Rydberg mediated interactions: atom-by-atom and photon-by-photon

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

Massachusetts Institute of Technology
MIT-Harvard Center for Ultracold Atoms

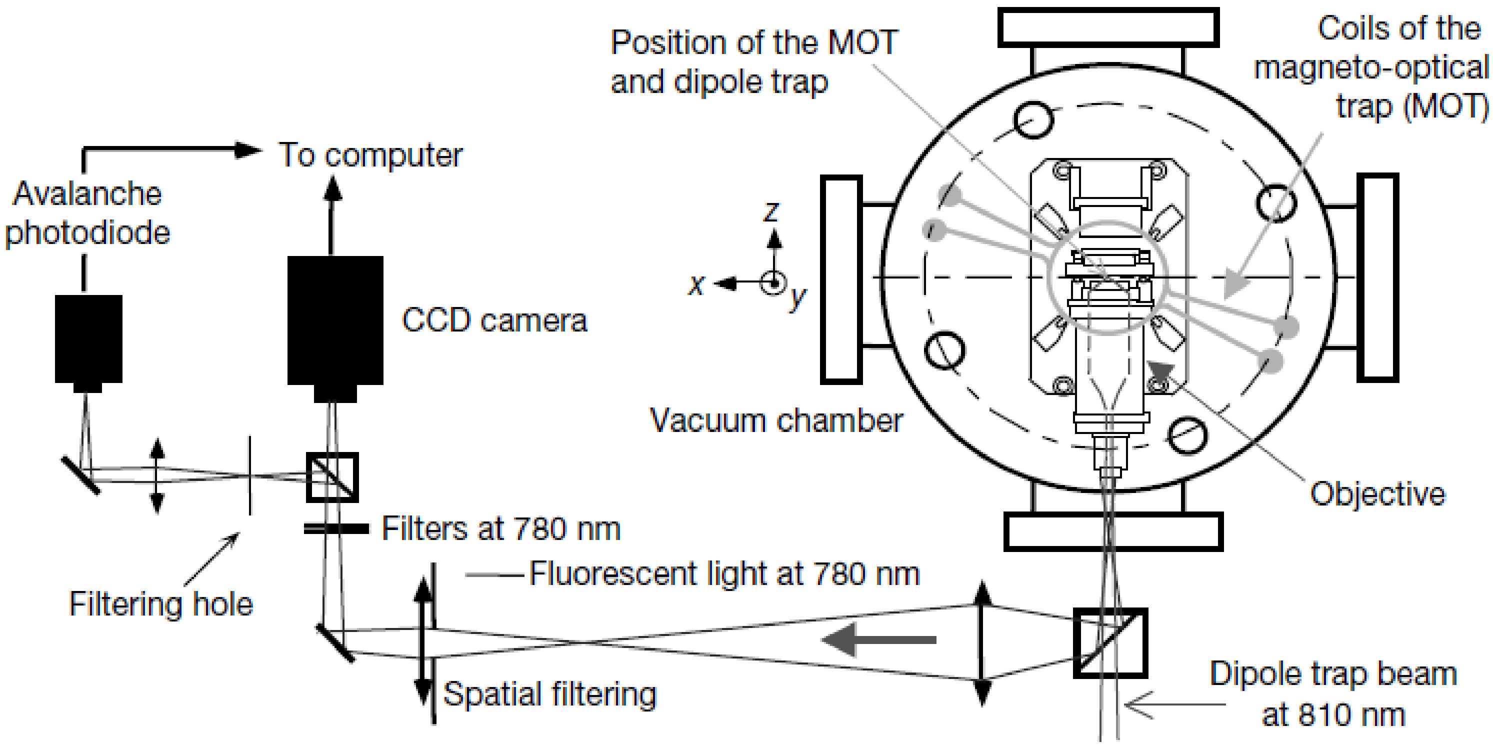
Rydberg mediated interactions: atom-by-atom and photon-by-photon

- Photon by Photon: Use Rydberg interaction in combination with electromagnetically induced transparency to generate strong interactions between individual photons

- Atom by Atom: Use Rydberg interactions in array of individually trapped atoms to realize strongly interacting spin models

Preface: Trapping individual atoms and inducing interactions over optically resolvable distances

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

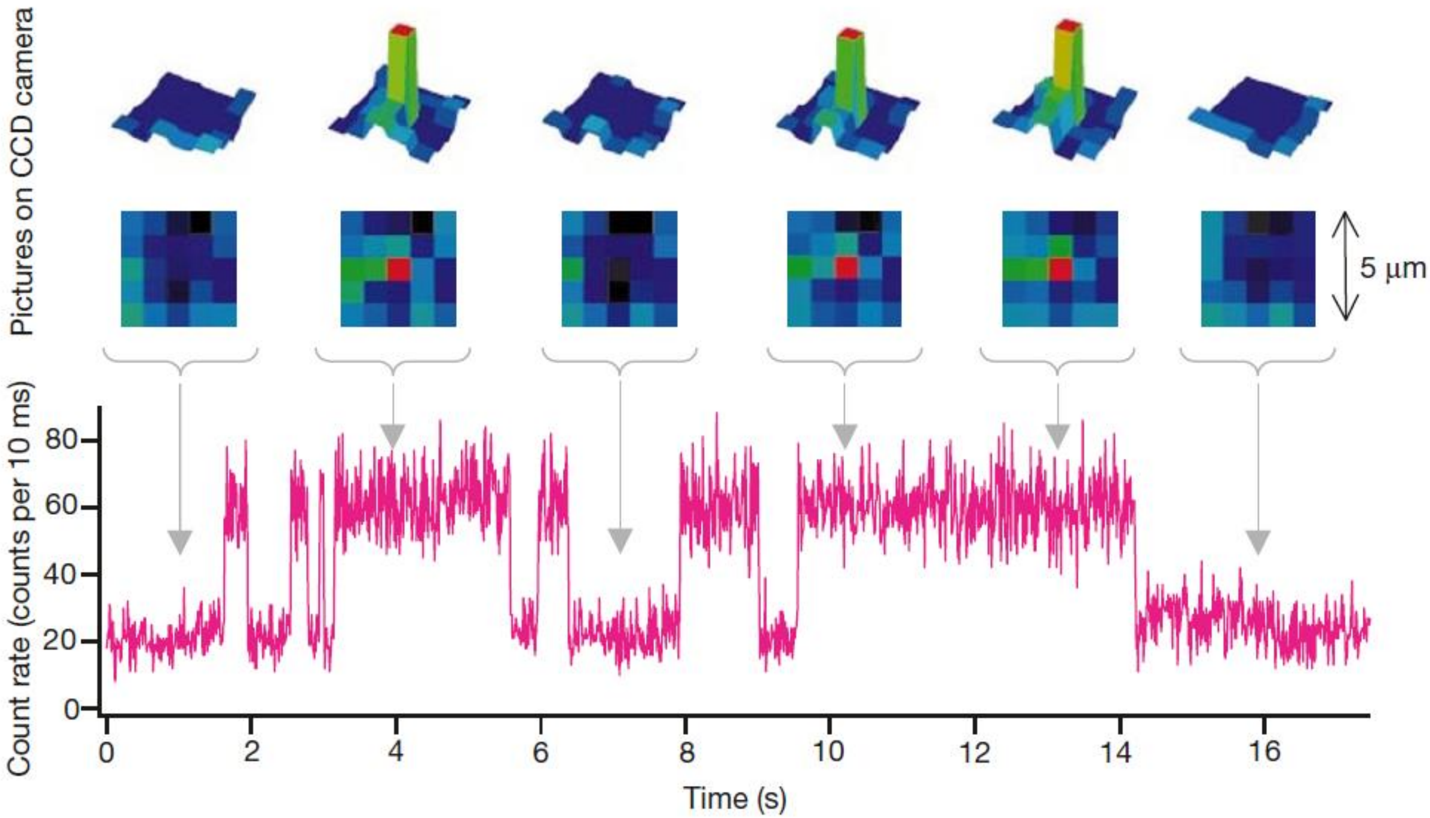


N. Schlosser, G. Reymond, I. Protsenko, P. Grangier, Nature **411**, 1024 (2001)

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)

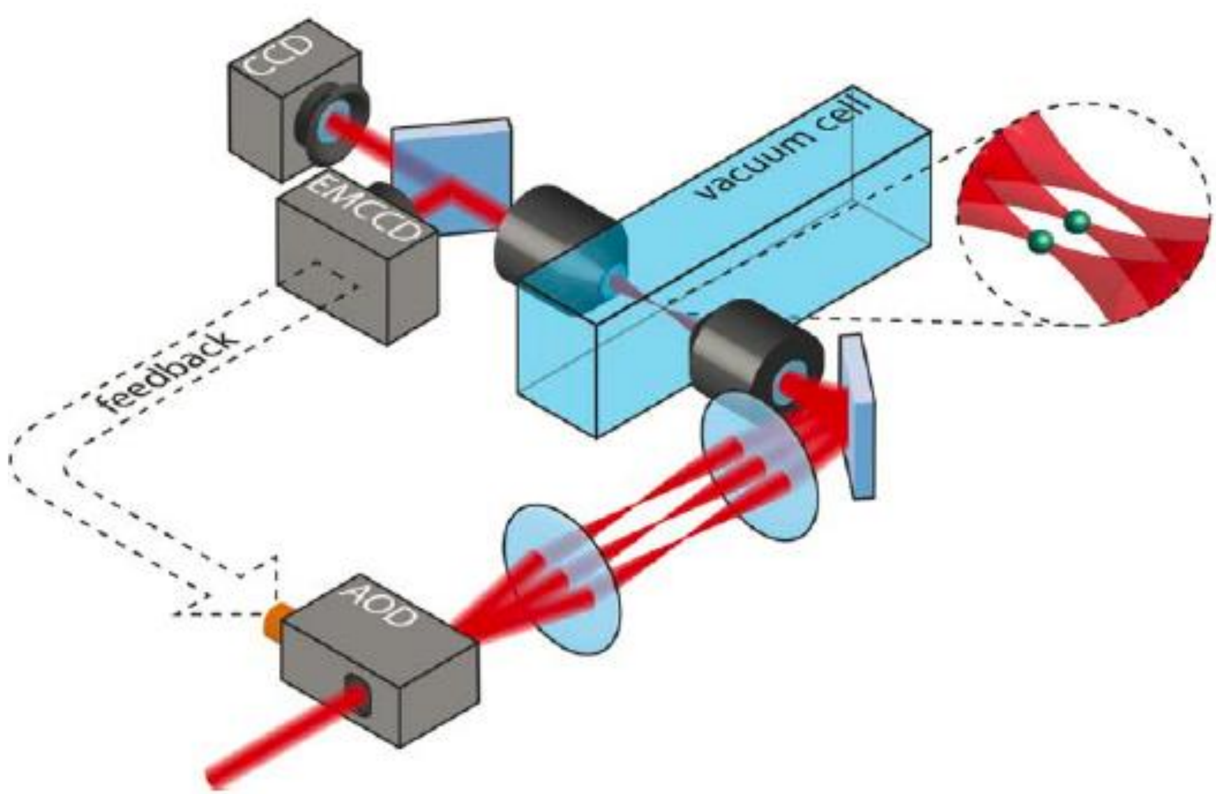


~~51~~ 256-atom quantum simulator

In collaboration with Mikhail Lukin and Markus Greiner (Harvard)

Pioneering work in this field: Antoine Browaeys' group

Trapping many single atoms deterministically



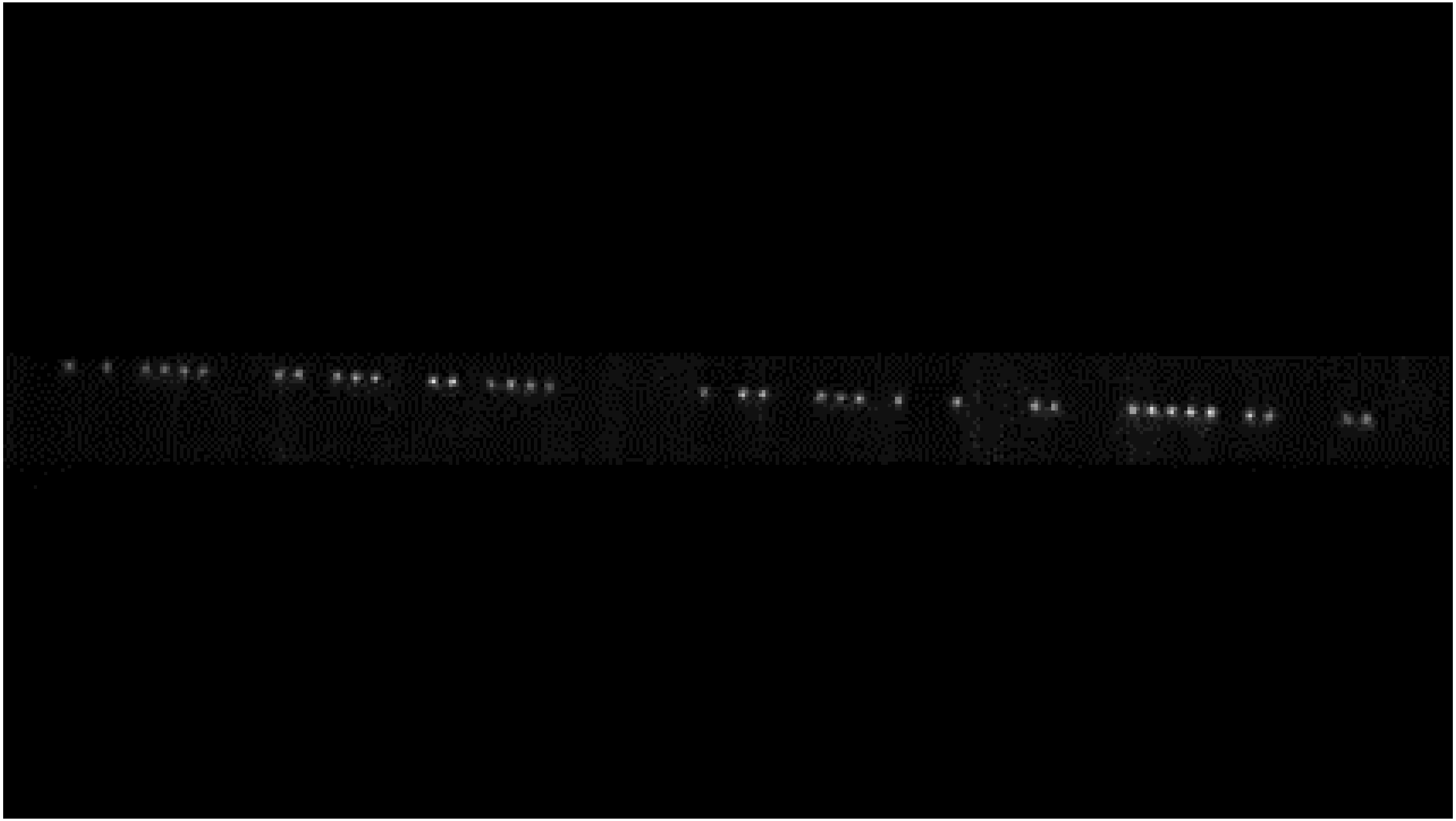
Problem: each trap is only loaded with ~50% probability.

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).

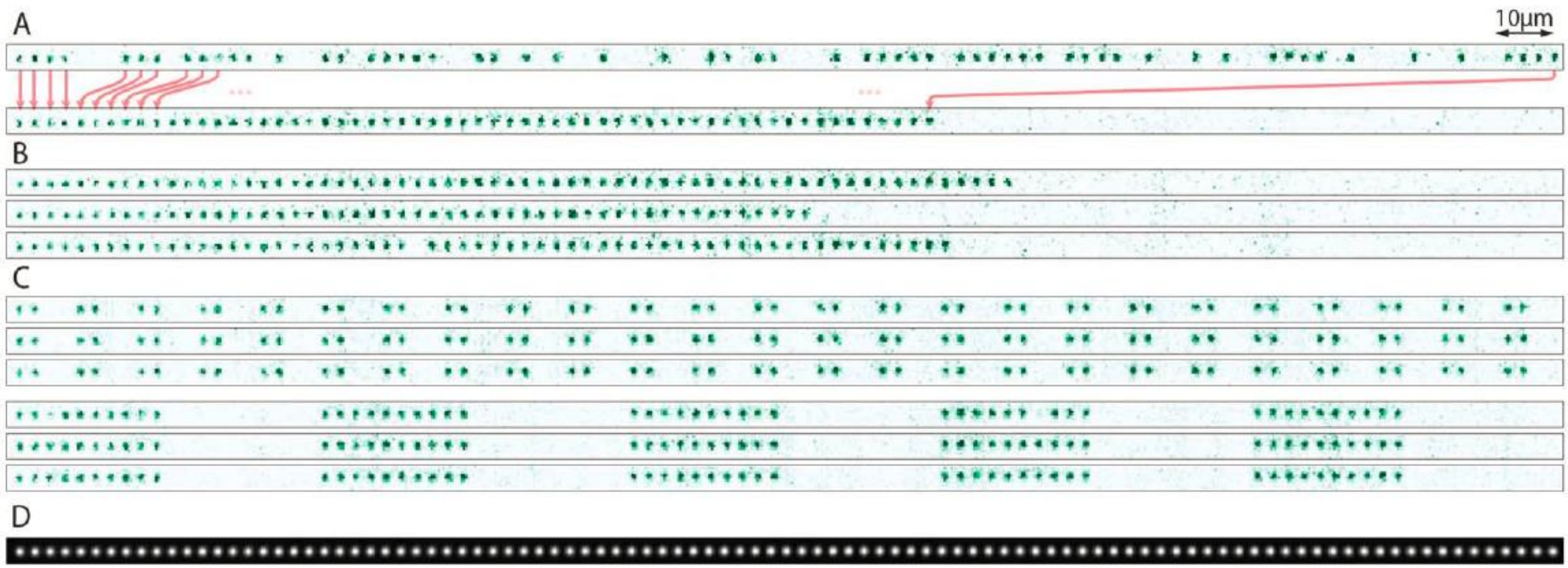
Individual atoms in reconfigurable traps

Greiner – Lukin – Vuletic collaboration



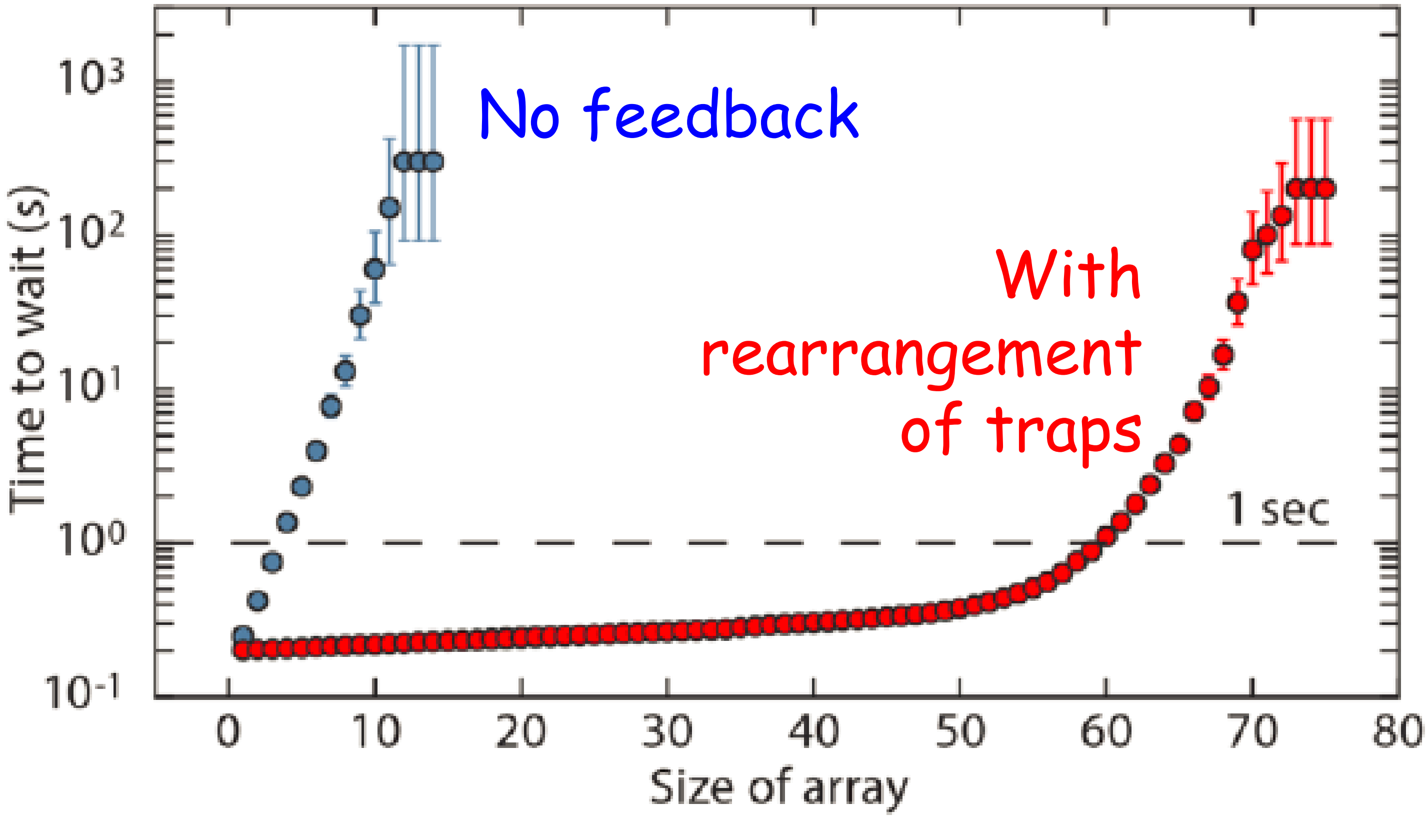
M. Endres, H. Bernien, A. Keesling, H. Levine, E. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletić, M. Greiner, and M.D. Lukin, Science **354**, 1024-1027 (2016).

Trapped atoms in different configurations



Green color: real images of individual atoms

Feeback (rearrangement) is crucial



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:

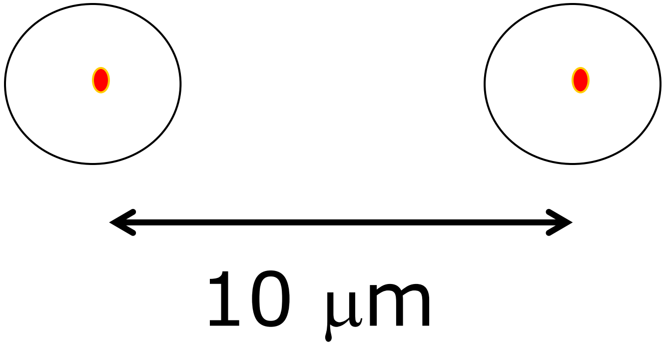
D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin, Phys. Rev. Lett. **85**, 2208 (2000).

Rydberg states

Very highly excited hydrogen-like states

Extremely large size, dipole moment, polarizability

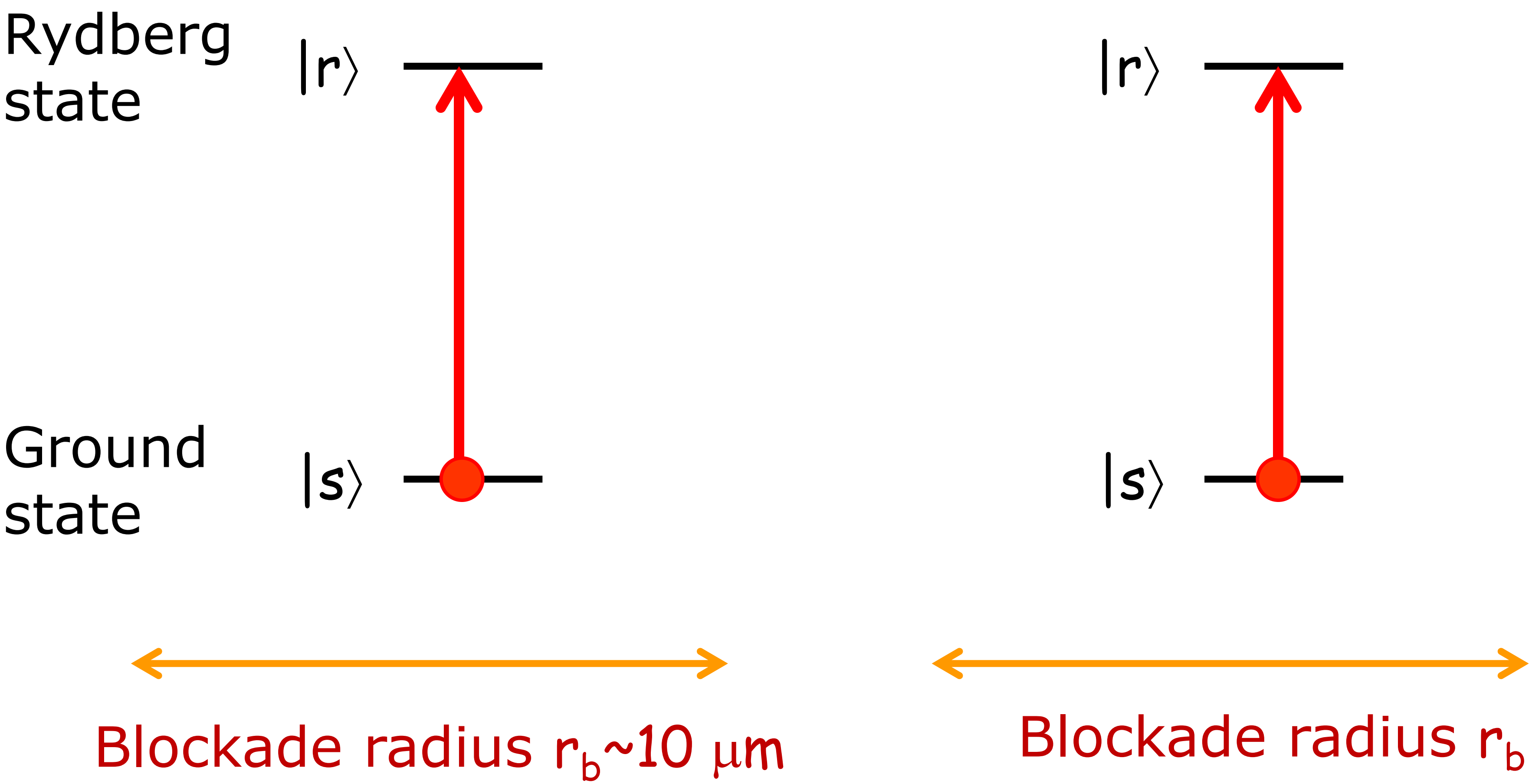
Strong Rydberg-Rydberg interactions $V(R)=C_6/R^6$



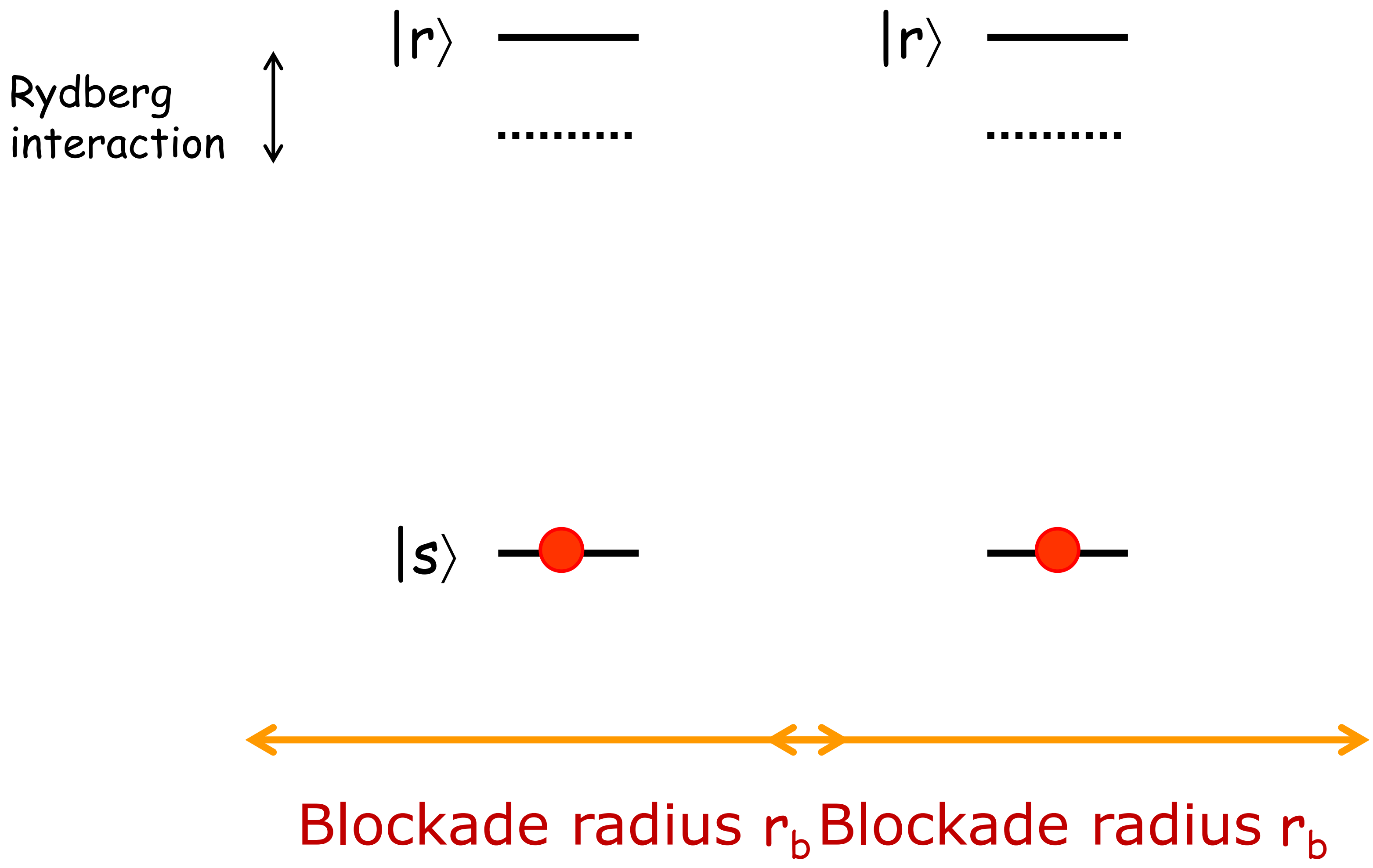
MHz interaction strength over optically resolvable 10 μm distance scale

Rydberg-Rydberg interactions can be used to implement strong atom-atom or photon-photon interactions

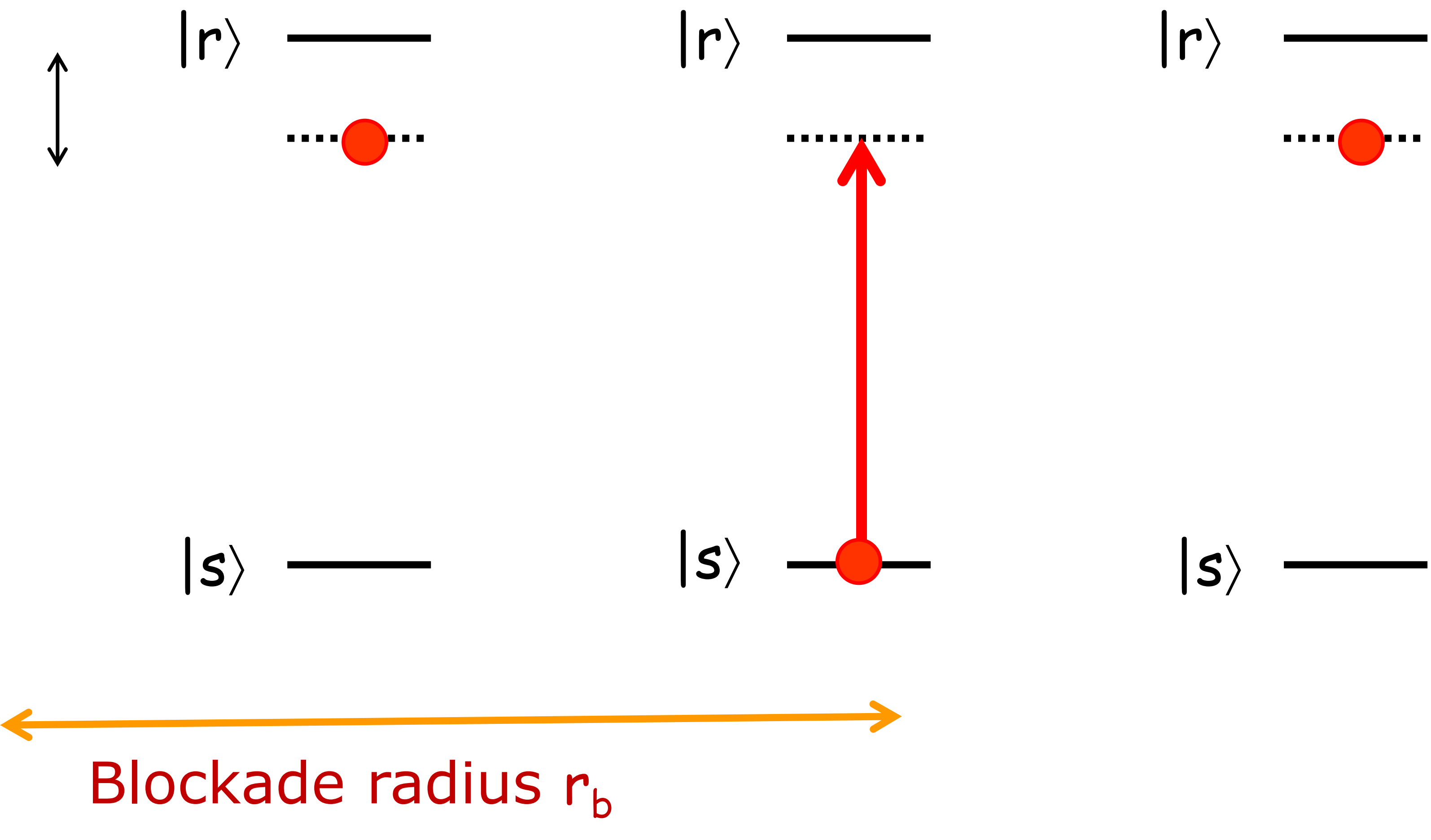
Rydberg interactions



Rydberg interactions



Rydberg interactions



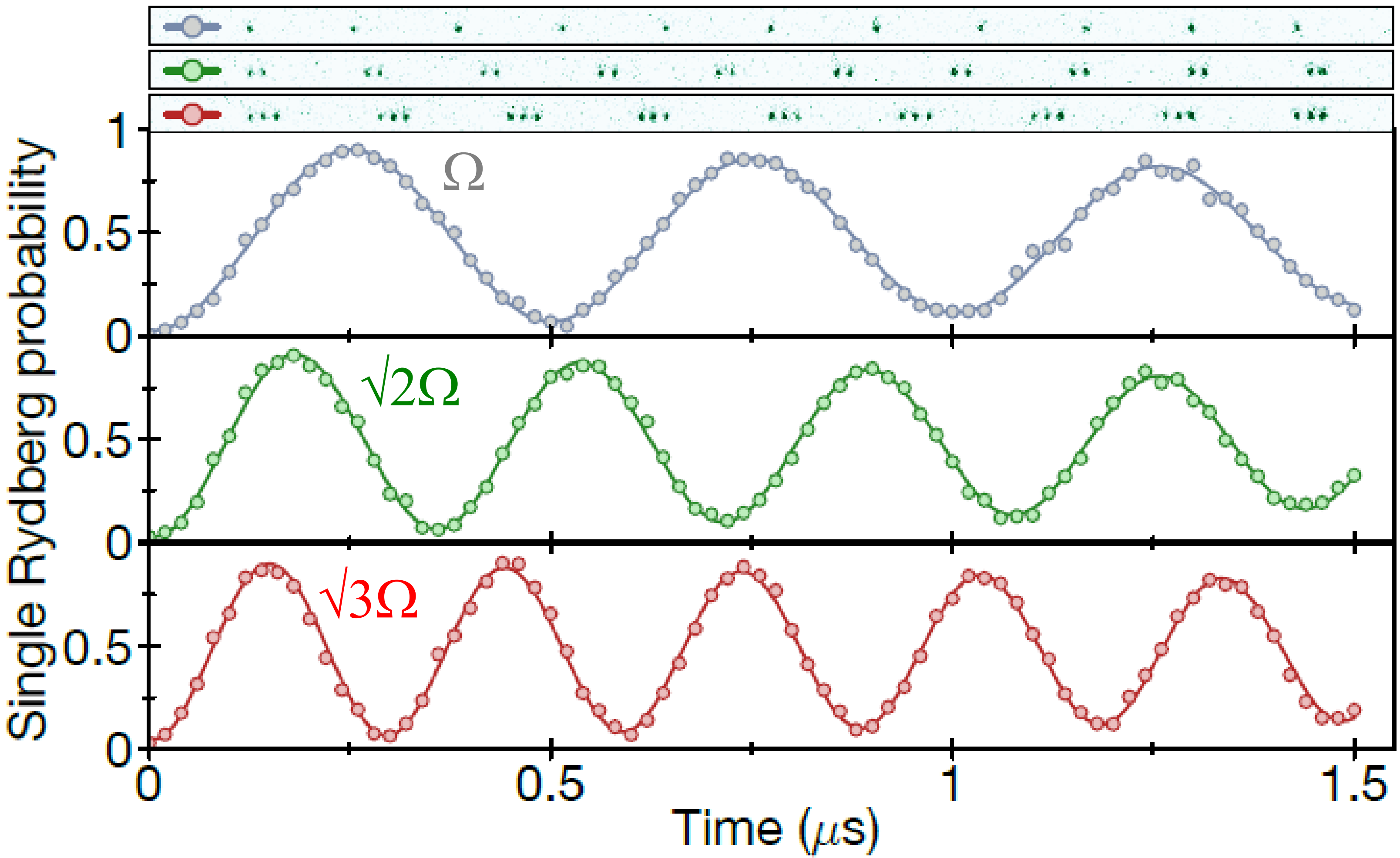
System Hamiltonian

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

Model ground-Rydberg system as spin ½

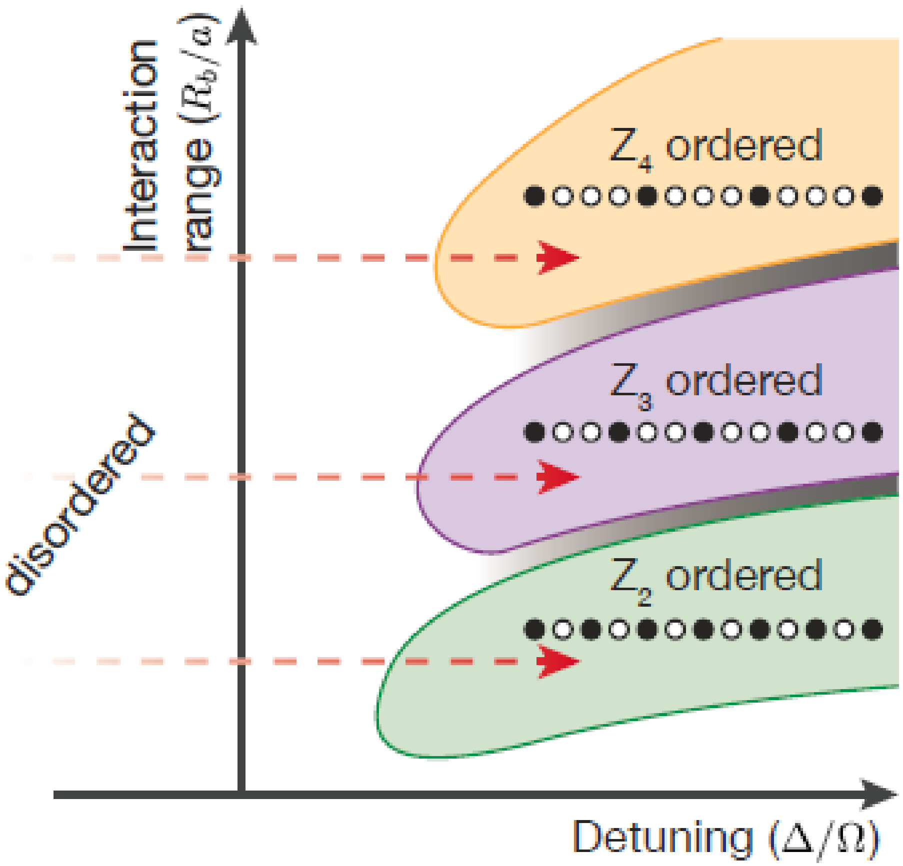
Collective Rabi flopping under Rydberg blockade

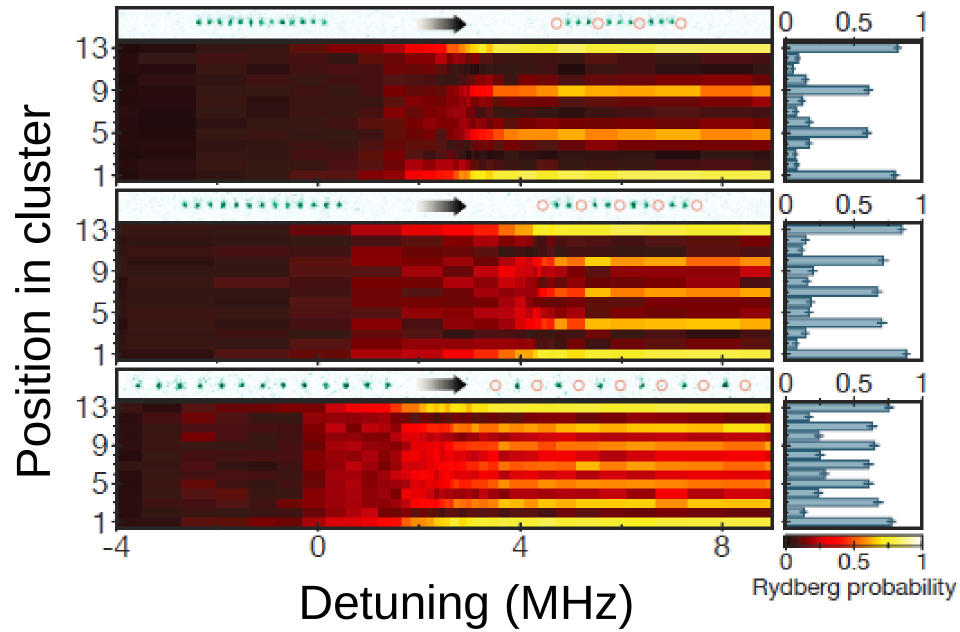
Small trap separation $d=2.9\ \mu m \ll$ blockade radius r_b



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

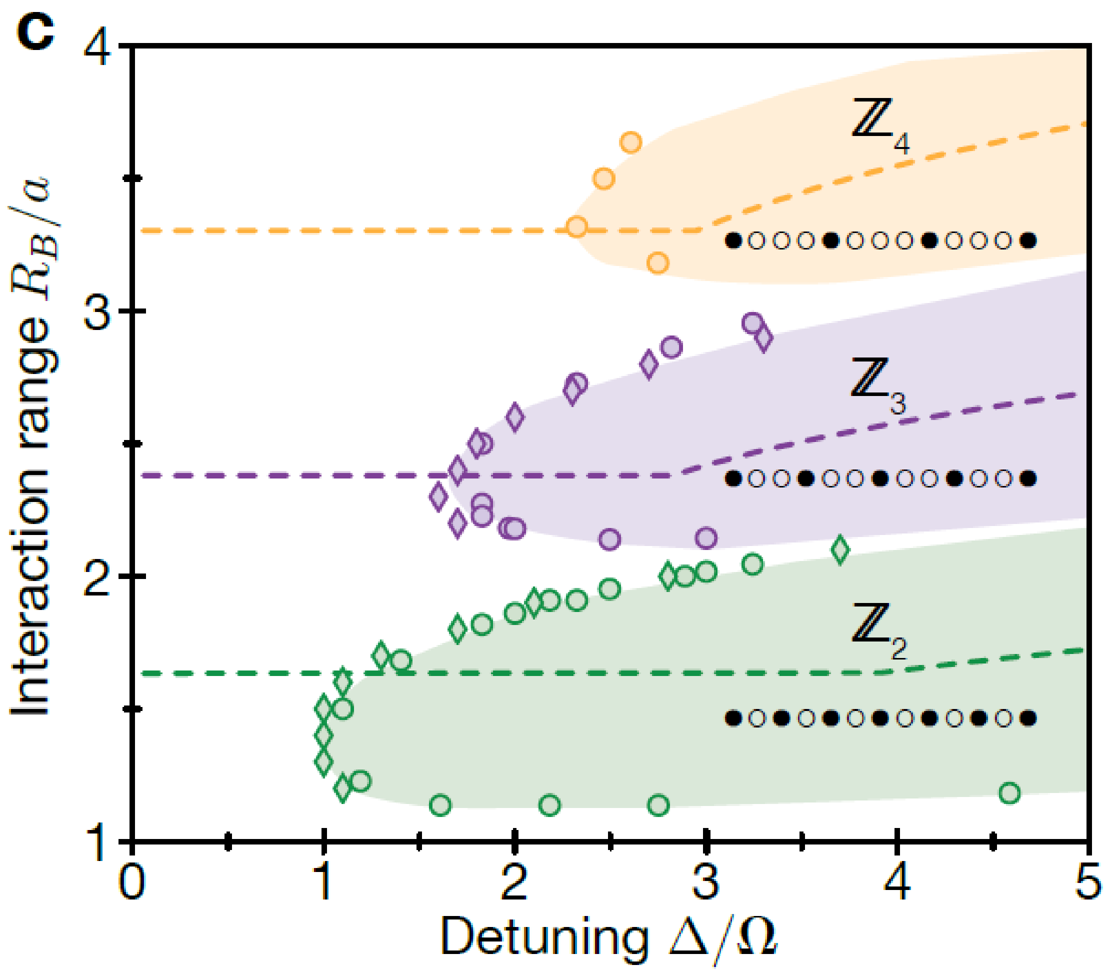
Different ordered phases

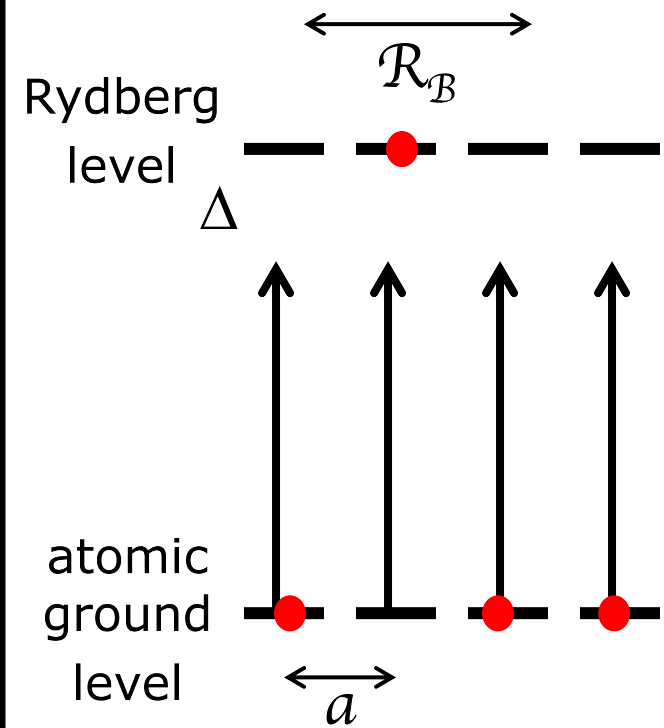




Order of ground state depends on trap distance relative to blockade radius

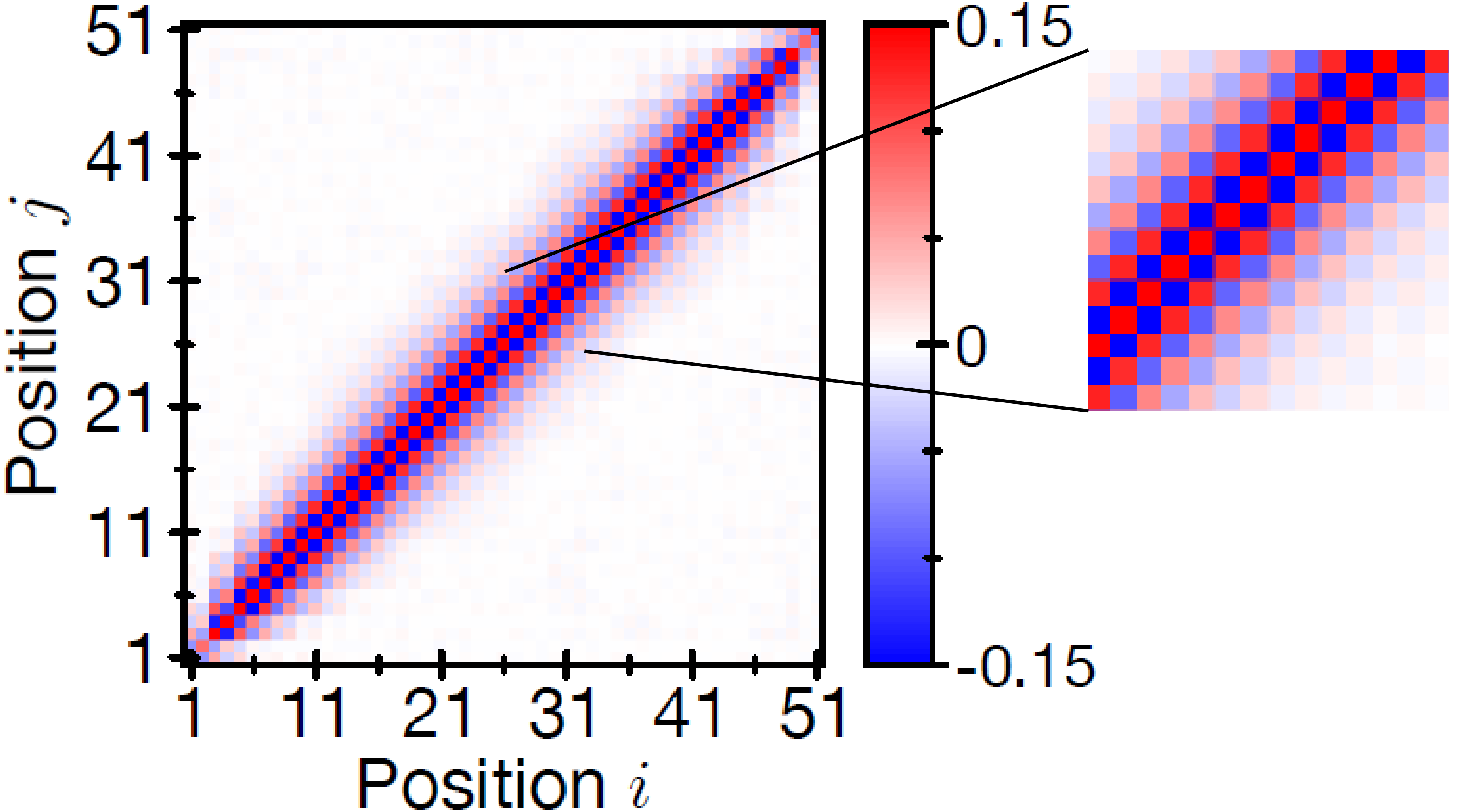
Phase boundaries for ordered phases





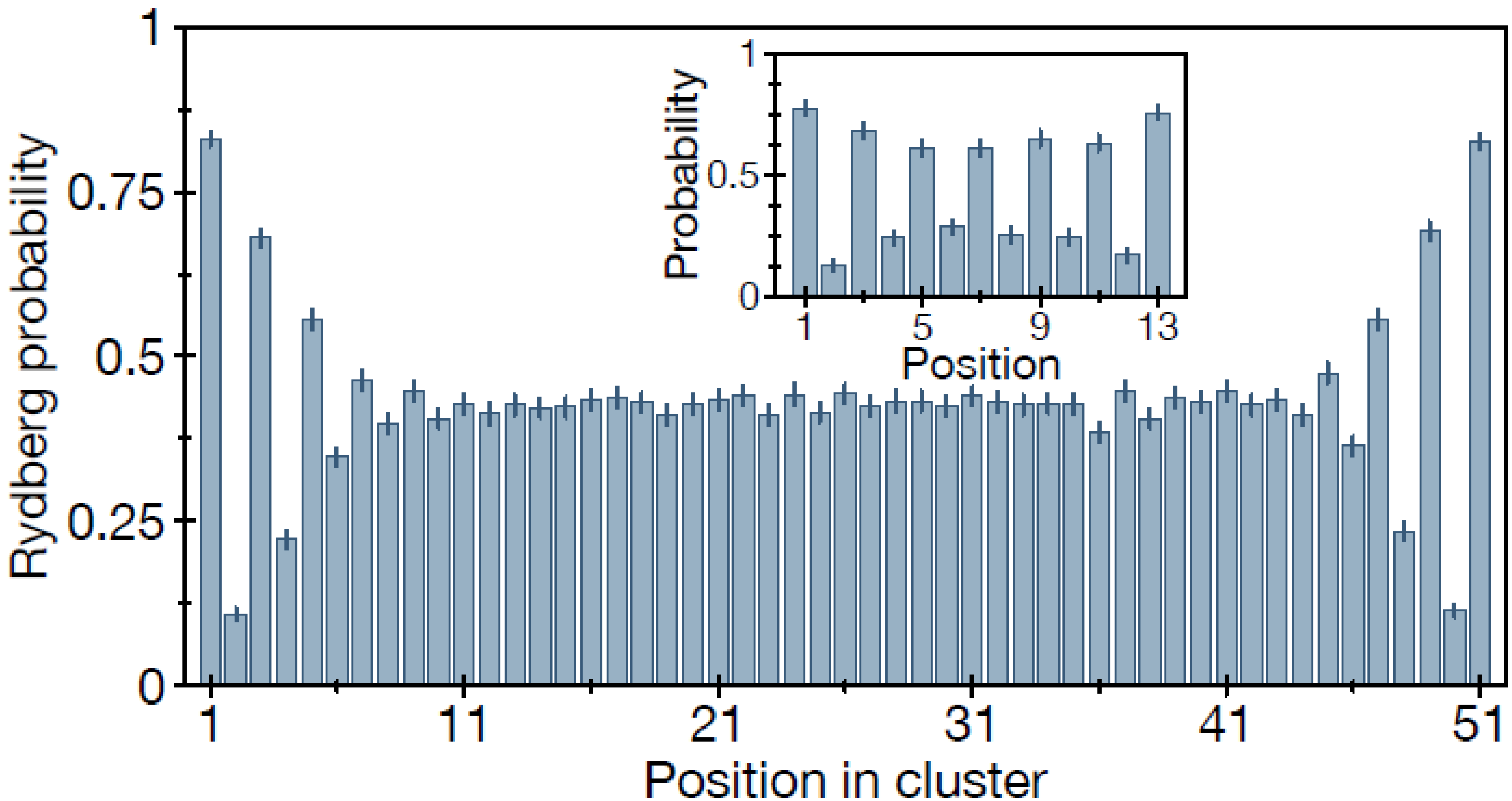
Order of ground state depends on trap distance relative to blockade radius

Antiferromagnetic correlations due to Rydberg blockade

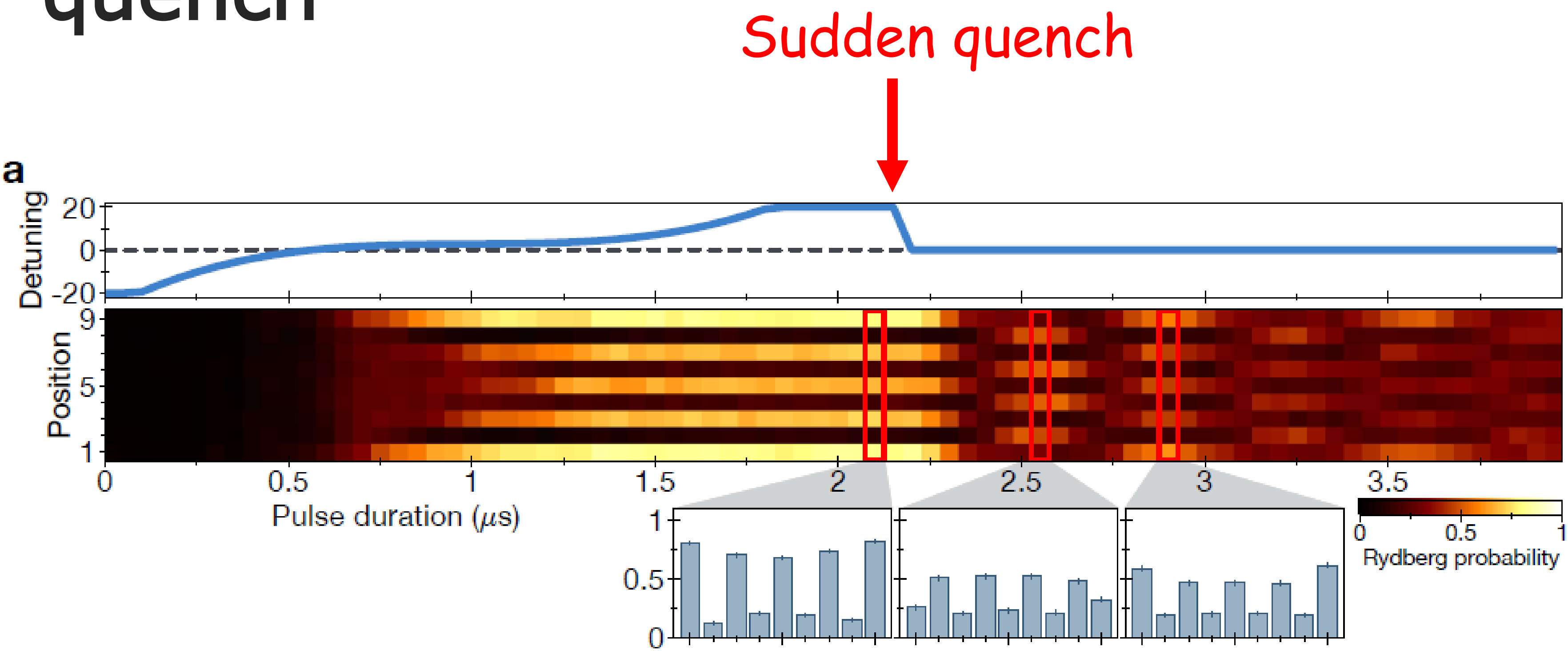


H. Bernien et al., Nature **551**, 579 (2017)

Small systems dominated by edge effects

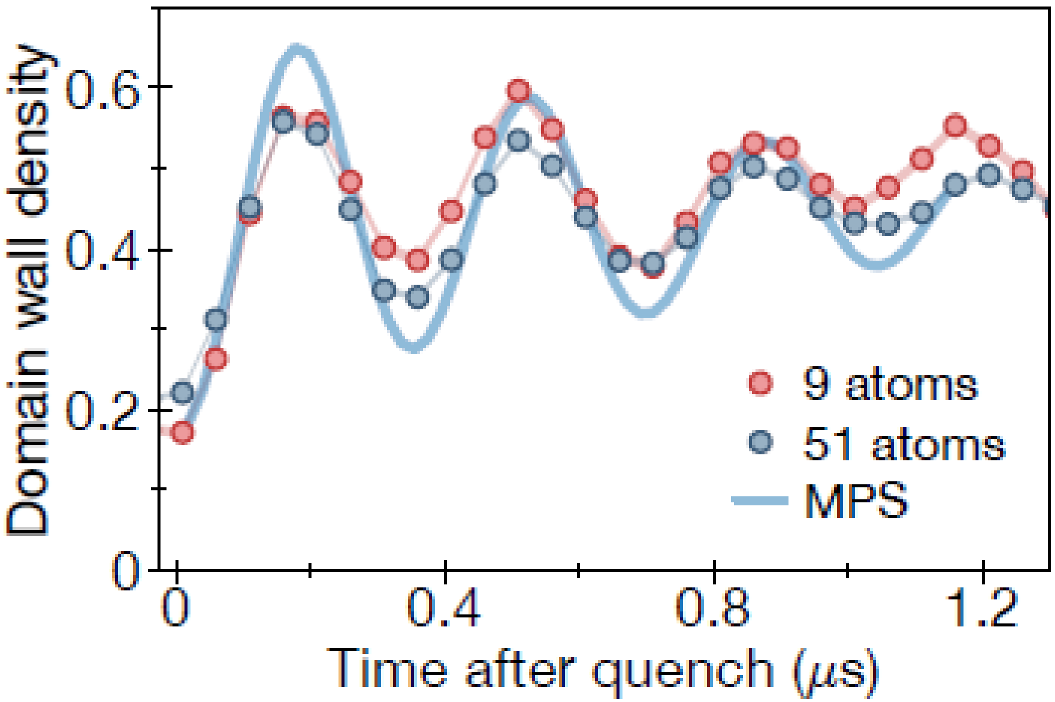


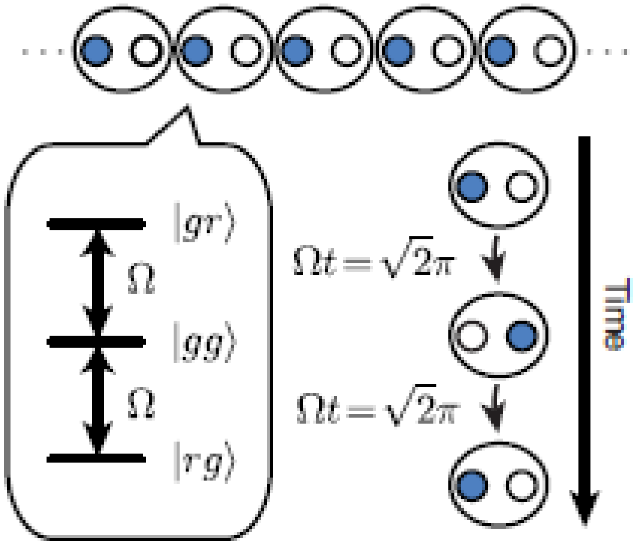
Collective oscillations after a sudden quench



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

Collective oscillations after a sudden quench





Quantum many-body scars?

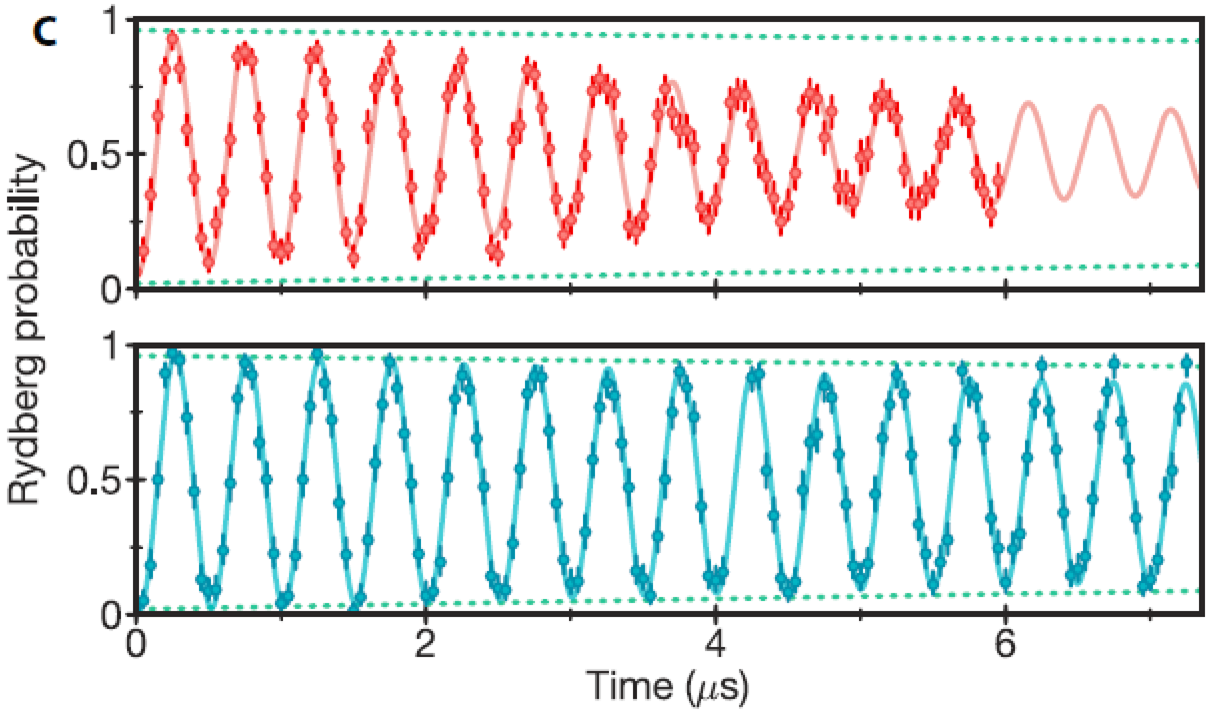
C. J. Turner, A. A. Michailidis, D. A. Abanin, M. Serbyn, and Z. Papic, arxiv 1711.03528 (2017).

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).

Characterization of Rydberg quantum gates

Single-qubit Rabi flopping

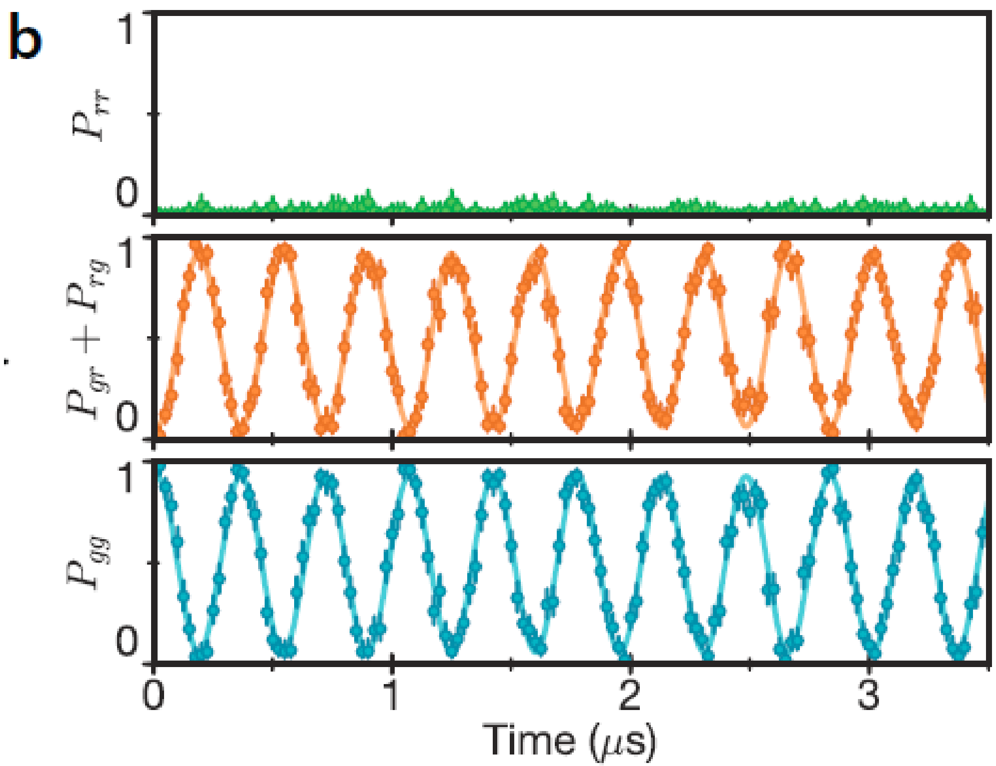


Before

After improvement of laser linewidth

Characterization of two-qubit quantum gates

Two-qubit quantum gate



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

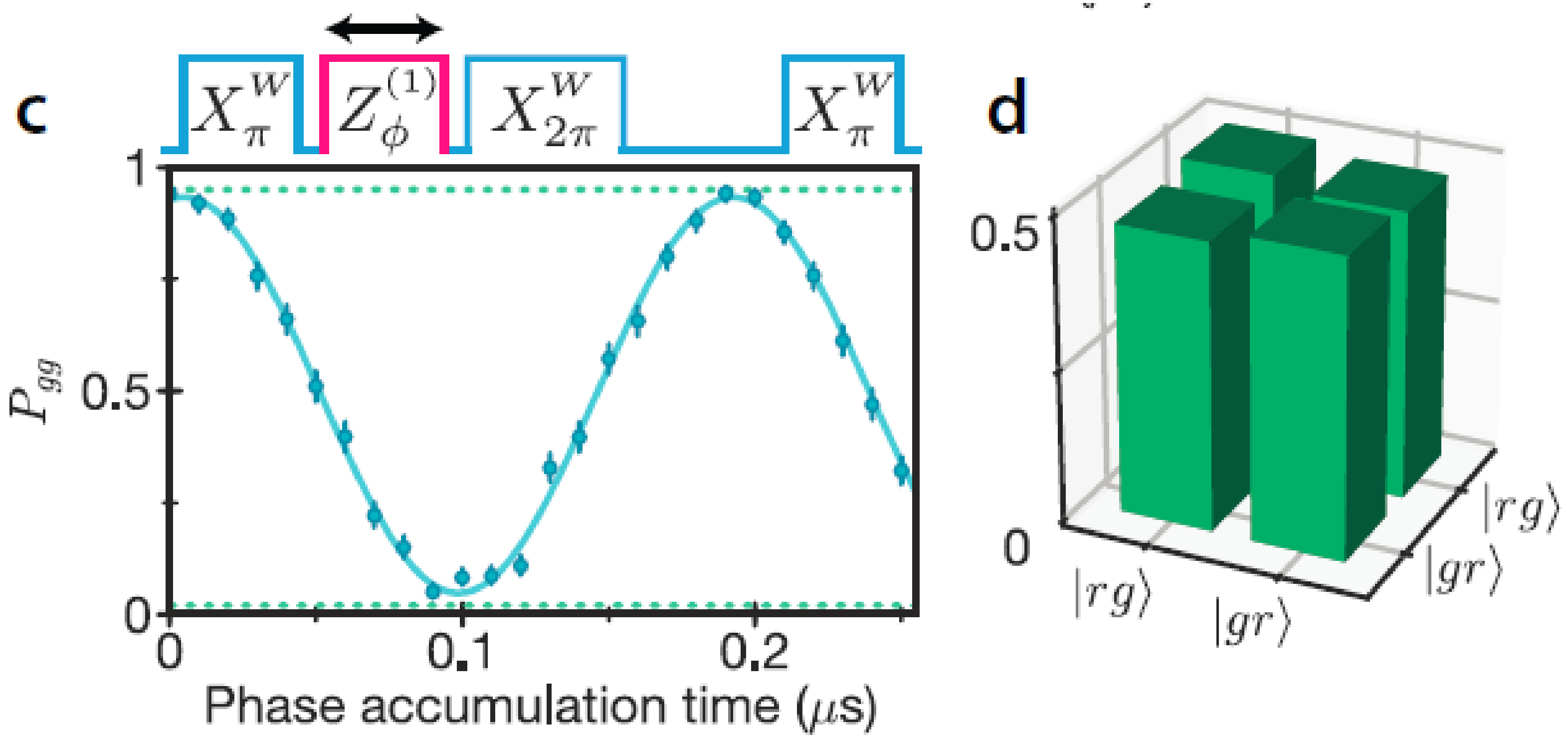
One Rydberg atom $|rg\rangle + |gr\rangle$

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%

Creation of large GHZ state

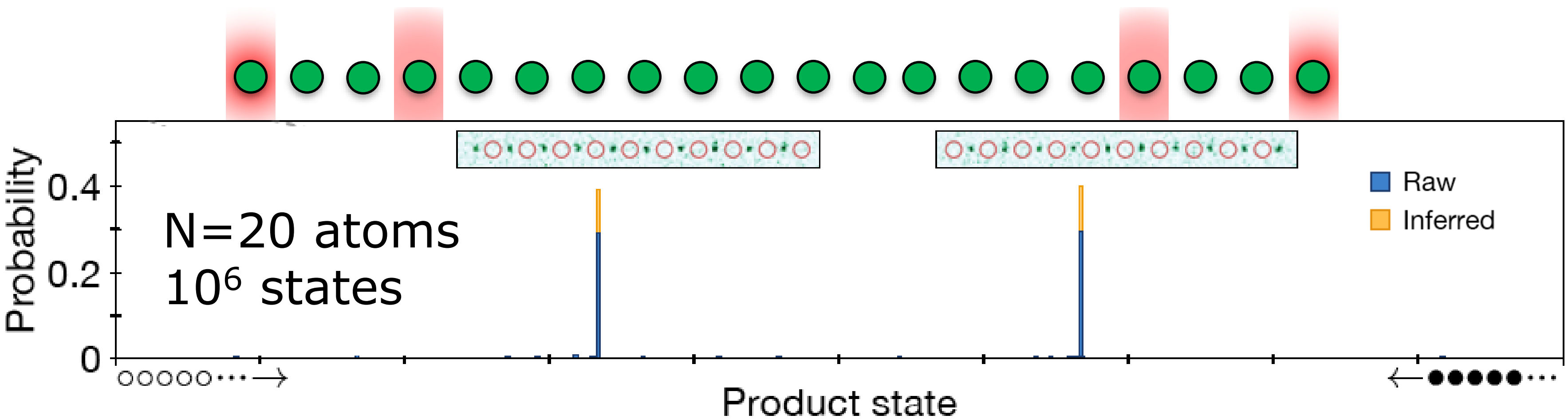
A. Omran et al., Science **365**, 570 (2019)

Creation of GHZ state

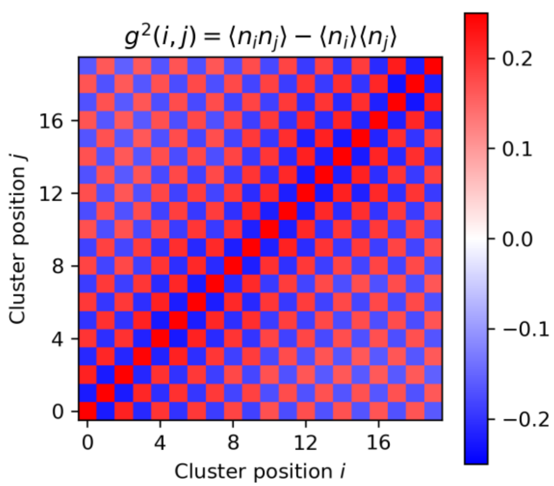
- We are seeking to make GHZ state of the form

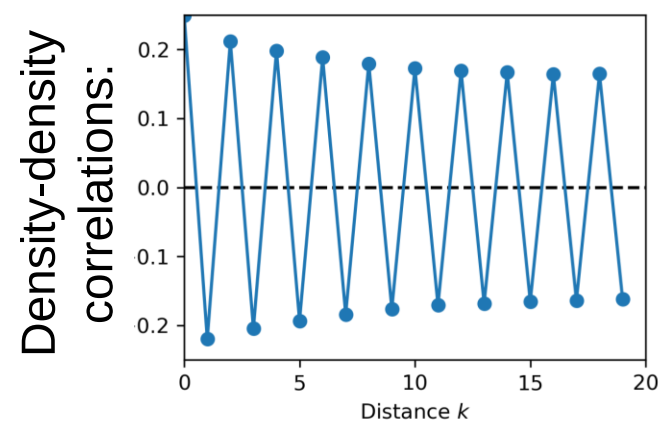
  $|grgr\ldots gr\rangle + |rgrg\ldots rg\rangle$
- This state should be produced if we try to excite a string with even total atom number to the Rydberg state
- Problem: edge effects, it takes little energy to excite atoms at end of string to Rydberg state
- Solution: energy shift on edge atoms

Creation of large GHZ states via evolution from ground state



Density-density correlations:

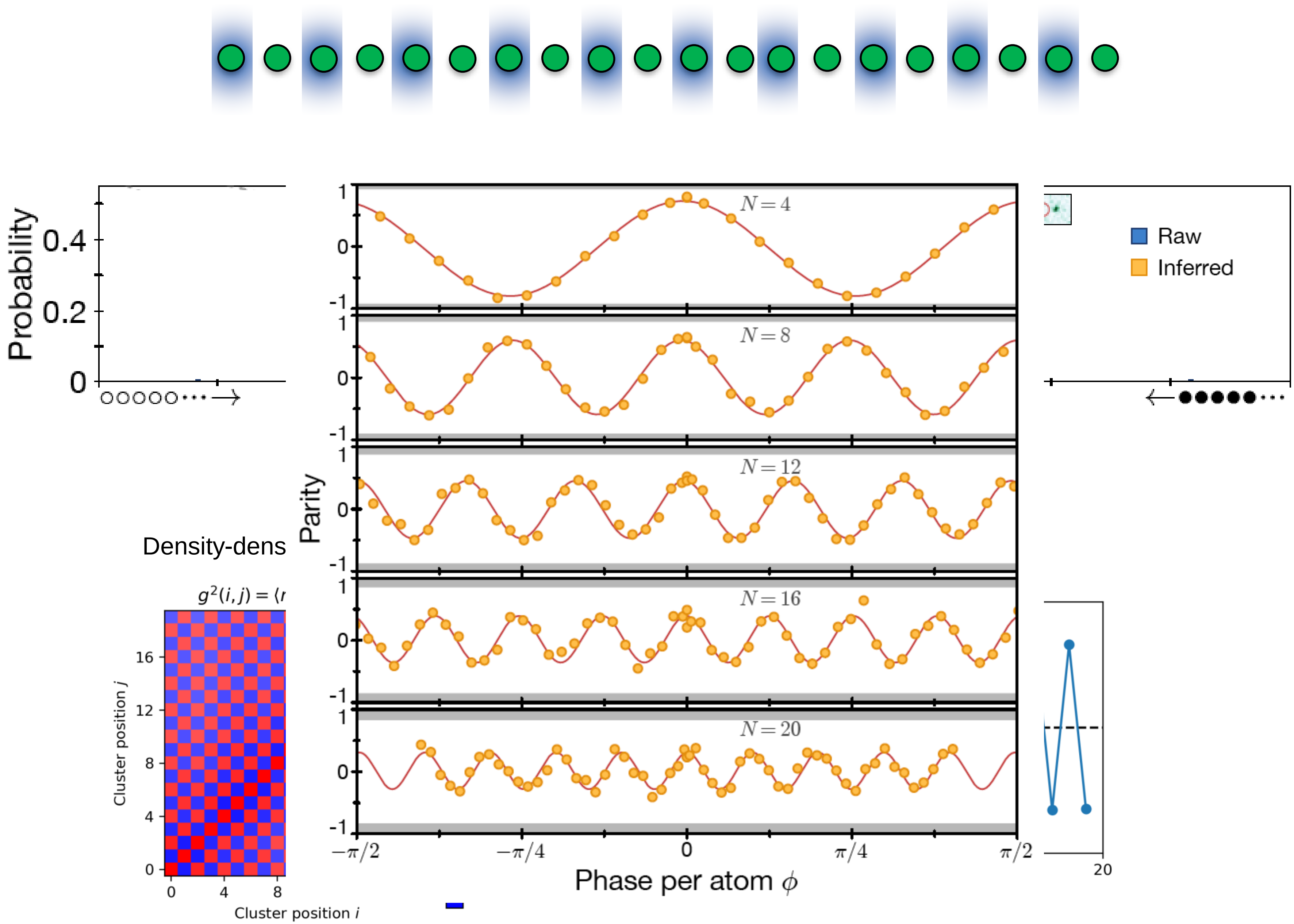




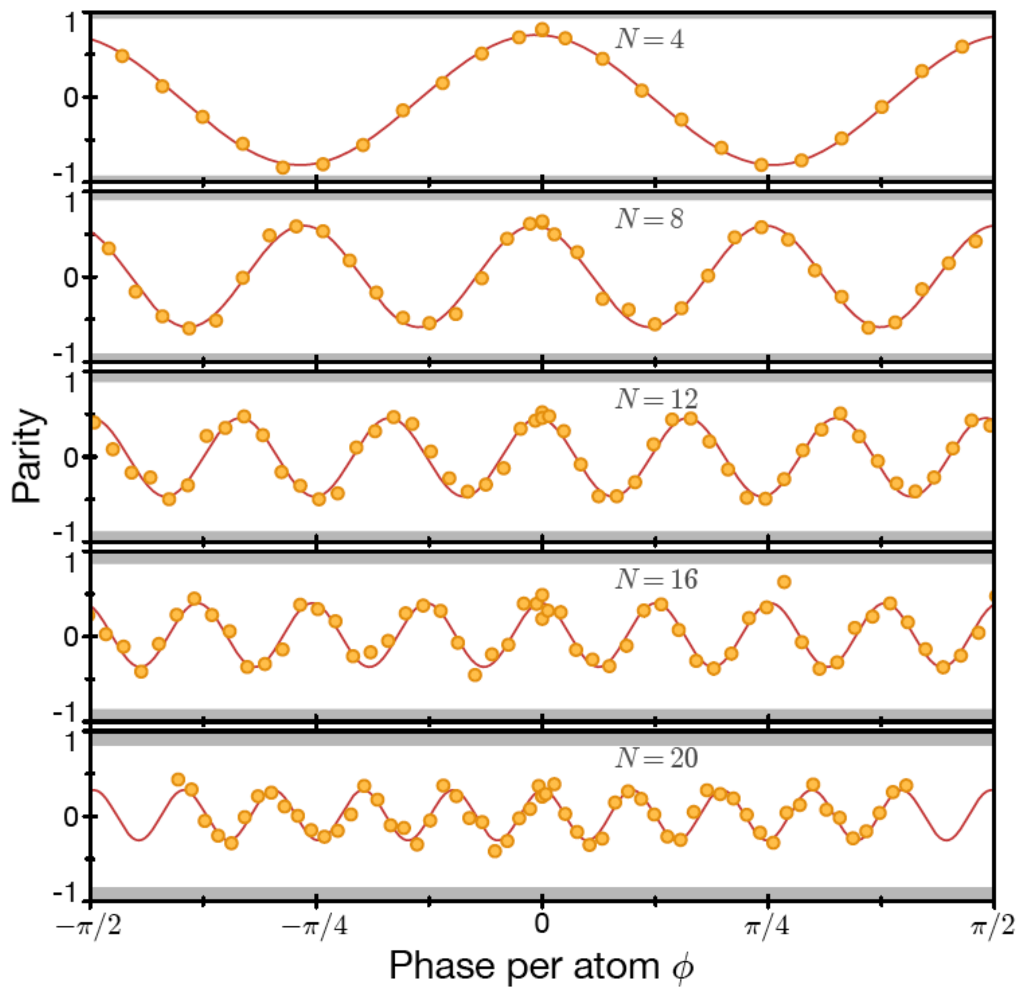
Phase measurement

- 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



Creation of large GHZ states via ground-state evolution



4 atoms

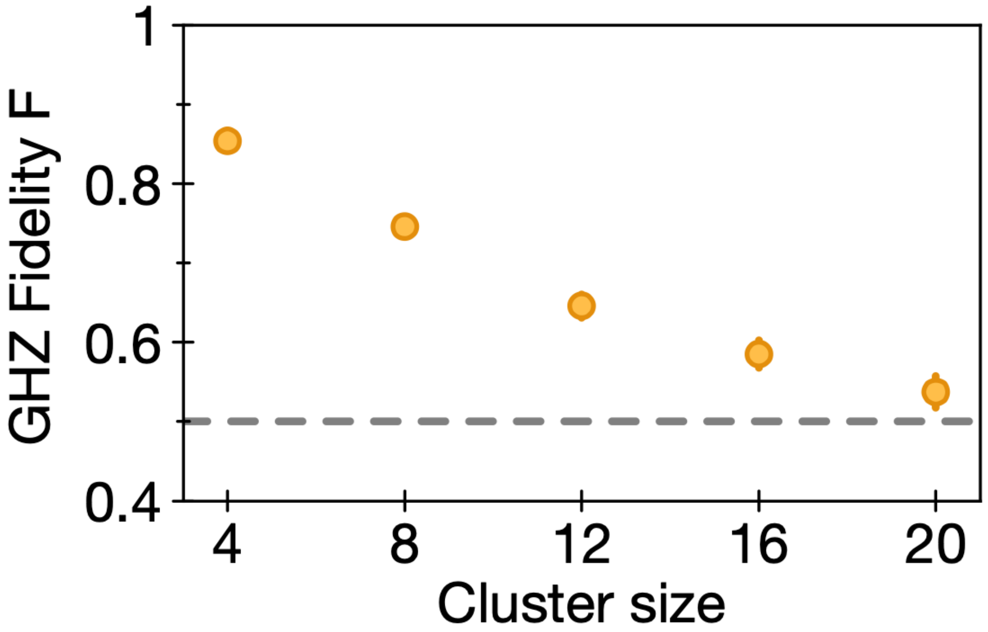
8 atoms

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*

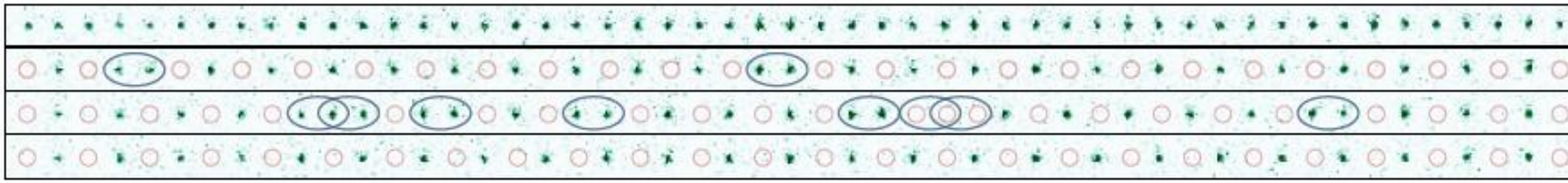
K.X.Wei et al arXiv:1905.05720 *F= 0.517±0.004*

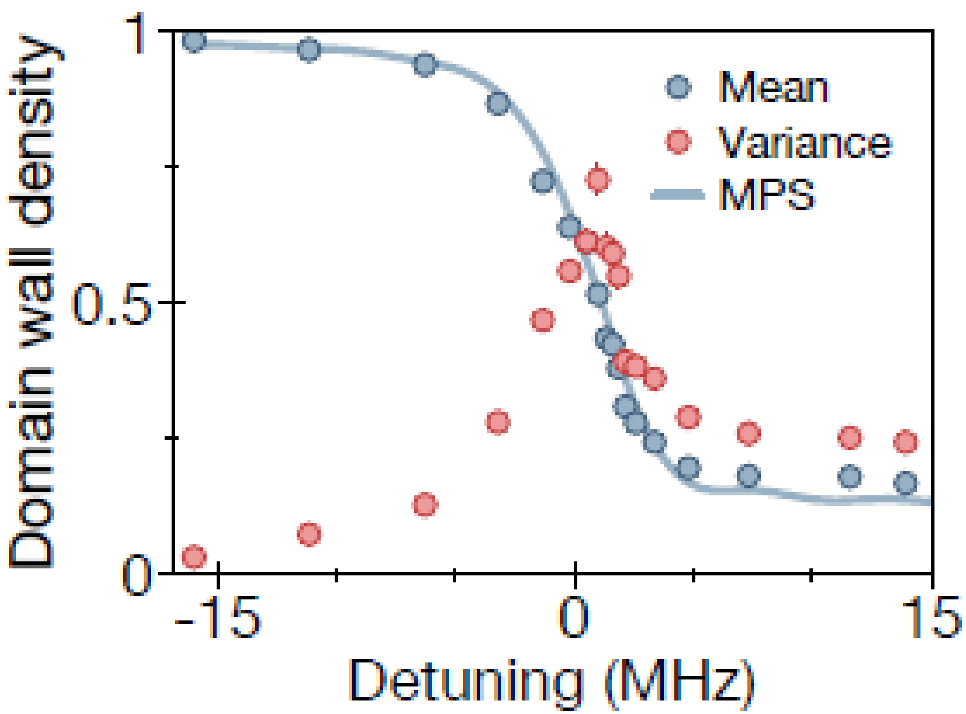
20 ion qubits (non-GHZ) N. Friis, et. al. PRX 8, 021012 (2018)

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);

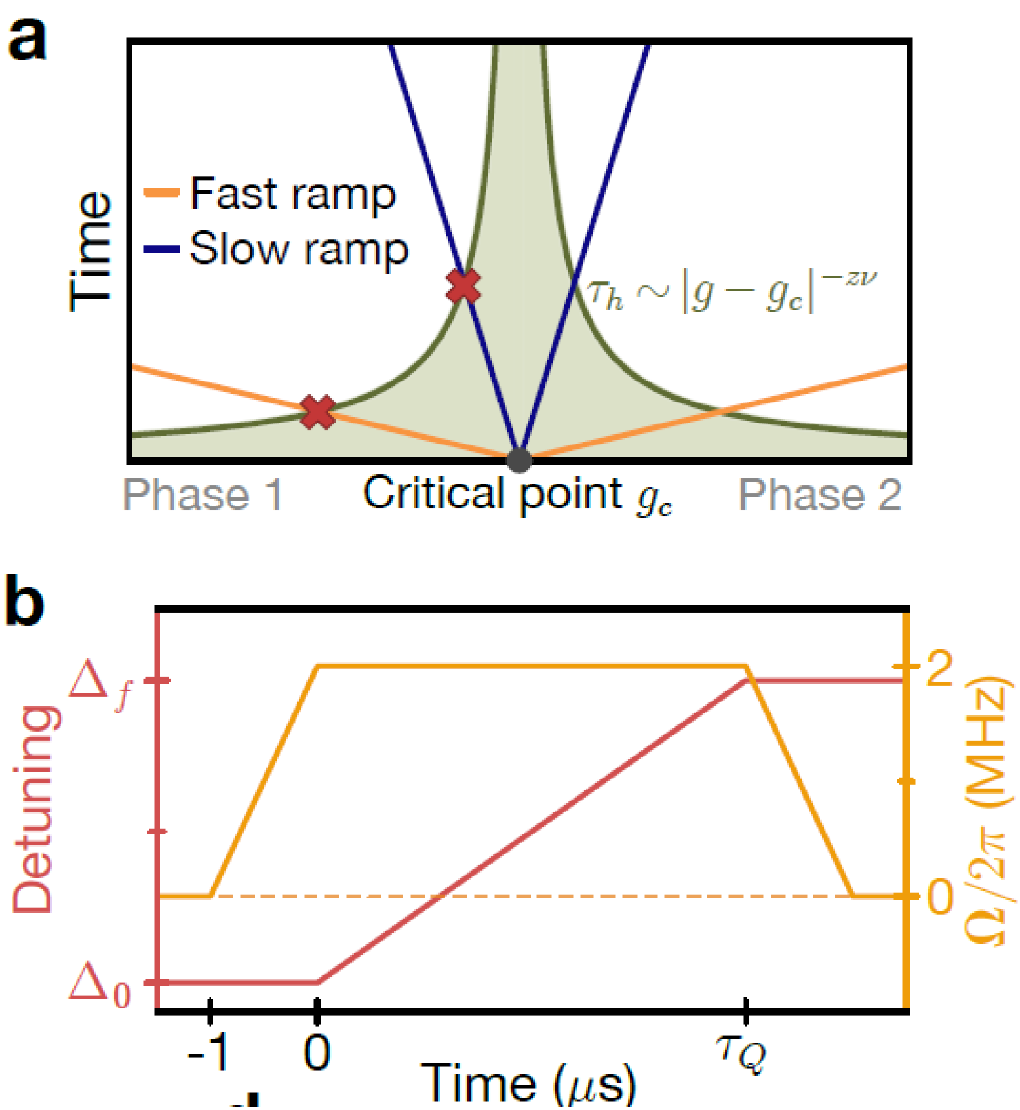
Crystal preparation at finite speed





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

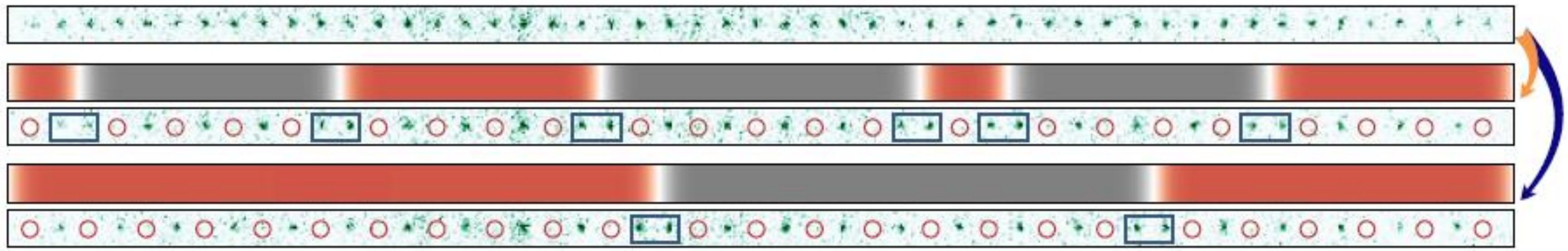
Kibble-Zurek mechanism



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

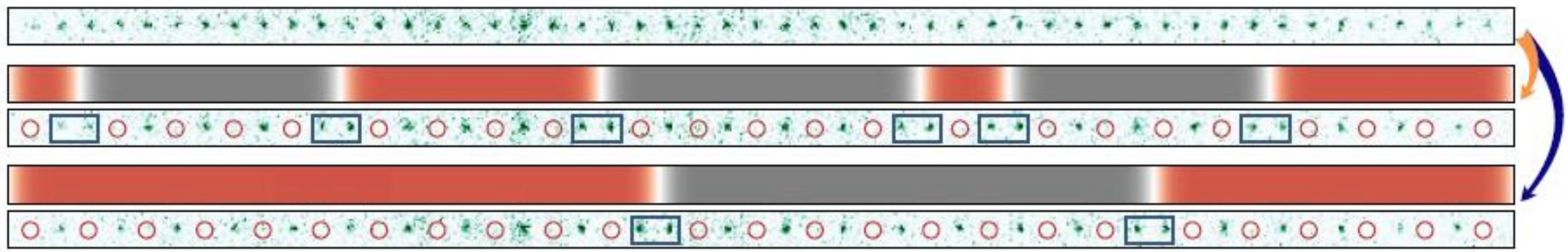
Ramping across phase transition and measuring density of defects in antiferromagnet.

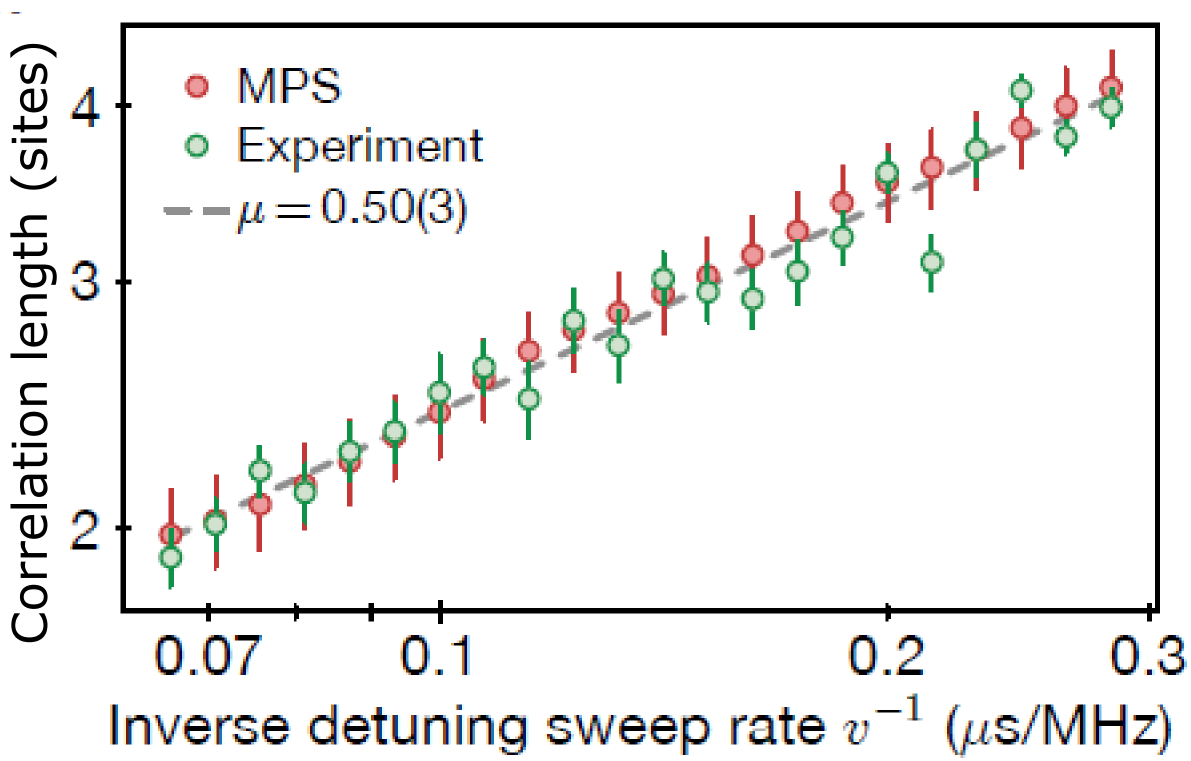
Appearance of domain walls at finite sweep rate into ordered phase



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.

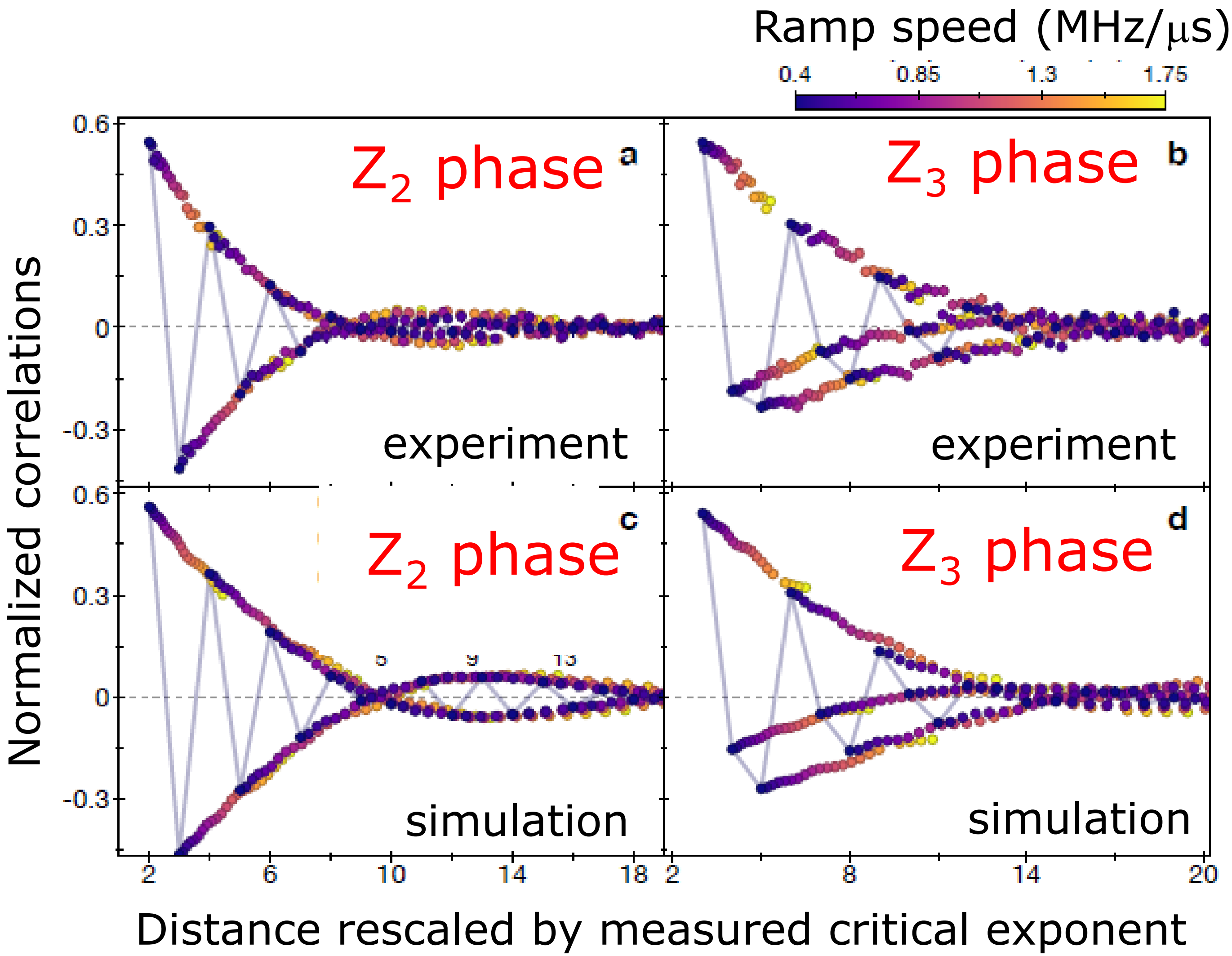
Kibble-Zurek mechanism for quantum phase transition into Z_2 phase





Critical exponent extracted from observed power law

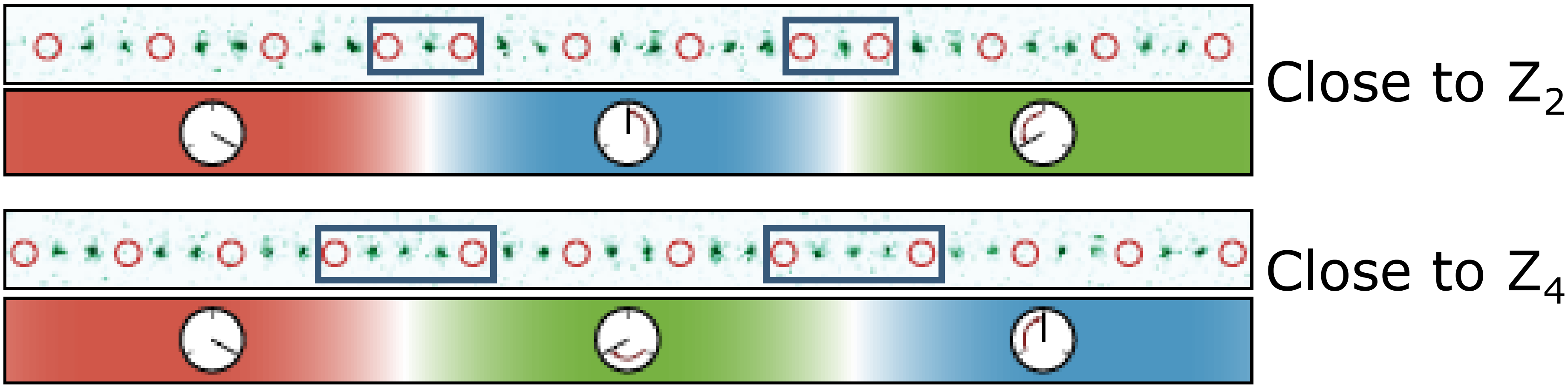
Universality of correlations



Different branches correspond to different types of defect

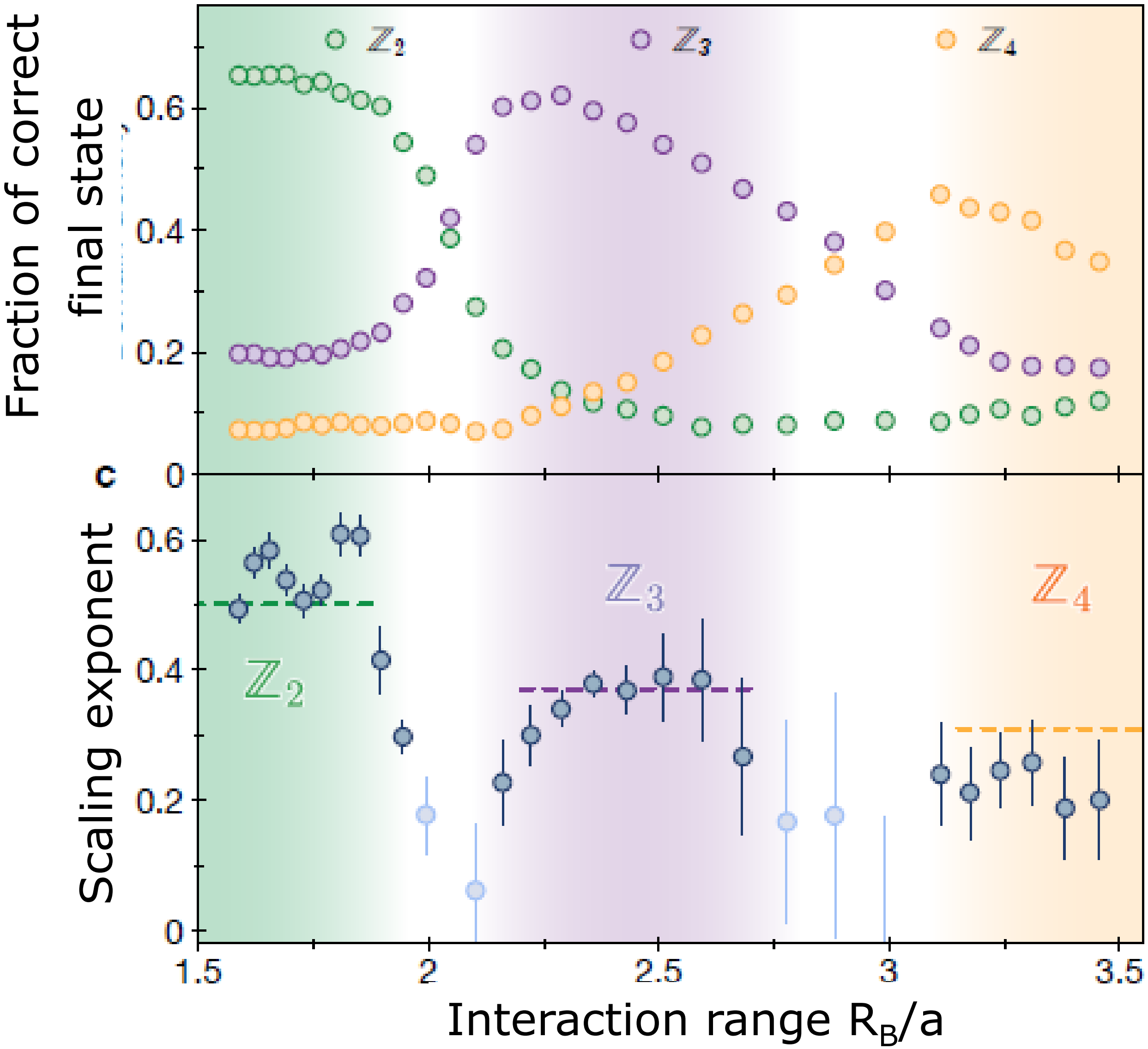
Nontrivial correlations between domain walls.

Different defects in Z_3 phase



Type of defects changes with atomic distance a/R_B.

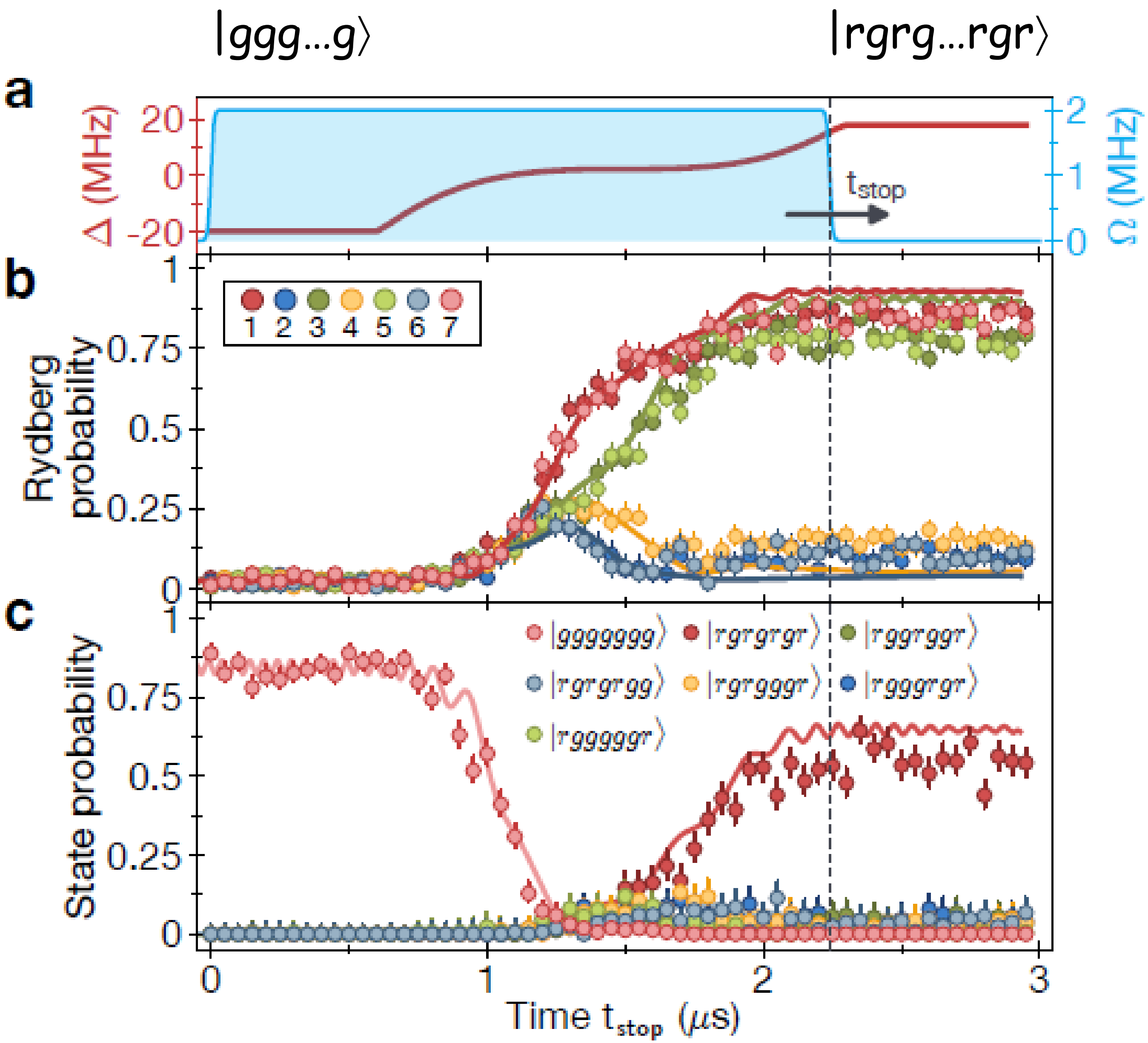
Power law scaling for different distances



Fraction of correct final state for different orders.

Scaling exponent varies near phase boundaries.

Adiabatic ramp across phase transition

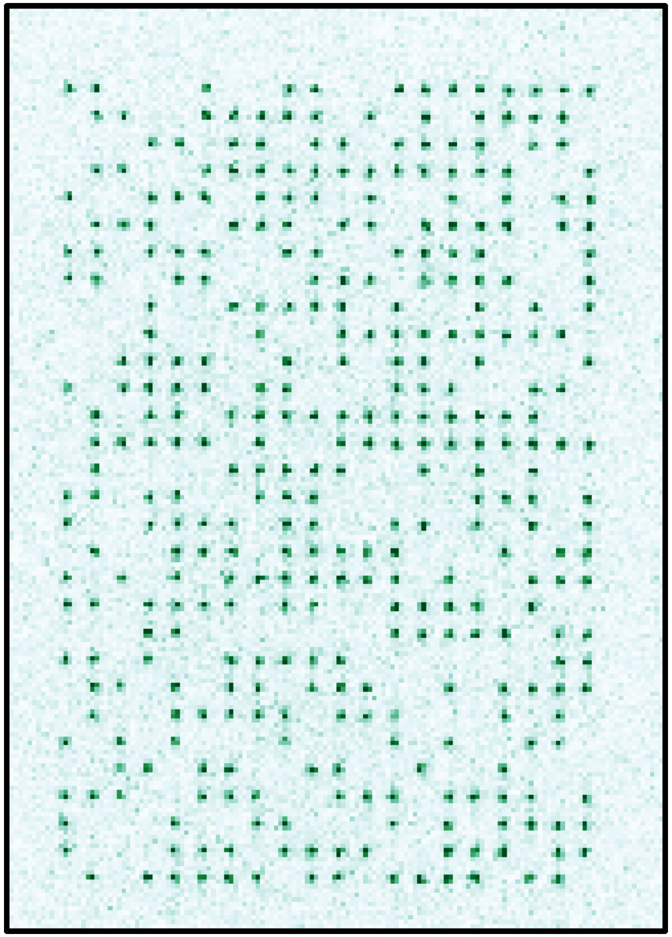


Two-dimensional arrays

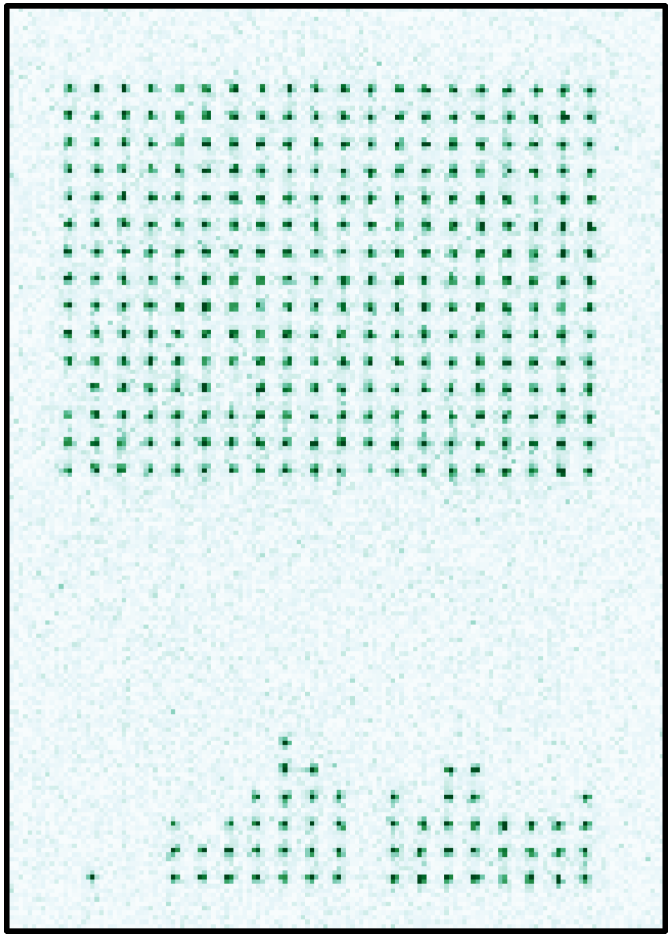
Quantum Phases of Matter on a 256-Atom Programmable Quantum Simulator. S. Ebadi, T.T. Wang, Levine, A. Keesling, G. Semeghini, A. Omran, D. Bluvstein, R. Samajdar, H. Pichler, W.W. Ho, S. Choi, S. Sachdev, M. Greiner, V. Vuletić, and M.D. Lukin, Nature (2021).

Sorting 300 atoms in two dimensions

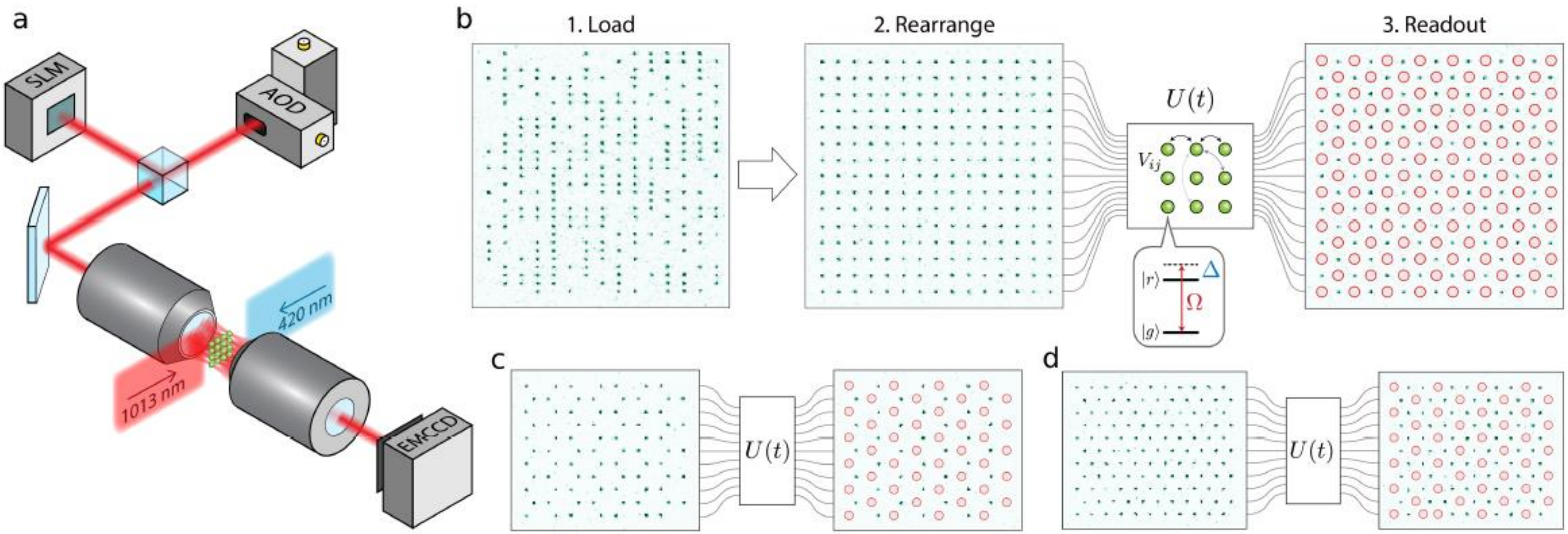
Initial loading:



After sorting:

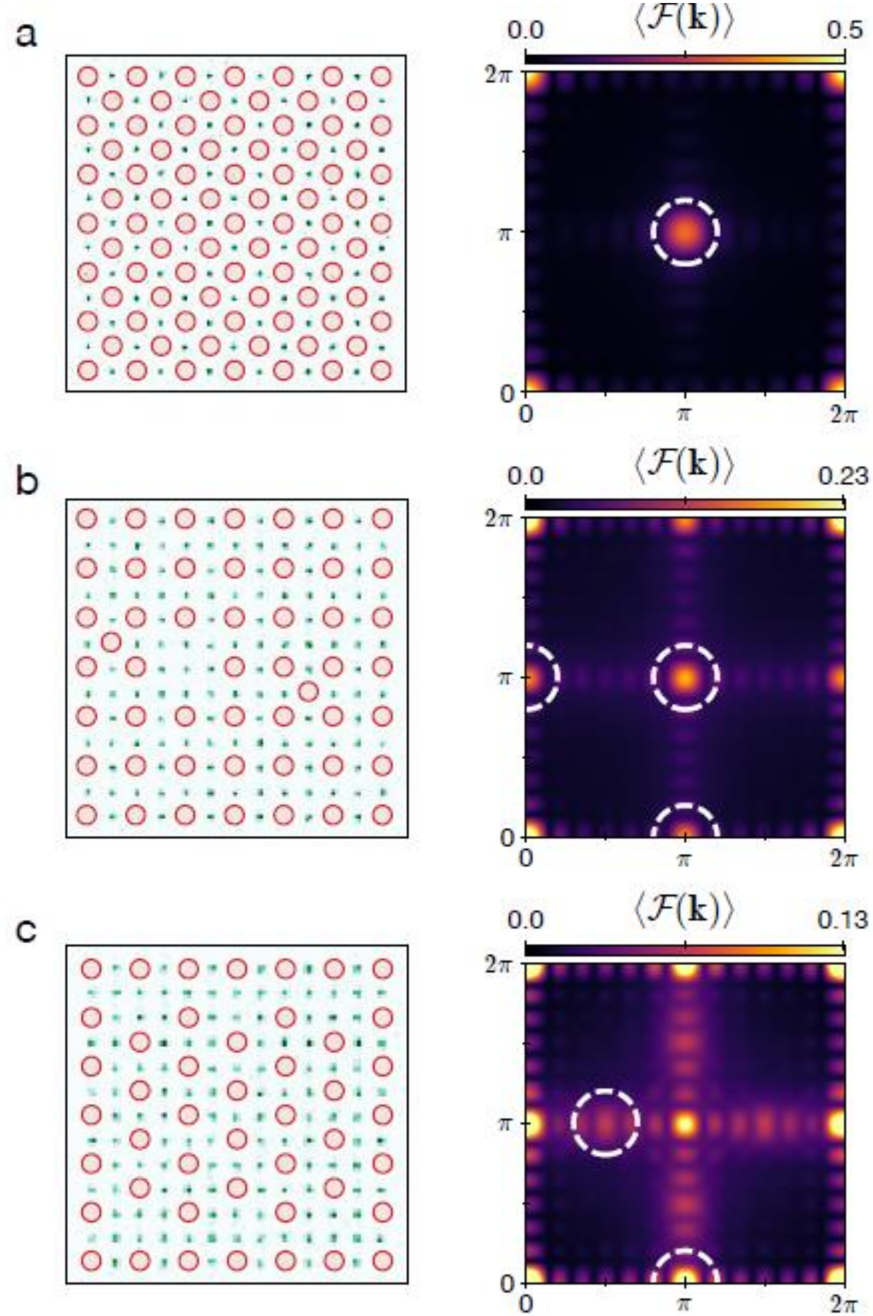


> 98% filling fraction



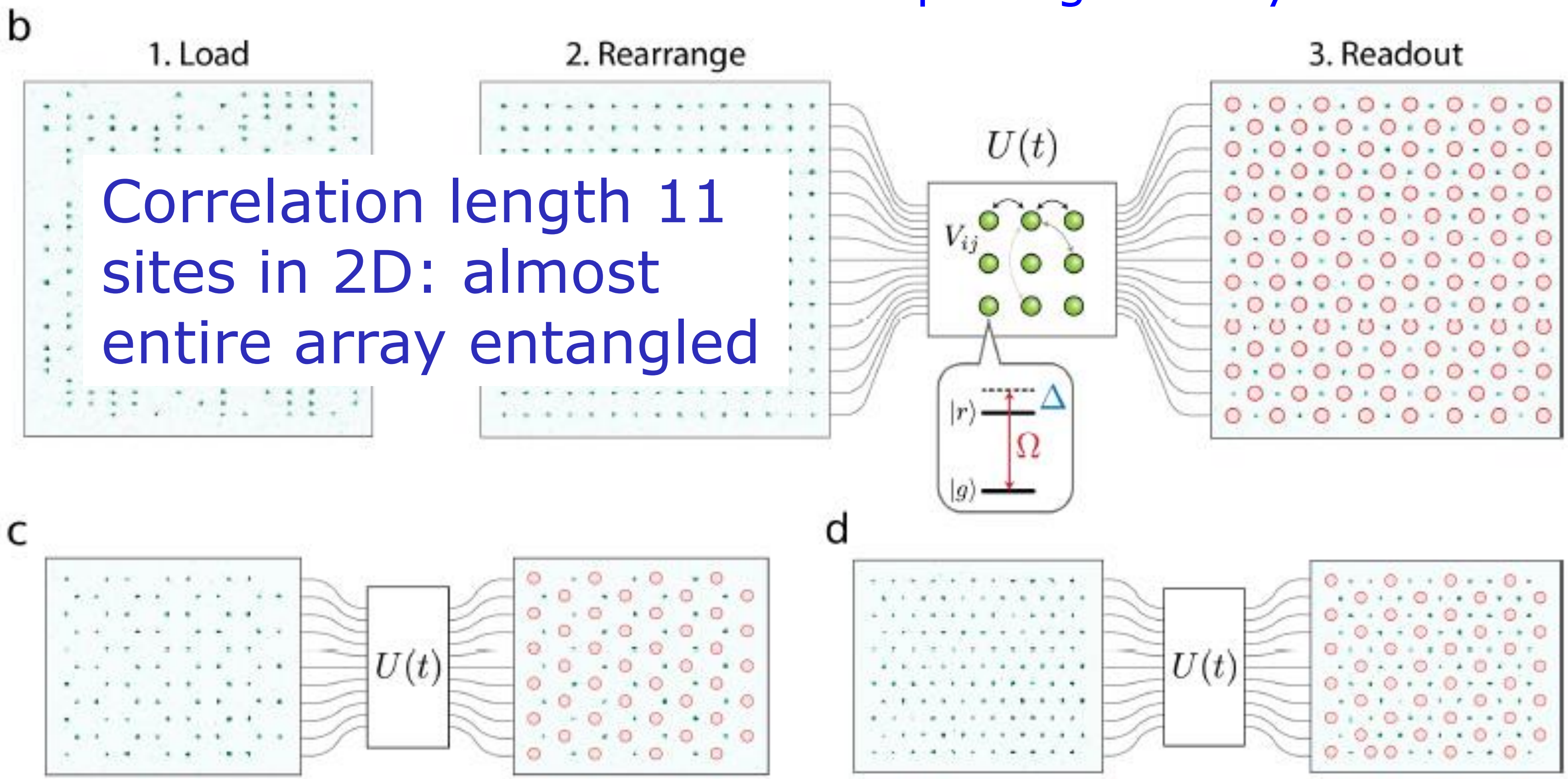
a
SLM
AOD
420 nm
1013 nm
EMCCD
b
1. Load
2. Rearrange
3. Readout
$U(t)$
V_{ij}
$|r\rangle$
Δ
Ω
$|g\rangle$
c
$U(t)$
d
$U(t)$

Antiferromagnetic phases on square lattice for different interaction strengths



Antiferromagnetic correlations in 2D

Square geometry



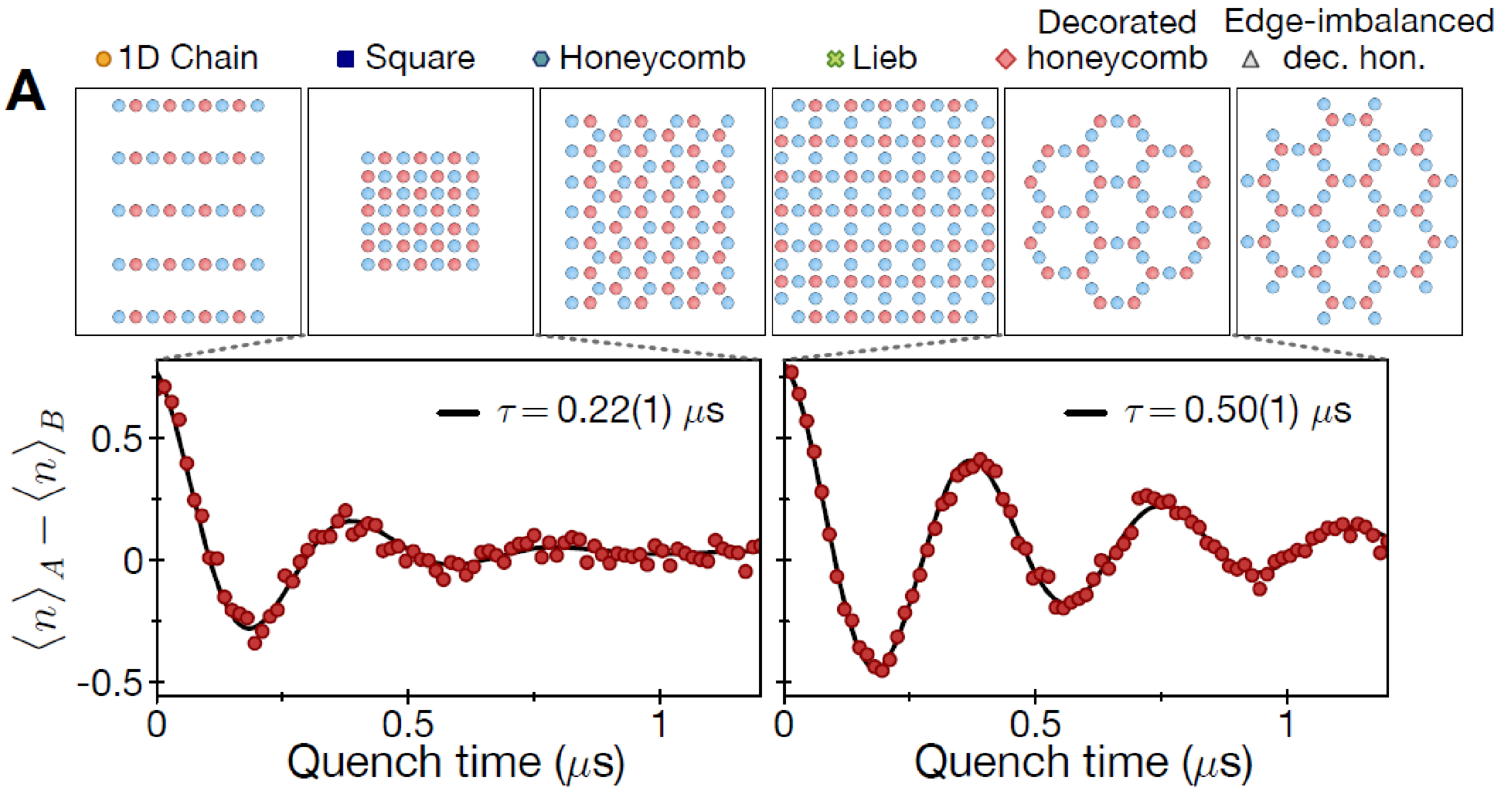
Correlation length 11 sites in 2D: almost entire array entangled

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, arxiv (2020).

Quantum many-body scars in 2D



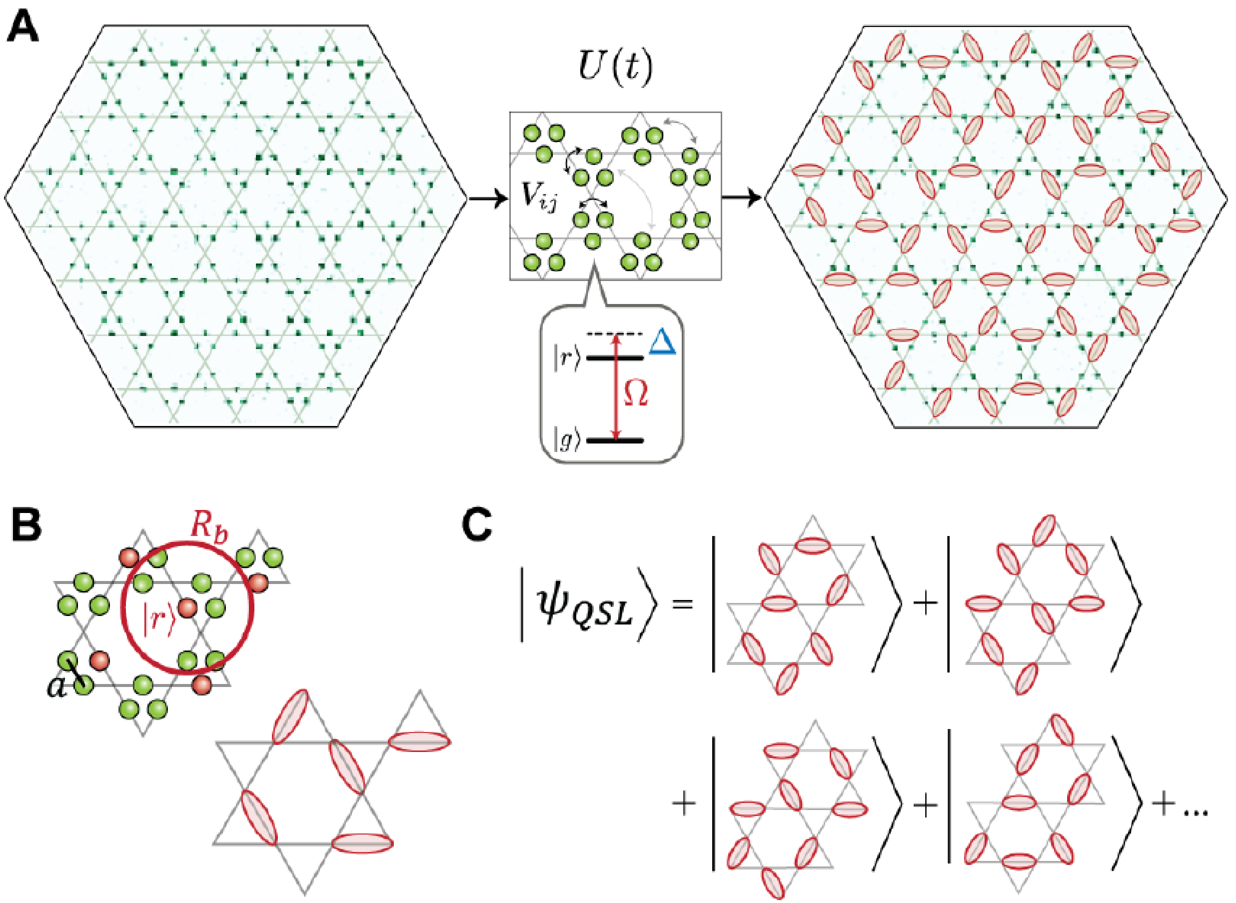
We discovered that quantum many-body scars can be stabilized by driving.

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, to appear in Science (2021).

Probing topological spin liquids on a kagome lattice

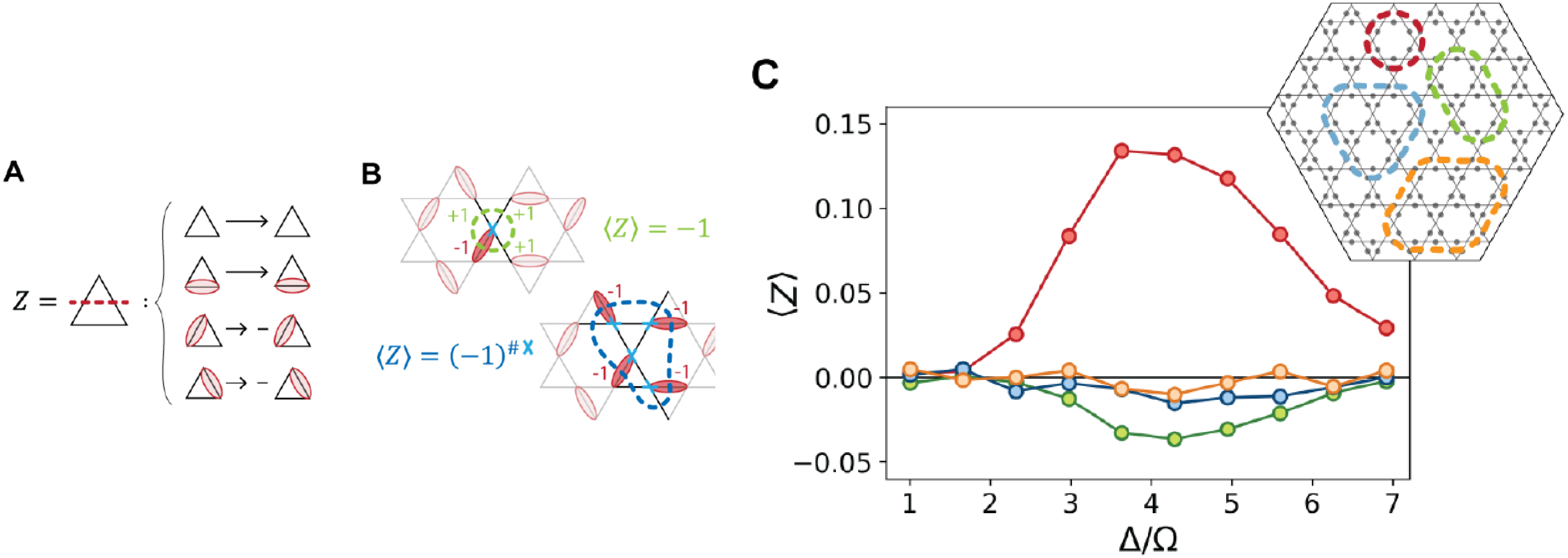
Probing Topological Spin Liquids on a Programmable Quantum Simulator. G. Semeghini, H. Levine, A. Keesling, S. Ebadi, T. T. Wang, D. Bluvstein, R. Verresen, H. Pichler, M. Kalinowski, R. Samajdar, A. Omran, S. Sachdev, A. Vishwanath, M. Greiner, V. Vuletić, and M.D. Lukin, submitted to Science

Spin liquid on a kagome lattice



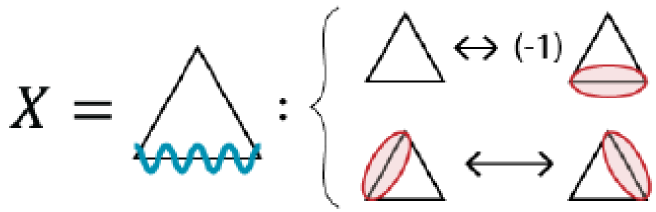
$$\frac{H}{\hbar} = \frac{\Omega(t)}{2} \sum_i \sigma_i^x - \Delta(t) \sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

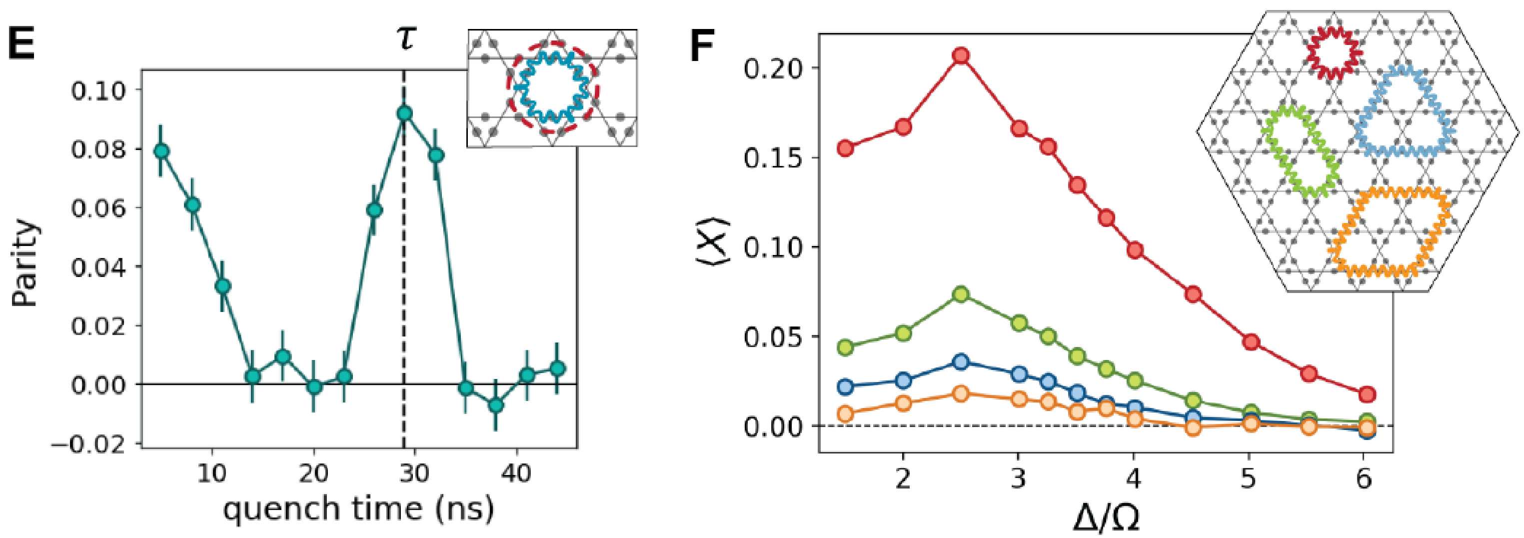
Probing topological parameters of potential spin liquid state



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

Probing topological parameters of potential spin liquid state



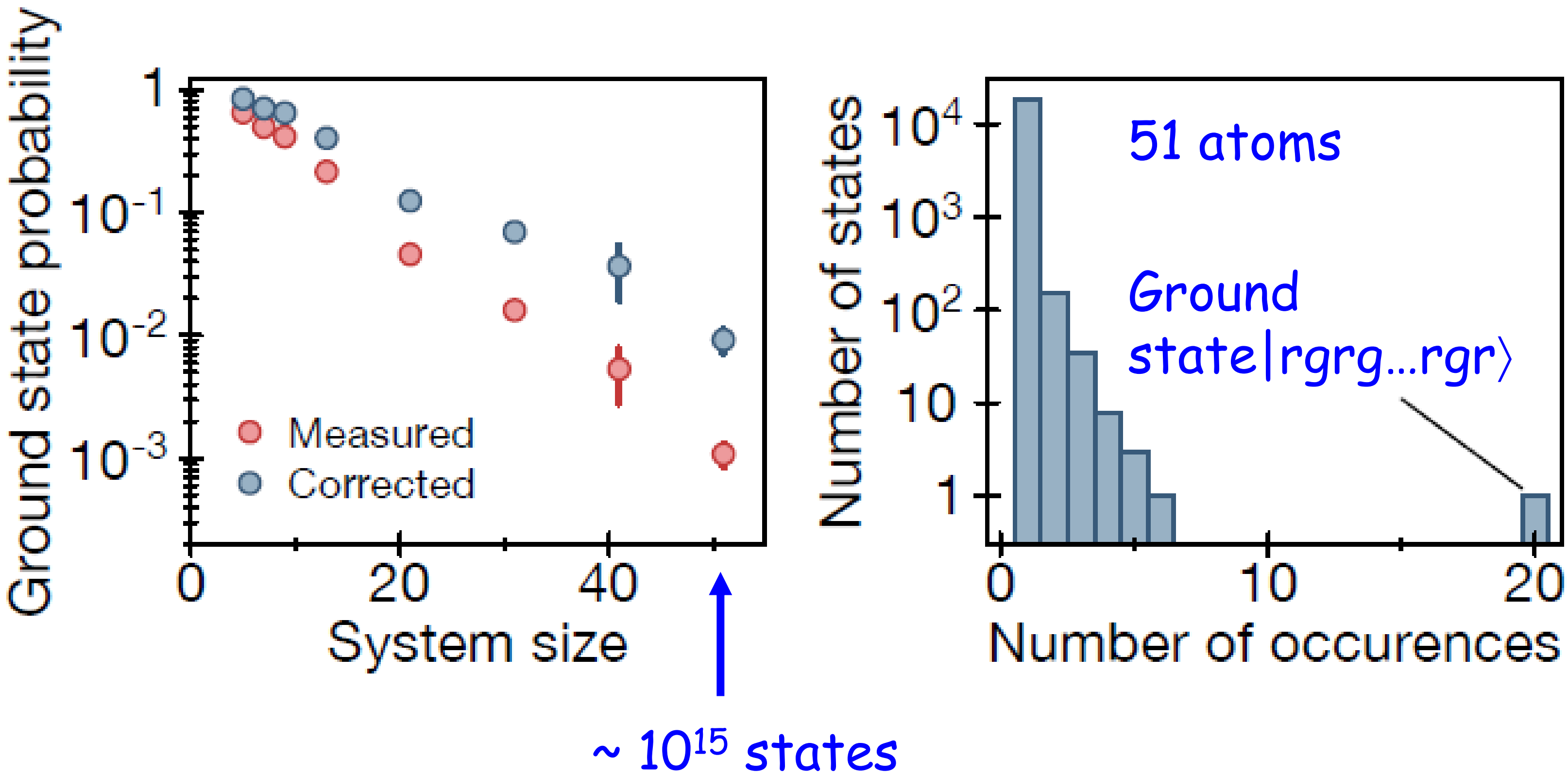


X parameter (coherence) measured by quenching and measuring Z parity

Outlook

- Towards large quantum simulators
  - 300-1000 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)?

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



Ground state reached much more often than any other state.

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