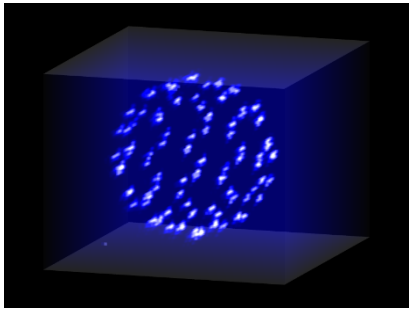
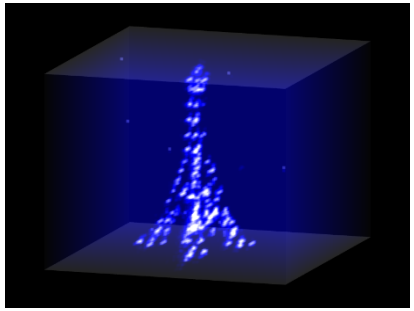
Etudier le problème à *N*-corps

avec quelques atomes

Antoine Browaeys

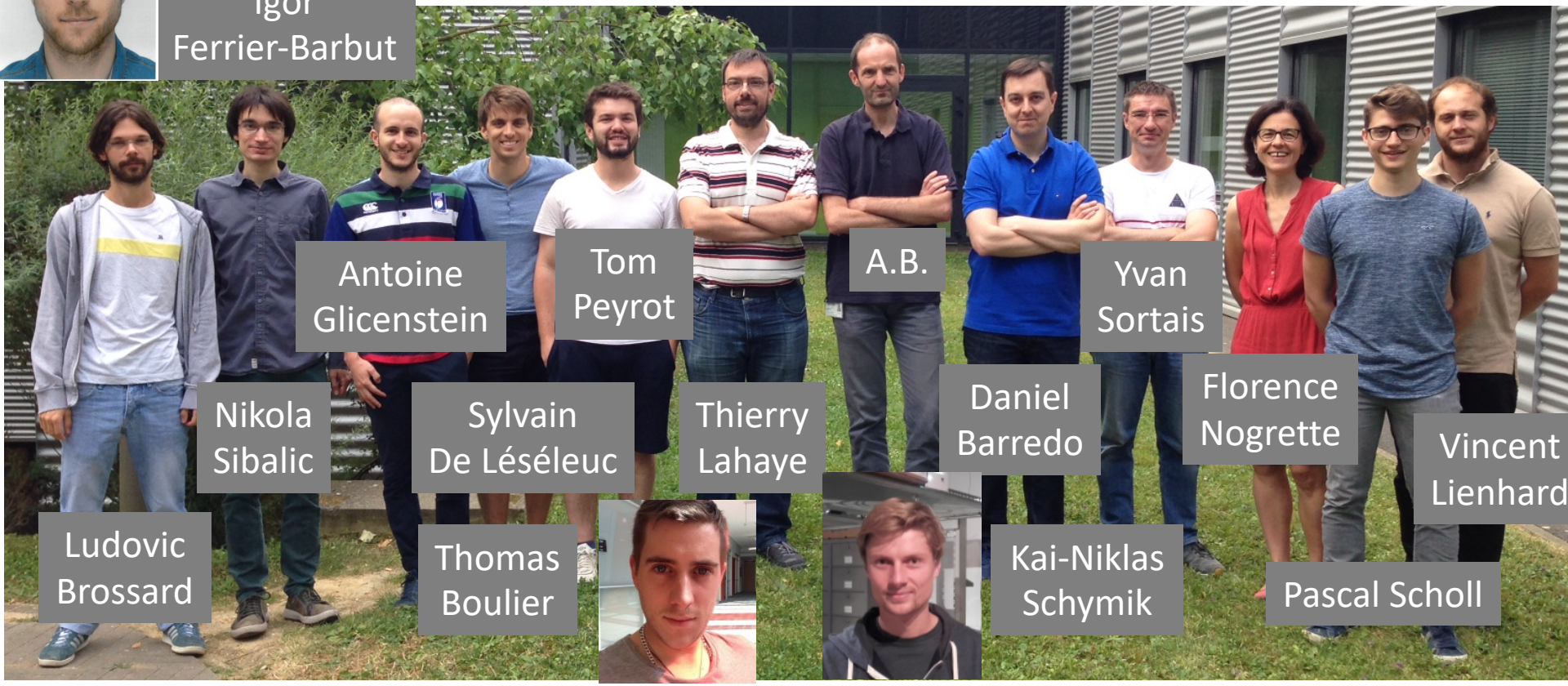
Laboratoire Charles Fabry,
Institut d'Optique, CNRS, FRANCE





Congrès Général SFP, 11 juillet 2019

The team (atom-tweezers-io.org)



Theory

T. Macrì (Natal)

A. Läuchli (Innsbruck)

H.-P. Büchler, (Stuttgart)

DGA

PALM Laboratoire d'Excellence Physique : Atomes Lumière Matière

SIR TEQ

îledeFrance

PASQuanS

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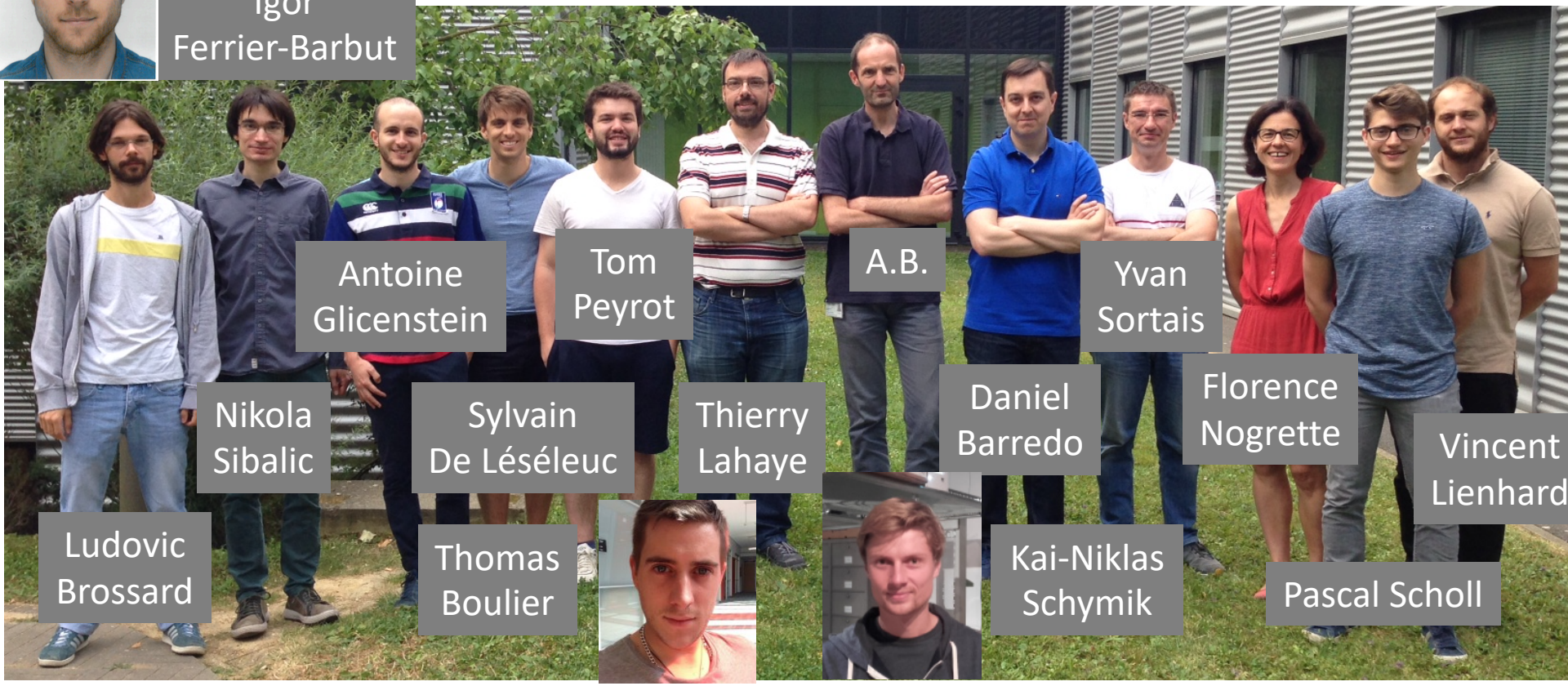

Looking for PhD students and Post-docs!!

DGA

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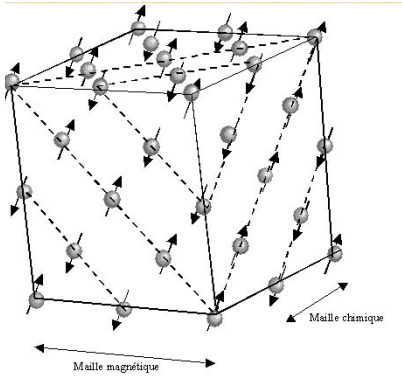
Many-body physics

Goal: Understand ensembles of interacting quantum particles

superfluidity

superconductivity



magnetism

neutron star

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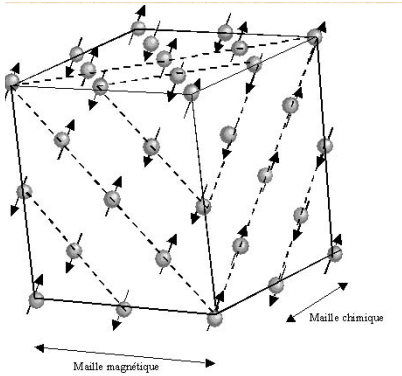

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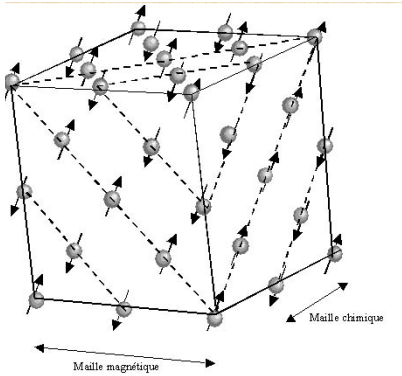

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Experiments on real system

Model Hamiltonian

$$H_{\text{model}} = -\sum_{i,j} J_{ij} a_i^\dagger a_j + \sum_i g (a_i^\dagger)^2 (a_i)^2$$

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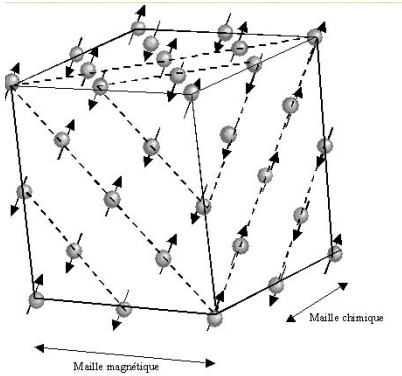

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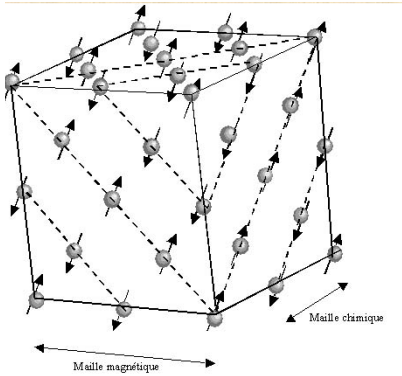

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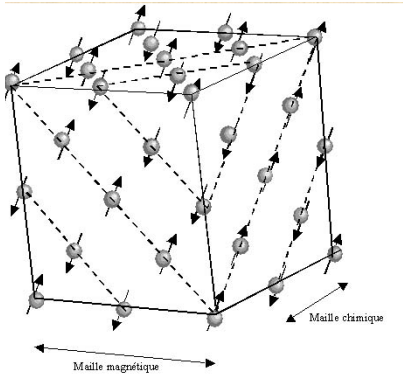

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Calculation too hard…

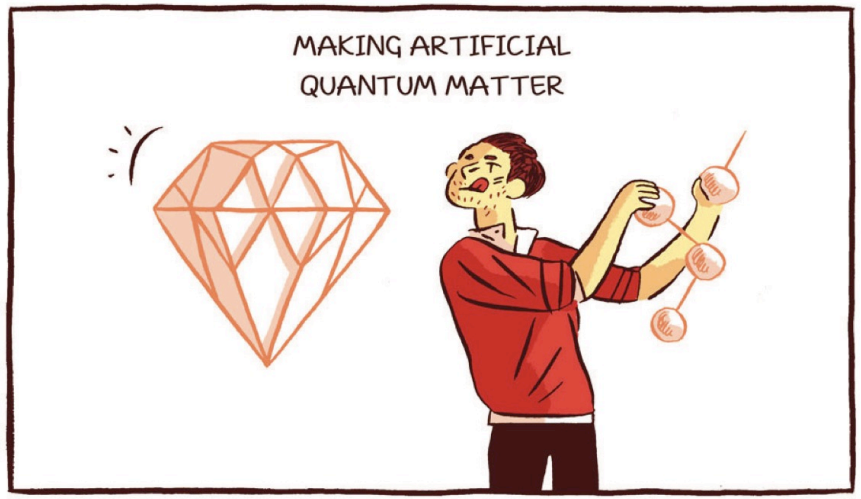
Exponential scaling of Hilbert space

Ex: *N*-spin ½ $\Rightarrow \dim \mathcal{H} = 2^N$ Record ab-initio: *N* ~ 42

Many-body physics with artificial matter: quantum simulation

R.P. Feynman

Simulating Physics with Computers, Int. J. Theo. Phys. **21** (1982)



Héloïse Chochois, Labex PALM

i.e. **well-controlled** quantum systems implementing
many-body Hamiltonians (including “mathematical” ones…)

Georgescu, Rev. Mod. Phys. (2014)

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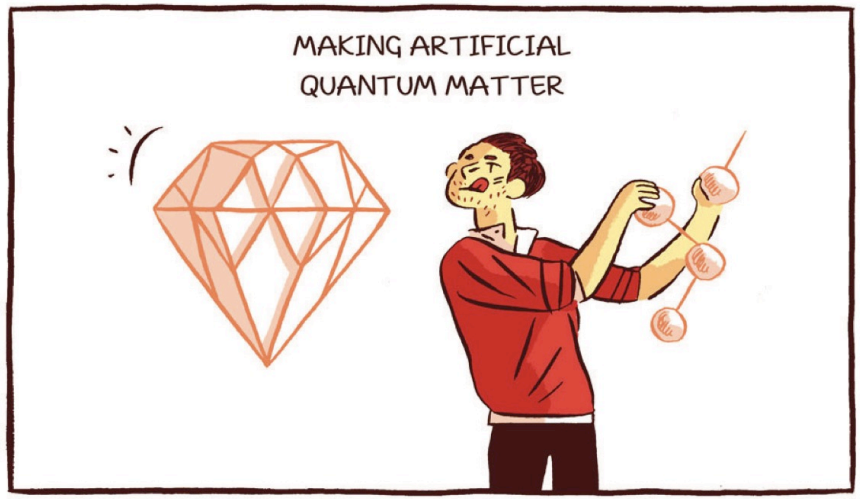

Héloïse Chochois, Labex PALM

i.e. **well-controlled** quantum systems implementing
many-body Hamiltonians (including "mathematical" ones…)

Larger tunability than "real" systems (geometry, parameters…)

+

New types of probe & methods (e.g. out-of-equilibrium)

Georgescu, Rev. Mod. Phys. (2014)

Artificial matter can do more…!

Controlled quantum systems = machine to prepare quantum states

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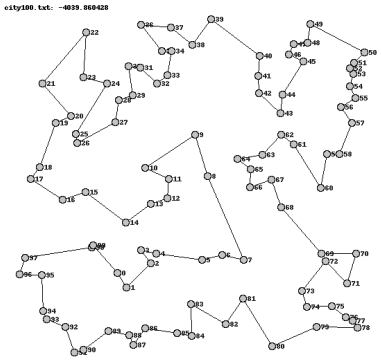
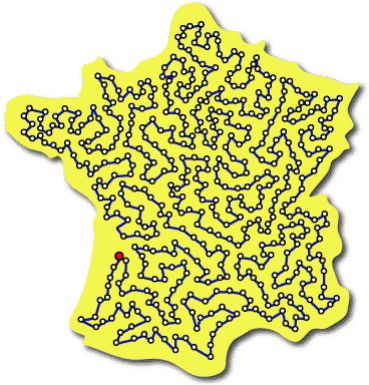
Optimization problems

problème du voyageur de commerce





O. Ezratti

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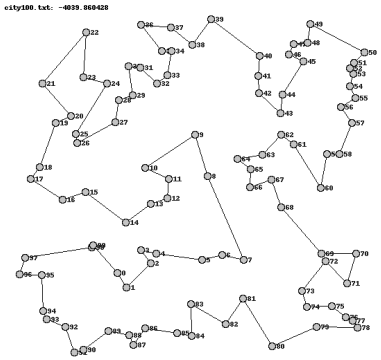
Optimization problems

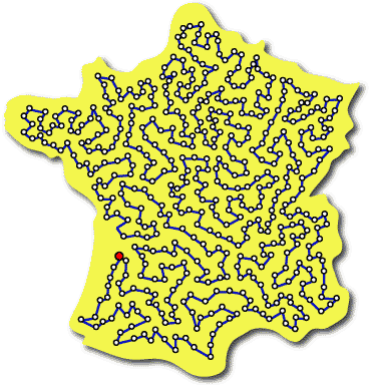
Mapped onto Ising model

$$H = \sum_i h_i n_i + \sum_{i<j} J_{ij} n_i n_j \ , \quad n_i = 0, 1$$

Solution = ground-state

problème du voyageur de commerce





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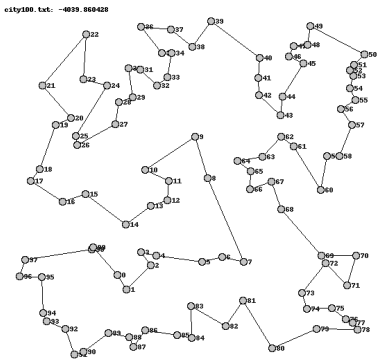
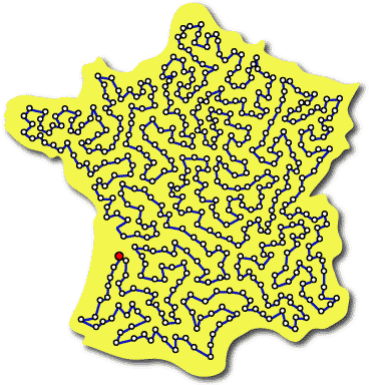
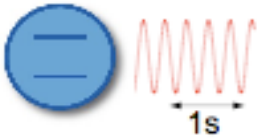




O. Ezratti

Quantum metrology



$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{\sqrt{N}} \xrightarrow{\text{Entangled states}} \frac{\Delta\nu}{\nu_0} \propto \frac{1}{N}$$

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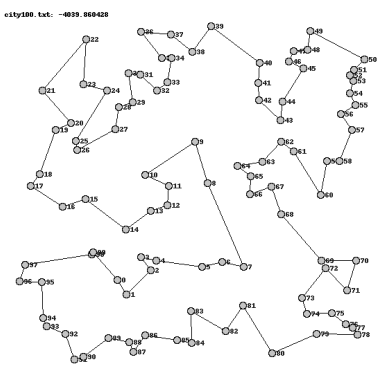

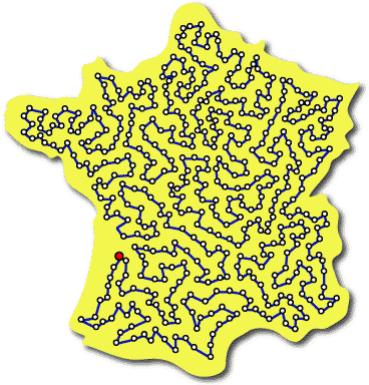

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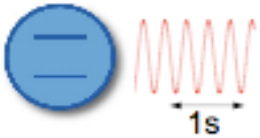

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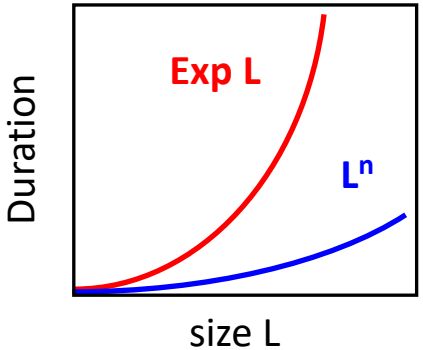
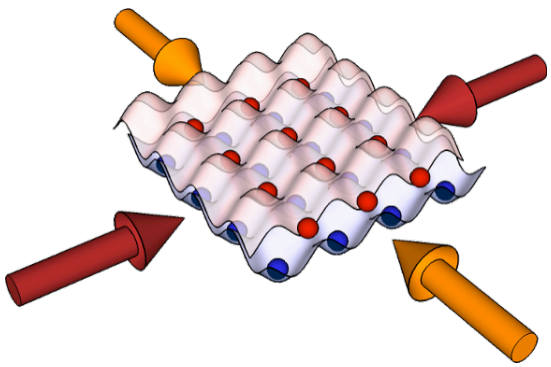
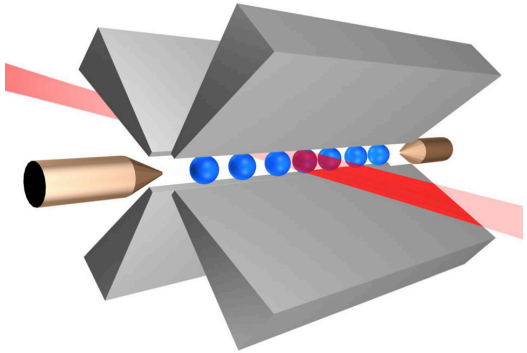
Quantum computer (long-term…)



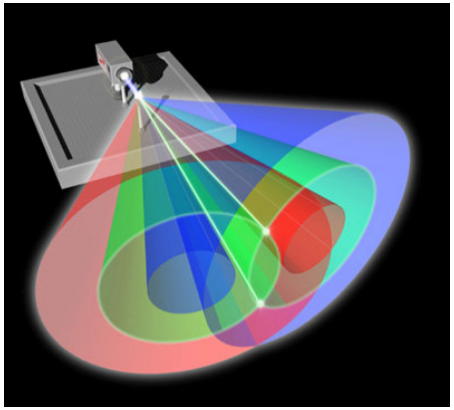
Quantum state engineering with individual systems



Neutral atoms

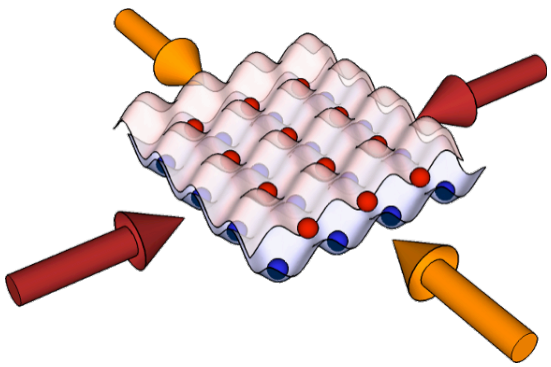


Trapped ions



Photons

Quantum state engineering with individual systems



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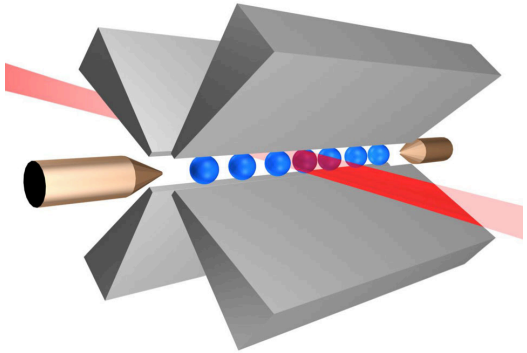

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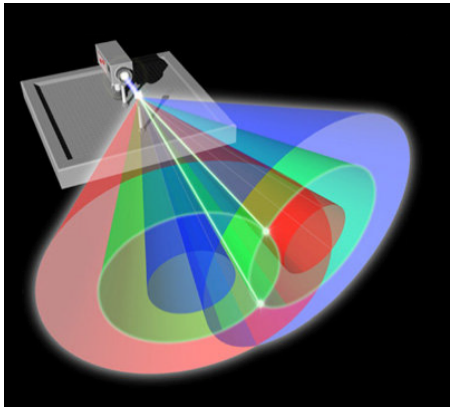

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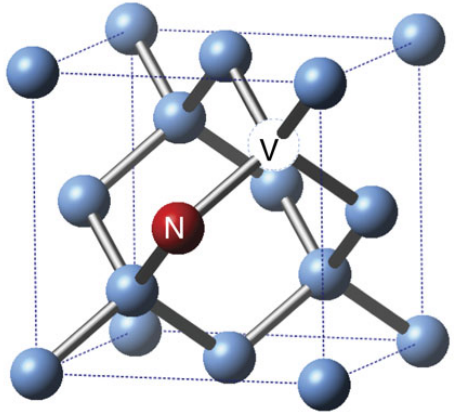
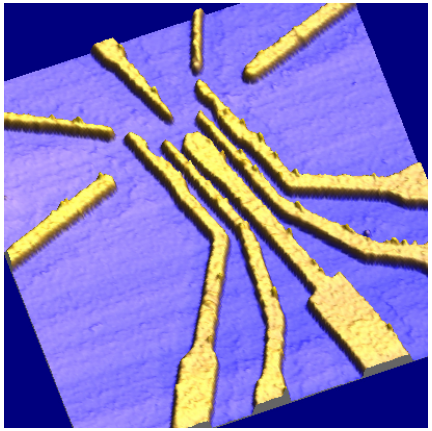
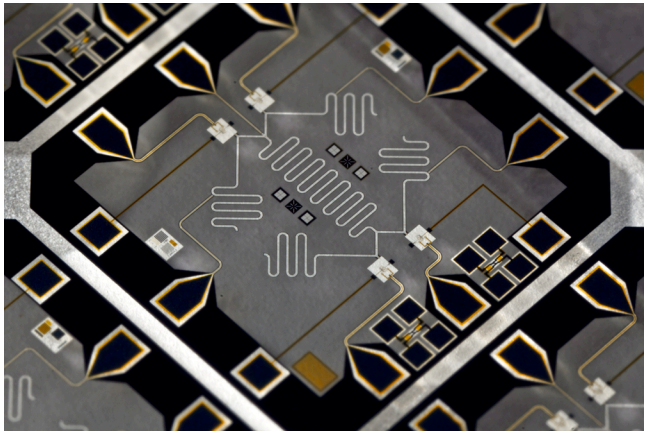


NV centers

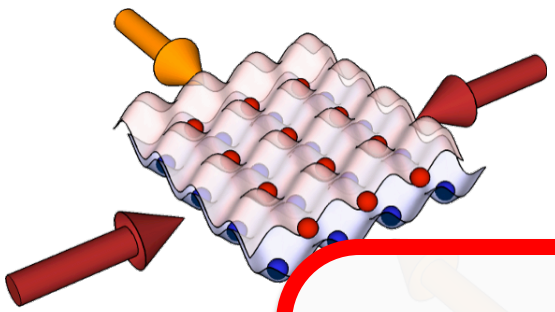


Quantum dots



Superconducting qubits

Quantum state engineering with individual systems



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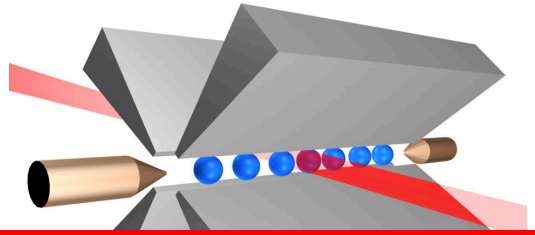
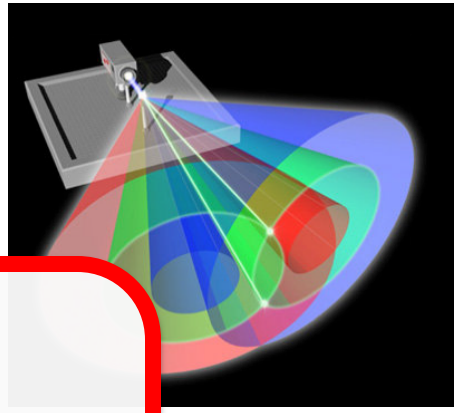
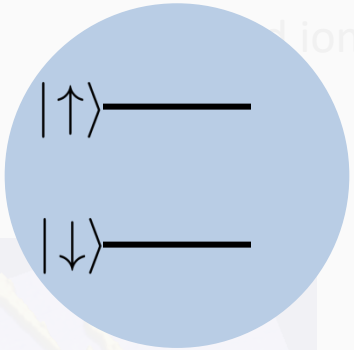


Ions

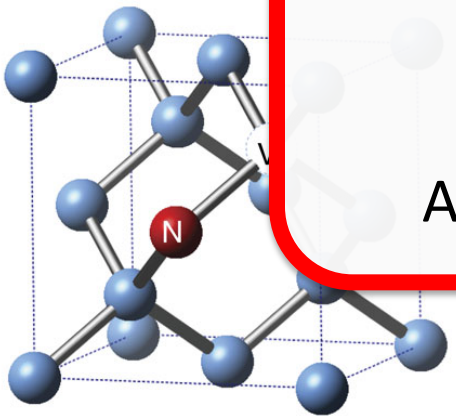


Photons

Two-level systems to encode a spin:



Addressable + controlled interactions



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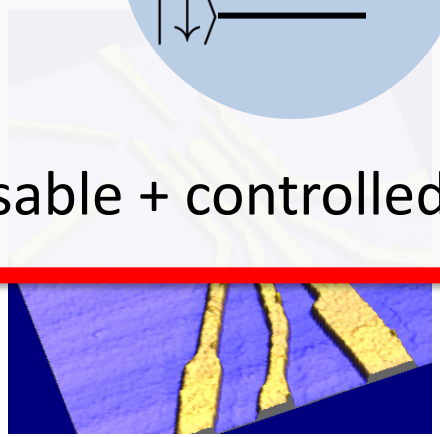

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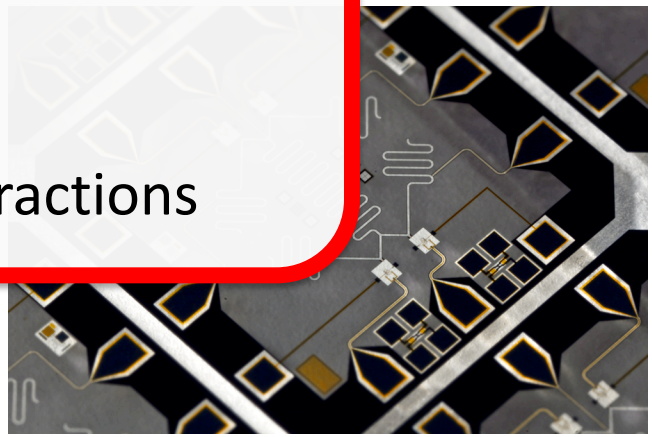
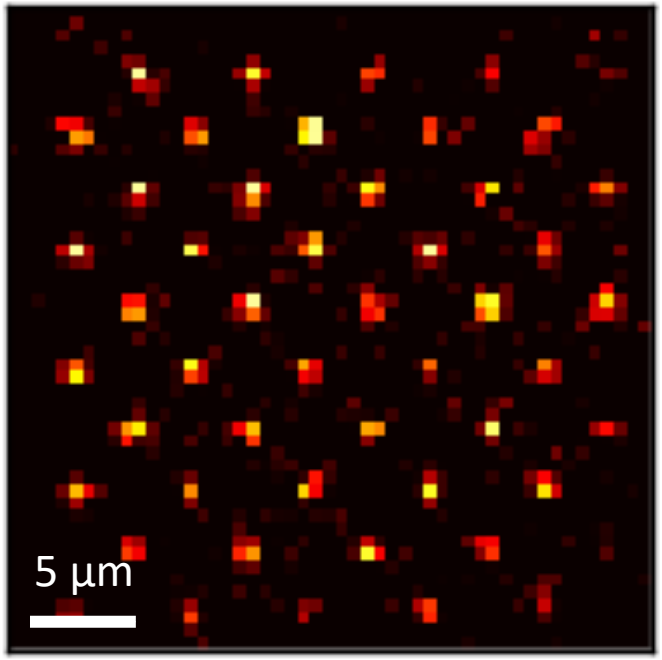


Superconducting qubits

Our platform: arrays of interacting Rydberg atoms

Arrays of atoms (~70 at.)



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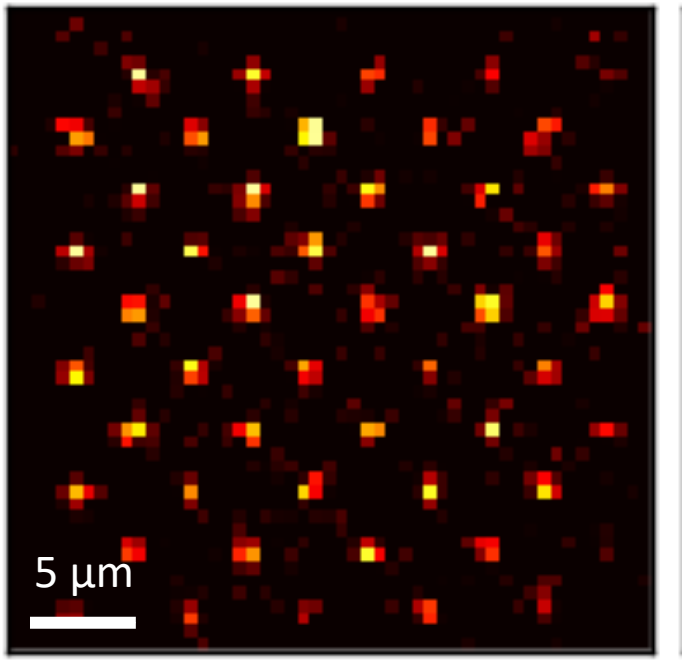

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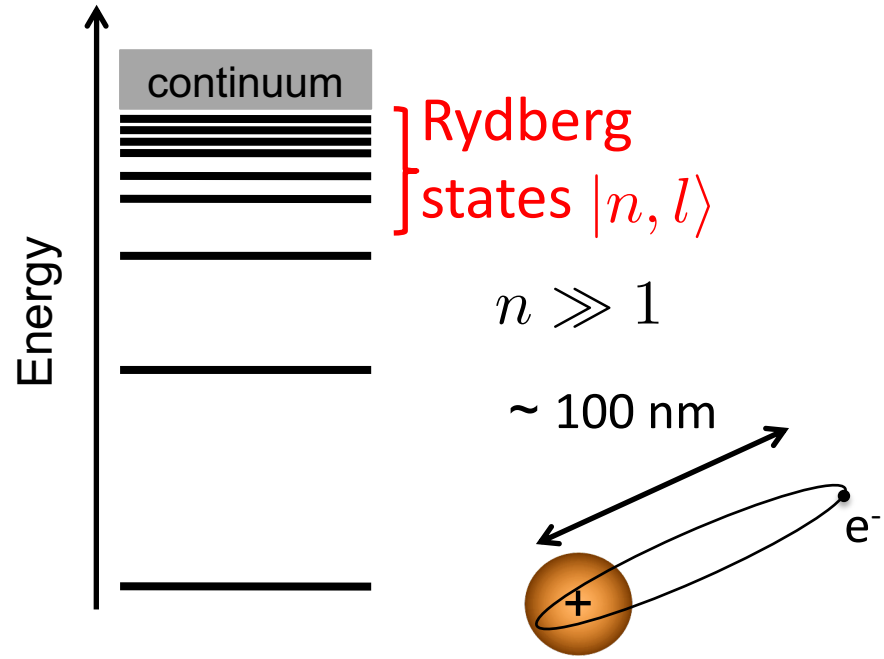
Rydberg atoms



Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, JPhysB 2016

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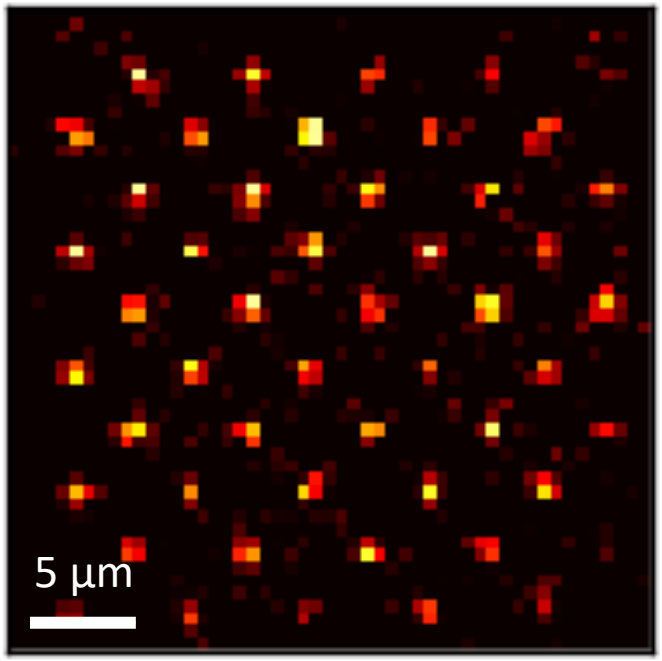

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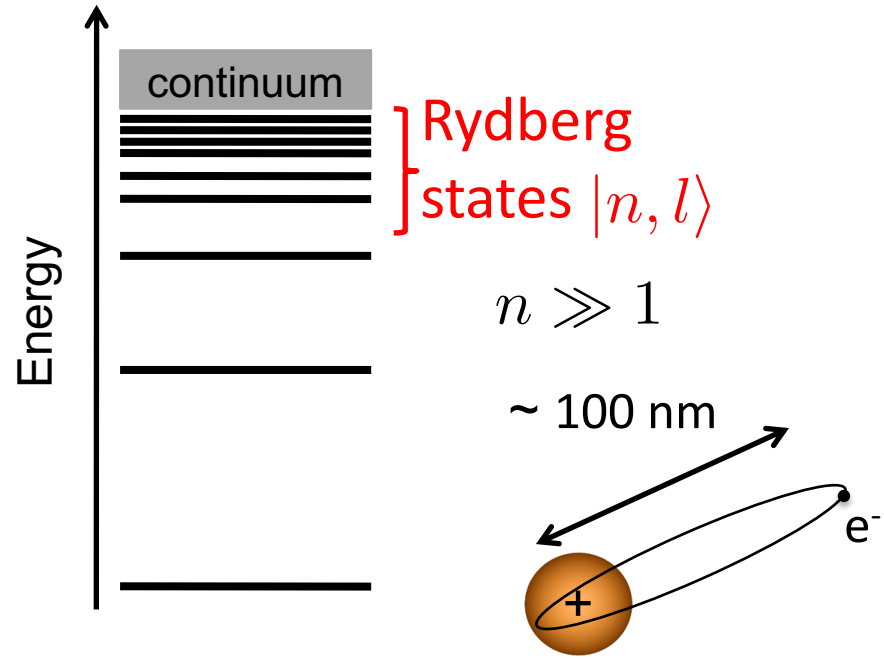

Lifetime > 100 µs

Transition dipole: $d \sim n^2 e a_0$

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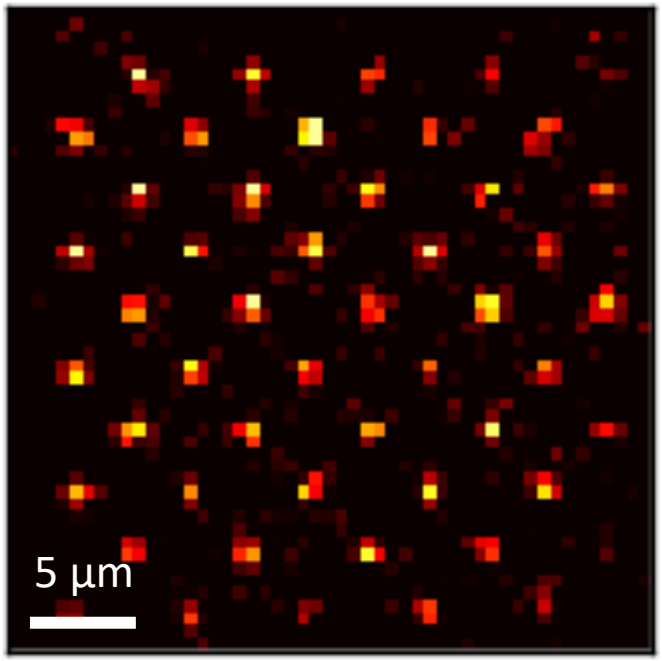

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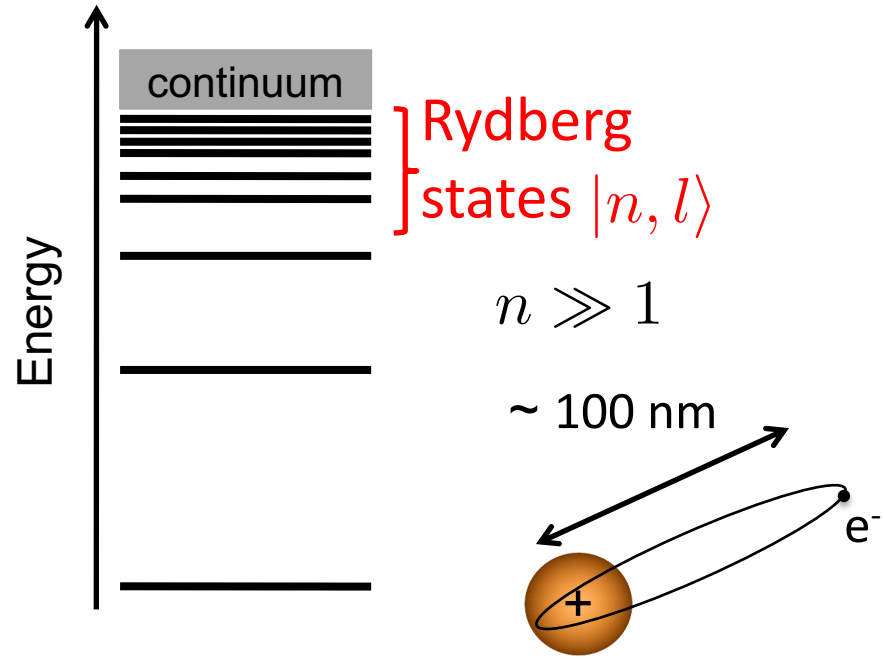

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⇒ Large dipole-dipole interactions

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

⇒ timescales < µsec

Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, JPhysB 2016

Outline

1. Assembled arrays of atoms

2. Magnetism: Ising model with van der Waals interactions

3. Topological matter with resonant dip.-dip. interactions

arXiv:1810.13286

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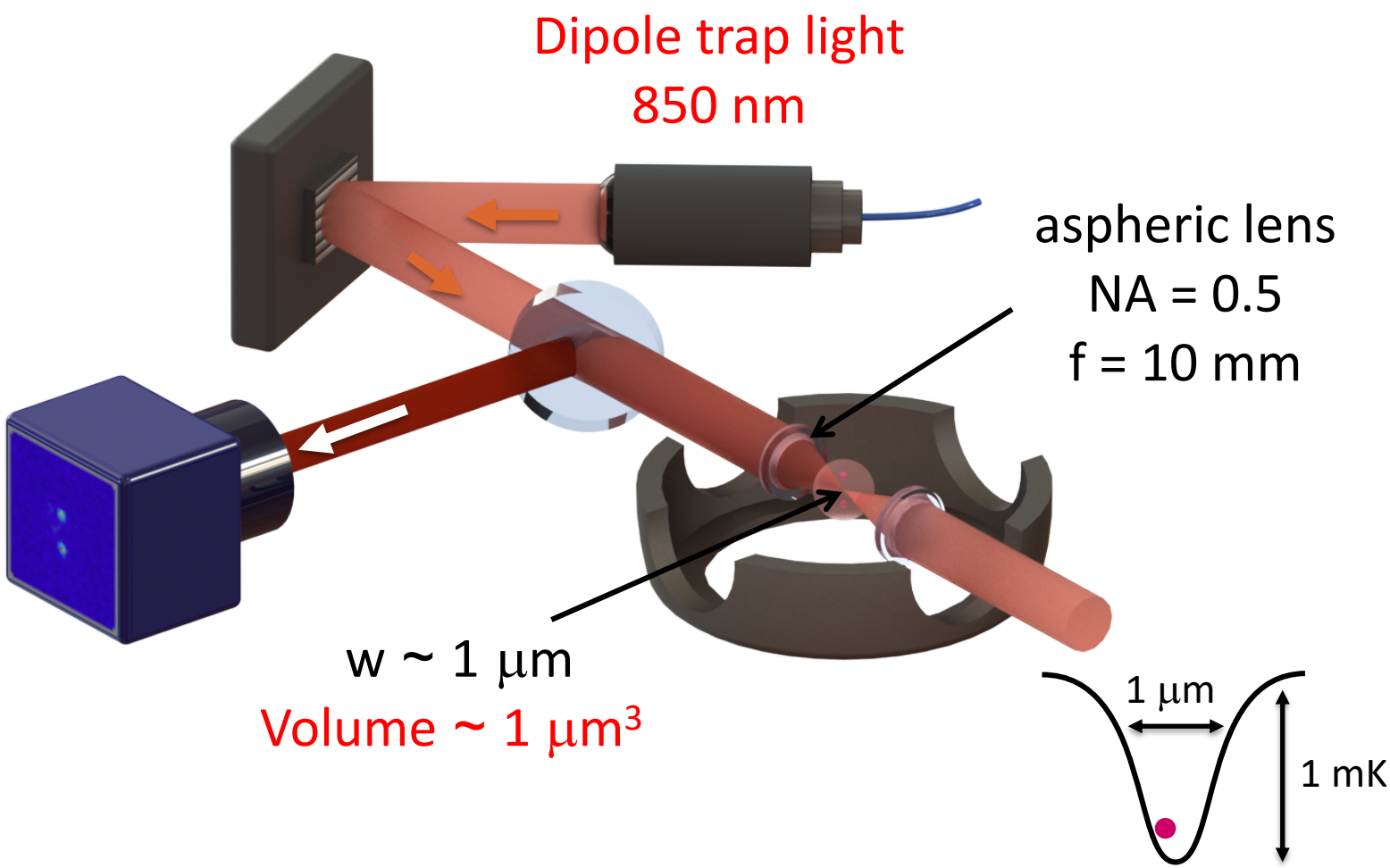
Single atoms in optical tweezers

Schlosser, Nature (2001); Sortais, PRA (2007)



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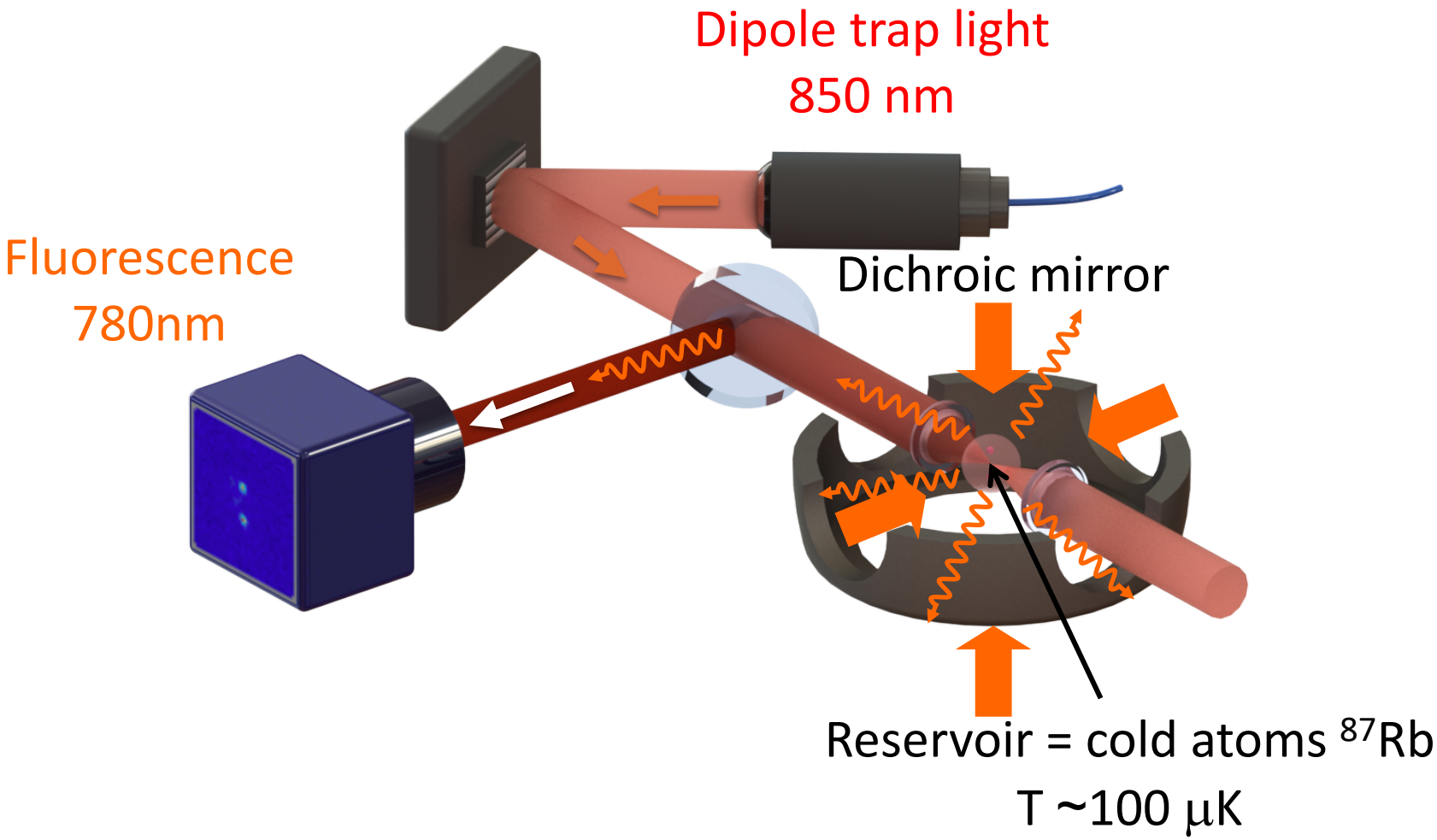

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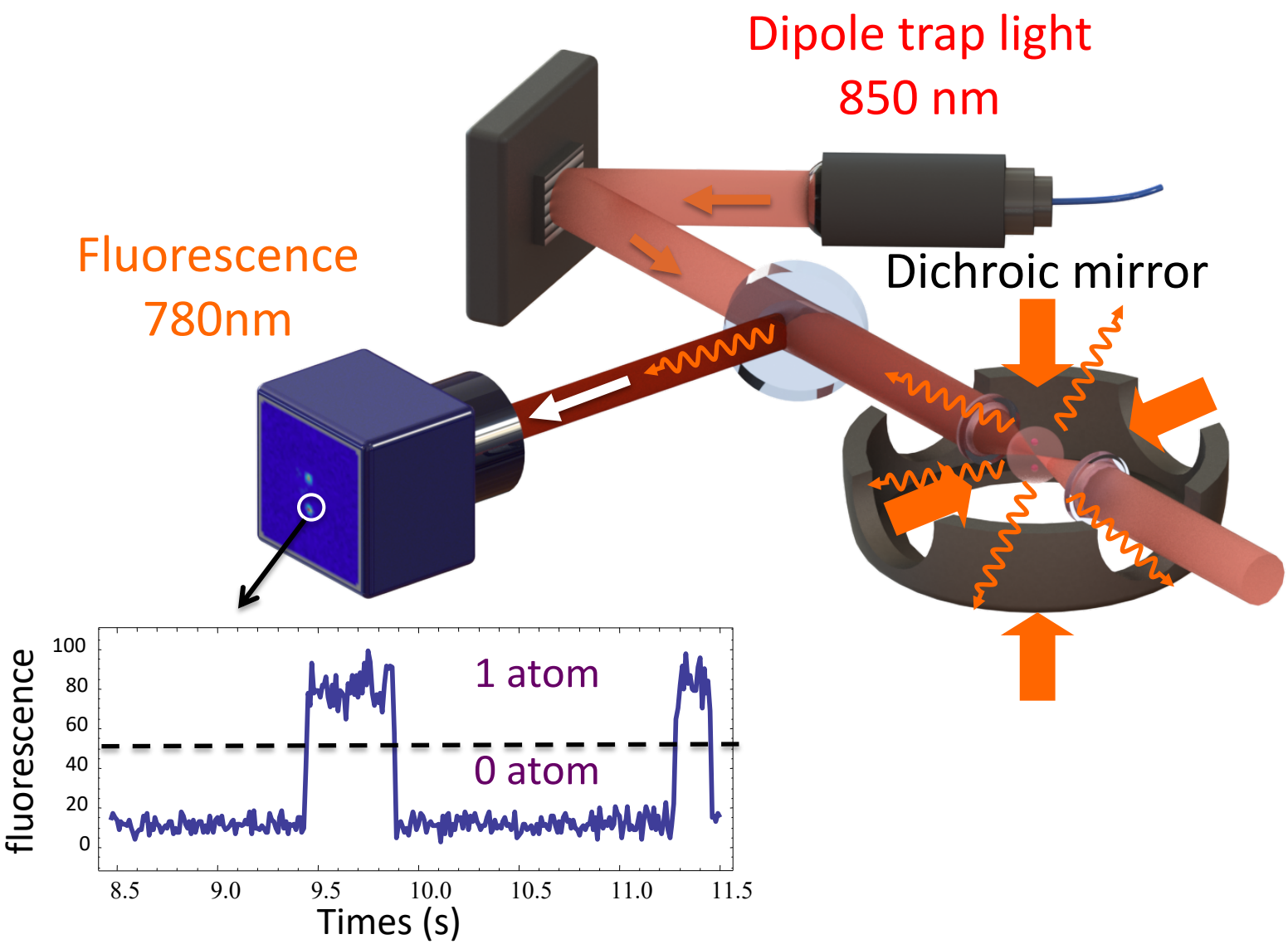

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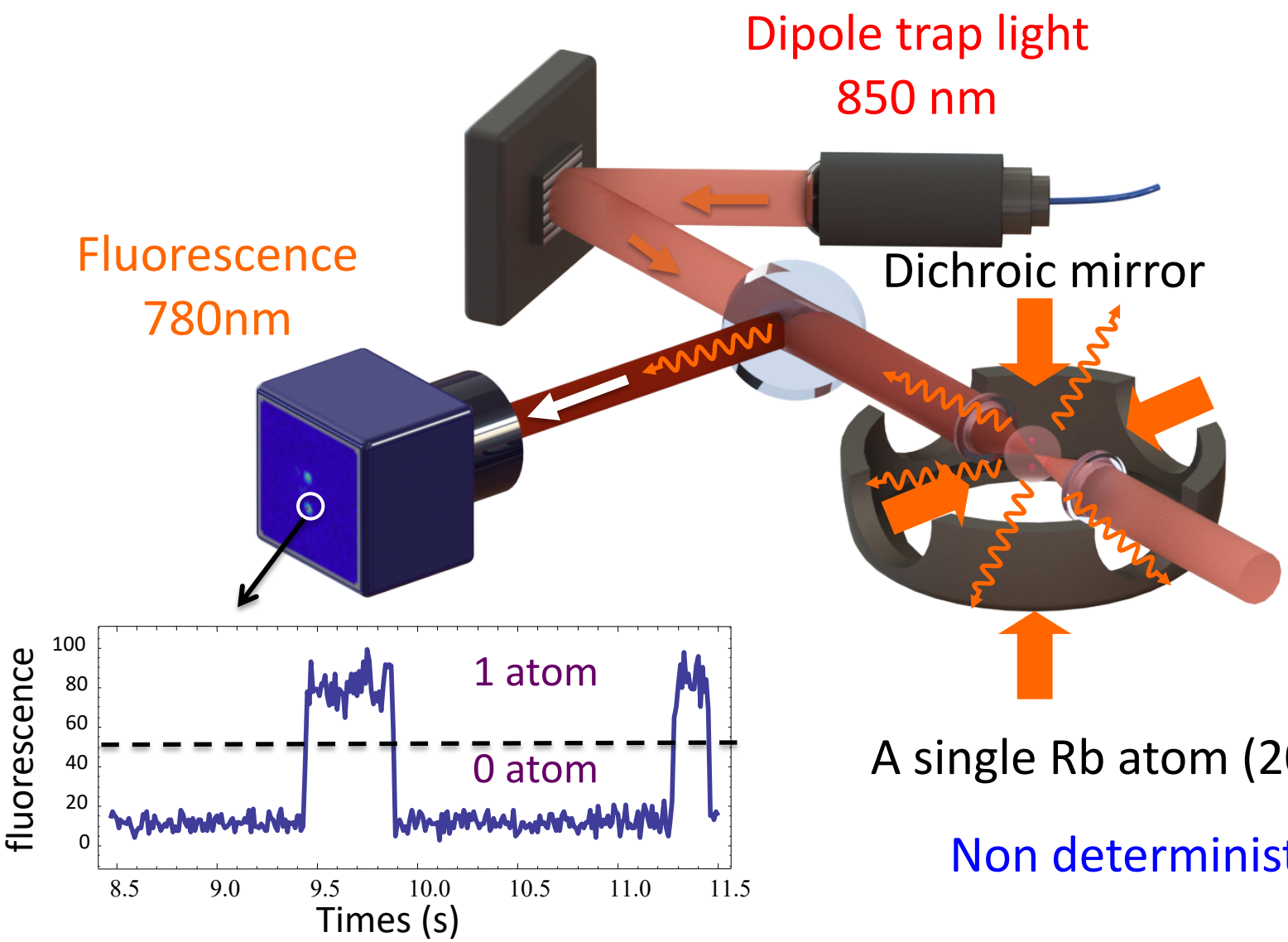
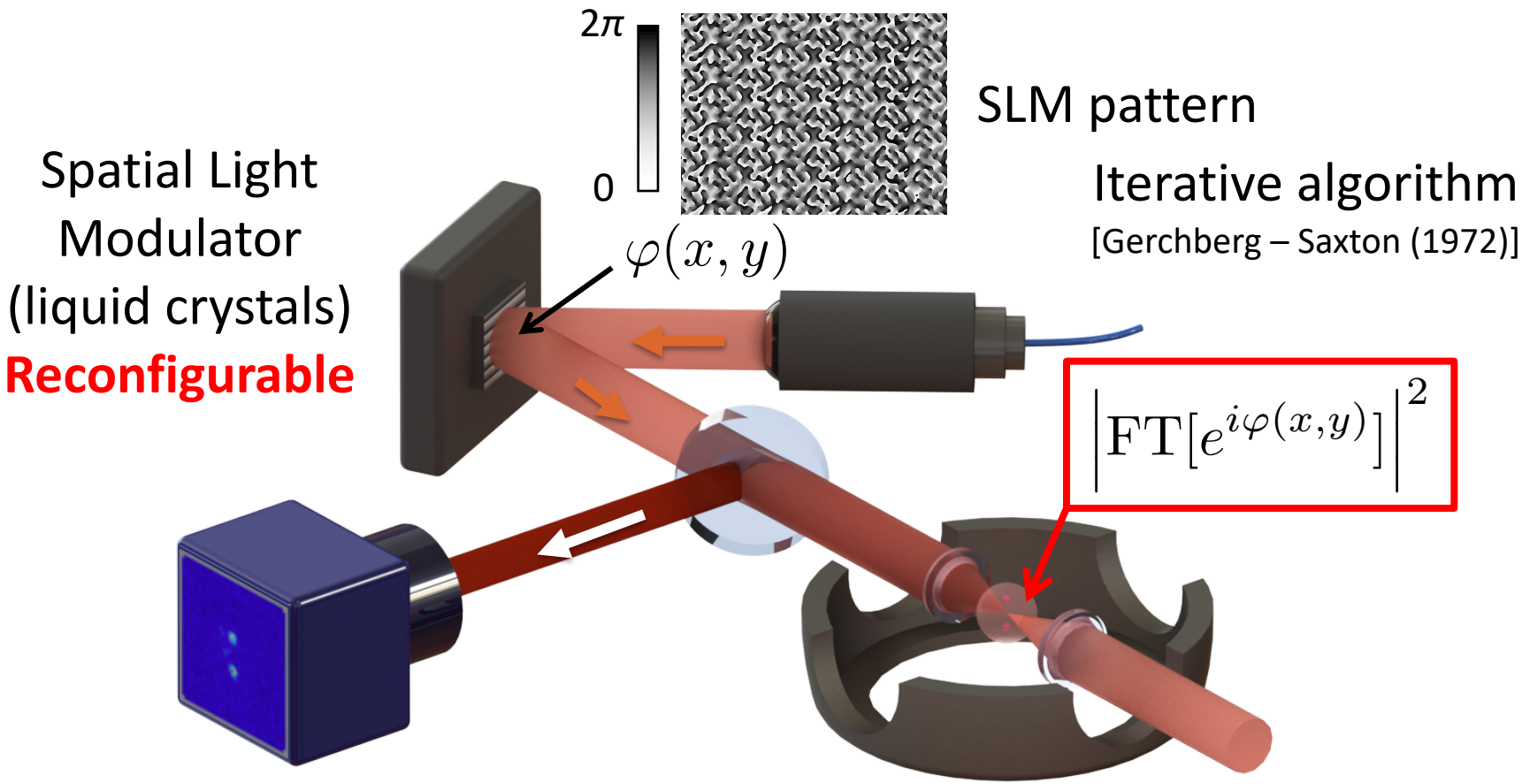


A single Rb atom (20 µK)!

Non deterministic

Holographic 2D arrays of tweezers



Bergamini, JOSA B **21**, 1889 (2004)
Nogrette, PRX **4**, 021034 (2014)

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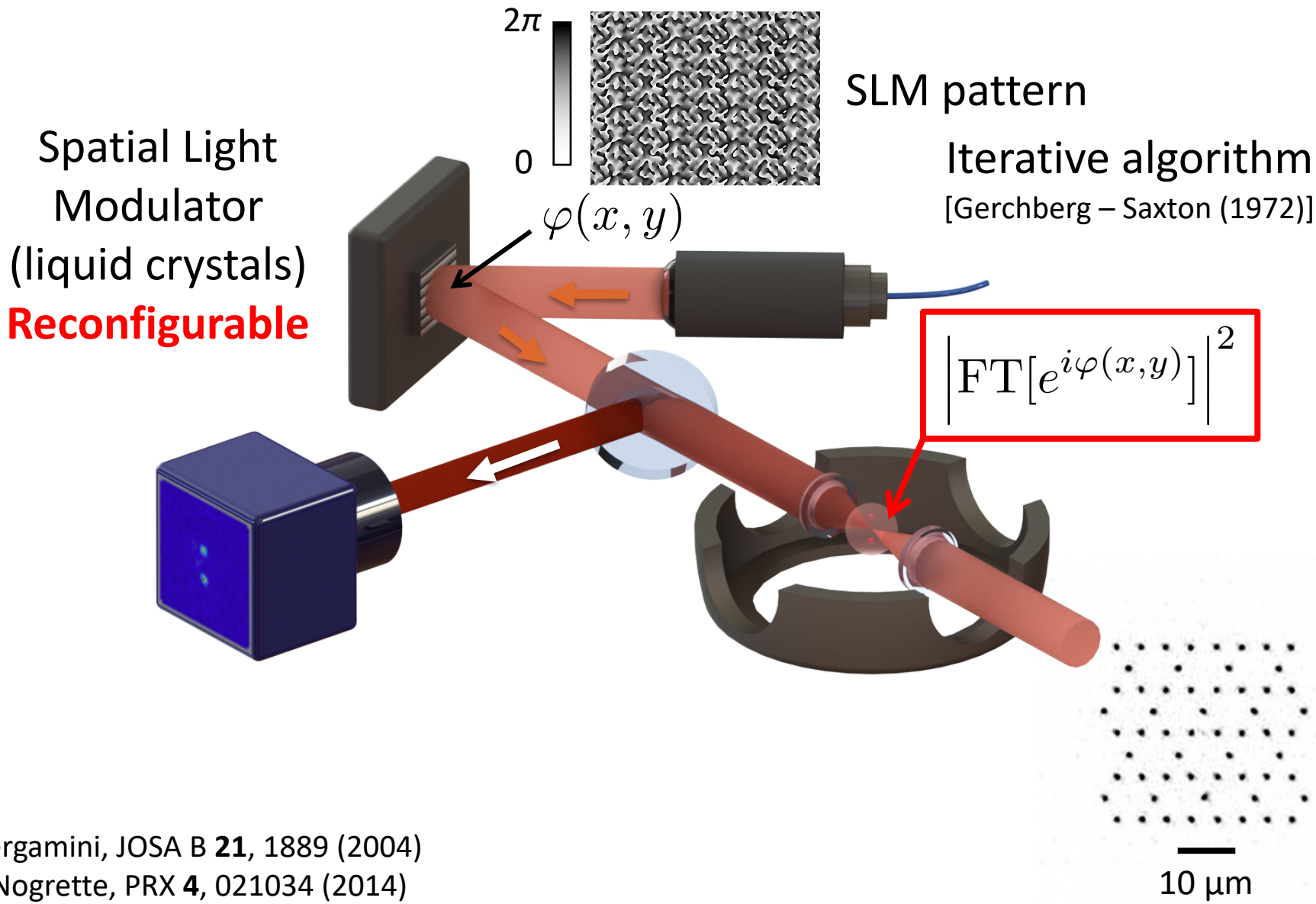

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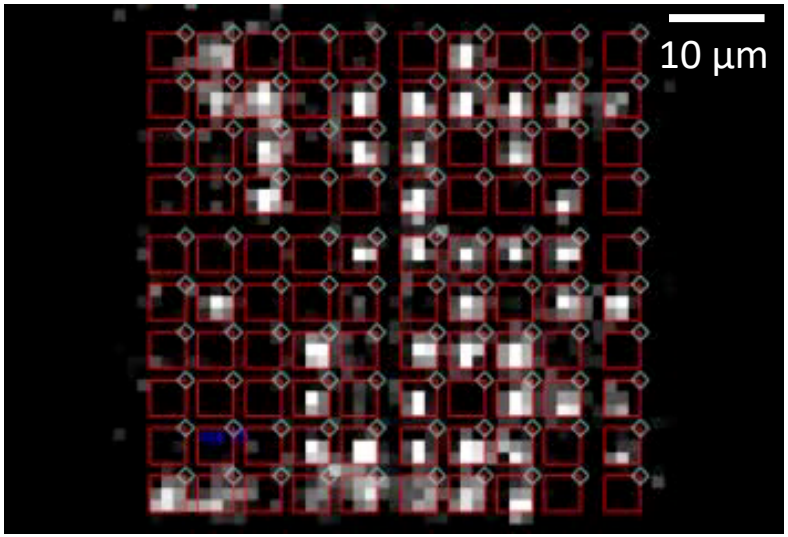
Atom-by-atom assembling of 2D arrays



Problem: stochastic loading ($p \sim 0.5$)

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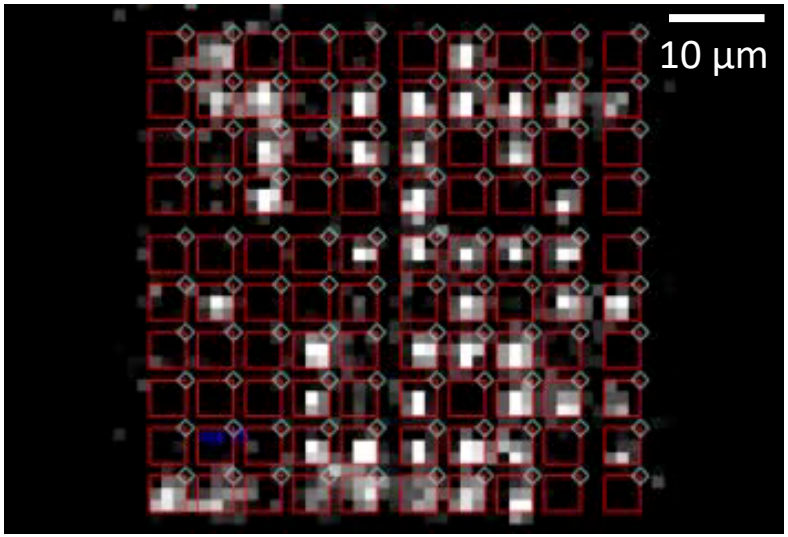

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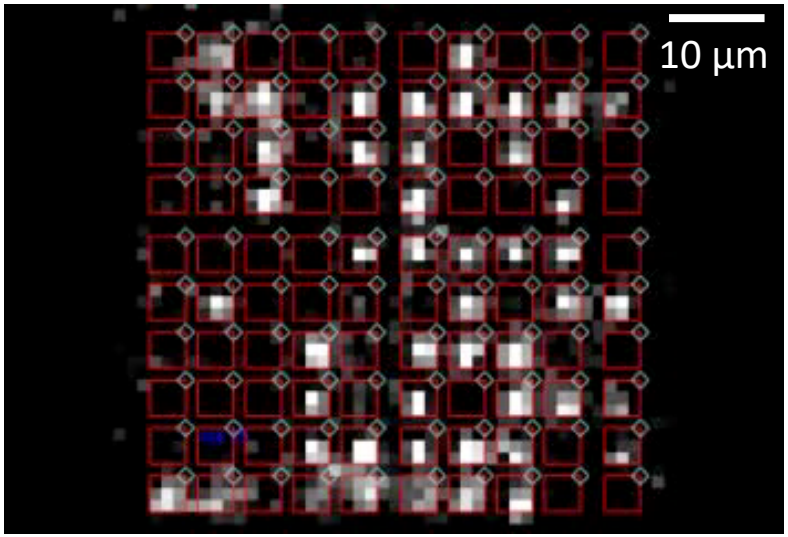

Problem: stochastic loading ($p \sim 0.5$)

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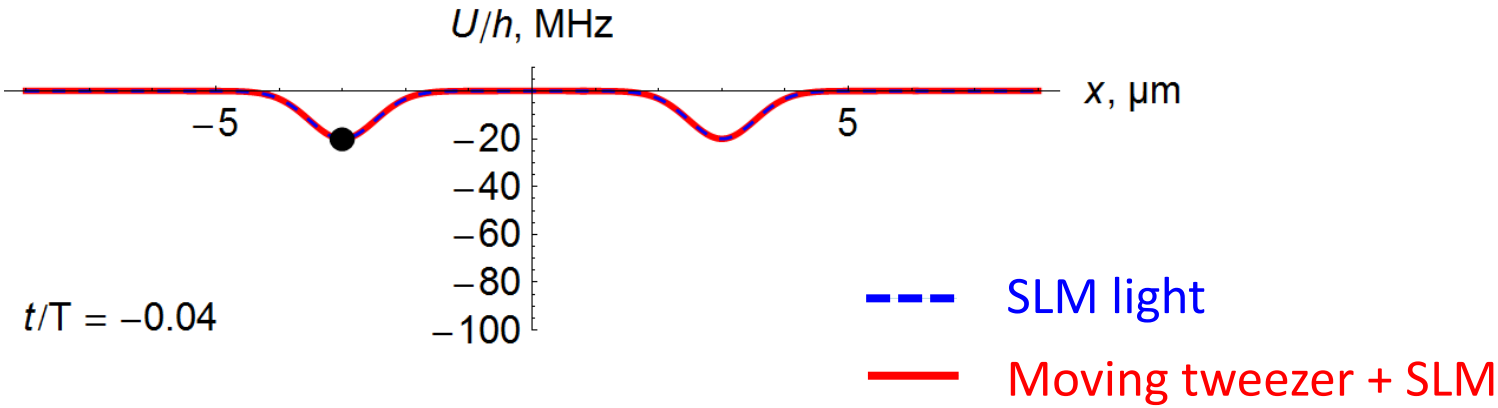
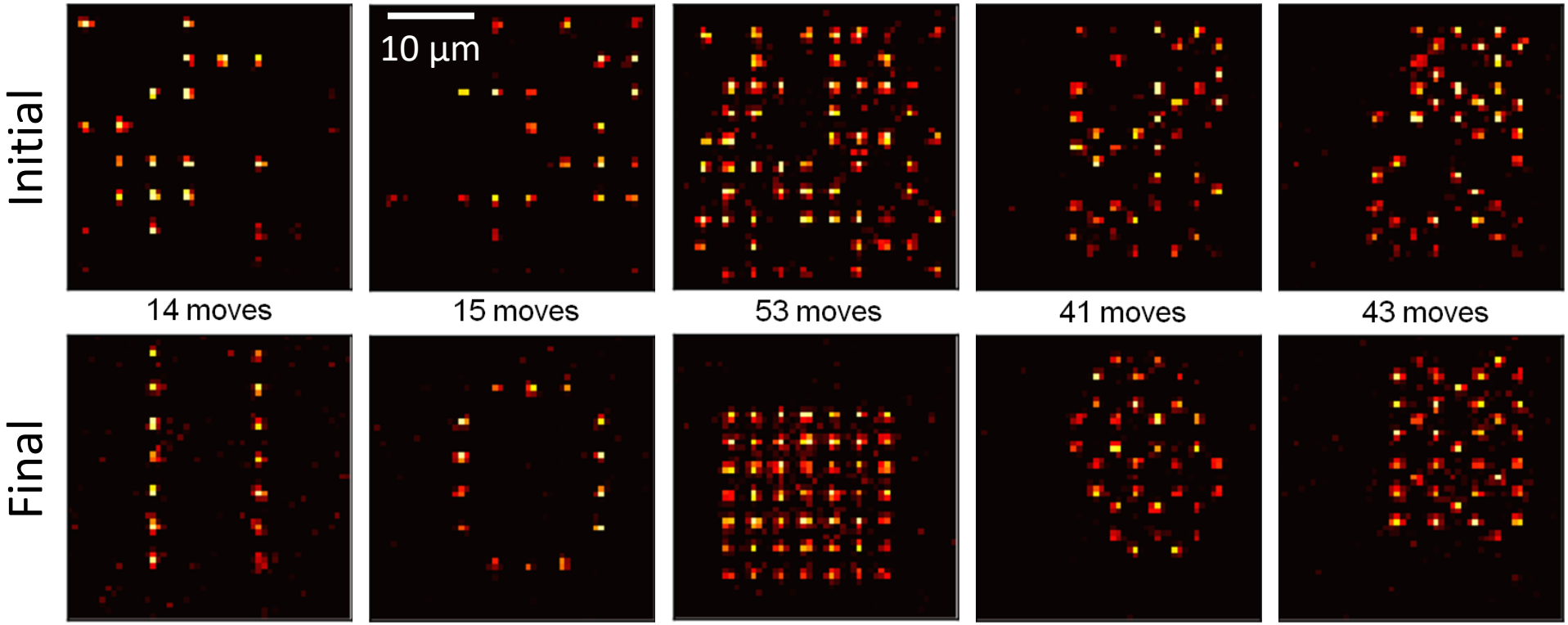
Moving atoms with a tweezers



$p \sim 0.993(1)$

Gallery of assembled 2D arrays… (single-shot images…)



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

Related works Harvard (1D) Science **354**,1024 (2016)
Korea (2D) Nat. Comm. **7**, 13317 (2016)

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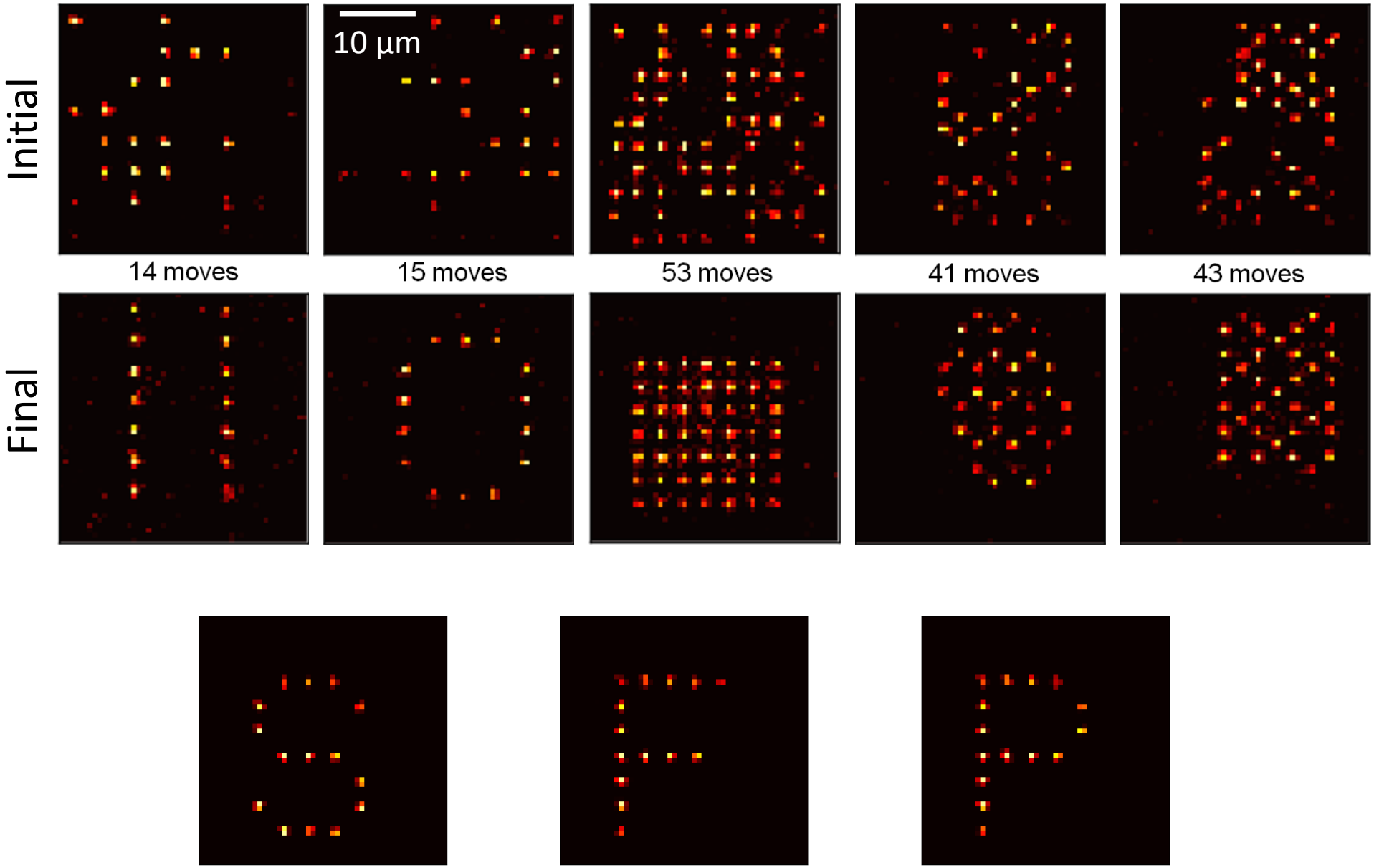

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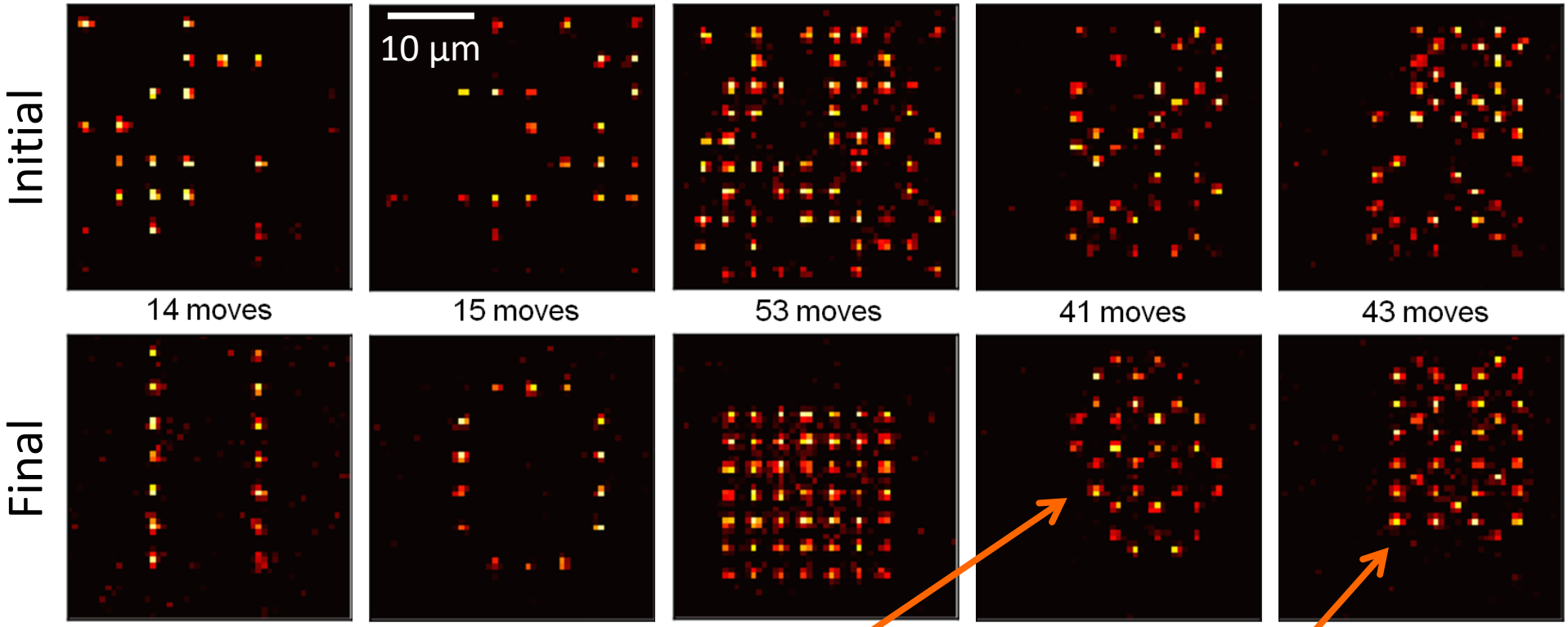
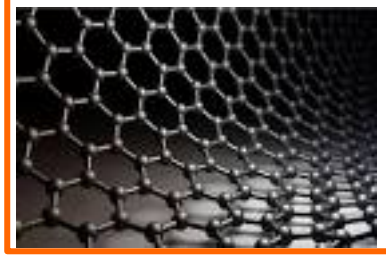


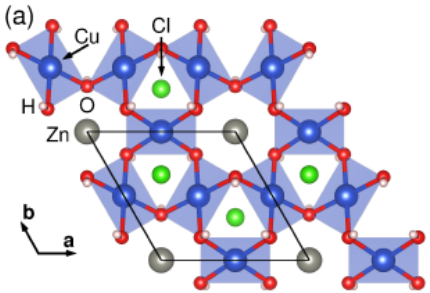
Hexagonal



graphene

Kagome: Herbertsmithite

$ZnCu_3(OH)_6Cl_2$

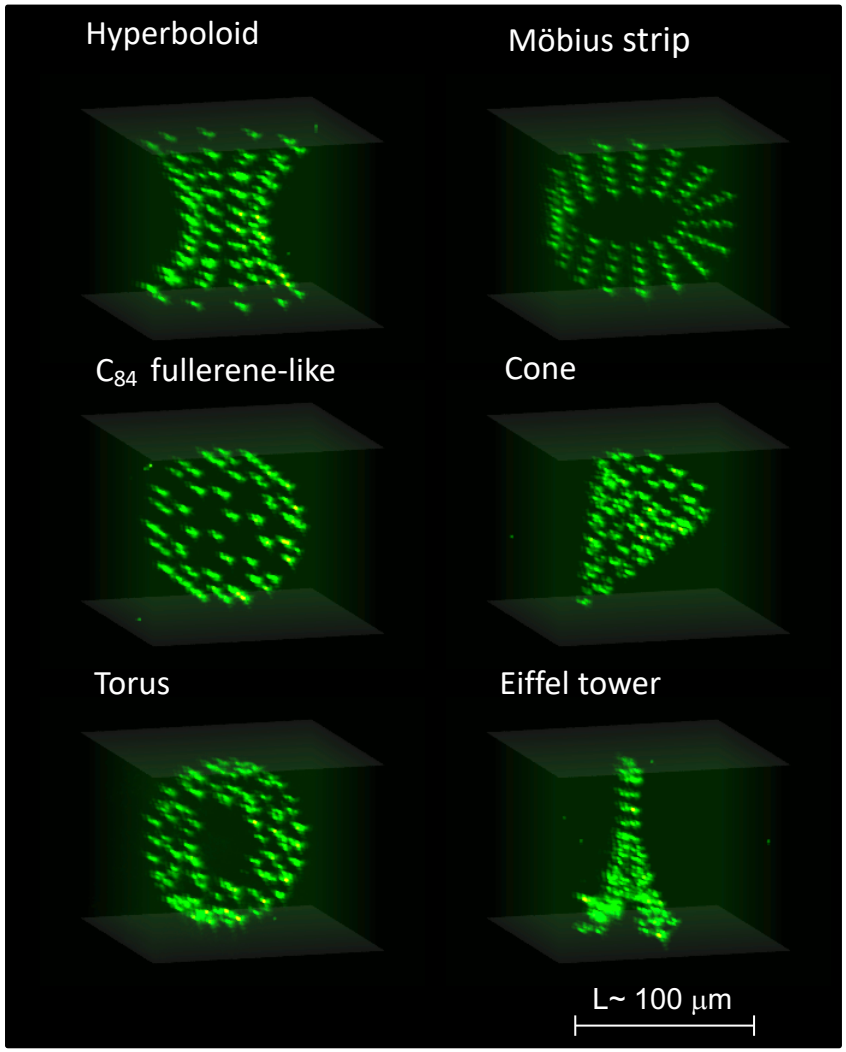


It also works in 3d!

Di Leonardo, Optics Express **15**, 1913 (2007)

Averaged fluorescence

imaged "slice-by-slice"



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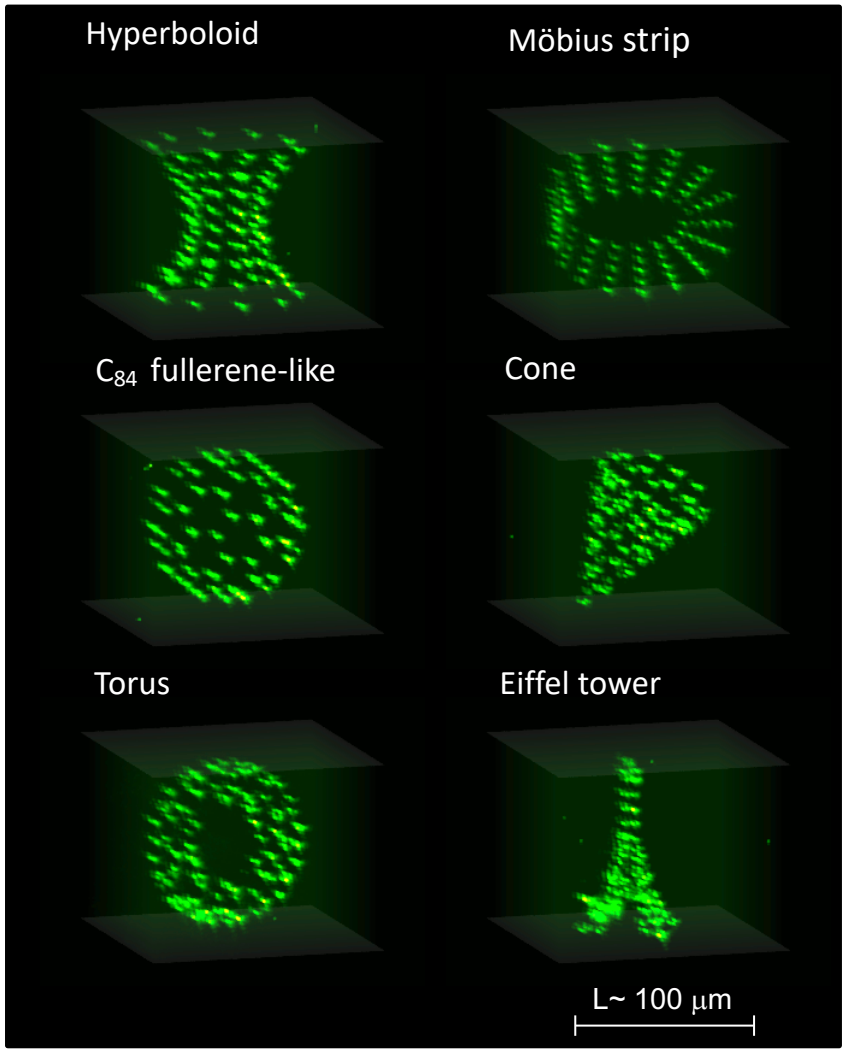
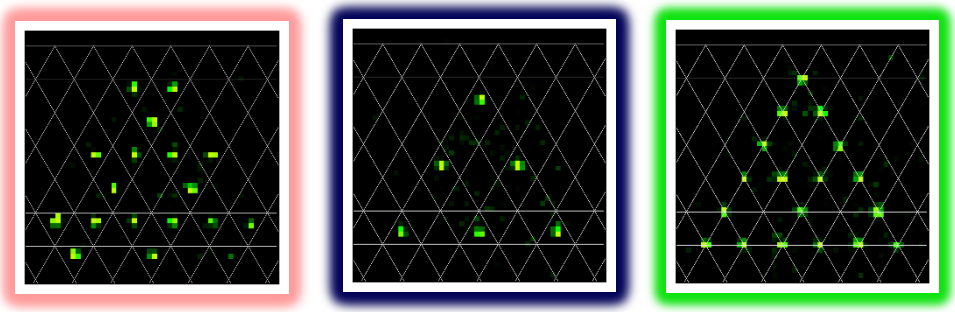


Assembled Pyrochlore lattice

Plane 1 Plane 2 Plane 3



Front view Side view

Barredo, Nature (2018)

Also: Weiss, Nature (2018); Ahn, Opt. Exp (2016)

Outline

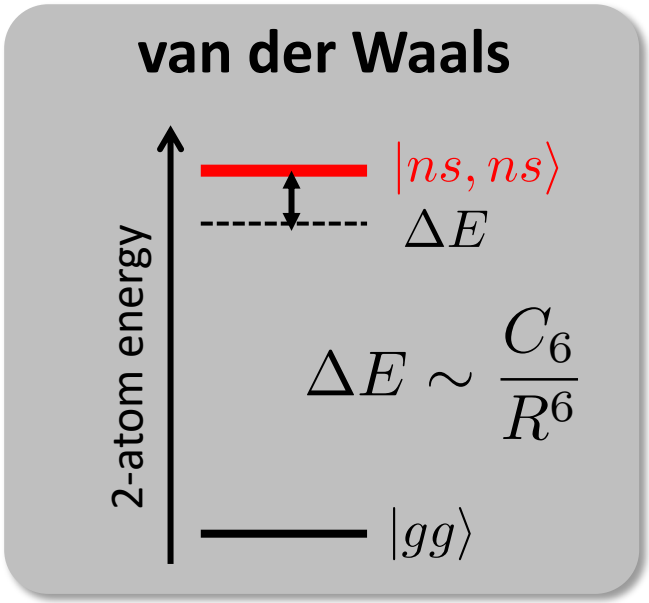
1. Assembled arrays of atoms

2. Magnetism: Ising model with van der Waals interactions

3. Topological matter with resonant dip.-dip. interactions

arXiv:1810.13286

From van der Waals interactions to Ising model…



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

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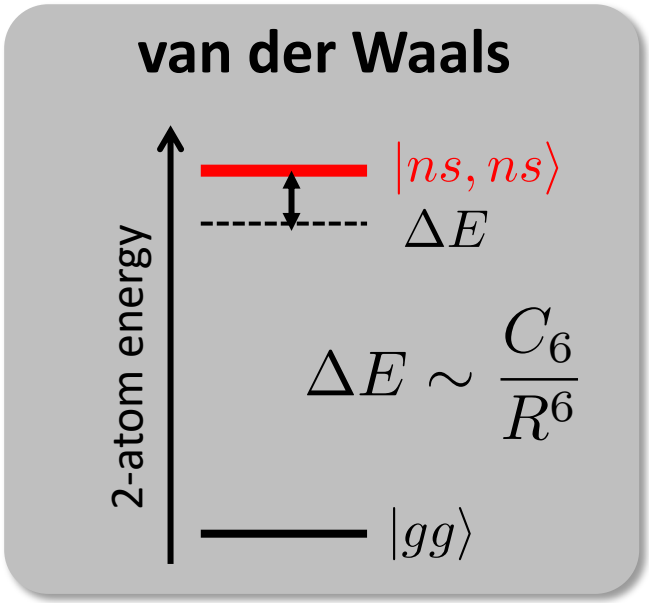

$C_6 \propto n^{11}$ $\Rightarrow$ switchable interaction

$$\hat{H}_{\text{int}} = \frac{C_6}{R^6}\hat{n}_1\hat{n}_2$$

Rydberg occupation number

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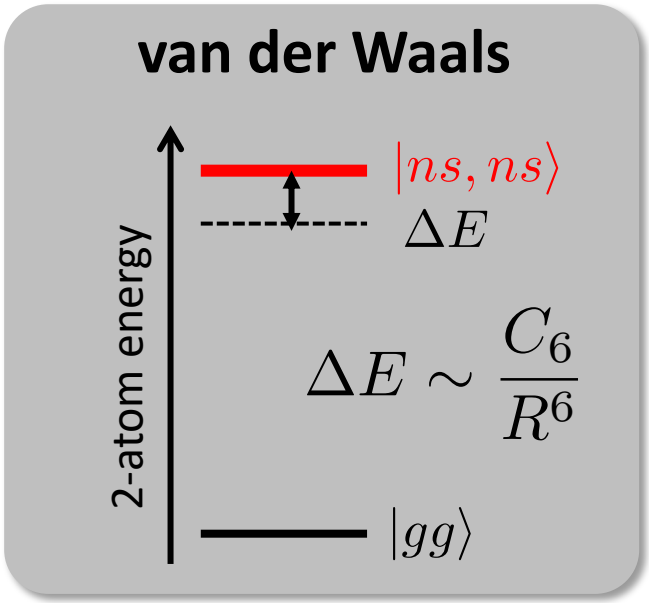

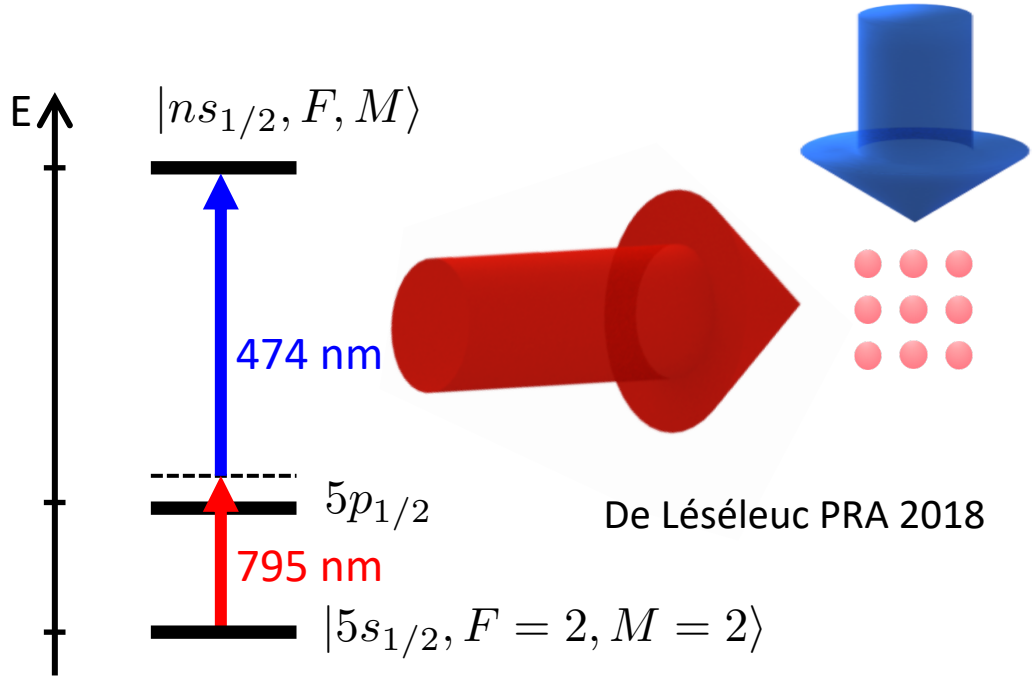

De Léséleuc PRA 2018

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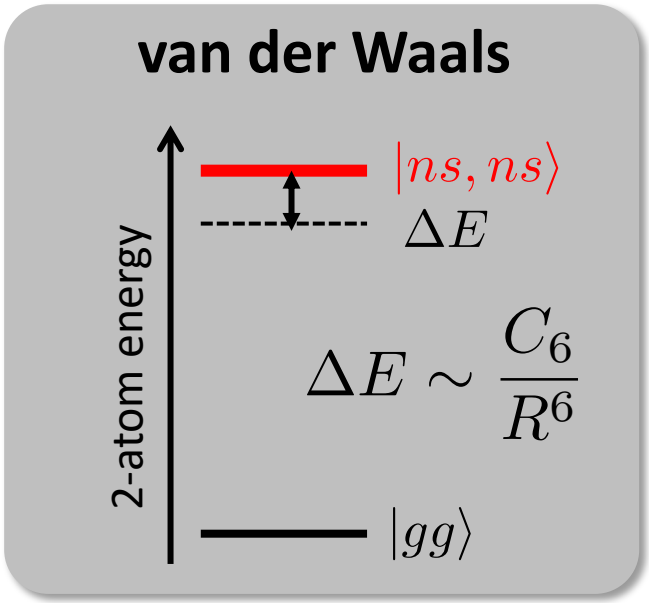

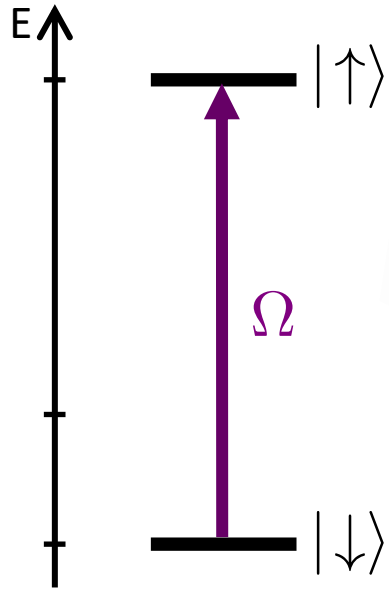

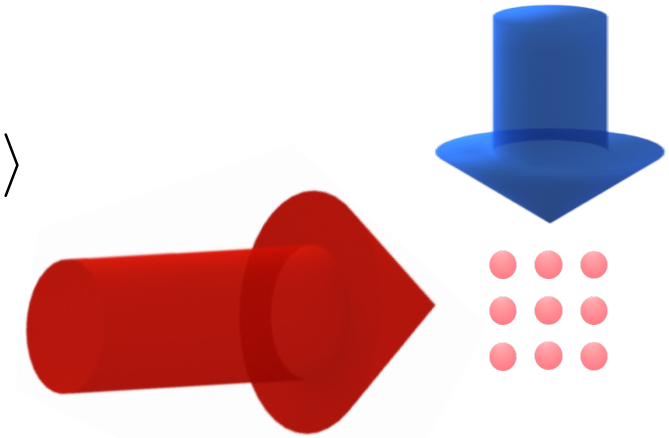

De Léséleuc PRA 2018

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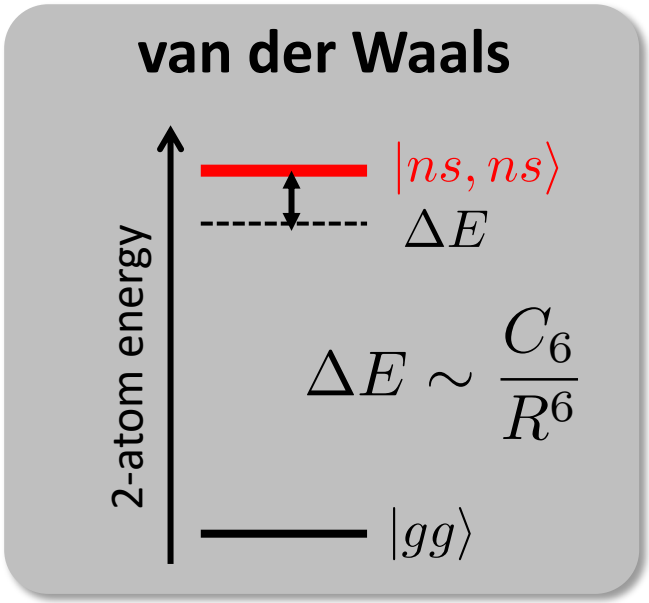

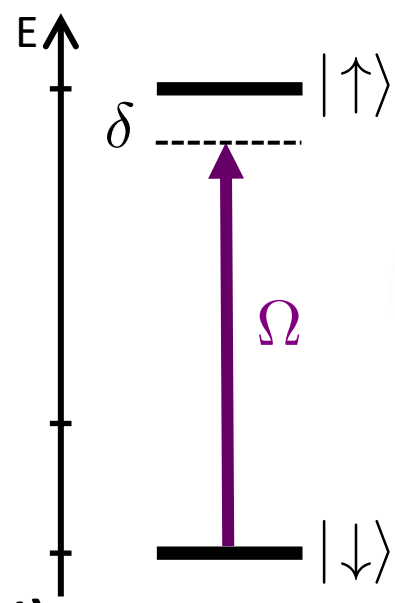

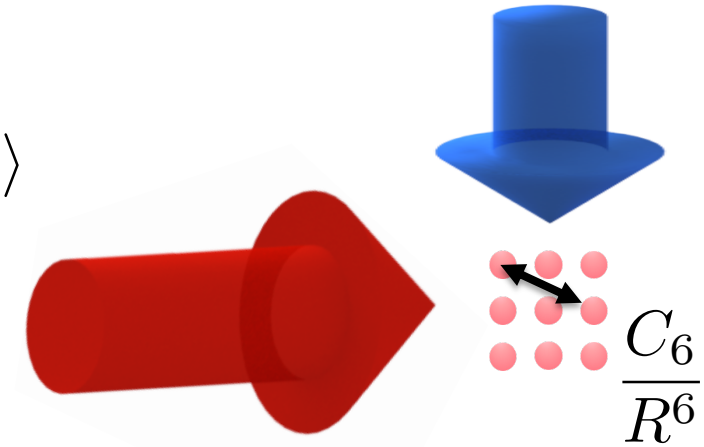

De Léséleuc PRA 2018

Quantum Ising-like model (s=½):

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

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

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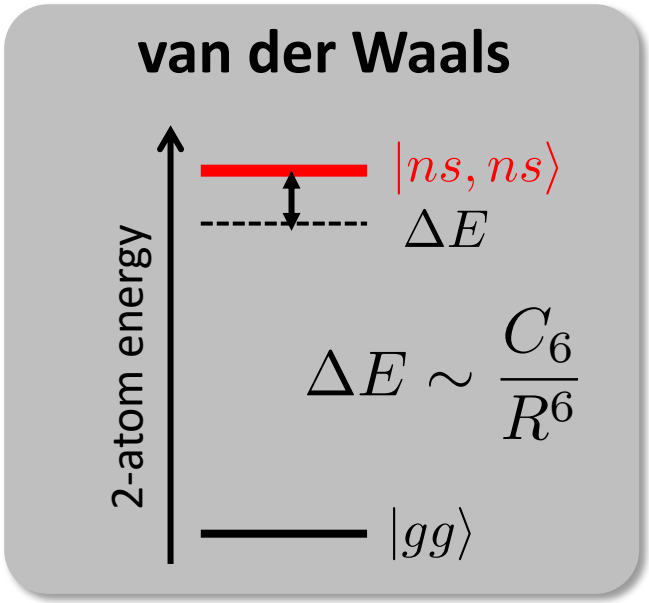

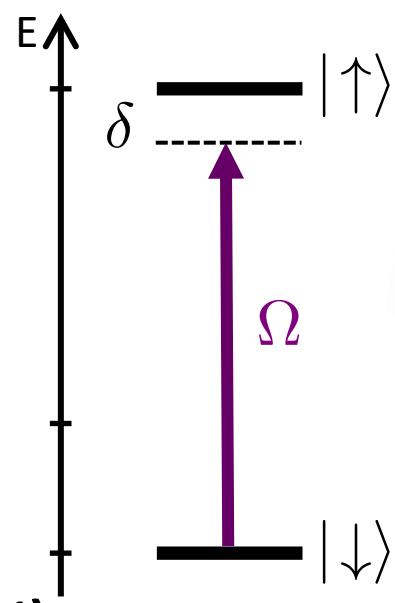

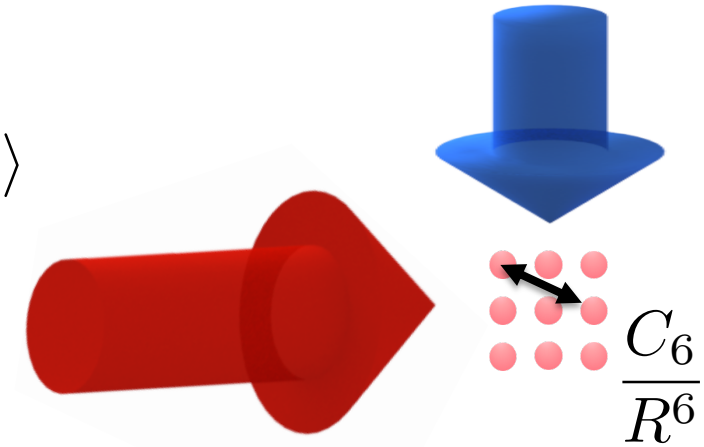

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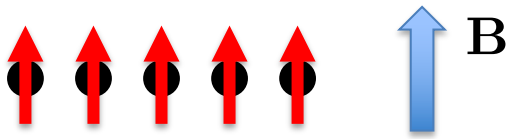
Experimt^t.

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

Quench in Ising-like Hamiltonian



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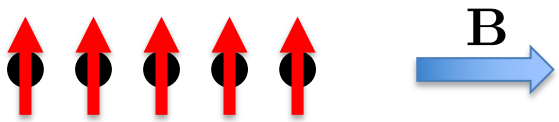

$\Rightarrow ??$

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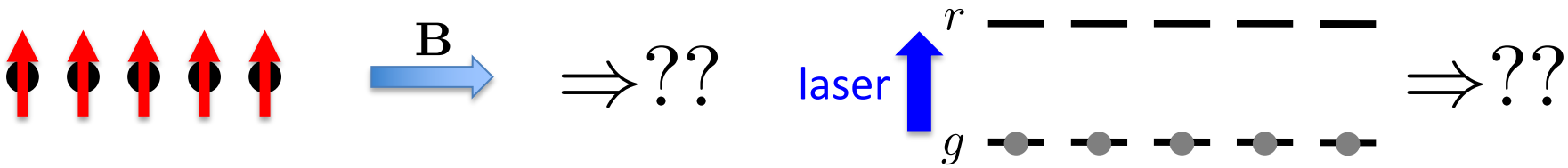

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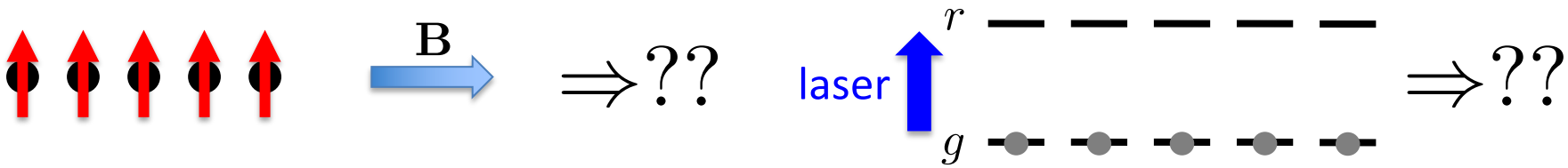
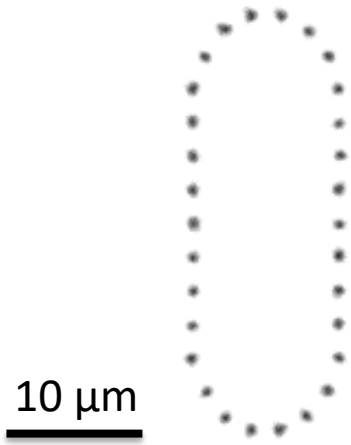


Calculable (*N*<40) ⇒ test

20 at.



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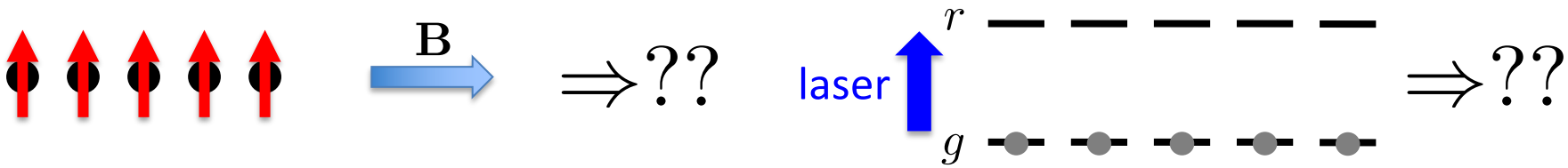

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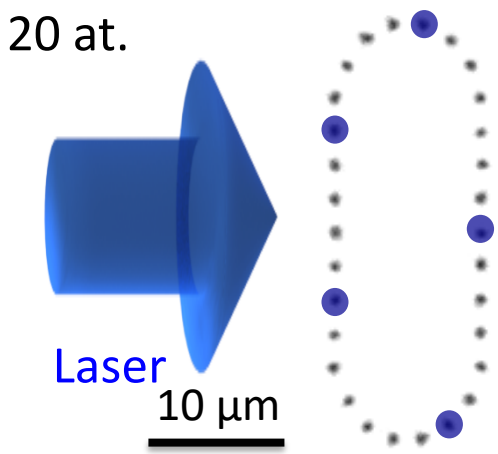

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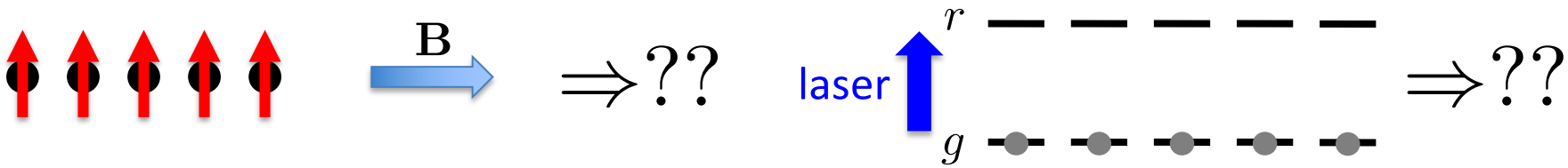

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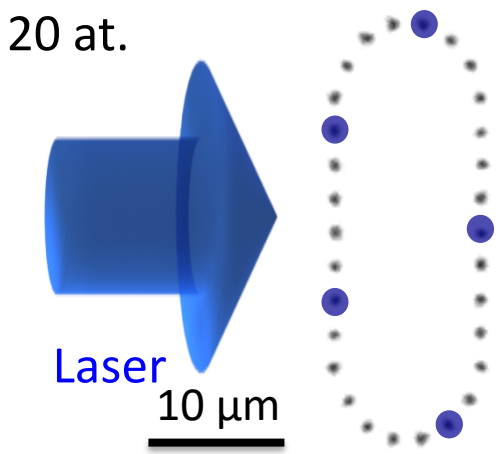
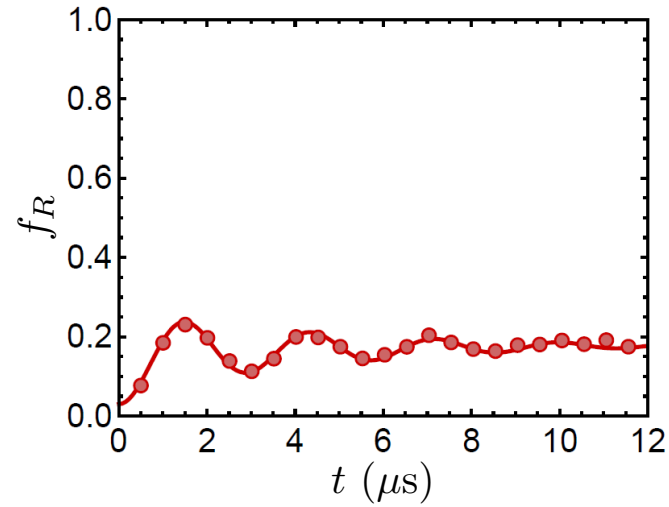


"Magnetization"

$$f_{\mathrm{r}} = \frac{\langle N_{\mathrm{r}} \rangle}{N}$$



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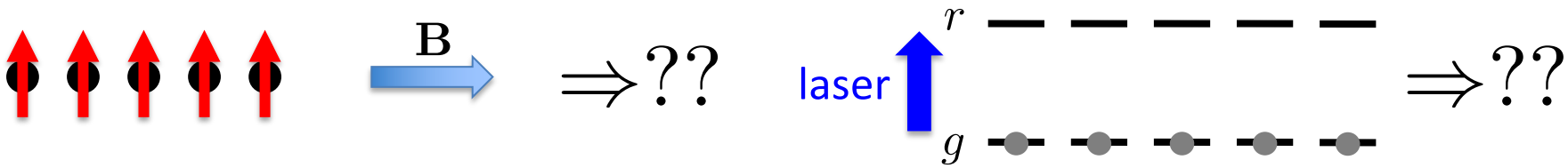

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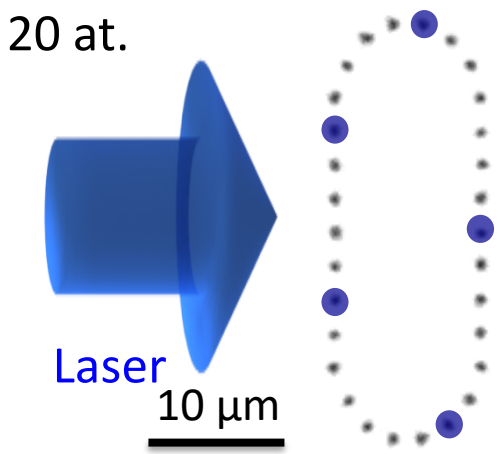

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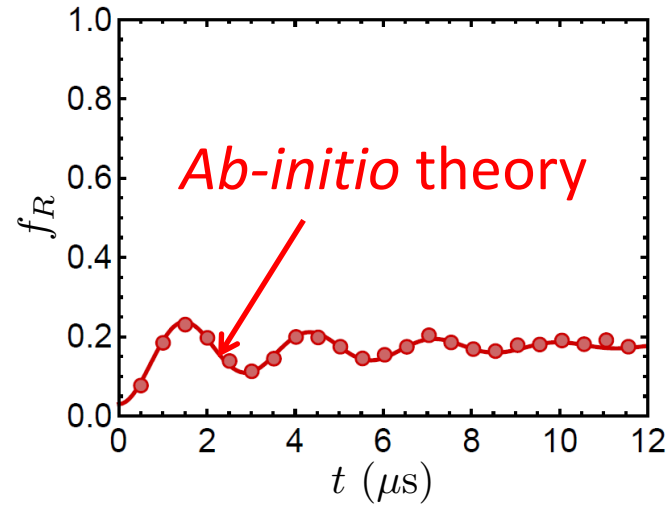

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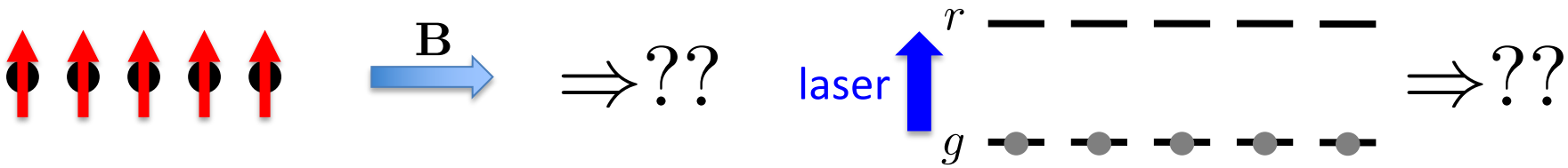

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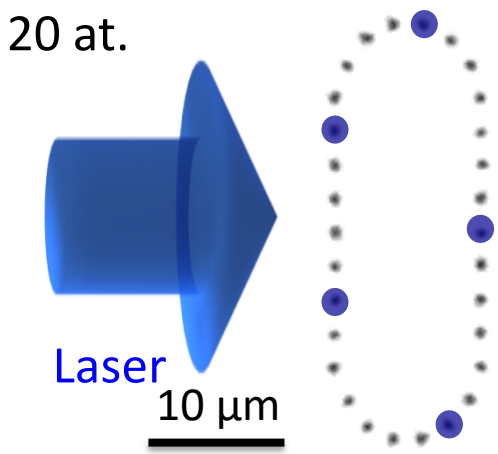

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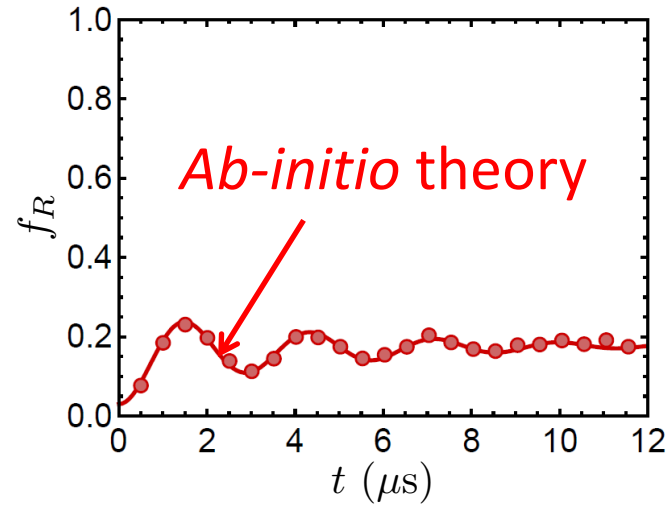
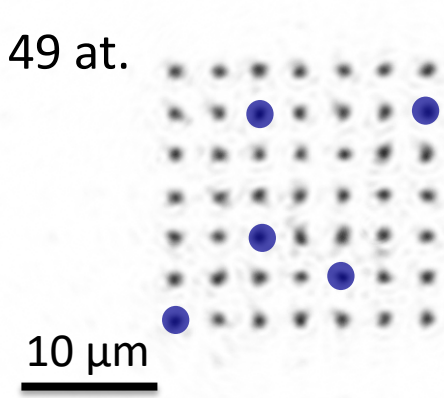
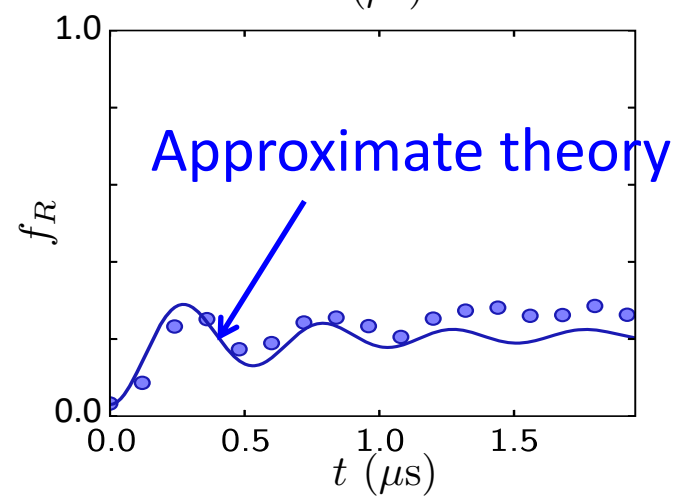


Non-calculable (N>40)





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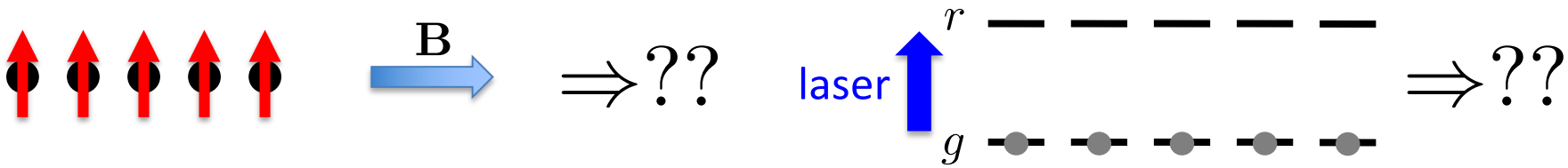

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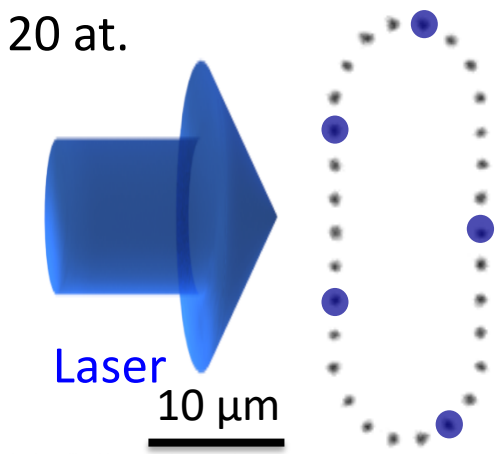

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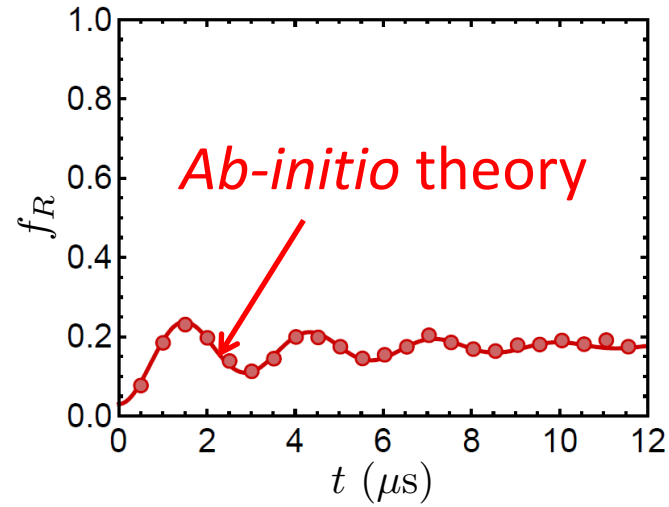

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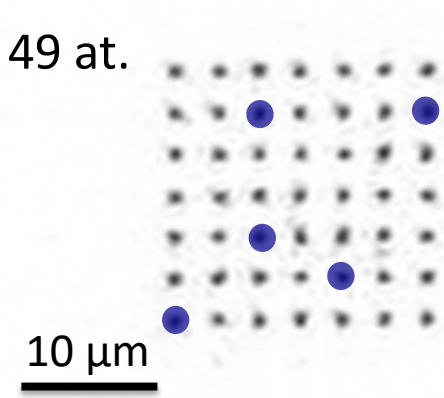
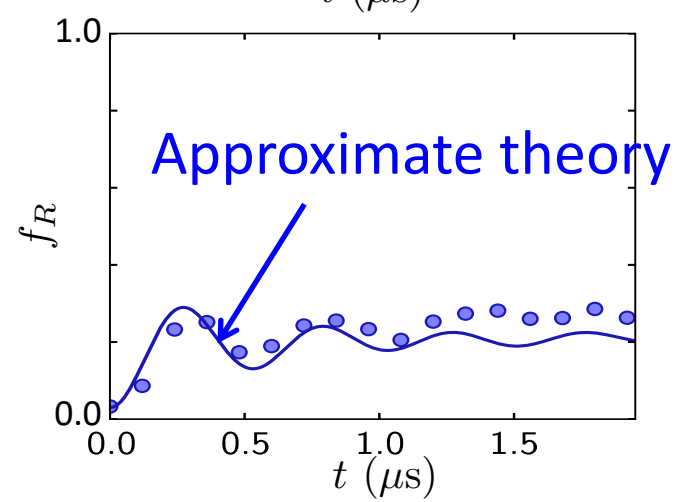
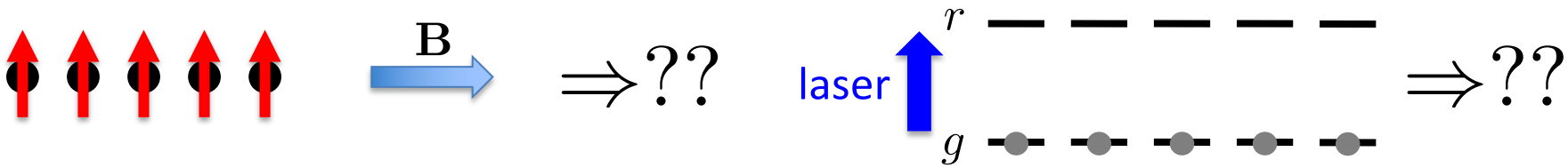


Comparison exp / theo

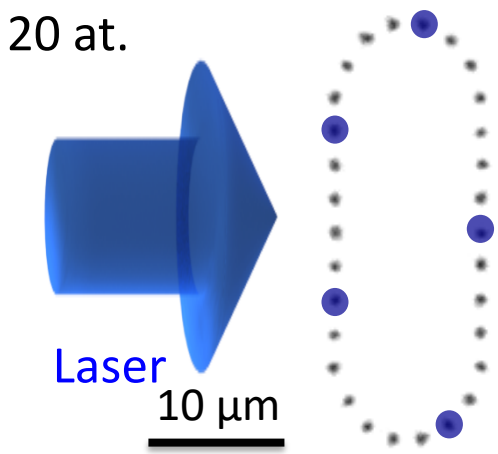
Validate hypothesis theo & experiments



Quench in Ising-like Hamiltonian

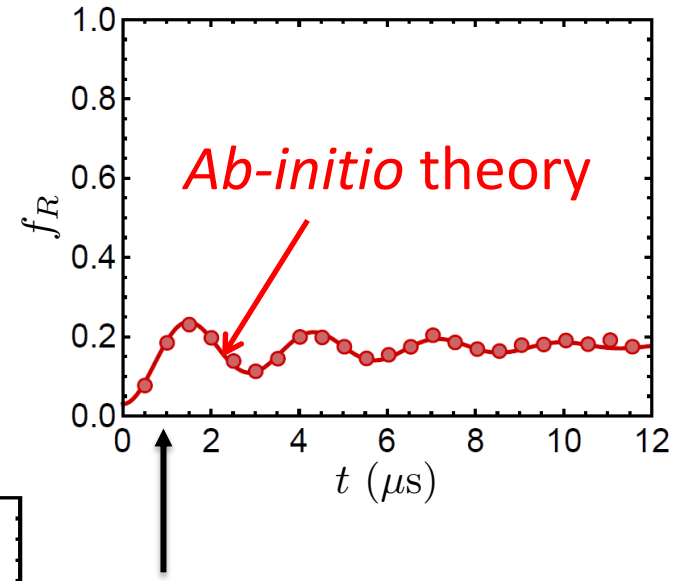


Calculable (*N*<40) ⇒ test



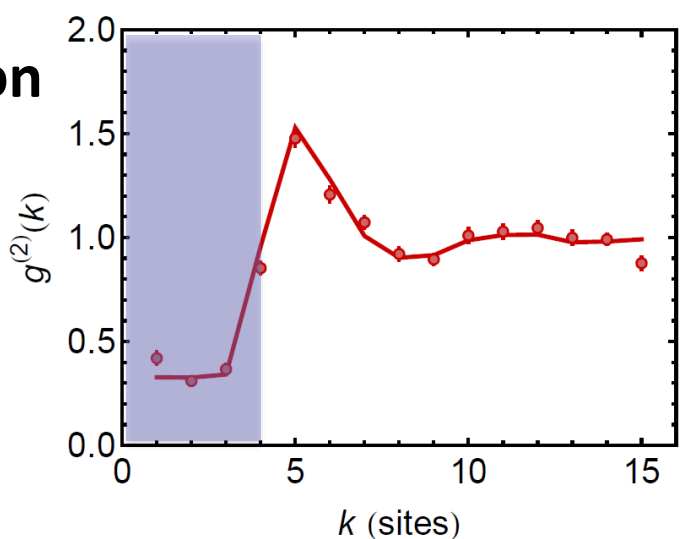
"Magnetization"

$$f_{\mathrm{r}} = \frac{\langle N_{\mathrm{r}} \rangle}{N}$$



Spin-spin correlation

$$\sim \langle n_j n_{j+k} \rangle$$



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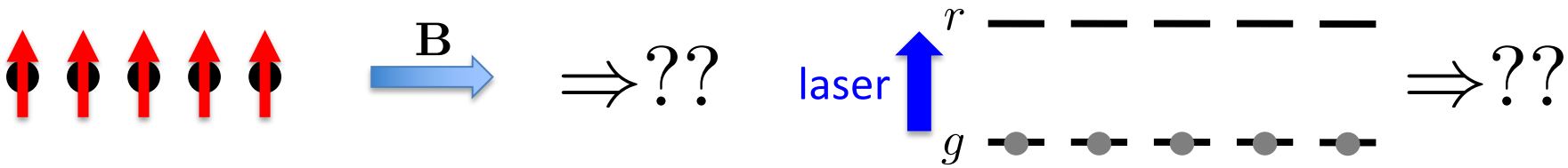

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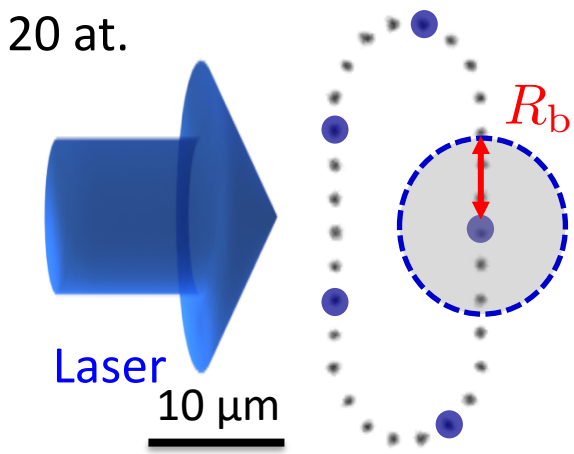

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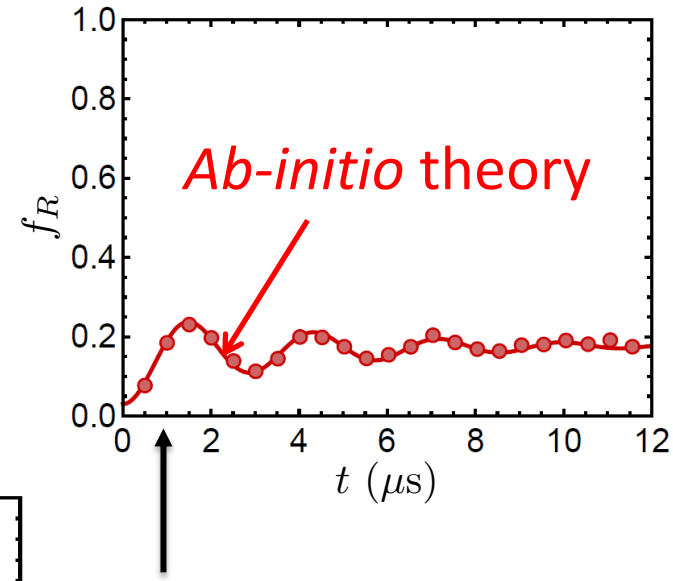

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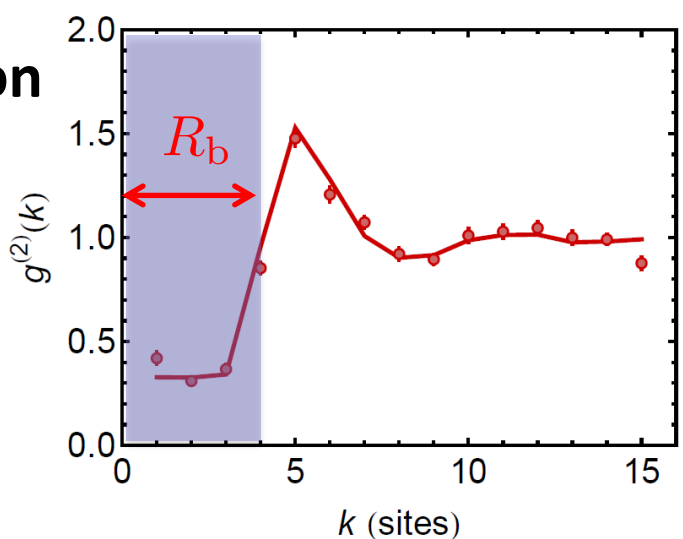
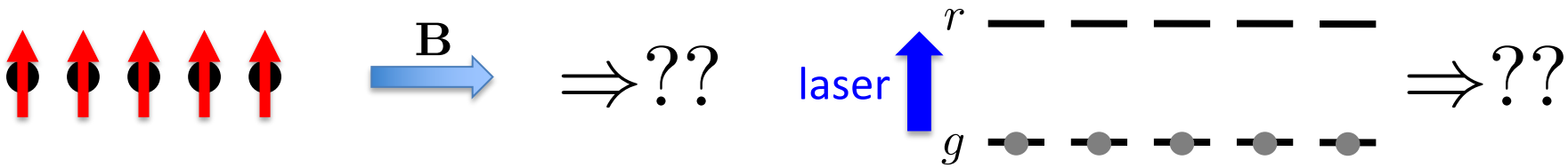


1 Rydberg atom
= hard sphere R_b

Quench in Ising-like Hamiltonian



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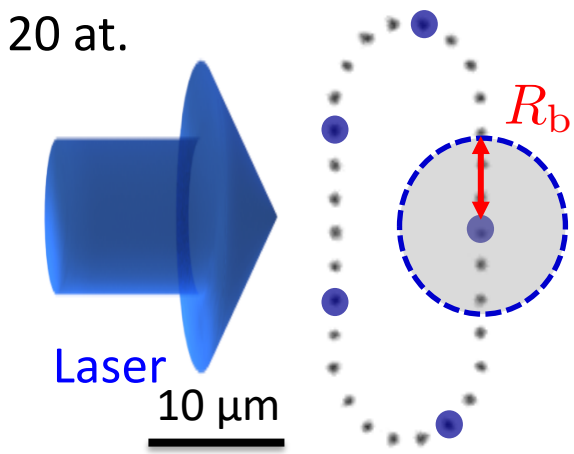

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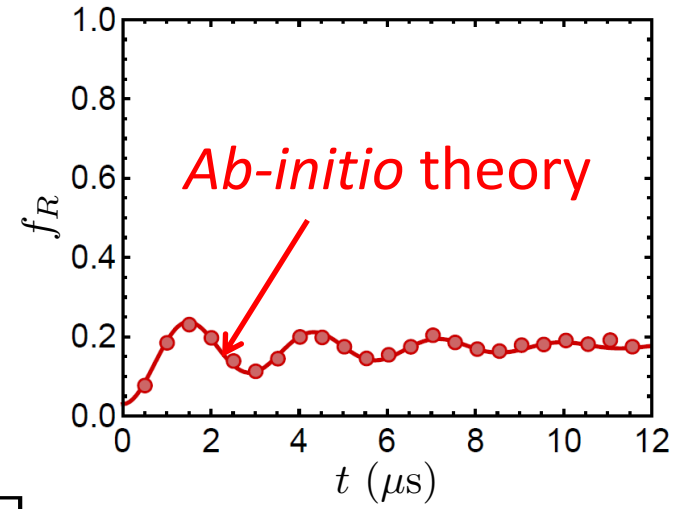

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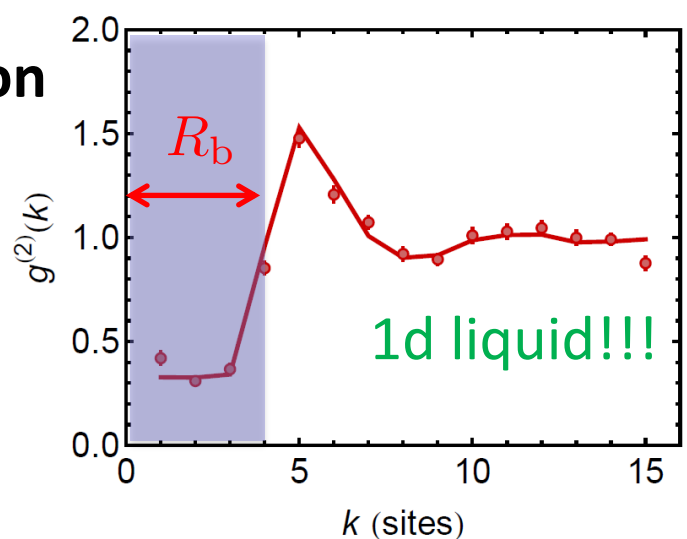
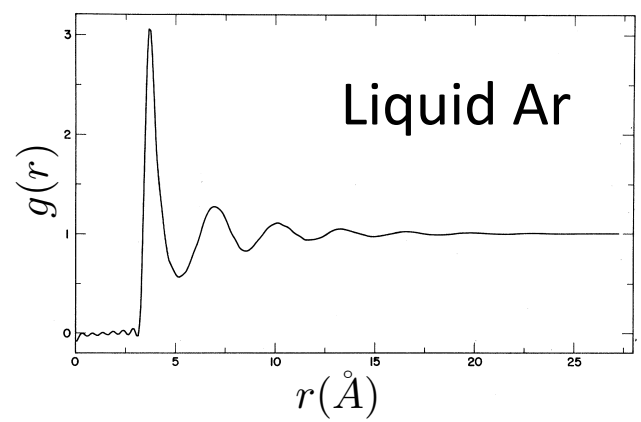




Outline

1. Assembled arrays of atoms

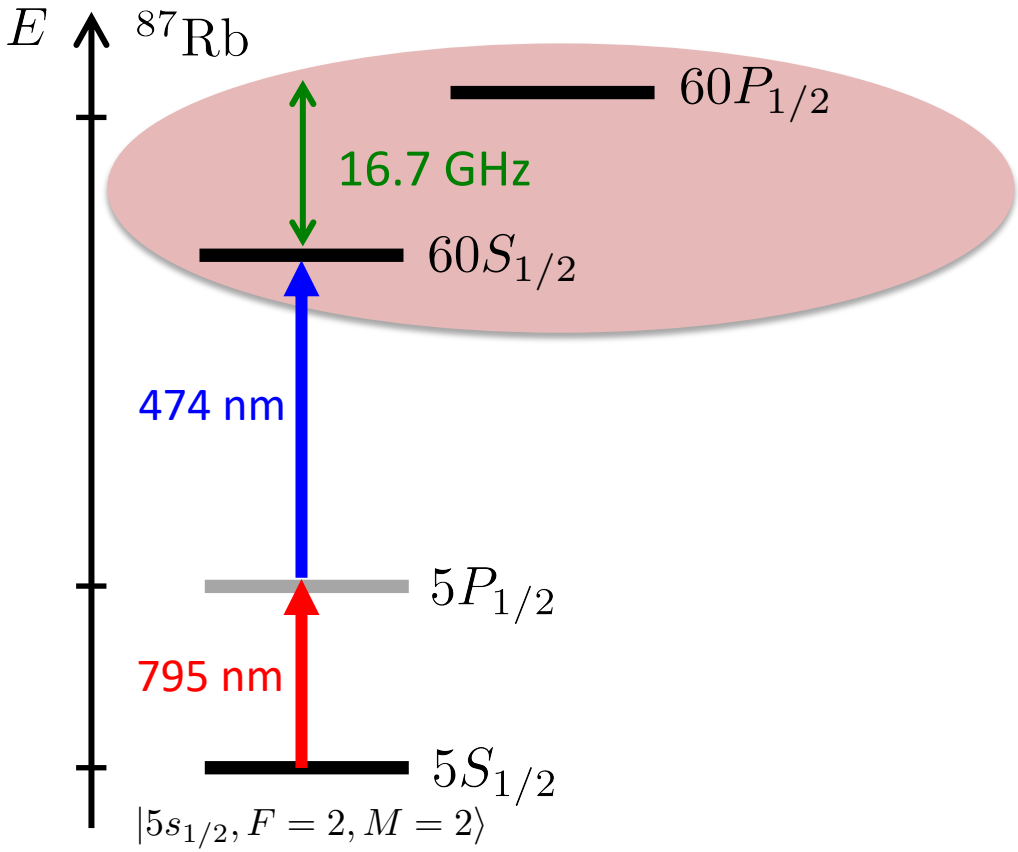
2. Magnetism: Ising model with van der Waals interactions

H.-P. Büchler
S. Weber, N. Lang

3. Topological matter with resonant dip.-dip. interactions

arXiv:1810.13286

Resonant dipole-dipole interaction between Rydberg atoms



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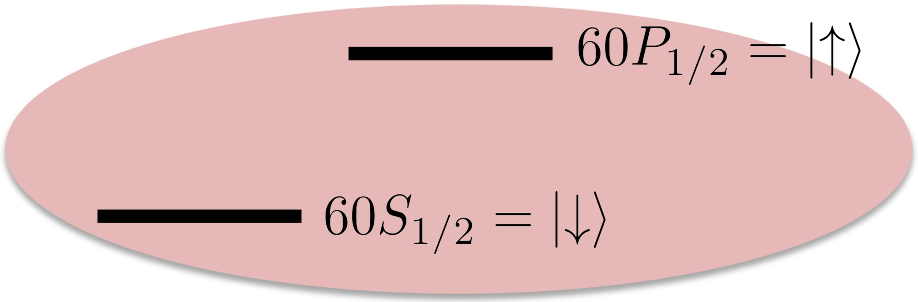

Mapping on
spin ½ system

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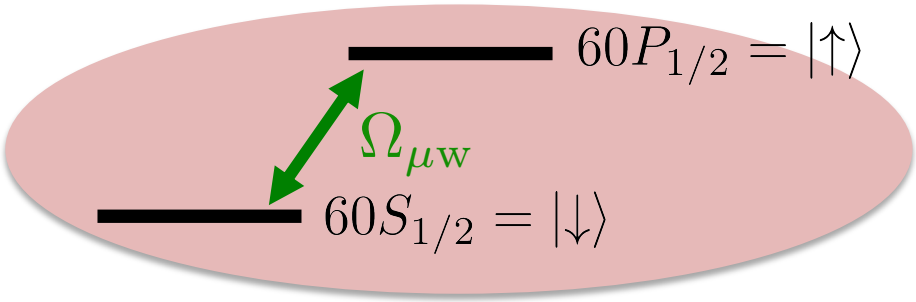

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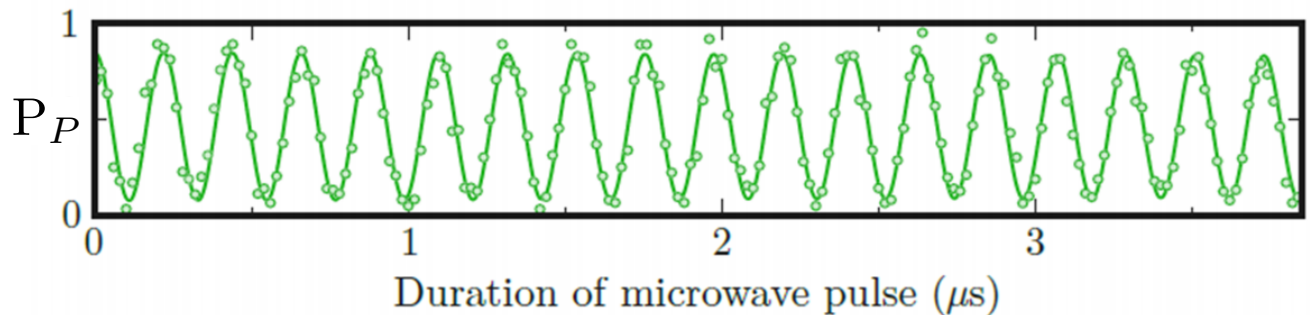

Barredo, PRL **114**, 113002 (2015)

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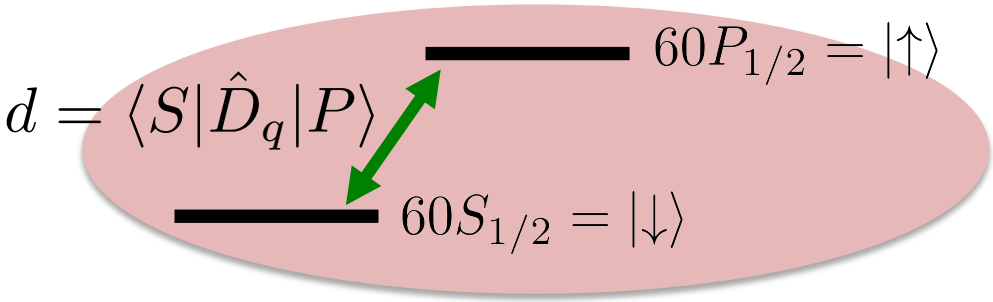

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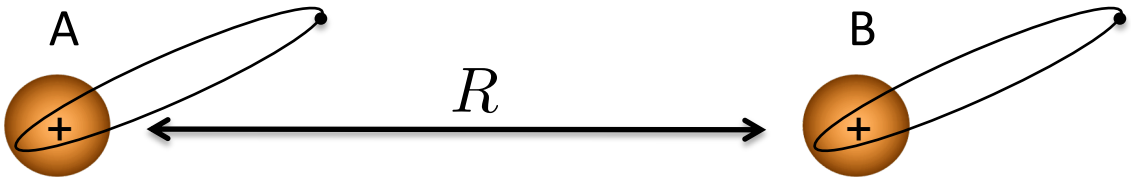

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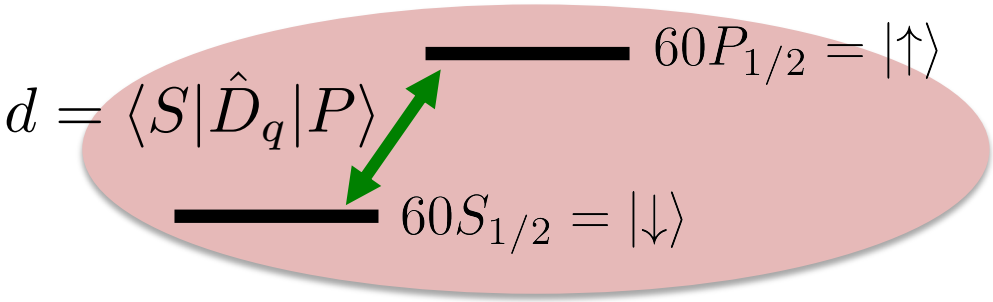

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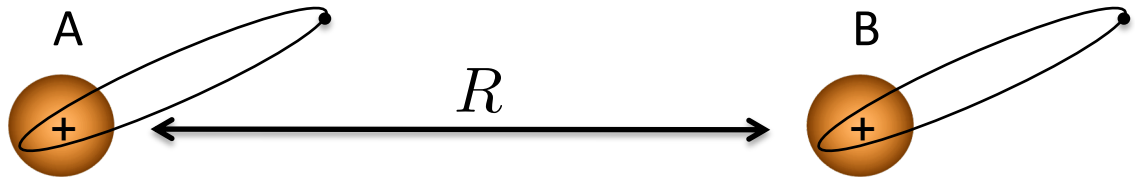
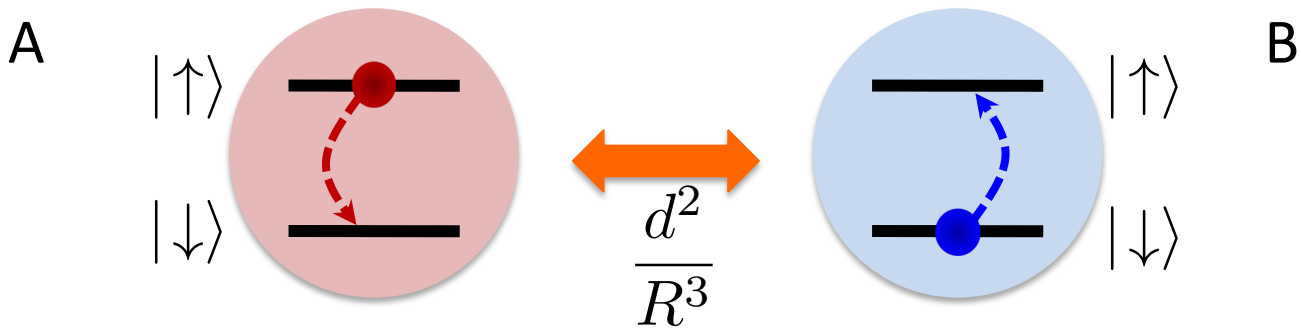




$$\hat{H} = \frac{d^2}{4\pi\epsilon_0 R^3}\left(\hat{\sigma}_A^+\hat{\sigma}_B^- + \hat{\sigma}_A^-\hat{\sigma}_B^+\right)$$

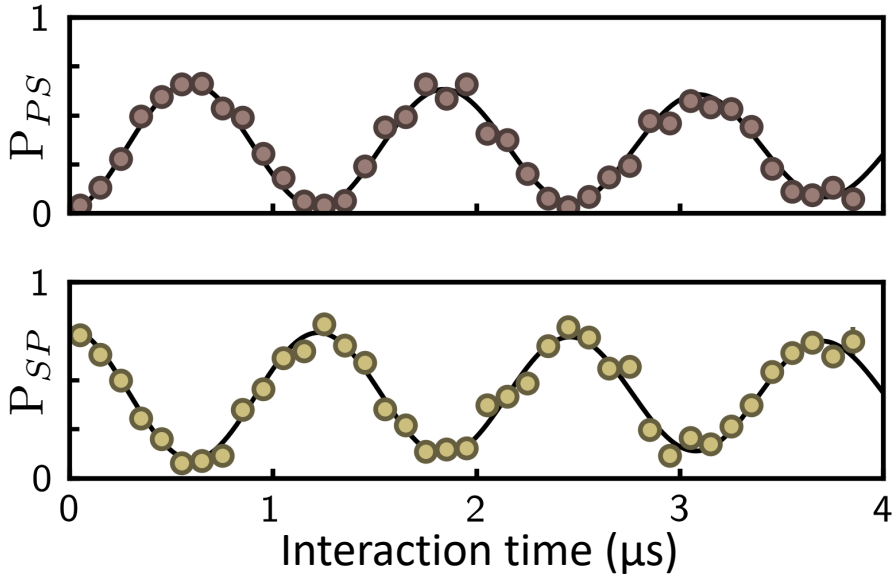
"exchange" of excitation

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)

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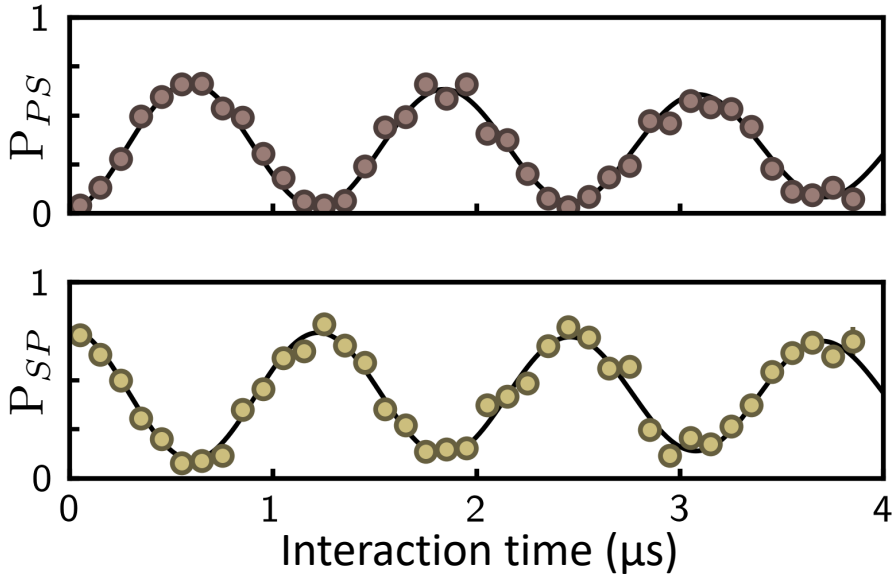

Barredo PRL (2015)
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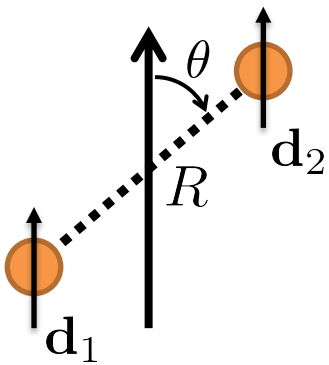
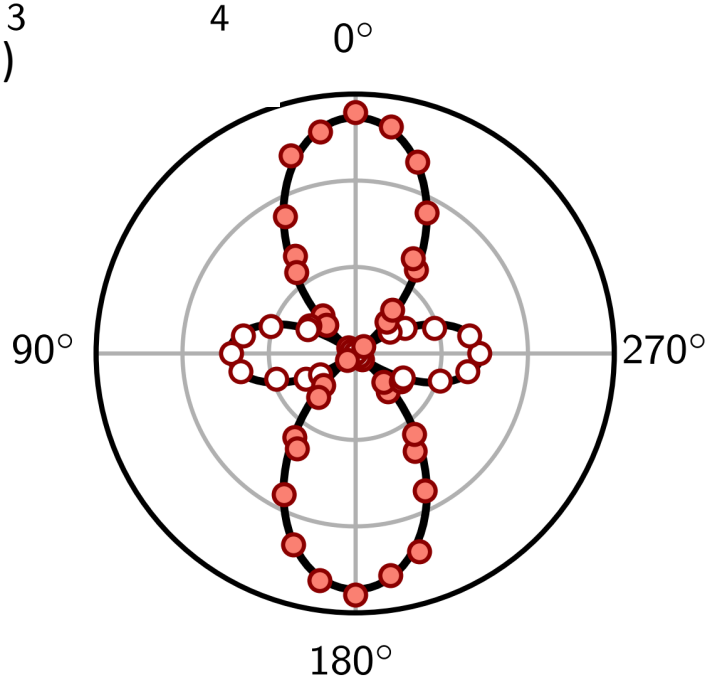
Quantization axis (B)



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



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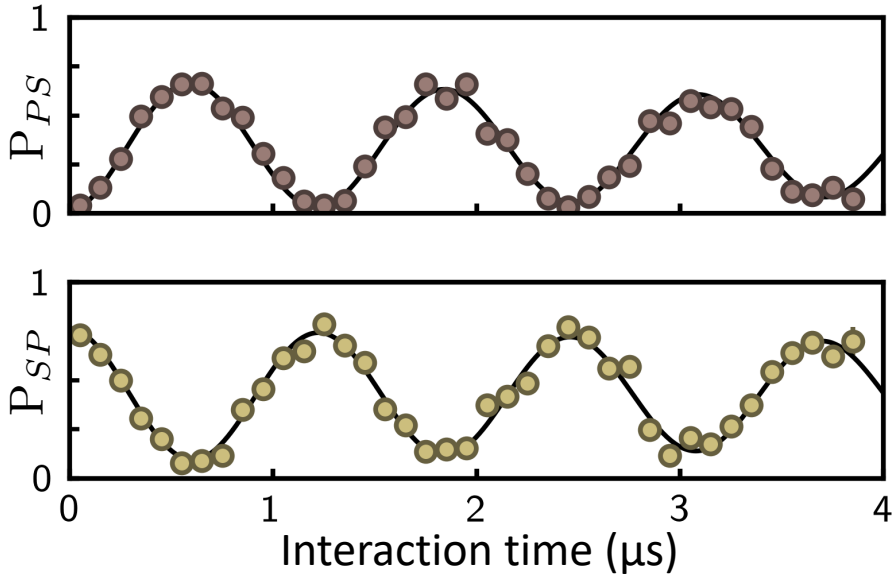

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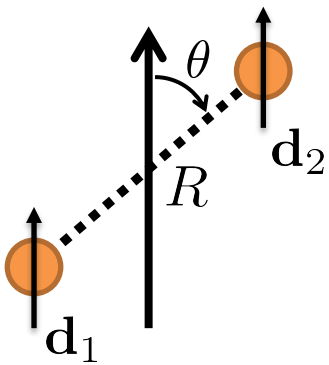

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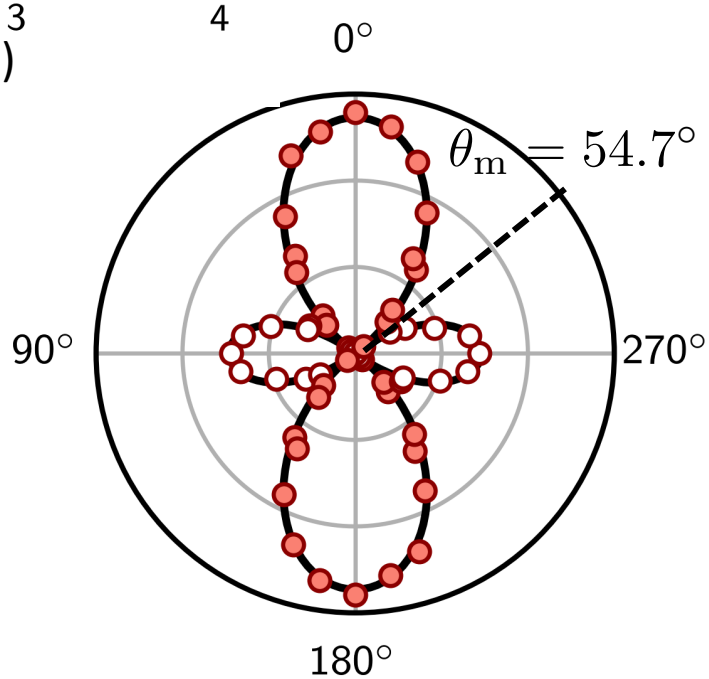

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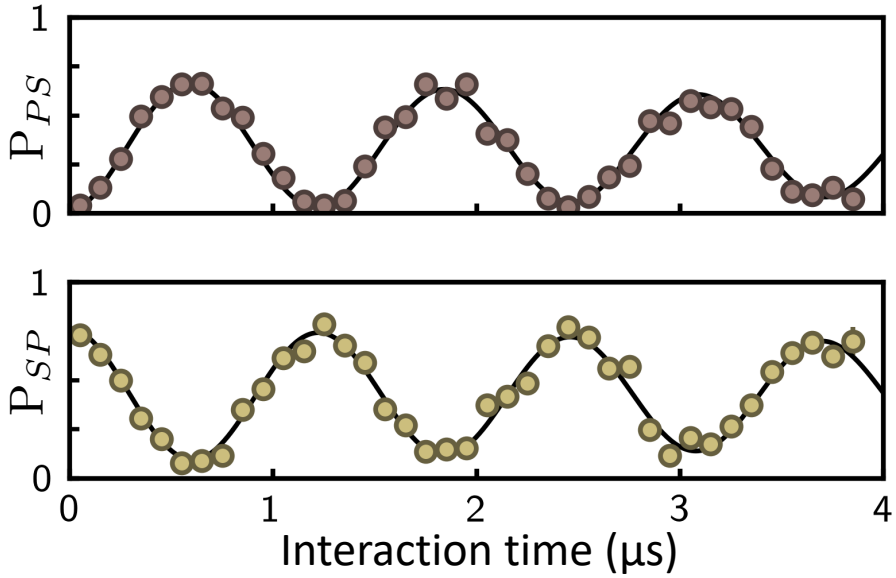

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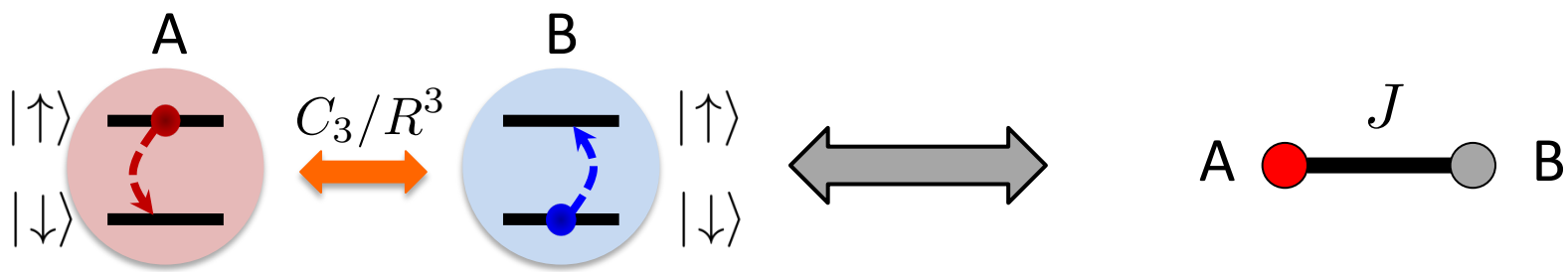


Spin excitation exchange

$$J\,\hat{\sigma}_A^+\hat{\sigma}_B^-$$

Particle hopping

$$J|A\rangle\langle B|$$

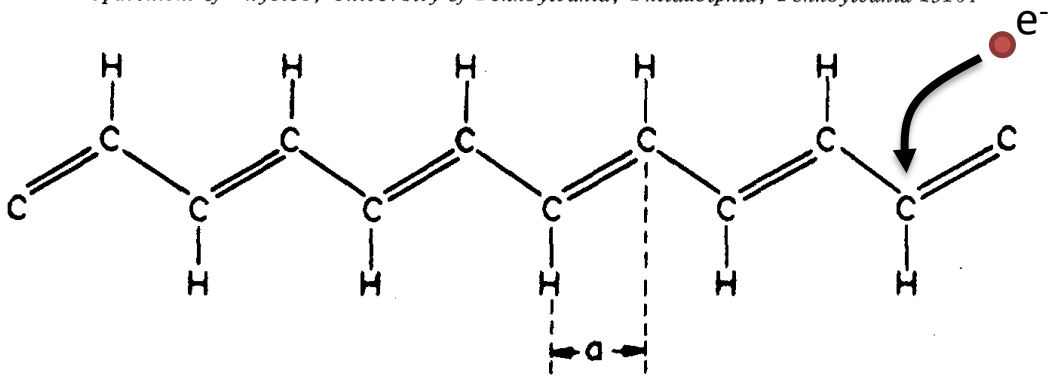
The Su-Schrieffer-Heeger model

- Introduced to explain conductivity in polymers

VOLUME 42, NUMBER 25 PHYSICAL REVIEW LETTERS 18 JUNE 1979

Solitons in Polyacetylene

W. P. Su, J. R. Schrieffer, and A. J. Heeger
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104



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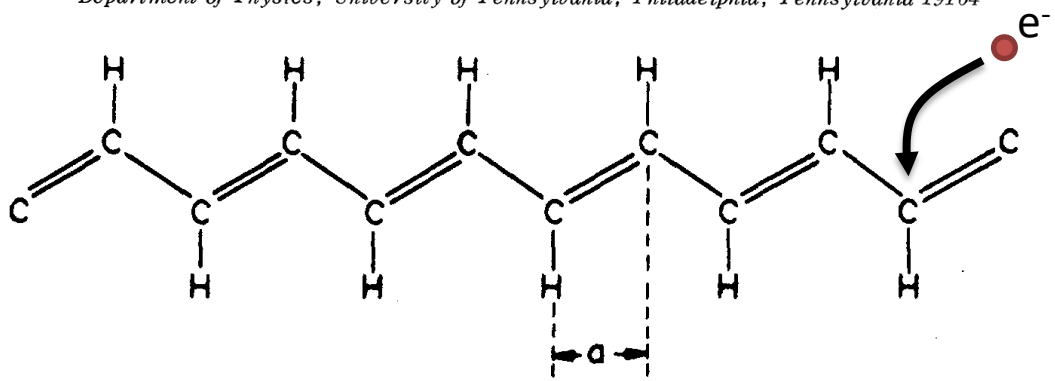

- Now, considered as simplest example of topological model

Asboth, arXiv:1509.02295, Cooper, arXiv:1803.00249

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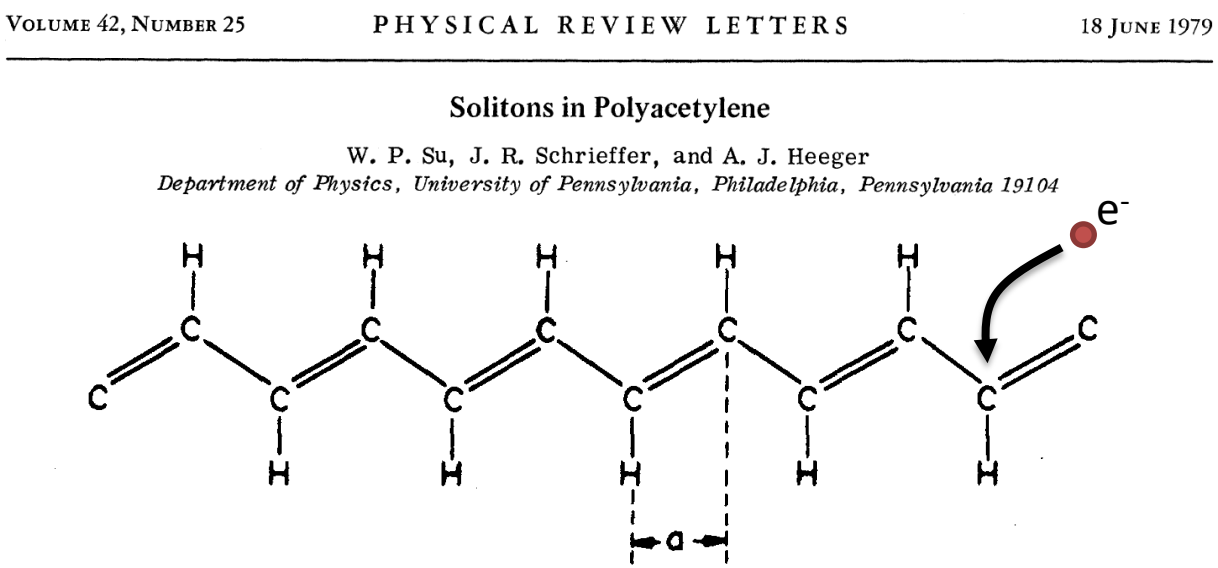

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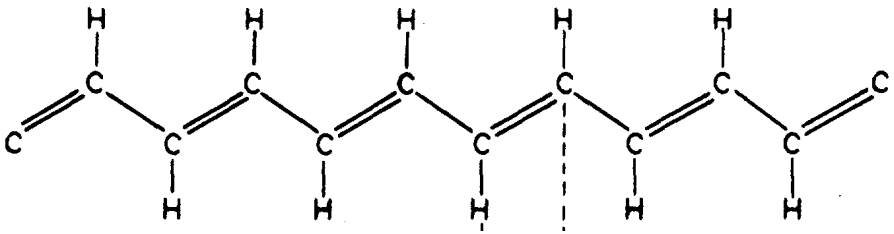
- **Goal:** build an artificial SSH system to explore role
  - Symmetries
  - Interactions
  - …

Single-particle SSH spectrum (finite chain): edge states



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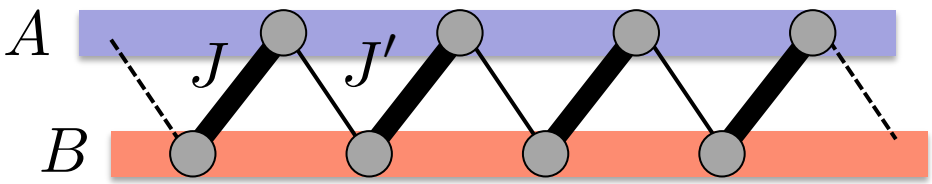

Model: tight-binding
dimerization: $J > J'$

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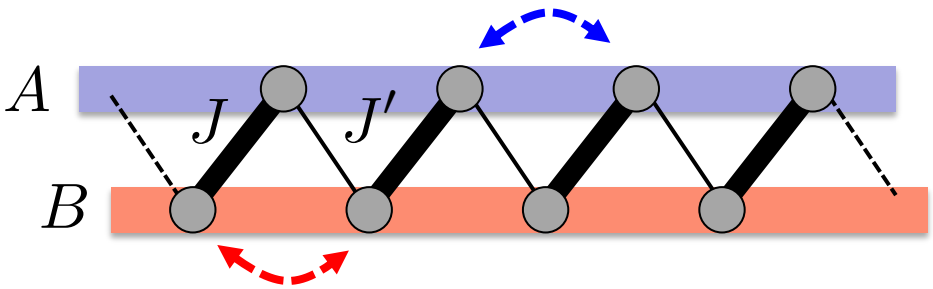

Model: tight-binding
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$J'' = 0$: **chiral symmetry** $\Rightarrow$ symmetric **single particle** spectrum

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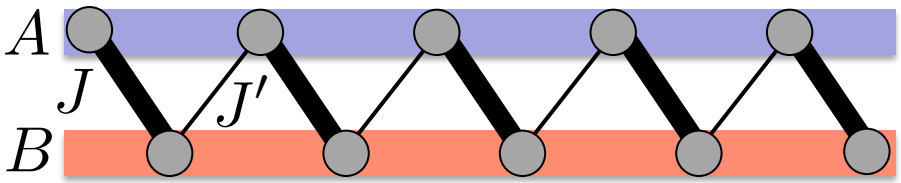

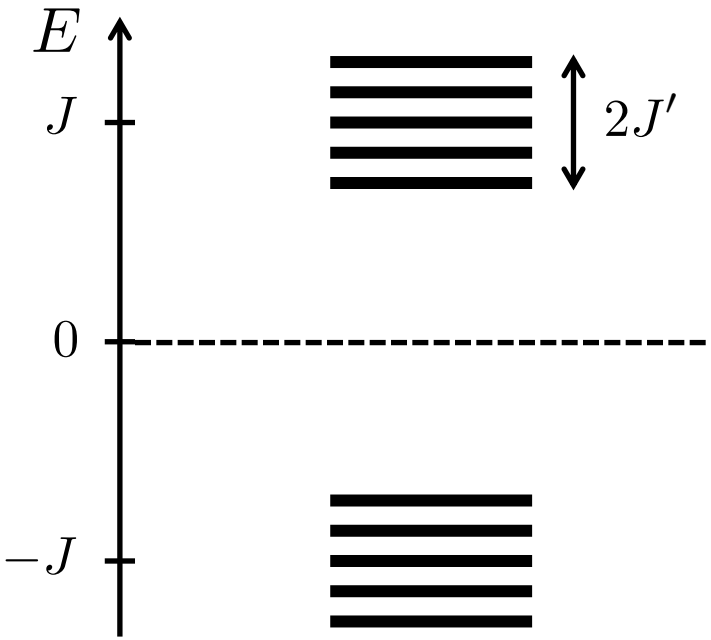

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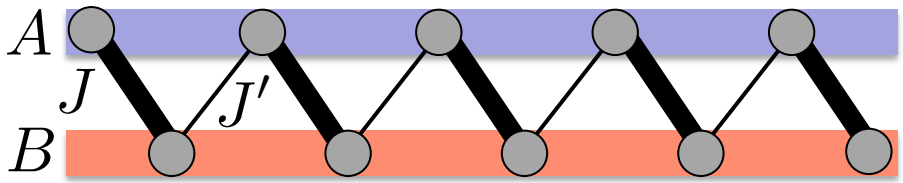

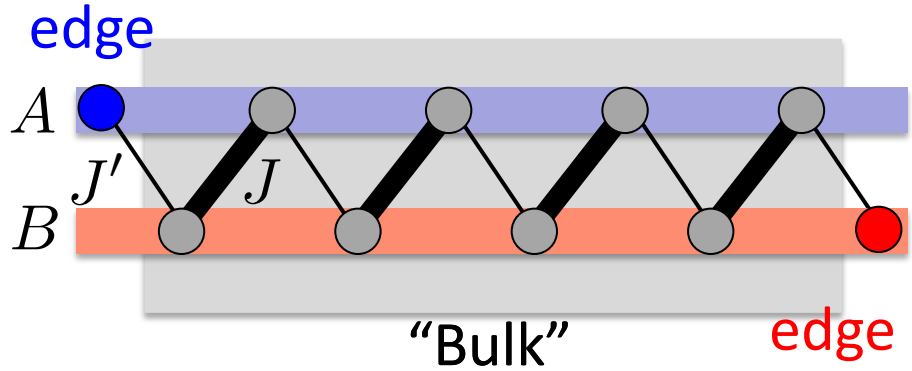

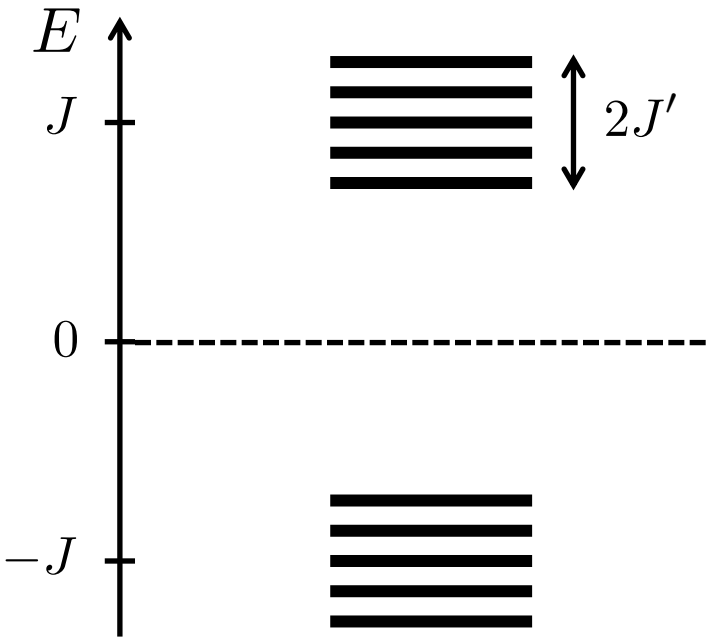

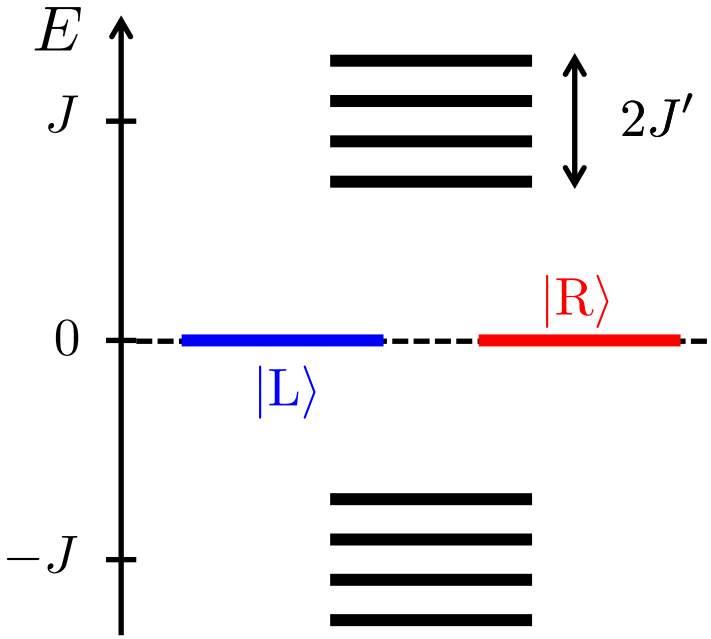

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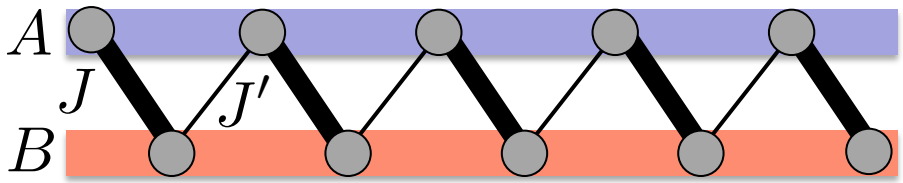
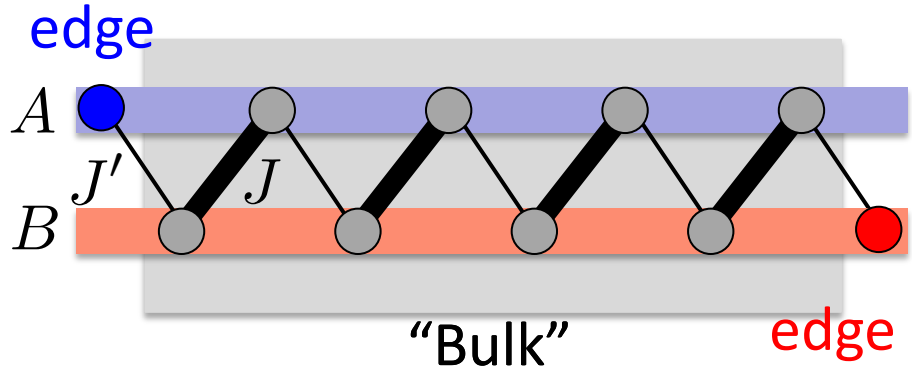
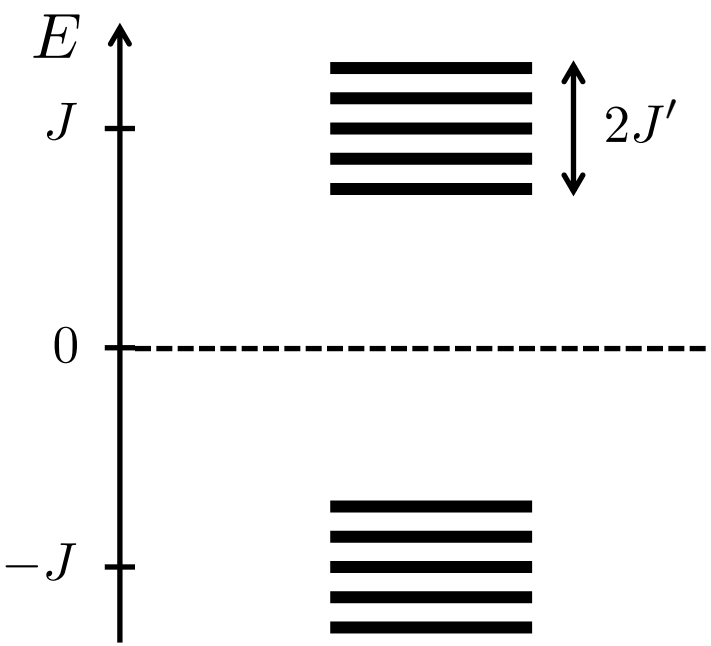
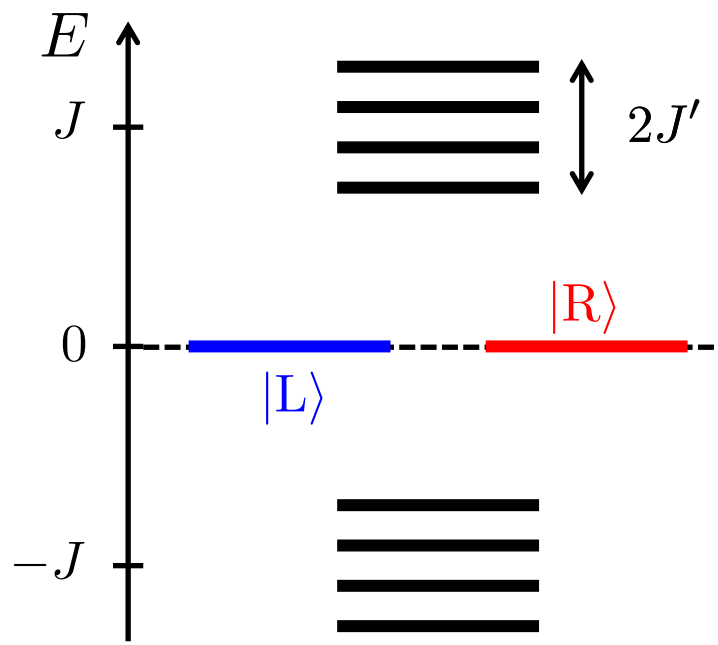






Normal



Topological

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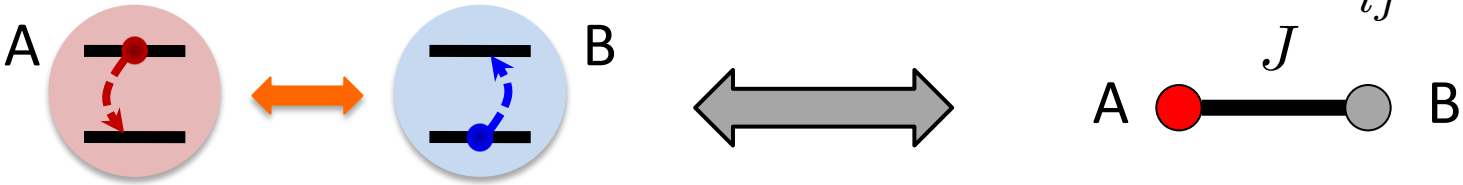
Implementation of SSH spin chain with Rydberg atoms

Couplings J_{ij} **:** resonant dipole-dipole interaction $\dfrac{C_3(\theta_{ij})}{R_{ij}^3}$



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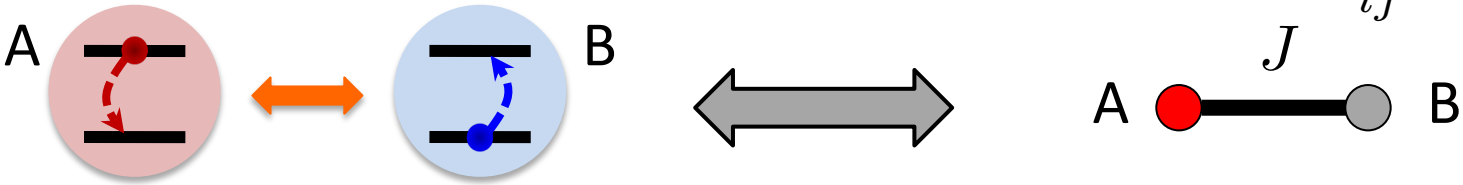
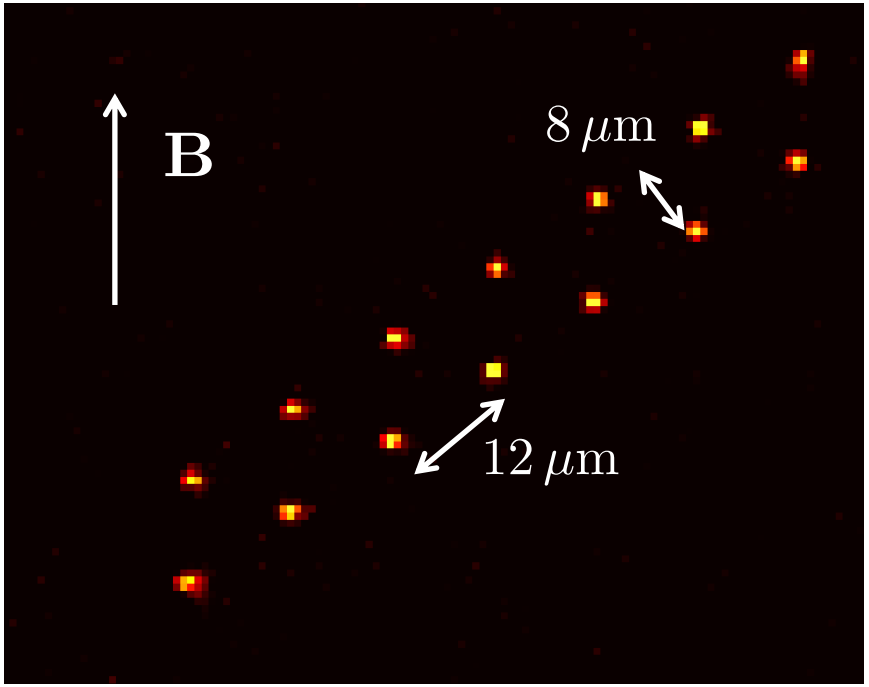
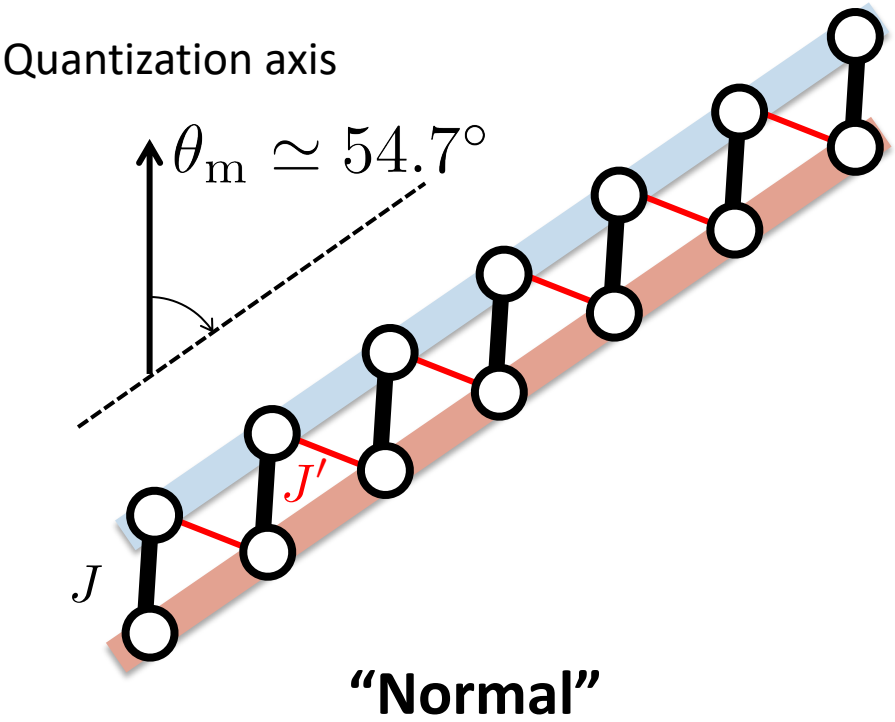


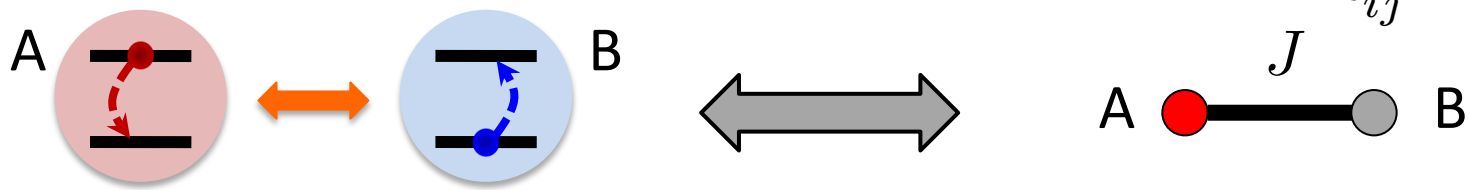
Chain at magic angle $\Rightarrow$ **chiral symmetry** (no A-A or B-B hopping)





Implementation of SSH spin chain with Rydberg atoms

Couplings J_{ij} **:** resonant dipole-dipole interaction $\dfrac{C_3(\theta_{ij})}{R_{ij}^3}$



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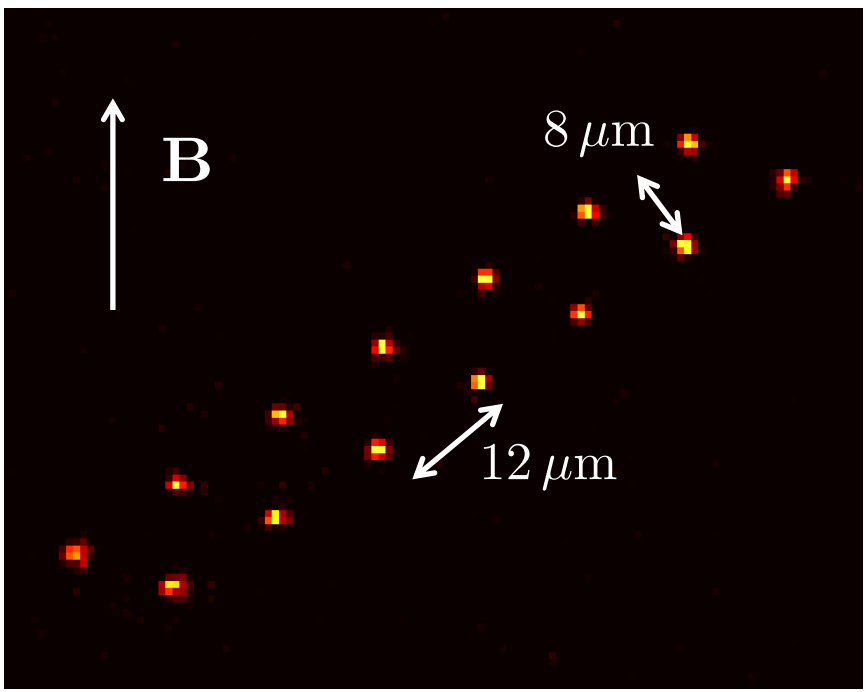
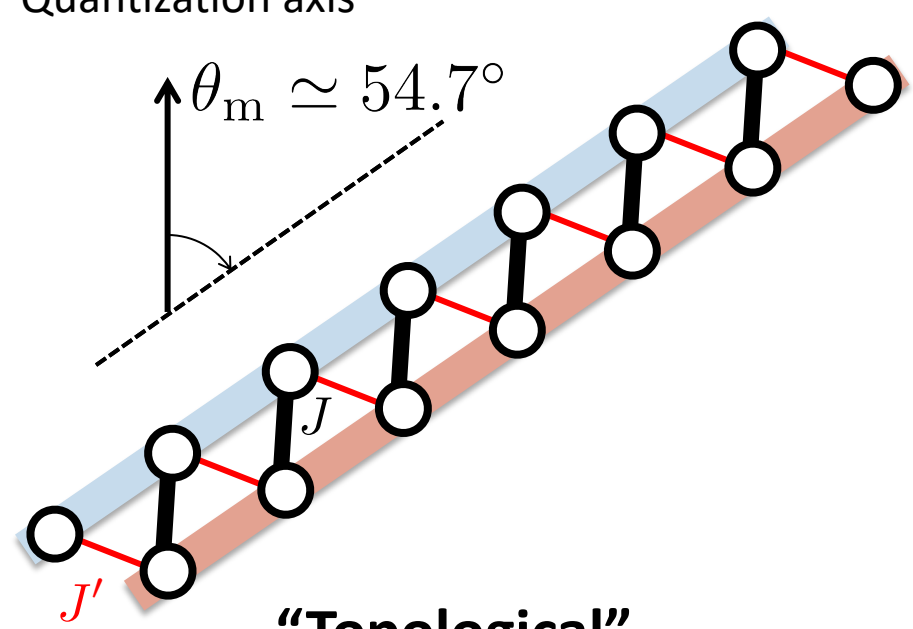
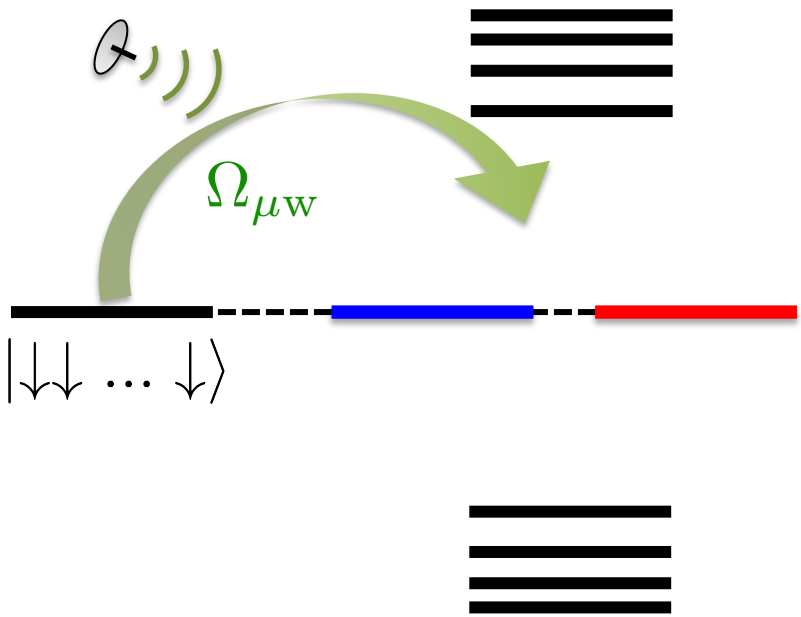


Quantization axis



"Topological"

Probing the single-particle SSH spectrum



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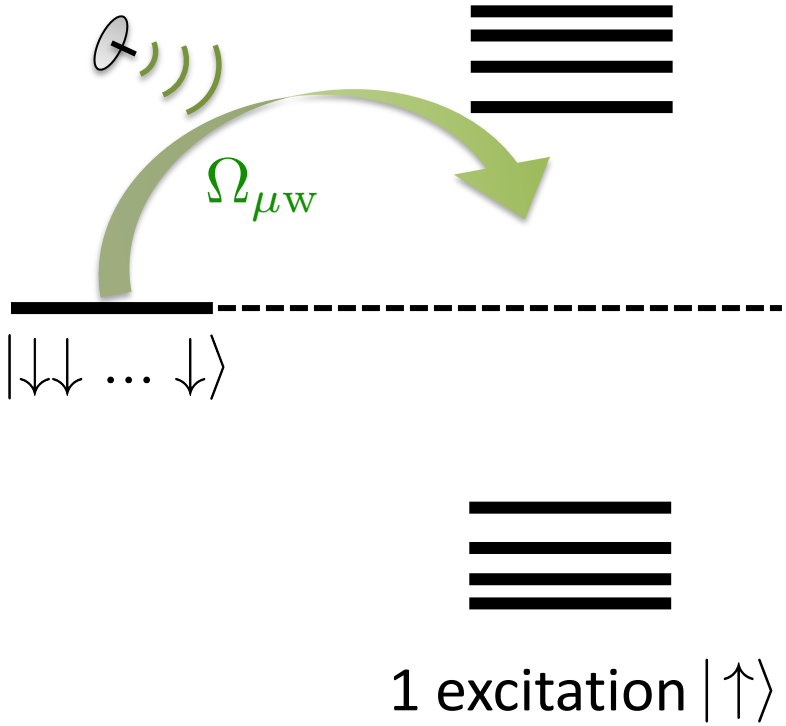

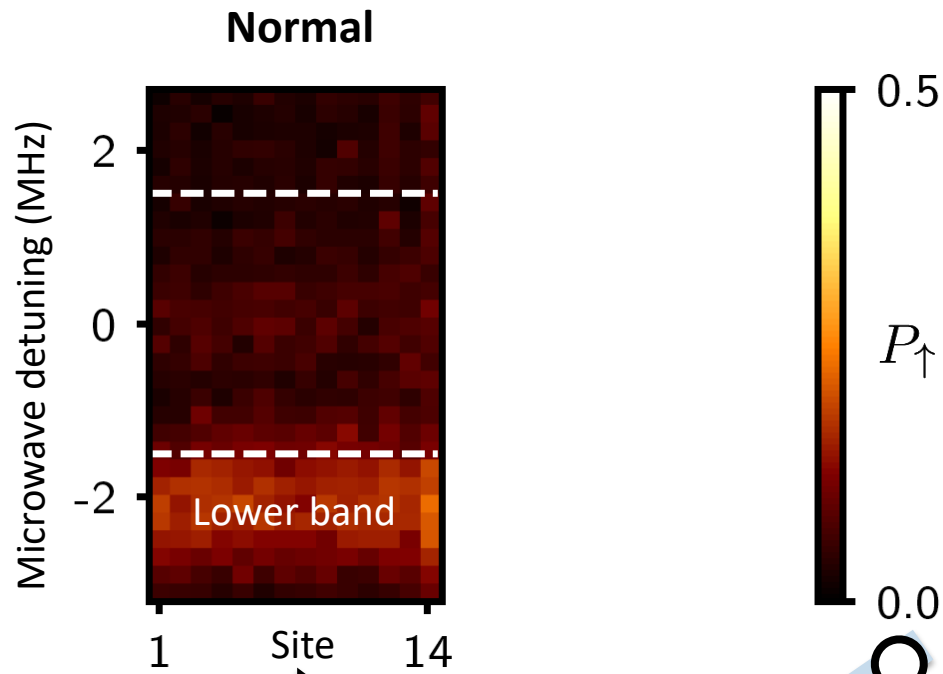

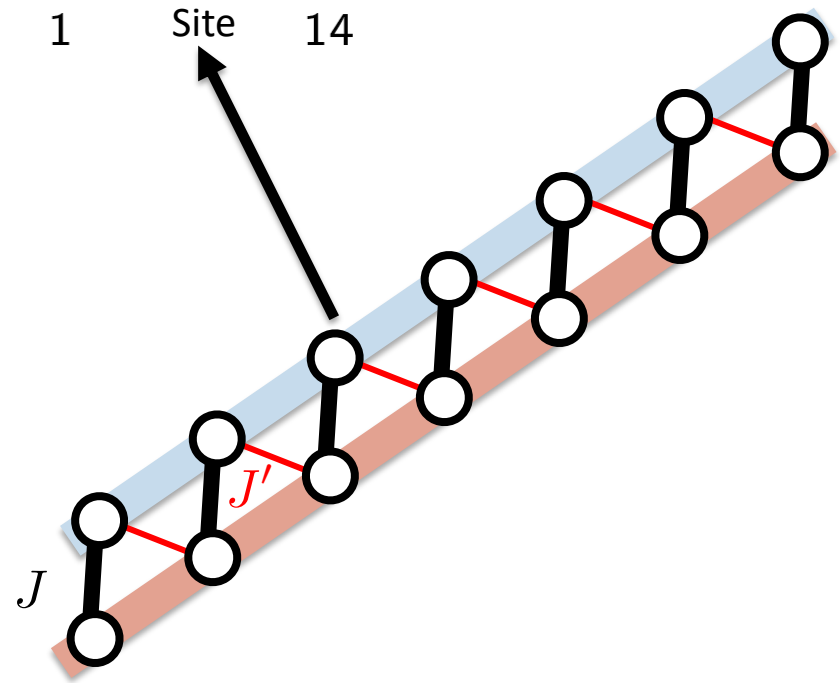

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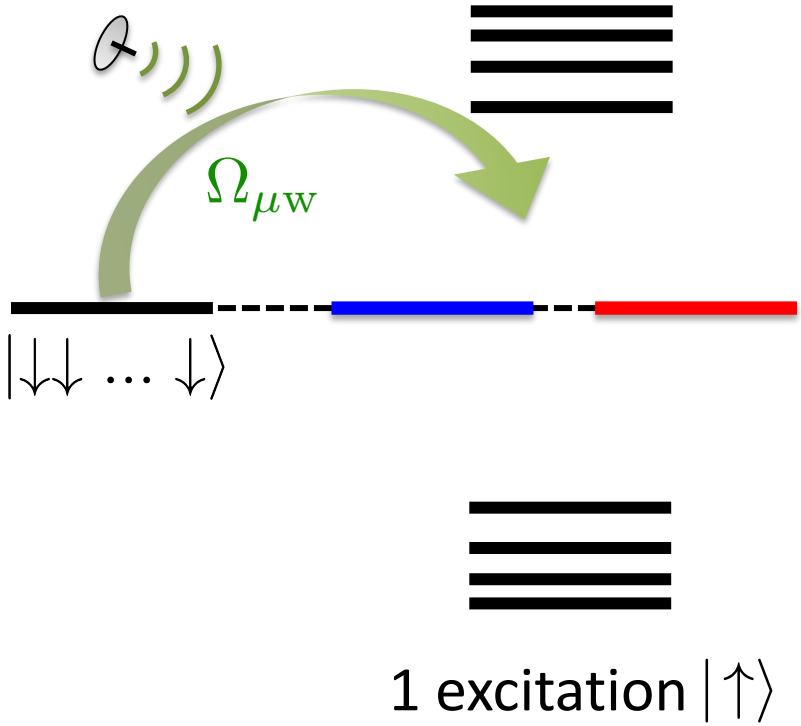
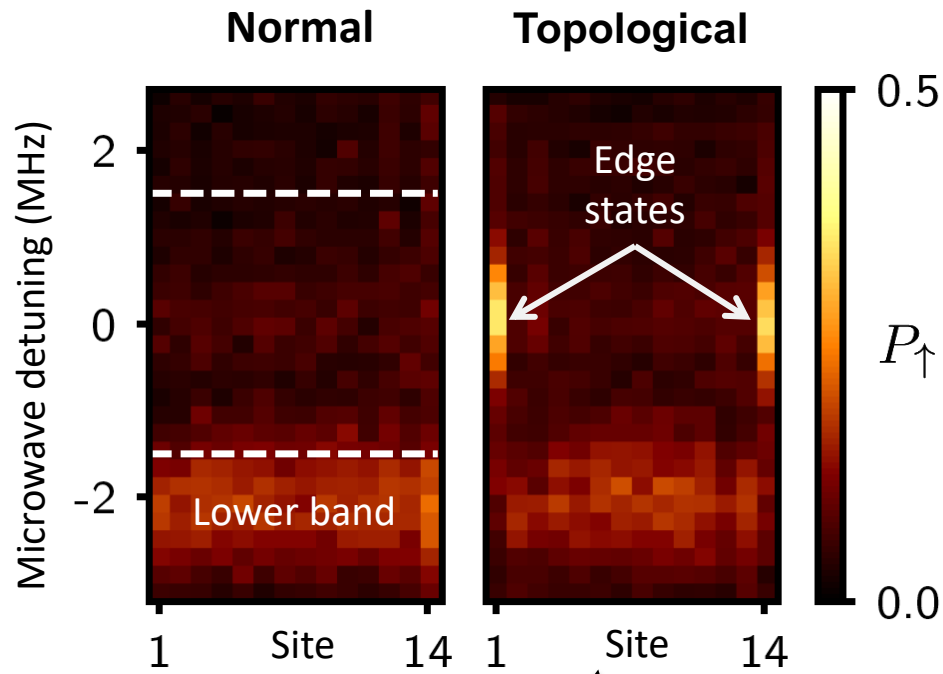
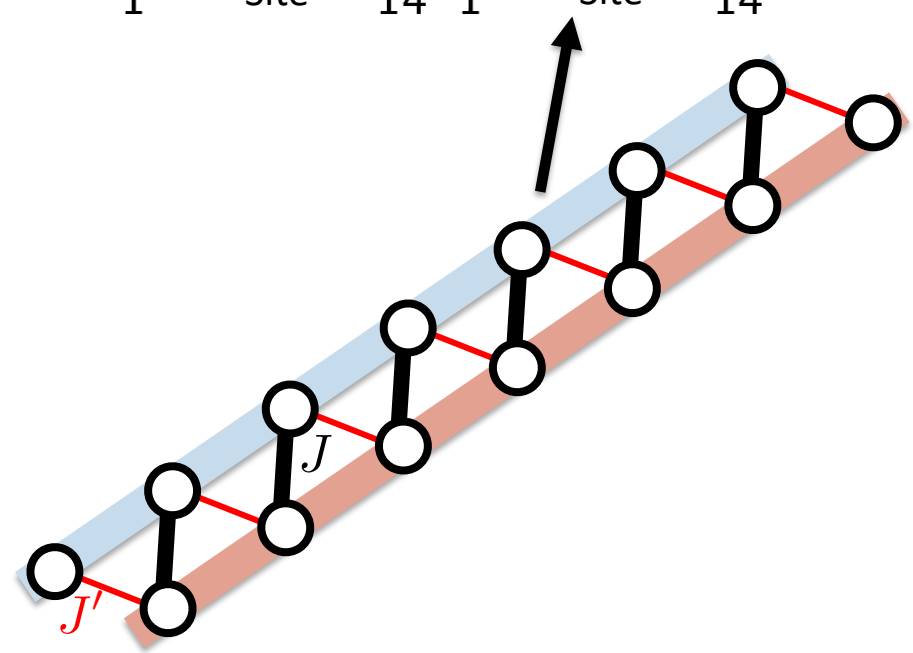
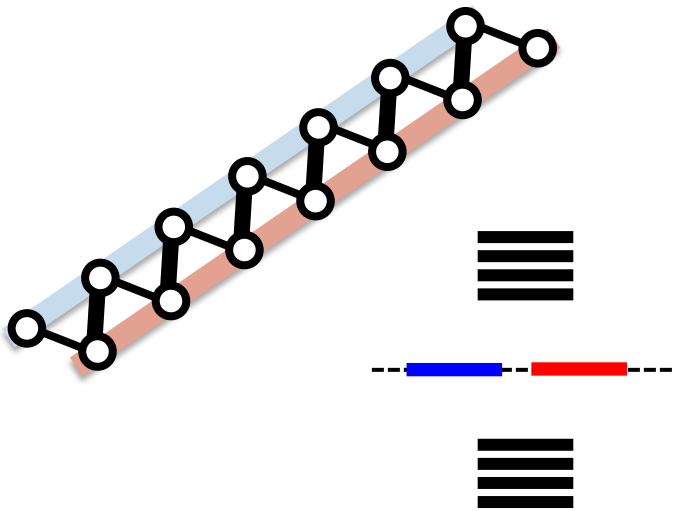
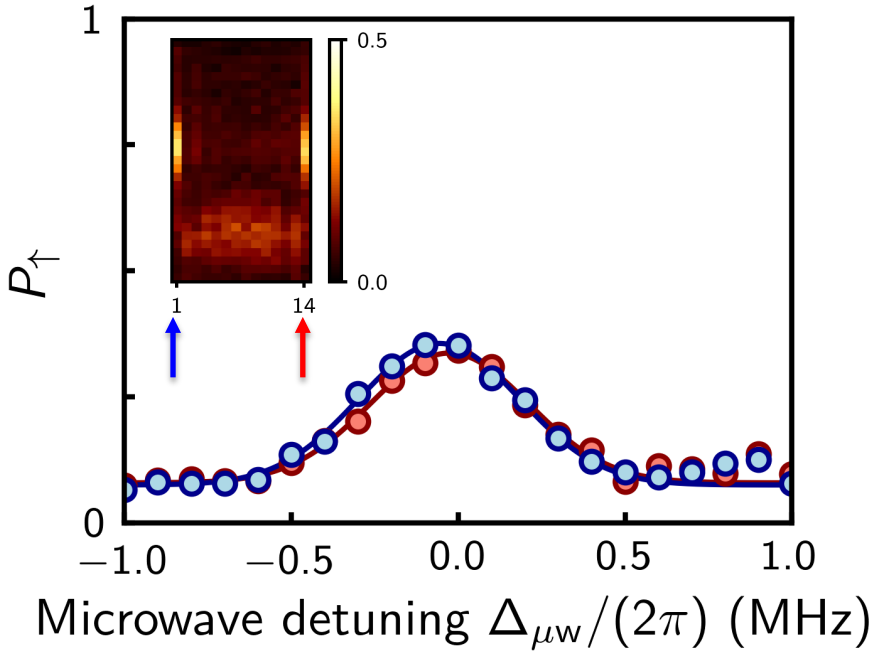






Breaking the chiral symmetry (single-particle)





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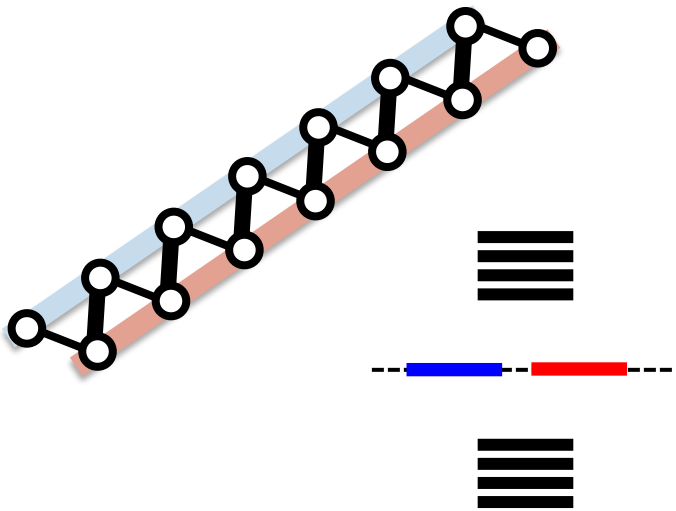

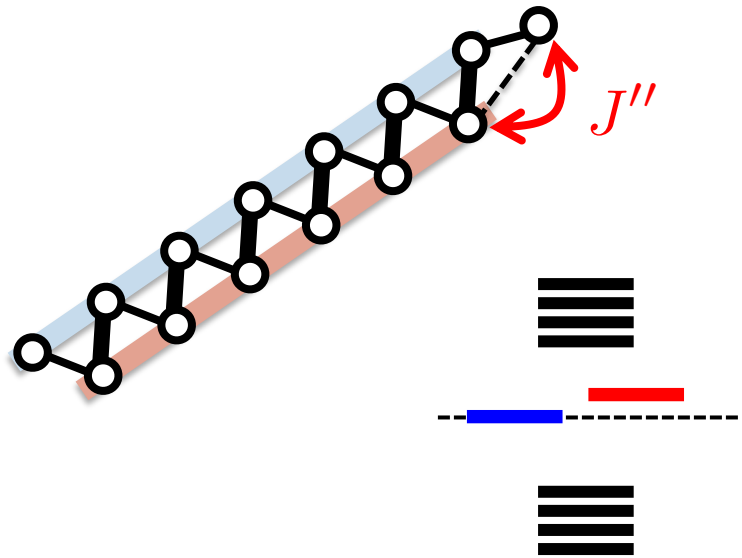

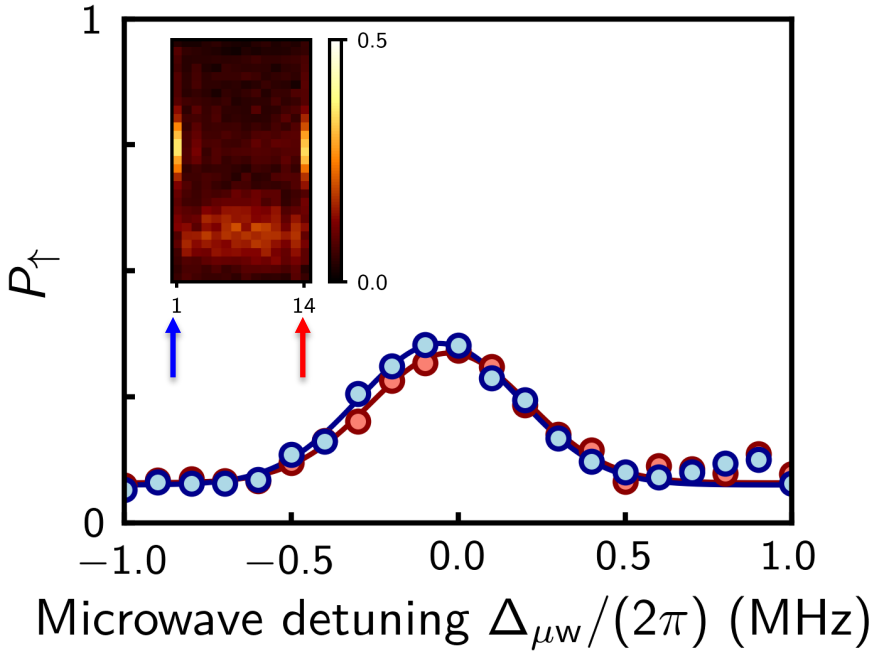

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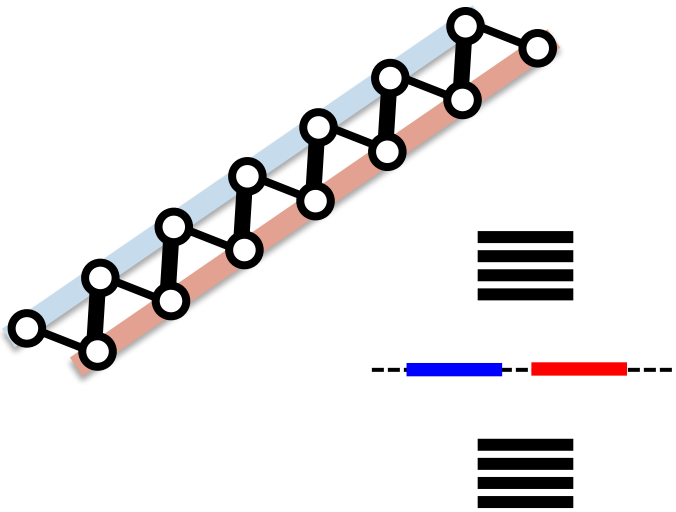
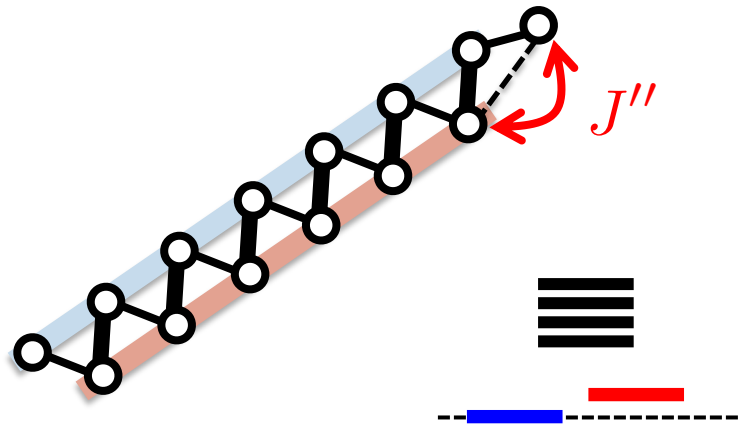
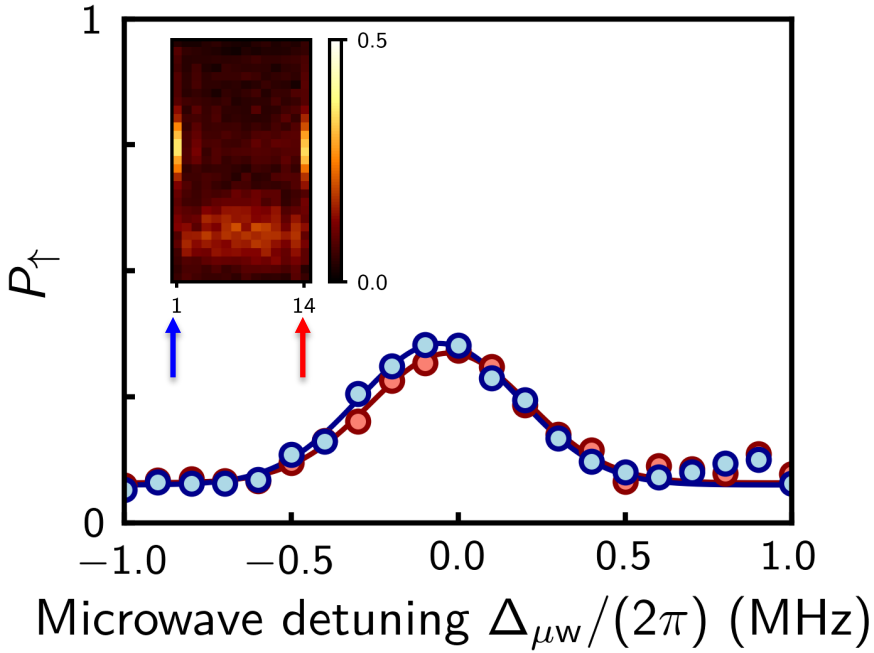
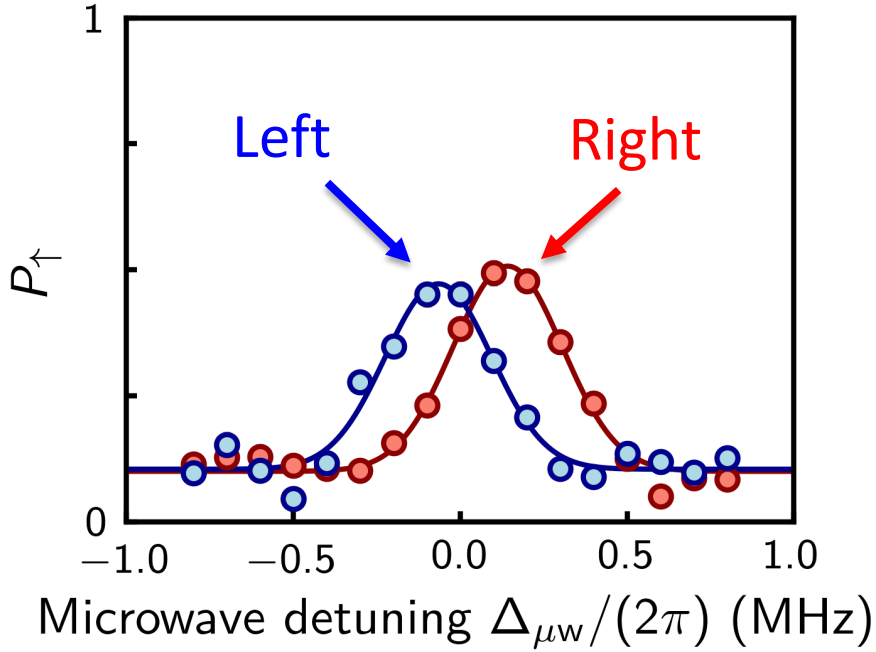




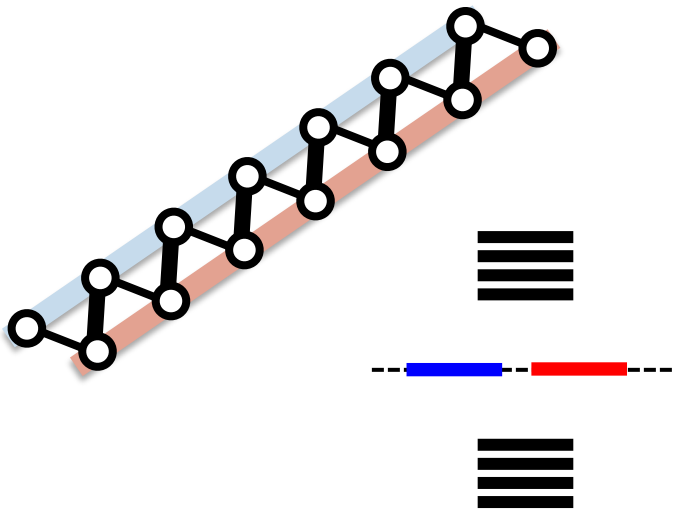
Broken chiral symmetry
$\Rightarrow$ lifts degeneracy

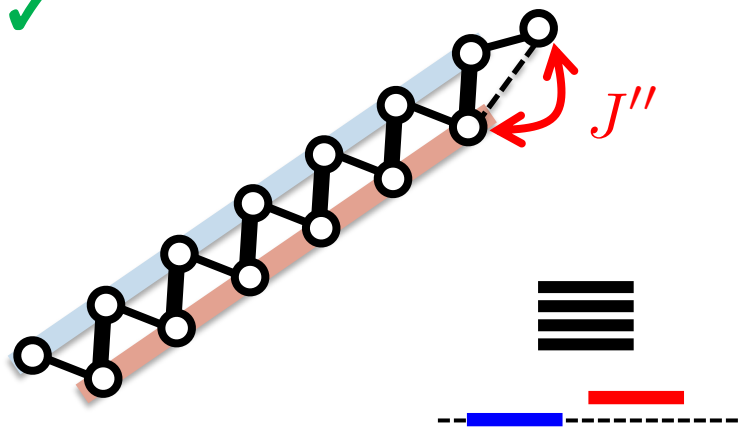




Breaking the chiral symmetry (single-particle)

Chiral symmetry ✓





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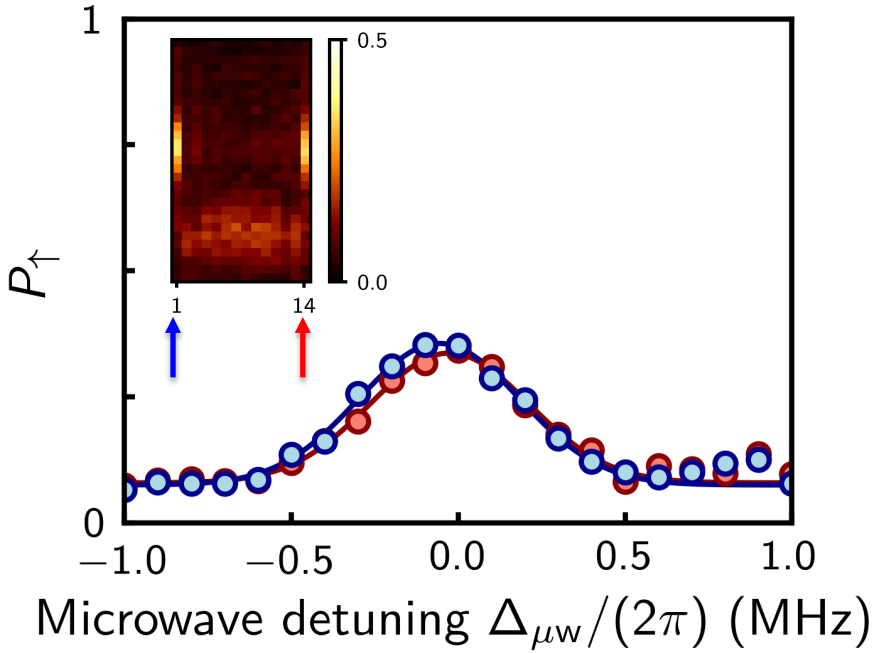
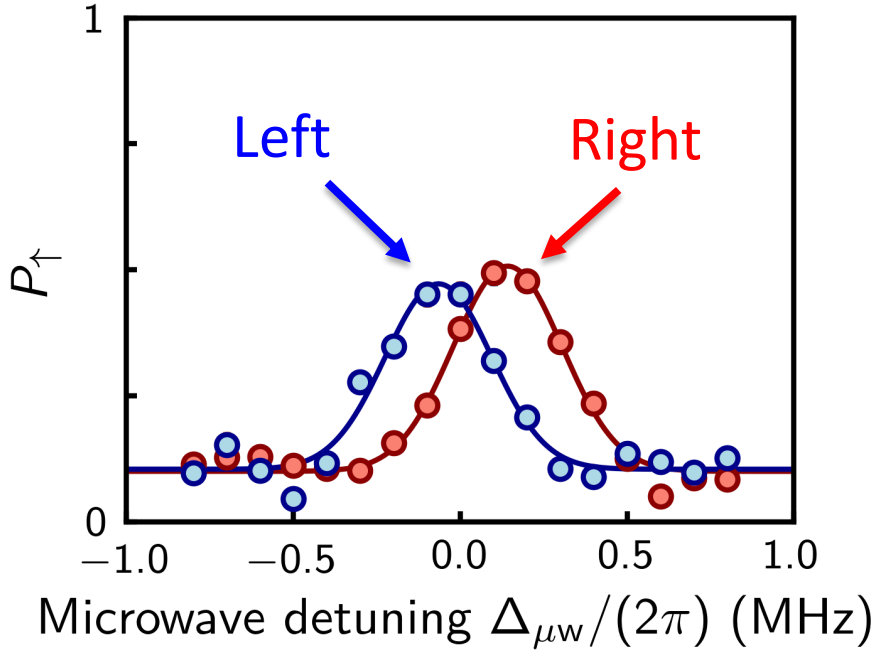
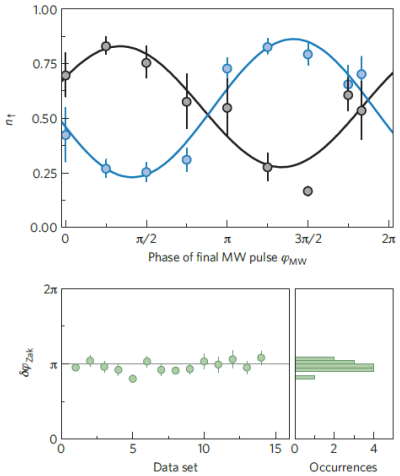




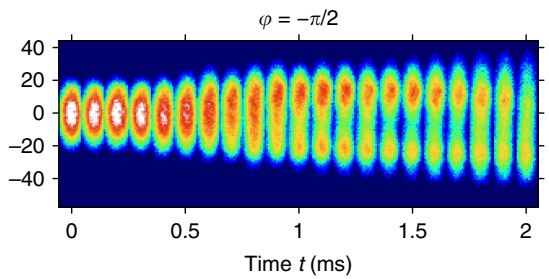
Examples of artificial SSH chains (non-interacting regime)

Ultracold atoms in superlattices

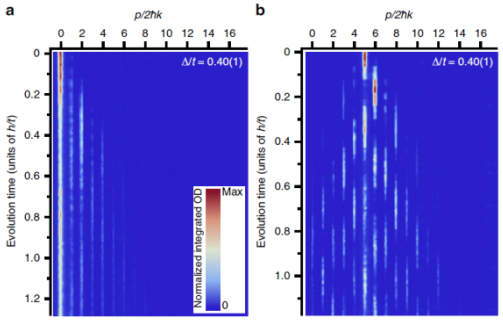


I. Bloch, Nat. Phys. 2013

Bragg diffraction of matter waves

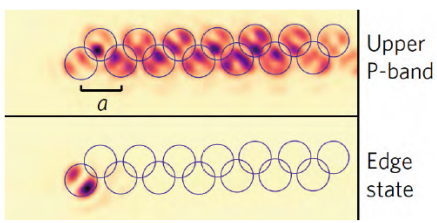


Weitz,
Nat. Comm. 2016

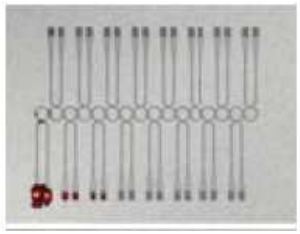


Gadway,
Nat. Comm. 2016

Photonic devices

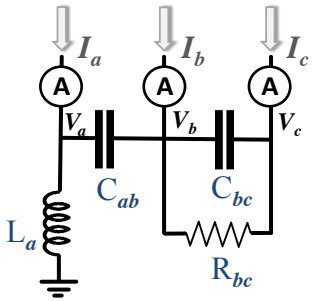


J. Bloch
Nat. Phot. 2017



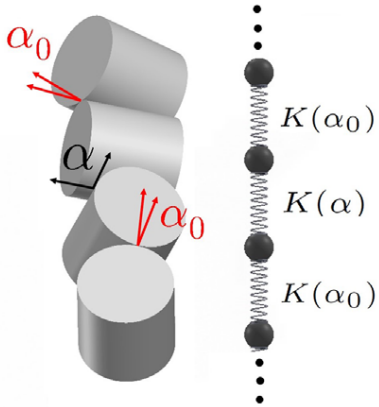
Khajavikhan
PRL2017

Lumped circuits



arXiv:1705.01077

Mechanical oscillators



Chaunsali, PRL 2017

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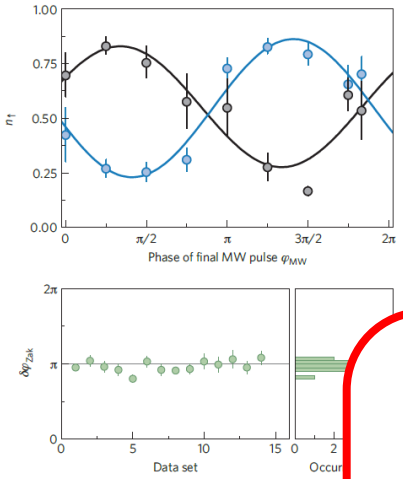

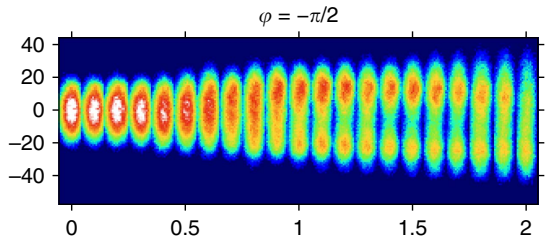

I. Bloch, Nat. Phys.

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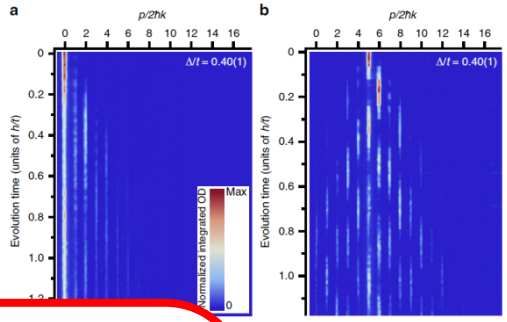
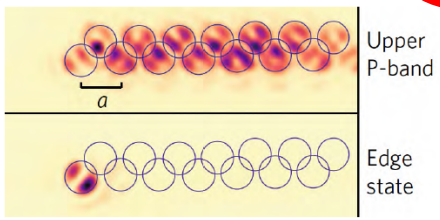


dway,
mm. 2016

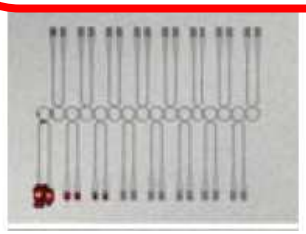
Challenge / questions

interplay topology - interactions

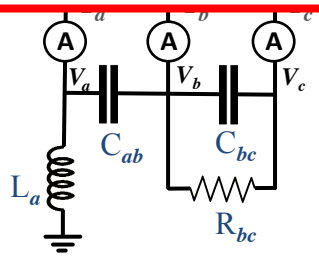
Photonic



J. Bloch
Nat. Phot. 2017



Khajavikhan
PRL2017



arXiv:1705.01077

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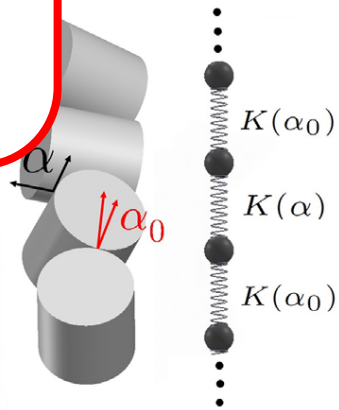
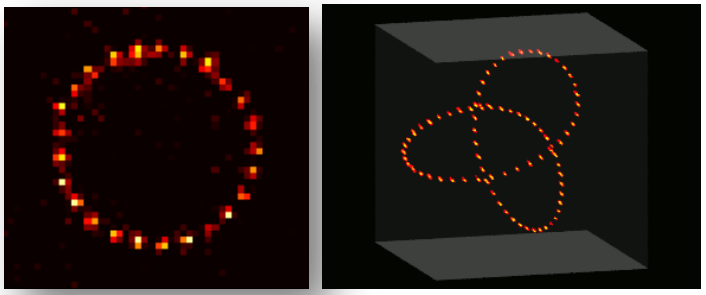


Chaunsali, PRL 2017

Conclusion and outlook

A nice system to build artificial matter



- ✓ Single-particle resolution & addressing
- ✓ Up to **70 atoms**, arbitrary geometries in 2 & 3D
- ✓ Tunable interactions ⇒ implementation of **many-body *H***

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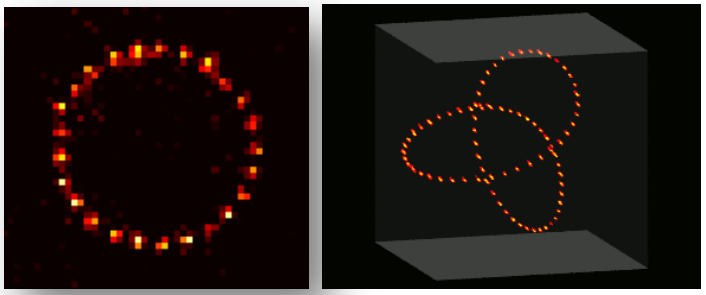
A nice system to build artificial matter



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Platform mature enough to envision startups…

pasqal.io

PASQAL

Industrial developments of Rydberg–based Quantum Simulator + solve optimization use cases