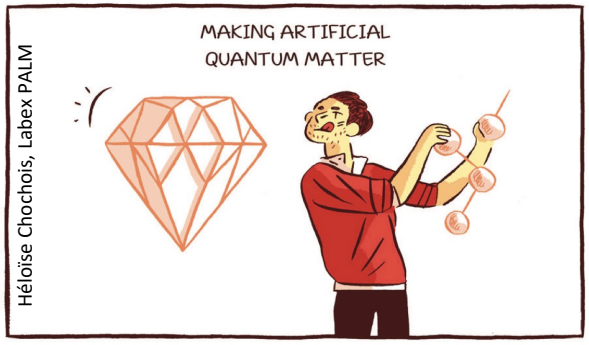
Many-body physics with

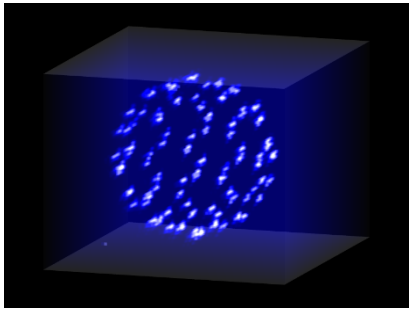
arrays of individual Rydberg atoms

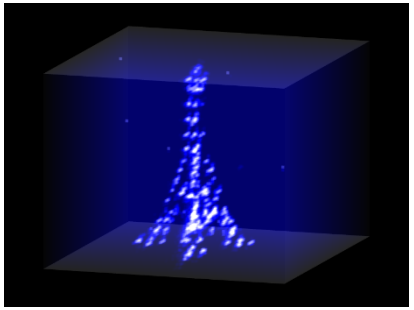
and optical dipoles



Antoine Browaeys

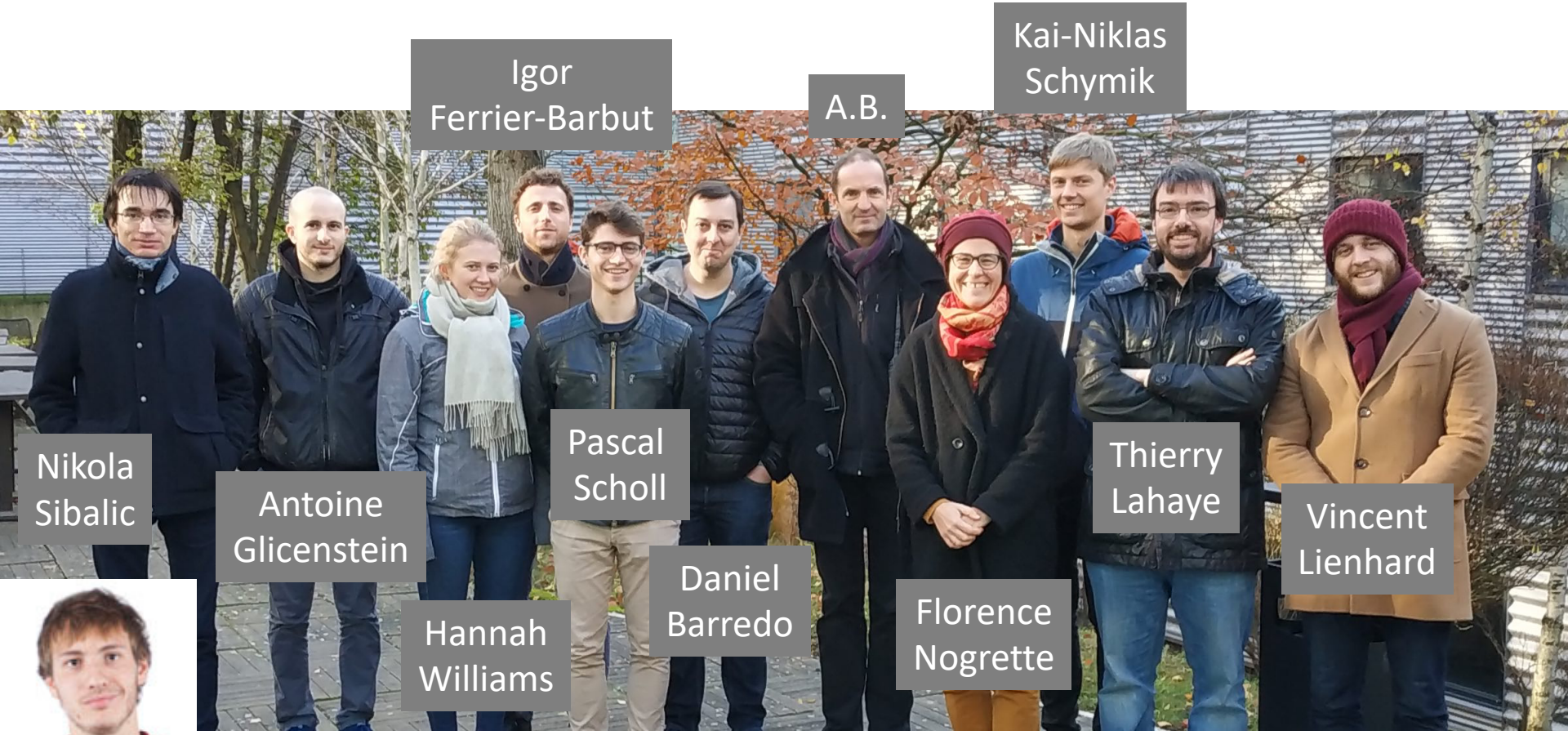
Laboratoire Charles Fabry,
Institut d'Optique, CNRS, FRANCE





Quantum Science Seminar, July 23rd 2020

The team (atom-tweezers-io.org)



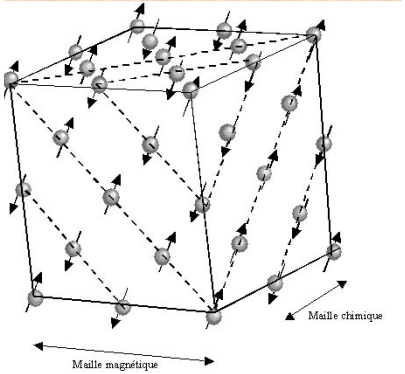
Giovanni Ferioli

Collaborators A. Läuchli, Hans Peter Büchler
C.S. Adams & I. Hughes, D.E. Chang

DGA PALM Laboratoire d'Excellence Physique : Atomes Lumière Matière SIRTEQ îledeFrance PASQuanS

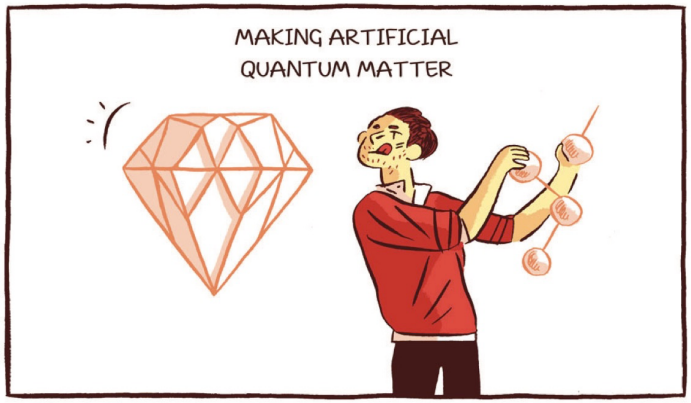
Many-body physics with synthetic matter

Goal: Understand ensembles of interacting quantum particles



superfluidity superconductivity magnetism neutron star

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



Héloïse Chochois, Labex PALM

R.P. Feynman

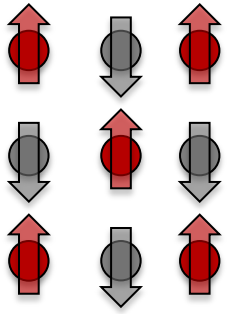
Use experimental control to

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

Larger **tunability** than « real » systems

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

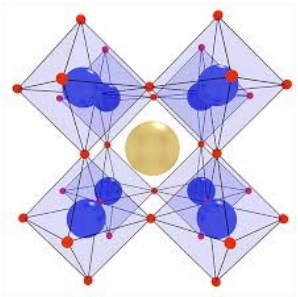
Interacting spin ½ particles on a lattice:



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

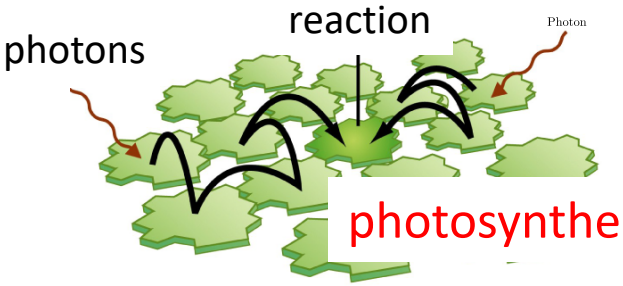
XY model $$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+ \right)$$

Magnetism



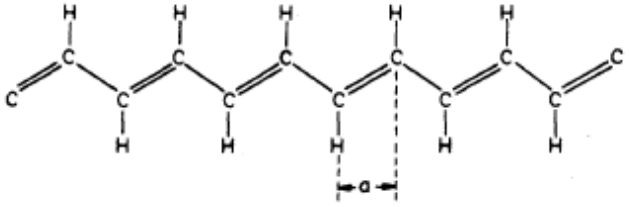
Perovskite
$Y_2Ti_2O_7$

Transport of excitations



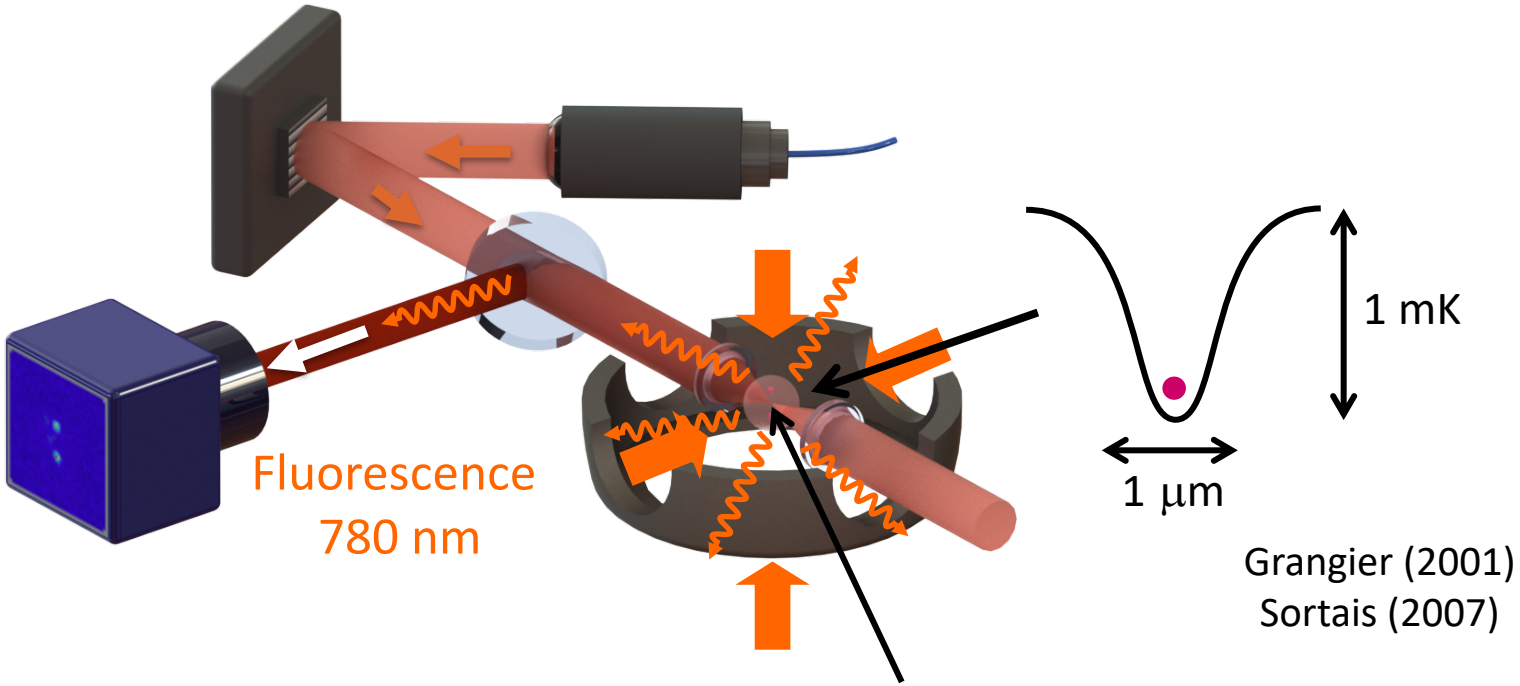
Light scattering

excitons



Realizations: artificial atoms (QD, circuits…), molecules, ions, atoms (lattices, magnetic), photons, photon + atoms, …

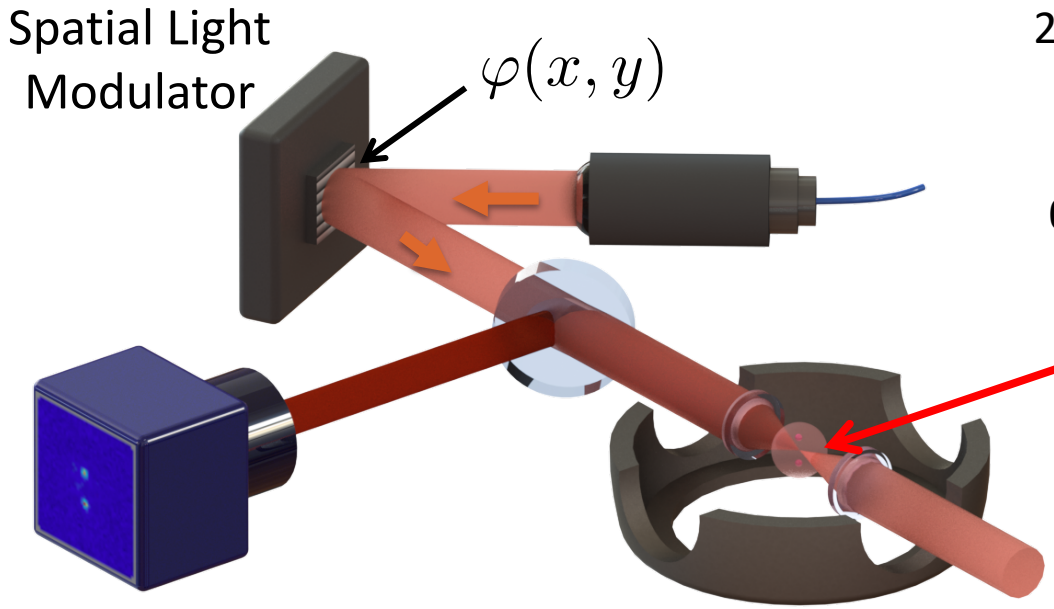
Our platform: atoms in arrays of optical tweezers

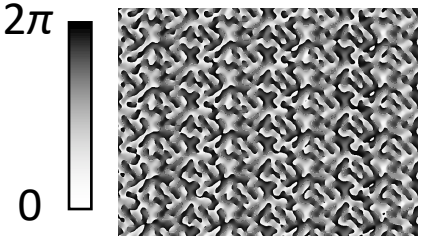


Reservoir = cold atoms ^{87}Rb

T ~100 μK

Our platform: atoms in arrays of optical tweezers





SLM pattern

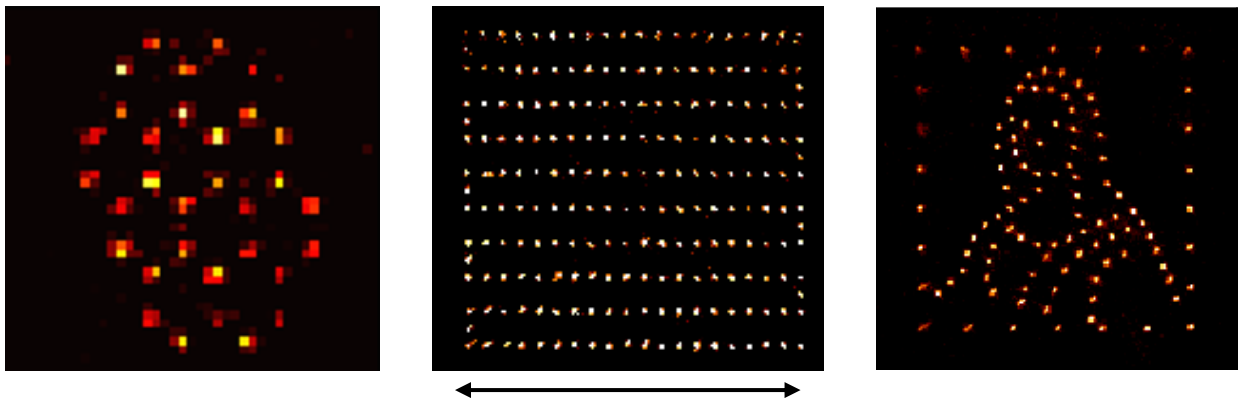
Nogrette, PRX (2014)

$$\left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$

Assembled arrays of individual atoms ($N \sim 200$)

~3-10 μm

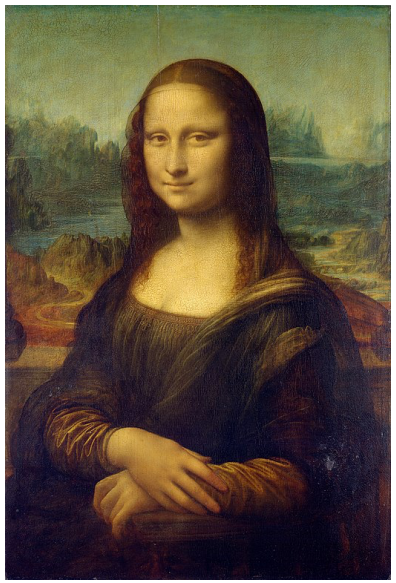
Fluorescence: single shot!!



~100 μm

Barredo, Science (2016)

L. da Vinci



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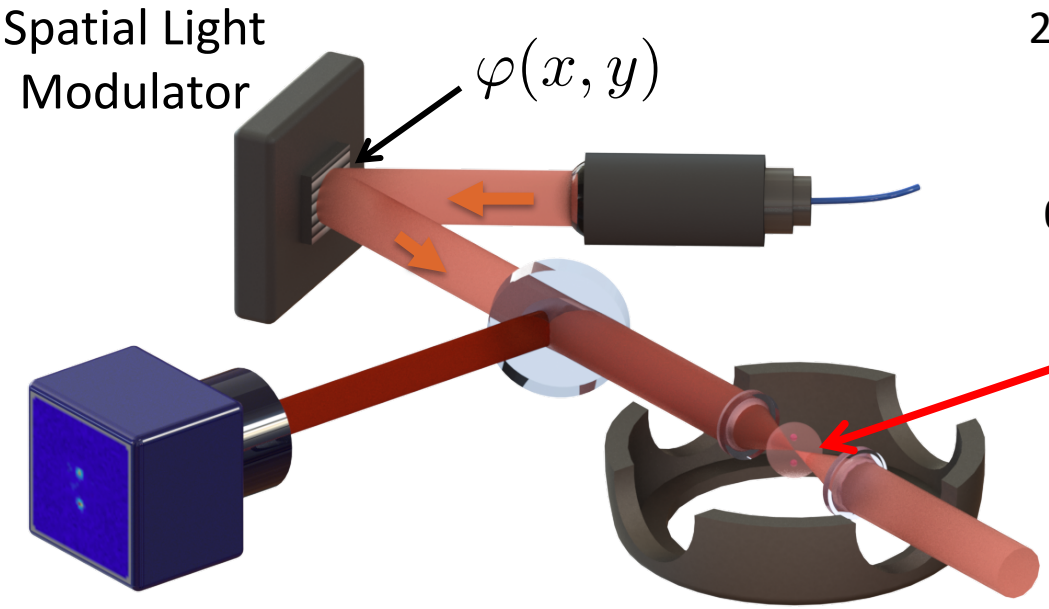

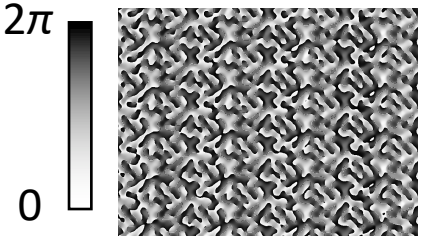

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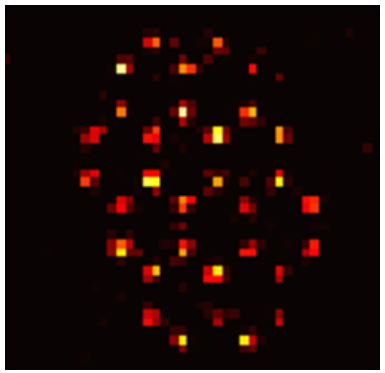
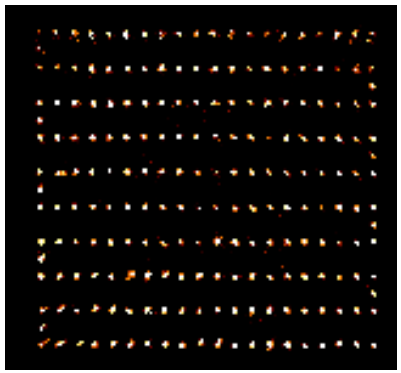
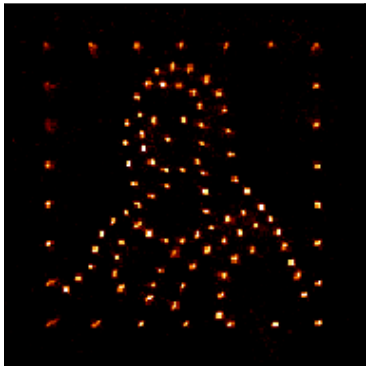
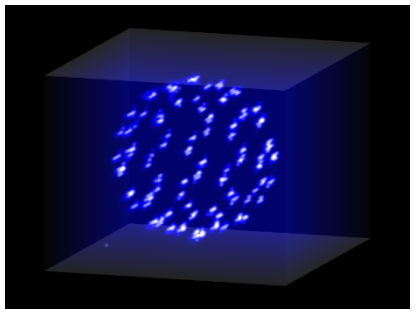




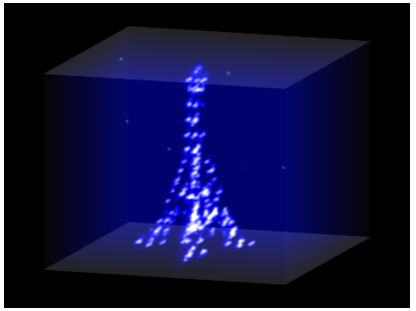


~100 μm

Barredo, Science (2016)



(averaged)



Barredo, Nature (2018)

Outline

A. Läuchli
M. Schuler
(Innsbruck)

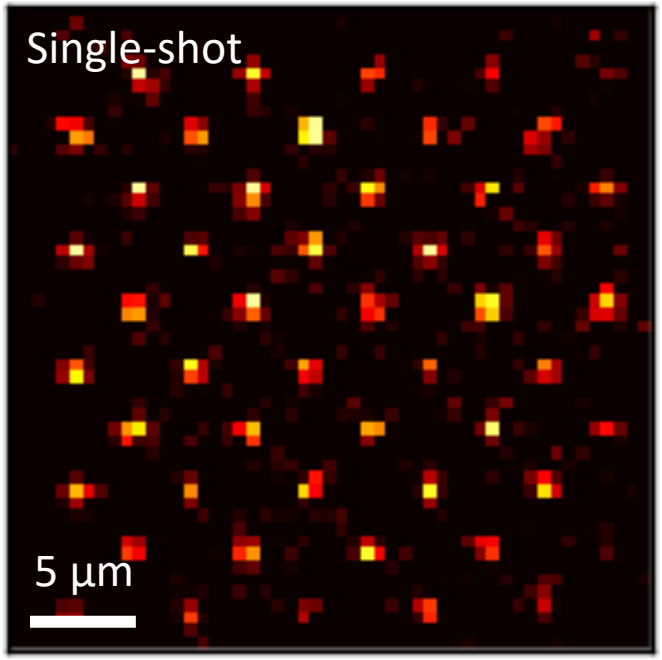
1. Magnetism: Ising model with van der Waals interactions

2. Topological matter with resonant dipole interactions

3. Collective light scattering and resonant dip. interactions

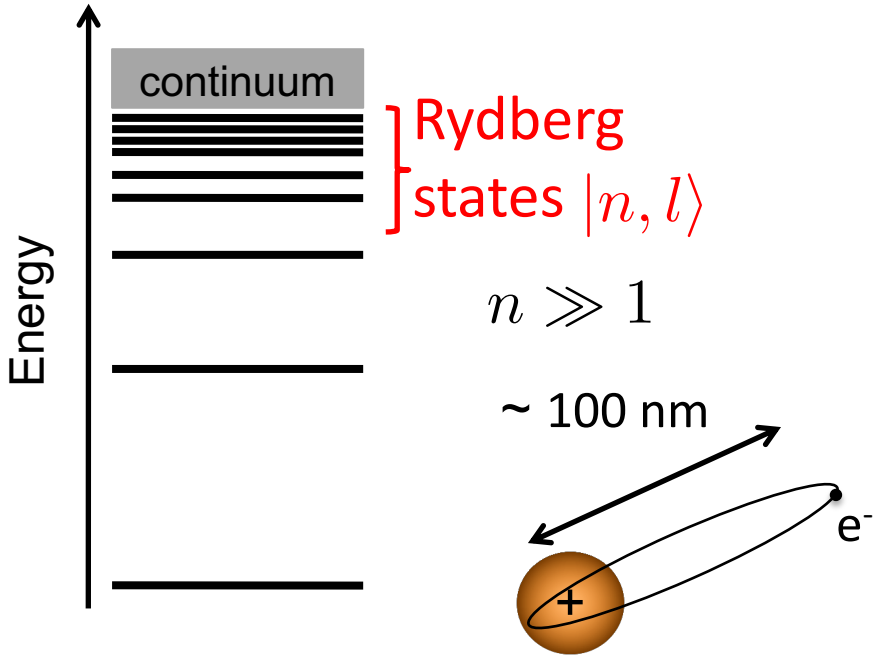
Arrays of interacting Rydberg atoms

Arrays of atoms



Addressable!!

Rydberg atoms



Lifetime > 100 µs

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

⇒ Large dipole-dipole interactions

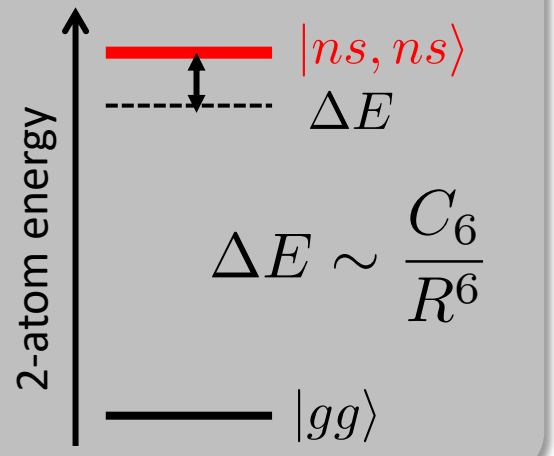
$$R = 10\ \mu\text{m} \Rightarrow V_{\text{int}}/h \sim 1 - 10\ \text{MHz}$$

⇒ timescales < µsec

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

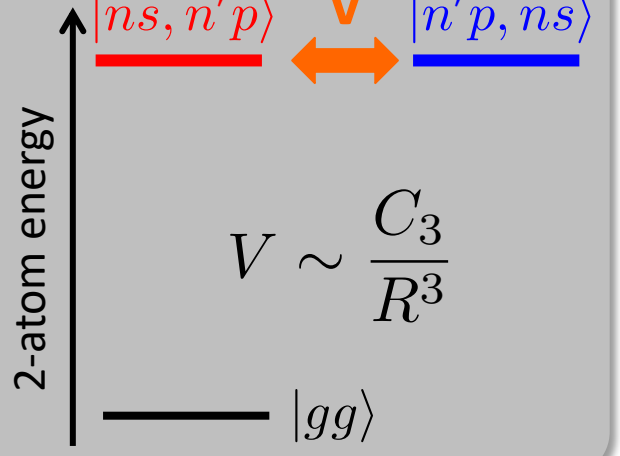
Interactions between Rydberg atoms

van der Waals



Ising-like model

Resonant dipole

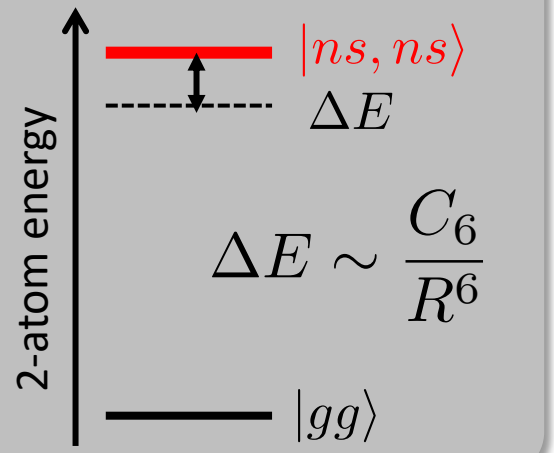


XY model

Browaeys & Lahaye, Nat.Phys. (2020)

From van der Waals interactions to Ising model…

van der Waals



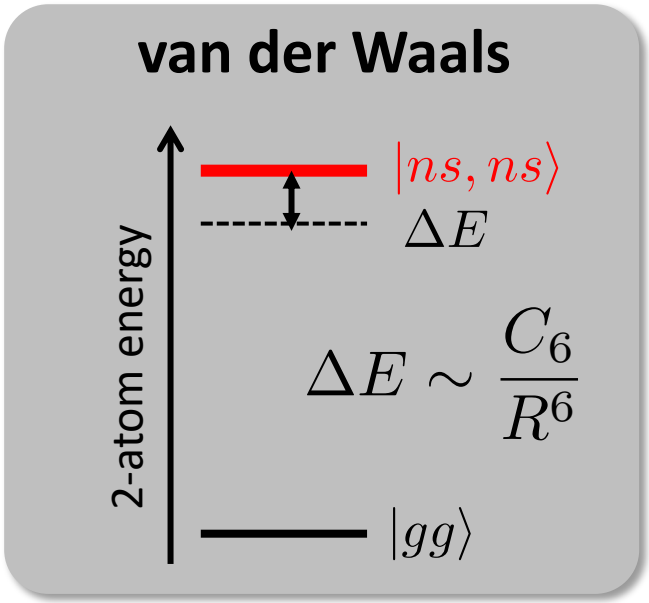
$$\Delta E \sim \frac{C_6}{R^6}$$

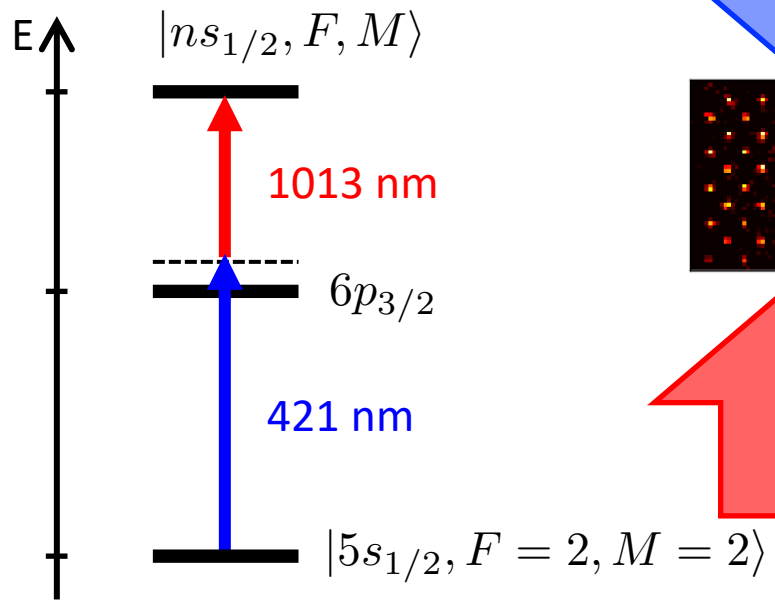
$C_6 \propto n^{11} \Rightarrow$ switchable interaction

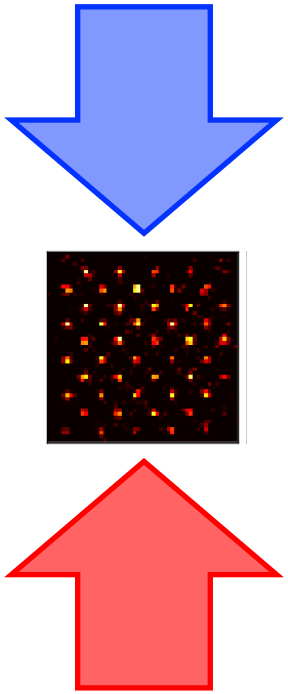
$$\hat{H}_{\text{int}} = \frac{C_6}{R^6}\hat{n}_1\hat{n}_2$$

Rydberg occupation number

From van der Waals interactions to Ising model…

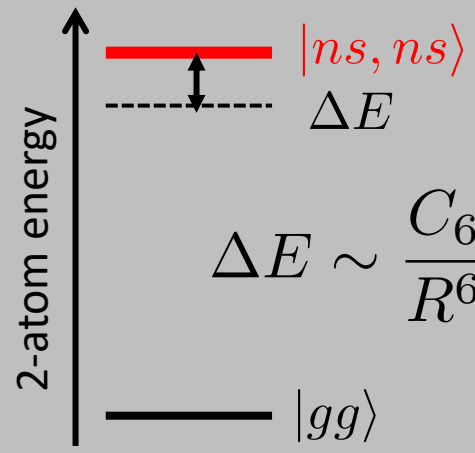




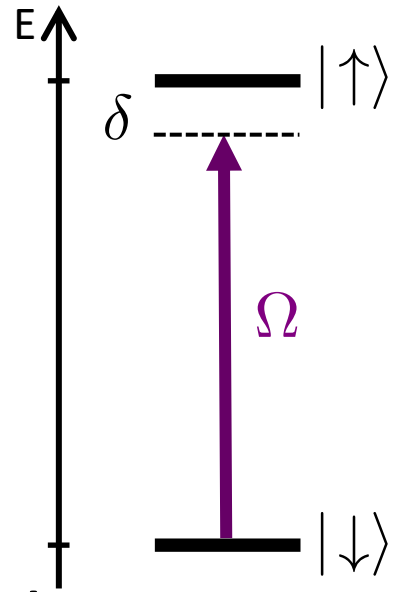


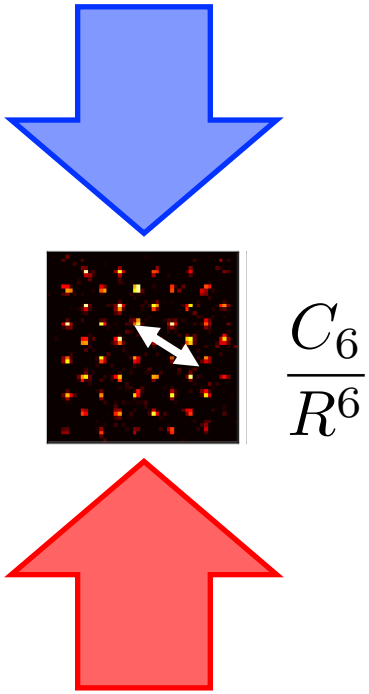
From van der Waals interactions to Ising model…

van der Waals



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





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**

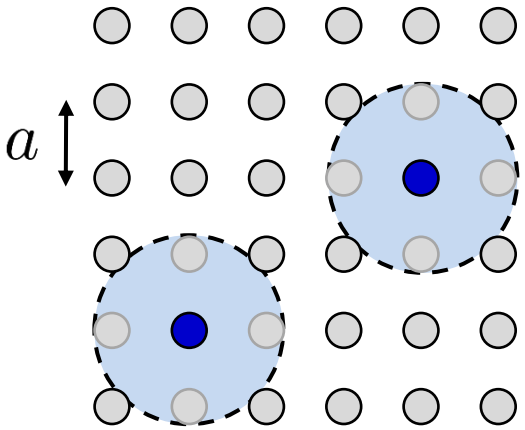
Experimt[t].

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

2D Ising anti-ferromagnet

Nearest neighb. interaction

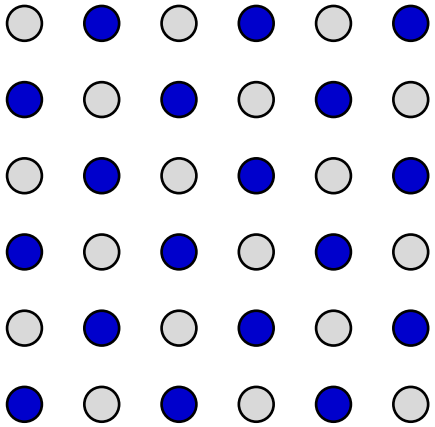
Anti-ferromagnetic ground state

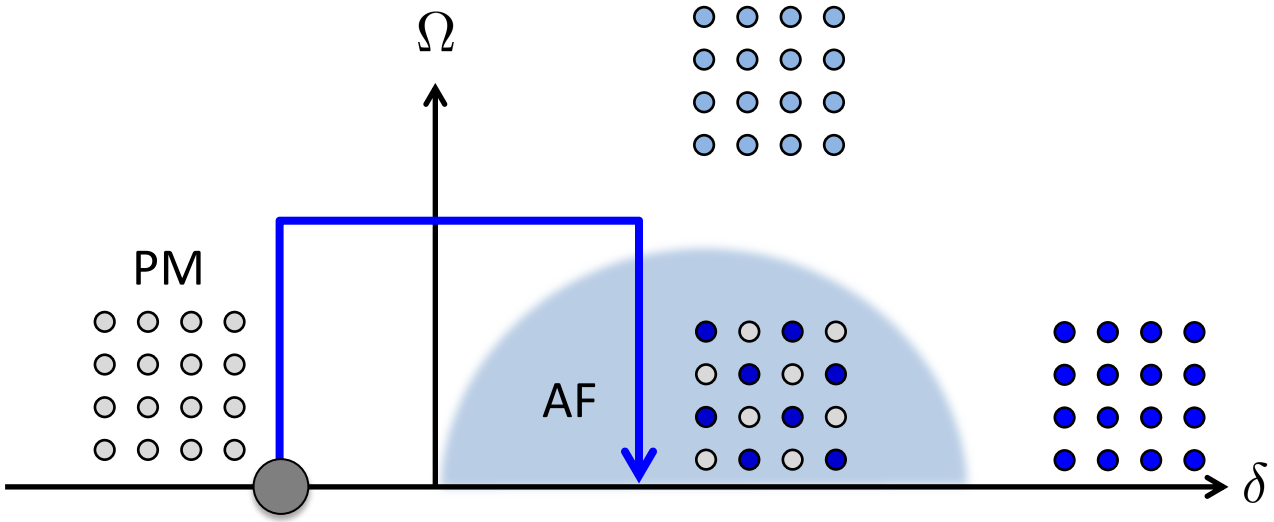


$$\frac{C_6}{a^6} \sim \Omega$$

$$\circ = |g\rangle$$

$$\bullet = |r\rangle$$



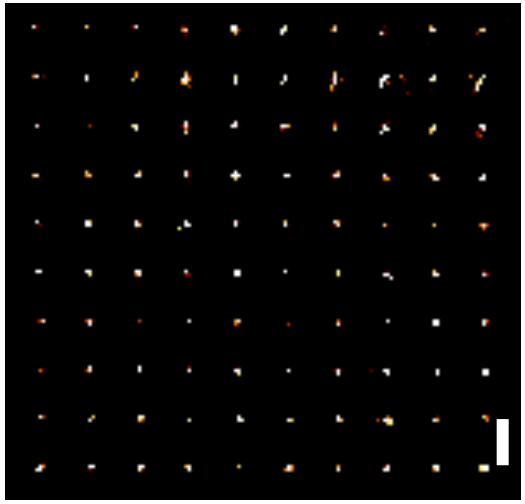


$$H = \sum_i \left(\frac{\hbar\Omega(t)}{2} \sigma_x^i - \hbar\delta(t)\hat{n}_i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} \hat{n}_i \hat{n}_j$$

Adiabatic preparation of a 2D Ising anti-ferromagnet

Work in progress

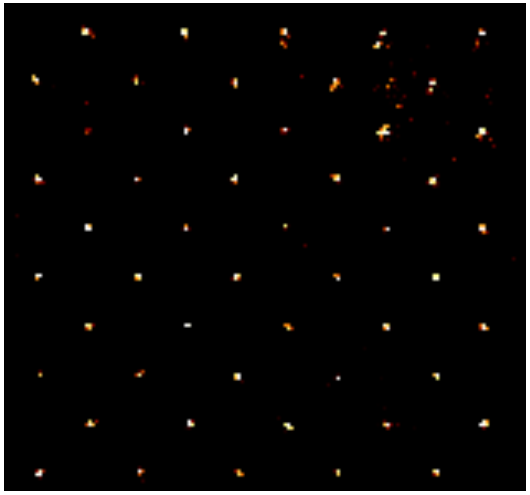
10 × 10 square array



10 µm

sweep

n=75s



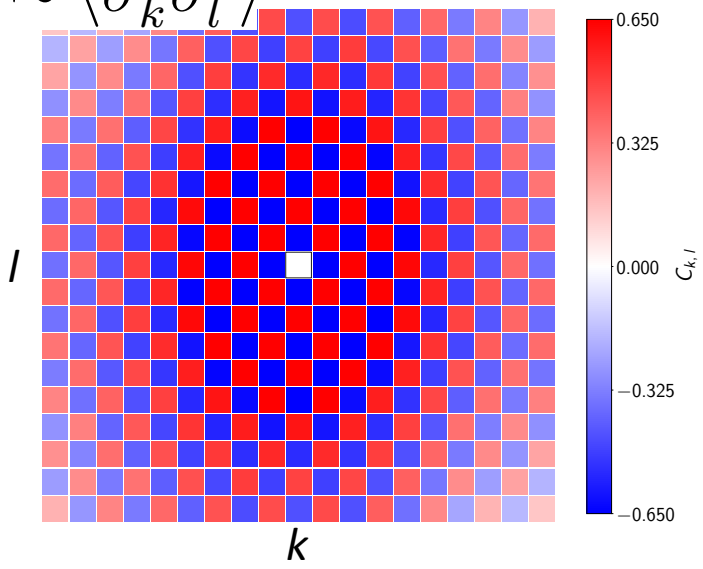
Early work in 2D: Lienhard PRX 2018, Bakr PRX 2018

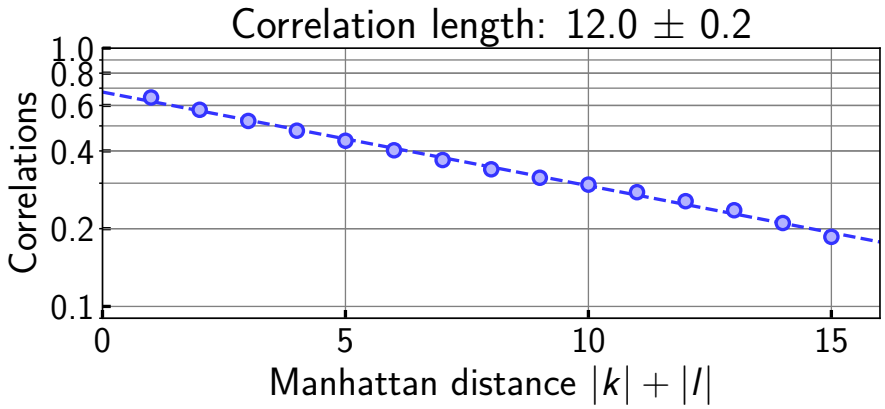
Missing atoms = Rydberg

Perfect AF (Néel) ordering!

(1 shot in 500)

$C_{k,l} \sim \langle \sigma_k^z \sigma_l^z \rangle$





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

Adiabatic preparation of a 2D Ising anti-ferromagnet

Early work in 2D: Lienhard PRX 2018, Bakr PRX 2018

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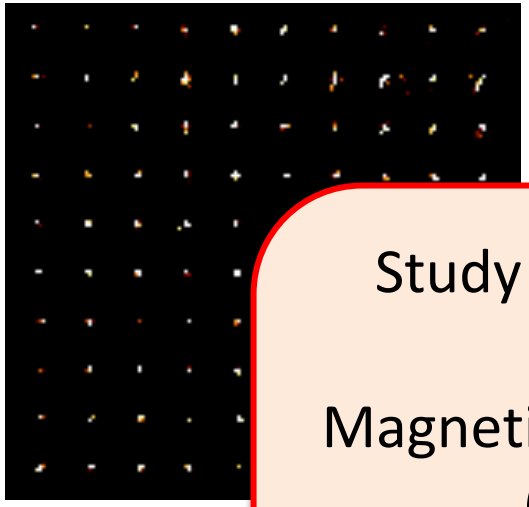
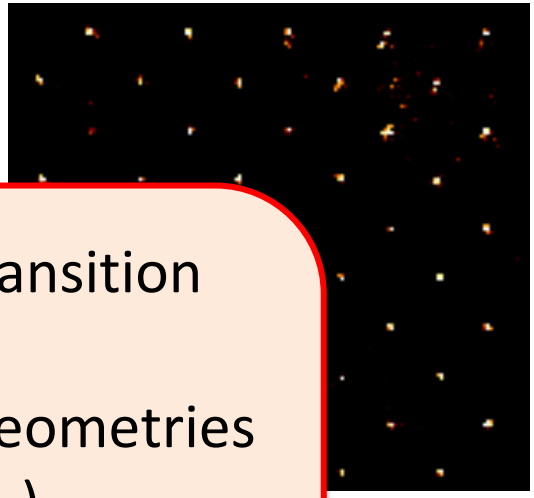
10×10 square array





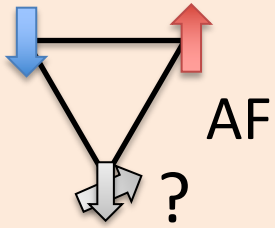
= Rydberg

l) ordering!

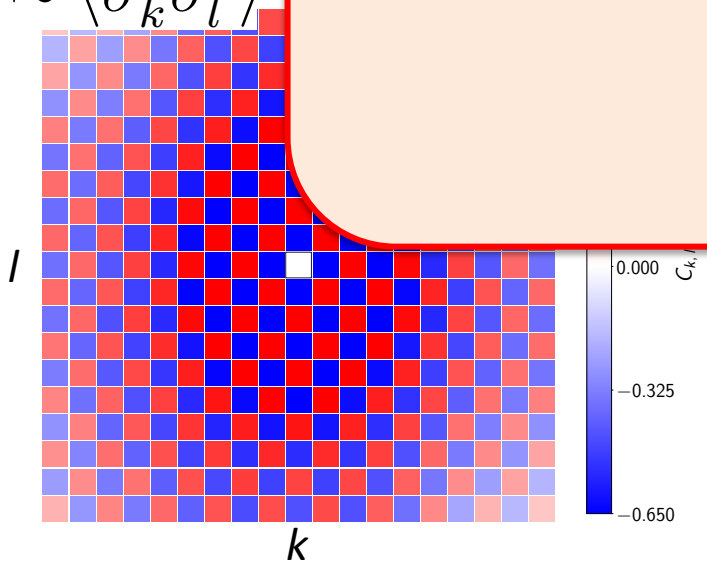
500)

Study quantum phase transition

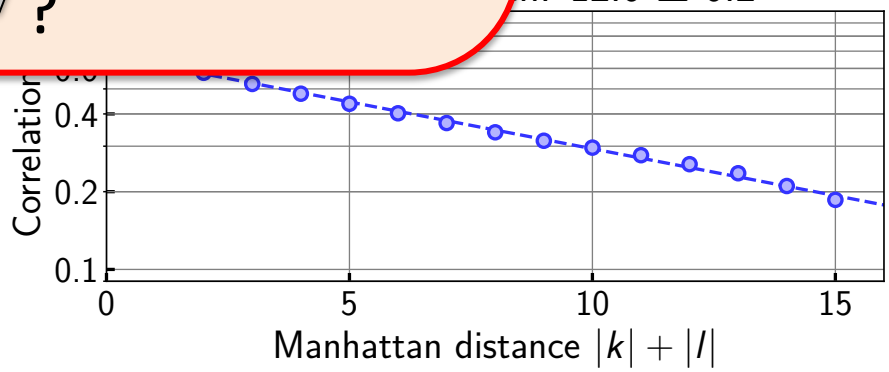
Magnetism in frustrated geometries (triangle, Kagomé…)



$C_{k,l} \sim \langle \sigma_k^z \sigma_l^z \rangle$



h: 12.0 ± 0.2



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

Outline

1. Magnetism: Ising model with van der Waals interactions

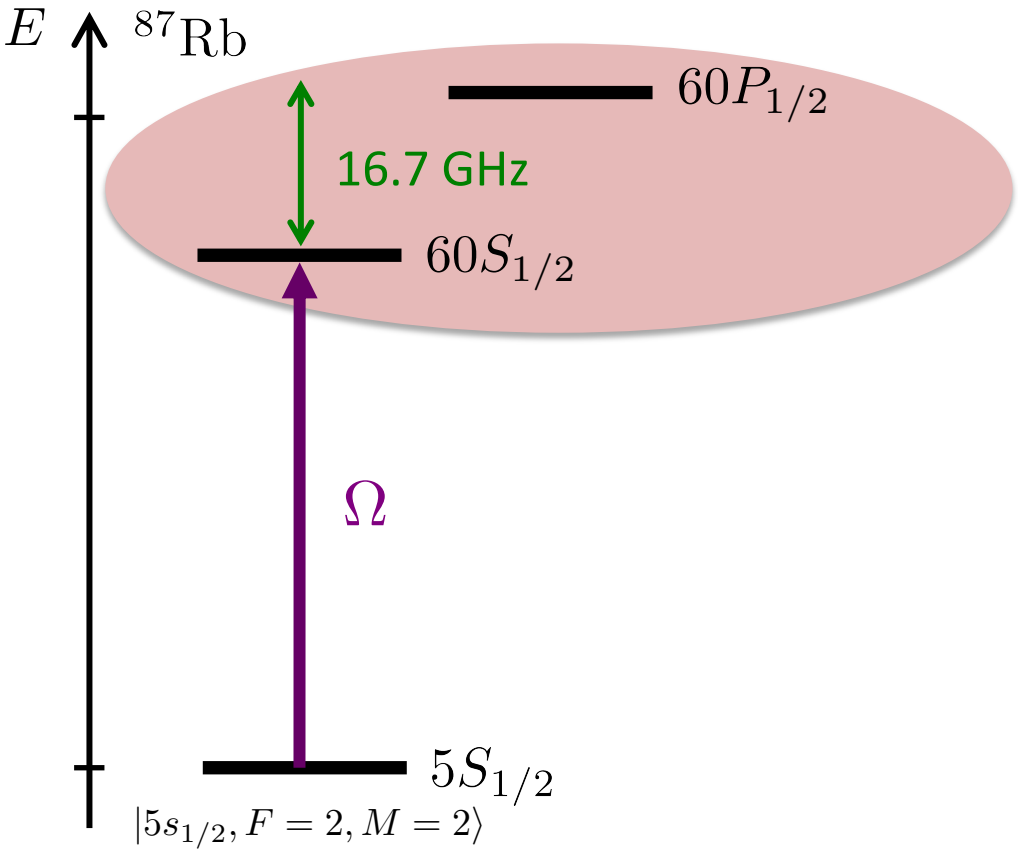
H.-P. Büchler
S. Weber, N. Lang

2. Topological matter with resonant dipole interactions

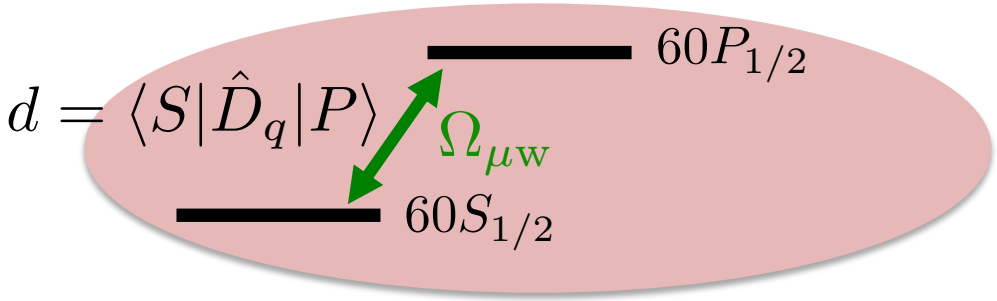
Science **365**, 775 (2019)

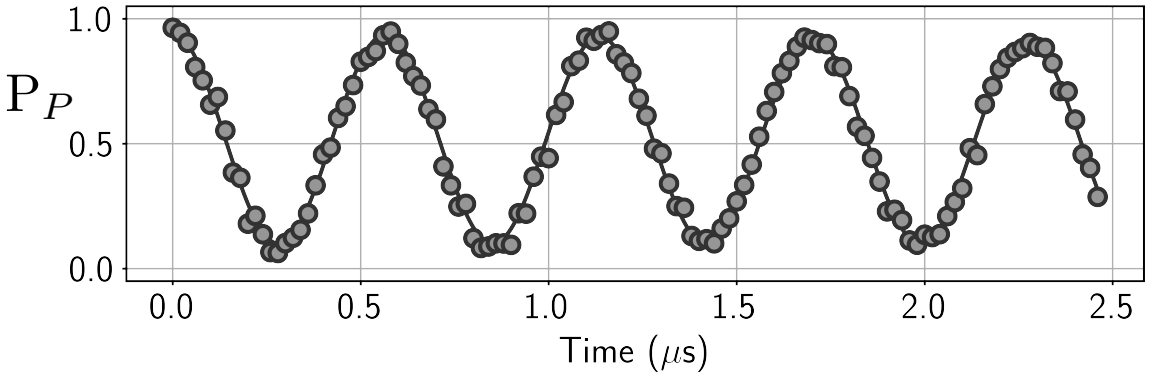
3. Collective light scattering and resonant dip. interactions

Resonant dipole-dipole interaction between Rydberg atoms



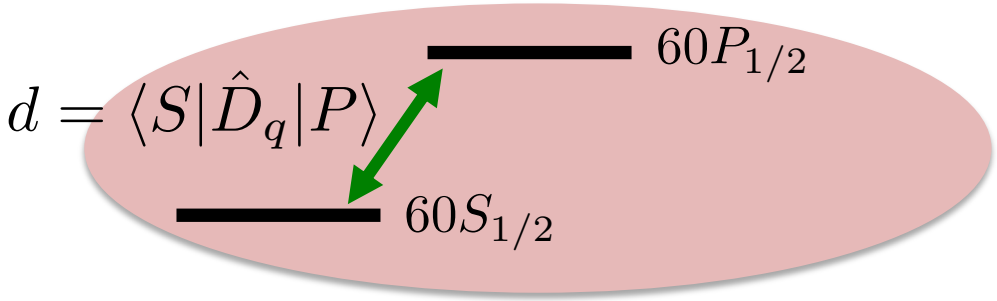
Resonant dipole-dipole interaction between Rydberg atoms





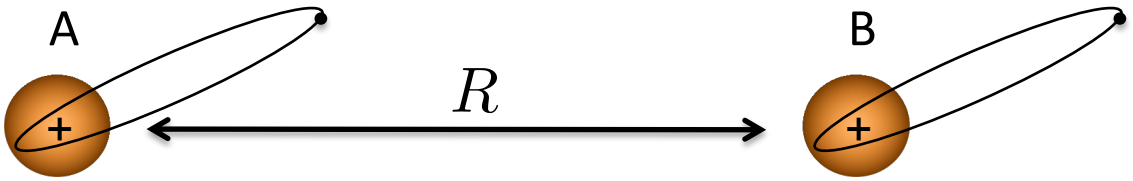
D. Barredo, PRL **114**, 113002 (2015)

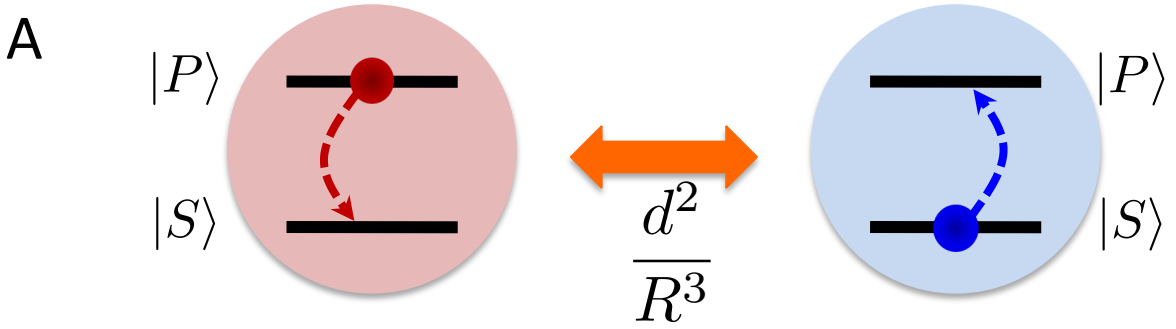
Resonant dipole-dipole interaction between Rydberg atoms



Mapping on spin ½ system:

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





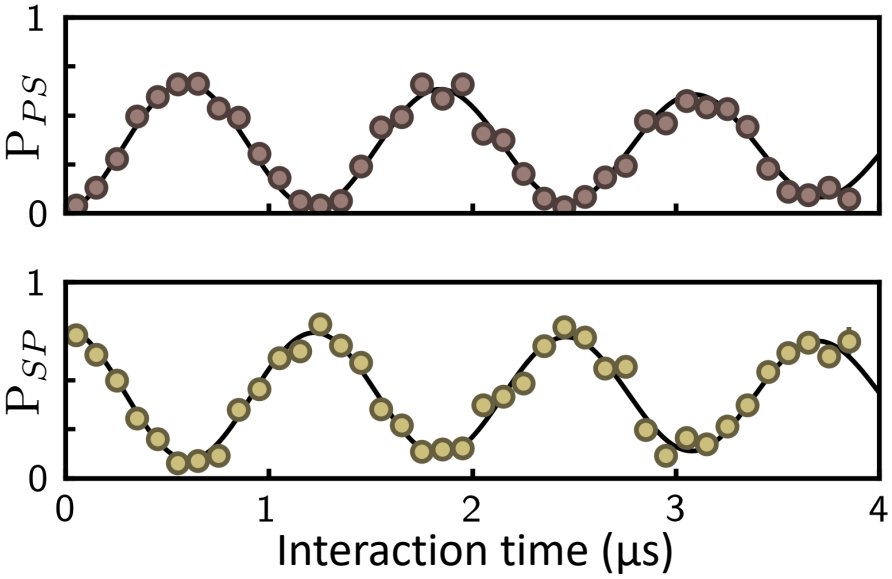
$$\hat{H} = \frac{d^2}{4\pi\epsilon_0 R^3}\left(\hat{\sigma}_A^+\hat{\sigma}_B^- + \hat{\sigma}_A^-\hat{\sigma}_B^+\right)$$

"exchange" of *P* excitation (XY model)

Resonant dipole-dipole interaction between Rydberg atoms

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

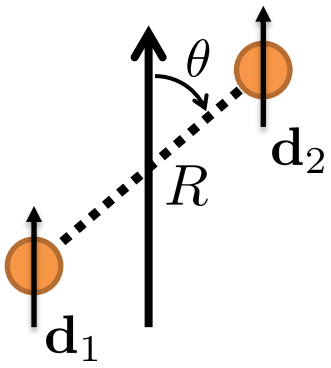
R = 30 µm



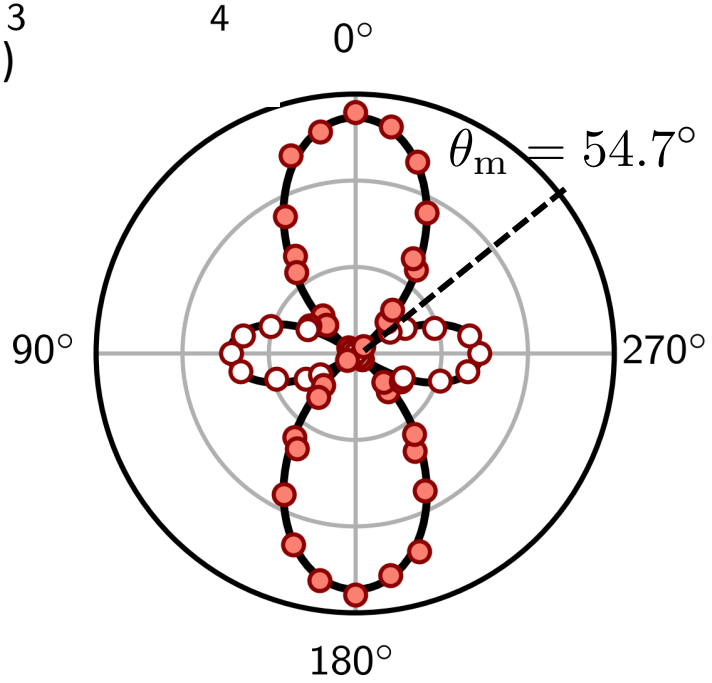
Barredo PRL (2015)
de Léséleuc, PRL (2017)

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

Quantization axis (B)



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



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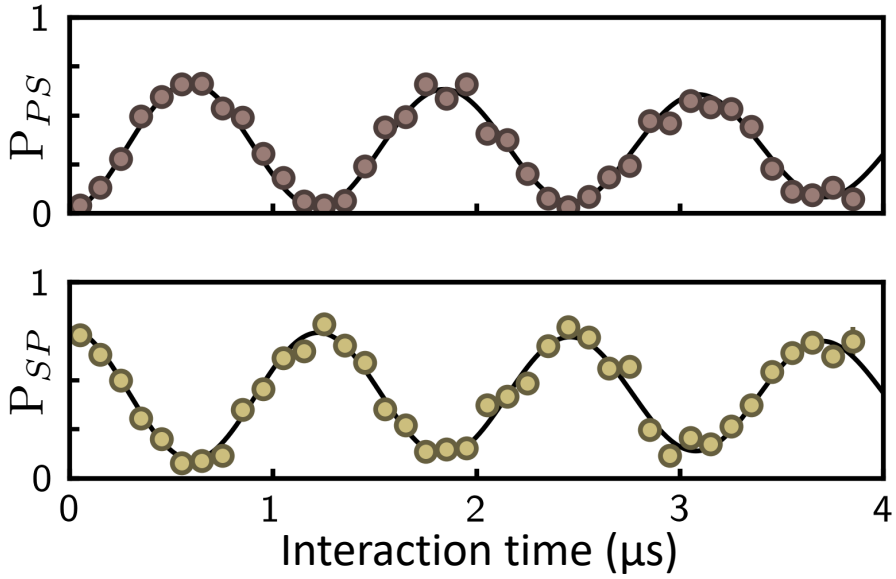
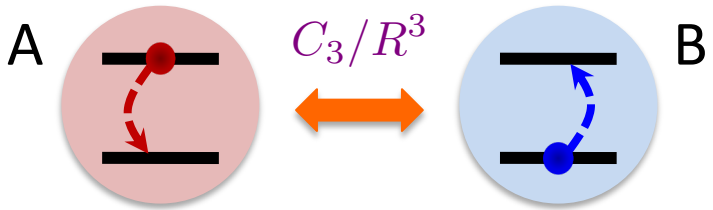
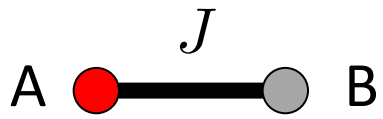


Barredo PRL (2015)
de Léséleuc, PRL (2017)

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



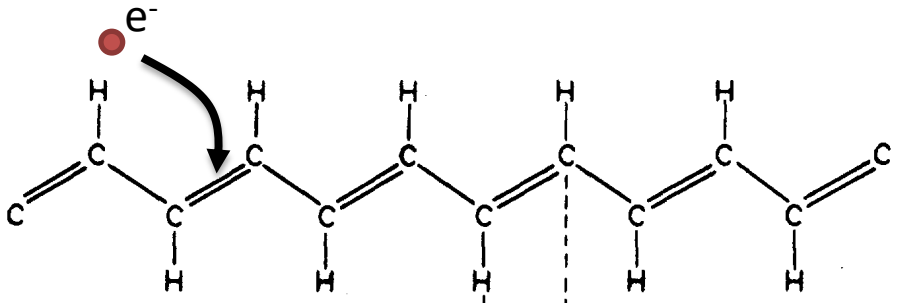
P excitation exchange



Particle hopping

$J|A\rangle\langle B|$

The Su-Schrieffer-Heeger model



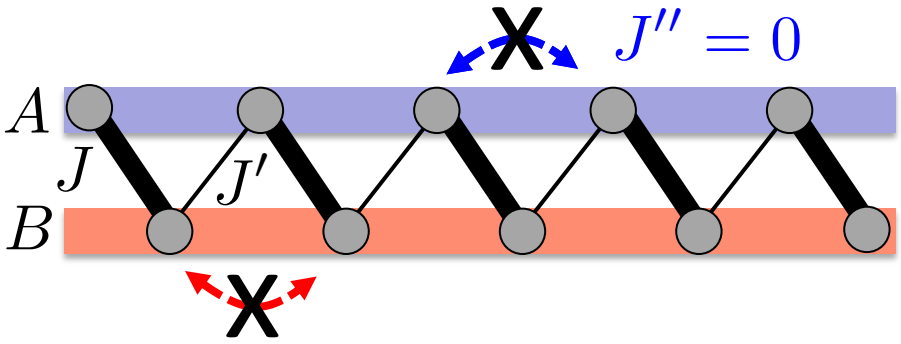
Electronic transport in polyacetylene

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

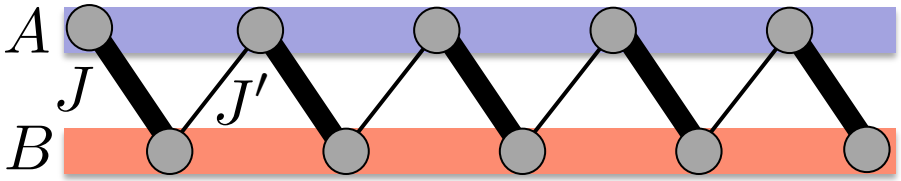


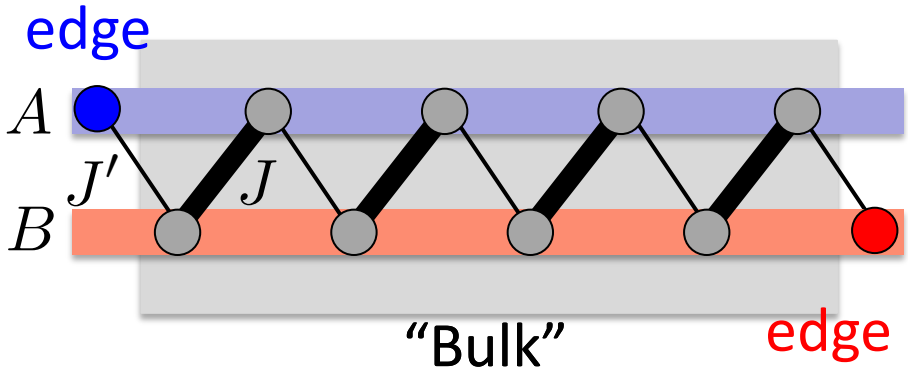
Model: tight-binding
dimerization: $J > J'$

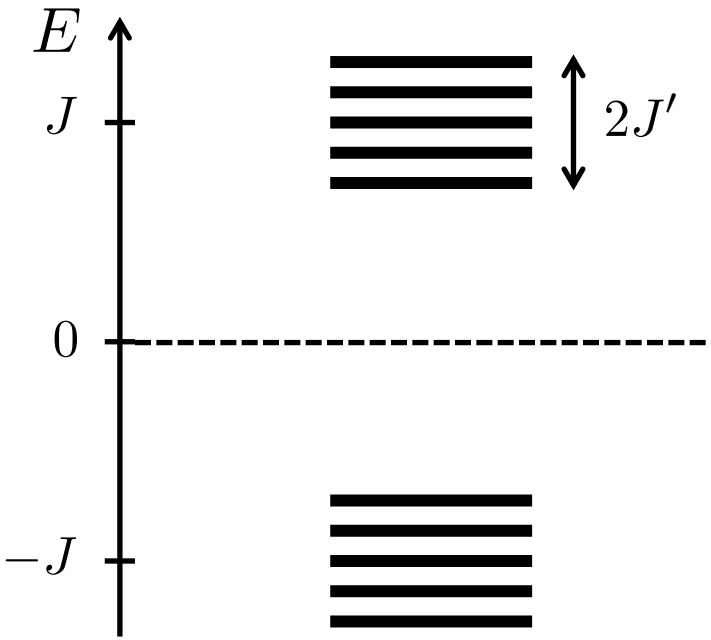
Sub-lattice symmetry $\Rightarrow$ symmetric **single particle** spectrum

Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

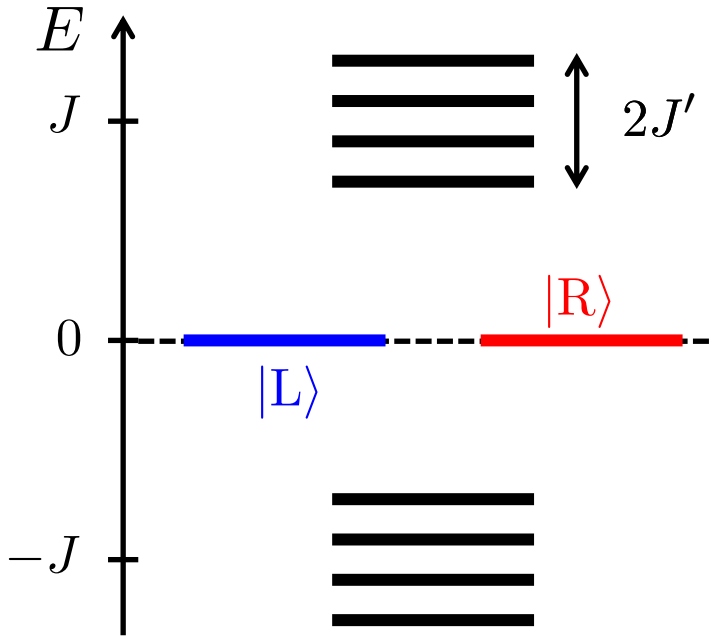
Single-particle SSH spectrum (finite chain): edge states







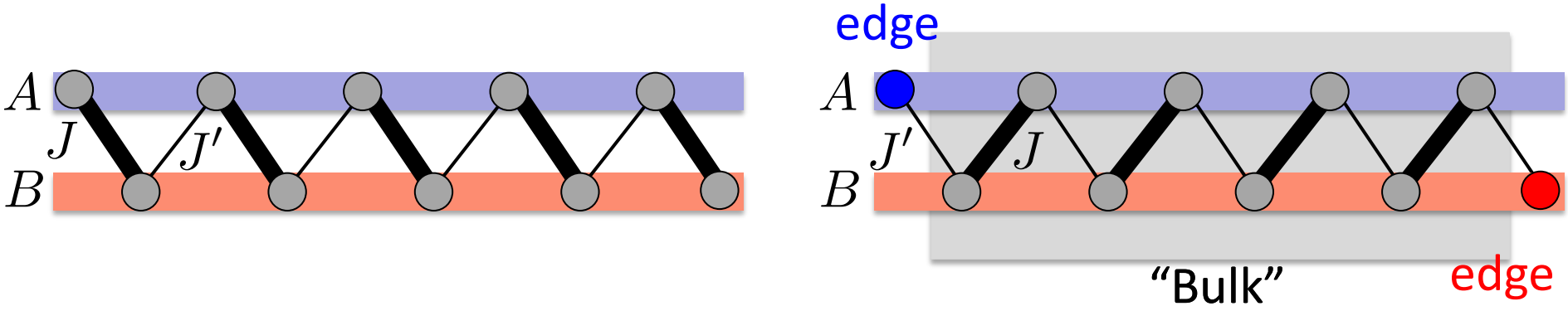
Normal

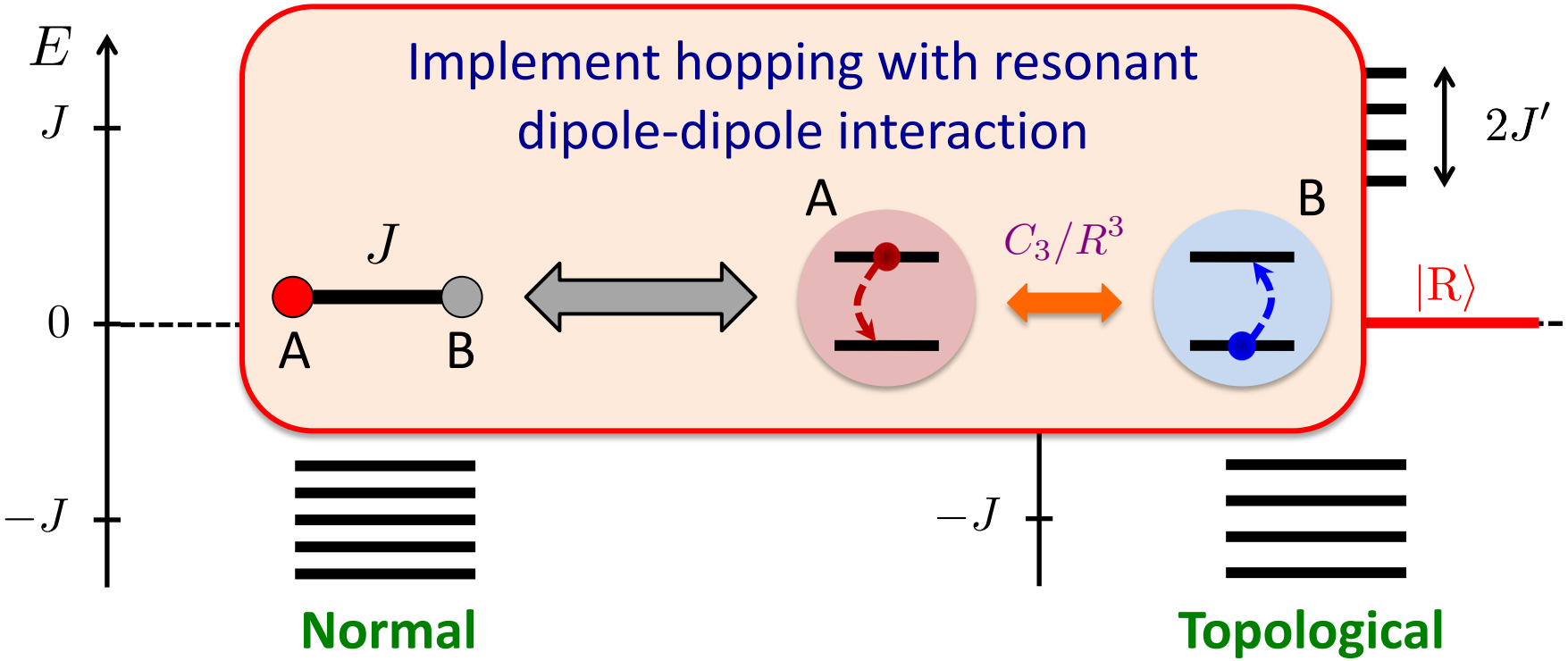


Topological

Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

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

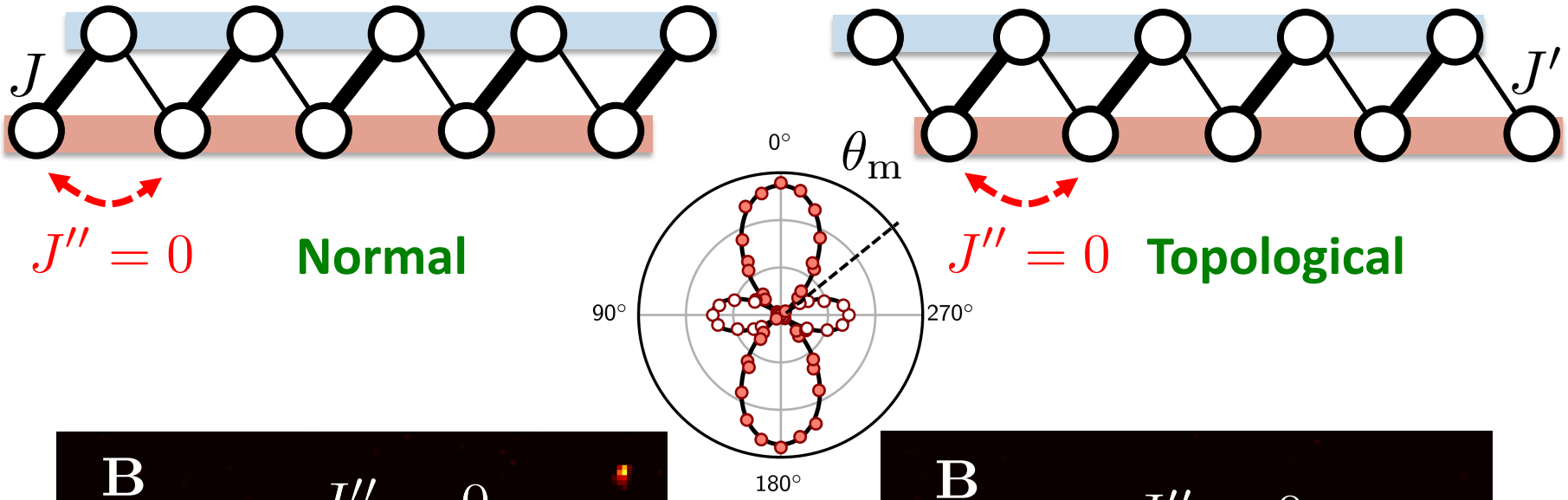


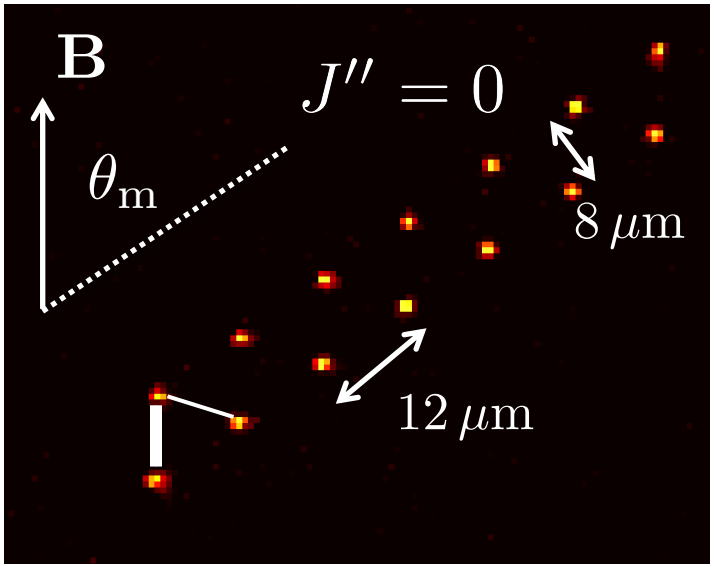


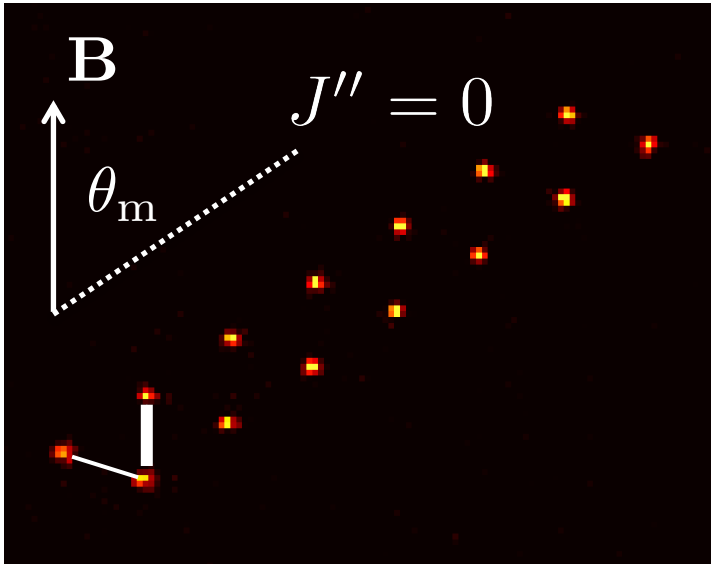
Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

Implementation of SSH spin chain with Rydberg atoms

Science **365**, 775 (2019)

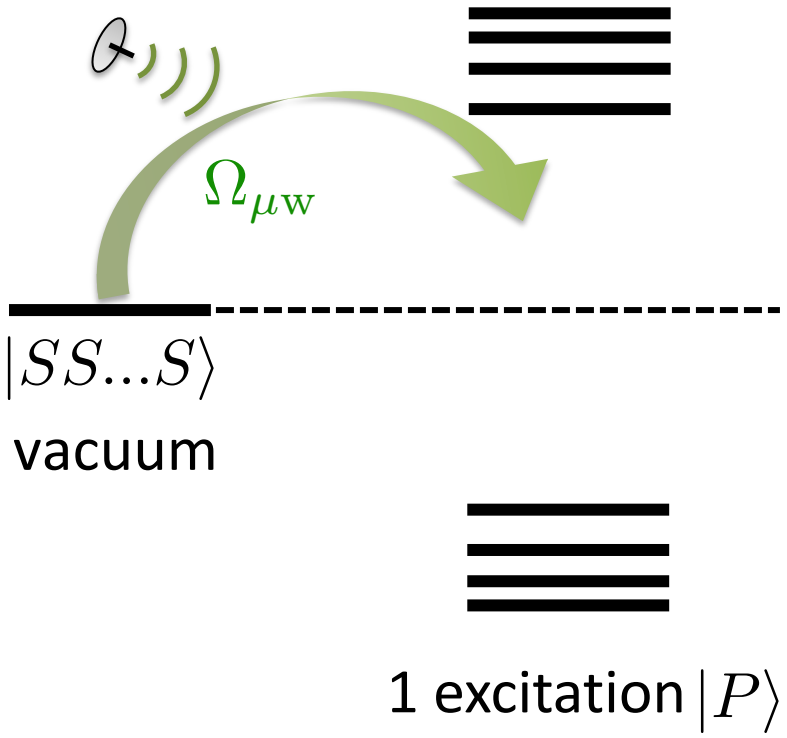


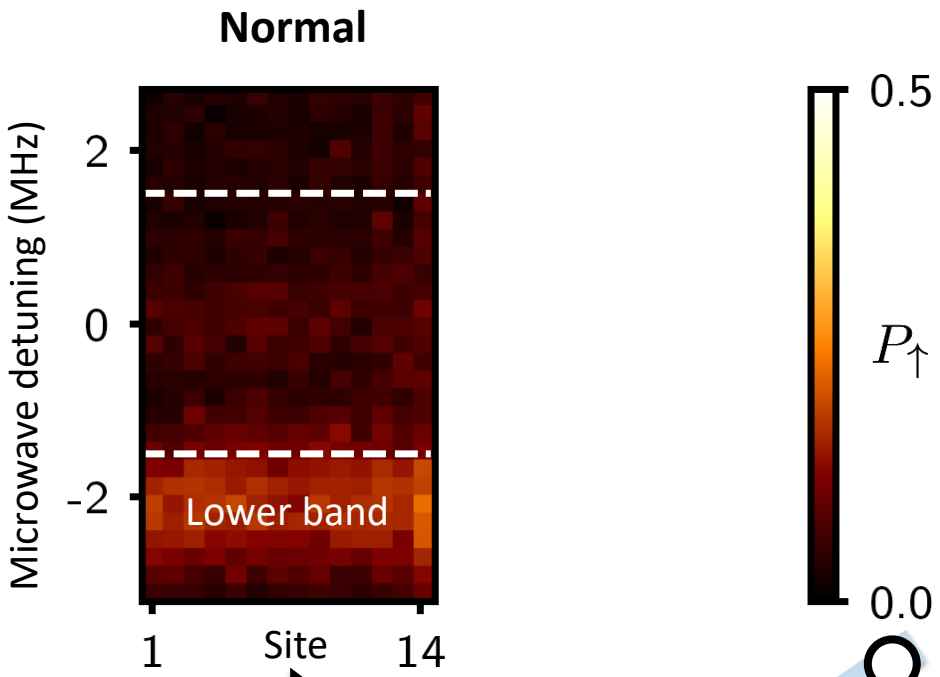


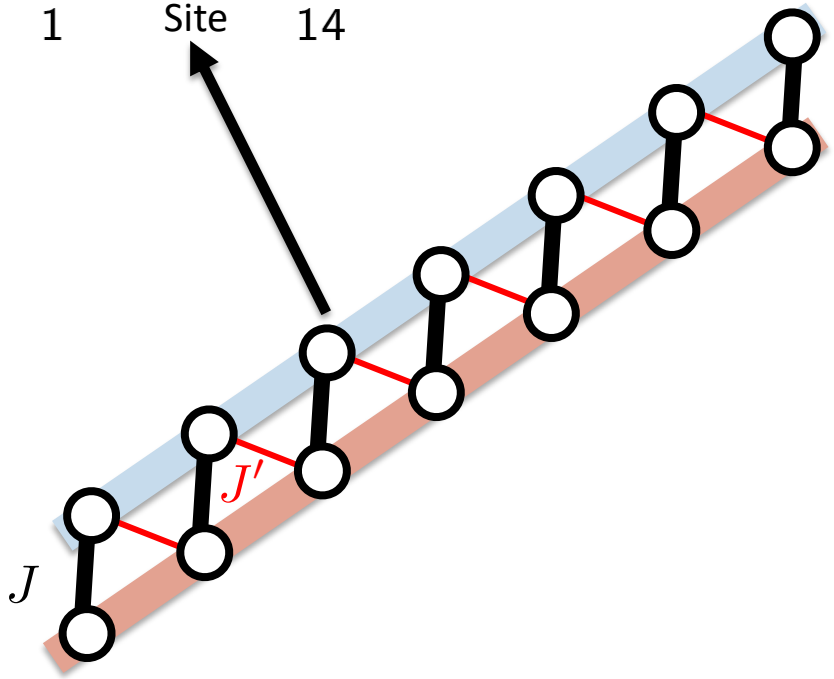


$J/h = 2.4\,\mathrm{MHz}$ $J'/h = -0.9\,\mathrm{MHz}$

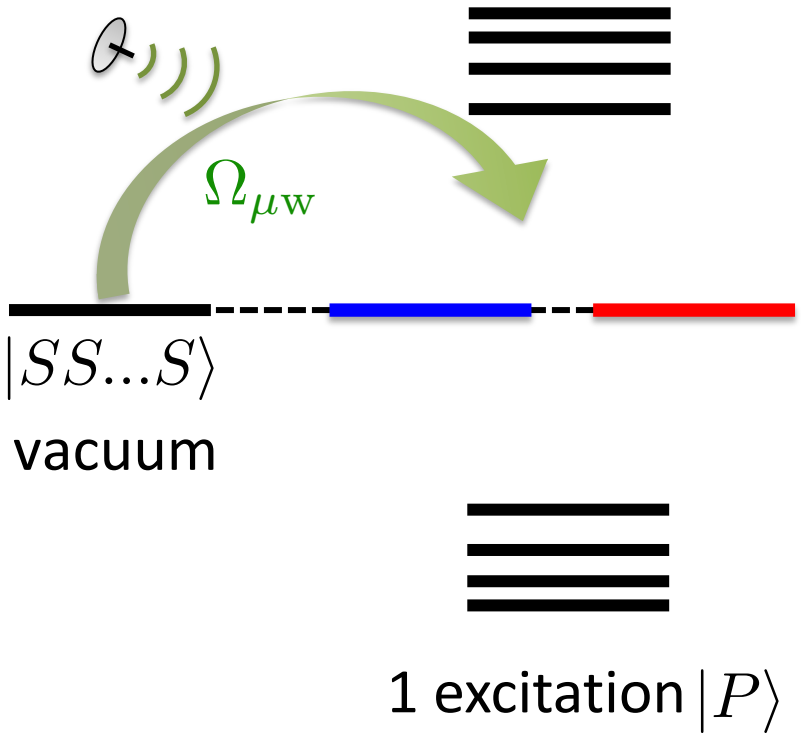
Probing the single-particle SSH spectrum

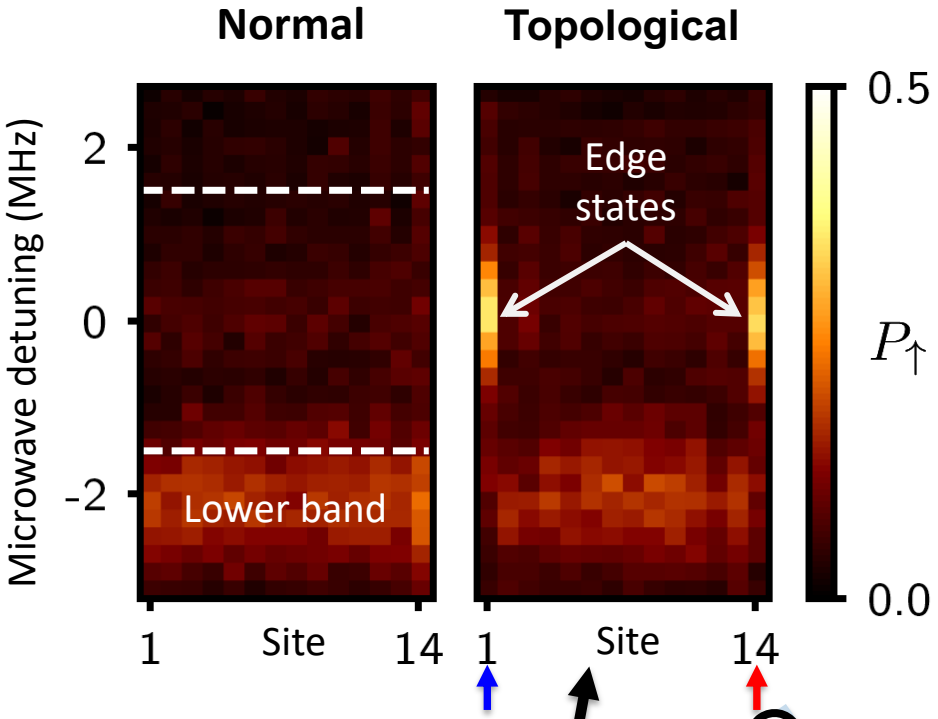


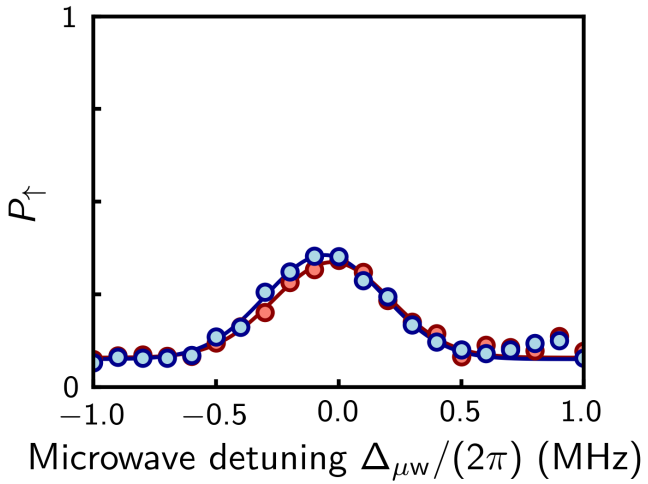


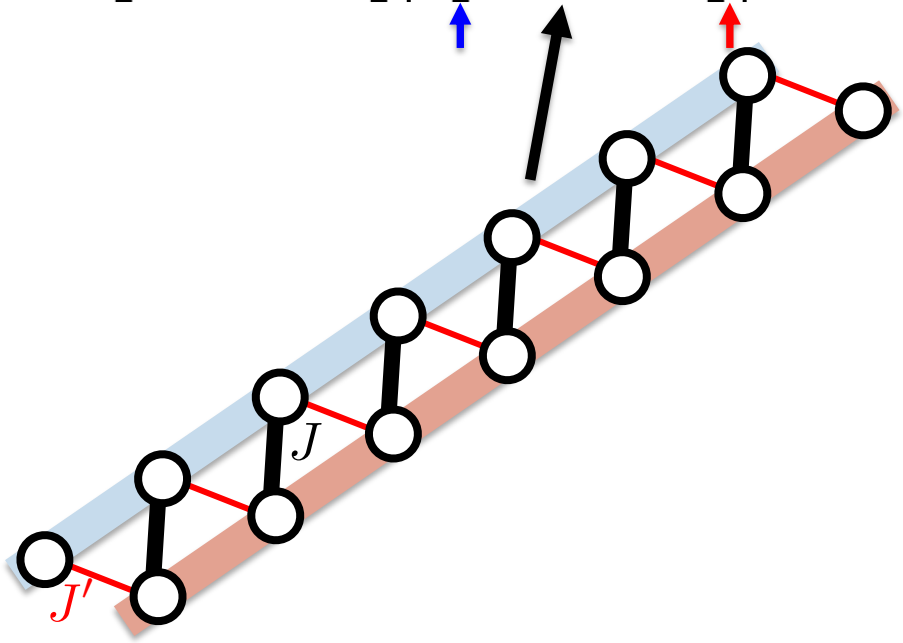


Probing the single-particle SSH spectrum

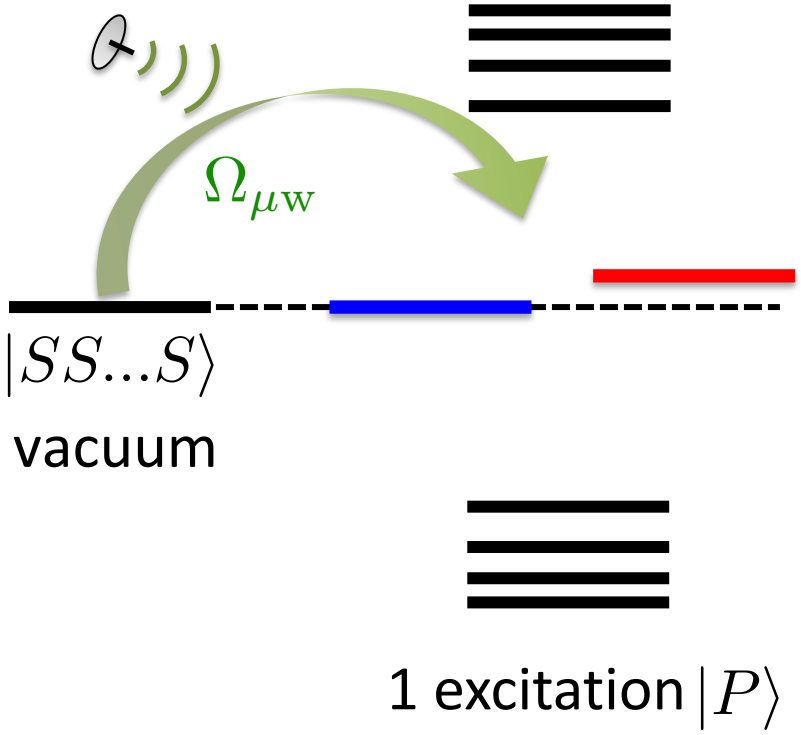




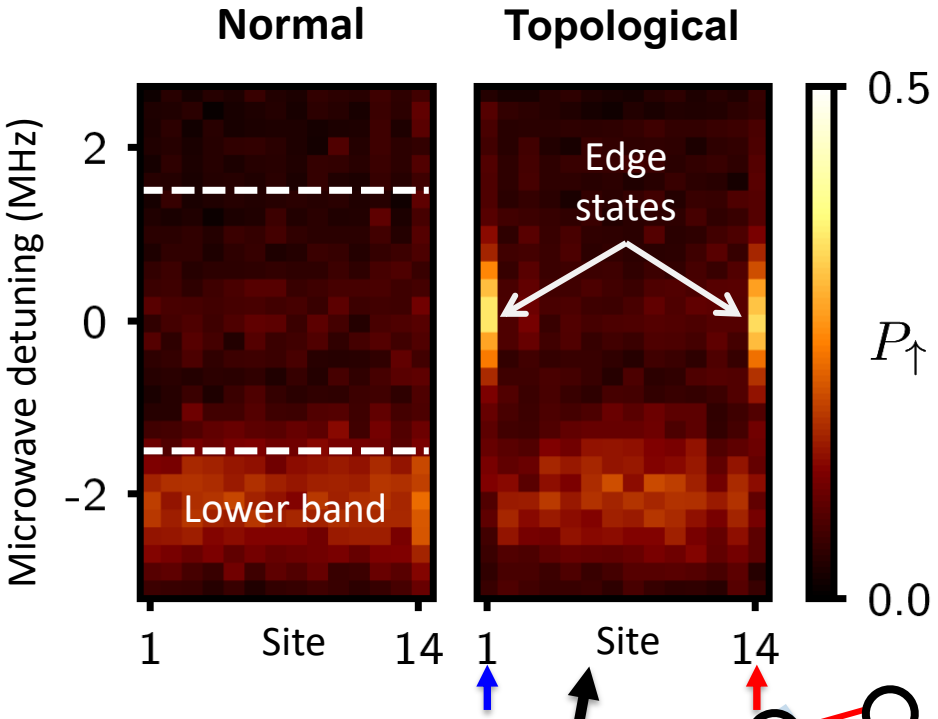


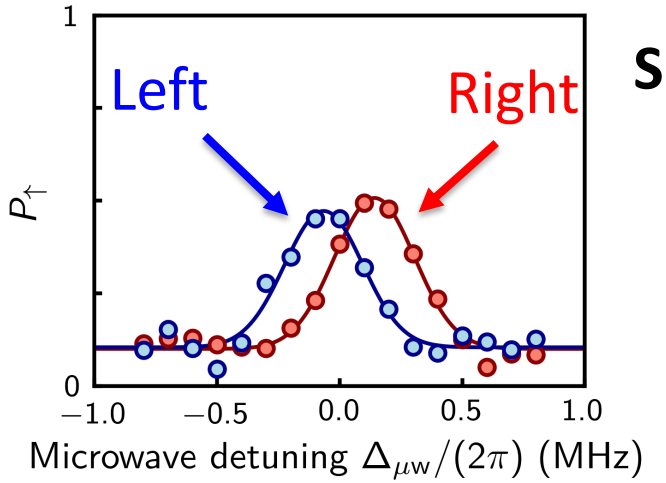


Probing the single-particle SSH spectrum

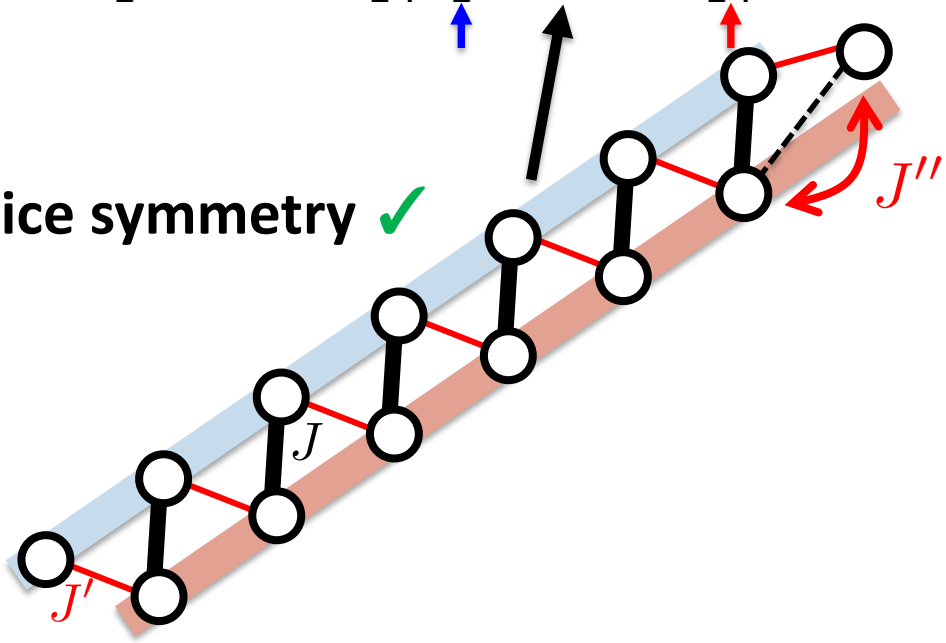


1 excitation $|P\rangle$

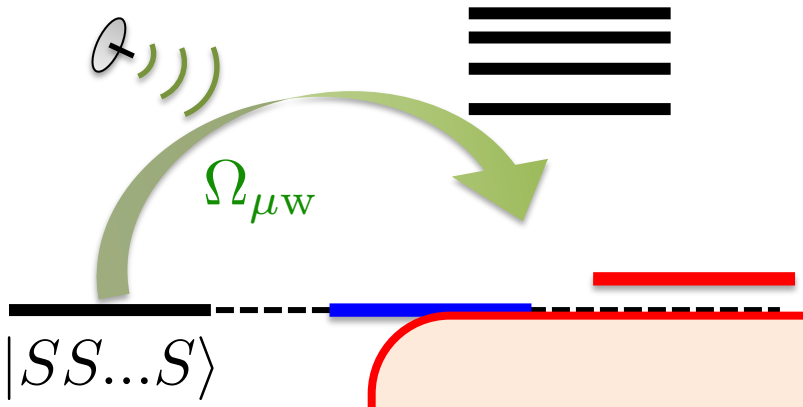


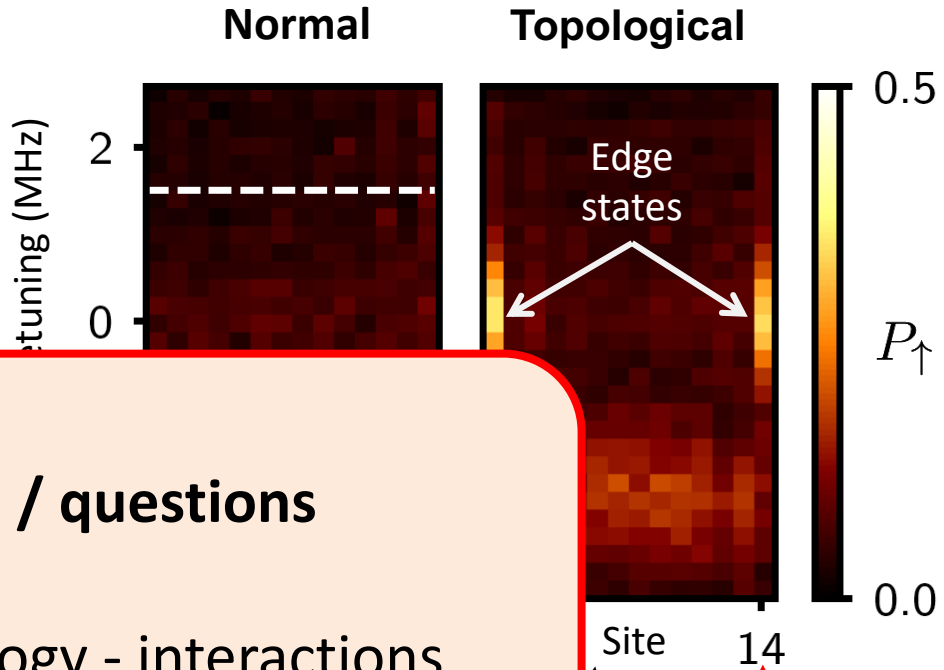


Sub-lattice symmetry ✓



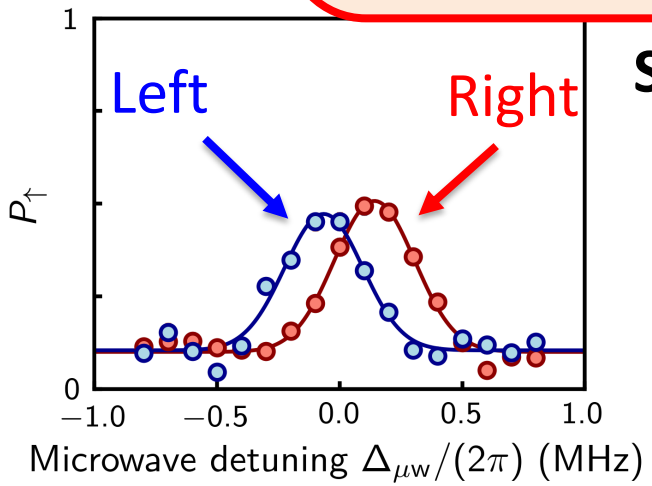
Probing the single-particle SSH spectrum



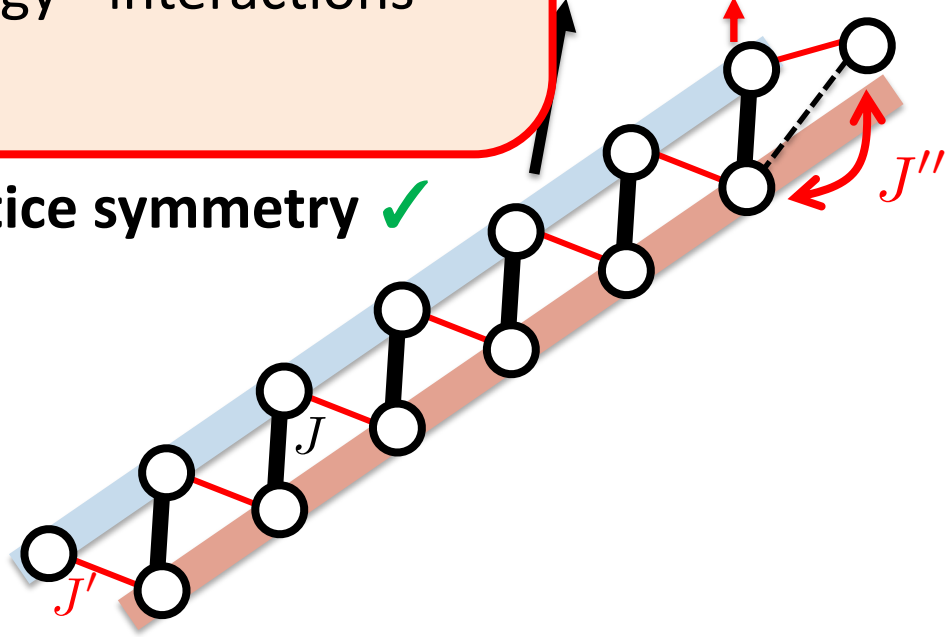


Challenge / questions

interplay topology - interactions



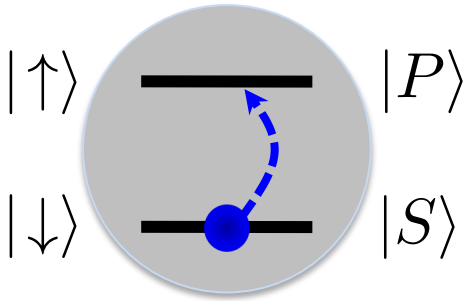
Sub-lattice symmetry ✓



Spin excitations are interacting particles!

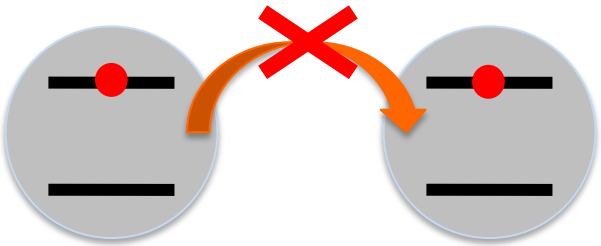
Mapping

Spin excitation = “particle”



Carusotto PRA 2016
Fleischhauer PRA 2013
…

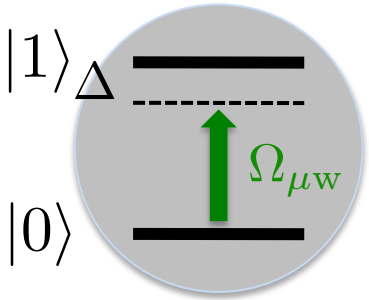
Atom cannot carry 2 excitations ⇒ excitations = **hard-core bosons**

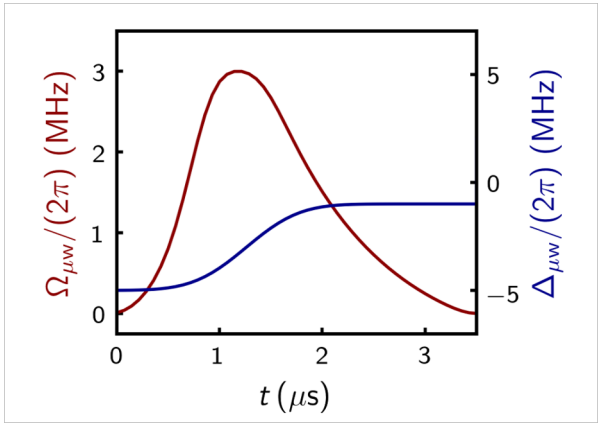


On-site interaction

$$U \to \infty$$

μW sweep ⇒ add excitations 1 by 1 ⇒ ground state of interacting SSH





A symmetry protected topological phase

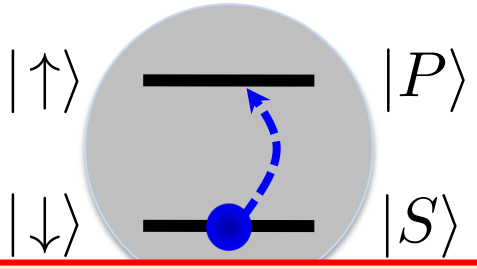
= only possible topological order in 1d

Science **365**, 775 (2019)

Spin excitations are interacting particles!

Mapping

Spin excitation = “particle”



Carusotto PRA 2016
Fleischhauer PRA 2013
…

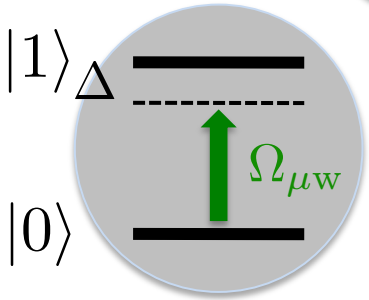
Atom cannot

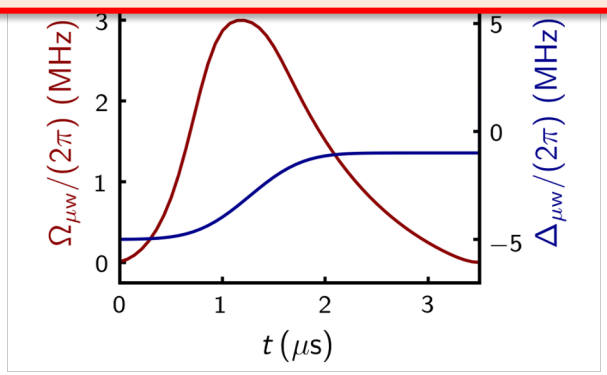
core bosons

ction

μW sweep ⇒ a

nteracting SSH



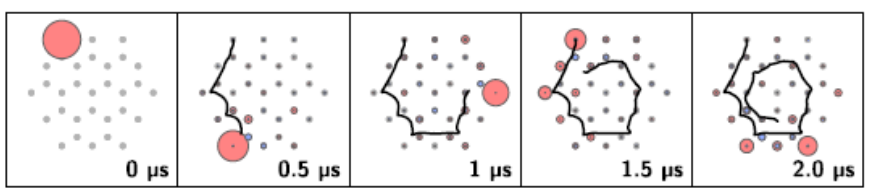


Symmetry protected topological phase

= only possible topological order in 1d

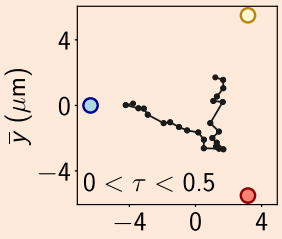
Science **365**, 775 (2019)

Towards topology in 2D



Weber, QST **3**, 044001 (2018)

Spin-orbit coupling:



Lienhart, PRX (2020)

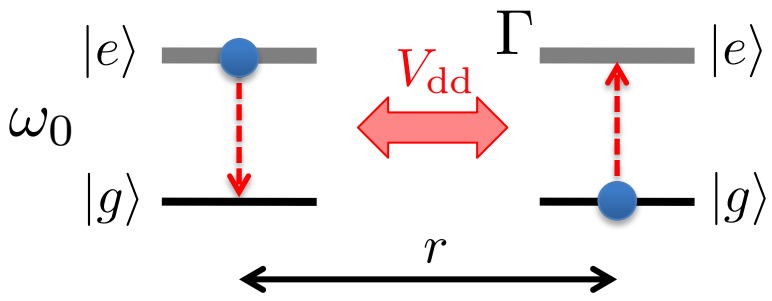
Outline

1. Magnetism: Ising model with van der Waals interactions

2. Topological matter with resonant dipole interactions

3. Collective light scattering and resonant dip. interactions

Resonant dipole interaction: near-field vs. far-field



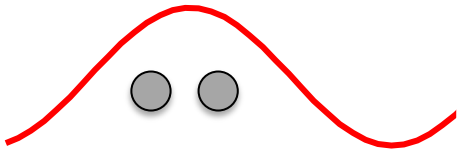
Kiffner, Progress in optics **55**, 85 (2010)

$$\hat{H} = V_{\rm dd}\left(\hat{\sigma}_A^+\hat{\sigma}_B^- + \hat{\sigma}_A^-\hat{\sigma}_B^+\right)$$

Non hermitian!

Lengthscales: r and $\lambda_0 = 2\pi c/\omega_0$

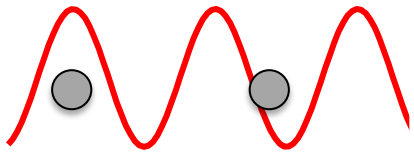
$r \ll \lambda_0$



$$V_{\rm dd} = \frac{d_{eg}^2}{4\pi\epsilon_0 r^3} \quad \Rightarrow \text{“}\textbf{coherent}\text{” interaction}$$

Rydberg: microwave $\lambda_0 \sim \mathrm{mm}, \mathrm{cm}$

$r \gtrsim \lambda_0$ $\quad k = 2\pi/\lambda_0$

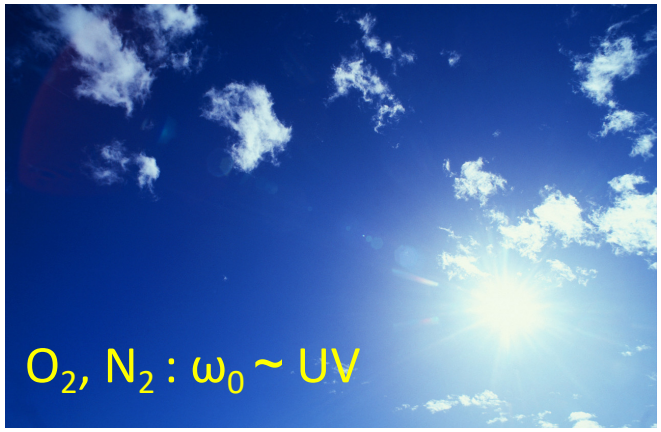


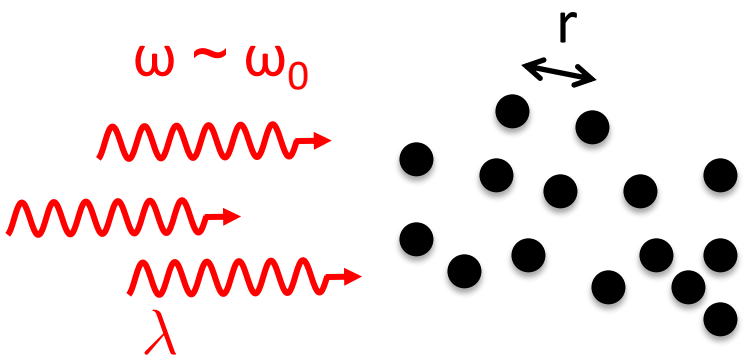
$$V_{\rm dd} = \frac{d_{eg}^2 k^3}{4\pi\epsilon_0} e^{ikr}\left[\left(\frac{1}{(kr)^3} - \frac{i}{(kr)^2}\right) - \frac{1}{kr}\right]$$

$\Rightarrow$ Collective dissipative spin models $\quad \mathrm{Re}[V_{\rm dd}] \sim \mathrm{Im}[V_{\rm dd}] \sim \Gamma$

Optical transition: $\lambda_0 \sim \mu\mathrm{m}$ + Photons!!

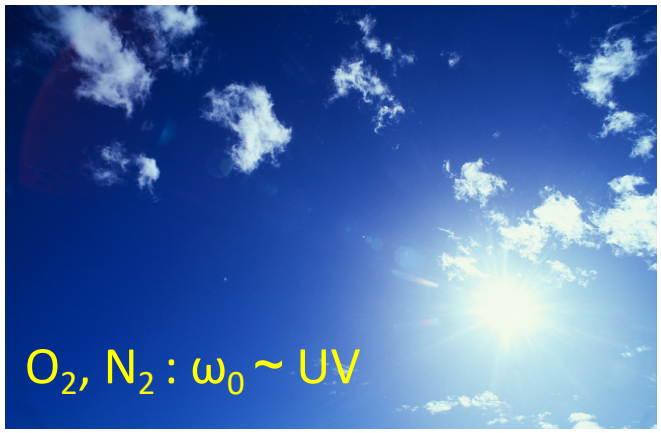
Light scattering in dense media and dipole interactions

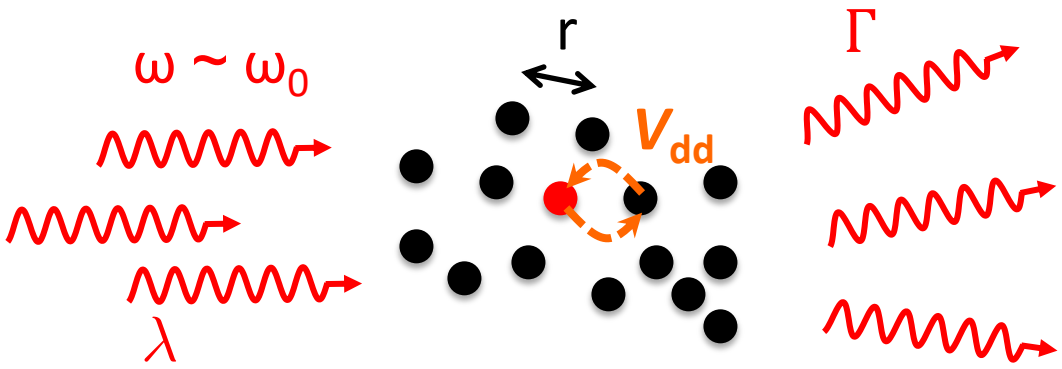




?

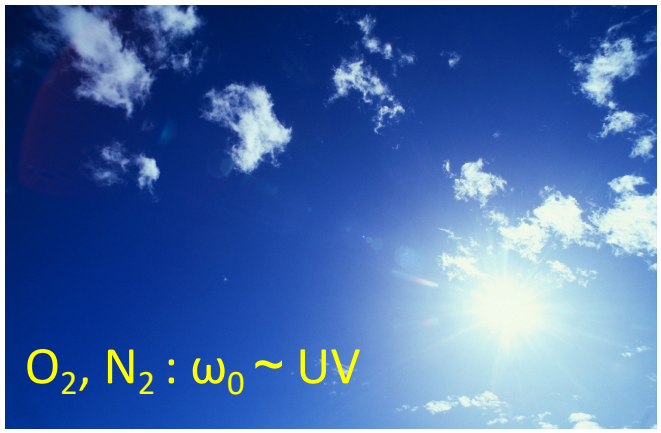
Light scattering in dense media and dipole interactions

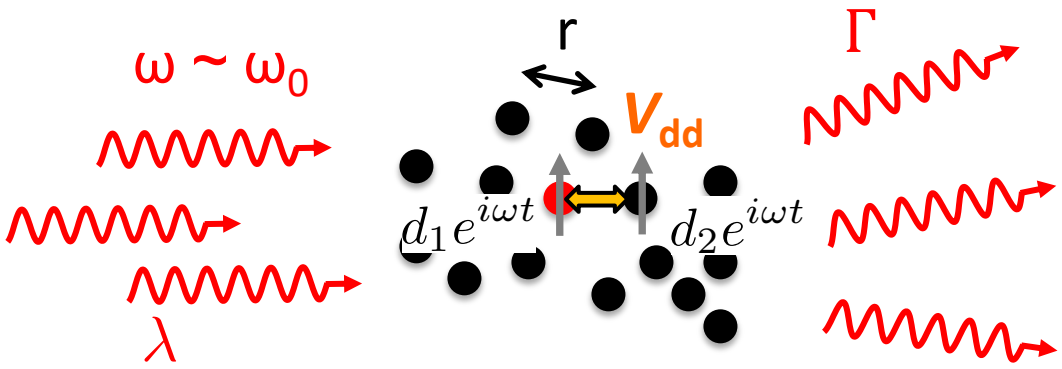




Interactions $\Rightarrow$ **collective response**

Light scattering in dense media and dipole interactions

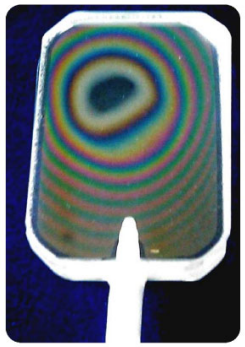




Interactions $\Rightarrow$ **collective response**

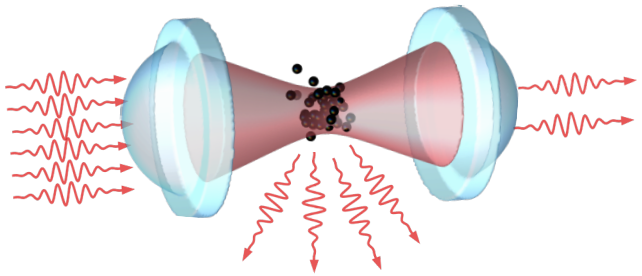
Classically: interaction between light-induced dipoles

Experimental investigations: random ensembles



Hot vapors

Adams & Hughes, Durham
Löw, Stuttgart
Browaeys



Dense cold clouds

Browaeys, Dalibard & Beugnon

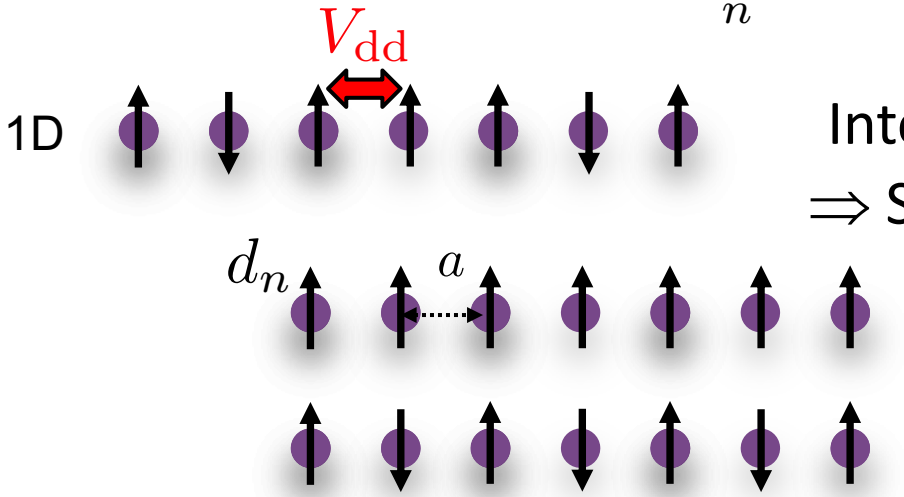
Dilute cold clouds

Kaiser, Courteille, Havey, Ye…

Structured atomic arrays ⇒ enhance collective response

$$V_{\rm dd} \sim \frac{\hbar\Gamma}{kr} e^{ikr}$$

Random: $\sum_n e^{ikr_n} \ll 1$ Structured: $\sum_n e^{ikna} \sim N$

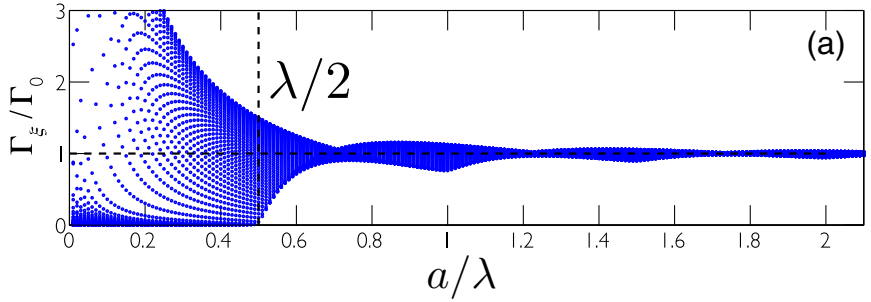


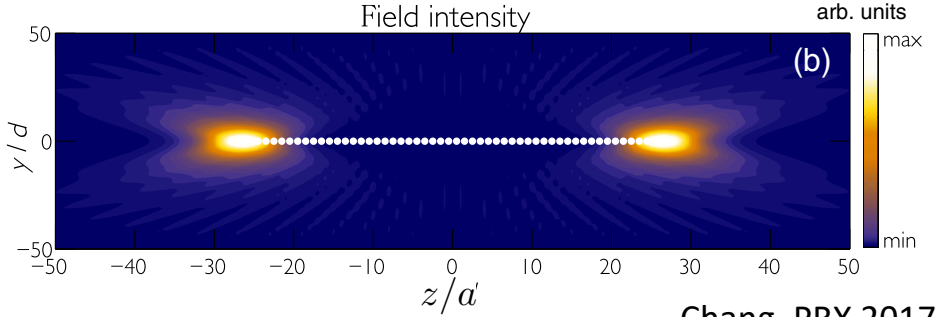
Interaction between induced dipoles

⇒ Strong, controlled collective effects

Superradiance $\Gamma_{\rm sup} \gg \Gamma$

Sub-radiance $\Gamma_{\rm sub} \ll \Gamma$

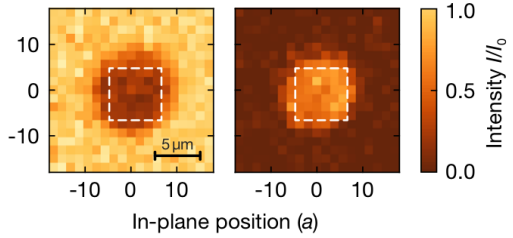




Chang, PRX 2017

Adams, Yelin &Lukin, Chang, Asenjo-Garcia Ruostekoski, Zoller…

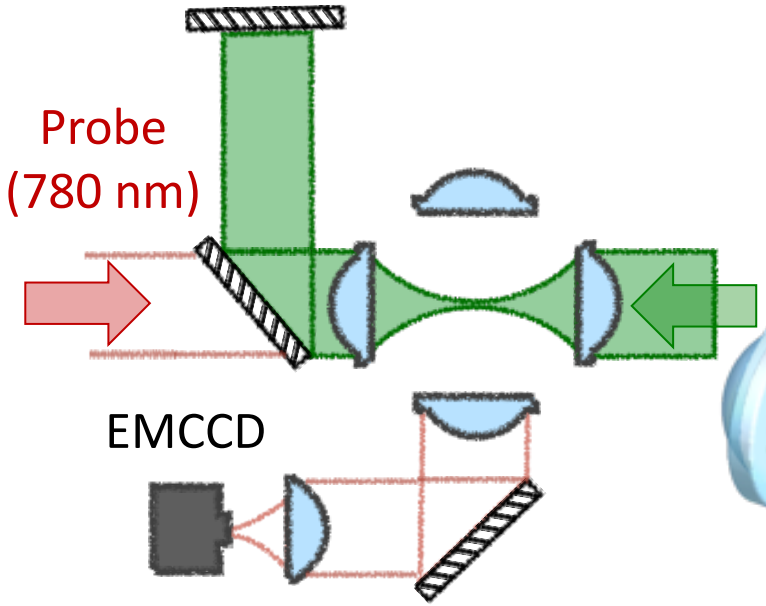
Also in 2D:

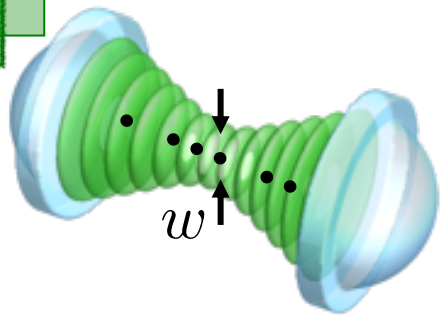


Bloch, Nature 2020

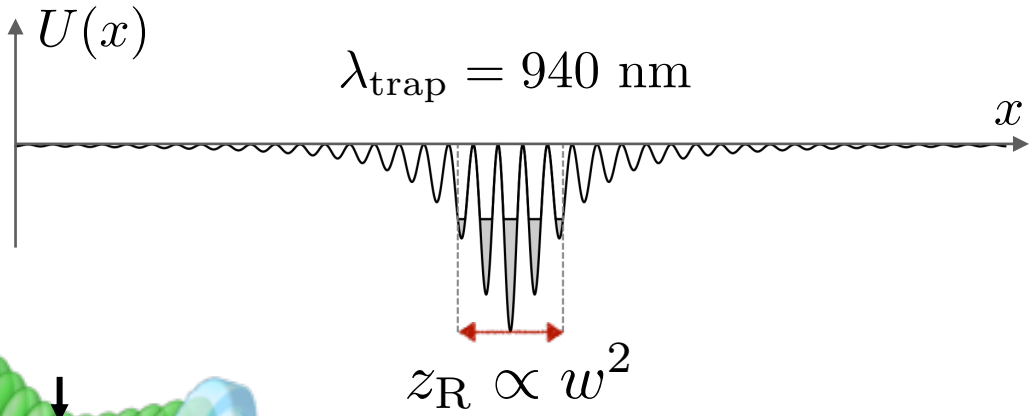
A 1D chain of atoms: tweezer + lattice

Optical lattice



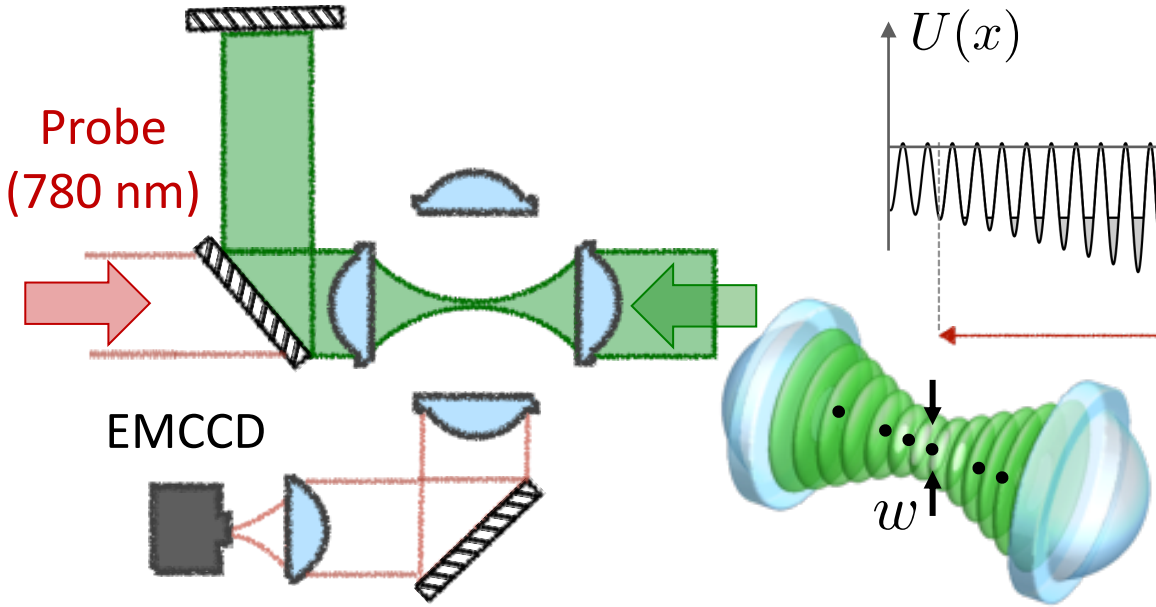


Changing the waist (and Rayleigh length)

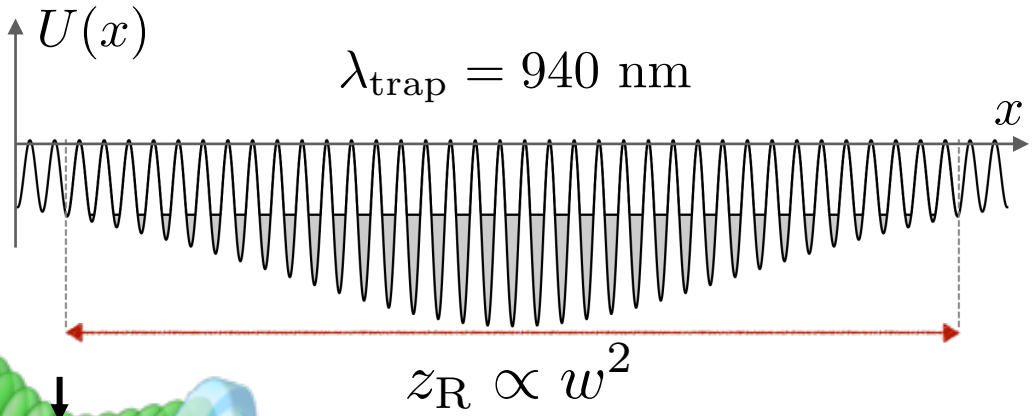


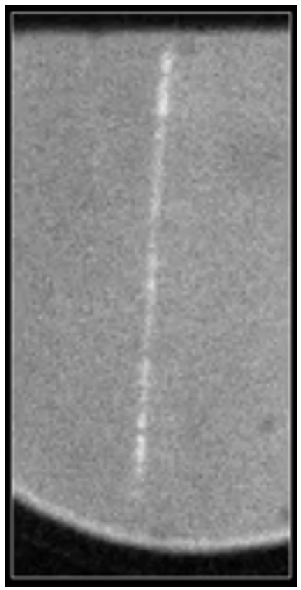
A 1D chain of atoms: tweezer + lattice

Optical lattice



Changing the waist (and Rayleigh length)

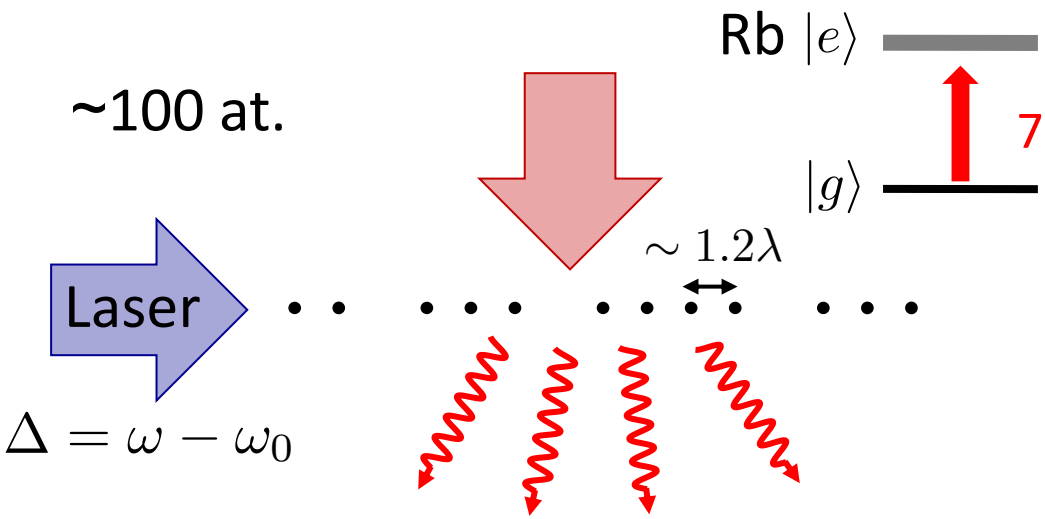


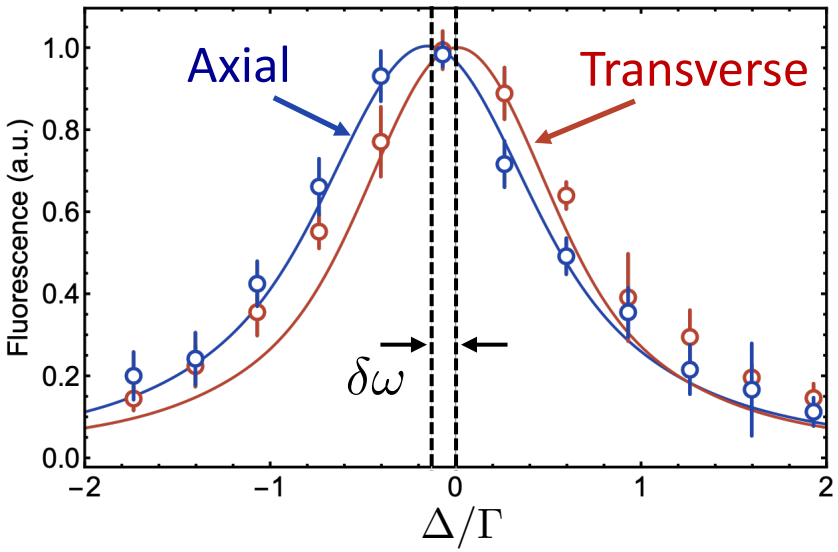


~ 200 sites, filling ~ 50%,
T = 20 µK

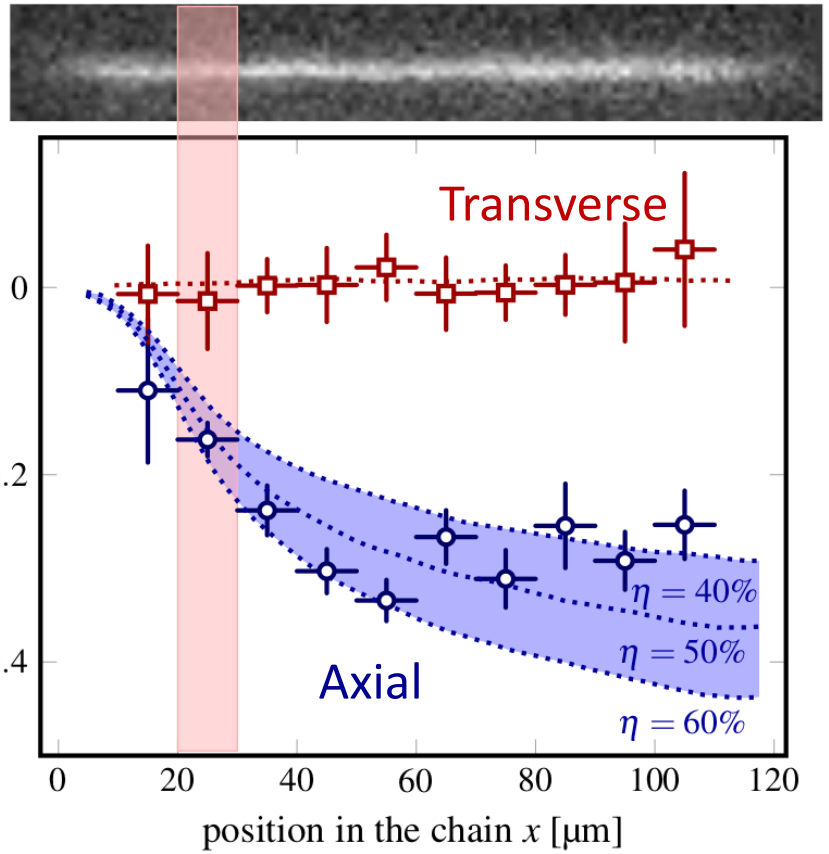
Collective light scattering on a 1D chain

Glicenstein, PRL 2020





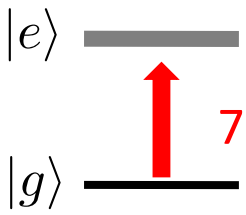
Position resolved spectrum

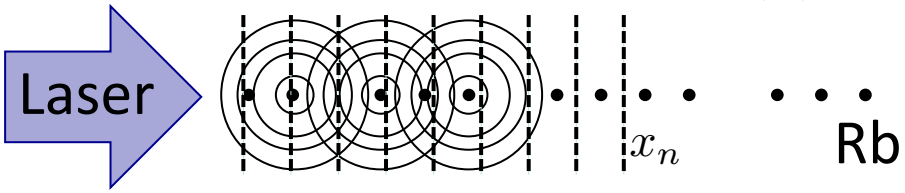


Collective light scattering on a 1D chain

Glicenstein, PRL 2020

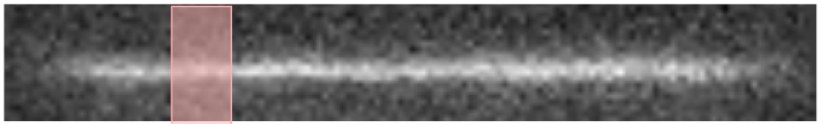
~100 at.

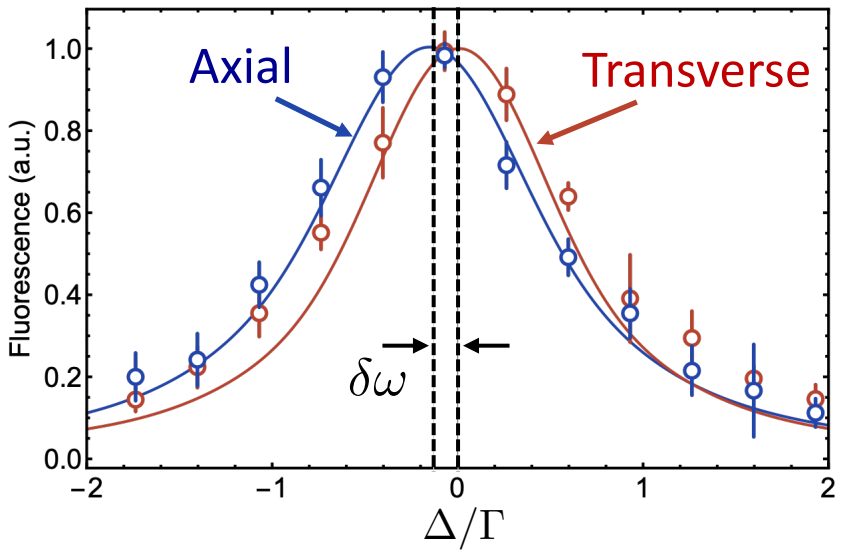


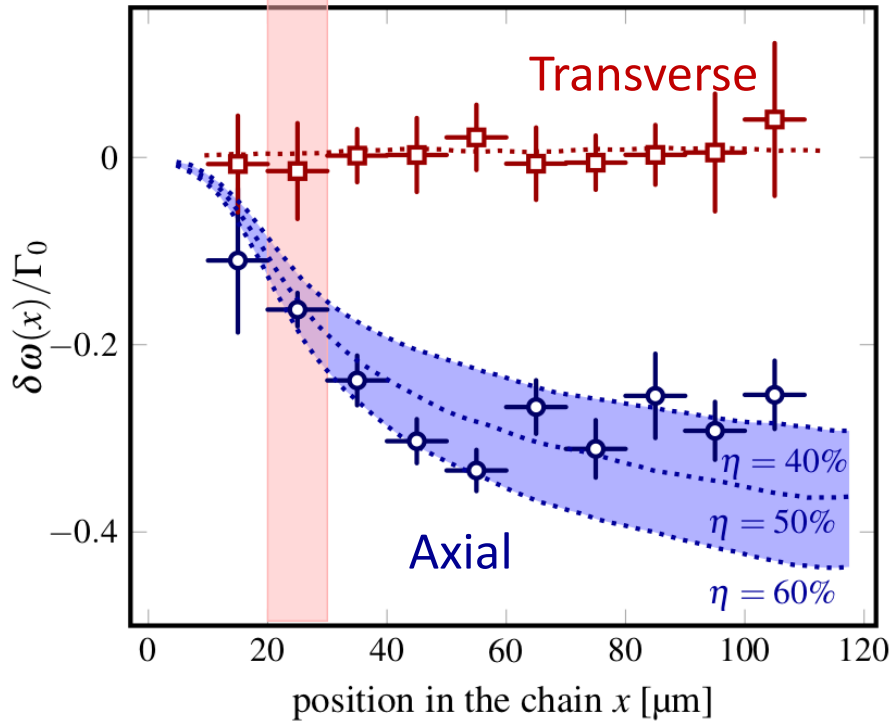


$\Delta = \omega - \omega_0$

Position resolved spectrum





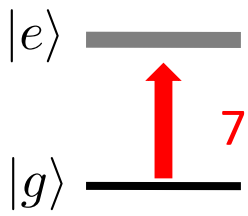


Forward interferences: $\delta\omega_n \sim \sum_{m<n} V_{\mathrm{dd}}^{mn} \sim -\sum_{m<n} \frac{\Gamma}{k|x_m - x_n|}$

Collective light scattering on a 1D chain

Glicenstein, PRL 2020

~100 at.

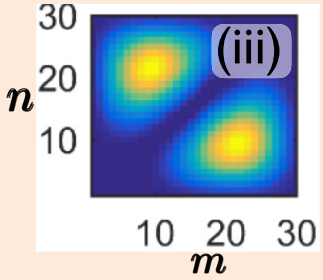


Position resolved spectrum

Laser

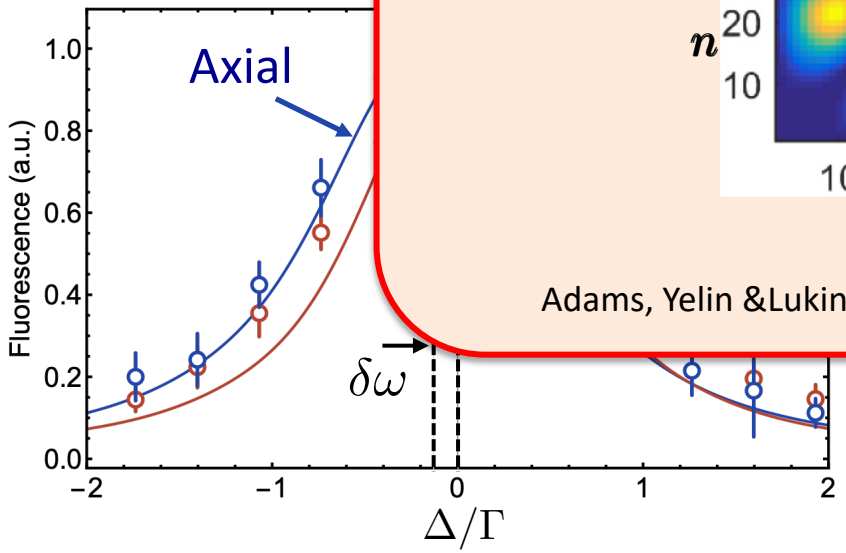
$\Delta = \omega - \omega_0$

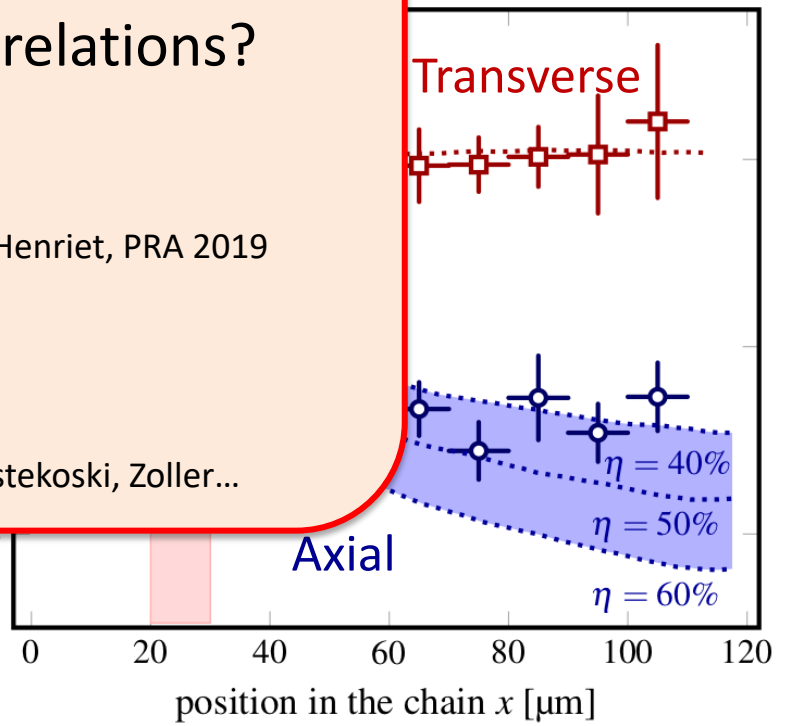
1D sub-λ arrays:
subradiance and correlations?



Henriet, PRA 2019

Adams, Yelin &Lukin, Chang, Ruostekoski, Zoller…

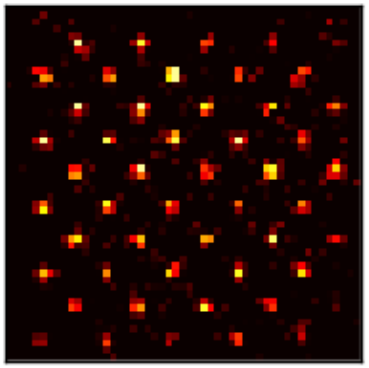




Forward interferences: $\delta\omega_n \sim \sum_{m<n} V_{\mathrm{dd}}^{mn} \sim -\sum_{m<n} \frac{\Gamma}{k|x_m - x_n|}$

Conclusion and outlook

Arrays of atoms + dipole interactions



- Explore many-body physics in hard situations: topology, out-of-eq, dissipative…
- Atom-light interface, non-linearity…