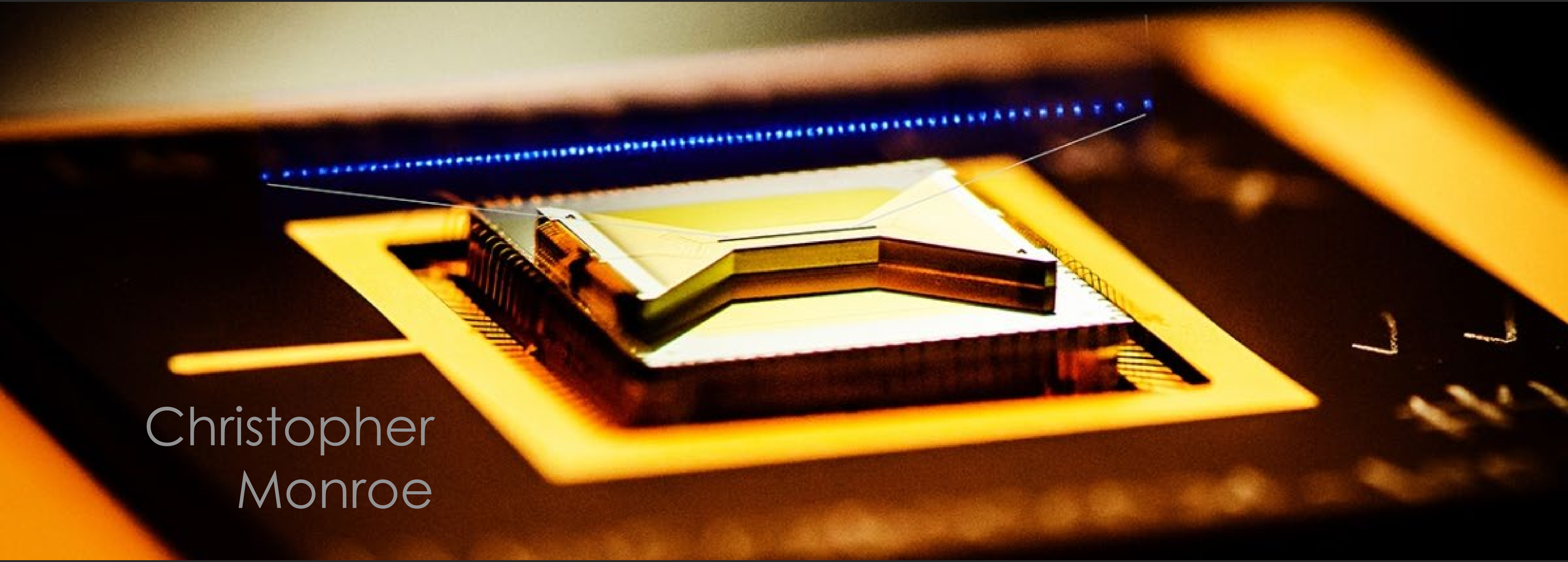
Quantum Simulation and Computing with Atomic Ions



Christopher
Monroe

UNIVERSITY OF
MARYLAND

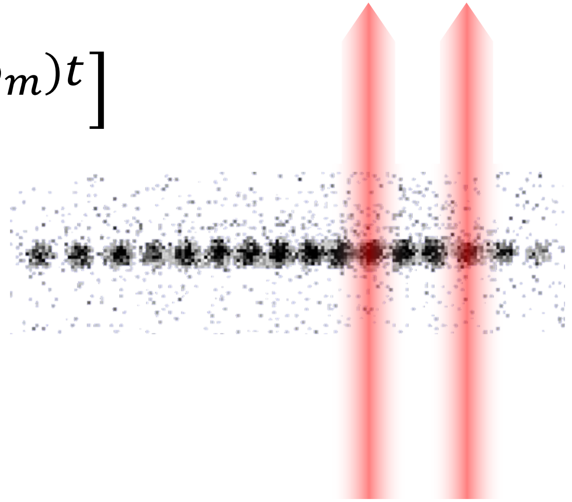
Duke
UNIVERSITY

Duke
Quantum
Center

IONQ

Many ions: many phonon modes

$$H = \sum_{i,m} \eta_{im} \Omega_i \sigma_x^i \left[a_m e^{-i(\mu-\omega_m)t} + a_m^\dagger e^{i(\mu-\omega_m)t} \right]$$



ion i
mode m

$$\eta_{im} = \sqrt{\frac{\hbar k^2}{2m\omega_m}}\, b_{i,m}$$

displacement eigenvector
mode m with ion i

$$\sum_{i=1}^{N} b_{i,m} b_{i,n} = \delta_{mn} \qquad \sum_{m=1}^{N} b_{i,m} b_{j,m} = \delta_{ij}$$

evolution operator (Magnus expansion)

$$U(\tau) = \exp\left[-i\int_0^\tau dt H(t) - \frac{1}{2}\int_0^\tau dt_2 \int_0^{t_2} dt_1 [H(t_2), H(t_1)] - \frac{i}{6}\int_0^\tau dt_3 \int_0^{t_3} dt_2 \int_0^{t_2} dt_1 [H(t_3),[H(t_2), H(t_1)]] + \ldots \right]$$

$$U(\tau) = \exp\left[\sum_i \hat{\zeta}_i(\tau) \sigma_x^{(i)} + i \sum_{i,j} \chi_{i,j}(\tau) \sigma_x^{(i)} \sigma_x^{(j)} \right]$$

Many ions: many phonon modes

$$U(\tau) = \exp\left[\sum_i \hat{\zeta}_i(\tau)\sigma_x^{(i)} - i\sum_{i,j}\chi_{i,j}(\tau)\sigma_x^{(i)}\sigma_x^{(j)}\right]$$

phonons

$$\hat{\zeta}_i(\tau) = \sum_m [\alpha_i^m(\tau)a_m^\dagger - \alpha_i^{m*}(\tau)a_m]$$

$$\alpha_i^m(\tau) = \frac{-i\eta_{i,m}\boxed{\Omega_i}}{2\boxed{(\mu-\omega_m)}}\left[1 - e^{-i(\boxed{\mu}-\omega_m)\tau}\right]$$

Soln 1: Modulate Laser → **Quantum Computer**

Soln 2: Detune far → **Quantum Simulator**

$\alpha_i^m(\tau)$ is a circle in phase space

$x_i^m \sim Re\ \alpha_i^m(\tau)$

$p_i^m \sim Im\ \alpha_i^m(\tau)$

interaction between qubits (entanglement)

$$\chi_{i,j}(\tau) = \Omega_i\Omega_j\omega_R\sum_m \frac{b_{i,m}b_{j,m}}{2\omega_m(\mu-\omega_m)}\left[\tau - \frac{\sin(\mu-\omega_m)\tau}{\mu-\omega_m}\right]$$

$$\omega_R = \frac{\hbar k^2}{2m}$$

"recoil frequency"

Solution 1: Individual addressing of ions.
UNIVERSAL QUANTUM GATES

Segment pulse in time $\Omega_i = \Omega_i(t)$

$$\alpha_i^m(\tau) = \frac{-i\eta_{i,m}\Omega_i(t)}{2(\mu - \omega_m)}\left[1 - e^{-i(\mu-\omega_m)\tau}\right]$$

for all modes m

2N motional conditions

$$\chi_{i,j}(\tau) = \Omega_i\Omega_j\omega_R \sum_m \frac{b_{i,m}b_{j,m}}{2\omega_m(\mu - \omega_m)}\left[\tau - \frac{\sin(\mu - \omega_m)\tau}{\mu - \omega_m}\right] = \frac{\pi}{4}$$

1 gate condition

2N+1 constraints
→ *break $\Omega(t)$ into 2N+1 segments*

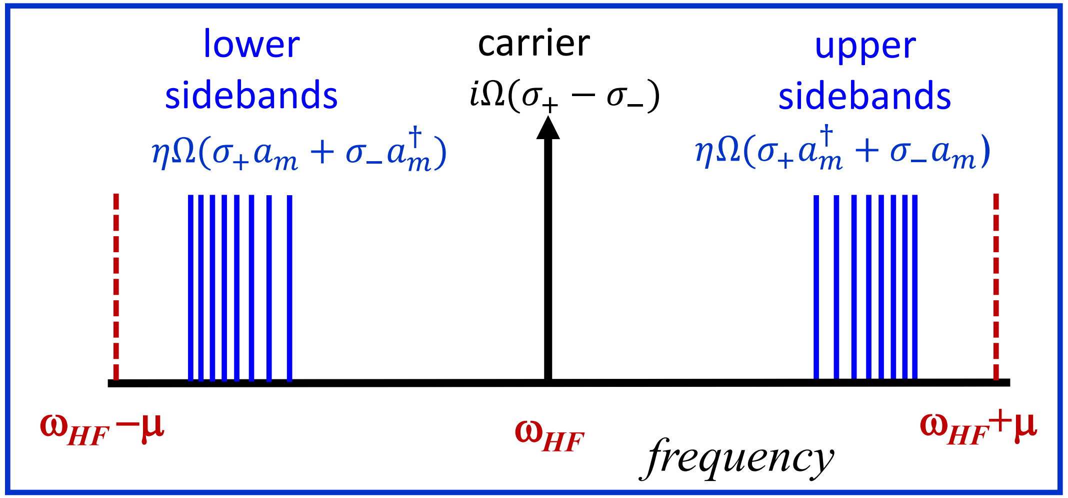
S.-L. Zhu, et al., Europhys Lett. 73 (4), 485 (2006)

Solution 2: Large-Detuned Limit
PURE SPIN HAMILTONIANS

set $|\mu - \omega_m| \gg \eta\Omega$

$$\alpha_i^m(\tau) = \frac{-i\eta_{i,m}\Omega_i(t)}{2(\mu - \omega_m)}\left[1 - e^{-i(\mu-\omega_m)\tau}\right] \rightarrow 0$$

for all modes m

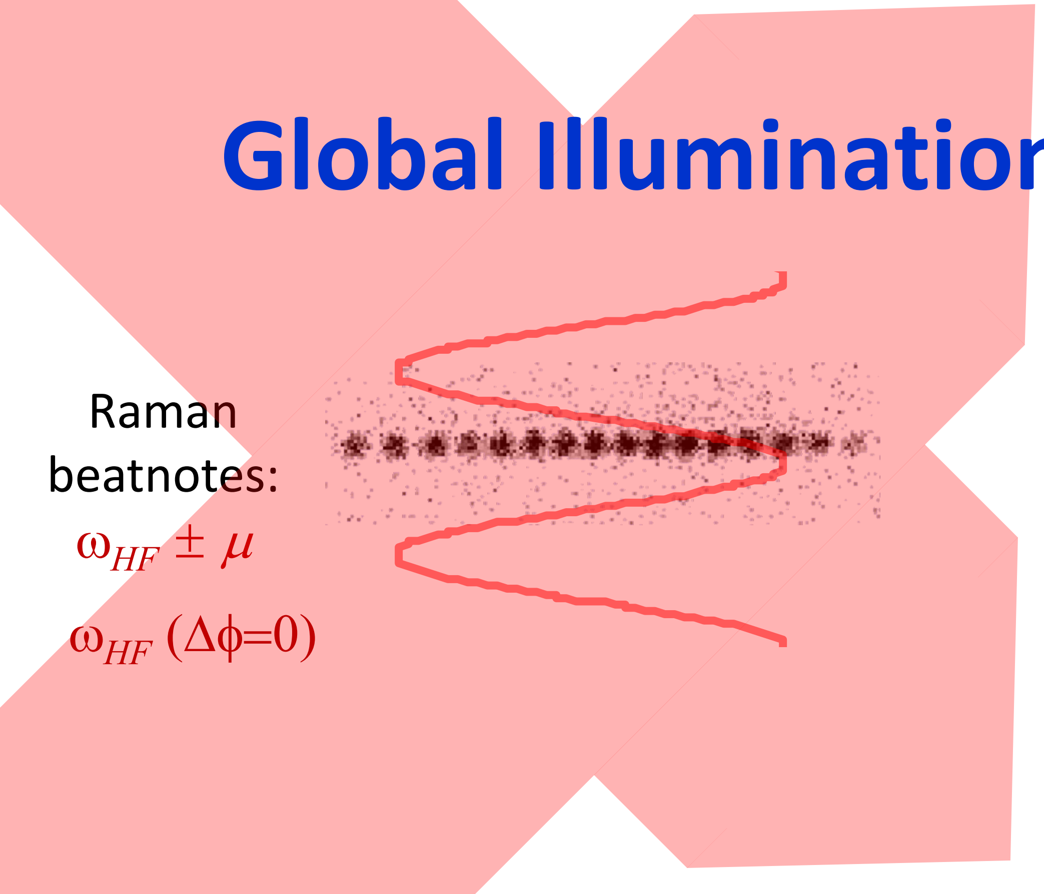


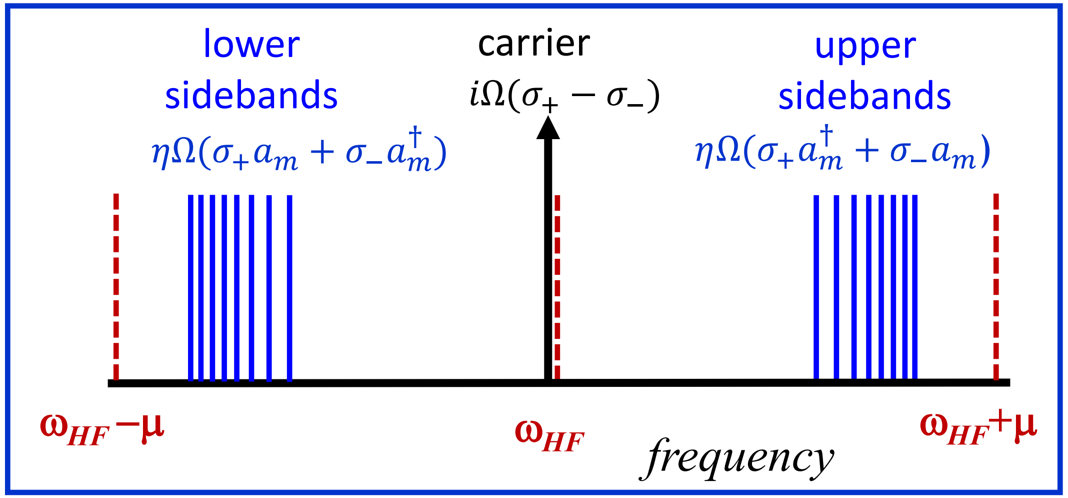
$$\chi_{i,j}(\tau) = \Omega_i\Omega_j\omega_R\tau\sum_m \frac{b_{i,m}b_{j,m}}{2\omega_m(\mu - \omega_m)}$$

$$J_{i,j} = \Omega_i\Omega_j\omega_R\sum_m \frac{b_{i,m}b_{j,m}}{2\omega_m(\mu - \omega_m)}$$

$$U(\tau) = \exp\left[-i\sum_{i,j}\chi_{i,j}(\tau)\sigma_x^{(i)}\sigma_x^{(j)}\right] = \exp\left[-i\tau\underbrace{\sum_{i,j}J_{i,j}\sigma_x^{(i)}\sigma_x^{(j)}}\right]$$

Global Illumination (Fully-connected Ising system)



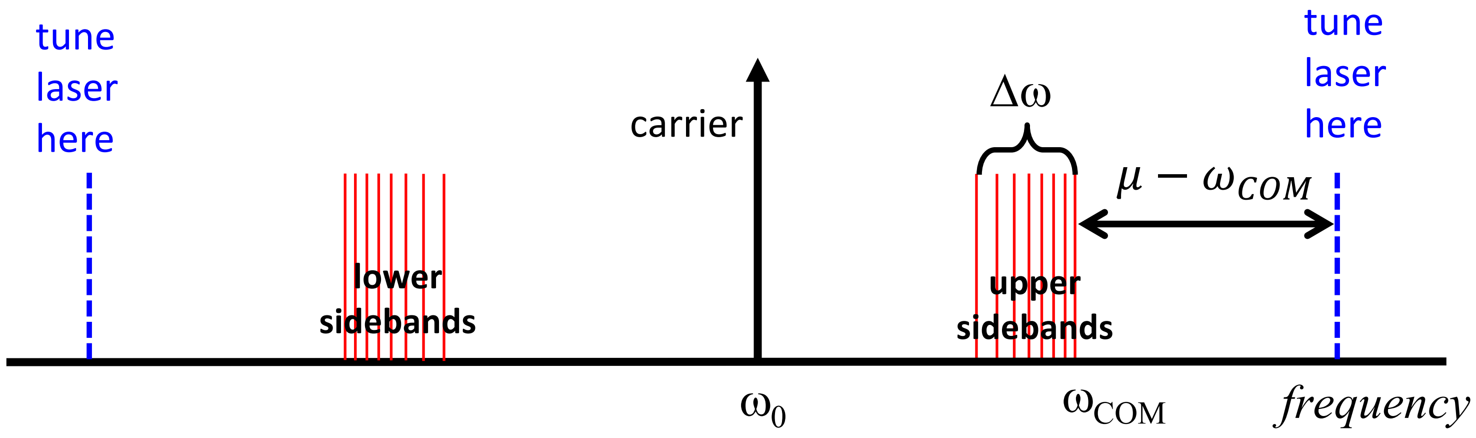


$$H = \sum_{i<j} J_{ij} \sigma_x^i \sigma_x^j + B \sum_i \sigma_y^i$$

$$J_{i,j} = \Omega^2 \omega_R \sum_m \frac{b_{i,m} b_{j,m}}{2\omega_m(\mu - \omega_m)}$$

Porras and Cirac, Phys. Rev. Lett. 92, 207901 (2004)
K. Kim, et al., New J. Phys. 13, 105003 (2011)
Monroe, et al., Rev. Mod. Phys. 93, 025001 (2021)

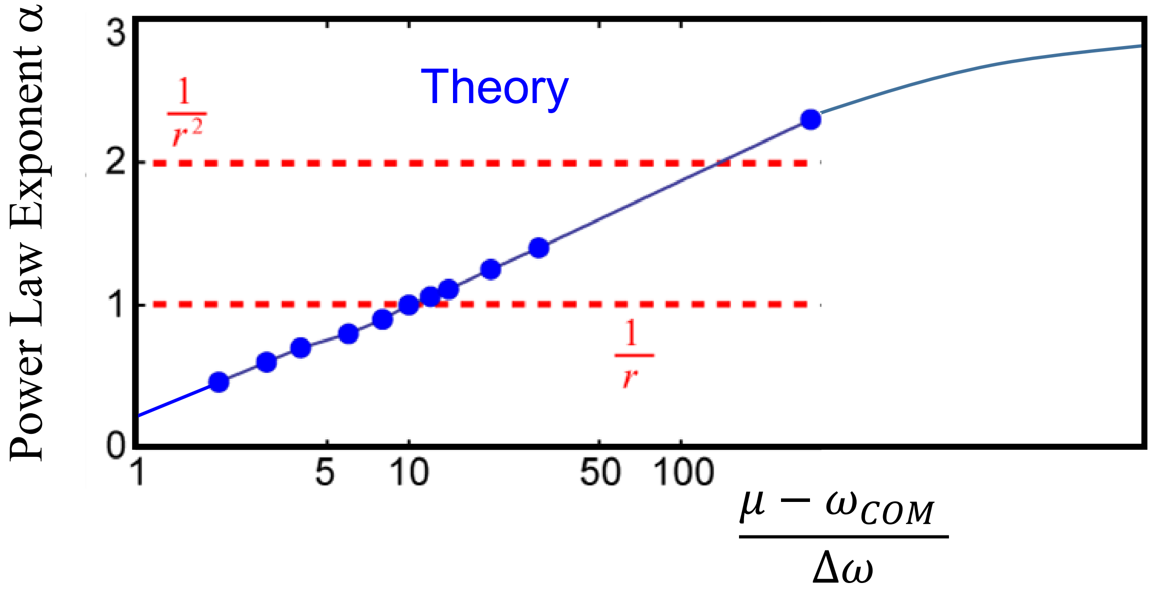
Control Range of Interaction with laser detuning!



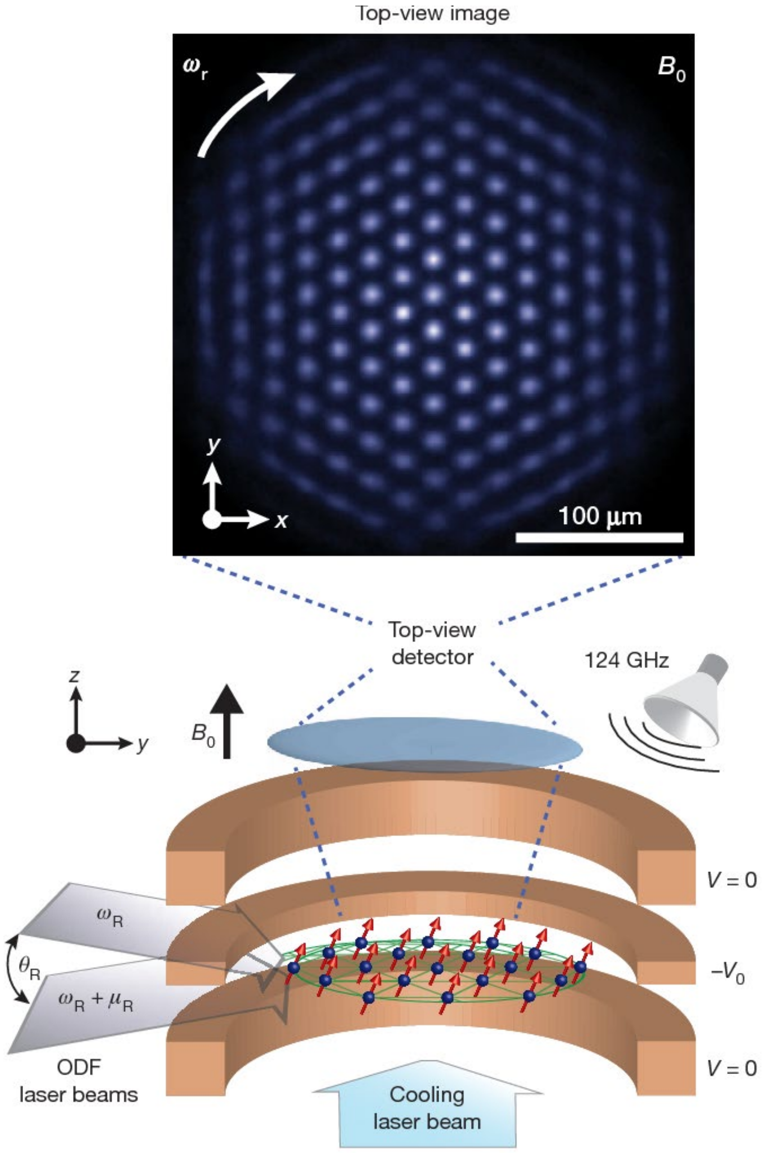
$$J_{ij} = \Omega^2 \omega_R \sum_m \frac{b_i^m b_j^m}{2\omega_m(\mu - \omega_m)}$$

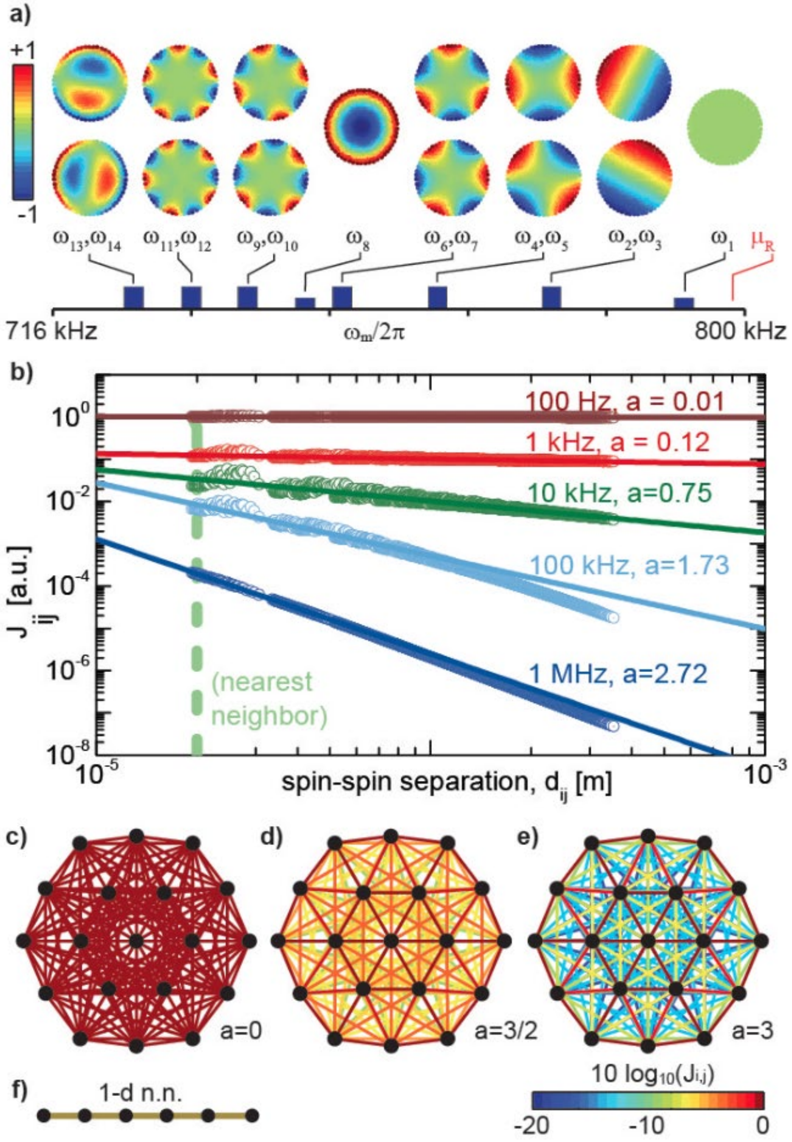
$$\sim \frac{J_0}{|i-j|^\alpha}$$

$0 < \alpha < 3$
$J_0 \sim 2\pi(1\ \mathrm{kHz})$
$J_0\tau \sim 50$



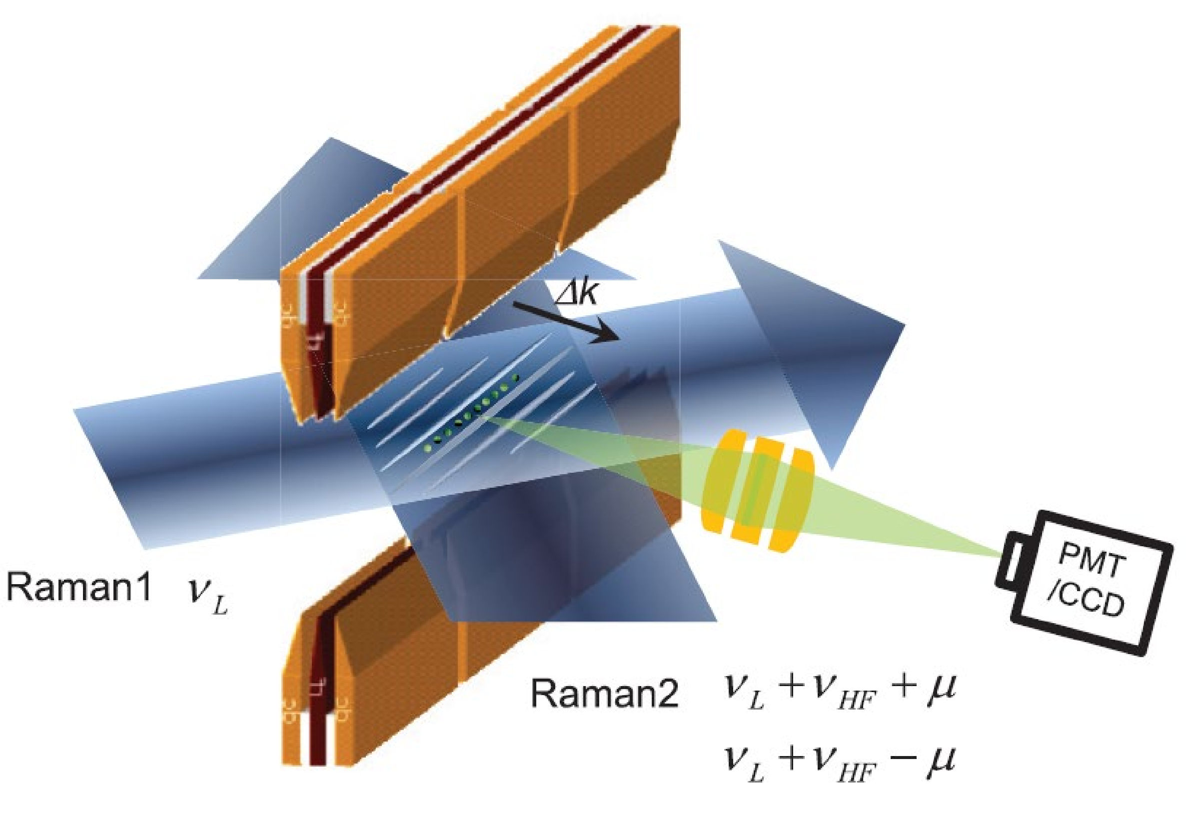
2D Trapped Ion Crystals (Penning Trap)

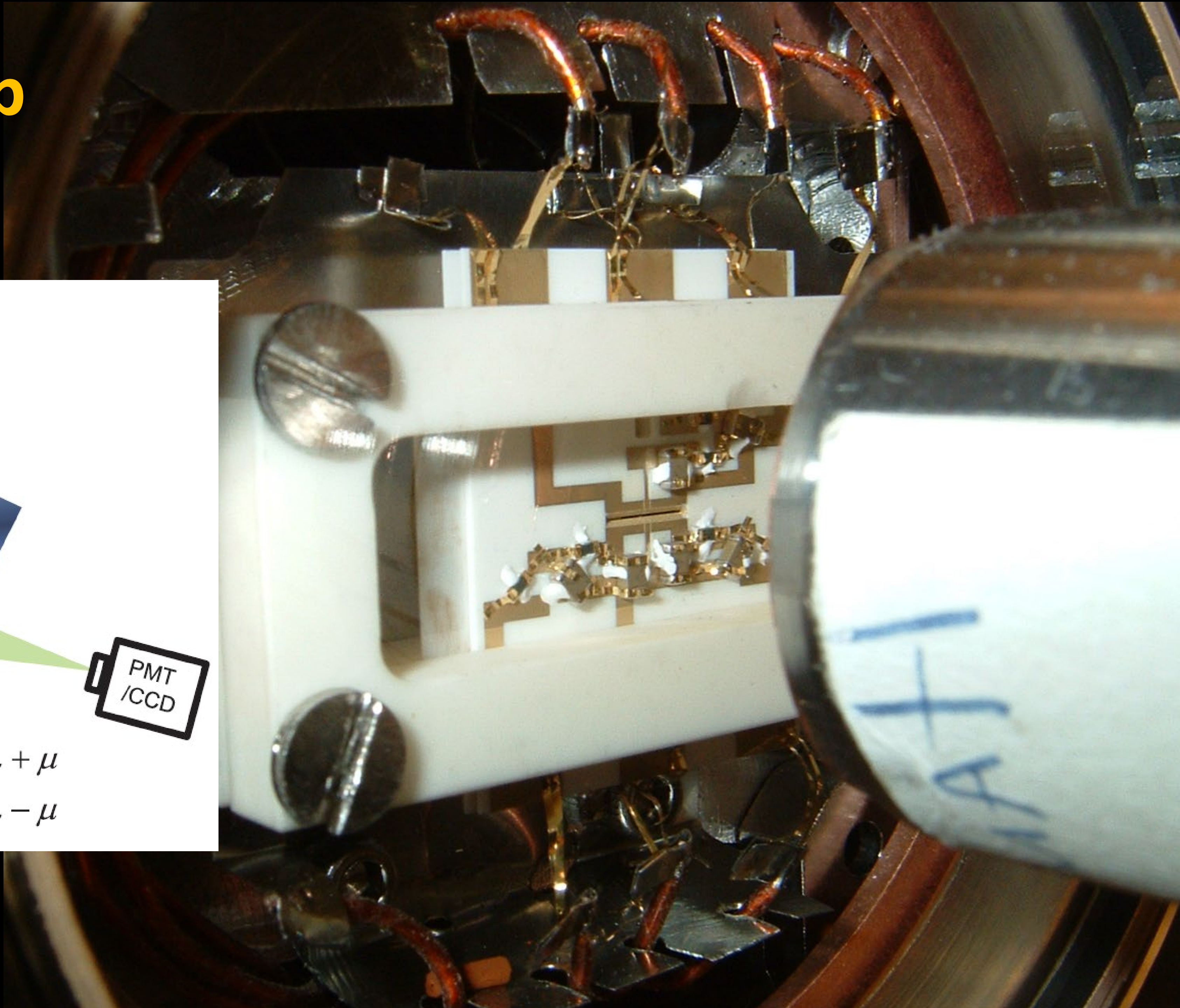




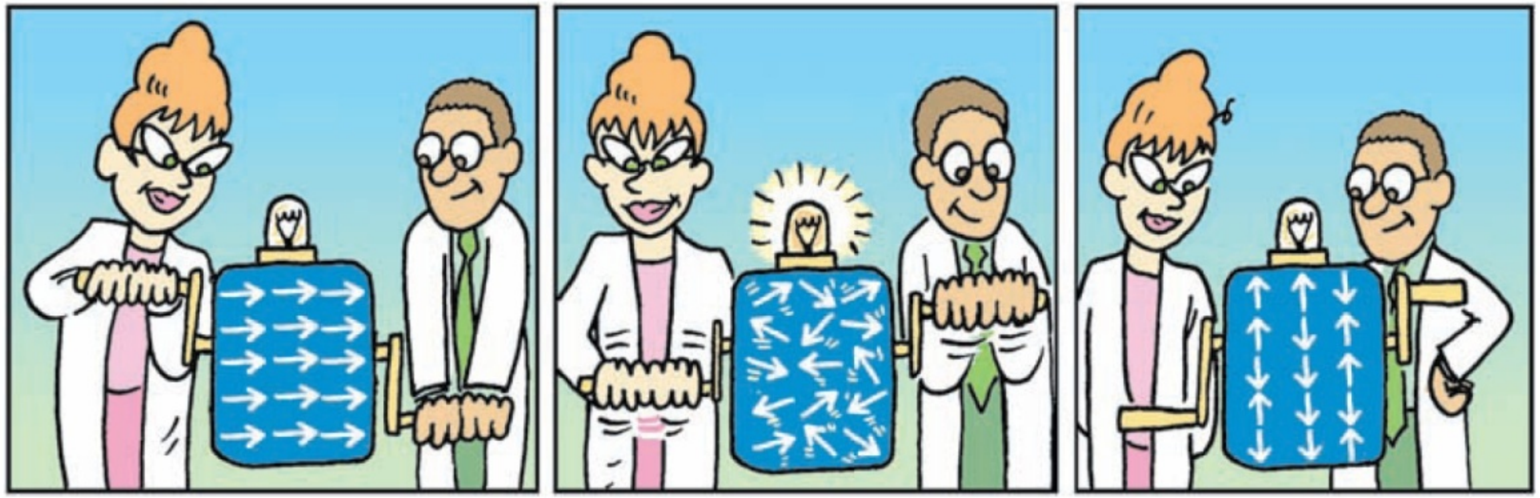
NIST-Boulder (J. Bollinger)
Nature 484, 489-492 (2012)
Science 352, 1297 (2016)
Nature Phys. 13, 781 (2017)
Phys. Rev. Lett. 118, 263602 (2017)

3-Layer Linear Trap (2009-present)





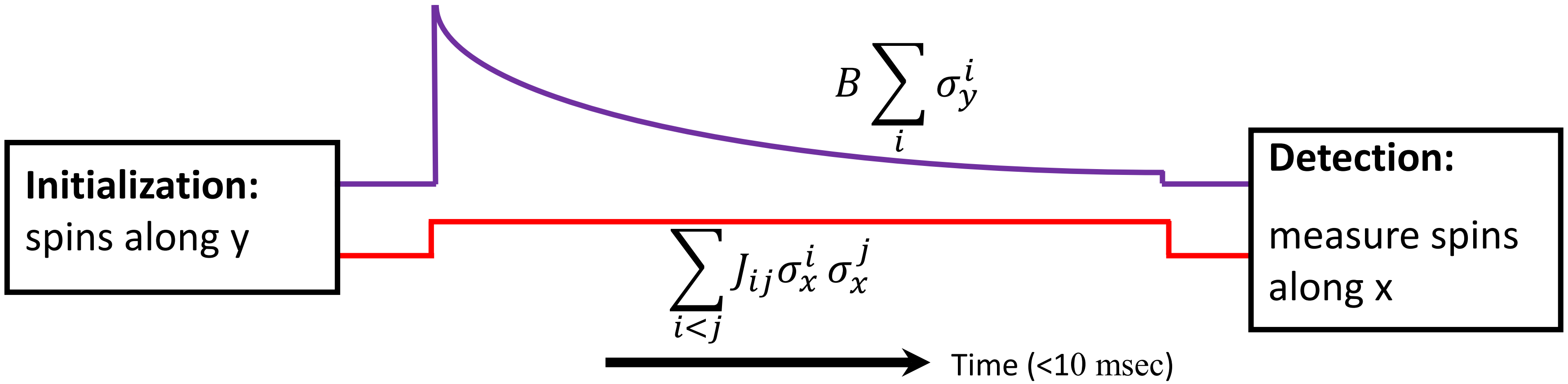
Adiabatic Evolution of Hamiltonian



S. Lloyd, Science **319**, 1209 (2008)

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

$$J_{ij} = \frac{J_0}{|i-j|^\alpha} \qquad 0 < \alpha < 3$$



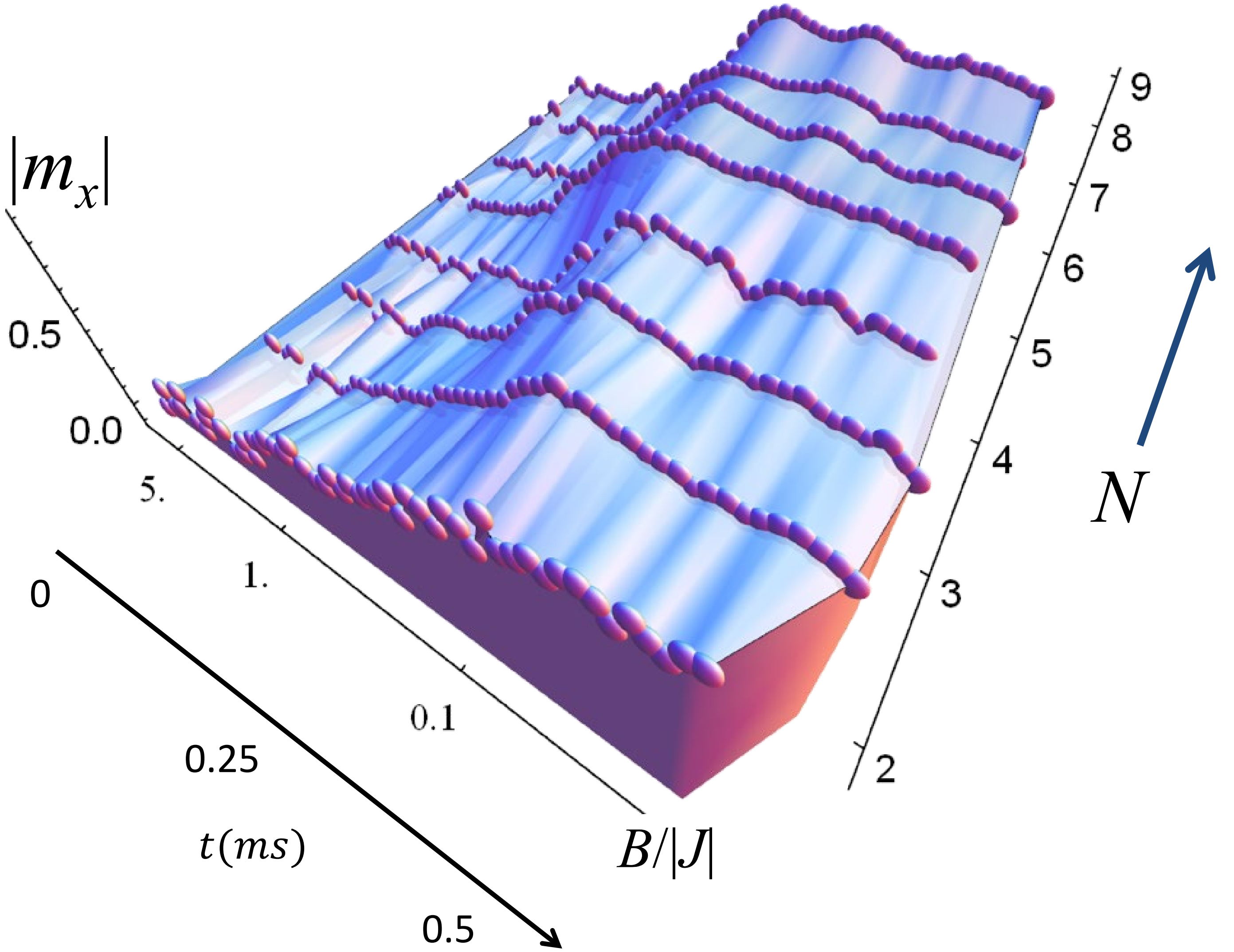
Emergence of ferromagnetism vs. # spins N

(all FM couplings: $J_0 < 0$)

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

$$J_{ij} = \frac{J_0}{|i-j|^\alpha}$$

$\alpha \approx 0.35$

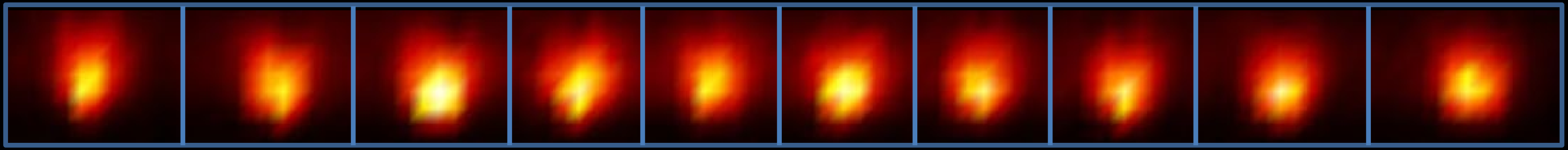


R. Islam et al., Nature Communications 2, 377 (2011)

Antiferromagnetic Néel order of N=10 spins

2600 runs, α=1.12

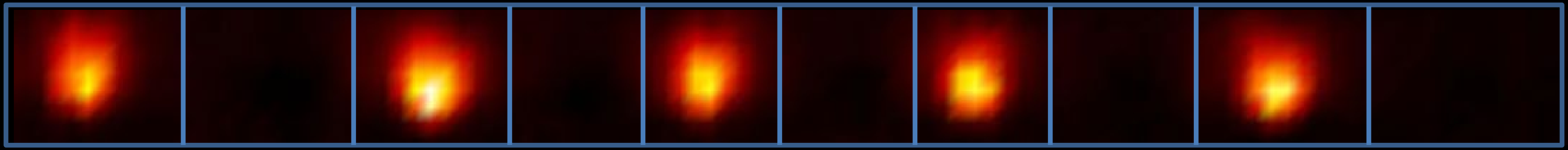
All in state $\uparrow$



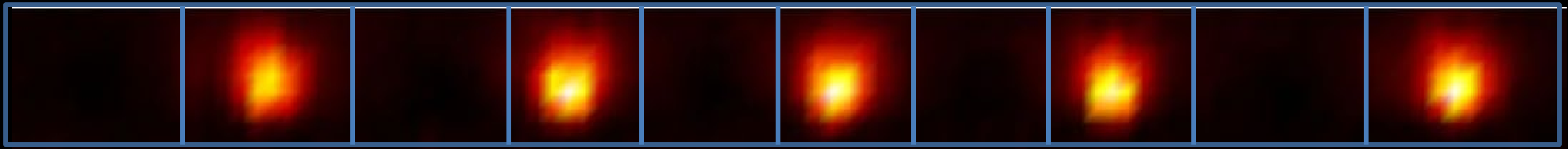
All in state $\downarrow$

AFM ground state order

222 events



219 events



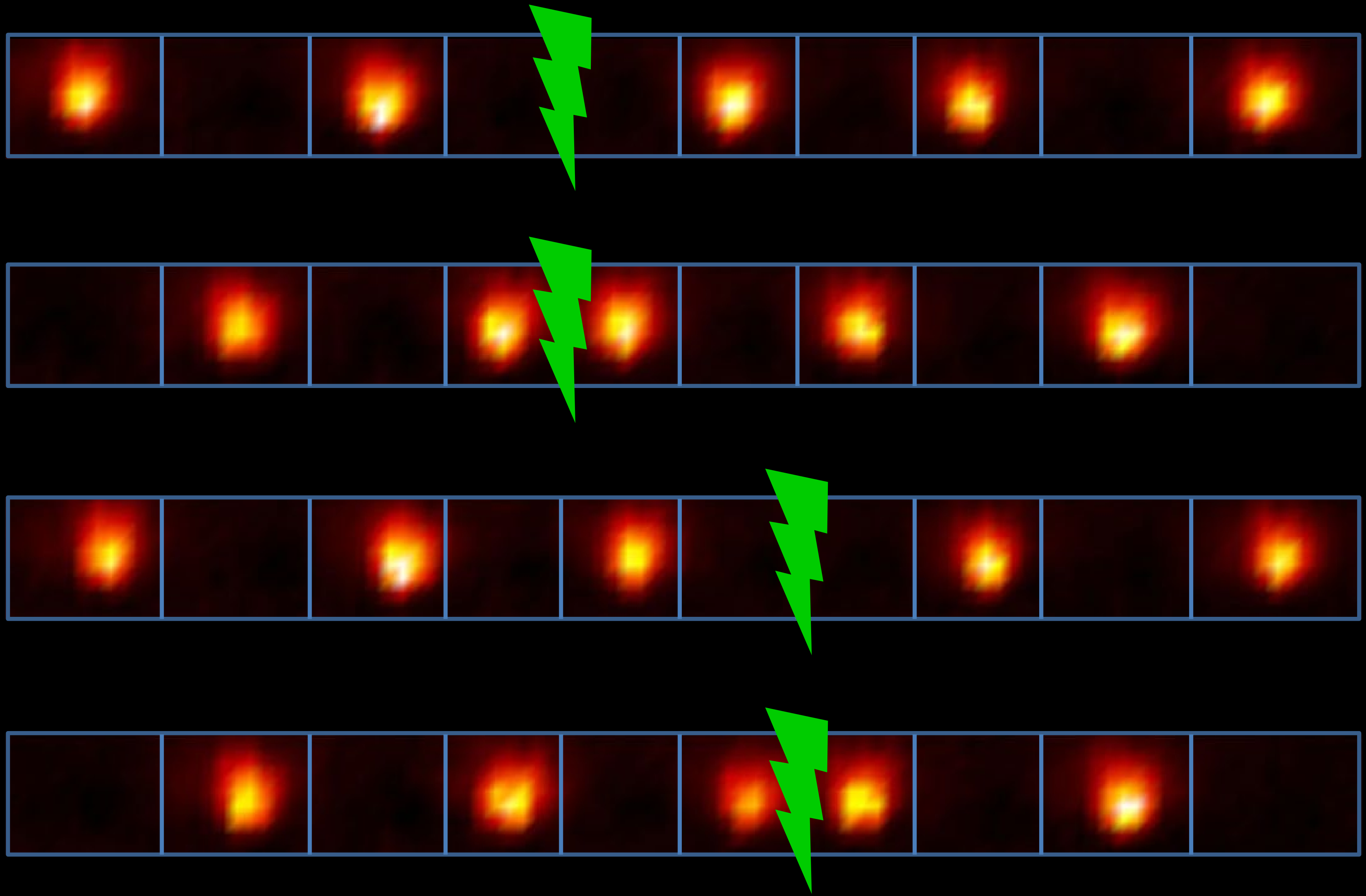
441 events out of 2600 = 17%

Prob of any state at random $=2 \times (1/2^{10}) = 0.2\%$

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

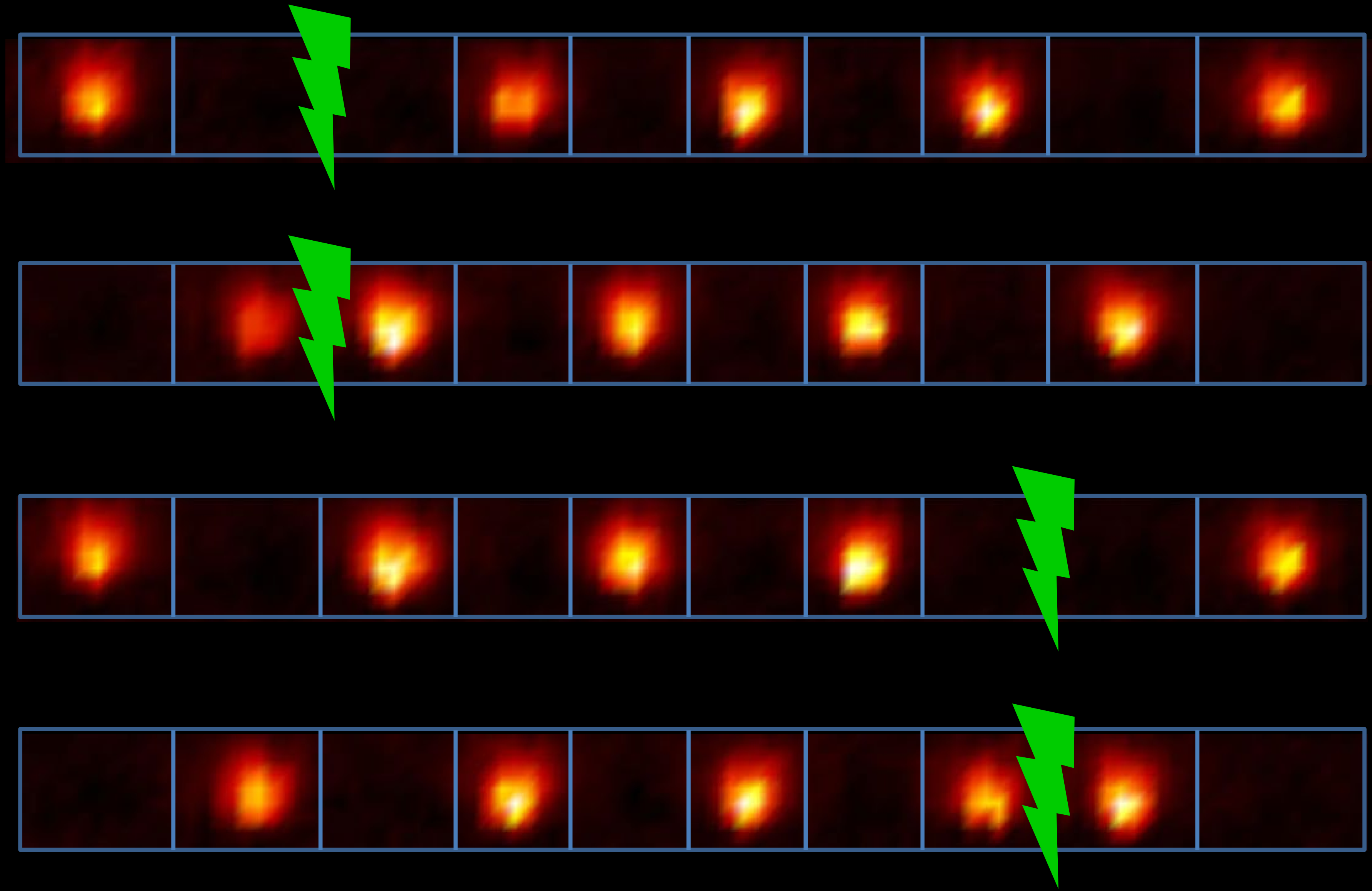
First Excited States

(Pop. ~2% each)

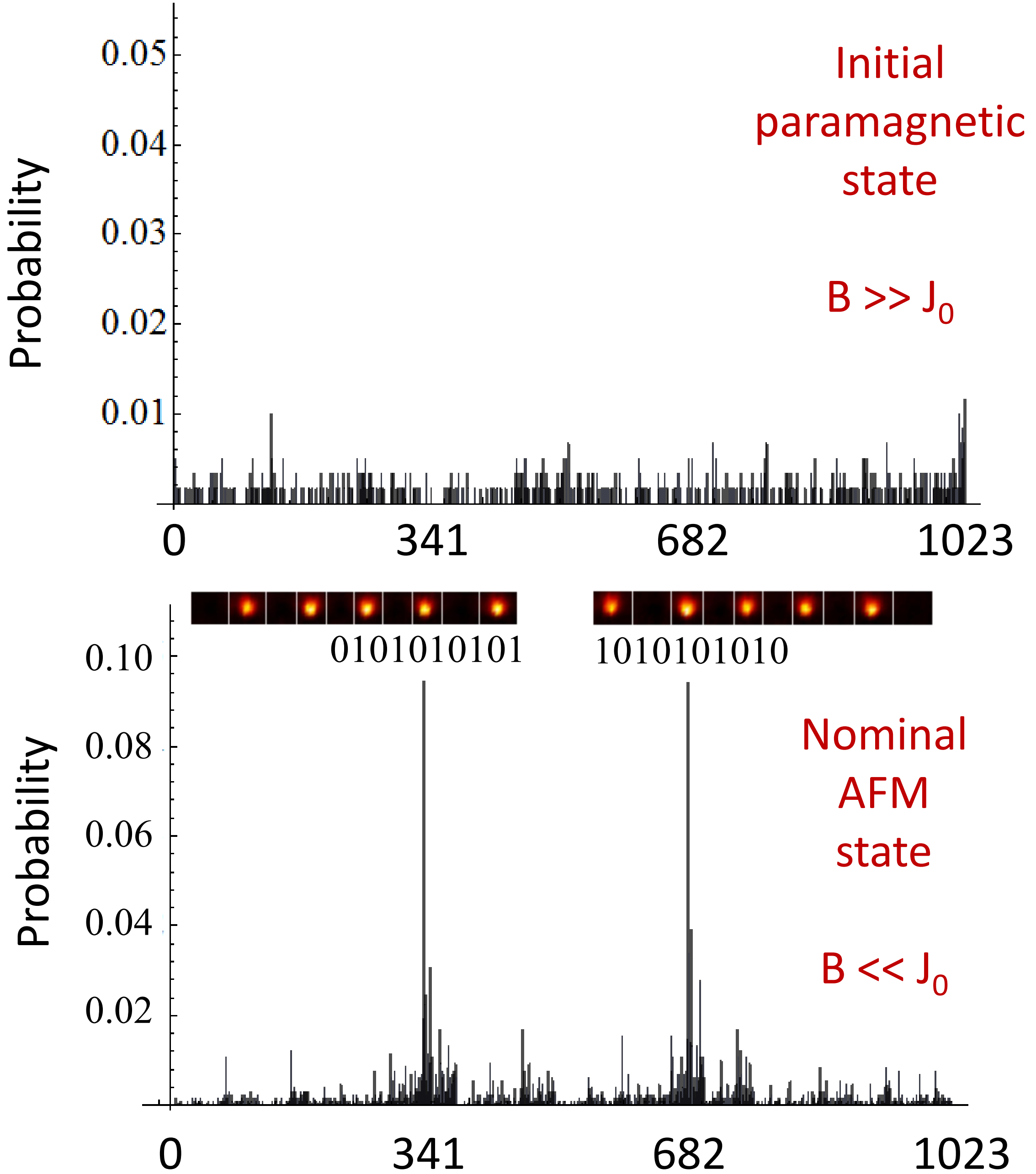


Second Excited States

(Pop. ~1% each)

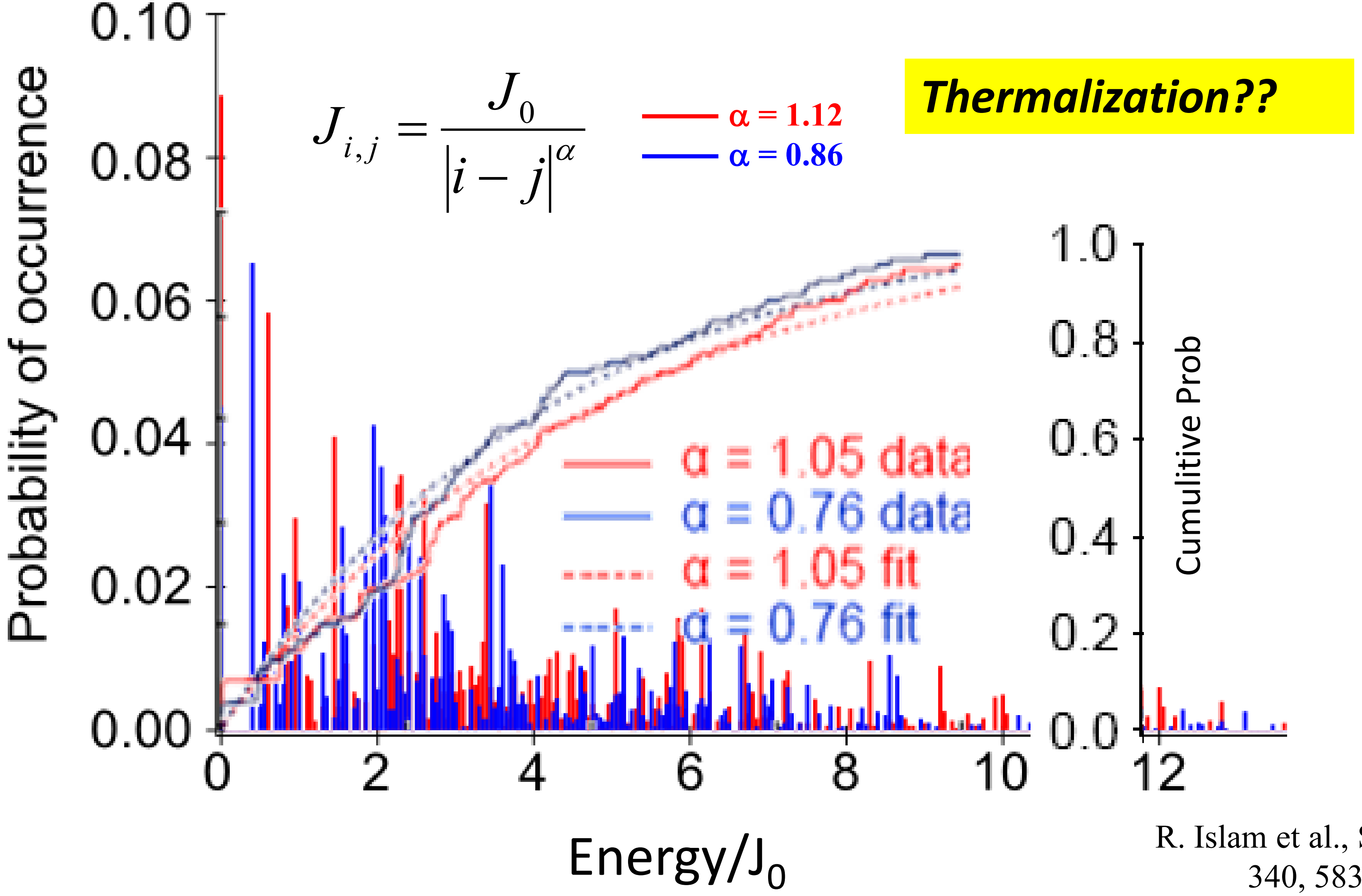


Distribution of all $2^{10} = 1024$ states



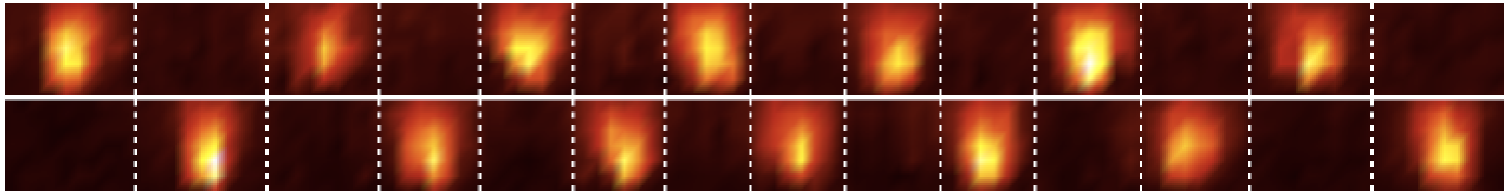
R. Islam et al., Science 340, 583 (2013)

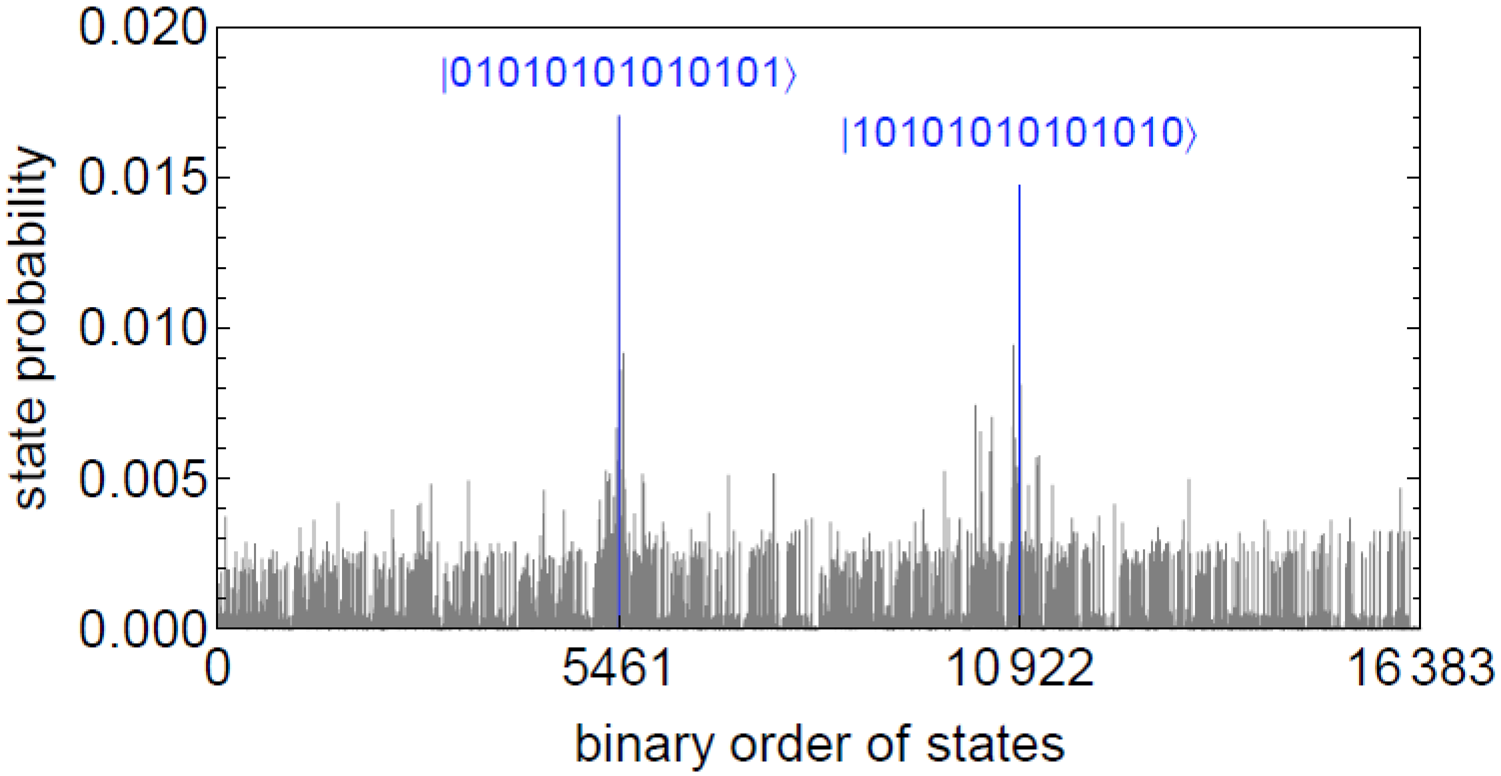
Distribution of states ordered by energy (N=10)



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

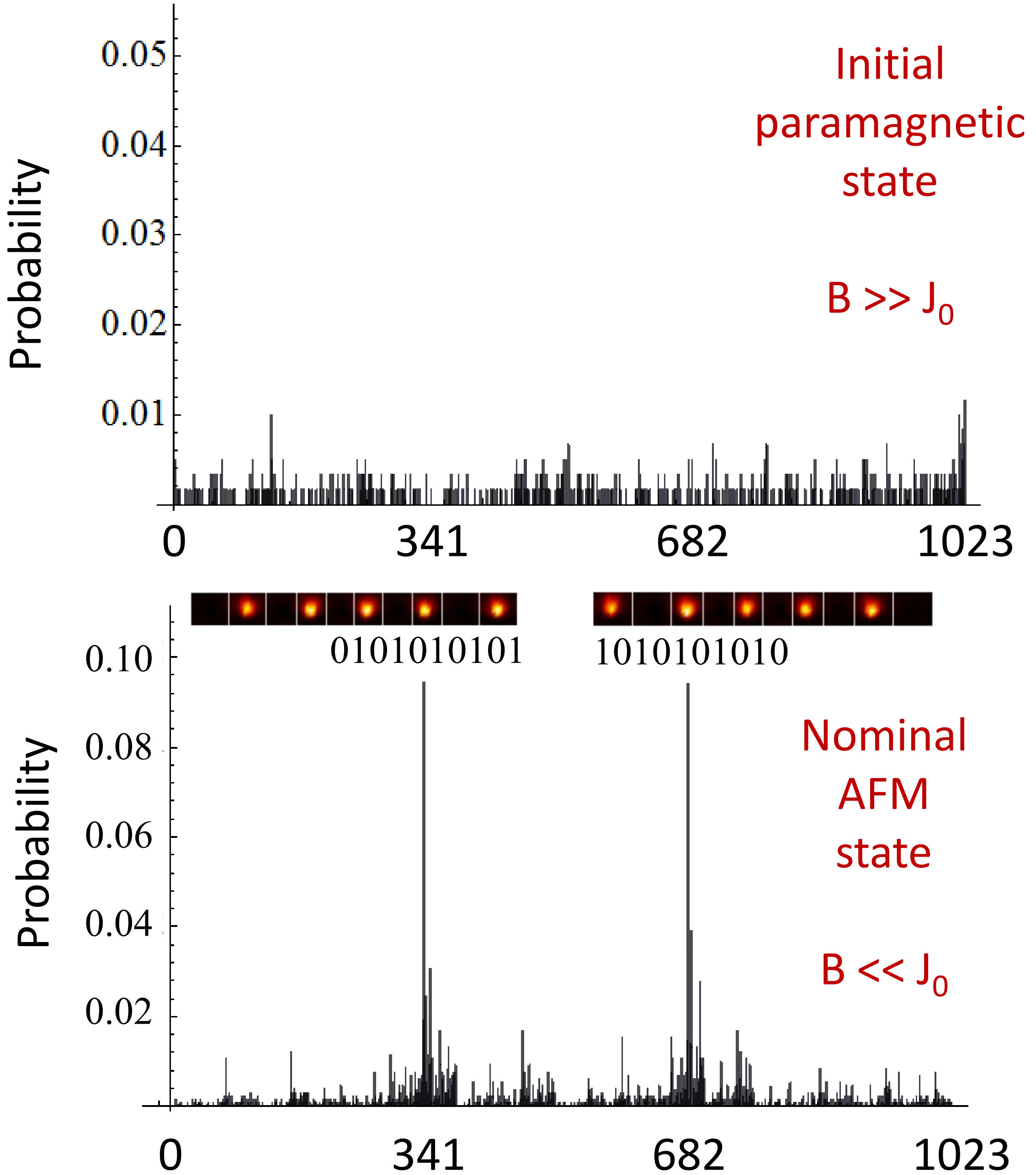
AFM order of N=14 qubits (16,384 configurations)





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

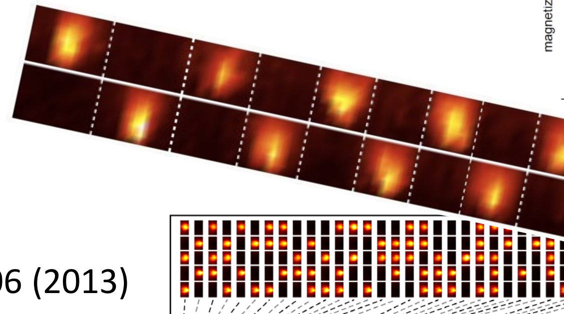
Distribution of all $2^{10} = 1024$ states

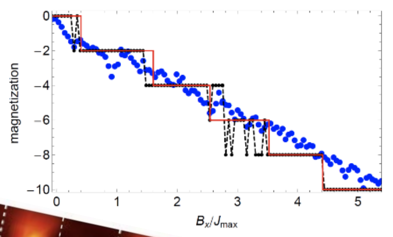


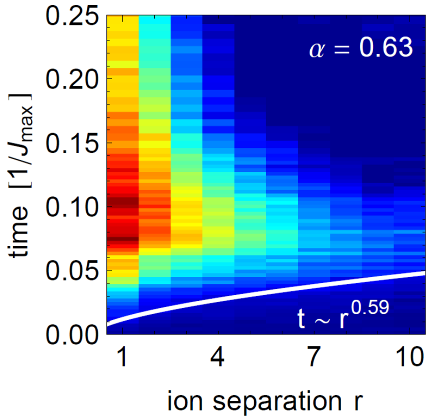
R. Islam et al., Science 340, 583 (2013)

Global Interaction Simulations

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



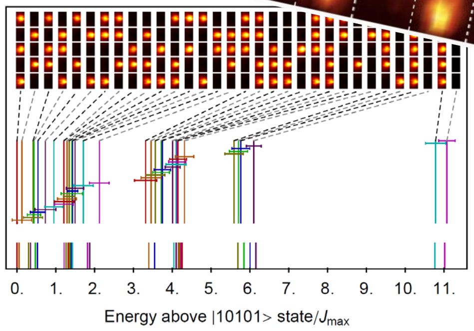


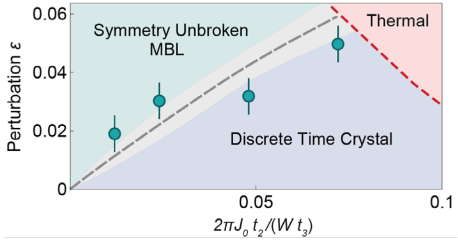


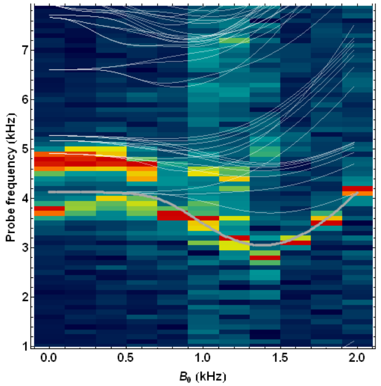
FM and AFM order, Devil's Staircase

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

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)

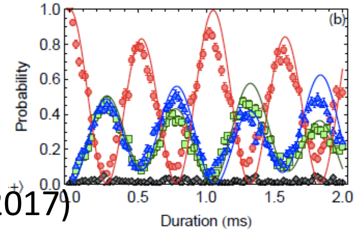
Many-Body Spectroscopy

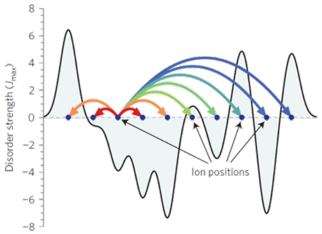
C. Senko et. al., *Science* **345**, 430 (2014)

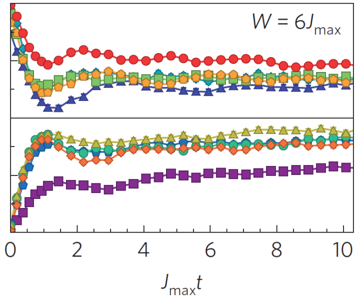
P. Jurcevic, et al., *Phys. Rev. Lett.* **115**, 100501 (2015)

Spin-1 Dynamics

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



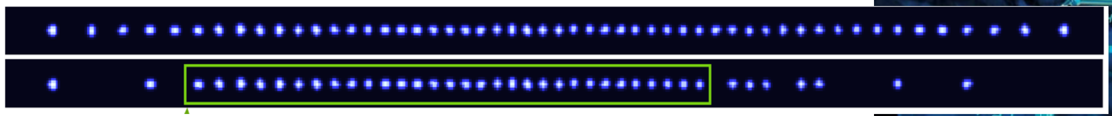




Quantum Prethermalization/Manybody Localization

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

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



Observation of a Time Crystal

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

A. Kyprianidis, et al., *Science* **372**, 1192 (2021)

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

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

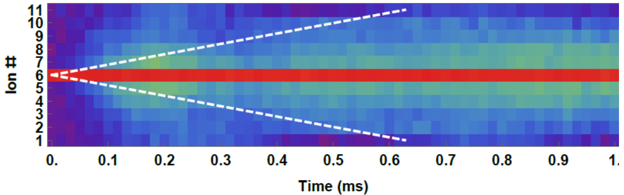
$H_3 = \sum_i D_i \sigma_i^x$ time t_3

Dynamical Phase Transition

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

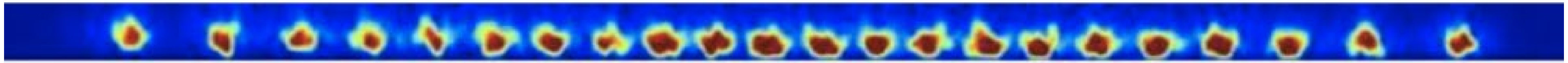
Simulation of Quasiparticle Confinement

F. Liu, et al., *PRL* 122, 150601 (2019); W. L. Tan, et al., *Nat. Phys.* 17, 742 (2021)

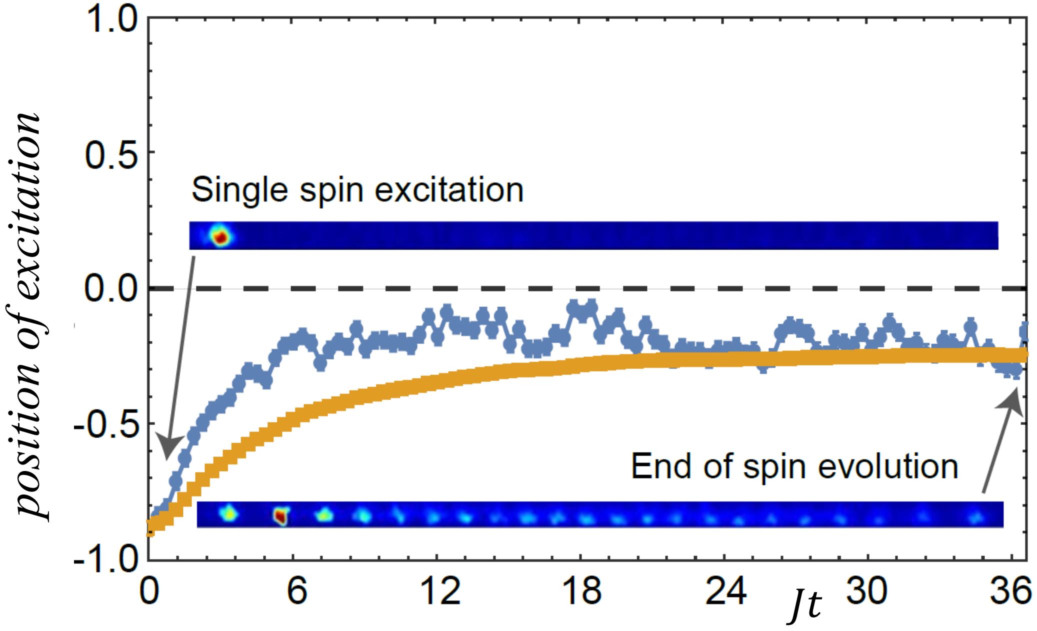


Pre-Thermalization

$$H_{XY} = \sum_{i<j} J_{ij}\left(\sigma_+^i \sigma_-^j + \sigma_-^i \sigma_+^j\right) \qquad J_{ij} = \frac{J}{|i-j|^{0.6}}$$

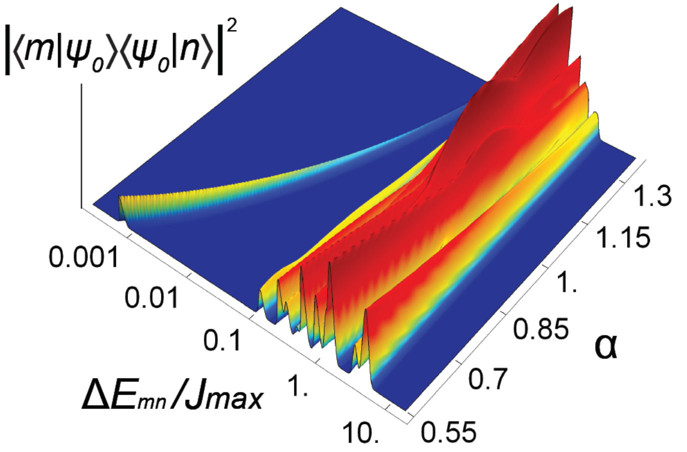


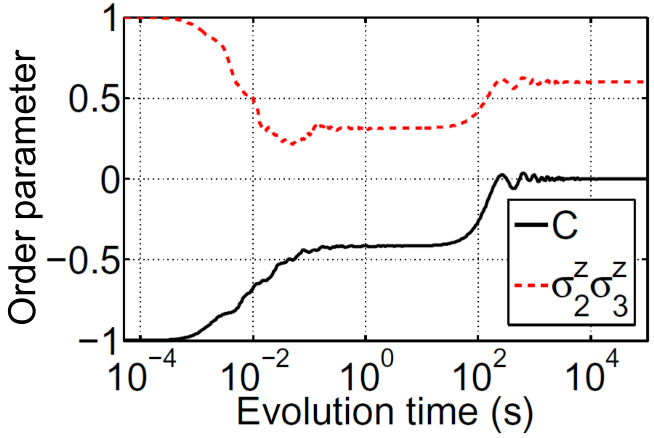
state measured at $Jt = 36$



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

Distribution of energy splitings

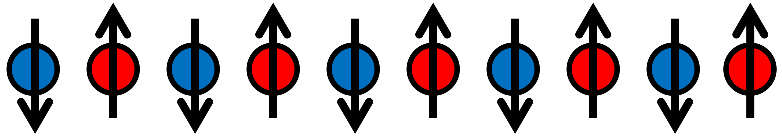




Z. Gong and L.-M. Duan, *NJP* **15,** 113051 (2013)

Many Body Localization (N=10)

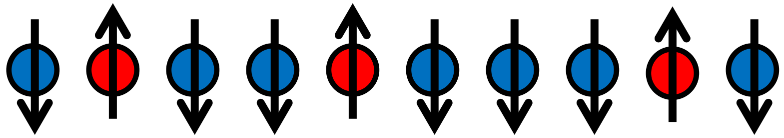
Step 1: Initialize spins staggered along z (“$kT=\infty$”)



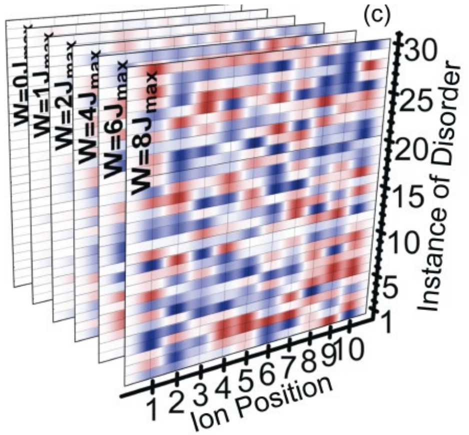
Step 2: Quench to transverse Ising model with random disorder

$$H_{MBL} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B\sum_i \sigma_z^i + \sum_i \tilde{B}_z^i\sigma_z^i \qquad \tilde{B}_z^i \in [-W, W]$$

Step 3: Measure each spin along z after time t



Step 4: Repeat for many different disorder instances and strengths



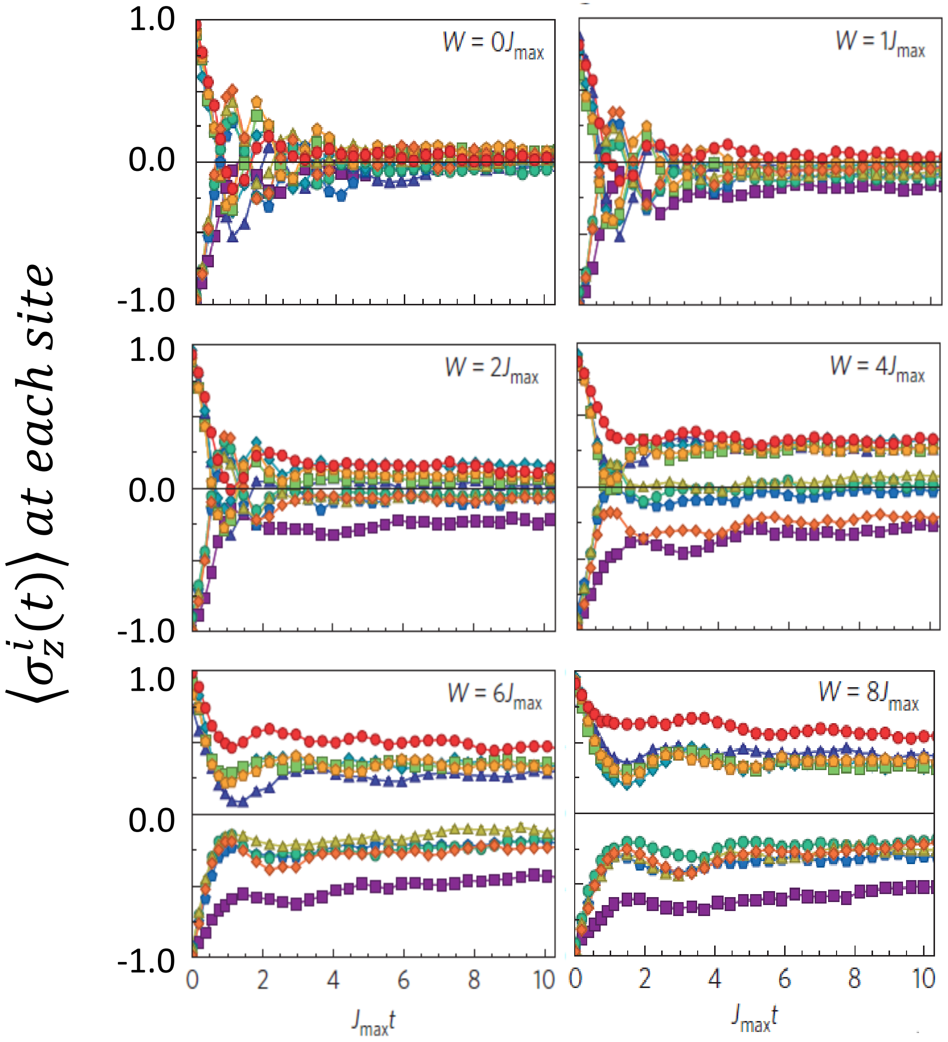
J. Smith et al., Nature Physics 12, 907 (2016)

Many body localization
N=10 spins

$$H_{MBL} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B\sum_i \sigma_z^i + \sum_i \tilde{B}_z^i\sigma_z^i$$

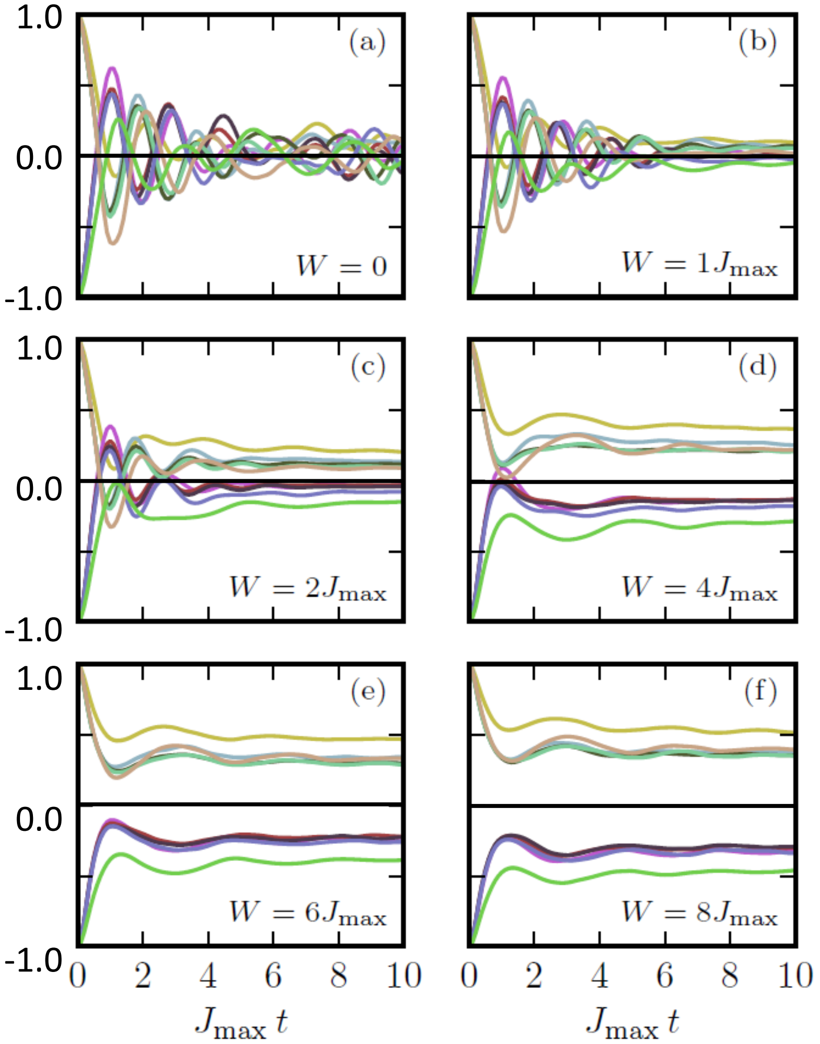
Experiment

J. Smith et al., Nat. Phys. 12, 907 (2016)



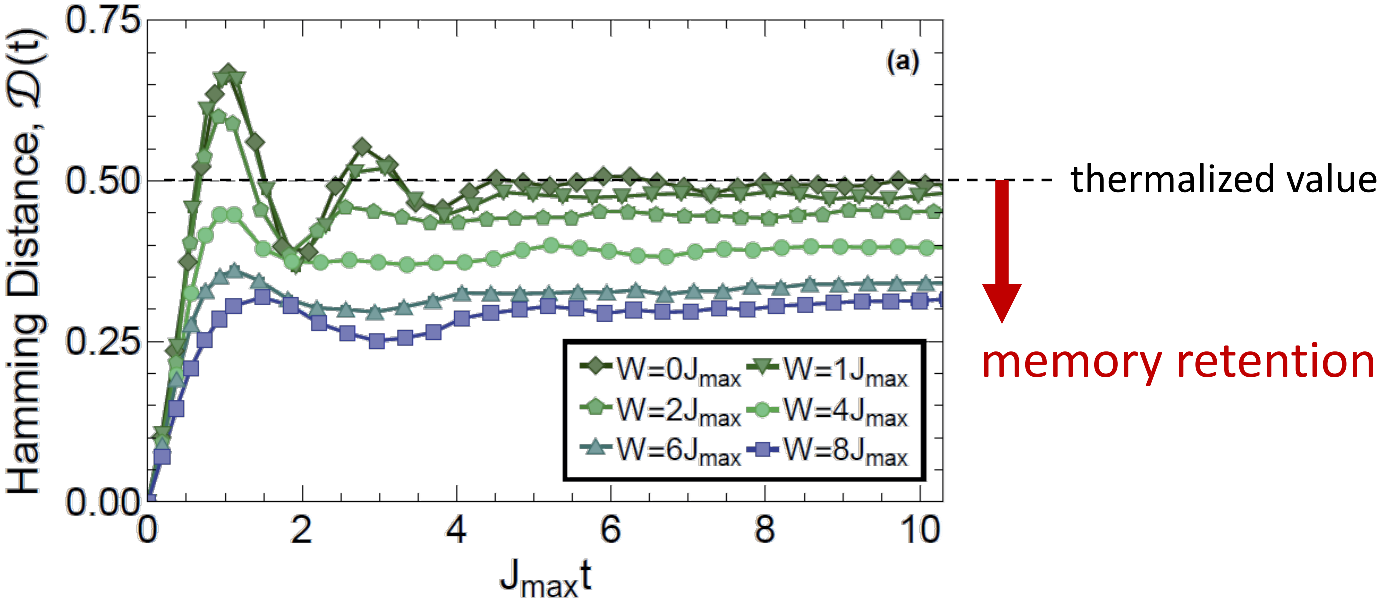
Theory

Y-L Wu and S. Das Sarma, PRA 93, 022332 (2016)



Hamming distance from initial state:

$$\mathcal{D}(t) = \frac{1}{2} - \frac{1}{2N} \sum_i \langle \psi_0 | \, \sigma_i^z(t) \sigma_i^z(0) \, | \psi_0 \rangle$$



J. Smith et al., Nature Physics 12, 907 (2016)

Exotic Magnetism

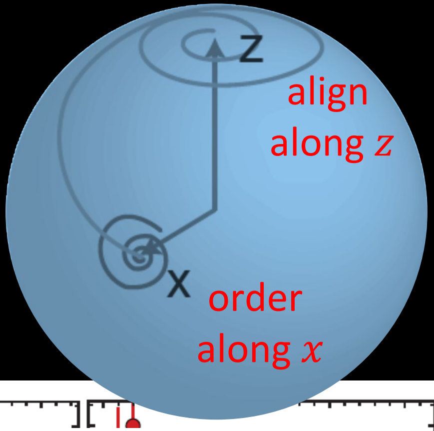
Dynamical Phase Transition with 50+ Qubits

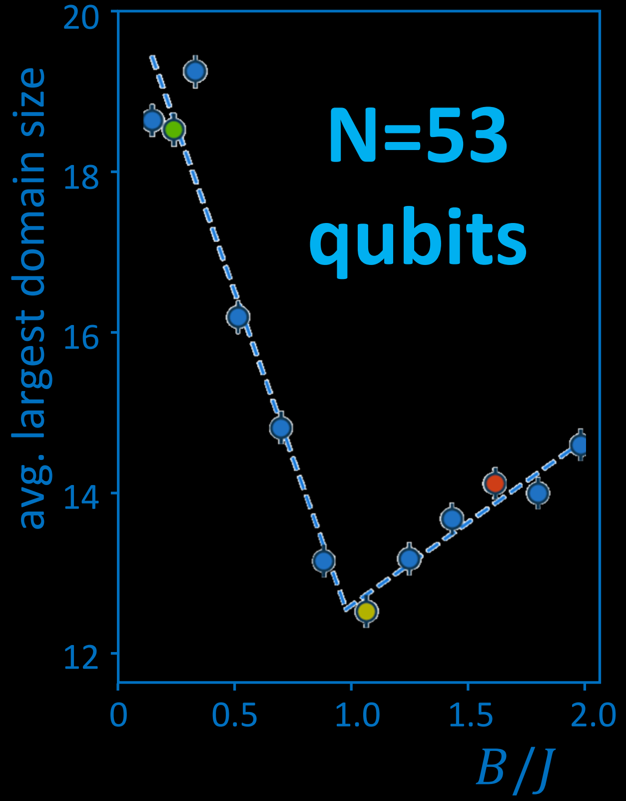
J. Zhang, et al., Nature 551, 601 (2017)

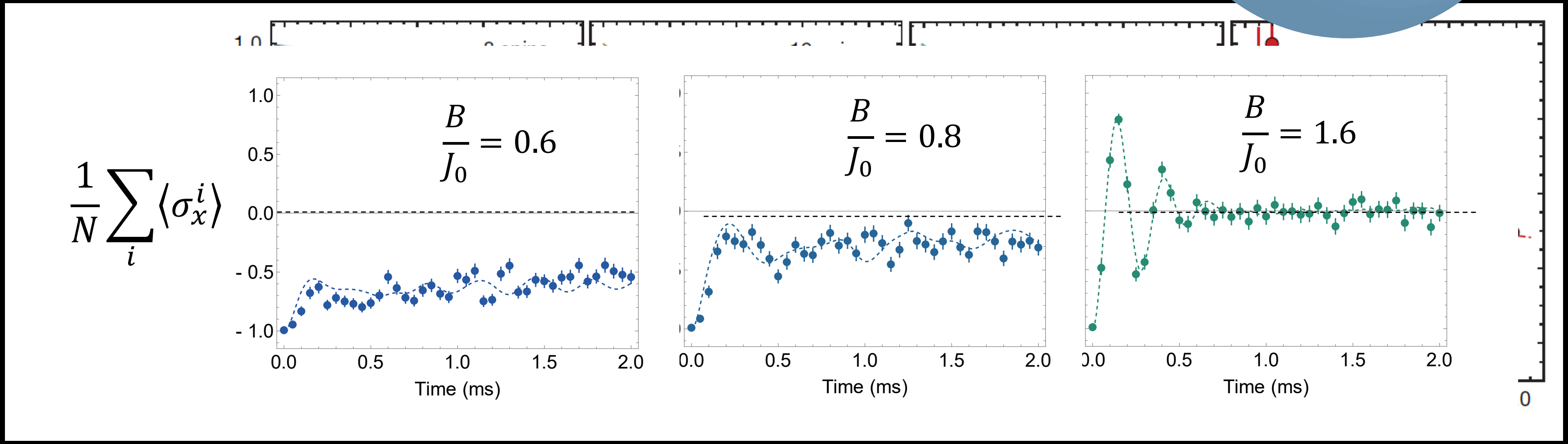
(1) Prepare spins along x

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

(3) Measure along x





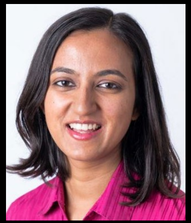


Recent Quantum Simulations

Asymptotic confinement: W. L. Tan, et al., Nature Physics (2021)
Prethermal Time Crystal: A. Kyprianidis, et al., arXiv:2102.01695 (2021)
Stark Manybody Localization: W. Morong, et al., arXiv:2102.07250 (2021)
Measurement-induced phase transition: C. Noel, et al., in preparation (2021)


Alexey Gorshkov (NIST/JQI)


David Huse (Princeton)

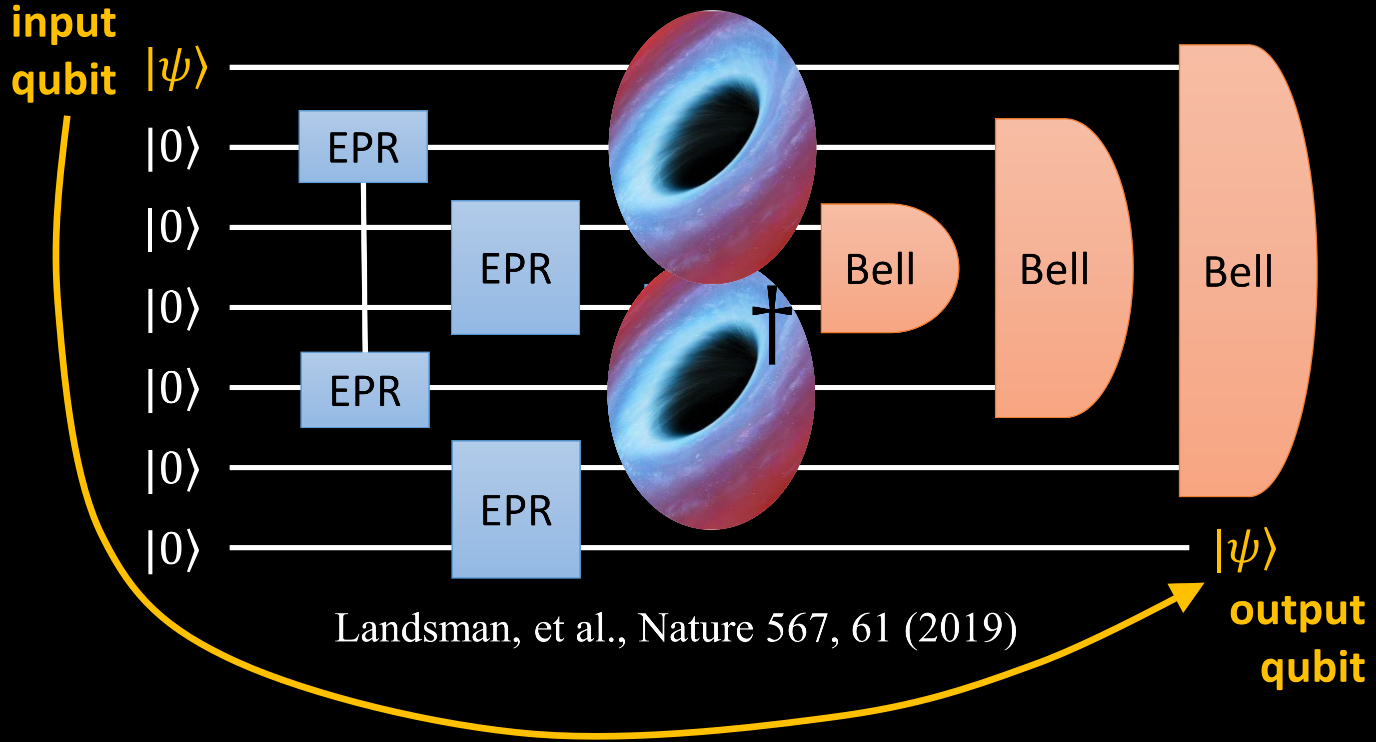

Sonika Johri (Intel/IonQ)


Norm Yao (Berkeley)

Cosmology + Quantum Gravity
Quantum Scrambling

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

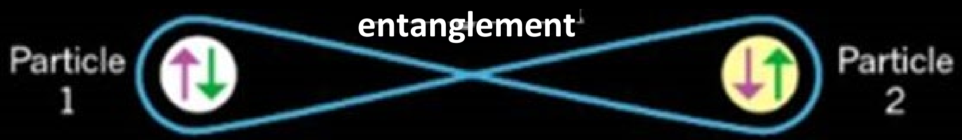
Scrambling: "complete diffusion" of quantum information, relevant to information evolution in black holes



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 Error Correction

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

error prob. p

error prob. p (<u>per qubit</u>)

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

$$\boxed{p \Longrightarrow Cp^2}$$

Quantum Error Correction

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

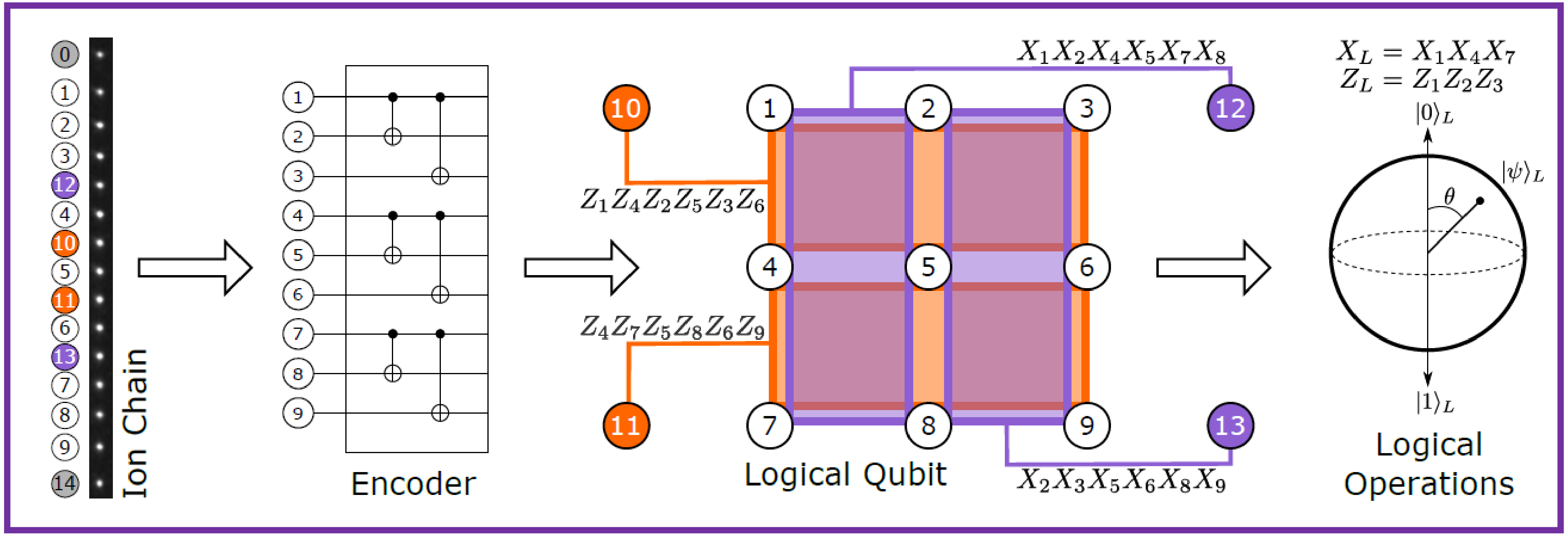
Bacon-Shor 13:1 Fault-Tolerant Error Correction

Ken Brown
(Duke)

Bacon-Shor [[9,1,3]] Subsystem Code
- Can correct any single qubit error (Distance-3)
- Fault tolerant encoding, gates, stabilizer readout, and measurement

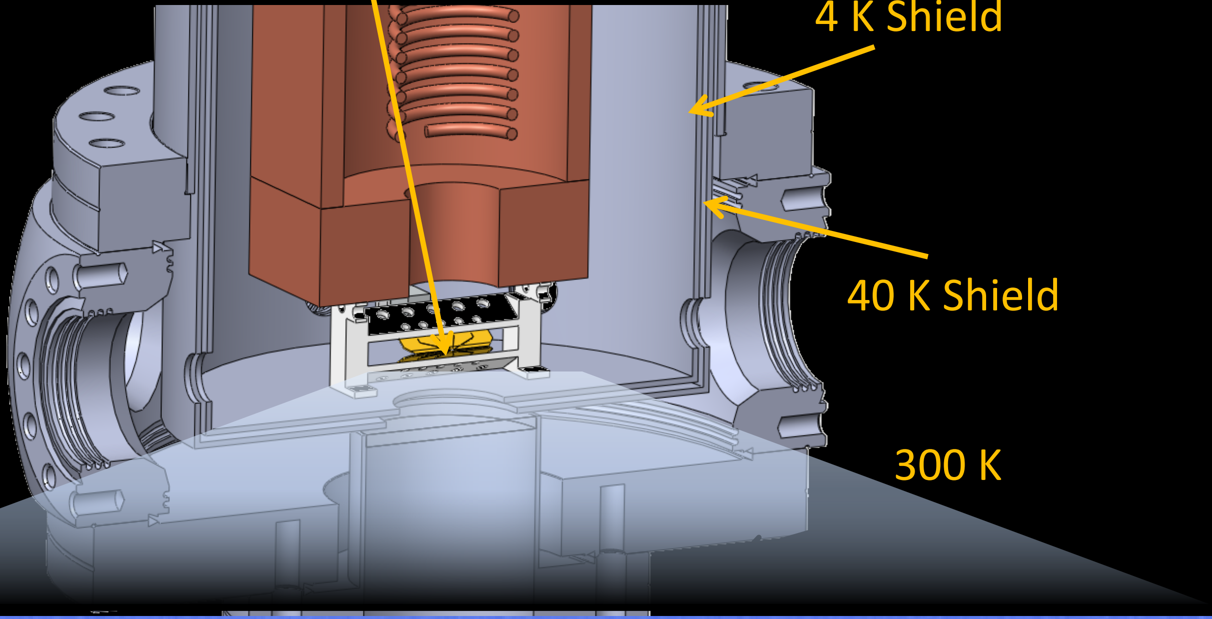
4 Weight-6 Stabilizers
- $Z_1Z_4Z_2Z_5Z_3Z_6$
- $Z_4Z_7Z_5Z_8Z_6Z_9$
- $X_1X_2X_4X_5X_7X_8$
- $X_2X_3X_5X_6X_8X_9$

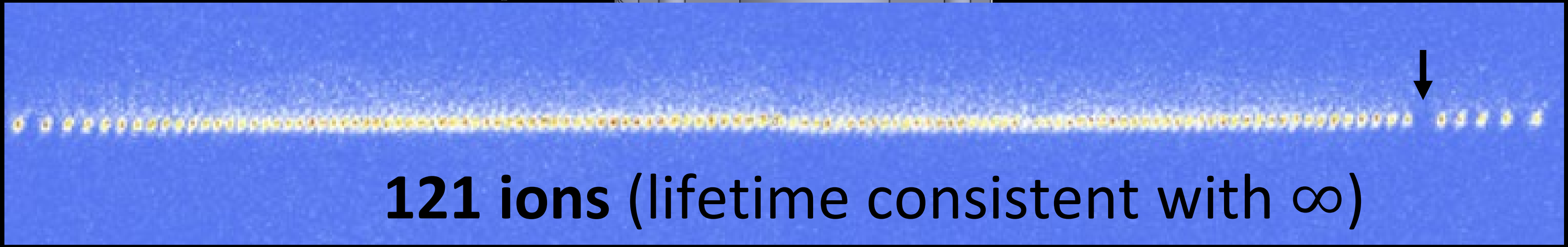
On a 15 ion chain
- 9 Data qubits
- 4 Ancilla qubits
- 2 idle qubits

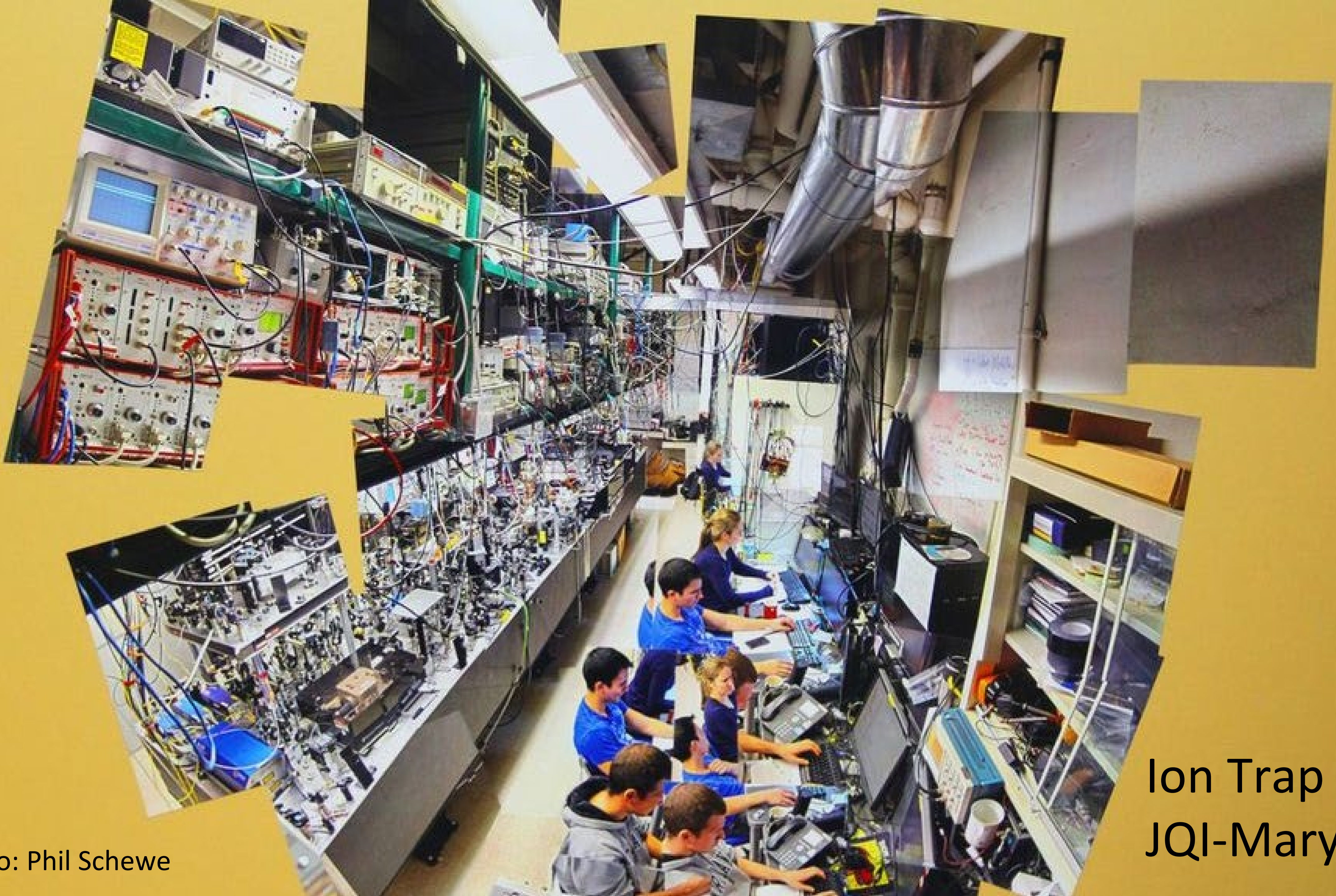


L. Egan, et al., arXiv 2009.11482 (2020)

Scaling Up: 4K environment (better vacuum!)

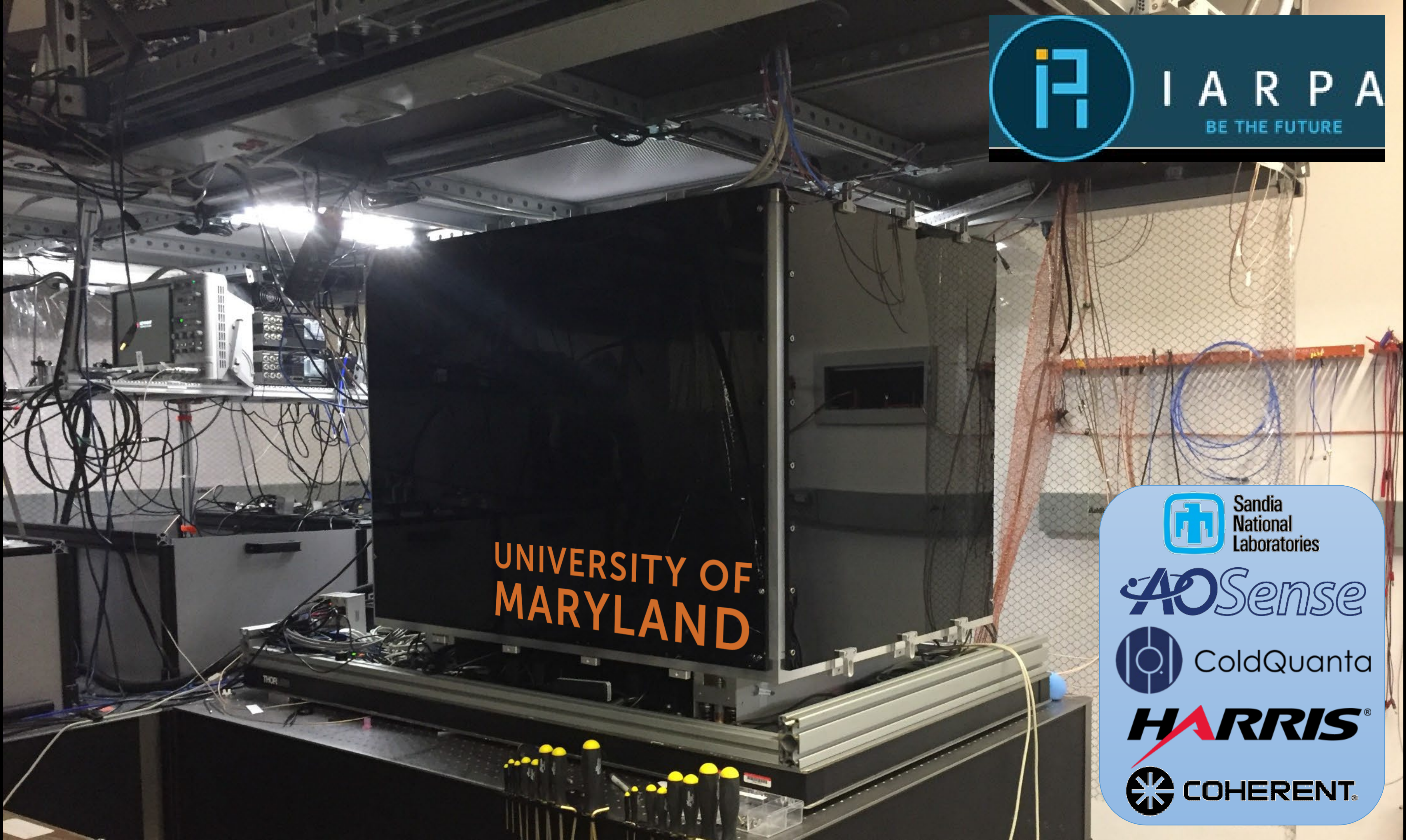




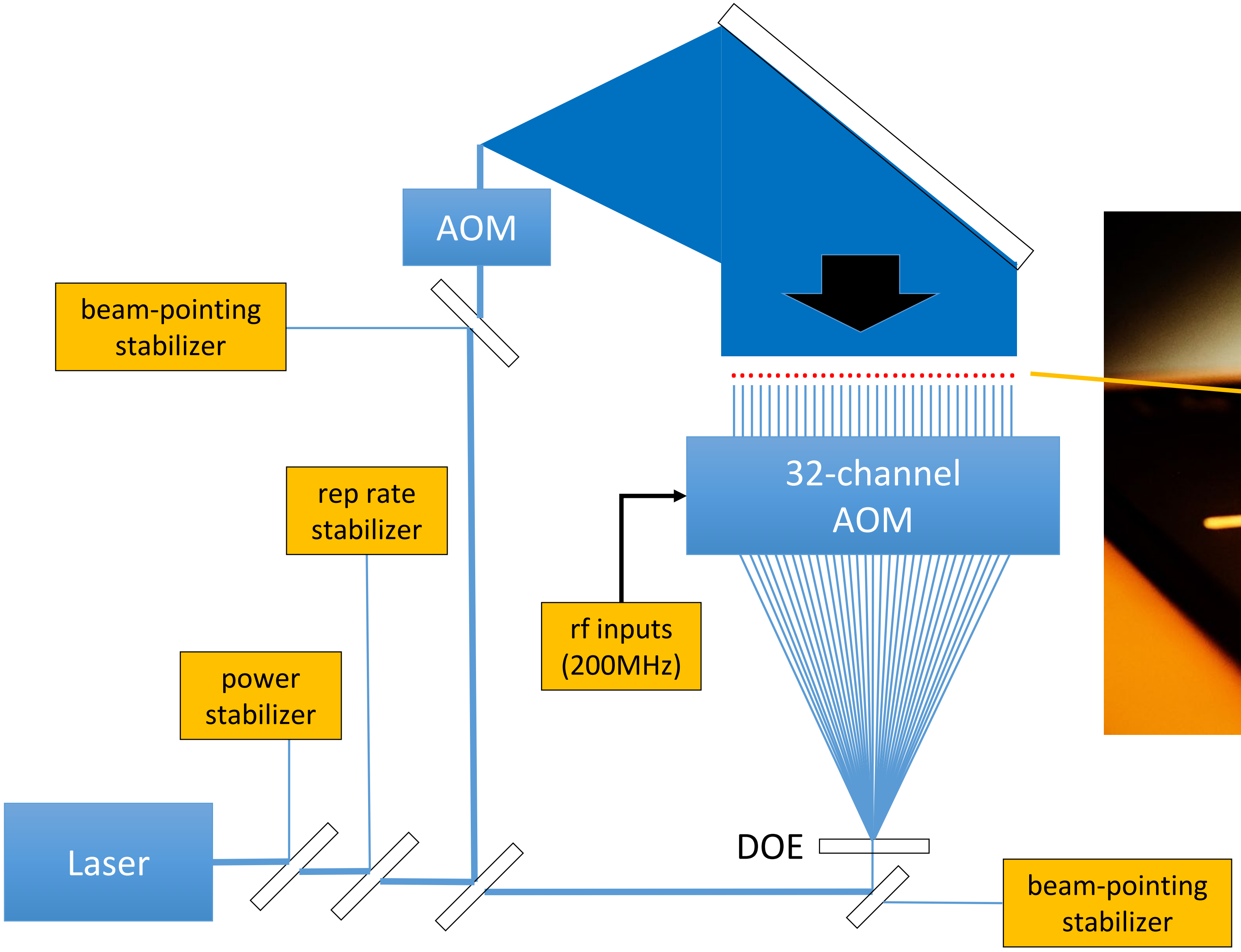


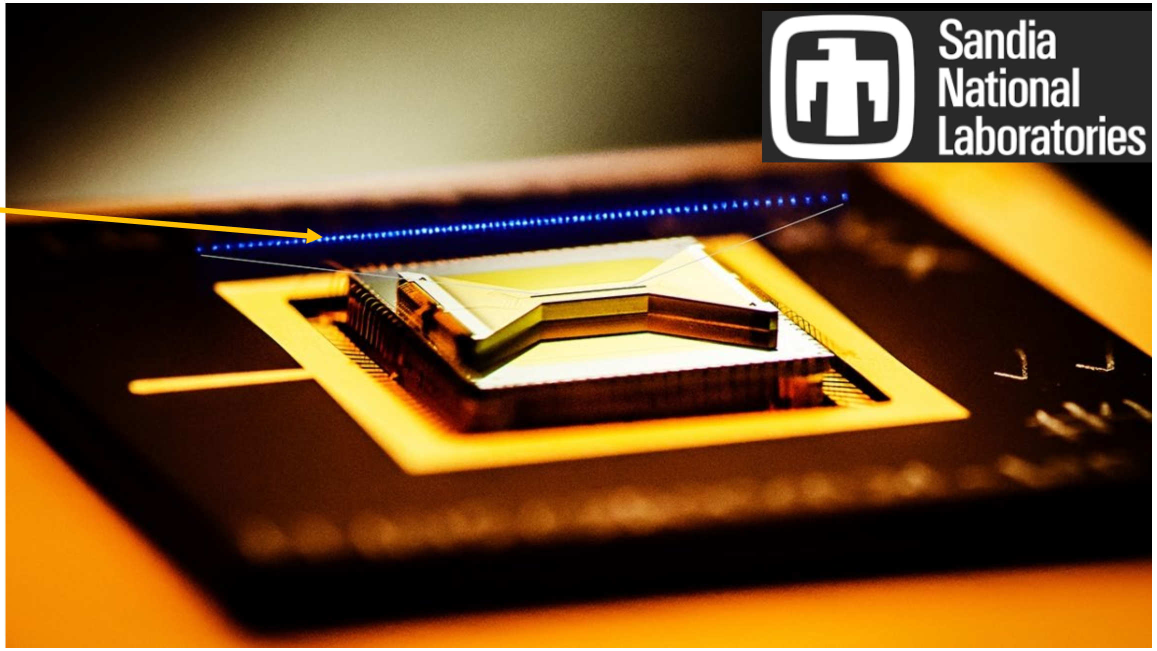
Ion Trap Lab at JQI-Maryland

Photo: Phil Schewe


IARPA
BE THE FUTURE
UNIVERSITY OF MARYLAND
Sandia National Laboratories
AOSense
ColdQuanta
HARRIS
COHERENT

Quantum Computer Optical Controller






Newport
RS 4000™
Sealed Hole Table Top with Tuned Damping
IONQ
System 1


System 3
System 2
IONQ

IonQ Systems on the cloud

PICTURED: IONQ'S NEXT-GEN SYSTEM

IONQ benchmark algorithms

Bernstein-Vazirani 'oracle' algorithm

Given $f(x) = \boldsymbol{c} \cdot \boldsymbol{x}$

Find n-bit string c

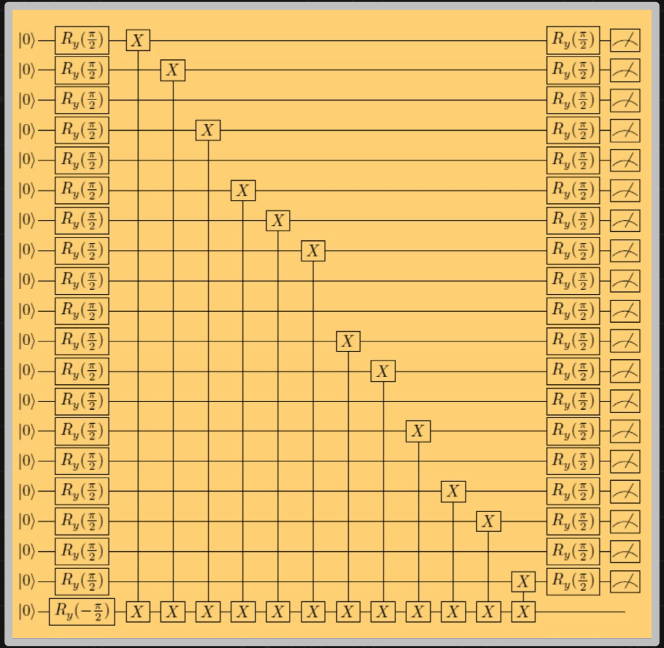
Classical

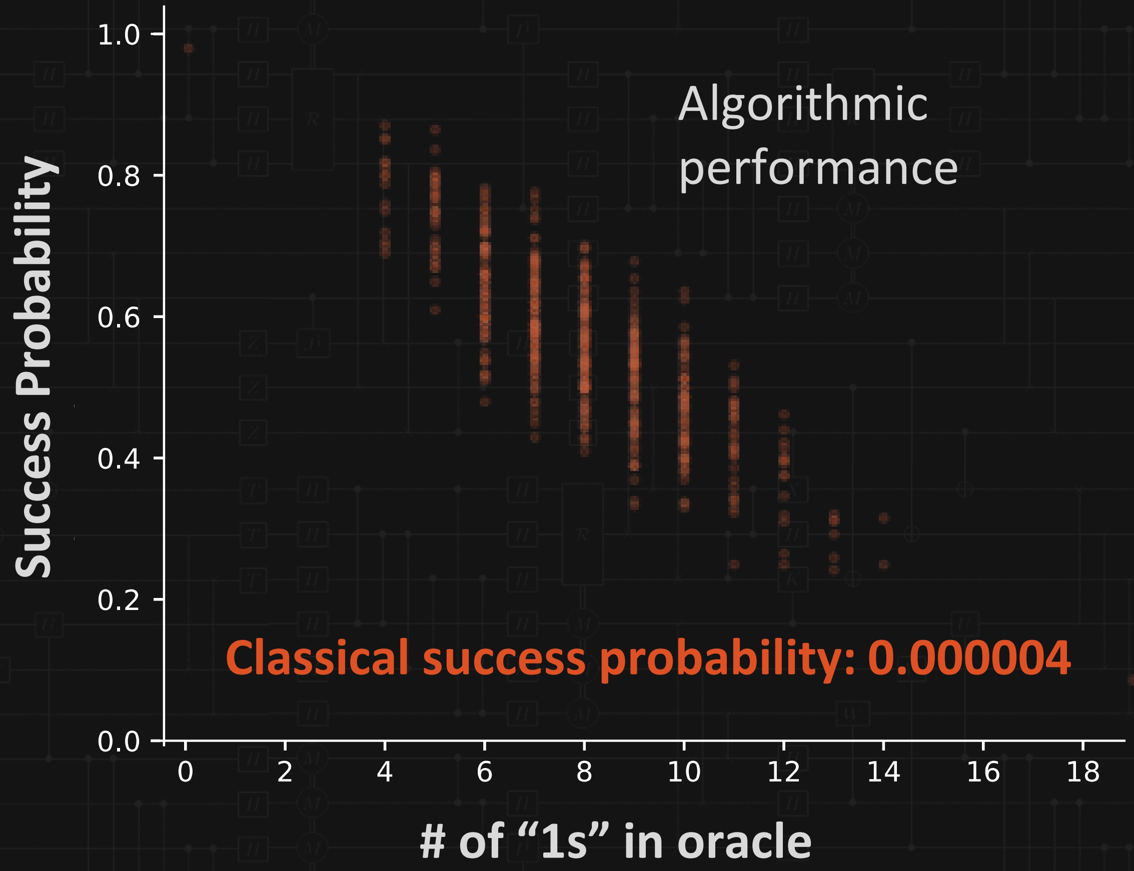
requires n queries

Quantum

requires only 1 query

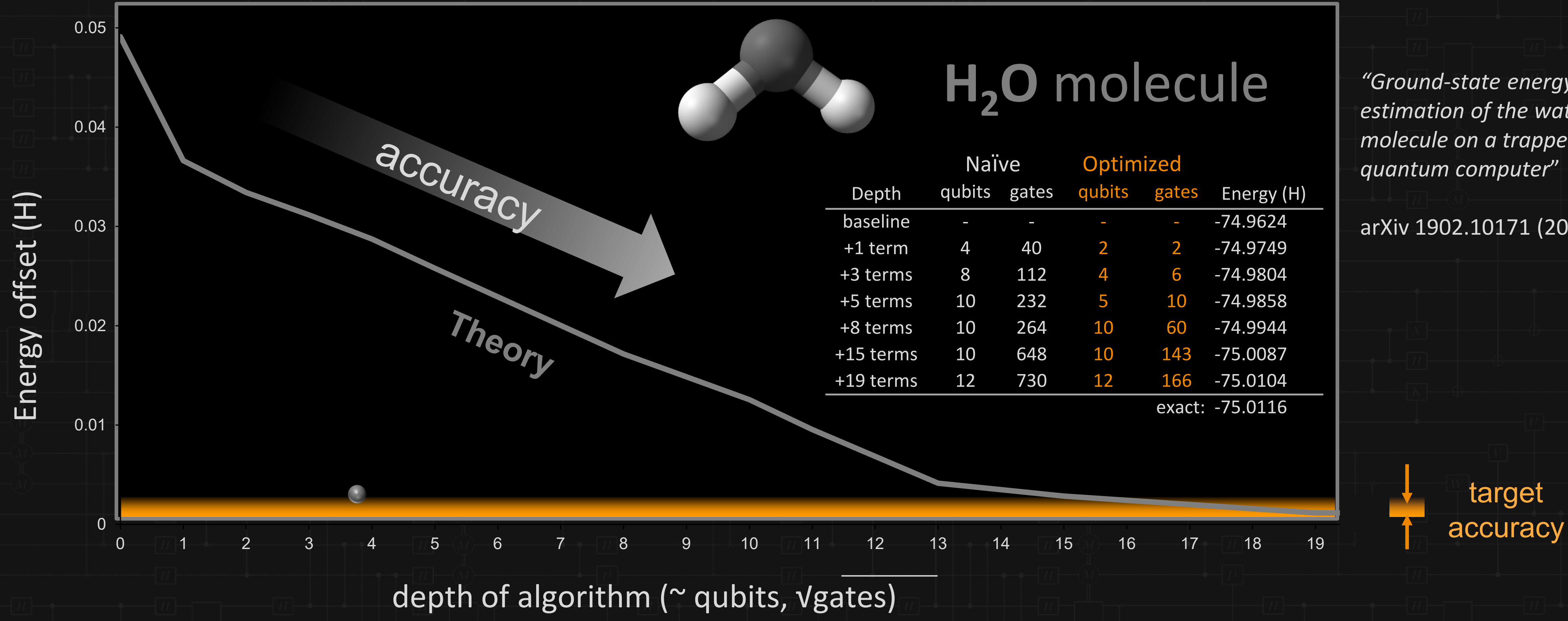
example circuit: c = 1101011100110101101





"Benchmarking an 11-qubit quantum computer," Nature Comm. **10**, 5464 (2019)

IONQ molecular quantum simulation

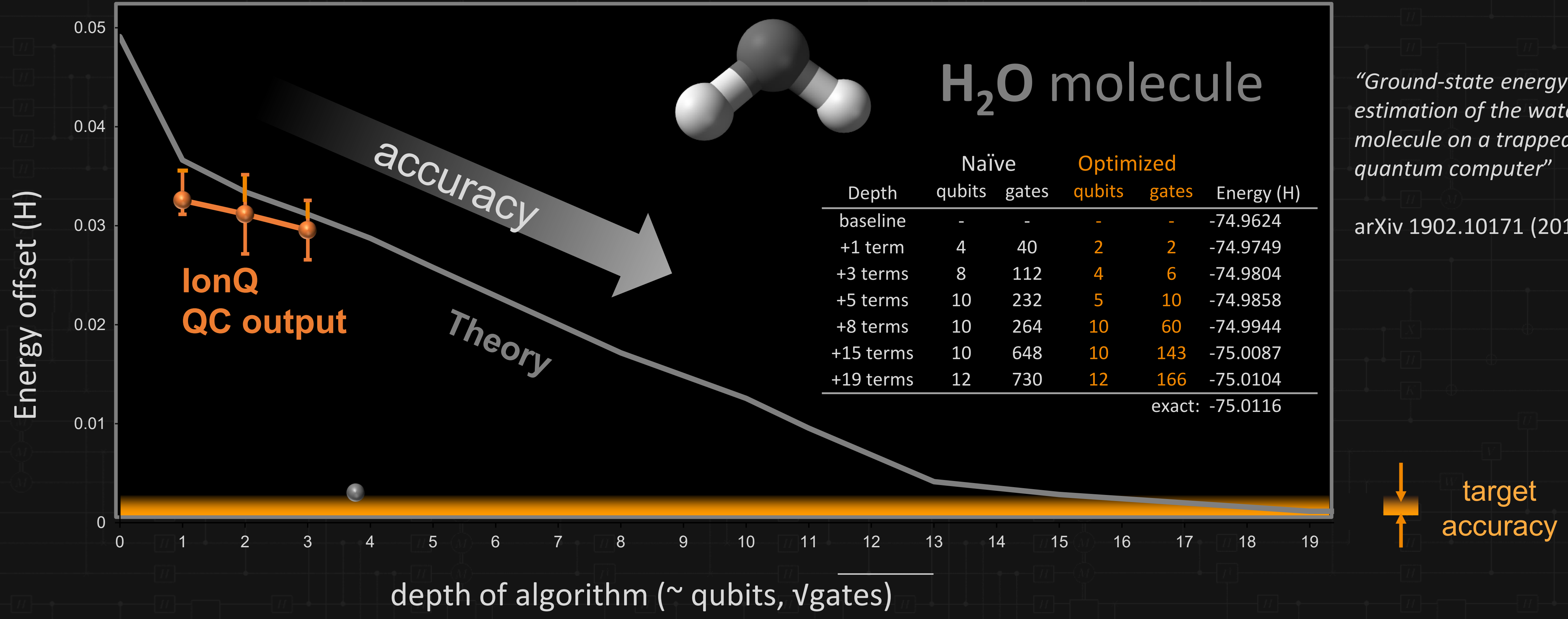


Depth	Naïve qubits	Naïve gates	Optimized qubits	Optimized gates	Energy (H)
baseline	-	-	-	-	-74.9624
+1 term	4	40	2	2	-74.9749
+3 terms	8	112	4	6	-74.9804
+5 terms	10	232	5	10	-74.9858
+8 terms	10	264	10	60	-74.9944
+15 terms	10	648	10	143	-75.0087
+19 terms	12	730	12	166	-75.0104
				exact:	-75.0116

"Ground-state energy estimation of the water molecule on a trapped ion quantum computer"

arXiv 1902.10171 (2019)

IONQ molecular quantum simulation



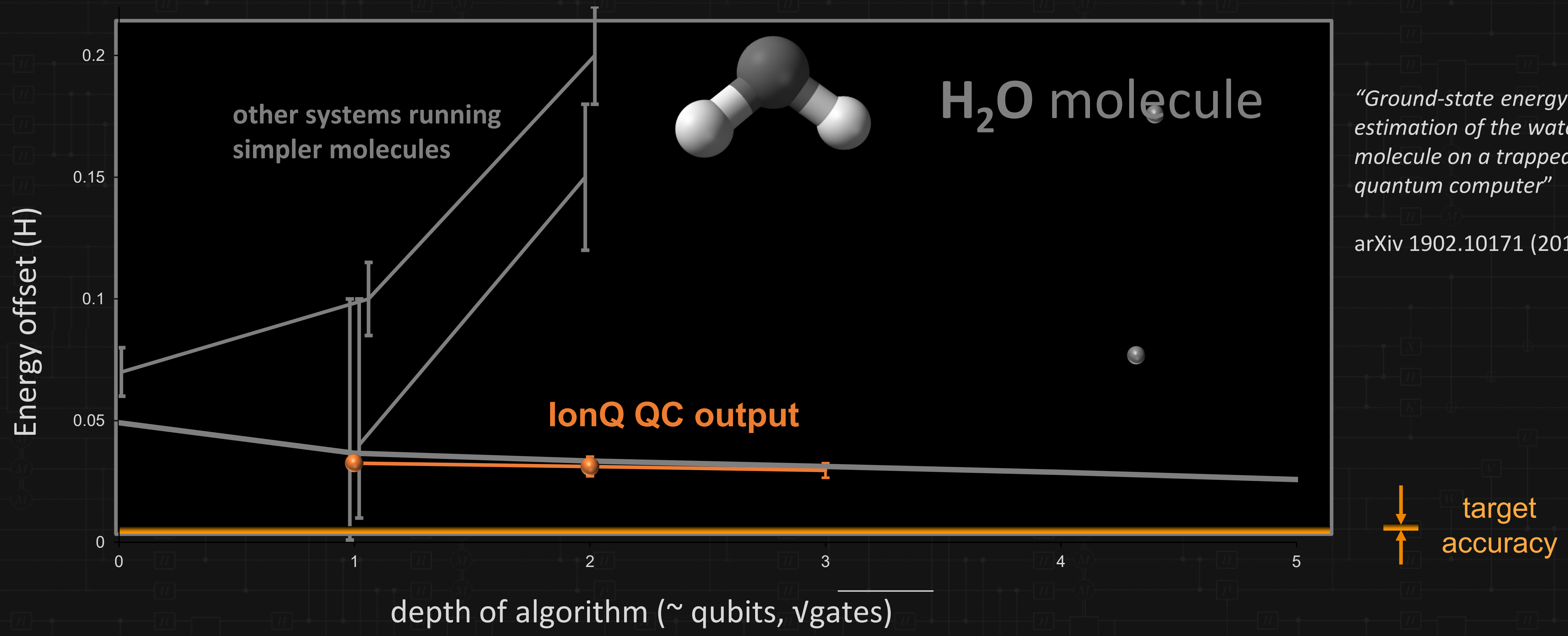
H_2O molecule

Depth	Naïve qubits	Naïve gates	Optimized qubits	Optimized gates	Energy (H)
baseline	-	-	-	-	-74.9624
+1 term	4	40	2	2	-74.9749
+3 terms	8	112	4	6	-74.9804
+5 terms	10	232	5	10	-74.9858
+8 terms	10	264	10	60	-74.9944
+15 terms	10	648	10	143	-75.0087
+19 terms	12	730	12	166	-75.0104
				exact:	-75.0116

"Ground-state energy estimation of the water molecule on a trapped ion quantum computer"

arXiv 1902.10171 (2019)

IONQ molecular quantum simulation

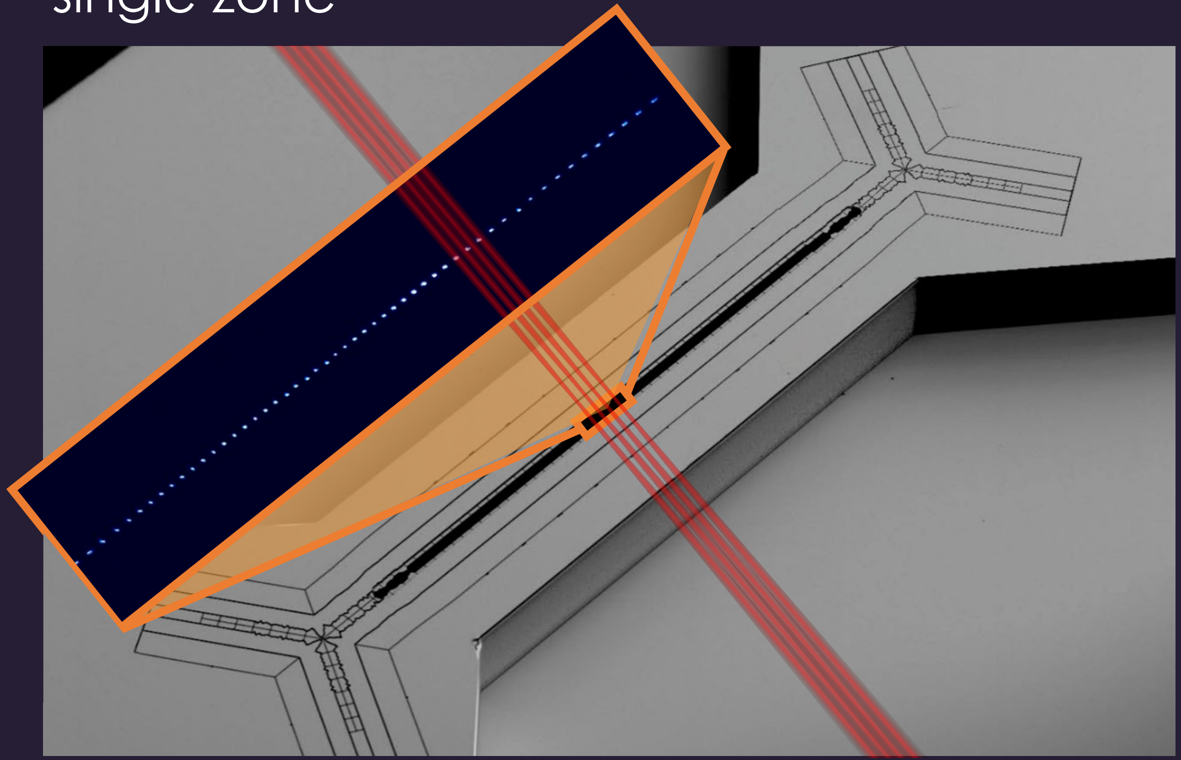


"Ground-state energy estimation of the water molecule on a trapped ion quantum computer"

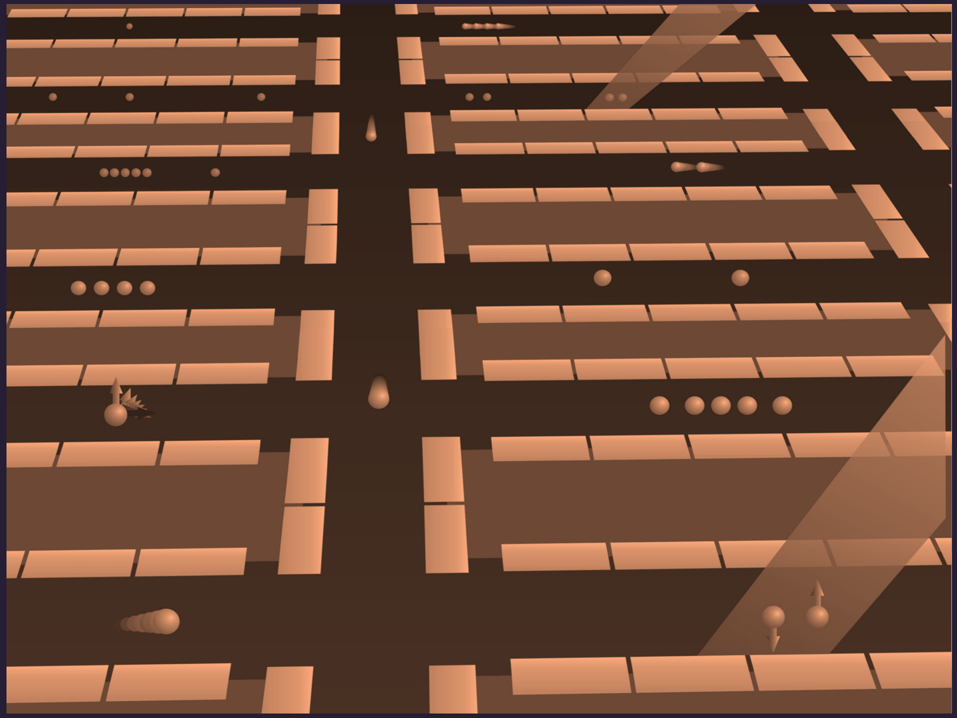
arXiv 1902.10171 (2019)

Quantum Computer Scaling >100 qubits

Linear shuttling through single zone



Shuttling between multiple zones



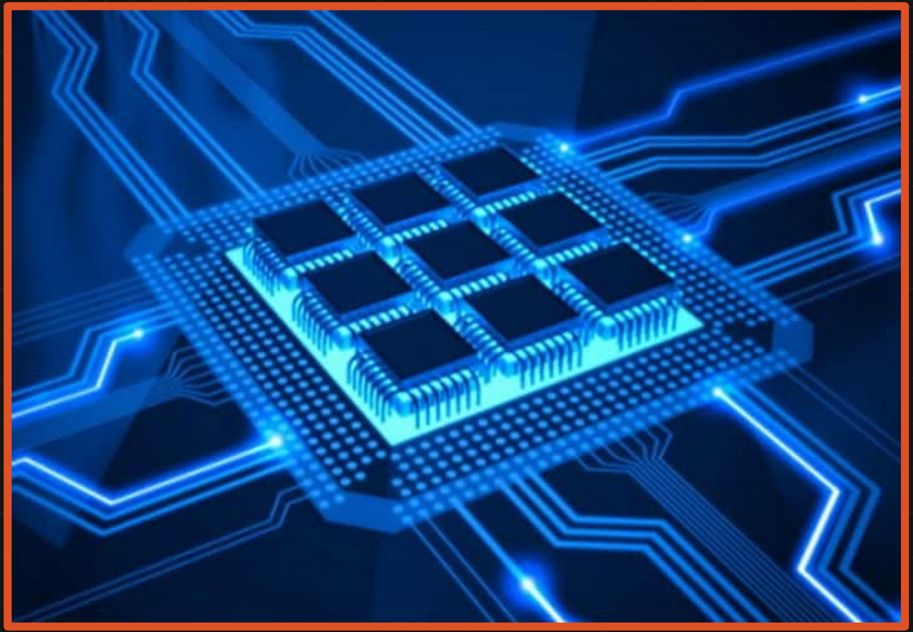
NIST-Boulder
Univ. Mainz

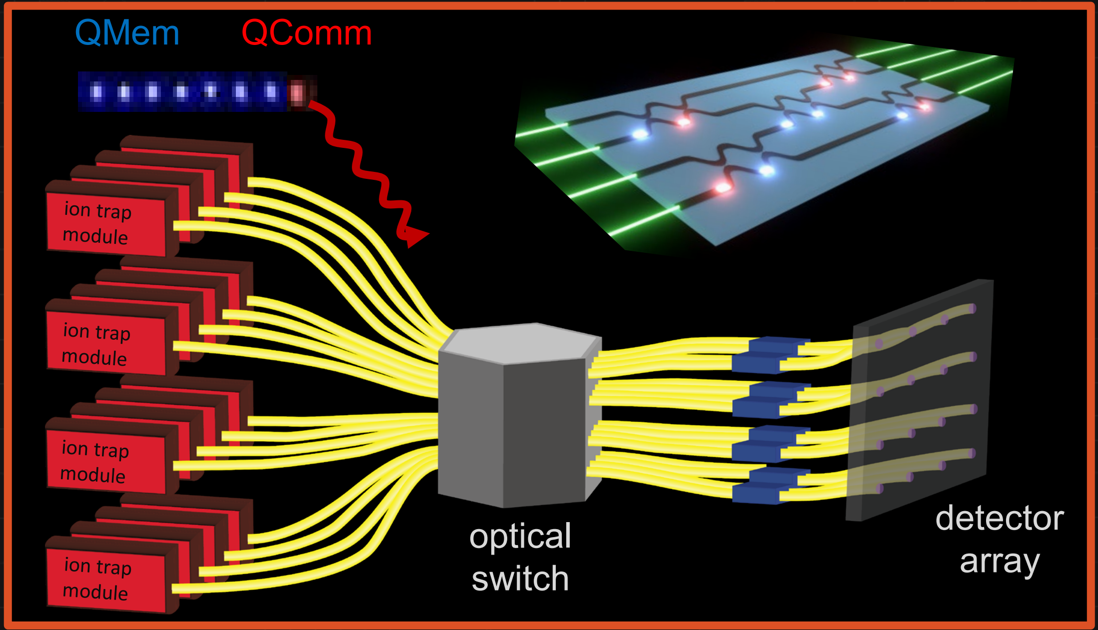
Nature 417, 709 (2002)
Science Advances 3, e1601540 (2017)

Quantum Computer Scaling >1000 qubits

Plan: Multicore quantum processing

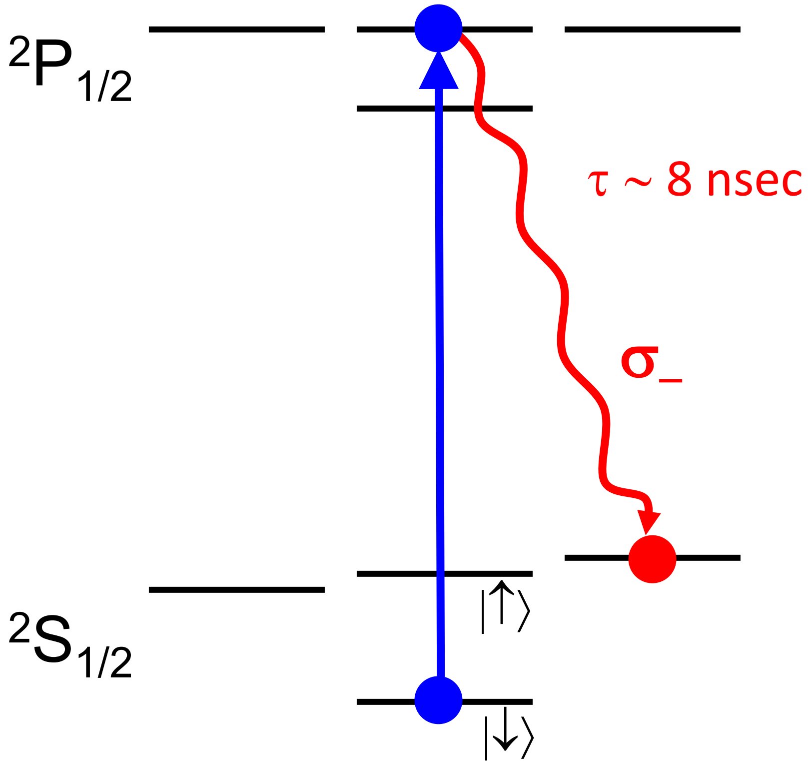
Technology: Integrated photonics and switches, SNSPD detector array





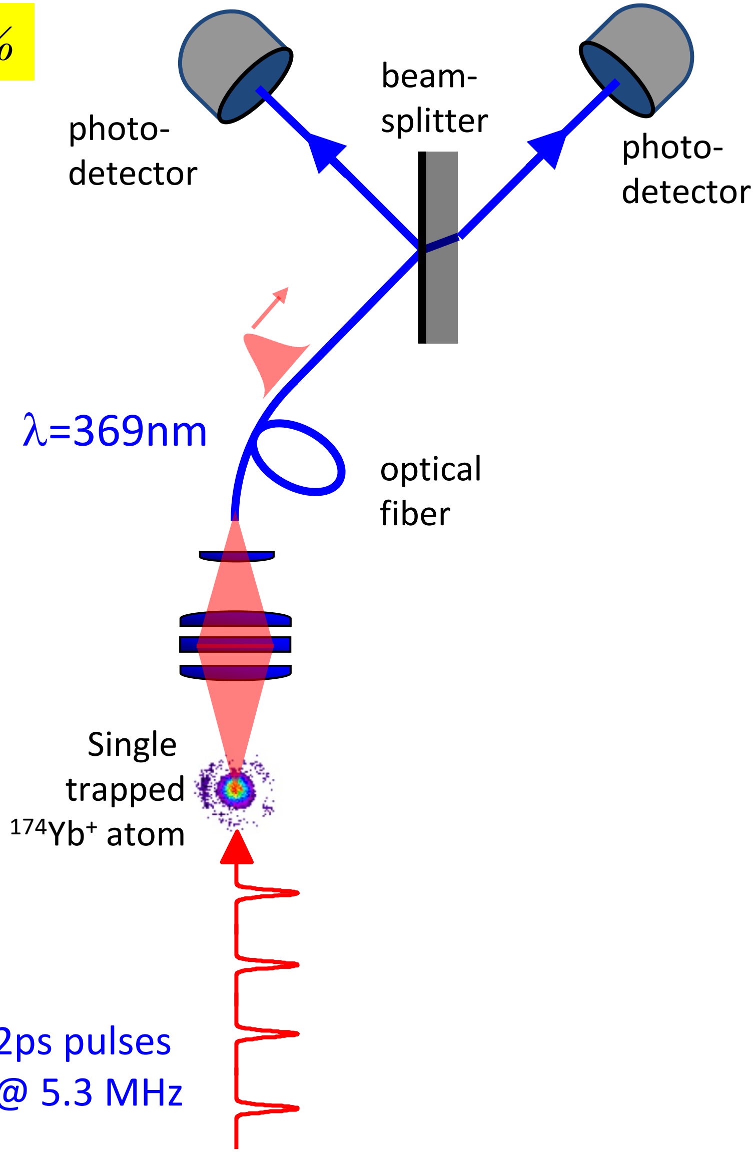
Making single photons

$^{171}Yb^{+}$

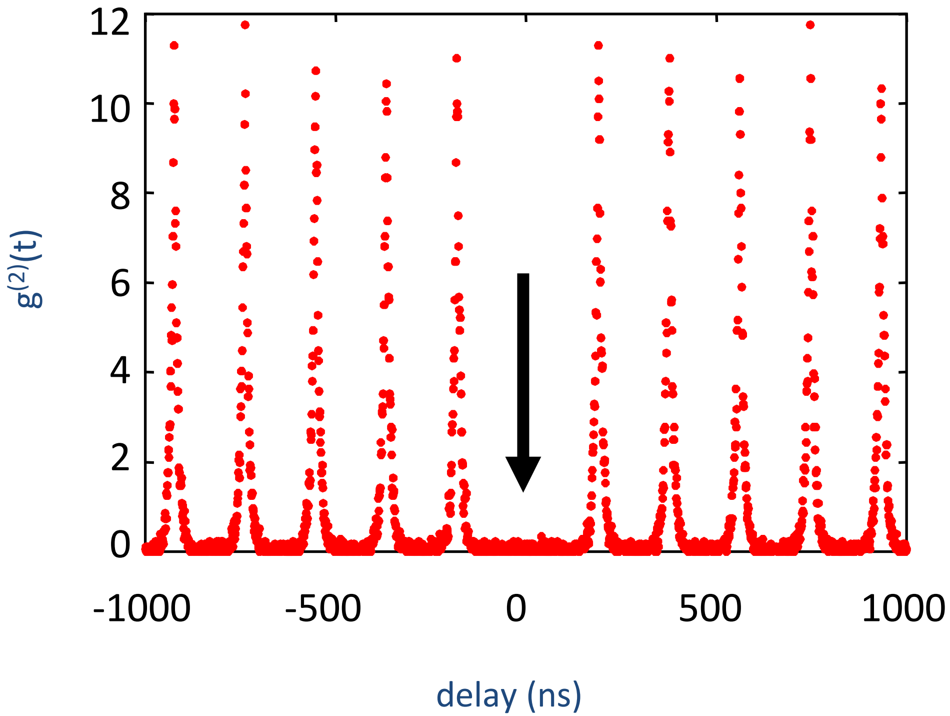


Making single photons

$p < 1\%$

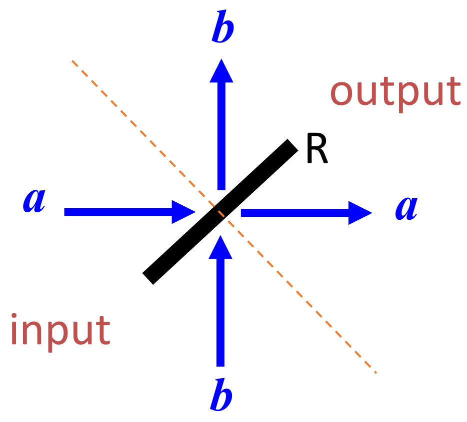


excellent probabilistic
single photon source



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

The beamsplitter and Angular Momentum



effective angular momentum (Schwinger)

$$J = (n_a + n_b)/2 \qquad J_z = (n_a - n_b)/2$$

$$J_y = -i(a^\dagger b - b^\dagger a)$$

$$|n_a\, n_b\rangle \Rightarrow e^{-i\theta \hat{J}_y} |n_a\, n_b\rangle \qquad \theta = \pi R$$

Yurke, et al., Phys. Rev. A **33** 4033 (1986)

$n_a + n_b = 0$ *photons* J=0: $|0_a 0_b\rangle \Rightarrow |0_a 0_b\rangle$

$n_a + n_b = 1$ *photon* J=1/2:

$$|0_a 1_b\rangle \Rightarrow \cos(\theta/2)\,|0_a 1_b\rangle + \sin(\theta/2)\,|1_a 0_b\rangle$$

$$|1_a 0_b\rangle \Rightarrow -\sin(\theta/2)\,|0_a 1_b\rangle + \cos(\theta/2)\,|1_a 0_b\rangle$$

$n_a + n_b = 2$ *photons* J=1:

$$|0_a 2_b\rangle \Rightarrow \cos^2(\theta/2)\,|\mathbf{0}_a \mathbf{2}_b\rangle + (1/\sqrt{2})\sin(\theta)\,|\mathbf{1}_a \mathbf{1}_b\rangle + \sin^2(\theta/2)\,|\mathbf{2}_a \mathbf{0}_b\rangle$$

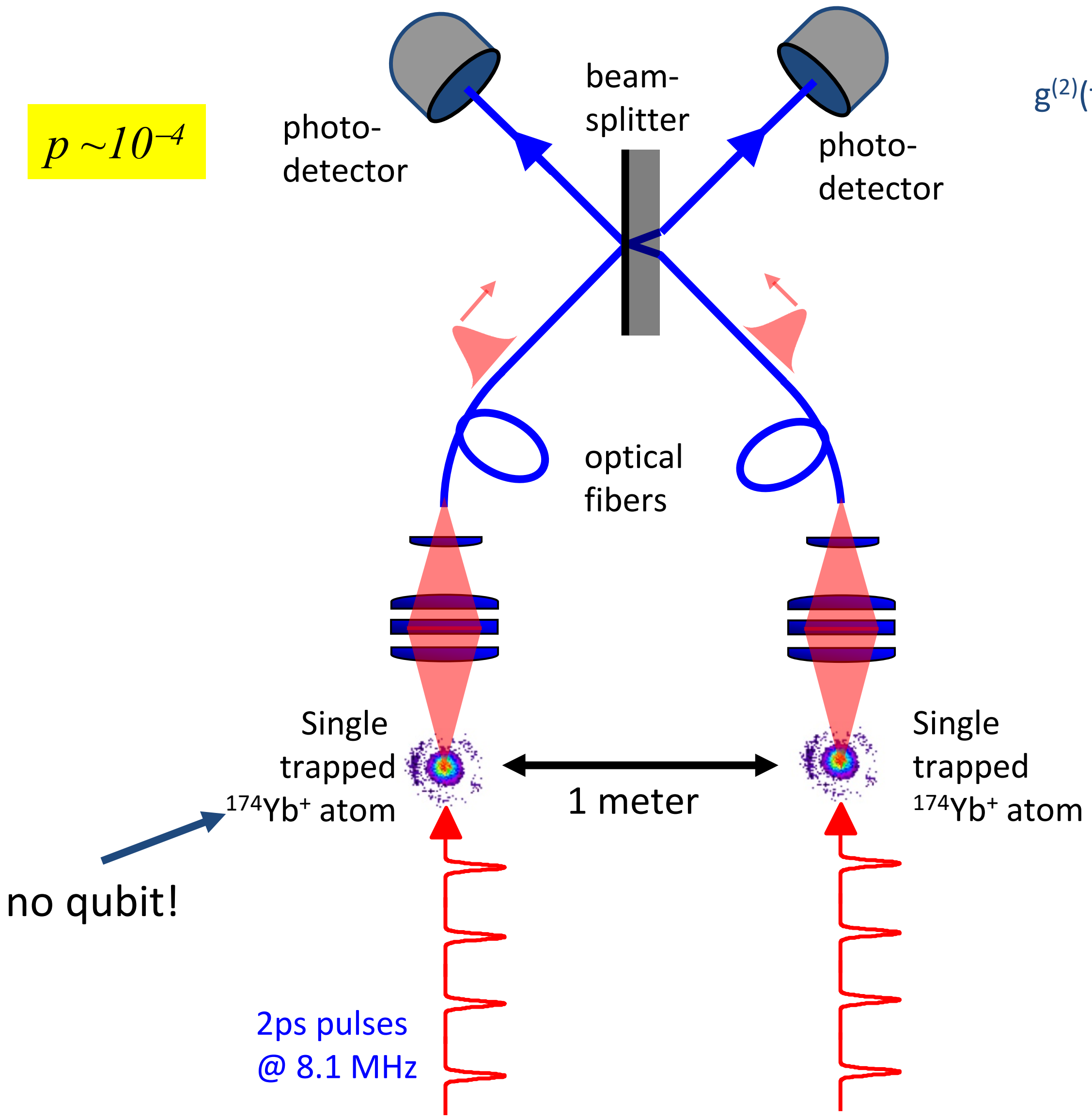
$$|1_a 1_b\rangle \Rightarrow -(1/\sqrt{2})\sin(\theta)\,|\mathbf{0}_a \mathbf{2}_b\rangle + (1/\sqrt{2})\cos(\theta)\,|\mathbf{1}_a \mathbf{1}_b\rangle + (1/\sqrt{2})\sin(\theta)\,|\mathbf{2}_a \mathbf{0}_b\rangle$$

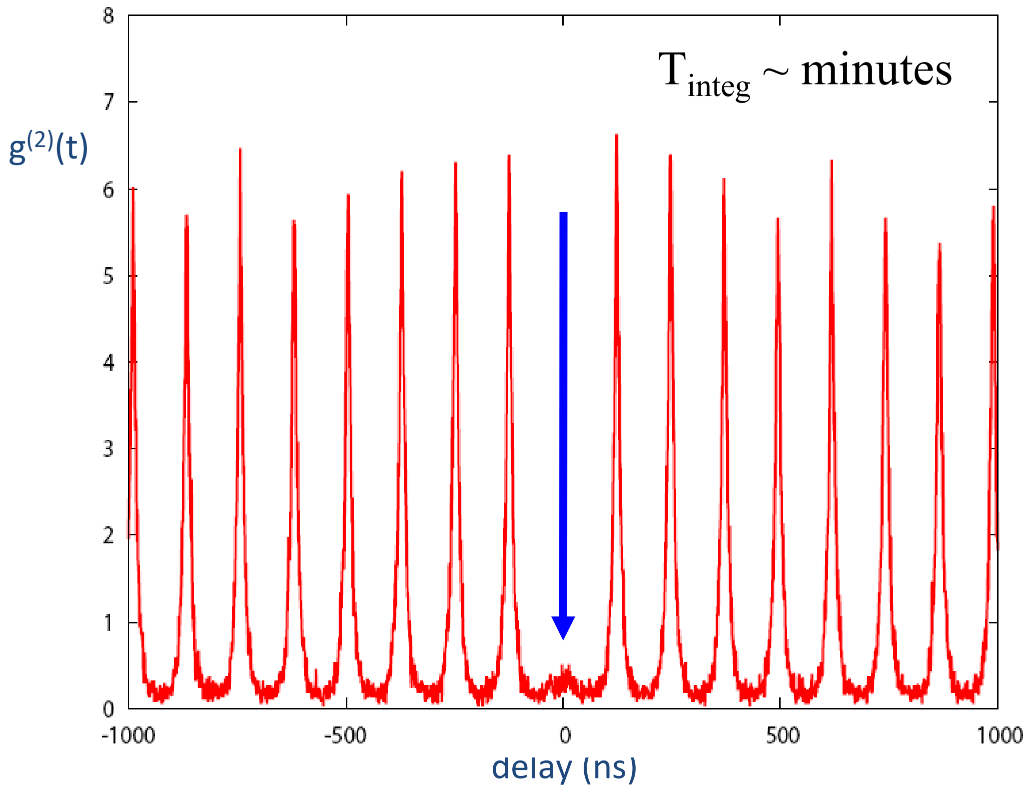
$$|2_a 0_b\rangle \Rightarrow \sin^2(\theta/2)\,|\mathbf{0}_a \mathbf{2}_b\rangle + (1/\sqrt{2})\sin(\theta)\,|\mathbf{1}_a \mathbf{1}_b\rangle + \sin^2(\theta/2)\,|\mathbf{0}_a \mathbf{2}_b\rangle$$

Etc…

2-photon interference

$p \sim 10^{-4}$

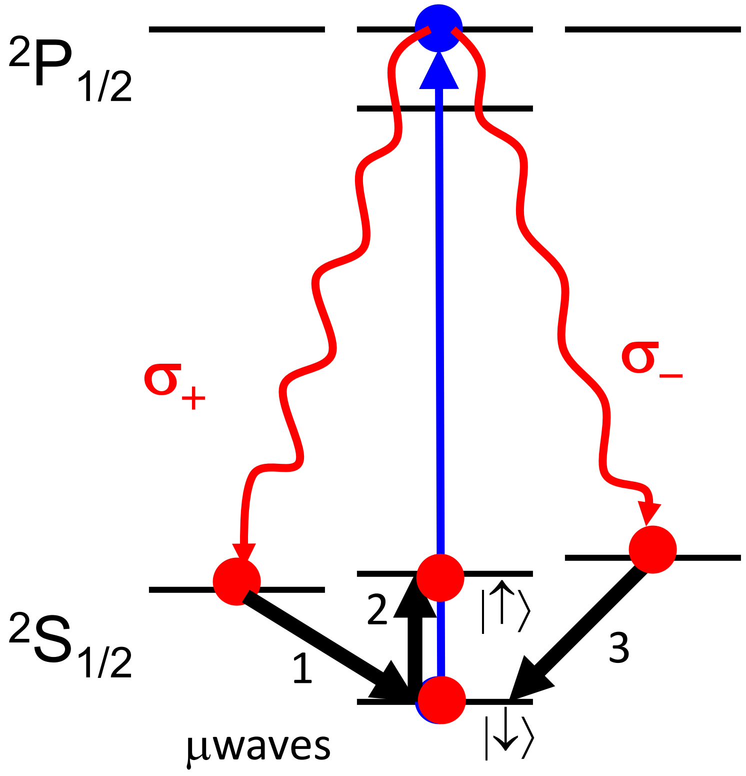




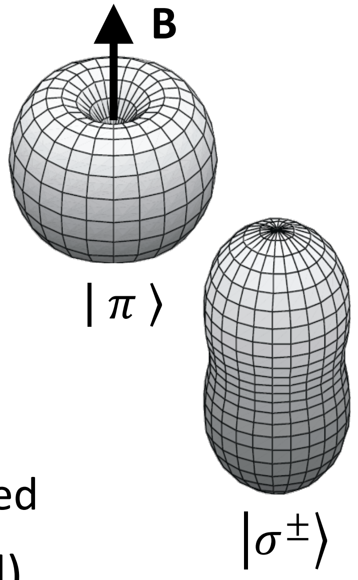
Hong, Ou, Mandel, PRL 59, 2044 (1987)
Y.H. Shih & C. O. Alley, PRL 61, 2921 (1988)
Santori, et al., Nature, 419, 594 (2002)
Kaltenbaek, et al, PRL, 96, 240502 (2006)
Legero, et al., PRL, 93, 070503 (2004)
Thompson, et al., Science, 313, 74 (2006)
Felinto, et al. Nature Physics, 2, 844 (2006)
Beugnon,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

Mapping qubits from atoms to photons

$^{171}Yb^{+}$



No π-photons into fiber along ***B***
(even for high solid angle)
T. Kim, et al., *PRA* **84**, 063423 (2011)



Given photon is collected and detected

$|\psi\rangle = |\downarrow\rangle|-\rangle + |\uparrow\rangle|+\rangle$ (post-selected)

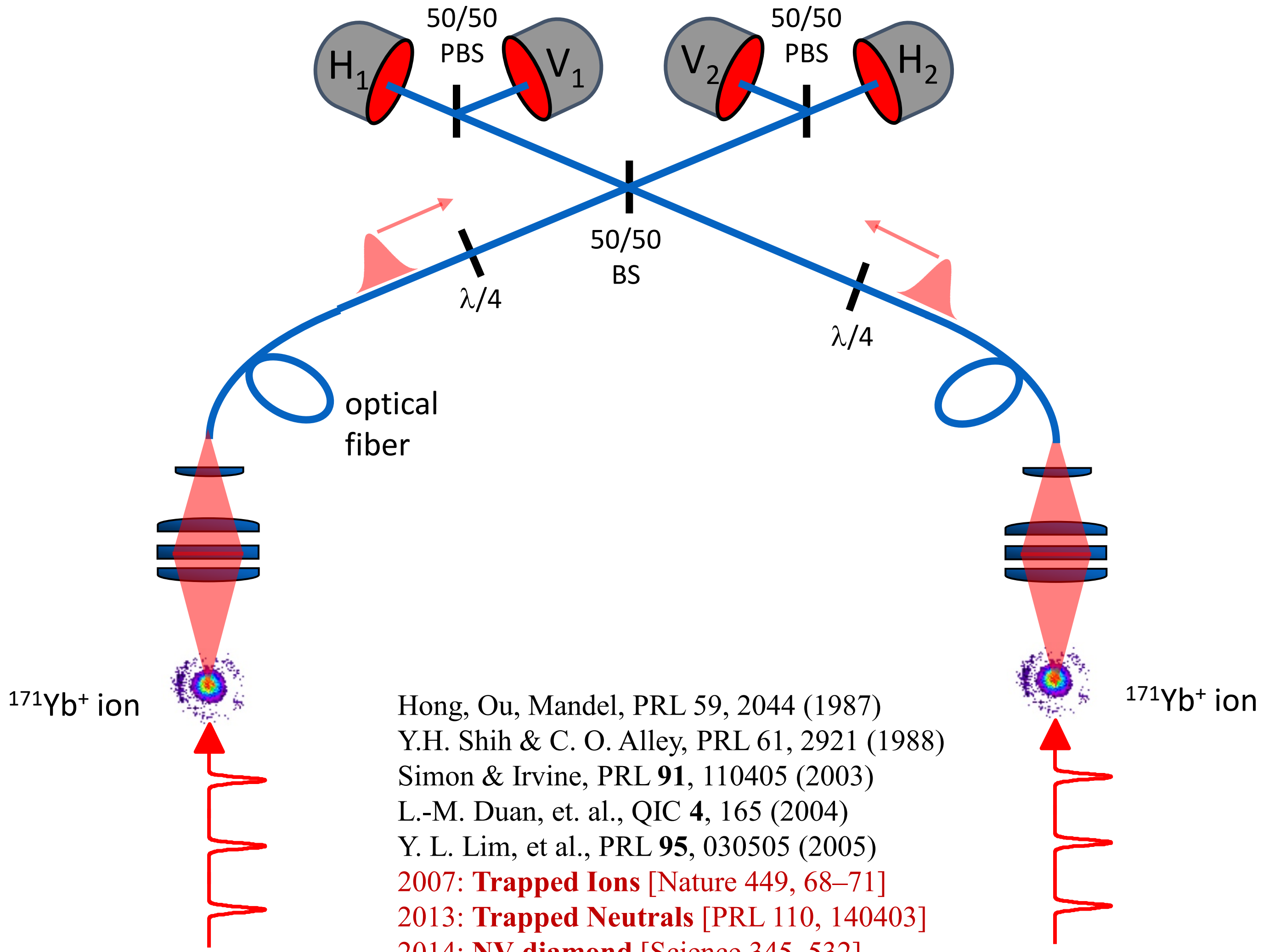
Current State-of-art:

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

$$R = 1\ MHz$$

$$\boldsymbol{Rp \approx 2{\times}10^4\ sec^{-1}}$$

Photonic Linkage between Atomic Qubits



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]

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) $\rightarrow |\uparrow\uparrow\rangle$

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

Current State-of-art:

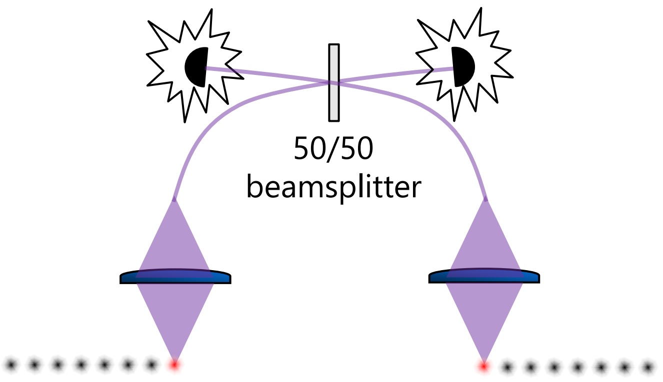
$$p = \eta_D \, T \frac{d\Omega}{4\pi} = (.35)(.6)(.1) = 2\%$$

$$R = 1\ MHz$$

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

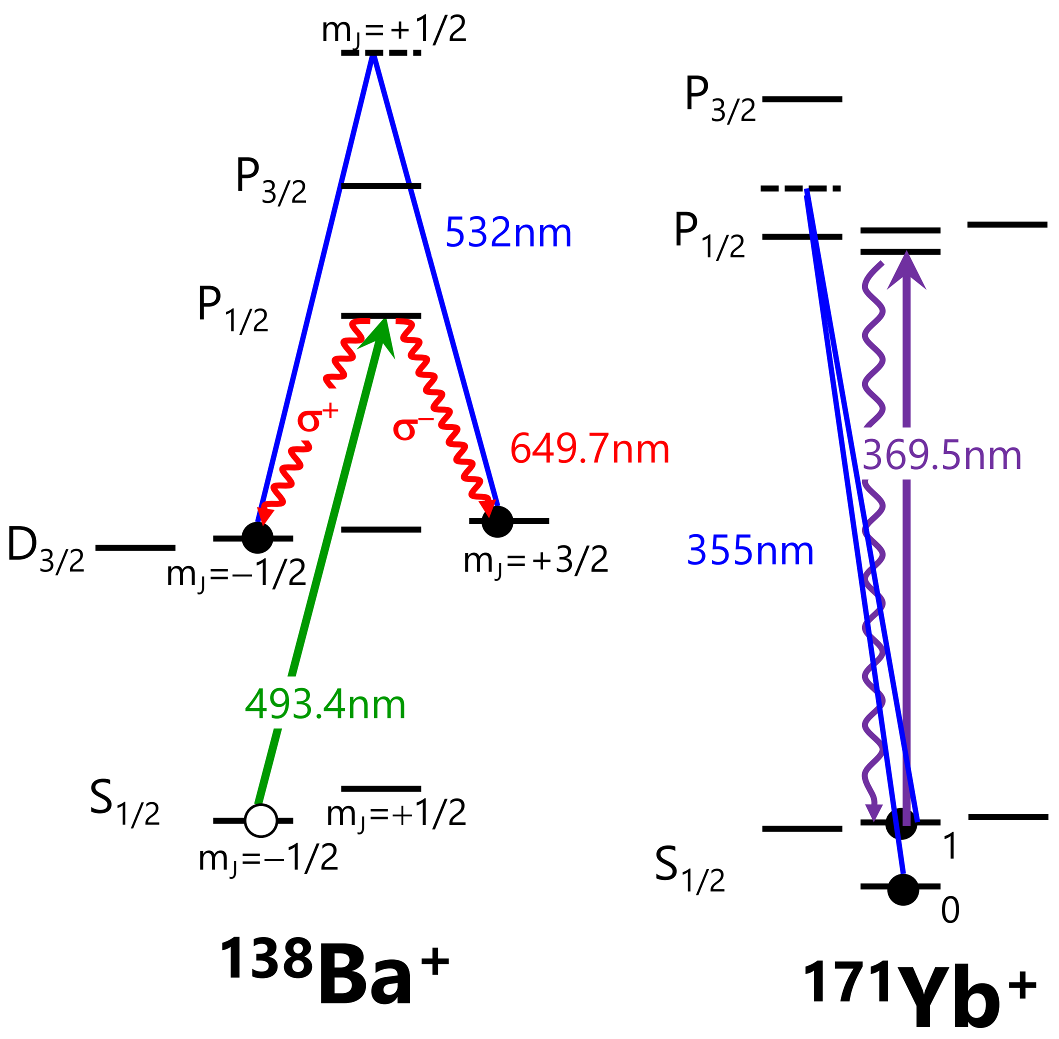
D. Hucul, et al., Nature Phys. 11, 37 (2015)
C. Balance, et al, arXiv:1911.10841 (2019)

Mixed species required for modular architecture



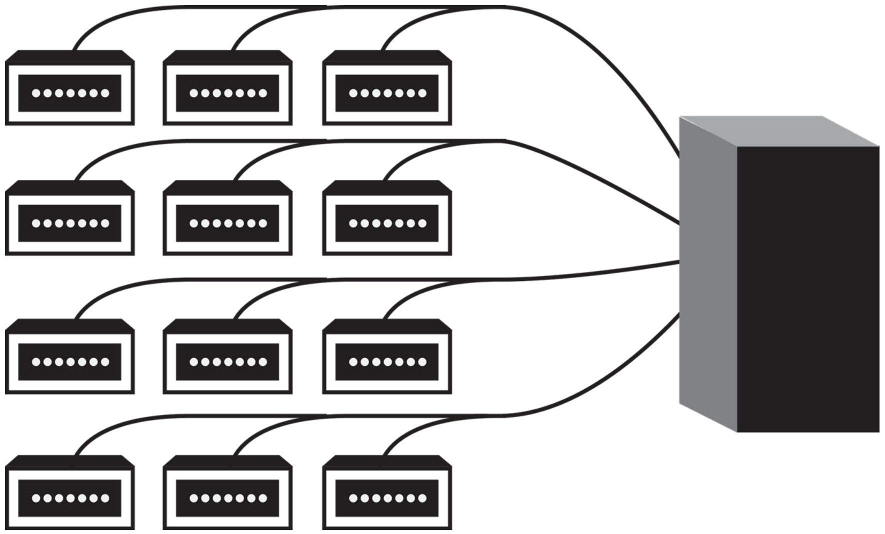
$^{171}Yb^{+}$ ●	● $^{138}Ba^{+}$
excellent memory	poor memory
excellent readout	poor readout
UV photons	**visible photons**

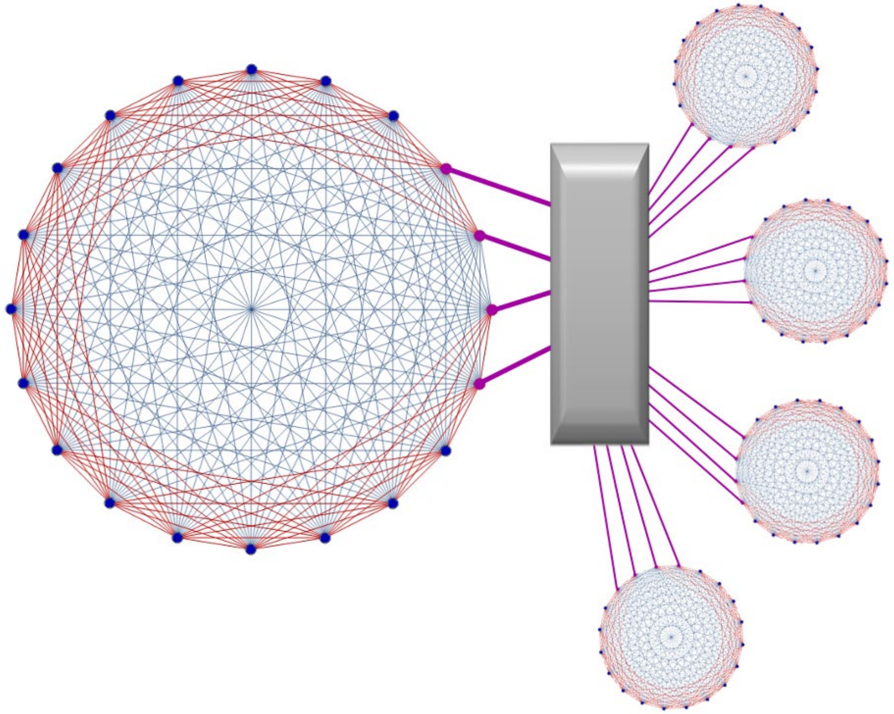
P.O. Schmidt et al., *Science* **309**, 749 (2005)
J. Home, *Adv. AMO Phys.* **62**, 231 (2013)
I. V. Inlek, et al., *PRL* **118**, 250502 (2017)



Scaling to 1000s of qubits and beyond

Modular optical interconnects





Phys. Rev. A 89, 022317 (2014)
Nature Quant. Inf. 2, 16034 (2016)

Summary

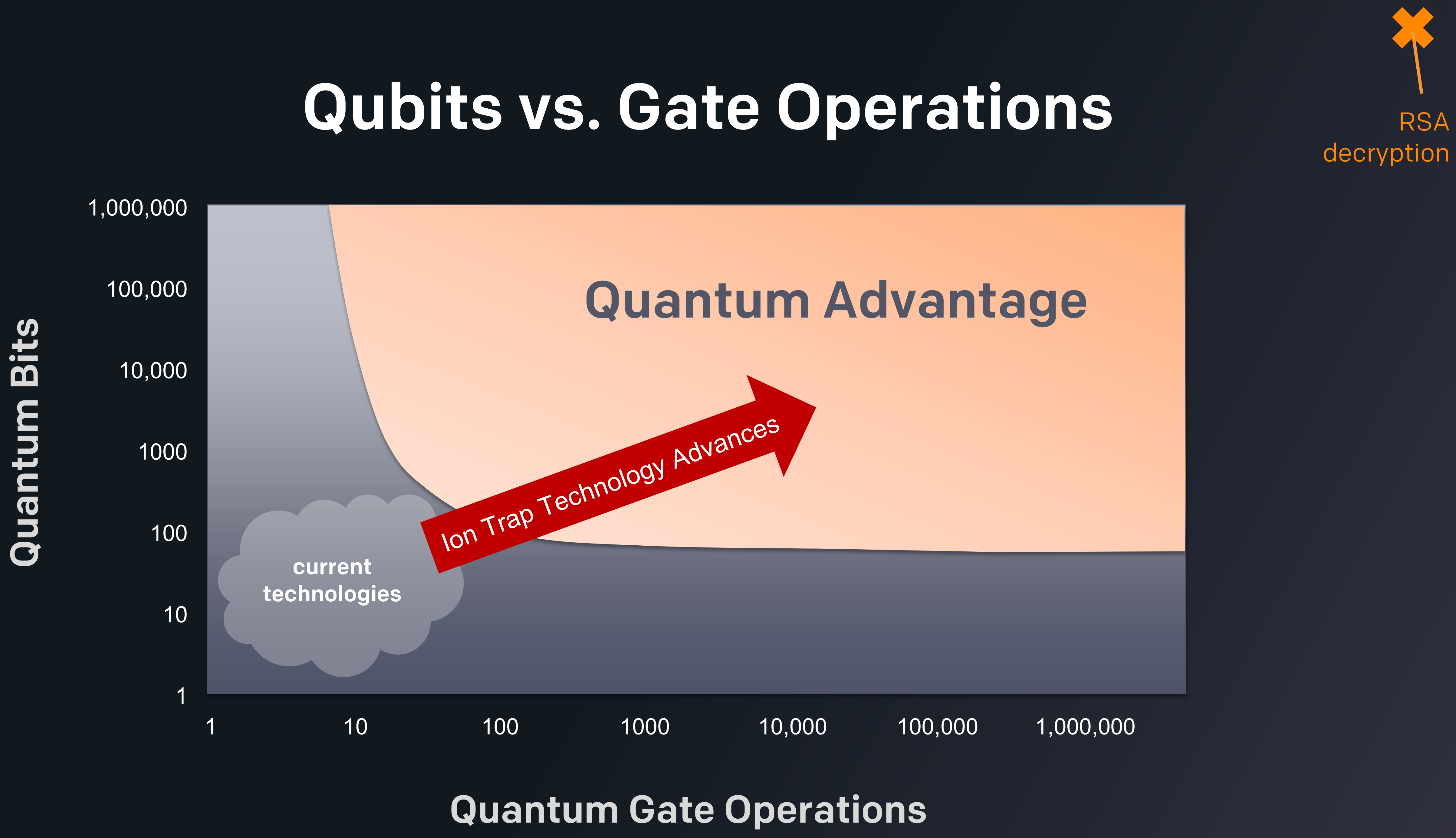
- Ion trap qubits/spins are among the cleanest available for quantum computing and quantum simulation

- We will not likely gain more understanding of individual atoms, so ion trap development has left the realm of atomic physics and is now firmly an engineering task…

- … but using trapped ions as effective spins with engineered entanglement is allowing new studies of many-body physics and impacting condensed matter and other fields of physics

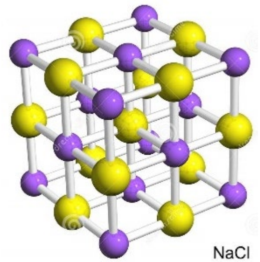
- When you hear that “ion traps don’t scale,” be careful. Ion traps may be the ONLY physical platform that CAN scale. They are being scaled deliberately, as the operations become more clean

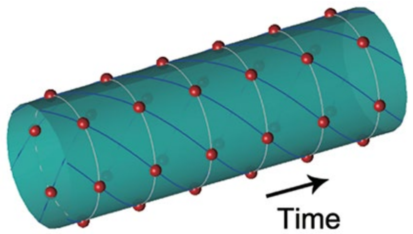
Qubits vs. Gate Operations



Extra Slides

Time Crystals





F. Wilcek (2011): Can the symmetry of ***time*** be broken to yield a "temporal crystal"?

Phys. Rev. Lett. 109, 160401 (2012)

Answer: No*

P. Bruno, Phys. Rev. Lett. 110, 118901 (2013)
P. Bruno, Phys. Rev. Lett. 111, 070402 (2013)
H. Watanabe & M. Oshikawa, Phys. Rev. Lett. 114, 251603 (2015)

* loophole: a "discrete time symmetry can be broken!"

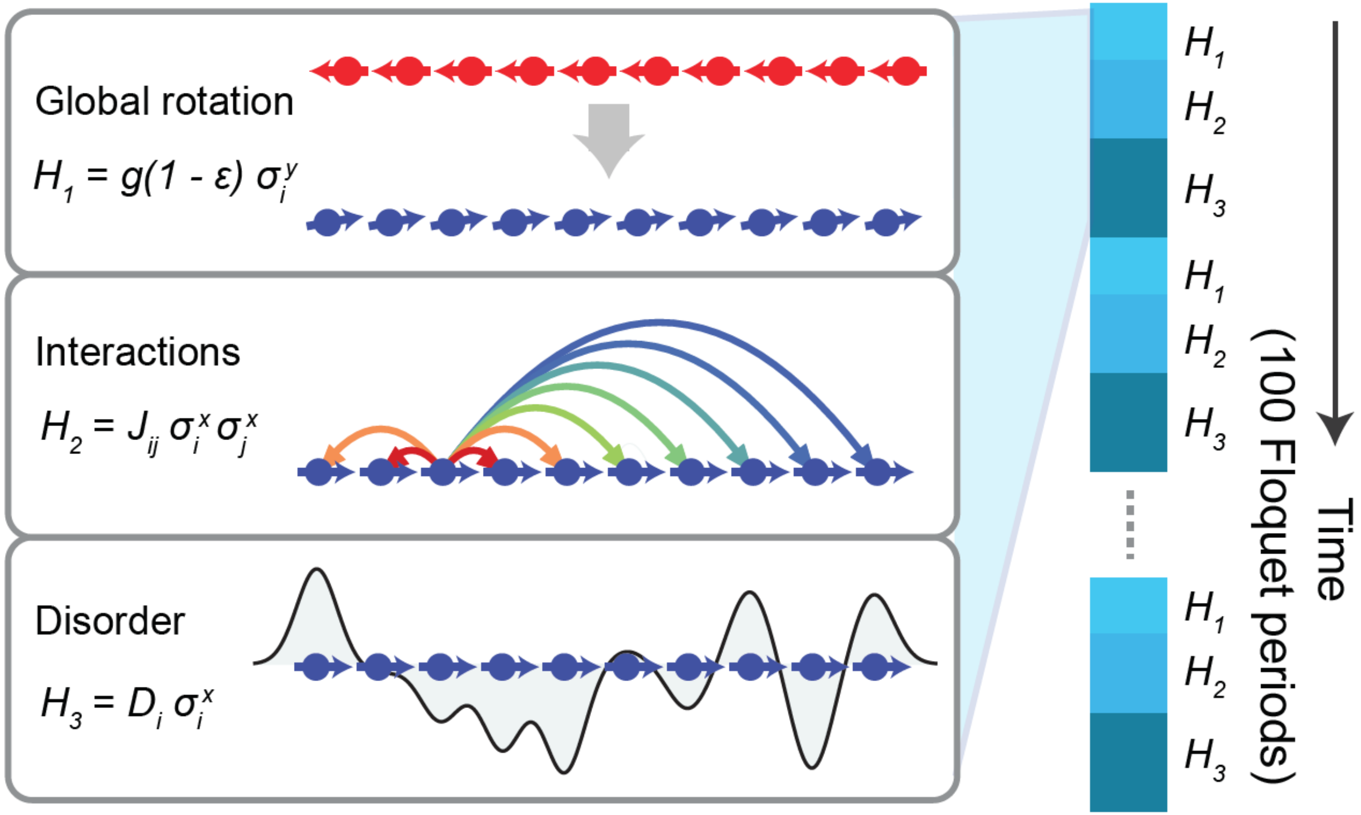
V. Khemani, et al., Phys. Rev. Lett. 116, 250401 (2016)
D. Else, B. Bauer & C. Nayak, Phys. Rev. Lett. 117, 090402 (2016)
C. von Keyserlingk, V. Khemani & S. Sondhi, Phys. Rev. B 94, 260 085112 (2016)
N. Yao, et al., Phys. Rev. Lett. 118, 030401 (2017)

Tricks

- Need to enforce a default time symmetry in the problem
  (e.g.: a periodic 'Floquet' Hamiltonian)
- Need to ensure driven system does not evolve toward $T = \infty$
  (e.g.: Many-body localize a driven system!)

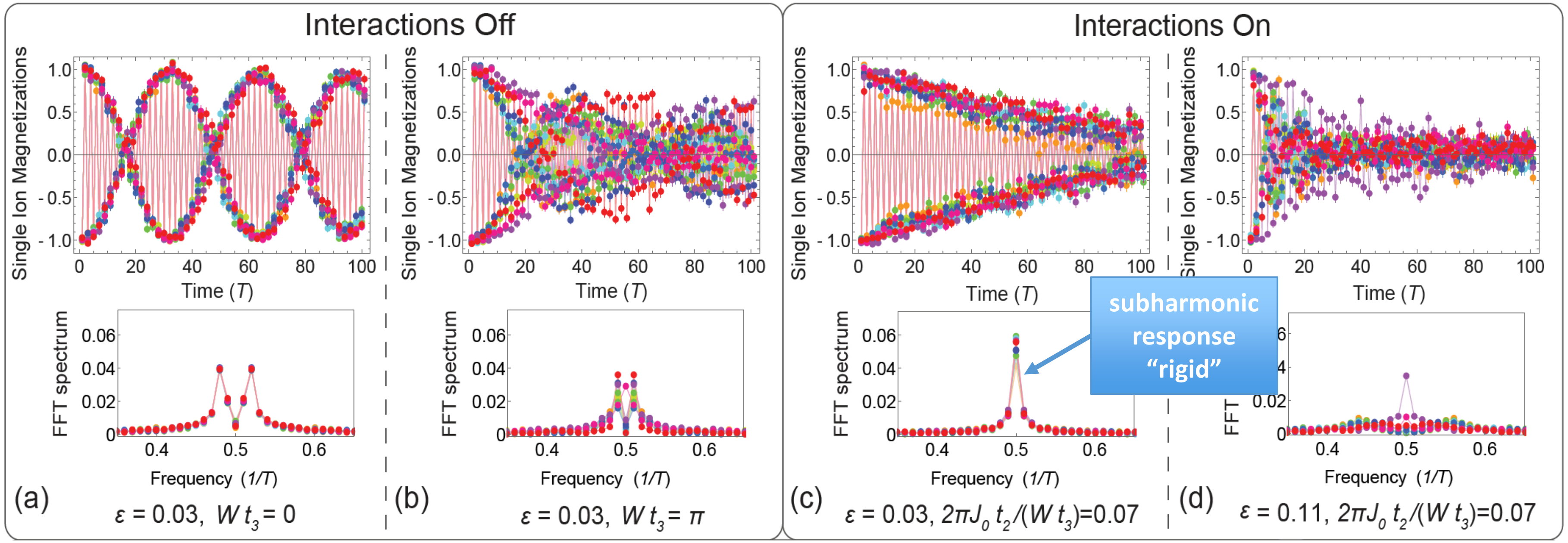
Observation of a Discrete Time Crystal

Periodically drive a chain of N=10 spins under MBL conditions

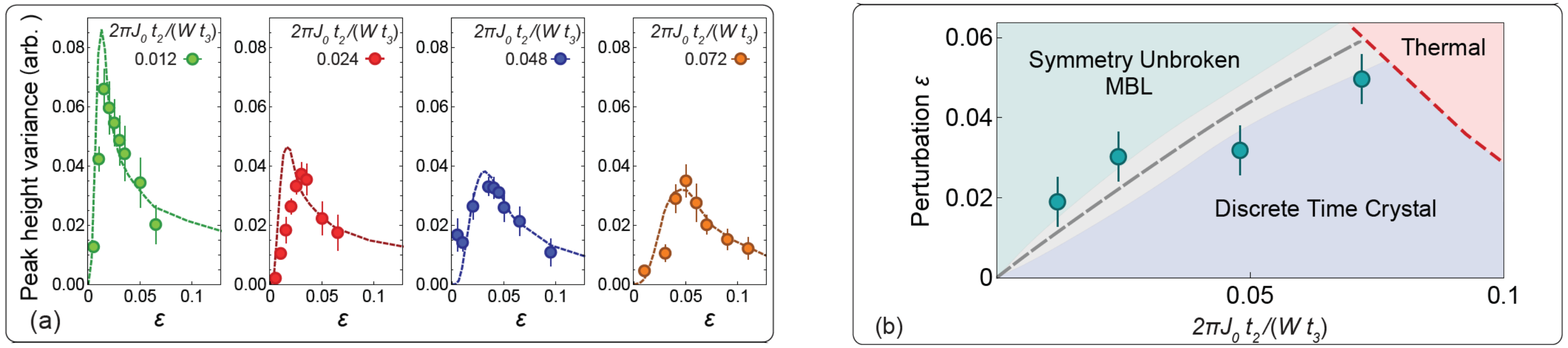


J. Zhang, et al., Nature 543, 217 (2017)

Measurements of spin magnetizations (N=10 spins, 10 instances of disorder)



Subharmonic peak height variance (a measure of fluctuations)

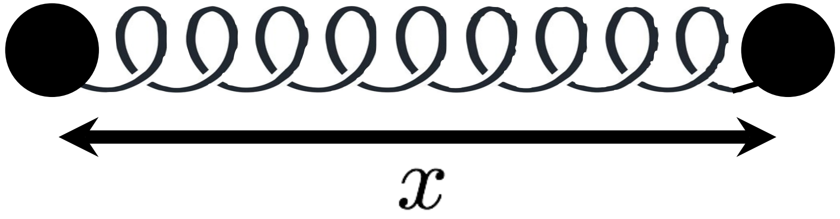


J. Zhang, et al., Nature 543, 217 (2017)
S. Choi, et al., Nature 543, 221 (2017)

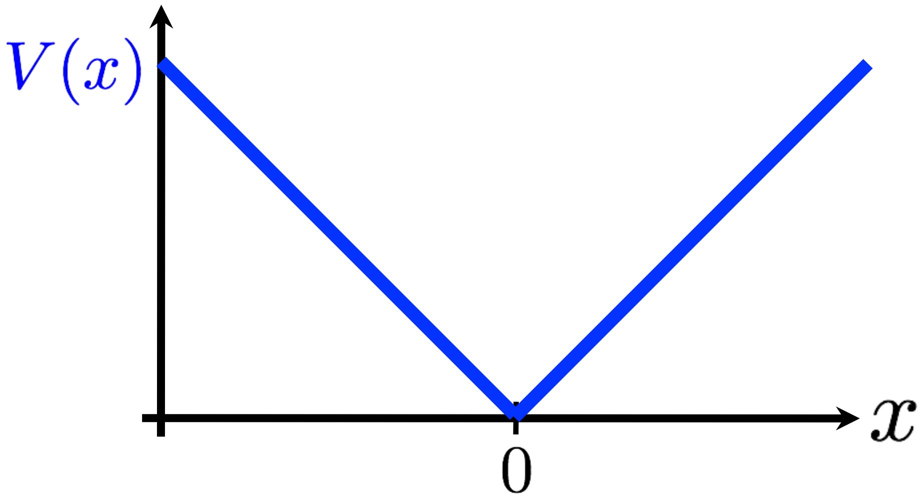
Simulation of Asymptotic Confinement

Confinement in high-energy physics

- Quarks cannot be isolated since they are clumped together to form hadrons



- Quarks held together by the strong nuclear force: constant regardless of separation (gluon field forming a narrow flux tube)



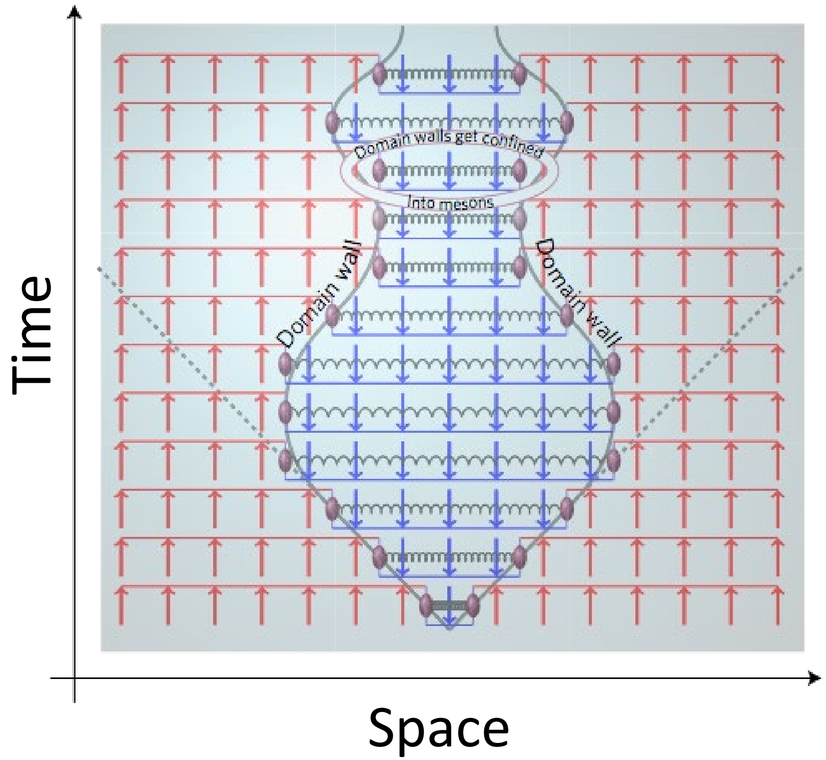
- meson = hadron formed by bound state of quark and antiquark

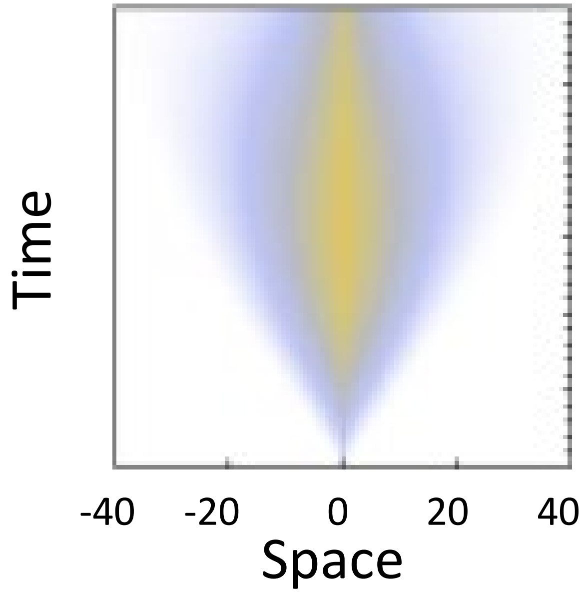
Simulation of Asymptotic Confinement

Analogous confinement in spin chains

Nearest-neighbor Ising model with *longitudinal* field:

$$H = -\sum_j \sigma_j^z \sigma_{j+1}^z - B\sum_j \sigma_j^x - B_z \sum_j \sigma_j^z$$



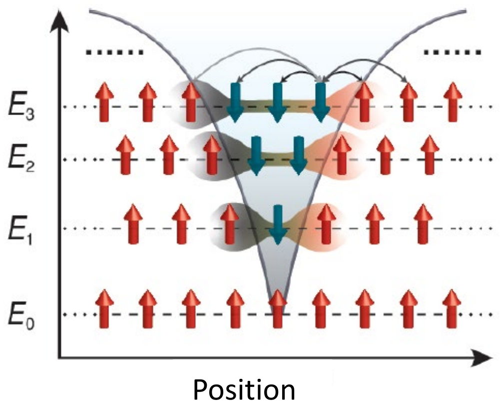


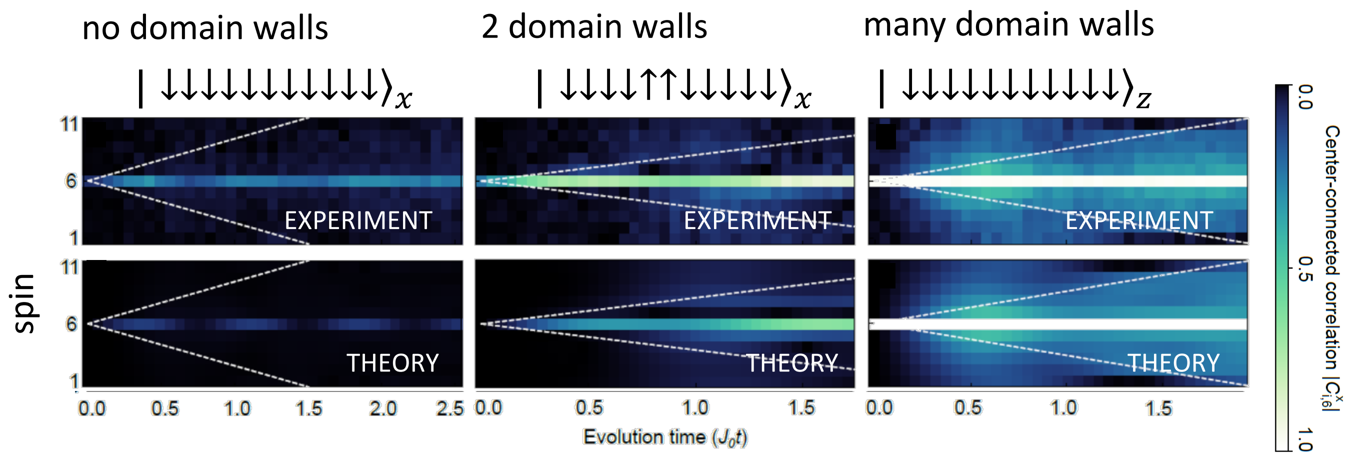
McCoy, Wu, PRD (1978)
Kormos et al, Nat Phys (2017)

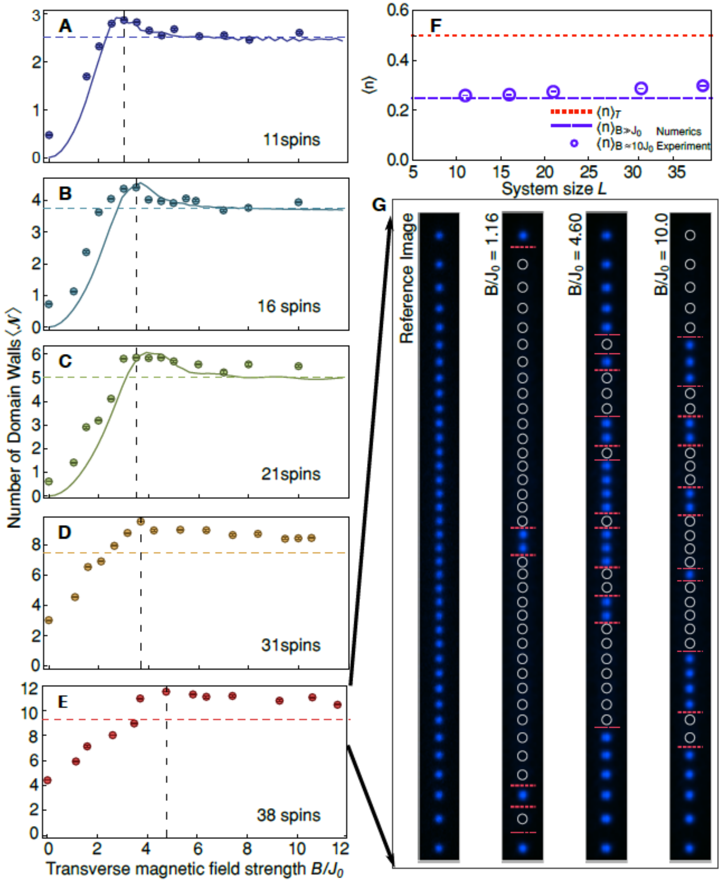
Simulation of Asymptotic Confinement

11-spin chain quenched to

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







domain walls versus B/J_0 for L=11-38 spins, saturating at expected value $(L-1)/4$ when $B \gg J_0$ and the dynamics are prethermal

"Observation of Domain Wall Confinement and Dynamics in a Quantum Simulator," W. L. Tan, et al., *Nat. Phys.* 17, 742 (2021)

with A. Bapat, A. Gorshkov (JQI/QuICS/NIST)
S. Jordan (Microsoft)
G. Pagano, et al., arXiv 1906.02700 (2019)

Global control QAOA (up to 40 spins)

Goal: create (approximate) ground state of

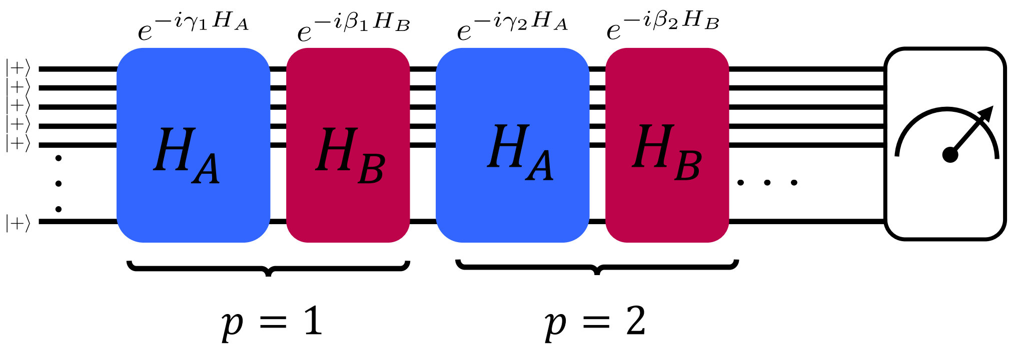
$$H = \underbrace{\sum_{i<j} \frac{J_0}{|i-j|^{\alpha}} \sigma_x^i \sigma_x^j}_{H_A} + \underbrace{B \sum_i \sigma_y^i}_{H_B}$$

(1) Prepare the ground state of H_B

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

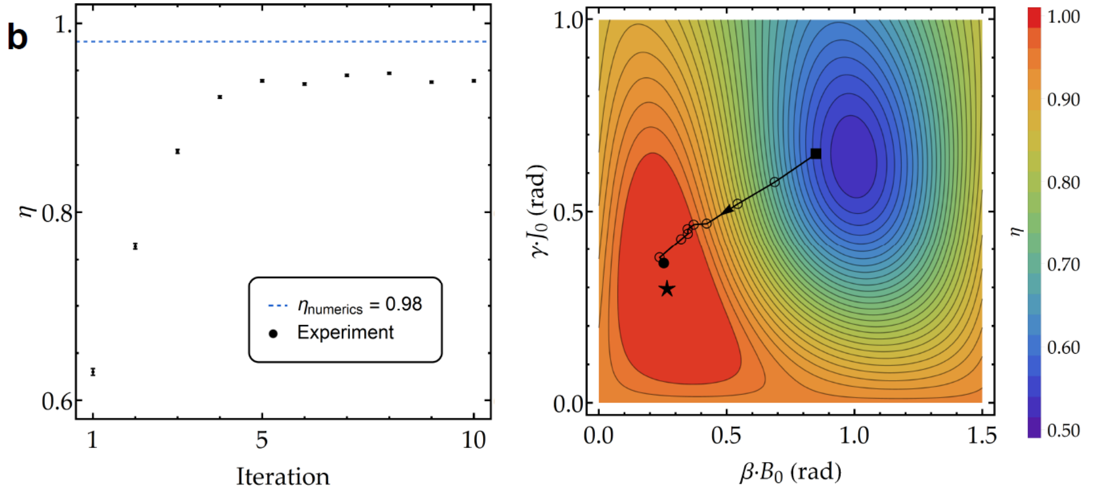
(3) Measure the the energy or complete state distribution

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



Measured energy: $E(\vec{\beta},\vec{\gamma}) = < \psi(\vec{\beta},\vec{\gamma})|H|\, \psi(\vec{\beta},\vec{\gamma}) >$

Figure of Merit: $\eta \equiv \dfrac{E(\vec{\beta},\vec{\gamma}) - E_{max}}{E_{gs} - E_{max}}$

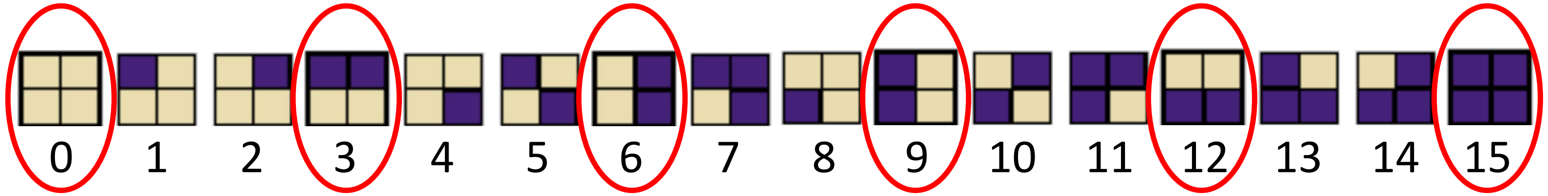


Generative Modeling Optimization

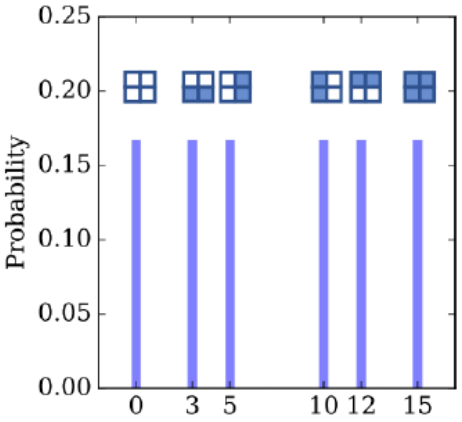
arXiv 1812.08862 (2018)
with A. Perdomo-Ortiz (NASA)
M. Benedetti (UC London)

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

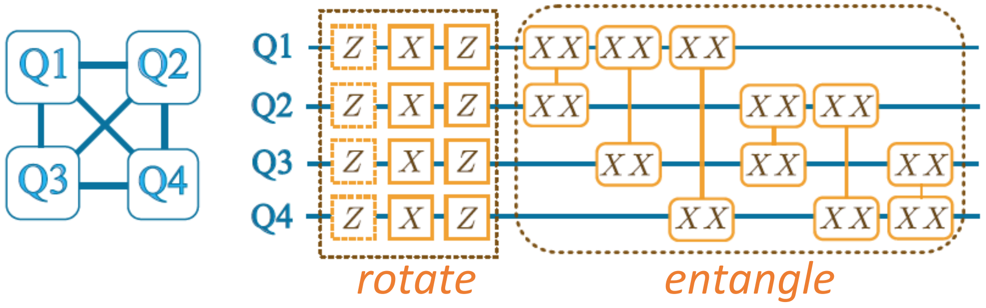
N=4 qubits encodes "Bars and Stripes" patterns



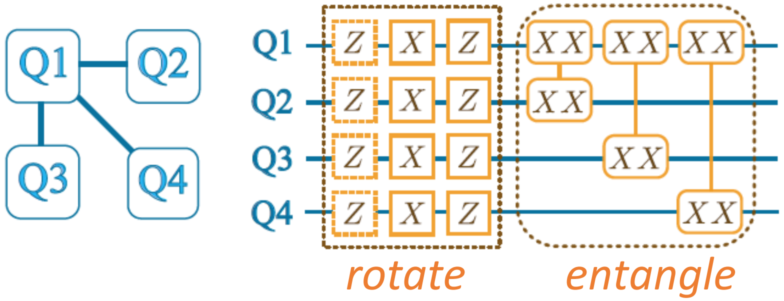
Our task:
prepare equal superposition of all B&S states



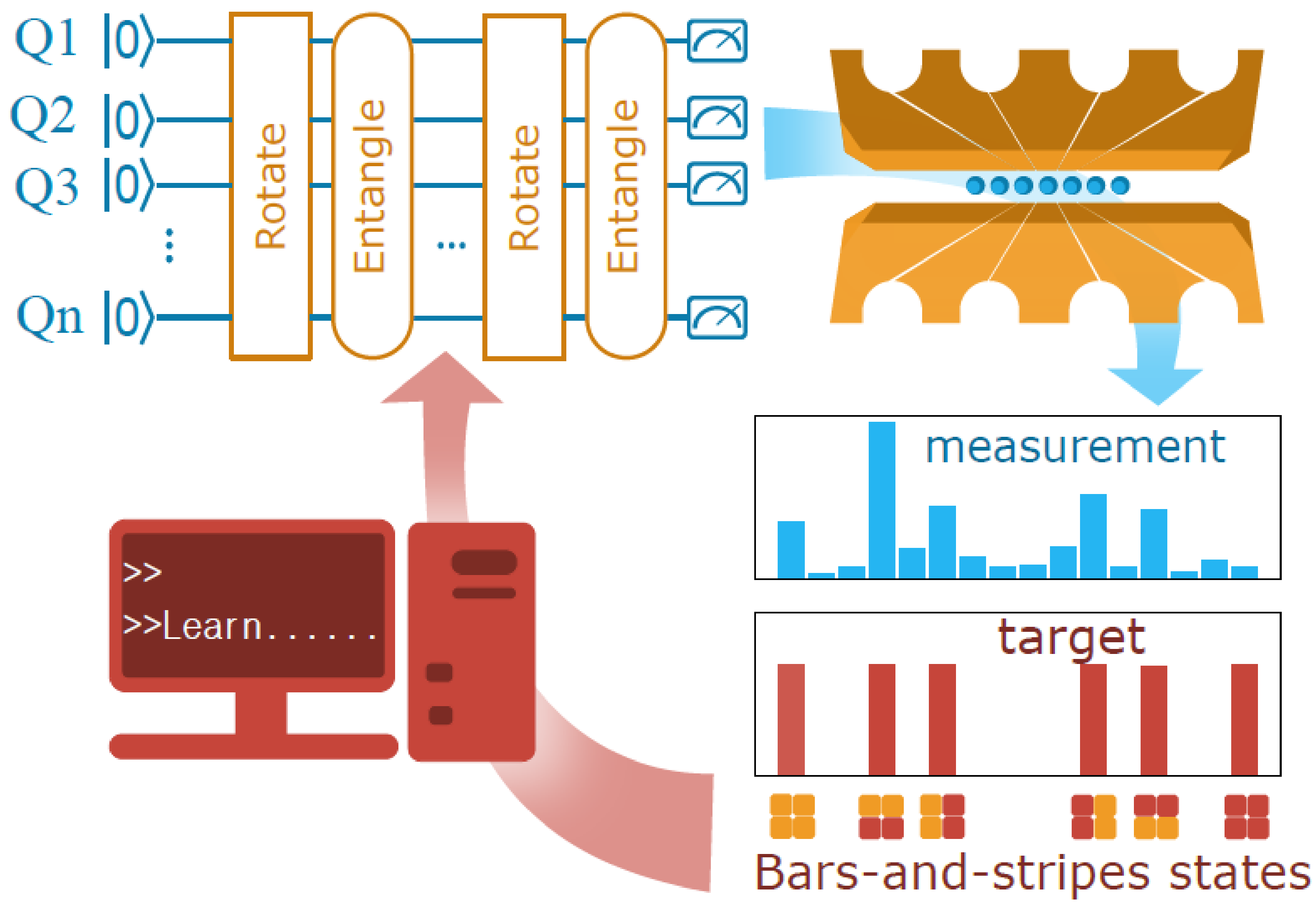
14 parameters



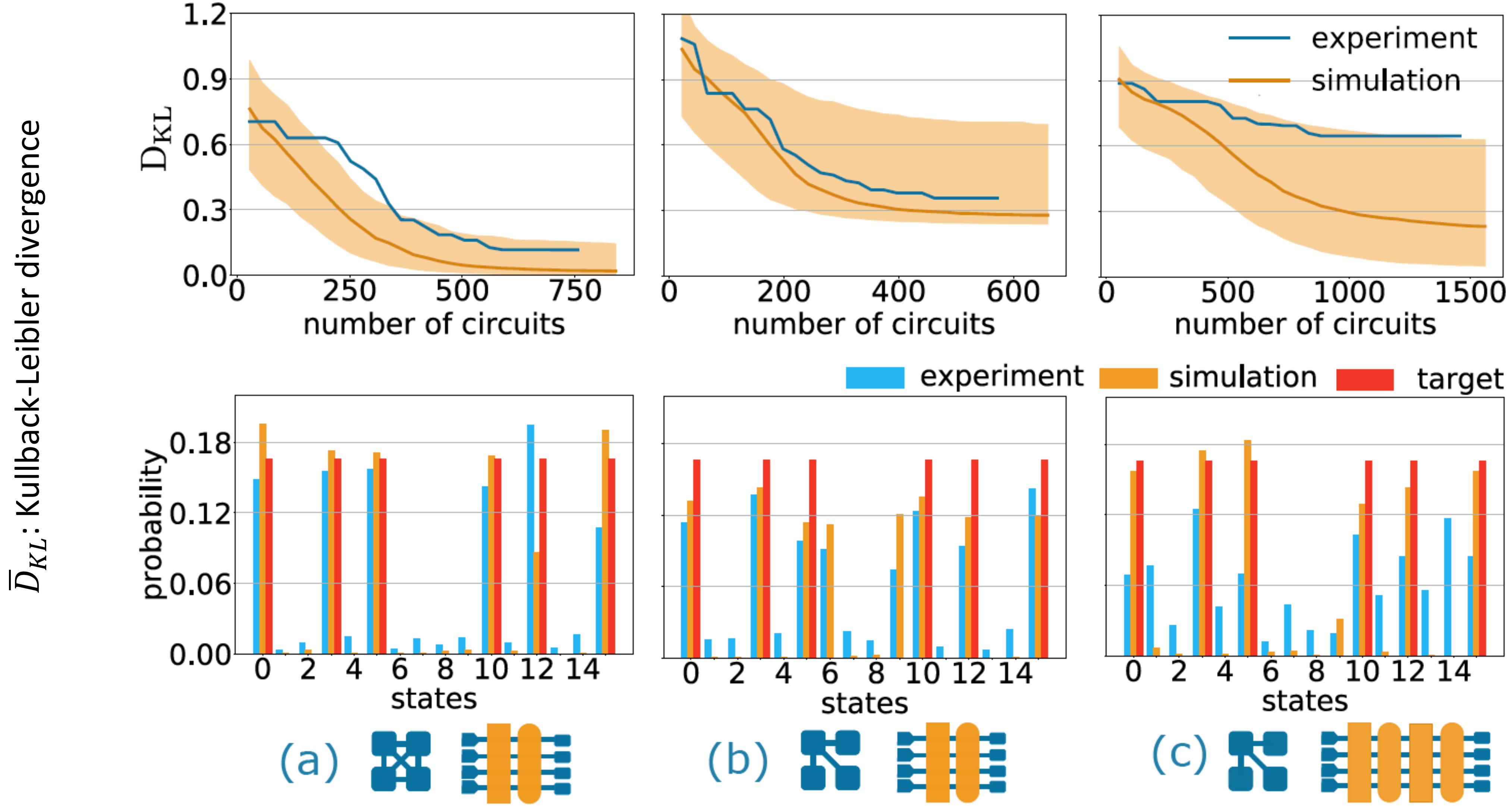
11 parameters



Hybrid Quantum-Classical Learning Loop



Particle Swarm (classical) optimization



Bayesian (classical) optimization