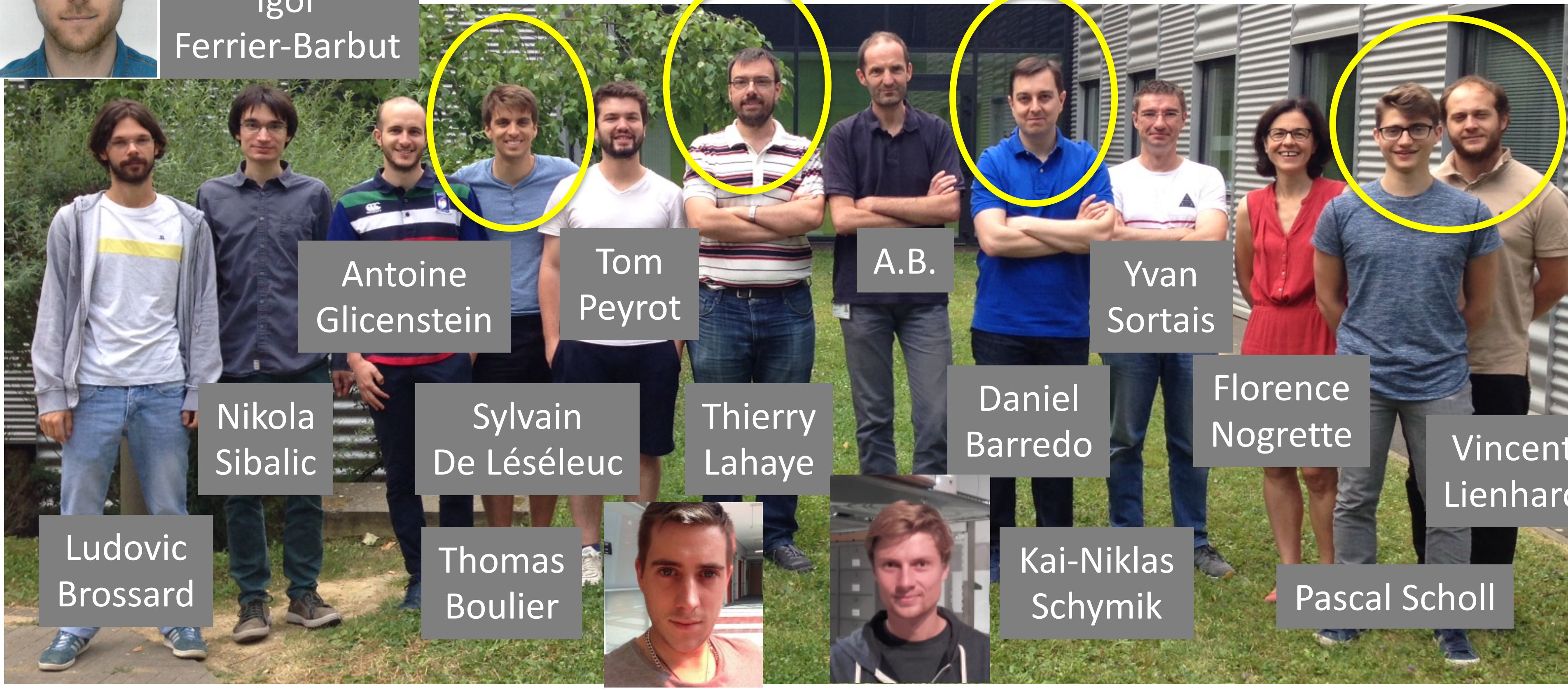
Dipole-dipole interactions between atoms for many-body physics and quantum information

Lecture 1: Dipole-dipole interaction between atoms

Lecture 2: Basics of Rydberg physics. Arrays of cold atoms. Rydberg blockade & QIP

Lecture 3: Many-body physics with Rydberg atoms.

The team (atom-tweezers-io.org)



Theory

H.-P. Büchler (Stuttgart)

N. Lang (Stuttgart)

S. Weber (Stuttgart)

DGA

PALM Laboratoire d'Excellence Physique : Atomes Lumière Matière

SIRTEQ

îledeFrance

PASQuanS

Outline

1. Quantum simulation and spin models

2. Simulation of Ising model using van der Waals interactions

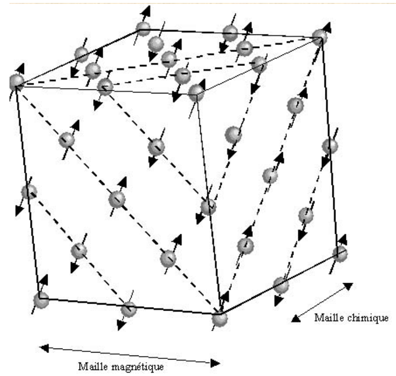
3. Topological systems using resonant dipole interactions

Many-body physics and quantum simulation

Goal: Understand ensembles of interacting quantum particles

superfluidity

superconductivity



magnetism

neutron star

Questions: phase diagram, excitation spectrum, dynamics, transport…

Experiments on real system → simplify → Model Hamiltonian

Model Hamiltonian ⇏ Experiments on real system: **Calculation too hard…**

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

Exponential scaling of Hilbert space

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

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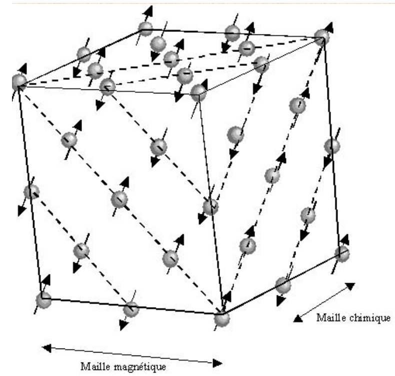

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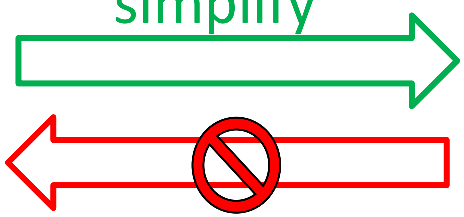
Experiments on real system

simplify



Calculation too hard…

Model Hamiltonian

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

Careful: approximate methods ($10^2 < N < 10^5$) exist!!!!

DMRG, Monte Carlo, density functionnal, mean field…

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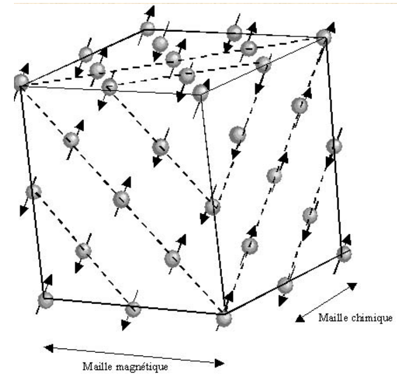

magnetism

neutron star

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Experiments on real system → simplify → Model Hamiltonian

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

Lab…

"Preparable"

$$|\psi(t)\rangle = e^{-\frac{i}{\hbar} H_{\text{model}} t} |\psi(0)\rangle$$

Quantum simulator = engineer ensemble of "atoms" ruled by H_{model}

Mesure outcome of simulator: **ground state = supercond.?**

The original idea…

R.P. Feynman

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

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

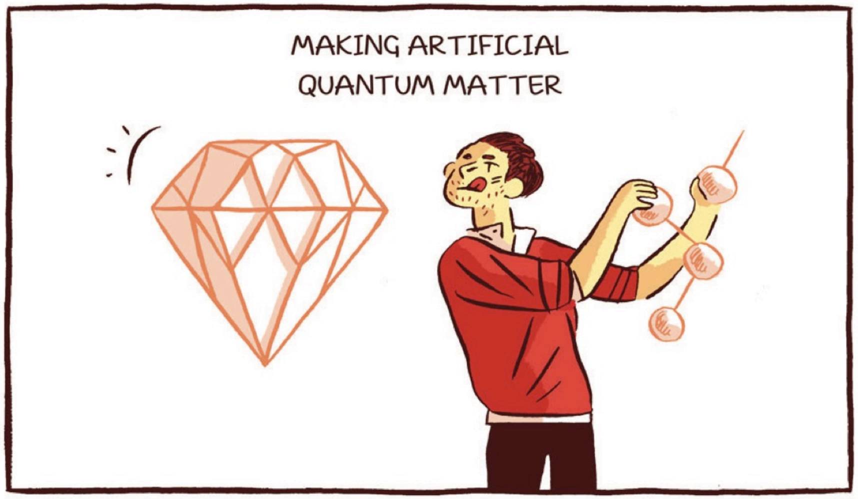
with it, with quantum-mechanical rules). For example, the spin waves in a spin lattice imitating Bose-particles in the field theory. I therefore believe it's true that with a suitable class of quantum machines you could imitate any quantum system, including the physical world. But I don't know whether the general theory of this intersimulation of quantum systems has ever been worked out, and so I present that as another interesting problem: to work out the classes of different kinds of quantum mechanical systems which are really intersimulatable—which are equivalent—as has been done in the case of classical computers. It has been found that there is a kind of

Many-body physics with synthetic matter

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…)

Larger tunability than “real” systems (geometry, parameters…)

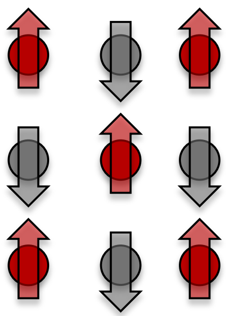
+

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

Georgescu, Rev. Mod. Phys. (2014)

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

Interacting spin ½ particles on a lattice:

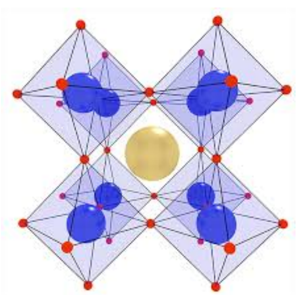


$$\hat{H}_{ij} = J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$$

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

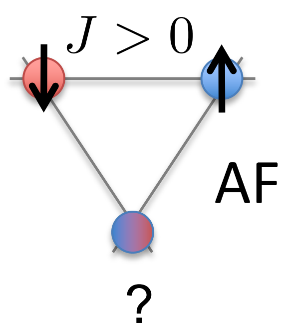
XY model $$\hat{H} = \sum_{i \neq j} J_{ij}\left(\hat{\sigma}_i^+\hat{\sigma}_j^- + \hat{\sigma}_i^-\hat{\sigma}_j^+\right)$$

Magnetism

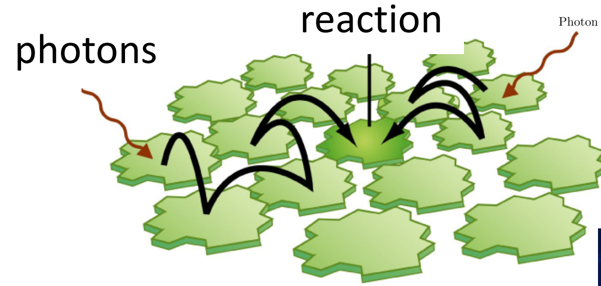


Perovskite

$Y_2Ti_2O_7$



Transport of excitations



photosynthesis

Light scattering
(dissipative)

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

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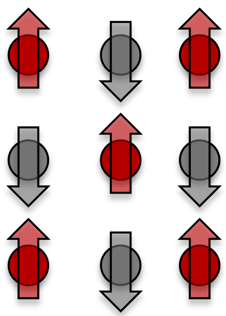

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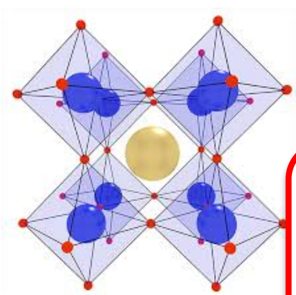
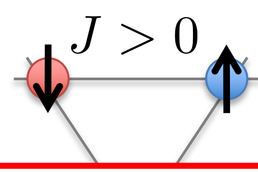
Magnetism





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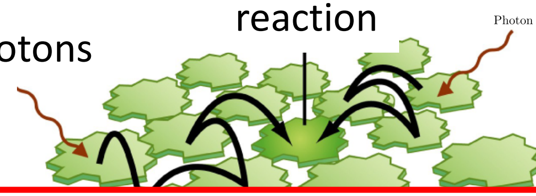


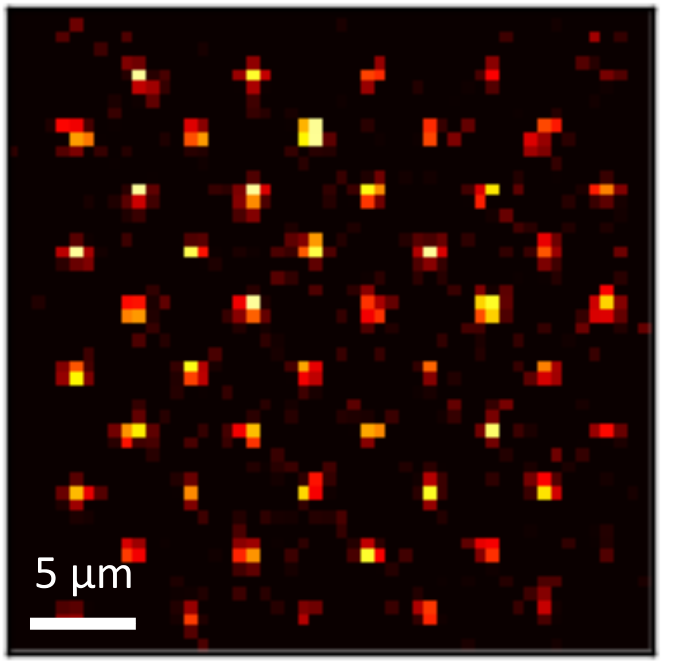
photosynthesis

Use control over artificial quantum matter

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

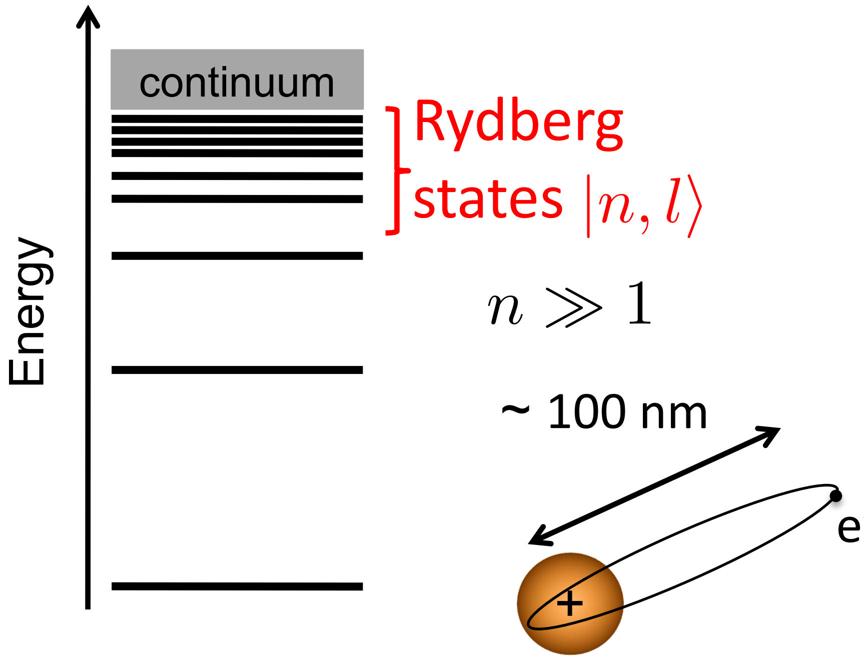
Arrays of interacting Rydberg atoms

Arrays of atoms (~70 at.)



Addressable!!

Rydberg atoms



Lifetime > 100 μs

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

$\Rightarrow$ **Large dipole-dipole interactions**

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

$\Rightarrow$ **timescales < μsec**

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

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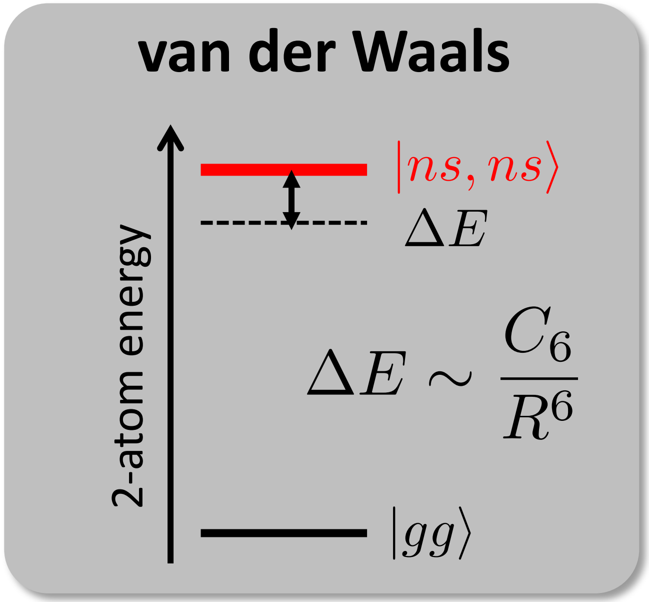
From van der Waals interactions to Ising model…

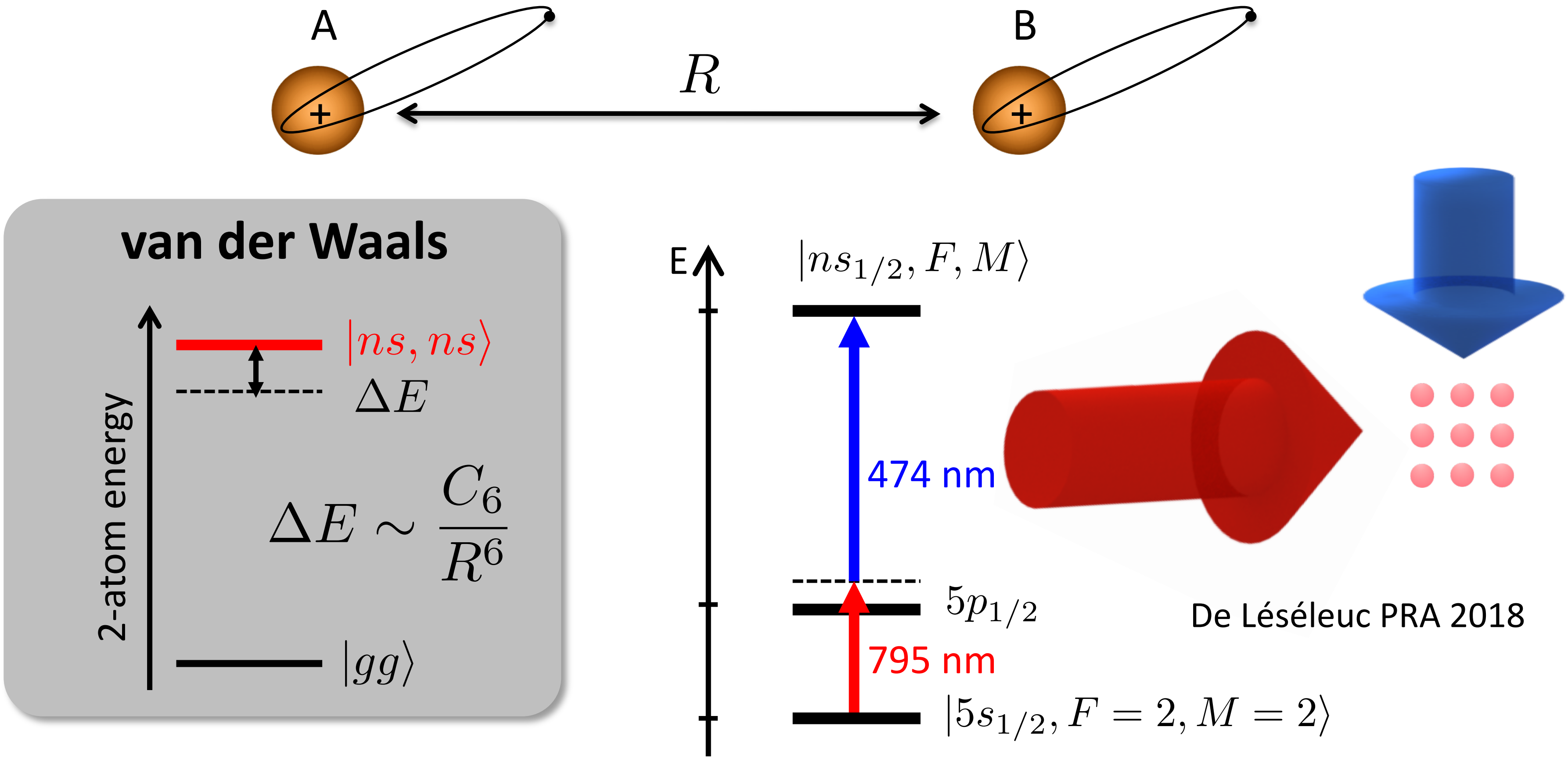


$C_6 \propto n^{11}$ $\Rightarrow$ switchable interaction

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

Rydberg occupation number

From van der Waals interactions to Ising model…



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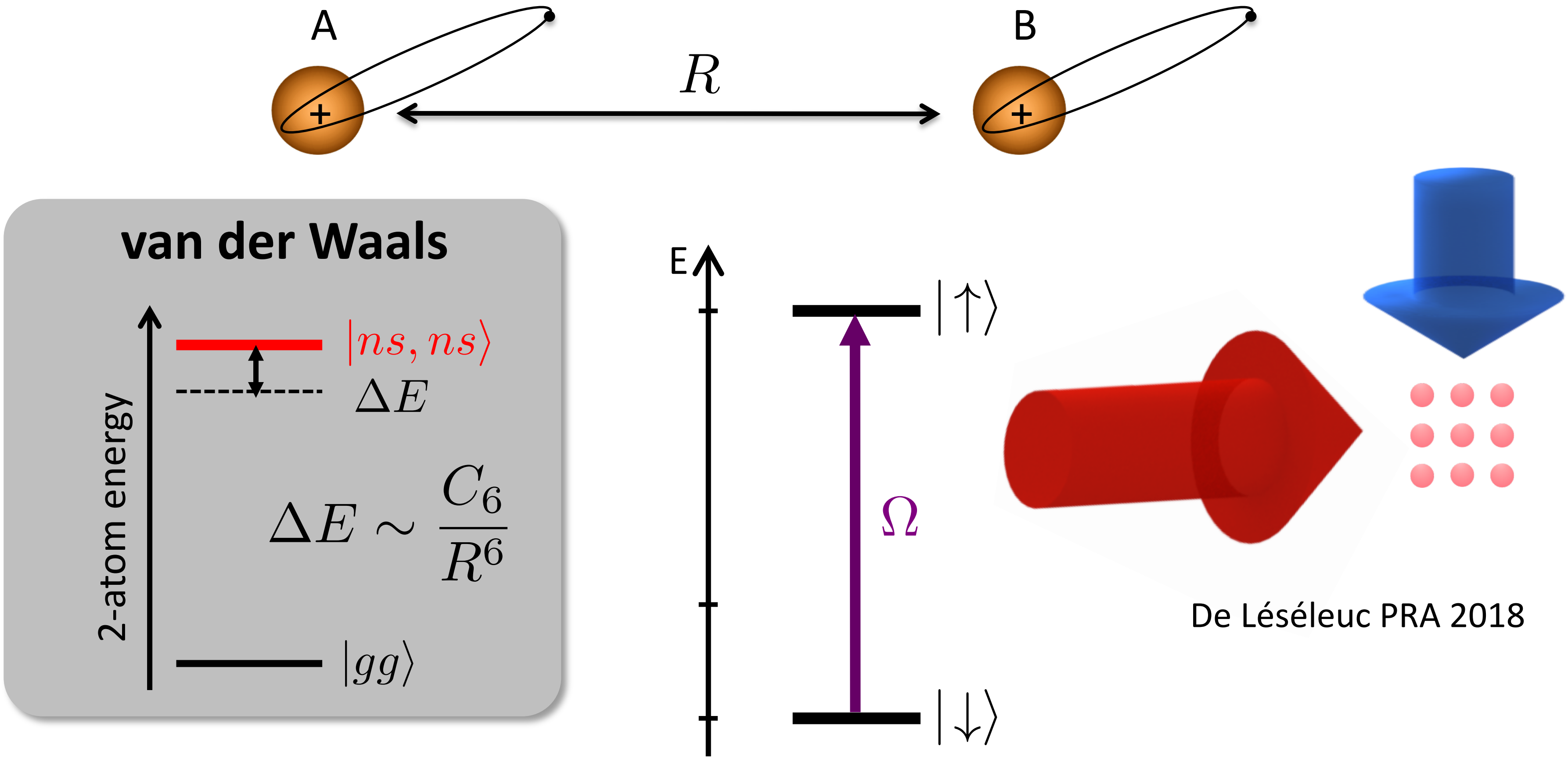

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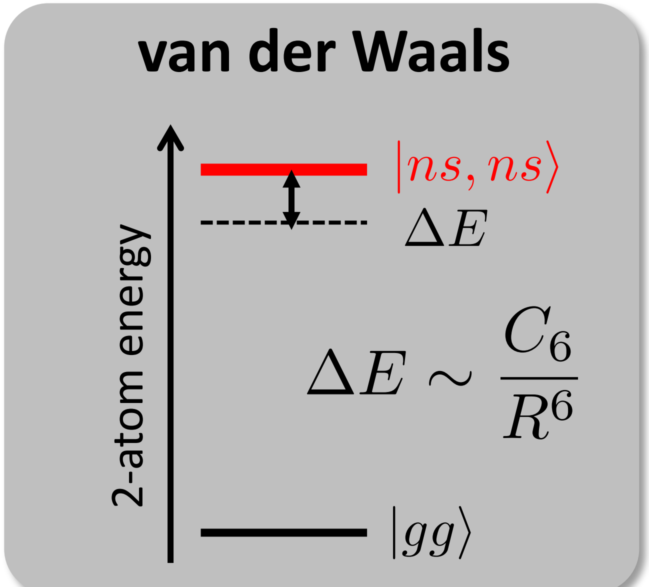
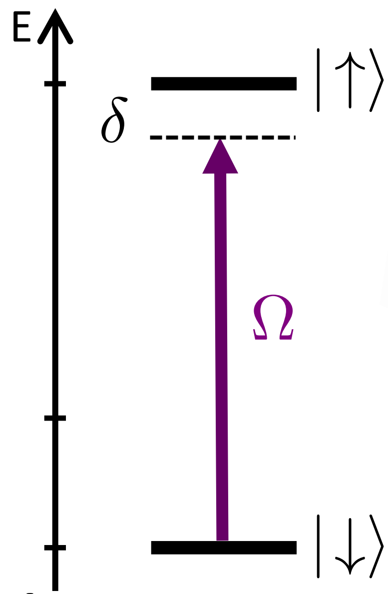
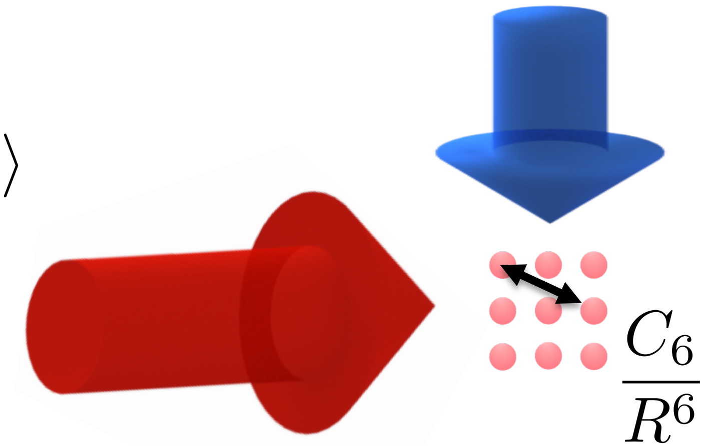






De Léséleuc PRA 2018

Quantum Ising-like model (s=½):

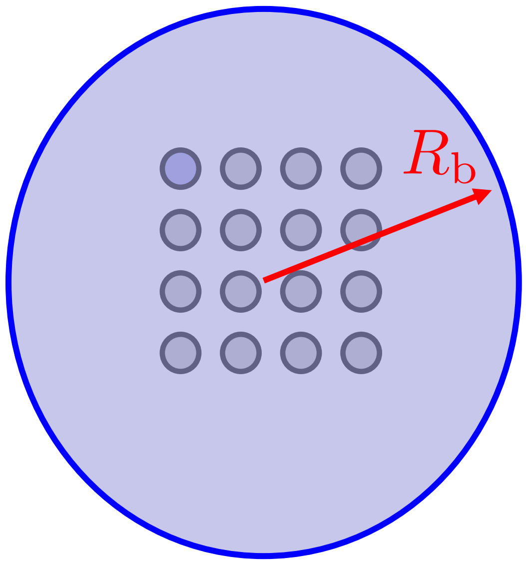
$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i - \hbar\delta\sum_i \hat{n}_i + \sum_{i<j}\frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

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

Experimt^{t}.

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

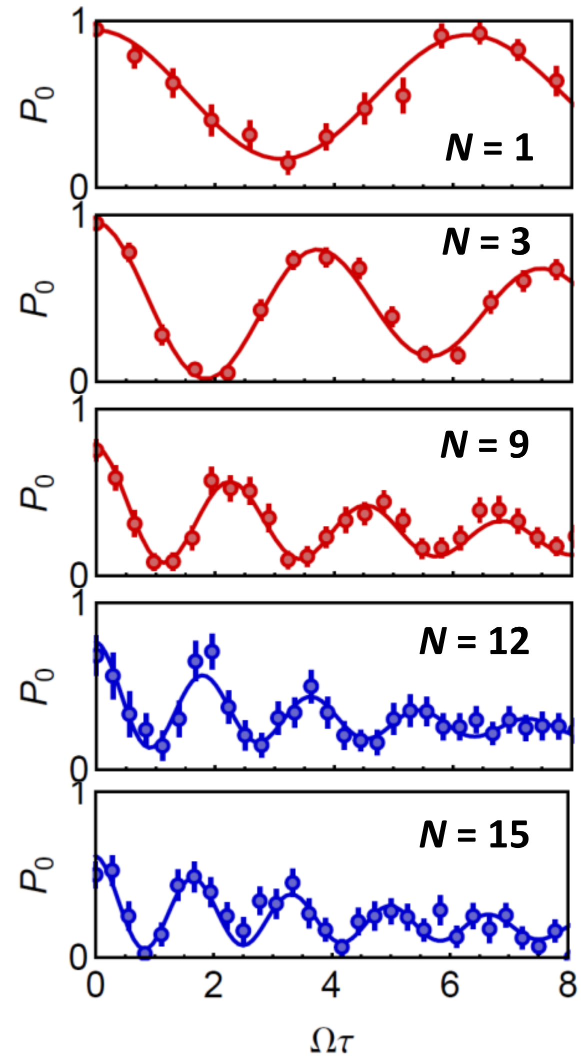
From blockade to many-body physics with “many” atoms



dim H = 2

Two (collective) states

$$|ggg\ldots\rangle \Longleftrightarrow \frac{1}{\sqrt{N}}\sum_i |g\ldots r_i g\ldots\rangle$$



Labuhn *et al.*, Nature **534**, 667 (2016)
Also: Saffman, Kuzmich, Bloch, Pfau, Ott…

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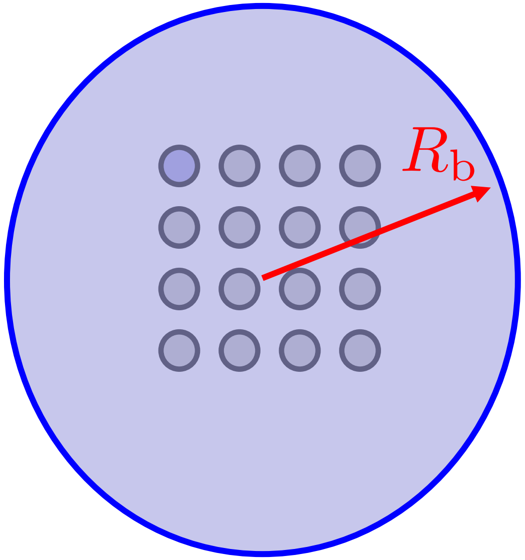

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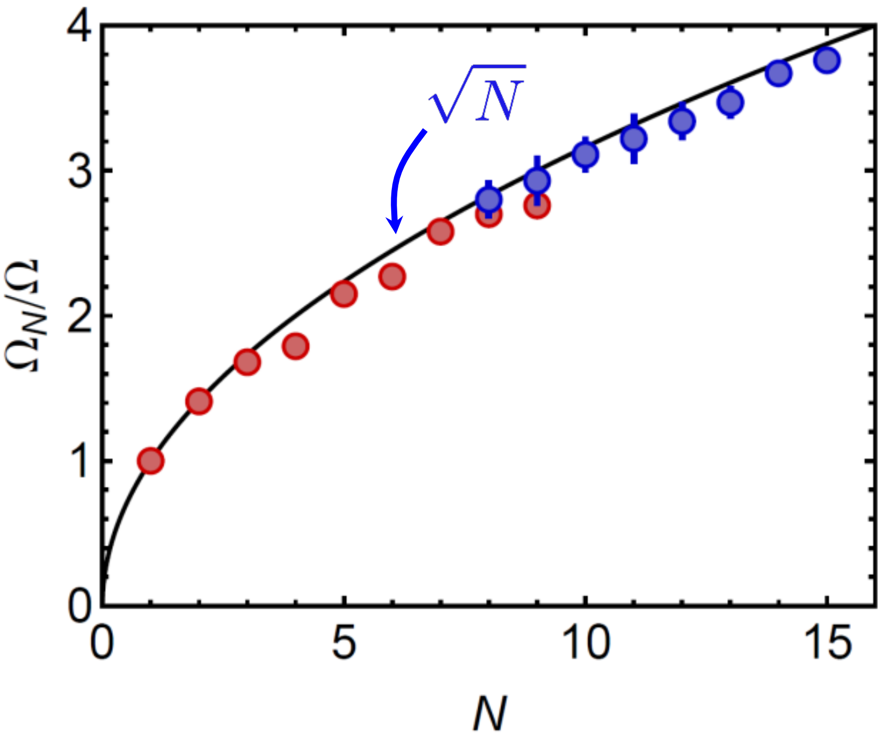

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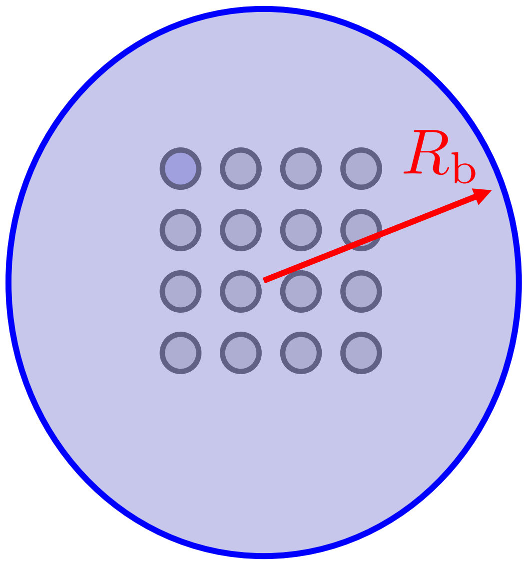

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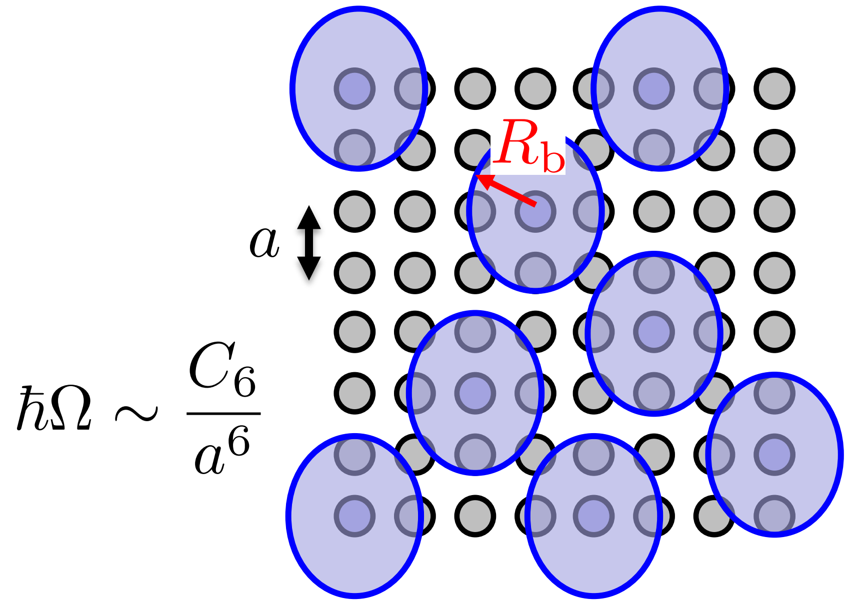


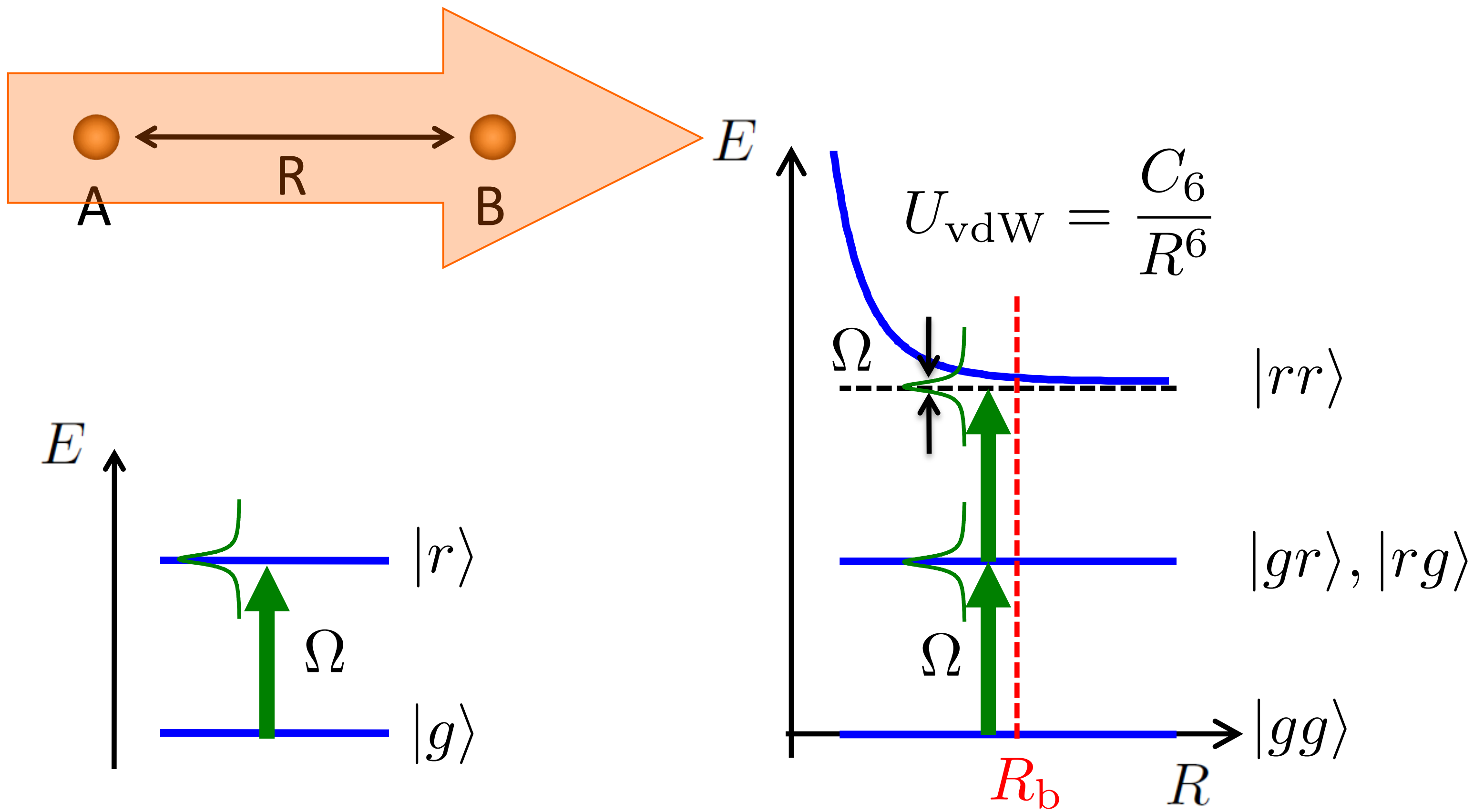
dim $H \sim 2^N$

Strongly correlated many-body system!

Out-of-equilibrium: sudden variation (“quench”) of parameters

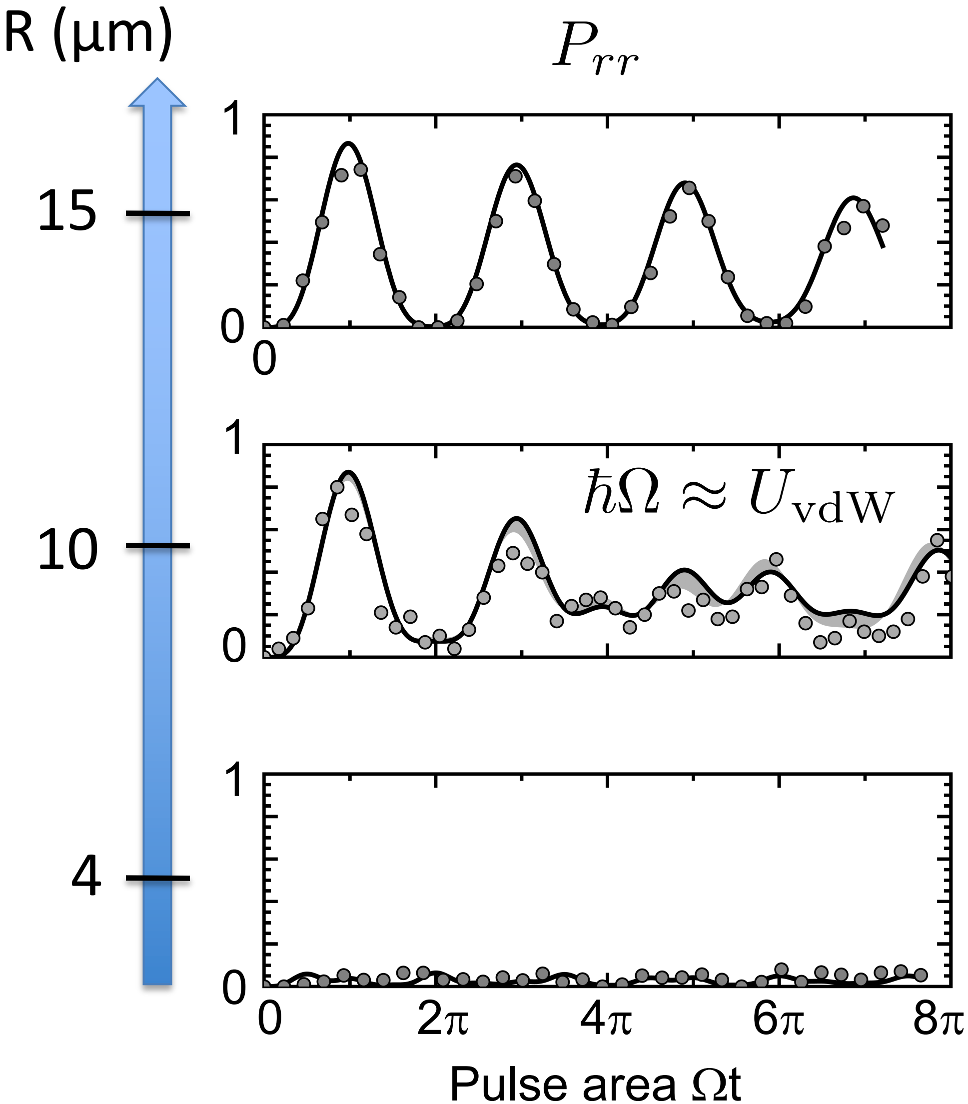
Equilibrium: preparation of ground states

Collective excitation of two interacting Rydberg atoms



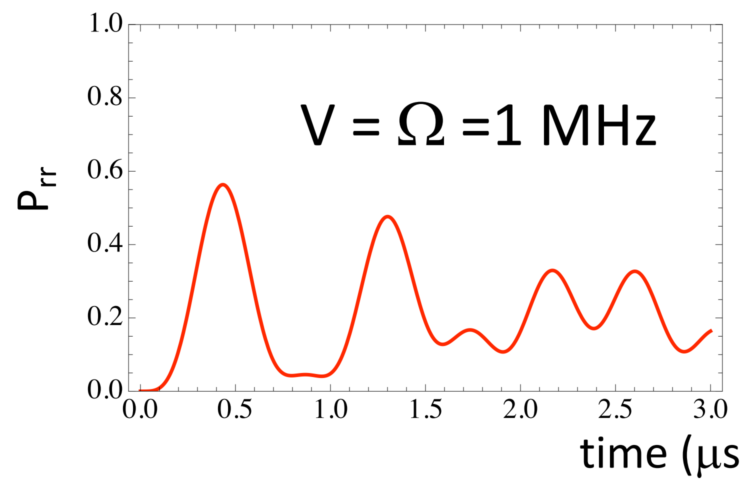
If $\hbar\Omega \approx U_{\mathrm{vdW}}$: dynamics governed by Ω **and** U_{vdW}

From independent atoms to blockade ($62d_{3/2}$)



$\hbar\Omega \gg U_{\mathrm{vdW}}$

Theory (Schrödinger eq.)



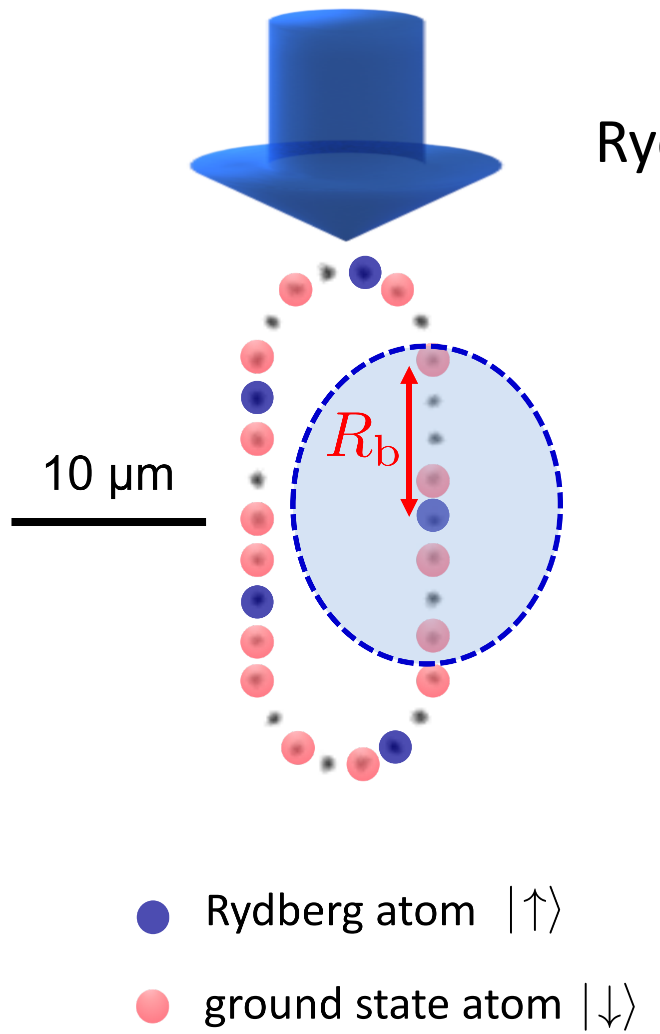
$\hbar\Omega \ll U_{\mathrm{vdW}}$

Fit $\Rightarrow$ extract U_{vdW}

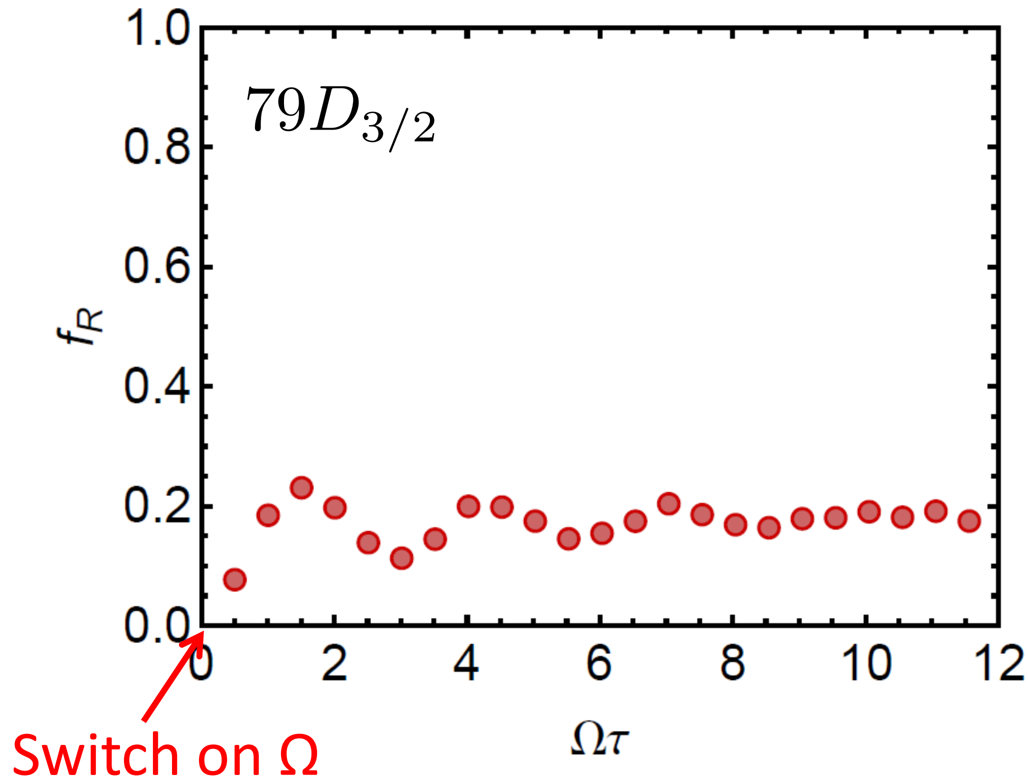
“Quench” in Ising Hamiltonian: 1D with periodic boundary

Labuhn *et al.*, Nature **534**, 667 (2016)

Partially loaded 1D ring (30 traps, 20 atoms)



Rydberg fraction: $f_r = \dfrac{\langle N_r \rangle}{N}$ **~ magnetization**



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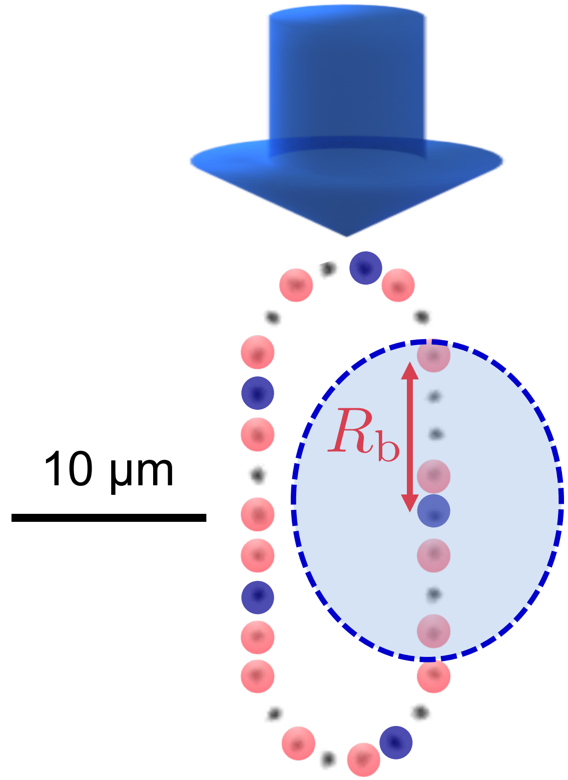

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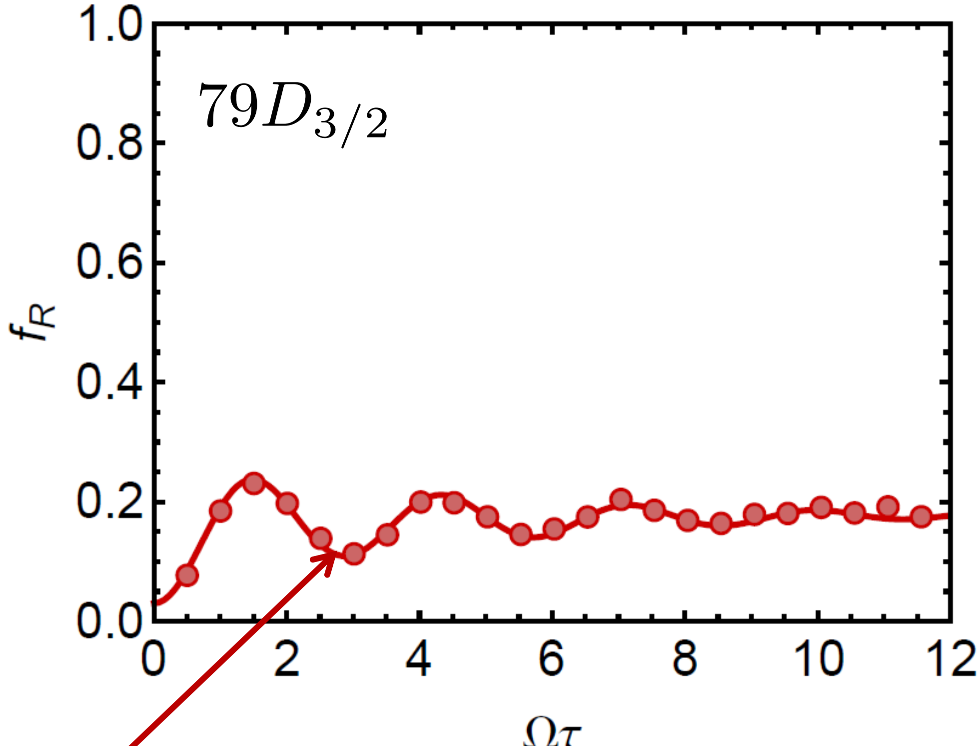

Spin ½ model (Schrödinger), no adjustable parameters…!

Includes detection efficiency (T. Macri)

"Quench" in Ising Hamiltonian: 1D with periodic boundary

Labuhn *et al.*, Nature **534**, 667 (2016)

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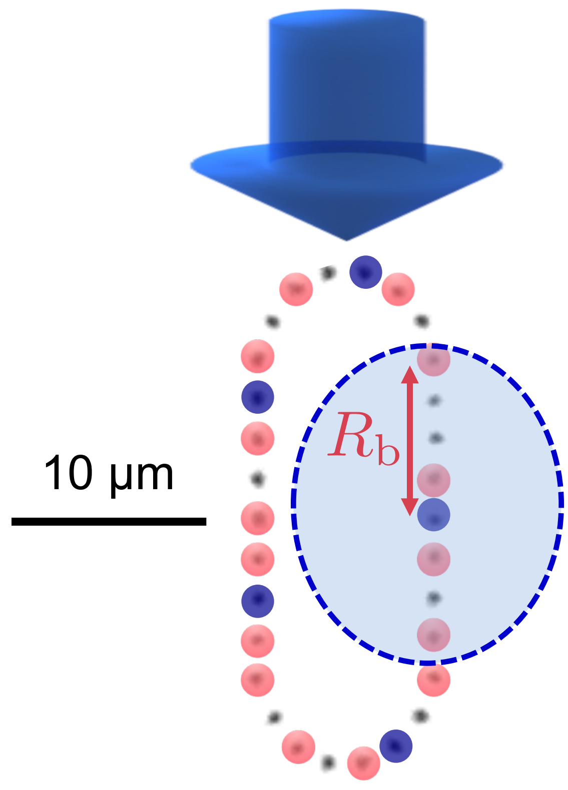

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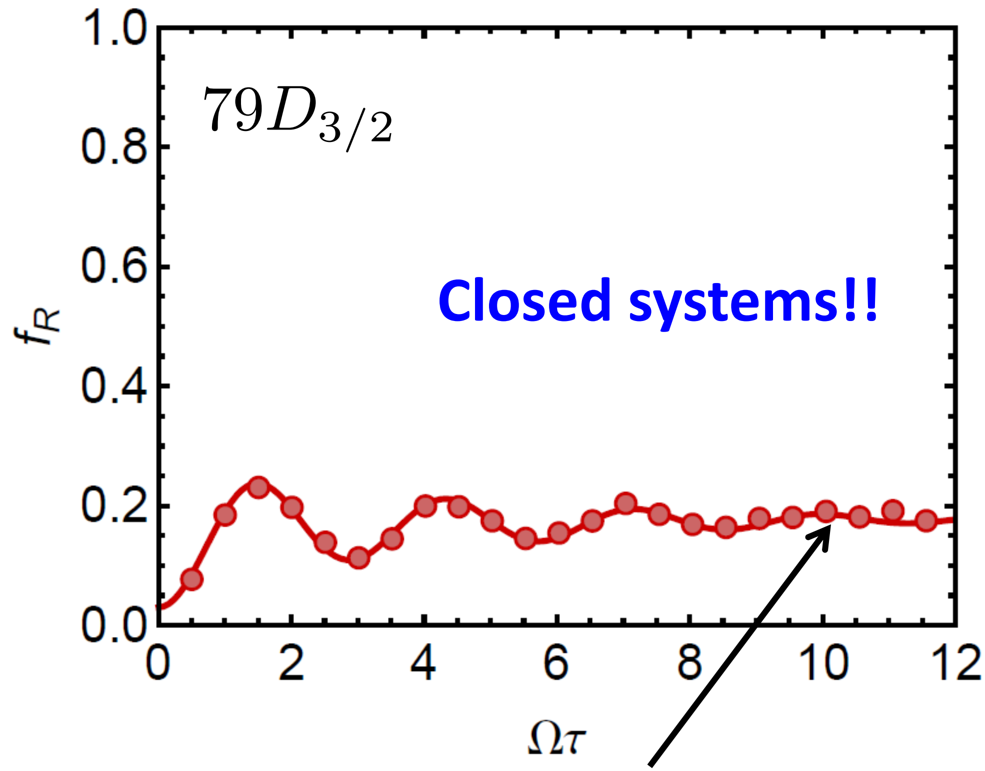

"Damping" = dephasing of 2^{20} eigenenergies

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Labuhn *et al.*, Nature **534**, 667 (2016)

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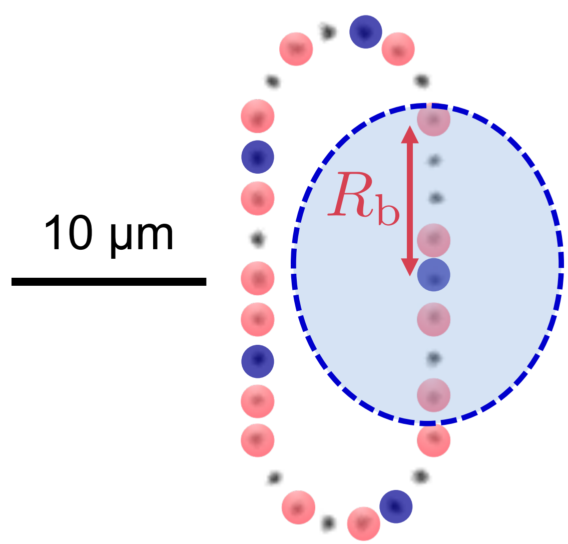
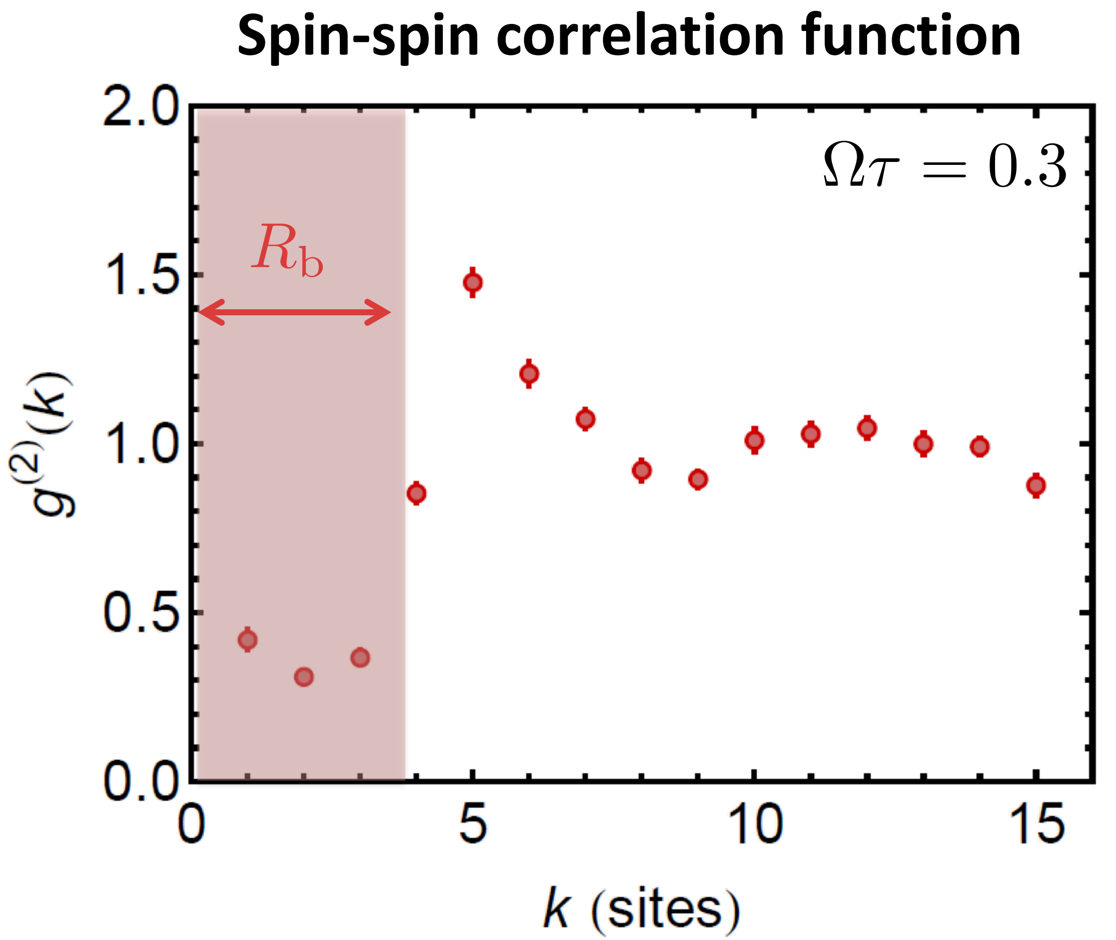


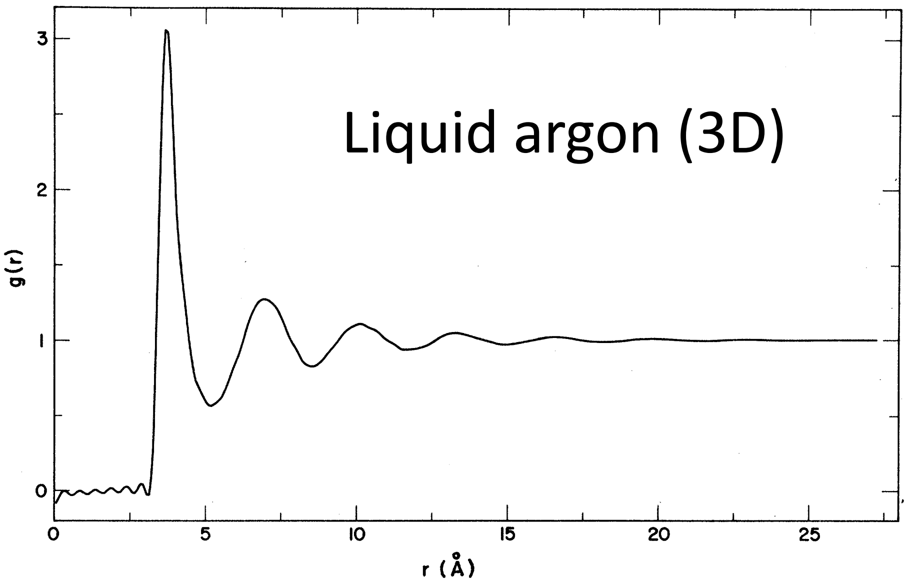


Pair correlation function:

$$g^{(2)}(k) = \frac{1}{N_{\mathrm{tot}}} \sum_i \frac{\langle n_i n_{i+k} \rangle}{\langle n_i \rangle \langle n_{i+k} \rangle}$$

A 1D Ising chain (periodic cond.) = 1D liquid!

Labuhn *et al.*, Nature **534**, 667 (2016)

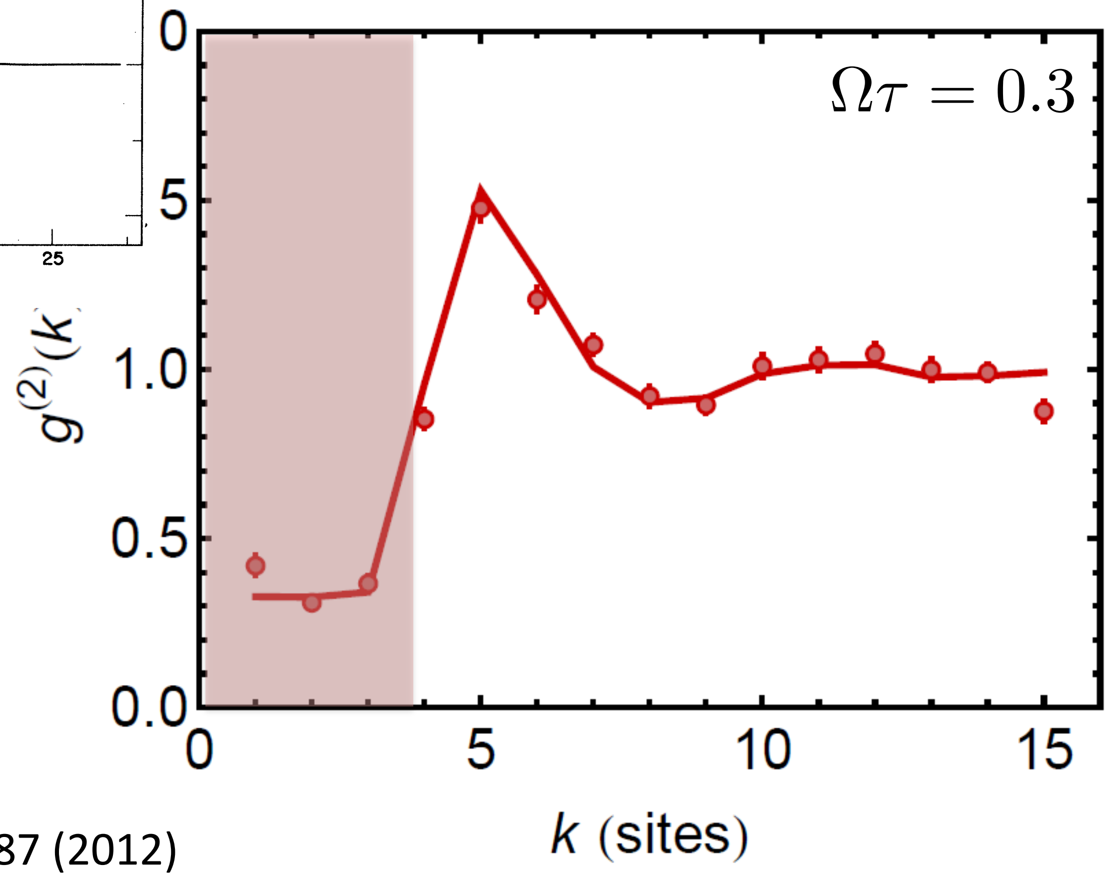


PRA **7**, 2130 (1973)

Analogous to 1D liquid:

hard sphere R_b

Spin-spin correlation function

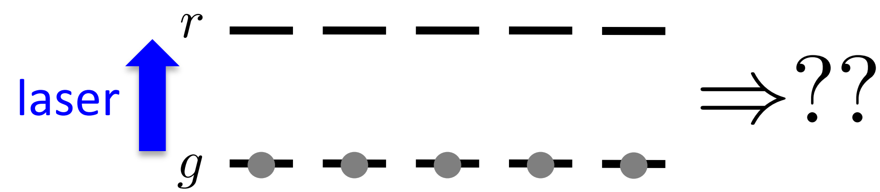


Also in Munich (2D), Nature **491**, 87 (2012)

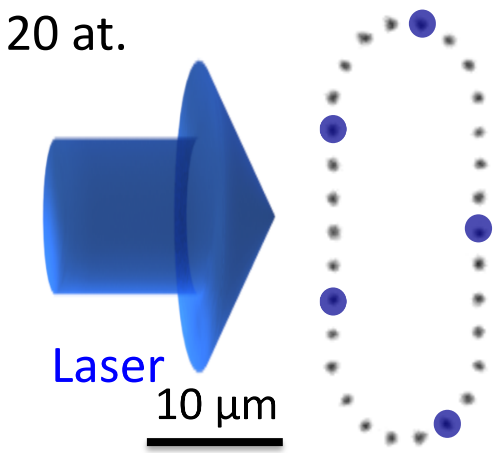
Ates & Lesanovsky, PRA **86**, 013408 (2012)

Petrosyan, PRA **87** 053414 (2013)

Quench in Ising-like Hamiltonian

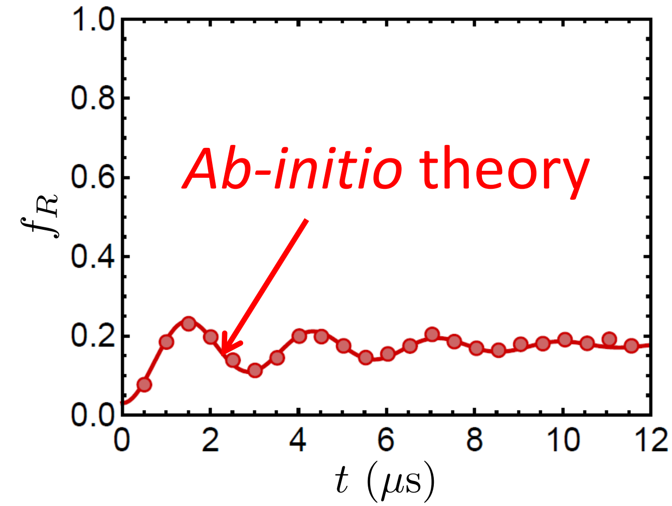


Calculable (*N*<40) ⇒ test

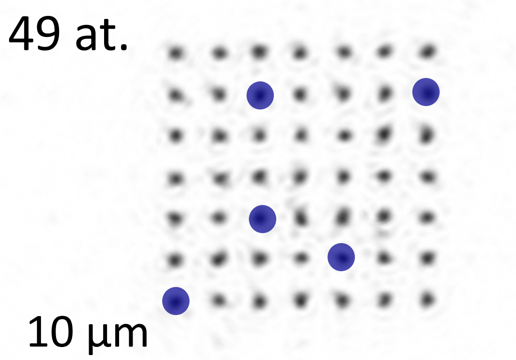


"Magnetization"

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

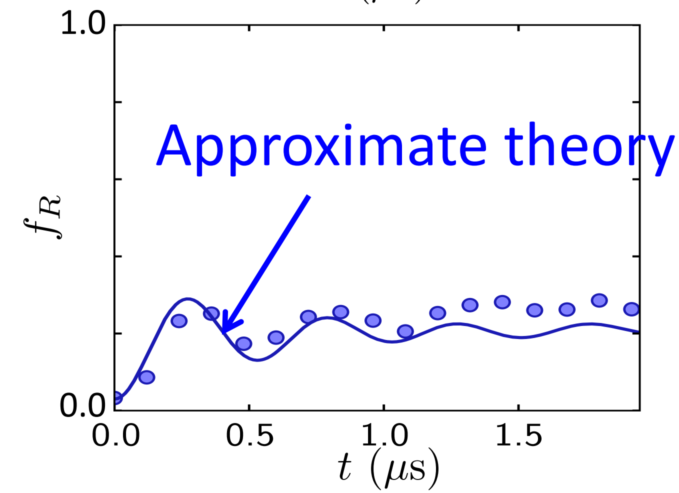


Non-calculable (N>40)



Comparison exp / theo

Validate hypothesis theo & experiments



Adiabatic preparation of an Ising antiferromagnet

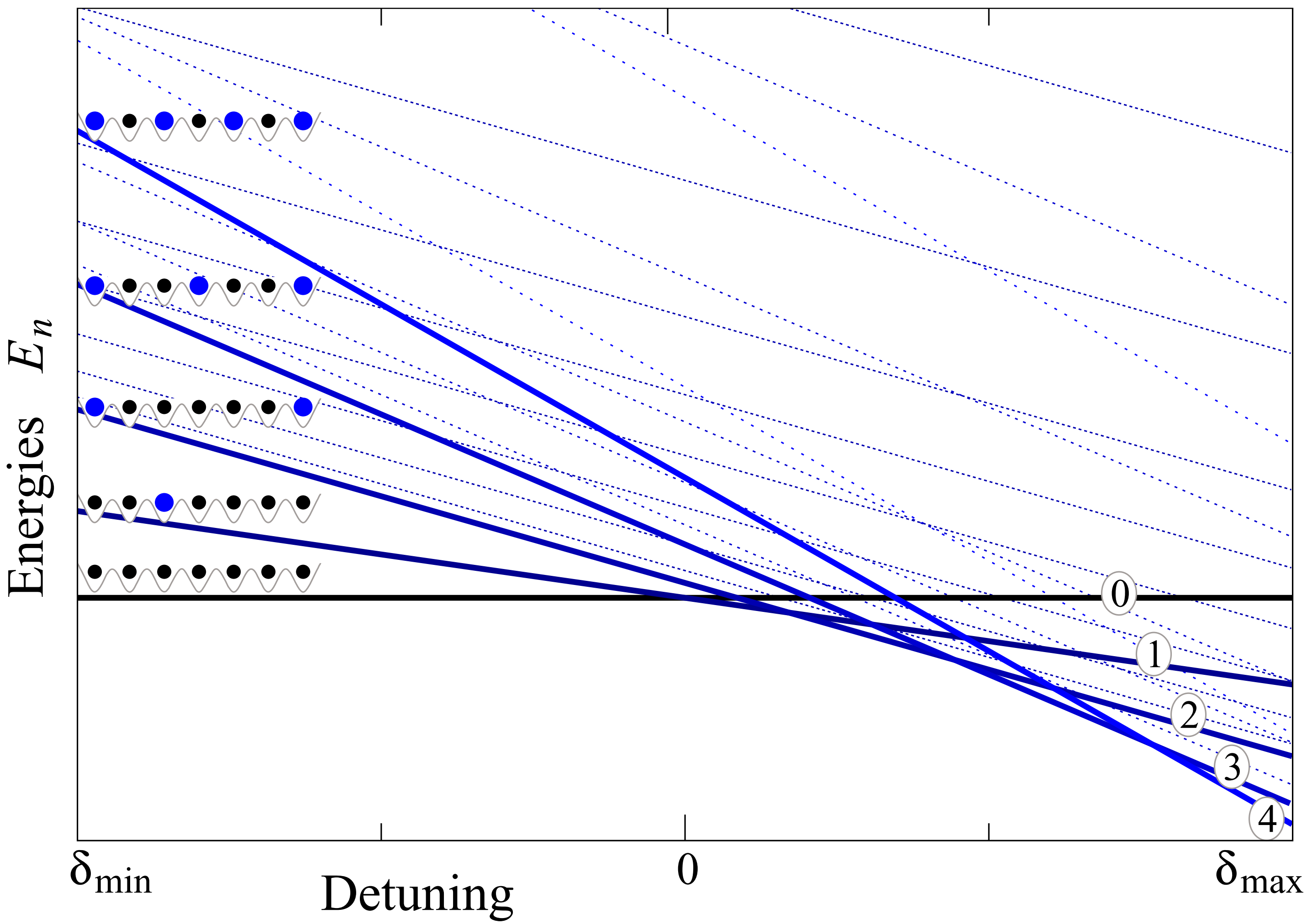
V. Lienhard, PRX **8**, 021070 (2018)

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

Vary slowly Rabi freq. and detuning

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

Adiabatic preparation of spatially-ordered 1D Rydberg chains



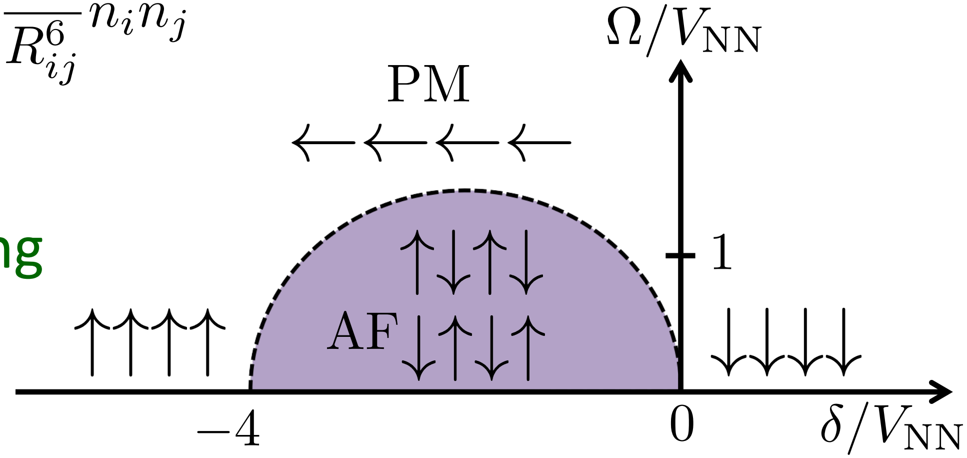
Petrosyan *et al.*, J. Phys. B **49**, 084003 (2016)

Adiabatic preparation of an Ising antiferromagnet

V. Lienhard, PRX **8**, 021070 (2018)

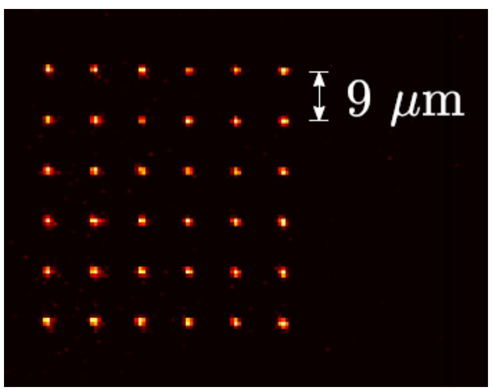
$$H = \sum_i \left(\frac{\hbar\Omega(t)}{2}\sigma_x^i - \hbar\delta(t)\hat{n}_i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

Vary slowly Rabi freq. and detuning



Nearest nearest neighbor

$N = 36, R_{\mathrm{b}} \sim a$



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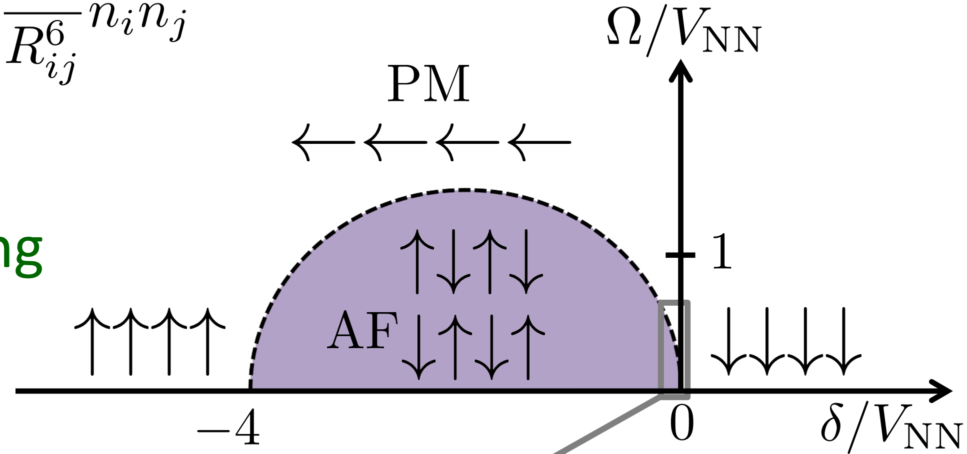
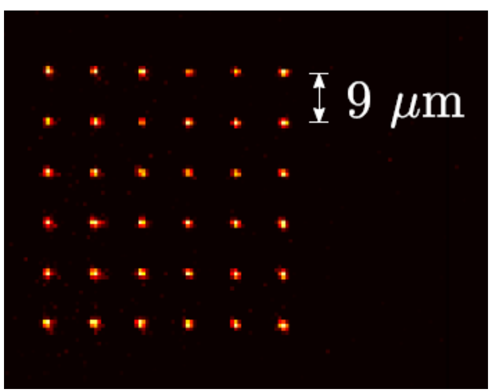
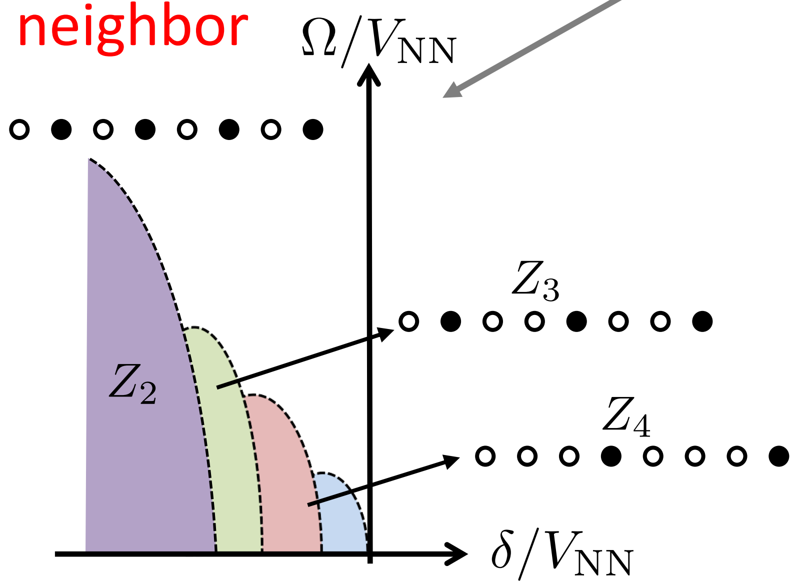


Beyond nearest neighbor

$N = 36, R_b \sim a$





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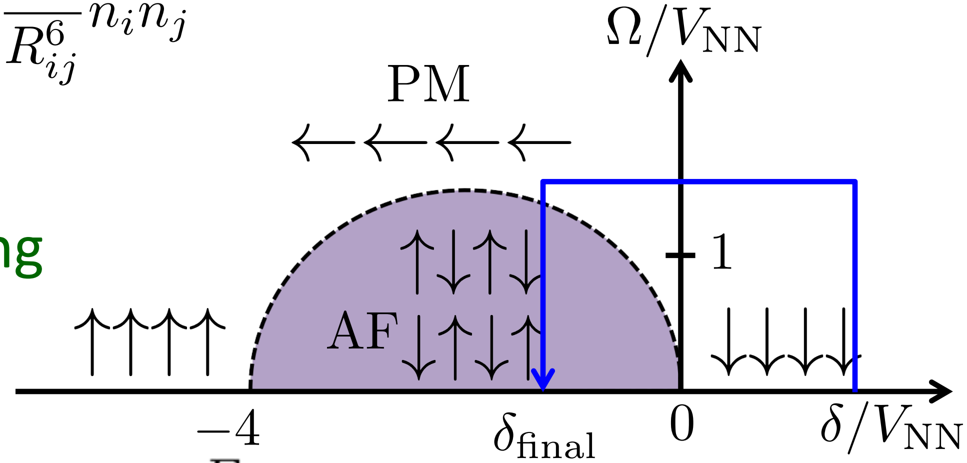
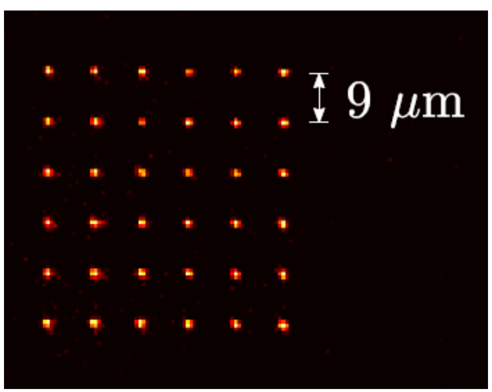
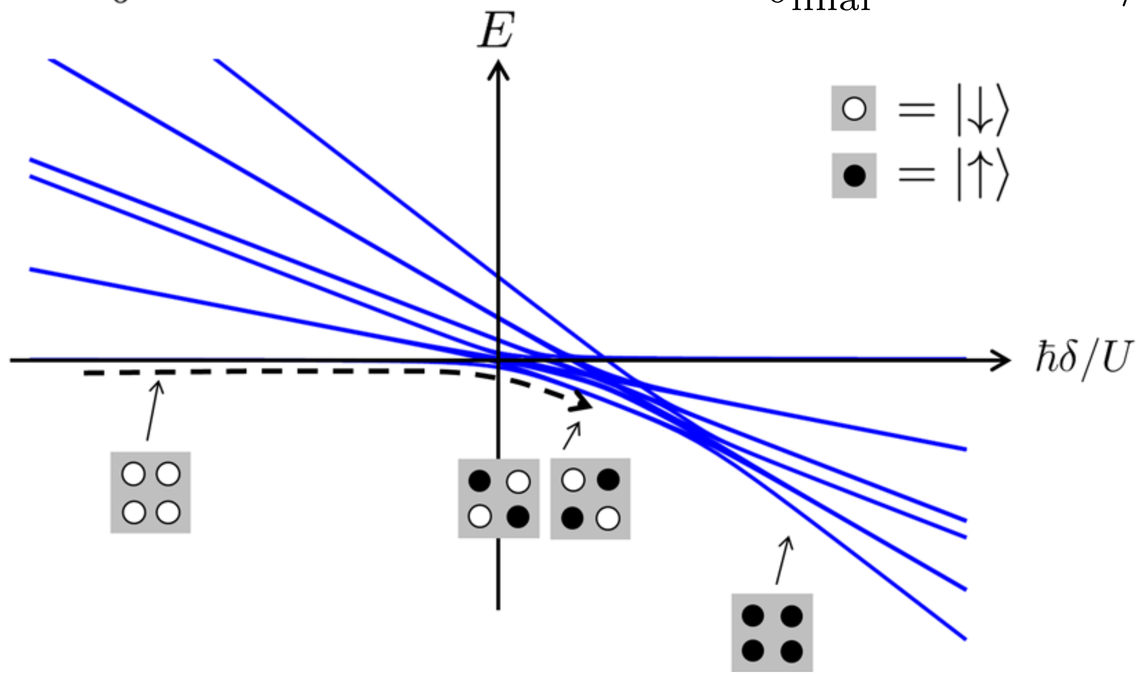


$C_6 > 0$

$N = 36, R_{\rm b} \sim a$





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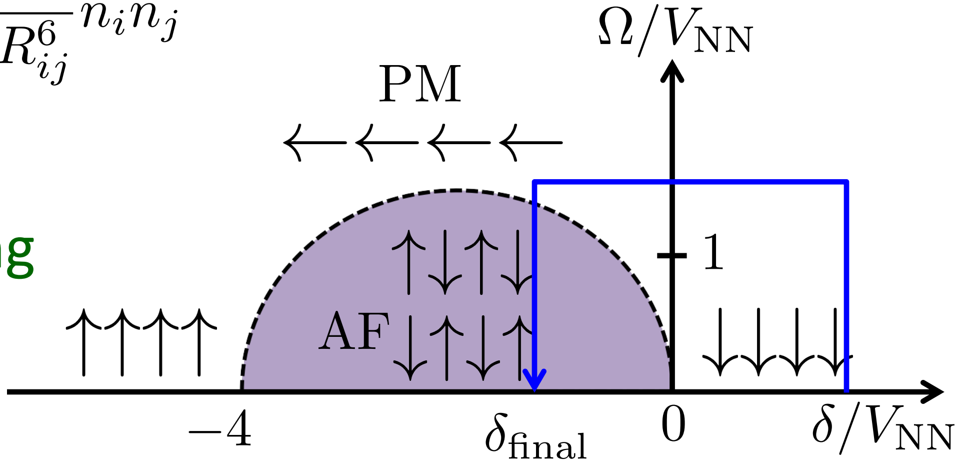

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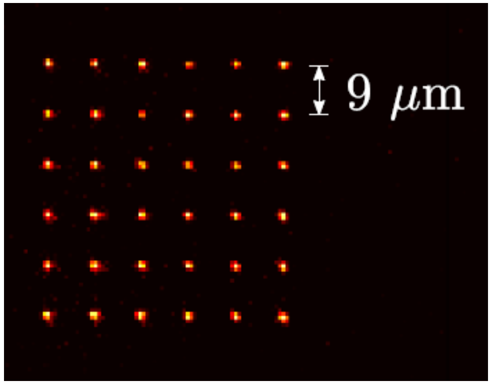
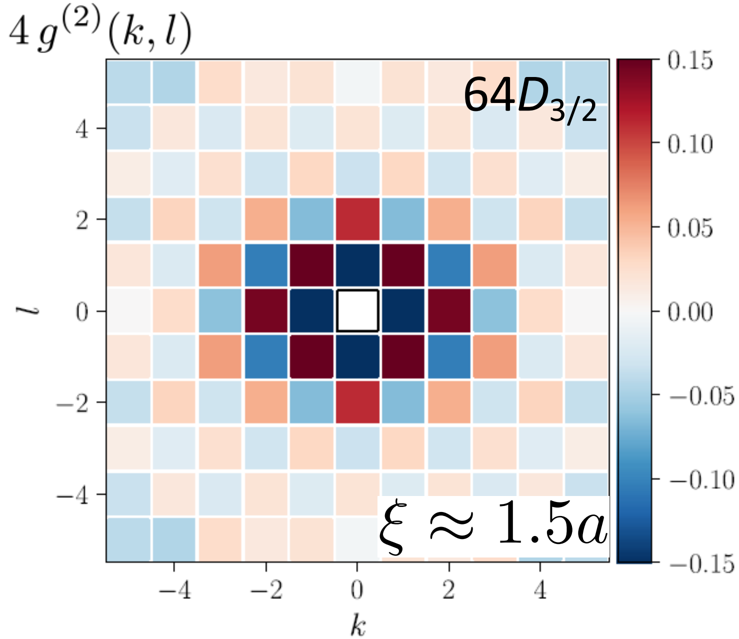




Onset of AF correlations

Study growth with x, t

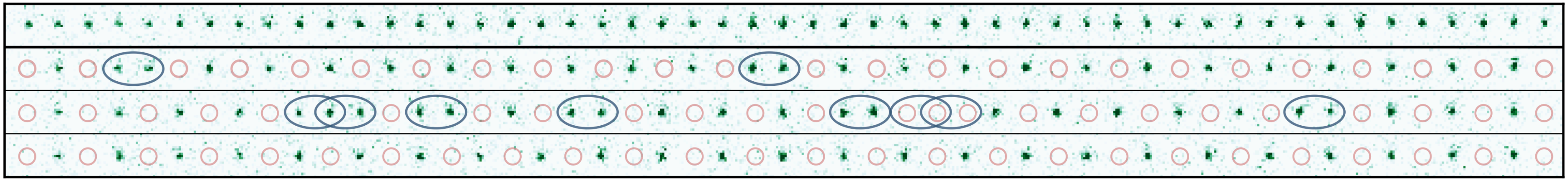
Also: Bakr, PRX **8**, 021069 (2018)

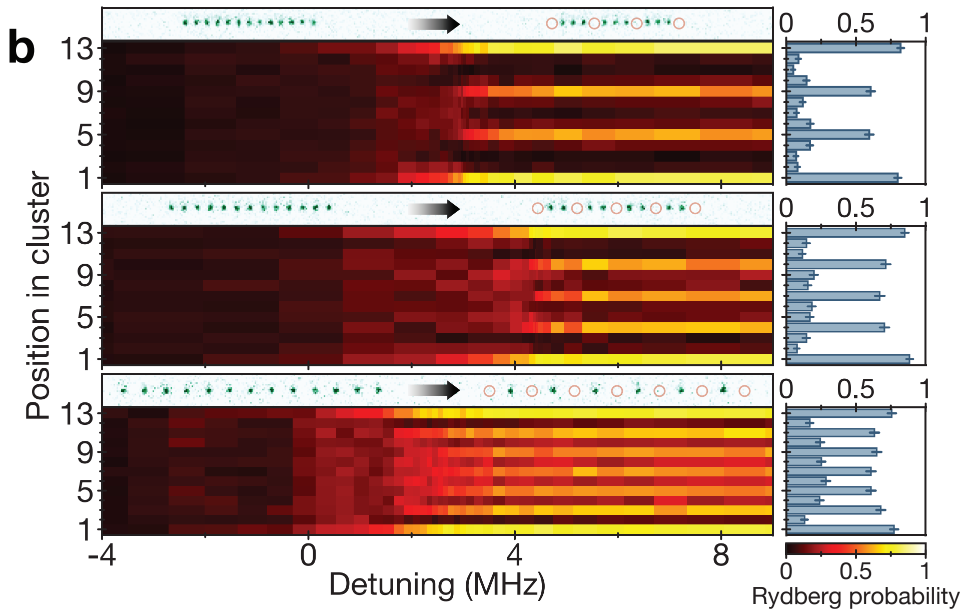
1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019

A 51-atom "quantum simulator" (Harvard-MIT)

$$R_b \sim a$$

H. Bernien, Nature (2017)





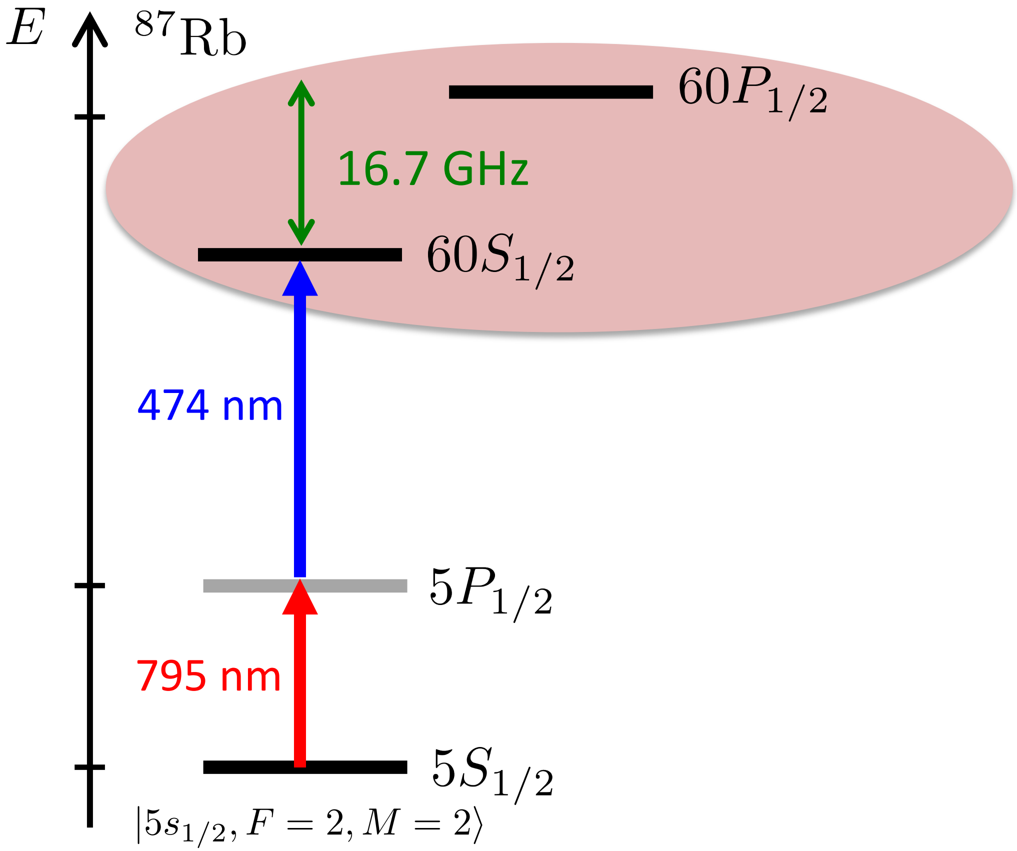
Outline

1. Quantum simulation and spin models

2. Simulation of Ising model using van der Waals interactions

3. Topological systems using resonant dipole interactions

Resonant dipole-dipole interaction between Rydberg atoms



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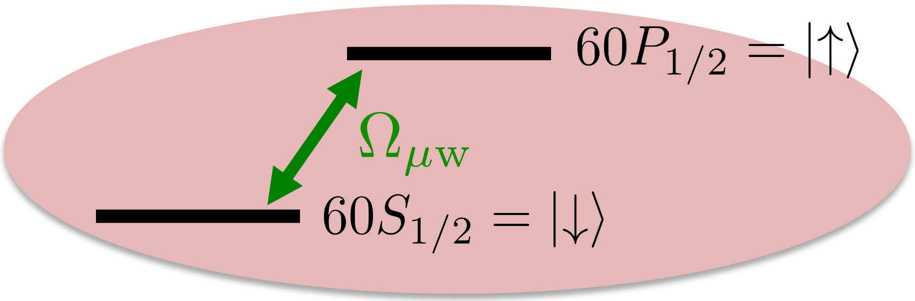
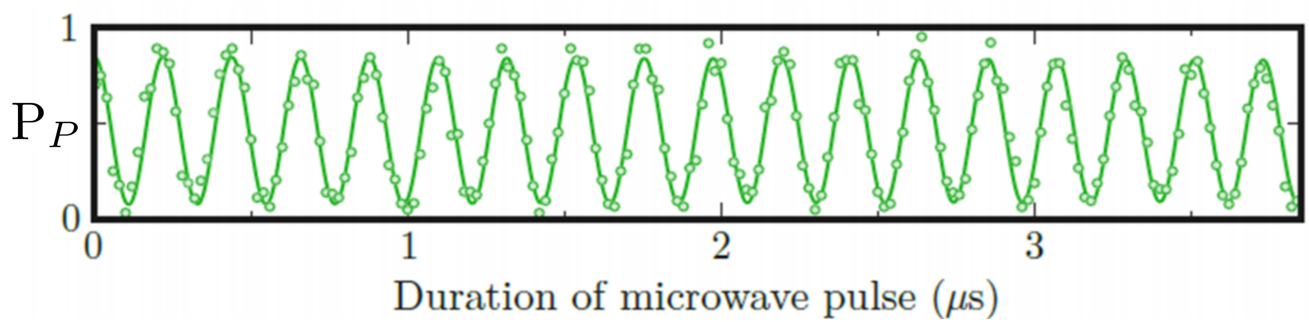
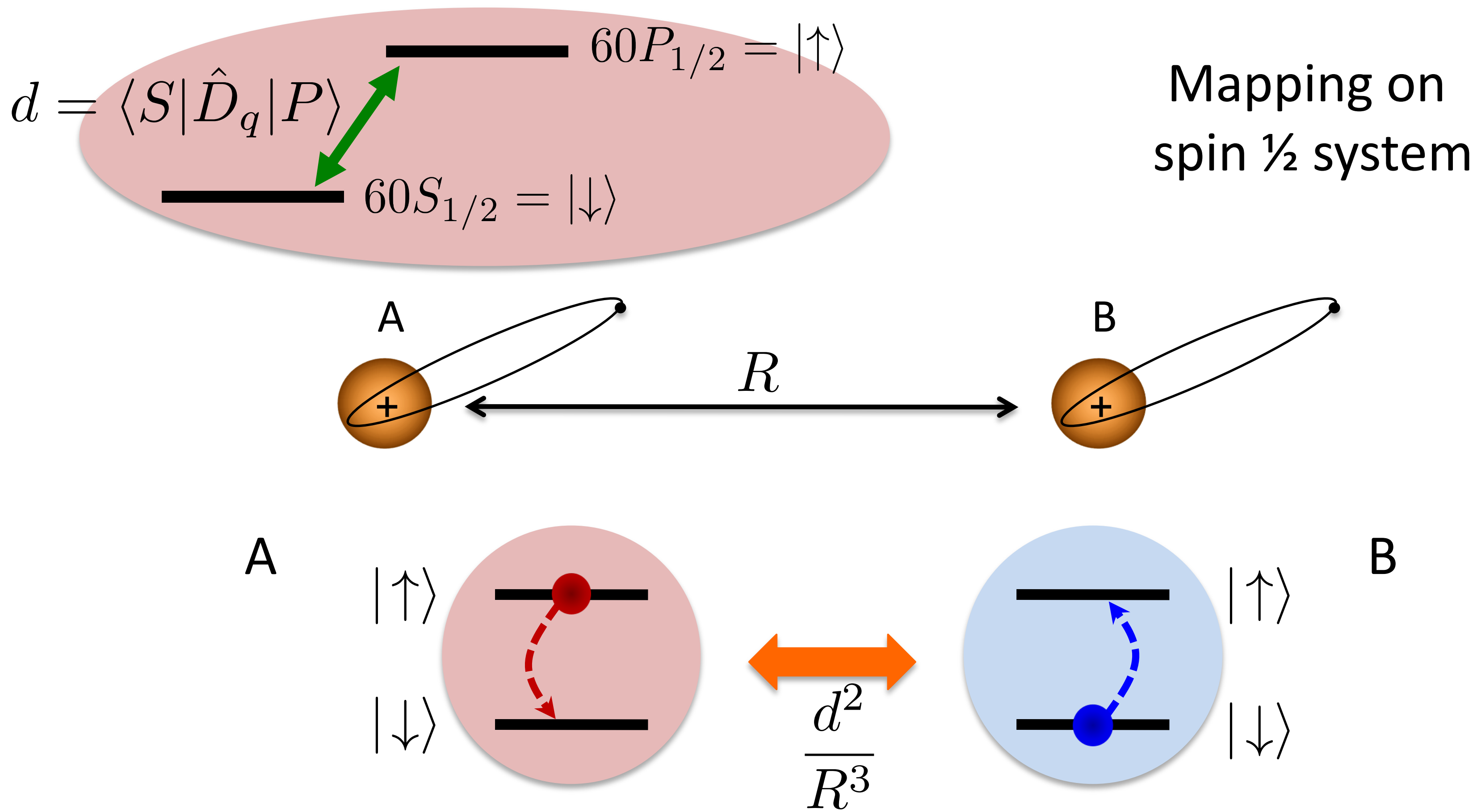


Mapping on
spin ½ system



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

Resonant dipole-dipole interaction between Rydberg atoms



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

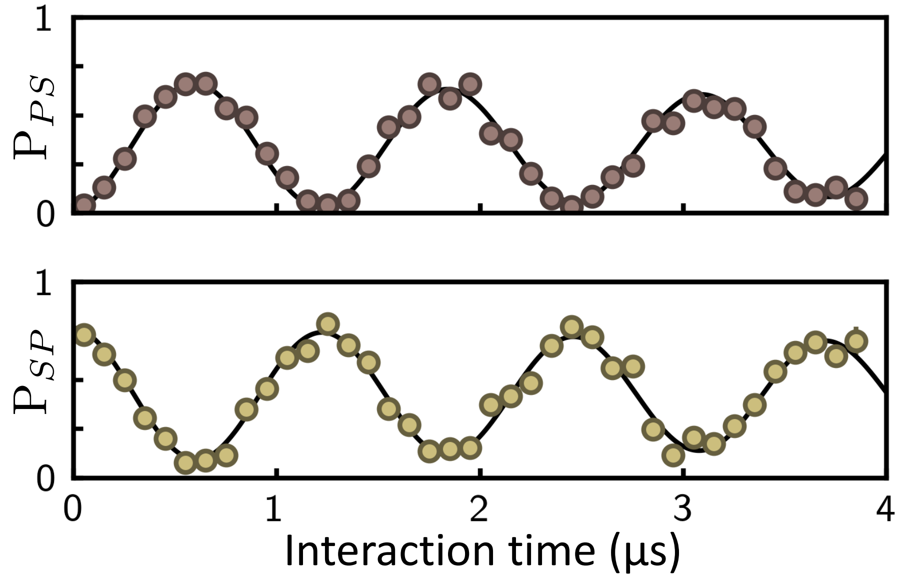
"exchange" of excitation

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

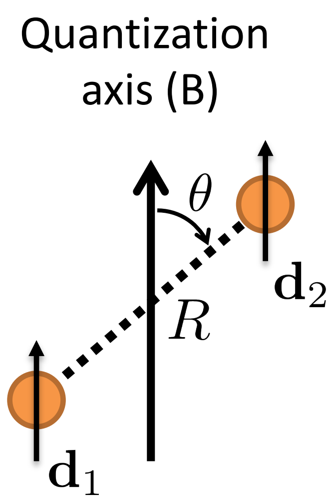
Prepare $|\uparrow\downarrow\rangle$ using microwaves + addressing beam

R = 30 µm

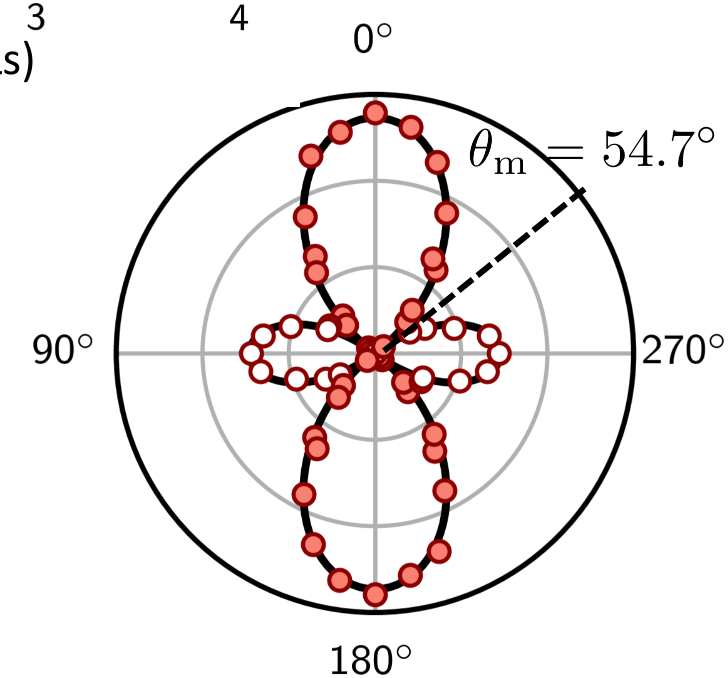
Frequency: $\dfrac{2C_3}{R^3}$



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



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



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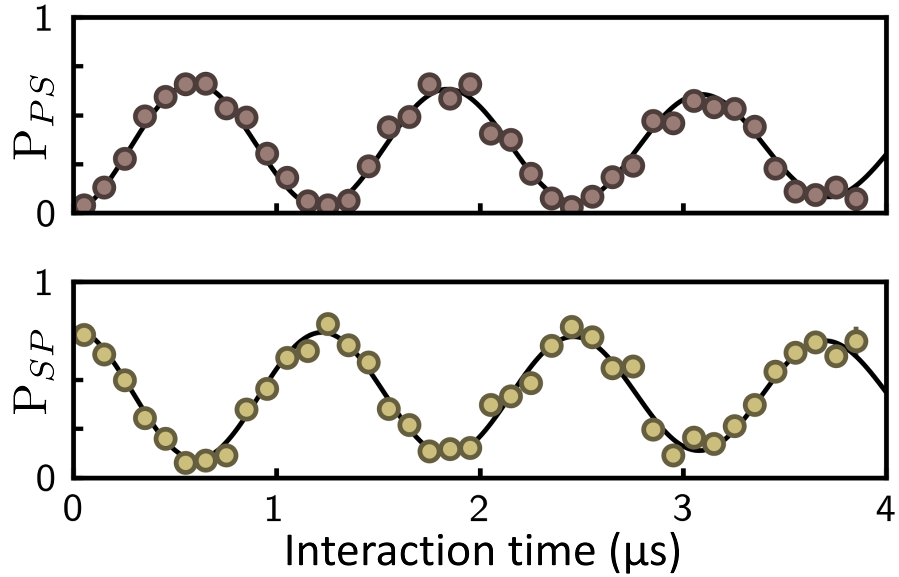

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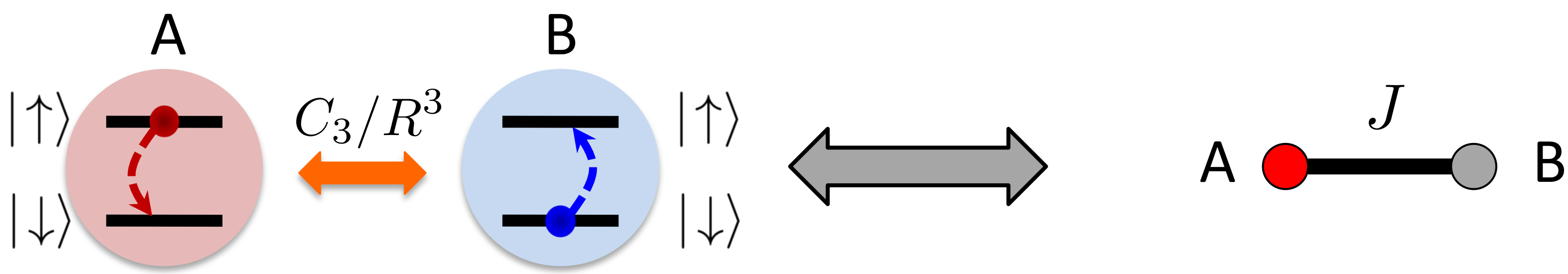


Spin excitation exchange

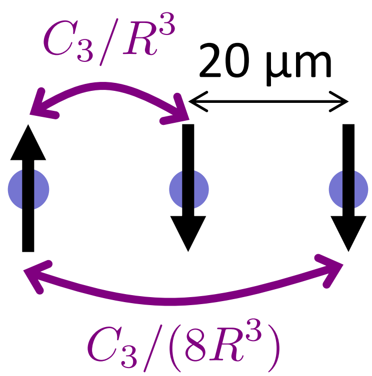
Particle hopping

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

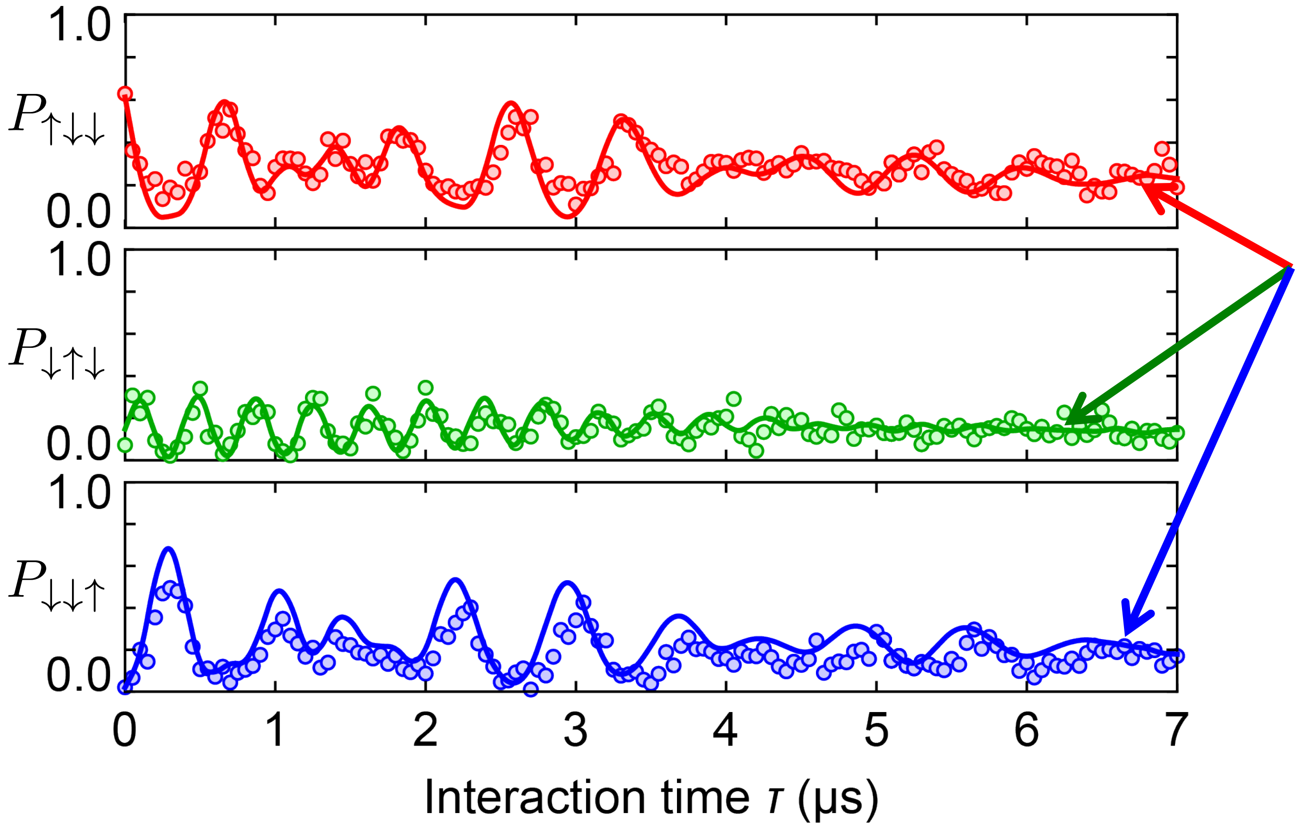
$J|A\rangle\langle B|$

Observation of spin exchange in a 3-atom chain

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



Prepare $|\uparrow\downarrow\downarrow\rangle$ at t = 0,
and let the system evolve

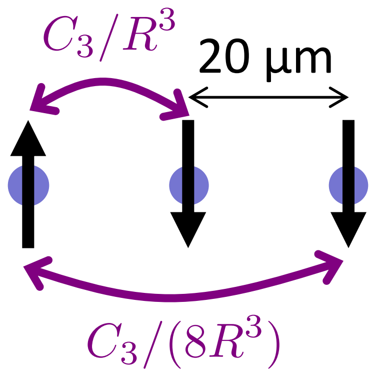


XY model
(Schrödinger)
+ imperfections

No adjustable
parameter

Optical lattices Nat. Phys. **9**, 235 (2013) ; trapped ions Nature, **511**, 198 & 202 (2014)

Three-atom "spin-chain": what to expect (theory) ?



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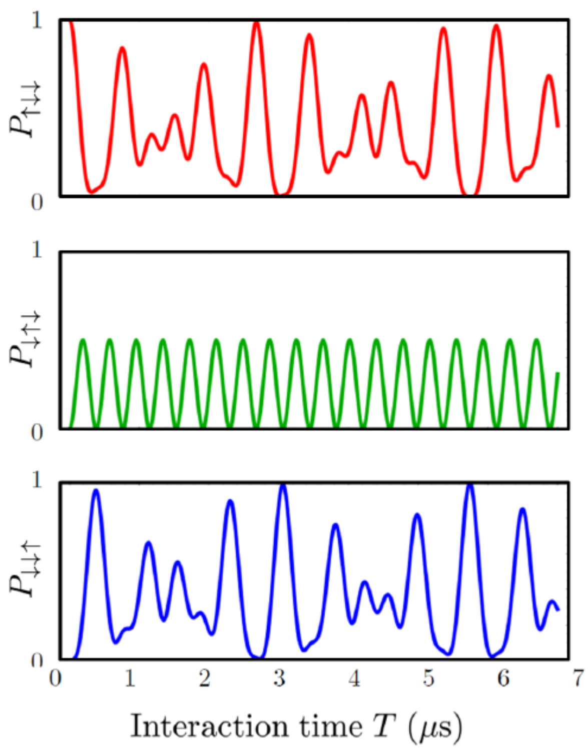
1/R³ interaction

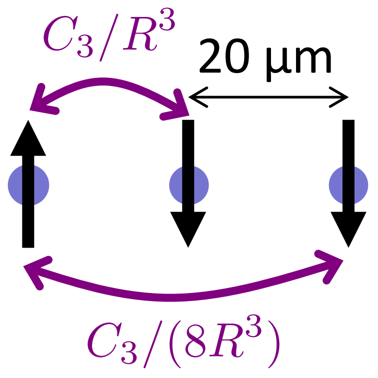


2 off-diagonal couplings: V & V / 8

⇒ eigenvalues (incommensurate):

$$\frac{V}{16}\left(1+3\sqrt{57}\right) \ , \ \frac{V}{16}\left(1-3\sqrt{57}\right) \ , \ -\frac{V}{8}$$

Three-atom "spin-chain": what to expect (theory) ?



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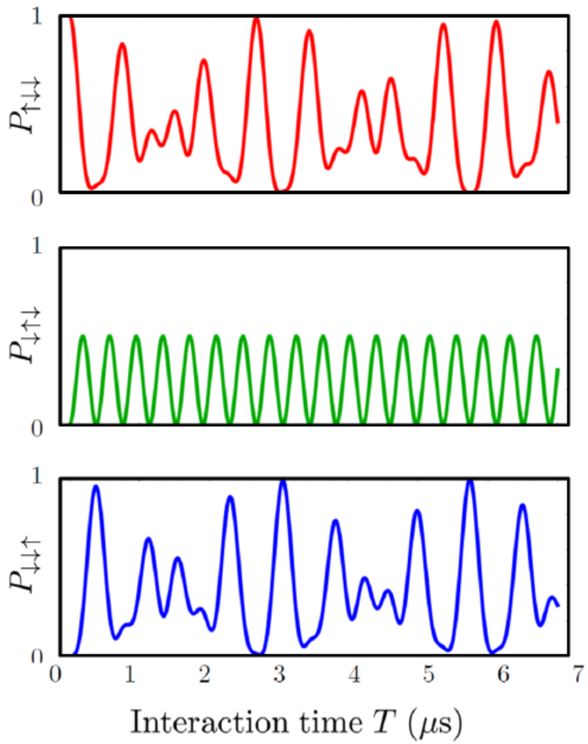
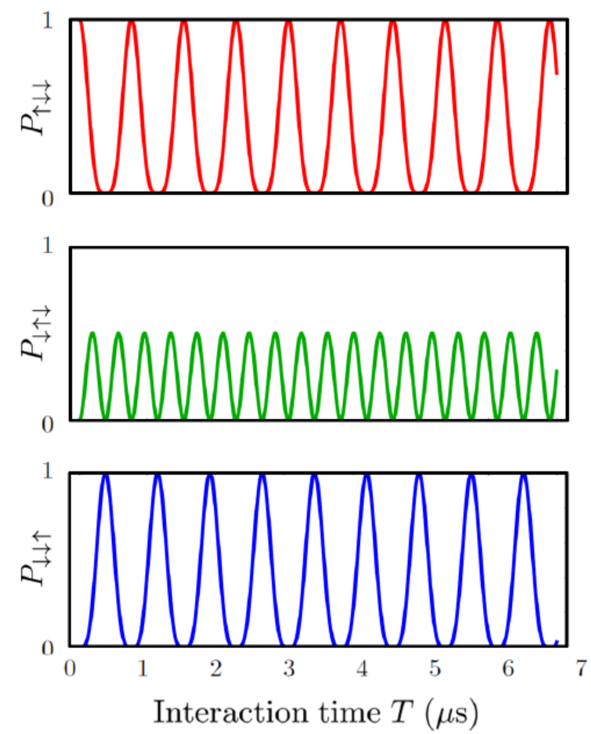


Nearest-neighbor only



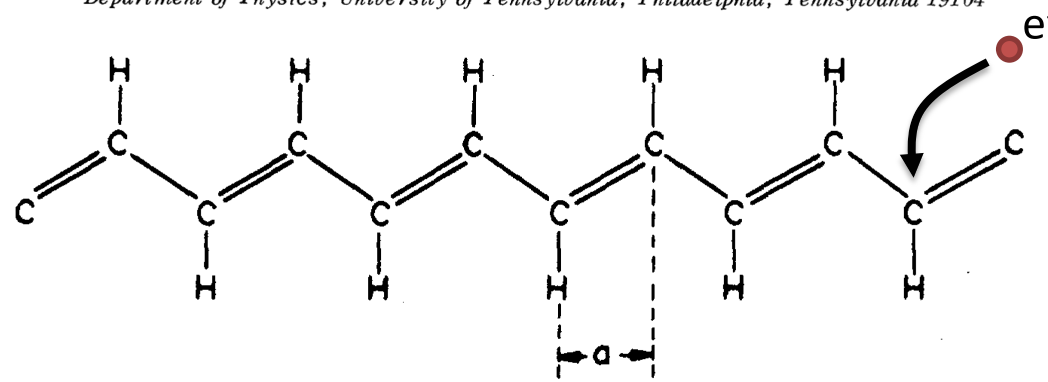
The Su-Schrieffer-Heeger model

- 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

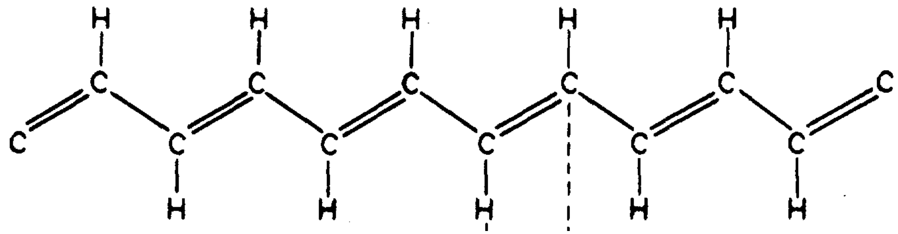
Asboth, arXiv:1509.02295, Cooper, arXiv:1803.00249

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

H.-P. Büchler
S. Weber, N. Lang

Science **365**, 775 (2019)

The Su-Schrieffer-Heeger model: single-particle



Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

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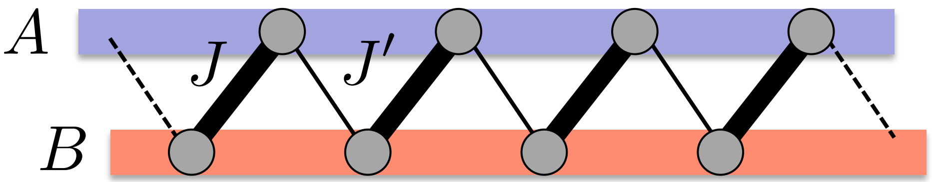
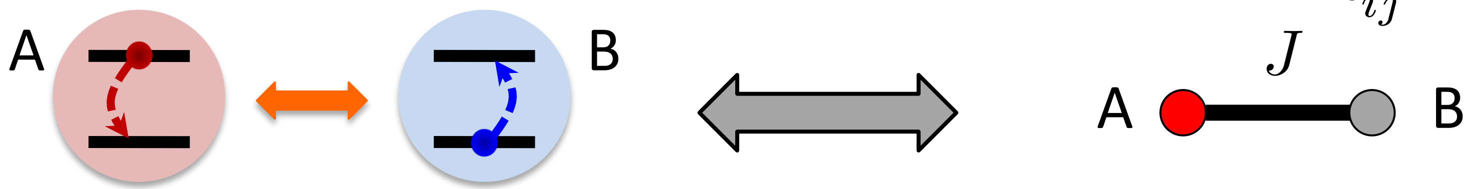


Model: tight-binding
dimerization: $J > J'$

Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

Implementation of SSH spin chain with Rydberg atoms

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



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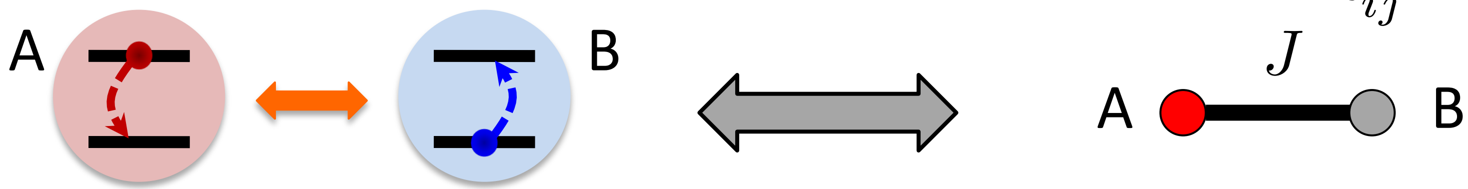

Chain at magic angle $\Rightarrow$ **chiral symmetry** (no A-A or B-B hopping)

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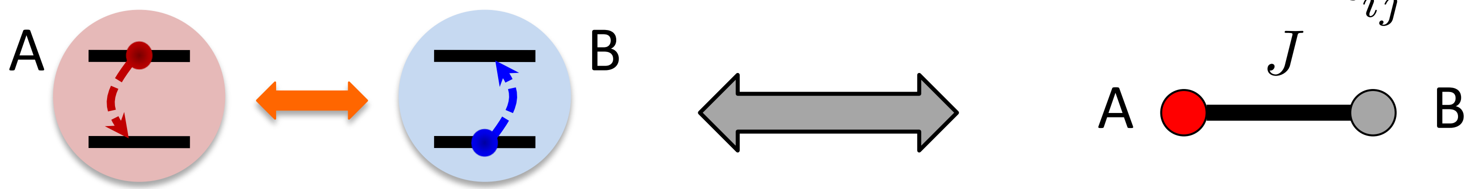

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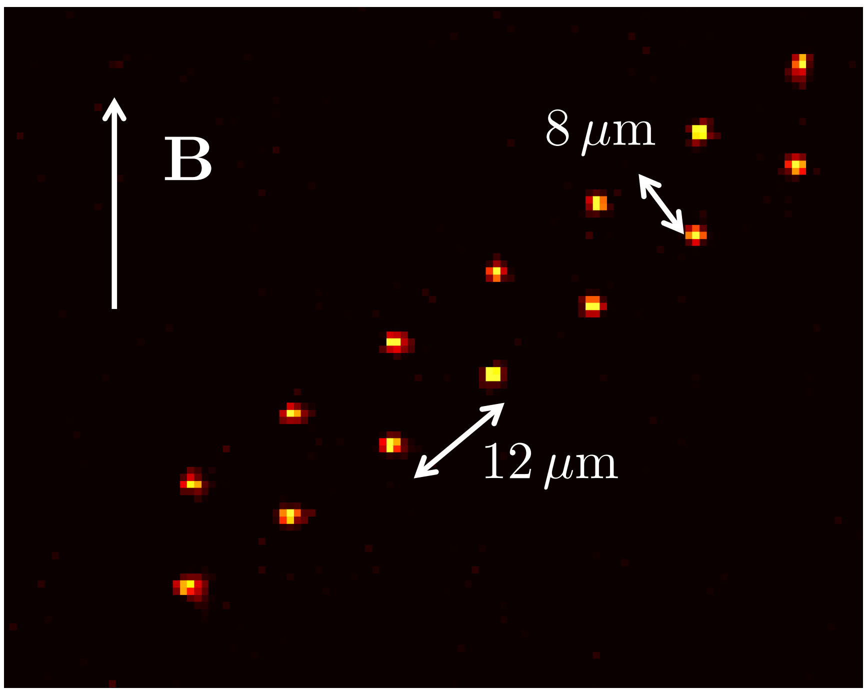

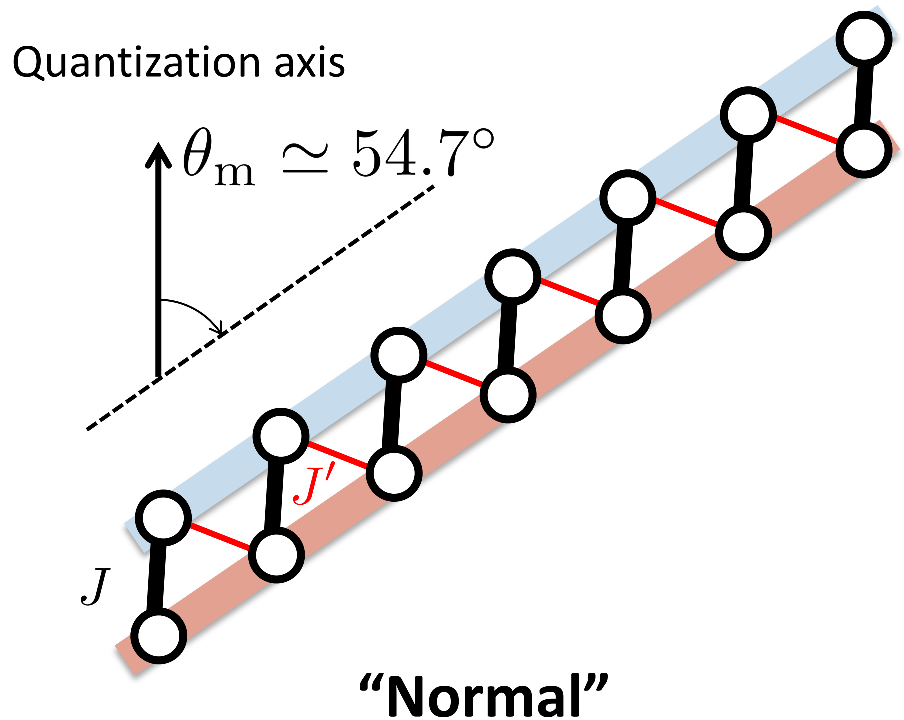

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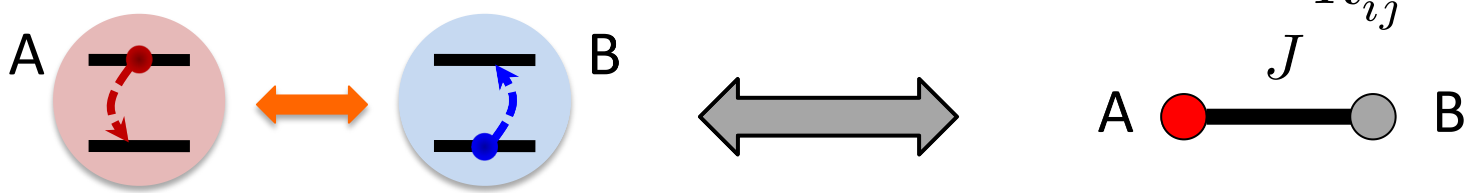

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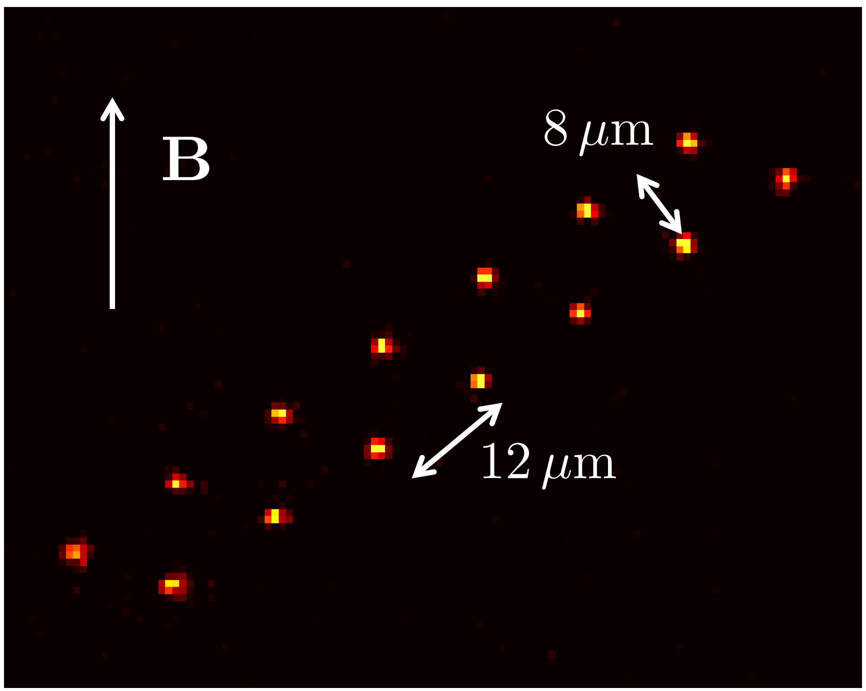
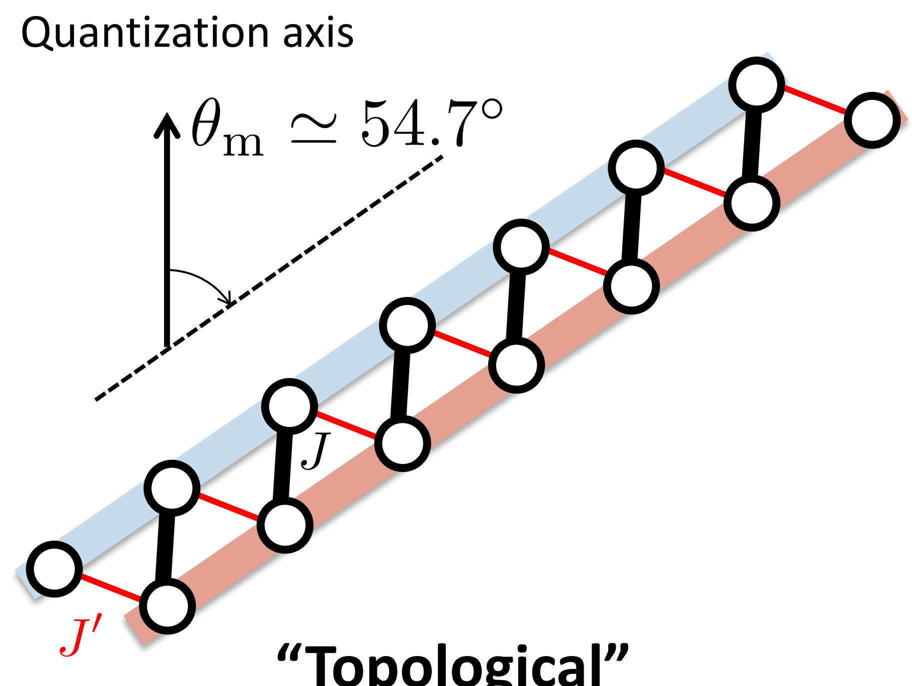




Conclusion

Rydberg interactions are strong & controllable

1. Resonant interaction
2. Van der Waals

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

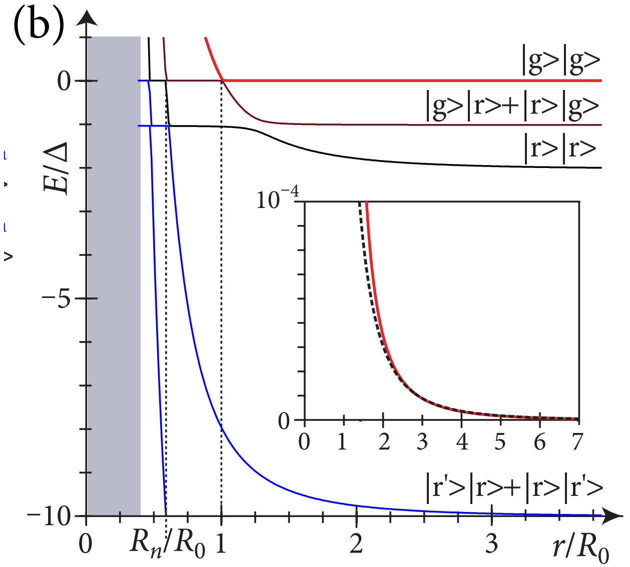
$\Rightarrow$ timescales < μsec

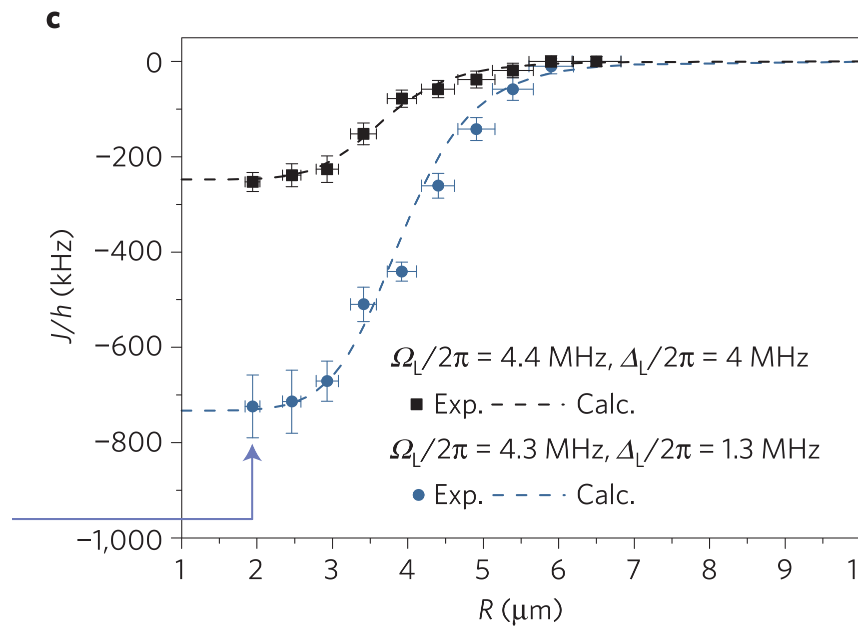
Rydberg blockade useful for quantum information & quantum optics

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

New / other directions: tailored interactions

Bouchoule Moelmer (PRL 2002)
Pupillo, Zoller (PRL 2010)



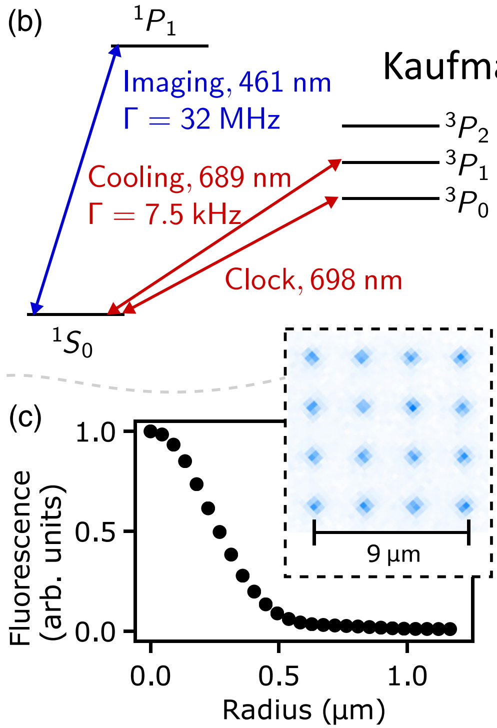


Experiments: Biedermann (Nat. Phys. 2015) 2 atoms
Zeiher (Nat. Phys. 2016) lattices
Porto (PRL 2016) ensemble + lattices

Challenging…: unwanted collective decay channels

New / other directions: 2-e atoms (Sr, Yb, Ba…)

Sr



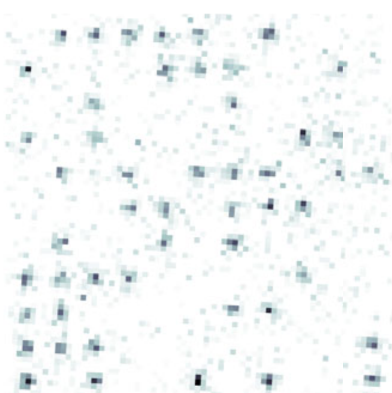
Kaufmann PRX 2018

"Recent advances in Rydberg physics using alkaline-earth atoms ", Dunning, Killian, Yoshida, Burgdörfer, J. Phys. B **49**, 112003 (2016)

Two electrons = two "handles":

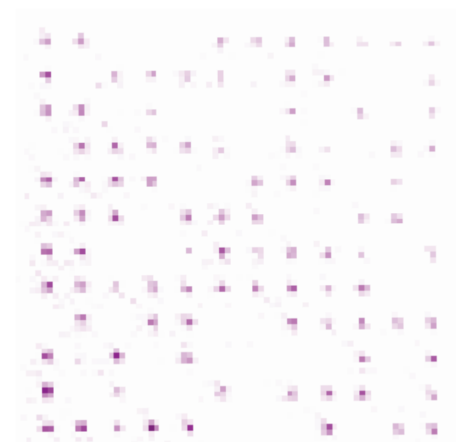
- One e- to Rydberg states
- One e- for laser trapping, or imaging

Sr



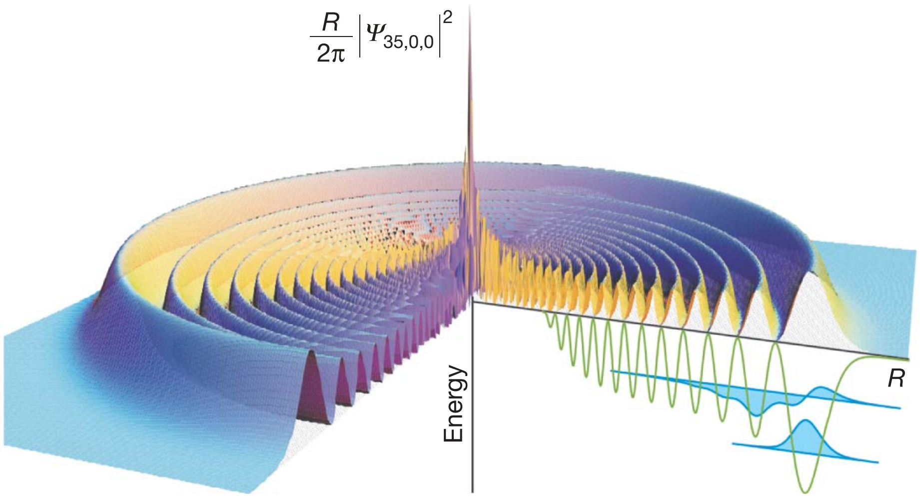
Endres PRX 2018

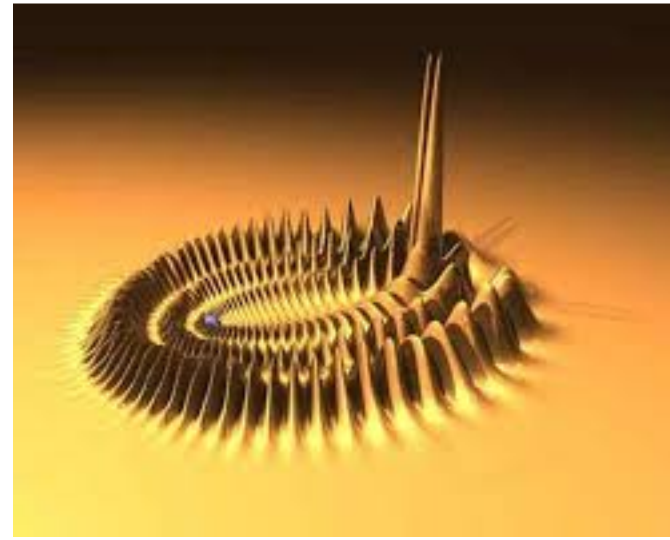
Yb



Thompson, PRL 2019

New / other directions: Rydberg molecules



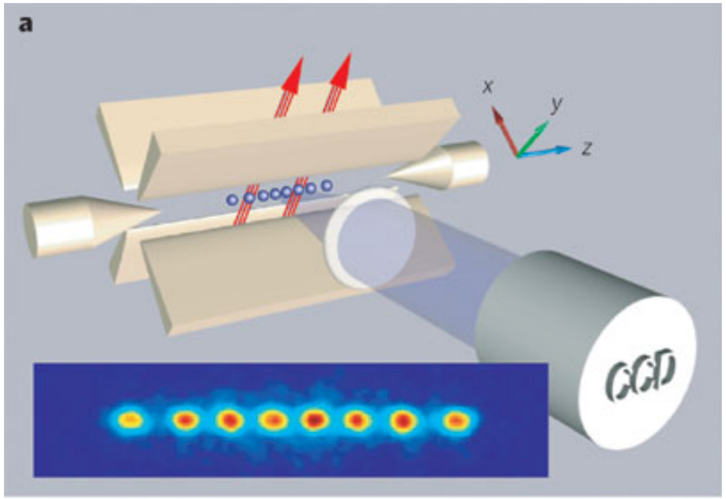


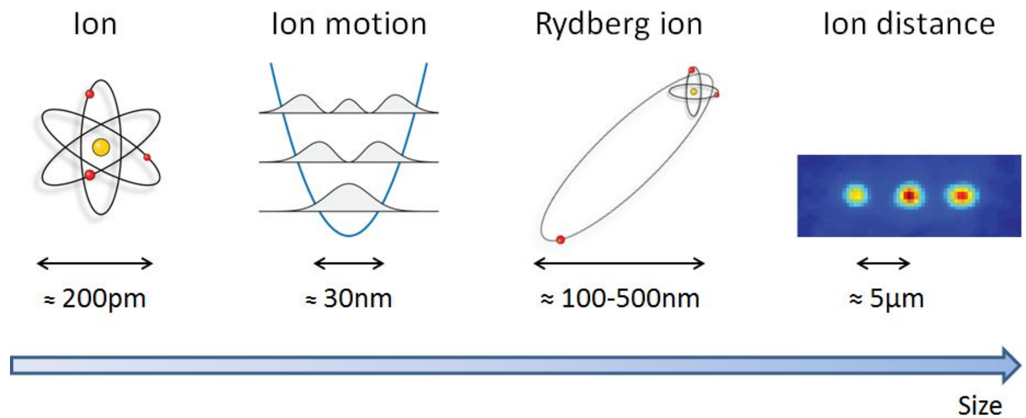
Pfau, Nature (2009)

A “new” binding mechanism beyond
Molecular (vdW) bound
Covalent bound
Ionic bound

Scattering of Rydberg e^- on atomic core [Fermi 1934…]

New / other directions: Rydberg ions

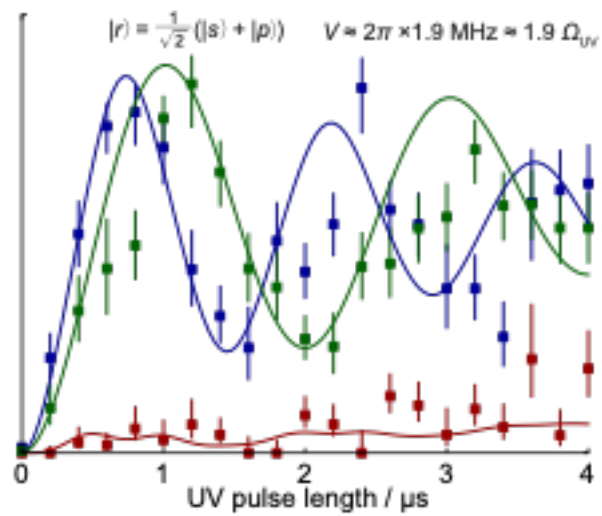




Faster gates (ns instead ms)
Scalable

F. Schmidt-Kaller et al., NJP (2011)

$^{88}Sr^{+}$

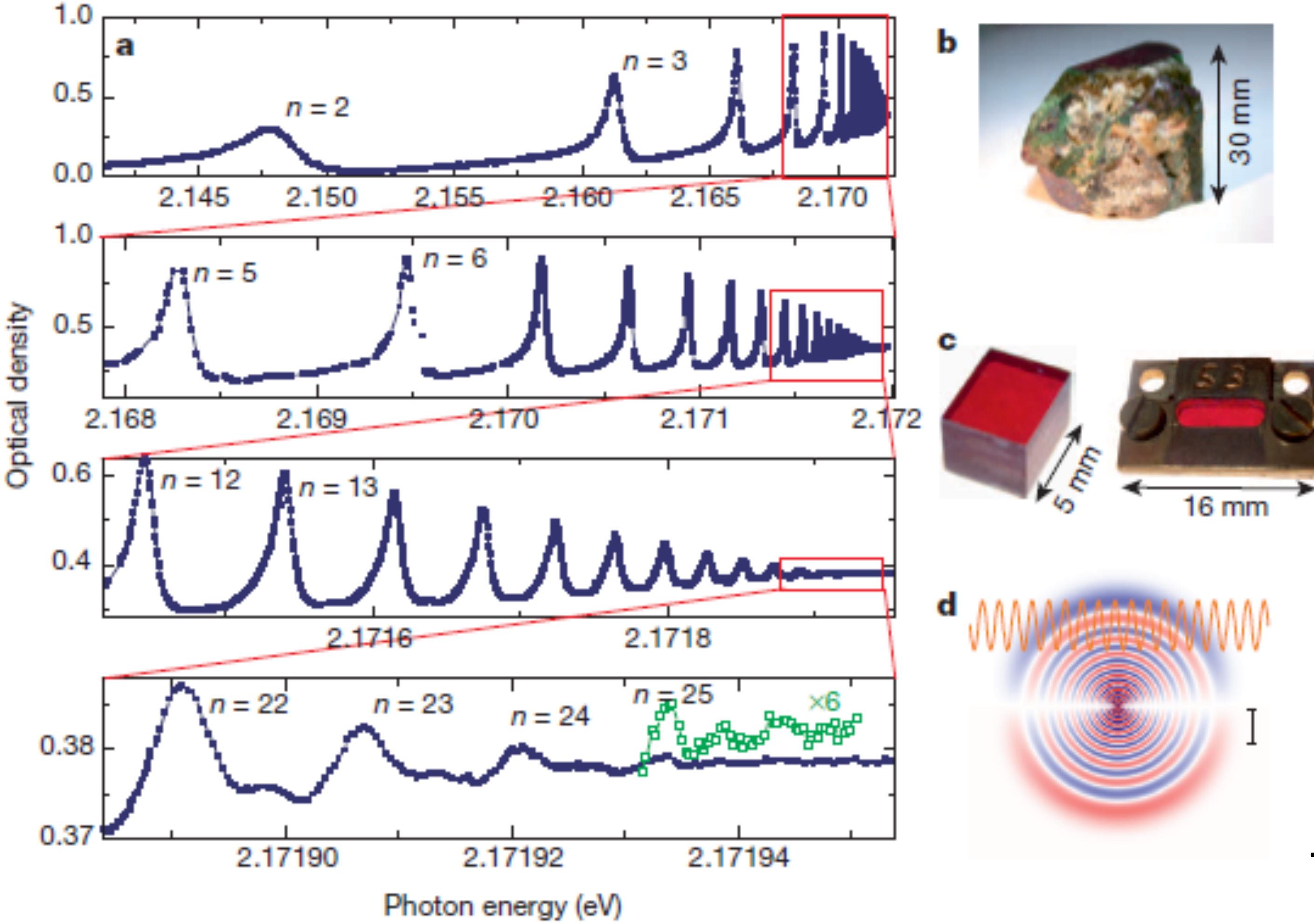


F = 78%

Hennrich, arXiv 1908.11284

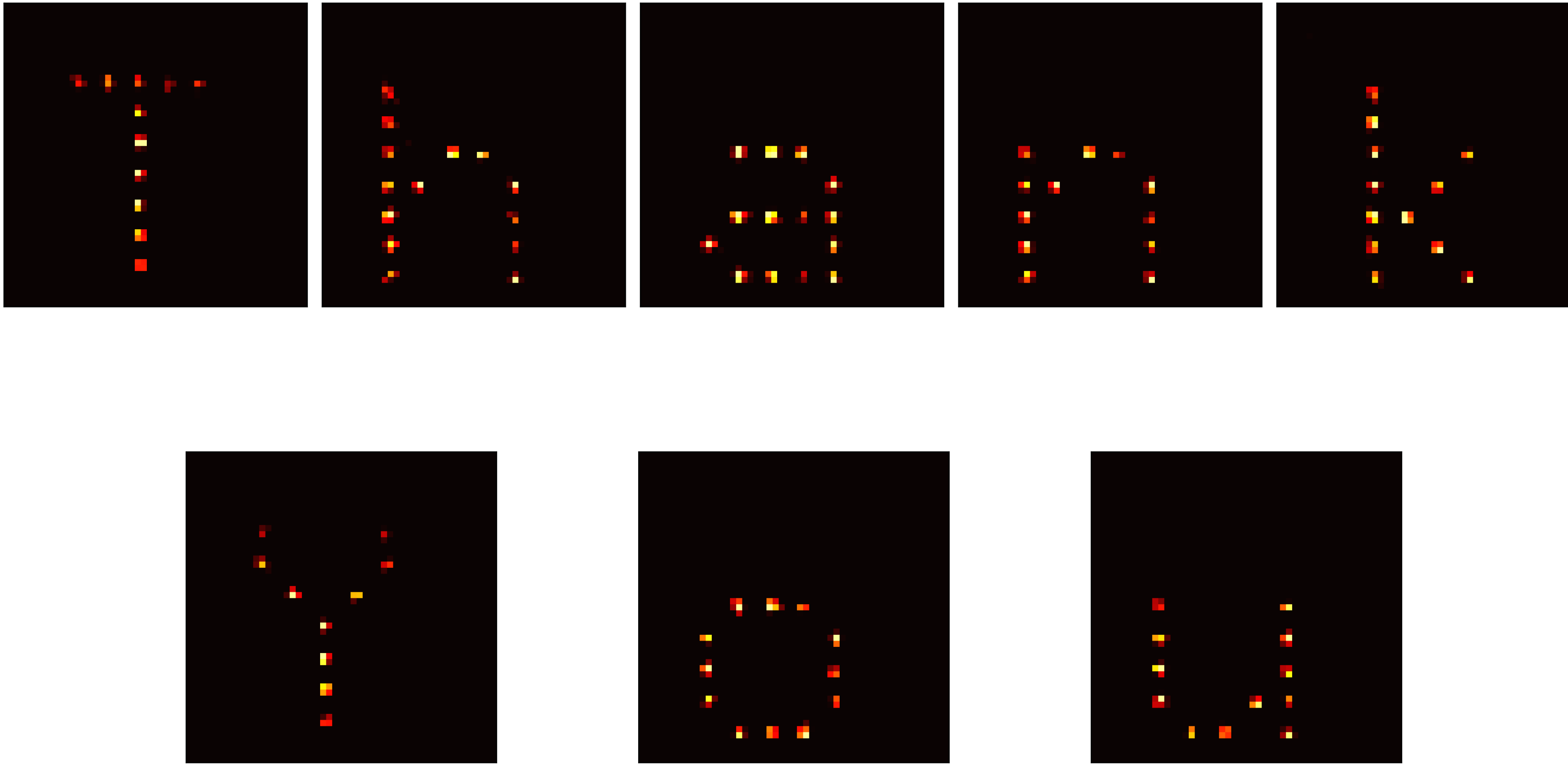
New / other directions: Rydberg states excitons in Cu_2O

T. Kazimierczuk *et al.*, Nature 2014



T = 1 K

Evidence of blockade!


Thank you