1. Opening

This first lecture gives an overview of the entire course which covers a rich set of contents, including algorithms, hardware, and software tools. The course is specifically tailored to what we call the “utility era”, and you will see what it means by the end of the lecture.

We will start with a brief history of quantum computing, and then show what the quantum computers look like.

東京大学
THE UNIVERSITY OF TOKYO

Invitation to the Utility Era

2024/04/05

Tamiya Onodera
IBM Research – Tokyo
tonodera@jp.ibm.com

The University of Tokyo
Special Lectures in Information Science II
Introduction to Near-Term Quantum Computing
情報科学科特別講義Ⅱ/量子計算論入門
2024年度の計画

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.

Schedule: Every Friday from 16:50 to 18:20 (except May 15 (Wed), May 30(Thu))

Notes: All lectures will be held in person. Recording also will be available for reviewing.

Course Schedule 2024

Date	Lecture Title	Lecturer	Date	Lecture Title	Lecturer
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
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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

Lecturer
Tamiya Onodera

東京大学
THE UNIVERSITY OF TOKYO

IBM Research – Tokyo Deputy Director
IBM Distinguished Engineer

Joined IBM in 1988 after obtaining Ph.D. in Information Science from University of Tokyo. My research interests include programming languages and software stack for quantum computing.

Kanji of IPSJ SIG on Quantum Software (2020 -)
Vice Chair of for Quantum Computing Promotion Committee of Quantum ICT Forum (2019 -)

IPSJ 2023 Achievement Award in Computer Science
JSSST 2022 Basic Research Award

Association for Computing Machinery
Distinguished Scientist (2014 -)

Japan Society of Software Science and Technology
Fellow (2018 -)

* IPSJ = Information Processing Society of Japan

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."

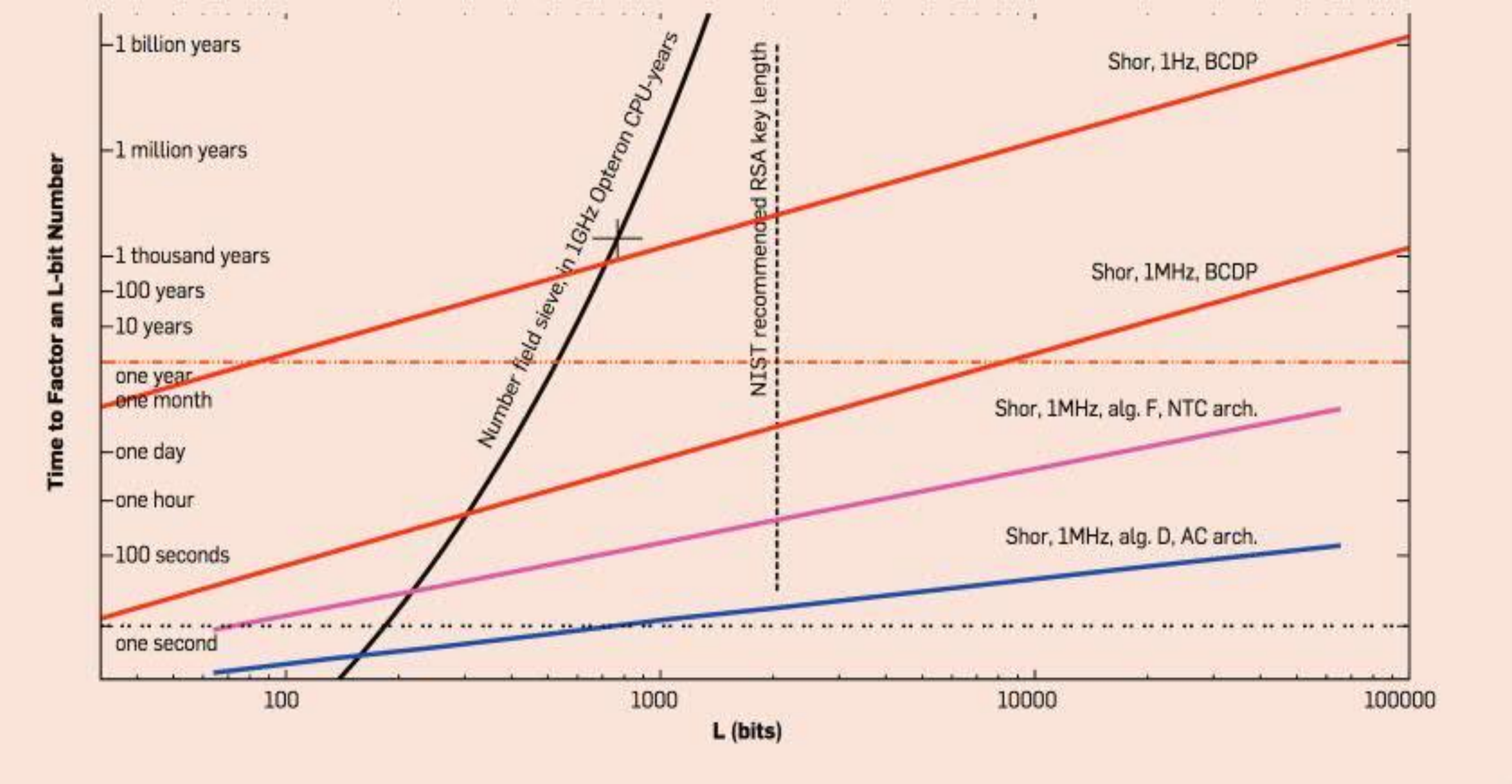
Algorithms for Quantum Computation: Discrete Logarithms and Factoring

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*



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

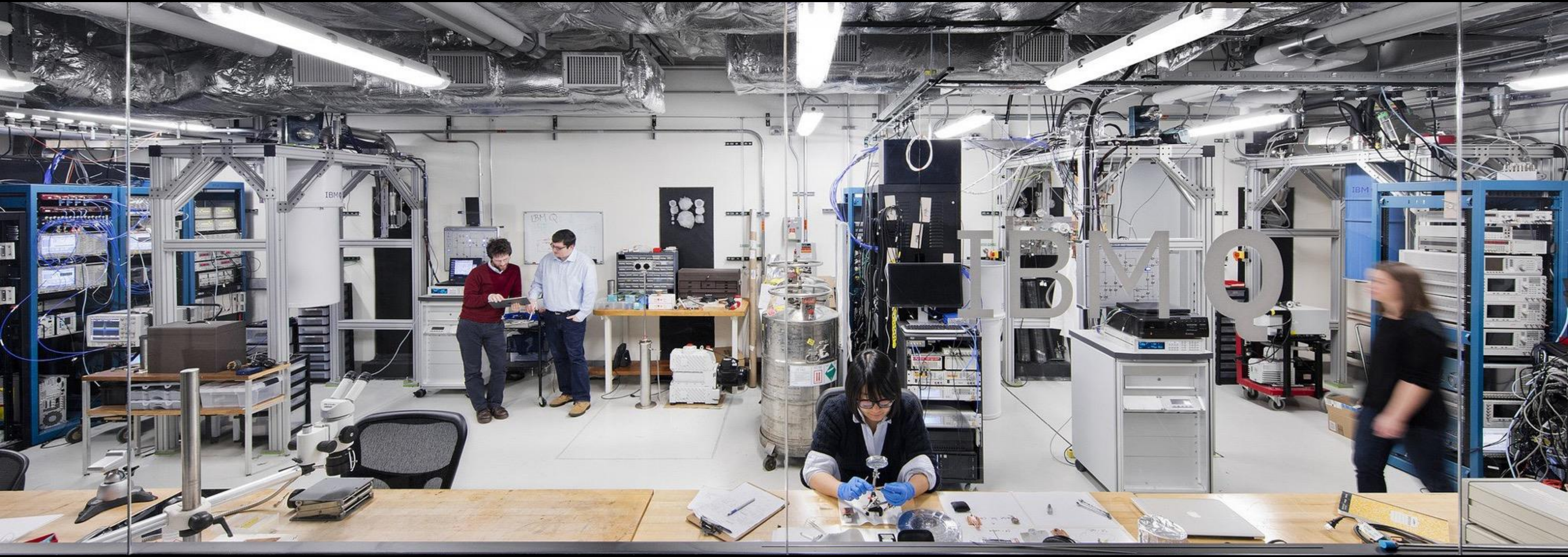
Proceedings of the 35th Annual Symposium of Foundations of Computer Science, Pages 124-134

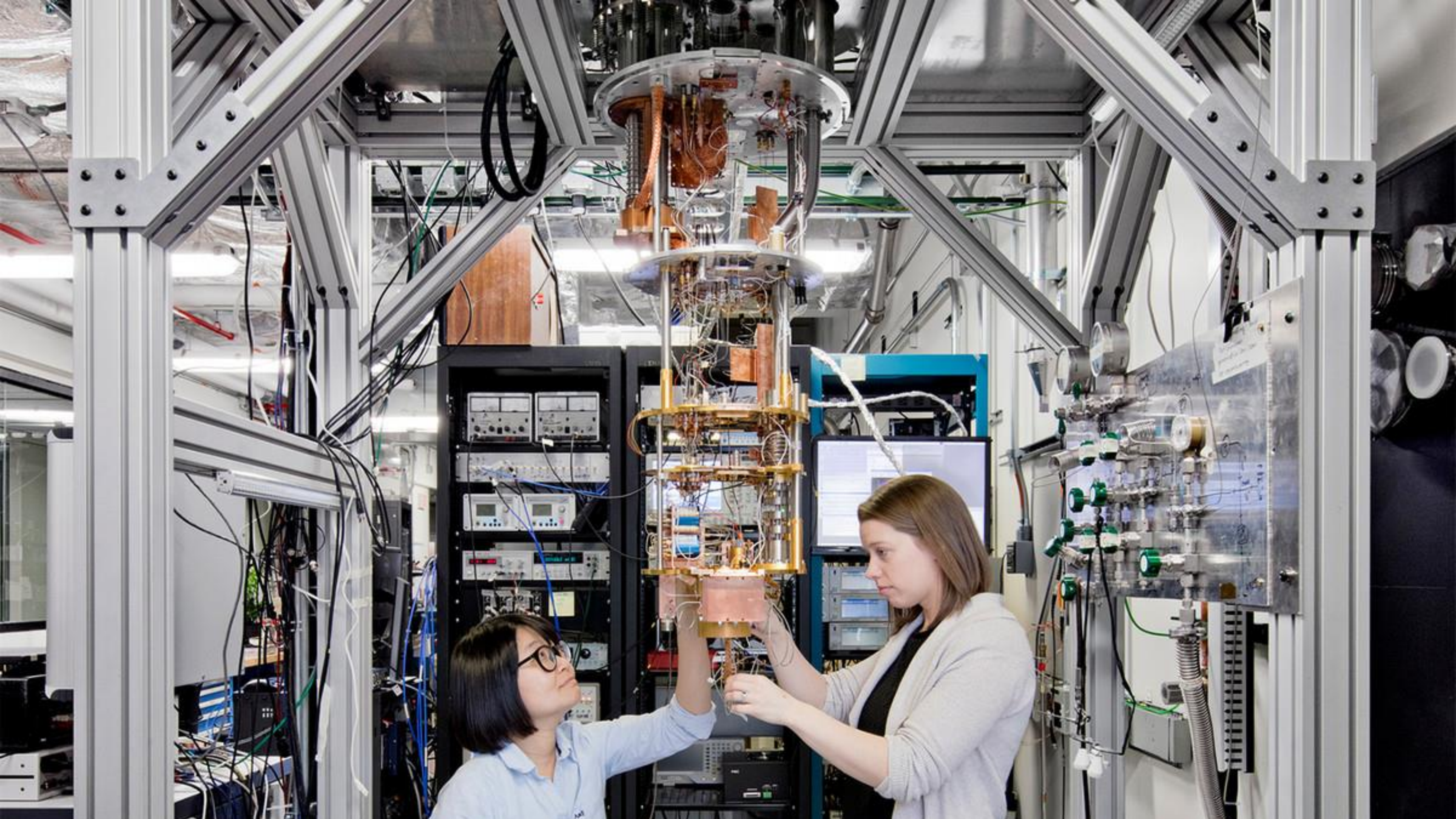
"Currently, nobody knows how to build a quantum computer,"

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

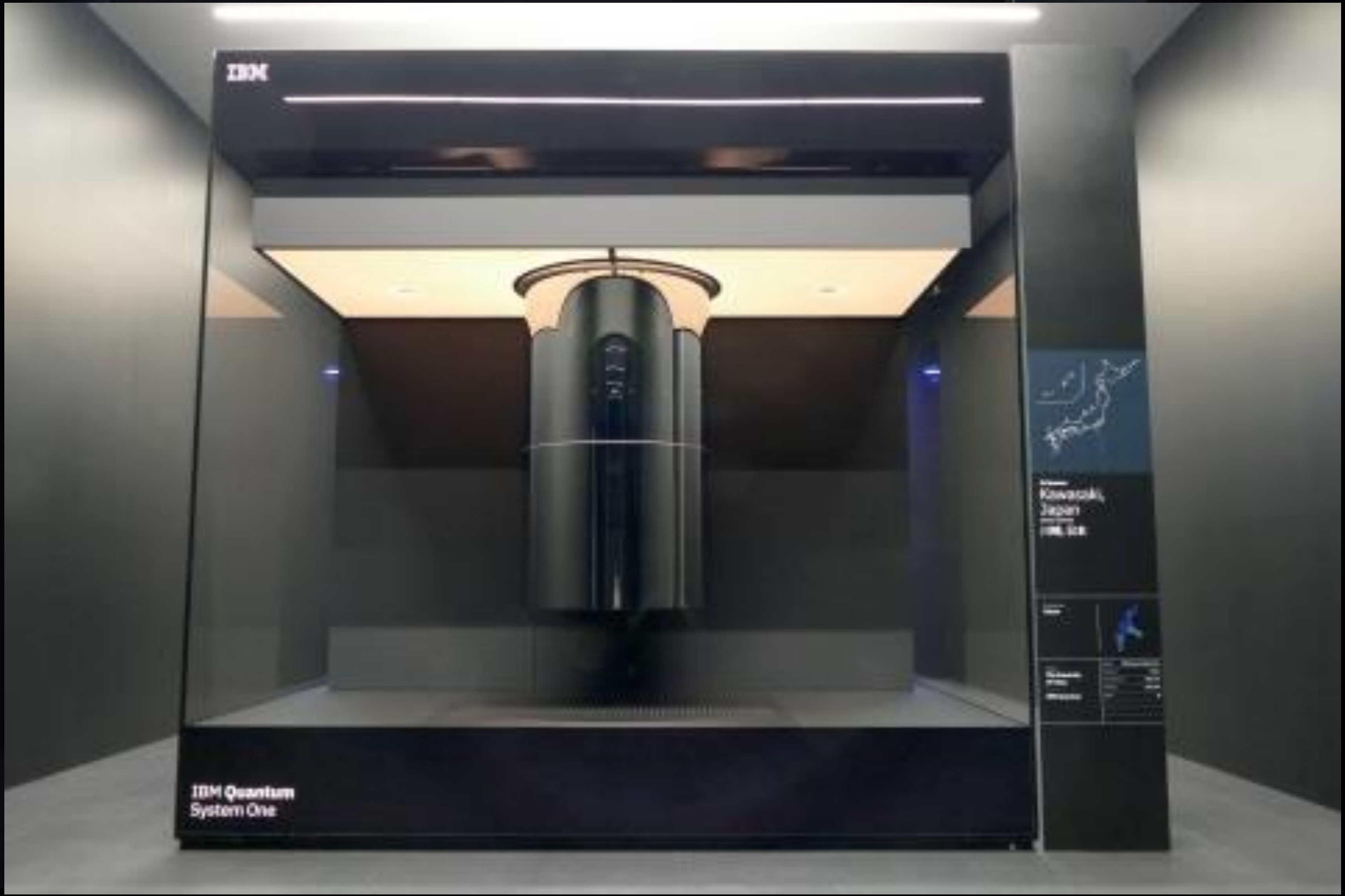
The IBM Quantum Experience
May 2016

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

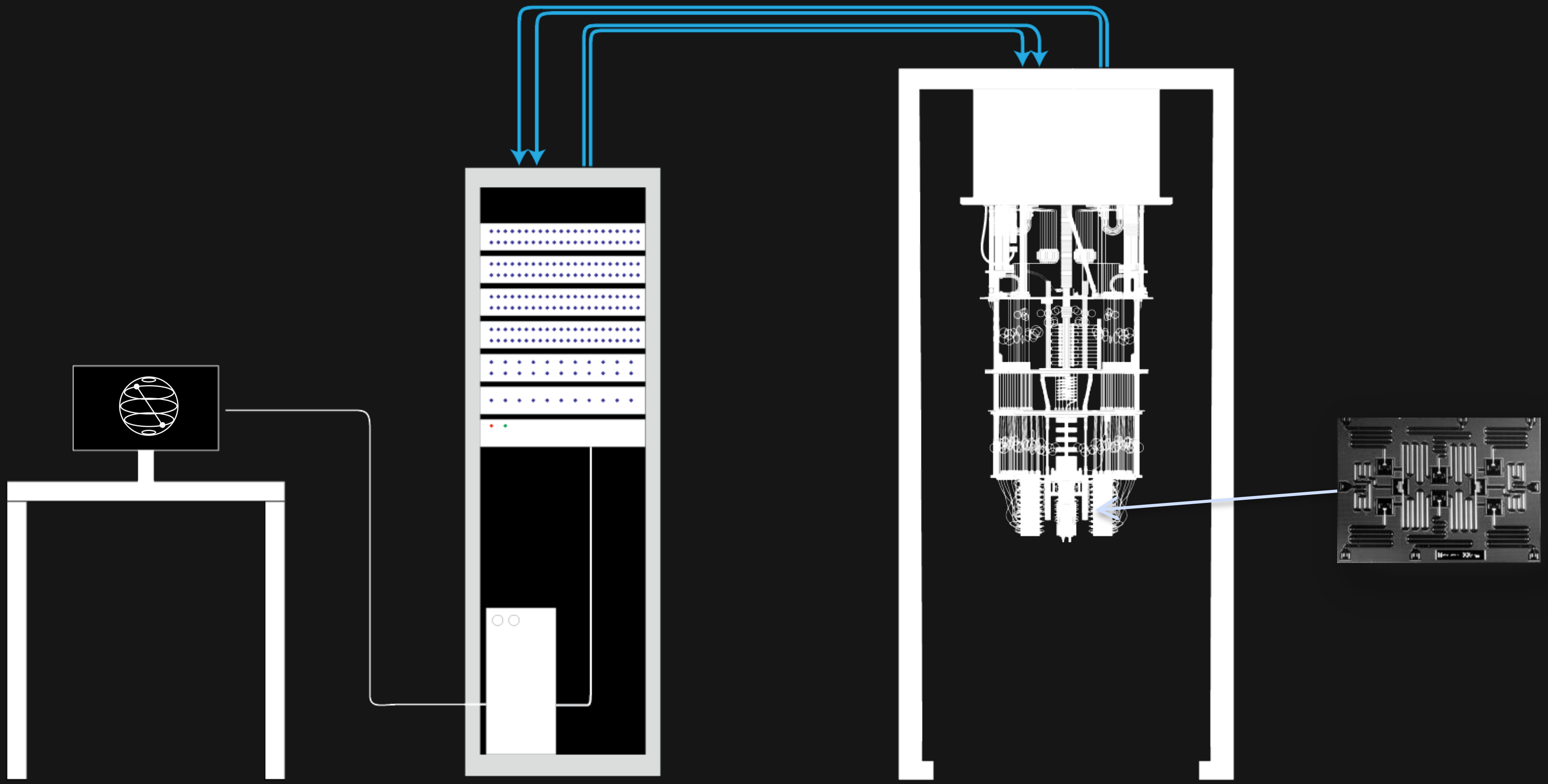

IBM Q



IBM Quantum System One at Shin-Kawasaki



Quantum Computers



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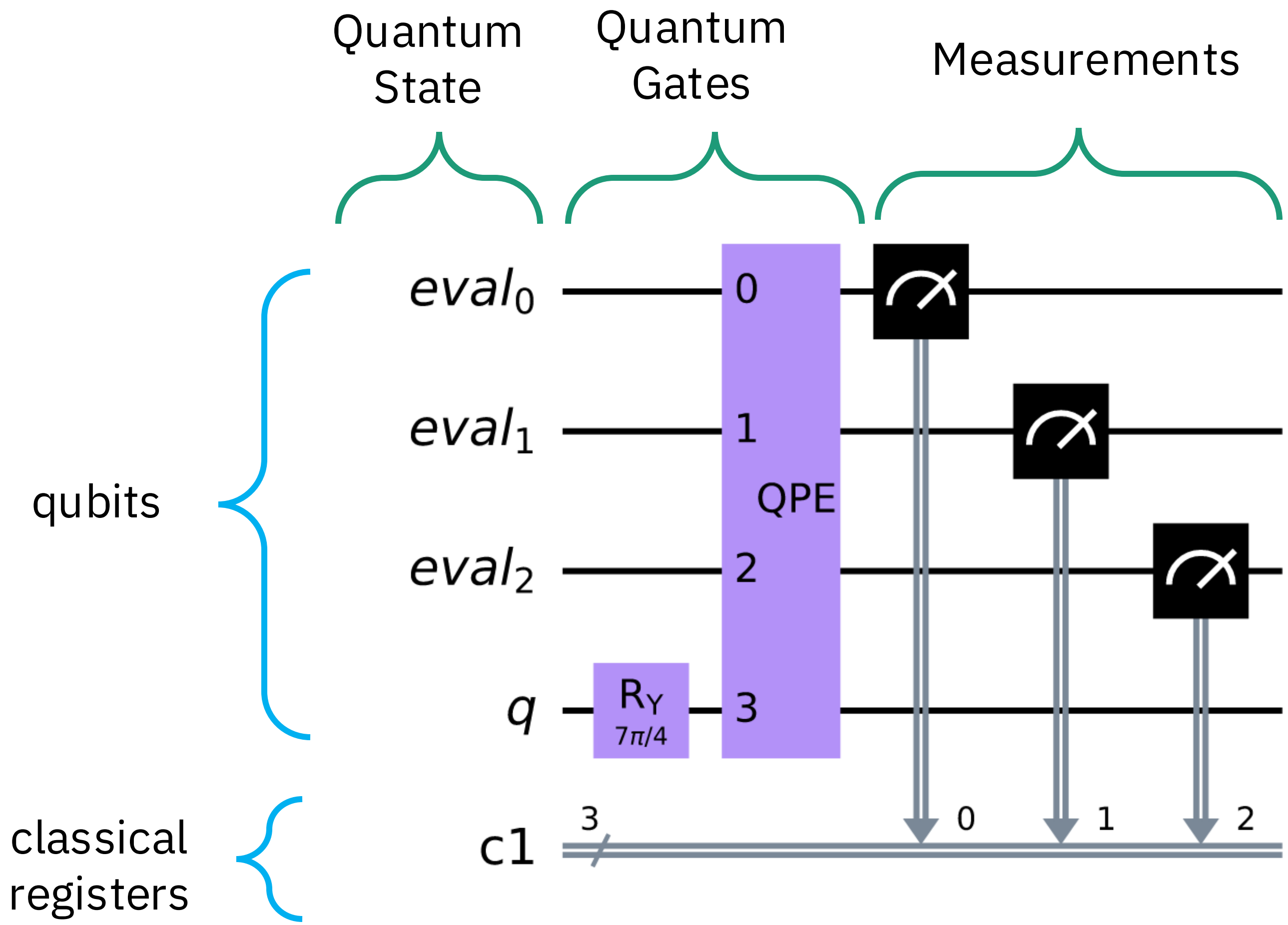
2. Quantum Circuits

We now show what “quantum programming” looks like. Actually, it means building “quantum circuits”, that is, preparing quantum states, applying gates to manipulate the states, and making measurements to get outcomes. .

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 $\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$:

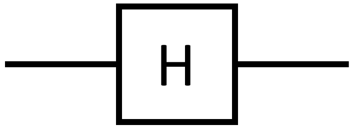
$$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} \otimes \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} \otimes \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} = \frac{1}{\sqrt{8}}\begin{pmatrix}1\\1\\1\\1\\1\\1\\1\\1\end{pmatrix}$$

where the computational basis are

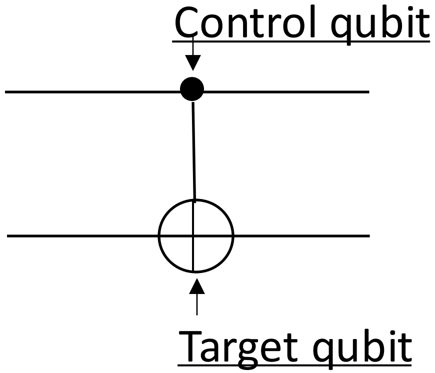
$|000\rangle$ (= $|0\rangle \otimes |0\rangle \otimes |0\rangle$), $|001\rangle$, $|010\rangle$, $|011\rangle$, $|100\rangle$, $|101\rangle$, $|110\rangle$, $|111\rangle$

Quantum Gate: *n*-qubit

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



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



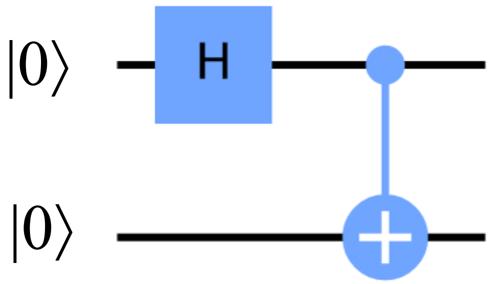
$$\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{pmatrix}$$

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

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

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

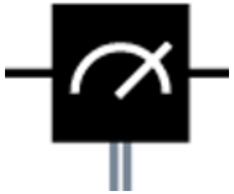
Example



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

- 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

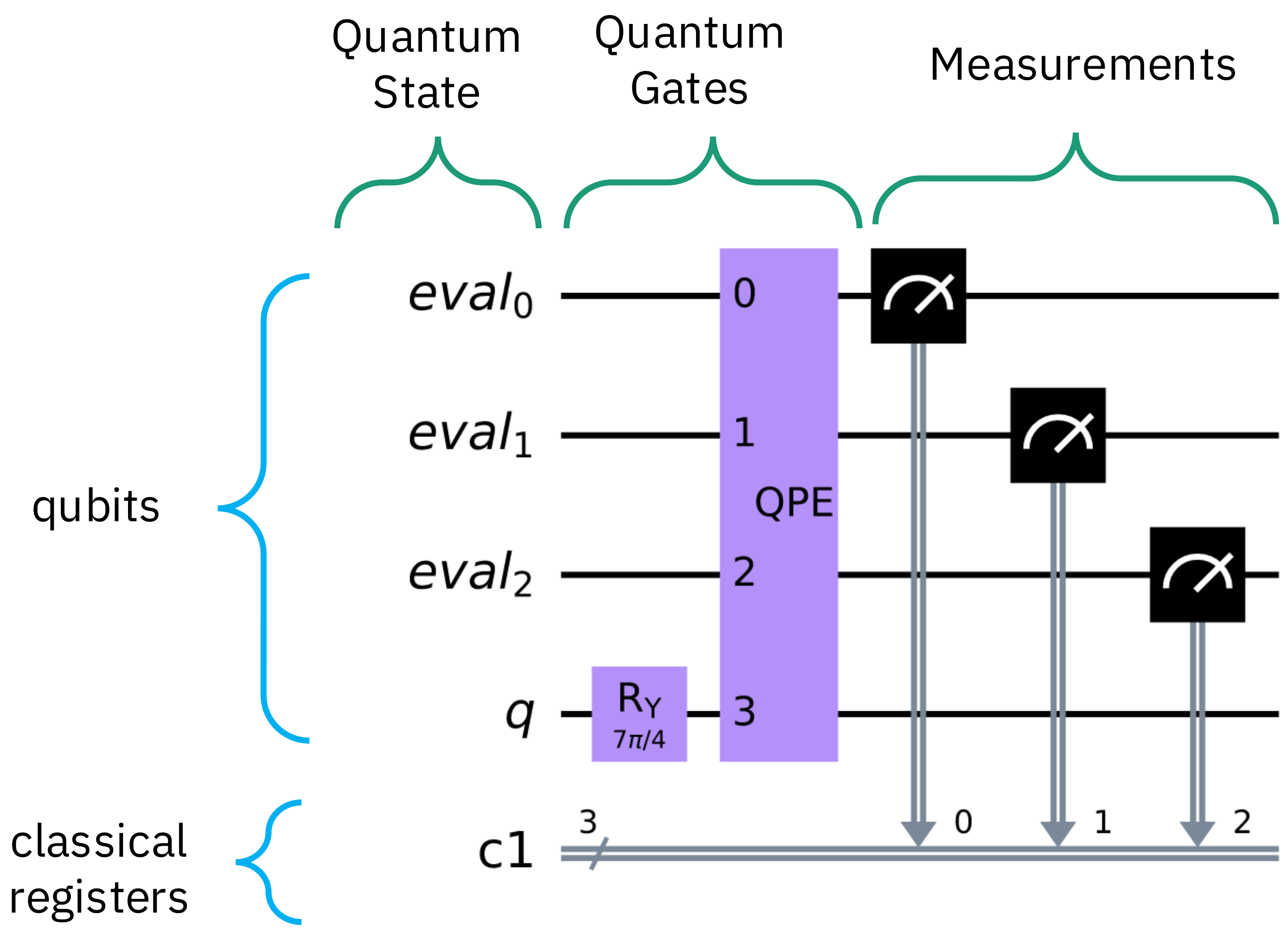


- The only way to access the state of a qubit.

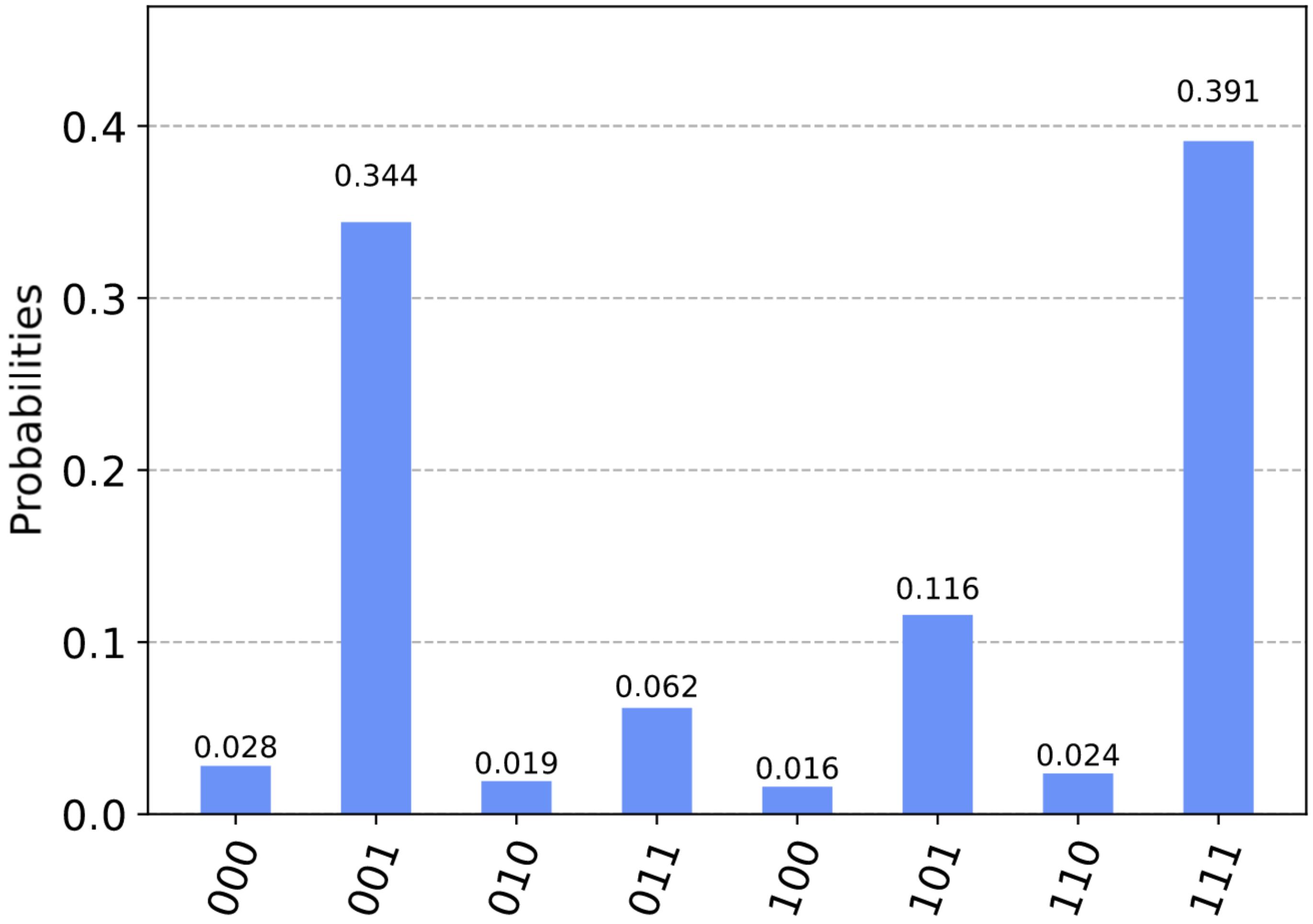
- Assume that the state is $\alpha|0\rangle + \beta|1\rangle$ s.t. $|\alpha|^2 + |\beta|^2 = 1$.

- 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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3. Quantum Algorithms and Noisy Quantum Computers

We introduce “famous quantum algorithms”, or its very brief history. We then take a closer look at IBM quantum computers, showing that the current quantum computers are inherently “noisy”.

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)

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

Harrow, Hassidim Lloyd, PRL 2009

Variational Quantum Eigensolvers (VQE)

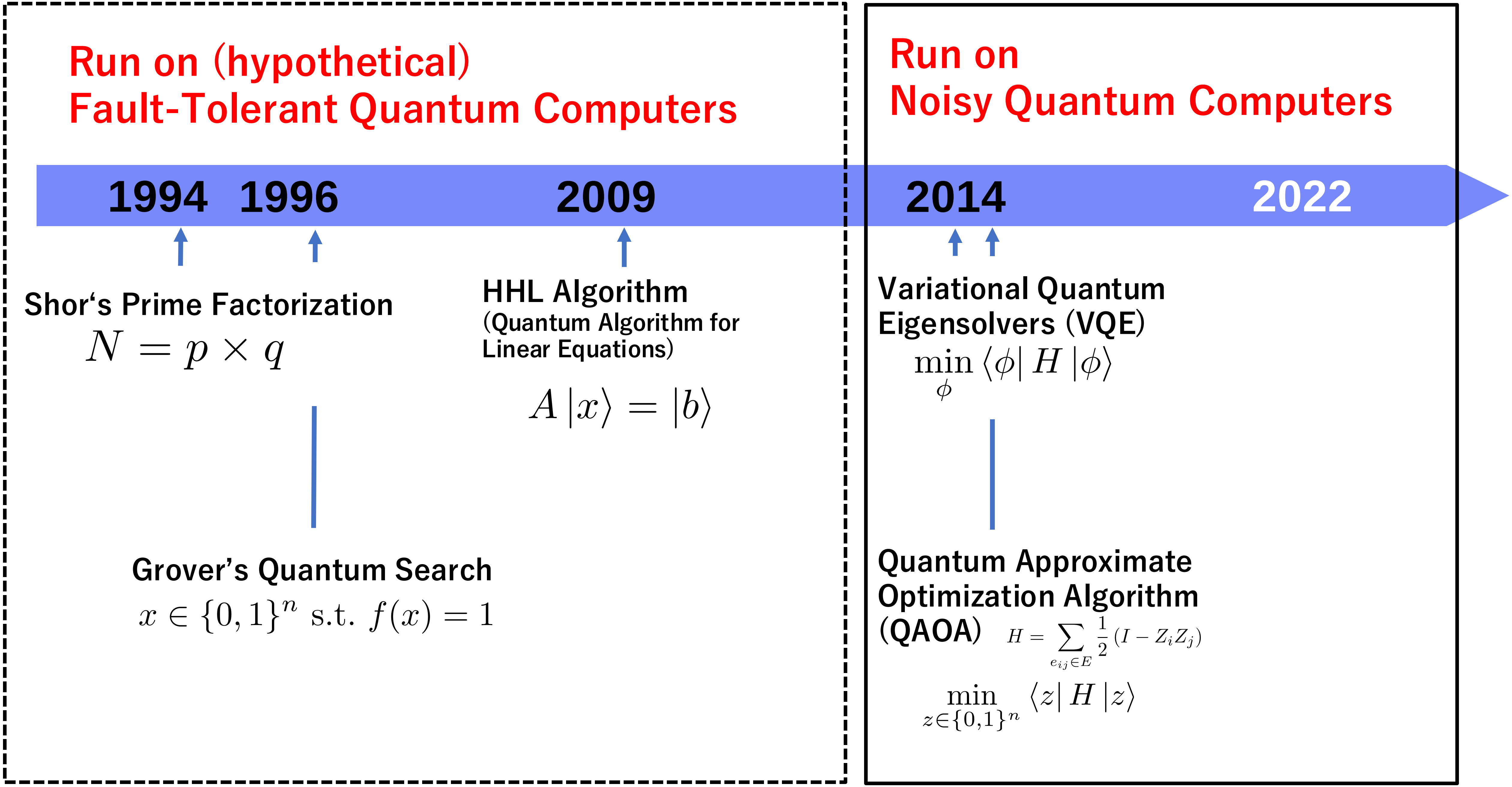
$$\min_{\phi} \langle\phi| H |\phi\rangle$$

Peruzzo et al., Nat. Comm 2014

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

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

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)
$H = \sum_{e_{ij} \in E} \frac{1}{2}(I - Z_i Z_j)$
$\min_{z \in \{0,1\}^n} \langle z| H |z\rangle$

Course Schedule 2024

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4/19	Quantum Gates, Circuits, and Measurements	Kifumi Numata	6/14	Quantum Hardware	Masao Tokunari
4/26	LOCC (Quantum teleportation/superdense coding/Remote CNOT)	Kifumi Numata/ Atsushi Matsuo	6/21	Quantum Circuit Optimization (transpiler)	Toshinari Itoko
5/10	Quantum Algorithms: Grover's algorithm	Atsushi Matsuo	6/28	Pauli twirling and Noise model (Pauli Transfer Matrix) Error mitigation (PEC, ZNE (PEA))	Toshinari Itoko
5/15 (Wed)	Quantum Algorithms: Phase estimation	Kento Ueda	7/5	Quantum Utility I (127Qubit GHZ)	Kifumi Numata
5/24	Quantum Algorithms: Variational Quantum Algorithms (VQA)	Takashi Imamichi	7/12	Quantum Utility II (Utility paper implementation)	Tamiya Onodera
5/30 (Thu)	Quantum simulation (Ising model, Heisenberg, XY model), Time evolution (Suzuki Trotter, QDrift)	Yukio Kawashima	7/19	Quantum Utility III (Krylov subspace expansion)	Yukio Kawashima

https://quantum.ibm.com

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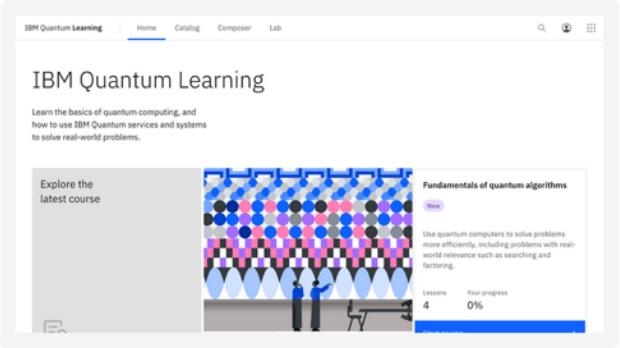
IBM Quantum

Use our suite of applications to support your quantum research and development needs.

Learning

Take a course, browse tutorials, and start experimenting with Composer or Lab.



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New to IBM Quantum?

Create an IBMid

Having trouble signing in?

Try signing in with an IBMid. If you are still having issues, contact the IBMid help desk.

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

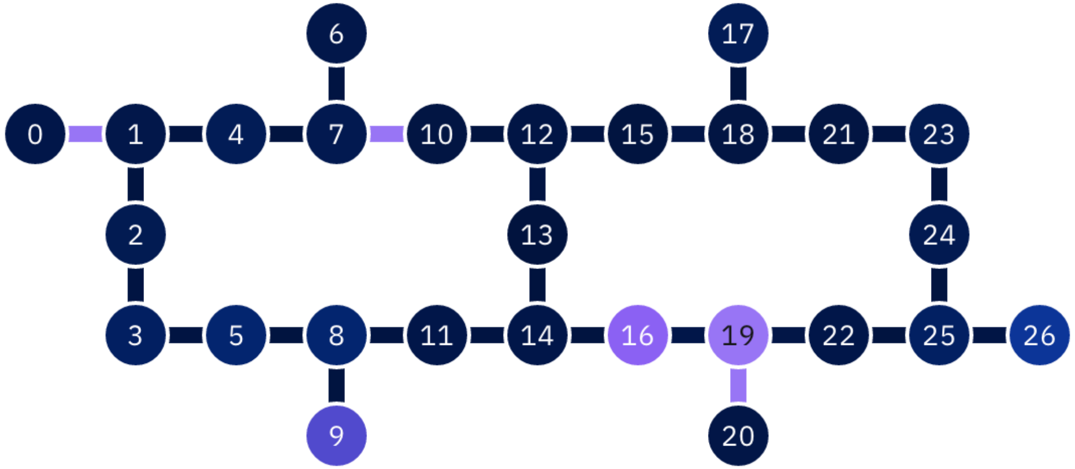
min 6.300e-3 max 1.516e-1

Connection:

CNOT error

Median 1.146e-2

min 4.583e-3 max 1.000e+0



ibm_kyoto

OpenQASM 3

Details

127 Qubits	Status:	Online	Median ECR error:	8.299e-3
3.6% EPLG	Total pending jobs:	2 jobs	Median SX error:	2.543e-4
5K CLOPS	Processor type:	Eagle r3	Median readout error:	1.550e-2
	Version:	1.2.38	Median T1:	217.71 us
	Basis gates:	ECR, ID, RZ, SX, X	Median T2:	119.17 us
	Your instance usage:	4 jobs		

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

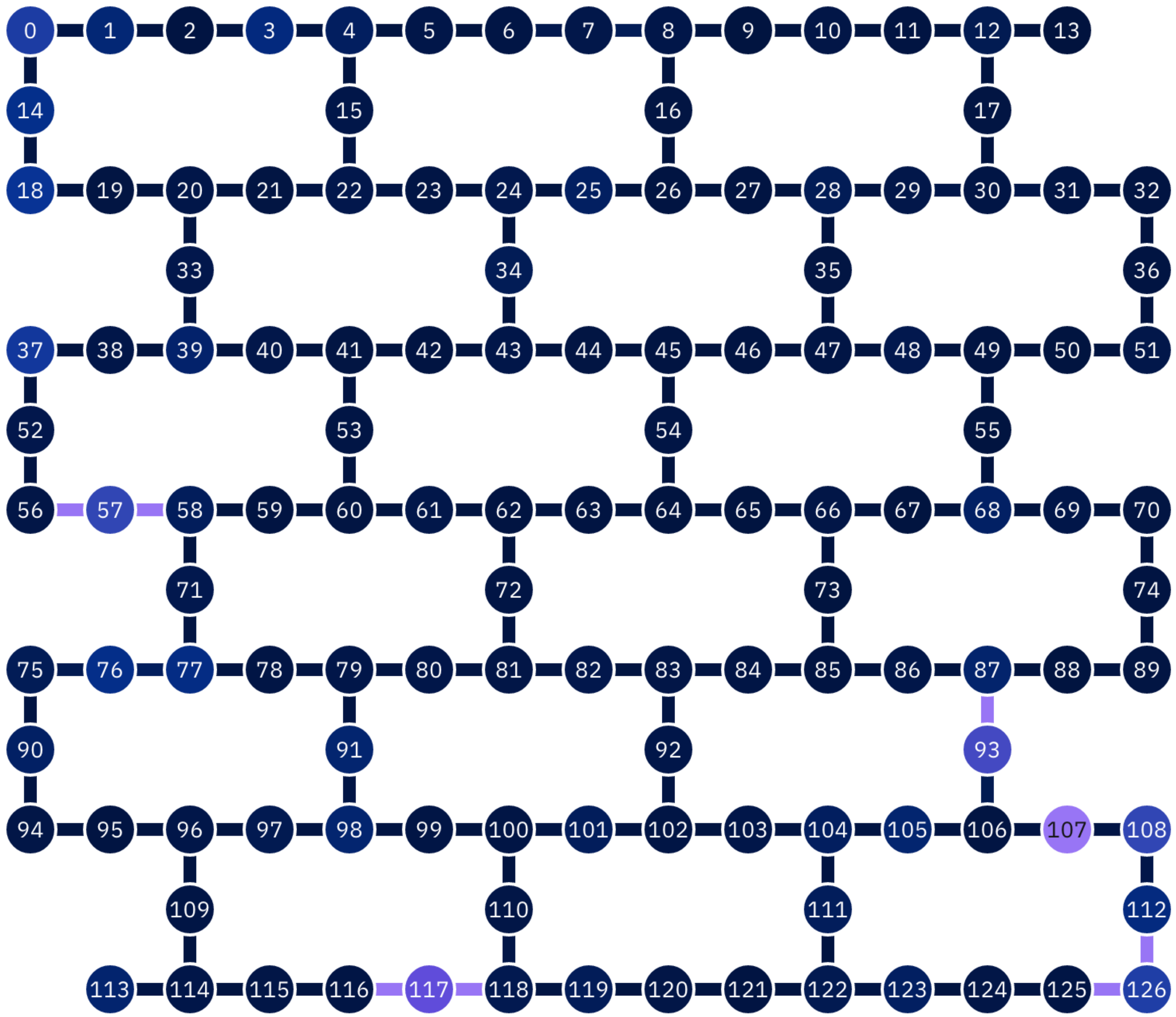
Median 1.550e-2

min 3.300e-3 max 4.857e-1

Connection: ECR error

Median 8.299e-3

min 3.615e-3 max 1.000e+0



4. Transpilation, error mitigation, and Nature papers

We talk about transpiling logical circuits to ISA (Instruction Set Architecture) circuits. We then switch to error mitigation which is crucial to reap meaningful results from noisy devices. We then introduce two Nature papers from IBM, one in 2017 and the other in 2023.

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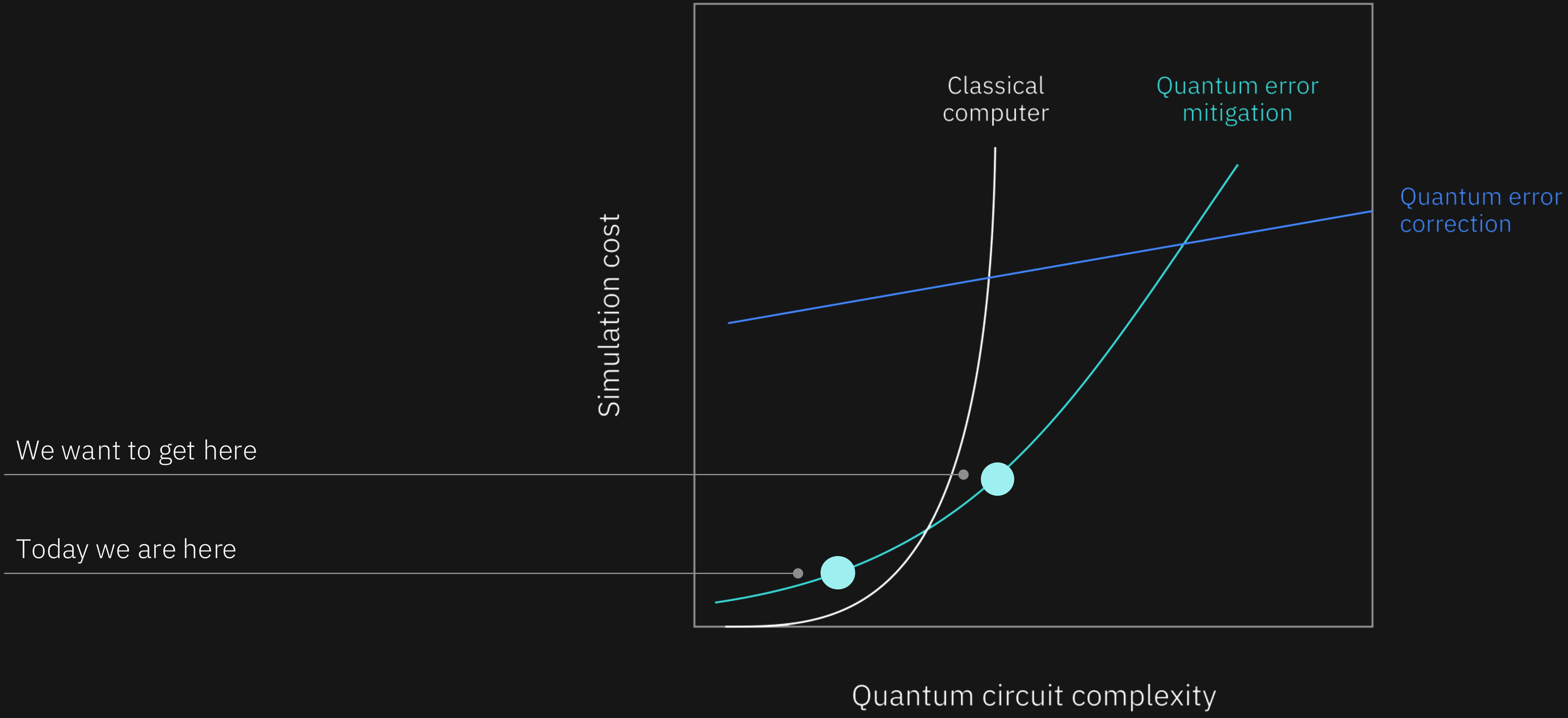
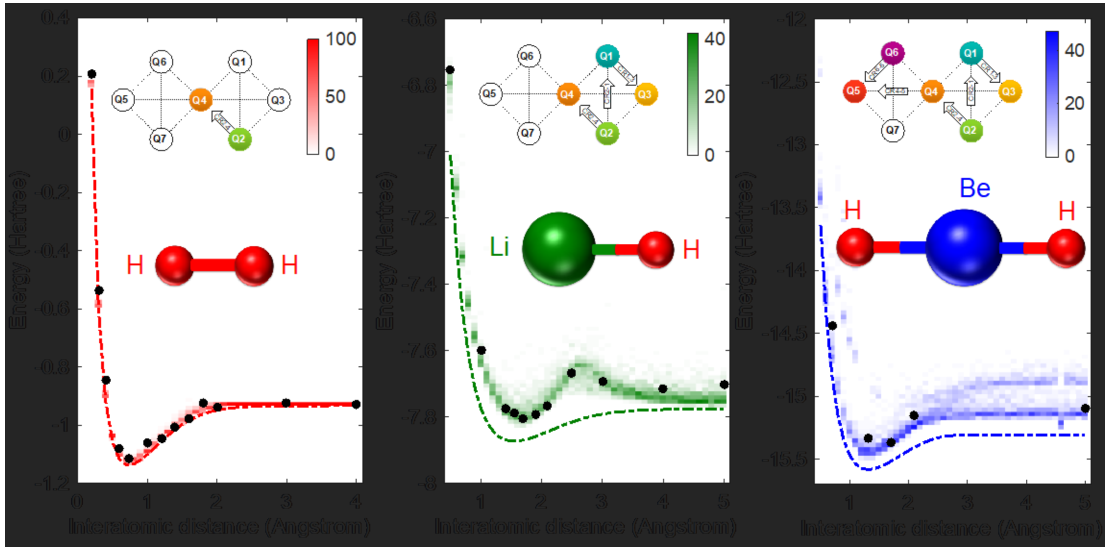
Quantum Error Mitigation and Correction

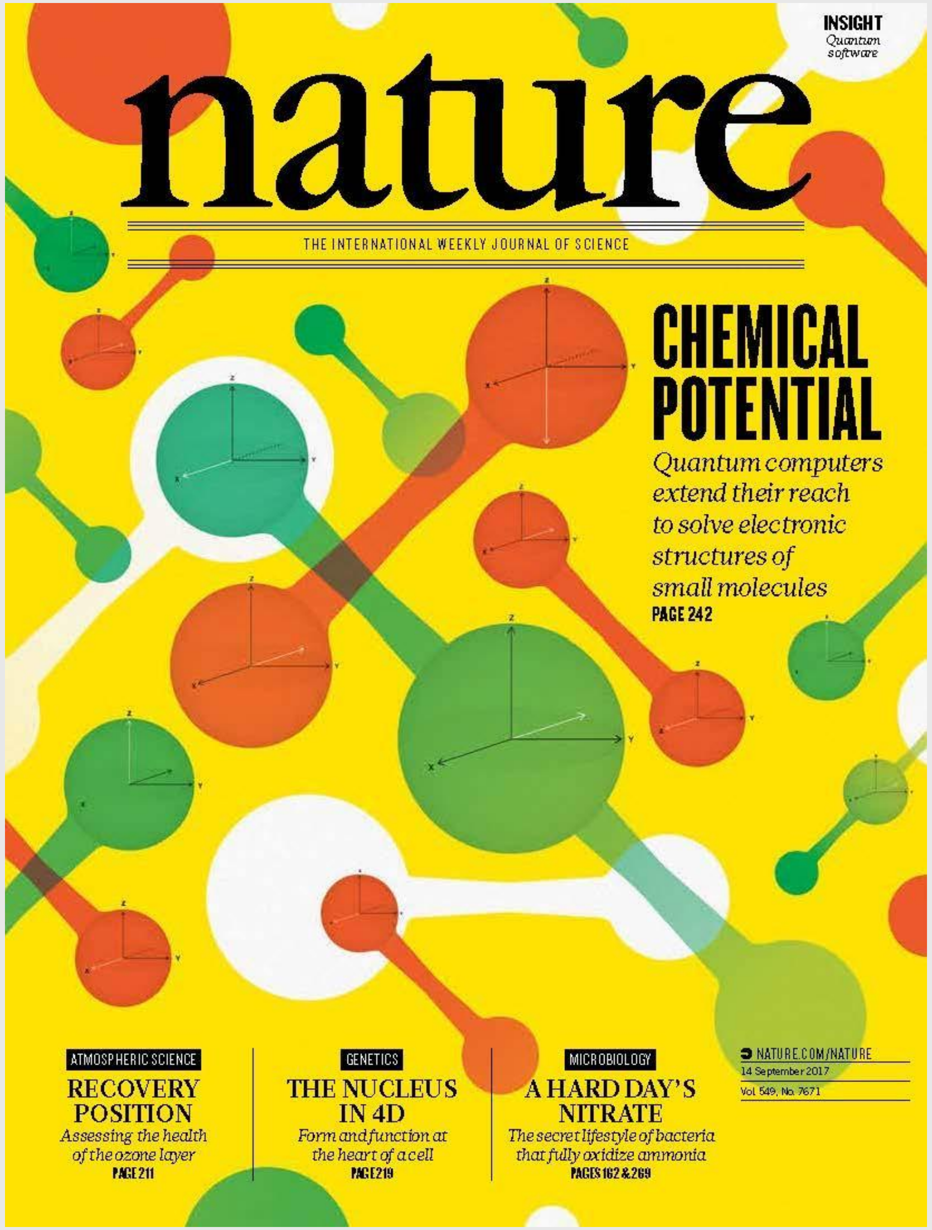


The IBM Quantum Experience
May 2016

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

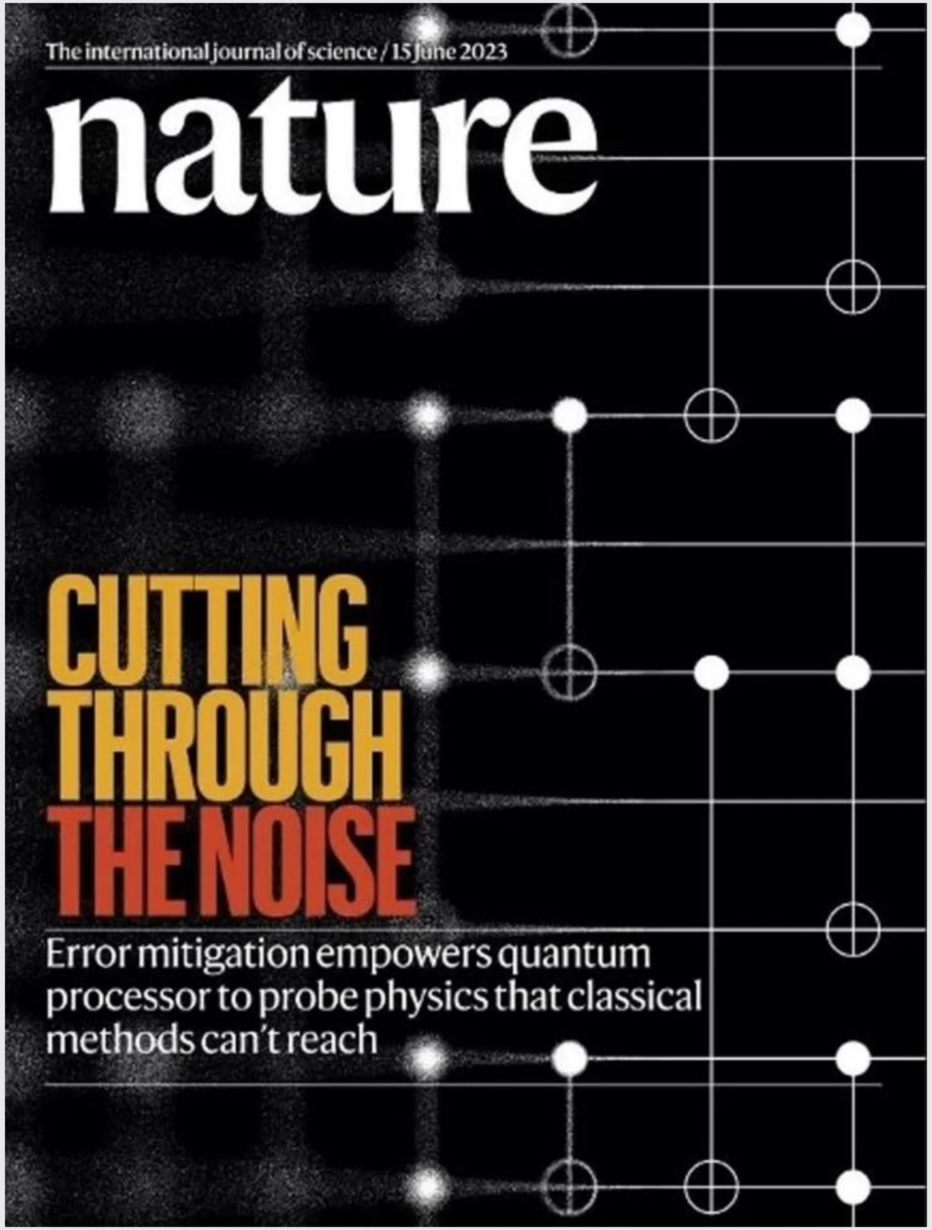
September 2017



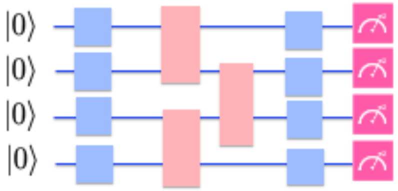


June 2023

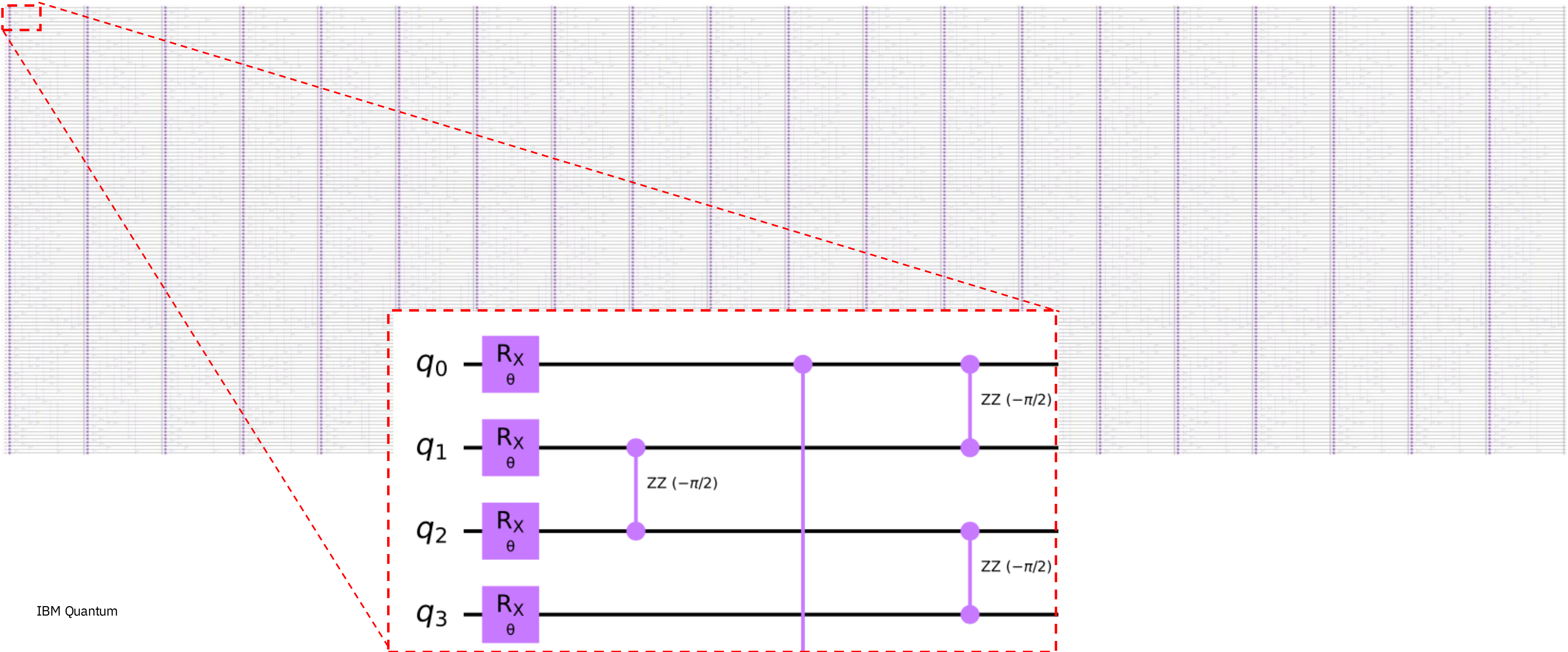
A new era has begun:
Quantum Utility



127 qubit x 60 entangling layers



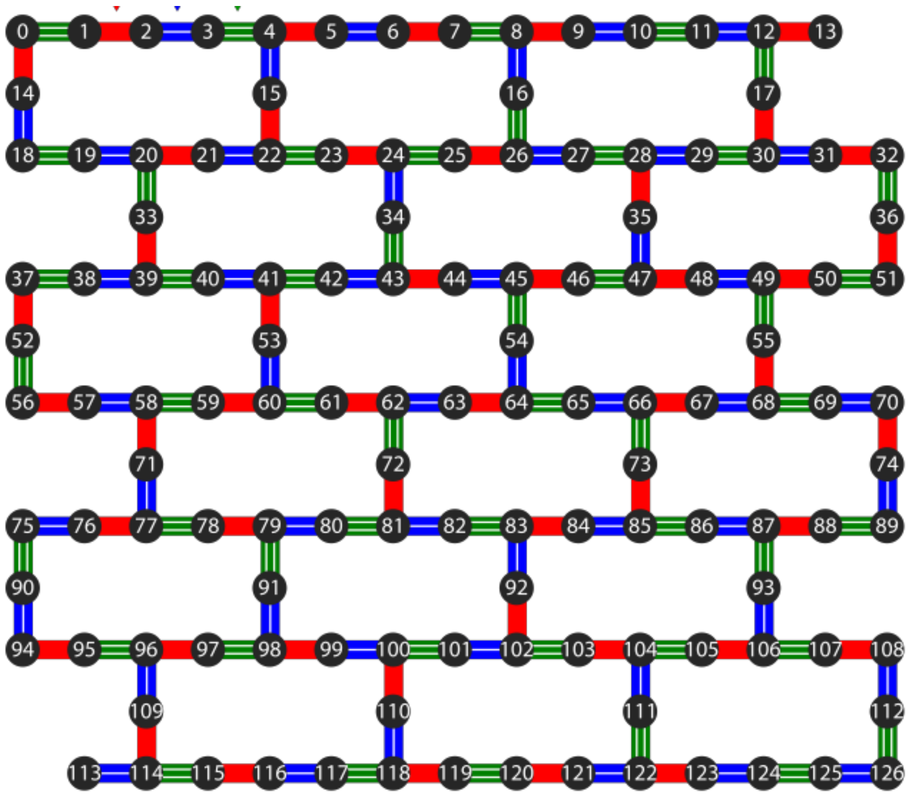
2017: 4 qubit, depth 2



The experiment

- 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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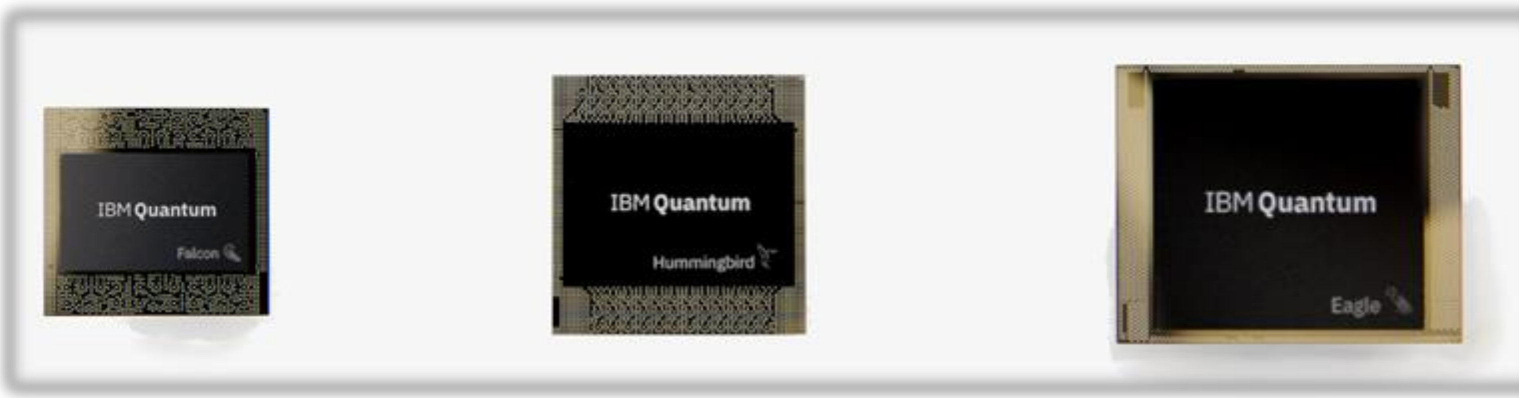
5. What made the utility-scale experiment possible?

The 2023 Nature paper reports the experiments of running circuits beyond brute-force classical simulation, ushering in the era of quantum utility. What made this possible? In short, a tremendous progress of all the fronts, hardware, software, and theory!

What made this experiment possible?

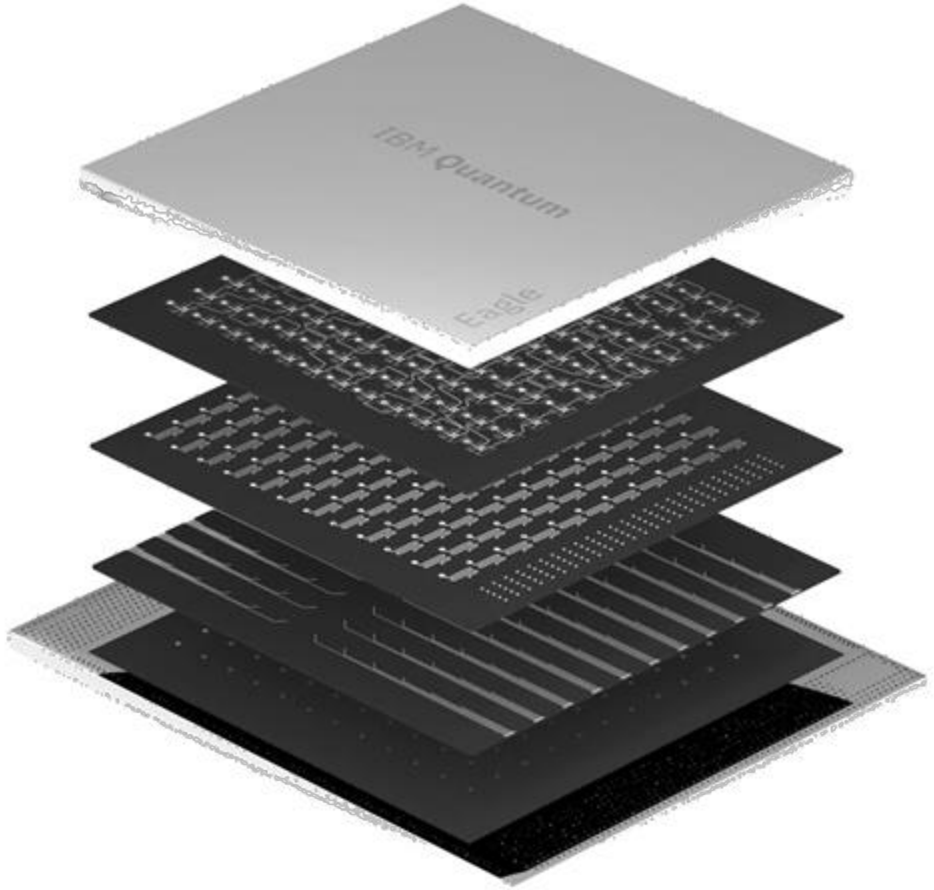
- Building a 127 qubit system



2019
Falcon
27 Qubits

2020
Hummingbird
65 Qubits

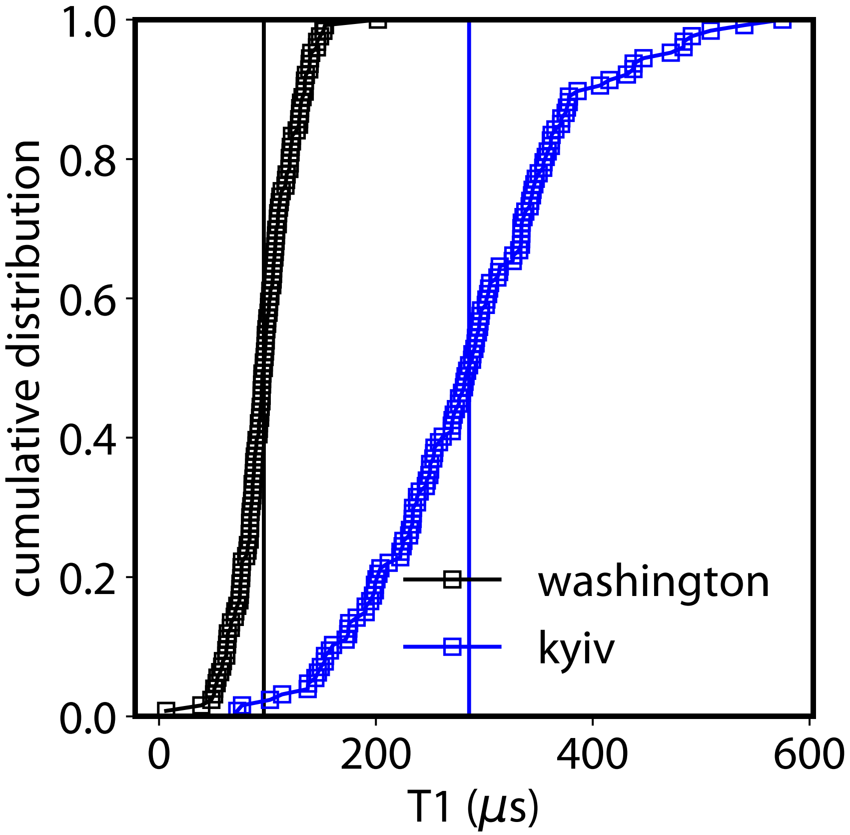
2021
Eagle
127 Qubits

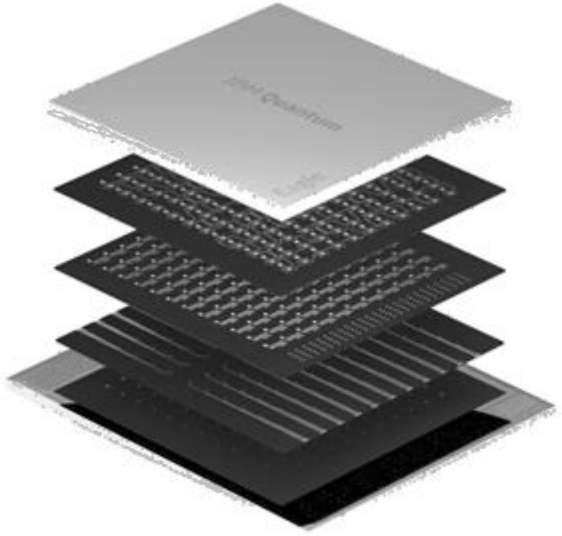


What made this experiment possible?

IBM **Quantum**

- Building a 127 qubit system
- Coherence improvements





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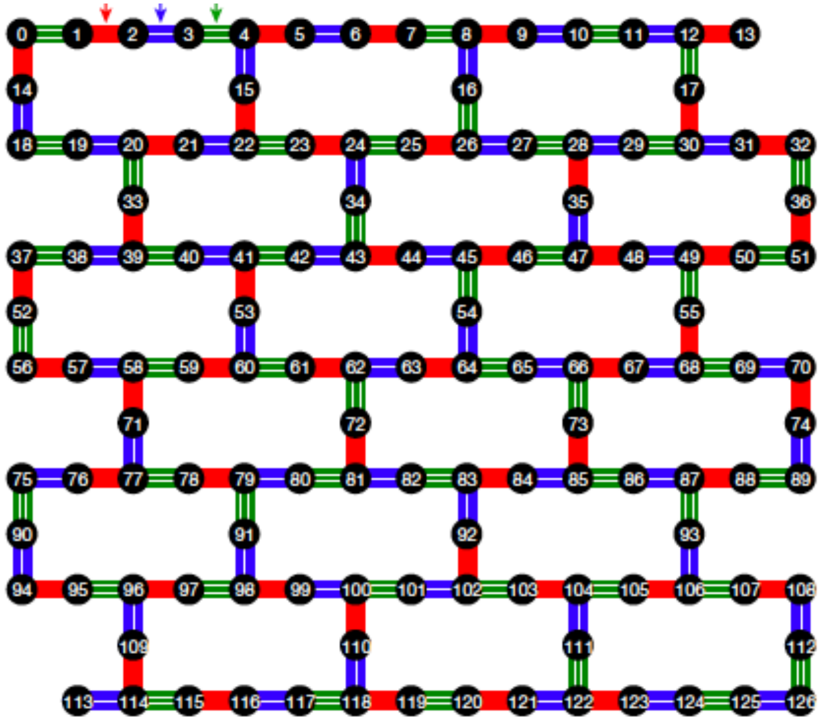

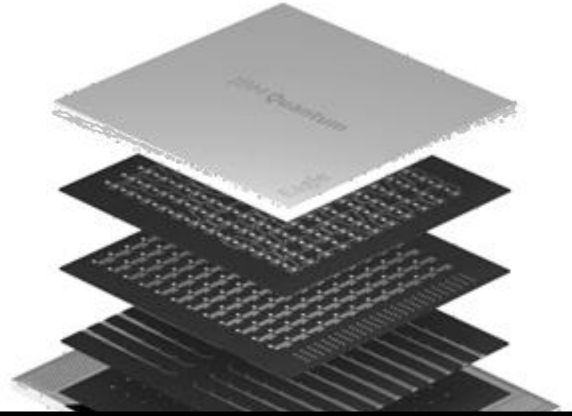

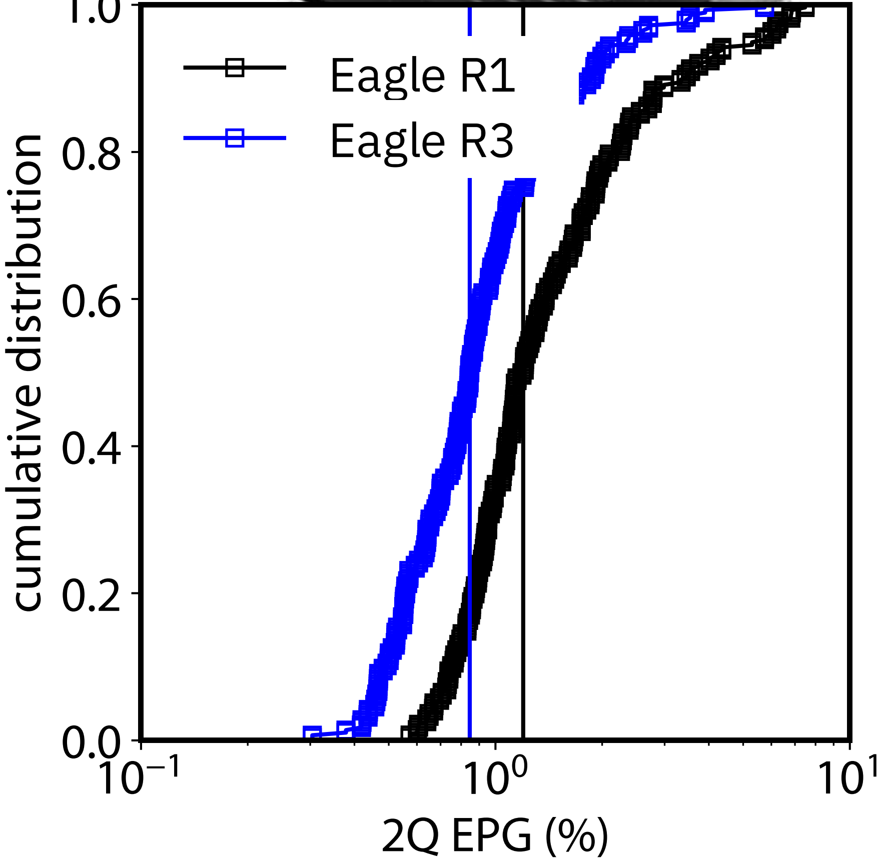

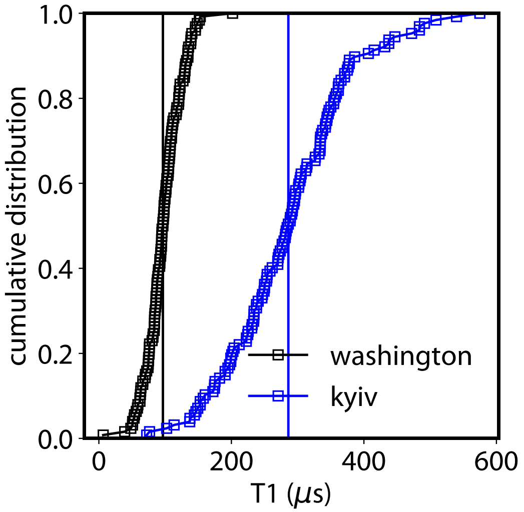

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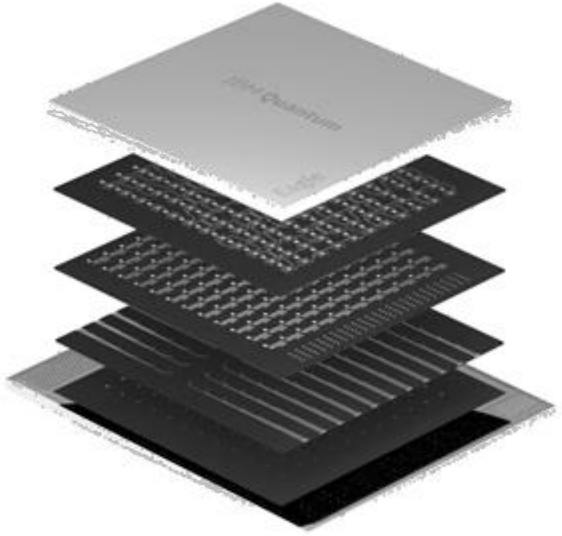
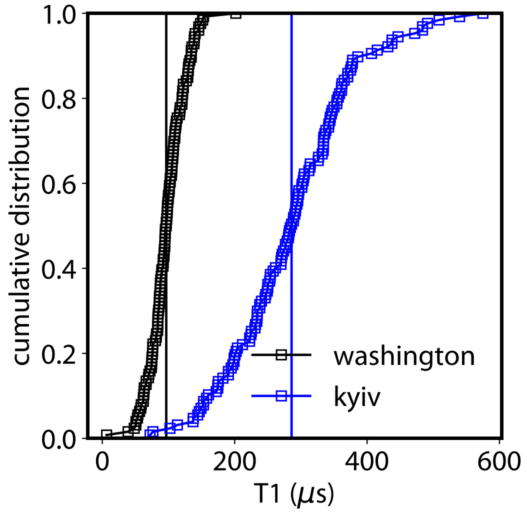
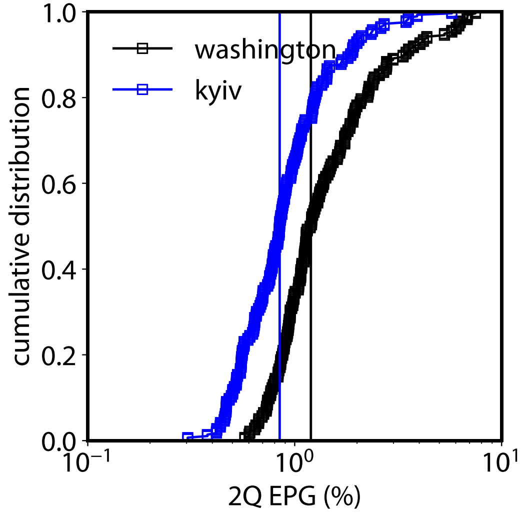
(1) Scalable noise characterization

(2) More accurate noise amplification





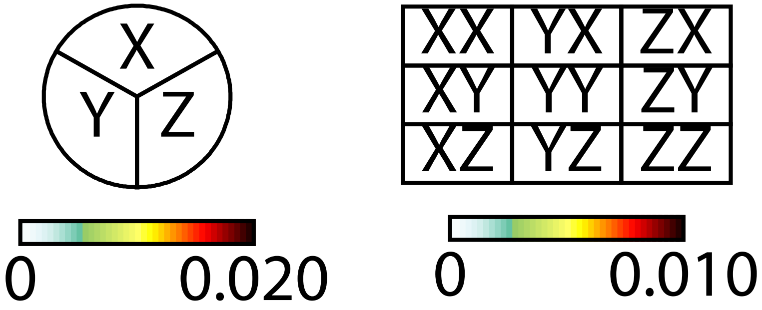


An efficiently learnable noise model

IBM Quantum

Reduced model complexity:

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



Course Schedule 2024

Date	Lecture Title	Lecturer	Date	Lecture Title	Lecturer
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

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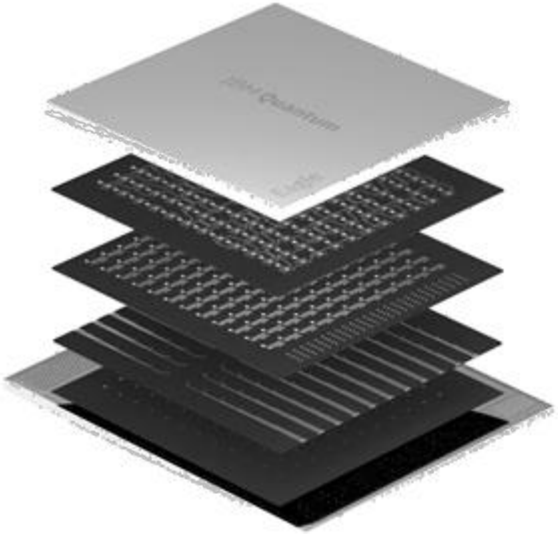
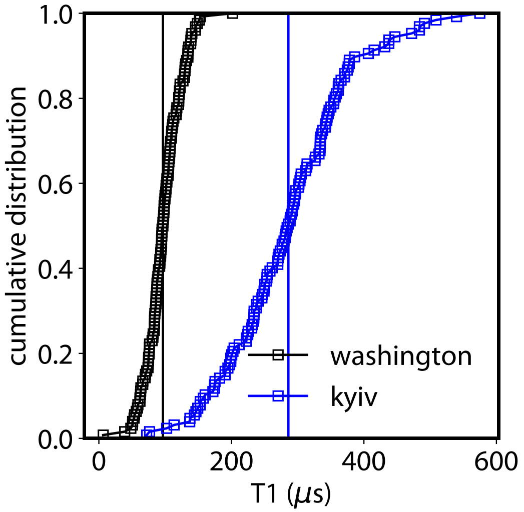
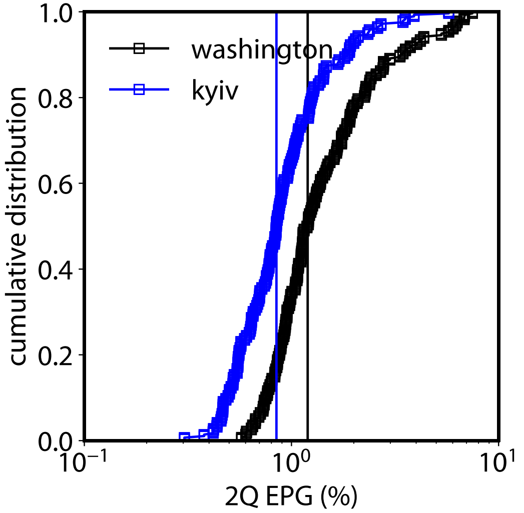
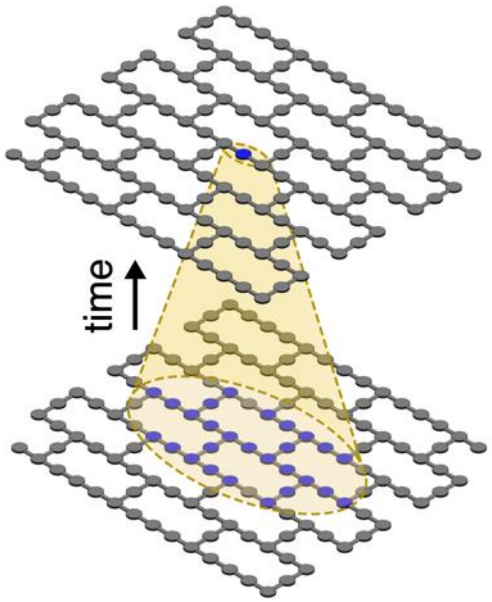


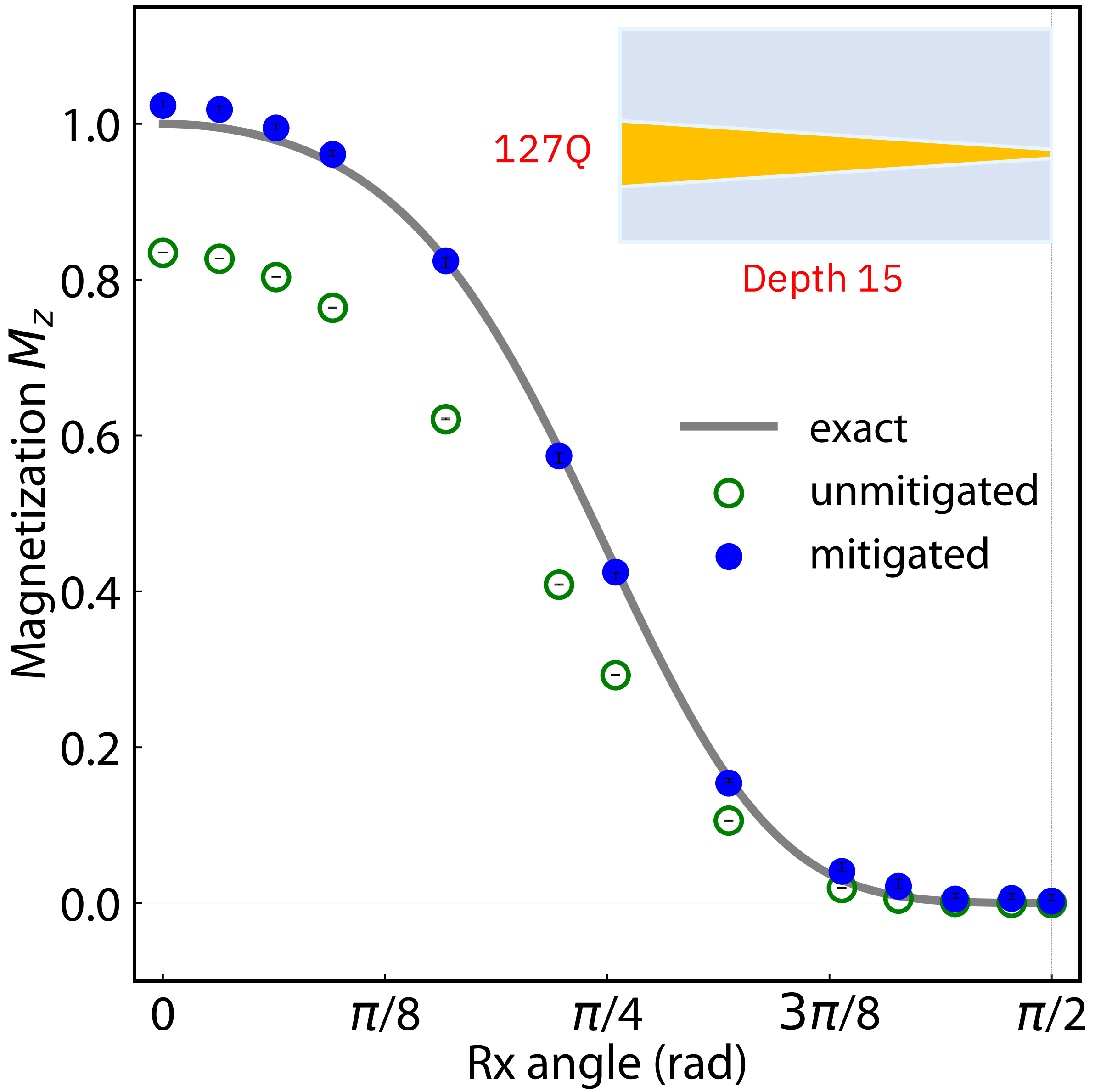




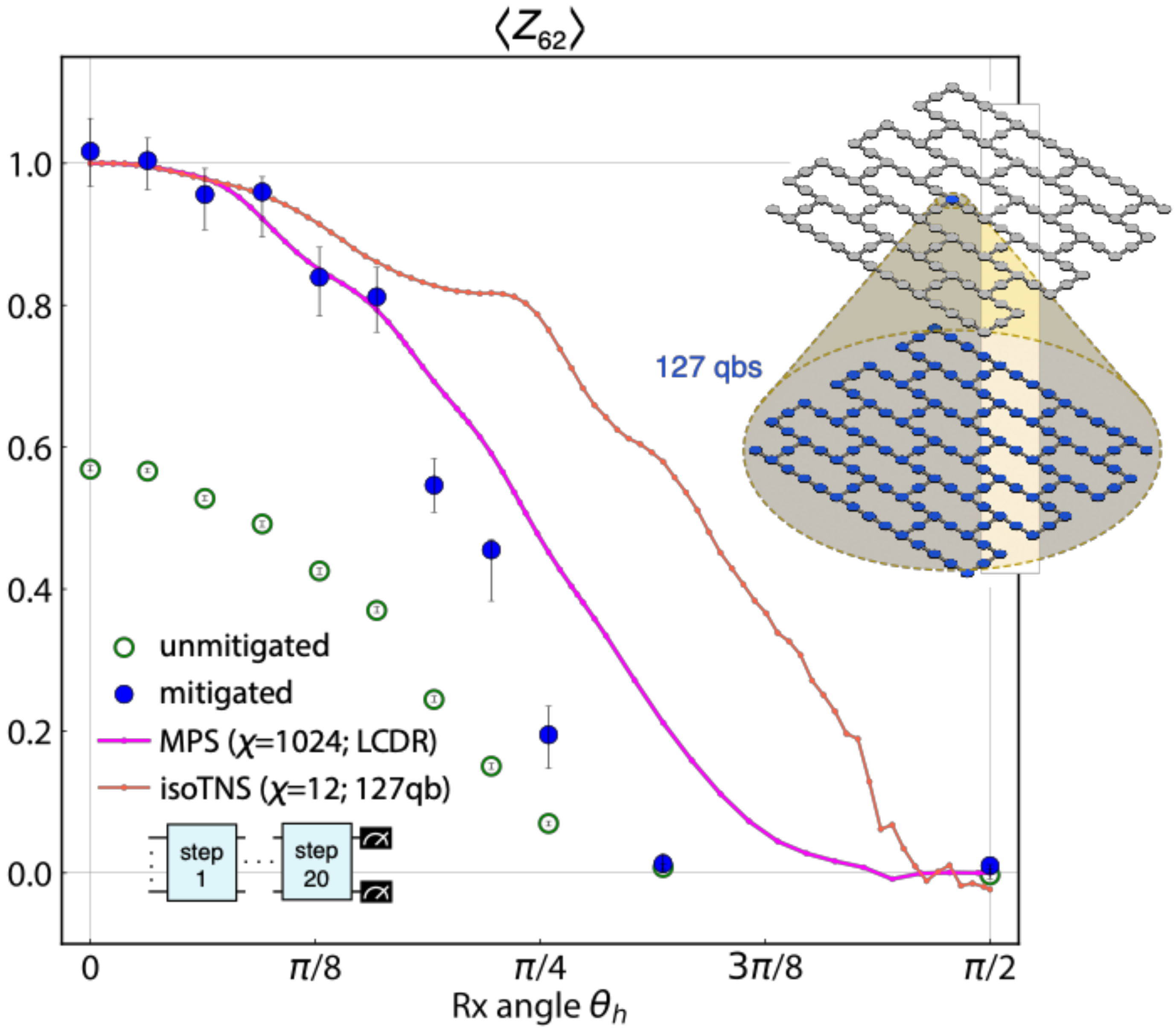
127 qubit x 15 entangling layers

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





127 qubit x 60 entangling layers

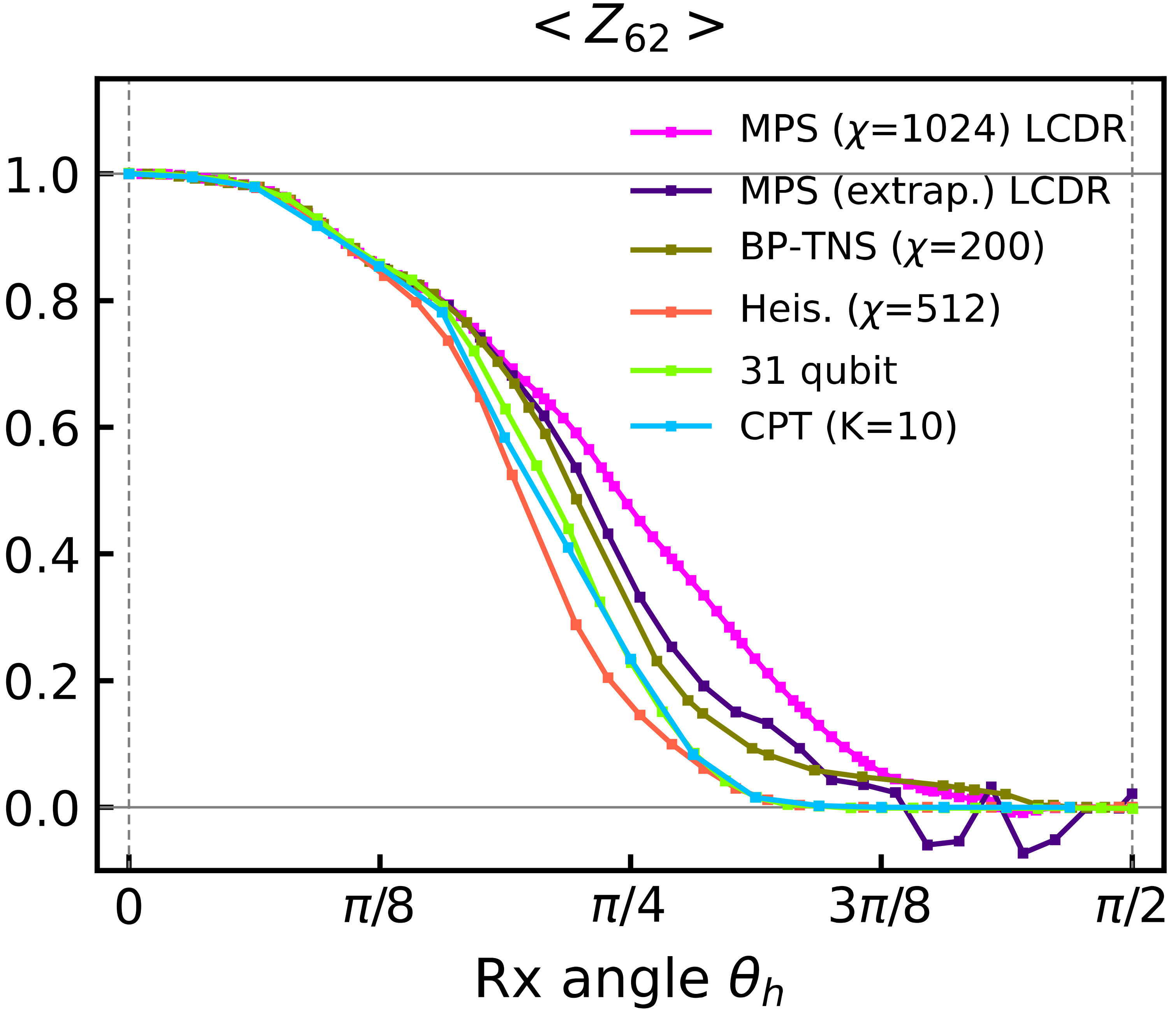


Quantum computers today can provide reliable results at a scale that is beyond exact, brute-force classical computation.

(this is not a quantum advantage claim)

Classical benchmarking of ZNE beyond exact verification

IBM **Quantum**



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

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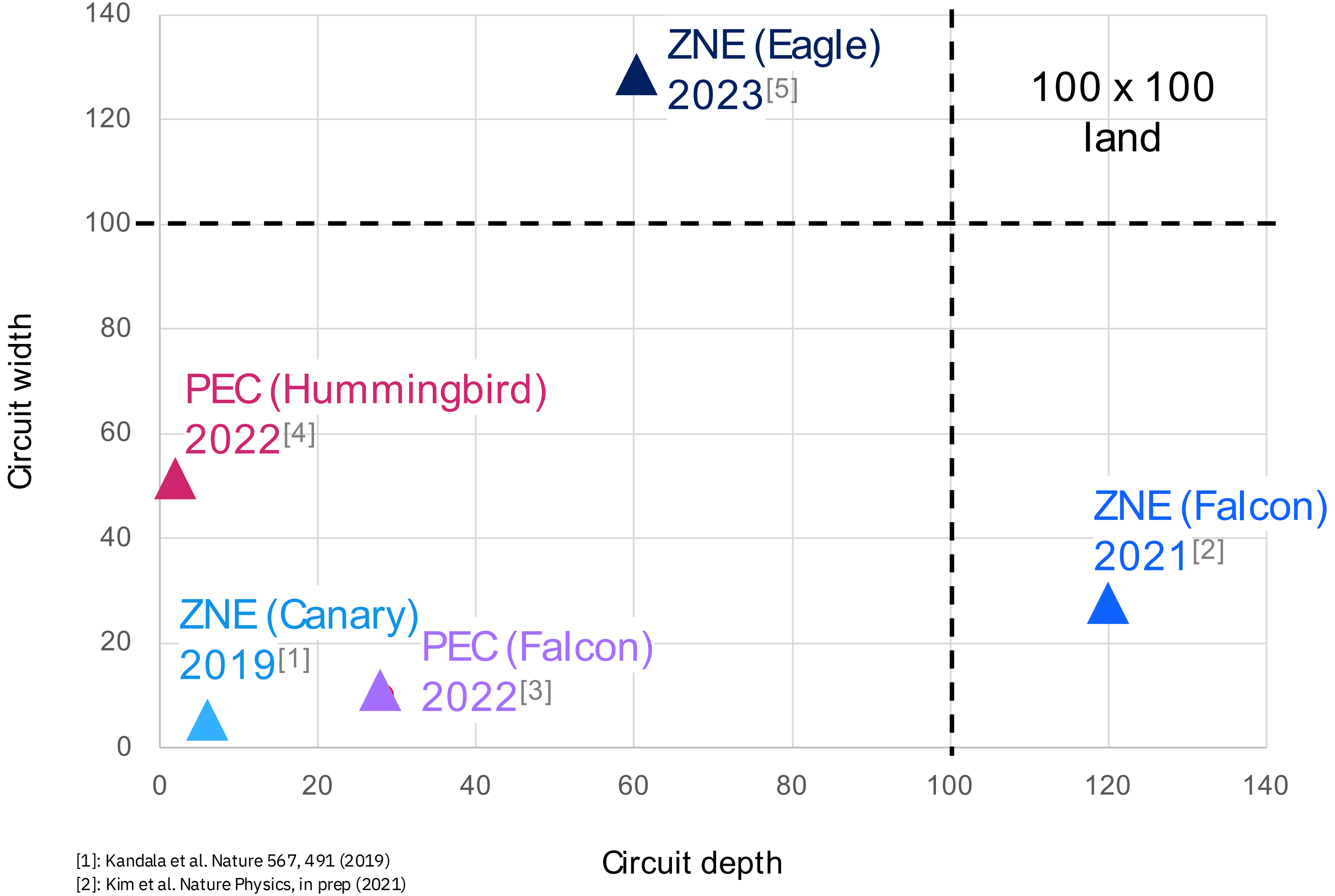
Mapping the path to useful quantum computing

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
```