Quantum simulation in arrays of single Rydberg atoms

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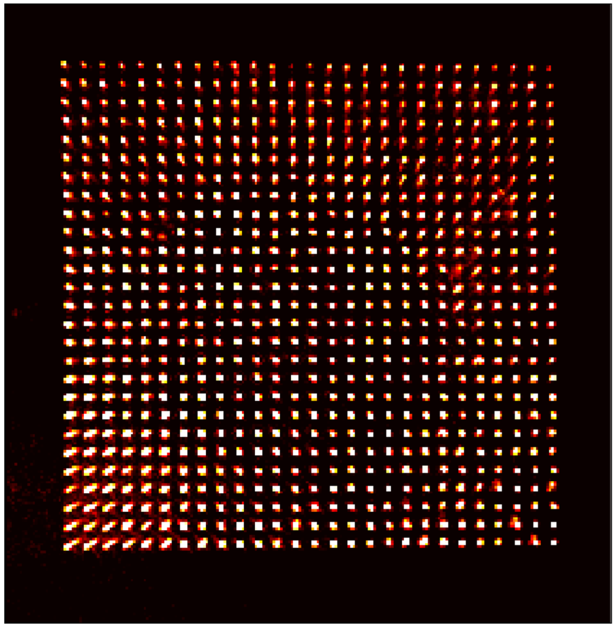
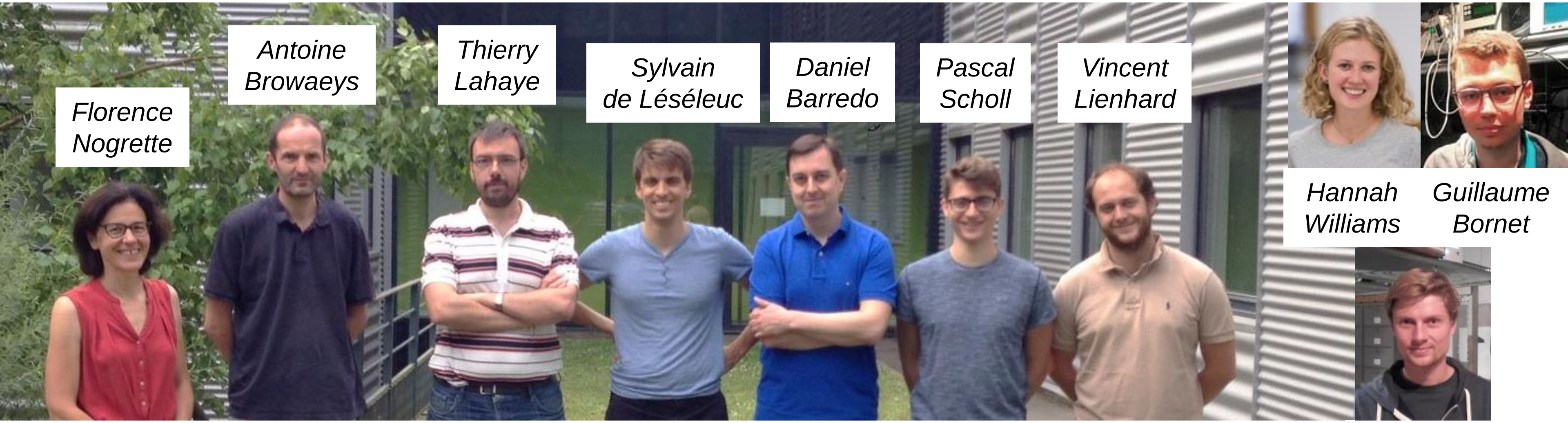
Laboratoire Charles Fabry
CNRS & Institut d'Optique, Palaiseau, France



Virtual AMO Seminar, 29 January 2020

The Rydberg team in Palaiseau



Kai-Niklas Schymik

Collaborators (theory):
H.-P. Büchler (Stuttgart), A. Läuchli (Innsbruck)

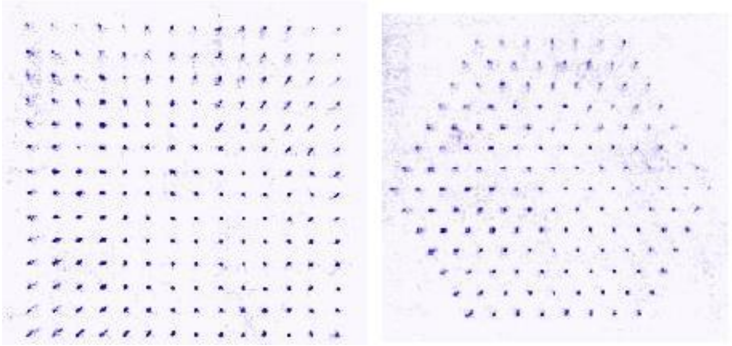
https://atom-tweezers-io.org/

Funding: SIRTEQ, îledeFrance, Agence Nationale de la Recherche ANR, Quantum Flagship, PASQuanS

Arrays of single Rydberg atoms

- **Arrays of single atoms with arbitrary geometries**

Up to > 200 atoms
Spacing: a few microns



- **Strong interactions via Rydberg excitation**

$U\,/\,h$ ~ 1 to 10 MHz for R ~ 5 µm
Lifetime 100s of µs

Implement spin models

Ising (vdW interactions)

$$\hat{H} \sim \sum_{i,j} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}$$

XY (resonant dipole-dipole interaction)

$$\hat{H} \sim \sum_{i,j} J_{ij}\sigma_+^{(i)}\sigma_-^{(j)}$$

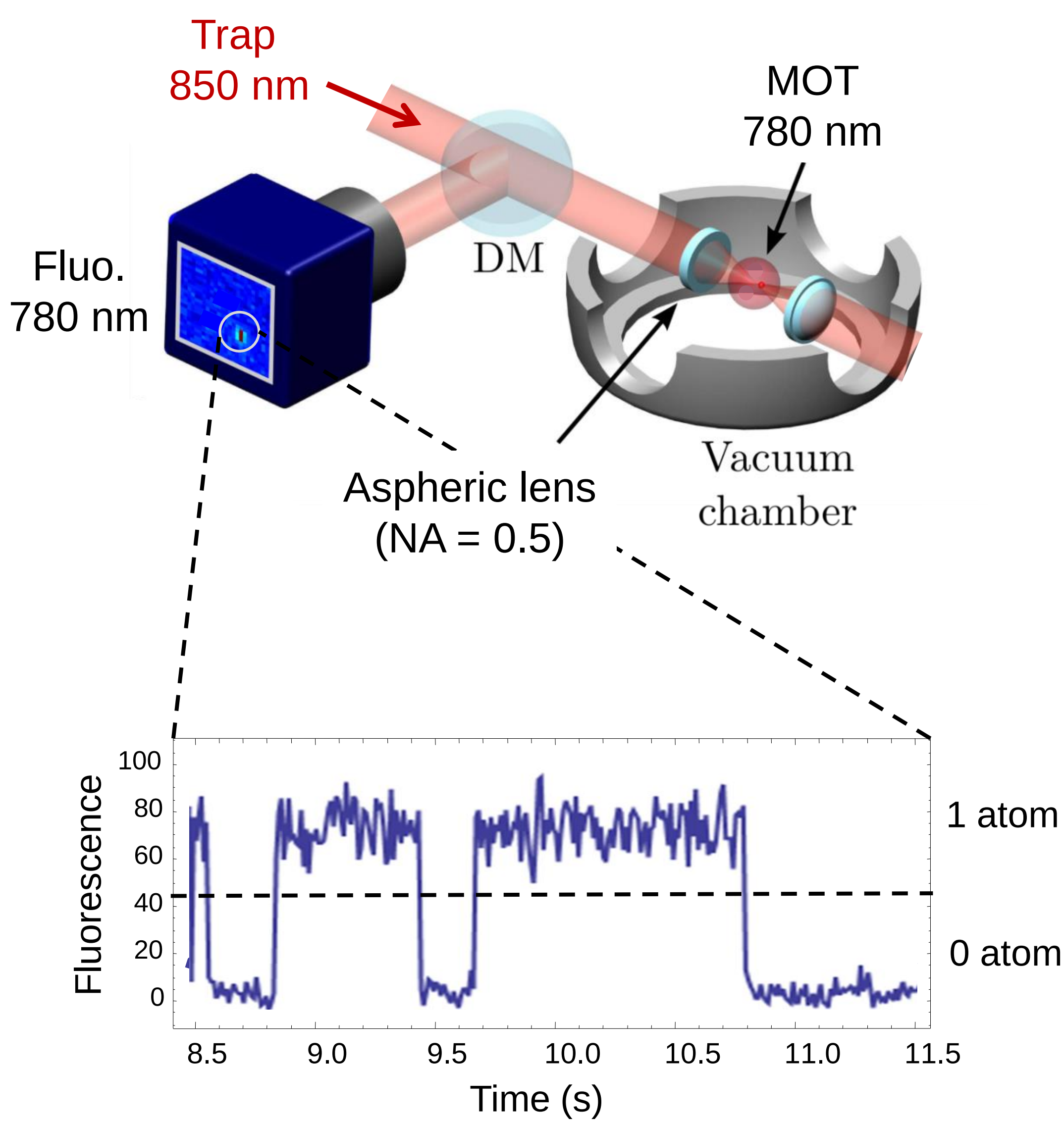
Outline

1. ***Tweezer arrays & Rydberg atoms***

2. ***Quantum simulation of spin Hamiltonians***

1. Tweezer arrays & Rydberg atoms

Single atoms in optical tweezers

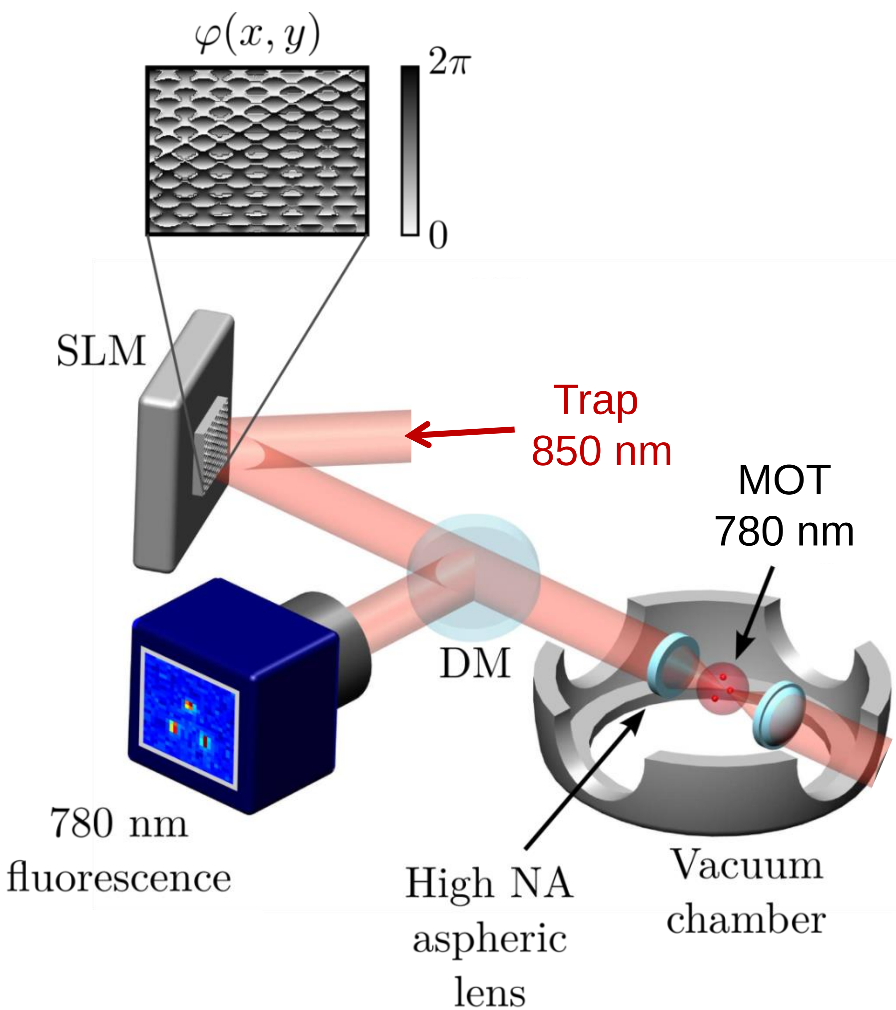


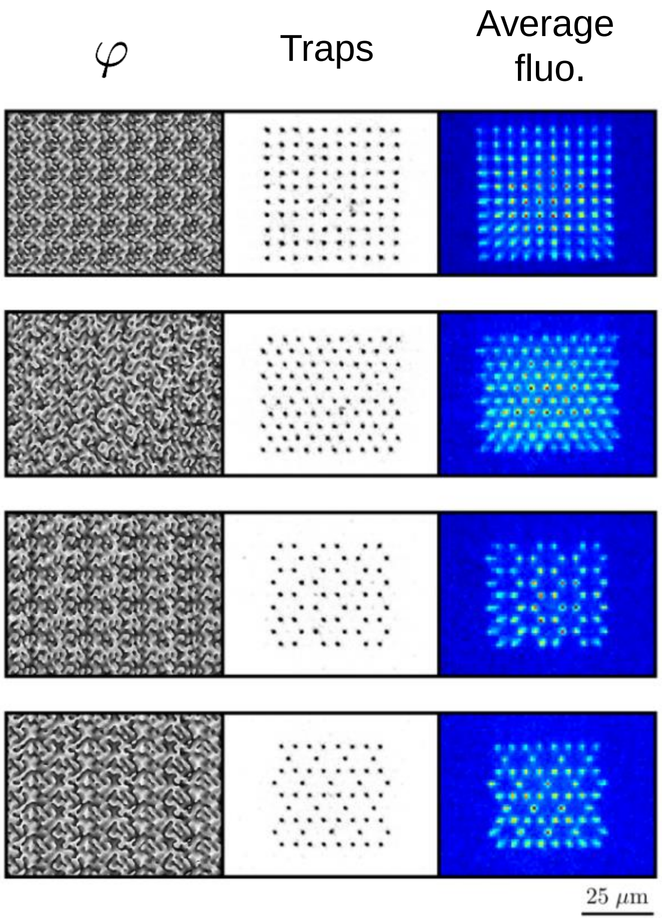
- 1 µm waist optical tweezers loaded from MOT
- At most one atom due to light-assisted collisions
- 50% loading probability:

  Non-deterministic single-atom source!

Schlosser *et al.*, Nature 2001

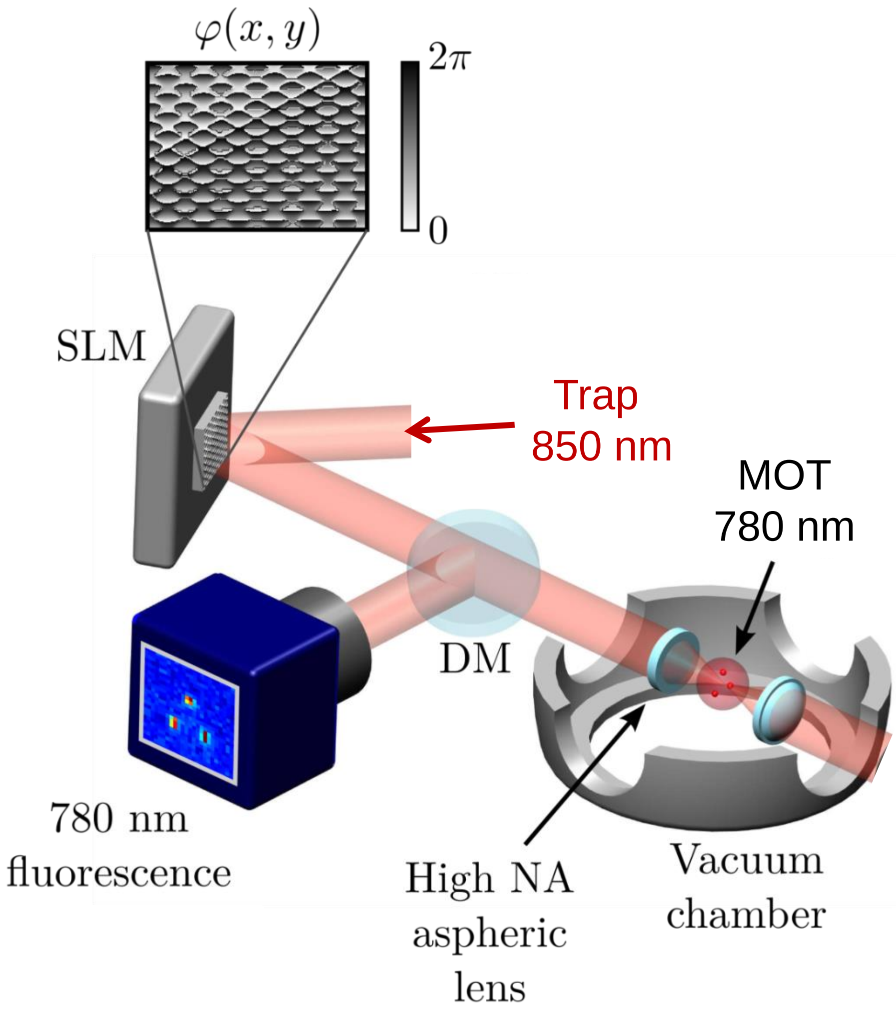
Arrays of single atoms

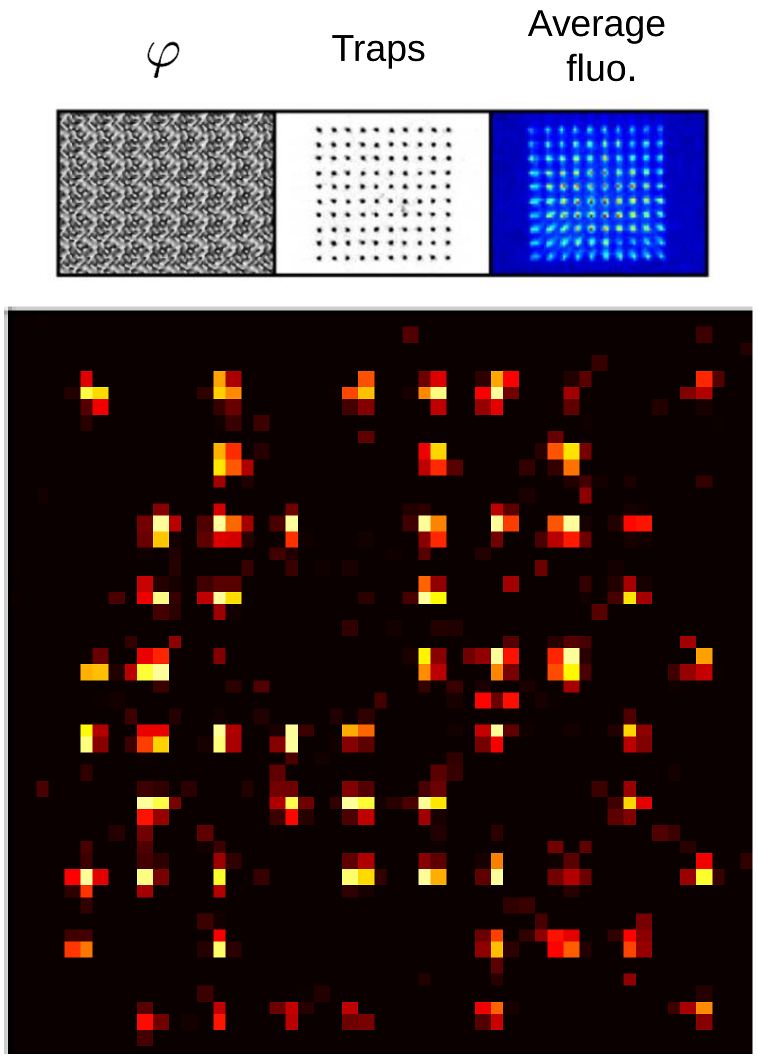




Nogrette *et al.*, PRX **4**, 021034 1021 (2014)

Arrays of single atoms

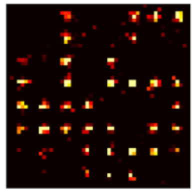




Nogrette *et al.*, PRX **4**, 021034 1021 (2014)

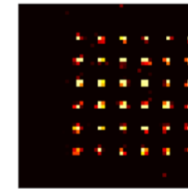
Atom-by-atom assembly

Load 2*N* traps with ~ *N* atoms ➡ Initial image ➡ Compute moves ➡ Move atoms with 2d AOD ➡ Check image

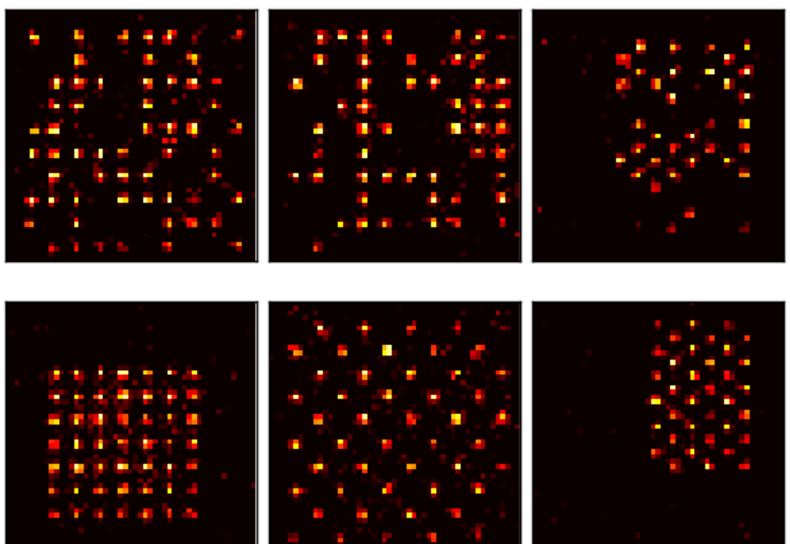


< 1 ms

~1 ms per move



Total assembly time ~ 50 ms

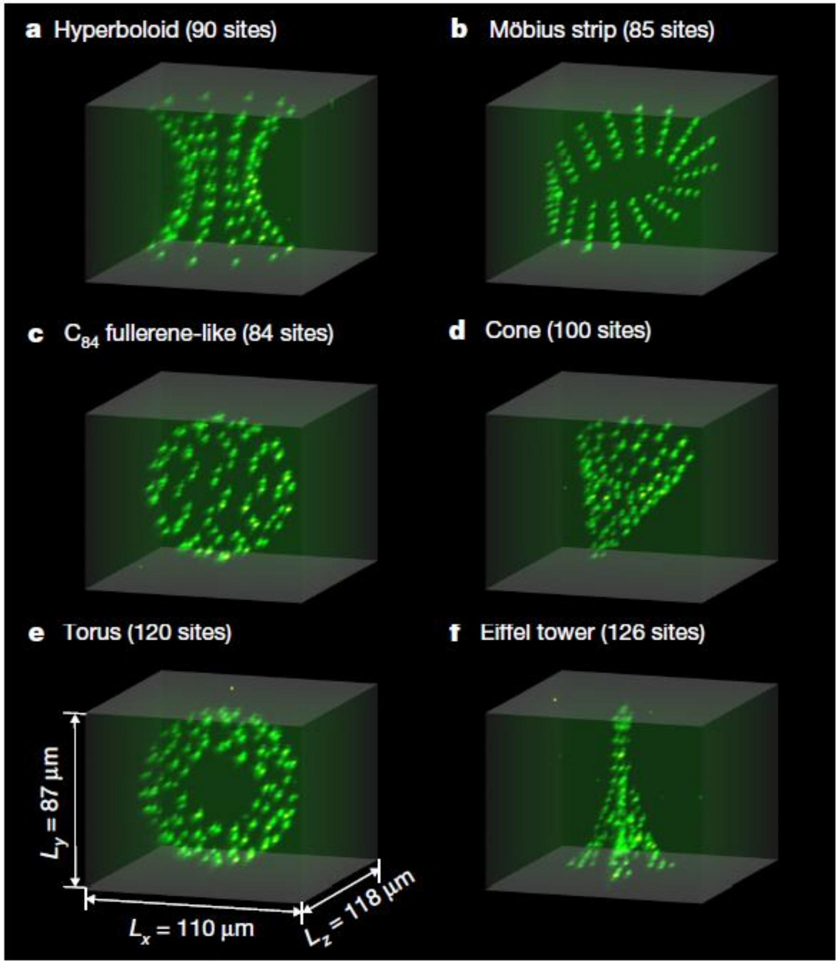


- Fully loaded arrays up to 50 atoms
- 98% filling fraction
- Rep. rate up to ~ 4 Hz

Barredo *et al.*, Science **354**, 1021 (2016)

See also:
Endres *et al.*, Science **354**, 1024 (2016)
Kim *et al.*, Nature Comm. **7**, 13317 (2016)

Extension to 3D arrays

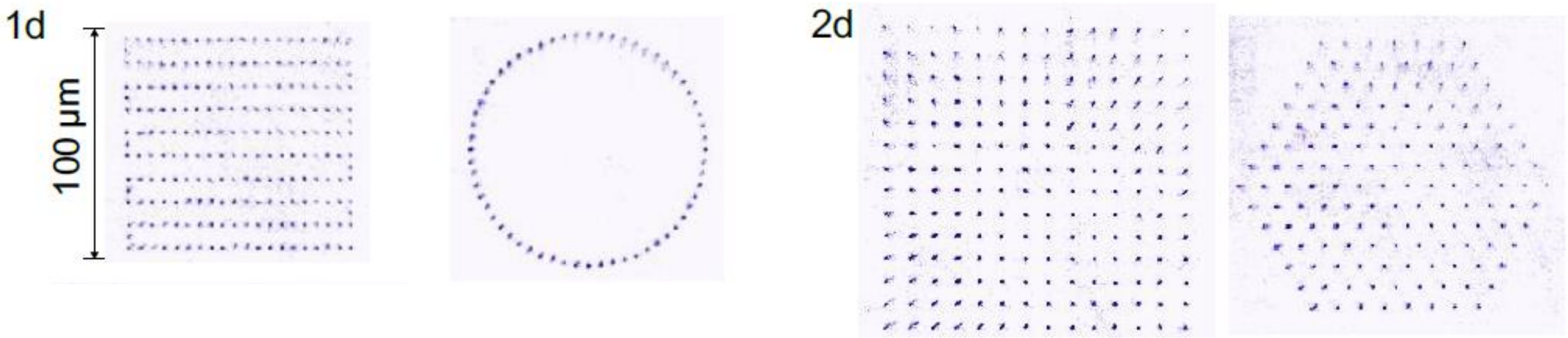


Barredo *et al.*, Nature **561**, 79 (2018)

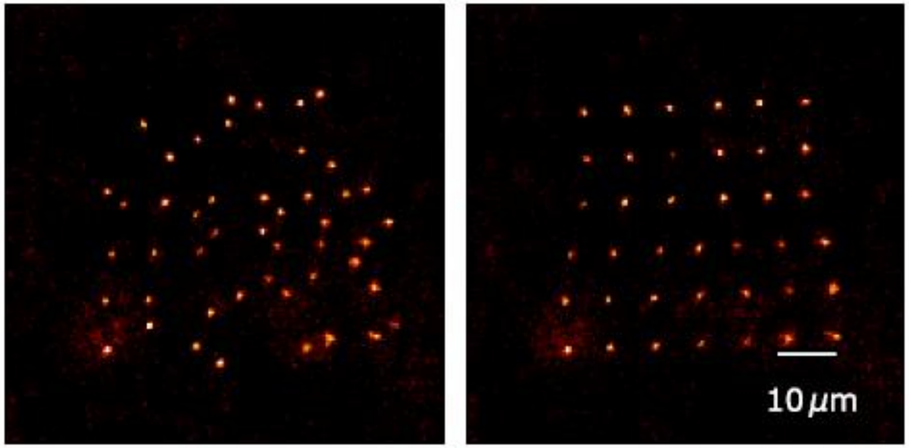
Recent improvements

Improved assembler algorithms
K.-N. Schymik *et al.*, Phys. Rev. A **102**, 063107 (2020)

- ***Up to > 200 atoms***



- ***Geometries not limited to a regular array***



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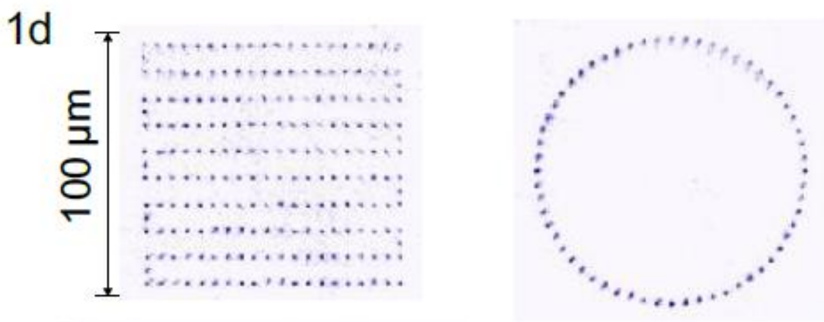

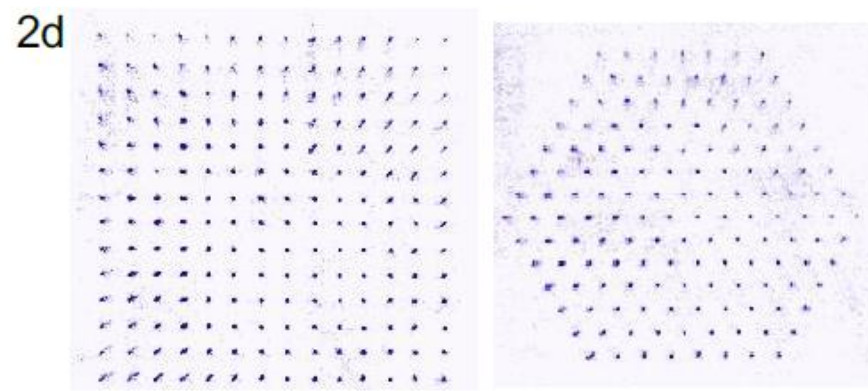

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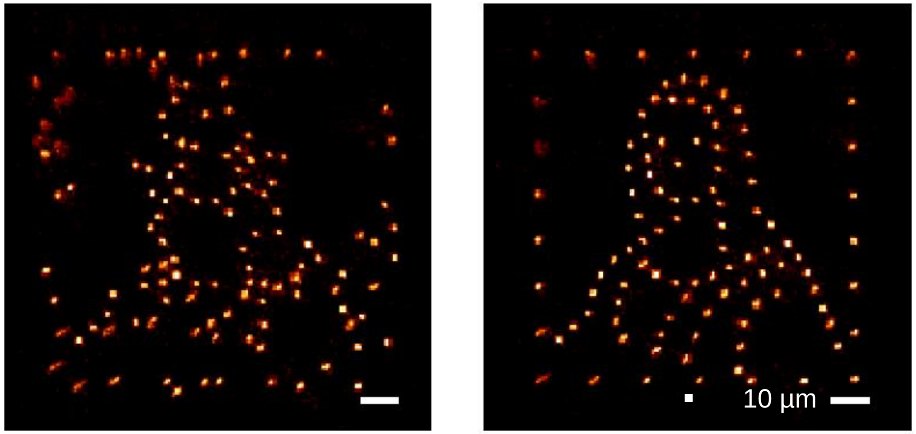
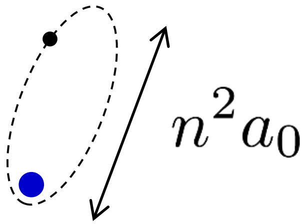


Rydberg atoms

Large principal quantum number: $n \gg 1$

$n \sim 50 - 100$



Exaggerated properties:

Electric dipole $\langle nS | \, d \, | nP \rangle \sim n^2$

Lifetime $\tau \sim n^3$ (100s of µs)

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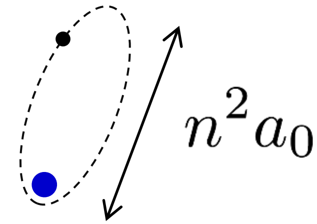

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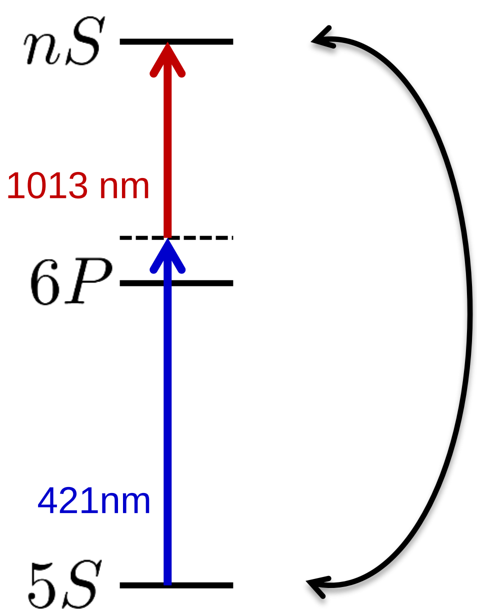
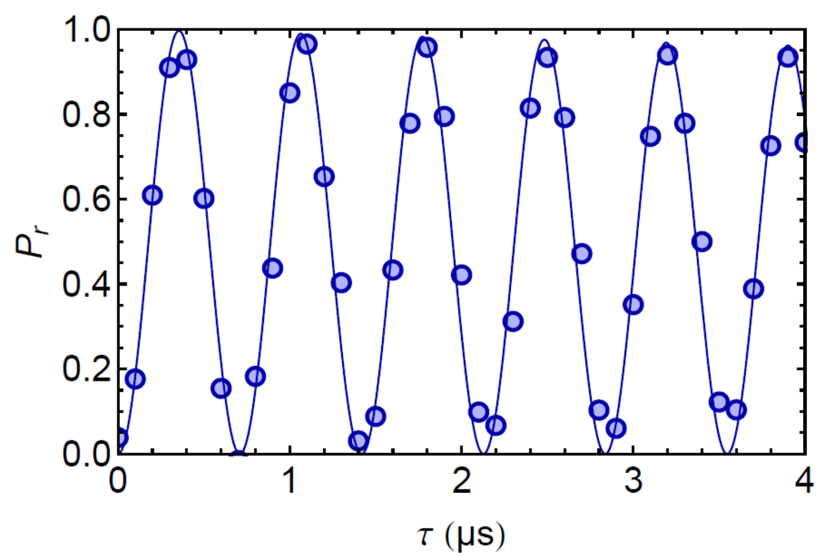


5S – *nS* Rabi oscillations



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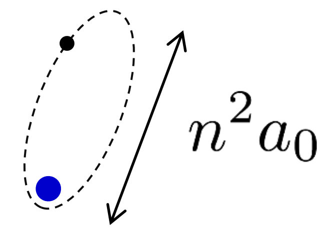

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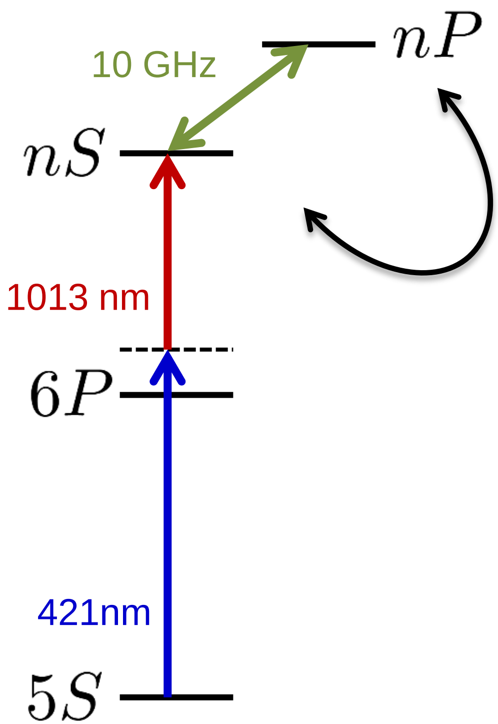

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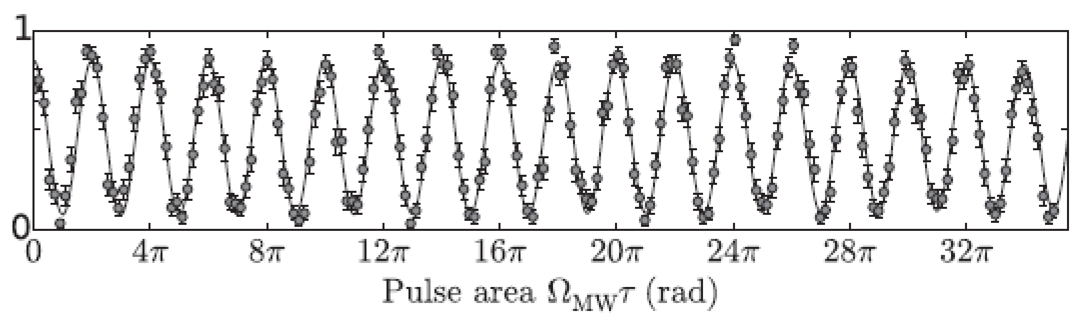


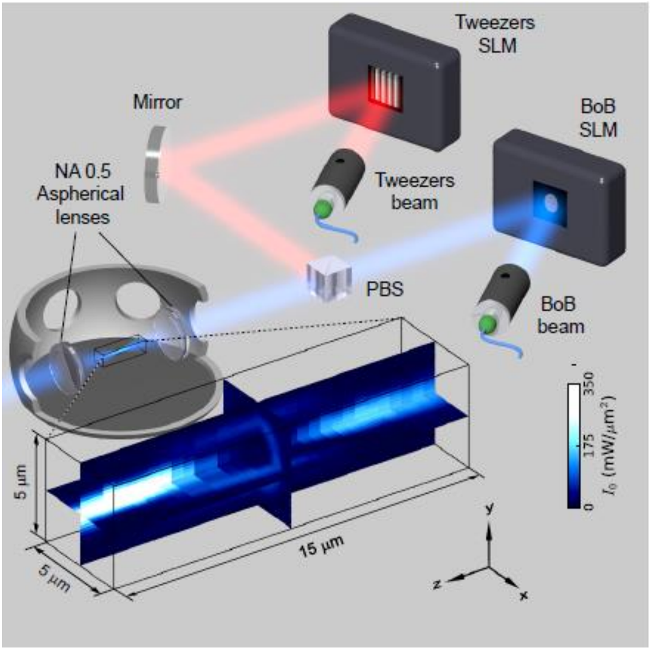
Trapping of Rydberg atoms

Ponderomotive 'Bottle beam' trap

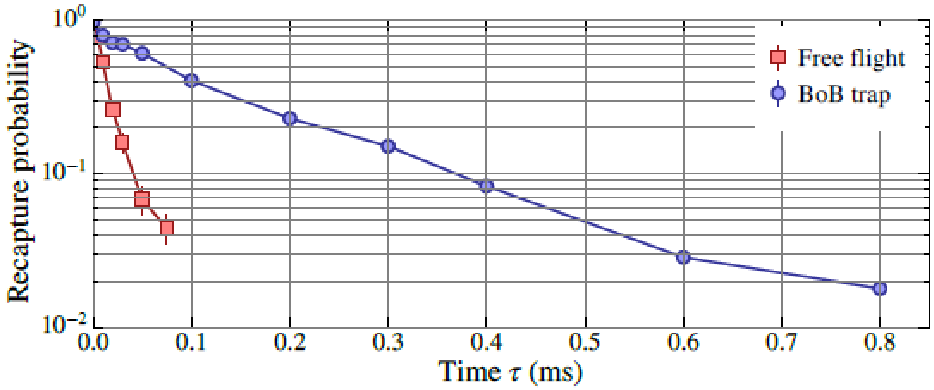
$$U_{nljm_j}(\boldsymbol{R}) = \int d^3r\, V_P(\boldsymbol{R}+\boldsymbol{r})\, |\psi_{nljm_j}(\boldsymbol{r})|^2$$

Ponderomotive potential
for the electron (repulsive)

$$V_P(\boldsymbol{r}) = \frac{q_e^2 I(\boldsymbol{r})}{2m_e\varepsilon_0 c\,\omega_L^2}$$

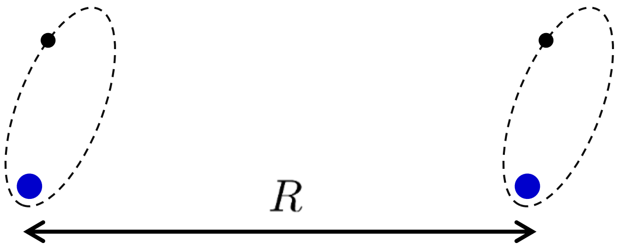


Increased time for simulation



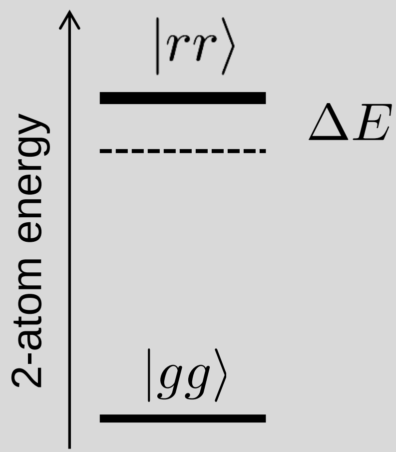
D. Barredo *et al.*,
Phys. Rev. Lett. **124**, 023201 (2020)

Interactions between Rydberg states



$$\hat{V}_{\rm ddi} = \frac{1}{4\pi\varepsilon_0}\frac{\hat{\boldsymbol{d}}_1\cdot\hat{\boldsymbol{d}}_2 - 3(\hat{\boldsymbol{d}}_1\cdot\hat{\boldsymbol{n}})(\hat{\boldsymbol{d}}_2\cdot\hat{\boldsymbol{n}})}{R^3}$$

van der Waals

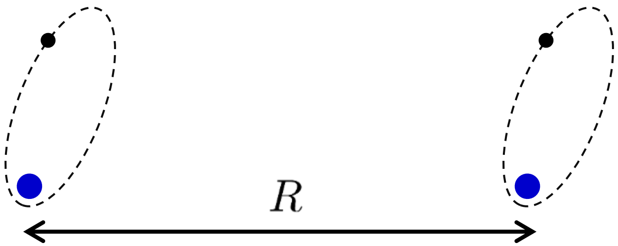


$$\Delta E \sim \frac{C_6}{R^6}$$

$$\begin{cases} |g\rangle \to |{\downarrow}\rangle \\ |r\rangle \to |{\uparrow}\rangle \end{cases}$$

Ising-like interaction

Interactions between Rydberg states



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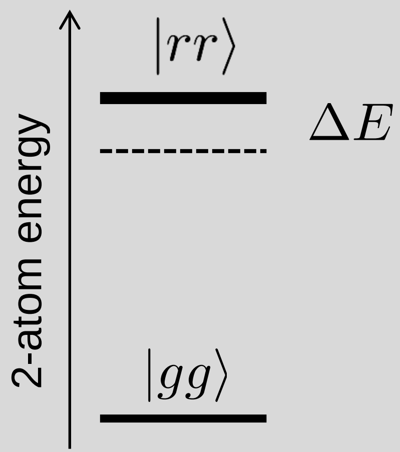
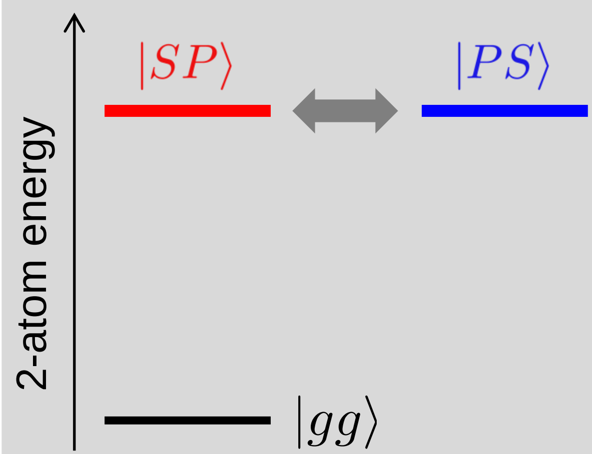


$$\Delta E \sim \frac{C_6}{R^6}$$

$$\begin{cases} |g\rangle \rightarrow |\downarrow\rangle \\ |r\rangle \rightarrow |\uparrow\rangle \end{cases}$$

Ising-like interaction

Resonant DDI



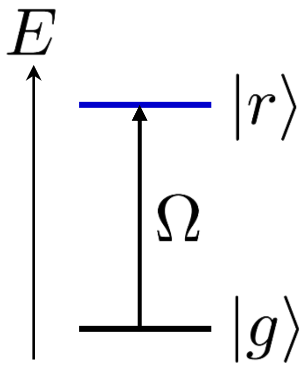
$$V \sim \frac{C_3}{R^3}$$

$$\begin{cases} |S\rangle \rightarrow |\downarrow\rangle \\ |P\rangle \rightarrow |\uparrow\rangle \end{cases}$$

XY interaction (flip-flop)

Rydberg blockade

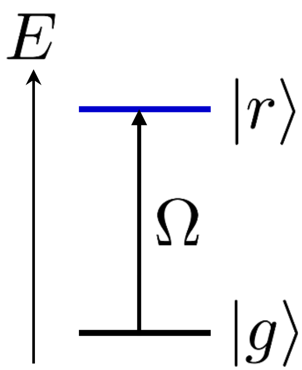
One atom

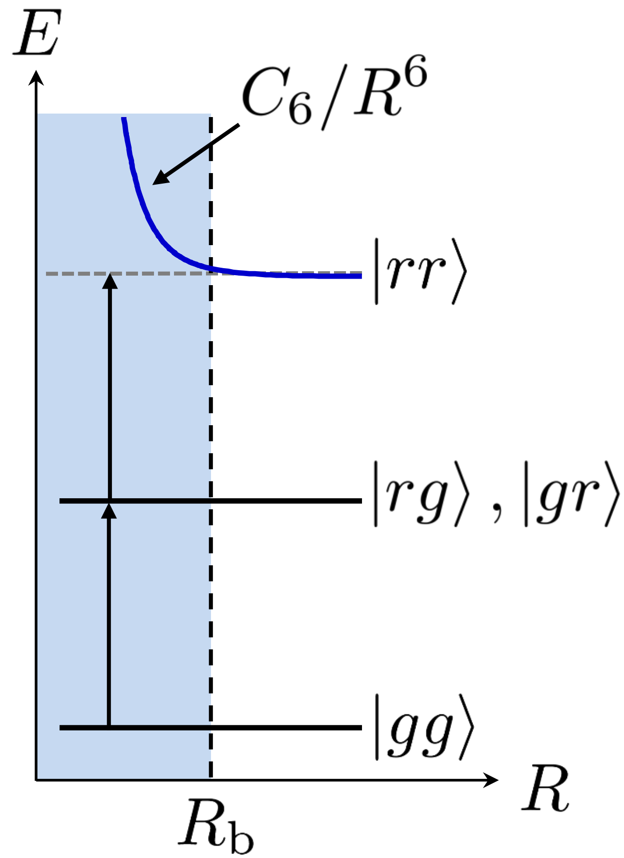


Rydberg blockade

Two atoms

One atom

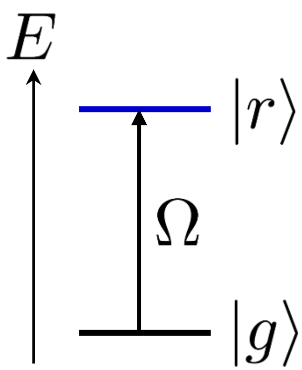




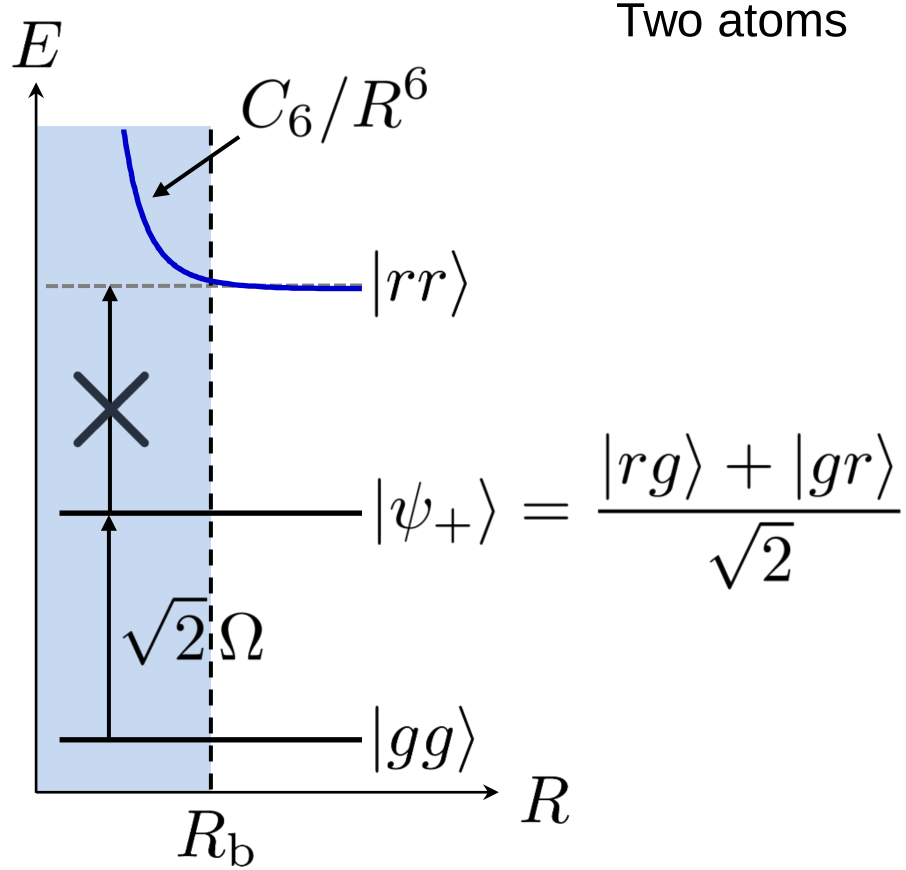
Blockade radius: $\hbar\Omega = C_6/R_\mathrm{b}^6$

Rydberg blockade

One atom



Two atoms



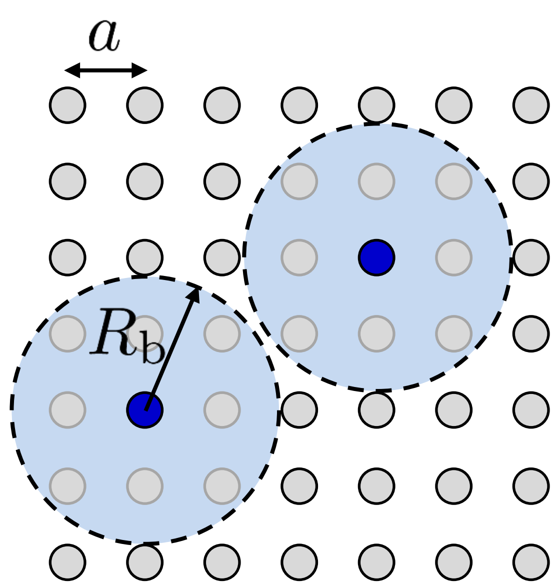
- Generate entanglement
- Basis of two-qubit gates
- Extends to *N* atoms in a blockade volume

D. Jaksch *et al*. PRL 2000

Rydberg blockade

Several blockade volumes in the array:

Strongly correlated quantum many-body systems!

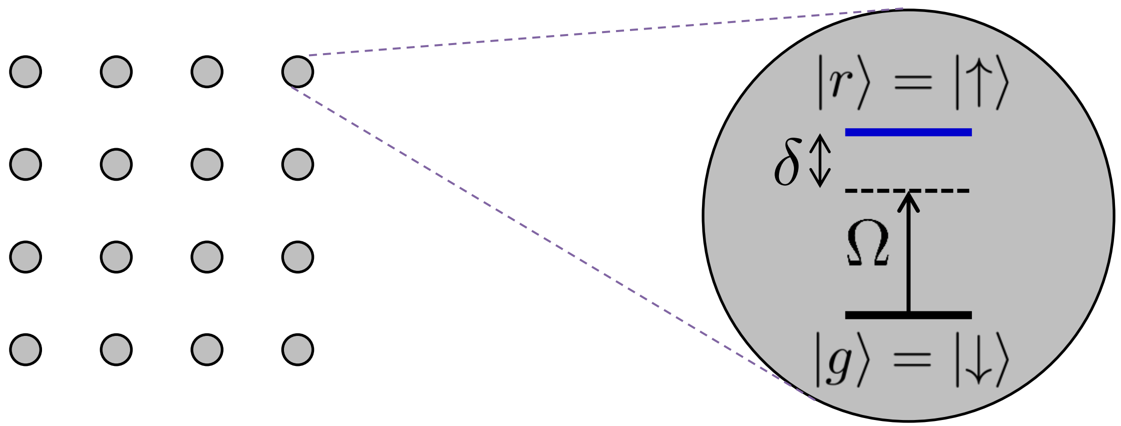


Questions?

2. Quantum simulation of spin Hamiltonians

Review:
A. Browaeys & T. Lahaye, Nature Phys. **16**, 132 (2020)

Blockade: quantum Ising model

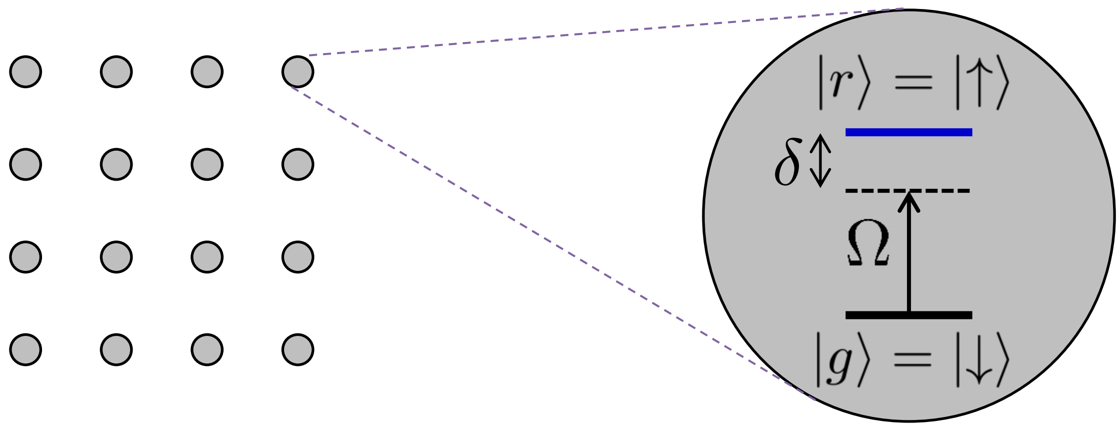


$$n^i = |r_i\rangle \langle r_i|$$

$$H = \sum_i \left(\frac{\hbar\Omega}{2}\sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Rabi frequency Laser detuning van der Waals interactions

Blockade: quantum Ising model



$$n^i = |r_i\rangle \langle r_i| = \left(1 + \sigma_z^i\right)/2$$

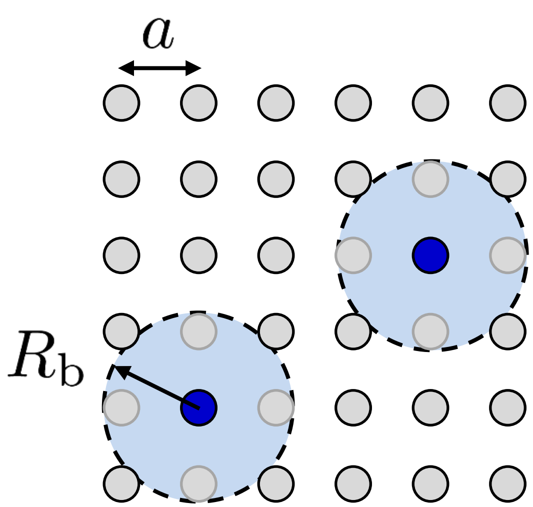
$$H = \sum_i \left(\frac{\hbar\Omega}{2}\sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Transverse B Longitudinal B Ising couplings

Ising model: adiabatic preparation

$$R_{\mathrm{b}} = 1.2a$$

Nearest-neighbor blockade



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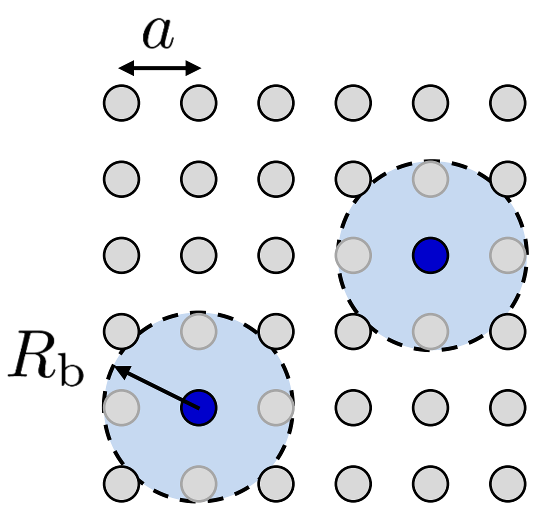
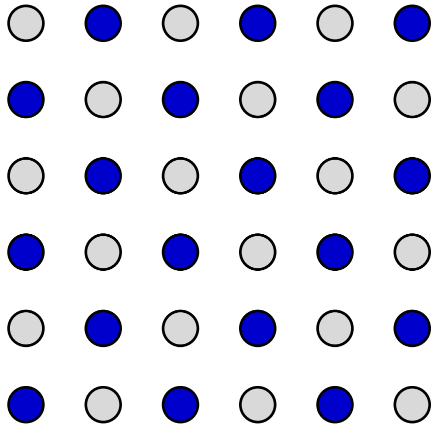


Antiferromagnetic ground state



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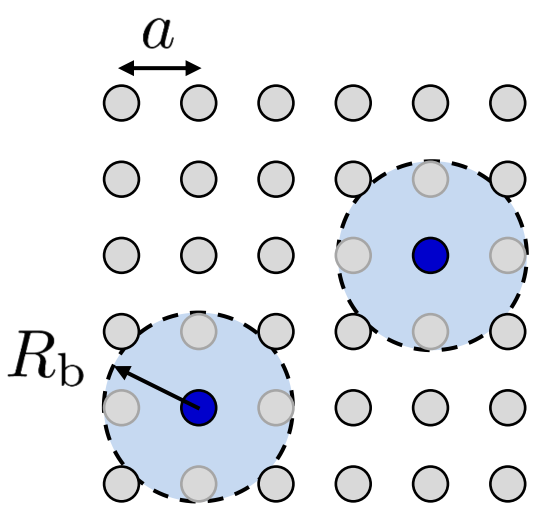

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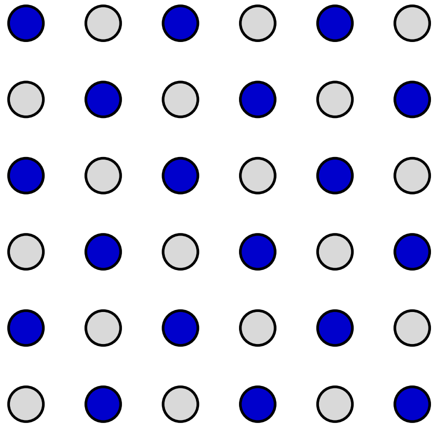
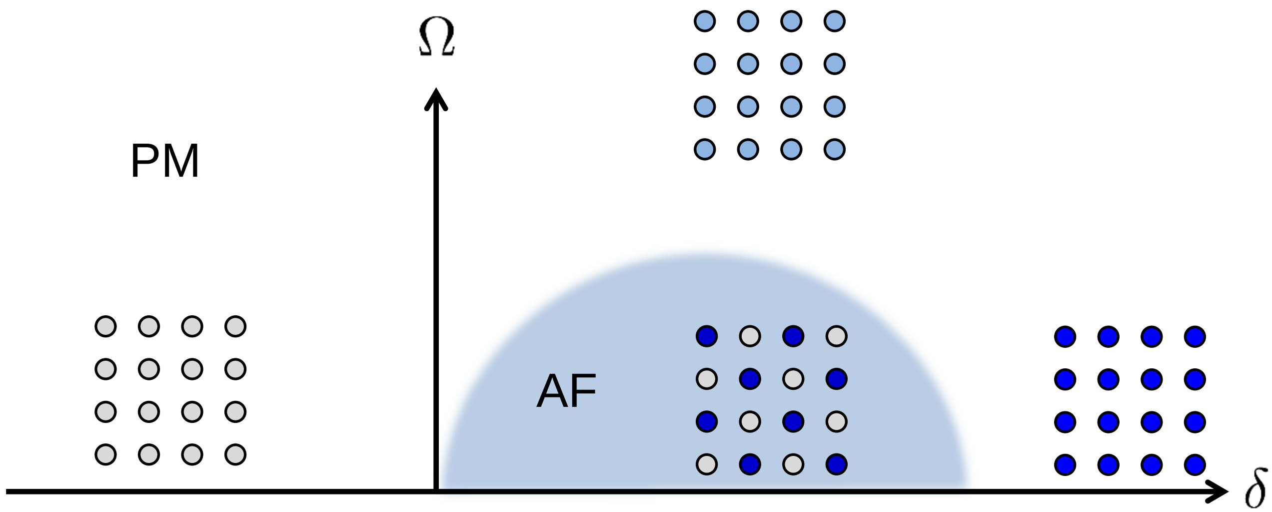


Ising model: adiabatic preparation

Ising AF phase diagram



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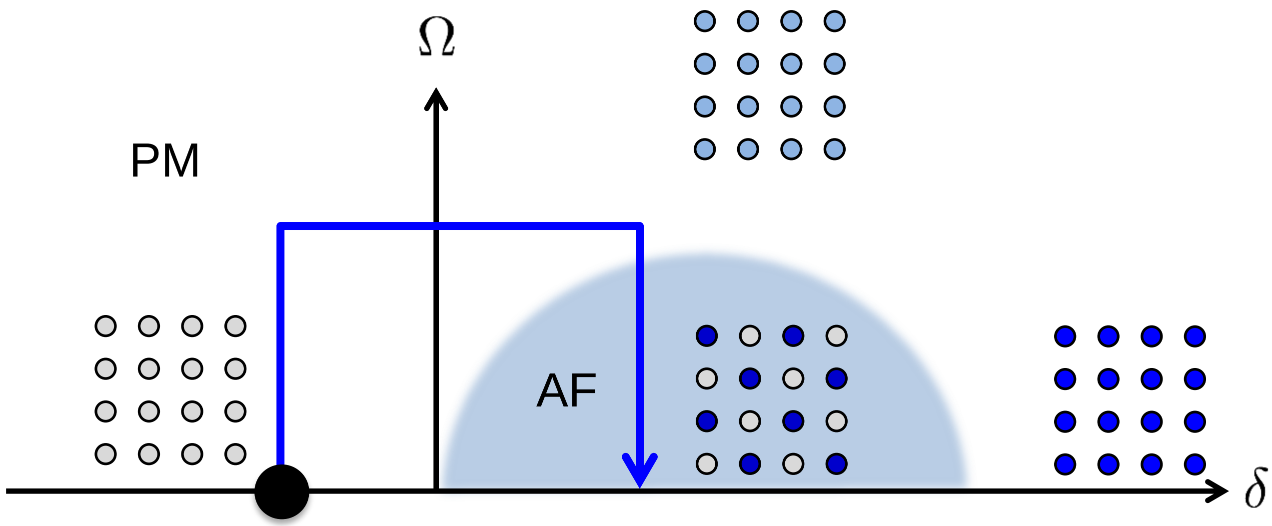


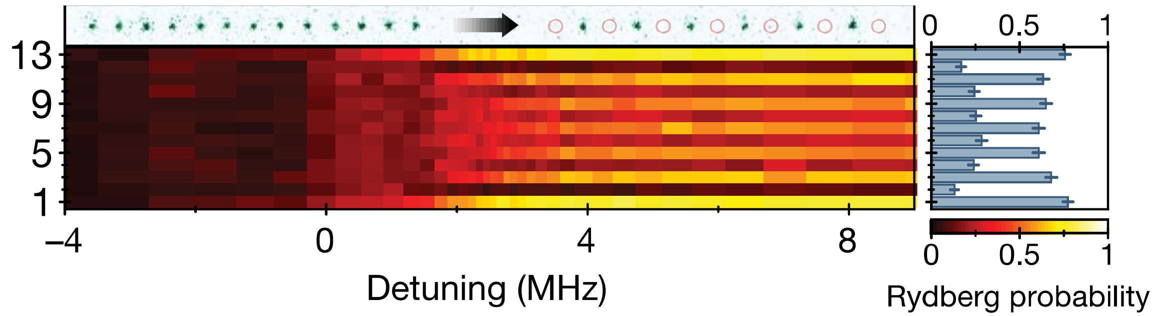
$$H = \sum_i \left(\frac{\hbar\Omega}{2}\sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Vary slowly Rabi frequency and detuning
to explore the phase diagram

Previous work

1D chains

Lukin group, Nature 2018



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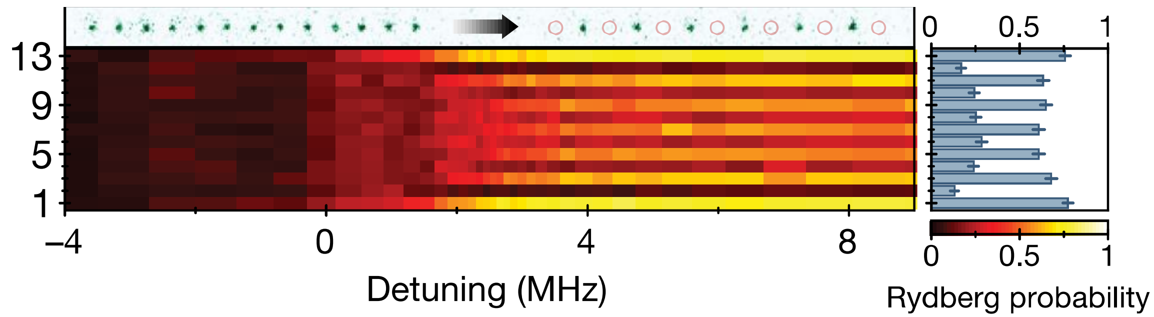
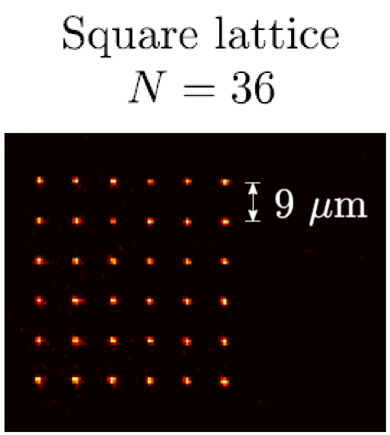
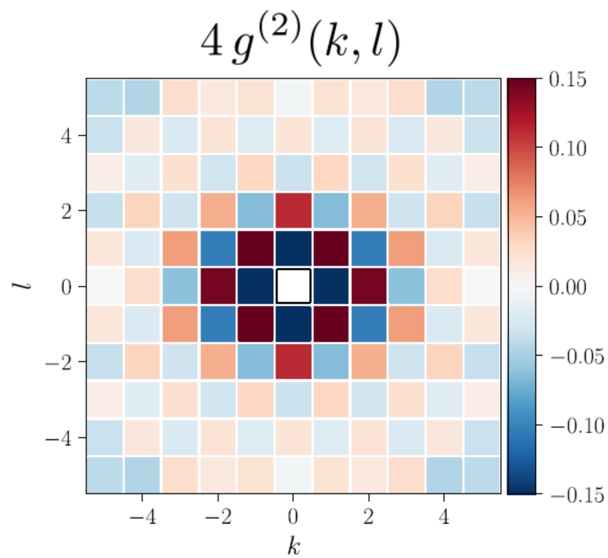


2D arrays





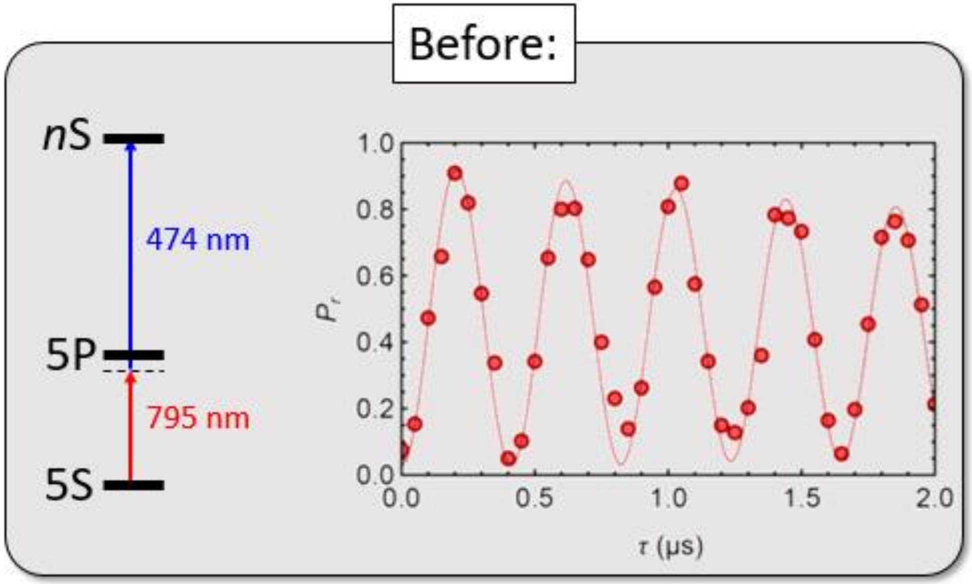
- Onset of AF correlations
- Correlation length

$$\xi \simeq 1.5a$$

Limited by dephasing & sp. em.

V. Lienhard *et al.*, Phys. Rev. X **8**, 021070 (2018)
See also Bakr group

Improved Rydberg excitation



"Regular" scheme

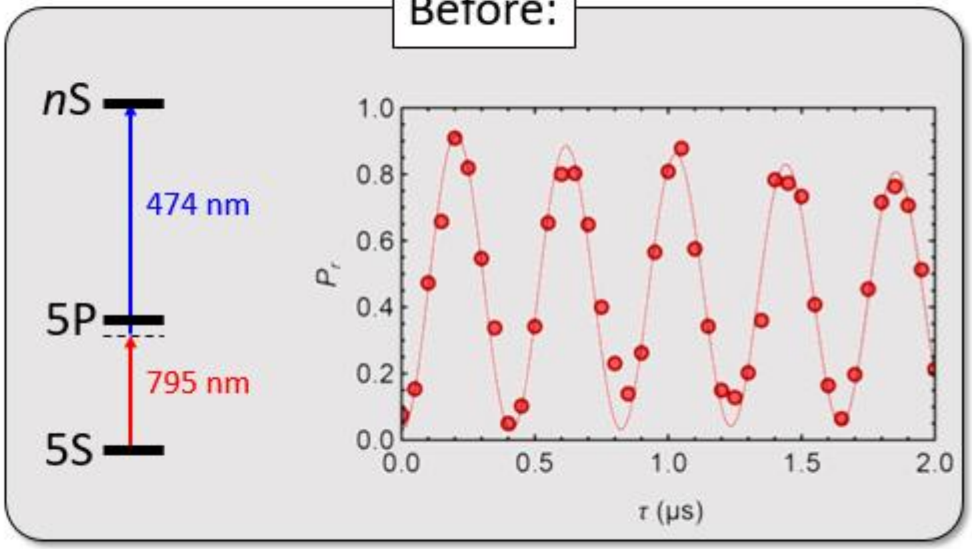
Laser diodes: phase noise

Intermediate state 5P: short lifetime

S. de Léséleuc *et al.*,
PRA **97**, 053803 (2018)

Improved Rydberg excitation

Before:



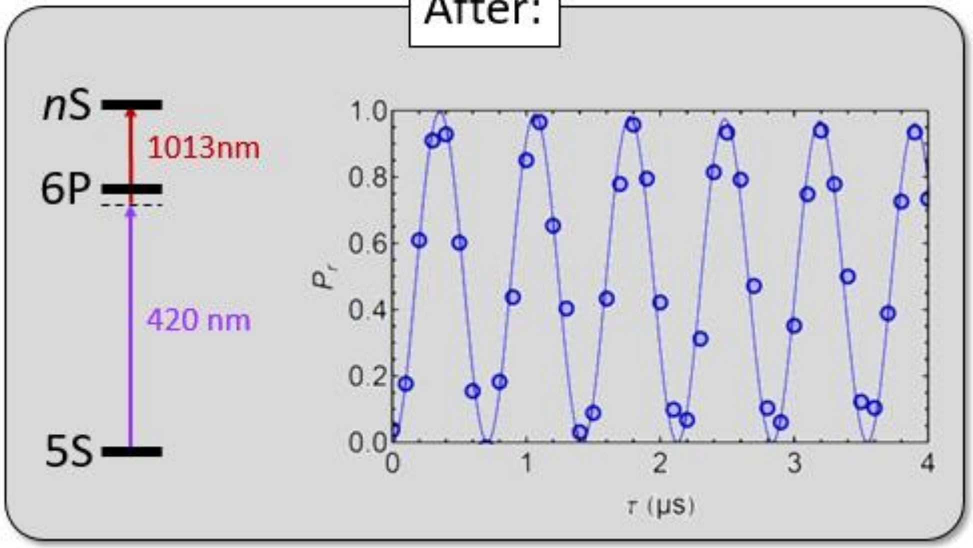
"Regular" scheme

Laser diodes: phase noise

Intermediate state 5P: short lifetime

S. de Léséleuc *et al.*,
PRA **97**, 053803 (2018)

After:



"Inverted" scheme

420nm: Ti:Sapph + doubling cavity
1013nm: Ti:Sapph + fiber amplifier

- Less laser phase noise
- 5 times less spontaneous emission via intermediate state

Programmable quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms

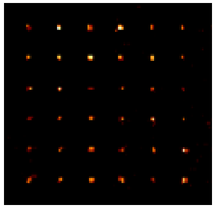
P. Scholl *et al.*, arXiv:2012.12268

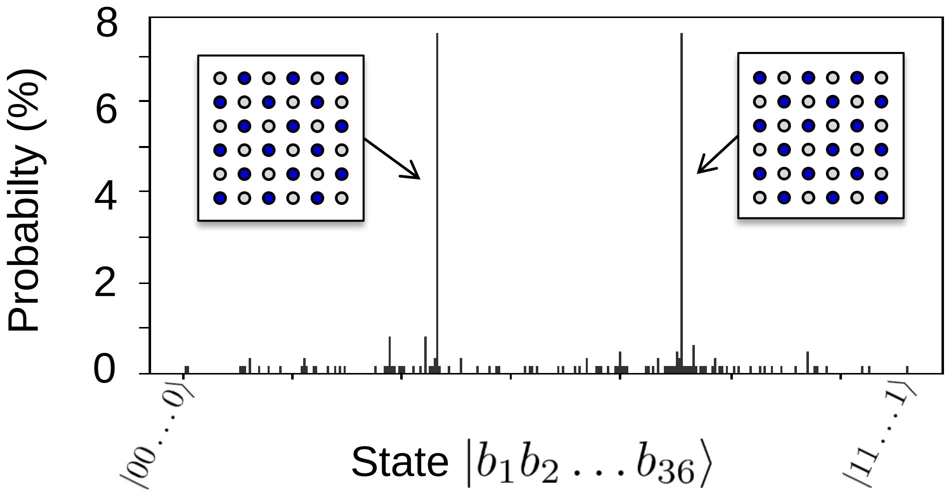
Similar results at Harvard: S. Ebadi *et al.*, arXiv:2012.12281

Theory: Andreas Läuchli, Innsbruck

‘Adiabatic’ preparation on a square array

6×6
square array





$2^{36} \approx 7.10^{10}$ states!

‘Adiabatic’ preparation on a square array

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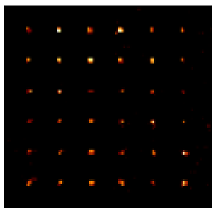
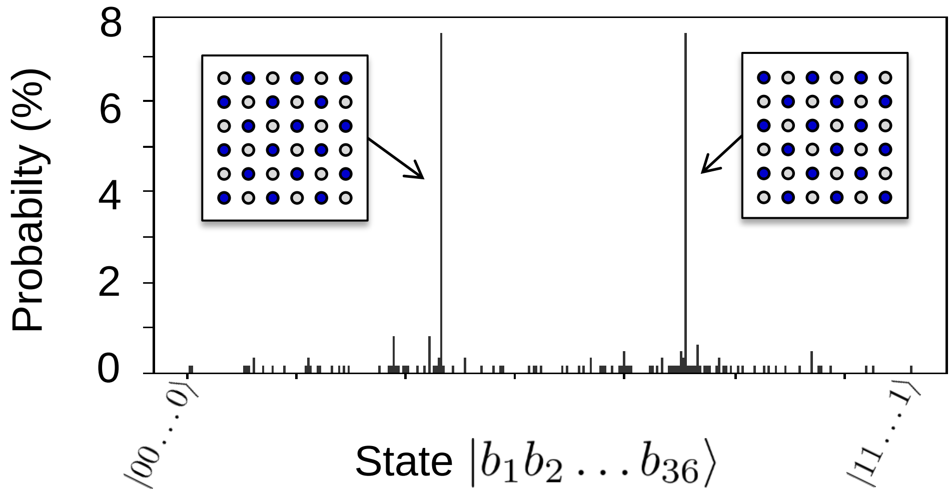
square array





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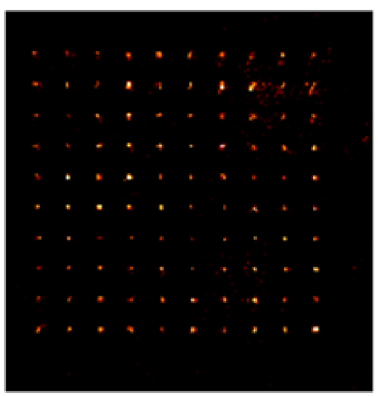
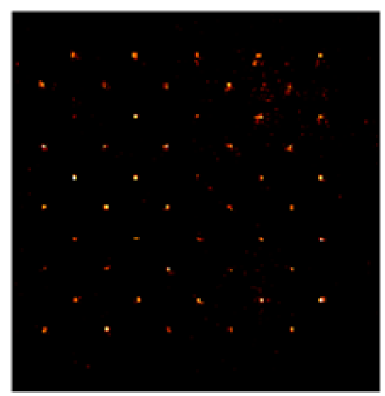
10×10



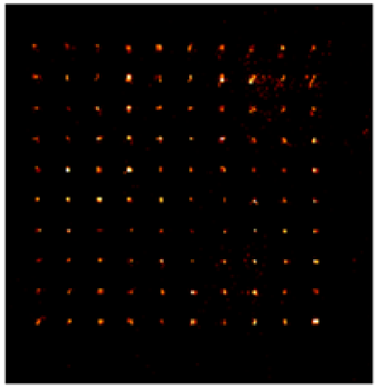
sweep



Perfect AF ordering!

(1 shot in 500)

‘Adiabatic’ preparation



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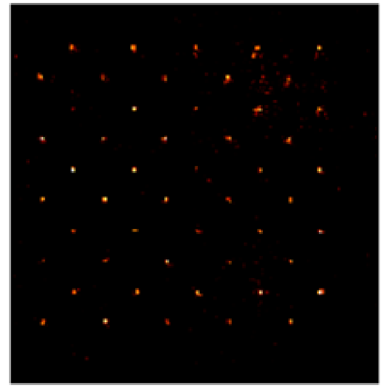

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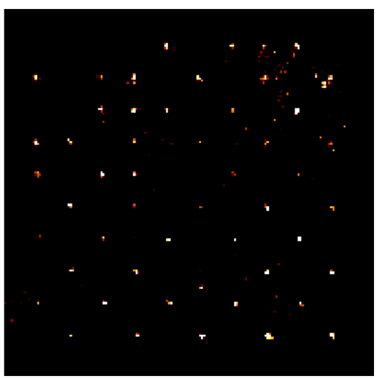
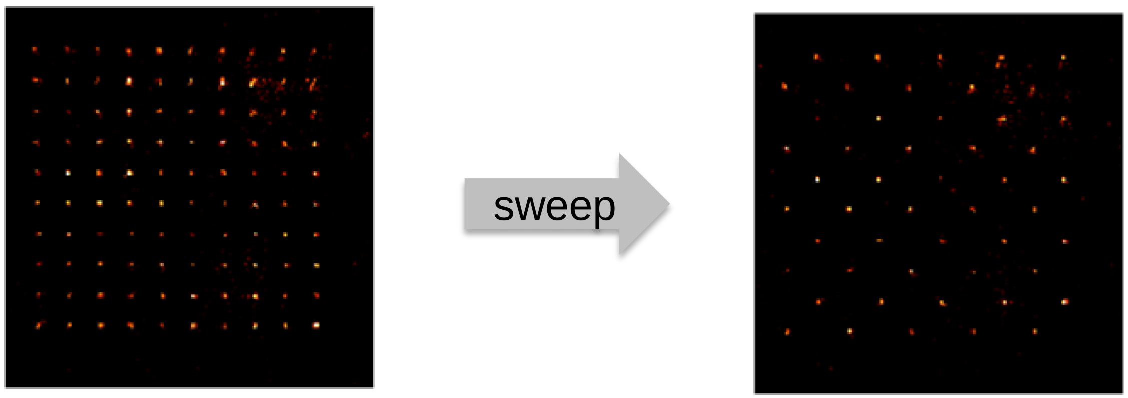


Domain sizes



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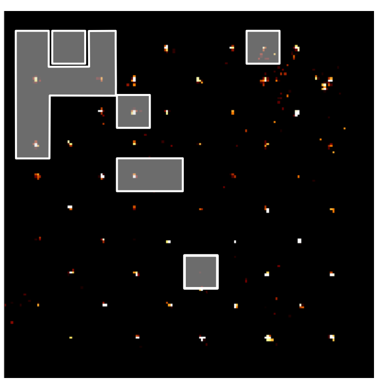
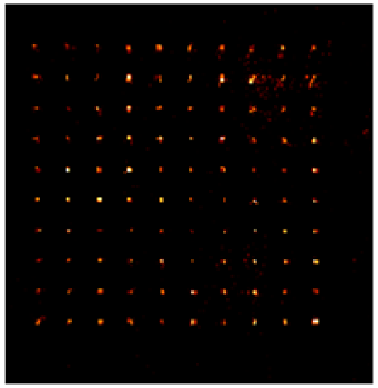


Size of largest AF domain:
$s_{\max} = 87$

Domain sizes



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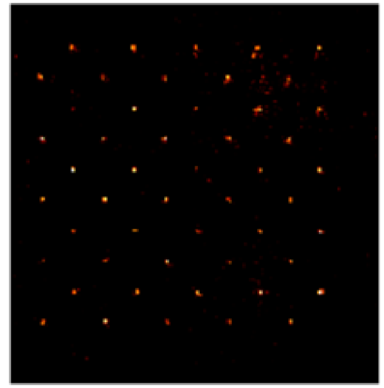

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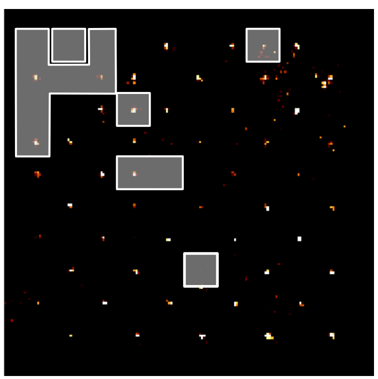

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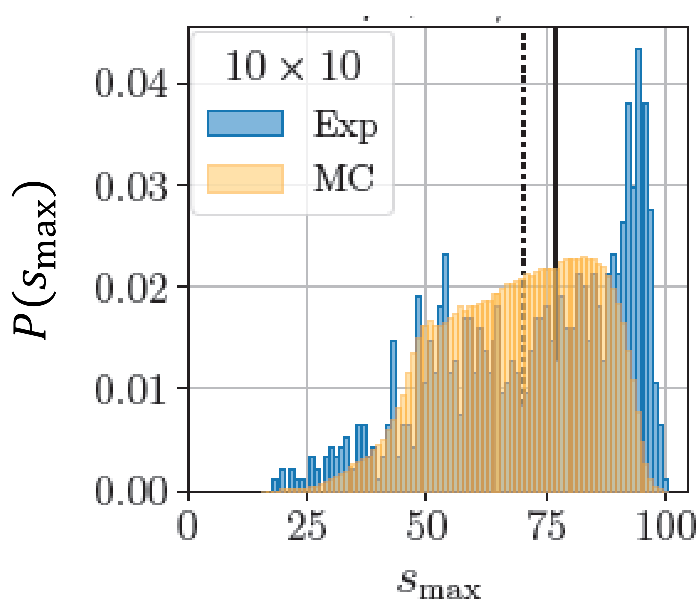
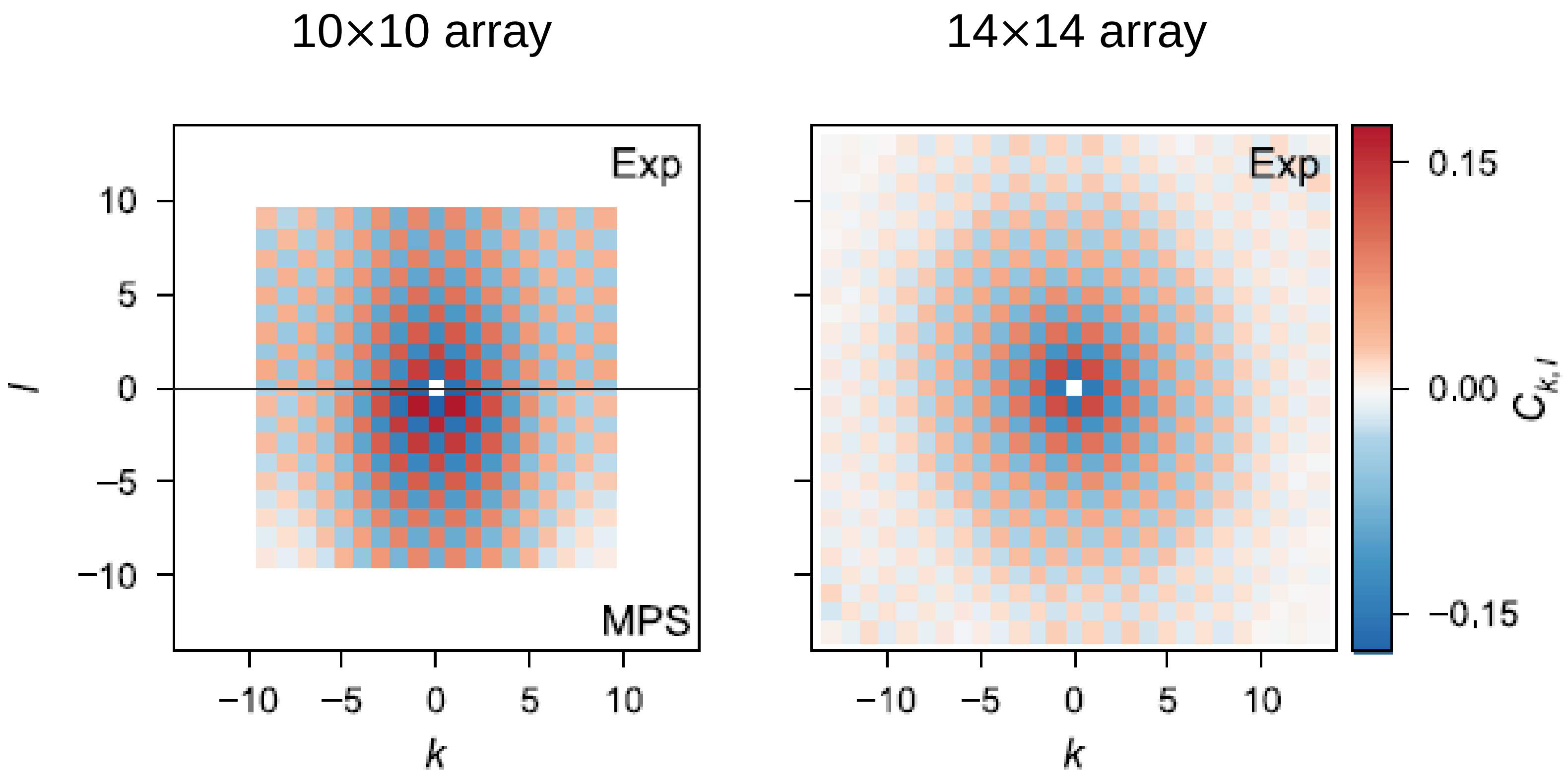


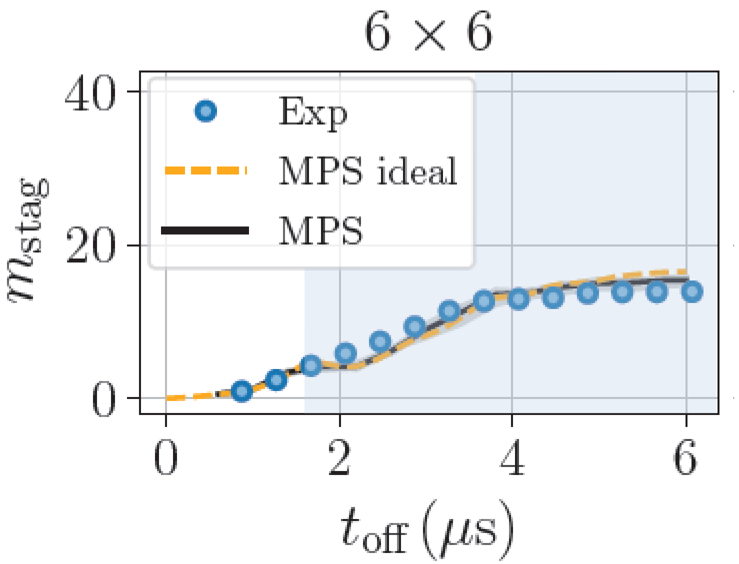
Correlation functions

$$C_{k,l} = \frac{1}{N_{k,l}} \sum_{i,j} \langle n_i n_j \rangle - \langle n_i \rangle \langle n_j \rangle$$



Dynamics along the sweep

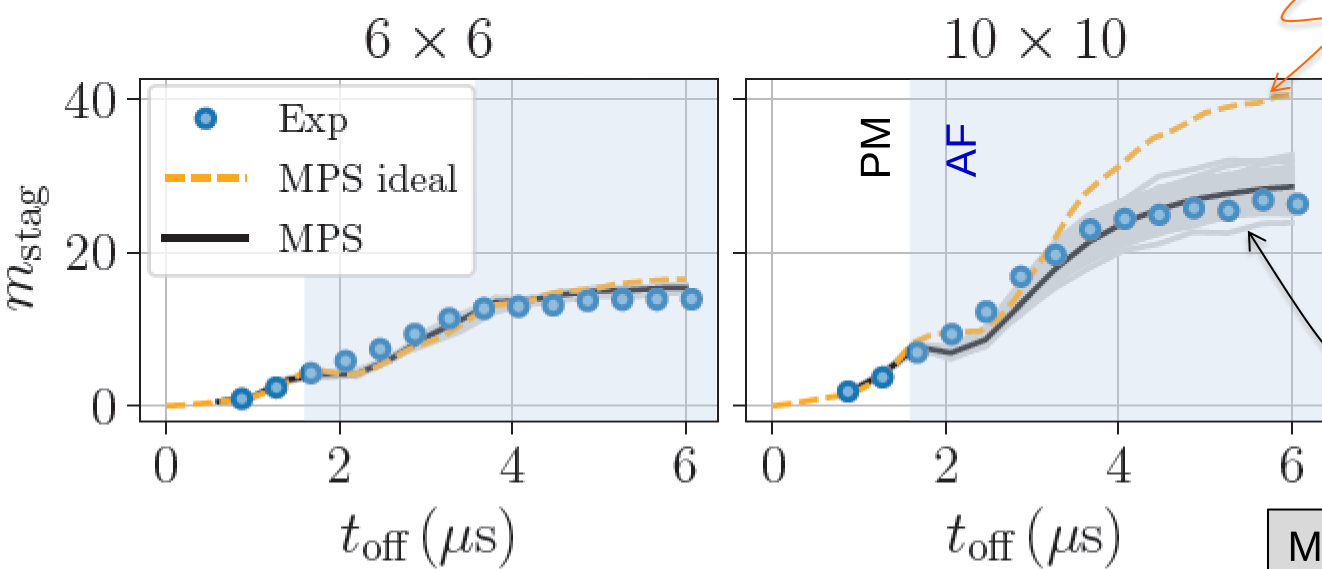
MPS simulations, up to 10x10 spins



Dynamics along the sweep

MPS simulations, up to 10x10 spins

MPS for ideal Hamiltonian



MPS with measured exp. imperfections (positional disorder + beam inhomogeneity) but no decoherence

Dynamics along the sweep

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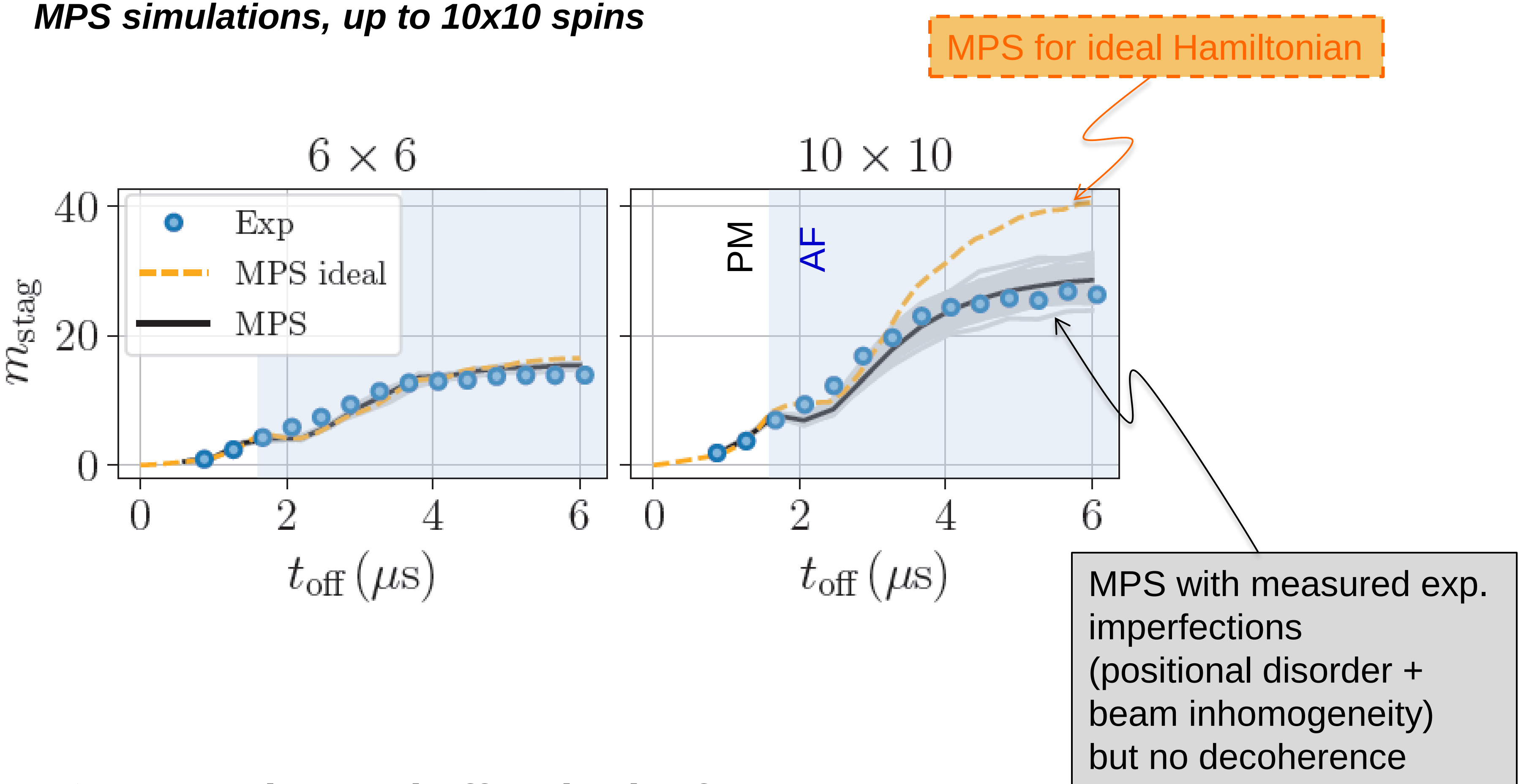
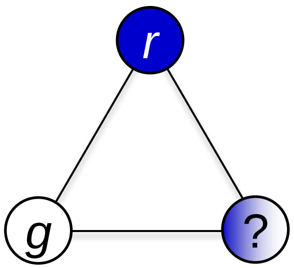


➢ ***Experimental effort in the future:***
beam homogeneity, better arrays

Triangular lattice

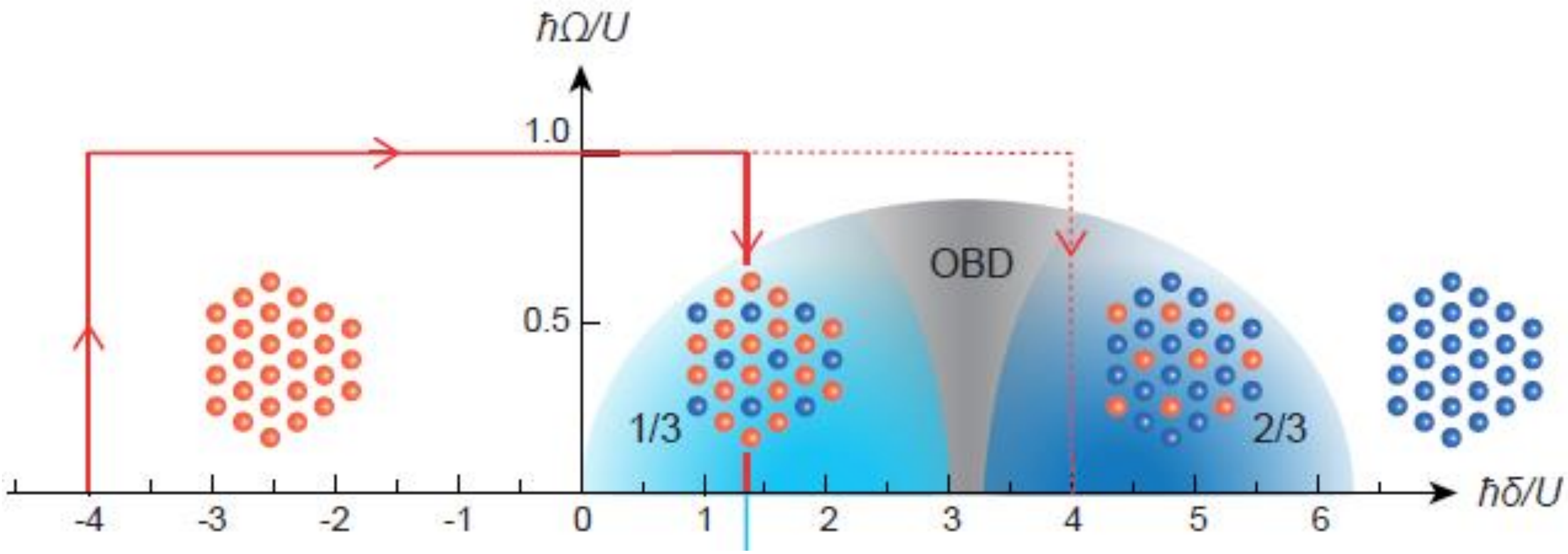
Antiferromagnetism is frustrated!



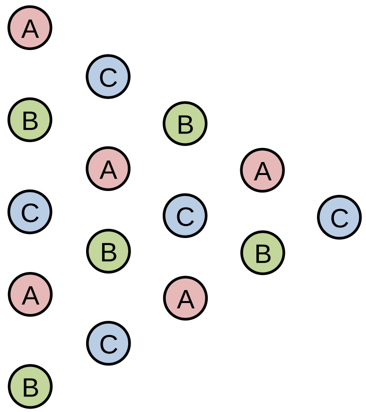
Classical ground state at half filling has a macroscopic degeneracy [Wannier, Phys. Rev. 1950]

Triangular lattice

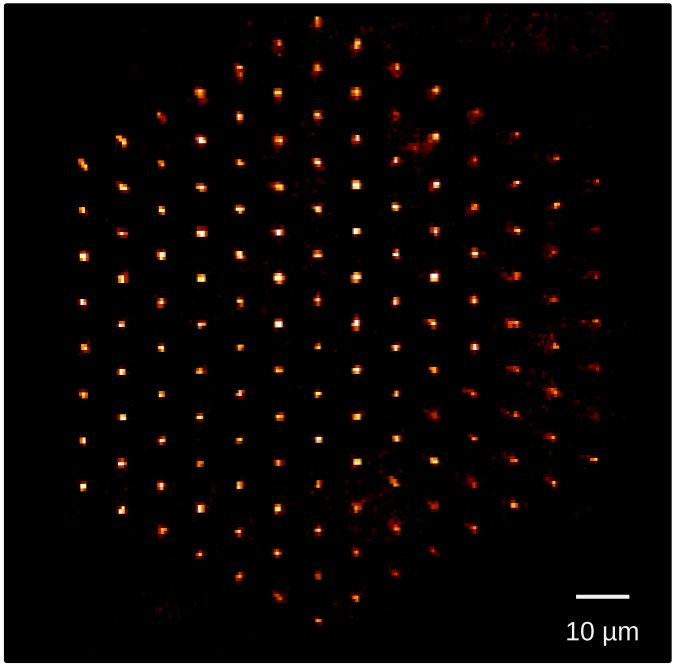
Phase diagram for an infinite lattice



Ordered phases at 1/3 and 2/3 Rydberg fraction:
orgnaization on the A, B, C sub-lattices

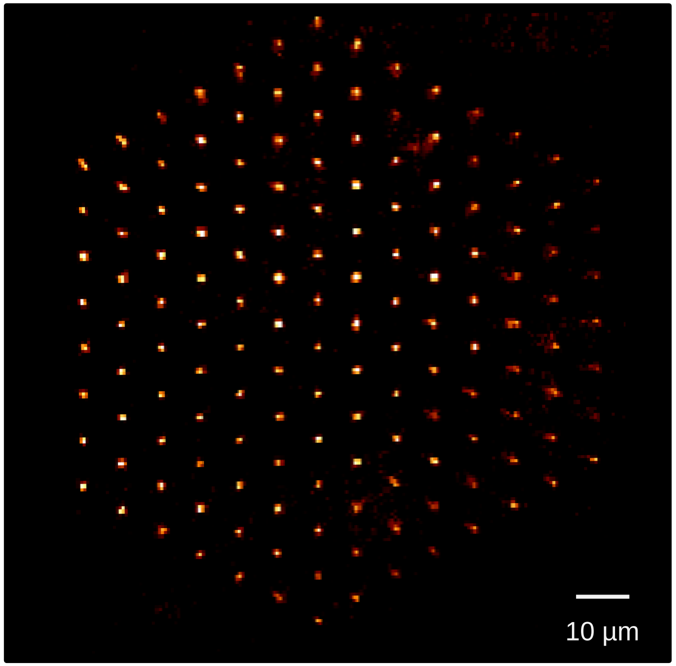


Ordering on a triangular lattice



$N = 147$

Ordering on a triangular lattice



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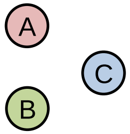
Triangular arrays with equal numbers of sites in A, B, C sub-lattices



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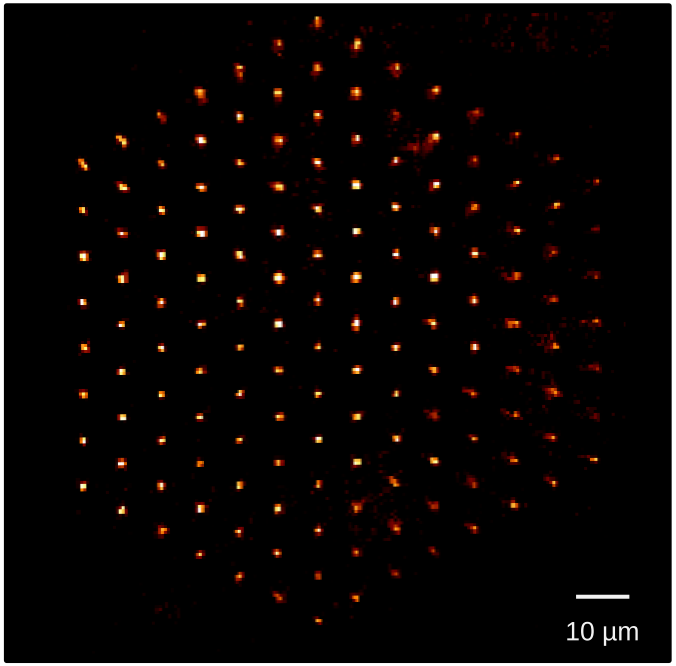

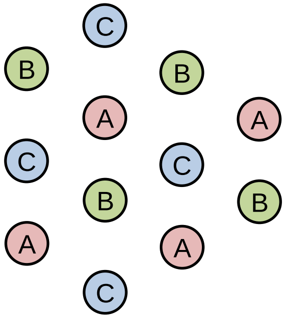

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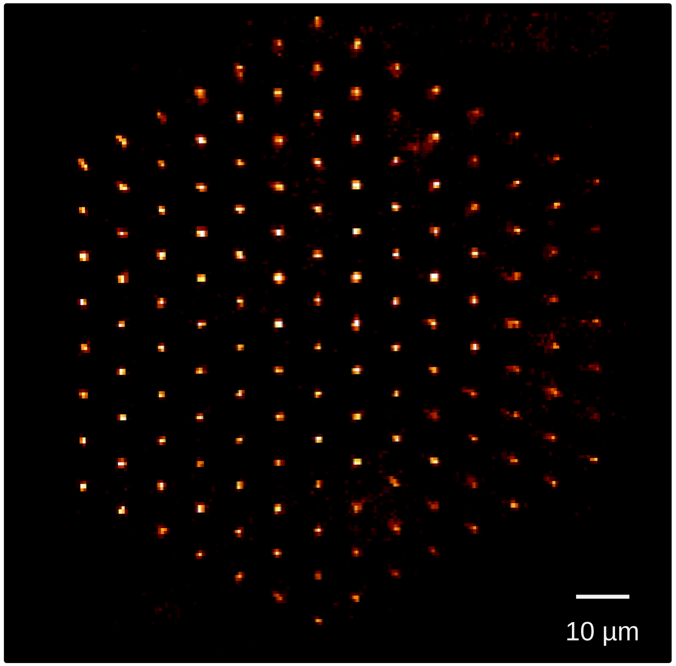

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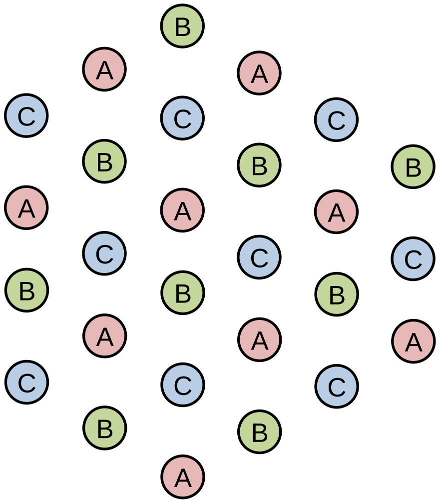

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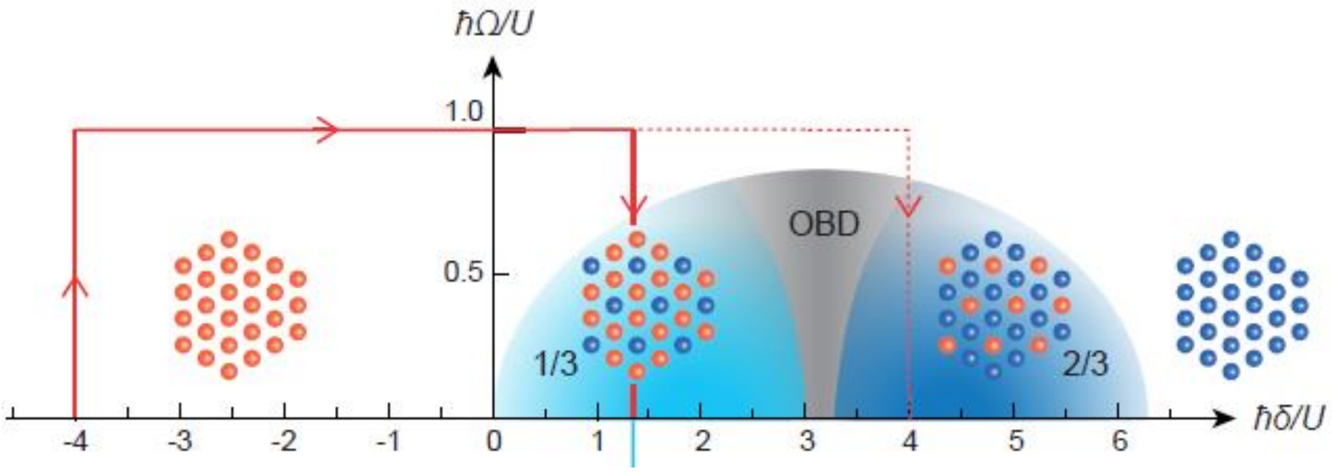
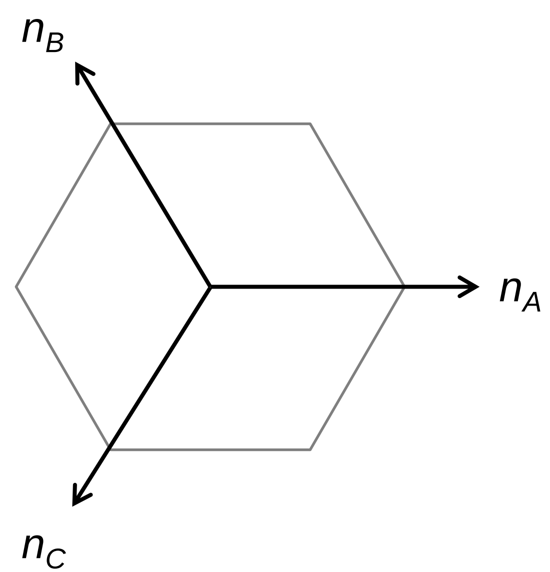


"Sub-lattice histograms": plot in complex plane

$$n_A + n_B e^{2i\pi/3} + n_C e^{-2i\pi/3}$$

n_X = number of Rydberg atoms on sub-lattice X



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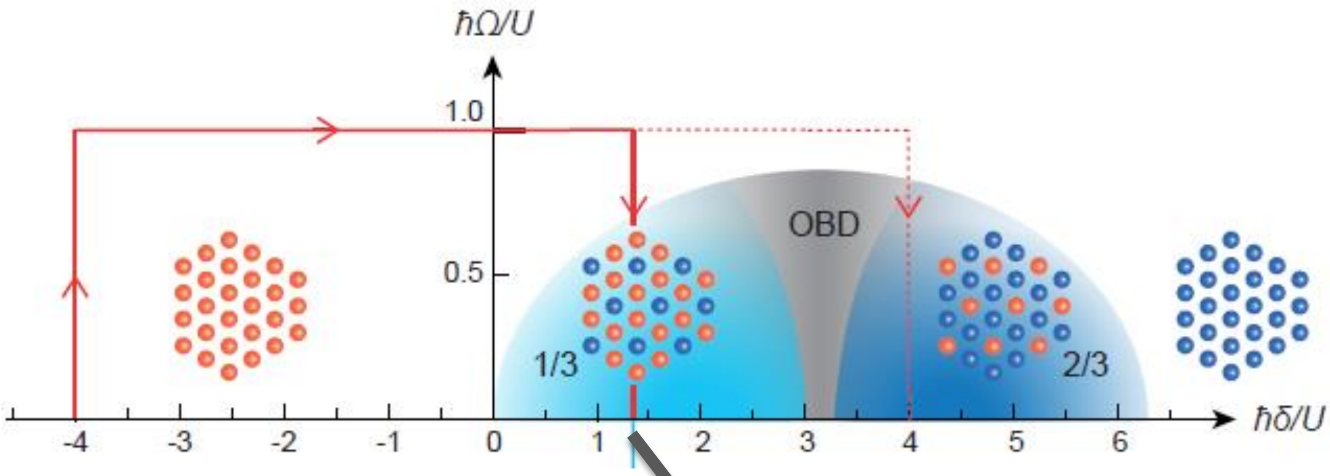

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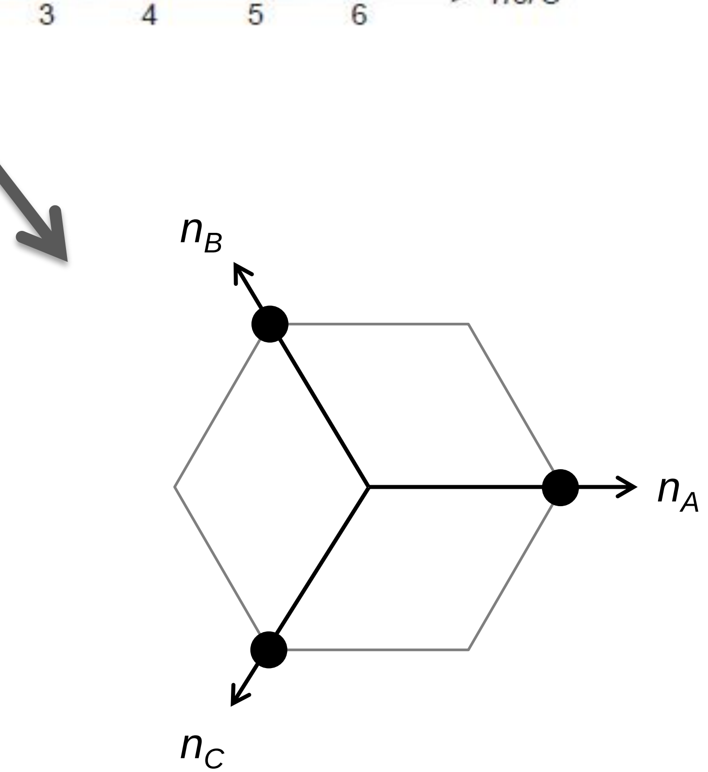

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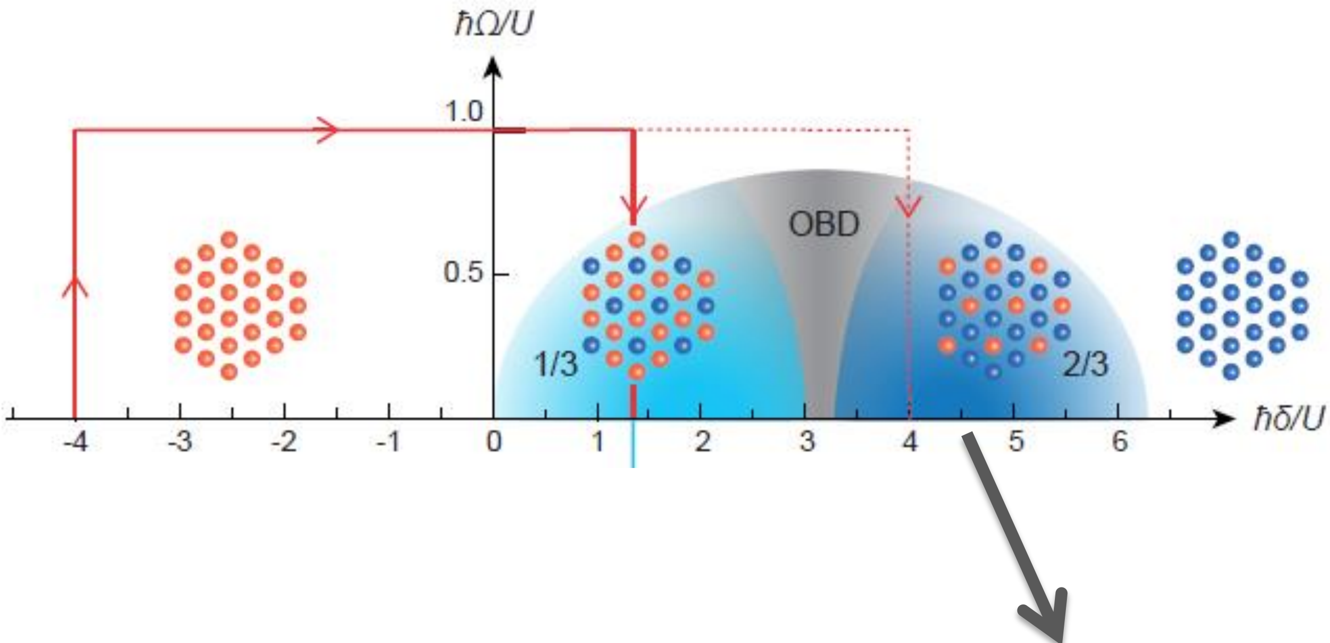

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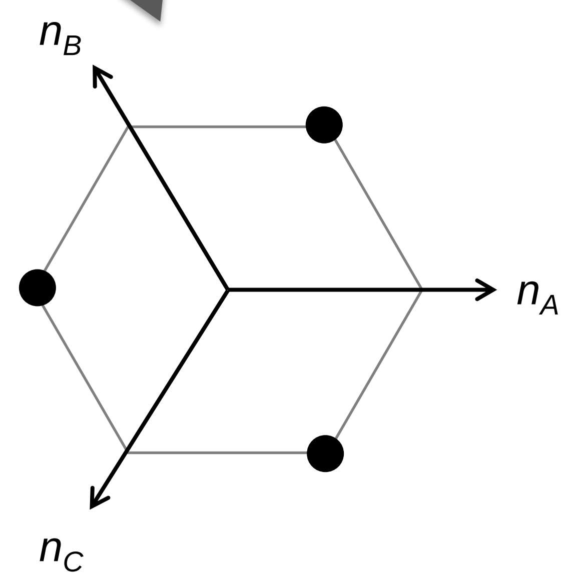
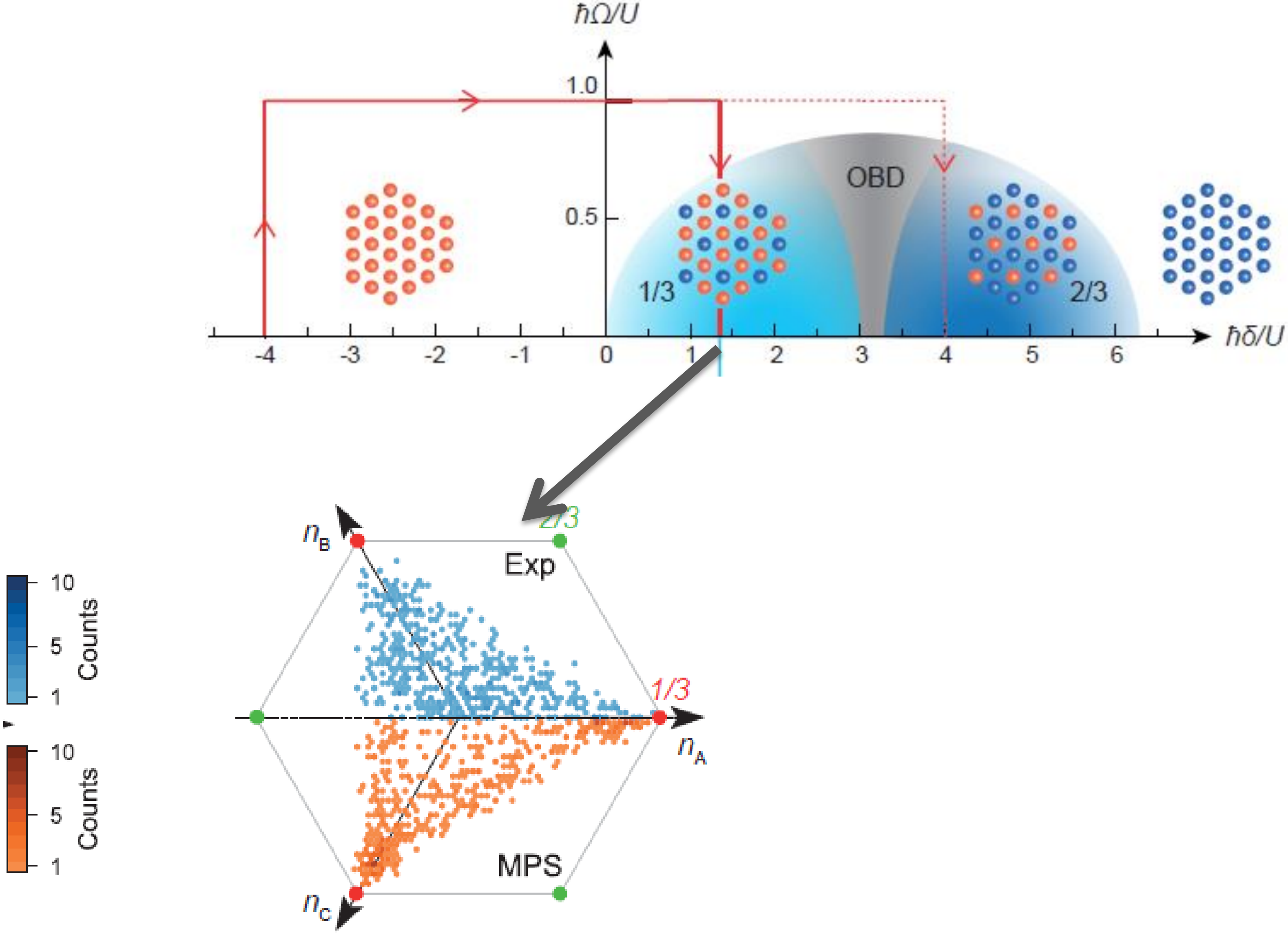


Let's run our simulator! 1/3 phase



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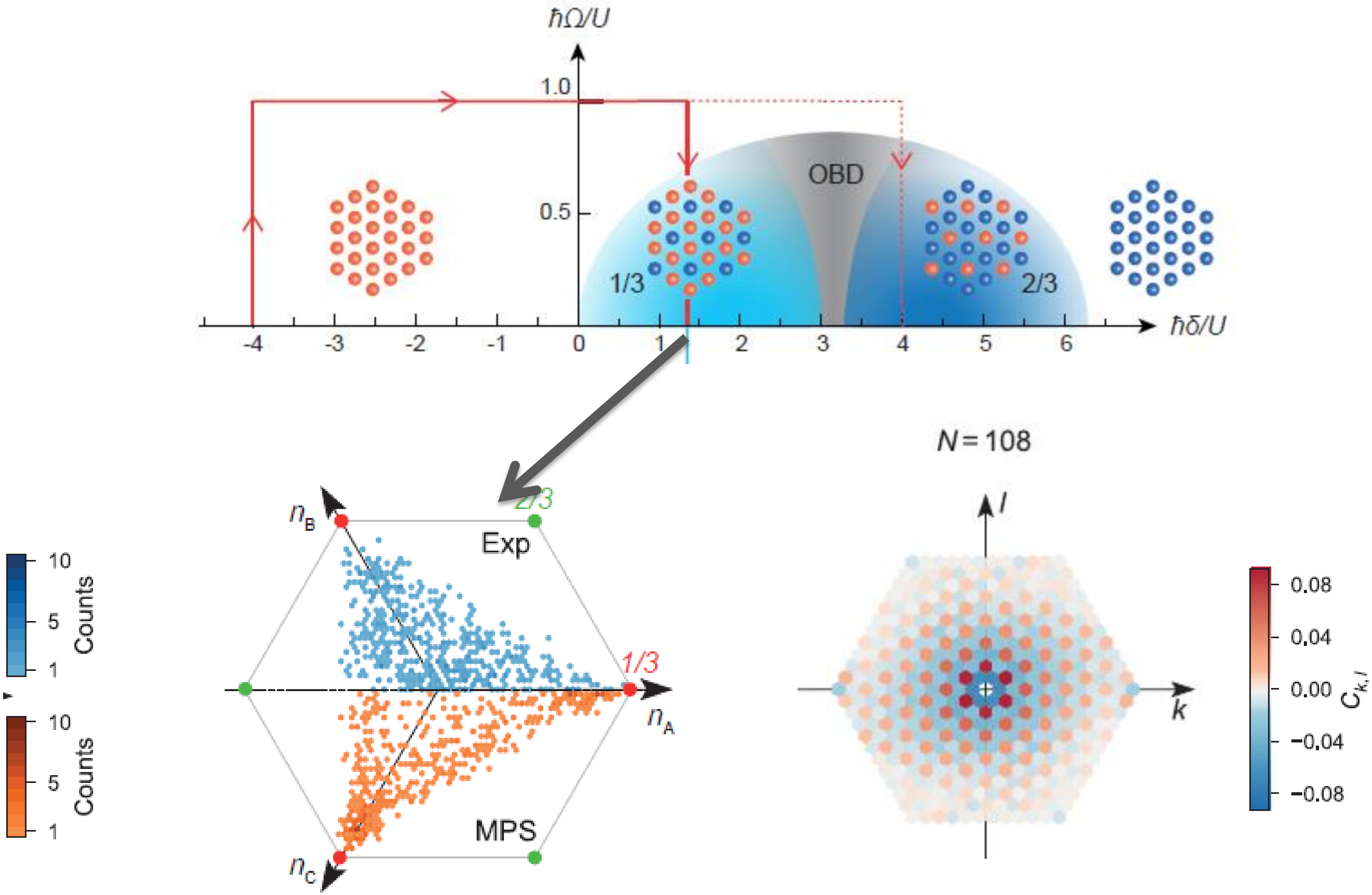
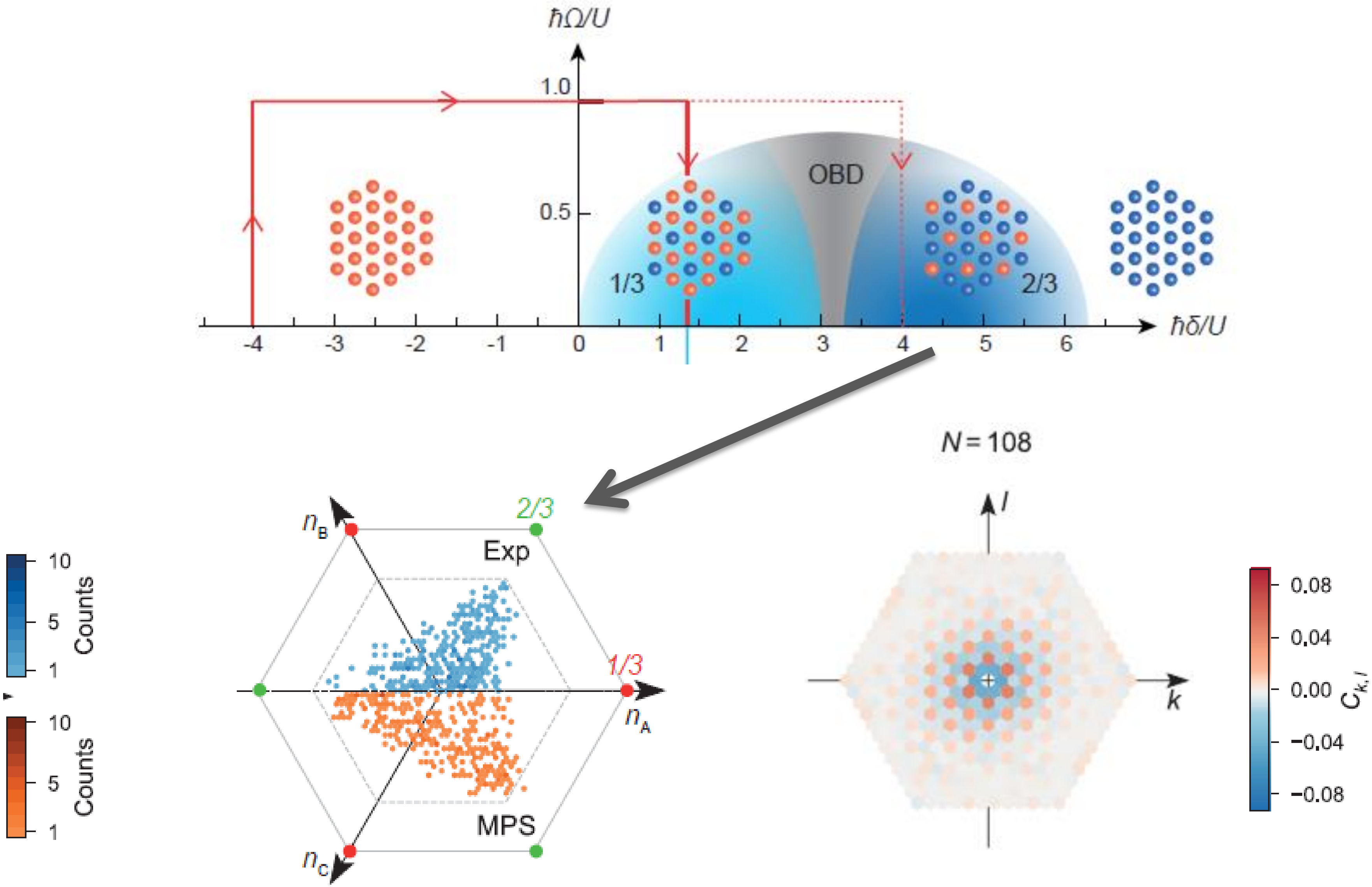


Let's run our simulator! 2/3 phase



Questions?

XY spin models for realizing synthetic topological matter

S. de Léséleuc *et al*., Science **365**, 775 (2019)

V. Lienhard *et al*., PRX **10**, 021031 (2020)

Theory: Hans Peter Büchler, Stuttgart

XY spin models

- Use *resonant* dipole-dipole interaction: XY model

- Excitation exchange: map onto a hopping particle

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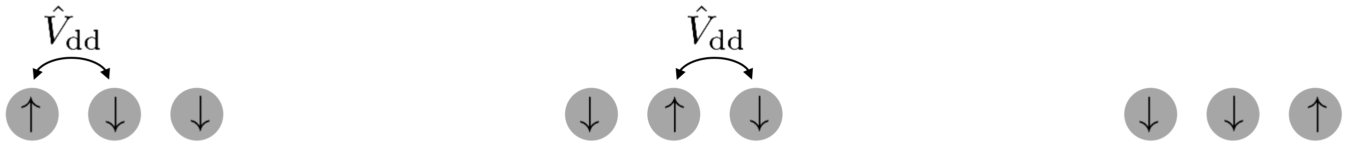

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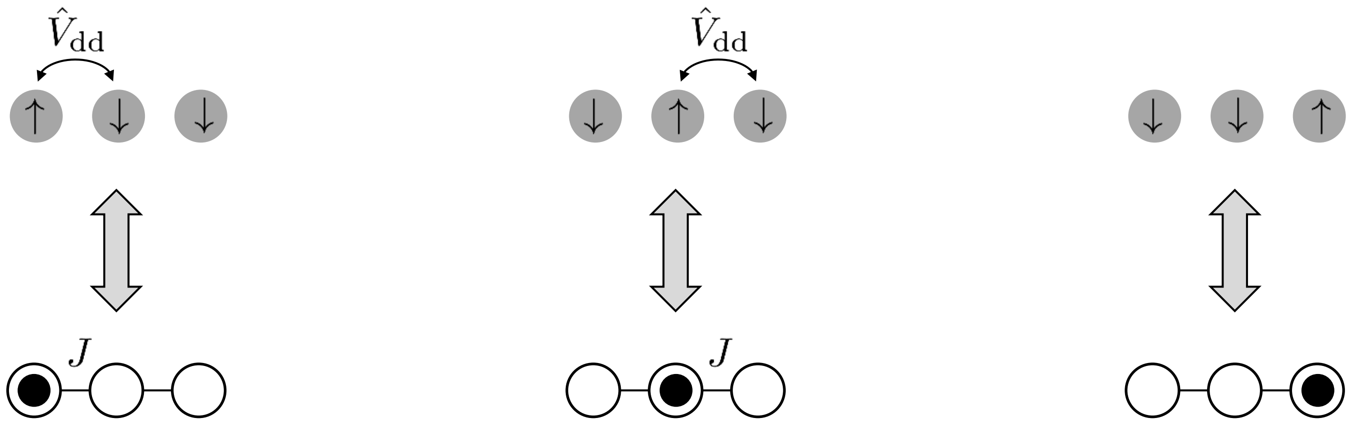

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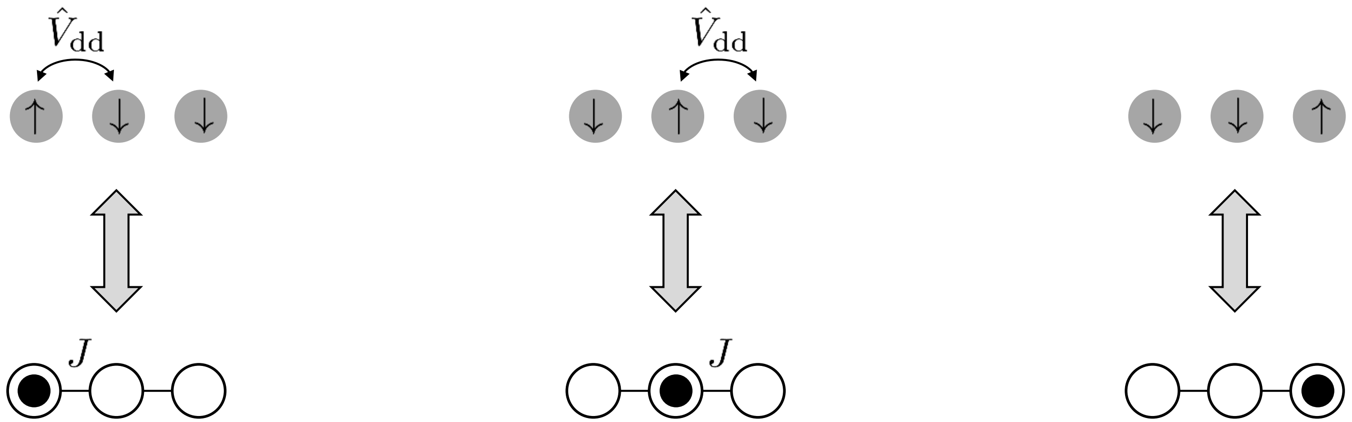
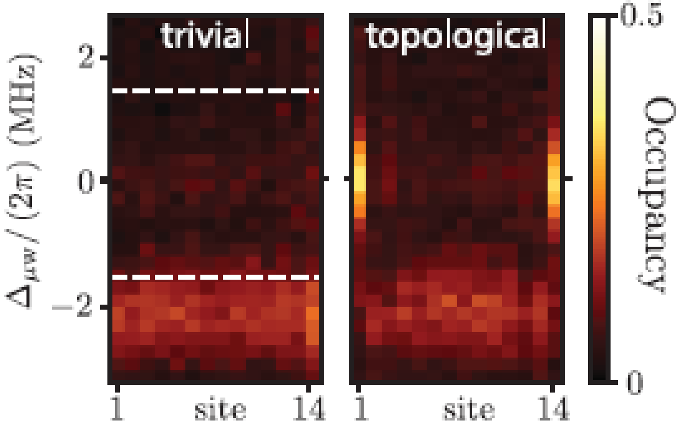


- Equivalent to a system of *hard-core* bosons

Topological matter

- 1d: SSH model with hard-core bosons:
  Symmetry-protected topological phase

  S. de Léséleuc *et al*., Science **365**, 775 (2019)



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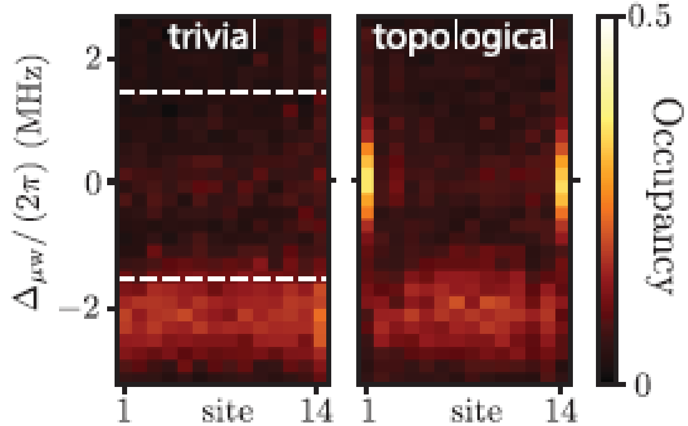

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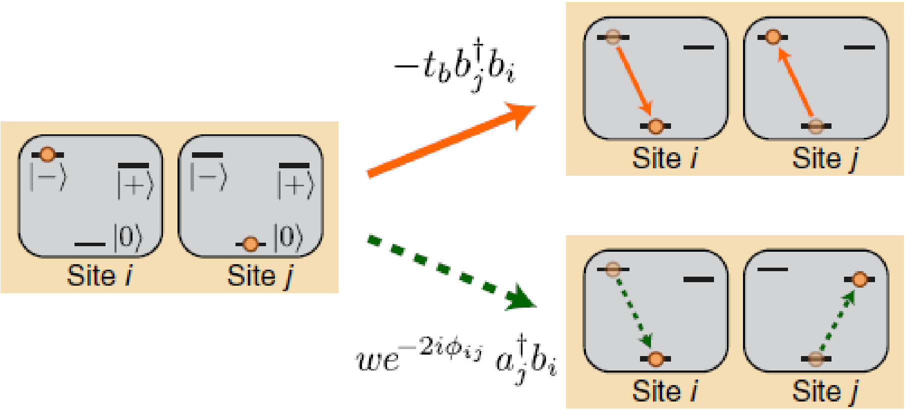
  V. Lienhard *et al*., PRX **10**, 021031 (2020)



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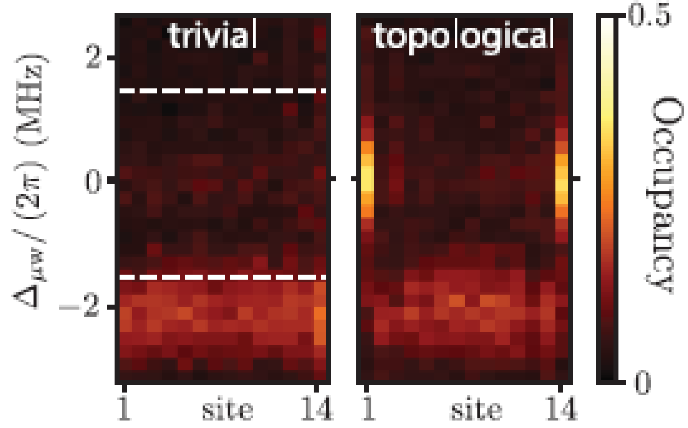

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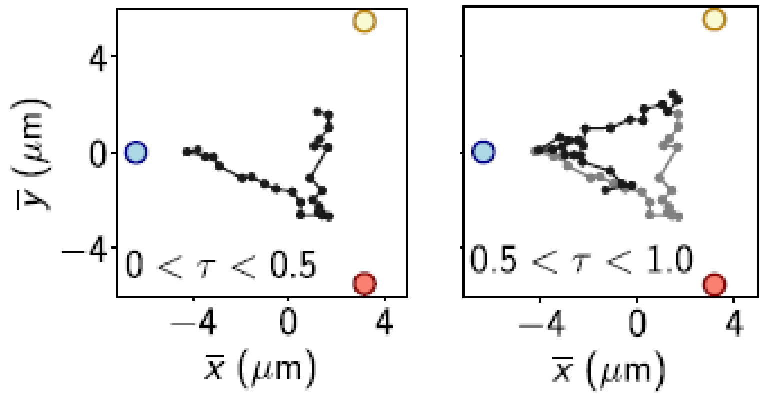
  Chiral motion of a spin excitation



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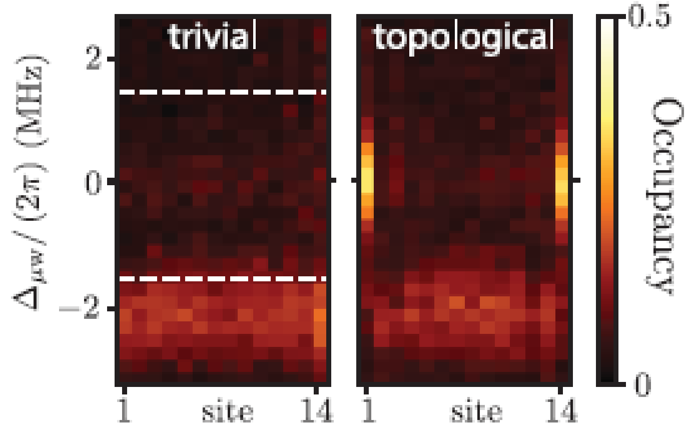

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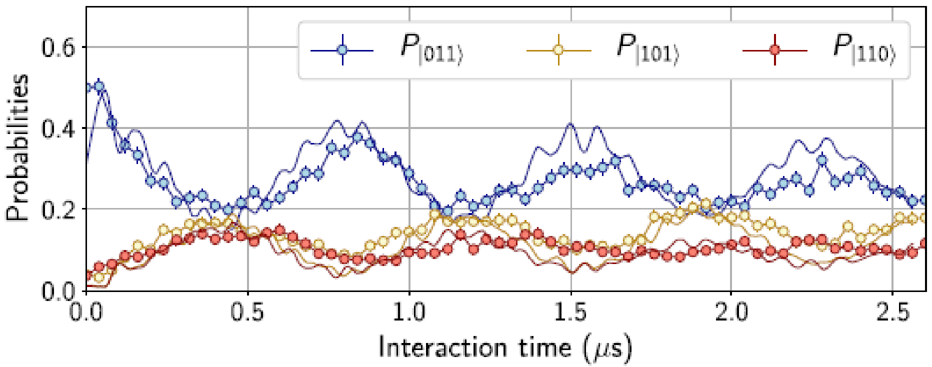
  Two spin excitations: no chiral motion!



Conclusion

- ✓ Rydberg arrays: ideal platform for quantum simulation of spin models
- ✓ Scalability to 1000 spins realistic in near term (cryogenic setup)
- ✓ Fidelities steadily improving

Lukin group, Rb: CZ gate 97.4% [Levine *et al*., PRL 2019]
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- ✓ Now even startup companies!

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Thanks for your attention!