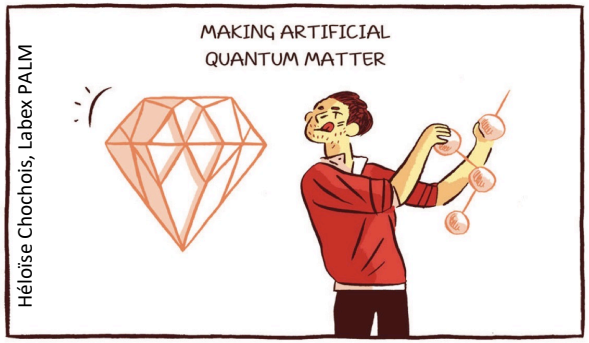
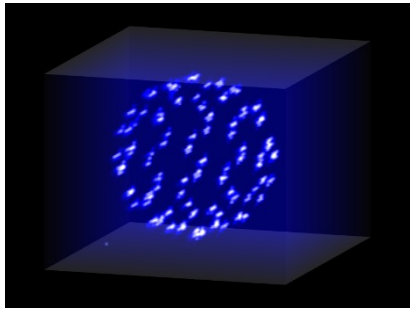
Many-body physics with arrays of atoms

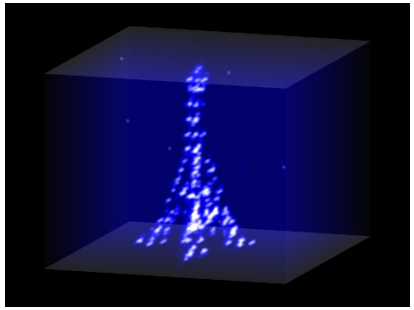


Antoine Browaeys

Laboratoire Charles Fabry,
Institut d'Optique, CNRS, FRANCE

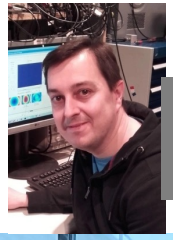
QCMB, November 23rd 2022



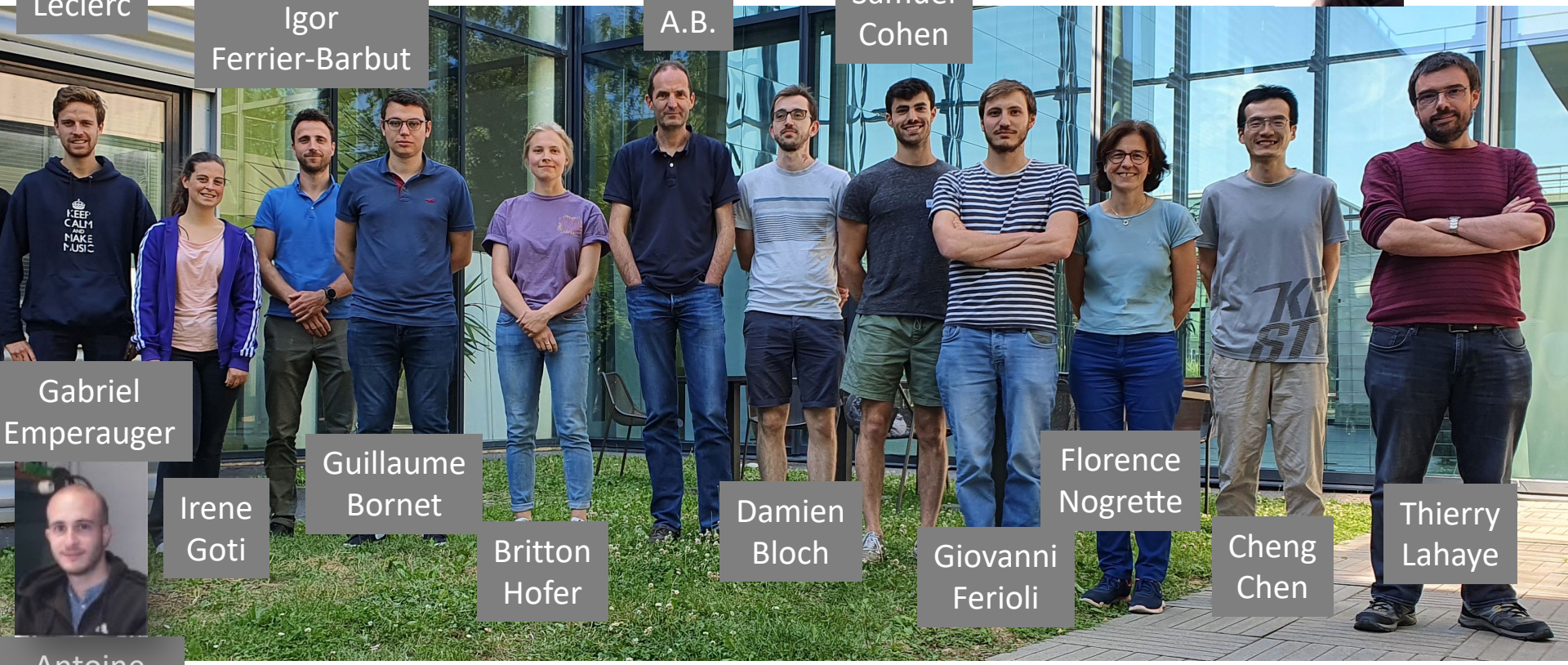


The team (atom-tweezers-io.org)

Lucas Leclerc



Daniel Barredo



Igor Ferrier-Barbut

A.B.

Samuel Cohen

Gabriel Emperauger

Antoine Glicenstein

Irene Goti

Guillaume Bornet

Britton Hofer

Damien Bloch

Giovanni Ferioli

Florence Nogrette

Cheng Chen

Thierry Lahaye

AGENCE INNOVATION DÉFENSE

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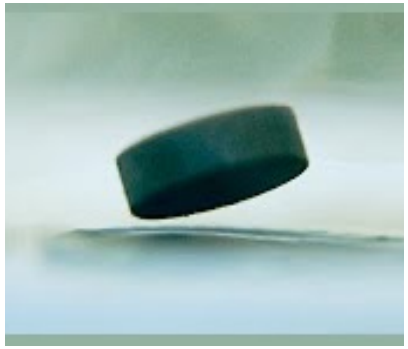
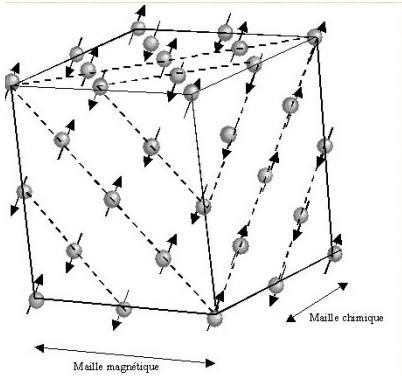
Many-body physics with synthetic matter

Goal: Understand ensembles of interacting quantum particles

superfluidity



superconductivity



magnetism

neutron star

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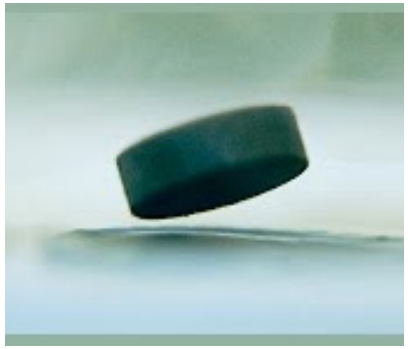

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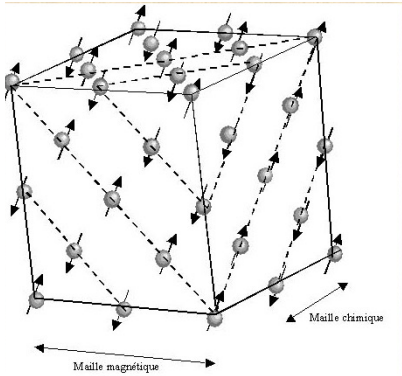

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Open questions: Phase diagram, dynamics (hard for N>40…)
Topology, disorder, entanglement,…

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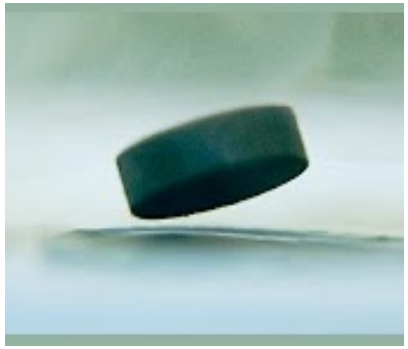

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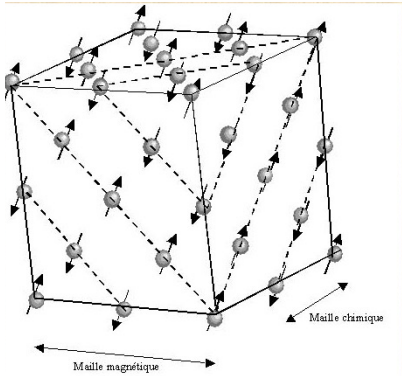

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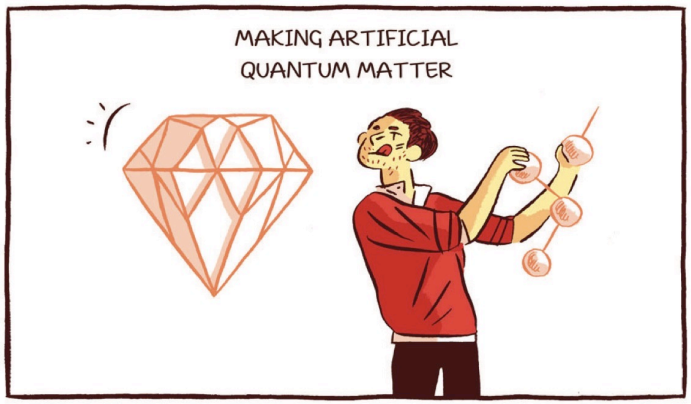

Héloïse Chochois, Labex PALM

R.P. Feynman

Use experimental control to

Implement **many-body Hamiltonians**
(including "mathematical" ones…)

Larger **tunability** than « real » systems

Many-body physics with synthetic matter

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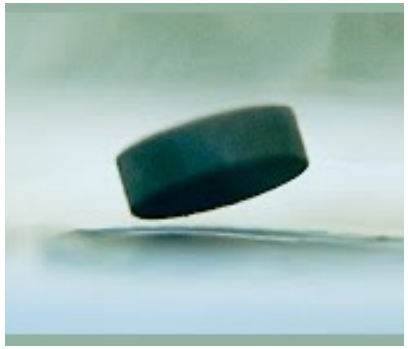

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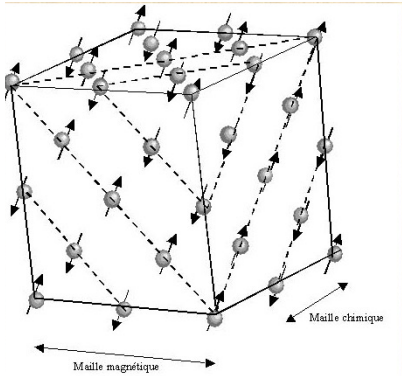

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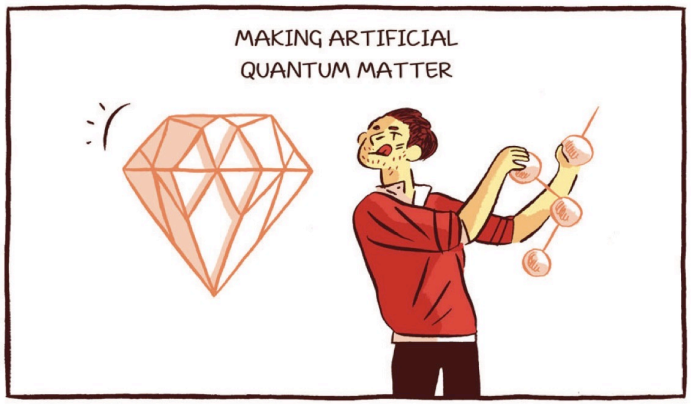

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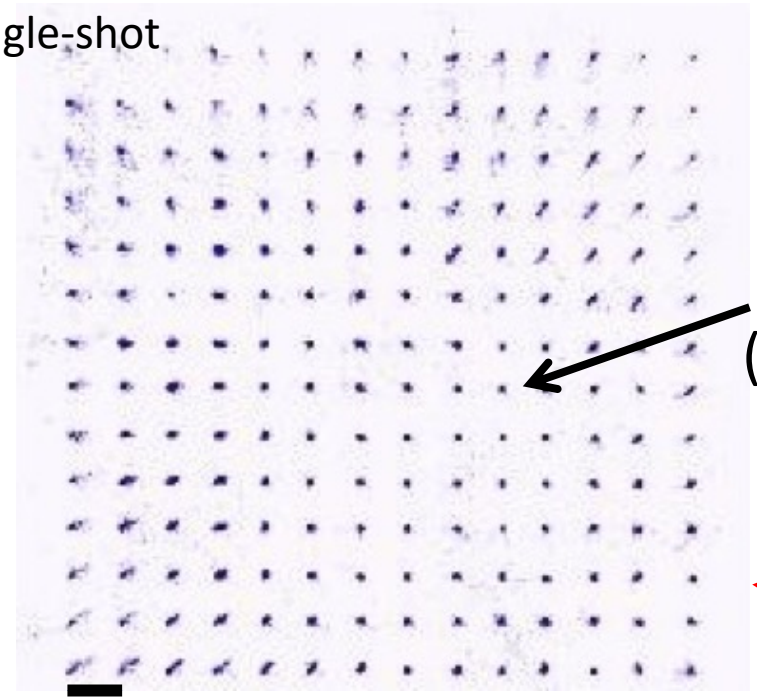
= QUANTUM SIMULATION

Our platform: Arrays of interacting Rydberg atoms

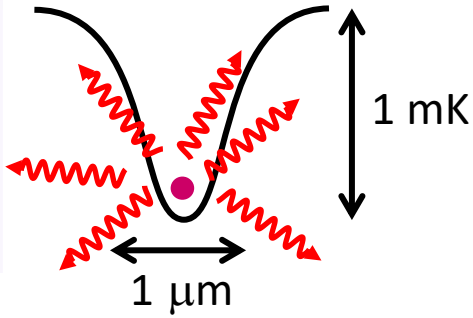
Arrays of atoms

Single-shot



5 µm

1 Rb atom
(fluorescence)



Grangier (2001)
Sortais (2007)

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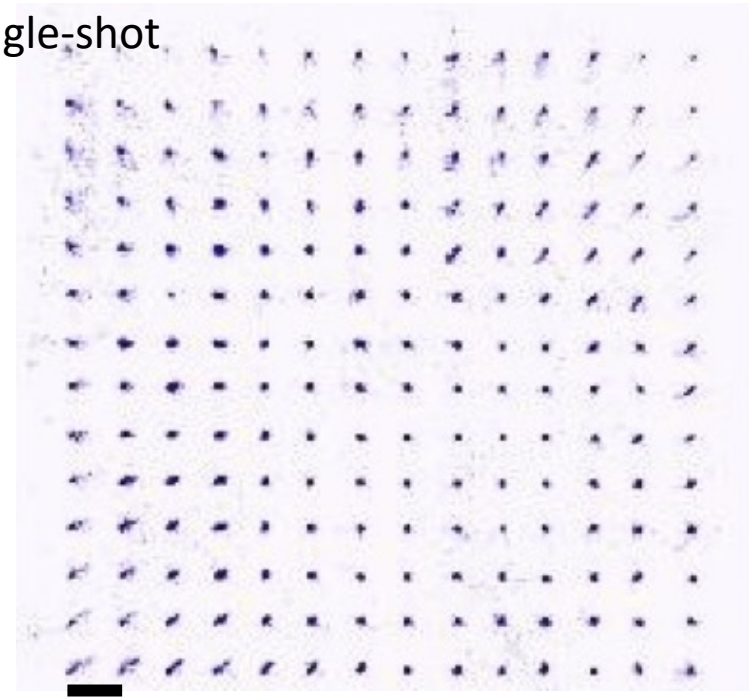
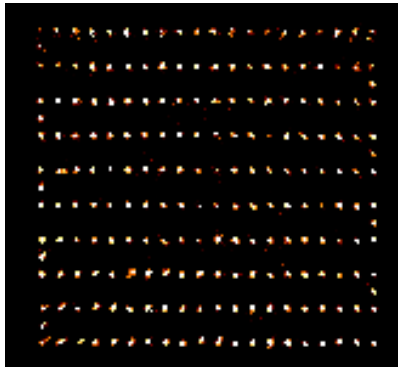
Single-shot

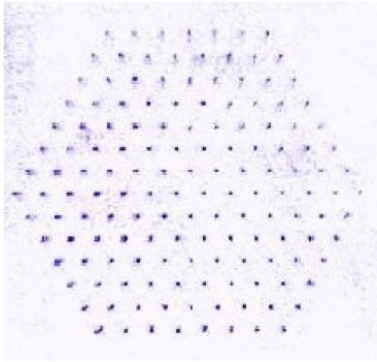


5 µm

1D



2D



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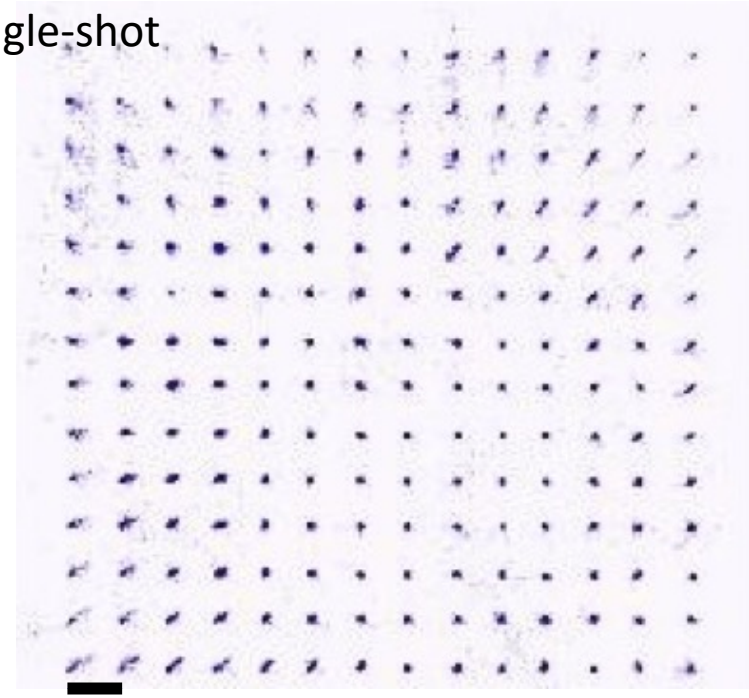
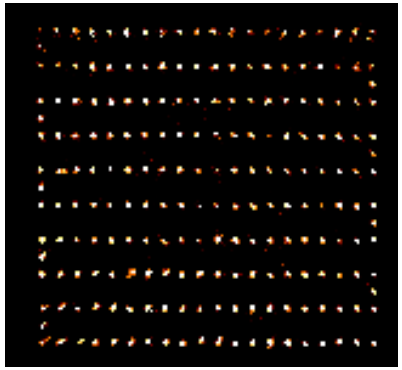
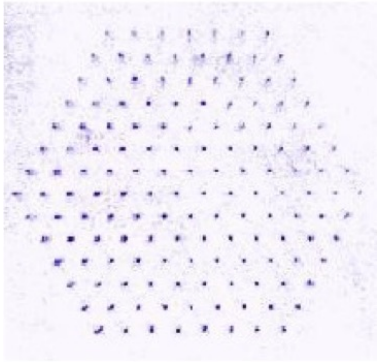


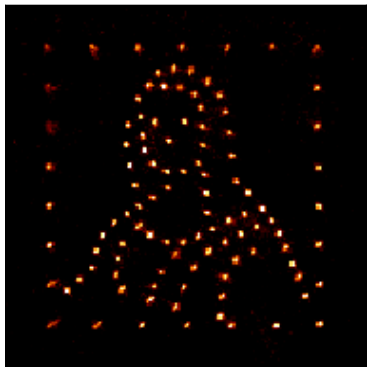
5 µm

1D



2D





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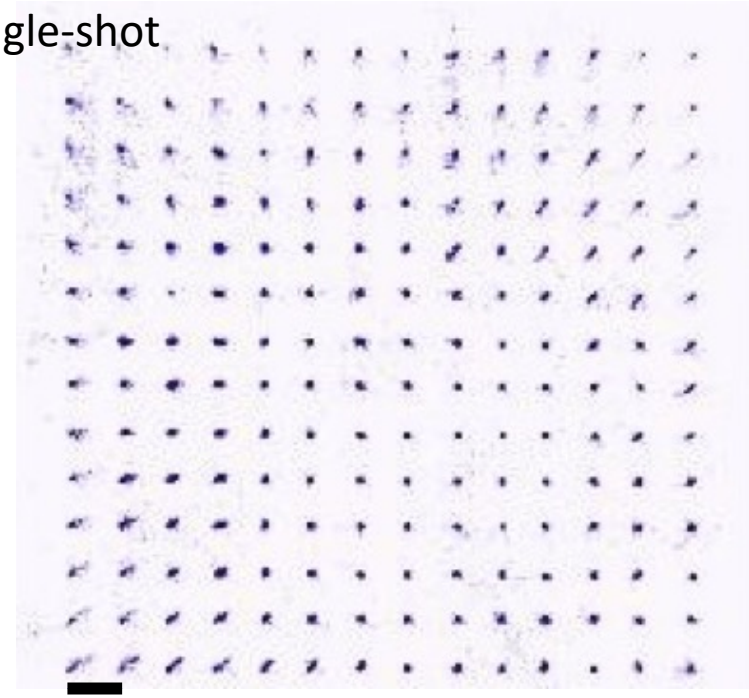

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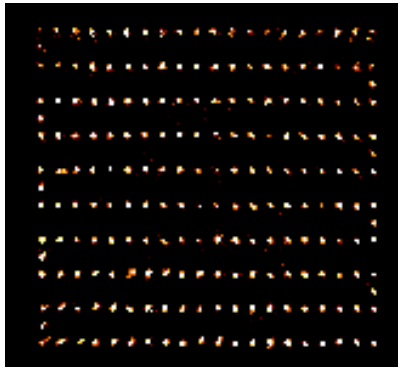
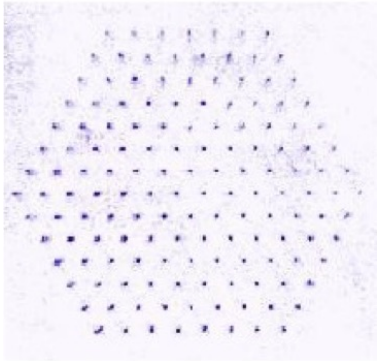
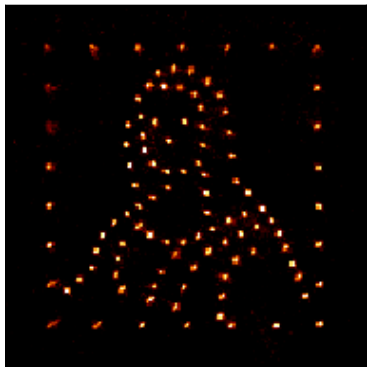


2D





L. da Vinci

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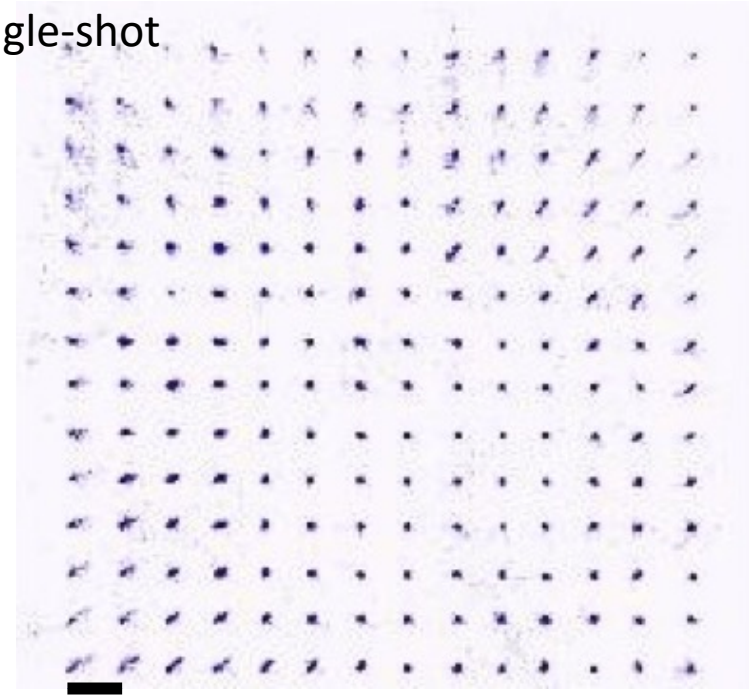

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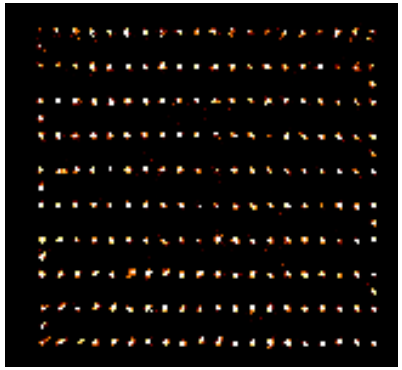

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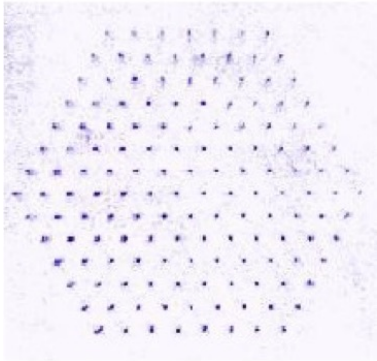

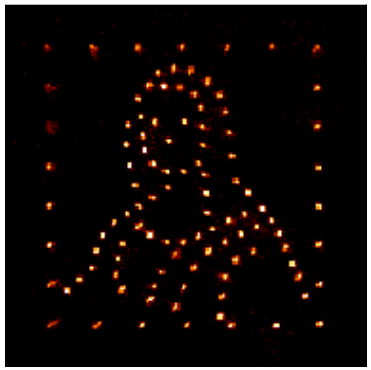

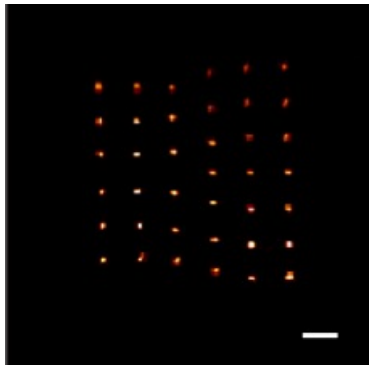

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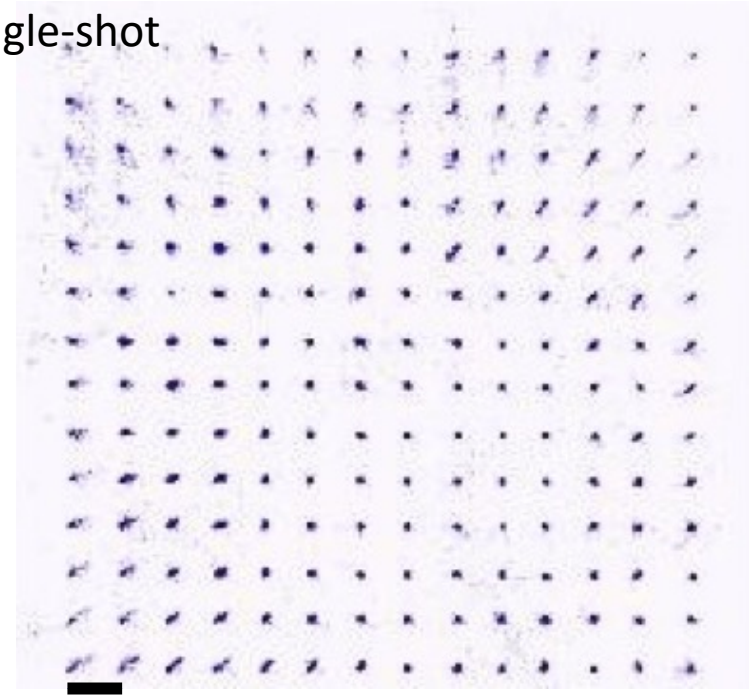
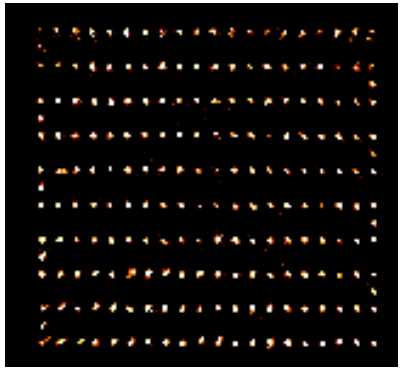
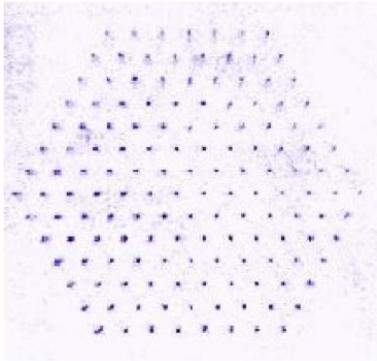


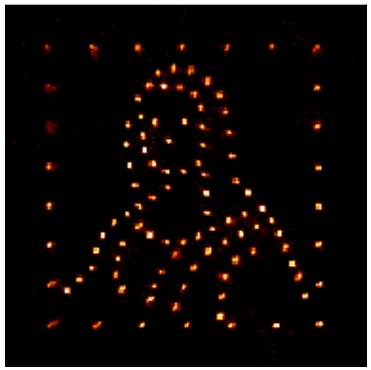
5 µm

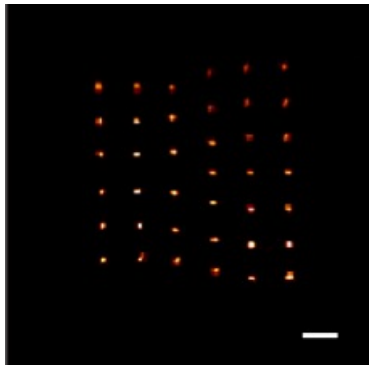
1D



2D







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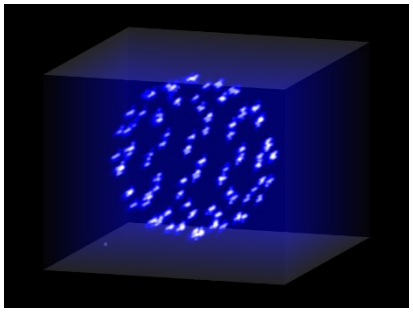

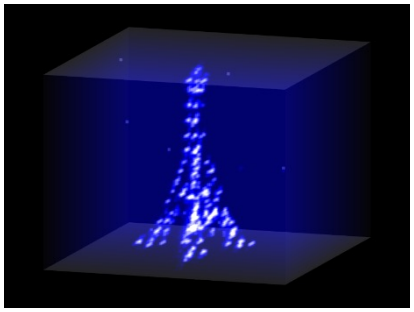

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Arrays of atoms

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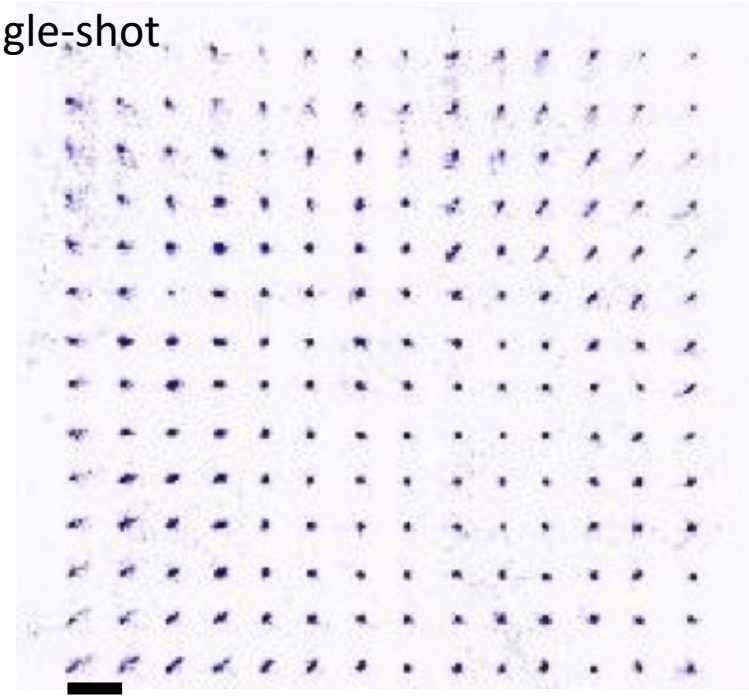

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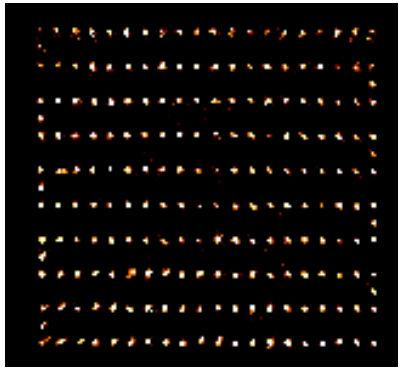

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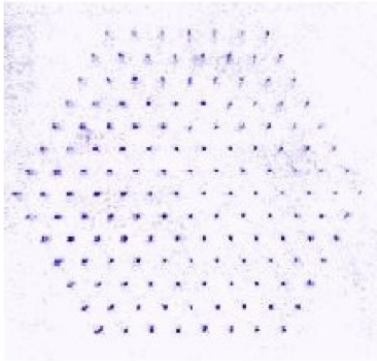
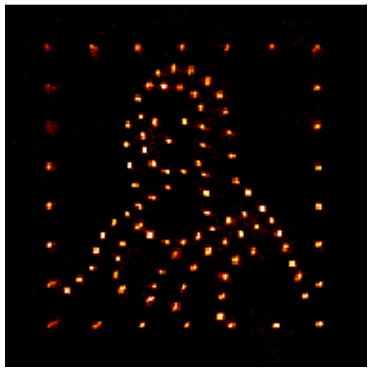
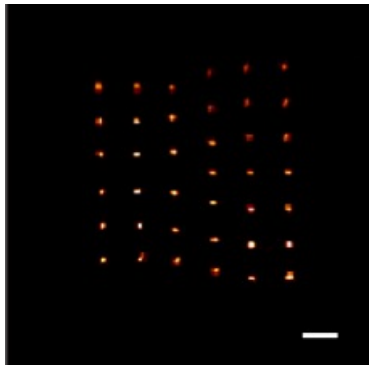




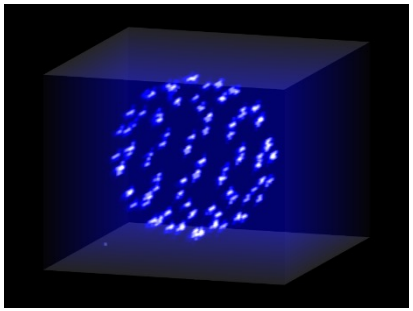


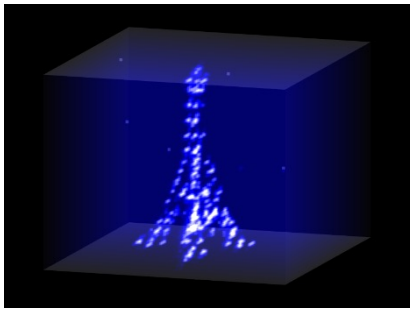
Addressable:

local manipulations and measurement

$$\langle \sigma_i^\alpha \rangle, \langle \sigma_i^\alpha \sigma_j^\beta \rangle, \ldots$$

(Averaged)





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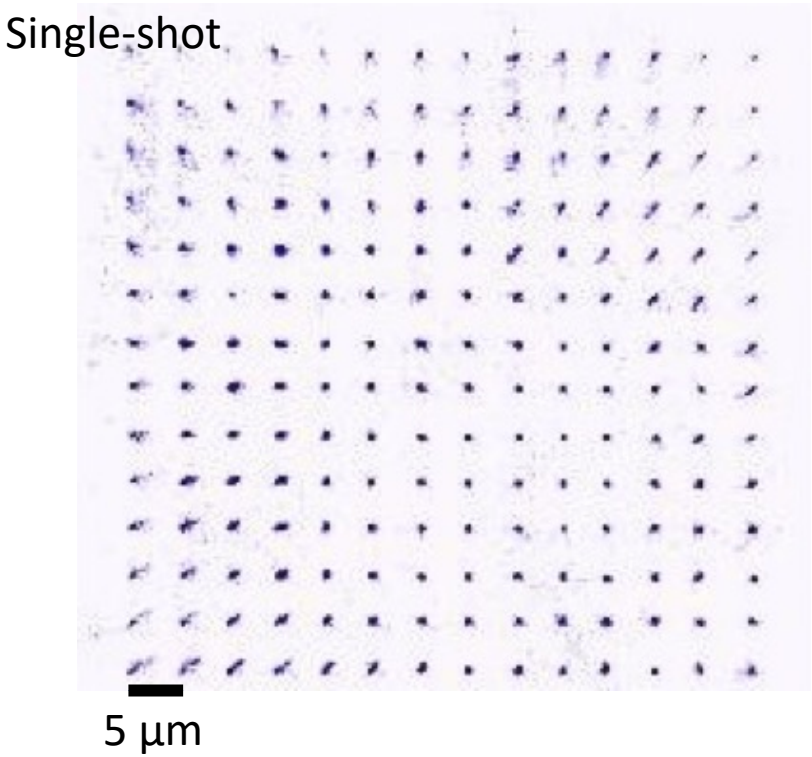
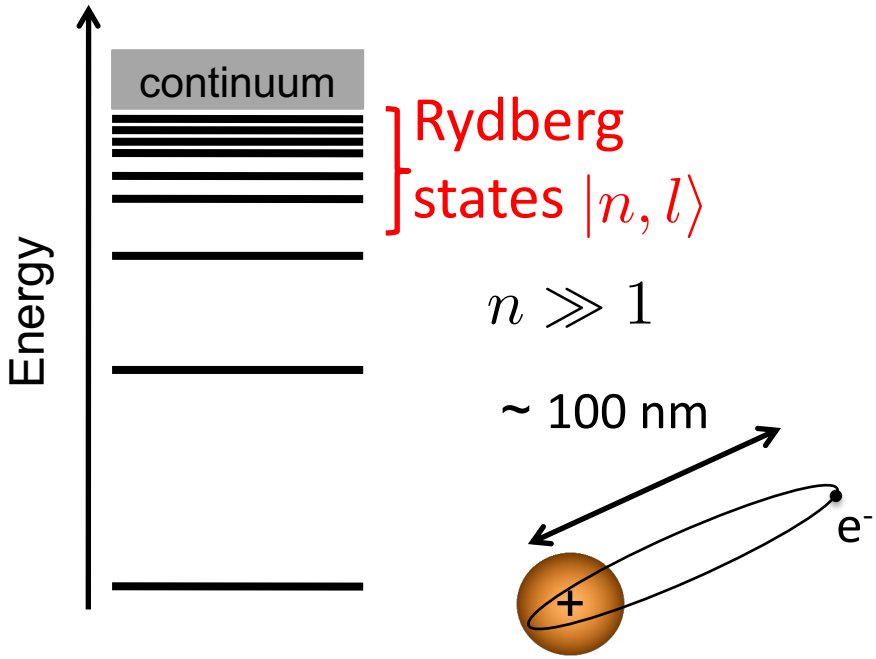


Rydberg atoms



Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat Phys 2020

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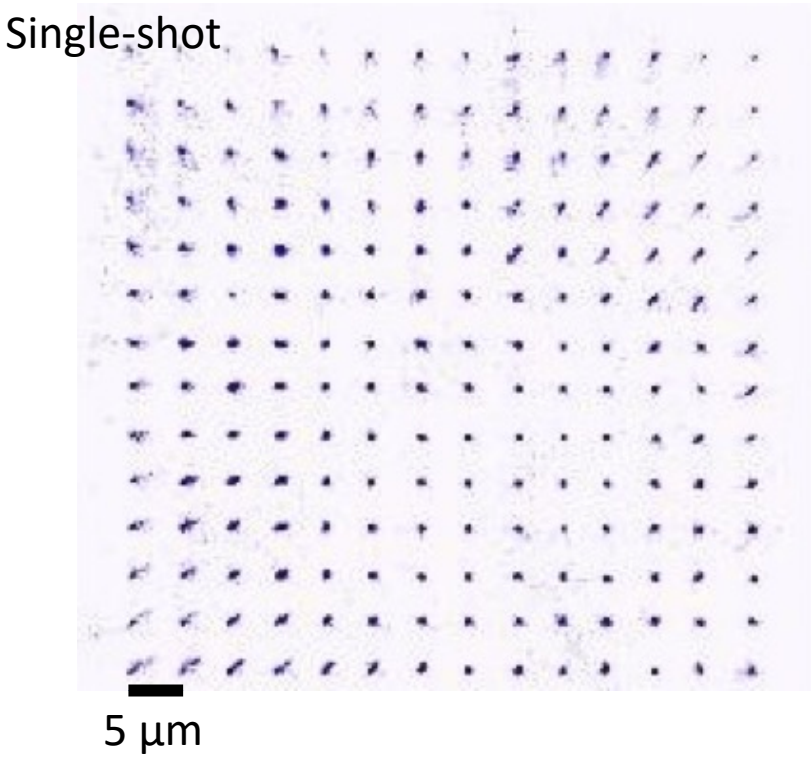

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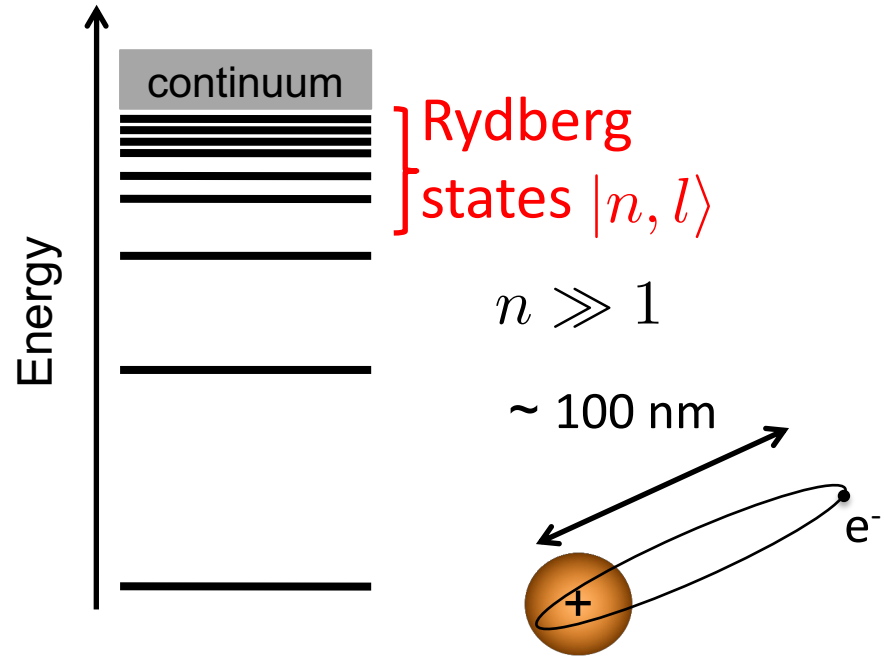

Lifetime > 100 µs

Transition dipole: $d_{n,n\pm1} \sim n^2 e a_0$

Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat Phys 2020

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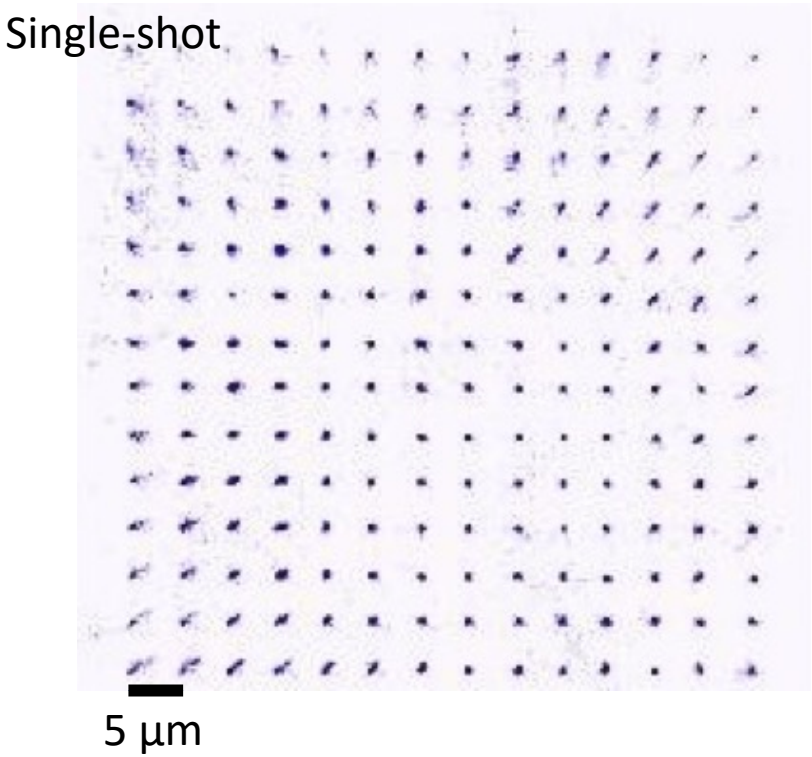
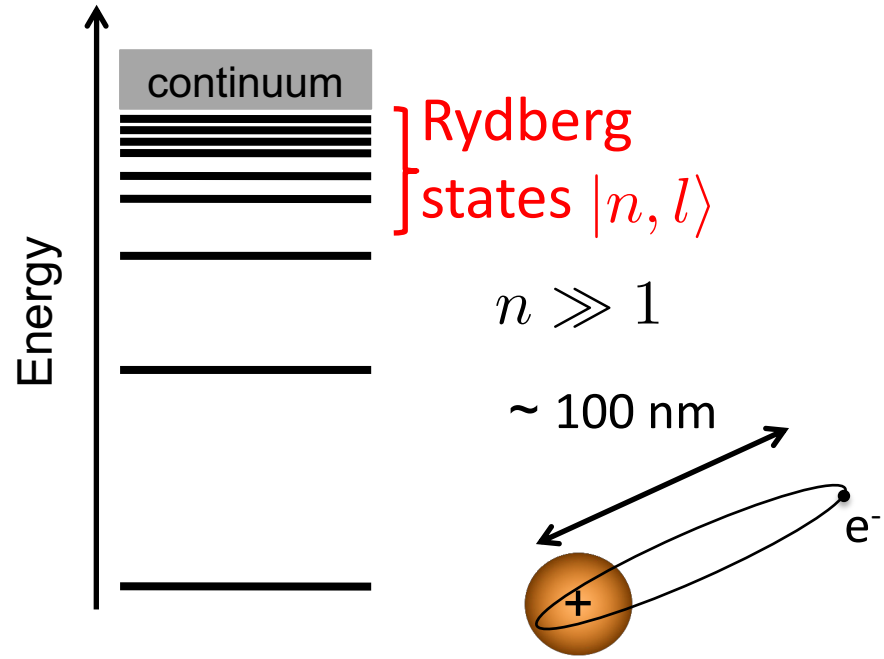


Rydberg atoms



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⇒ Large dipole-dipole interactions

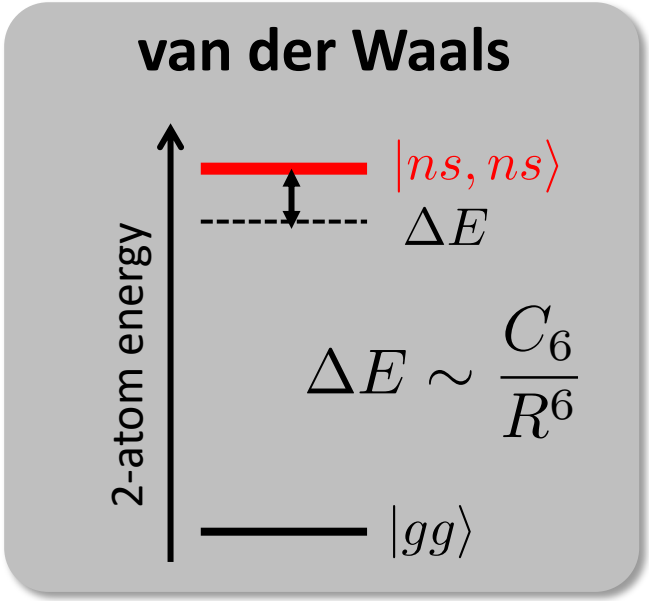
$$R = 10\ \mu\text{m} \Rightarrow V_{\text{int}}/h \sim 1 - 10\ \text{MHz}$$

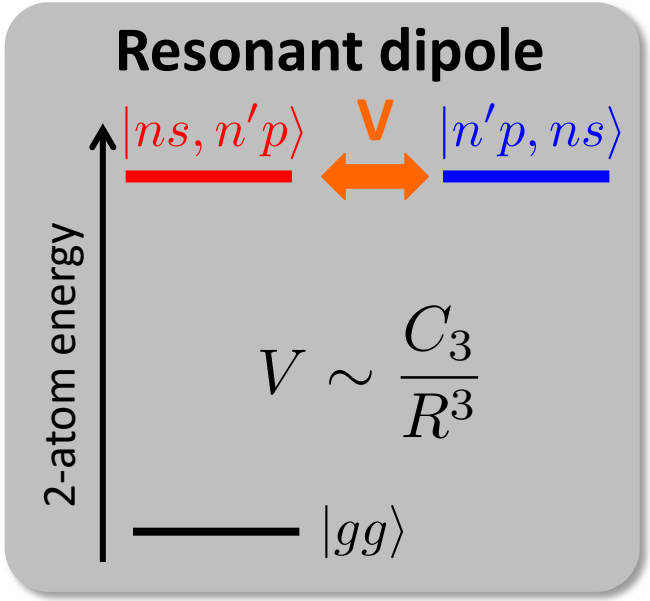
⇒ timescales < µsec

Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat Phys 2020

Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)

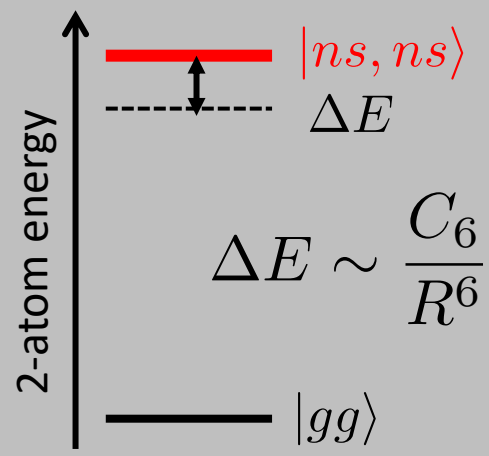




Interactions between Rydberg atoms and spin models

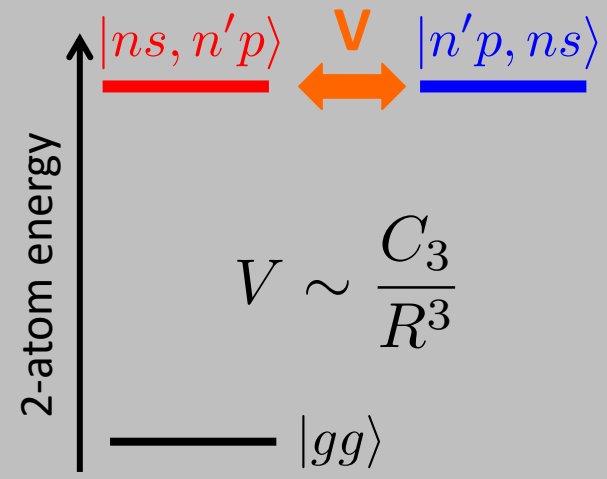
Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals



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

Resonant dipole

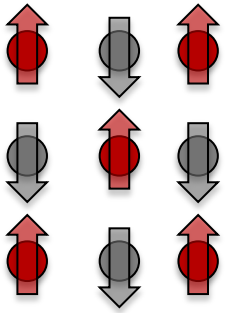


$$V \sim \frac{C_3}{R^3}$$

Quantum Ising

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{n}_i \hat{n}_j$$

Spin 1/2



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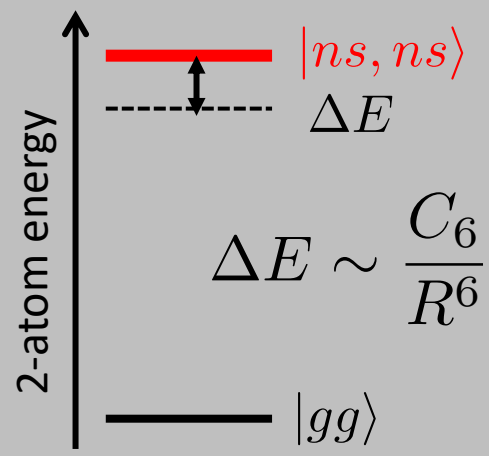

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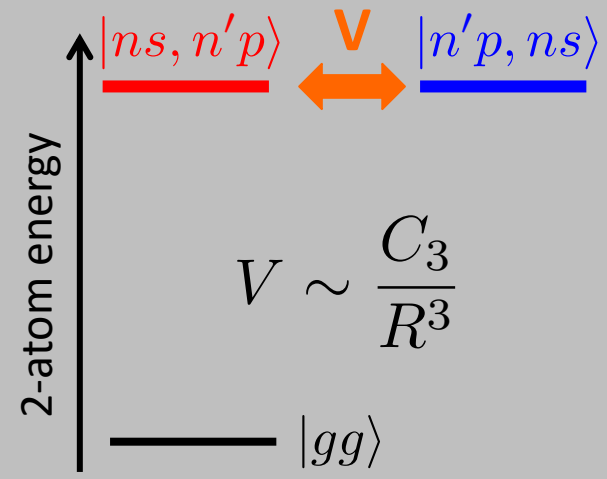

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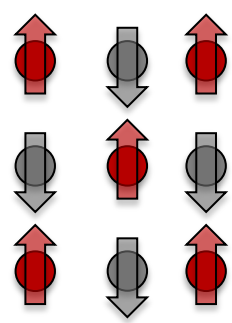

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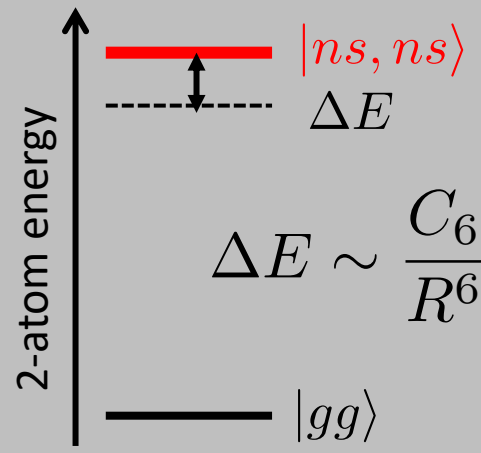

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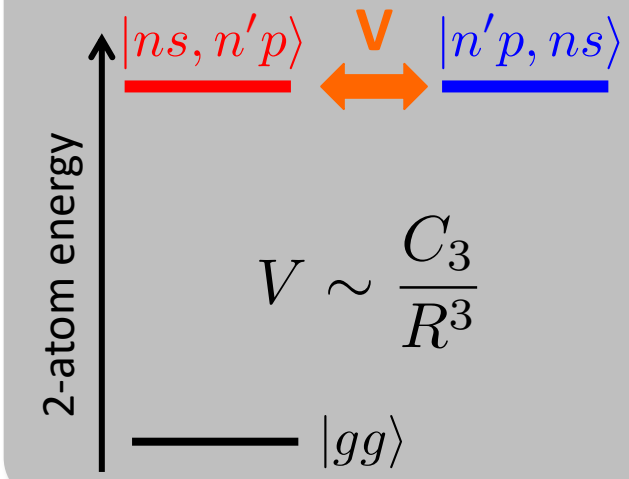

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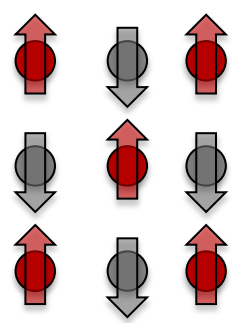

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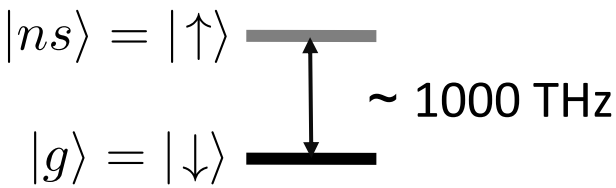

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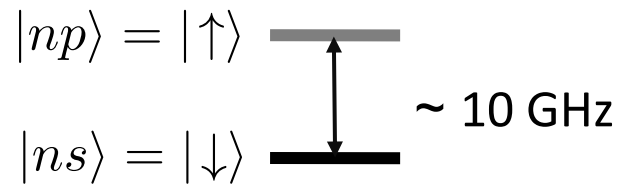

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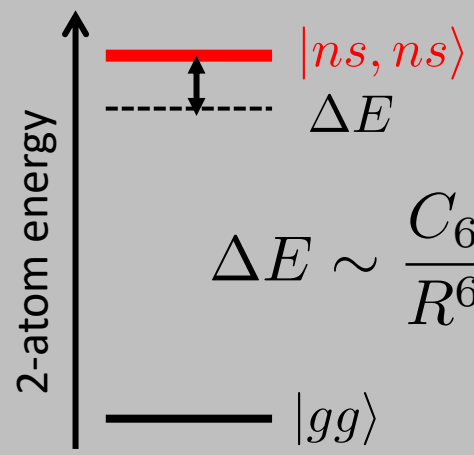

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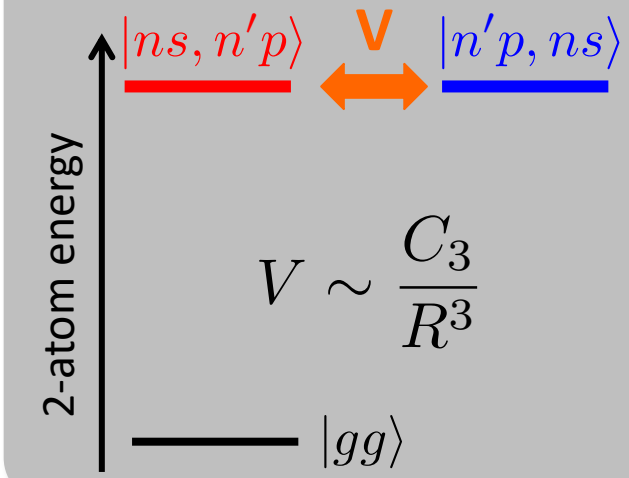

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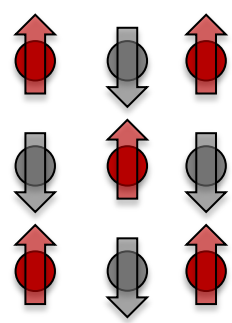

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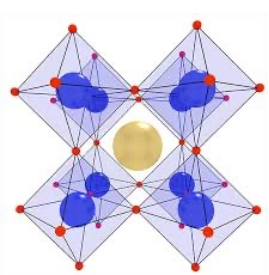

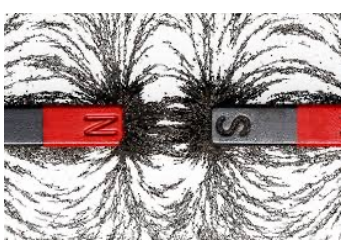

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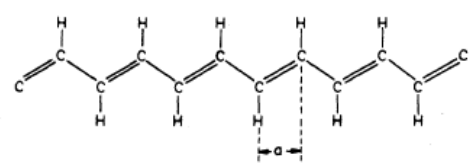

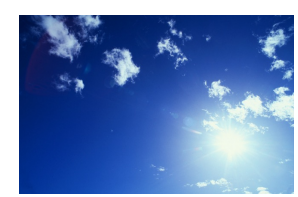

Outline

1. Magnetism: Ising model with van der Waals interactions

2. The interacting SSH model with resonant interaction

3. Heisenberg model with resonant interaction and Floquet engineering

Outline

A. Läuchli
M. Schuler
T. Lang
A. Eberharter
(Innsbruck)

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2. The interacting SSH model with resonant interaction

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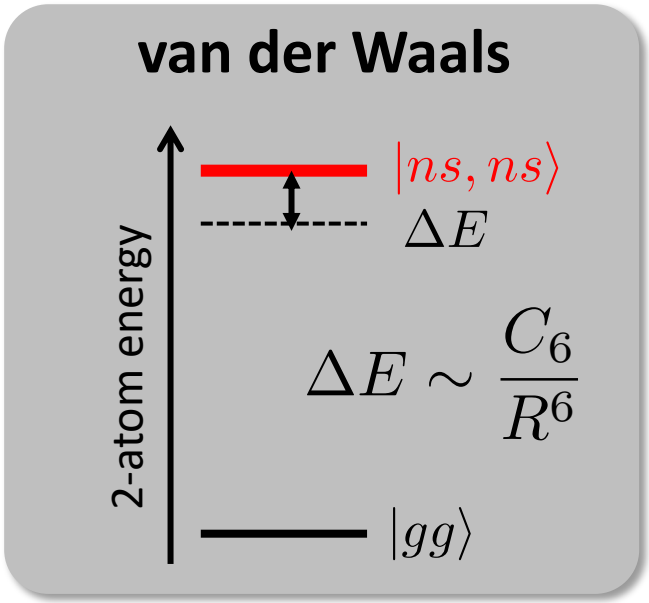
From van der Waals interactions to Ising model…



$C_6 \propto n^{11}$ $\Rightarrow$ switchable interaction

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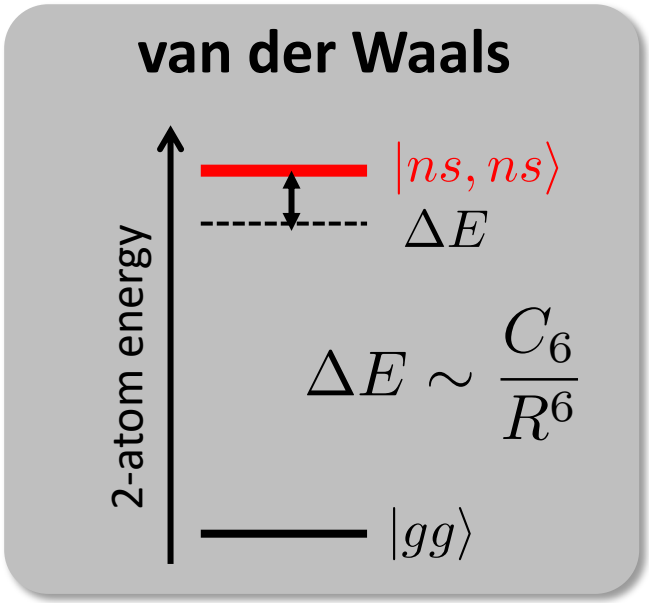

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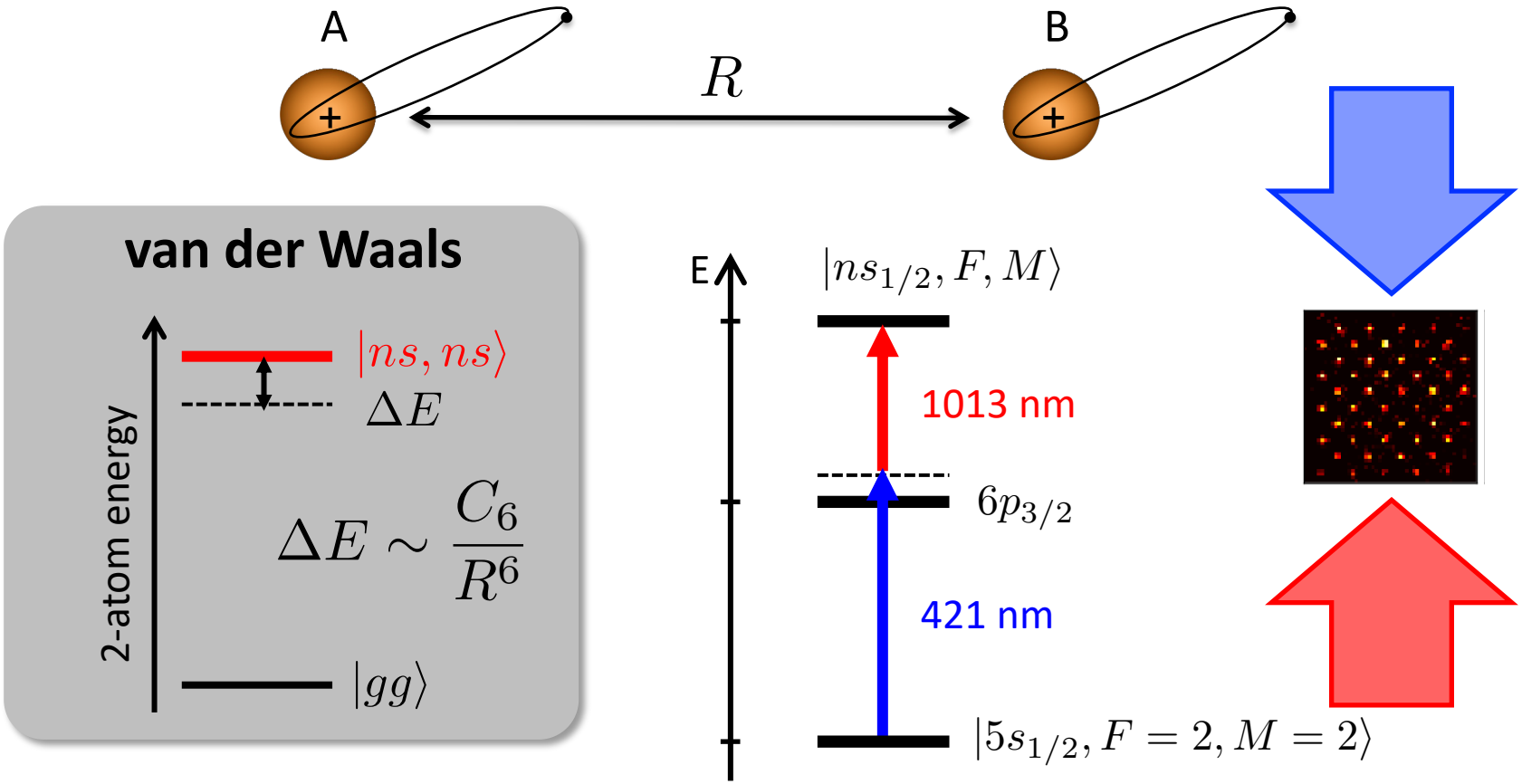
$$\hat{H}_{\text{int}} = \frac{C_6}{R^6}\hat{n}_1\hat{n}_2 \sim J\,\hat{\sigma}_1^z\hat{\sigma}_2^z$$

Rydberg occupation number

From van der Waals interactions to Ising model…



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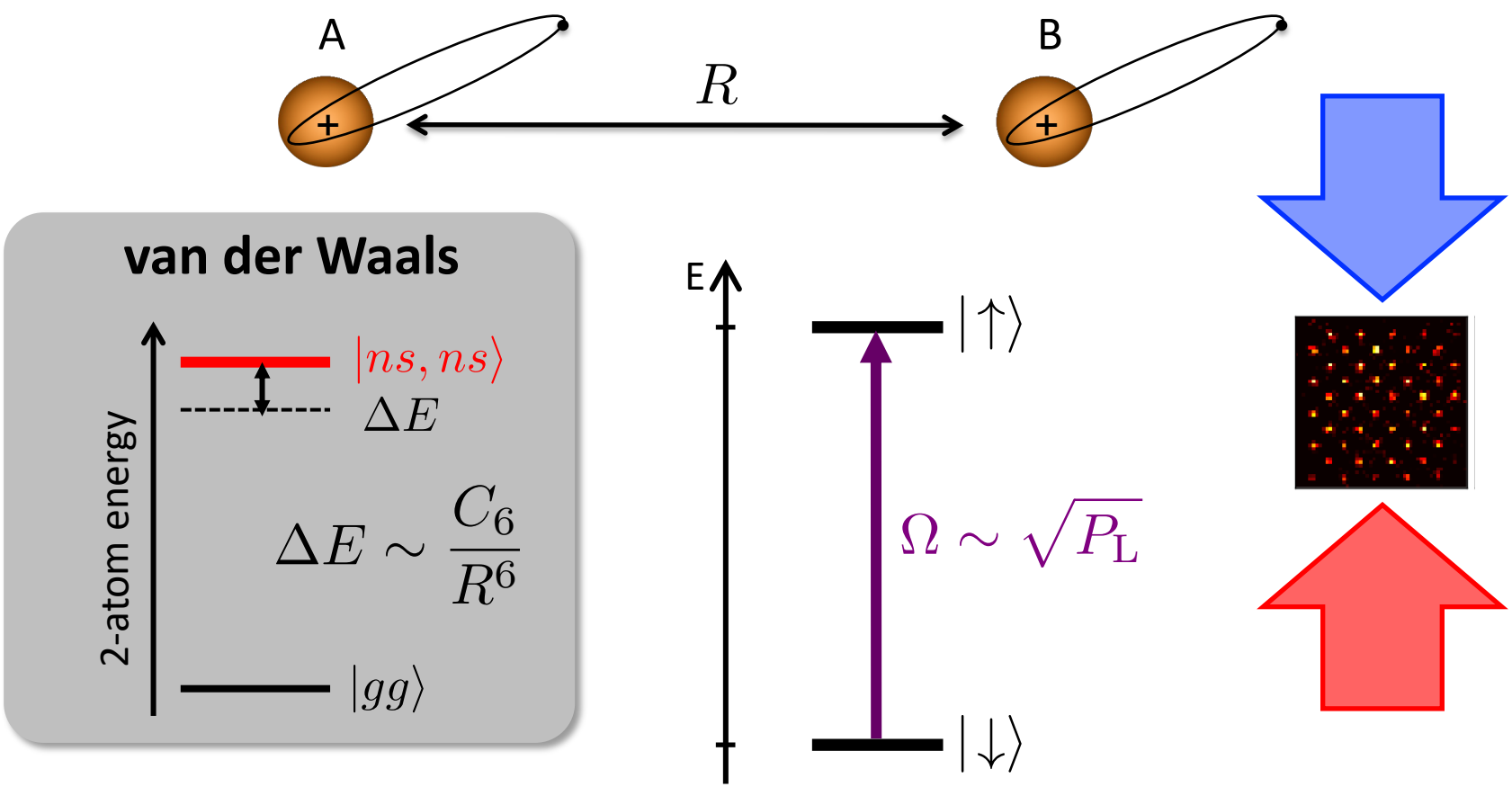

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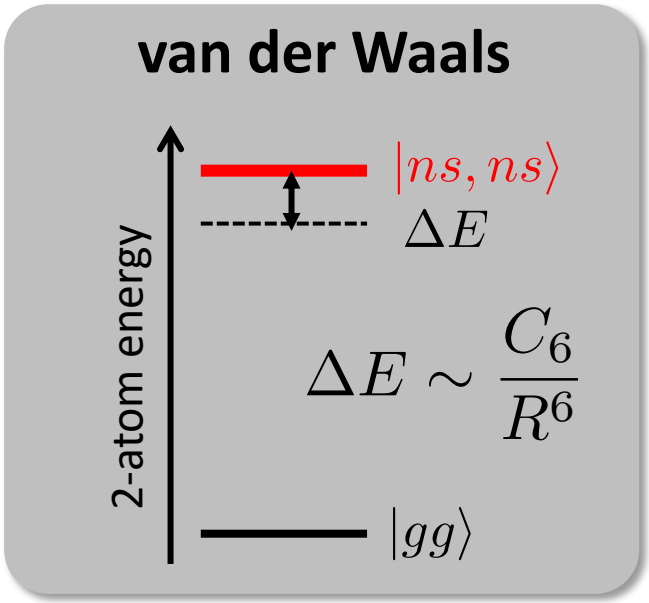

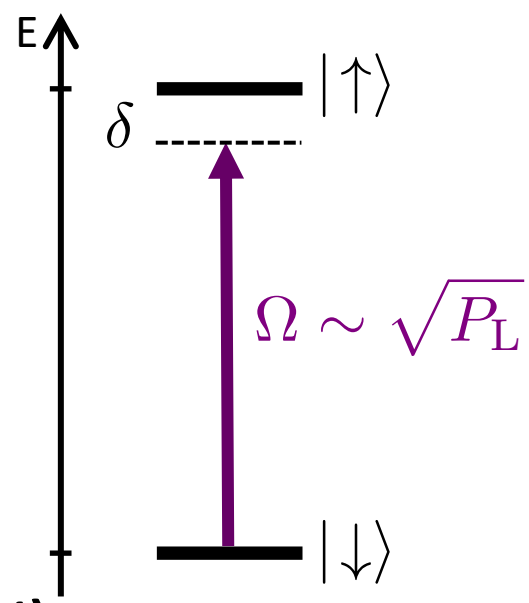

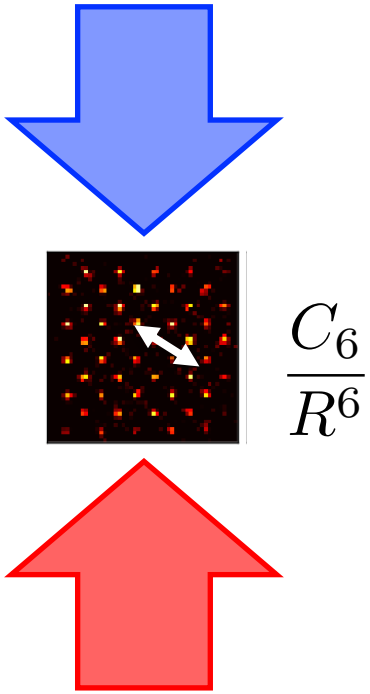

Quantum Ising-like model (s=½):

$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i + \hbar\delta\sum_i \hat{n}_i + \sum_{i<j}\frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

Laser: $B_\perp$ $B_\parallel$ Spin-spin interaction

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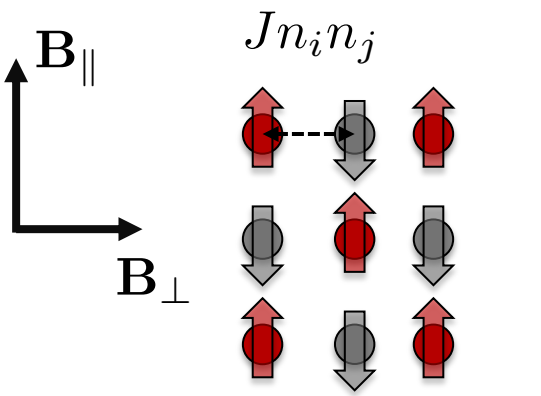
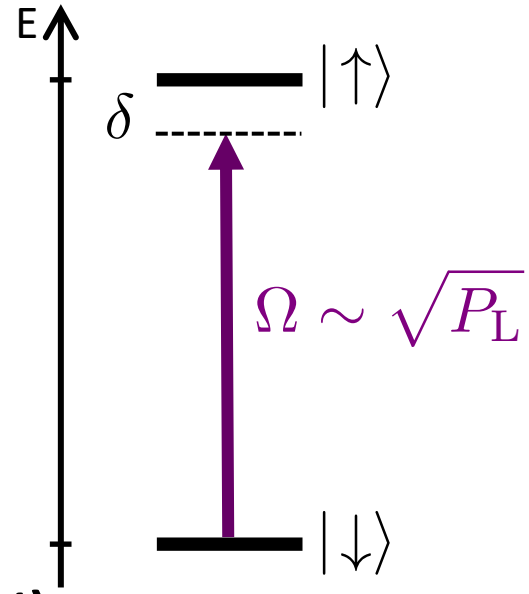
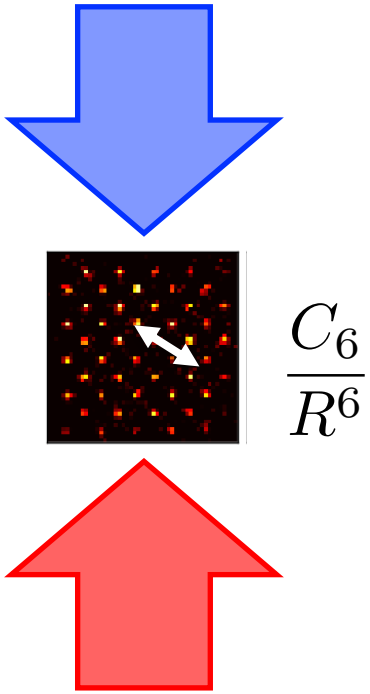


$$\sim \mu B_{\perp}\hat{\sigma}_x + \mu B_{\parallel}\hat{\sigma}_z$$





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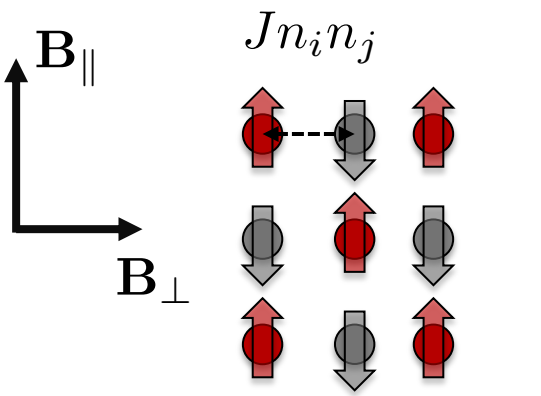

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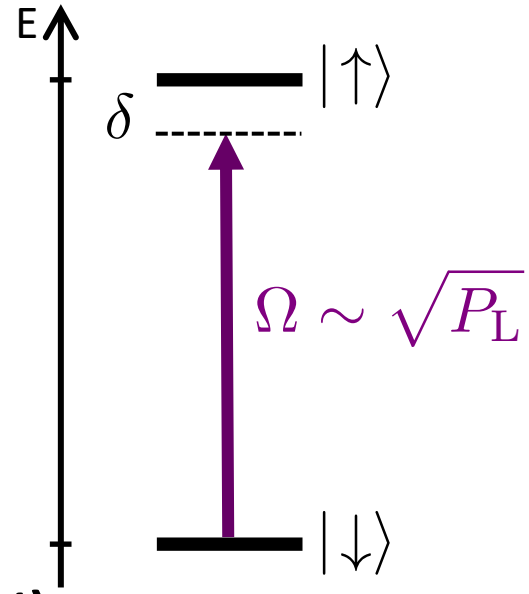

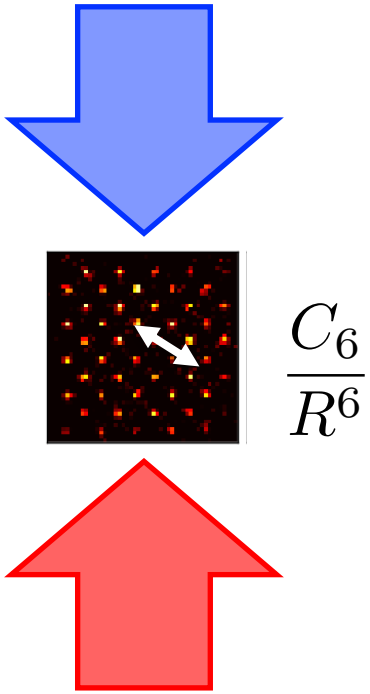

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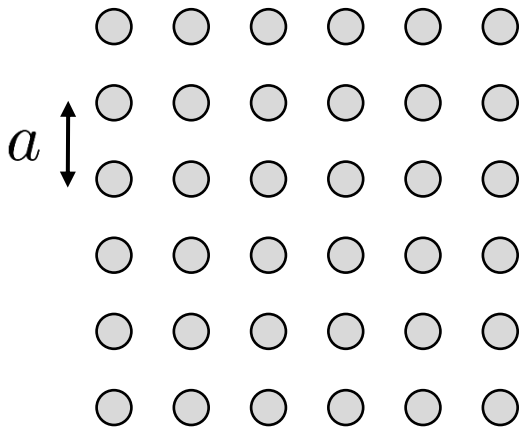
Experimt[t].

$$\frac{C_6/a^6}{\Omega} = [0-20]$$

Laser: $B_{\perp}$ $B_{\parallel}$ Spin-spin interaction

2D Ising anti-ferromagnet on a square

Nearest neighb. interaction



$\bigcirc = |g\rangle$

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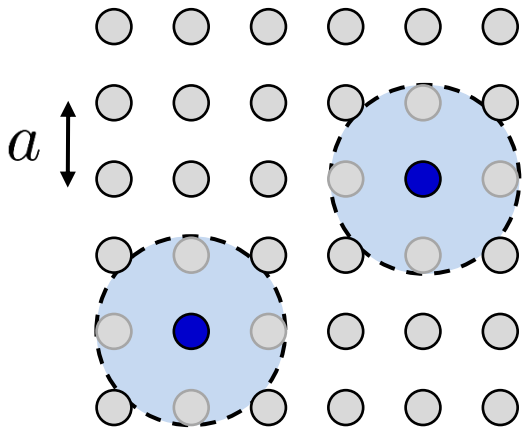

$$\frac{C_6}{a^6} \sim \Omega$$

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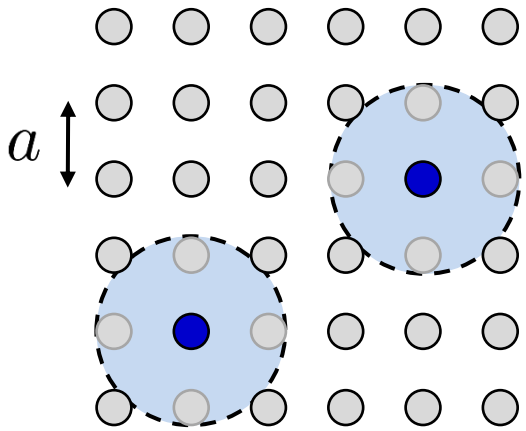

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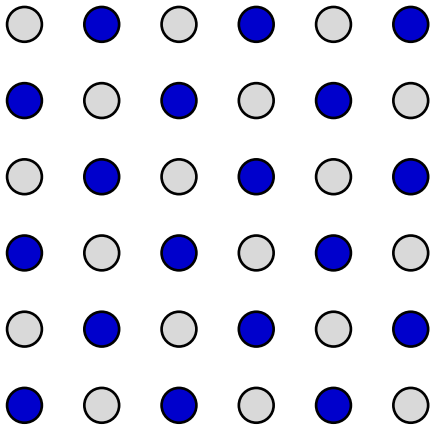
Anti-ferromagnetic ground state



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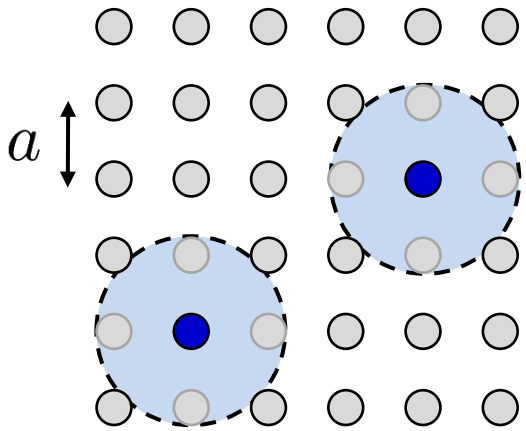

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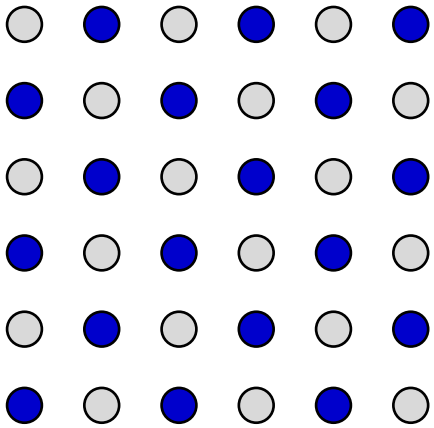
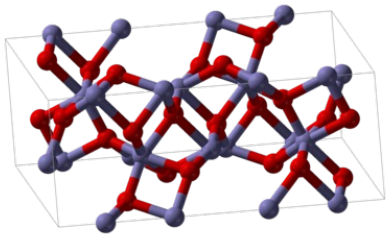


Ex of antiferromagnets: MnO, FeO, CoO, NiO, $FeCl_2$...



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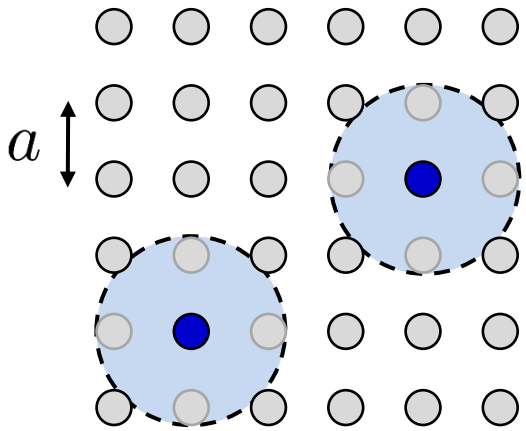

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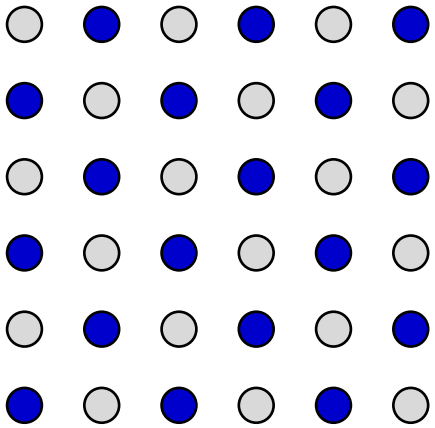
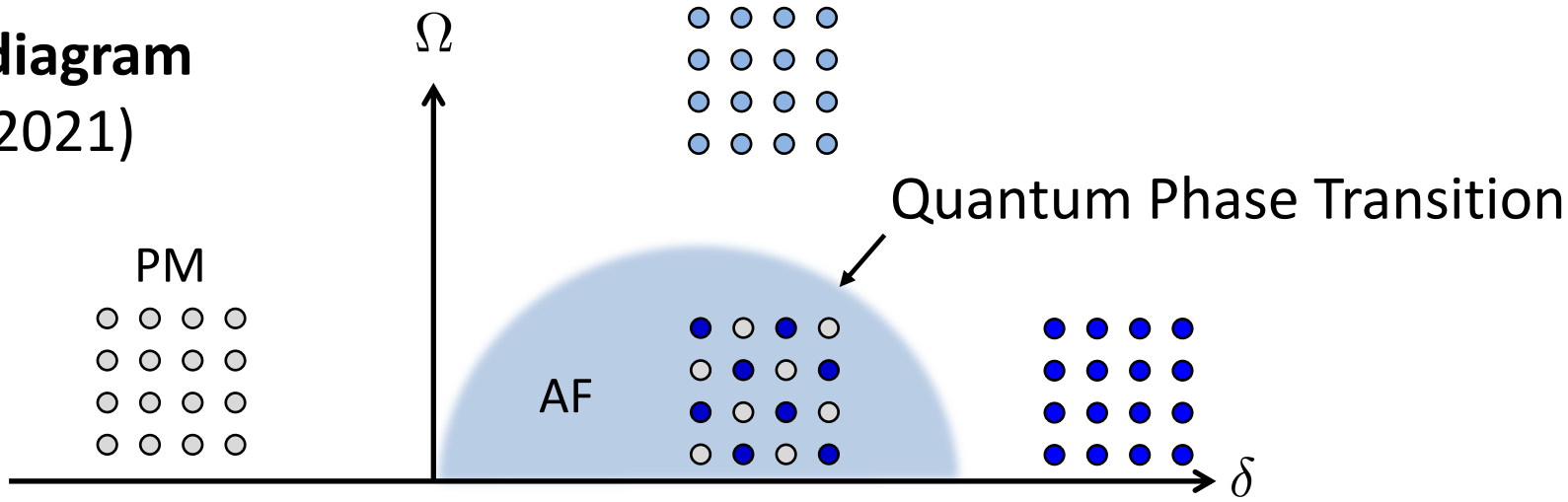


2D phase diagram
(1970 - 2021)



Fey, Schmidt PRL 2019
Sachdev & Lukin PRL 2020

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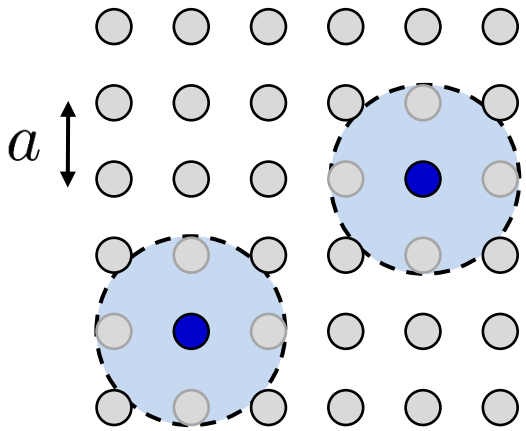

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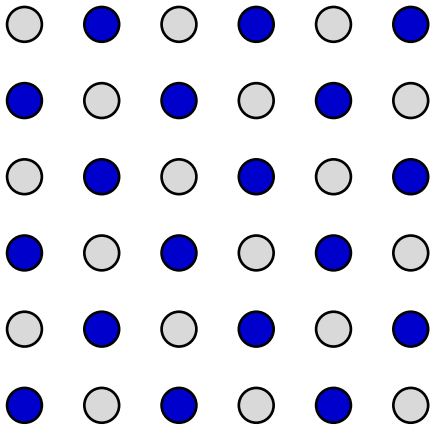

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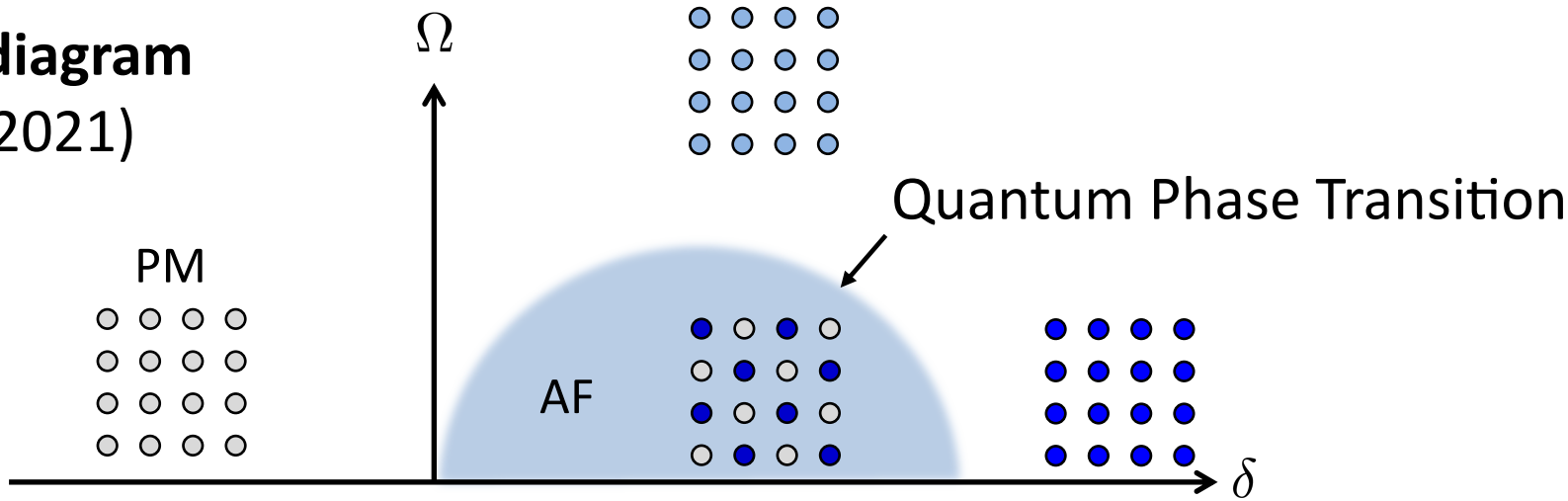

Known by Quantum Monte-Carlo

Never measured in 2D…!!!

Fey, Schmidt PRL 2019
Sachdev & Lukin PRL 2020

2D Ising anti-ferromagnet on a square

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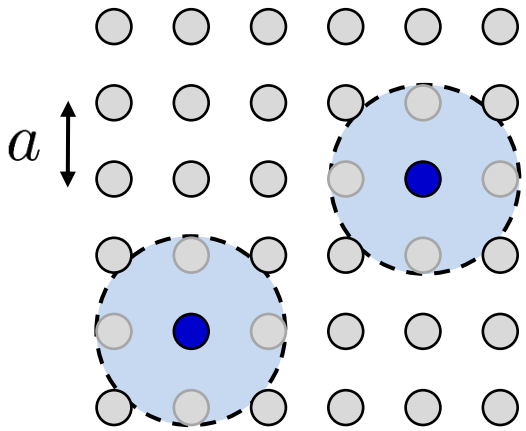

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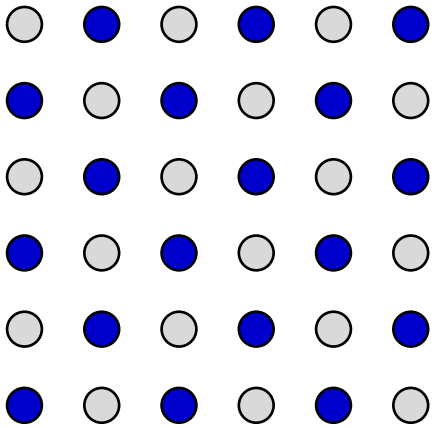
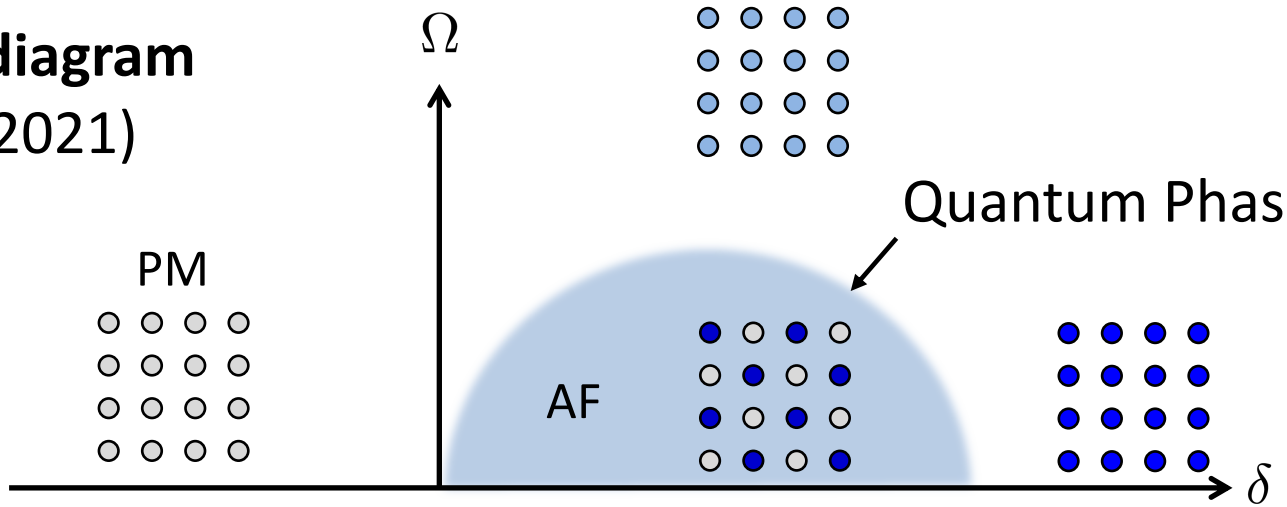


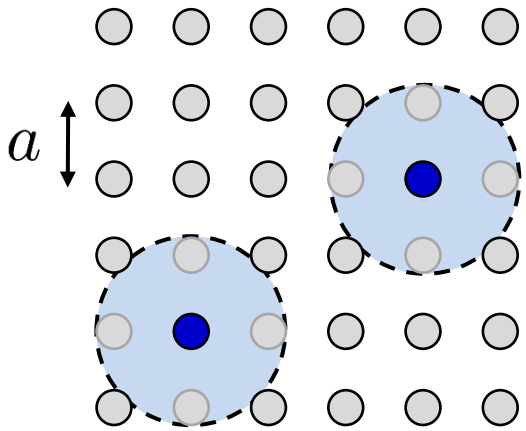
2D phase diagram
(1970 - 2021)



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

2D Ising anti-ferromagnet on a square

Nearest neighb. interaction

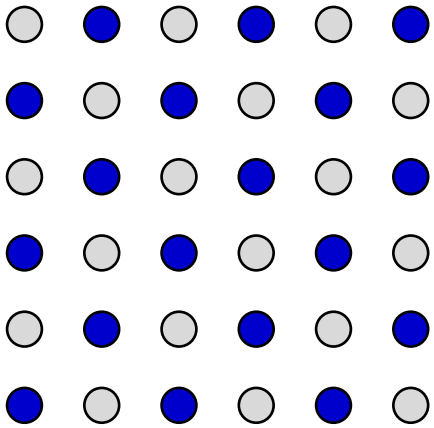


$$\frac{C_6}{a^6} \sim \Omega$$

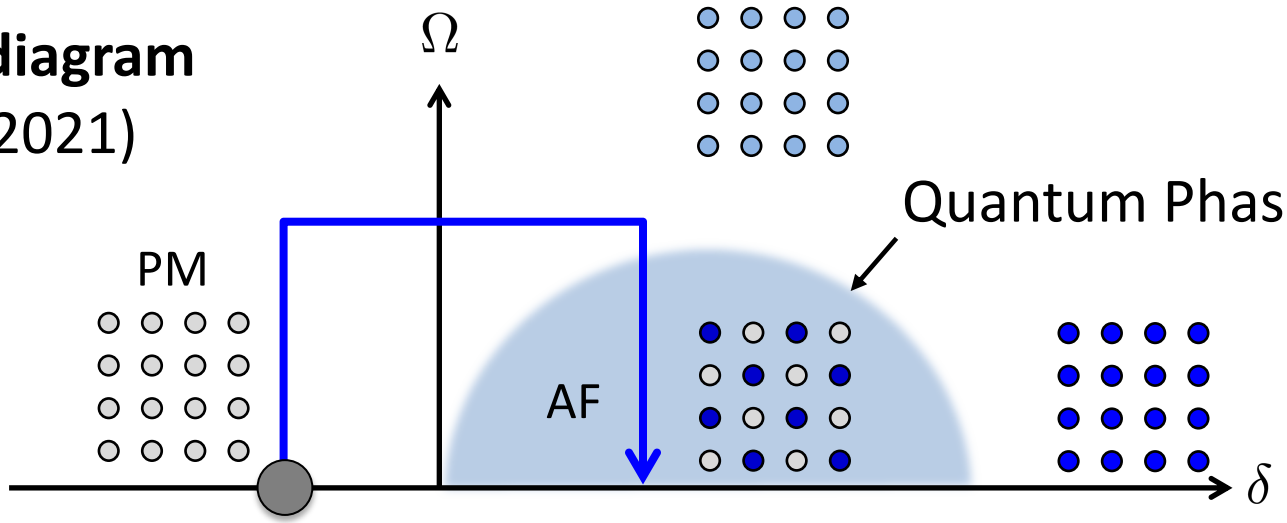
$$\bigcirc = |g\rangle$$

$$\bullet = |r\rangle$$

Anti-ferromagnetic ground state



2D phase diagram
(1970 - 2021)



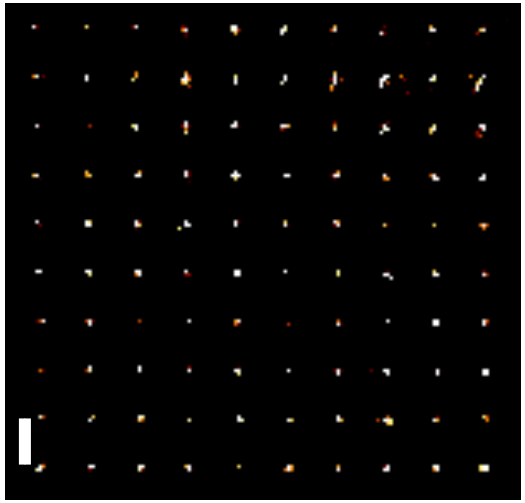
Quantum Phase Transition

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

Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

10×10 square array



10 μm

1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;
2D: Lienhard PRX 2018, Bakr PRX 2018; Lukin Nature 2021

Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

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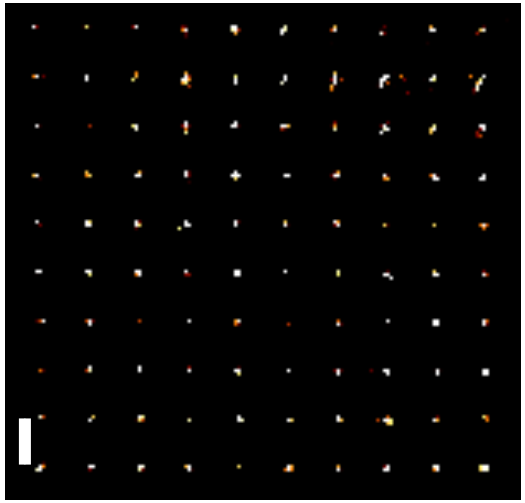
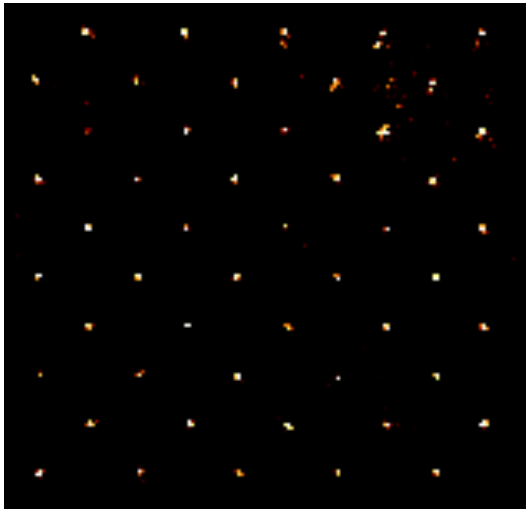


10 µm

$\Omega(t), \delta(t)$

sweep



n=75s

1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;
2D: Lienhard PRX 2018, Bakr PRX 2018; Lukin Nature 2021

Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

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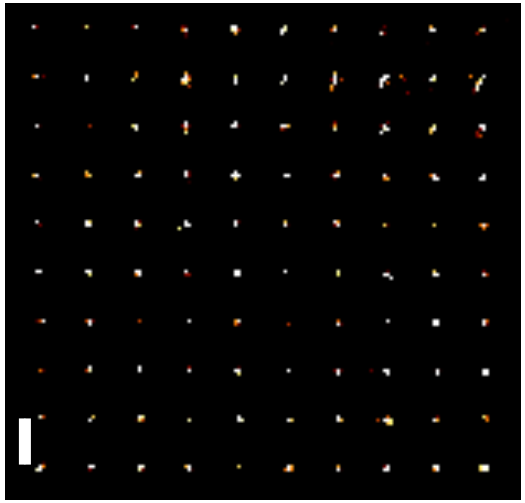


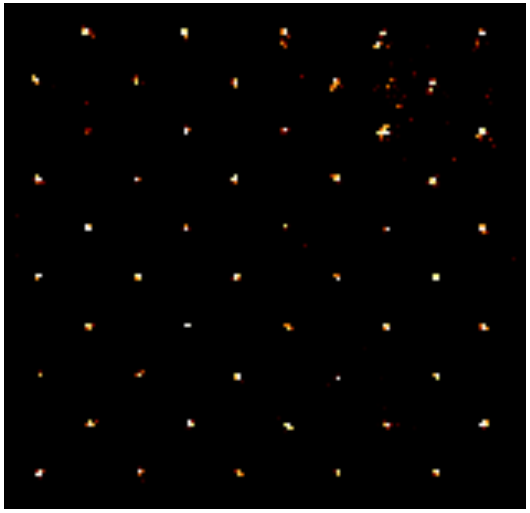
10 µm

$\Omega(t), \delta(t)$

sweep

$= |g\rangle$ bright

$= |r\rangle$ dark



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1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;
2D: Lienhard PRX 2018, Bakr PRX 2018; Lukin Nature 2021

Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

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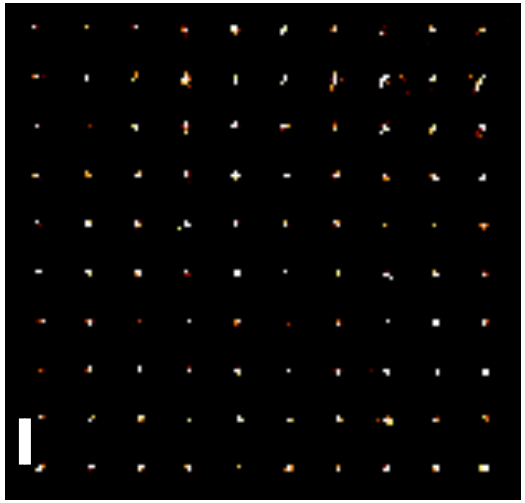
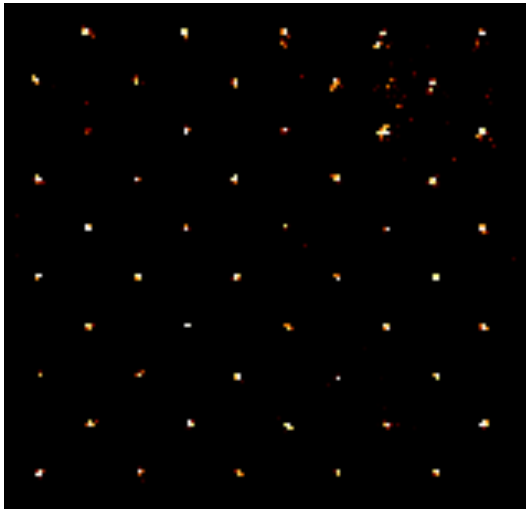


10 µm

$\Omega(t), \delta(t)$

sweep

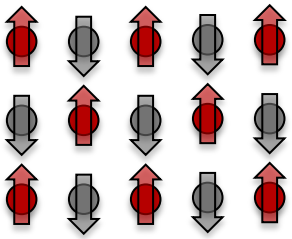


n=75s

$= |g\rangle$ bright

$= |r\rangle$ dark

Perfect AF (Néel) ordering!



1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;
2D: Lienhard PRX 2018, Bakr PRX 2018; Lukin Nature 2021

Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

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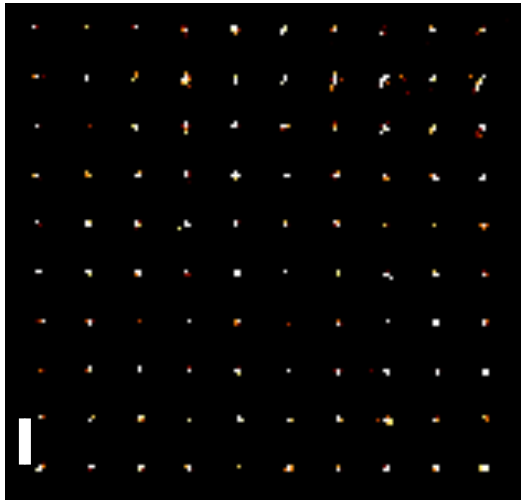
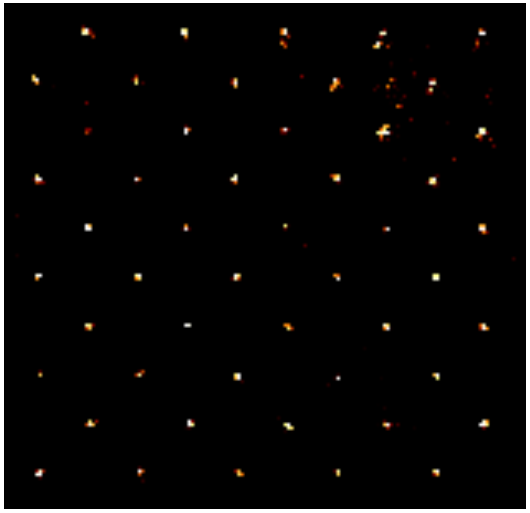


10 µm

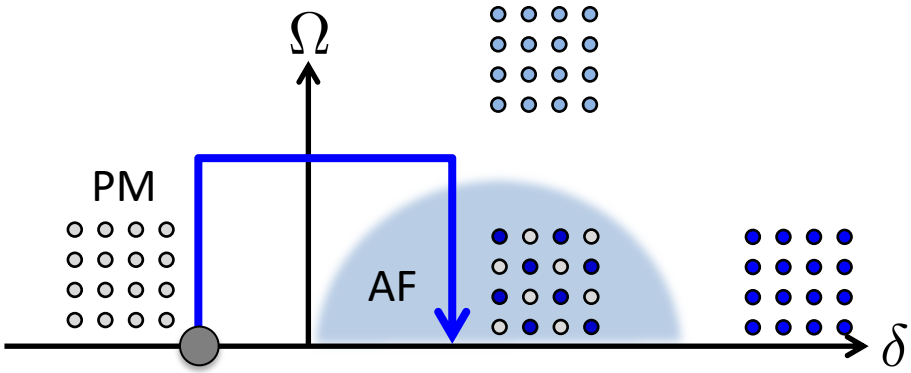
$\Omega(t), \delta(t)$

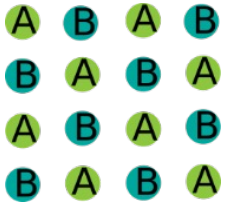
sweep



n=75s

Staggered magnetization: $m_{\text{stag}} = \langle |n_A - n_B| \rangle$

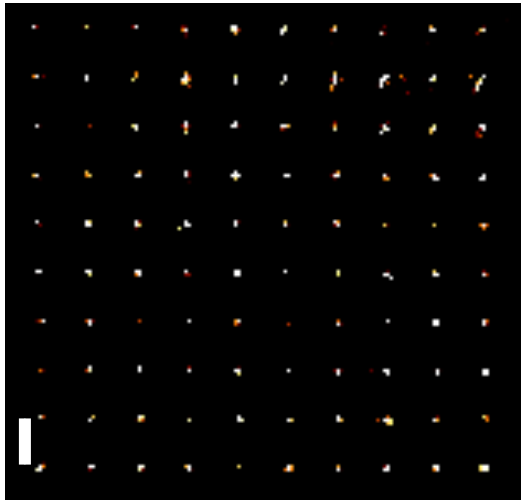




Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

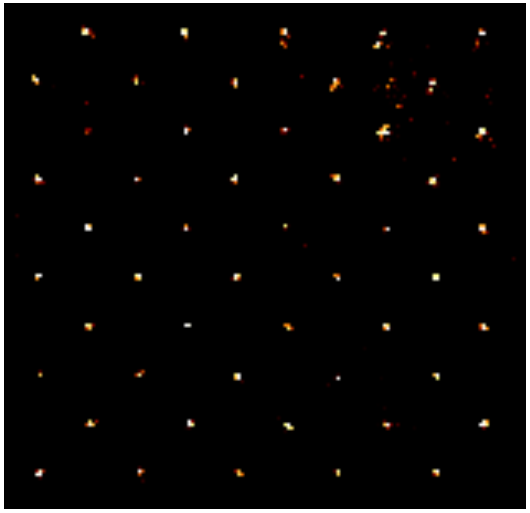
10 × 10 square array



10 µm

$\Omega(t), \delta(t)$

sweep



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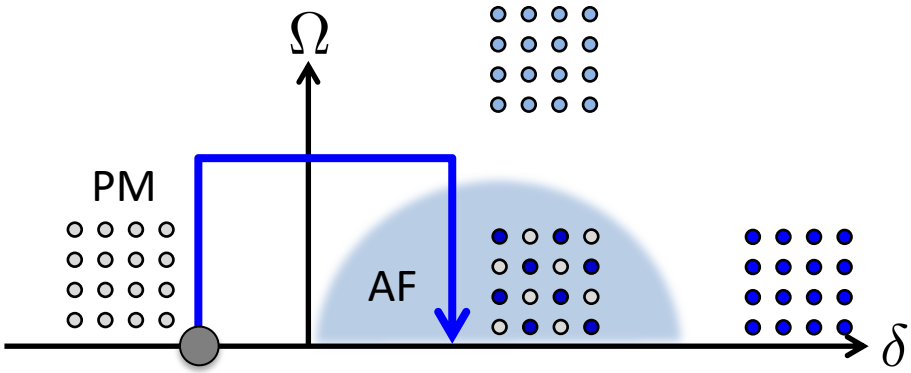
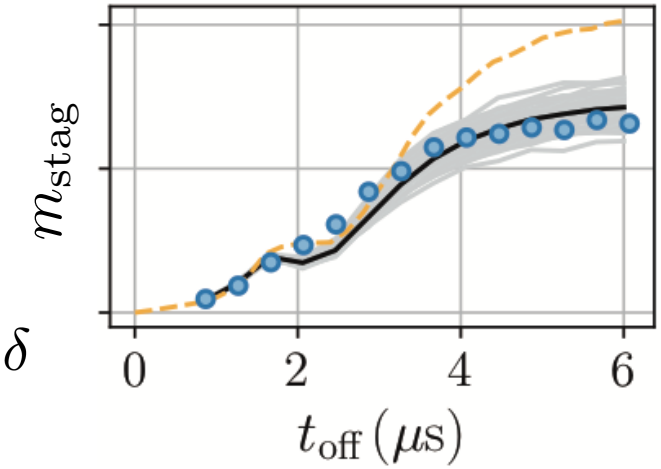


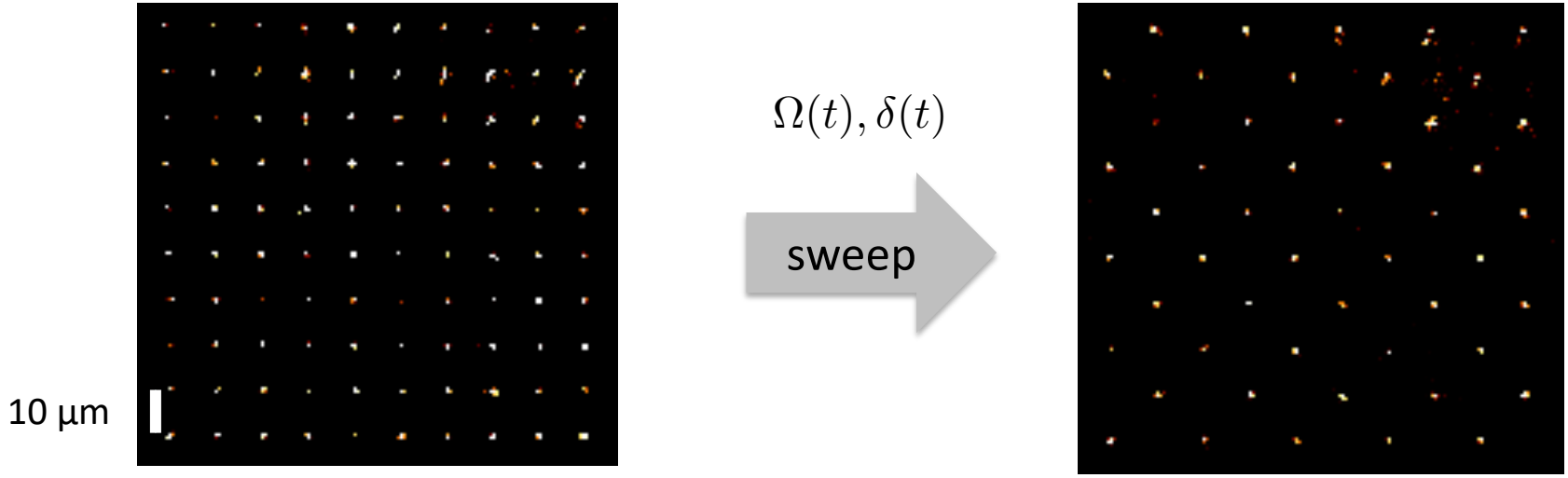


Including experimental imperfections: $U_{ij}, \Omega_i, \delta_i$, real ramp…

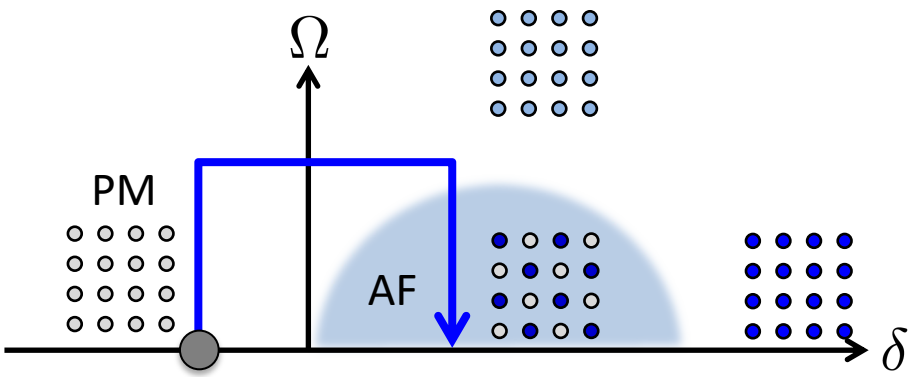
Preparation of a 2D Ising anti-ferromagnet on a square

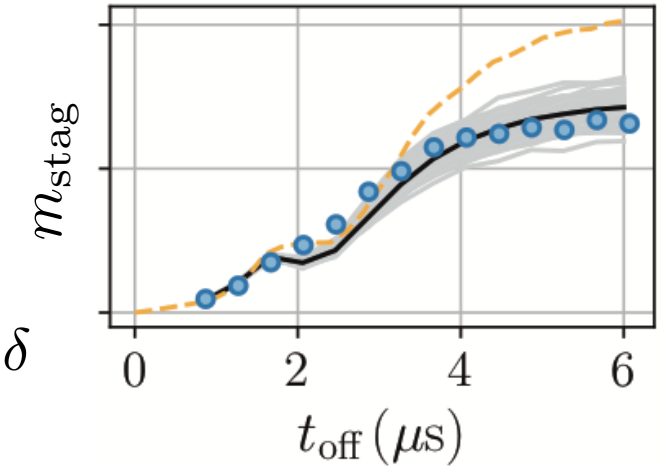
Scholl et *al.* Nature (2021)

10 × 10 square array



Staggered magnetization: $m_{\text{stag}} = \langle |n_A - n_B| \rangle$





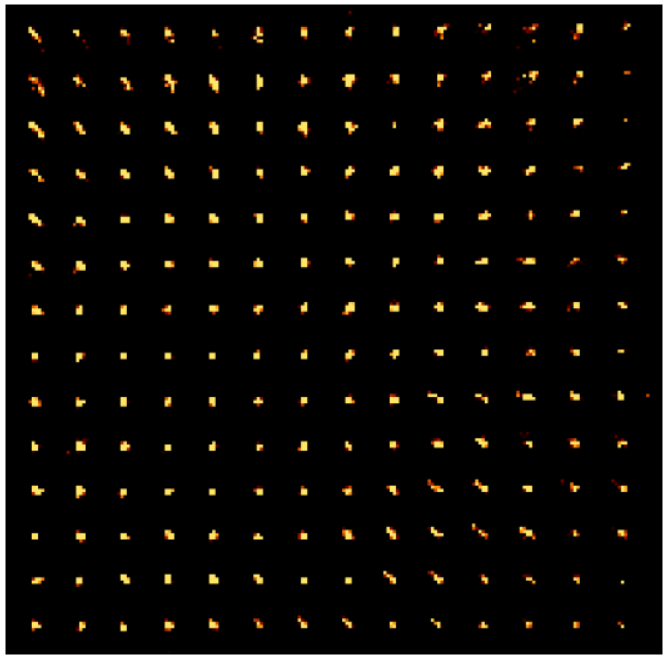
Accurate MPS limited to 10 x 10 (14 days!!)

Including experimental imperfections: $U_{ij}, \Omega_i, \delta_i$, real ramp…

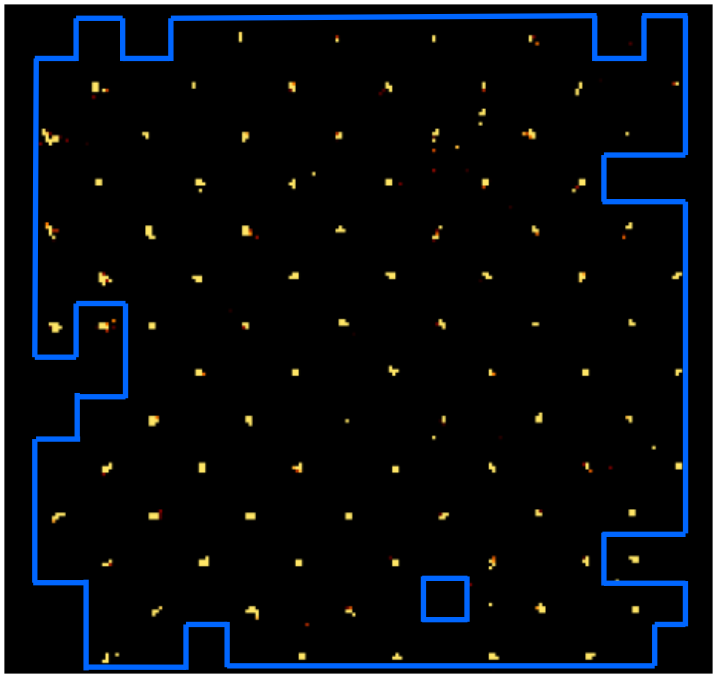
Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

14x14 square array



sweep

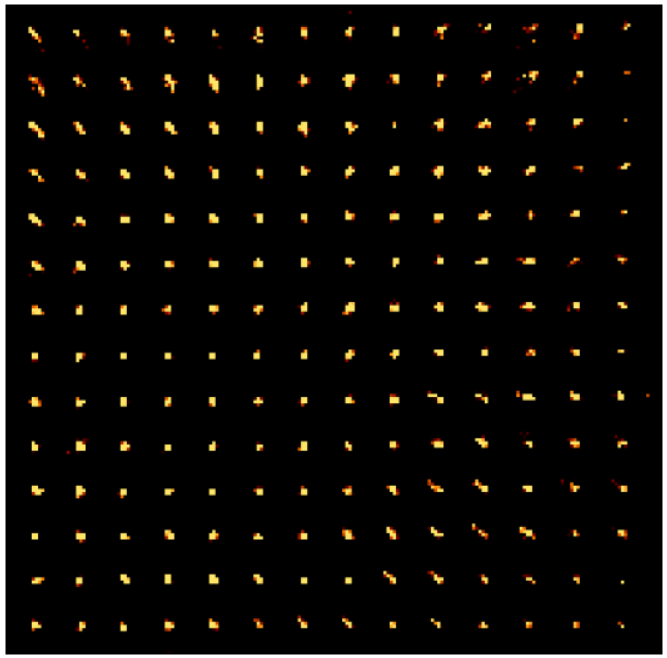


182-atom antiferromagnetic cluster!

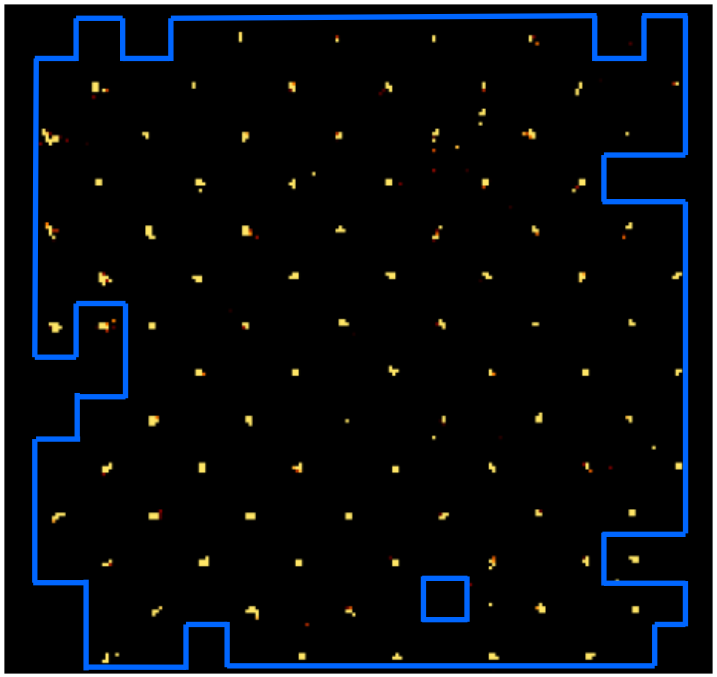
Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

14x14 square array



sweep



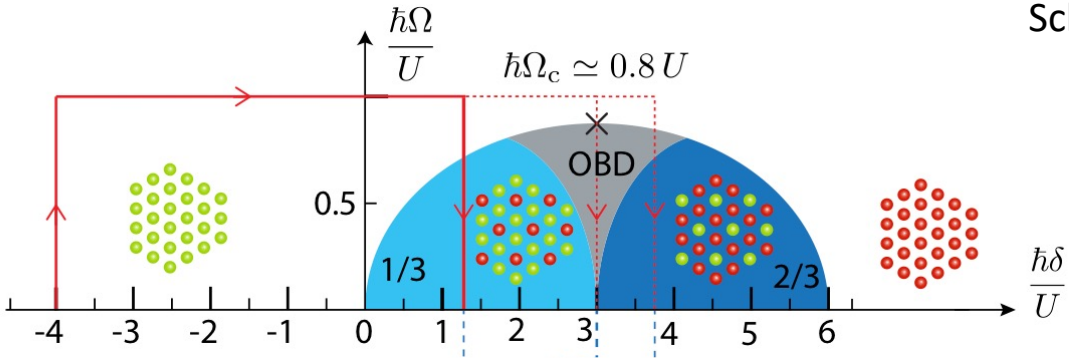
182-atom antiferromagnetic cluster!

2022: Data beyond $N > 100$ to test of tensor network methods…!!

M. Heyl, M. Dalmonte, S. Montangero

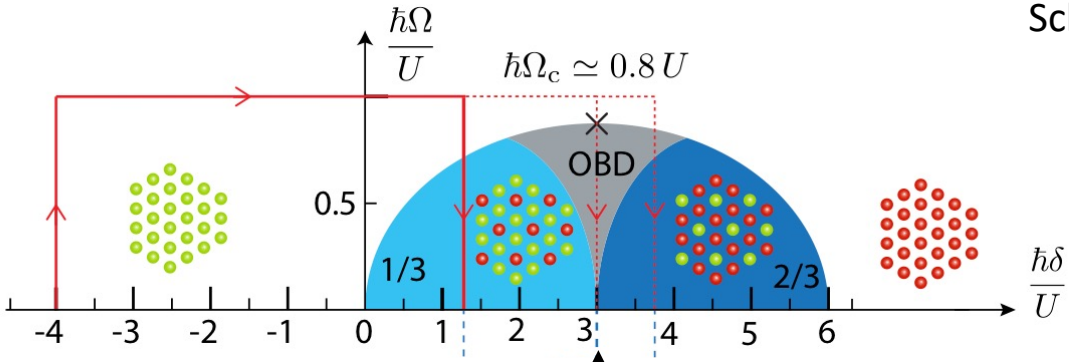
2D Ising anti-ferromagnet on a triangle

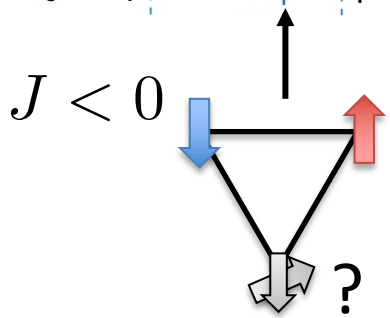
Scholl et *al.* Nature (2021)



2D Ising anti-ferromagnet on a triangle

Scholl et *al.* Nature (2021)

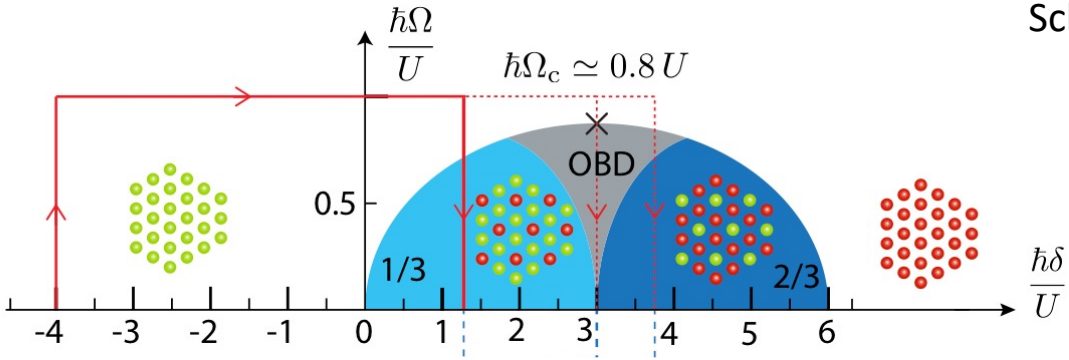




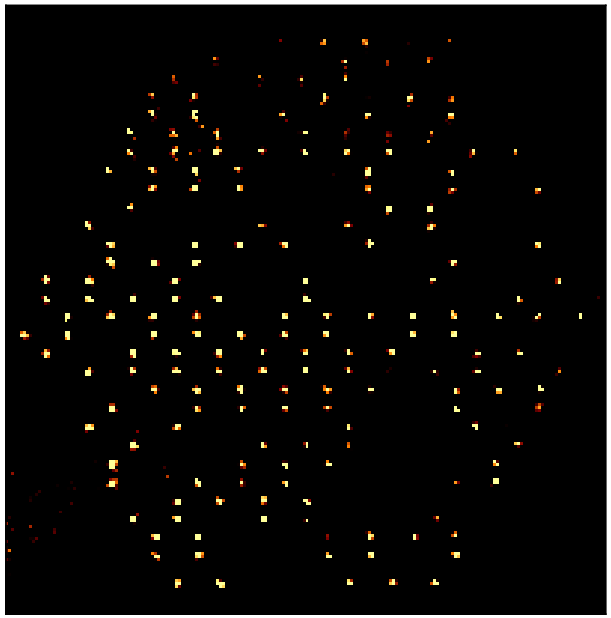
Geometrical frustration

2D Ising anti-ferromagnet on a triangle

Scholl et *al.* Nature (2021)

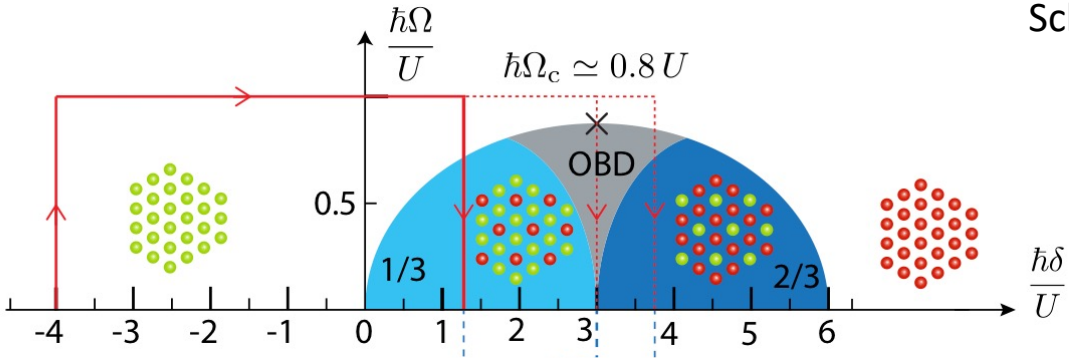


Initial



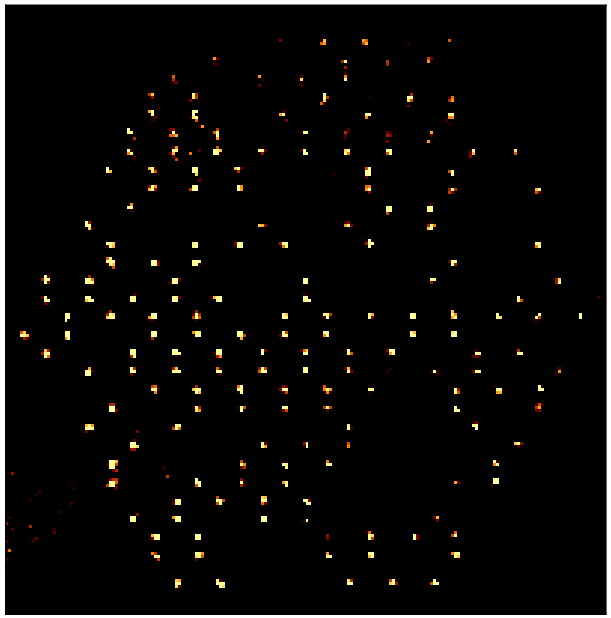
2D Ising anti-ferromagnet on a triangle

Scholl et *al.* Nature (2021)

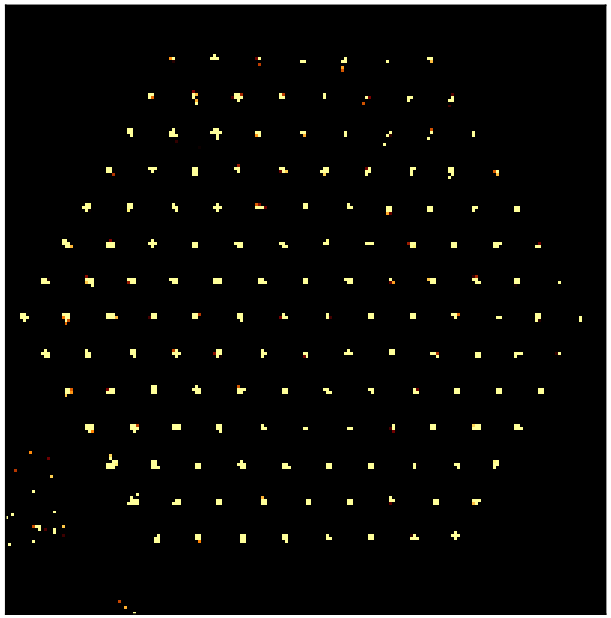


147 atoms

Initial

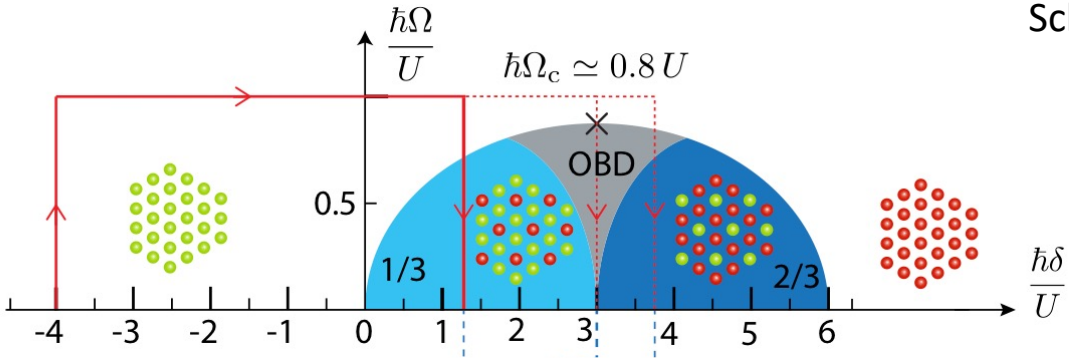


Assembled



2D Ising anti-ferromagnet on a triangle

Scholl et *al.* Nature (2021)



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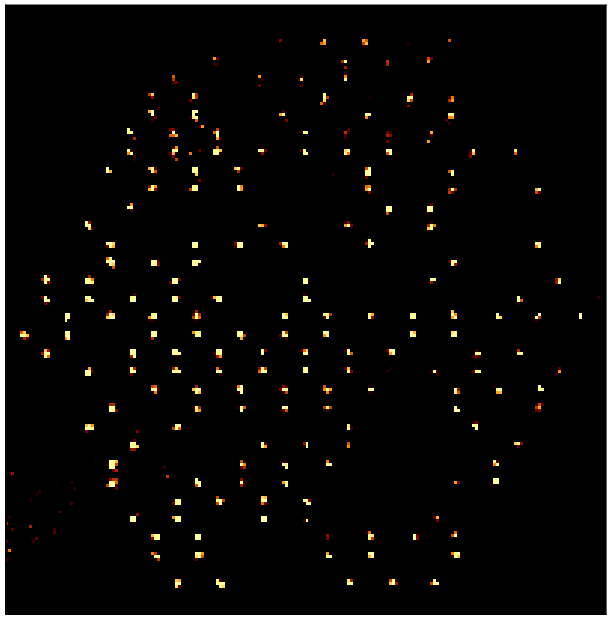
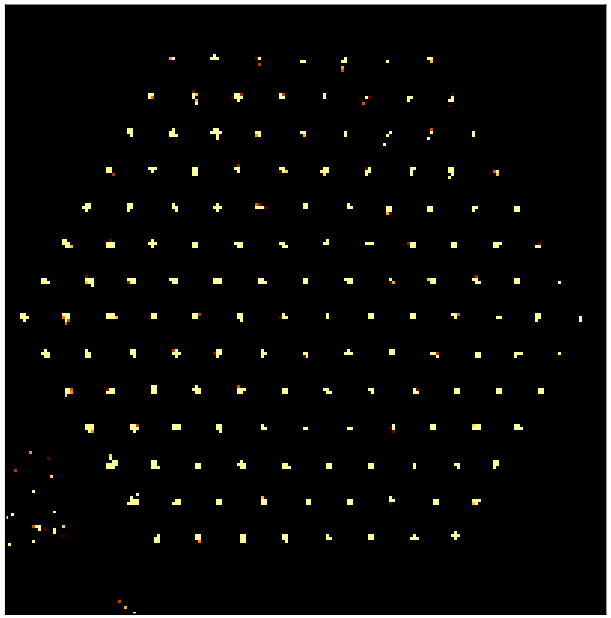
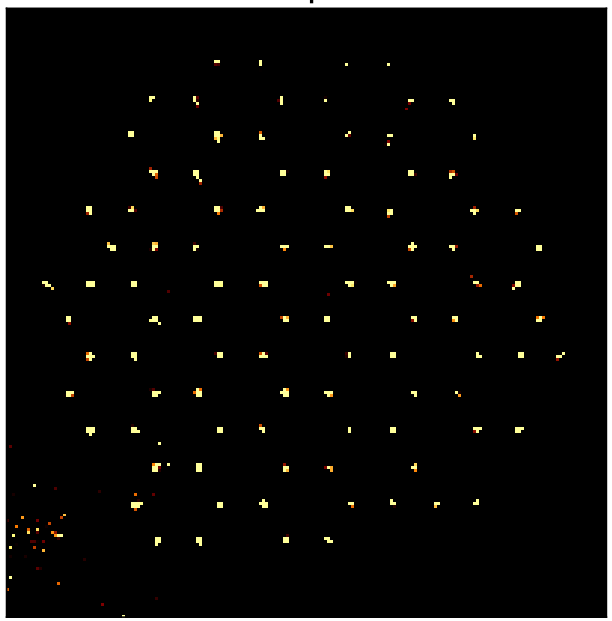


Assembled



Recapture



2D Ising anti-ferromagnet on a triangle

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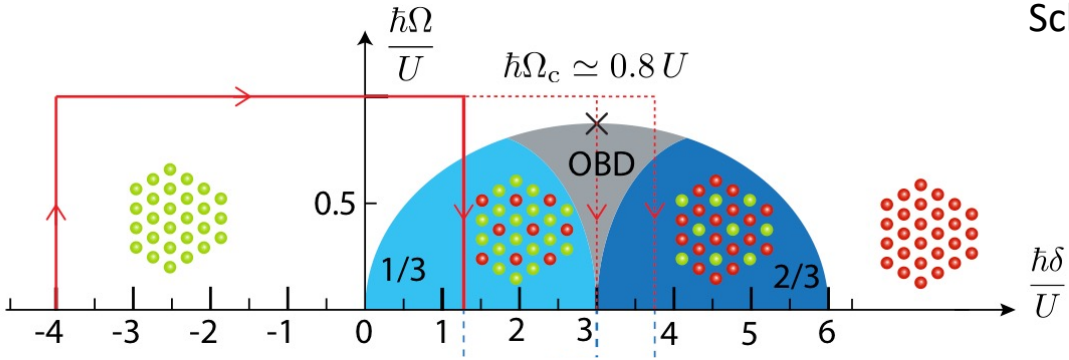
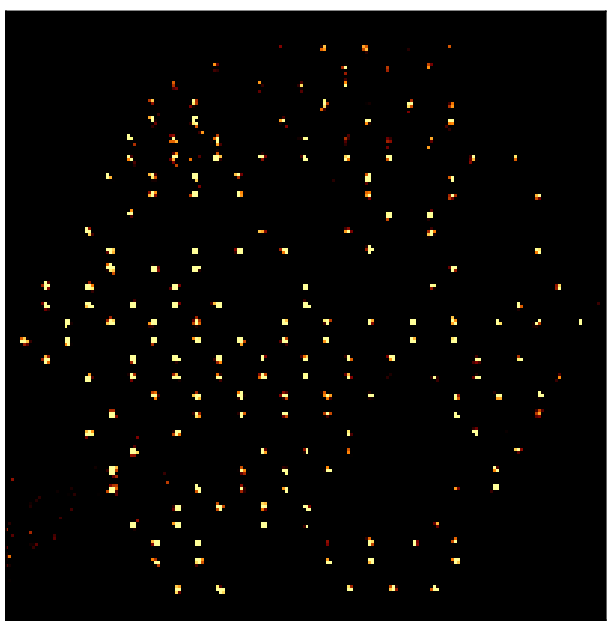


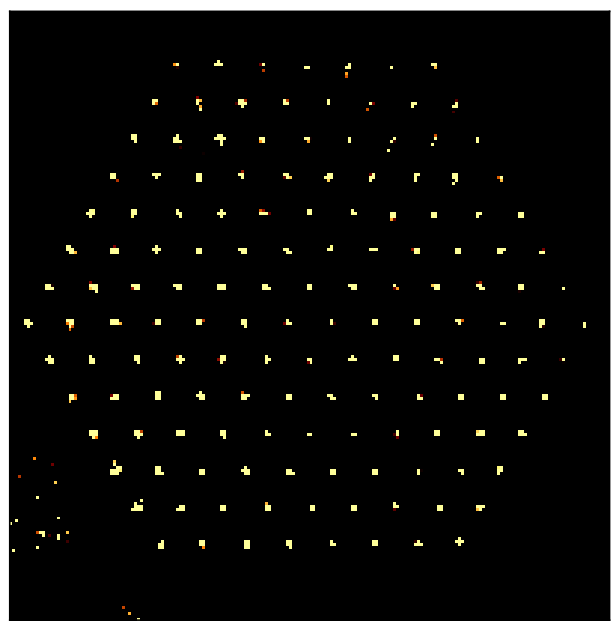
147 atoms

Perfect 1/3 AF!

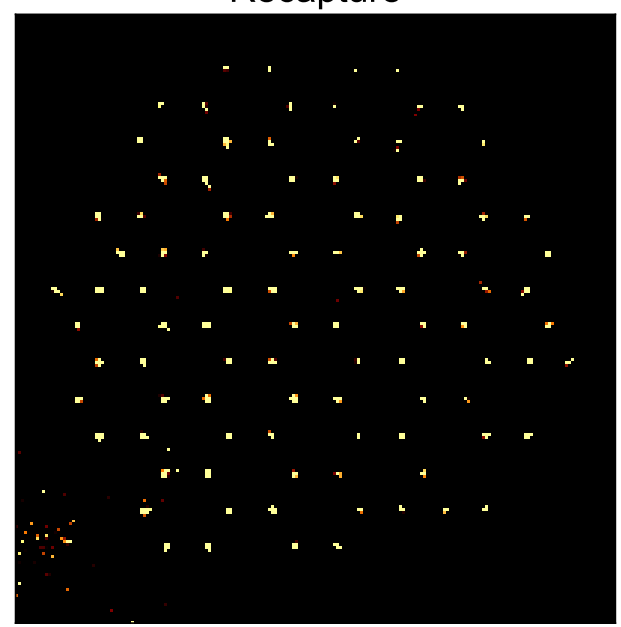
Initial



Assembled



Recapture



Outline

1. Magnetism: Ising model with van der Waals interactions

2. The interacting SSH model with resonant interaction

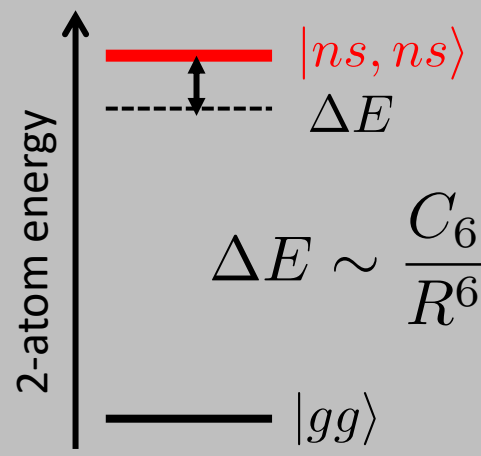
3. Heisenberg model with resonant interaction and Floquet engineering

H.-P. Büchler
S. Weber, N. Lang

Interactions between Rydberg atoms and spin models

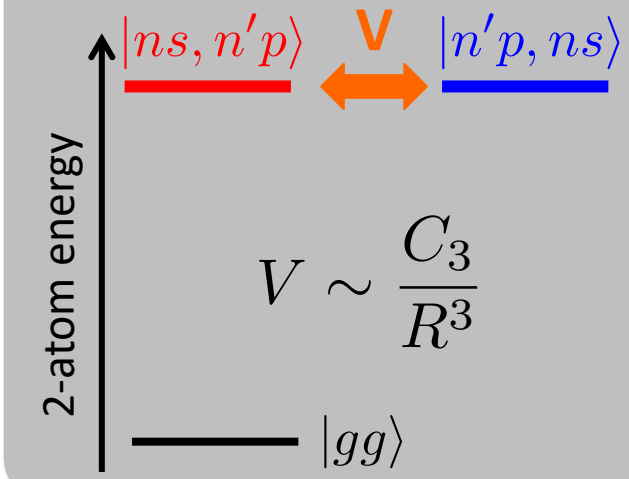
Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals



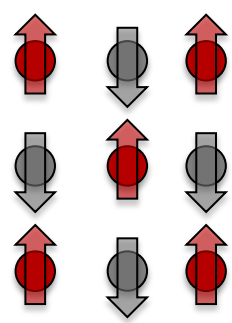
$$\Delta E \sim \frac{C_6}{R^6}$$

Resonant dipole



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

Spin 1/2



Quantum Ising

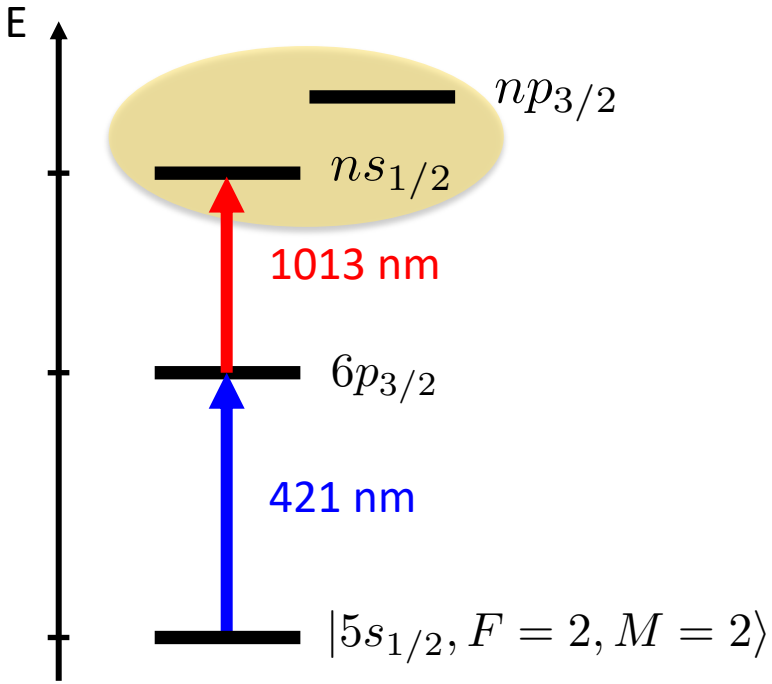
$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

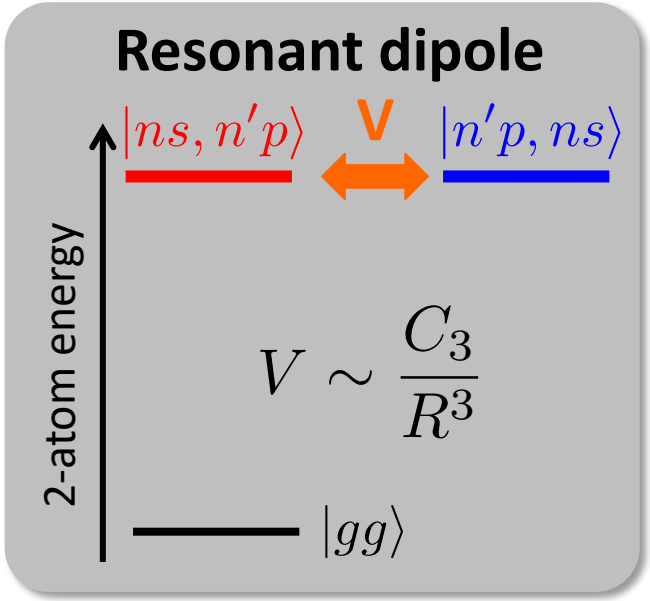
XY model

$$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+ \right)$$

Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)





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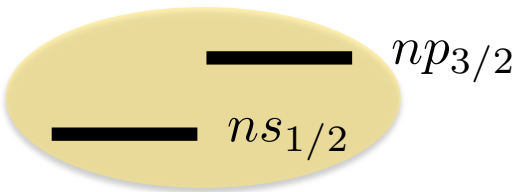
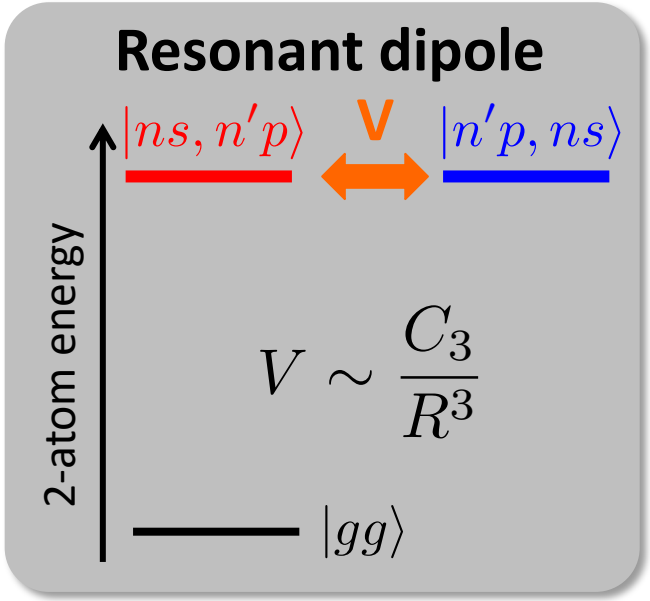
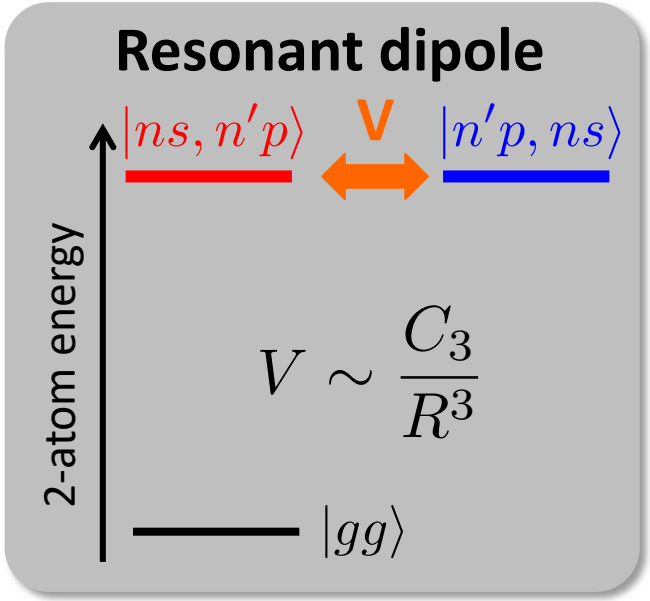
Browaeys & Lahaye, Nat.Phys. (2020)

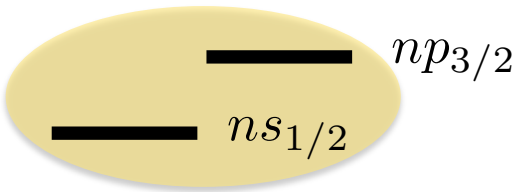


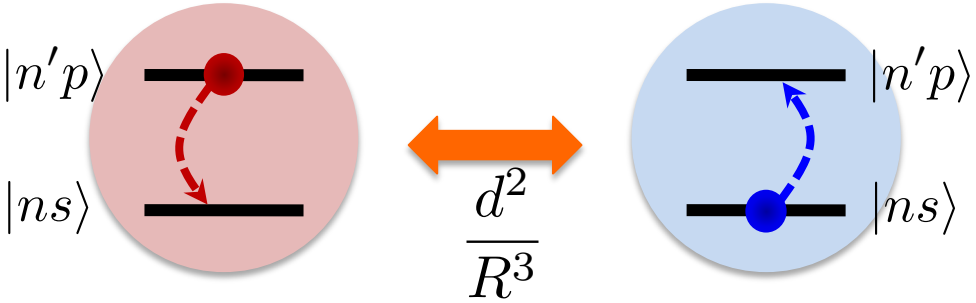


Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)







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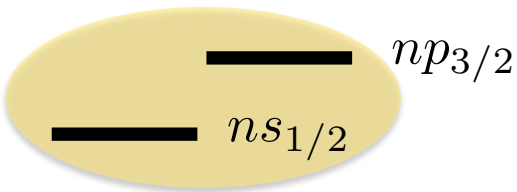
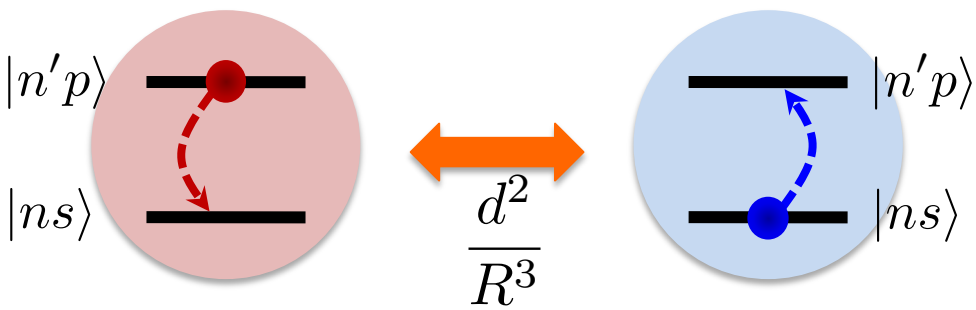
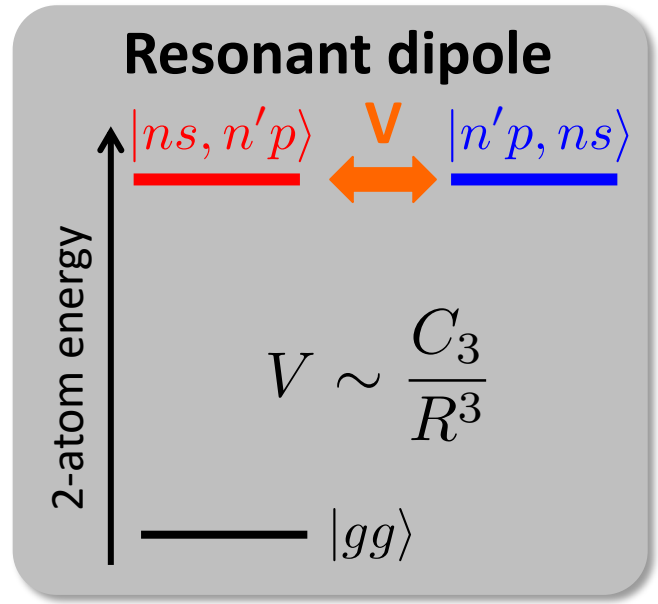






XY model

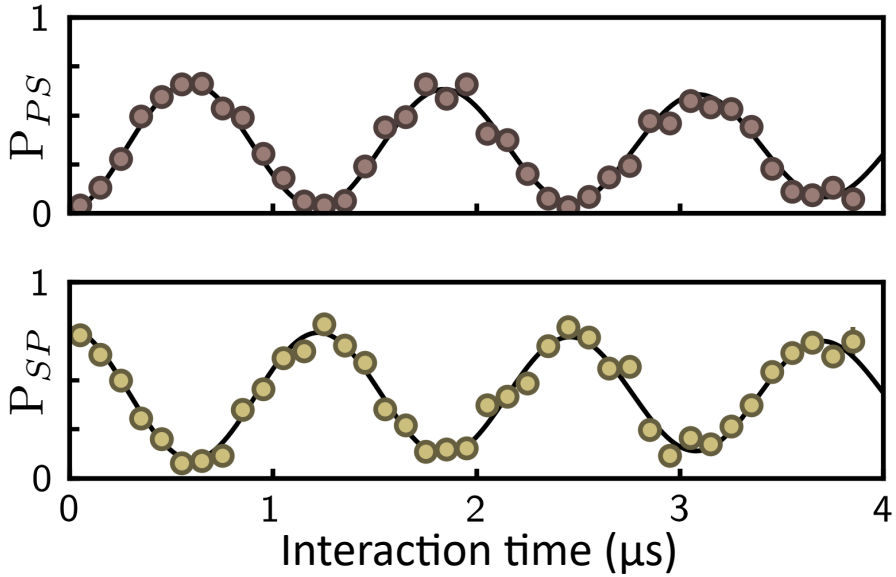
$$\hat{H} = \sum_{i \neq j} \frac{d^2}{R_{ij}^3} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$

Resonant dipole-dipole interaction between Rydberg atoms

Prepare $|PS\rangle$ using microwaves + addressing beam

R = 30 µm

Frequency: $\frac{2C_3}{R^3}$



Barredo PRL (2015)
de Léséleuc, PRL (2017)

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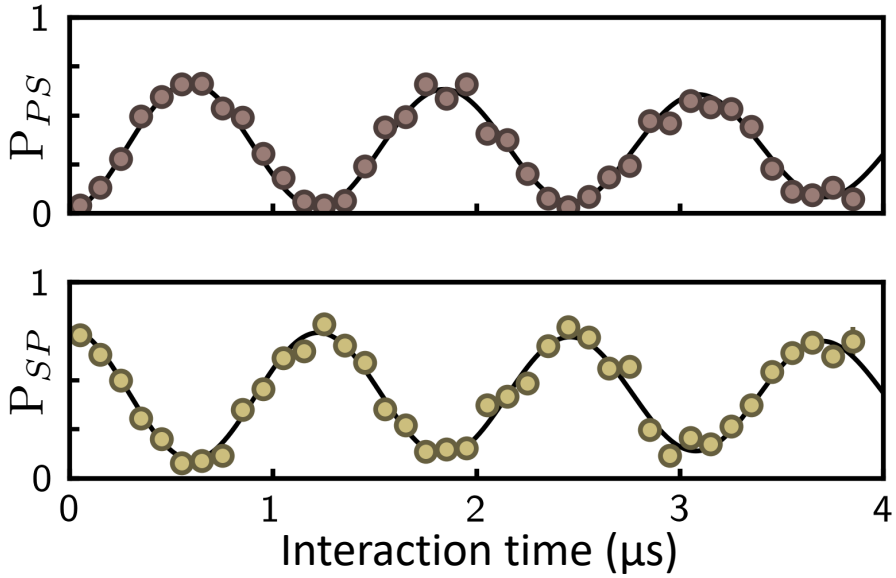

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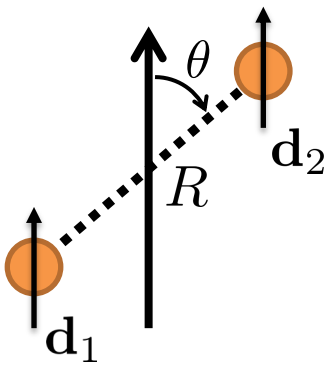
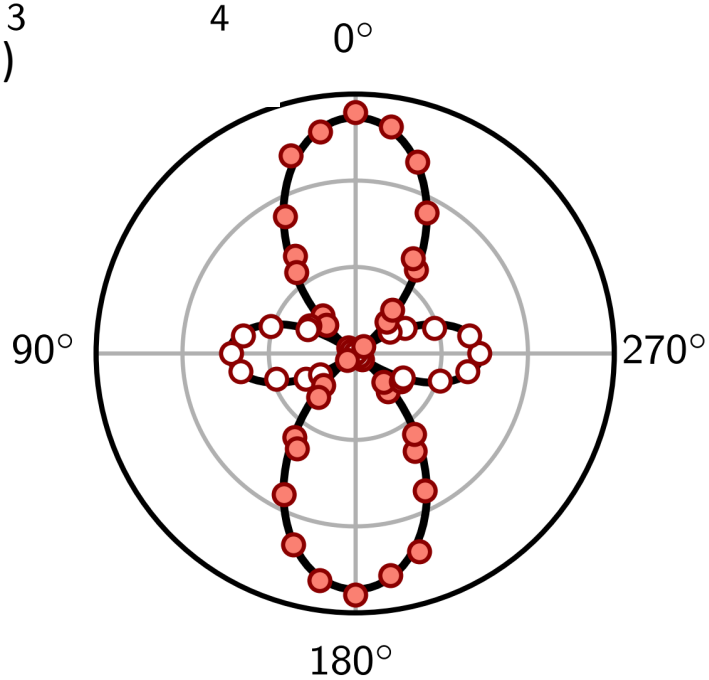
Quantization axis (B)



$$C_3(\theta) \propto 1 - 3\cos^2\theta$$



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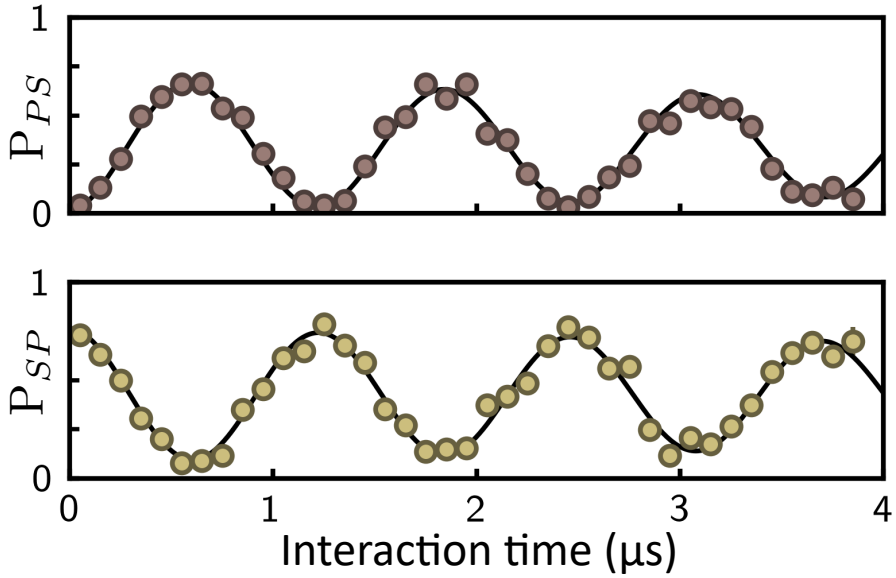

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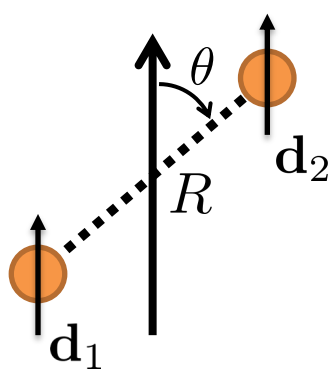

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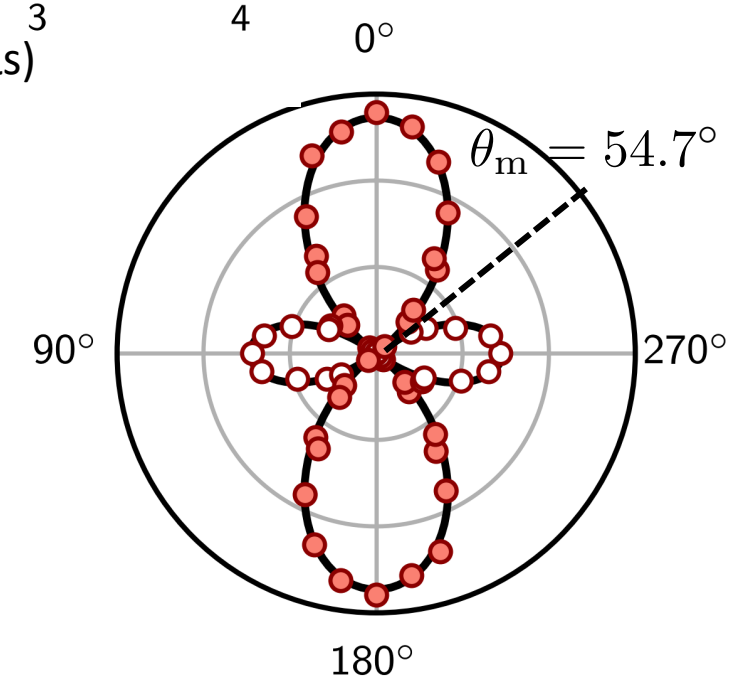

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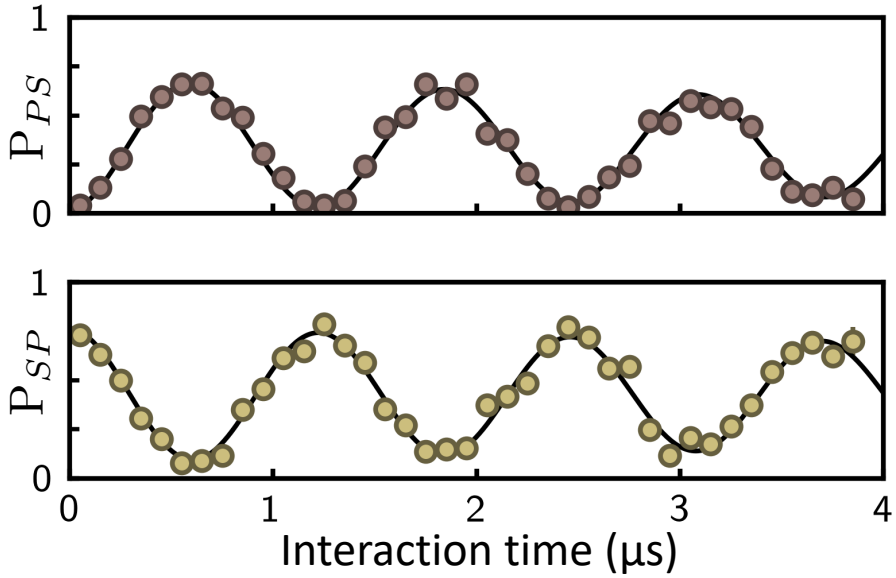

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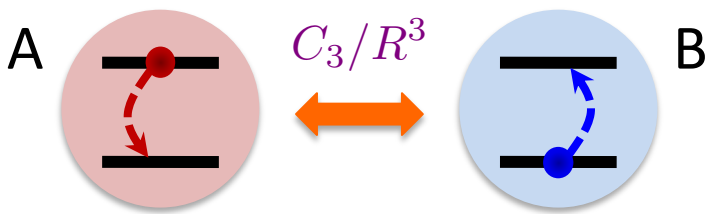
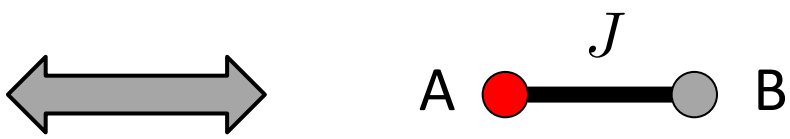


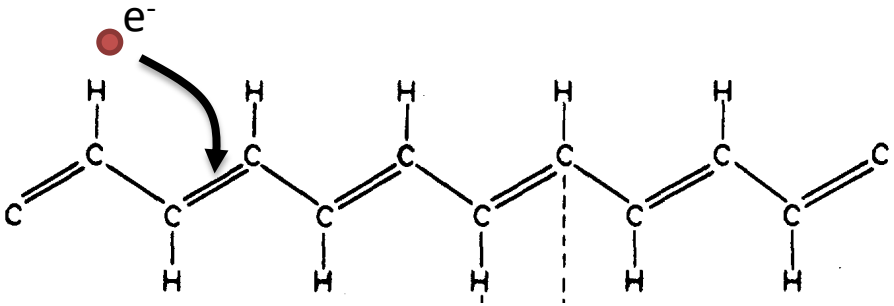
P excitation exchange



Particle hopping

$J|A\rangle\langle B|$

The Su-Schrieffer-Heeger model

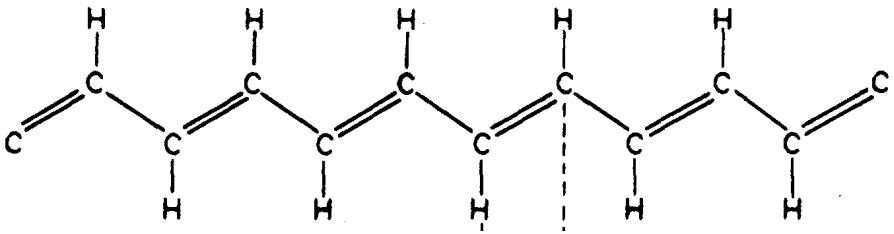


Electronic transport in polyacetylene

PRL **42**, 1698 (1979)

Now, considered as simplest example of topological model

The Su-Schrieffer-Heeger model



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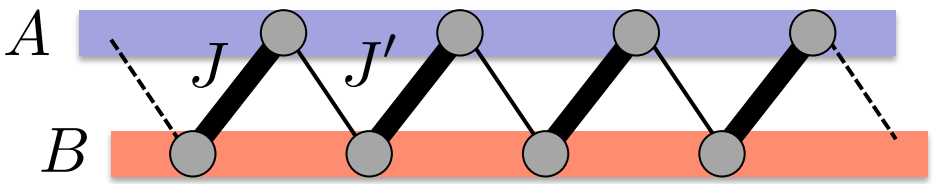

Model: tight-binding
dimerization: $J > J'$

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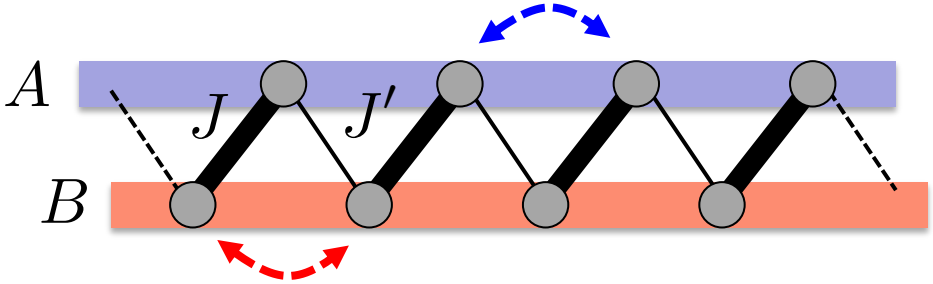

Model: tight-binding
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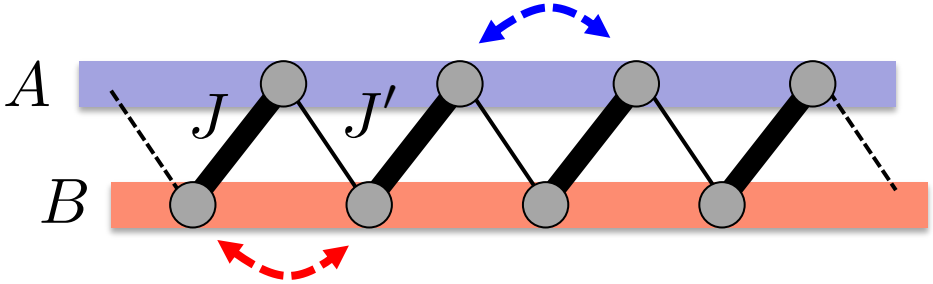
$J'' = 0$: **chiral symmetry** $\Rightarrow$ symmetric **single particle** spectrum

Implementation of SSH spin chain with Rydberg atoms

Science **365**, 775 (2019)



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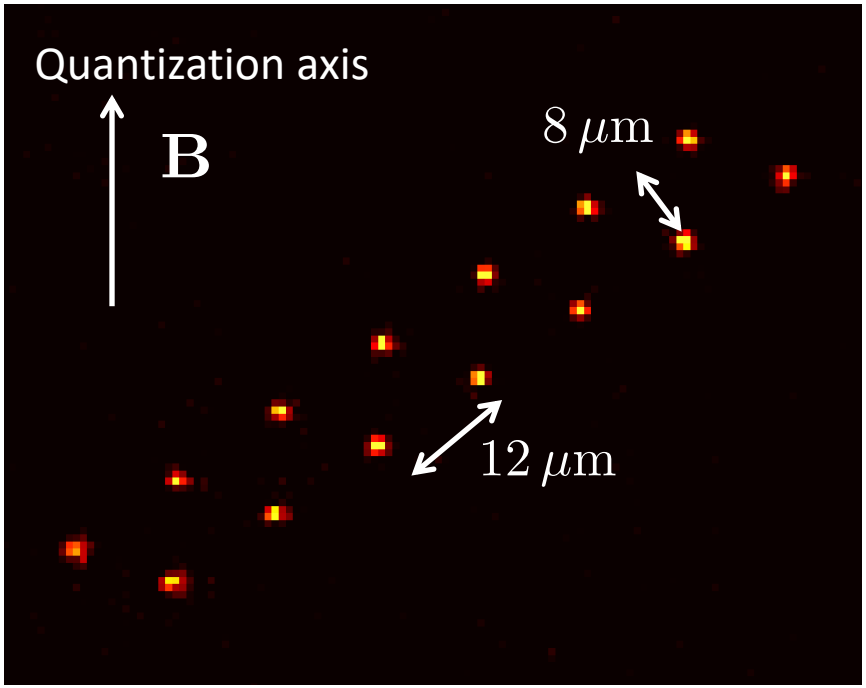
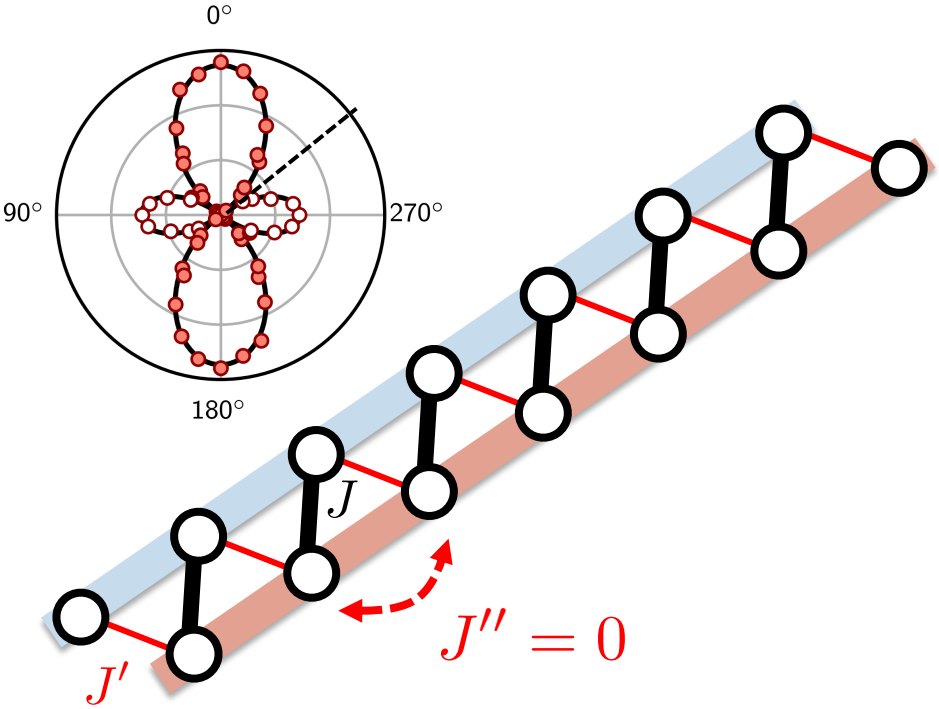
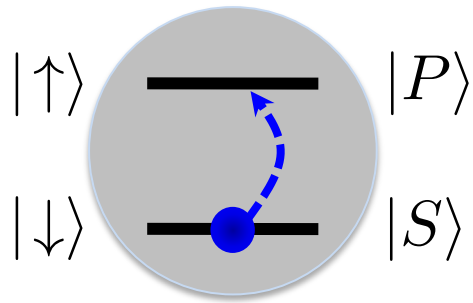




Spin excitations interact!!

Spin excitation = “particle”



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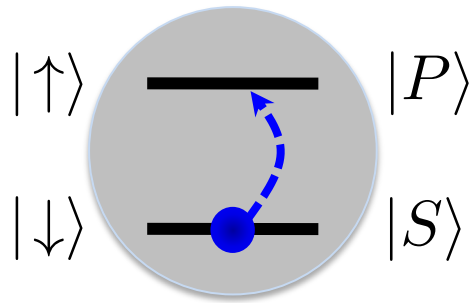
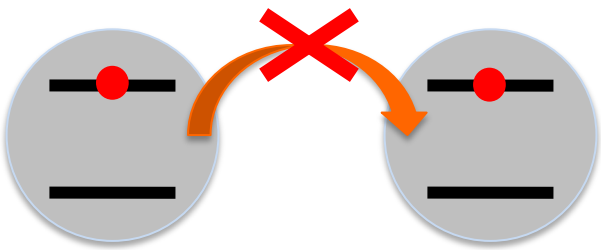


Atom cannot carry 2 excitations $\Rightarrow$ excitations = **hard-core bosons**



On-site interaction $U \to \infty$

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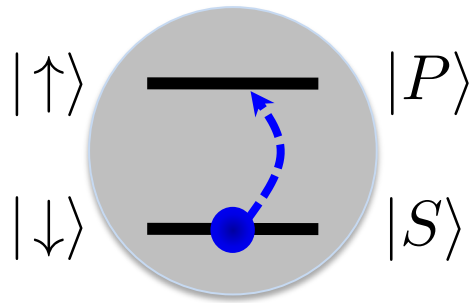

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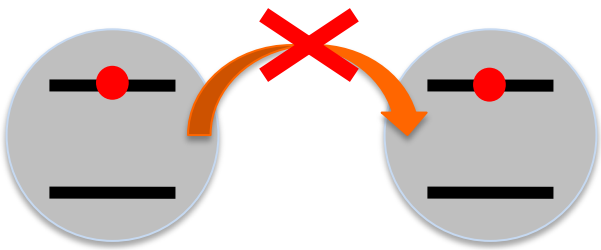

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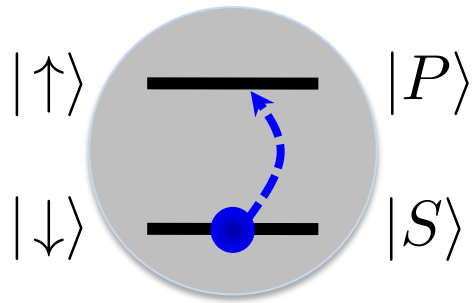

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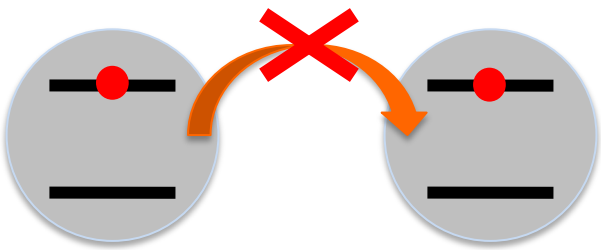

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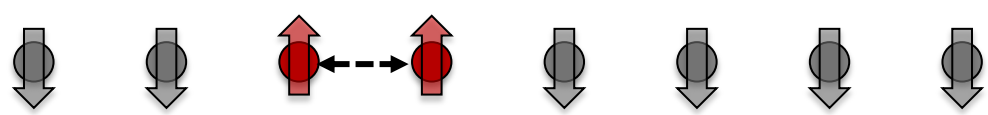


$\Rightarrow$ The first symmetry protected topological phase…

Predicted in 2012

Science **365**, 775 (2019)

Outline

1. Magnetism: Ising model with van der Waals interactions

2. The interacting SSH model with resonant interaction

3. Heisenberg model with resonant interaction and Floquet engineering

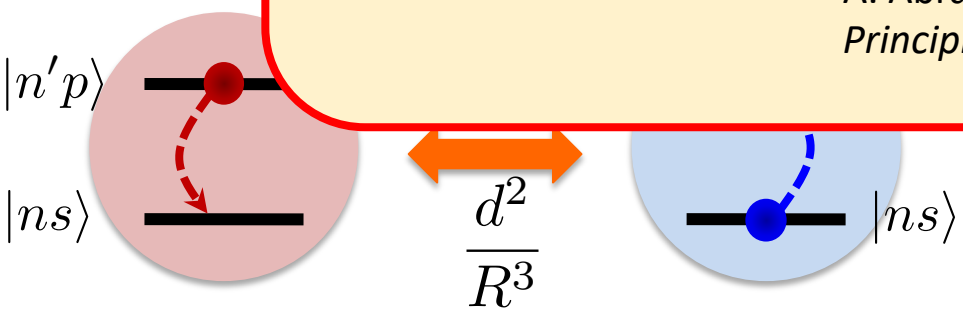
Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)

Extend to more general XYZ spin models

$$\hat{H}_{\mathrm{XYZ}} = \sum_{i \neq j} J^x_{ij}\,\sigma^x_i \sigma^x_j + J^y_{ij}\,\sigma^y_i \sigma^y_j + J^z_{ij}\,\sigma^z_i \sigma^z_j$$

A. Abragham,
Principle of Nuclear Magnetism (1983)



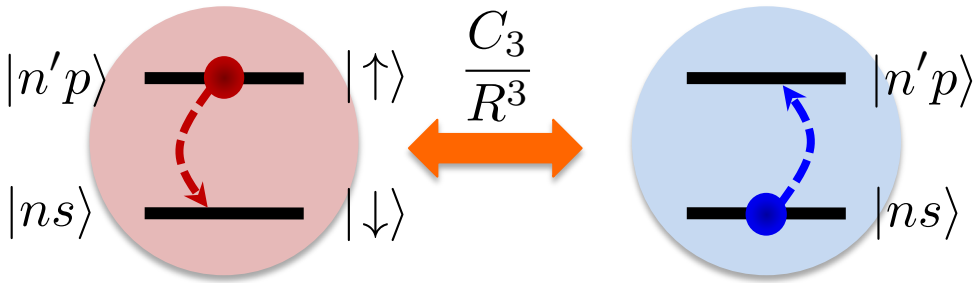
XY model

$$\hat{H} = \sum_{i \neq j} \frac{d^2}{R^3_{ij}} (\hat{\sigma}^+_i \hat{\sigma}^-_j + \hat{\sigma}^-_i \hat{\sigma}^+_j)$$

Engineering the XYZ model with microwaves

Combine:

Naturally occuring XY interaction



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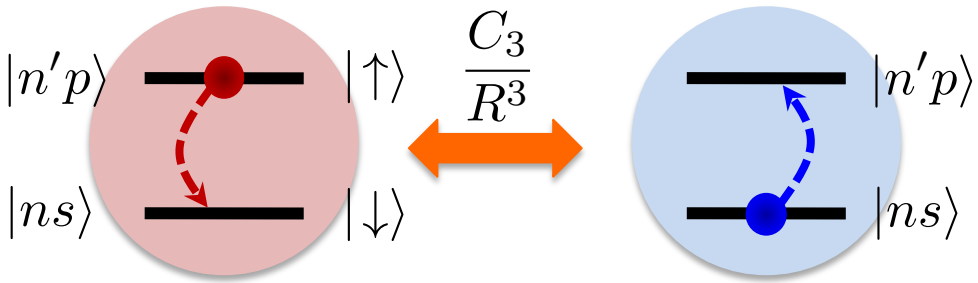
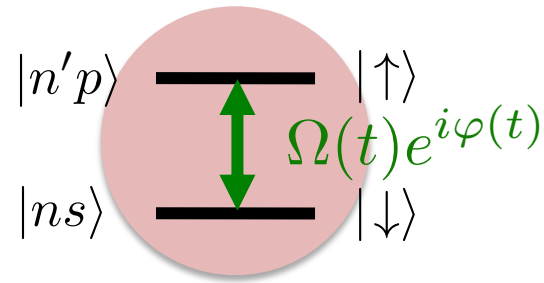
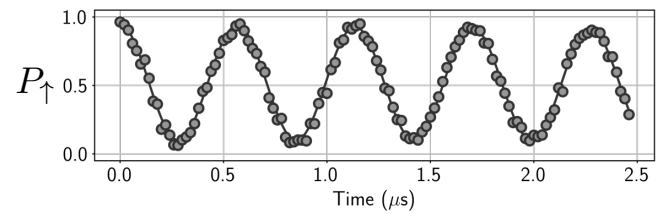


Microwave driving





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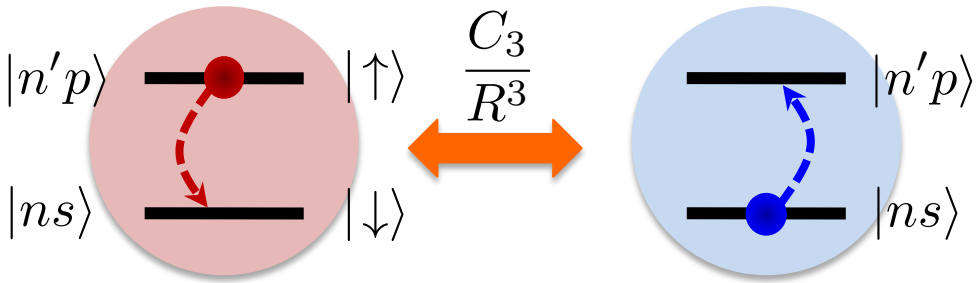

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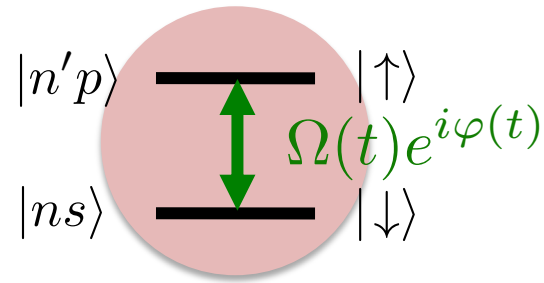
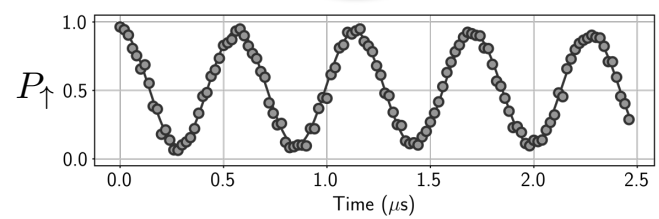


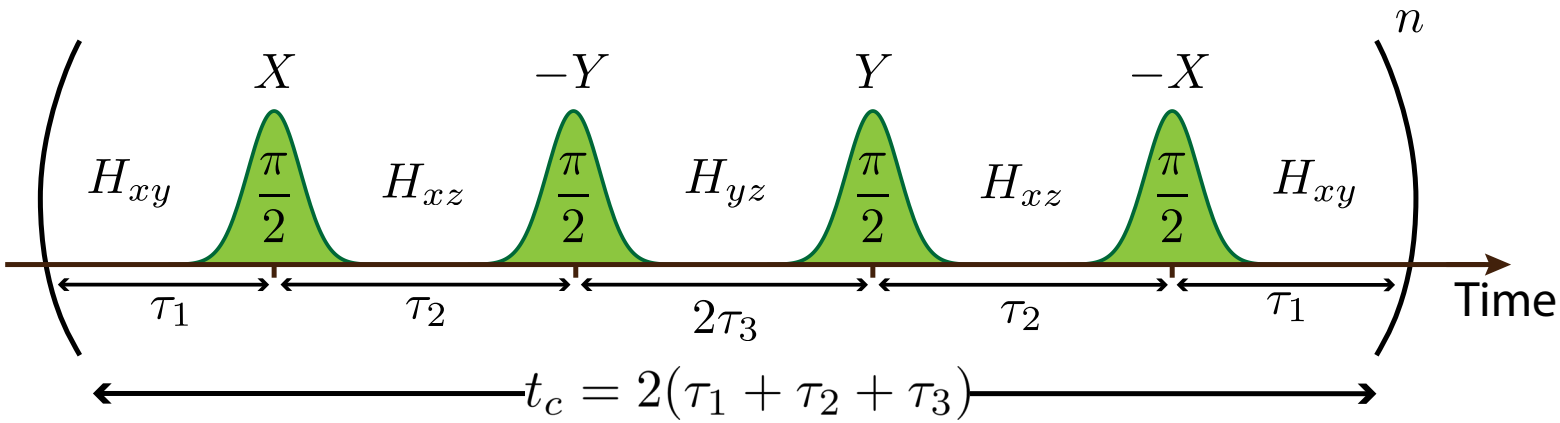


XY model + external (on-resonance) microwave field:

$$\hat{H}_{\text{driv}} = \sum_{i \neq j} \frac{C_3}{R_{ij}} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y) + \frac{\hbar\Omega(t)}{2} \sum_i \cos\varphi(t)\, \hat{\sigma}_i^x + \sin\varphi(t)\, \hat{\sigma}_i^y$$

Engineering the XYZ model with microwaves

Microwave pulse sequence $\Omega(t)$:



(infinitely short pulses)

Vandersypen, RMP 2006

Choi *et al.*, PRX **10**, 031002 (2020)

Engineering the XYZ model with microwaves

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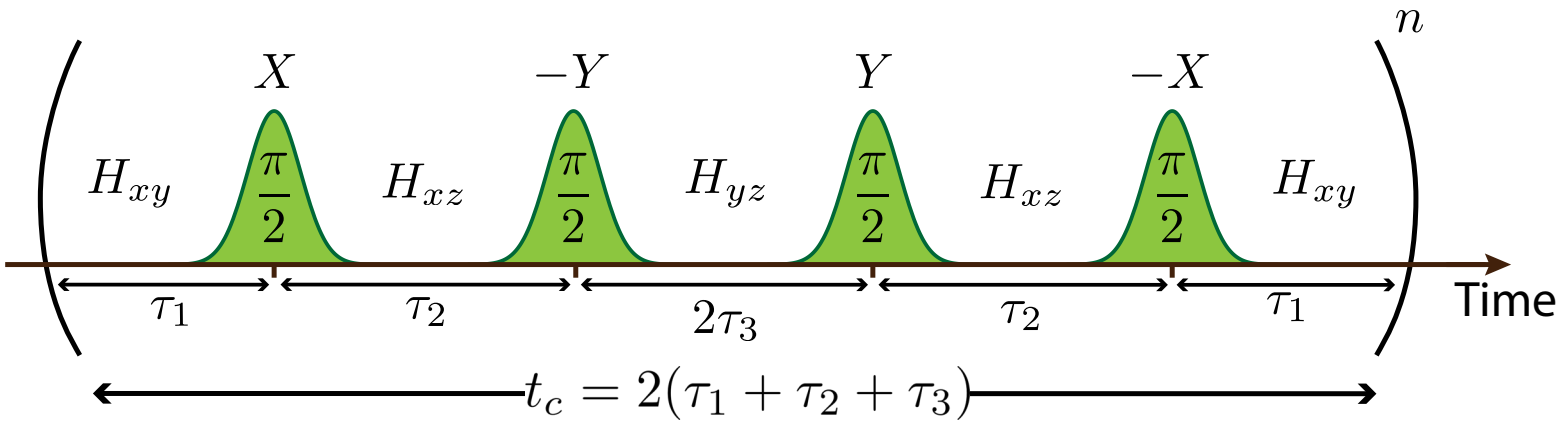

(infinitely short pulses)

$$\frac{C_3}{R_{ij}^3}\, t_c \ll 1 \;\Rightarrow \text{averaged hamiltonian:} \quad H_{\rm av} = \frac{1}{t_c}\int_0^{t_c} H(t)\, dt$$

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Choi *et al.*, PRX **10**, 031002 (2020)

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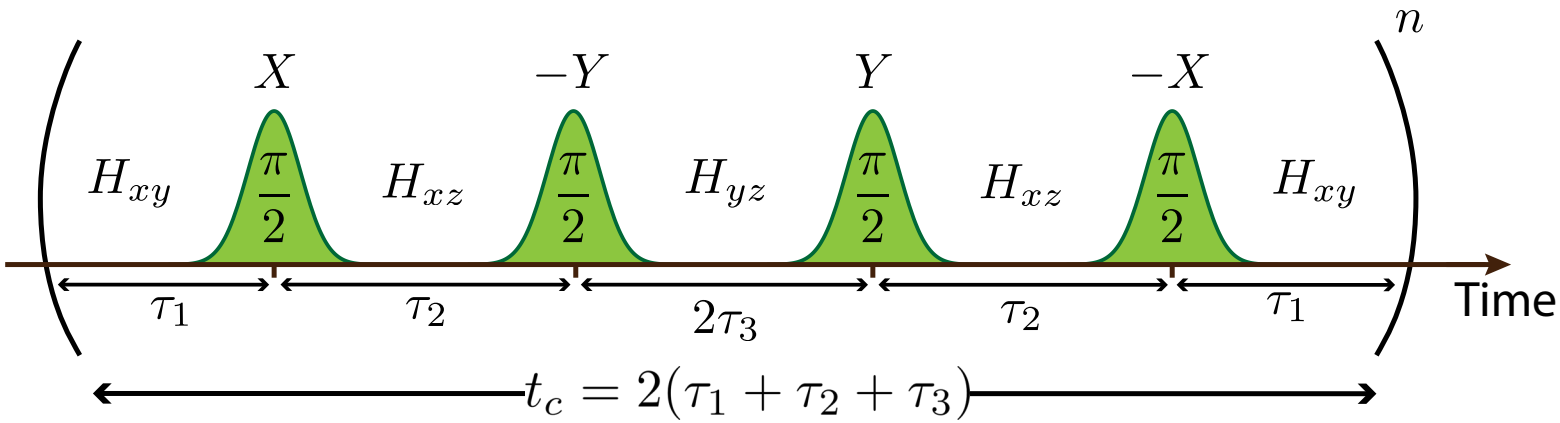

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Vandersypen, RMP 2006

Choi *et al.*, PRX **10**, 031002 (2020)

Engineering the XYZ model with microwaves

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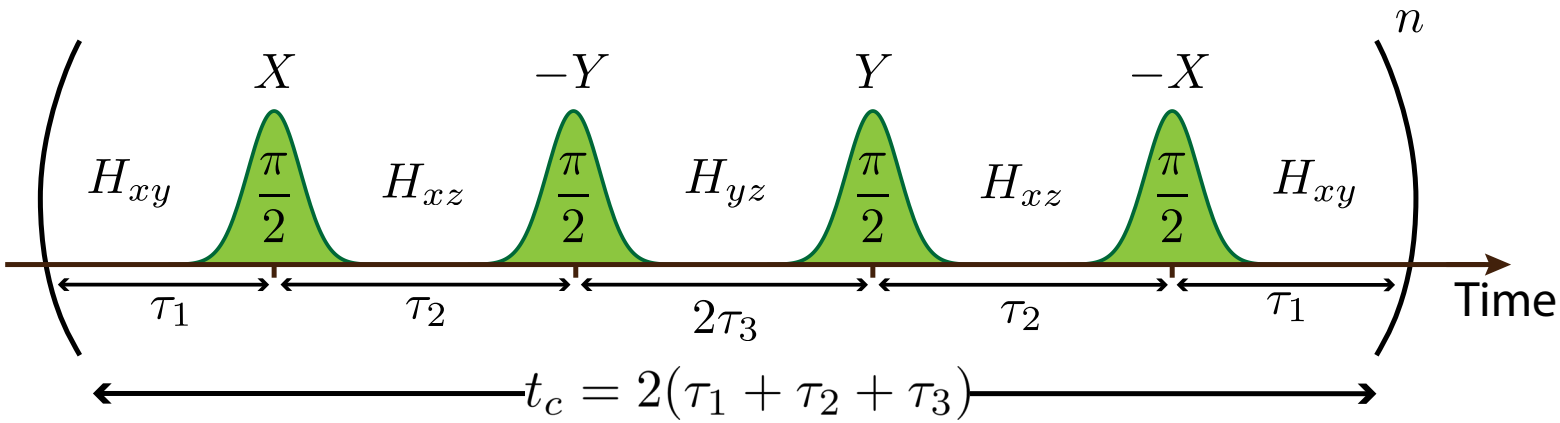

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$\Rightarrow$ Programmable XYZ Hamiltonians!

Vandersypen, RMP 2006

Choi *et al.*, PRX **10**, 031002 (2020)

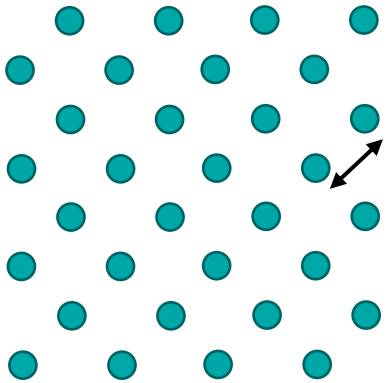
Heisenberg XXX engineering in 2D

Scholl, arXiv:2107.14459

32 atoms

$$\hat{H}_{\text{Heis.}} = \sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

$$|\downarrow\rangle = |75S\rangle; |\uparrow\rangle = |75P\rangle$$



$\sqrt{2}\times 20\ \mu\text{m}$

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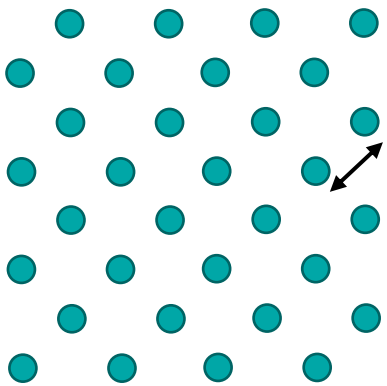

$\sqrt{2}\times 20\ \mu\text{m}$

Initial state: $(|\rightarrow\rangle_y)^{\otimes N}$

Heisenberg XXX engineering in 2D

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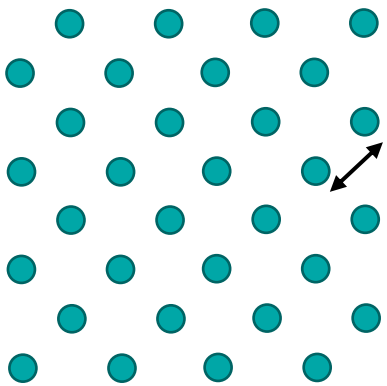
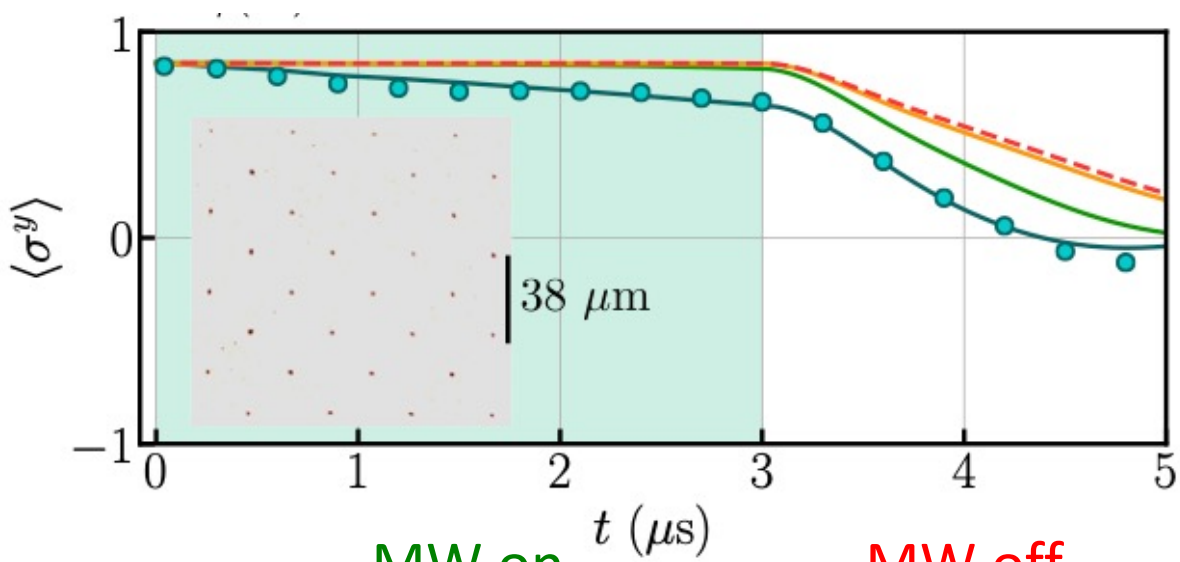


$\sqrt{2}\times 20\ \mu\text{m}$

Initial state: $(|\rightarrow\rangle_y)^{\otimes N}$



MW on

MW off

Heisenberg XXX engineering in 2D

Scholl, arXiv:2107.14459

32 atoms

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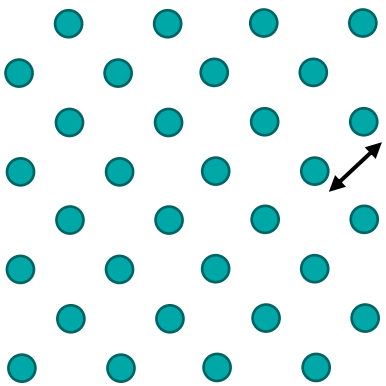

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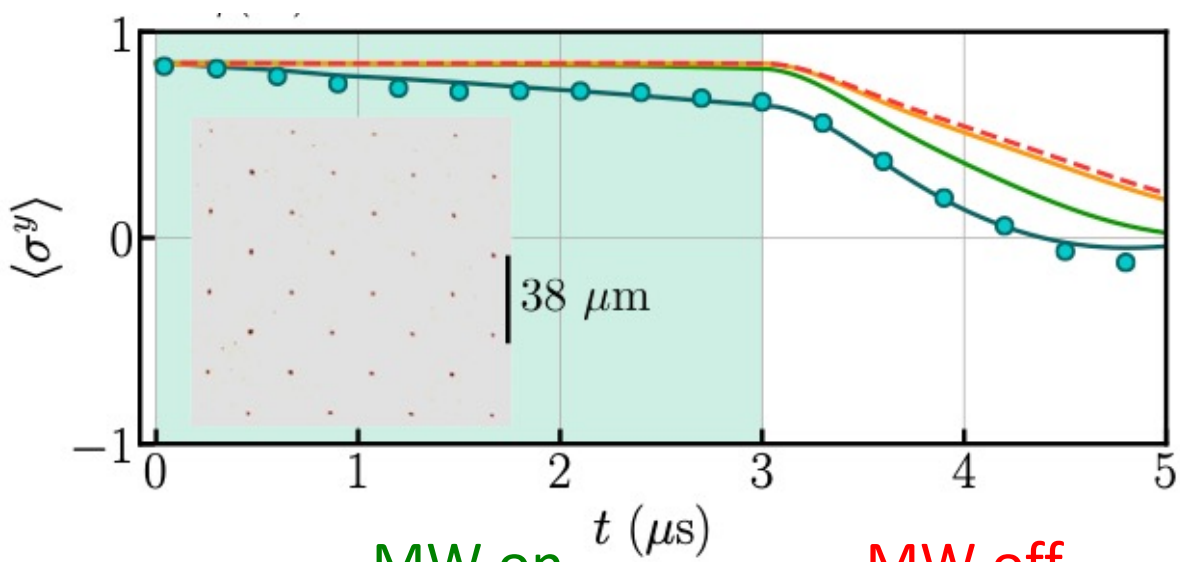

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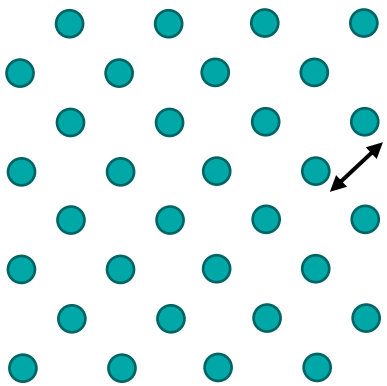

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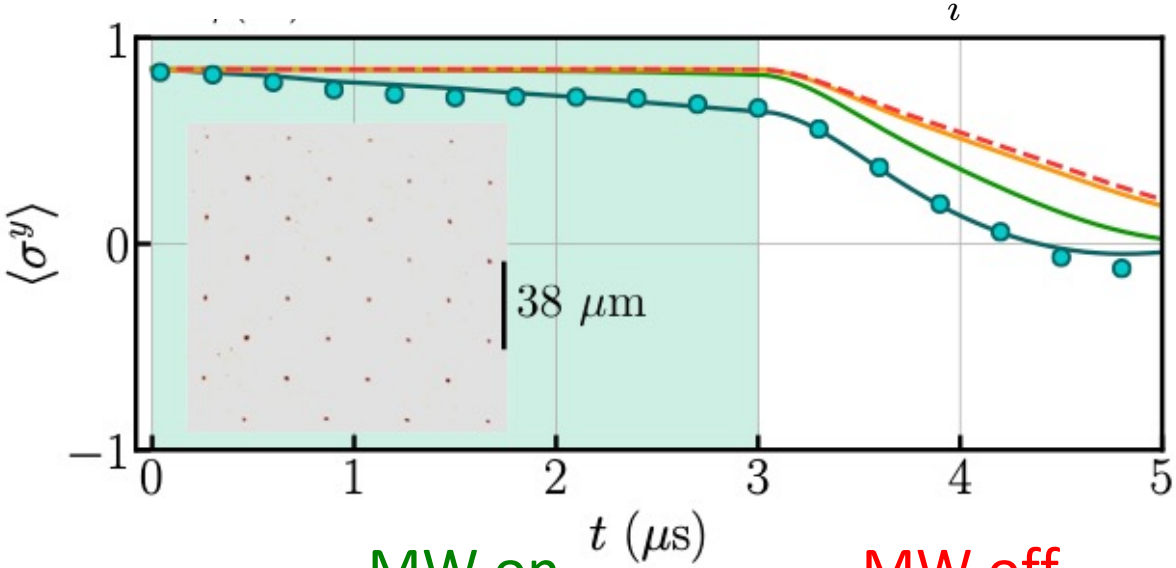
SU(2) symmetry: $[\hat{H}_{\text{Heis.}}, \sum_i \mathbf{S}_i] = 0$



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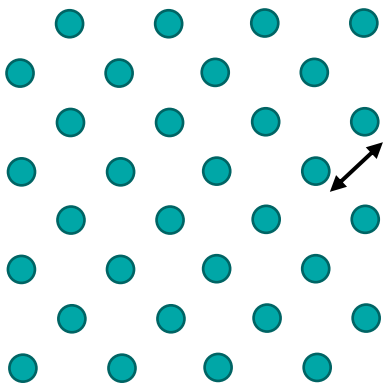

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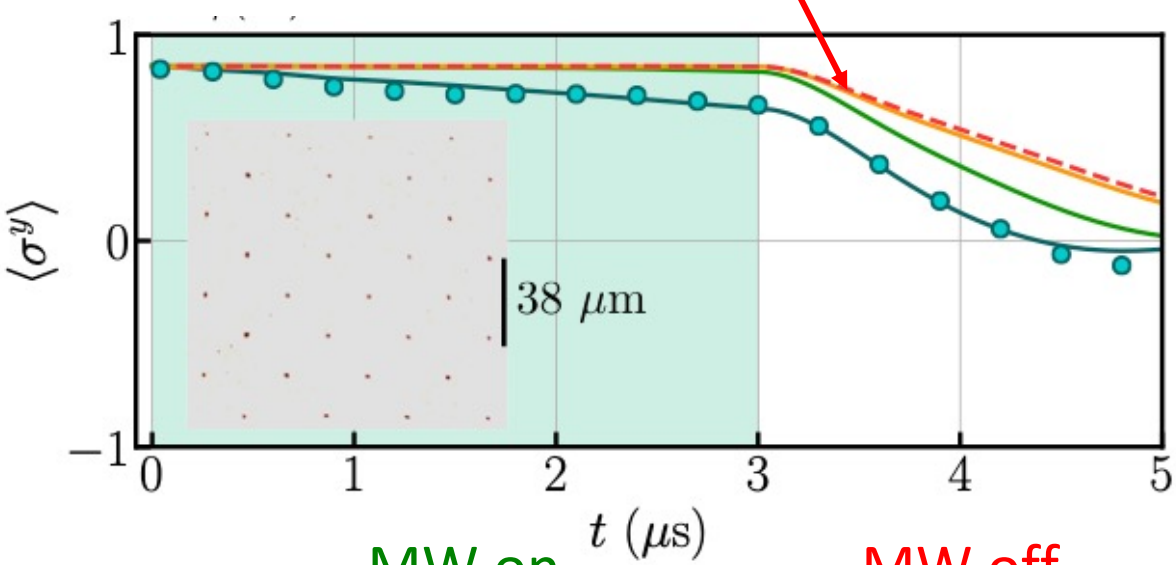
$H_{\text{Heis.}} \rightarrow H_{\text{XX}}$



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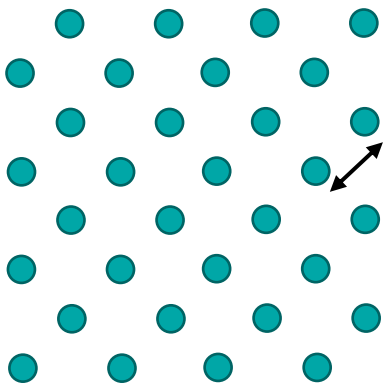

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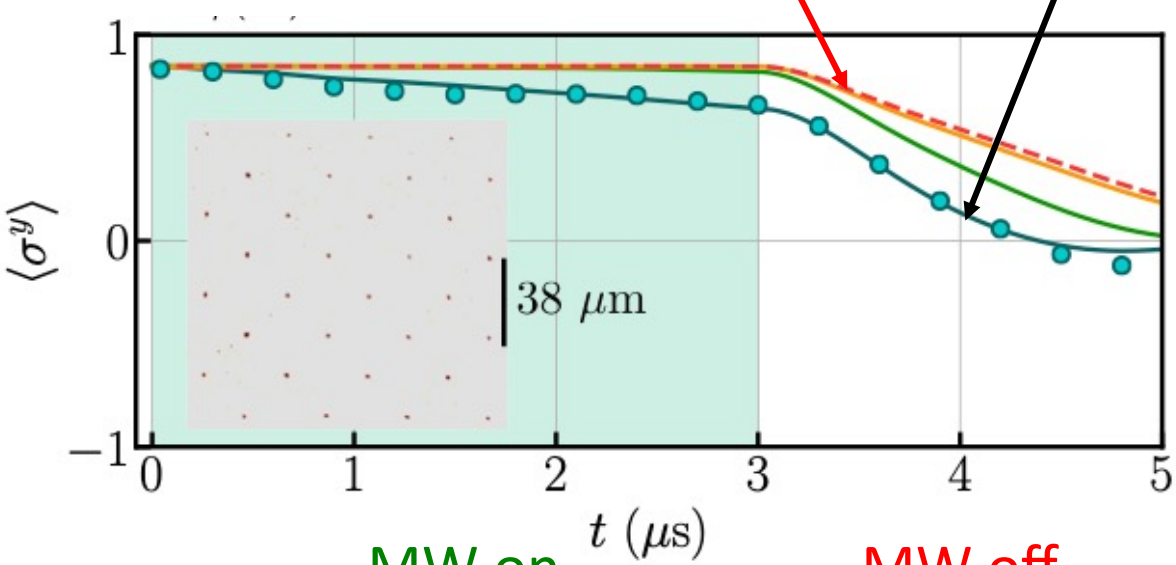
MACE simulation H_{driv}

Hazzard, PRL 2014



No adjustable parameter, includes MW imperfections

MW on

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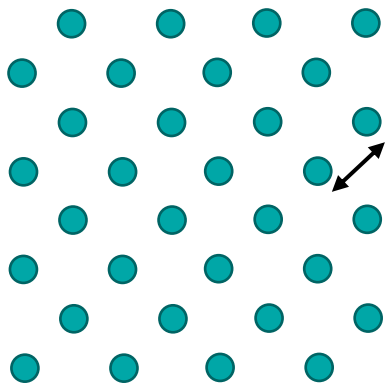

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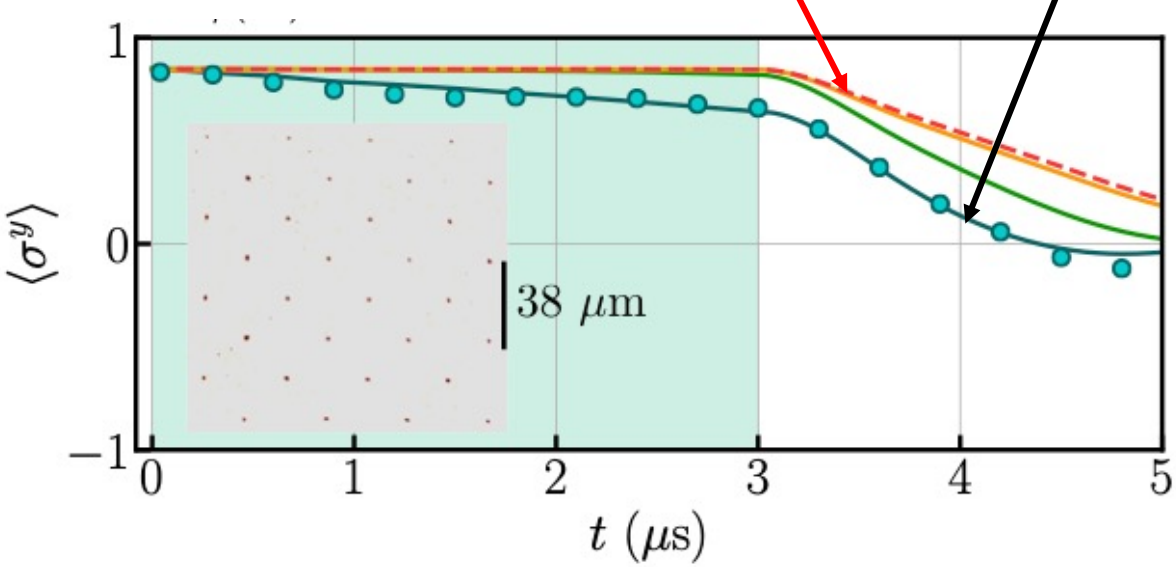

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Limitations: finite MW pulse duration + imperfections

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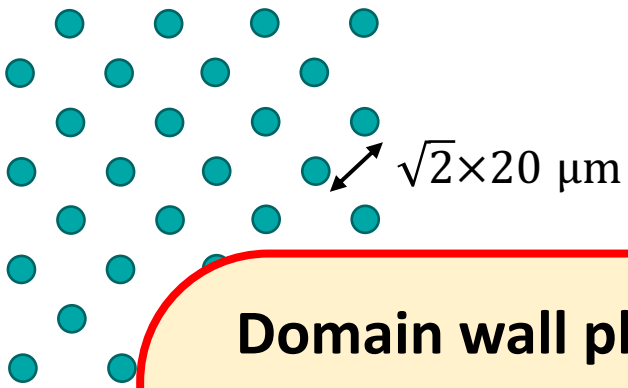
Scholl, arXiv:2107.14459

32 atoms



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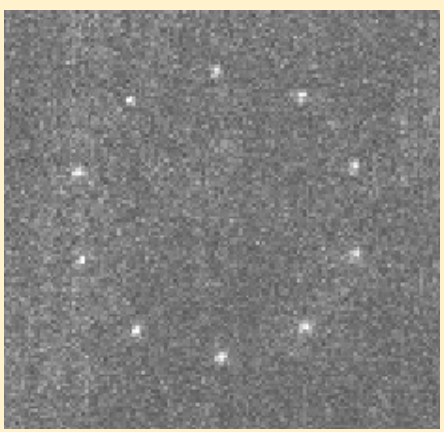
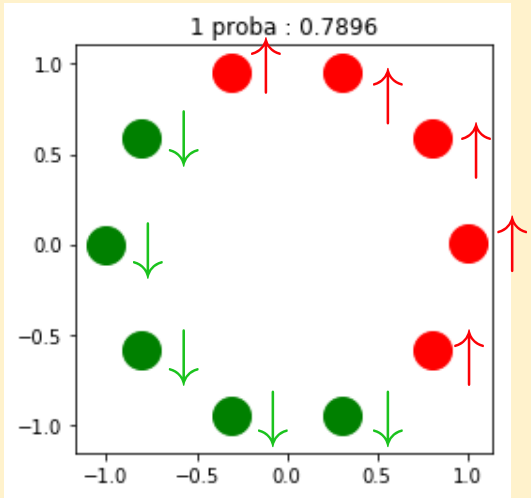
Domain wall physics in 1D with XXZ model





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Conclusion

Rydberg arrays: A platform to explore spin models… and beyond…

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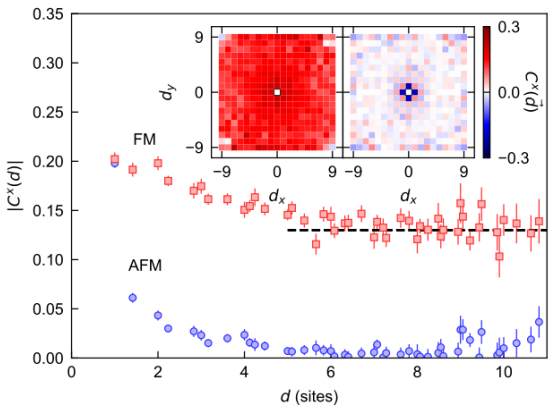
Continuous symmetry breaking in XY model



Cheng, arXiv:2207.12930

Conclusion

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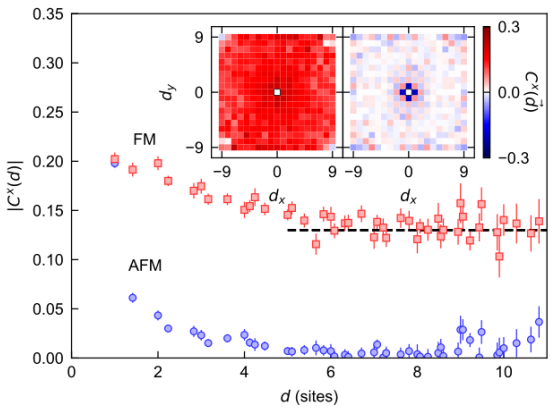

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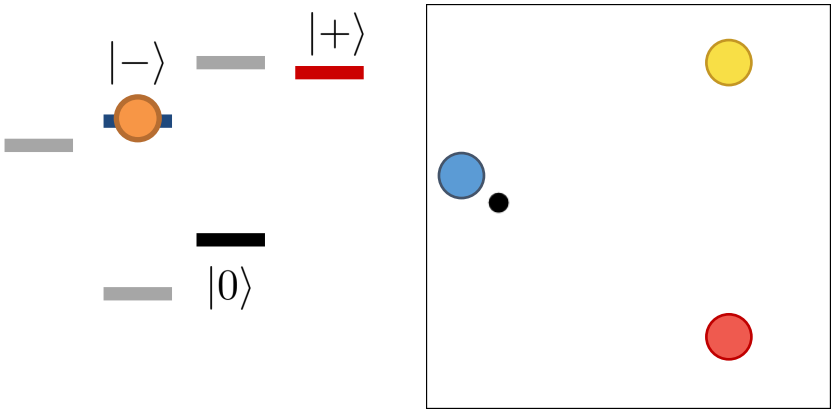
Spin-orbit coupling



Lienhard, PRX 2021

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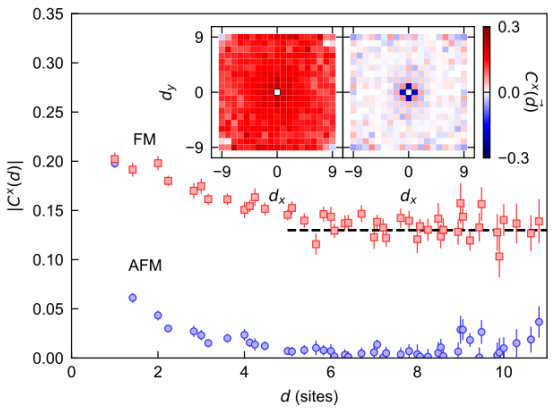

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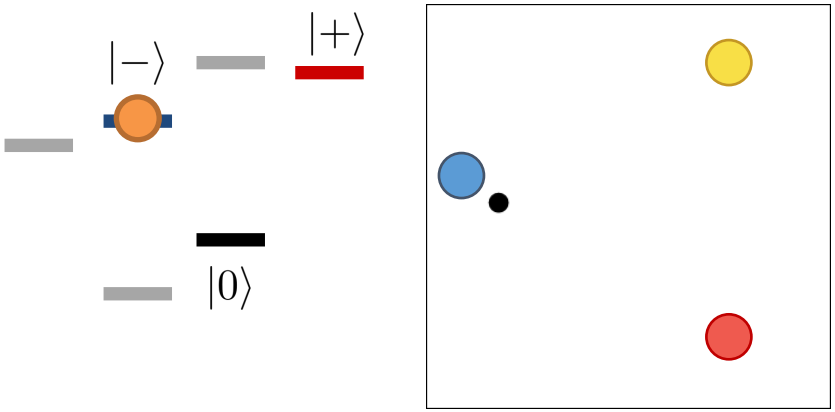

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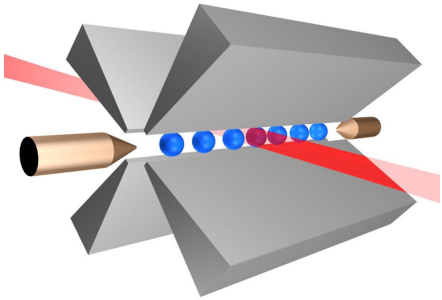
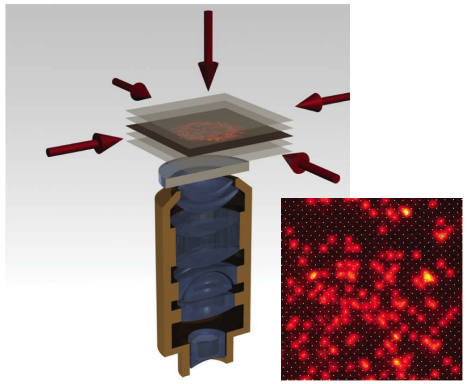
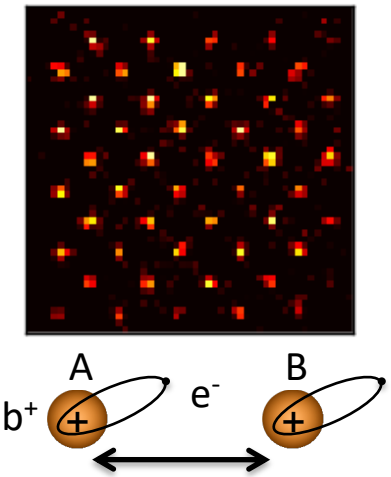
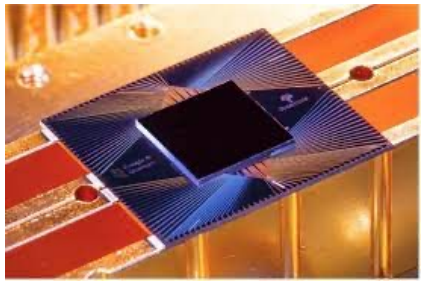
Useful quantum simulators already exist, and challenge theory!!









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