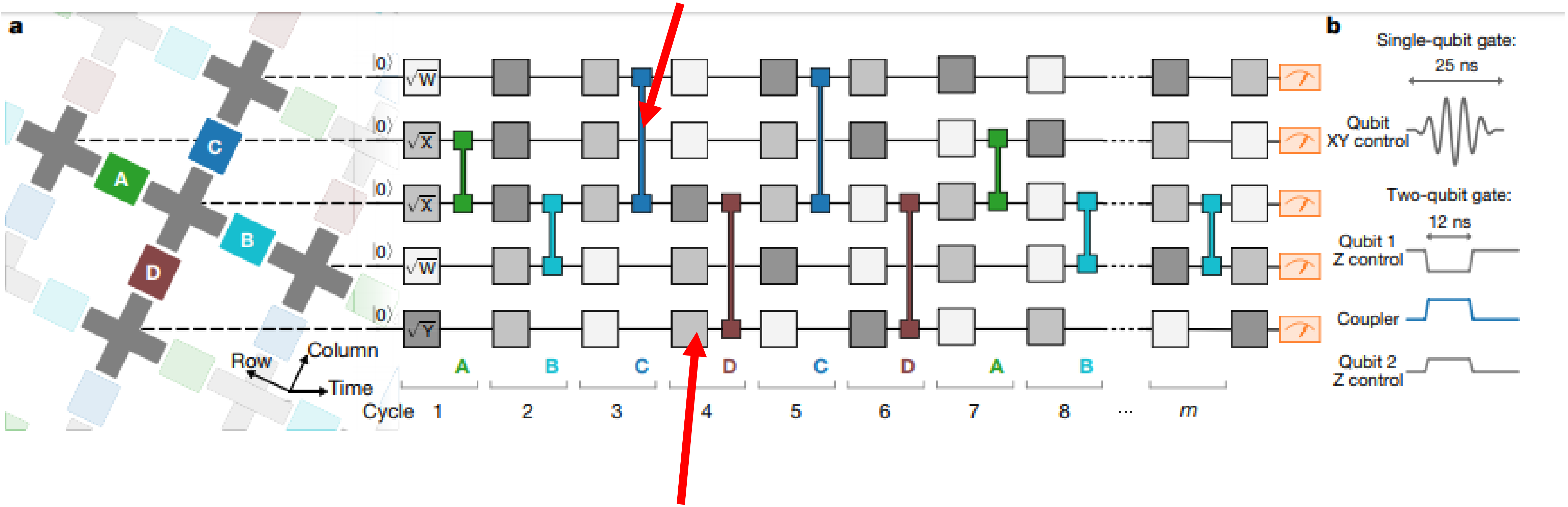
Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



Martinis et al., 10.1038/s41586-019-1666-5 (2019)

What is the program?

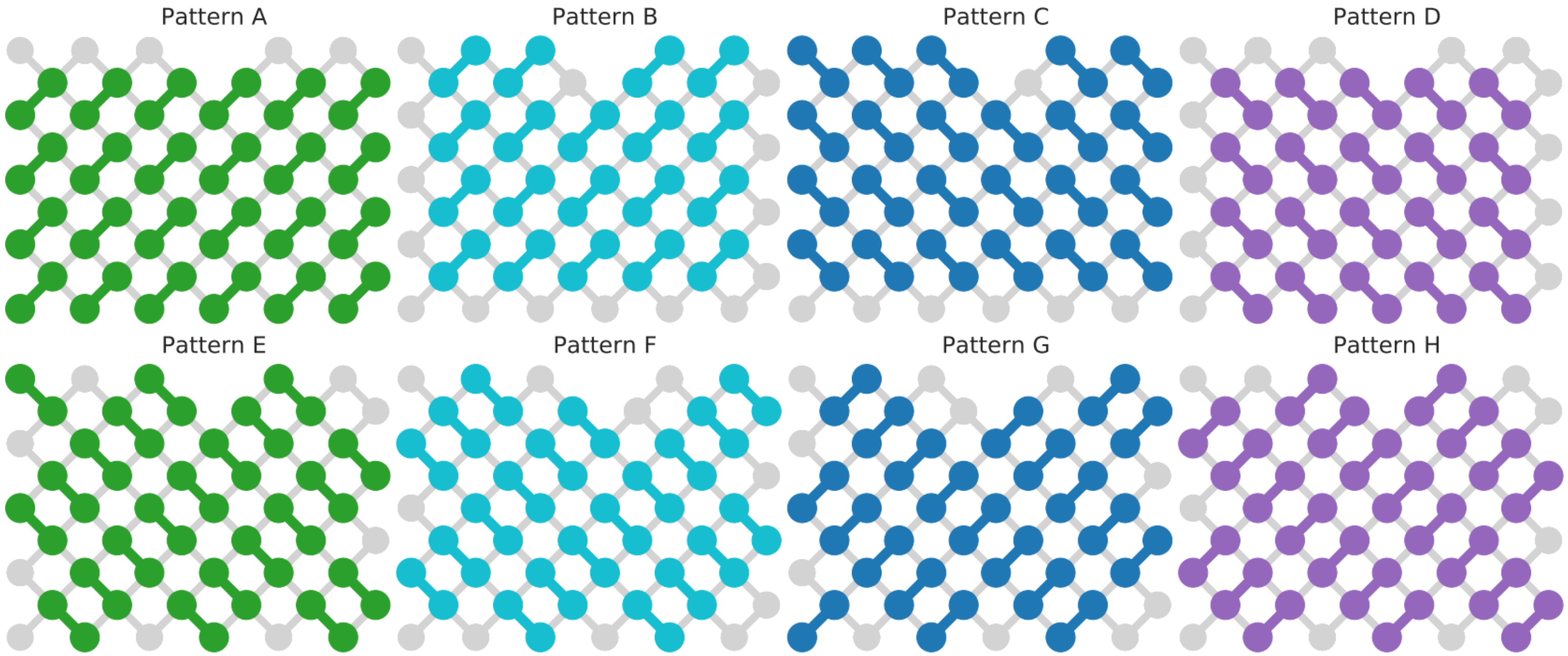
iSWAP: 20-MHz coupling for 12 ns



Randomly chosen single Qubit gates
25-ns microwave pulses, coupling turned off

Martinis et al., 10.1038/s41586-019-1666-5 (2019)

Pattern simulation: simple or hard?



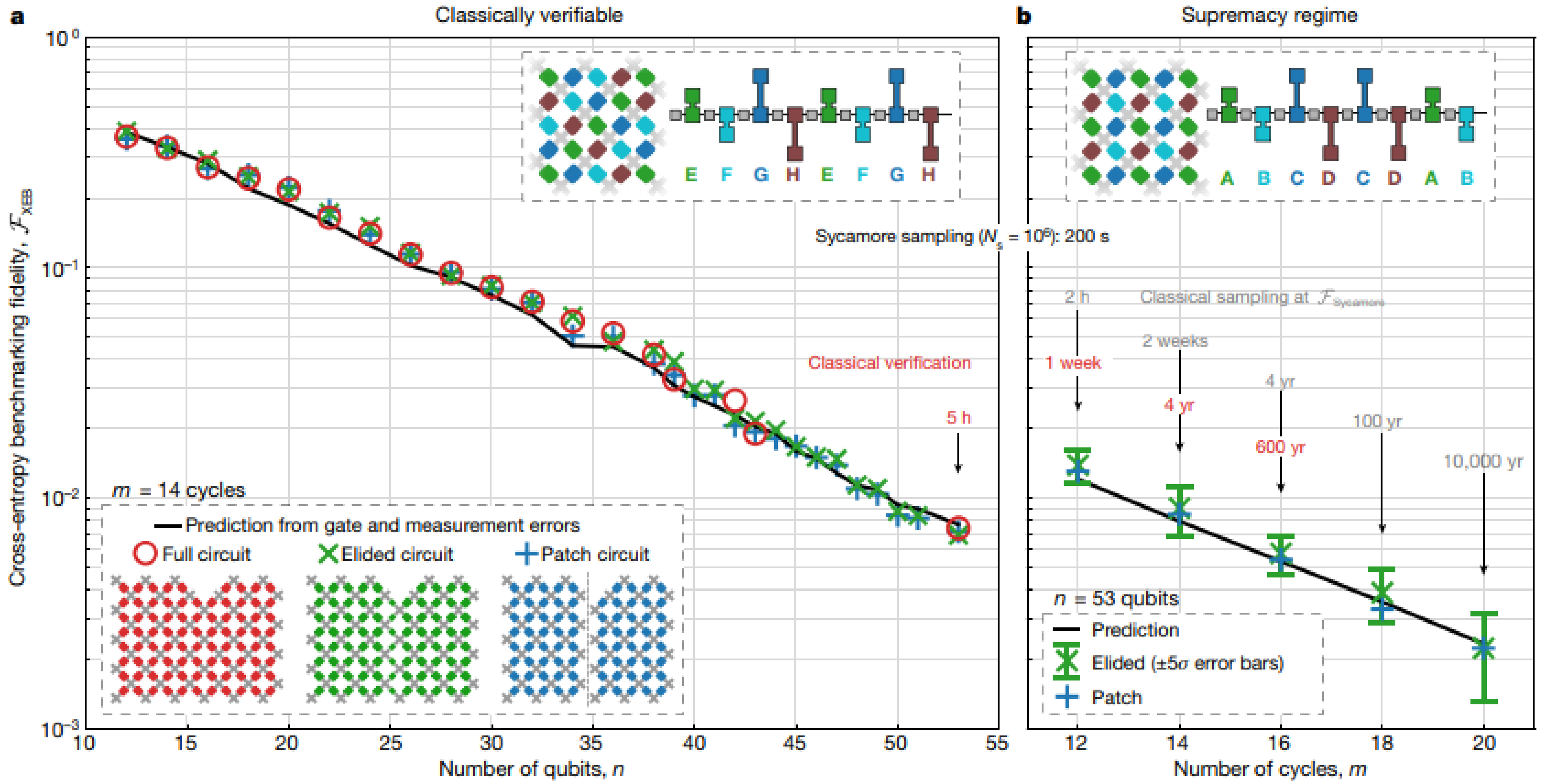
➔ hard

➔ simple

Circuit variant	Gates elided	Sequence of patterns
non-simplifiable full	none	ABCDCDAB
non-simplifiable elided	some	ABCDCDAB
non-simplifiable patch	all	ABCDCDAB
simplifiable full	none	EFGH
simplifiable elided	some	EFGH
simplifiable patch	all	EFGH

Martinis et al., 10.1038/s41586-019-1666-5 (2019)

Demonstration of Quantum Supremacy



Circuit variant	Gates elided	Sequence of patterns
non-simplifiable full	none	ABCDCDAB
non-simplifiable elided	some	ABCDCDAB
non-simplifiable patch	all	ABCDCDAB
simplifiable full	none	EFGH
simplifiable elided	some	EFGH
simplifiable patch	all	EFGH

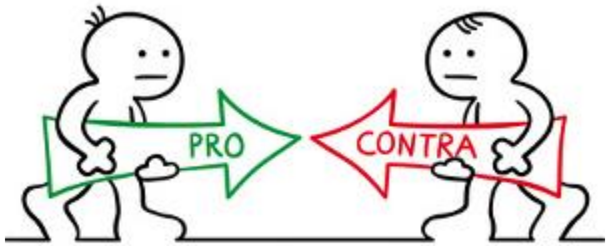
- Simulating the fidelity of the elided and patch circuit is easier
- Assumption: Fidelity is product of fidelities of the two circuits

➔ Use elided and patch circuit for fidelity validation

Martinis et al., 10.1038/s41586-019-1666-5 (2019)

Discussion

Quantum Supremacy?



+ Per Definition: yes
+ To this day no equivalent classical simulation was performed

- Very specific protocol
- Same fidelity not reproduced with arbitrary gates yet
- Often new classical algorithms are found with similar runtime scaling