Convergence: The Promise and Reality of AI & Quantum

November 14, 2022

Introduction to Quantum Computing

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MIT CSAIL Computer Science & Artificial Intelligence Laboratory

MIT Center for Quantum Engineering

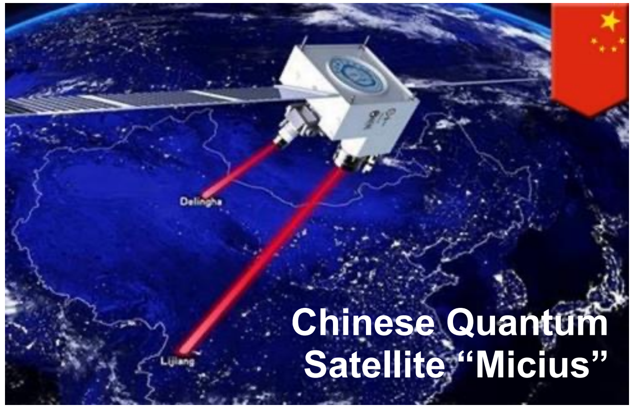
2nd Quantum Revolution

Quantum Information Science and Technology

Quantum Sensing

Improves sensitivity, drift, & spatial resolution

Quantum Networks



Enables distributed quantum states

Quantum Computing

Solves select problems that are intractable with classical computing

Quantum 2.0 utilizes quantum mechanics to sense, communicate, and process information in ways unobtainable by conventional, classical means

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Computing Development Timeline

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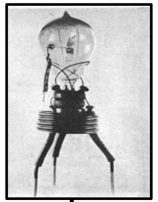
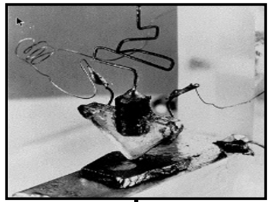
Classical Computing (Electronic)

Vacuum tube (1906)



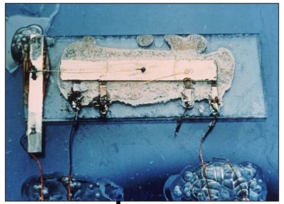
ENIAC (1946)

Transistor (1947)

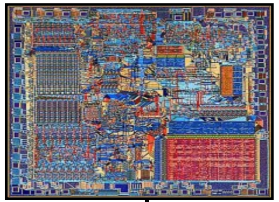


TX-0 (1956)

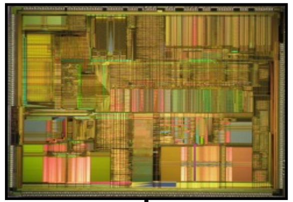
Integrated circuit (1958)



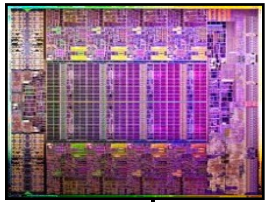
2K transistors i4004 (1971)



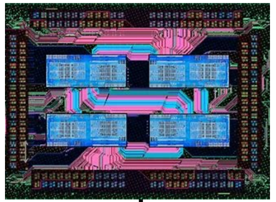
5.5M transistors Pentium Pro (1995)



18 cores 5.5B transistors Xeon Haswell (2014)



32 cores 19.2B transistors Epyc GPU (2017)



Quantum computing is transitioning from scientific curiosity to technical reality.

Advancing from discovery to useful machines takes time & engineering

You must be in the game to play

Quantum Computing

Grover (1996)

Factor 15 (2002)

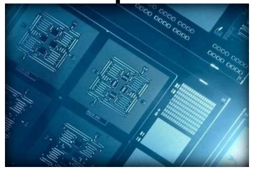
Few-qubit processors (2010-2016)

Business development (2019-2021)

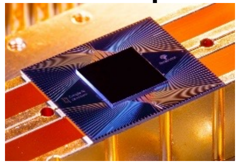
Quantum simulator proposed (1981)

Shor's algorithm & CSS error correction (1994-95)

Quantum annealing & adiabatic QC (1998-2000)



Cloud-based QCs (2017)



Quantum Advantage 53-qubit QCs (2019)

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Nascent Commercial Quantum Processors

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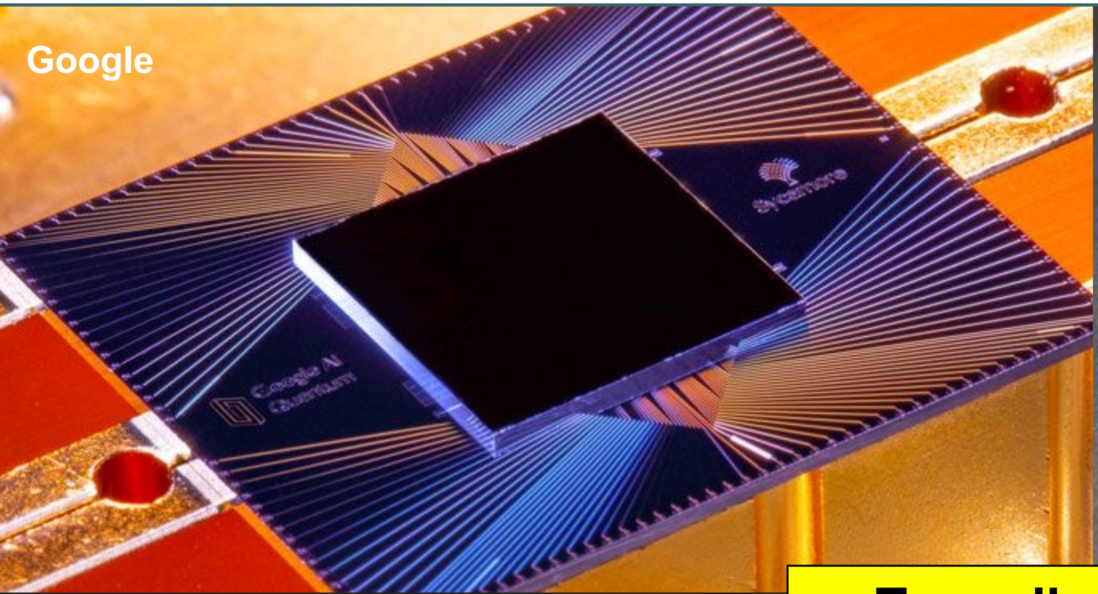
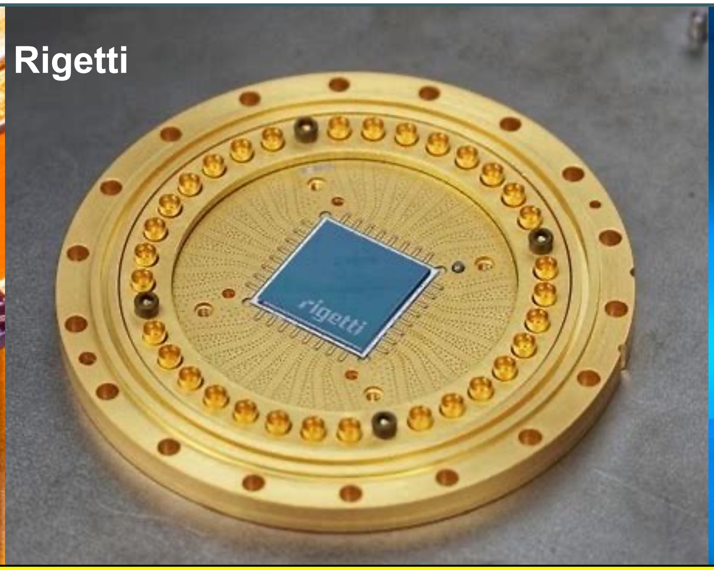
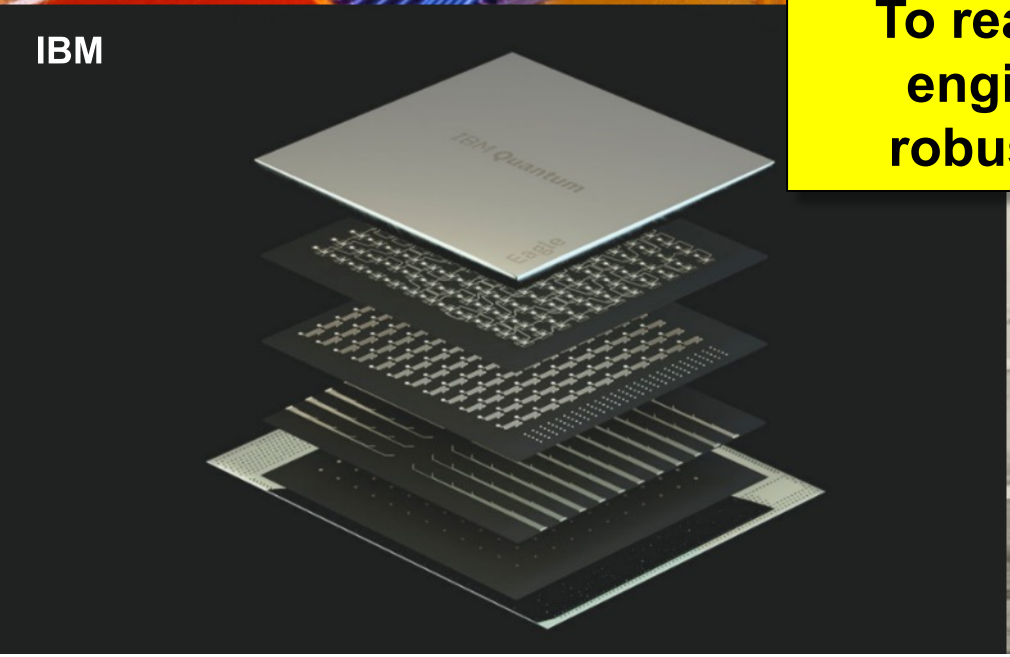
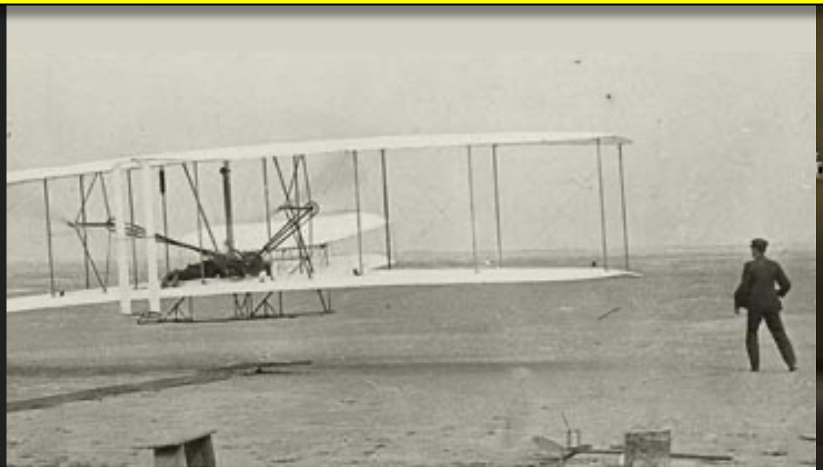




To realize the promise of QC, we must engineer quantum systems that are robust, reproducible, and extensible.





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How is a Quantum Computer Different?

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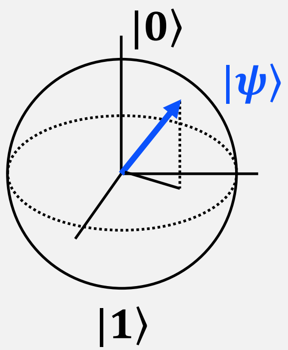
Classical Computer

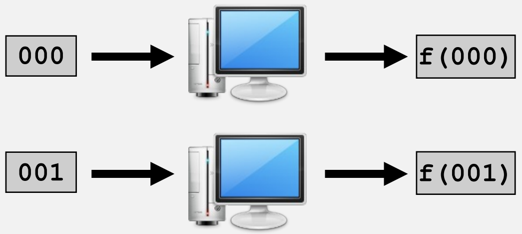
Fundamental logic element	**"Bit" : classical bit** **(transistor, spin in magnetic memory, …)**
State	**0 "Or" 1**
Measurement	• ***Discrete*** **states** • **Deterministic measurement:** **Ex: Set as 1, measure as 1**

How is a Quantum Computer Different?

	Classical Computer	Quantum Computer
Fundamental logic element	**"Bit" : classical bit** (transistor, spin in magnetic memory, …)	**"Qubit" : quantum bit** (any coherent two-level system)
State	**0 "Or" 1**	 **Superposition:** $\alpha\vert 0\rangle + \beta\vert 1\rangle$ $\vert 0\rangle$ **"And"** $\vert 1\rangle$ $\vert \psi\rangle = \alpha\begin{bmatrix}1\\0\end{bmatrix} + \beta\begin{bmatrix}0\\1\end{bmatrix}$
Measurement	• ***Discrete*** **states** • **Deterministic measurement:** **Ex: Set as 1, measure as 1**	• ***Superposition*** **states** • **Probabilistic measurement:** **Ex: If** $\vert\alpha\vert = \vert\beta\vert$, **50%** $\vert 0\rangle$, **50%** $\vert 1\rangle$

Quantum computers rely on encoding information in a fundamentally different way than classical computers

How is a Quantum Computer Different?

	Classical Computer
Fundamental logic element	**"Bit" : classical bit** **(transistor, spin in magnetic memory, …)**
Computing	• **N bits: One N-bit state** **000, 001, …, 111 (N = 3)** • **Change a bit: new calculation (classical parallelism)** 

How is a Quantum Computer Different?

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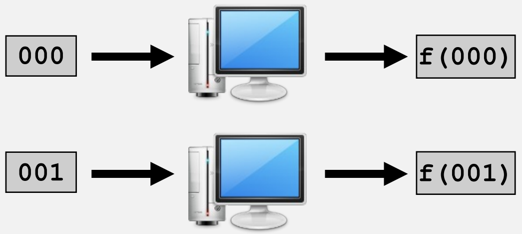
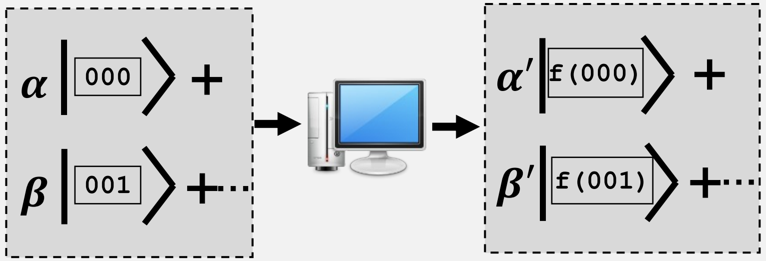
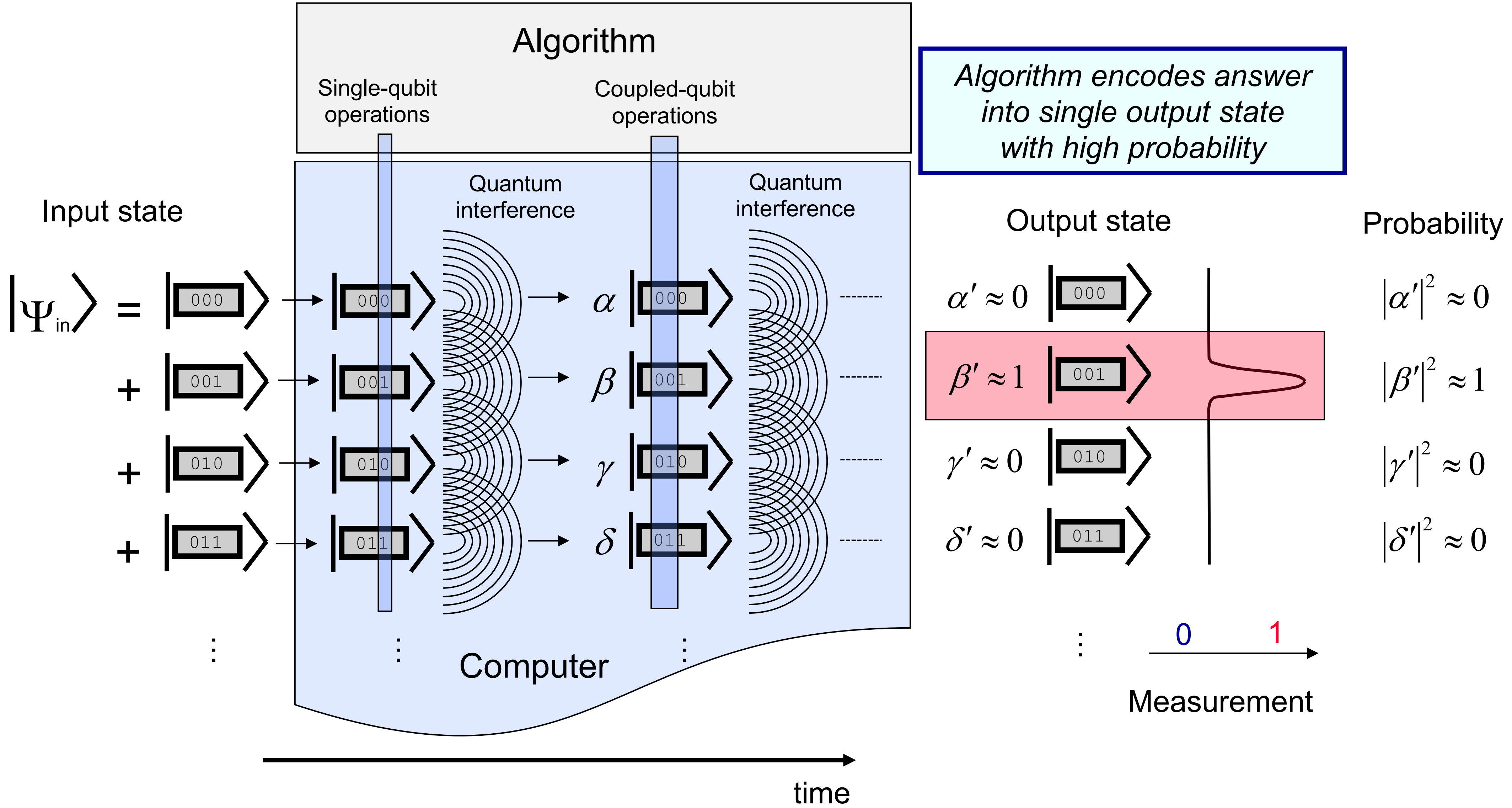
Computing	• **N bits: One N-bit state** **000, 001, …, 111 (N = 3)** • **Change a bit: new calculation (classical parallelism)**	• **N qubits: 2^N components to one state** $\alpha\|000\rangle + \beta\|001\rangle + \cdots + \gamma\|111\rangle$ **(N = 3)** • **Quantum parallelism & interference**





How do we take advantage of this hardware?

Quantum Algorithm (Digital)



Algorithm encodes answer into single output state with high probability

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Quantum Algorithms: Two Paths

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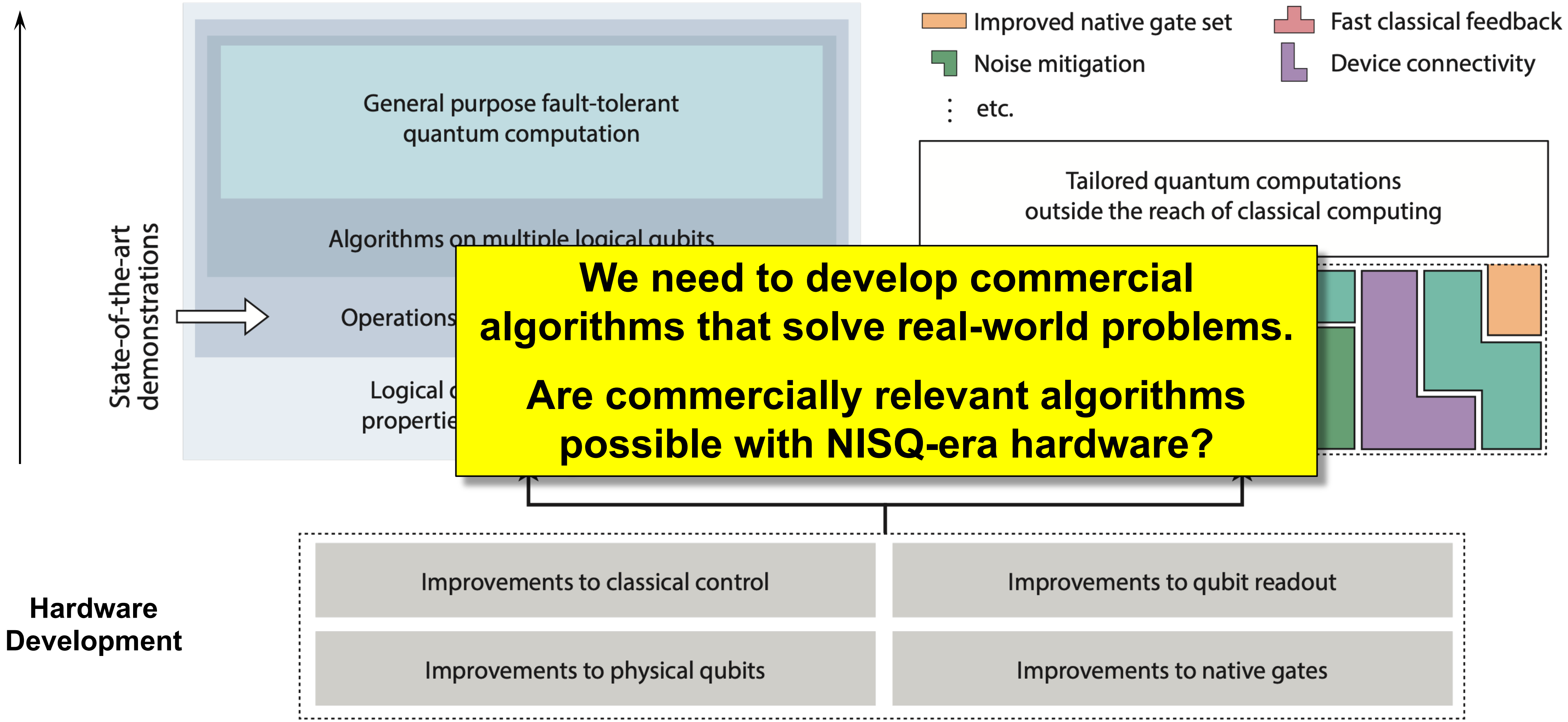
Fault-tolerant quantum computers

NISQ-era quantum computers

time &
performance

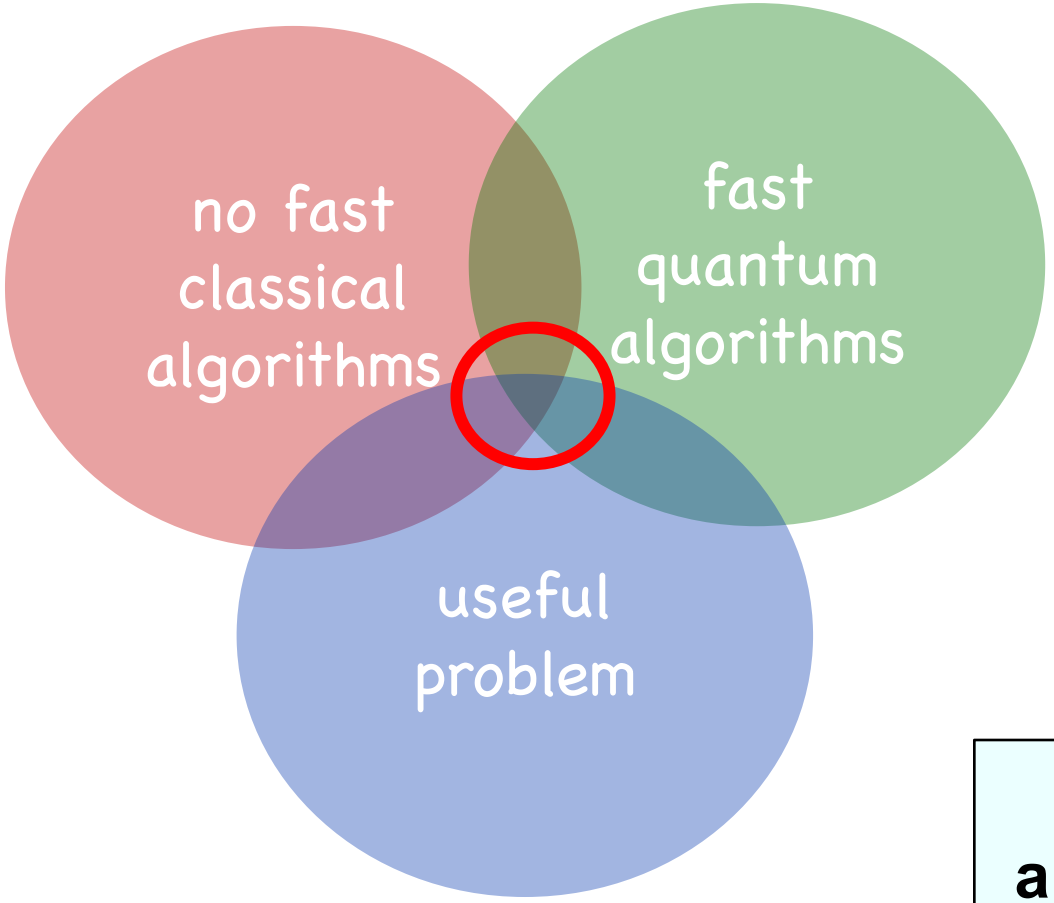


We need to develop commercial algorithms that solve real-world problems.

Are commercially relevant algorithms possible with NISQ-era hardware?

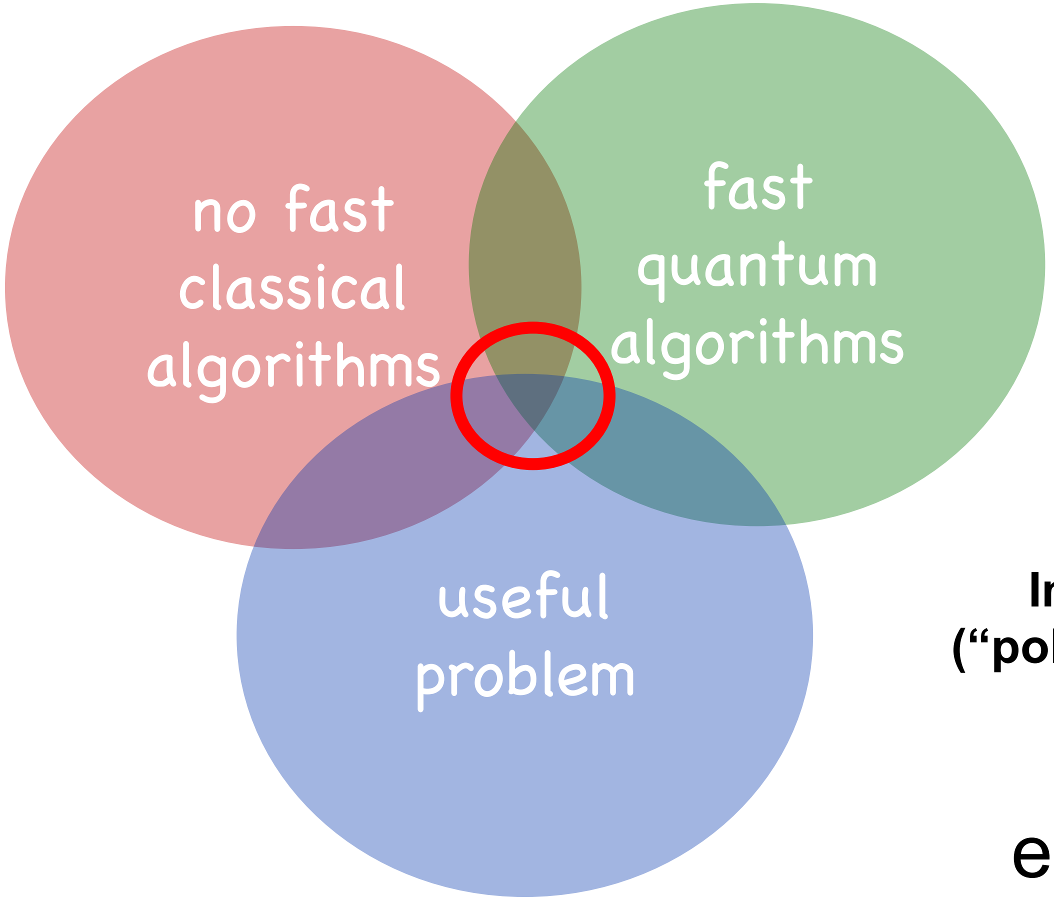
M. Kjaergaard, WDO, et al., Annual Reviews of CMP 11, 369-395 (2020)

Ingredients for Commercial Quantum Advantage



Small region where useful quantum algorithms exist (as we know them today)

Types of Quantum Advantage



Two Types of Quantum Advantage

- System size,
- Time to solution,
- Other resources

$$\propto A(N)\exp(\beta N)$$

Improve the prefactor ("polynomial improvement")

Reduce exp. to polynomial ("exponential improvement")

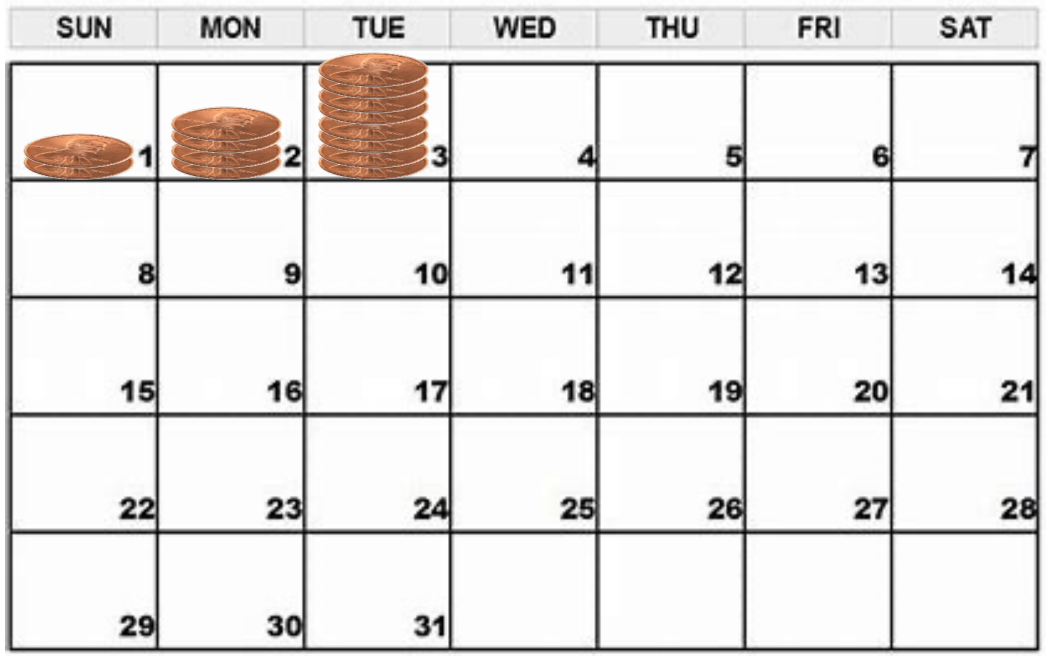
e.g., $N \rightarrow N^{1/2}$

e.g., $2^N \rightarrow N^3$

Exponential Growth

Exponential Growth:
Doubling Pennies Every Day for 1 Month

2^0 = 1 penny



2^1 = 2 pennies
2^2 = 4 pennies
2^3 = 8 pennies

⋮

After 31 days, would you take the pennies or $10M?

Exponential Growth

Exponential Growth:
Doubling Pennies Every Day for 1 Month

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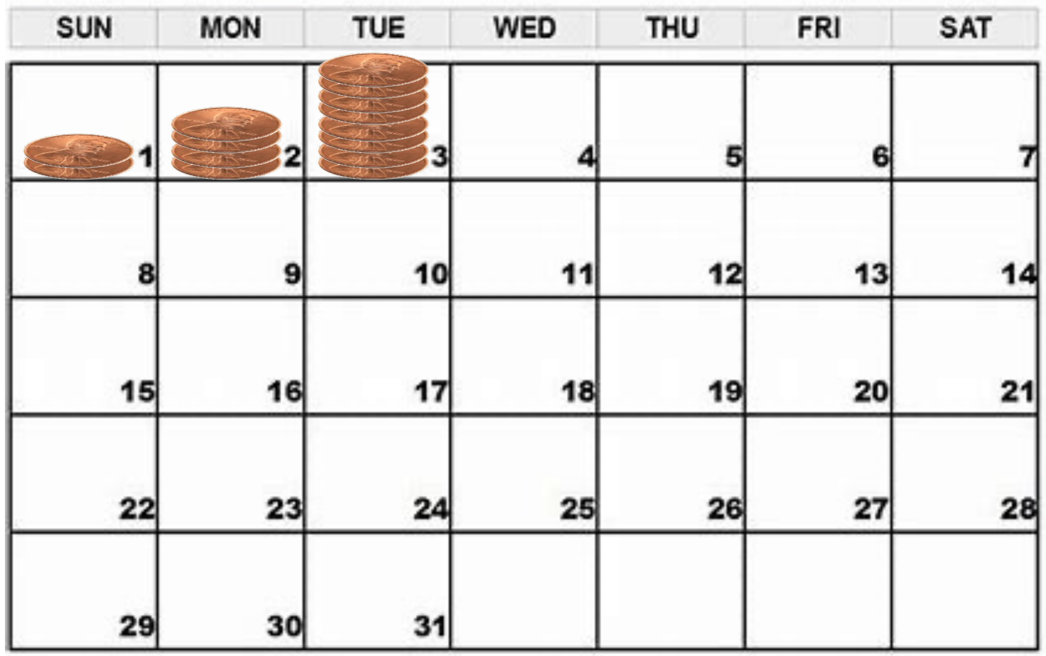

2^1 = 2 pennies
2^2 = 4 pennies
2^3 = 8 pennies
⋮

2^{31} = 2,147,483,648 pennies > $21M !!

Simulating Quantum Computers

- **Simulating quantum computers (QCs) on classical computers**

Qubits	Size of simulator
30	laptop

Simulating Quantum Computers

- **Simulating quantum computers (QCs) on classical computers**

Qubits	Size of simulator
30	laptop
50	supercomputer

Simulating Quantum Computers

- **Simulating quantum computers (QCs) on classical computers**

Qubits	Size of simulator
30	laptop
50	supercomputer
80	all computers on Earth

Simulating Quantum Computers

- **Simulating quantum computers (QCs) on classical computers**

Qubits	Size of simulator
30	laptop
50	supercomputer
80	all computers on Earth
160	all Si atoms in Earth

Simulating Quantum Computers

- **Simulating quantum computers (QCs) on classical computers**

Qubits	Size of simulator
30	laptop
50	supercomputer
80	all computers on Earth
160	all Si atoms in Earth
300	> all atoms than in known universe

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Quantum Algorithms and Speed-Up

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Algorithm	Classical Time	Quantum Time	Speedup	Limitation
Simulation[1] (quantum chemistry)	2^N (for N atoms)	N^c	Exp. in space, polynomial in time	Mapping problem to qubits
Factoring[2] (+ related number theoretic)	2^N (for N digits)	N^3	Exponential	Classical runtime limit unproven
Linear systems[3] (Ax=b)	2^N (for N digits)	~N	Exponential	Strict conditions, e.g. sparse matrix
Optimization[4]	2^N	?	?	Empirical
Search[5] (unsorted / unstructured data)	N	$\sqrt{N}$	Polynomial ($\sqrt{N}$)	Data loading


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Math


Ike Chuang[1]
EECS, Physics


Seth Lloyd [2,3]
Mech. Eng.


Aram Harrow[3]
Physics


Eddie Farhi[4]
Physics, Google


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Michael Carbin
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Troy Van Voorhis
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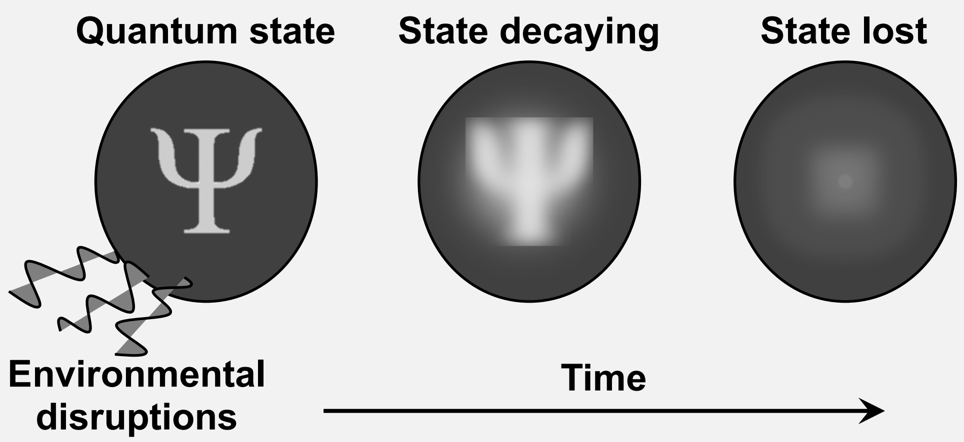
Coherence & Gate Time

Coherence time t_{coh}: The qubit's lifetime



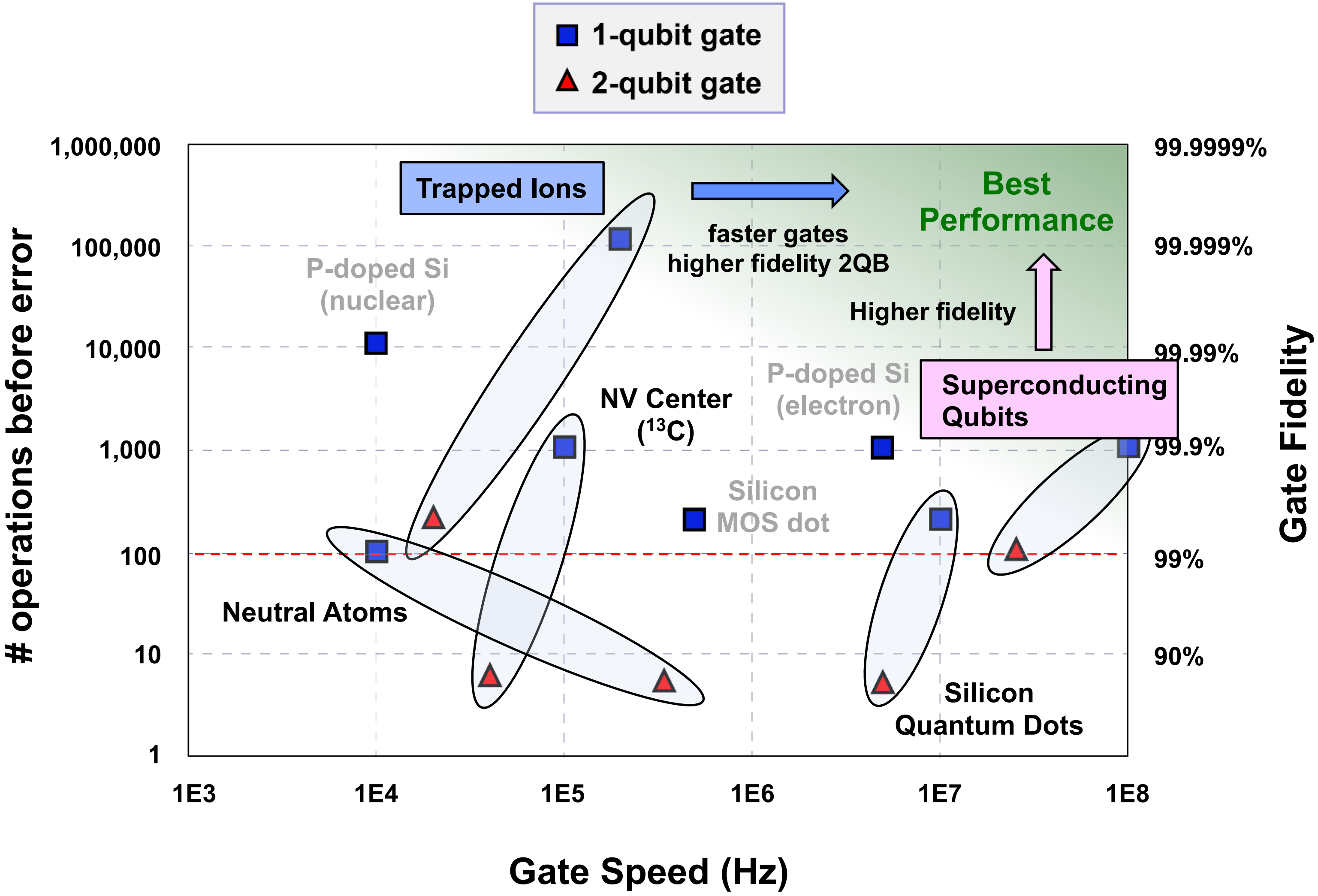
Gate time t_{gate}: Time required for a single gate operation

Figure of Merit * : # of gates per coherence time = t_{coh}/t_{gate}

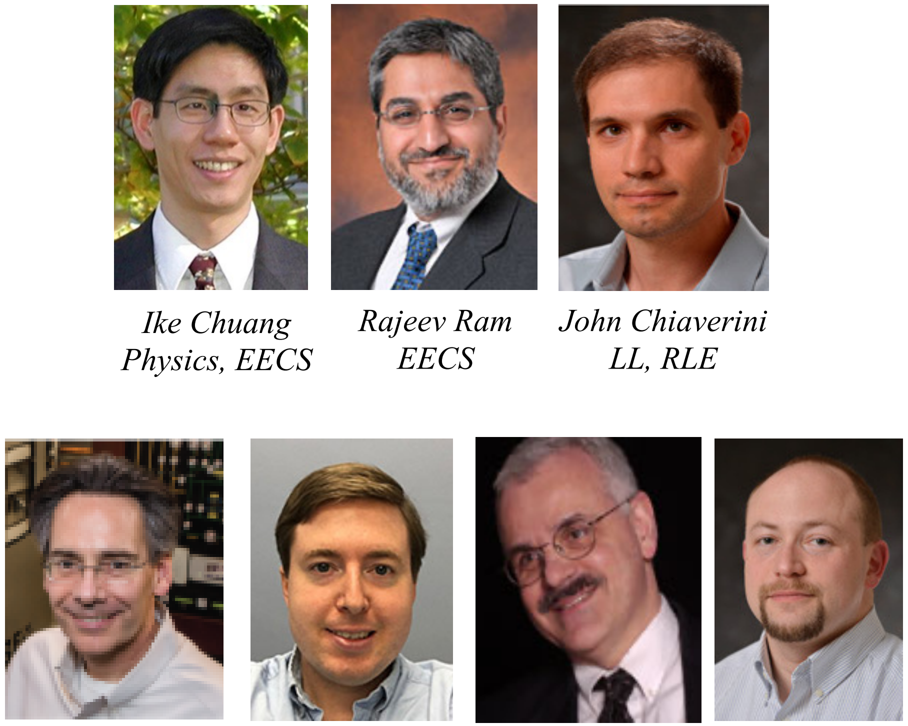
(* Rigorous metric: gate & readout fidelity)

Long coherence times are not sufficient, it's the number of gates before an error

Qubit Modalities
(extensible platforms, benchmarked, ca. 2019)



MIT Campus **MIT Lincoln Lab**



Ike Chuang Physics, EECS
Rajeev Ram EECS
John Chiaverini LL, RLE
Will Oliver EECS, LL
Kevin O'Brien EECS
Terry Orlando EECS
Jamie Kerman LL

and large teams at MIT & LL

Thanks to: P. Cappellaro, J. Chiaverini, D. Englund, T. Ladd, A. Morello, J. Petta, M. Saffman, J. Sage

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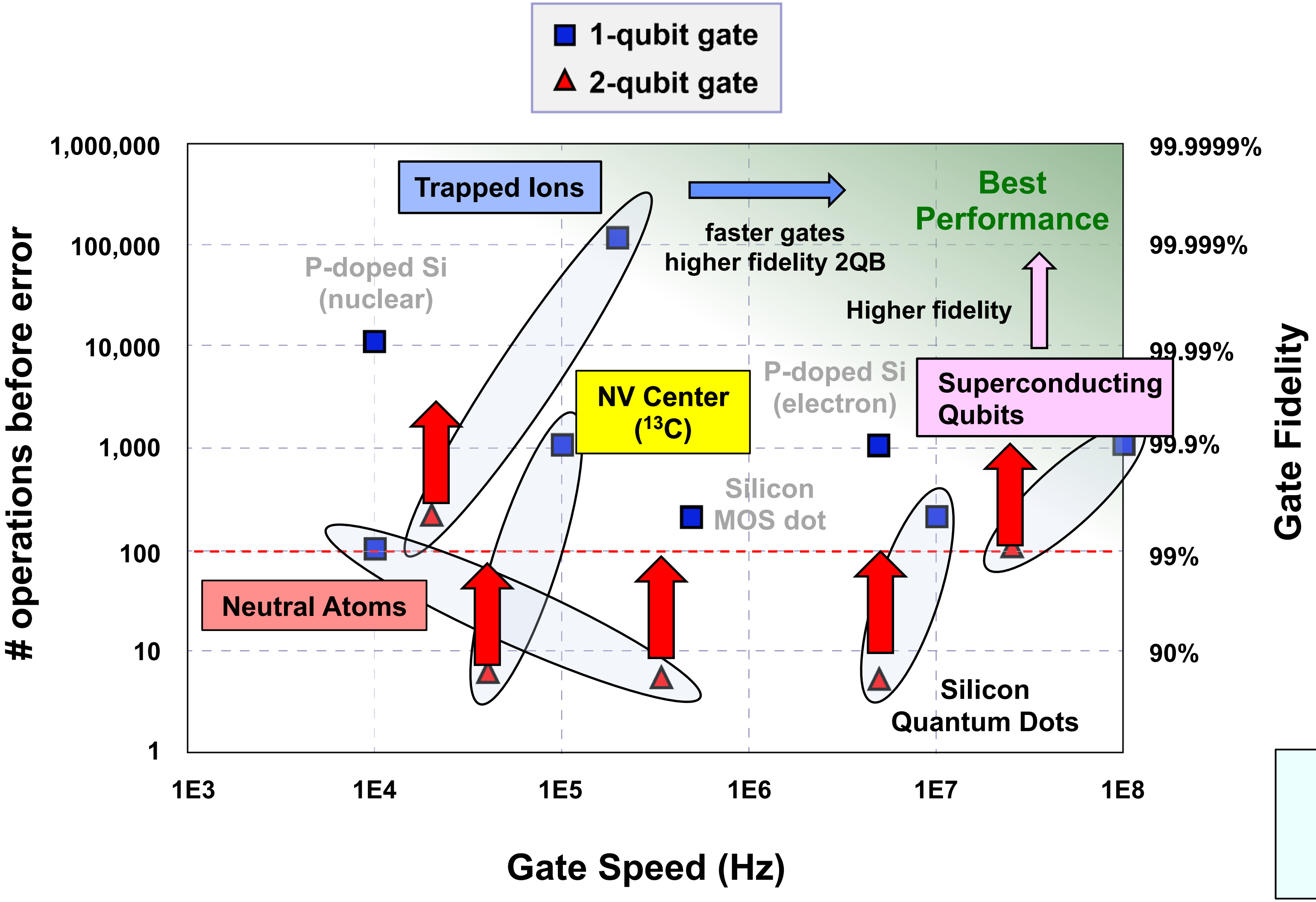

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Wolfgang Ketterle
MIT Physics

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MIT Physics

Dirk Englund
EECS

Paola Cappellaro
NSE

Danielle Braje
QuIIN

Many candidate technologies under development to realize the promise of quantum computation

Thanks to: P. Cappellaro, J. Chiaverini, D. Englund, T. Ladd, A. Morello, J. Petta, M. Saffman, J. Sage

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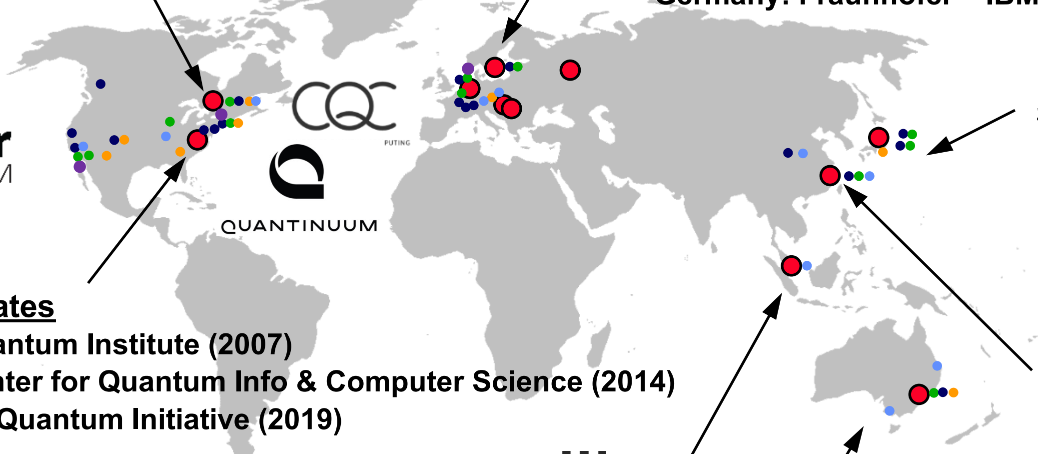
Quantum Worldwide
(not an exhaustive list)

Canada
- Inst. for Quantum Computing (2002)
- Inst. Quantique (2015)

Europe
- Netherlands: QuTech (2014)
- United Kingdom: National Quantum Technologies Program (2014)
- EU: Quantum Flagship (2016)
- Sweden: Wallenberg Center for Quantum Technology (2017)
- Germany: Fraunhofer – IBM alliance (2019)



Japan
- Gate-model and QA
- JST, RIKEN, AIST, NICT

United States
- Joint Quantum Institute (2007)
- Joint Center for Quantum Info & Computer Science (2014)
- National Quantum Initiative (2019)

China
- Key Lab, Quantum Information, CAS (2001)
- Satellite quantum communication (2016)
- Alibaba – CAS cloud computer (2018)

Australia
- ARC Centers of Excellence
  - Center for Quantum Computing Technology (2000)
  - Engineered Quantum Systems (2011)
- CommBank – Telstra – UNSW (2015)

Singapore
- Research Center on Quantum Information Science and Technology (2007)

● Superconducting qubits ● Ion trap qubits ● Semiconducting qubits ● Quantum optics ● NV centers

* European Commission

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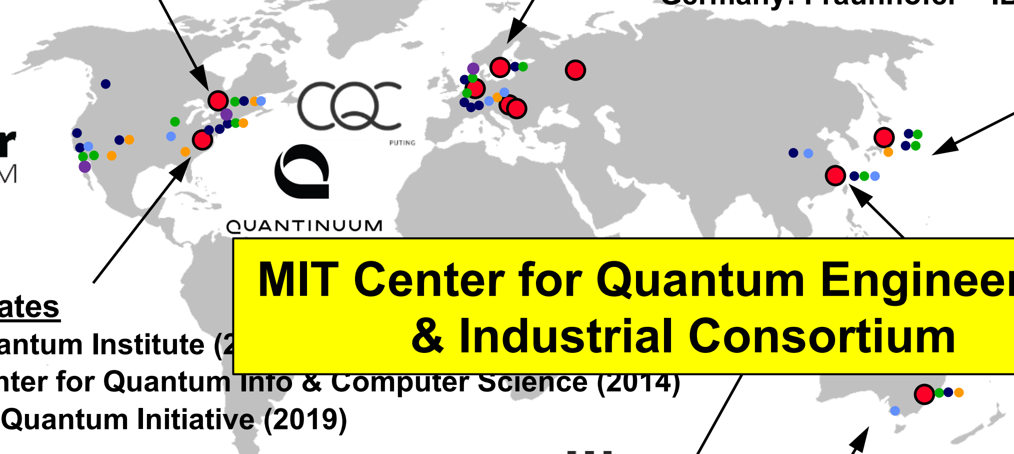

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MIT Center for Quantum Engineering & Industrial Consortium

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Booz | Allen | Hamilton

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* European Commission

MIT Center for Quantum Engineering

- **Mission Statement:**
  - *Academic pursuit and practice of quantum science & engineering to accelerate the practical application of quantum technology*

- **Objectives:**
  - Define quantum engineering
  - Educate tomorrow's quantum engineers
  - Partner with industry via consortium model
  - Advance quantum science and engineering

cqe.mit.edu

CQE Membership (partial list)

CQE

MIT CSAIL

Terry Orlando
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Simon Gustavsson
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Will Oliver
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Jamie Kerman
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Kevin O'Brien
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Kevin Obenland
Lincoln

Ike Chuang
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Jeremy Sage
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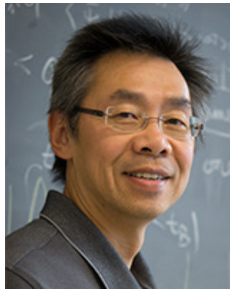

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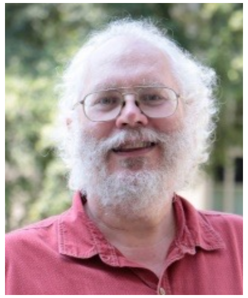

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& Physics

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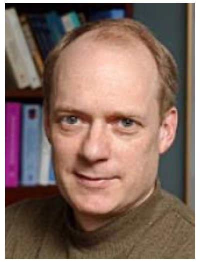

Tim Swager
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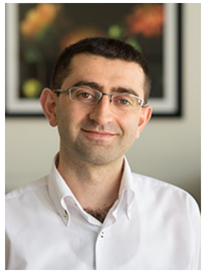
Rafael Gomez-
Bombarelli - MS

Troy Van Voorhis
Chemistry

Lindley Winslow
Physics

Joe Formaggio
Physics

Riccardo Comin
Physics



Nuh Gedik
Physics

Pablo J-Herrero
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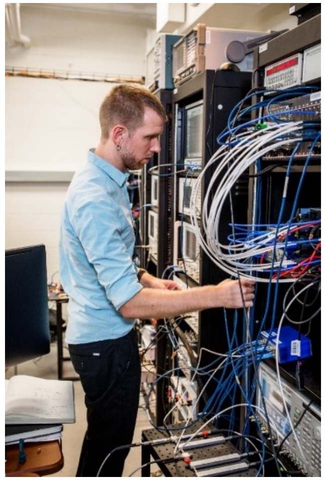
Eddie Farhi
Google/Physics

Aram Harrow
Physics

CQE Engagements

- **MIT xPRO professional development courses**
  - **Sponsored by IBM**
  - **Fundamentals of Quantum Computing**
  - **Practical Realities of Quantum Computing**
- **CQE – LPS "Doc Bedard" Program**
  - **3-year graduate fellowships**
  - **Sponsored research programs**
  - **Quantum curriculum development**
- **QSEC Industry Membership Group**

Fernand "Doc" Bedard
NSA Laboratory for Physical Sciences



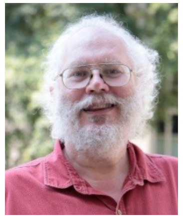
Professional Development Courses

https://learn-xpro.mit.edu/quantum-computing

MIT xPRO

Will Oliver

Ike Chuang



Peter Shor

Aram Harrow

MIT's QUANTUM SCIENCE AND ENGINEERING CONSORTIUM ECOSYSTEM

Founding Members

Quantum AI

KEYSIGHT TECHNOLOGIES

Sustaining Members

AIRBUS

ANALOG DEVICES

BMW

DELL Technologies

equinor

GRIFFISS INSTITUTE

HSBC

JPMORGAN CHASE & CO.

HYUNDAI

ZAPATA

Startup Members

NanoQT
Nanofiber Quantum Technologies

|QuEra>
COMPUTING, INC.

TURING

MIT'S QUANTUM SCIENCE AND ENGINEERING CONSORTIUM MEMBERS 2022

QSEC Algorithm Program

MIT Quantum Science and Engineering Consortium → **Co-develop quantum algorithms targeting problems of relevance**

Ken Kennedy & Marcin Ziolkowski

BMW researchers

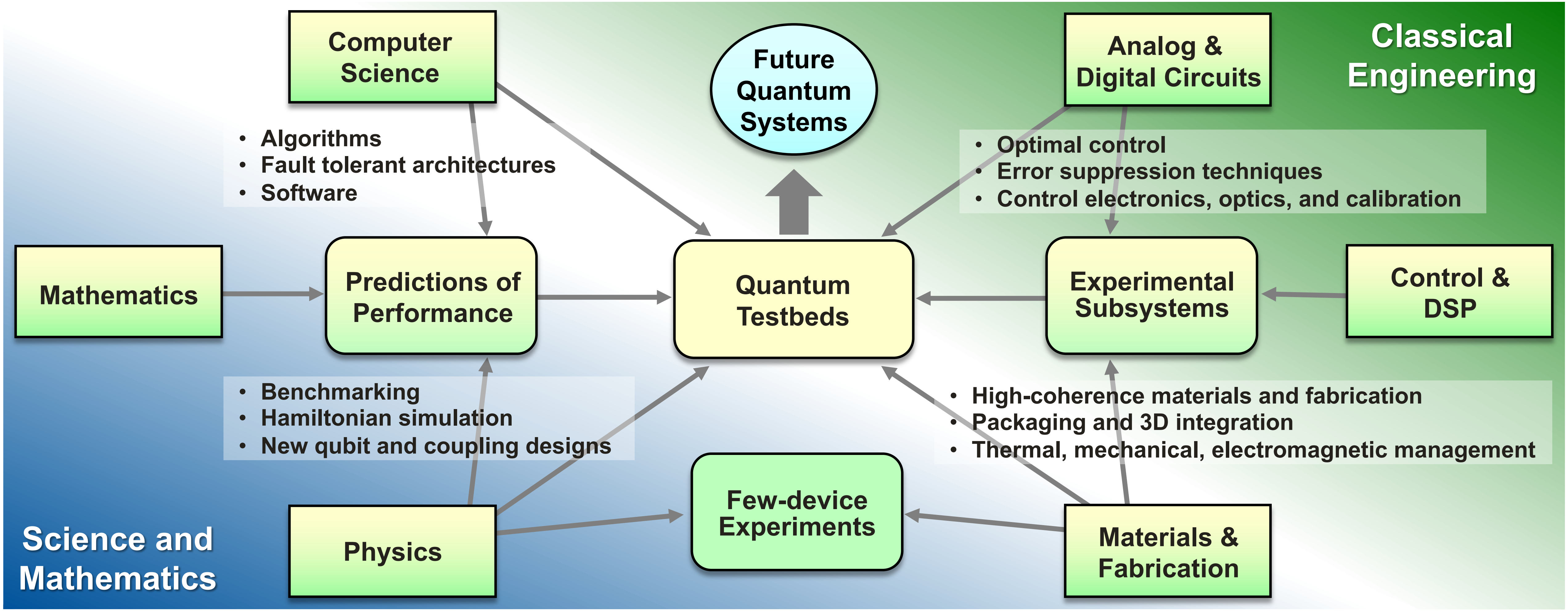
MIT faculty & students

Zapata researchers & prototyping

Tim Menke

Christopher Savoie

Interdisciplinary Quantum Engineering



Quantum Engineering is the bridge connecting science, mathematics, and classical engineering

Convergence: The Promise and Reality of AI & Quantum

November 14, 2022

To realize the promise of quantum computing, we need to

- Develop algorithms with commercial quantum advantage
- Develop error-resilient hardware
- Avoid the over-hype and create the reality

We need your help to do this!

William D. Oliver

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MIT CSAIL Computer Science & Artificial Intelligence Laboratory

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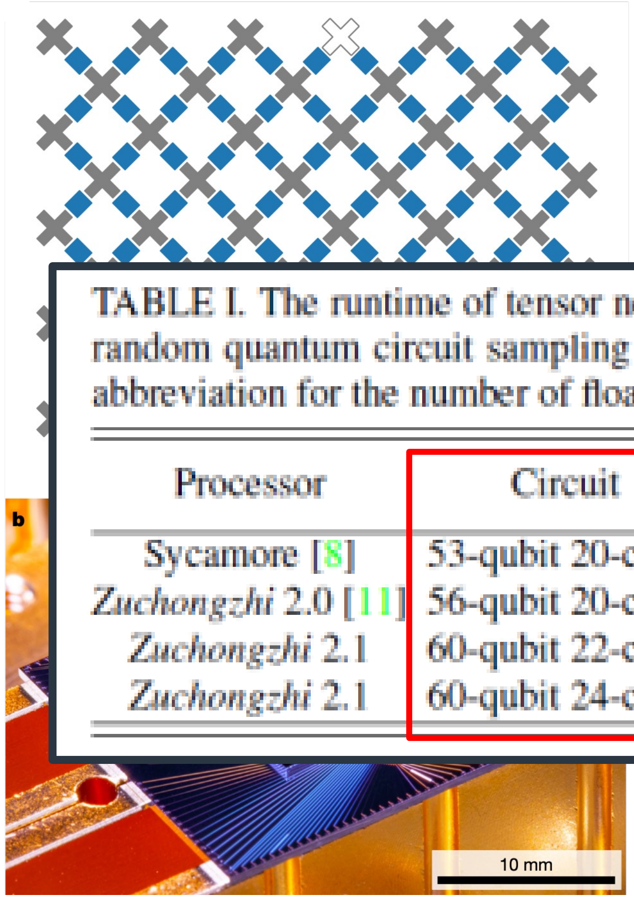
Quantum Advantage Demonstrations

MIT CSAIL



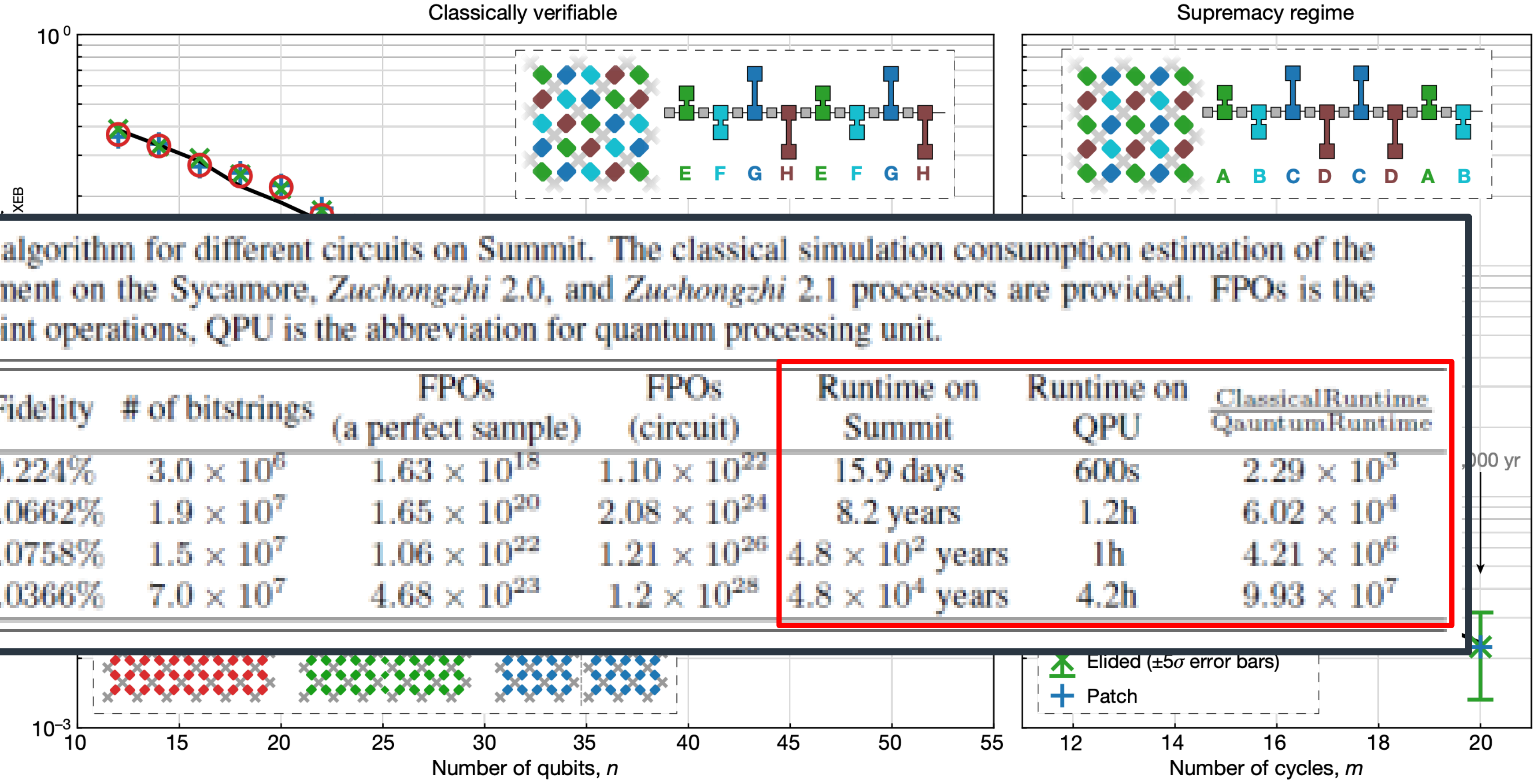


TABLE I. The runtime of tensor network algorithm for different circuits on Summit. The classical simulation consumption estimation of the random quantum circuit sampling experiment on the Sycamore, *Zuchongzhi* 2.0, and *Zuchongzhi* 2.1 processors are provided. FPOs is the abbreviation for the number of floating point operations, QPU is the abbreviation for quantum processing unit.

Processor	Circuit	Fidelity	# of bitstrings	FPOs (a perfect sample)	FPOs (circuit)	Runtime on Summit	Runtime on QPU	ClassicalRuntime / QauntumRuntime
Sycamore [8]	53-qubit 20-cycle	0.224%	3.0×10^6	1.63×10^{18}	1.10×10^{22}	15.9 days	600s	2.29×10^3
Zuchongzhi 2.0 [11]	56-qubit 20-cycle	0.0662%	1.9×10^7	1.65×10^{20}	2.08×10^{24}	8.2 years	1.2h	6.02×10^4
Zuchongzhi 2.1	60-qubit 22-cycle	0.0758%	1.5×10^7	1.06×10^{22}	1.21×10^{26}	4.8×10^2 years	1h	4.21×10^6
Zuchongzhi 2.1	60-qubit 24-cycle	0.0366%	7.0×10^7	4.68×10^{23}	1.2×10^{28}	4.8×10^4 years	4.2h	9.93×10^7

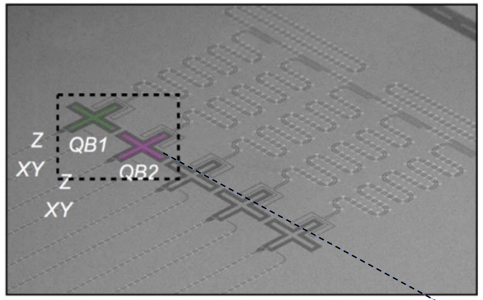
The Google Quantum AI team demonstrated
a calculation in ~200s with one chip, 53 superconducting qubits, drawing around 100 kW of power

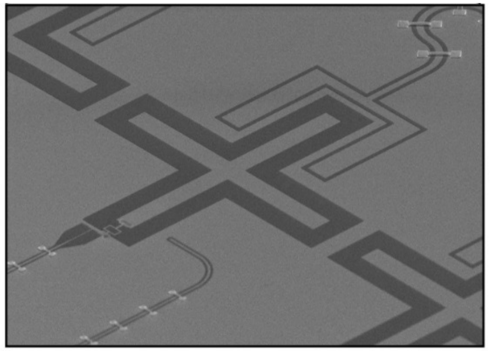
On the Summit supercomputer (Oak Ridge National Laboratory),
it would take several days, with all 40,000 CPUs & GPUs, 10^{17} transistors & memory, and 100's MW of power

Google AI, Nature 505, 574 (2019); USTC, arXiv:2109.03494 (2021)

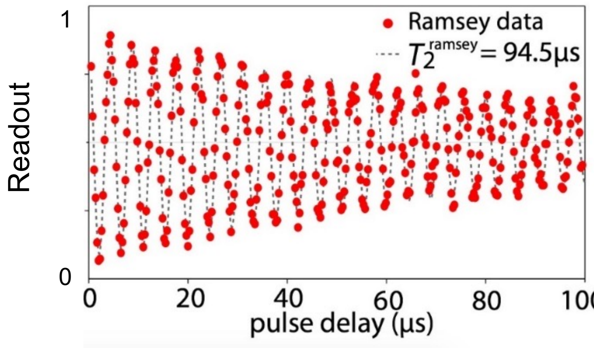
Superconducting Qubits

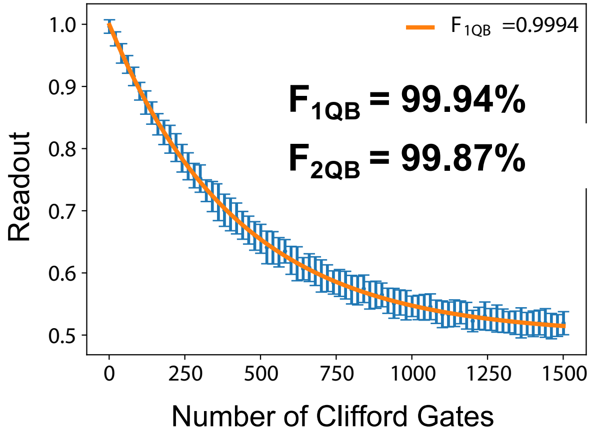
Superconducting Qubits





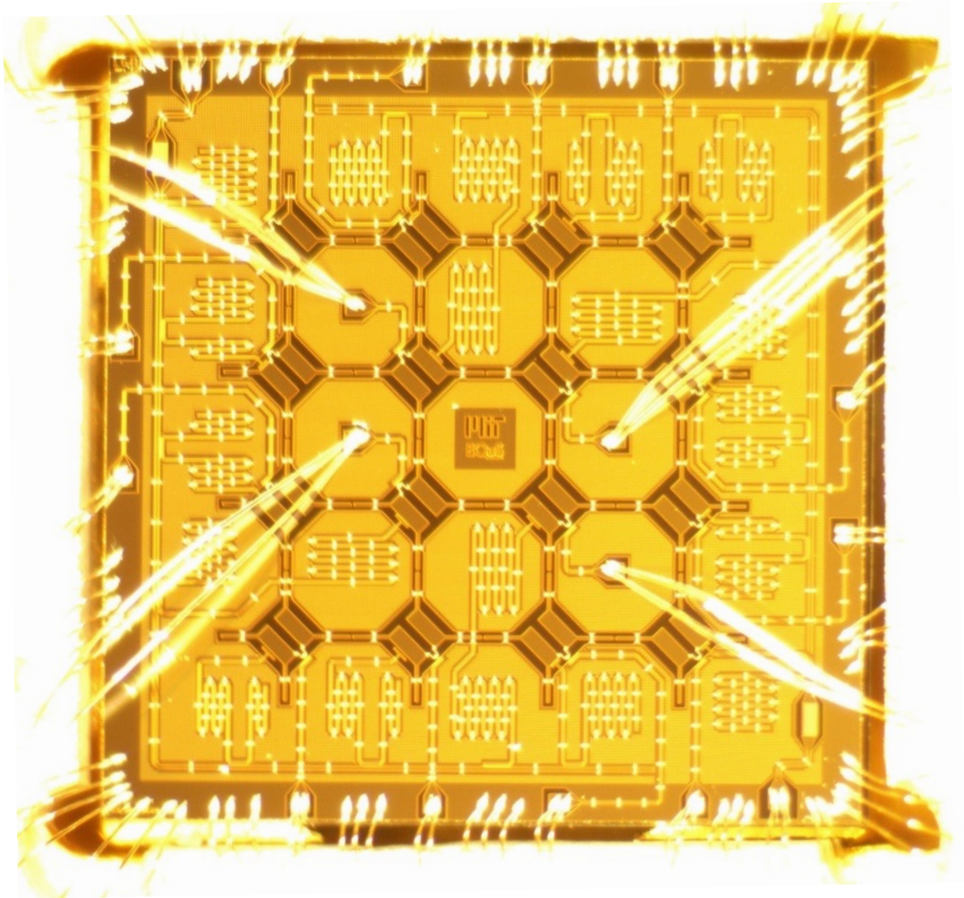
Coherence & Gate Fidelity





2D Arrays of Qubits

Lattices, Error Propagation, Coherent Errors, …



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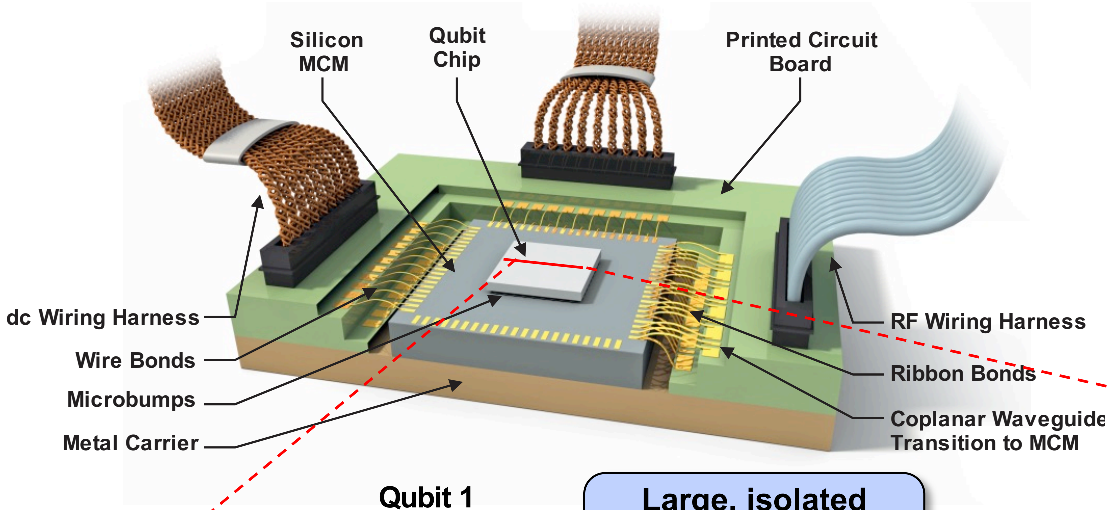
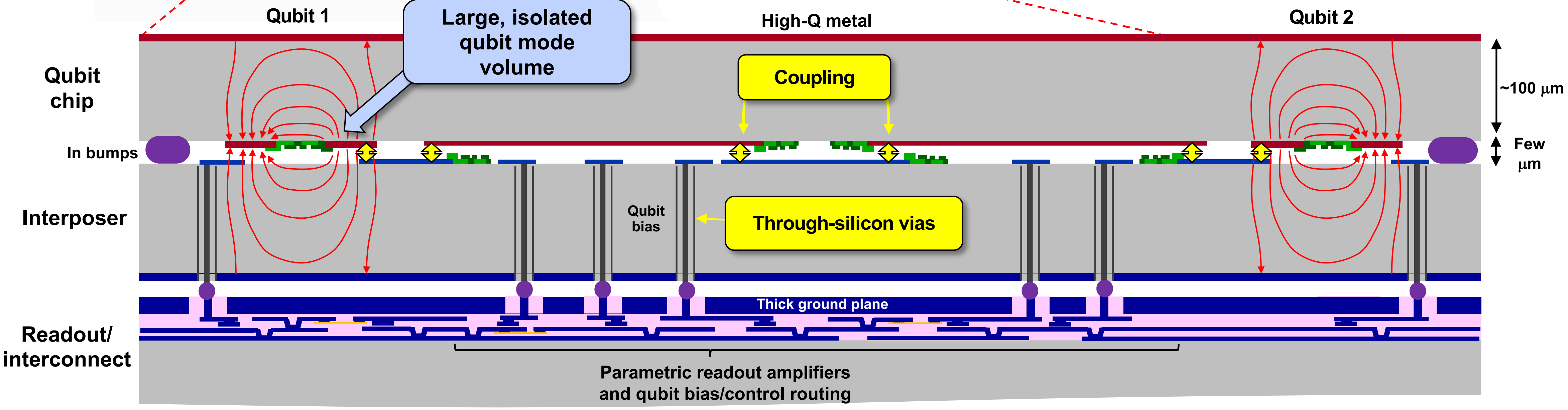
3D Integration for Quantum Processors

IARPA Quantum Enhanced Optimization



3-Stack enables high connectivity while maintaining high qubit coherence



MIT Lincoln Laboratory, multiple patents, npj Quant. Inf. (2017); IEEE ECTC (2018); IEEE IEDM (2019); npj Quant. Inf. (2020); IEEE Microwave Mag (2020)