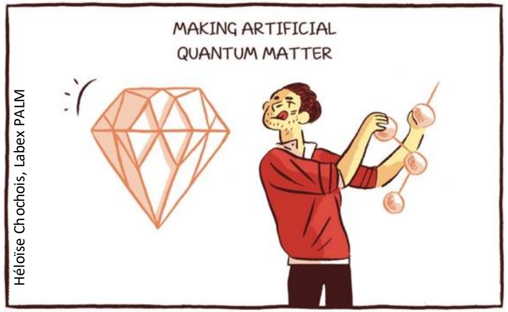
Many-body physics

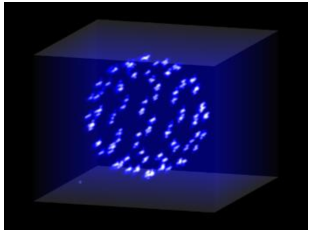
with arrays of Rydberg atoms (I)

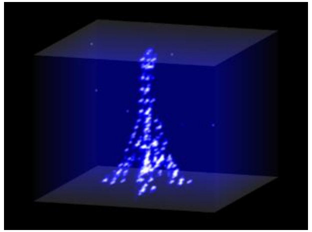


Antoine Browaeys

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

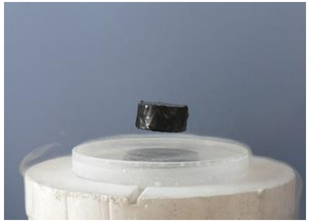
ICTP Summer School, august 21st, 2025



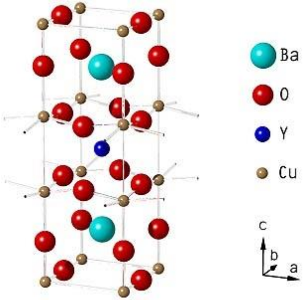


The many-body problem: the art of modelling...

wikipedia



YBaCuO



Observe unexpected effects

Ex: high-T_c superconductivity

Microscopic understanding?

Experiment on "real" system

simplify

Cook up a model

$$H_{\text{model}} = -t \sum_{\langle i,j \rangle, \sigma} (c^\dagger_{i\sigma} c_{j\sigma} + \text{h.c.}) + U \sum_i n_{i\downarrow} n_{i\uparrow}$$

Too hard to calculate...

Problem: exponential complexity

2 d. of freedom (spin...) $\psi_i = \begin{pmatrix} a \\ b \end{pmatrix}$

Many-body wavefunction: $\Psi = \Psi(1, 2, ..., N) \Rightarrow \Psi$ requires 2^N numbers

Record *ab-initio* calculation (2025) $N \sim 50 \Rightarrow 2^{50} \sim 10^{15}$ = 1000 Tb RAM !!

The many-body problem: the art of modelling…

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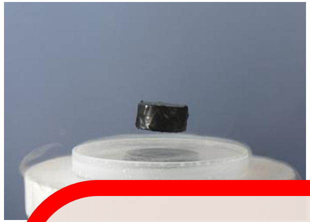

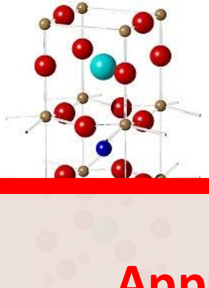

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Too hard to calculate…

Approximations possible!!

mean-field, perturbation theory, Monte-Carlo,
variational methods: DFT, MPS, Neural Quantum States…

But… can be poorly controlled or not valid
when *interactions dominate*

= **Strongly correlated** systems

Problem: exponential complexity

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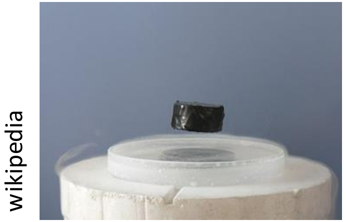
One approach: build a synthetic many-body quantum systems



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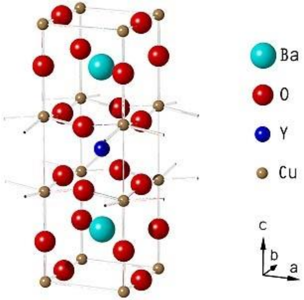

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Lab…

Engineer a system ruled by H_{model}

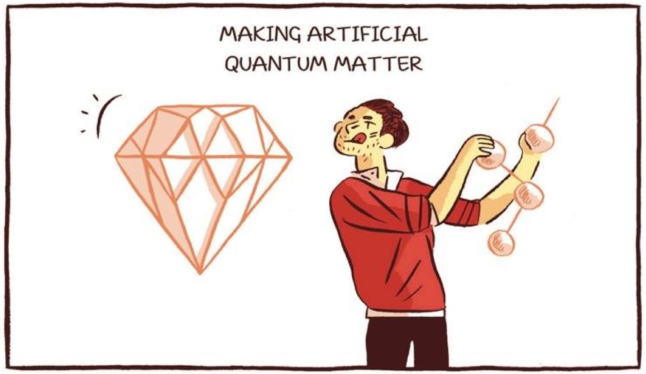
Measure on system:
Supercond. or not?

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…)

Analog versus digital quantum simulation

Analog

The platform implements directly H_{model}

$$|\psi(t)\rangle = \exp\left(-\frac{i}{\hbar}\int_0^t H_{\text{mod}}(t')dt'\right)|\psi(0)\rangle$$

e.g.: Fermi Hubbard, spin models, electrons in B-fields…

Non-universal

Digital

H_{model} synthesized digitally

$$H_{\text{mod}} = \sum_{n=1}^{N} H_n$$

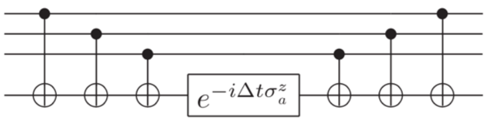
e.g. single & 2-qbit operations

$$e^{-iH_{\text{mod}}t} \approx$$

$$\left(e^{-iH_1 t/n} e^{-iH_2 t/n} \ldots e^{-iH_3 t/n}\right)^n$$

= “universal” quantum simulation

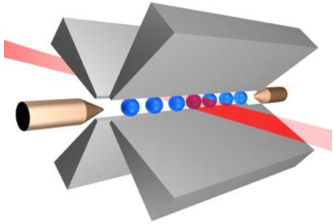
Ex:



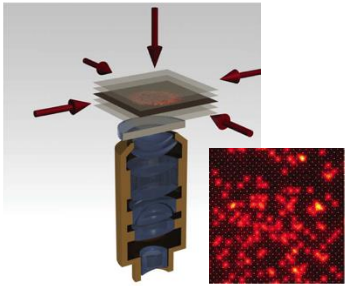
$$H_{\text{mod}} = \sigma_1^z \otimes \sigma_2^z \otimes \sigma_3^z$$

Georgescu, Rev. Mod. Phys. (2014)

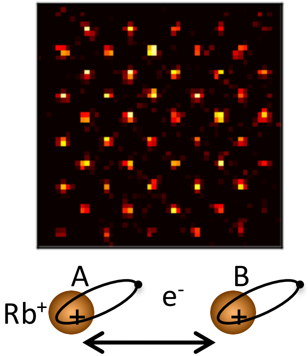
Engineering with individual quantum systems (examples)



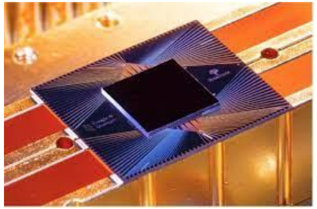
Trapped ions



Atoms in optical lattices



Atoms in tweezer arrays



Supercond. Circuits

IBM, Google…

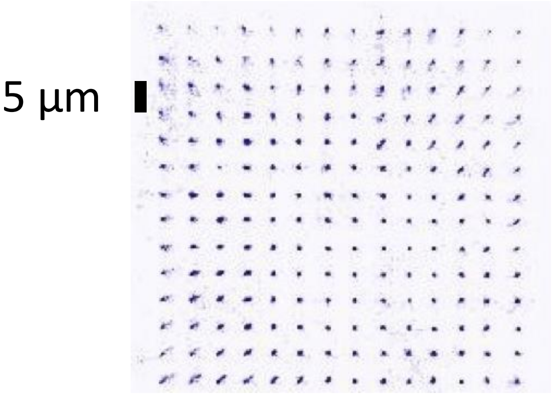
Scalable: beyond 100 particles ; potential > 1000

Addressability: local manipulations and measurement

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

Programmable: controlled geometry, interactions…

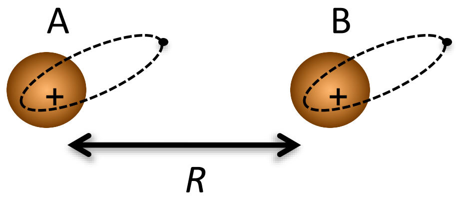
These lectures: combining arrays of atoms and Rydberg interactions



Addressable!!

+

Rydberg interactions



Van der Waals

$$\frac{C_6}{R^6}$$

resonant

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

Quantum simulation (mainly spin models)

Quantum information processing

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

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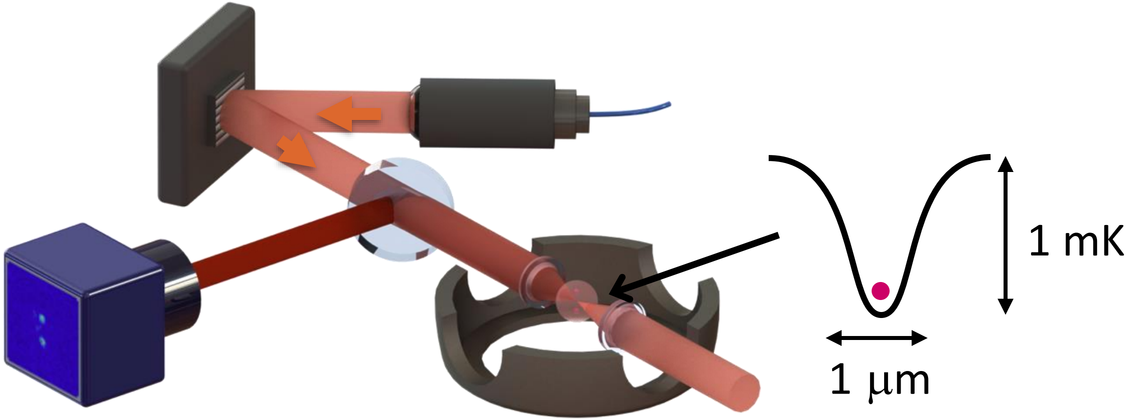
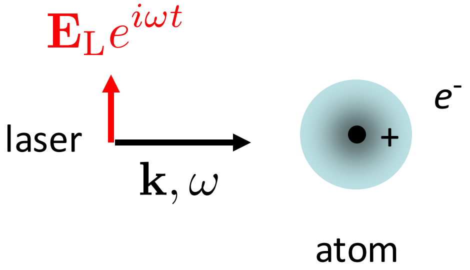
A single Rb atom in an optical tweezer



Grangier (2001)
Sortais (2007)

Dipole force



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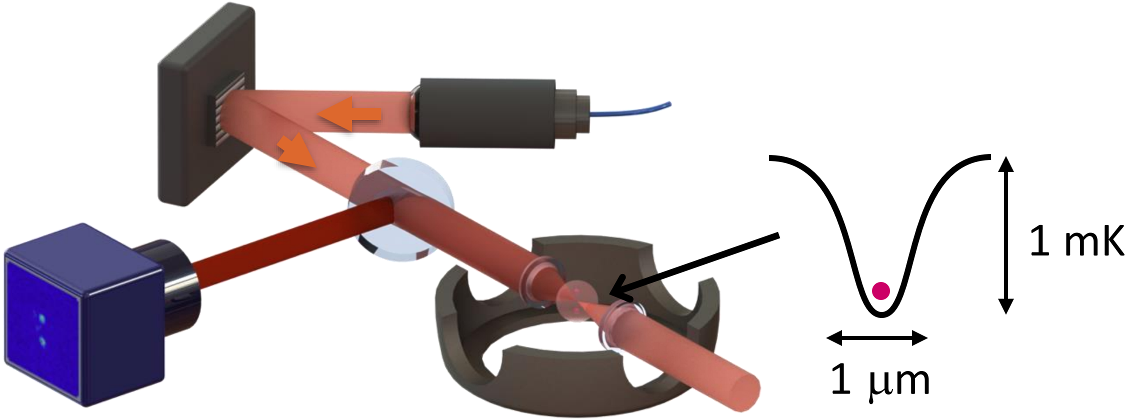

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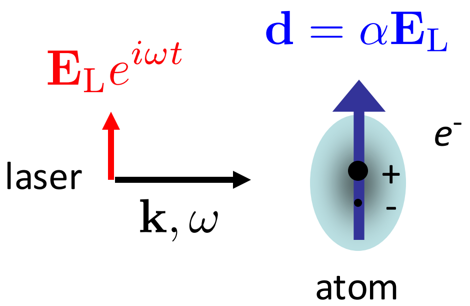
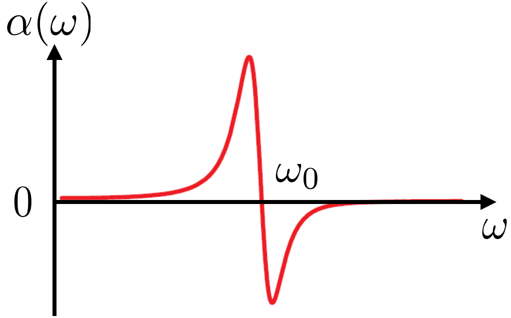


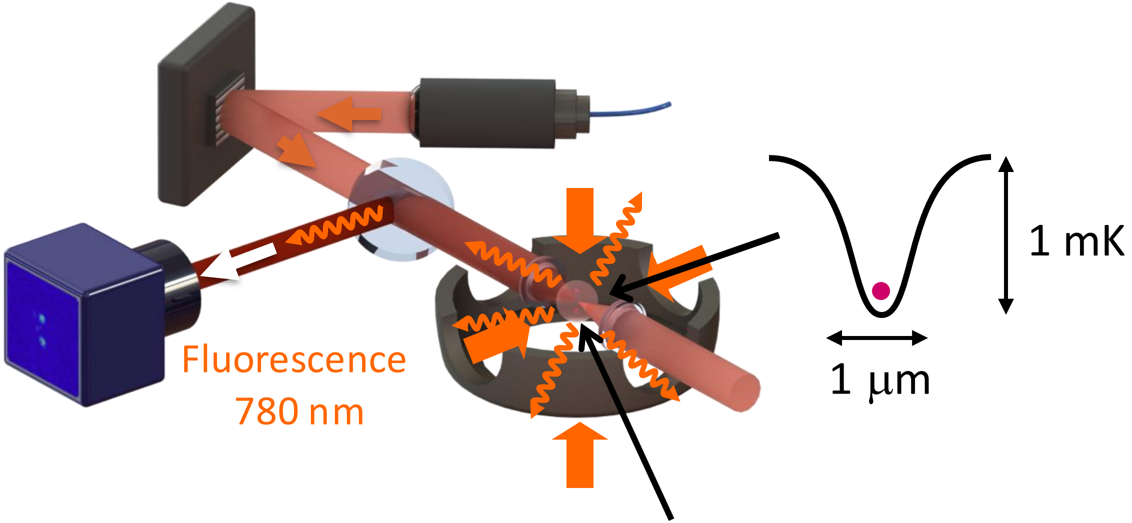
$$U = -\frac{1}{2}\langle \mathbf{d} \cdot \mathbf{E}_{\mathrm{L}} \rangle$$
$$= -\frac{1}{2}\alpha \langle \mathbf{E}_{\mathrm{L}}^2 \rangle$$



$\omega < \omega_0 \Rightarrow$ high-intensity seeker

Ex: 1 mW on 1 μm $\Rightarrow$ **Trap depth = 1 mK** $\Rightarrow$ Laser cooled atoms…

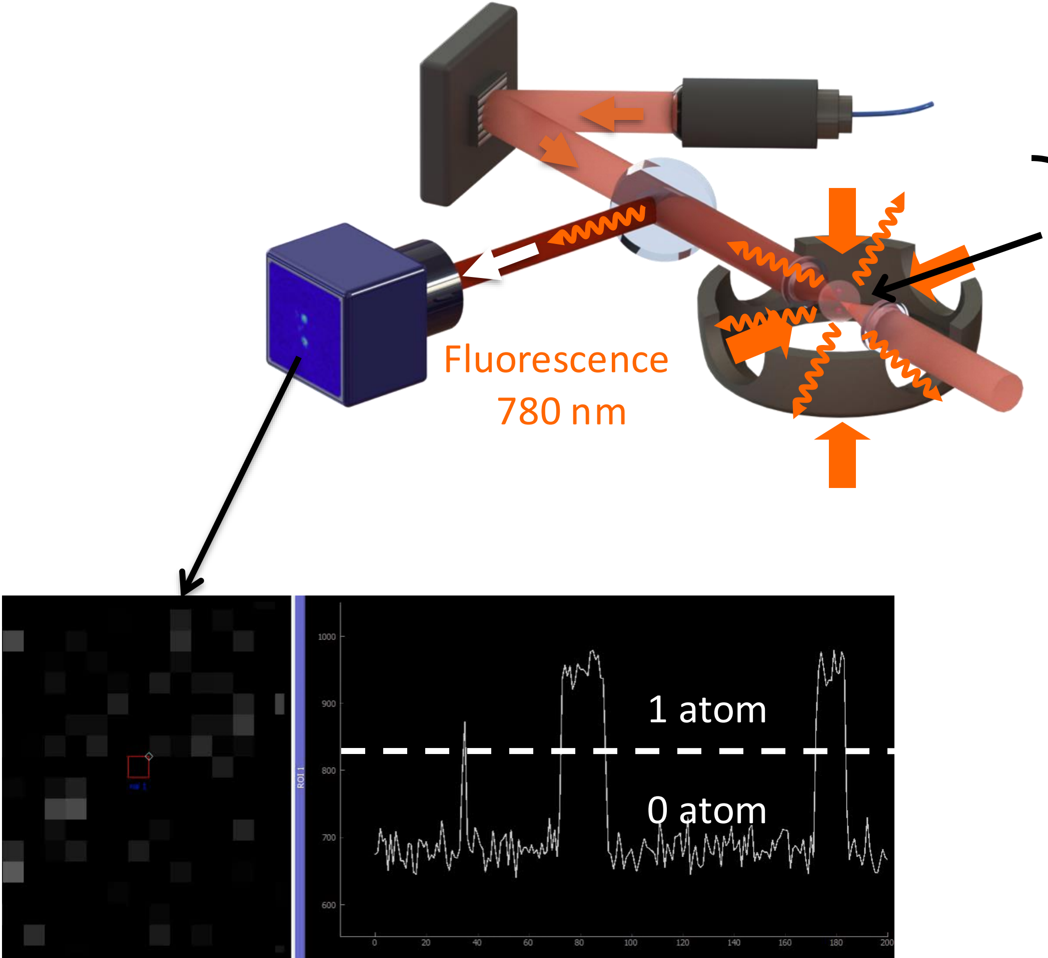
A single Rb atom in an optical tweezer

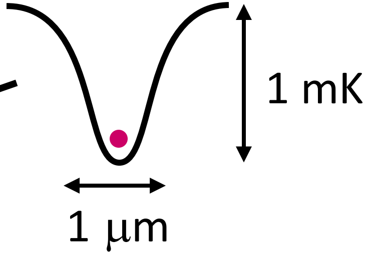


Reservoir = laser-cooled Rb atoms
T ~ 100 μK

Grangier (2001)
Sortais (2007)

A single Rb atom in an optical tweezer





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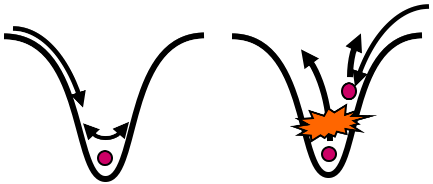
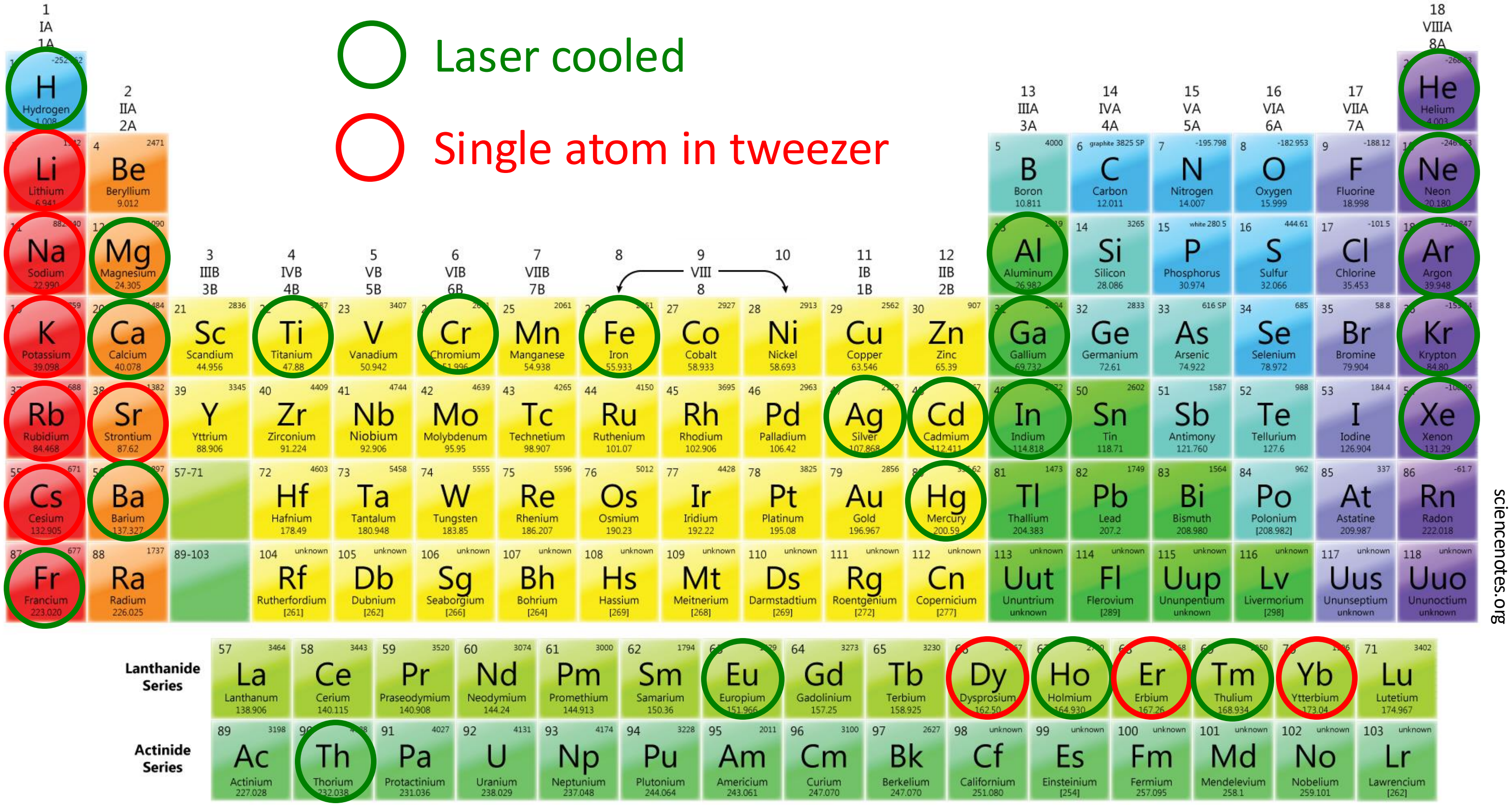


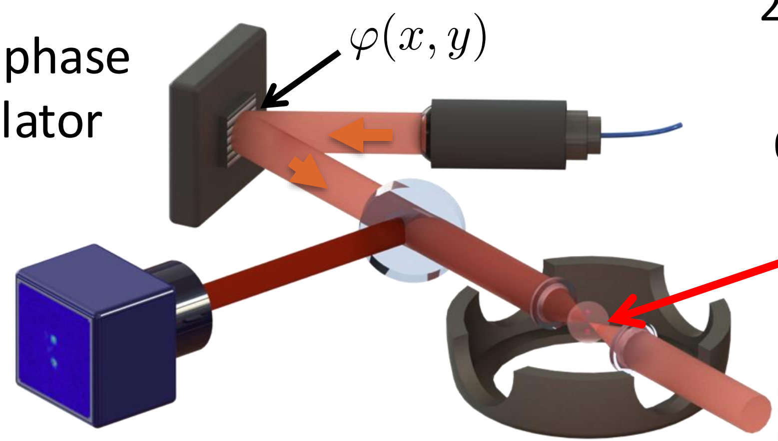
Non-deterministic
single-atom source

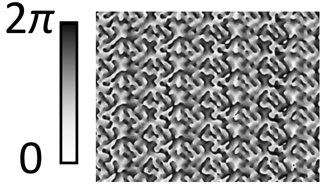
Single-atom trapping zoo (2025)



Atoms in arrays of optical tweezers

Spatial phase modulator

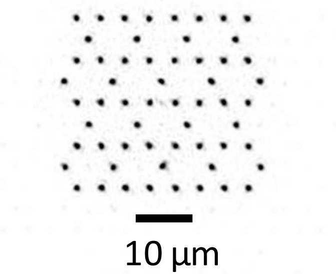




Phase mask

Nogrette, PRX (2014)

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



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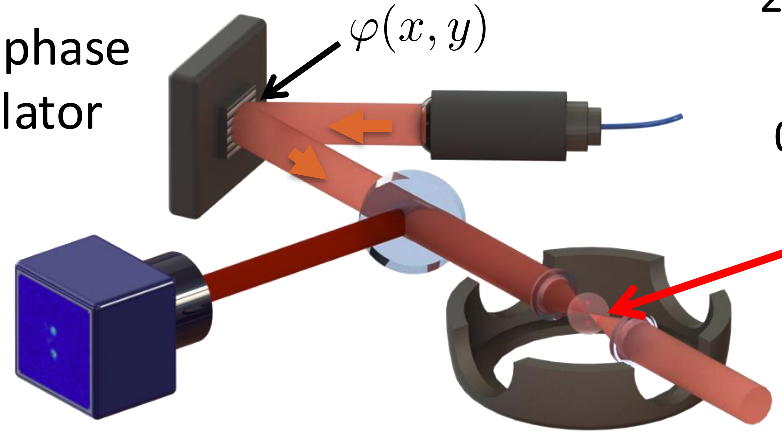

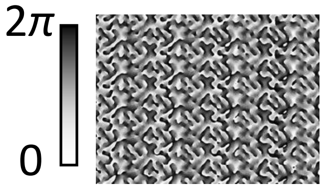

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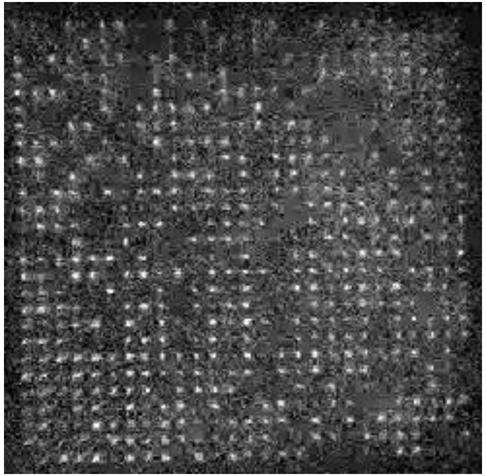
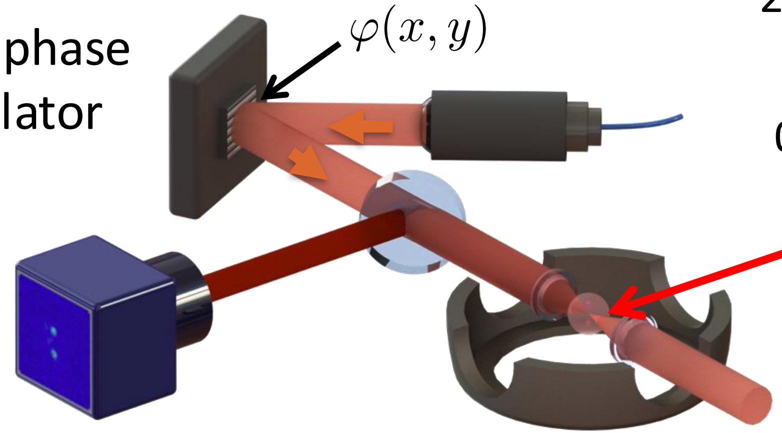
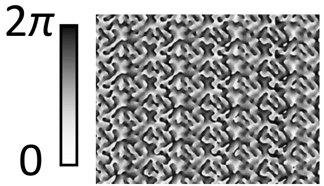


Fluorescence (729 traps)

Atoms in arrays of optical tweezers

Spatial phase modulator





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Nogrette, PRX (2014)

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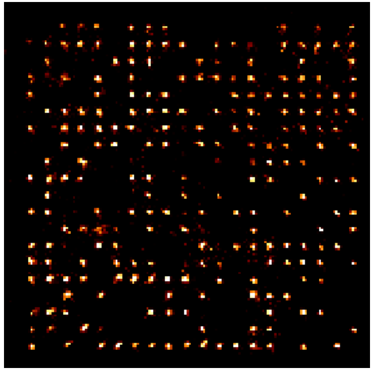
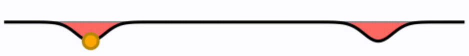
First demo (1D): Meschede, Nature (2006); Beugnon, Nat. Phys. (2007)

Initial configuration



Assembling process



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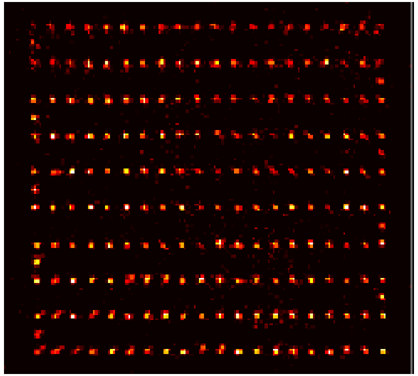
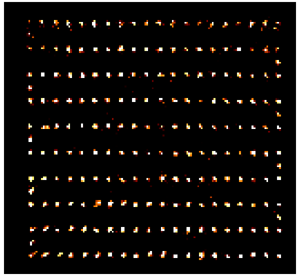


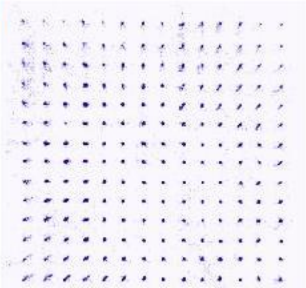
Atoms in arrays of optical tweezers (single-shot images)

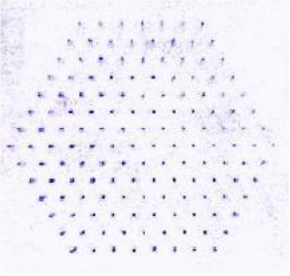
1D

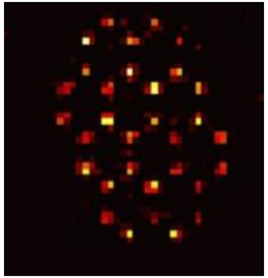


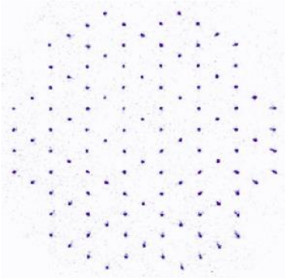
~100 μm

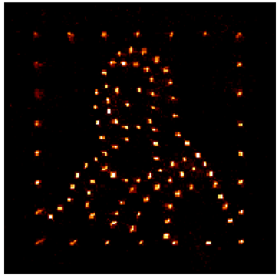
2D











L. da Vinci

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

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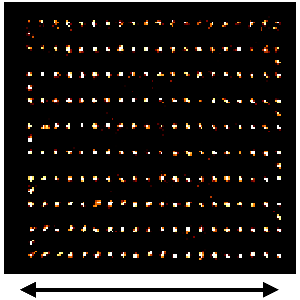

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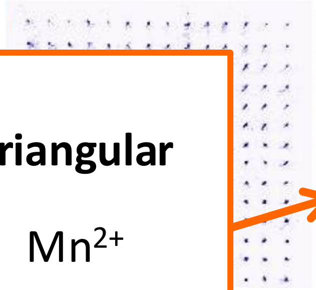
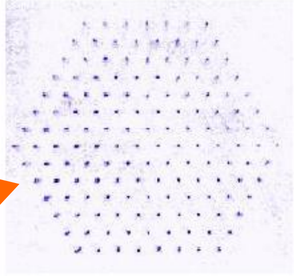
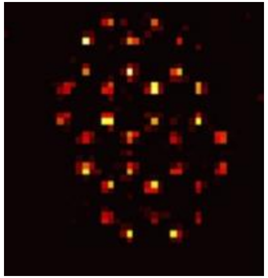
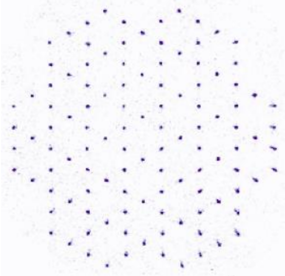
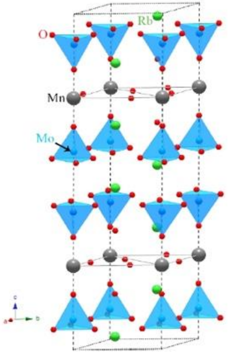
2D







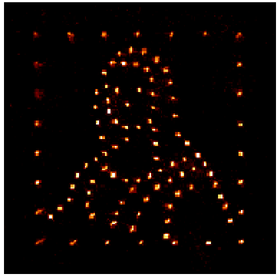




Triangular

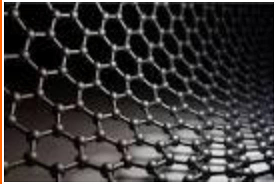
Mn^{2+}

$Rb_4Mn(MoO_4)_3$



L. da Vinci

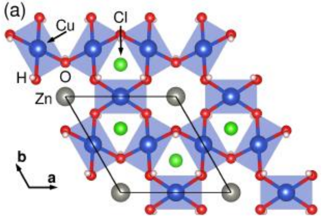
Hexagonal



graphene

Kagome: Herbertsmithite

$ZnCu_3(OH)_6Cl_2$



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

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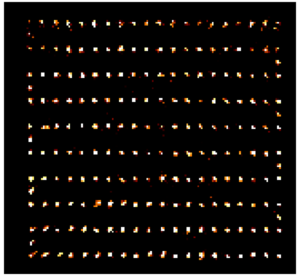
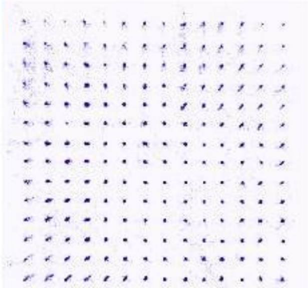
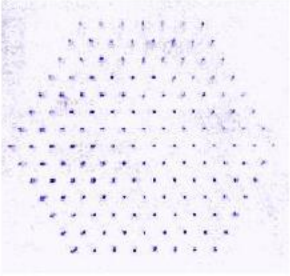


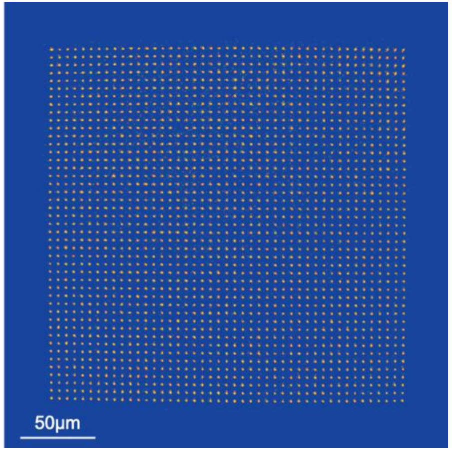
~100 μm

2D



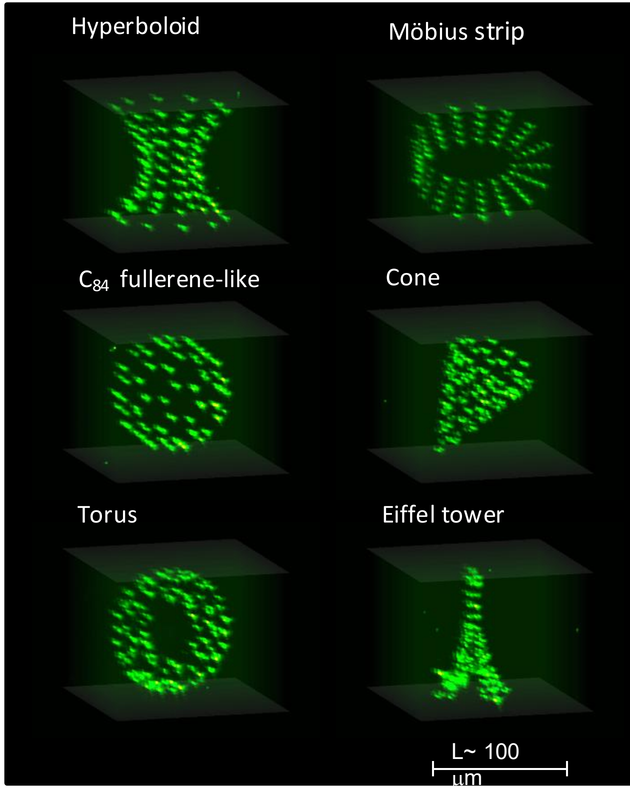


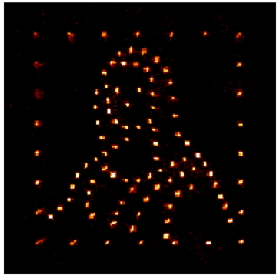
2024 atoms (AI + fast SLM)



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)

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

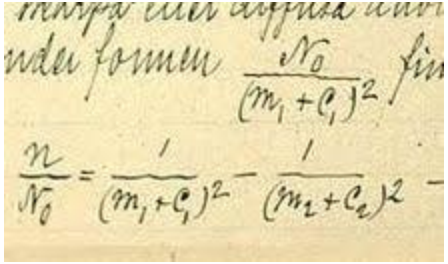
Rydberg atoms: the discovery

1814 Joseph von Fraunhofer

observation of dark lines in spectrum of the sun

1888 "Rydberg formula"

Johannes Rydberg
1854-1919



$$\frac{1}{\lambda_{nm}} = R_{\mathrm{H}} \left(\frac{1}{n^2} - \frac{1}{m^2} \right)$$

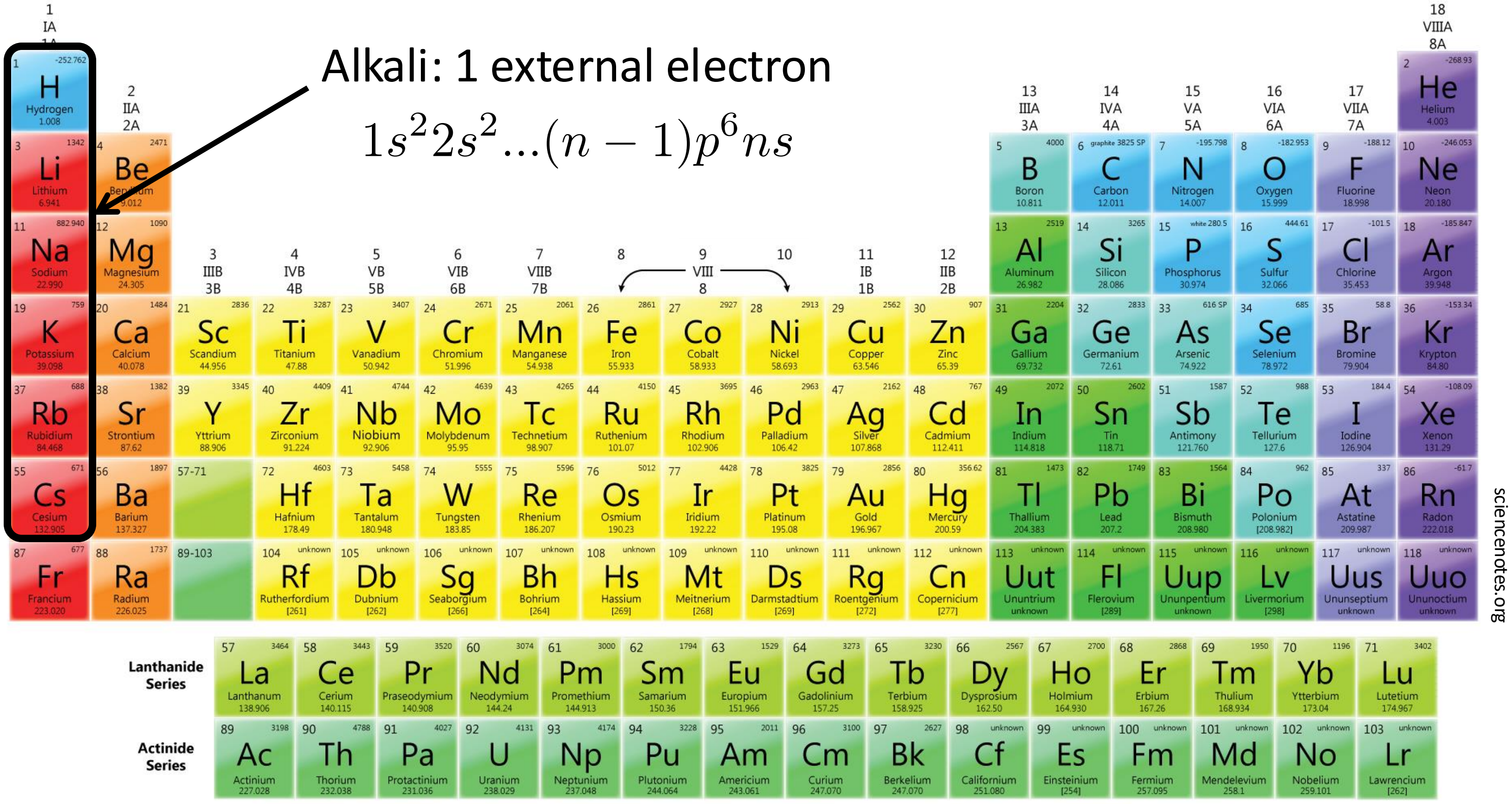
Idea of an infinite series

$\Rightarrow$ highly excited states

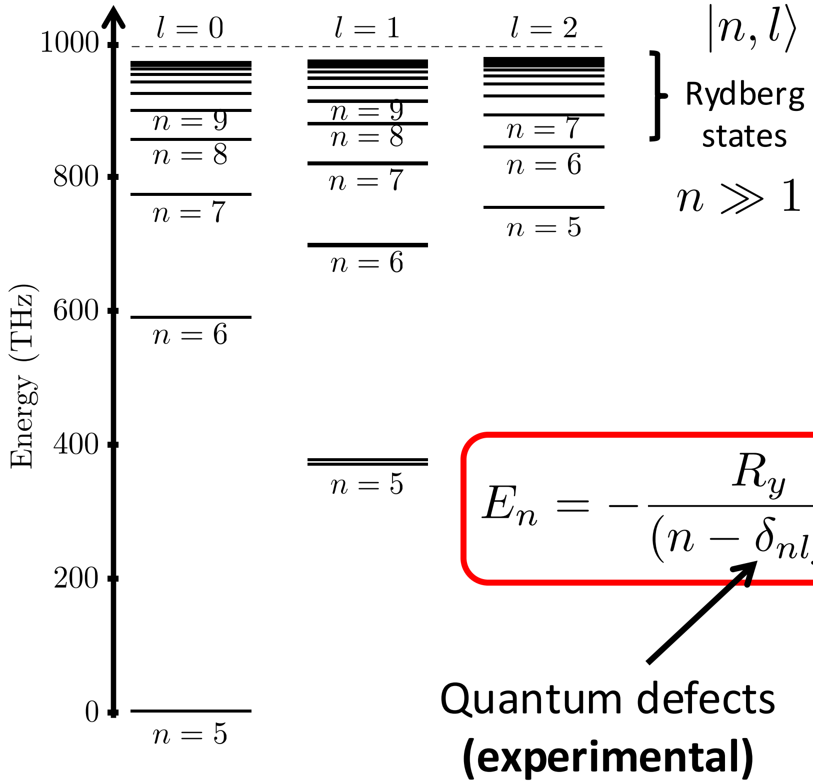
Examples: alkali atoms

Alkali: 1 external electron

$$1s^2 2s^2 \ldots (n-1)p^6 ns$$



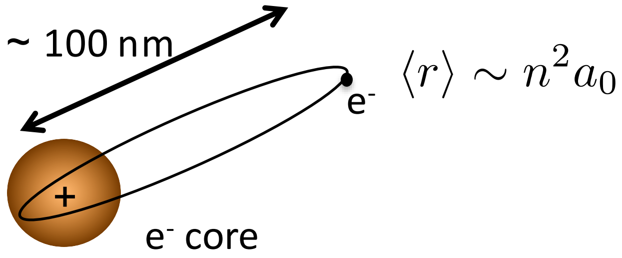
“Rydberg atom” = a highly excited atom (e.g. Rb)

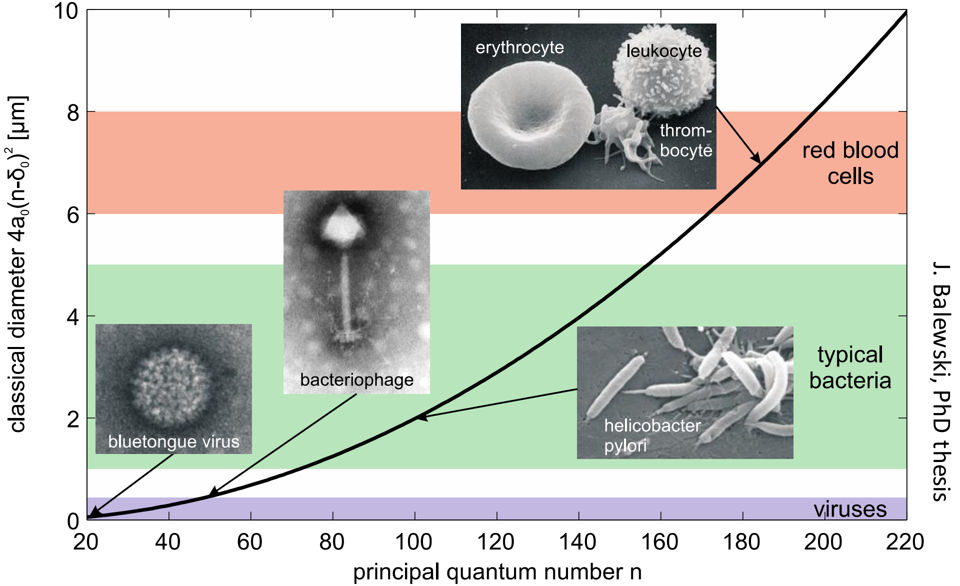


$$E_n = -\frac{R_y}{(n - \delta_{nlj})^2}$$

Quantum defects

(experimental)





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

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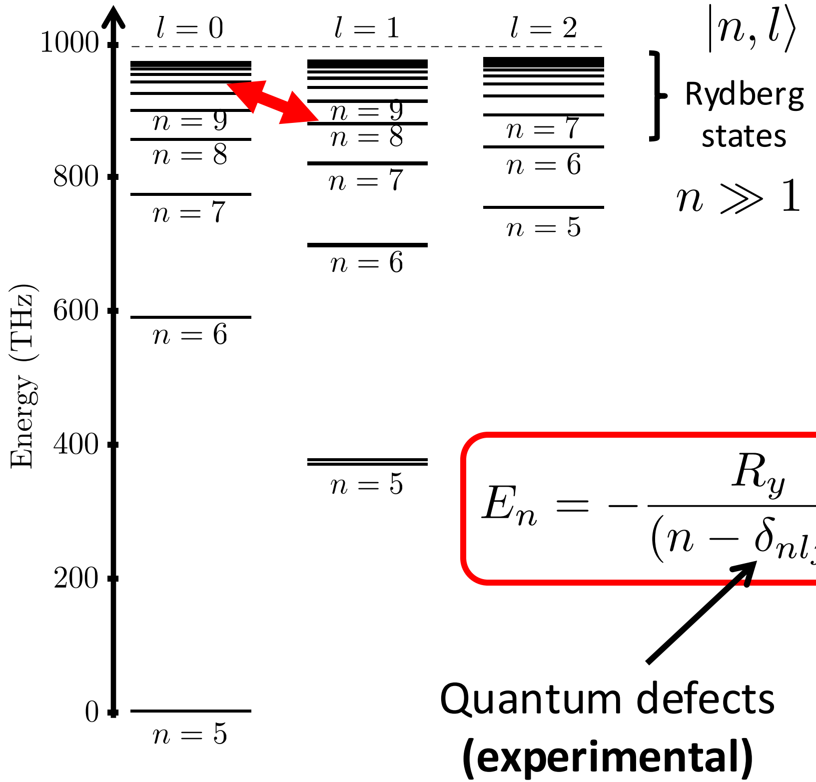

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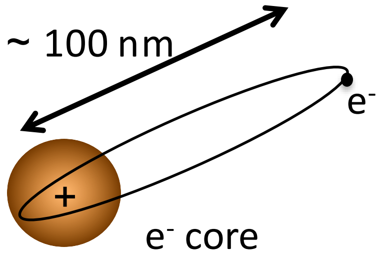
Quantum defects
(experimental)



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

$\Rightarrow$ $n > 60$, $\tau > 100\ \mu s$

Large transition dipole:

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

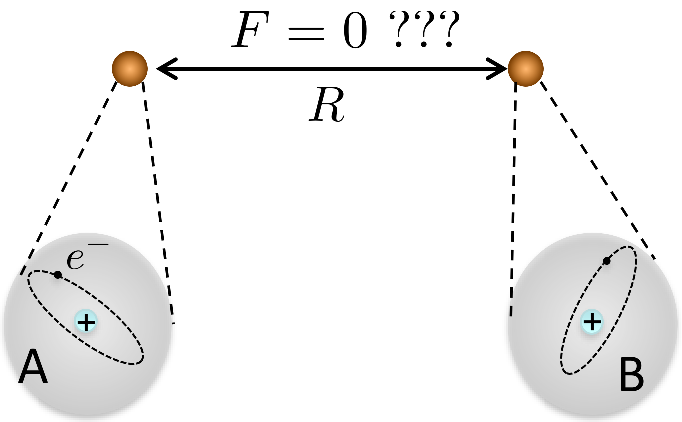
Large polarizability: $\alpha \sim n^7$

$\Rightarrow$ **Exaggerated properties:**

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

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

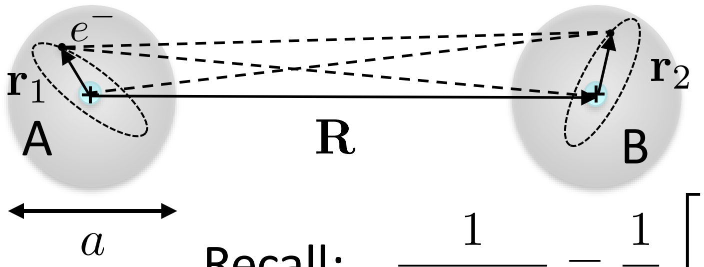
Dipolar Interaction between atoms



Dipolar Interaction between atoms

$$e^2 = \frac{q^2}{4\pi\epsilon_0}$$

$$H = \frac{p_1^2}{2m} - \frac{e^2}{r_1} + \frac{p_2^2}{2m} - \frac{e^2}{r_2}$$
$$- \frac{e^2}{|\mathbf{R} - \mathbf{r}_1|} - \frac{e^2}{|\mathbf{R} + \mathbf{r}_2|} + \frac{e^2}{|\mathbf{R} + \mathbf{r}_2 - \mathbf{r}_1|} + \frac{e^2}{R}$$



Recall: $$\frac{1}{|\mathbf{R} - \mathbf{r}|} = \frac{1}{R}\left[1 - \frac{\mathbf{r}\cdot\mathbf{R}}{2R^2} - \frac{r^2}{2R^2} + \frac{3}{2}\left(\frac{\mathbf{r}\cdot\mathbf{R}}{R^2}\right)^2\right] + \mathcal{O}\left(\frac{r^4}{R^4}\right)$$

Dipole-dipole interaction: $$H_{\rm dd} = \frac{1}{4\pi\epsilon_0 R^3}\left[\mathbf{d}_1\cdot\mathbf{d}_2 - 3(\mathbf{d}_1\cdot\mathbf{u})(\mathbf{d}_2\cdot\mathbf{u})\right]\ , \quad \mathbf{u} = \frac{\mathbf{R}}{R}$$

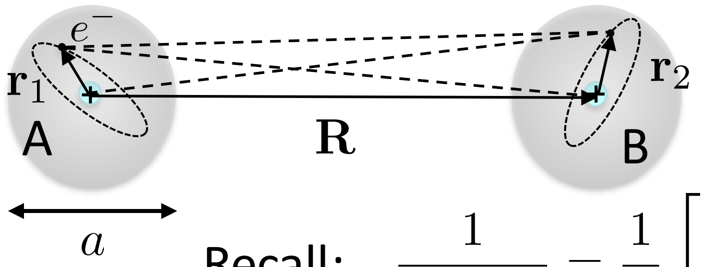
$a \ll R$

with dipoles: $$\mathbf{d}_{1,2} = q\,\mathbf{r}_{1,2}$$

Dipolar Interaction between atoms

$$e^2 = \frac{q^2}{4\pi\epsilon_0}$$

$$H = \frac{p_1^2}{2m} - \frac{e^2}{r_1} + \frac{p_2^2}{2m} - \frac{e^2}{r_2} - \frac{e^2}{|\mathbf{R}-\mathbf{r}_1|} - \frac{e^2}{|\mathbf{R}+\mathbf{r}_2|} + \frac{e^2}{|\mathbf{R}+\mathbf{r}_2-\mathbf{r}_1|} + \frac{e^2}{R}$$



Recall: $$\frac{1}{|\mathbf{R}-\mathbf{r}|} = \frac{1}{R}\left[1 - \frac{\mathbf{r}\cdot\mathbf{R}}{2R^2} - \frac{r^2}{2R^2} + \frac{3}{2}\left(\frac{\mathbf{r}\cdot\mathbf{R}}{R^2}\right)^2\right] + \mathcal{O}\left(\frac{r^4}{R^4}\right)$$

Dipole-dipole interaction: $$\hat{H}_{\mathrm{dd}} = \frac{1}{4\pi\epsilon_0 R^3}\left[\hat{\mathbf{d}}_1\cdot\hat{\mathbf{d}}_2 - 3(\hat{\mathbf{d}}_1\cdot\mathbf{u})(\hat{\mathbf{d}}_2\cdot\mathbf{u})\right] \;,\quad \mathbf{u} = \frac{\mathbf{R}}{R}$$

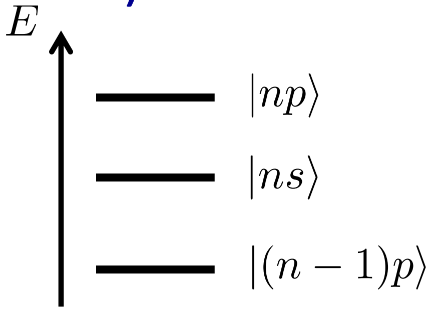
$a \ll R$

with dipoles: $$\hat{\mathbf{d}}_{1,2} = q\,\hat{\mathbf{r}}_{1,2}$$

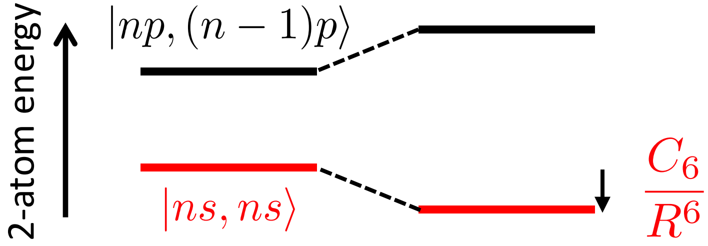
2 atom basis: $$\{|n,l,m\rangle \otimes |n',l',m'\rangle\}$$

Interactions between Rydberg atoms (simplified…)

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



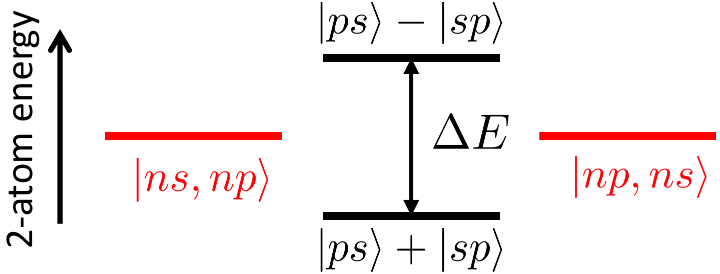
van der Waals regime



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

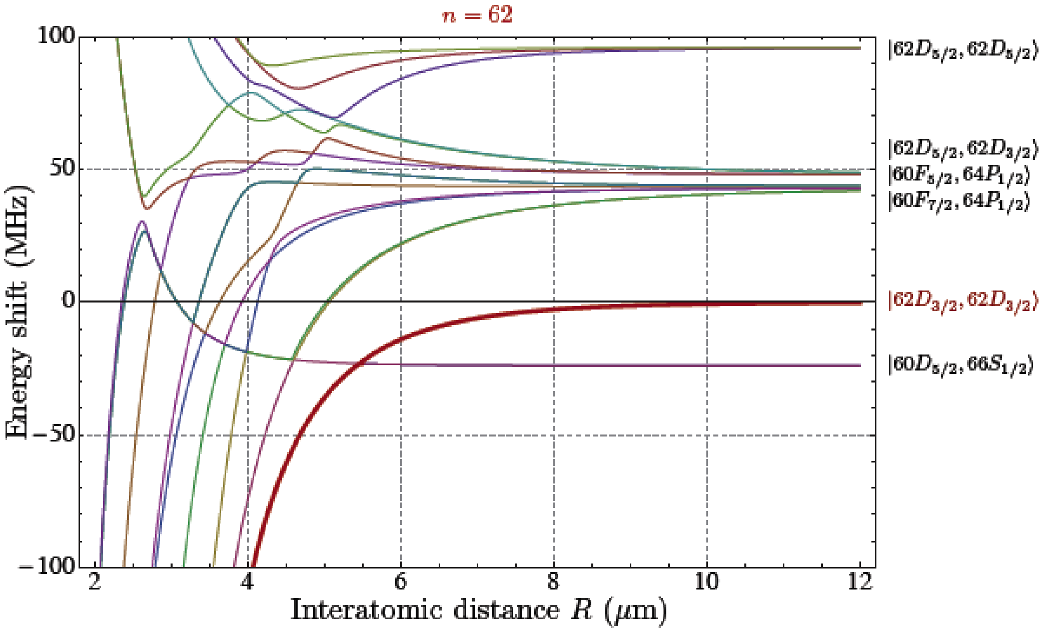
$$\propto \frac{d^4_{sp}}{E_{ss}-E_{pp}}\frac{1}{R^6} = \frac{C_6}{R^6} \qquad C_6 \propto n^{11}$$

Resonant regime



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

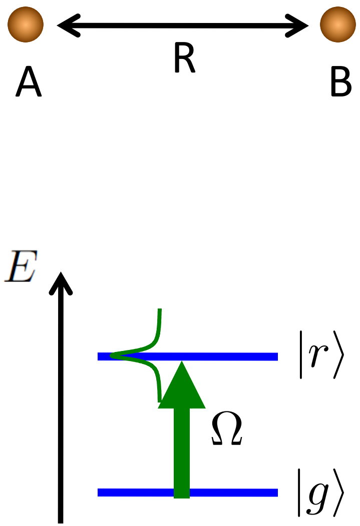
Interactions between “real” Rydberg atoms

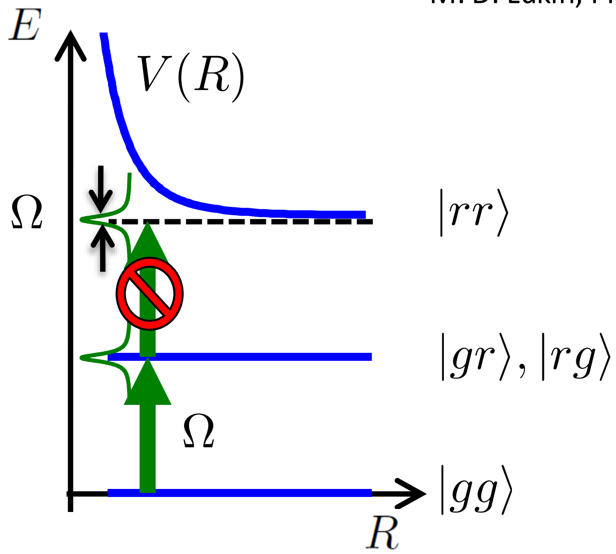


$R = 10\ \mu\text{m} \Rightarrow V_{\text{int}}/h \sim 1 - 10\ \text{MHz}$ **⇒ timescales < μsec**

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

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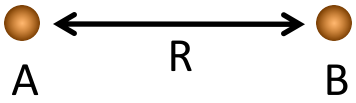

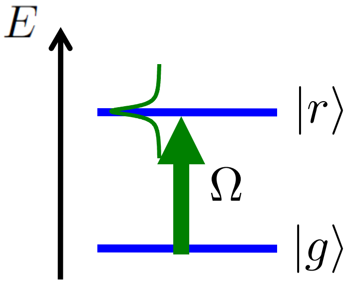

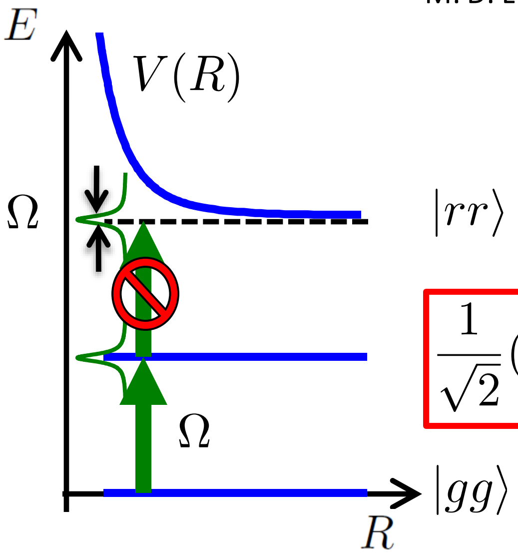

$$\frac{1}{\sqrt{2}}(|gr\rangle + |rg\rangle)$$

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

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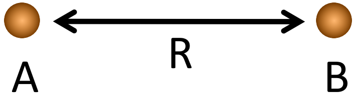
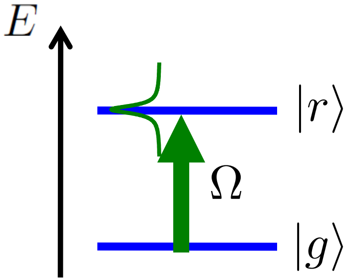
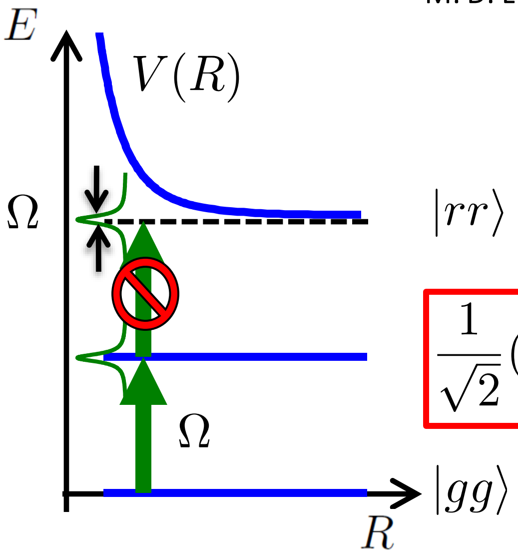
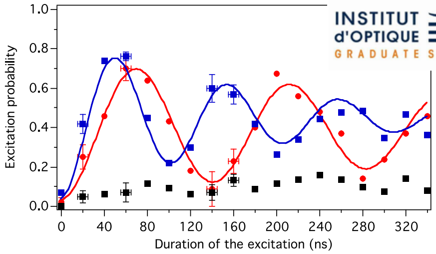




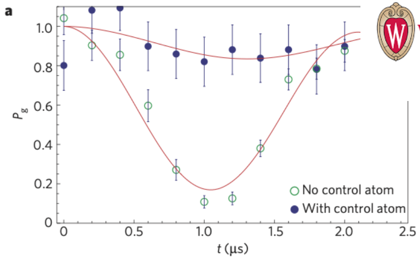


$$\frac{1}{\sqrt{2}}(|gr\rangle + |rg\rangle)$$

1st demonstrations of controlled Rydberg interactions

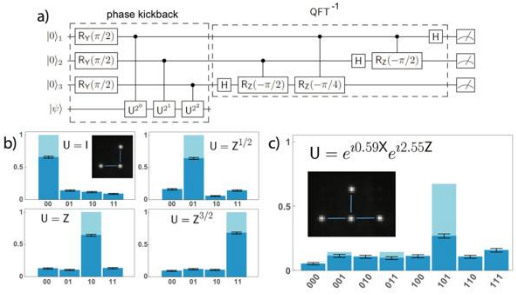


Nat. Phys. 2009

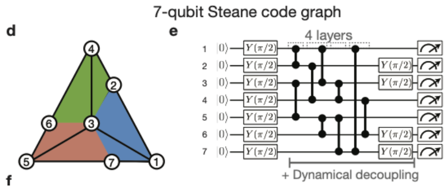


And now (2025)… a few examples

QIP: entanglement and gates



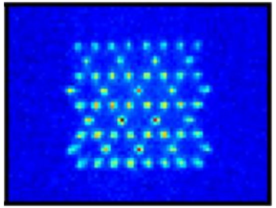
Saffman, Nature 2022

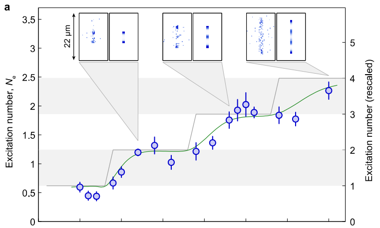


Lukin, Nature 2022-25

Saffman, RMP **82**, 2313 (2010)
Henriet, Quantum (2020)
Whitlock, AVS Quantum Science (2021)

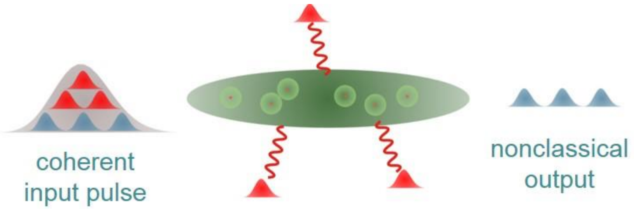
Many-body physics
Quantum simulation





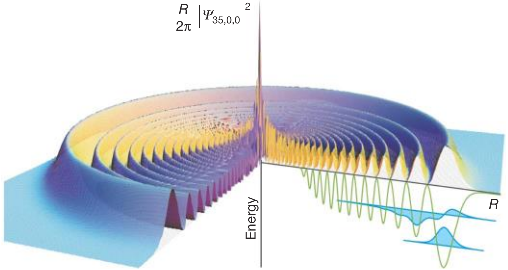
Schauss Quantum Sci. Techno 2018
Browaeys, Lahaye Nat. Phys. 2020

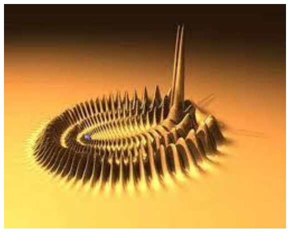
Non-linear classical & quantum optics



Firstenberg, J Phys. B (2016)

Exotic long-range molecules





Pfau, Nature 2009

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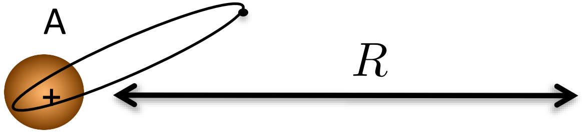
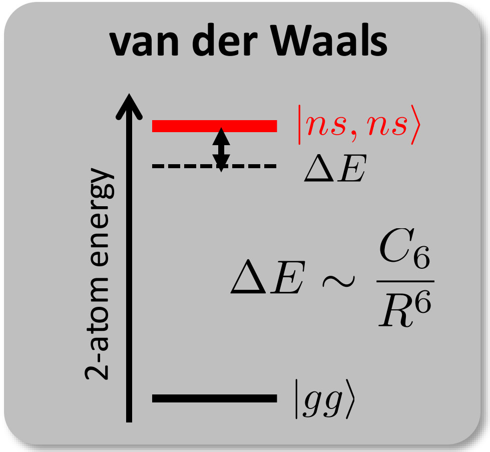
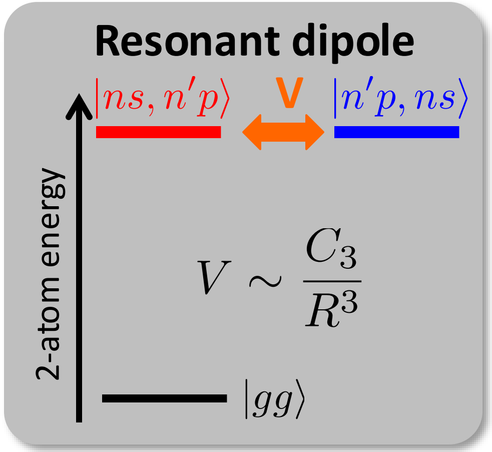
Interactions between Rydberg atoms and spin models

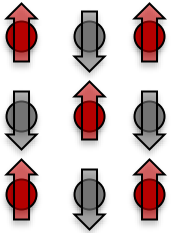


Browaeys & Lahaye, Nat.Phys. (2020)



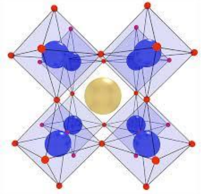


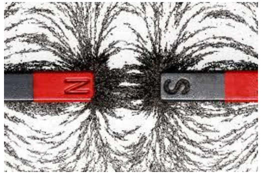
Spin 1/2



Ising model

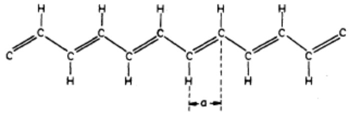
$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{n}_i \hat{n}_j$$



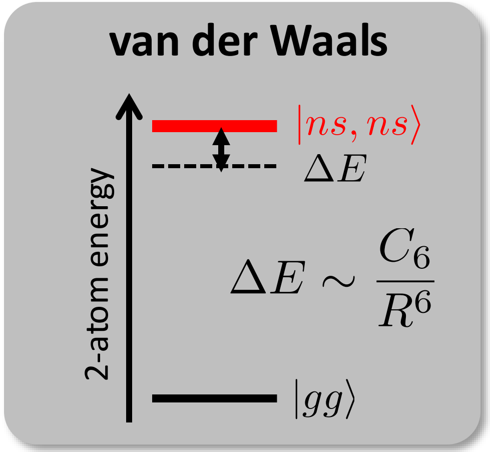


XY model

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



From van der Waals interaction to spin models…



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

Ground state: $n = 5$

Rydberg: $n = 50$

$\times 10^{11}$

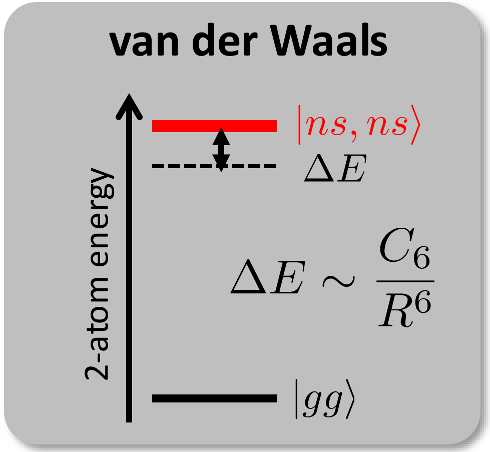
Ising - like!!

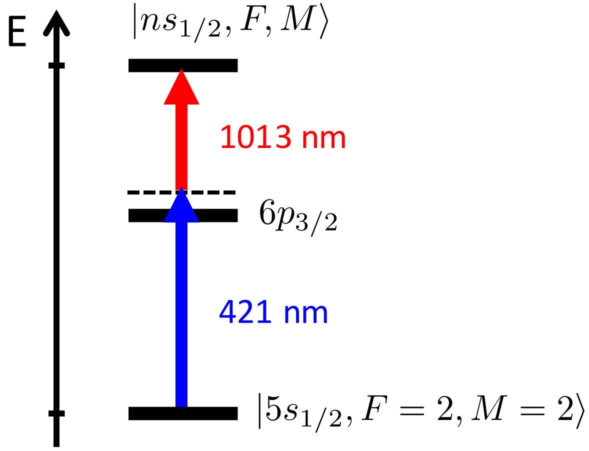
$$\hat{H}_{\text{int}} = \frac{C_6}{R^6} \hat{n}_1 \hat{n}_2 \sim J\, \hat{\sigma}_1^z \hat{\sigma}_2^z$$

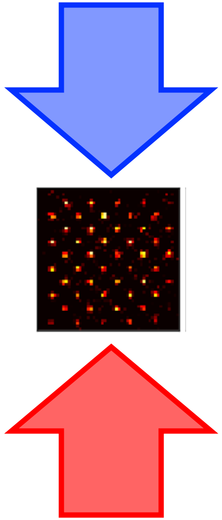
Rydberg $n_{1,2} = 1$

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

From van der Waals interaction to spin models…







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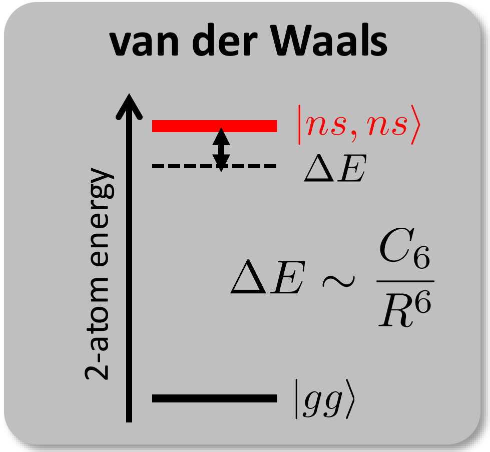
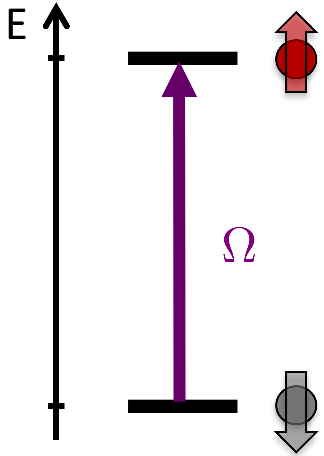
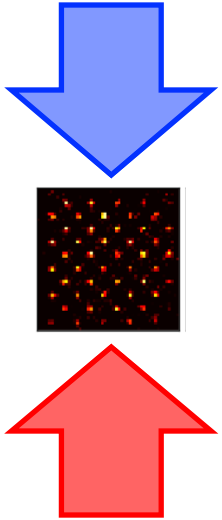
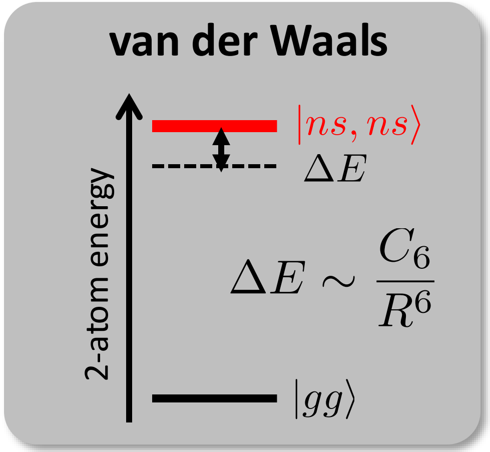
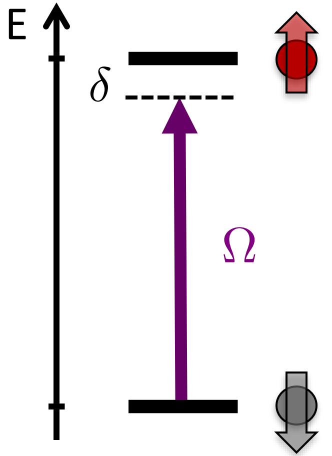


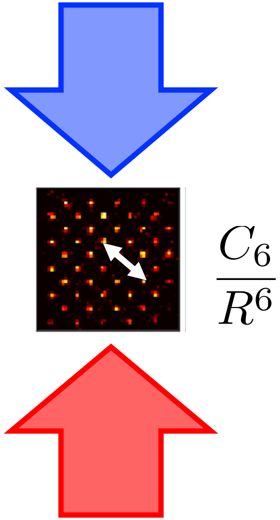




From van der Waals interaction to spin models…

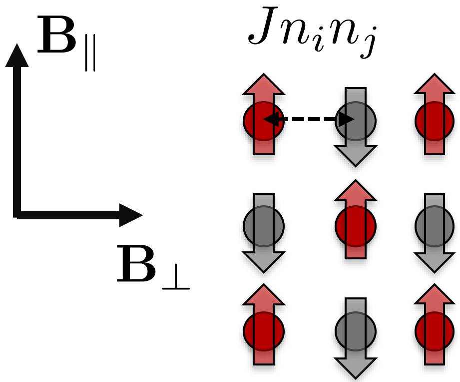




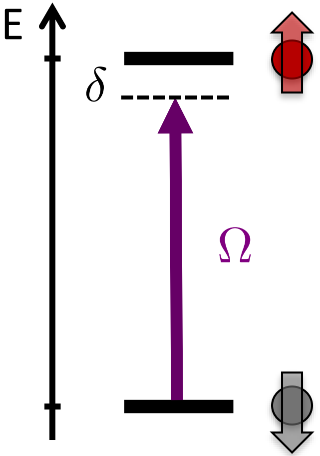


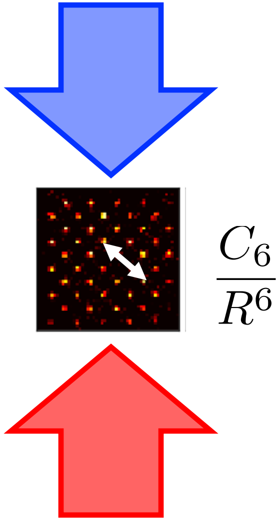
$$H = \frac{\hbar\Omega}{2}\sum_i \hat{\sigma}_x^i + \hbar\delta\sum_i \hat{\sigma}_z^i + \sum_{i<j}\frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

From van der Waals interaction to spin models…



$$\sim \mu B_{\perp}\hat{\sigma}_x + \mu B_{\parallel}\hat{\sigma}_z$$



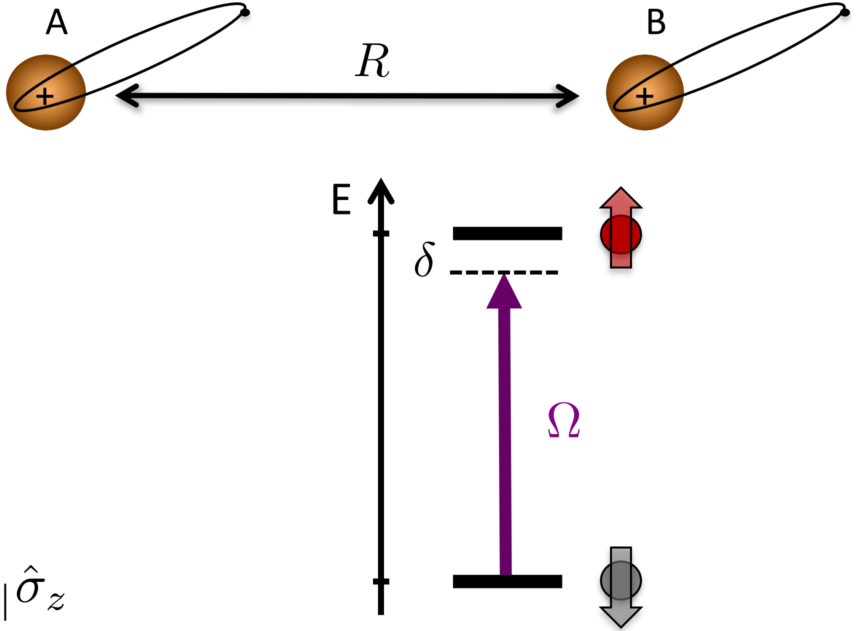


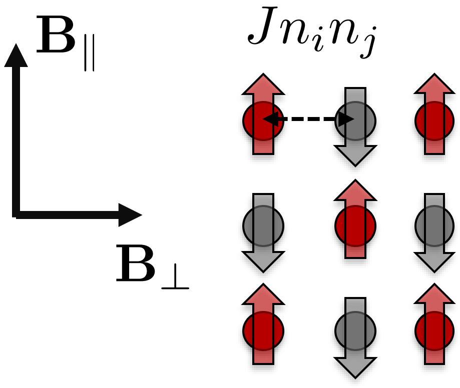
Transverse Field Ising model:

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

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

From van der Waals interaction to spin models…





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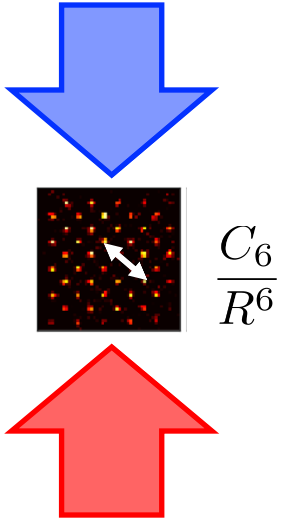

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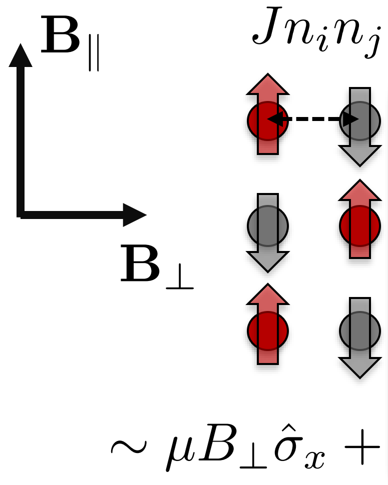
Laser: $B_\perp$ $B_\parallel$ spin-spin interactions

Controlled parameters:

From negligible to dominant interactions

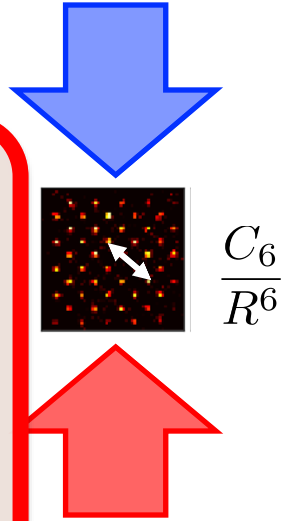
From van der Waals interaction to spin models…



Quantum simulation:

Emulate a system by another one

Similar equations lead to same solutions!!



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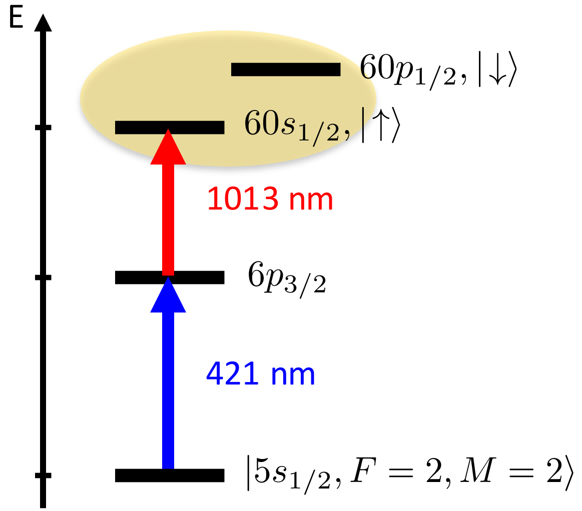
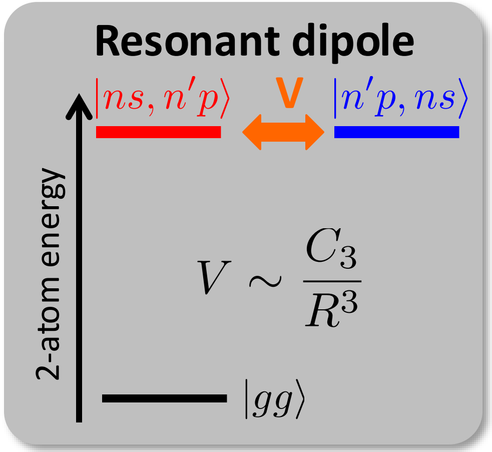
Resonant interaction between Rydbergs and XY spin model

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





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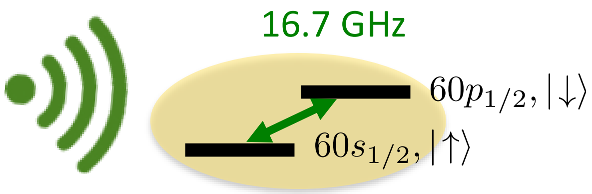

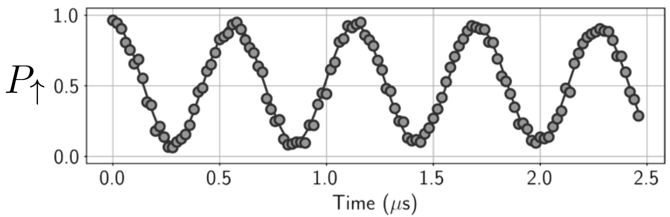

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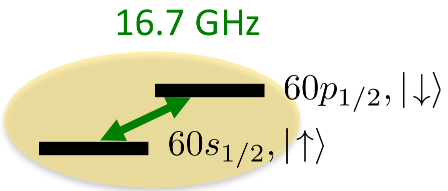
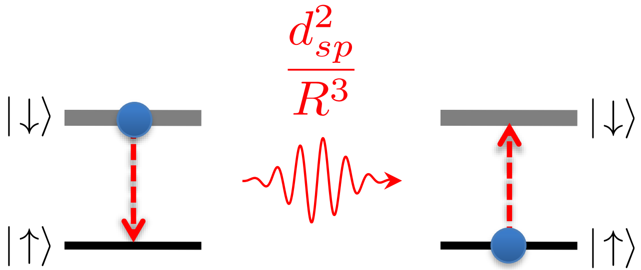
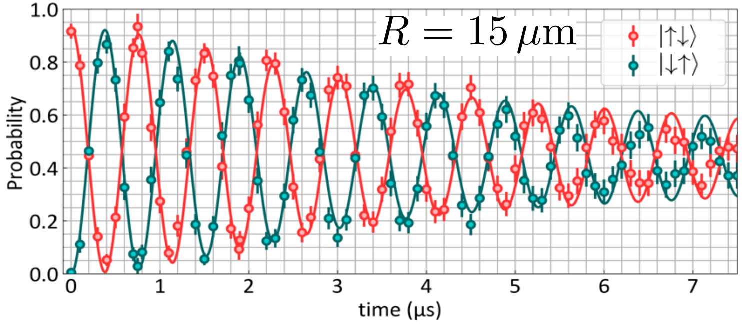




Non radiative "exchange" of excitation



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

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

Resonant interaction between Rydbergs and XY spin model

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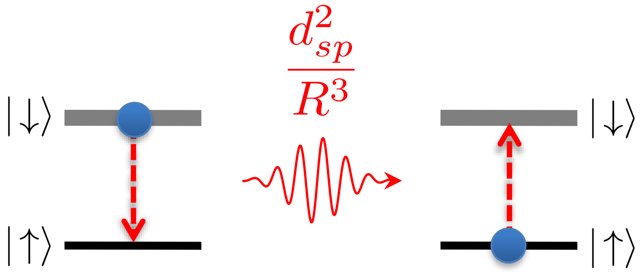
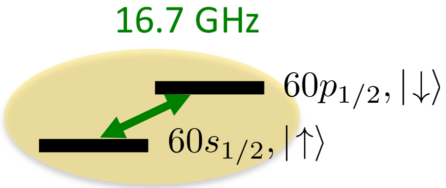
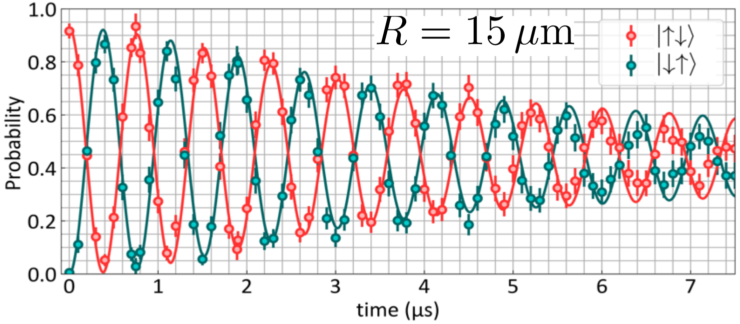
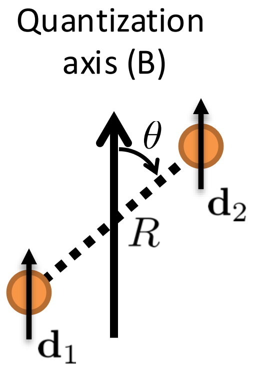
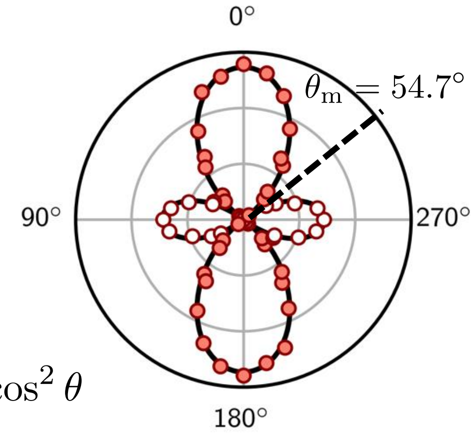


Non radiative "exchange" of excitation







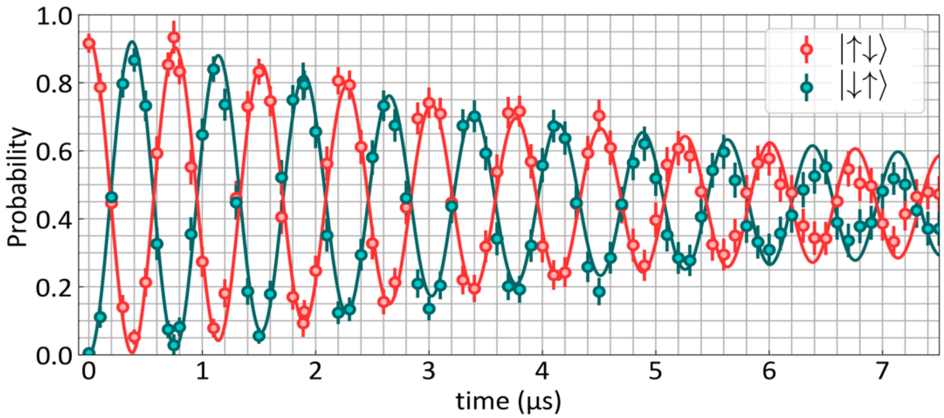


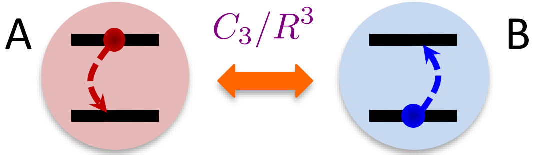
$$C_3(\theta) \propto 1 - 3\cos^2\theta$$

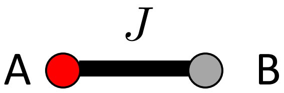
$$\hat{H}_{XY} = \frac{C_3}{R_{ij}^3}(\hat{\sigma}_i^+\hat{\sigma}_j^- + \hat{\sigma}_i^-\hat{\sigma}_j^+)$$

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

XY spin model and transport of excitations







Particle hopping

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

Outline – Lecture 1

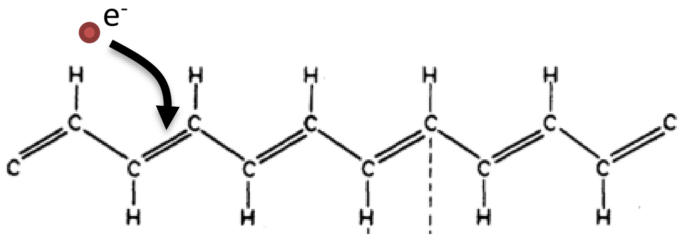
1. Arrays of individual atoms in optical tweezers

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

The Su-Schrieffer-Heeger model



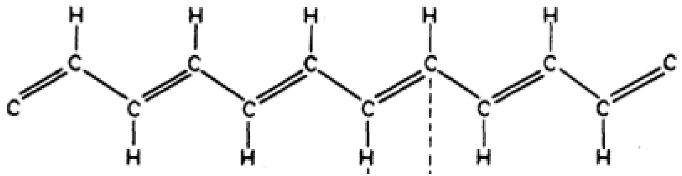
Electronic transport in polyacetylene

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



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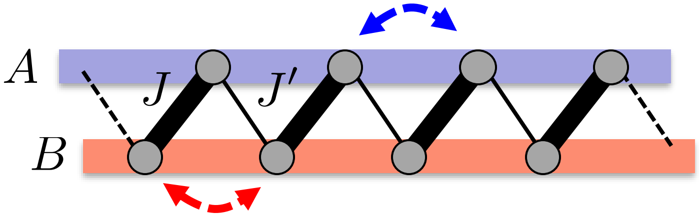


Model: tight-binding

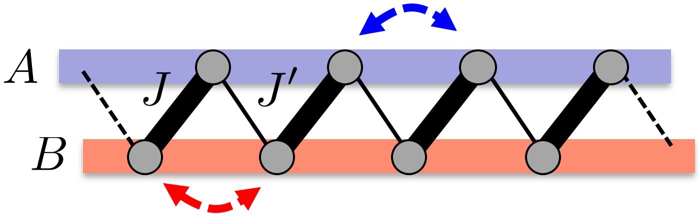
dimerization: $J > J'$

$J'' = 0$: **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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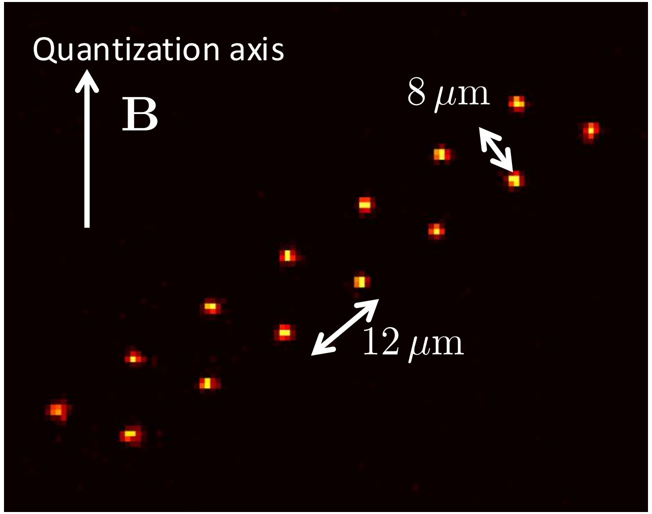

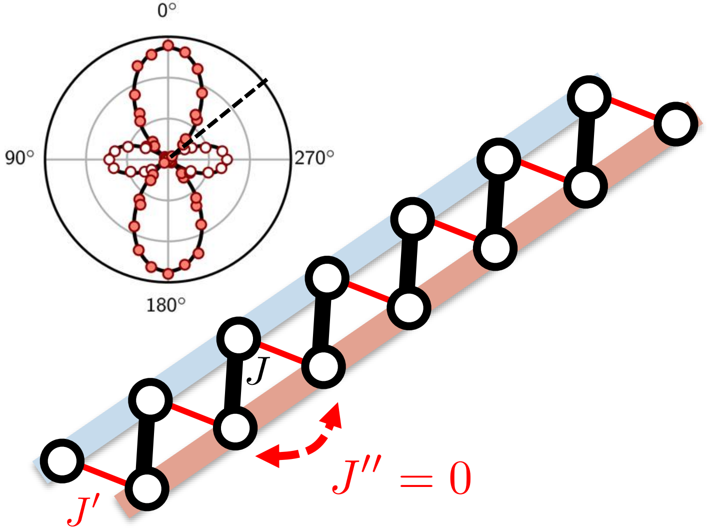

Asboth, arXiv:1509.02295

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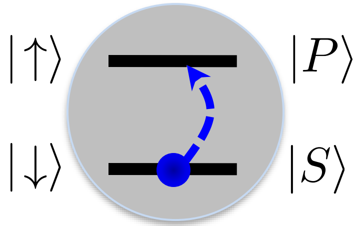
Spin excitations interact: hard core bosons

Spin excitation = "particle"

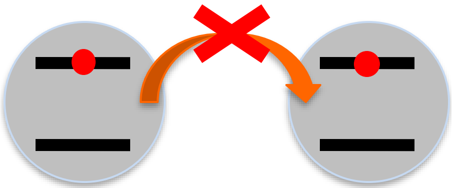


$$\hat{\sigma}^+ \to \hat{b}^\dagger \;,\; b^\dagger|0\rangle = |1\rangle$$

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

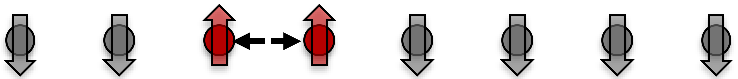
$$[\hat{b}_i, \hat{b}_j^\dagger] = \delta_{ij}$$

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



On-site interaction $U \to \infty$

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



$\Rightarrow$The first symmetry protected topological phase...

Predicted in 2012

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

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