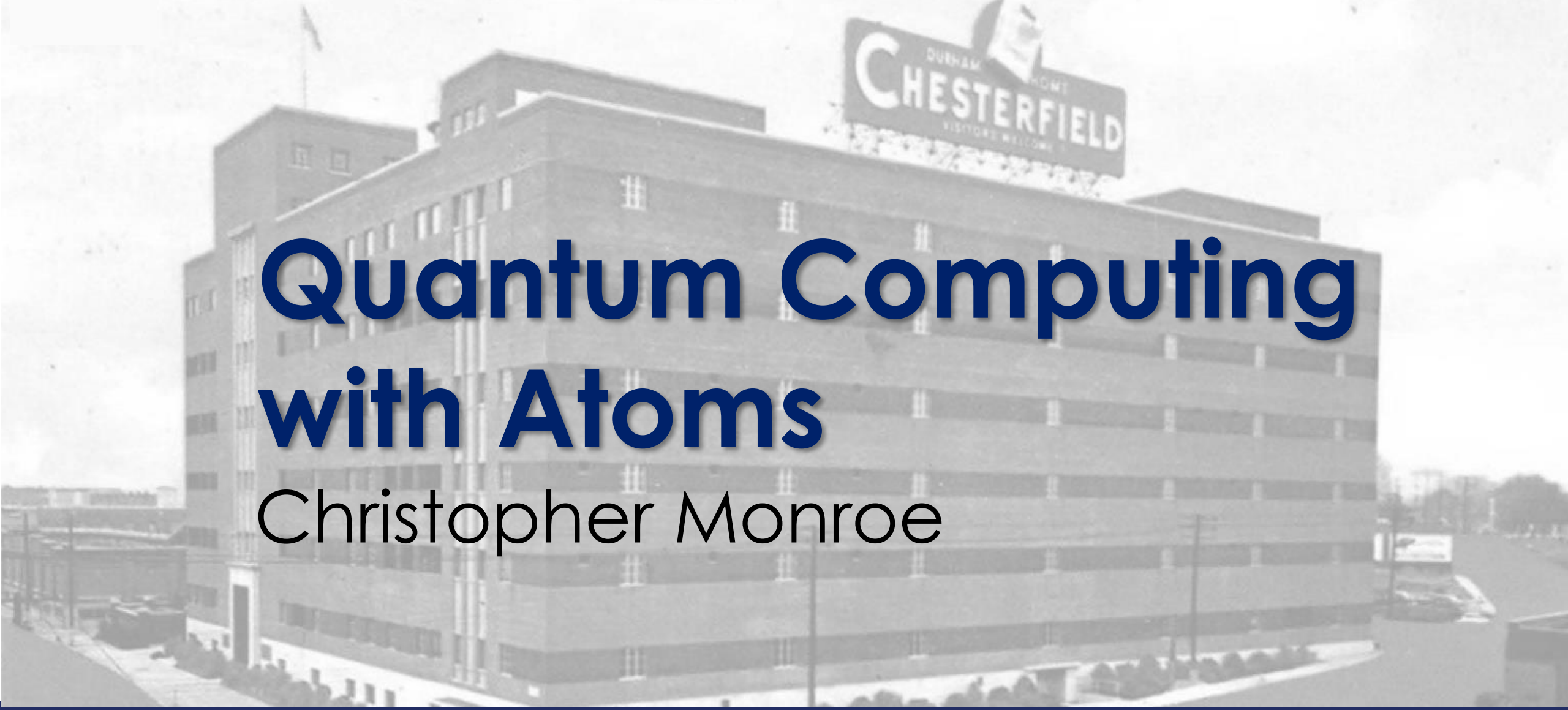


Quantum Computing with Atoms

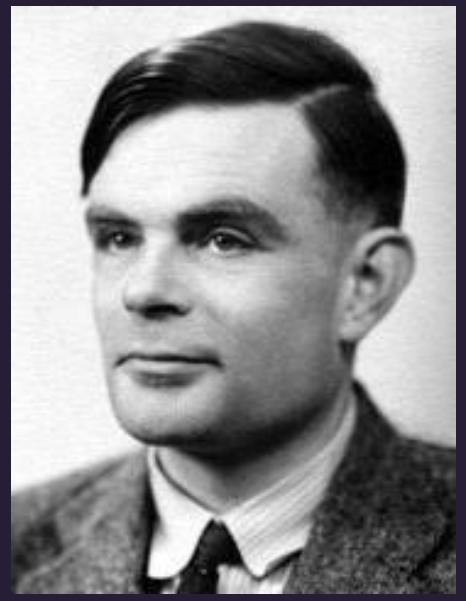
Christopher Monroe

Duke Quantum Center

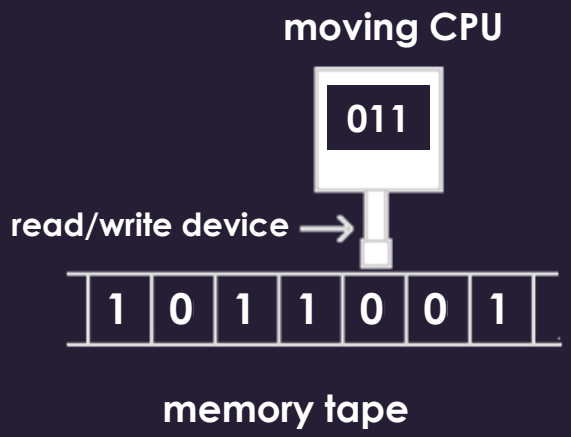
IONQ

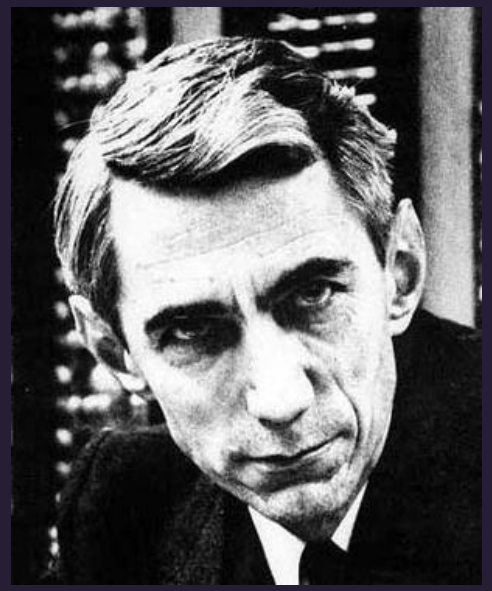
UNIVERSITY OF MARYLAND 18 56

Computing and Information



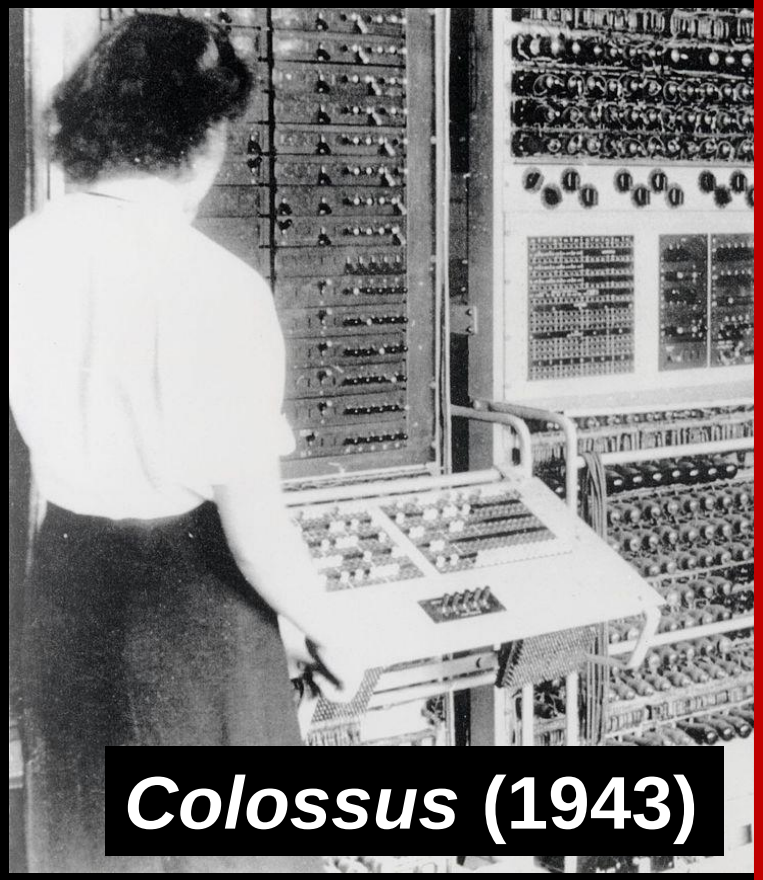
Alan Turing (1912-1954)
universal computing machines



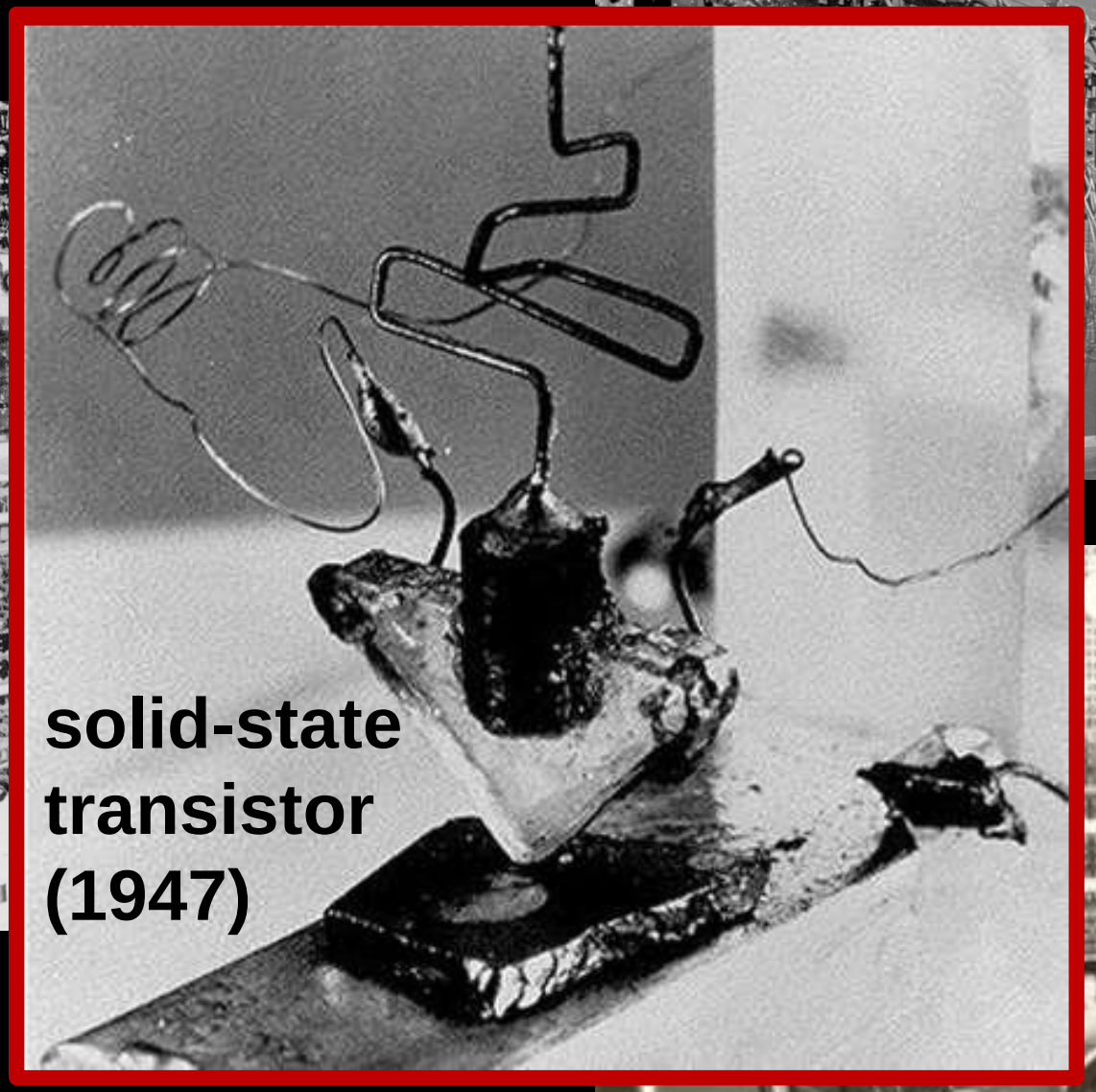


Claude Shannon (1916-2001)
quantify information: the bit

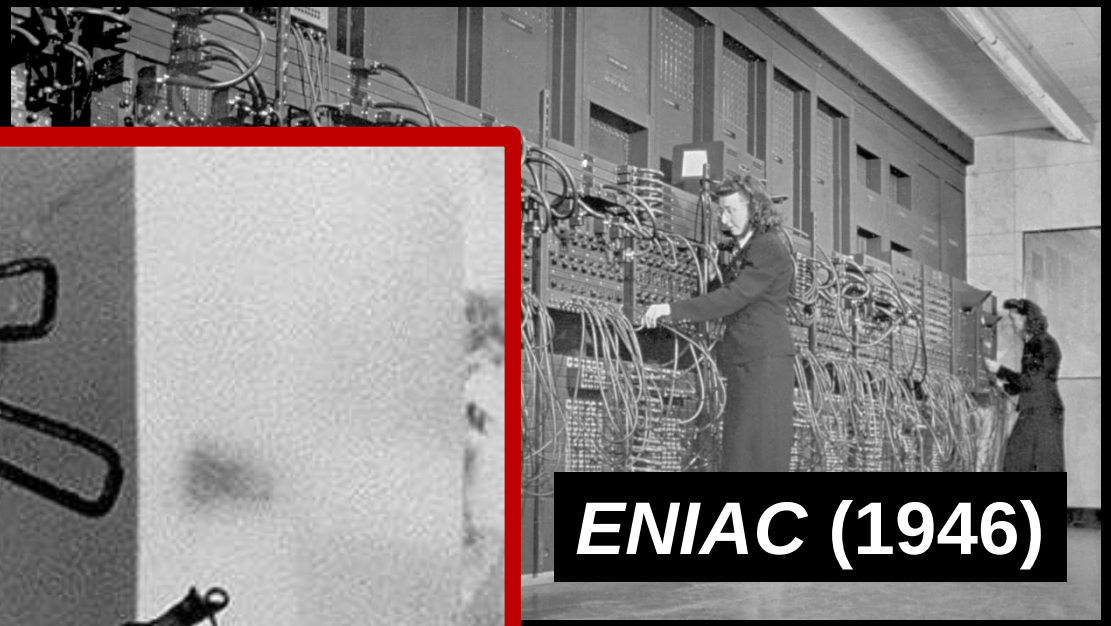
$$H = -\sum_{i=1}^{k} p_i log_2 p_i$$



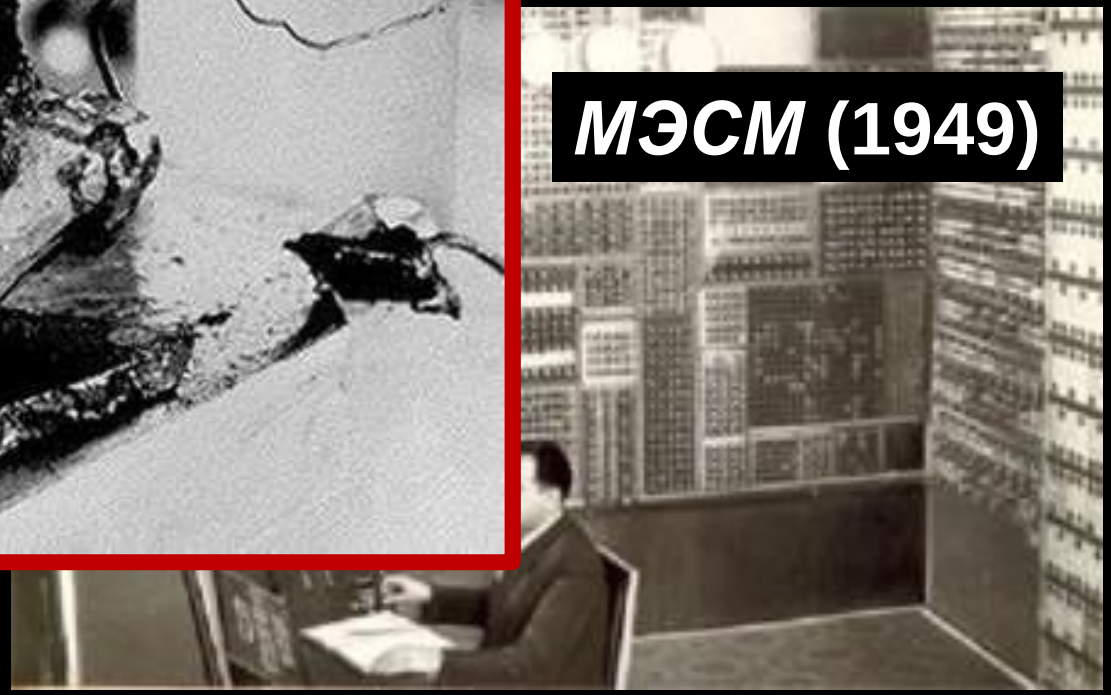
Colossus (1943)



solid-state transistor (1947)



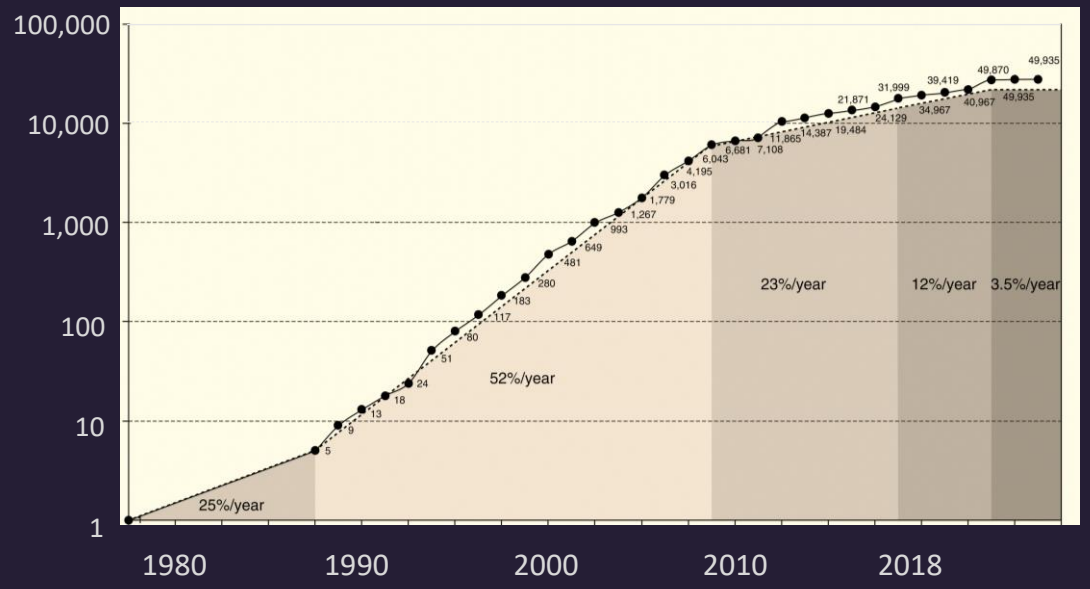
ENIAC (1946)



МЭСМ (1949)

Moore's Law
exponential growth in computing

Transistor density relative to 1978



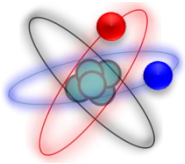
Richard Feynman

***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****…"*

Quantum Information Science

Quantum bits

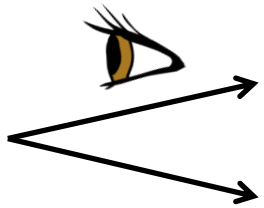


$|0\rangle$ state

$|1\rangle$ state

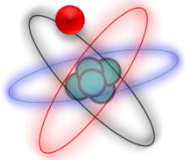
superposition

$\alpha|0\rangle + \beta|1\rangle$



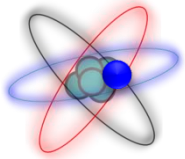
measurement:

"state collapse"



$|0\rangle$ state

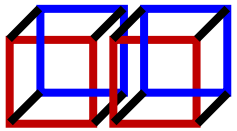
Prob = $|\alpha|^2$



$|1\rangle$ state

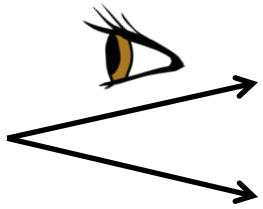
Prob = $|\beta|^2$

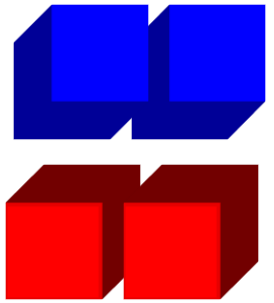
Entanglement



superposition

$\alpha|0\rangle|0\rangle + \beta|1\rangle|1\rangle$





$|0\rangle|0\rangle$ state

OR

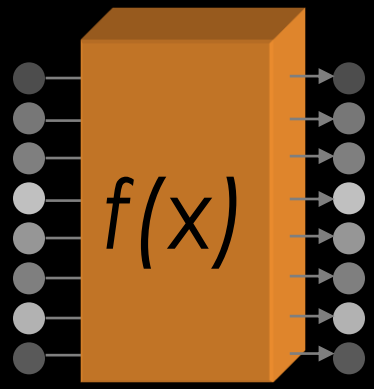
$|1\rangle|1\rangle$ state

entanglement: "wiring *without wires*"

Good News…

parallel processing
on 2^N inputs

e.g., N=3 qubits

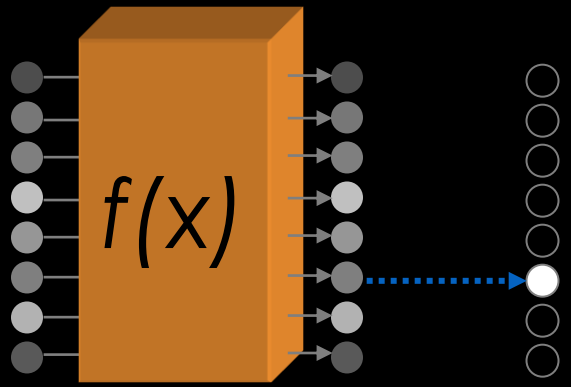


$a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle$
$a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$

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

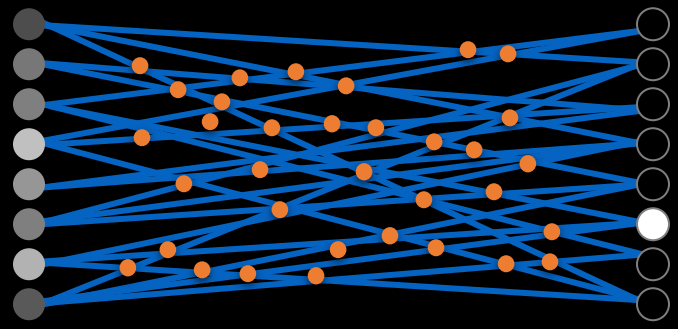
…Bad News…

measurement gives
random result



…Good News!

quantum interference



depends on *all* inputs

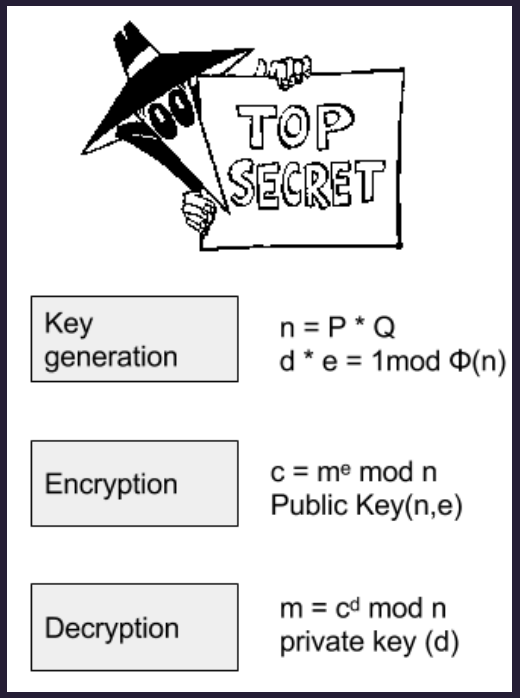
David Deutsch
(early 1990s)

Application: Factoring Numbers

A quantum computer can factor numbers
exponentially faster than classical computers

P. Shor (1994)

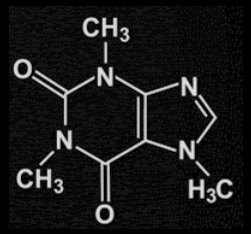
39 = 3 × 13 (…easy)
3864788462100938762143232563 1 = **?** × **?**

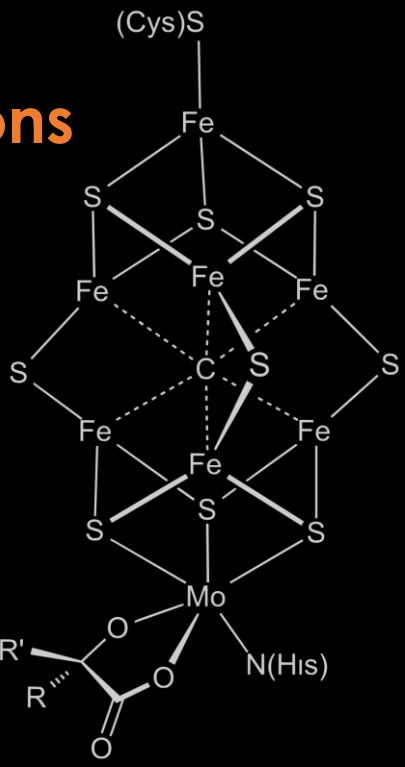


Application: Optimization

Molecular Simulations

- designer materials
- new catalysts
- protein folding

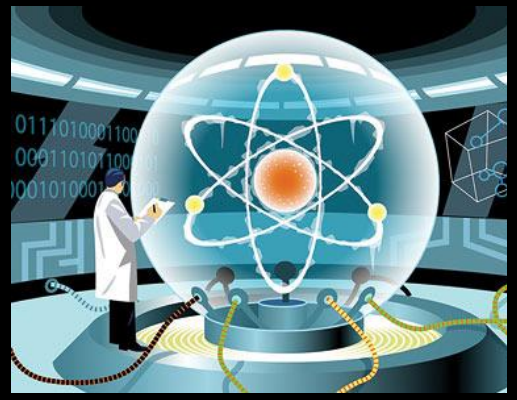




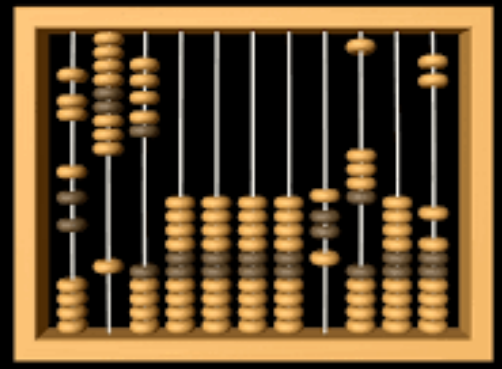
Traveling Salesman problem

what is the shortest path through *N* cities?

A quantum computer differs more from a laptop…

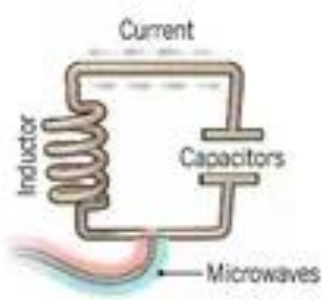


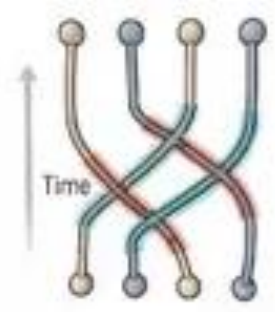
…than a laptop differs from an ABACUS”

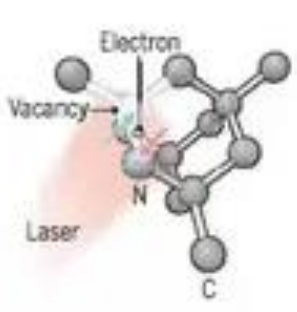


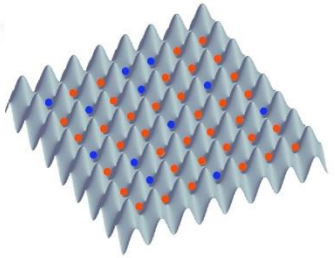
Quantum Computer Technologies

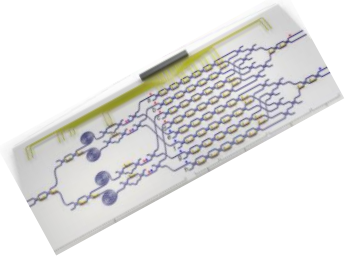
adapted from Science, Dec 2016





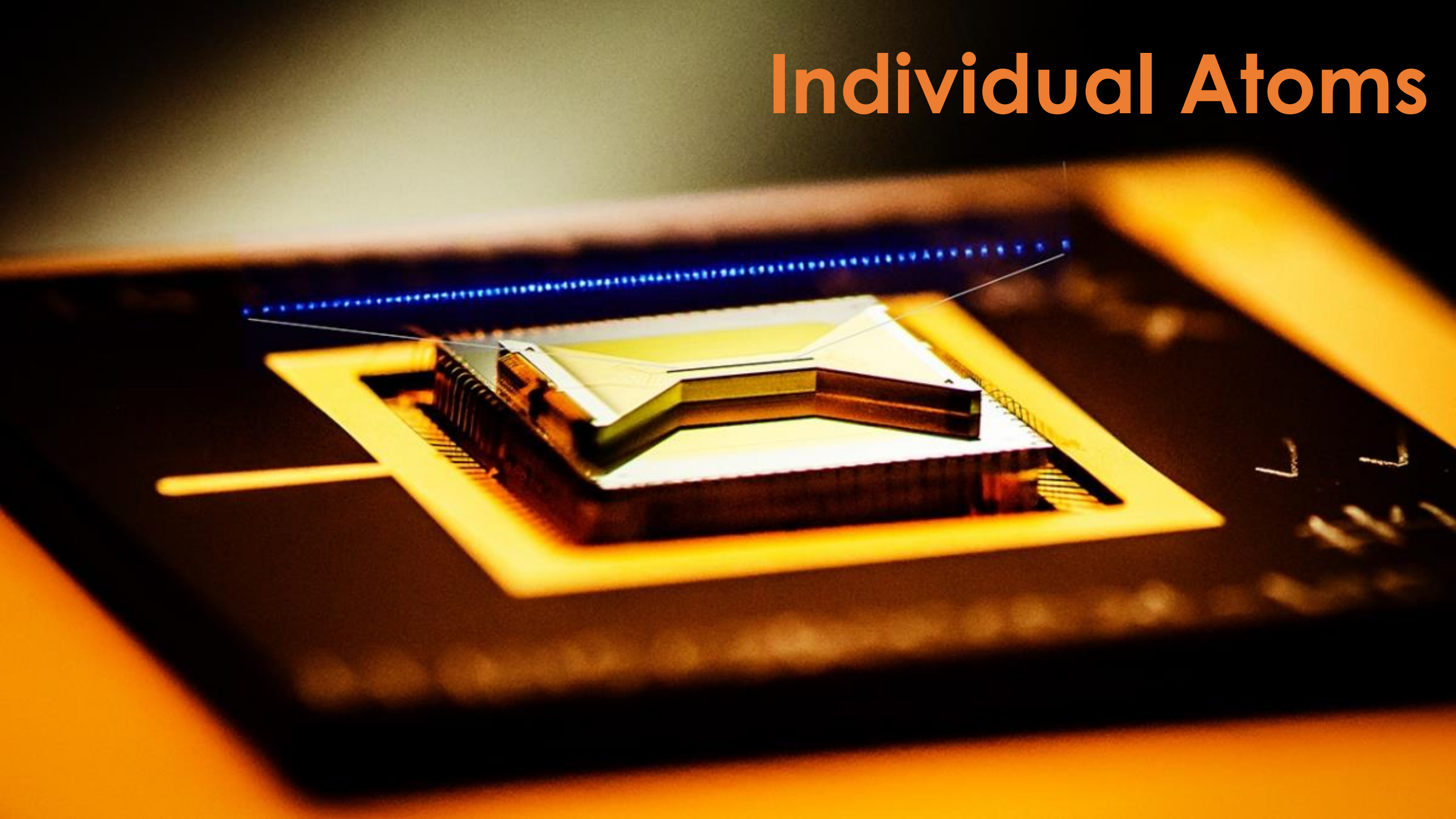




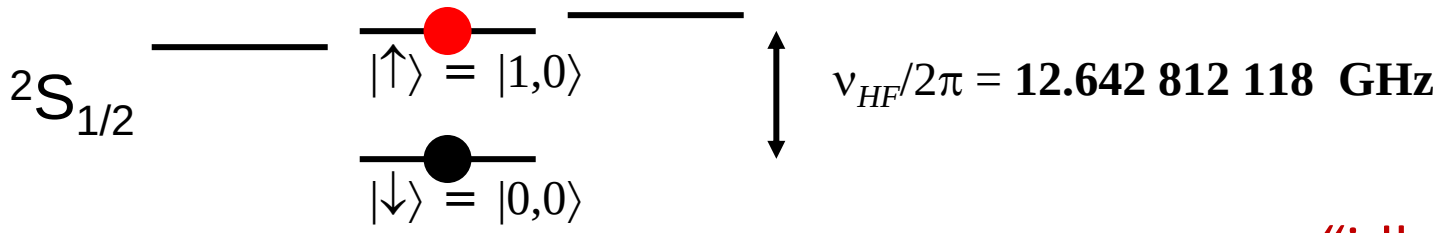


	Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**	**Neutral atoms**	**Photonics**
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition 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 semiconductor 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.	Neutral atoms, like ions, store qubits within electronic states. Interactions through excitation to Rydberg states	Photonic qubits interact via linear elements
Longevity (seconds)	0.00005	>1000	0.03	N/A	10	1	
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%	97%	
Number entangled	9	14	2	N/A	6	20	
Company support	Google, IBM, Rigetti, QCI,..	IonQ, Honeywell	Intel, HRL, SQC	Microsoft	Quantum Diamond Technologies	Atom Computing QuEra ColdQuanta	PsiQuantum Xanadu
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.	Many qubits, 2D and maybe 3D	Linear optical gates, integrated on-chip
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.	Lasers needed, spaghetti physics, atoms escape	No memory, not clear how to scale

Individual Atoms

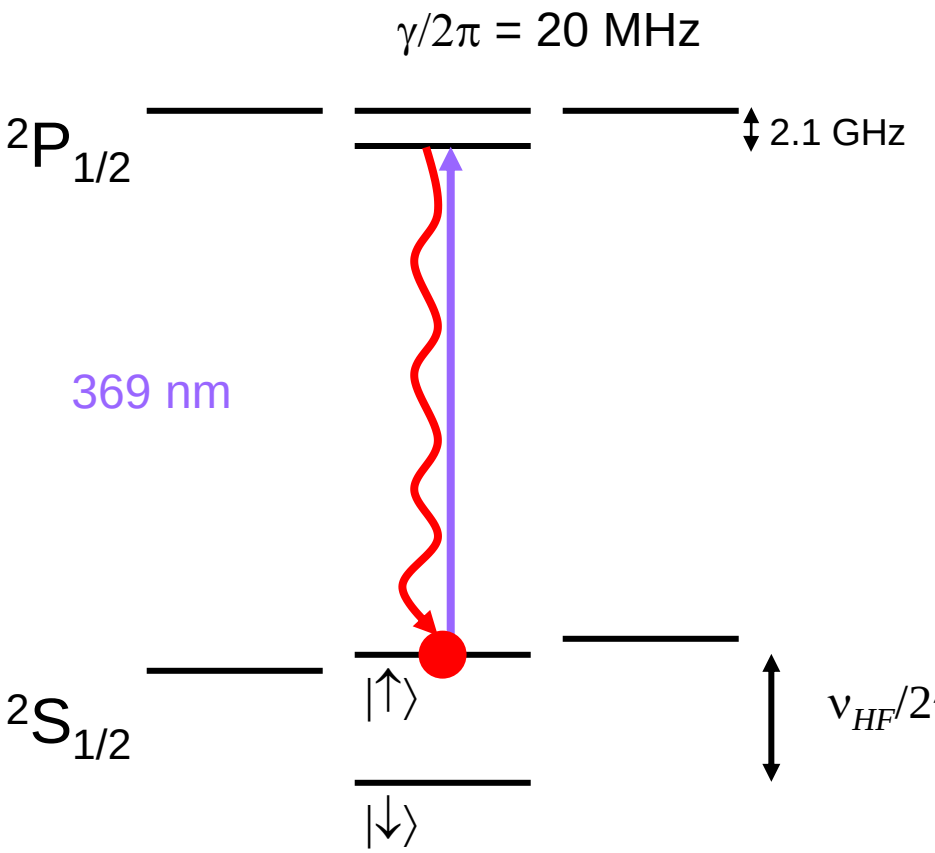


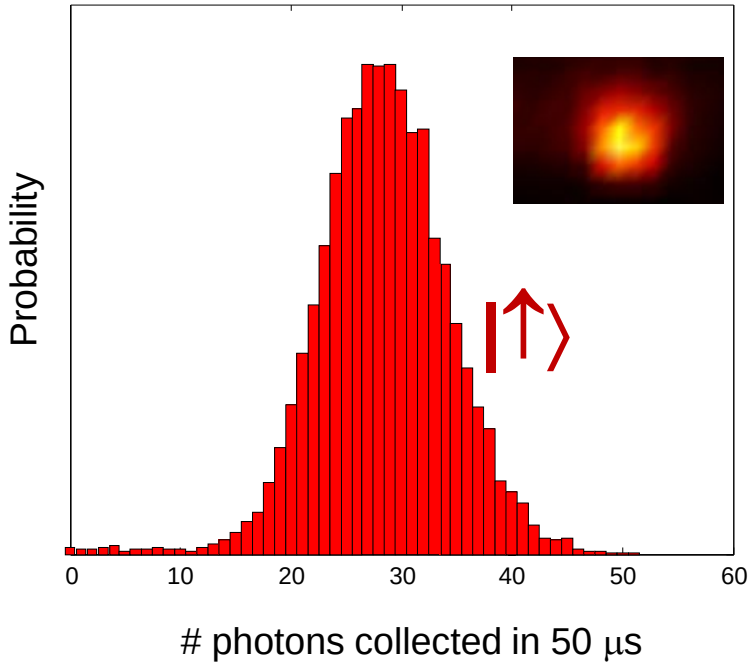
Atomic (hyperfine) qubit ($^{171}Yb^{+}$)



"idle coherence time = ∞"

$^{171}Yb^{+}$ Qubit Detection

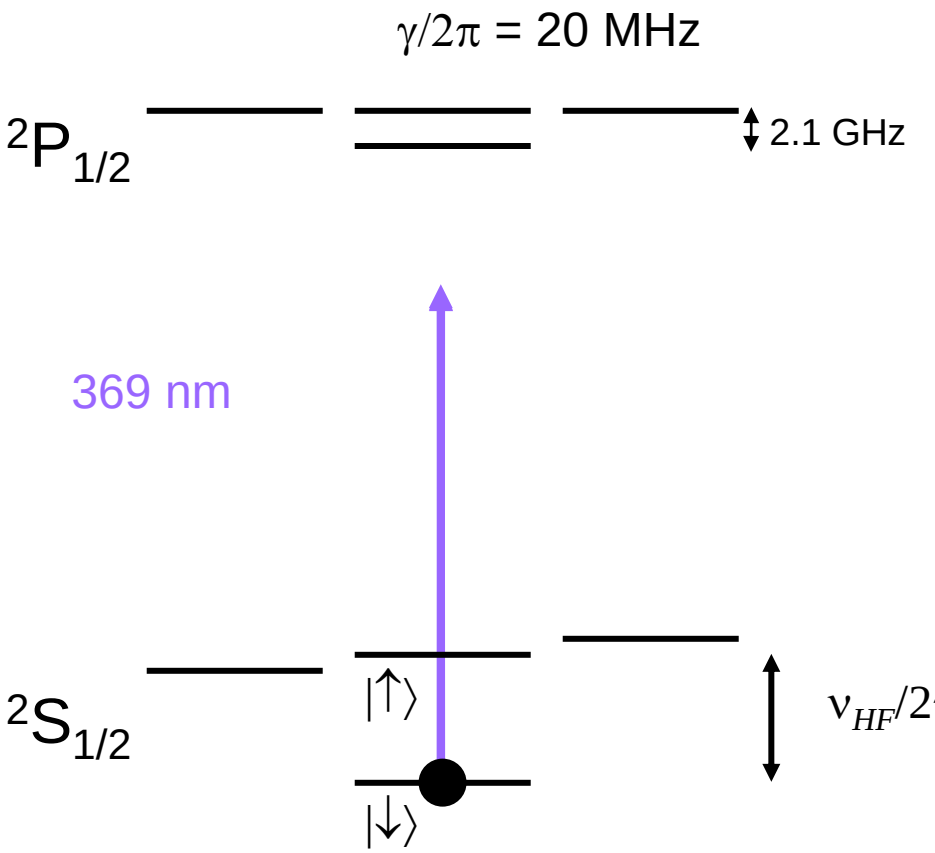


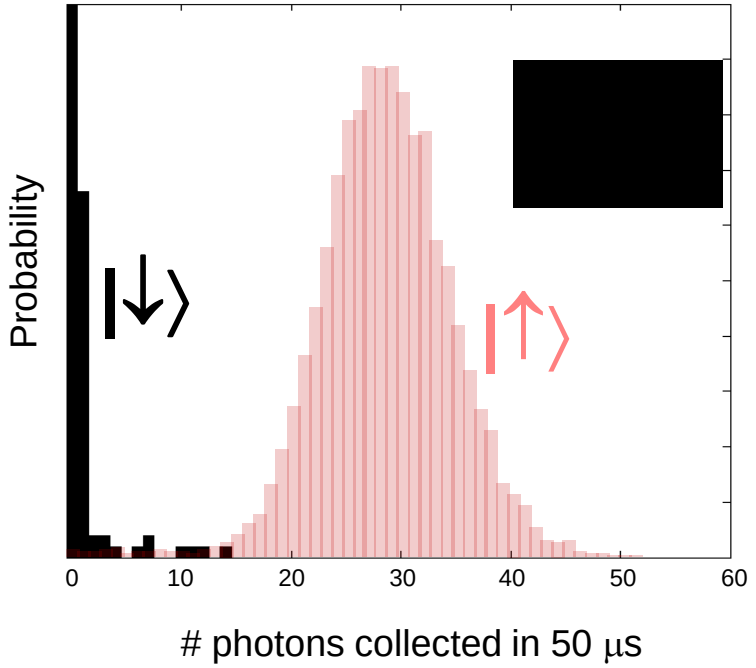


$\nu_{HF}/2\pi$ = **12.642 812 118 GHz**

$^{171}Yb^{+}$ Qubit Detection

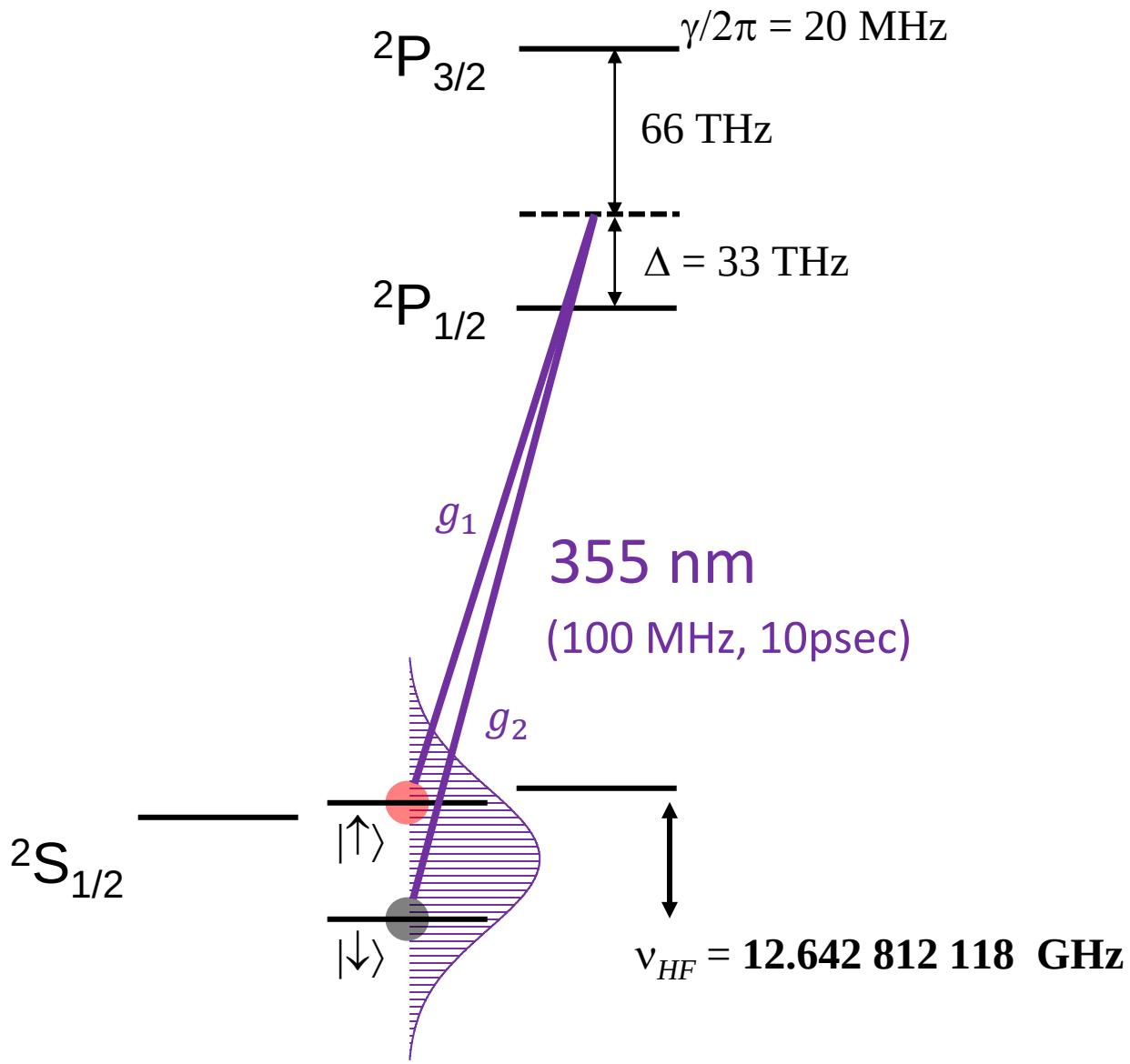
High-NA collection + SNSPD (J. Kim, Duke)
- 6.5% of fluorescence detected
- **99.93% qubit detection in 12 μs**

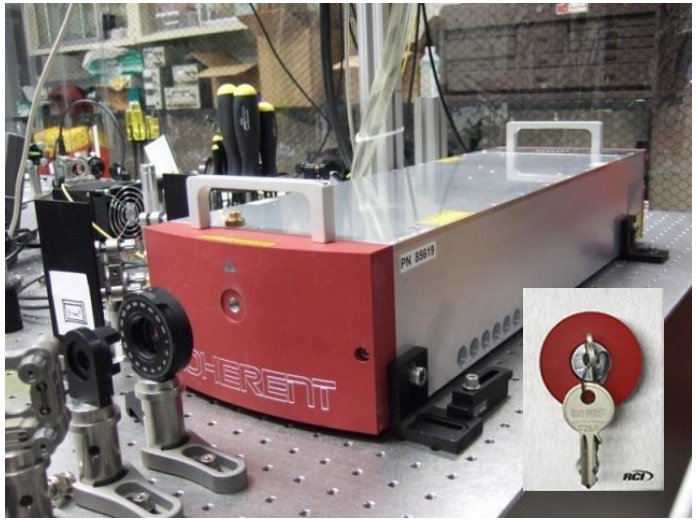




$\nu_{HF}/2\pi$ = **12.642 812 118 GHz**

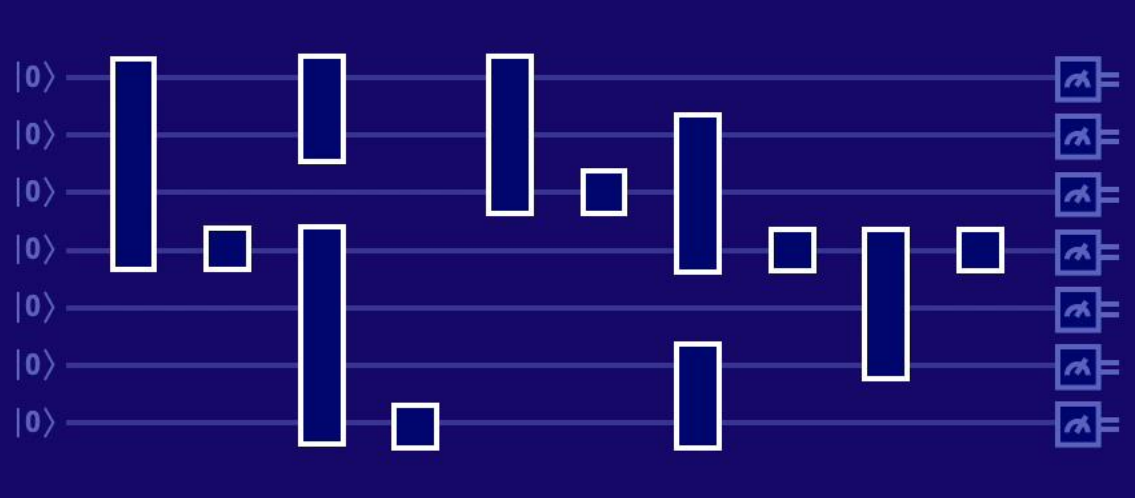
$^{171}Yb^{+}$ Qubit Manipulation

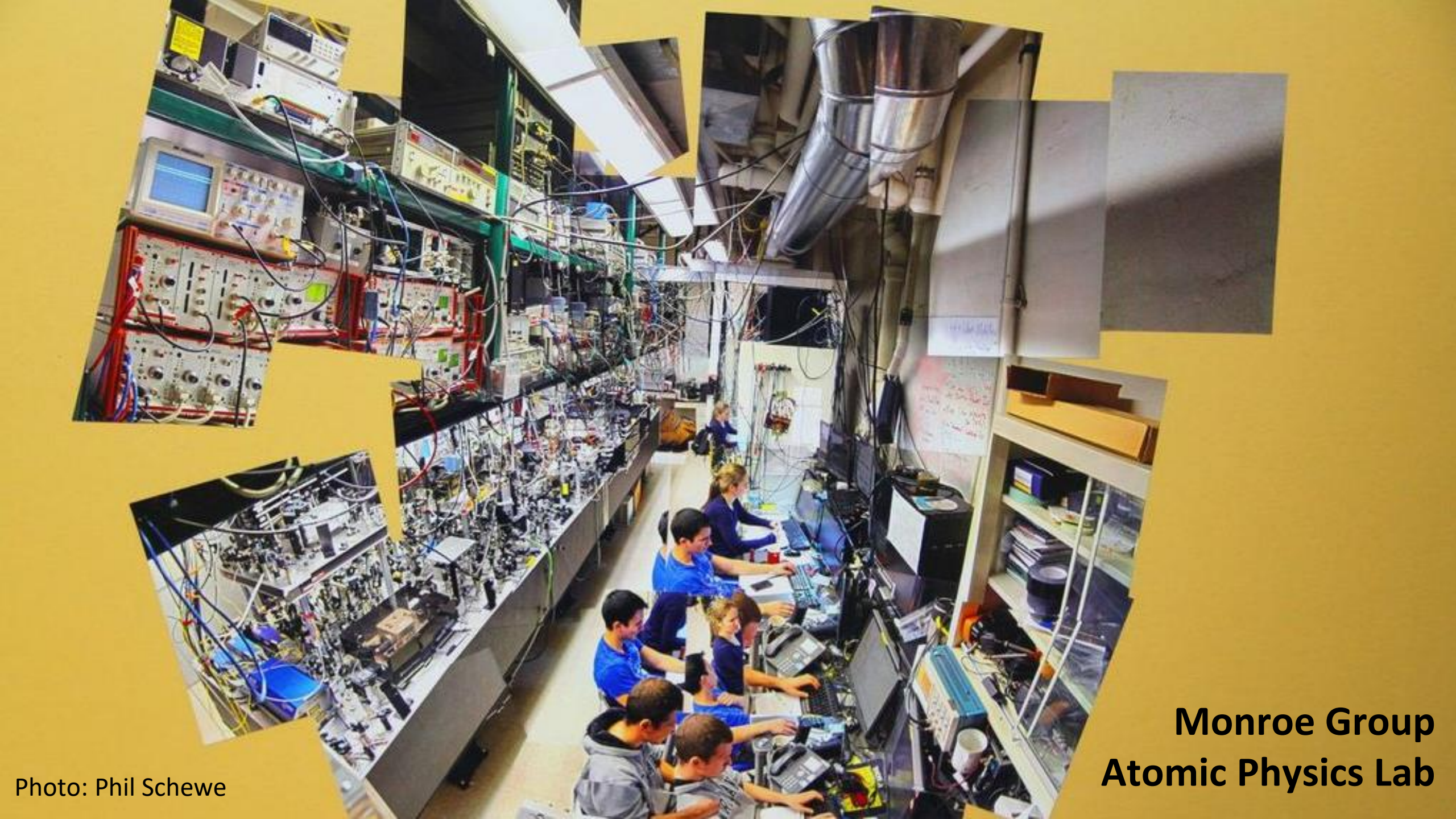




D. Hayes et al., PRL 104, 140501 (2010)

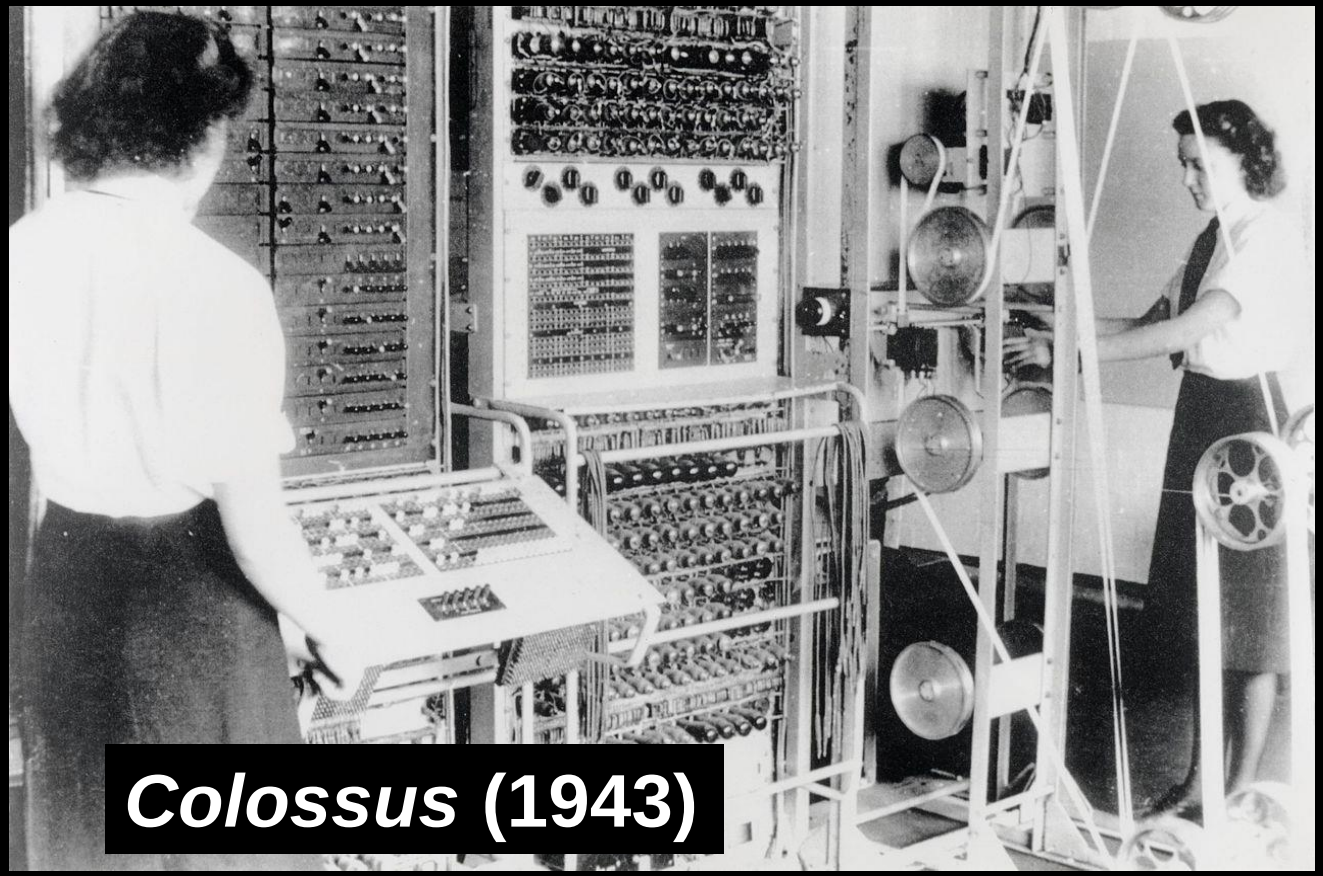
Initialization

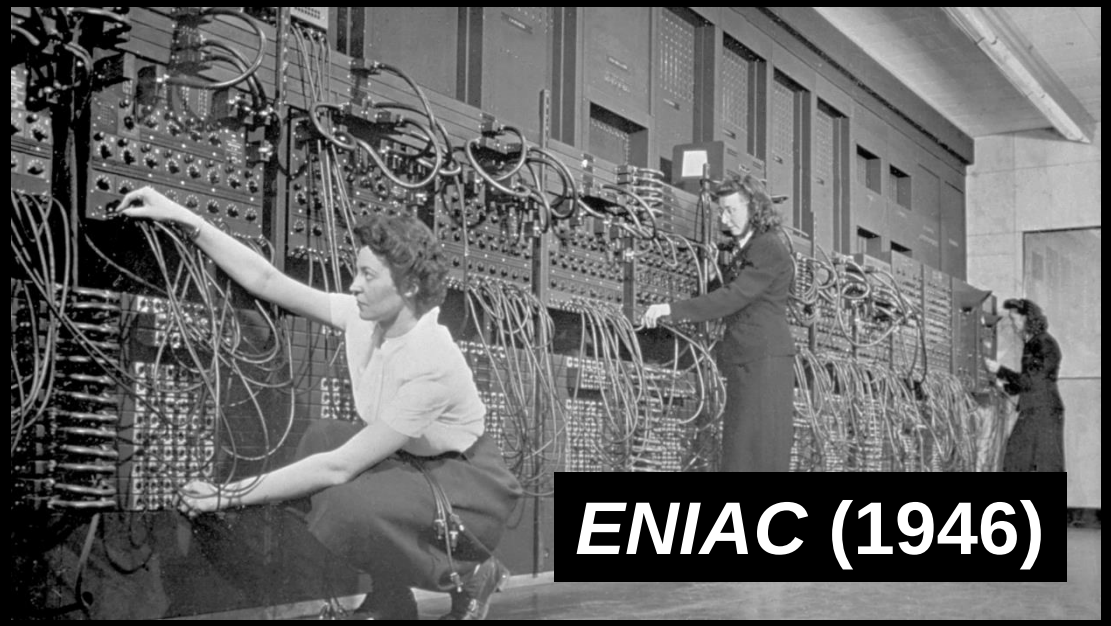




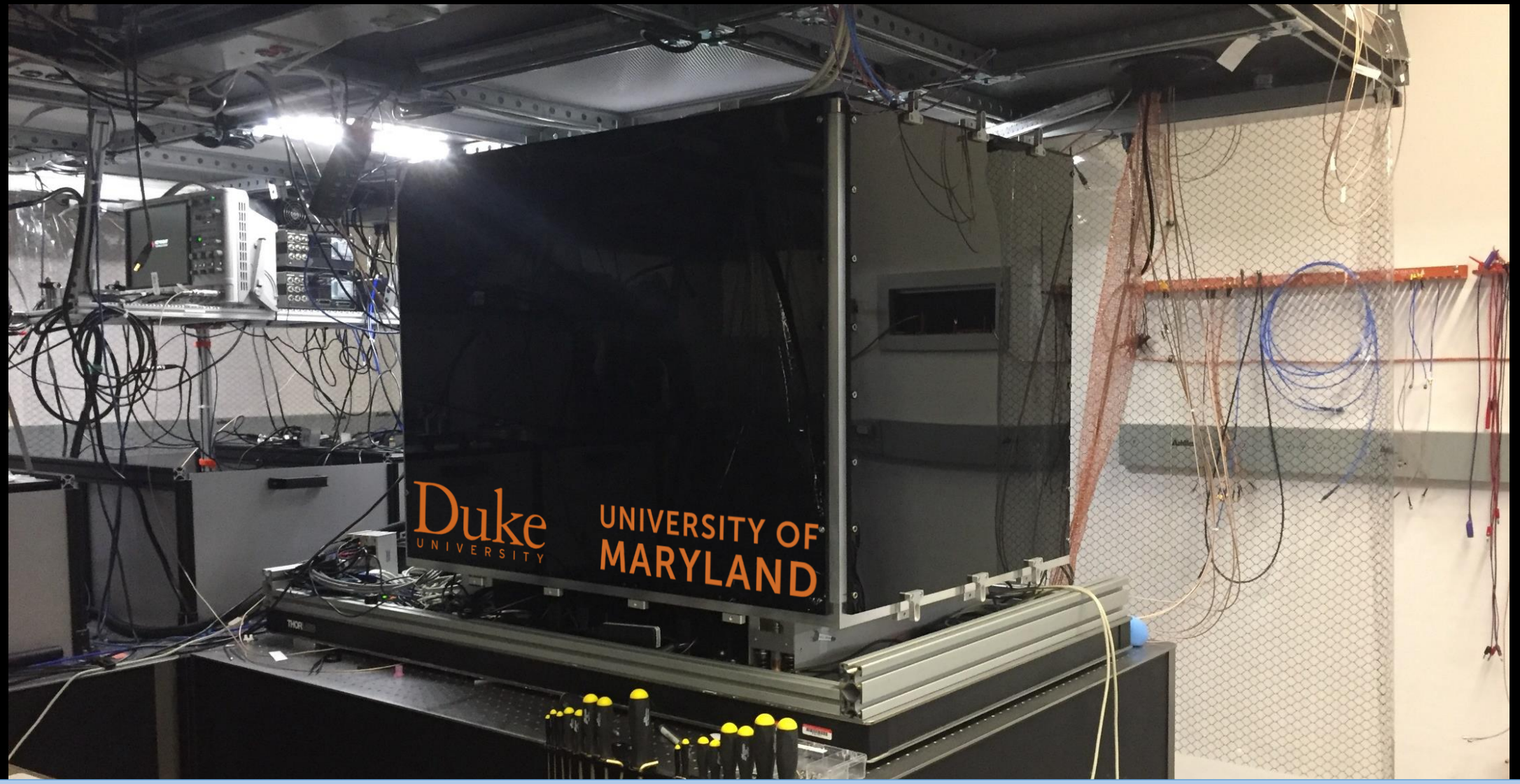
Monroe Group
Atomic Physics Lab

Photo: Phil Schewe


Colossus (1943)


ENIAC (1946)

МЭСМ (1949)



IARPA
BE THE FUTURE

NSF

STAQ

Sandia
National
Laboratories

ColdQuanta

AOSense

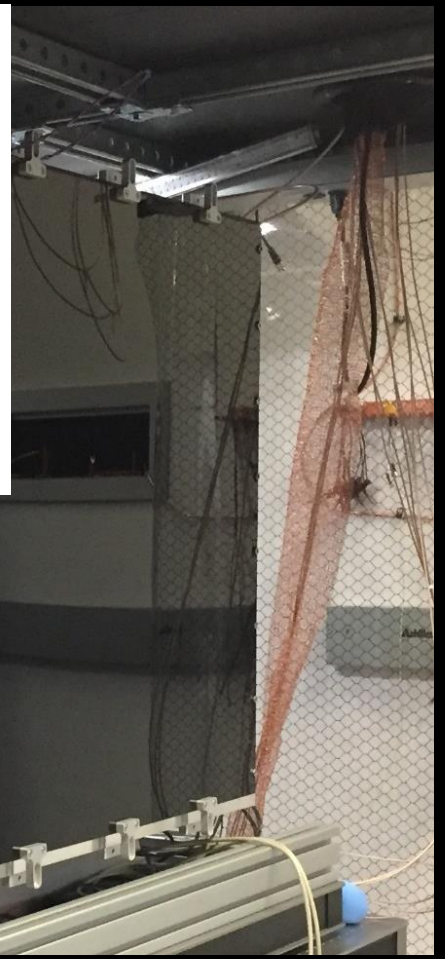
L3HARRIS

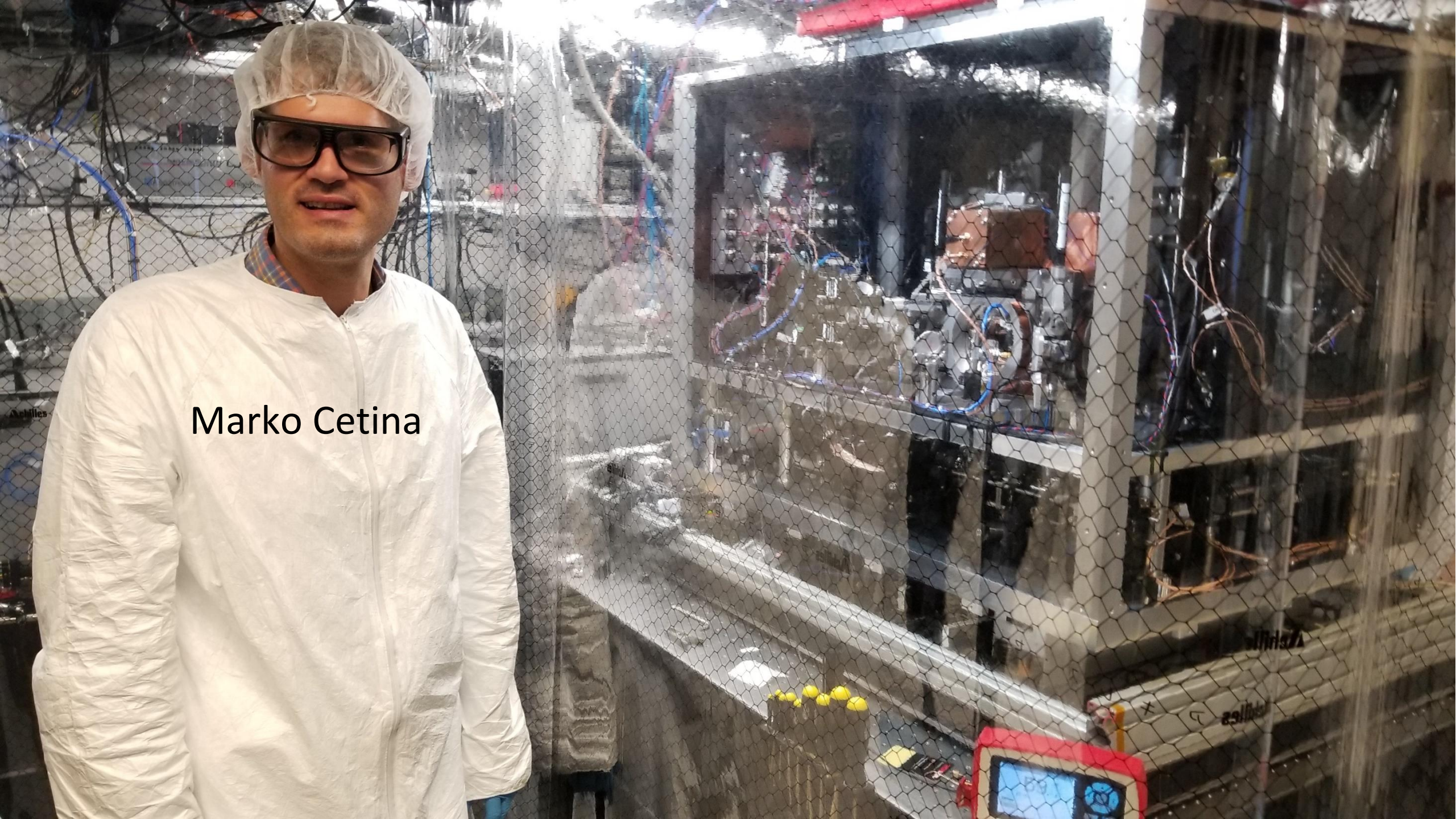
COHERENT

Nature **583**, 10 (2020)

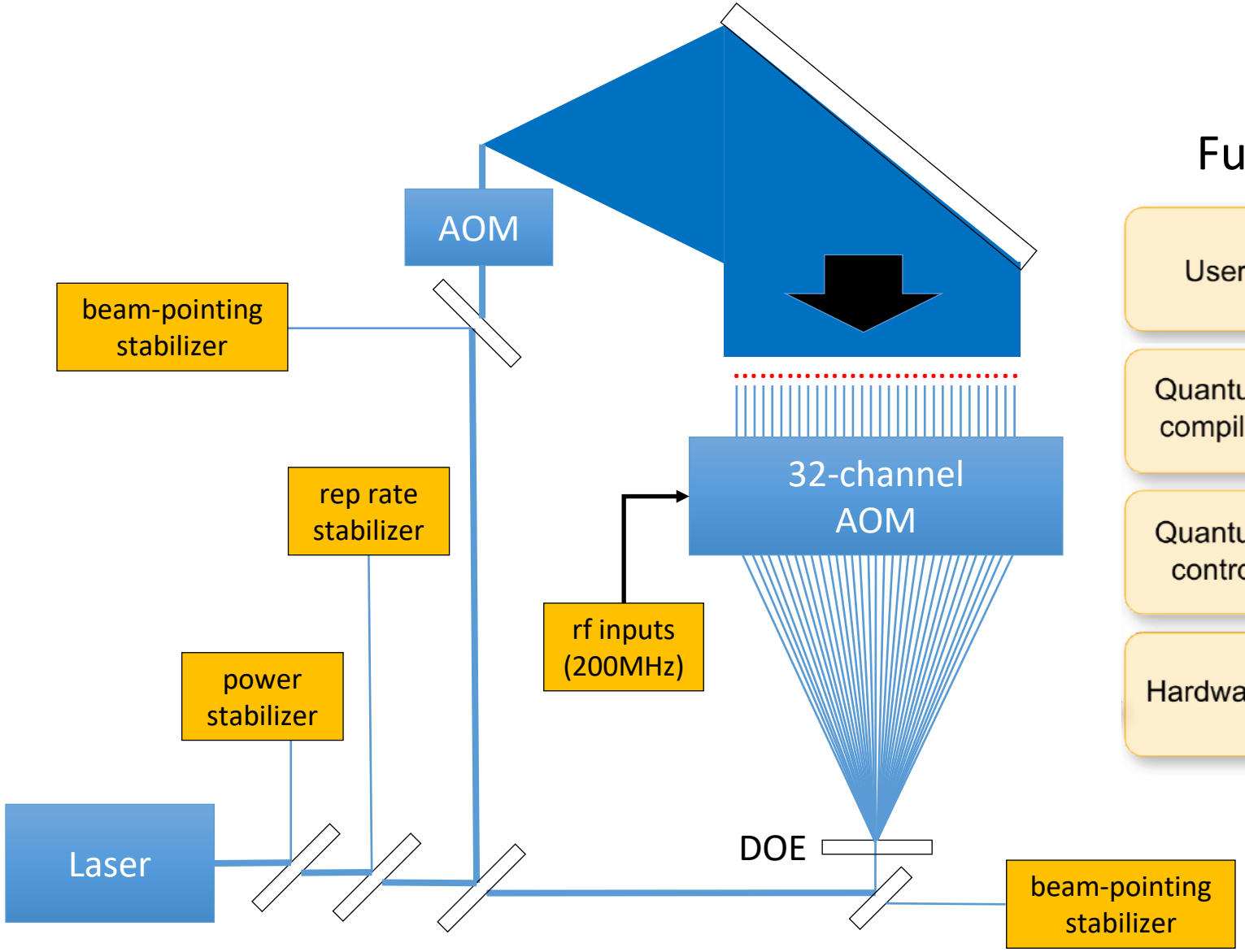
Remote quantum computing is the future

Conditions created by the COVID-19 shutdown are delivering one experiment's 'best data ever'.




Marko Cetina

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

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 Deconv			Harvard
	Measureme			NIST, Princeton, Berkeley
	Classical Ver			Berkeley, CalTech
	Cross platfor			Innsbruck
	Lattice Gaug			UMD
	Ising Scatter			U. Iowa
	Circuit-base			Intel Corp.
	Schwinger m			UMD
	Envariance r			Los Alamos
	Para-particle			UMD, INAOE
	Edge-cover p			Innsbruck, Rice
	Lee-Yang Zer			NCSU
	Triangle gam			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

Norbert Linke
(UMD/JQI)

Marko Cetina
(UMD/JQI)
new faculty @Duke

Crystal Noel
(UMD/JQI)
new faculty @Duke

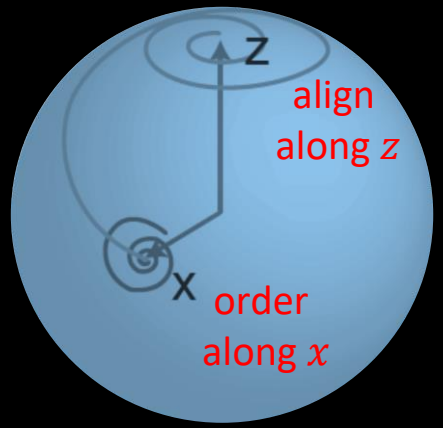
Exotic Magnetism
Dynamical Phase Transition with 50+ Qubits

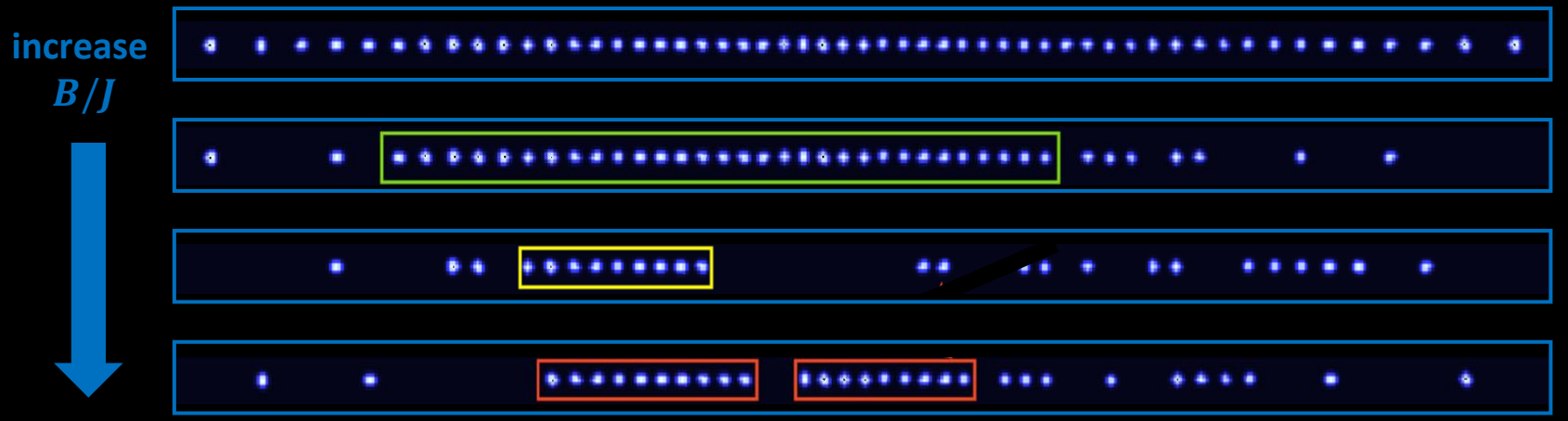
A. Gorshkov (JQI/NIST)
D. Huse (Princeton)
S. Johri (Intel)

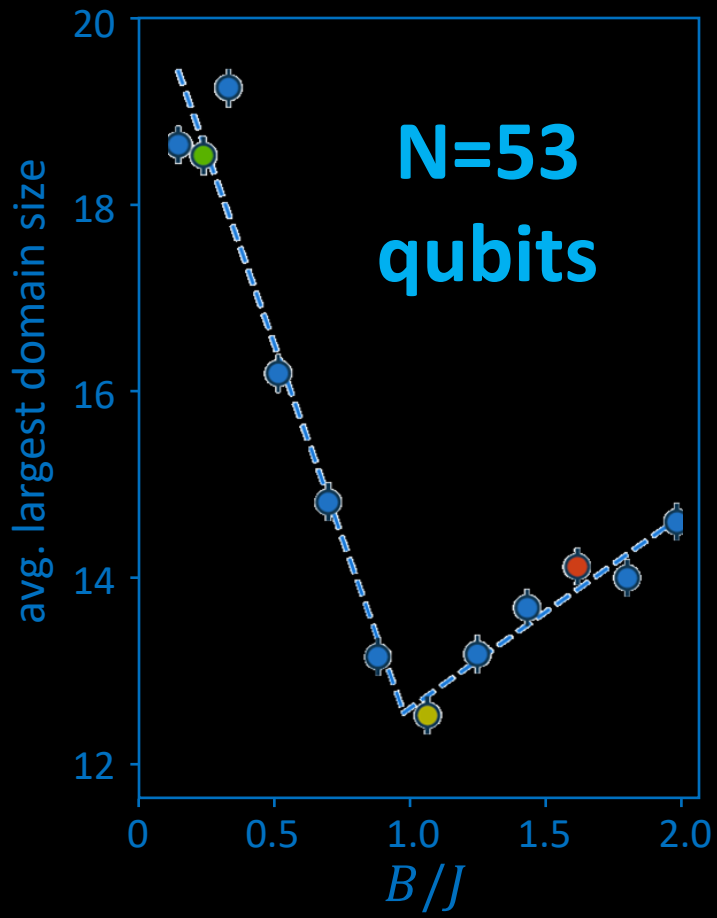
(1) Prepare spins along x

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

(3) Measure along x



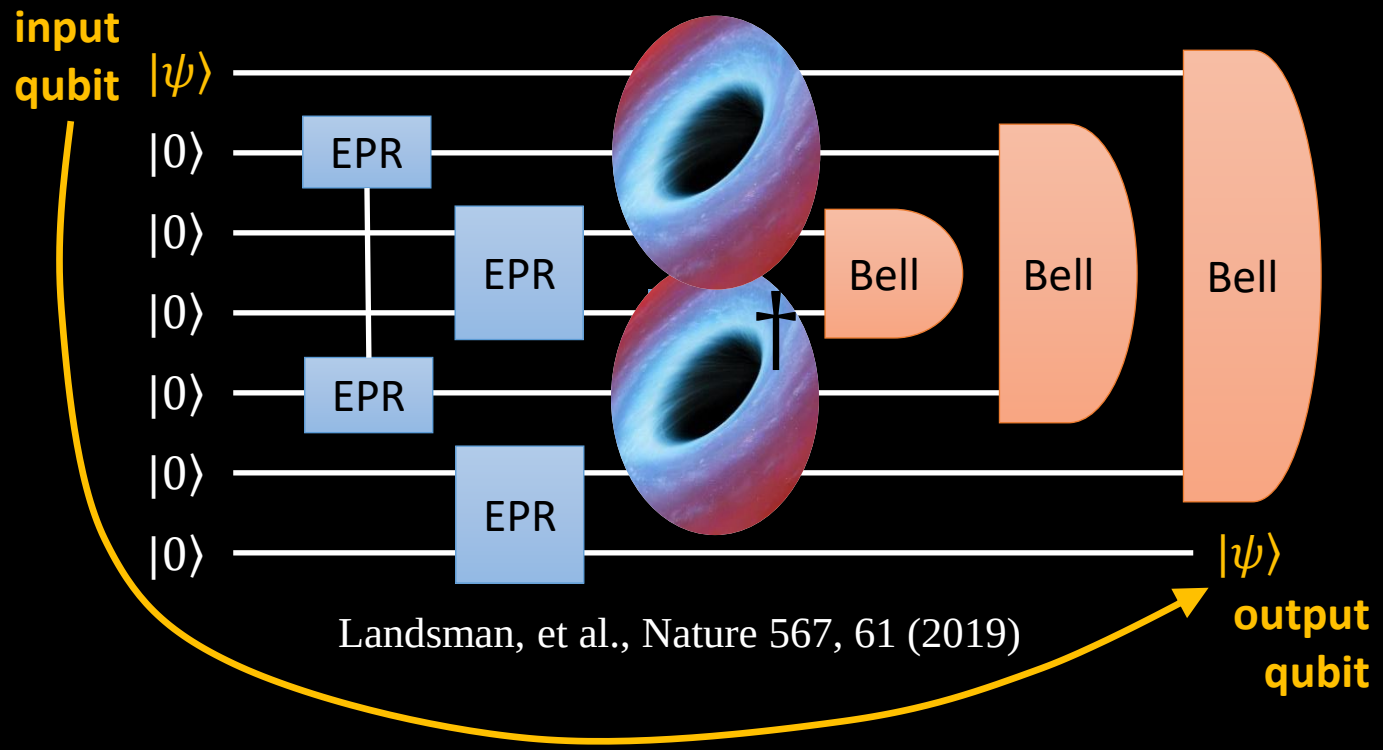




Cosmology + Quantum Gravity
Quantum Scrambling

N. Yao (UC Berkeley)
B. Yoshida (Perimeter)
L. Susskind (Stanford)

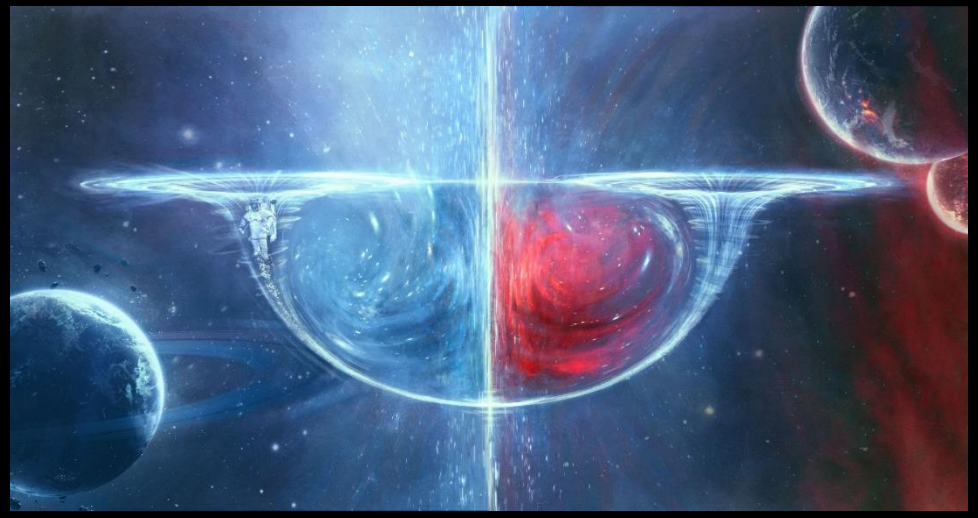
Scrambling: "complete diffusion" of quantum information, relevant to information evolution in black holes



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**

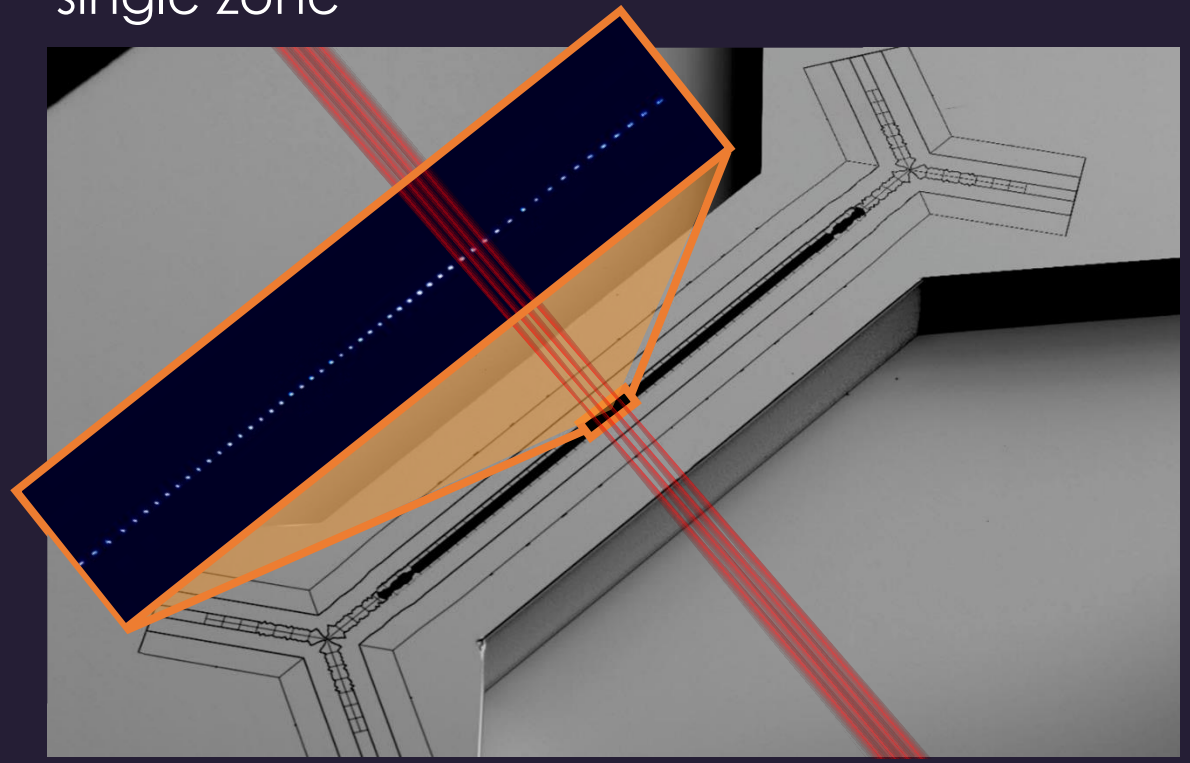


Physicists suspect that the connection in a wormhole and the connection in quantum entanglement **are the same thing, just on a vastly different scale!**

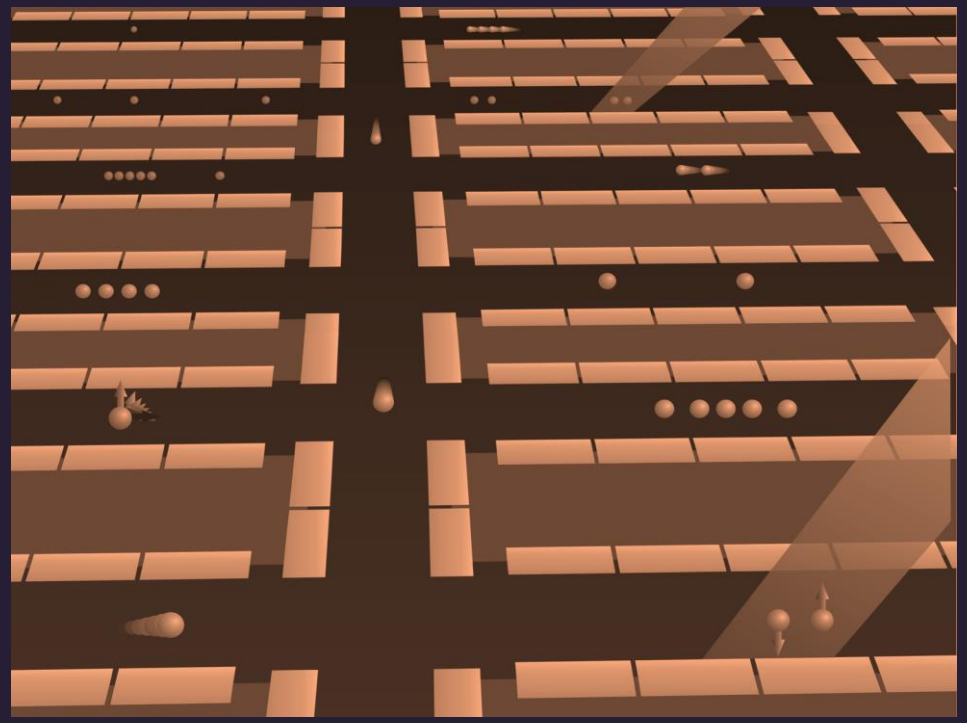
Quantum Computer Scaling I

>100 qubits

Linear shuttling through single zone



Shuttling between multiple zones



NIST-Boulder

Univ. Mainz

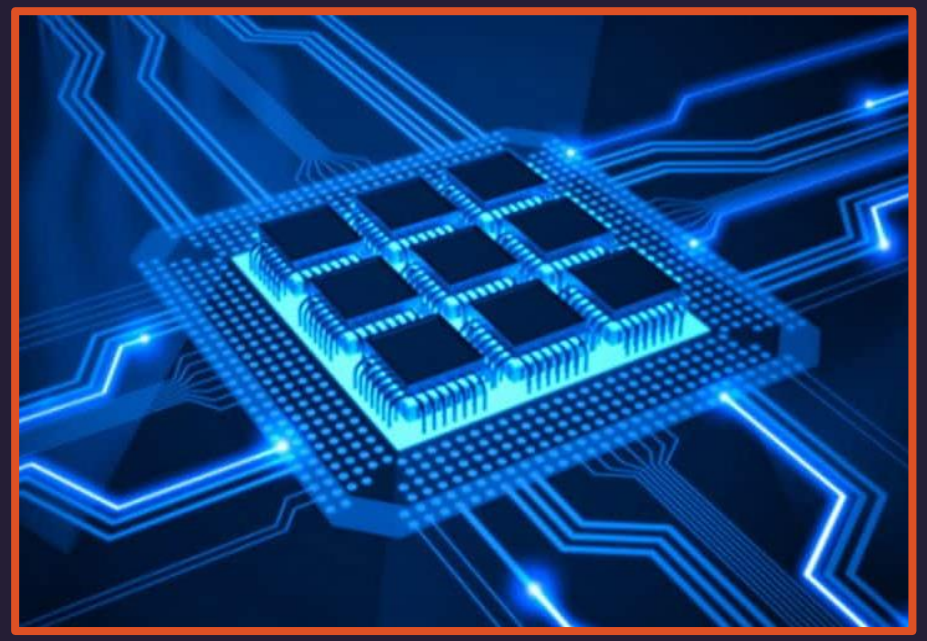
Nature 417, 709 (2002)

Science Advances 3, e1601540 (2017)

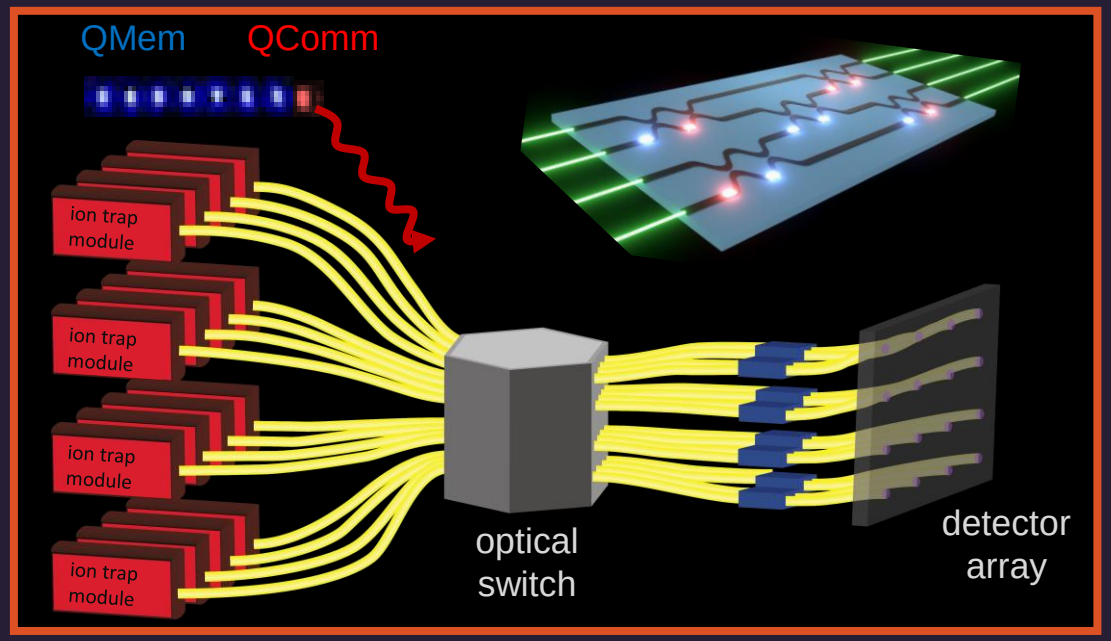
Quantum Computer Scaling II

>1000 qubits

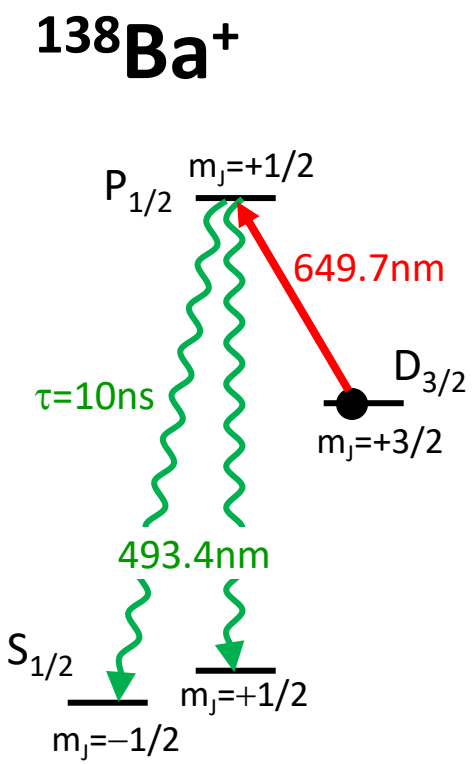
Plan: Multicore quantum processing

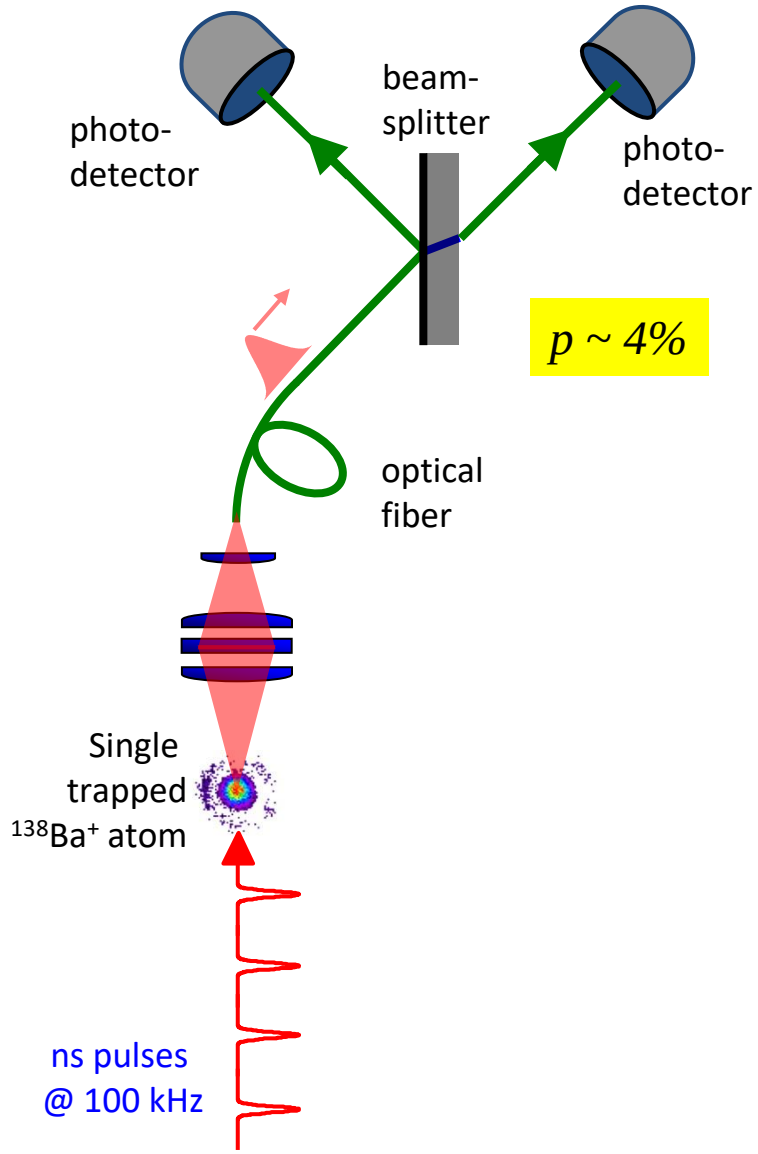


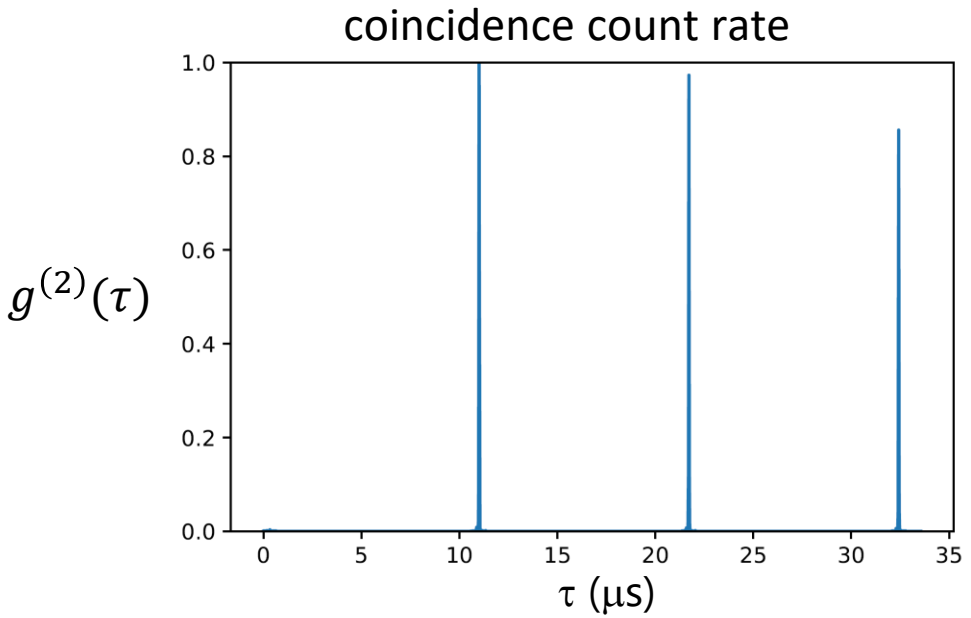
Technology: Integrated photonics and switches, SNSPD detector array

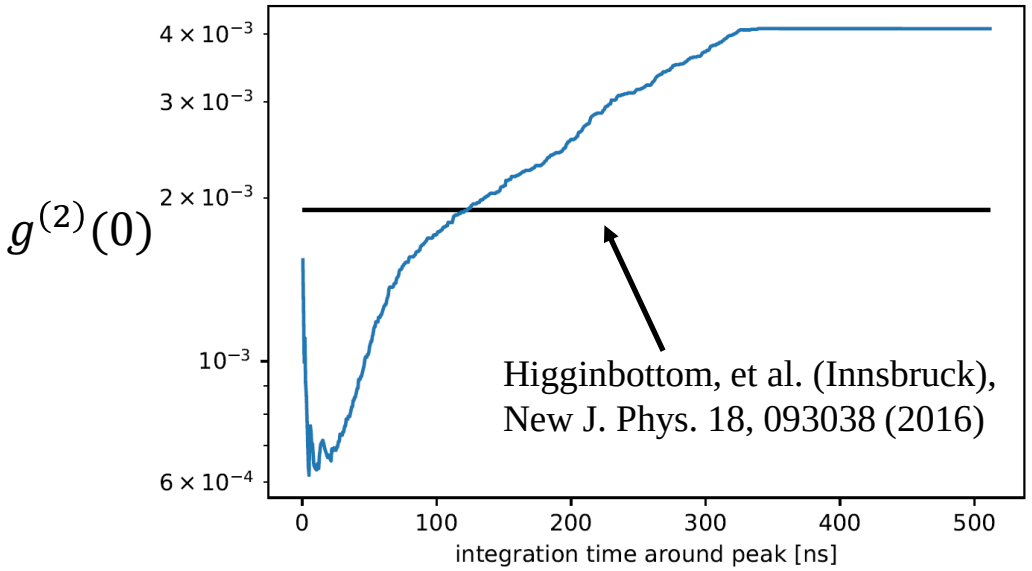


Making single photons





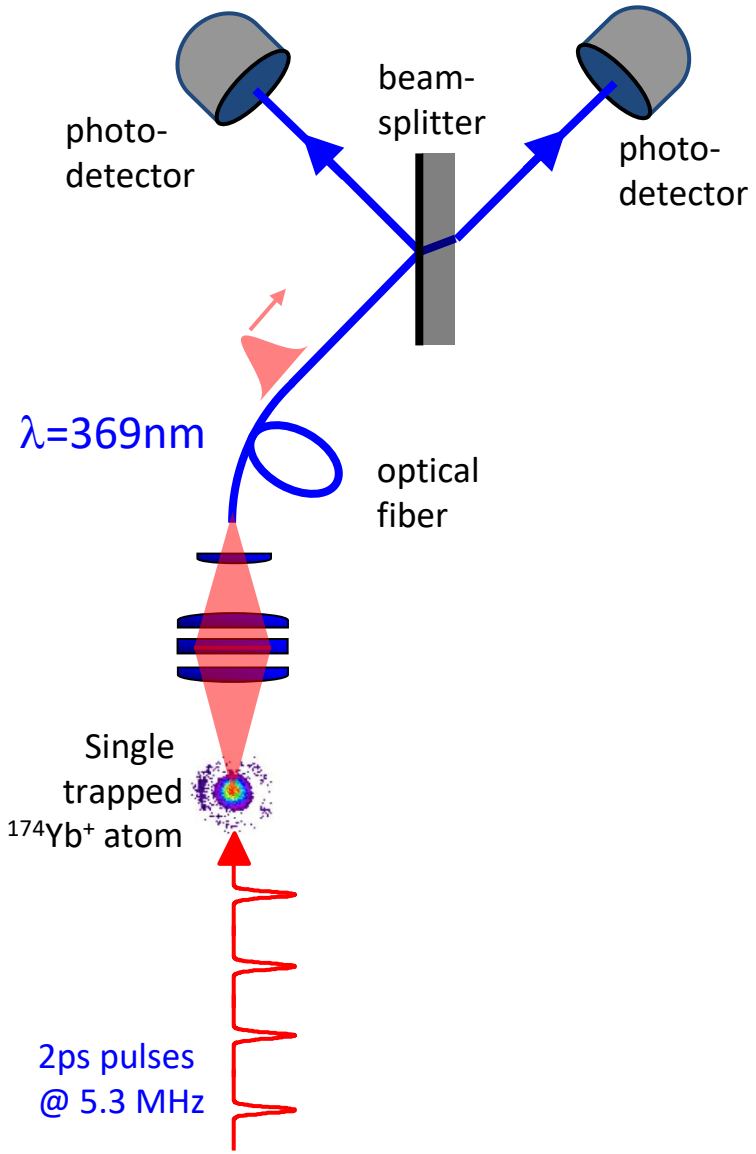




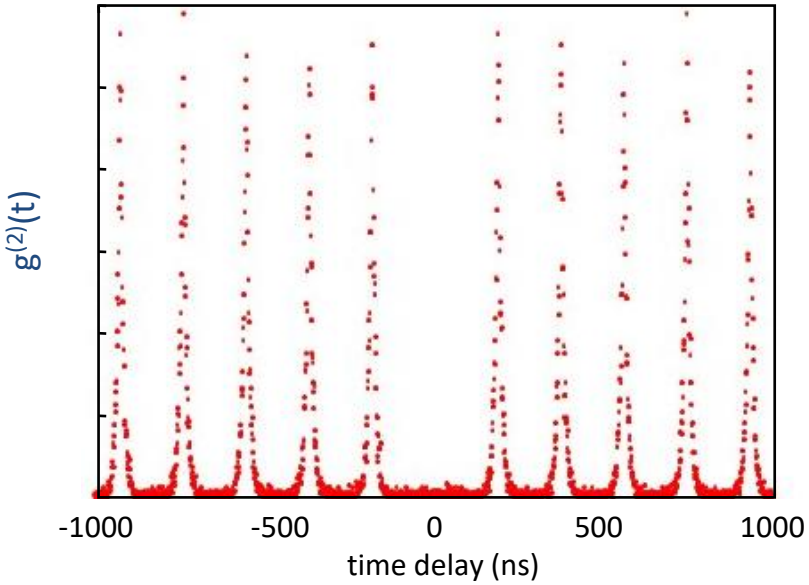
C. Crocker, et al., Optics Express 27, 28143 (2019)

Making single photons

$p \sim 3\%$

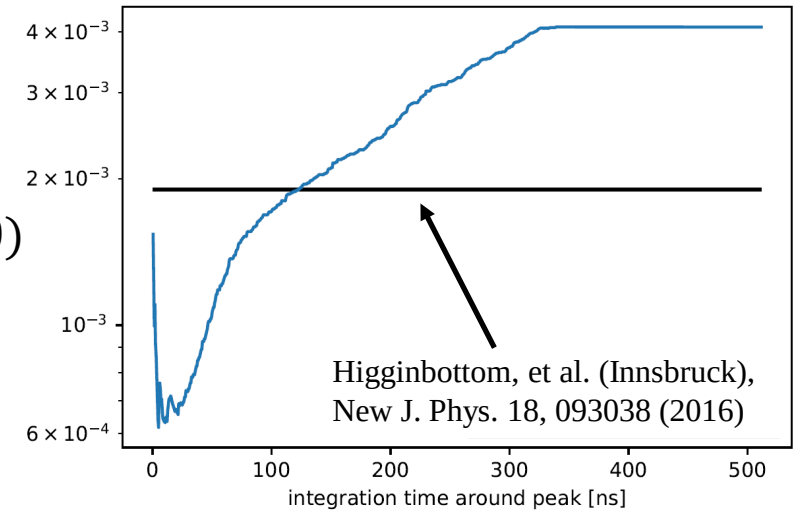


excellent single photon source



P. Maunz, et al., *Nature Physics* **3**, 538 (2007)

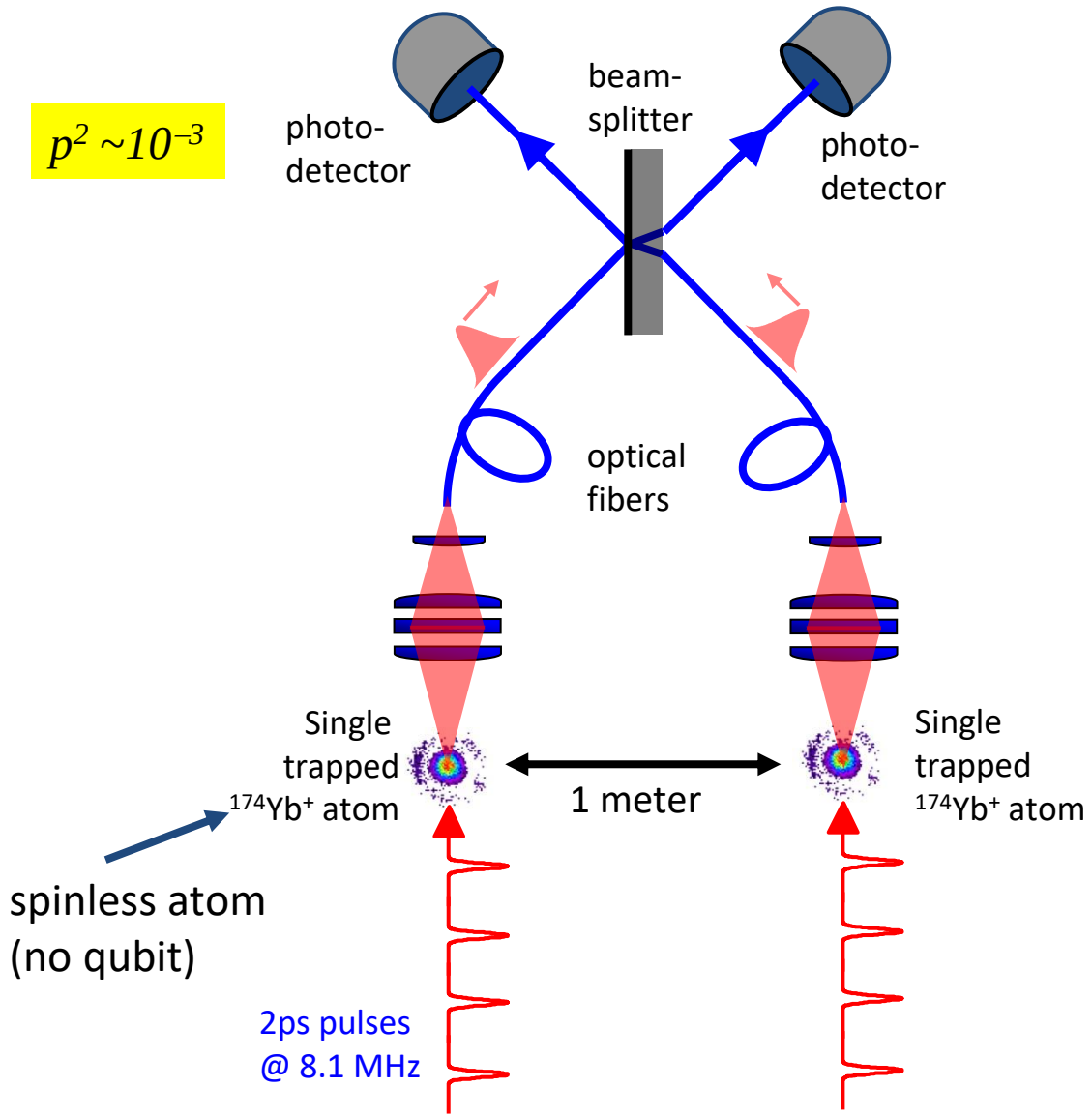
$g^{(2)}(0)$

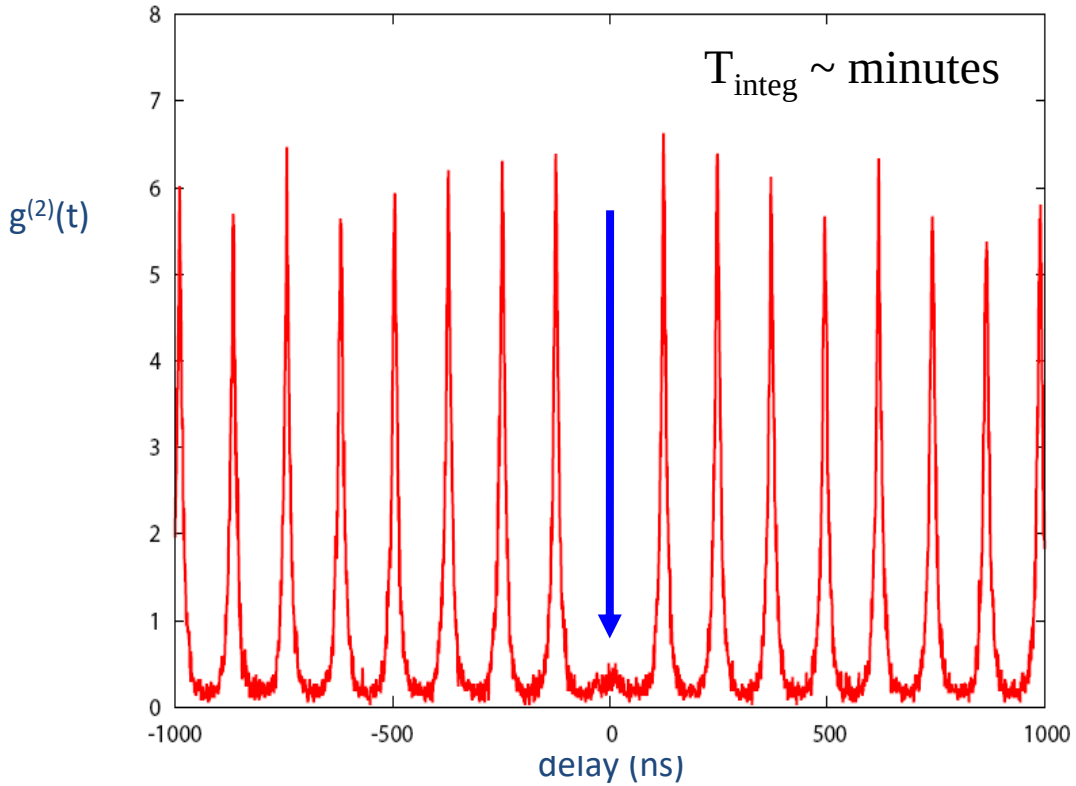


C. Crocker, et al., Optics Express 27, 28143 (2019)

2-photon interference

$p^2 \sim 10^{-3}$

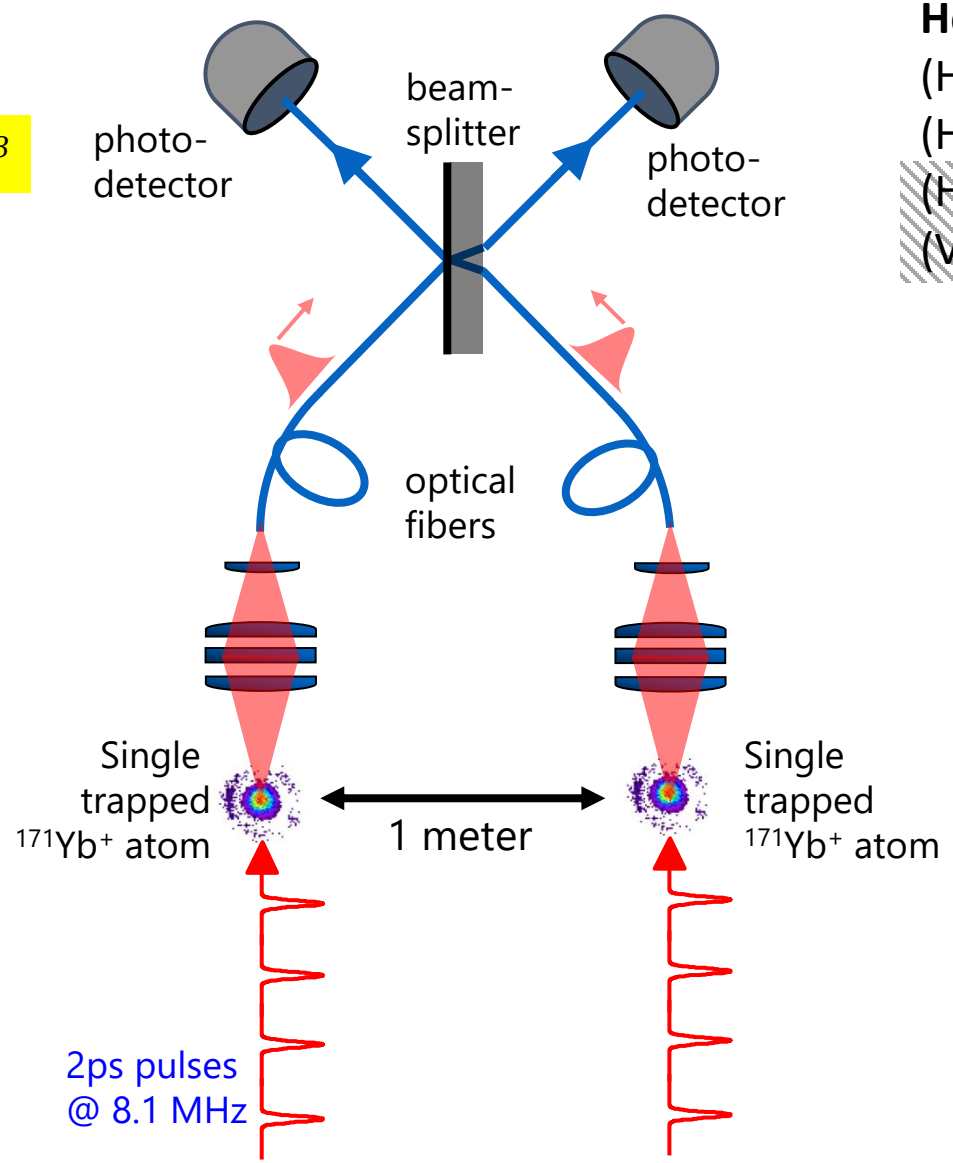




Hong, Ou, Mandel, PRL 59, 2044 (1987)
Y.H. Shih & C. O. Alley, PRL 61, 2921 (1988)
Santori, et al., Nature, 419, 594 (2002)
Kaltenbaek, et al, PRL, 96, 240502 (2006)
Legero, et al., PRL, 93, 070503 (2004).
Thompson, et al., Science, 313, 74 (2006).
Felinto, et al. Nature Physics, 2, 844 (2006).
Beugnon, et al. Nature, 440, 779 (2006).
P. Maunz, et al., Nature Physics 3, 538 (2007)

Photonic Linkage between Atomic Qubits

$p^2 \sim 10^{-3}$



Heralded coincident events:

$(H_1 \,\&\, V_2)$ or $(V_1 \,\&\, H_2) \rightarrow |{\downarrow\uparrow}\rangle - |{\downarrow\uparrow}\rangle$

$(H_1 \,\&\, V_1)$ or $(V_2 \,\&\, H_2) \rightarrow |{\downarrow\uparrow}\rangle + |{\downarrow\uparrow}\rangle$

$(H_1 \,\&\, H_1)$ or $(H_2 \,\&\, H_2) \rightarrow |{\downarrow\downarrow}\rangle$

$(V_1 \,\&\, V_1)$ or $(V_2 \,\&\, V_2) \rightarrow |{\uparrow\uparrow}\rangle$

Hong, Ou, Mandel, PRL 59, 2044 (1987)
Y.H. Shih & C. O. Alley, PRL 61, 2921 (1988)
Simon & Irvine, PRL **91**, 110405 (2003)
L.-M. Duan, et. al., QIC **4**, 165 (2004)
Y. L. Lim, et al., PRL **95**, 030505 (2005)
2007: **Trapped Ions** [Nature 449, 68–71]
2013: **Trapped Neutrals** [PRL 110, 140403]
2014: **NV-diamond** [Science 345, 532]
2015: **Quantum Dots** [Nature Phys. 12, 218]
2016: **Superconductors** [PRX 6, 031036]

$$R_{ent} = \frac{1}{2} R p^2$$

Current State-of-art:

$$p = \eta_D \, T \frac{d\Omega}{4\pi} = (.35)(.6)(.1) = 2\%$$

$$R = 1 \, MHz$$

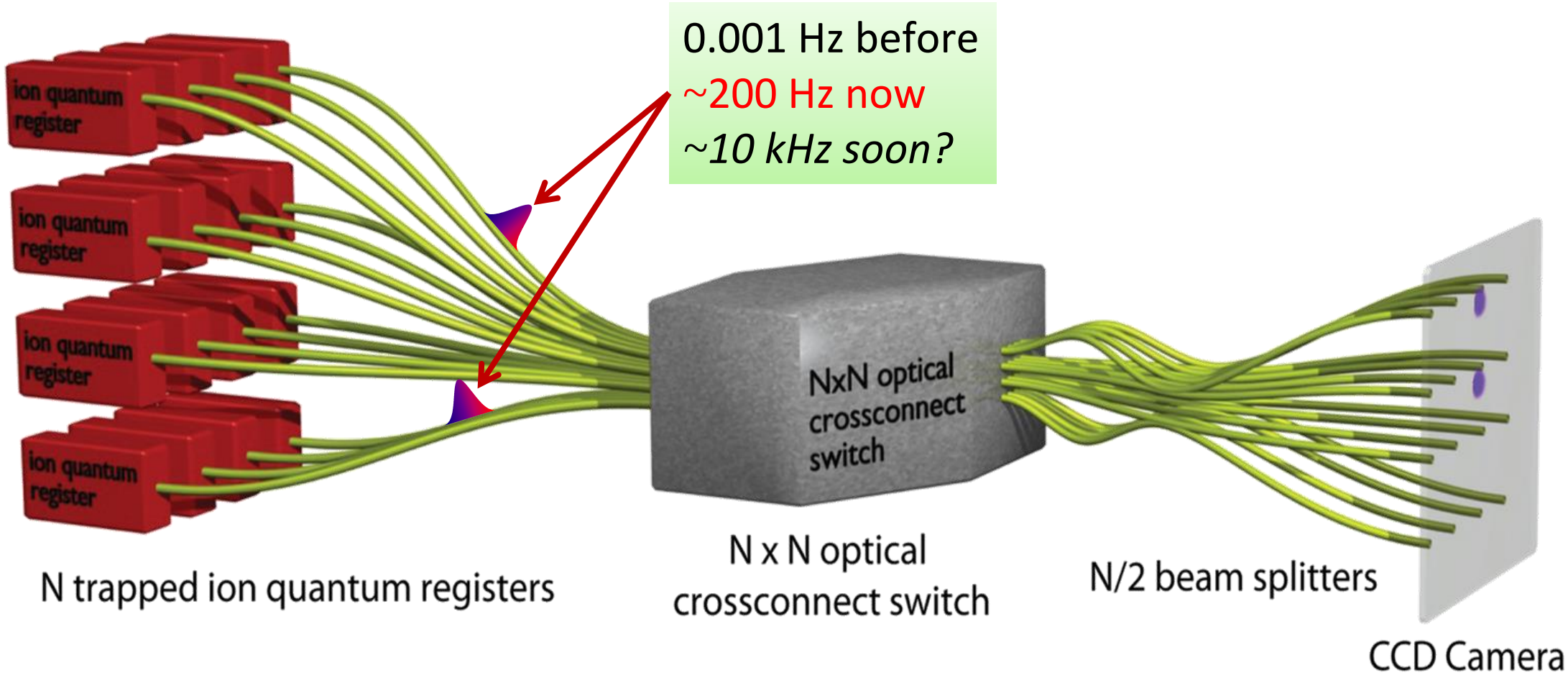
$$\boldsymbol{R_{ent} \approx 180 \, sec^{-1}}$$

D. Hucul, et al., Nature Phys. 11, 37 (2015)

C. Balance, et al, Phys. Rev. Lett. 124, 110501

Soon: $\sim 10^4 \, sec^{-1}$ ...slow, but ***we have time***

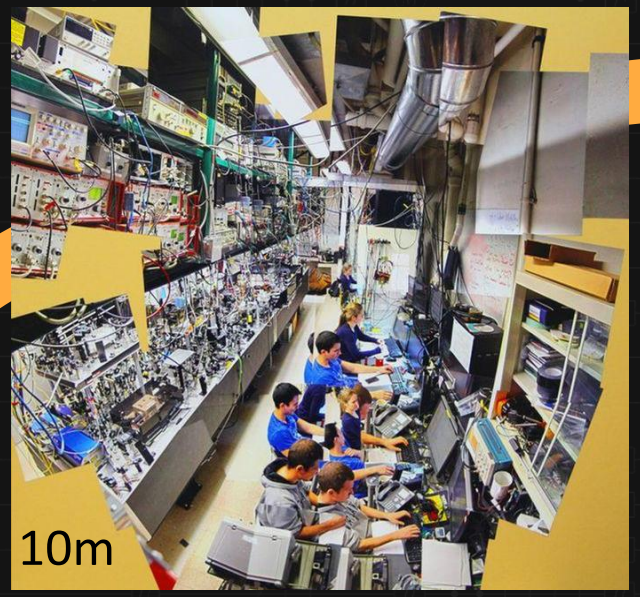
Vision I: Modular Scaling with Photonic Interconnects



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)

Ion Trap QC Path to Scale

2016

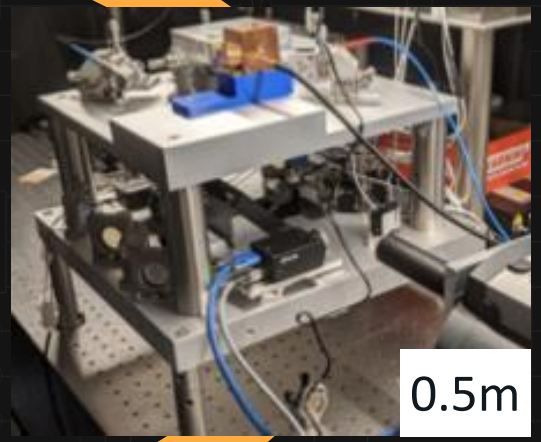


Lab scale

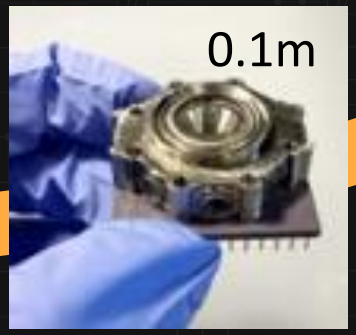
2018

Bench scale

2020

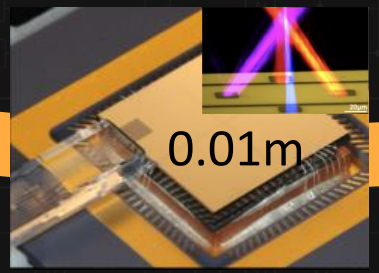


2021



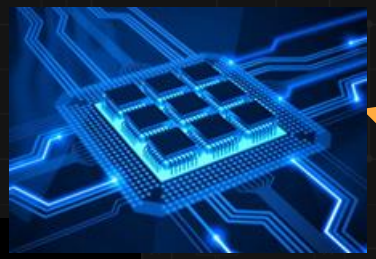
Rackmount scale

2023



Chip scale

2025



IONQ

IonQ was founded in 2015 by
Chris Monroe and Jungsang Kim,
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.

www.ionq.com

College Park, MD

70 employees

Venture Investors ($84M raised)

New Enterprise Associates

Google Ventures

SAMSUNG

MUBADALA

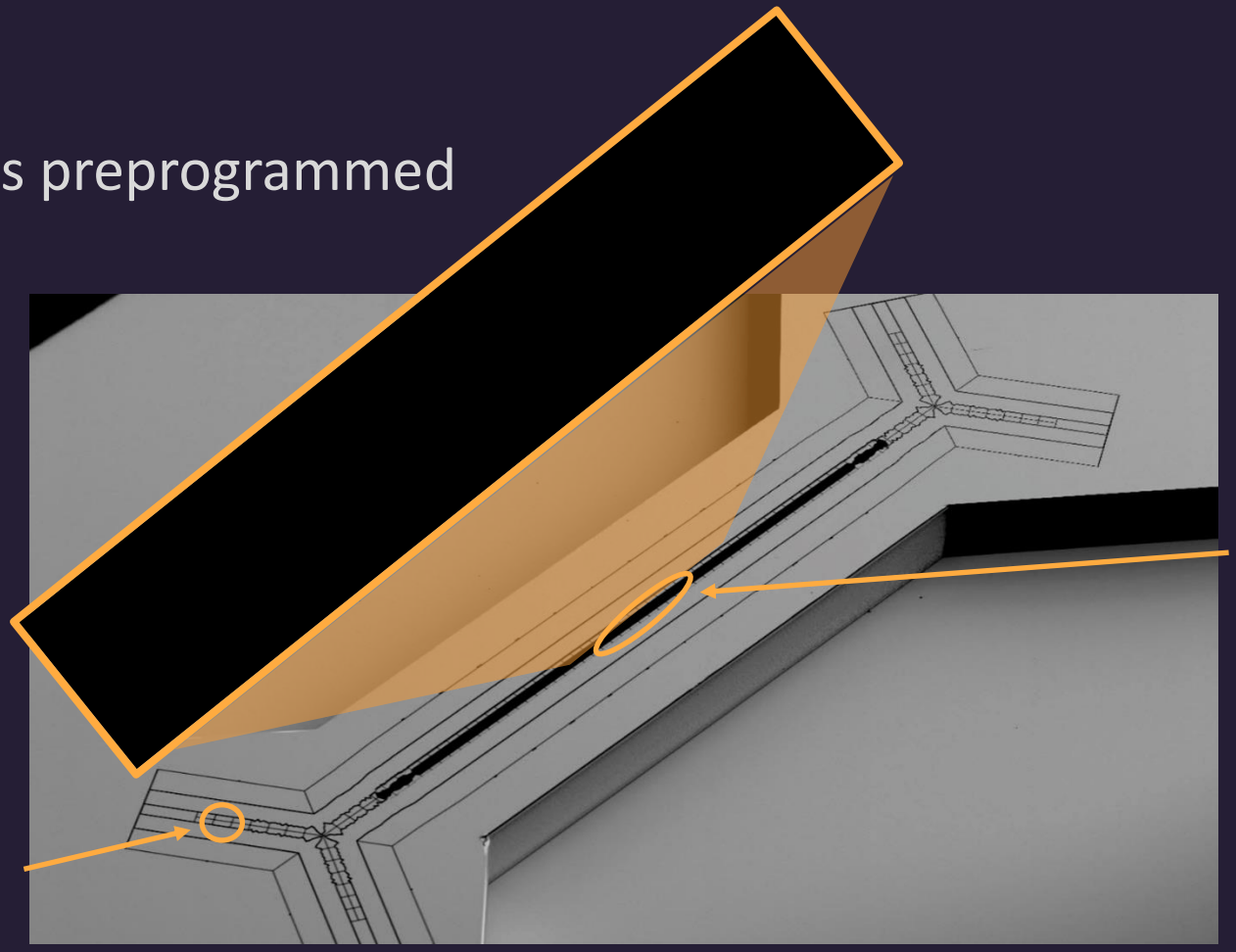
IONQ Quantum computer
www.ionq.com

IonQ Systems on the cloud

PICTURED: IONQ'S NEXT-GEN SYSTEM

IONQ autoloading register

N=24 qubits preprogrammed



Quantum Computing zone

Loading zone

Lower Errors through Encoding

$$\alpha|0\rangle + \beta|1\rangle \implies$$

error prob. p

error prob. p (per qubit)

$$\alpha\begin{pmatrix} |00000\rangle + |10010\rangle + |01001\rangle + |10100\rangle \\ +|01010\rangle - |11011\rangle - |00110\rangle - |11000\rangle \\ -|11101\rangle - |00011\rangle - |11110\rangle - |01111\rangle \\ -|10001\rangle - |01100\rangle - |10111\rangle + |00101\rangle \end{pmatrix} + \beta\begin{pmatrix} |11111\rangle + |01101\rangle + |10110\rangle + |01011\rangle \\ +|10101\rangle - |00100\rangle - |11001\rangle - |00111\rangle \\ -|00010\rangle - |11100\rangle - |00001\rangle - |10000\rangle \\ -|01110\rangle - |10011\rangle - |10111\rangle + |11010\rangle \end{pmatrix}$$

$$p \implies Cp^2$$

Quantum Error Correction

C. Shannon (classical)
P. Shor
R. Calderbank
A. Steane

University

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

?

Industry

- ✗ *Not so familiar with quantum physics*
- ✗ *May not build things for science*
- ✓ *Engineering, manufacturing, reliability*

National Laboratory

- ✓ *No problem with quantum physics*
- ✓ *Research for science and applications*
- ✓ *Engineering, manufacturing, reliability*
- ✗ *Little history in the field (for now)*

U.S. National Quantum Initiative Act (2018)

White House OSTP
@WHOSTP

Follow

Tonight @realdonaldtrump signed the National Quantum Initiative Act into law to help drive American leadership in #QIS innovation! Joining him: @WhiteHouse Deputy Chief of Staff Chris Liddell, @WHOSTP's Michael Kratsios, & @IvankaTrump. Text of the Act at bit.ly/2RbBIWh

The NPI Team behind the NQI

H.R. 6227

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Ed White
NPI

David Lang
OSA

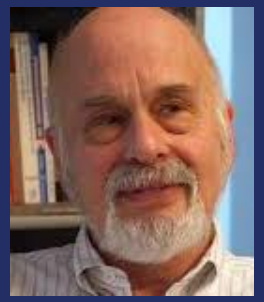
Jennifer O'Bryan
SPIE

Duke Quantum Center

A Quantum Computer User Facility that will

- **Build quantum computers** from the highest performance components
- **Use quantum computers** for science
- **Co-design** next generation quantum computers based on scientific use cases
- **Translate** quantum technology to national and commercial societal needs

Ken Brown



Robert Calderbank

Marko Cetina

Jungsang Kim

Chris Monroe

Crystal Noel

- **Physics**
- **Electrical & Computer Engineering**
- **Chemistry**
- **Mathematics**
- **Computer Science**