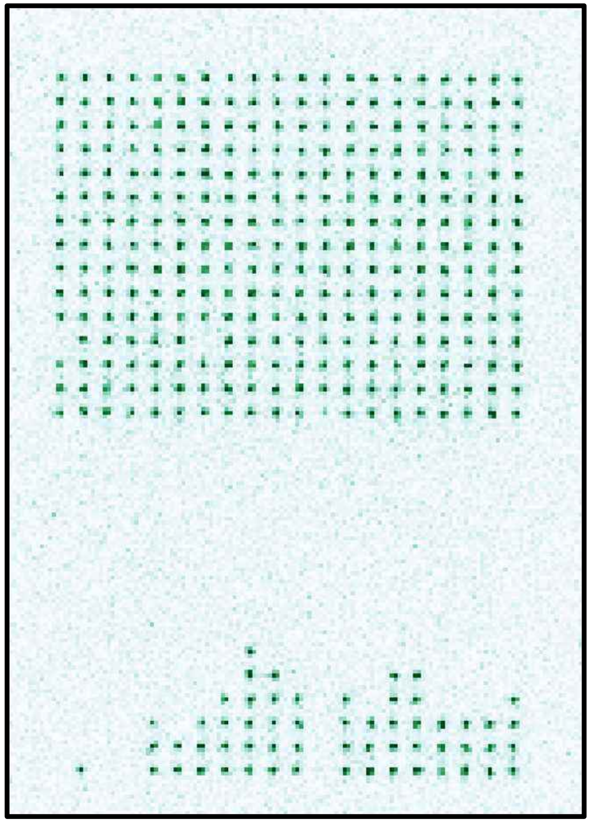
The Quantum Age: From Bell Pairs to Quantum Computers



Vladan Vuletić,
in collaboration with Mikhail Lukin and Markus Greiner (Harvard)

Massachusetts Institute of Technology
MIT-Harvard Center for Ultracold Atoms

Outline

- Individual cold and trapped atoms as quantum bits
- Arranging many individual atoms deterministically in arrays of optical traps
- Strongly interacting spin models via Rydberg blockade
- Analog quantum simulation with neutral atoms
- Towards error corrected quantum computing

Preface: Trapping individual atoms and inducing controlled two-atom interactions over optically resolvable distances

A quantum computing device with individual atoms …

Richard Feynman

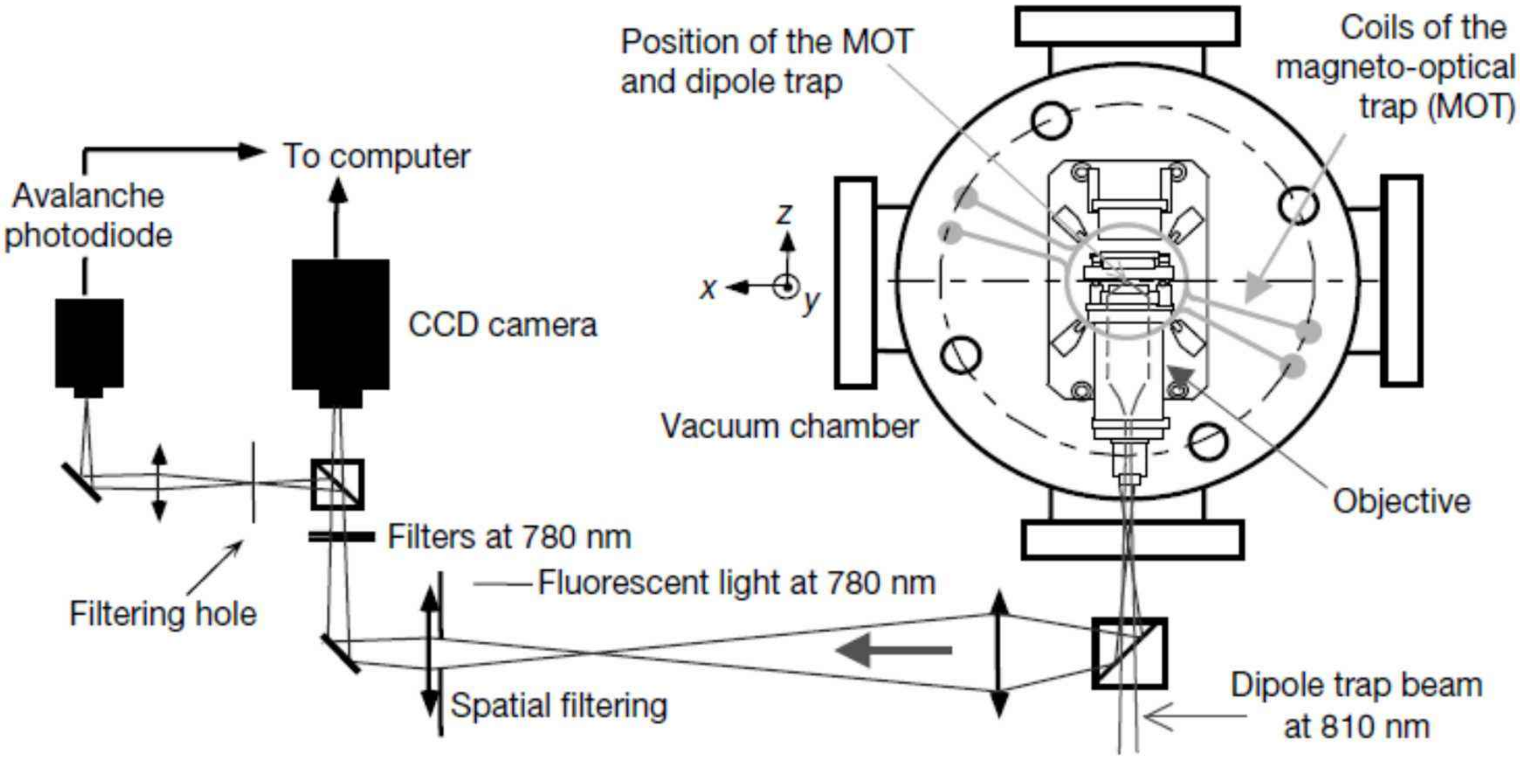
"Now, we can, in principle make a computing device in which the numbers are represented by a row of atoms with each atom in either of the two states. That's our input. [Then the] Hamiltonian starts.. The ones move around, the zeros move around. Finally, .. a particular bunch of atoms.. represents the answer. Nothing could be made smaller.. Nothing could be more elegant."*

Tiny computers obeying Quantum Mechanics Laws.
Los Alamos (1983)

* R. P. Feynman, 1983, Tiny Computers Obeying Quantum Mechanical Laws. Talk delivered at Los Alamos National Laboratory.

Controlling individual atoms

Trapping a single atom in a strongly focused laser beam (optical tweezer)

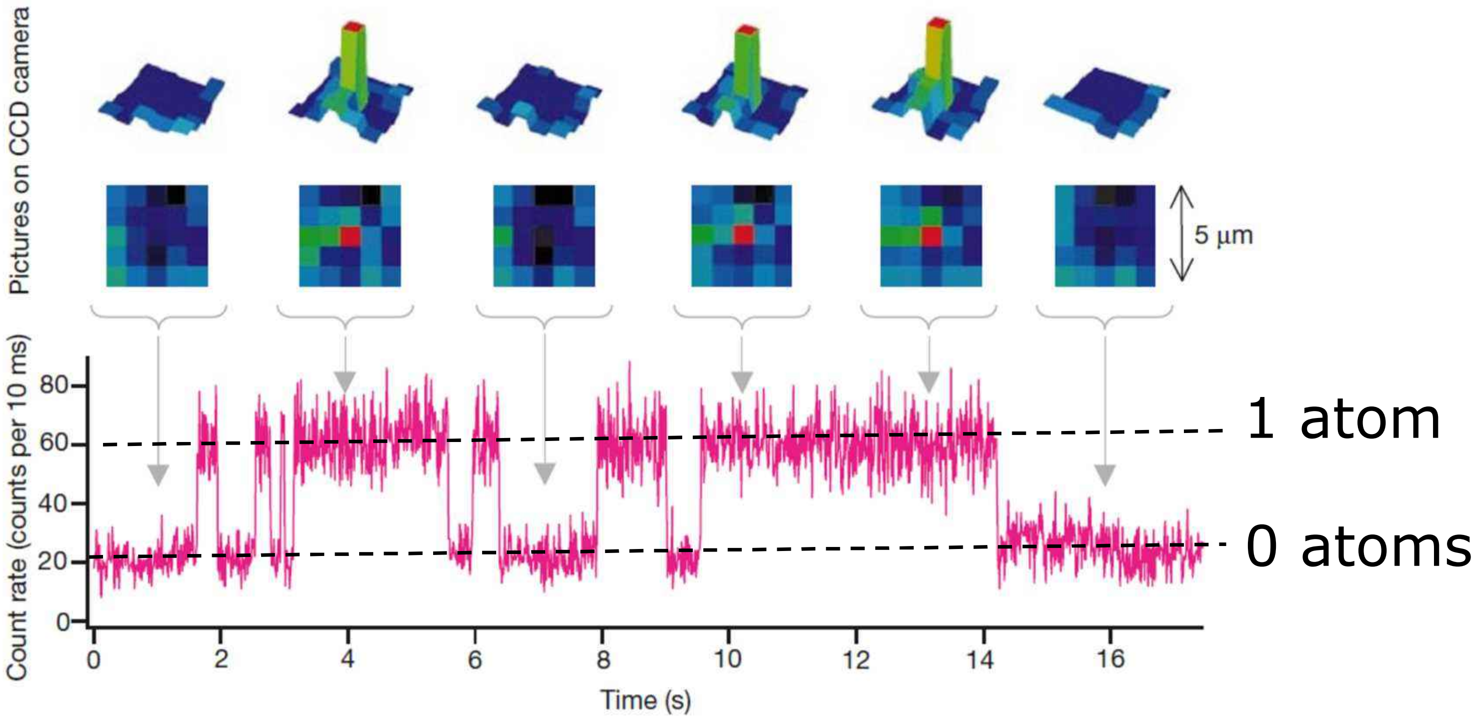


N. Schlosser, G. Reymond, I. Protsenko, P. Grangier, Nature **411**, 1024 (2001)

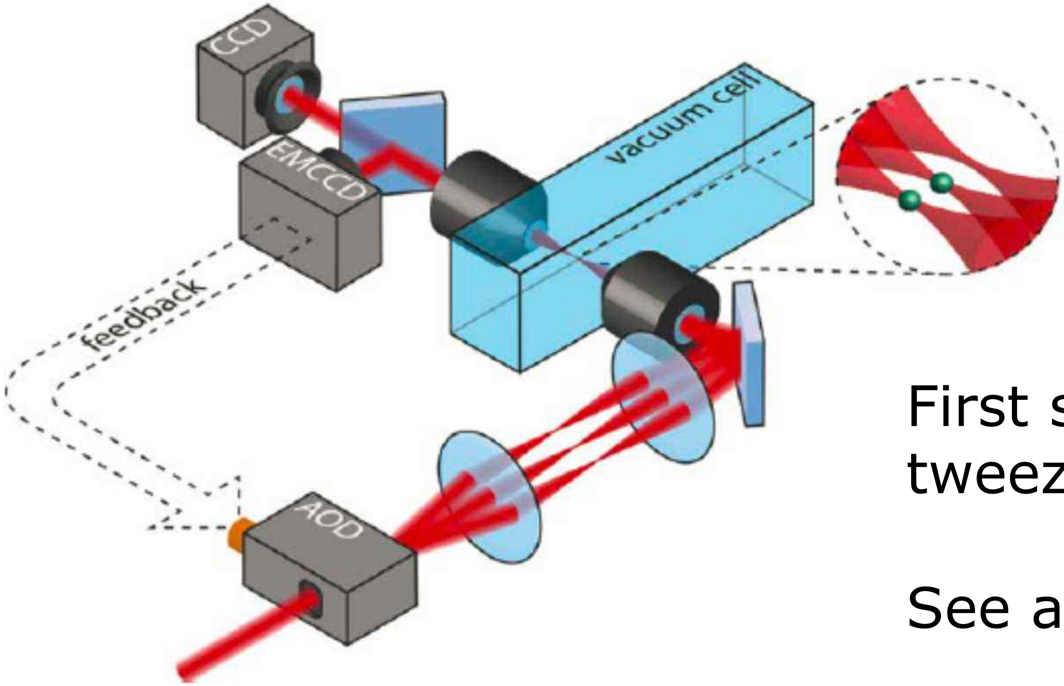
Trapping single atoms

- Single neutral atoms can be trapped and imaged in focused laser beams

N. Schlosser, G. Reymond, I. Protsenko, P. Grangier, Nature **411**, 1024 (2001).



Trapping many single atoms deterministically



First single-atom optical tweezer: P. Grangier

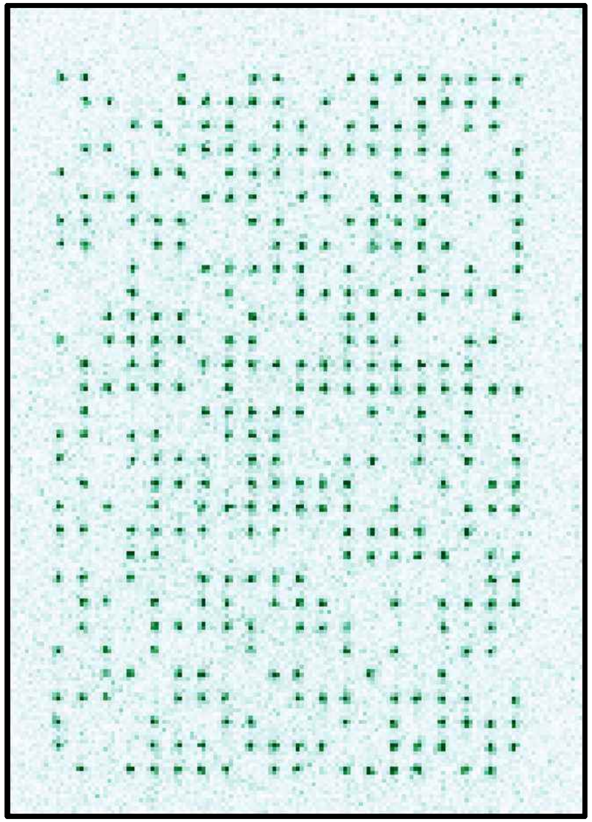
See also: A. Browaeys work

Problem: each trap is only loaded with ~50% probability.
Solution: real-time rearrangement after imaging (feedback)

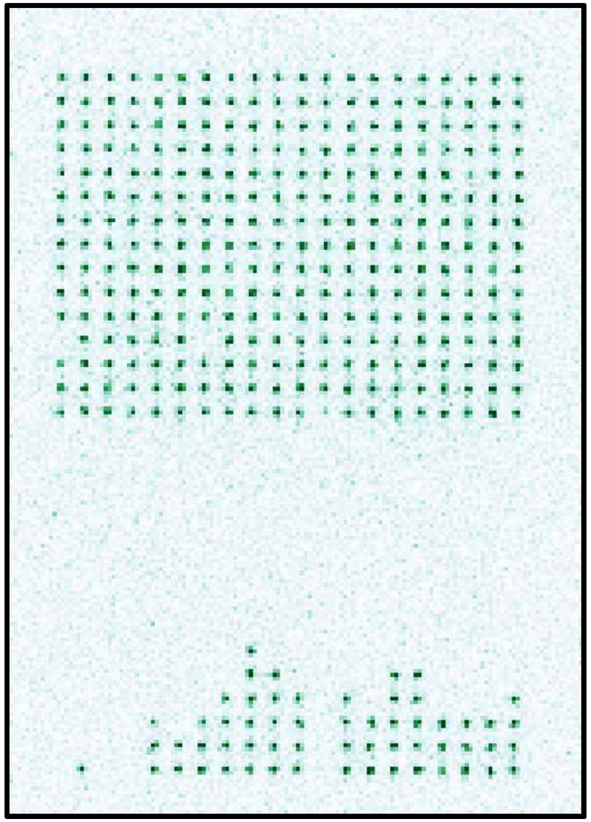
M. Endres, H. Bernien, A. Keesling, H. Levine, E. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletić, M. Greiner, and M.D. Lukin, Science **354**, 1024-1027 (2016).

Sorting 300 atoms in two dimensions

Initial loading:

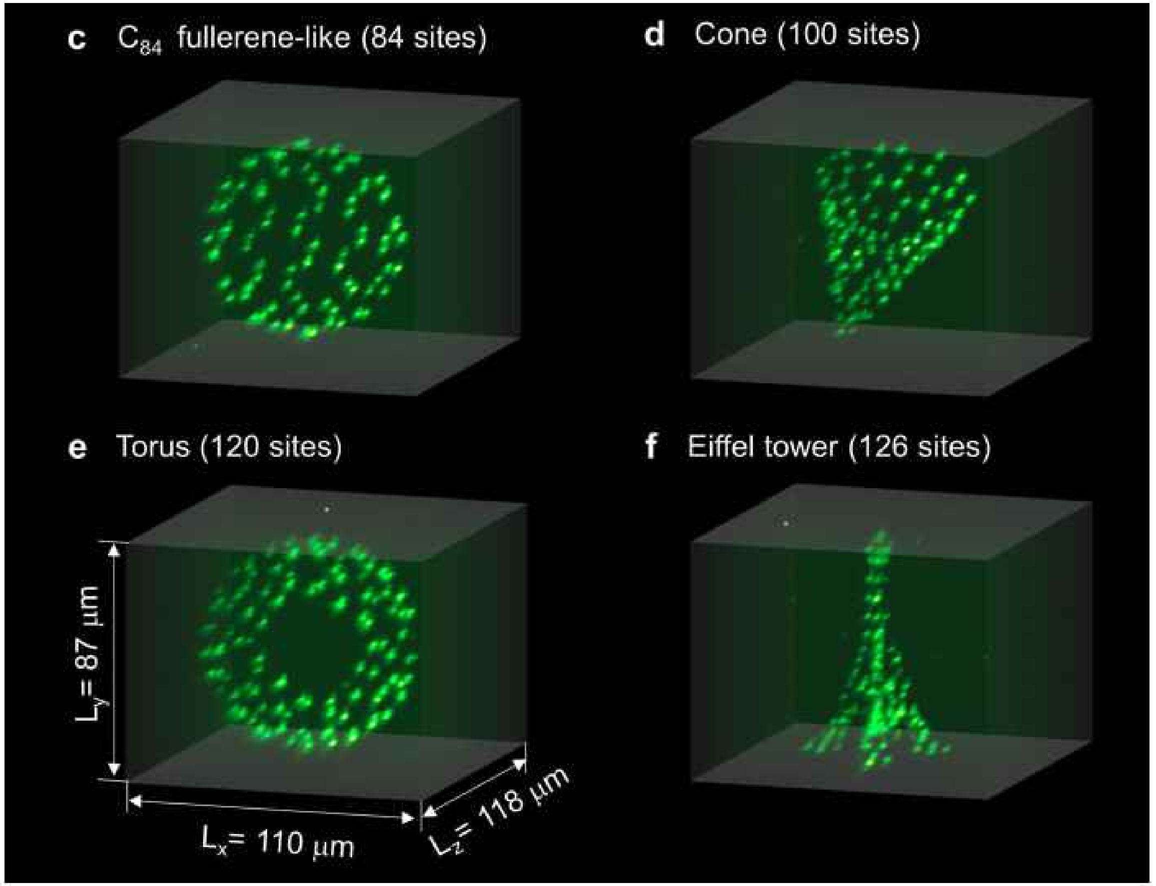


After sorting:



> 98% filling fraction

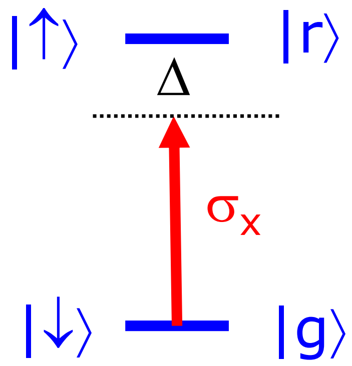
Three dimensional arrays also possible



Synthetic three-dimensional atomic structures assembled atom by atom. D. Barredo, V. Lienhard, S. de Léséleuc, T. Lahaye & A. Browaeys, Nature **561**, 79–82 (2018).

Inducing interactions over optically resolvable distances

System Hamiltonian

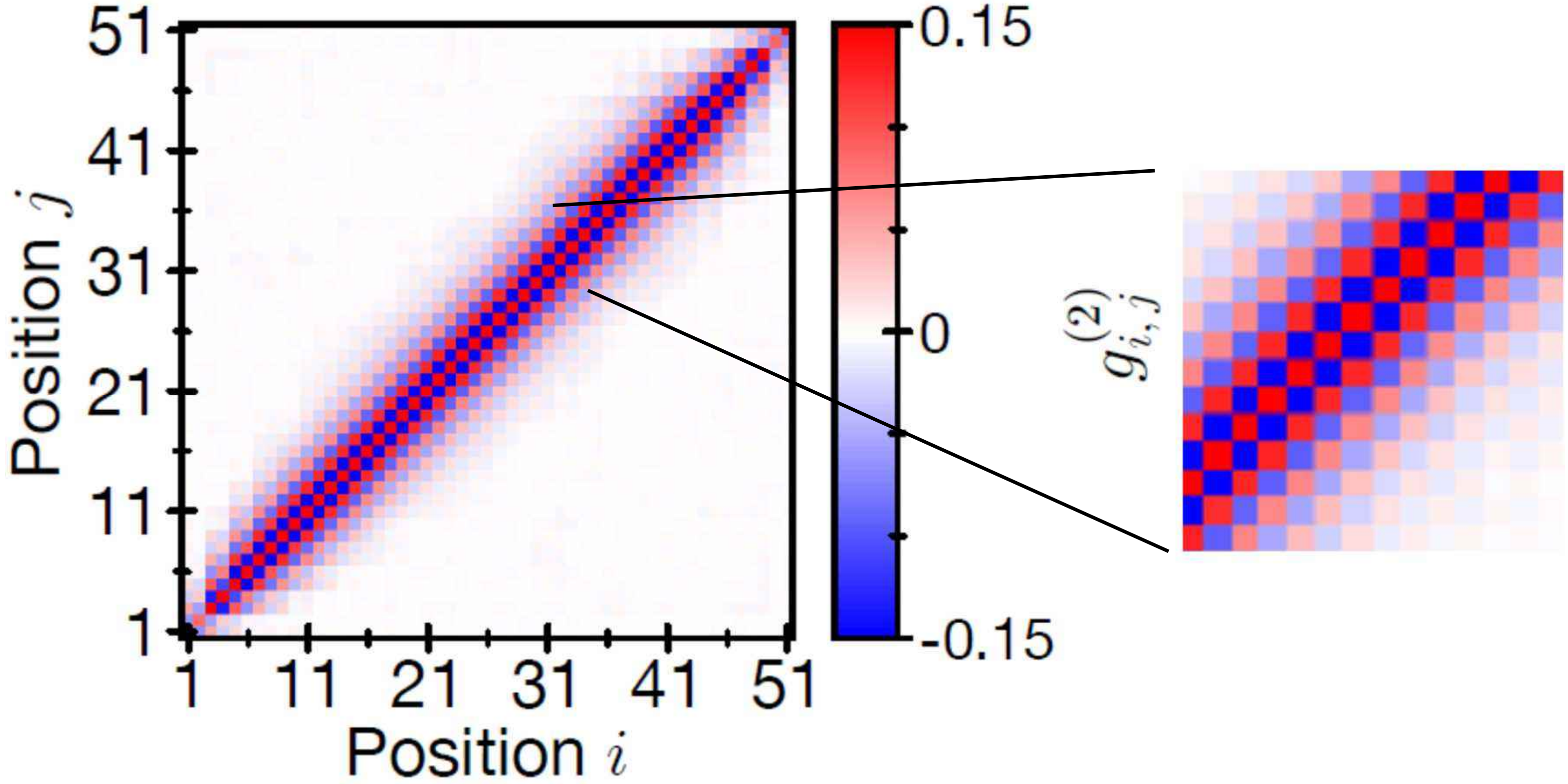


$$\frac{H}{\hbar} = \frac{\Omega(t)}{2}\sum_i \sigma_i^x - \Delta(t)\sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

Ground-Rydberg system as spin ½ system (qubit).

Quantum Simulation

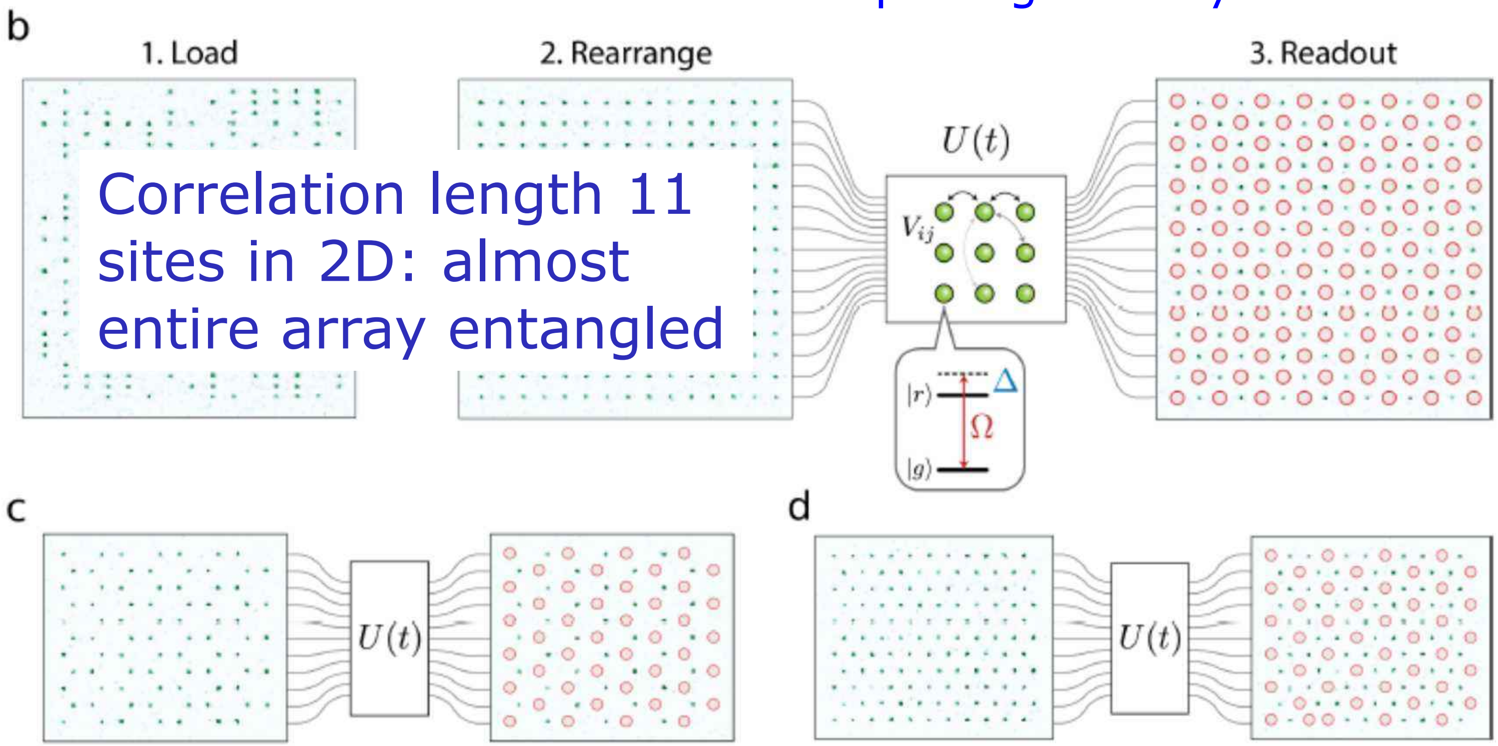
Antiferromagnetic correlations due to Rydberg blockade in 1D chain



Probing many-body dynamics on a configurable 51-atom quantum simulator. H. Bernien, S. Schwartz, A. Keesling, H. Levine, A. Omran, H. Pichler, S. Choi, A.S. Zibrov, M. Endres, M. Greiner, V. Vuletić, and M.D. Lukin, Nature **551**, 579-584 (2017);

Quantum Simulator of condensed-matter systems

Square geometry



Correlation length 11 sites in 2D: almost entire array entangled

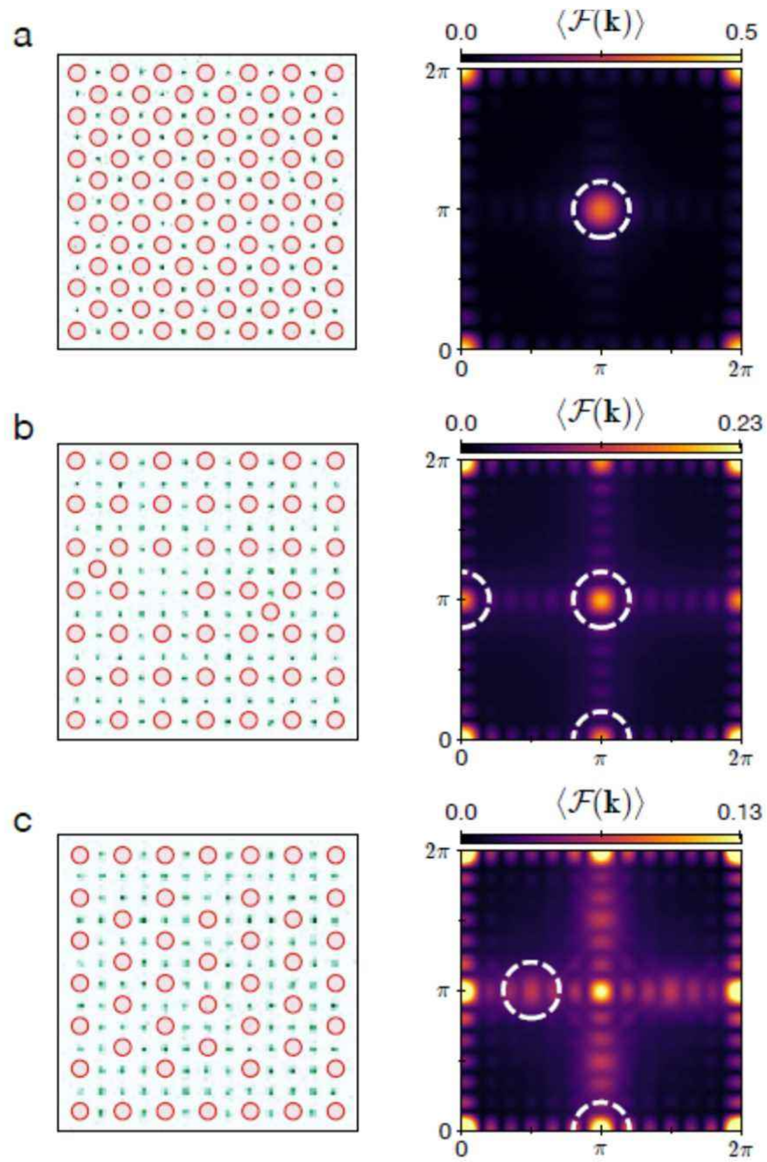
Hexagonal geometry

Triangular geometry

S. Ebadi, T.T. Wang, Levine, A. Keesling, G. Semeghini, A. Omran, D. Bluvstein, R. Samajdar, H. Pichler, W.W. Ho, S. Choi, S. Sachdev, M. Greiner, V. Vuletić, and M.D. Lukin, Nature **595**, 227-232 (2021).

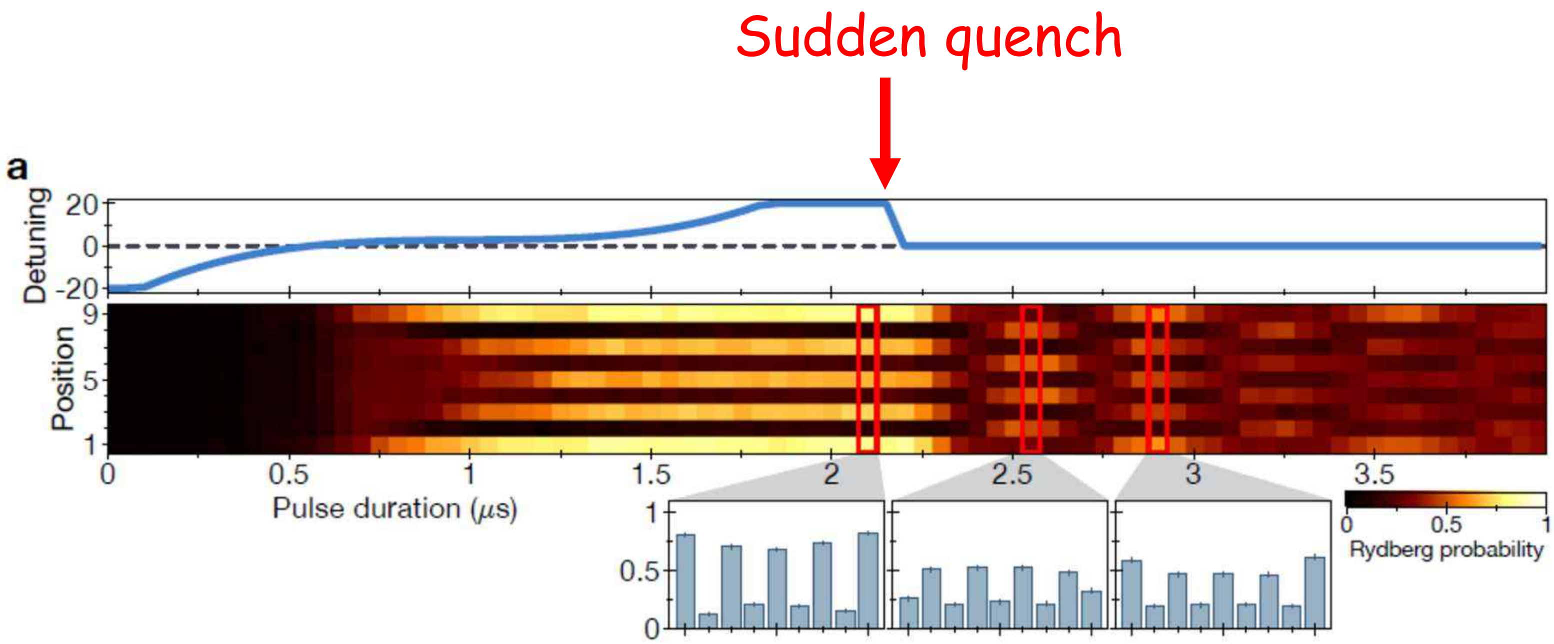
Antiferromagnetic phases on square lattice for different interaction strengths:

Different emerging orders



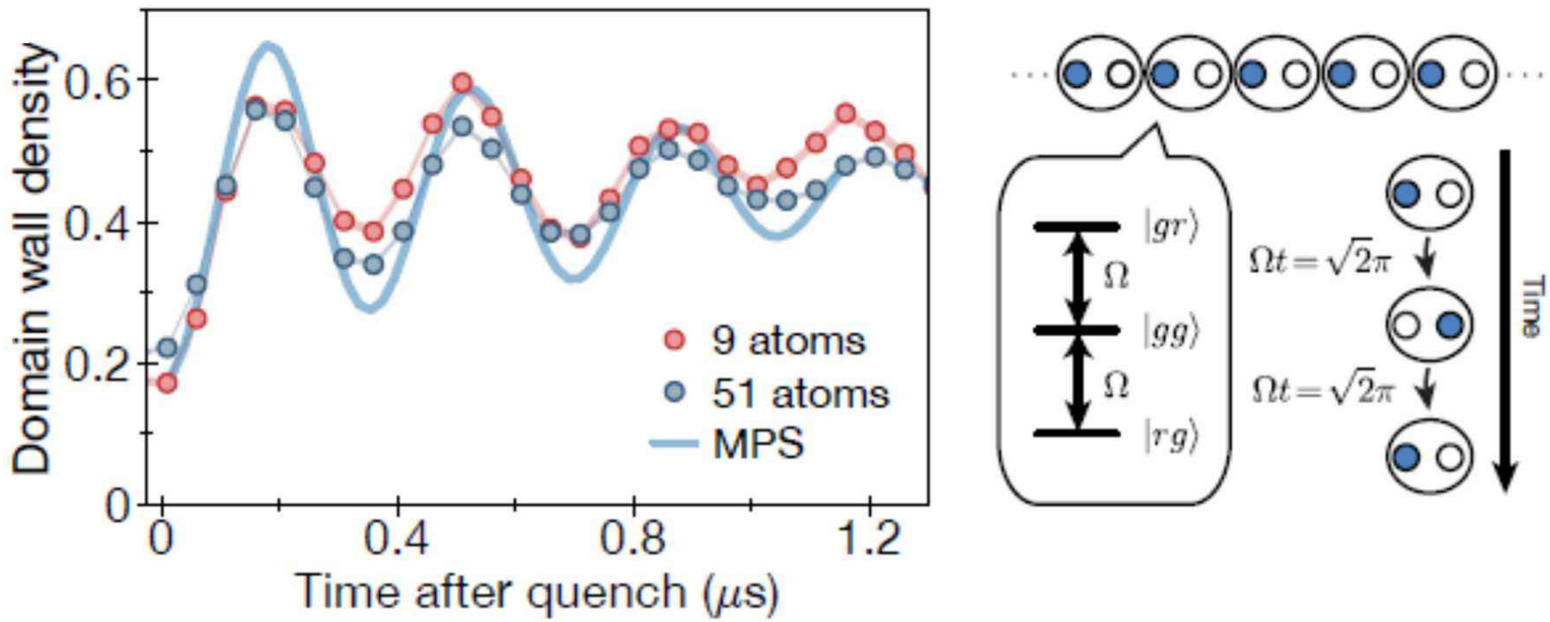
Quantum Many-Body Scars

Collective oscillations after a sudden quench



Surprisingly long-lived oscillations between two macroscopic antiferromagnetic states observed.

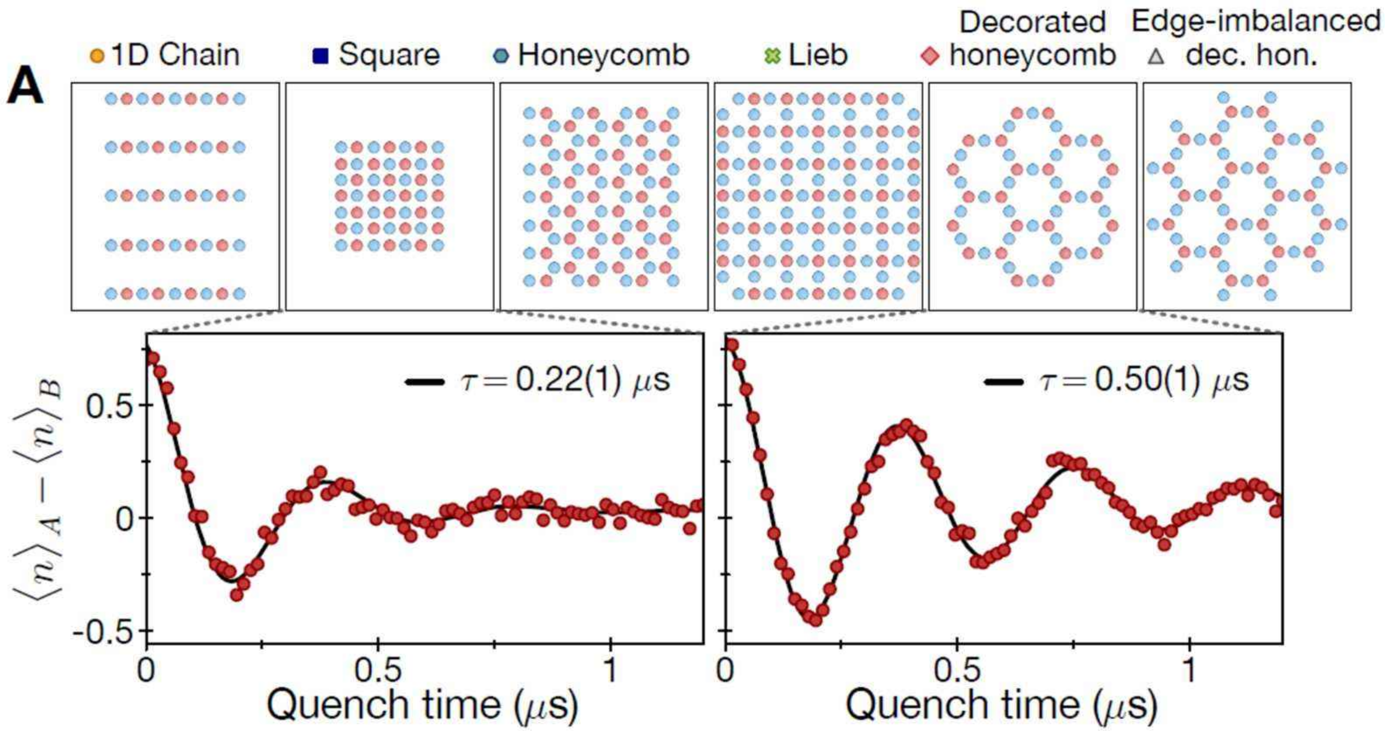
Collective oscillations after a sudden quench



Quantum many-body scars

C. J. Turner, A. A. Michailidis, D. A. Abanin, M. Serbyn, and Z. Papic, arxiv 1711.03528 (2017).

Quantum many-body scars in 2D



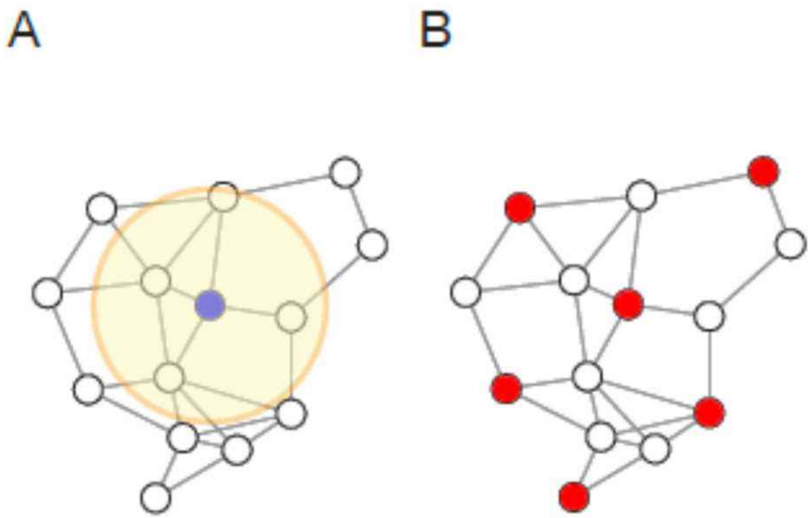
We discovered that quantum many-body scars can be stabilized by driving.

Controlling many-body dynamics with driven quantum scars in Rydberg atom arrays.

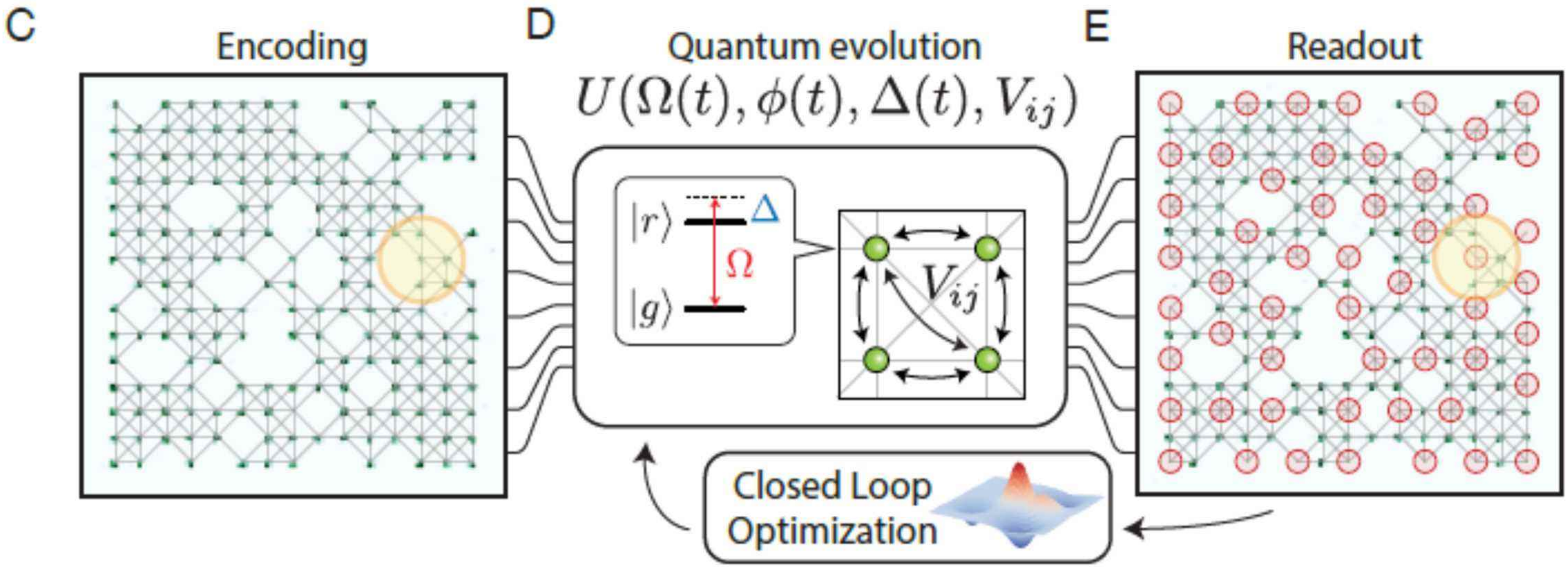
D. Bluvstein, A. Omran, H. Levine, A. Keesling, G. Semeghini, S. Ebadi, T. T. Wang, A. A. Michailidis, N. Maskara, W. W. Ho, S. Choi, M. Serbyn, M. Greiner, V. Vuletić, and M.D. Lukin, Science **371**, 1355–1359 (2021).

Analog simulation of optimization problem

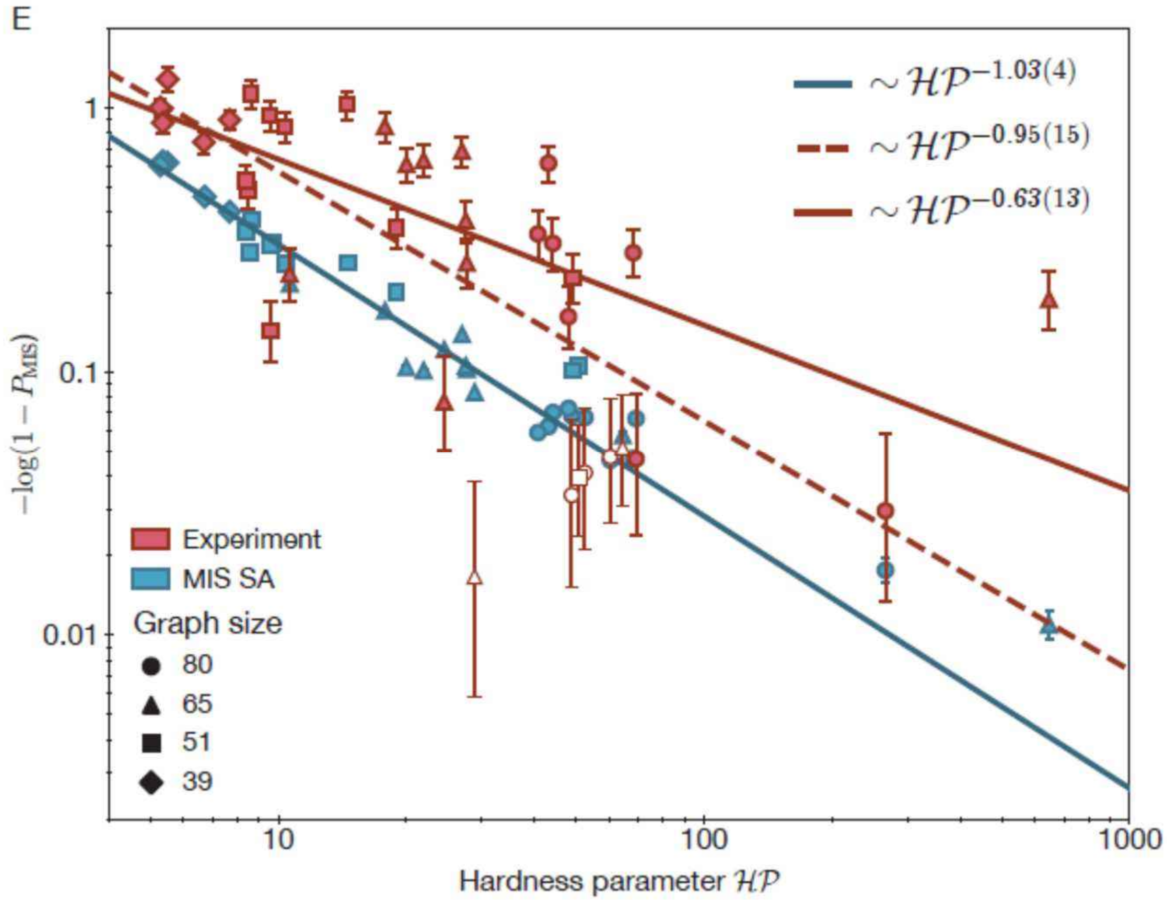
Maximally independent set – problem setup



Maximally independent set



Quadratic speedup in quantum simulator



Quantum optimization of maximum independent set using Rydberg atom arrays. S. Ebadi, A. Keesling, M. Cain, T. T. Wang, H. Levine, D. Bluvstein, G. Semeghini, A. Omran, J.-G. Liu, R. Samajdar, X.-Z. Luo, B. Nash, X. Gao, B. Barak, E. Farhi, S. Sachdev, N. Gemelke, L. Zhou, S. Choi, H. Pichler, S.-T. Wang, M. Greiner, V. Vuletić, and M.D. Lukin, Science **376**, 1209–1215 (2022).

Quera Computing (Boston-based startup)

4 full-time scientists

36 full-time scientists, engineers, developers

March 2020 — **Laboratory Commissioned**

Vacant building space retrofitted as AMO laboratory

October 2020 — **Functional Build of QC**

All technical portions of Rydberg atom simulator built and ready to be integrated into a quantum computer

January 2020 — **Software and Algorithms Toolset Completed**

Rydberg atom emulator and stochastic optimizer suites built.

July 2021 — **Proof-of-Concept Cloud Service Integrations**

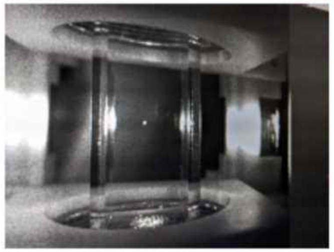
Commercial cloud services with neutral atom computers

December 2021 — **High-fidelity sorting of >256 atoms**

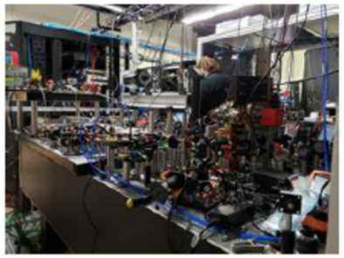
July 2022 — **Testing and integration with cloud service, two new machines under construction**

December 2022 — **Public availability of Machines through Amazon Web Services' Braket Platform**

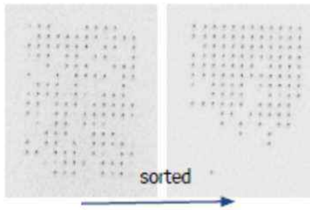
First laboratory move-in



Trapped atoms



Quantum compute engine



Programmable neutral atom arrays

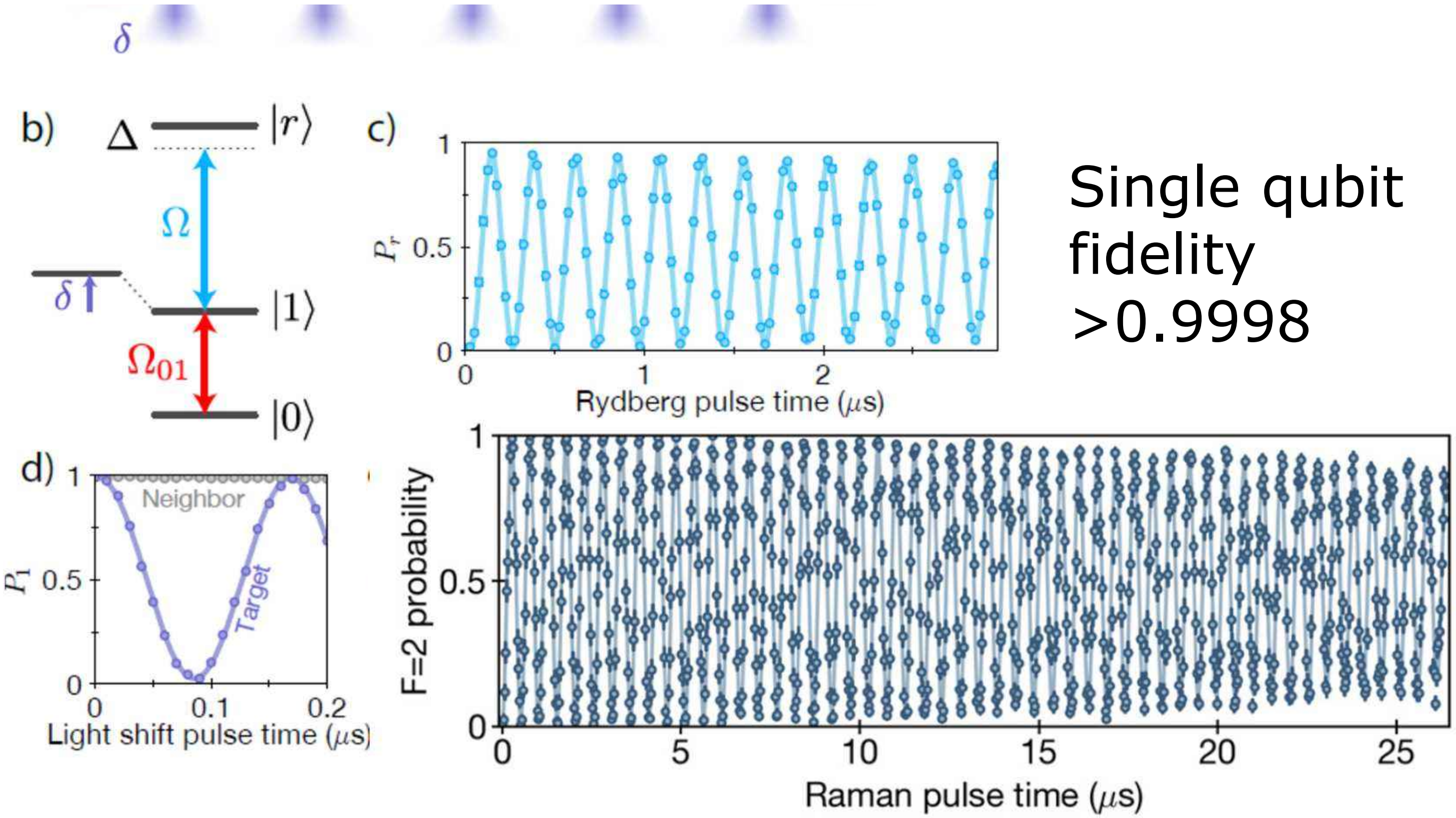
Aquila, first cloud-connection ready neutral atom machine (two more under construction)

Rydberg quantum gates

H. Levine, A. Keesling, A. Omran, H. Bernien, S. Schwartz, A.S. Zibrov, M. Endres, M. Greiner, V. Vuletić, and M.D. Lukin, Phys. Rev. Lett. **121**, 123603 (2018).
H. Levine, A. Keesling, G. Semeghini, A. Omran, T. T. Wang, S. Ebadi, H. Bernien, M. Greiner, V. Vuletić, H. Pichler, and M. D. Lukin, Phys. Rev. Lett. **123**, 170503 (2019).
S. Evered, D. Bluvstein, M. Kalinowski, S. Ebadi, T. Manowitz, H. Zhou, S.H. Li, A.A. Geim, T. T. Wang, N. Maskara, H. Levine, G. Semeghini, M. Greiner, V. Vuletić, and M.D. Lukin, arXiv:2304.05420

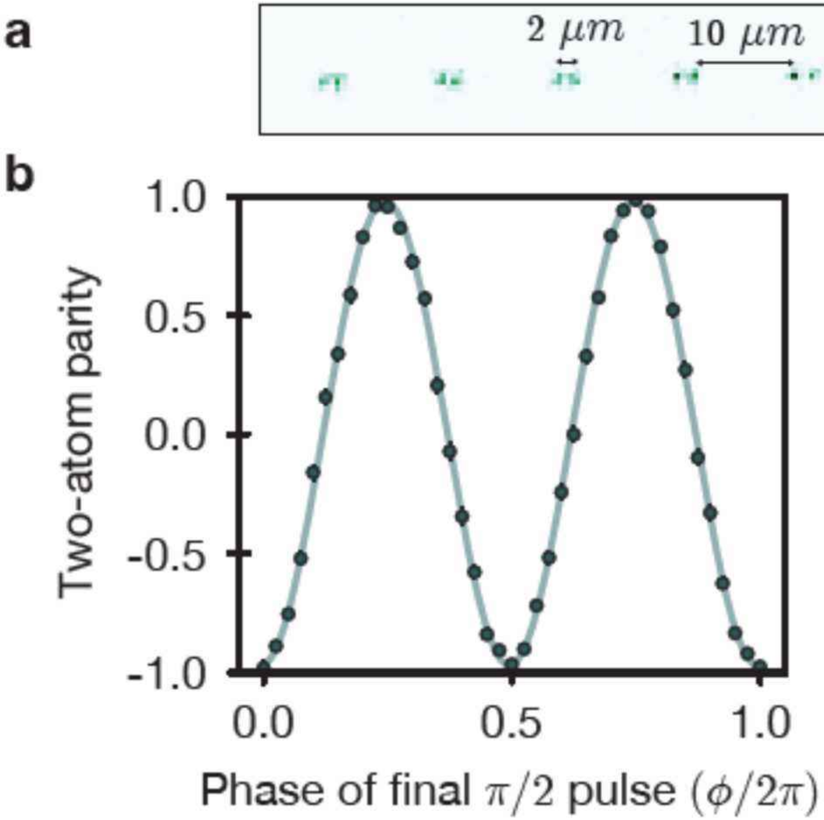
Characterization of single-qubit gate

Dispersive optical systems for scalable Raman driving of hyperfine qubits. H. Levine, D. Bluvstein, A. Keesling, T. T. Wang, S. Ebadi, G. Semeghini, A. Omran, M. Greiner, V. Vuletić, and M.D. Lukin, Phys. Rev. A **105**, 032618 (2022);



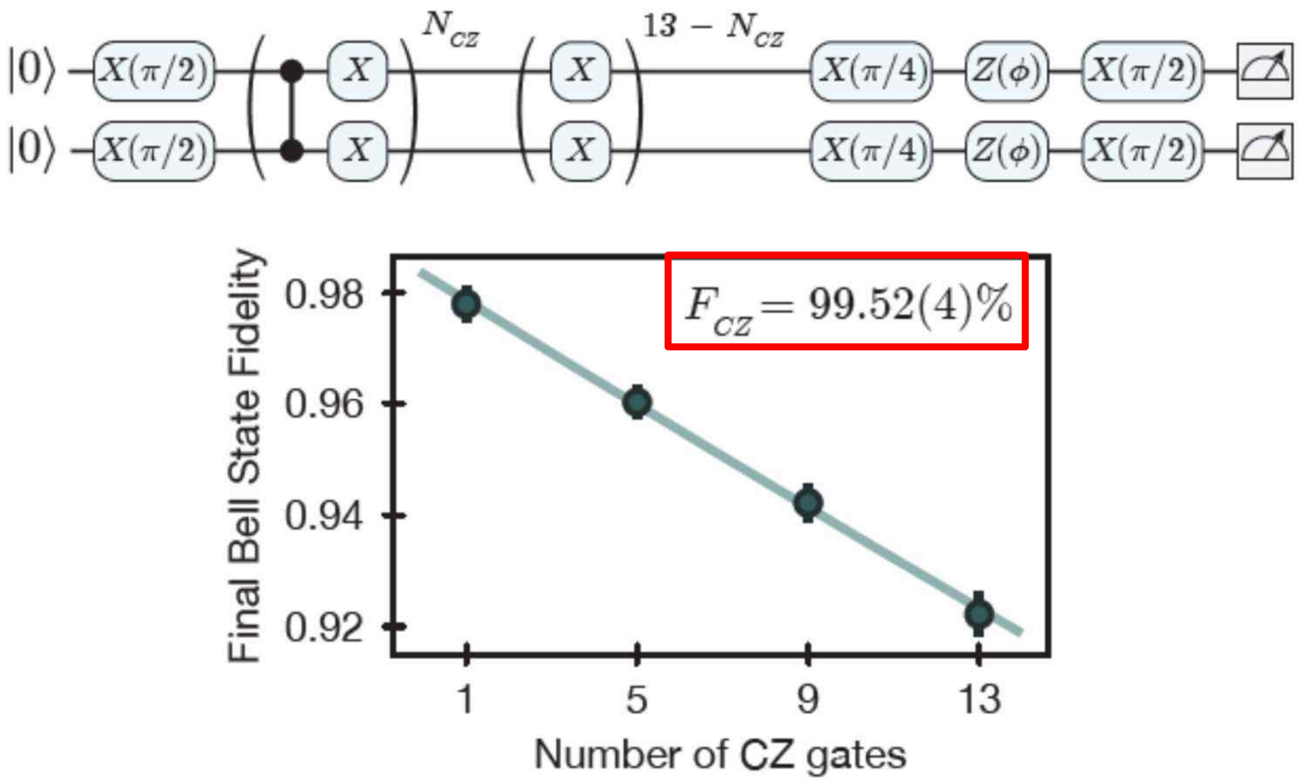
Single qubit fidelity >0.9998

Two-qubit gates



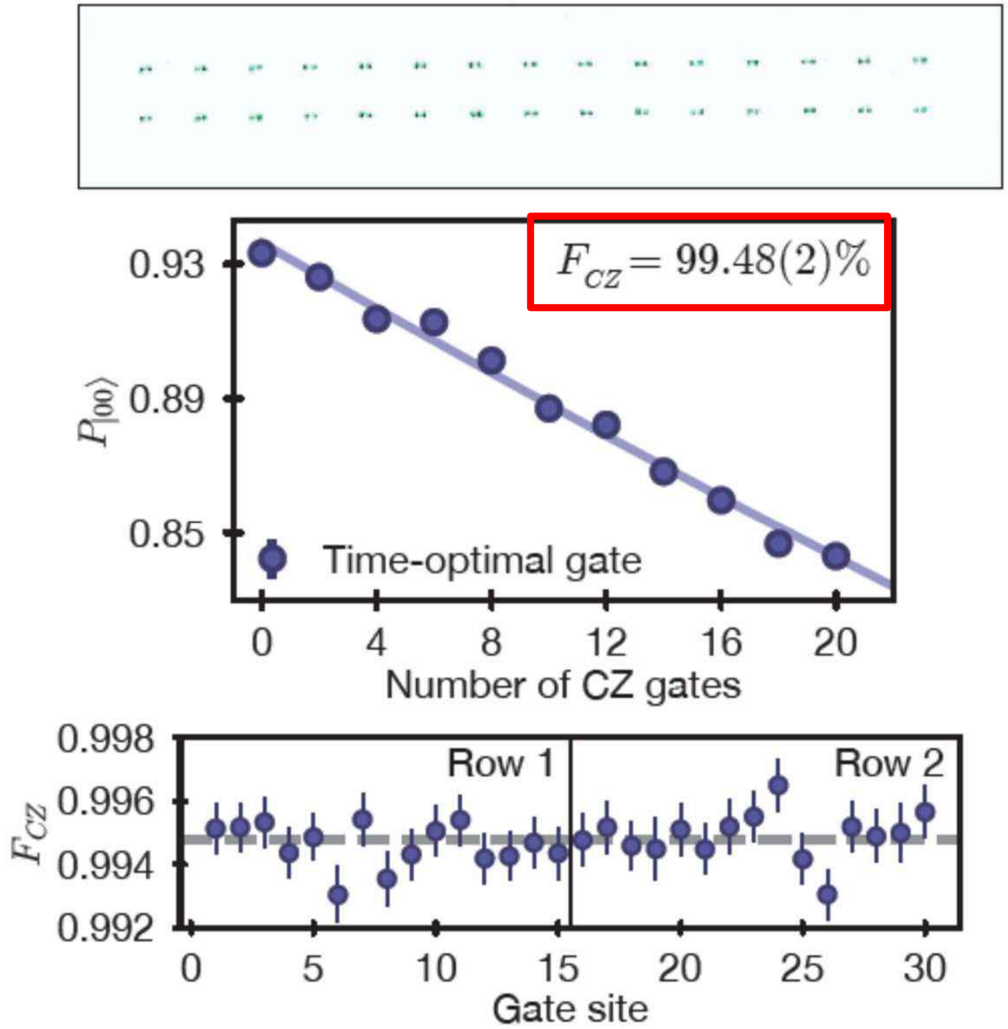
Parallel two-qubit gates on 10 pairs of atoms

Two-qubit gate fidelity



Parallel two-qubit gates on 10 pairs of atoms.

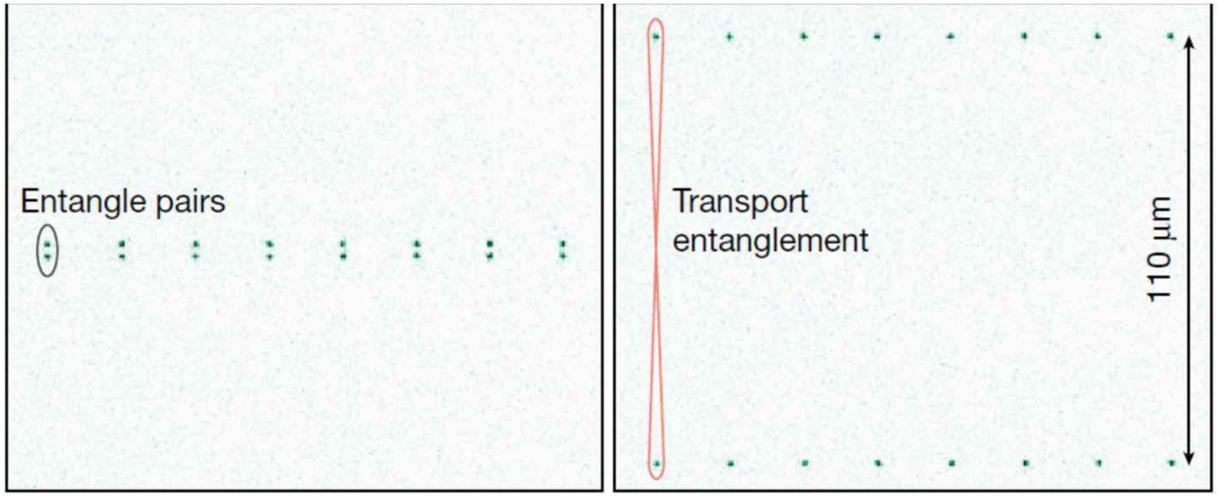
Two-qubit gate fidelity

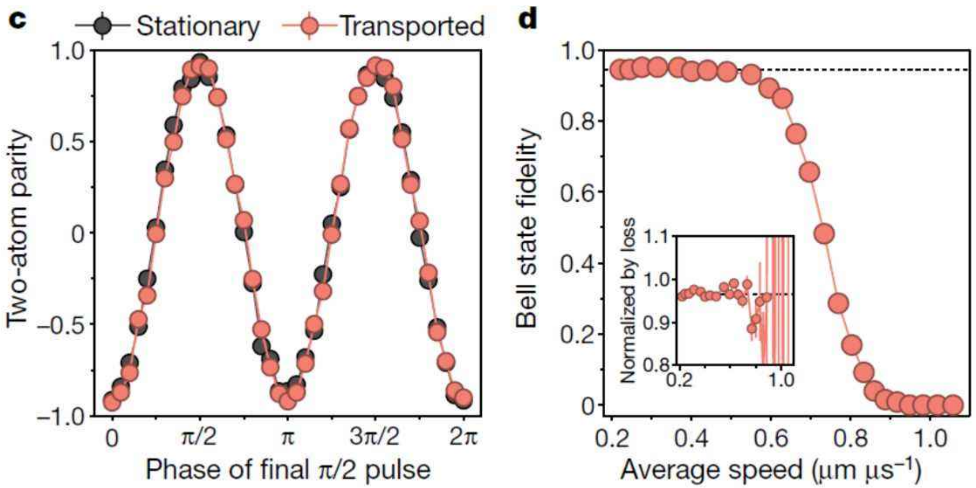


Parallel two-qubit gates on 30 pairs of atoms.
Randomized benchmarking.
99.5% gate fidelity
Error below 1% threshold of surface code.

Transporting entangled states
Towards quantum error correction

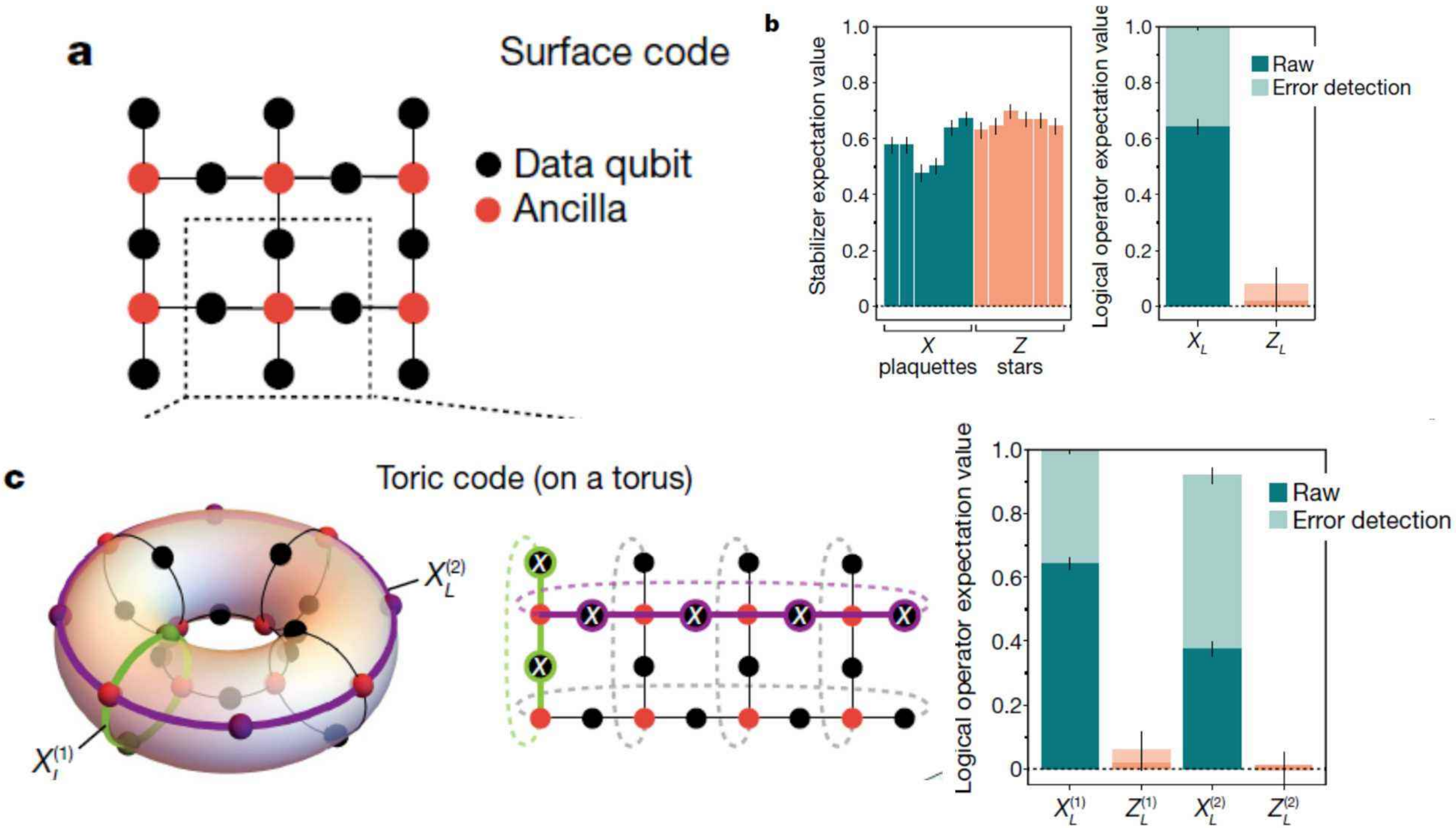
Transporting entanglement



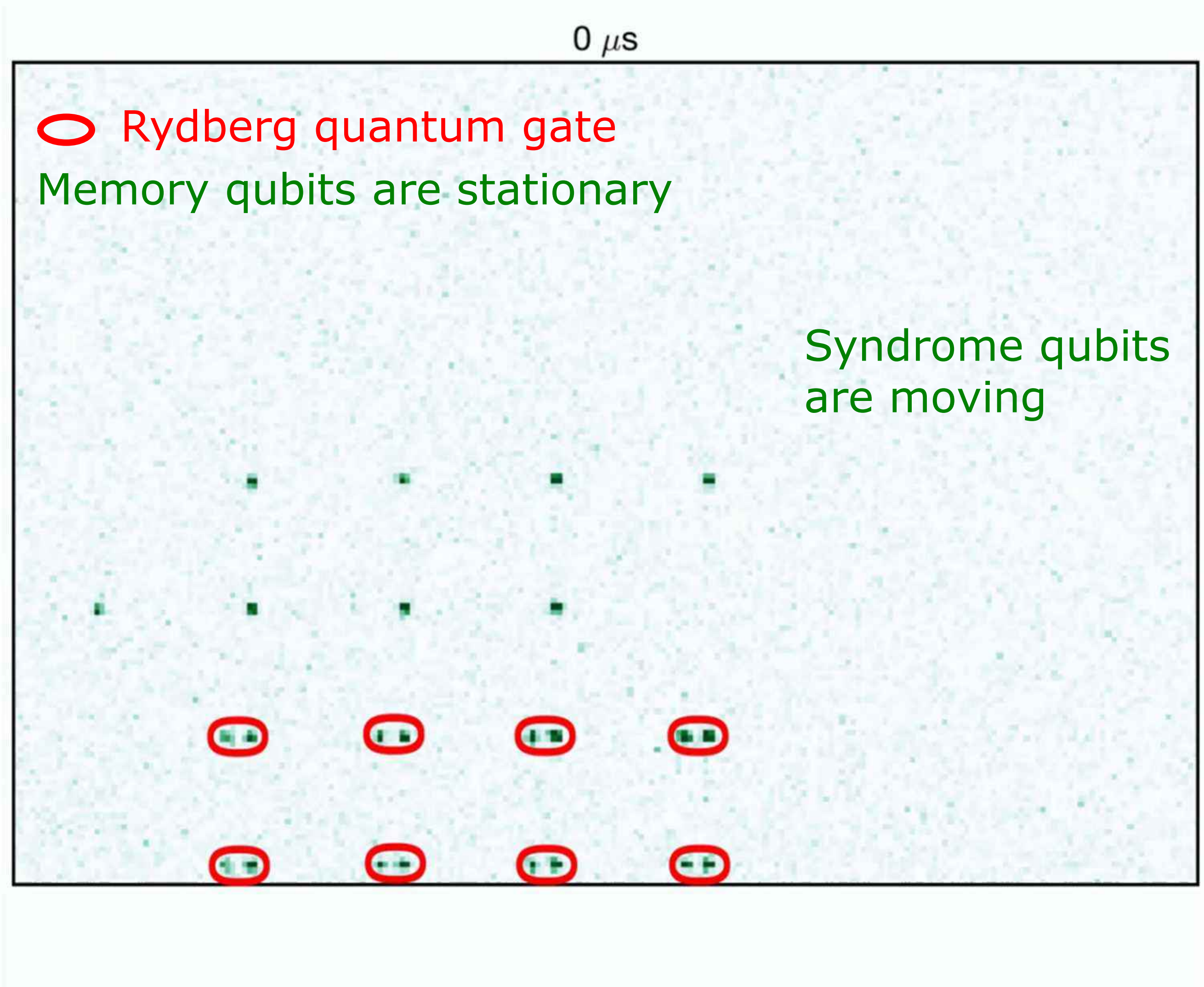


No deterioration in entanglement observed for transported Bell pair

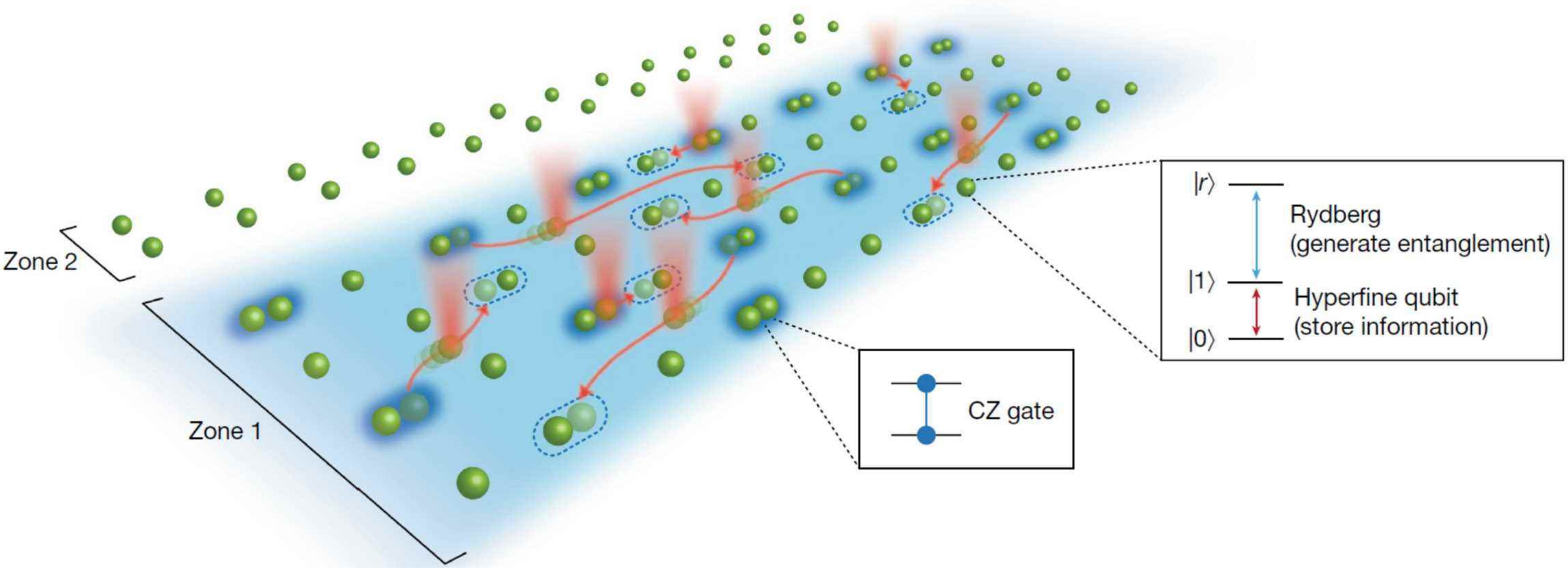
Syndrome measurements for quantum error correction codes



Implementation of Toric code



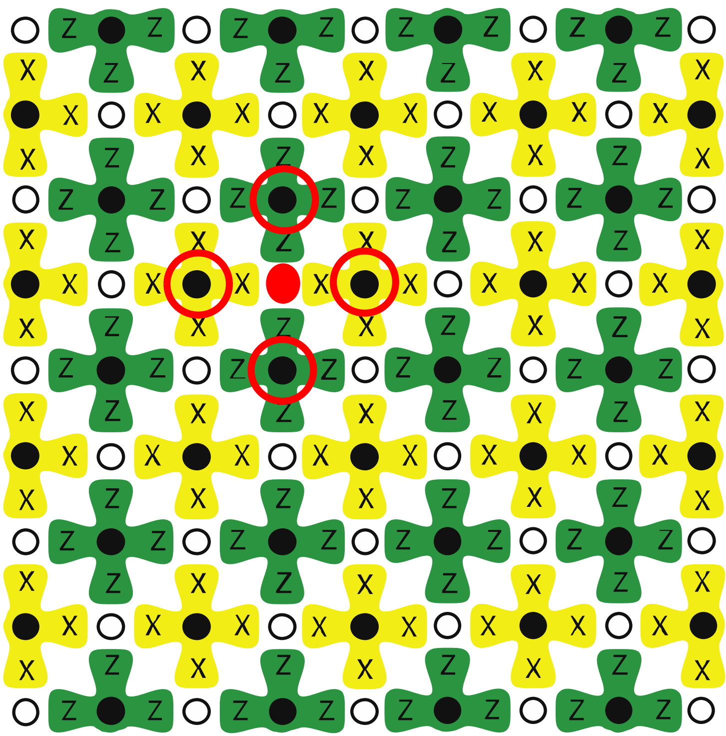
Quantum processor architecture



Scaling up quantum computers: Quantum connection between modules?

Quantum error correction

- It is possible to compare the state of two or several qubits without ever revealing the state



○ Computation qubit

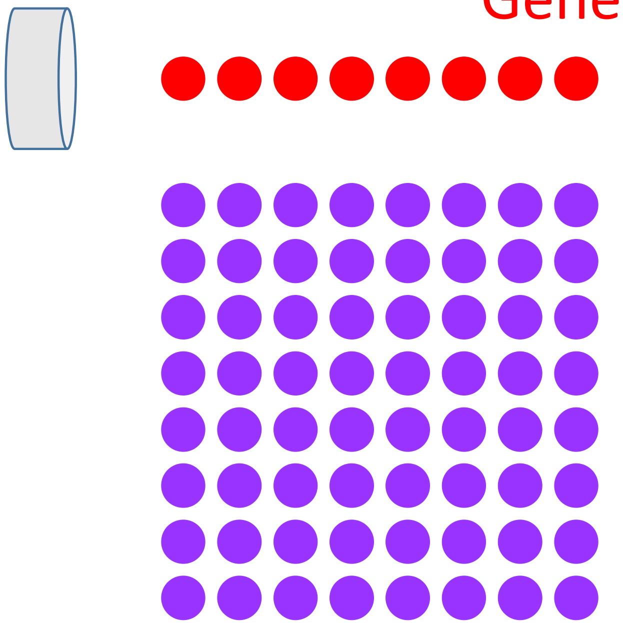
● Ancilla (error syndrome) qubit

Quantum computing with modules

- Two-dimensional modules seem most natural as they allow easy individual optical access via the third direction
- There will be a physical size limit between 10,000 and 100,000 physical qubits in the module due to:
  - (a) field of view of microscope objective (10^5 atoms per mm^2)
  - (b) Trap and addressing laser power (1mW per trap)
- 20 to 10^4 physical qubits will be required for one logical qubit
- For real calculations one will need more than one module
- How to create quantum connections between the modules?

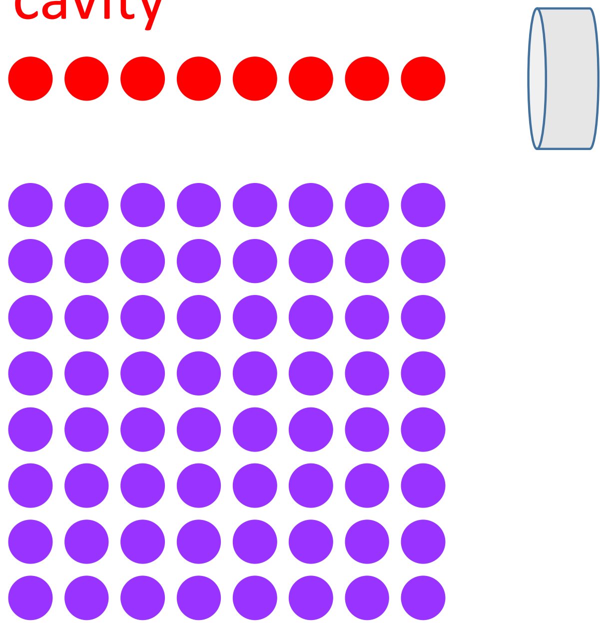
Connecting quantum modules optically

Generate remote Bell pairs off line via cavity



After Bell pair generation, perform teleported quantum gates between modules 1 and 2.

Weave in remote entanglement through local error correction.

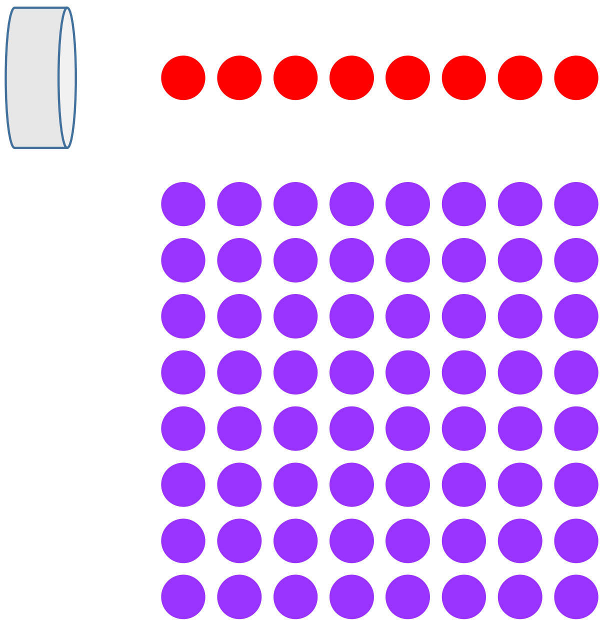


Module 1

Module 2

J. Ramette, J. Sinclair, Z. Vendeiro, A. Rudelis, M. Cetina, and V. Vuletić, PRX Quantum **3**, 010344 (2022)

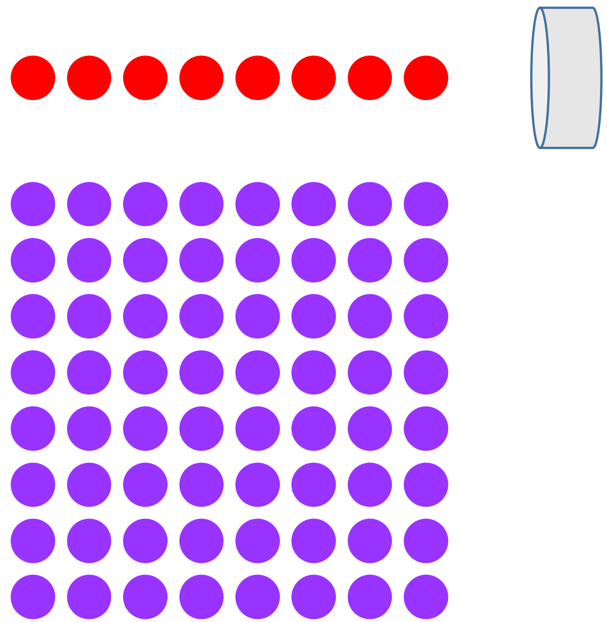
Connecting quantum modules optically



Module 1

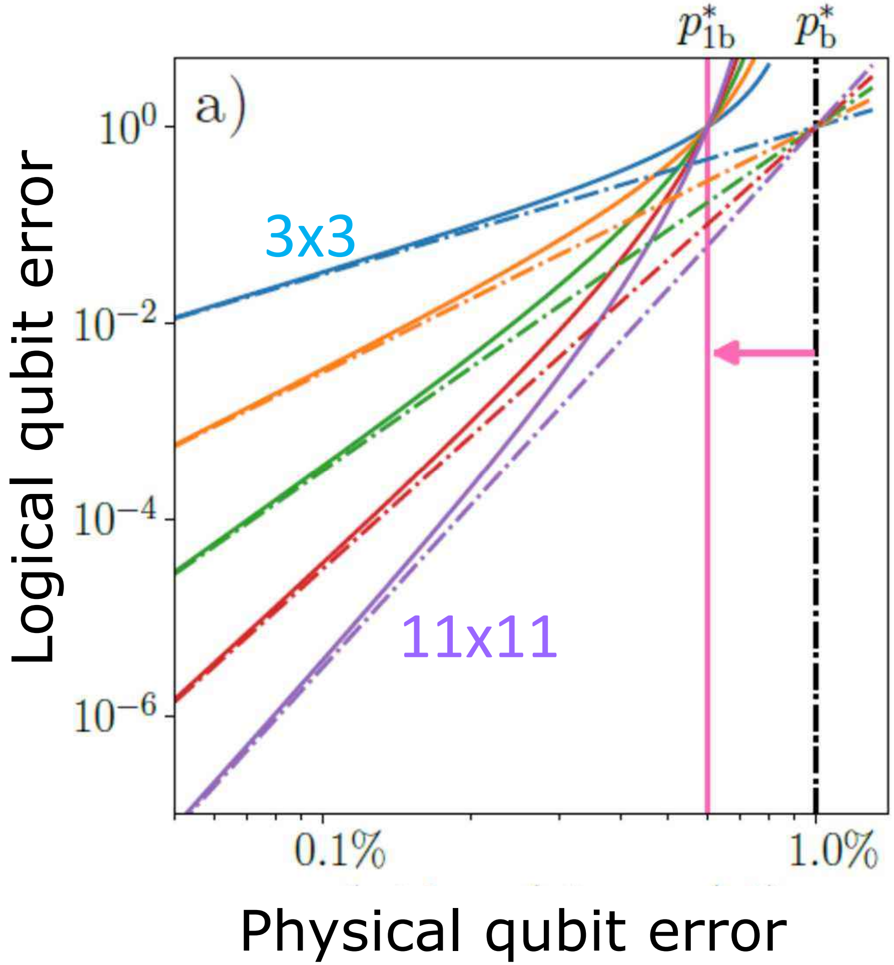
If local quantum error correction within module is functioning, the error of remote Bell pairs can be as large as 10%

J. Ramette, J. Sinclair, N.P. Breuckmann, and V. Vuletić, arXiv:2302.01296 (2/2023).



Module 2

Error rate with error correction and Bell pairs



10 % Bell pair error

Summary and Outlook

- Entanglement is transforming from a surprising (disturbing?) concept into a useful tool
- Large-scale entanglement is now experimentally possible;
- Path towards large quantum simulators:
  - 1000 to 10,000 qubits within reach in next 1-2 years
  - Quantum simulators with be useful for science
  - Quantum error corrections seems feasible
  - Are there practical computing problems beyond scientific applications that we can solve?