Quantum Simulation and Computation with Neutral Atoms

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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
- 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 …

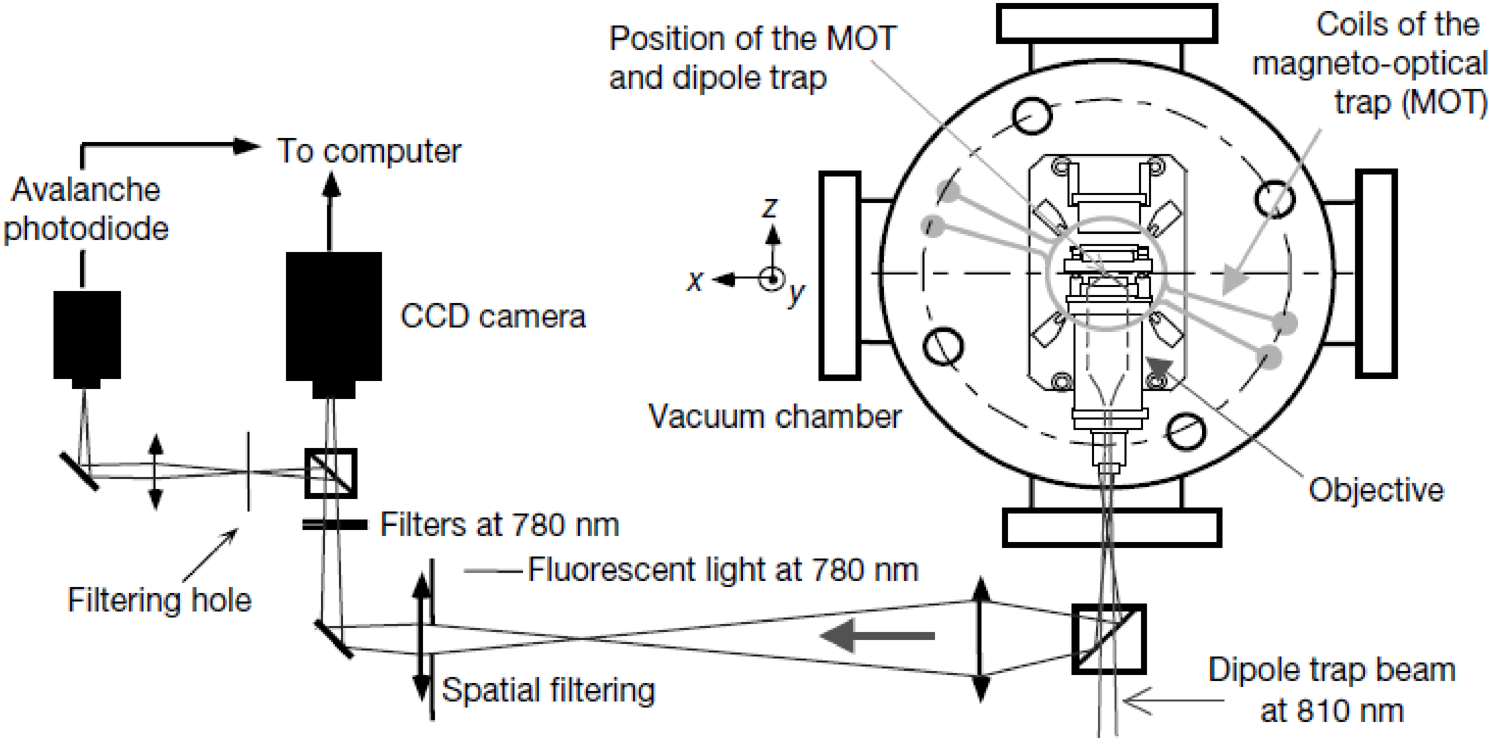
Richard Feynman

"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.

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

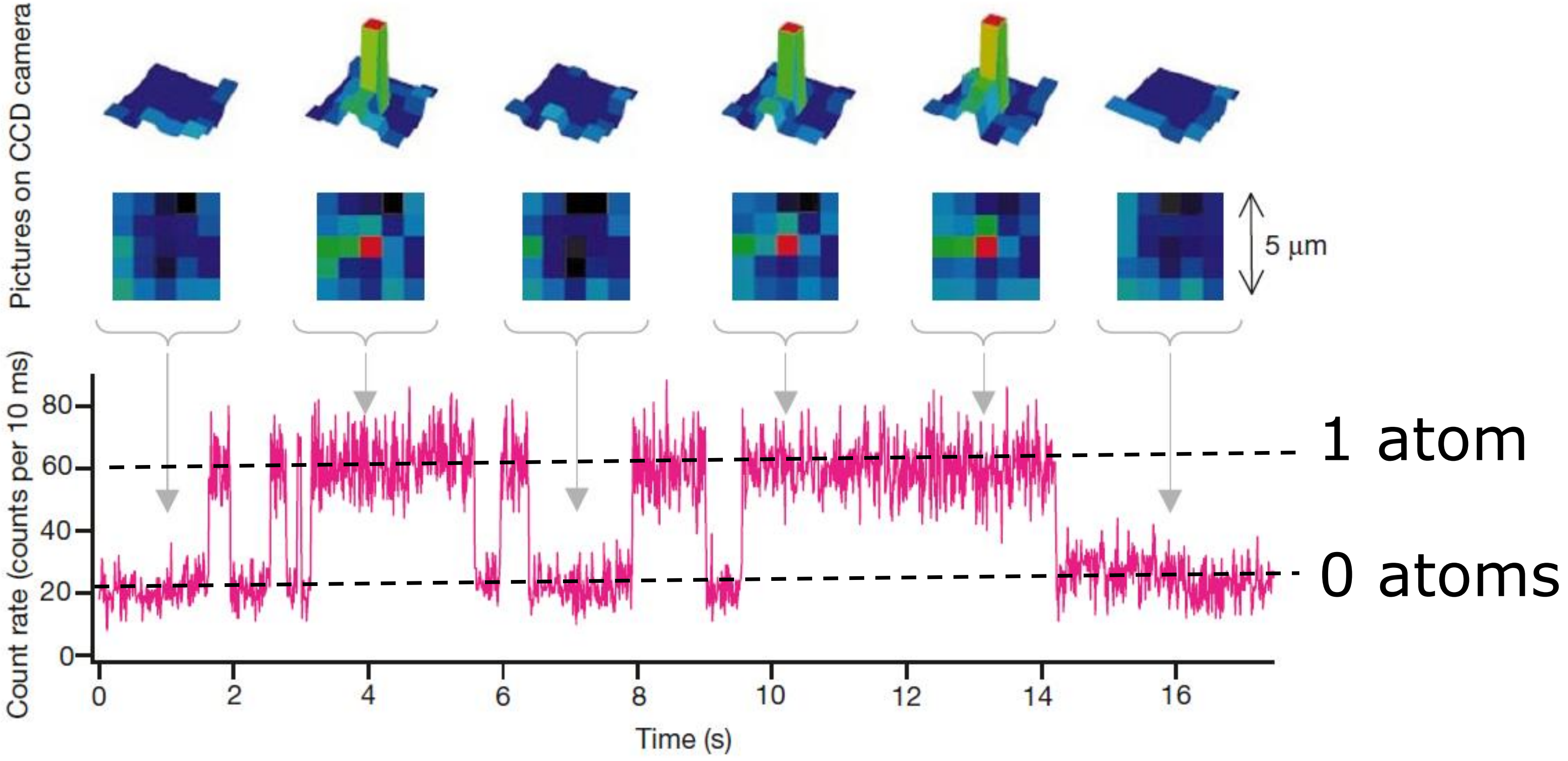


N. Schlosser, G. Reymond, I. Protsenko, P. Grangier, Nature **411**, 1024 (2001)

Trapping single atoms

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

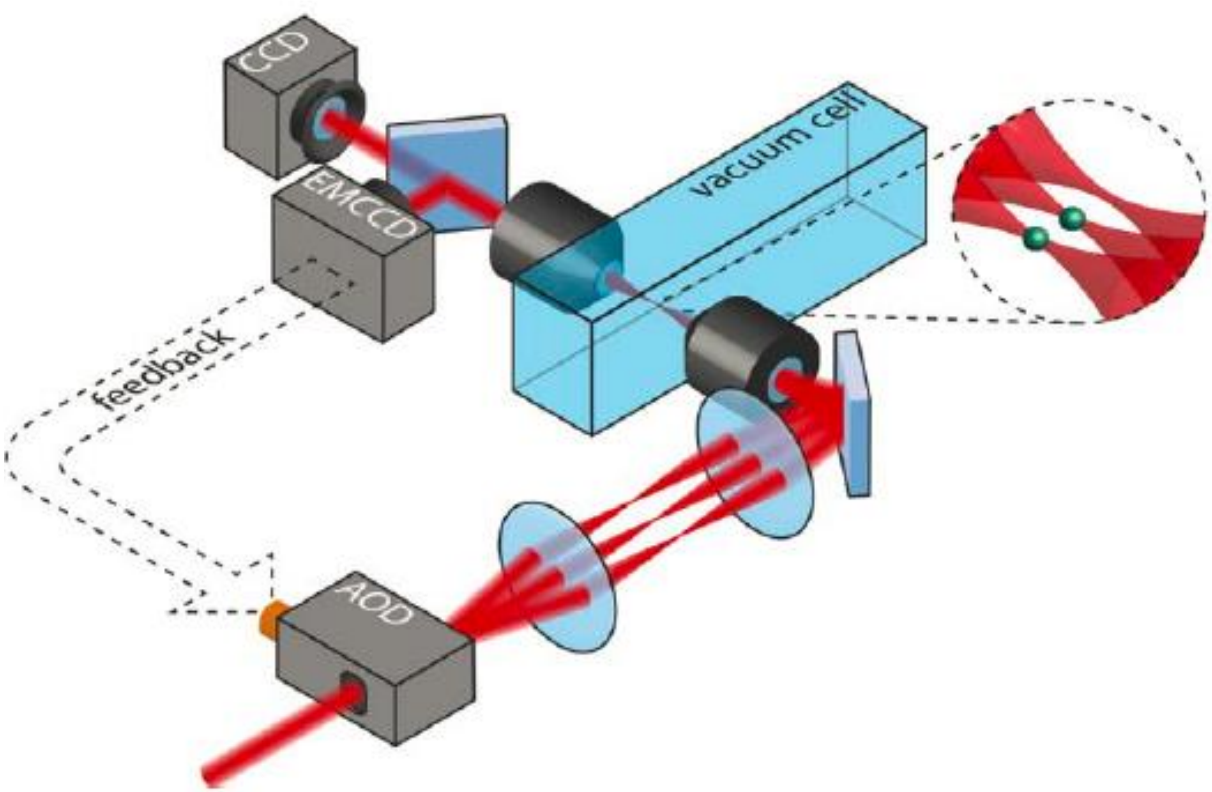
N. Schlosser, G. Reymond, I. Protsenko, P. Grangier, Nature **411**, 1024 (2001)



Trapping many single atoms

- Problem: probability to trap a single atom is only 50-60%
- The probability to trap N atoms simultaneously in N traps is exponentially small
- Solution: observation and real-time feedback

Trapping many single atoms deterministically



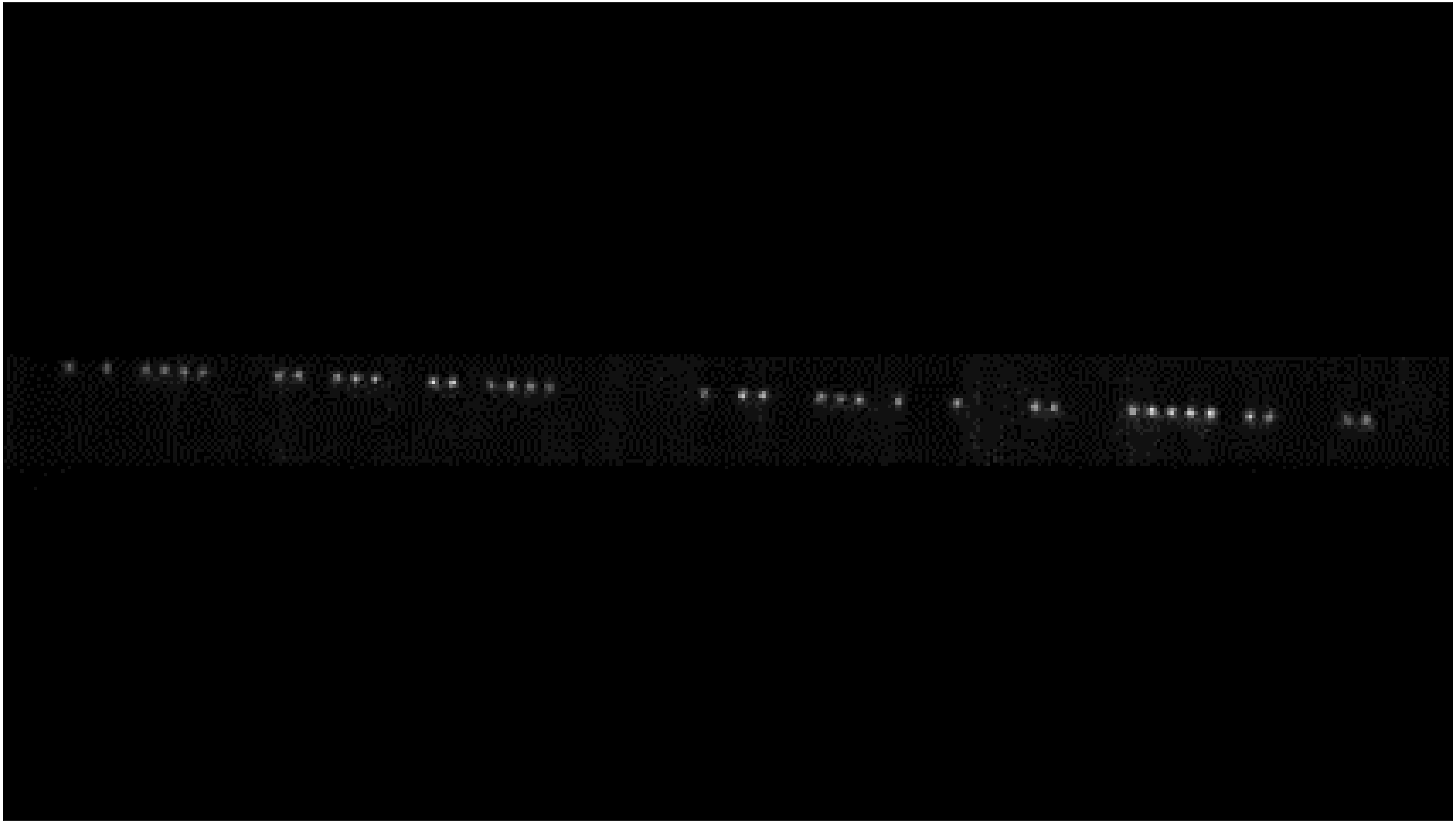
Problem: each trap is only loaded with ~50% probability.

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).

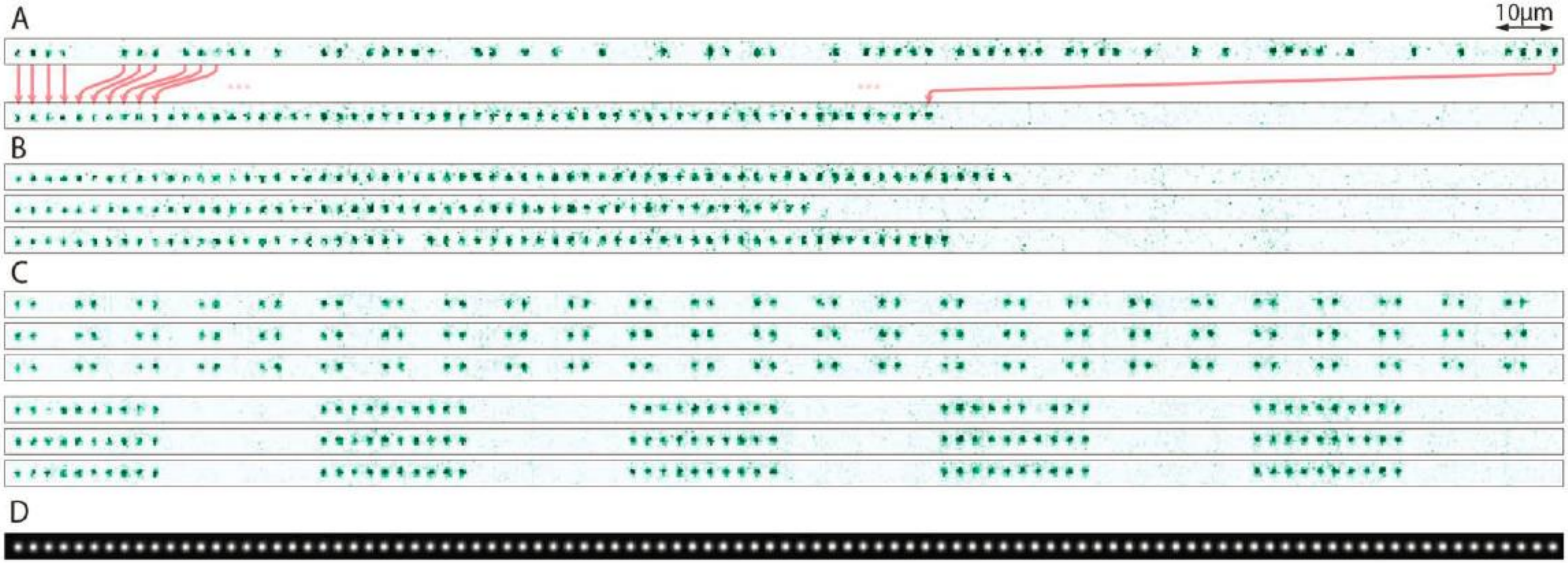
Individual atoms in reconfigurable traps

Greiner – Lukin – Vuletic collaboration



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).

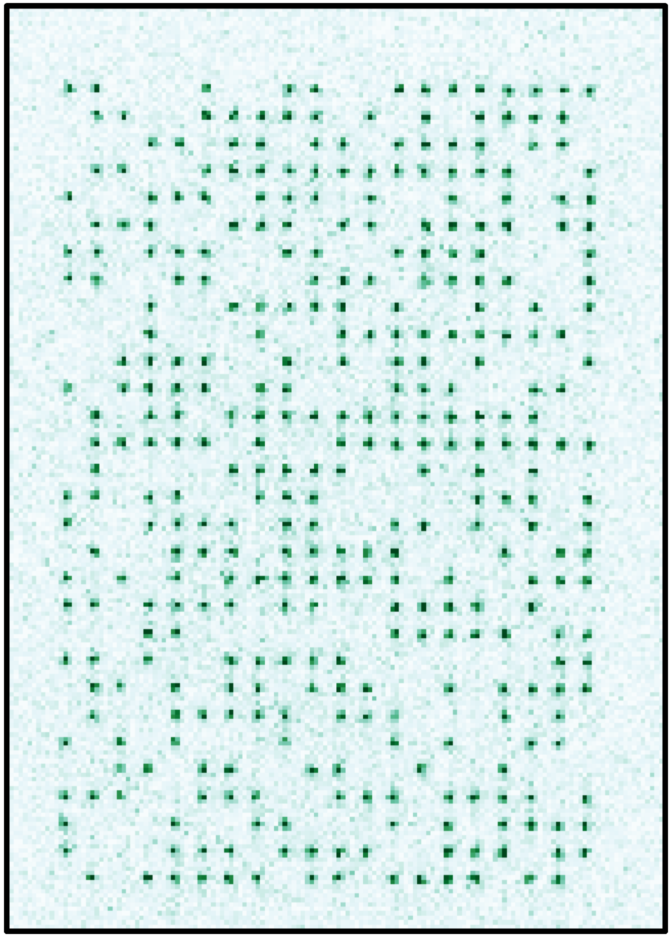
Trapped atoms in different configurations



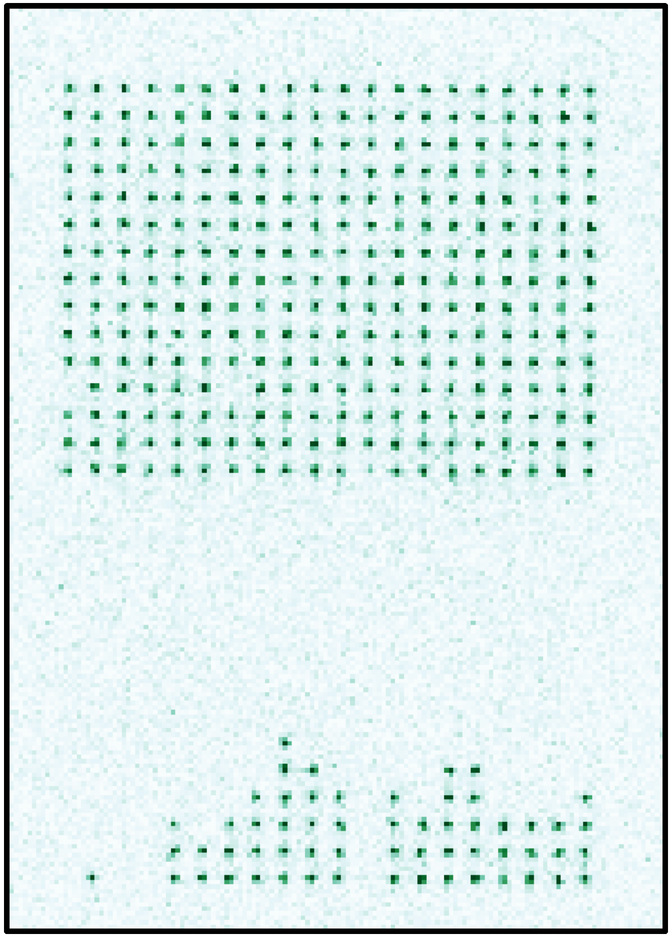
Green color: real images of individual atoms

Sorting 300 atoms in two dimensions

Initial loading:

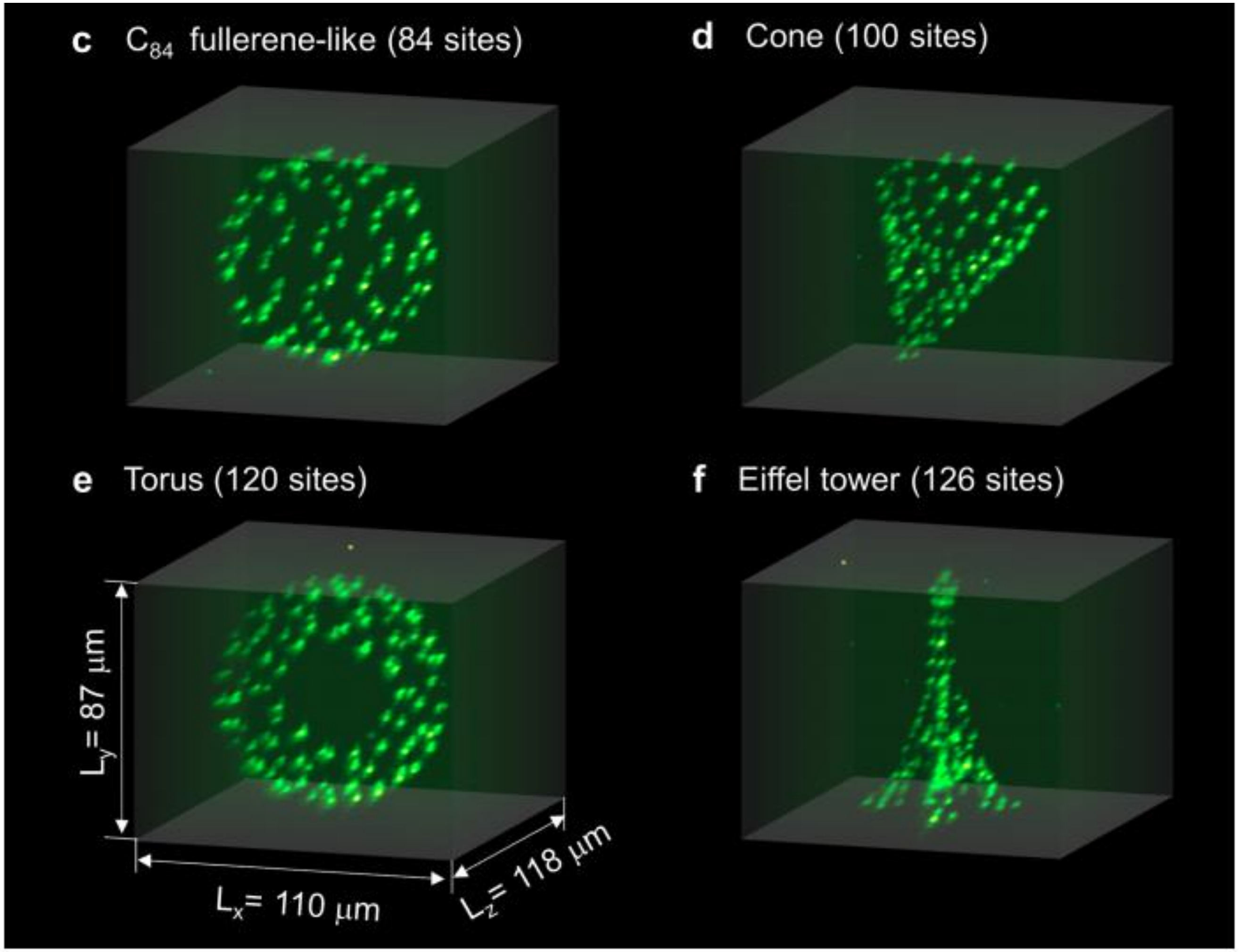


After sorting:



> 98% filling fraction

Three dimensional arrays also possible

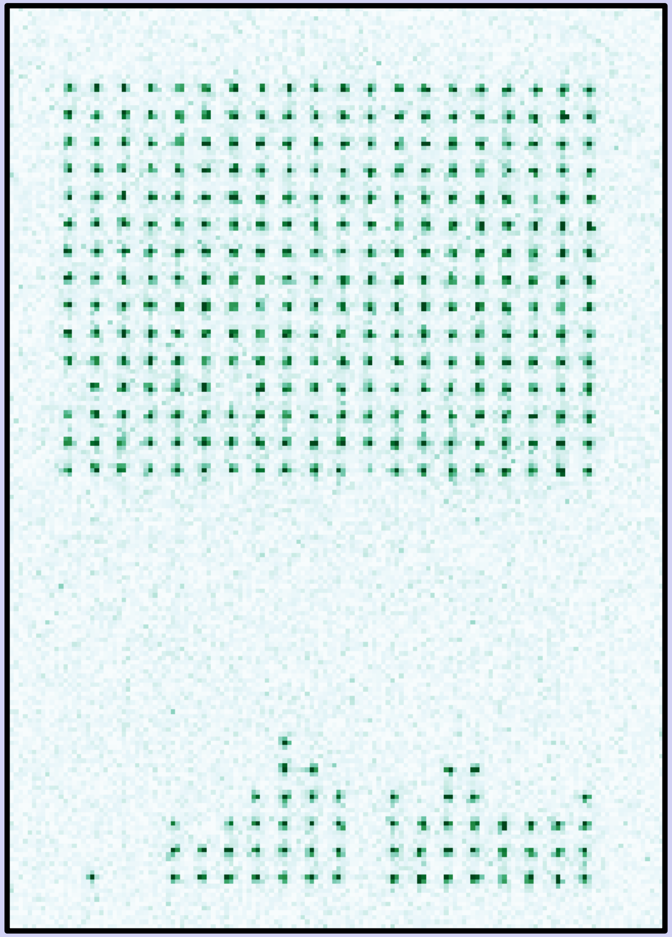


Synthetic three-dimensional atomic structures assembled atom by atom. D. Barredo, V. Lienhard, S. de Léséleuc, T. Lahaye & A. Browaeys, Nature **561**, 79–82 (2018).

>256-atom quantum simulator

In collaboration with Mikhail Lukin and Markus Greiner (Harvard)

Other pioneering work in this field: Antoine Browaeys' group



Making controllable spin systems

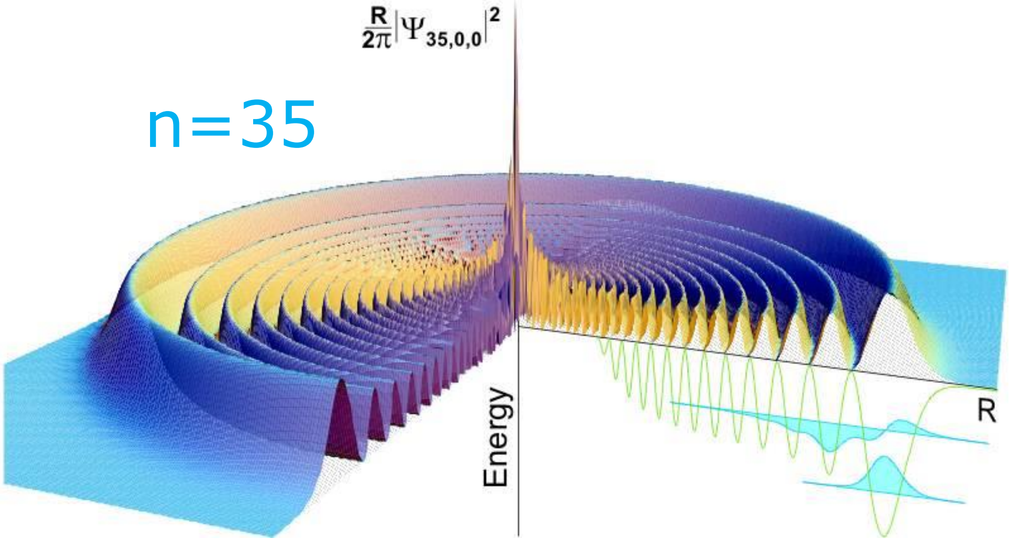
- Atom can be addressed to create effective spin ½ system
- We can trap and image individual atoms with optically resolvable separation (few μm)
- Can we make atoms interact over those distances?

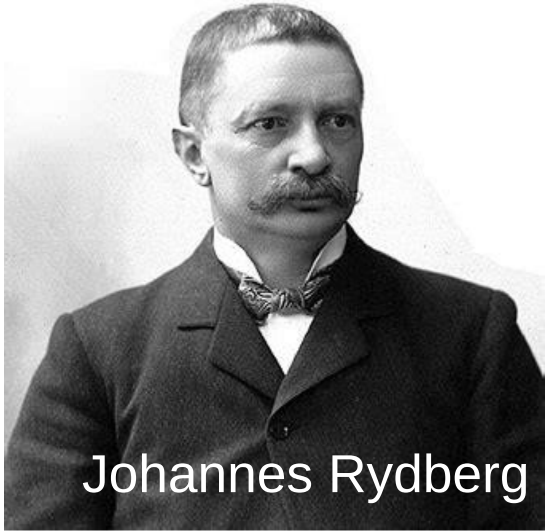
- Rydberg blockade:

  D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin, Phys. Rev. Lett. **85**, 2208 (2000).

Rydberg atoms

- Hydrogen-like atoms with one electron in a highly excited state: n=50-100
- Spectroscopically explored by Johannes Rydberg

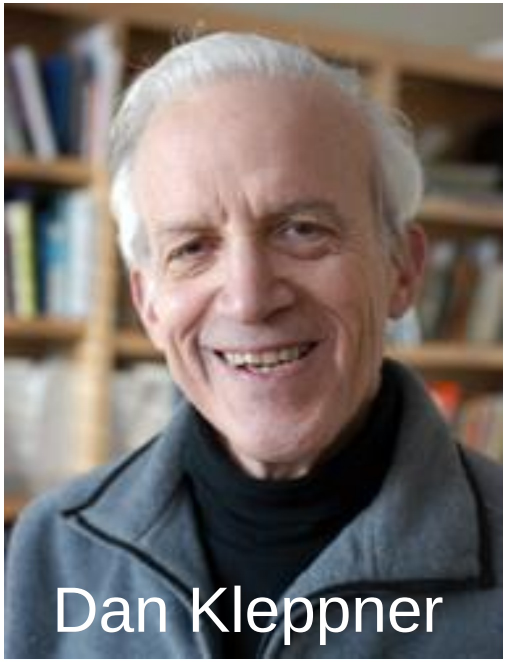



Johannes Rydberg


Niels Bohr

Rydberg atoms

- Extensively studied by Dan Kleppner.
- Electron very far from nucleus, very large dipole moment, strong interaction with electromagnetic fields.
- Serge Haroche – Nobel Prize 2012 for work in cavity quantum electrodynamics.
- Very large polarizability, strong Rydberg-Rydberg interactions.


Dan Kleppner

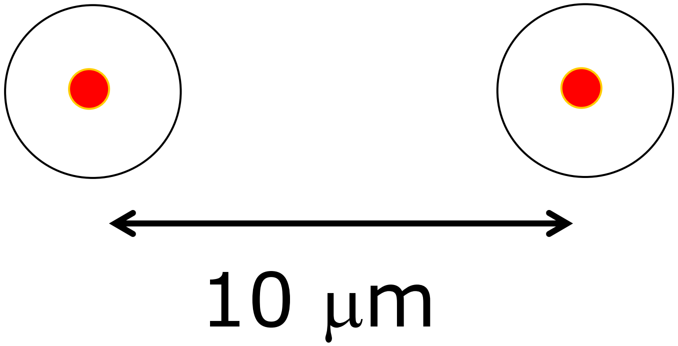

Serge Haroche

Rydberg states

Very highly excited hydrogen-like states

Extremely large size, dipole moment, polarizability

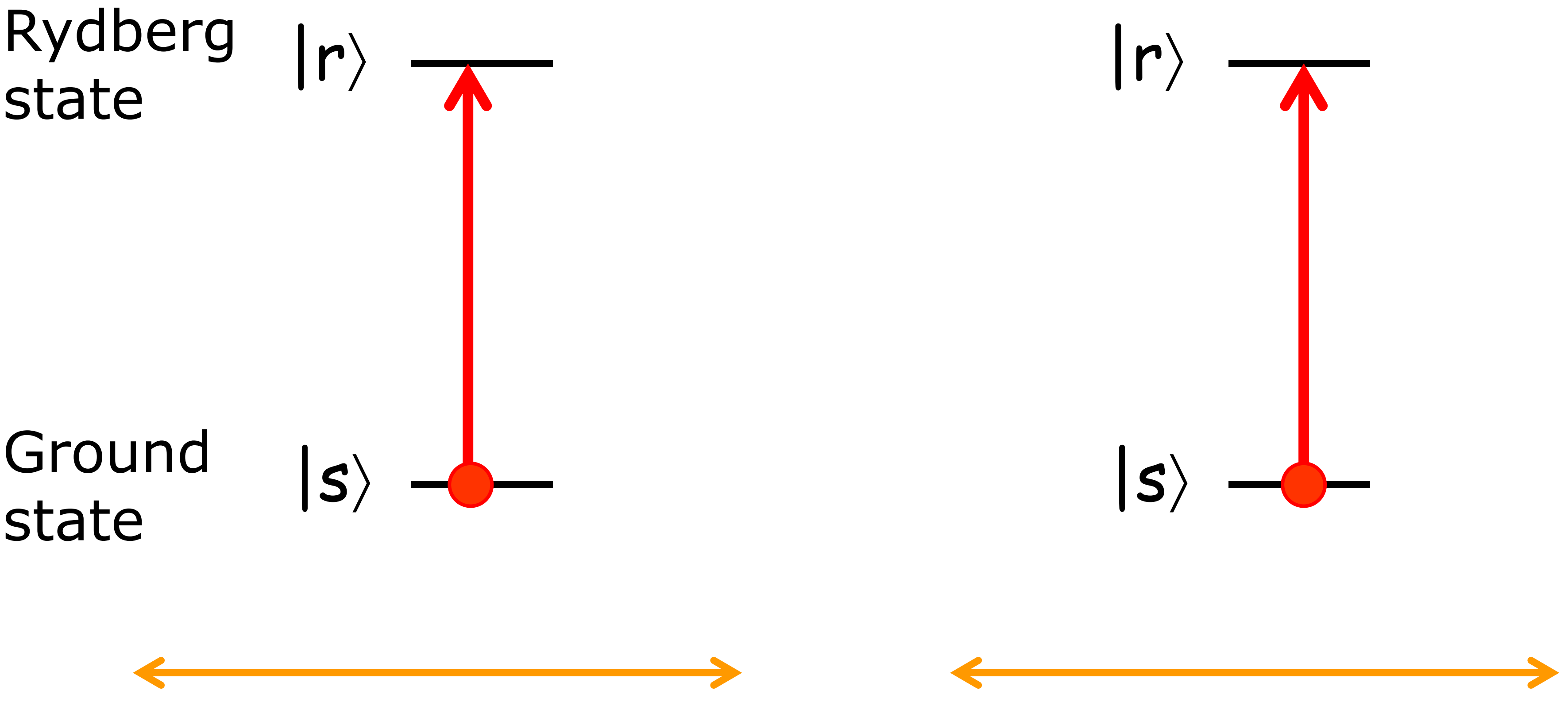
Strong Rydberg-Rydberg interactions $V(R)=C_6/R^6$



MHz interaction strength over optically resolvable 10 μm distance scale

Rydberg-Rydberg interactions can be used to implement strong spin-spin interactions over optically resolvable distances

Rydberg interactions



Rydberg state $|r\rangle$

Ground state $|s\rangle$

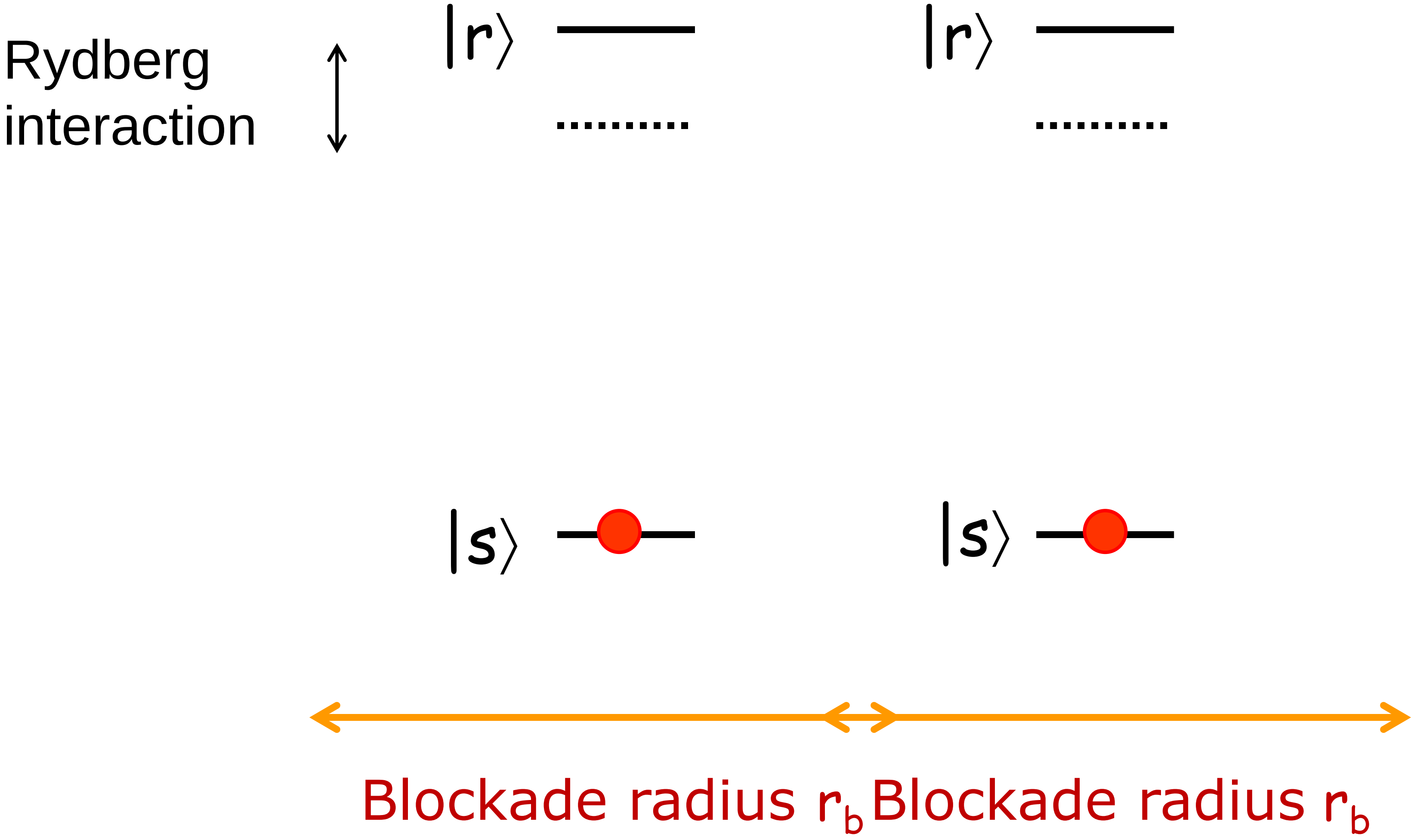
$|r\rangle$

$|s\rangle$

Blockade radius $r_b \sim 10\ \mu m$

Blockade radius r_b

Rydberg interactions



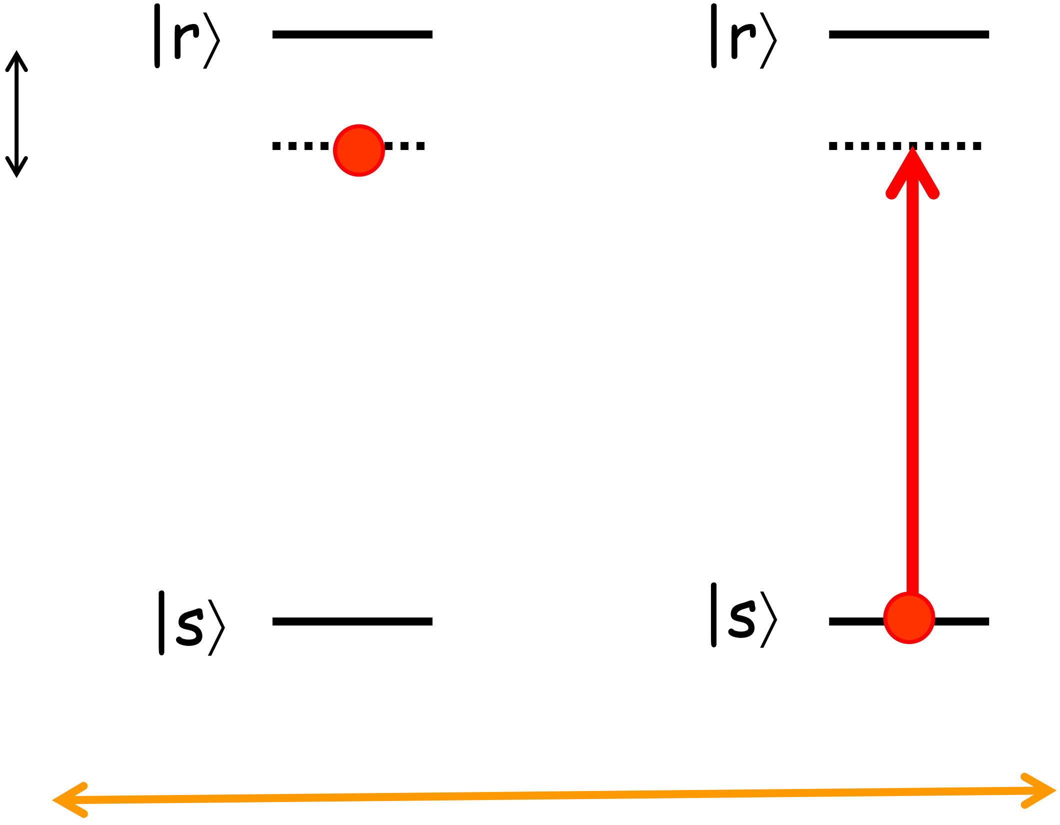
Rydberg interaction

$|r\rangle$ $|r\rangle$

$|s\rangle$ $|s\rangle$

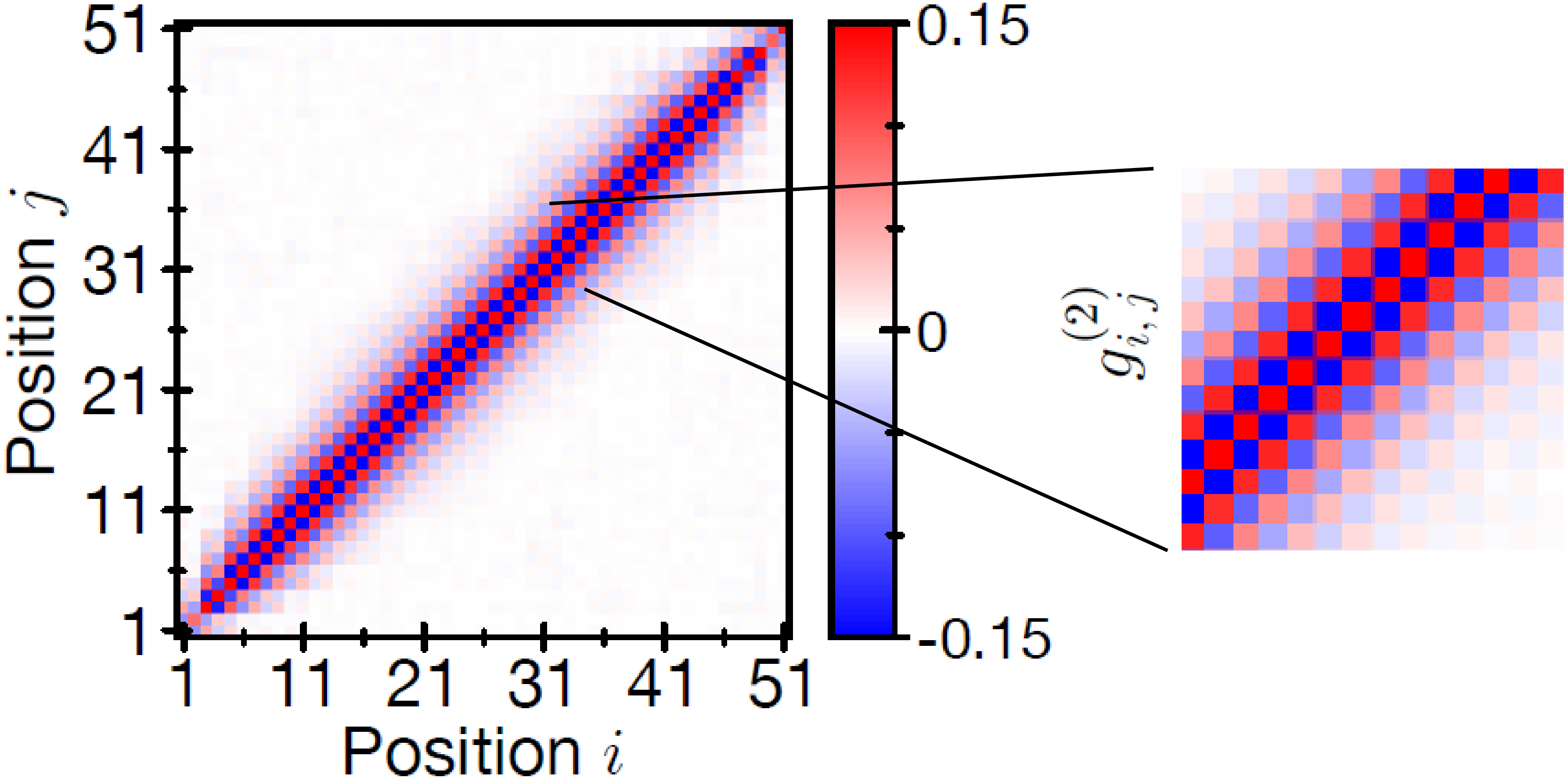
Blockade radius r_b Blockade radius r_b

Rydberg interactions



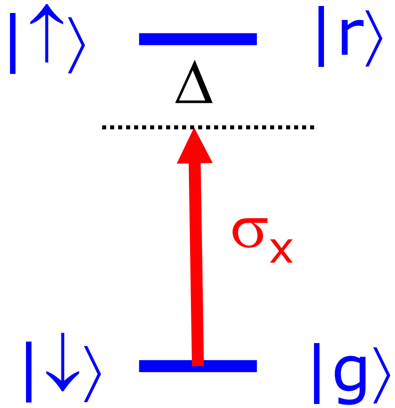
Blockade radius r_b

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);

System Hamiltonian

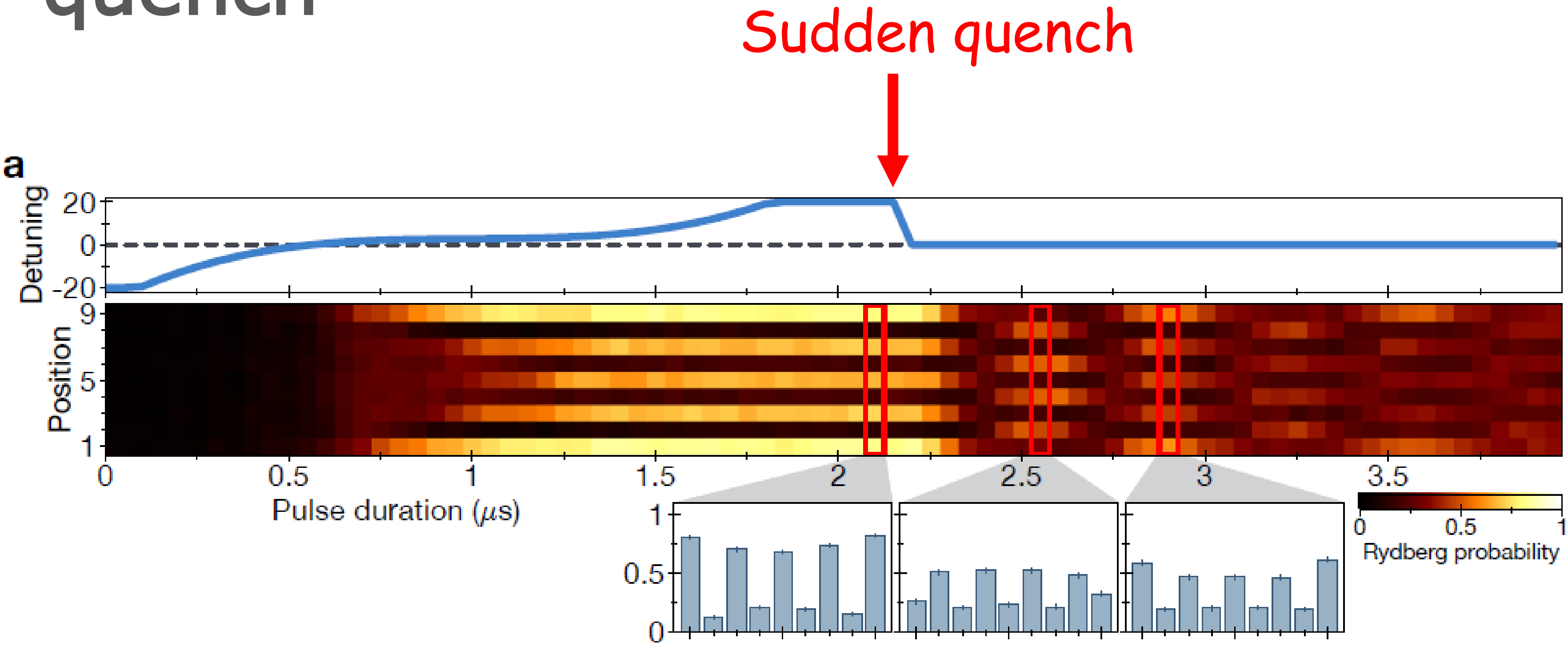


$$\frac{H}{\hbar} = \frac{\Omega(t)}{2}\sum_i \sigma_i^x - \Delta(t)\sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

Ground-Rydberg system as spin ½

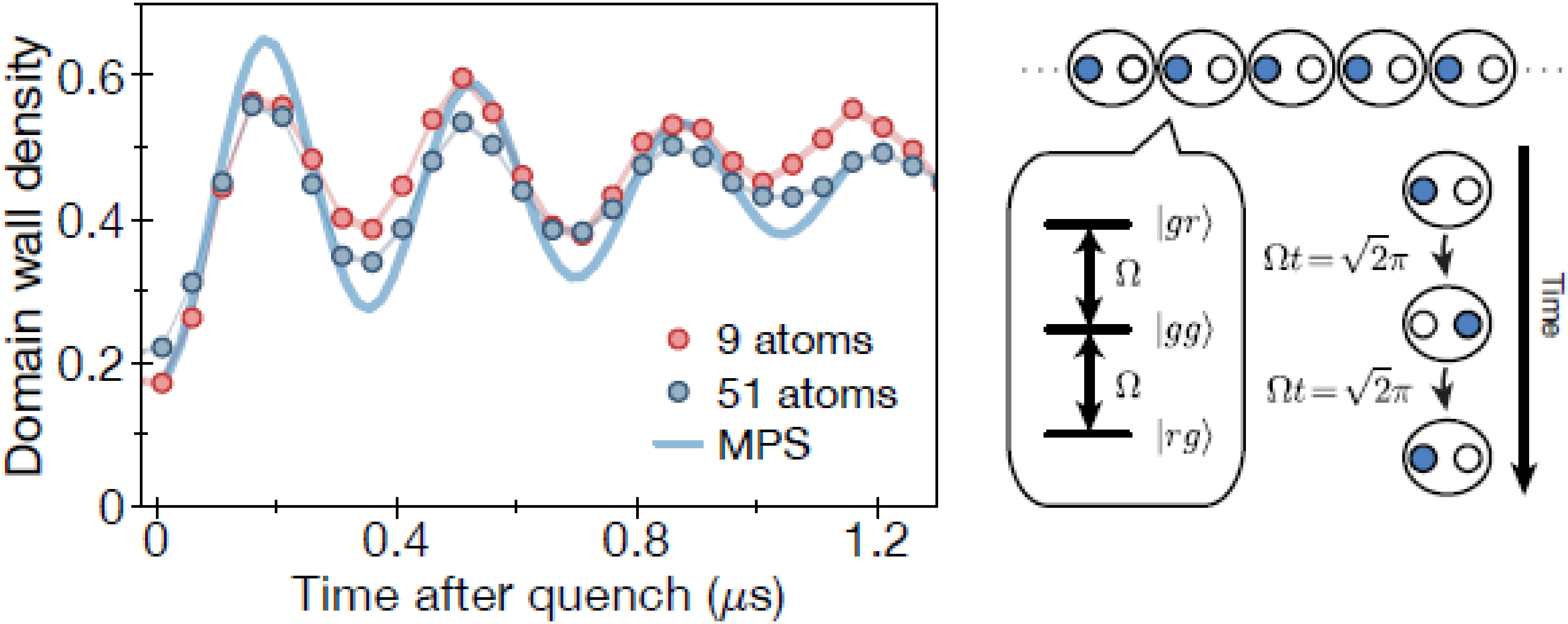
Quantum Many-Body Scars

Collective oscillations after a sudden quench



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

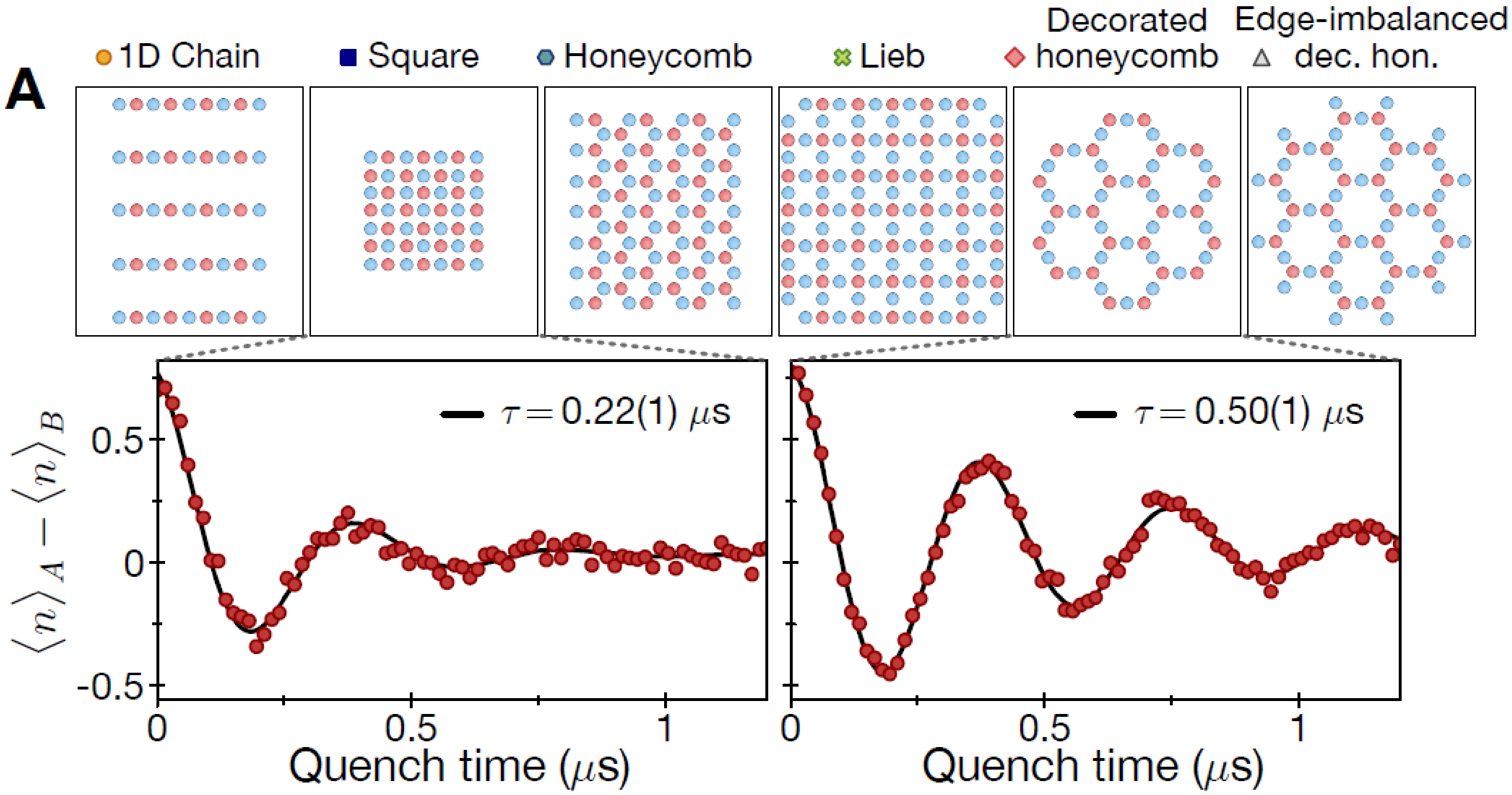
Collective oscillations after a sudden quench



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.

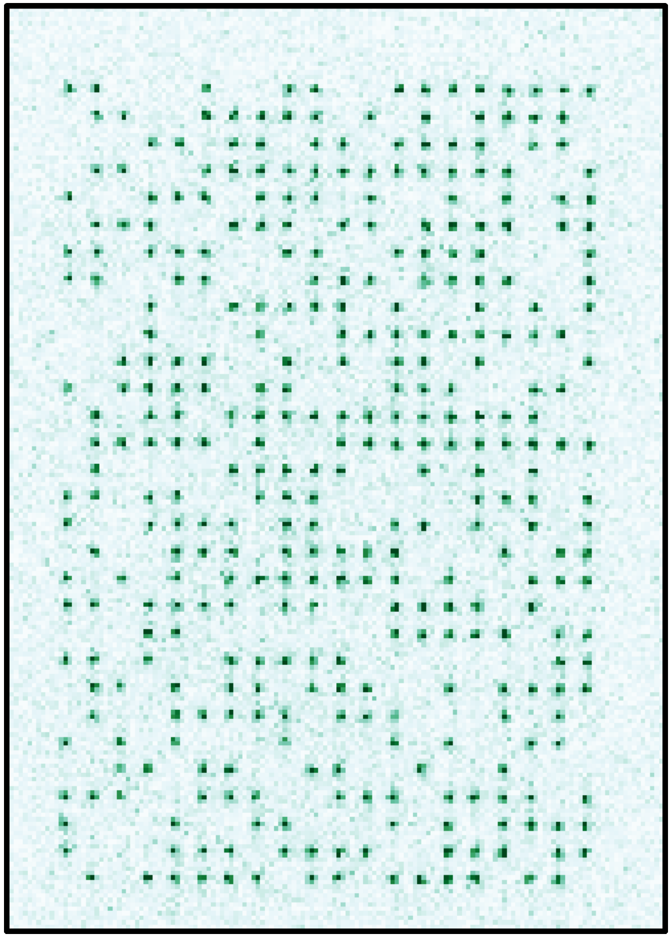
D. Bluvstein, A. Omran, H. Levine, A. Keesling, G. Semeghini, S. Ebadi, T. T. Wang, A. A. Michailidis, N. Maskara, W. W. Ho, S. Choi, M. Serbyn, M. Greiner, V. Vuletić, and M.D. Lukin, Science **371**, 1355–1359 (2021).

Two-dimensional arrays

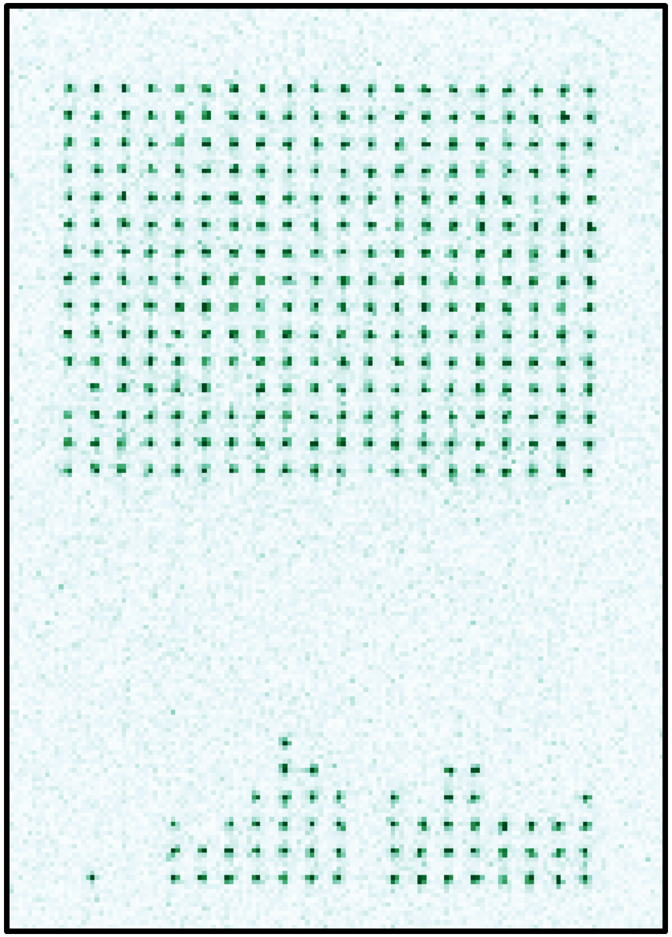
Quantum Phases of Matter on a 256-Atom Programmable Quantum Simulator.
S. Ebadi, T.T. Wang, Levine, A. Keesling, G. Semeghini, A. Omran, D. Bluvstein, R. Samajdar, H. Pichler, W.W. Ho, S. Choi, S. Sachdev, M. Greiner, V. Vuletić, and M.D. Lukin, Nature **595**, 227-232 (2021);

Sorting 300 atoms in two dimensions

Initial loading:



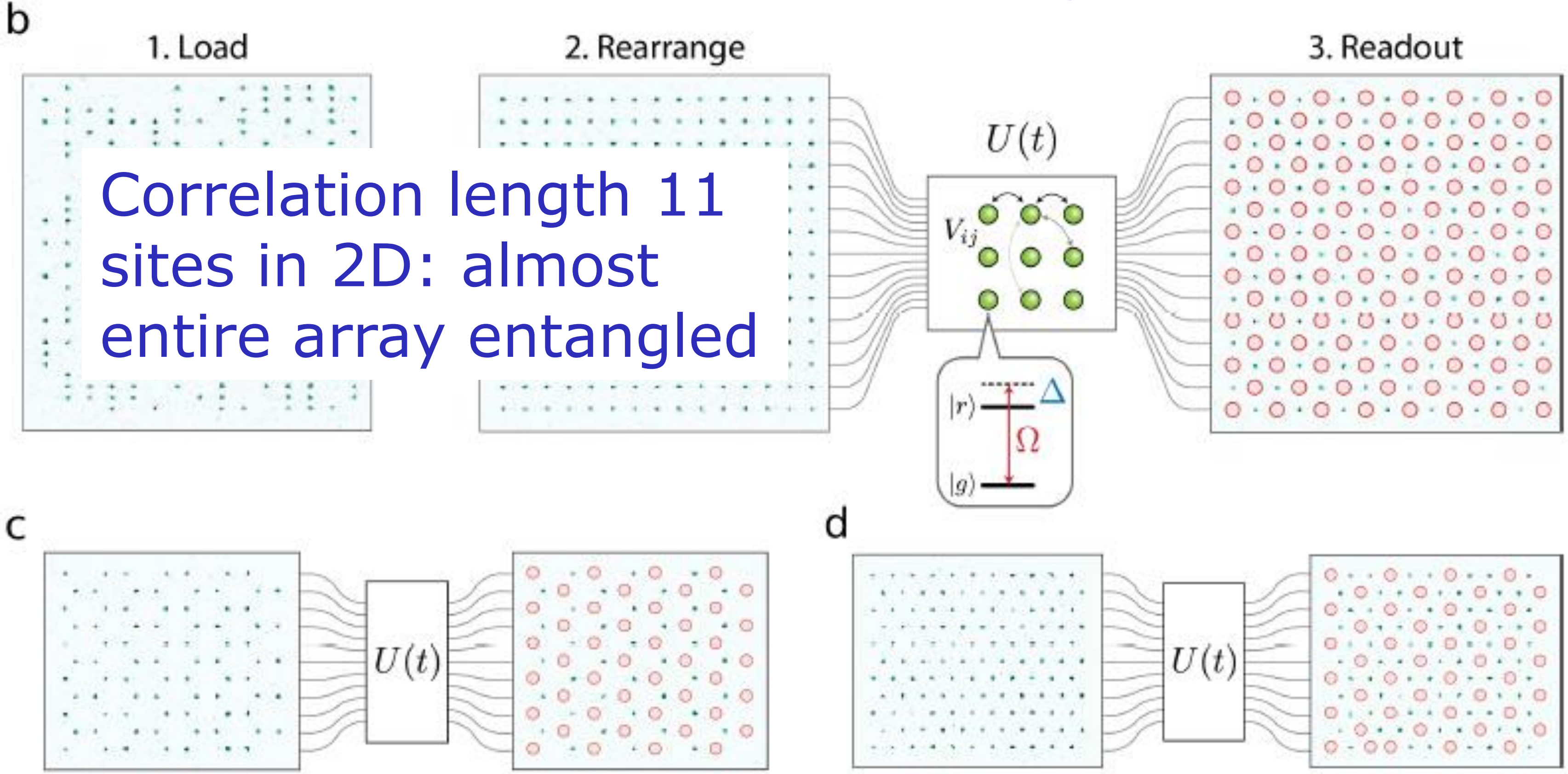
After sorting:



> 98% filling fraction

Antiferromagnetic correlations in 2D

Square geometry



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

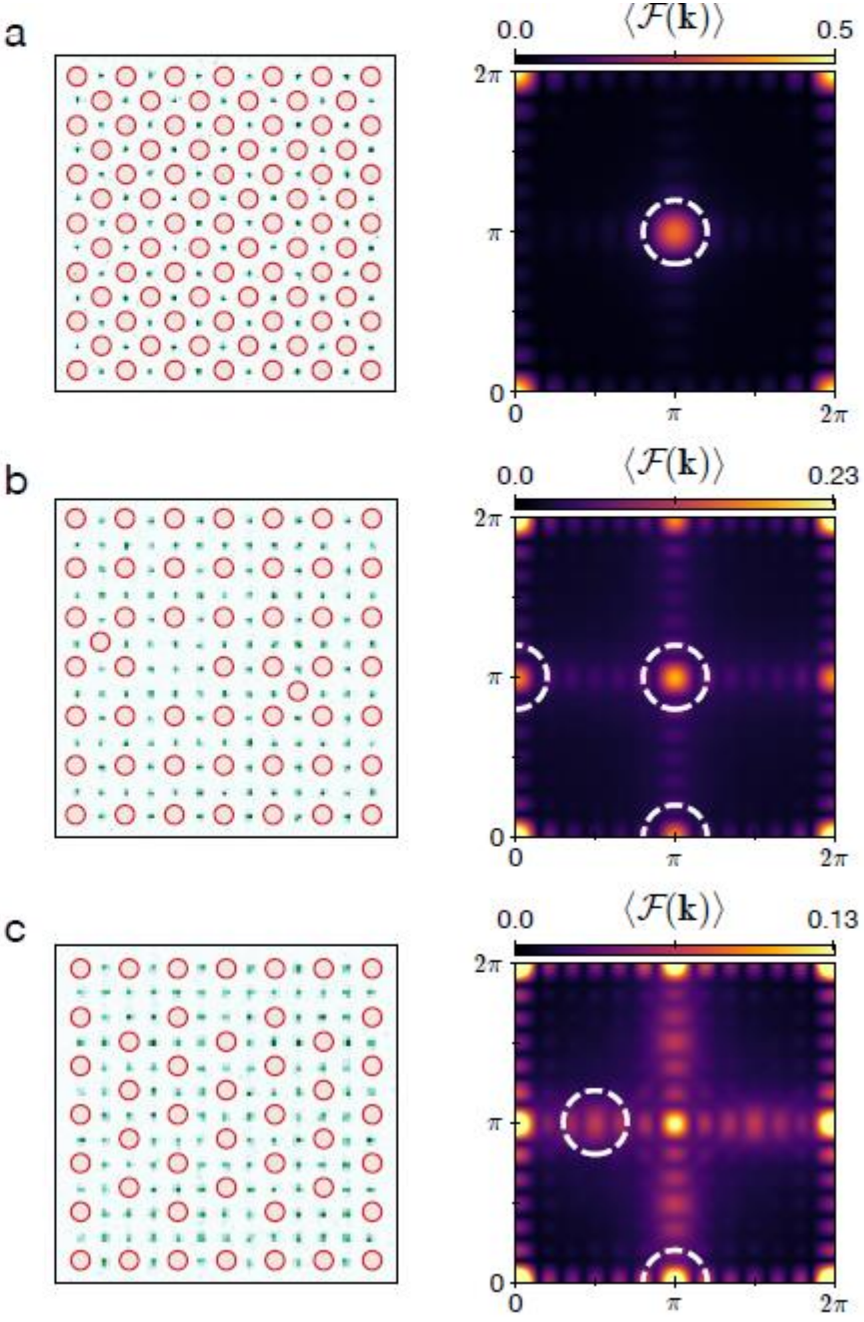
Hexagonal geometry

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

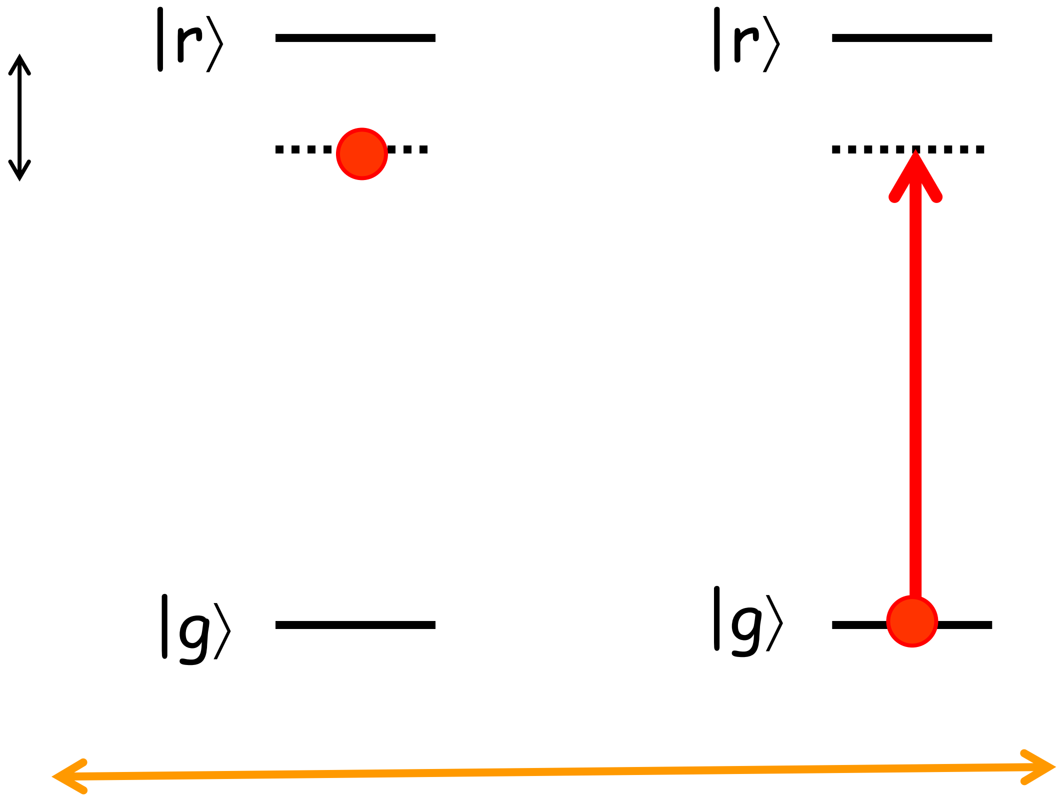


Rydberg quantum gates

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).

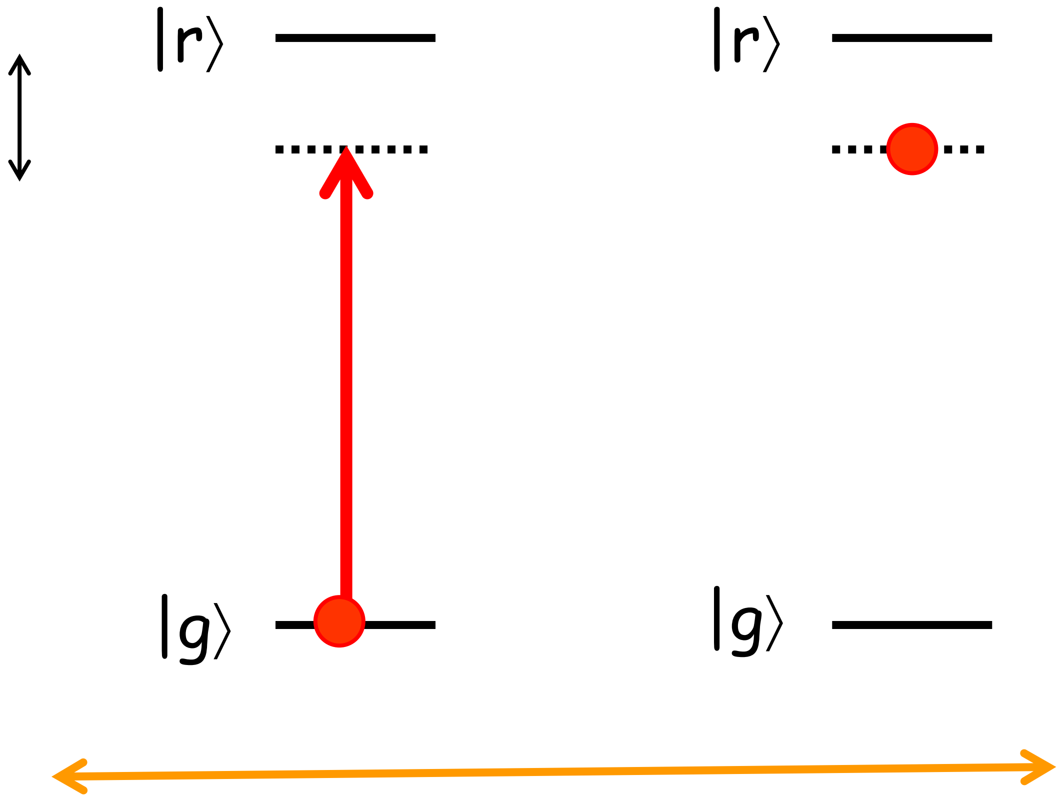
H. Levine, A. Keesling, G. Semeghini, A. Omran, T. T. Wang, S. Ebadi, H. Bernien, M. Greiner, V. Vuletić, H. Pichler, and M. D. Lukin, Phys. Rev. Lett. **123**, 170503 (2019).

Rydberg blockade and collective Rabi flopping



Blockade radius r_b

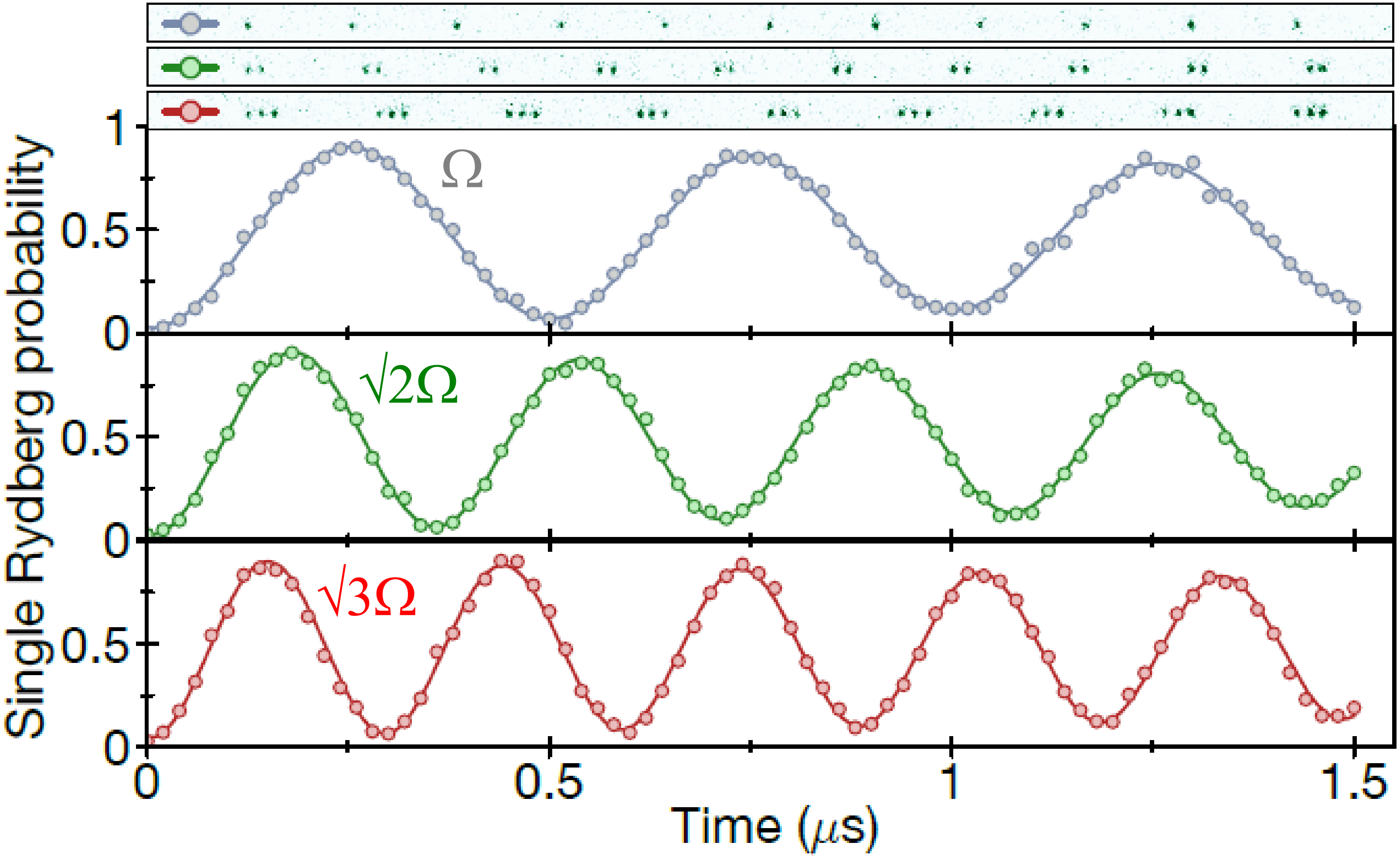
Rydberg blockade and collective Rabi flopping



Blockade radius r_b

Collective Rabi flopping under Rydberg blockade

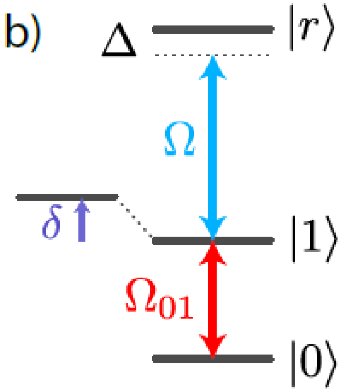
Small trap separation d=2.9 μm « blockade radius r_b

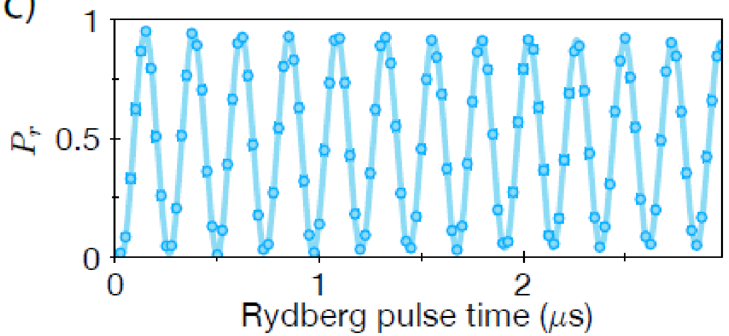


$N^{1/2}$ scaling of collective Rabi frequency observed.

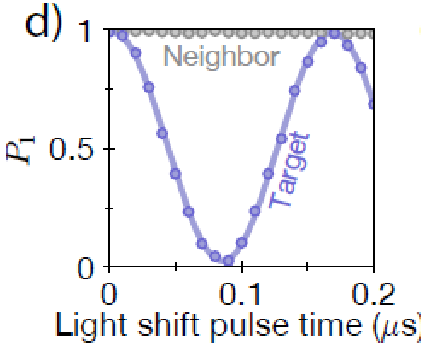
Characterization of Rabi flopping

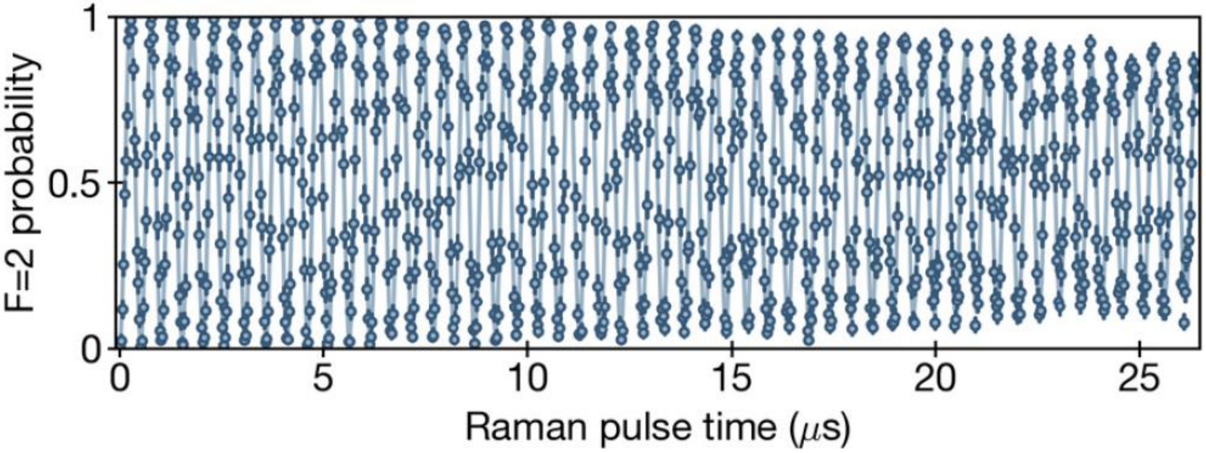
Dispersive optical systems for scalable Raman driving of hyperfine qubits. H. Levine, D. Bluvstein, A. Keesling, T. T. Wang, S. Ebadi, G. Semeghini, A. Omran, M. Greiner, V. Vuletić, and M.D. Lukin, Phys. Rev. A **105**, 032618 (2022);



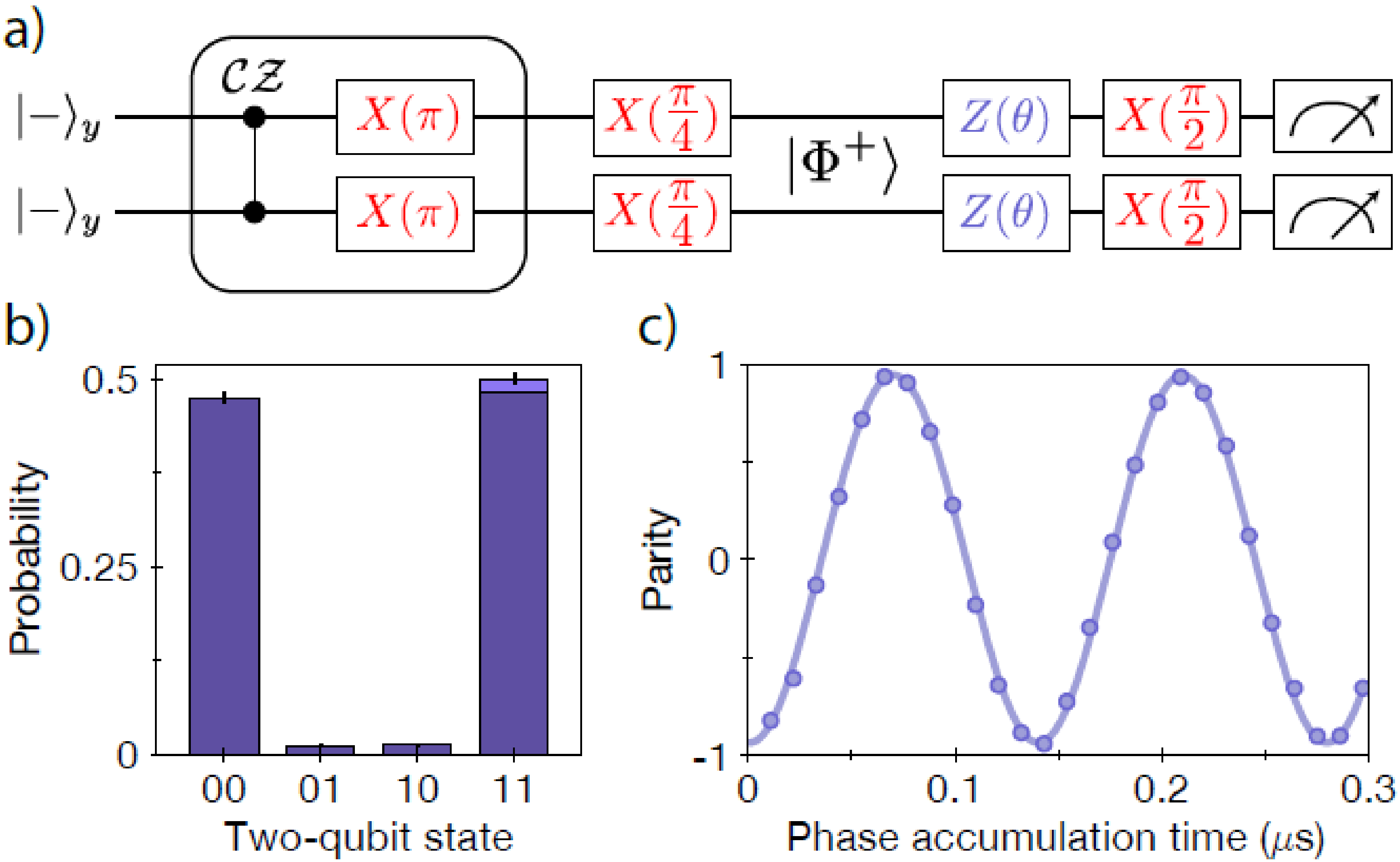


Single qubit fidelity >0.9998



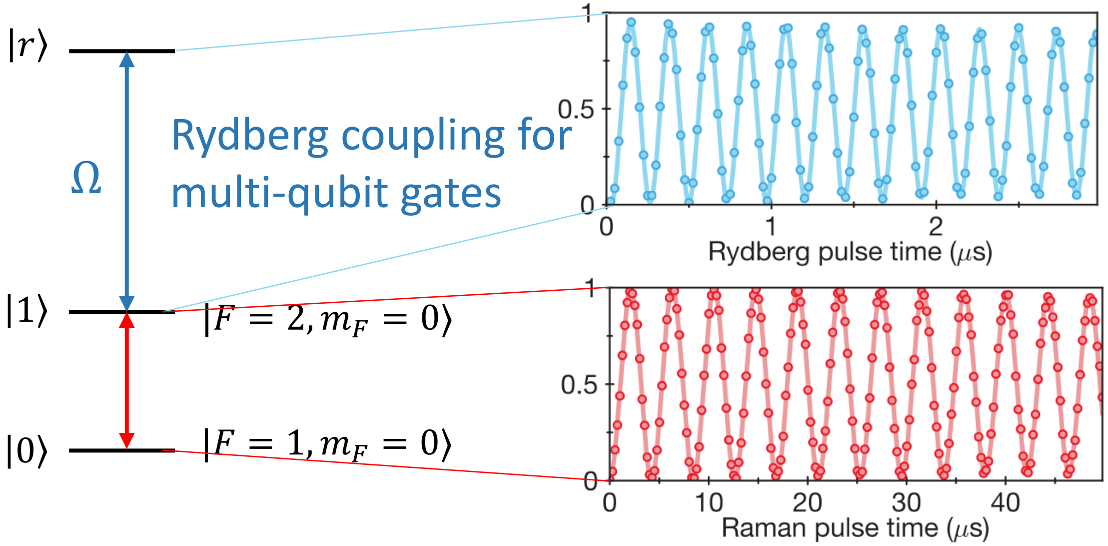


Two-qubit gate



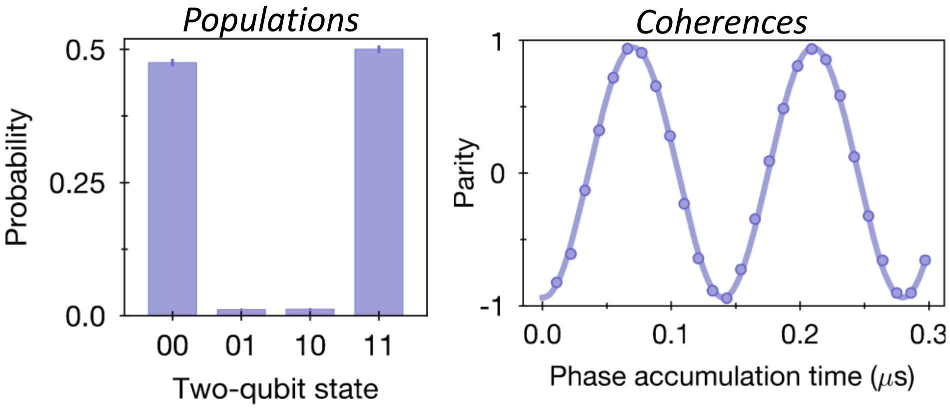
Fidelity > 0.976

Extension to 3-qubit Toffoli gates



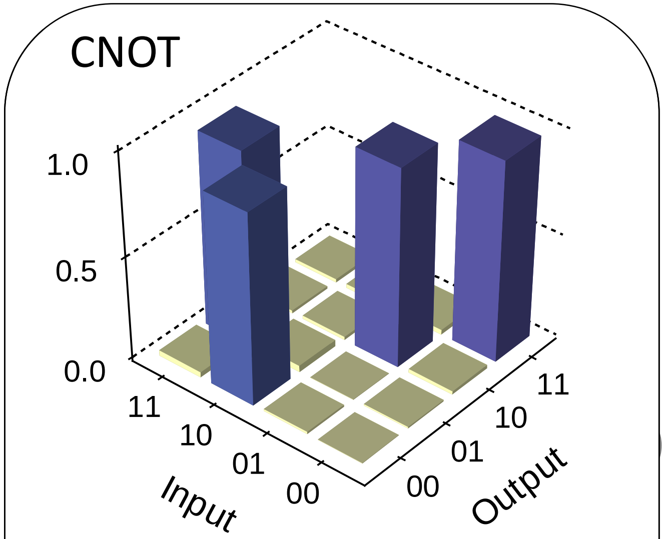
Rydberg coupling for multi-qubit gates

High-fidelity entanglement of hyperfine states

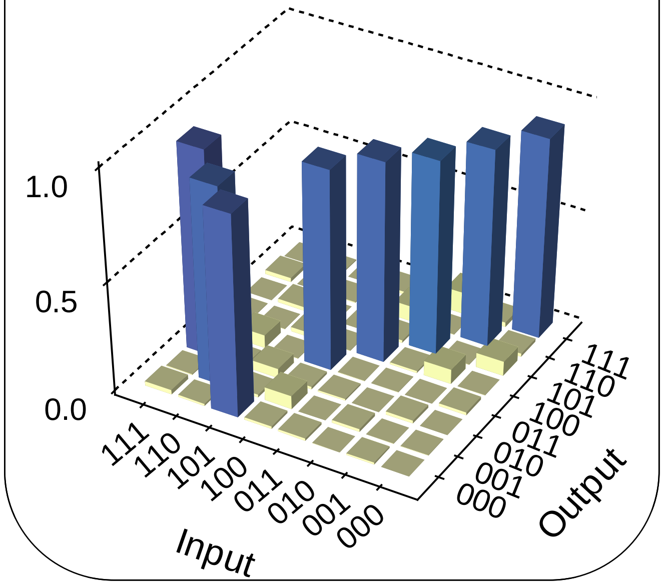


Controlled-phase gate fidelity: $\mathcal{F} = 97.4(3)\%$

CNOT



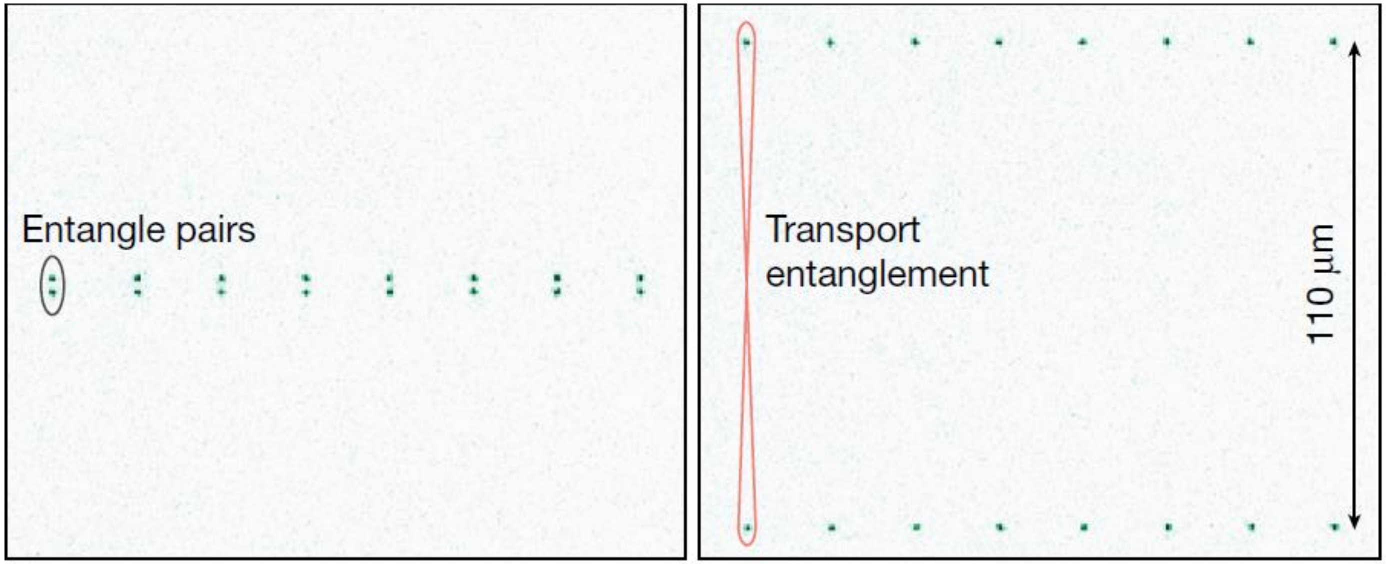
Extension to 3-Toffoli

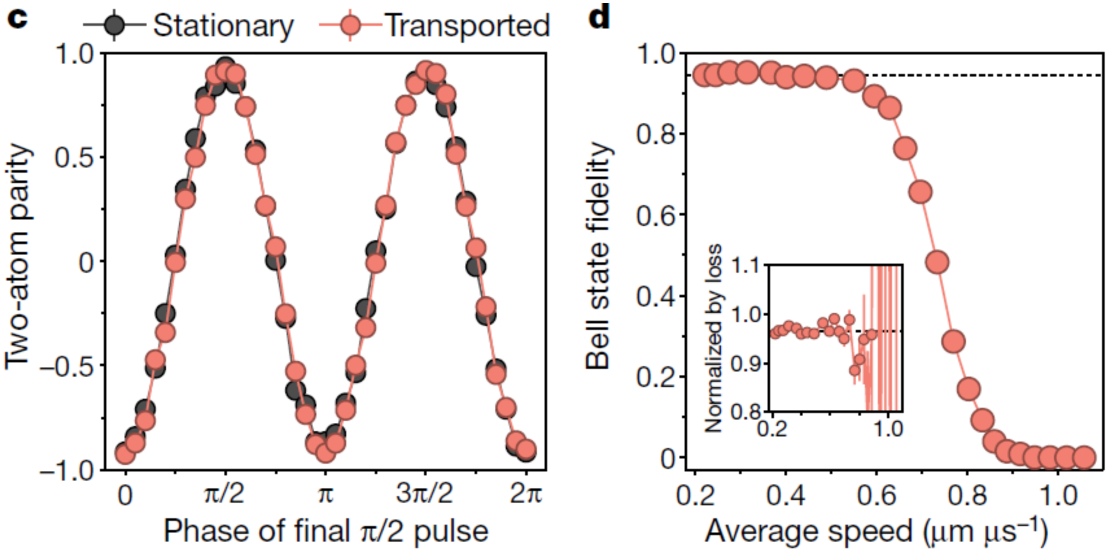


H. Levine, et. al. *PRL* (2019)

Transporting entangled states
Towards quantum error correction

Transporting entanglement

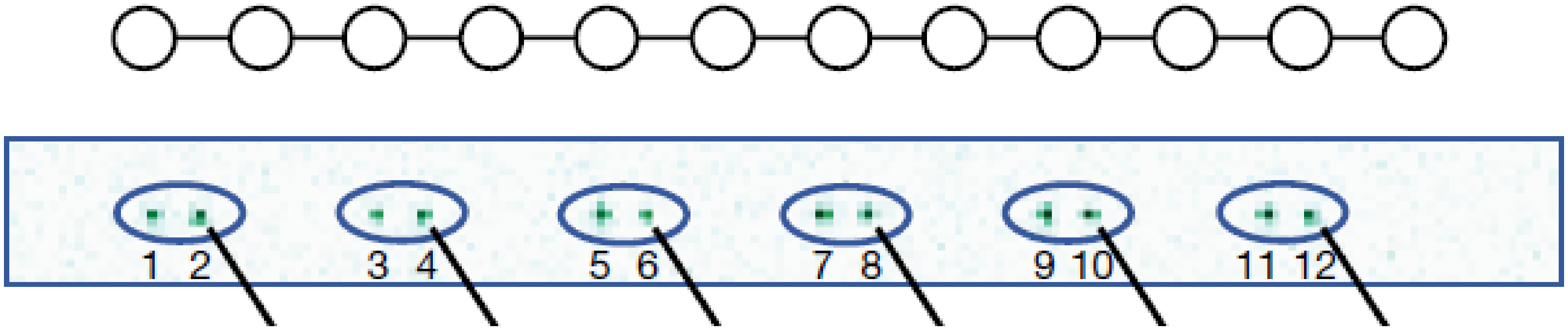




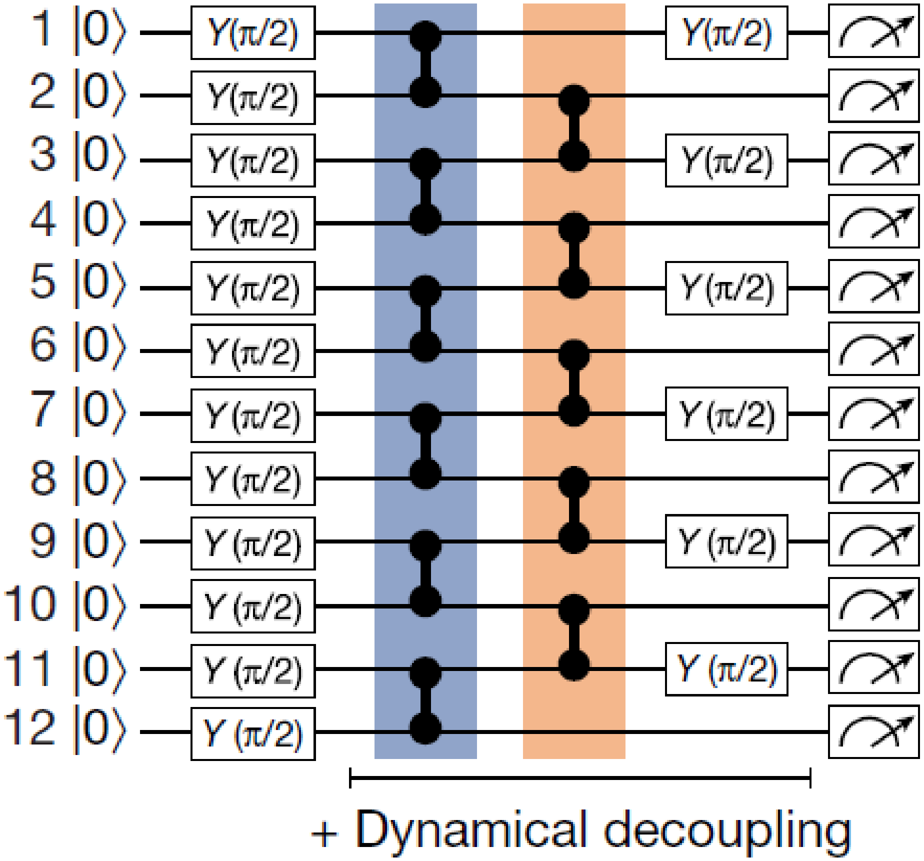
No deterioration in entanglement observed for transported Bell pair

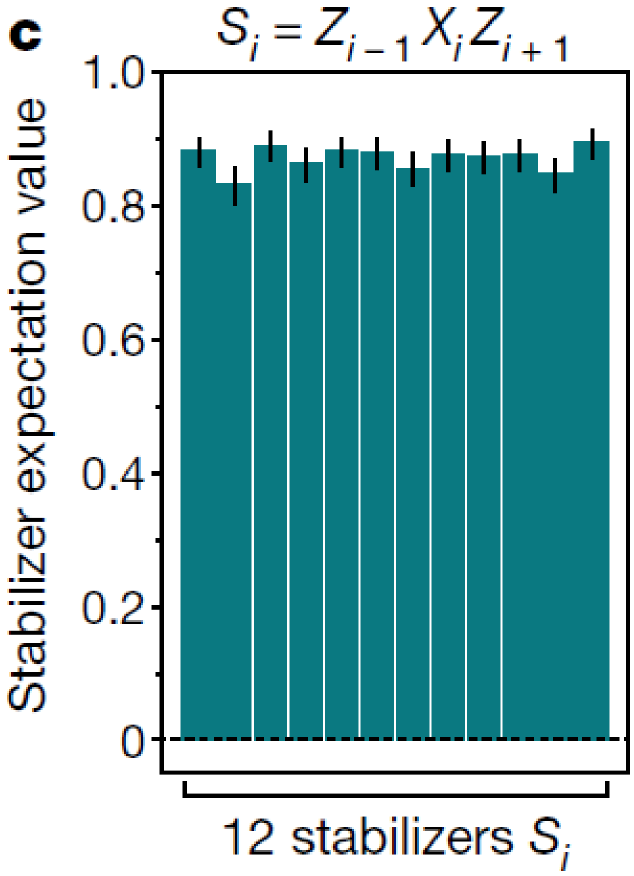
1D cluster state generation by atom transport

1D cluster state graph

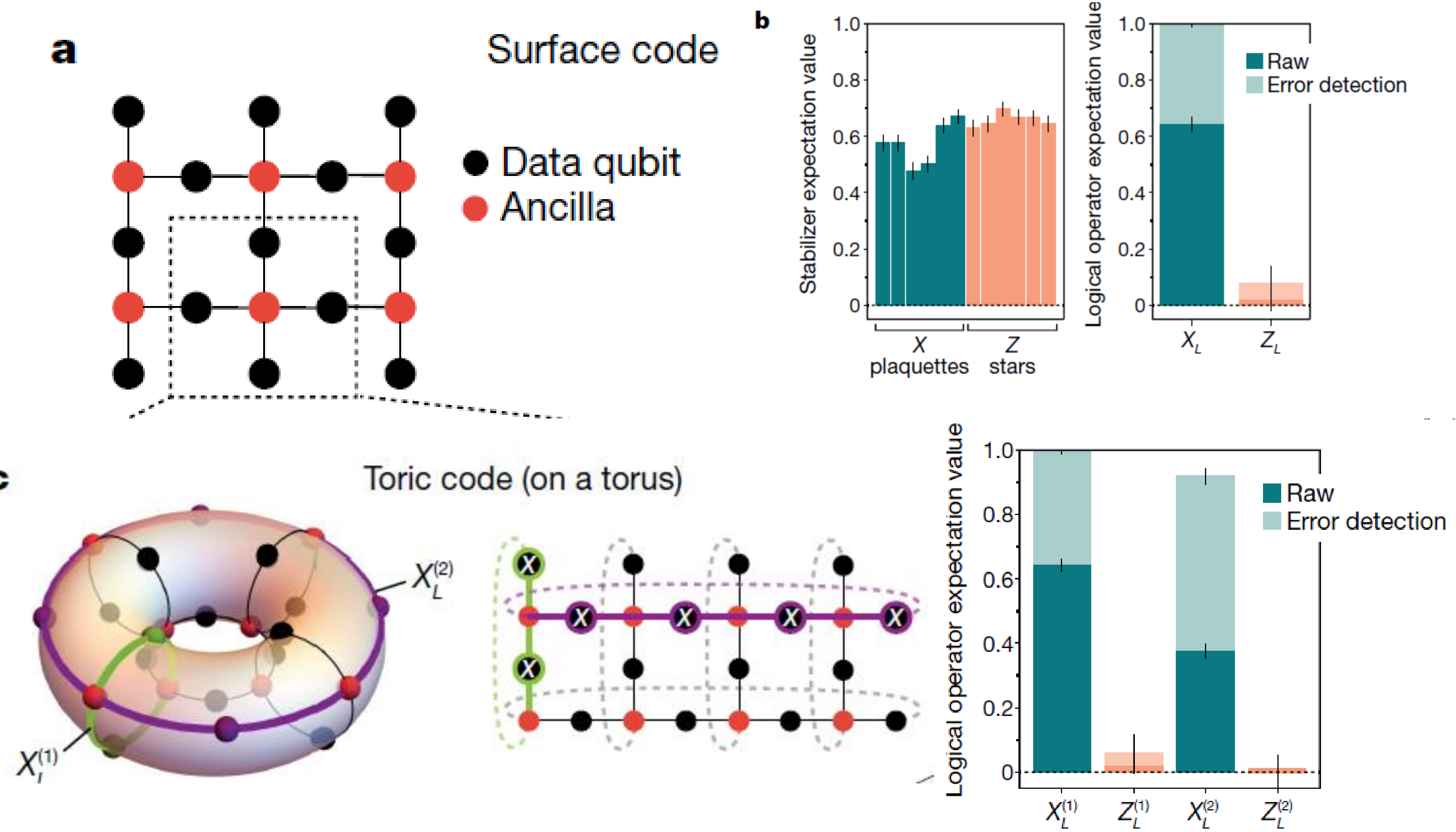


Measure stabilizers for future error correction (1D cluster state)

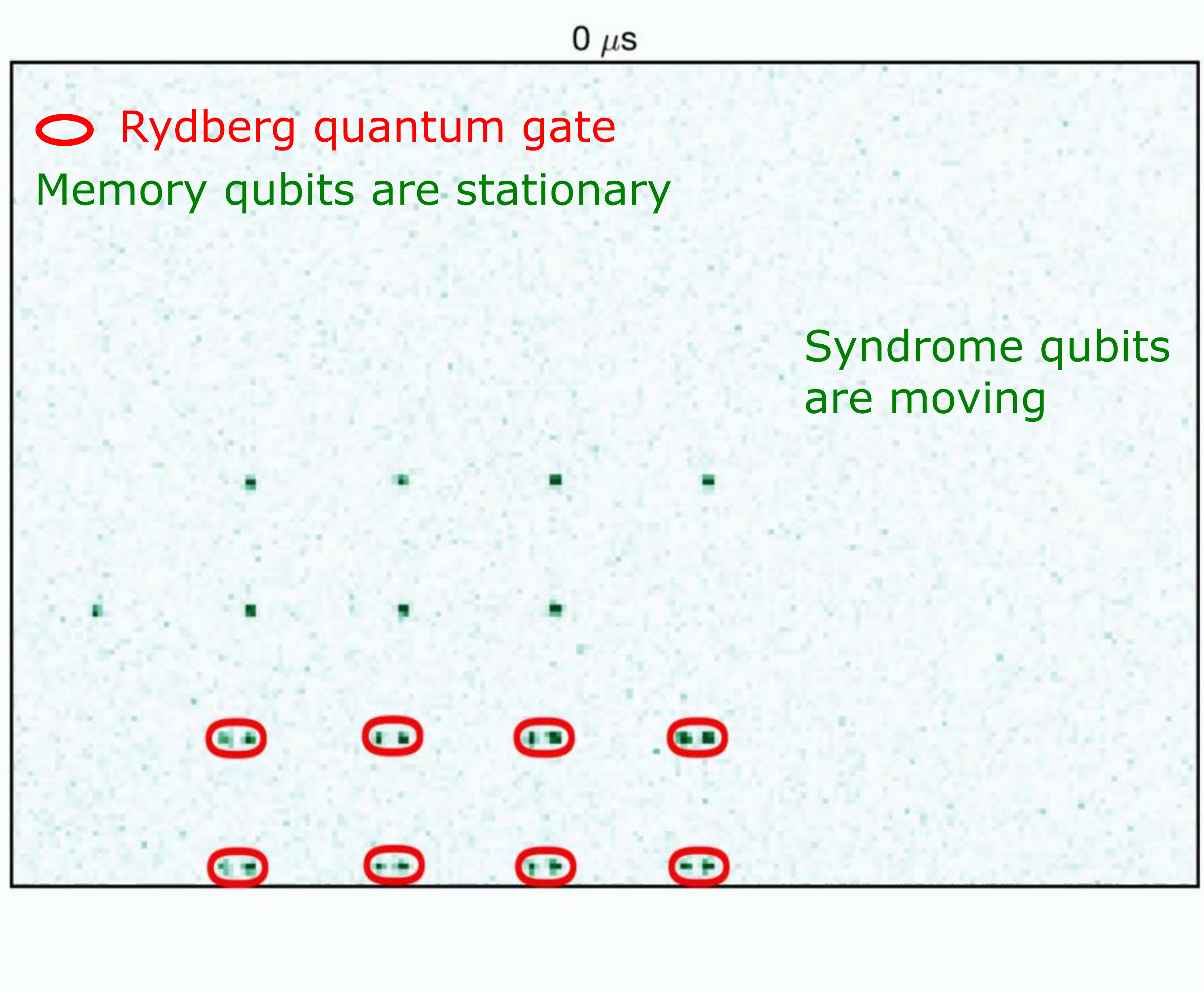




Syndrome measurements for quantum error correction codes



Implementation of Toric code

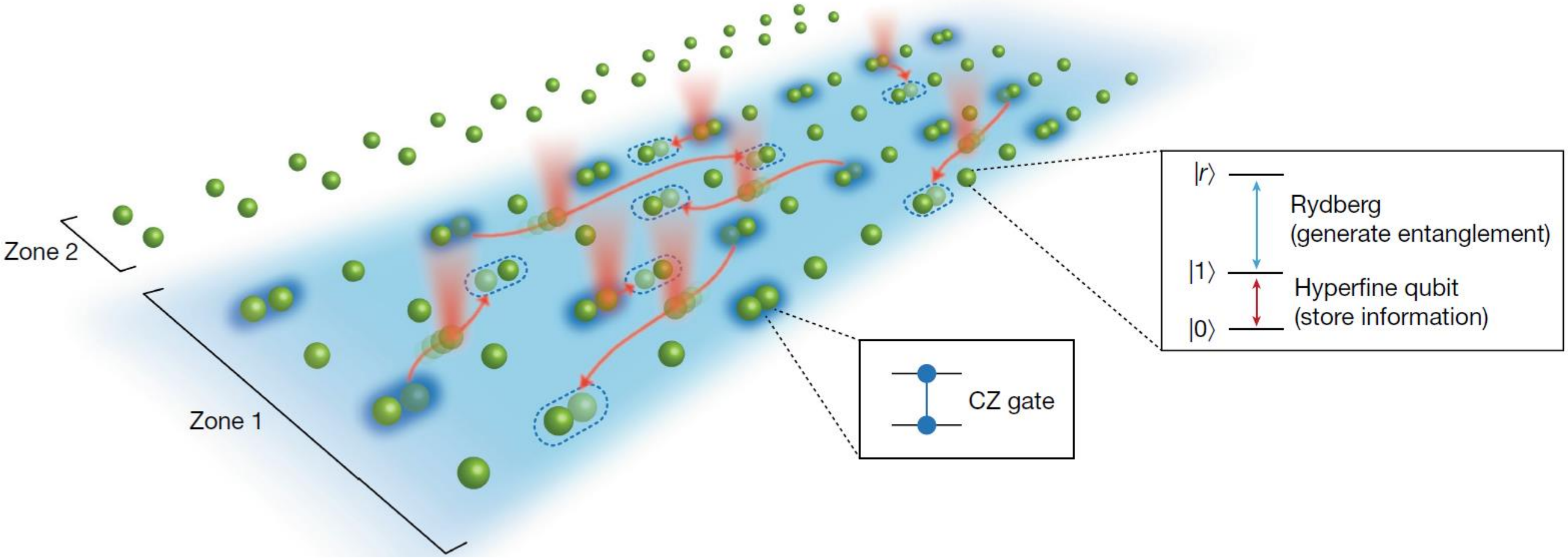


○ Rydberg quantum gate

Memory qubits are stationary

Syndrome qubits are moving

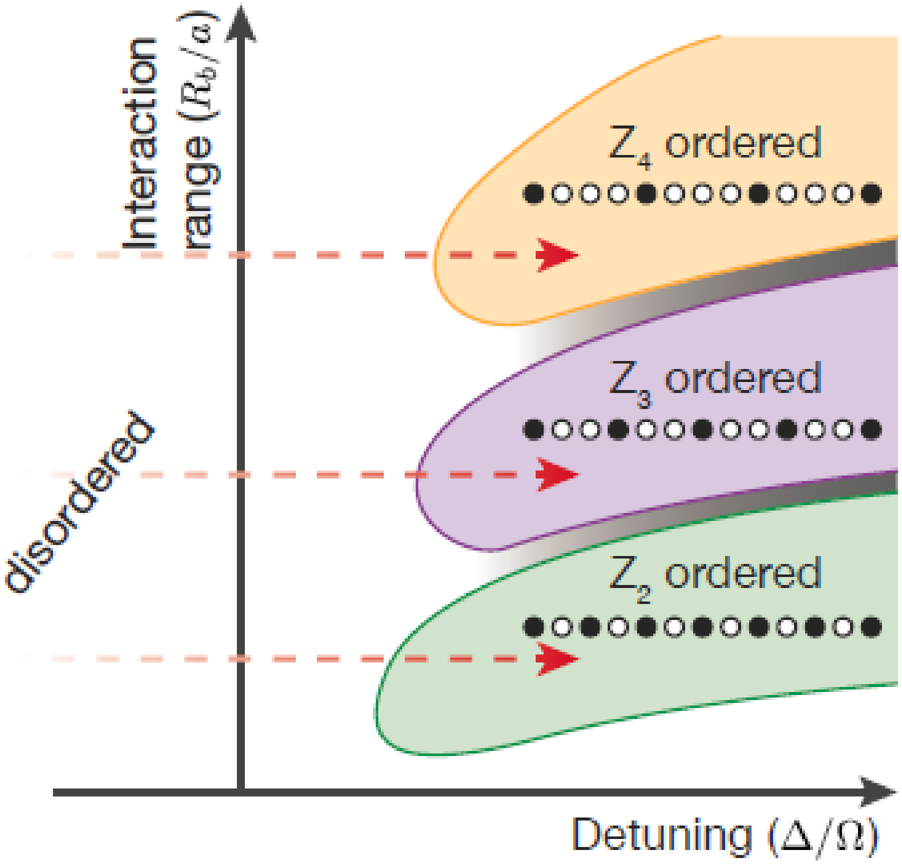
Vision for quantum processor

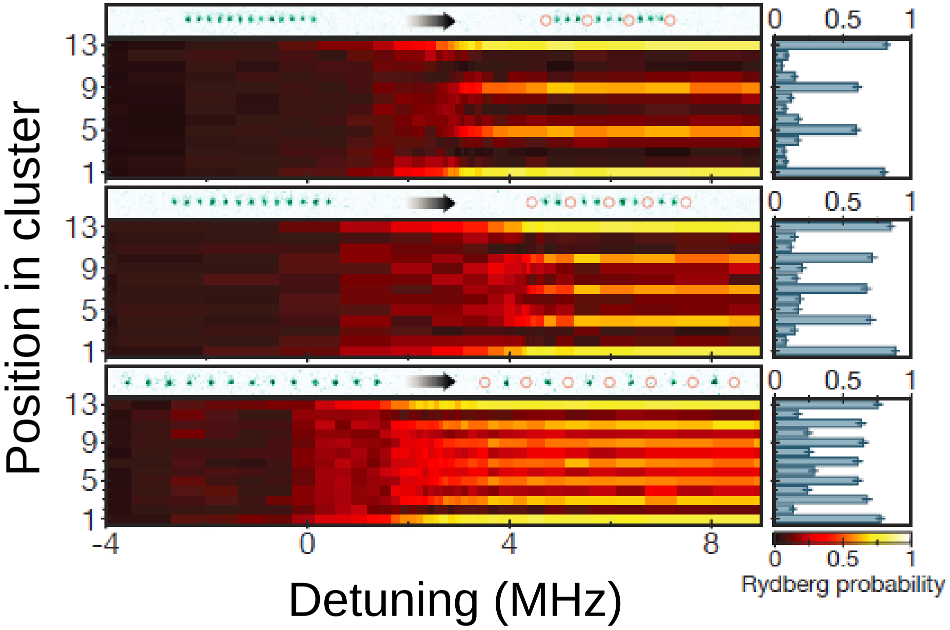


Summary and Outlook

- Large-scale entanglement, both for collective spin states, and individually controlled spins, 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?

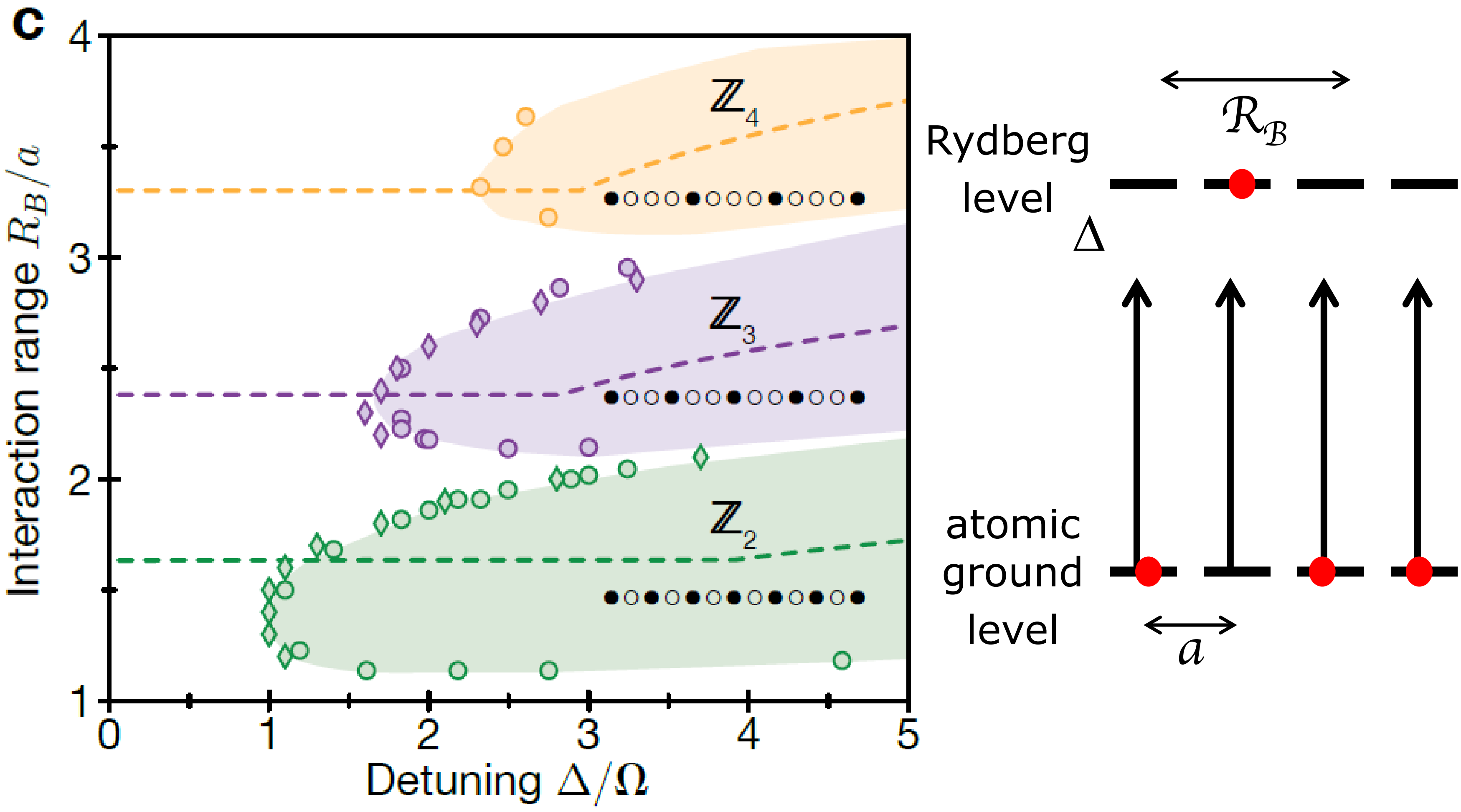
Different ordered phases





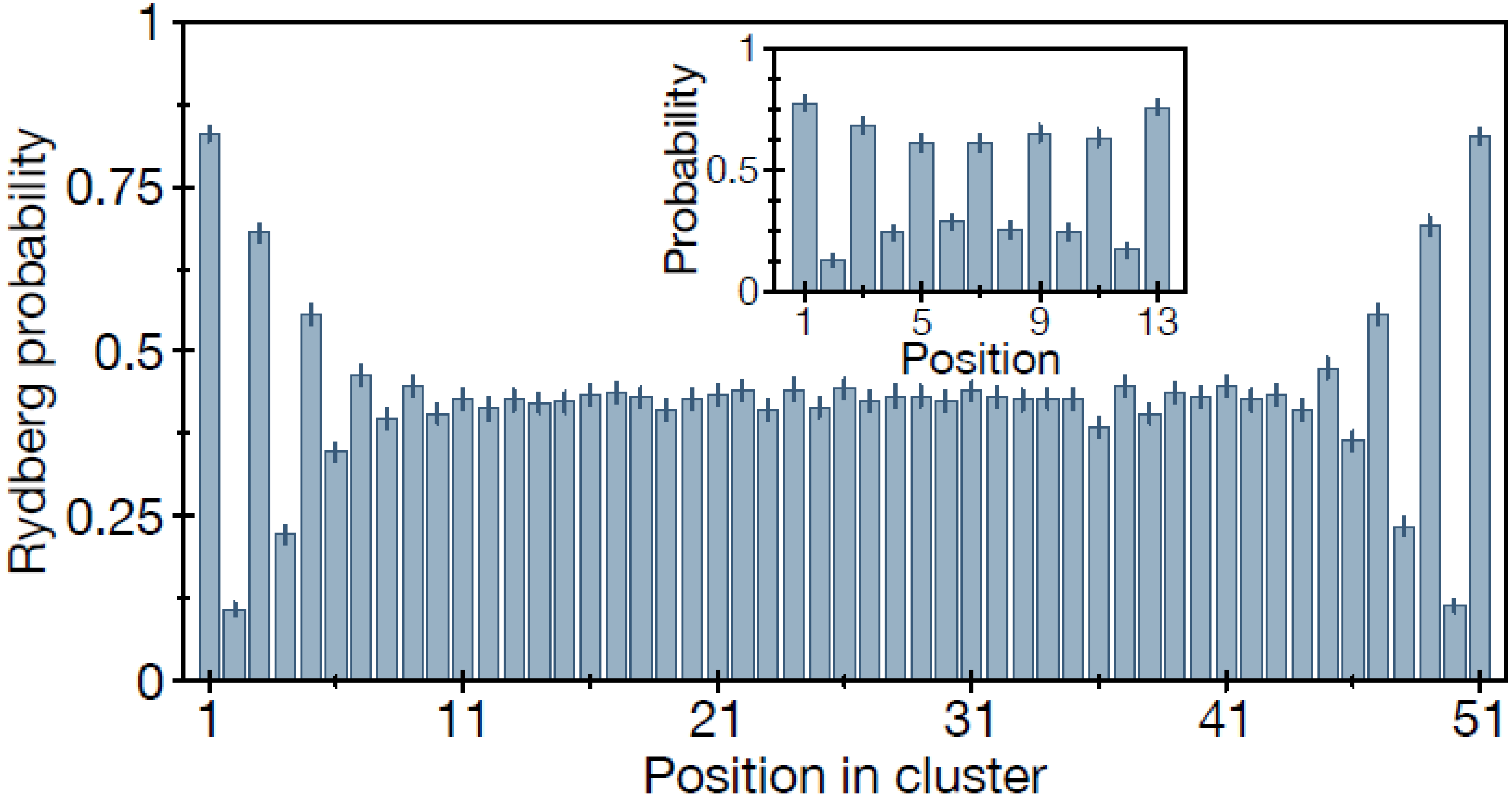
Order of ground state depends on trap distance relative to blockade radius

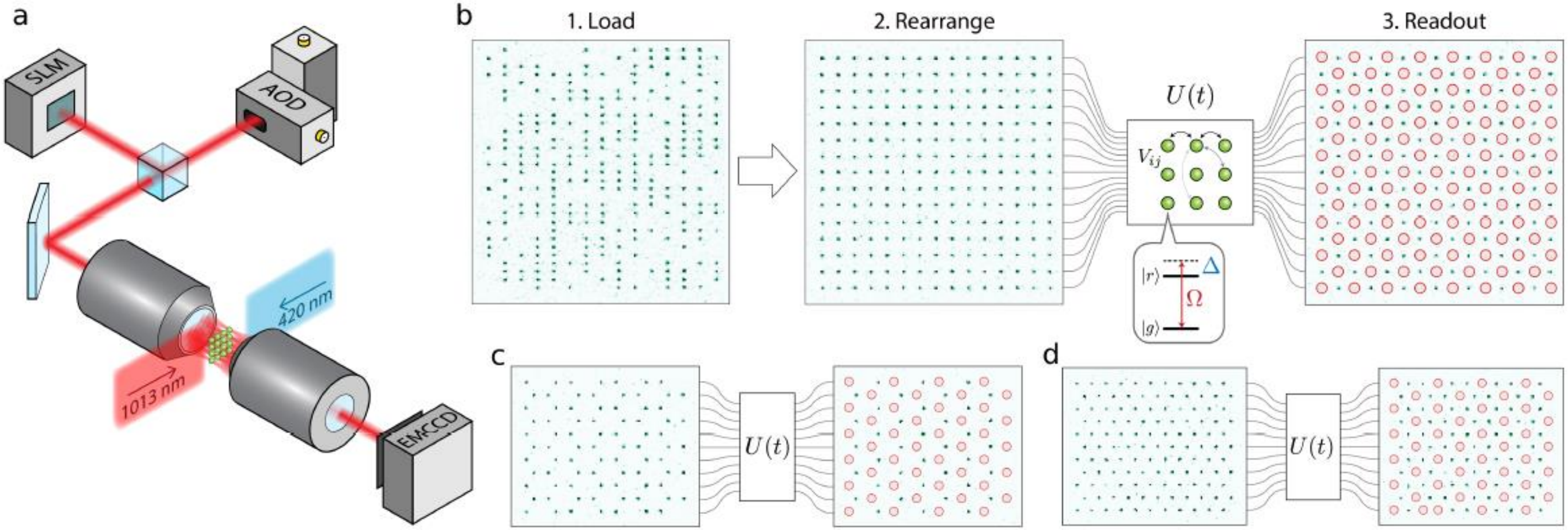
Phase boundaries for ordered phases



Order of ground state depends on trap distance relative to blockade radius

Small systems dominated by edge effects

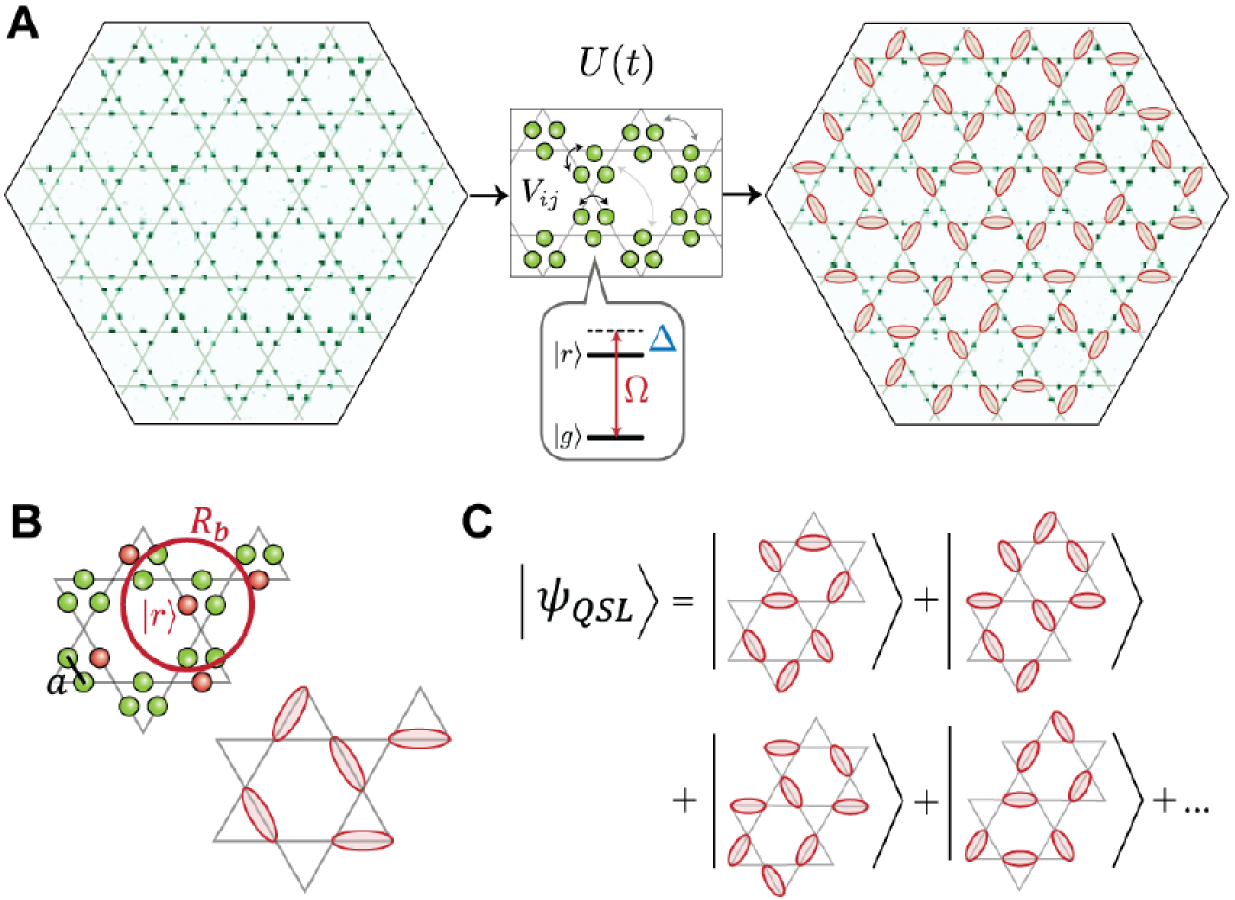



a
SLM
AOD
420 nm
1013 nm
EMCCD
b
1. Load
2. Rearrange
3. Readout
$U(t)$
V_{ij}
$|r\rangle$
$|g\rangle$
Δ
Ω
c
$U(t)$
d
$U(t)$

Probing topological spin liquids on a kagome lattice

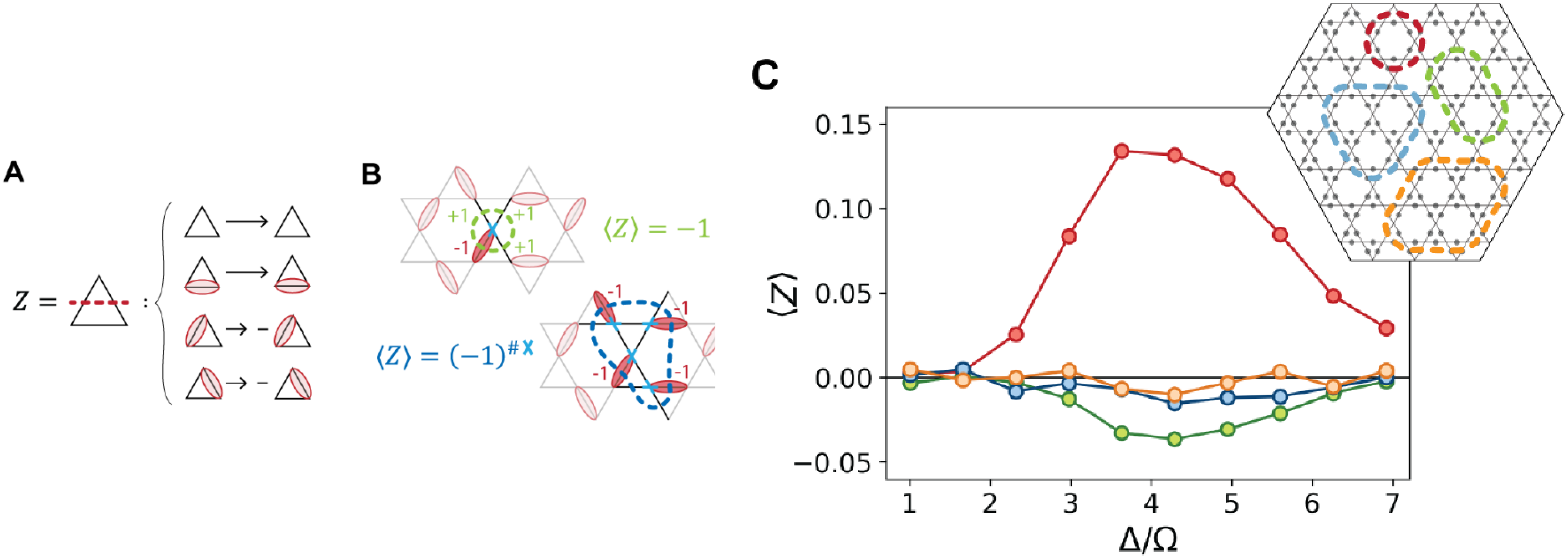
Probing Topological Spin Liquids on a Programmable Quantum Simulator. G. Semeghini, H. Levine, A. Keesling, S. Ebadi, T. T. Wang, D. Bluvstein, R. Verresen, H. Pichler, M. Kalinowski, R. Samajdar, A. Omran, S. Sachdev, A. Vishwanath, M. Greiner, V. Vuletić, and M.D. Lukin, submitted to Science

Spin liquid on a kagome lattice



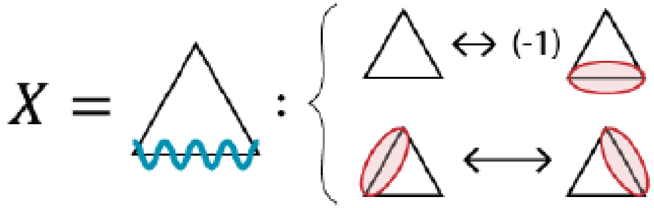
$$\frac{H}{\hbar} = \frac{\Omega(t)}{2}\sum_i \sigma_i^x - \Delta(t)\sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

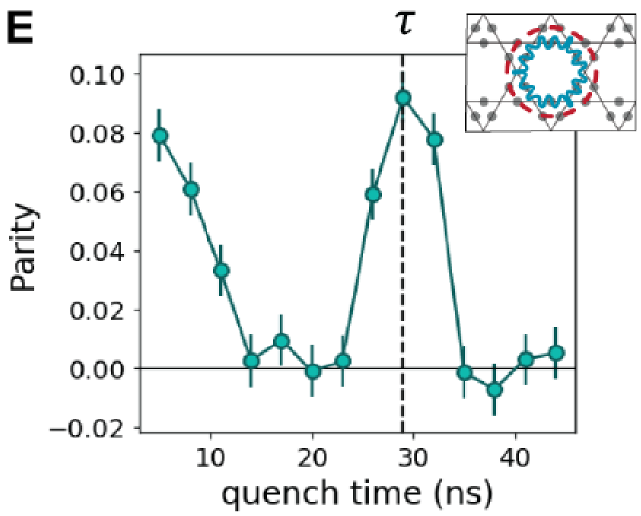
Probing topological parameters of potential spin liquid state

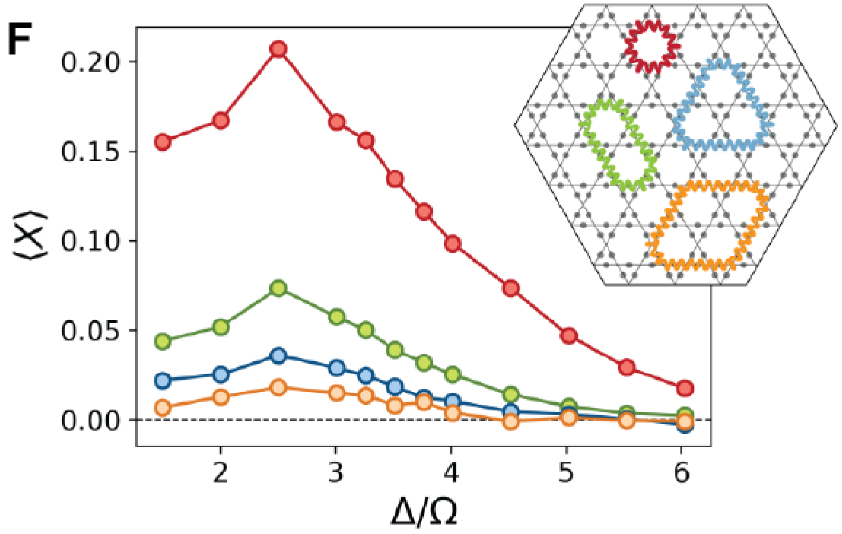


$$\langle Z\rangle = (-1)^{\#\text{ enclosed vertices}}$$

Probing topological parameters of potential spin liquid state







X parameter (coherence) measured by quenching and measuring Z parity

Creation of large GHZ state

A. Omran et al., Science **365**, 570 (2019)

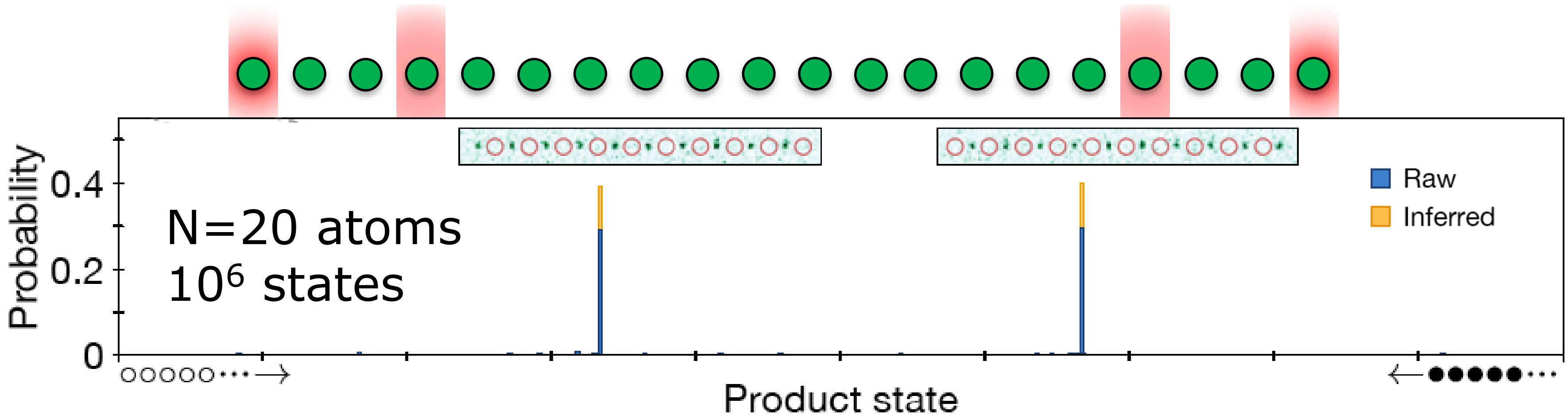
Creation of GHZ state

- We are seeking to make GHZ state of the form

  $|grgr\ldots gr\rangle + |rgrg\ldots rg\rangle$

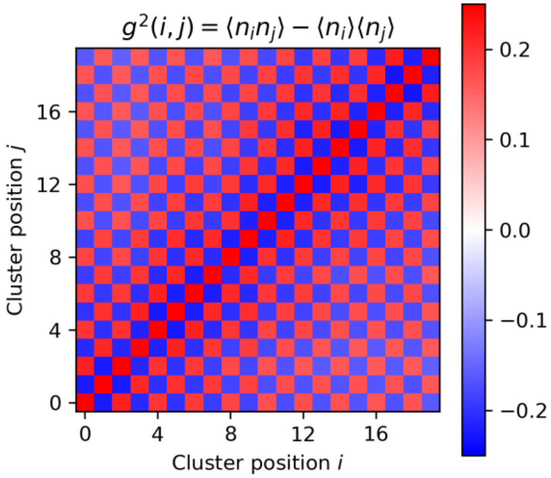
- This state should be produced if we try to excite a string with even total atom number to the Rydberg state
- Problem: edge effects, it takes little energy to excite atoms at end of string to Rydberg state
- Solution: energy shift on edge atoms

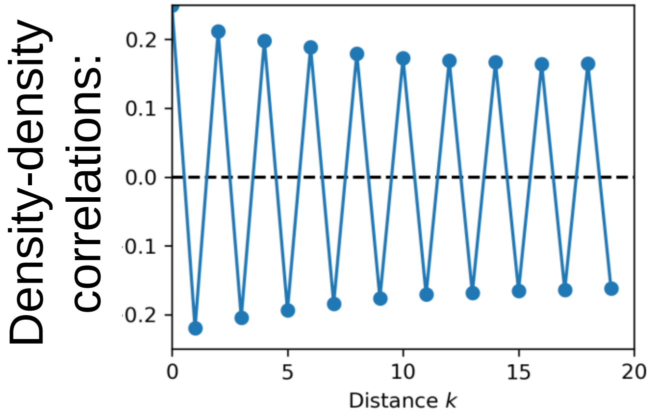
Creation of large GHZ states via evolution from ground state



N=20 atoms
10^6 states

Density-density correlations:

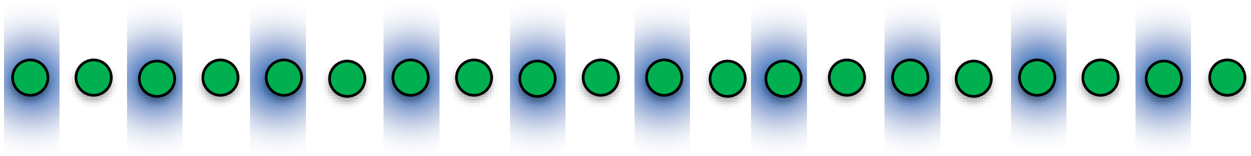


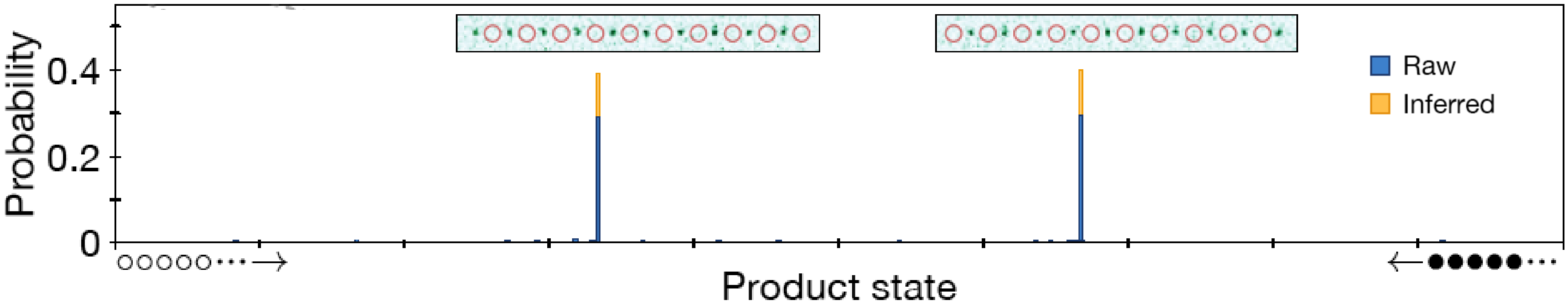


Phase measurement

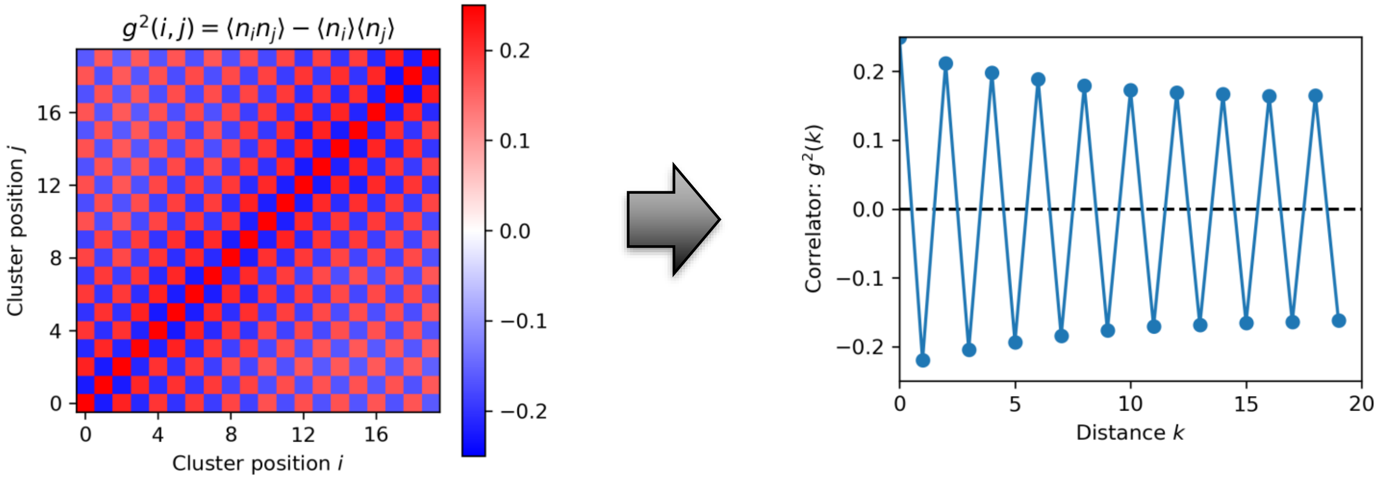
- How to measure the relative phase $|grgr\ldots gr\rangle + e^{i\phi} |rgrg\ldots rg\rangle$?
- Apply light shift on ground state to every second atom.

20 atom results

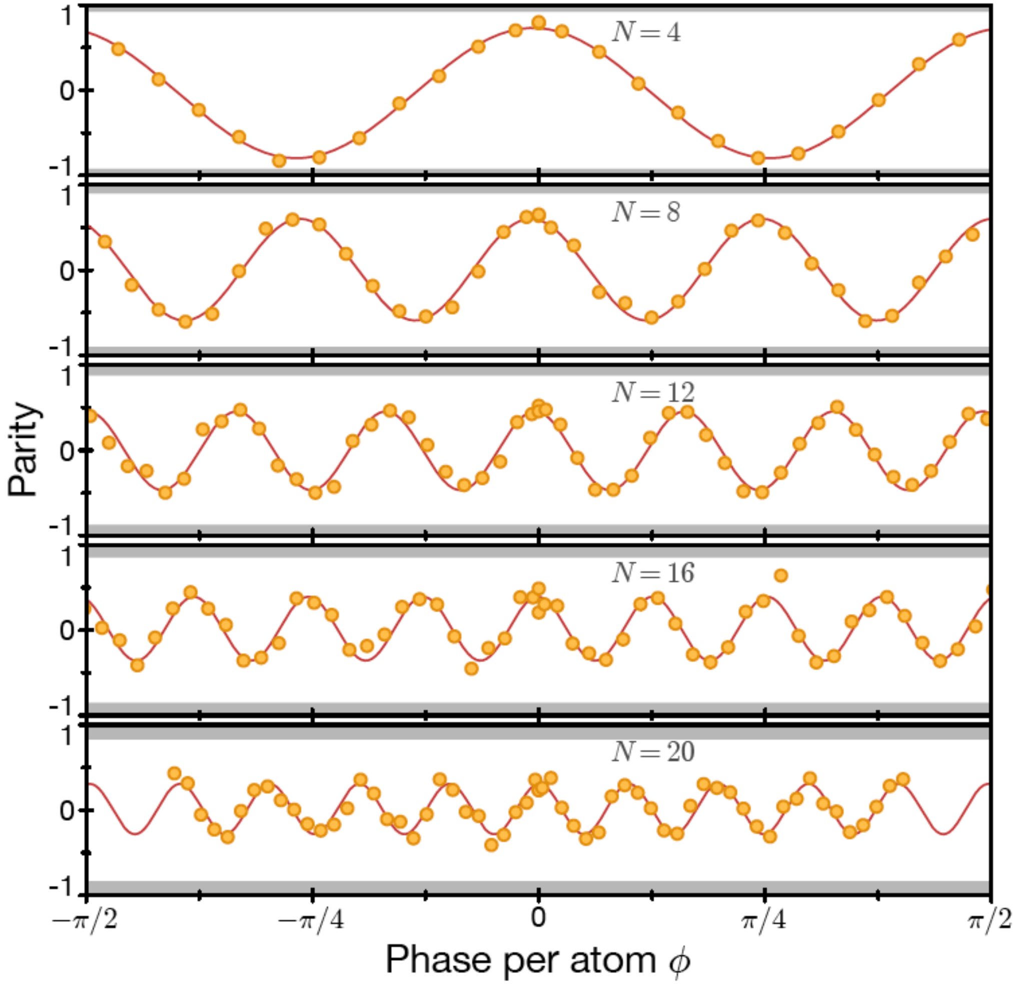




Density-density correlations:



Creation of large GHZ states via ground-state evolution



4 atoms

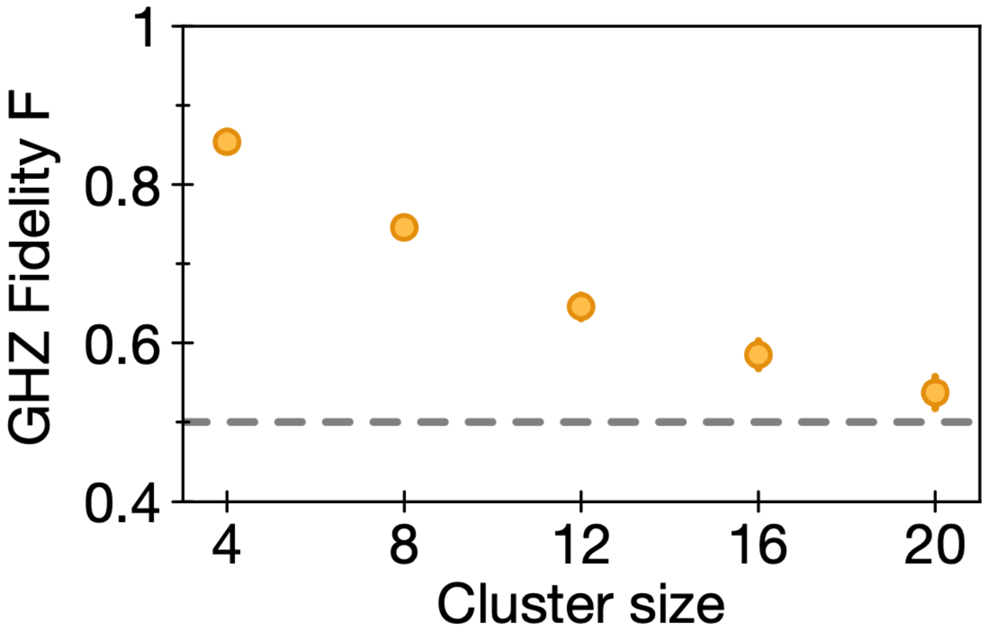
8 atoms

12 atoms

16 atoms

20 atoms

Creation of large GHZ states via ground-state evolution



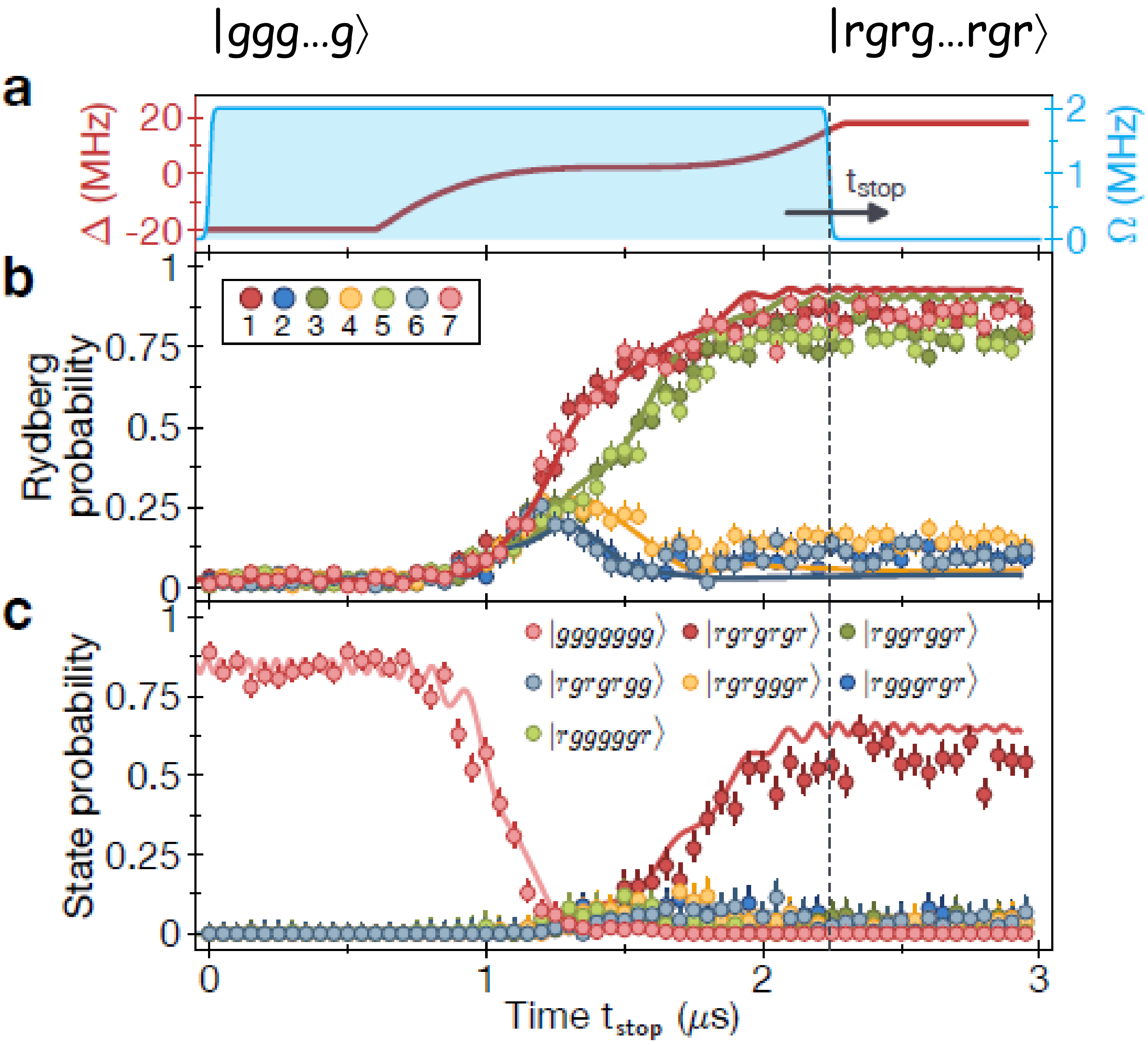
14 ion qubits: T. Monz et al, PRL 106, 130506 (2011) *F=0.58 ±0.09*

18 superconducting qubits: C.Song arXiv: 1905.00320 *F=0.525±0.005*

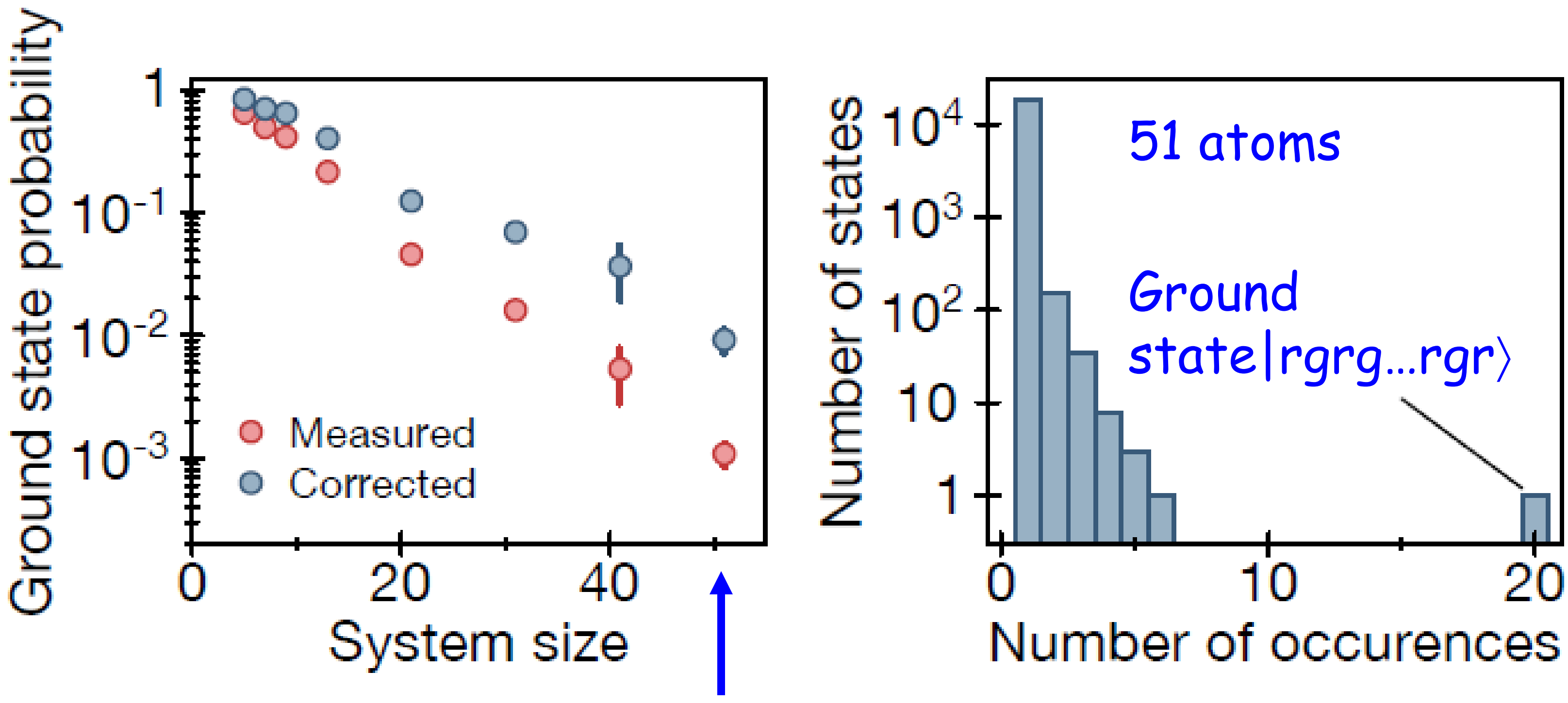
K.X.Wei et al arXiv:1905.05720 *F= 0.517±0.004*

20 ion qubits (non-GHZ) N. Friis, et. al. PRX 8, 021012 (2018)

Adiabatic ramp across phase transition



Macroscopic population of ground state prepared adiabatically for up to 51 atoms



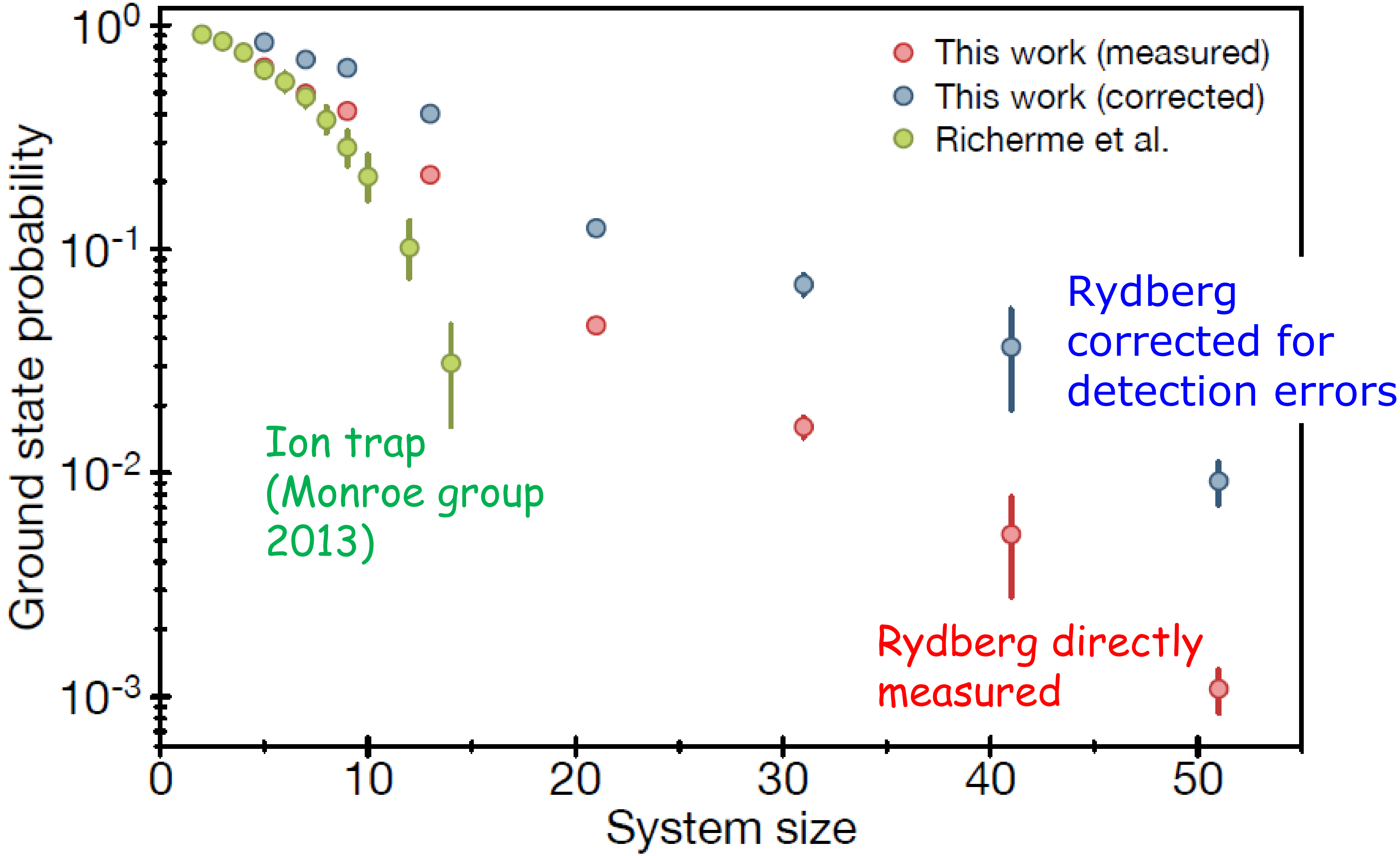
51 atoms

Ground state$|rgrg\ldots rgr\rangle$

~ 10^{15} states

Ground state reached much more often than any other state.

Macroscopic population of ground state prepared adiabatically for up to 51 atoms



Ion trap (Monroe group 2013)

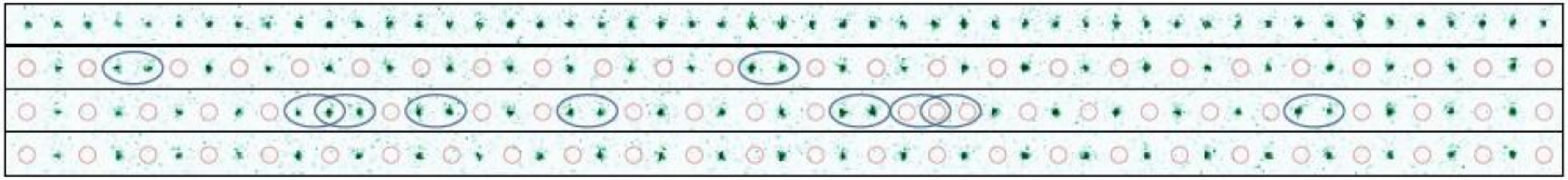
Rydberg corrected for detection errors

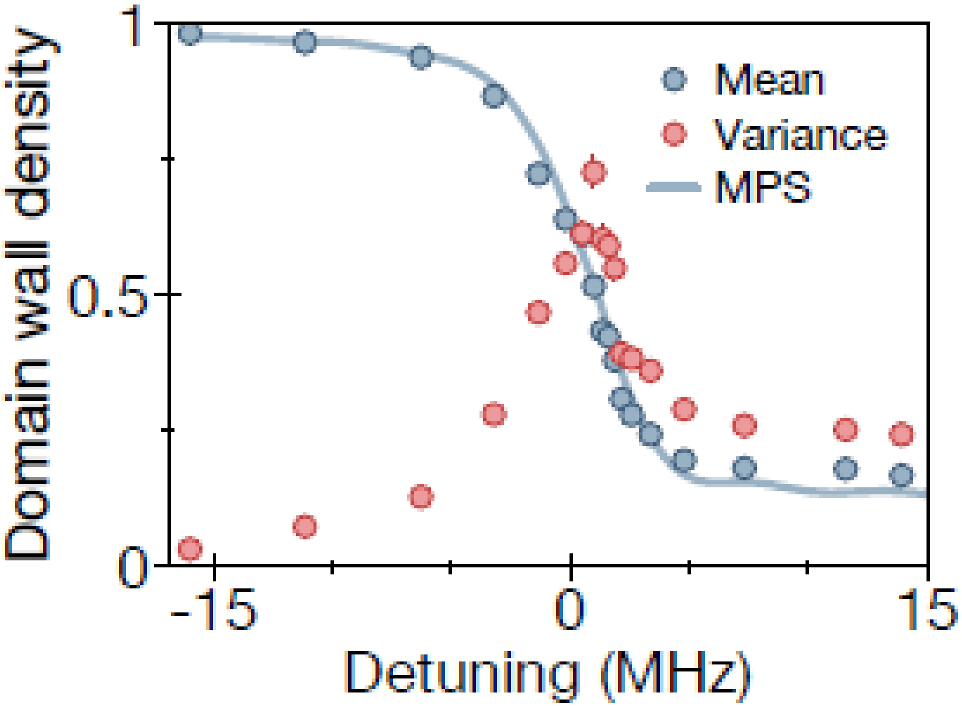
Rydberg directly measured

Quantum Kibble-Zurek mechanism

Quantum Kibble-Zurek mechanism and critical dynamics on a programmable Rydberg simulator. A. Keesling, A. Omran, H. Levine, H. Bernien, H. Pichler, S. Choi, R. Samajdar, S. Schwartz, P. Silvi, S. Sachdev, P. Zoller, M. Endres, M. Greiner, V. Vuletić, and M.D. Lukin, Nature **568**, 207-211 (2019);

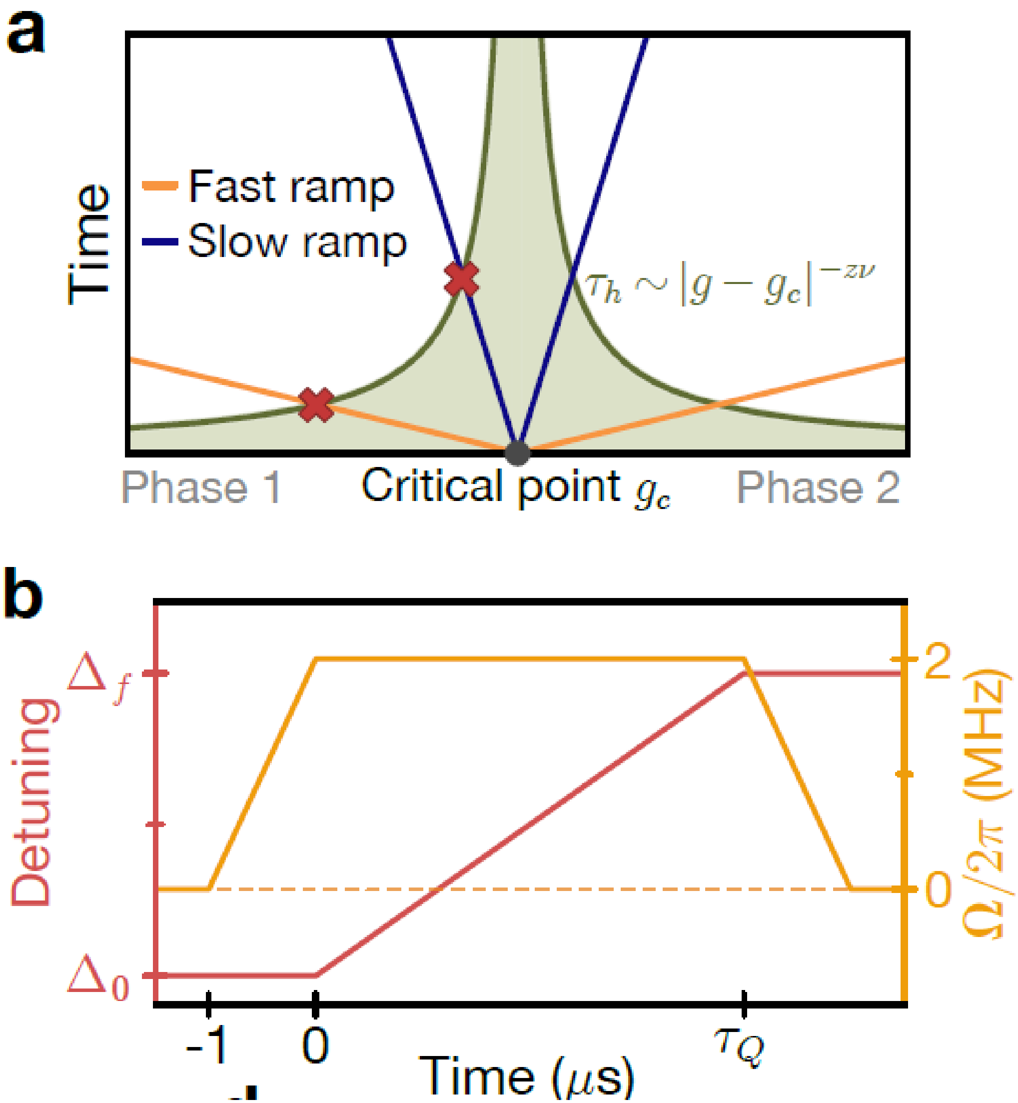
Crystal preparation at finite speed





The crystal is not perfect, but contains domain walls, due to finite preparation speed, or imperfect state detection.

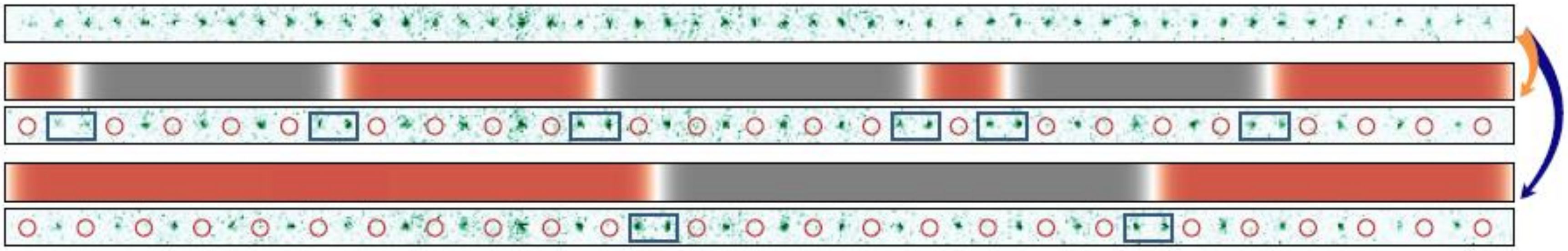
Kibble-Zurek mechanism



Freezing out of correlations when ramp timescale exceeds correlation formation timescale near critical point.

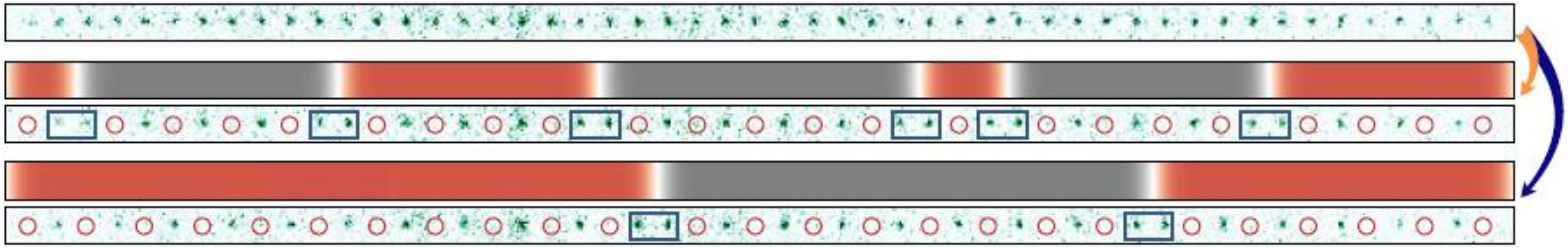
Ramping across phase transition and measuring density of defects in antiferromagnet.

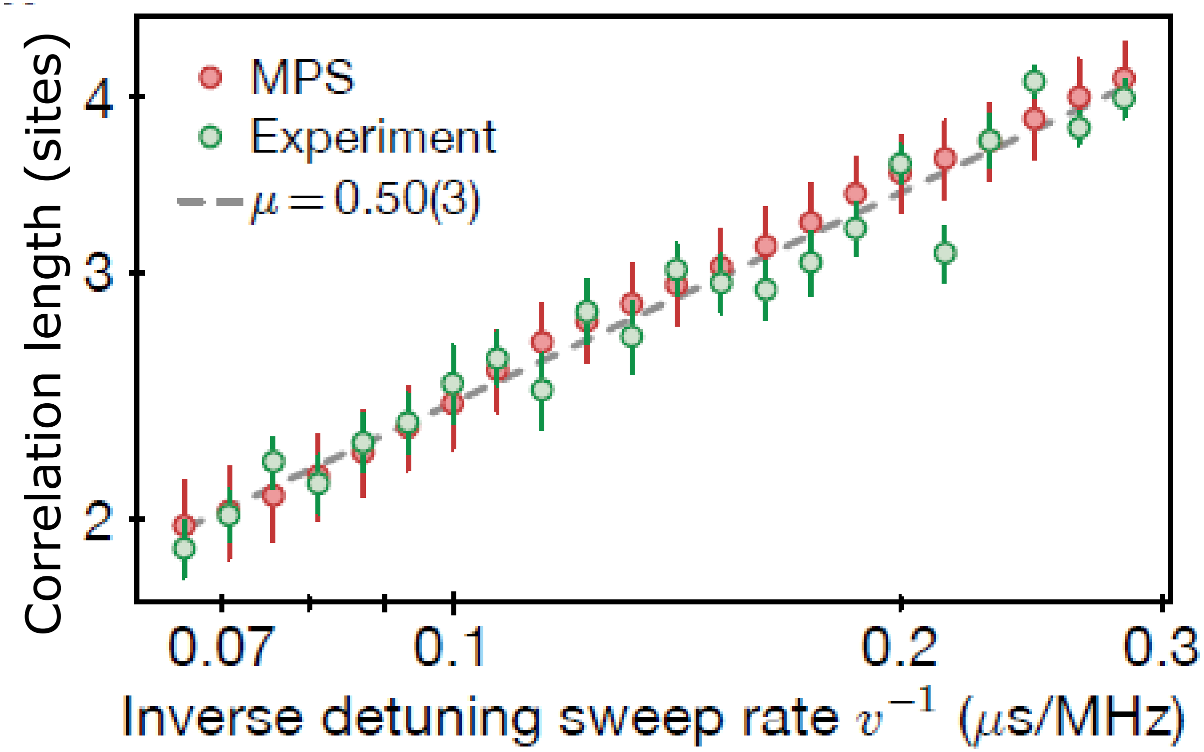
Appearance of domain walls at finite sweep rate into ordered phase



At finite sweep rate, random phase boundaries (domain walls) appear as sweep time becomes faster than equilibration time. The average density of domain walls increases for faster sweeps.

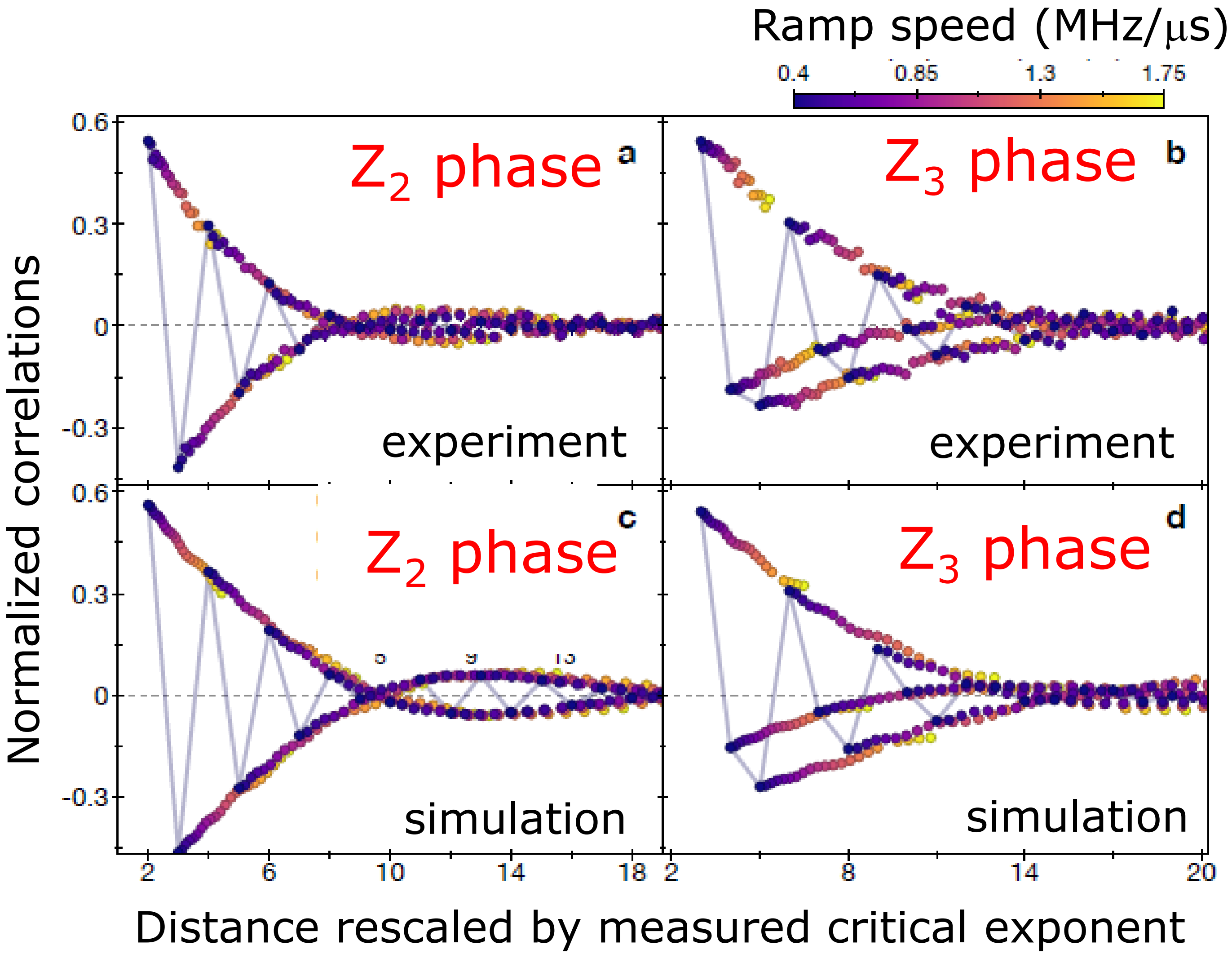
Kibble-Zurek mechanism for quantum phase transition into Z_2 phase





Critical exponent extracted from observed power law

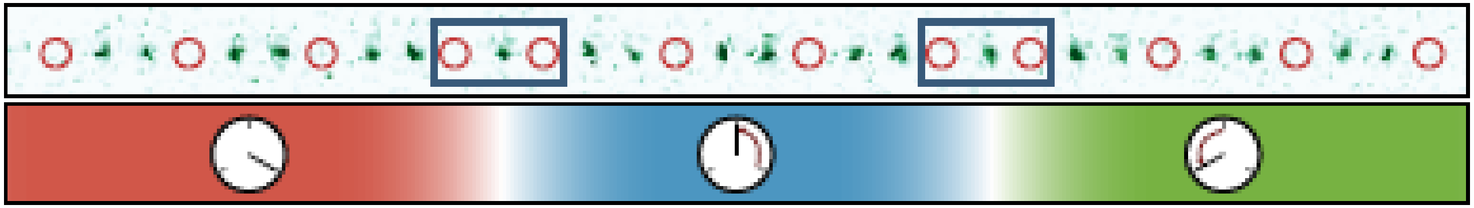
Universality of correlations



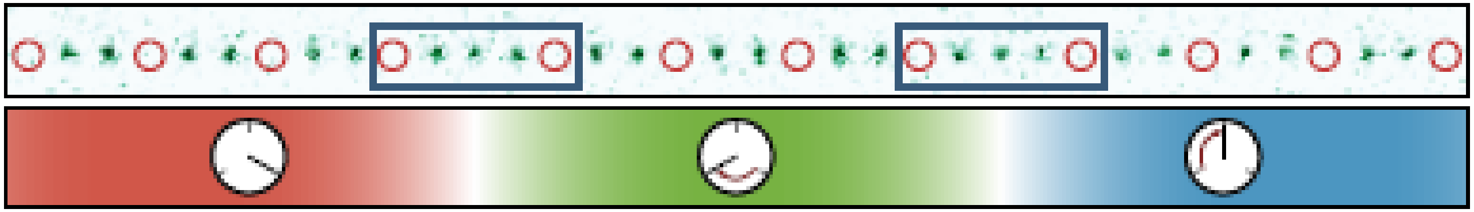
Different branches correspond to different types of defect

Nontrivial correlations between domain walls.

Different defects in Z_3 phase



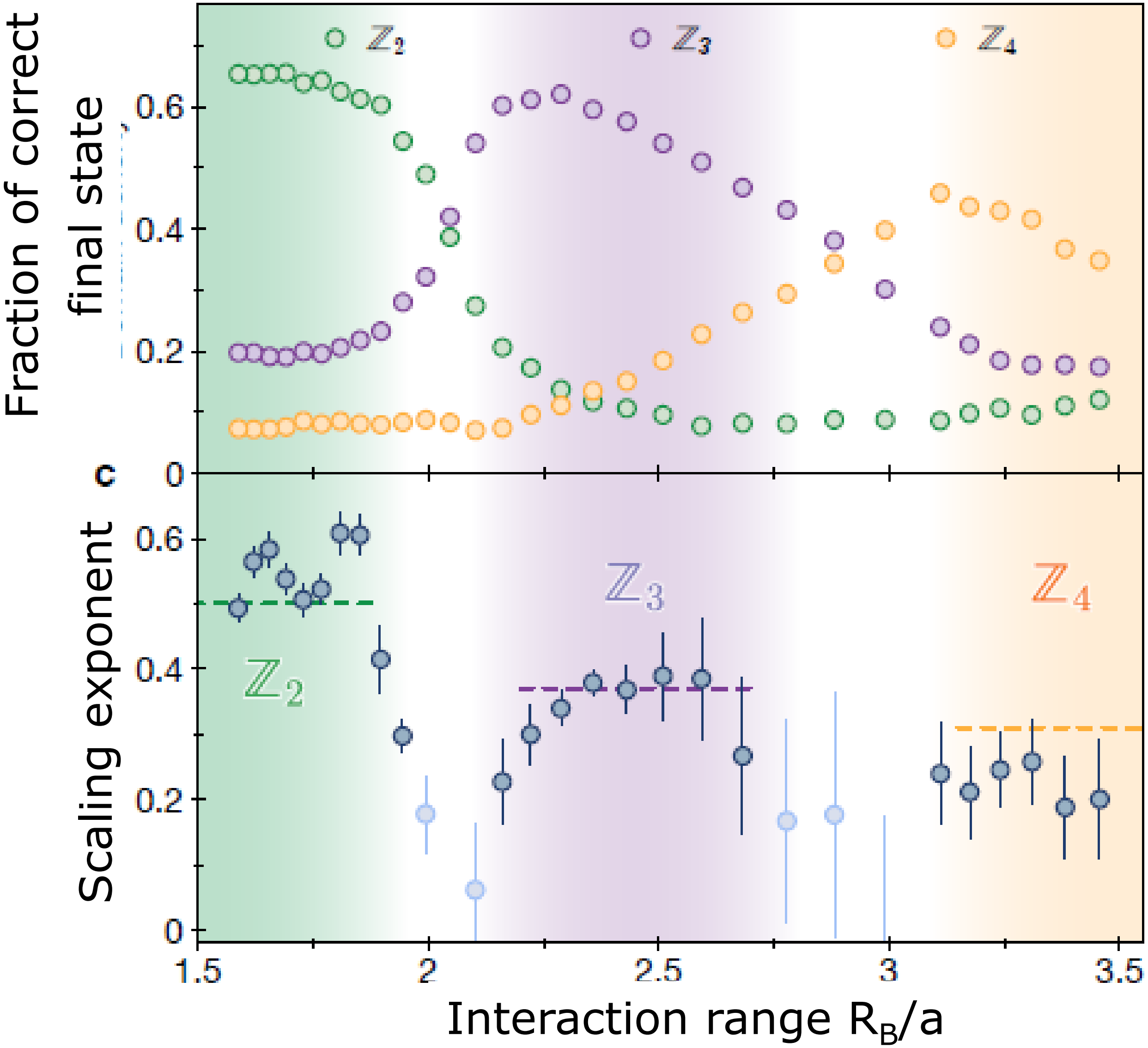
Close to Z_2



Close to Z_4

Type of defects changes with atomic distance a/R_B.

Power law scaling for different distances

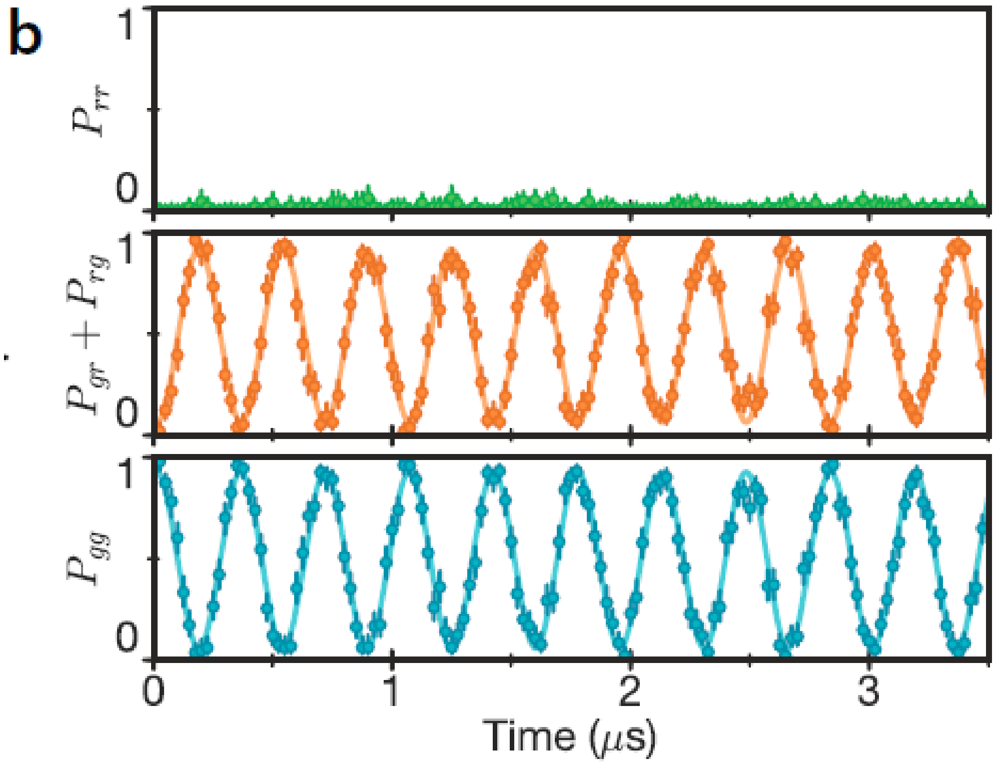


Fraction of correct final state for different orders.

Scaling exponent varies near phase boundaries.

Characterization of two-qubit quantum gates

Two-qubit quantum gate



Two Rydberg atoms $|rr\rangle$ (blockade)

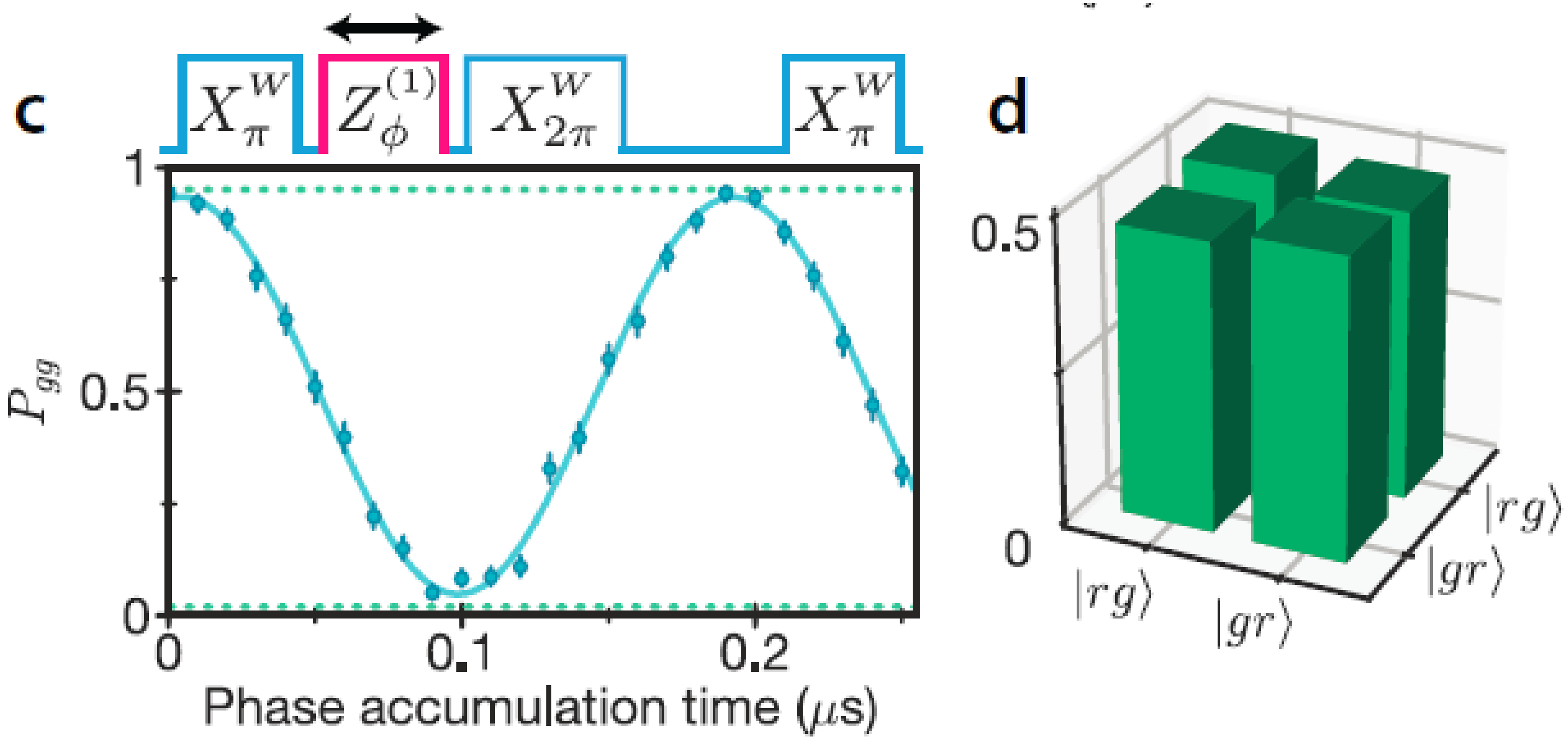
One Rydberg atom $|rg\rangle + |gr\rangle$

Two ground-state atoms $|gg\rangle$

H. Levine, A. Keesling, A. Omran, H. Bernien, S. Schwartz, A.S. Zibrov, M. Endres, M. Greiner, V. Vuletic, and M.D. Lukin, submitted to PRL (2018).

Characterization of Rydberg quantum gates

Two-qubit quantum gate



Two-qubit quantum gate fidelity F=0.97 before detection errors (2018); now approaching 99%

Outlook

- Towards large quantum simulators
  - 1000 qubits within reach in next 1-2 years
  - Transition to 2D arrangement
  - Study strongly interacting spin models
  - Local addressing to be implemented
  - Can we find the solutions to hard classical calculations via adiabatic evolution (adiabatic quantum computing, quantum approximate optimization algorithm)?