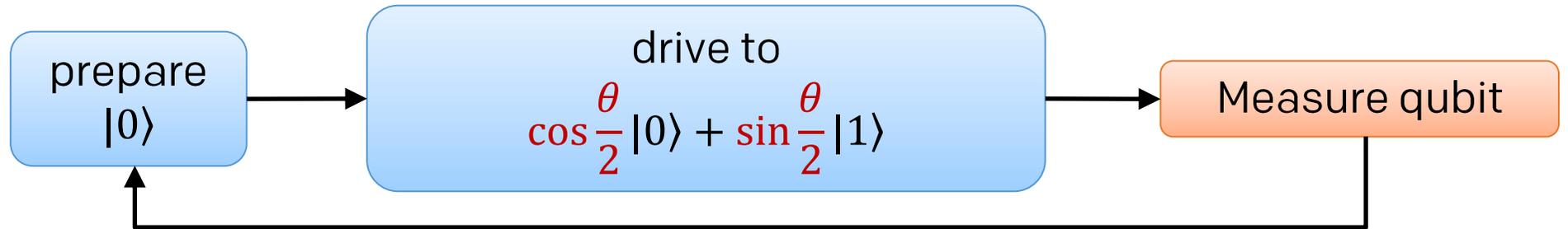


Quantum Computer Systems

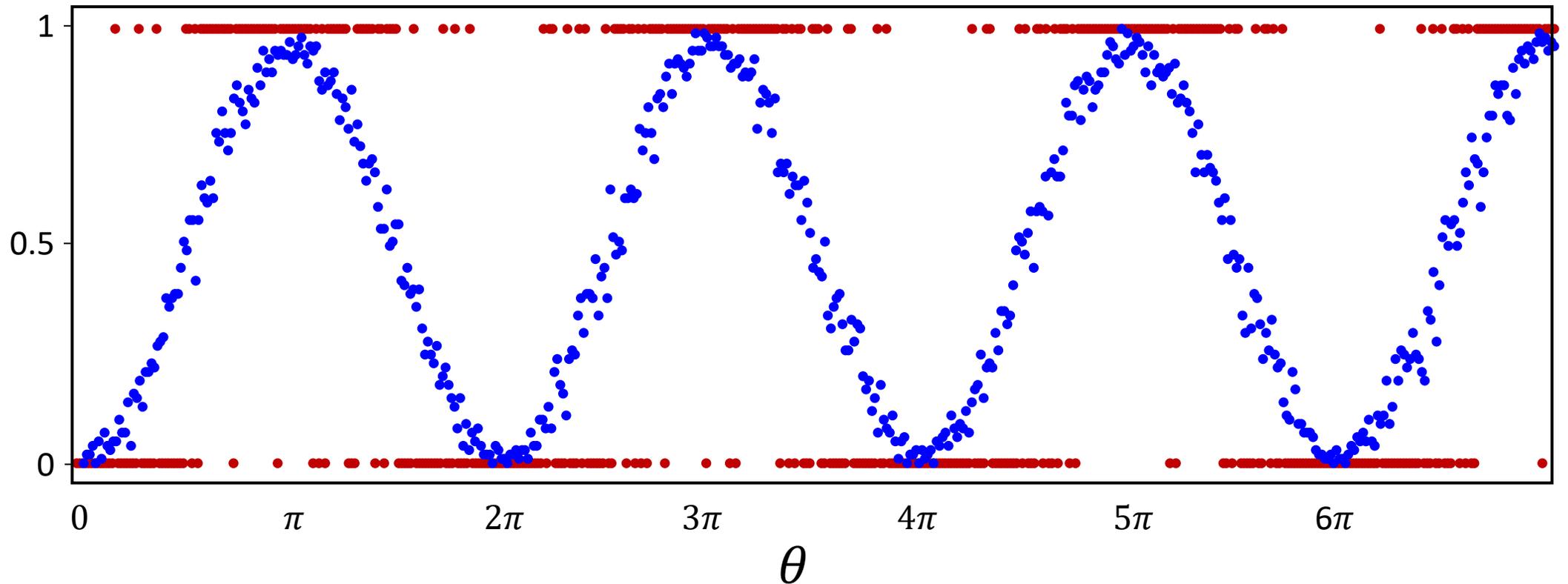
Christopher
Monroe



Coherence and Measurement of a single qubit



average
qubit
result
Prob($|1\rangle$)





John Bell (1928-1990)



NOBELPRISET I FYSIK 2022 THE NOBEL PRIZE IN PHYSICS 2022



KUNGL.
VETENSKAPS-
AKADEMIEN

THE ROYAL SWEDISH ACADEMY OF SCIENCES



Photo: Royal Society

Alain Aspect

Université Paris-Saclay &
École Polytechnique, France

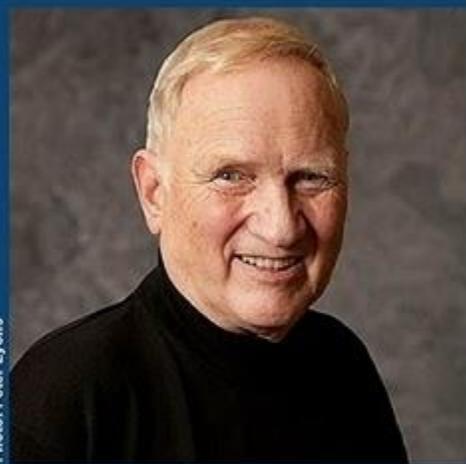


Photo: Peter Lyons

John F. Clauser

J.F. Clauser & Assoc.,
USA

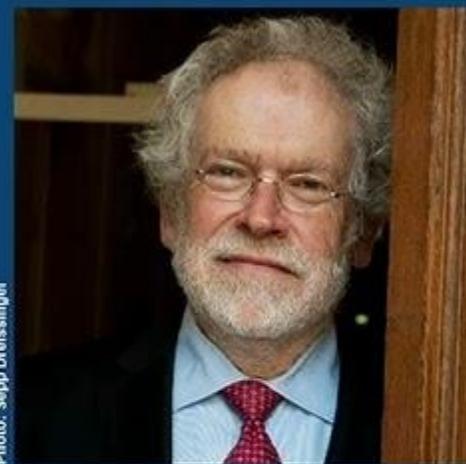


Photo: Sepp Dreissinger

Anton Zeilinger

University of Vienna,
Austria

”för experiment med sammanflätade fotoner som påvisat brott mot Bell-olikheter och banat väg för kvantinformationsvetenskap”

“for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”

#nobelprize

THE
NOBEL
PRIZE

Application: Factoring Numbers

A quantum computer can factor numbers exponentially faster than classical computers

$$39 = 3 \times 13 \text{ (...easy)}$$

$$38647884621009387621432325631 = ? \times ?$$

P. Shor (1994)

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

$$n = P \cdot Q \\ d \cdot e = 1 \pmod{\Phi(n)}$$

Encryption

$$c = m^e \pmod{n} \\ \text{Public Key}(n, e)$$

Decryption

$$m = c^d \pmod{n} \\ \text{private key } (d)$$

Application: Optimization



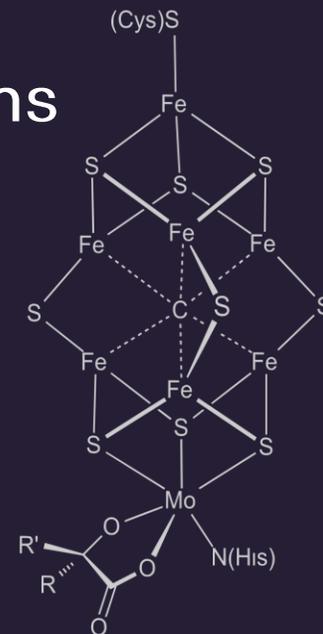
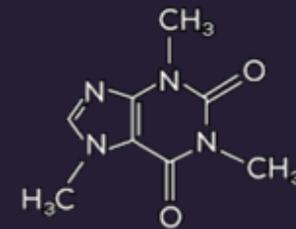
Traveling Salesman problem

what is the shortest path through N cities?



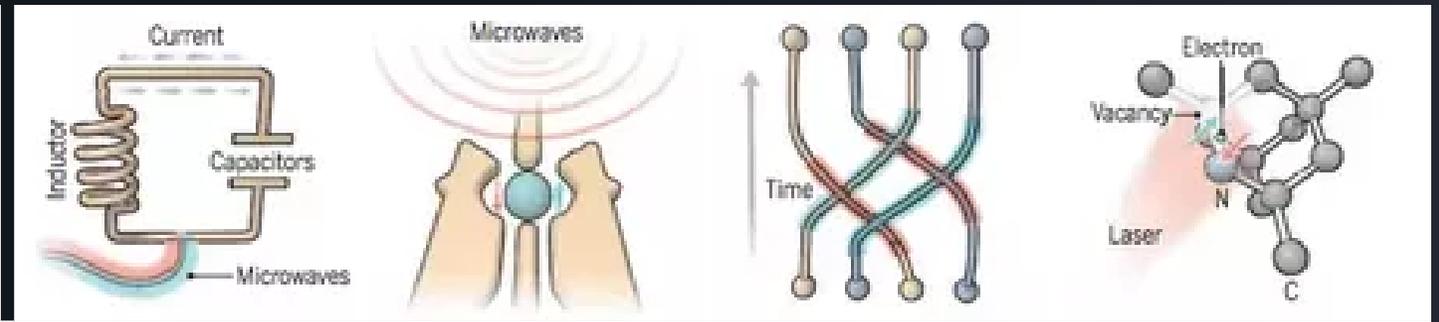
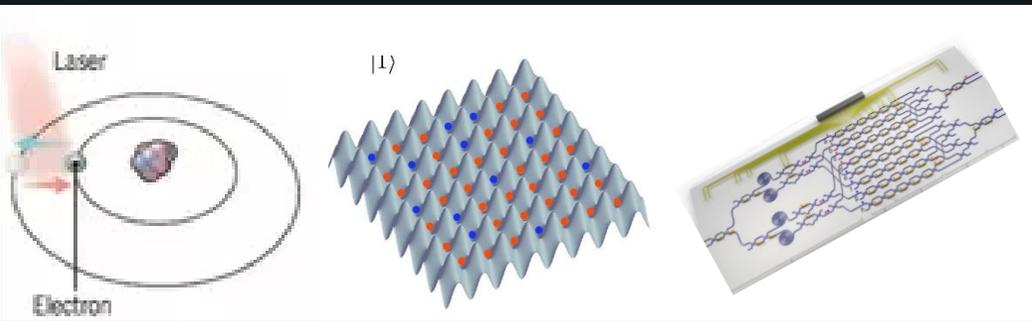
Molecular Simulations

designer materials
new catalysts



Quantum Computer Technologies

Natural Qubits Synthetic Qubits



Trapped Ions
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
Neutral atoms, like ions, store qubits within electronic states. Laser activates the electrons to create interaction between qubits.

Photonics
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.

Superconducting Loops
A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.

Silicon Quantum Dots
These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.

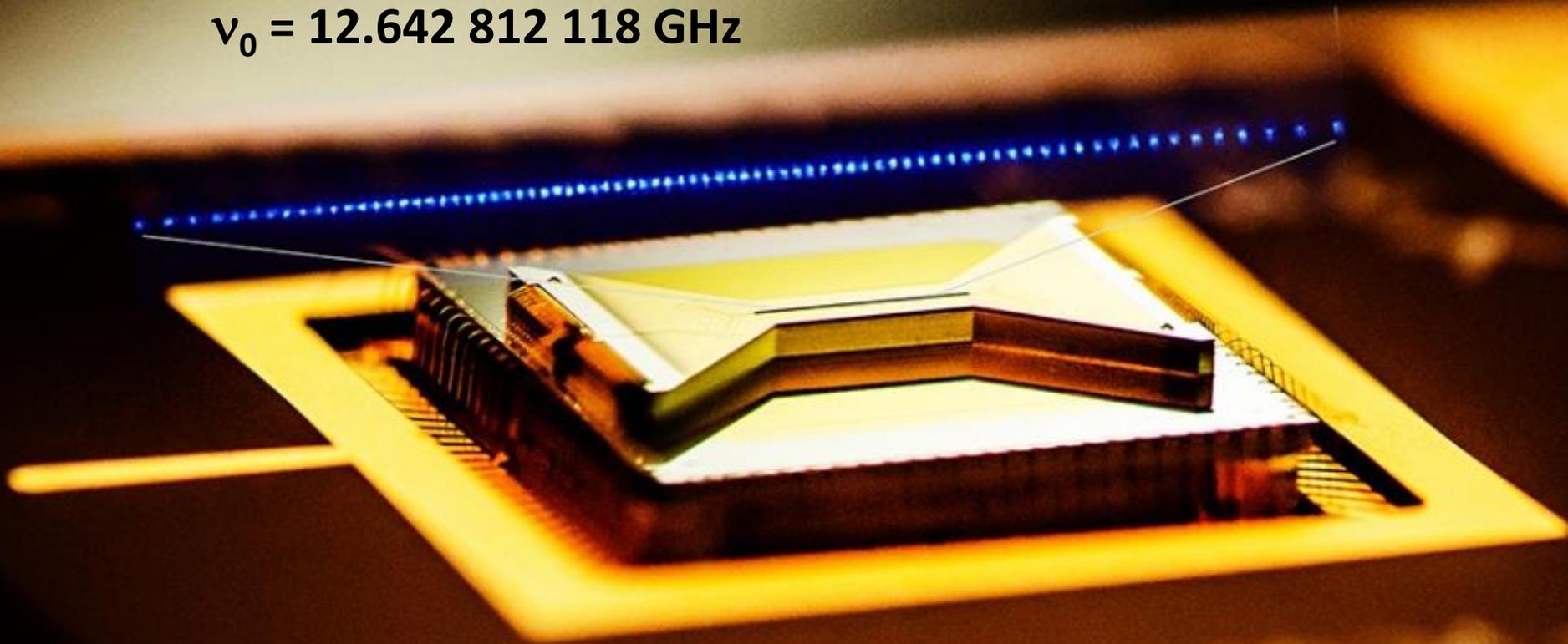
Topological Qubits
Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.

Diamond Vacancies
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	--
Fidelity	99.9%	97%	--
Qubits Connected	High	Very high; low individual control	--
Companies	IonQ, Honeywell/Quantinuum, AQT, Oxford Ionics	Atom Computing, ColdQuanta, QuEra, Pasqal, Planq	Psiquantum, Xanadu
Pros	Very stable. Highest achieved gate fidelities.	Many qubits, 2D and maybe 3D.	Linear optical gates, integrated on-chip.
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.

Qubit Coherence Time (sec)	0.00005	0.03	N/A	10
Fidelity	99.4%	~99%	N/A	99.2%
Qubits Connected	High	Very Low	N/A	Low
Companies	Google, IBM, QCI, Rigetti	HRL, Intel, SQC	Microsoft	Quantum Diamond Technologies
Pros	Can lay out physical circuits on chip.	Borrows from existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	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.

$^{171}\text{Yb}^+$ atoms (80 ion string)
4 μm spacing, 100 μm altitude
 $\nu_0 = 12.642\ 812\ 118\ \text{GHz}$



Quantum Gates between Trapped Ions



dipole-dipole coupling $\Delta E = \frac{e^2}{\sqrt{r^2 + \delta^2}} - \frac{e^2}{r} \approx -\frac{(e\delta)^2}{2r^3}$ $\delta \sim 10 \text{ nm}$
 $e\delta \sim 500 \text{ Debye}$

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

for full entanglement

Native Ion Trap Operation: "Ising" gate

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

$$T_{gate} \sim 10\text{--}200 \mu\text{s}$$

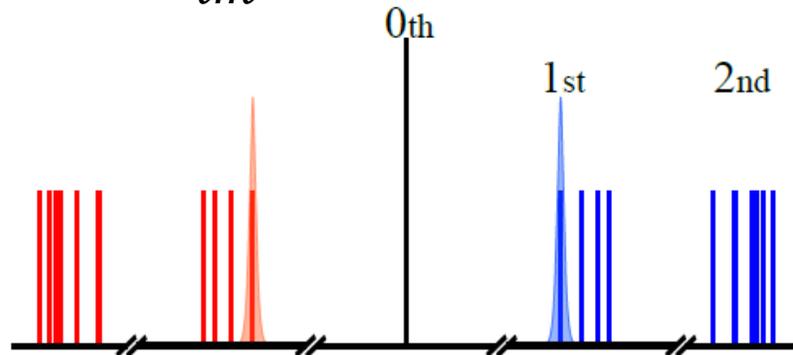
$$F \sim 98\% \text{--} 99.9\%$$

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

Engineering N-body Interactions $U[\varphi] = e^{-i\sigma_x^{(1)}\sigma_x^{(2)}\dots\sigma_x^{(N)}\varphi}$

2-body interaction Milburn, et al., (2000)

$$H = \sum_{im} \eta_{im} \Omega_i \sigma_x^i (a_m^\dagger + a_m)$$

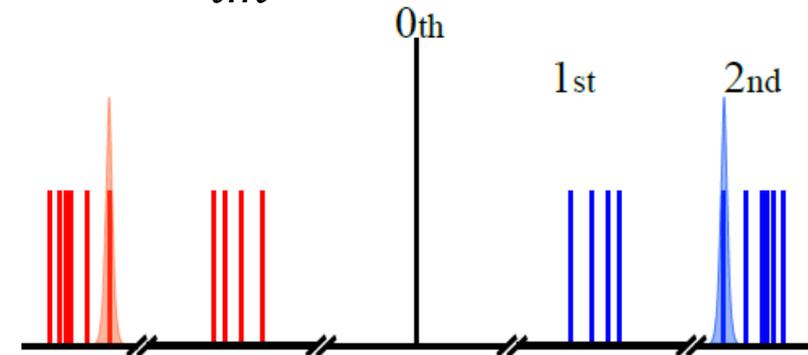


$$\begin{aligned} U &= \mathcal{D}(-i\beta) \mathcal{D}(-\alpha) \mathcal{D}(i\beta) \mathcal{D}(\alpha) \\ &= \mathcal{D}(-i\beta) \mathcal{D}(i\beta) \mathcal{D}(-\alpha) \mathcal{D}(\alpha) e^{-2i\alpha\beta} \\ &= e^{-2i\alpha\beta} \end{aligned}$$

$$H_{eff} = \sum_{ij} J_{ij} \sigma_x^i \sigma_x^j$$

N-body interaction Katz, et al., (2022)

$$H = \frac{1}{2} \sum_{im} \eta_{im}^2 \Omega_i \sigma_x^i (a_m^{\dagger 2} + a_m^2)$$



$$\begin{aligned} U &= \mathcal{S}(-\xi) \mathcal{D}(-iB) \mathcal{S}(\xi) \mathcal{D}(-A) \mathcal{S}(-\xi) \mathcal{D}(iB) \mathcal{S}(\xi) \mathcal{D}(A) \\ &= \mathcal{D}(-iBe^\xi) \mathcal{D}(-A) \mathcal{D}(iBe^\xi) \mathcal{D}(A) \\ &= e^{-2iABe^\xi} \end{aligned}$$

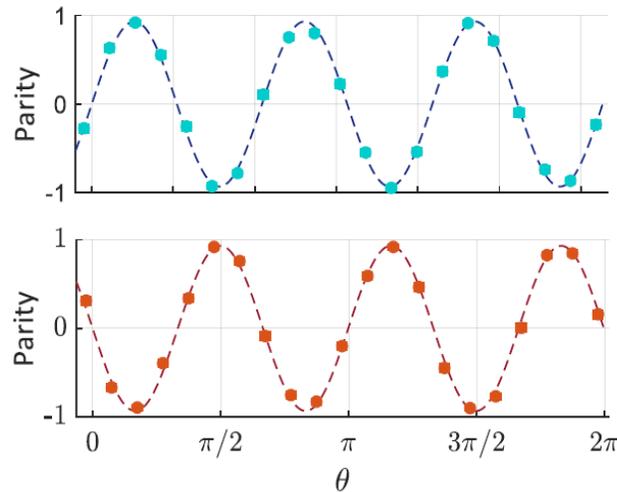
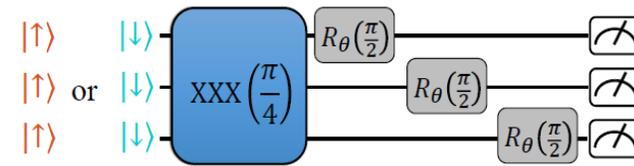
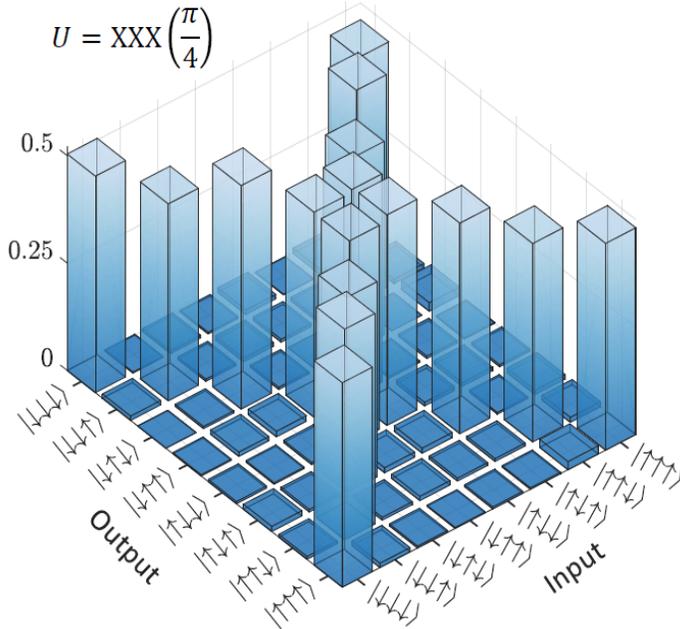
$$H_{eff} = J \prod_i (\mathbb{I} \cosh \xi_i + \sigma_x^i \sinh \xi_i) \quad \xi \sim 1 \text{ will do!}$$

Engineering N-body Interactions

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

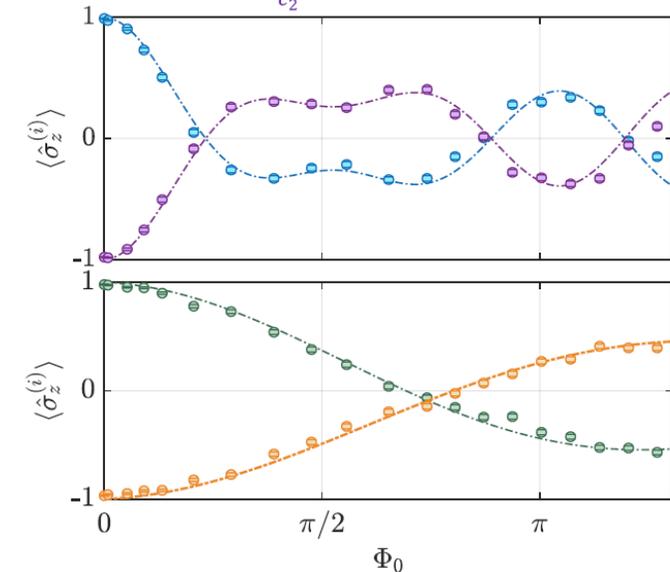
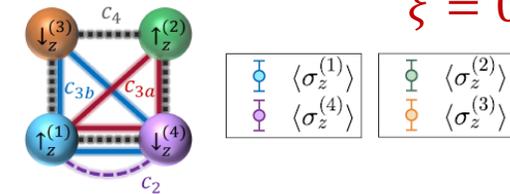
N=3 experiment

$F = 95\%$
 $\tau = 300 \text{ ms}$
 $\xi = 0.255 \text{ (1 dB)}$



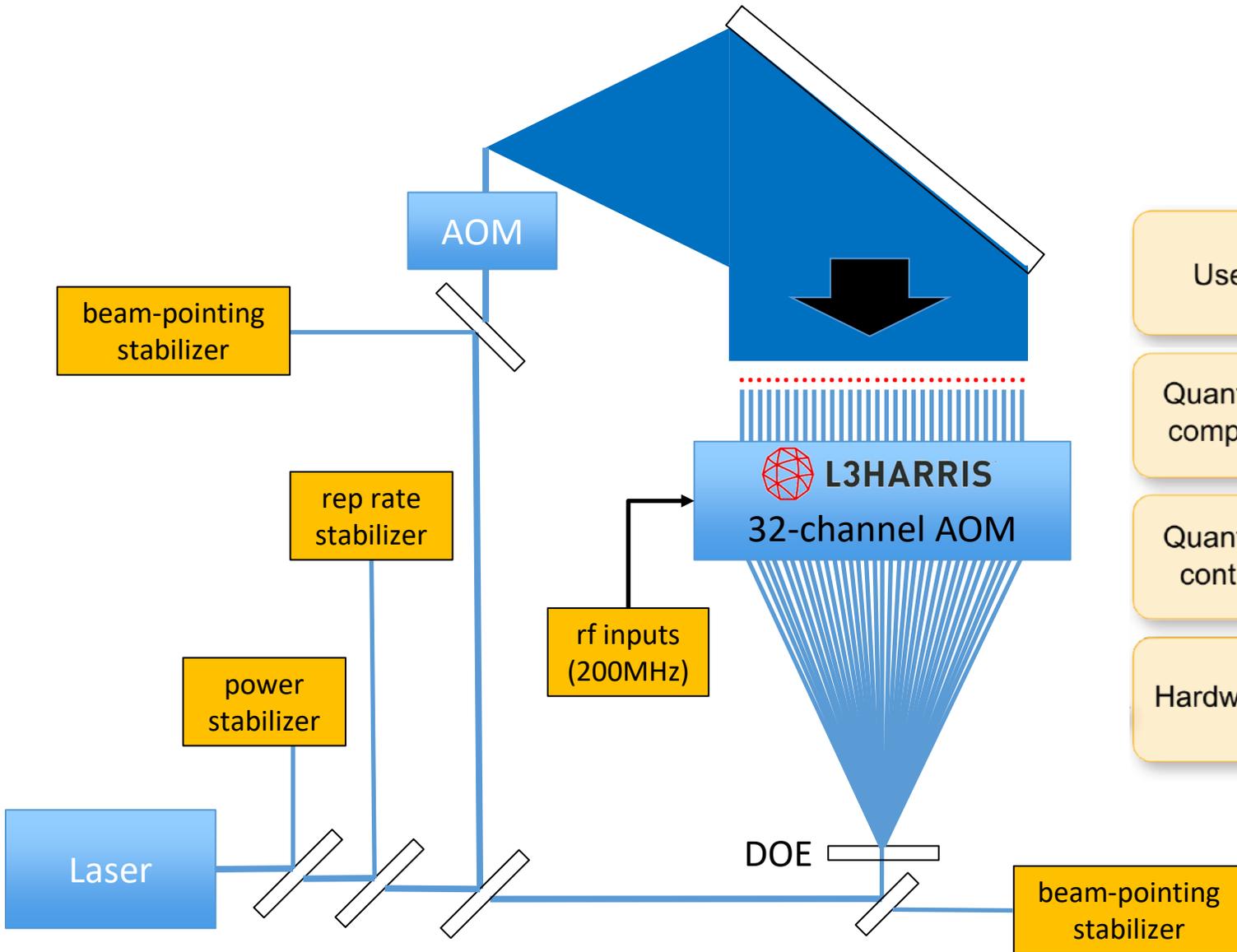
N=4 experiment

$F > 94\%$
 $\tau = 400 \text{ ms}$
 $\xi = 0.32 \text{ (1.4 dB)}$



- O. Katz, M. Cetina, C. Monroe, Phys. Rev. Lett. 129, 063603 (2022) – basic idea
- O. Katz, M. Cetina, C. Monroe, arXiv:2207.10550 (2022) – multimode case and scaling
- O. Katz, L. Feng, A. Risinger, C. Monroe, M. Cetina, arXiv:2209.05691 (2022) – demonstration

Quantum Computer Optical (Raman) Controller



The “Quantum Stack”

User	Quantum Algorithms: <i>Shor, VQE, QSim., etc.</i>
Quantum compiler	Universal gates: <i>Hadamard, C-NOT, C-Phase, etc.</i> Native gates: <i>XX-Gates, R-gates</i>
Quantum control	Pulse shaping: <i>Optimization of XX- and R-Gates</i>
Hardware	Optical addressing: <i>Qubit manipulation/ detection</i> Ion trap: <i>Linear ion-chain, optical access, etc.</i>

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

N. Linke,... *PNAS* **114**, 13 (2017)

Applications/Collaboration Highlights

Year	Application	Reference	Collaborator	Institute
2017	Time Crystal Observation	<i>Nature</i> 543, 217	N. Yao	Berkeley
	Dynamical Phase Transition	<i>Nature</i> 551, 601	A. Gorshkov	NIST
2018	Bayesian Game	<i>QST</i> 3, 045002	N. Solmeyer	Army Res. Lab.
	Machine learning for qubit detection	<i>J. Phys. B</i> 51174006	M. Hafezi	JQI
	Full Adder, Parallel CNOT	<i>Nature</i> 567, 61	D. Maslov	NSF
2019	Generative-modeling ML	<i>Science Adv.</i> 5, eaaw9918	A. Perdomo-Ortiz	NASA
	Deuteron structure simulation	<i>PRA</i> 100, 62319	R. Pooser, O. Shehab	ORNL, IonQ
	Quantum Scrambling and Black Holes	<i>Nature</i> 567, 61	B. Yoshida, N. Yao	Perimeter, Berkeley
	Circuit			Perimeter, Intel Corp.
	Analog			T, Microsoft Inc.
2020	Quasi			T
	Many-			Erlangen
	Quant			, Chennai
	Fault-			Q
2021	Preth			keley
	NMR S			ward
	Meas			T, Princeton, Berkeley
	Certif			keley, CalTech
	Cross			sbruck
	Ising S			owa
	Schw			D
	Quant			sbruck, UMD
2022	Edge-			sbruck, Rice
	Triangle game	<i>in progress</i>	Akimasa Miyake	UNM
	Molecular Cluster simulations	<i>in progress</i>	Nicolas Sawaya	Intel Corp.
	Ring-molecule simulation	<i>in progress</i>	Rob Parrish	QCWare



Norbert Linke
Asst. Prof.
Duke Physics



Marko Cetina
Asst. Prof.
Duke Physics



Crystal Noel
Asst. Prof.
Duke ECE and Physics

Quantum Simulation of Exotic Magnetism

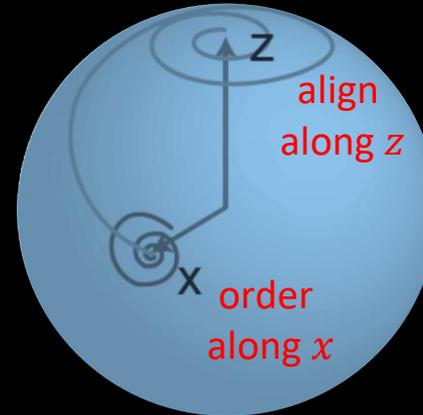
Dynamical Phase Transition with 50+ Qubits

J. Zhang, et al., Nature 551, 601 (2017)

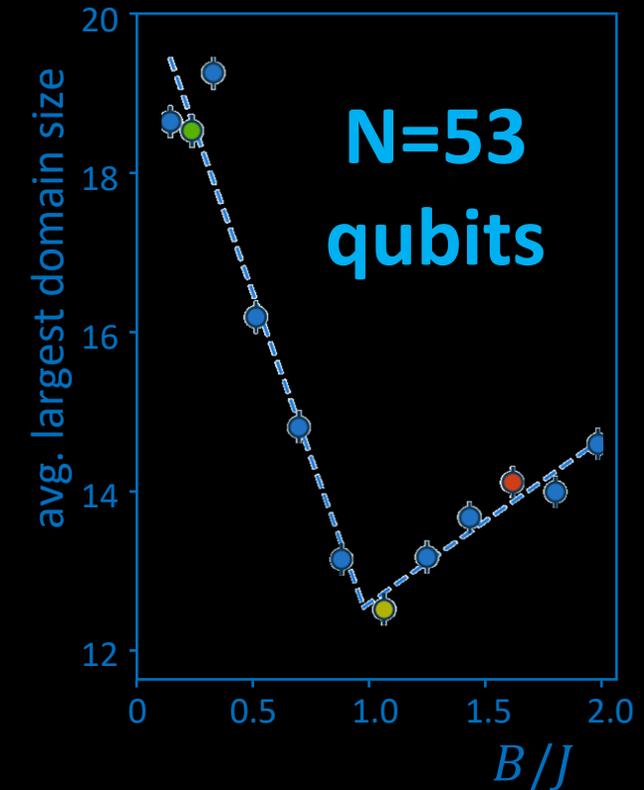
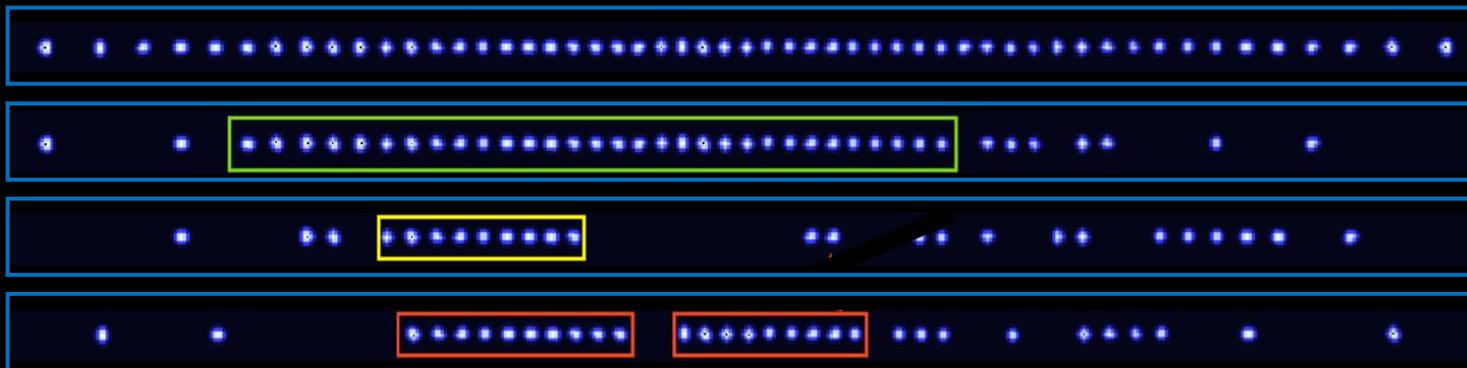
(1) Prepare spins along x

(2) Quench spins to $H = \sum_{i<j} \frac{J}{|i-j|^\alpha} \sigma_x^i \sigma_x^j + \mathbf{B} \sum_i \sigma_z^i$

(3) Measure along x



increase B/J



Recent Quantum Simulations

- Asymptotic confinement: W. L. Tan, et al., Nature Physics (2021)
- Prethermal Time Crystal: A. Kyriianidis, et al., Science 372, 1192 (2021)
- Stark Manybody Localization: W. Morong, et al., Nature 599, 393 (2021)
- Measurement percolation phases: C. Noel, et al., Nature Physics 18, 760 (2022)



Alexey Gorshkov
(NIST/JQI)



David Huse
(Princeton)



Sonika Johri
(Intel/IonQ)

See also:
Innsbruck (ions)
Harvard (neutrals)

Cosmology + Quantum Gravity

Quantum Scrambling



Beni Yoshida
(Waterloo/CalTech)

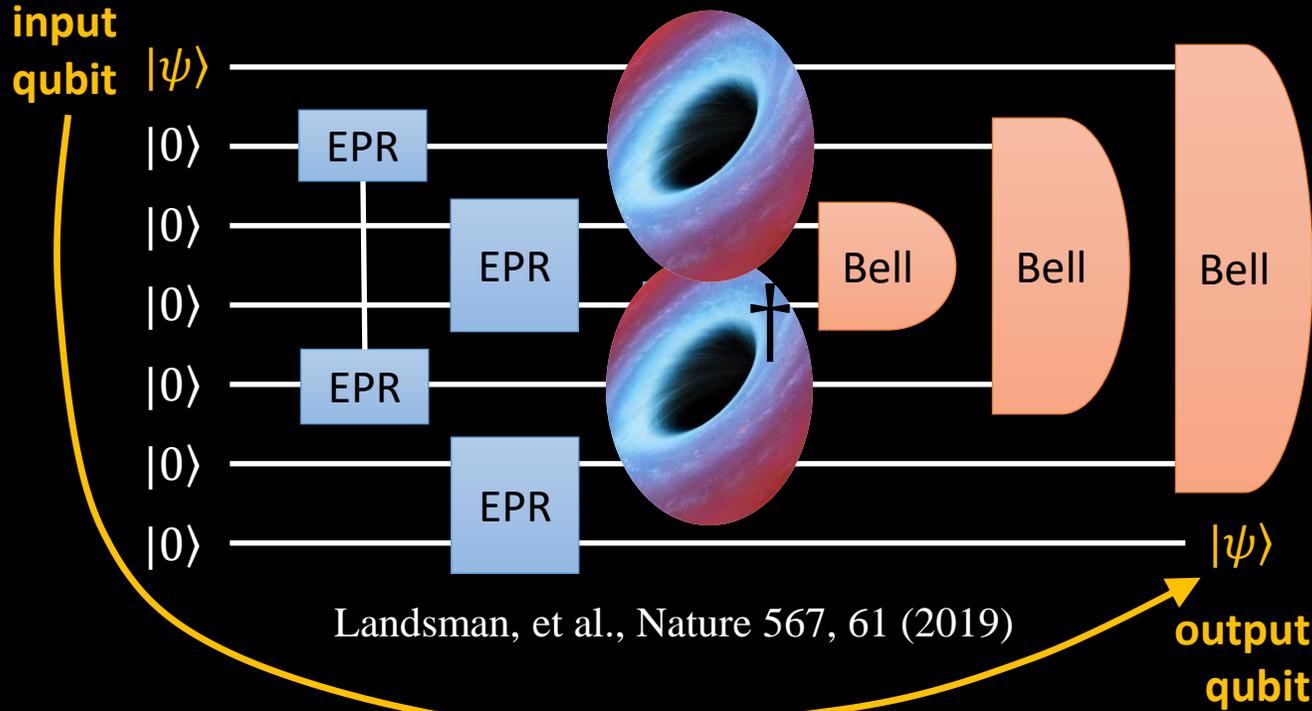


Leonard Susskind
(Stanford)



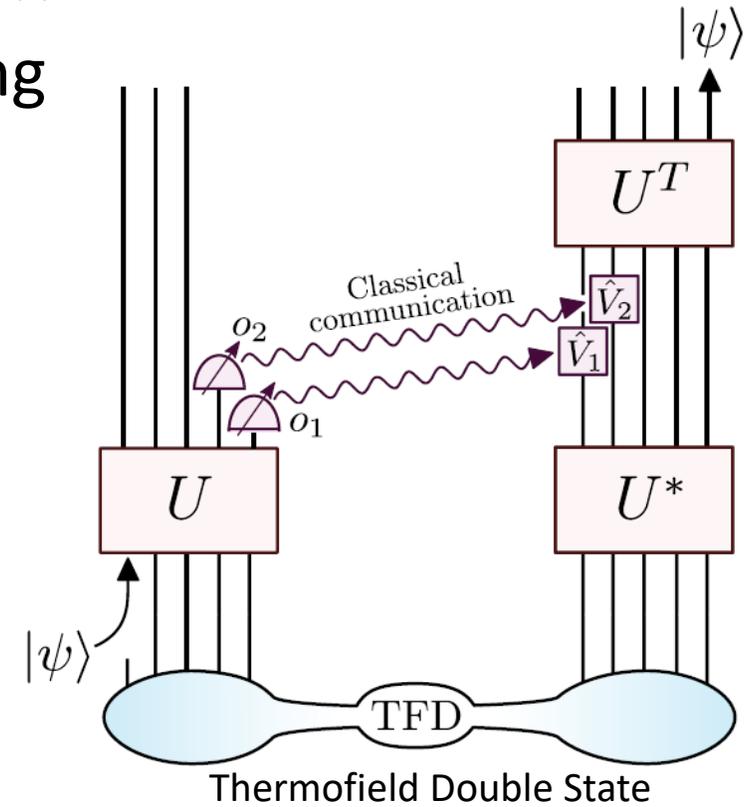
Norman Yao
(Berkeley)

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



Successful teleportation if U scrambles

Coming
Soon



T. Schuster, B. Kobrin, P. Gao, I. Cong, E. T. Khabiboulline, N. M. Linke, M. D. Lukin, C. Monroe, B. Yoshida, and N. Y. Yao, PRX 12, 031013 (2022).

Ion Trap Laboratory 2014

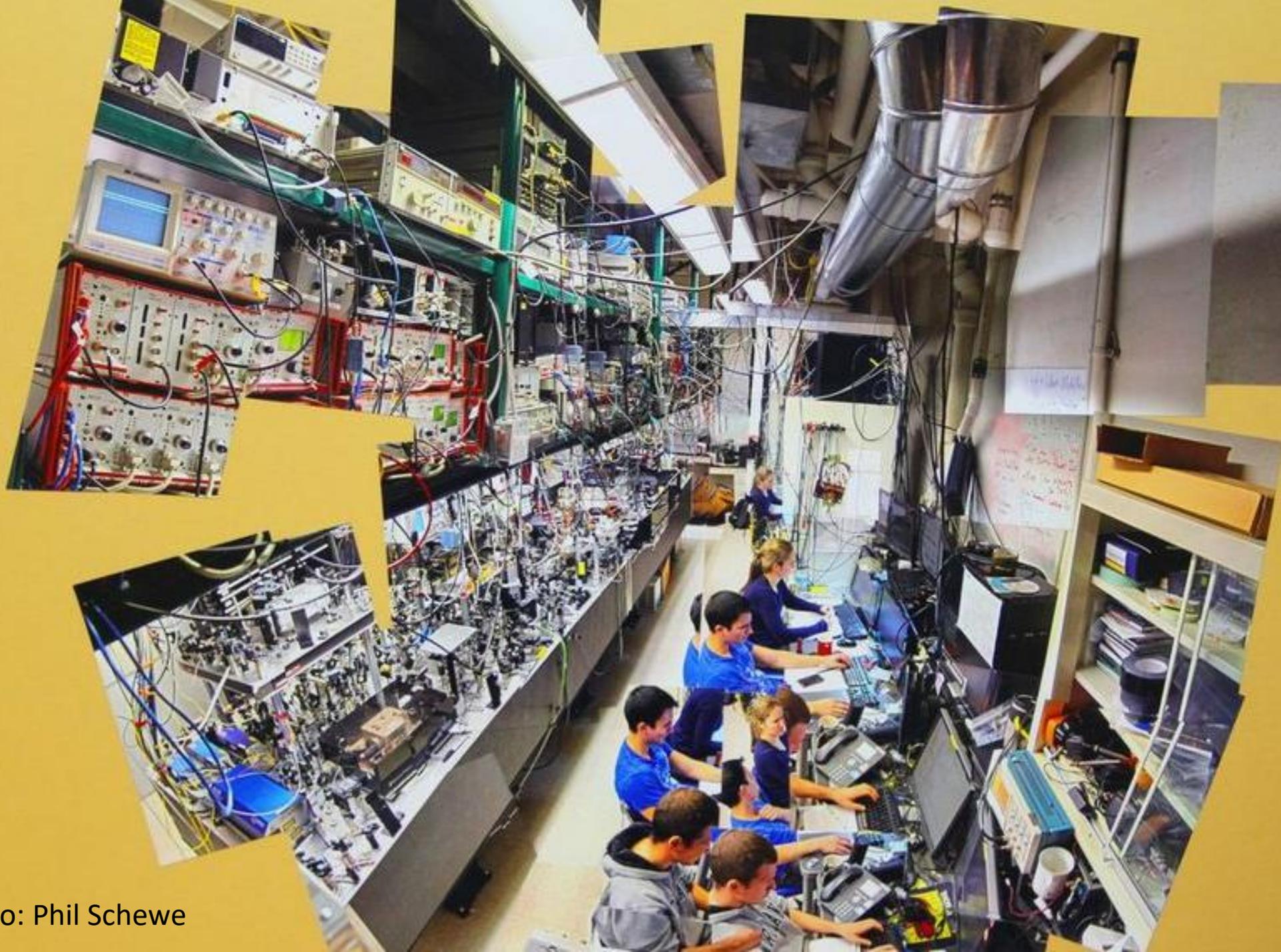
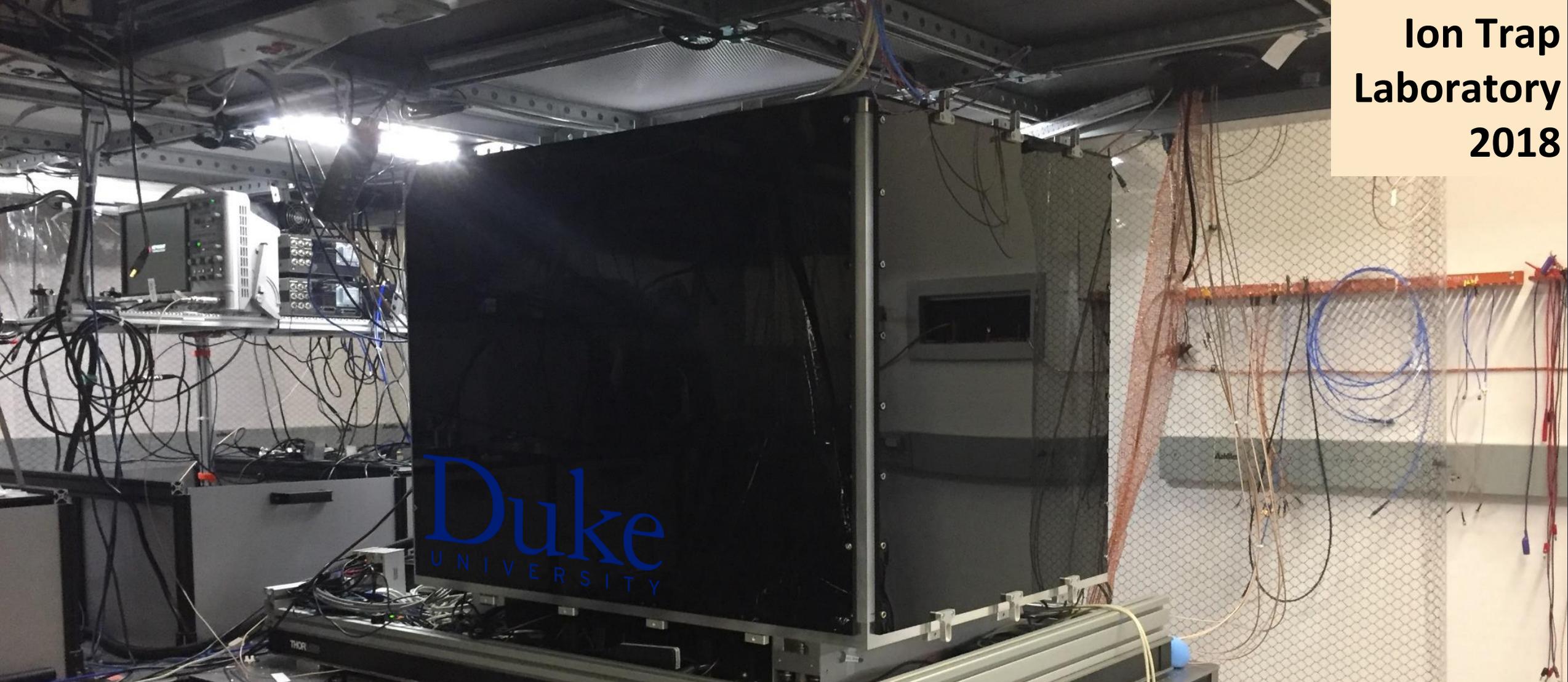


Photo: Phil Schewe

Ion Trap Laboratory 2018





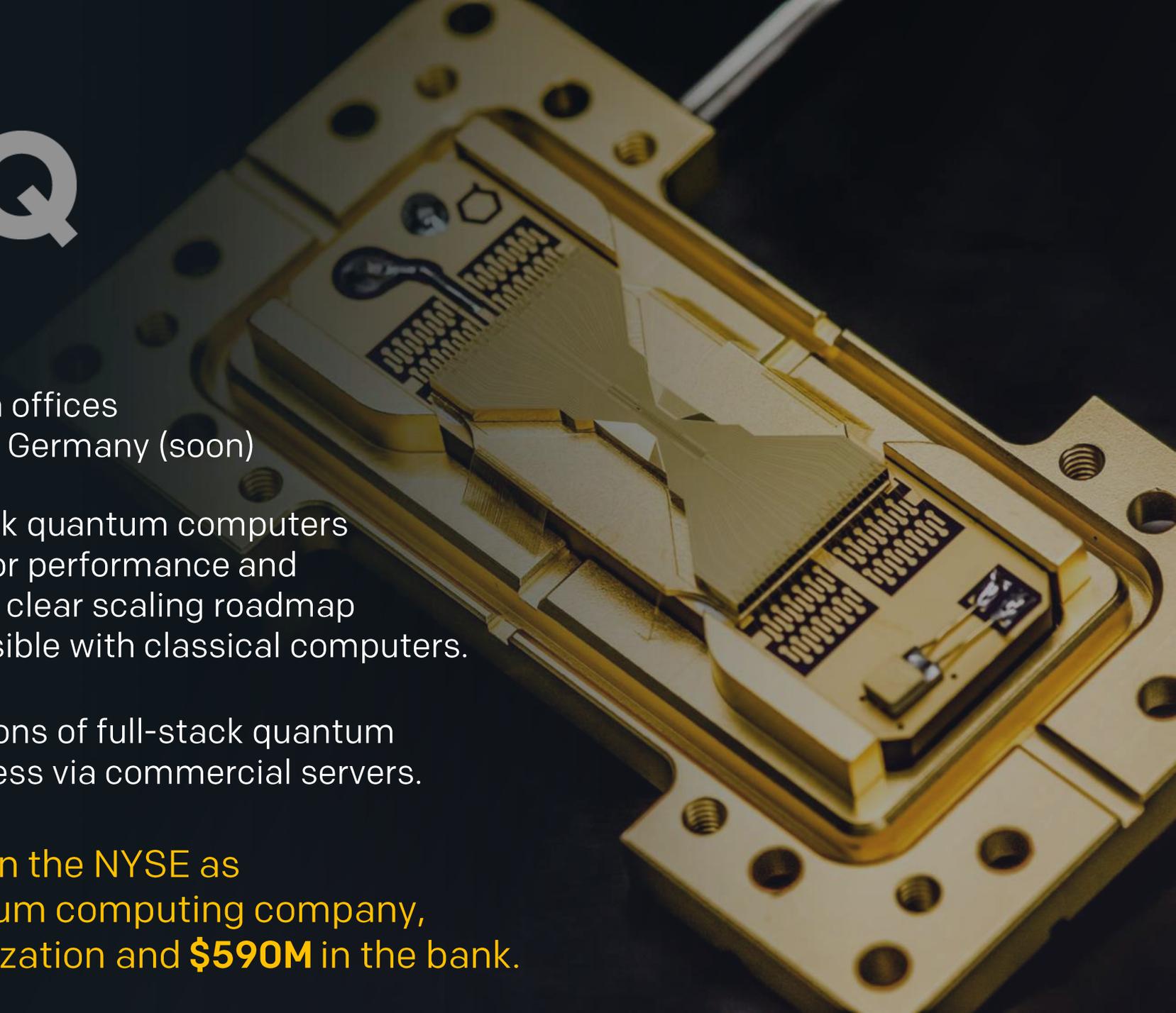
IONQ

IonQ was founded in 2015 by Jungsang Kim & Chris Monroe, with offices in College Park MD, Seattle WA and Germany (soon)

IonQ is a leader in building full-stack quantum computers based on trapped ions, with superior performance and reconfigurable circuitry. IonQ has a clear scaling roadmap to tackle problems that are impossible with classical computers.

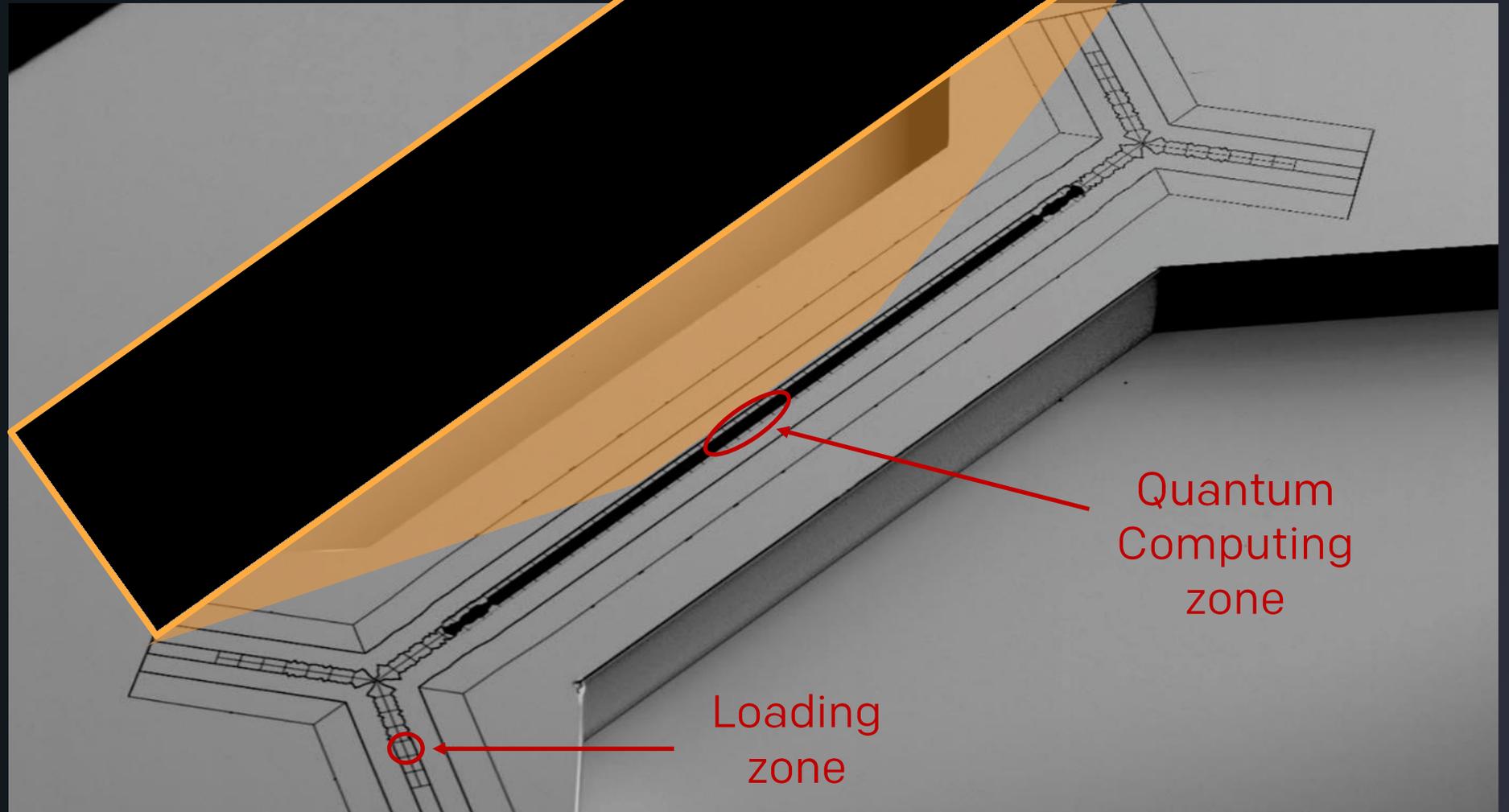
IonQ has released several generations of full-stack quantum computer systems, with cloud access via commercial servers.

On Oct 1, 2021 IonQ was listed on the NYSE as the first public pure-play quantum computing company, with a **\$2 billion** market capitalization and **\$590M** in the bank.

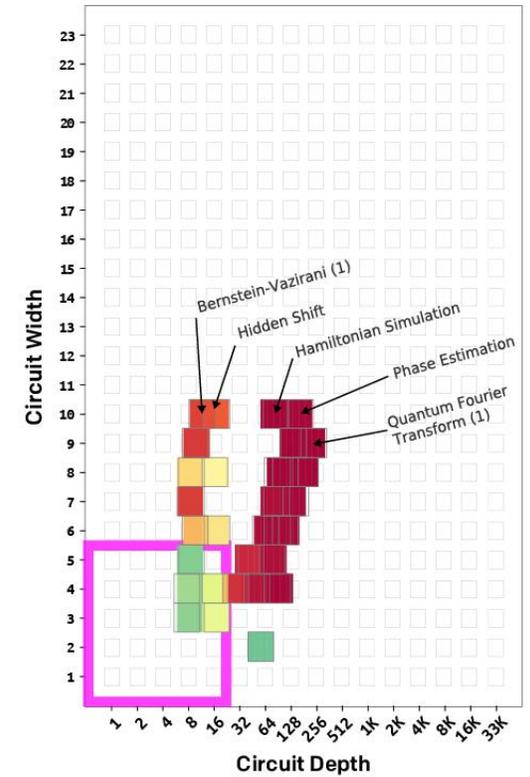
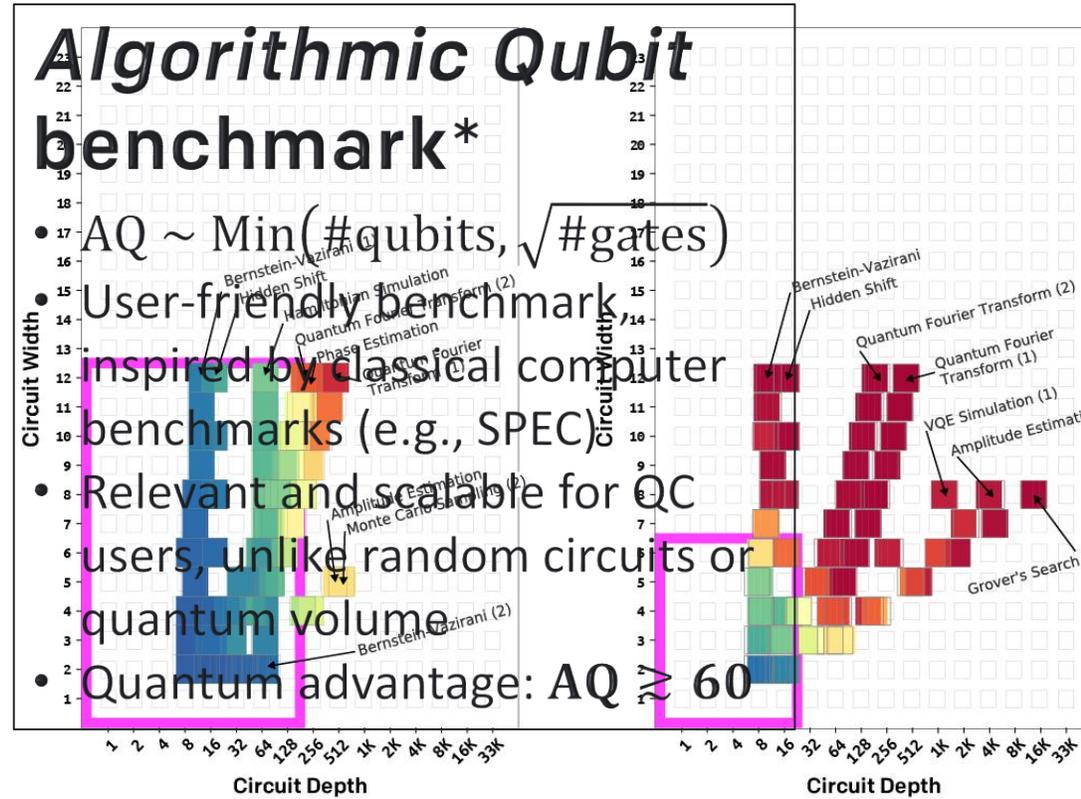
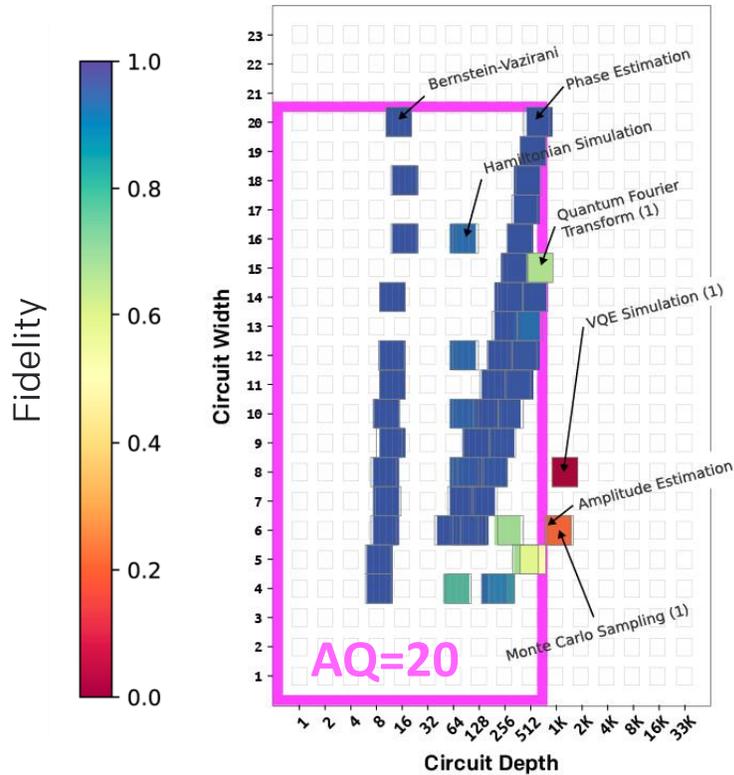


Autoloading register

N=24 qubits request



IonQ Aria System Performance (Gen 5)



Quantinuum

Model H1.1

IBM

Falcon r4P (Guadalupe)

Rigetti

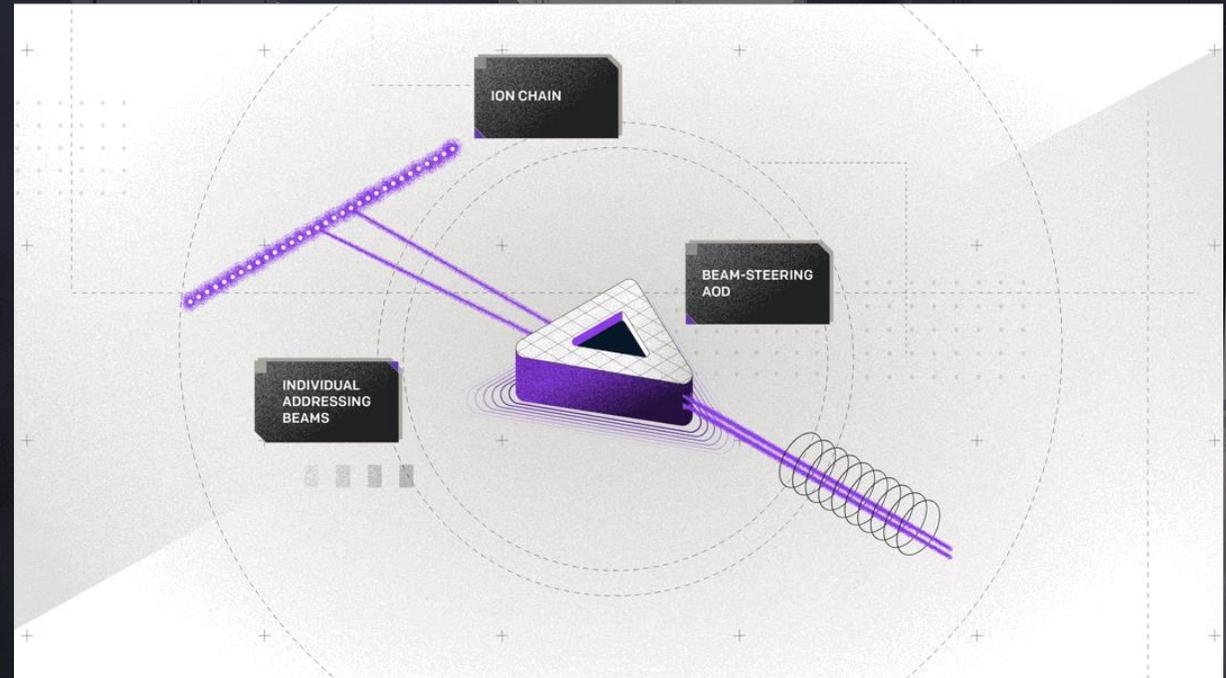
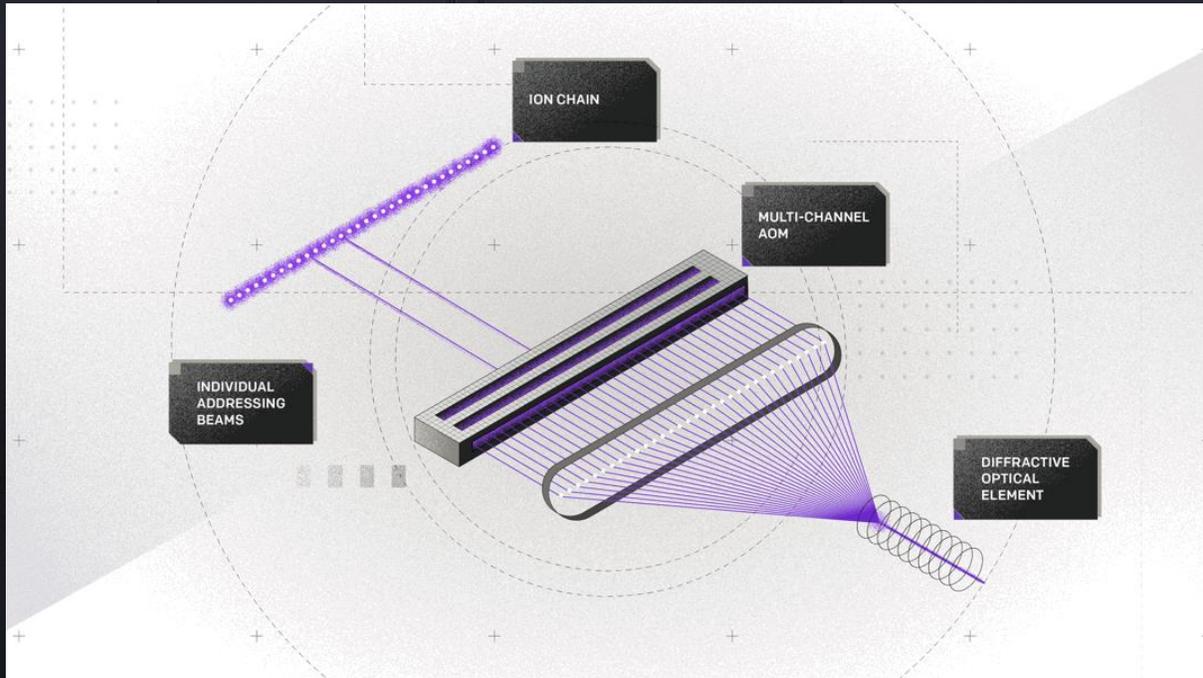
Aspen-M-1

* <https://ionq.com/posts/february-23-2022-algorithmic-qubits>

IBM and Quantinuum data adapted from US Quantum Economic Development Consortium, arXiv 2110.03137 (2022); Rigetti data taken on AWS-Bracket (Feb 2022)

IonQ Forte The Latest Quantum Computer (Gen 6)

Forte, IonQ's second system with a capacity of up to 32 qubits, uses a software-enabled dynamic laser system to improve gate performance



Illustrated comparison of the AOD architecture in IonQ Forte (left) and the AOM architecture (right) in earlier IonQ systems

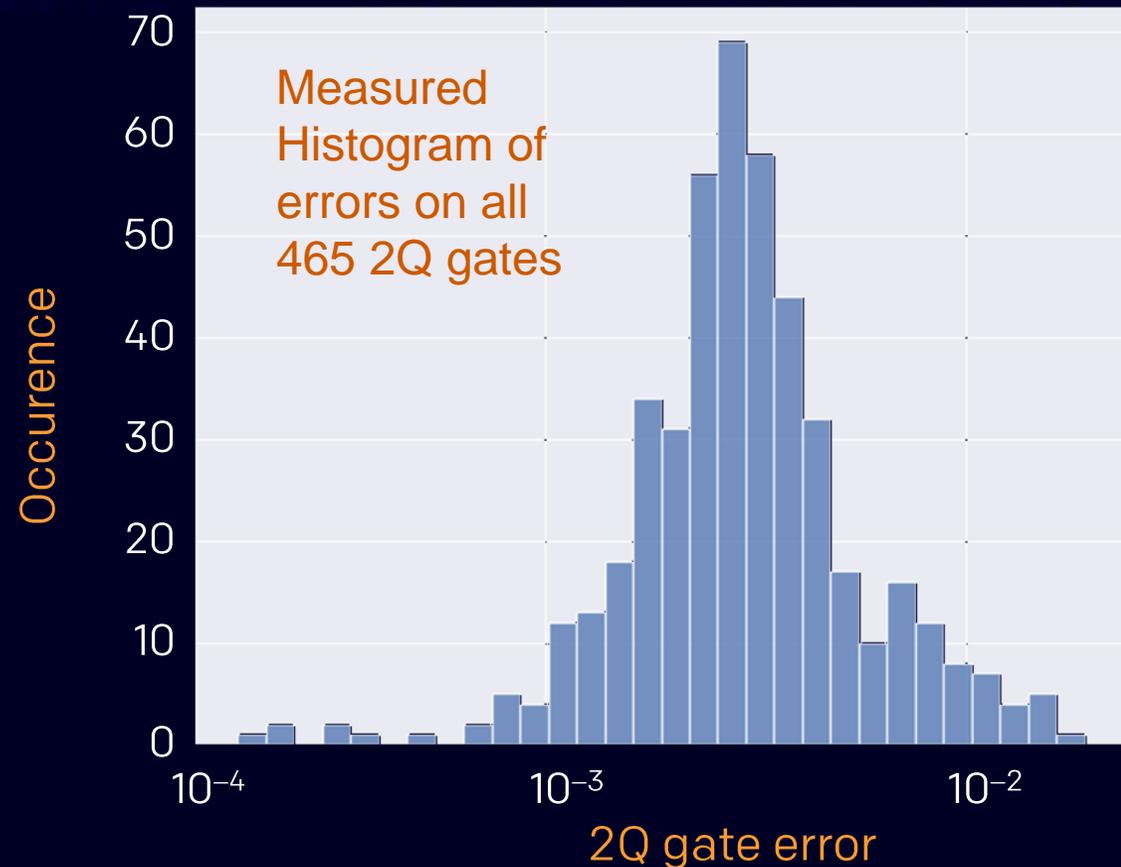
IonQ Forte The Latest Quantum Computer (Gen 6)



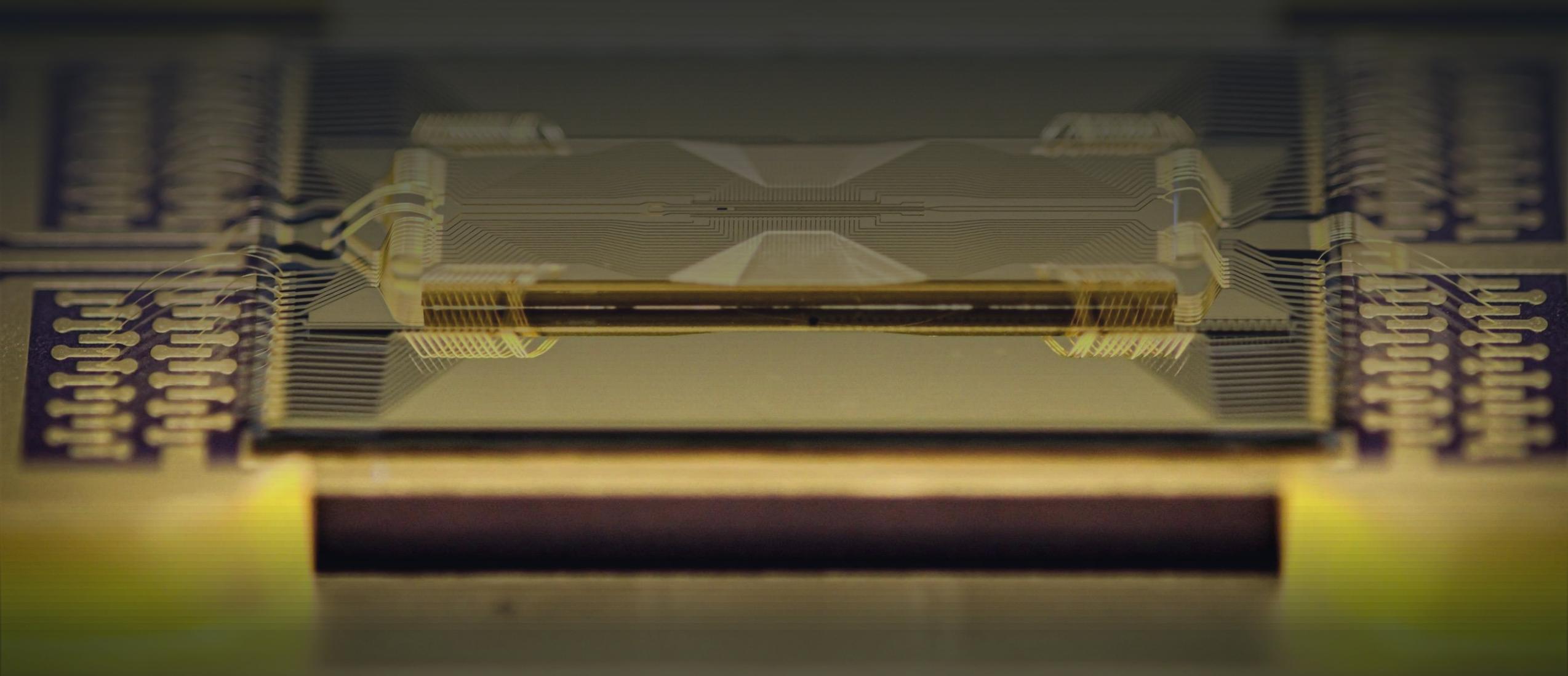
Single Core: $N_i=35$ ions
 $N_q=31$ qubits

$\binom{31}{2} = 465$ possible 2Q gates

**99.6% avg. 2Q fidelity on
31 fully-connected qubits**



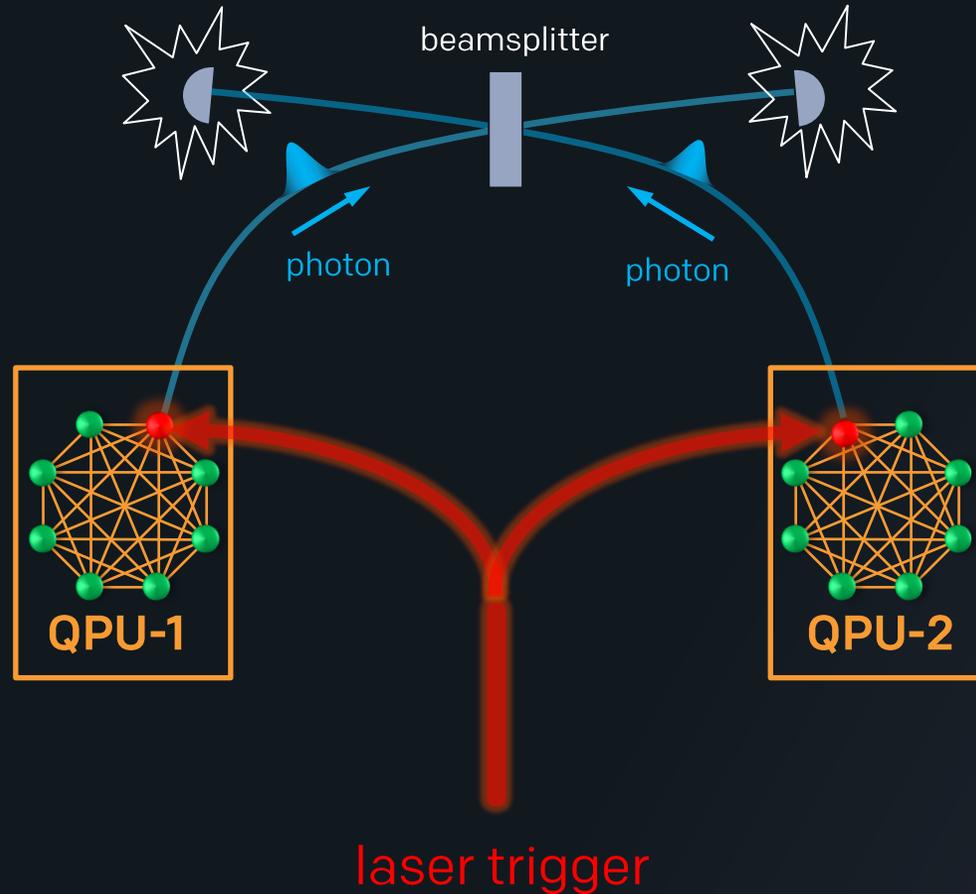
Modular Scaling I: ion shuttling between zones



Modular Scaling I: ion shuttling between zones

Kielpinski, Monroe, Wineland, Nature 417, 709 (2002)
Pino, et al. (Honeywell) Nature 592 209-213 (2021)

Modular Scaling II: photonic interconnects between chips



Hong, Ou, Mandel, PRL 59, 2044 (1987)
Y.H. Shih & C. O. Alley, PRL 61, 2921 (1998)
Simon & Irvine, PRL 91, 110405 (2003)
L.-M. Duan, et. al., QIC 4, 165 (2004)
Y. L. Lim, et al., PRL 95, 030505 (2005)

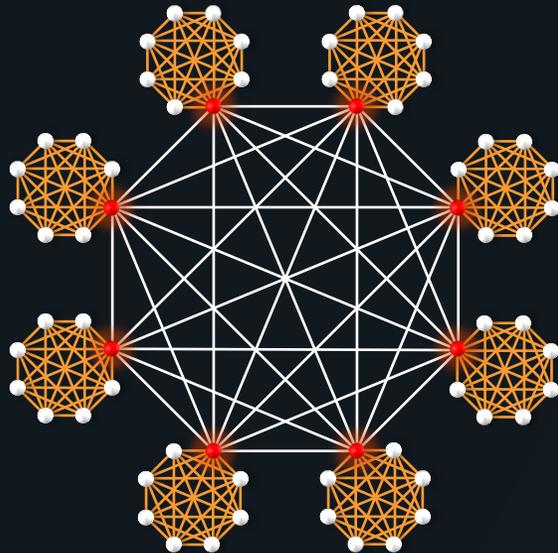
Trapped Ions [Nature 449, 68–71] (2007)
Trapped Neutrals [PRL 110, 140403] (2013)
NV-diamond [Science 345, 532] (2014)
Quantum Dots [Nature Phys. 12, 218] (2015)
Superconductors [PRX 6, 031036] (2016)

Modular Scaling II: photonic interconnects between chips

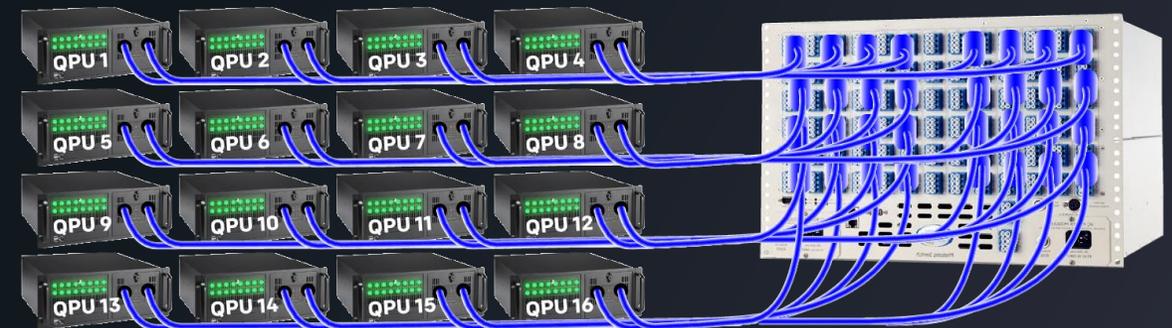
Individual **QPU units** connected via **photonic networking**.

- Utilizes **existing, well-understood photonic** and optical fiber technology
- Reconfigurable optical switching allows for **full modular connectivity**

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



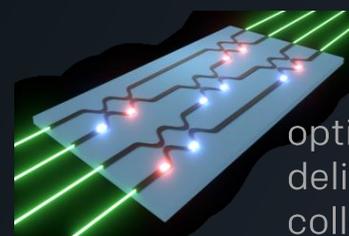
Ion Trap Modules



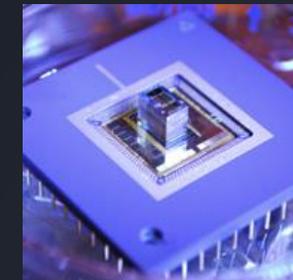
Multiport Optical Switch

Optical Fibers

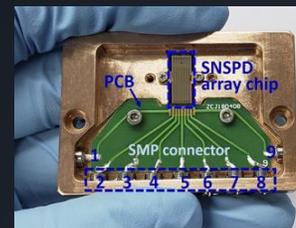
Integrated Optical Technology



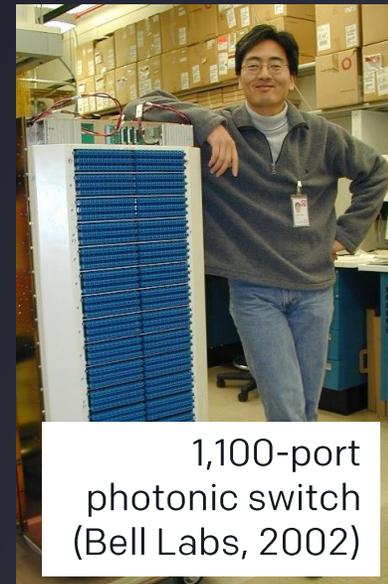
optical delivery & collection



optical cavities



SNSPD detectors



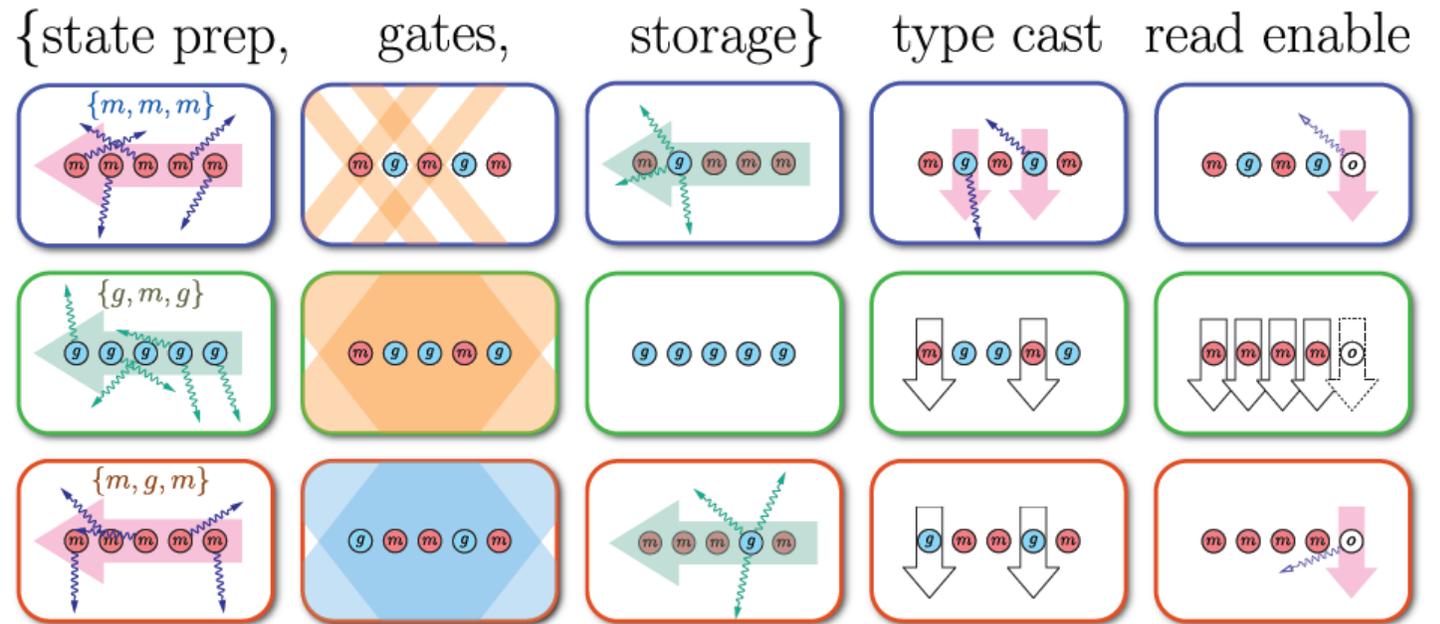
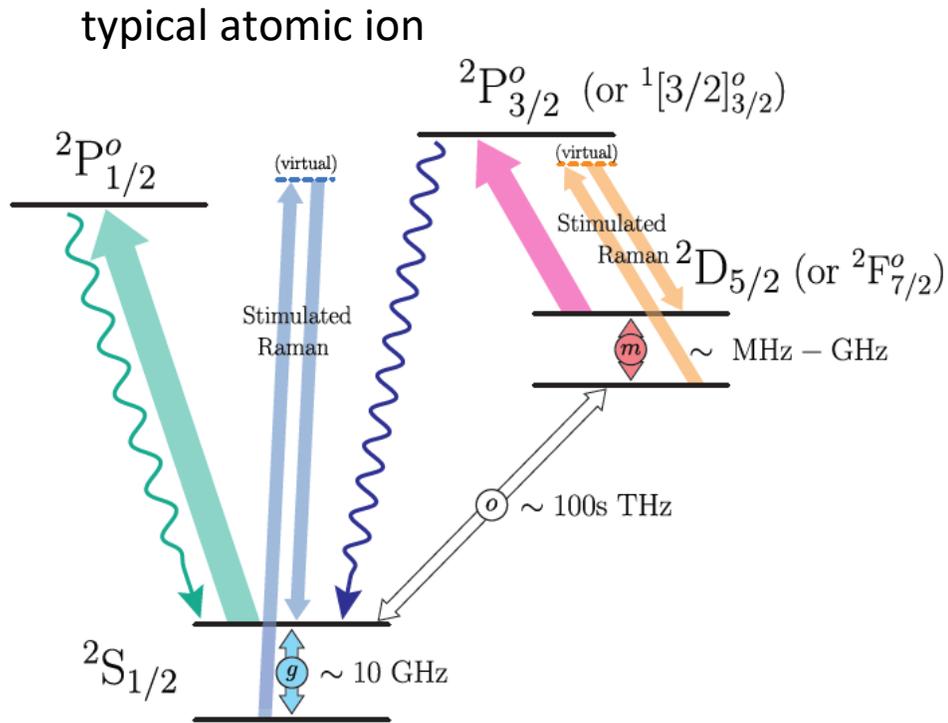
1,100-port photonic switch (Bell Labs, 2002)

Software-defined ion functionality

“OMG” architecture
(optical/metastable/ground)

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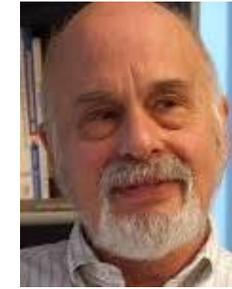




Duke Quantum Center



Brown



Calderbank



Cetina



Kim

A Quantum Computer User Facility that

BUILDS quantum computers from the highest performance components

USES quantum computers for science

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

TRANSLATES quantum technology to national and commercial societal needs



Klco



Kozhanov



Linke

Physics

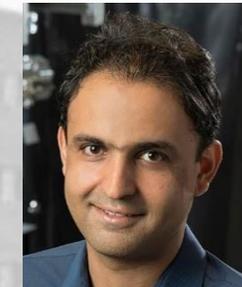
Electrical/Computer Engineering

Chemistry

Biology & Life Sciences

Mathematics

Computer Science



Marvian



Monroe



Noel



Pfister



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