Rydberg atoms in optical tweezers

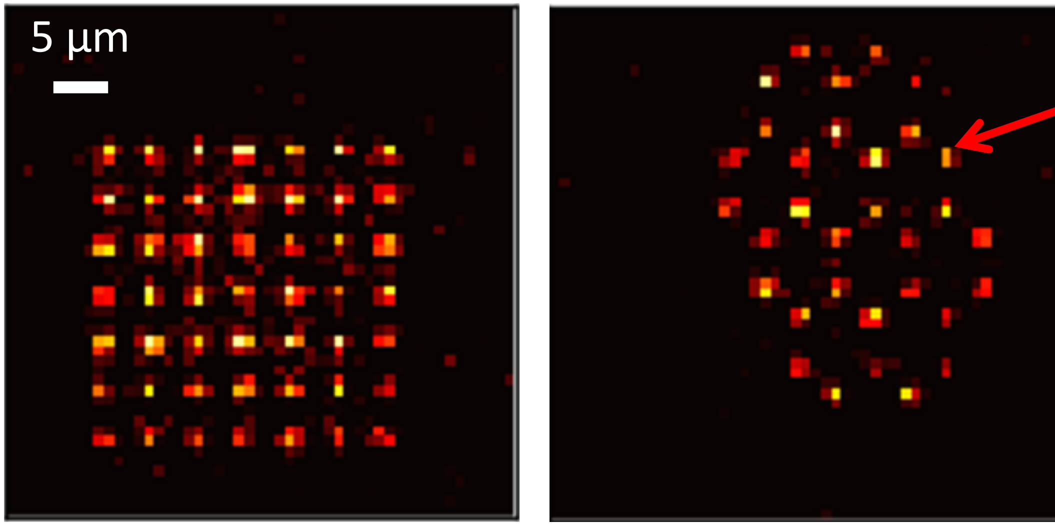
Lecture 1: Dipolar interactions between atoms

Lecture 2: Arrays of atoms. Basics of Rydberg physics. Rydberg blockade

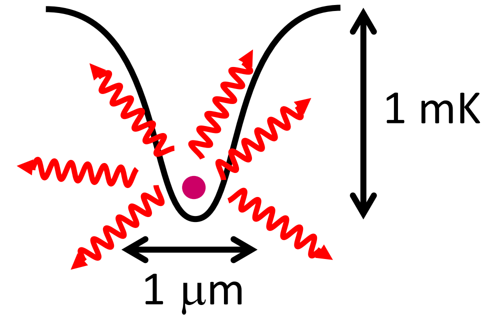
Lecture 3: Many-body physics with Rydberg atoms: spin models and transport

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

Recap lecture 2: tweezer, arrays & Rydberg

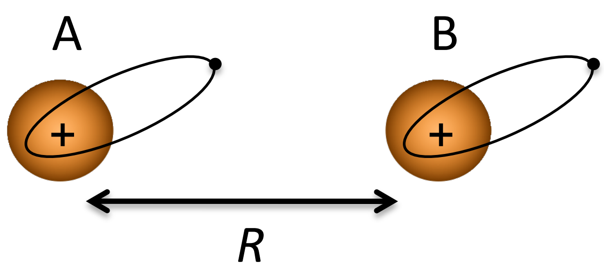


1 Rb atom
(fluorescence)



Grangier (2001)
Sortais (2007)

Rydberg interactions



Van der Waals

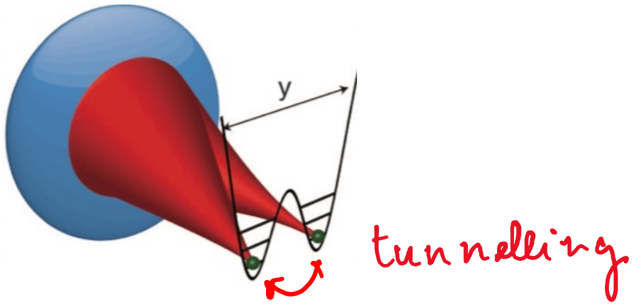
$$\frac{C_6}{R^6}$$

resonant

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

Tweezers and tweezer arrays: what for?

Quantum simulation



Regal, Kaufman, Thomson…

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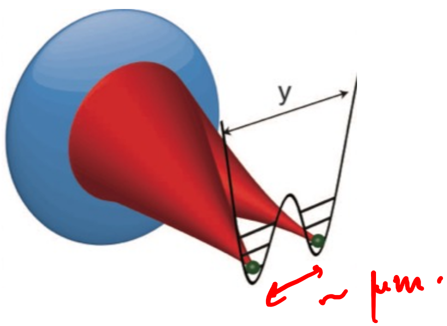

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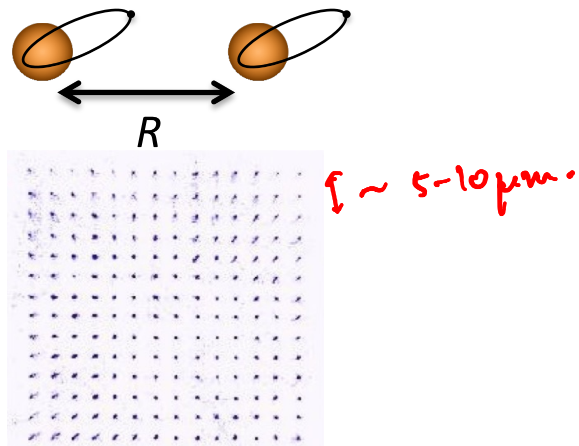

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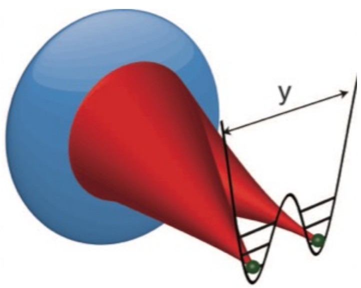

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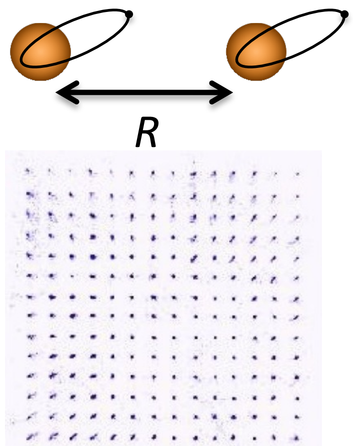

Optical clocks

PHYSICAL REVIEW X **9**, 041052 (2019)

Featured in Physics

An Atomic-Array Optical Clock with Single-Atom Readout

Ivaylo S. Madjarov,[1] Alexandre Cooper,[1] Adam L. Shaw,[1] Jacob P. Covey,[1] Vladimir Schkolnik,[2] Tai Hyun Yoon,[1,†] Jason R. Williams,[2] and Manuel Endres[1,*]

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Received: 18 June 2020

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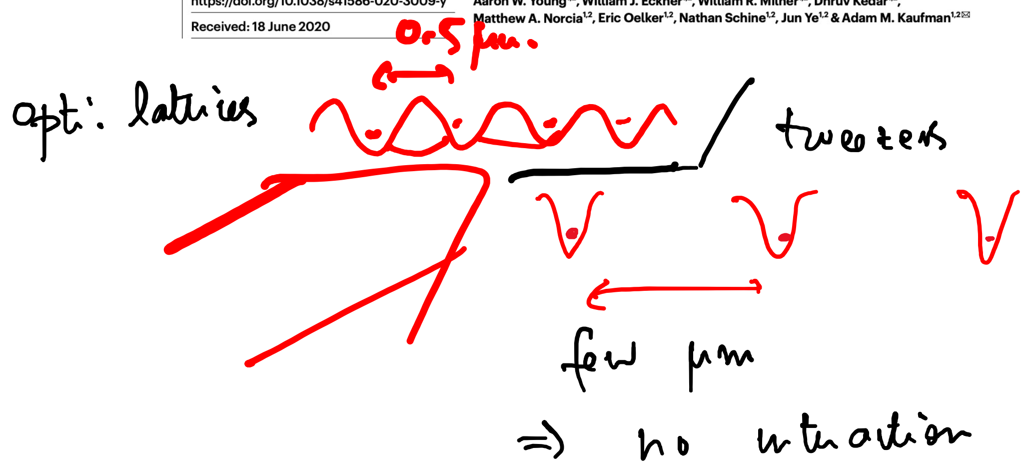

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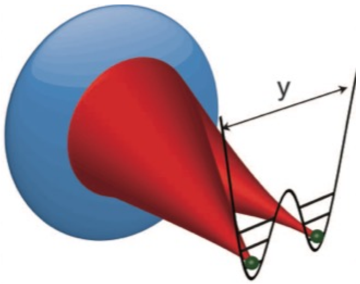

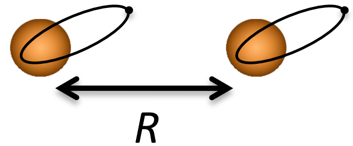

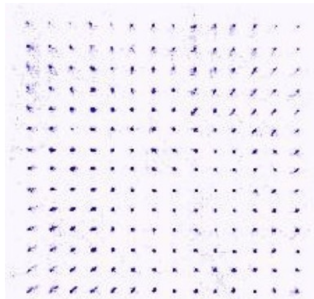

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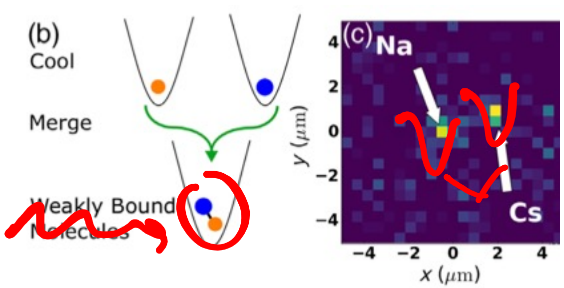
Molecule engineering



CaF

Ni, Doyle…

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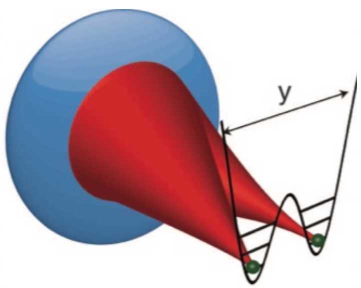

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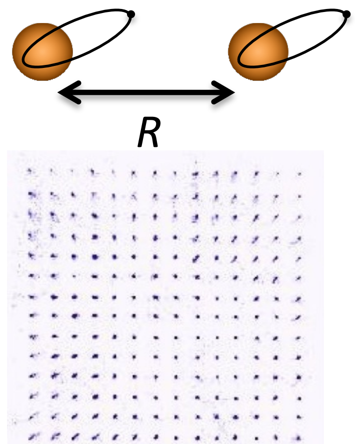

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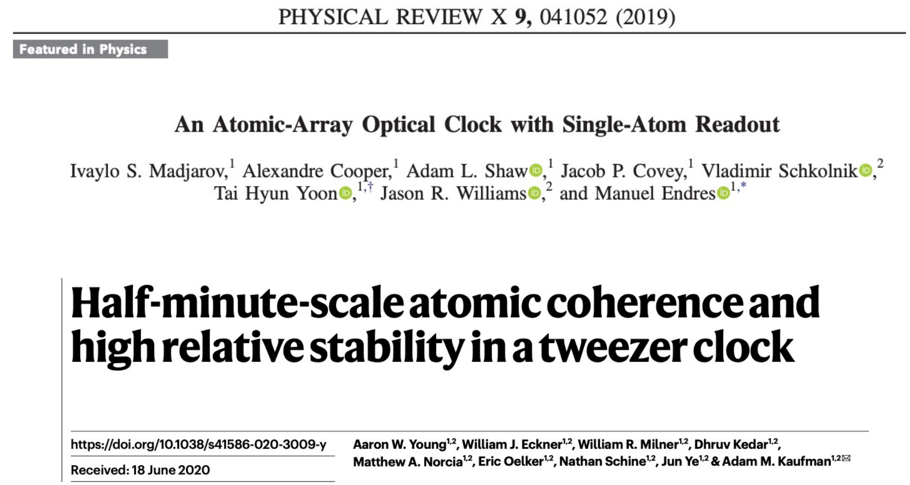
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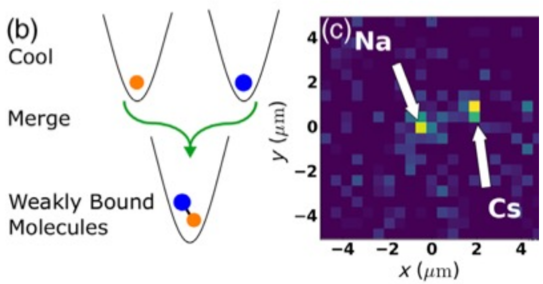

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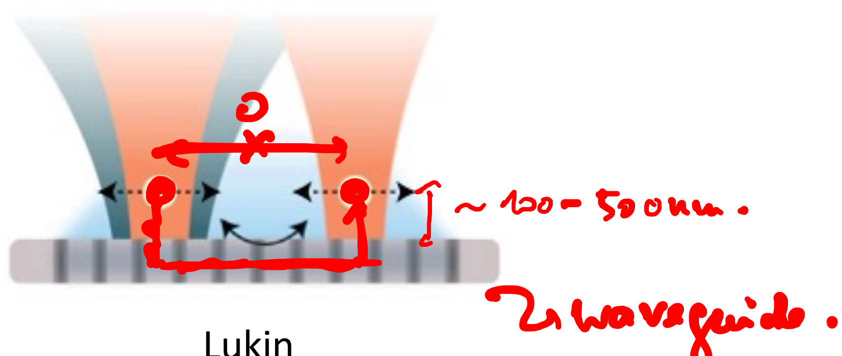
Tool for cQED



Lukin

Tweezers and tweezer arrays: what for?

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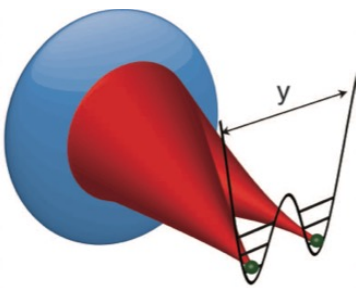

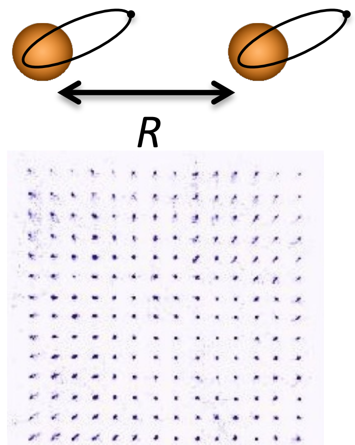

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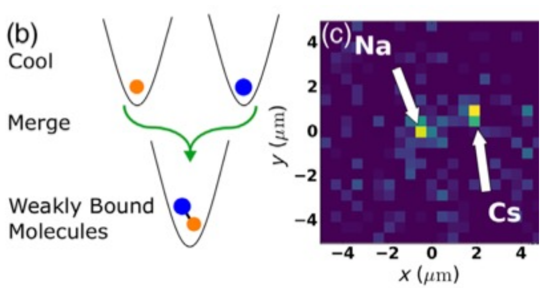

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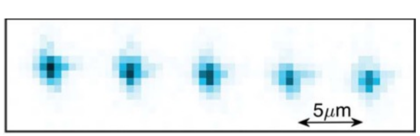

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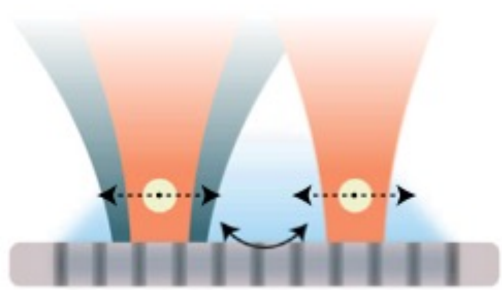
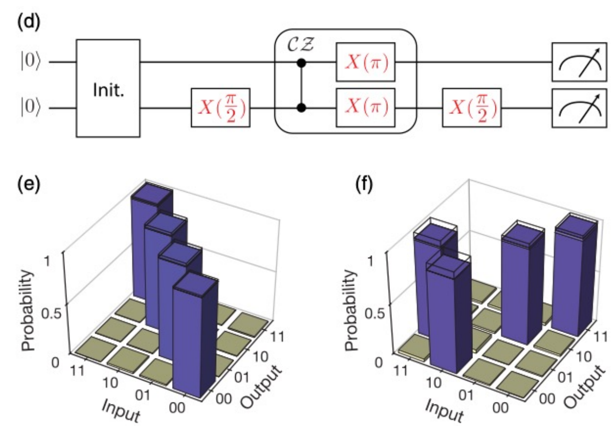


Lukin

Quantum gates



Saffman, Lukin…

Outline

1. Quantum simulation and spin models

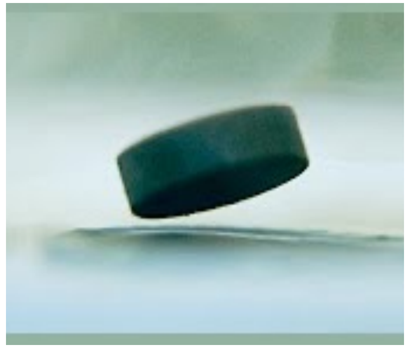
2. Simulation of the quantum Ising model using van der Waals interactions: quantum magnetism

3. Topological systems using resonant dipole interactions

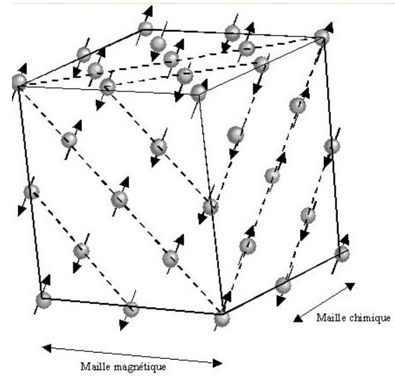
Many-body physics with synthetic matter

Goal: Understand ensembles of interacting quantum particles

superfluidity



superconductivity



magnetism

neutron star

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

↑ —
↓ —

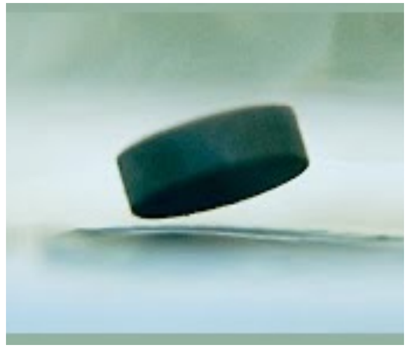
$\dim \mathcal{E} = 2^N$

Record ab initio : N ~ 46 atoms spins.

Many-body physics with synthetic matter

Goal: Understand ensembles of interacting quantum particles

superfluidity



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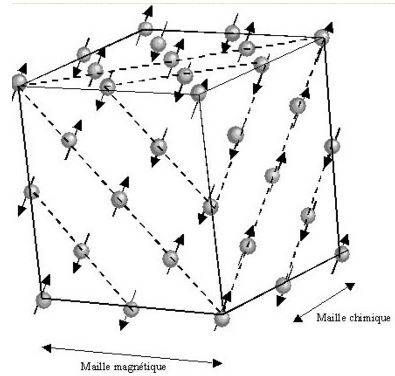

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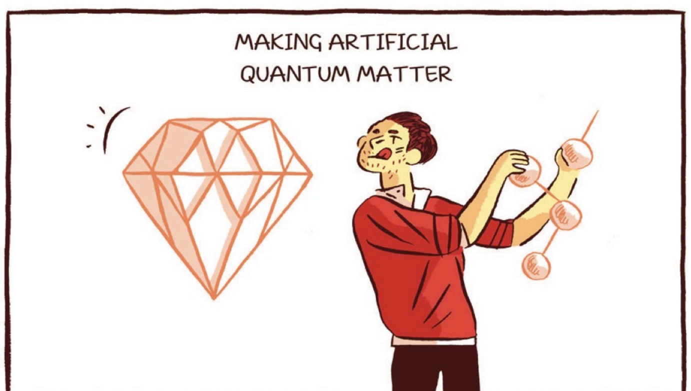

Héloïse Chochois, Labex PALM

R.P. Feynman

Use experimental control to

Implement **many-body Hamiltonians** (including “mathematical” ones...)

Larger **tunability** than « real » systems

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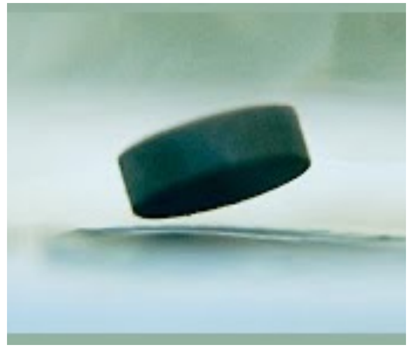

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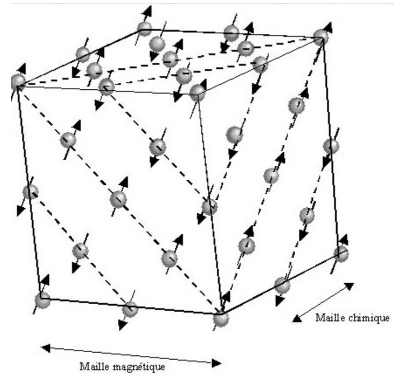

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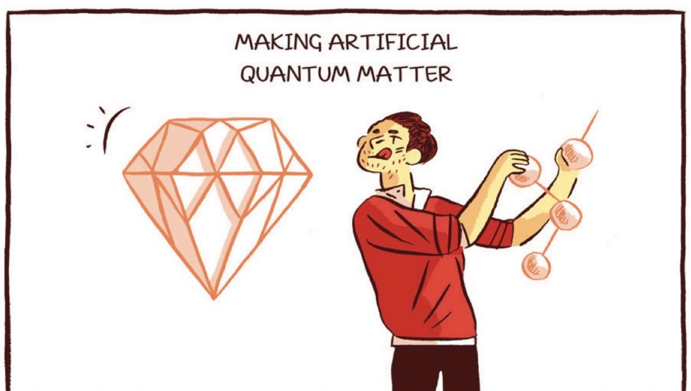

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Use experimental control to

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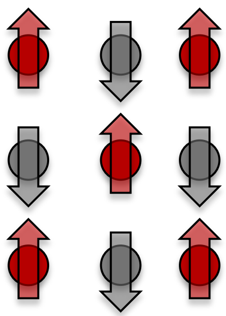
Larger **tunability** than « real » systems

= QUANTUM SIMULATION

Spin models: one of the "simplest" many-body problem

Interacting spin ½ particles on a lattice:



$$\hat{H}_{ij} = J_{ij}\hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j$$

$$\vec{S} = \frac{\hbar}{2}\vec{\sigma}$$

$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}_{\uparrow,\downarrow} \qquad \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_+ = |\uparrow\rangle\langle\downarrow| \qquad \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_- = (\sigma_+)^\dagger$$

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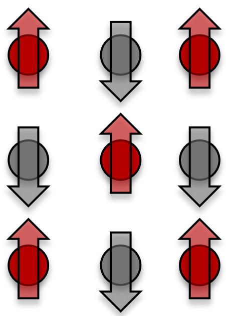

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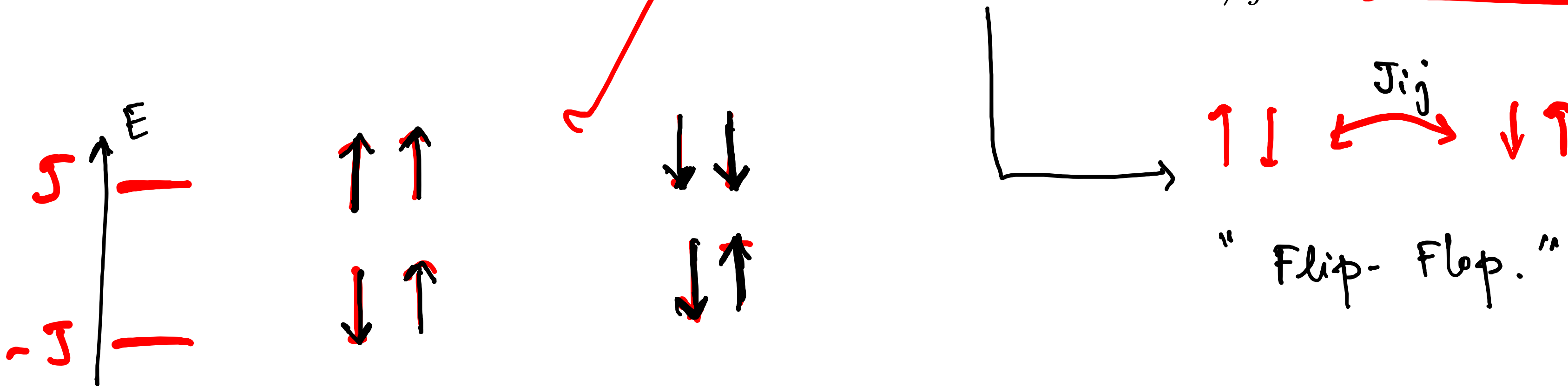
Ising $$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}$$

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



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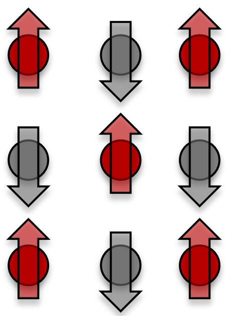

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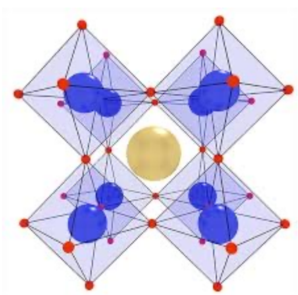
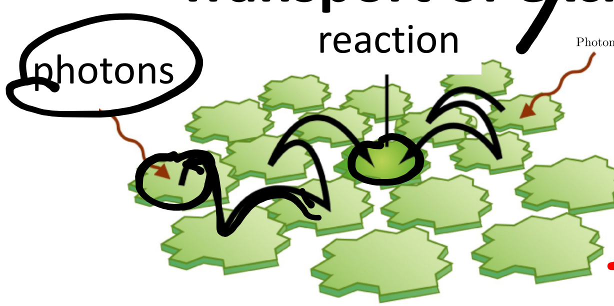
Magnetism



Perovskite

$Y_2Ti_2O_7$

Transport of excitations



photosynthesis

Light scattering (dissipative)

$J_{ij} \in \mathbb{C}$

dissipative

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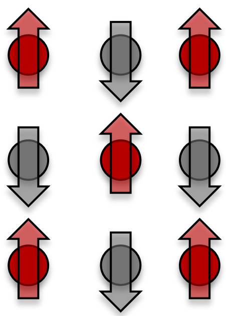

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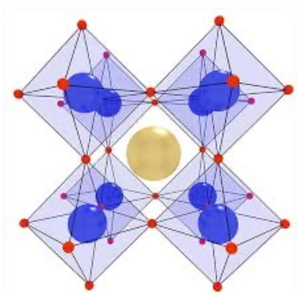
$(\hat{\sigma}_x\hat{\sigma}_x + \hat{\sigma}_y\hat{\sigma}_y)$

Magnetism



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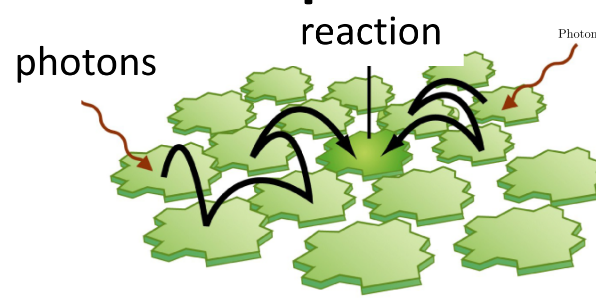

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Light scattering
(dissipative)

Open questions: Dynamics (hard for N>30, long range…)
Entanglement, disorder, topology…
Geometry (frustration: spin liquids?) …

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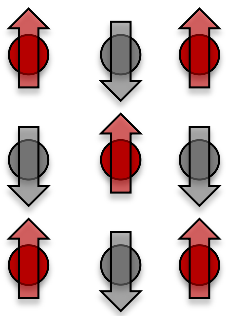

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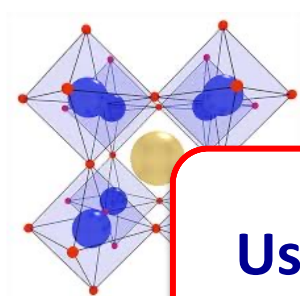

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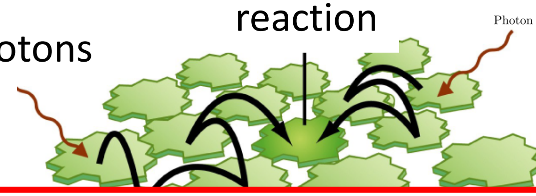

photosynthesis

(dissipative)

Use control over artificial quantum matter

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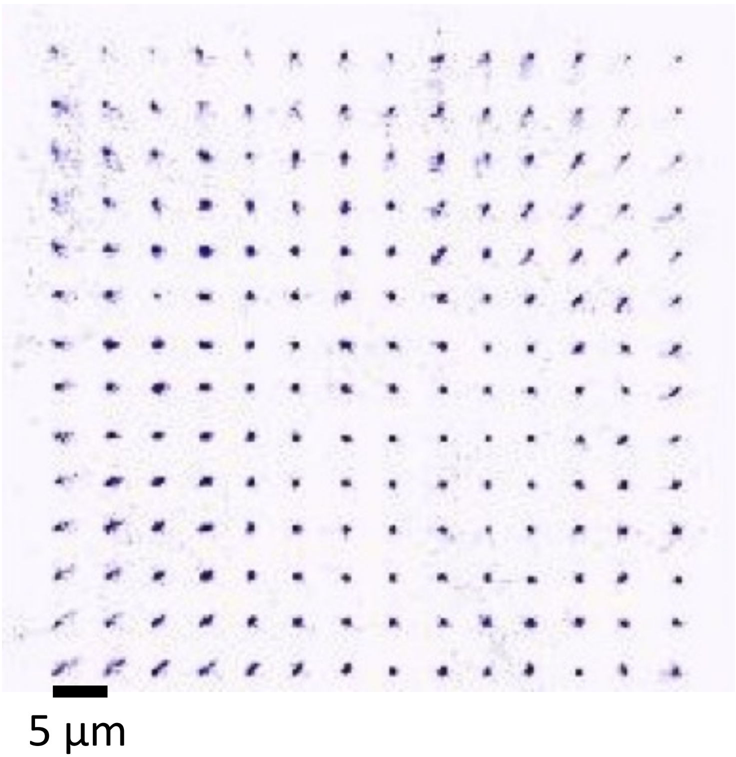
Our platform: arrays of interacting Rydberg atoms

Individual atoms in assembled arrays of tweezers (~200 at.)



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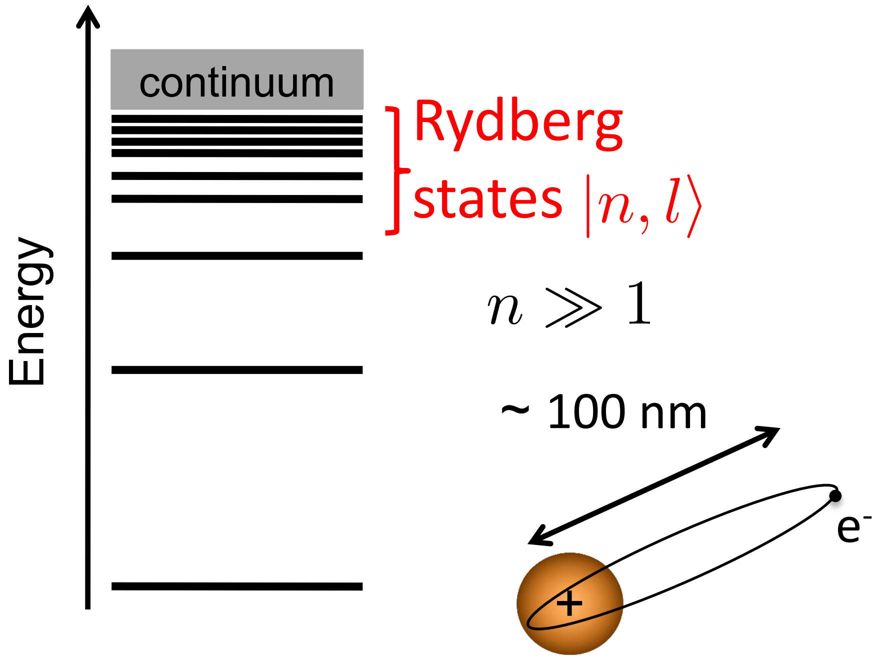

Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat. Phys. 2020

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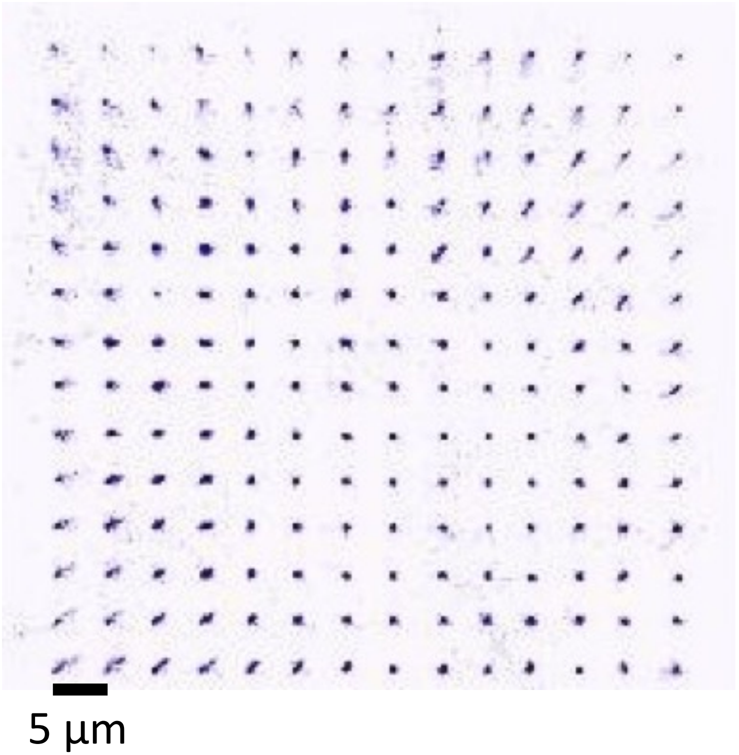

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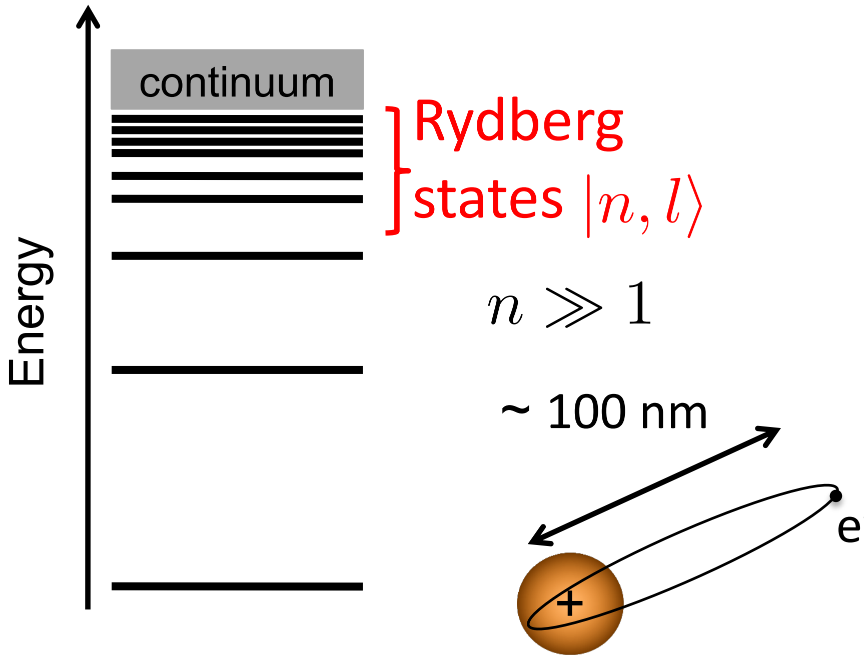

Lifetime > 100 µs

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

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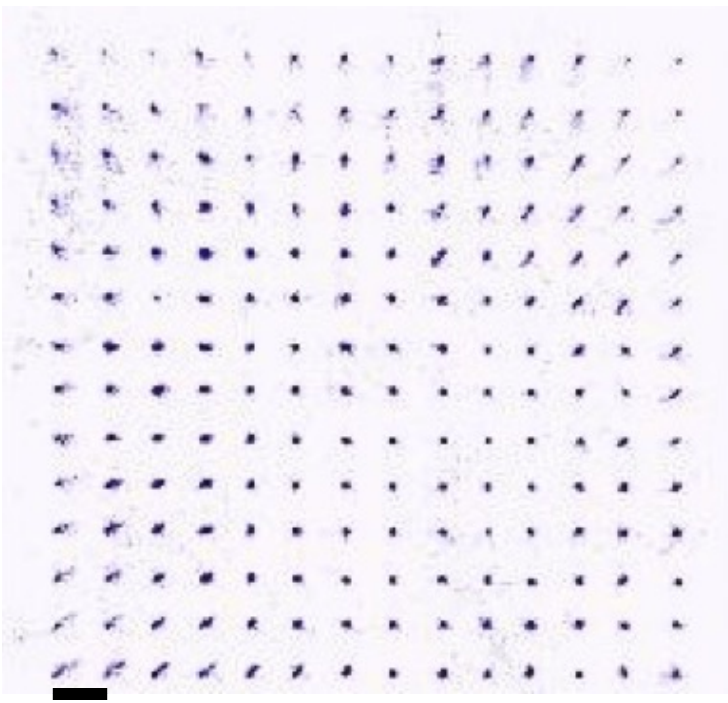
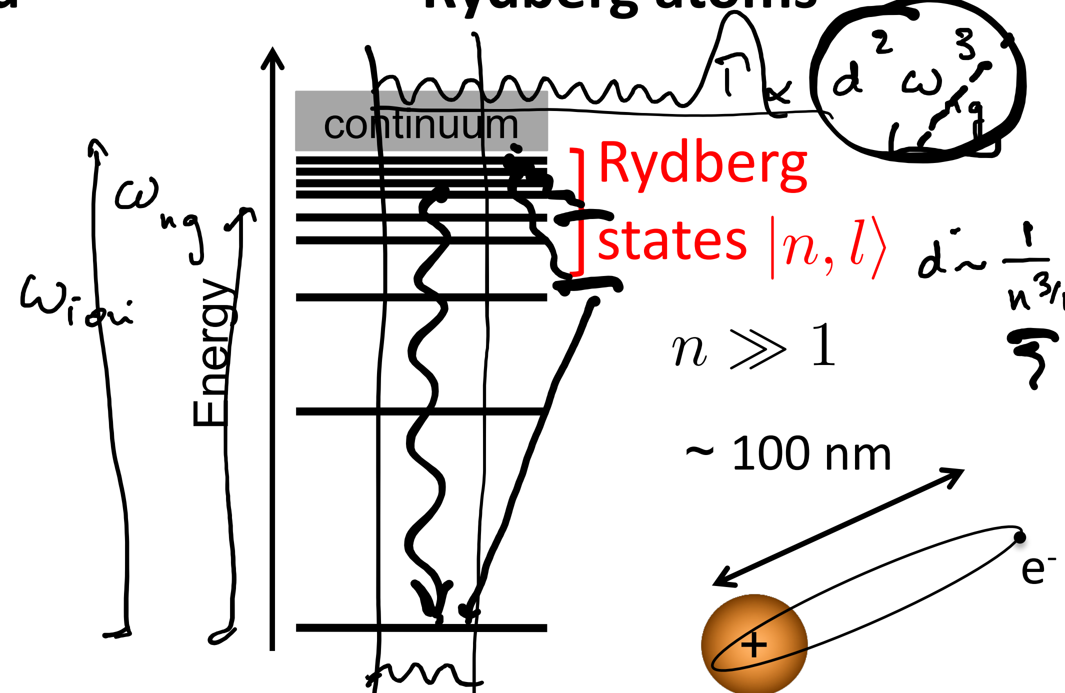


Rydberg atoms



Lifetime > 100 µs

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

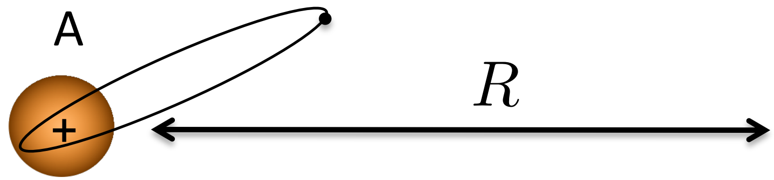
⇒ Large dipole-dipole interactions

$n \sim 60, R = 10\ \mu\text{m} \Rightarrow V_{\text{int}}/h \sim 1 - 10\ \text{MHz}$

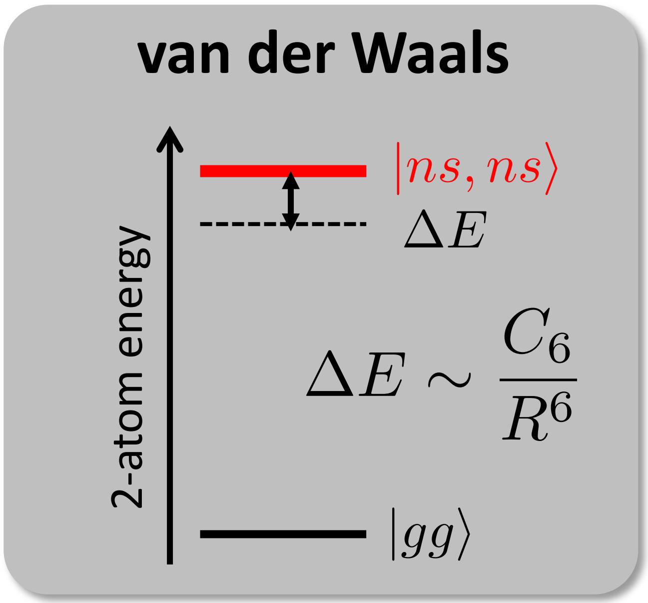
⇒ timescales < µsec

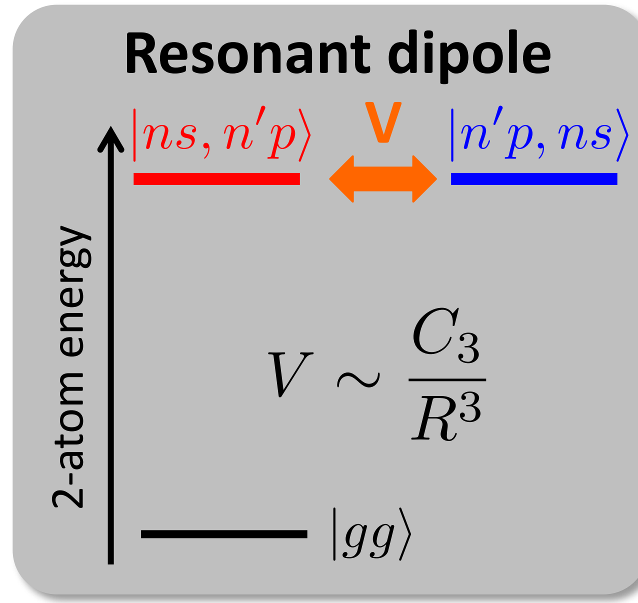
Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat. Phys. 2020

Interactions between Rydberg atoms and spin models

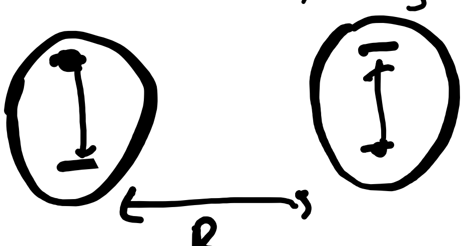


Browaeys & Lahaye, Nat.Phys. (2020)



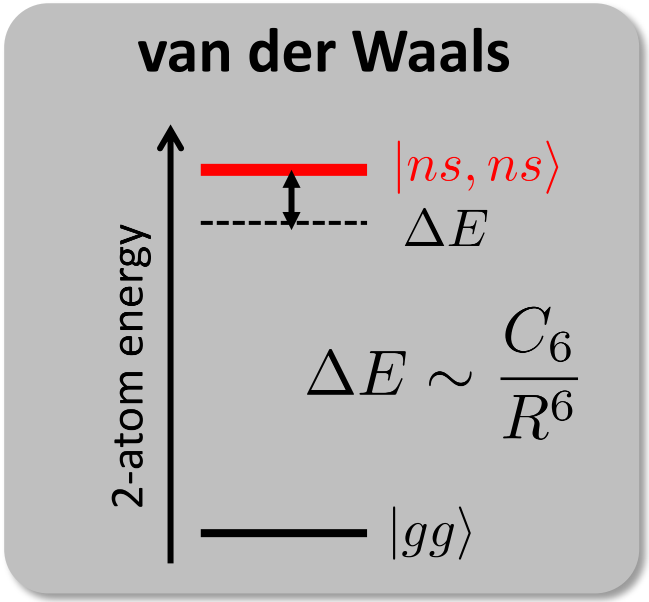


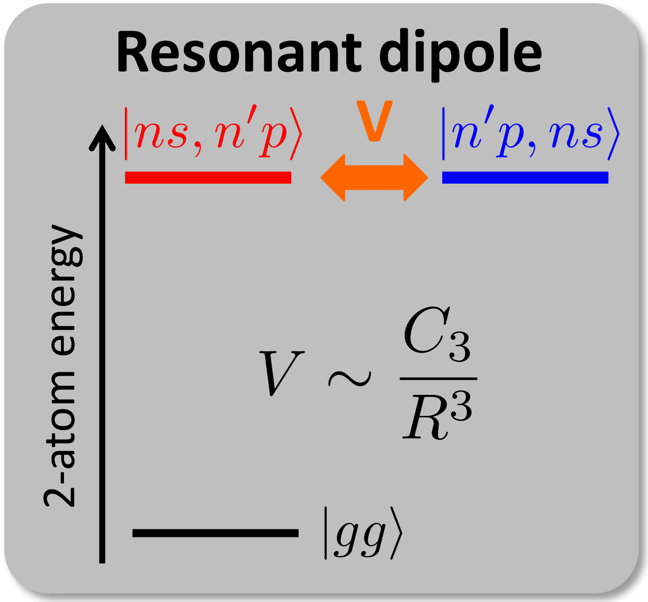
$C_6 , C_3 \sim (d^2_{n n\pm 1})$ $\Gamma_{n n\pm 1} \sim d^2$



Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)





Quantum Ising

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}$$

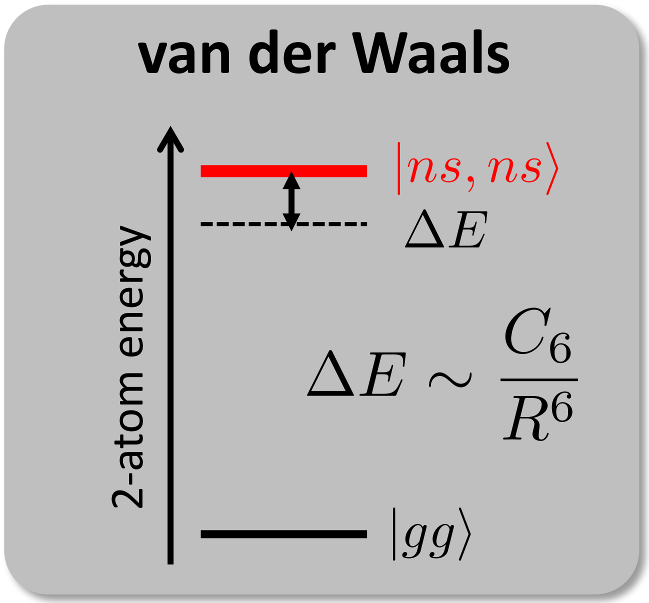
XY model

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

Outline

1. Quantum simulation and spin models
2. Simulation of the quantum Ising model using van der Waals interactions: quantum magnetism
3. Topological systems using resonant dipole interactions

From van der Waals interactions to Ising model...



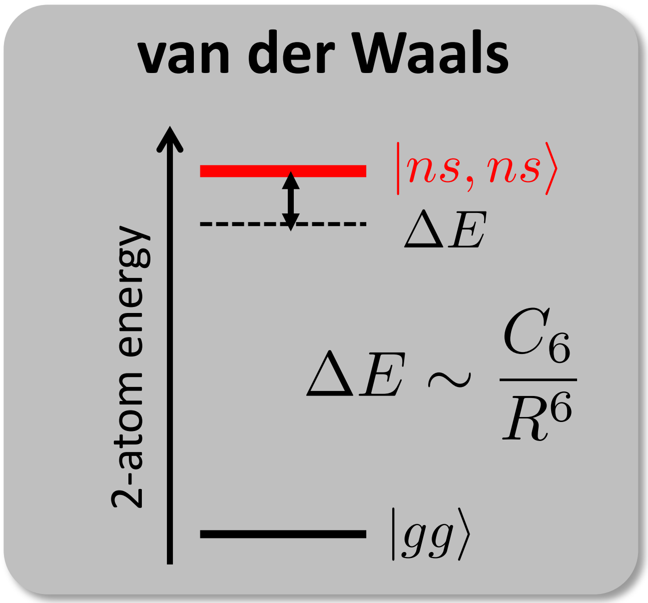
$C_6 \propto n^{11} \Rightarrow$ switchable interaction

ns n's

n = 5 groundstate → n = 50

$C_6 \propto 10^{11}$

From van der Waals interactions to Ising model…



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

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

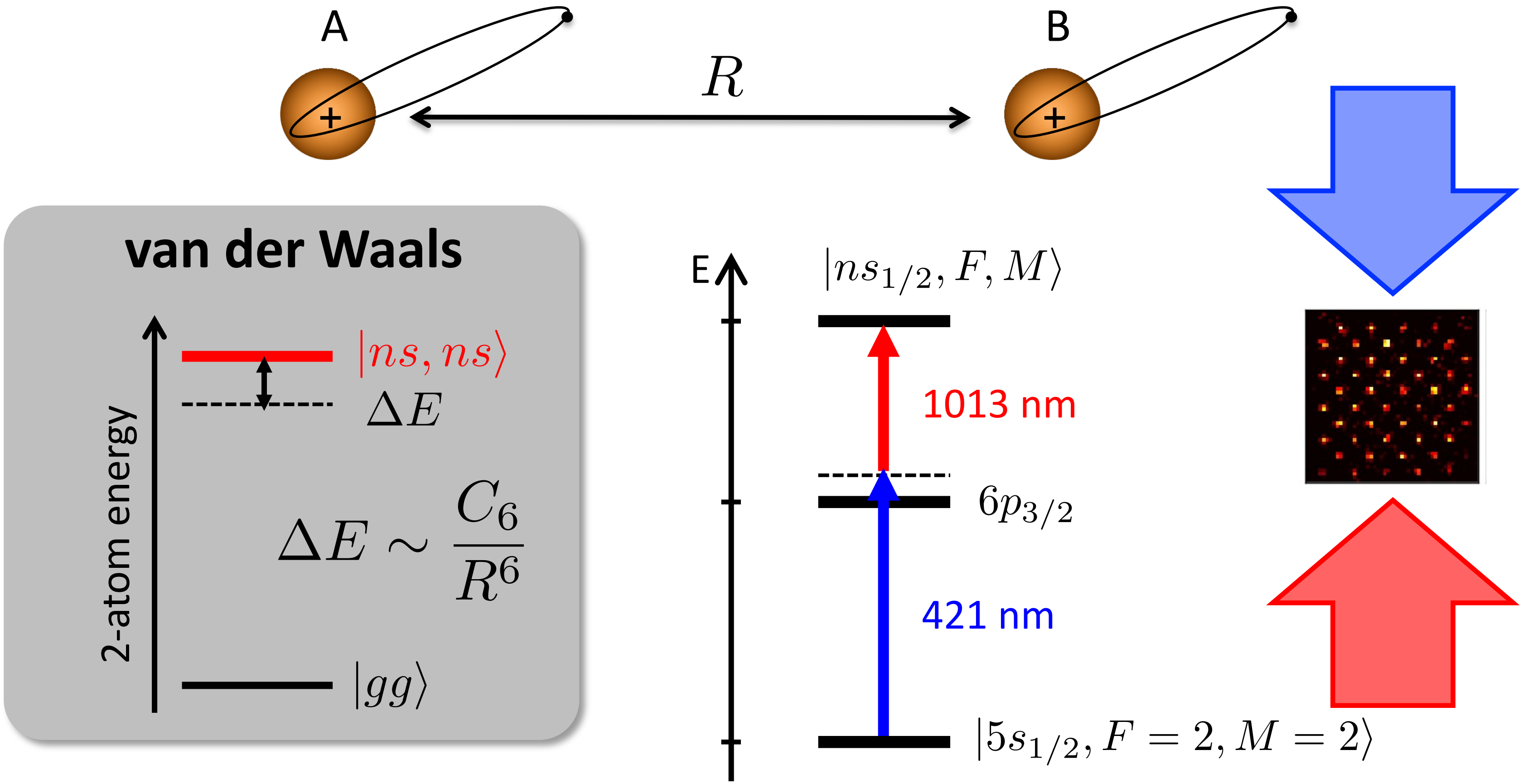
$n = 0, 1.$

Rydberg occupation number

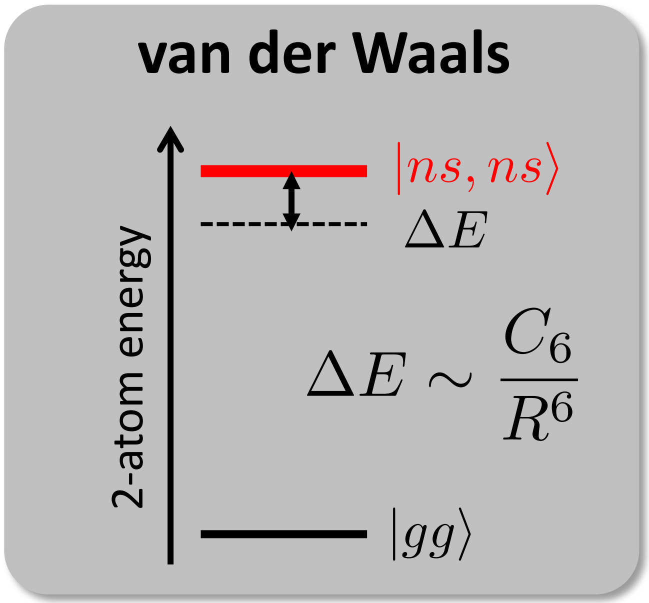
$$\hat{n} = \frac{1 + \hat{\sigma}_z}{2}$$

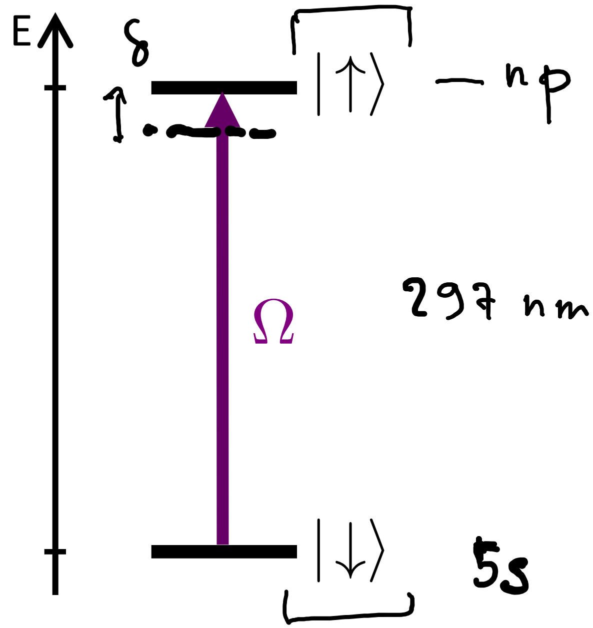
As: $\hat{n} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = \frac{1}{2}\left[\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \hat{1}\right]$

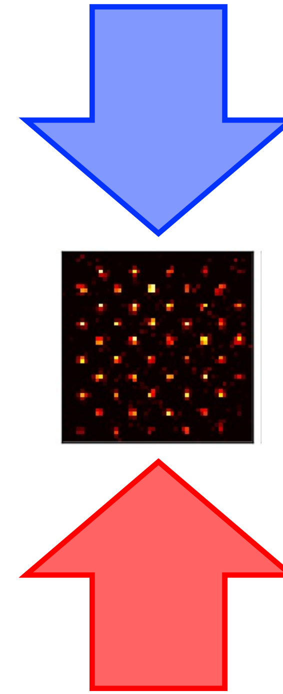
From van der Waals interactions to Ising model...



From van der Waals interactions to Ising model…





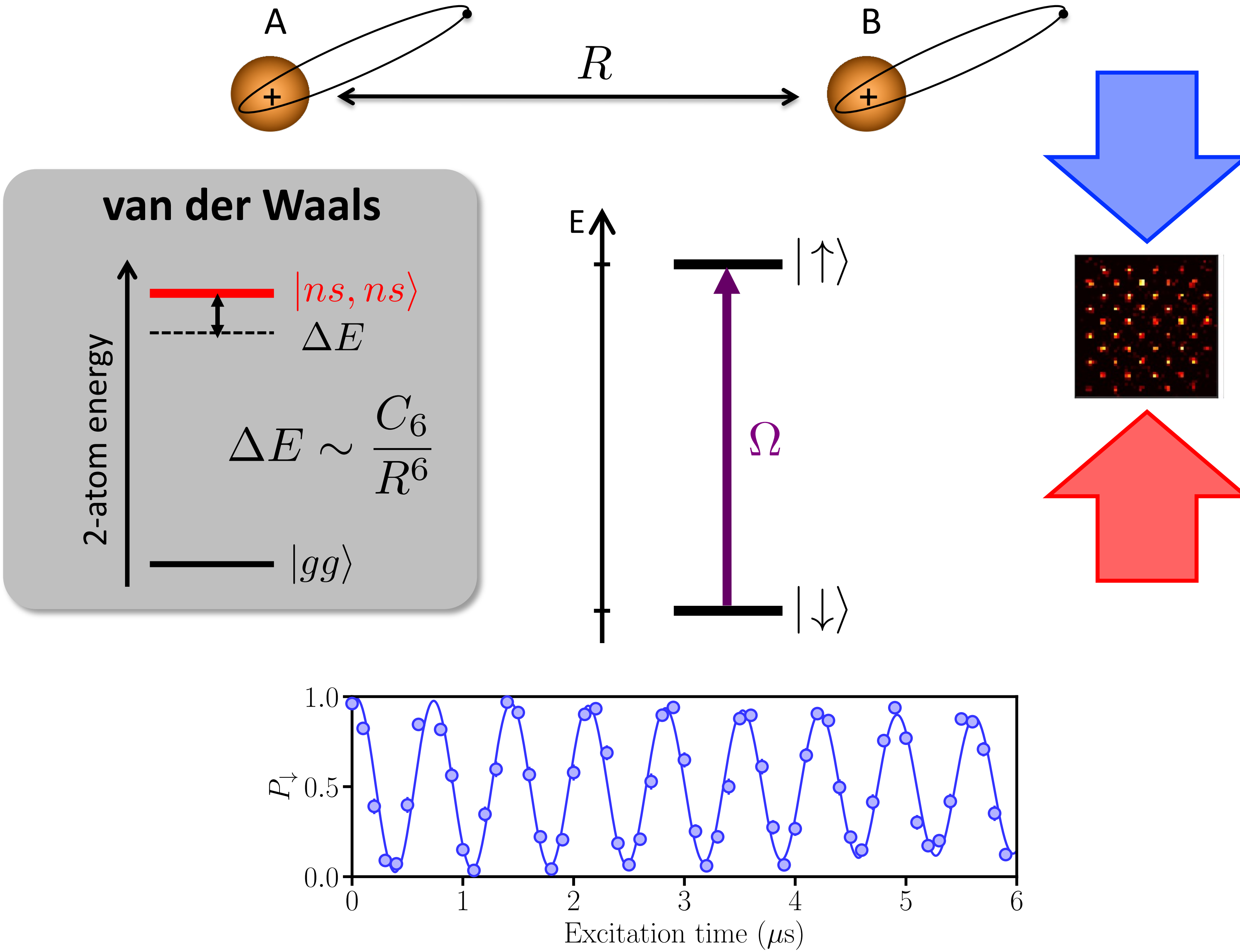


$$H_{laser} = \frac{\Omega}{2}\hat{\sigma}_x - \delta\hat{\sigma}_z \quad \text{with } \delta = \omega_L - \omega_0$$

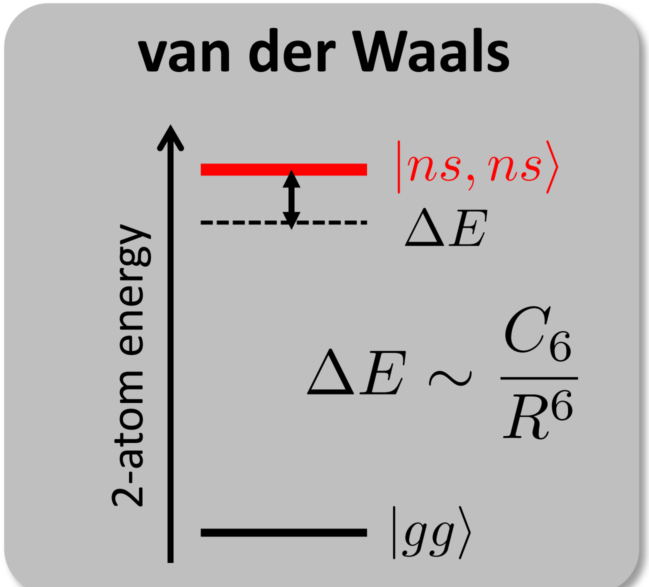
(RWA)

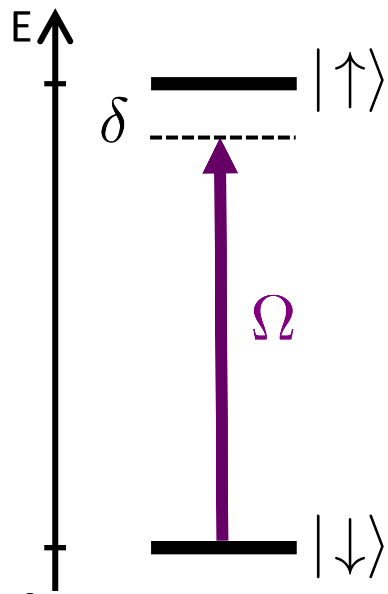
And $\sigma_x = \sigma_+ + \sigma_-$

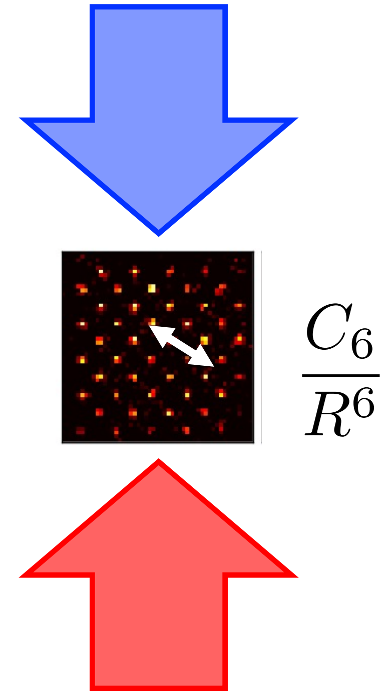
From van der Waals interactions to Ising model…



From van der Waals interactions to Ising model…







Quantum Ising-like model (s=½):

Ising-interaction.

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

H_L ; $\hat{n}_i \to \sigma_z^i$

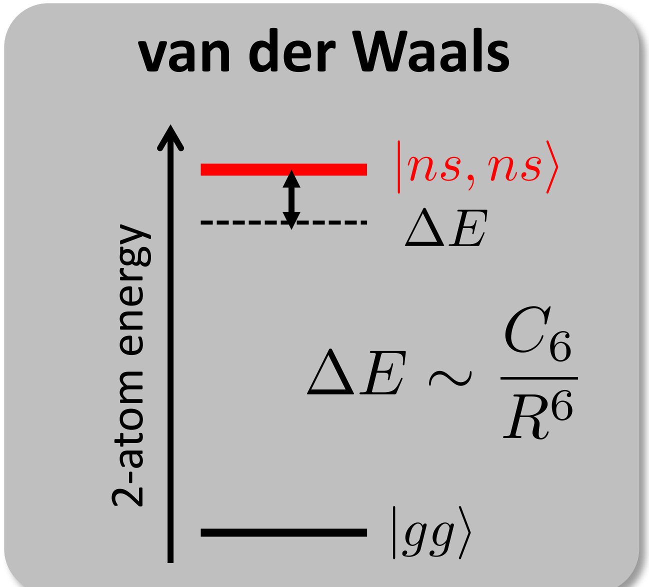
$[\sigma_x, n_i n_j] \neq 0$

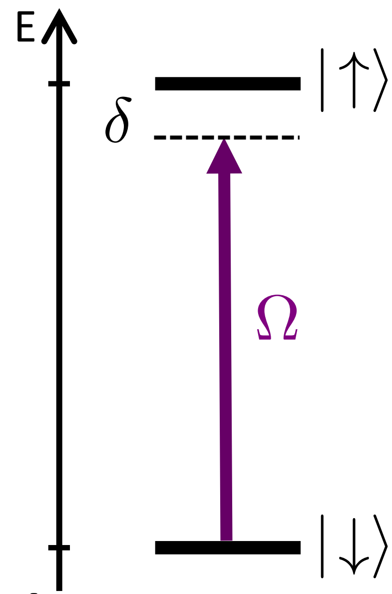
$\Downarrow$

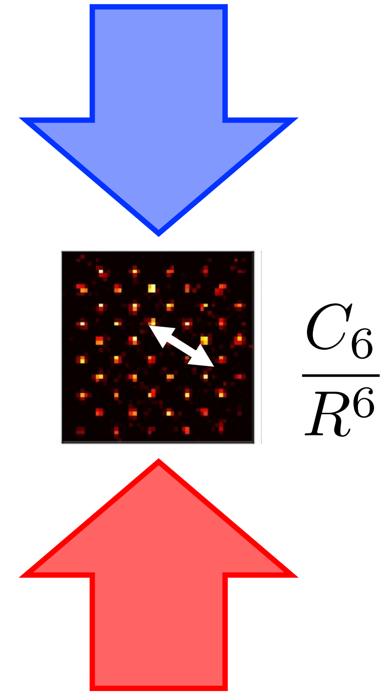
"quantum"

Transverse B **Longitudinal B** **Spin-spin interaction**

From van der Waals interactions to Ising model…







Quantum Ising-like model (s=½):

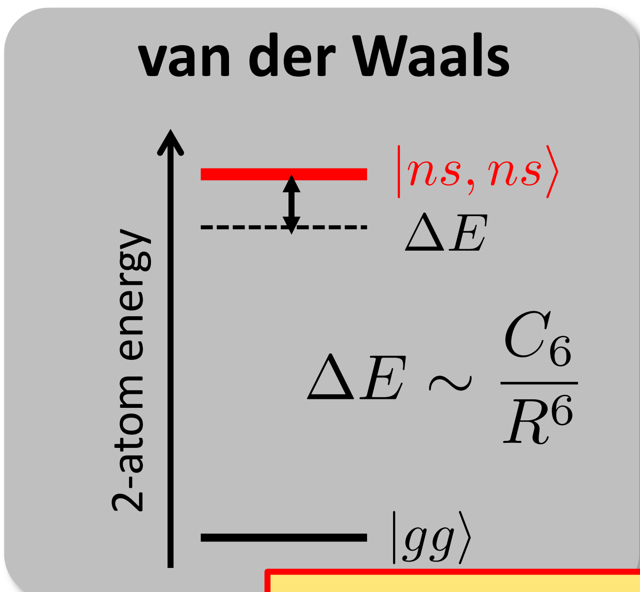
$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i + \hbar\delta\sum_i \hat{n}_i + \sum_{i<j}\frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

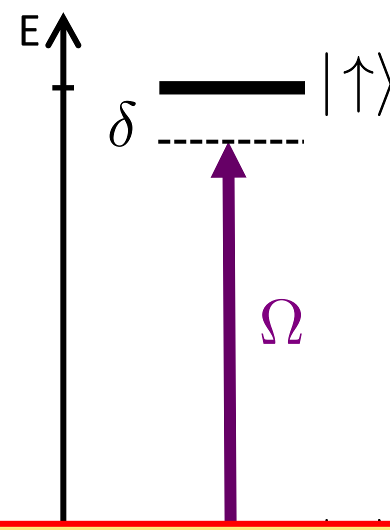
Transverse B **Longitudinal B** **Spin-spin interaction**

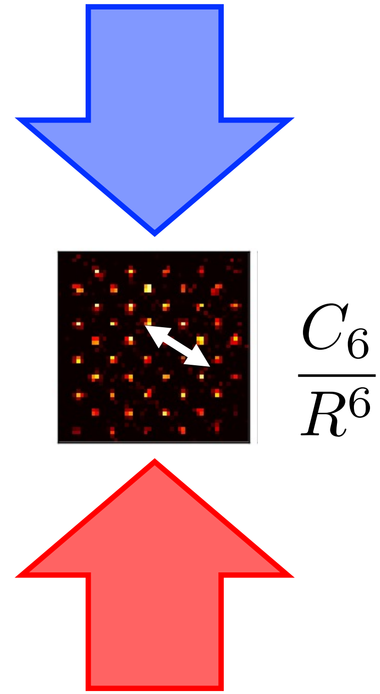
Experimt[t].

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

From van der Waals interactions to Ising model…







Quantum Is

$$H = \frac{\hbar\Omega}{2}$$

Equilibrium: preparation of ground states

Out-of-equilibrium: sudden variation ("quench") of parameters

perimt.

$= [0 - 20]$

Transver

Outline

1. Quantum simulation and spin models

2. Simulation of the quantum Ising model using van der Waals interactions: quantum magnetism

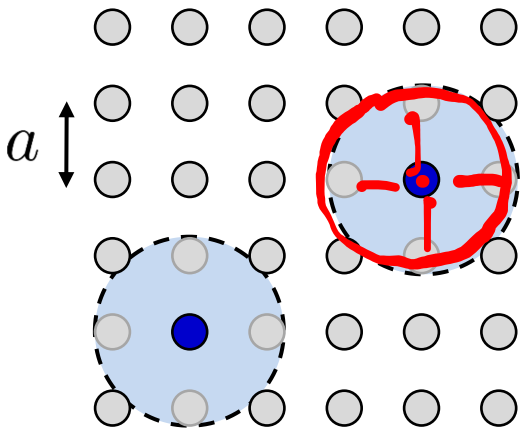
   - Preparation of ground states

   - Out-of-equilibrium situations

3. Topological systems using resonant dipole interactions

2D Ising anti-ferromagnet on a square

Nearest neighb. interaction



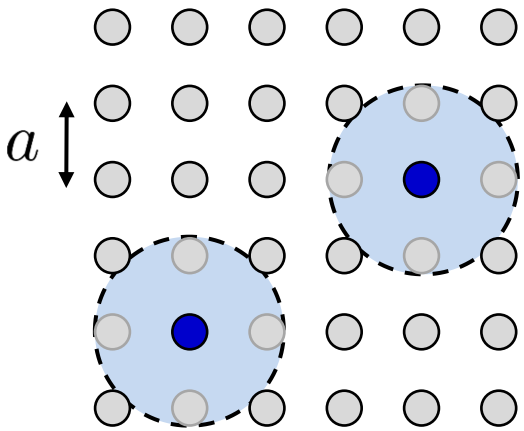
$$\frac{C_6}{a^6} \sim \Omega$$

○ $= |g\rangle$

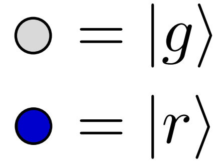
● $= |r\rangle$

2D Ising anti-ferromagnet on a square

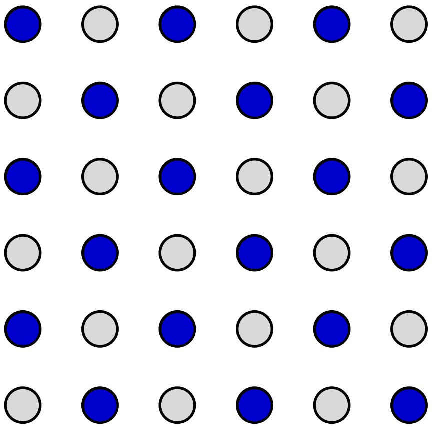
Nearest neighb. interaction



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

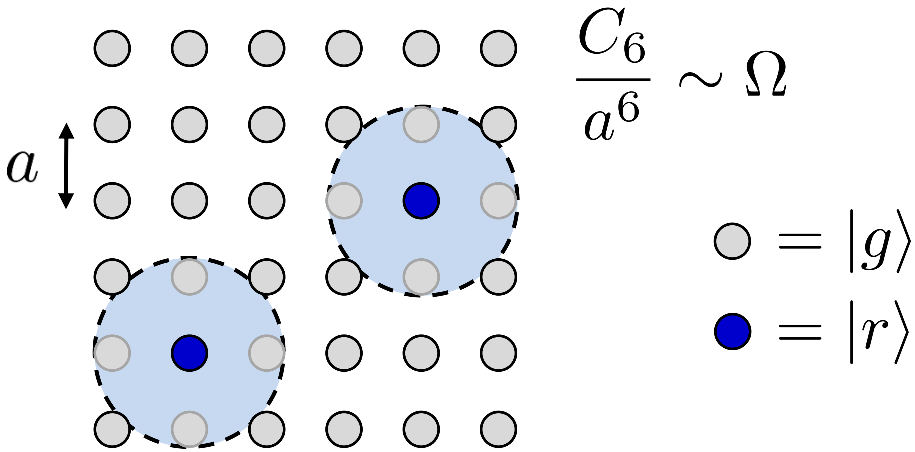


Anti-ferromagnetic ground state

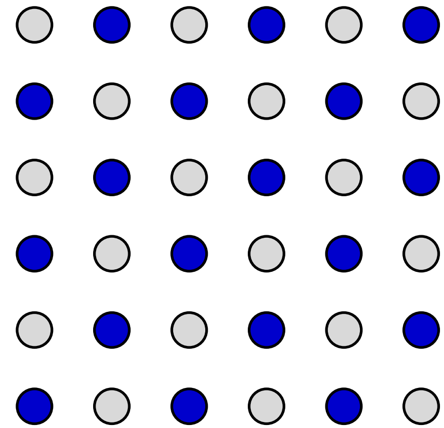


2D Ising anti-ferromagnet on a square

Nearest neighb. interaction

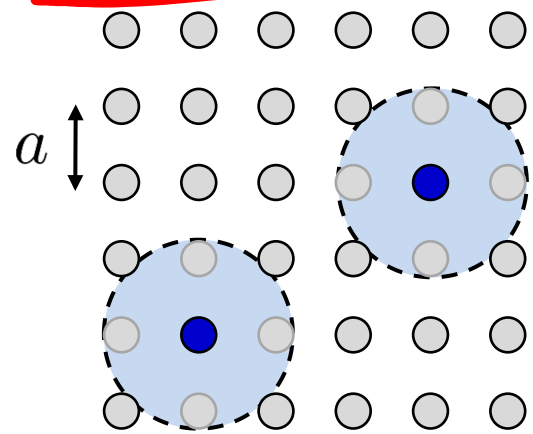


Anti-ferromagnetic ground state



2D Ising anti-ferromagnet on a square

Nearest neighb. interaction



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

○ $= |g\rangle$

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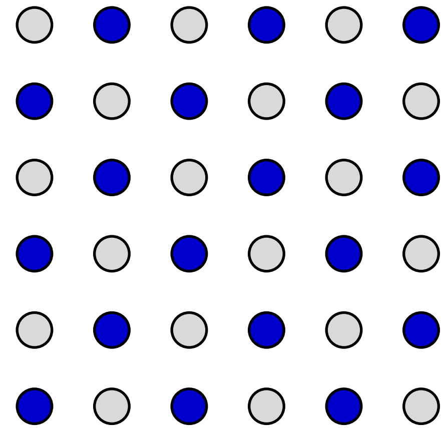
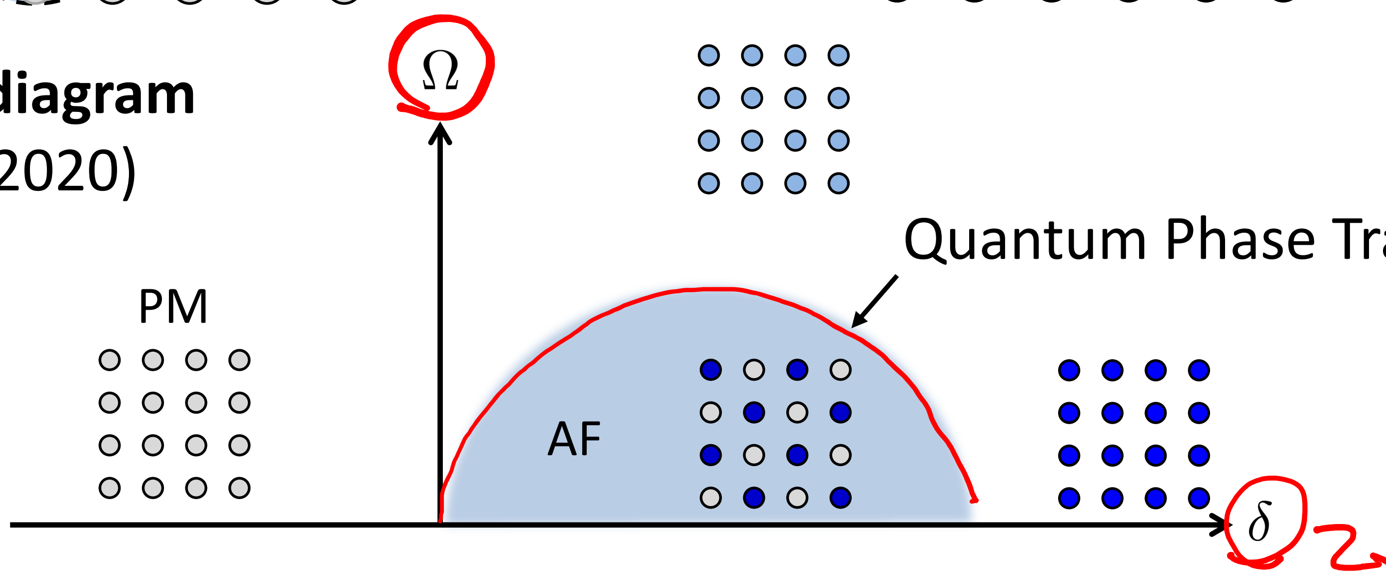
Anti-ferromagnetic ground state



2D phase diagram

(1970 - 2020)

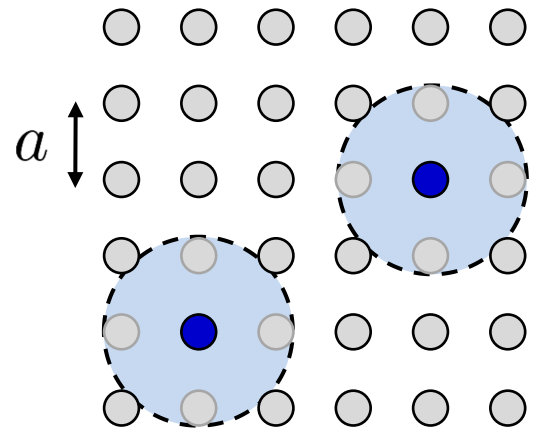


Known by Quantum Monte-Carlo

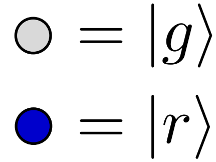
Never implemented and measured in 2D…!!!

2D Ising anti-ferromagnet on a square

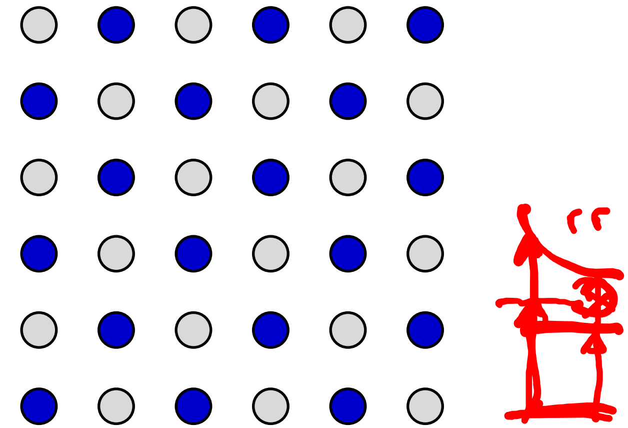
Nearest neighb. interaction



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

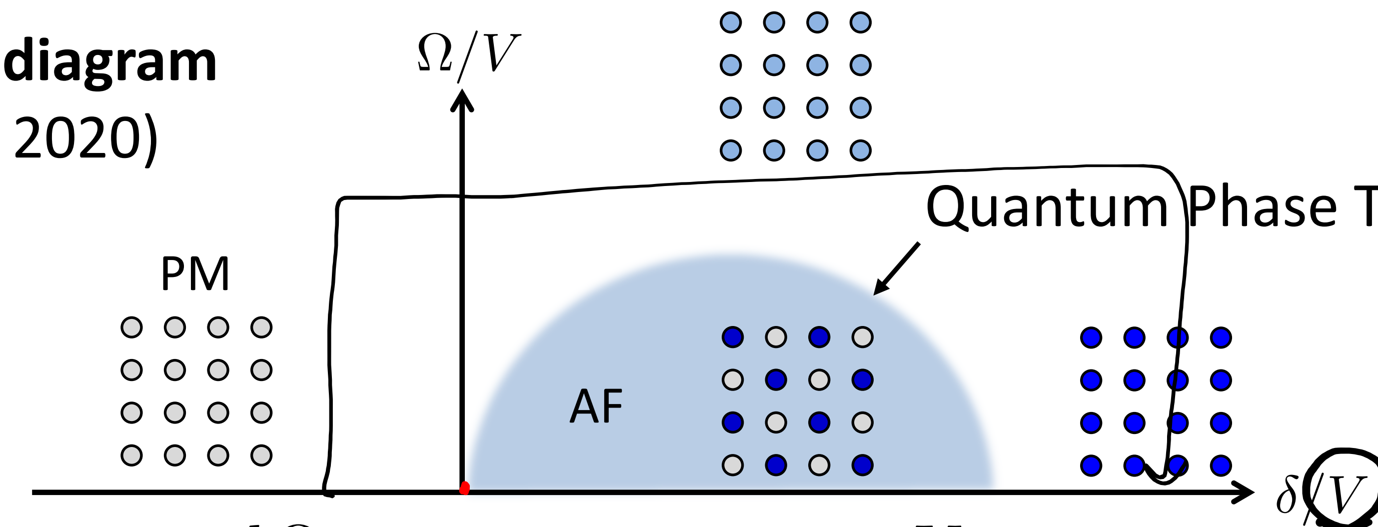


Anti-ferromagnetic ground state



2D phase diagram

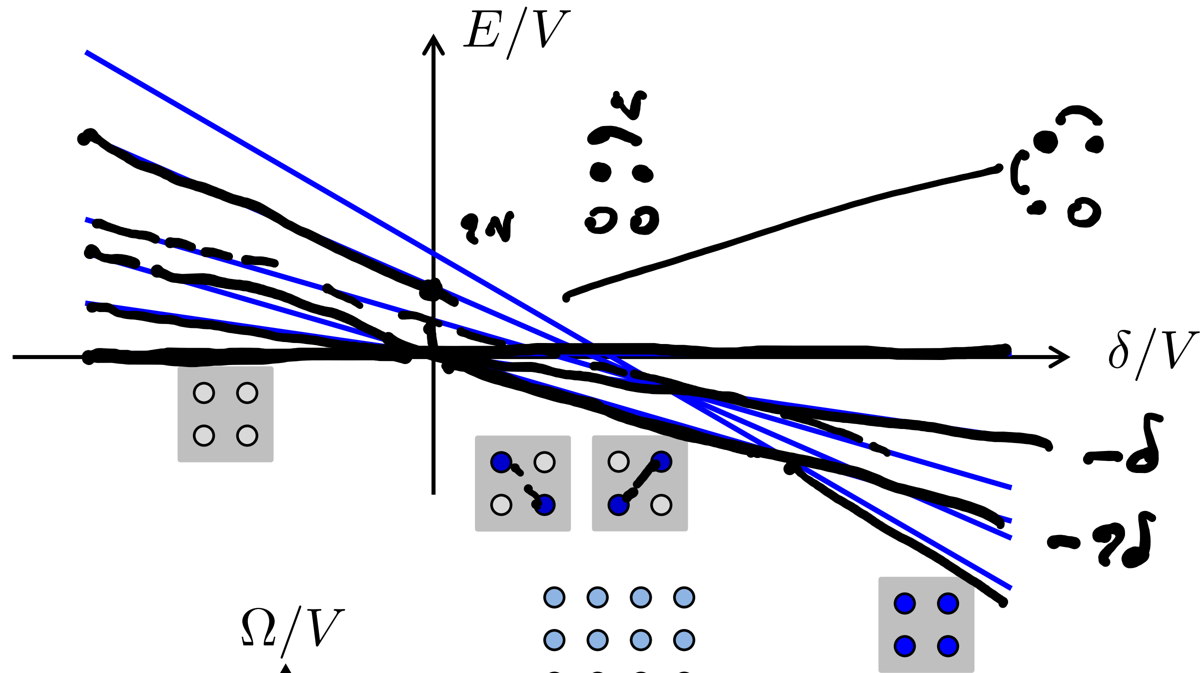
(1970 - 2020)

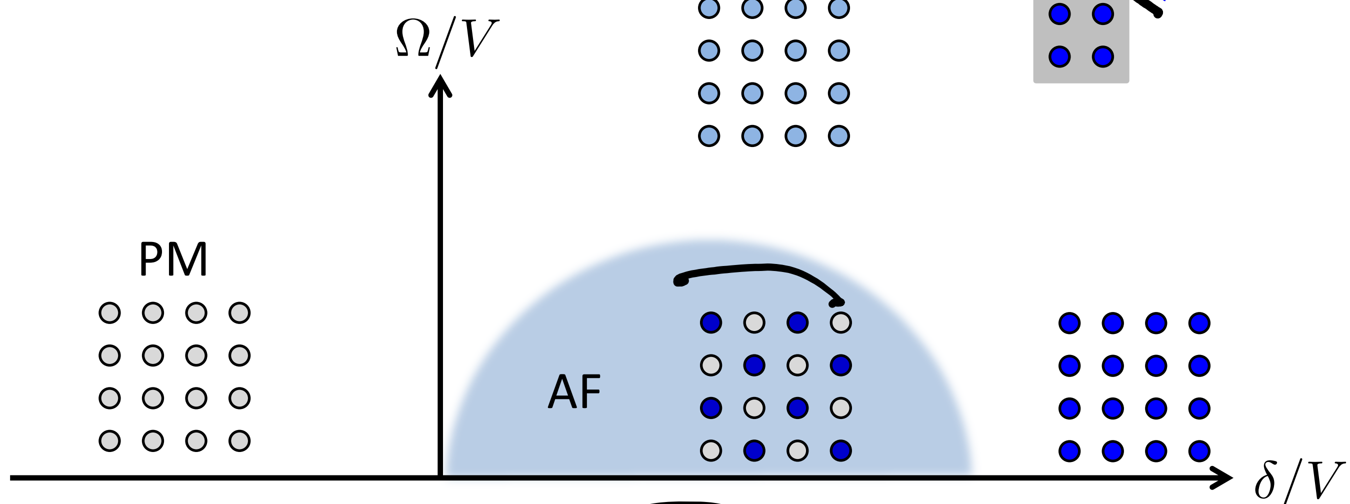


$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i - \hbar\delta\sum_i \hat{n}_i + \frac{V}{2}\sum_i \hat{n}_i\hat{n}_{i+1}$$

2D Ising anti-ferromagnet on a square

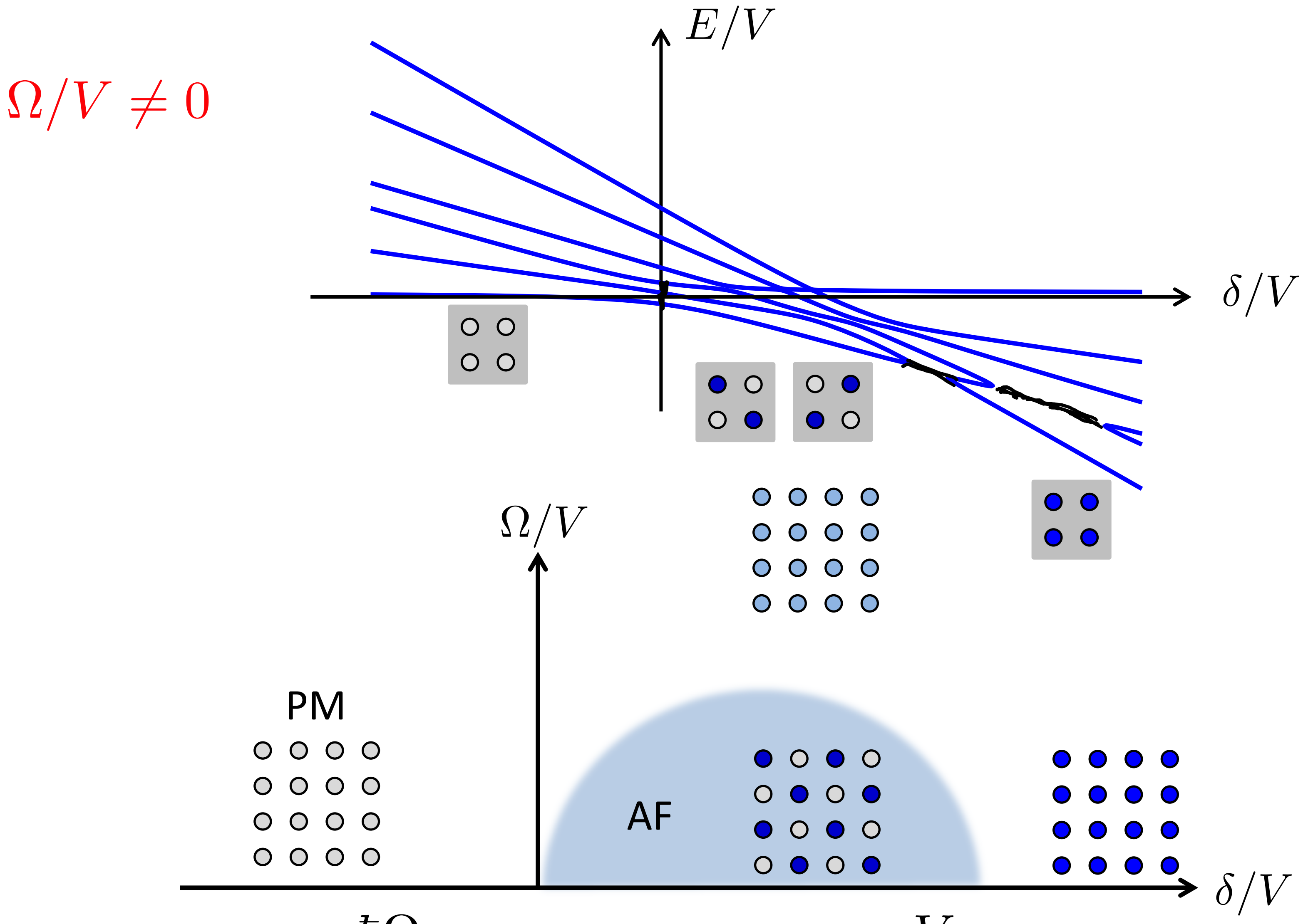
$\Omega/V = 0$





$$H = -\hbar\delta\sum_i \hat{n}_i + \frac{V}{2}\sum_i \hat{n}_i\hat{n}_{i+1}$$

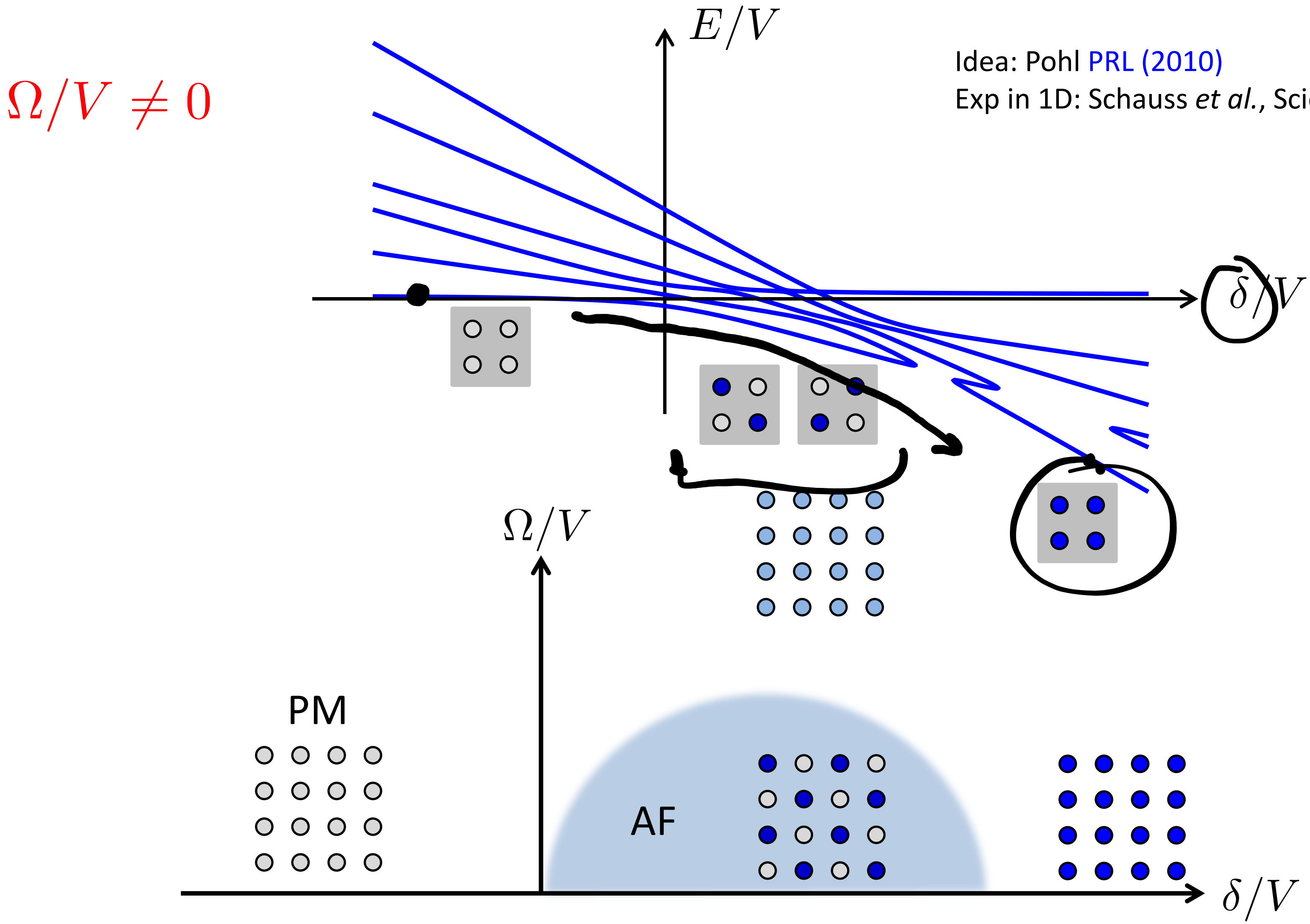
2D Ising anti-ferromagnet on a square



$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i - \hbar\delta\sum_i \hat{n}_i + \frac{V}{2}\sum_i \hat{n}_i\hat{n}_{i+1}$$

Adiabatic preparation of a 2D Ising anti-ferromagnet

Idea: Pohl PRL (2010)
Exp in 1D: Schauss *et al.*, Science (2015)

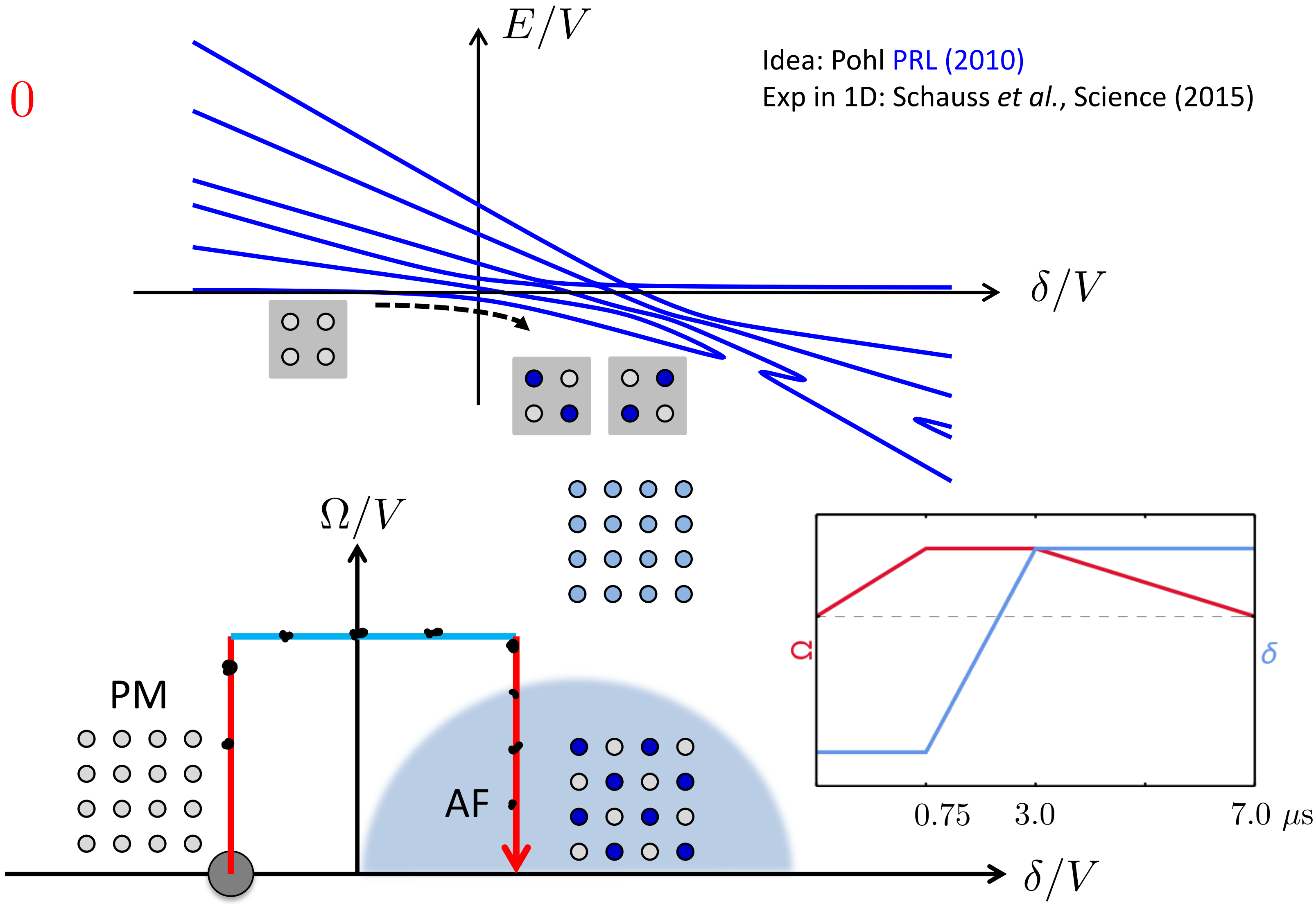


$$H = \sum_i \left(\frac{\hbar\Omega(t)}{2} \sigma_x^i - \hbar\delta(t)\hat{n}_i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} \hat{n}_i \hat{n}_j$$

Adiabatic preparation of a 2D Ising anti-ferromagnet

$\Omega/V \neq 0$

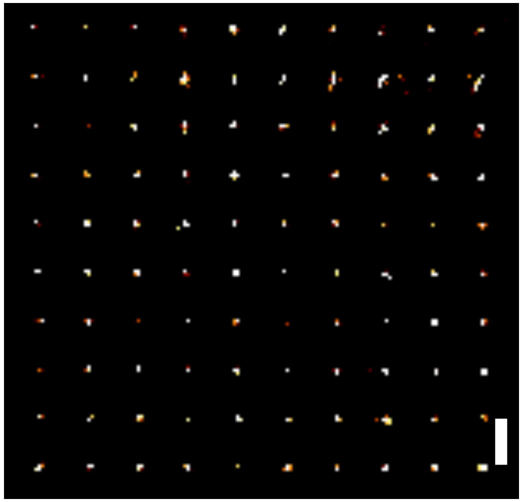
Idea: Pohl PRL (2010)
Exp in 1D: Schauss *et al.*, Science (2015)



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

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

10 × 10 square array

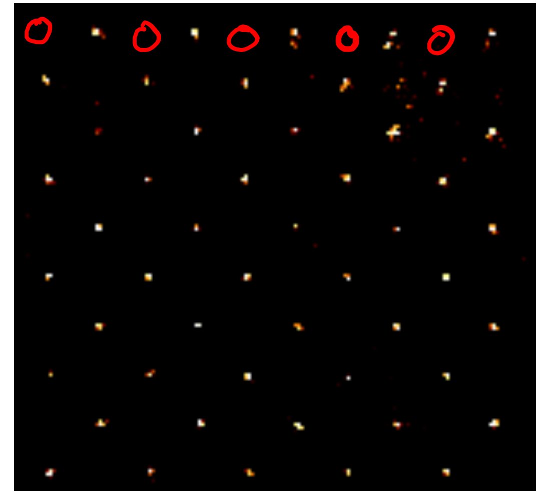


10 μm

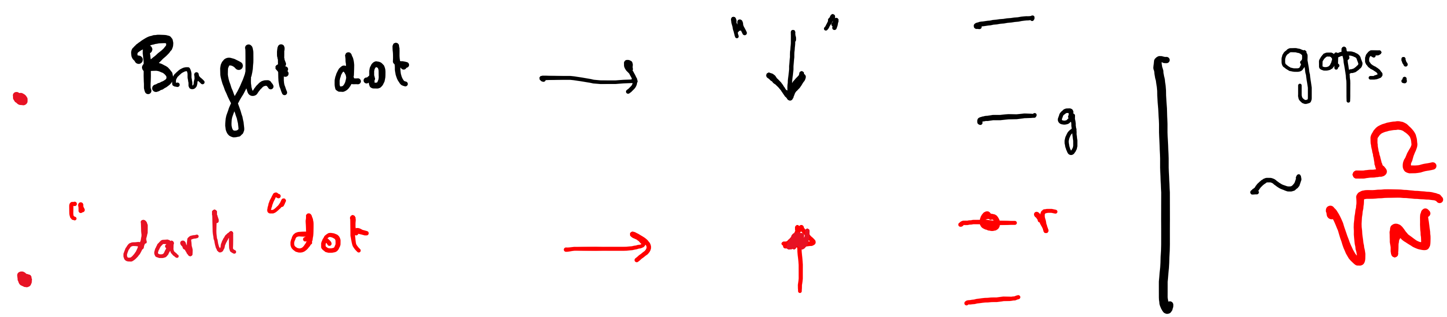
sweep

n=75s

Scholl, arXiv:2012.12268



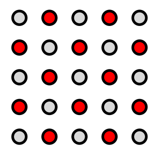
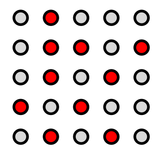
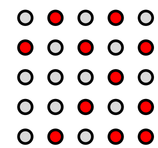
Missing atoms = Rydberg



1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;
2D: Lienhard PRX 2018, Bakr PRX 2018; Lukin arXiv:2012.12281

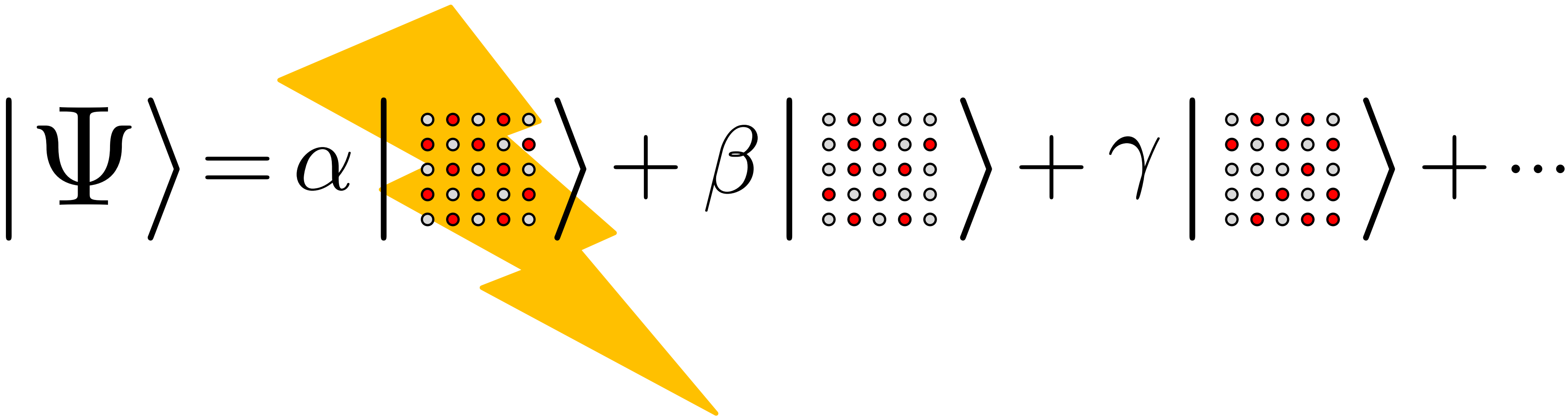
Seeing the many-body wavefunction…

At the end of experiment:

$|\Psi\rangle = \alpha\,|$  $\rangle + \beta\,|$  $\rangle + \gamma\,|$  $\rangle + \cdots$

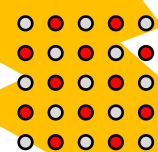
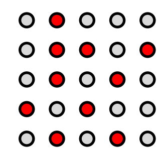
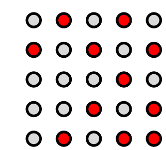
Seeing the many-body wavefunction…

At the end of experiment:

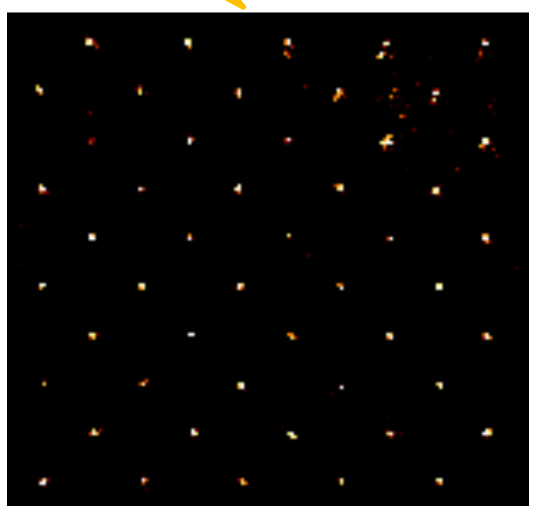


Seeing the many-body wavefunction…

At the end of experiment:

$|\Psi\rangle = \alpha \, |$  $\rangle + \beta \, |$  $\rangle + \gamma \, |$  $\rangle + \cdots$

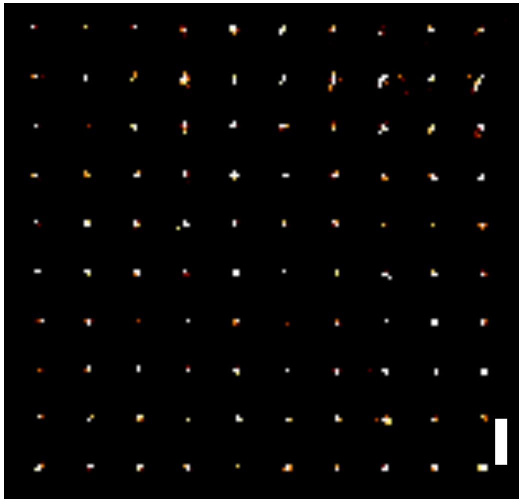
$$|\Psi_{\mathrm{f}}\rangle =$$



probability $|\alpha|^2$

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

10 × 10 square array

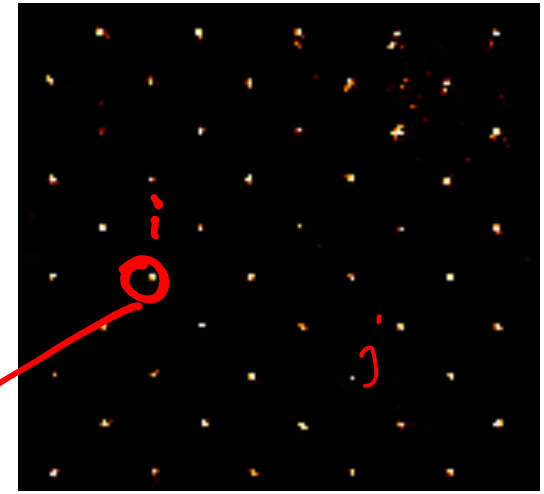


10 µm

sweep

n=75s

Scholl, arXiv:2012.12268



Missing atoms = Rydberg

Perfect AF (Néel) ordering!

(proba < 1%)

$\sigma_i^z \quad \sigma_j^z$

↑

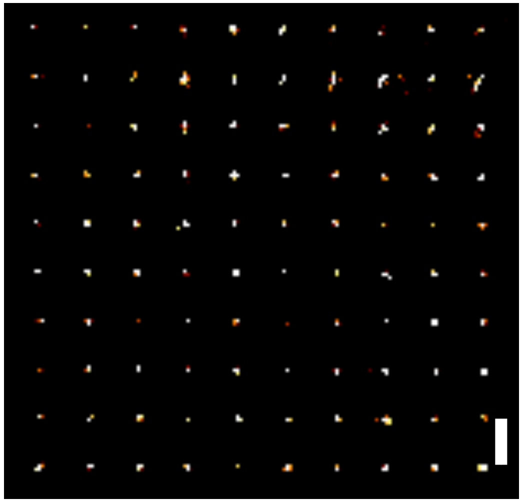
↓

1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;

2D: Lienhard PRX 2018, Bakr PRX 2018; Lukin arXiv:2012.12281

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

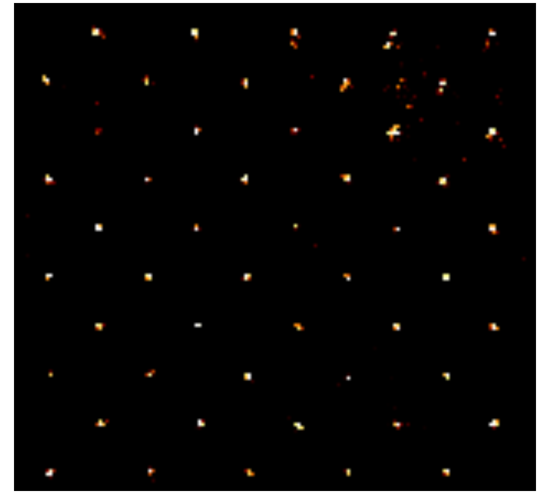
10 × 10 square array



sweep

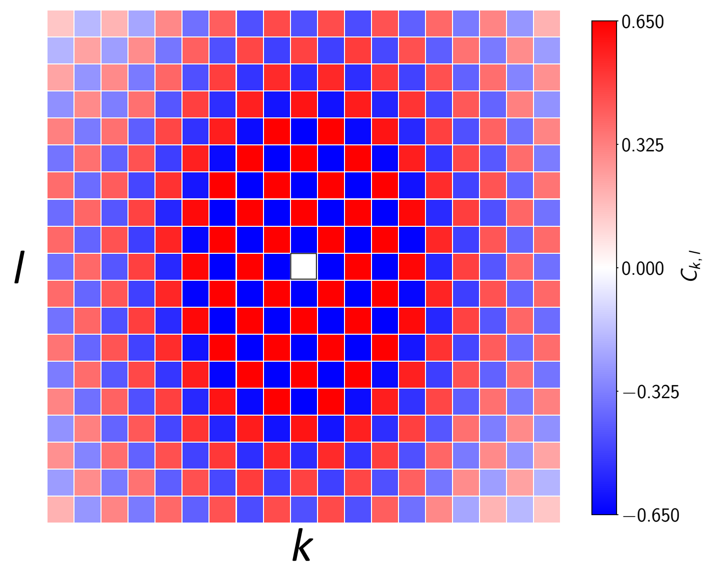
n=75s

Scholl, arXiv:2012.12268



Missing atoms = Rydberg

$$C_{kl} \sim \langle n_k n_l \rangle - \langle n_k \rangle \langle n_l \rangle \sim \langle \sigma_k^z \sigma_l^z \rangle$$

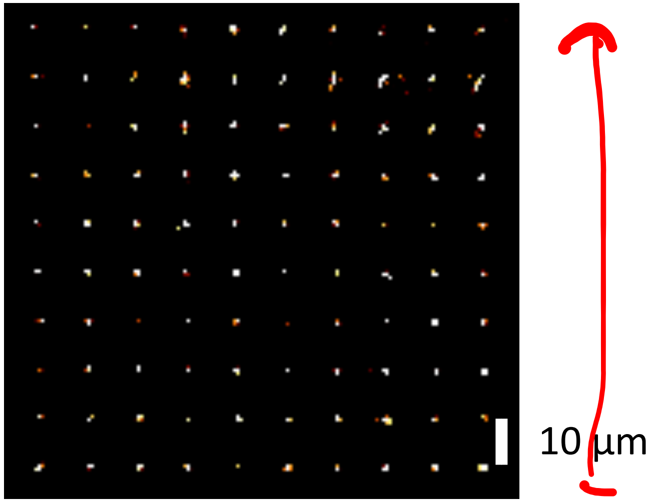


Also: Lukin arXiv:2012.12281

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

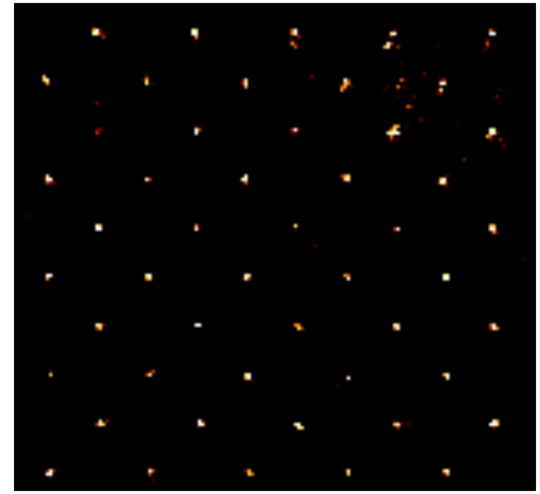
10 × 10 square array

Scholl, arXiv:2012.12268



sweep

n=75s



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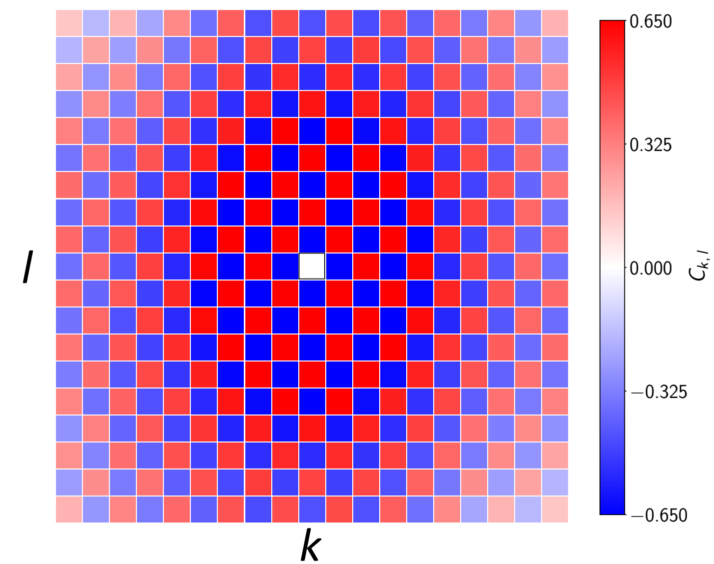
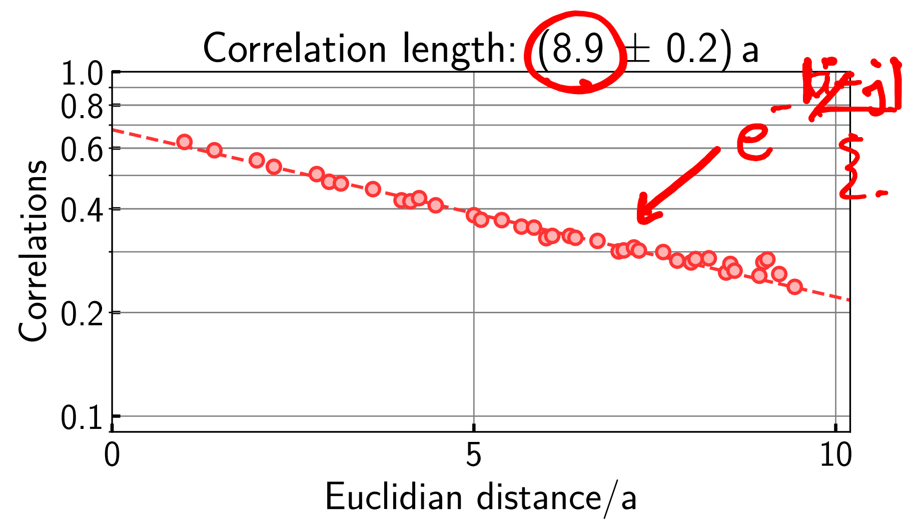


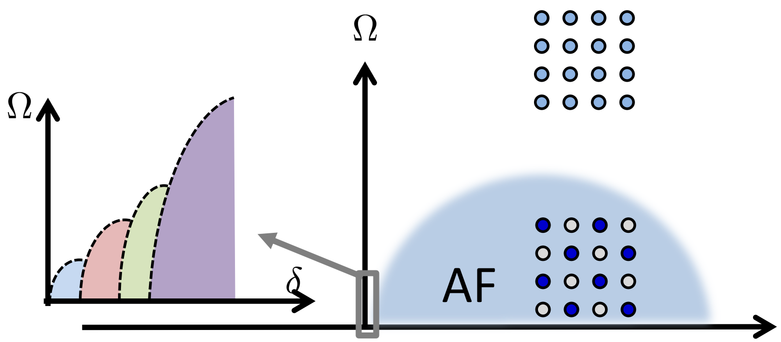


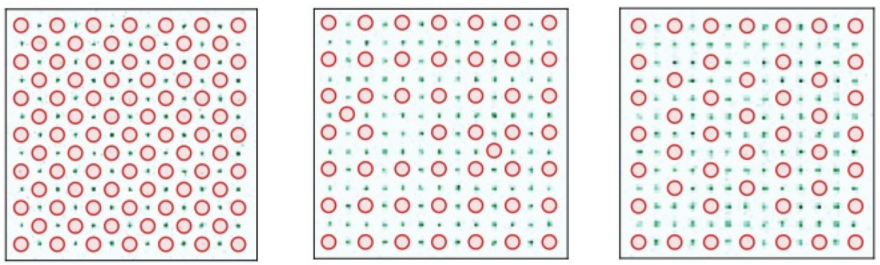
Also: Lukin arXiv:2012.12281

2D Ising anti-ferromagnet on a square beyond NN interactions

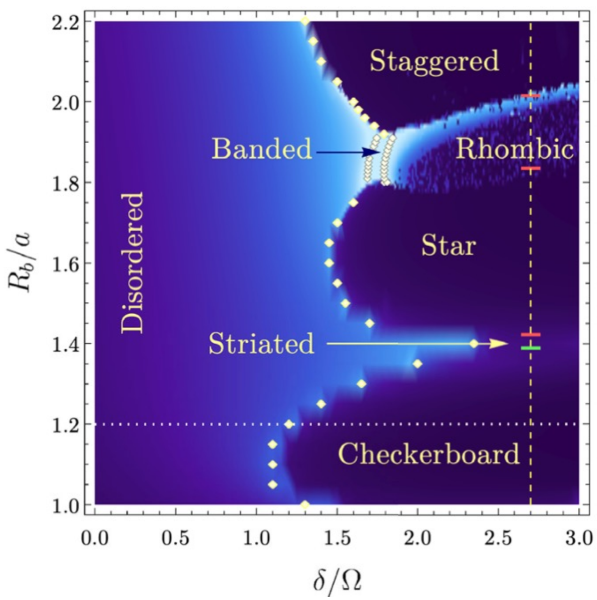
Lukin arXiv:2012.12281

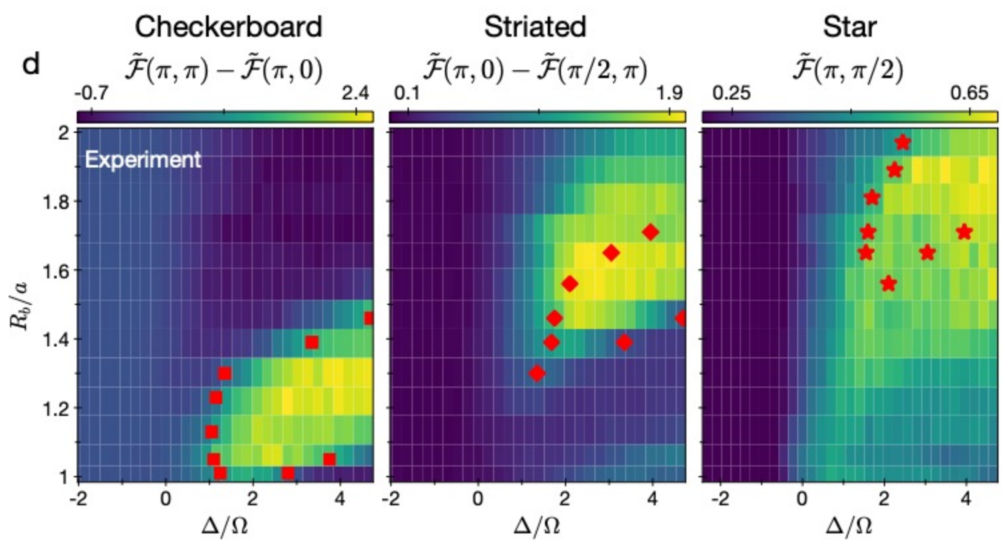
Samajdar *et al.* PRL (2020)





Vary $(C_6/a^6)/\Omega$





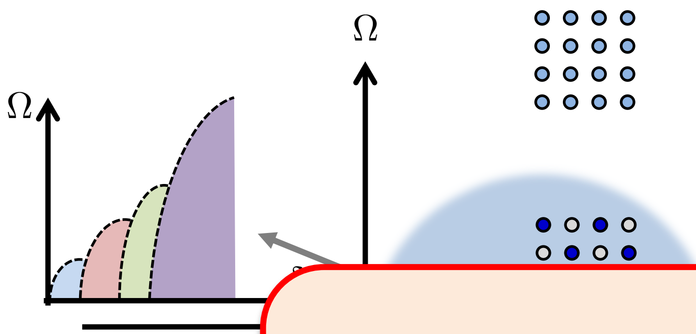
Order parameters:

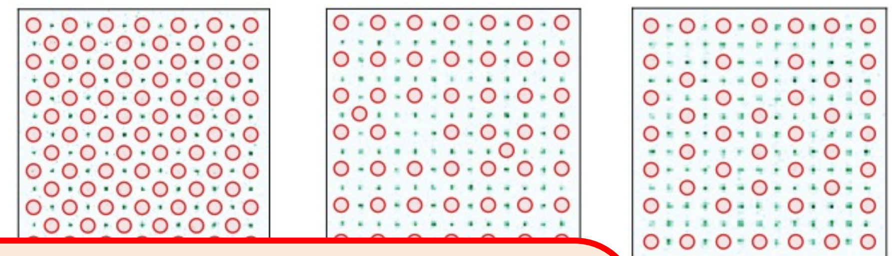
$$\mathcal{F}(\mathbf{k}) = \frac{1}{\sqrt{N}} \sum_i n_i \, e^{i\mathbf{k}\cdot\mathbf{x}_i}$$

2D Ising anti-ferromagnet on a square beyond NN interactions

Lukin arXiv:2012.12281

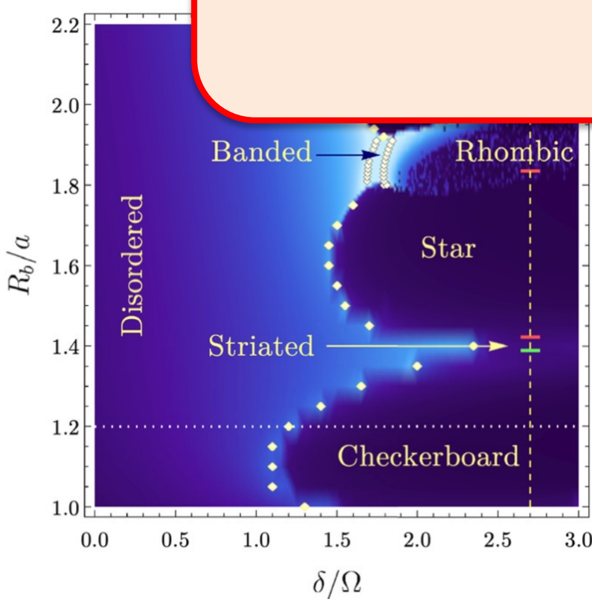
Samajdar *et al.* PRL (2020)

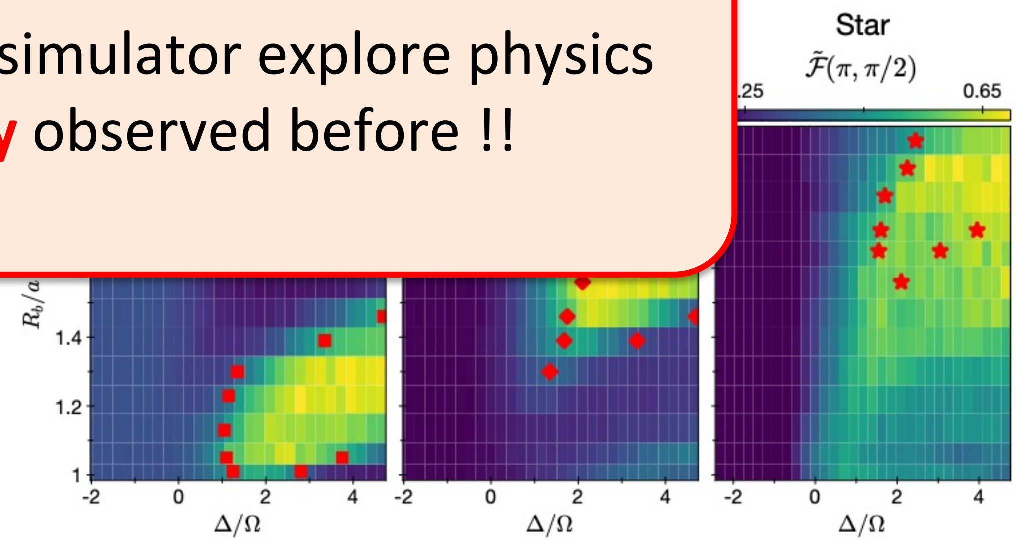




Vary $(C_6$

Rydberg quantum simulator explore physics
never directly observed before !!



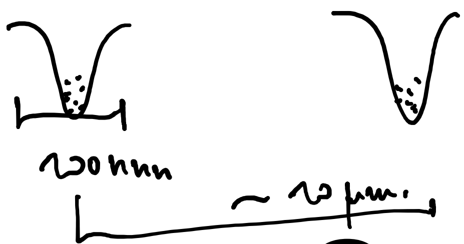


Order parameters:

$$\mathcal{F}(\mathbf{k}) = \frac{1}{\sqrt{N}} \sum_i n_i \, e^{i\mathbf{k}\cdot\mathbf{x}_i}$$

Role of Shot-to-shot fluctuations: in positions of the atoms.

$J \sigma_i^z \sigma_j^z$ $\qquad \frac{C_6}{R_{ij}^6}$



Questions ?

Outline

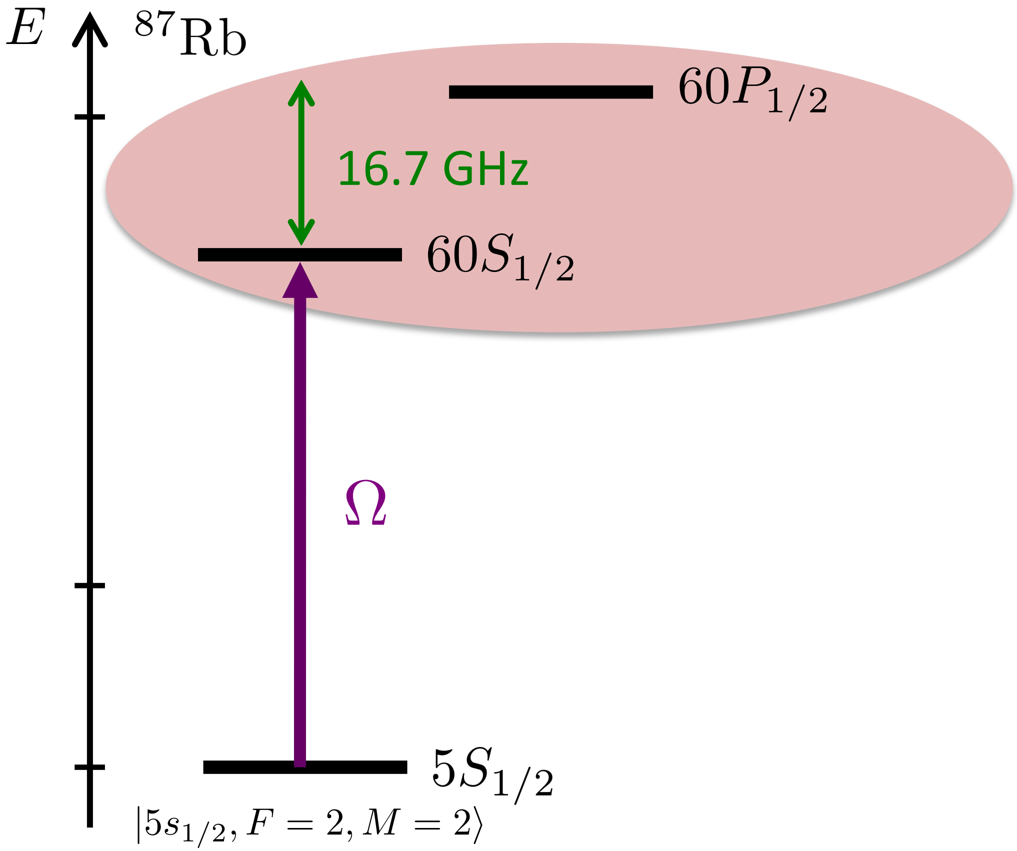
1. Quantum simulation and spin models

2. Simulation of Ising model using van der Waals interactions

3. Topological systems using resonant dipole interactions

H.-P. Büchler
S. Weber, N. Lang

Resonant dipole-dipole interaction between Rydberg atoms



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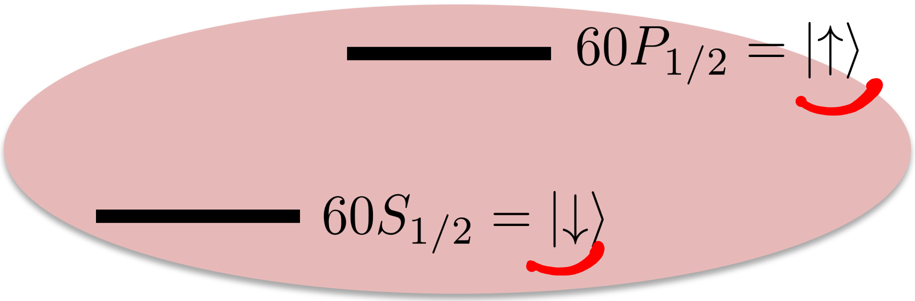
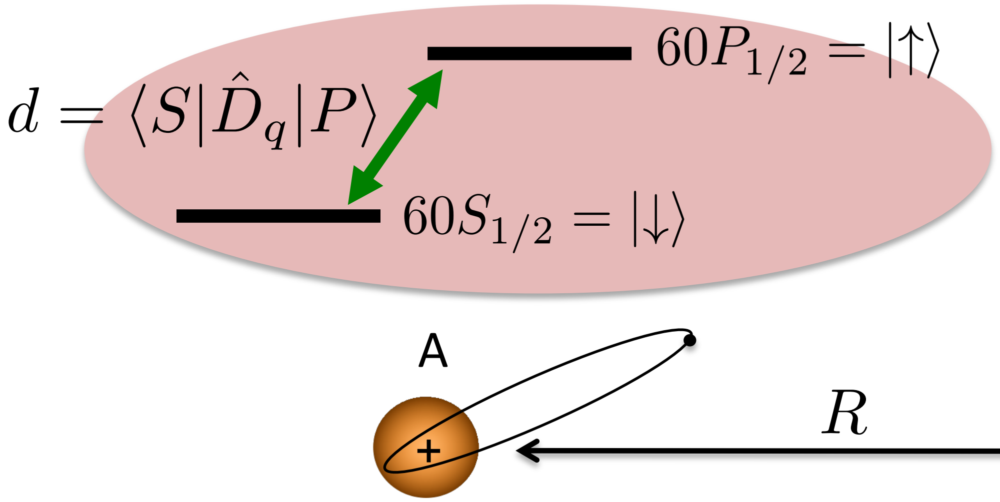


Mapping on
spin ½ system

Resonant dipole-dipole interaction between Rydberg atoms



Mapping on
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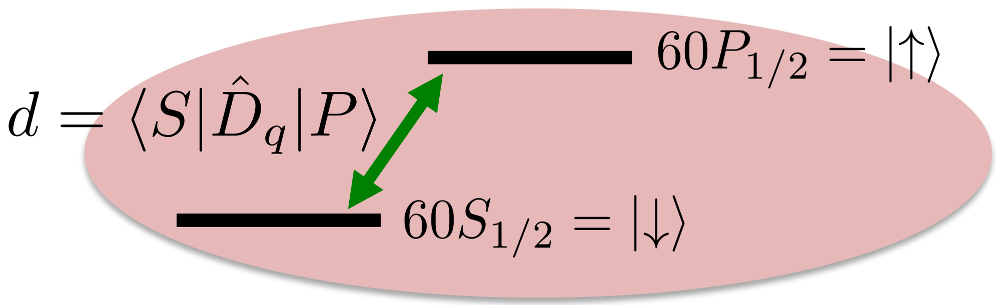
Resonant dipole-dipole interaction between Rydberg atoms



Mapping on
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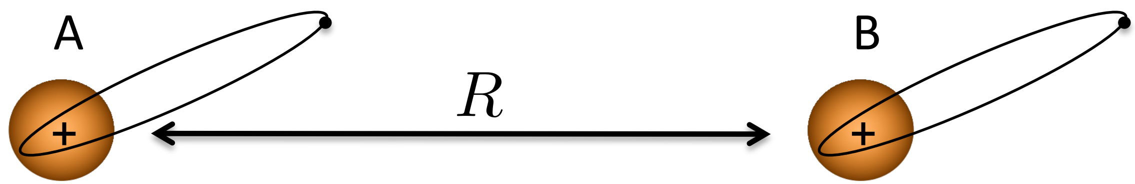
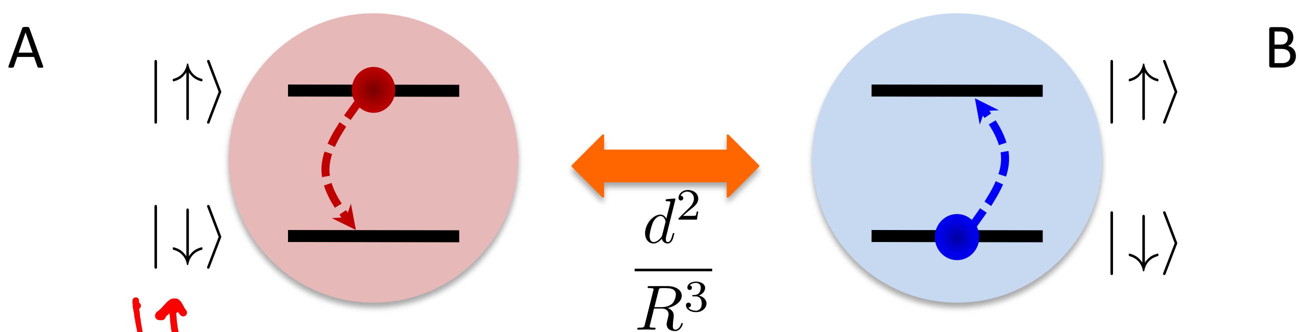
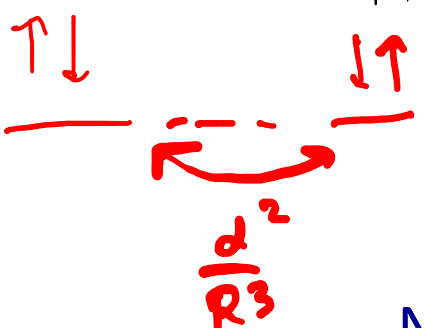






$$\hat{H} = \frac{d^2}{4\pi\epsilon_0 R^3}\left(\hat{\sigma}_A^+\hat{\sigma}_B^- + \hat{\sigma}_A^-\hat{\sigma}_B^+\right)$$

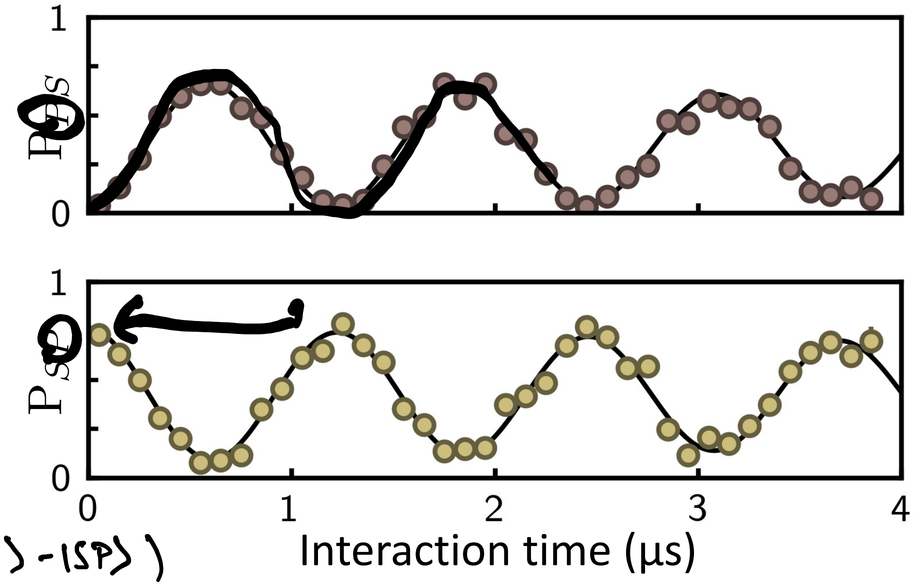
Non radiative “exchange” of excitation

Observation of resonant dip.-dip. interaction with 2 atoms

Prepare $|\uparrow\downarrow\rangle$ using microwaves + addressing beam

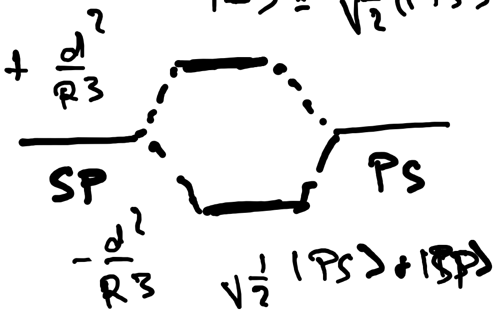
R = 30 µm

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



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

$|-\rangle = \frac{1}{\sqrt{2}}(|PS\rangle - |SP\rangle)$



$$|\psi(0)\rangle = |PS\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle + |-\rangle\right)$$

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(e^{-i\frac{d^2}{R^3}t/\hbar}|+\rangle + e^{+i\frac{d^2}{R^3}t/\hbar}|-\rangle\right)$$

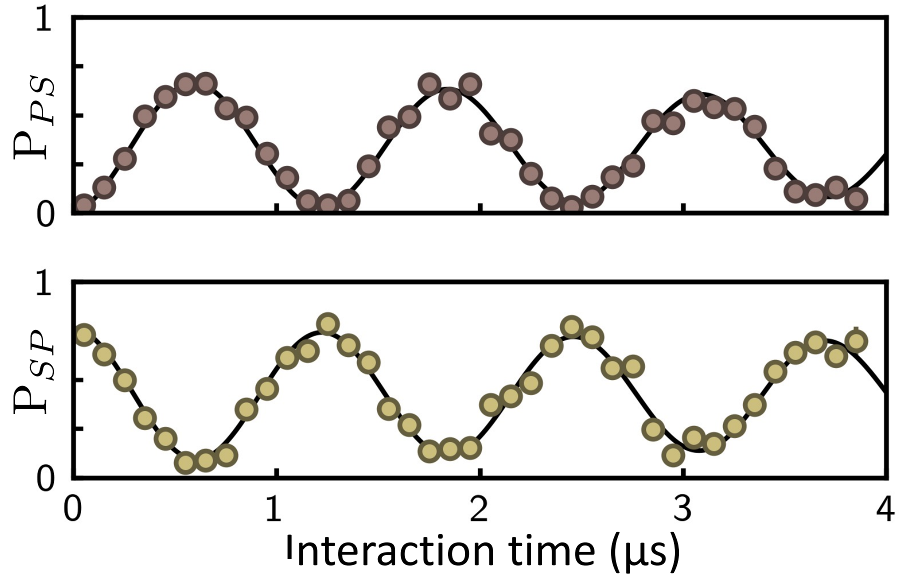
$$|\langle PS|\psi(t)\rangle|^2 = P_{PS} = \cos^2\left(\frac{d^2}{R^3}t/\hbar\right)$$

Observation of resonant dip.-dip. interaction with 2 atoms

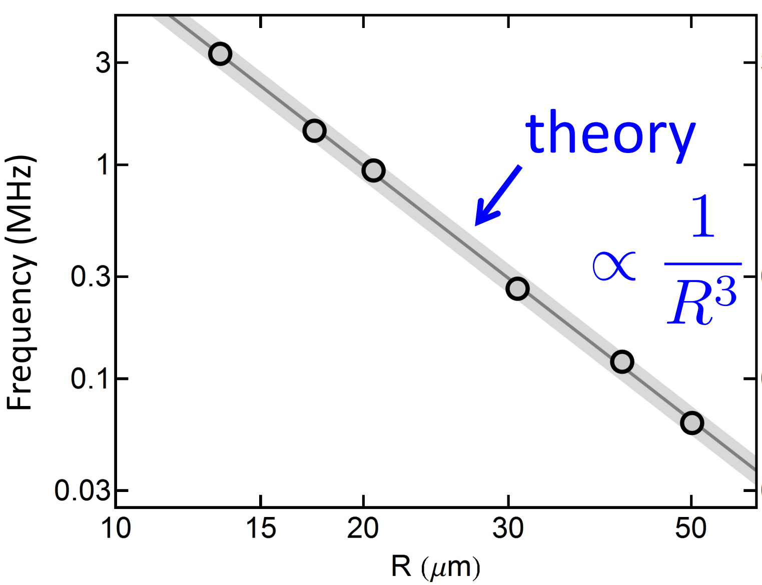
Prepare $|\uparrow\downarrow\rangle$ using microwaves + addressing beam

R = 30 µm

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



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



Thickness:

Paper sheet ~ 100 µm

Hair ~ 50 – 100 µm

Observation of resonant dip.-dip. interaction with 2 atoms

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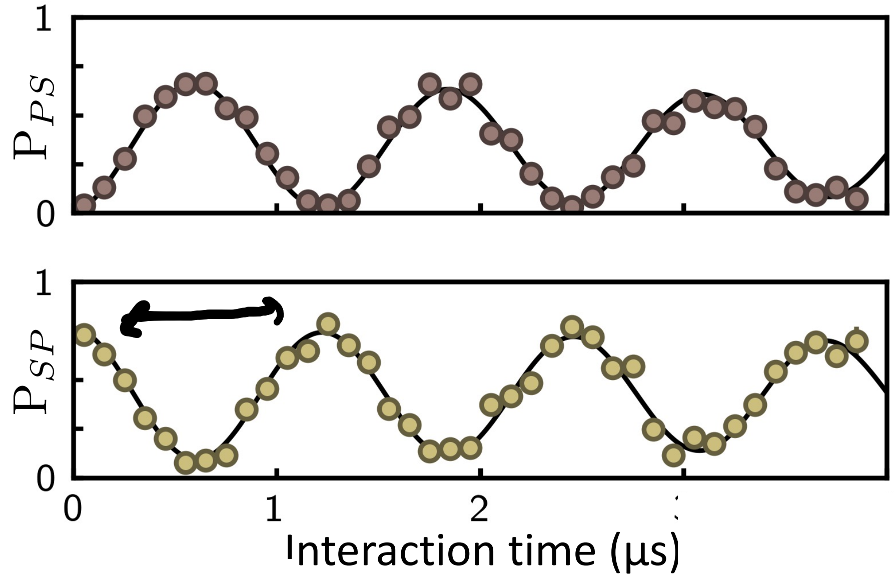
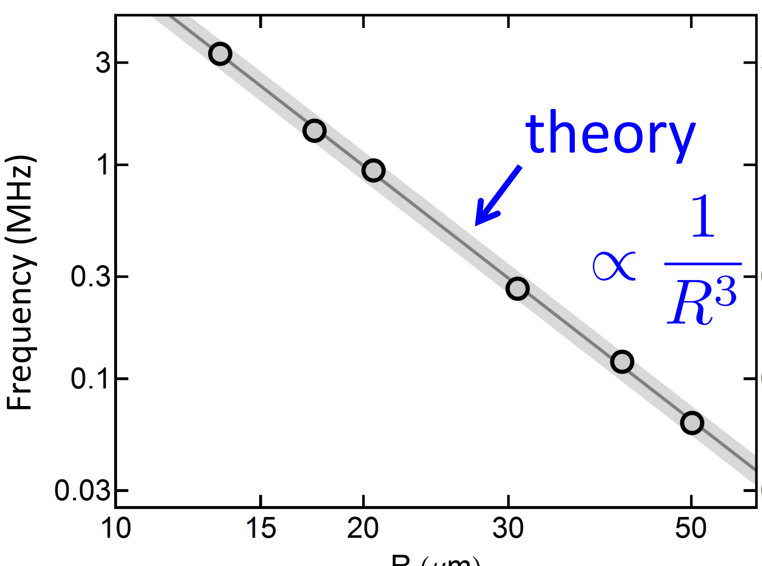
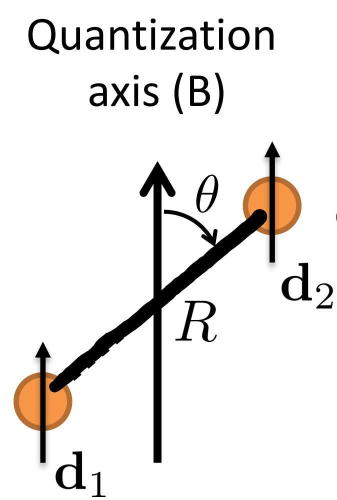
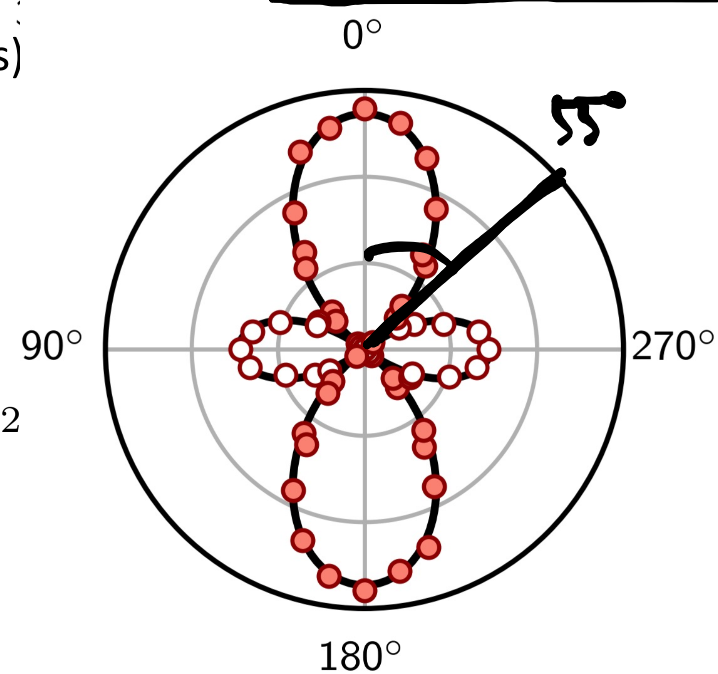


Barredo PRL (2015)
de Léséleuc, PRL (2017)

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







Observation of resonant dip.-dip. interaction with 2 atoms

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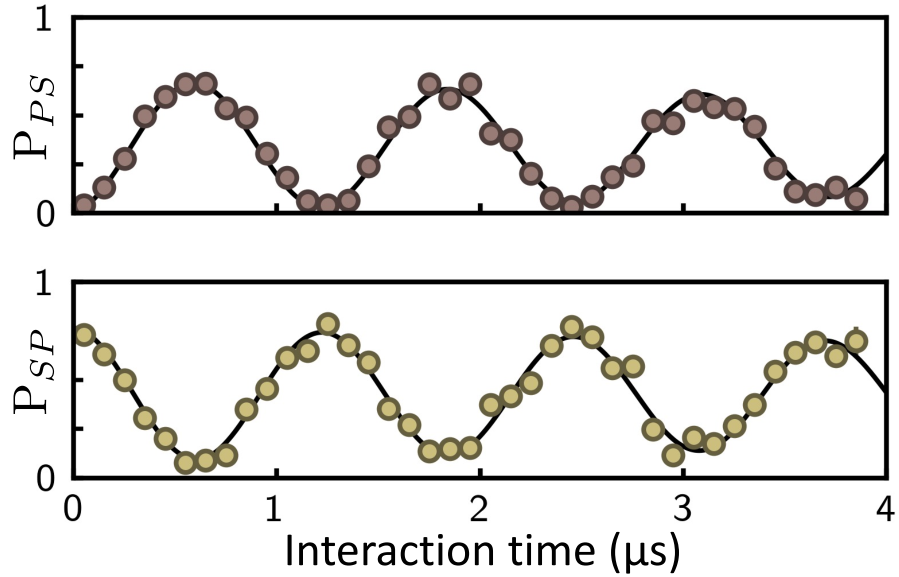

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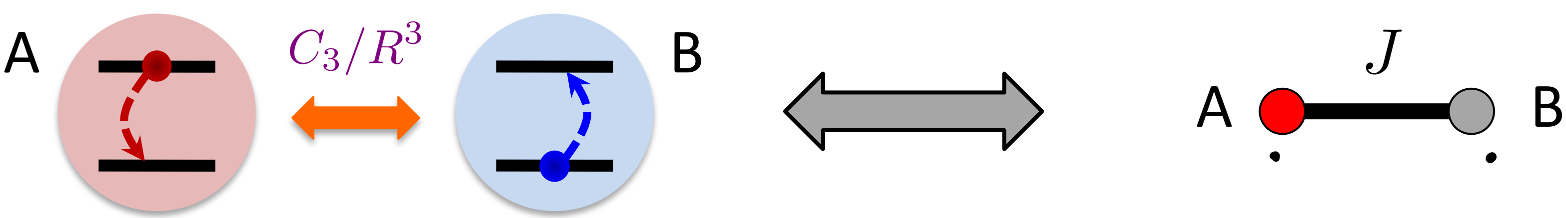
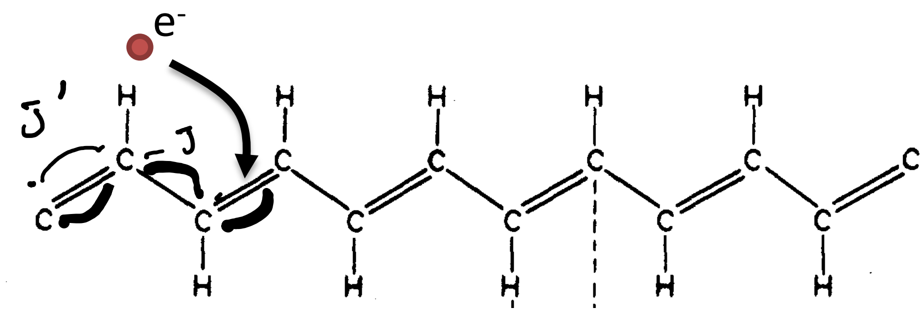


P excitation exchange

Particle hopping

$J|A\rangle\langle B|$

The Su-Schrieffer-Heeger model



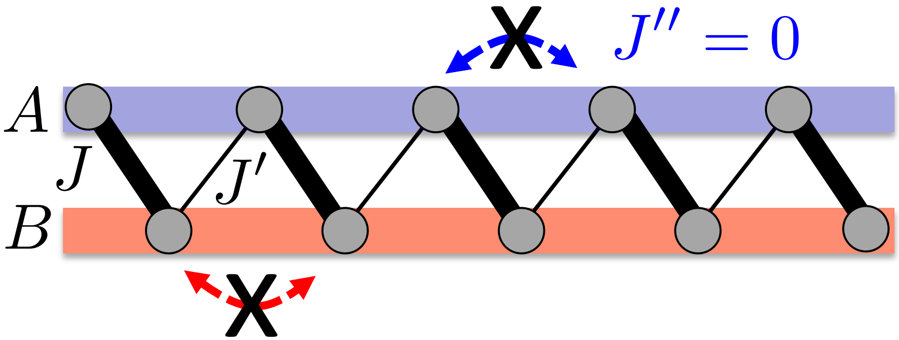
Electronic transport in polyacetylene

PRL **42**, 1698 (1979)

Now, considered as simplest example of topological model

Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

The Su-Schrieffer-Heeger model



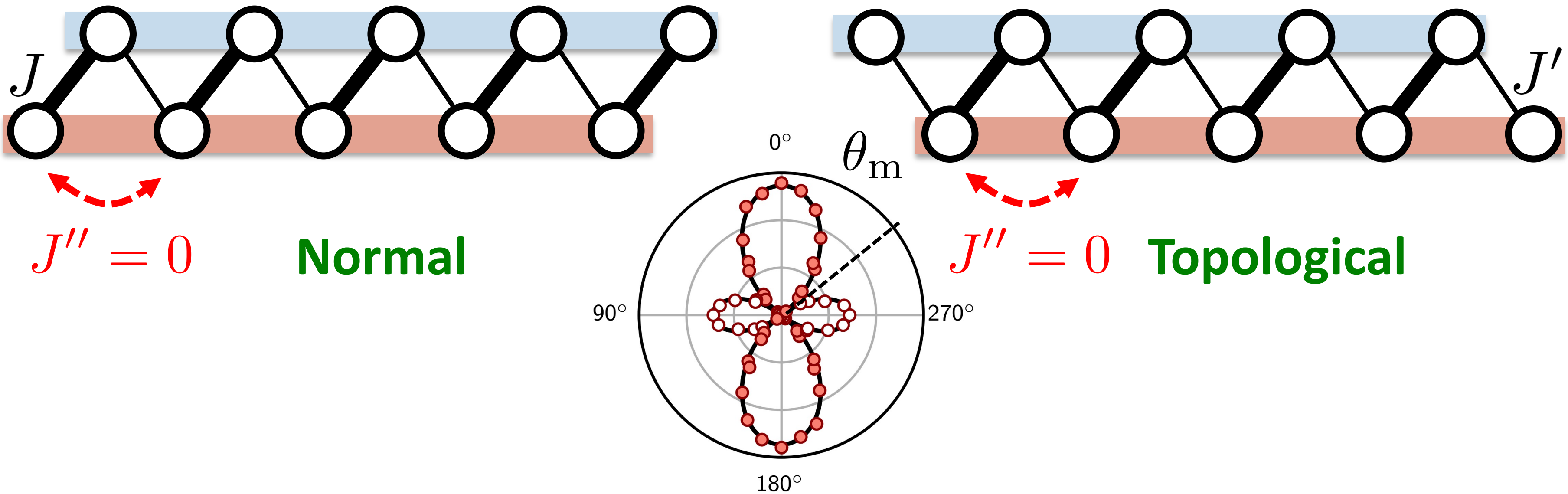
Model: tight-binding
dimerization: $J > J'$

Sub-lattice symmetry $\Rightarrow$ symmetric **single particle** spectrum

Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

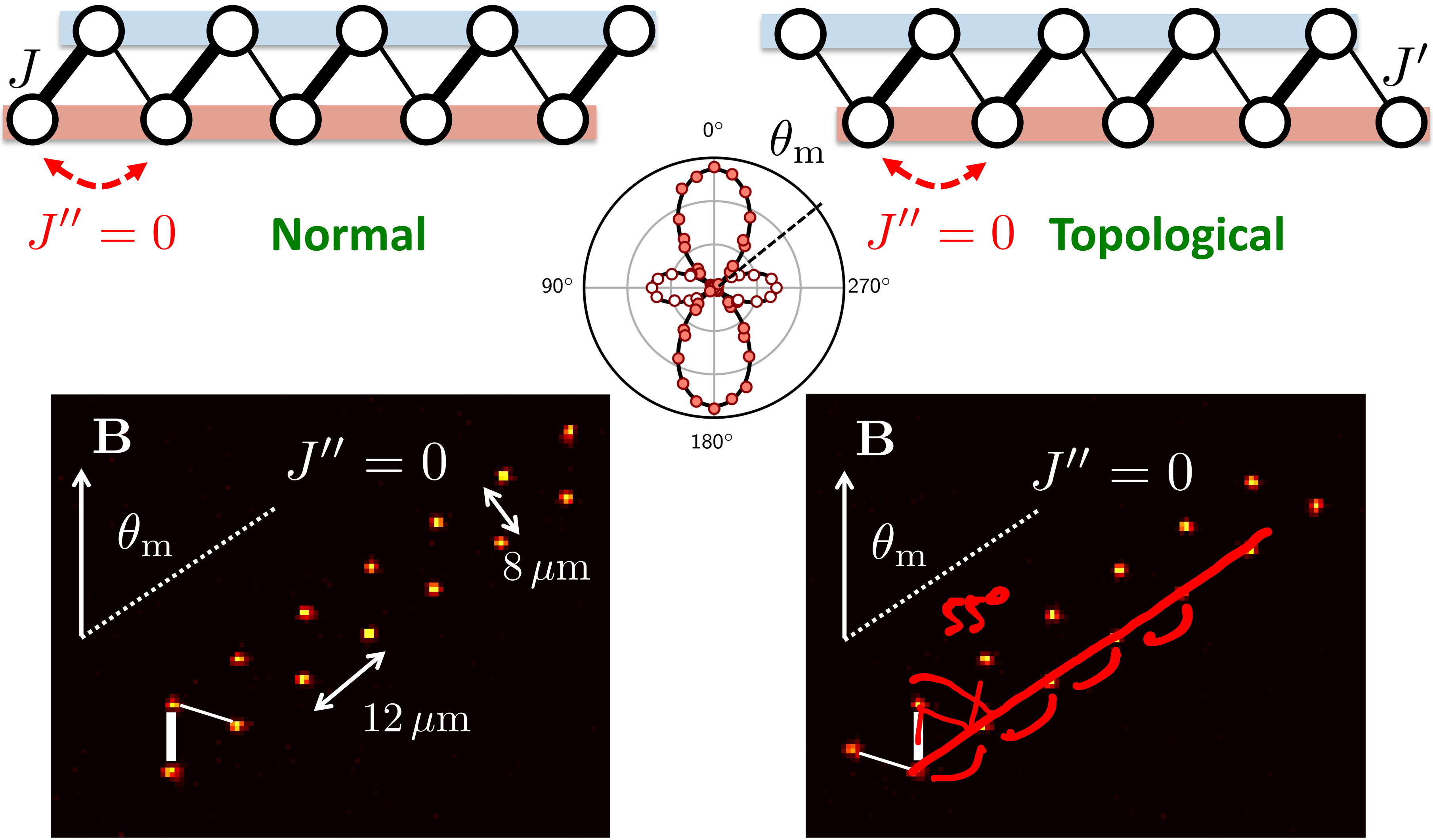
Implementation of SSH spin chain with Rydberg atoms

Science **365**, 775 (2019)



Implementation of SSH spin chain with Rydberg atoms

Science **365**, 775 (2019)



$J/h = 2.4\,\mathrm{MHz}$ $J'/h = -0.9\,\mathrm{MHz}$

Conclusion

Rydberg interactions are strong & controllable

1. Resonant interaction
2. Van der Waals

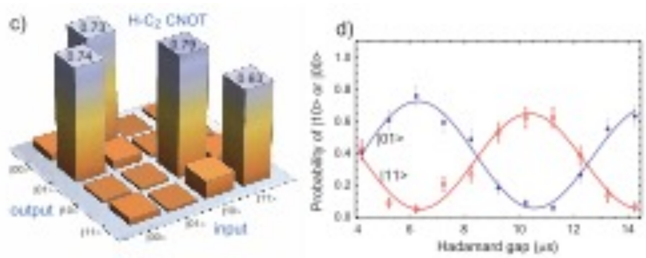
$$R = 10\ \mu\text{m} \Rightarrow V_{\text{int}}/h \sim 1 - 10\ \text{MHz}$$

⇒ timescales < µsec

Control over interaction useful for many-body physics & quantum simulation

New / other directions: … a few examples

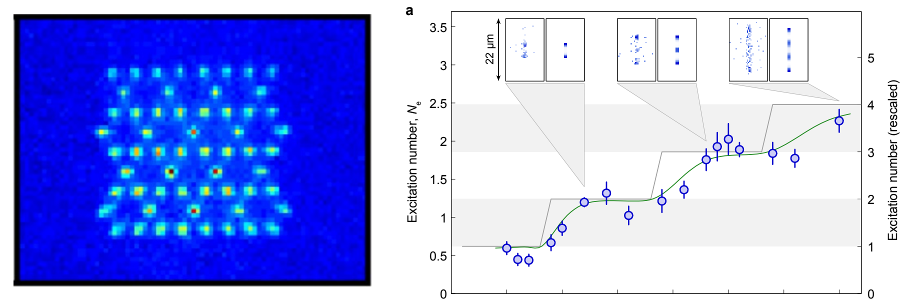
QIP: entanglement and gates



Saffman RMP **82**, 2313 (2010)

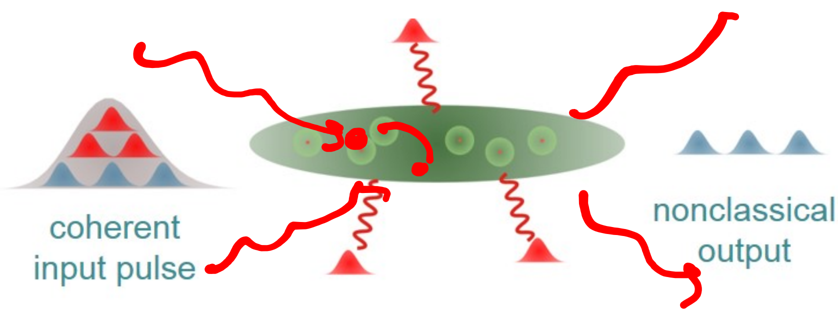
Saffman, Biedermann, Lukin…

Many-body physics Quantum simulation



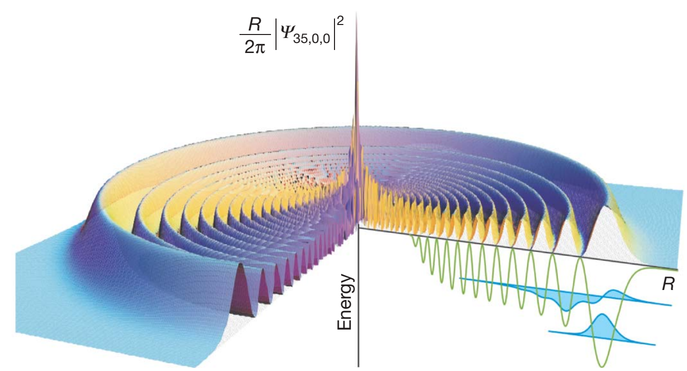
Browaeys, Lukin, Bloch, Pillet, Weidemuller, Morsch…

Non-linear classical & quantum optics



Adams, Hofferbert, Firstenberg, Lukin, Vuletic…

Exotic long-range molecules



Pfau-Löw, Ott, Shaeffer …

Platform mature enough to envision applications…

Startups recently created to develop industry graded simulators

INSTITUT d'OPTIQUE GRADUATE SCHOOL

PASQAL

|QuEra⟩

ColdQuanta

atom computing

Applications: scientific computing, optimization in finance and industry…