Invitation to the Utility Era

2024/04/05

Tamiya Onodera

IBM Research – Tokyo

Path to the Utility era in Quantum Computing

The goal of this course is to learn how to implement utility-scale applications on a quantum computer. To achieve the goal, the course covers from the basics of quantum information to recent advances of quantum algorithms for noisy quantum devices as well as circuit optimization and error mitigation techniques. The course also introduces how to implement quantum algorithms using open-source framework of quantum computing and real quantum device with more than 127 qubits. The course is intended to help students understand the potential and limitations of currently available quantum devices.

In May of 1981, IBM and MIT hosted the Physics of Computation Conference

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1982

“Nature isn’t classical, dammit,
and if you want to make a simulation of nature,
you’d better make it quantum mechanical,
and by golly, it’s a wonderful problem,
because it doesn’t look so easy.”

Algorithms for Quantum Computation: Discrete Logarithms and Factoring

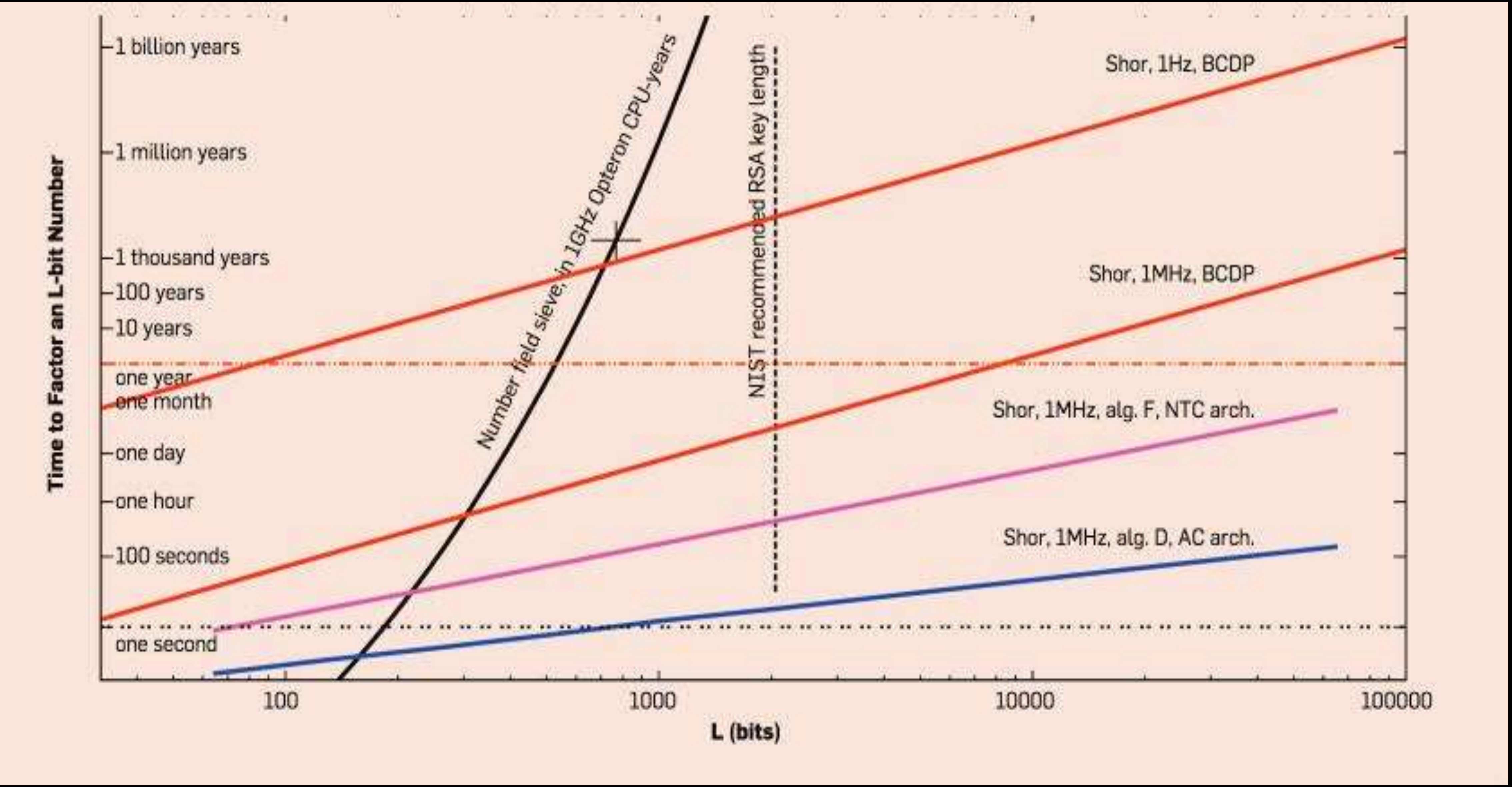
Peter W. Shor
AT&T Bell Labs
Room 2D-149
600 Mountain Ave.
Murray Hill, NJ 07974, USA

1994

Proceedings of the 35th Annual Symposium of Foundations of Computer Science, Pages 124-134

"This paper gives Las Vegas algorithms for finding discrete logarithms and factoring integers on a quantum computer that take a number of steps which is polynomial in the input size,"

R. Van Meter and C. Horsman, “A Blueprint for Building a Quantum Computer”, Communications of the ACM, October 2013



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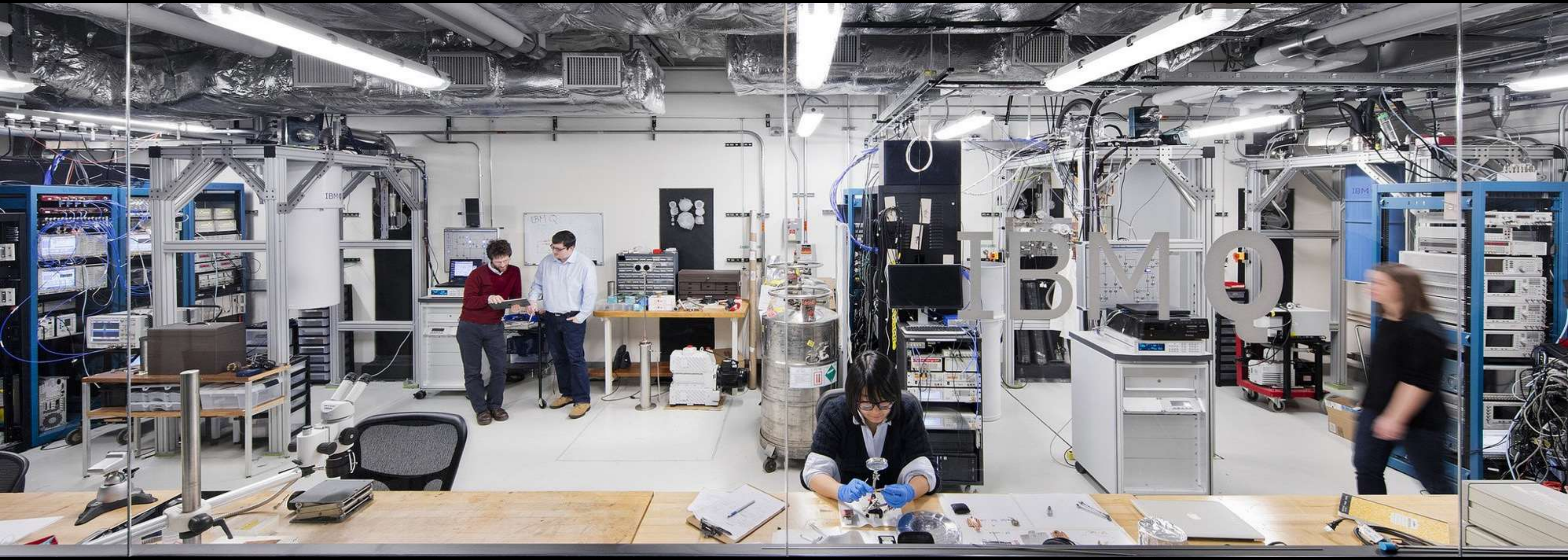
Proceedings of the 35th Annual Symposium of Foundations of Computer Science, Pages 124-134

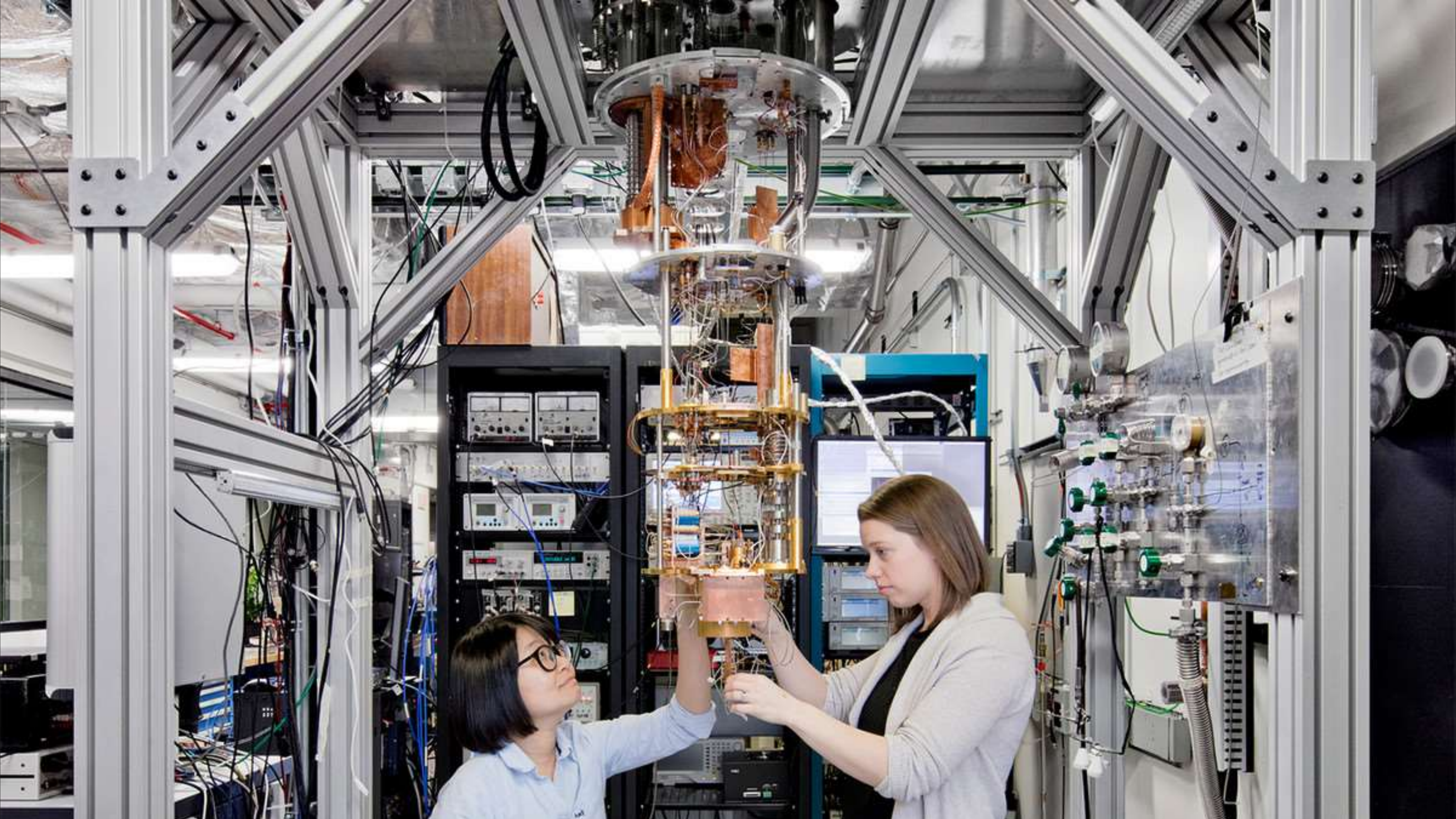
“Currently, nobody knows how to build a quantum computer,”

”It is hoped that this paper will stimulate research on whether it is feasible to actually con-struct a quantum computer.”

The IBM Quantum Experience
May 2016

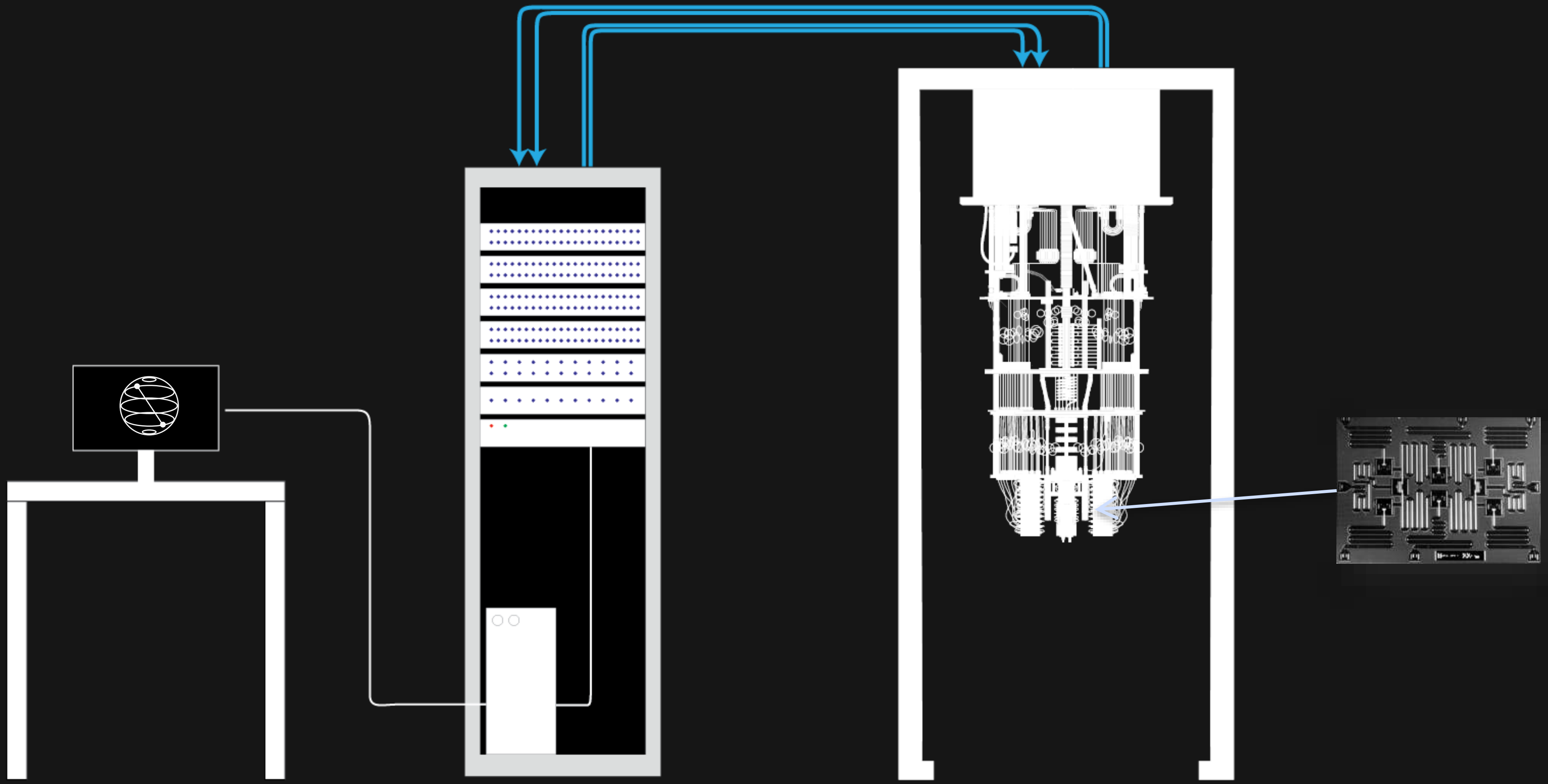
https://quantum-computing.ibm.com/


IBMQ



IBM Quantum System One at Shin-Kawasaki

Quantum Computers



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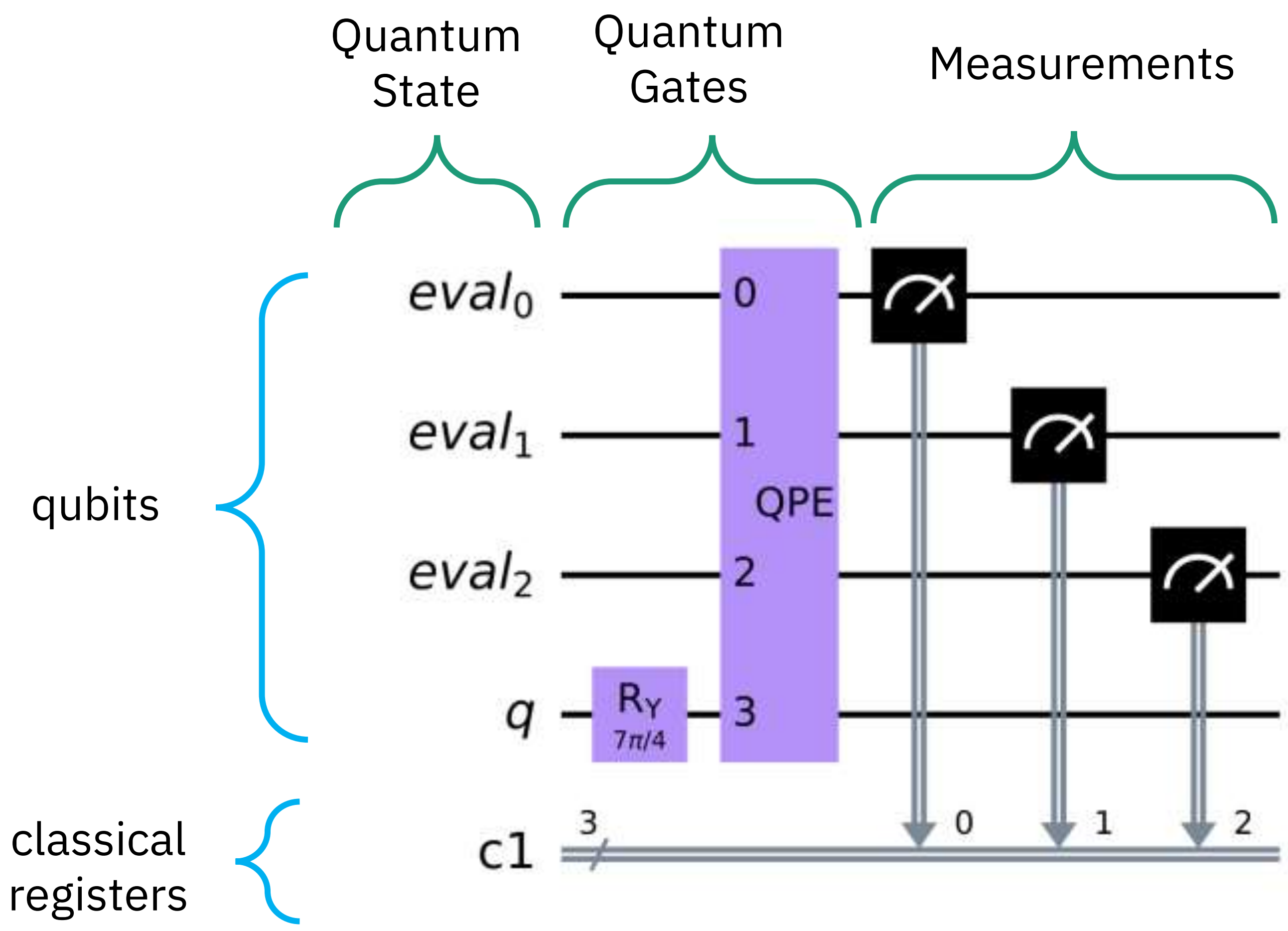
Quantum Circuits



Quantum State: a single qubit

- Mathematically represented as a unit vector in a 2-dimensional complex vector space

- The special states known as computational basis.

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

- The arbitrary state can be represented as a linear combination of the two.

$$\alpha|0\rangle + \beta|1\rangle \quad \text{s.t. } |\alpha|^2 + |\beta|^2 = 1$$

Quantum State: *n*-qubit

- Mathematically represented as a unit vector in a 2^n -dimensional complex vector space
- For instance, the 3-qubit state with each being $\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$:

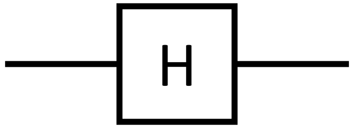
$$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} \otimes \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} \otimes \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} = \frac{1}{\sqrt{8}}\begin{pmatrix}1\\1\\1\\1\\1\\1\\1\\1\end{pmatrix}$$

where the computational basis are

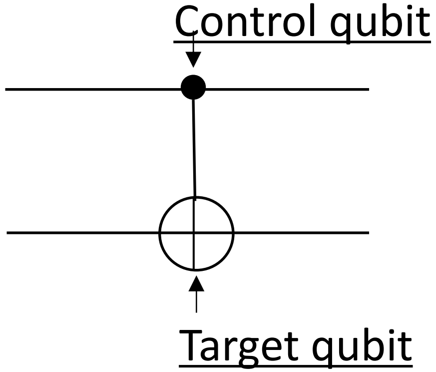
$|000\rangle$ (= $|0\rangle \otimes |0\rangle \otimes |0\rangle$), $|001\rangle$, $|010\rangle$, $|011\rangle$, $|100\rangle$, $|101\rangle$, $|110\rangle$, $|111\rangle$

Quantum Gate: *n*-qubit

- Mathematically represented as a 2^n by 2^n unitary matrix



$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}$$



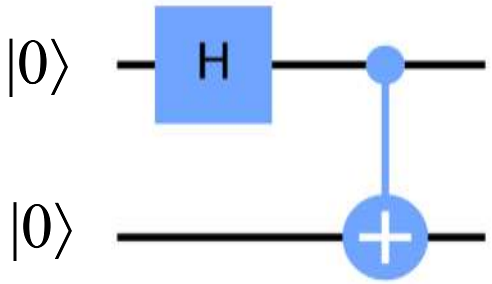
$$\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{pmatrix}$$

$$\mathrm{H}|0\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

$$\mathrm{H}|1\rangle = \frac{1}{\sqrt{2}}|0\rangle - \frac{1}{\sqrt{2}}|1\rangle$$

$$CNOT|00\rangle = |00\rangle$$
$$CNOT|01\rangle = |01\rangle$$
$$CNOT|10\rangle = |11\rangle$$
$$CNOT|11\rangle = |10\rangle$$

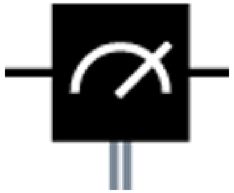
Example



$$
\begin{aligned}
&(CNOT \circ (H \otimes I))\ (|0\rangle \otimes |0\rangle) \\
&= CNOT((\tfrac{1}{\sqrt{2}}|0\rangle + \tfrac{1}{\sqrt{2}}|1\rangle) \otimes |0\rangle) \\
&= CNOT(\tfrac{1}{\sqrt{2}}|0\rangle \otimes |0\rangle + \tfrac{1}{\sqrt{2}}|1\rangle \otimes |0\rangle) \\
&= \tfrac{1}{\sqrt{2}}|0\rangle \otimes |0\rangle + \tfrac{1}{\sqrt{2}}|1\rangle \otimes |1\rangle
\end{aligned}
$$

- The resulting state is called an entangled state.
  - Cannot be represented as a tensor product
  - The source of the tremendous computational power of quantum computation.

Measurement

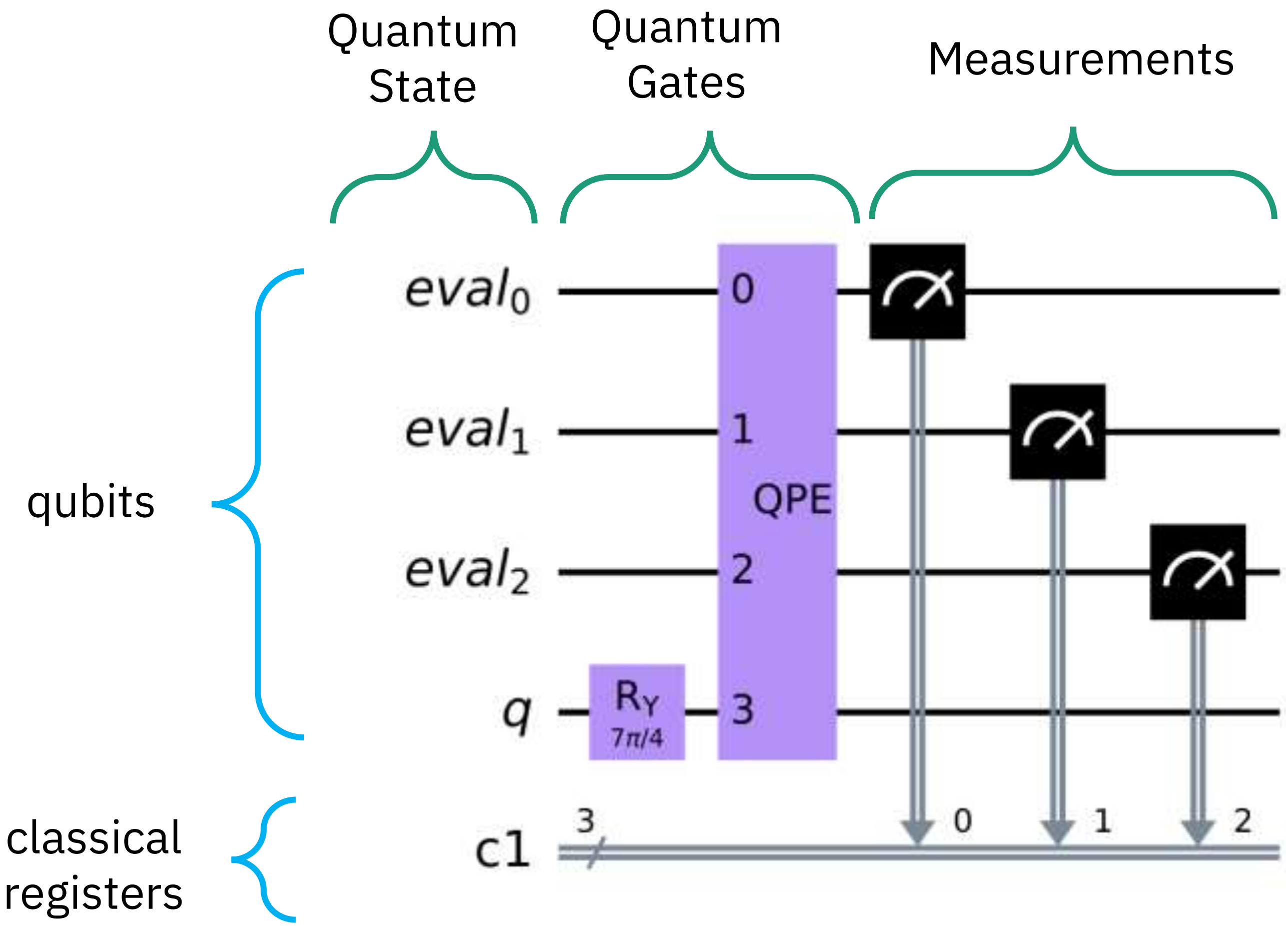


- The only way to access the state of a qubit.

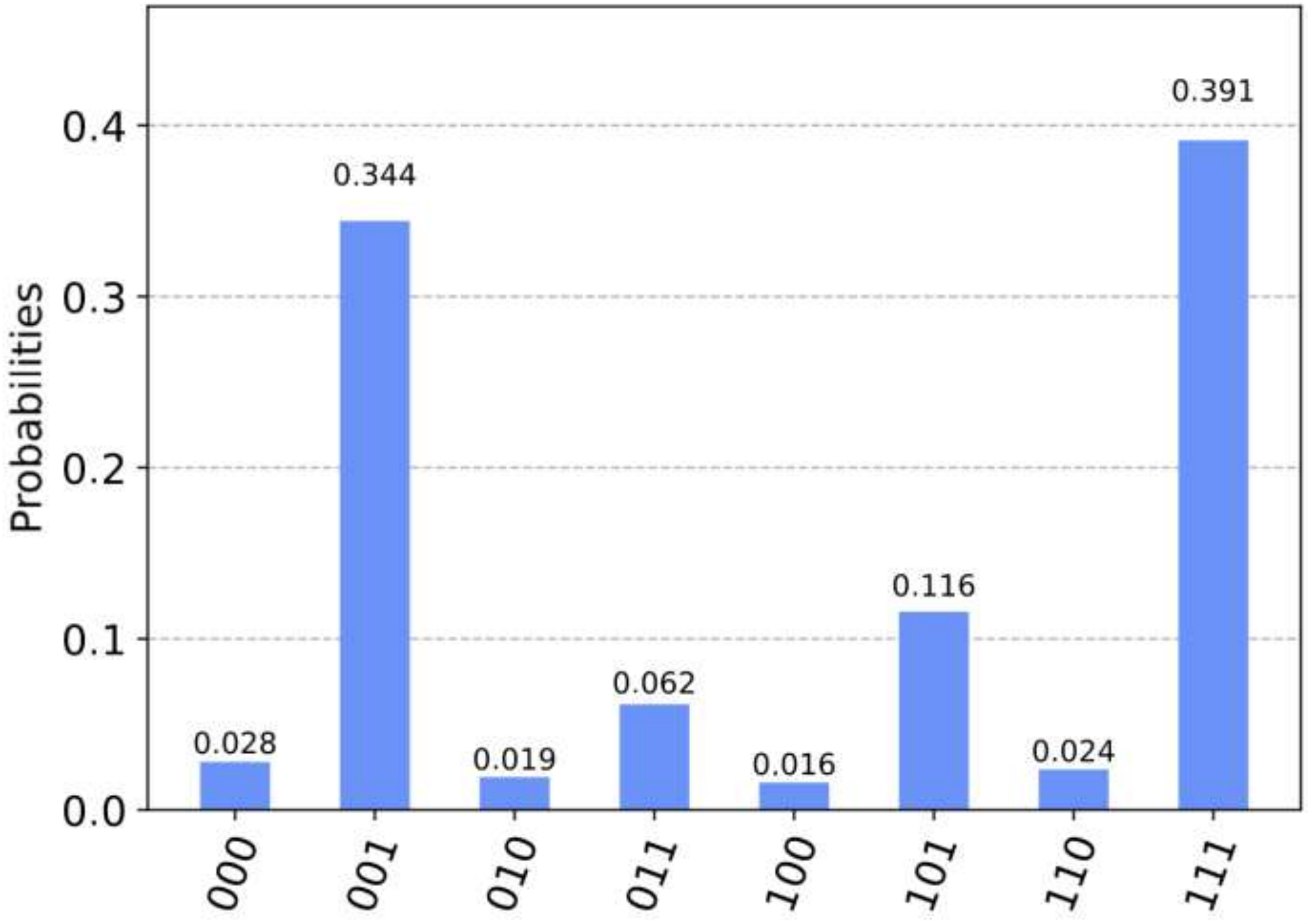
- Assume that the state is $\alpha|0\rangle + \beta|1\rangle$ s.t. $|\alpha|^2 + |\beta|^2 = 1$.

- Measuring the qubit in the computational basis, we will obtain the outcome 0 or 1 with the probabilities $|\alpha|^2$and $|\beta|^2$, respectively.
  - The final state is in the state $|0\rangle$ or $|1\rangle$, corresponding to the outcome.
  - The superposition collapsed!

Quantum Circuits



An Example of Execution Results



Exponential growth

$$2^n$$

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Important Landmarks of Quantum Algorithms

1994 1996 2009 2014 2022

Shor's Prime Factorization

$$N = p \times q$$

FOCS 1994

Grover's Quantum Search

$$x \in \{0,1\}^n \text{ s.t. } f(x) = 1$$

STOC 1996

HHL Algorithm
(Quantum Algorithm for Linear Equations)

$$A\left|x\right\rangle = \left|b\right\rangle$$

Harrow, Hassidim Lloyd, PRL 2009

Variational Quantum Eigensolvers (VQE)

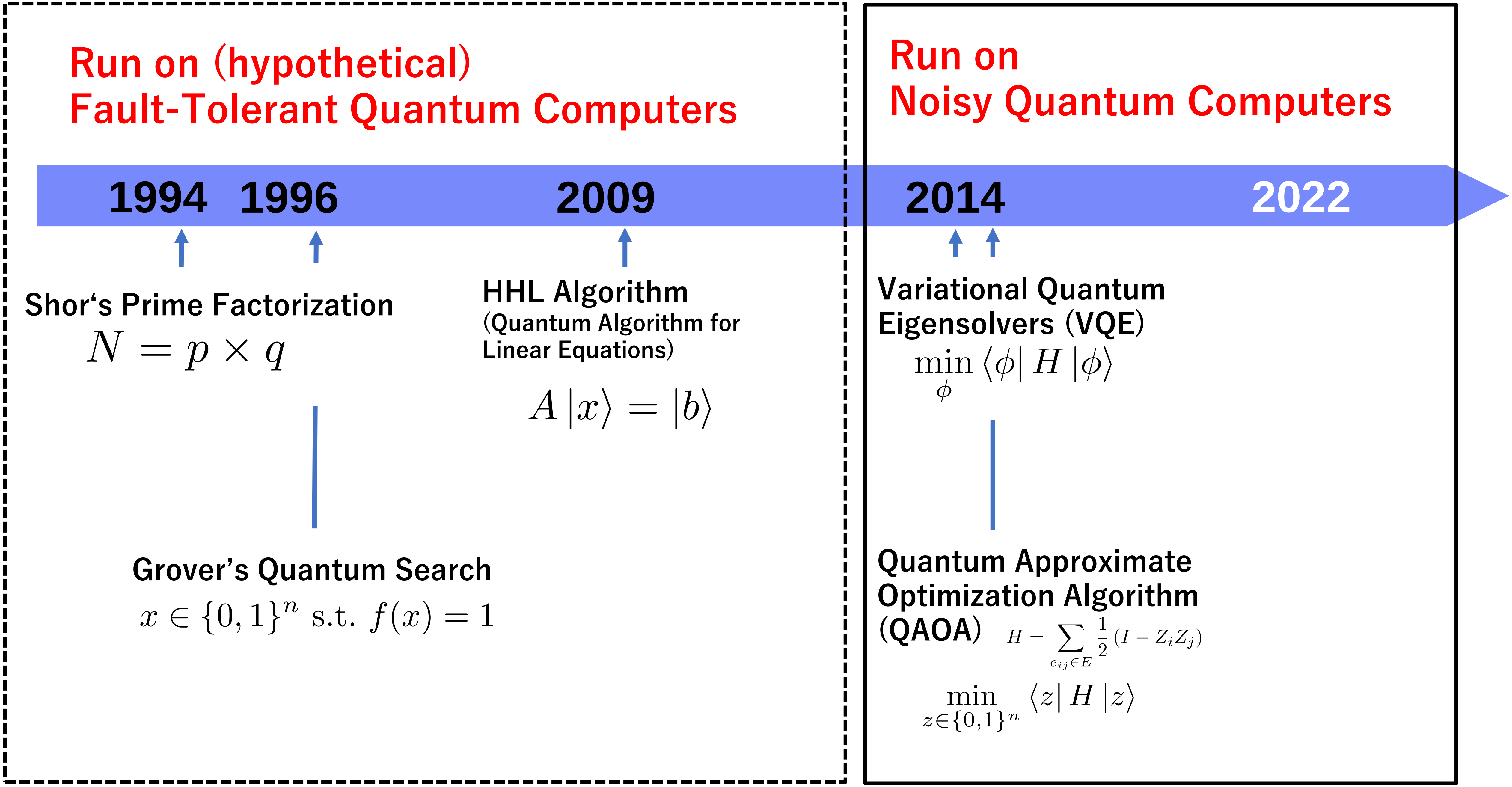
$$\min_{\phi} \left\langle\phi\right| H \left|\phi\right\rangle$$

Peruzzo et al., Nat. Comm 2014

Quantum Approximate Optimization Algorithm (QAOA) $H = \sum_{e_{ij}\in E} \frac{1}{2}(I - Z_i Z_j)$

$$\min_{z\in\{0,1\}^n} \left\langle z\right| H \left|z\right\rangle$$

Farhi, Goldstone, Gutmann, 2014


Run on (hypothetical)
Fault-Tolerant Quantum Computers
Run on
Noisy Quantum Computers
1994
1996
2009
2014
2022
Shor's Prime Factorization
$N = p \times q$
HHL Algorithm
(Quantum Algorithm for Linear Equations)
$A |x\rangle = |b\rangle$
Grover's Quantum Search
$x \in \{0,1\}^n$ s.t. $f(x) = 1$
Variational Quantum Eigensolvers (VQE)
$\min_{\phi} \langle\phi| H |\phi\rangle$
Quantum Approximate Optimization Algorithm (QAOA)
$H = \sum_{e_{ij} \in E} \frac{1}{2}(I - Z_i Z_j)$
$\min_{z \in \{0,1\}^n} \langle z| H |z\rangle$

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https://quantum.ibm.com

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ibm_cairo

OpenQASM 3

Details

27
Qubits

2.4K
CLOPS

Status:	Online
Total pending jobs:	0 jobs
Processor type ⓘ:	Falcon r5.11
Version:	1.3.7
Basis gates:	CX, ID, RZ, SX, X
Your instance usage:	14 jobs

Median CNOT error:	1.146e-2
Median SX error:	2.540e-4
Median readout error:	1.360e-2
Median T1:	88.57 us
Median T2:	94.91 us

Instance access limits

Your upcoming reservations 0

Calibration data Last calibrated: 31 minutes ago

Error per layered gate

ibm_cairo OpenQASM 3

Details

Instance access limits

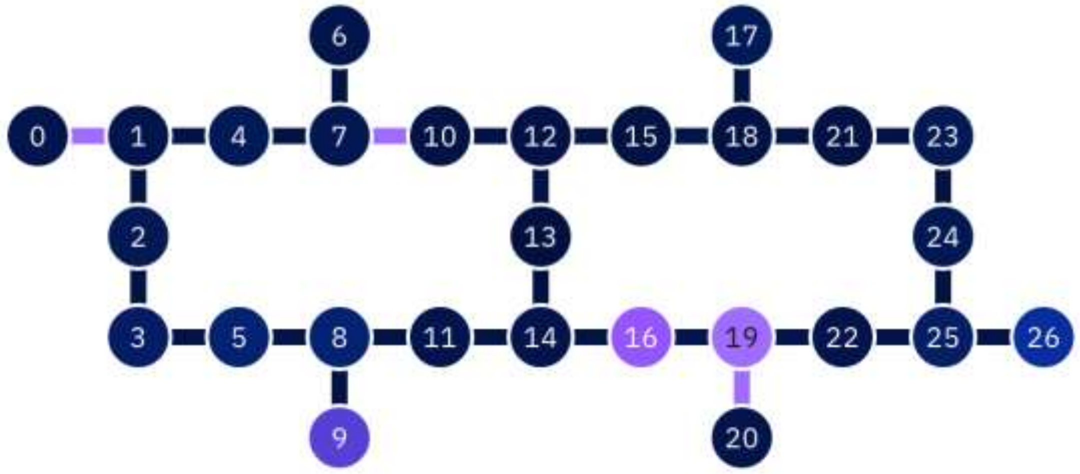
Your upcoming reservations 0

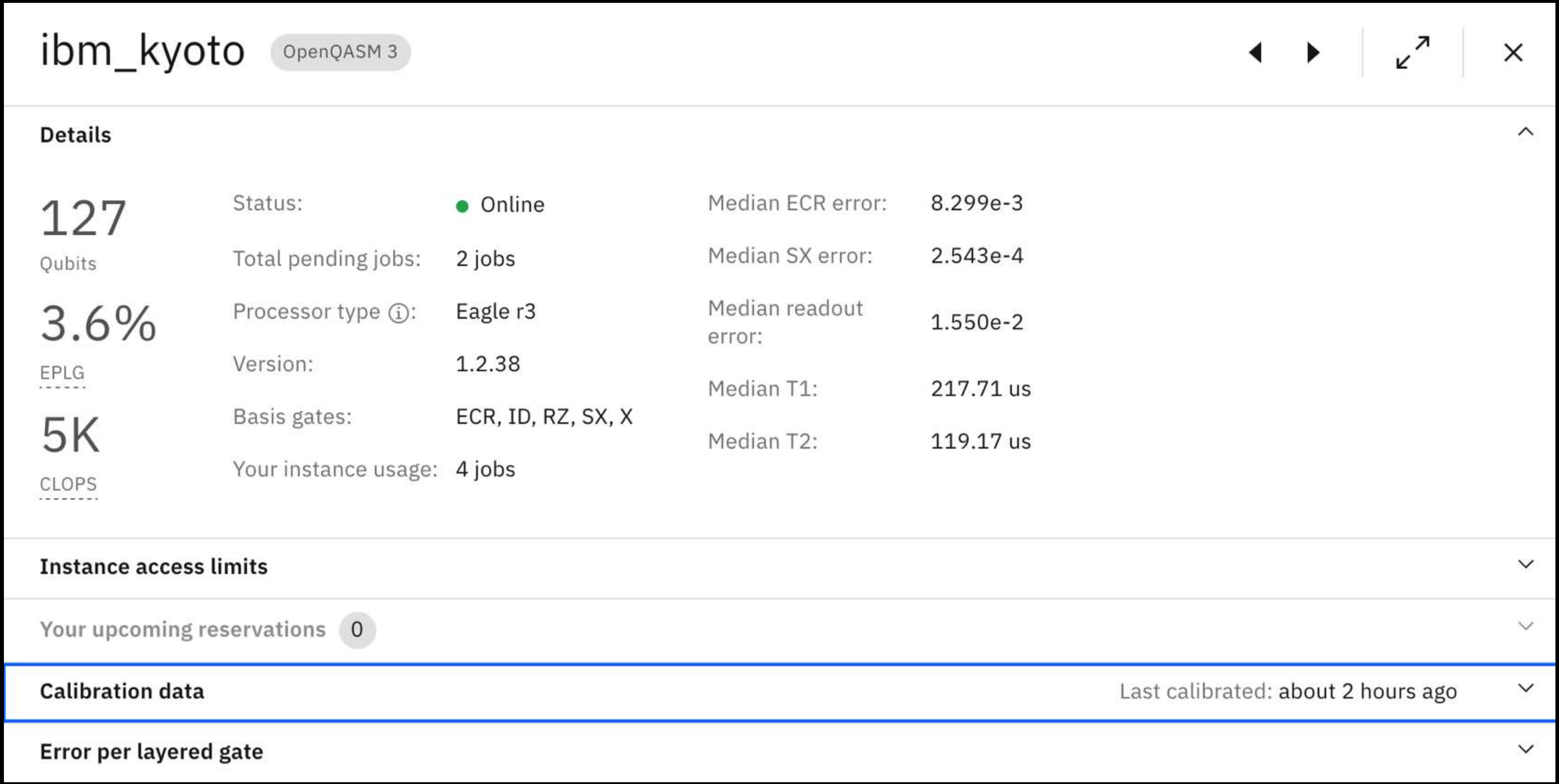
Calibration data Last calibrated: 31 minutes ago

Map view | Graph view | Table view | Expand map view

Qubit: Readout assignment error — Median 1.360e-2, min 6.300e-3, max 1.516e-1

Connection: CNOT error — Median 1.146e-2, min 4.583e-3, max 1.000e+0




ibm_kyoto
OpenQASM 3
Details
127
Qubits
3.6%
EPLG
5K
CLOPS
Status:
Online
Total pending jobs:
2 jobs
Processor type:
Eagle r3
Version:
1.2.38
Basis gates:
ECR, ID, RZ, SX, X
Your instance usage:
4 jobs
Median ECR error:
8.299e-3
Median SX error:
2.543e-4
Median readout error:
1.550e-2
Median T1:
217.71 us
Median T2:
119.17 us
Instance access limits
Your upcoming reservations
0
Calibration data
Last calibrated: about 2 hours ago
Error per layered gate

ibm_kyoto OpenQASM 3

Qubit: Readout assignment error

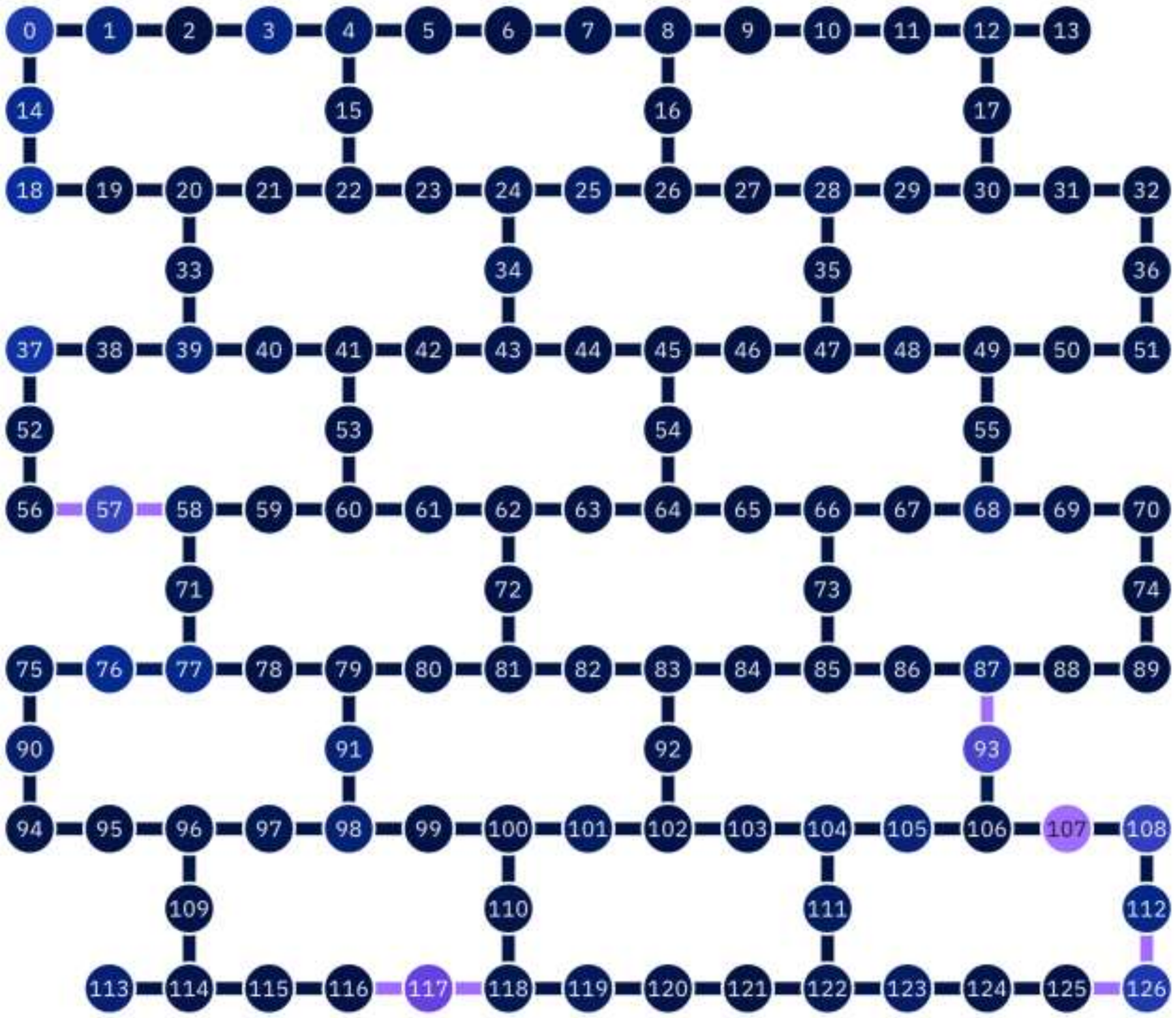
Median 1.550e-2

min 3.300e-3 max 4.857e-1

Connection: ECR error

Median 8.299e-3

min 3.615e-3 max 1.000e+0



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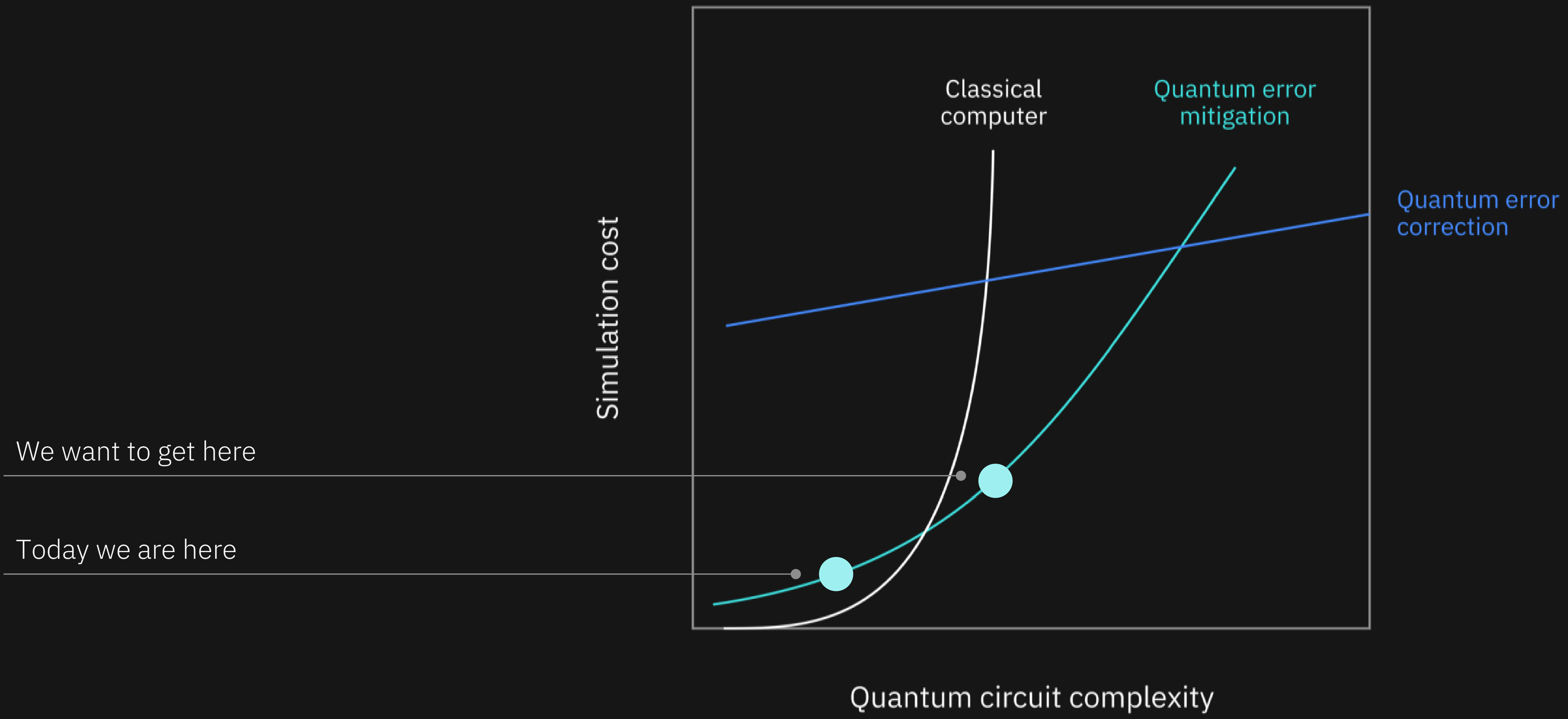
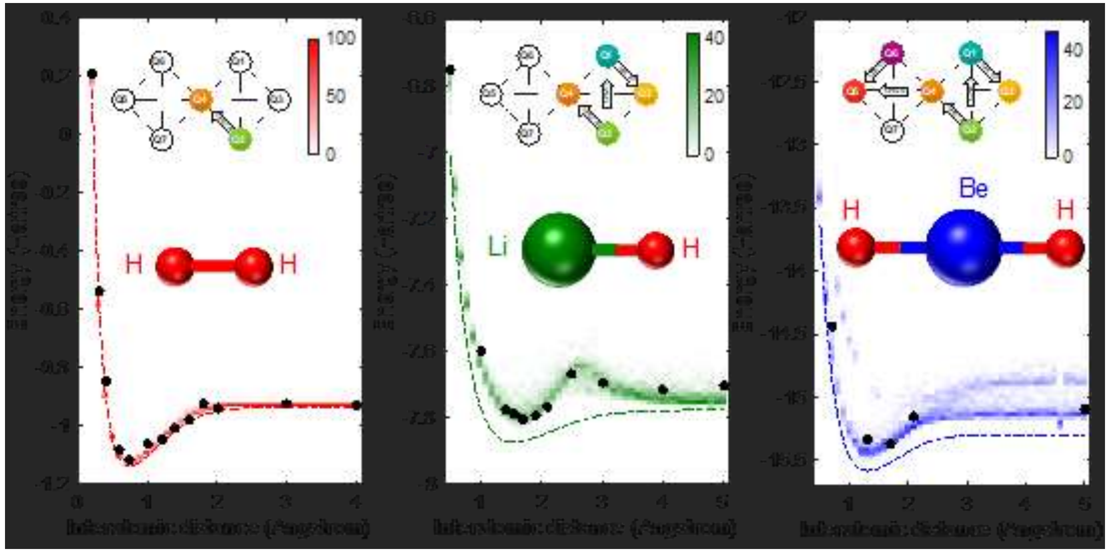
Quantum Error Mitigation and Correction

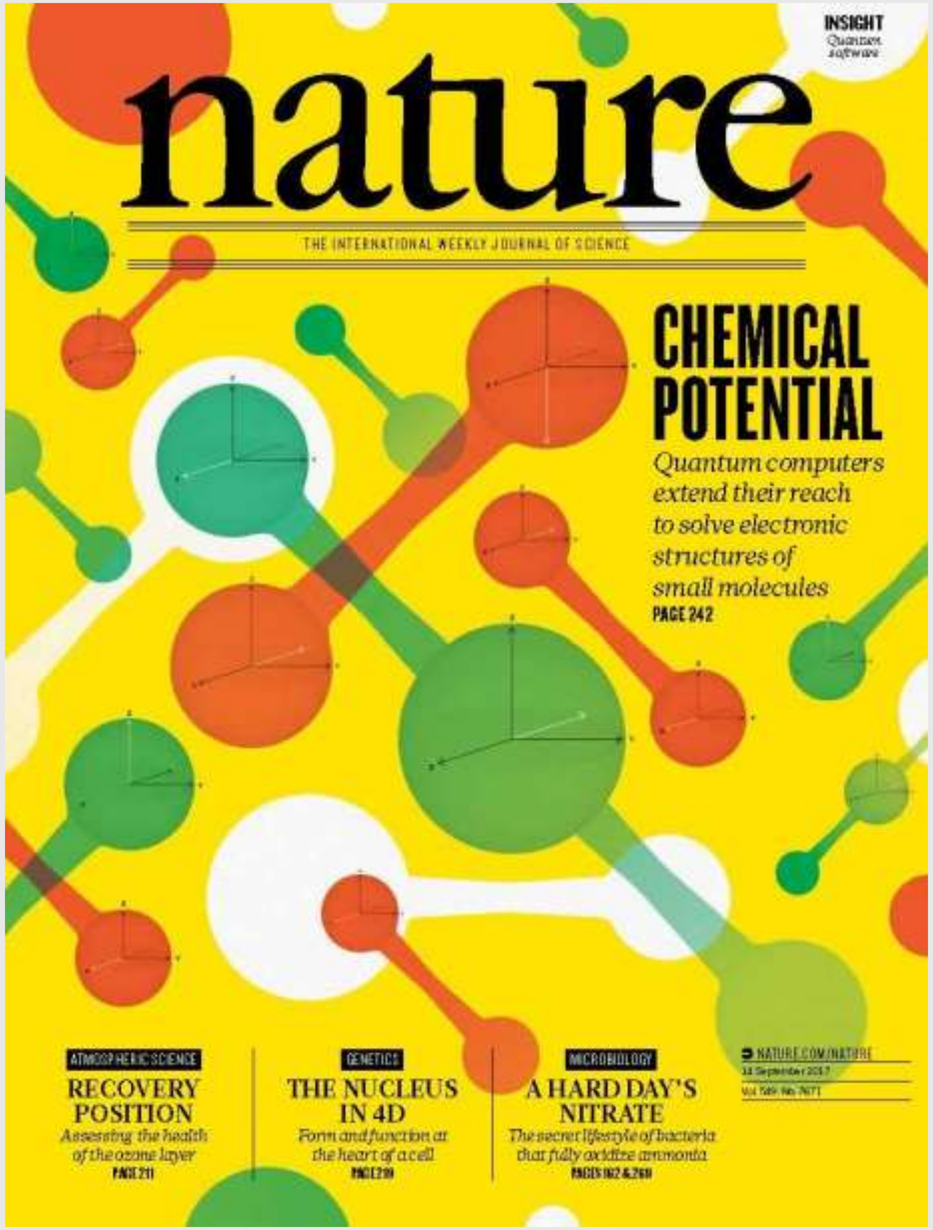


The IBM Quantum Experience
May 2016

https://quantum-computing.ibm.com/

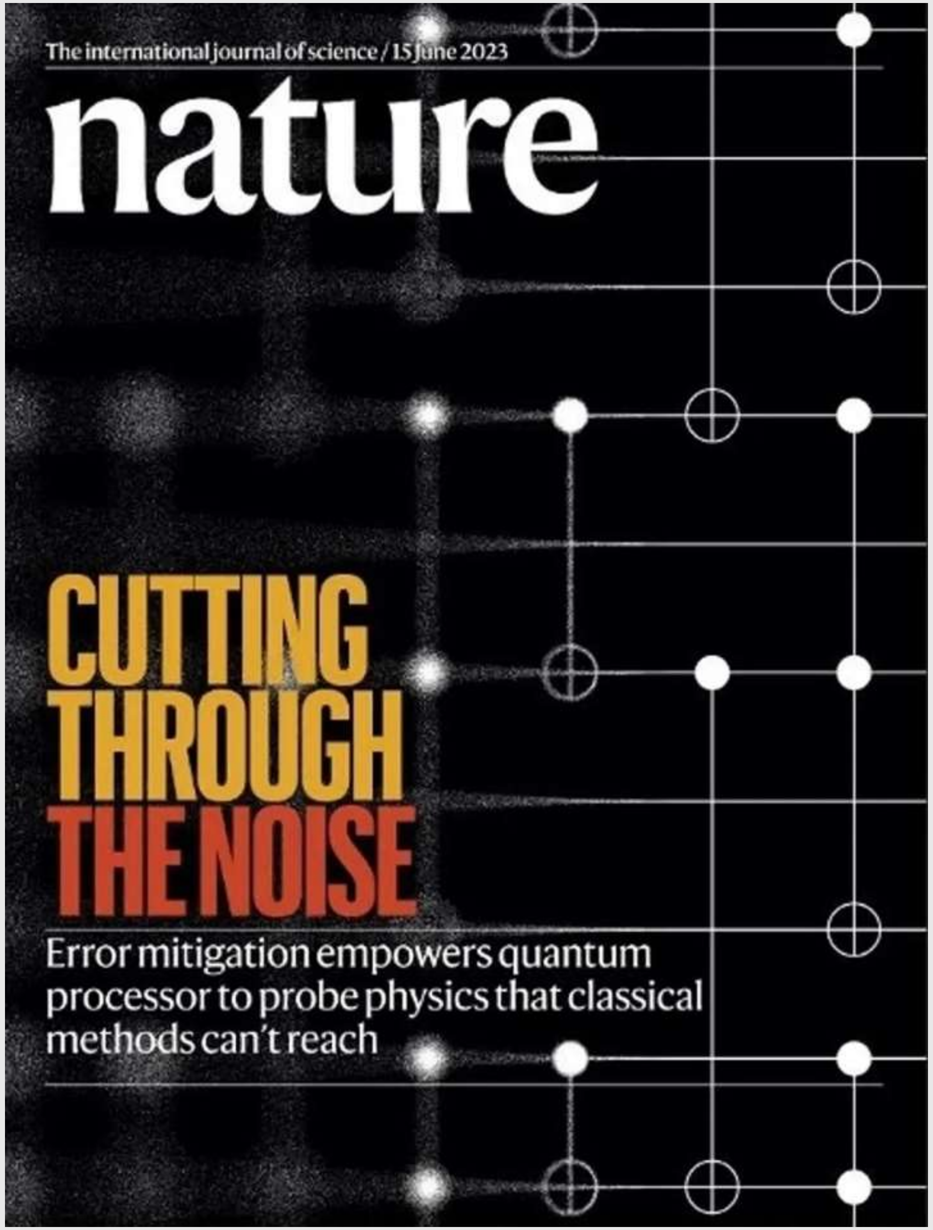
September 2017



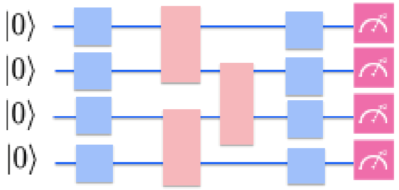


June 2023

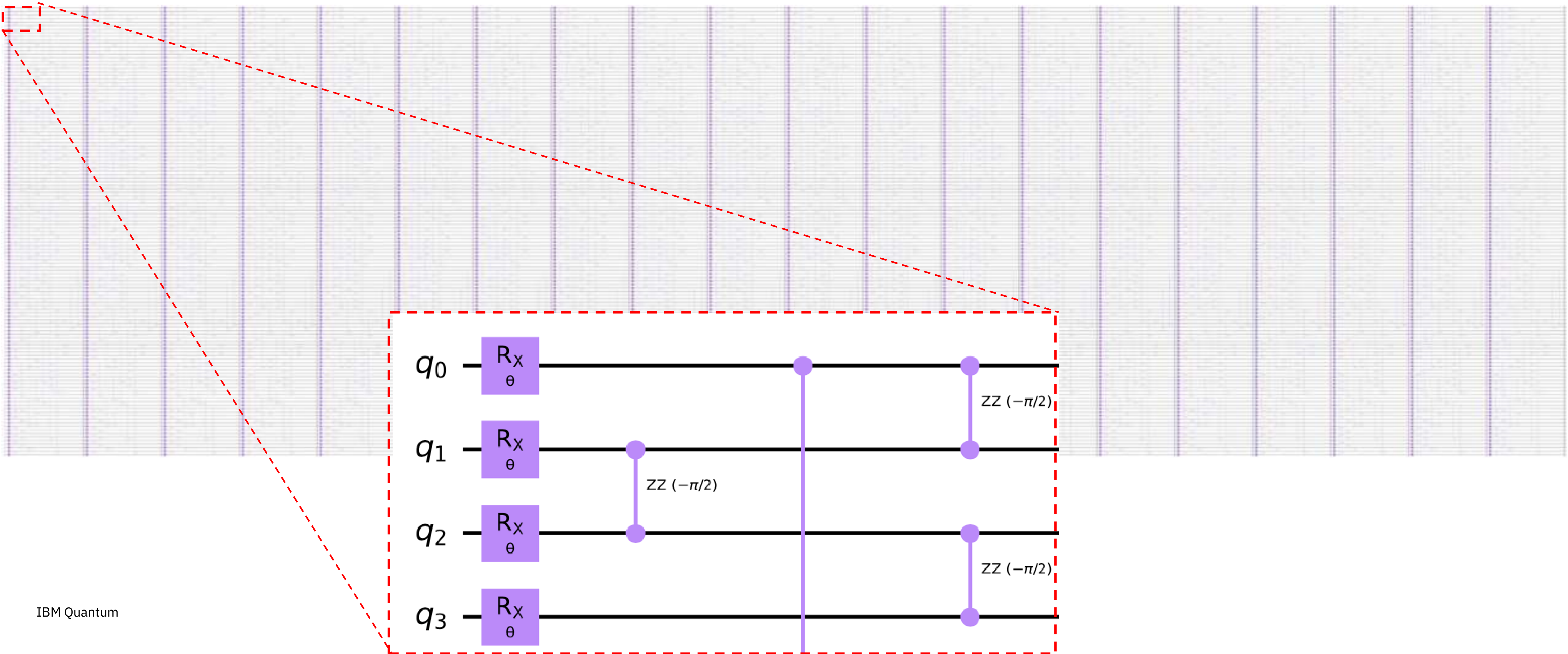
A new era has begun: Quantum Utility



127 qubit x 60 entangling layers



2017: 4 qubit, depth 2

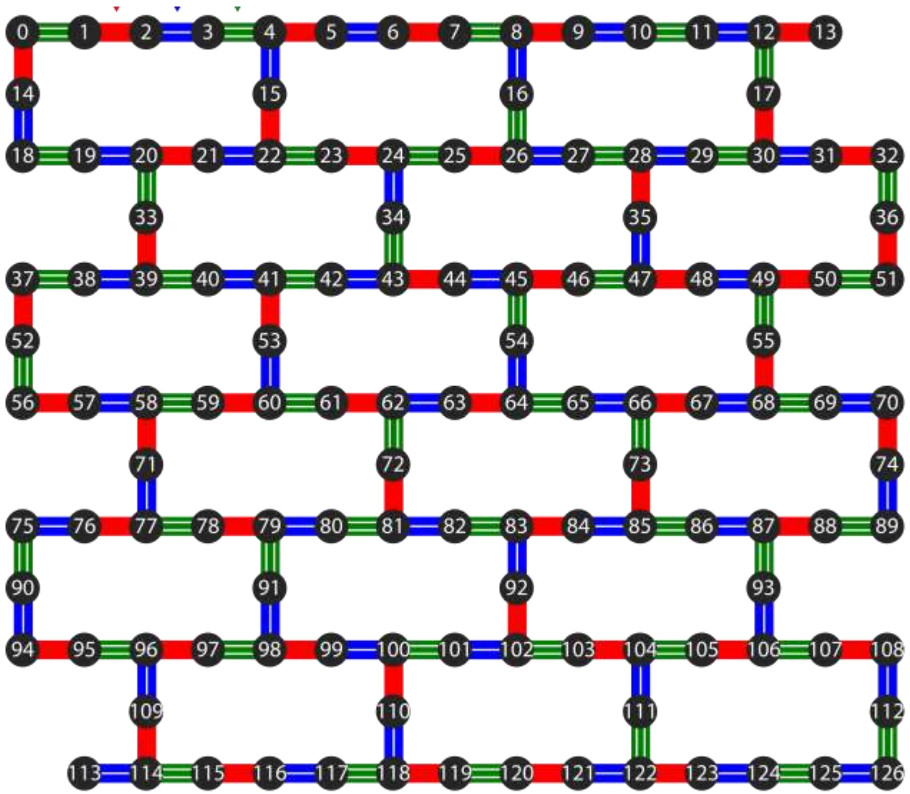


The experiment

IBM **Quantum**

- Spin lattice shares **hardware topology** (127Q device)

$$H = -J \sum_{(i,j)\in E} Z_i Z_j + h \sum_{i\in V} X_i$$



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What made this experiment possible?

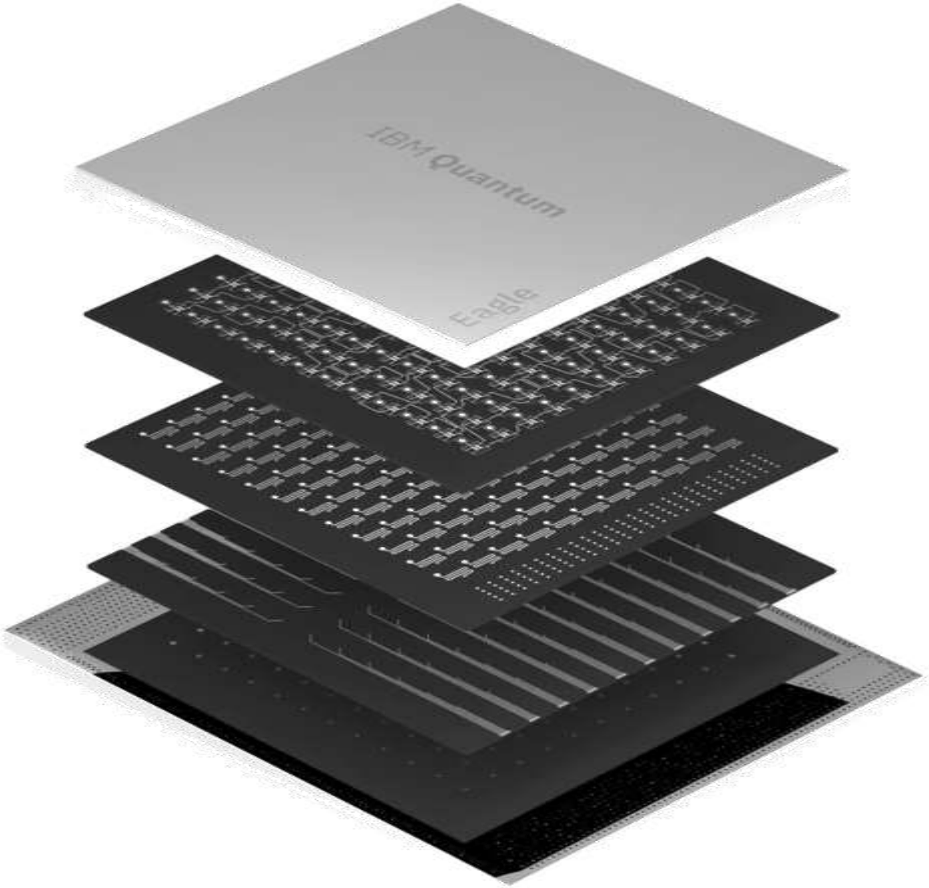
IBM **Quantum**

- Building a 127 qubit system

2019
Falcon
27 Qubits

2020
Hummingbird
65 Qubits

2021
Eagle
127 Qubits



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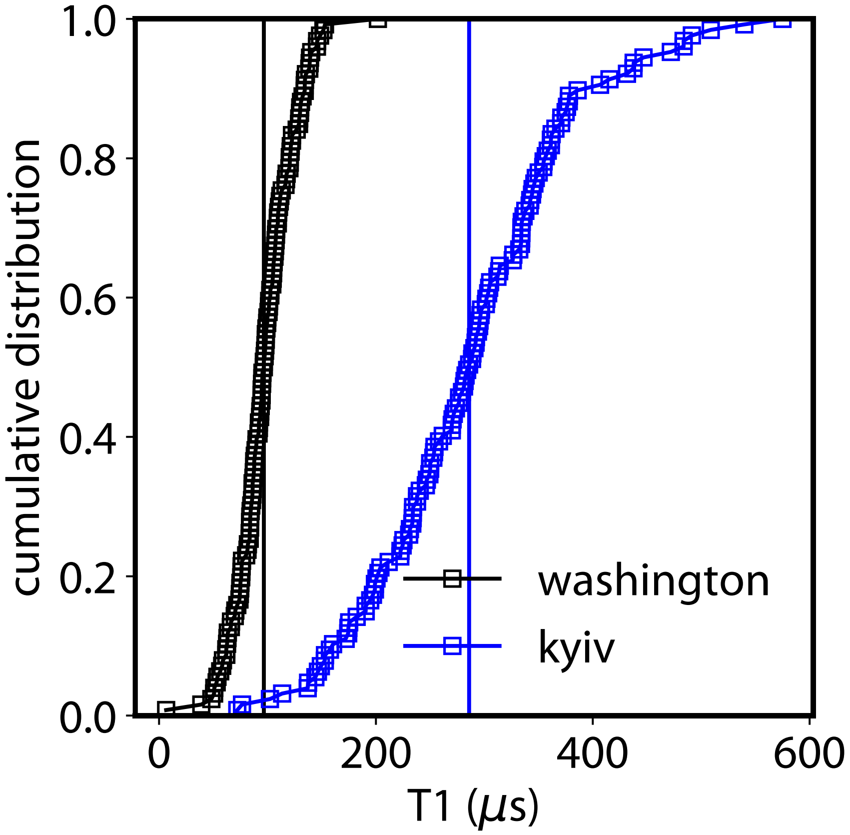
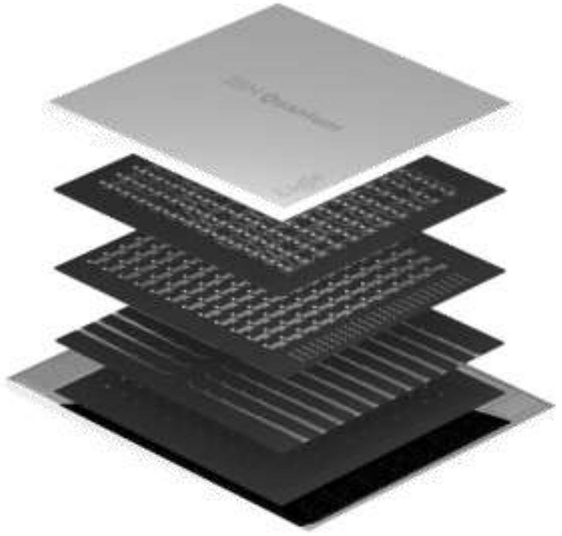
IBM **Quantum**

- Building a 127 qubit system
- Coherence improvements

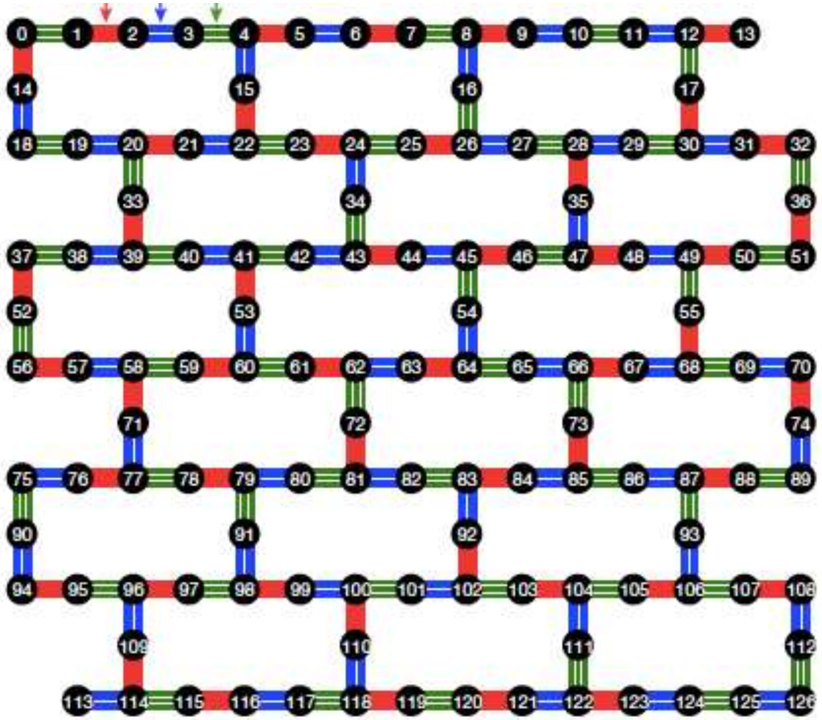


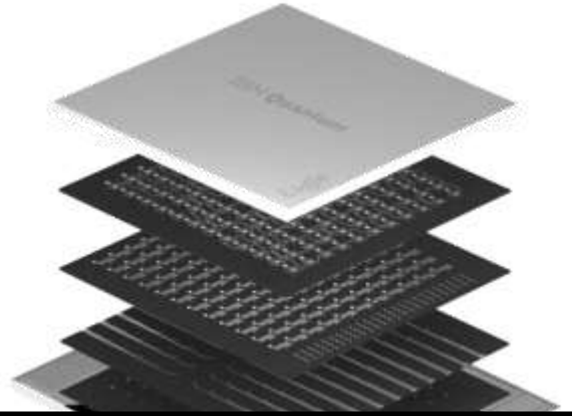


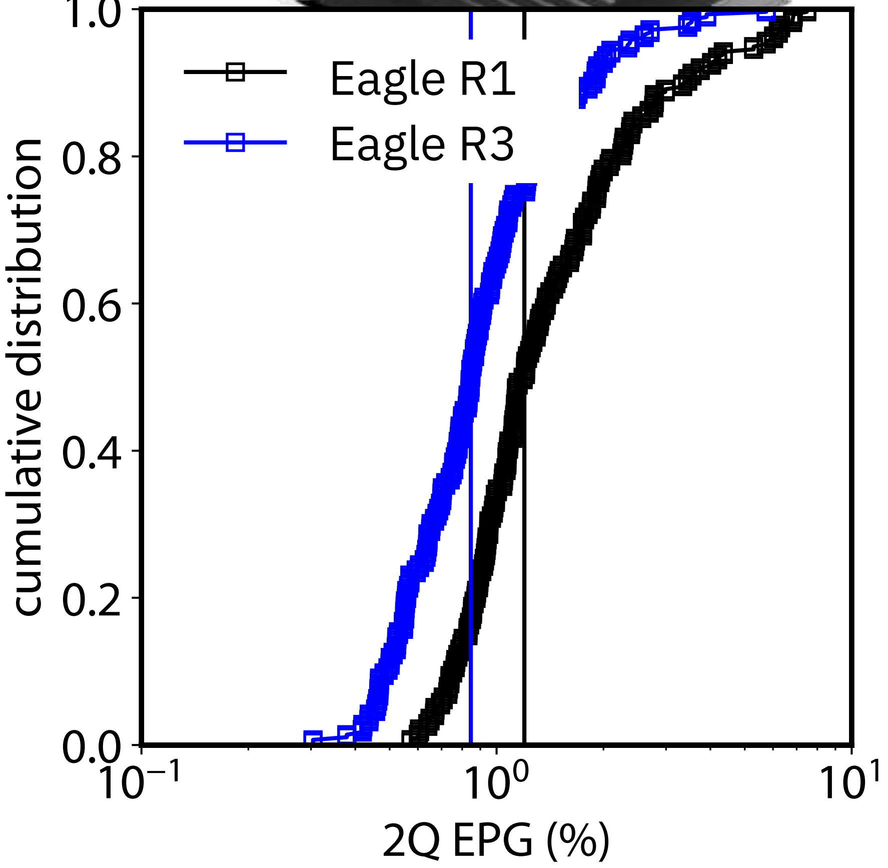
What made this experiment possible?

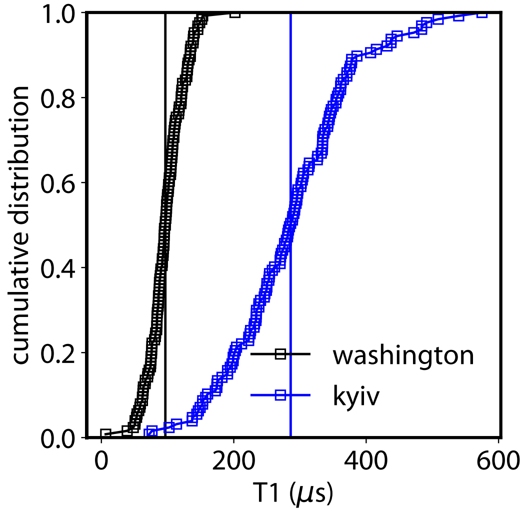
IBM **Quantum**

- Building a 127 qubit system
- Coherence improvements
- Advances in device calibration









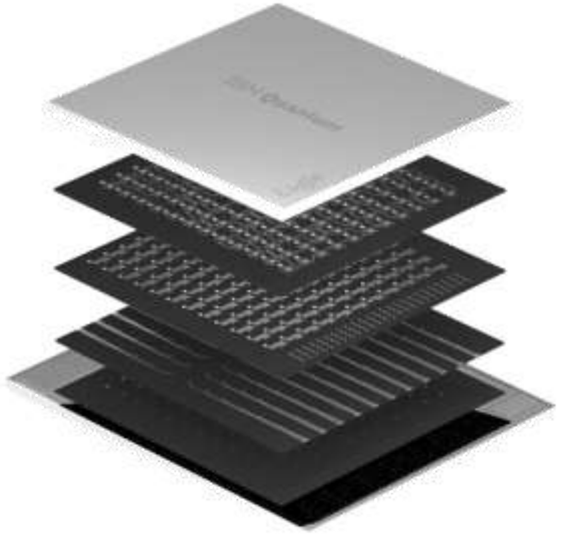
What made this experiment possible?

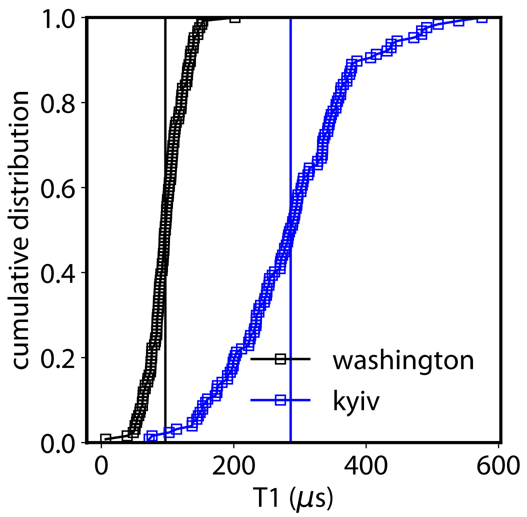
IBM **Quantum**

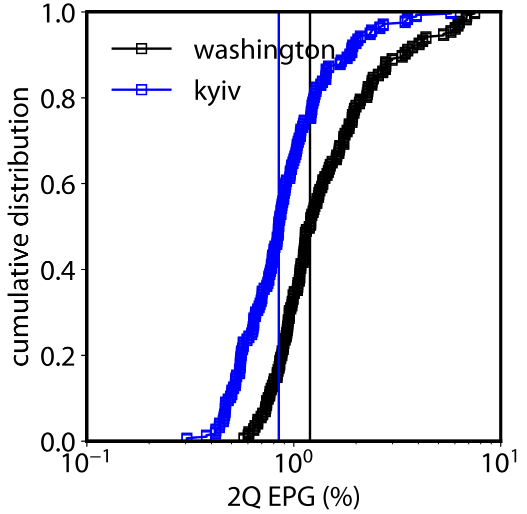
- Building a 127 qubit system
- Coherence improvements
- Advances in device calibration
- Noise modeling & error mitigation

(1) Scalable noise characterization

(2) More accurate noise amplification







An efficiently learnable noise model

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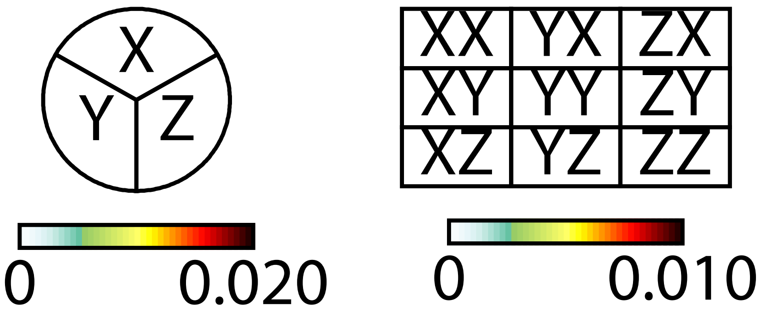
Reduced model complexity:

$\sim 4^{127} \rightarrow \sim 1700$ parameters



Course Schedule 2024

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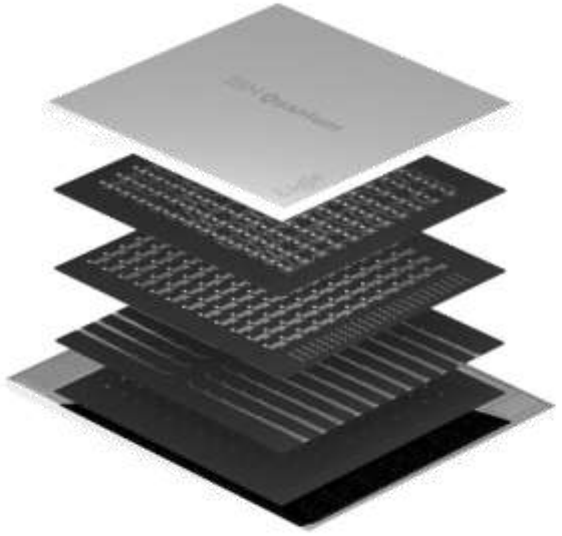
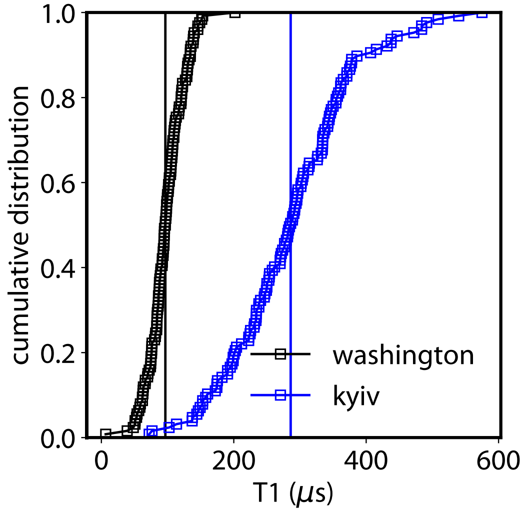
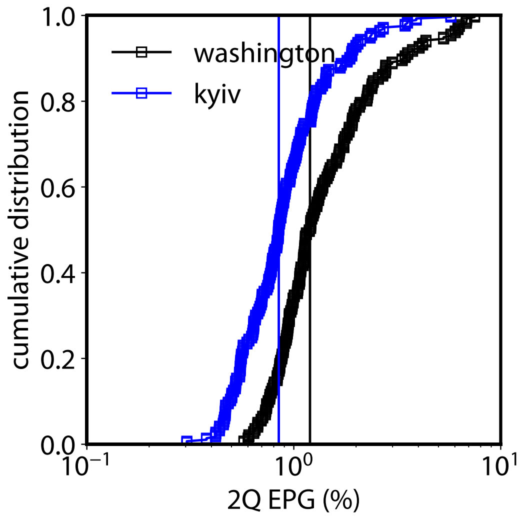
4/5	Invitation to the Utility Era	Tamiya Onodera	6/7	Classical Simulation (Clifford Circuit, Tensor Network)	Yoshiaki Kawase
4/19	Quantum Gates, Circuits, and Measurements	Kifumi Numata	6/14	Quantum Hardware	Masao Tokunari / Tamiya Onodera
4/26	Quantum Teleportation / Superdense Coding	Kifumi Numata	6/21	Quantum Circuit Optimization (Transpilation)	Toshinari Itoko
5/10	Quantum Algorithms: Grover Search	Atsushi Matsuo	6/28	Quantum Noise and Quantum Error Mitigation	Toshinari Itoko
5/15 (Wed)	Quantum Algorithms: Phase Estimation	Kento Ueda	7/5	Utility Scale Experiment I	Tamiya Onodera
5/24	Quantum Algorithms: Variational Quantum Algorithms (VQA)	Takashi Imamichi	7/12	Utility Scale Experiment II	Yukio Kawashima
5/30 (Thu)	Quantum Simulation (Ising model, Heisenberg, XY model), Time Evolution (Suzuki Trotter, QDrift)	Yukio Kawashima	7/19	Utility Scale Experiment III	Kifumi Numata / Tamiya Onodera/ Toshinari Itoko

What made this experiment possible?

- Building a 127 qubit system
- Coherence improvements
- Advances in device calibration
- Noise modeling & error mitigation





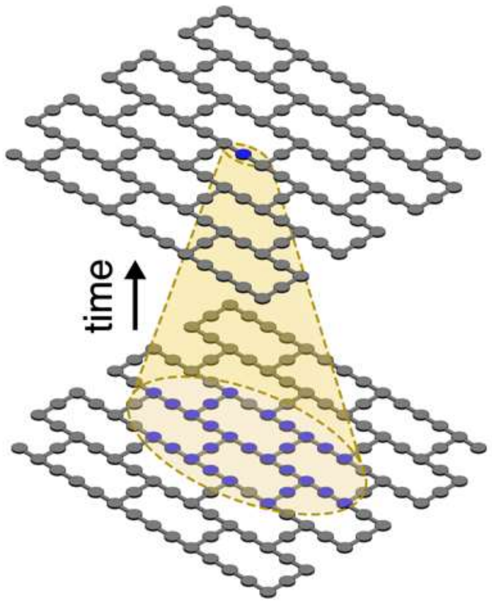


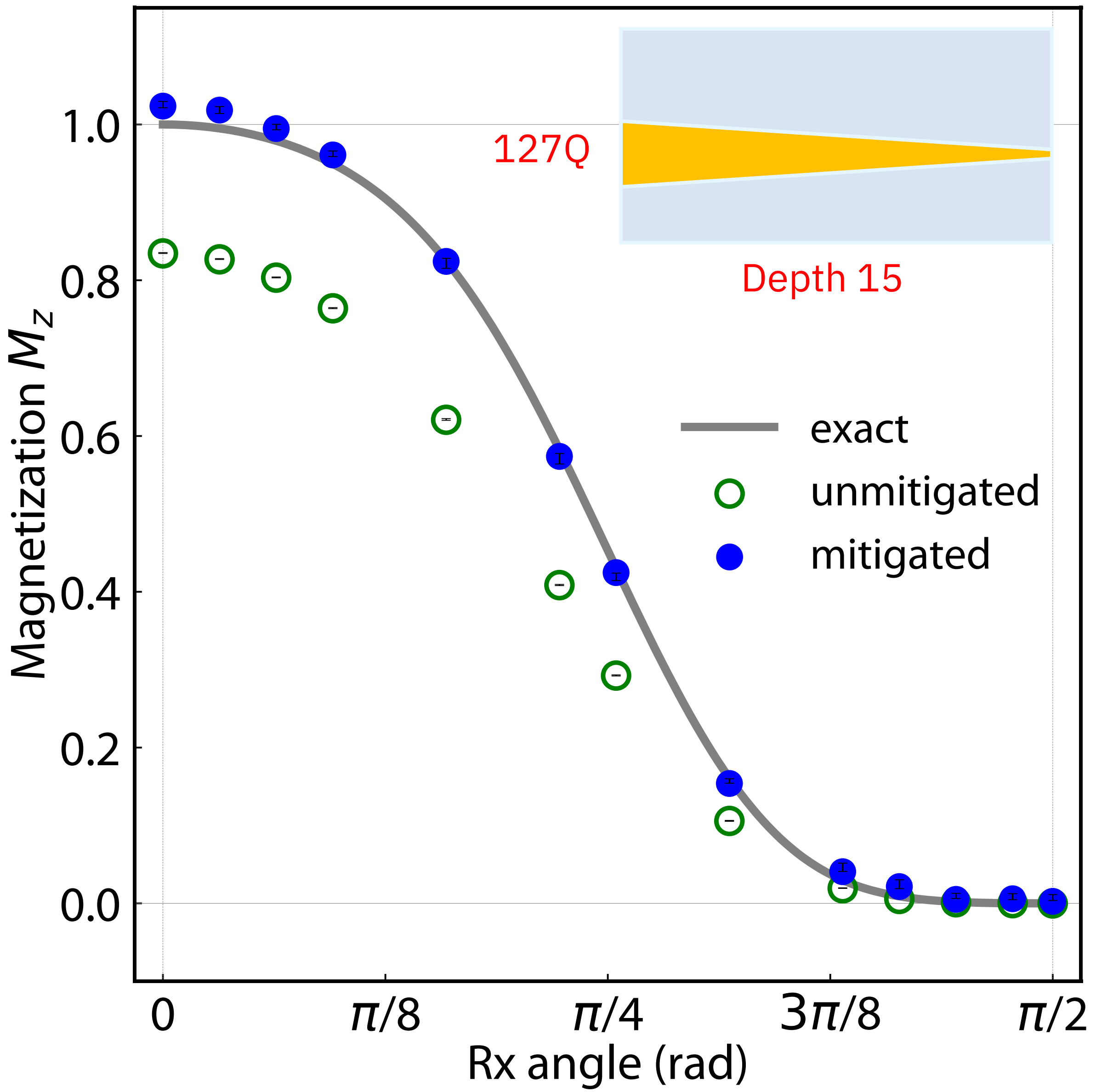
(1) Scalable noise characterization

(2) More accurate noise amplification

127 qubit x 15 entangling layers

- Light cone reductions enable exact verification at Non-Clifford points





127 qubit x 60 entangling layers

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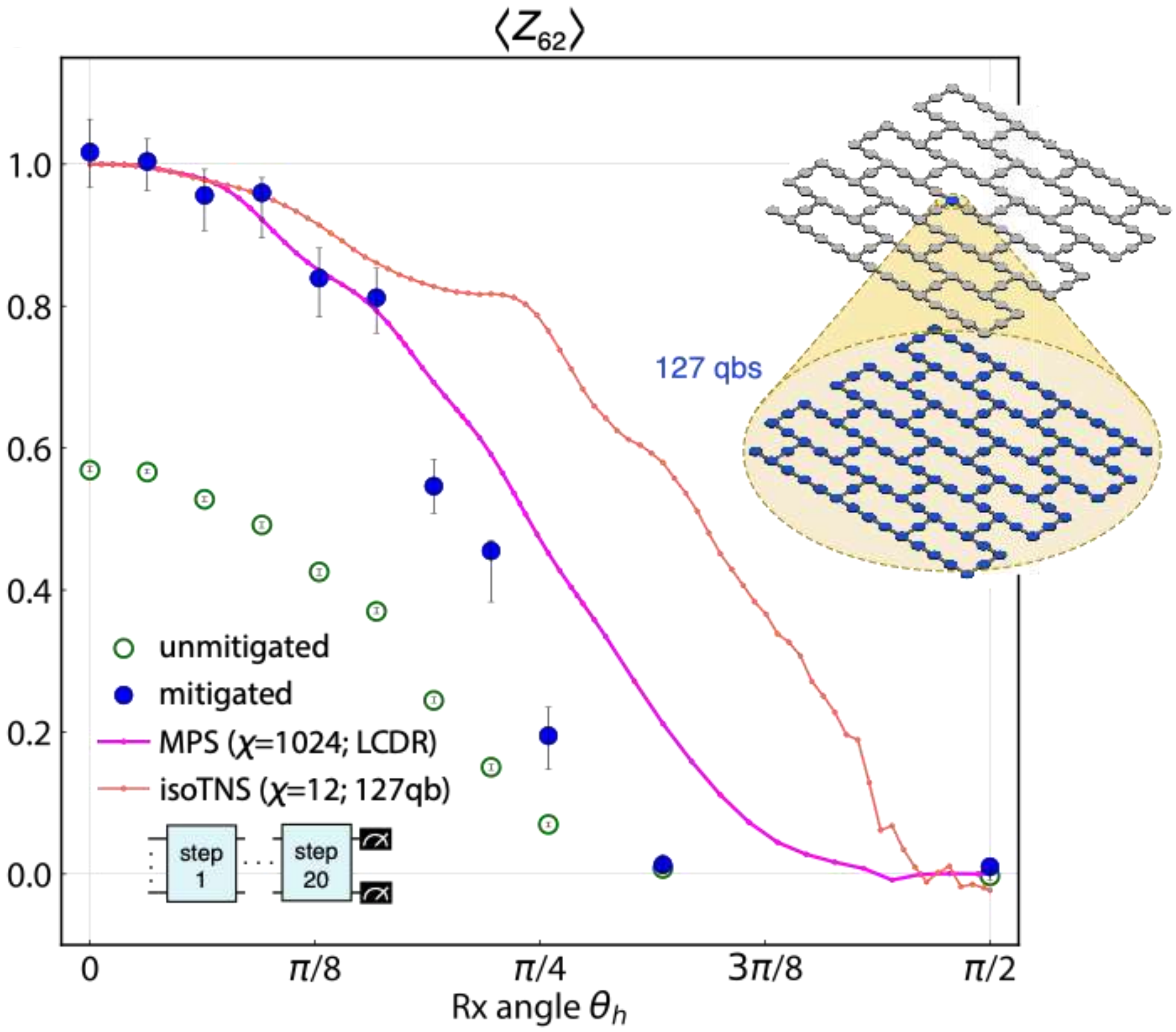

Quantum computers today can provide reliable results at a scale that is beyond exact, brute-force classical computation.

(this is not a quantum advantage claim)

Classical benchmarking of ZNE beyond exact verification

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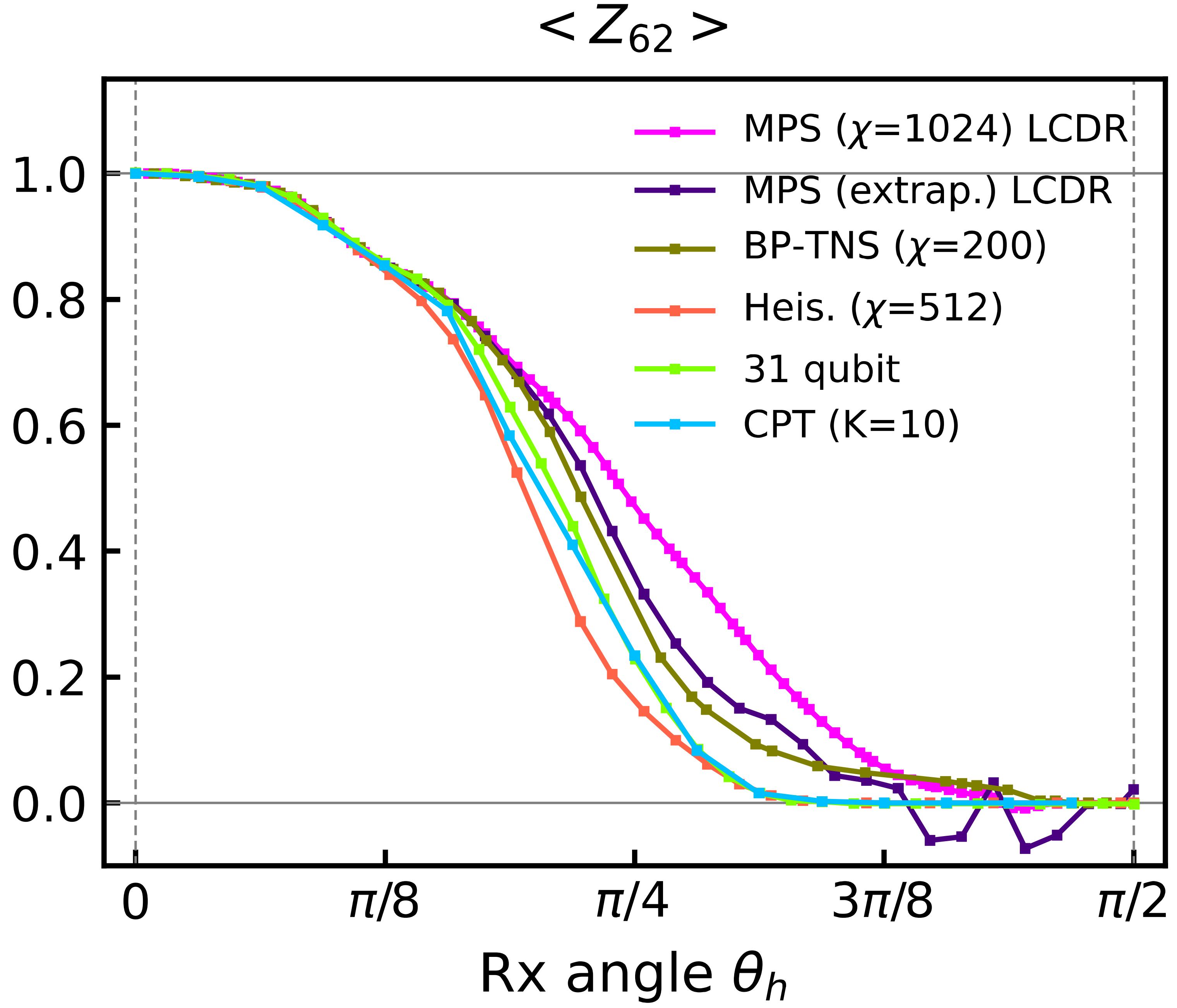

arXiv:2306.14887 (BP-TNS)
arXiv:2306.16372 (CPT)
arXiv:2306.15970 (31 qubit)
arXiv:2306.17839 (MPS extrap., Heis.)

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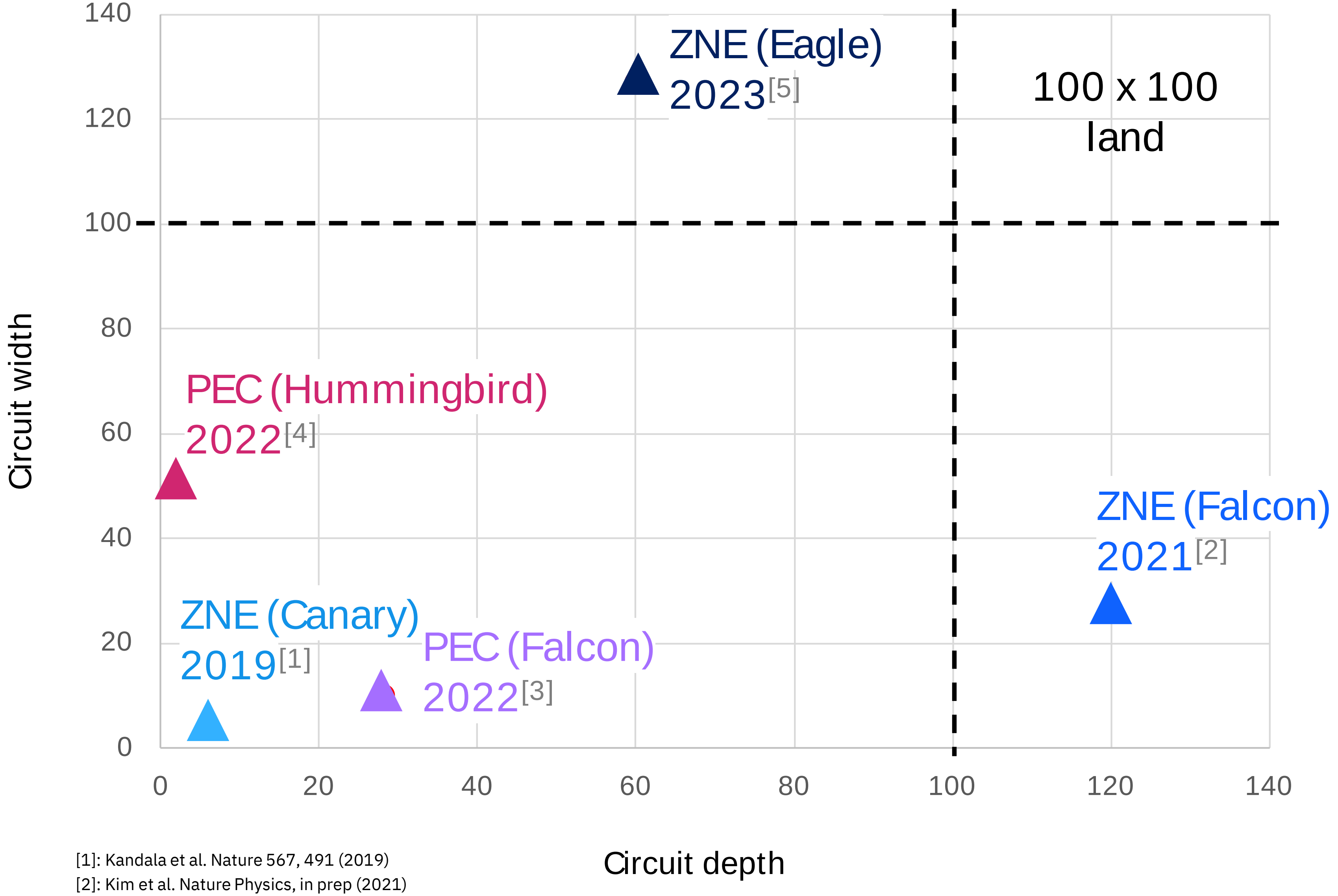
Mapping the path to useful quantum computing

100x100 land is where we predict we can start looking for quantum advantage



[1]: Kandala et al. Nature 567, 491 (2019)
[2]: Kim et al. Nature Physics, in prep (2021)
[3]: van den Berg et al. arXiv:2201.09866 (2022)
[4]: Temme et al. https://research.ibm.com/blog/gammabar-for-quantum-advantage
[5]: Kim et al., Nature **618**, 500–505 (2023), O. Shtanko, et al. arXiv:2307.07552 (2023)

If you’re not using 100+ qubits, you’re not doing quantum.

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References

- Kim, Y., Eddins, A., Anand, S. *et al.* Evidence for the utility of quantum computing before fault tolerance. *Nature* **618**, 500–505 (2023). https://doi.org/10.1038/

- Evidence for the Utility of Quantum Computing before Fault Tolerance | Qiskit Seminar Series, https://www.youtube.com/watch?v=hIUydsivY9k

Thank you

Install and set up Qiskit 1.x (macOS)

- Reference URL : https://docs.quantum.ibm.com/guides/install-qiskit (For non-macOS users, please refer this.)
- Caution: You must start a new virtual environment to install Qiskit 1.x. It is very tricky and error-prone to upgrade an existing installation of Qiskit 0.x in-place to Qiskit 1.x.

1. Create a new virtual environment, using Python 3.8 or later.

```
python3 -m venv qiskit-1.x-venv
```

2. Activate the environment.

```
source qiskit-1.x-venv/bin/activate
```

3. Install Qiskit.

```
pip install qiskit
```

4. Install the necessary packages.

```
pip install qiskit-ibm-runtime
pip install qiskit[visualization]
pip install jupyter
pip install qiskit-aer
```

zsh users need to put 'qiskit[visualization]' in single quotes.

5. With the following command, you can launch Jupyter notebook and start using Qiskit.

```
jupyter notebook
```

6. Try the first cell of Hello world by copy and paste, and execute it by “Shift”+”Enter”.

6. If you are not planning to use the environment immediately, use the deactivate command to leave it.

```
deactivate
```

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