Quantum Gates and Quantum Simulations with Atoms

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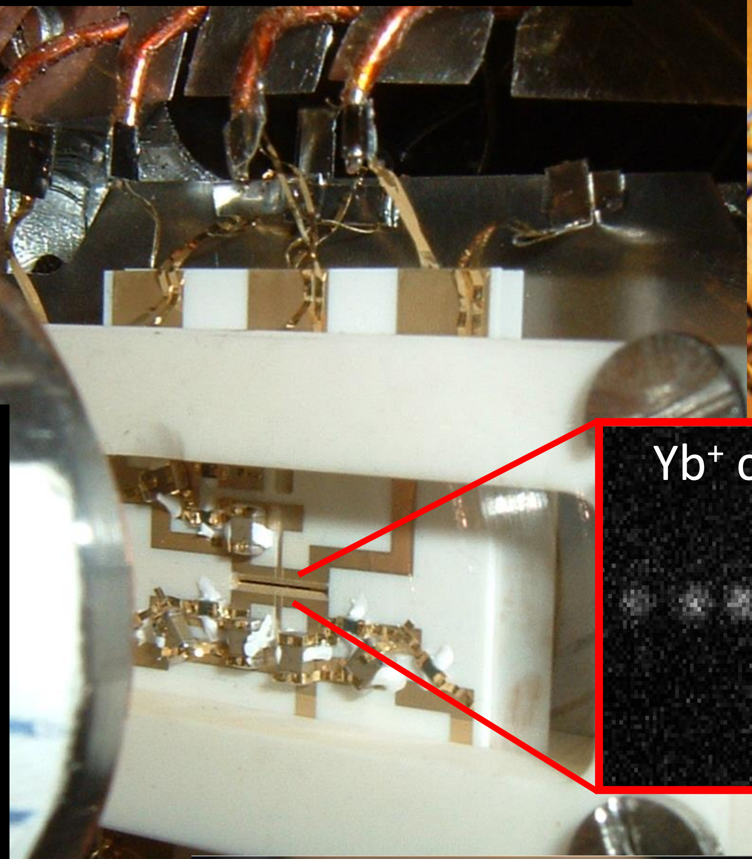
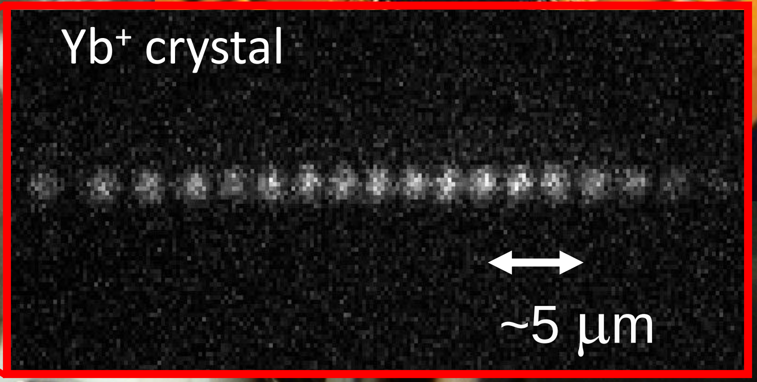
JOINT QUANTUM INSTITUTE

University of Maryland

Trapped Atomic Ions





Aarhus
Amherst
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Georgia Tech
Griffith
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Honeywell
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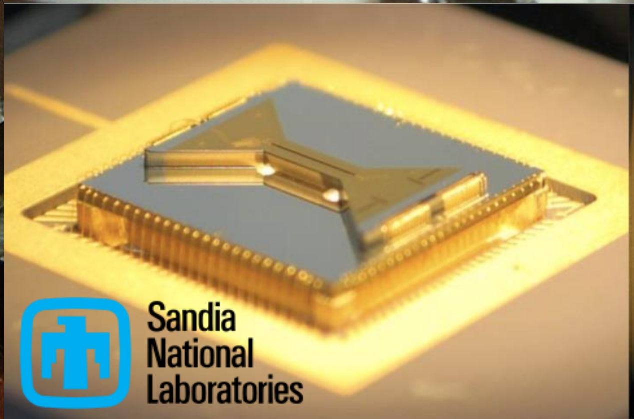
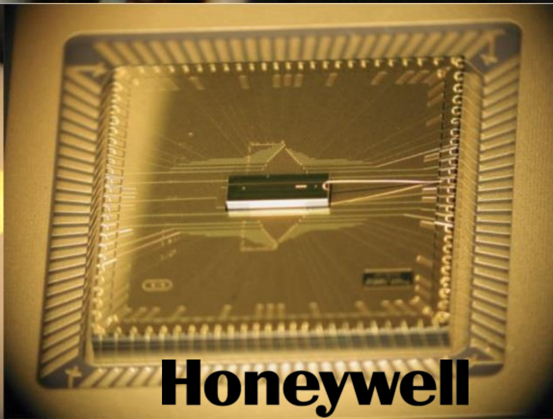
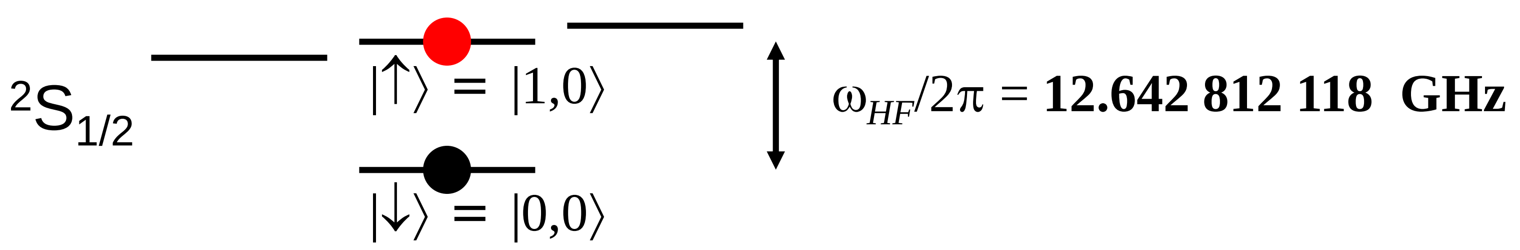
Lincoln Labs
Lockheed
Maryland/JQI
Mainz
MIT
Munich
NIST-Boulder
Northwestern
NPL-Teddington
Osaka
Oxford
Paris
Pretoria
PTB-Braunschweig
Saarbrucken
Sandia
Siegen
Simon Fraser
Singapore
Sussex
Sydney
Tsinghua-Beijing
UCLA
Washington-Seattle
Weizmann
Williams

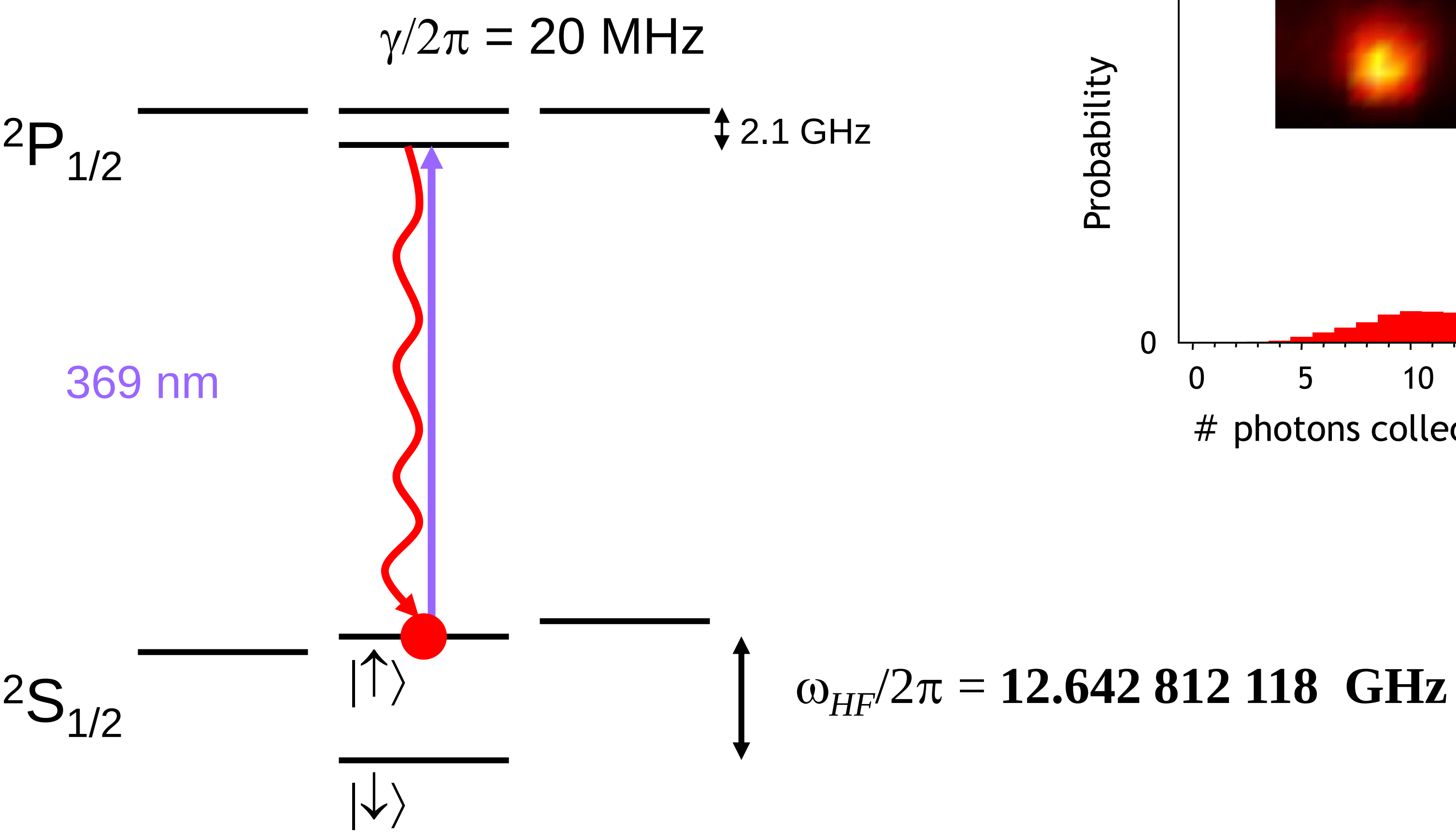


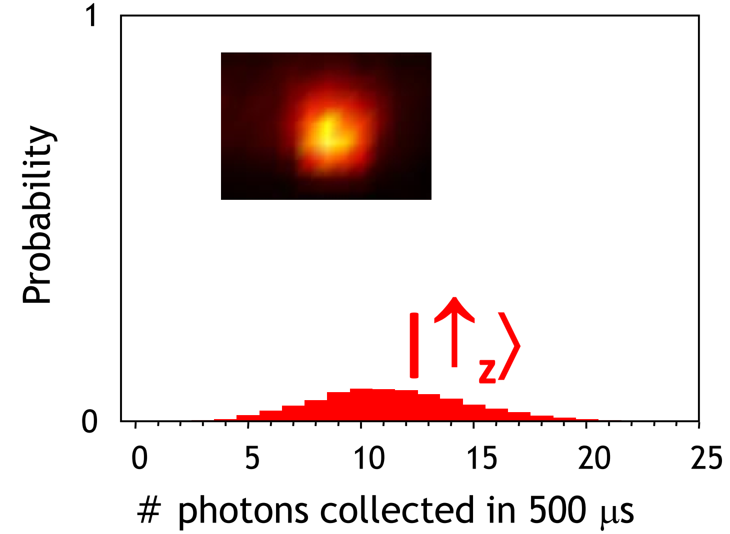


Atomic Qubit ($^{171}Yb^+$)

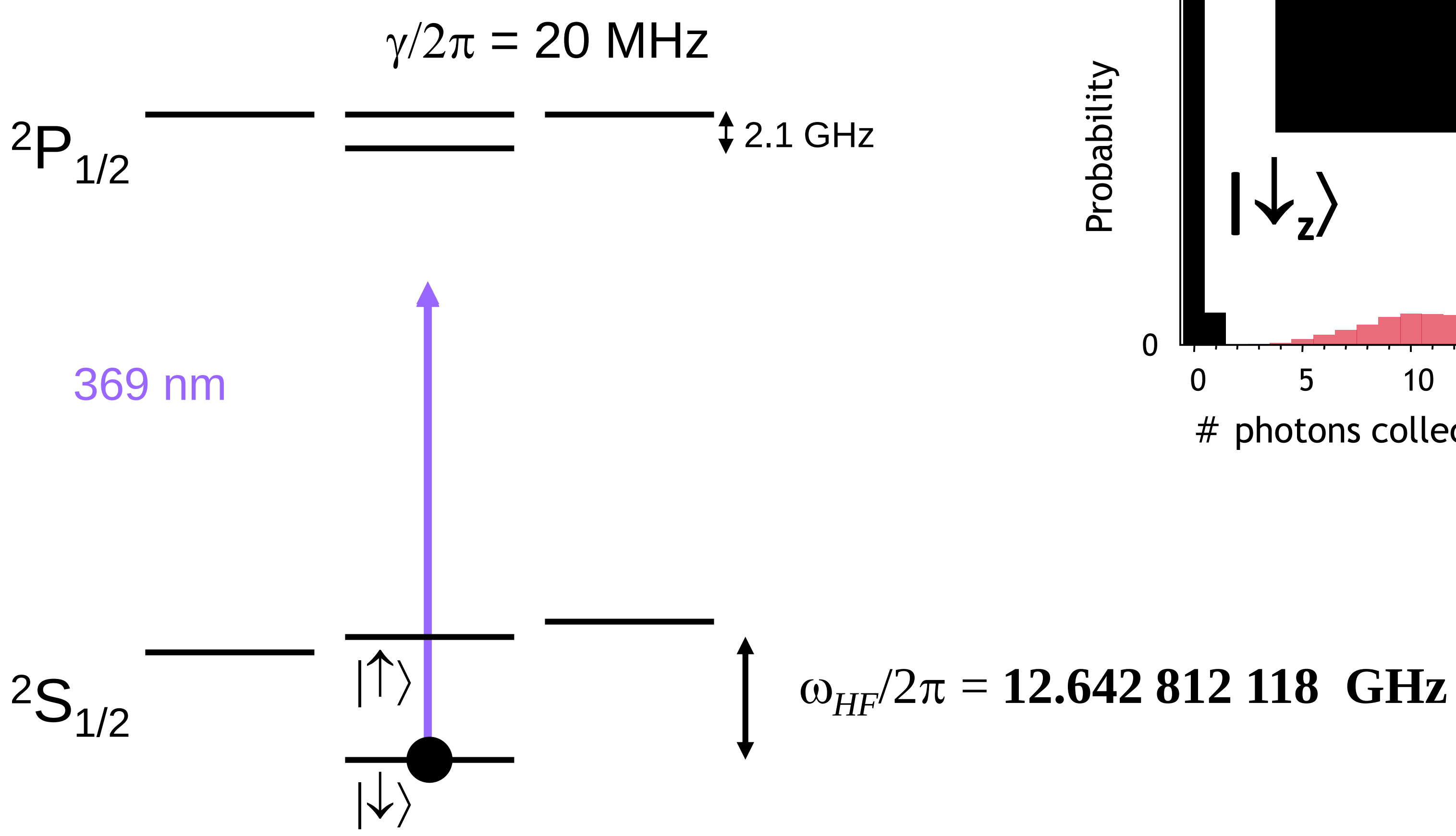


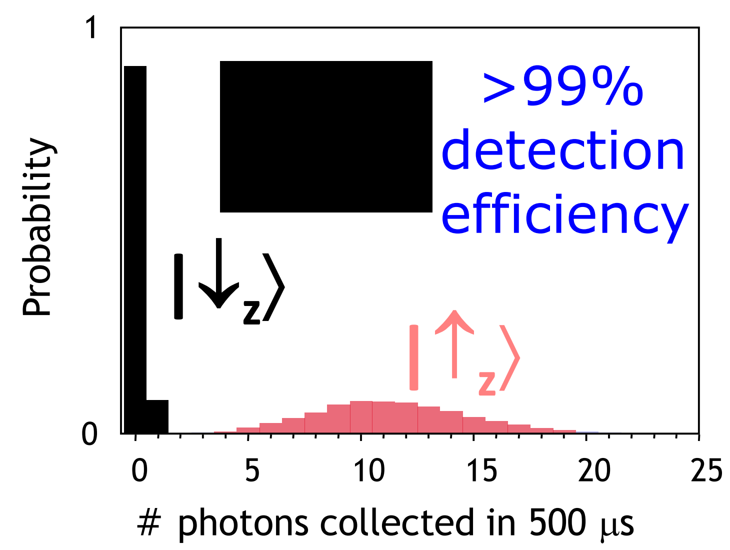
Atomic Qubit Detection



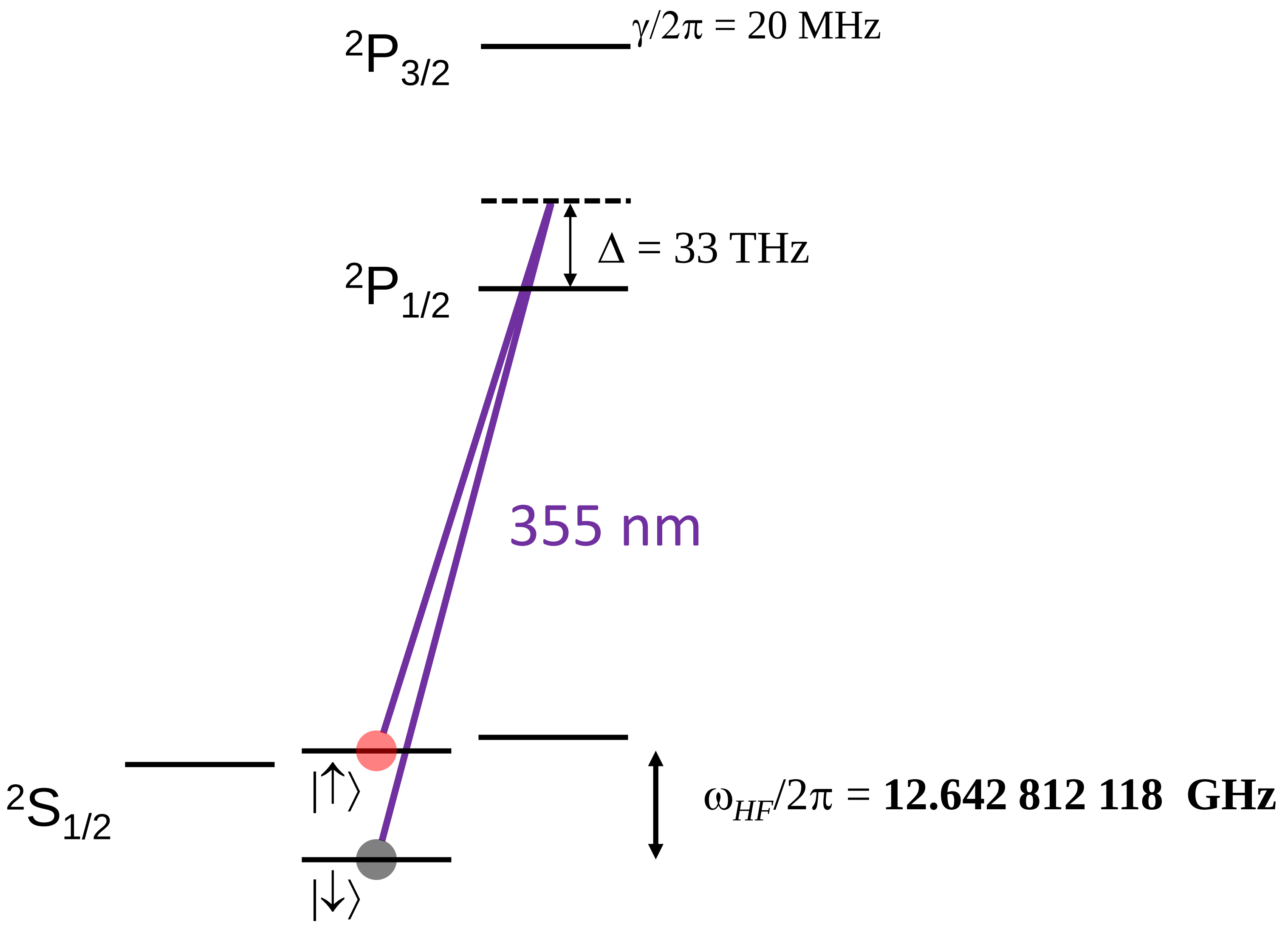


Atomic Qubit Detection

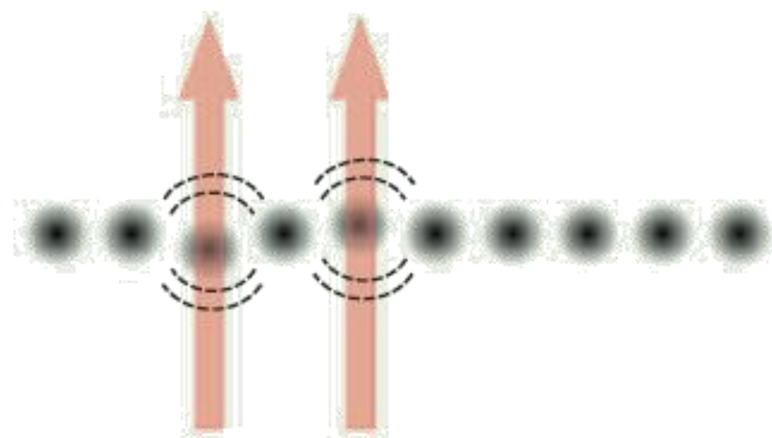




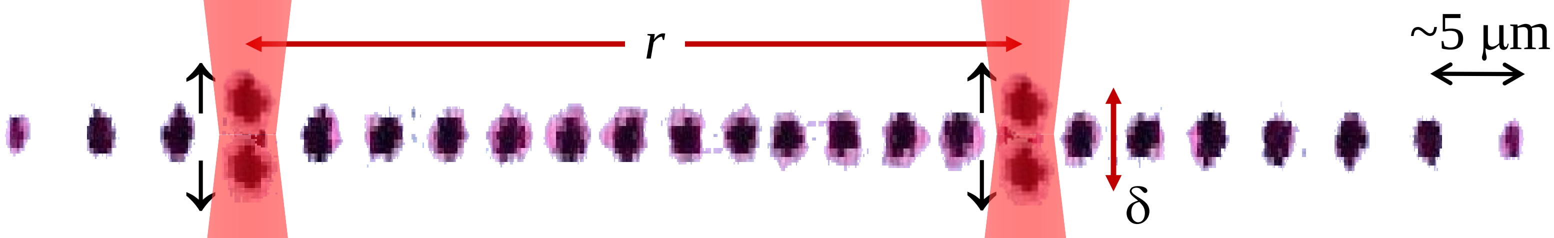
Atomic Qubit Manipulation



Quantum Gates



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

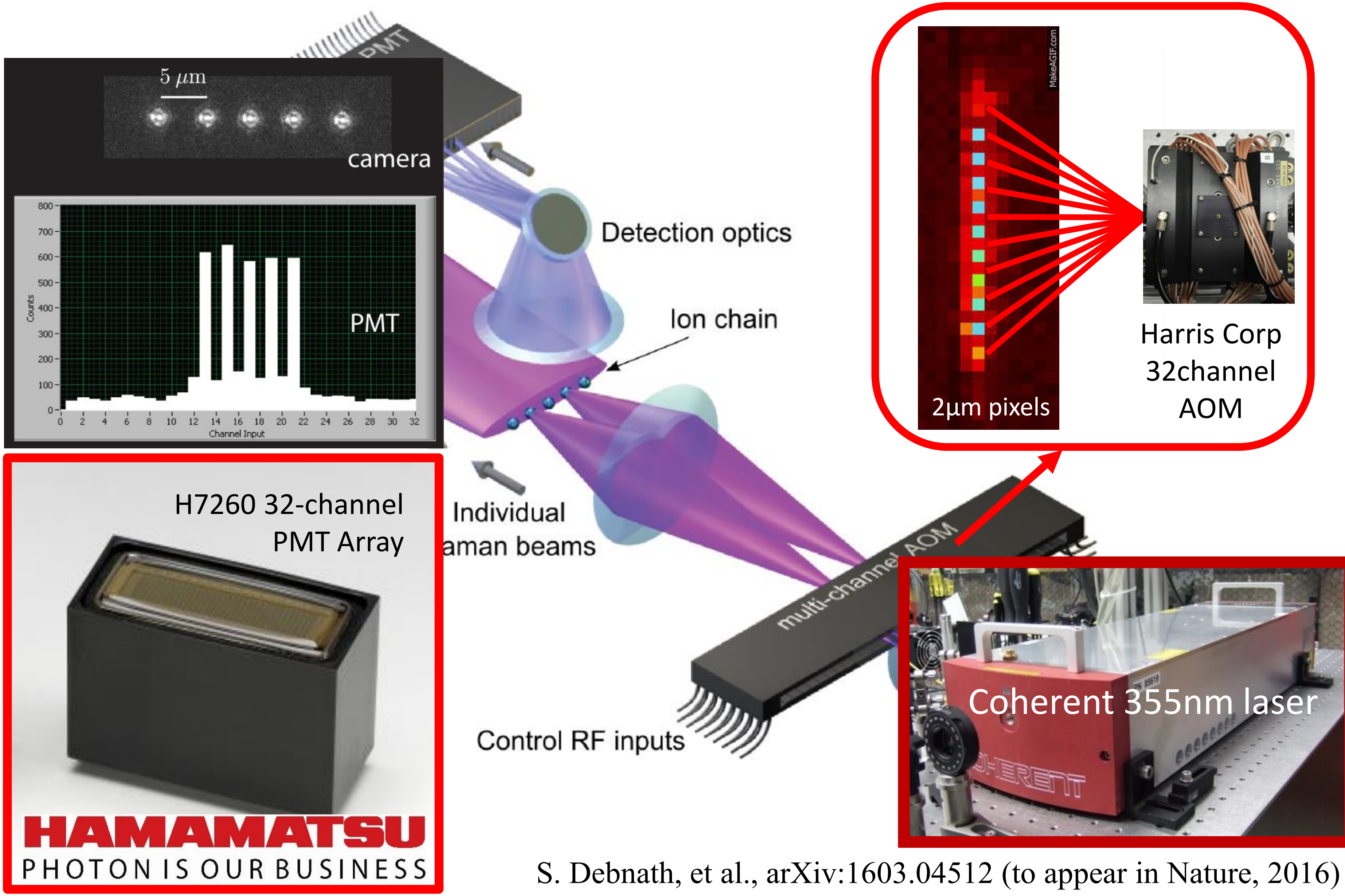
Cirac and Zoller (1995)
Mølmer & Sørensen (1999)
Solano, de Matos Filho, Zagury (1999)
Milburn, Schneider, James (2000)

Programmable Quantum Computer Module (5 qubits)

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.*

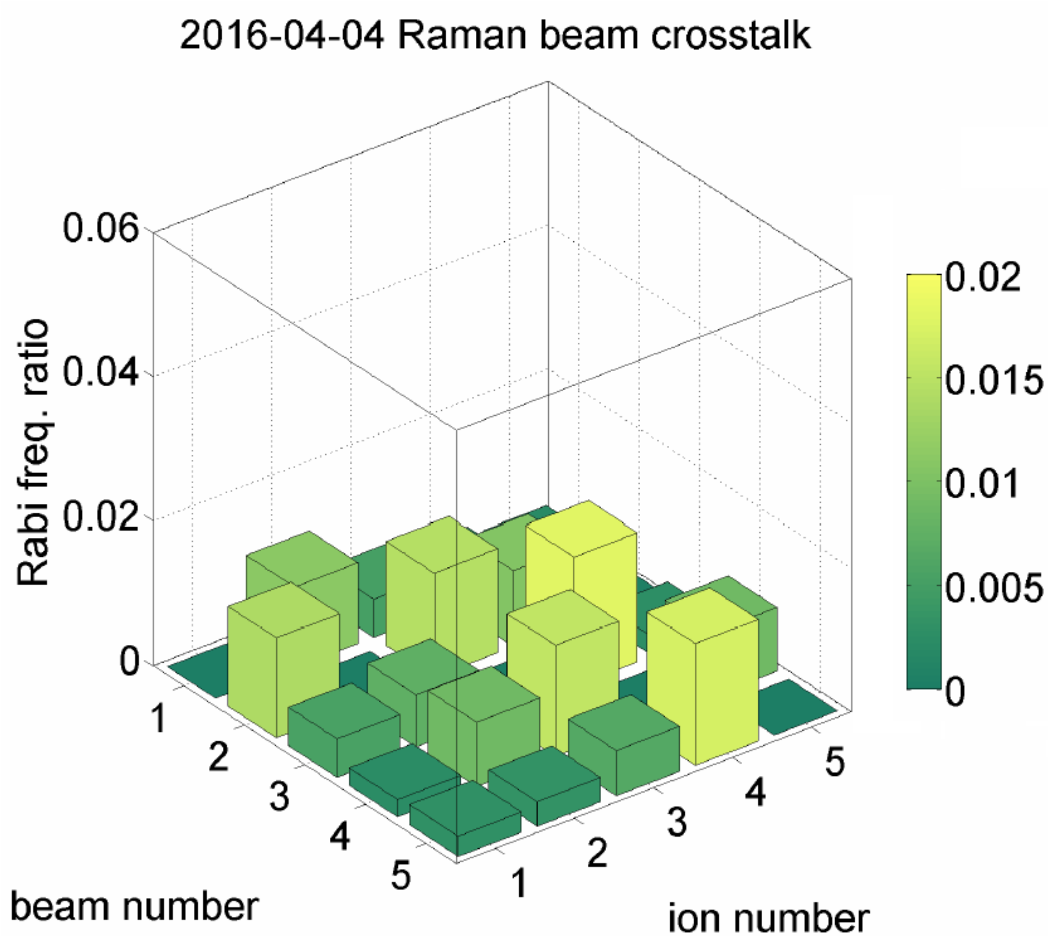
S. Debnath, et al., arXiv:1603.04512 (to appear in Nature, 2016)

Programmable Quantum Computer… Physical Layer



S. Debnath, et al., arXiv:1603.04512 (to appear in Nature, 2016)

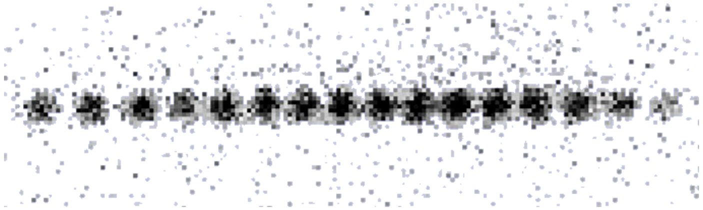
Addressing crosstalk measurements (~1% nearest-neighbor)



S. Debnath, et al., arXiv:1603.04512 (to appear in Nature, 2016)

Many ions: phonon modes

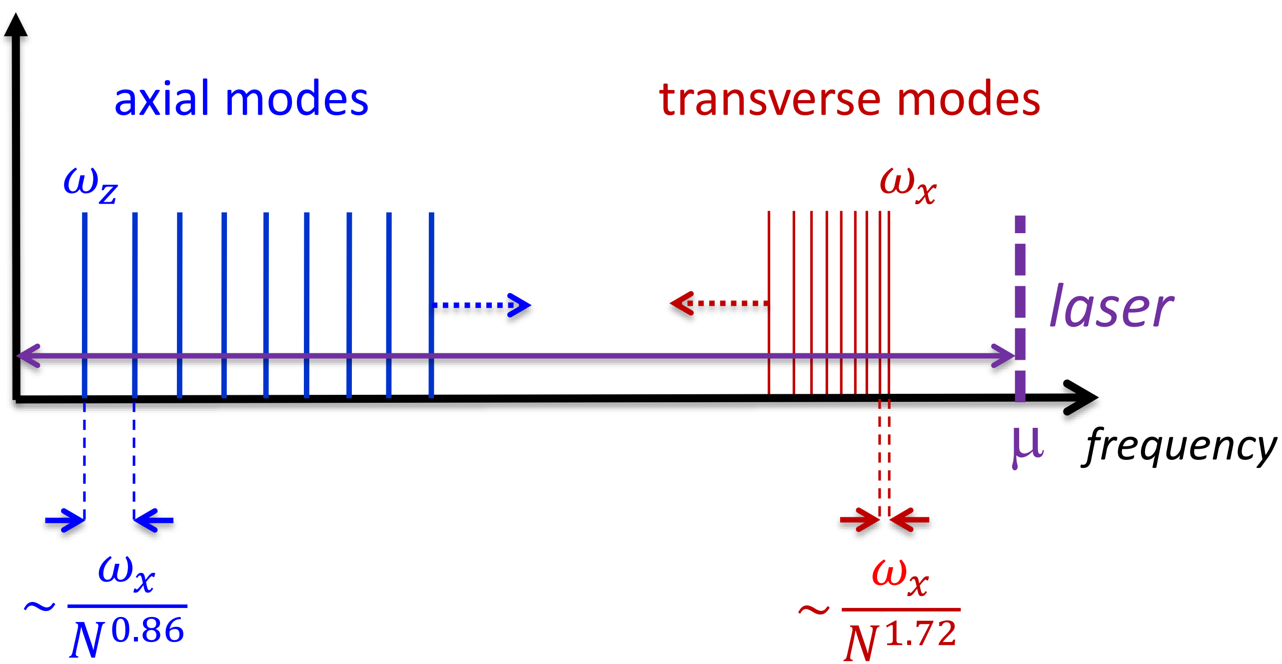
***N* ions in a line**



transverse trap frequency ω_x = high as you can go

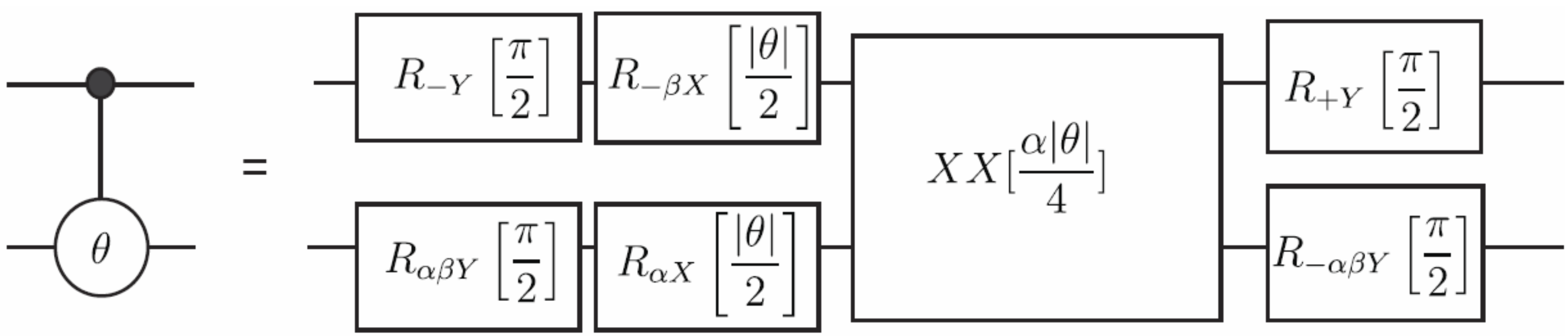
axial trap frequency $\omega_z < \frac{\omega_x}{N^{0.86}}$

J. P. Schiffer, Phys. Rev. Lett. 70, 818 (1993)



Ising XX gate:
pulse-shape laser
to decouple all
modes of motion

Controlled-Phase Gate



$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\beta|\theta|} \end{bmatrix}$$

$$\alpha = sign(J_{ij})$$

← ± phase of Ising coupling

$$\beta = sign(\theta)$$

S. Debnath, et al., arXiv:1603.04512 (to appear in Nature, 2016)

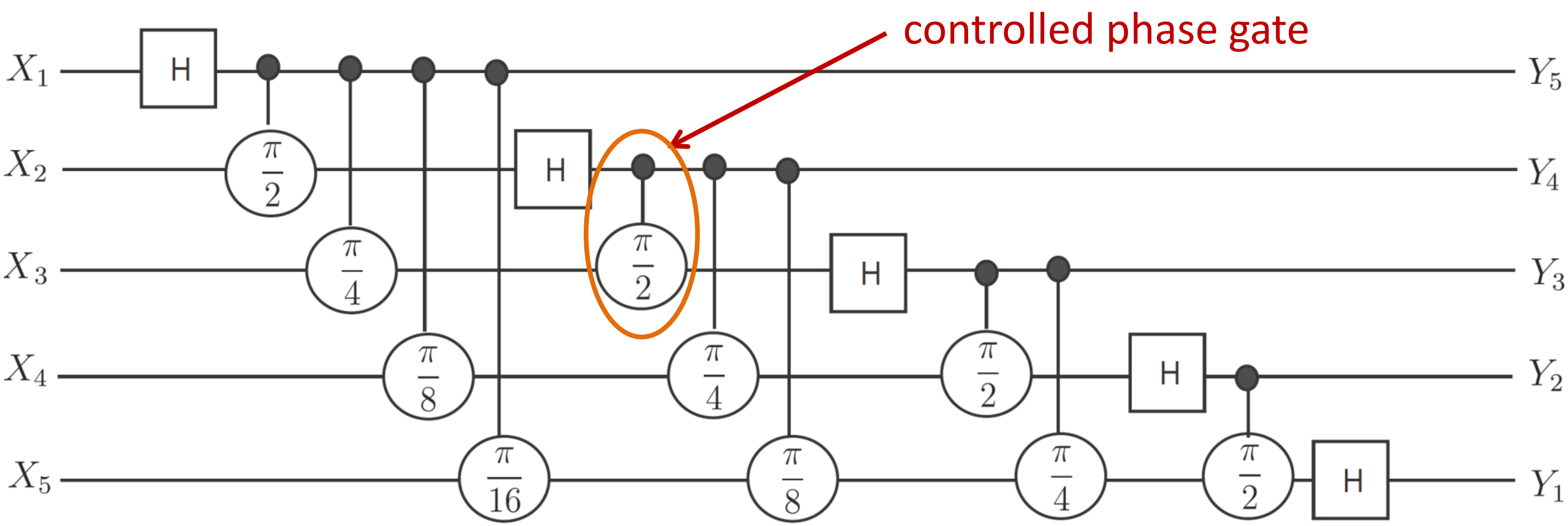
Quantum Fourier Transform (QFT)

$$y_k = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} e^{2\pi i \frac{jk}{N}} x_j \qquad N = 2^n$$

output amplitudes

input amplitudes

QFT circuit (*n*=5 qubits)



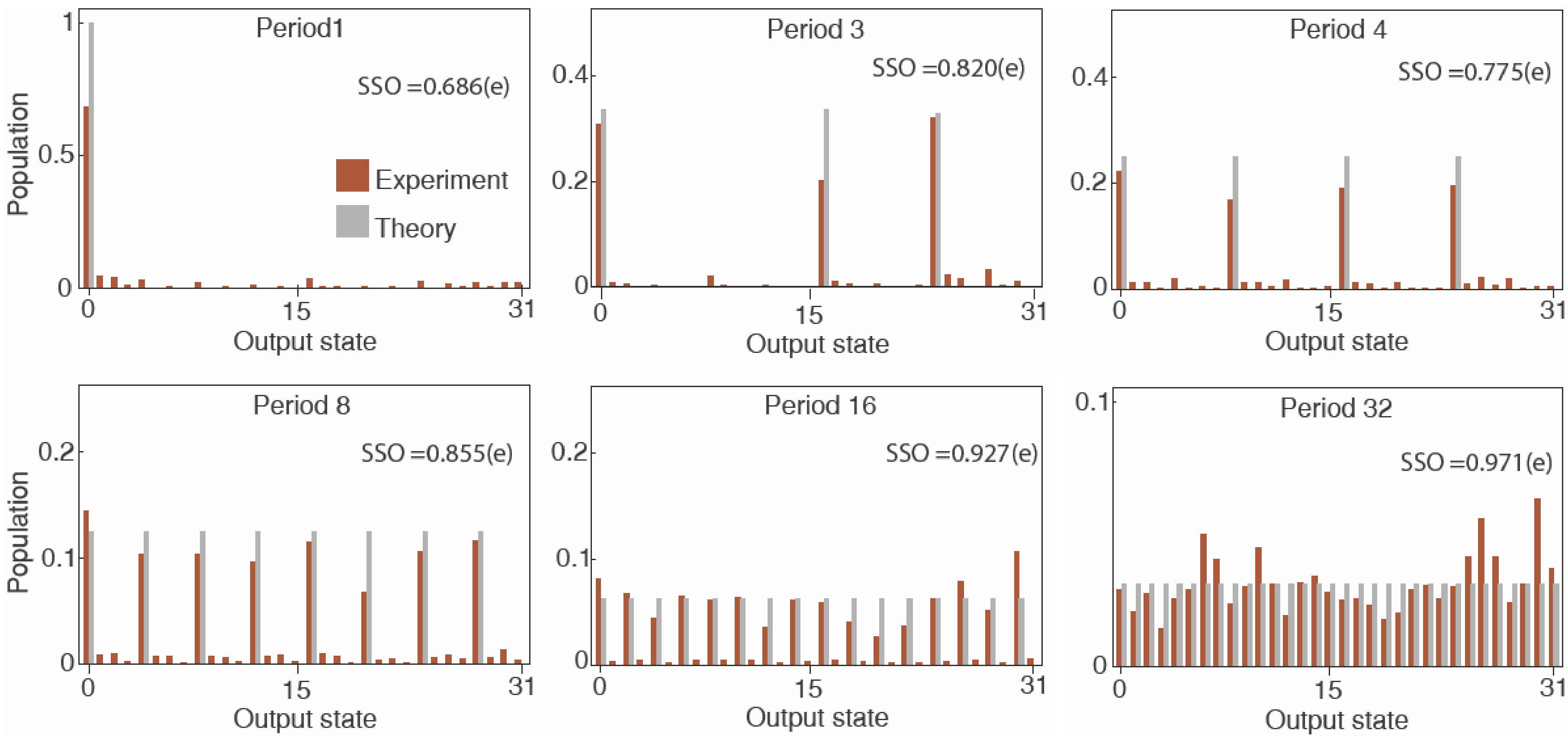
S. Debnath, et al., arXiv:1603.04512 (to appear in Nature, 2016)

QFT: Period Finding

state preparation

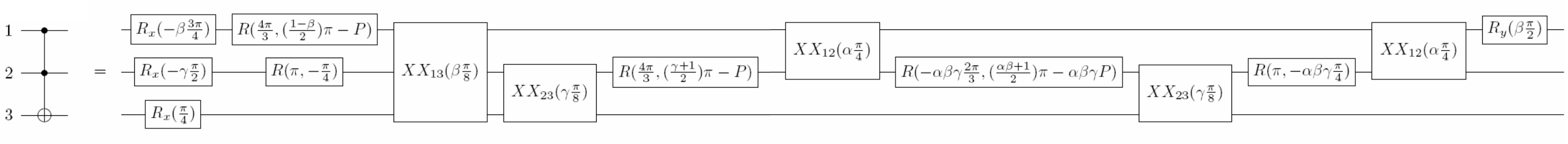
e.g. state with **period 8** = $\underbrace{|00111\rangle}_{7}+\underbrace{|01111\rangle}_{15}+\underbrace{|10111\rangle}_{23}+\underbrace{|11111\rangle}_{31}=(|0\rangle+|1\rangle)(|0\rangle+|1\rangle)|\overbrace{111}\rangle$

results

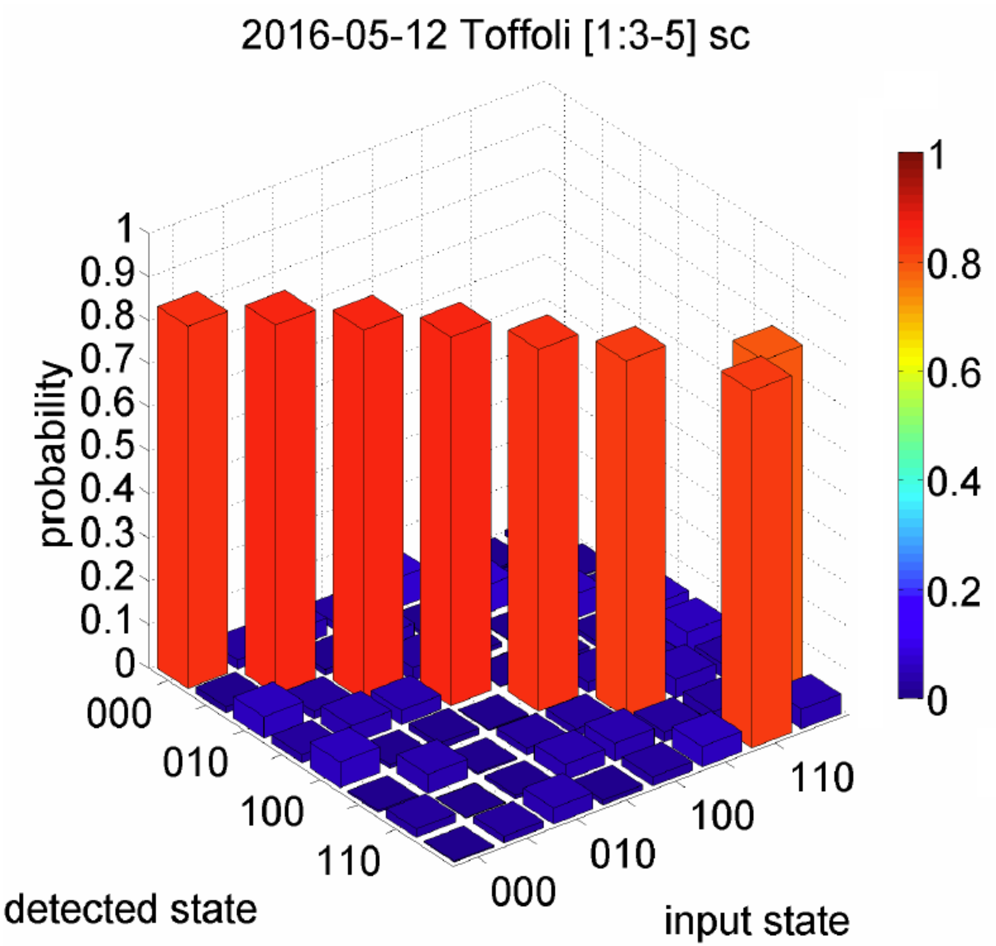


S. Debnath, et al., arXiv:1603.04512 (to appear in Nature, 2016)

Toffoli gate



$\alpha = sgn(\chi_{12})$, $\beta = sgn(\chi_{13})$, $\gamma = sgn(\chi_{23})$, and $P = \arcsin\sqrt{\frac{2}{3}}$



fidelity 83%

(excl. spam ~1.4%)

Journal of Statistical Physics, Vol. 29, No. 3, 1982

Quantum Mechanical Hamiltonian Models of Turing Machines

Paul Benioff[1]

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Received October 5, 1981;

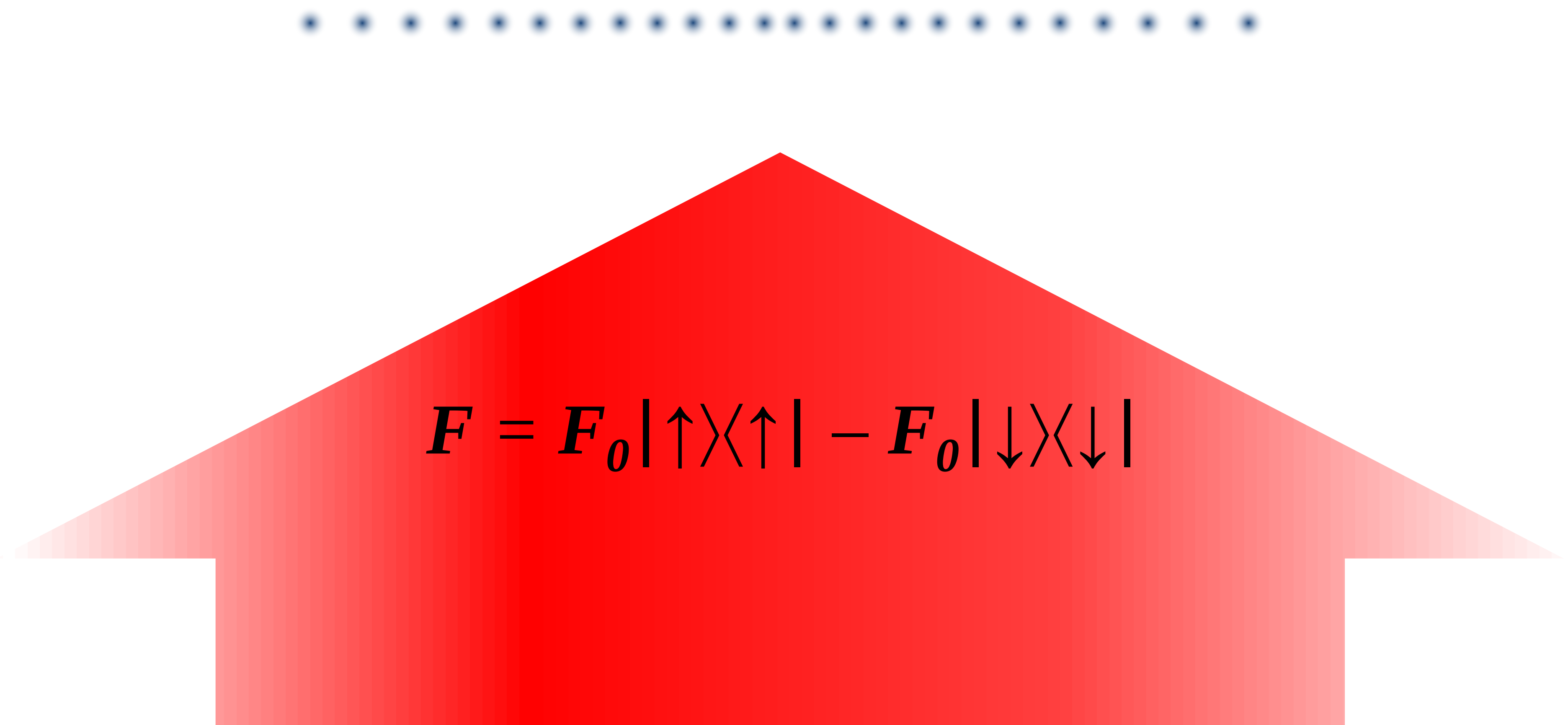
Quantum mechanical Ha
finite number of steps of a
on a finite lattice of spin-1
to different components o
sive states of any machin
configuration states. Both
models are constructed h
energy or degrade the sy:
quantum limit in that the
close to the limit given b
model evolution is time
time-dependent models dc
and the Hamiltonian is le

Simulating Physics with Computers

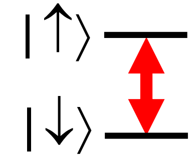
Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

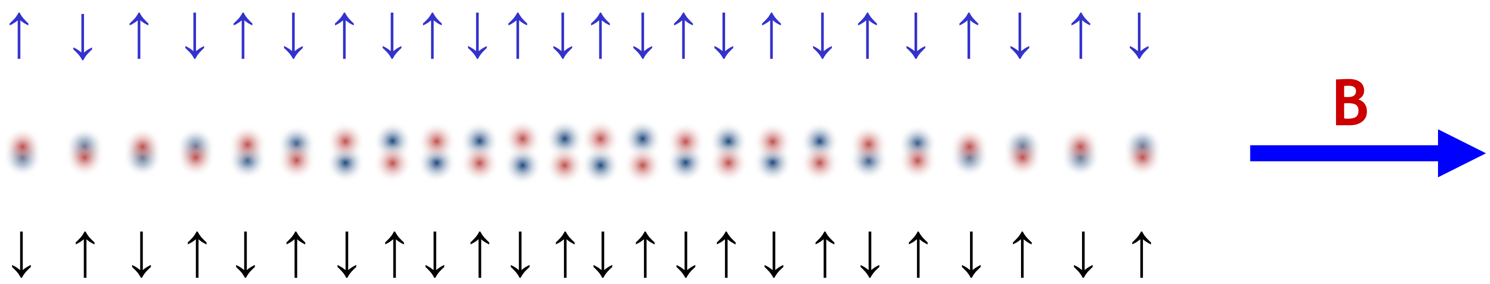
weak/slow global spin-dependent force



global spin-dependent force



ADD: Independent spin flips

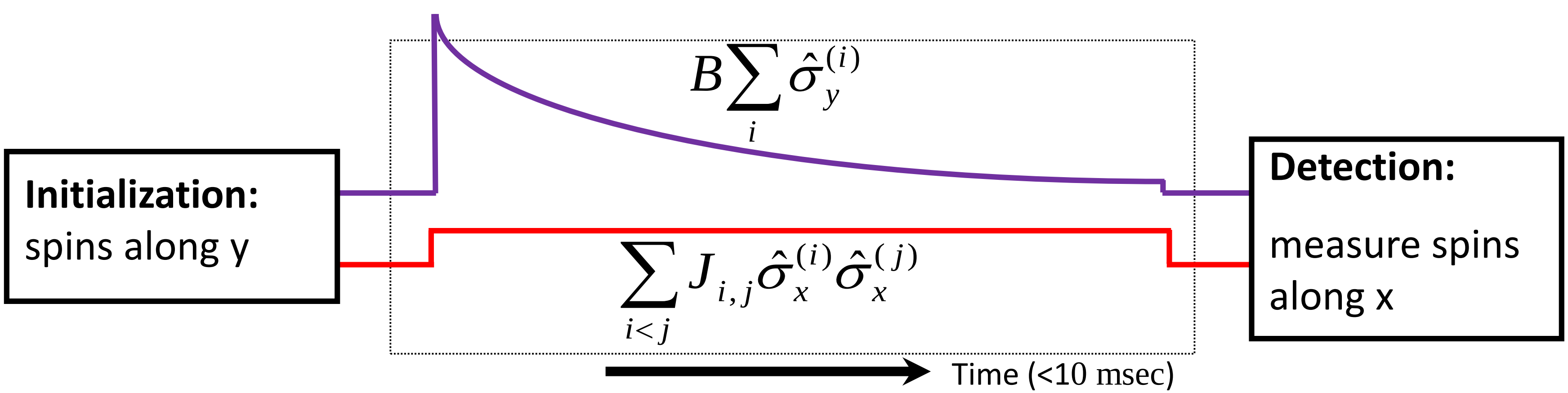


$$F = F_0|\uparrow\rangle\langle\uparrow| - F_0|\downarrow\rangle\langle\downarrow|$$

Adiabatic Quantum Simulation

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

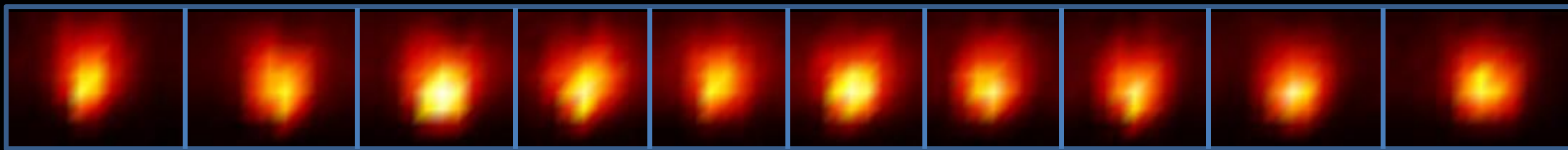
$$H = \sum_{i<j} \frac{J_0}{|i-j|^{\alpha}} \sigma_x^i \sigma_x^j + B \sum_i \sigma_y^i \qquad 0 < \alpha < 3$$



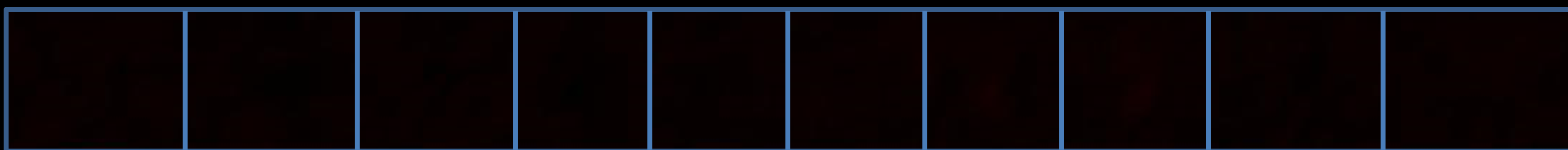
Antiferromagnetic Néel order of N=10 spins

2600 runs, α=1.12

All in state ↑

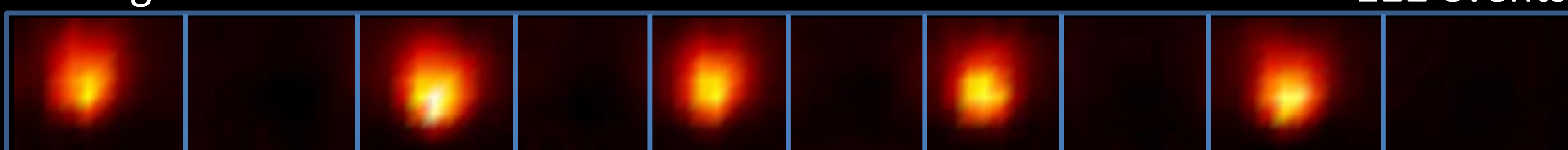


All in state ↓

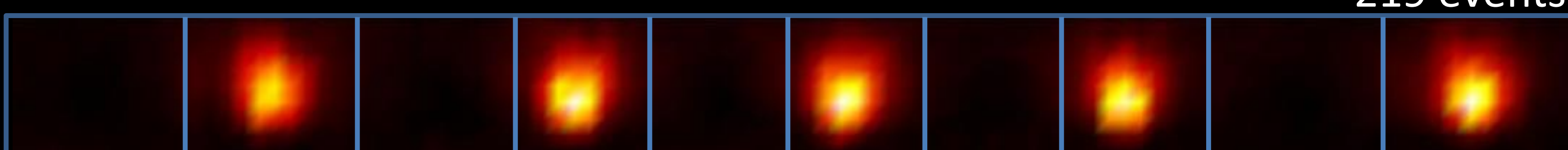


AFM ground state order

222 events



219 events



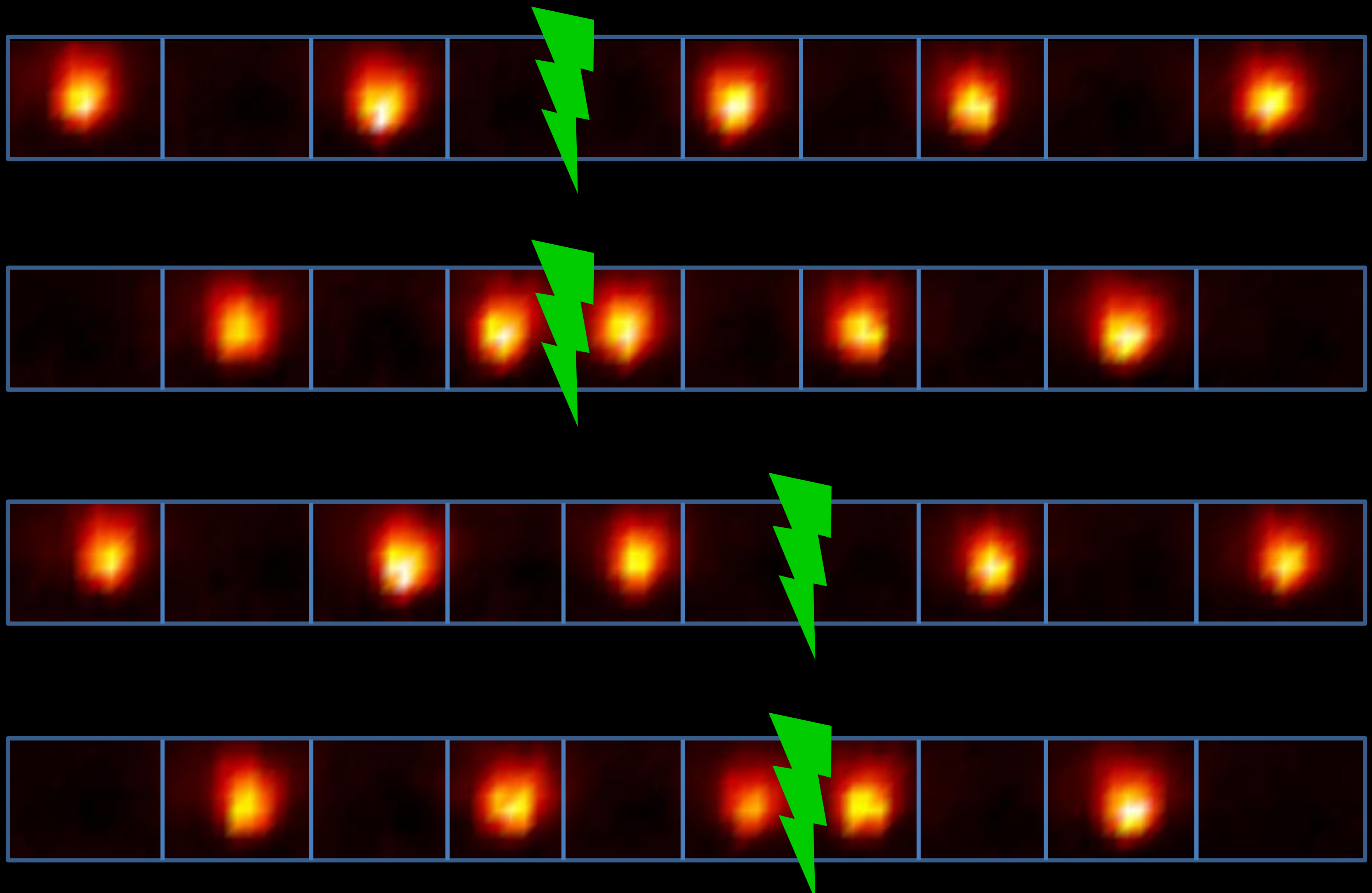
441 events out of 2600 = 17%

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

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

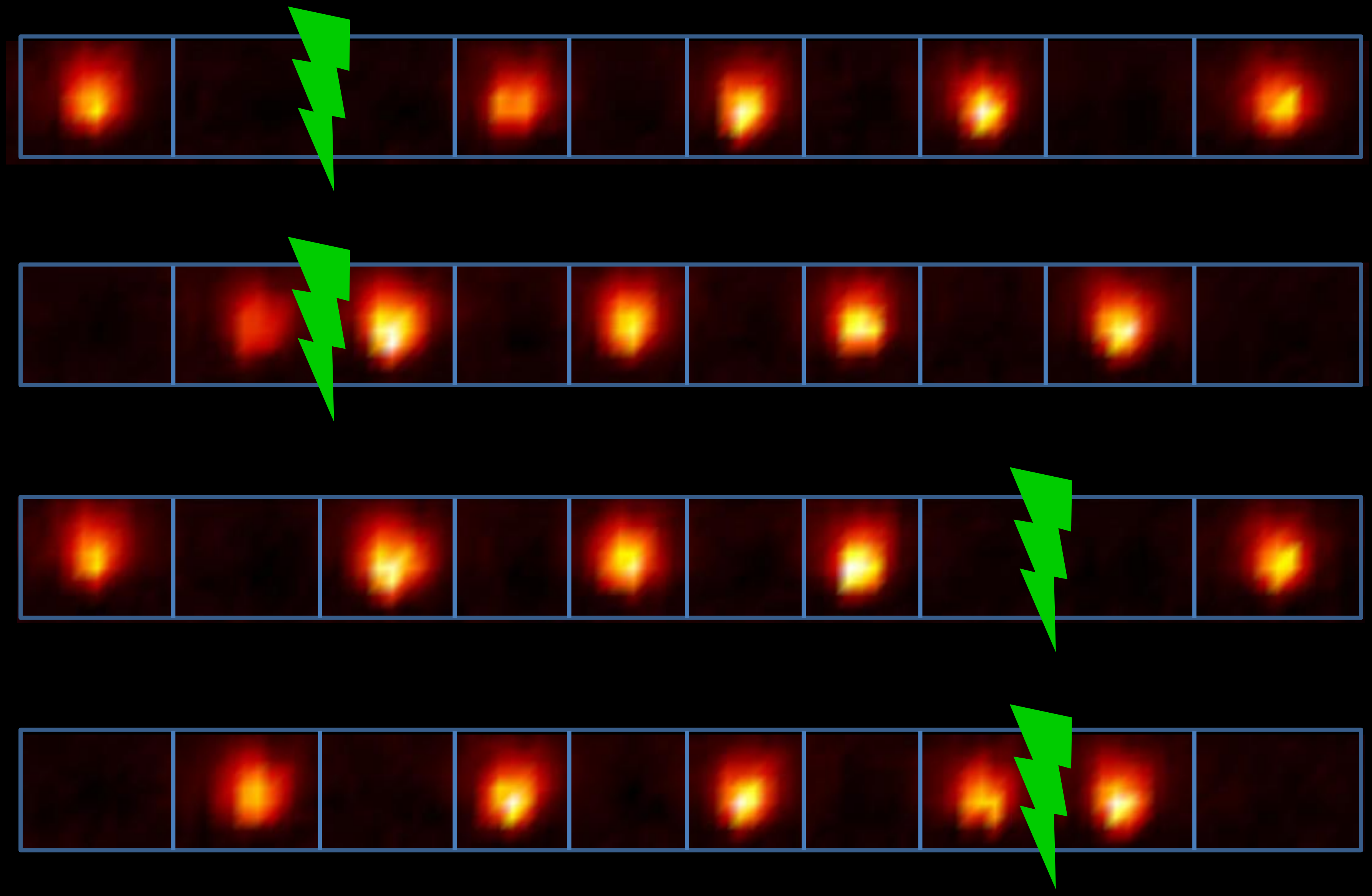
First Excited States

(Pop. ~2% each)

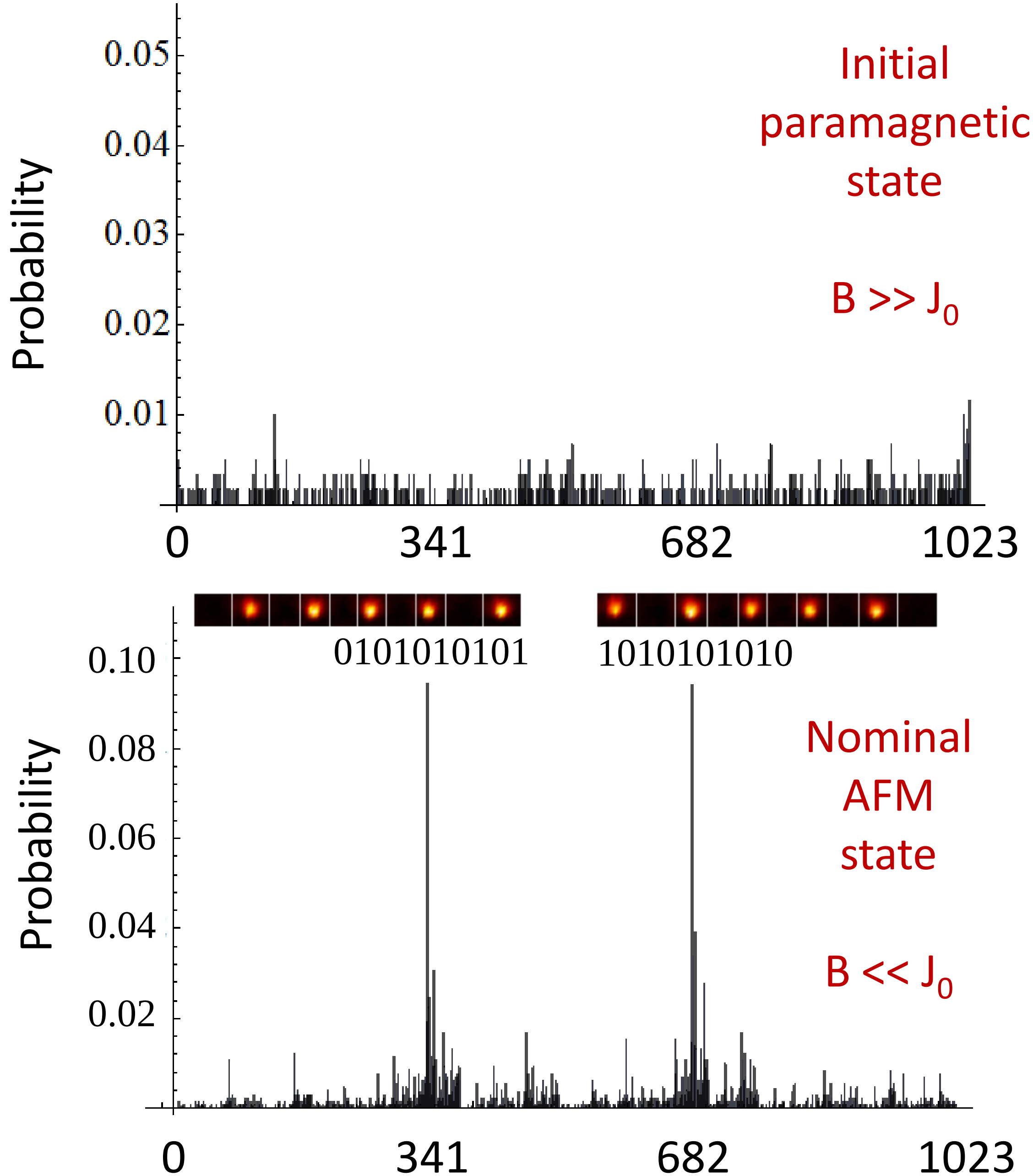


Second Excited States

(Pop. ~1% each)

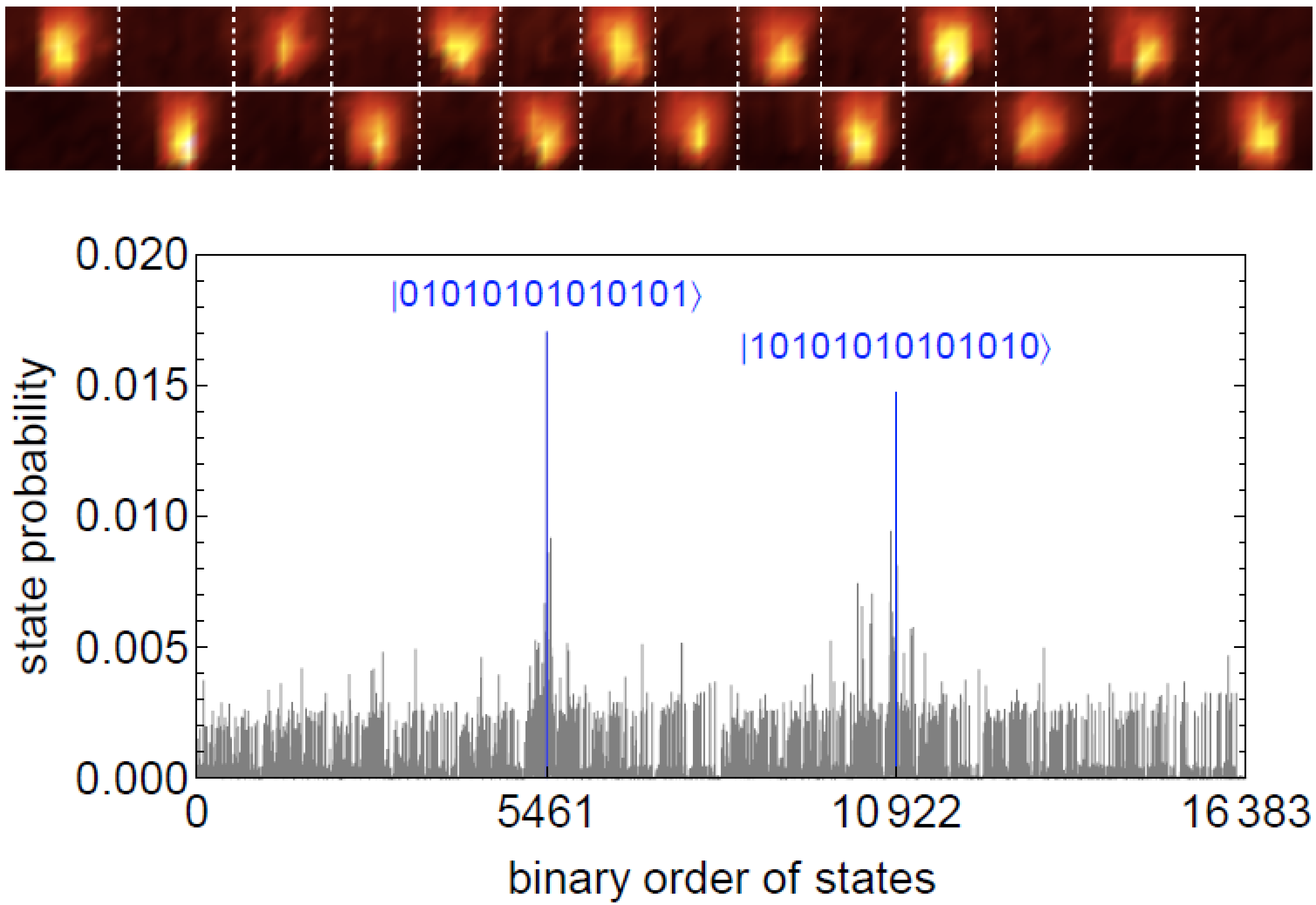


Distribution of all 2^{10} = 1024 states

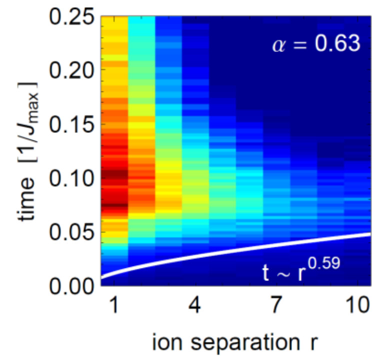


R. Islam et al., Science 340, 583 (2013)

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



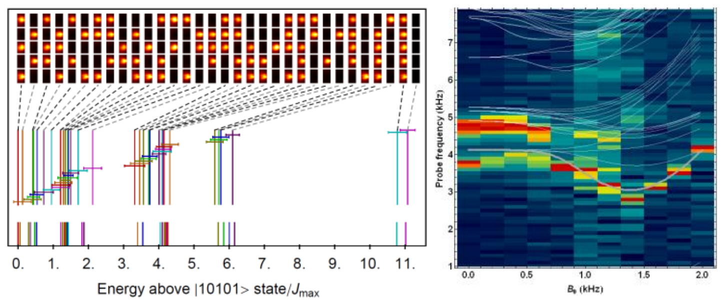
etc…



Propagation of correlations and entanglement with long-range interactions

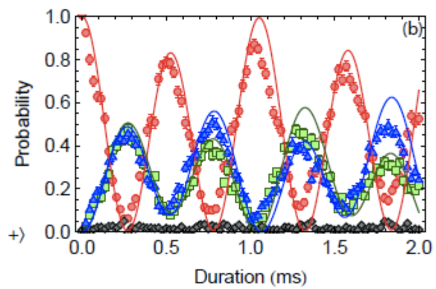
P. Richerme et. al., *Nature* **511**, 198 (2014)

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



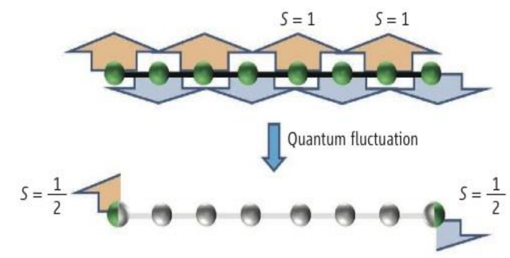
Many-Body Spectroscopy

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



Spin-1 Dynamics

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



Many-body Localization

J. Smith, et al., arXiv 1508.07026 (2015)

Dynamics of N=22 spins

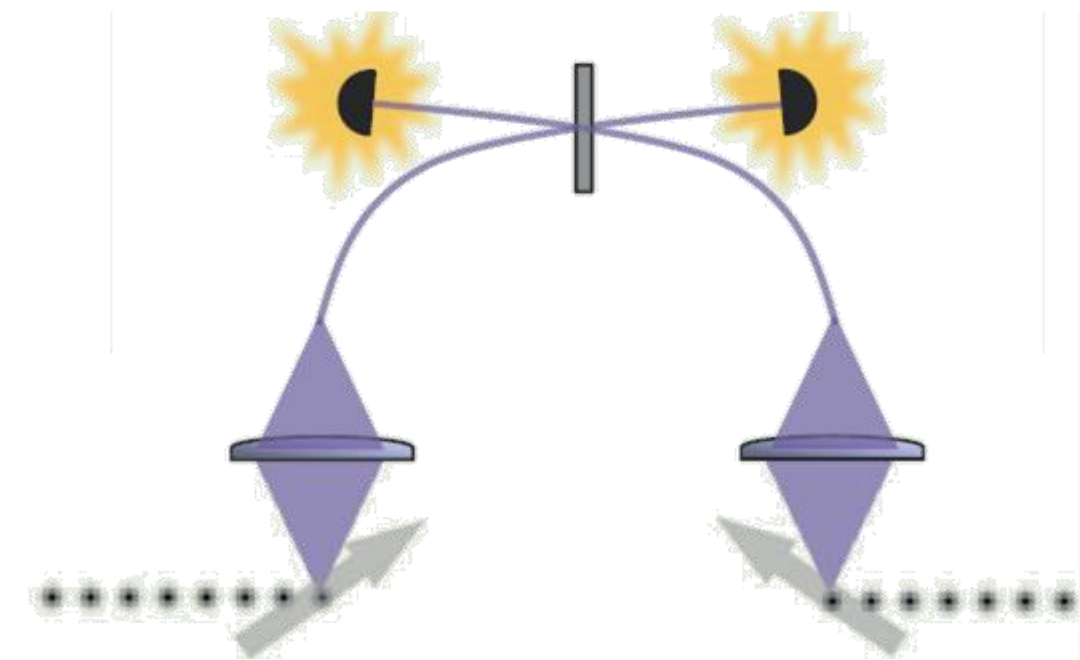
$$H_{XY} = \sum_{i<j} \frac{J_0}{|i-j|^\alpha} \left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j \right)$$

$\alpha = 0.6$

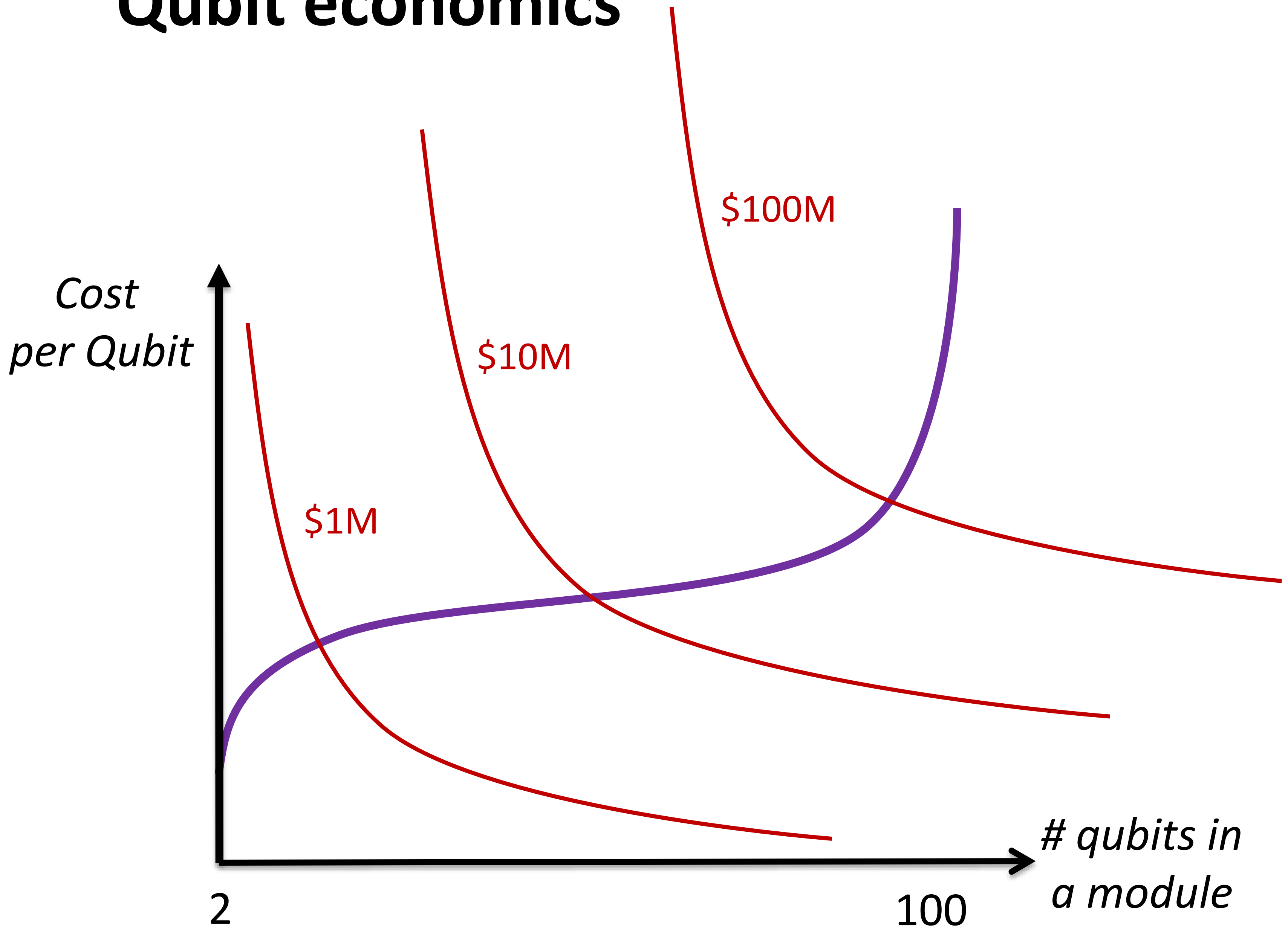
state measured at $J_0 t = 36$

B. Neyenhuis et al., in preparation (2015)

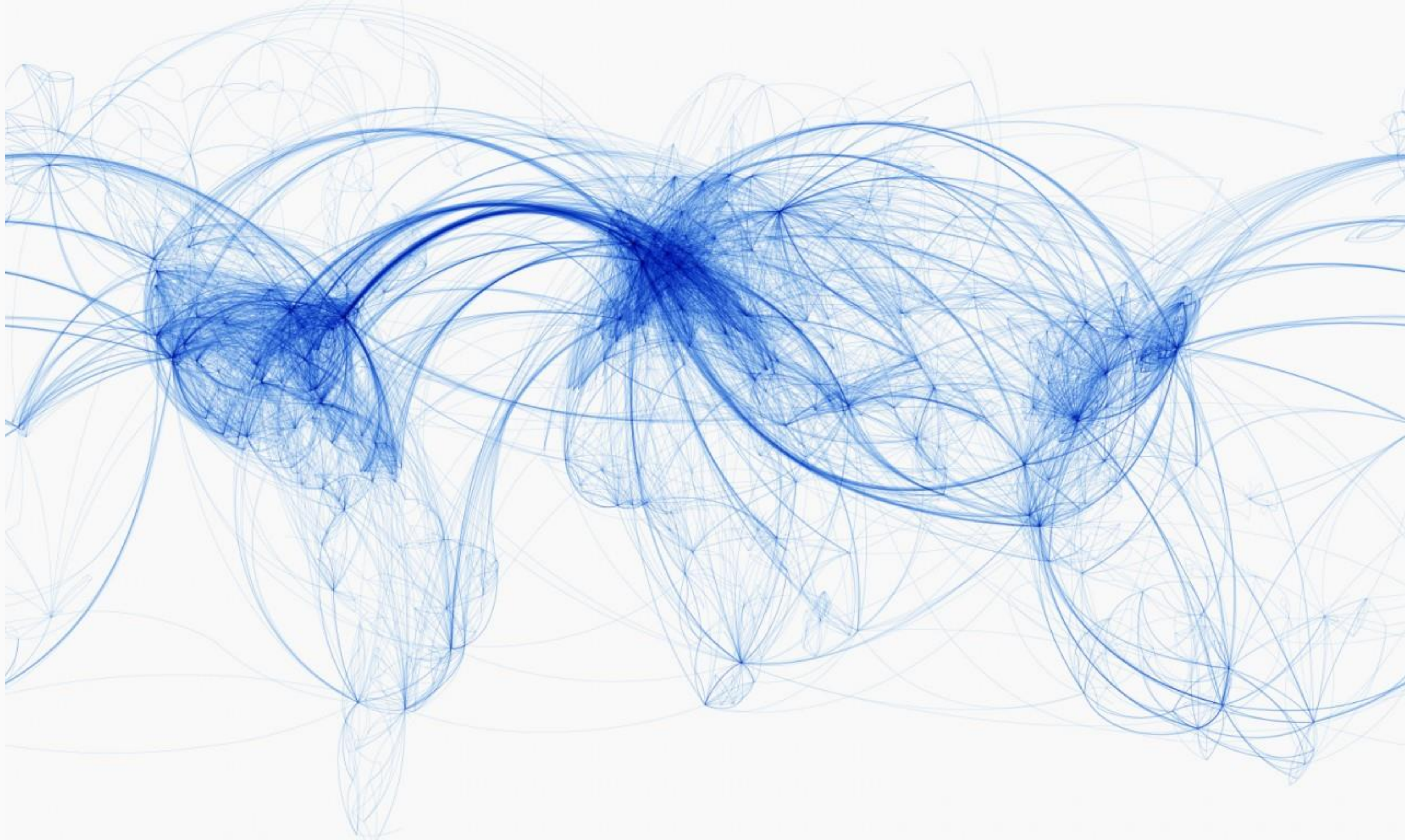
Scaling Up



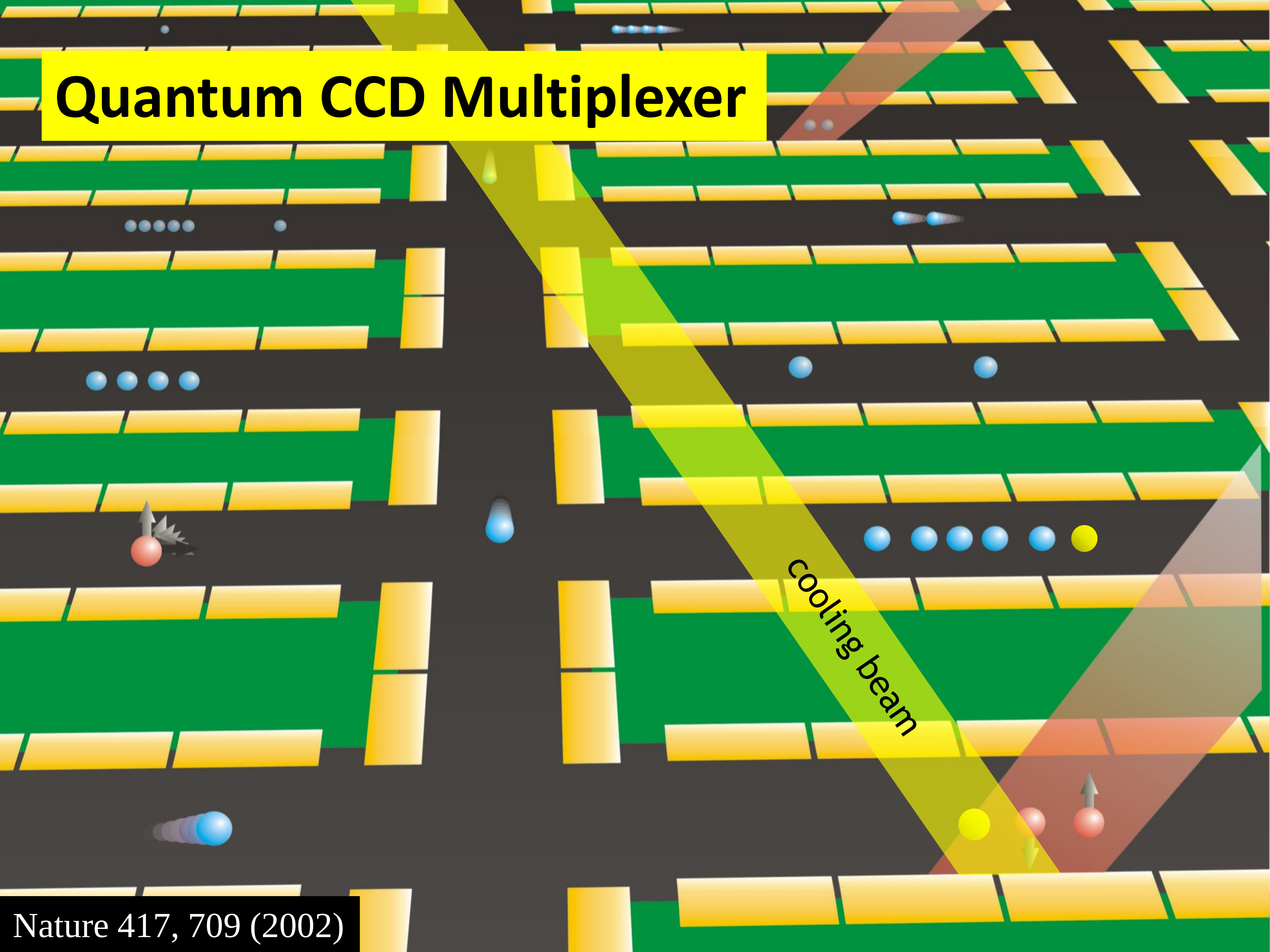
Qubit economics



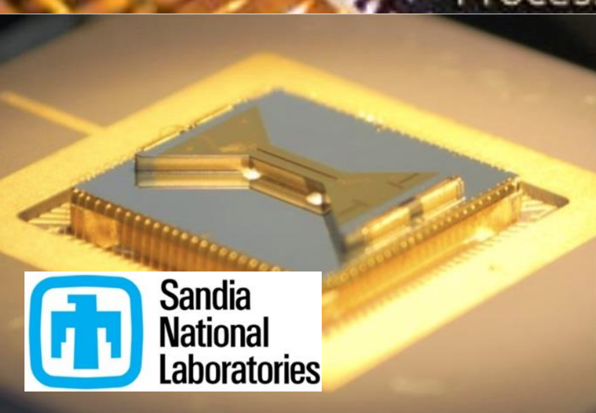
Scaling through Modularity



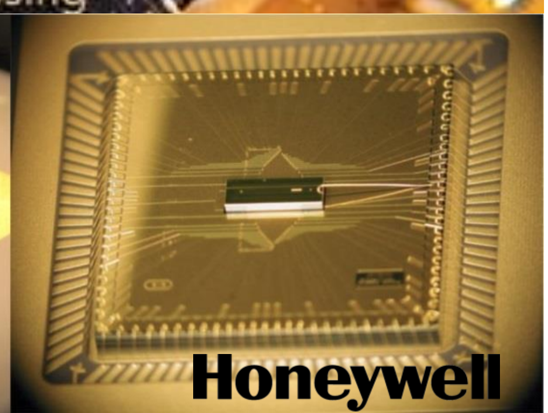
Quantum CCD Multiplexer



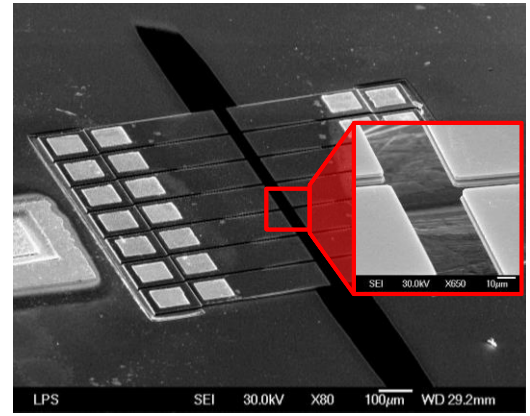
Nature 417, 709 (2002)



Sandia National Laboratories

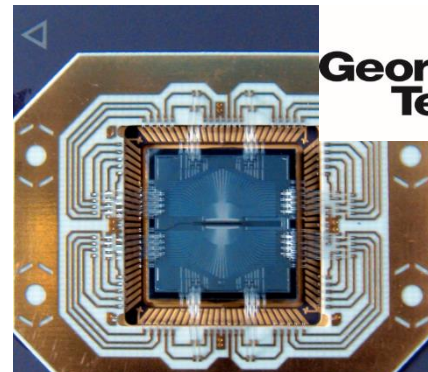


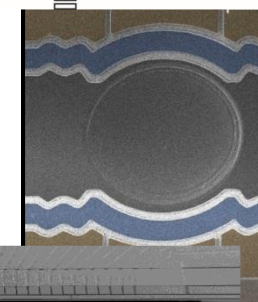
Honeywell

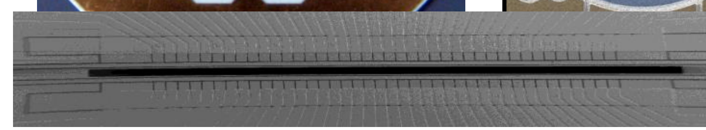


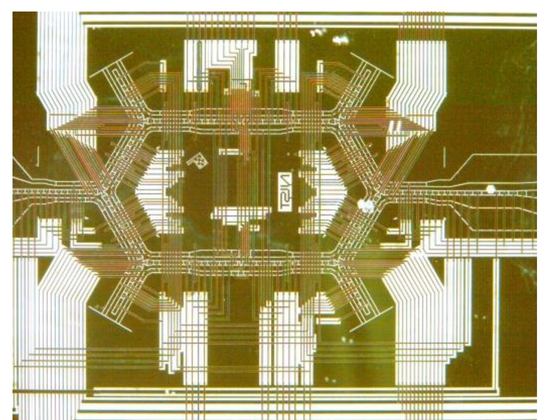
The Laboratory for Physical Sciences

Georgia Tech Research Institute



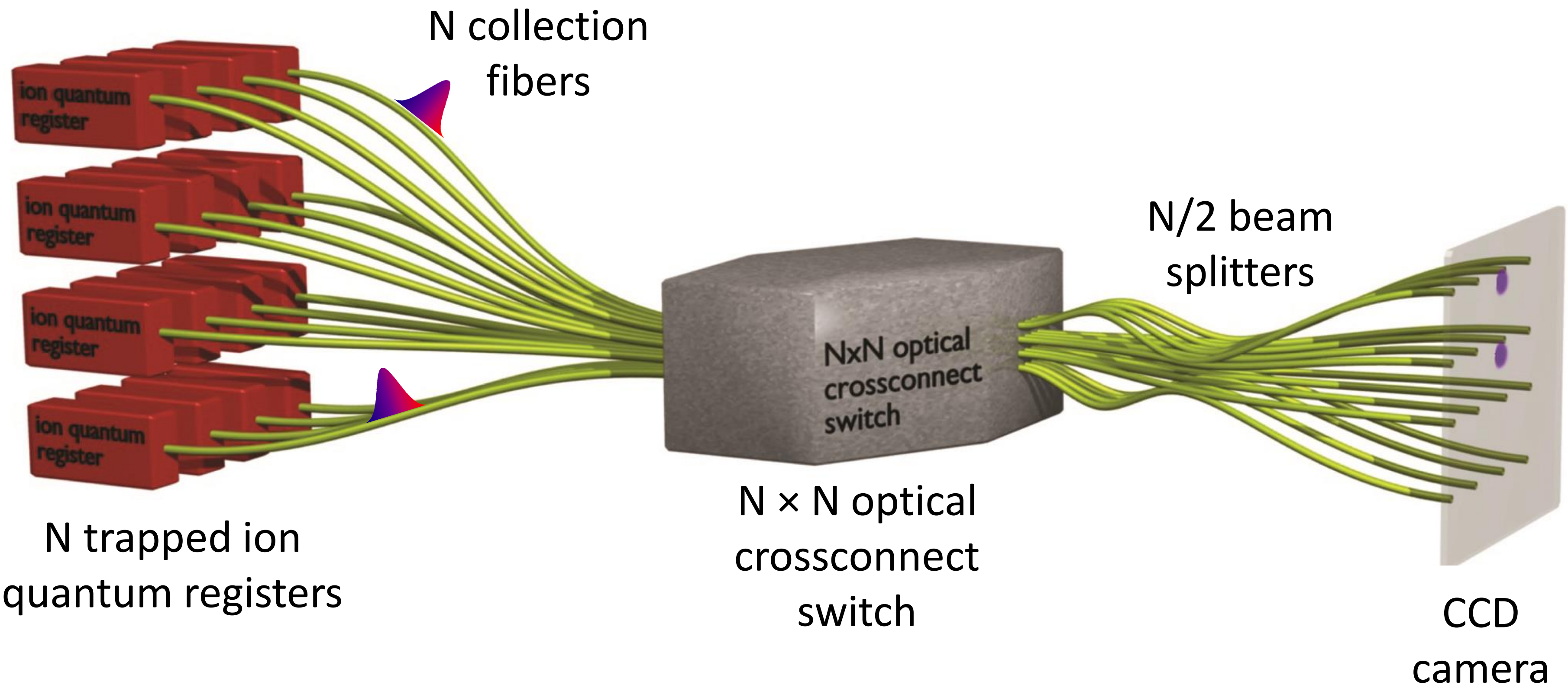






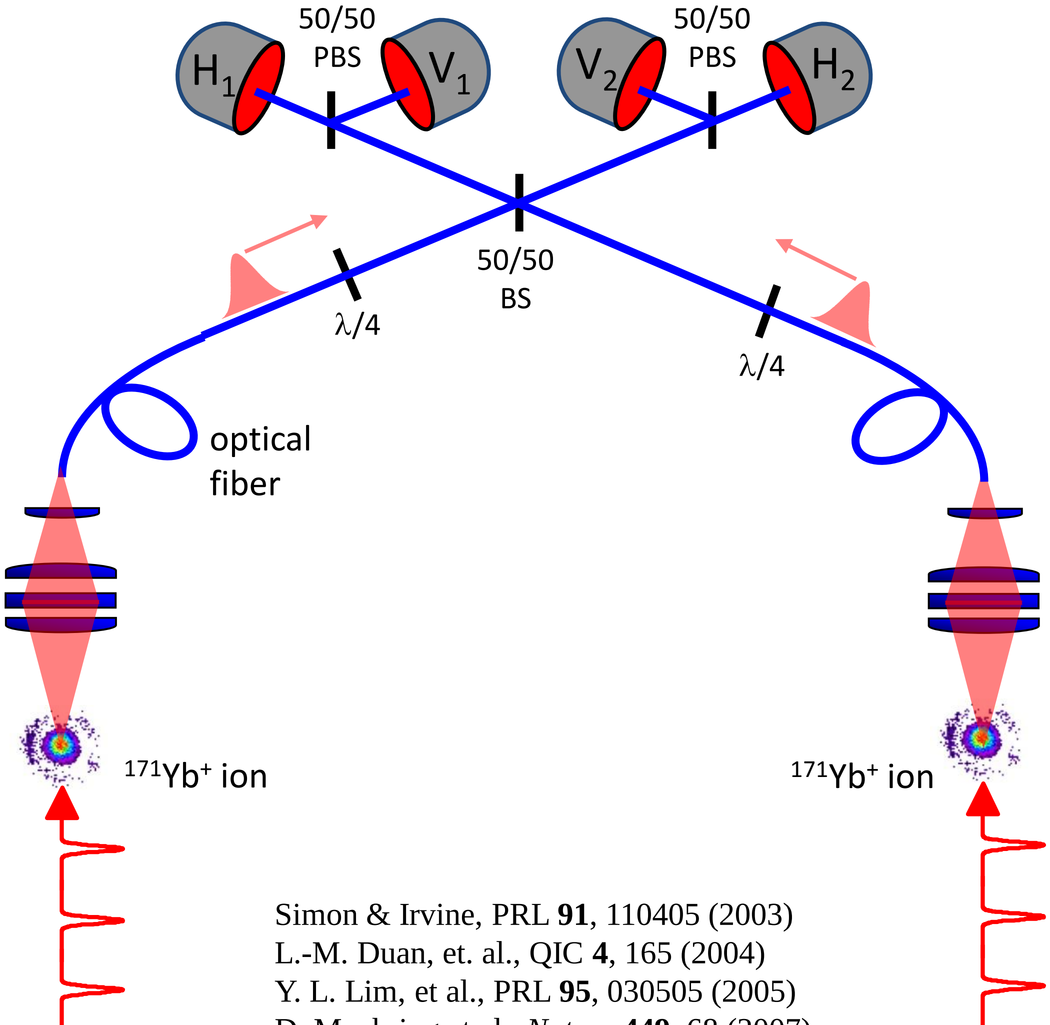
NIST

(to 1,000,000 qubits?)



C. Monroe, J. Kim, et al., Phys. Rev. A 89, 022317 (2014)

Linking remote atoms with photons



Simon & Irvine, PRL **91**, 110405 (2003)
L.-M. Duan, et. al., QIC **4**, 165 (2004)
Y. L. Lim, et al., PRL **95**, 030505 (2005)
D. Moehring et al., *Nature* **449**, 68 (2007)

Heralded coincident events (p_{suc}=1/2):

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

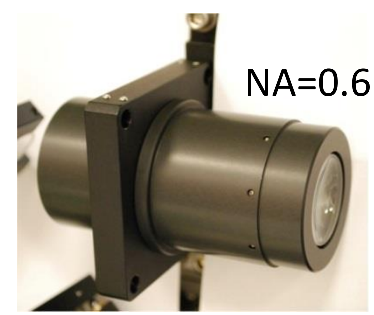
$$R_{ent} = \frac{1}{2} R p^2$$

Current:

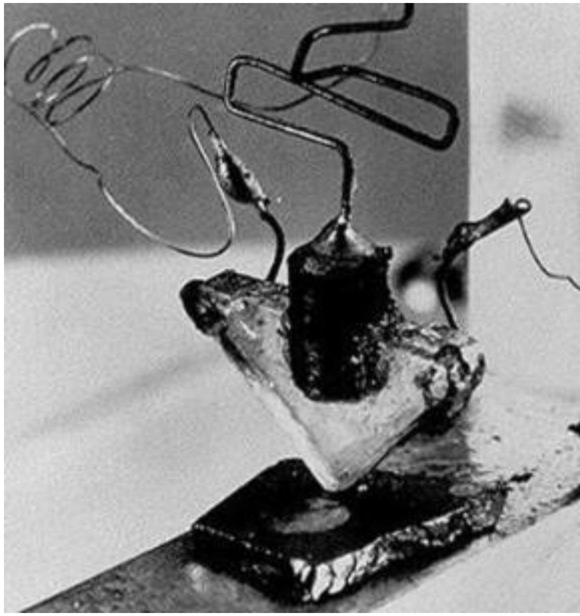
$$R = 600 kHz$$

$$p = h_D \cdot F \cdot \frac{dW}{4p} = (0.25)(0.20)(0.10)$$

$$R_{ent} = 6 s^{-1}$$

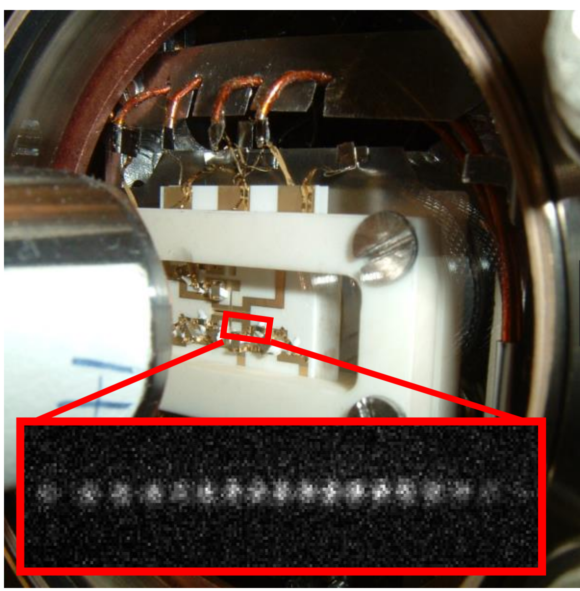


D. Hucul, et al., Nature Phys. 11, 37 (2015)

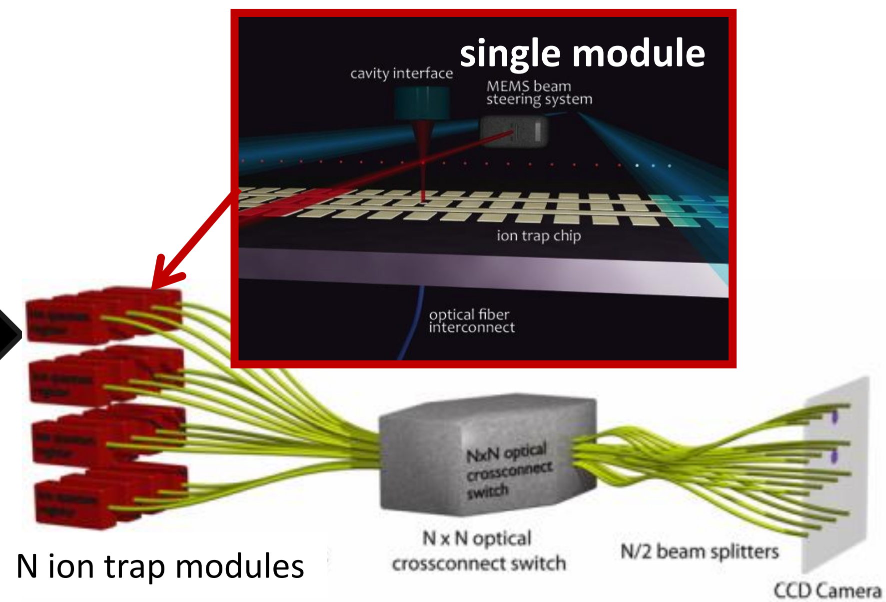


1947: first transistor

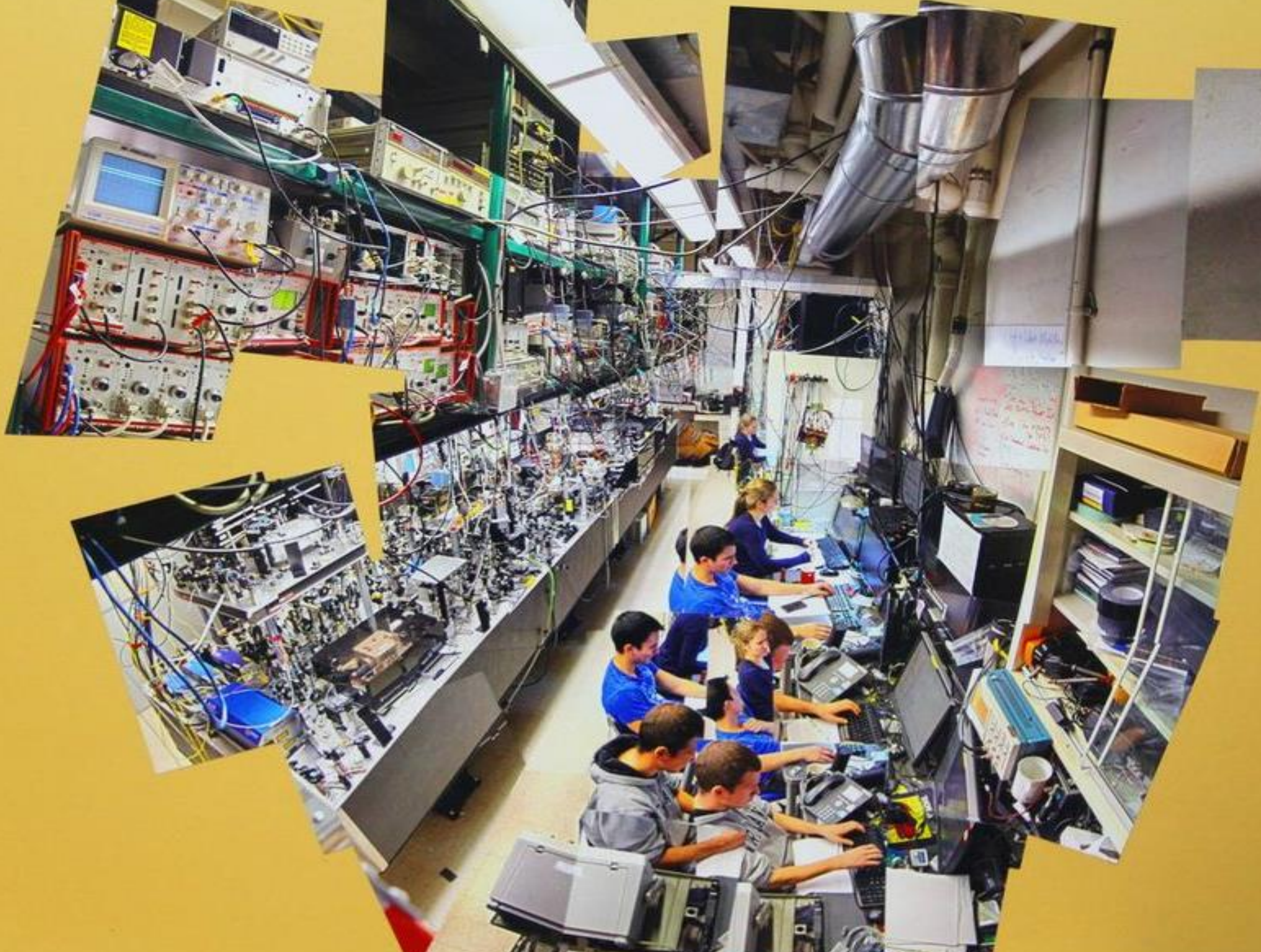
2000: integrated circuit



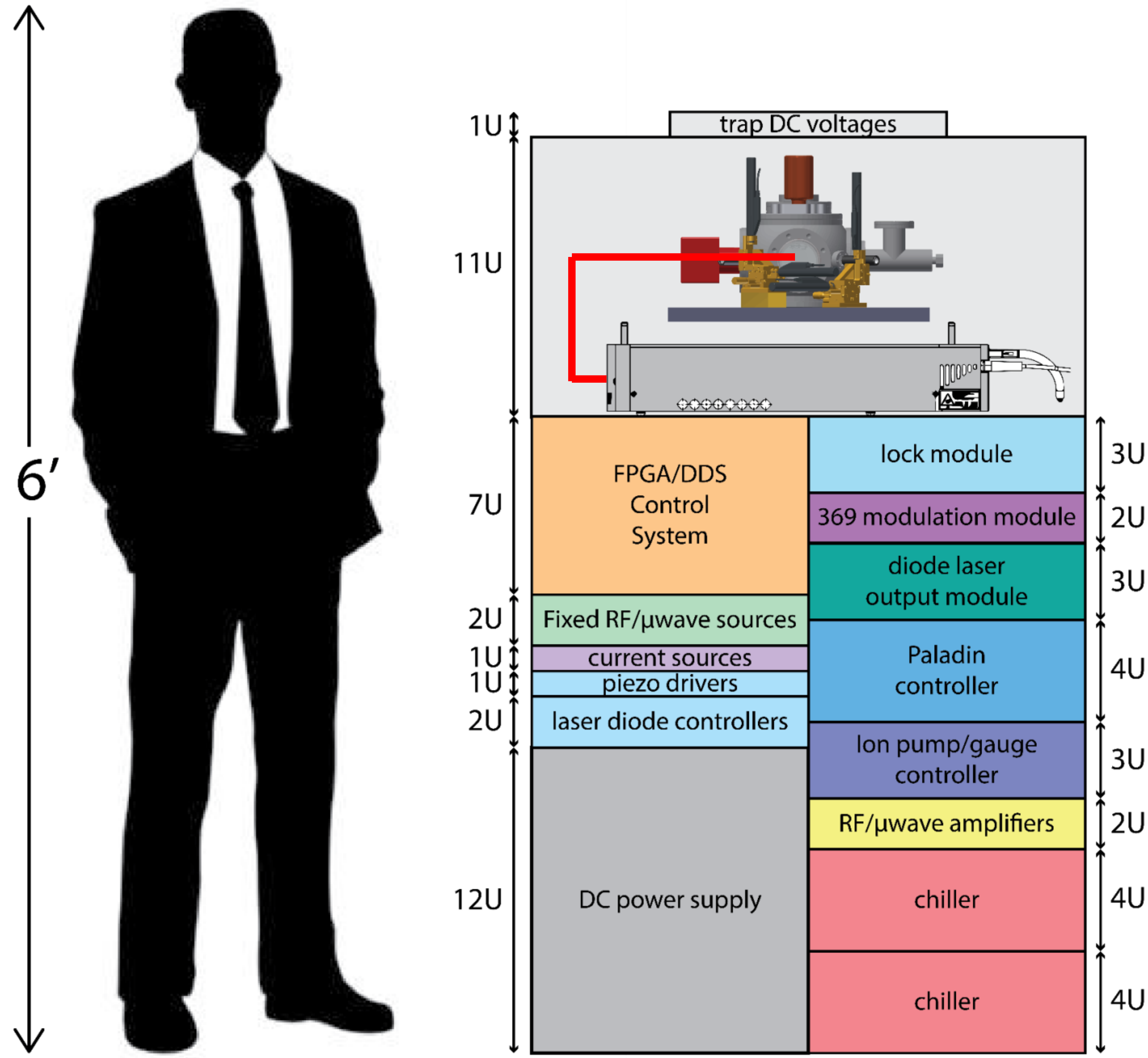
2015: qubit collection



Large scale quantum network?

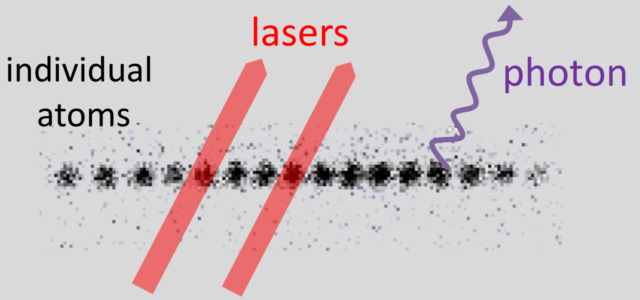


Single Module ~100 spins on two 19” Racks



Leading Quantum Computer Hardware Candidates

Trapped Atomic Ions



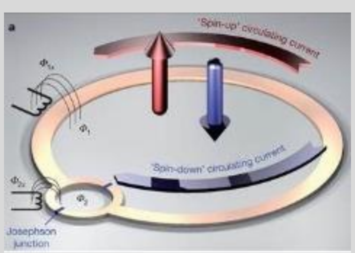
Atomic qubits connected through laser forces on motion or photons

FEATURES & STATE-OF-ART
- very long (>>1 sec) memory
- 5-20 qubits demonstrated
- **atomic qubits all identical**
- **connections reconfigurable**

CHALLENGES
- lasers & optics
- slow gates
- high vacuum
- **engineering needed**

Investments: IARPA, Lockheed, GTRI, UK Gov't, Sandia

Superconducting Circuits



Superconducting qubit: "right or left current"

FEATURES & STATE-OF-ART
- connected with wires
- fast gates
- 5-10 qubits demonstrated
- **printable 2D circuits and VLSI**

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

LARGE Investments: Google/UCSB, IBM, Lincoln Labs, Intel/Delft

Trapped Ion Quantum Information

www.iontrap.umd.edu

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LPS/NSA ARO