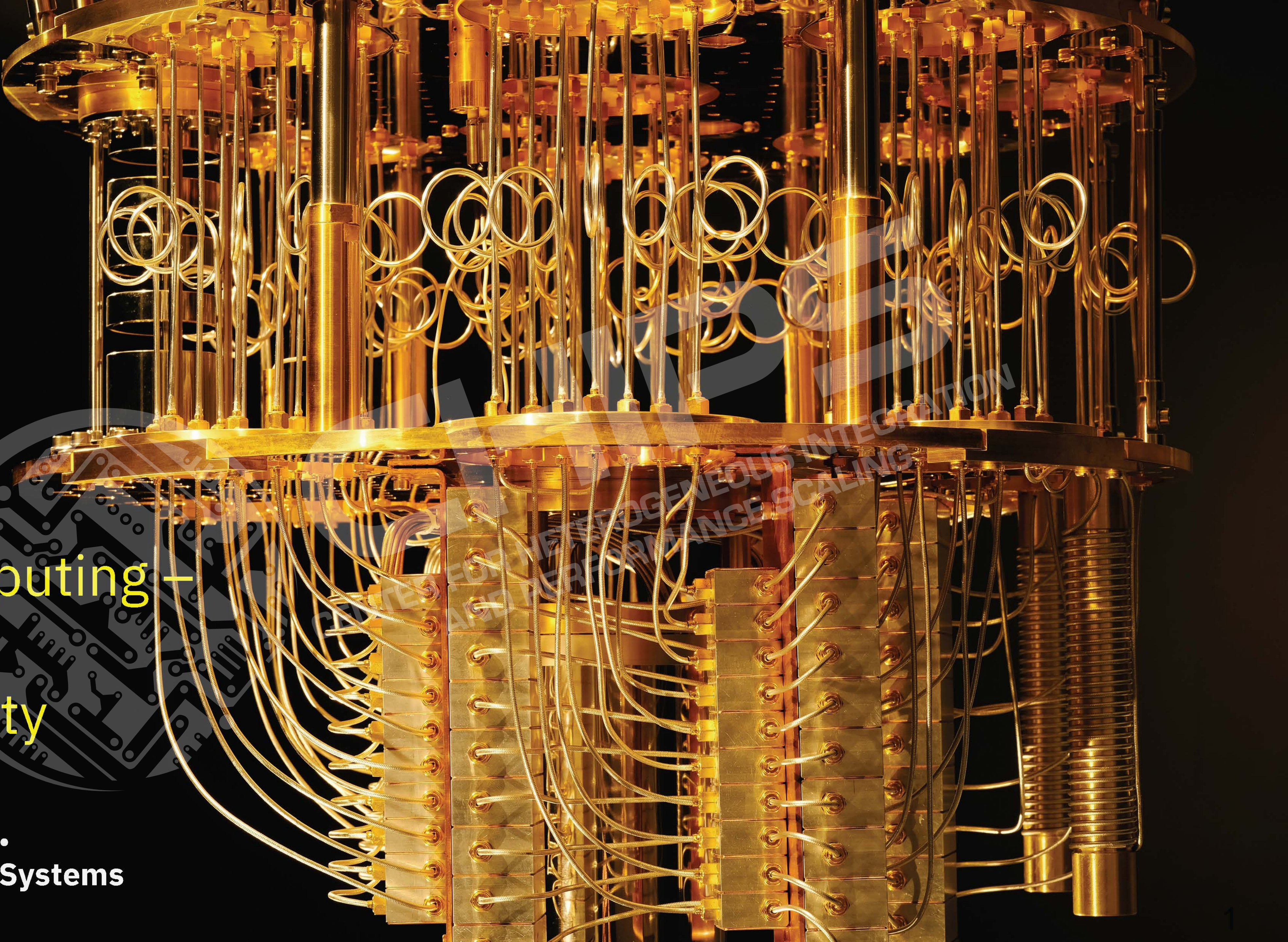


# Quantum Computing –

# Myth and Reality

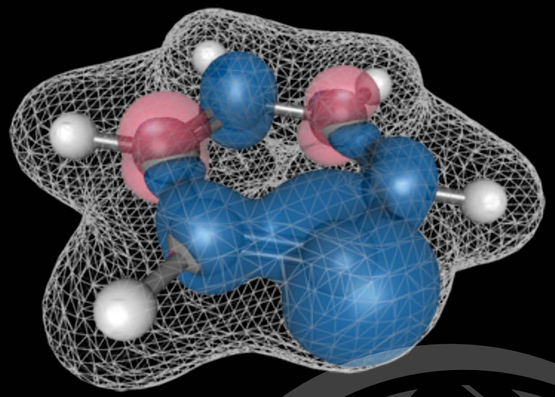
**Rajeev Malik, Ph.D.**
**Program Director, IBM Q Systems**
(malikra@us.ibm.com)

# Outline

1. Why do we need Quantum Computing?
2. What makes a quantum computer tick?
3. Early work on applications & use cases
4. Learning about quantum

# Our intuition about what we can compute is wrong

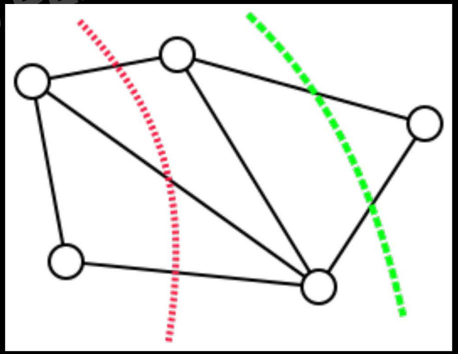
IBM Q

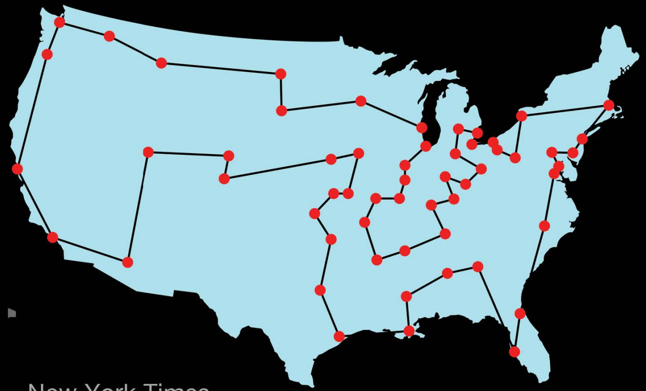


A 50 electron system becomes impractical to simulate for classical computing because the runtime scales exponentially with electrons



Many optimization problems have a runtime that grows exponentially with input size

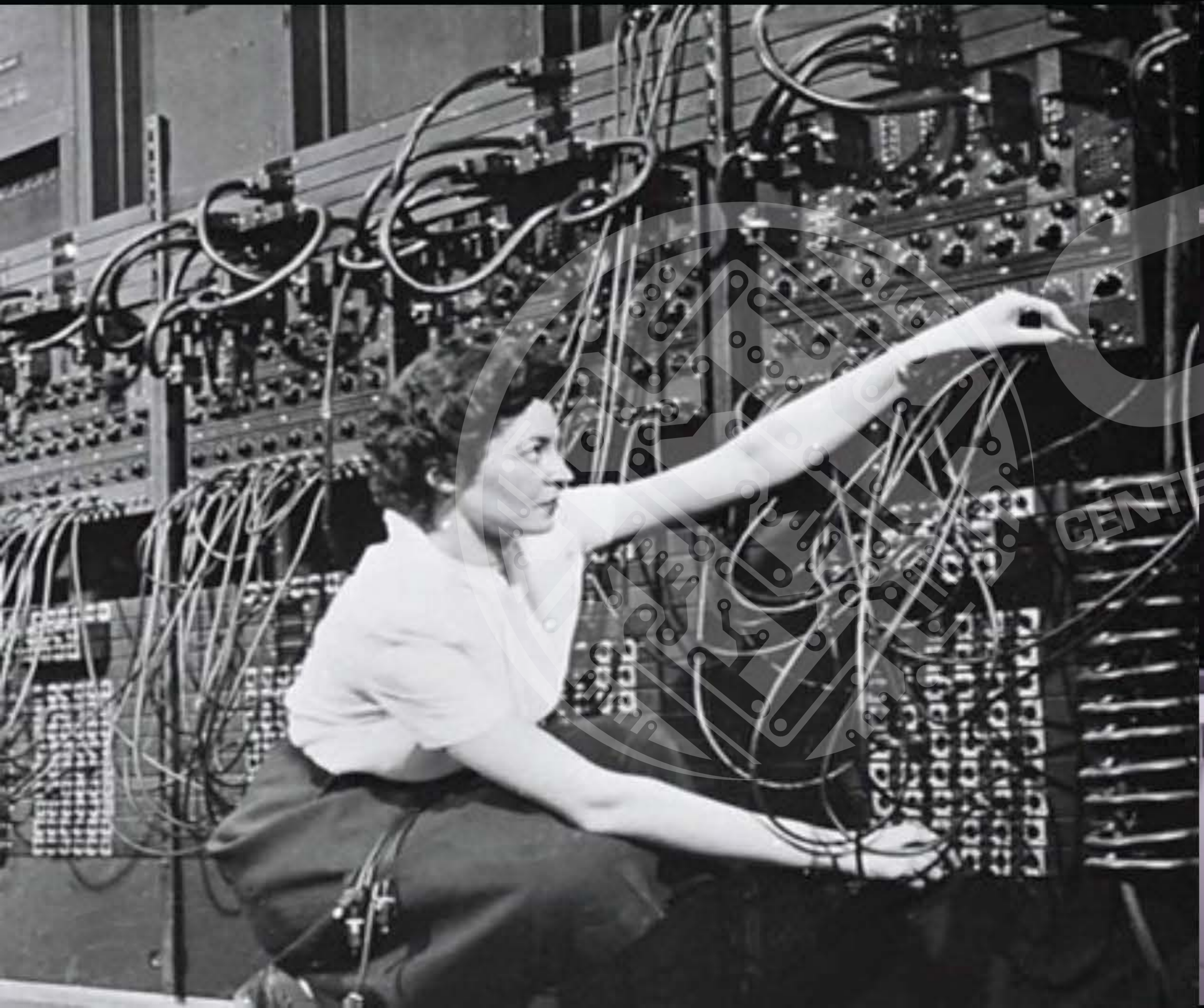




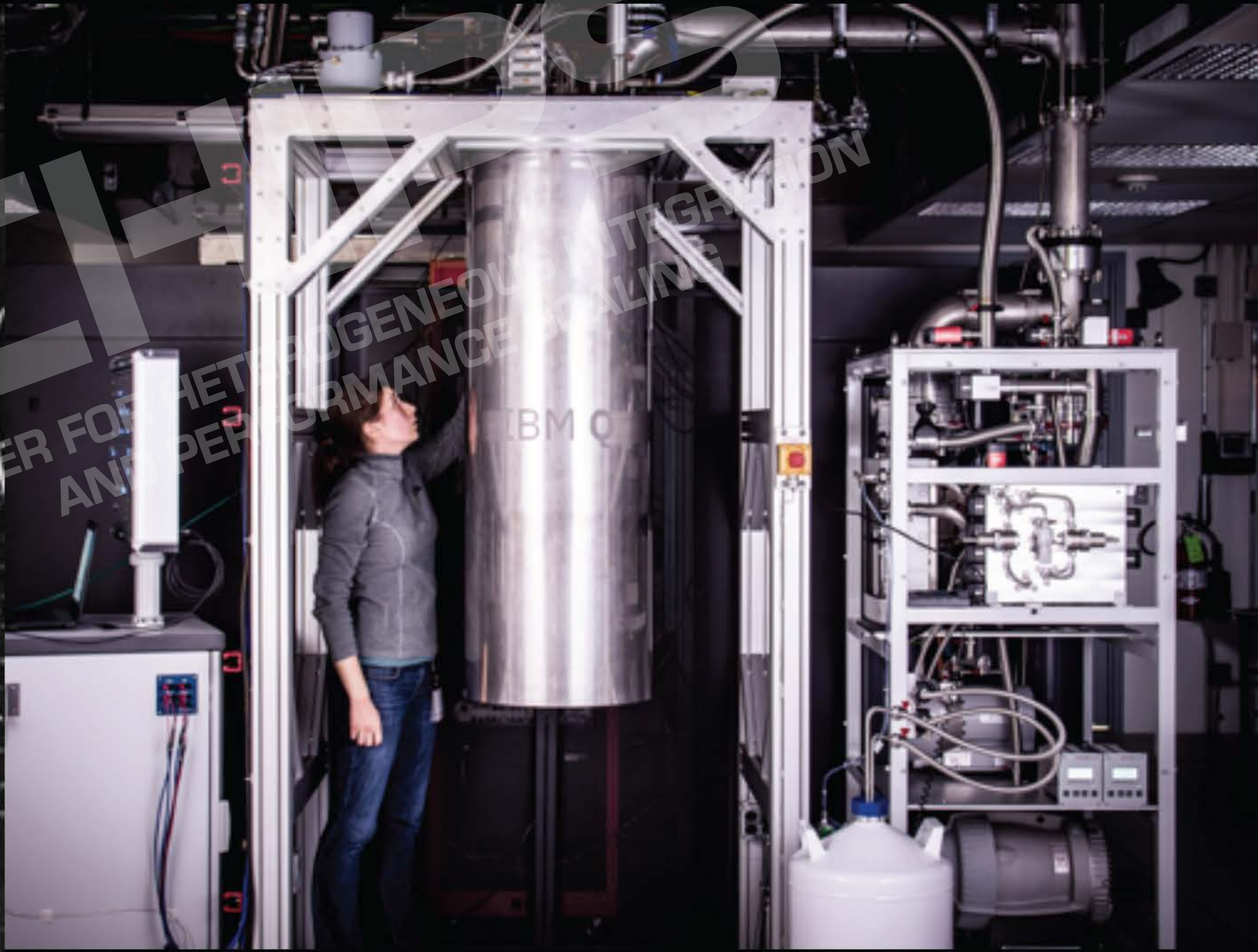
New York Times

# We are at beginning of new age of computation

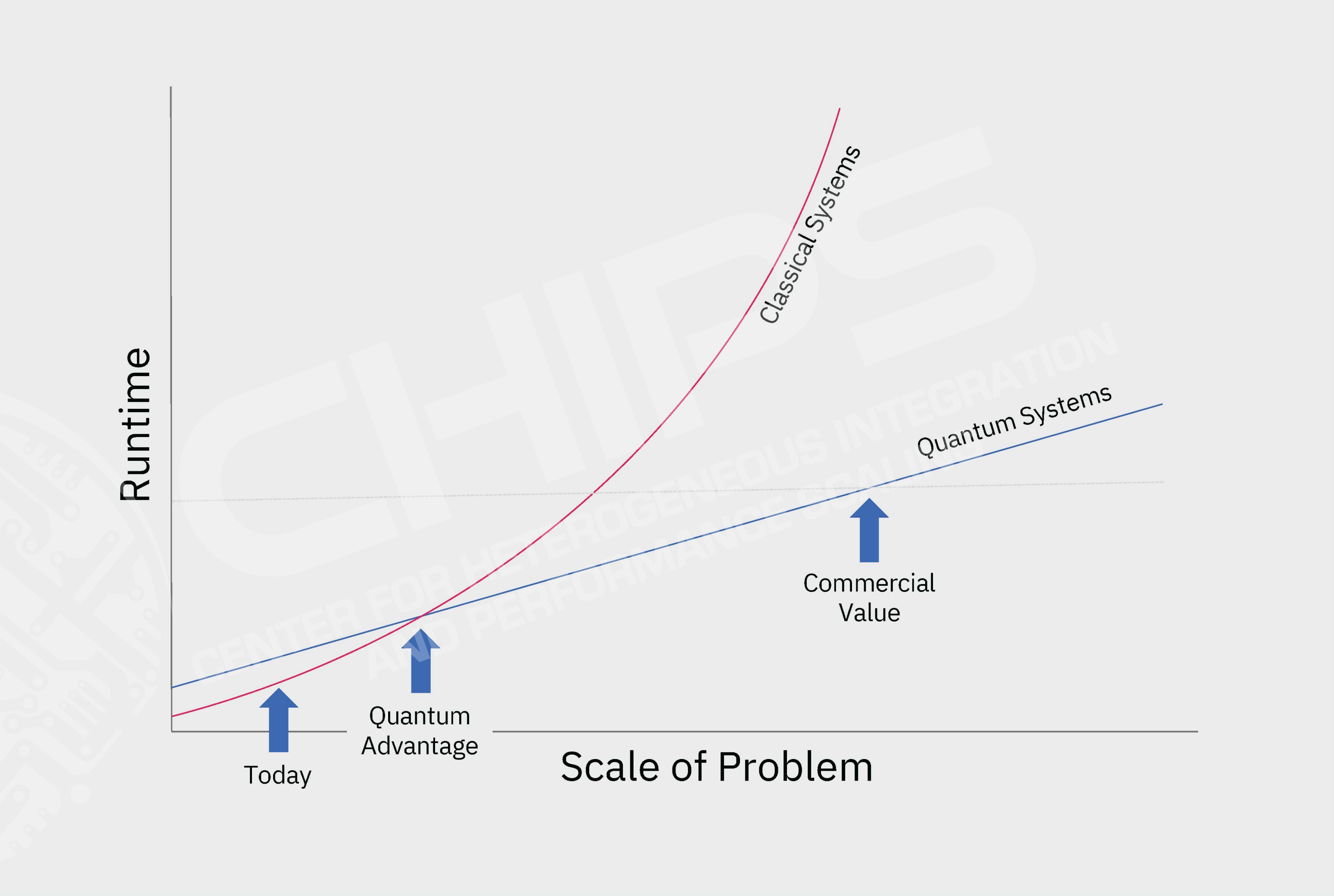
**ENIAC**
**First electronic digital programmable computing device**



**IBM Q**
First quantum computing device made available to public



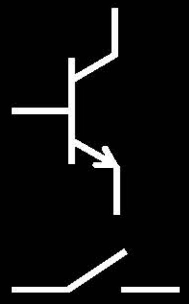
# The value of Quantum Computing becomes apparent as problems scale

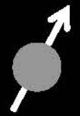



IBM

# Classical Bits vs. Quantum Bits (Qubits)

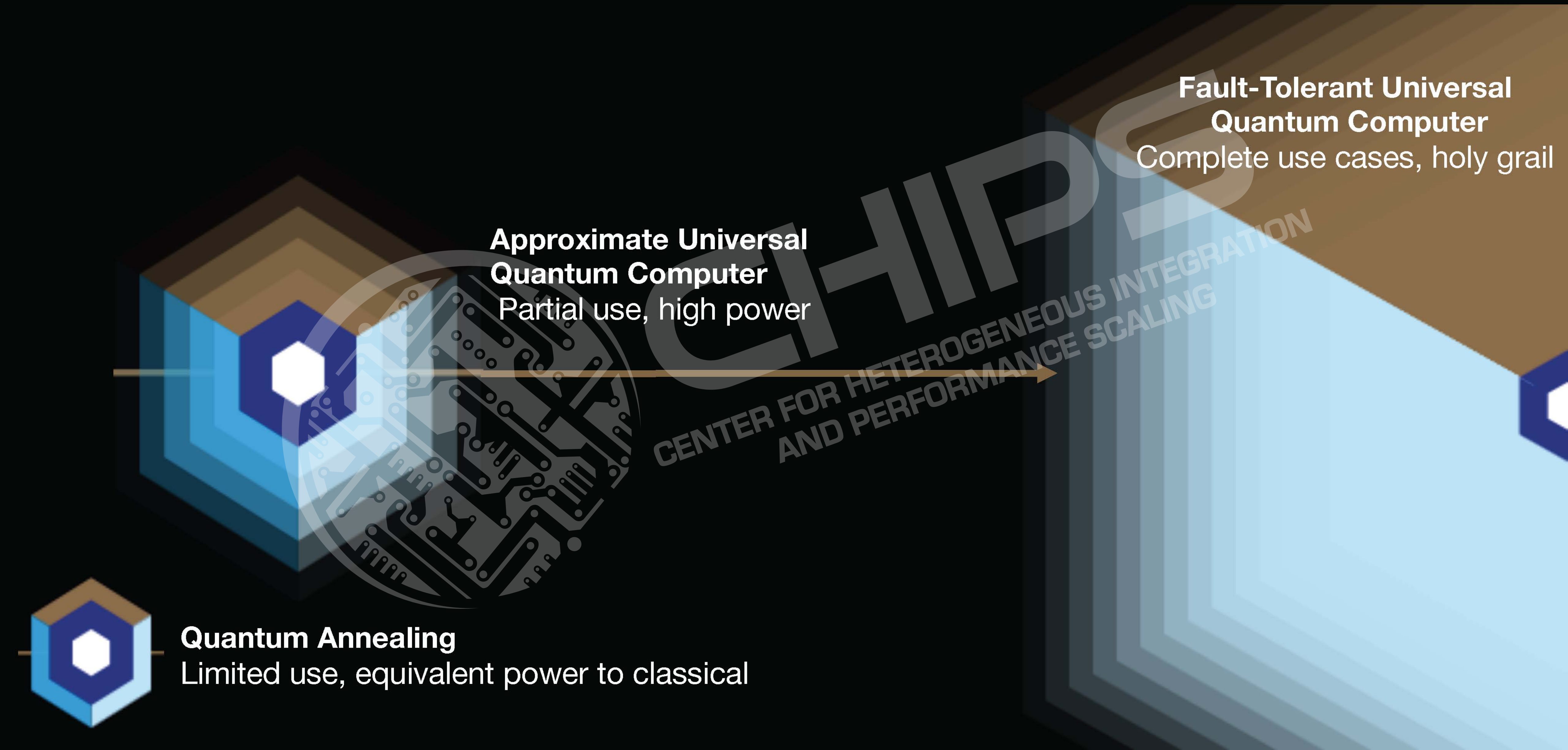
| | Classical Bit | Quantum Bit |
|---|---|---|
| Possible States: | 0, 1 | \|0>, ← \|0> + \|1>, \|1> |
| Functionality & Implementation: | transistor, on/off switch | spin ½ |

# There are different types of quantum computing

IBM Q



# Classical computers aren't going away…

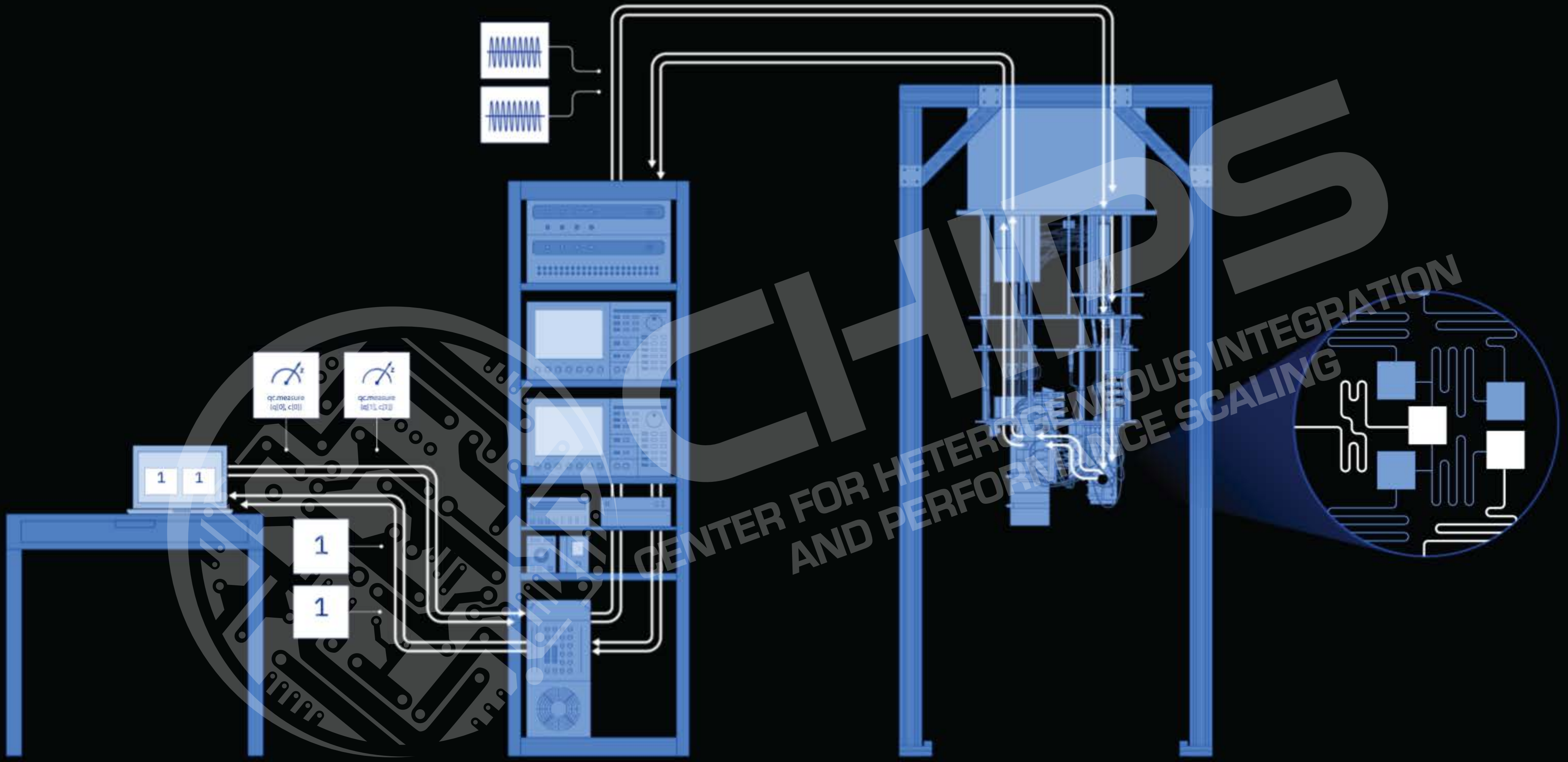

**Modern Infrastructure for Big Data & AI**

Store, manage and process huge quantities of data to extract insights and take business action.

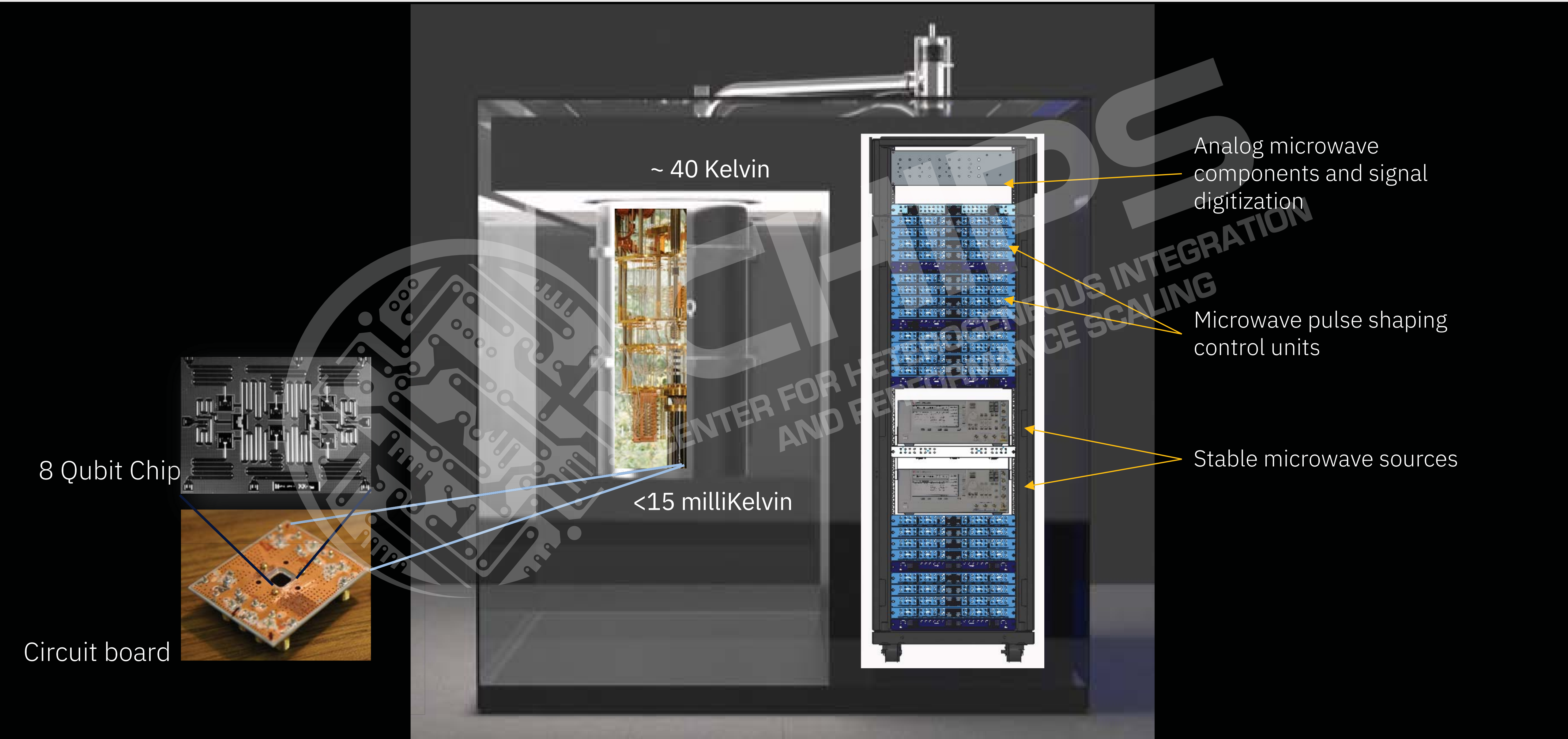
**Quantum Computers**

Explore large set of possibilities and identify optimal answer to drive business value.

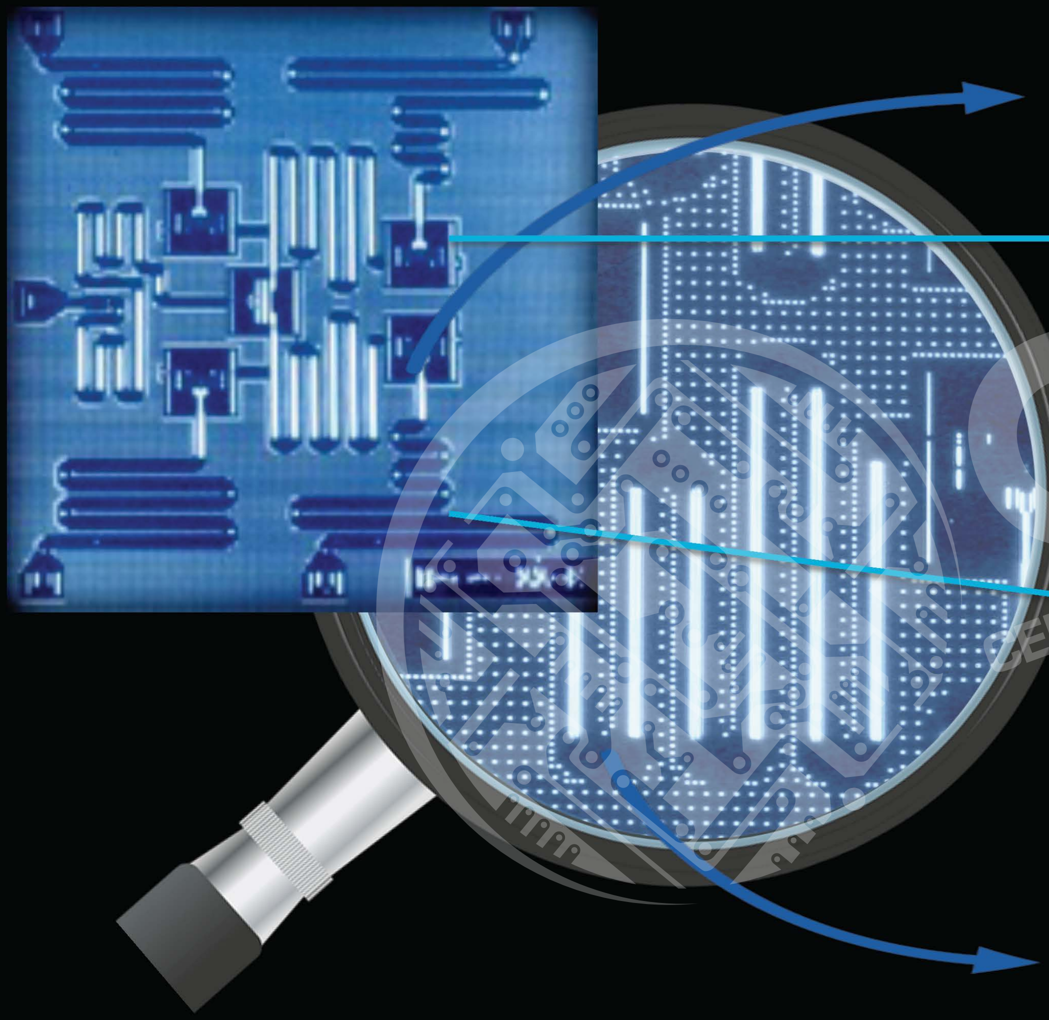
# "Flow" of information in a quantum computer



# Inside an IBM Q System

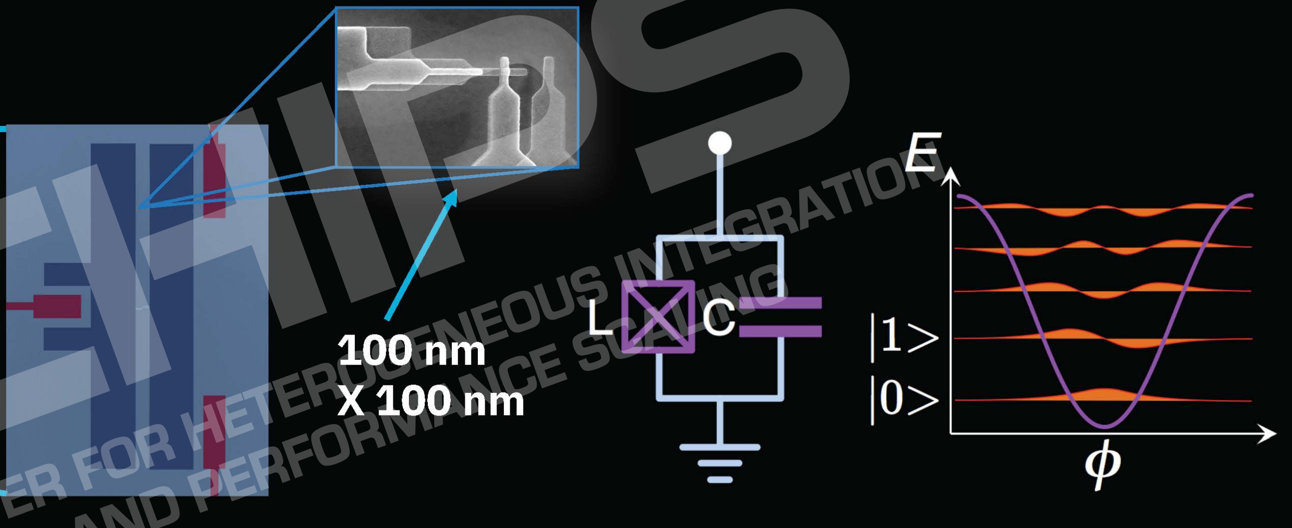


# Inside an IBM **Q** quantum computing system: Anatomy of a superconducting qubit



**Superconducting Qubit:**

- Josephson Junction as a non-linear inductor



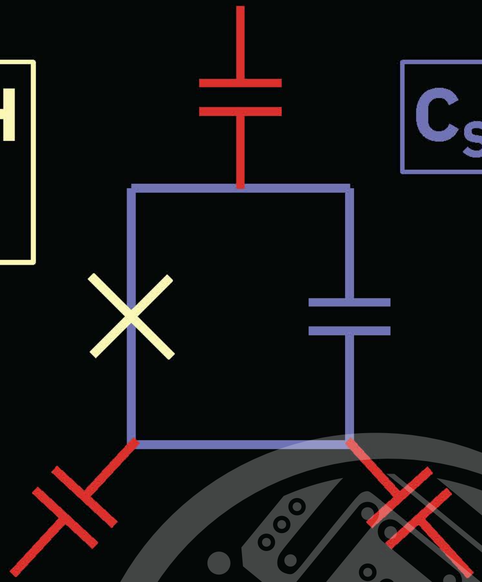

$E_{01} \approx 5\ GHz \approx\ 240\ mK$

**Superconducting Microwave Resonators:**

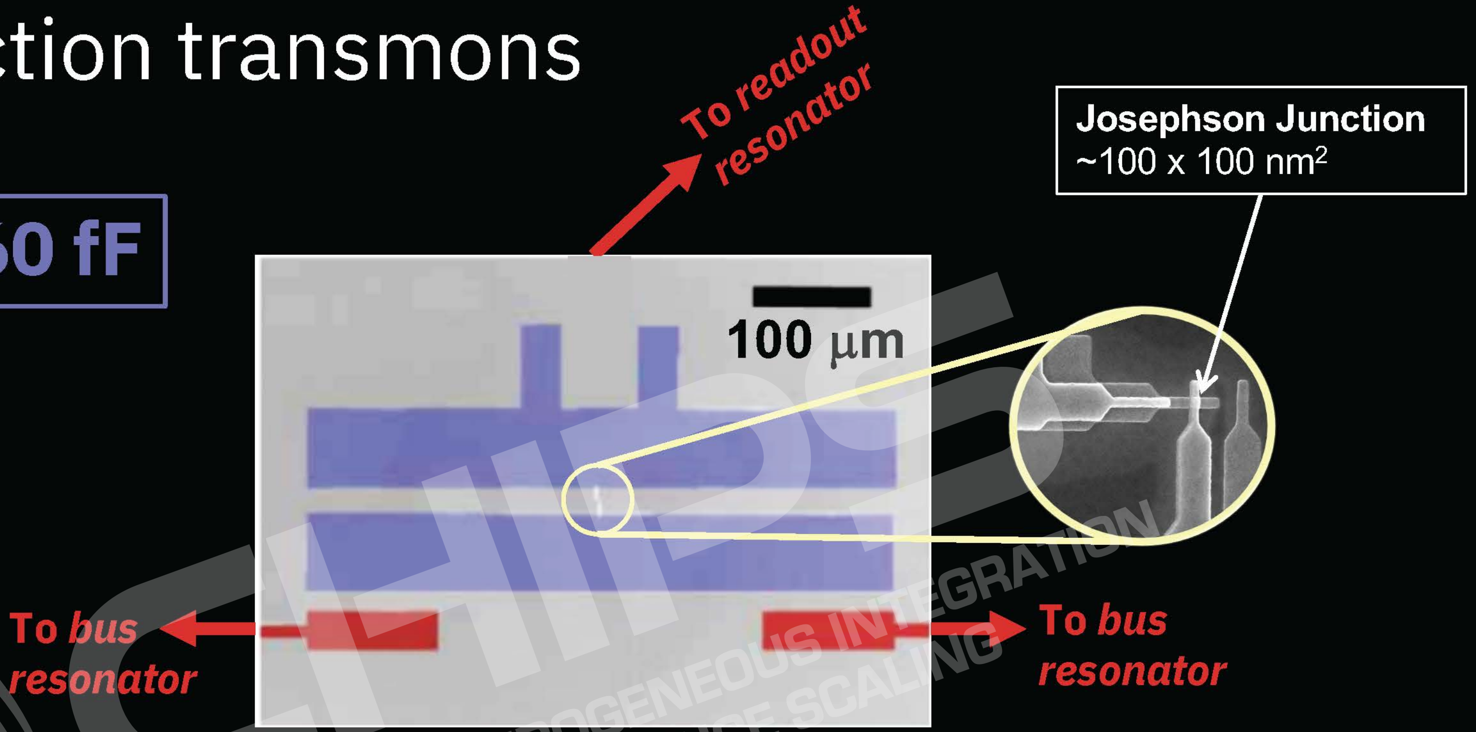
- read-out of qubit states
- multi-qubit quantum bus
- noise filter

# IBM qubits: single-junction transmons

$L_J$ ~ 20 nH
$C_J$ ~ 1 fF



$C_S$ ~ 60 fF




Patterned superconducting metal (**niobium** + **aluminum**) on silicon

– Total capacitance dominated by **shunting capacitance $C_S$**

Interactions mediated by **capacitively coupled co-planar waveguide resonators**

– *Bus resonators* provide controlled coupling to adjacent qubits

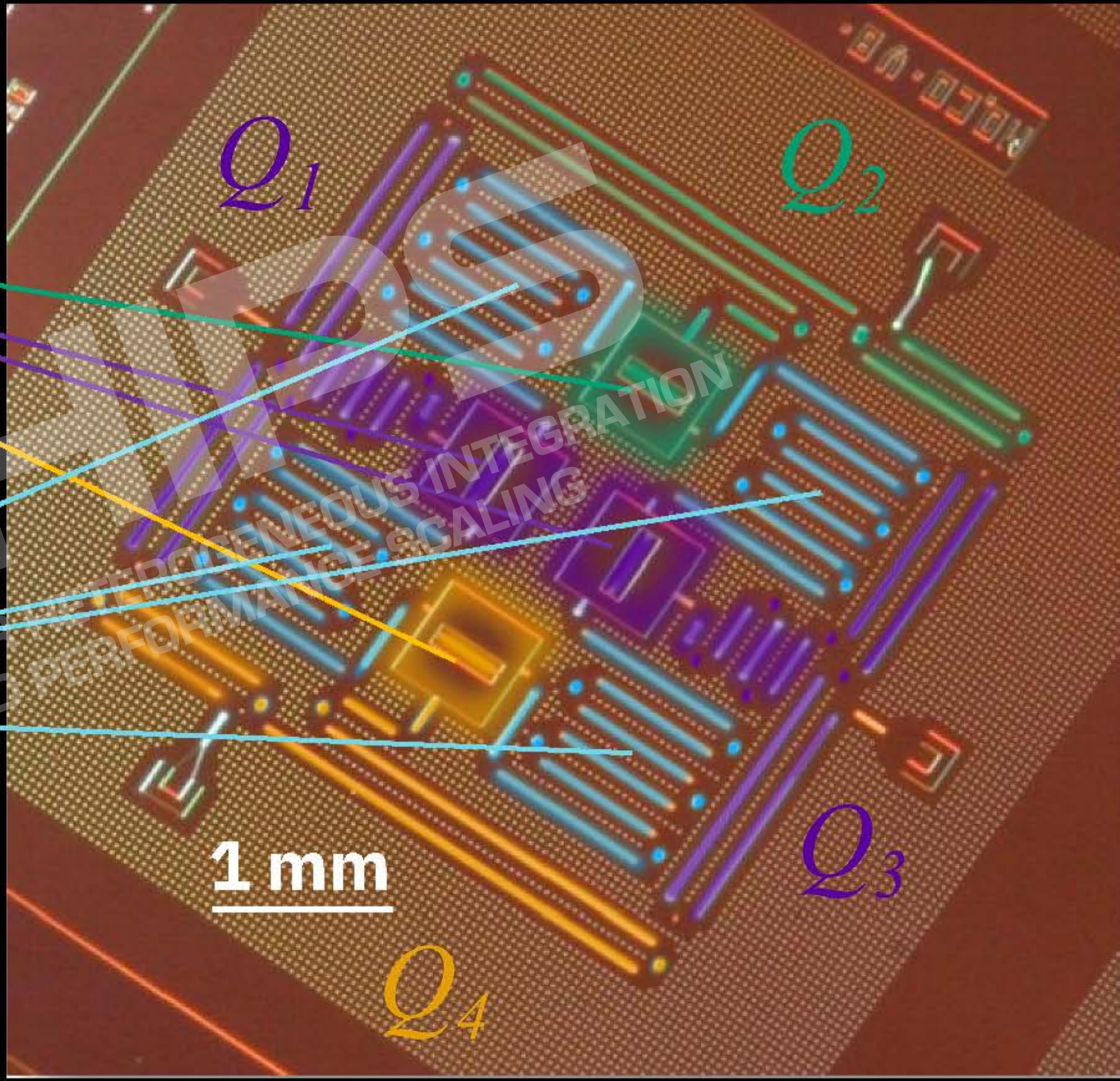
– *Readout resonators* couple to outside world; resonant frequency shifts with qubit state

# Anatomy of a quantum chip

**Qubits:**
Single-junction transmon
Frequency ~ 5 GHz
Anharmonicity ~ 0.3 GHz

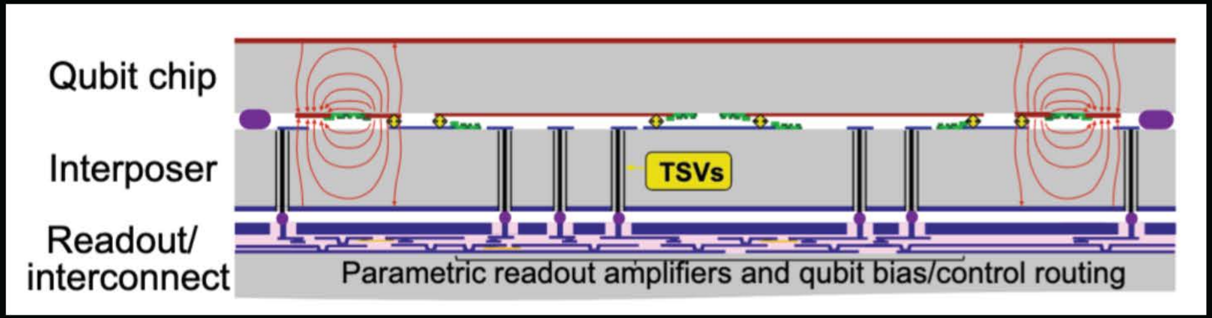
**Resonators:**
Co-planar waveguide
Frequency ~ 6 – 7 GHz
**Roles:**
1. Individual qubit readout
2. Qubit coupling (“bus”)

**Ground plane**
Periodic holes prevent stray magnetic field from hurting superconductor performance

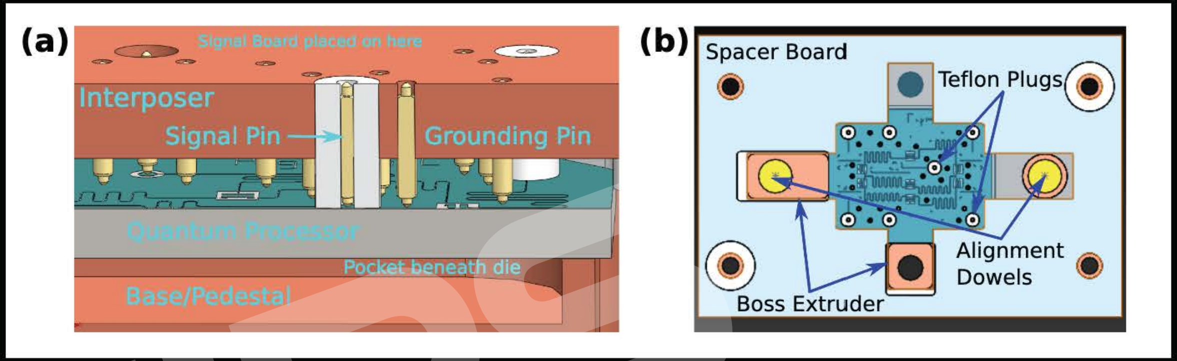



Corcoles et al., Nat. Commun. 6, 6979 (2015)

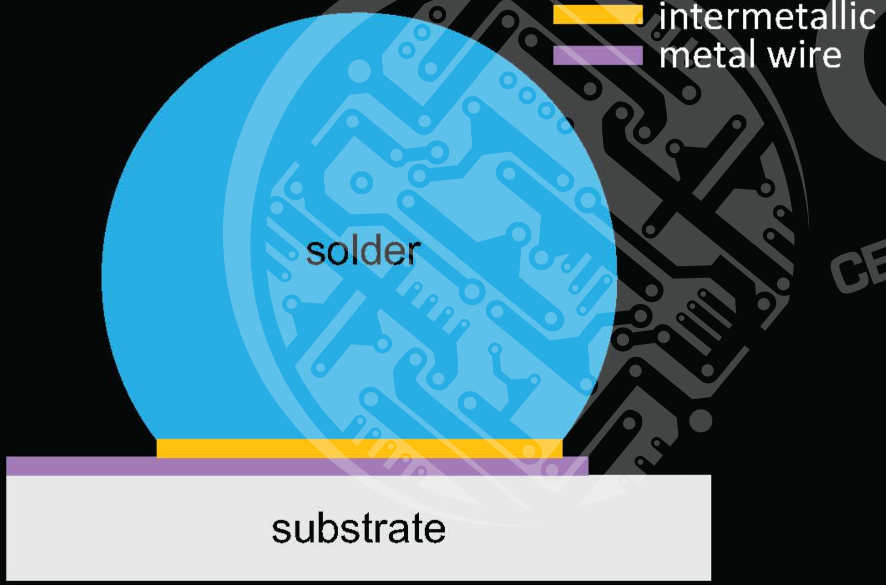
# Packaging of a quantum chip – breaking the 2D plane

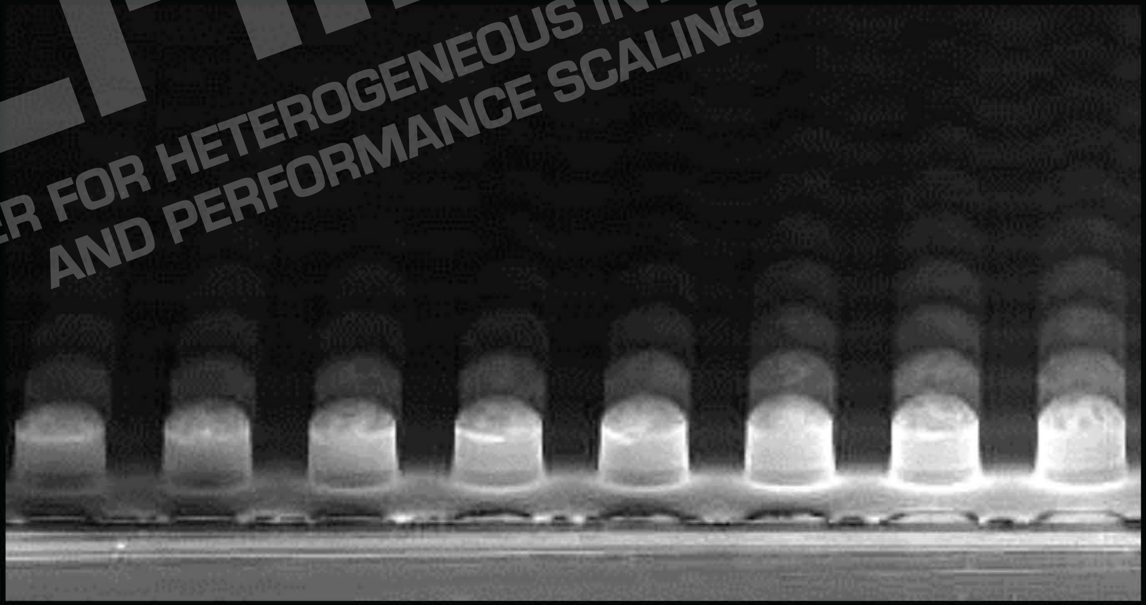



Rosenberg et al, https://www.nature.com/articles/s41534-017-0044-0.pdf




Bronn et al, https://arxiv.org/pdf/1709.02402.pdf



*Flip Chip packaging with solder bumps*

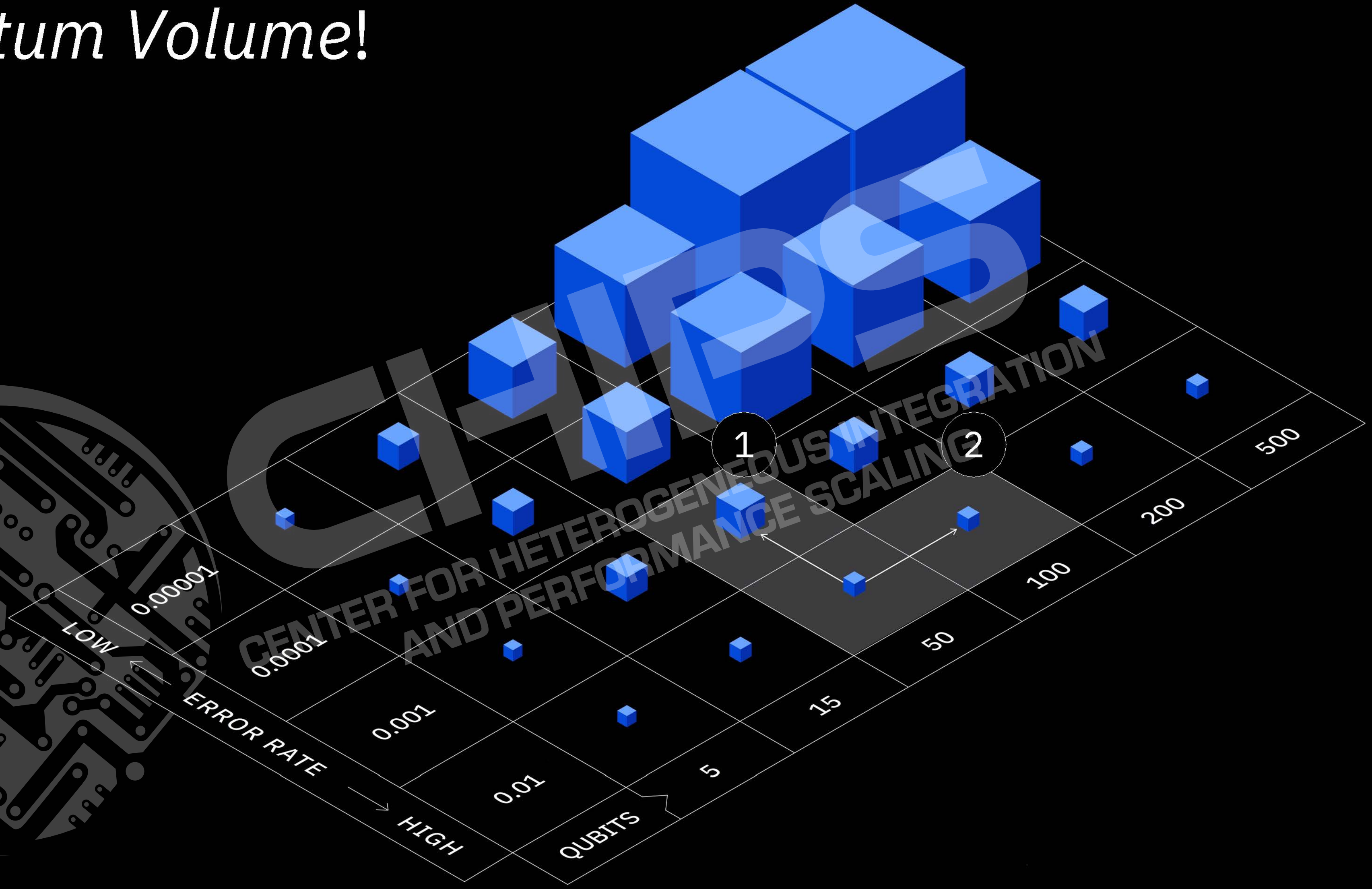
# Forget the qubit race, it's all about *Quantum Volume*!

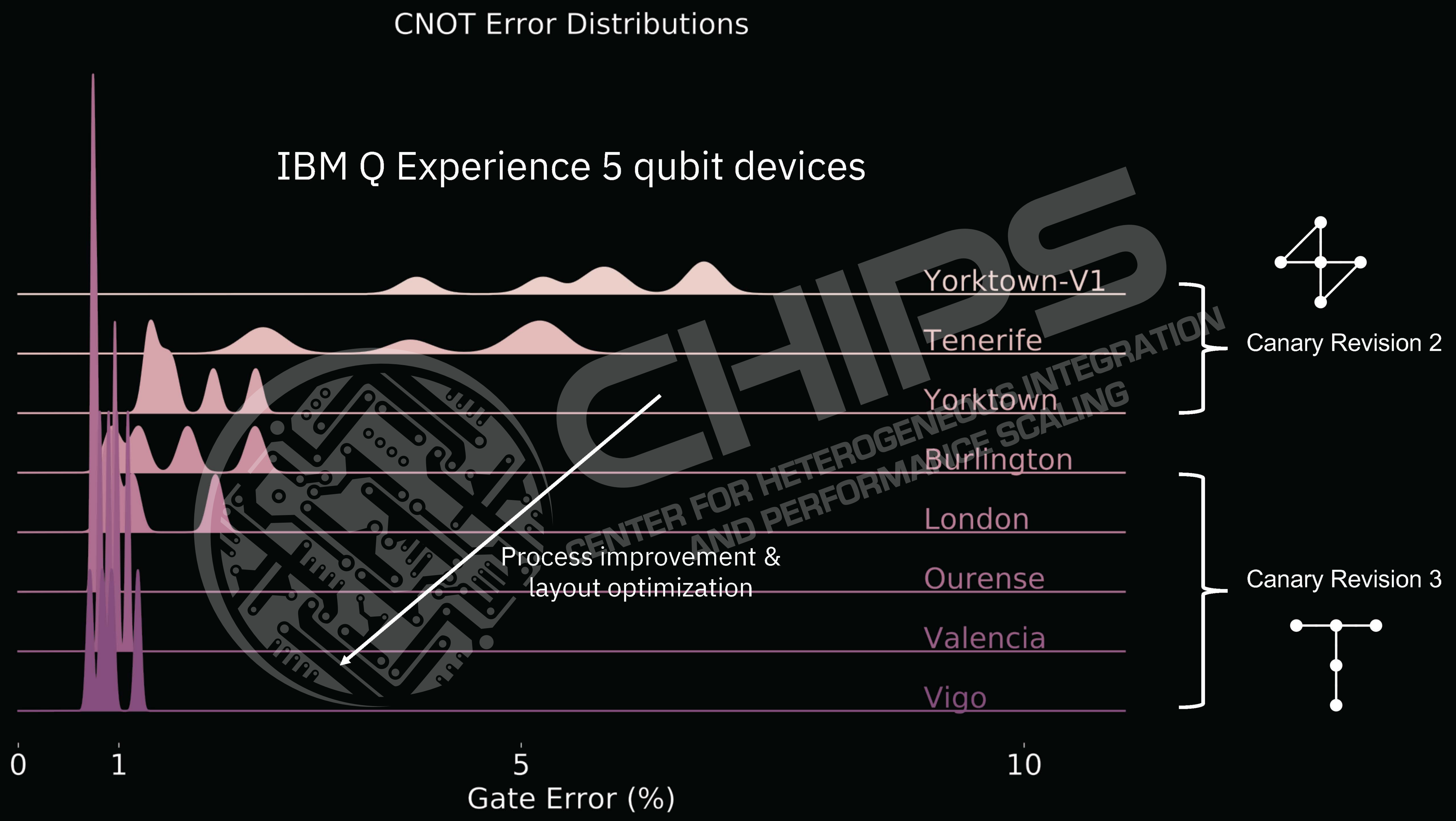
1

Qubits added: 0
Error rate decrease: 10x
Quantum volume increase: 500x

2

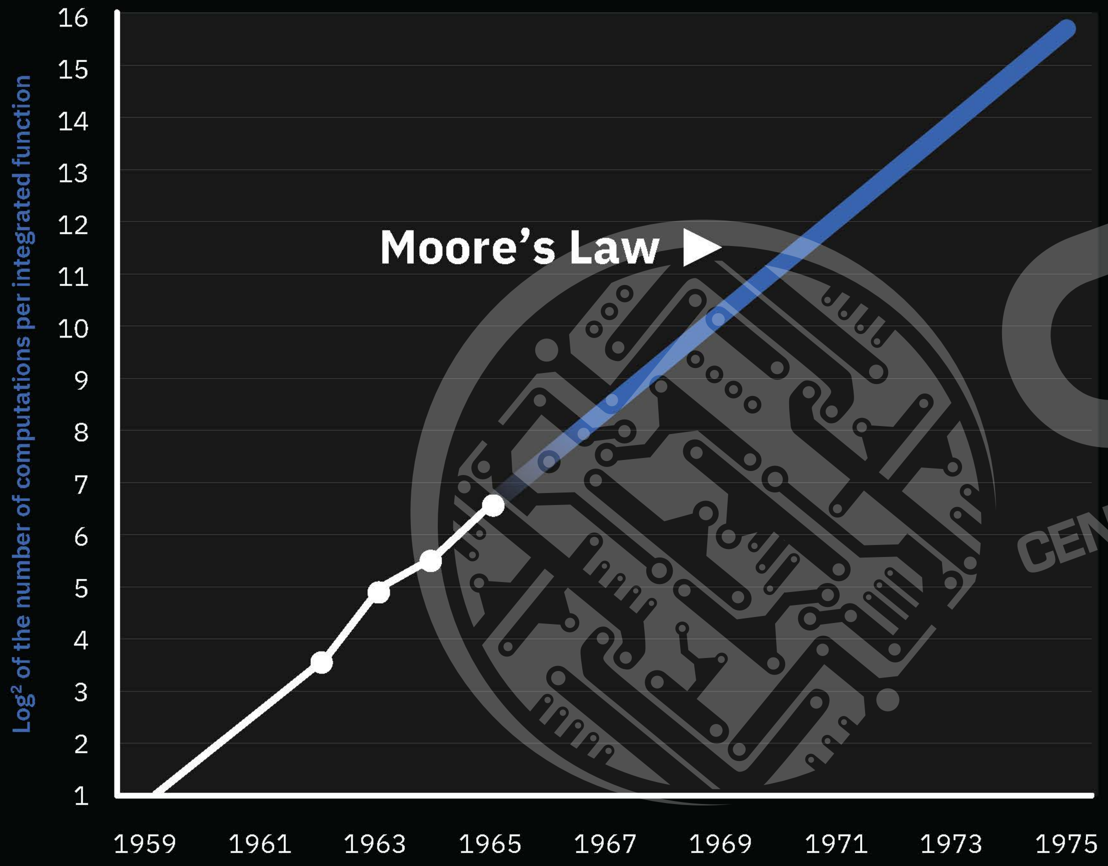
Qubits added: 50
Error rate decrease: 0x
Quantum volume increase: 0x

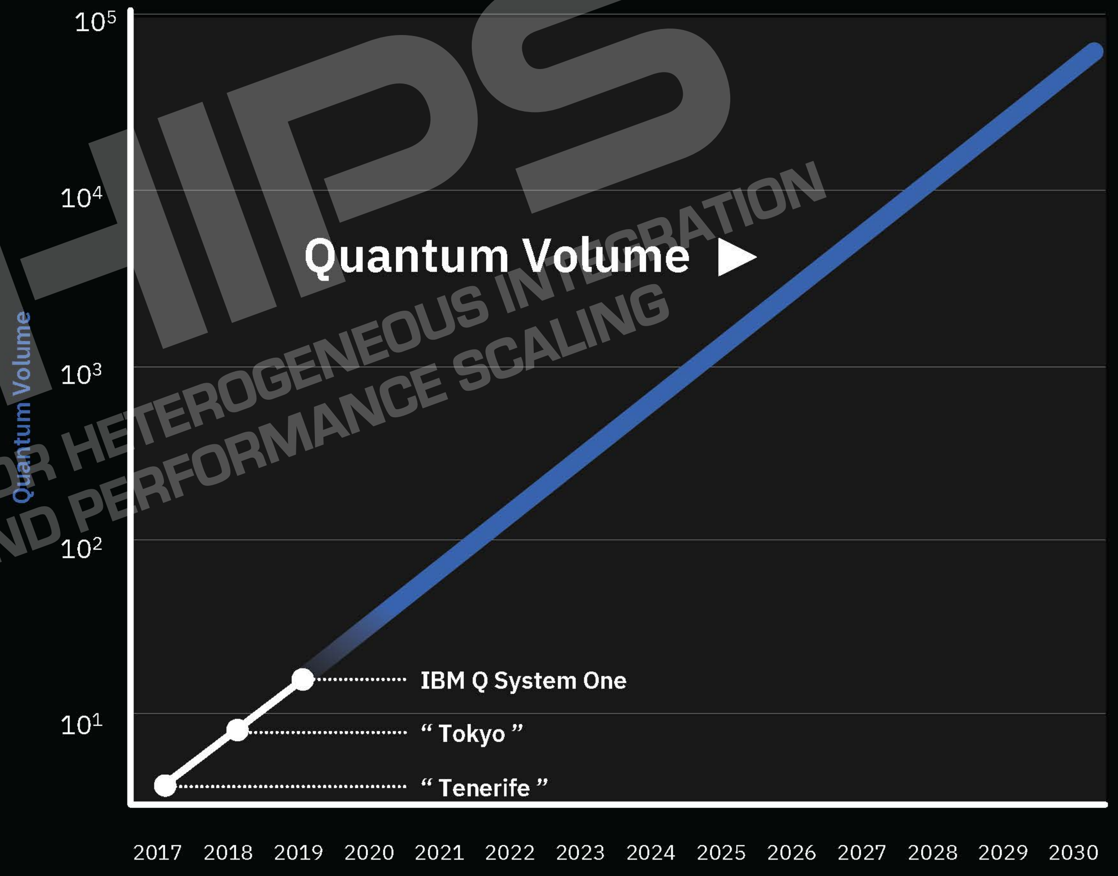



CNOT Error Distributions
IBM Q Experience 5 qubit devices
Yorktown-V1
Tenerife
Yorktown
Burlington
London
Ourense
Valencia
Vigo
Canary Revision 2
Canary Revision 3
Process improvement &
layout optimization
0
1
5
10
Gate Error (%)
CHIPS
CENTER FOR HETEROGENEOUS INTEGRATION
AND PERFORMANCE SCALING

# A New Exponential

## Scaling quantum volume by 2x/year



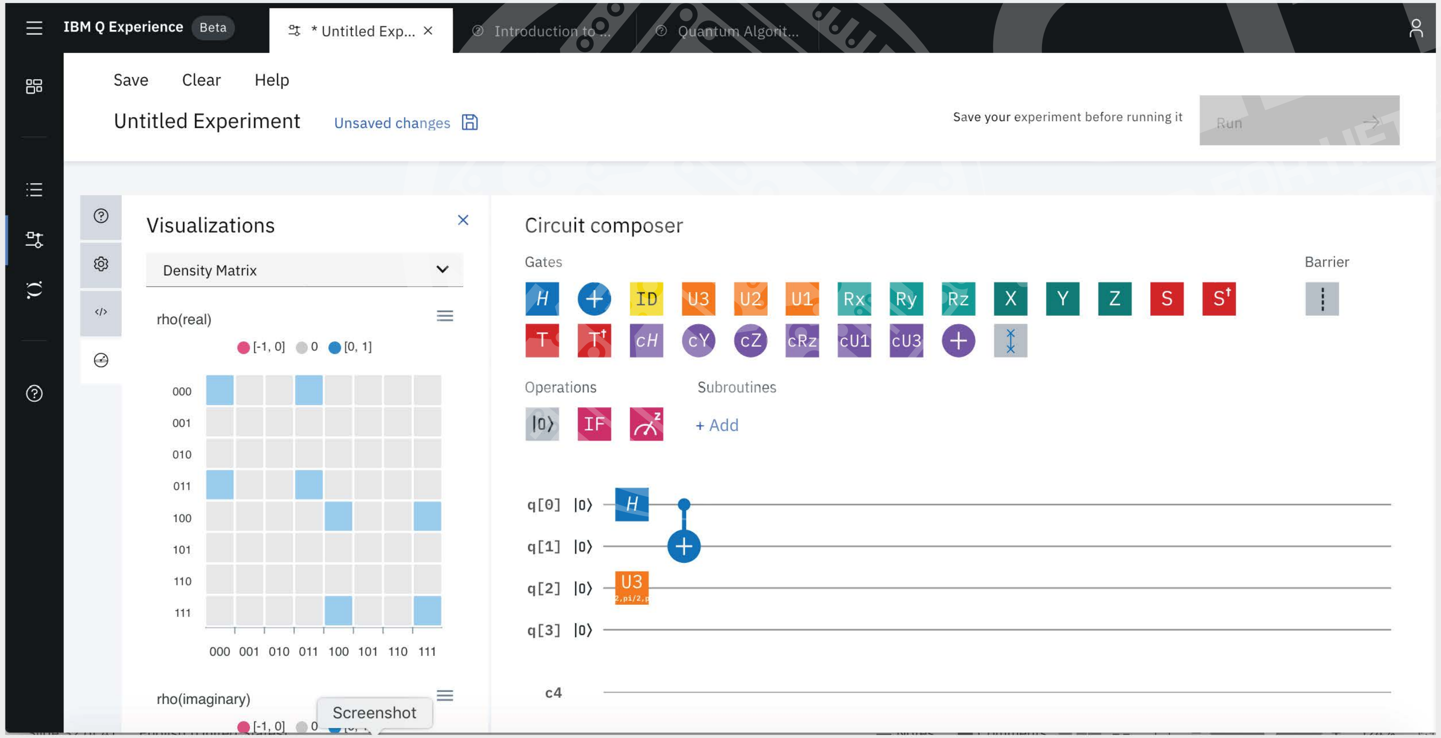
# IBM is committed to building the open source community

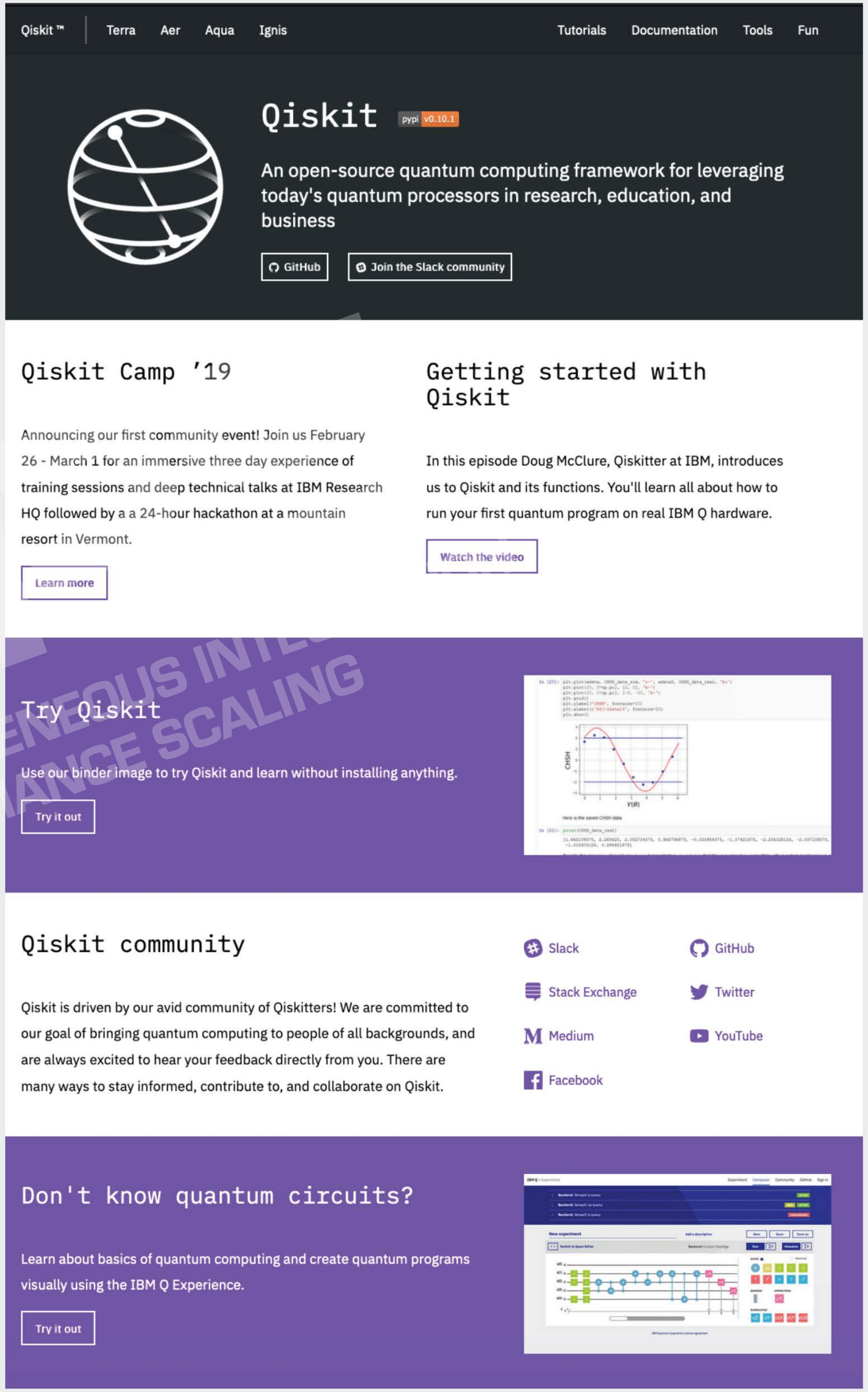
## Qiskit

Collaboratively advance quantum science with open source tools and capabilities in a modular framework

## IBM Q Experience

Provides quantum cloud services, tools and capabilities optimized for IBM Q systems



# IBM Q Experience has been the most widely used and accessible platform for business and science.

**1**

First quantum computer on the cloud in **2016** Several IBM Q systems are available to clients and the public.

**2**

Release of open specifications for quantum cloud apis has enabled the growth of Qiskit with over **260k downloads**

**3**

Real research is happening with IBM Q Experience. Quantum community published **217 third-party papers** testing fundamentals of science citing access to IBM Q tools.

**4**

An inflection point - users see more value in working with hardware than simulators as measured by the number of executions on each. Over **100 billion executions** have run on IBM Q Experience.

# The Qiskit software stack

Brings quantum computing out of the laboratory and into the laptops of developers

- Open Source (*Apache 2.0*)
- Written in Python
- Modular and extensible

## Terra

Improving circuit composition, circuit compilation methods, and pulse-level hardware access

## Aqua

Algorithms for near-term quantum applications

## Ignis

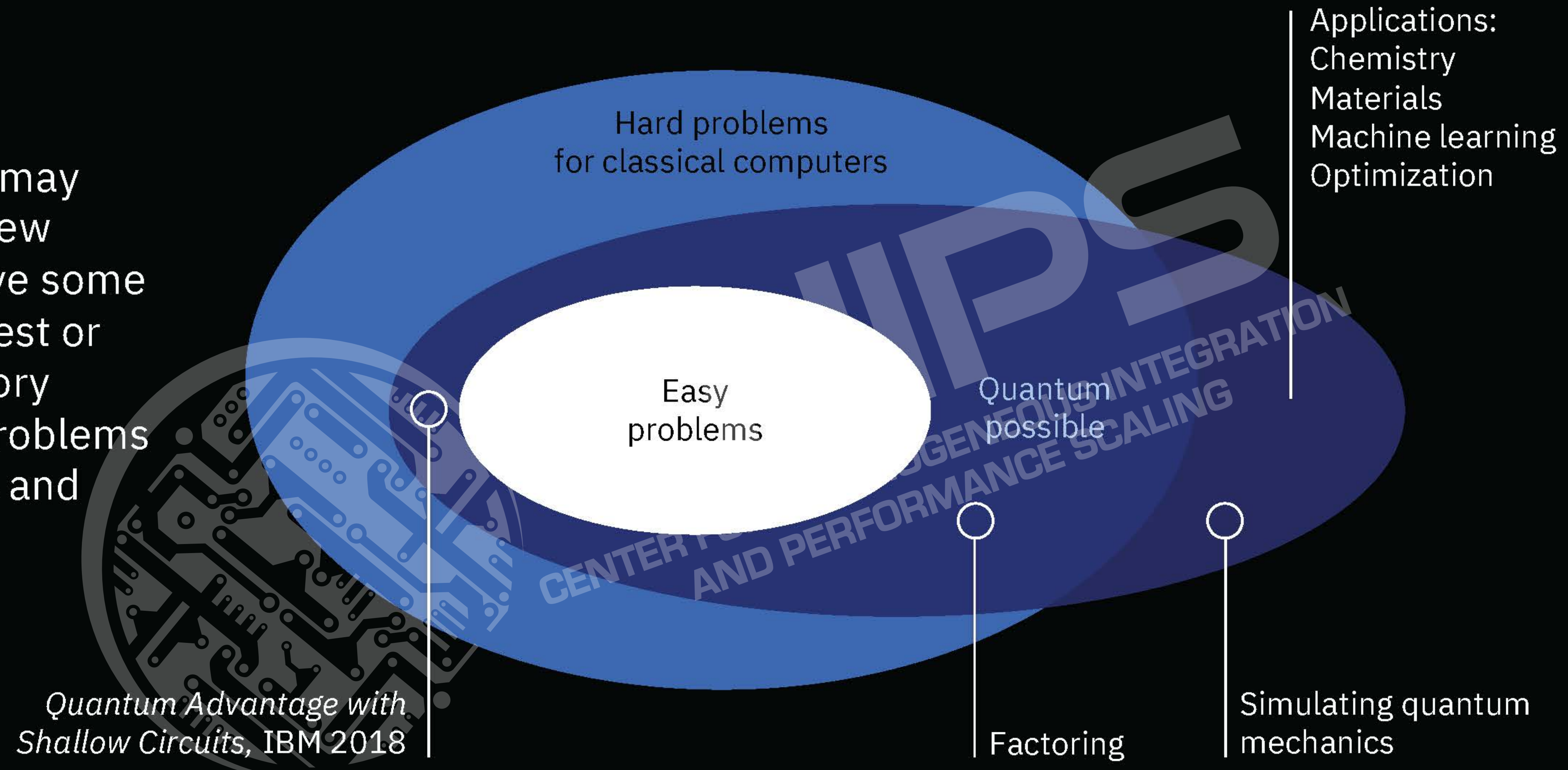
Compute in the presence of errors

## Aer

A high performance simulator framework for quantum circuits

# Applications of quantum computing

Quantum computing may provide a new path to solve some of the hardest or most memory intensive problems in business and science.



# IBM **Q** Network: Applications

In collaboration with IBM Q Network partners, IBM is driving advancements in software and algorithms to pursue use cases in:

## Simulating Quantum Systems

- Quantum chemistry
- Material science
- High energy physics

## Artificial Intelligence

- Better model training
- Pattern recognition
- Fraud detection

## Optimization / Monte Carlo

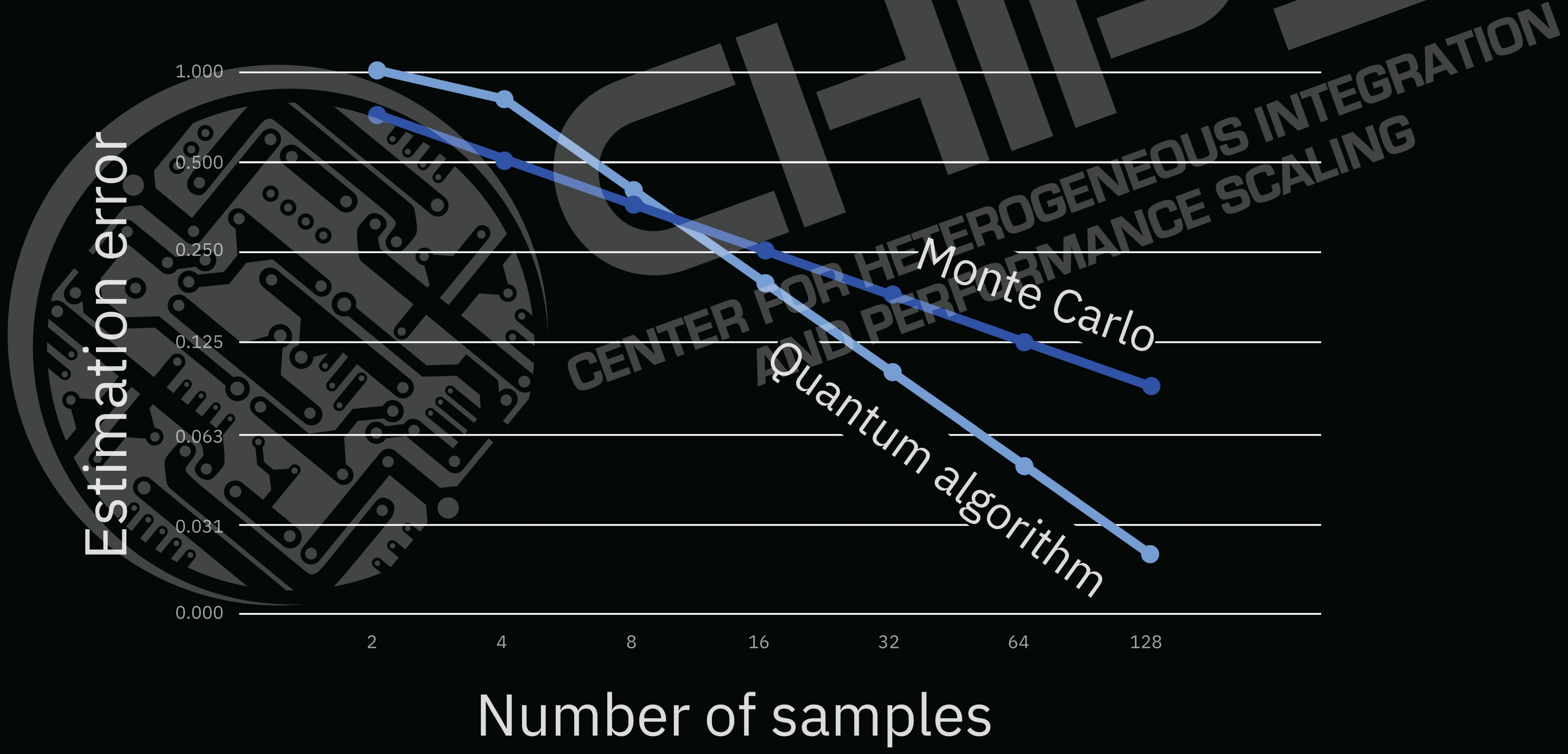
- Portfolio optimization
- Risk analysis
- Loans & credit scoring
- Monte Carlo-like applications

Quantum computers can **speed up** Monte Carlo sampling.

# Experimental results show **quadratic speedup** with quantum algorithm compared to Monte Carlo.

*npj Quantum Information* **5**, 15 (2019)

Quantum Amplitude Estimation to compute expected value of a T-bill (single-period binomial-tree model)



# This has spurred new research within the IBM Q Network.

A modification from the **Keio Hub collaboration with MUFG & Mizuho** reduces qubits and gates required by the quantum algorithm.

Amplitude Estimation without Phase Estimation

Yohichi Suzuki[1,+], Shumpei Uno[1,2,+], Rudy Raymond[1,3], Tomoki Tanaka[1,4], Tamiya Onodera[1,3], and Naoki Yamamoto[1,*]

**April 2019**
**arXiv:1904.10246**

This allowed us to model option pricing on **real quantum hardware** with **J.P. Morgan Chase & Co**.

**Option Pricing using Quantum Computers**

Nikitas Stamatopoulos,[1] Daniel J. Egger,[2] Yue Sun,[1] Christa Zoufal,[2,3] Raban Iten,[2] Ning Shen,[1] and Stefan Woerner[2]

[1] *J.P. Morgan Chase - Quantitative Research*
[2] *IBM Research – Zurich*
[3] *ETH Zurich*

**May 2019**
**arXiv:1905.02666**

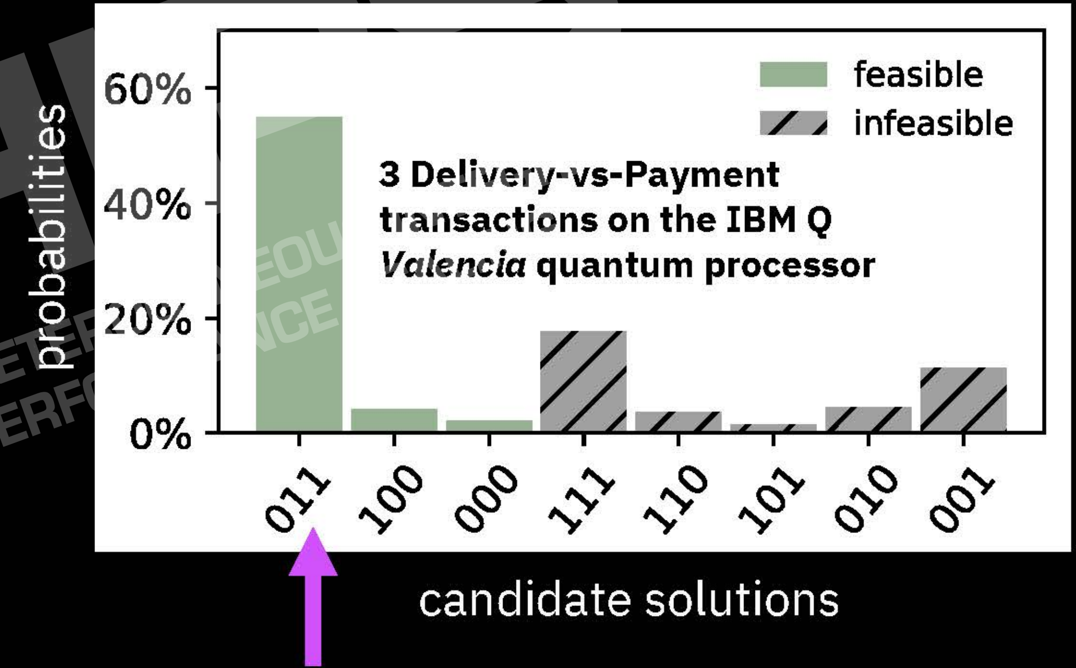
# We've extended quantum optimization approaches to model securities transaction settlement.

**In collaboration with Barclays**, we've developed methods for **mixed binary optimization**, and applied them to **optimize efficiency of securities transaction settlement**.

***$1.85 quadrillion*** of securities transactions processed by subsidiaries of the post-trade market infrastructure DTCC in 2018*.

**October 2019**
**arXiv:1910.05788**

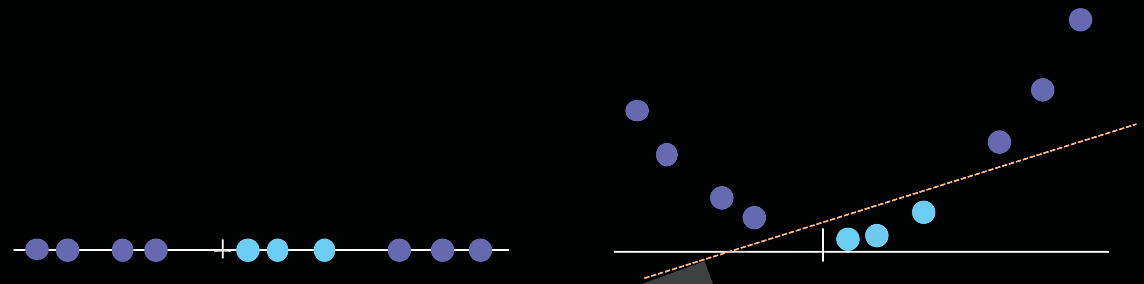
**Experimental demonstration of the transaction settlement problem:**



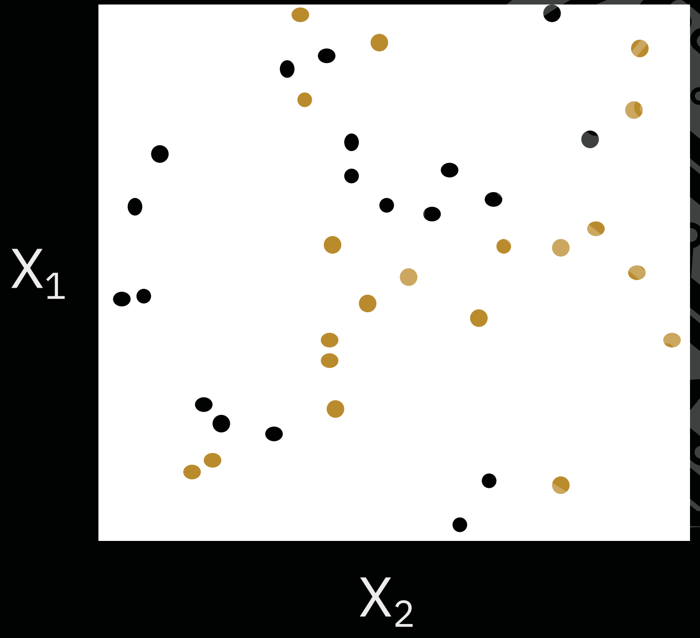

Quantum algorithm finds globally optimal solution:
"011" → settle transactions 2 and 3

* http://www.dtcc.com/annuals/2018/#/financial-performance

# IBM Q has **experimentally demonstrated** the accurate classification of data using two quantum algorithms.



1 Training set




2 Generate a quantum feature map

Use **entanglement** to encode many different attributes in an **exponential** number of states

3 Process the data

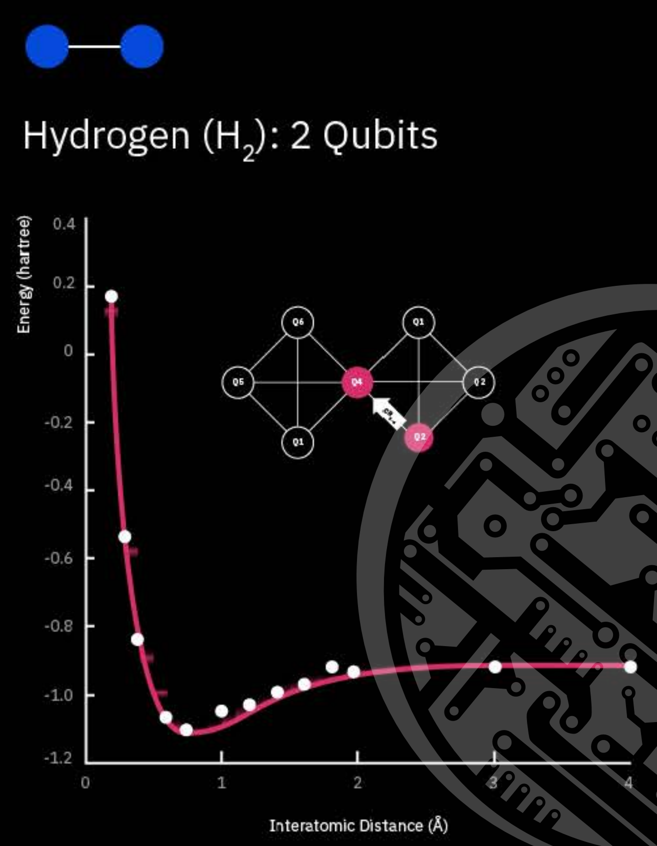
**black**

**gold**

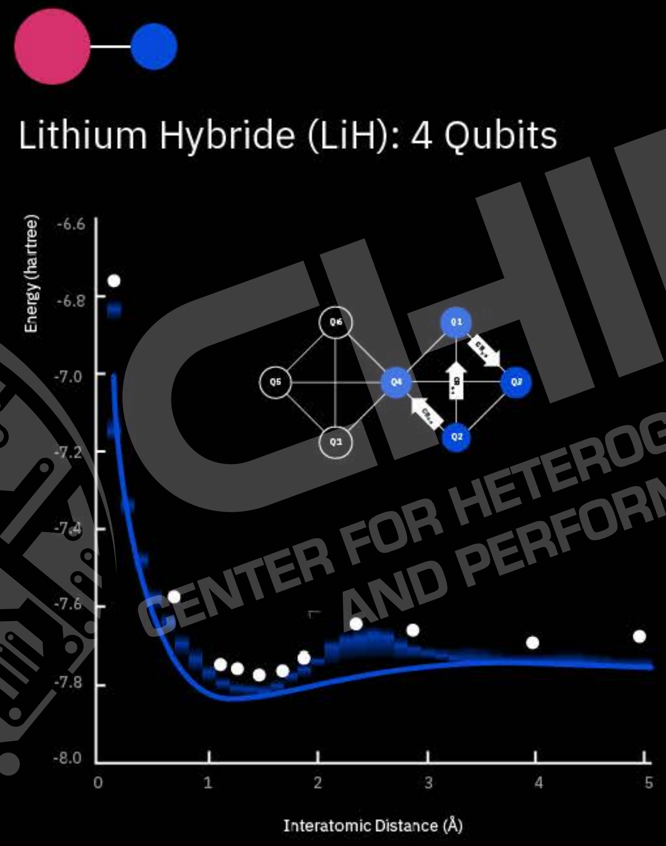
*Nature* **567**, 209-212 (2019)

# Chemistry with a real quantum computer

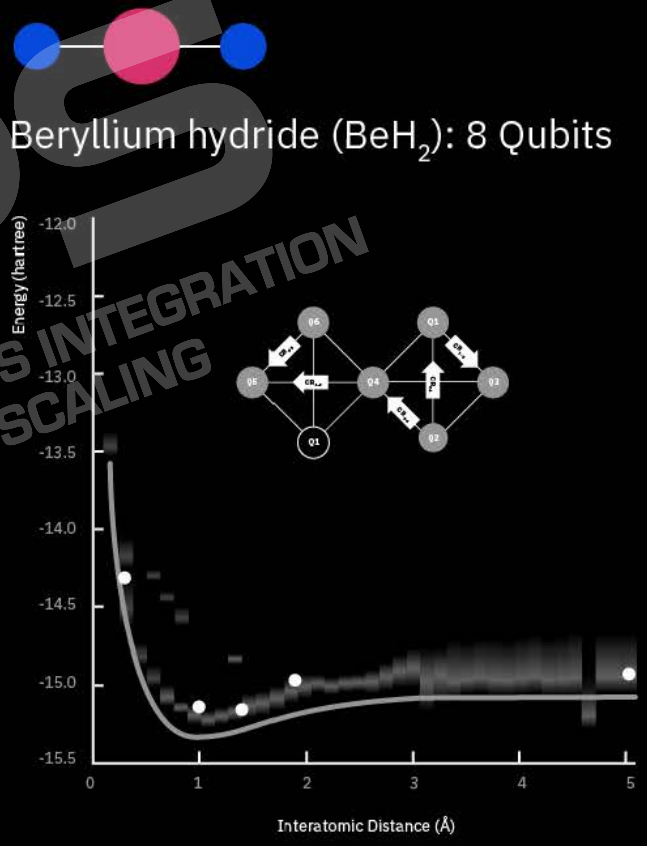
Hydrogen ($H_2$): 2 Qubits




Lithium Hybride (LiH): 4 Qubits



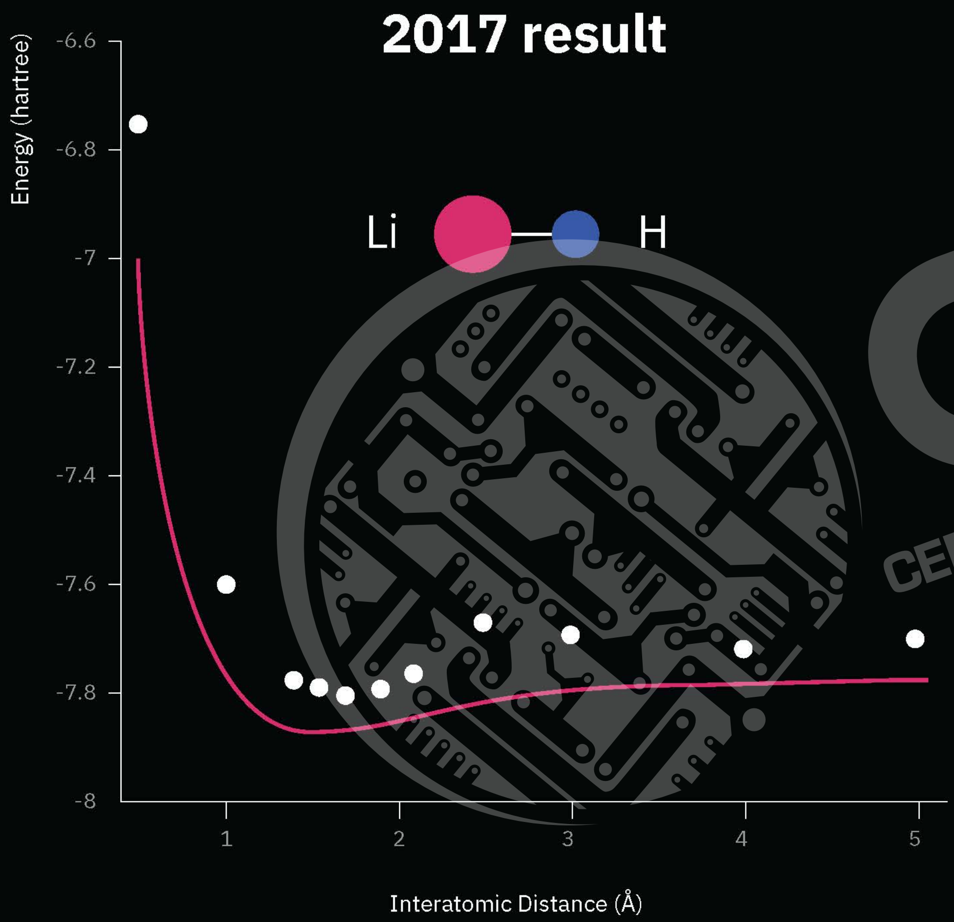

Beryllium hydride ($BeH_2$): 8 Qubits

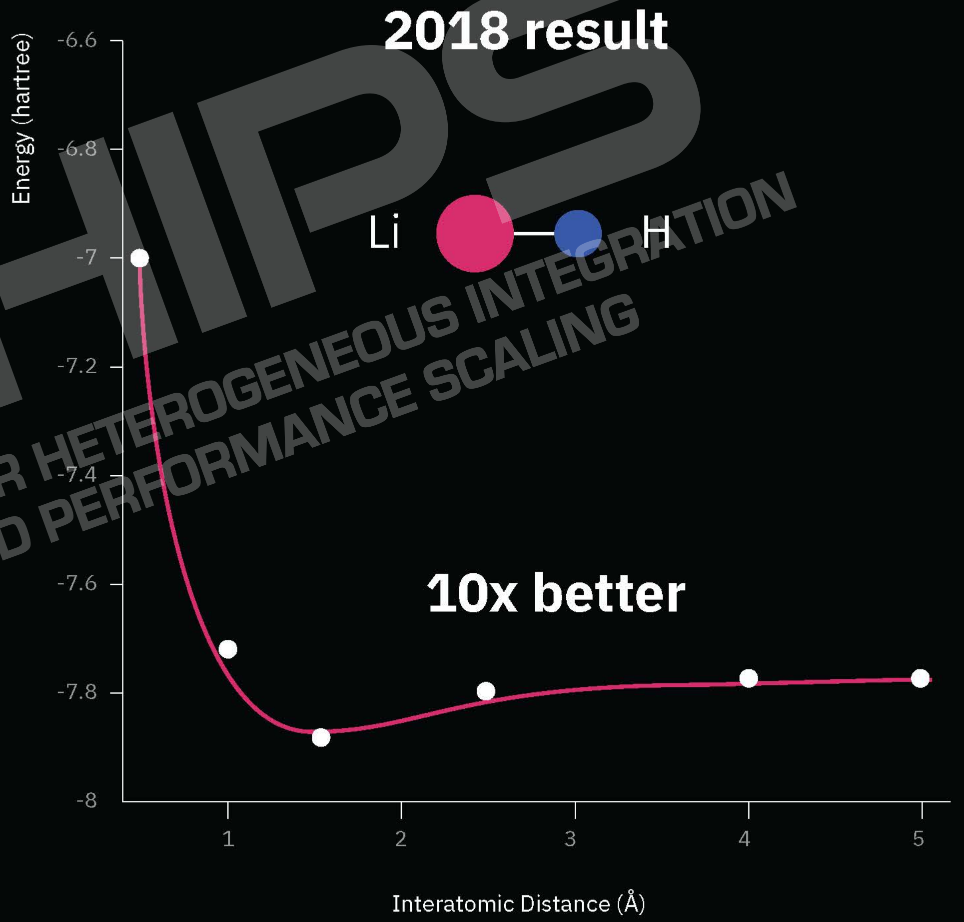


# Error Mitigation for Quantum Chemistry

**Extending the computational reach of a noisy superconducting quantum processor**

Abhinav Kandala, Kristan Temme, Antonio D. Córcoles, Antonio Mezzacapo, Jerry M. Chow, Jay M. Gambetta
*IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA*
(Dated: May 14, 2018)



# Possible Extensions

- **Material** **Discovery**
- **Protein** Simulation and enzyme design
- **Polymer** **material design** and computation of properties
- **Molecular structure** chemistry

### Quantum optimization using variational algorithms on near-term quantum devices

Nikolaj Moll[1], Panagiotis Barkoutsos[1], Lev S. Bishop[2], Jerry M. Chow[2], Andrew Cross[2], Daniel J. Egger[1], Stefan Filipp[1], Andreas Fuhrer[1], Jay M. Gambetta[2], Marc Ganzhorn[1], Abhinav Kandala[2], Antonio Mezzacapo[2], Peter Müller[1], Walter Riess[1], Gian Salis[1], John Smolin[2], Ivano Tavernelli[1], and Kristan Temme[2]
[1] IBM Research – Zurich, Säumerstrasse 4, 8803 Rüschlikon, Switzerland
[2] IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA

### Quantum algorithms for electronic structure calculations: particle/hole Hamiltonian and optimized wavefunction expansions

Panagiotis Kl. Barkoutsos,[1,2] Jerome F. Gonthier,[3] Igor Sokolov,[1,2] Nikolaj Moll,[1] Gian Salis,[1] Andreas Fuhrer,[1] Marc Ganzhorn,[1] Daniel J. Egger,[1] Matthias Troyer,[2,4] Antonio Mezzacapo,[5] Stefan Filipp,[1] and Ivano Tavernelli[1,*]
[1] *IBM Research GmbH, Zurich Research Laboratory, Säumerstrasse 4, 8803 Rüschlikon, Switzerland*
[2] *Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*
[3] *Kenneth S. Pitzer Center for Theoretical Chemistry, Department of Chemistry, University of California, Berkeley, CA 94720, USA*
[4] *Microsoft Quantum, Microsoft, Redmond, WA 98052, USA*
[5] *IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA*

### Gate-efficient simulation of molecular eigenstates on a quantum computer

M. Ganzhorn, D.J. Egger, P. Barkoutsos, P. Ollitrault, G. Salis, N. Moll, A. Fuhrer, P. Mueller, S. Woerner, I. Tavernelli and S. Filipp
*IBM Research Zurich, Säumerstrasse 4, 8803 Rüschlikon, Switzerland*
(Dated: September 14, 2018)

### Improving Variational Quantum Optimization using CVaR

Panagiotis Kl. Barkoutsos,[1] Giacomo Nannicini,[2] Anton Robert,[1,3] Ivano Tavernelli,[1] and Stefan Woerner[1,*]
[1] *IBM Research – Zurich*
[2] *IBM T.J. Watson Research Center*
[3] *École Normale Supérieure, Paris*

### Resource-Efficient Quantum Algorithm for Protein Folding

Anton Robert,[1,2] Panagiotis Kl. Barkoutsos,[1] Stefan Woerner,[1,*] and Ivano Tavernelli[1,†]
[1] *IBM Research GmbH, Zurich Research Laboratory, Säumerstrasse 4, 8803 Rüschlikon, Switzerland*
[2] *PASTEUR, Département de chimie, École Normale Supérieure, PSL University, Sorbonne Université, CNRS, 75005 Paris, France*
(Dated: July 29, 2019)

**78** members

**7** industry partners

**9** hubs

**17** hub members

**19** startups

**26** academic partners

# IBM Q Network established in 2017

Accelerate quantum research

Develop commercial applications

Promote, Educate and Prepare

# The Role of Colleges and Universities

# Academic research

Academic research in quantum computing drives core advances across many fields including physics, mathematics, computer science, and engineering.

It also will drive innovation in quantum computing applications in chemistry, materials science, economics, applied mathematics, and AI.

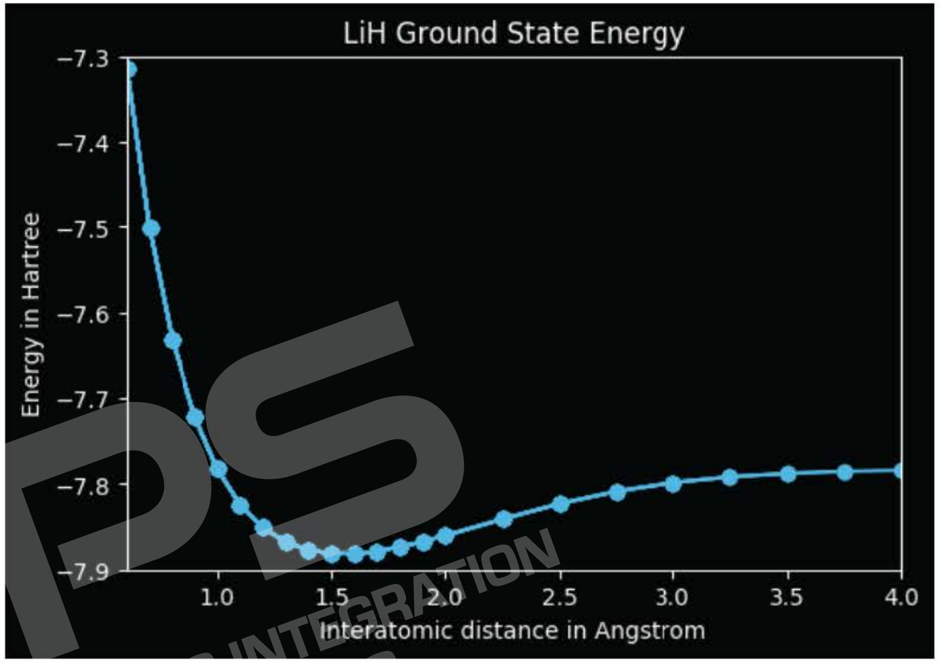
University research teams will want access to the latest hardware, control software, and software libraries.

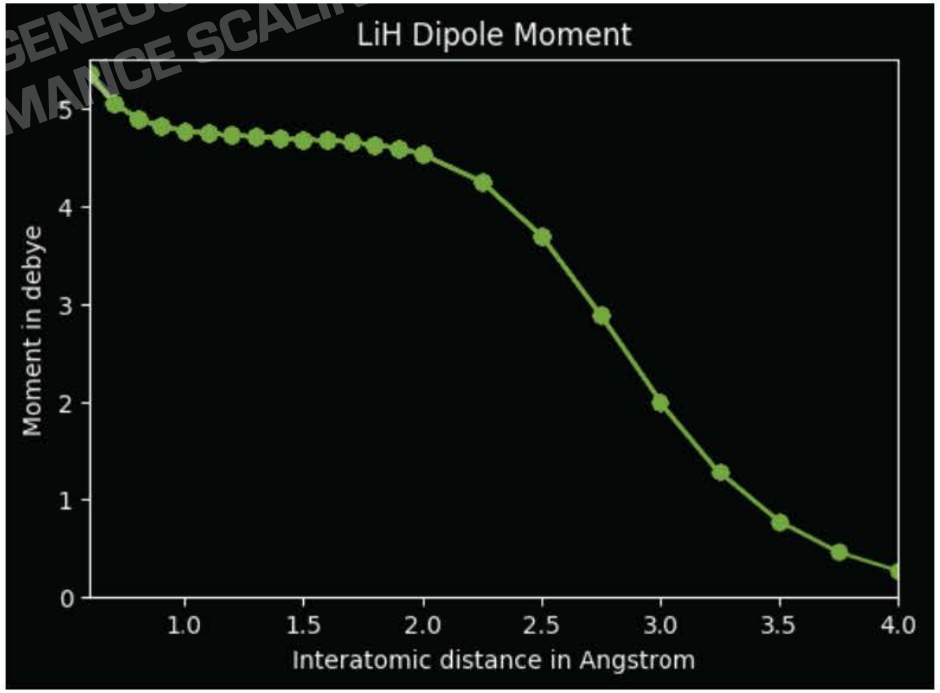
# Education

If quantum computing starts to show early advantage in 3 to 5 years, who better to educate than those who are in college today?

While standalone quantum computing classes are being created and taught, many more students will be reached by modules in existing classes:

- Quantum physics
- Applied mathematics
- Computer architecture
- Software compilers
- Nanotechnology
- Linear algebra
- Chemistry



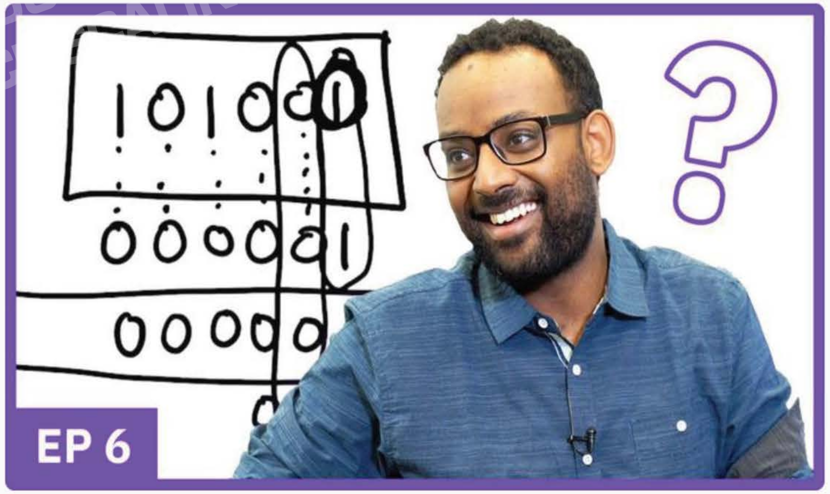
# Quantum computers are complex, but learning to develop on them shouldn’t have to be.


## Qiskit for Educators

Qiskit makes it easy to start learning quantum software to run on real quantum hardware. Teach your students with the same tools used by scientists and engineers worldwide to accelerate research towards practical applications for quantum computing.

## Qiskit Textbook

Leverage the power of quantum computing using Qiskit with this university course supplement covering introductory materials, advanced algorithms and hardware. Include problem sets and exercises for students.




# What’s Next?

Deliver more advanced quantum devices and software to our partners and community

Continue to grow and cultivate a collaborative IBM Q Network

Drive industry use cases, research demonstrations and differentiation with IBM Q hardware and software

Partner with educators to advance the teaching of quantum and create new skills for growing demand

Continue to drive open source contributions, content and advocacy within our rapidly growing Qiskit community

# **Learn** about quantum...

**Qiskit open source community**

github.com/qiskit

**IBM Q Experience**

quantum-computing.ibm.com

**Qiskit slack workspace**

qiskit.slack.com

**Quantum Education**

youtube.com/qiskit

edx.org

**Qiskit tutorials & Documentation**

qiskit.org

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