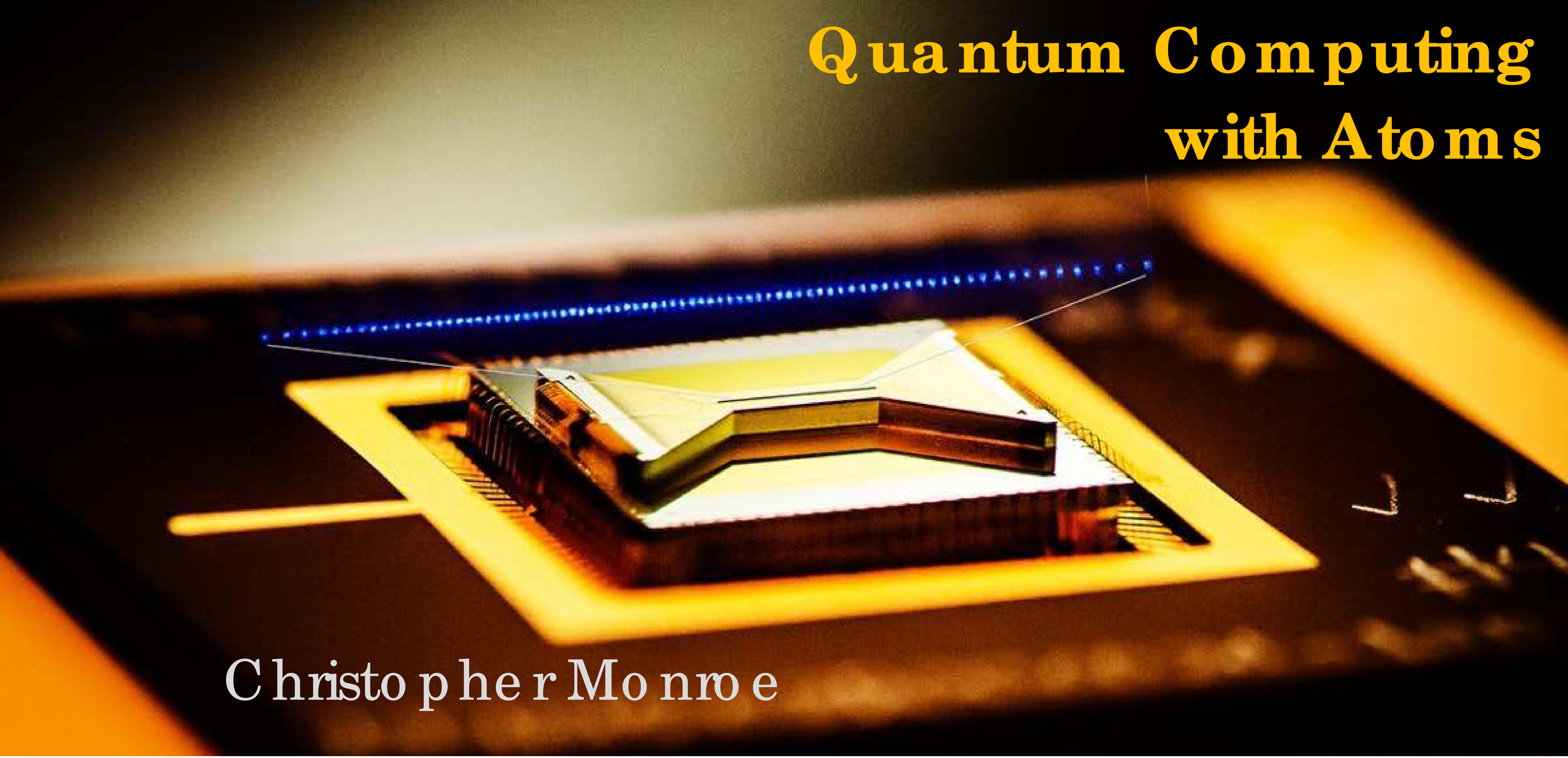
Quantum Computing with Atoms



Christopher Monroe

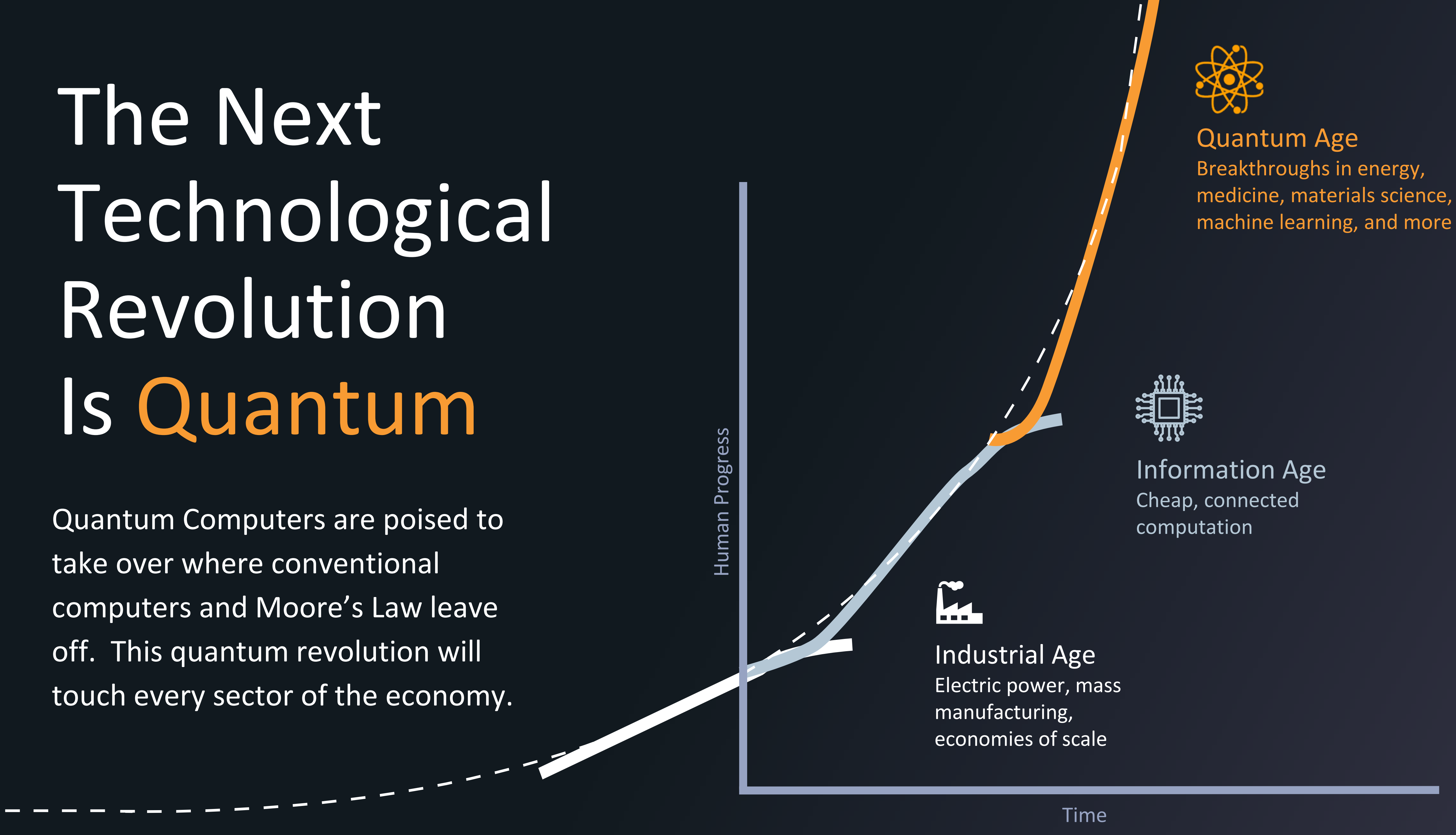
Duke University

Duke Quantum Center

IONQ

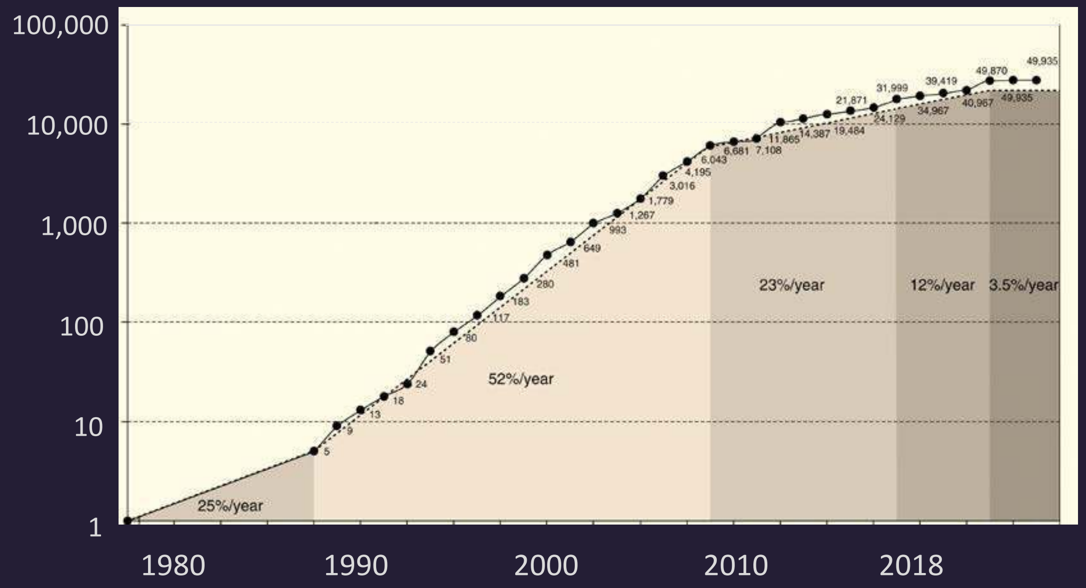
The Next Technological Revolution Is Quantum

Quantum Computers are poised to take over where conventional computers and Moore's Law leave off. This quantum revolution will touch every sector of the economy.



Moore's Law: exponential growth in computing power

Transistor density relative to 1978



Richard Feynman

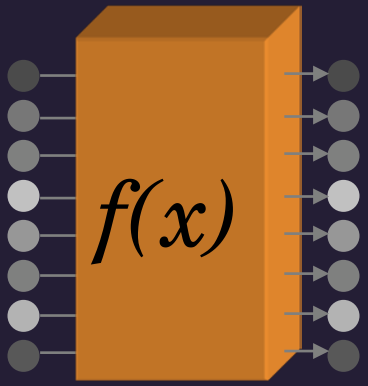
There's Plenty of Room at the Bottom **(1959)**

"When we get to the very, very small world – say circuits of seven atoms – we have a lot of new things that would happen that represent ***completely new opportunities for design****. Atoms on a small scale behave like nothing on a large scale, for they satisfy the* ***laws of quantum mechanics****..."*

Good News…

parallel processing
on 2^N inputs

e.g., $N=3$ qubits

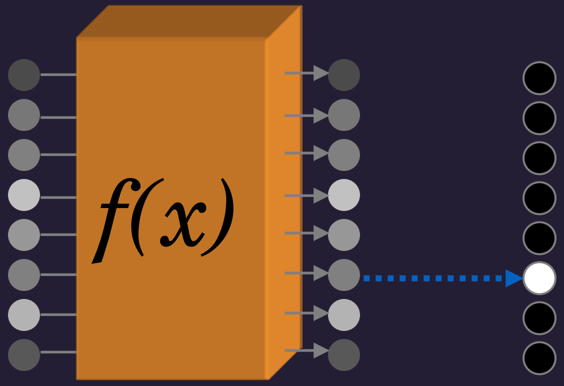


$a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle$
$a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$

N=300 qubits have more configurations than there are particles in the universe!

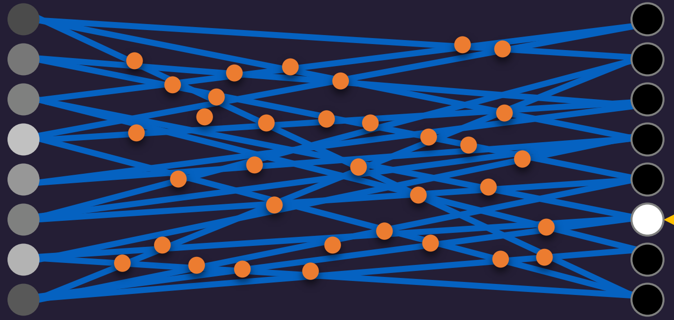
…Bad News…

measurement gives
random result



…Good News!

quantum interference



depends on *all* inputs

David Deutsch
(early 1990s)

Application: Factoring Numbers

A quantum computer can factor numbers **exponentially faster** than classical computers

P. Shor (1994)

39 = 3 × 13 (…easy)

386478846210093876214323256 31 = ? × ?

Key generation	$N = P * Q$ $d * e = 1 \bmod \Phi(N)$
Encryption	$c = m^e \bmod N$ Public Key(N,e)
Decryption	$m = c^d \bmod N$ private key (d)

<u>Factor N (n bits)</u>

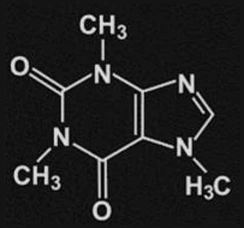
Best classical algorithm: $time \sim e^{n^{1/3}(log n)^{2/3}}$

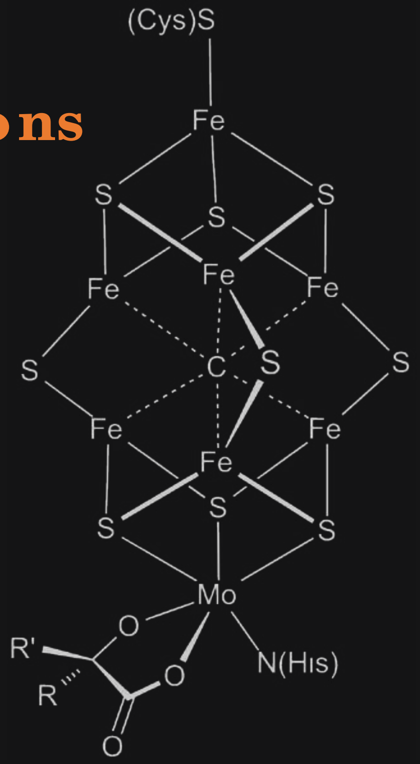
Shor's quantum algorithm: $time \sim (loglog n)(log n)n^2$

Application: Optimization

Molecular Simulations

- designer materials
- new catalysts
- protein folding

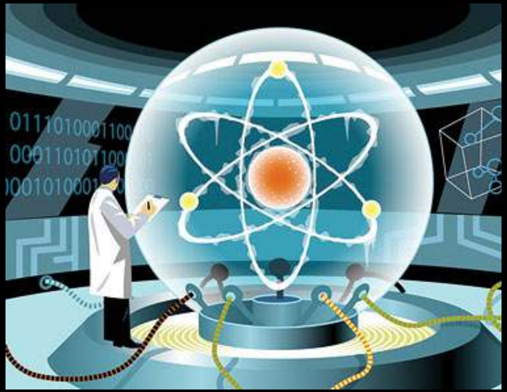




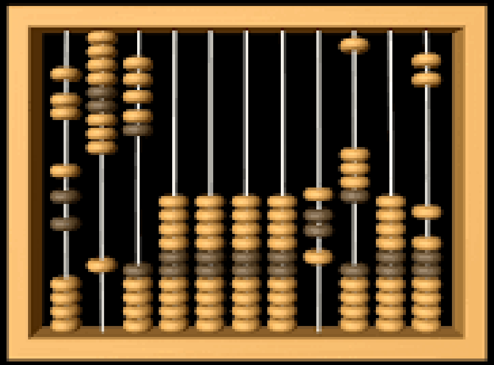
Traveling Salesman problem

what is the shortest path through N cities?

A quantum computer differs more from a laptop…

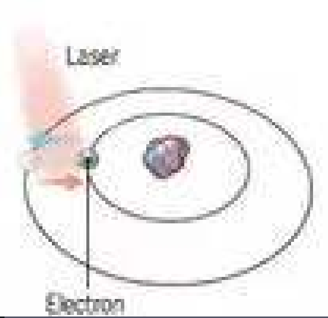


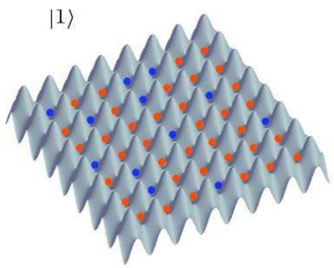
…than a laptop differs from an ABACUS”

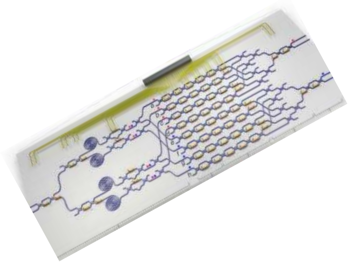
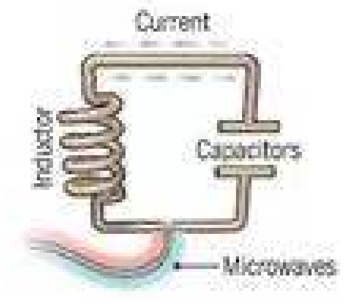


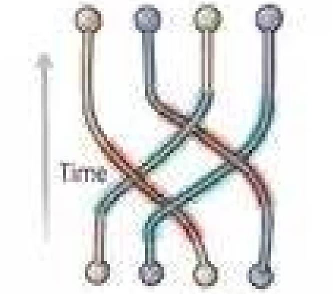
Quantum Computer Technologies

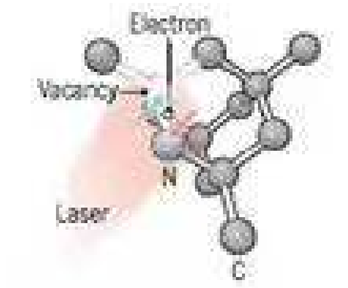
Natural Qubits | **Synthetic Qubits**





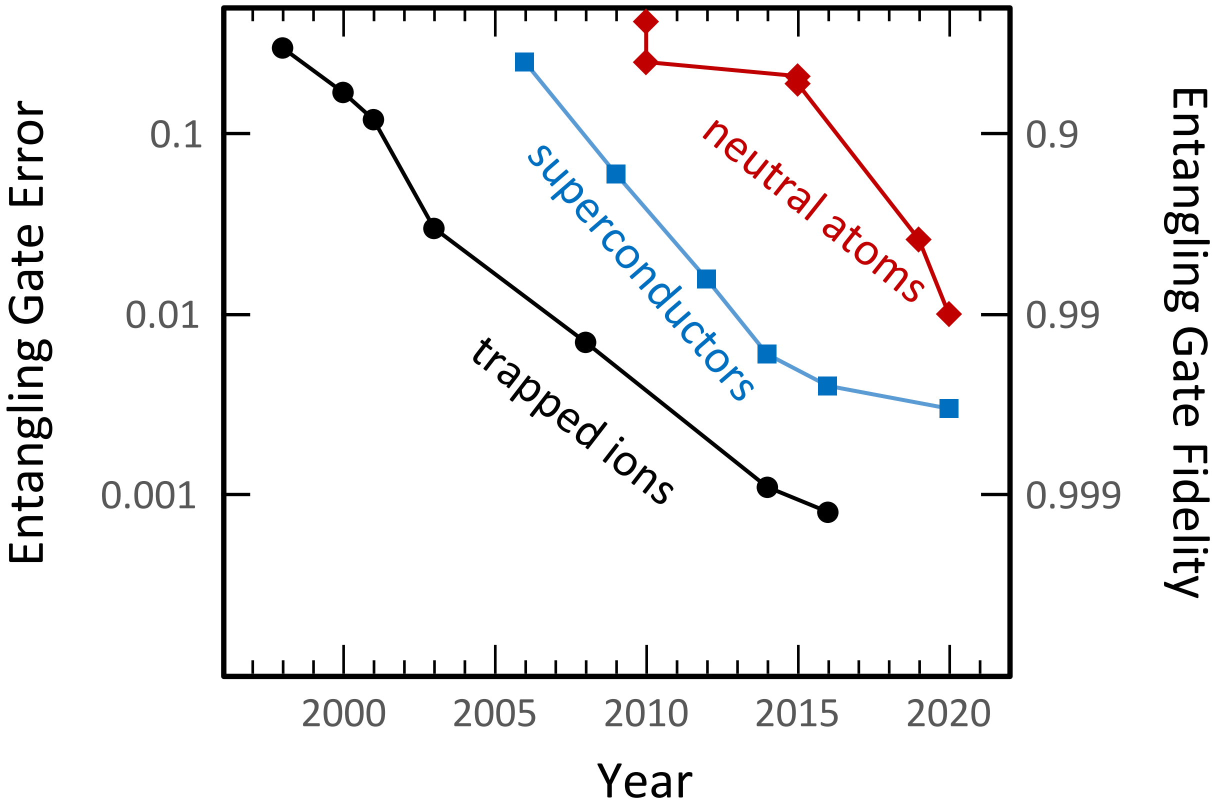




	Trapped Ions	Neutral Atoms	Photonics	Superconducting Loops	Silicon Quantum Dots	Topological Qubits	Diamond Vacancies
	Electrically charged atoms, or ions, are held in place with electric fields. Qubits are stored in electronic states. Ions are pushed with laser beams to allow the qubits to interact.	Neutral atoms, like ions, store qubits within electronic states. Laser activates the electrons to create interaction between qubits.	Photonic qubits (light particles) are sent through a maze of optical channels on a chip to interact. At the end of the maze, the distribution of photons is measured as an output.	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Qubit Coherence Time (sec)	>1000	1	--	0.00005	0.03	N/A	10
Fidelity	99.9%	97%	--	99.4%	~99%	N/A	99.2%
Qubits Connected	High	Very high; low individual control	--	High	Very Low	N/A	Low
Company Support	IONQ, AQT, Honeywell, Oxford Ionics	Atom Computing, ColdQuanta, QuEra	Psiquantum, Xanadu	Google, IBM, QCI, Rigetti	HRL, Intel, SQC	Microsoft	Quantum Diamond Technologies
Pros	Very stable. Highest achieved gate fidelities.	Many qubits, 2D and maybe 3D.	Linear optical gates, integrated on-chip.	Can lay out physical circuits on chip.	Borrows from existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Slow operation. Many lasers are needed.	Hard to program and control individual qubits; prone to noise.	Each program requires its own chip with unique optical channels. No memory.	Must be cooled to near absolute zero. High variability in fabrication. Lots of noise.	Only a few connected. Must be cooled to near absolute zero. High variability in fabrication.	Existence not yet confirmed.	Difficult to create high numbers of qubits, limiting compute capacity.

Source: Science, Dec. 2016

Two-Qubit (Entangling) Gate Performance



Note: All data performed on exactly 2 qubits

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J. Benhelm... Nature Physics 4, 463 (2008)
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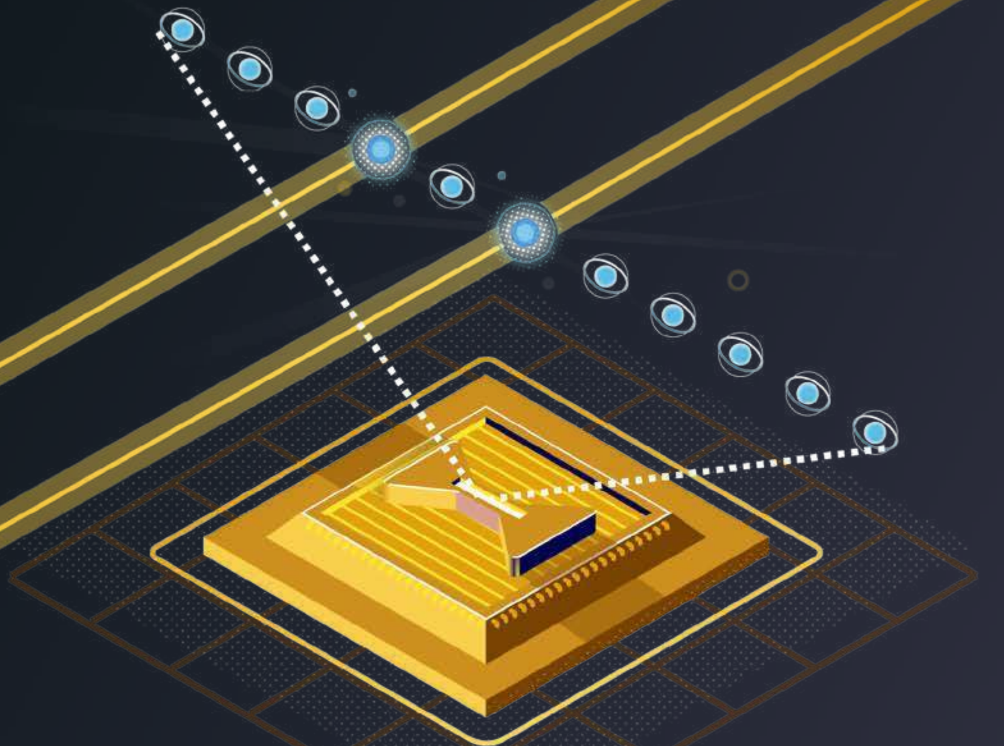
I. S. Madjarov... arXiv 2001.04455 (2020)

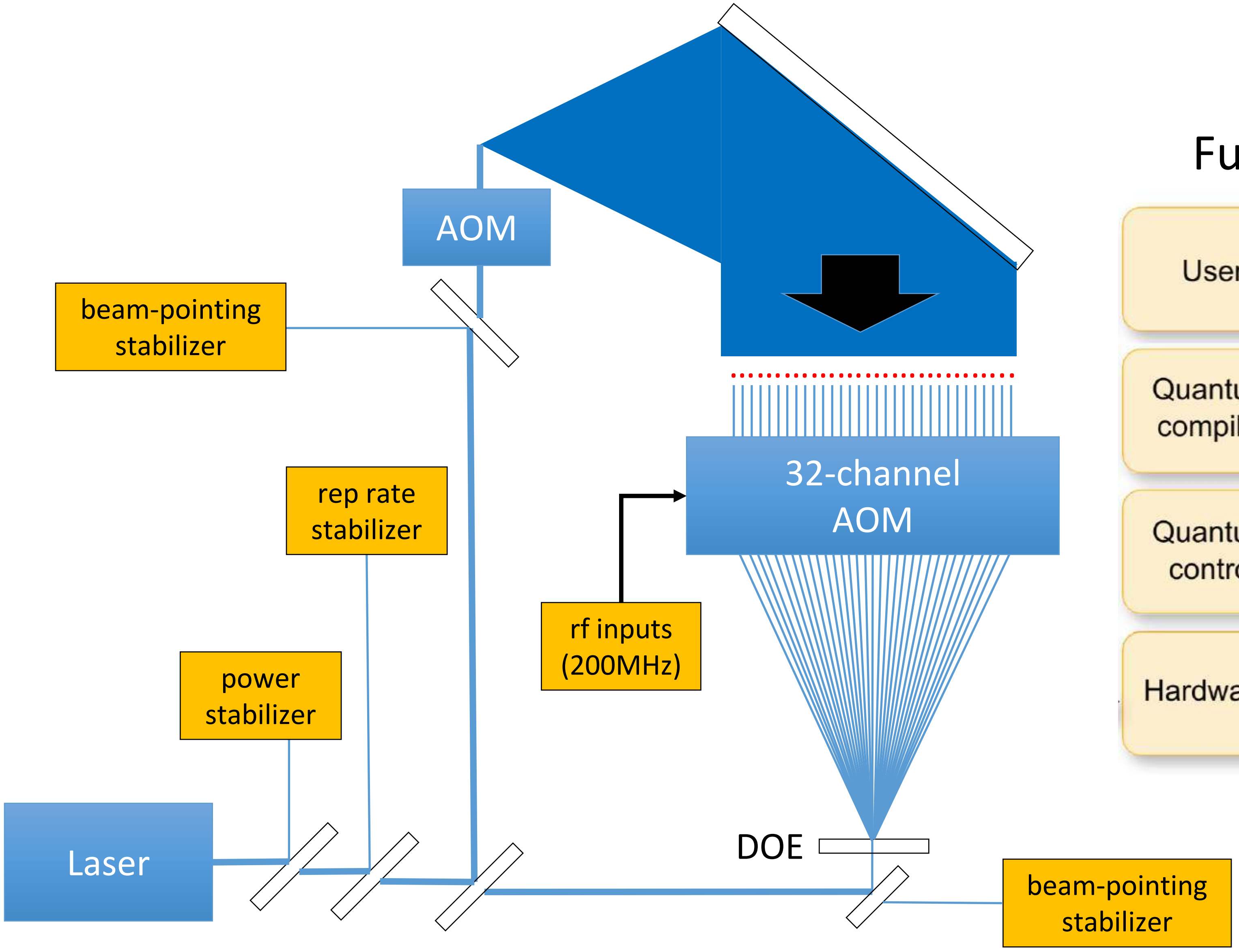
Trapped Atomic Ion Quantum Computer

Individual atomic ion qubits in an electromagnetic trap are well-isolated, allowing for nearly perfect idle qubit performance

- identical and naturally quantum
- nearly perfectly isolated from environmental influences
- capable of running at room temperature
- reconfigurable and highly-connected
- unparalleled inherent performance
- longest qubit lifetime



Quantum Computer Optical Controller



Full “Quantum Stack” architecture

User	**Quantum Algorithms:** *Deutsch-Jozsa, QFT, etc.*
Quantum compiler	**Universal gates:** *Hadamard, C-NOT, C-Phase, etc.* **Native gates:** *XX-Gates, R-gates*
Quantum control	**Pulse shaping:** *Optimization of XX- and R-Gates*
Hardware	**Optical addressing:** *Qubit manipulation/ detection* **Ion trap:** *Linear ion-chain, optical access, etc.*

S. Debnath,... *Nature* **536**, 63 (2016)
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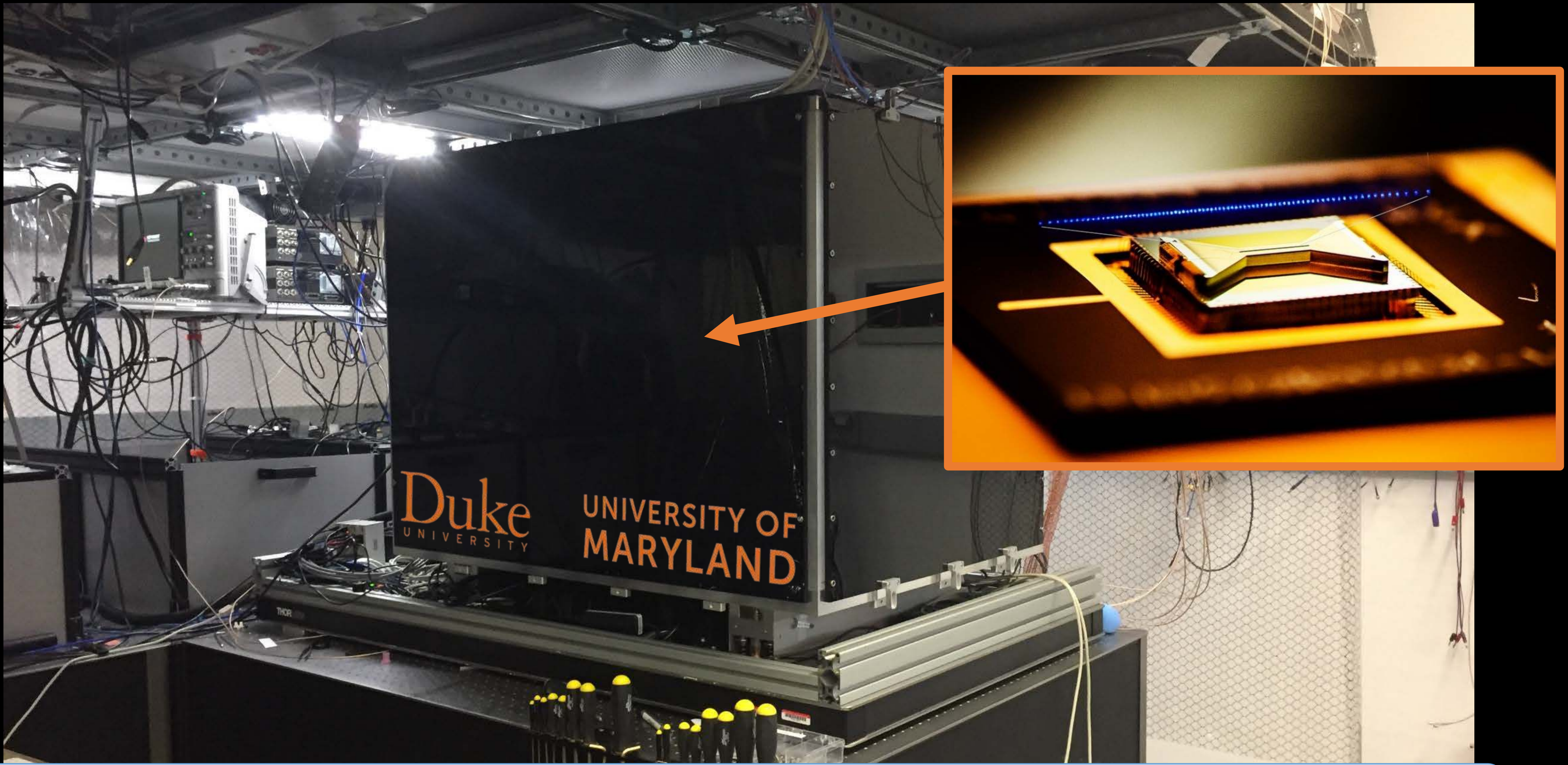


IARPA
BE THE FUTURE
NSF
STAQ
Sandia National Laboratories
ColdQuanta
AOSense
L3HARRIS
COHERENT

Recent Quantum Computer Collaborations

Year	Application	Reference	Collaborator	Institute
2013	Frustration and AFM order	Science 340, 583	J. Freericks	Georgetown
2014	Lieb-Robinson propagation	Nature 511, 198	A. Gorshkov	NIST
2015	Spin-1 Dynamics	Phys. Rev. X 5, 021026	A. Retzker	Hebrew University
2016	Manybody Localization	Nat. Physics 12, 907	D. Huse, P. Hauke	Princeton, Innsbruck
2017	Hidden Shift, Toffoli-3 Gate	PNAS 114, 13	M. Roetteler	Microsoft, Inc.
	Grover	Nat. Comm. 8, 1918	D. Maslov	NSF
	Toffoli-4 Gate	Thesis, Debnath	D. Maslov	NSF
	Prethermalization	Science Adv. 3, e1700672	Z. Gong, A. Gorshkov	NIST
	Time Crystaline Order	Nature 543, 217	N. Yao	Berkeley
	Dynamical Phase Transition	Nature 551, 601	A. Gorshkov	NIST
	[[4,2,2]] Error Detection	Science Adv. 3, e1701074	K. Brown	Duke
2018	Fredkin Gate, Fermi-Hubbard	PRA 98, 052334	S. Johri	Intel Corp.
	Bayesian Game	QST 3, 045002	N. Solmeyer	ARL
	Qubit Detection ML	J. Phys. B 51 174006	M. Hafezi	JQI
2019	Full Adder, Parallel CNOTs	Nature 567, 61	D. Maslov	NSF
	Generative Modeling ML	Science Adv. 5, eaaw9918	A. Perdomo-Ortiz	NASA
	Deuteron VQE Simulation	PRA 100, 62319	R. Pooser, O. Shehab	ORNL, IonQ
	Validating stabilizer states	Phys. Rev. A 99, 042337	Amir Kalev	QuICS UMD
	Quantum Scrambling	Nature 567, 61	B. Yoshida, N. Yao	Perimeter, Berkeley
	Circuit QAOA	arXiv:1906.02699	T. Hsieh, S. Johri	Perimeter, Intel Corp.
	Benchmarks and Comparison	arXiv: 1905.11349	M. Martonosi	Princeton
	Analog QAOA	arXiv:1906.02700	A. Gorshkov, S. Jordan	NIST, Microsoft Inc.
	Quasiparticle Confinement	arXiv: 1912.11117	A. Gorshkov	NIST
	Efficient QAOA (Max-Cut, Deuteron)	arXiv:1906.00476	Isaac Kim, Omar Shehab	Stanford, IonQ
	Dynamical mean field theory	arxiv: 1910.04735	Ross Duncan, Ivan Rungger	Cambridge QC, NPL

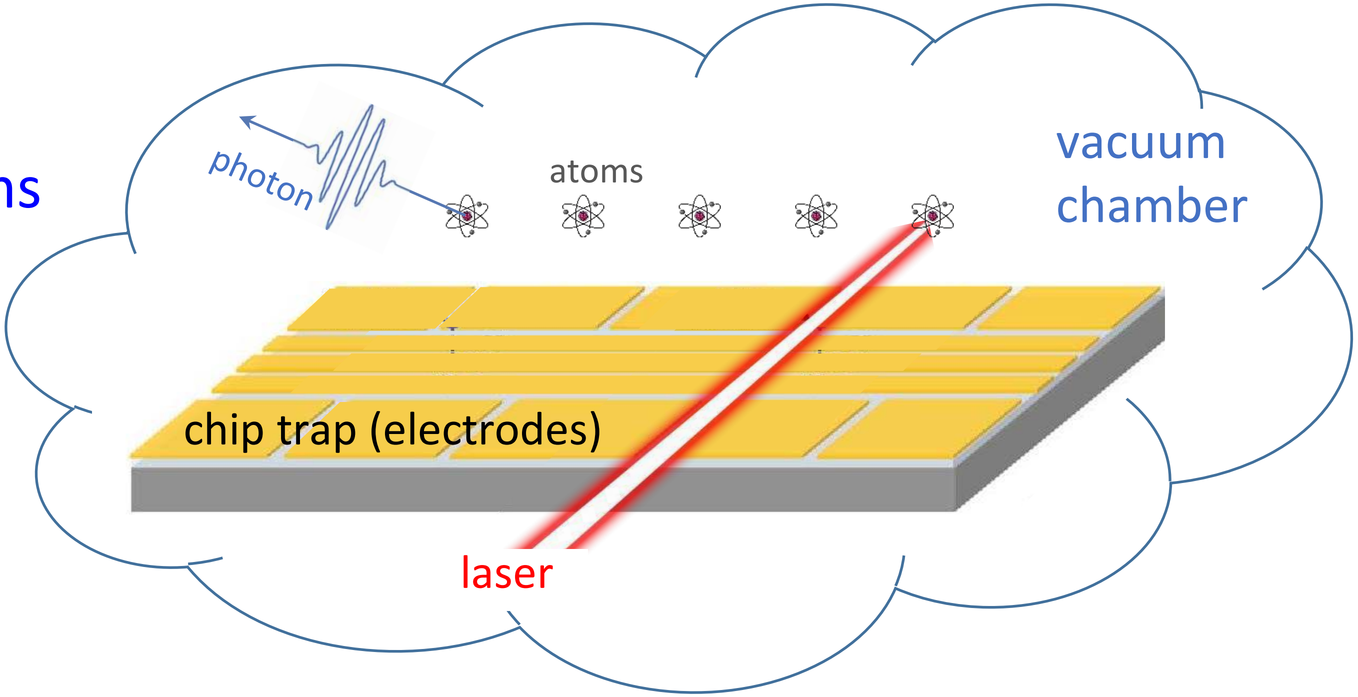
Recent Quantum Computer Collaborations

Year	Application	Reference	Collaborator	Institute
2020	Many-body dephasing	arXiv: 2001.02477	F. Marquardt	MPL Erlangen
	Quantum walks theory	arXiv:2001.11197	B. Radhakrishnan, C. Chandrashekar	ARL, Chennai
	Quantum walks, cellular automaton	arXiv:2002.02537	B. Radhakrishnan, C. Chandrashekar	ARL, Chennai
	[[9,1,3]] Bacon/Shor code	arXiv:2009.11482	K. Brown	Duke
	NMR Deconvolution	in progress	E. Demler	Harvard
	Measurement-induced phase xsition	in progress	M. Gullens, D. Huse, N. Yao	NIST, Princeton, Berkeley
	Classical Verification of QC	in progress	U. Vazarani, N. Yao, T. Vidick	Berkeley, CalTech
	Cross platform benchmarking	in progress	Peter Zoller	Innsbruck
	Lattice Gauge Thy	in progress	Z. Davoudi	UMD
	Ising Scattering	in progress	Yannick Meurice	U. Iowa
	Circuit-based MBL	in progress	Sonika Johri	Intel Corp.
	Schwinger model simulation	in progress	Zohreh Davoudi	UMD
	Envariance measures	in progress	Wojciech Zurek	Los Alamos
	Para-particle simulations	in progress	C. M. Alderete, Blas R. Lara	UMD, INAOE
	Edge-cover problem QAOA	in progress	B. Sundar, K. Hazzard	Innsbruck, Rice
	Lee-Yang Zeroes	in progress	Lex Kemper	NCSU
	Triangle game	in progress	Akimasa Miyake	UNM
	Molecular Cluster simulations	in progress	Nicolas Sawaya	Intel Corp.
	Ring-molecule dynamics Q-Sim	in progress	Rob Parrish	QCWare
	Chaos-QAOA	in progress	Gregory Quiroz, O. Shehab	APL, IonQ
	GAN-compression of circuits	in progress	Xiaodi Wu	QuICS UMD
	QFT- based benchmarking	in progress	Yannick Meurice	U. Iowa
	Block-diagonalization via Grover	in progress	Sonika Johri	Intel Corp.
	term-ordered VQE	in progress	M. Martonosi	Princeton
	Cluster state generation	in progress	Robert Raussendorf, Vito Scarola	UBC, VaTech
	Block-optimized VQE	in progress	Peter Zoller	Innsbruck

Quantum Tech: Science or Engineering?

Natural platforms

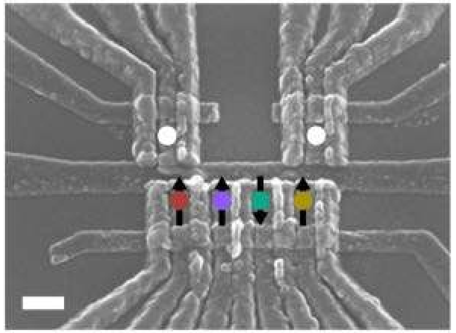
- atomic ions
- neutral atoms
- molecules
- photons

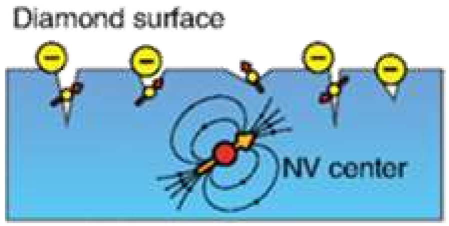


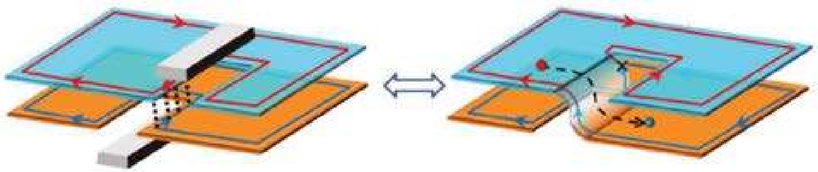
Control Engineering Needed

Synthetic platforms

- superconductors
- spins in solids
- quantum dots
- optical defects







topological qubit: *self-correcting*

Science Needed

Expected Phases of Quantum Computing Maturity

Boston Consulting Group Analysis

Phase I

Estimated Timeline:

3-5 Years

Estimated Impact (Operating Income):

$2-5 Billion

Technical Barrier To Entry

Error Reduction

Phase II

Estimated Timeline:

10+ Years

Estimated Impact (Operating Income):

$25-50 Billion

Technical Barrier To Entry

Error Correction

Phase III

Estimated Timeline:

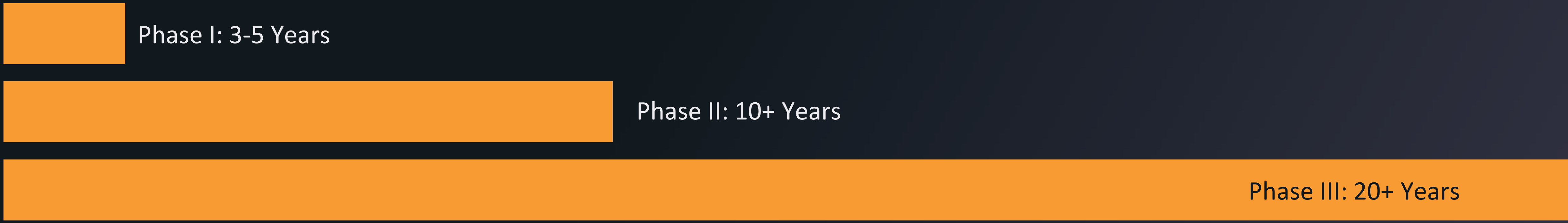
20+ Years

Estimated Impact (Operating Income):

$450-850 Billion

Technical Barrier To Entry

Modular Architecture



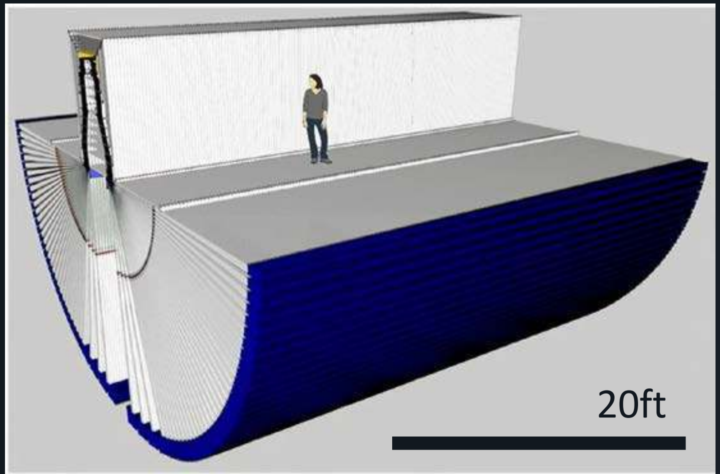
Source Where Will Quantum Computers Create Value—and When? *Boston Consulting Group* (2019)

Scaling will require SWAP-C (size/weight/power/cost)

IBM

An IBM engineer working on the custom-built dilution refrigerator casing for a single QPU

Google



Google rendering of a planned million-physical-qubit system

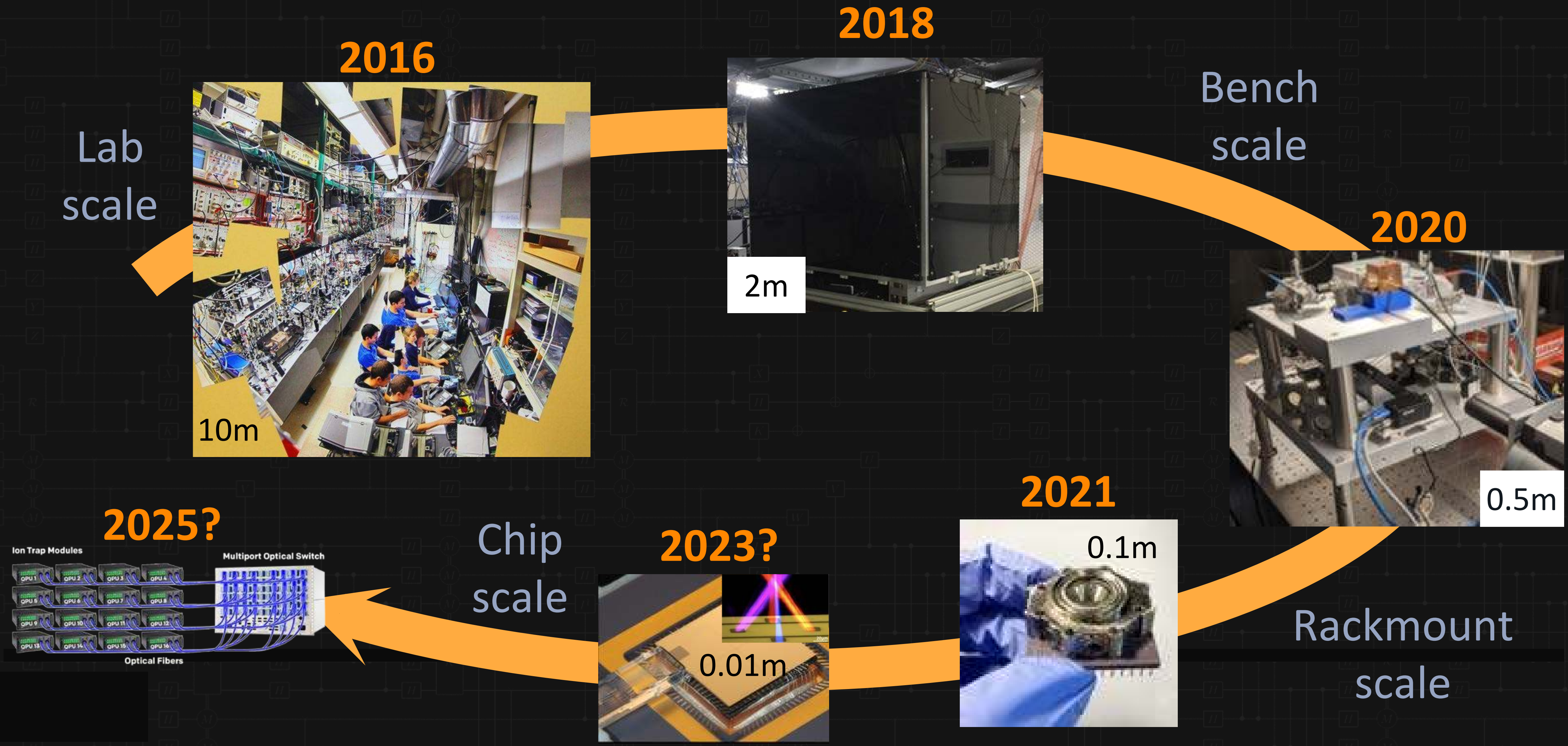
IONQ

IonQ ion trap and vacuum chamber in a single, minuscule package.

Superconductor Error Correction overhead:
1,000 – 100,000

Ion Trap Error Correction overhead:
10 – 100

Ion Trap QC path to scale

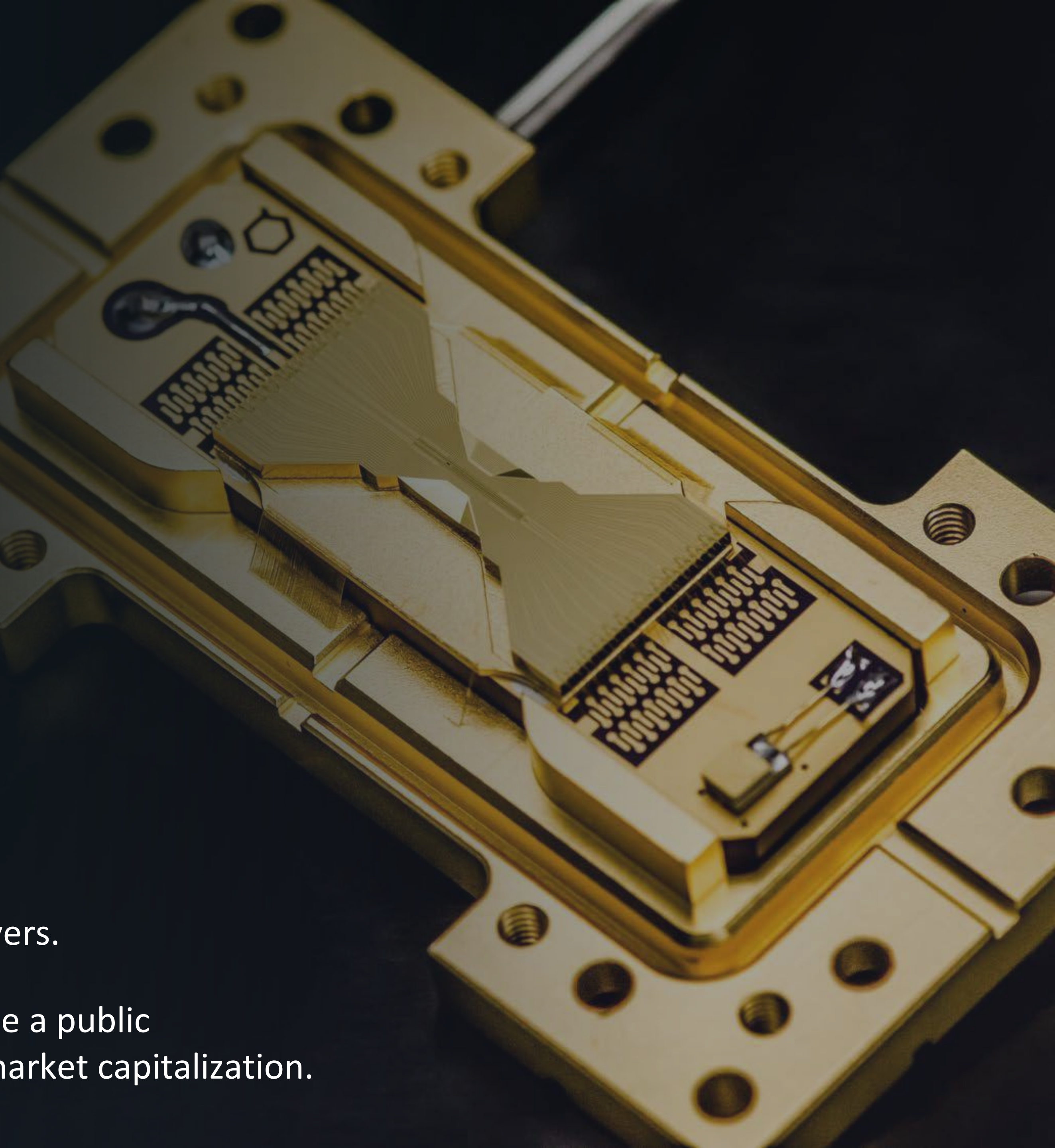


IonQ was founded in 2015 by Jungsang Kim and Chris Monroe, headquartered in College Park, MD

IonQ is a leader in quantum computing, with technology based on **individual atomic qubits**, having high quality and reconfigurable quantum operations. We have a clear scaling roadmap to tackle problems that are impossible with classical computers.

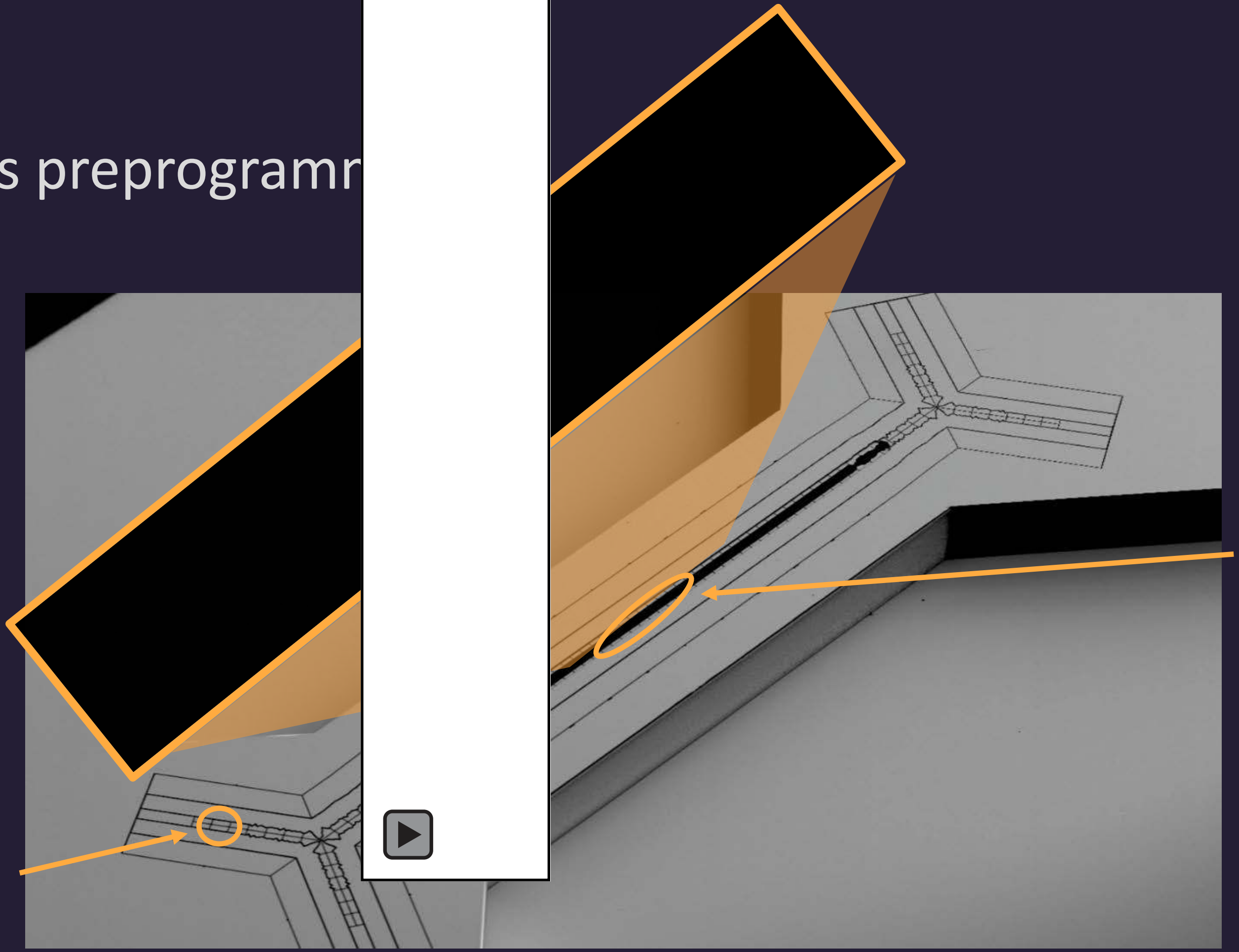
We have built several generations of full-stack quantum computer systems, with cloud access via commercial servers.

IonQ has raised $84 million privately, and is set to become a public company in summer 2021, with an estimated $2 billion market capitalization.



IONQ autoloading register

N=24 qubits preprogramr

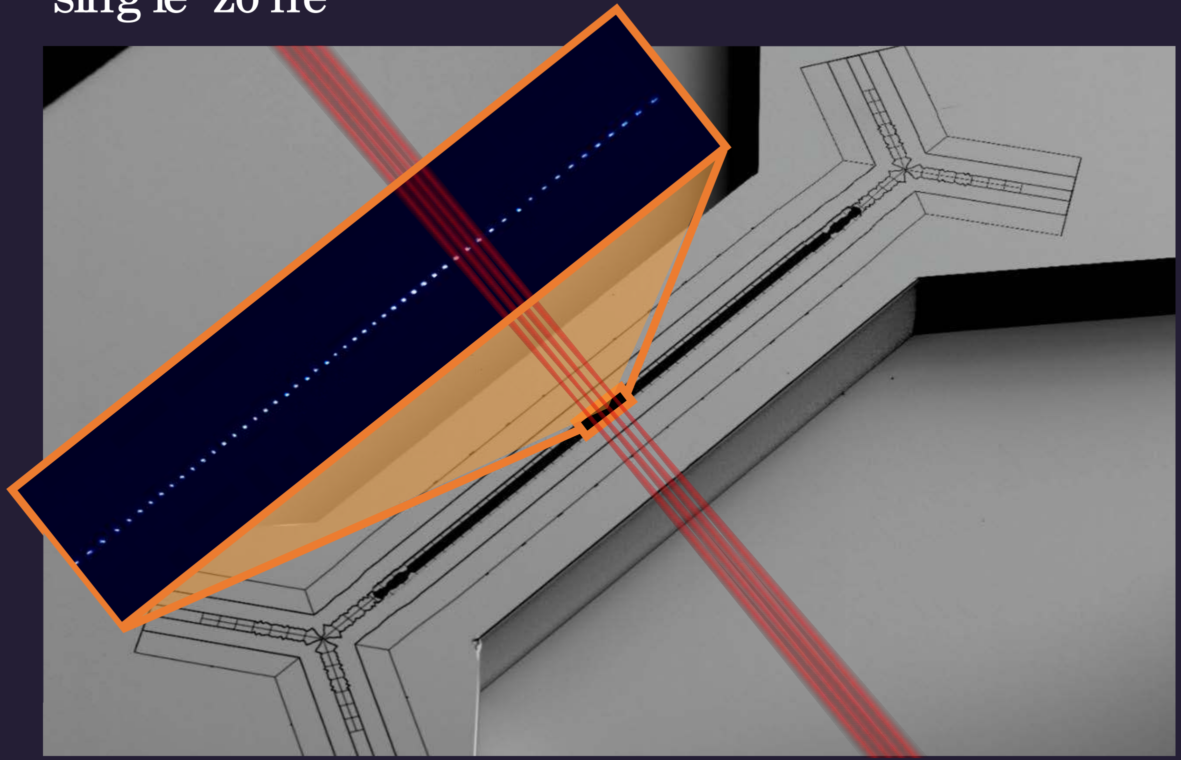


IonQ Systems on the cloud

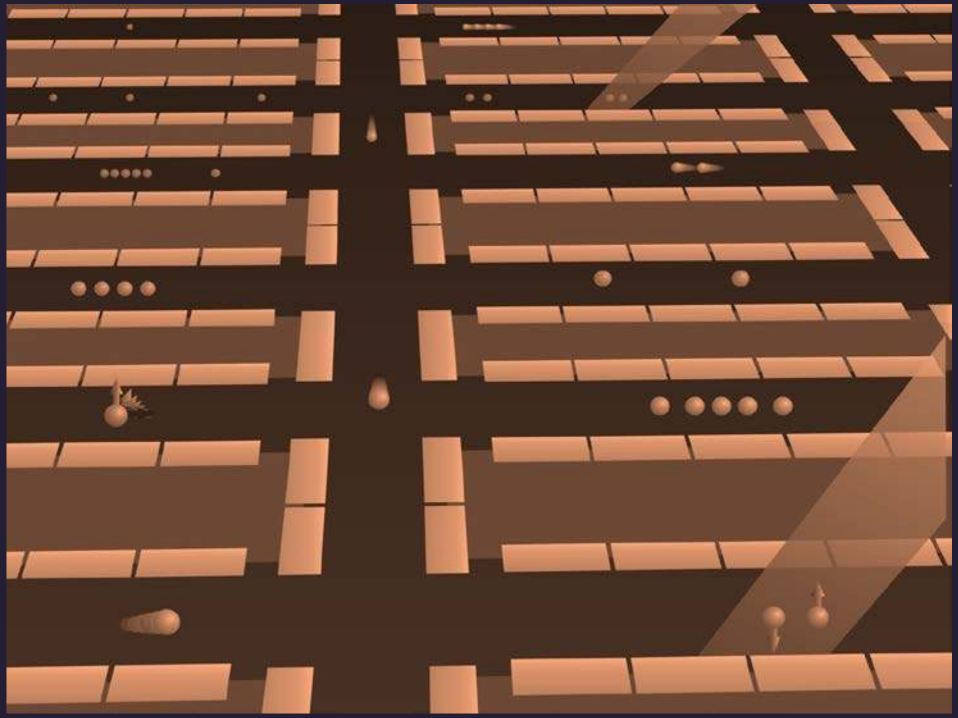
PICTURED: IONQ’S NEXT-GEN SYSTEM

Atomic Quantum Computer Scaling I >100 qubits

Linear shuttling through single zone



Shuttling between multiple zones

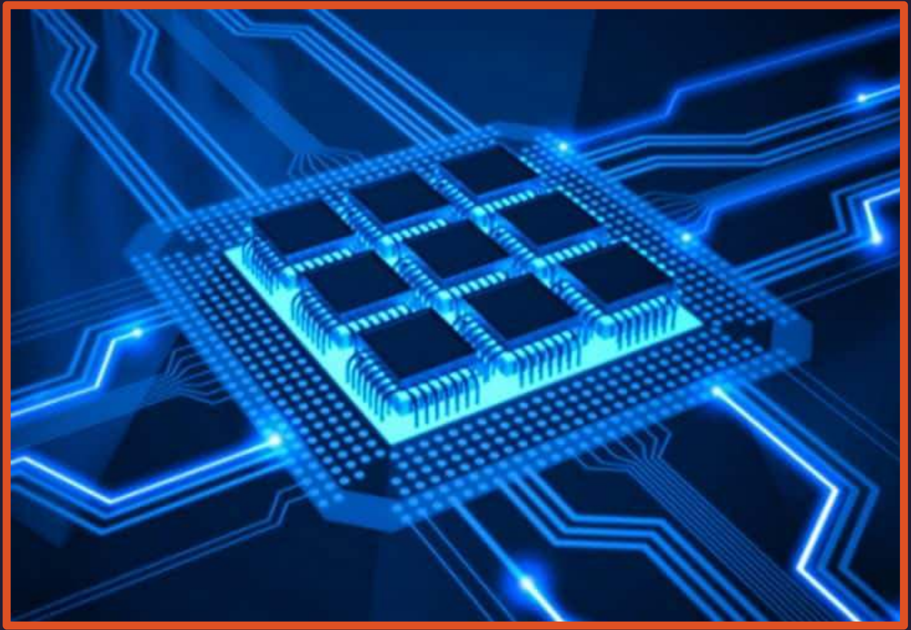


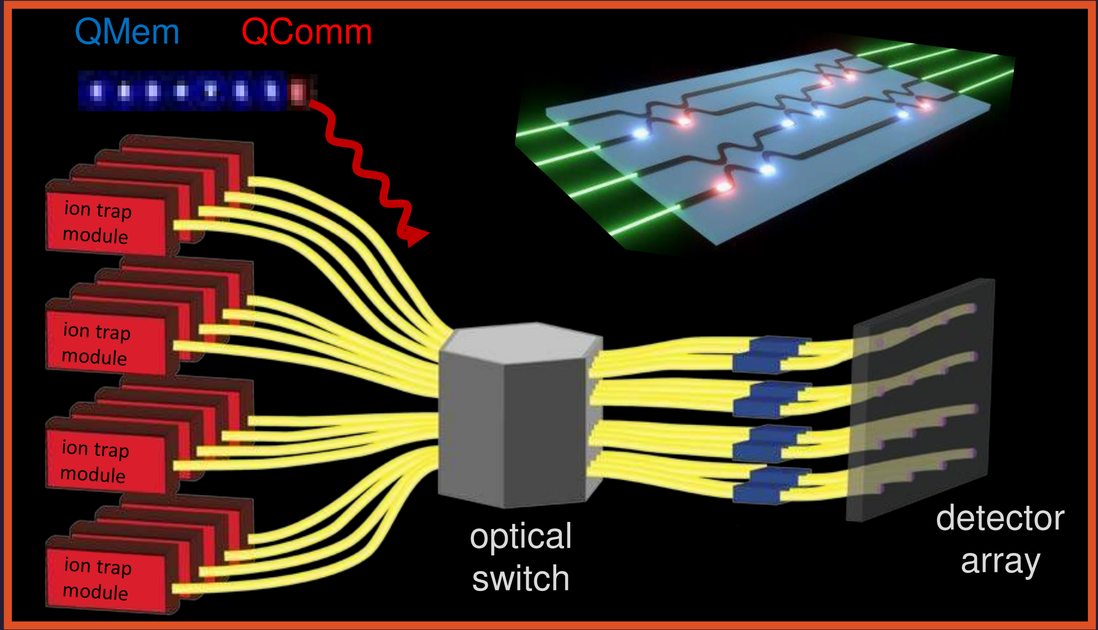
NIST-Boulder Nature 417, 709 (2002)
Univ. Mainz Science Advances 3, e1601540 (2017)

Atomic Quantum Computer Scaling II >1000 qubits

Plan: Multicore quantum processing

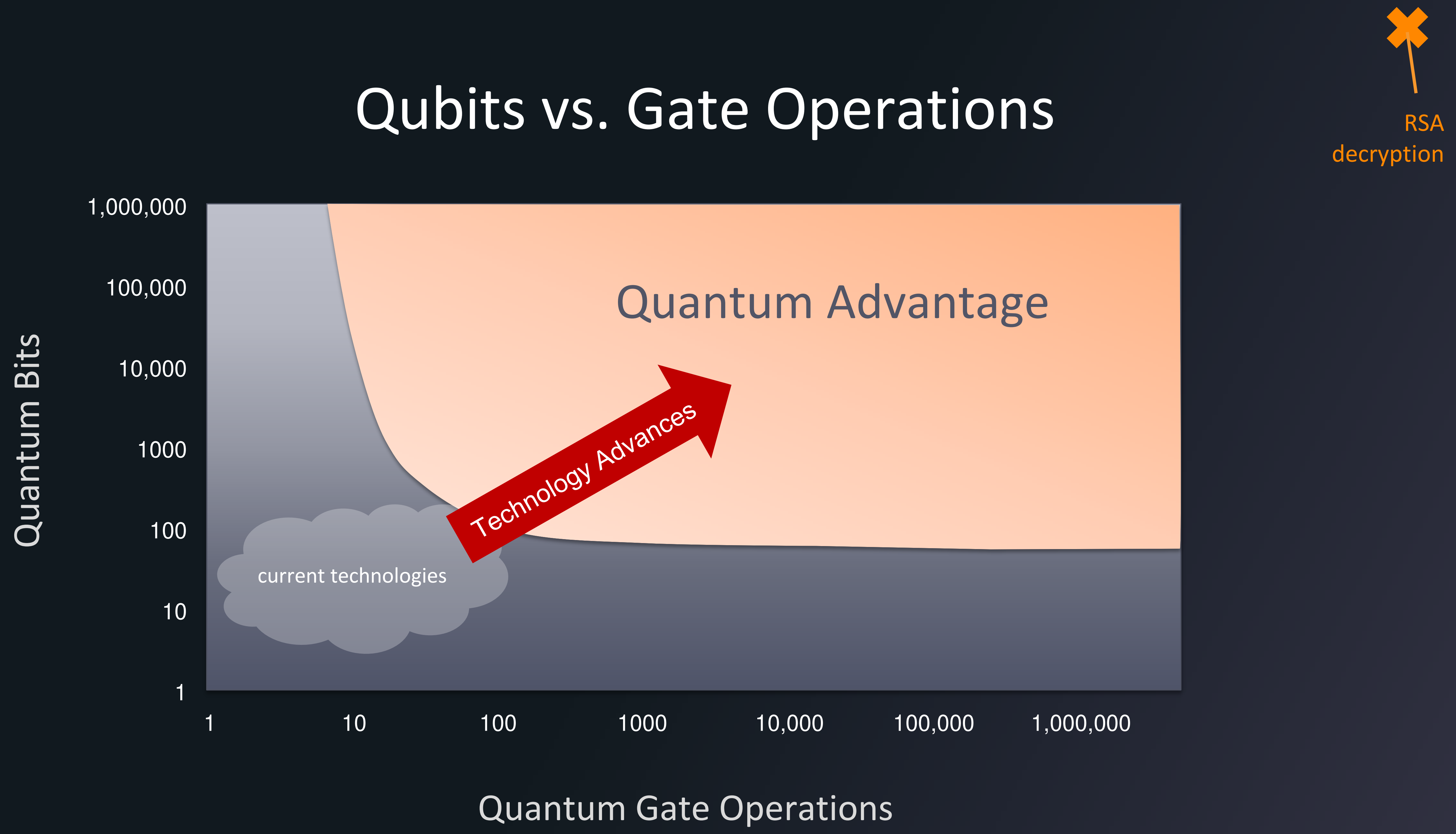
Technology: Integrated photonics and switches, SNSPD detector array





Duan and Monroe, *Rev. Mod. Phys.* **82**, 1209 (2010)
Li and Benjamin, *New J. Phys.* **14**, 093008 (2012)
Monroe, et al., *Phys. Rev. A* **89**, 022317 (2014)

Qubits vs. Gate Operations



Hype Cycle of Emerging Technologies