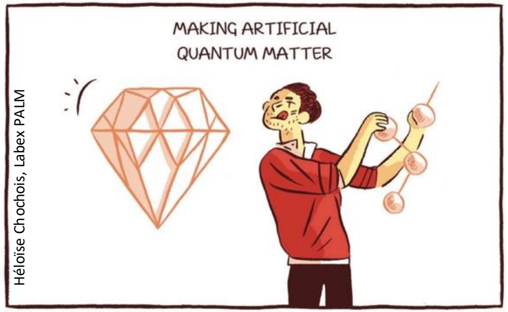
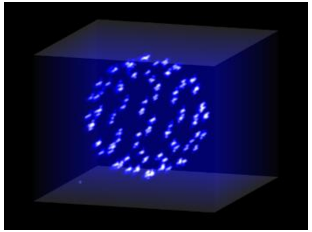
Exploring many-body physics with arrays of Rydberg atoms (I)

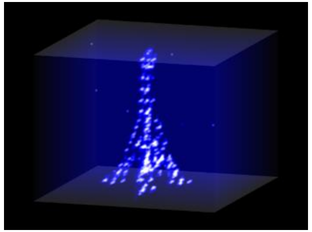


Héloïse Chochois, Labex PALM

Antoine Browaeys

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





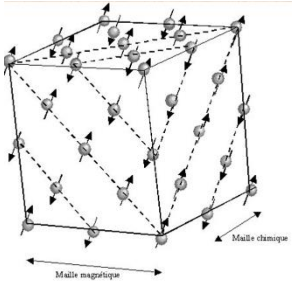
Benasque Workshop, february 24-25, 2025

The context: "many-body problem"

Goal: Understand ensembles of ***strongly*** interacting quantum particles

superfluidity

superconductivity



magnetism

neutron star

Questions: phase diagram, excitation, dynamics, …

The equation to solve: $i\hbar \frac{\partial \Psi}{\partial t} = H_{\mathrm{tot}} \Psi$

$$H_{\mathrm{tot}} = \sum_{i=1}^{N} -\frac{\hbar^2}{2m_i} \nabla_i^2 + \sum_{i=1}^{N} \sum_{j \neq i} \frac{q_i q_j}{r_{ij}} + \frac{\mu_{\mathrm{B}}^2}{r_{ij}^3} \mathbf{s}_i \cdot \mathbf{s}_j$$

Very, very, very well known…

Difficulty: exponential scaling of $\dim \mathcal{H} \sim d^N$ Record *ab-initio* for s = ½ : $N \lesssim 50$

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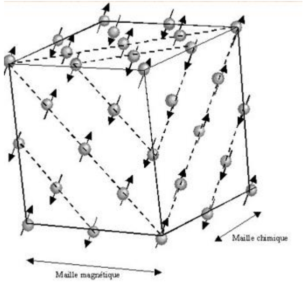

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Approximations possible !!

But… poorly controlled or not valid when interactions dominate

= **Strongly correlated** systems

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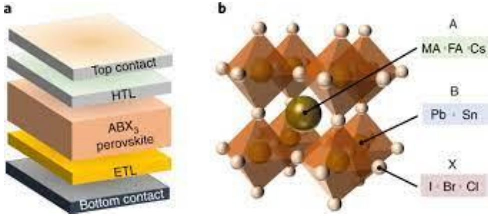
The context: “many-body problem”

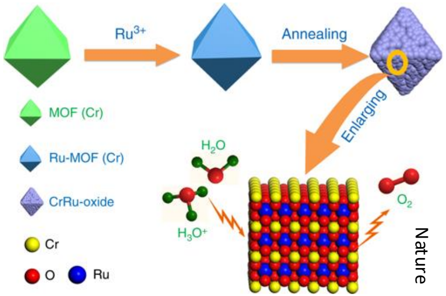
Perovskite:
solar panels

Fraunhofer

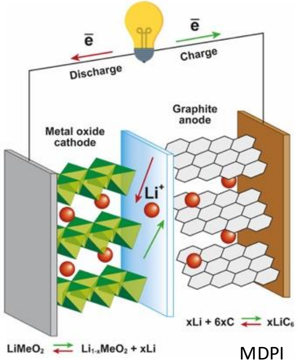


Nature

Catalysis



Batteries &
cathode



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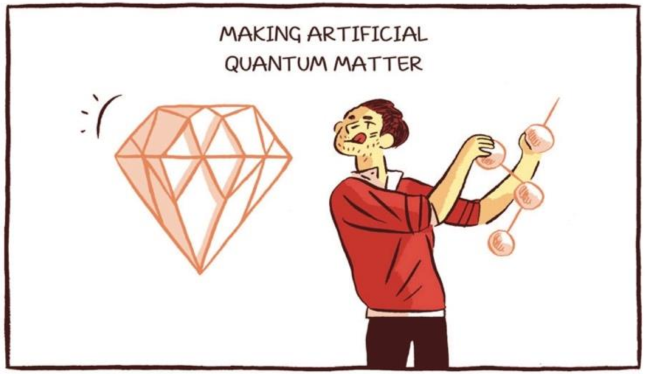
= **Strongly correlated** systems

One approach: many-body physics with synthetic quantum systems

R.P. Feynman

Int. J. Theo. Phys. **21** (1982)

Héloïse Chochois, Labex PALM



Quantum simulation

Georgescu, Rev. Mod. Phys. (2014)

Well-controlled quantum systems implementing many-body Hamiltonians
= quantum simulator

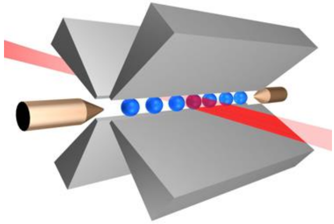
Larger tunability than “real” systems (geometry, interactions…)

+

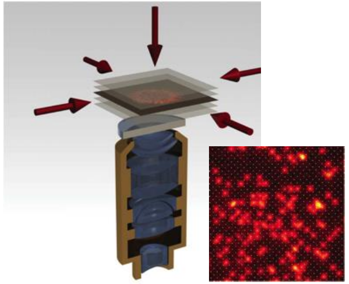
New types of probe & methods (e.g. out-of-equilibrium)

A new way to look at many-body using quantum information concepts
(entanglement…)

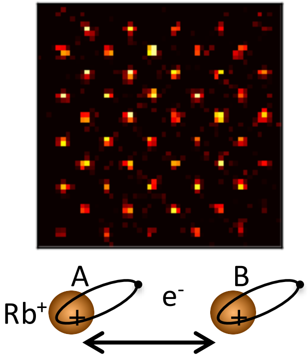
Engineering with individual quantum systems (examples)



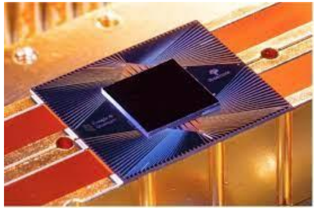
Trapped ions



Atoms in optical lattices



Atoms in tweezer arrays



Supercond. Circuits

IBM, Google…

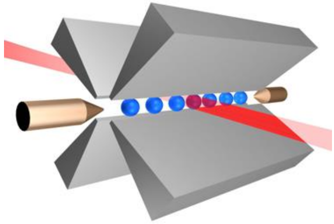
Scalable: beyond 100 particles ; potential > 1000

Addressability: local manipulations and measurement

$$\langle \sigma_i^\alpha \rangle, \langle \sigma_i^\alpha \sigma_j^\beta \rangle, \ldots$$

Programmable: controlled geometry, interactions…

Engineering with individual quantum systems (examples)



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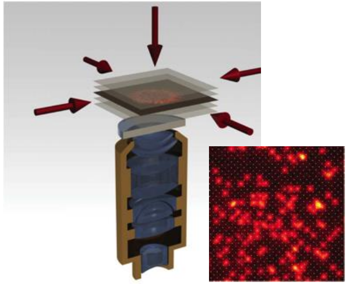
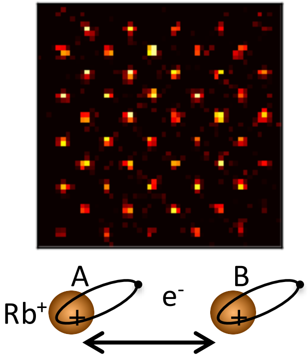


Atoms in optical lattices



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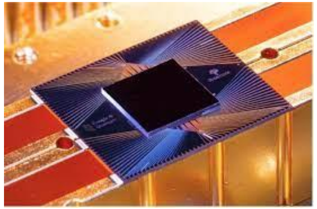

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Programmable: controlled geometry, interactions…

The program

Lecture 1: Arrays of atoms & “Rydbergology”
Rydberg Interactions and spin models
Engineering many-body Hamiltonians

Lecture 2: Examples of quantum simulations in
and out-of-equilibrium: quantum magnetism

Outline – Lecture 1

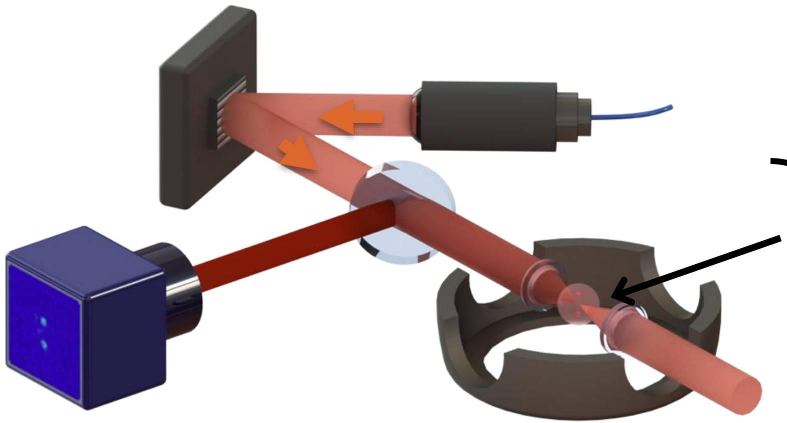
1. Arrays of individual atoms in optical tweezers

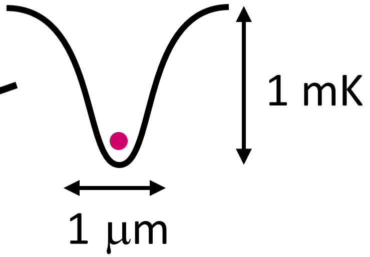
2. Basics of Rydberg physics and their interaction

3. Interaction between Rydberg atoms and spin models

   - "Natural": Ising and XY Hamiltonians
   - Hard-core bosons and $t-J$ model
   - Floquet engineering of XYZ models

A single Rb atom in an optical tweezer





Grangier (2001)
Sortais (2007)

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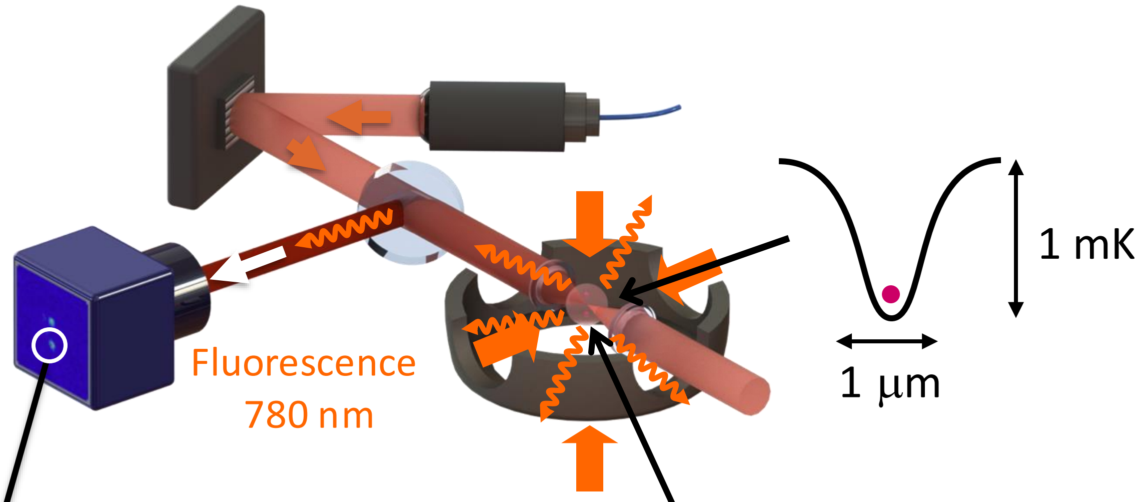
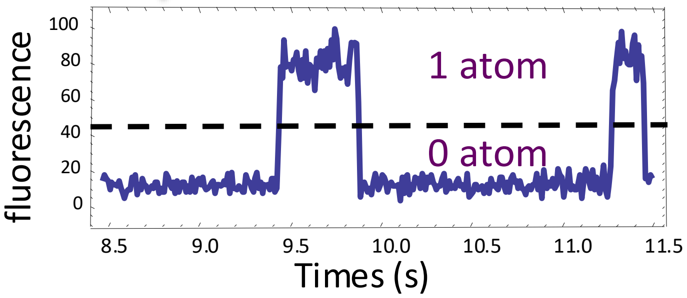


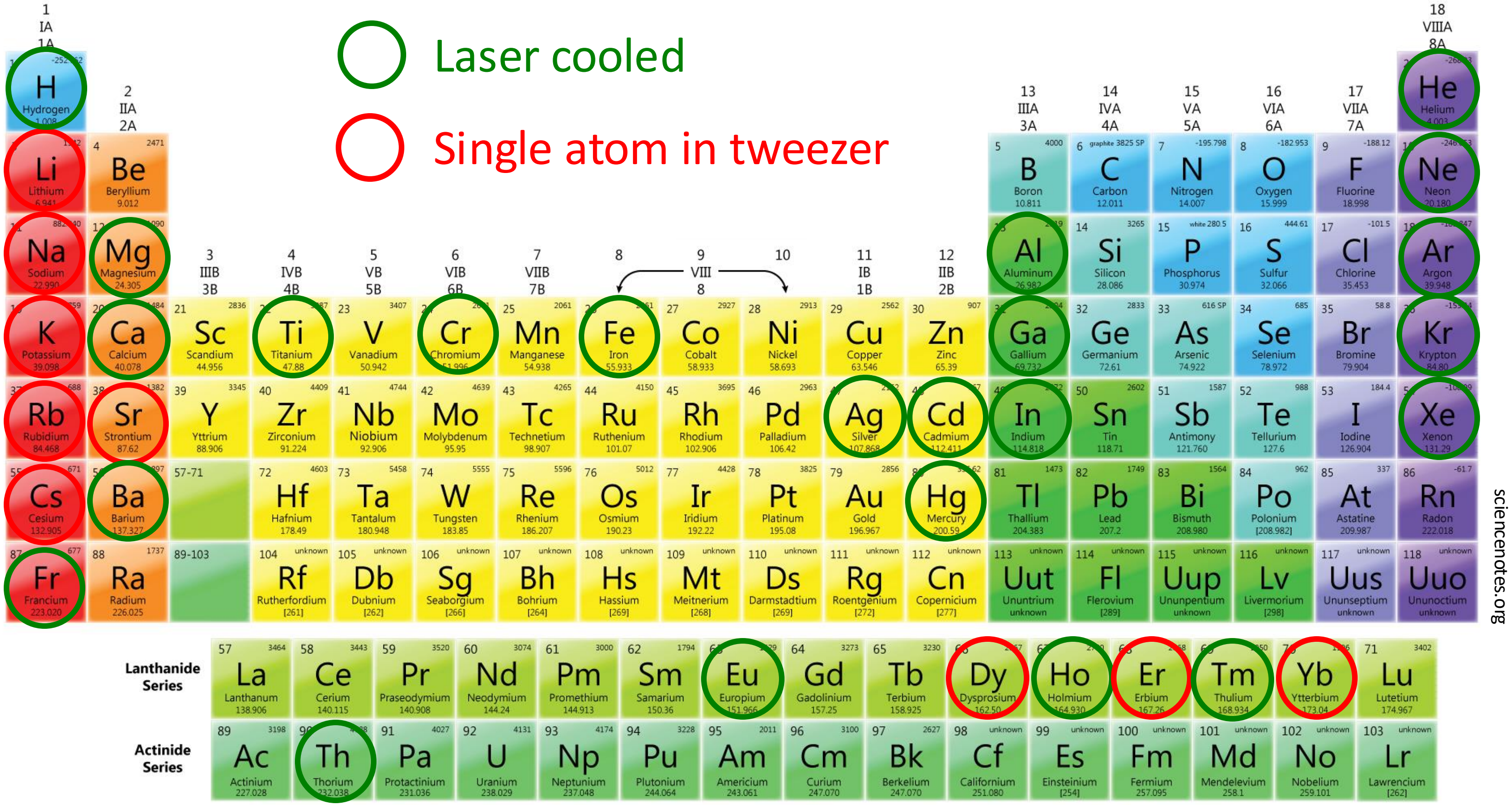
Grangier (2001)
Sortais (2007)

Reservoir = laser-cooled Rb atoms
T ~ 100 μK



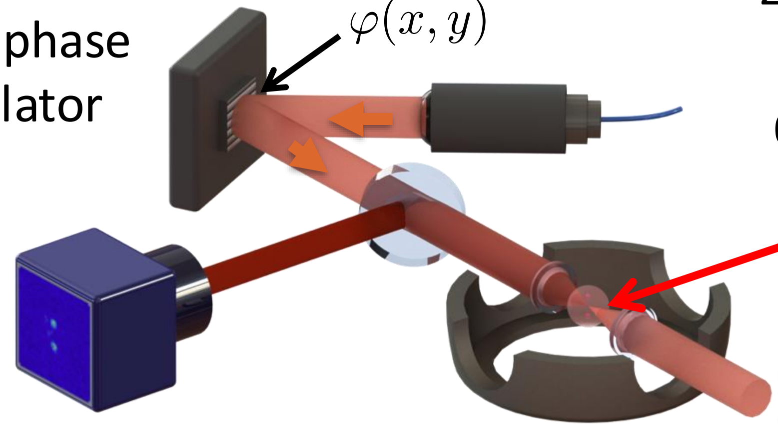
Non-deterministic
single-atom source

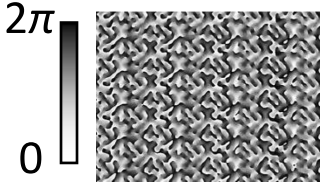
Single-atom trapping zoo (2024)



Atoms in arrays of optical tweezers

Spatial phase modulator

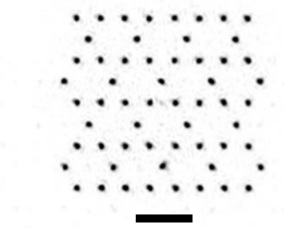




Phase mask

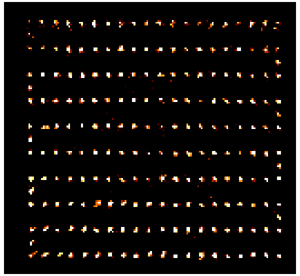
Nogrette, PRX (2014)

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



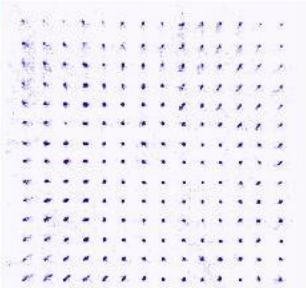
Atoms in arrays of optical tweezers (single-shot images)

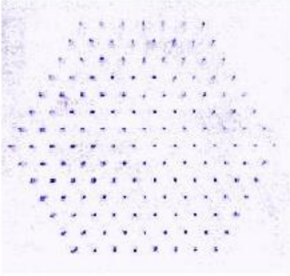
1D

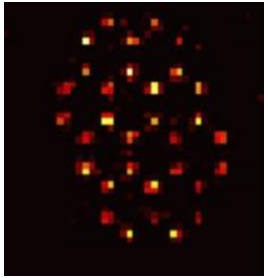


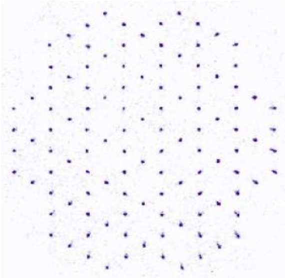
~100 μm

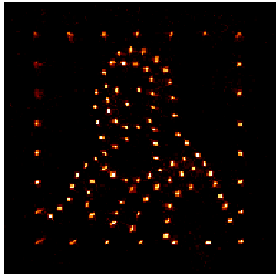
2D









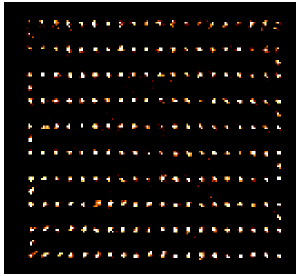


L. da Vinci

Barredo, Nature 2016 ; Schymik, PRA 2020, 2022; PRAppl. 2021

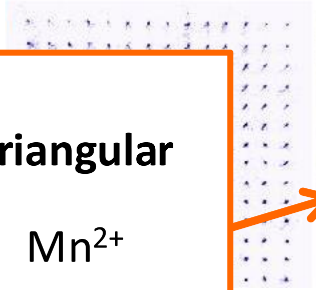
Atoms in arrays of optical tweezers (single-shot images)

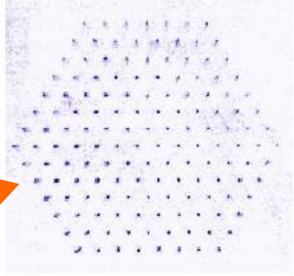
1D

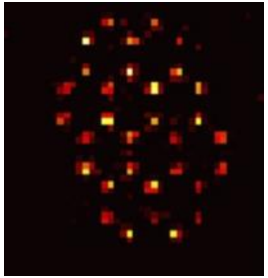


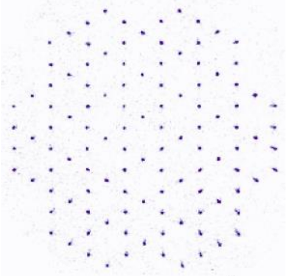
~100 µm

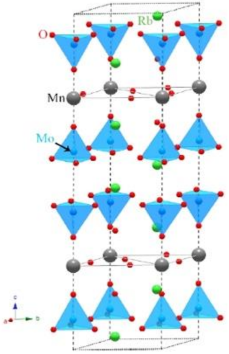
2D







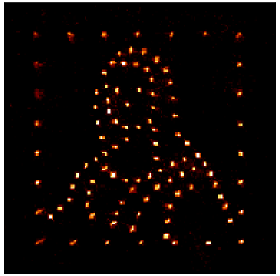




Triangular

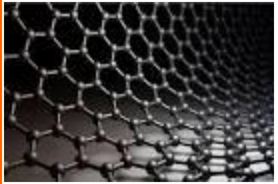
Mn^{2+}

$Rb_4Mn(MoO_4)_3$



L. da Vinci

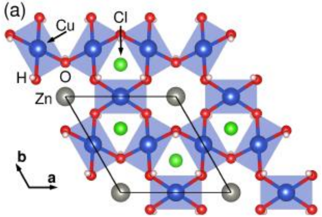
Hexagonal



graphene

Kagome: Herbertsmithite

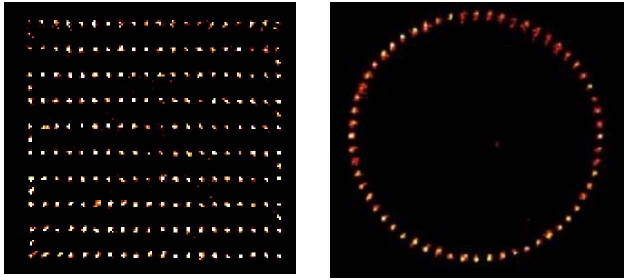
$ZnCu_3(OH)_6Cl_2$



Barredo, Nature 2016 ; Schymik, PRA 2020, 2022; PRAppl. 2021

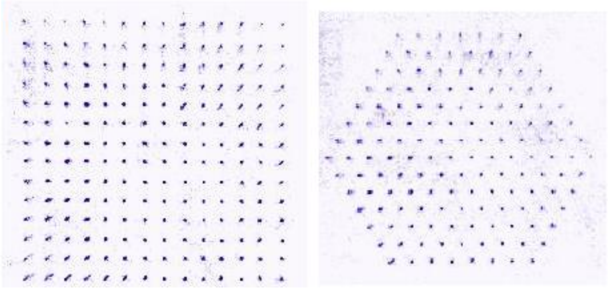
Atoms in arrays of optical tweezers (single-shot images)

1D

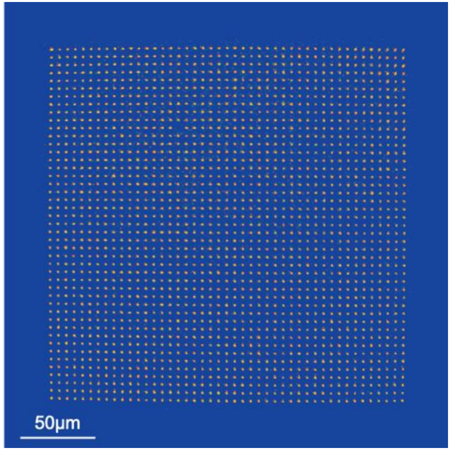


~100 μm

2D

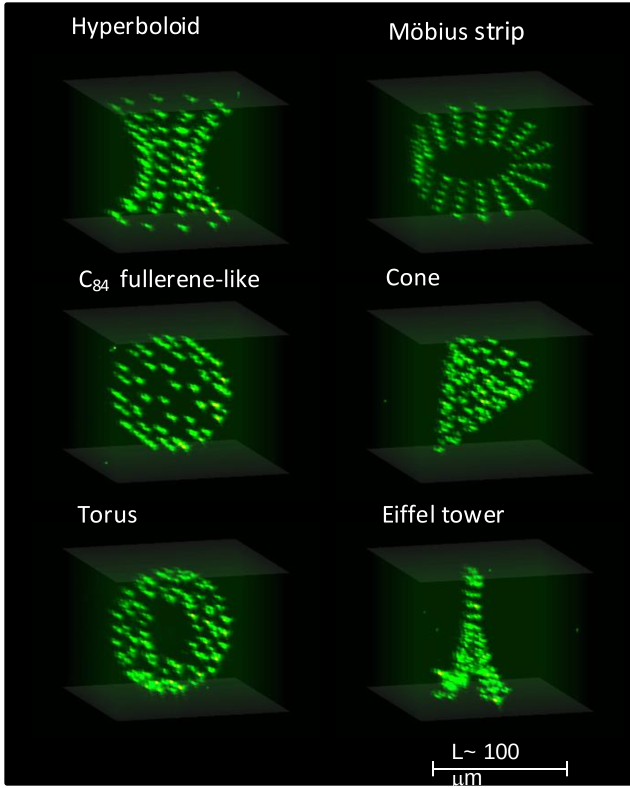


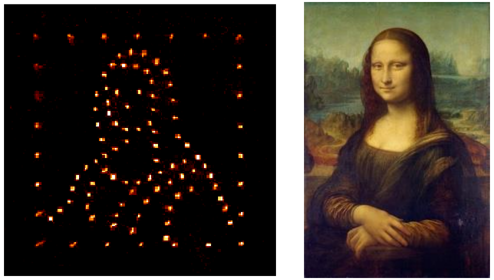
2024 atoms (AI + fast SLM)



3D

Barredo, Nature (2018)





L. da Vinci

Barredo, Nature 2016 ; Schymik, PRA 2020, 2022; PRAppl. 2021

arXiv:2412.14647

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

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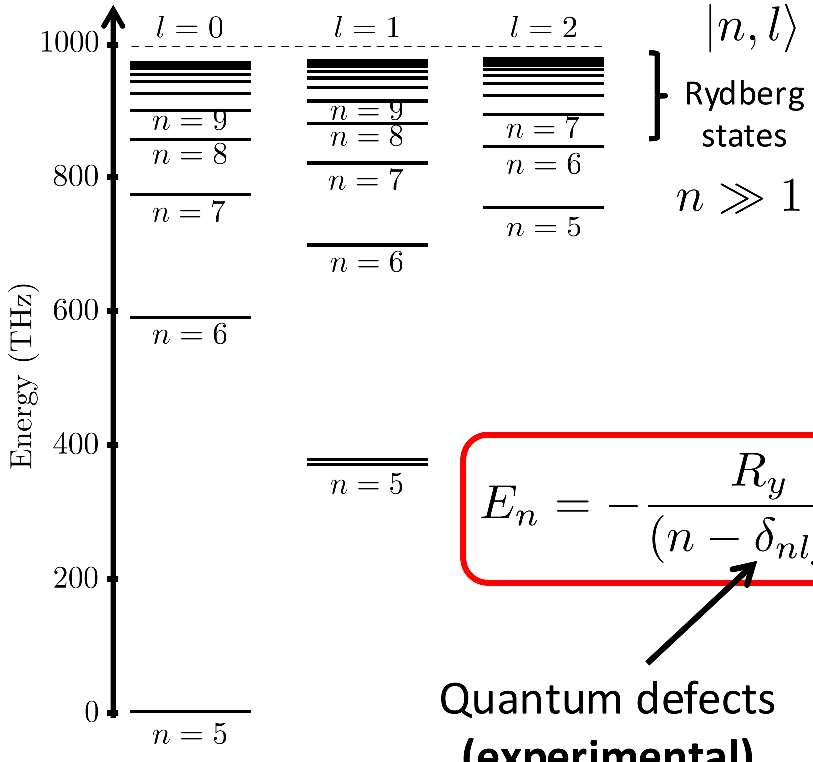
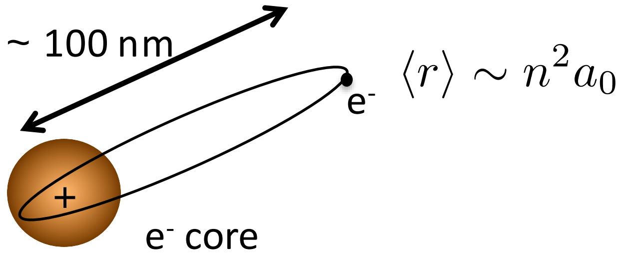
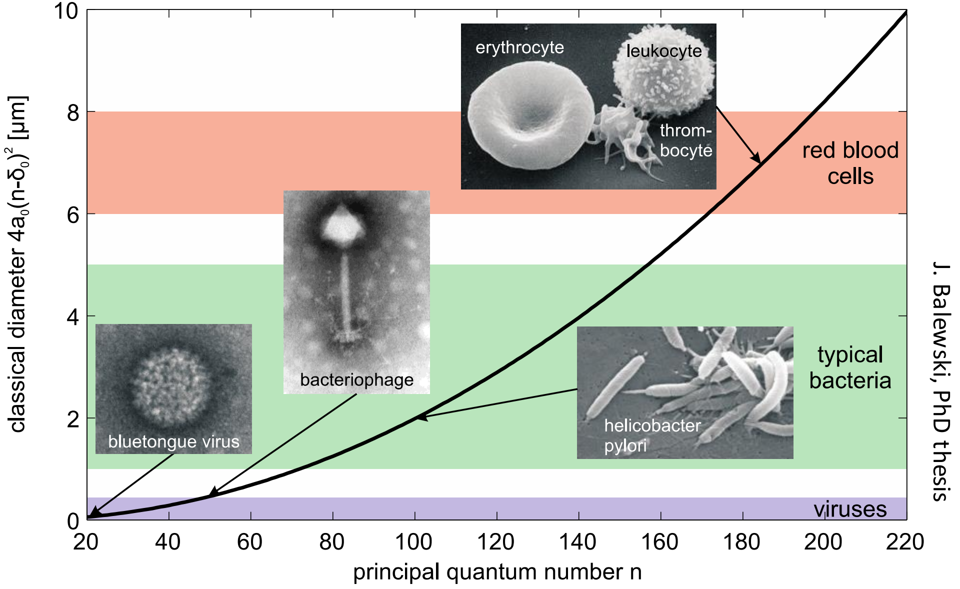
“Rydberg atom” = a highly excited atom (e.g. Rb)



$$E_n = -\frac{R_y}{(n-\delta_{nlj})^2}$$

Quantum defects
(experimental)





Browaeys, Barredo, Lahaye, J. Phys. B 2016

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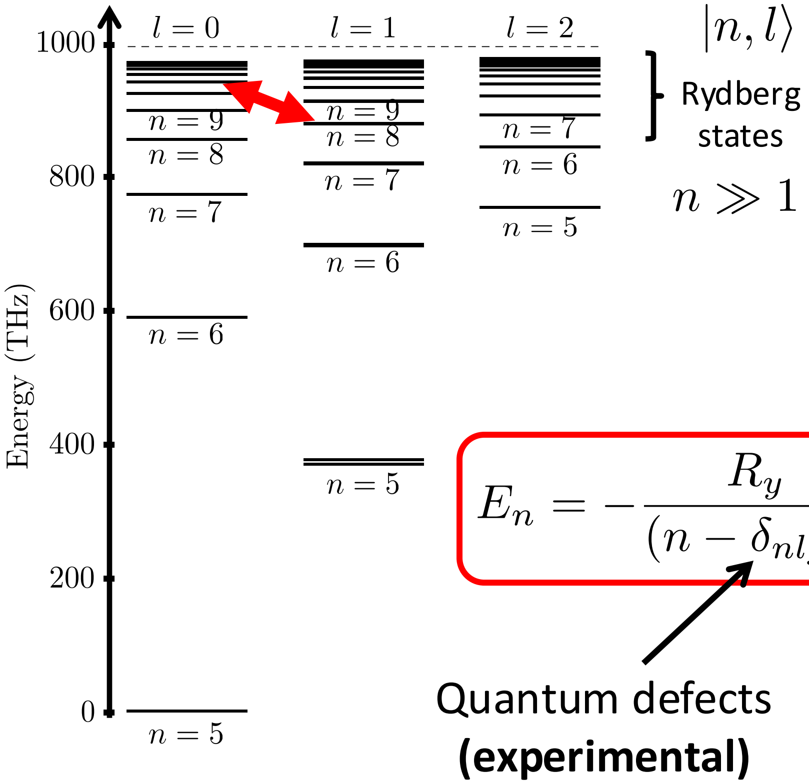

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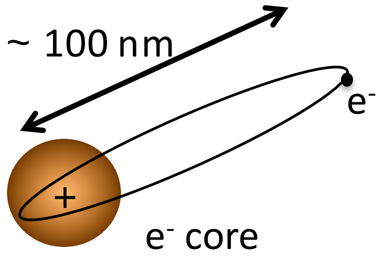


$\langle r \rangle \sim n^2 a_0$

Long lifetime: $\tau \sim n^3$

$\Rightarrow$ *n* > 60, τ > 100 µs

Large transition dipole:

$$\langle n, l | \hat{D} | n, l \pm 1 \rangle \sim n^2 e a_0$$

Large polarizability: $\alpha \sim n^7$

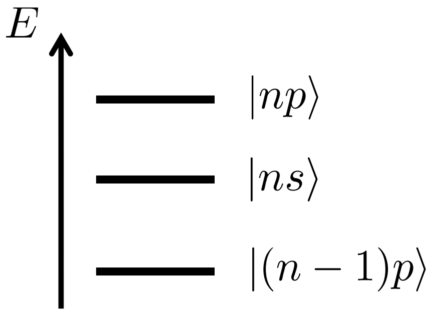
$\Rightarrow$ **Exaggerated properties:**

- strong interaction
- strong coupling to fields (DC, MW)

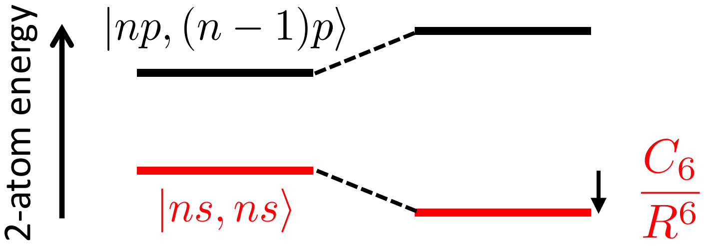
Browaeys, Barredo, Lahaye, J. Phys. B 2016

Interactions between Rydberg atoms

$$\hat{H}_{\text{dd}} = \frac{1}{4\pi\epsilon_0}\frac{\hat{d}_{Az}\hat{d}_{Bz}}{R^3}$$



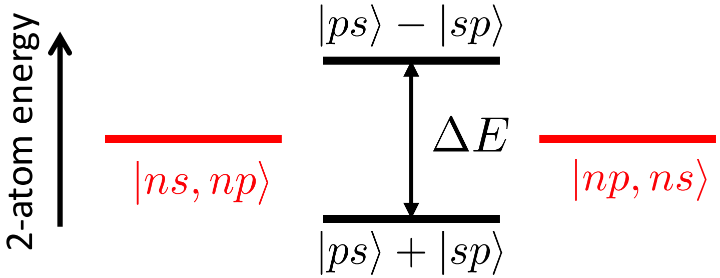
van der Waals regime



$$\Delta E_{ss}^{(2)} \approx \frac{|\langle np,(n-1)p|\hat{H}_{\text{dd}}|ns,ns\rangle|^2}{E_{ss}-E_{pp}}$$

$$\propto \frac{d_{sp}^4}{E_{ss}-E_{pp}}\frac{1}{R^6} = \frac{C_6}{R^6} \qquad C_6 \propto n^{11}$$

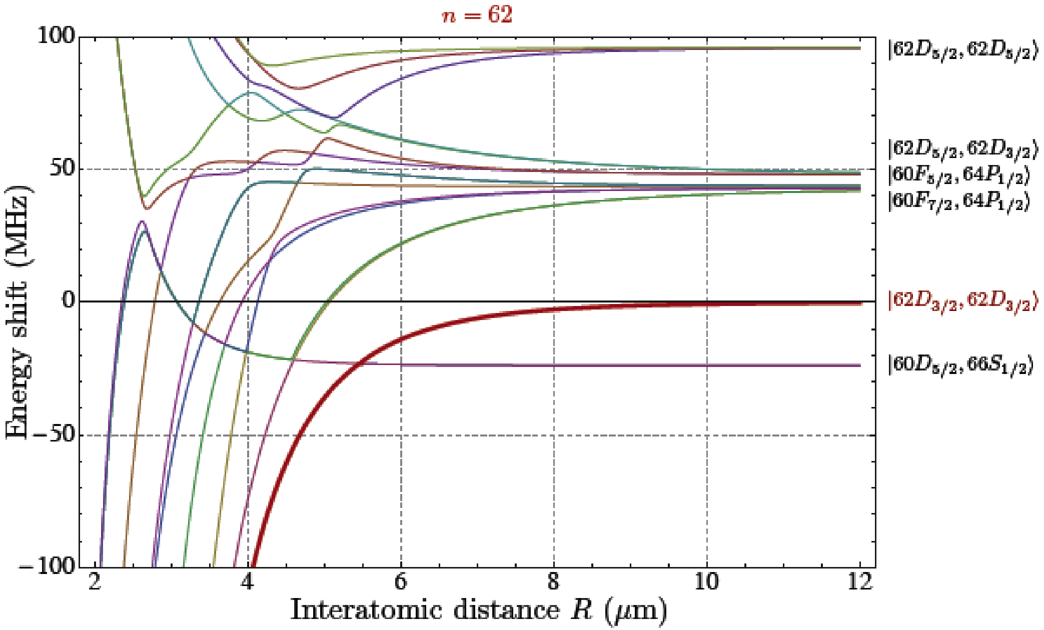
Resonant regime



$$\Delta E \propto \langle sp|\hat{H}_{\text{dd}}|ps\rangle = \frac{d_{sp}^2}{R^3} \propto n^4$$

$$R = 10\ \mu\text{m} \Rightarrow V_{\text{int}}/h \sim 1-10\ \text{MHz}$$ **⇒ timescales < µsec**

Interactions between “real” Rydberg atoms



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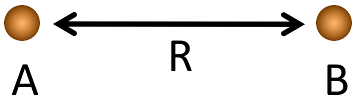
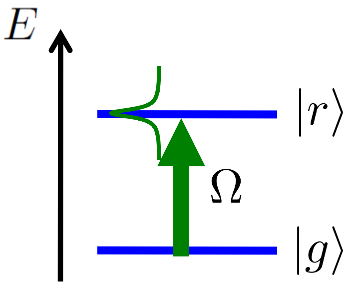
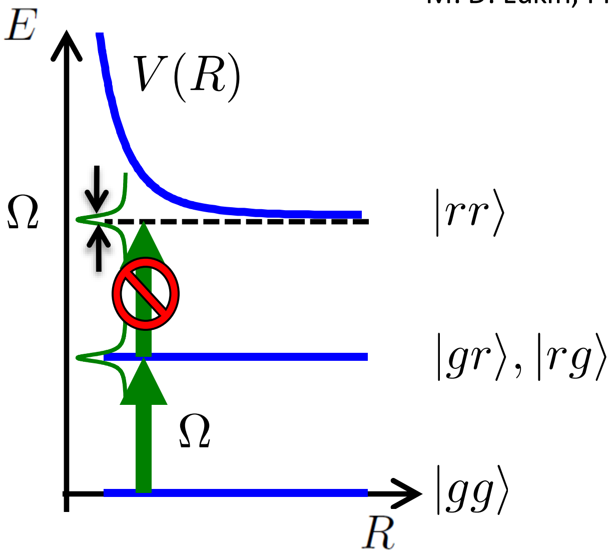
A fruitful idea: the Rydberg blockade

D. Jaksch, PRL **85**, 2208 (2000)
M. D. Lukin, PRL **87**, 037901 (2001)



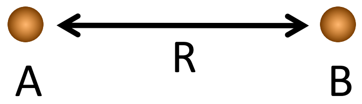


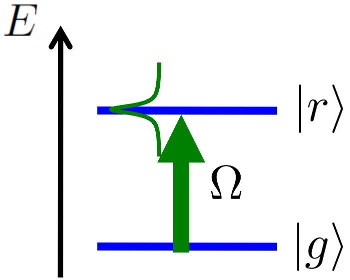


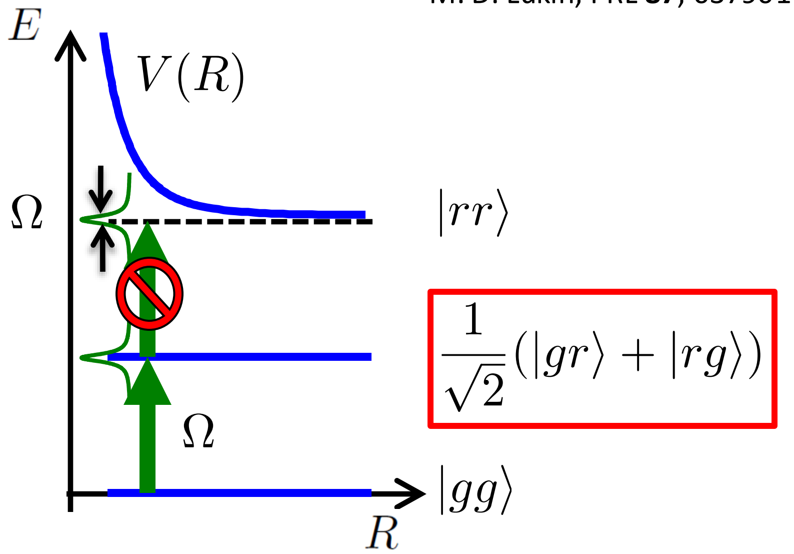
If $\hbar\Omega \ll V(R)$: no excitation of $|rr\rangle$ $\Rightarrow$ **blockage**

A fruitful idea: the Rydberg blockade

D. Jaksch, PRL **85**, 2208 (2000)
M. D. Lukin, PRL **87**, 037901 (2001)







Blockade $\Rightarrow$ **entanglement and gates!!**

A fruitful idea: the Rydberg blockade

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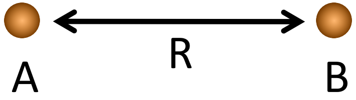
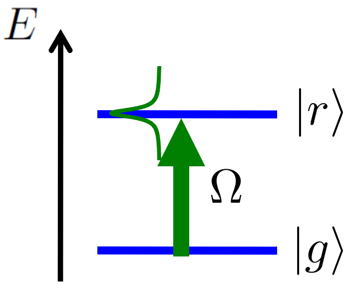
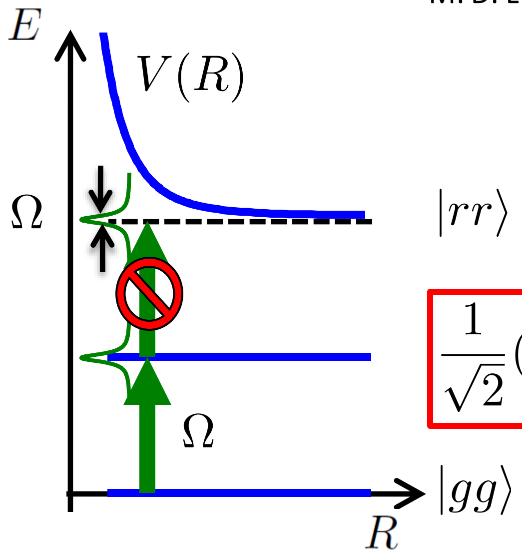
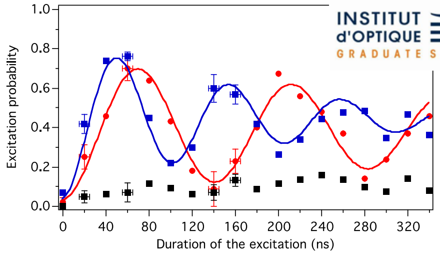






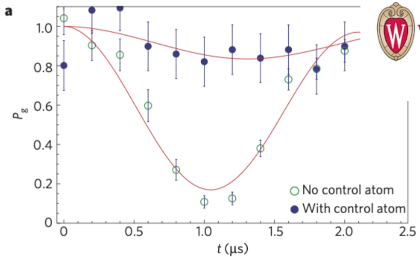
$$\frac{1}{\sqrt{2}}(|gr\rangle + |rg\rangle)$$

1[st] demonstrations of controlled Rydberg interactions



INSTITUT d'OPTIQUE GRADUATE SCHOOL

Nat. Phys. 2009



WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Outline – Lecture 1

1. Arrays of individual atoms in optical tweezers

2. Basics of Rydberg physics and their interaction

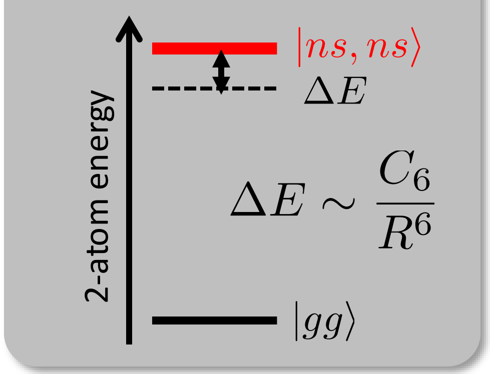
3. Interaction between Rydberg atoms and spin models

   - “Natural”: Ising and XY Hamiltonians
   - Hard-core bosons and $t - J$ model
   - Floquet engineering of XYZ models

Interactions between Rydberg atoms and spin models

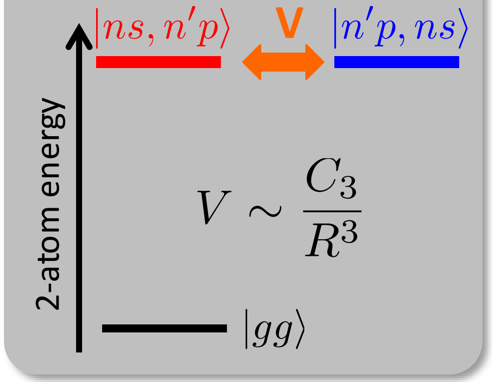
Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals



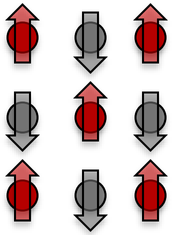
$$\Delta E \sim \frac{C_6}{R^6}$$

Resonant dipole



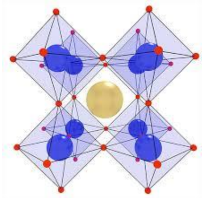
$$V \sim \frac{C_3}{R^3}$$

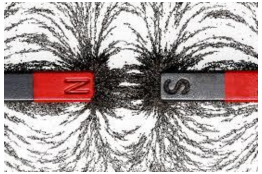
Spin 1/2



Ising model

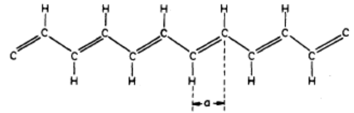
$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{n}_i \hat{n}_j$$



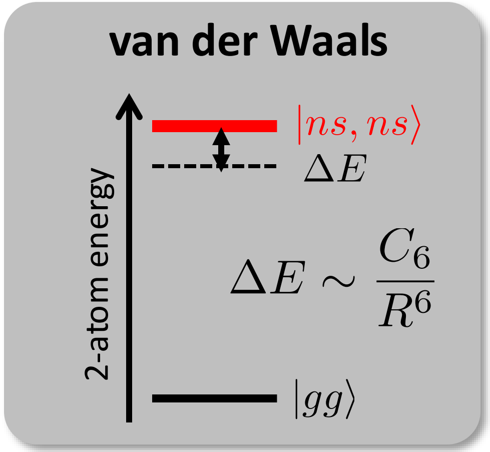


XY model

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



From van der Waals interaction to spin models...



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

Ground state: $n = 5$

Rydberg: $n = 50$

$\times 10^{11}$

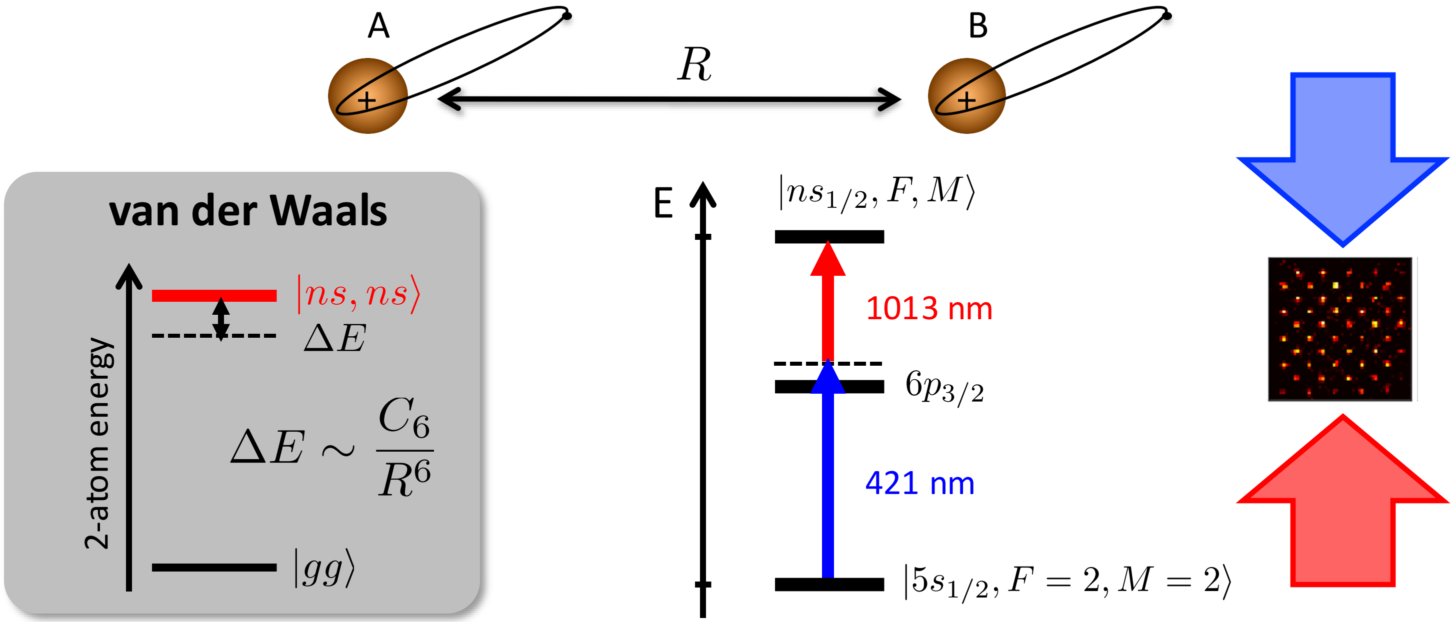
Ising - like!!

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

Rydberg $n_{1,2} = 1$

Ground state $n_{1,2} = 0$

From van der Waals interaction to spin models...



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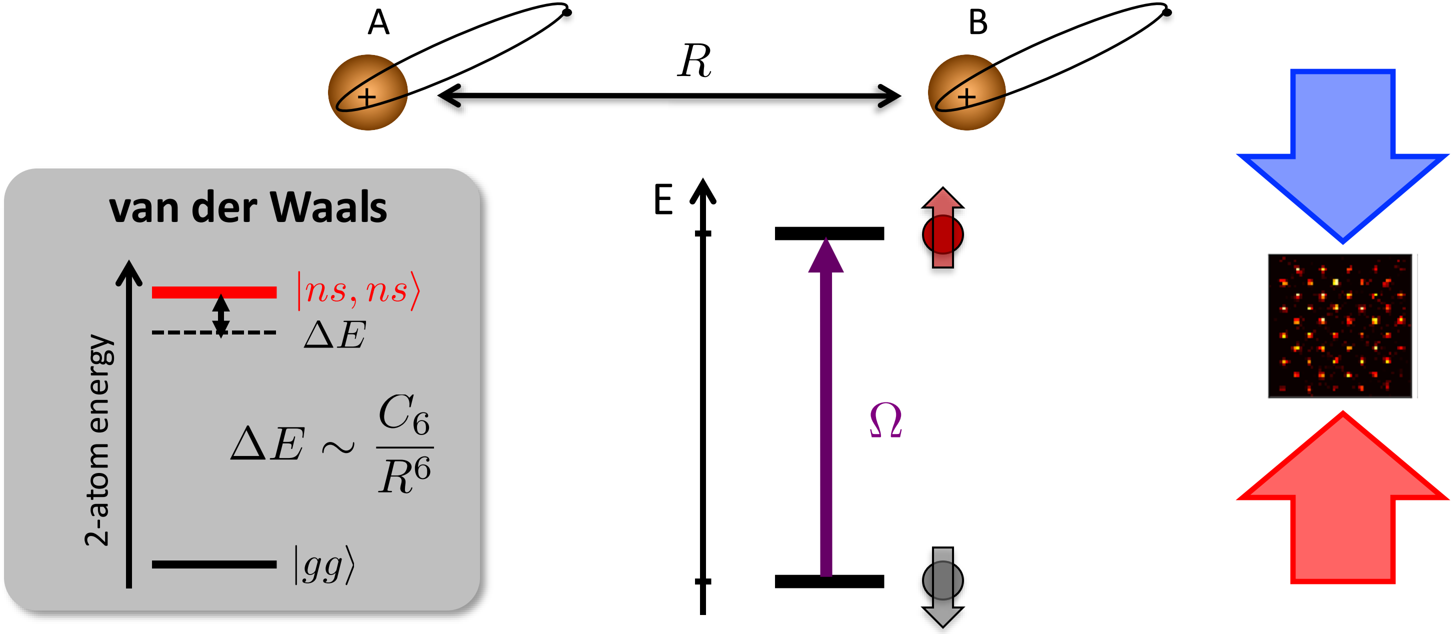
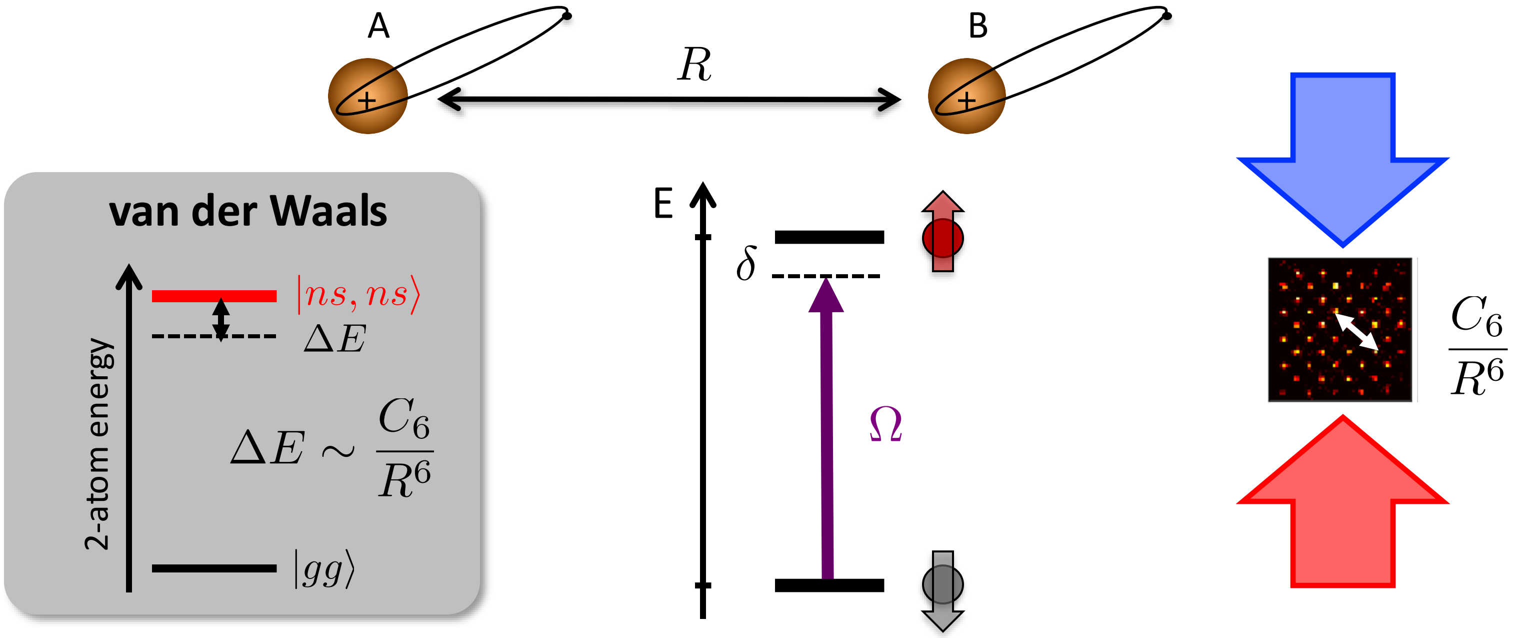
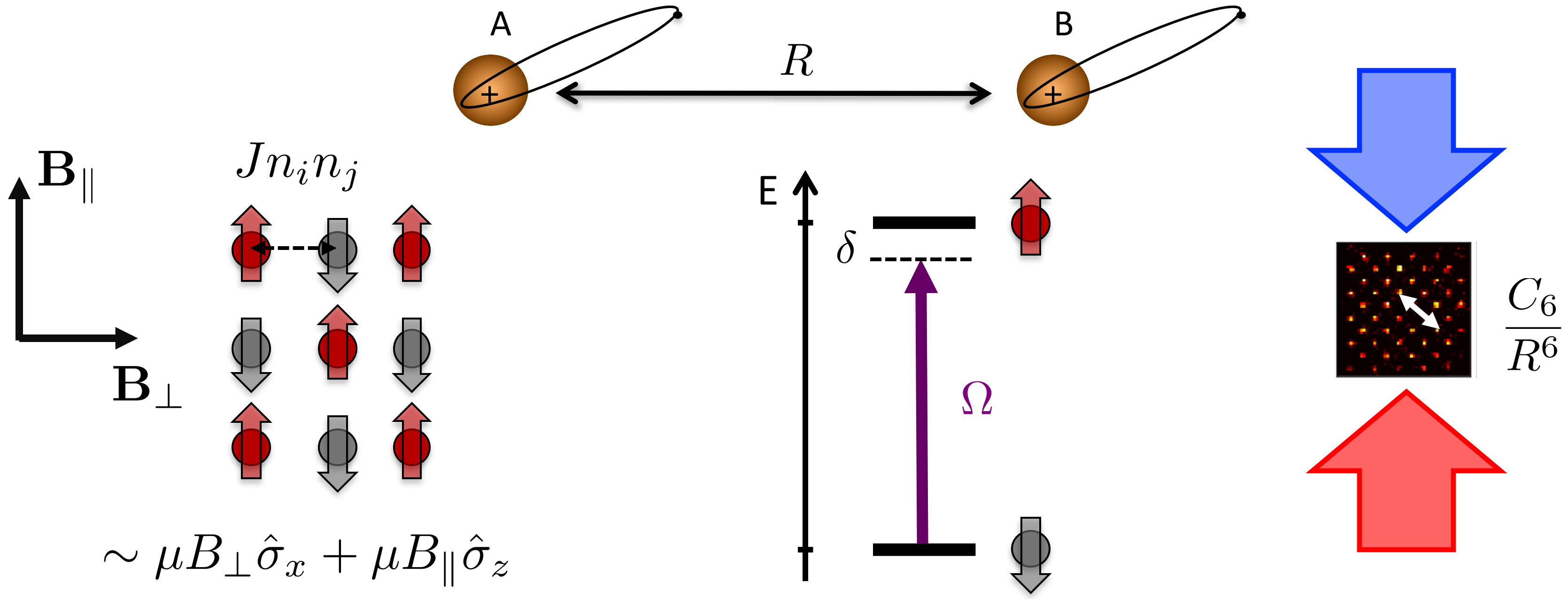


From van der Waals interaction to spin models...



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

From van der Waals interaction to spin models…

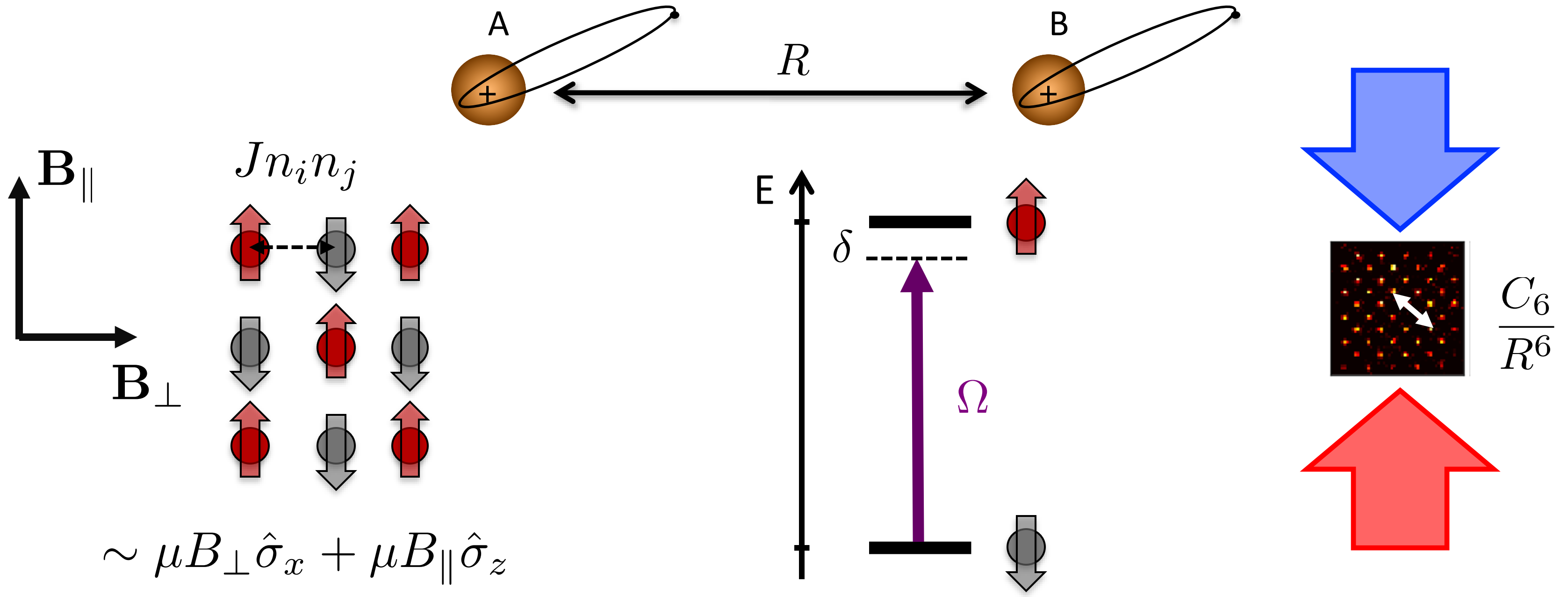


Transverse Field Ising model:

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

Laser: $B_{\perp}$ $B_{\parallel}$ spin-spin interactions

From van der Waals interaction to spin models...



Transverse Field Ising model:

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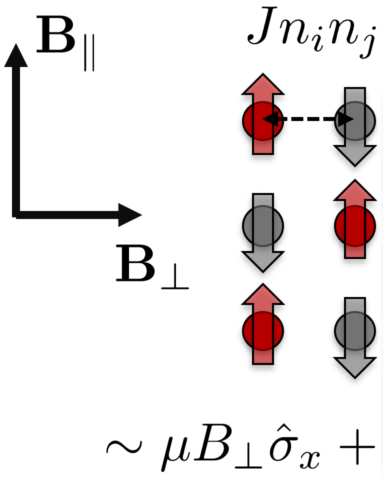
Laser: $B_{\perp}$ $B_{\parallel}$ spin-spin interactions

Controlled parameters:

From negligible to dominant interactions

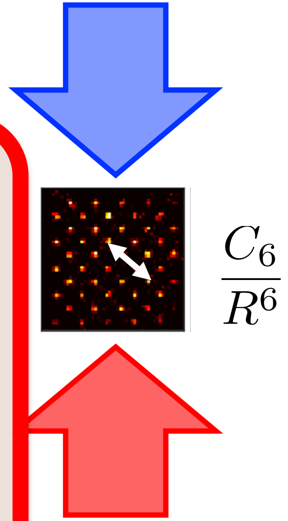
From van der Waals interaction to spin models…



Quantum simulation:

Emulate a system by another one

Similar equations lead to same solutions!!



Transverse Field Ising model:

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

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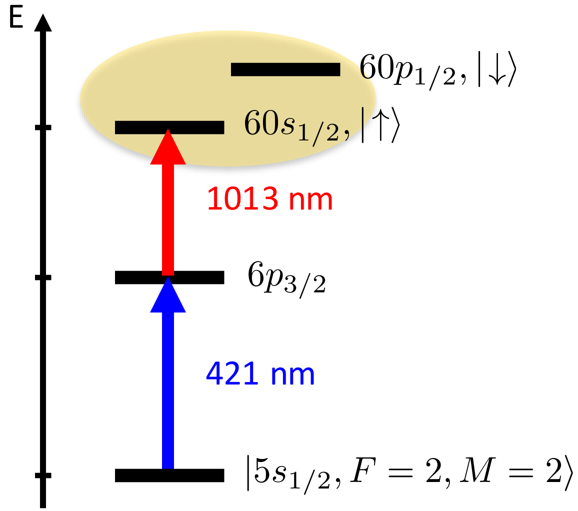
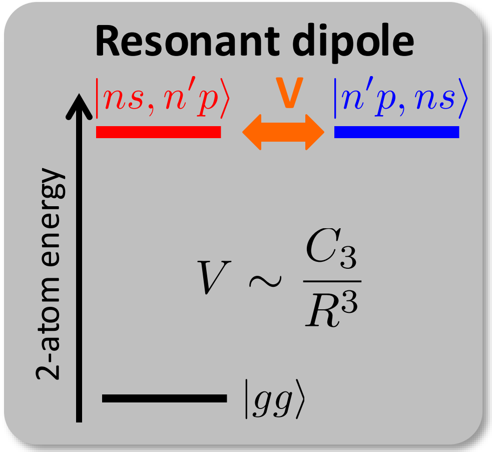
From negligible to dominant interactions

Resonant interaction between Rydbergs and XY spin model

Browaeys & Lahaye, Nat.Phys. (2020)
Barredo PRL (2015), de Léséleuc, PRL (2017)





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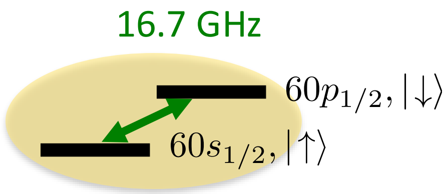

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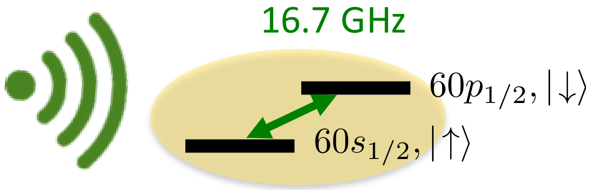

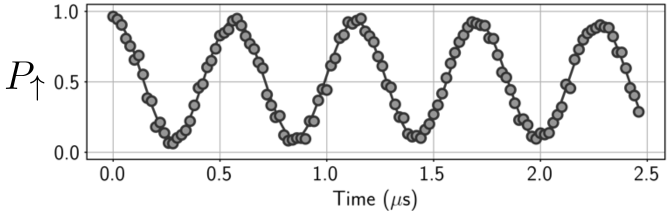

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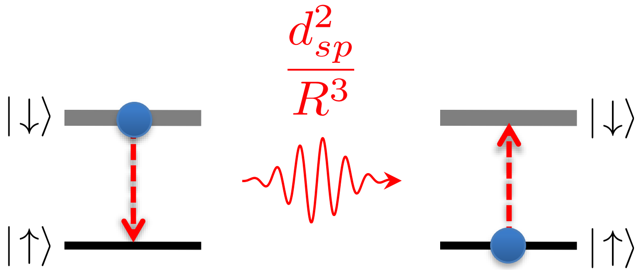
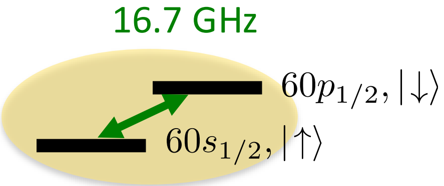
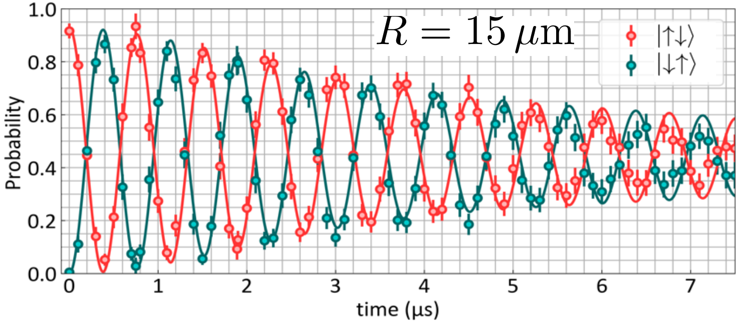
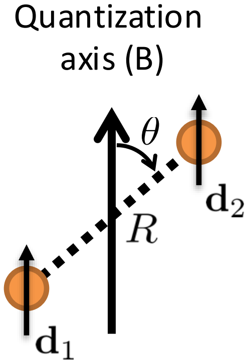
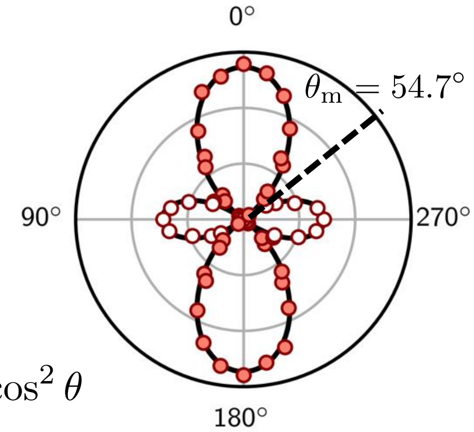


Non radiative "exchange" of excitation







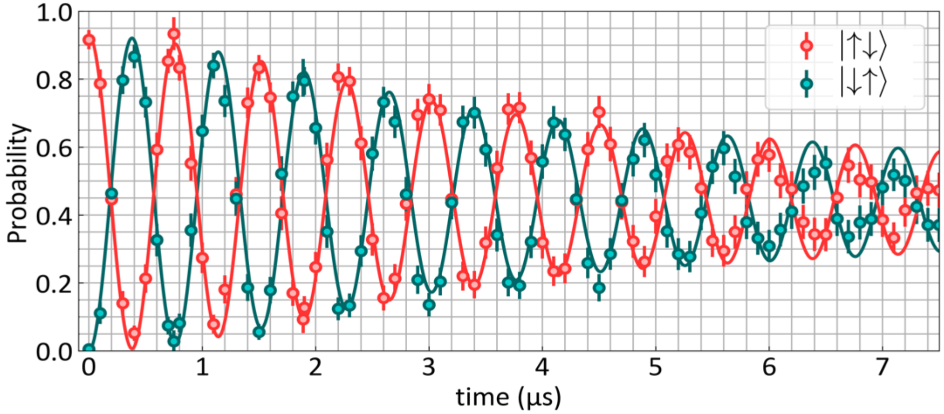


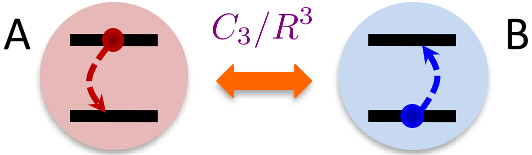
$$C_3(\theta) \propto 1 - 3\cos^2\theta$$

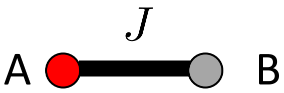
$$\hat{H}_{XY} = \frac{C_3}{R_{ij}^3}(\hat{\sigma}_i^+\hat{\sigma}_j^- + \hat{\sigma}_i^-\hat{\sigma}_j^+)$$

$$= 2\frac{C_3}{R_{ij}^3}(\hat{\sigma}_i^x\hat{\sigma}_j^x + \hat{\sigma}_i^y\hat{\sigma}_j^y)$$

XY spin model and transport of excitations







Particle hopping

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

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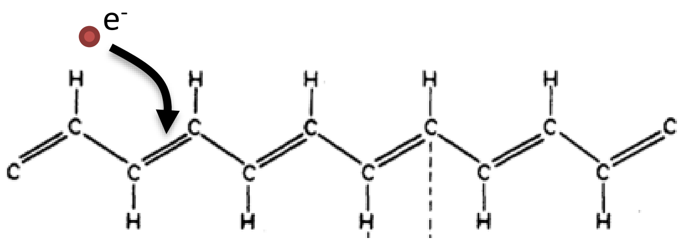
The Su-Schrieffer-Heeger model



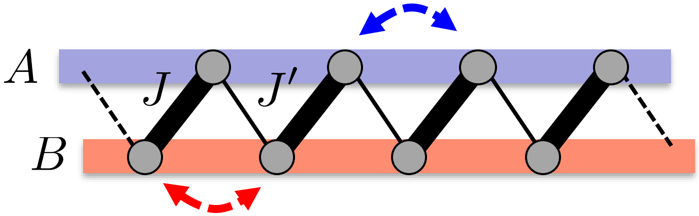
Electronic transport in polyacetylene

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

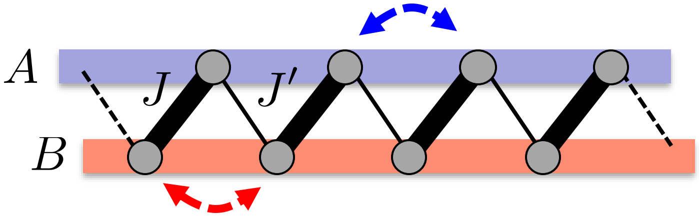
dimerization: $J > J'$

$J'' = 0$: **chiral symmetry** $\Rightarrow$ symmetric **single particle** spectrum

Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

Implementation of SSH spin chain with Rydberg atoms

Déléseleuc, Science **365**, 775 (2019)



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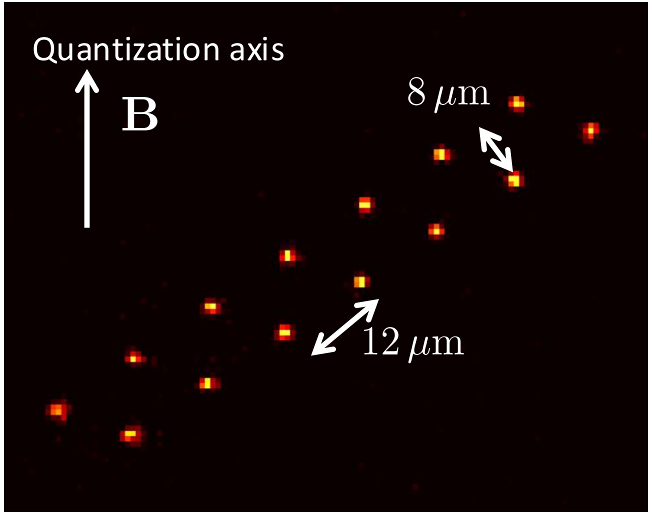
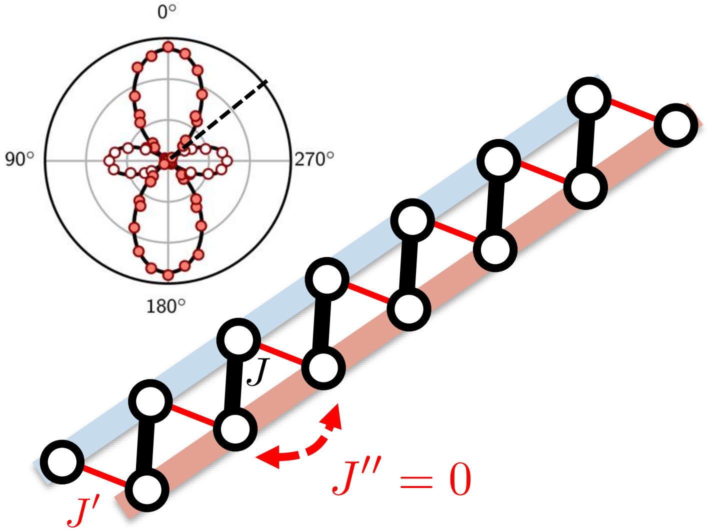


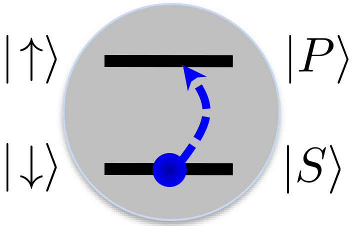


Asboth, arXiv:1509.02295

Cooper, arXiv:1803.00249

Spin excitations interact: hard core bosons

Spin excitation = "particle"

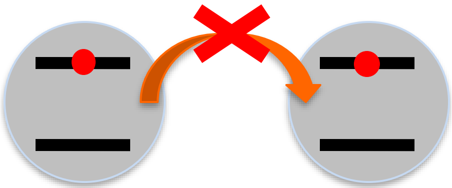


$$\hat{\sigma}^{+} \rightarrow \hat{b}^{\dagger} \; , \; b^{\dagger}|0\rangle = |1\rangle$$

$$\hat{\sigma}^{-} \rightarrow \hat{b} \; , \; b|1\rangle = |0\rangle$$

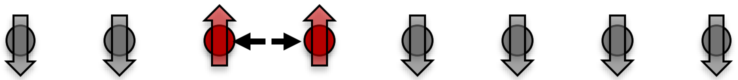
$$[\hat{b}_i, \hat{b}_j^{\dagger}] = \delta_{ij}$$

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



On-site interaction $U \rightarrow \infty$

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



$\Rightarrow$The first symmetry protected topological phase…

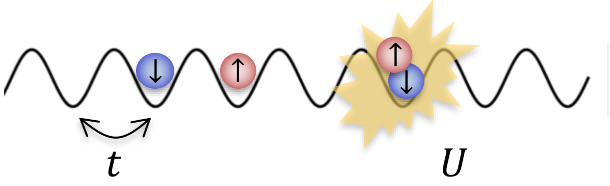
Predicted in 2012

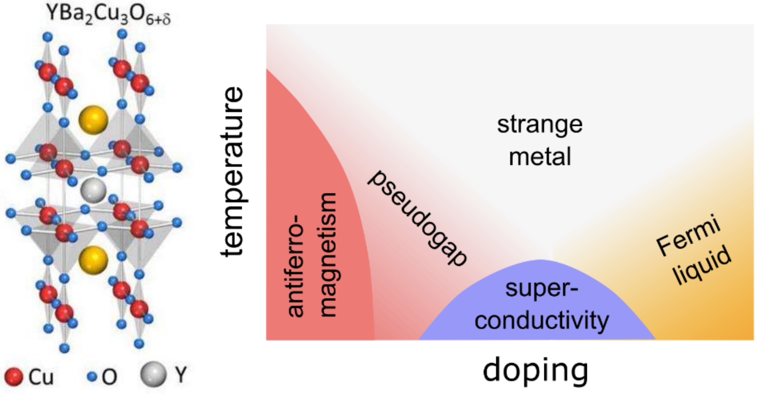
Déléseleuc, Science **365**, 775 (2019)

Doped magnets and $t-J$ model

Hubbard model

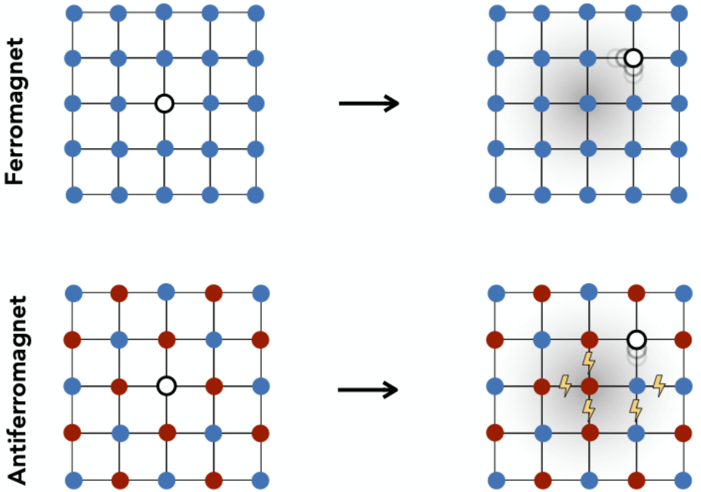
$$H_{\mathrm{FH}} = -t \sum_{\langle i,j\rangle,\sigma} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i n_{i\downarrow} n_{i\uparrow}$$





Doping = 0 + $U \gg t \Rightarrow H_{\mathrm{FH}} = \frac{4t^2}{U} \sum_{\langle i,j\rangle} \mathbf{S}_i \cdot \mathbf{S}_j$

Doping $\neq$ 0: hole motion coupled to magnetic background



$t-J$ model

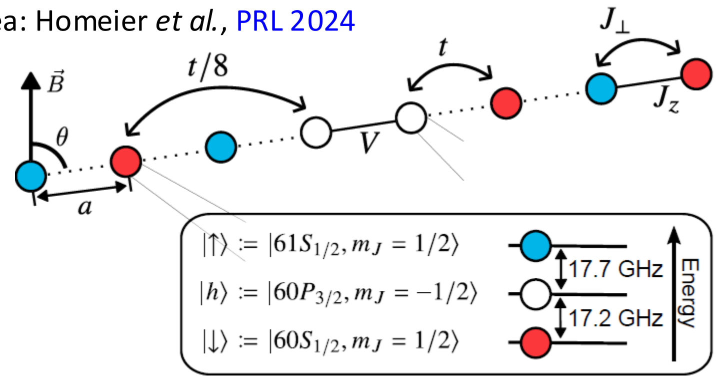
Auerbach, Wiley 1994

$$H_{\mathrm{FH}} = -t \sum_{\langle i,j\rangle,\sigma} c^\dagger_{i\sigma} c_{j\sigma} + J \sum_{\langle i,j\rangle} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{n_i n_j}{4} \right) + \mathcal{O}(t^3/U^2)$$

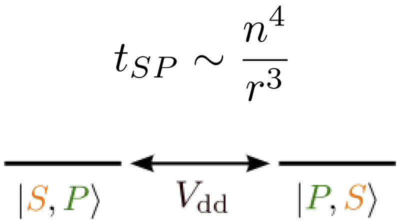
L. Homeier, thesis

Mapping onto three Rydberg states: $t-J-V$ model

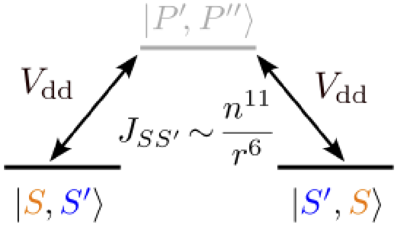
Idea: Homeier *et al.*, PRL 2024



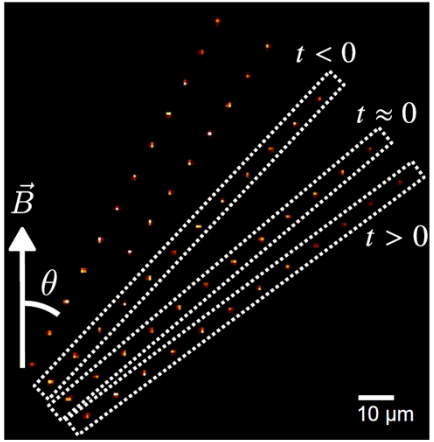
First-order exchange



2nd-order exchange



Tunability: vary θ and r



$$\hat{H}_{tJV} = \hat{H}_t + \hat{H}_J + \hat{H}_V$$

$$\hat{H}_t = -\sum_{i<j}\sum_{\sigma=\downarrow,\uparrow} \frac{t_\sigma}{r_{ij}^3}\left(\hat{a}^\dagger_{i,\sigma}\hat{a}^\dagger_{j,h}\hat{a}_{i,h}\hat{a}_{j,\sigma} + \text{ h.c. }\right)$$

Resonant dip.-dip. *S, P*

$$\hat{H}_J = \sum_{i<j}\frac{1}{r_{ij}^6}\left[J^z\hat{S}^z_i\hat{S}^z_j + \frac{J_\perp}{2}\left(\hat{S}^+_i\hat{S}^-_j + \text{h.c. }\right)\right]$$

vdW *S,S'*: diag. (J_z) and off-diag. ($J_\perp$)

$$\hat{H}_V = \sum_{i<j}\frac{V}{r_{ij}^6}\hat{n}^h_i\hat{n}^h_j$$

vdW *PP*: interaction between holes

M. Qiao *et al.*, arXiv:2501.08233

Outline – Lecture 1

1. Arrays of individual atoms in optical tweezers

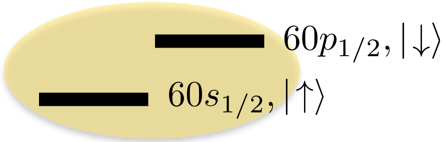
2. Basics of Rydberg physics and their interaction

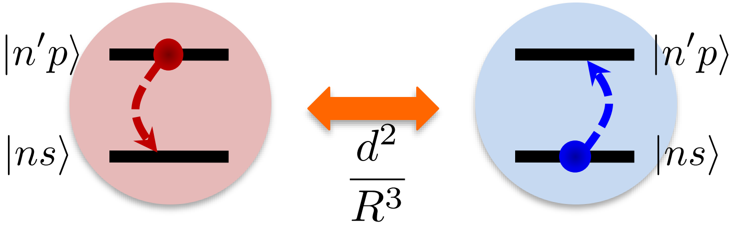
3. Interaction between Rydberg atoms and spin models

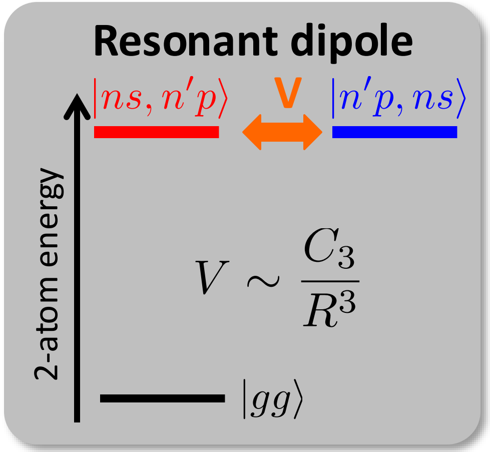
    - “Natural”: Ising and XY Hamiltonians
    - Hard-core bosons and $t-J$ model
    - Floquet engineering of XYZ models

Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)







XY model

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

Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)

nt dipole

V $|n'p, ns\rangle$

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

$g\rangle$

$|n'p\rangle$

$|ns\rangle$

del

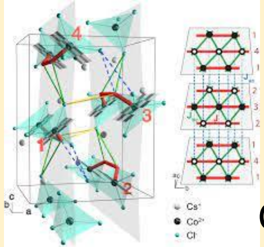
$\sigma_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$ $i \neq j$

Extend to more general XYZ spin models

$$\hat{H}_{\rm XYZ} = \sum_{i \neq j} J_{ij}^x \, \sigma_i^x \sigma_j^x + J_{ij}^y \, \sigma_i^y \sigma_j^y + J_{ij}^z \, \sigma_i^z \sigma_j^z$$

A. Abragham,
Principle of Nuclear Magnetism (1983)

XXZ



Cs_2CoCl_4

Whitlock, J. Phys. B 2017

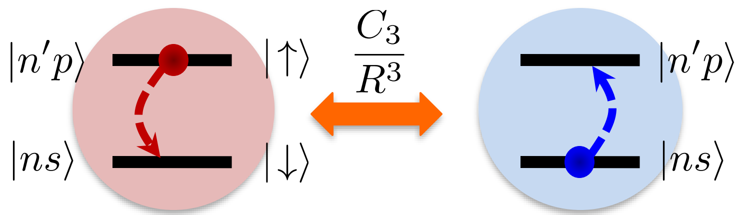
Heisenberg

$$\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

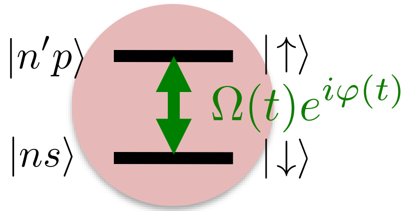
Engineering the XYZ model with microwaves

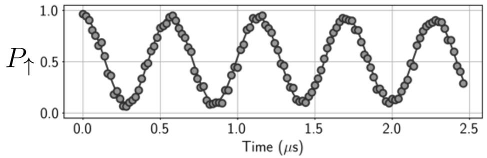
Combine:

Naturally occuring XY interaction



Microwave driving



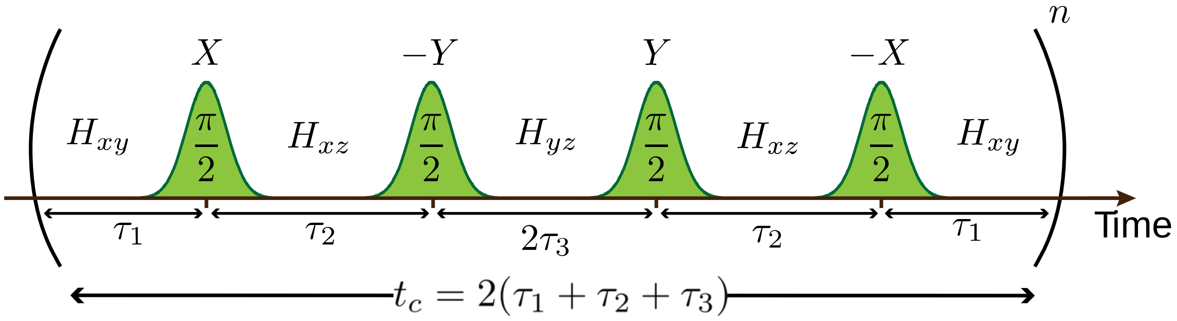


XY model + external (resonant) microwave field:

$$\hat{H}_{\mathrm{driv}} = \sum_{i \neq j} \frac{C_3}{R_{ij}} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y) + \frac{\hbar \Omega(t)}{2} \sum_i \cos\varphi(t)\, \hat{\sigma}_i^x + \sin\varphi(t)\, \hat{\sigma}_i^y$$

XYZ model with microwaves: Floquet engineering

Microwave pulse sequence $\Omega(t)$:



(infinitely short pulses)

$\frac{C_3}{R_{ij}^3} t_c \ll 1$ $\Rightarrow$ averaged hamiltonian: $H_{\mathrm{av}} = \frac{1}{t_c}\int_0^{t_c} H(t)\,dt$

$$\Rightarrow H_{\mathrm{av}} = 2\sum_{i\neq j} \frac{C_3}{R_{ij}^3}\left(\frac{\tau_1+\tau_2}{t_c}\,\sigma_i^x\sigma_j^x + \frac{\tau_1+\tau_3}{t_c}\,\sigma_i^y\sigma_j^y + \frac{\tau_2+\tau_2}{t_c}\,\sigma_i^z\sigma_j^z\right)$$

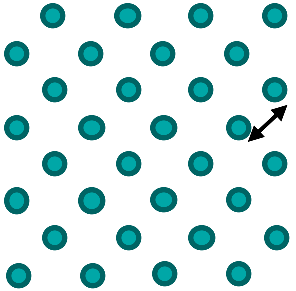
$\Rightarrow$ Programmable XYZ Hamiltonians!

Vandersypen, RMP 2006
Choi *et al.*, PRX **10**, 031002 (2020)

Heisenberg XXX engineering in 2D

Scholl, PRX Quantum 2022

32 atoms



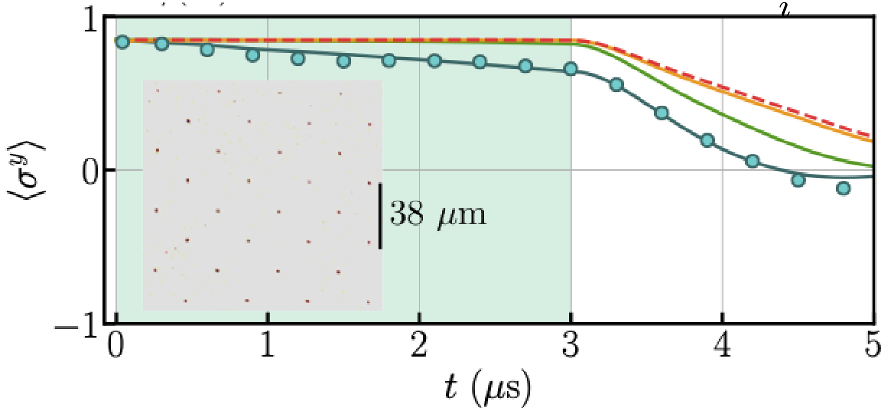
$$\hat{H}_{\text{Heis.}} = \sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

y-magnetization nearly conserved

SU(2) symmetry: $[\hat{H}_{\text{Heis.}}, \sum_i \mathbf{S}_i] = 0$

$|\downarrow\rangle = |75S\rangle; |\uparrow\rangle = |75P\rangle$

Initial state: $(|\rightarrow\rangle_y)^{\otimes N}$

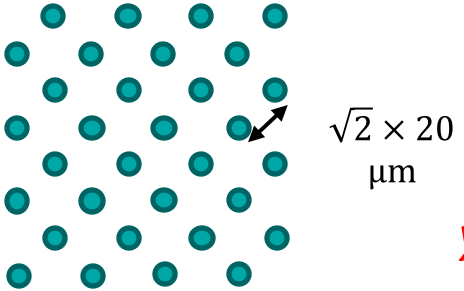


Expt: cloud of atoms
Geier, Science 2021

Heisenberg XXX engineering in 2D

Scholl, PRX Quantum 2022

32 atoms



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y-magnetization nearly conserved

$H_{\text{Heis.}} \to H_{\text{XX}}$

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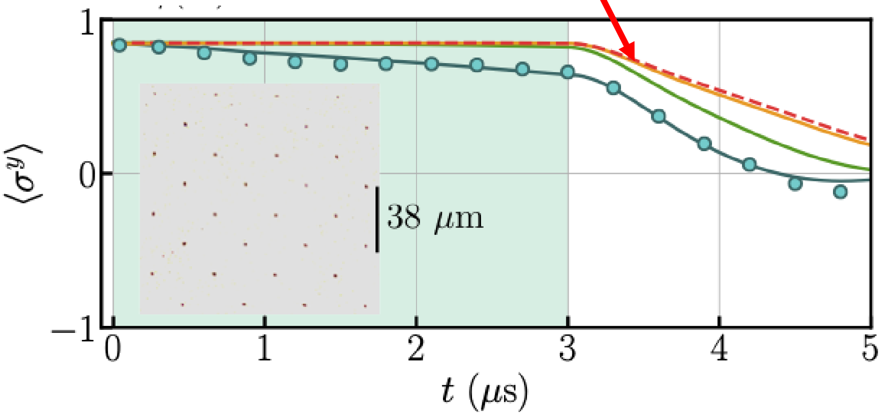
Initial state: $(|\rightarrow\rangle_y)^{\otimes N}$



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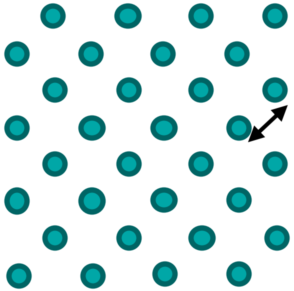


$\sqrt{2} \times 20$ µm

$$\hat{H}_{\text{Heis.}} = \sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

y-magnetization nearly conserved

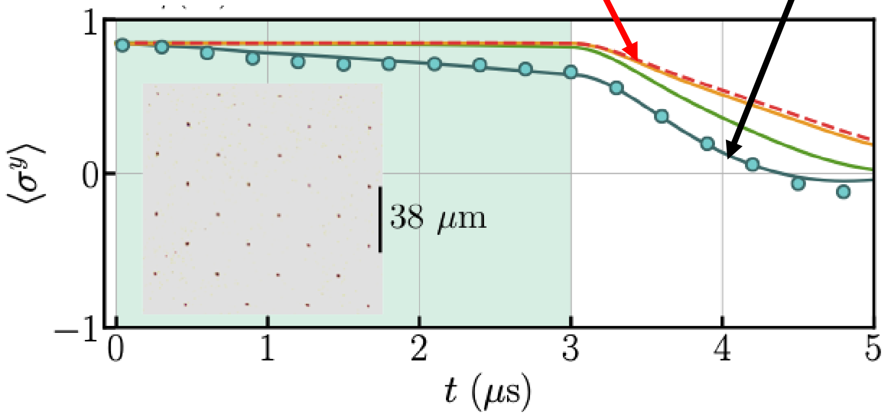
$H_{\text{Heis.}} \rightarrow H_{\text{XX}}$

MACE simulation H_{driv}

Hazzard, PRL 2014

$|\downarrow\rangle = |75S\rangle; |\uparrow\rangle = |75P\rangle$

Initial state: $(|\rightarrow\rangle_y)^{\otimes N}$



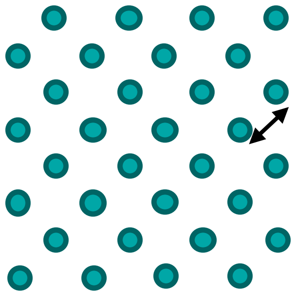
No adjustable parameter, includes MW imperfections

Expt: cloud of atoms
Geier, Science 2021

Heisenberg XXX engineering in 2D

Scholl, PRX Quantum 2022

32 atoms



$\sqrt{2} \times 20$ μm

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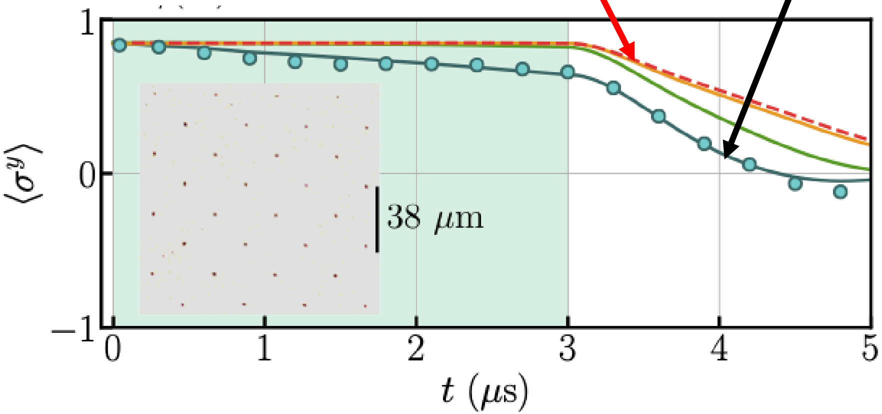


No adjustable parameter, includes MW imperfections

Expt: cloud of atoms
Geier, Science 2021

Limitations: finite MW pulse duration + imperfections

Conclusion: many variants of spin Hamiltonians

Quantum Ising
s = 1/2

Hardcore boson

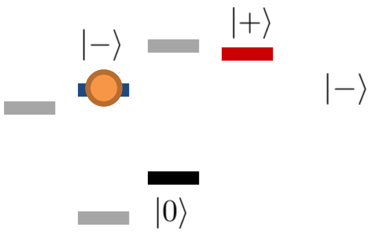
Bosons/ Fermions
Softcore potential

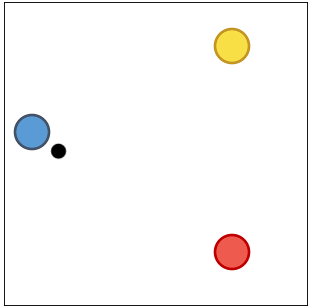
XY, s = 1/2
$\frac{1}{R^3}, \frac{1}{R^6}$

XYZ Heisenberg
s = 1/2
Floquet

t- J model

Spin-orbit coupling





Lienhard, PRX 2021

In various *addressable* geometries: 1D (OBC, PBC), 2D : square, triangle, Kagome…

Warning: mapping is only approximate (on top of uncontrolled parameters)…:

XY has small Ising; neglect quadrupolar interactions; not exactly 2 levels…

Hard to assess the impact…!!