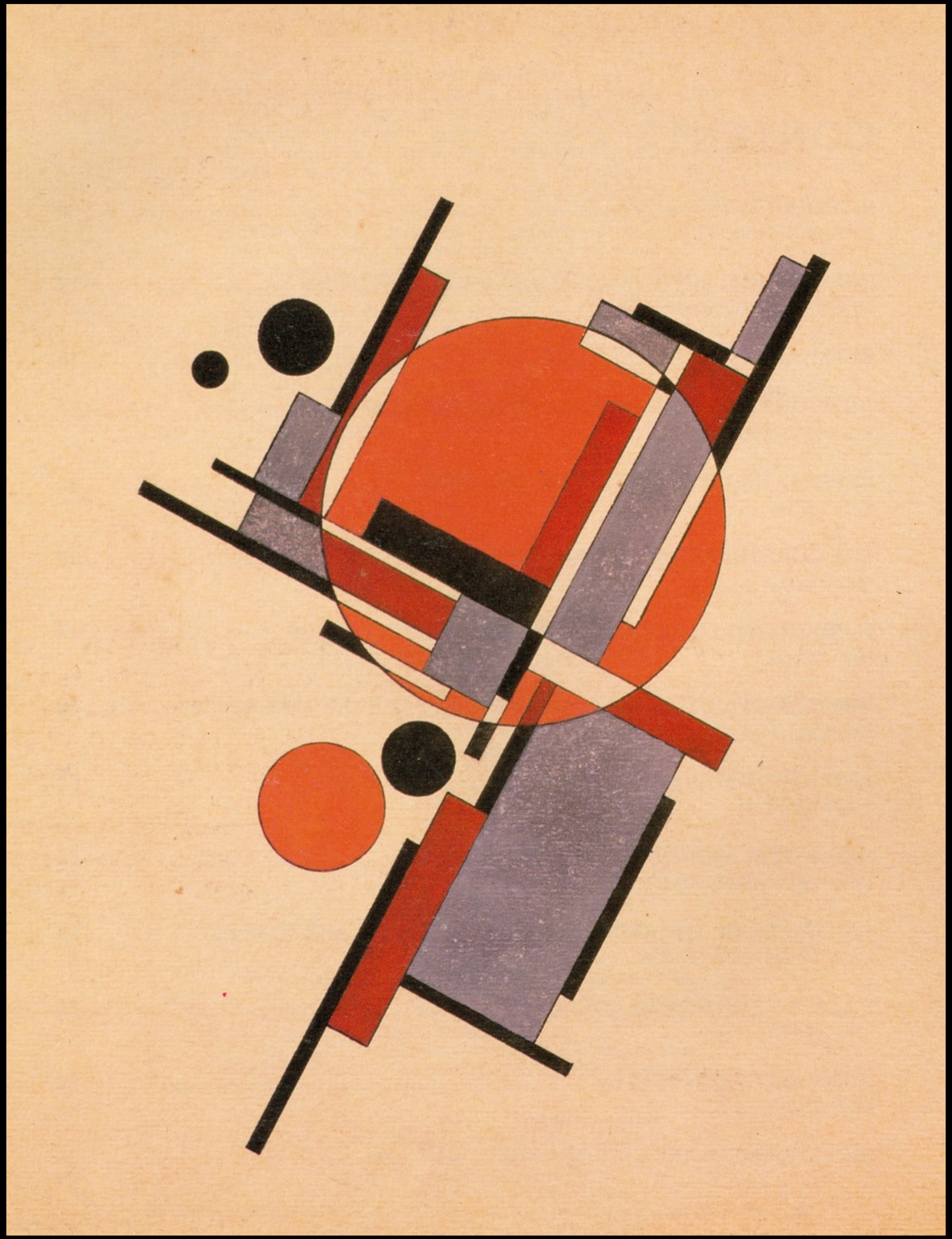
Superconducting qubits
State-of-the-art and where do we go from here?



Postdoctoral associate
Engineering Quantum Systems
Massachusetts Institute of Technology

Danish Quantum Community Conference
Oct 7th 2020
Morten Kjaergaard

(starting Nov 2020)
Assistant Professor
Center for Quantum Devices
University of Copenhagen

Quantum computing: What's the point?

DQC Conference
Oct 7th, 2020

Computations using quantum bits (performed in a highly specific way) can provide computational speedups (for certain problems)

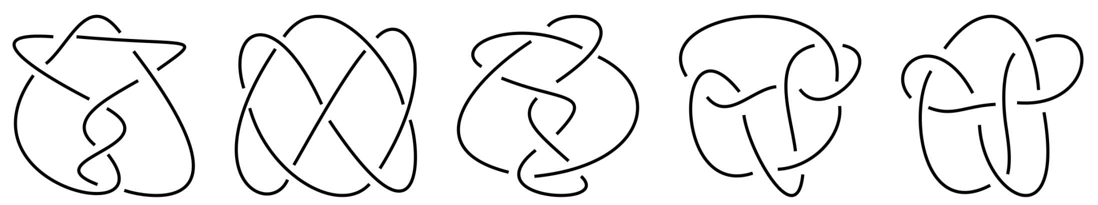
P
Efficiently solvable
and checkable
on classical computer

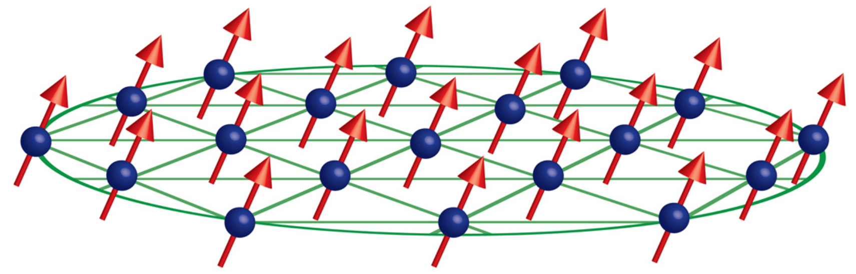
BQP
Efficiently solvable
on a **quantum** computer

NP
Efficiently checkable
(but **not** efficiently solvable)
on classical computer

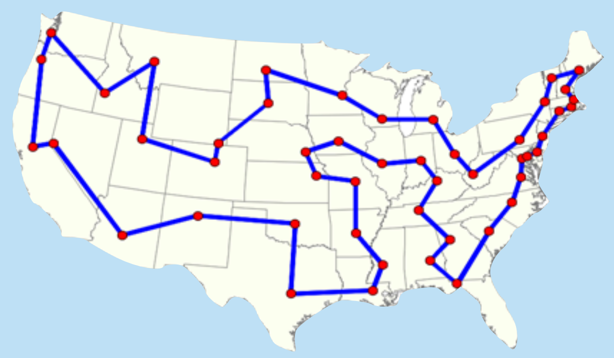
EXAMPLES

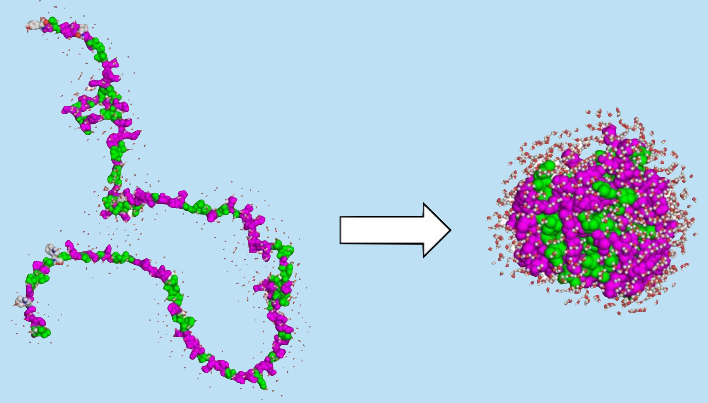
What are the prime factors of 179,424,673?

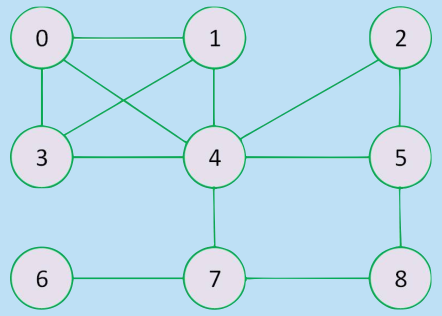




EXAMPLES

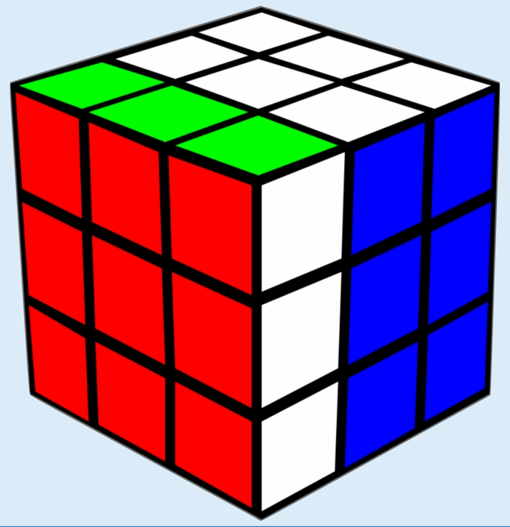


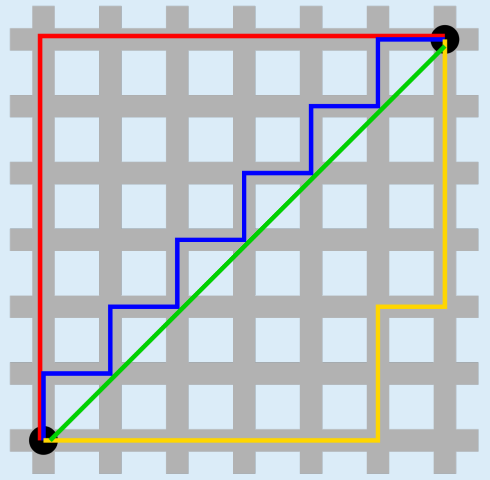




EXAMPLES

Is 179,424,673 a prime number?





Quantum computers fundamentally changes what is *computationally feasible*

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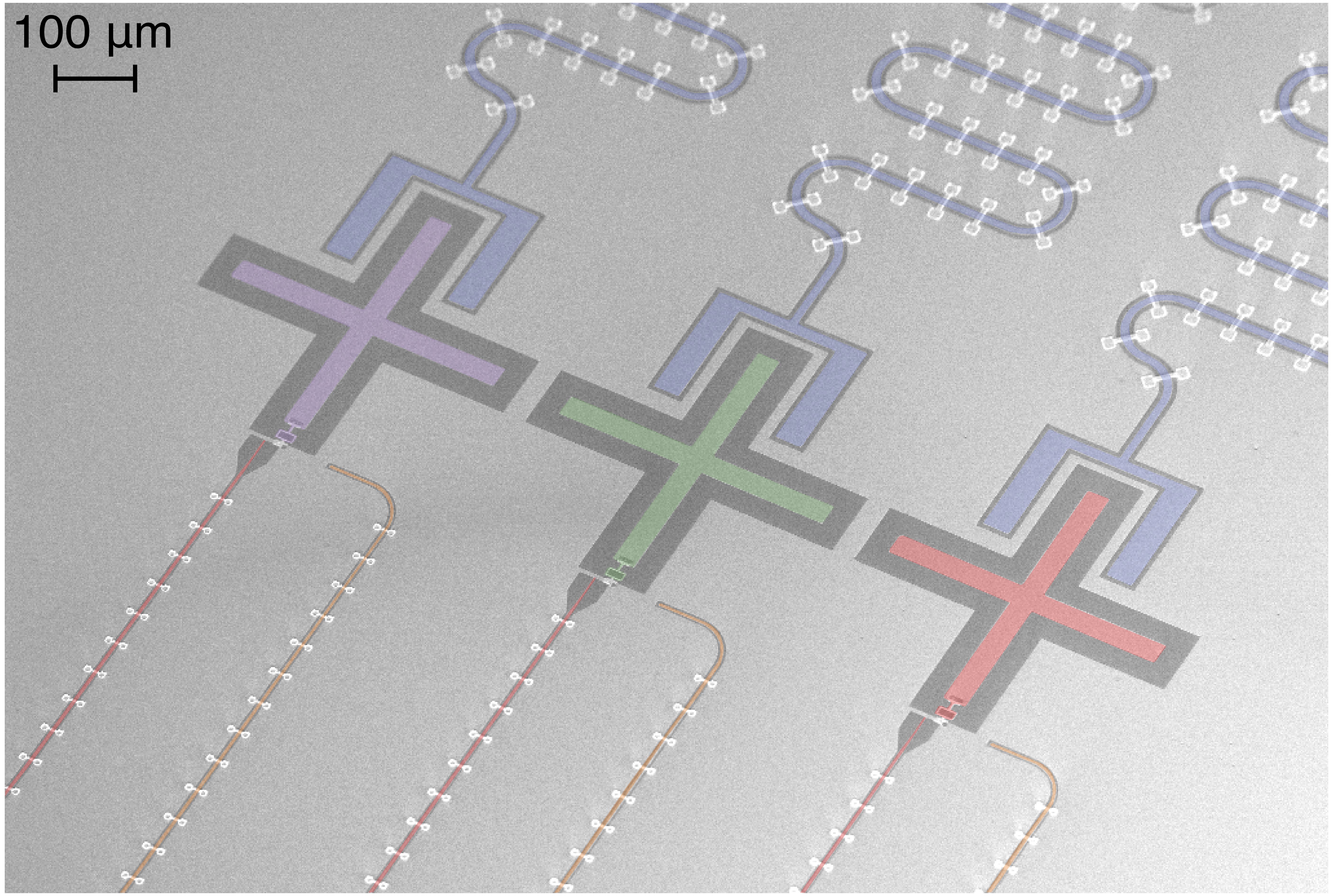
Superconducting quantum computers: What are they?



Electrical circuits fabricated using superconducting materials and patterned with nano- and microlithography techniques:

- *Quantum* properties can be changed, just by changing electrical pattern
- *Exceedingly* reproducible -> can be prototyped and optimized very quickly

Figure from MK et al, arXiv:2001.08838
Original design from R. Barends et al, Nature, 500, 508 (2014)

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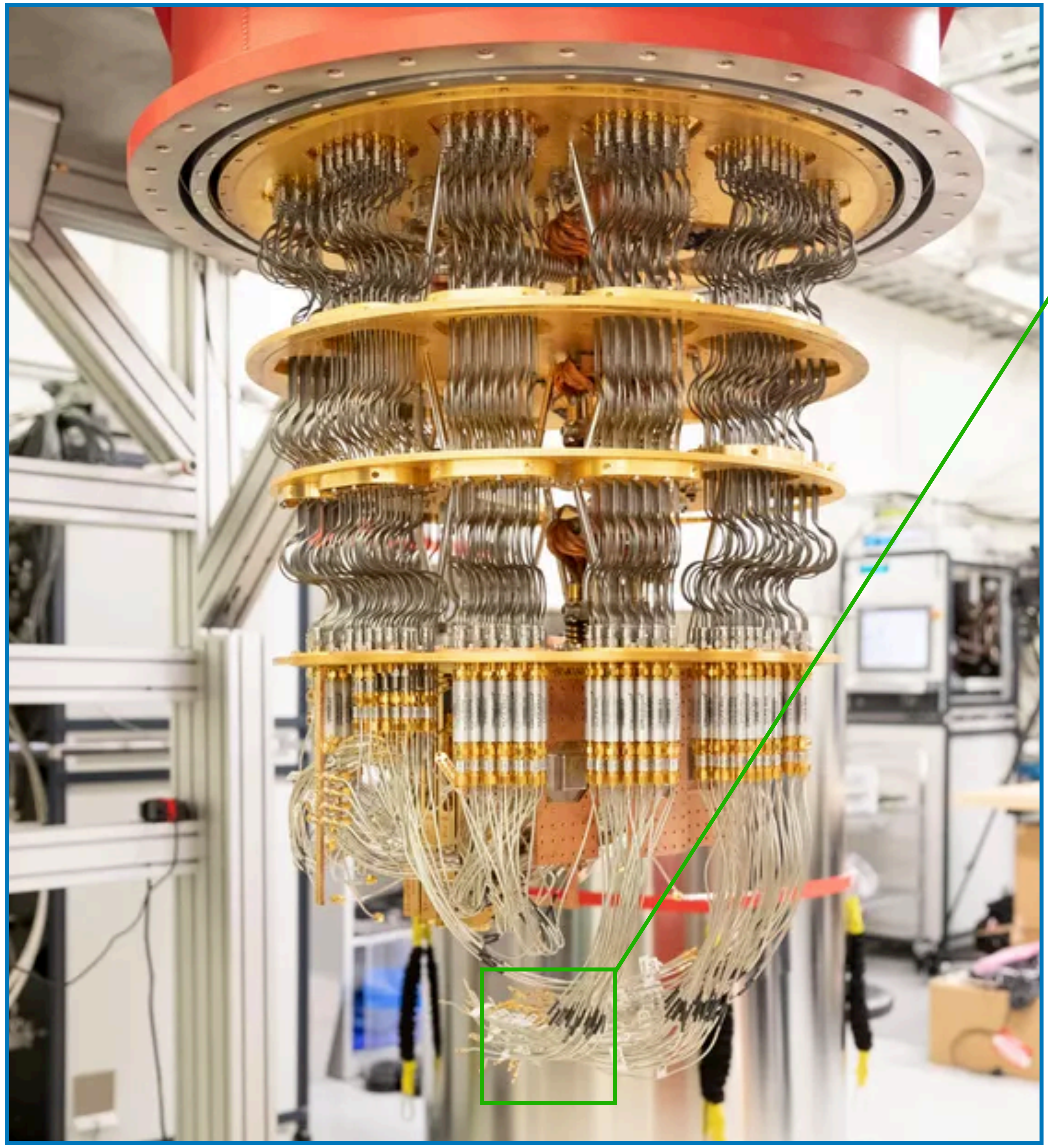
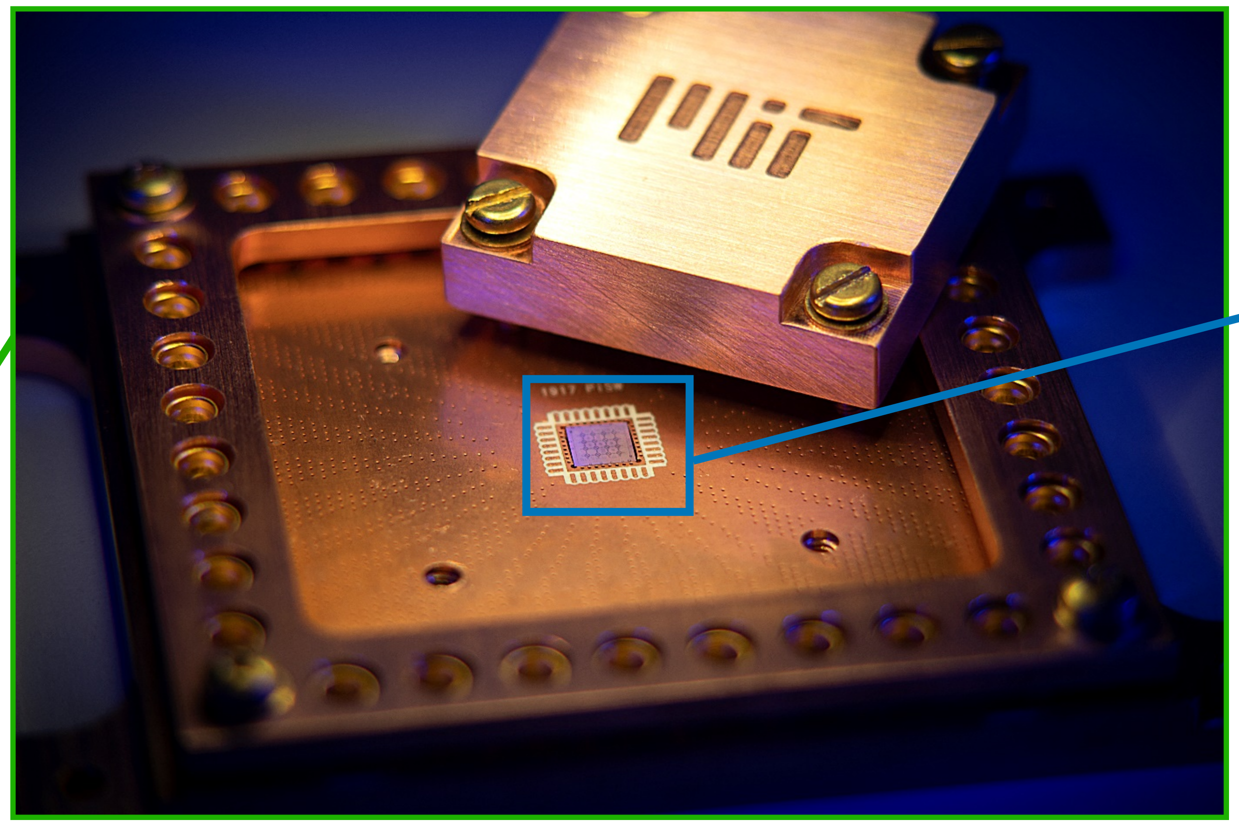
Superconducting quantum computing: What do they look like?

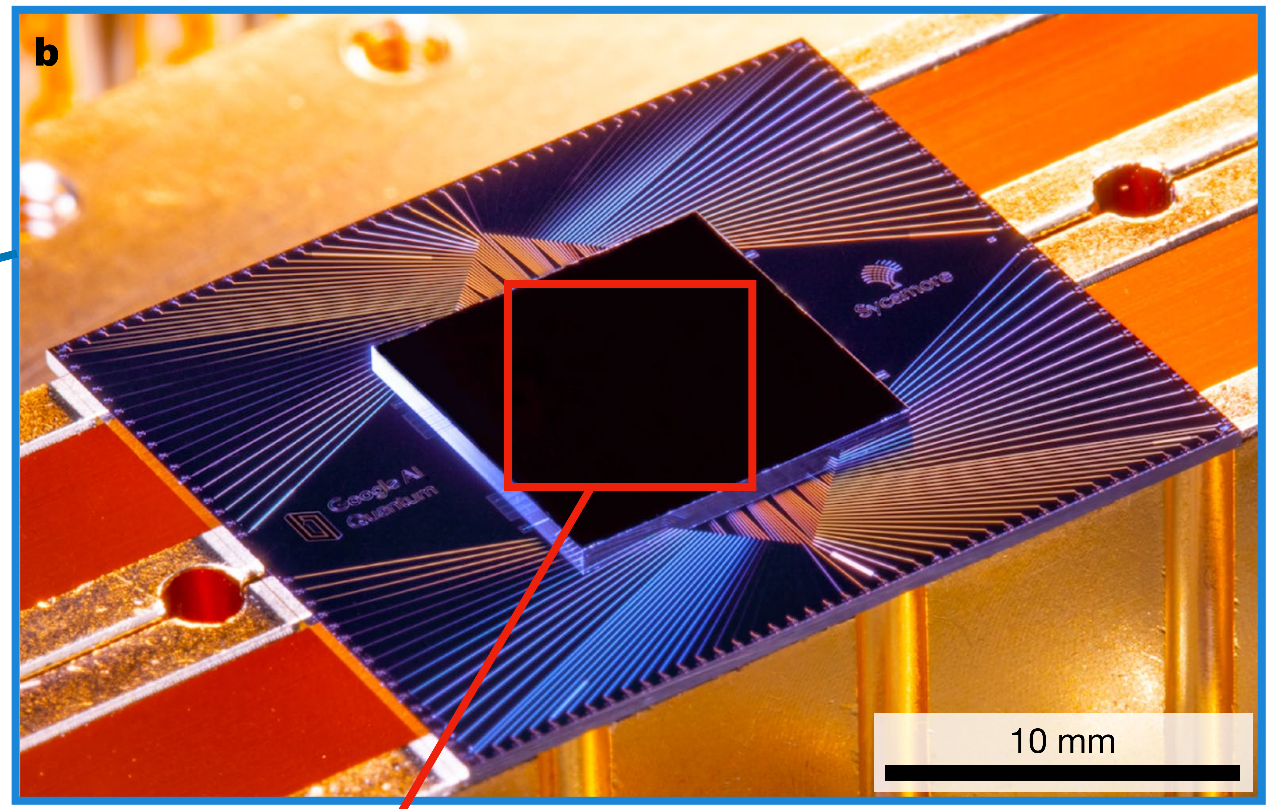
Google Quantum AI



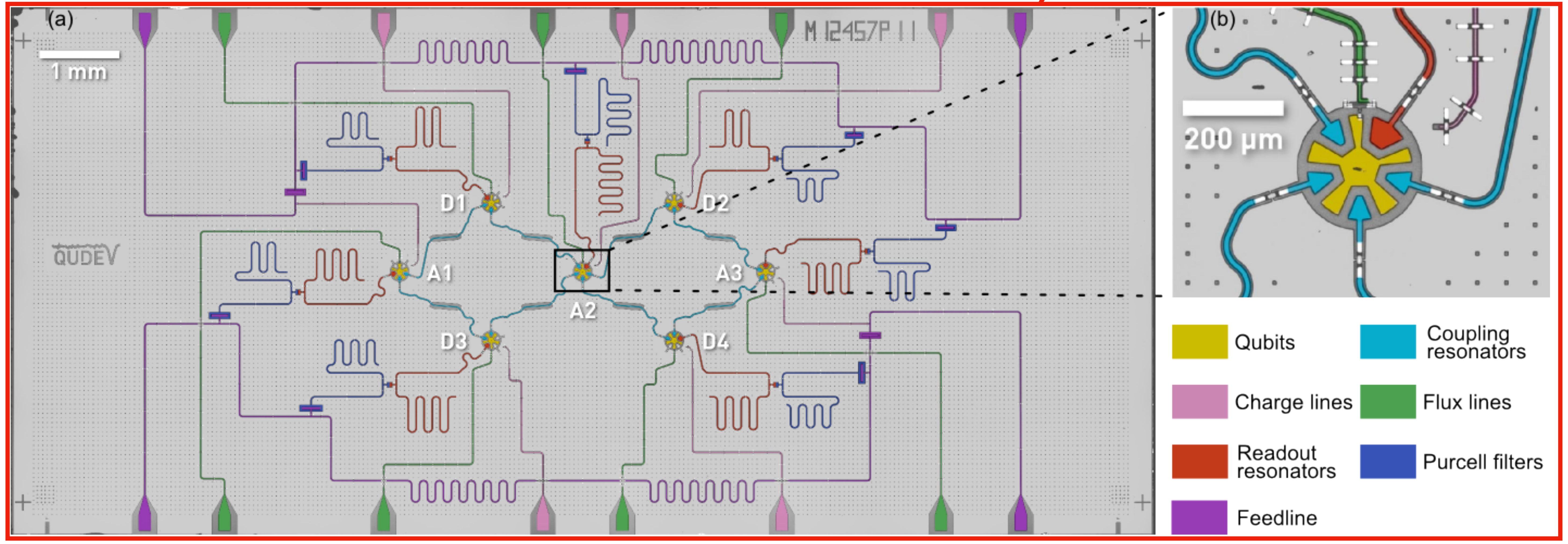
EQuS (MIT)



Google Quantum AI



Wallraff Group (ETH Zurich)



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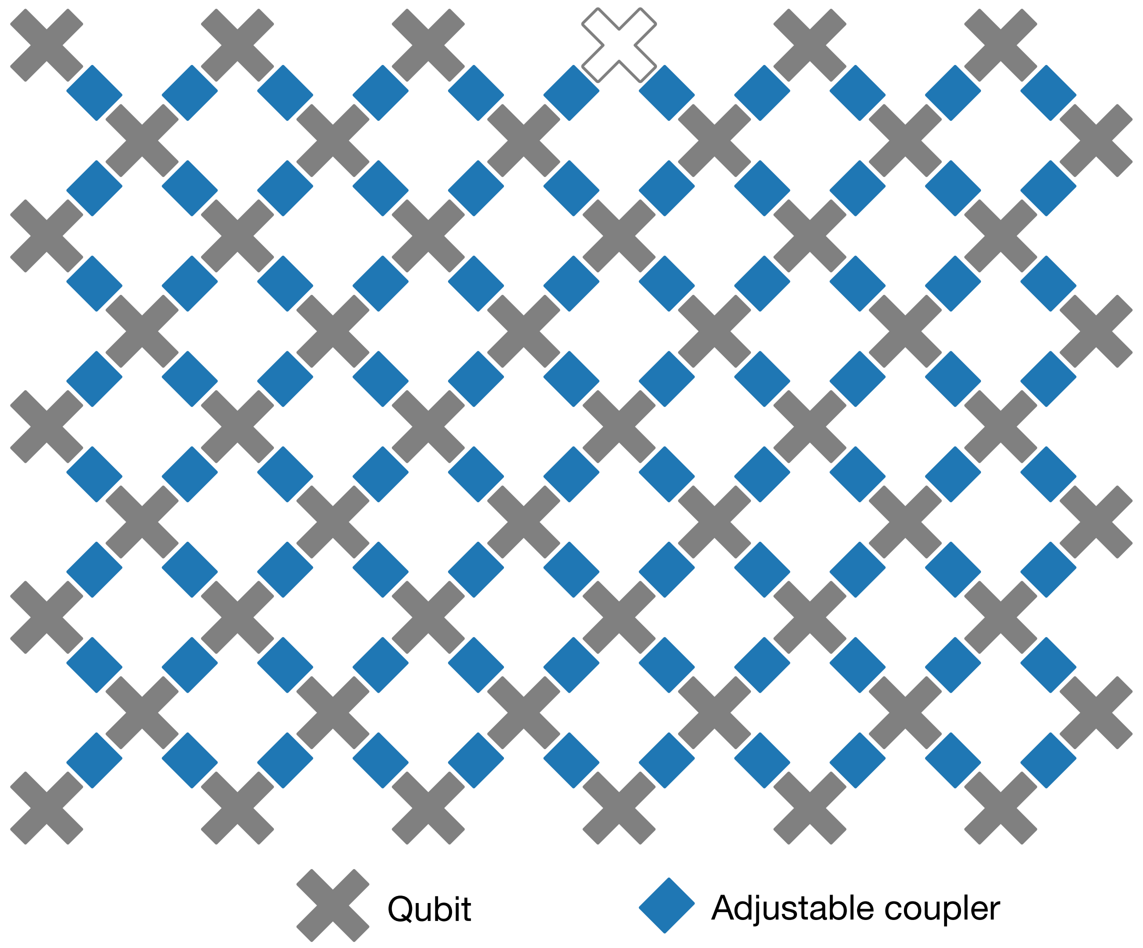
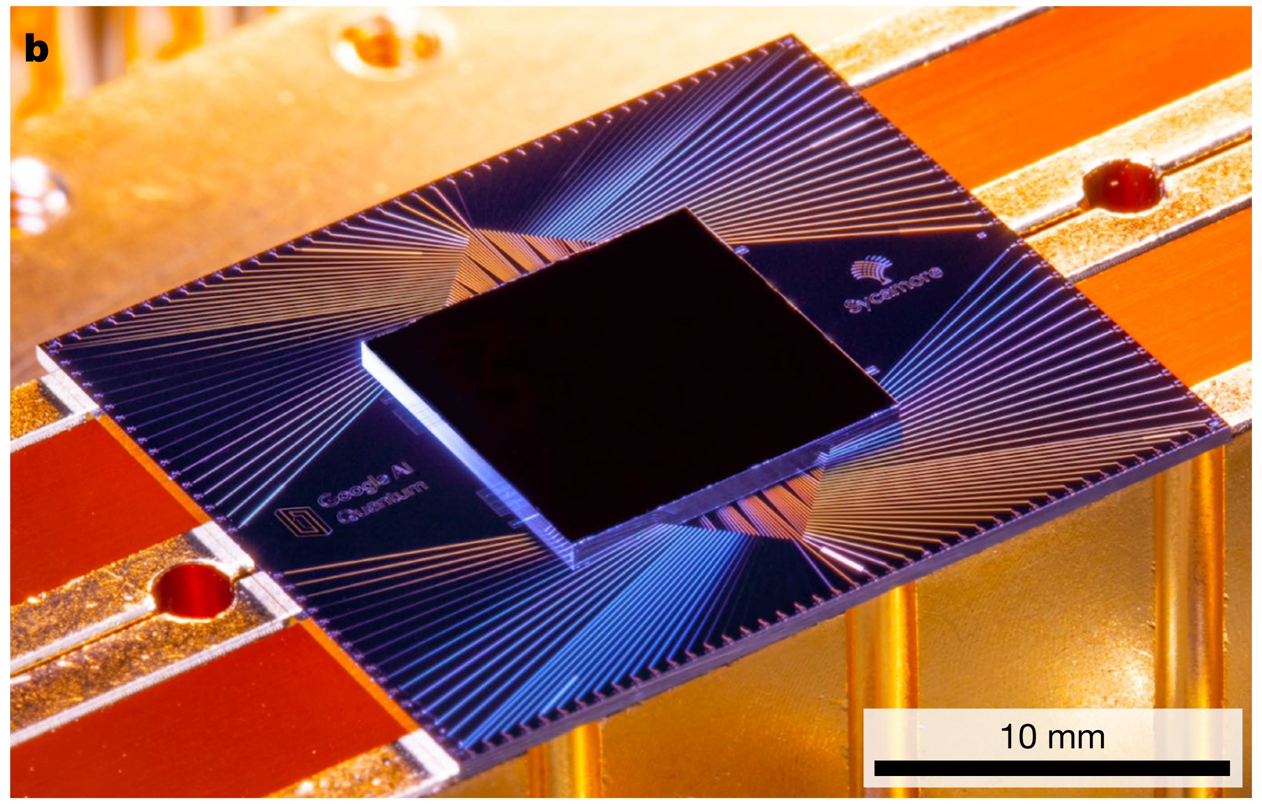
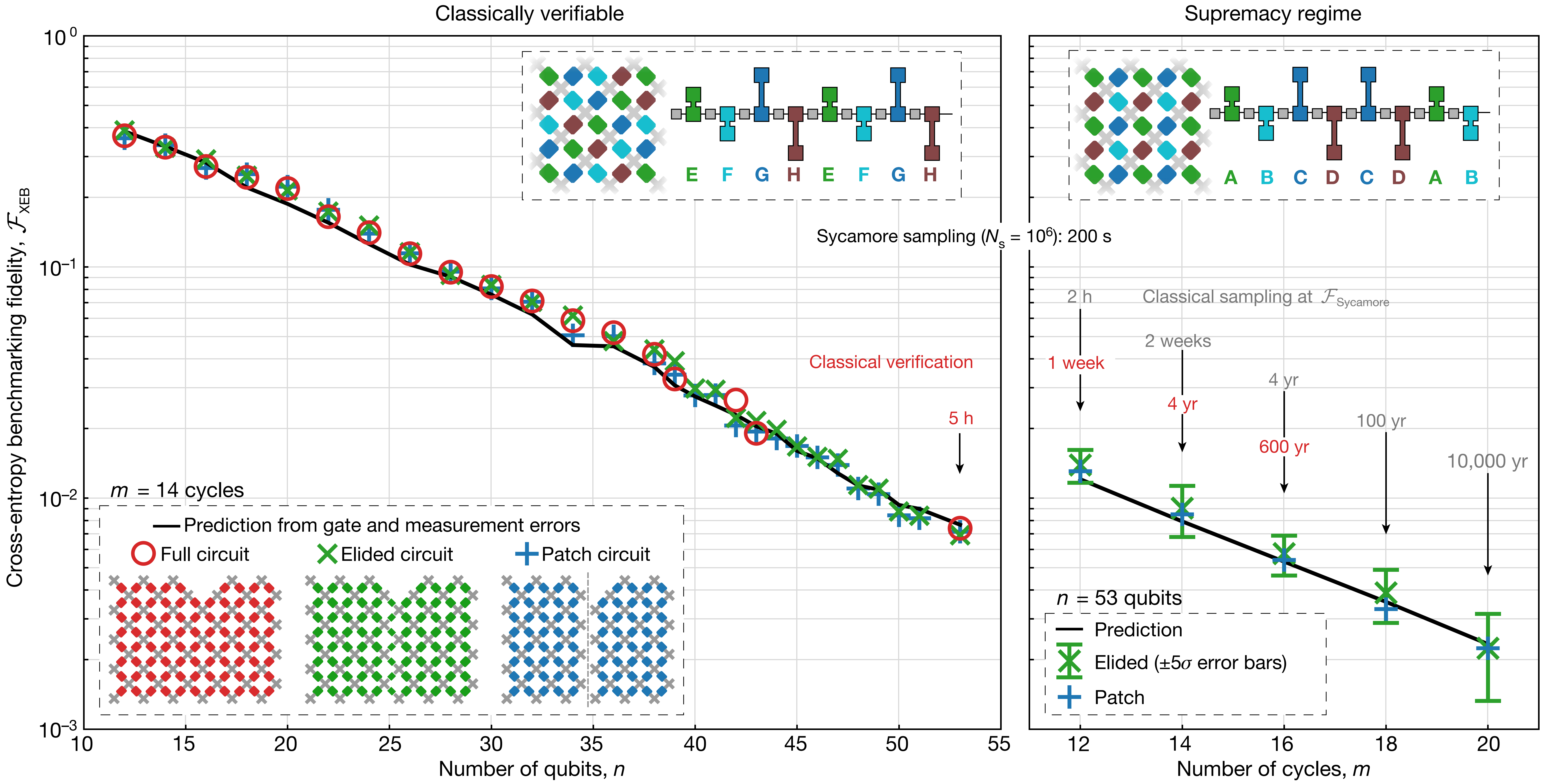
Superconducting quantum computers: Where are we now?

Late last year a *superconducting* quantum computer outperformed the worlds largest classical supercomputer:







Using 53 superconducting qubit (of the *transmon* variety), the Google Quantum AI team demonstrated a calculation in ~200s that is expected to take between ~a few weeks and up to ~10.000 years on the Summit supercomputer

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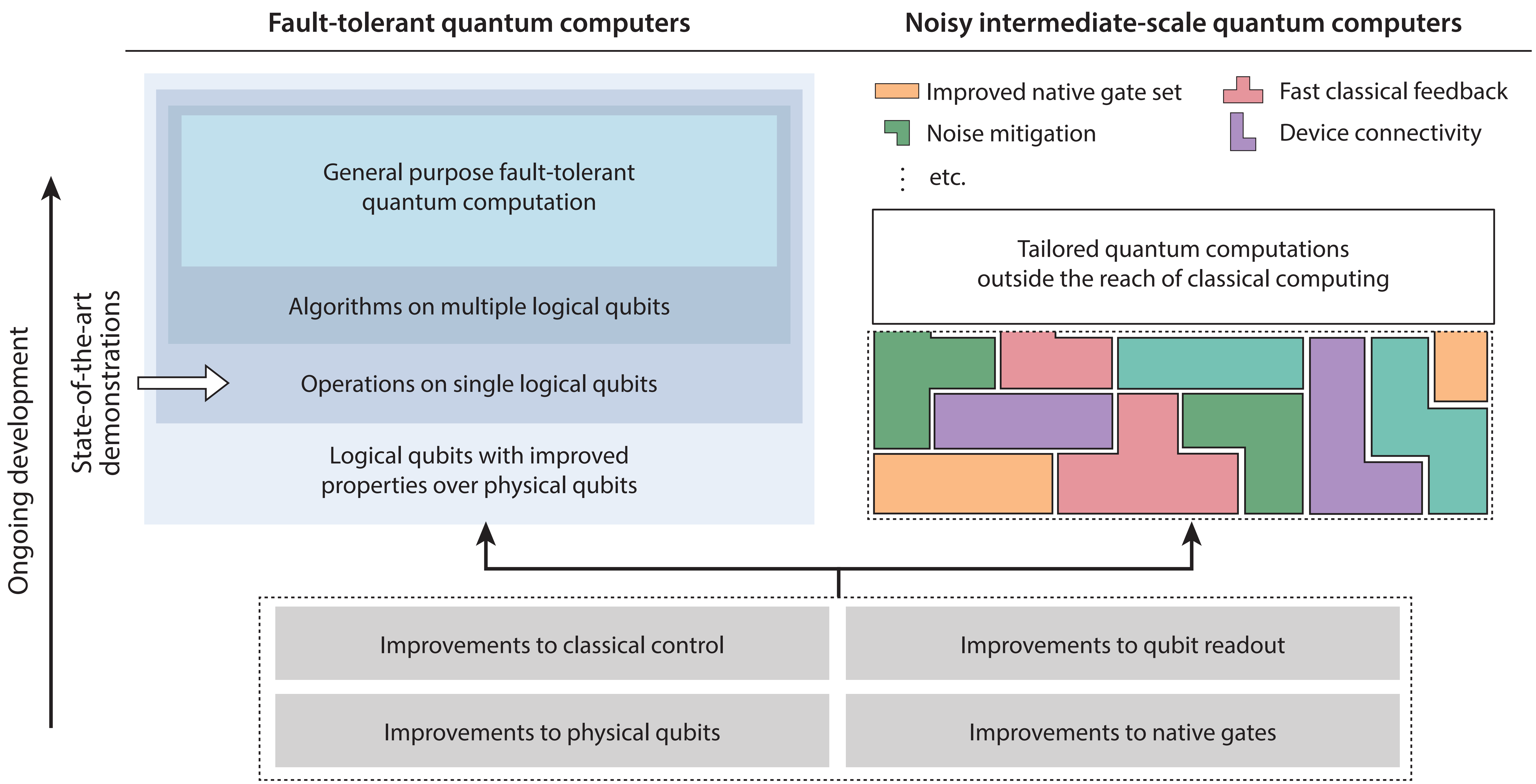
Google Quantum AI, Nature, 505, **574**, (2019)

Superconducting quantum computing: Where are we going?



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MK *et al*, Ann. Rev. Cond. Matt. **11**, 369-395, (2020)

Superconducting quantum computing: Where are we going?

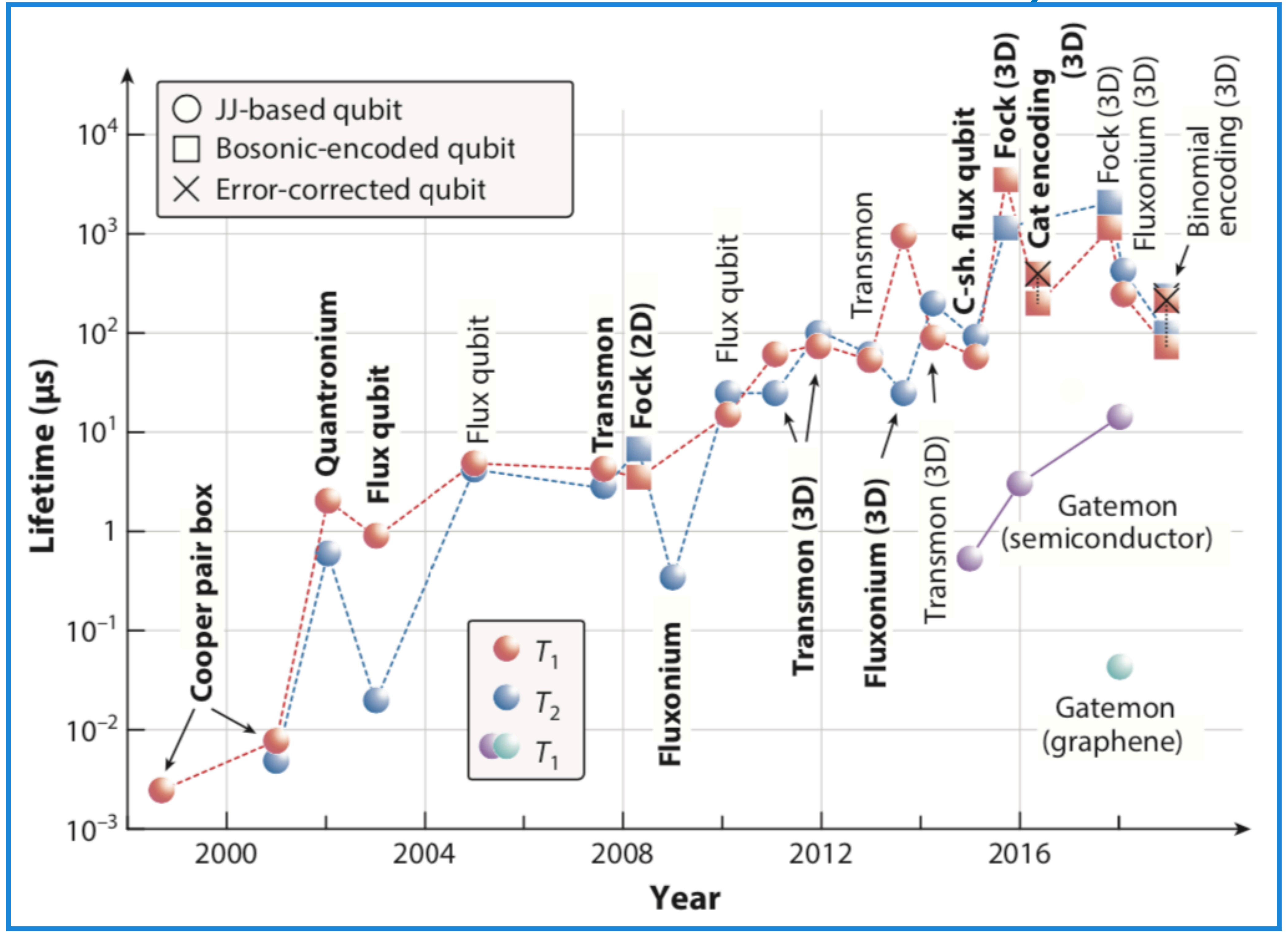
Ongoin

Improvements to classical control

Improvements to qubit readout

Improvements to physical qubits

Improvements to native gates



‘Lifetime’ is approximately the time for which the qubit ‘retains its memory’. *Key metric.*

Table 1 State-of-the-art high-fidelity, two-qubit gates in superconducting qubits[a]

Acronym[b]	Layout[c]	First demonstration [Year]	Highest fidelity [Year]	Gate time
CZ (ad.)	T–T	DiCarlo et al. (72) [2009]	99.4%[e] Barends et al. (3) [2014]	40 ns
			99.7%[e] Kjaergaard et al. (73) [2020]	60 ns
$\sqrt{\text{iSWAP}}$	T–T	Neeley et al. (81)[d] [2010]	90%[g] Dewes et al. (74) [2014]	31 ns
CR	F–F	Chow et al. (75)[h] [2011]	99.1%[e] Sheldon et al. (5) [2016]	160 ns
$\sqrt{\text{bSWAP}}$	F–F	Poletto et al. (76) [2012]	86%[g] Poletto et al. (76) [2012]	800 ns
MAP	F–F	Chow et al. (77) [2013]	87.2%[g] Chow et al. (75) [2011]	510 ns
CZ (ad.)	T–(T)–T	Chen et al. (55) [2014]	99.0%[e] Chen et al. (55) [2014]	30 ns
RIP	3D F	Paik et al. (78) [2016]	98.5%[e] Paik et al. (78) [2016]	413 ns
$\sqrt{\text{iSWAP}}$	F–(T)–F	McKay et al. (79) [2016]	98.2%[e] McKay et al. (79) [2016]	183 ns
CZ (ad.)	T–F	Caldwell et al. (80) [2018]	99.2%[e] Hong et al. (6) [2019]	176 ns
CNOT_{L}	BEQ-BEQ	Rosenblum et al. (13) [2018]	~99%[f] Rosenblum et al. (13) [2018]	190 ns
$\text{CNOT}_{\text{T-L}}$	BEQ-BEQ	Chou et al. (82) [2018]	79%[g] Chou et al. (82) [2018]	4.6 µs

‘Fidelity’ is approximately the ‘quality’ of the quantum operation that generates *entanglement* in the quantum processor. *Key metric.*

$$\text{operation count} = \frac{T_2 \text{ lifetime}}{\text{gate time}}$$

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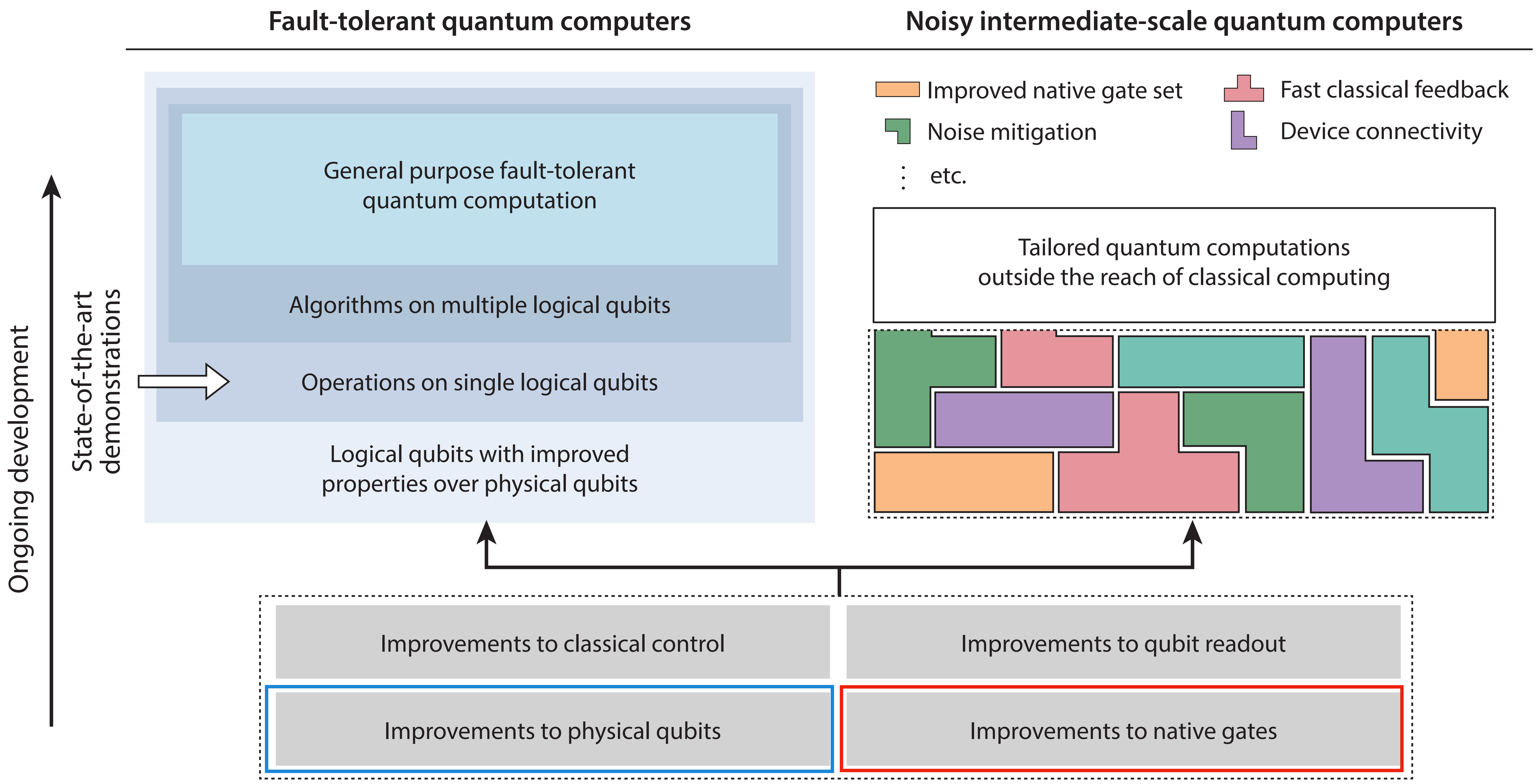
MK *et al*, Ann. Rev. Cond. Matt. **11**, 369-395, (2020)

Superconducting quantum computing: State-of-the-art experiments (a selection)



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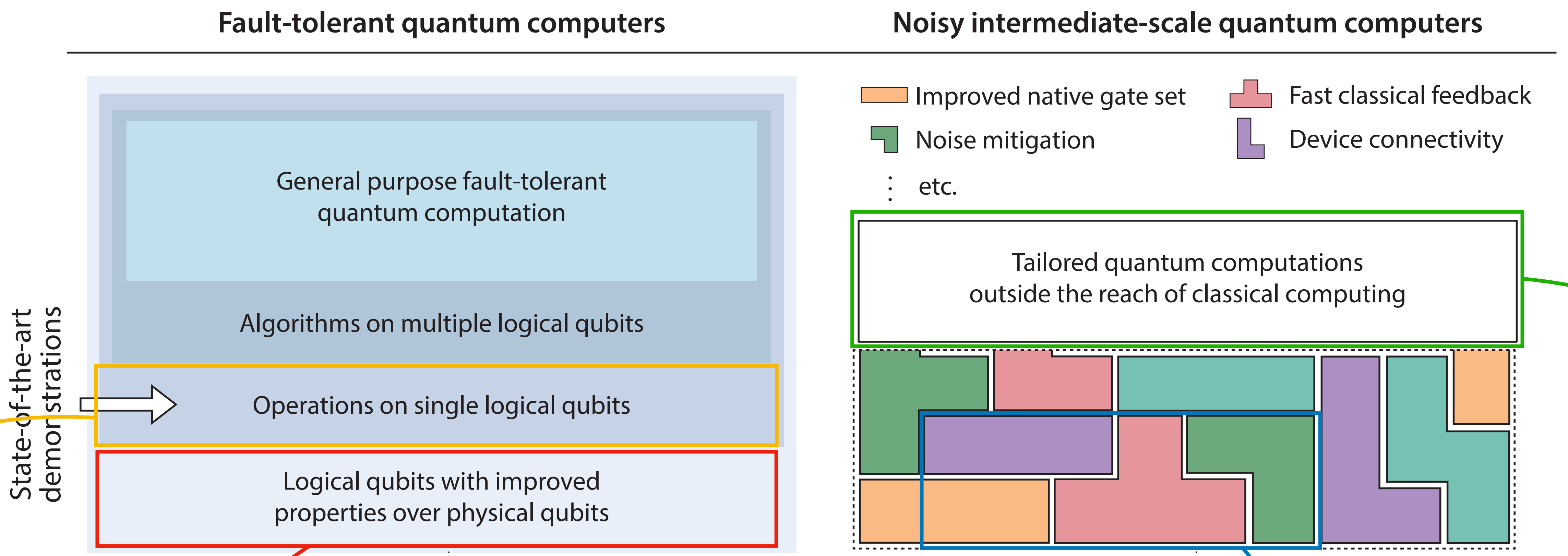
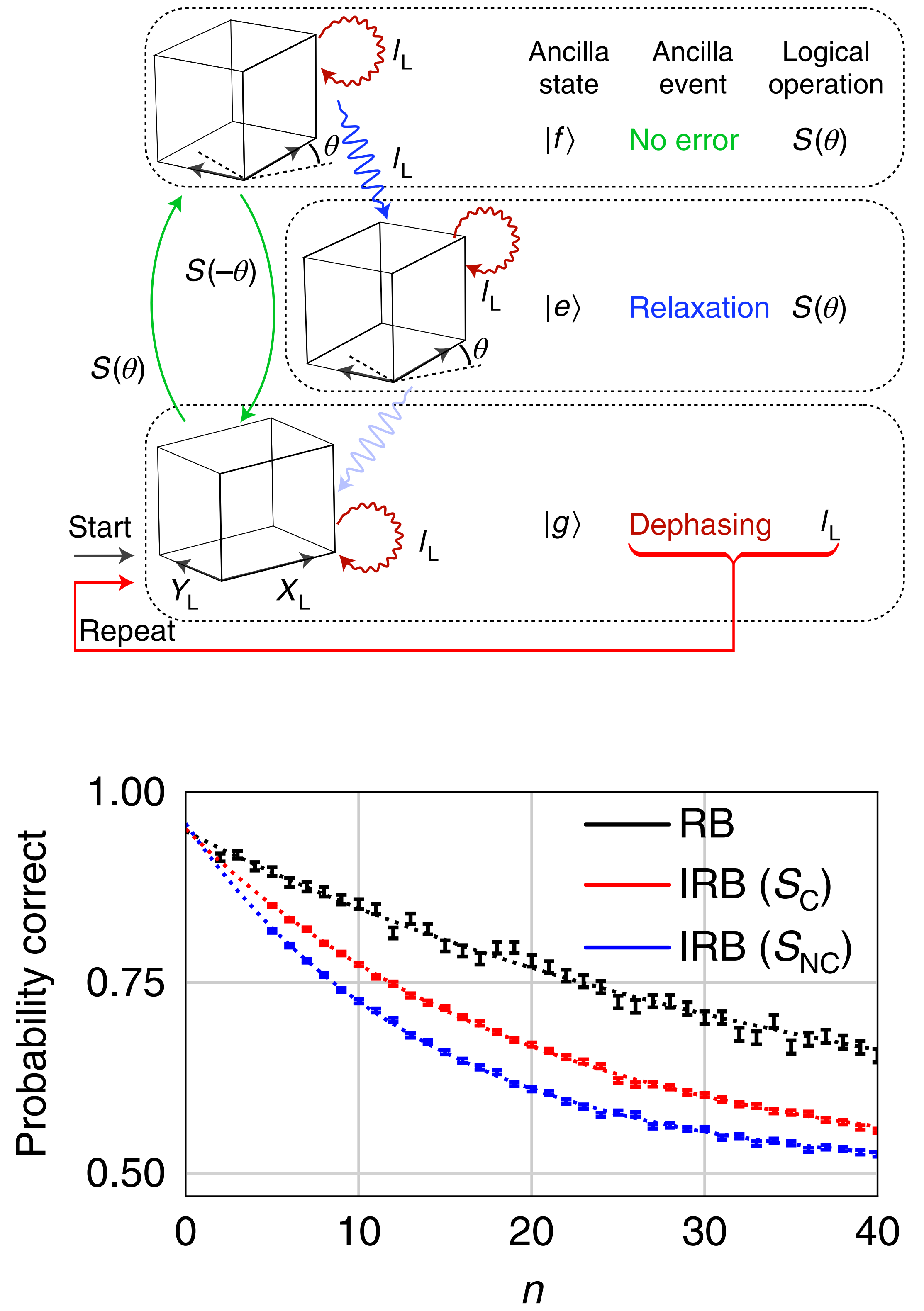
MK *et al*, Ann. Rev. Cond. Matt. **11**, 369-395, (2020)

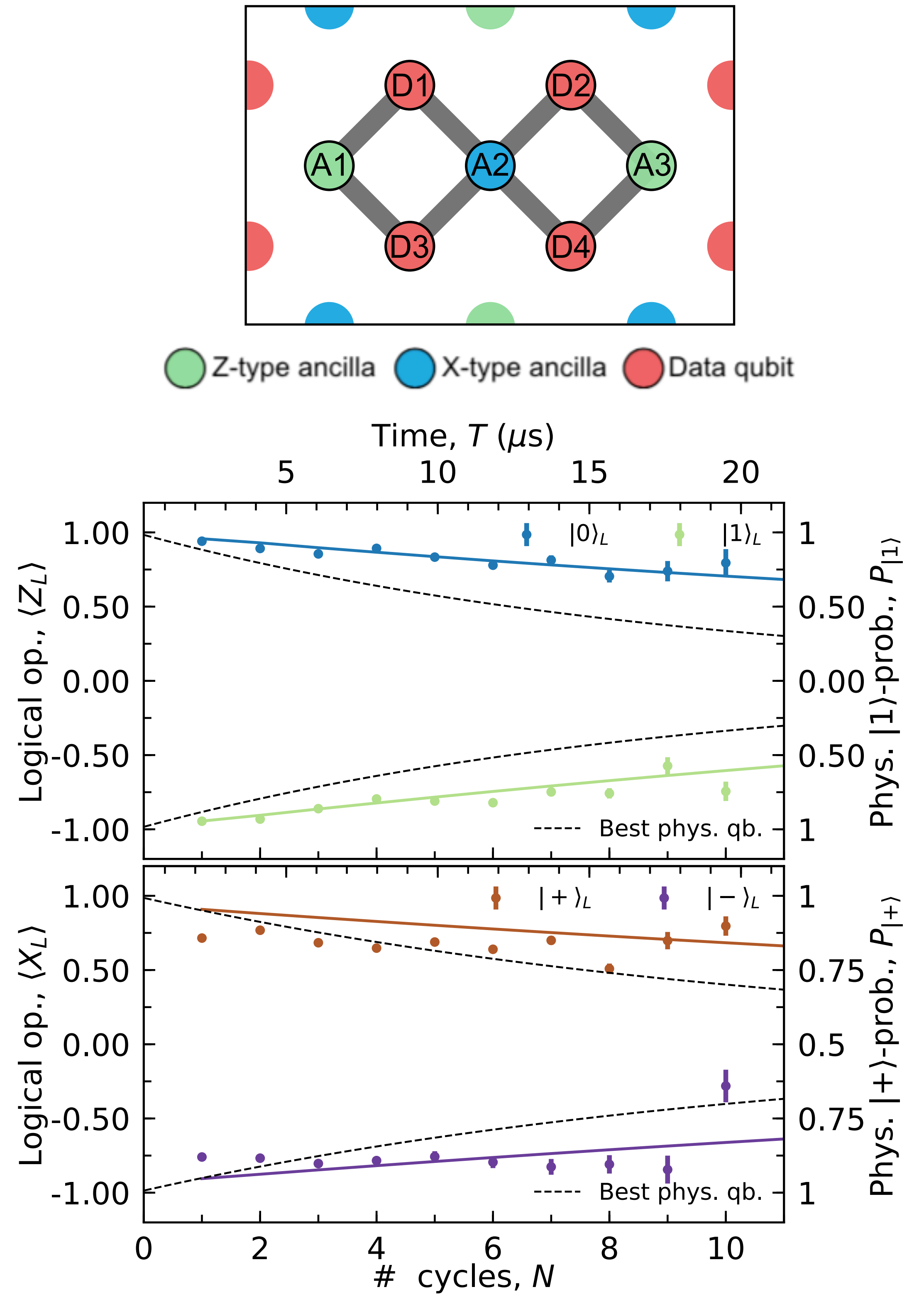
Superconducting quantum computing: State-of-the-art experiments (a selection)

DQC Conference
Oct 7th, 2020

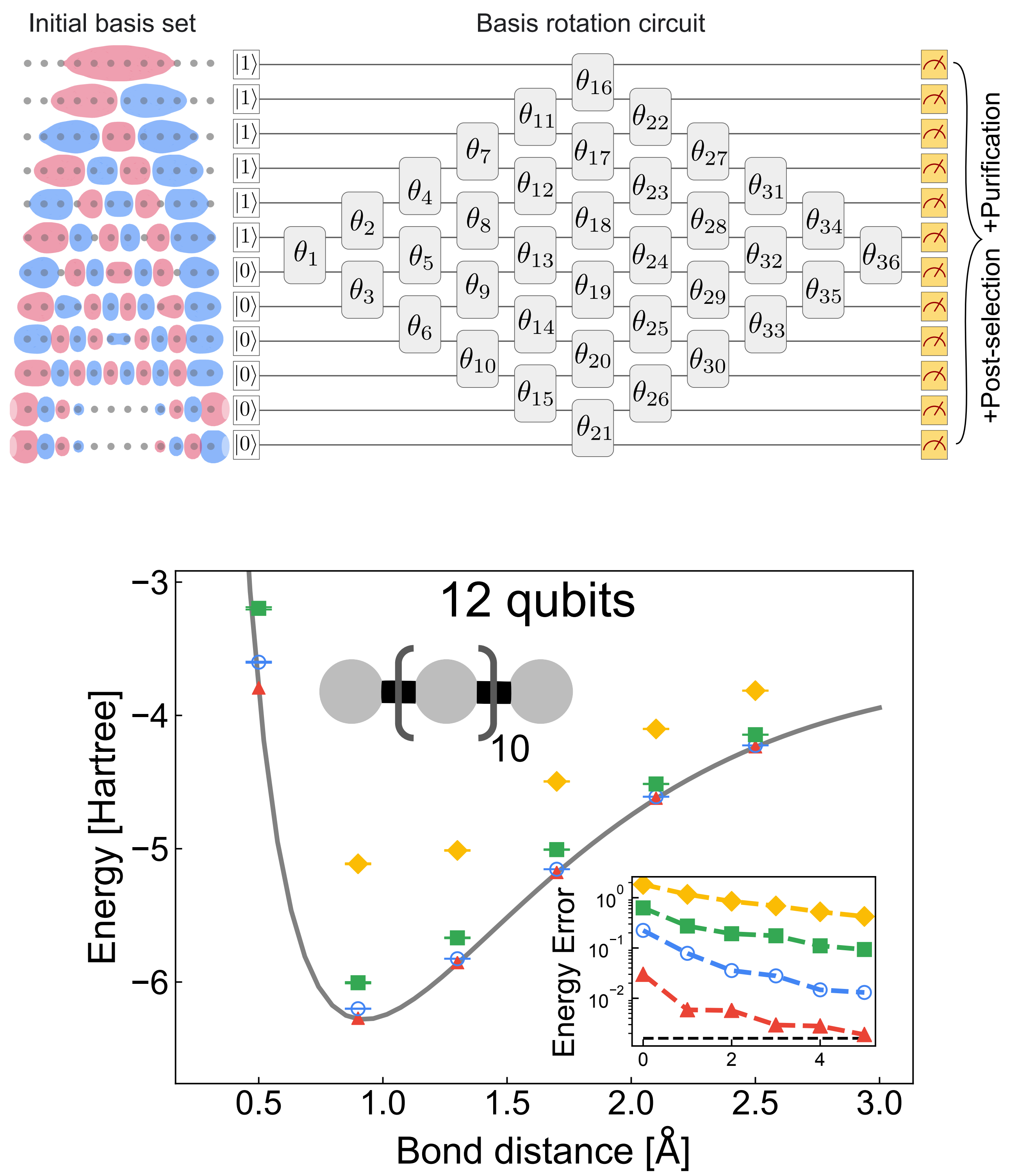




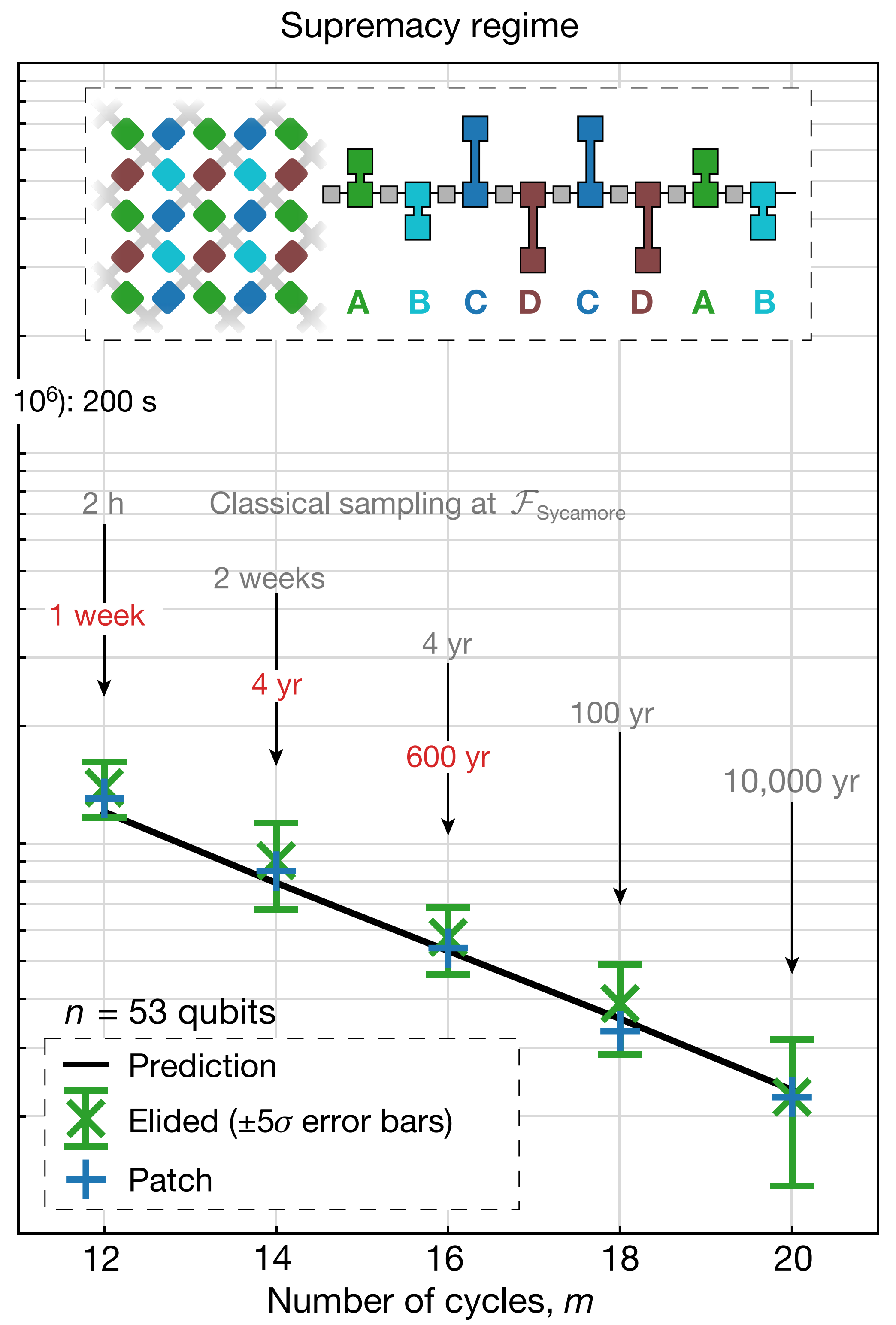
P. Reinhold, *et al*,
Nature Physics, 822, **16**, (2020)
dk



C. K. Andersen, *et al*,
Nature Physics, 875, **16**, (2020)



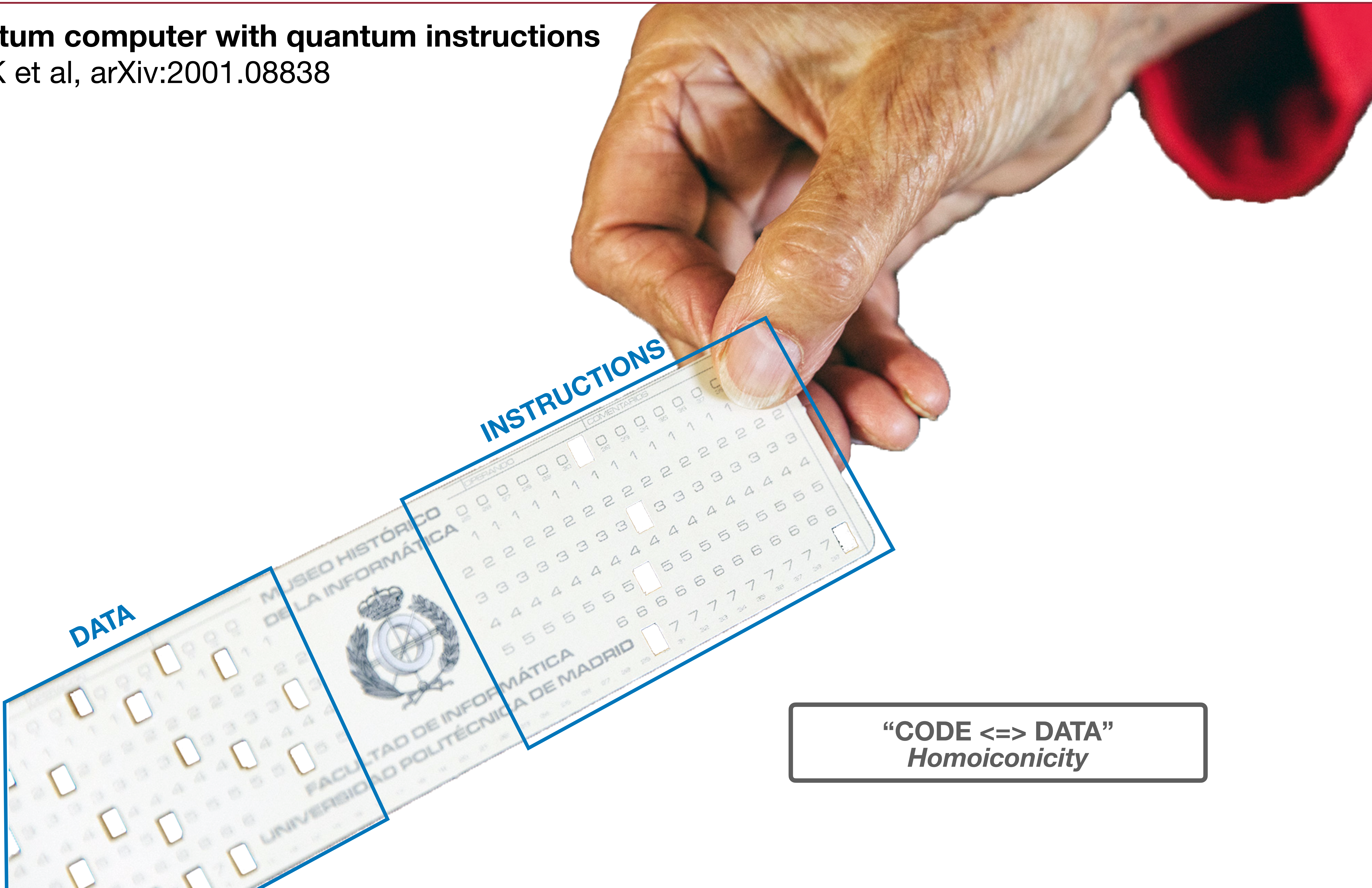
Google Quantum AI
Science, 1084, **369**, (2020)



Google Quantum AI,
Nature, 505, **574**, (2019)

Programming a quantum computer with quantum instructions

MK et al, arXiv:2001.08838



"CODE <=> DATA"
Homoiconicity

.dk

Restoring programming parity to quantum computers

"CODE <=> DATA"

CODE: CLASSICAL
DATA: CLASSICAL

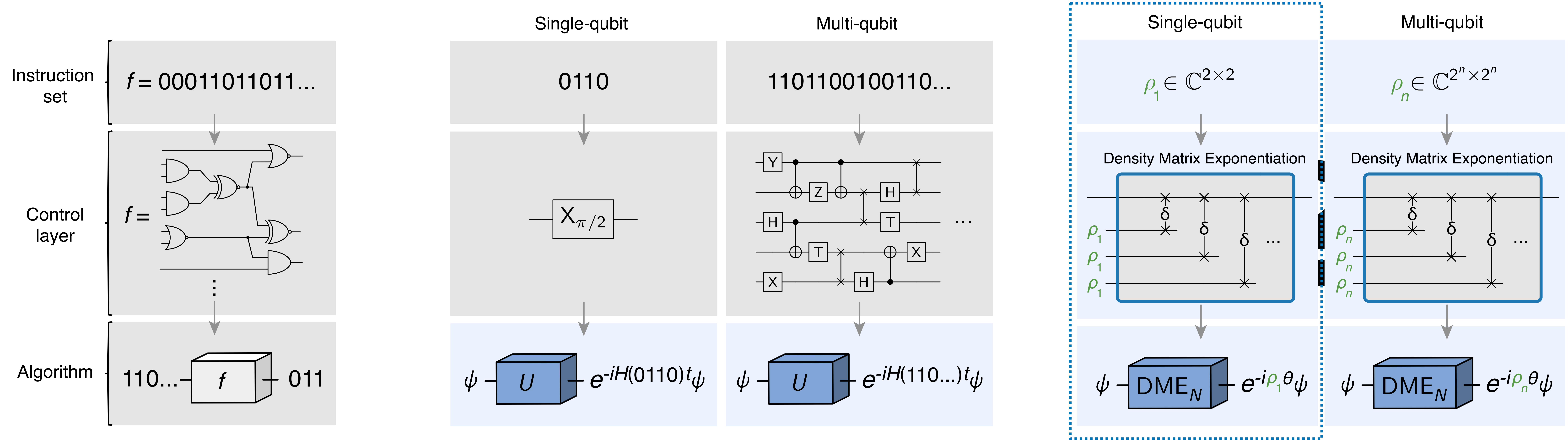
Classical instruction set for classical computing

CODE: CLASSICAL
DATA: QUANTUM

Classical instruction set for quantum computing

CODE: QUANTUM
DATA: QUANTUM

Quantum instruction set for quantum computing



Rest of this talk

Classical computing

Quantum computing

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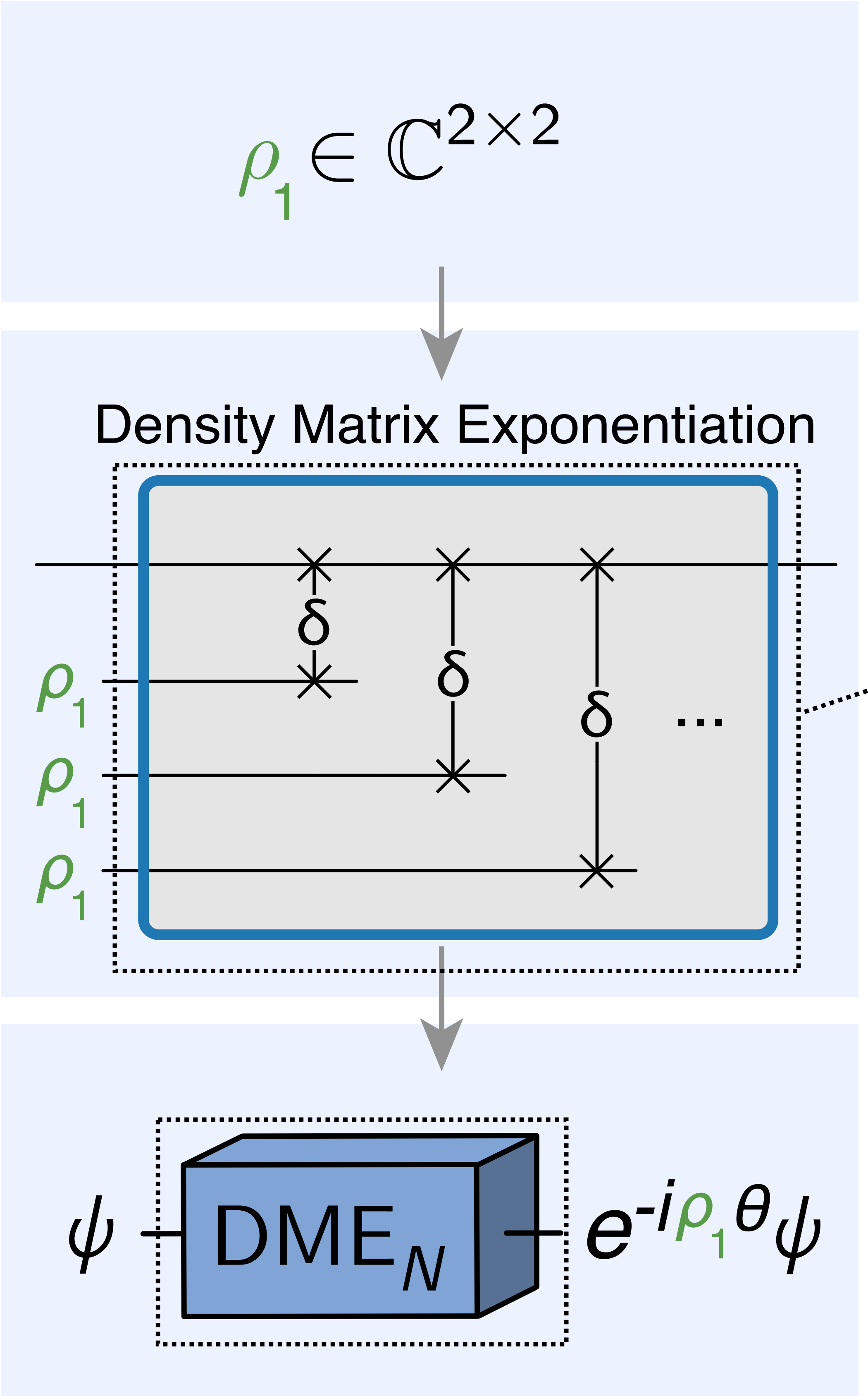
Density Matrix Exponentiation (DME): Operating principle



DME is a fixed protocol that implements an operation only dependent on the setting of the instruction state ρ:

$$\rho^{\otimes N} \xrightarrow{\mathbf{DME}_N} e^{-i\rho\theta} + \mathcal{O}(\theta^2/N)$$

(θ an angle)

Seth Lloyd *et al*, Nat. Phys. 2014

Conceptually

Density Matrix Exponentiation allows us to load a program into a state ('instruction state' or 'quantum program', ρ) and execute that quantum program on another quantum system

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Programming with quantum states

$$\sigma_{\text{in}} = |{+y}\rangle\langle{+y}| - \boxed{\mathrm{DME}(\underbrace{|{+x}\rangle\langle{+x}|}_{\substack{\text{Instruction}\\ \text{state}}},\ \underbrace{4}_{\substack{\text{Number of steps}\\ N}},\ \underbrace{\pi/2}_{\substack{\text{Total angle}\\ \theta}})} - \ \approx\ \sigma_{\text{in}} = |{+y}\rangle\langle{+y}| - \boxed{R_x(\pi/2)} -$$

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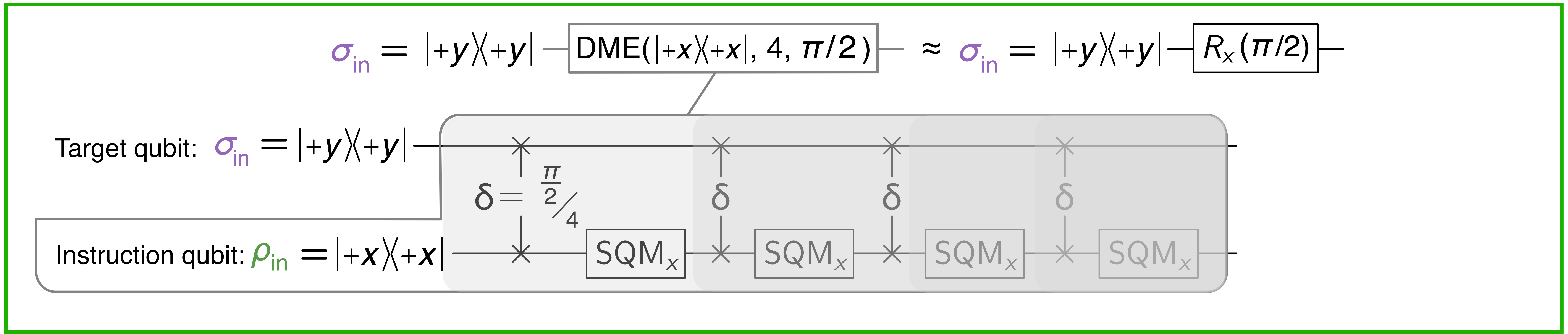
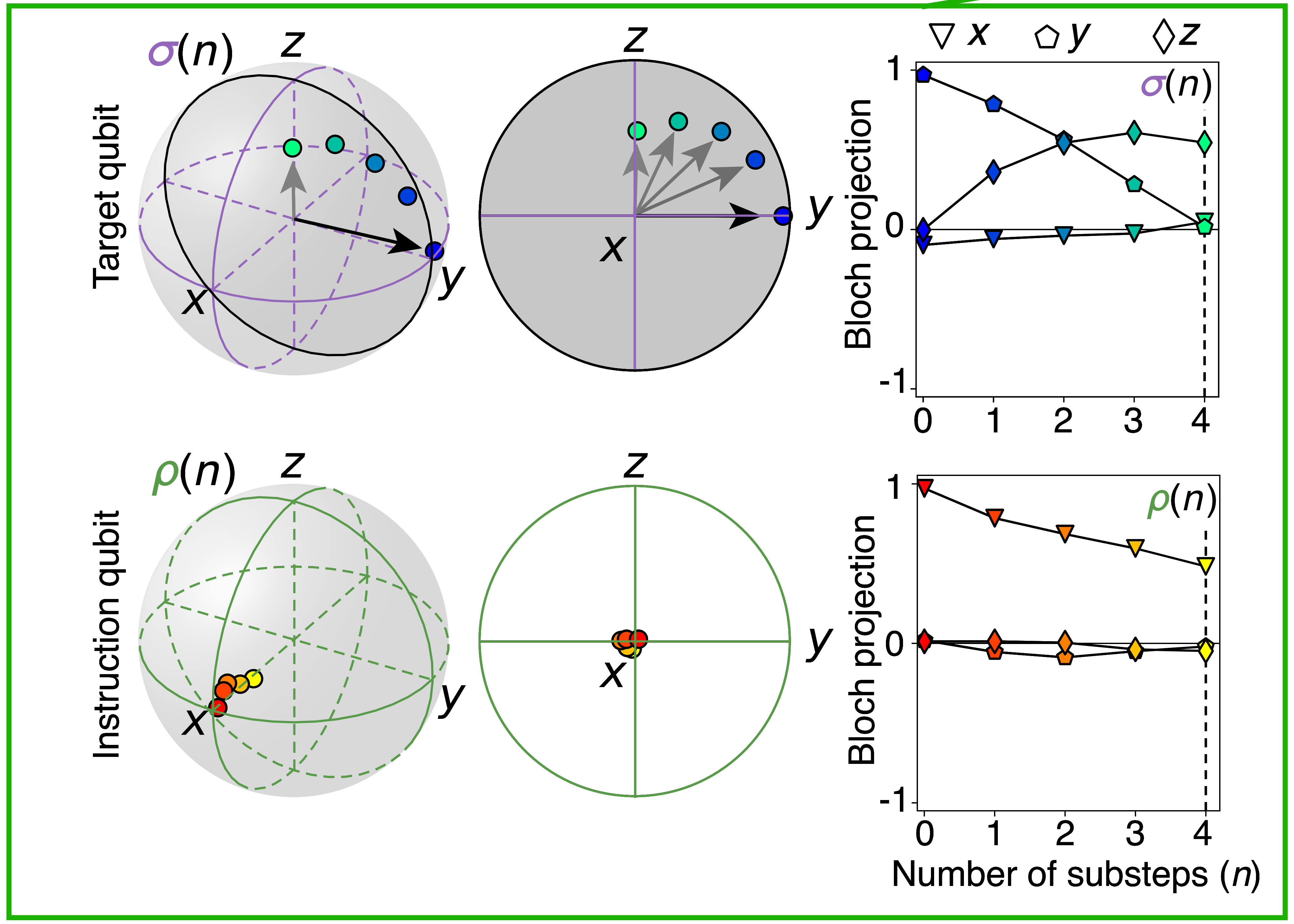
Programming with quantum states





Single qubit DME

Instruction state: $\rho = |+x\rangle\langle +x|$:

$$\rho = \boxed{|+x\rangle\langle +x|} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} = \frac{1}{2}(\mathbb{1} + \sigma_x)$$

Input to density matrix exponentiation:

$$e^{-i\rho\theta} = e^{-i\frac{1}{2}(\mathbb{1}+\sigma_x)\theta} \simeq e^{-i\sigma_x\frac{\theta}{2}} = \boxed{R_x(\theta)}$$

The setting of the instruction qubit "instructs" axis to rotate the target qubit about

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$\boxed{\mathrm{SQM}_v}$ Simulated Quantum Measurement Gate, *A. Greene, MK, et al. (in preparation, 2020)*

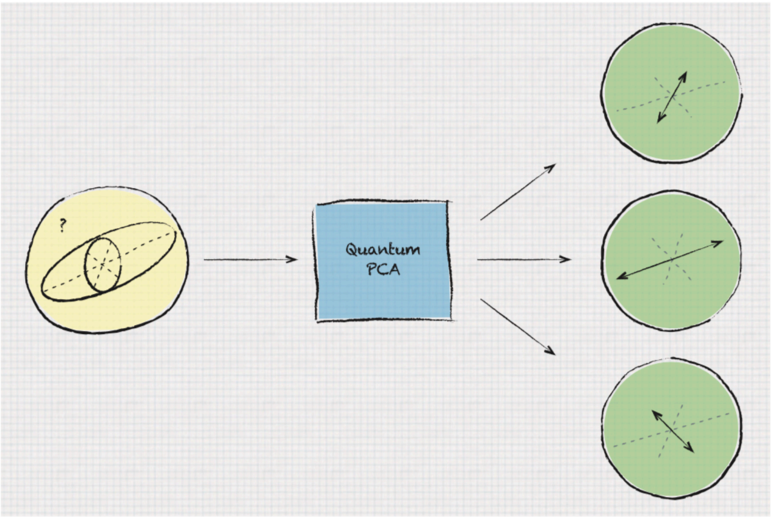
Why are quantum instructions interesting?

DME is exceedingly efficient for generating quantum instructions

Exponential reduction in resource requirements over *any* tomographic strategy
(Kimmel *et al*, npj QI 2017)

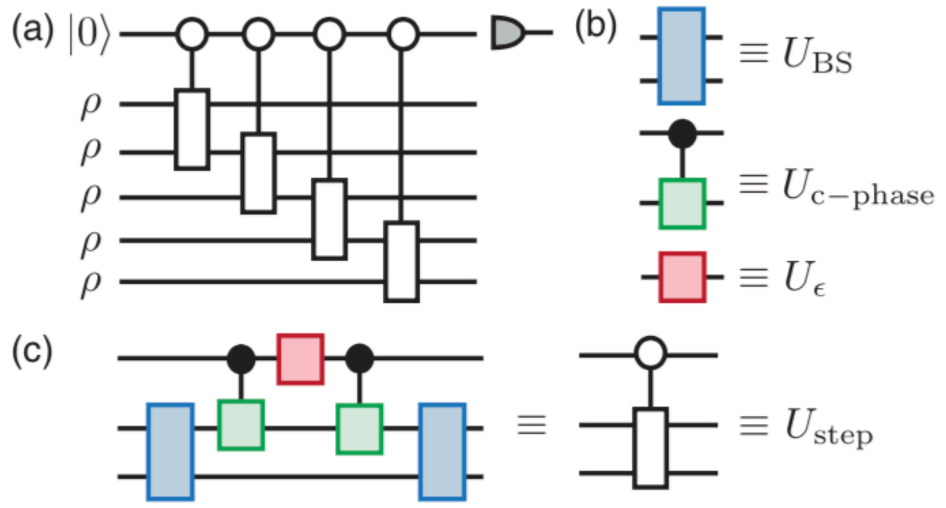
Algorithm runtime scales only logarithmically with dimension of instruction state
(Lloyd et al, Nat. Phys. 2014, Marvian & Lloyd (2016), Kimmel *et al*, npj QI 2017)

Quantum principal component analysis



Lloyd *et al*, Nat. Phys., **10** 631 (2014)

Efficient measurements of entanglement spectra



Pichler *et al*, PRX, **6** 041033 (2016)

Sample optimal Hamiltonian simulation

Theorem 2 *Let $f(t, \delta)$ be the number of copies of ρ required to implement the unitary $e^{-i\rho t}$ up to error δ in trace norm. Then as long as $\delta \leq 1/6$ and $\delta/t \leq 1/(6\pi)$, it holds that $f(t,\delta) = \Theta(t^2/\delta)$.*

Kimmel *et al*, npj QI, **3** 13 (2017)

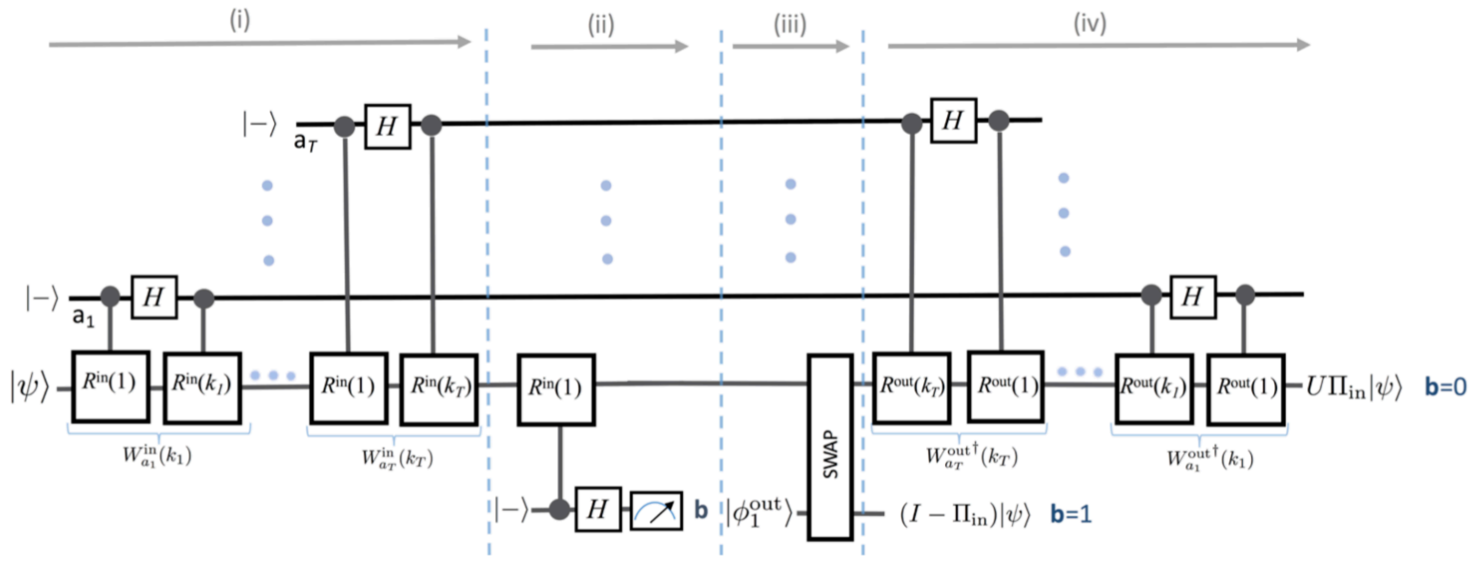
Quantum semi-definite programming

Algorithm 5: Efficiently testing the feasibility of SDPs: Quantum input model.

Initialize the weight matrix $W^{(1)} = I_n$, and $T = \frac{16 \ln n}{\epsilon^2}$;
for $t = 1, 2, \ldots, T$ **do**
  Prepare $\tilde{O}(\mathcal{S}_{\mathrm{Tr}}(B, \epsilon))$ samples of the Gibbs state $\rho^{(t)} = \frac{W^{(t)}}{\mathrm{Tr}[W^{(t)}]}$ by Definition 2;
  Using these $\tilde{O}(\mathcal{S}_{\mathrm{Tr}}(B, \epsilon))$ copies of $\rho^{(t)}$, search for a $j^{(t)} \in [m]$ such that $\mathrm{Tr}(A_{j^{(t)}}\rho^{(t)}) > a_{j^{(t)}} + \epsilon$ by Lemma 3 with $\delta = \frac{\epsilon^2}{400 \ln n}$. Take $M^{(t)} = \frac{1}{2}(I_n - A_{j^{(t)}})$ if such $j^{(t)}$ is found; otherwise, claim that $\mathcal{S}_\epsilon \neq \emptyset$ (the SDP is feasible);
  Define the new weight matrix: $W^{(t+1)} = \exp[-\frac{\epsilon}{2}\sum_{\tau=1}^{t} M^{(\tau)}]$;
Claim that $\mathcal{S}_0 = \emptyset$ and terminate the algorithm.

Brandao *et al*, arXiv:1710.02581 (2017)

Universal quantum emulation



Marvian & Lloyd, arXiv: 1606.02734 (2016)

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OUTRO

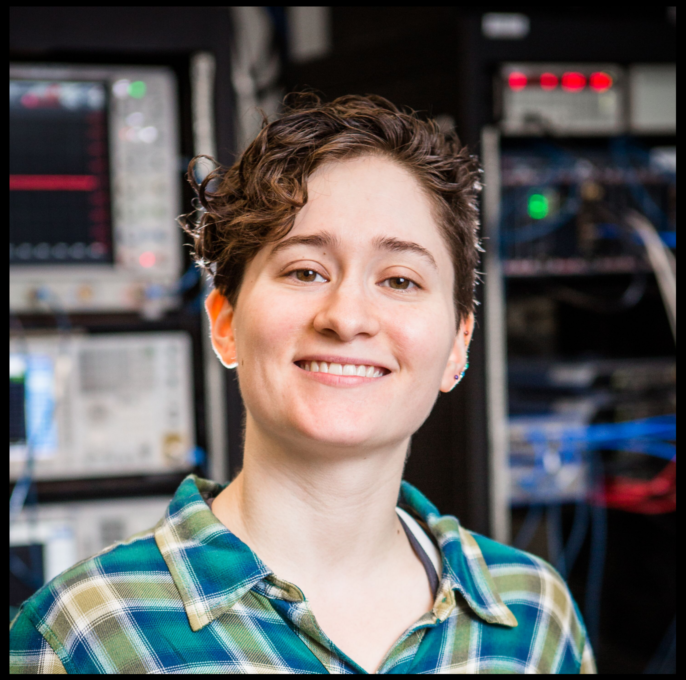
Programming parity can be restored to quantum computing using the **Density Matrix Exponentiation algorithm**

We demonstrated a proof of principle version of this algorithm using superconducting qubits, and a novel gate construction for approximately resetting a known state

More details: **www.arXiv.org/abs/2001.08838**

Cirq Labber QUANTUM

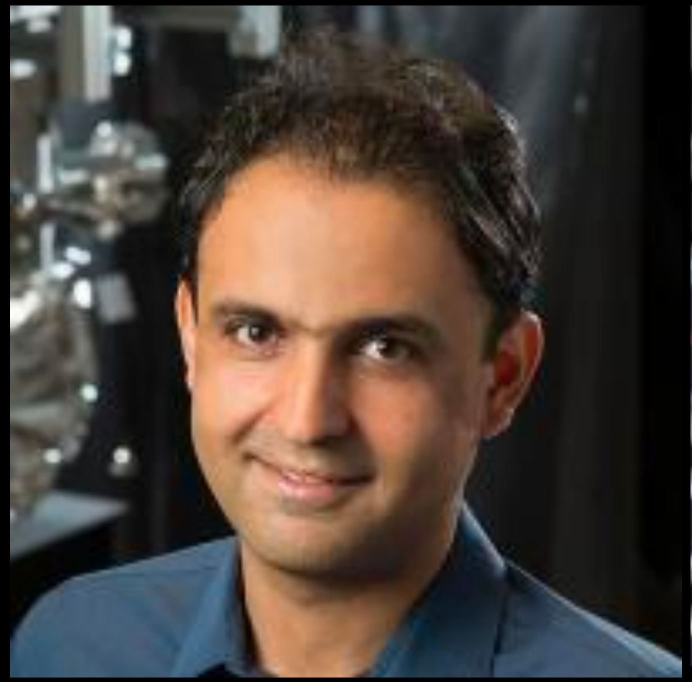

Mollie Schwartz
Lincoln Lab


Ami Greene
MIT


Gabriel Samach
MIT/Lincoln Lab


Andreas Bengtsson
Chalmers/Google


Chris McNally
MIT

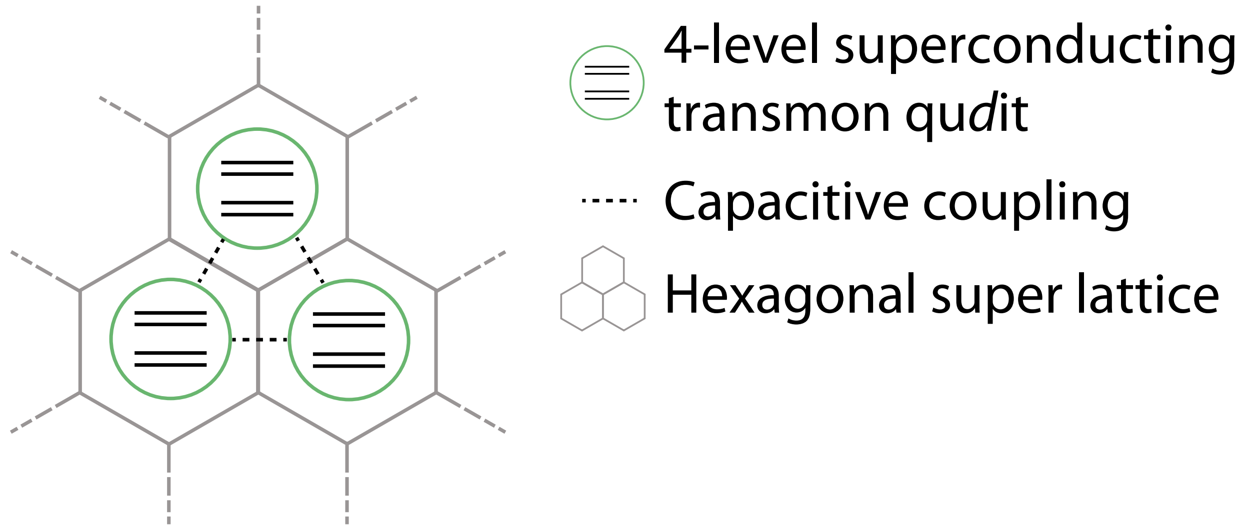

Iman Marvian
Duke

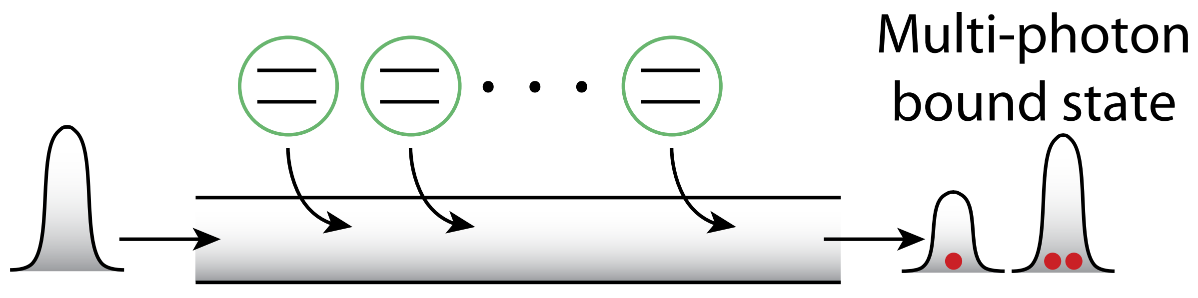

Will Oliver
MIT

Superconducting quantum computing in Denmark

XQCS quantum computer science group at Center for Quantum Devices, University of Copenhagen

Quantum algorithms and simulation

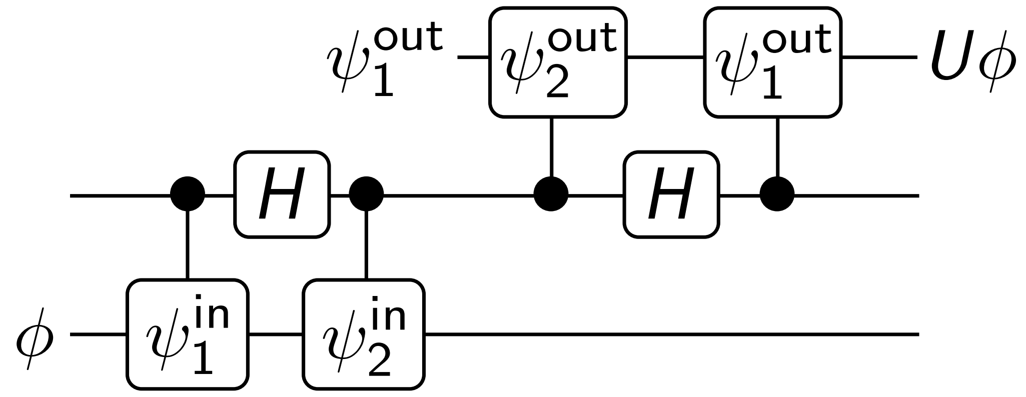




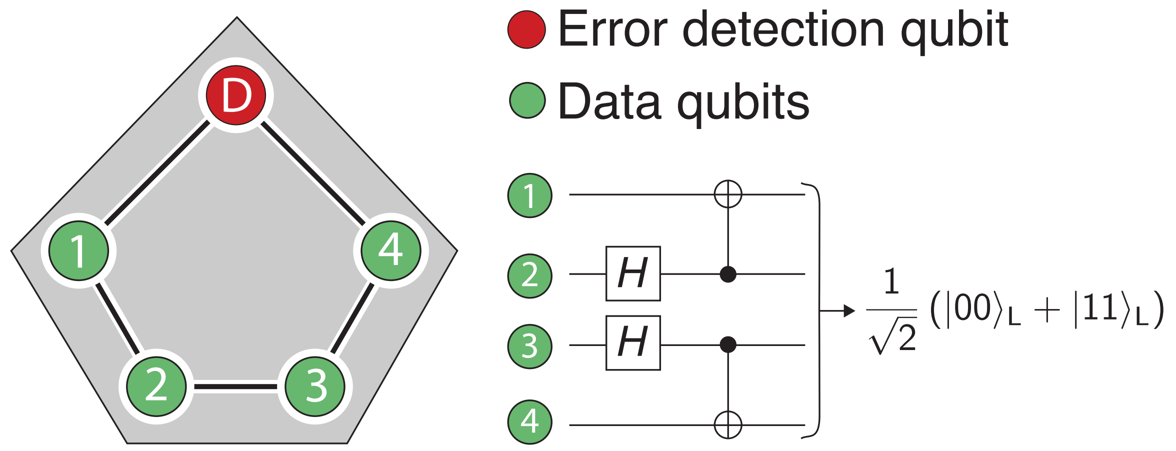
Quantum program stored in U

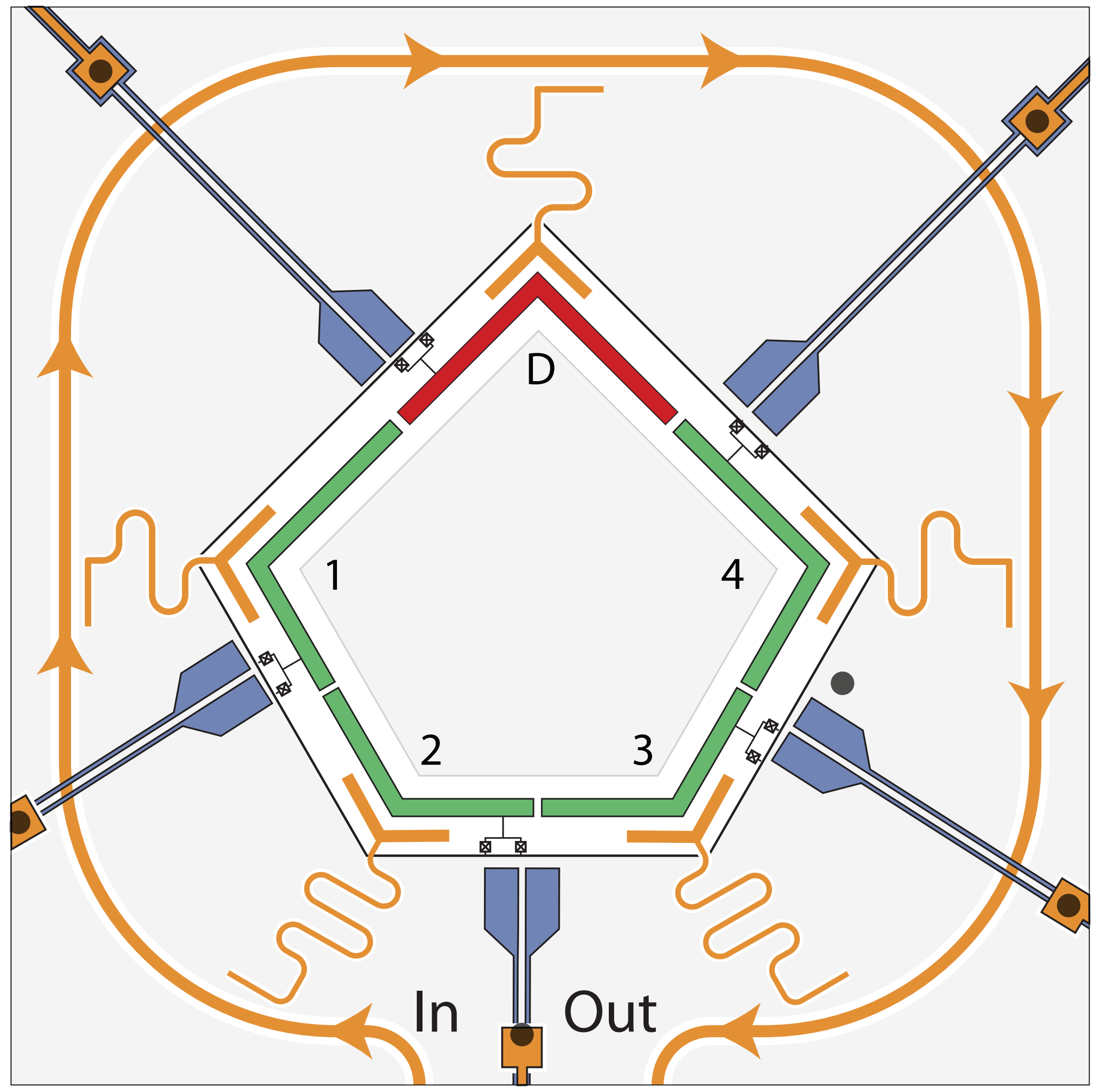
$$\psi_1^{\text{in}} - \boxed{U} - \psi_1^{\text{out}} \qquad \psi_2^{\text{in}} - \boxed{U} - \psi_2^{\text{out}}$$

Quantum emulation of U



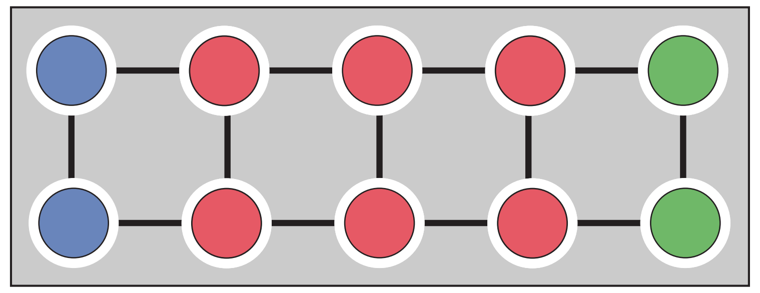
Quantum fault tolerance

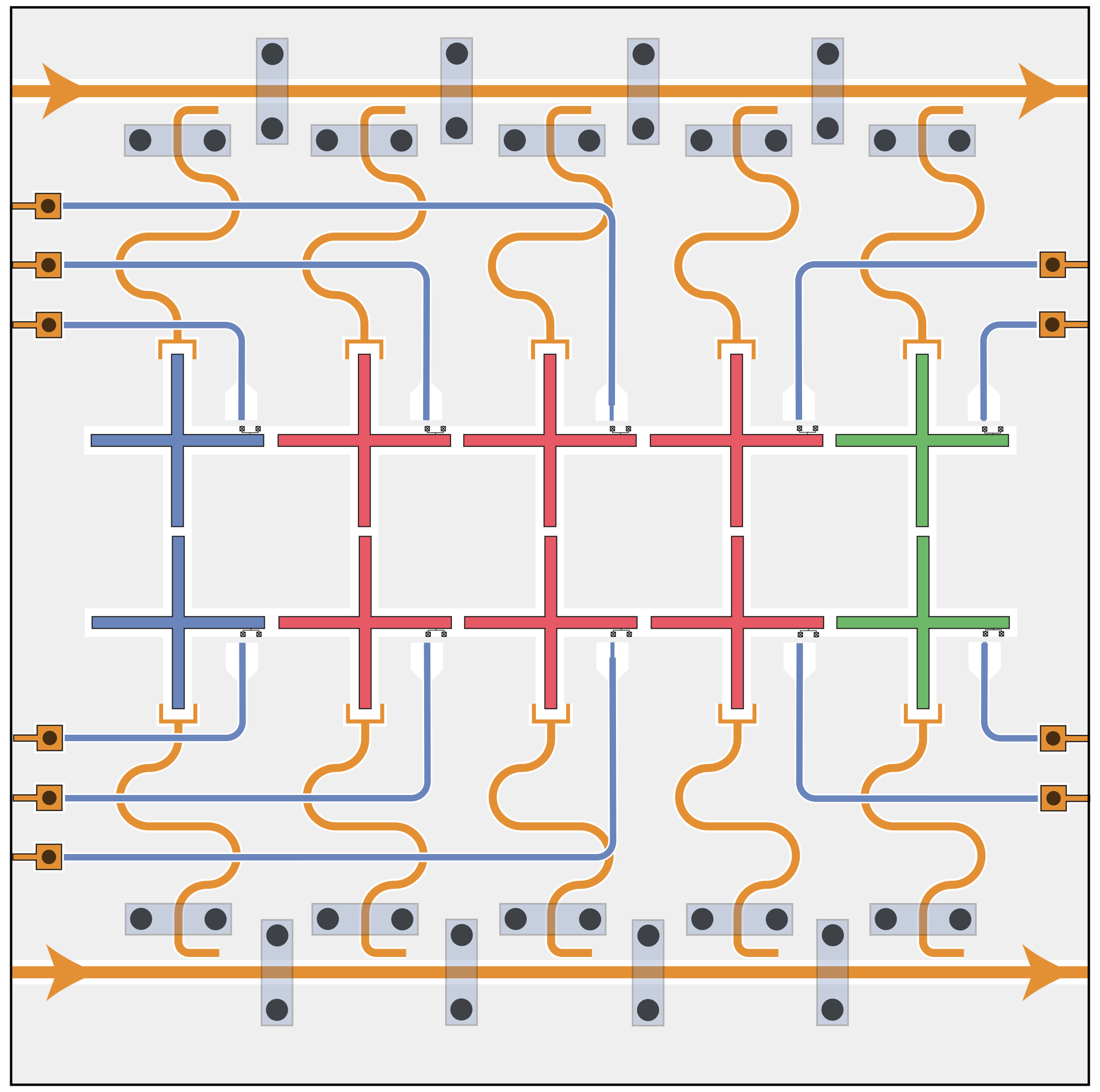




On-chip quantum communication protocols

Alice Noisy channel Bob





Want to study foundational problems and applications of superconducting qubits to quantum information processing?
We are looking for students and postdocs! Let me know at mkjaergaard@nbi.ku.dk