Quantum Computers: What, How, When?

Christopher Monroe

Duke Quantum Center

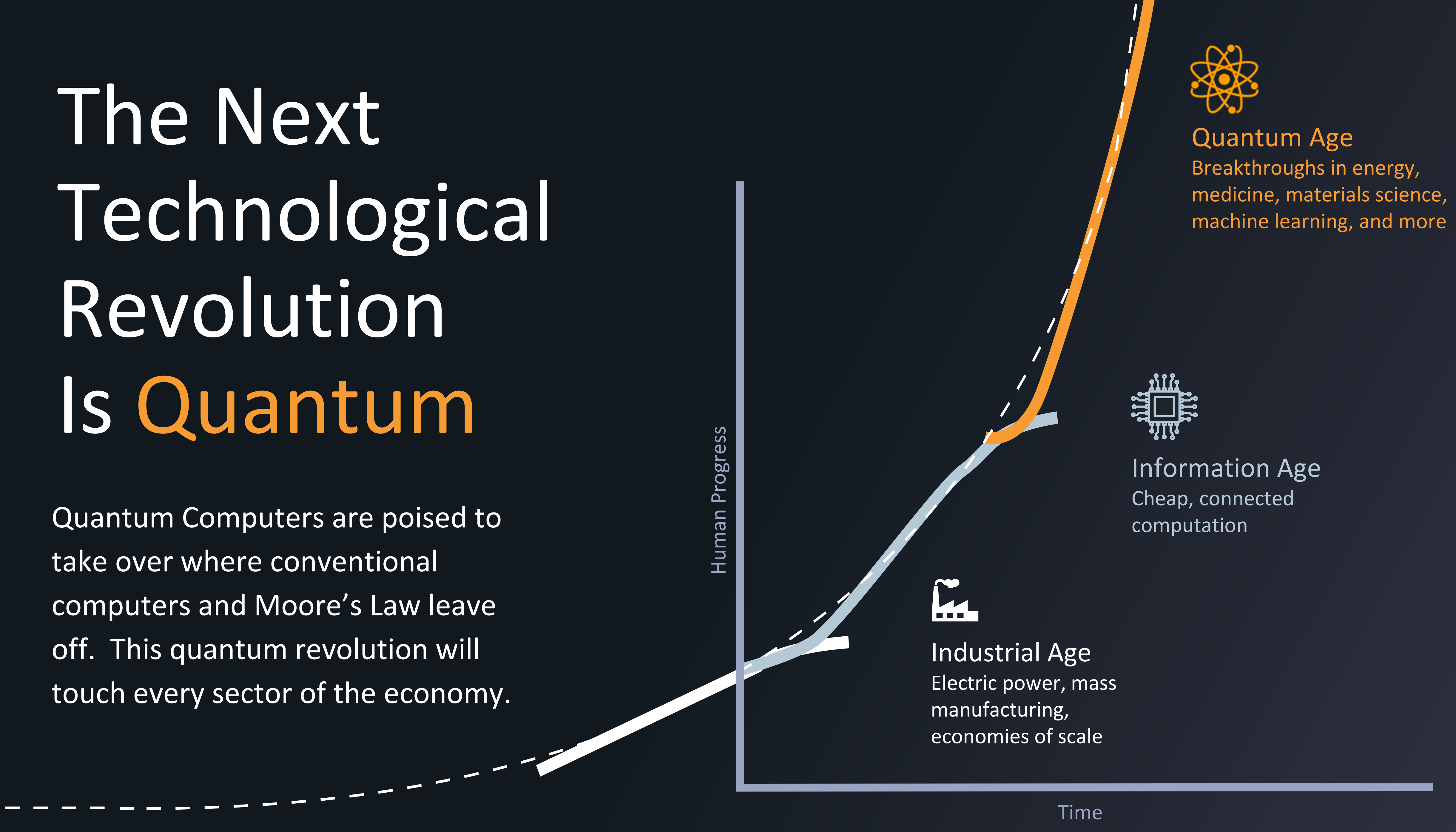
Duke University

Department of Elec. and Comp. Engineering
Department of Physics

IONQ

The Next Technological Revolution Is Quantum

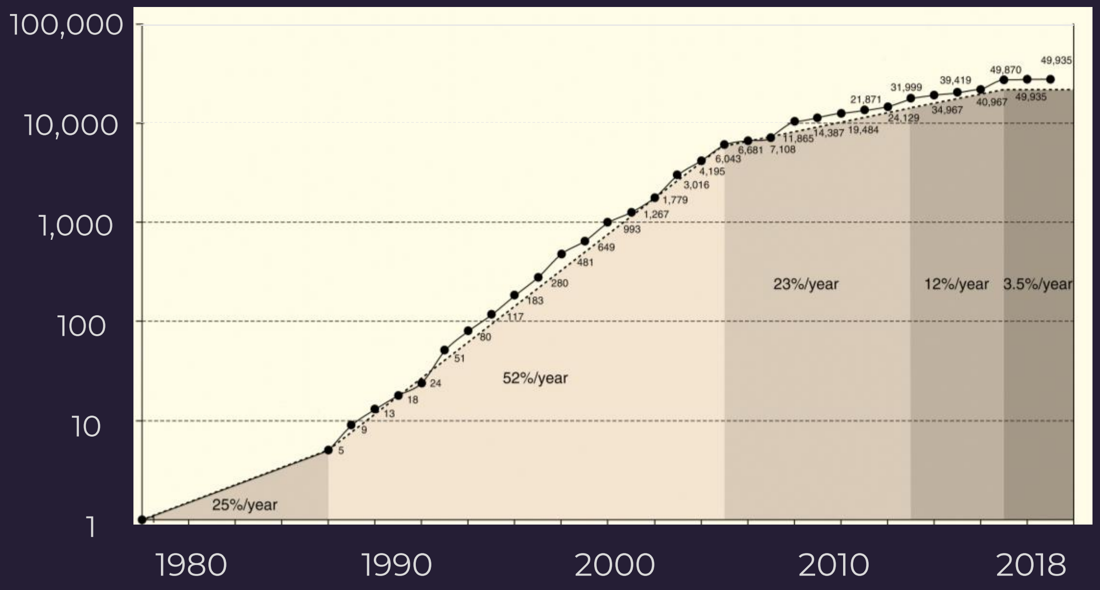
Quantum Computers are poised to take over where conventional computers and Moore's Law leave off. This quantum revolution will touch every sector of the economy.



Moore's Law

exponential growth in computing

Transistor density relative to 1978



Richard Feynman

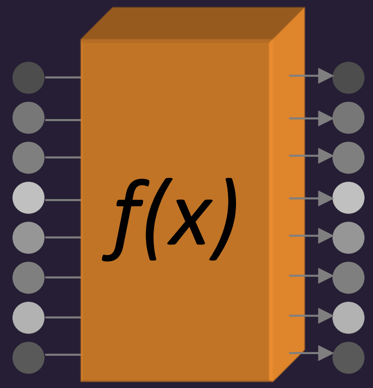
***There's Plenty of Room at the Bottom* (1959)**

*"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

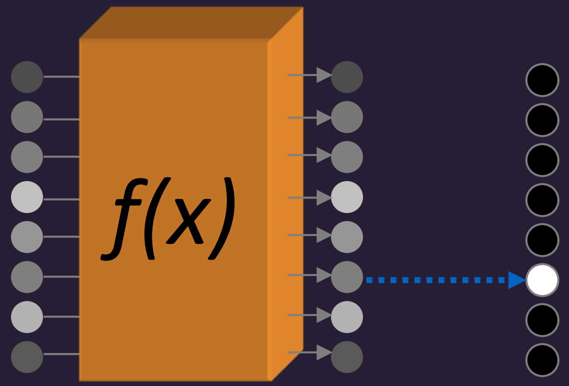


$$a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle$$
$$a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$$

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

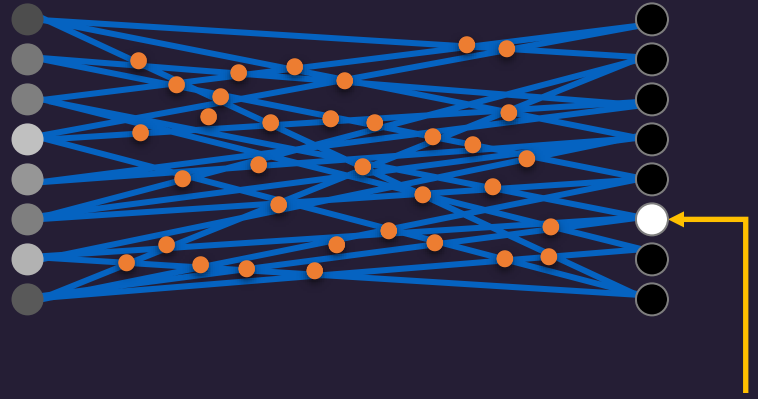
...Bad News...

measurement gives random result



...Good News!

quantum interference



depends on
<u>all</u> inputs

Application: Factoring Numbers

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

P. Shor (1994)

39 = 3 × 13 (…easy)
38647884621009387621432325631 = **? × ?**

Factor N (n bits)

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

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

use case: code-breaking

Key generation	n = P * Q d * e = 1mod Φ(n)
Encryption	c = m^e mod n Public Key(n,e)
Decryption	m = c^d mod n private key (d)

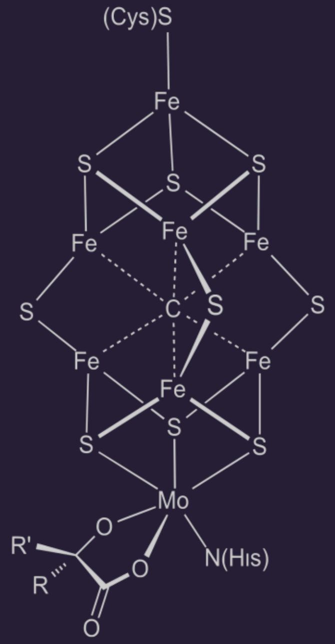
Application: Optimization

Traveling Salesman problem

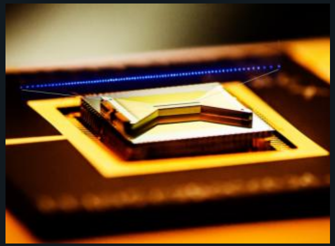
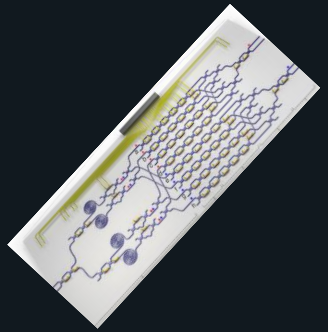
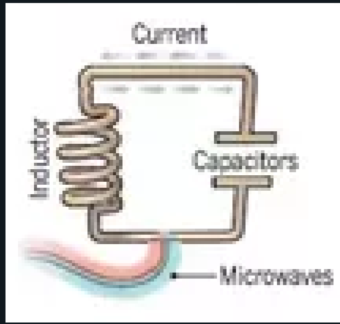
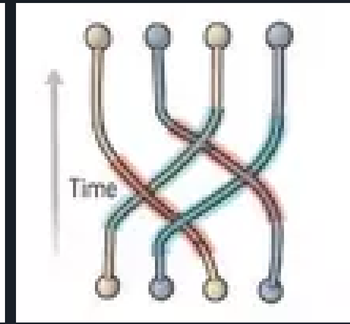
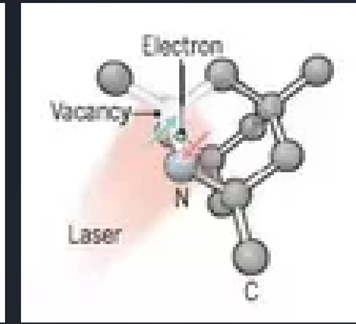
what is the
shortest path
through *N* cities?

Molecular Simulations

designer materials
new catalysts



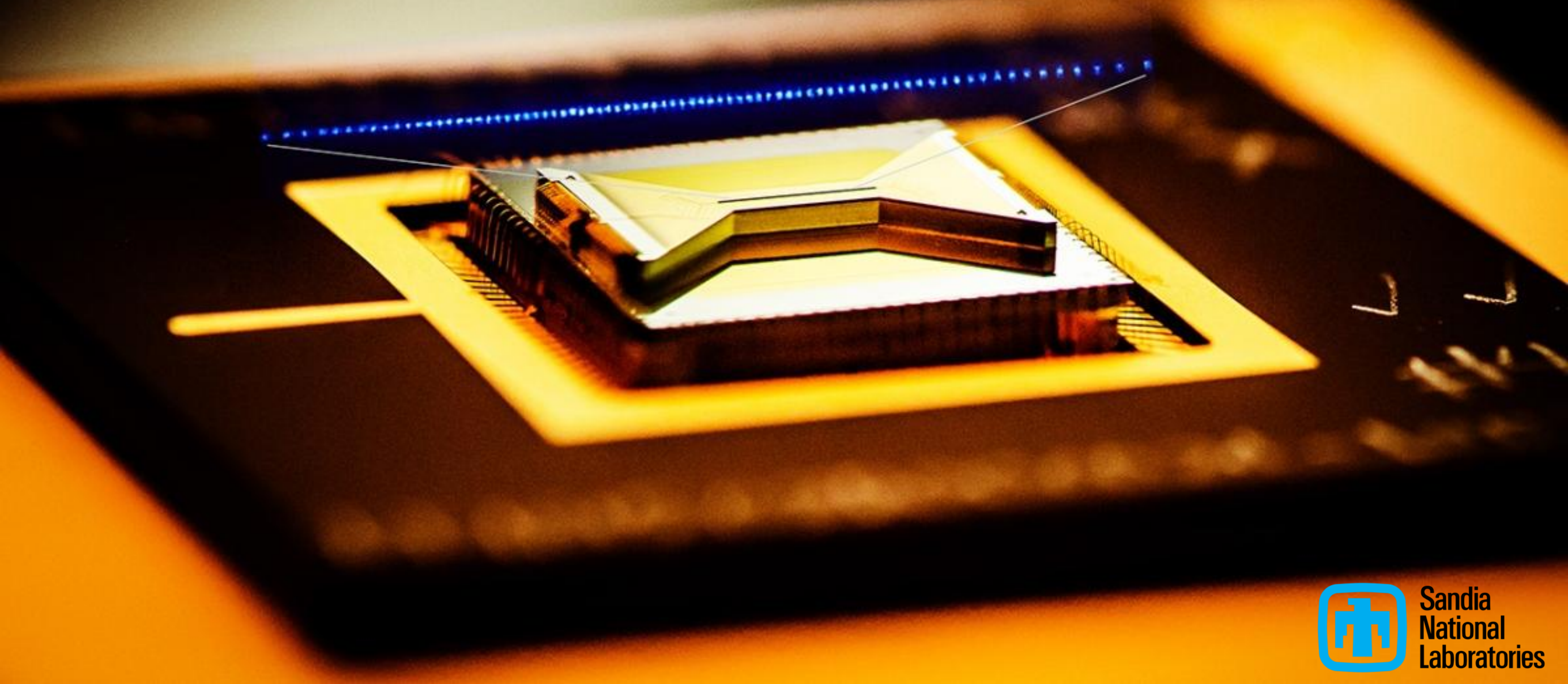
Quantum Technologies

	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 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 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%	99.5%	--	99.4%	~99%	N/A	99.2%
Qubits Connected	High	Very high; low individual control	--	High	Very Low	N/A	Low
Companies	IonQ, Quantinuum, AQT Oxford Ionics, Universal Qu.,…	Atom Computing, ColdQuanta, QuEra, Pasqal, Planqc, M[2]	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.

Adapted from: Science, Dec. 2016

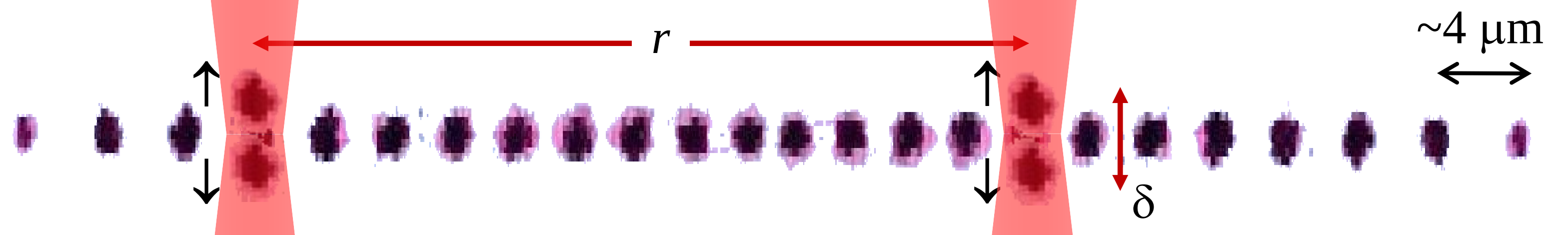
Ion Traps

$^{171}Yb^{+}$ atoms (80 ion string)
4 μm spacing, 100 μm altitude
ν_0 = 12.642 812 118 GHz



Sandia National Laboratories

“Standard” Gates between Trapped Ions



dipole-dipole coupling $$\Delta E = \frac{e^2}{\sqrt{r^2+\delta^2}} - \frac{e^2}{r} \approx -\frac{(e\delta)^2}{2r^3}$$

δ ~ 10 nm
$e\delta$ ~ 500 Debye

$$\begin{aligned}
|\downarrow\downarrow\rangle &\rightarrow |\downarrow\downarrow\rangle \\
|\downarrow\uparrow\rangle &\rightarrow e^{-i\varphi}|\downarrow\uparrow\rangle \\
|\uparrow\downarrow\rangle &\rightarrow e^{-i\varphi}|\uparrow\downarrow\rangle \\
|\uparrow\uparrow\rangle &\rightarrow |\uparrow\uparrow\rangle
\end{aligned}
\longrightarrow \varphi = \frac{\Delta E t}{\hbar} = \frac{e^2\delta^2 t}{2\hbar r^3} = \frac{\pi}{2}$$

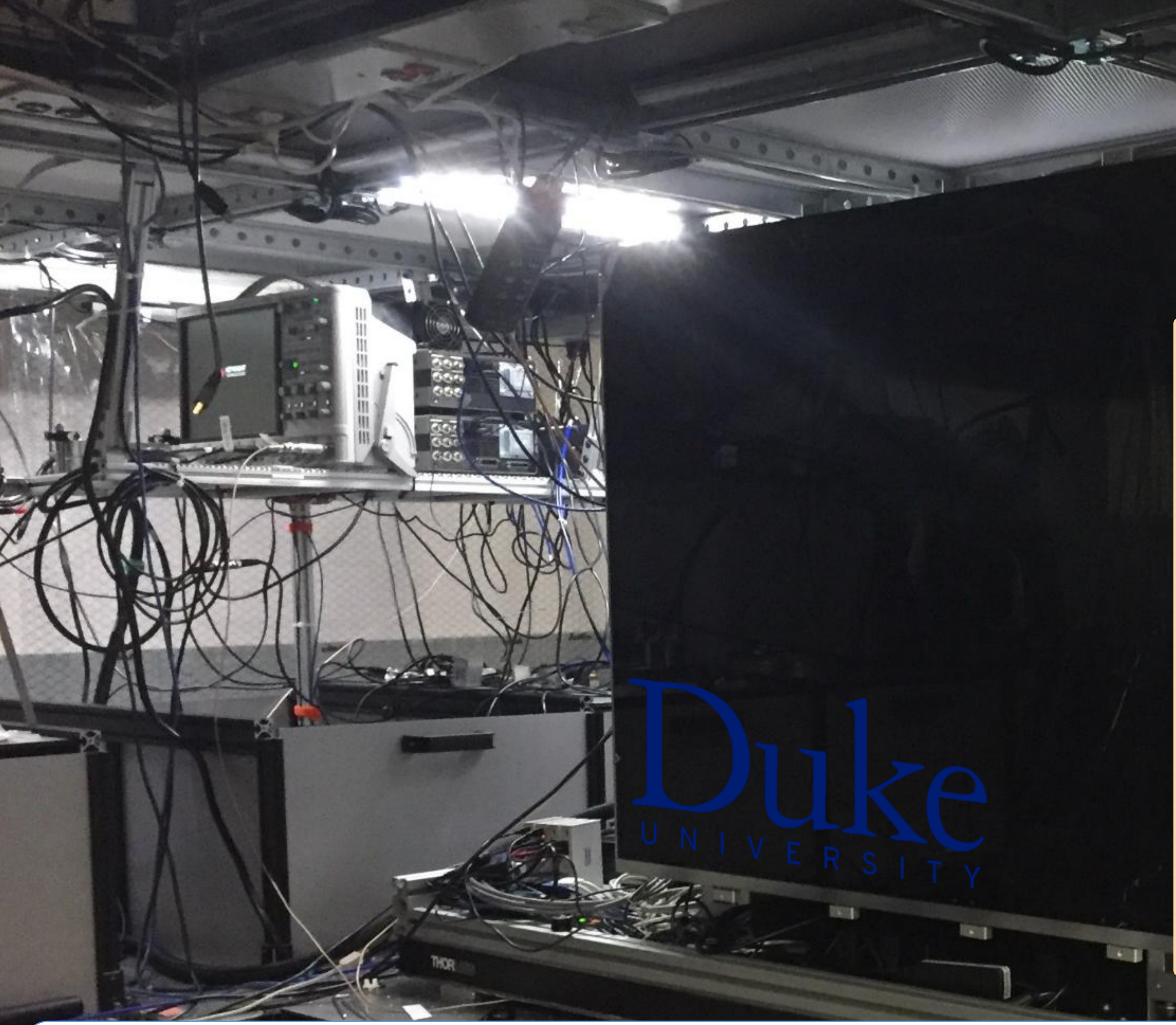
for full entanglement

Native Ion Trap Operation: “Ising” gate

$$XX[\varphi] = e^{-i\sigma_x^{(1)}\sigma_x^{(2)}\varphi}$$

τ_{gate} ~ 10–400 μs
F ~ 98% – 99.9x%

Cirac and Zoller (1995)
Mølmer & Sørensen (1999)
Solano, de Matos Filho, Zagury (1999)
Milburn, Schneider, James (2000)



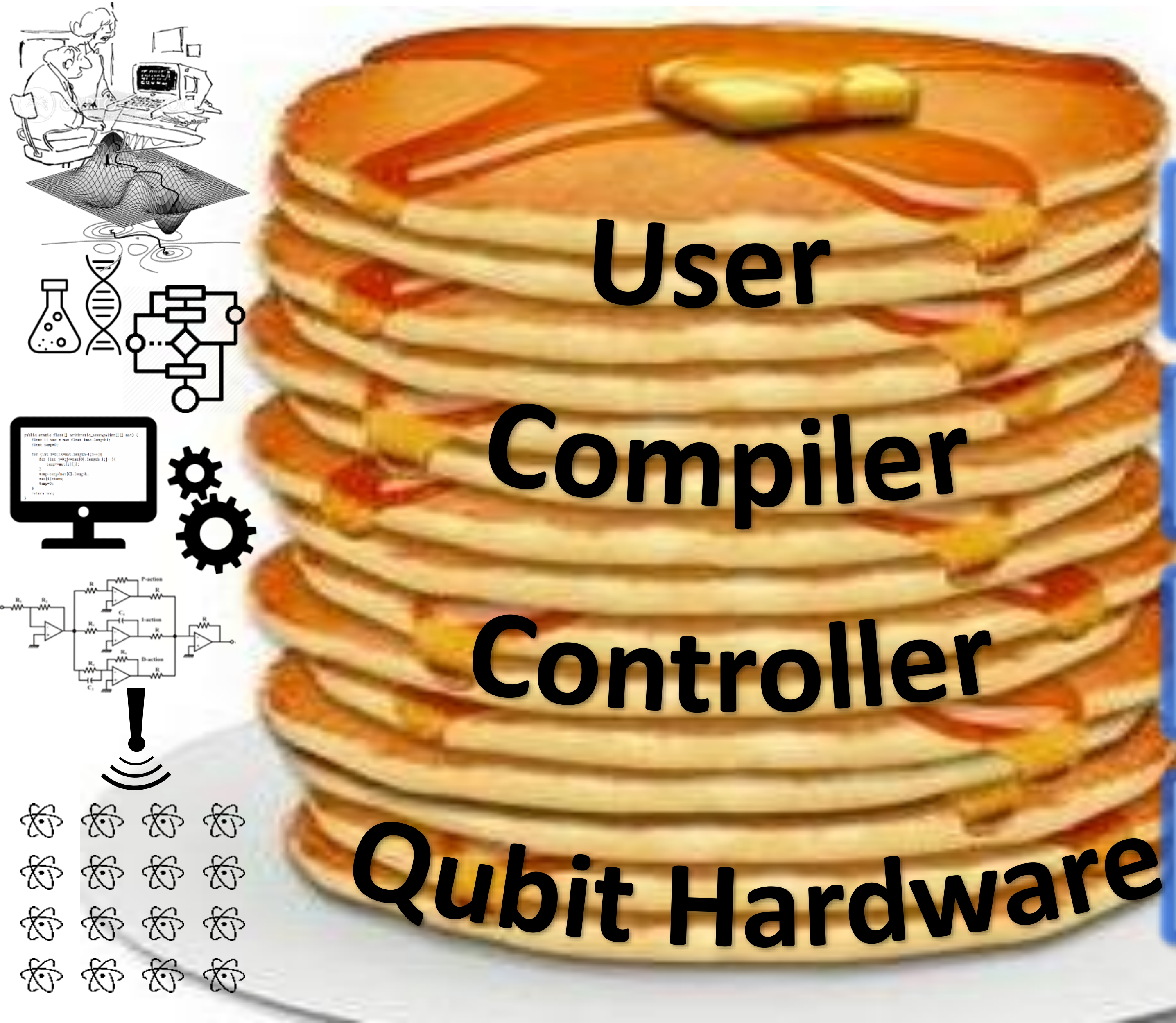
Latest package (J. Kim, Duke)

U.S. DEPARTMENT OF ENERGY
QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem

NSF STAQ
SOFTWARE-TAILORED ARCHITECTURES
for QUANTUM CO-DESIGN

Sandia National Laboratories
ColdQuanta
AOSense
L3HARRIS
COHERENT

Quantum Computer/Simulator “Stack”



PHYSICS, CHEMISTRY, BIOLOGY, AI/ML, ECONOMICS, etc…

COMPUTER SCIENCE

ENGINEERING

PHYSICS (AMO, CM, etc.)

Classical *Interactive* Certification of a Quantum Computation

Norman Yao (Harvard)

Umesh Vazirani (Berkeley)

Thomas Vidick (CalTech)

Examples of cryptographic functions with a "trap door"

1. Learning with Errors (LWE)

   Compute $f(b;x) = \boldsymbol{A}x + b\cdot(\boldsymbol{A}\boldsymbol{s}+e)$

   given matrix $\boldsymbol{A}$, and $\boldsymbol{A}\boldsymbol{s}+\boldsymbol{e}$ ($\boldsymbol{e}$: error vector)

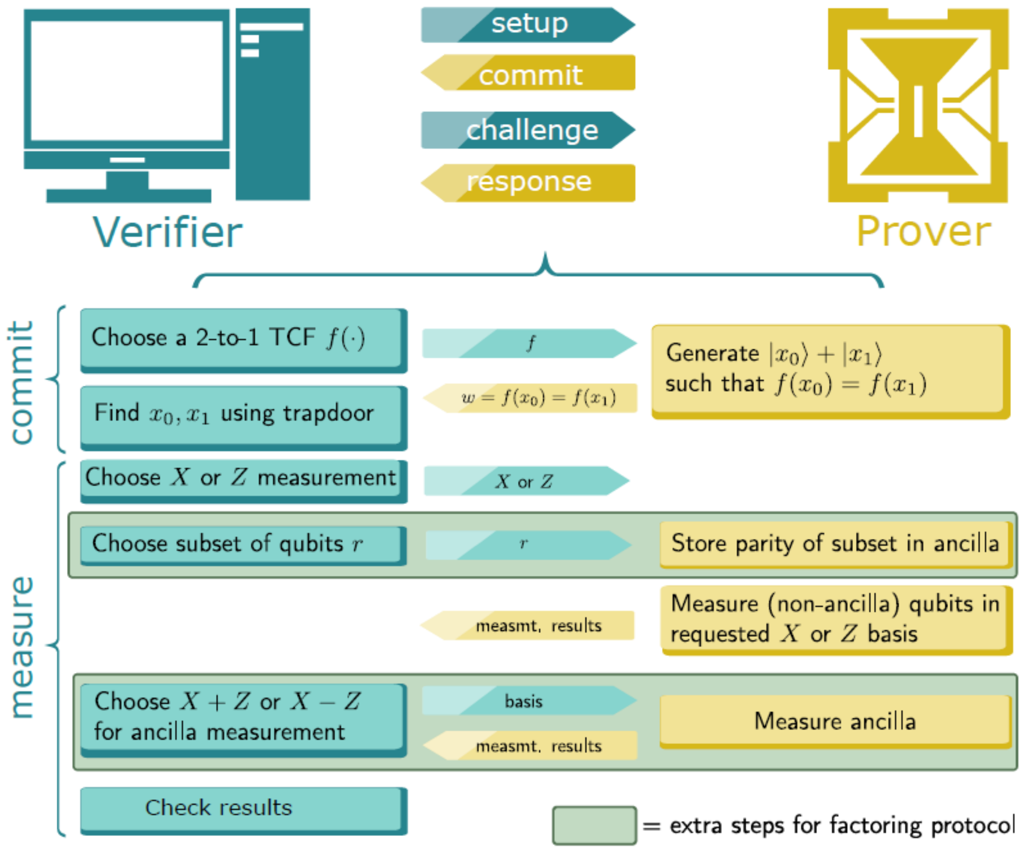
   → Find hidden vector $\boldsymbol{s}$

2. "Rabin" cryptographic encoding

   Compute $f(x) = x^2\ (Mod\ N)$ with $N = pq$

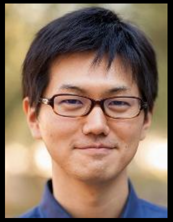
   $f(x)$ is 2:1, but if you know only one input, hard to find the other, unless you know p and q.

   → Determine if two colliding inputs have the same or opposite parity



D. Zhu, et al., Nature Phys 19, 1725 (2023)

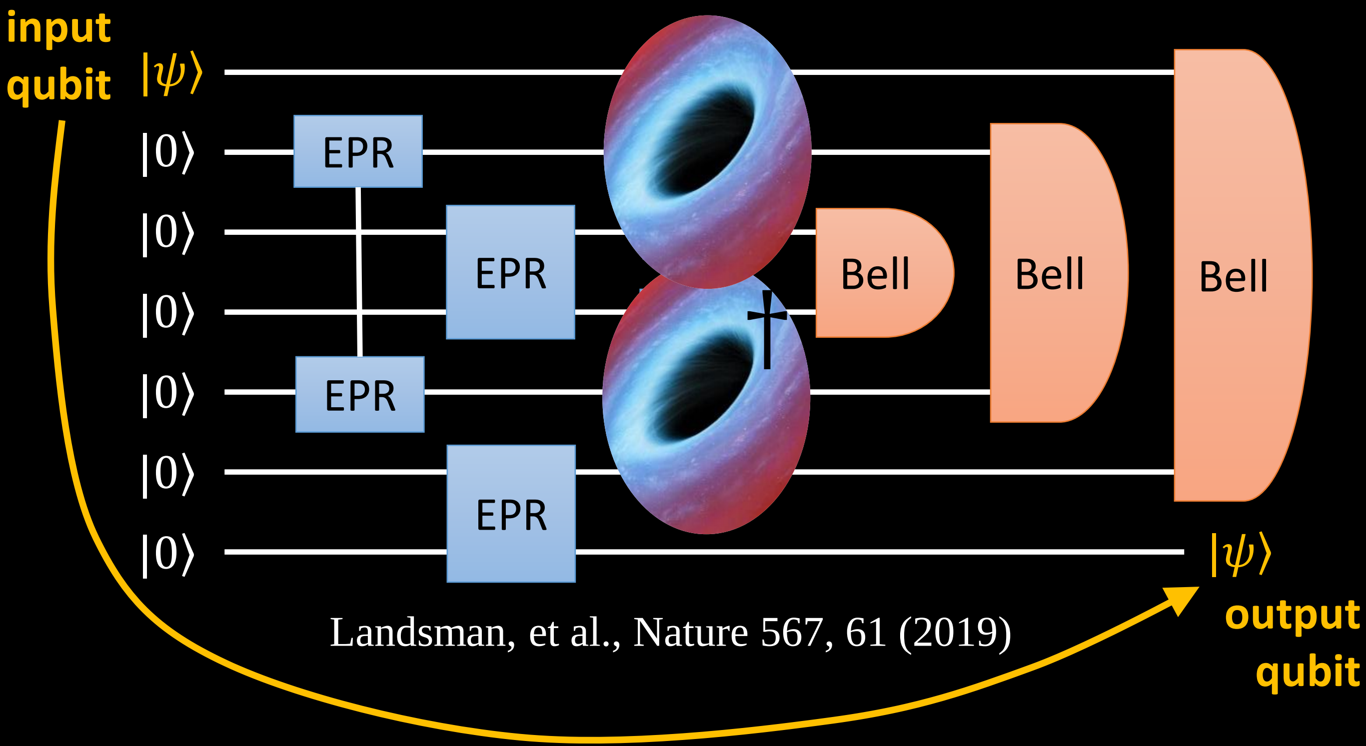
Cosmology + Quantum Gravity
Quantum Scrambling


Beni Yoshida (Waterloo/CalTech)


Leonard Susskind (Stanford)


Norman Yao (Berkeley)

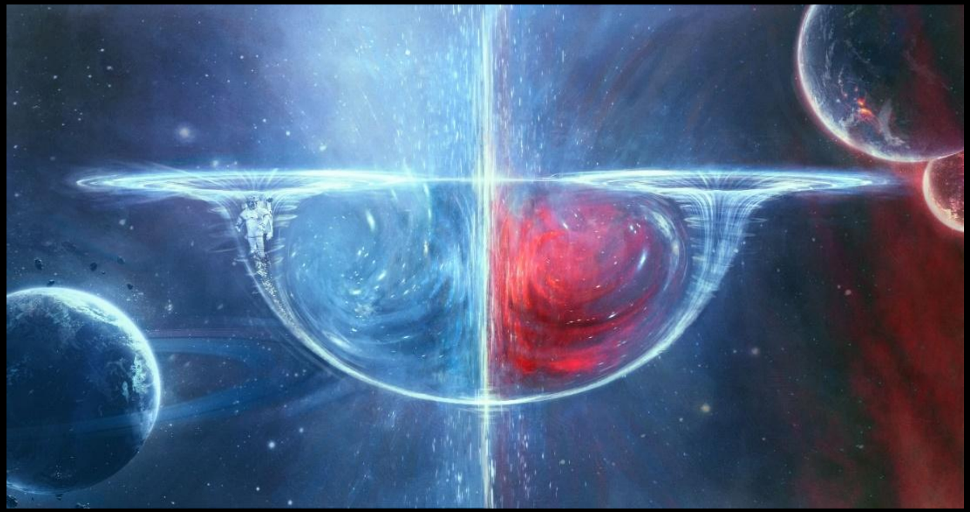
Scrambling: "complete diffusion" of quantum information, relevant to information evolution in black holes

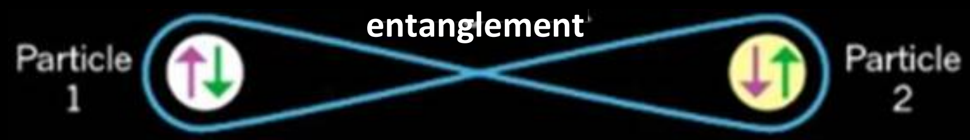


Landsman, et al., Nature 567, 61 (2019)

Successful teleportation if U ***scrambles***

In 1935, Einstein and Rosen showed that widely-separated black holes can be connected by a tunnel through space-time, now known as a ***wormhole***



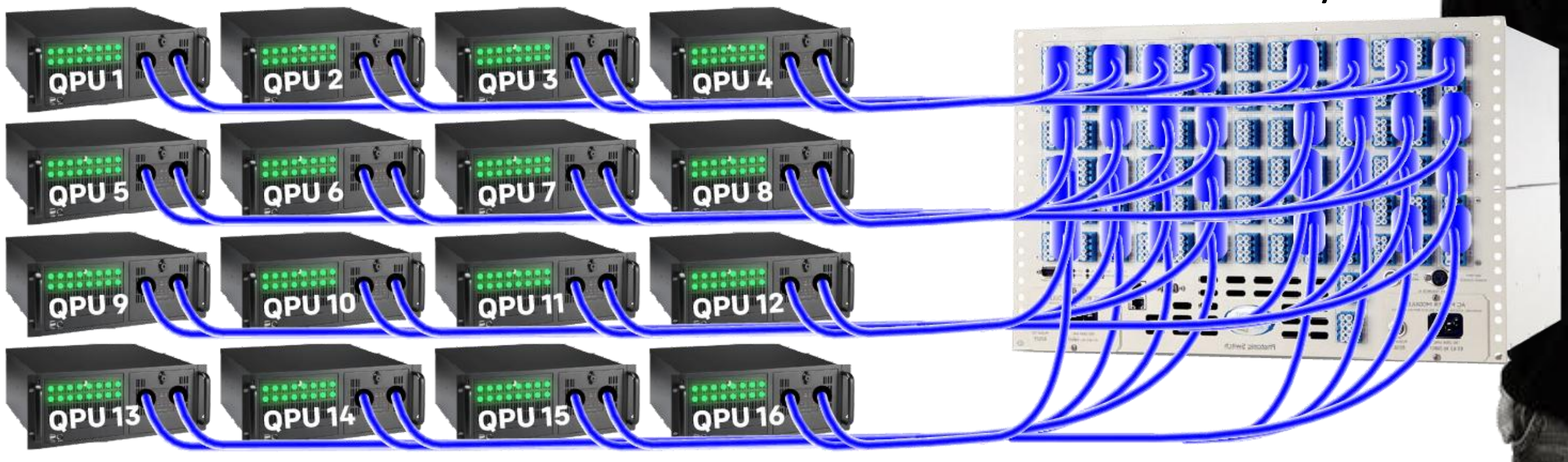


Physicists suspect that the connection in a wormhole and the connection in quantum entanglement ***are the same thing, just on a vastly different scale!***

PHYSICAL REVIEW A **89**, 022317 (2014)

Large-scale modular quantum-computer architecture with atomic memory and photonic interconnects

C. Monroe,[1] R. Raussendorf,[2] A. Ruthven,[2] K. R. Brown,[3] P. Maunz,[4,*] L.-M. Duan,[5] and J. Kim[4]



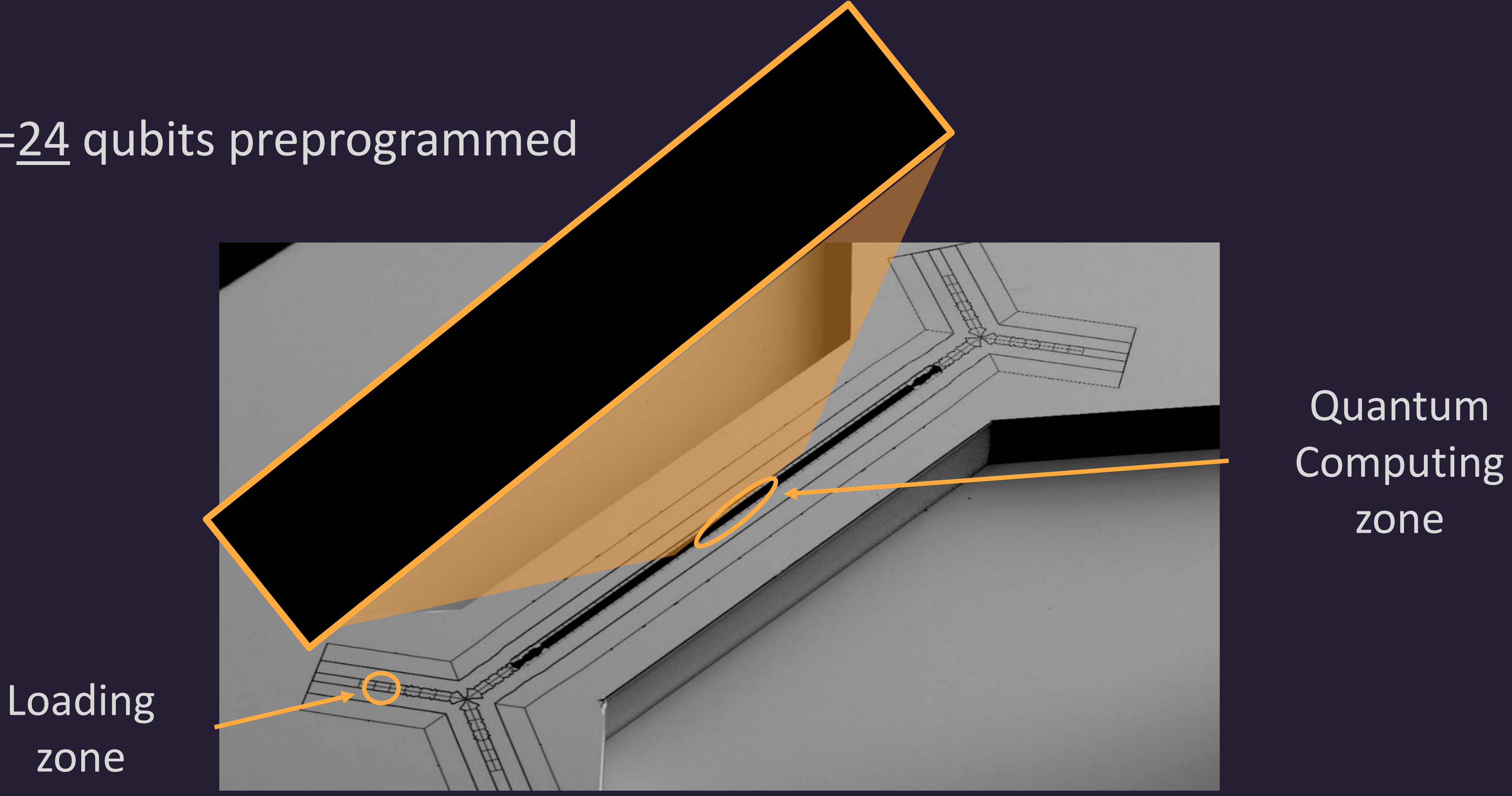
IONQ

This reads like a business plan!

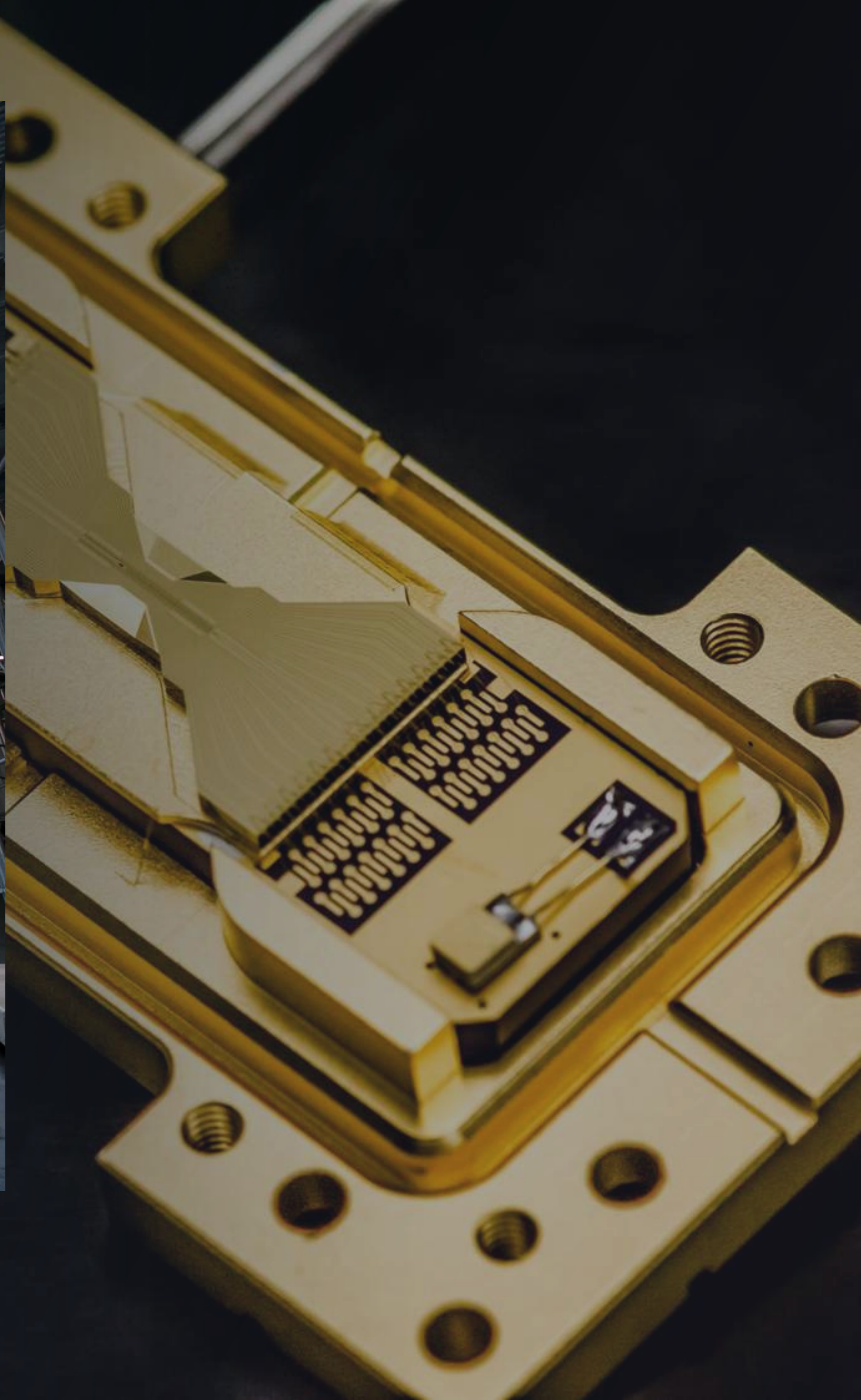
Harry Weller (1969-2016)
Venture Capitalist & Partner
New Enterprise Associates

IONQ autoloading register

N=24 qubits preprogrammed

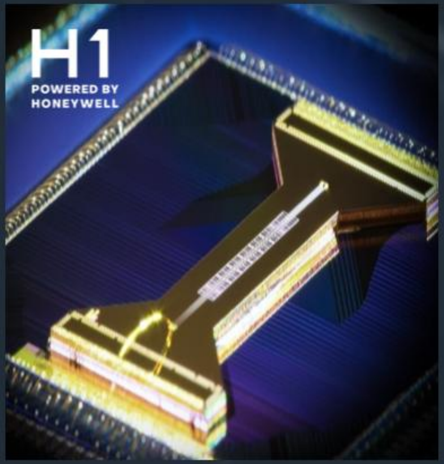


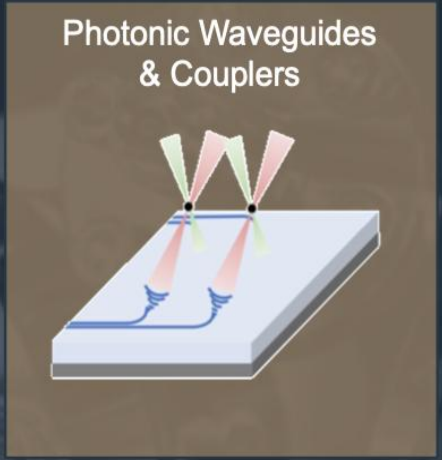
IonQ Systems on the cloud

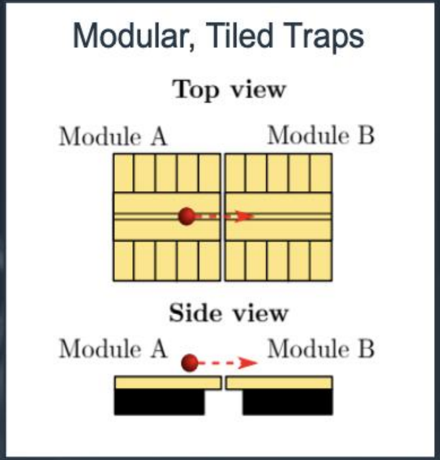


On Oct 1, 2021 IonQ was listed on the NYSE as the first public pure-play quantum computing company, with a current market cap of **$7 billion**

Scaling I: atom shuttling between zones





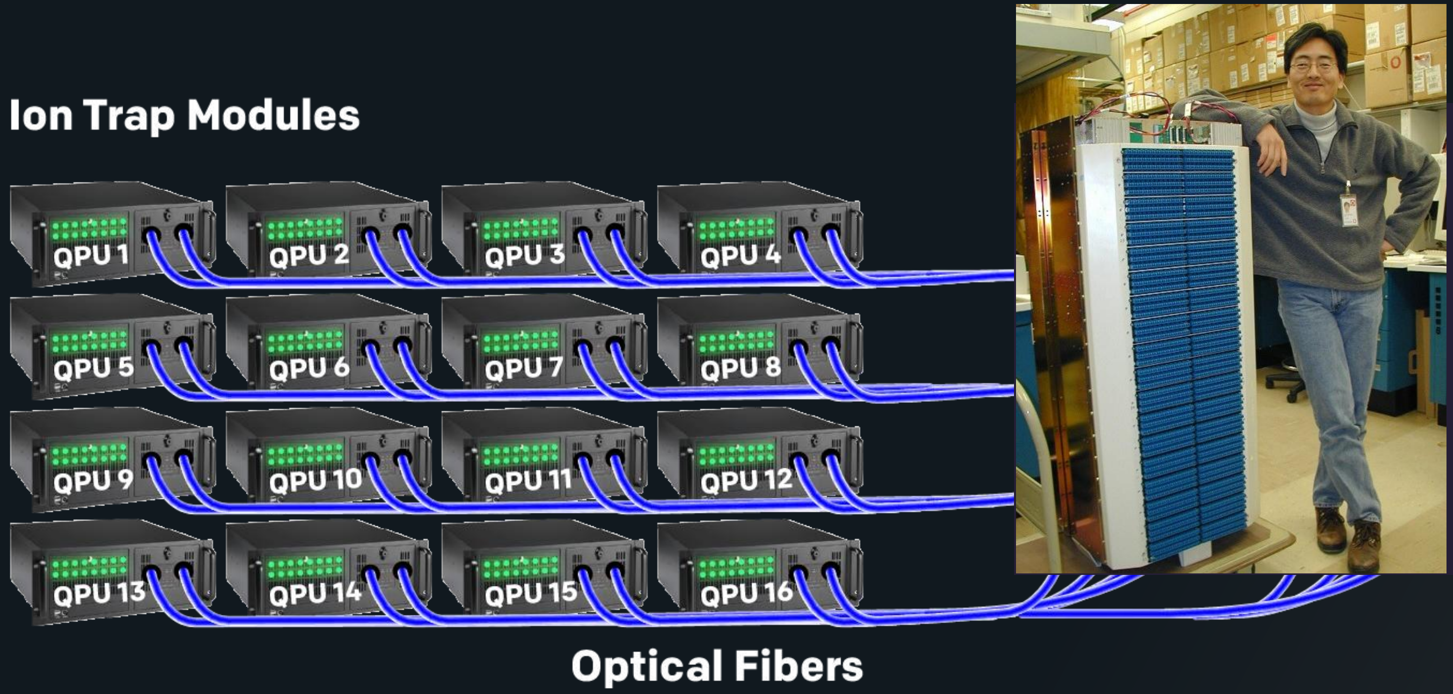


Akhtar et al, (Sussex/Universal Quantum)
arxiv.org/pdf/2203.14062.pdf

Kielpinski, Monroe, Wineland, Nature 417, 709 (2002)
Lekitsch, et al., Science Advances 3, 1601540 (2017)

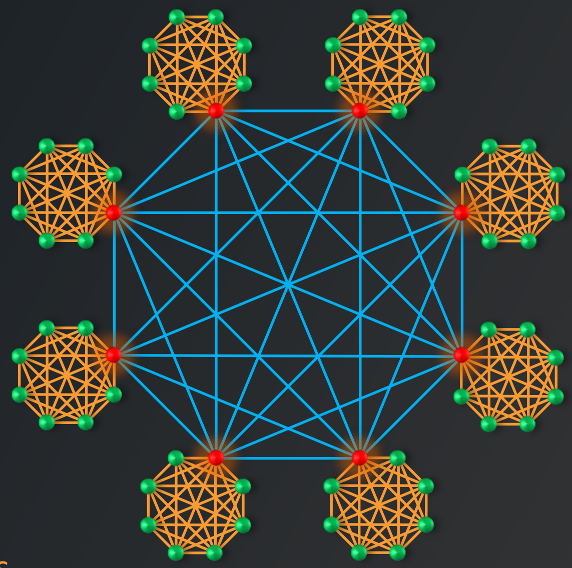
Kaushal, et al., AVS Quantum Sci. 2, 014101 (2020)
Pino, et al., Nature 592 209-213 (2021)

Scaling II: Modular (Photonic) Interconnects



1,100-port photonic switch
Jungsang Kim
Bell Labs (2002)

Full modular connectivity between all qubits



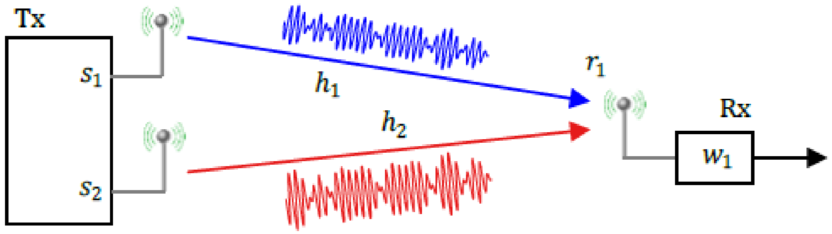
8 × 8 QPU network:
2,016 random access connections

Moehring, et al., Nature 449, 68 (2007)
D. Hucul, et al., Nature Phys. **11**, 37 (2015)
C. Balance, et al, PRL **124**, 110501 (2020)
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)

Error Correction vs. Error Mitigation[1]

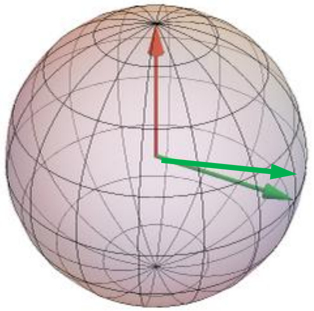
The ability to correct <u>arbitrary</u> errors is a triumph in theory. *But it may never be relevant in real systems.*

Instead: exploit what is known about the error channel (see classical wireless codes [2]).



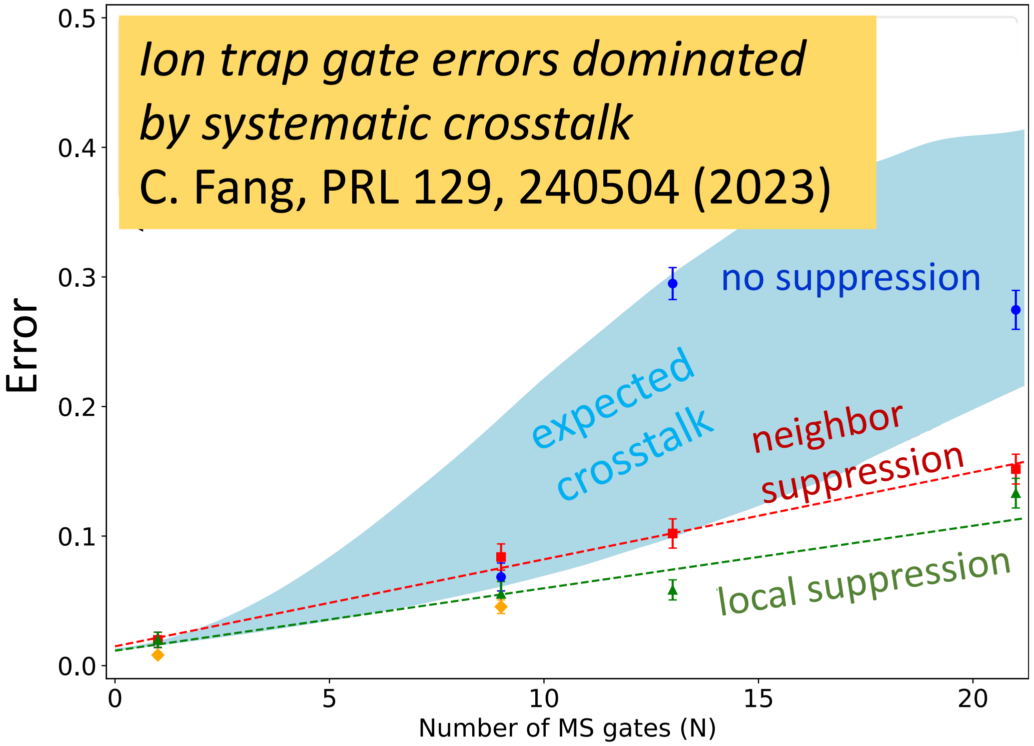
Space-Time codes

Robert Calderbank
(Duke Univ)



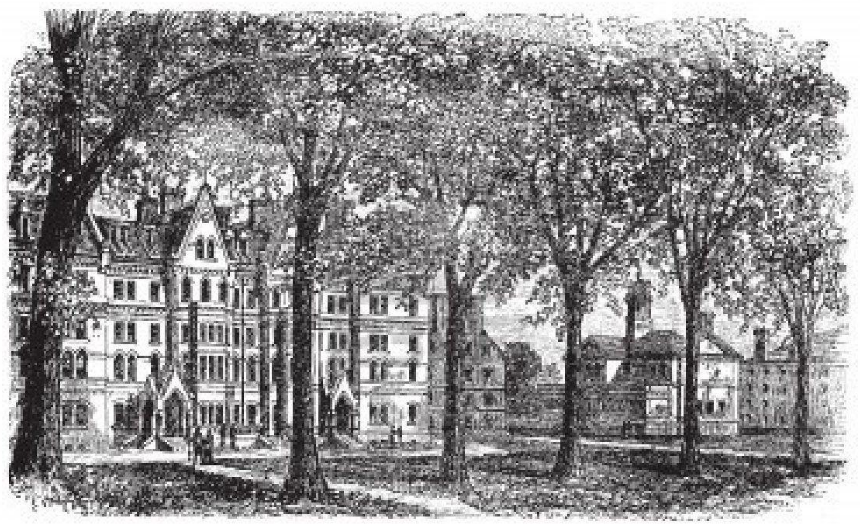
Errors in ion trap quantum computers dominated by control errors that don't necessarily spoil quantum coherence.

… Adapt EC codes to treat coherent errors [3] or deploy error mitigation techniques such as circuit diversification [4-6].



[1] Z. Cai, et al., Rev. Mod. Phys. 95, 045005 (2023)
[2] Tarokh, Seshadri, and Calderbank, IEEE Trans. Inf. Thy. **44**, 744 (1998)
[3] Hu, Liang, Rengaswamy, Calderbank, IEEE Trans. Inf. Thy., **68**, 1795 (2022)
[4] Tannu and Qureshi, IEEE/ACM MICRO-52 (2019)
[5] T. Patel and D. Tiwari, *SC20* (2020)
[6] A. Maksymkov, et al., arXiv:2301.07233 (2023)

Conventional University



- ✓ *No problem with quantum physics*
- ✓ *Take research "where it goes"*
- ✗ *Don't "build" things here*
- ✗ *$*

?

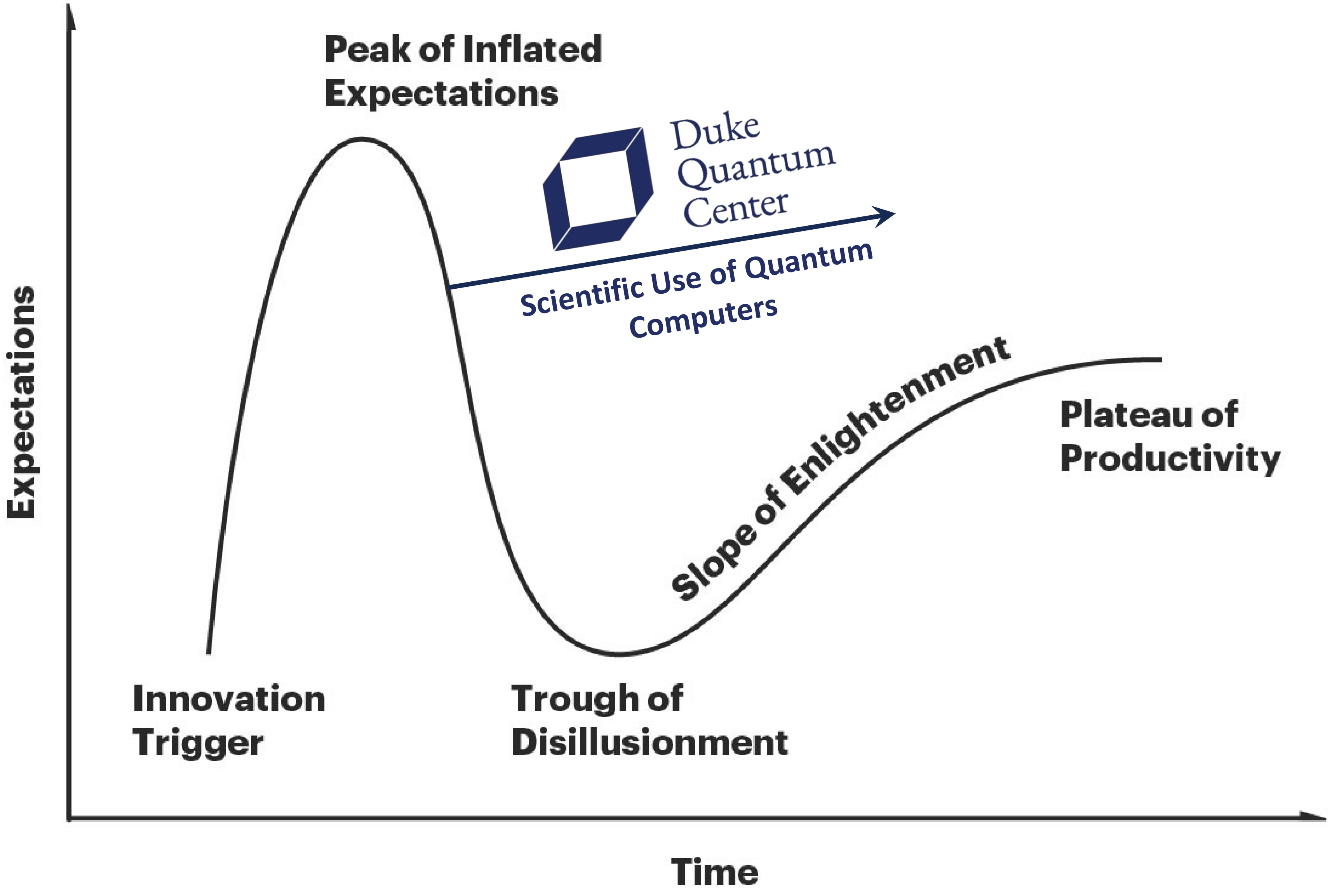
Industry

- ✗ *Not so familiar with quantum physics*
- ✗ *Favor conventional approaches (eg, solid state)*
- ✗ *May not build things for science*
- ✓ *Engineering, manufacturing, reliability*
- ✓ *$$$$$$$$*

National Lab/ Univ. Center

- ✓ *No problem with quantum physics*
- ✓ *Research for science <u>and</u> applications*
- ✓ *Engineering, manufacturing, reliability*

“Hype Cycle” of Quantum Computers



Duke Quantum Center

PRATT SCHOOL of ENGINEERING

TRINITY COLLEGE OF ARTS & SCIENCES

The world’s only Quantum Computer User Facility that is

BUILDING quantum computers from the highest performance components: ***individual atoms controlled with light***

USING quantum computers for science

CO-DESIGNING next-generation quantum computers based on scientific use cases

EDUCATING the future quantum workforce

TRANSLATING quantum technology to national and commercial societal needs (e.g., Duke startup IonQ is the first public pure-play quantum computing company)

Physics

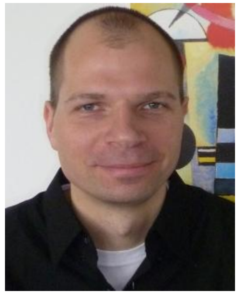
Elec & Computer Eng

Chemistry

Biology & Life Sciences

Mathematics

Computer Science

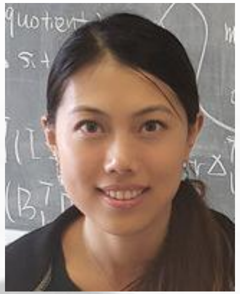

Barthel


Brown


Calderbank


Cetina


Edwards


Feng


Kim


Klco


Kozhanov


Linke


Loh

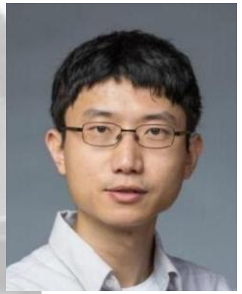

Marvian

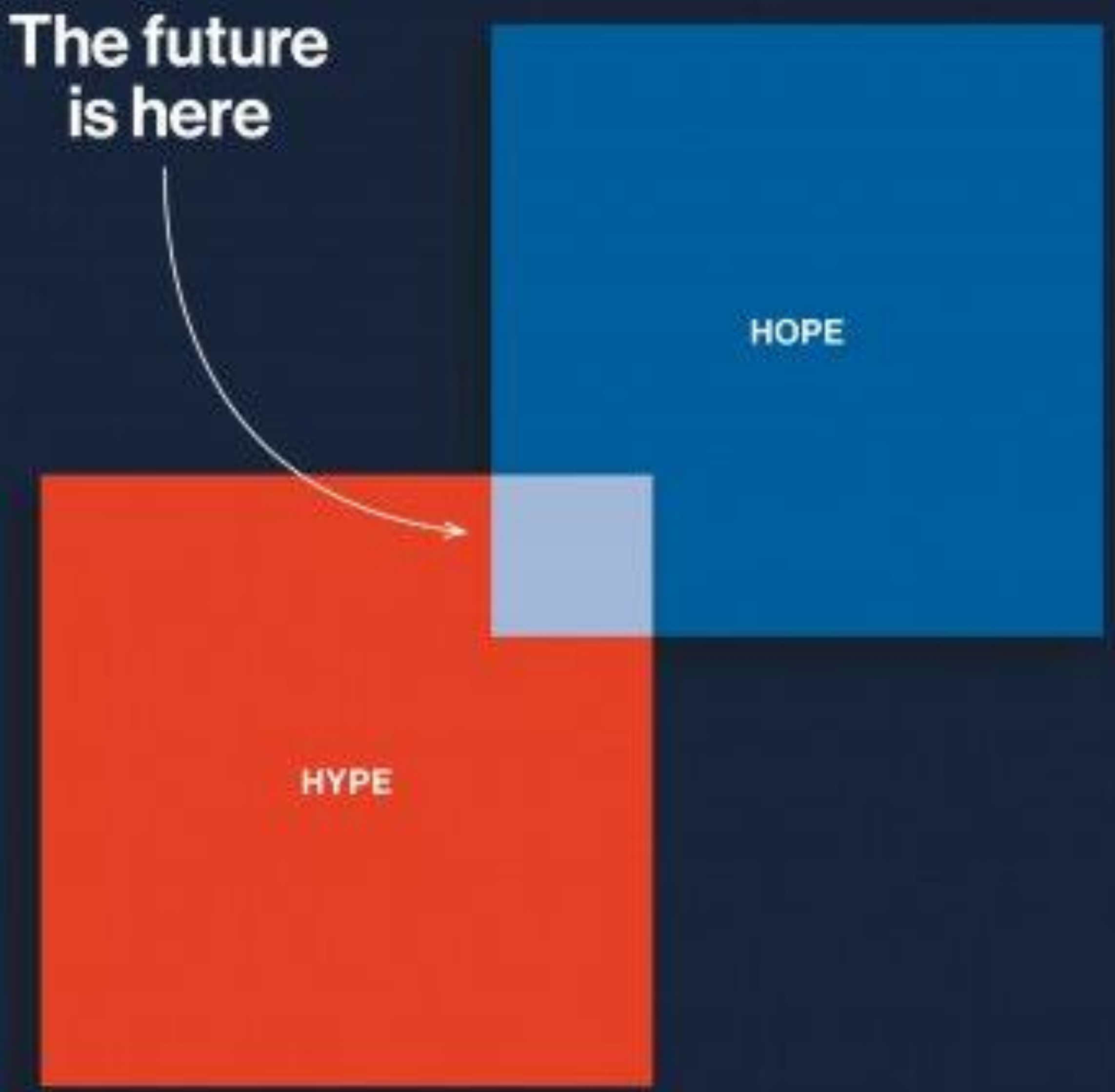

Monroe


Nicholson


Noel


Pfister


Tong



MIT Technology Review
May 2018

Aux Slides

Time-to-solution more important than clock speed

Time T_{app} for solution to application:
depends on architecture (and application)

$T_{app} = \tau_{gate} N_g$ (N_g gates)

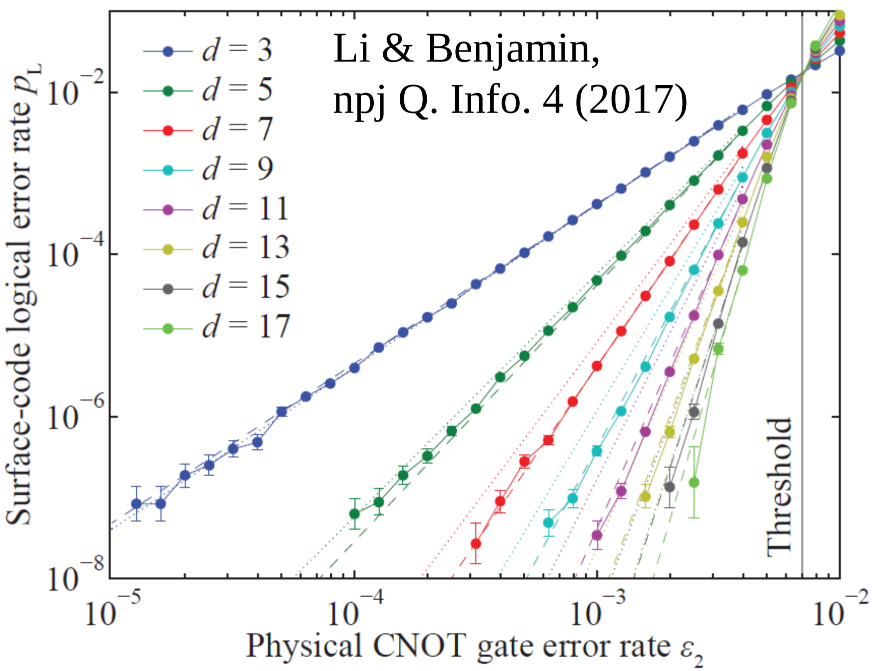
$\sim \tau_{gate} N^2$ (N “logical” qubits)

$\sim \tau_{gate} (NM)^2$ (M overhead factor for error correction: NM total qubits)

$\sim \tau_{gate} \left(NM\sqrt{N}\right)^2$ (connectivity limited in a 2D layout)

$T_{app} \sim \tau_{gate} N^3 M^2 (1+\epsilon)^{NM}$ (necessary repetitions with ϵ measurement error per qubit)

assumes application is useful
(not sampling from a random distribution)



e.g.: $NM = 10^6$ qubits and $\epsilon = 1\%$:
$1.01^{1000000} \sim$ **10^{4000} repetitions**