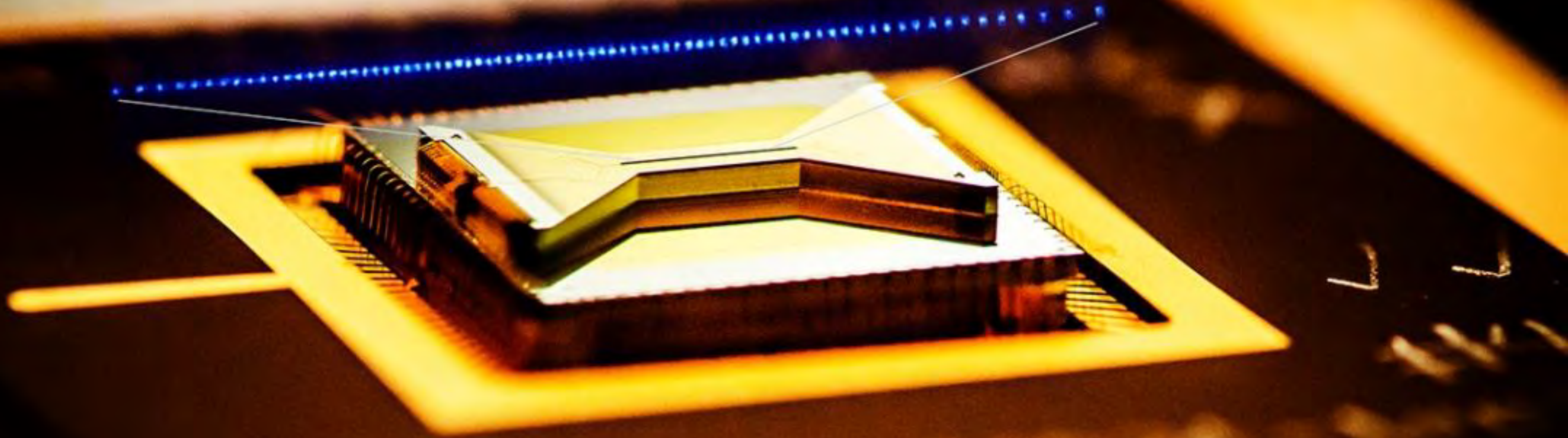
Quantum Circuits and Simulation with Individual Atoms



Christopher Monroe

Univ. Maryland, JQI, QuICS, and IonQ

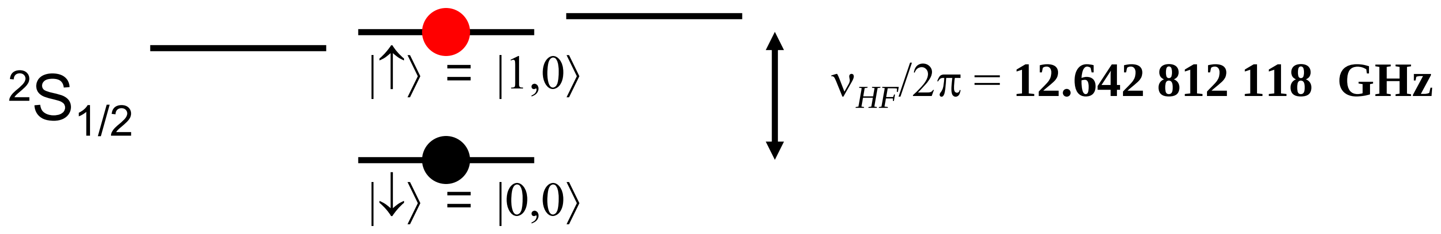
IONQ

University of Maryland 1856

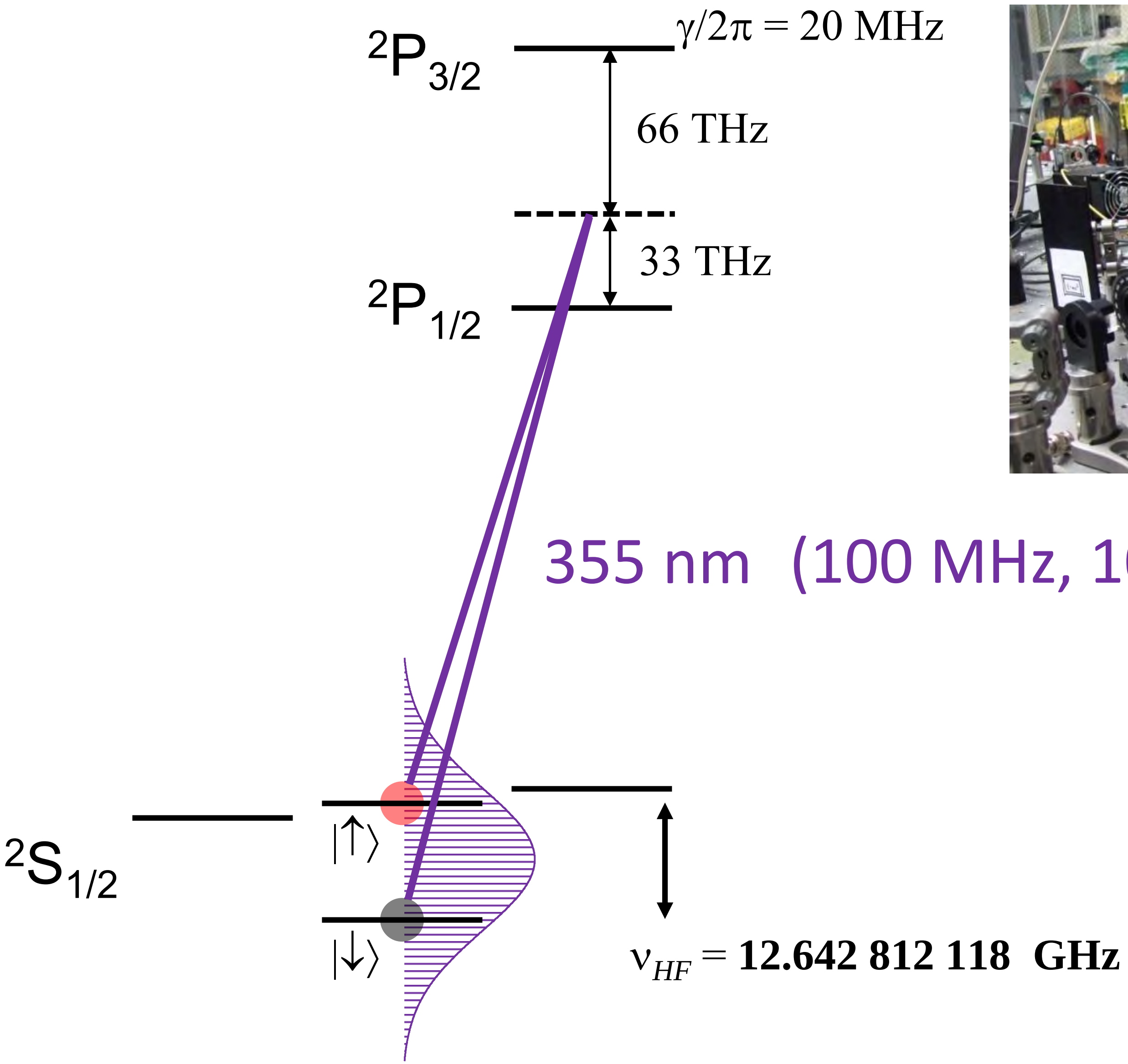
JQI JOINT QUANTUM INSTITUTE

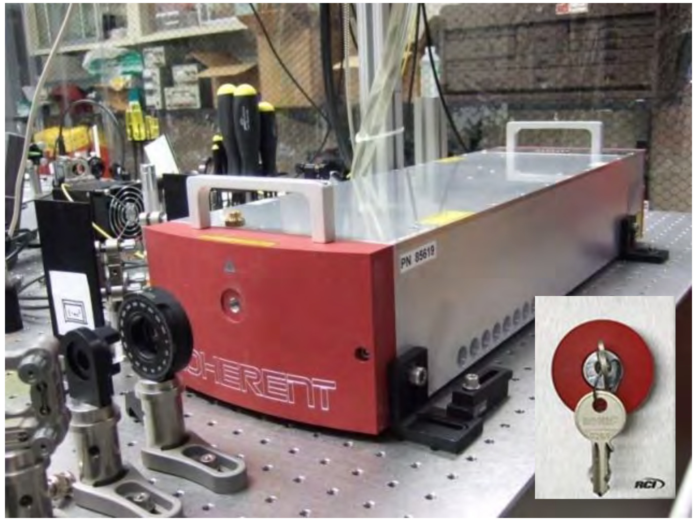
JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

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



$^{171}Yb^+$ Qubit Manipulation

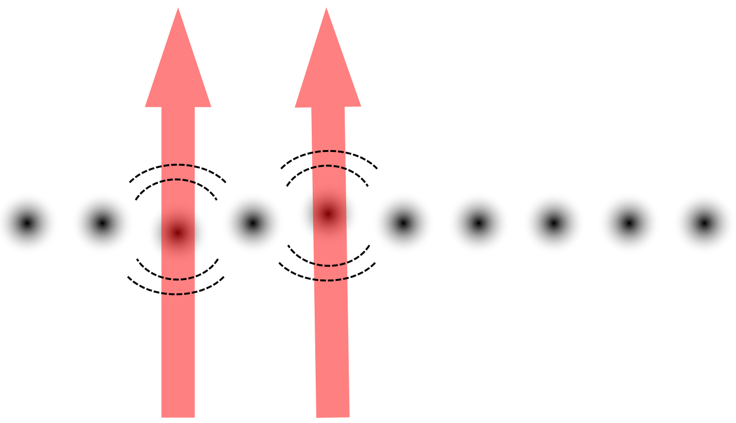




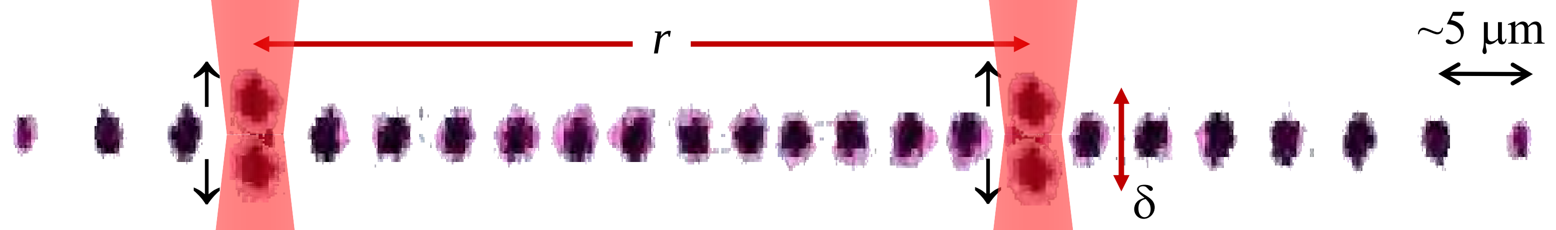
355 nm (100 MHz, 10psec)

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

Quantum Circuits and Algorithms



Quantum Entanglement of 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

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

for full entanglement

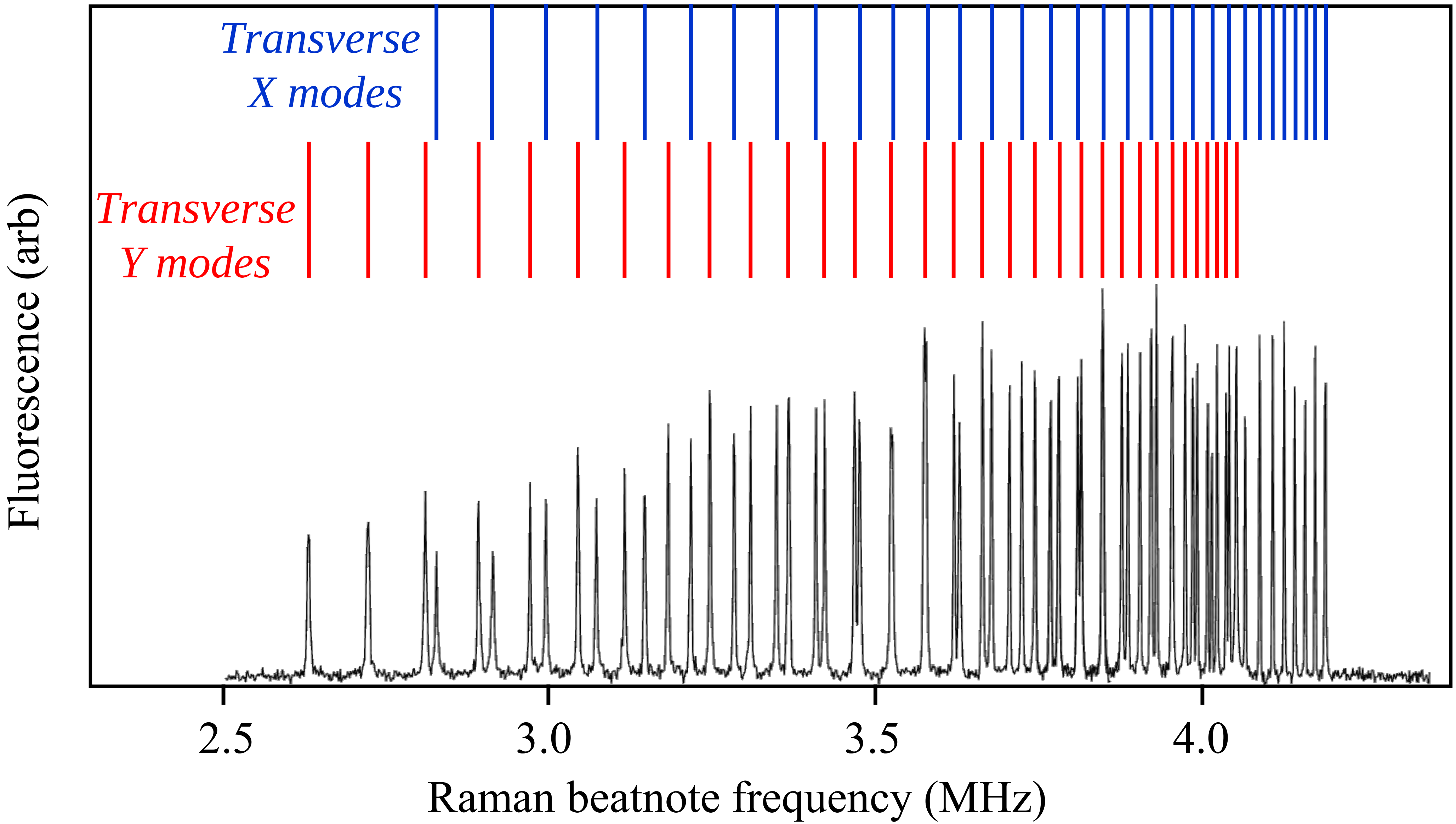
Native Ion Trap Operation: "Ising" gate

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

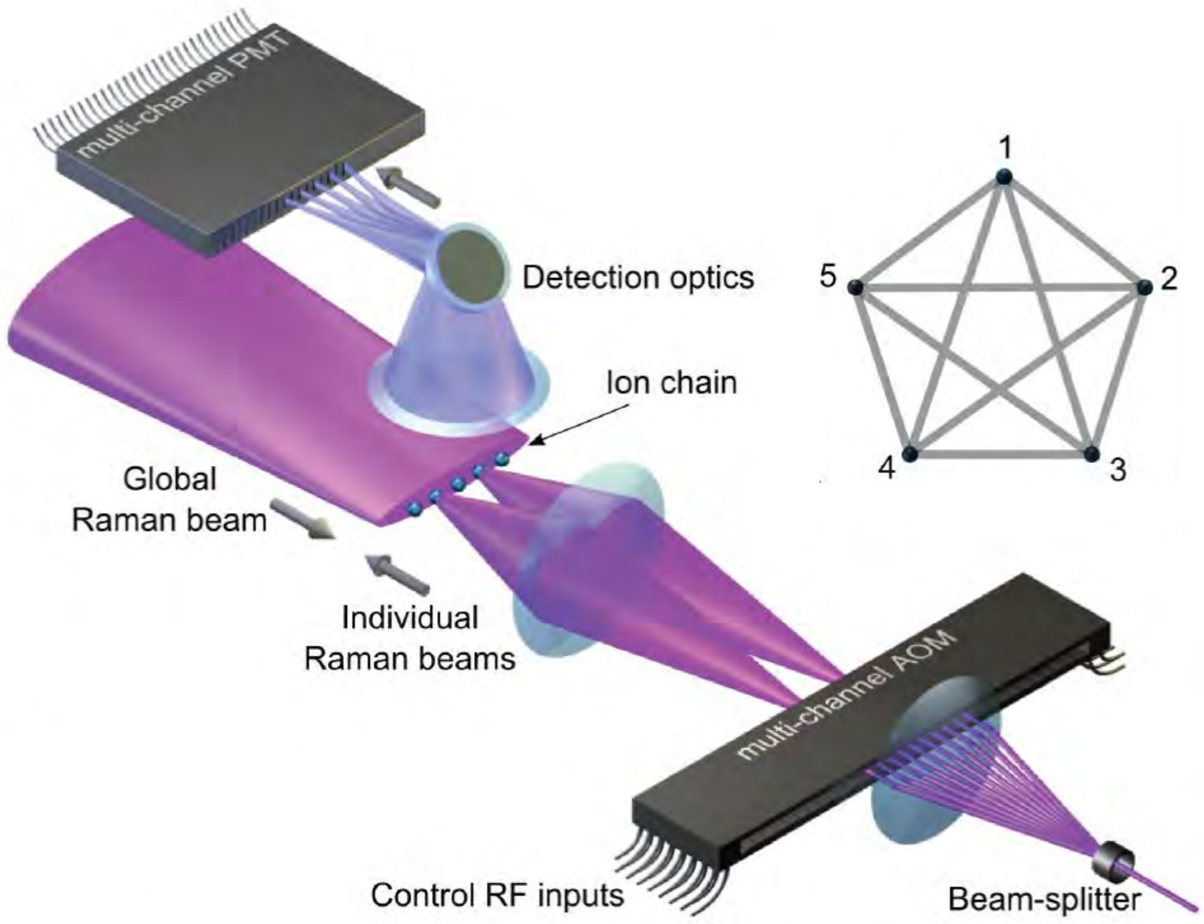
$T_{gate} \sim$ 10–100 μs
F ~ 98% – 99.9%

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

Raman Sideband Spectrum of 32 $^{171}Yb^{+}$ ions



Programmable/Reconfigurable Quantum Computer Module



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.*

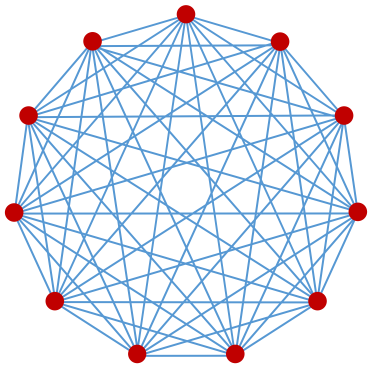
S. Debnath, et al., *Nature* **536**, 63 (2016)

Benchmarking 11-qubit register

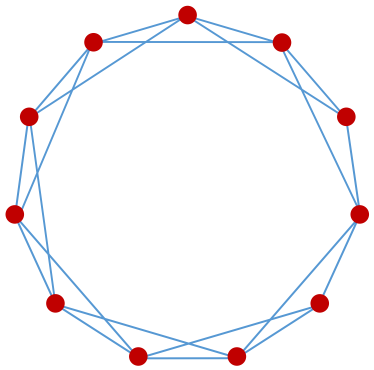
IONQ

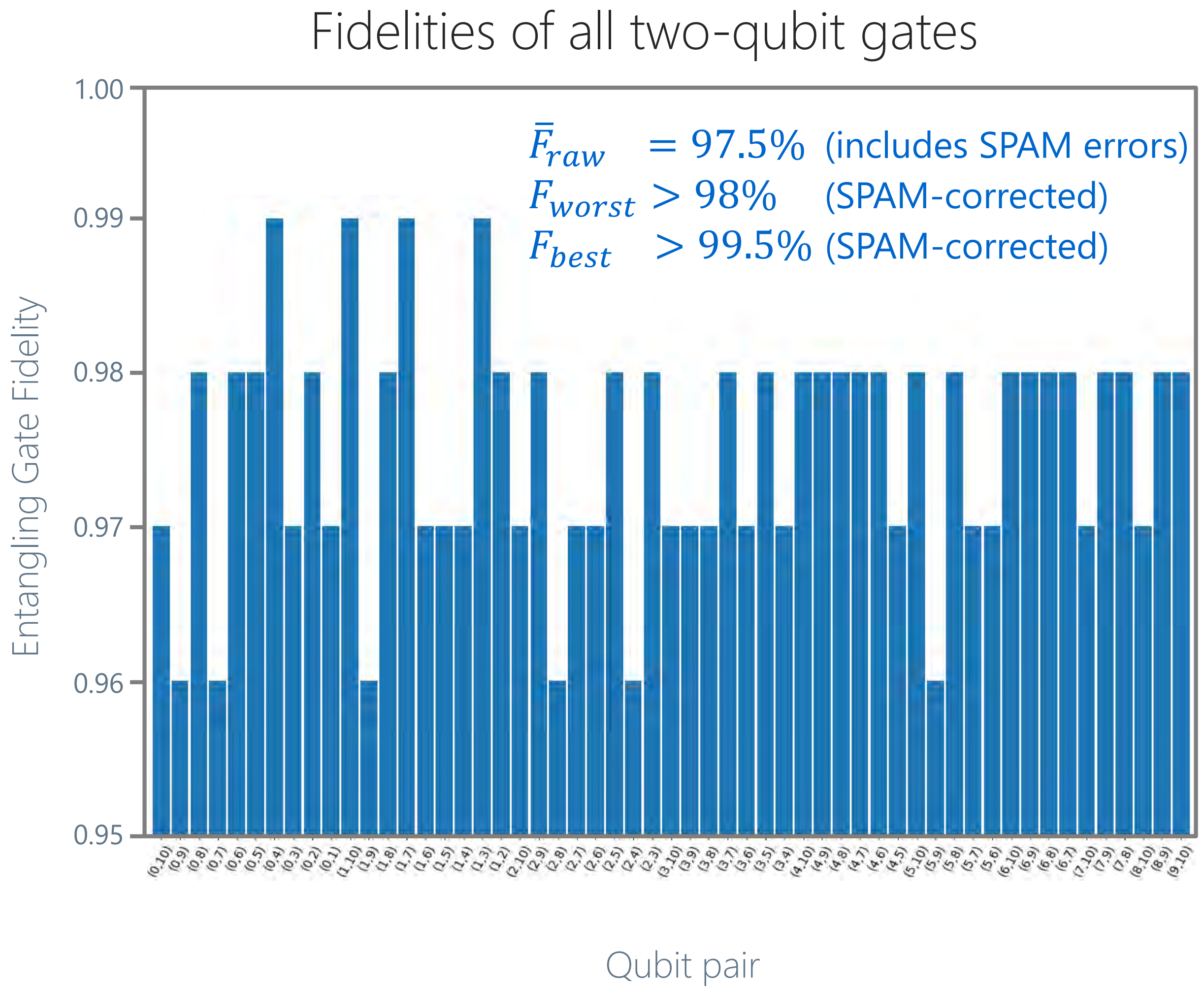
11 Trapped Ions
fully connected

$$\binom{11}{2} = 55 \text{ gates}$$



2D nearest-neighbor





Benchmarking 11-qubit register

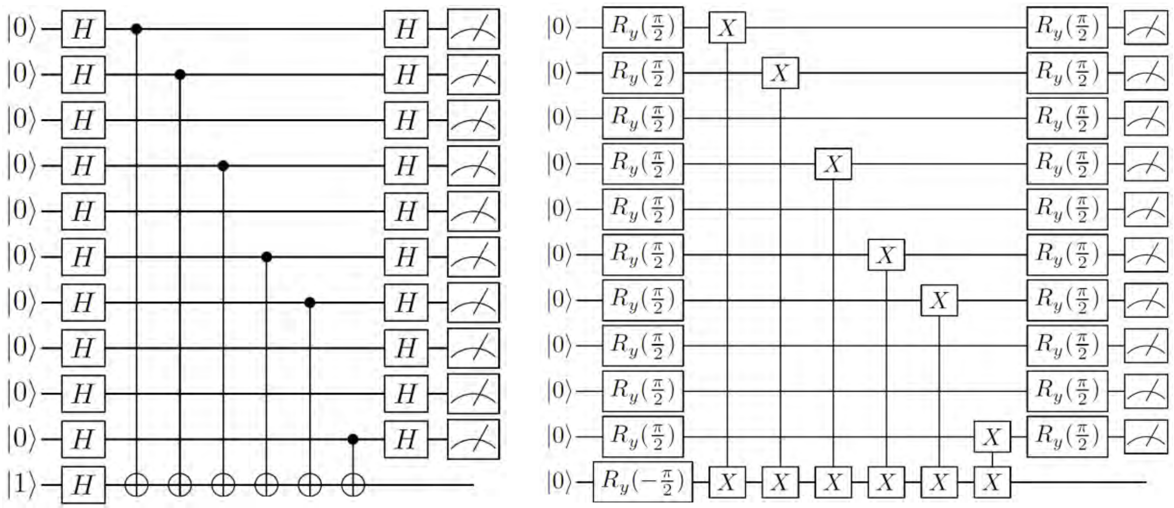
IONQ

Bernstein-Vazirani Algorithm

Given $f(\boldsymbol{x}) = \boldsymbol{c} \cdot \boldsymbol{x}$, find n-bit string $\boldsymbol{c}$

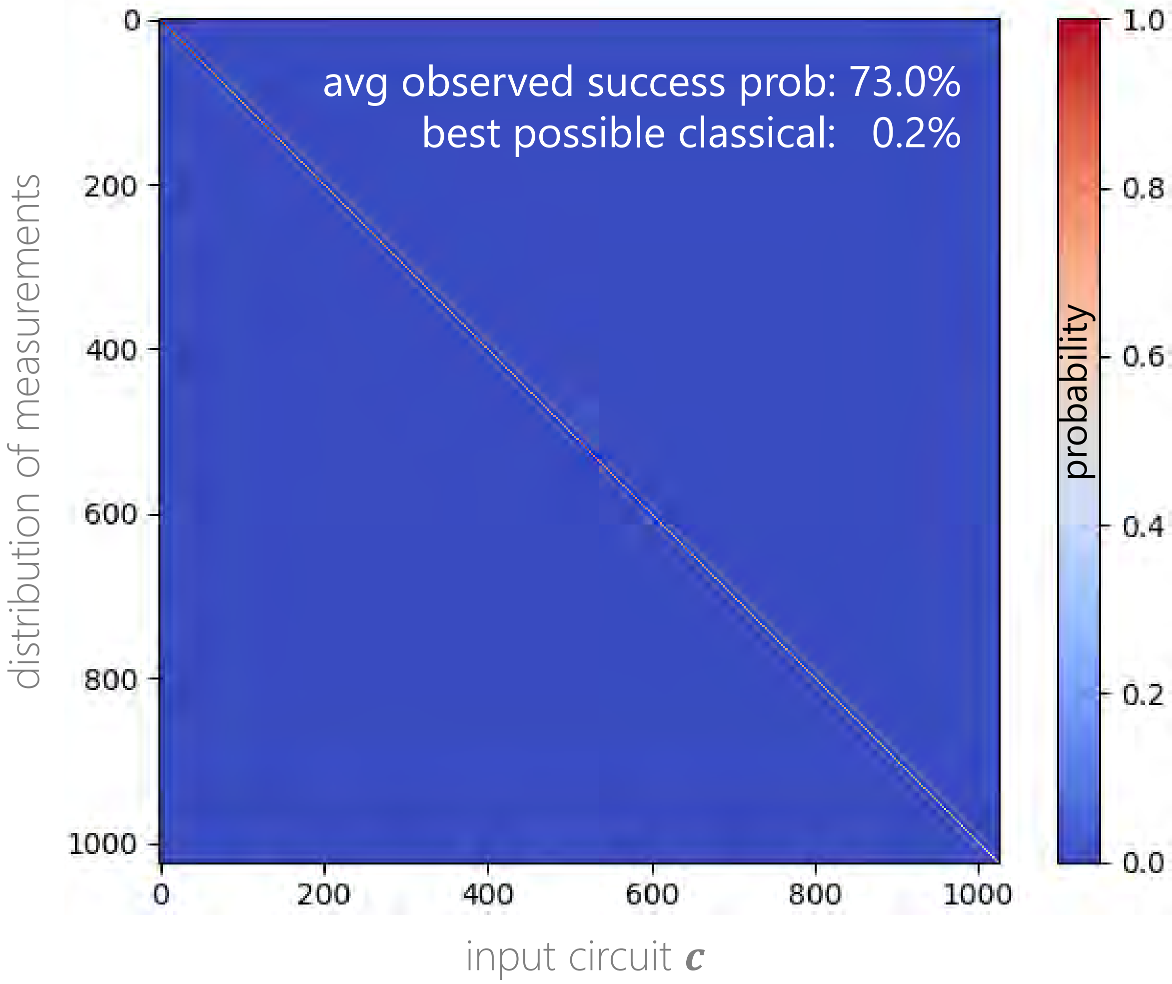
classical: n queries
quantum: 1 query

example: $\boldsymbol{c} = \mathbf{1101011001}$



textbook circuit

trapped ion circuit



Build it and they will come!

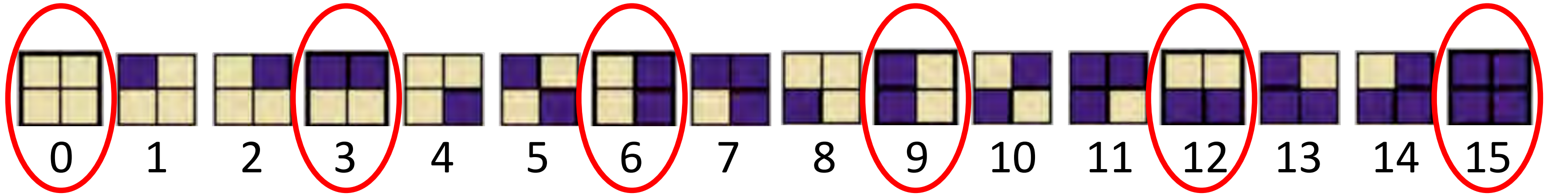
application	#qubits	# 2Q gates	# 1Q gates	fidelity	reference	collaborator
CNOT	2	1	3	99%	Nature 536, 63 (2016)	
QFT Phase est.	5	10	70-75	61.9%	Nature 536, 63 (2016)	
QFT period finding	5	10	70-75	695-97%	Nature 536, 63 (2016)	
Deutsch-Jozsa	5	1-4	13-34	93%-97%	Nature 536, 63 (2016)	
Bernstein-Vazirani	5	0-4	10-38	90%	Nature 536, 63 (2016)	
Hidden Shift	5	4	42-50	77%	PNAS 114, 13 (2017)	Microsoft
Grover Phase	3	10	35	85%	Nat. Comm. 8, 1918 (2017)	NSF
Grover Boolean	5	16	49	83%	Nat. Comm. 8, 1918 (2017)	NSF
Margolus	3	3	11	90%	PNAS 114, 13 (2017)	Microsoft
Toffoli	3	5	9	90%	PNAS 114, 13 (2017)	Microsoft
Toffoli-4	5	11	22	71%	Debnath Thesis	NSF
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%	arXiv: 1806.02807 (2018)	Perimeter, UCB
Bayesian Games	5	5	15		Qu. Sci. Tech 3, 045002 (2018)	Army Res. Lab.
Machine Learning (detection)	5	n/a	n/a		arXiv:1801.07686 (2018)	JQI
Machine Learning (state synth)	4	5*N	30*N	90%	arXiv 1812.08862 (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%	In preparation (2018)	NSF
Simultaneous CNOT	4	2	8	94%	In preparation (2018)	NSF
Deuteron Simulation	3	35	30	<0.5% error	In preparation (2019)	ORNL
Circuit QAOA	7-9	42	50		In preparation (2019)	Perimeter, Intel

Dynamical Circuits for Machine Learning

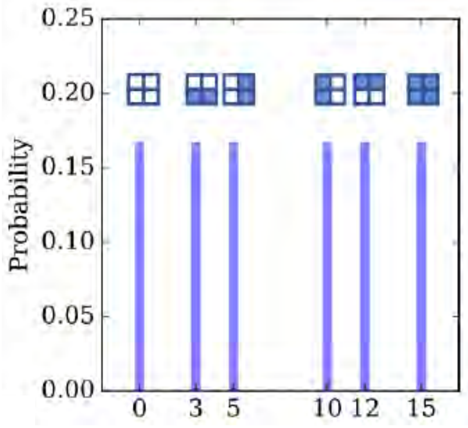
arXiv 1812.08862 (2018)
with A. Perdomo-Ortiz (NASA)
M. Benedetti (UC London)

see also E. Martinez et al., New J. Phys. 18, 063029 (2016)

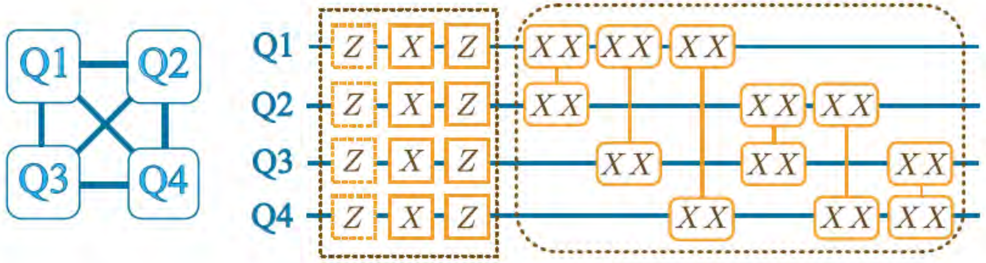
N=4 qubits encodes "Bars and Stripes" patterns



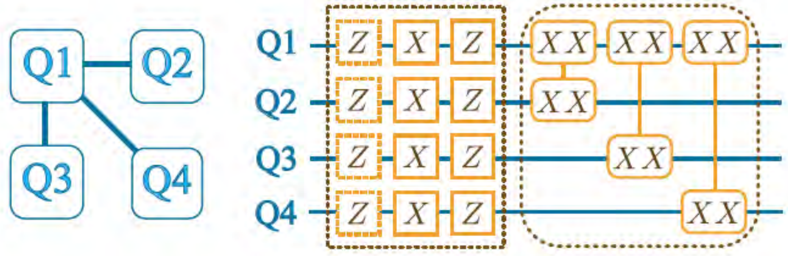
Our task:
prepare equal superposition of all B&S states



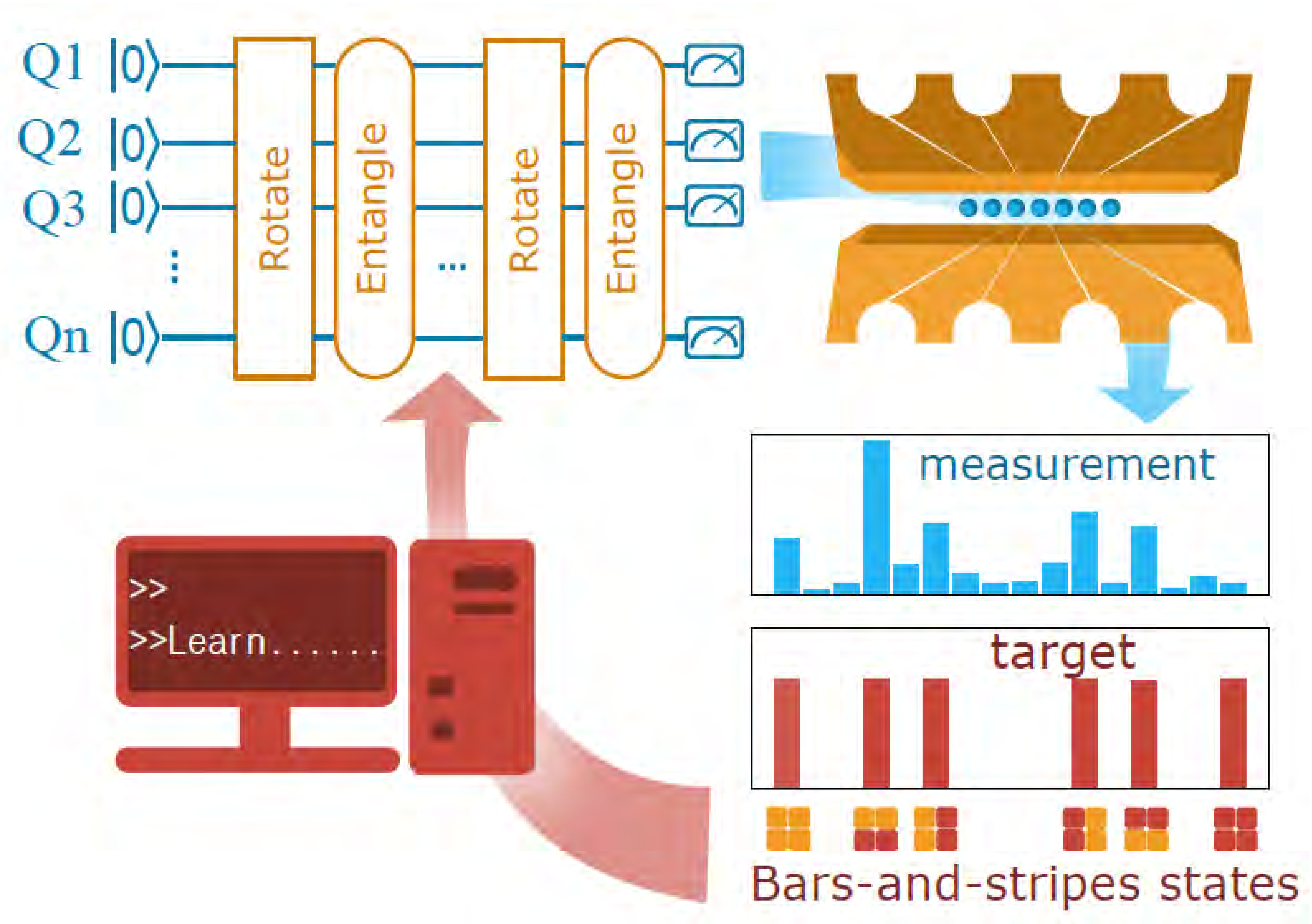
14 parameters



11 parameters

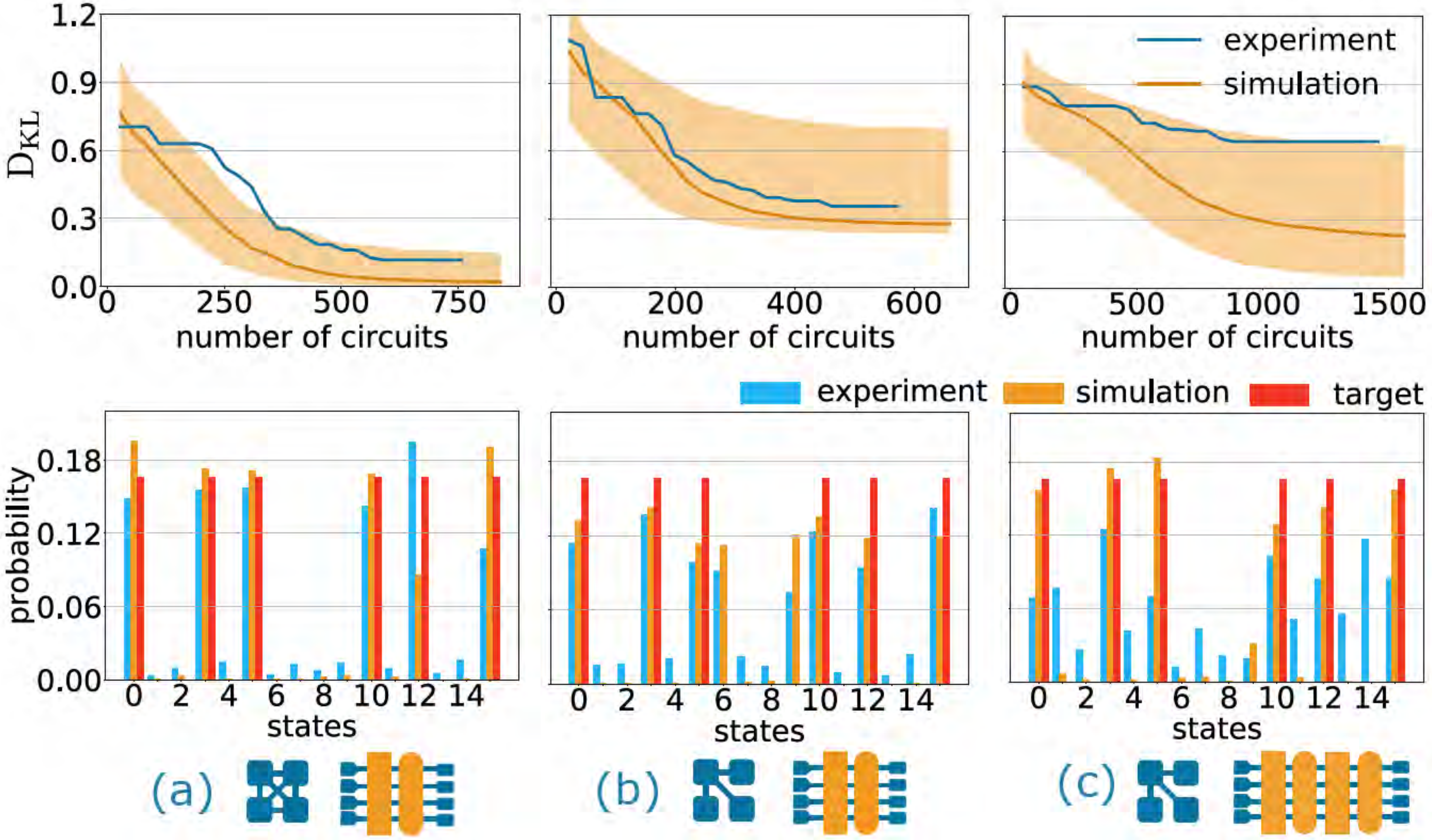


Hybrid Quantum-Classical Learning Loop



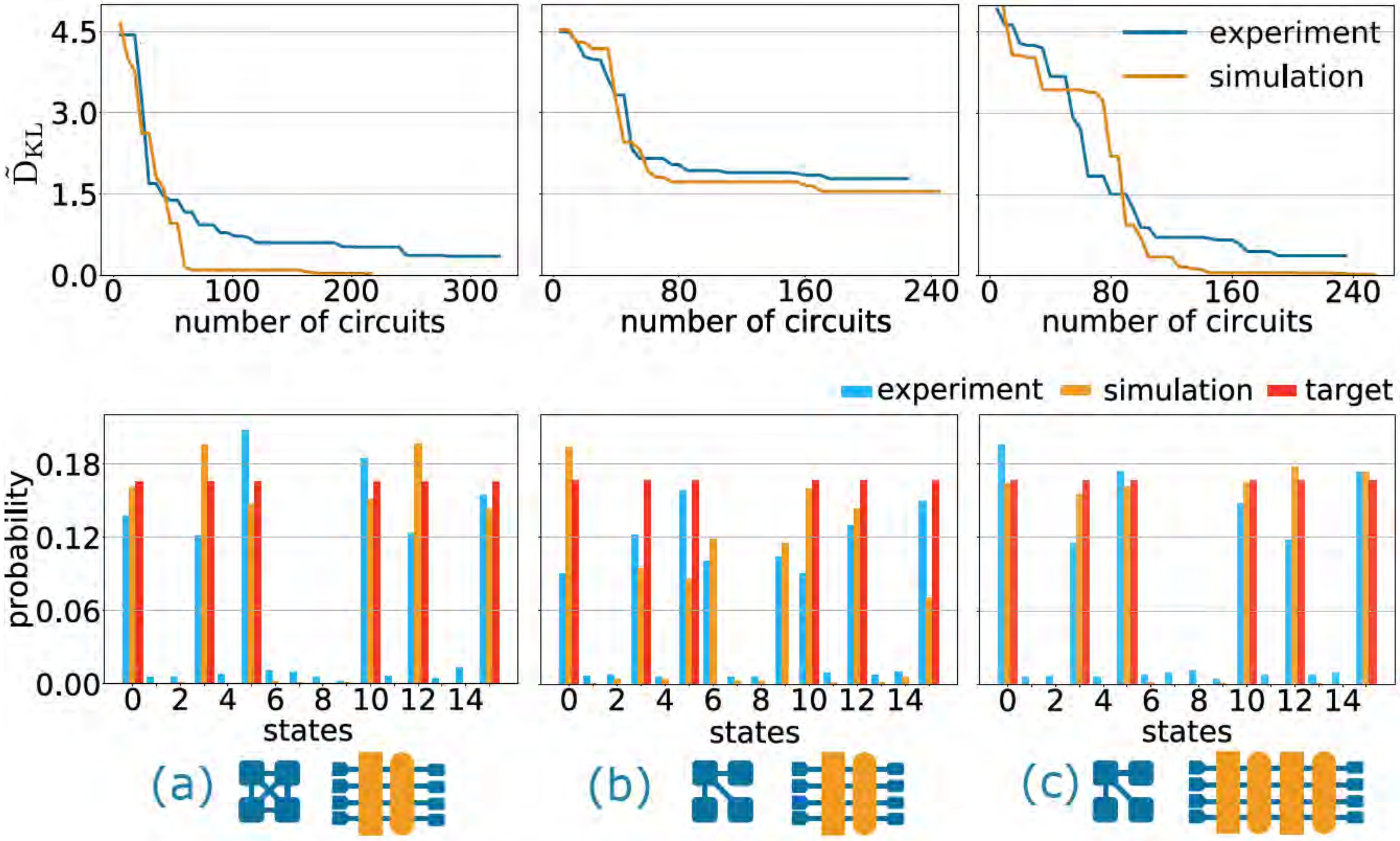
Particle Swarm (classical) optimization

$\overline{D}_{KL}$: Kullback-Leibler divergence



Bayesian (classical) optimization

$\overline{D}_{KL}$: Kullback-Leibler divergence

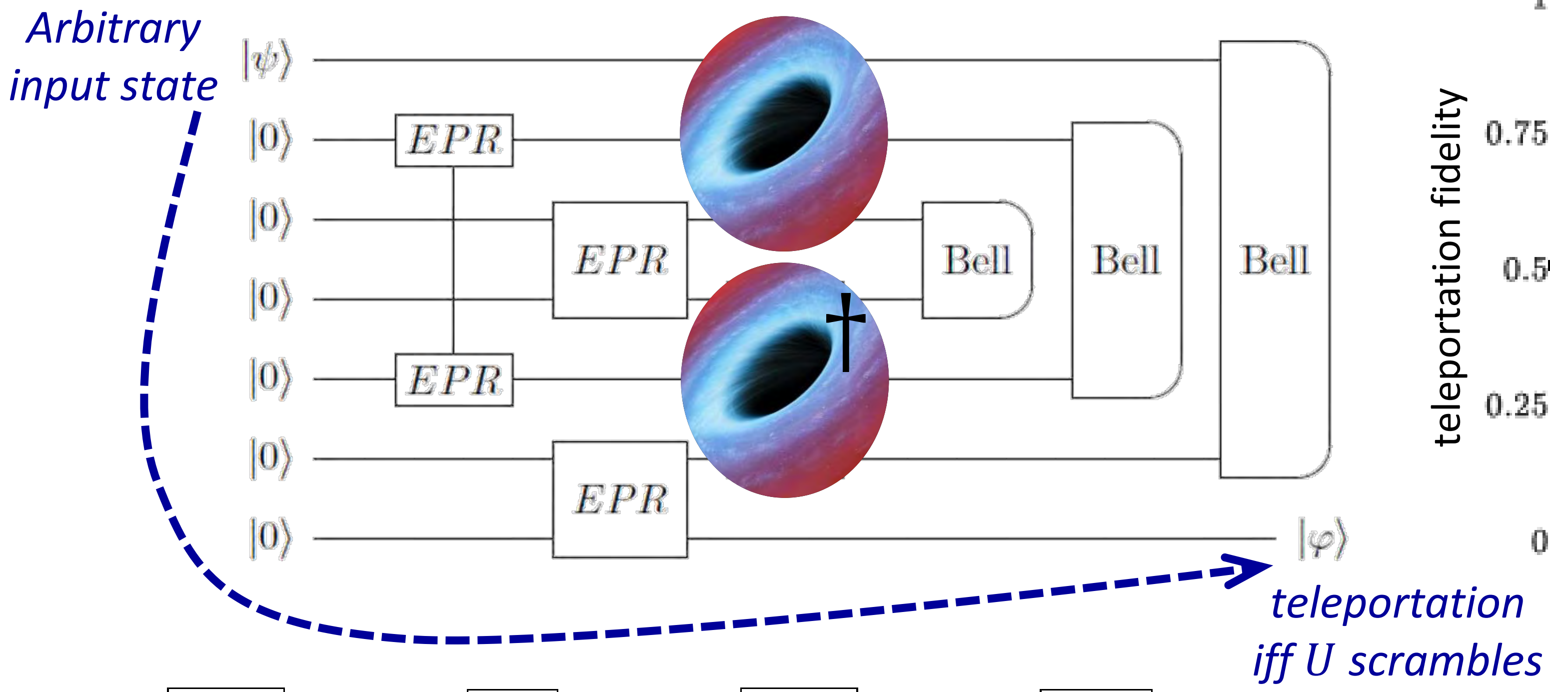


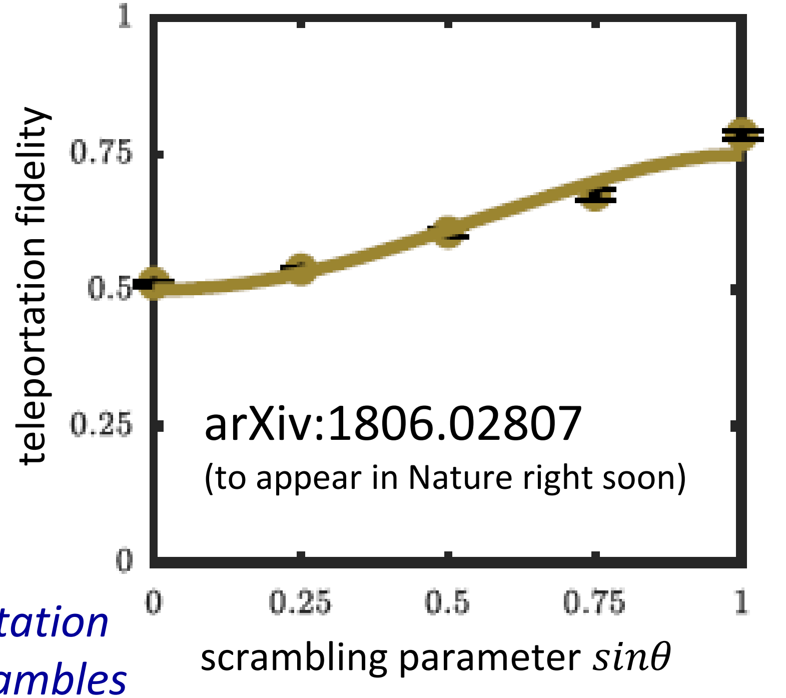
Quantum Scrambling Litmus Test (7 qubit circuit)

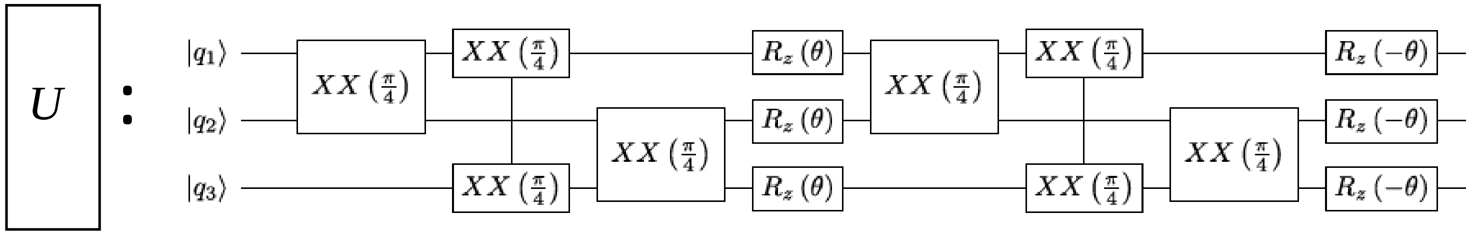
N. Yao (UC Berkeley)
B. Yoshida (Perimeter)
arXiv:1803.10772

Quantum scrambling

- The "complete diffusion" of entanglement within a system
- Relevant to information evolution in black holes
  Hayden and Preskill, J. HEP ***9****, 120 (2007); Susskind and Zhao, arXiv:1707.04354 (2017)*
- OTOC measurements can be ambiguous



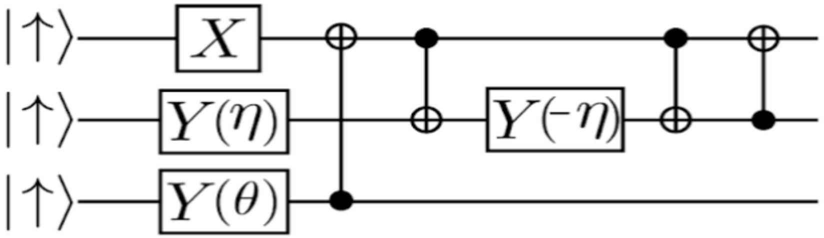




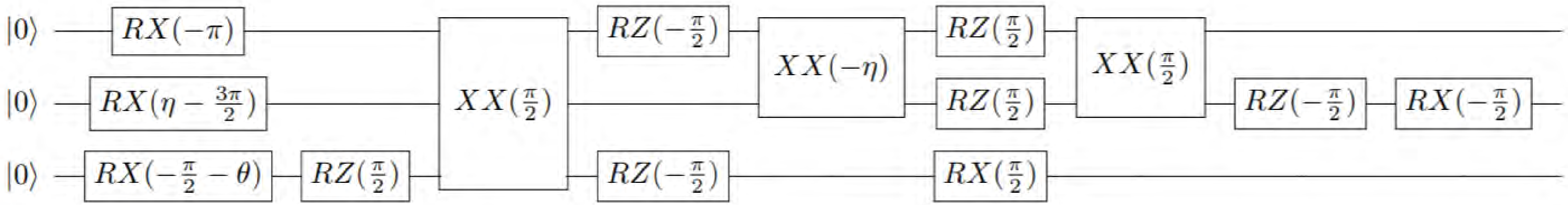
Simulating the Ground State of the Deuteron

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

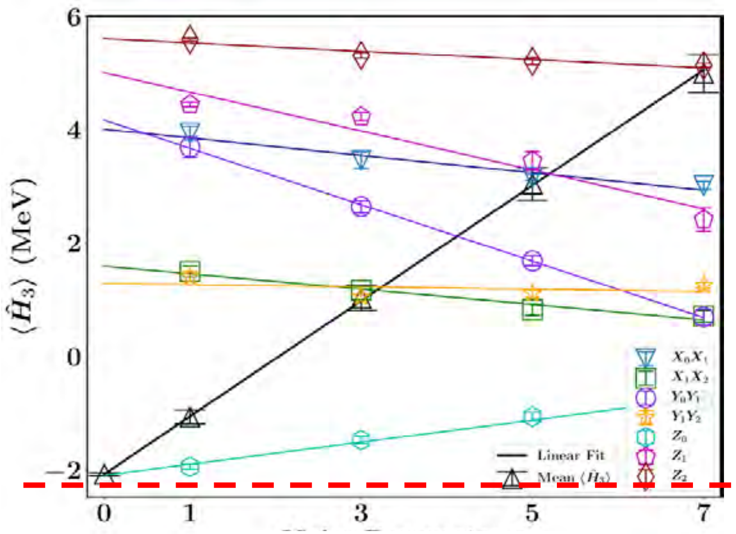


$$H = (15.531709)I + (0.218291)Z_0 - (6.125)Z_1 - (9.625)Z_2 - (2.143304)X_0X_1 - (2.143304)Y_0Y_1 - (3.913119)X_1X_2 - (3.913119)Y_1Y_2$$

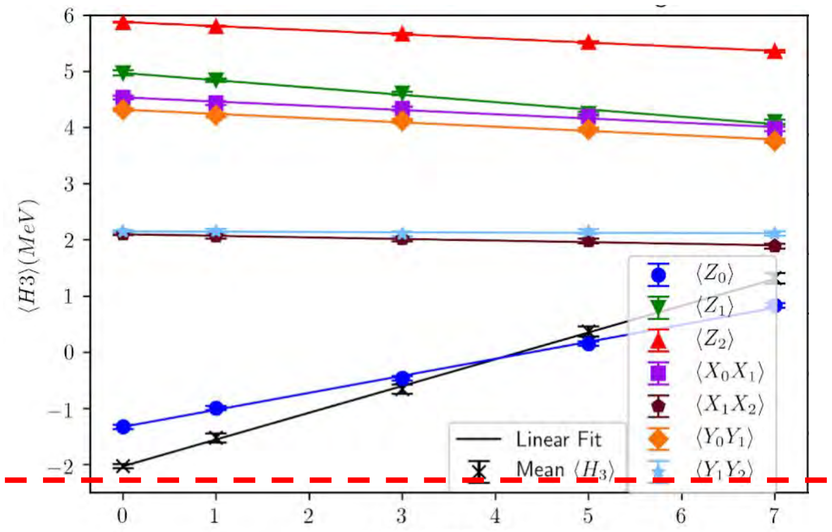
E.F. Dumitrescu et al., arXiv 1801.03897 (2018)

Simulating the Ground State of the Deuteron

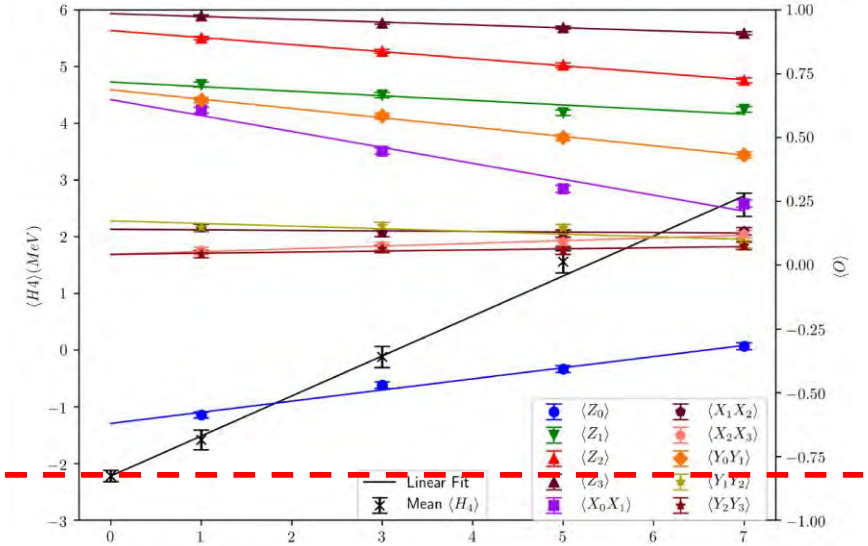
Extrapolated ground state energy for theoretically determined optimal angles (exact: -2.22 MeV):



Noise parameter r



Noise parameter r



Noise parameter r

IBM 3-qubit ansatz
3% error

E.F. Dumitrescu, et al., *Phys. Rev. Lett.* **120**, 210501 (2018)

UMD 3-qubit ansatz
0.7% error

O. Shehab, et al. (in preparation)

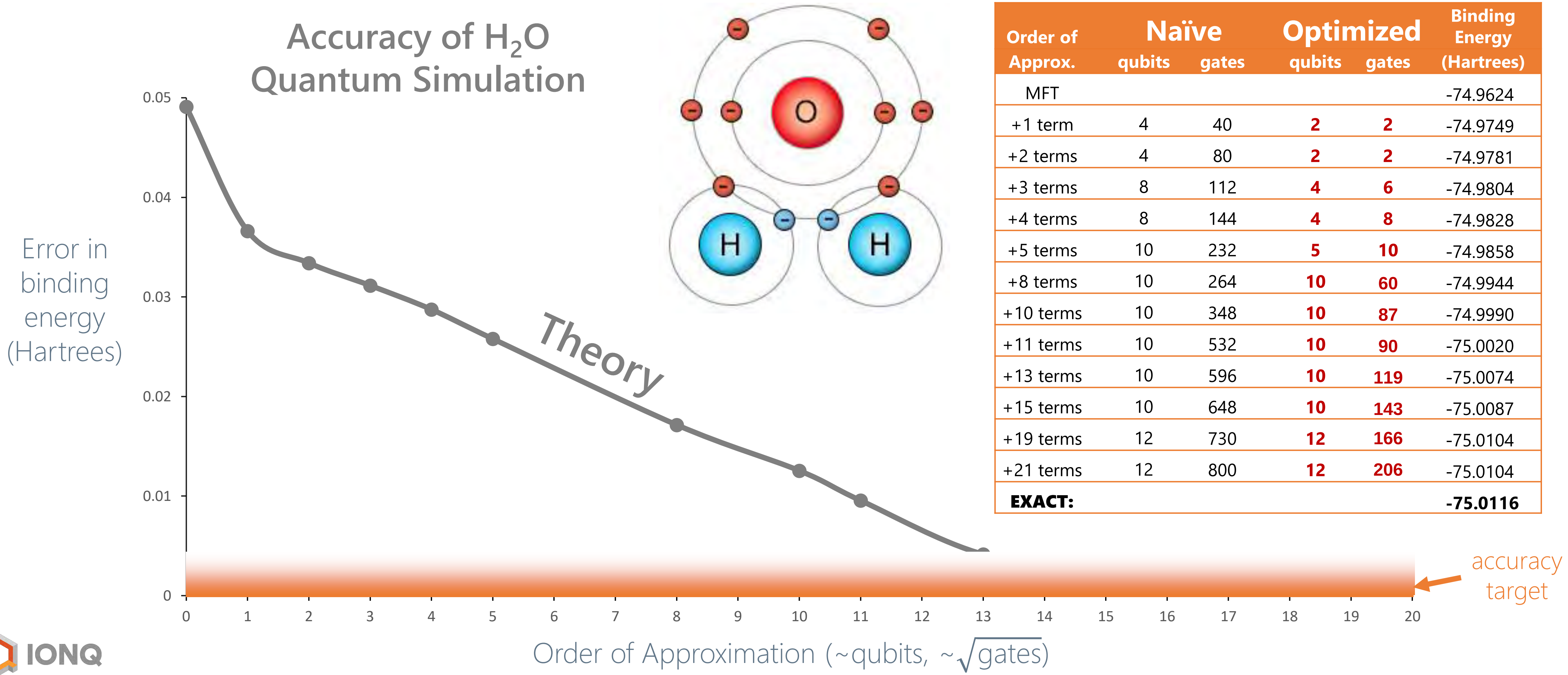
UMD 4-qubit ansatz
(<0.5% error)

O. Shehab, et al. (in preparation)

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

Variational Circuit Simulation of H_2O

The Theory of Variational Hybrid Quantum-Classical Algorithms, New J. Phys. **18**, 023023 (2016) [Aspuru-Guzik group]



Order of Approx.	Naïve qubits	Naïve gates	Optimized qubits	Optimized gates	Binding Energy (Hartrees)
MFT					-74.9624
+1 term	4	40	2	2	-74.9749
+2 terms	4	80	2	2	-74.9781
+3 terms	8	112	4	6	-74.9804
+4 terms	8	144	4	8	-74.9828
+5 terms	10	232	5	10	-74.9858
+8 terms	10	264	10	60	-74.9944
+10 terms	10	348	10	87	-74.9990
+11 terms	10	532	10	90	-75.0020
+13 terms	10	596	10	119	-75.0074
+15 terms	10	648	10	143	-75.0087
+19 terms	12	730	12	166	-75.0104
+21 terms	12	800	12	206	-75.0104
EXACT:					**-75.0116**

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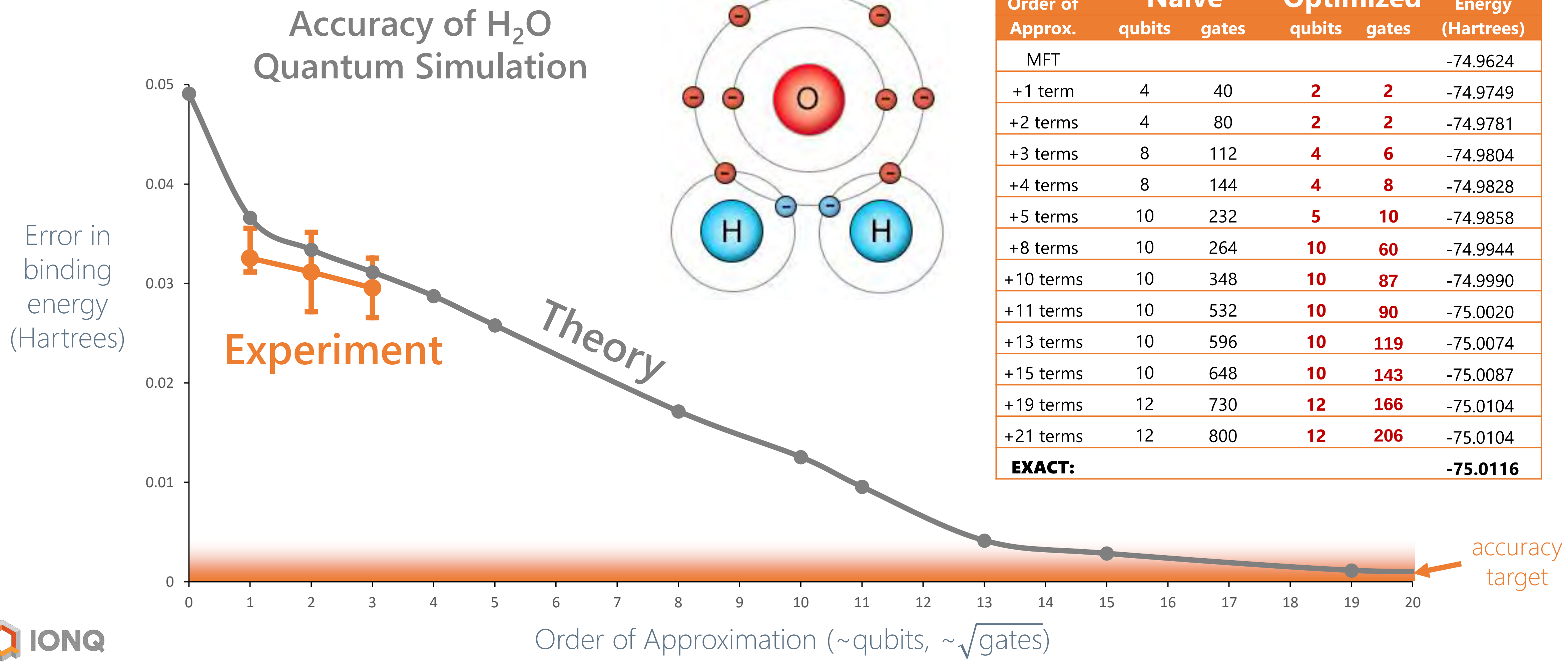

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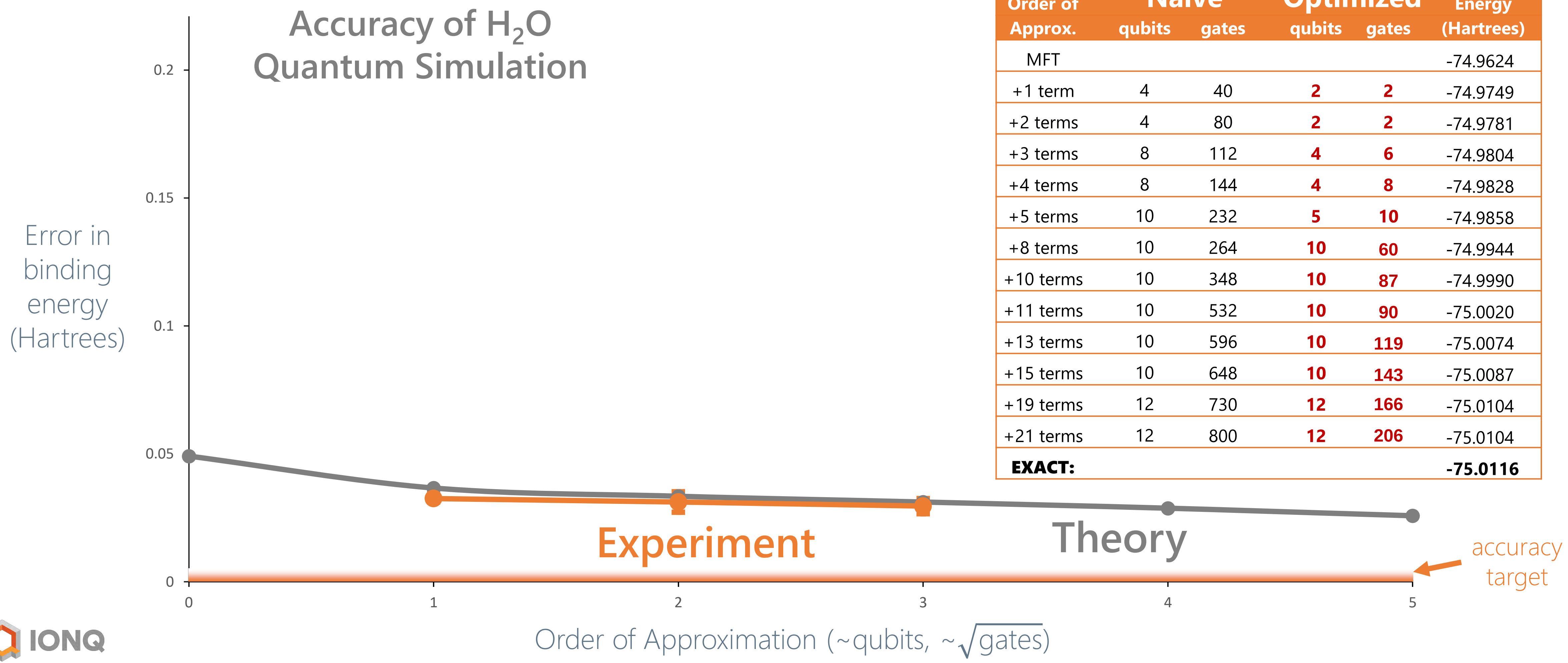

IONQ

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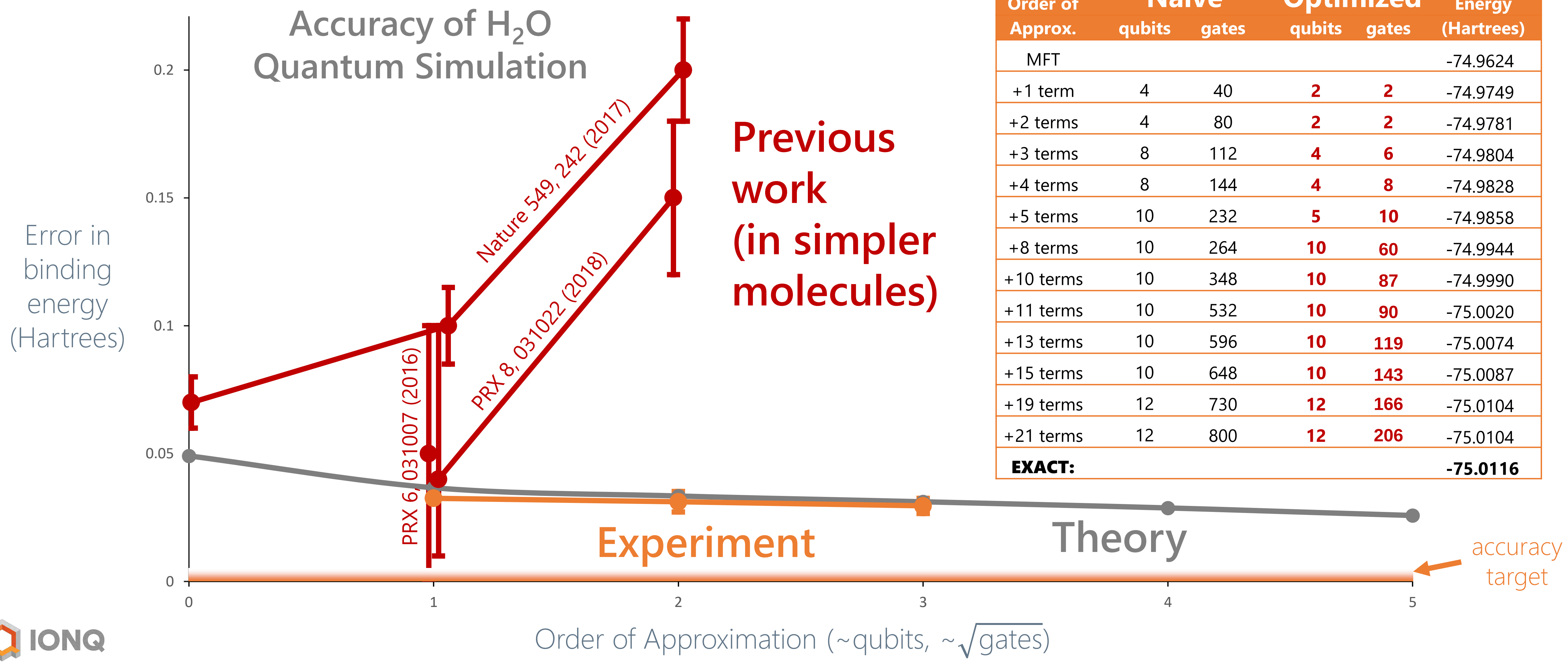

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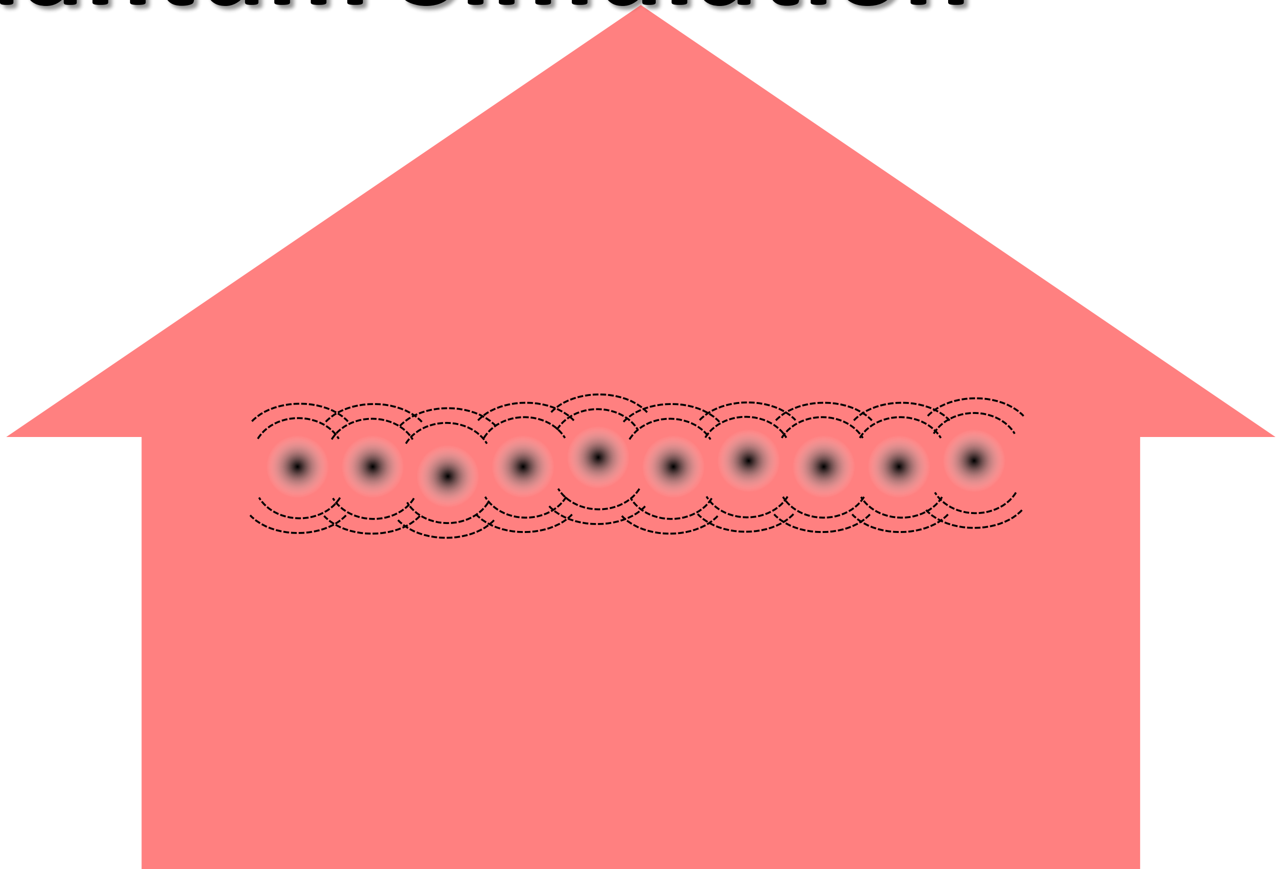
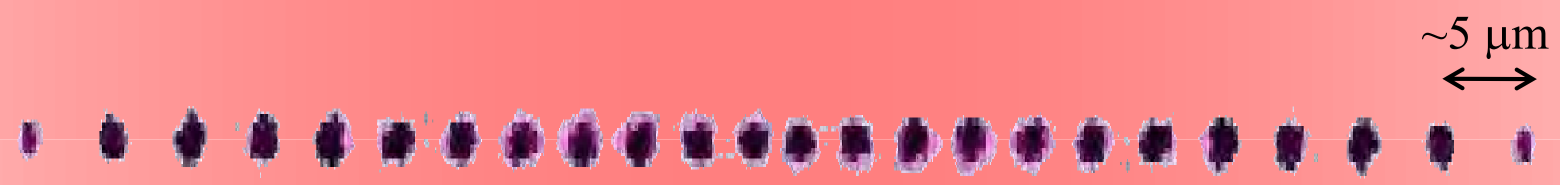
(Analog) Quantum Simulation



Global Entanglement of Trapped Ion Qubits



Long-range Ising Hamiltonian

$$H = \sum_{i<j} \frac{J_0}{|i-j|^{\alpha}} \sigma_x^i \sigma_x^j + B \sum_i \sigma_y^i \quad J_{ij} = \frac{J_0}{|i-j|^{\alpha}}$$

$0 < \alpha < 3$

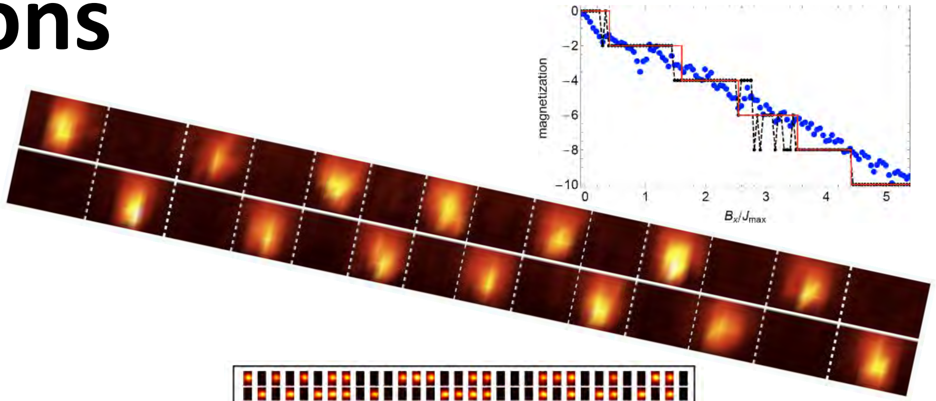
$J_0 \sim 2\pi(1\ \mathrm{kHz})$

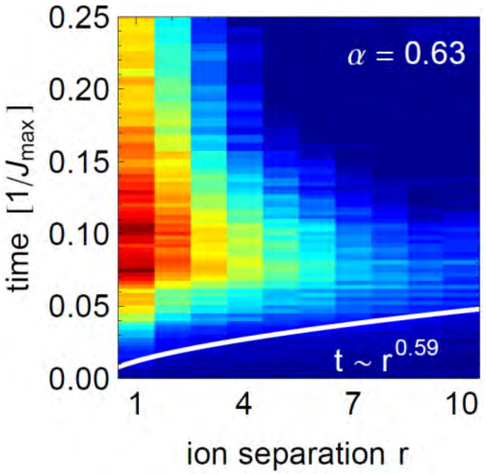
$J_0\tau \sim 50$

Porras and Cirac (2003)
Schaetz group [2 ions] (2008)
UMD [3-50 ions] (2008-)
Innsbruck [5-20 ions] (2012-)

Quantum Simulations

$$H = \sum_{i<j} \frac{J_0}{|i-j|^{\alpha}} \sigma_x^i \sigma_x^j + \sum_i B_i \sigma_y^i$$



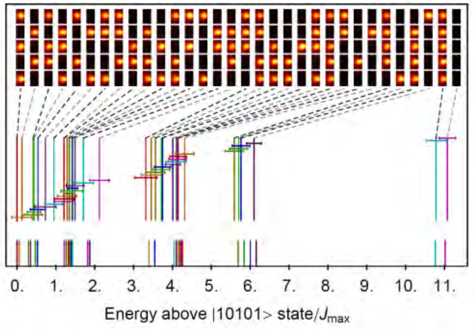


FM and AFM order

R. Islam, et al., *Science* **340**, 583 (2013)

Breakup of Ising ordering: Devil's Staircase

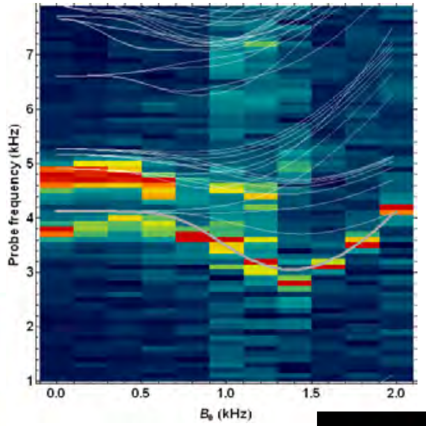
P. Richerme et. al., *Phys. Rev. Lett.* **111**, 100506 (2013)



Propagation of correlations and entanglement

P. Richerme et. al., *Nature* **511**, 198 (2014)

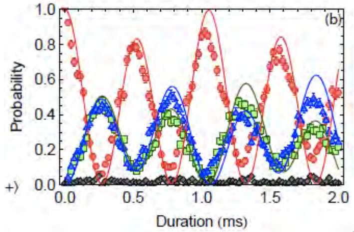
P. Jurcevic et al., *Nature* **511**, 202 (2014)

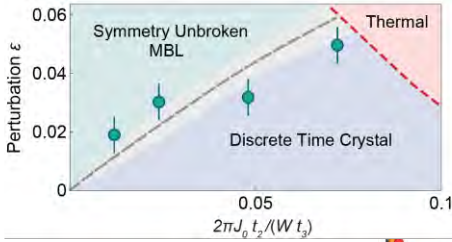


Many-Body Spectroscopy

C. Senko et. al., *Science* **345**, 430 (2014)

P. Jurcevic, et al., *Phys. Rev. Lett.* **115**, 100501 (2015)





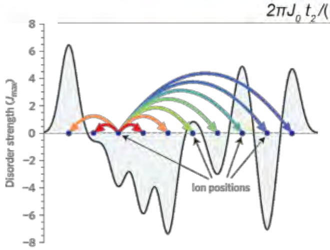
Spin-1 Dynamics

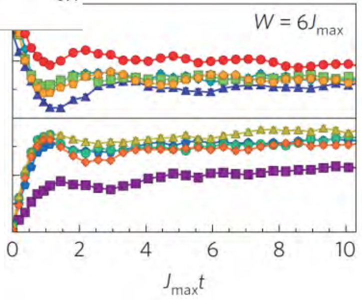
C. Senko, et al., *Phys. Rev.* X **5**, 021026 (2015)

Quantum Prethermalization/Manybody Localization

J. Smith, et al., *Nature Physics* **12**, 894 (2016)

B. Neyenhuis, et al., *Science Adv.* **3**, e1700672 (2017)





$H_1 = g(1-\varepsilon)\sum_i \sigma_i^y$, time t_1

$H_2 = \sum_i J_{ij}\sigma_i^x\sigma_j^x$, time t_2

$H_3 = \sum_i D_i\sigma_i^x$ time t_3

Observation of a Time Crystal

J. Zhang, et al., *Nature* **543**, 217 (2017)

Dynamical Phase Transition

P. Jurcevic, et al., *Phys. Rev. Lett.* 119, 080501 (2017)

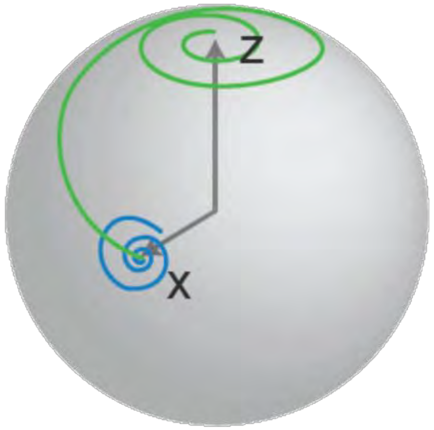
J. Zhang, et al., *Nature* **551**, 601 (2017)

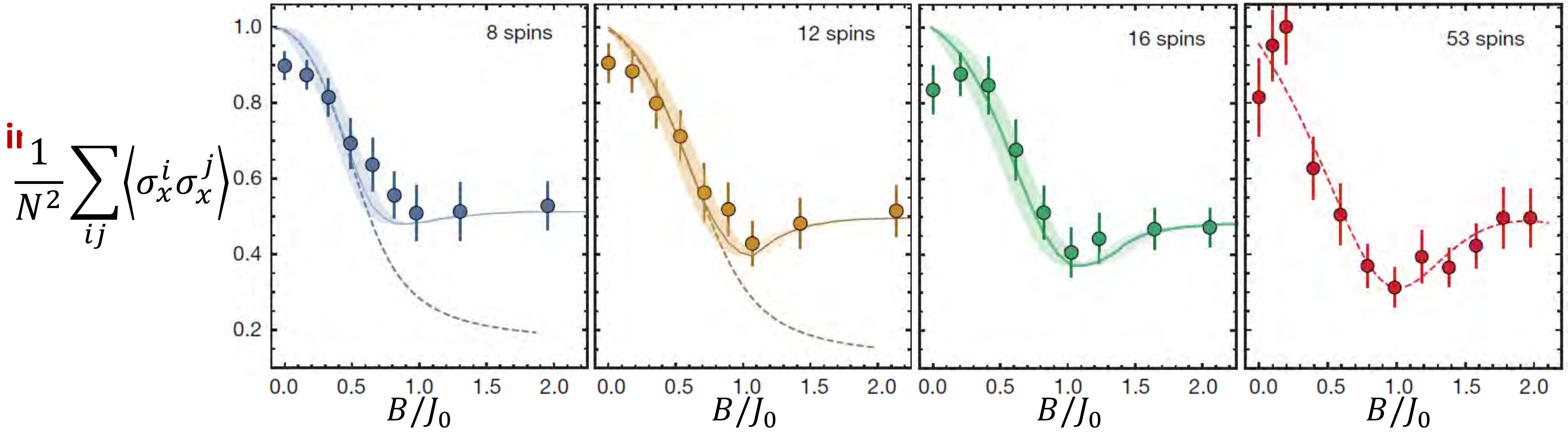
Dynamical Phase Transition with 50+ Qubits

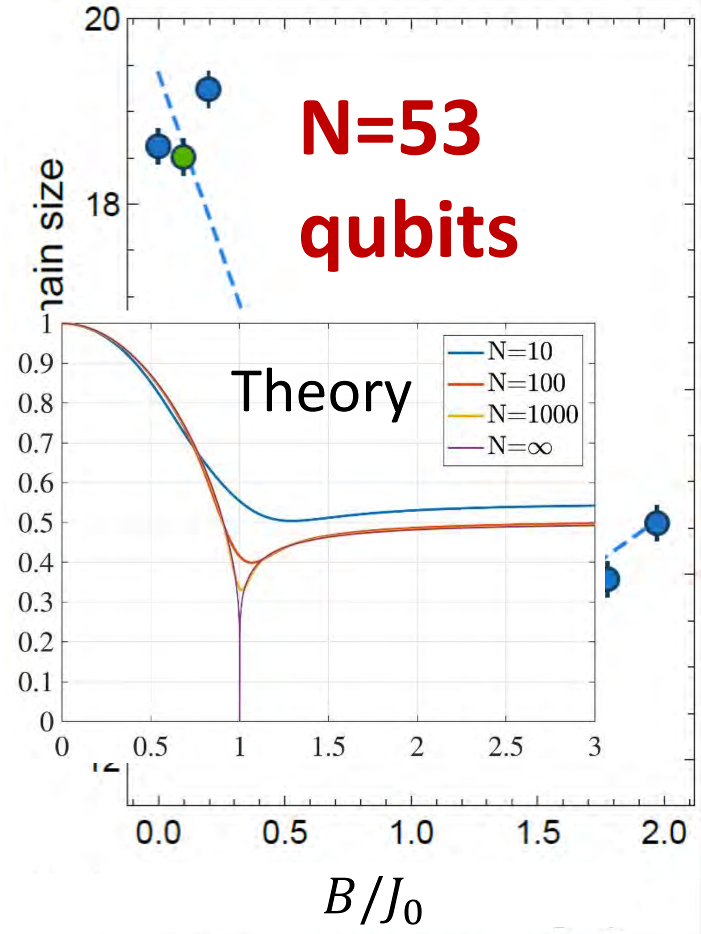
(1) Prepare spins along x

(2) Quench spins to $H = \sum_{i<j} \frac{J_0}{|i-j|^\alpha} \sigma_x^i \sigma_x^j + B \sum_i \sigma_z^i$

(3) Measure along x







see also: P. Jurcevic, et al., *PRL* **119**, 080501 (2017)

Quantum Approximate Optimization Algorithm (QAOA)

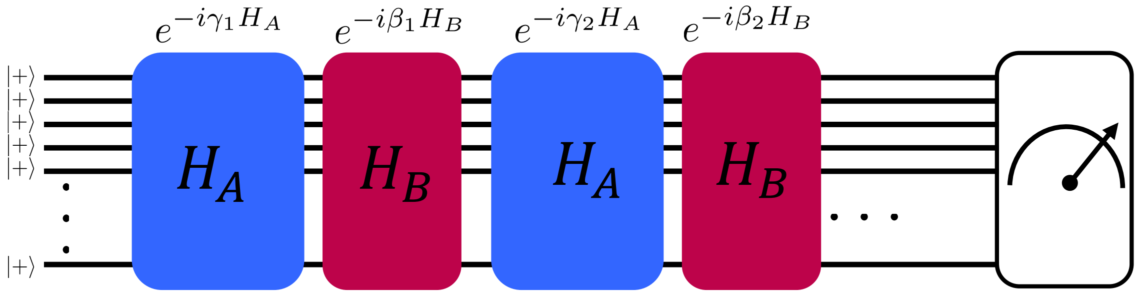
Goal: create (approximate) ground state of $H = \underbrace{\sum_{i<j} \frac{J_0}{|i-j|^{\alpha}} \sigma_x^i \sigma_x^j}_{H_A} + \underbrace{B \sum_i \sigma_y^i}_{H_B}$

(1) Prepare the ground state of H_B

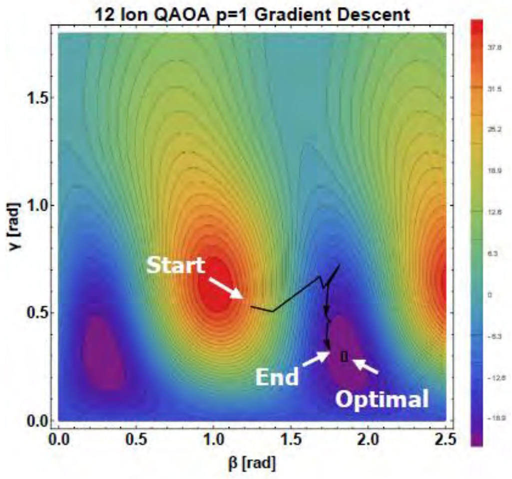
(2) Alternate H_A and H_B for p “layers” with evolution angles $\{\vec{\gamma}, \vec{\beta}\}$

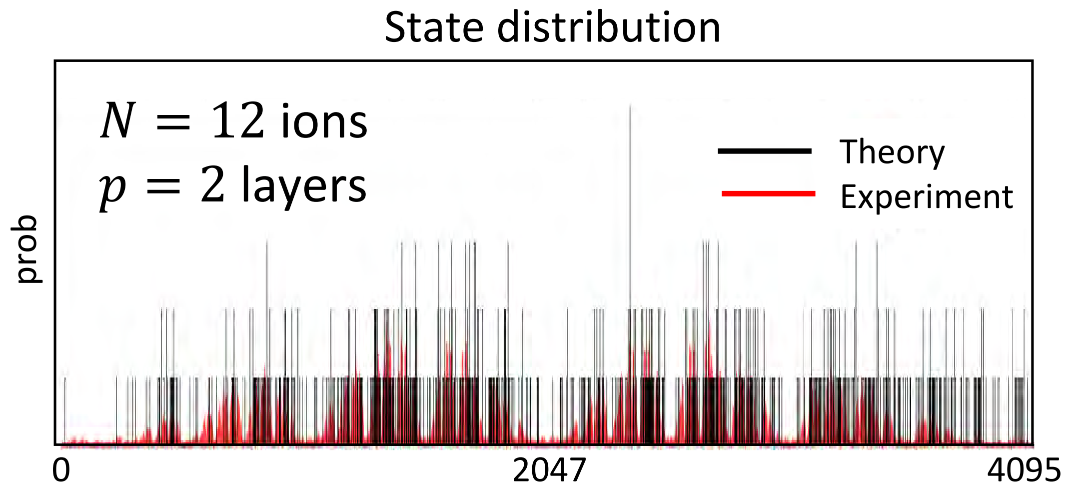
(3) Measure the the energy or complete state distribution

(4) Optimize $\{\vec{\gamma}, \vec{\beta}\}$ to minimize $\langle H \rangle$

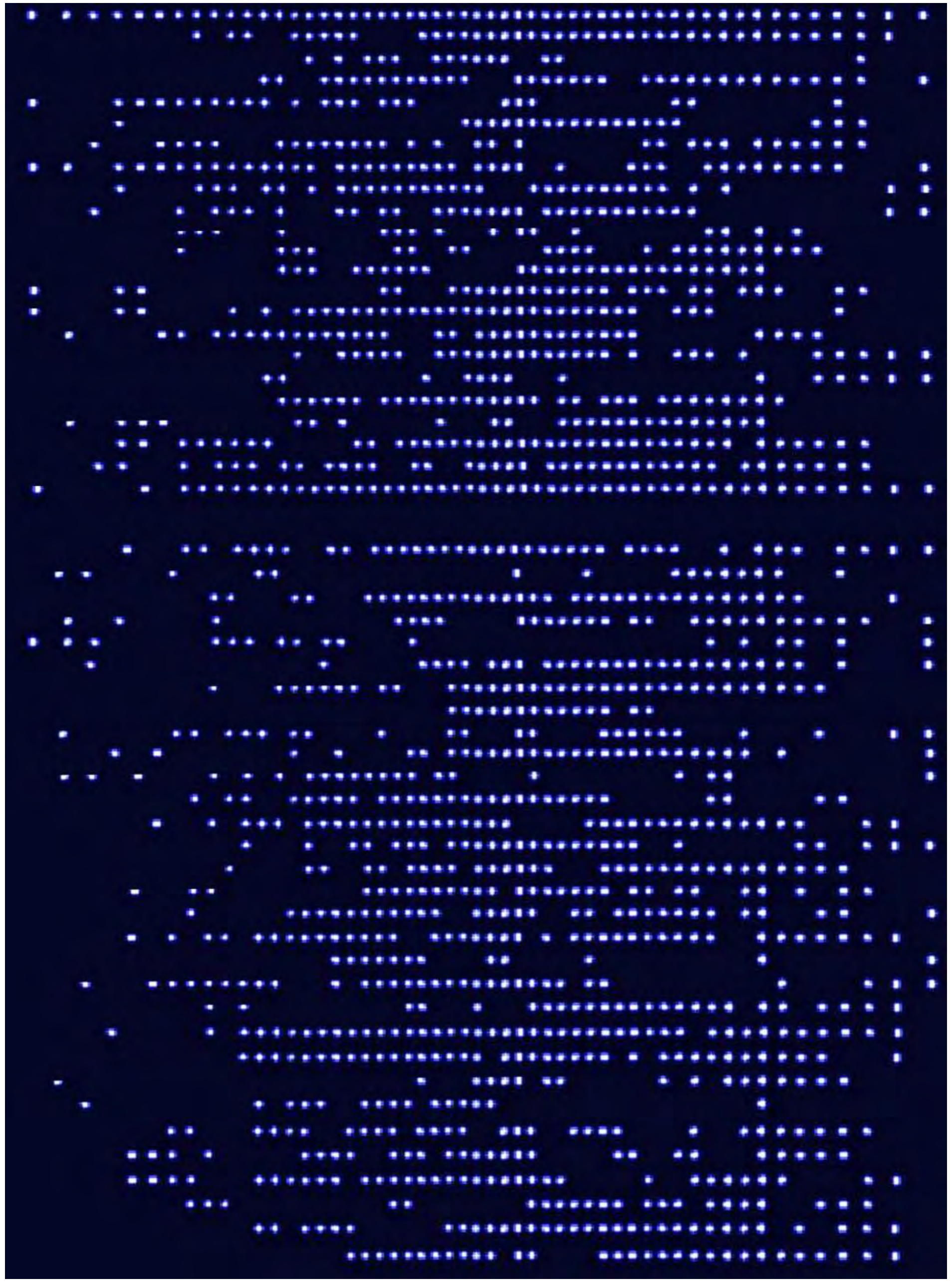


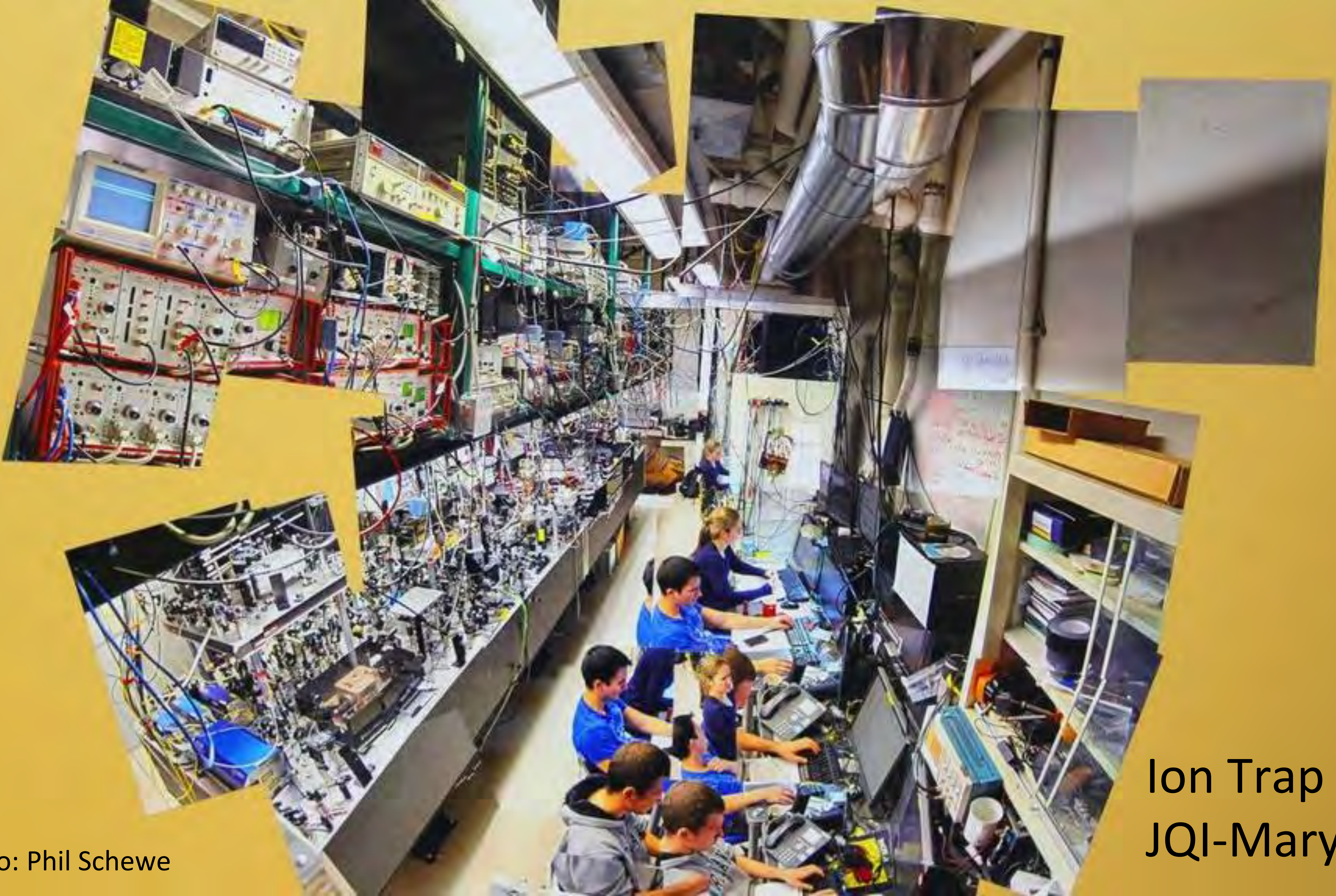
$N = 12$ ions
$p = 1$ layer





Scaling the System





Ion Trap Lab at JQI-Maryland

Photo: Phil Schewe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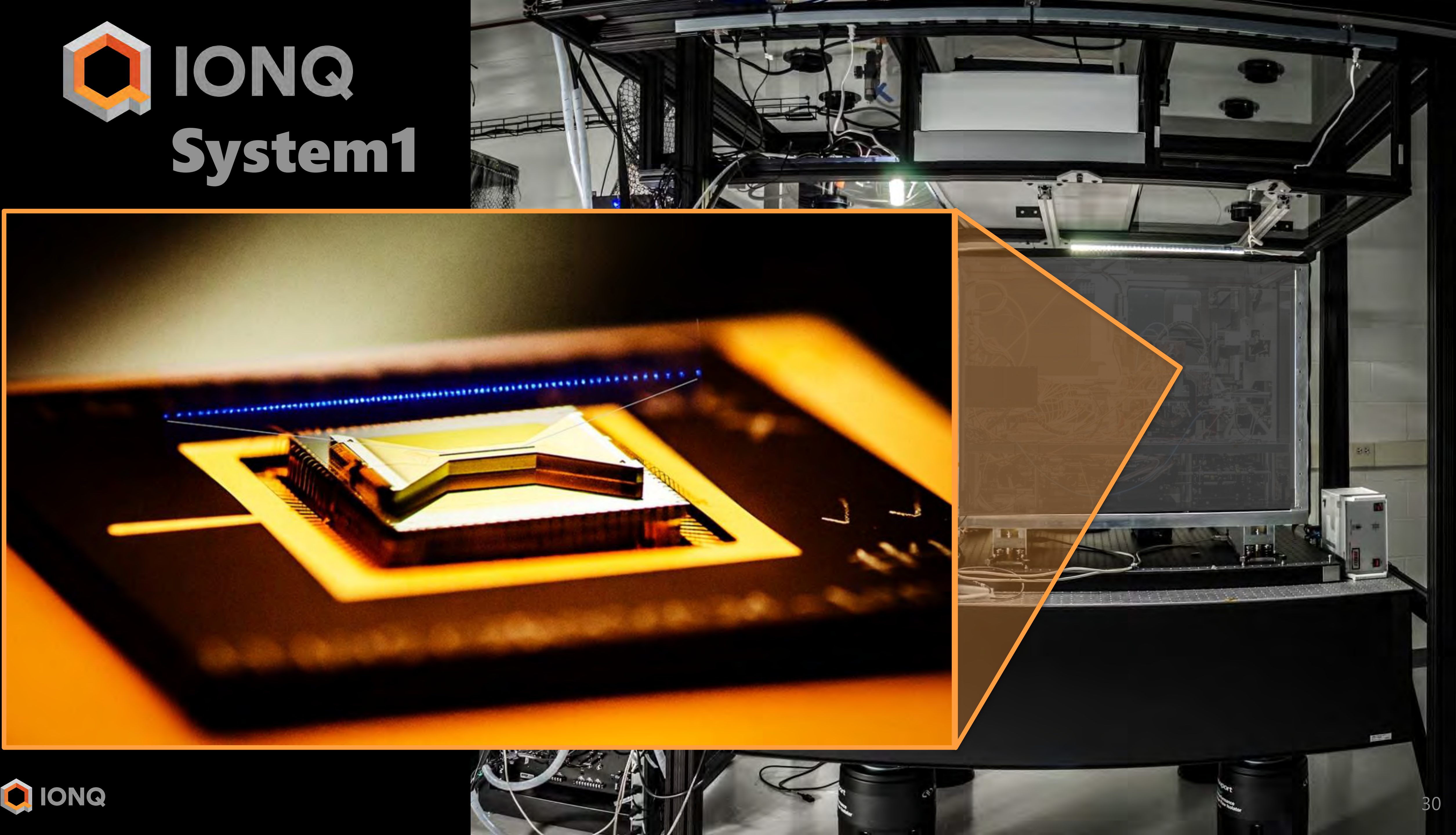
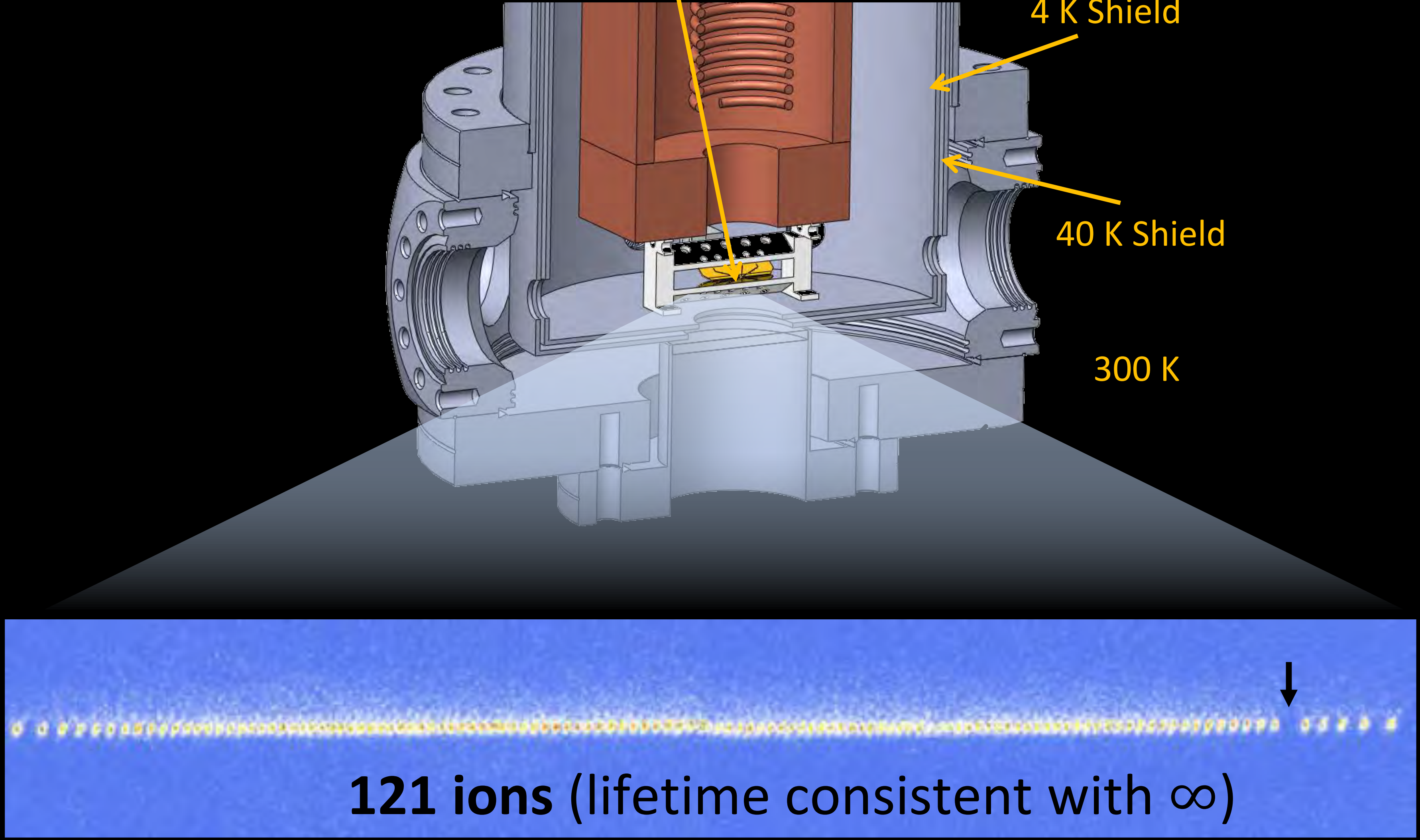
IONQ System1



4K environment (better vacuum!)

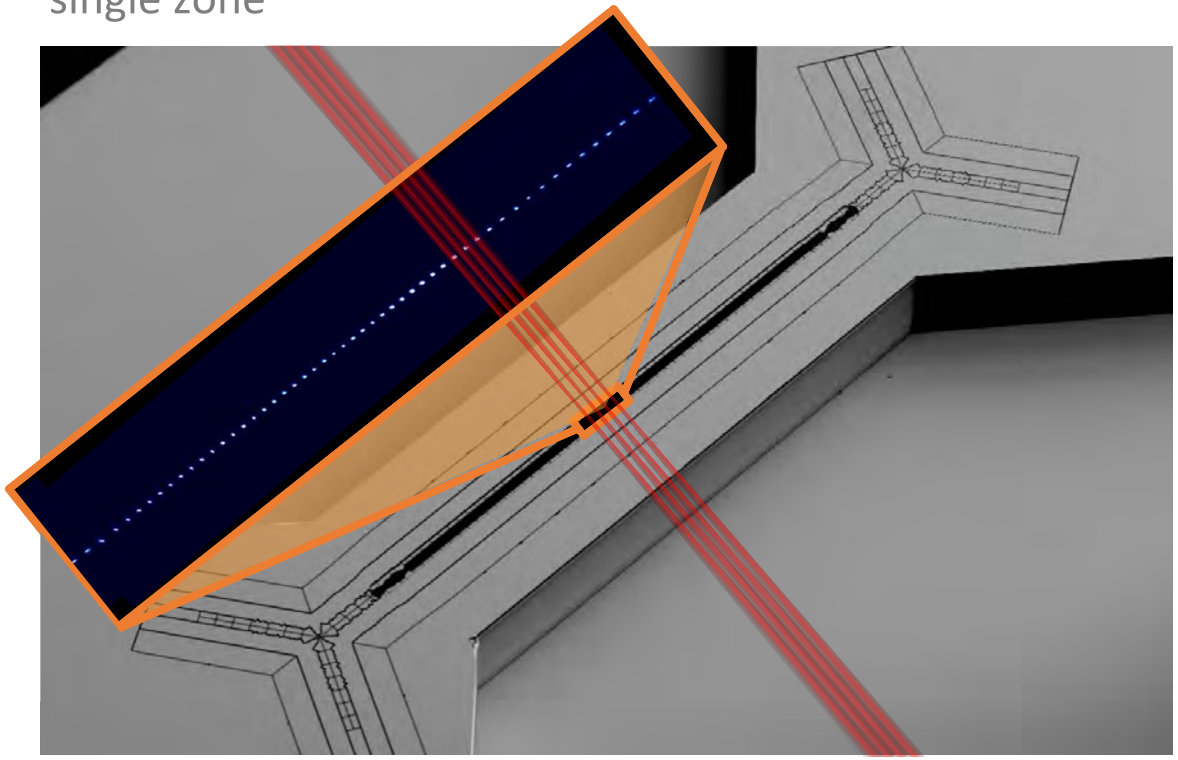
arXiv
1802.03118

Phil Richerme
Paul Hess
Guido Pagano

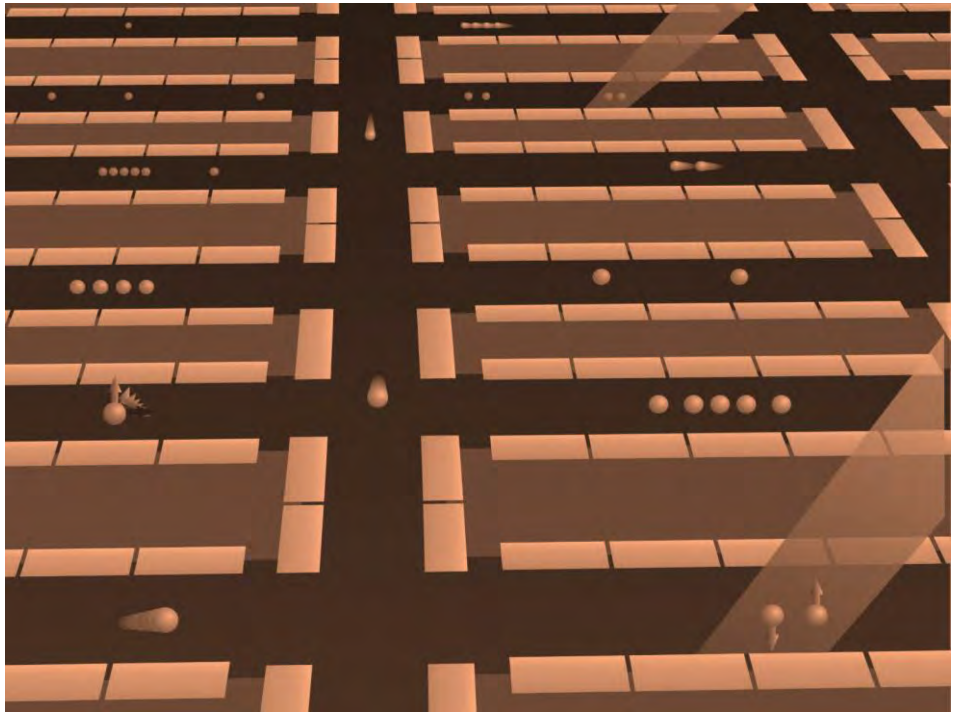


Scaling to 100-1000s of Qubits

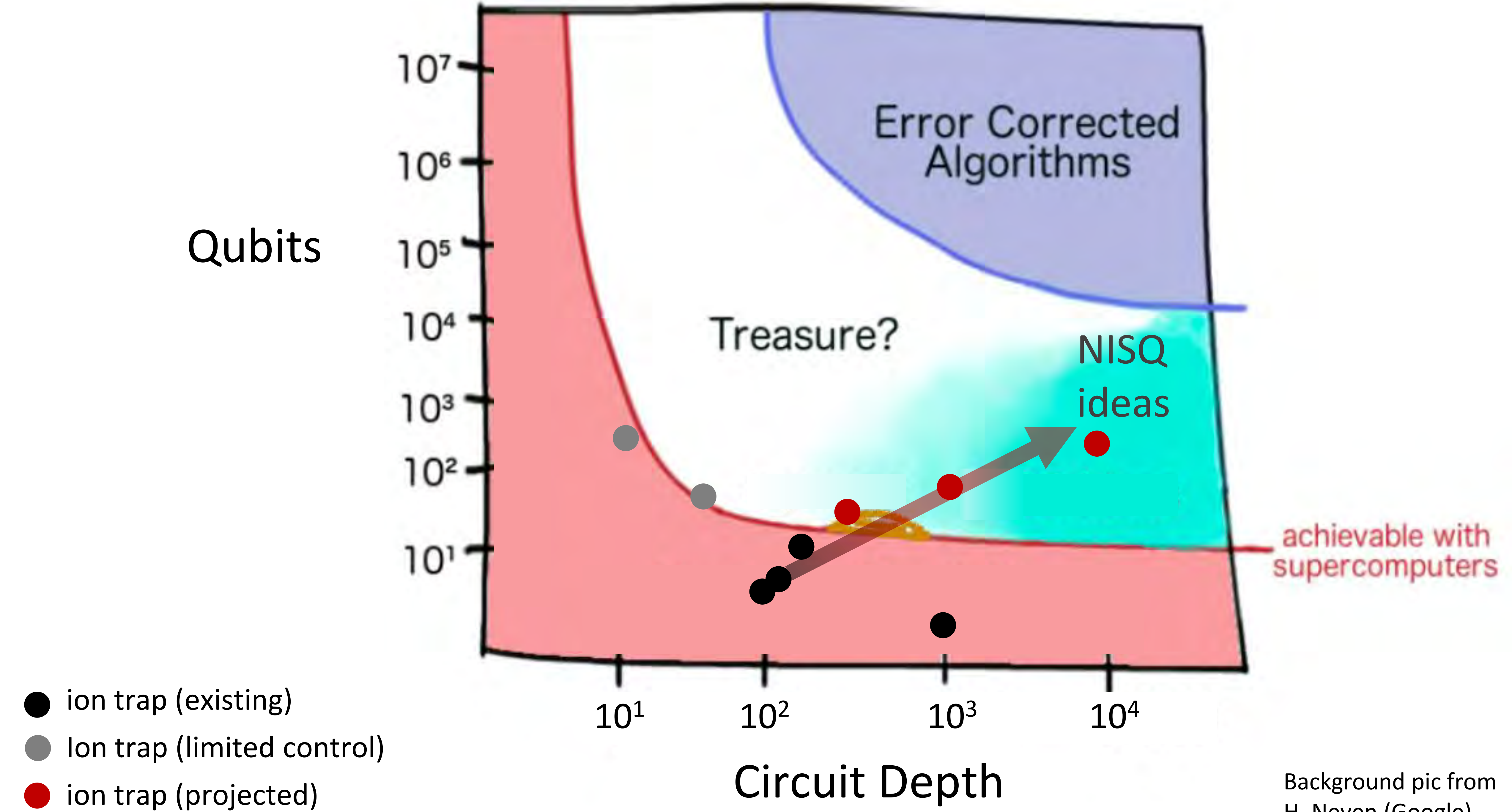
Linear shuttling through single zone



Modular shuttling between multiple zones



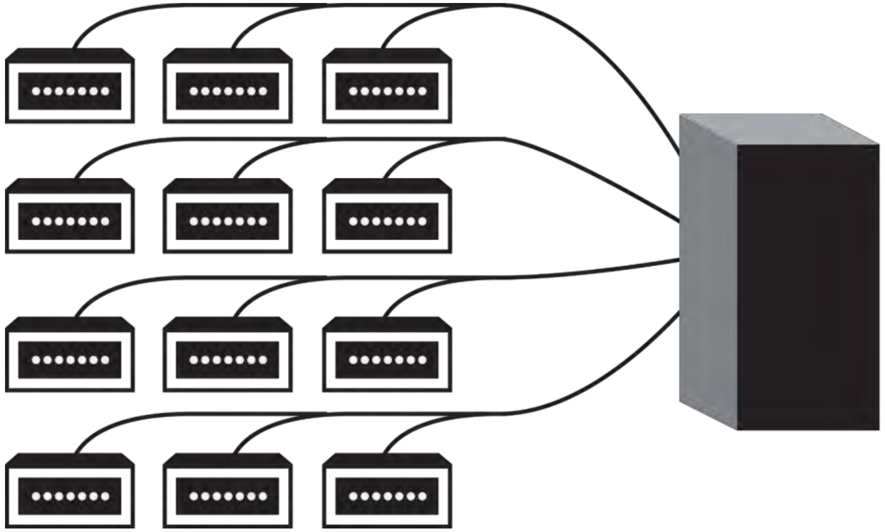
Kielpinski, Monroe, Wineland, Nature 417, 709 (2002)
Leikesh, et al., Science Advances 3, e1601540 (2017)

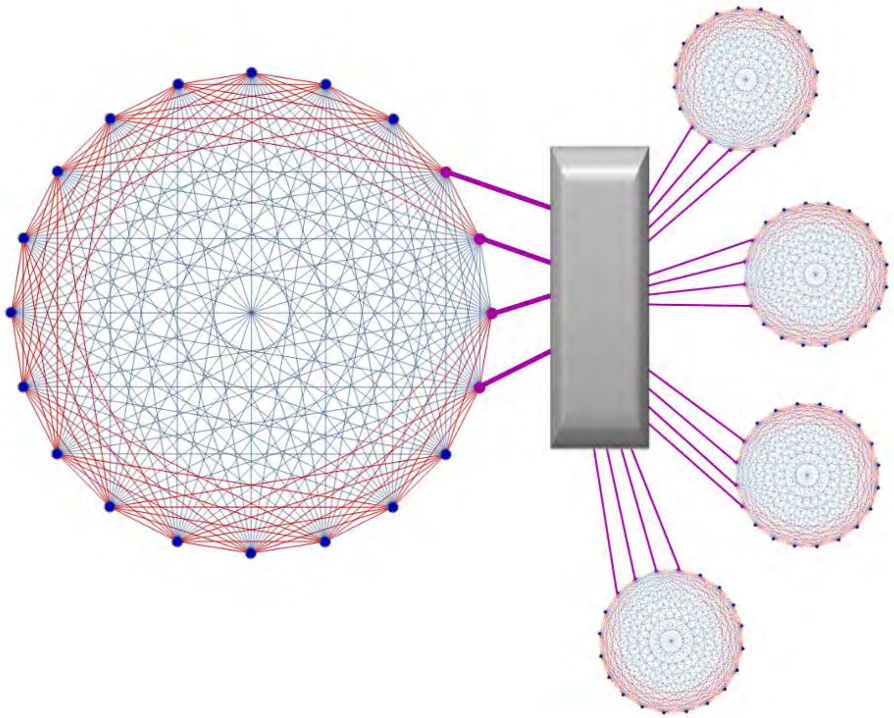


Background pic from H. Neven (Google)

Scaling beyond 1000s of Qubits: photonics

Modular optical 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)

Trapped Ion Quantum Information

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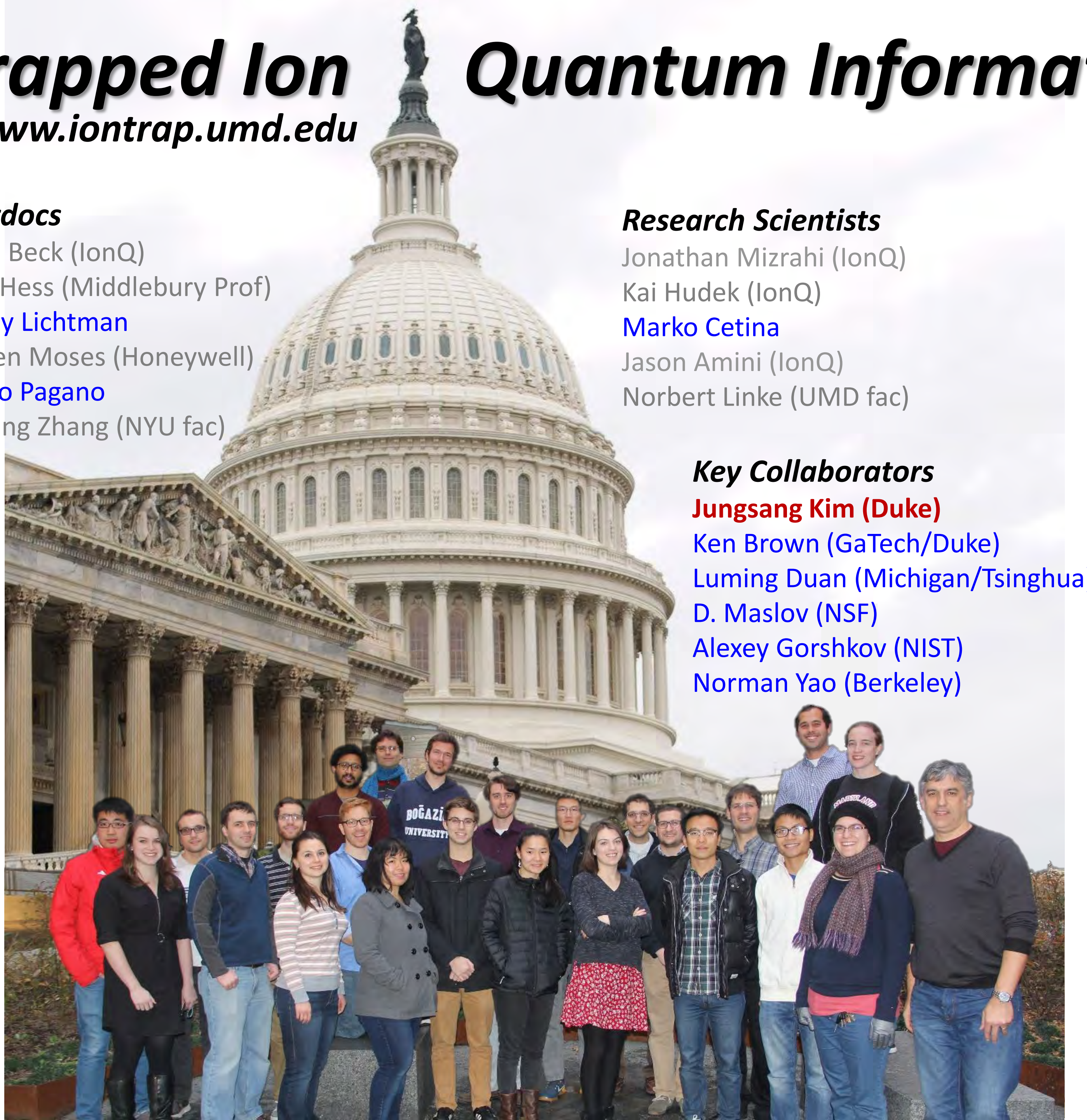

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