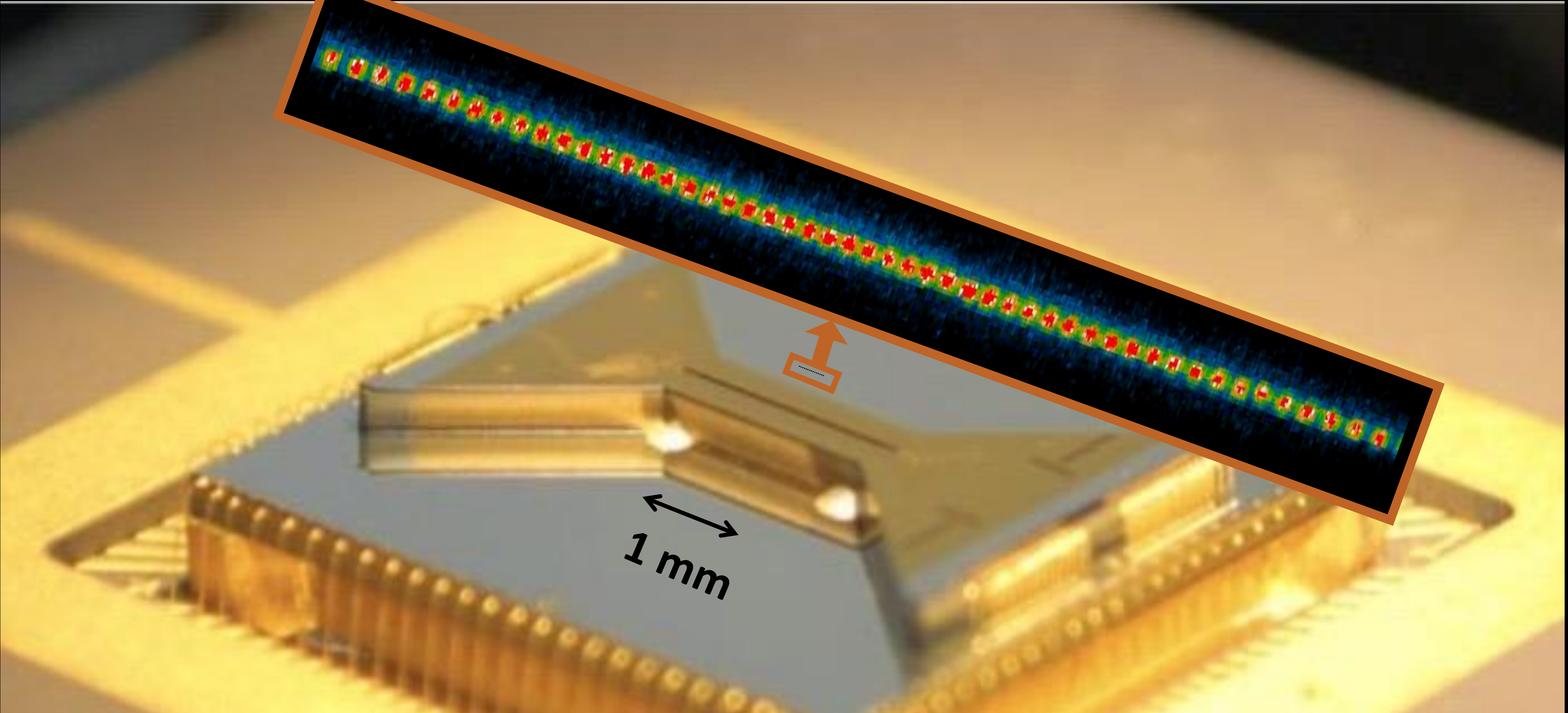


Reconfigurable Quantum Computers and Simulators with Atomic Ions

Christopher Monroe

University of Maryland, JQI, QuICS, and IonQ Inc.

University of Maryland

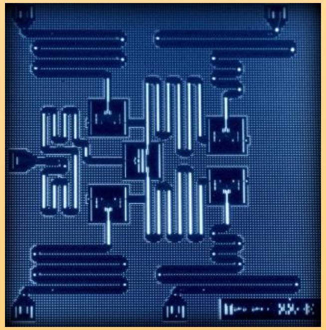
JOINT QUANTUM INSTITUTE

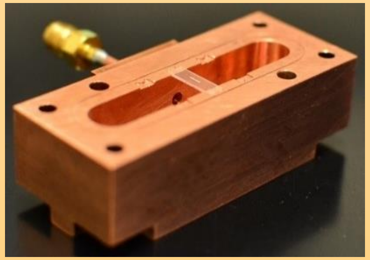
QuICS Center for Quantum Information & Computer Science

IONQ

Two Quantum Technologies Ready for Building

Superconducting Circuits





Superconducting qubit: phase/charge/current, capacitive or microwave photon couplings

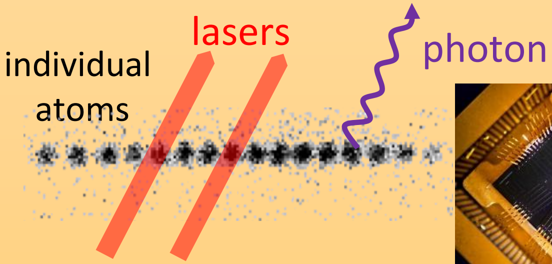
FEATURES & STATE-OF-ART
- connected with waveguides
- ~10 qubits demonstrated
- **fast clock speed**
- **printable circuits and VLSI**

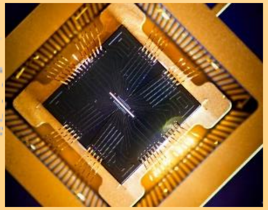
CHALLENGES
- short (10^{-6} sec) memory
- 0.05K cryogenics
- **all qubits different**
- **limited connectivity**
- **not reconfigurable**

Investments

IARPA
DoD
Lincoln Labs
IBM
Intel/Delft
Google/UCSB
Rigetti Computing
Quantum Circuits, Inc.

Trapped Atomic Ions





Atomic qubits connected through charge-coupled motion, shuttling, or photons

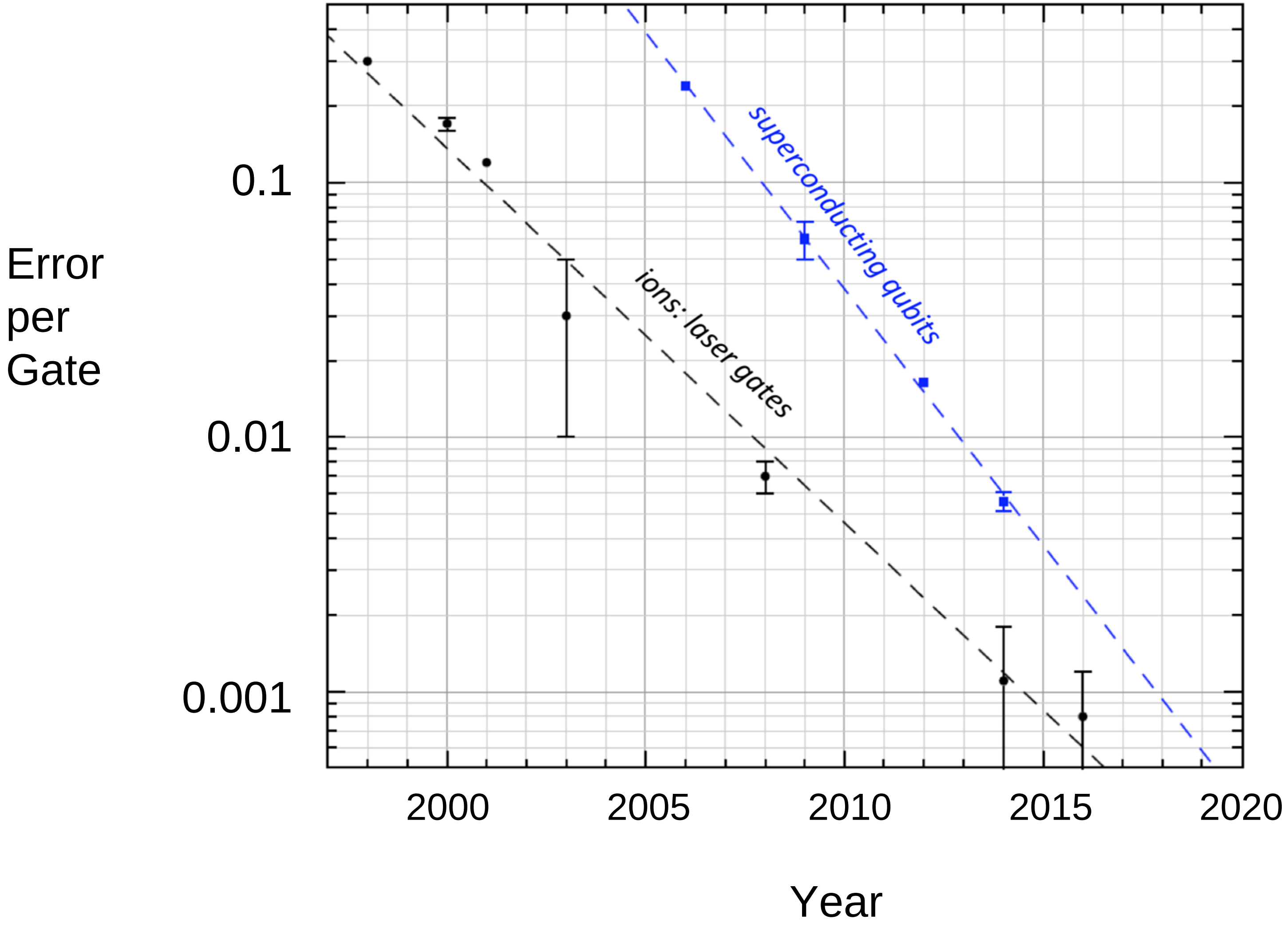
FEATURES & STATE-OF-ART
- very long (>>1 sec) memory
- ~20 qubits demonstrated
- **qubits all identical**
- **fully connected**
- **connections reconfigurable**

CHALLENGES
- lasers & optics
- high vacuum
- **slow clock speed**
- **engineering needed**

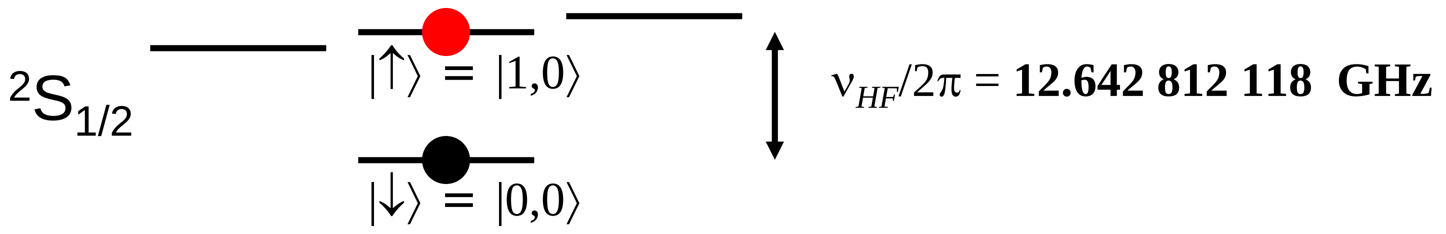
Investments

IARPA
DoD
Lincoln Labs
Sandia
UK Gov't
Honeywell
IonQ, Inc.

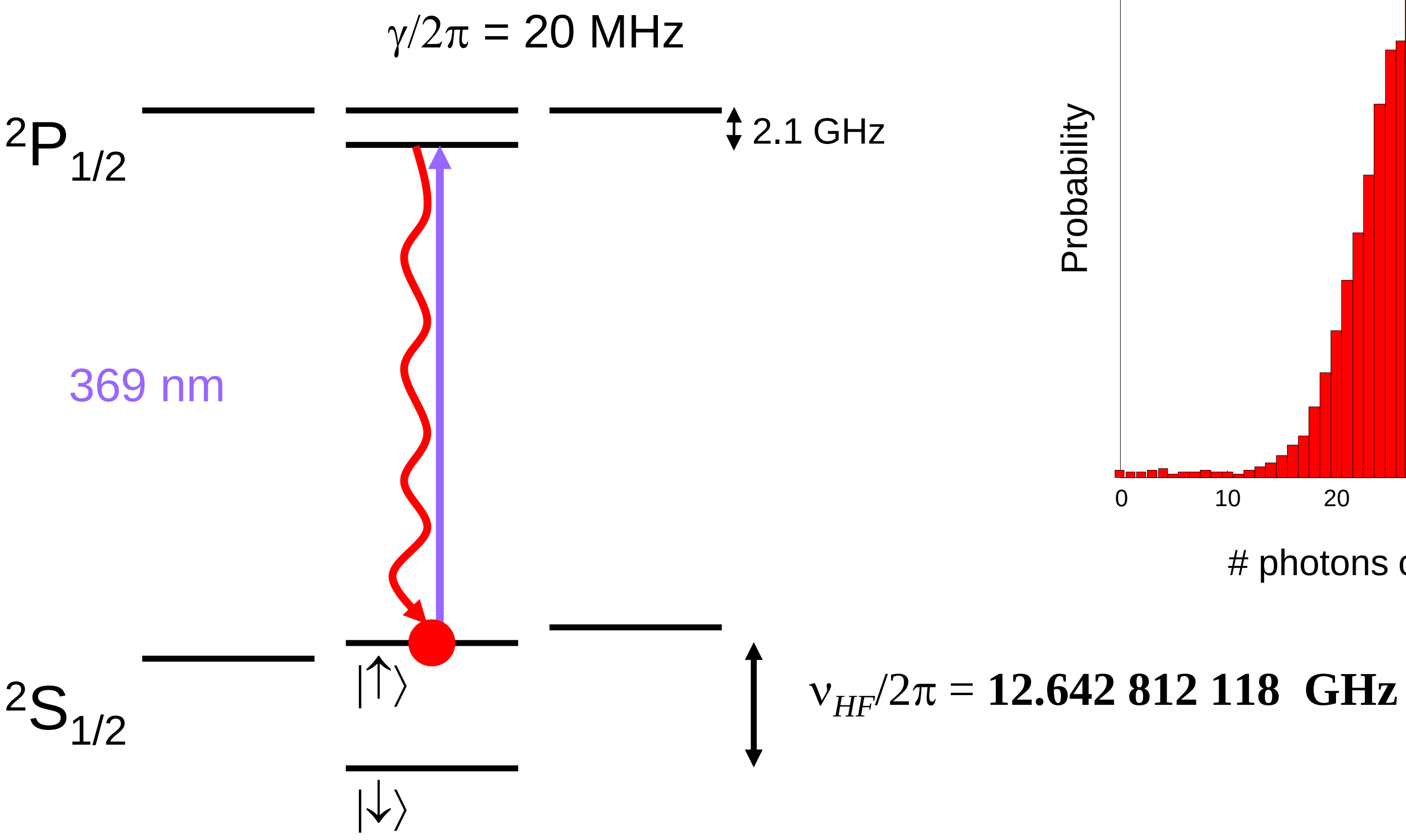
History of 2-Qubit Gate Performance

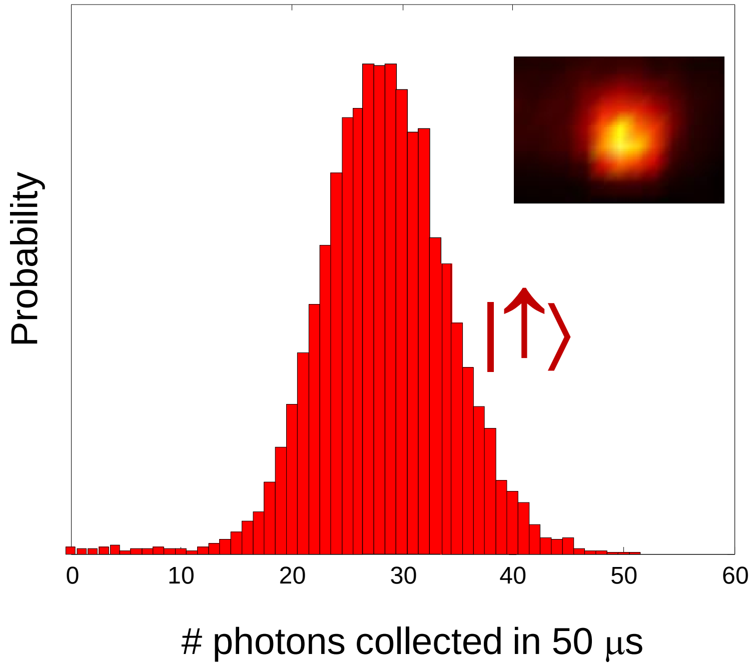


Atomic Qubit ($^{171}Yb^+$)

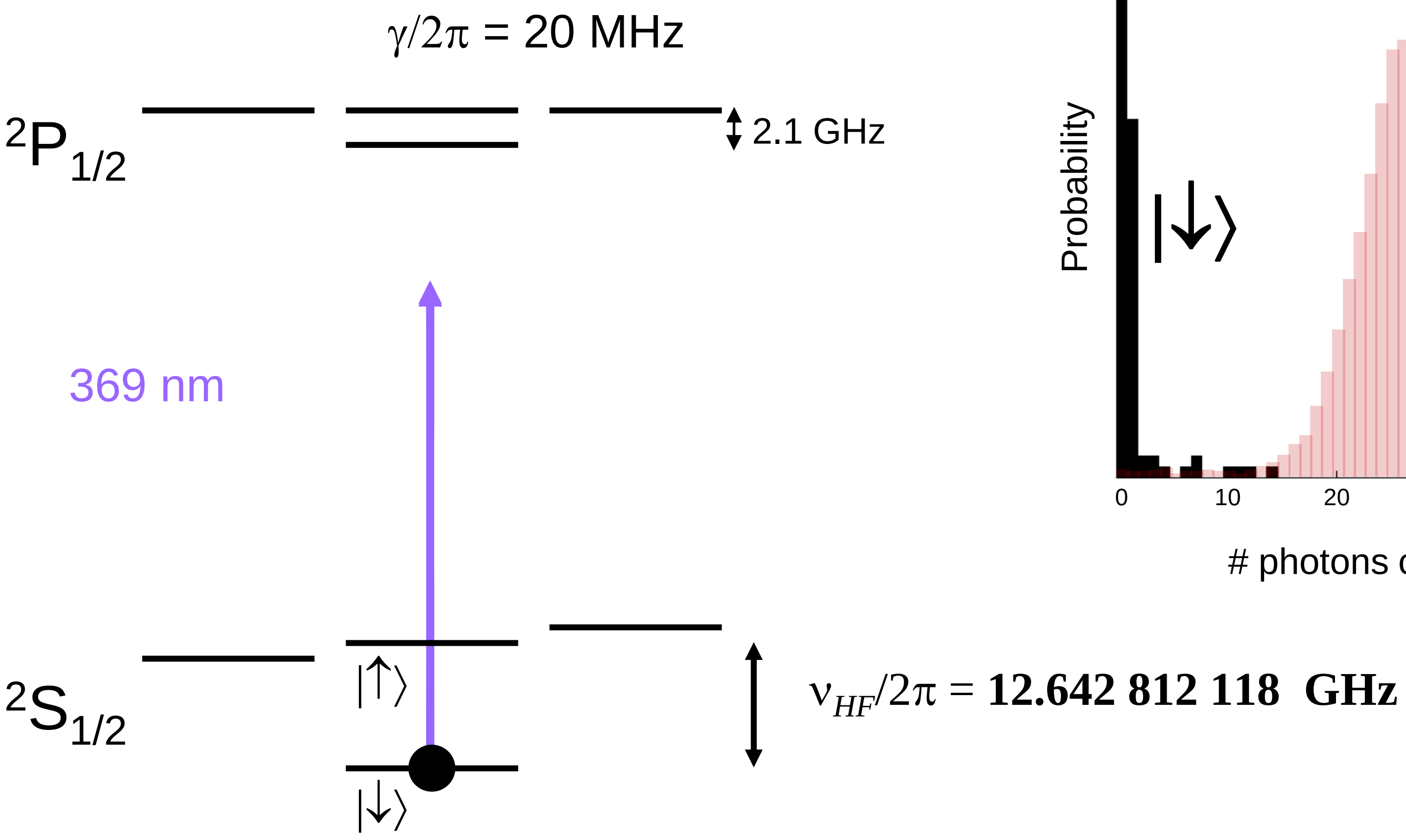


$^{171}Yb^+$ Qubit Detection

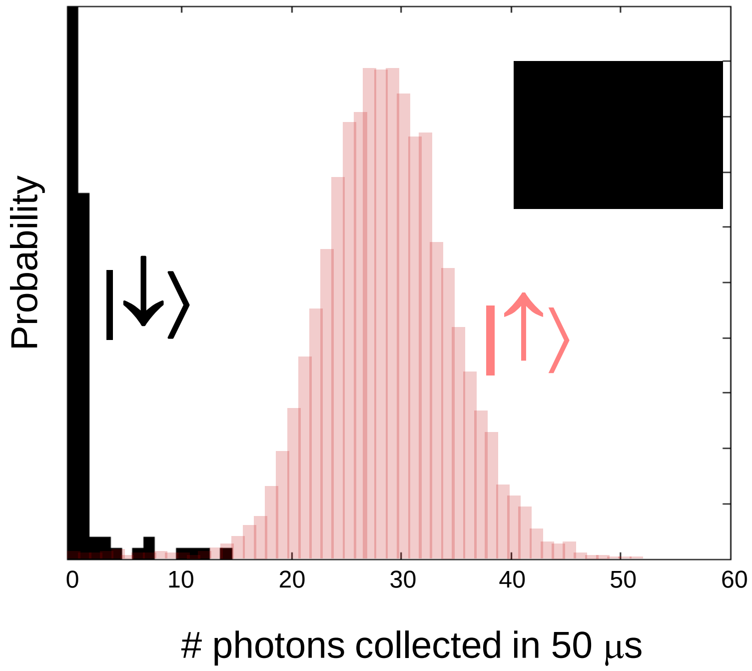




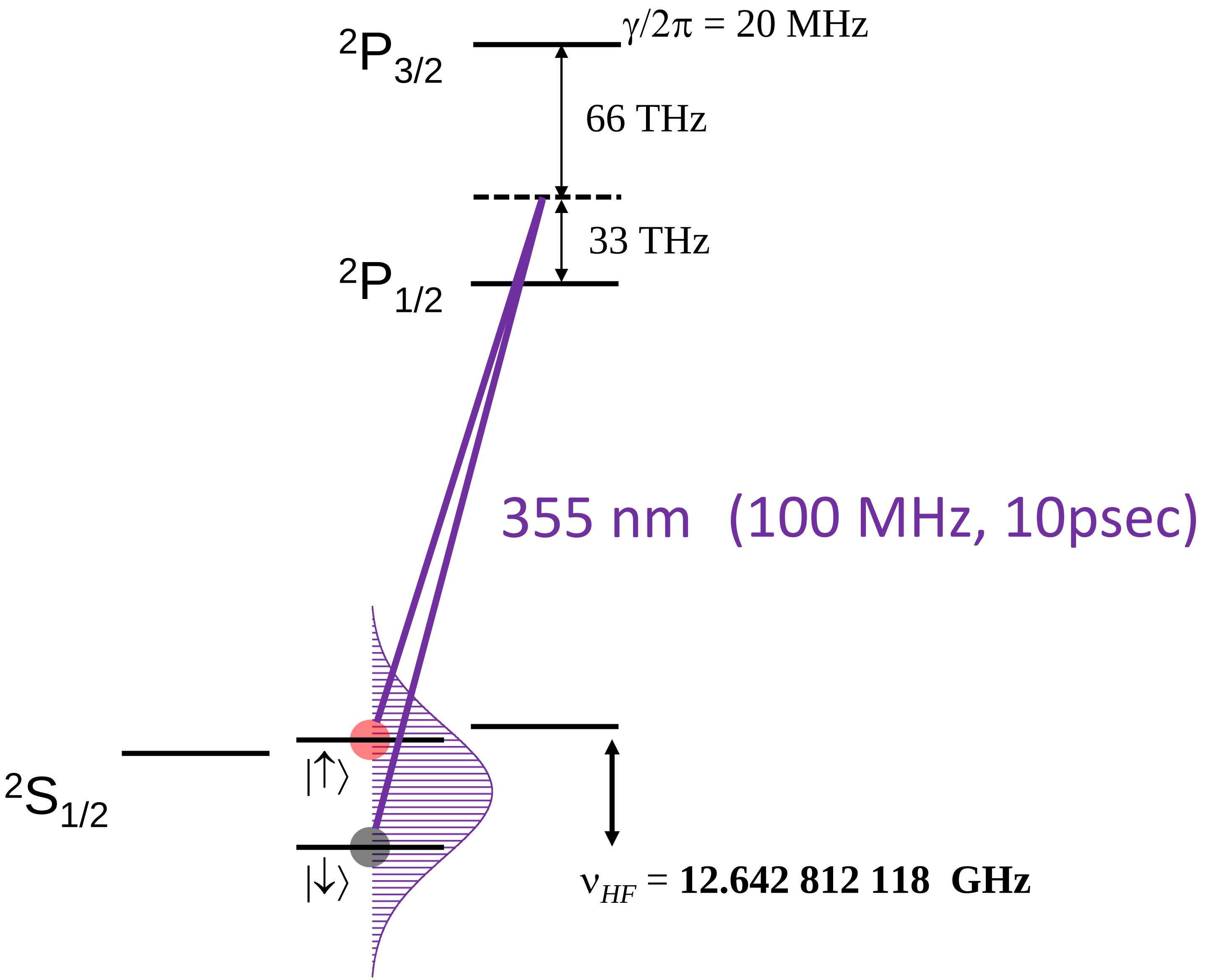
$^{171}Yb^+$ Qubit Detection



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



$^{171}Yb^+$ Qubit Manipulation



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

Entangling Trapped Ion Qubits

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
eδ ~ 500 Debye

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

for full entanglement

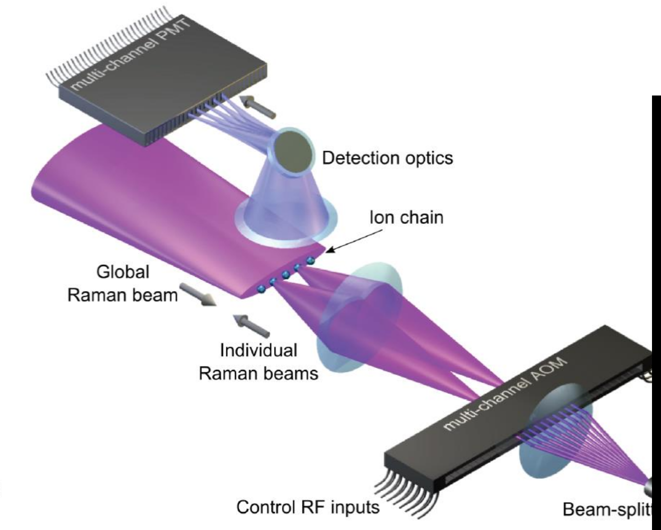
Native Ion Trap Operation: "Ising" gate

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

T_{gate} ~ 10–100 μs
F ~ 98% – 99.9%

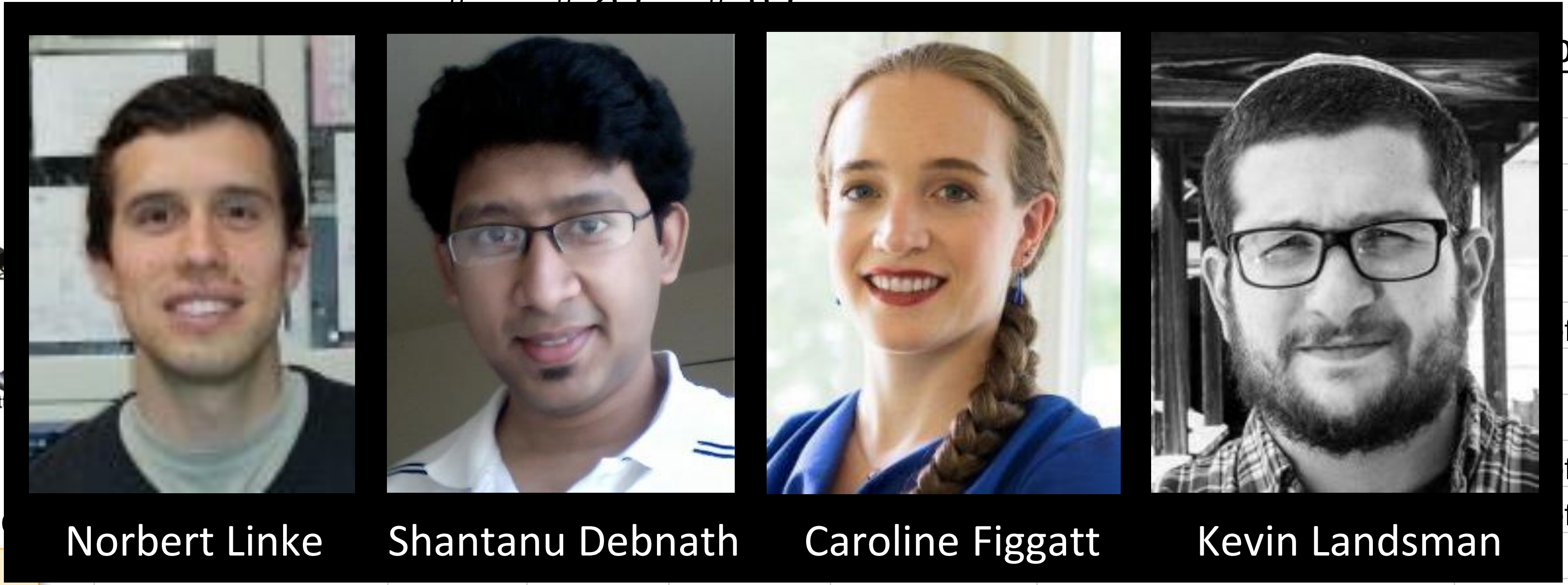
Cirac and Zoller (1995)
Mølmer & Sørensen (1999)
Solano, de Matos Filho, Zagury (1999)
Milburn, Schneider, James (2000)

Suite of Algorithms implemented on trapped ion qubits



Full "Quantum Stack" architectur

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.*



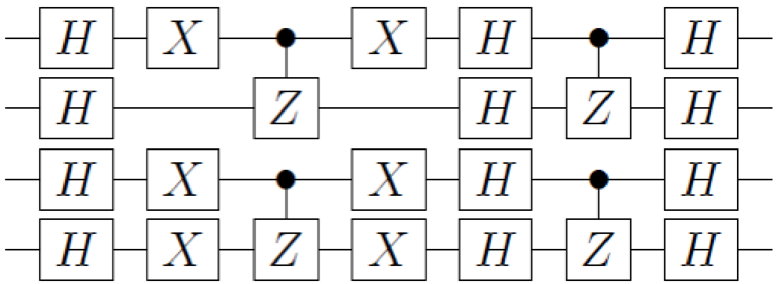
	#	# 2Q	# 1Q			orator
						ft
						ft
						ft
Fredkin Gate	3	7	14	86%	arXiv:1712.08581 (2017)	Intel
Fermi-Hubbard Sim.	5	31	132		arXiv:1712.08581 (2017)	Intel
Scrambling Test	7	15	30	75%	In preparation (2018)	Perimeter, UCB
Game Theory	5	5	15		In preparation (2018)	Army Res. Lab.
Machine Learning	4	6	8	90%	arXiv:1801.07686 (2018)	NASA
[[4,2,2]] Error Det.	5	6-7	20-25	98%-99.9%	Sci. Adv. 3, e1701074 (2017)	Duke
Full Adder	4	4	16	83%	Figgatt Thesis	NSF
Simultaneous CNOT	4	2	8	94%	Figgatt Thesis	NSF
Deuteron Simulation	3	21	11		In progress	ORNL

Hidden Shift algorithm

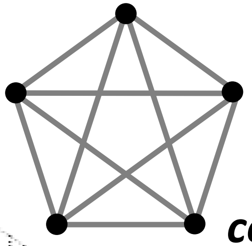
Given two *N*-bit functions $f(\mathbf{x}) = g(\mathbf{x}+\mathbf{s})$
find the hidden shift $\mathbf{s}$

Classical: $2^{N/2}$ queries of $f(x)$
Quantum: 1 query

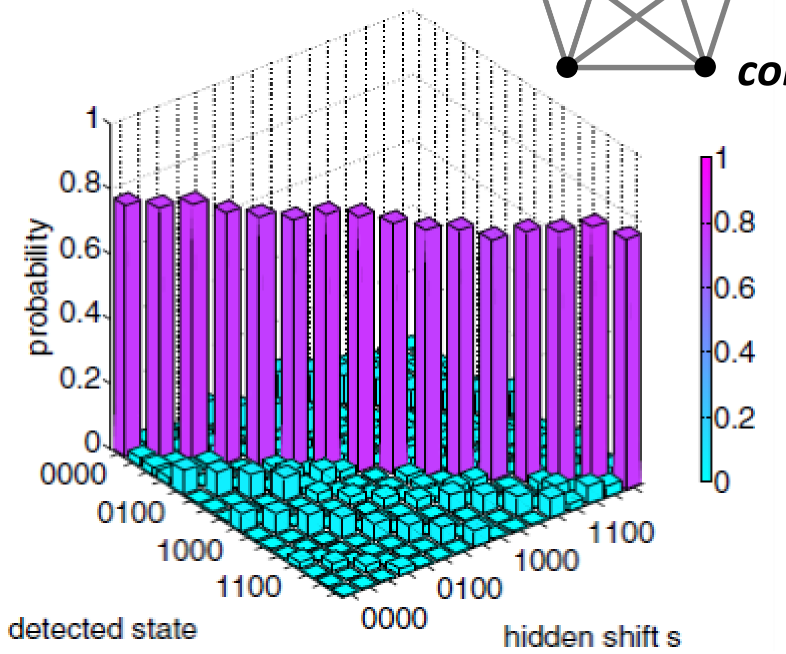
4-qubit circuit for $\mathbf{s}$ = 1010



5-qubit ion trap QC (UMaryland)



full connectivity



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

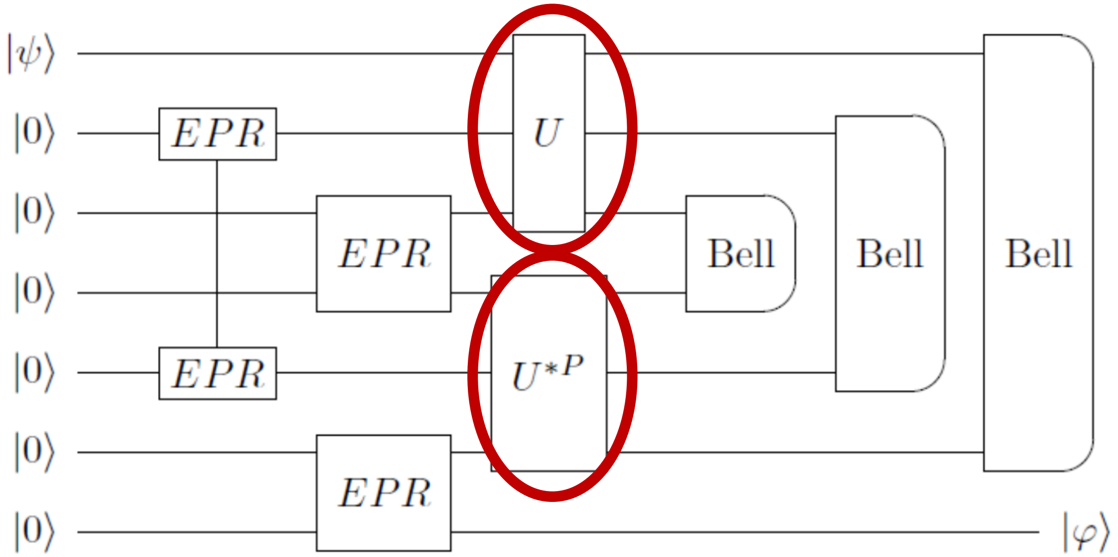
Scrambling litmus test circuit (7 qubits)

N. Yao (UC Berkeley)
B. Yoshida (Perimeter Inst.)
K. Landsman et al. (UMD)

Quantum scrambling

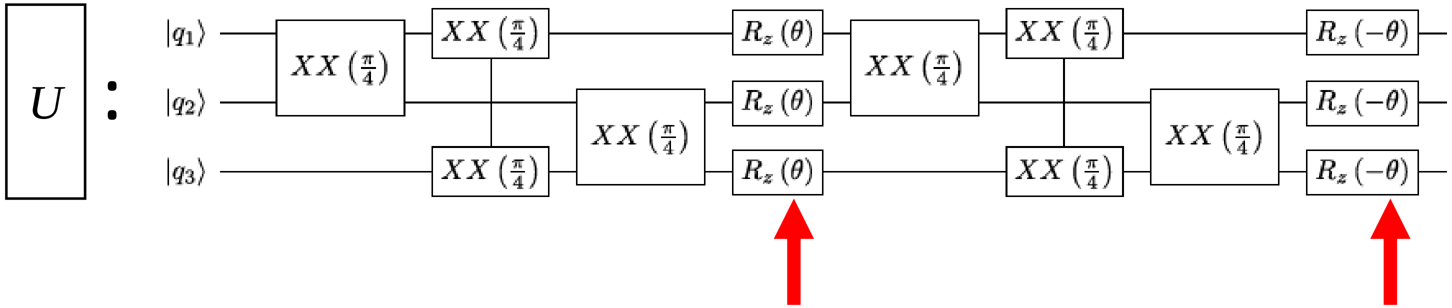
- Not just entanglement but the “complete diffusion” of entanglement within a system
- relevant to information evolution in black holes
- *P. Hayden and J. Preskill, J. HEP* ***9****, 120 (2007)*

arb. Input state



successful teleportation if U is “scrambling”

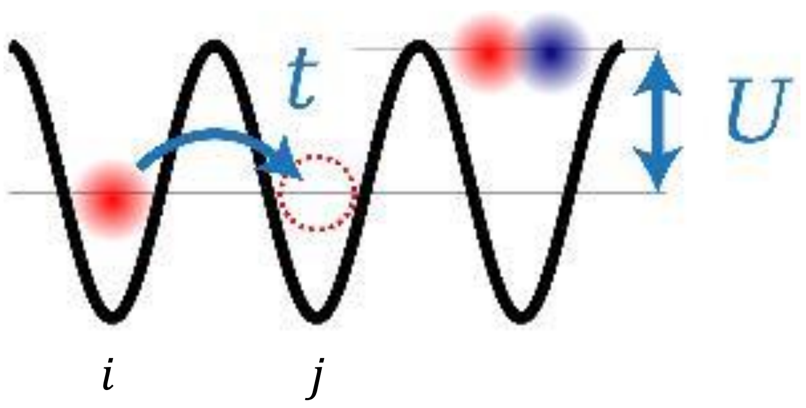
A sample 3-qubit unitary U. Degree of scrambling depends on rotation θ!



Simulating the 2-site Fermi-Hubbard Model

N. Linke, et al.,arXiv:171208581 (2017)

Two-site electronic Fermi-Hubbard model



$$H = -t \sum_{\langle i,j \rangle,\sigma} (c^\dagger_{i,\sigma} c_{j,\sigma} + c^\dagger_{j,\sigma} c_{i,\sigma}) + U \sum_{i=1}^{N} n_{i\uparrow} n_{i\downarrow}$$

$c^\dagger_{i,\sigma}$ = creation operator of electron of spin σ at site i

$n_{i,\sigma} = c^\dagger_{i,\sigma} c_{i,\sigma}$ = # electrons at site i

2 sites: encoding into 2 qubits (given conservation of electron number and total spin)

$$|00\rangle = \{1_\uparrow 1_\downarrow\}$$
$$|01\rangle = \{1_\uparrow 2_\downarrow\}$$
$$|10\rangle = \{2_\uparrow 1_\downarrow\}$$
$$|11\rangle = \{2_\uparrow 2_\downarrow\}$$

$$H = -t(X_1 + X_2) + \frac{U}{2} Z_1 Z_2$$

X, Z = qubit Pauli matrices

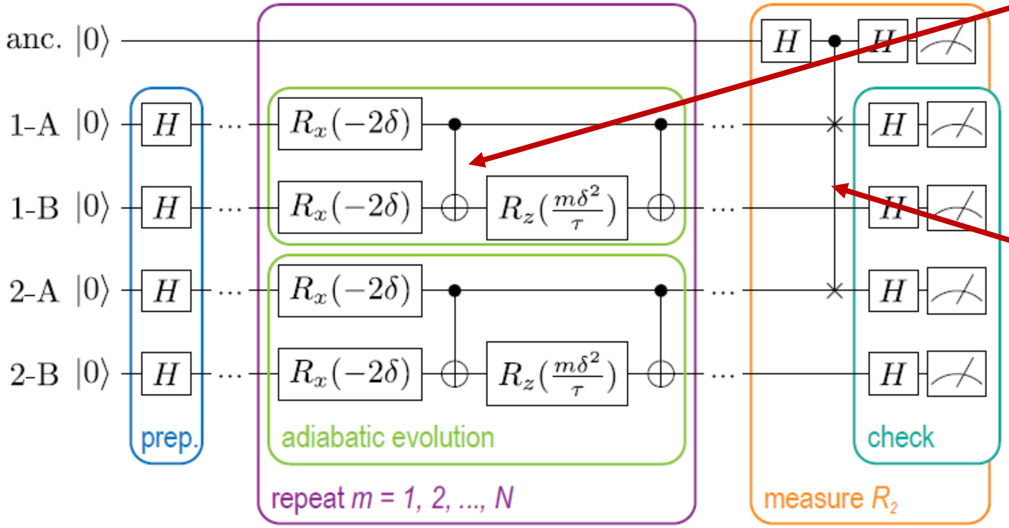
Simulating the 2-site Fermi-Hubbard Model

N. Linke, et al.,arXiv:171208581 (2017)

Renyi entropy $R_2 = Tr\{\rho_A^2\}$ measures system entanglement and allows estimation of Hamiltonian $\langle H \rangle$

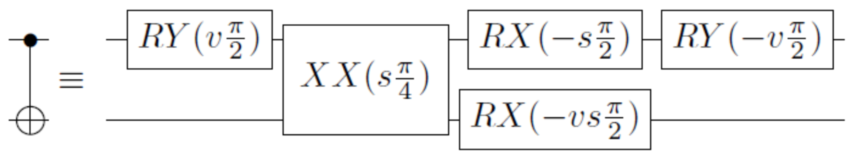
2 qubits, 2 copies + 1 ancilla = 5 qubits total

Trotter circuit to evaluate Hamiltonian

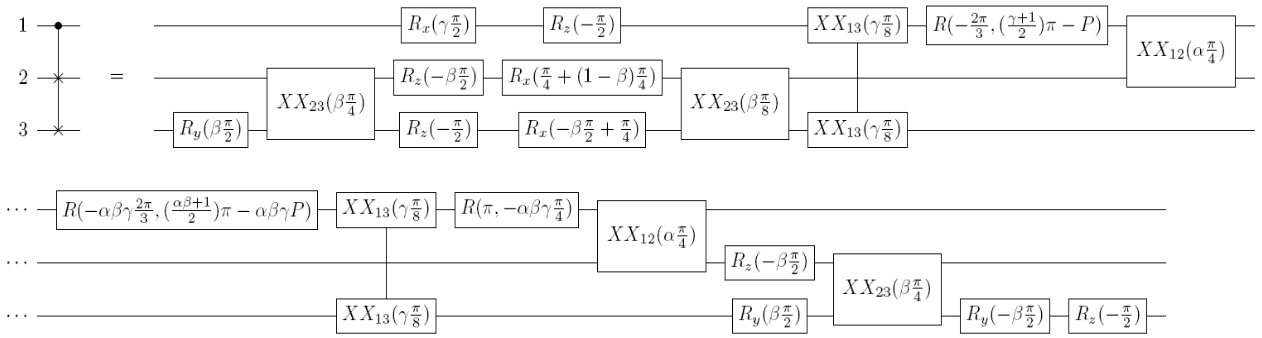


Number of iterations $N = U\tau/\delta$

C-NOT gate



C-Swap gate

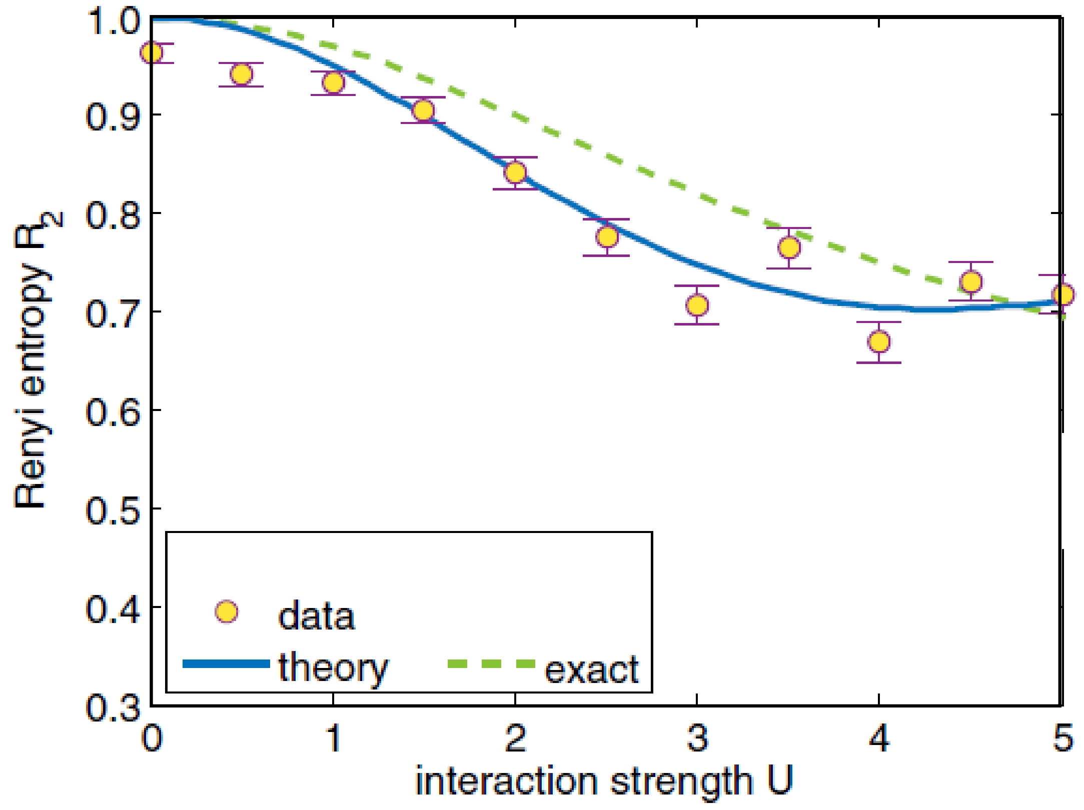


Implemented up to $N = 6$ iterations: **132 single-qubit gates, 31 dual-qubit gates**

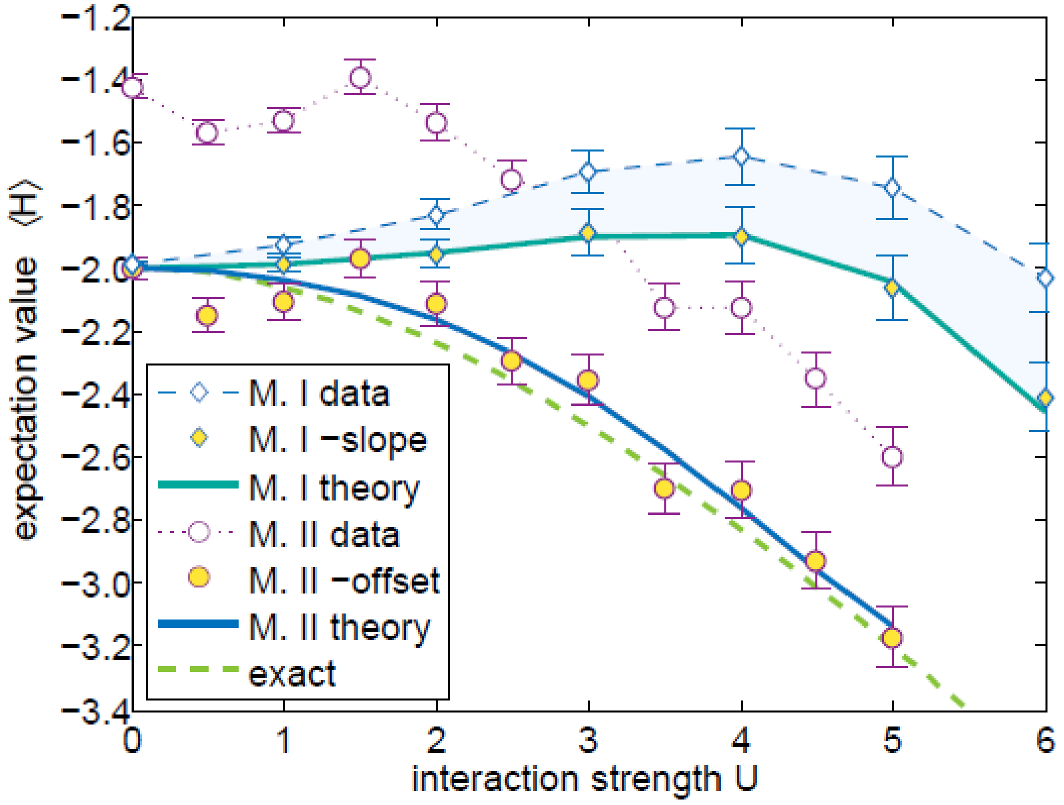
Simulating the 2-site Fermi-Hubbard Model

N. Linke, et al.,arXiv:171208581 (2017)

Measure of Renyi entropy $R_2 = Tr\{\rho_A^2\}$
$R_2 < 1$ shows entanglement



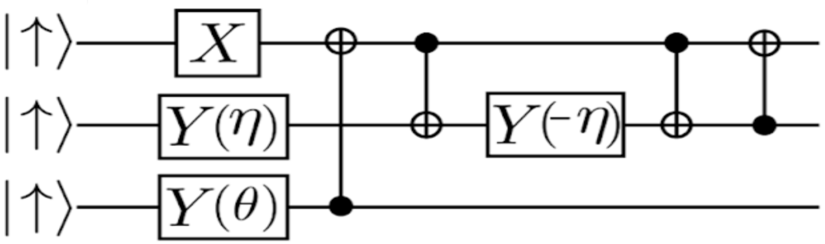
Measure of $\langle H \rangle = -t(\langle X_1 \rangle + \langle X_2 \rangle) + \frac{U}{2}\langle Z_1 Z_2 \rangle$



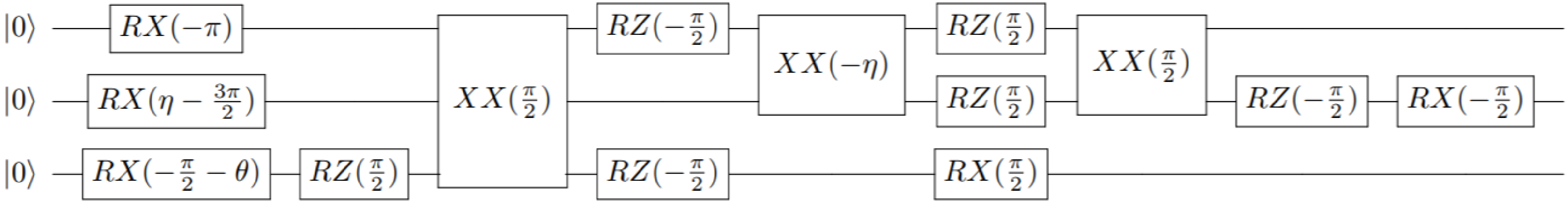
Simulating the Ground State of Deuteron

ORNL (R. Pooser, E. Dumitrescu, P. Lougovski, A. McCaskey)
UMD (K. Landsman, N. Linke, D. Zhu, CM)
IonQ (Y. Nam, O. Shehab, CM)

canonical UCC ansatz



… compiled to our native gate set

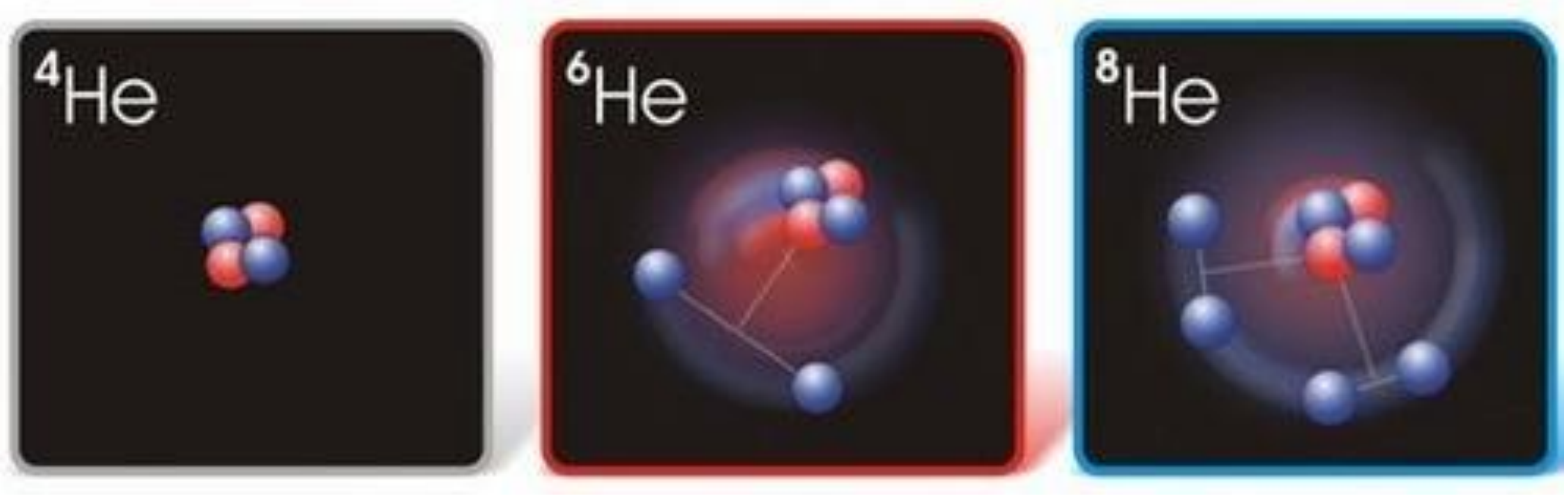


$$H = (15.531709)I + (0.218291)Z_0 - (6.125)Z_1 - (9.625)Z_2 - (2.143304)X_0X_1 - (2.143304)Y_0Y_1 - (3.913119)X_1X_2 - (3.913119)Y_1Y_2$$

E.F. Dumitrescu et al., arXiv 1801.03897 (2018)

Simulating the Ground State of Deuteron

Up Next (?)



IBM (error margin 3%)

IonQ-UMD (error margin 0.7%)

(Note: implementing 3-qubit ansatz on Rigetti system was not possible)

Quantum Simulation with 50+ Qubits

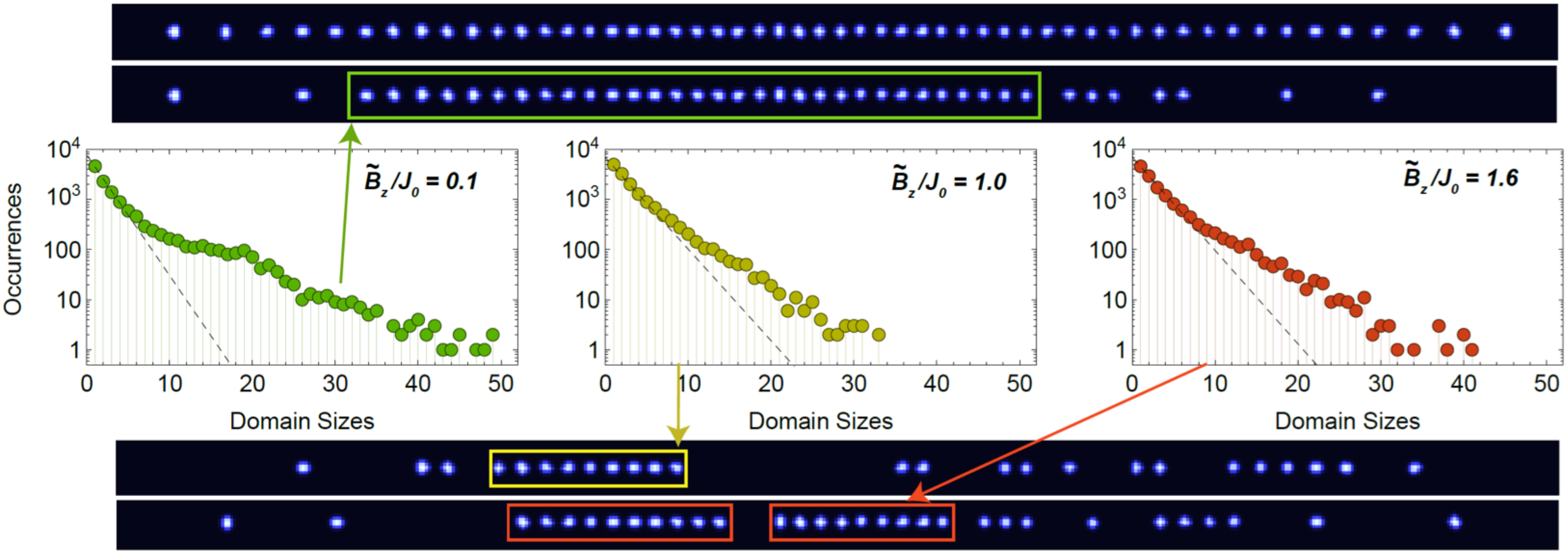
J. Zhang et al., Nature 551, 601 (2018)
(See Friday talk!)

(1) Prepare qubits (spins) along x

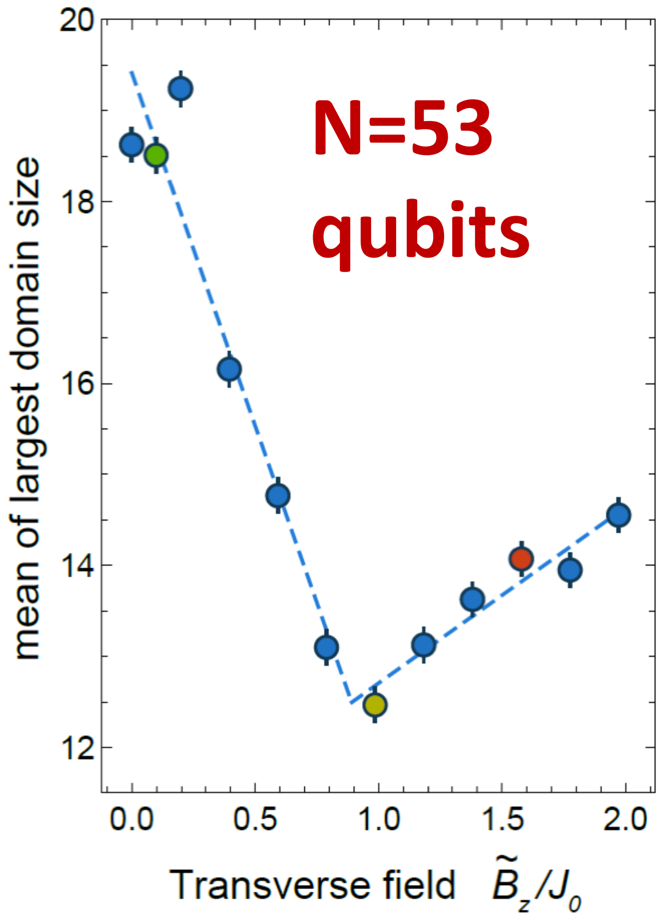
(2) Apply "all-on-all" entangling gates (long-range transverse Ising model)

$$H = \sum_{i<j} J_{ij} \sigma_x^i \sigma_x^j + B \sum_i \sigma_z^i$$

(3) Measure each qubit along x

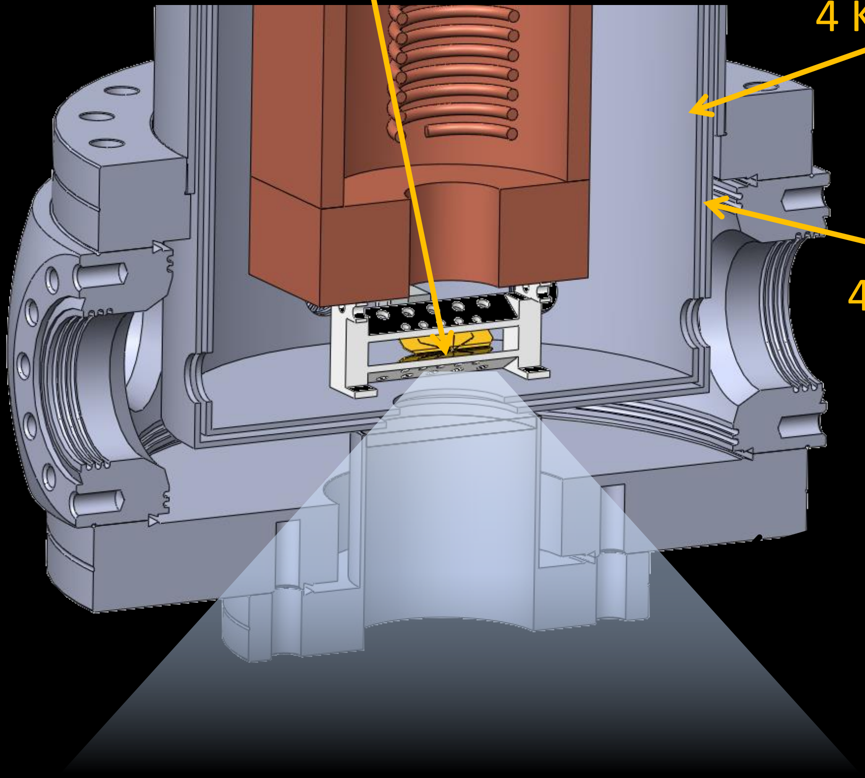


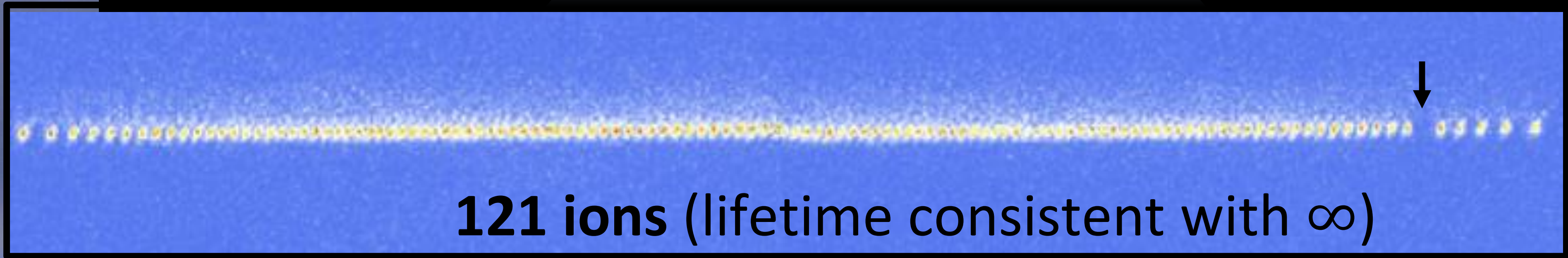
Dynamical Phase Transition



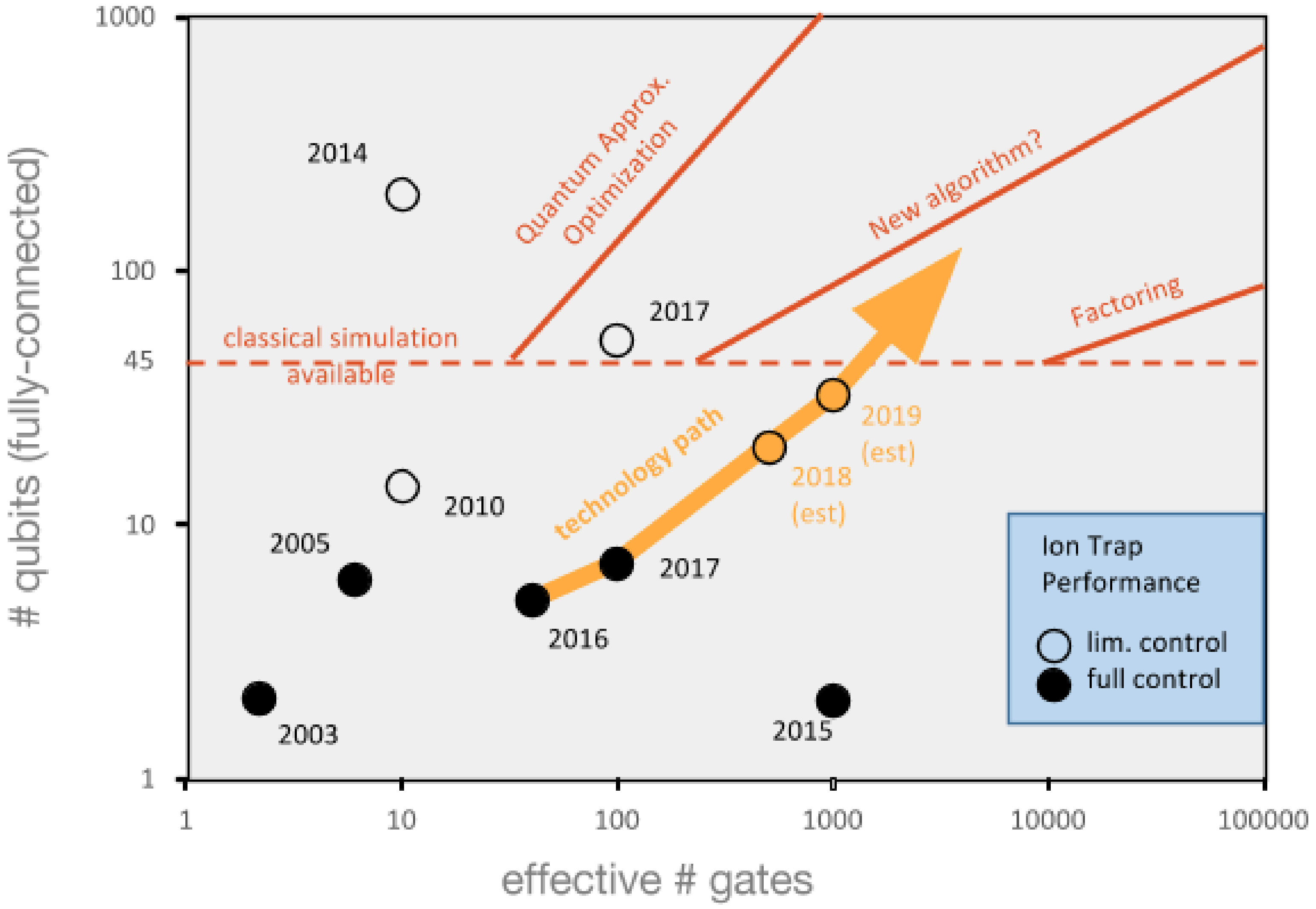
M. Heyl, et al., Phys. Rev. Lett. **110**, 135704 (2013)
P. Jurcevic, et al., Phys. Rev. Lett. **119**, 080501 (2017)
J. Zhang, et al., Nature 551, 601 (2017)

Scaling Up: 4K environment (better vacuum!)



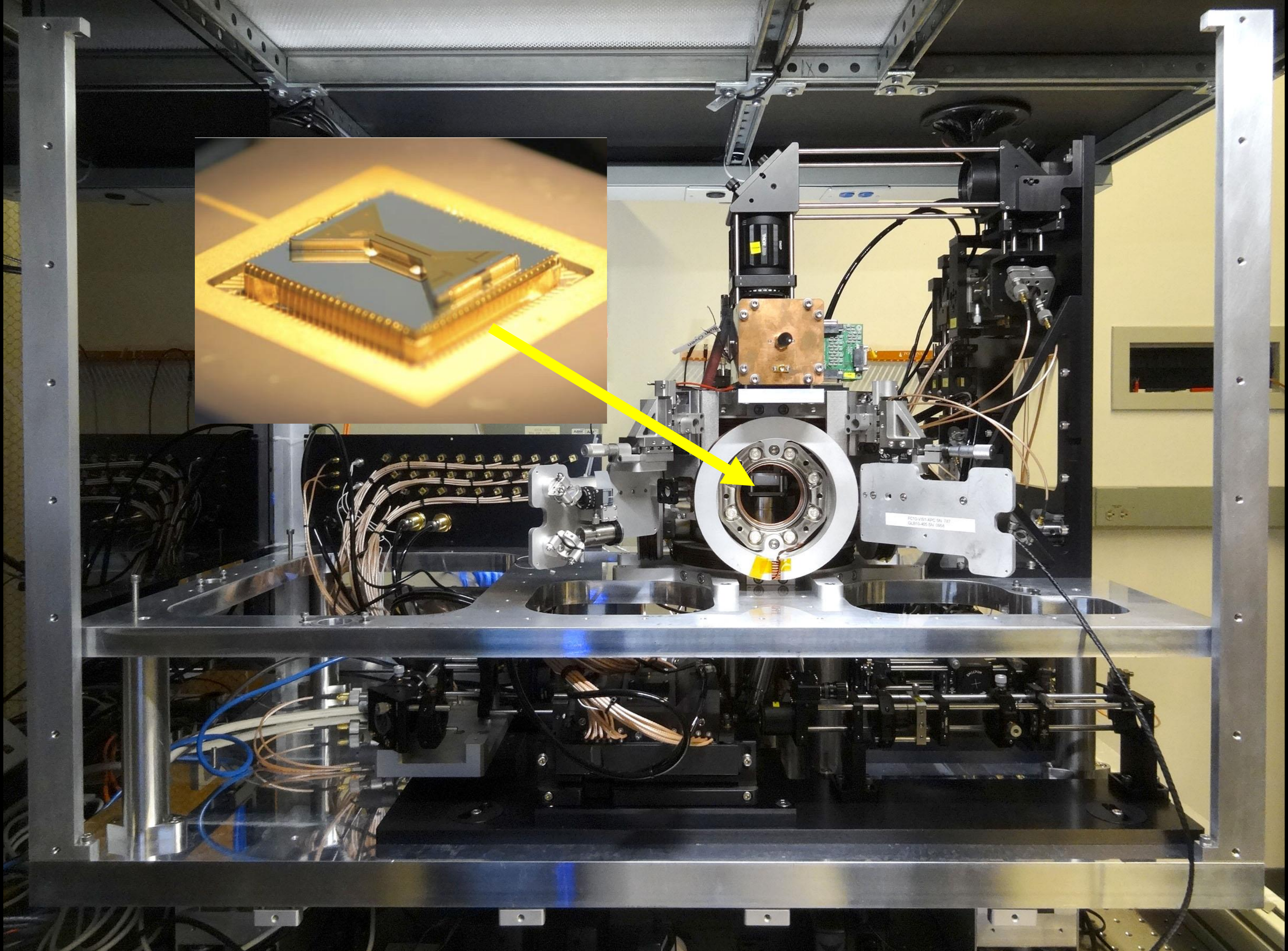


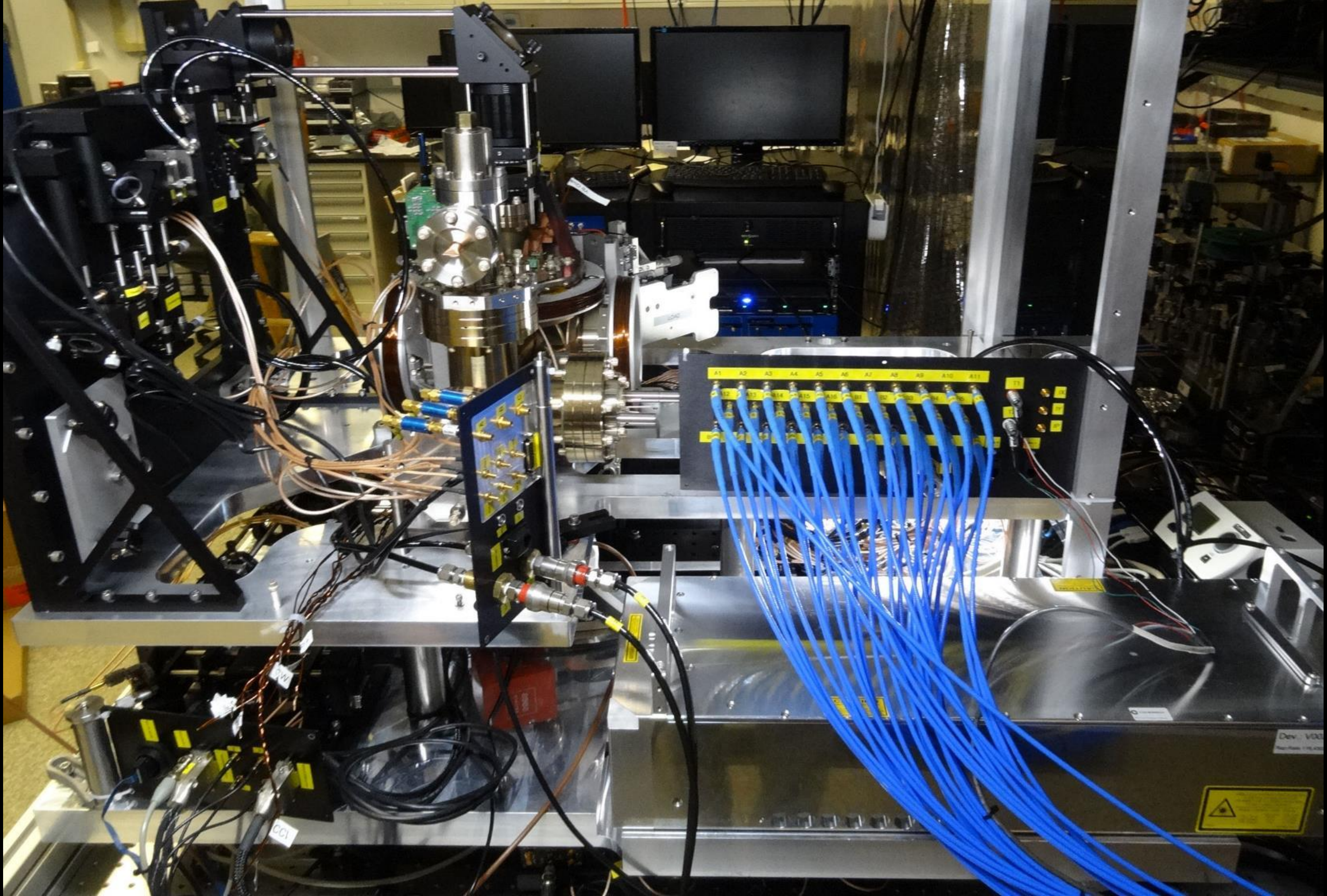
Quantum Number vs. Gate Count



Ion Trap Lab at JQI-Maryland

ENIAC (1946)




A1 A2 A3 A4 A5 A6 A7 A8 A9 A10 A11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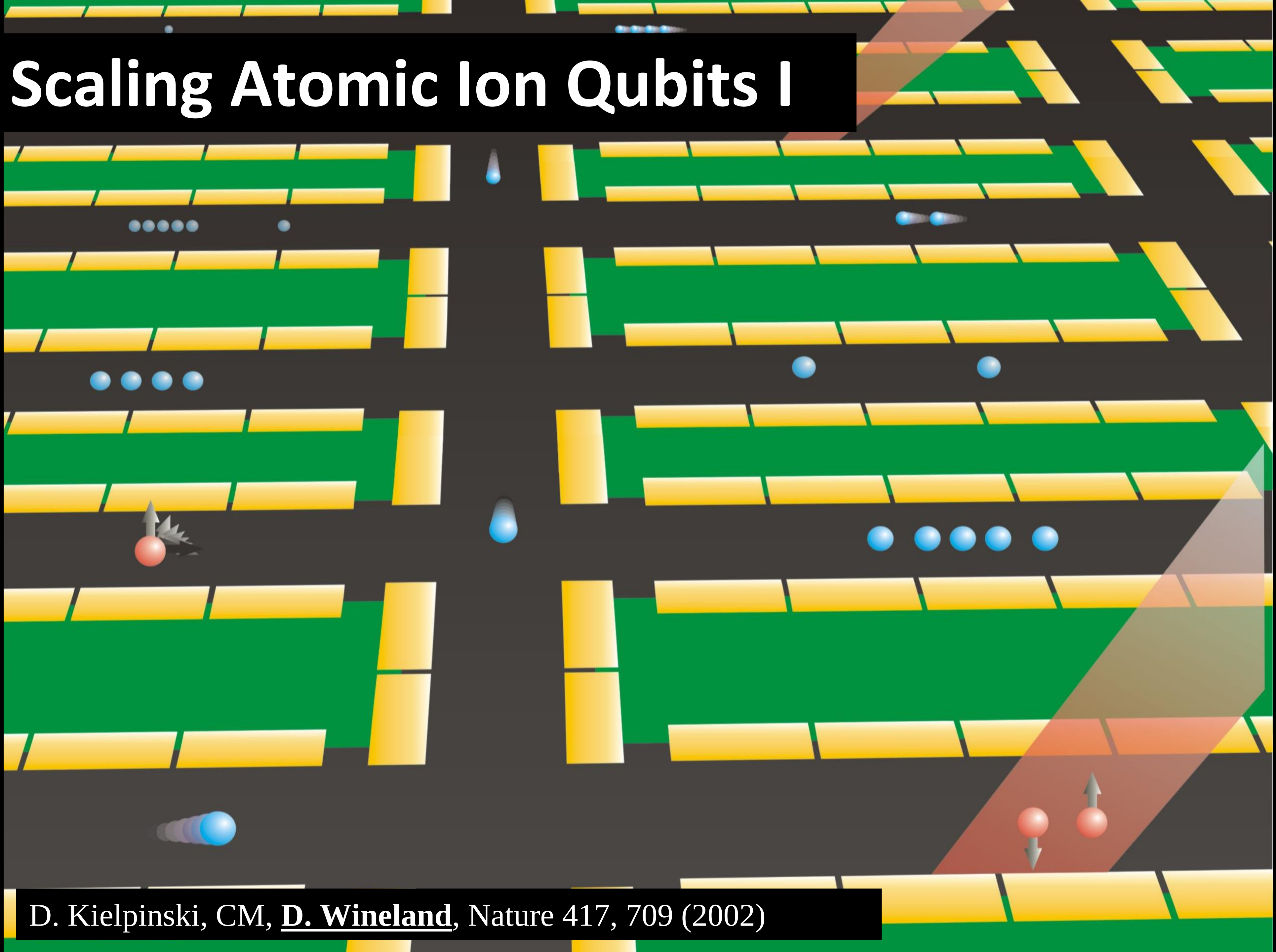
College Park, MD

27 employees

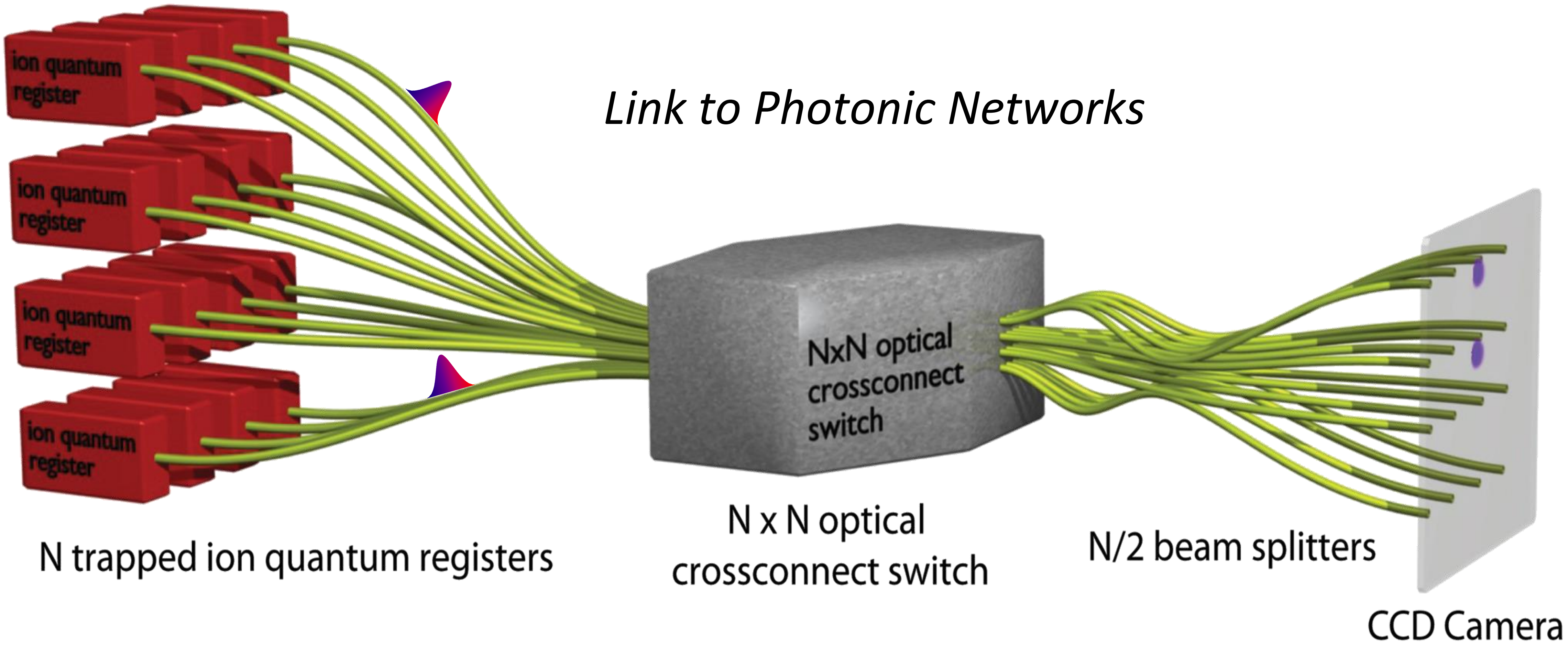
Scaling Atomic Ion Qubits I



D. Kielpinski, CM, **D. Wineland**, Nature 417, 709 (2002)

Scaling Atomic Ion Qubits II

Link to Photonic Networks



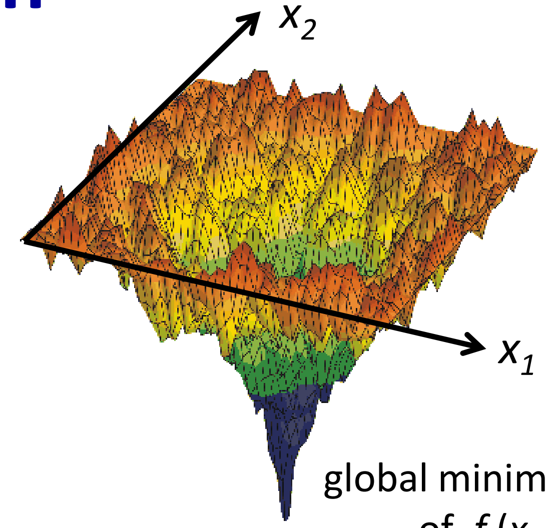
Duan and Monroe, *Rev. Mod. Phys.* **82**, 1209 (2010)
Li and Benjamin, *New J. Phys.* **14**, 093008 (2012)
Monroe, et al., *Phys. Rev. A* **89**, 022317 (2014)

Broad Area of Application: Quantum Optimization

Minimizing complex functions by "simultaneously sampling" entire space through quantum superposition

Logistics
Operations Research
Decision Making

Pattern Recognition
Machine Learning
Material Simulations



global minimum of $f\,(x_1,x_2)$

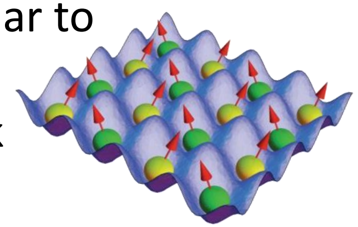
Examples

Quadratic Optimization

Minimize

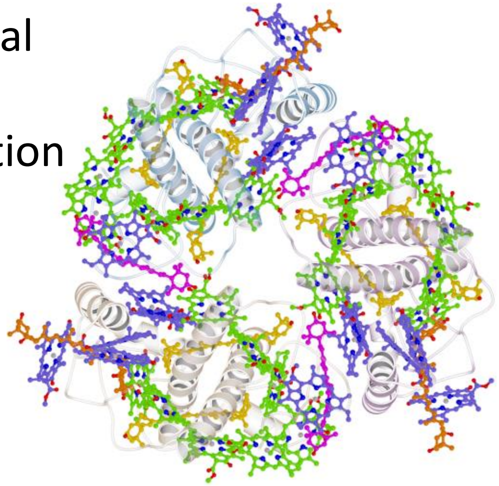
$$f\,(x_1, x_2, \ldots) = \sum_{i<j} q_{ij} x_i x_j + \sum_i c_i x_i$$

this function is similar to the total energy of a magnetic network

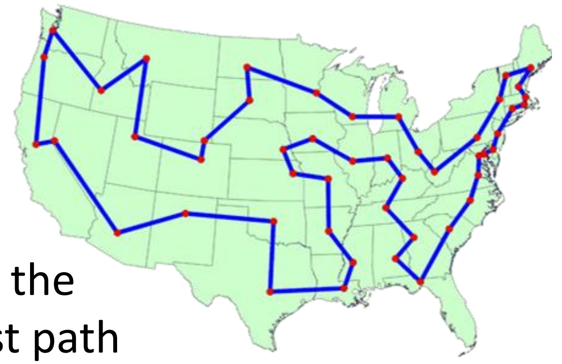


Quantum Chemistry

- complex material properties
- molecular function
- light harvesting processes



"Traveling Salesman" problem

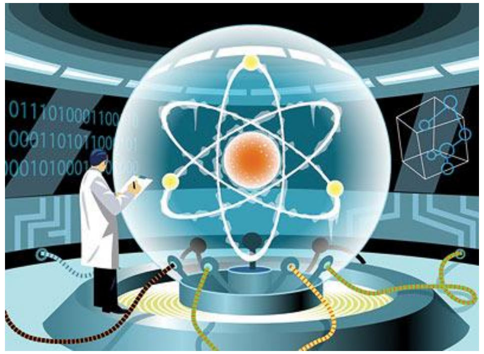


what is the shortest path through N cities?

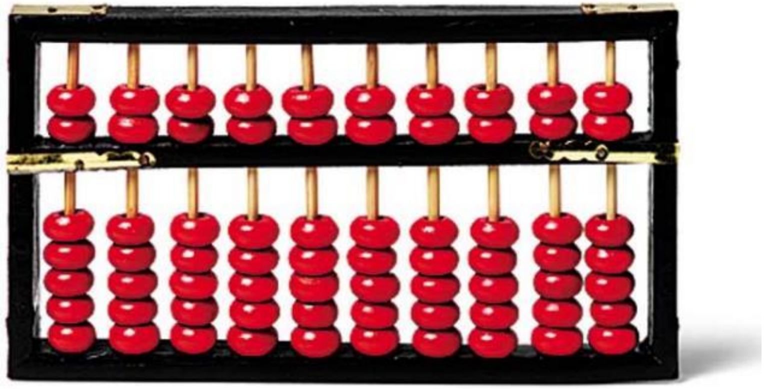
Bill Phillips

NIST/JQI

"A quantum computer differs more from a classical computer……



…than a classical computer differs from an **ABACUS**"



Trapped Ion Quantum Information

www.iontrap.umd.edu

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