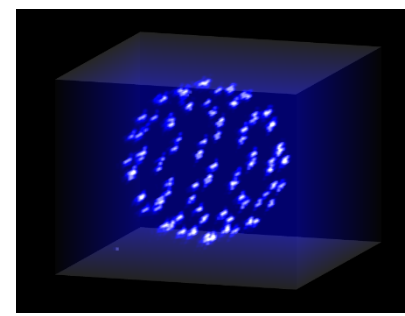
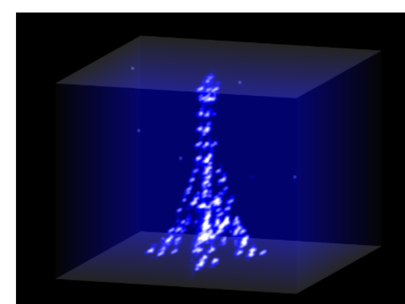
Many-body physics using

arrays of individual Rydberg atoms

(and optical dipoles…)

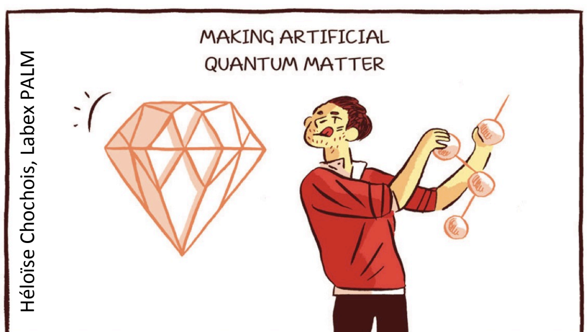




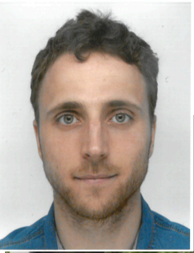
Antoine Browaeys

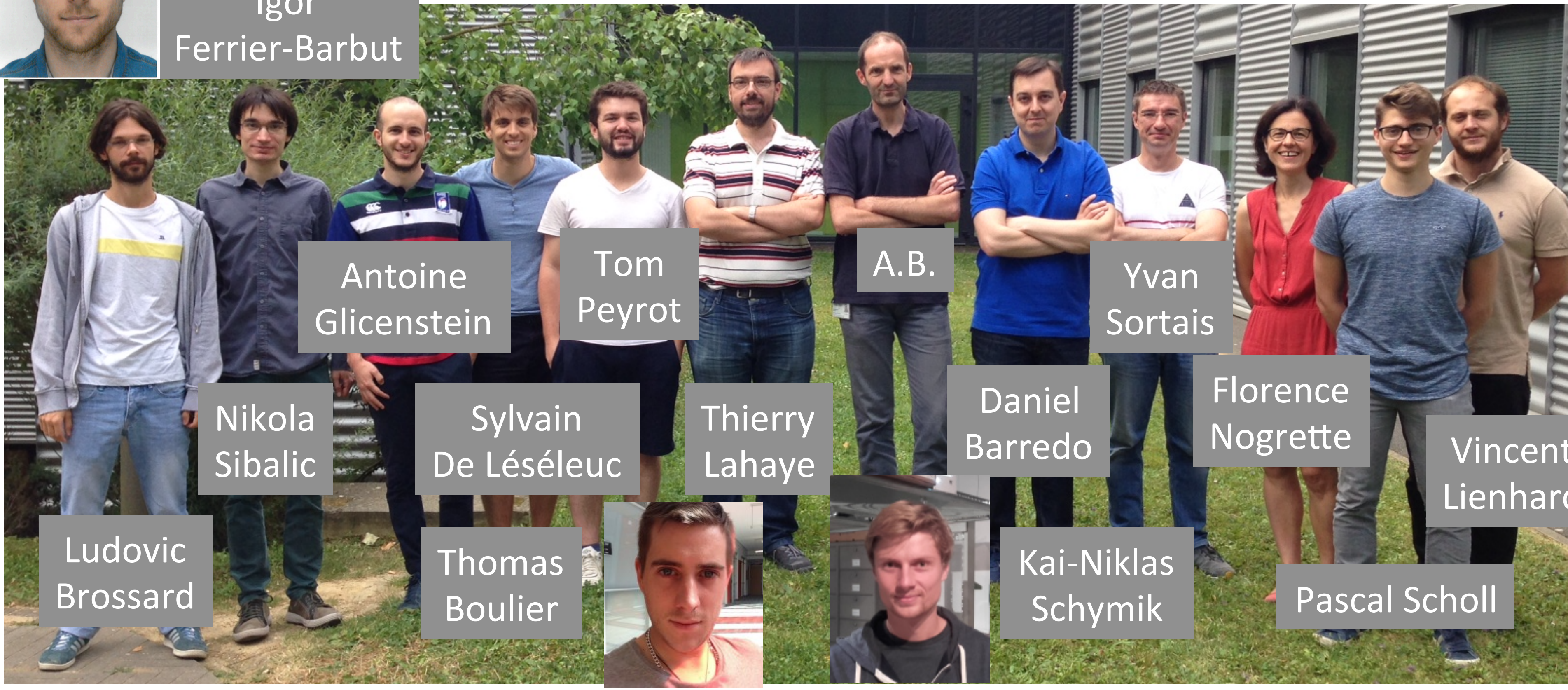
Laboratoire Charles Fabry,
Institut d'Optique, CNRS, FRANCE

KITP, may 1st 2019



The team (atom-tweezers-io.org)

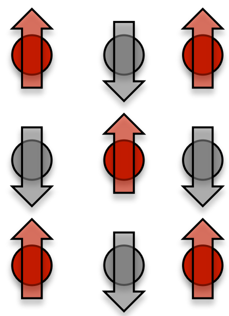




Collaborators T. Macri, A. Läuchli, Hans Peter Büchler, I. Lesanovsky
C.S. Adams & I. Hughes, J. Ruostekoski, J.-.J Greffet, P. Pillet,

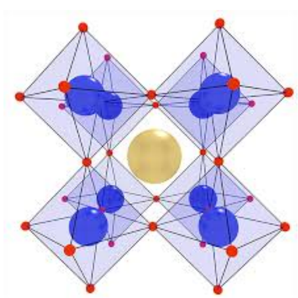
Spin models: one of the “simplest” many-body problem

Interacting spin ½ particles on a lattice:



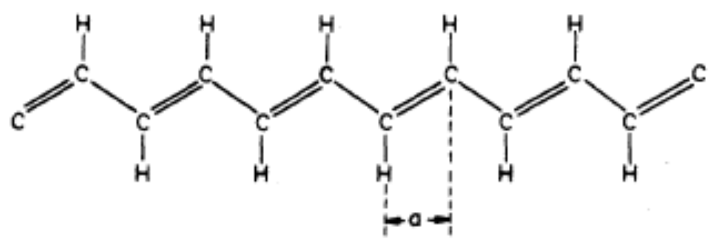
$$\hat{H} \sim J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$$

Magnetism



Perovskite
$Y_2Ti_2O_7$

Transport of excitations

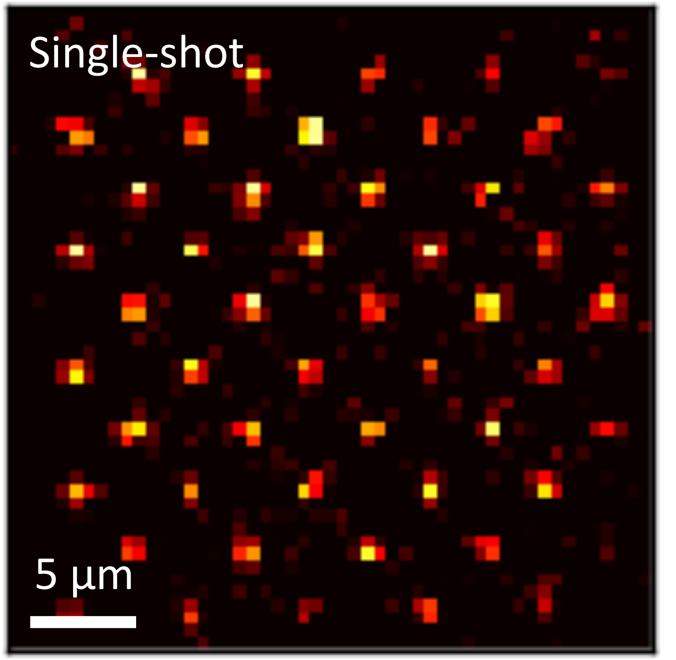


Open questions: Dynamics (hard for N>40, long range…)
Topology, disorder, dissipation…

Use control over artificial quantum matter
(circuits, ions, atoms, photons…)

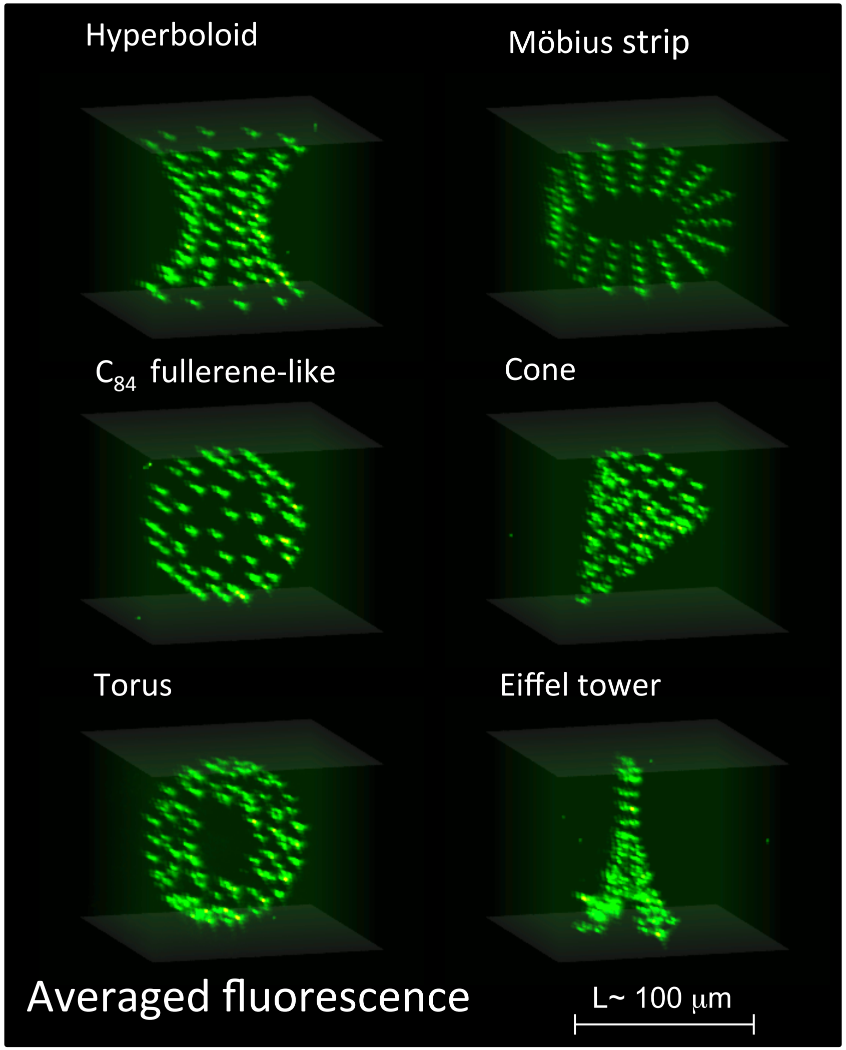
Our platform: arrays of interacting Rydberg atoms

Individual atoms in assembled arrays of tweezers (~70 at.)



Barredo, de Léséleuc, Science (2016)
Also Lukin (Harvard), Ahn (Korea)…

Also in 3d…!



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

Our platform: arrays of interacting Rydberg atoms

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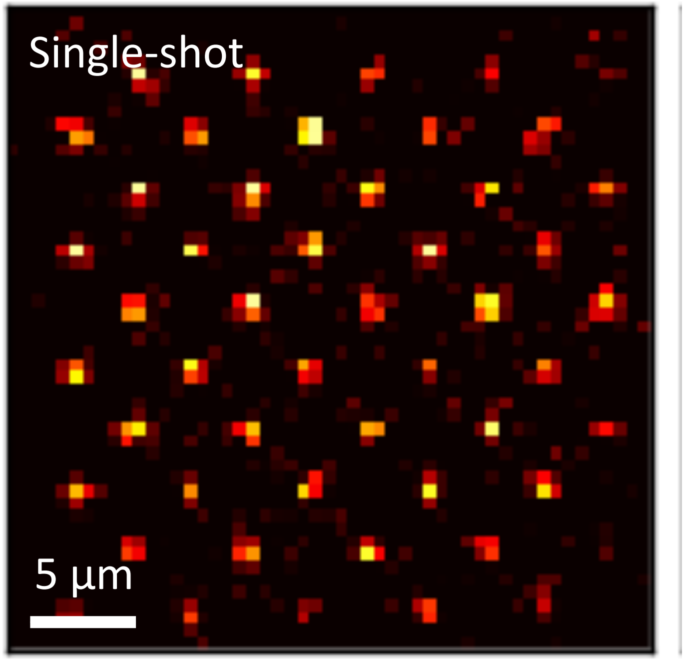
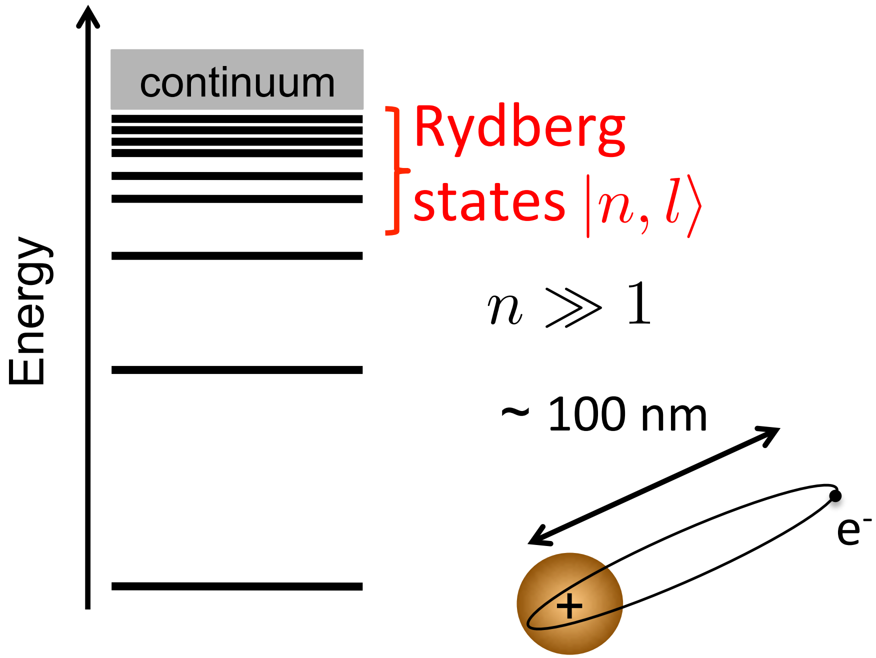


Barredo, de Léséleuc, Science (2016)
Also Lukin (Harvard), Ahn (Korea)…

Rydberg atoms



Lifetime > 100 µs

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

⇒ Large dipole-dipole interactions

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

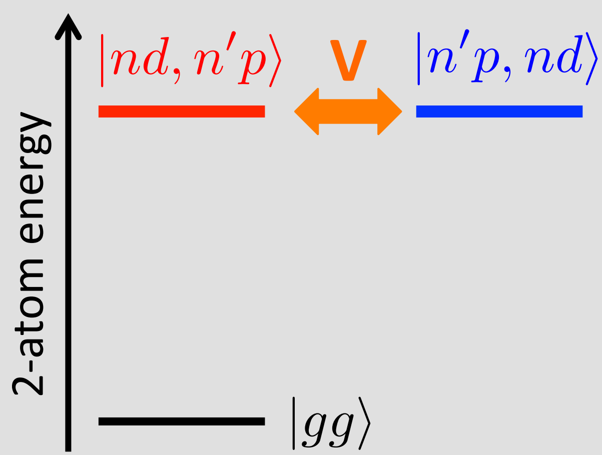
⇒ timescales < µsec

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

Rydberg atoms and their interactions

$$\hat{V} \sim \frac{\hat{d}_A \hat{d}_B}{4\pi\epsilon_0 R^3}$$

Resonant interaction

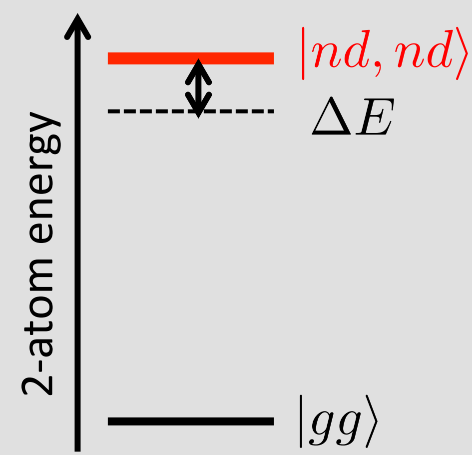


$$V \sim \frac{C_3}{R^3}$$

XY model

This talk!

van der Waals



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

Ising-like model

See I. Lesanovsky

Outline

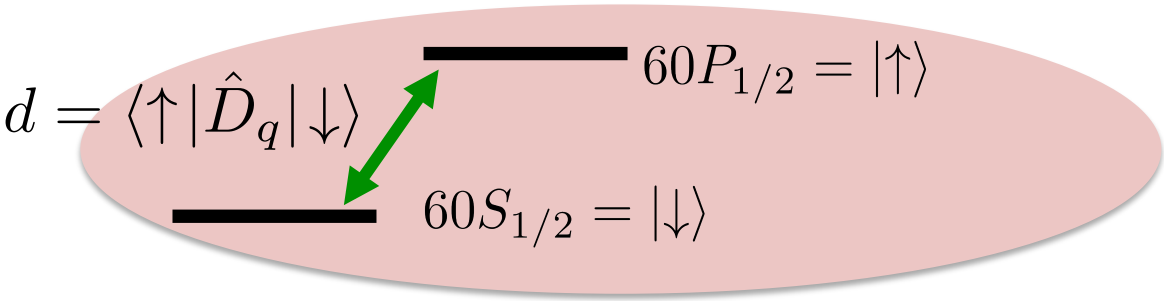
H.-P. Büchler
S. Weber, N. Lang

1. Topological matter with resonant dip.-dip. Interactions
the "coherent"

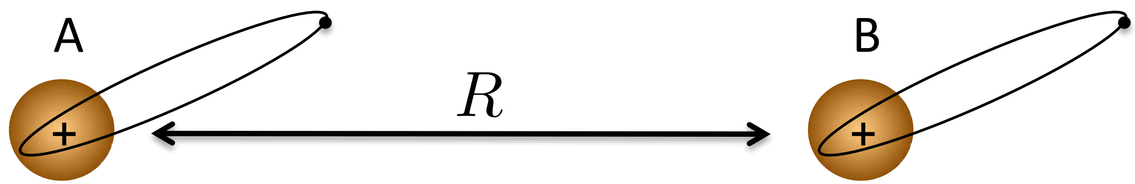
arXiv:1810.13286

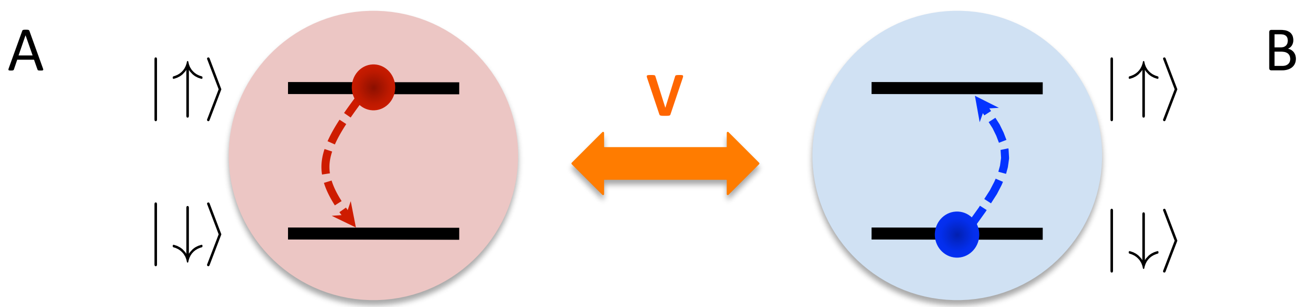
2. Resonant dipole interaction and quantum optics
the dissipative

Resonant dipole-dipole interaction between Rydberg atoms



Mapping on spin ½ system





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

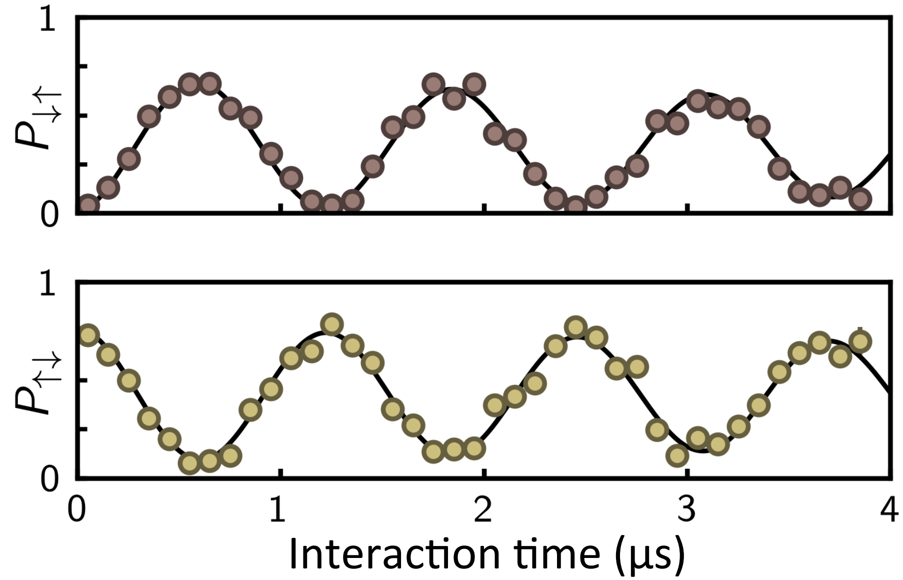
Spin “exchange”: **XY model**

Observation of spin exchange between 2 atoms

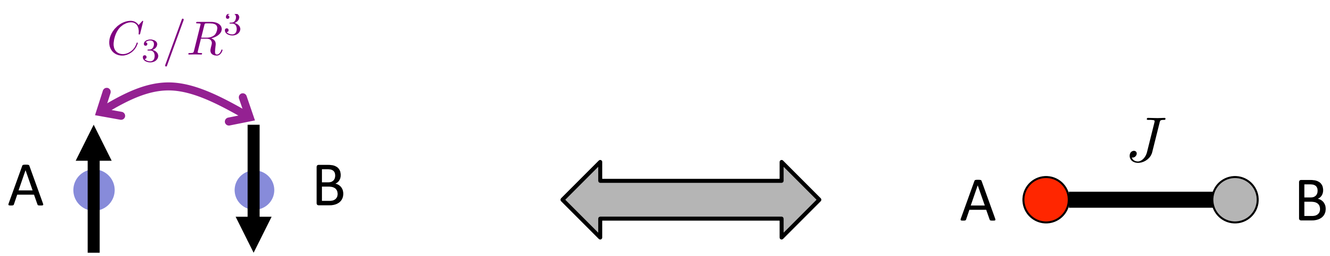
Prepare $|\uparrow\downarrow\rangle$ using microwaves + addressing beam

R = 30 µm

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



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



Spin exchange

Particle hopping

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

$J|A\rangle\langle B|$

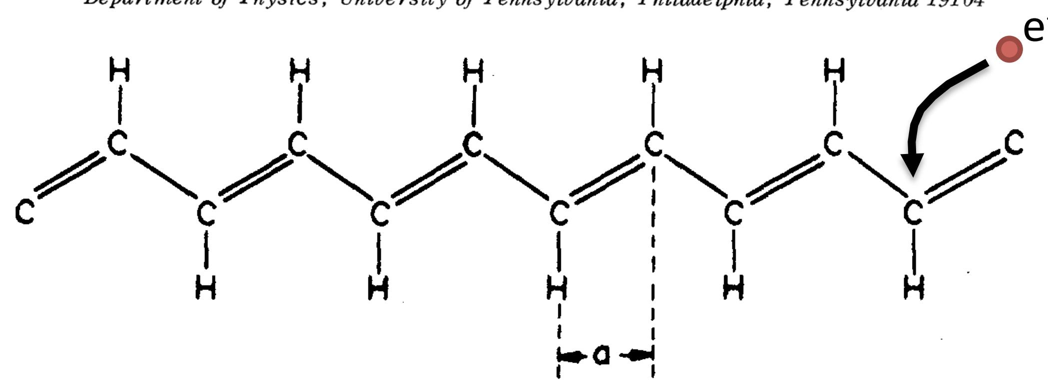
The Su-Schrieffer-Heeger model

- 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

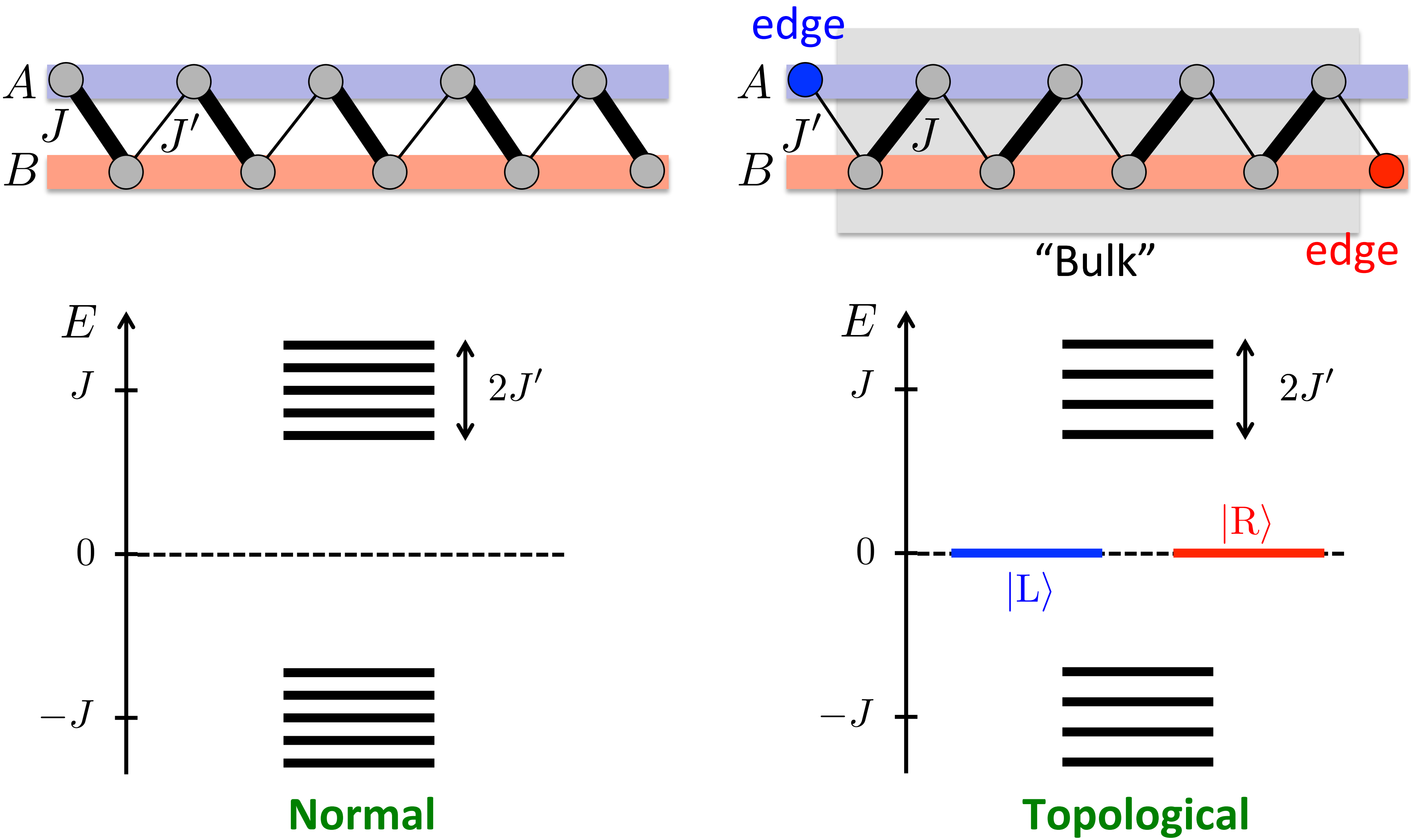


- Now, considered as simplest example of **topological model**

Asboth, arXiv:1509.02295, Cooper, arXiv:1803.00249

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

The Su-Schrieffer-Heeger model for a finite chain: edge states



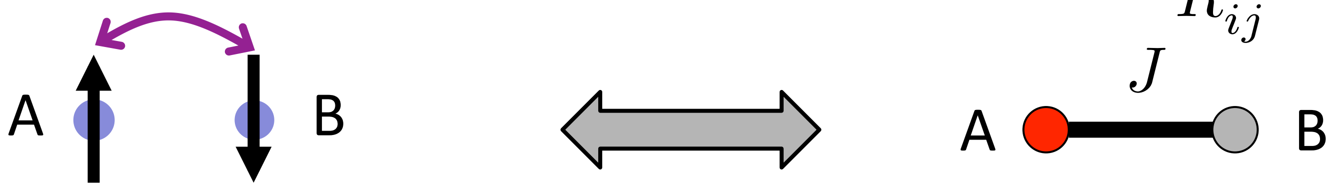
"Topological" protection

Ex. of "bulk – edge" correspondence

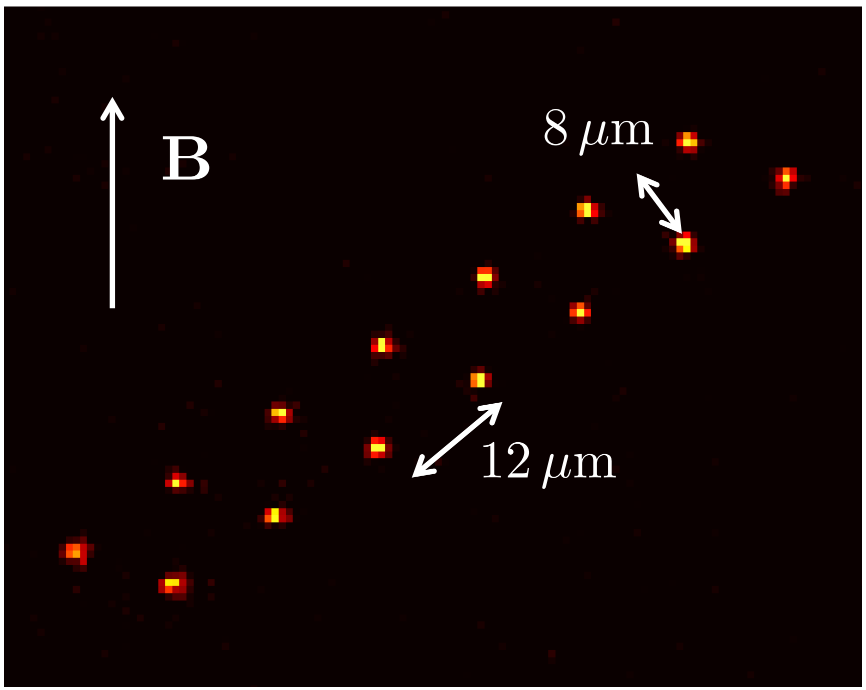
Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

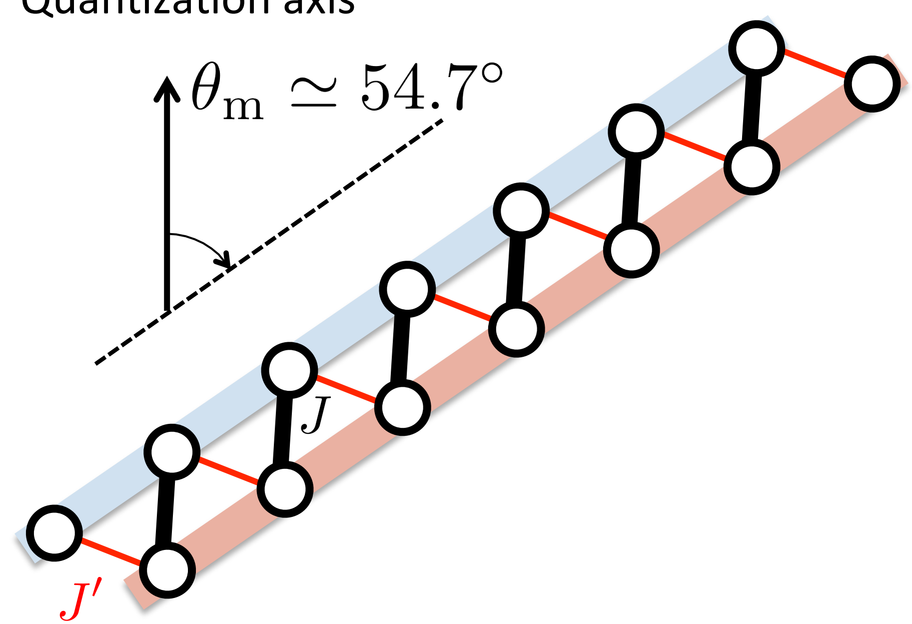
Implementation of SSH spin chain with Rydberg atoms

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



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



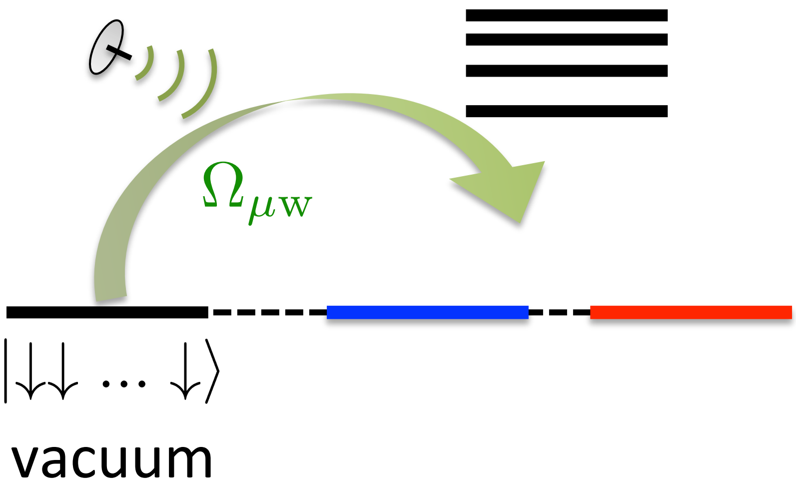


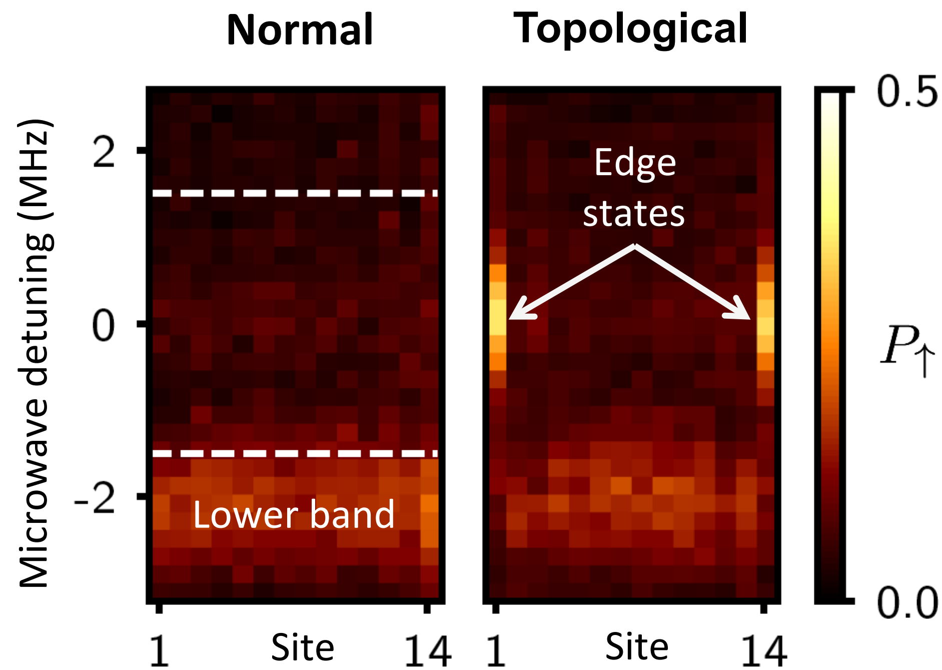
$J/h = 2.4\,\mathrm{MHz}$

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

“Topological”

Probing the single-particle SSH spectrum





Single-particle spectrum

1 excitation $|\uparrow\rangle$

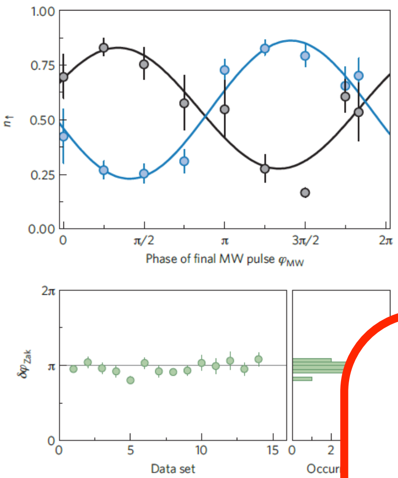
= quasi-particle

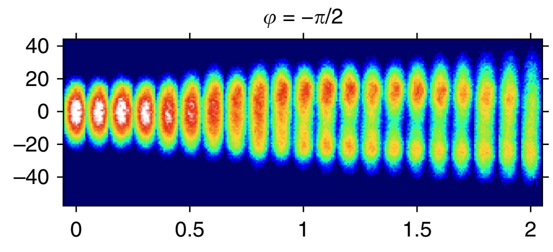
Chiral symmetry ✔

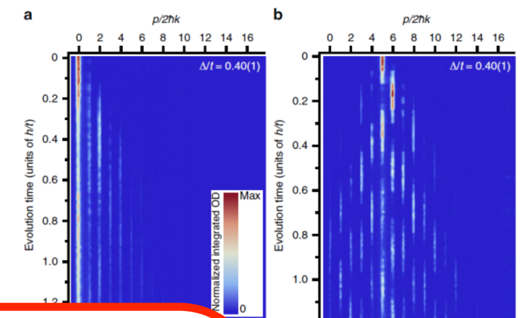
Recent examples of artificial SSH chains (non-interacting regime)

Ultracold atoms in superlattices

Bragg diffraction of matter waves







I. Bloch, Nat. Phys.

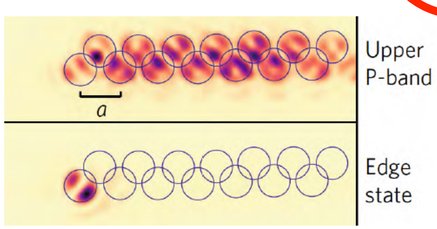
dway,
mm. 2016

Challenge / questions

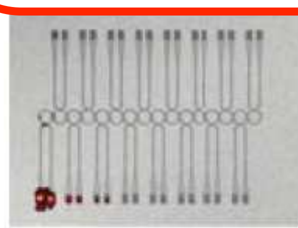
interplay topology - interactions

ical oscillators

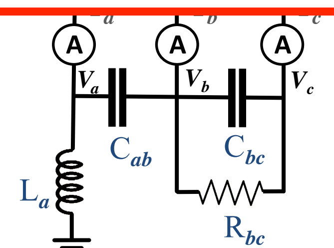
Photonic



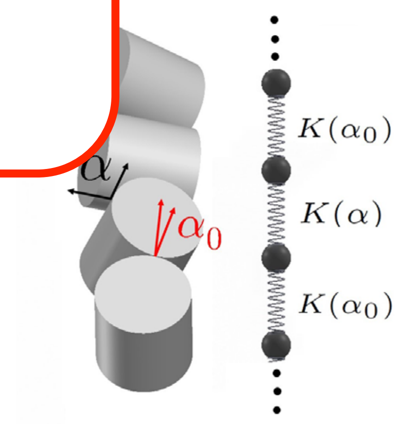
J. Bloch
Nat. Phot. 2017



Khajavikhan
PRL2017



arXiv:1705.01077

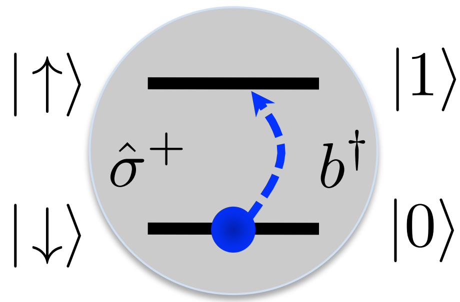


Chaunsali, PRL 2017

Spin excitations are hard-core bosons…

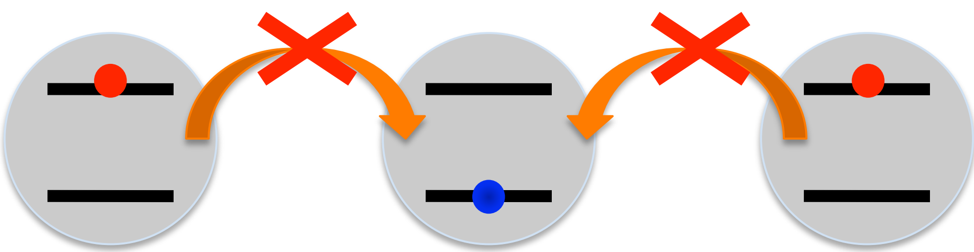
Note: initially SSH introduced for **non-interacting** fermions…

Spin ½ " = "bosons



Carusotto PRA 2016
Fleischhauer PRA 2013
…

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



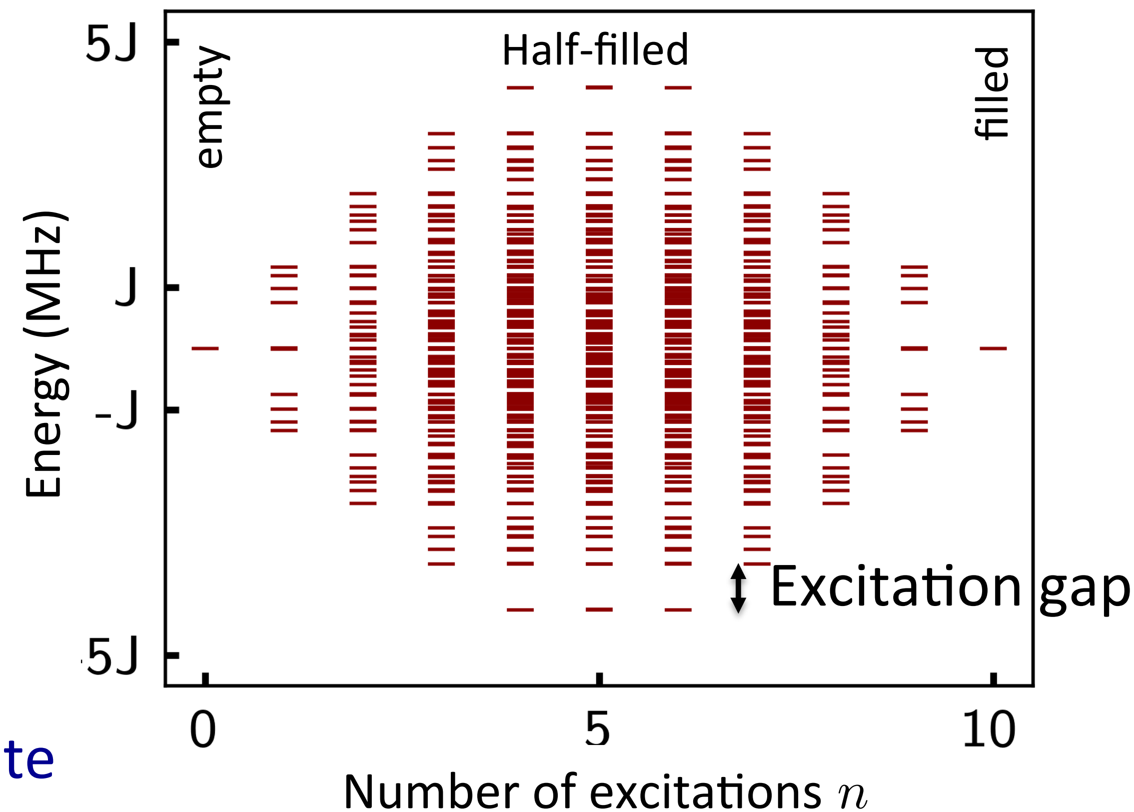
On-site interaction
$U \to \infty$

$$H_{\mathrm{B}} = \sum_{i\in A, j\in B} J_{ij}(b_i^\dagger b_j + b_i b_j^\dagger) \text{ with } (b_i^\dagger)^2 = 0$$

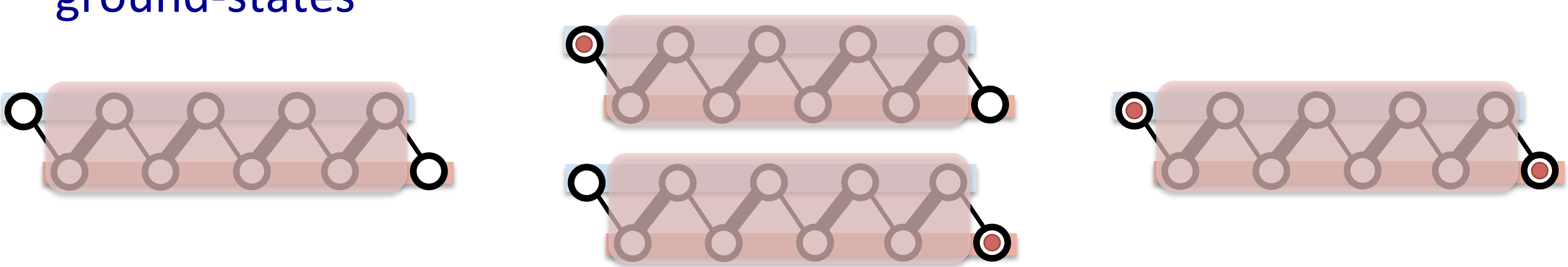
Spectrum of the many-body SSH model with hard-core bosons

$$H_{\mathrm{B}} = \sum_{i \in A, j \in B} J_{ij}(b_i^\dagger b_j + b_i b_j^\dagger)$$

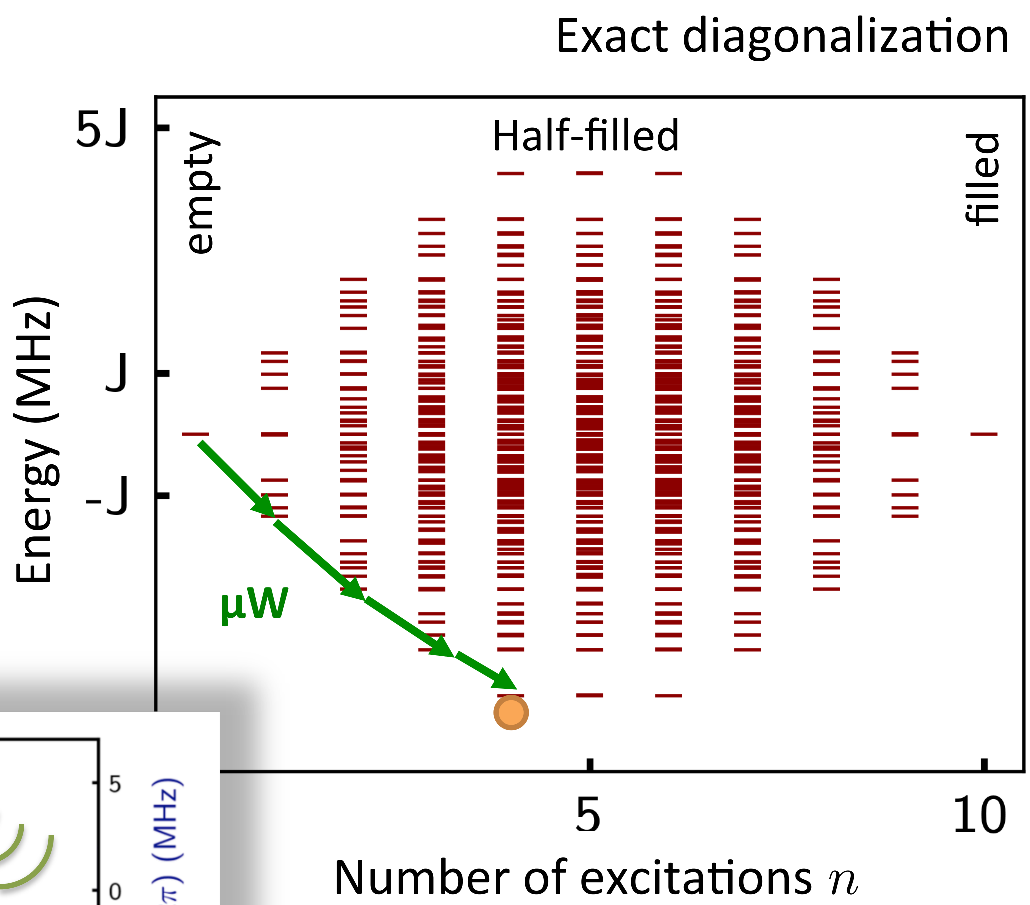
Exact diagonalization

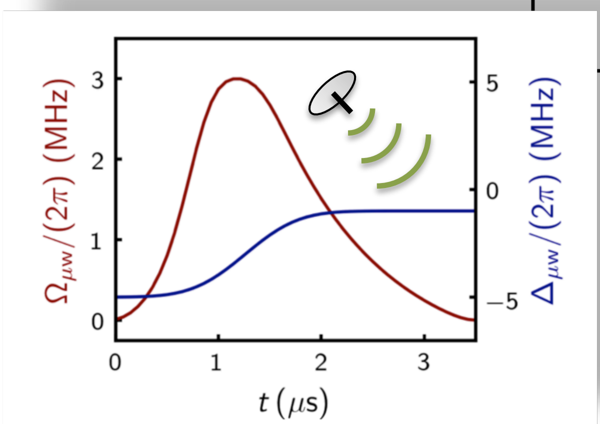


4 degenerate ground-states



Adiabatic preparation of the many-body ground state (14 sites)

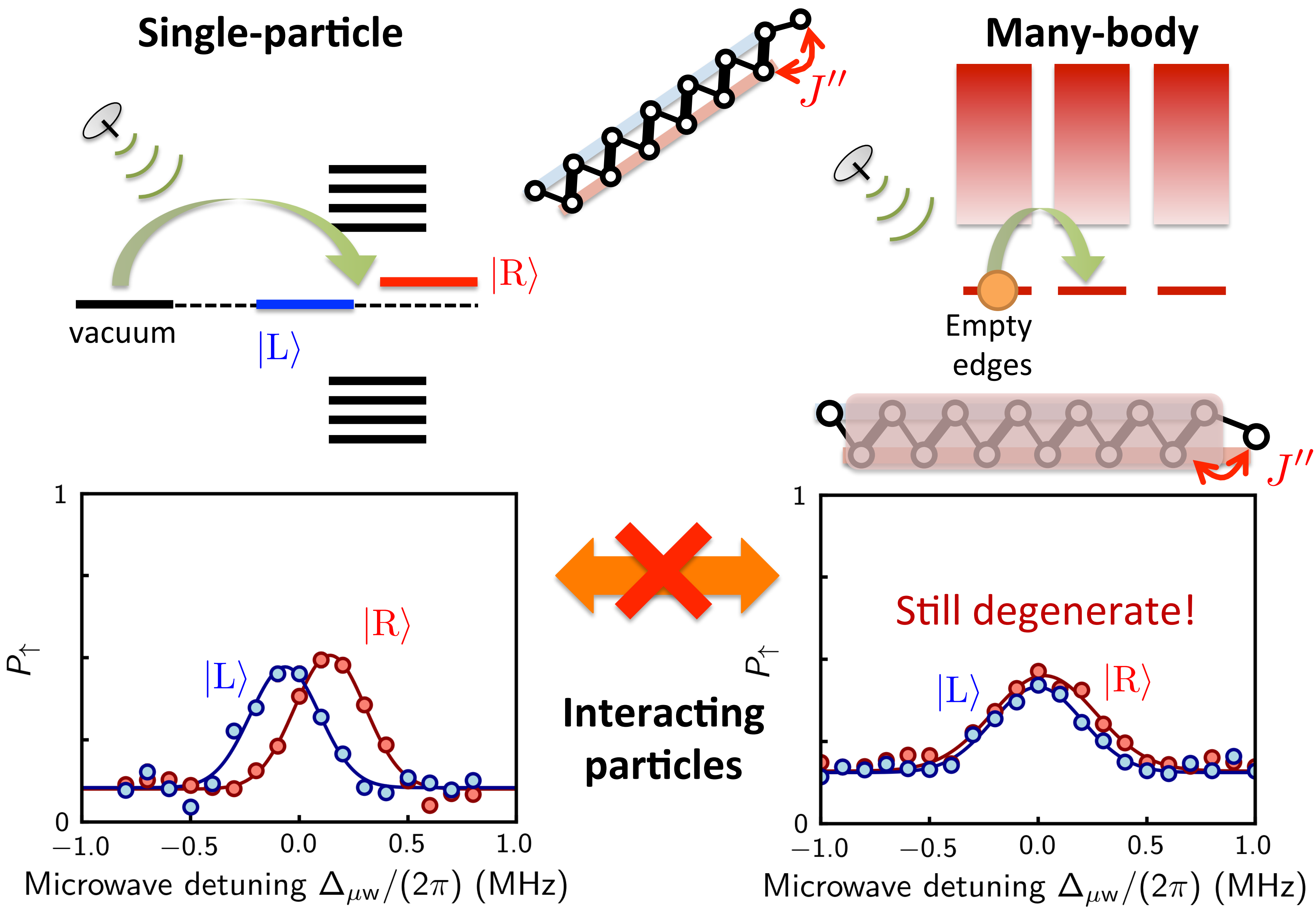




μW sweep ⇒ add excitations 1 by 1

⇒ Prepare ground state

Robustess of the g.s. degeneracy w.r. chiral symmetry breaking



A symmetry protected topological "phase" for bosons (1/2 filling)

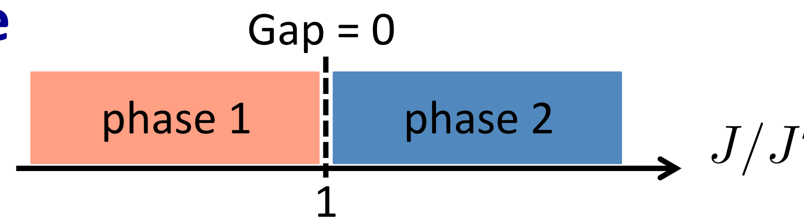
Degeneracy from symmetries for **many-body states:**

- part. / hole symmetry
- part. nb. conservation

Classification of topological phases according to $\hat{S}$ of $\hat{H}$

Symmetry protected topological phase

Pollman, PRB **85**, 075125 (2012)



SPT with interacting bosons: Chen, Science **338**, 1604 (2012); Chiu, RMP **88**, 035005 (2016)

Symmetry	$d = 0$	$d = 1$	$d = 2$	$d = 3$
$U(1) \rtimes Z_2^T$	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}_2^2$
Z_2^T	$\mathbb{Z}_1$	$\mathbb{Z}_2$	$\mathbb{Z}_1$	$\mathbb{Z}_2$
$U(1)$	$\mathbb{Z}$	$\mathbb{Z}_1$	$\mathbb{Z}$	$\mathbb{Z}_1$
$SO(3)$	$\mathbb{Z}_1$	$\mathbb{Z}_2$	$\mathbb{Z}$	$\mathbb{Z}_1$
$SO(3) \times Z_2^T$	$\mathbb{Z}_1$	$\mathbb{Z}_2^2$	$\mathbb{Z}_2$	$\mathbb{Z}_2^3$
Z_n	$\mathbb{Z}_n$	$\mathbb{Z}_1$	$\mathbb{Z}_n$	$\mathbb{Z}_1$
$Z_2^T \times D_2 = D_{2h}$	$\mathbb{Z}_2^2$	$\mathbb{Z}_2^4$	$\mathbb{Z}_2^6$	$\mathbb{Z}_2^9$

Only possible topological order in 1d!

Outline

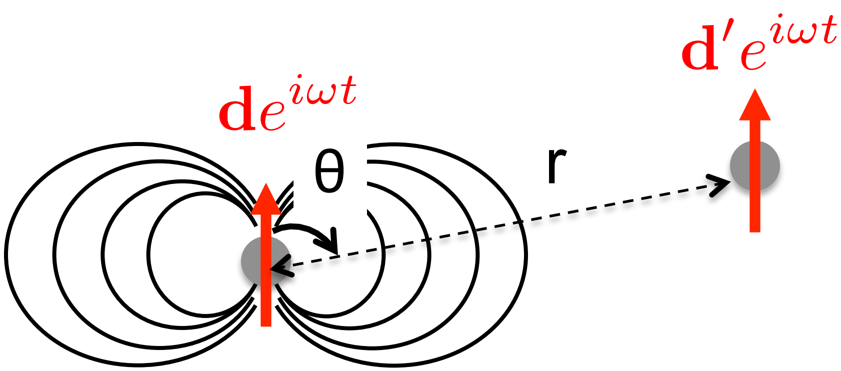
1. Topological matter with resonant dip.-dip. Interactions
the "coherent"
arXiv:1810.13286

2. Resonant dipole interaction and quantum optics
the dissipative

Pellegrino, PRL **113**, 133602 (2014)
Jenkins, PRL **116**, 183601 (2016)
Schilder, PRA **93**, 063835 (2016)
Jenkins, PRA **94**, 023842 (2016)
Jennewein, PRL **116**, 233601 (2016)
Jennewein, PRA **94**, 053828 (2016)
Schilder, PRA **96**, 013825 (2017)
Jennewein, PRA **97**, 053816 (2018)

Resonant dipole-dipole interaction as exchange interaction

Classical: dip.-dip. interaction

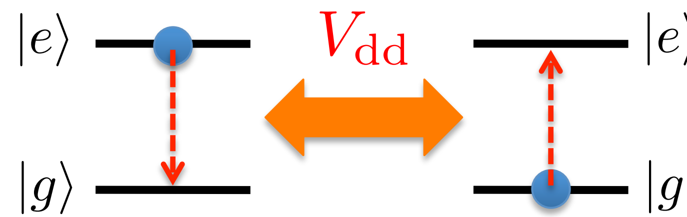


1. Radiative decay: $\Gamma \propto \dfrac{\mathbf{d}^2\omega_0^3}{\hbar c^3}$

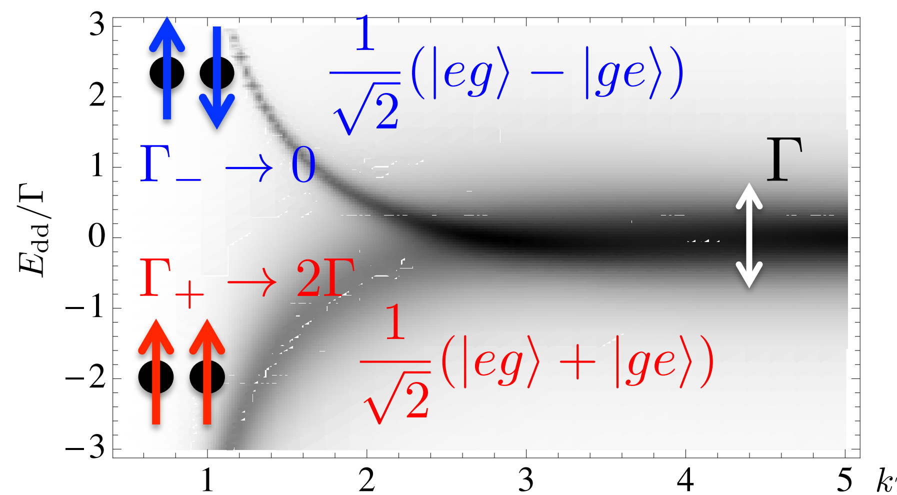
2. Dipole-dipole interaction

$$V_{\rm dd} = -\frac{1}{2}\mathbf{d}' \cdot \mathbf{E}^*$$

Quantum: exchange interaction



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



$$V_{\rm dd} = -\frac{3\hbar\Gamma}{4}e^{ikr}\left[\left(\frac{1}{(kr)^3} - \frac{i}{(kr)^2}\right)(3\cos^2\theta - 1) + \frac{\sin^2\theta}{kr}\right]$$

Near-field vs. far-field = coherent vs. collective dissipation

$$V_{\rm dd} = -\frac{3\hbar\Gamma}{4}\, e^{ikr}\left[\left(\frac{1}{(kr)^3} - \frac{i}{(kr)^2}\right)(3\cos^2\theta - 1) + \frac{\sin^2\theta}{kr}\right]$$

$kr \ll 1$

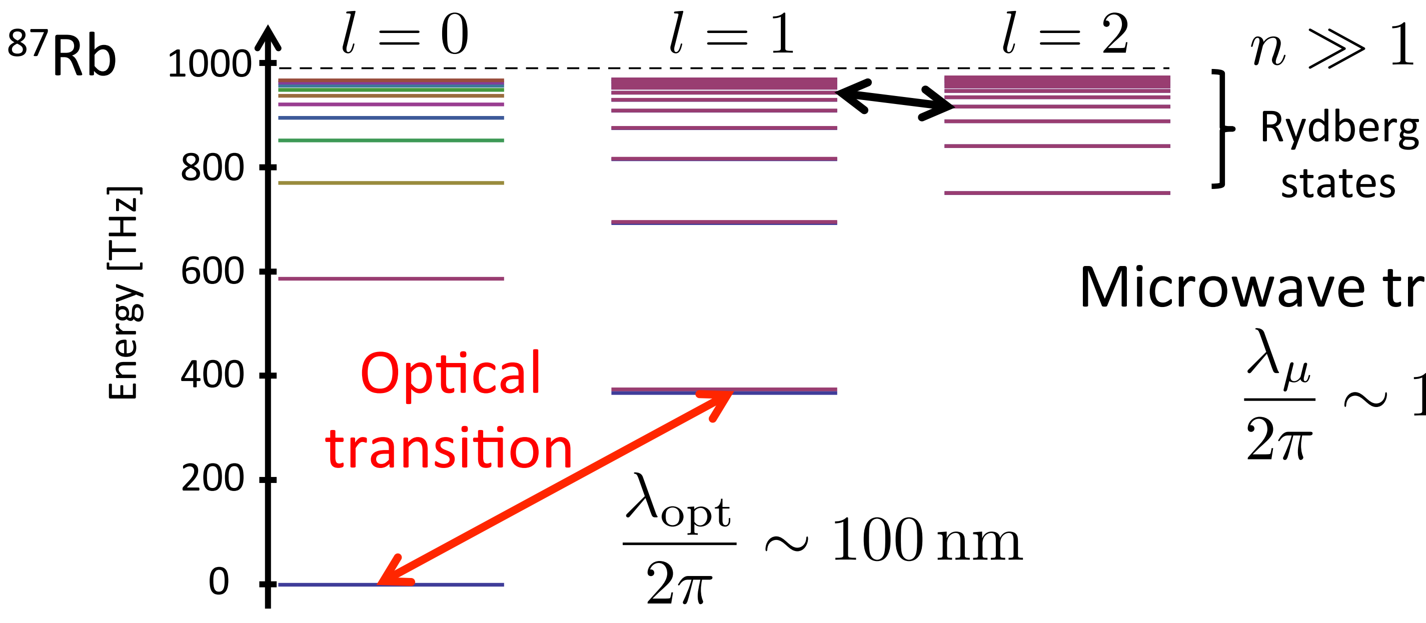
$$V_{\rm dd} \sim \frac{\hbar\Gamma}{(kr)^3} \gg \hbar\Gamma$$

$\Rightarrow$ "**coherent**" interaction

$kr \gtrsim 1$

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

$\Rightarrow$ **Dissipative** spin models

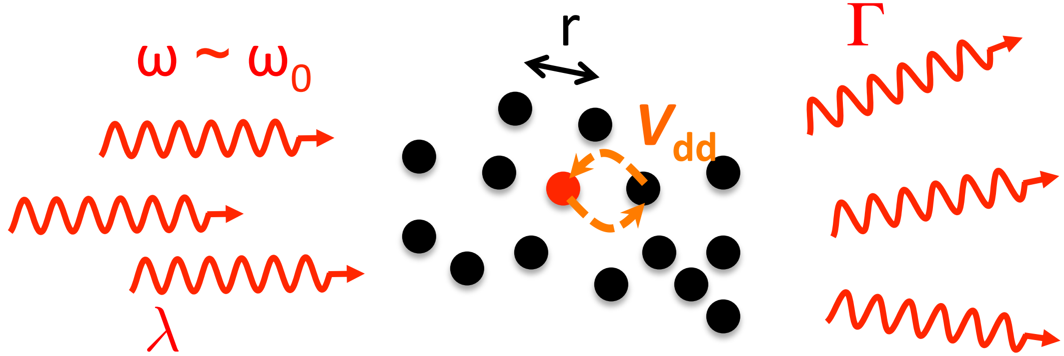


$$\frac{\lambda_{\rm opt}}{2\pi} \sim 100\,{\rm nm}$$

Microwave transition

$$\frac{\lambda_\mu}{2\pi} \sim 1\,{\rm cm}$$

Light scattering in dense media and dipole-dipole interactions



Interactions $\Rightarrow$ **collective response**

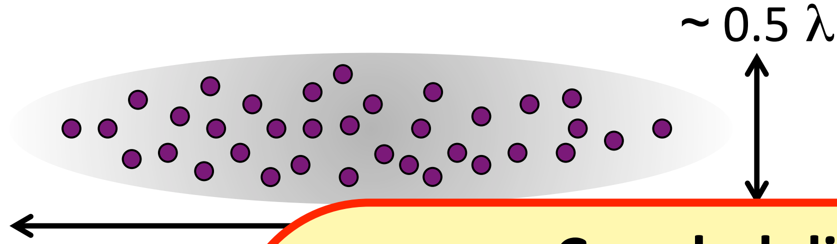
Dense: $r \lesssim \frac{\lambda}{2\pi}$ or $C = n/k^3 \gtrsim 1$ ($n \gtrsim 10^{14}$ at.cm^{-3}) $\Rightarrow V_{\rm dd} \gtrsim \hbar\Gamma$

Model: Lax PRA (1970), Ruostekoski PRA (1999) $\mathbf{E}_j = \mathbf{E}_0 + \sum_{l \neq j} \mathbf{E}_{l \rightarrow j}$ Local field

$\mathbf{d}_j = \epsilon_0 \alpha \, \mathbf{E}_j$ **(low intensity)** $\Rightarrow$ **coupled dipoles**

Diagonalization $\Rightarrow$ **eigen-modes** $E_\alpha - i\frac{\Gamma_\alpha}{2}$: $D_\alpha = \frac{\Omega_\alpha}{\Delta - E_\alpha - i\frac{\Gamma_\alpha}{2}}$

Observing resonant dip.-dip. interactions: incoherent scattering



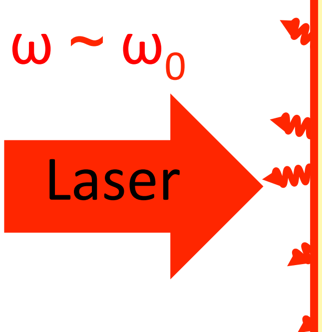
N ~ 1 - 100 atoms, T ~ 100 µK

Dense cloud: n ~ **10^14 at/cm^3**

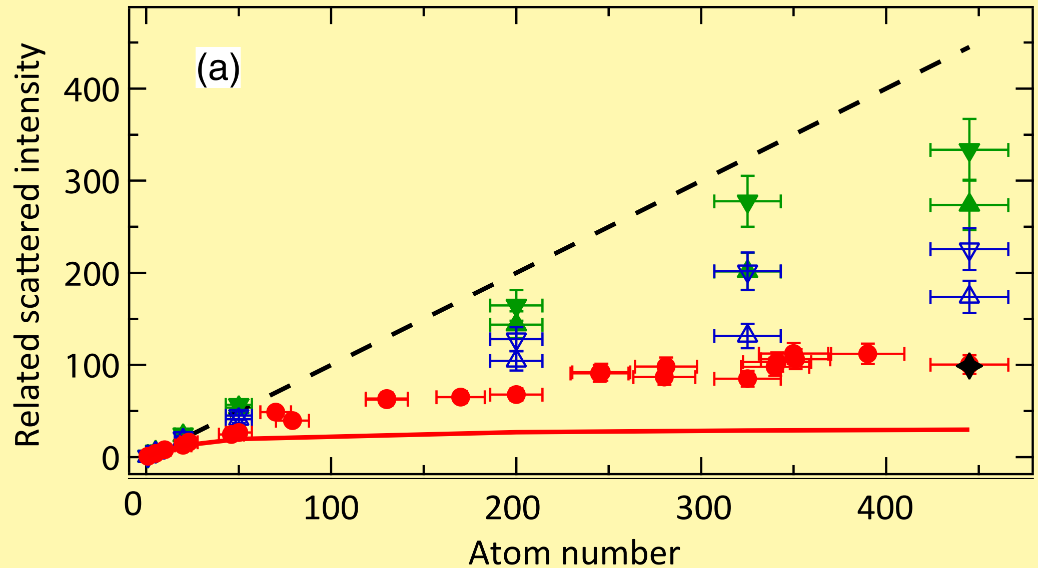
0.2

broadening

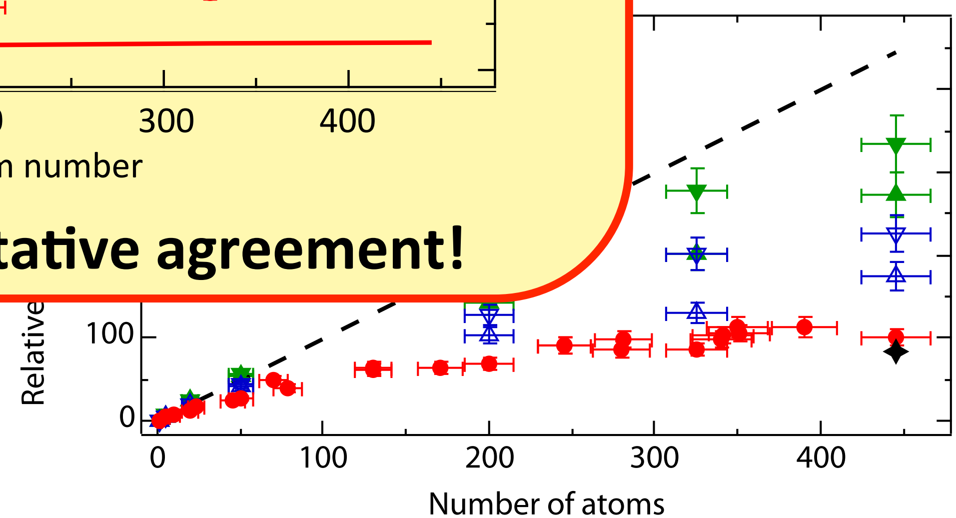
hift



Coupled dipoles model



~ OK...no quantitative agreement!



Pellegrino, PRL (2014)

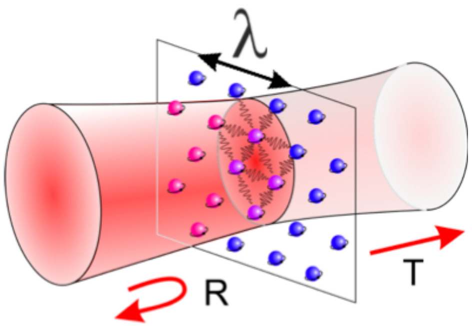
$$\mathbf{E}_{\rm sc}(\mathrm{r}) \propto \sum_j \mathbf{d}_j \, \frac{e^{ikr_j}}{r_j}$$

$$I_{\rm incoh} = \langle |\delta \mathbf{E}_{\rm sc}|^2 \rangle$$

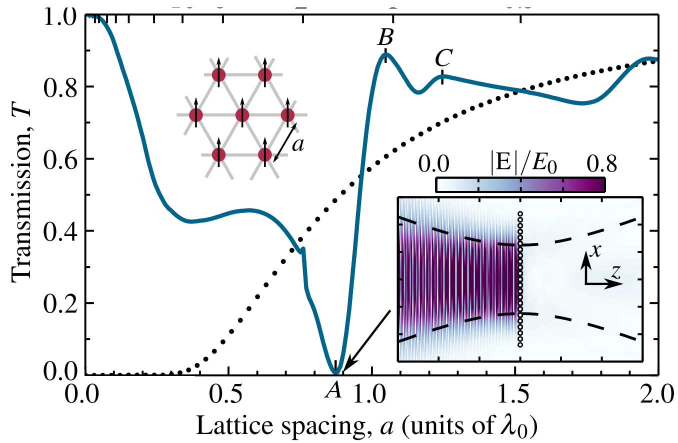
On-going work: structure the atomic response

Enhance the collective response + no averaging over random positions

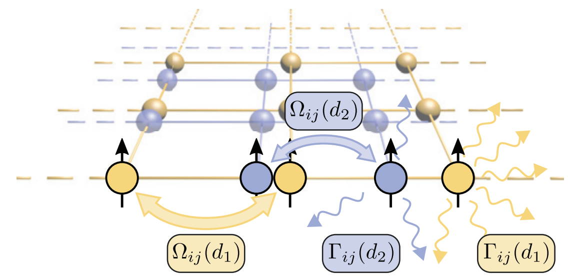
Atomic mirrors



Ruostekoski, PRA (2012)
Bettles, PRL (2016)
Shahmoon, PRL (2017)
Perczel, arXiv:1703.04849

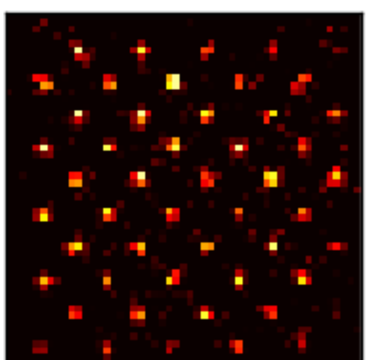


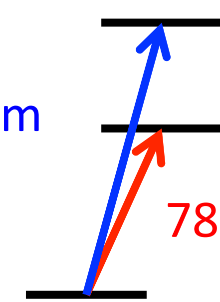
Optimized clocks



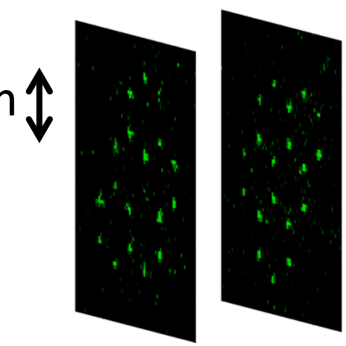
Ritsch EPL 2016

Techniques: extend SLM control to « sub-λ structuring »





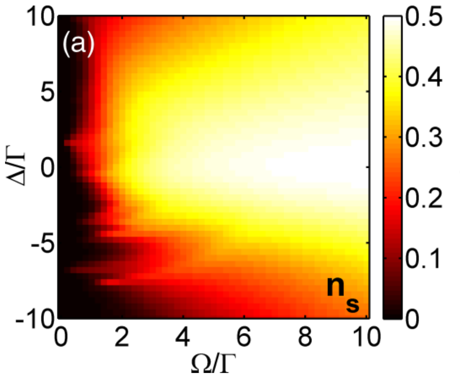
One idea: ~420 nm



Merge staggered bi-layers

Optical dipoles, many body physics & quantum optics

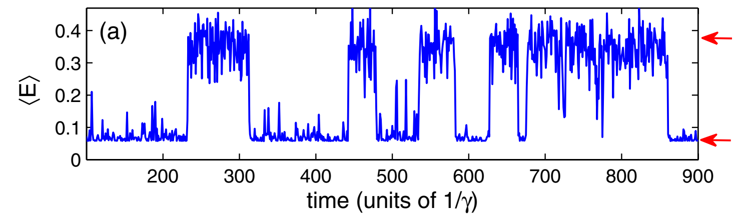
A driven, dissipative (collective...) many-body system



Phase diagram??
(OK mean-field +
small part. nb.)

Lesanovsky&Olmos...

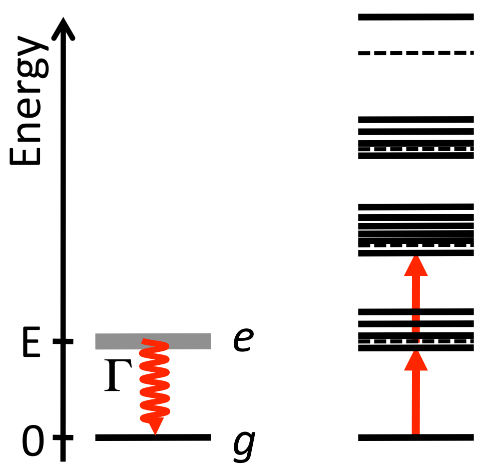
Dynamics: collective
quantum jumps??



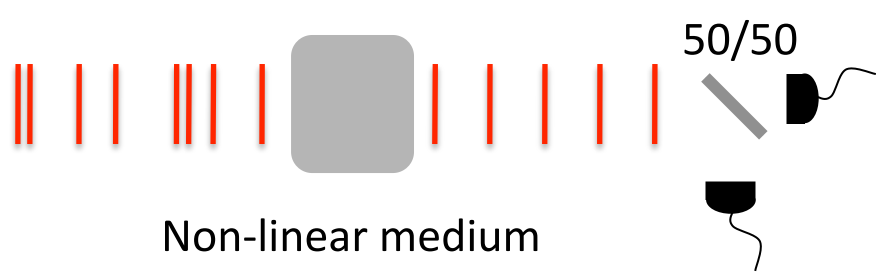
Haeffner PRL2012, Olmos...

+ Use scattered light as a probe

A "new" quantum optics platform?



non-linearity from dipole-dipole interactions
$\Rightarrow$ non-classical correlations on light??



Olmos (JPhysB 2016), Ott&Kaiser (PRA 2013), Ritsch (Opt.expr. 2012...)

Open questions

Rydberg: role of exp. imperfections and dephasing ("bad" dissipation)

Limits preparation of MB ground state

Limits duration of interaction driven dynamics

+ role of complex atomic structure

$\Rightarrow$ Model of dissipation?? Use dissipation to prepare MB states??

Optical dipoles ("good" dissipation)**:**

Strength of interaction-induced non-linearity?

Mapping atomic correlations onto light correlations?

Exp.: structure at sub-λ scale = hard

$\Rightarrow$ use low-lying Rydberg states??