Manipulating strongly interacting individual quanta: photon molecules and 51 atomic qubits

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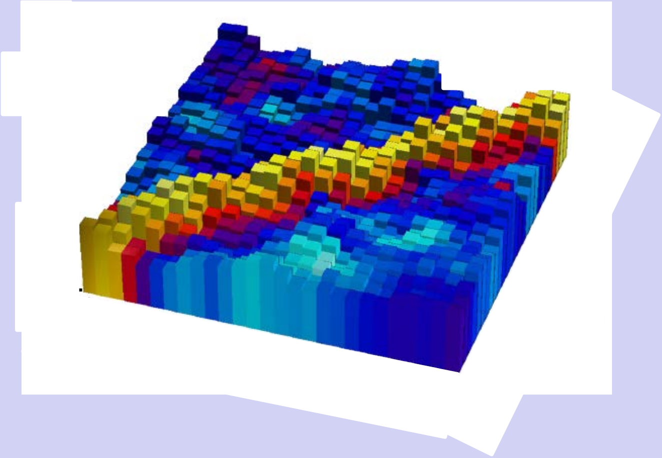
Outline

- Rydberg mediated photon-photon interactions
  - Principle: quasiparticles made of photons and collective atomic excitations
  - Dispersive interactions: bound states of two and three photons
  - Repulsive interactions between photons
- 51-atom quantum simulator
  - Deterministic preparation of many individual atoms
  - Quantum phase transition in Ising-type model
  - Rydberg quantum gates

Strong photon-photon interactions



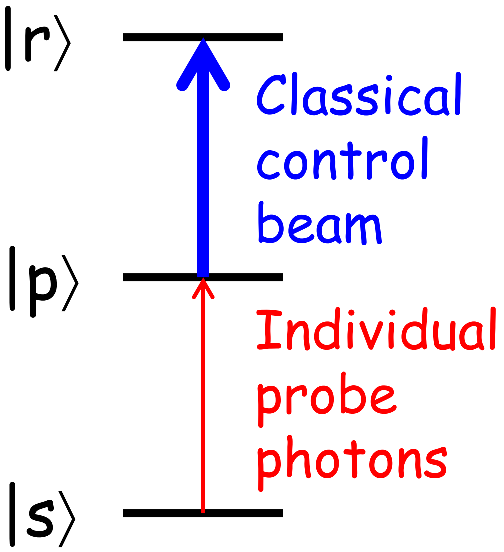
Joint experiment with Mikhail Lukin's group (Harvard)

T. Peyronel, O. Firstenberg, Q.-Y. Liang, S. Hofferberth, A.V. Gorshkov, T. Pohl, M.D. Lukin, and V. Vuletić, Nature **488**, 57-60 (2012).

O. Firstenberg, T. Peyronel, Q.-Y. Liang, A.V. Gorshkov, M.D. Lukin, and V. Vuletić, Nature **502**, 71-74 (2013).

Q.-Y. Liang, A.V. Venkatramani, S.H. Cantu,T.L. Nicholson, M.J. Gullans, A.V. Gorshkov, J.D. Thompson, C. Chin, M.D. Lukin, and V. Vuletić, Science **359**, 783 (2018).

Electromagnetically induced transparency (EIT) with interacting Rydberg atoms

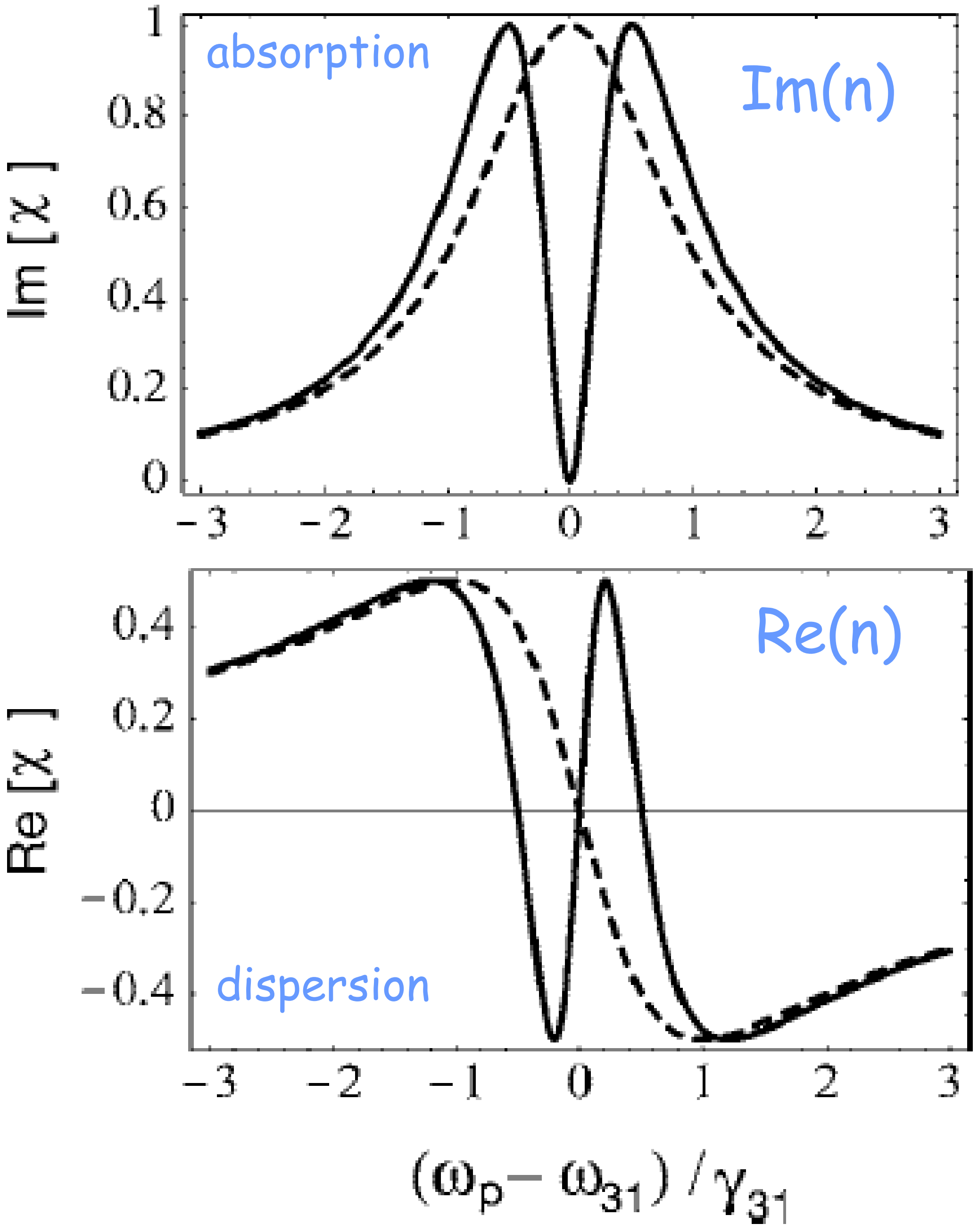


Metastable highly excited Rydberg state (principal quantum number n=100)

Unstable electronic excited P state

Stable ground state

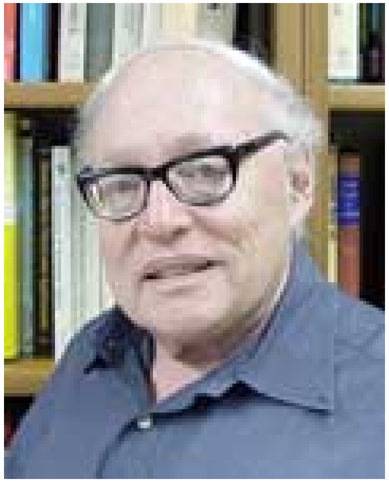
EIT to high-lying Rydberg state via unstable $|P\rangle$ level in dense cold ^{87}Rb gas



Sharp variation of transmission and dispersion with frequency in an otherwise opaque medium

Electromagnetically induced transparency

$$v_g = \frac{c}{n + \omega \frac{\partial n}{\partial \omega}}$$

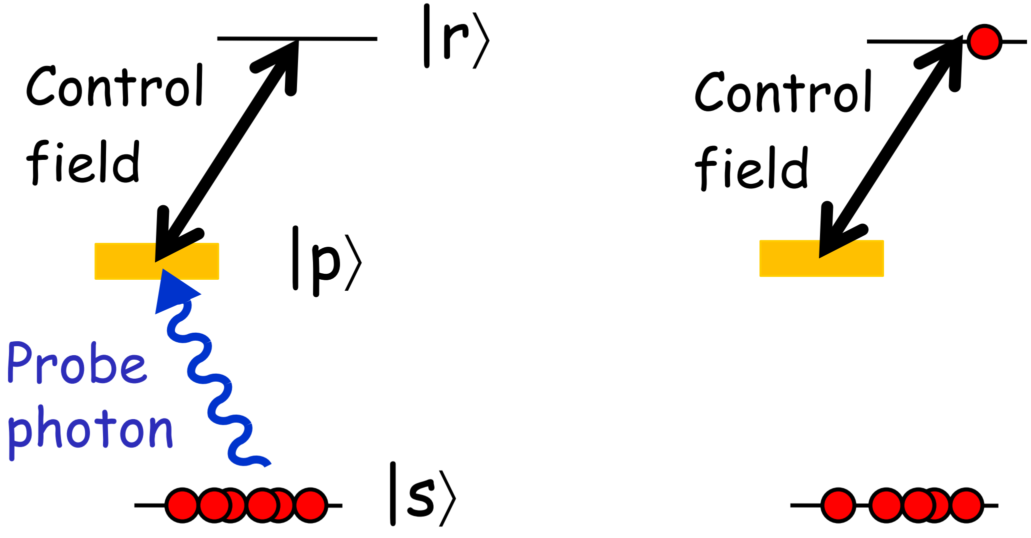


EIT for lasers without inversion
1989

Steve Harris

Electromagnetically Induced Transparency

- EIT produces slow light by converting photons into collective atomic (spin) excitations



slow-light polariton = photon + magnon

$0 < v < c$ $v=c$ $v=0$

Light travels at $v=1$ km/s for our conditions.

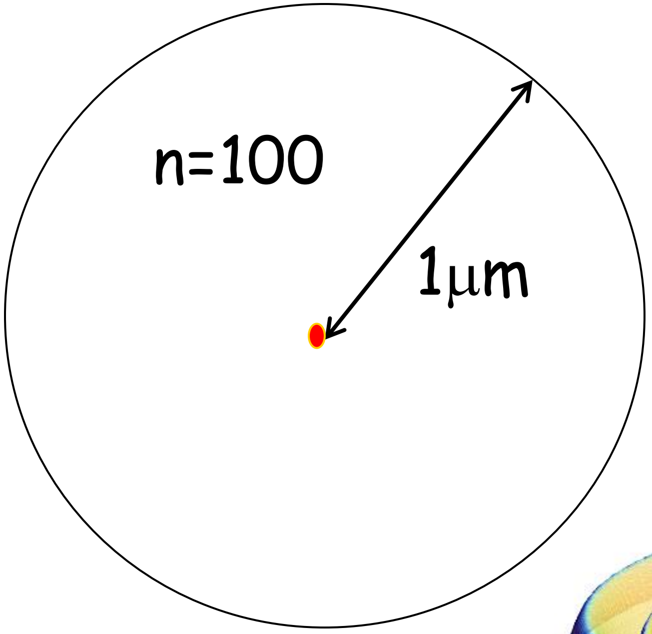
No population of unstable p state due to destructive interference: no absorption

Rydberg states

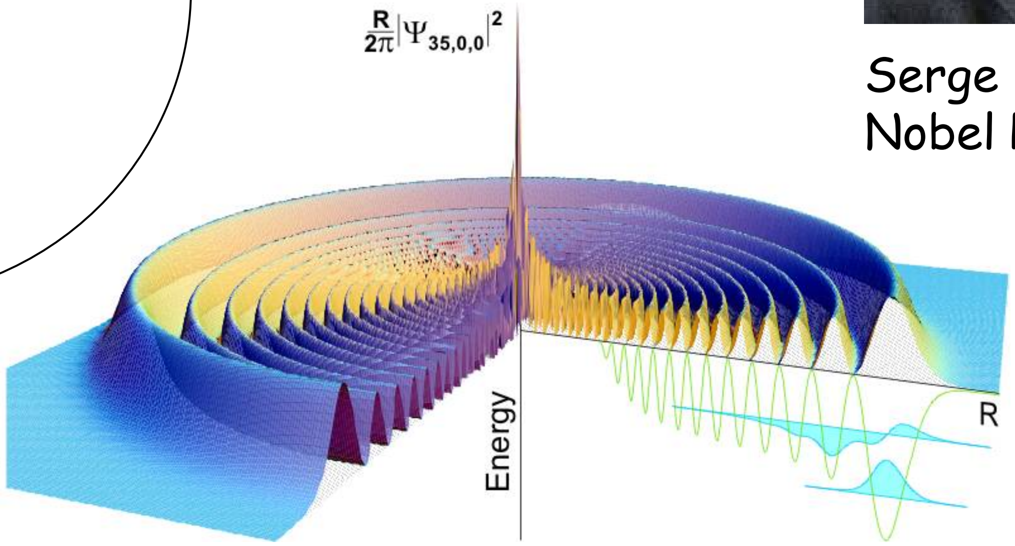
Very highly excited hydrogen-like states

Extremely large size, dipole moment, polarizability

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

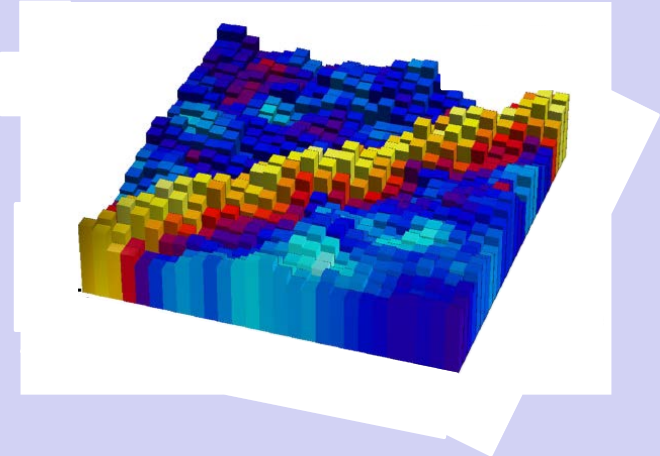


n=35



Serge Haroche,
Nobel Prize 2012

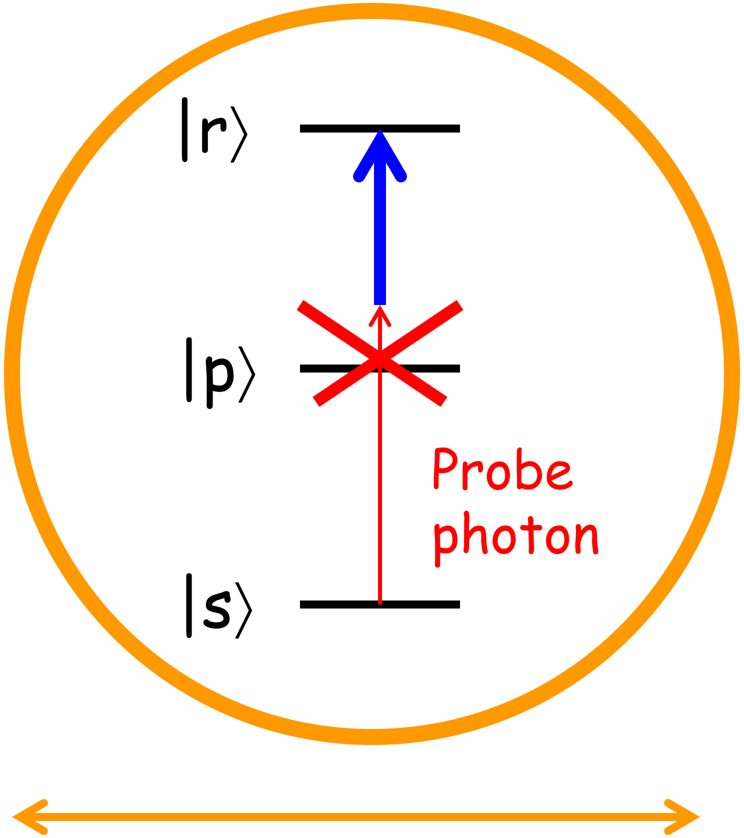
Detuned Rydberg EIT: Bound states of two and three photons



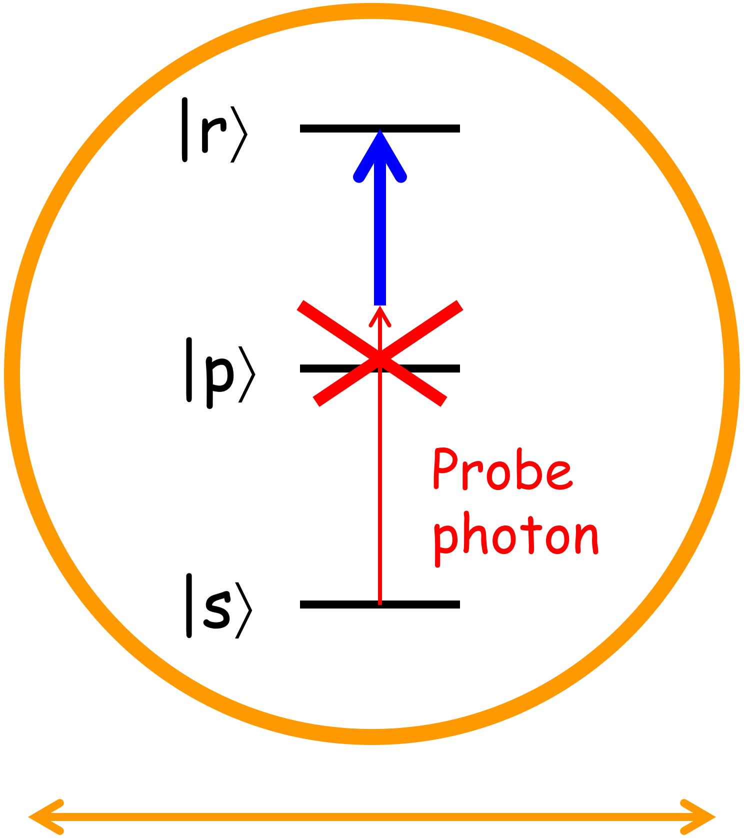
O. Firstenberg, T. Peyronel, Q.-Y. Liang, A.V. Gorshkov, M.D. Lukin, and V. Vuletic, Nature **502**, 71-74 (2013).

Q.-Y. Liang, A.V. Venkatramani, S.H. Cantu,T.L. Nicholson, M.J. Gullans, A.V. Gorshkov, J.D. Thompson, C. Chin, M.D. Lukin, and V. Vuletić, Science 359, 783–786 (2018).

Rydberg EIT off resonance

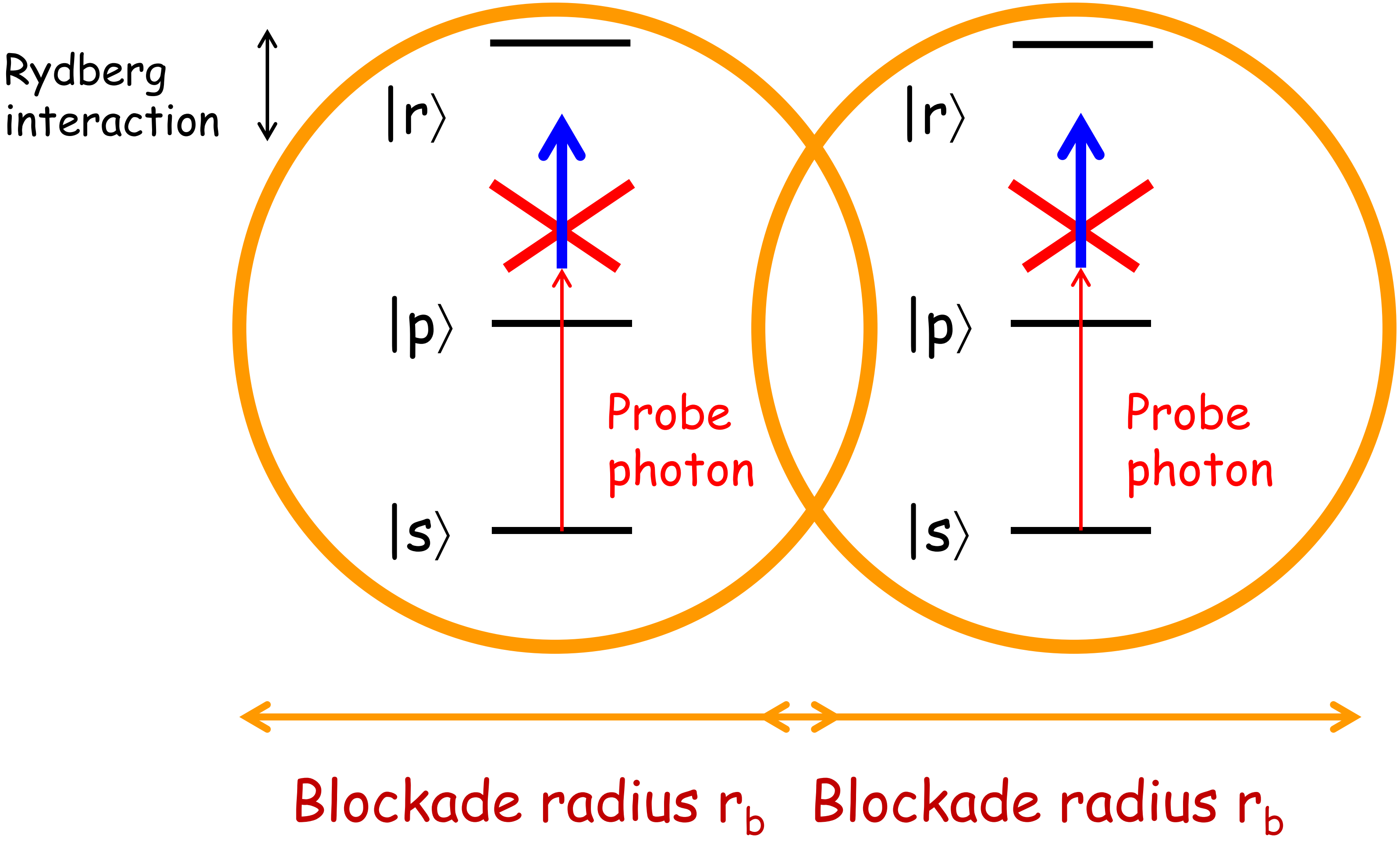


Blockade radius r_b



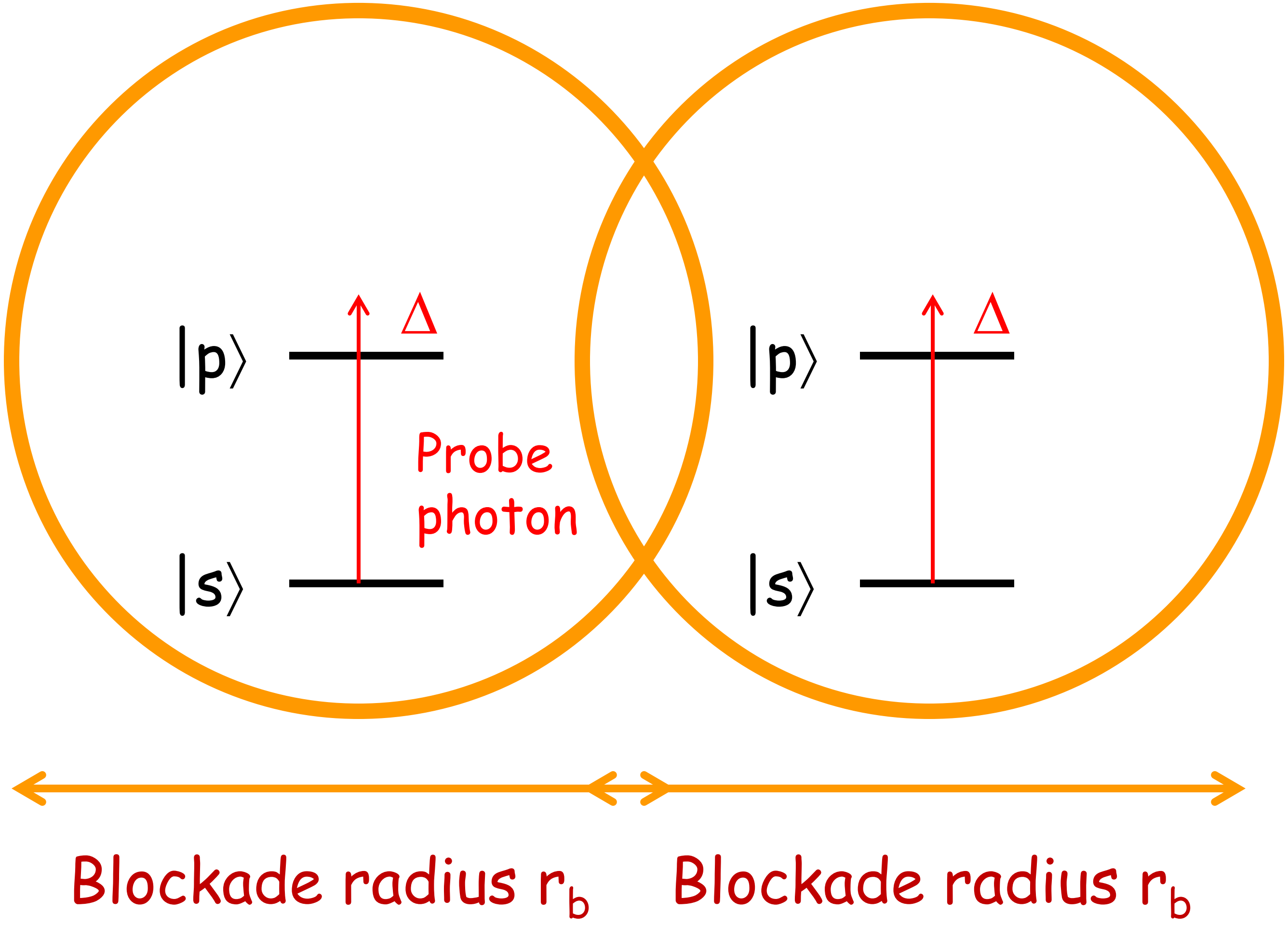
Blockade radius r_b

Rydberg EIT off resonance

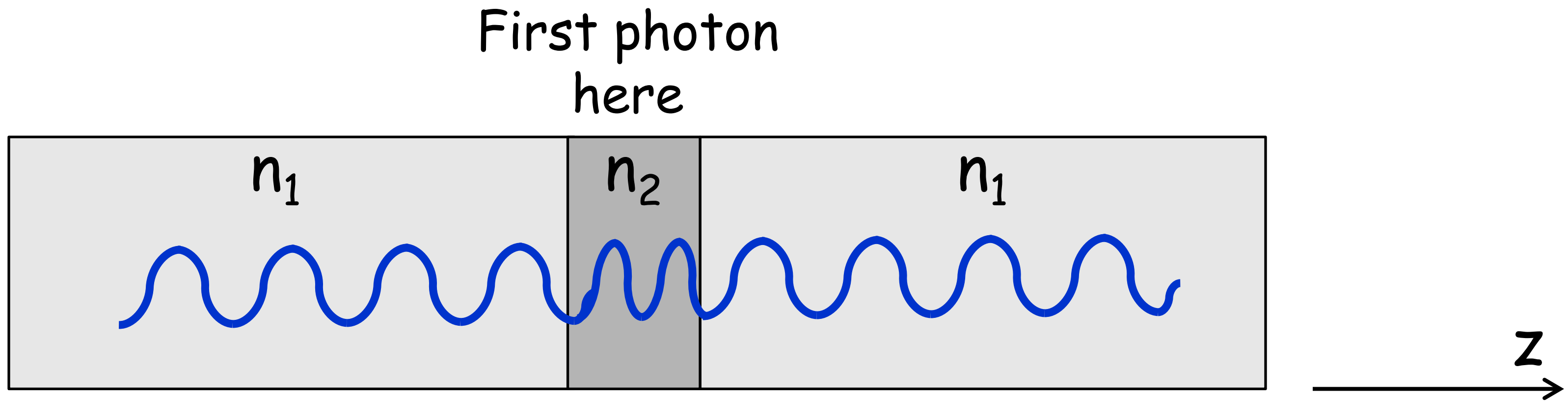


Rydberg EIT off resonance

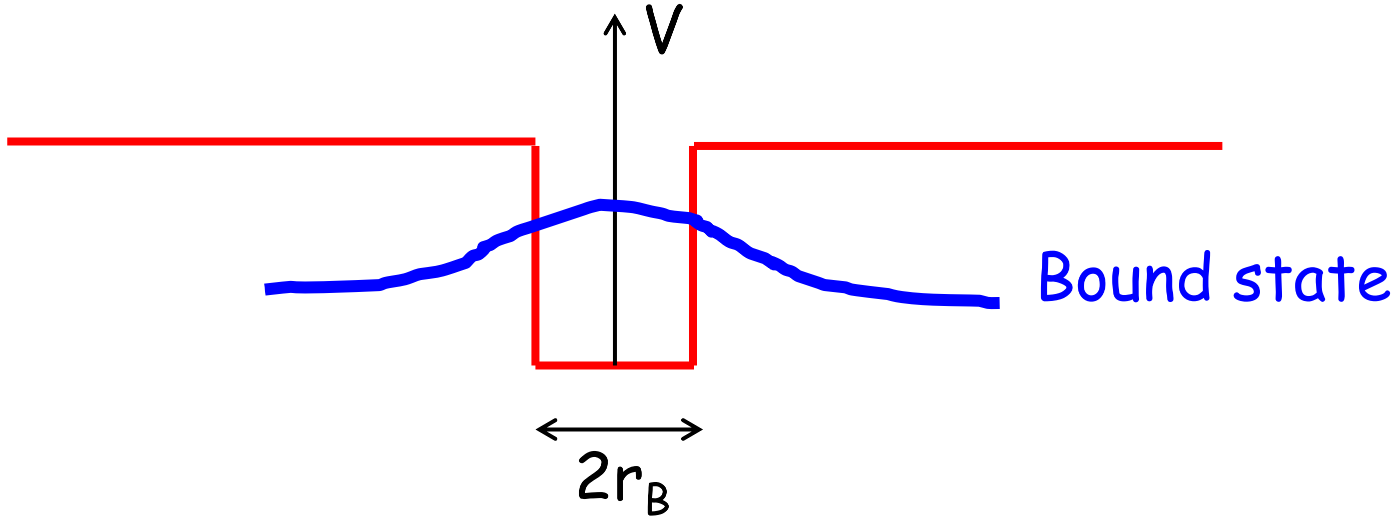
Probe photons experience index of refraction when close



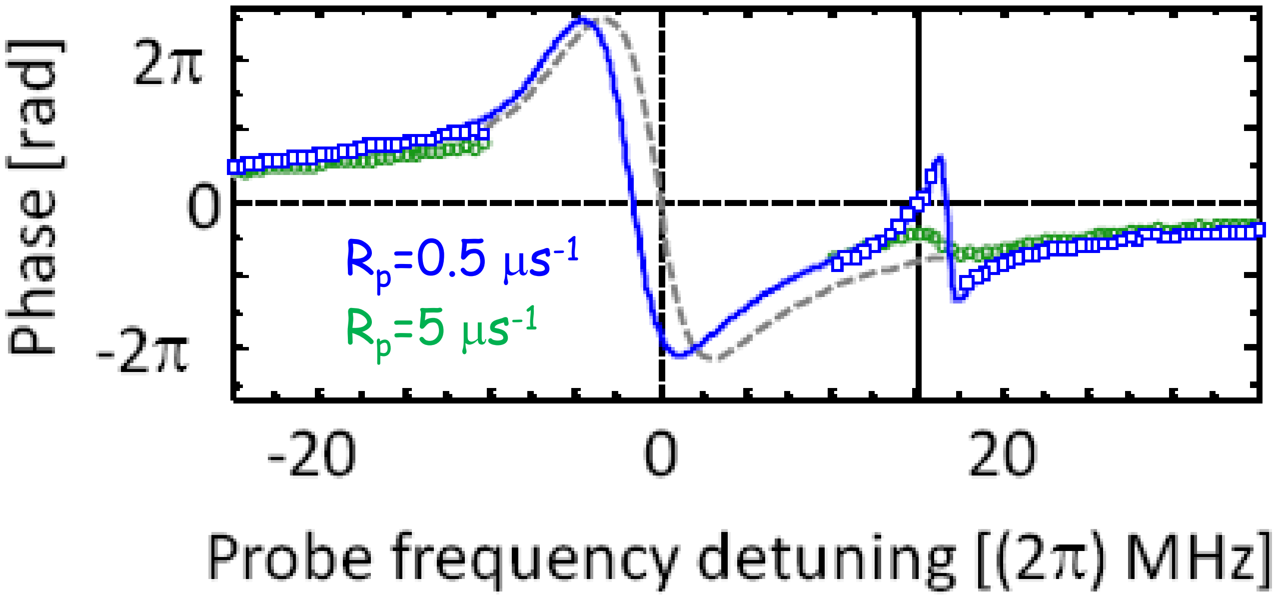
Rydberg blockade as square well potential

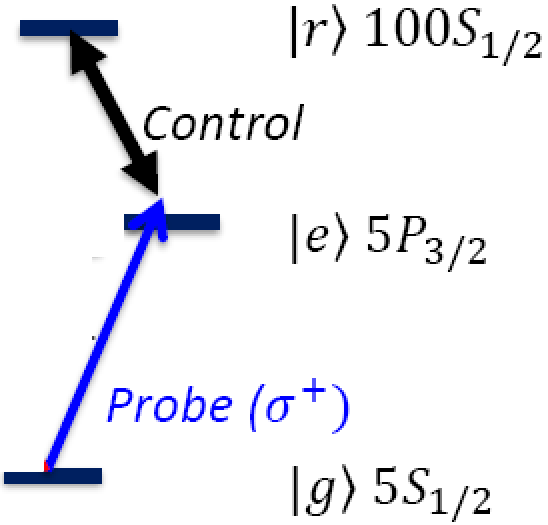


Index of refraction as experienced by 2nd photon



Rydberg induced nonlinear phase shift





No EIT for photons within blockade radius -> light experiences no phase shift outside blockade radius, but non-zero phase shift within blockade radius.

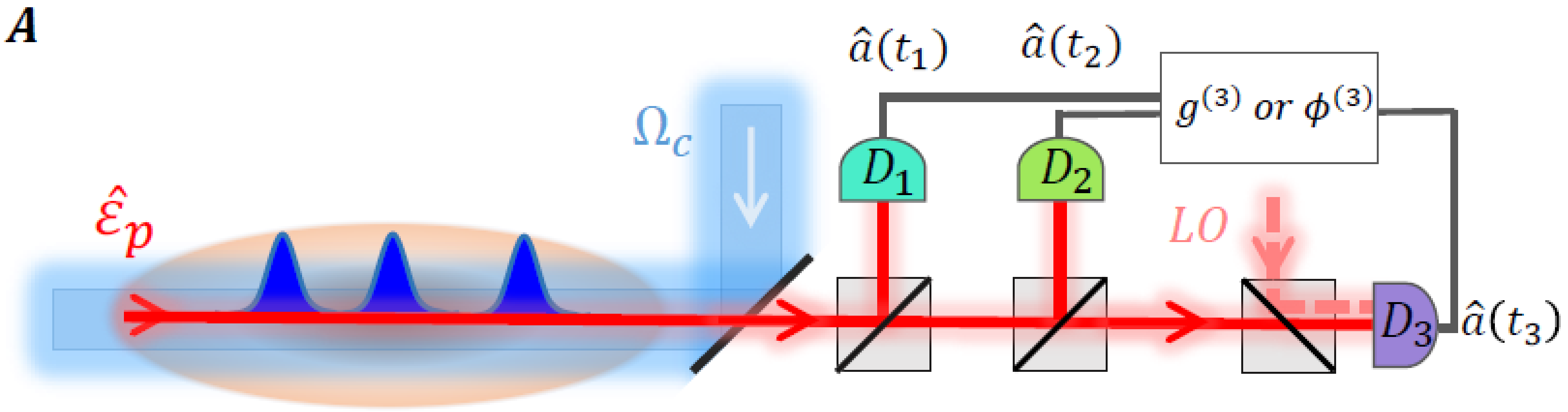
Curvature of dispersion relation:

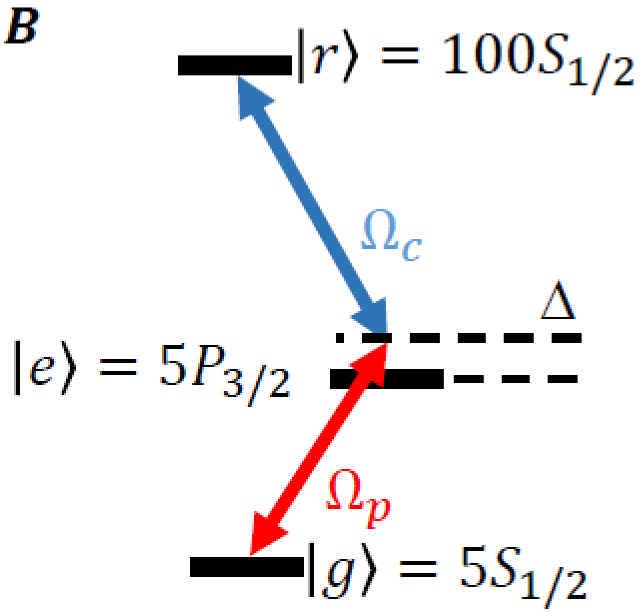
Photons also acquire mass ~1000 $\hbar\omega/c^2$

Typical group velocity v_g = 1000 m/s

Slow, massive photons

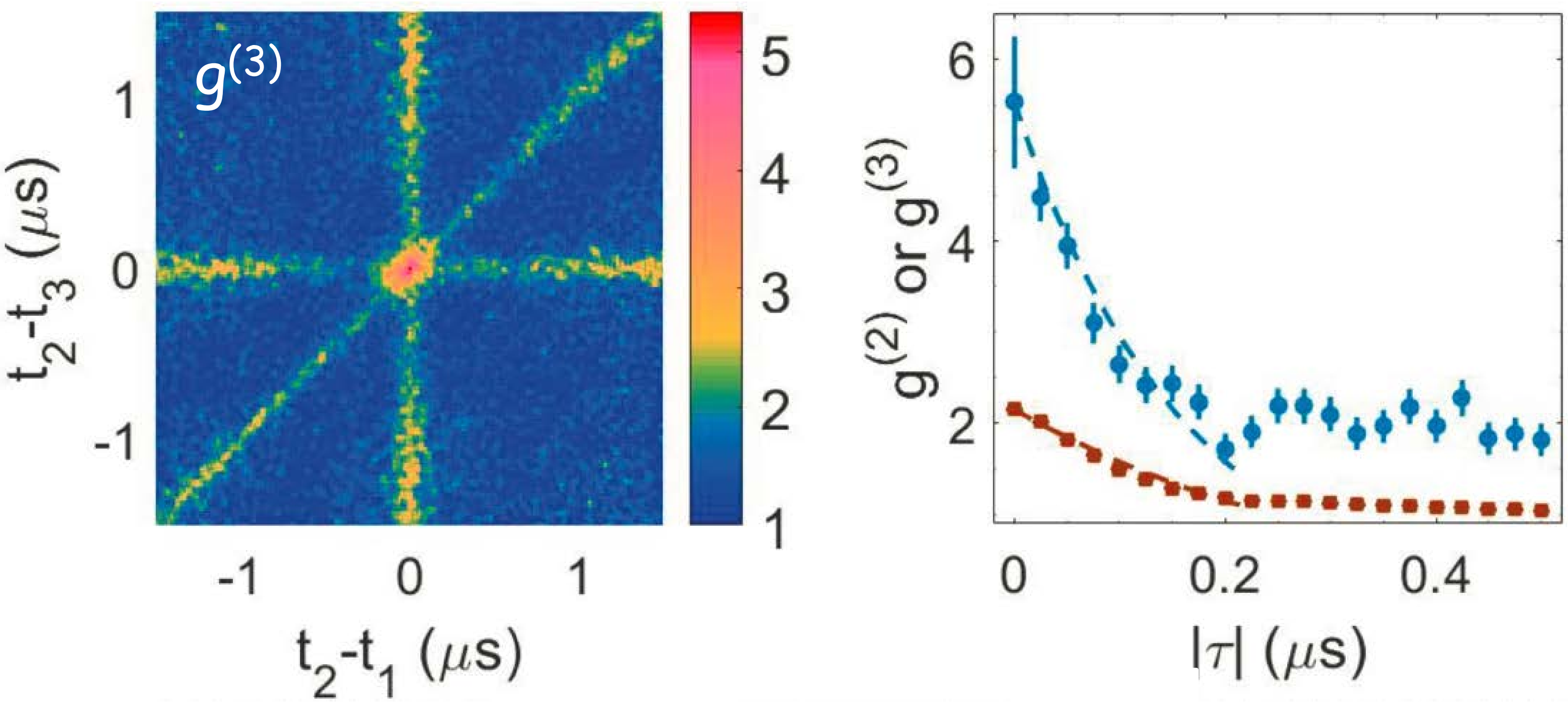
Three-photon correlations - setup





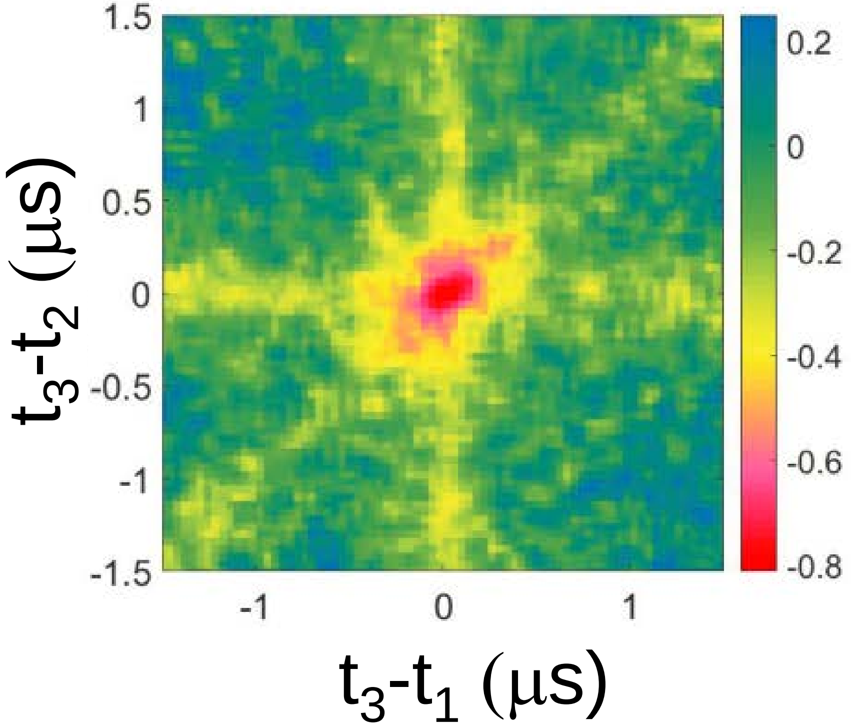
3-photon correlation function or 3- photon phase measurement (phase measurement conditioned on detection of two photons).

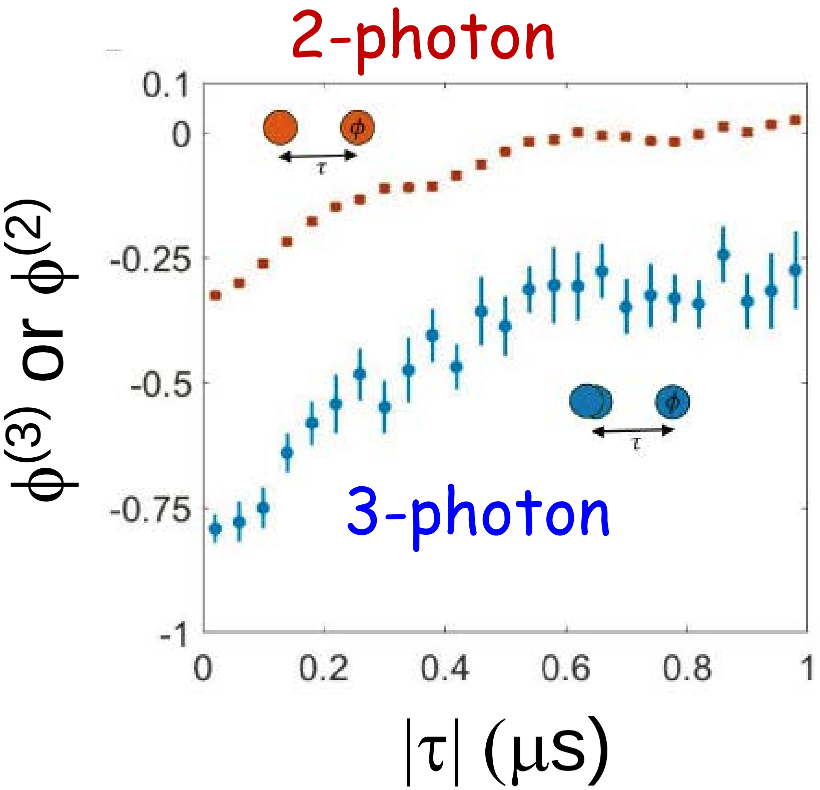
Three-photon correlation measurements



Three-photon wavefunction twice more tightly bound than two-photon wavefunction.

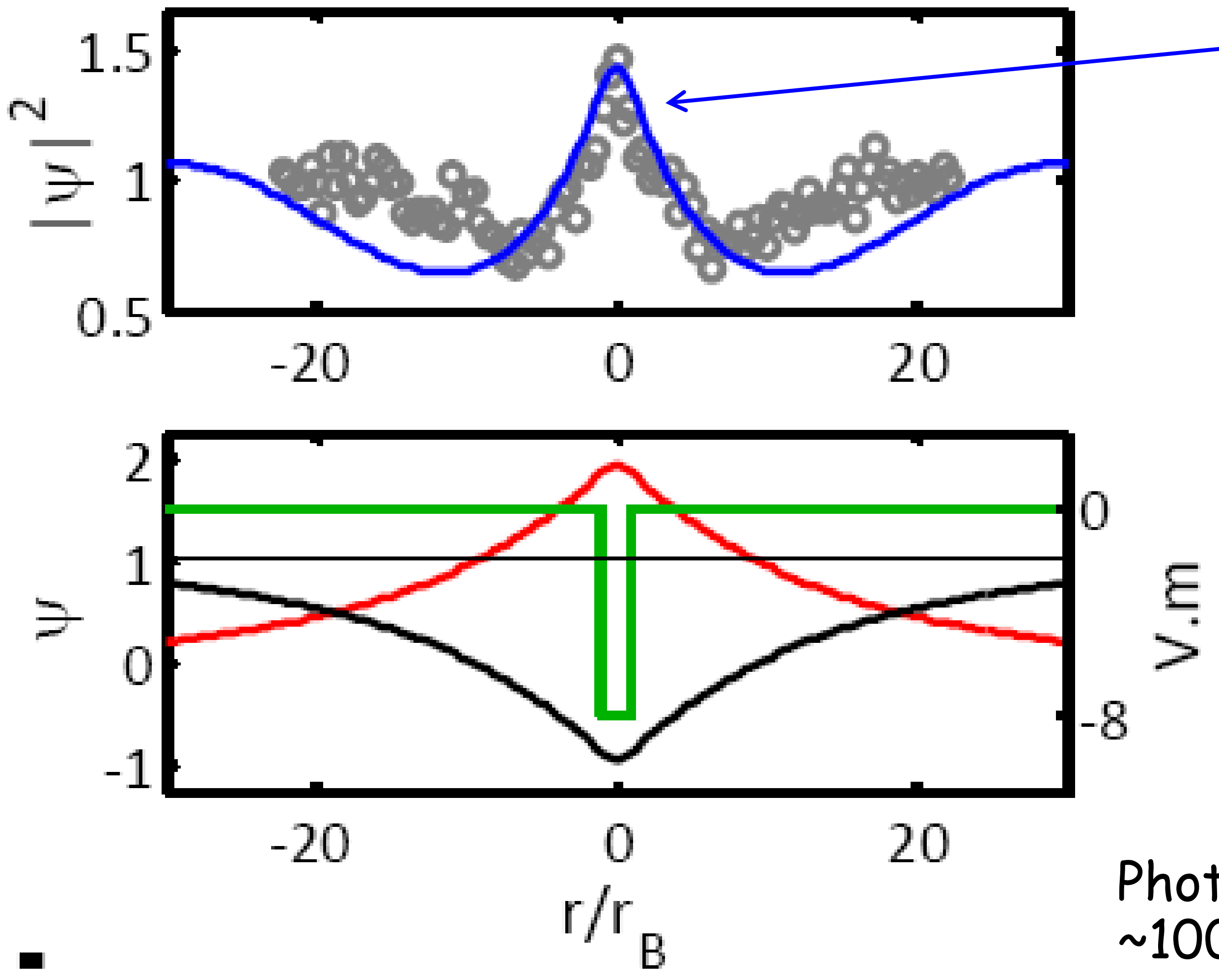
Conditional three-photon phase





Conditional 3-photon phase for two photons detected at time t=0

Two-photon bound state



Two-photon bound state

Experiment

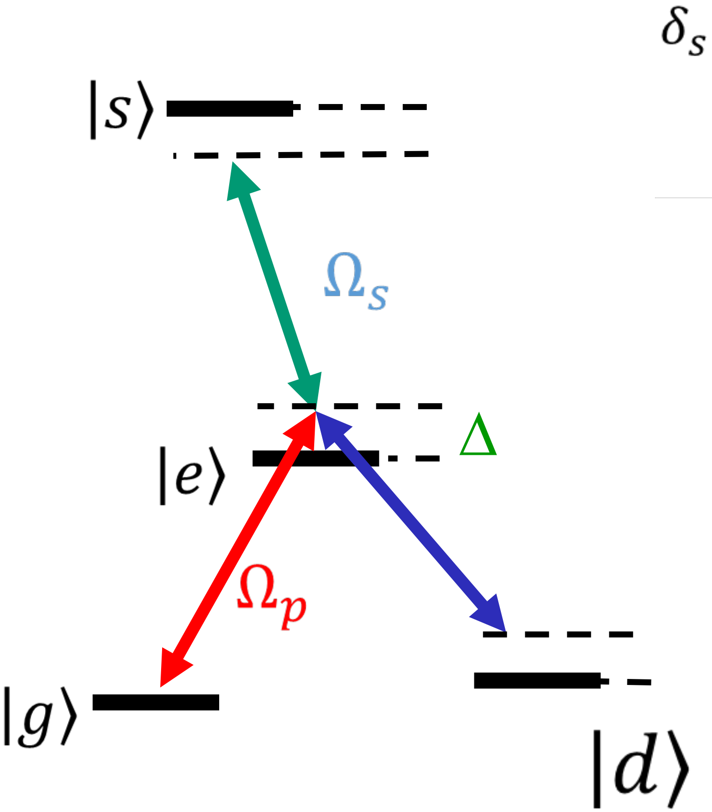
Simple theoretical picture (Schrödinger equation)

Photons also acquire mass ~1000 $\hbar\omega/c^2$ (curvature of dispersion).

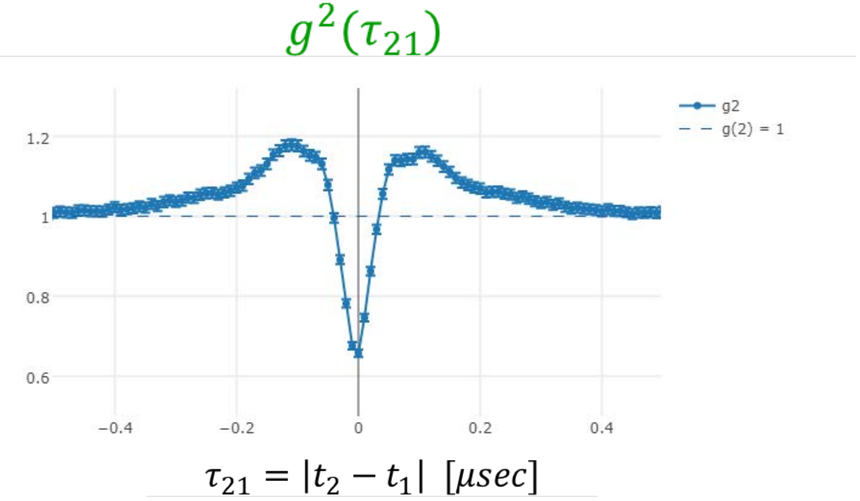
Repulsive interactions?

- Switching the sign of one-photon detuning switches the sign of Rydberg interaction, but also the sign of the mass:
- We can have $V<0$ and $m>0$ or $V>0$ and $m<0$, both map onto attraction for positive mass.
- Adding a second EIT process gives more free parameters to tune interaction and mass separately.
- Second EIT can be non-interacting, ground-state EIT.

Double EIT for repulsive interactions



Repulsive interactions

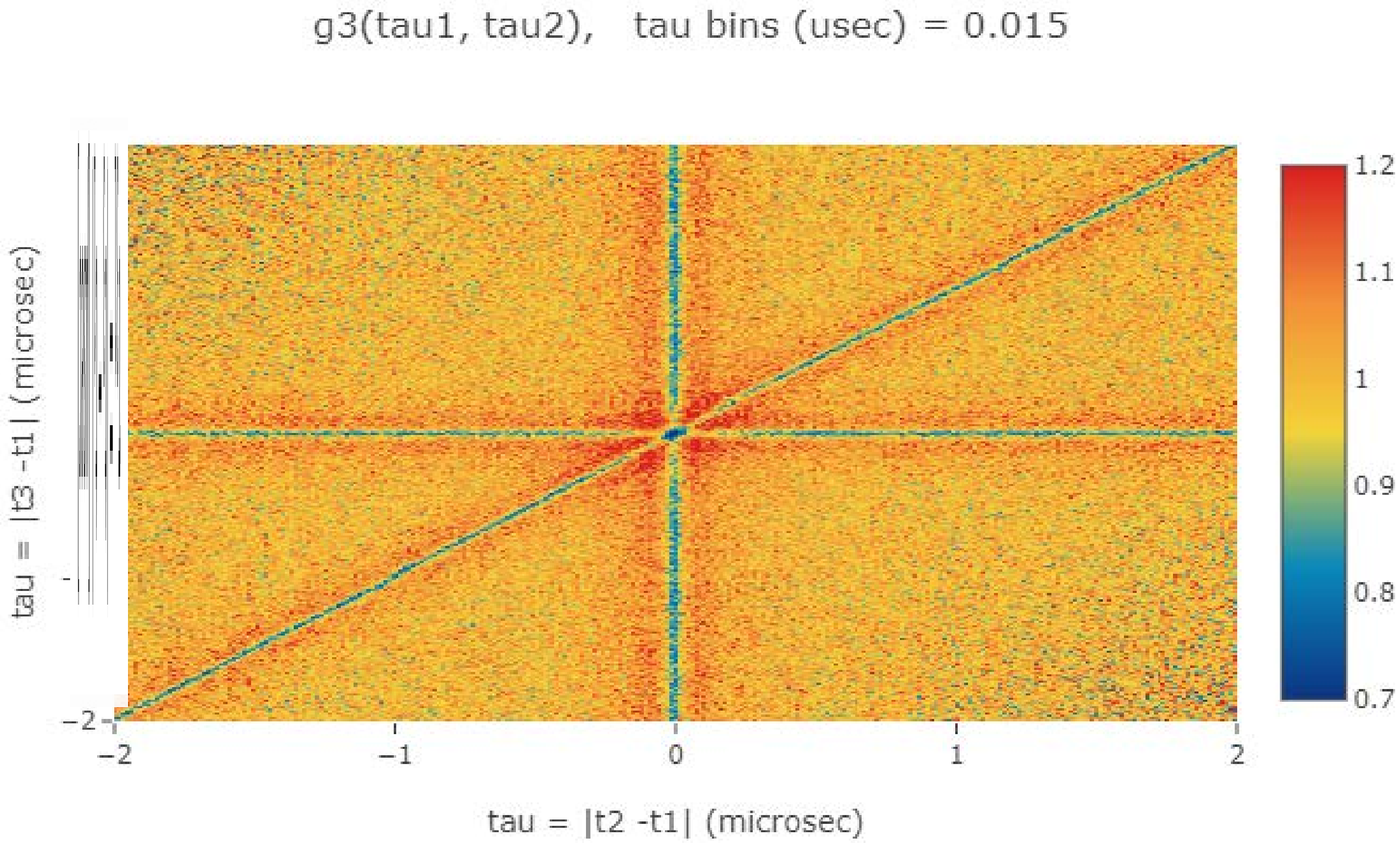


δ_d

Additional coupling to other hyperfine ground state yields independent control of photon interaction and mass.

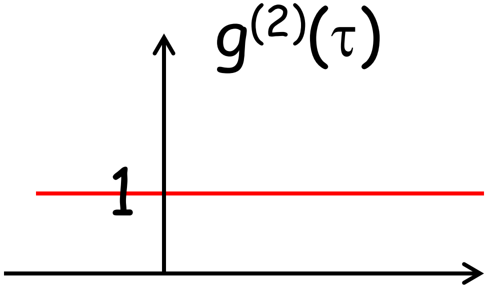
Two- and three-photon repulsive interactions

$$g^3(\tau_{31},\tau_{21})$$



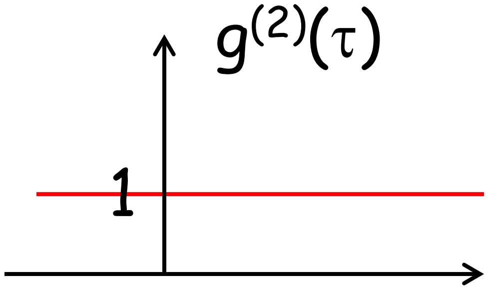
$$\tau_{21} = |t_2 - t_1| \ [\mu sec]$$

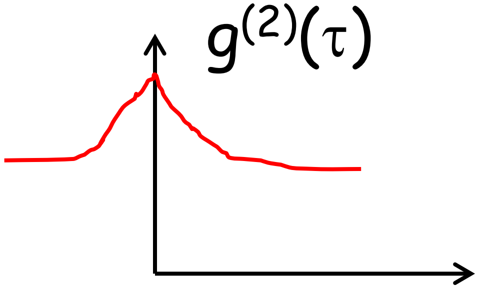
Photon bound state - disclaimer

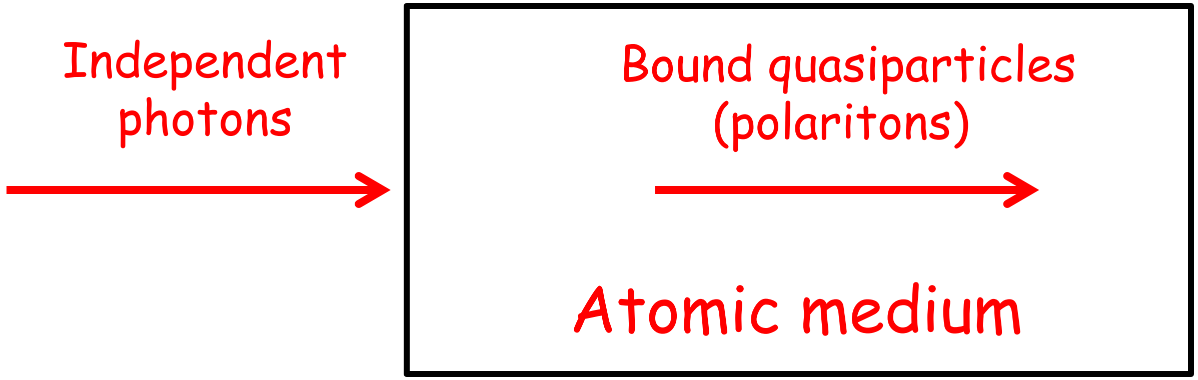


Independent photons

Photon bound state - disclaimer







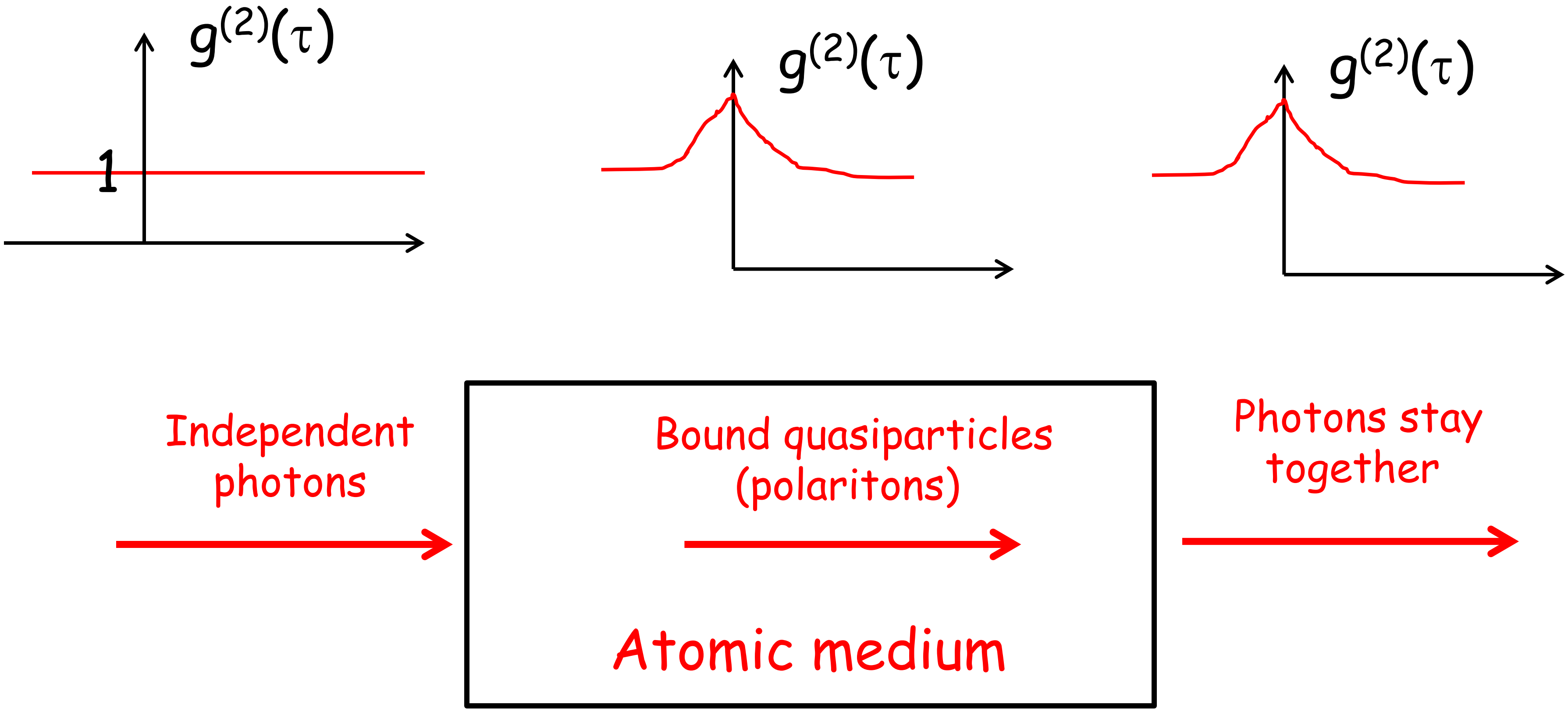
Independent photons

Bound quasiparticles (polaritons)

Atomic medium

Slow polaritons with mass, forces acting

Photon bound state - disclaimer



Independent photons

Bound quasiparticles (polaritons)

Atomic medium

Photons stay together

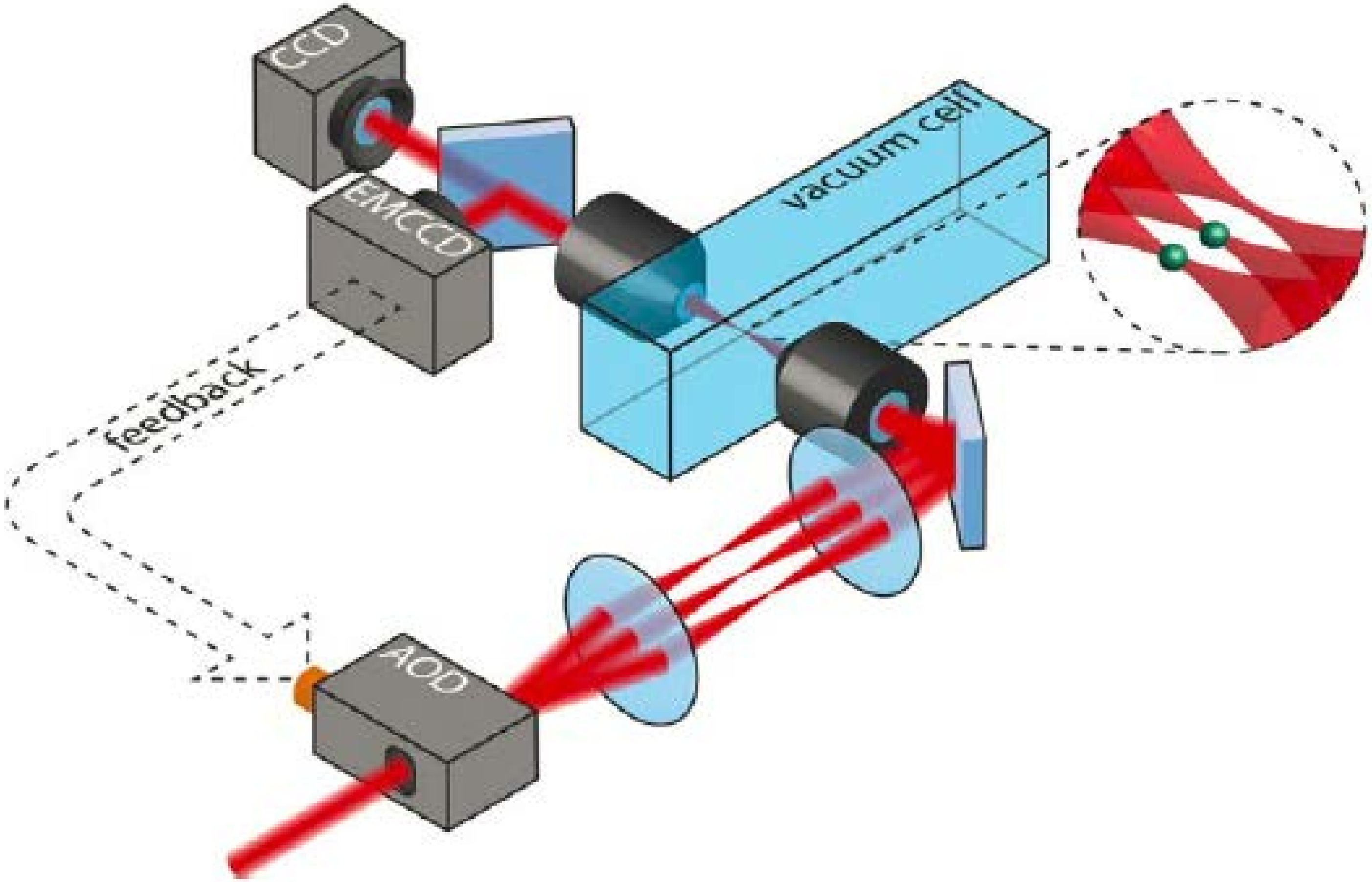
Slow polaritons with mass, forces acting

No dispersion

51-atom quantum simulator

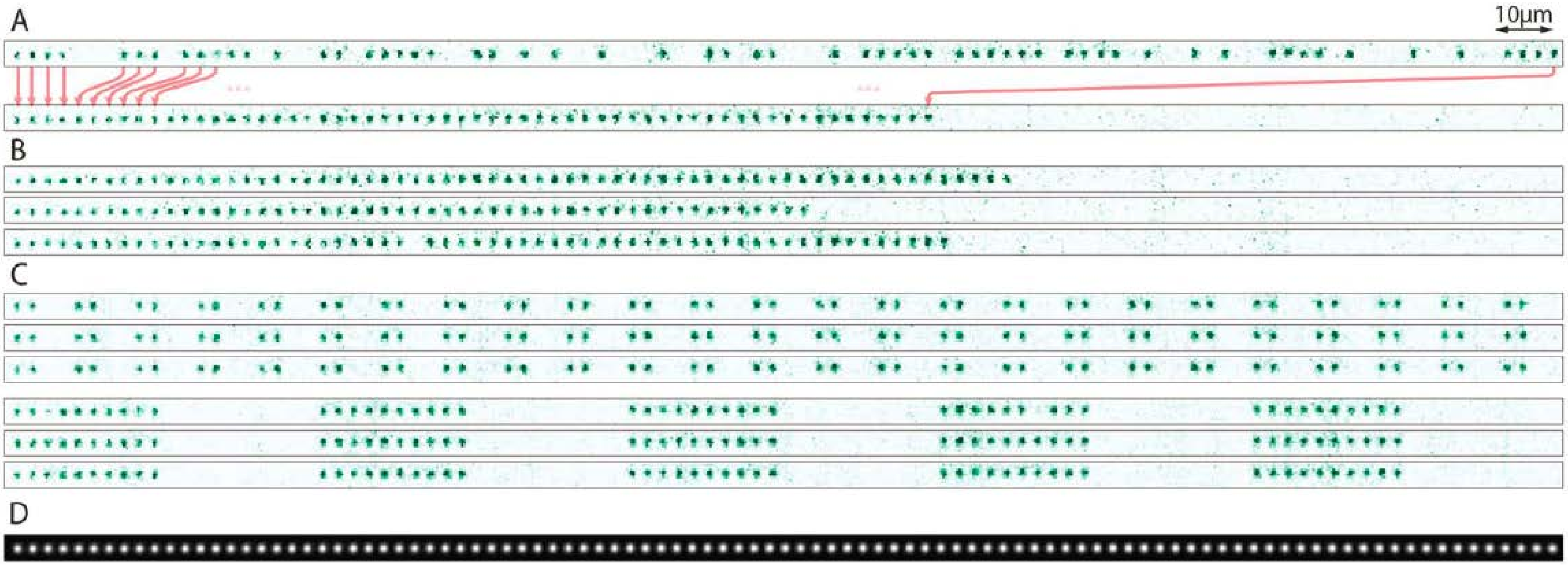
In collaboration with Mikhail Lukin and Markus Greiner (Harvard)

Array of individually trapped atoms



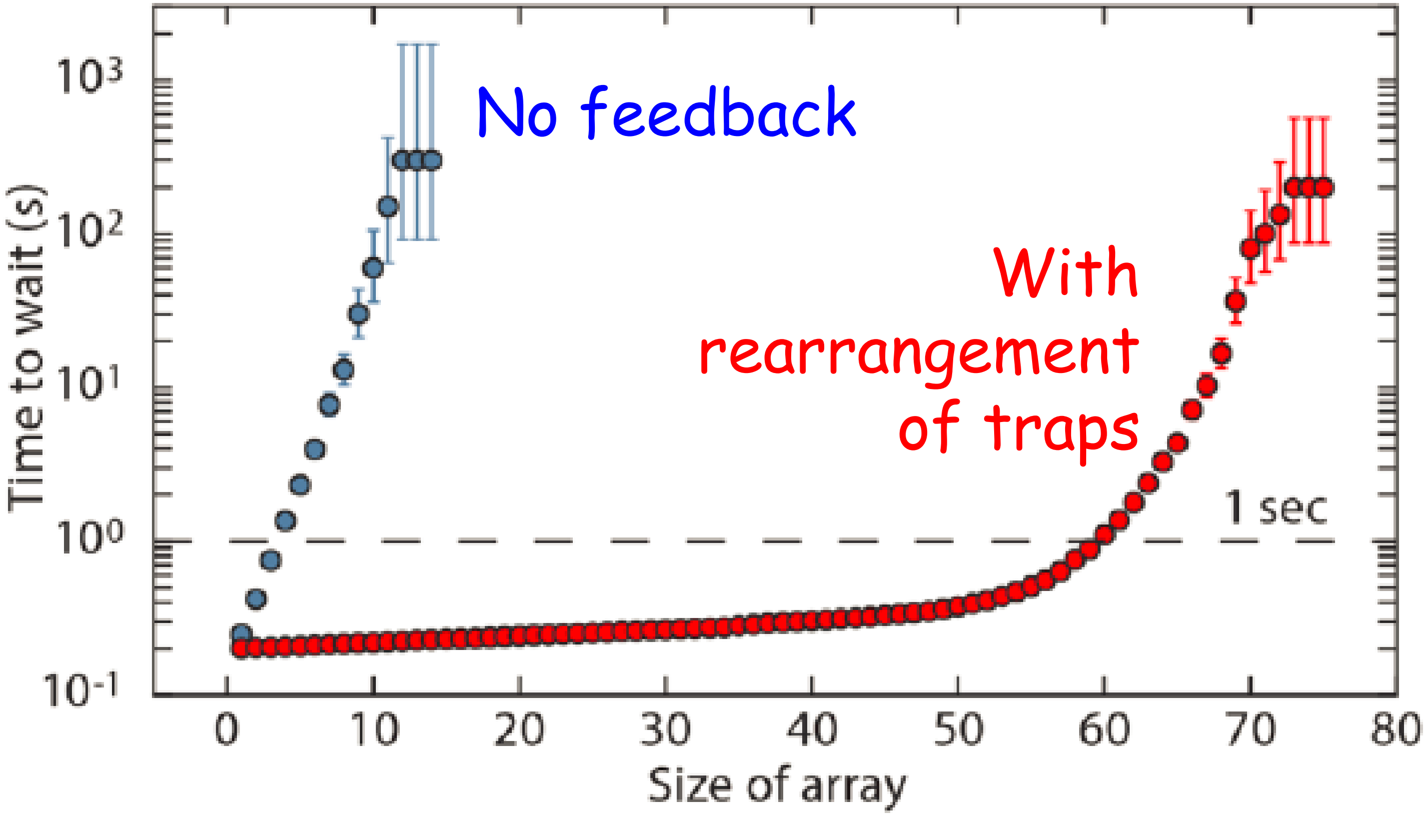
Problem: each trap is only loaded with ~50% probability

Trapped atoms in different configurations



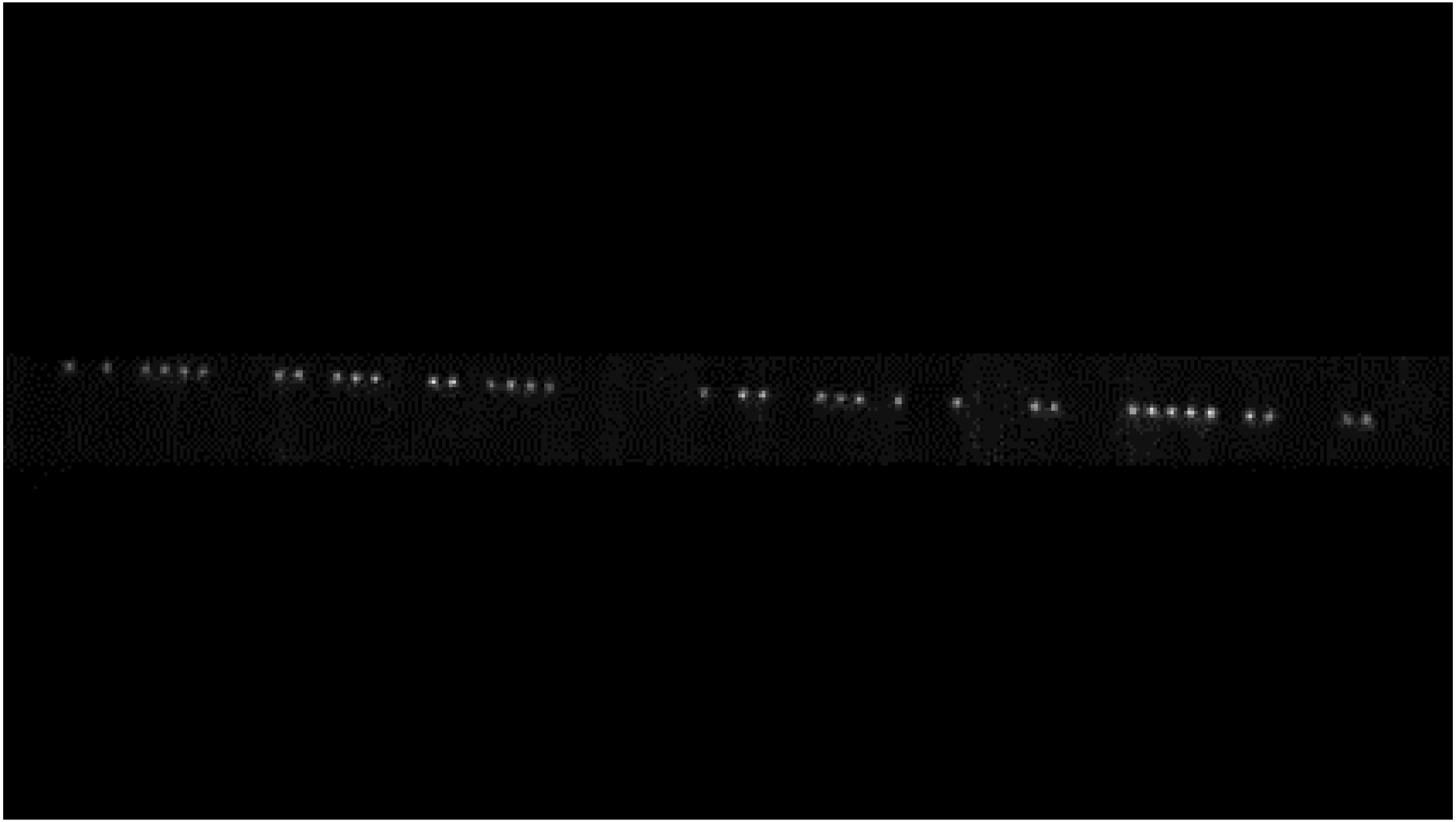
Green color: real images of individual atoms

Feeback (rearrangement) is crucial



Individual atoms in reconfigurable traps

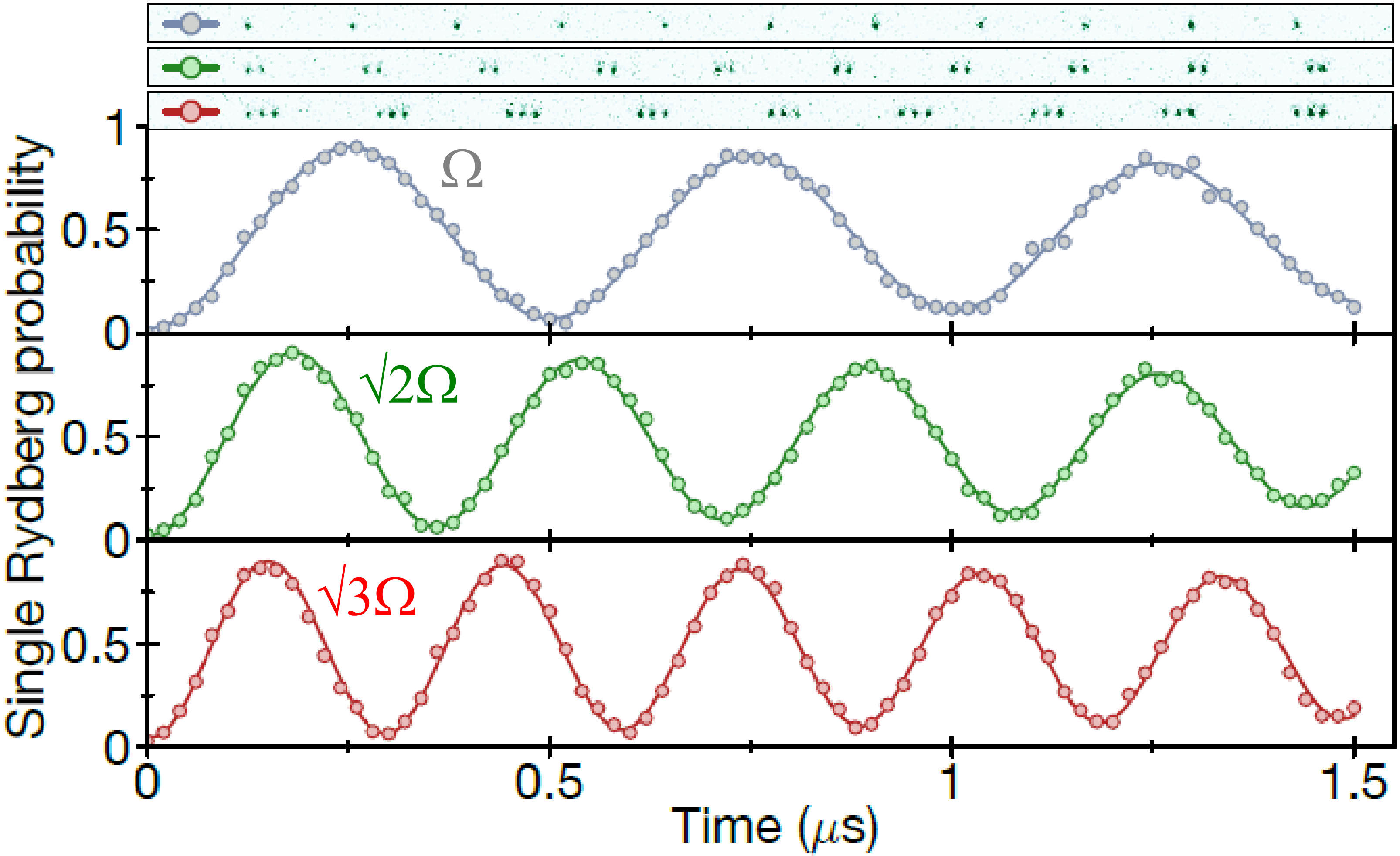
Greiner – Lukin – Vuletic collaboration



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).

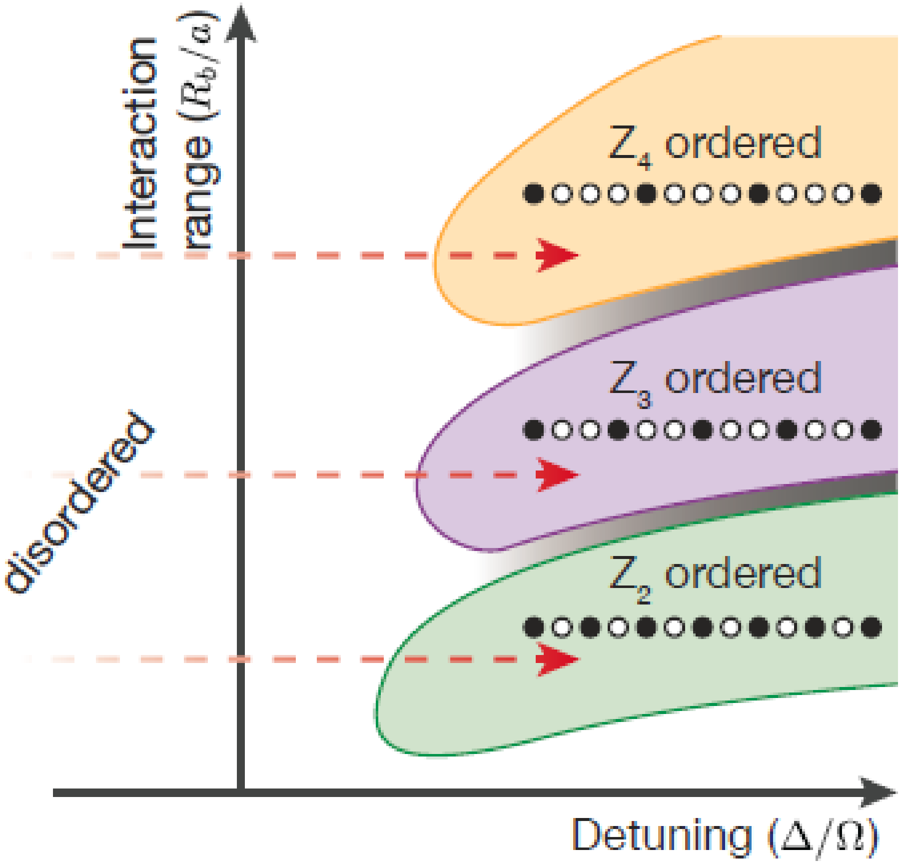
Collective Rabi flopping under Rydberg blockade

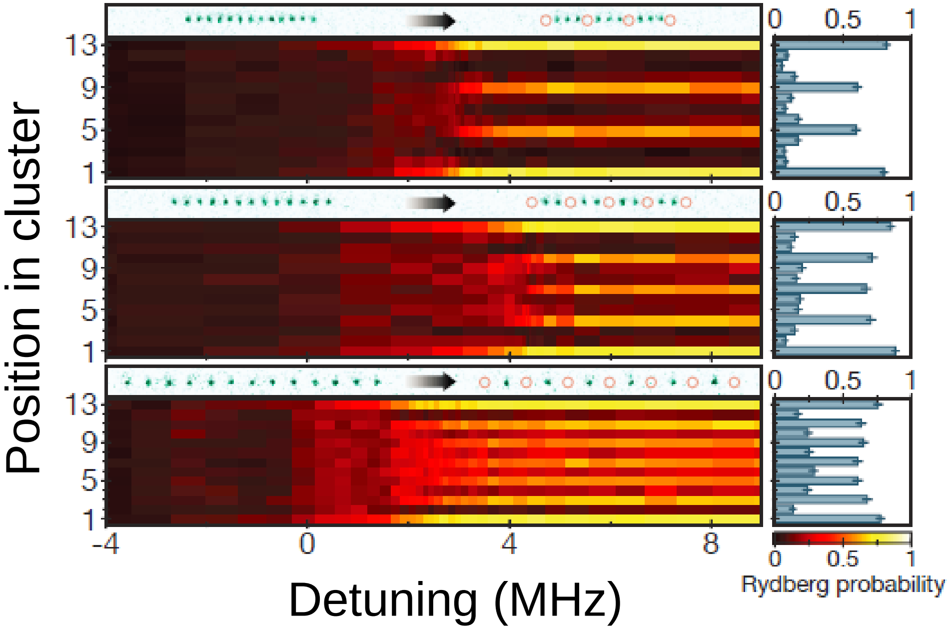
Small trap separation d=2.9 μm « blockade radius r_b



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

Different ordered phases

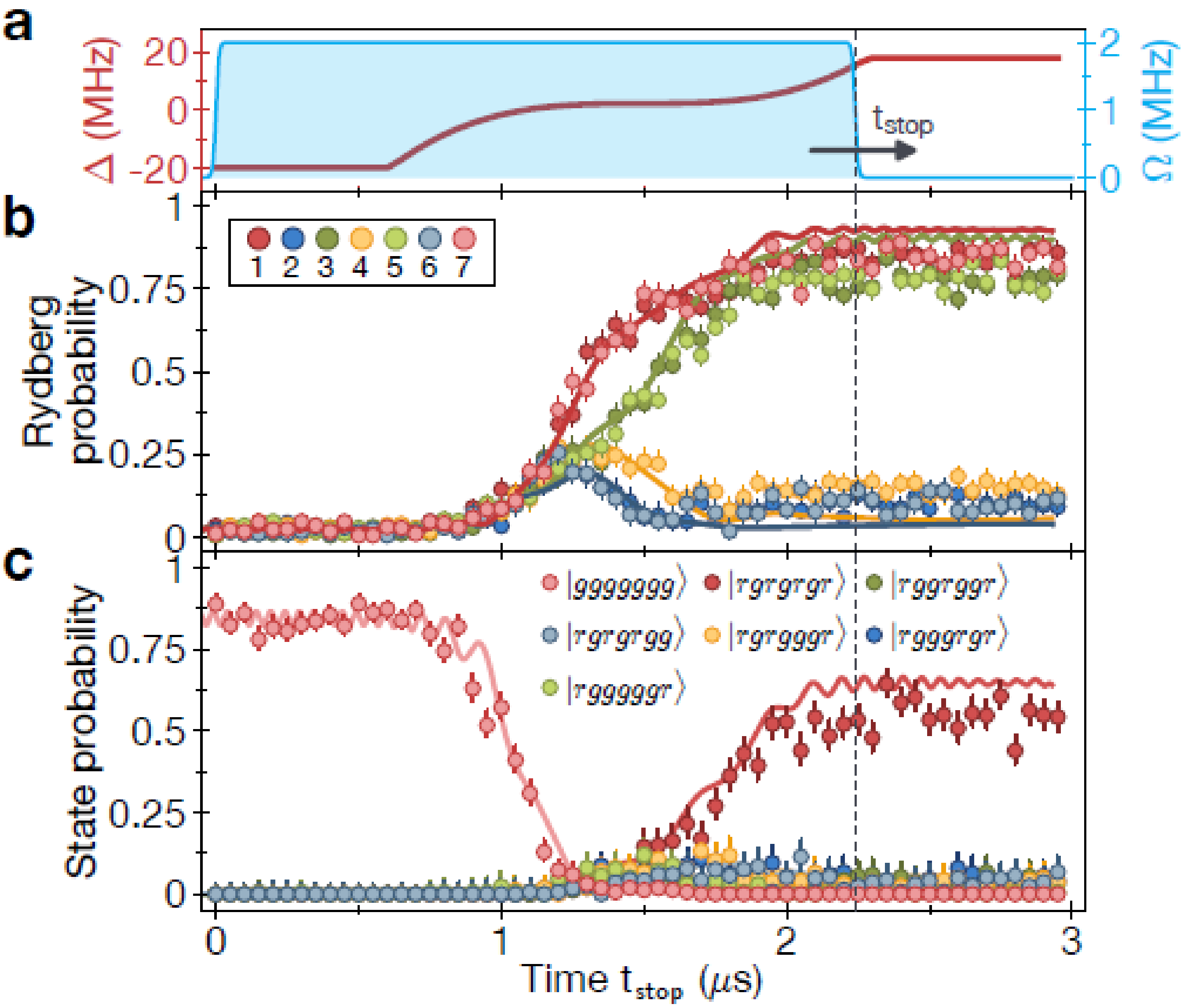




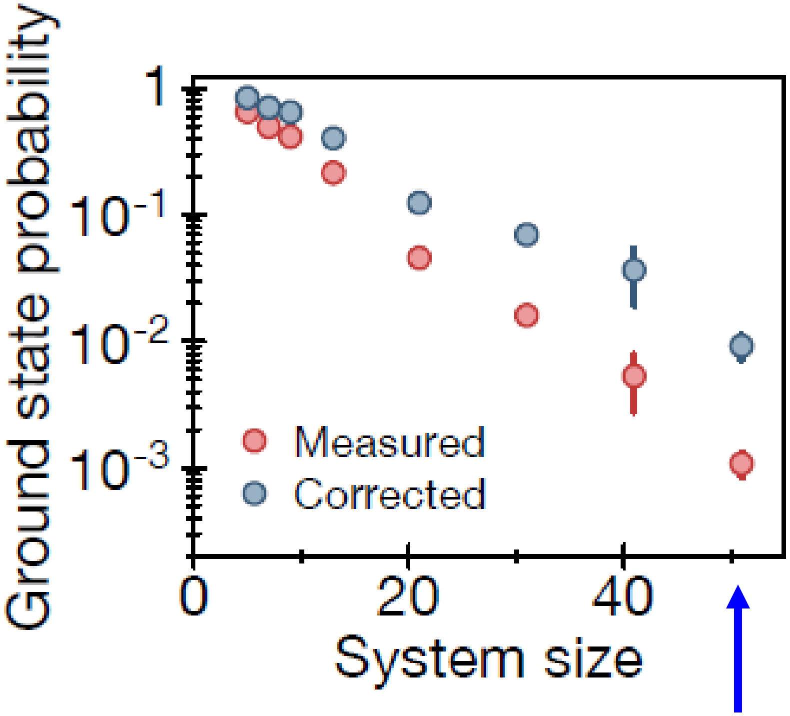
Order of ground state depends on trap distance relative to blockade radius

Adiabatic ramp across phase transition

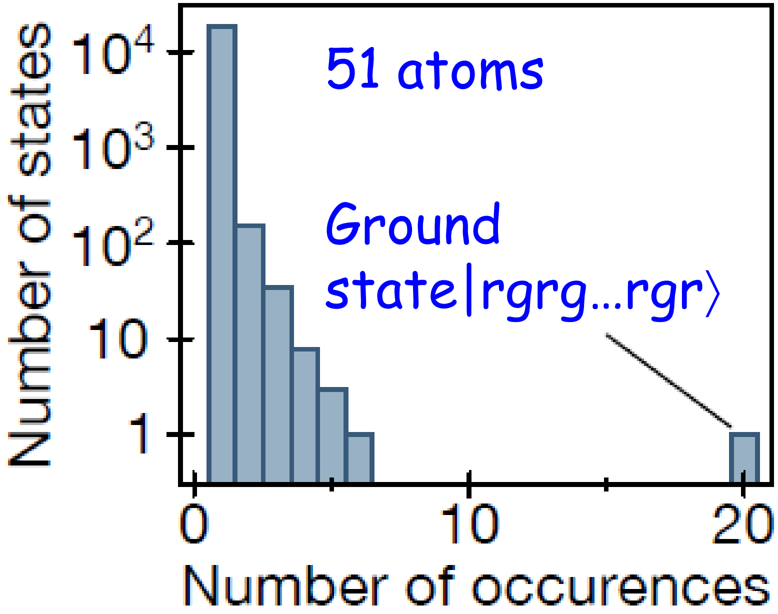
$|ggg\ldots g\rangle$ $|rgrg\ldots rgr\rangle$



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



~ 10^{15} states

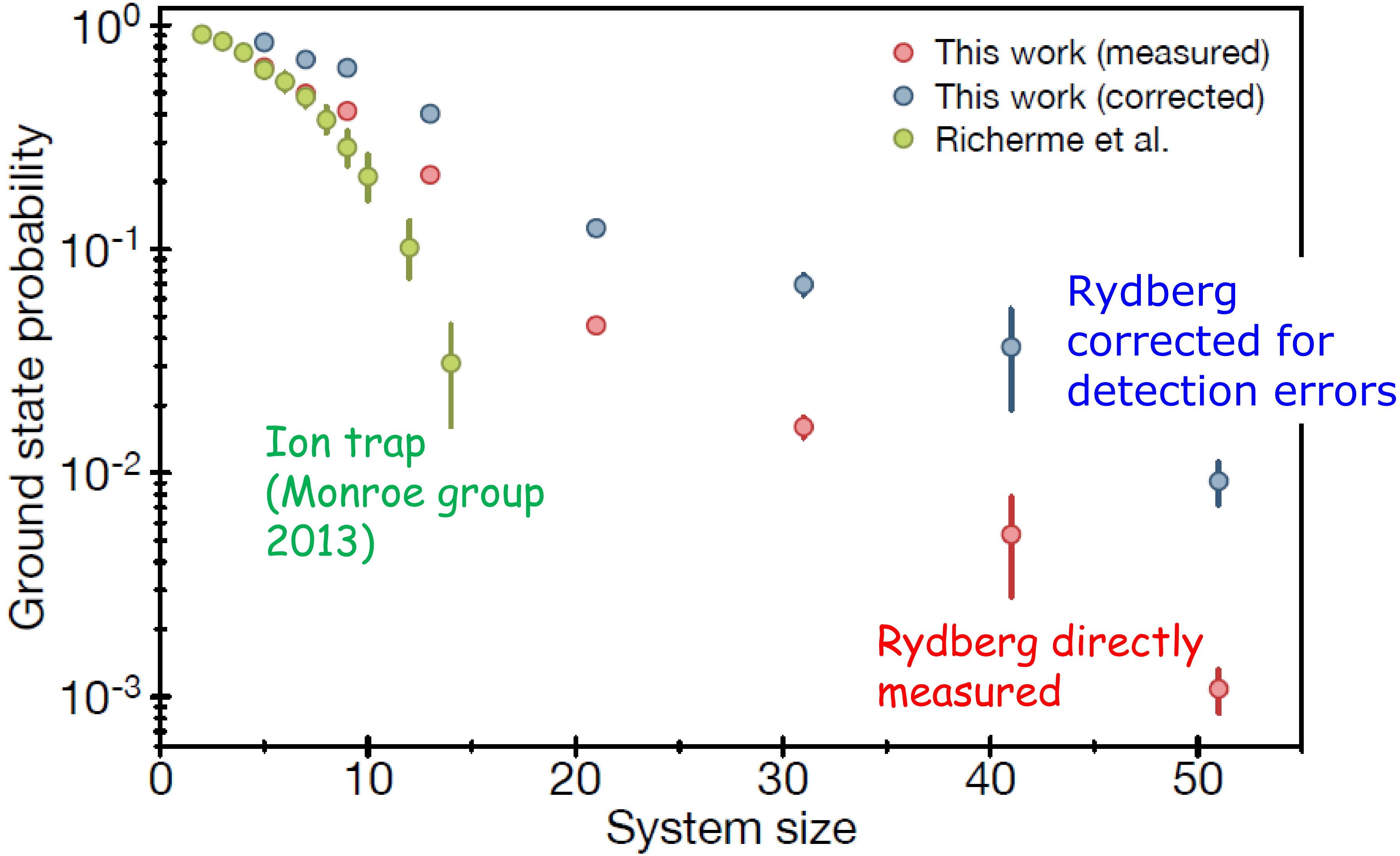


51 atoms

Ground state$|rgrg…rgr\rangle$

Ground state reached much more often than any other state.

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

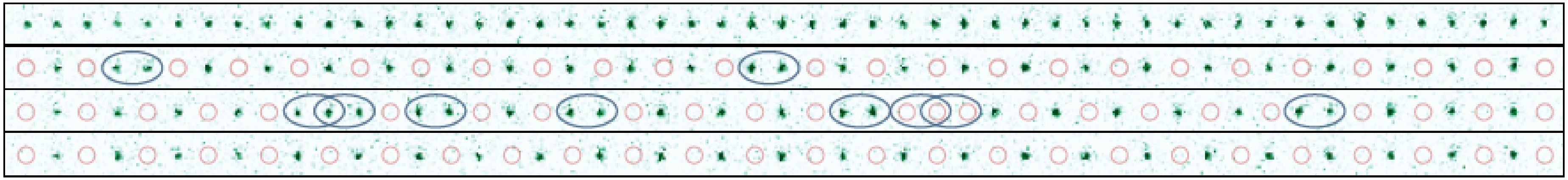


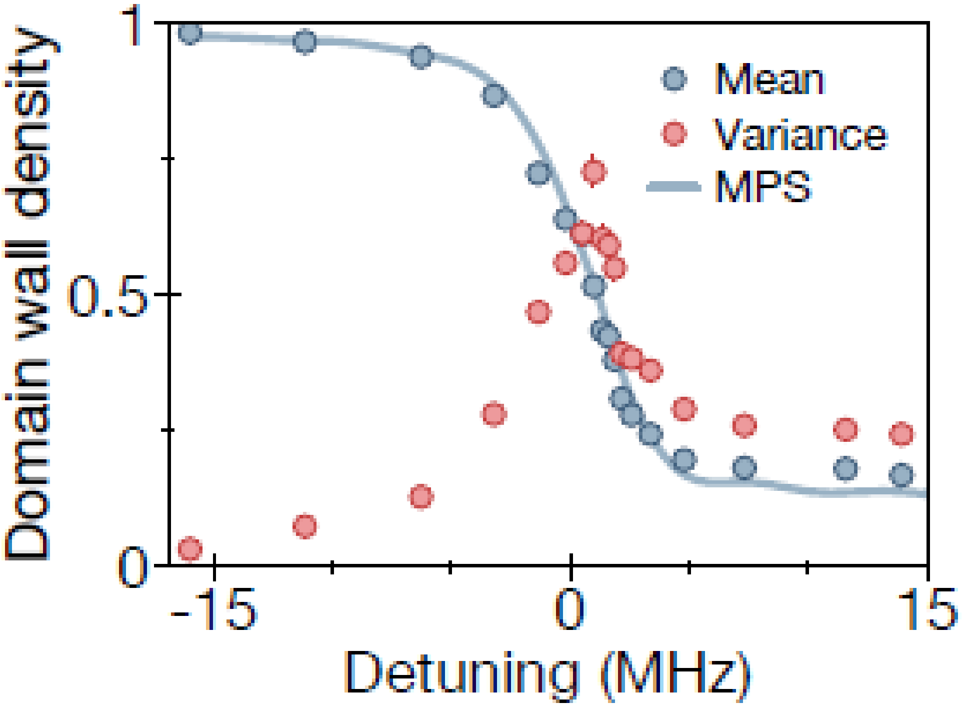
Rydberg corrected for detection errors

Ion trap (Monroe group 2013)

Rydberg directly measured

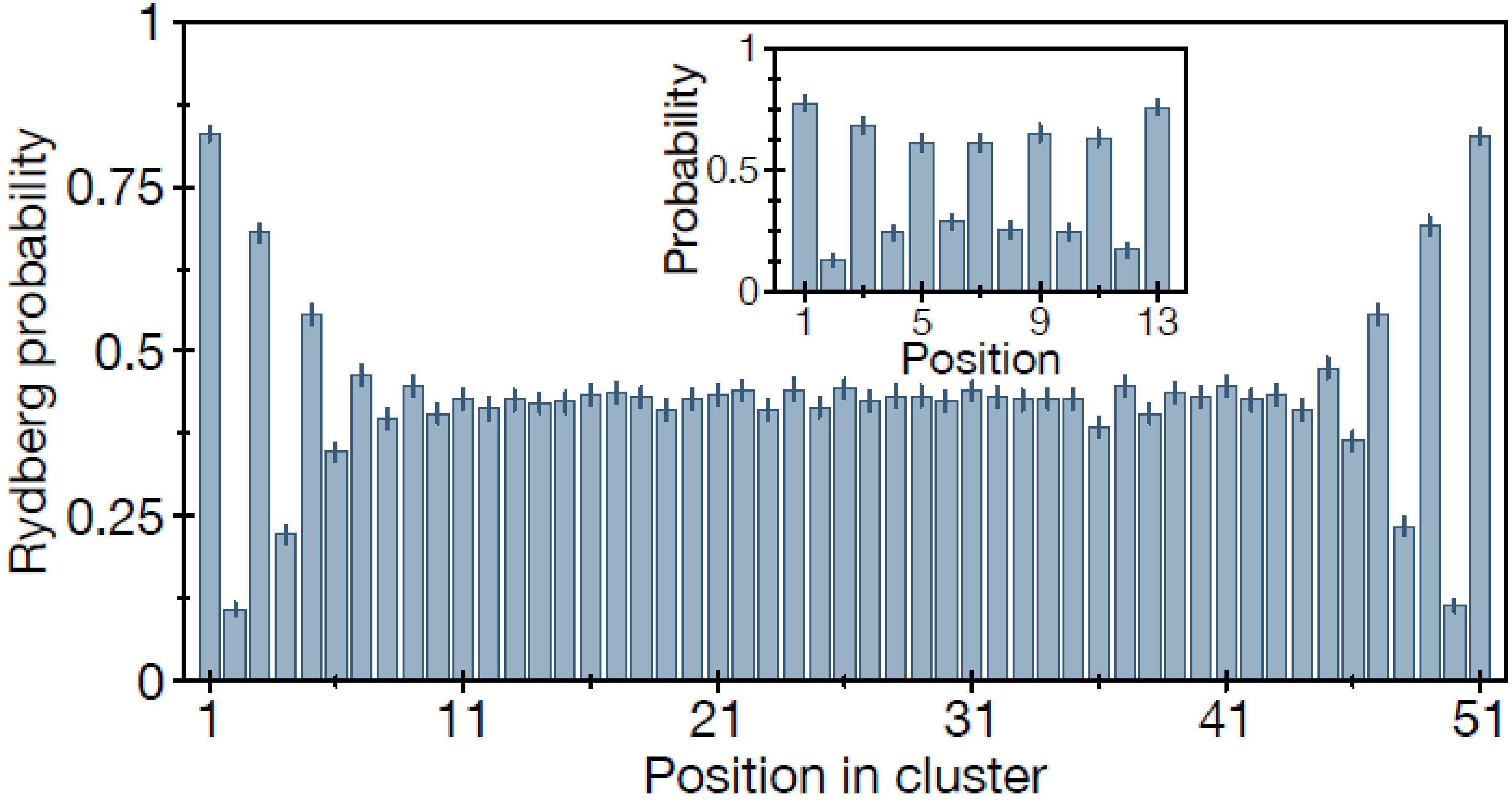
Crystal preparation at finite speed



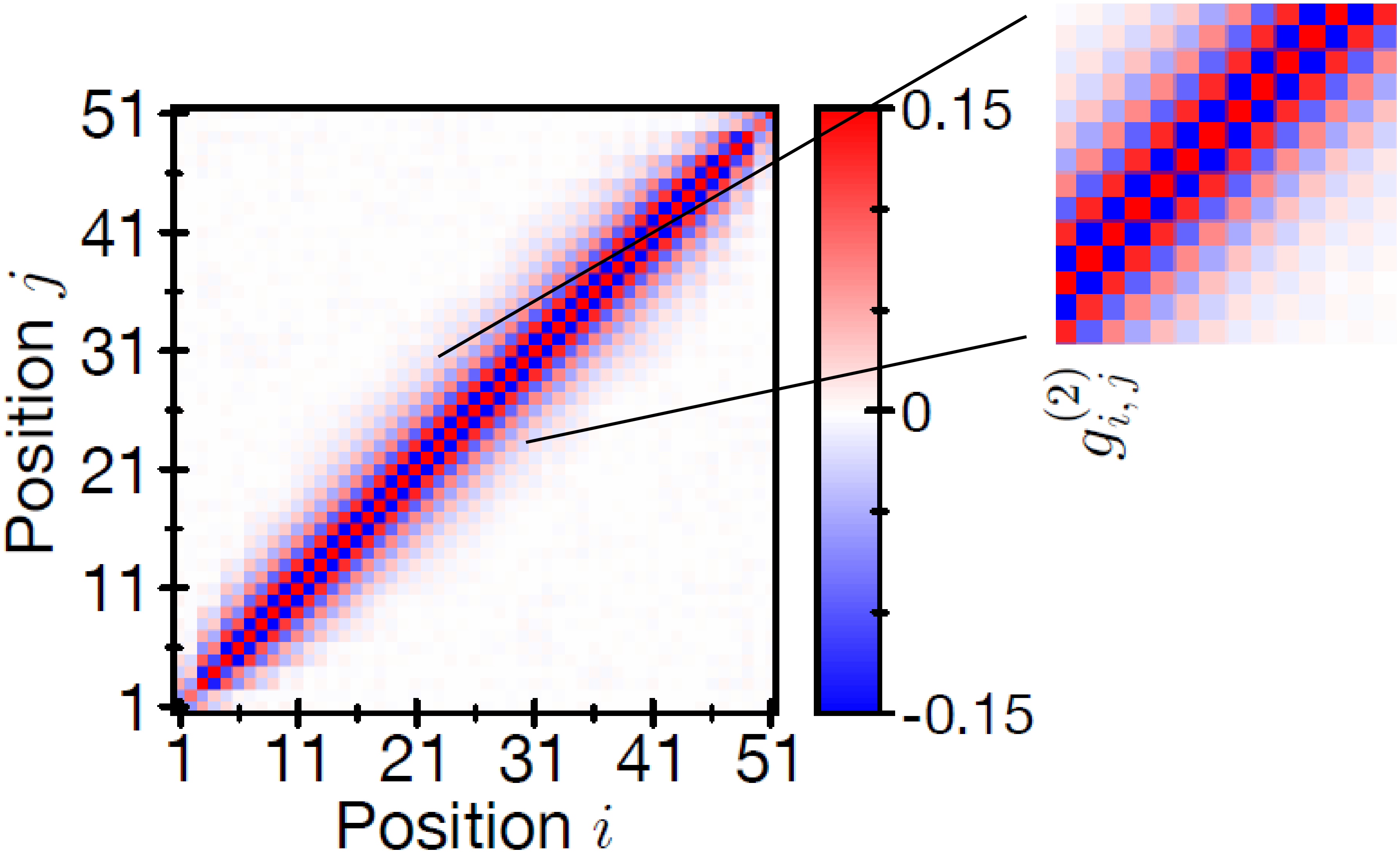


The crystal is not perfect, but contains domain walls, due to finite preparation speed, or imperfect state detection.

Small systems dominated by edge effects

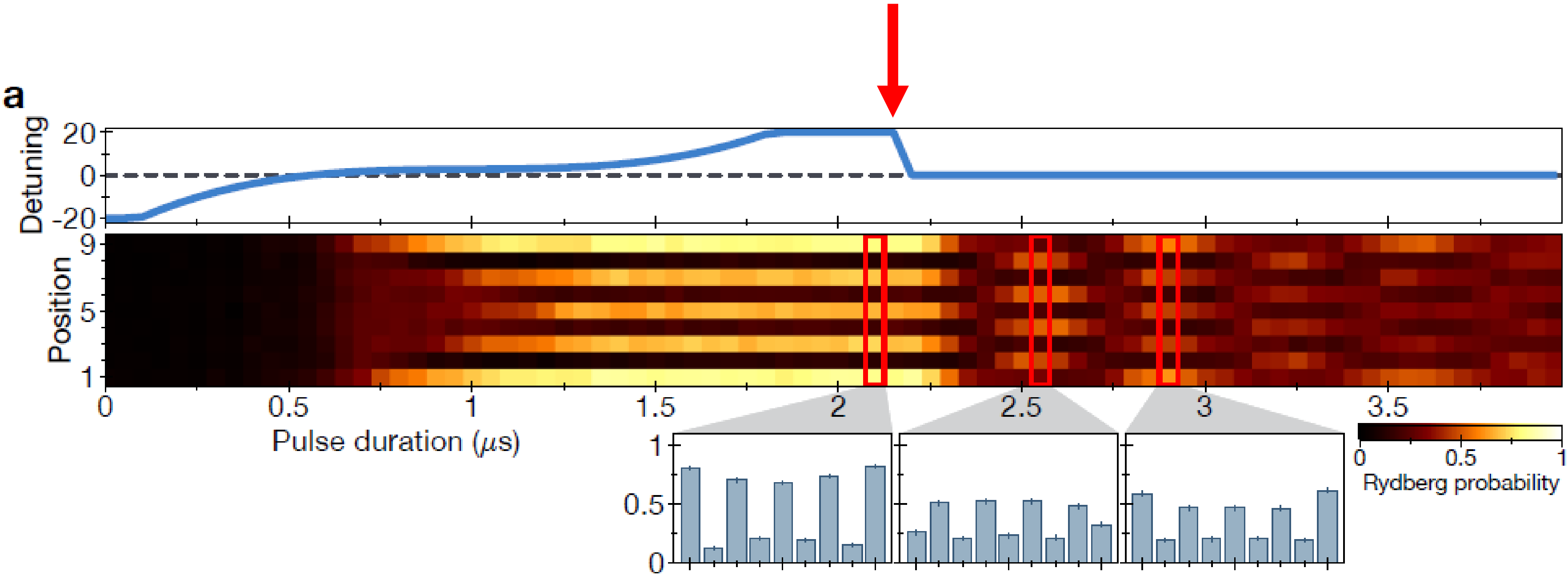


Antiferromagnetic correlations due to Rydberg blockade



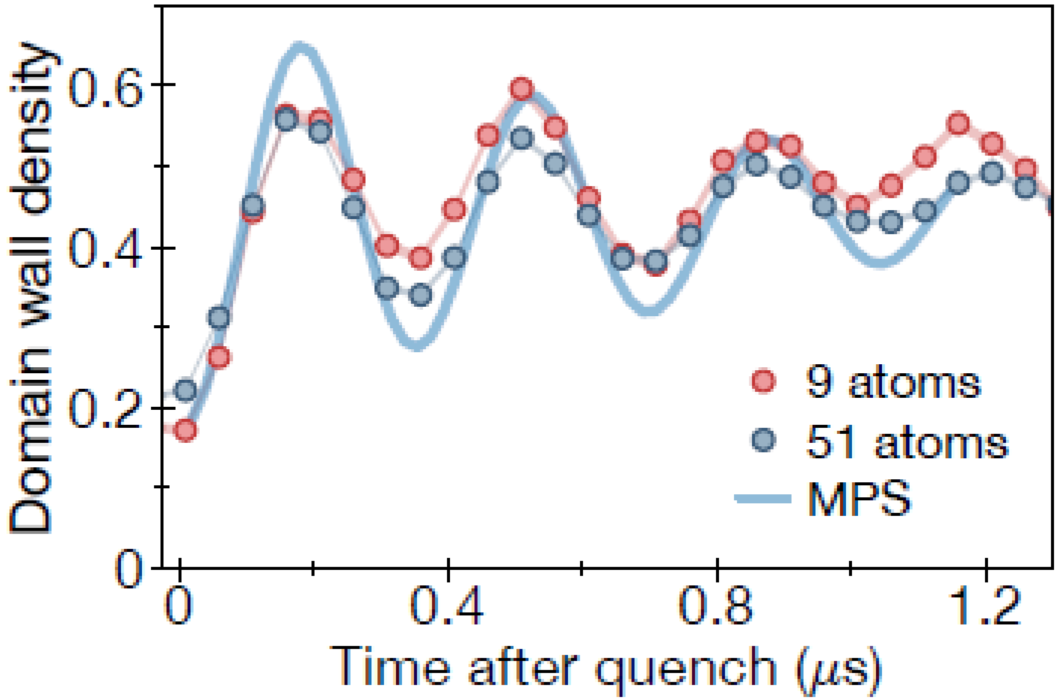
Collective oscillations after a sudden quench

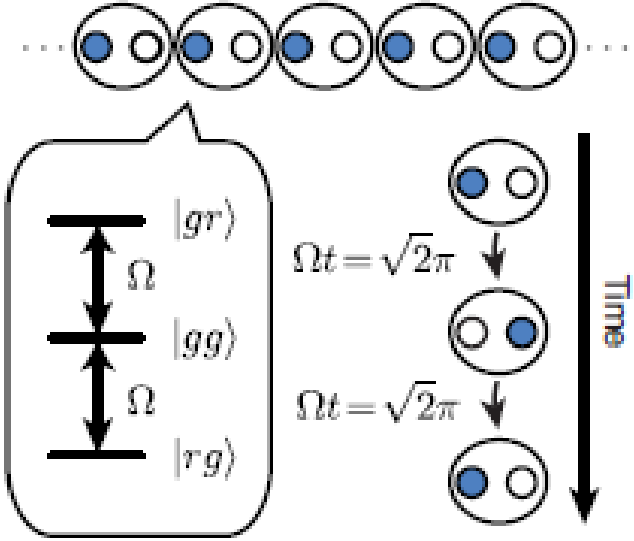
Sudden quench



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

Collective oscillations after a sudden quench





Quantum many-body scars?

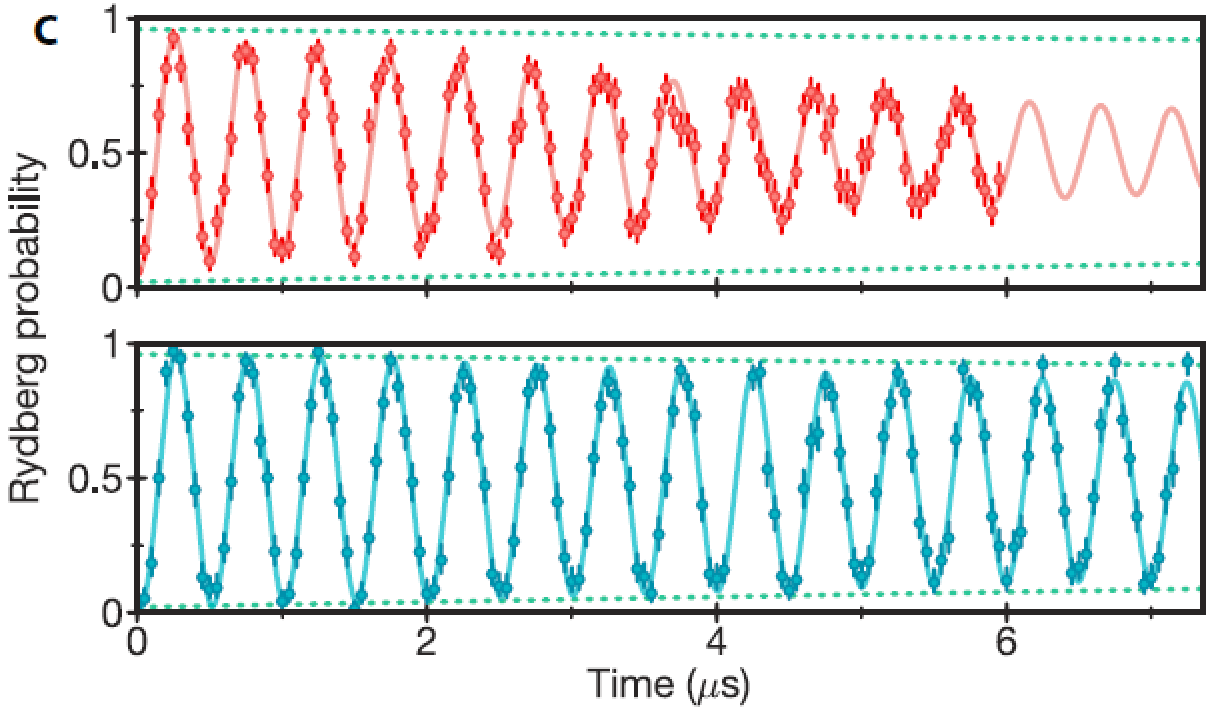
C. J. Turner, A. A. Michailidis, D. A. Abanin, M. Serbyn, and Z. Papic, arxiv 1711.03528 (2017).

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

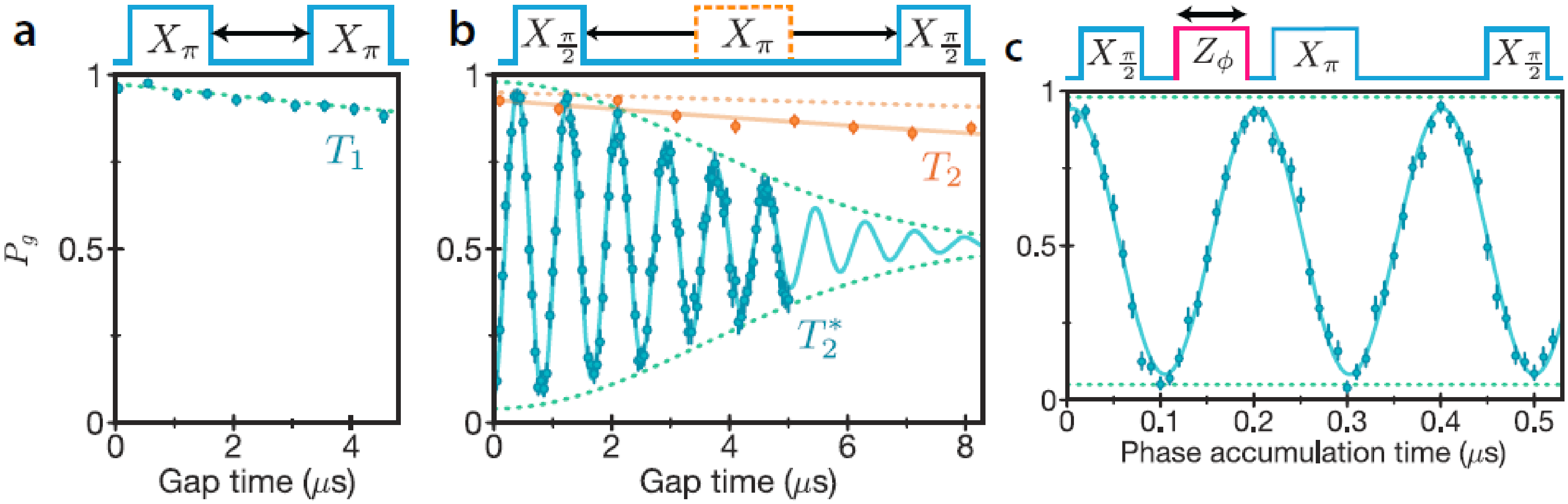


Before

After improvement of laser linewidth

Characterization of Rydberg quantum gates

Single-qubit coherence and phase control



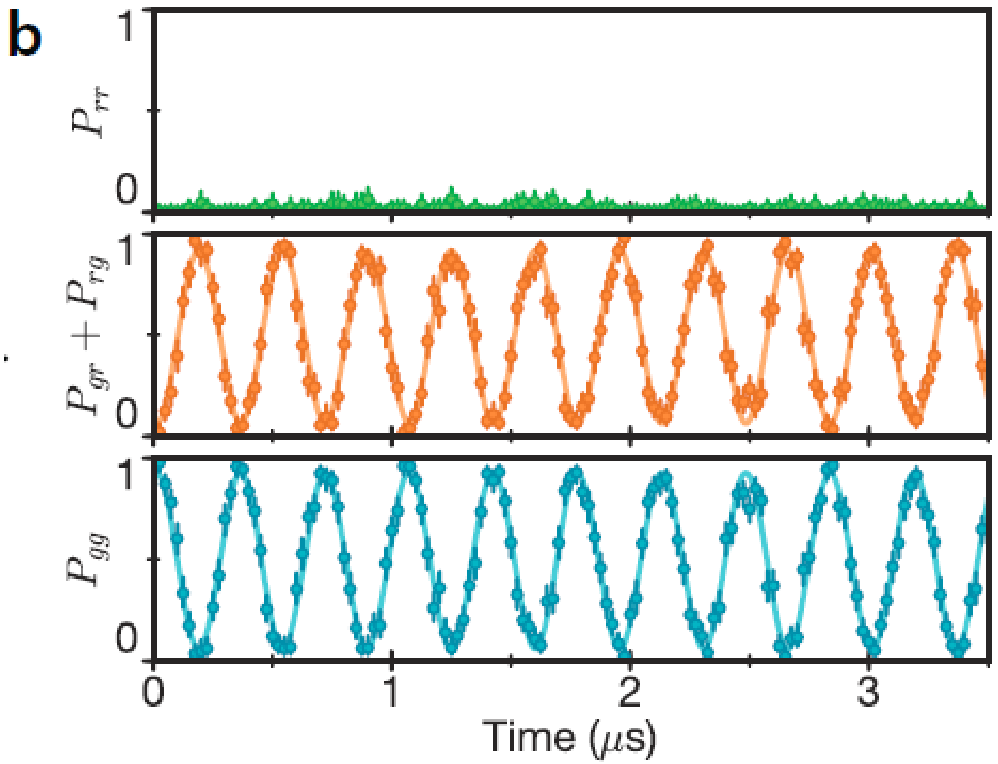
Rydberg lifetime

Phase coherence

Phase coherence with spin echo pulse

Characterization of Rydberg quantum gates

Two-qubit quantum gate



Two Rydberg atoms |rr⟩ (blockade)

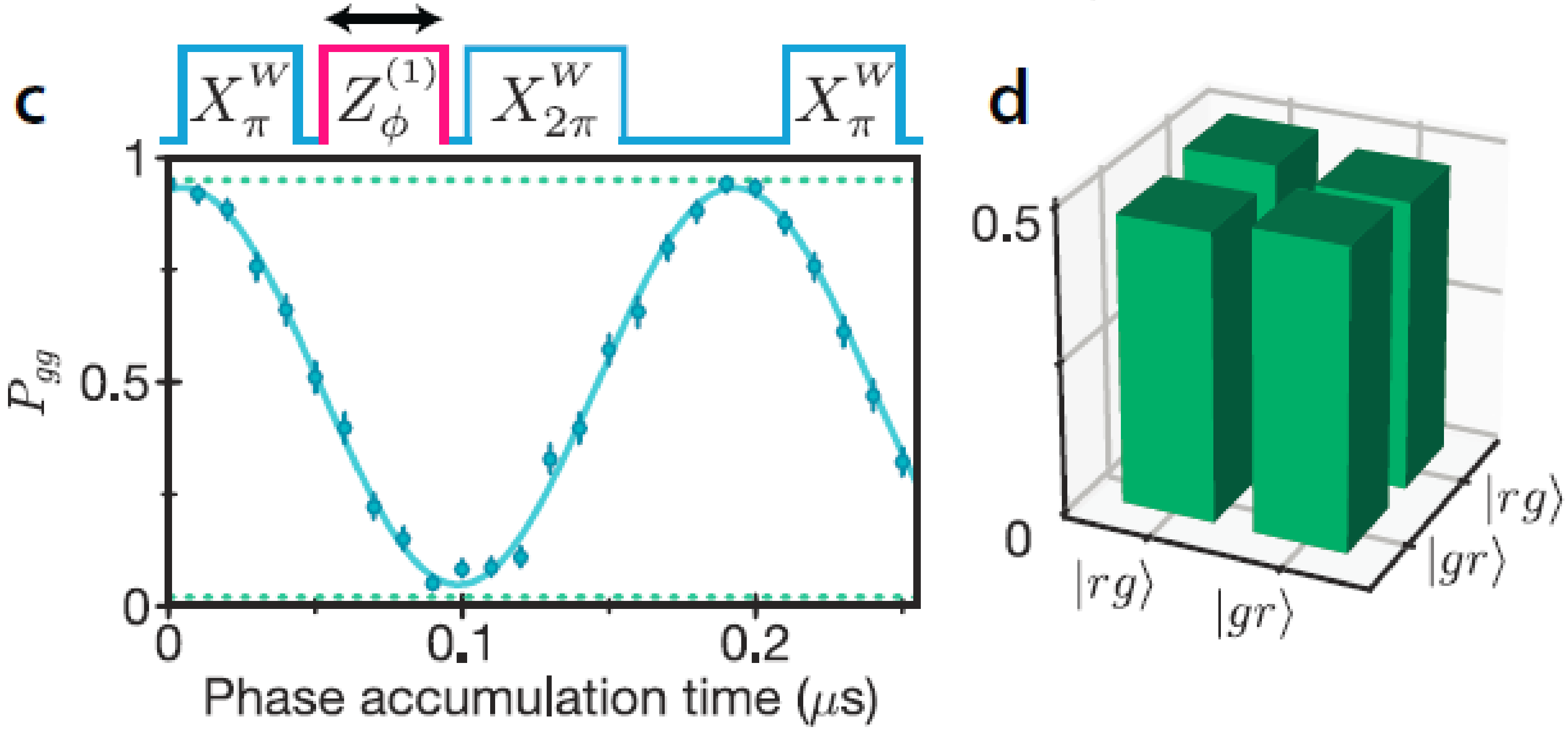
One Rydberg atom |rg⟩ + |gr⟩

Two ground-state atoms |gg⟩

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

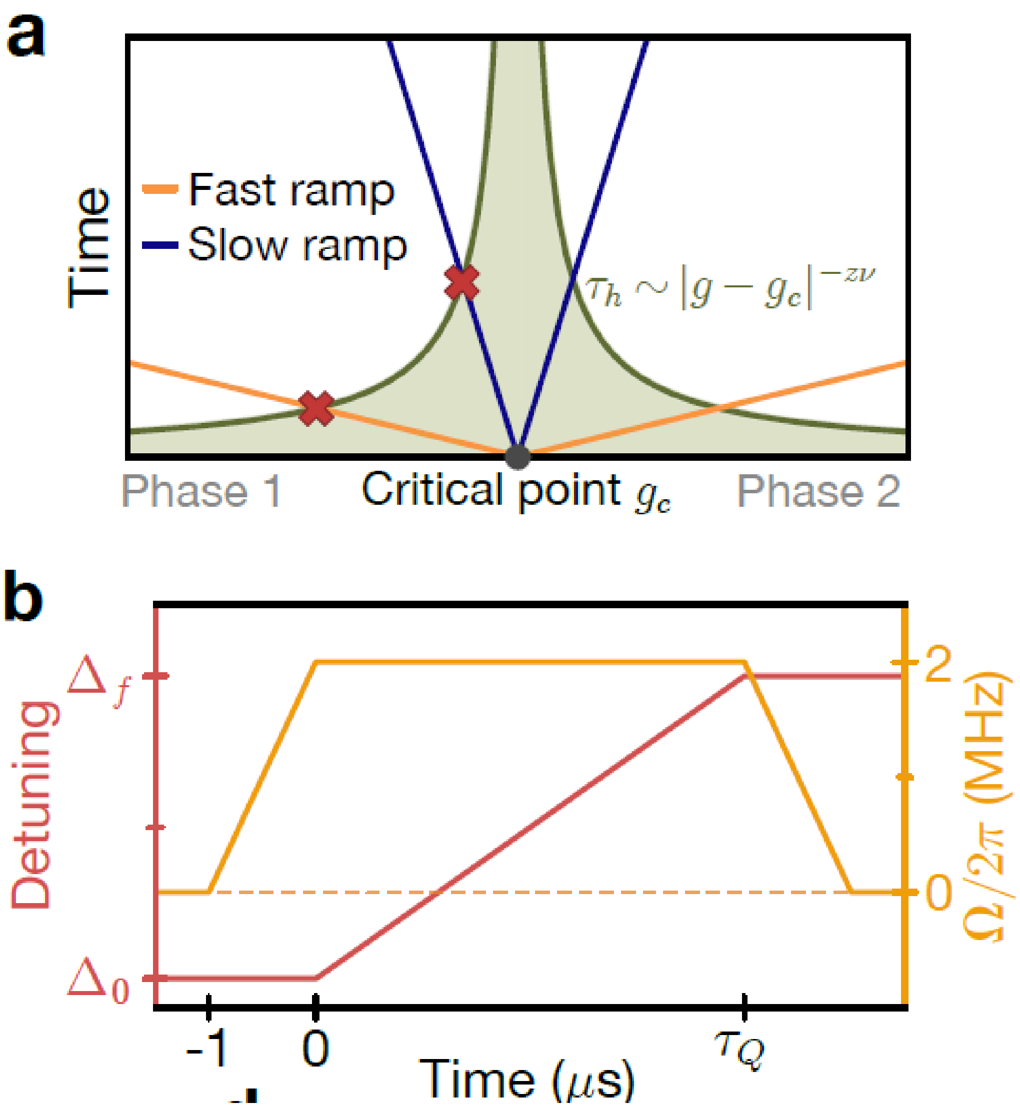
Outlook

- Strong interactions between individual photons (slow-light polaritons) demonstrated
  - Bound states of 2 and 3 photons observed
  - Towards repulsive photon-photon interactions (Tonks gas of photons?)
- Towards large quantum simulators
  - 100-300 qubits within reach in next 1-2 years
  - Transition to 2D arrangement
  - 10-atom correlation length and 10x10 qubits – system completely quantum coherent
  - Can we find the solutions to hard classical calculations via adiabatic evolution (adiabatic quantum computing, quantum approximate optimization algorithm)?

Quantum Kibble-Zurek mechanism

Probing critical dynamics across quantum phase transitions 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, submitted (9/2018).

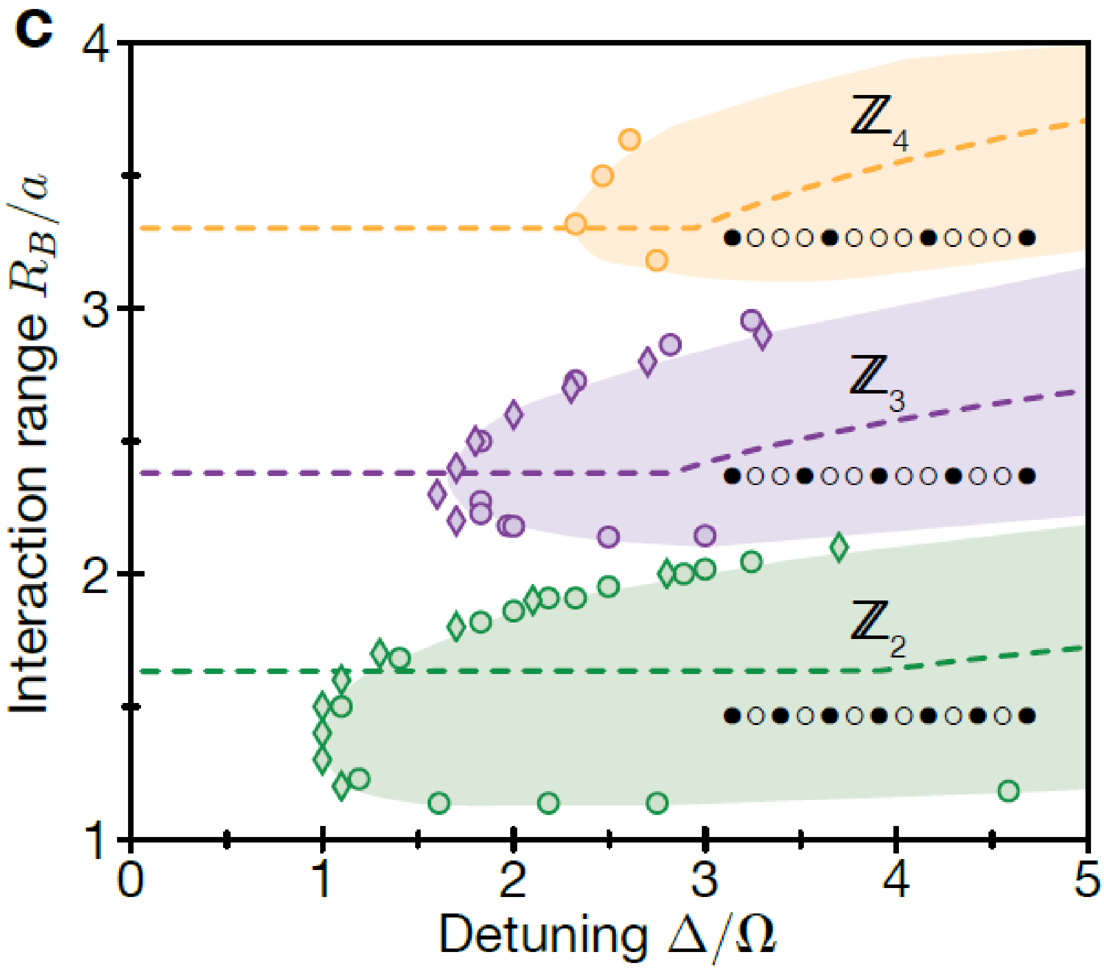
Kibble-Zurek mechanism

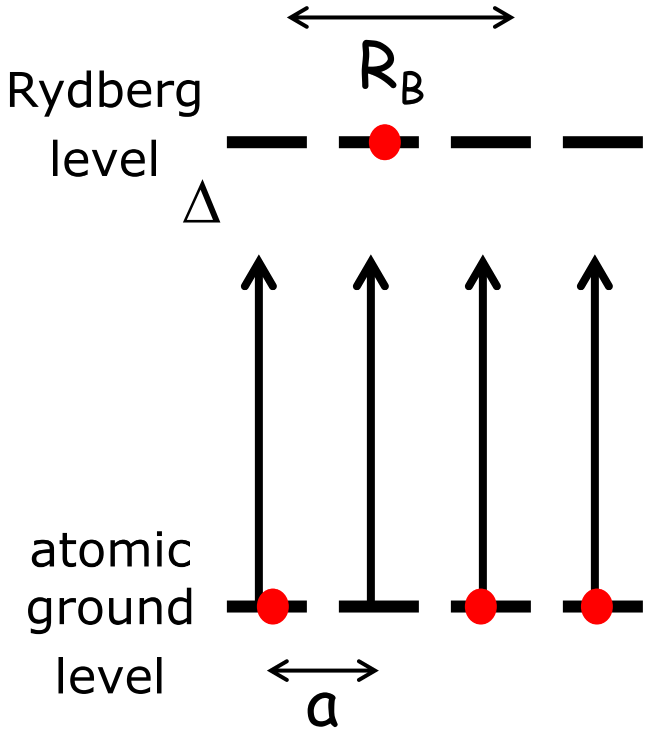


Freezing out of correlations when ramp timescale exceeds correlation formation timescale near critical point.

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

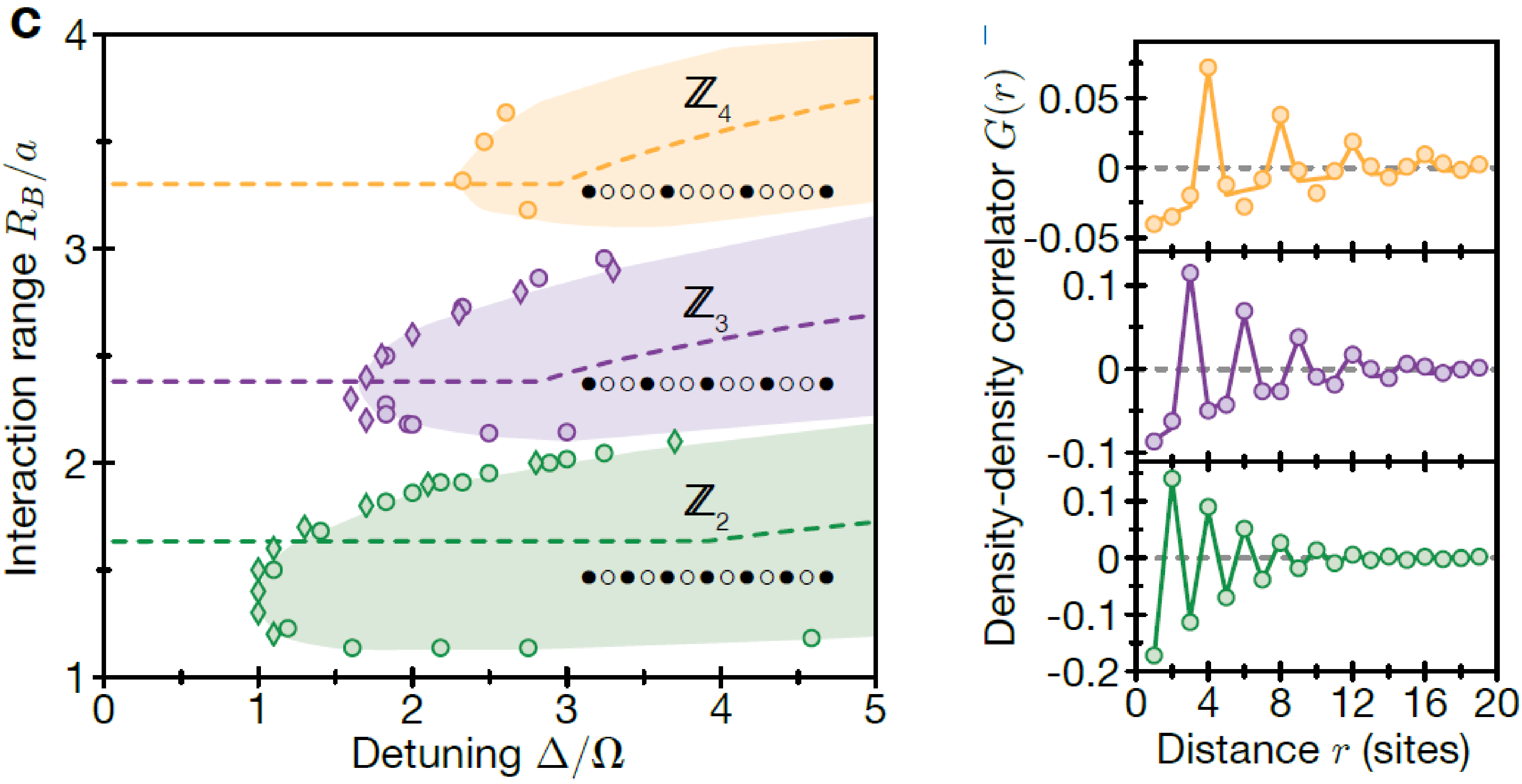
Phase boundaries for ordered phases





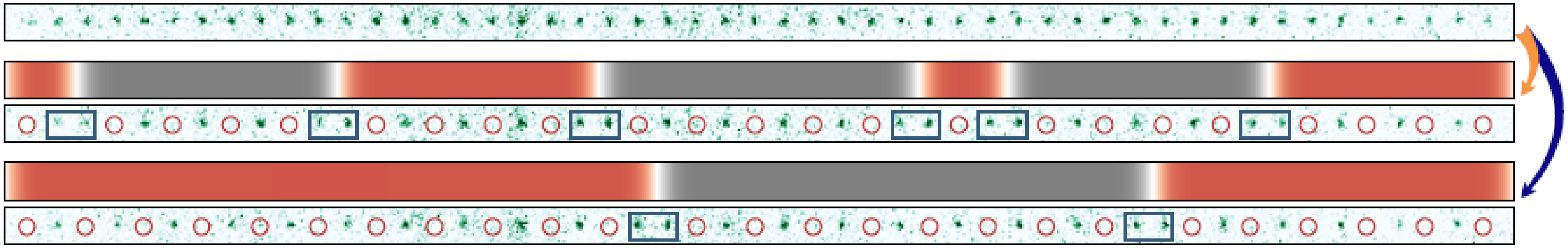
Order of ground state depends on trap distance relative to blockade radius

Phase boundaries for ordered phases



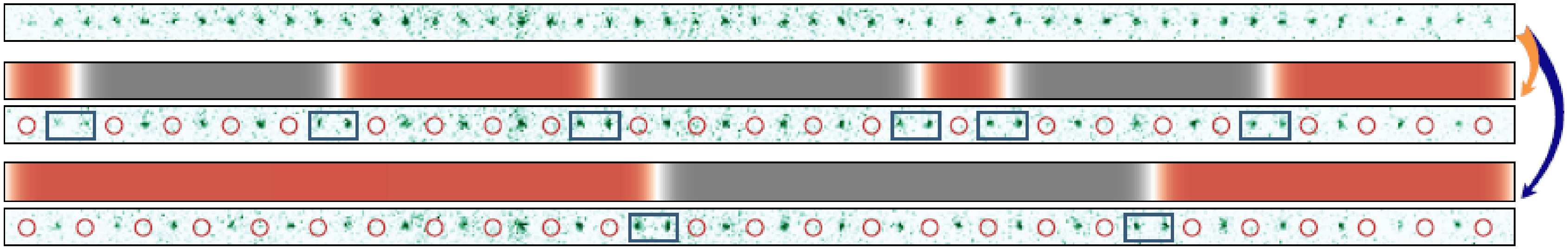
Order of ground state depends on trap distance relative to blockade radius

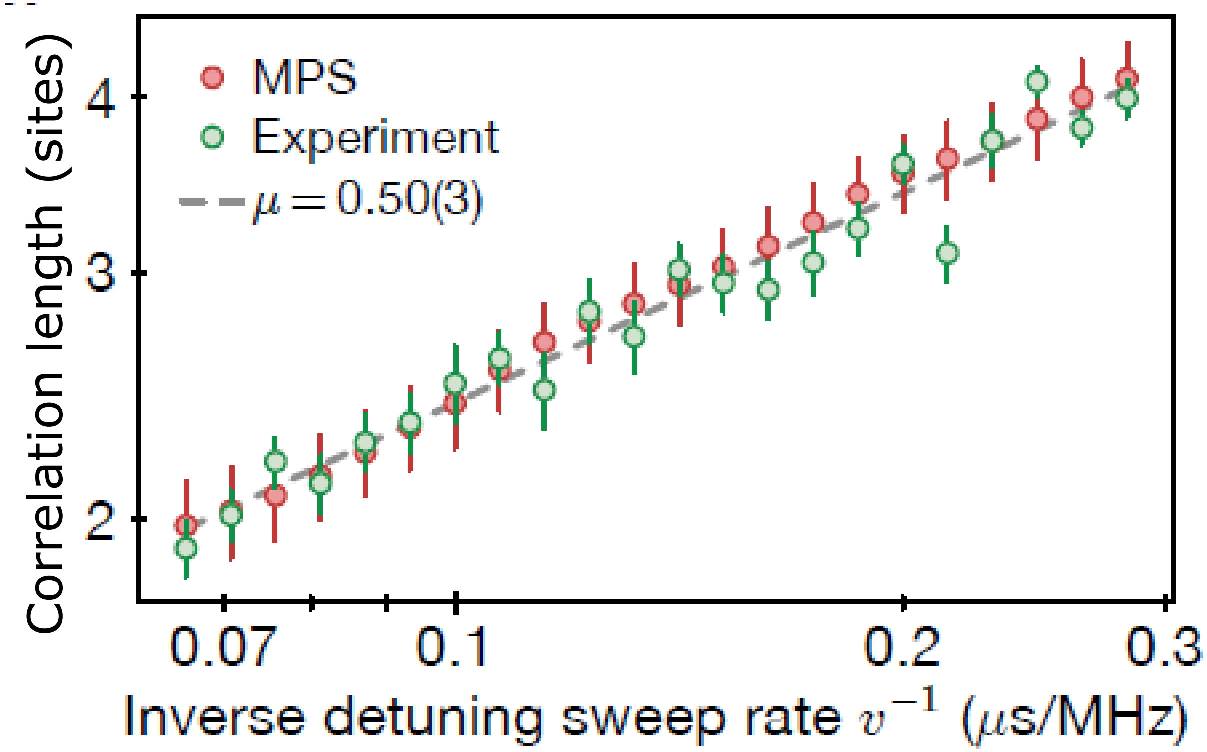
Appearance of domain walls at finite sweep rate into ordered phase



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.

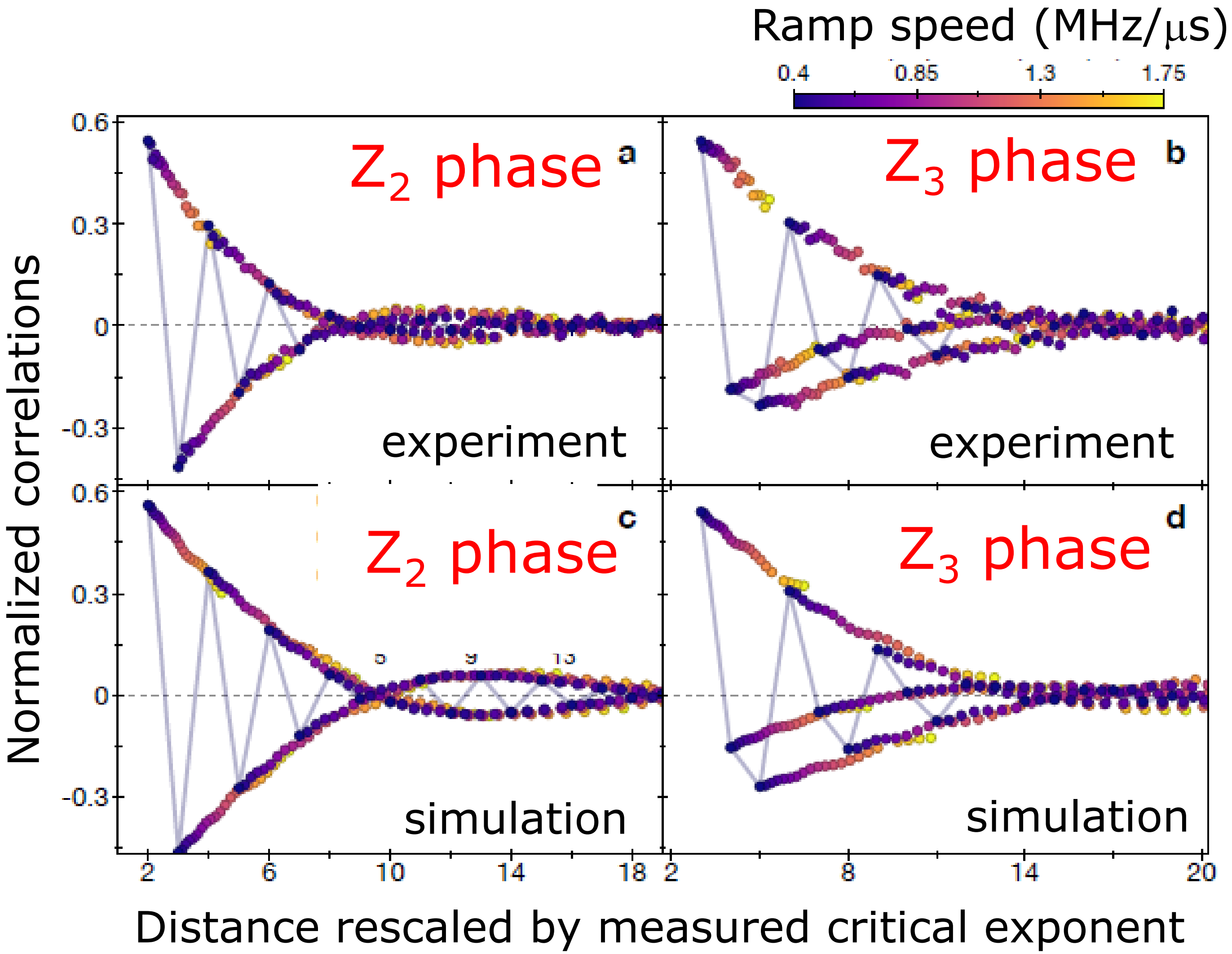
Kibble-Zurek mechanism for quantum phase transition into Z_2 phase





Critical exponent extracted from observed power law

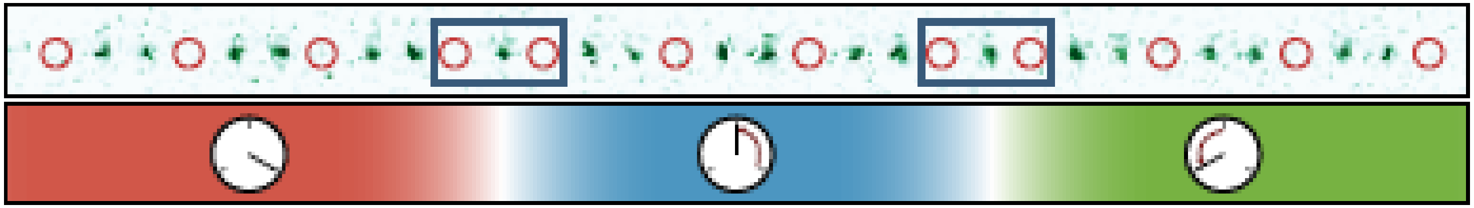
Universality of correlations



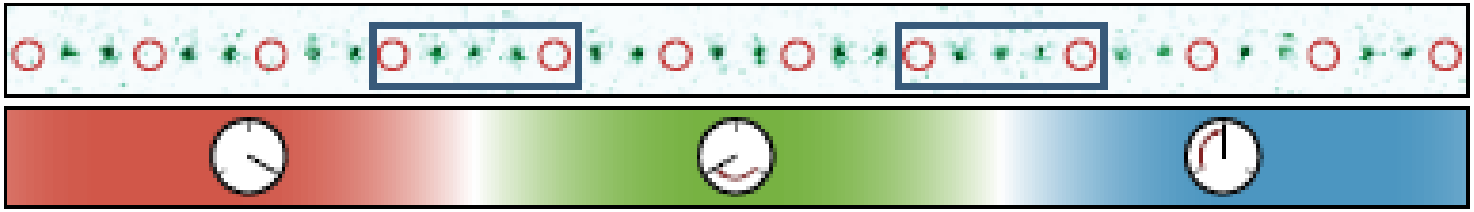
Different branches correspond to different types of defect

Nontrivial correlations between domain walls.

Different defects in Z_3 phase



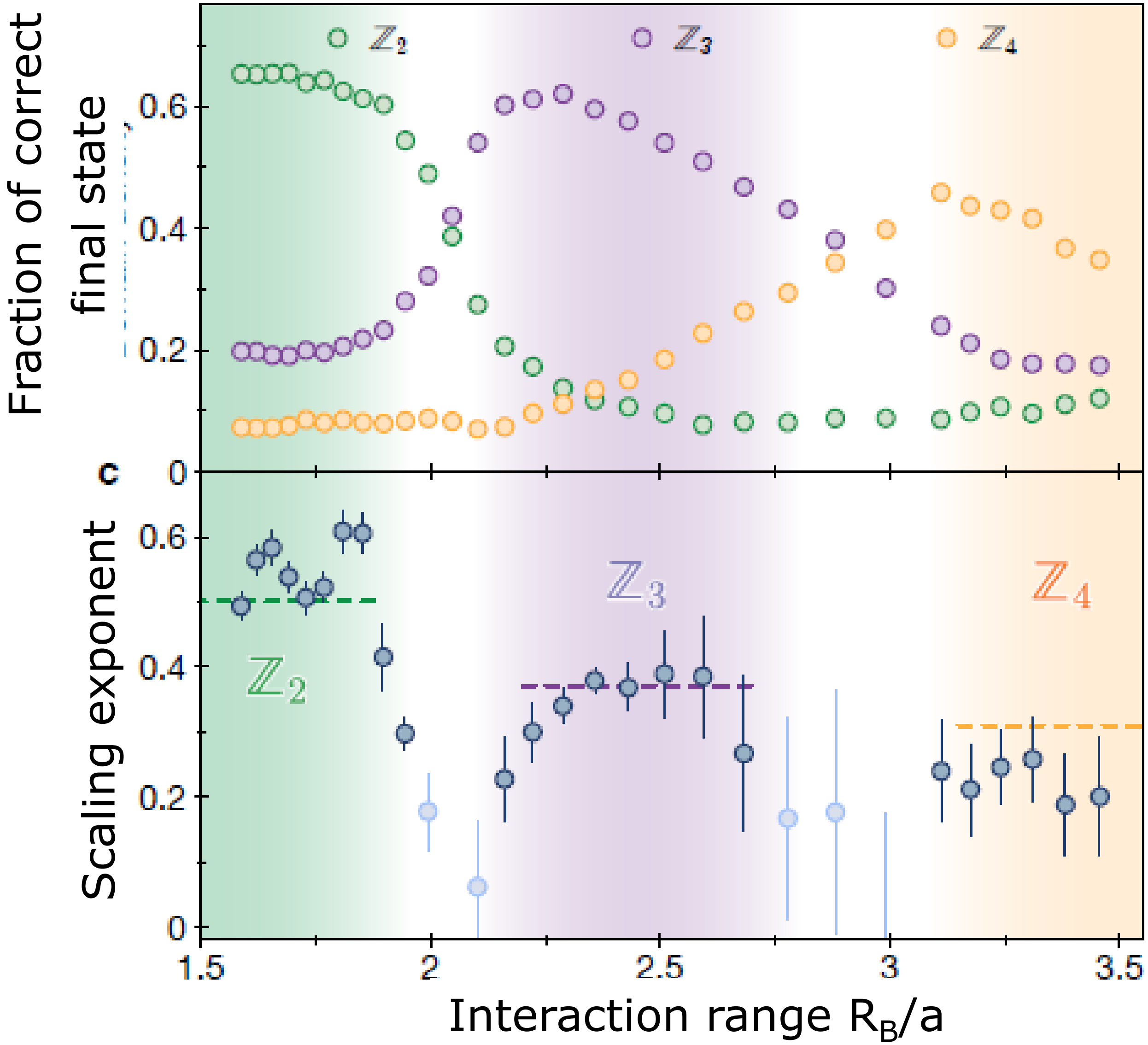
Close to Z_2



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.