Quantum Computing in Japan

Kohei M. Itoh

Professor and Founder of IBM Q Network Hub @ Keio University, Japan

Research Supervisor
Quantum State Control and Functionalization”
Japan Science and Technology Agency

Program Director
Quantum Information Technology
MEXT Quantum Leap Flagship Program

Q2B 2020

Global Trends

○*Many countries place **"quantum technology" as a key technology***

○***Governments and private sectors are increasing related budgets for R&D, establishing core research centers, and developing human resources strategically.***

○ National governments

Sep. 2018 **"National Strategic Overview for Quantum Information Science"** by National Science and Technology Council

Dec. 2018 **"National Quantum Initiative Act" (up to $1.3 billion for 5 years from 2019)**

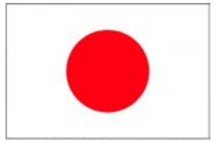
Jun. 2017 **Quantum manifest** by European Commission's advisory committee

2018 **EU Quantum Technology Flagship started (~€1 billion-scale for 10 year)**

Each nation has own R&D projects. Netherlands and UK have created international research hubs.

2016 **Quantum communication and computer** as **major projects** in "13th 5-year Plan on Science, Technology and Innovation"

National lab. for quantum information science and technology" under construction until 2020 ***(~$1 billion)***



Total Budget:

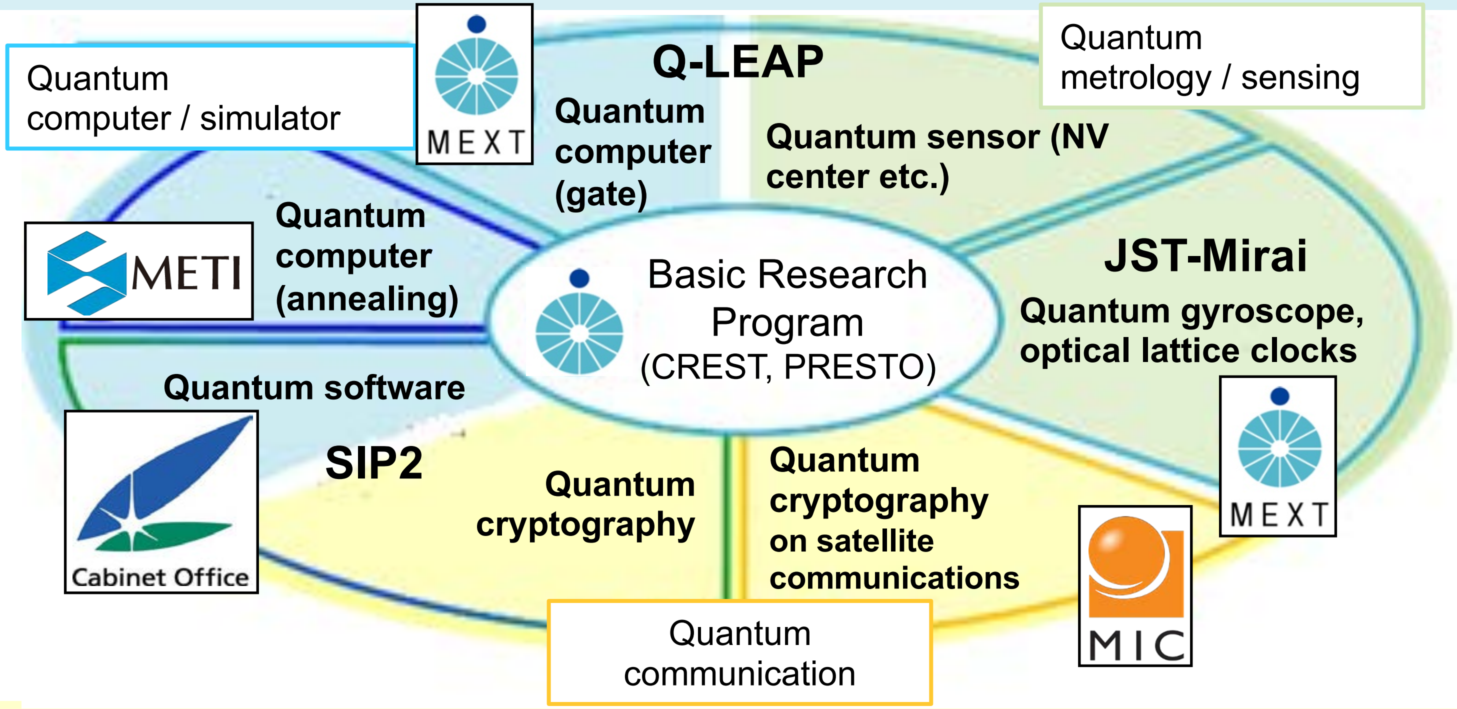
About $209 million for 2020

- **Q-LEAP Flagship Program**
  by Ministry of Education, Culture, Sports, Science and Technology (**MEXT**)
- **MIRAI**
  by Japan Science and Technology Agency (**JST**)
- **Innovative AI Chip & Next-Generation Computing Technology Development**
  by New Energy and Industrial Technology Development Organization (**NEDO**)
- **R&D of Quantum Cryptography in Satellite Communications**
  by Ministry of Internal Affairs and Communications (**MIC**)
- **Opto-quantum base technology**
  by Cross-ministerial Strategic Innovation Promotion Program (**SIP**)
- **MOONSHOT R&D Program**
  by Japan Science and Technology Agency (**JST**)

Efforts in Japan

- **Quantum technology** is recognized as an important core technology in the "**5th Science and Technology Basic Plan**" (approved by the Cabinet in January 2016).
- Maintain and improve world competitiveness in photonics and quantum technology specified in the **Integrated Innovation Strategy** (June 2018).

- **Ministries lead R&D projects on quantum technology**
- **Japan has been leading basic research on quantum computing**



1998 Prof. H. **Nishimori** (Tokyo Institute of Tech.) invented the concept of **Quantum Annealing**

2010 D-Wave Systems, Inc. (Canada) announced the world's first commercial quantum computer.

1999 Prof. Y. **Nakamura** and Prof. J. S. **Tsai** (NEC) developed **superconducting qubit**.

2016 IBM introduced a gate-based quantum computer on the cloud for public use (the first in the world).

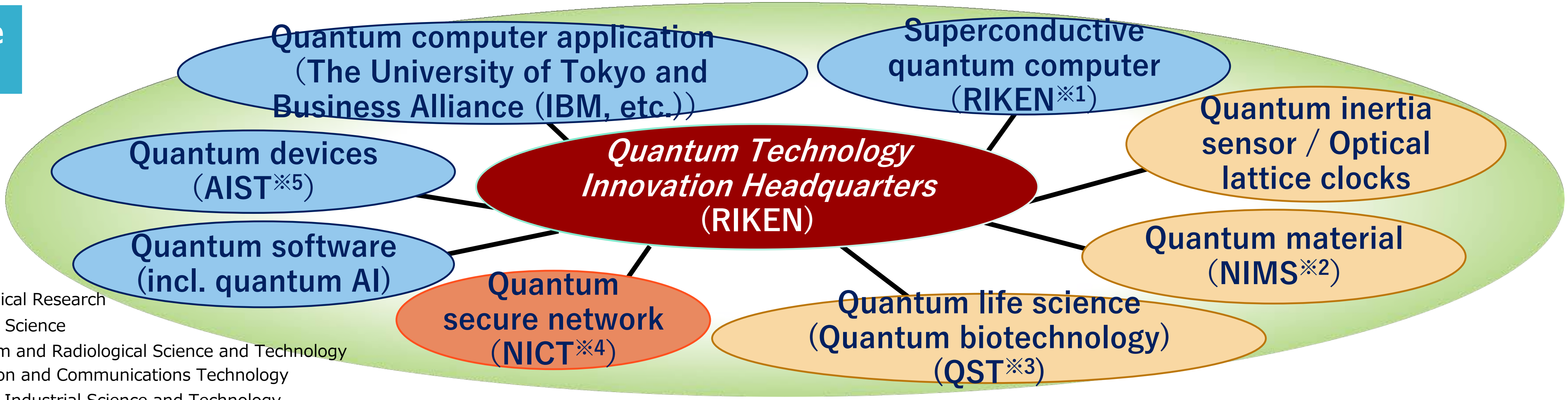
Promotion of the state-of-the-art research and industrial innovations

Quantum Technology Innovation Centers

Background

- Japan's Quantum Technology Innovation Strategy makes clear that the Quantum Technology Innovation Centers will be operated as hubs for integrated initiatives by industry, academia, and government, ranging from fundamental research to technology demonstration, intellectual property management, and human resources development.
- In a policy speech (Jan. 20, 2020), Prime Minister Abe stated, "As for quantum technology, which will be the foundation for next-generation encryption and more, we will move forward in developing innovation hubs that bring together top-class researchers and leading companies from within Japan and abroad."
- Relevant ministries will sequentially start installations at the centers from FY 2020, and funding for the centers will be earmarked in the FY 2021 general budget.

Conceptual image of Centers



※1 Institute of Physical and Chemical Research
※2 National Institute for Materials Science
※3 National Institutes for Quantum and Radiological Science and Technology
※4 National Institute of Information and Communications Technology
※5 National Institute of Advanced Industrial Science and Technology

Each domain will establish its center in an integrated way under the Headquarters

Requirements for Centers, ex.:

① Have outstanding researchers and highly internationally competitive core technology
② Expected to exponentially develop industry and innovation
③ Expected to receive investment from companies and attract excellent human resources
④ Will gather human resources, technologies, and funding effectively and efficiently

Quantum Technology and Innovation Strategy

〇**Quantum technology is an important fundamental technology** in terms of industry and security as well as brings drastic changes to economy and society.

〇**To achieve "quantum technology and innovation"** as soon as possible, Japan promotes R&D, industrialization and commercialization of key technologies with taking own advantage

Ⅰ *Priority areas*

Acceleration of innovation

- ✓**Set "Key Technology Areas" & "Integrated Quantum Innovation Areas" for priority support and investments**
- ✓**Create "Technology Roadmap" & "Integrated Area Roadmap"**

Ⅱ *Quantum hubs*

Tightly connected communication

- ✓**Establish international "Quantum technology Innovation Hubs"**

  (e.g. Quantum software hub, Quantum inertial sensor hub)

- ✓**Hub conducts basic research, demonstration and HR development**

Ⅲ *International collaboration*

Collaboration with US & EU in industrial and security issues

- ✓**Early development of multilateral/bilateral cooperative frameworks**

  (e.g. Japan-US-EU multilateral symposium in Dec. 2019)

- ✓**Ensure and strengthen security trade control**

Five pillars towards an achievement of quantum technology and innovation

(1) Technology development	**(2) International collaboration**	**(3) Industrialization and innovation**	**(4) Intellectual property and international standardization**	**(5) Human resource development**

MEXT - Quantum Leap Flagship Program

文部科学省

The **R&D program** to achieve *quantum leaps* in economical and societal goals by taking **advantage of quantum technology.**

Period: FY **2018** – FY **2029**

Research Area:

1. **Quantum IT (Computer, Simulator)**
   - ◆ Program Director : **K. ITOH**
     - ➢ *Superconducting Quantum Computers* : Prof. Y. NAKAMURA et.al.
     - ➢ *Quantum AI* : Prof. K. FUJII et.al.
2. **Quantum Metrology & Sensing**
   - ◆ Program Director: Y. ARAKAWA
     - ➢ *Solid Quantum Sensors* : Prof. M. Hatano et.al.
     - ➢ *Quantum Life-Science* : Ph.D. Y. Baba et.al.
3. **Next Generation Laser**
   - ◆ Program Director: A. ENDO
     - ➢ *Advanced Laser Innovation Centeors* : Prof. T. Fujii et.al.
4. **Development of Education Courses of Quantum Technologies**
   - ◆ Program Director: **K. ITOH**
     - ➢ *Common Core Program*: Prof. K. Nemoto et.al.
     - ➢ *Creative Sub Program01* : Prof. M. Ohzeki et.al.
     - ➢ *Creative Sub Program02* : Prof. A. Noguchi et.al.

Prof. **Yasunobu NAKAMURA**
Photo by Nikkei-Science magazine

MEXT - Quantum Leap Flagship Program

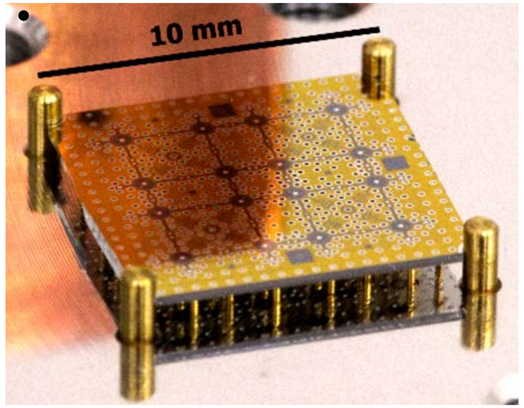
文部科学省

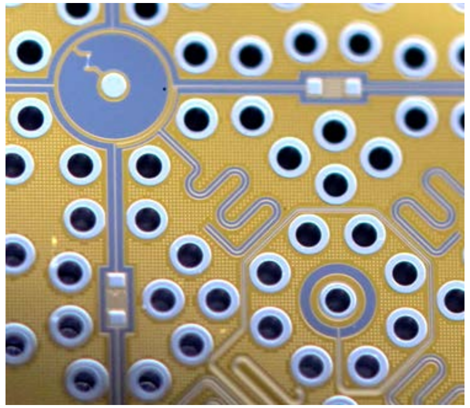
Quantum IT (Computer, Simulator)

Flagship01:
Superconducting Quantum Computers

After 2nd year

- **16-qubit system with T_1 = 20 μs**





5 -Year Plan

- **50-qubit system**
- **Cloud service** for the 50-qubits system

10 -Year Plan

- **100-qubit** system
- **Cloud service** for the 100-qubits system
- **Applications for practical issues**

Flagship02:
Quantum AI

NEW ! Since *Autumn. 2020*

- **Software architecture** for **NISQ**
- **Applications** taking advantage of a quantum supremacy
- Analysis of **practical issues** using the quantum AI.

Leader:
Prof. **K. Fujii**

5 -Year Plan

- **Algorithm library** for data classification, chemical reaction simulation and FinTech.
- **Cloud service** for Quantum circuit **analysis tools** and physics

10 -Year Plan

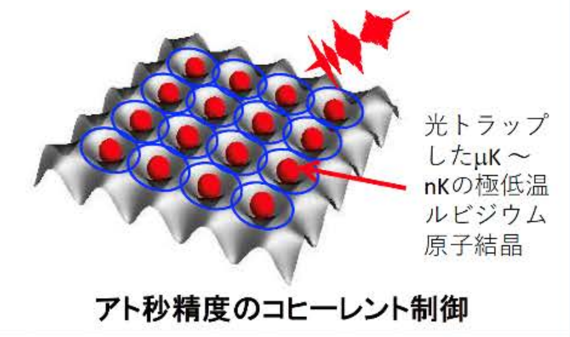
- **Quantum AI** for **condensed matter physics** and **Machine Learning** for **practical issues**
- **Cloud service** for quantum circuit **design tools for NISQ**
- **Quantum Software** on **the actual device**

MEXT - Quantum Leap Flagship Program

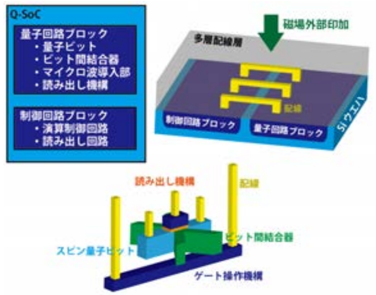
文部科学省

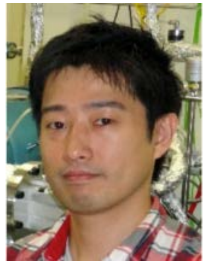
Quantum IT (Computer, Simulator)

and We also have other 6 R&D teams around the Flagship programs…

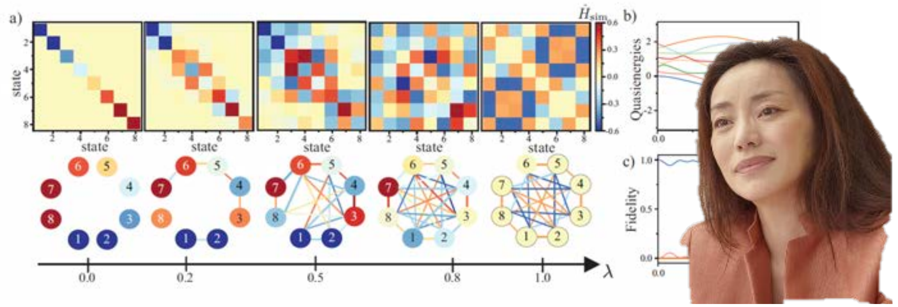


Leader:
Prof. ***K. Ohmori***

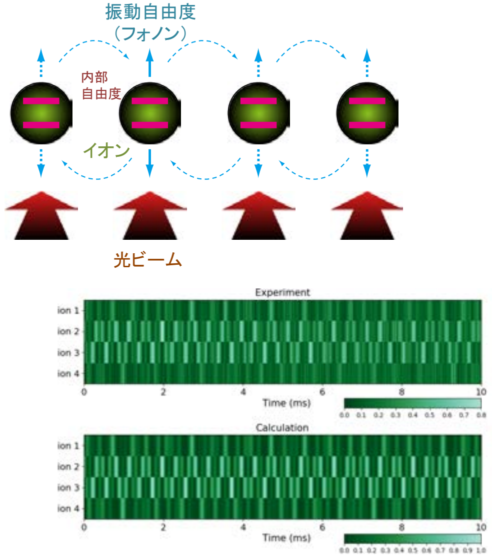




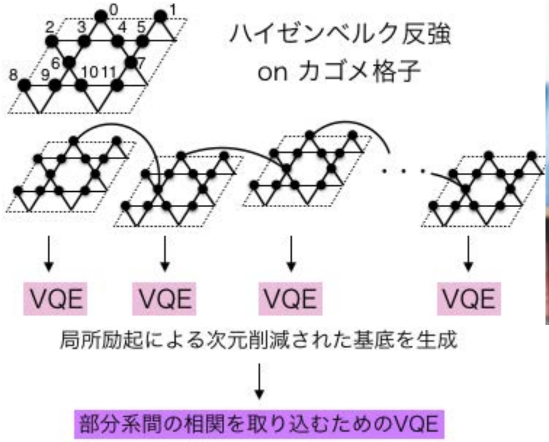
Leader:
Ph.D. ***T. Mori***



Leader:
Prof. ***K. Nemoto***



Leader:
Prof. ***K. Toyota***



Leader:
Prof. ***K. Fijii***

Leader:
Prof. ***N. Yamamoto***

MEXT - Quantum Leap Flagship Program

文部科学省

Development of Education Courses of Quantum Technologies

NEW !

Since *Oct. 2020*

Common Core Program:

Standard Program for a Higher Education Center

Development of **high-quality Standards** of **Higher Education** in **Quantum Technology**

Leader:
Prof. **K. Nemoto**

Creative Sub Program01 :

Development of Quantum Natives through Practical R6D

Building **a practical group learning program** to develop human resources who can use **quantum annealing** and **quantum machine learning** for computing in practice.

Leader:
Prof. **M. Ohzeki**

Creative Sub Program02 :

Online Course and Summer School Program for Quantum Technology Education

Development of an **online course** and **summer school program** to improve the quality and stratification of talented researchers and engineers involved in **quantum experiments** and **technologies**.

Leader:
Prof. **A. Noguchi**

Moonshot Goal #6

Goal 6

<u>Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050.</u>

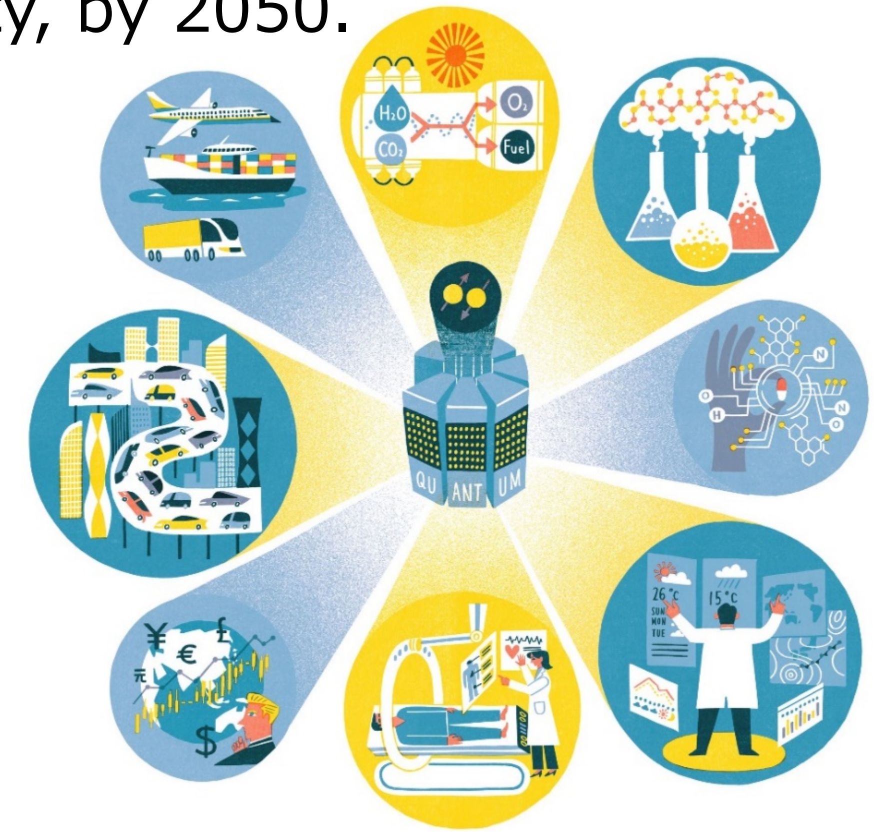
<Target of Moonshot Goal>

- Achievement of the large-scale integration required for fault-tolerant universal quantum computers*[1] by around 2050.
- Development of a certain scale of NISQ computer*[2] and demonstration of the effectiveness of quantum error correction by 2030.

(Reference: Future Visions to be achieved）

A universal quantum computer that will dramatically revolutionize our society

- Realization of a large-scale and multipurpose quantum computer that will revolutionize economy, industry and security, by 2050.



*1 Fault-tolerant universal quantum computer is a quantum computer that realizes large-scale integration while guaranteeing on sufficiently high accuracy for various applications.

*2 NISQ(Noisy-Intermediate Scale Quantum) is a small to medium scale quantum computer that does not have a function to correct errors.

[Moonshot Goal candidate]

2050 Realization of fault-tolerant universal quantum computers

2040 Demonstration of distributed NISQ computer & Calculation of useful tasks under quantum error correction

2030 Development of NISQ computers of a certain scale & Effectiveness demonstration of quantum error correction

Network

Development of quantum memory, establishment quantum interface technology between photons and quantum memory.

- Photon source & detector
- Quantum memory
- Quantum interface technology

Hardware

System design and implementation of quantum error correction, establishment of quantum bit and gate platforms.

Stage gate
Identify suitable & feasible physical system.

- Super-conducting qubits
- Photons
- Trapped-ions
- Silicon quantum dots

Software

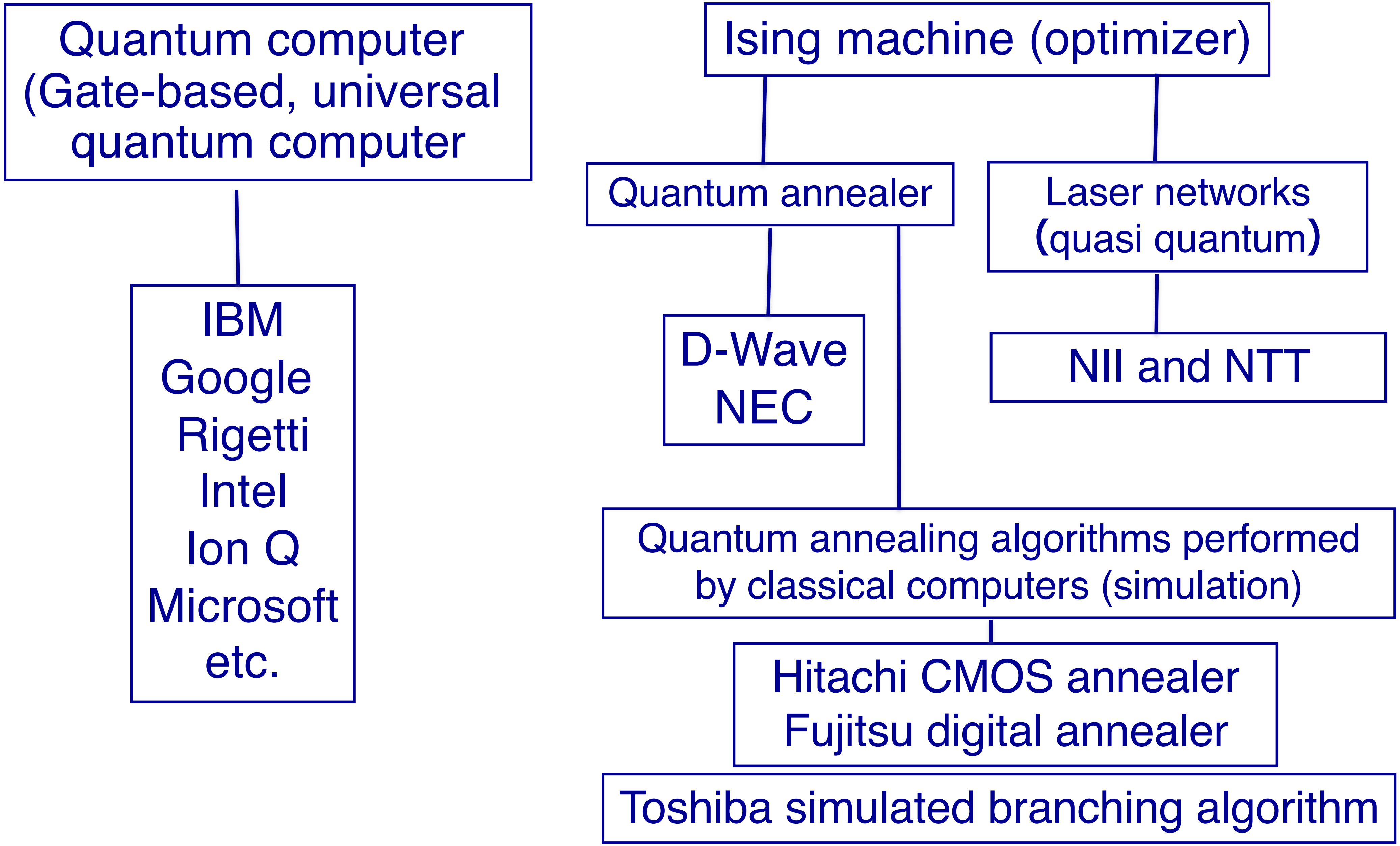
Development of low overhead quantum error correction code and quantum algorithms, development of measurement and control software.

- Quantum error correction theory
- Middleware, compiler
- Algorithms, applications

Related Quantum Technology

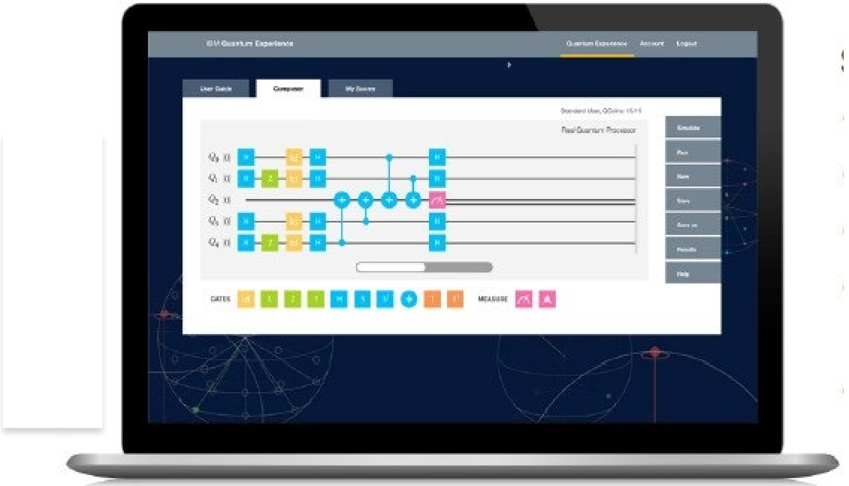
- Quantum sensors
- Quantum materials
- Basic and Fundamental Research

Classification of quantum computers



IBM Q Network Hub @ Keio University

Keio Yagami Campus
Yokohama, Japan
(Keio Q Hub)



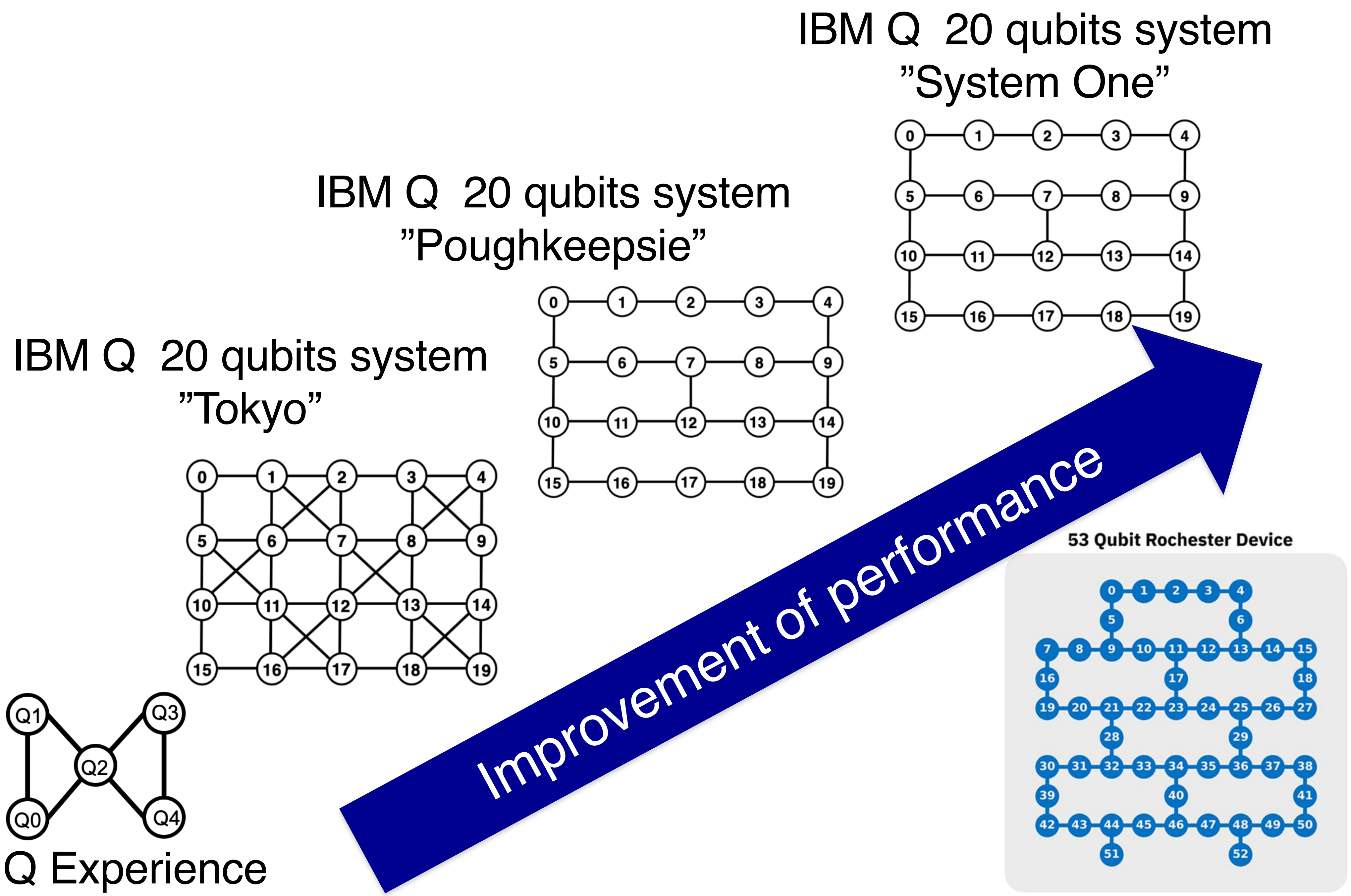
Cloud quantum computing

Program →

← Results

IBM Watson Research
(New York)

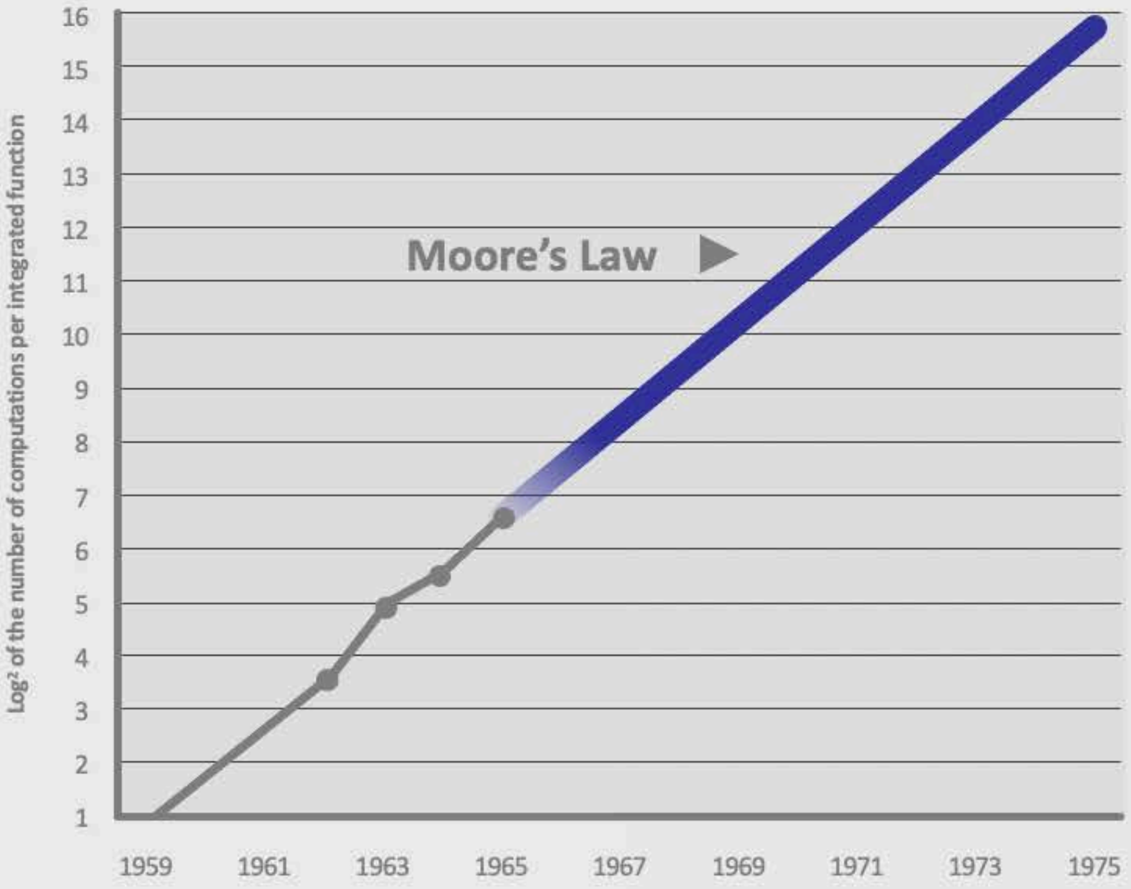
Rapid advancements of processors available in IBM Q

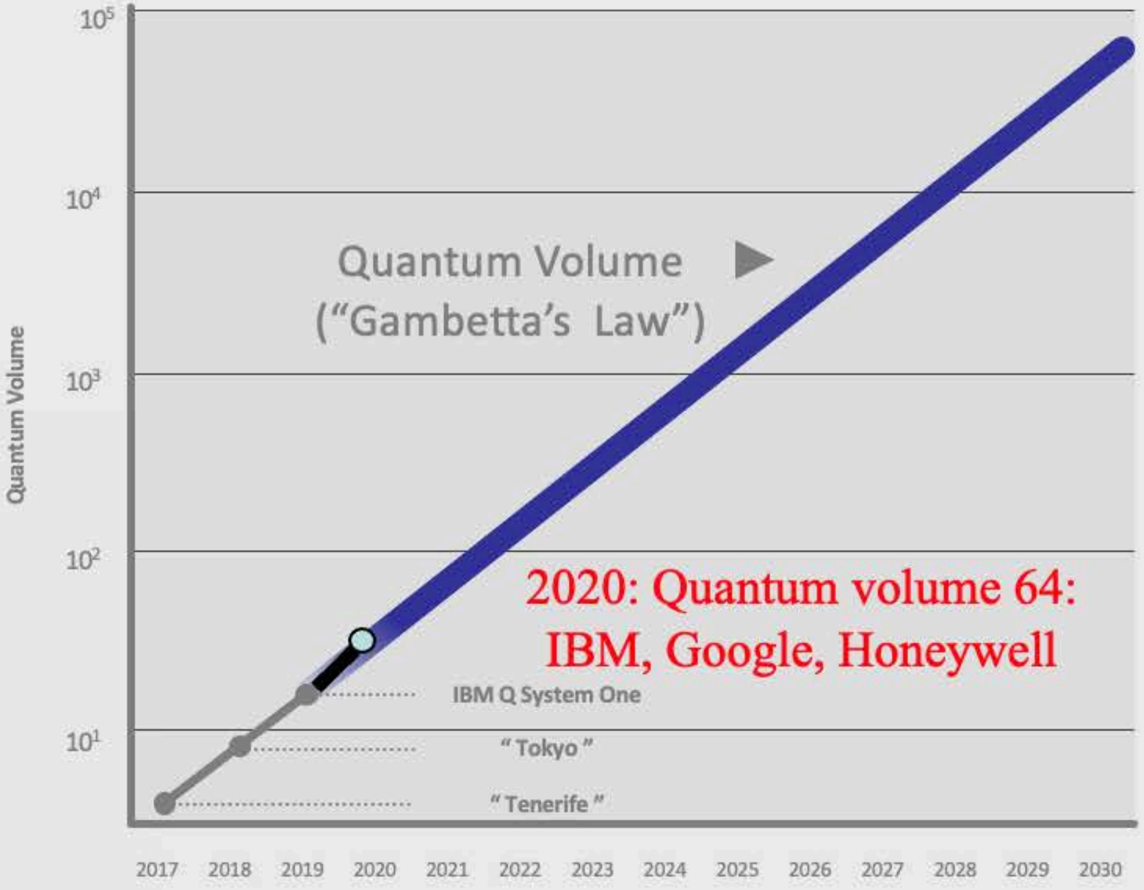


The Road Ahead

Quantum volume captures the largest arbitrary model circuit a quantum computer can successfully implement.

Higher number of qubits, more connectivity, larger gates set, lower error rates.



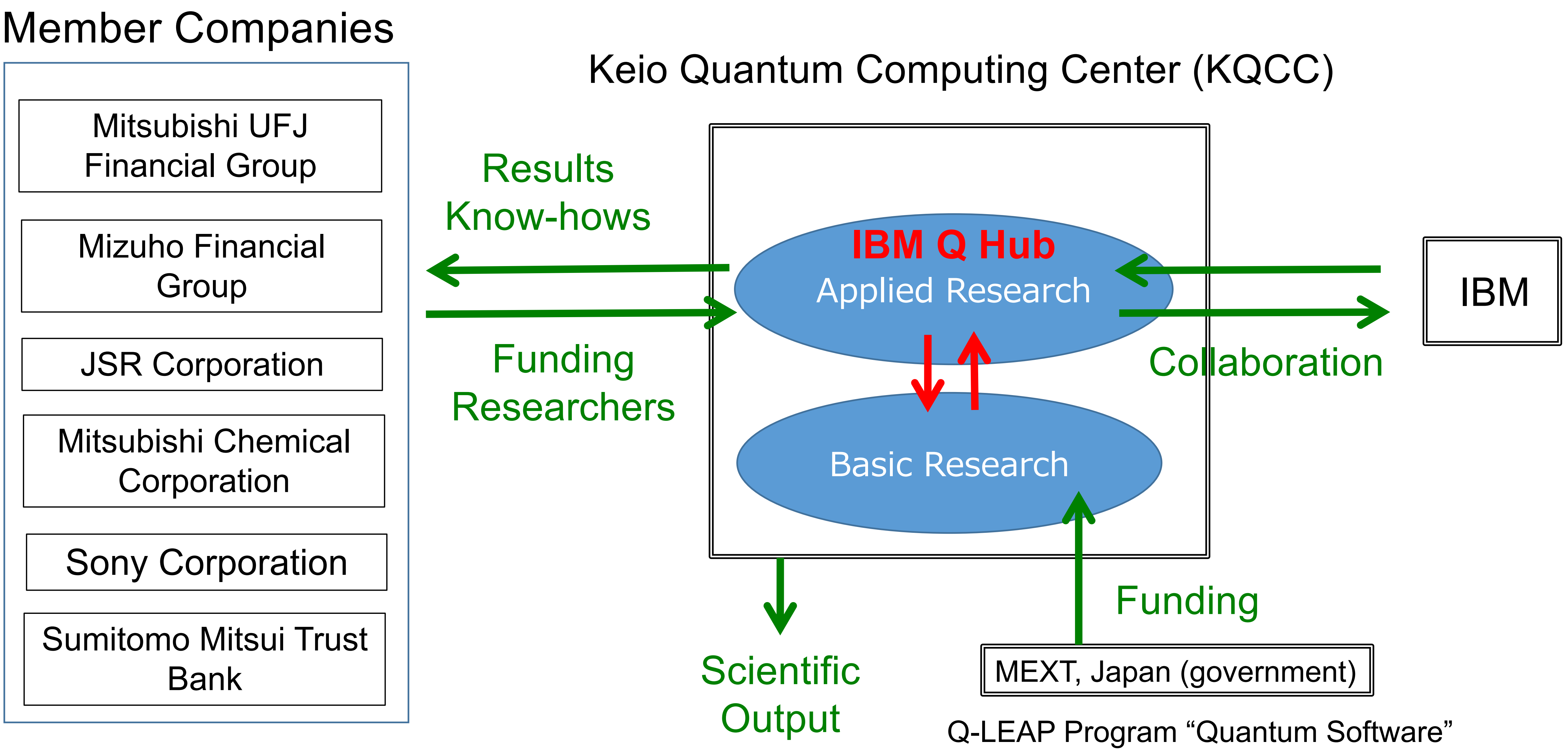


A New Exponential? Scale quantum volume

お帰りなさい。

Keio Quantum Computing Center

（Started May 2018, the first term ends on Dec, 2020, the second term starts on Jan. 2021）



Q-LEAP Program “Quantum Software”
PI: Prof. Naoki Yamamoto


Q

Q

McGill


Research topics at IBM Q Hub @ Keio

Basics & Application

< Quantum Finance Team >

Verification by simulator & IBM Q machine

< Quantum Chemical Team >

Chemical reaction calculation of lithium air battery using IBM Q machine

< Quantum AI Team >

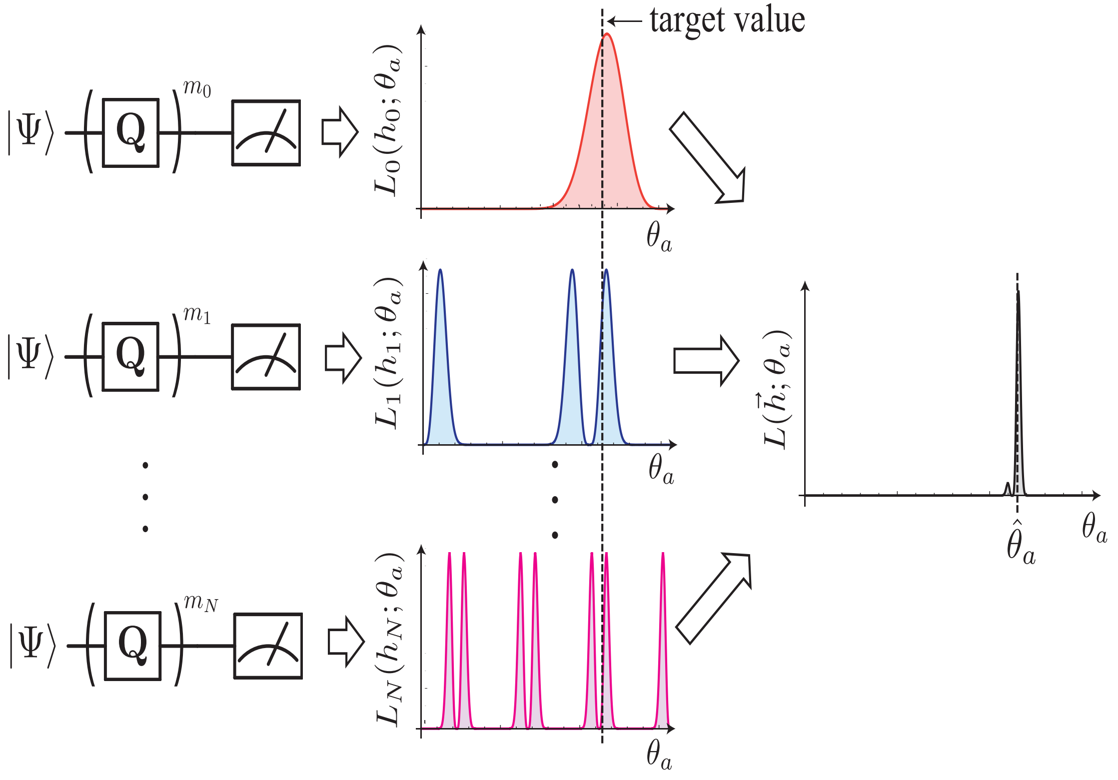
High accuracy data classification using IBM Q machine

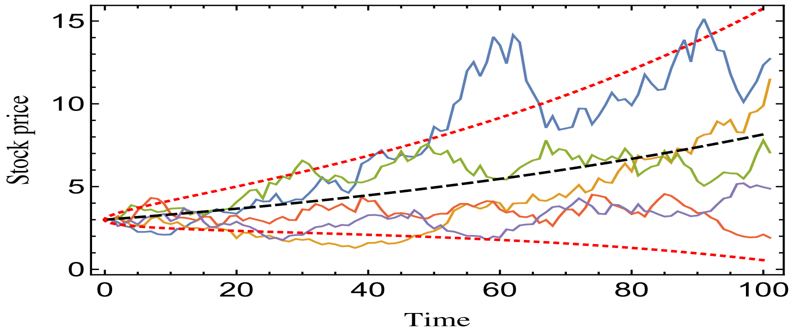
< System（Quantum Software Implementation）Team >

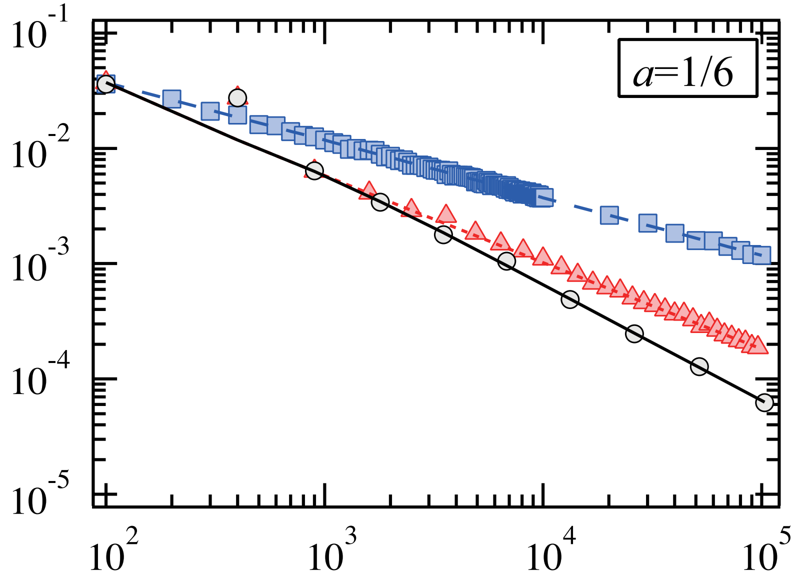
Connecting an abstract quantum circuit to a real machine

Quantum finance team :
Fast Monte Carlo calculation

Keio + Mizuho + MUFG + IBM

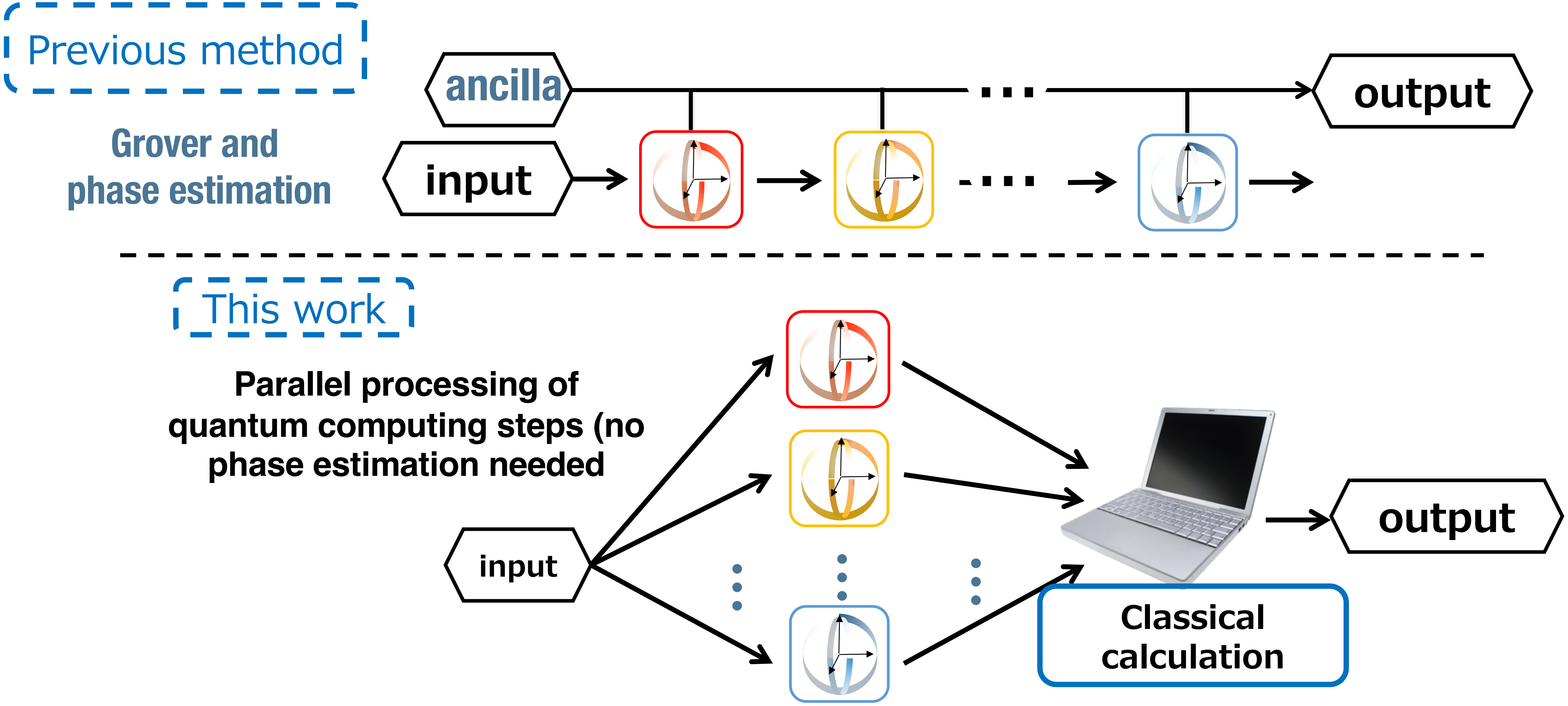




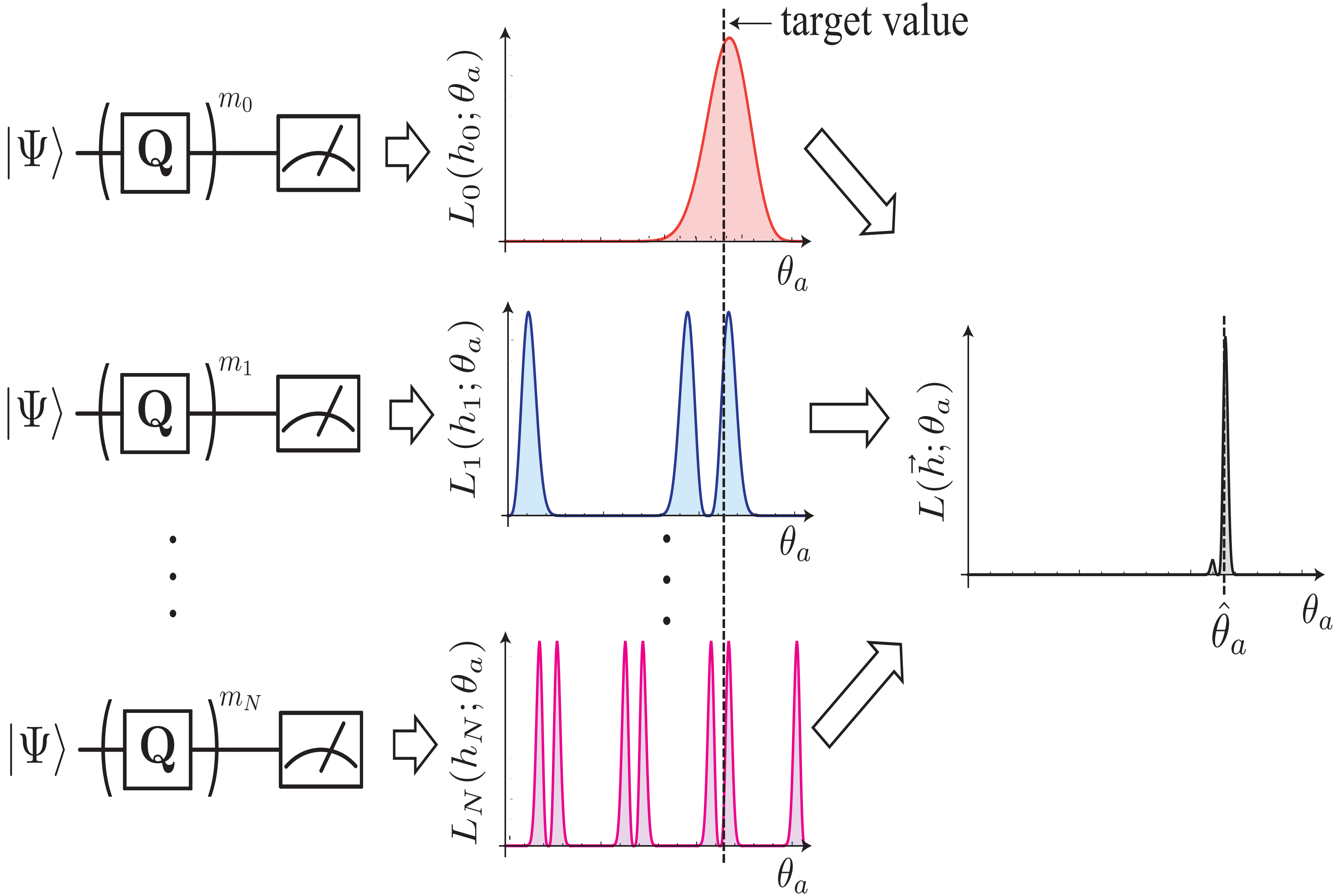


Verification using simulator and IBM Q real machine

Amplitude estimation algorithm for quantum square speed-up of Monte Carlo

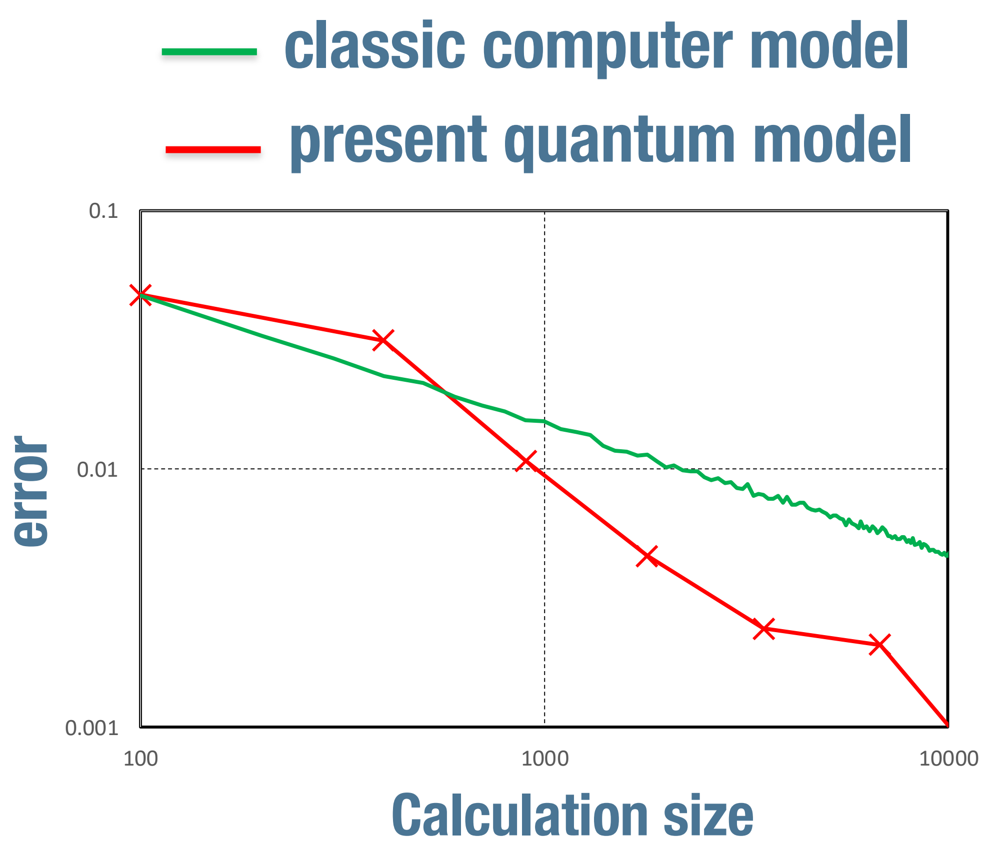


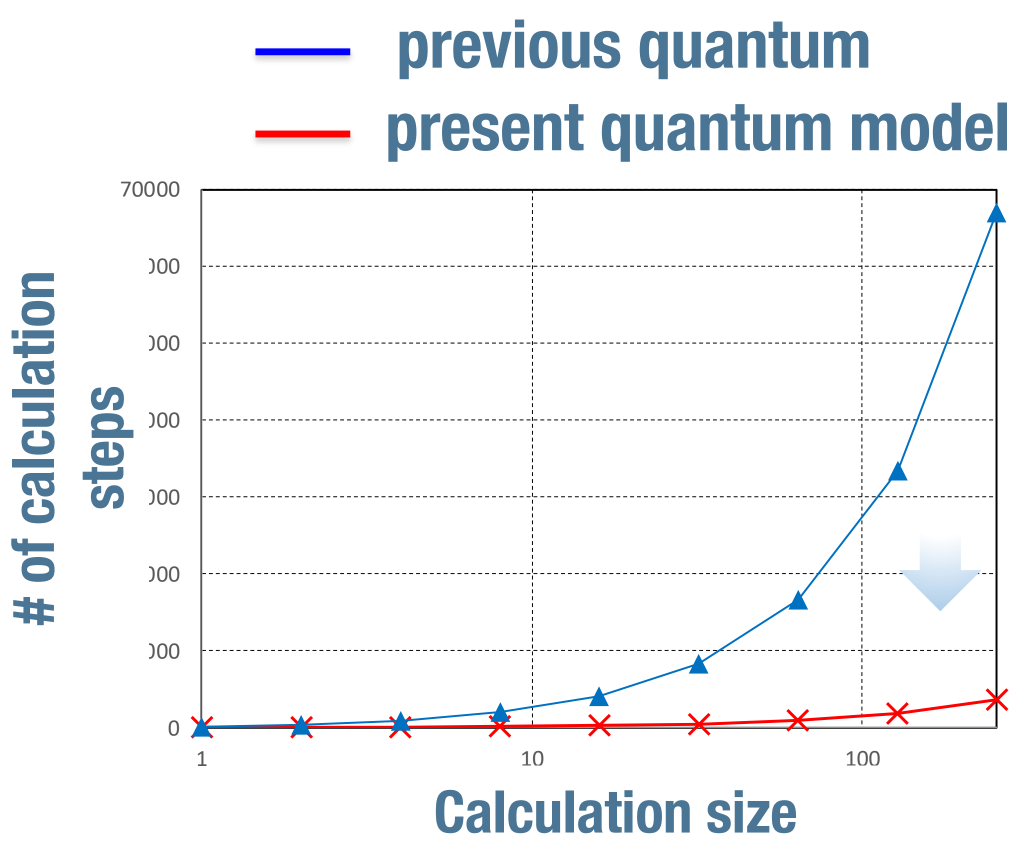
Amplitude Estimation without Phase Estimation, Quantum Information Processing 19, 75 (2020)



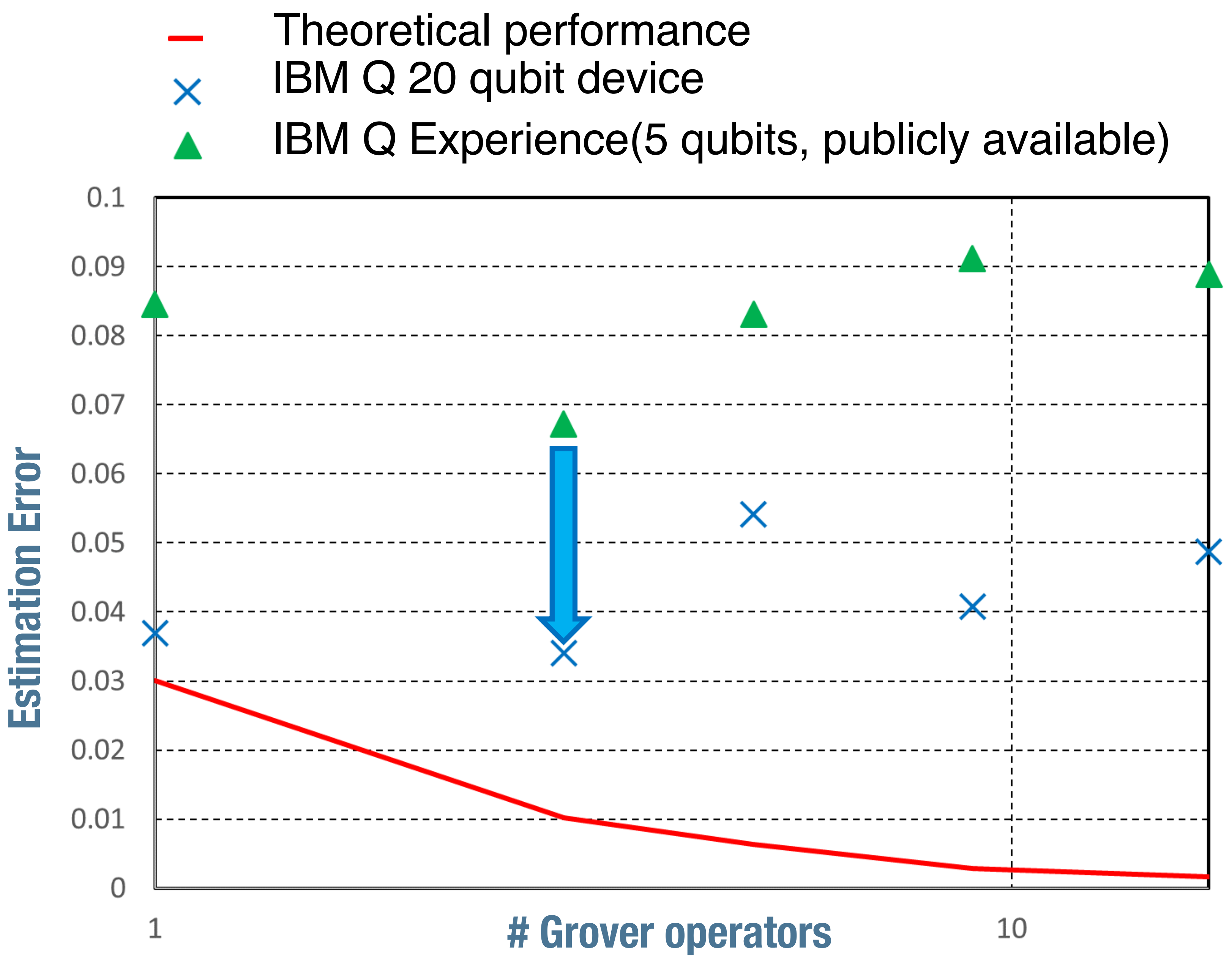
target value
$|\Psi\rangle$
Q
m_0
m_1
m_N
$L_0(h_0;\theta_a)$
$L_1(h_1;\theta_a)$
$L_N(h_N;\theta_a)$
$L(\vec{h};\theta_a)$
θ_a
$\hat{\theta}_a$

Monte Carlo Integration





Calculations by IBM Q



Quantum Filter Diagonalization: Quantum Eigendecomposition without Full Quantum Phase Estimation

Robert M. Parrish[1,*] and Peter L. McMahon[1,2]

[1] QC Ware Corporation, Palo Alto, CA 94301

[2] School of Applied Engineering and Physics, Cornell University, Ithaca, NY 14853

matrix elements in the quantum approach. It also worth pointing out that our QFD method was heavily inspired by Suzuki et al's recent method for amplitude estimation without phase estimation,[69] in which is was shown that the PEA portions of a Grover-type amplitude estimation algorithm could be largely replaced by a larger set of quantum measurements performed over a variety of quantum circuits.

Quantum Approximate Counting, Simplified

Scott Aaronson*   Patrick Rall†

As we were writing this paper, two other quantum algorithms for approximate counting were announced that avoid the use of QFTs. Surprisingly, both algorithms differ significantly from ours.

In April, Suzuki et al. [SUR+19] gave an $O\left(\frac{1}{\varepsilon}\sqrt{\frac{N}{K}}\right)$-query quantum algorithm that first collects samples from various Grover iterations, and then extracts an approximate value of K via maximum likelihood estimation. Finding the maximum of the likelihood function, according to Suzuki et al., incurs a $\log \frac{1}{\varepsilon}$ computational overhead. More importantly, even if we focus only on query complexity, Suzuki et al. do not prove their algorithm correct. Their analysis gives only a *lower* bound on the error, rather than an upper bound, so is supplemented by numerical experiments. By contrast, our analysis is fully rigorous. On the other hand, the Suzuki et al. algorithm has the interesting feature that its invocations of Grover's algorithm are nonadaptive (i.e., can be performed simultaneously), whereas our algorithm requires adaptivity.

In July, Wie [Wie19] sketched another $O\left(\frac{1}{\varepsilon}\sqrt{\frac{N}{K}}\right)$-query, QFT-free quantum approximate

arXiv, 2019, Sep 9

Quantum Finance Team (security) : Shore algorithm implementation

Keio + Univ of Tokyo + MUFG + Mizuho

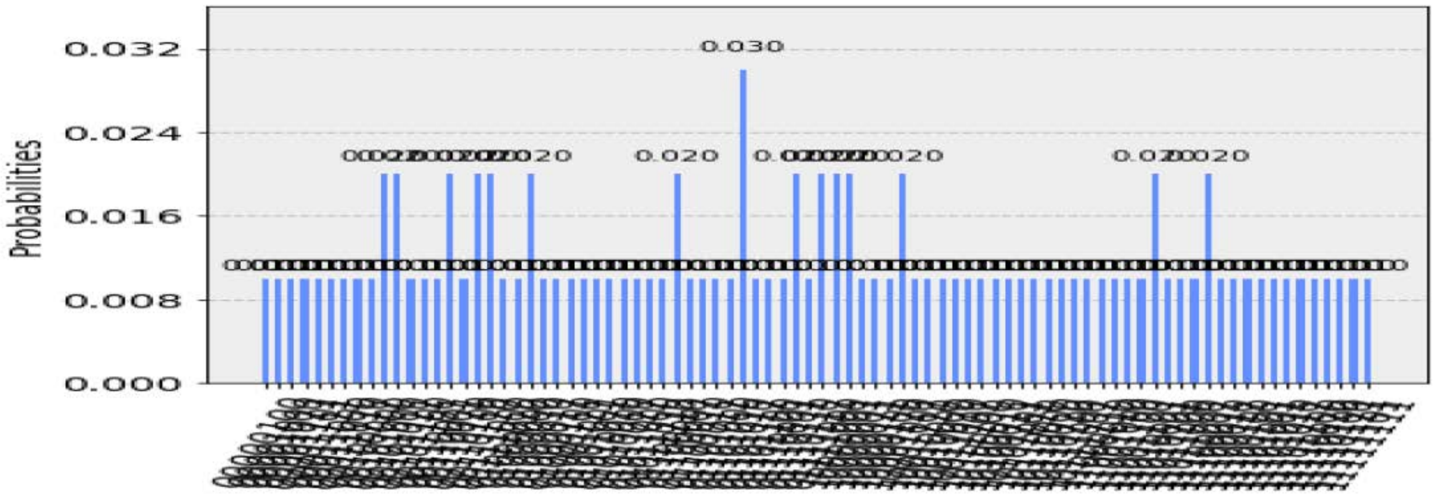
Shore algorithm – Can solve prime factorization in realistic time.
Big impact on RSA cryptography.

IBM 20Q Operation result

- Gate No : 63
- Circuit depth: 17

- Gate No : 331
- Circuit depth: 109

Real machine implementation



Challenge to implement Shore algorithm using IBM Q

Quantum chemistry team

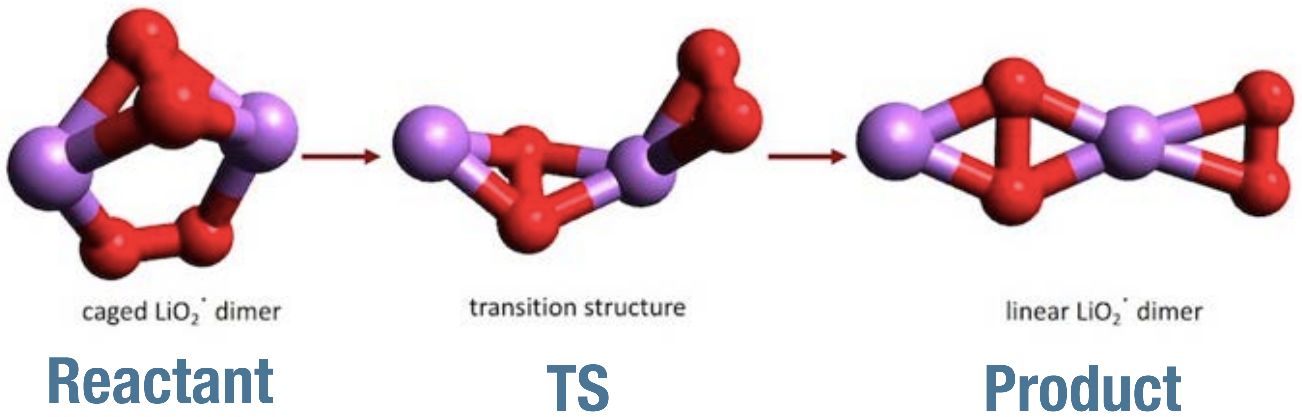
DESIGNLINES | POWER MANAGEMENT DESIGNLINE

Battery Research Advances Quantum Computing Capabilities

Studying reactions in Li-air batteries was also a research challenge for IBM.

EETimes
July 28, 2019

Li-air battery research collaboration between industry and academia goes back to the mid-1990s, said Dr. Naoki Yamamoto, associate professor and the chair of the Keio University Quantum Computing Center, which is part of the IBM Q Hub. "Because both the charge and discharge process in the lithium-air battery are very complicated and sensitive to the surrounding environment, it is still hard to elucidate the reaction mechanism at the atomic level, which has limited the progress of the technology."



Variational Quantum Eigensolver, VQE

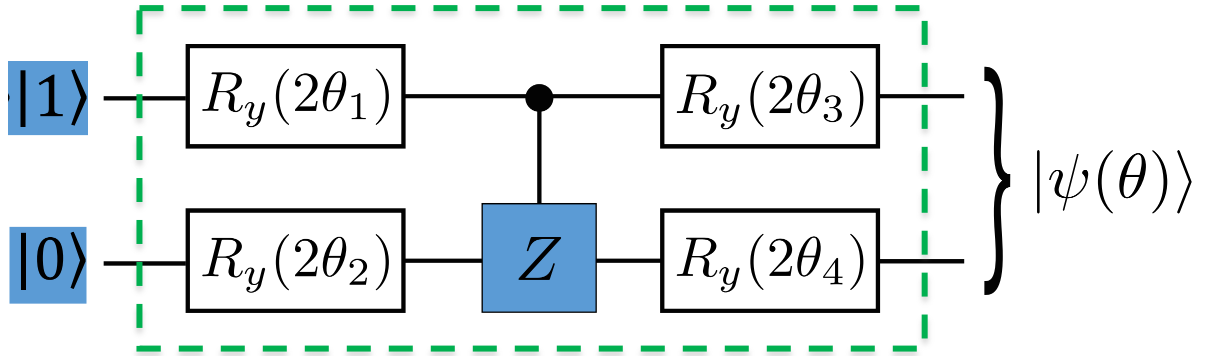
Ansatz state: $|\psi(\theta)\rangle = U(\theta)|\psi_0\rangle$

Minimize the energy value $\langle\psi(\theta)|H|\psi(\theta)\rangle$

by updating the parameter θ

Modeling by 2 qubits for each of three molecule Hamiltonian

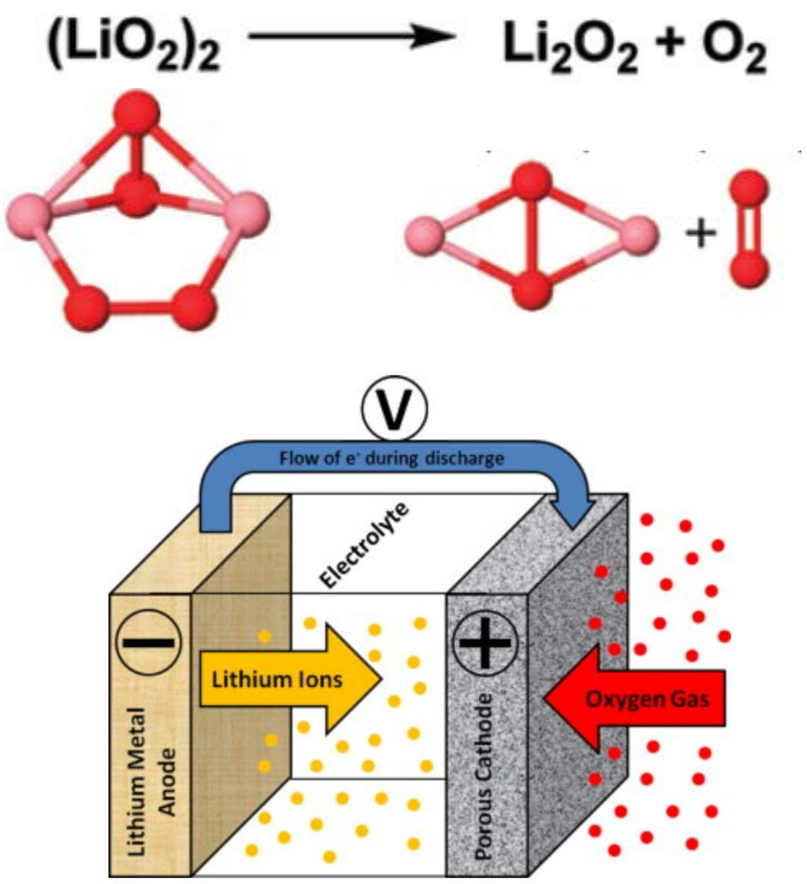
VQE for LiOx:

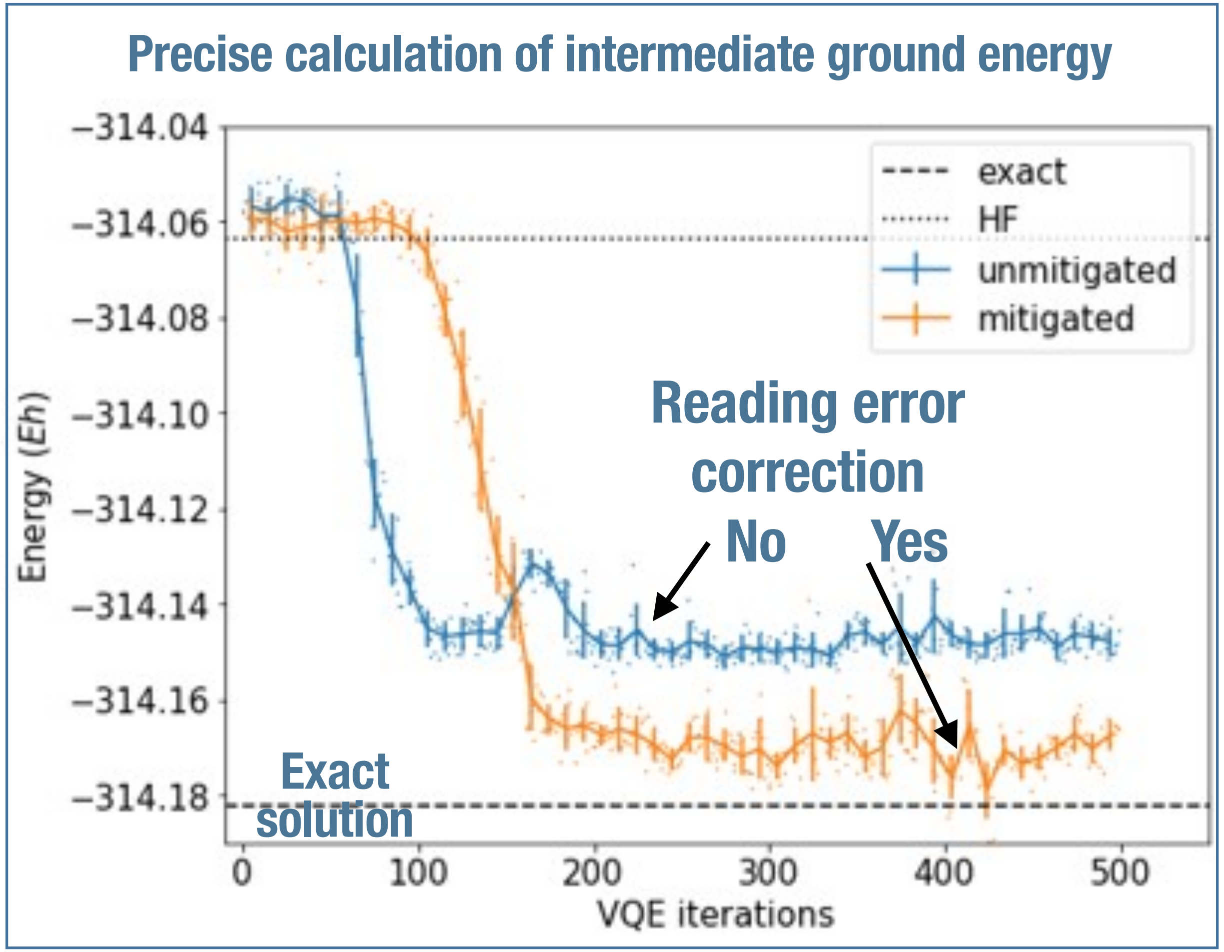


Computational Investigations of the Lithium Superoxide Dimer Rearrangement on Noisy Quantum Devices, Q. Gao, H. Nakamura, T. P. Gujarati, G. O. Jones, J. E. Rice, S. P. Wood, M. Pistoia, J. M. Garcia, and N. Yamamoto, arXiv:1906.10675.

Quantum chemistry team : Reaction analysis of lithium-air battery

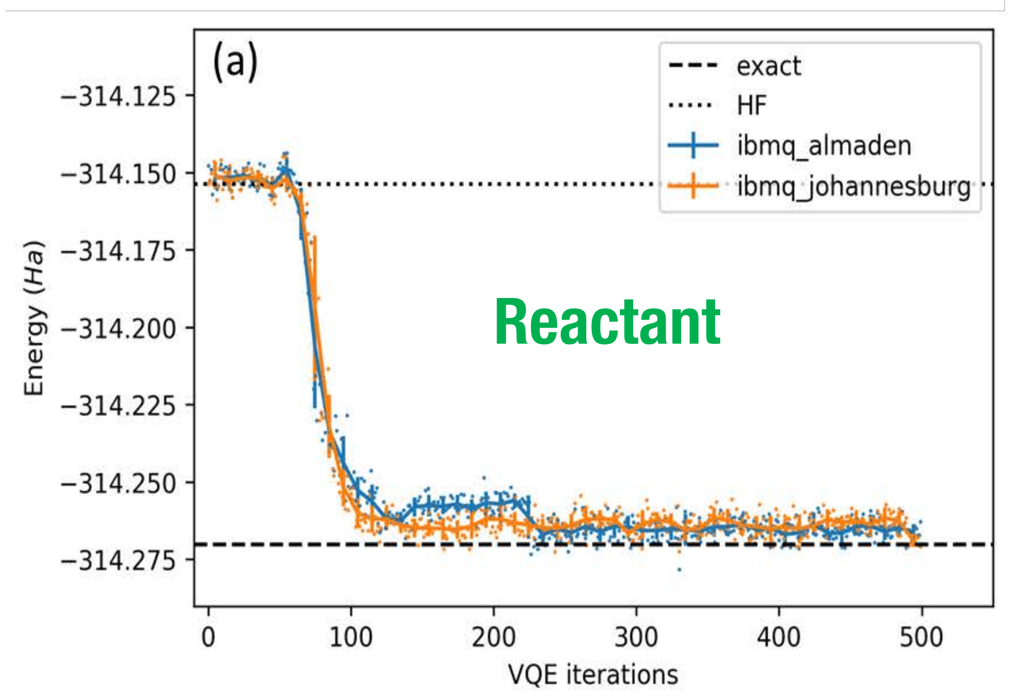
Keio + Mitsubishi Chemical + IBM

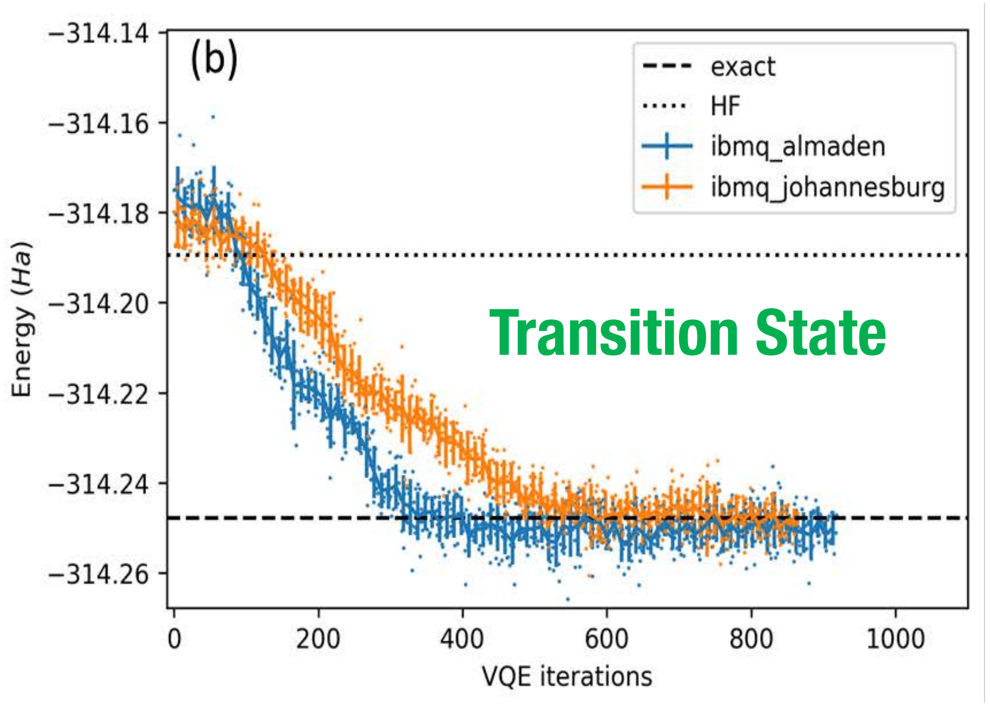


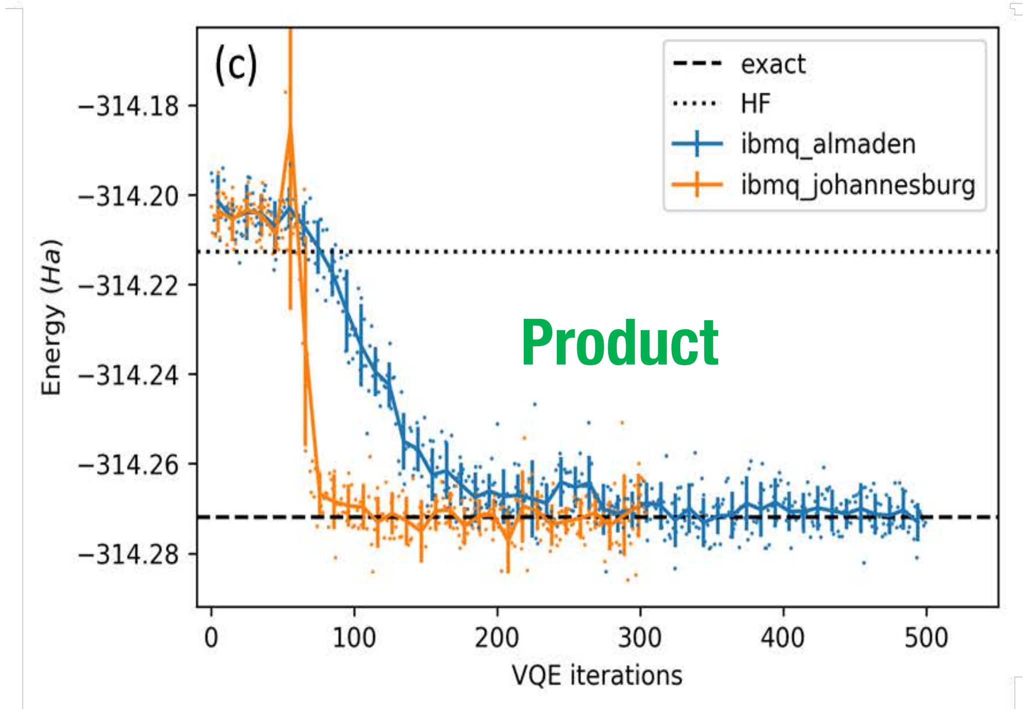


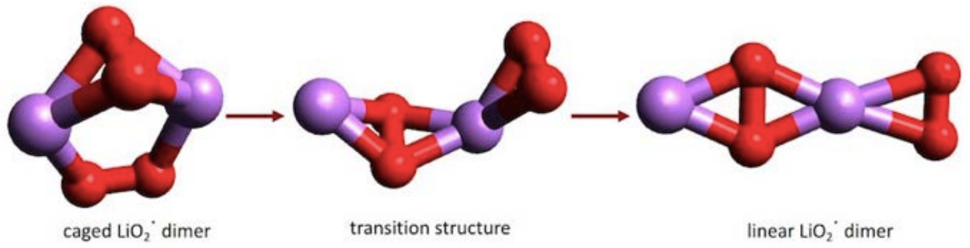
Successful calculation of chemical reaction of lithium air battery using IBM Q

Calculation by IBM Q

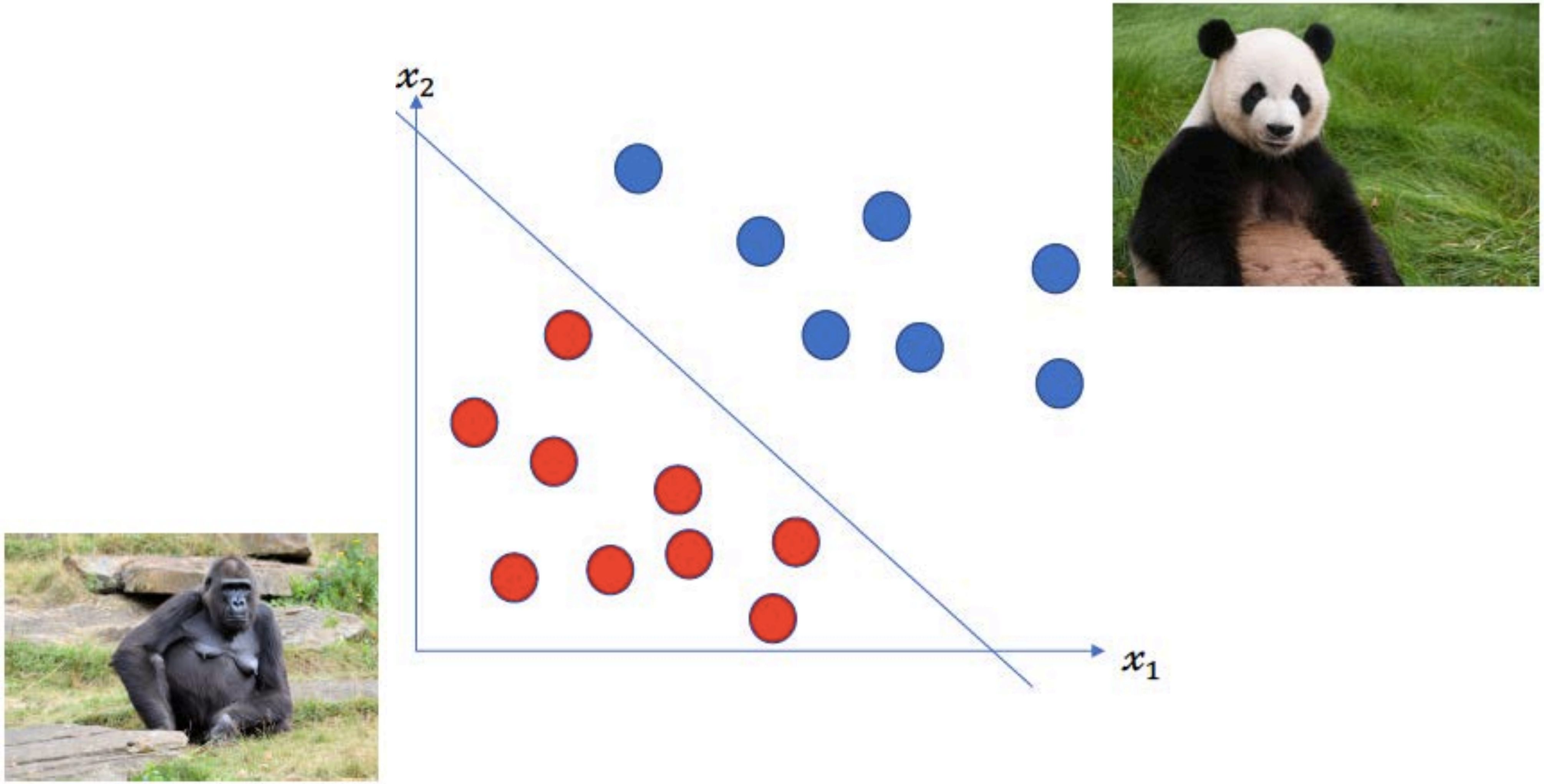








Quantum AI Team : Quantum Support Vector Machine
Classification problem



Kernel method

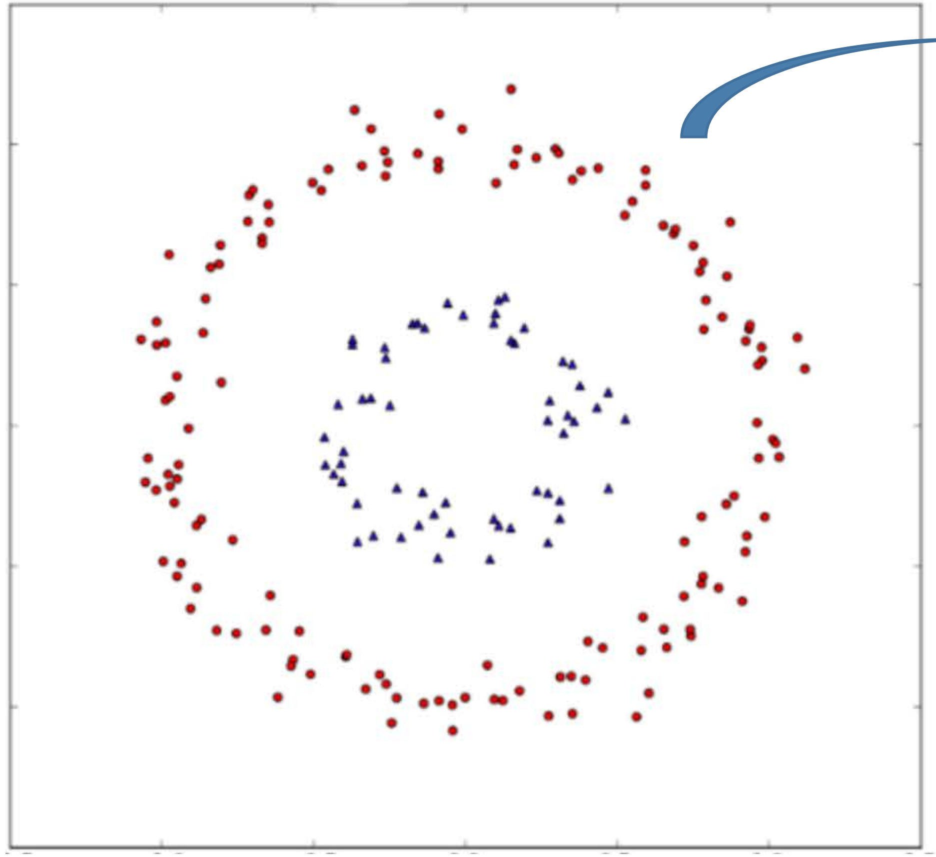
Projection of an input states to a higher order feature space

Kernel function

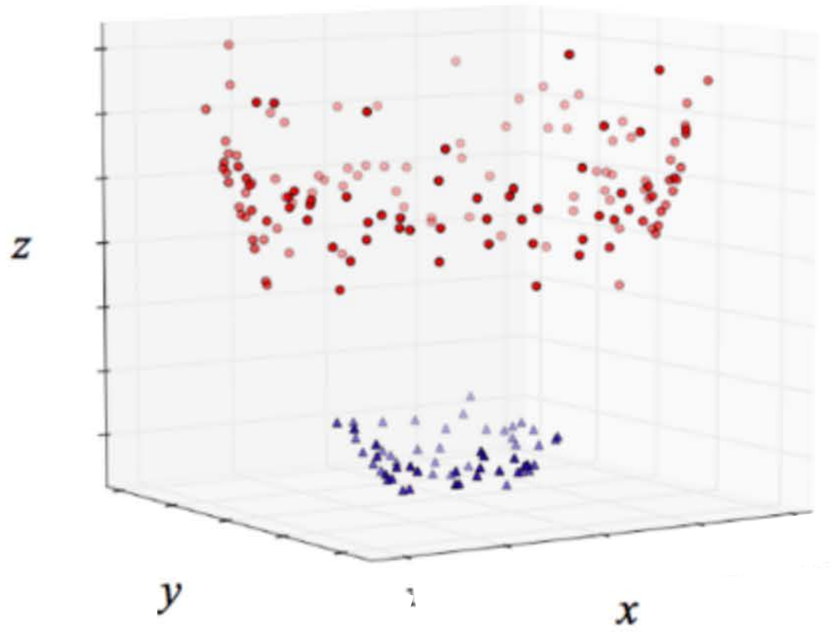
$$max\|\vec{w}\|^{-1} \Leftrightarrow max_\alpha L_D(\alpha) = -\frac{1}{2}\sum_{i,j=1}^{t} y_i y_j \alpha_i \alpha_j x_i \cdot x_j + \sum_{i=1}^{t} \alpha_i$$

$$K(x_i, x_j) = |\langle \Phi(x_i) | \Phi(x_j) \rangle|^2$$

input space



feature space



Cover, T. M. *IEEE transactions on electronic computers*, (3), 326-334. (1965)

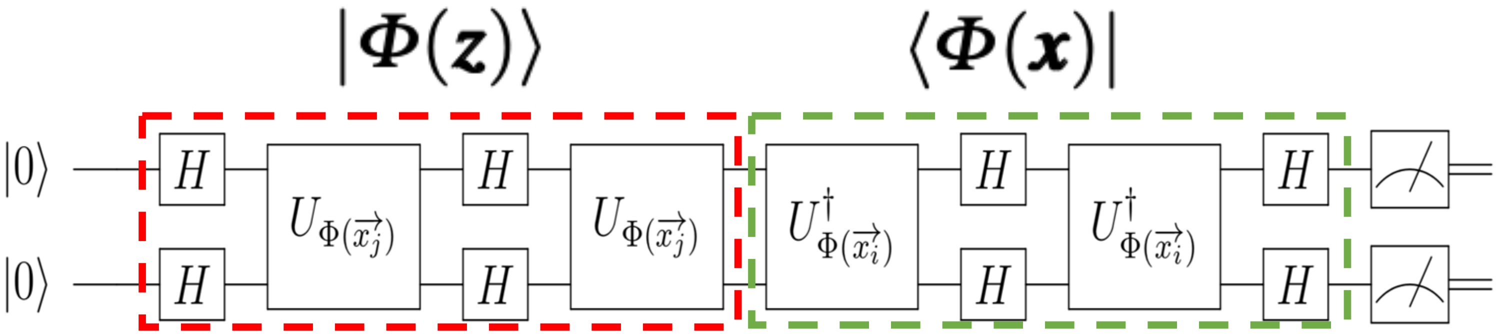
Quantum classification method proposed by IBM

LETTER

https://doi.org/10.1038/s41586-019-0980-2

Supervised learning with quantum-enhanced feature spaces

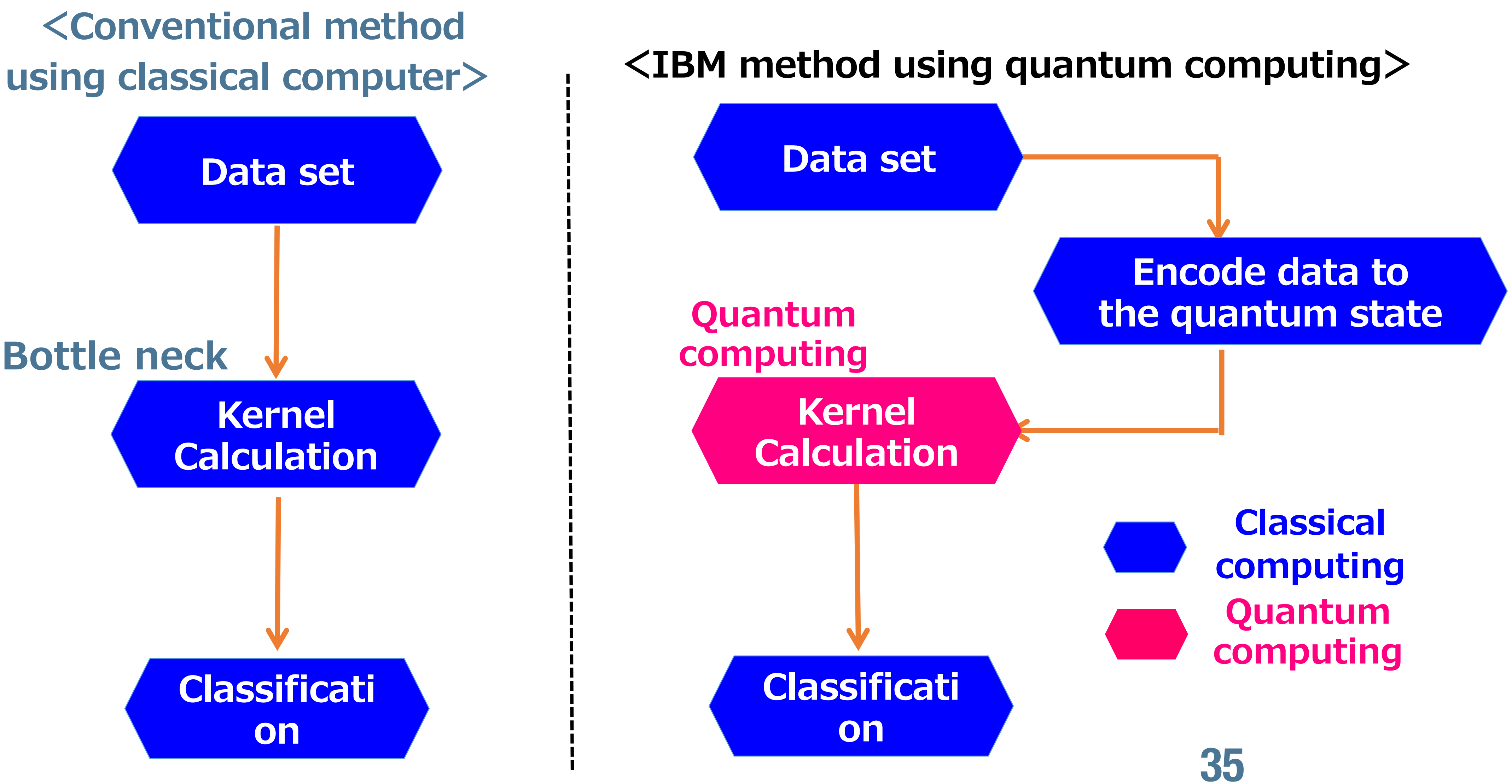
Vojtěch Havlíček[1,2], Antonio D. Córcoles[1]*, Kristan Temme[1]*, Aram W. Harrow[3], Abhinav Kandala[1], Jerry M. Chow[1] & Jay M. Gambetta[1]



Nature 567, 209 (2019)

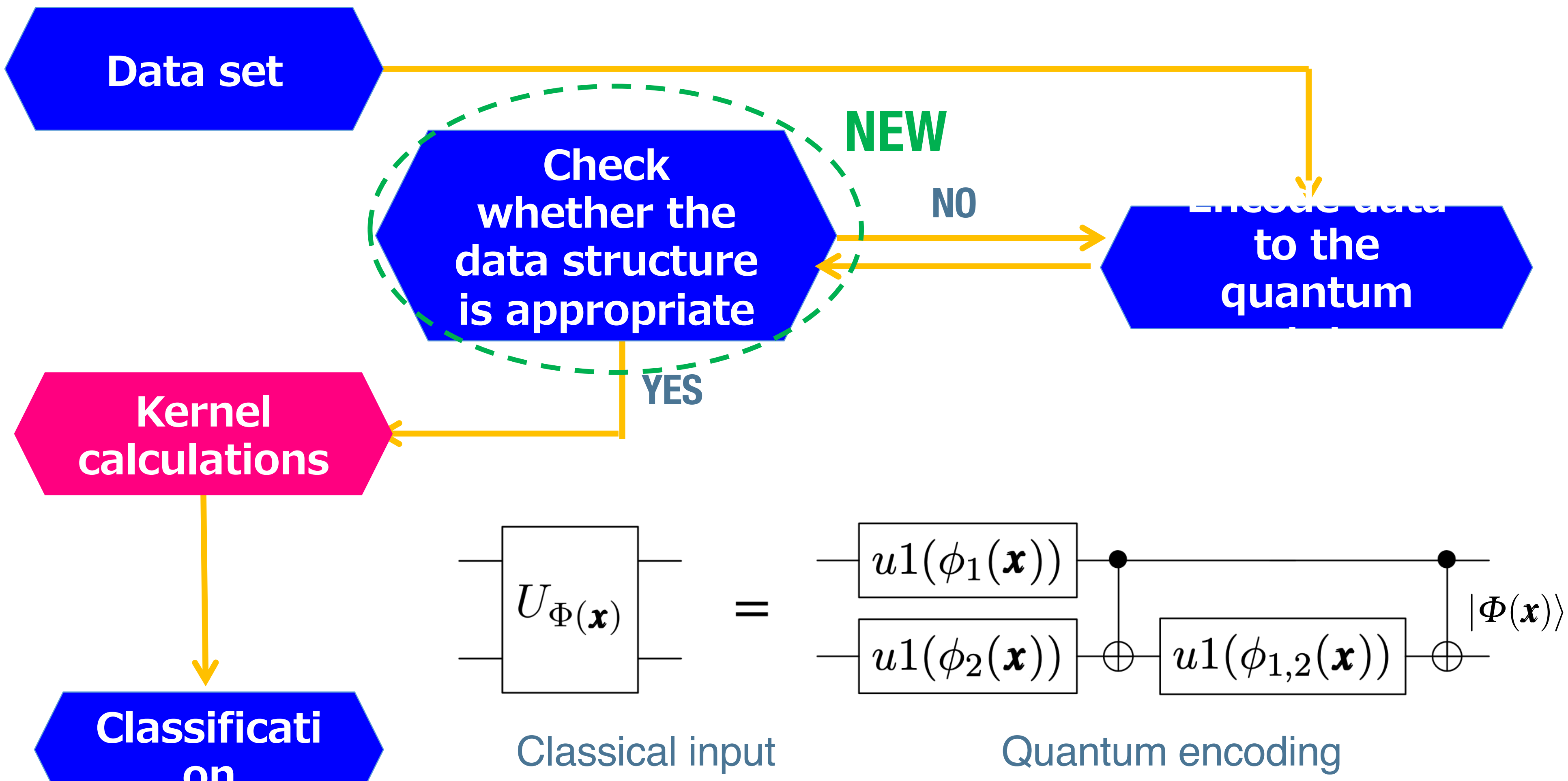
Quantum classification method proposed by IBM

- ✓ Bottleneck parts are calculated on quantum computers.
- ✓ Method of encoding data to the quantum state influence accuracy.



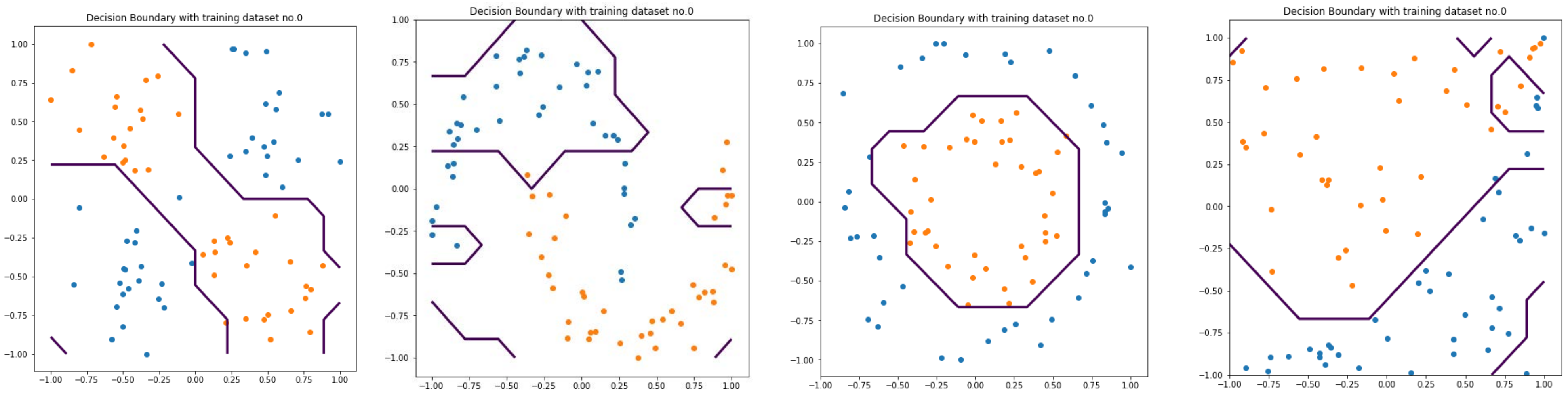
Modification by Keio Q Hub

Classical computing
Quantum computing



Analyzing feature space via Pauli decomposition for quantum classifier,
Y. Suzuki, H. Yano, Q. Gao, S. Uno, T. Tanaka, M. Akiyama, and N. Yamamoto,
arXiv:1906.10467

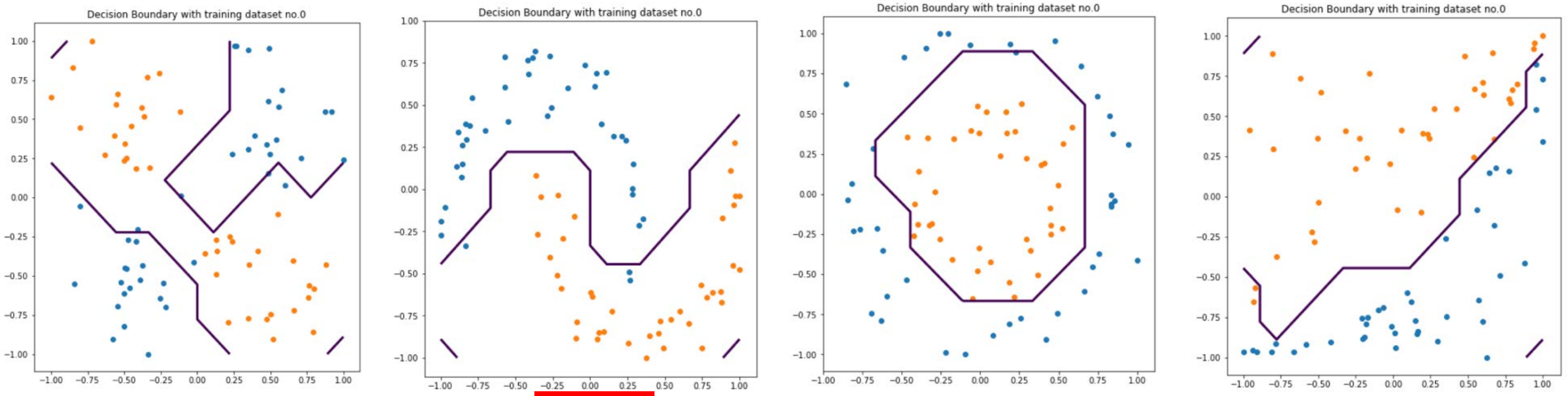
IBM's original method



0.81

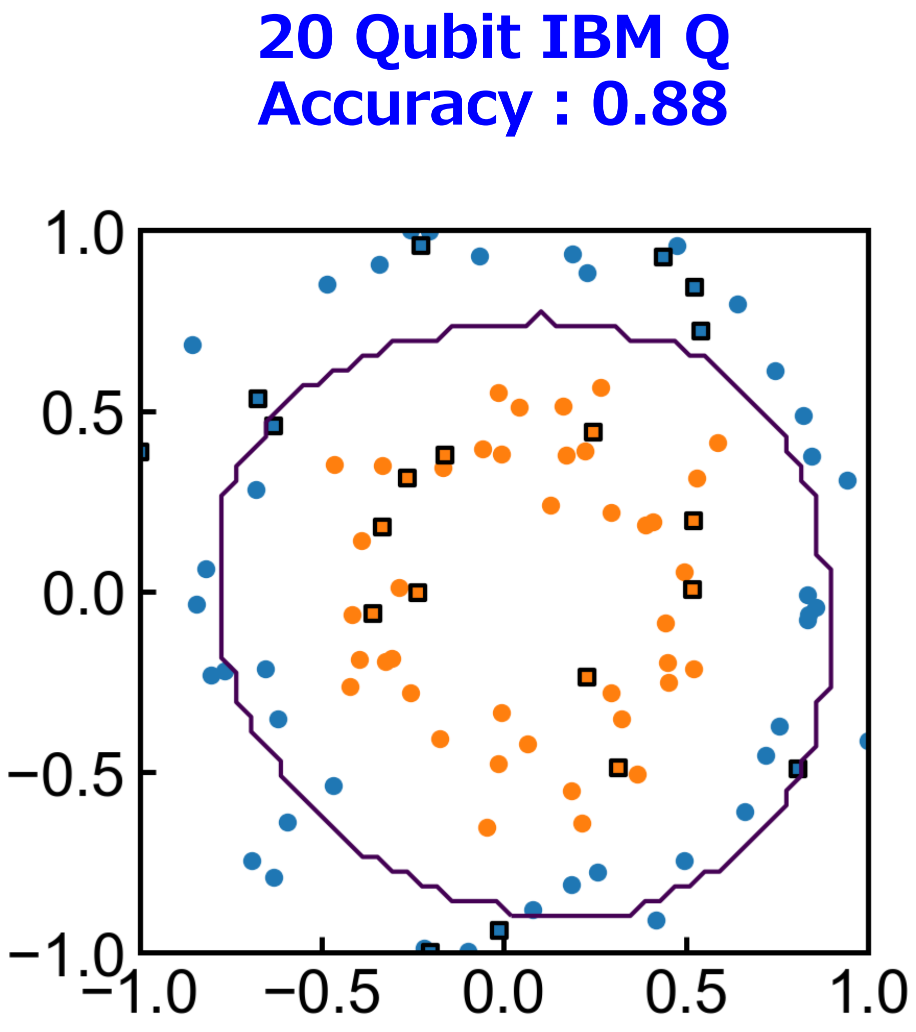
Improvement in choice of $\Phi(x)$

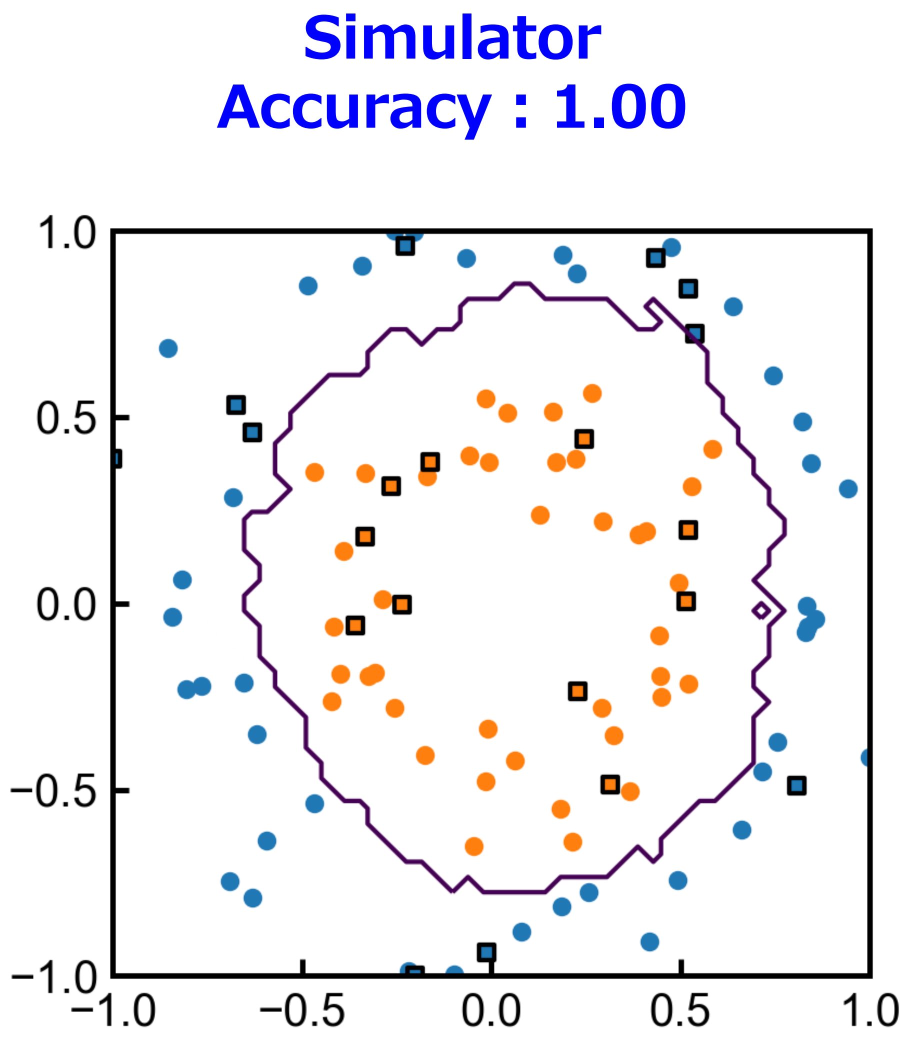
This work



0.99

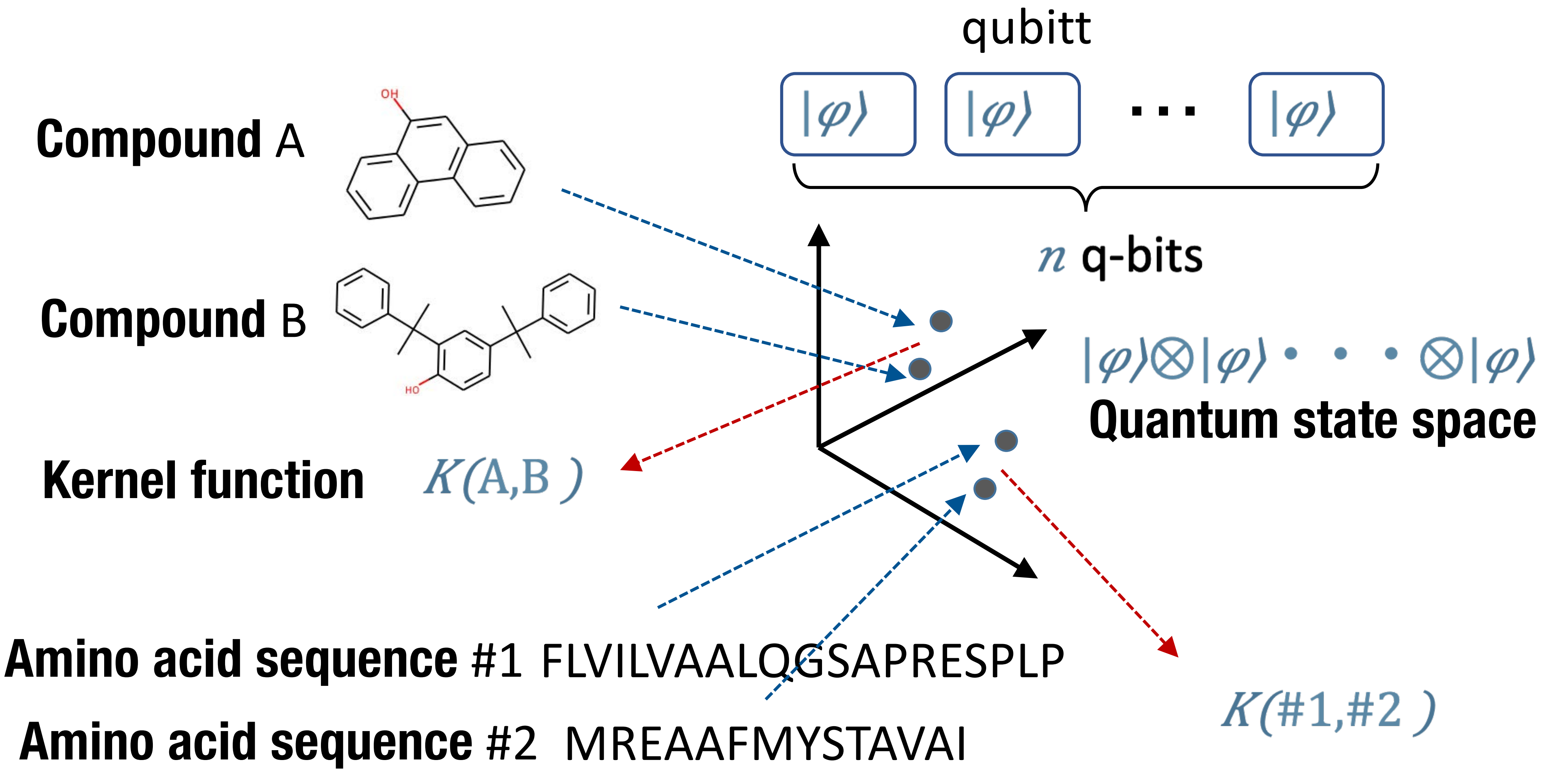
Quantum classification by IBM Q





Quantum drug discovery and life science initiatives

Keio（Faculty of Science and Engineering, School of Medicine）+ Waseda



Development of quantum kernel functions for unstructured data

Selected publications of Keio Q Hub

- Applications of Quantum Computing for Investigations of Electronic Transitions in Phenylsulfonyl-carbazole TADF Emitters, https://arxiv.org/abs/2007.15795
- Amplitude estimation via maximum likelihood on noisy quantum computer, https://arxiv.org/abs/2006.16223
- Attacking the Quantum Internet, https://arxiv.org/abs/2005.04617
- Computational Investigations of the Lithium Superoxide Dimer Rearrangement on Noisy Quantum Devices, https://arxiv.org/abs/1906.10675
- Analyzing feature space via Pauli decomposition for quantum classifier, https://arxiv.org/abs/1906.10467
- Extracting Success from IBM's 20-Qubit Machines Using Error-Aware Compilation, https://arxiv.org/abs/1903.10963
- Subdivided Phase Oracle for NISQ Search Algorithms, IEEE Transactions on Quantum Engineering
- Analysis and synthesis of feature map for kernel-based quantum classifier, Quantum Machine Intelligence, 2, 1-9 (2020)
- Temporal information processing on noisy quantum computers, Phys. Rev. Applied 14, 024065 (2020)
- Extracting Success from IBM’s 20-Qubit Machines Using Error-Aware Compilation, ACM Journal on Emerging Technologies in Computing Systems Vol. 16, No. 32
- Modeling of measurement-based quantum network coding on a superconducting quantum processor, PHYSICAL REVIEW A 101, 052301
- Amplitude Estimation without Phase Estimation, Quantum Information Processing 19, 75 (2020)