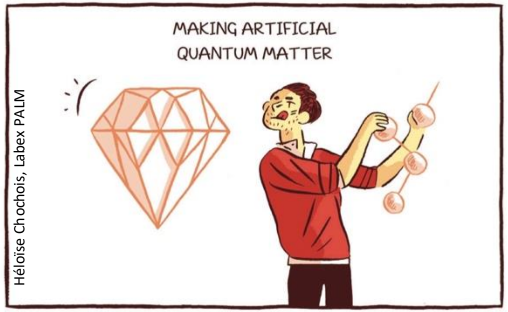
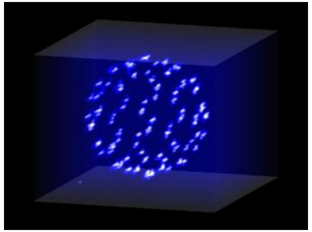
Exploring many-body physics with arrays of Rydberg atoms

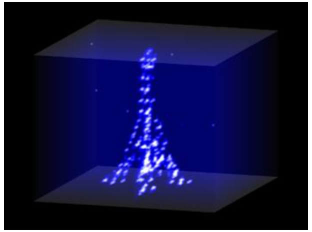


Antoine Browaeys

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

Benasque School, february 17-21, 2025





The program

Lecture 1: Many-body problem and quantum simulation
Arrays of atoms & “Rydbergology”
Interactions between atoms

Lecture 2: Rydberg Interactions and spin models
Engineering many-body Hamiltonians

Lecture 3: Examples of quantum simulations in
and out-of-equilibrium: quantum magnetism

Outline – Lecture 1

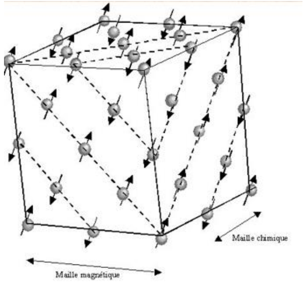
1. Many-body physics and quantum simulation
2. Arrays of individual atoms in optical tweezers
3. Basics of Rydberg physics
4. Interaction between Rydberg atoms

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: $i\hbar \frac{\partial \Psi}{\partial t} = H_{\rm tot} \Psi$

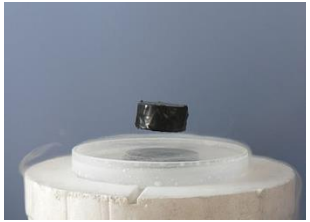
$$H_{\rm tot} = \sum_{i=1}^{N} -\frac{\hbar^2}{2m_i}\nabla_i^2 + \sum_{i=1}^{N}\sum_{j\neq i} \frac{q_i q_j}{r_{ij}} + \frac{\mu_{\rm B}^2}{r_{ij}^3}\mathbf{s}_i \cdot \mathbf{s}_j$$

Very, very, very well known…

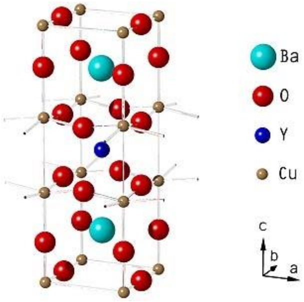
Problem: $N \approx 10^{23}$!!!

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*

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

Too hard to calculate...

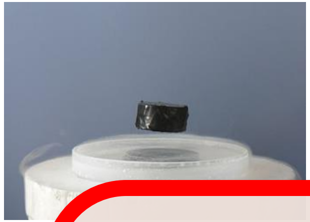
Problem: exponential complexity

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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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

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

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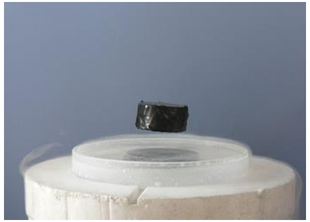

wikipedia

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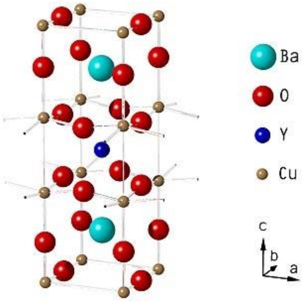

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Lab…

Quantum simulation =
Engineered system ruled by H_{model}

Measure on simulator:
Supercond. or not?

The original idea…

R.P. Feynman

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 universal computer that can do anything, and it doesn't make much difference specifically how it's designed. The same way we should try to find

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

Georgescu, Rev. Mod. Phys. (2014)

Digital

H_{model} synthesized digitally

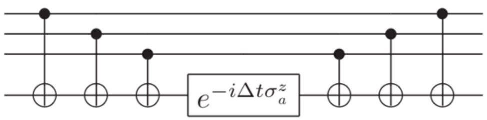
$$H_{\text{mod}} = \sum_{n=1}^{N} H_n$$

e.g. single & 2-qbit operations

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

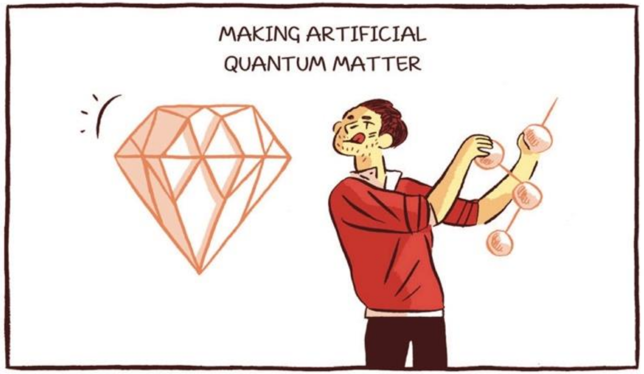
= "universal" quantum simulation

Ex:



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

Analog Quantum Simulation with synthetic systems



Héloïse Chochois, Labex PALM

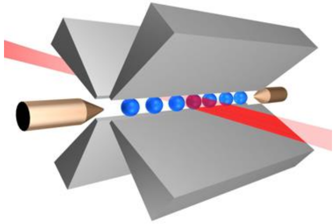
Georgescu, Rev. Mod. Phys. (2014)

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

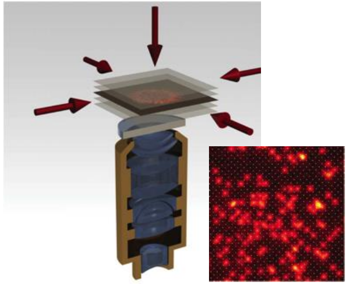
Larger tunability than "real" systems (geometry, interactions…)
Separate effects (impurities, role interactions…)
New types of probe & methods (e.g. out-of-equilibrium)

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

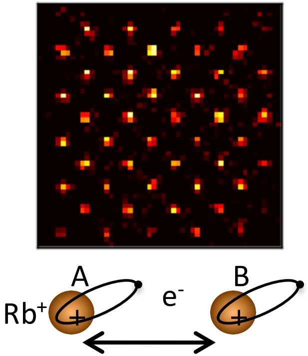
Engineering with individual quantum systems (examples)



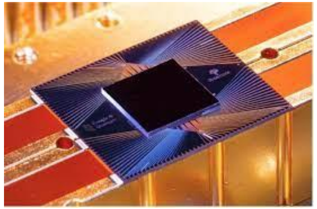
Trapped ions



Atoms in optical lattices



Atoms in tweezer arrays



Supercond. Circuits

IBM, Google…

Scalable: beyond 100 particles ; potential > 1000

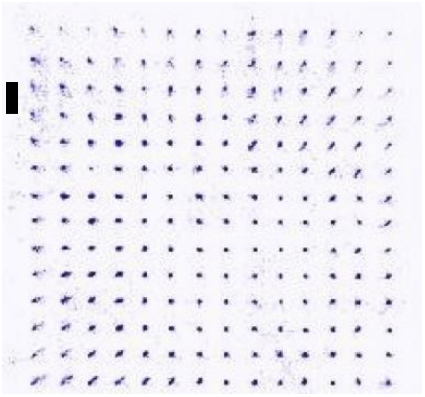
Addressability: local manipulations and measurement

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

Programmable: controlled geometry, interactions…

These lectures: combining arrays of atoms and Rydberg interactions

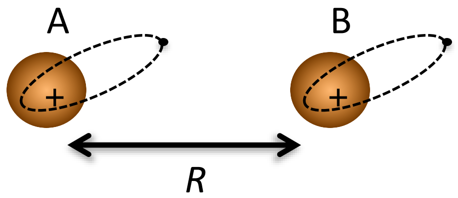
5 µm



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

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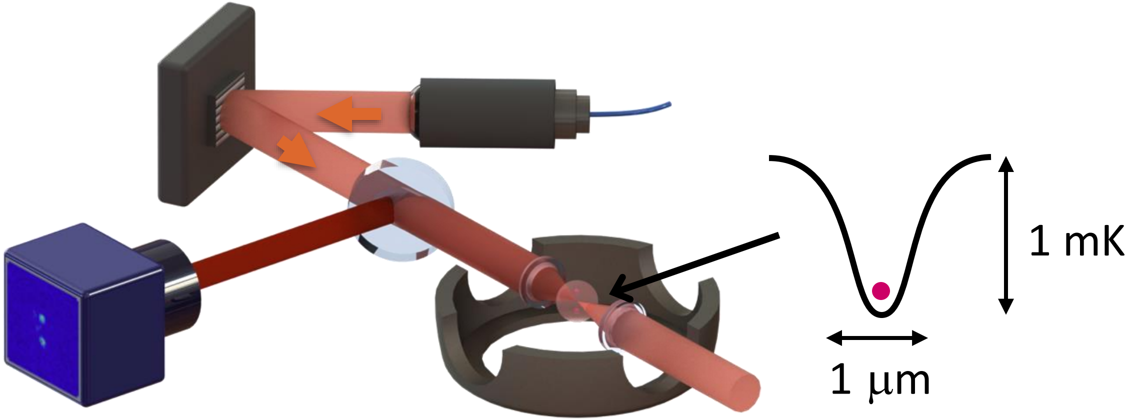
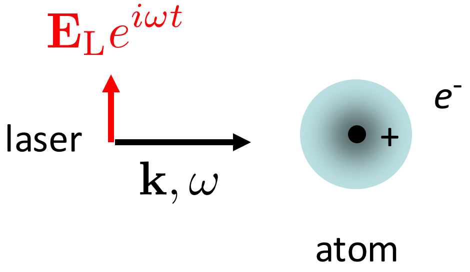
A single Rb atom in an optical tweezer

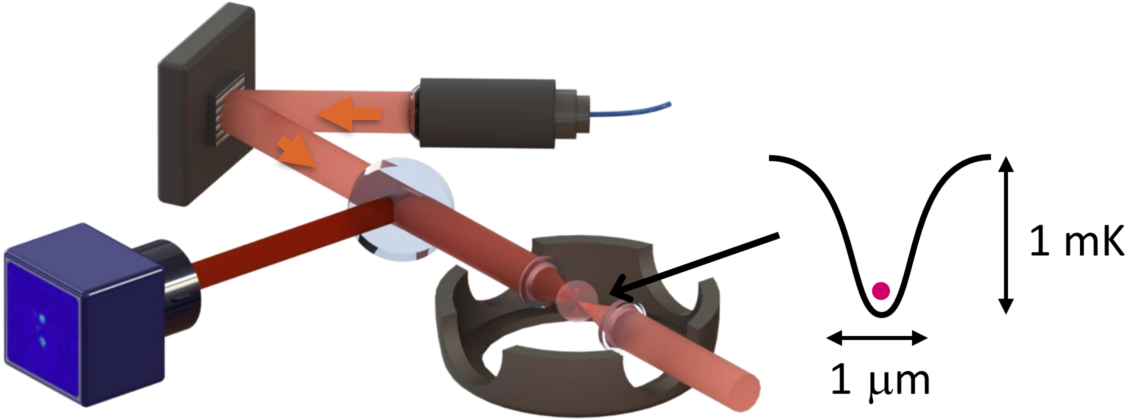


Grangier (2001)
Sortais (2007)

Dipole force



A single Rb atom in an optical tweezer

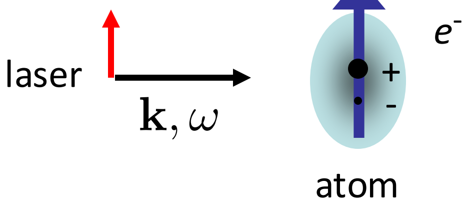


Grangier (2001)
Sortais (2007)

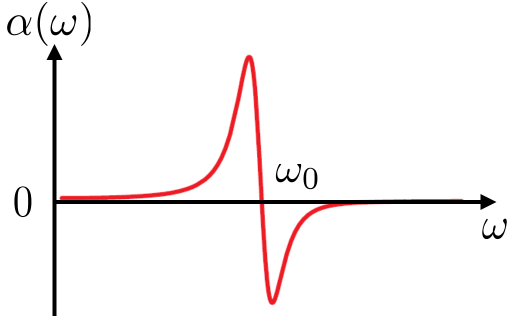
Dipole force

$\mathbf{d} = \alpha \mathbf{E}_\mathrm{L}$

$\mathbf{E}_\mathrm{L} e^{i\omega t}$



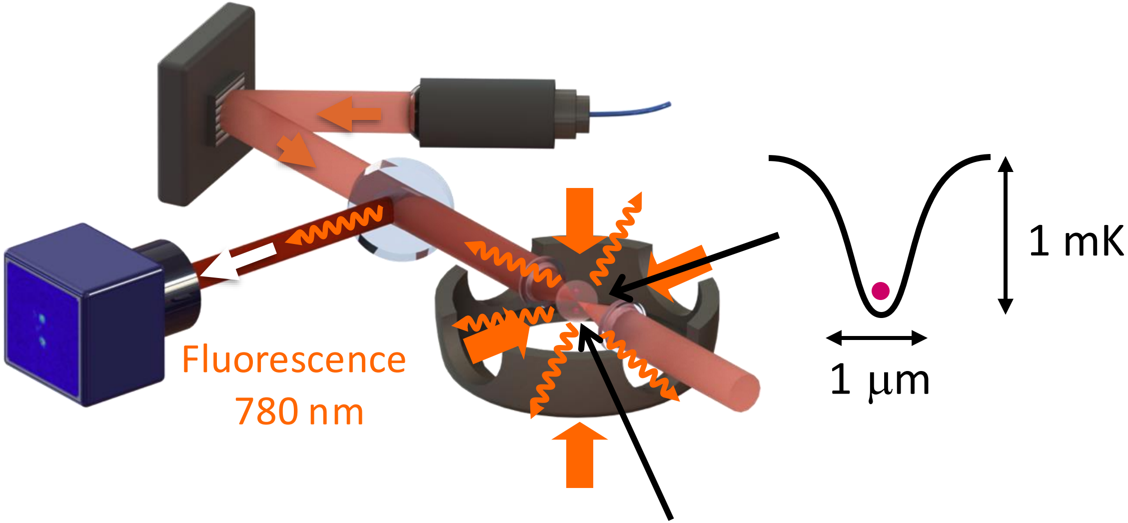
$$U = -\frac{1}{2}\langle \mathbf{d} \cdot \mathbf{E}_\mathrm{L} \rangle = -\frac{1}{2}\alpha \langle \mathbf{E}_\mathrm{L}^2 \rangle$$



$\omega < \omega_0 \Rightarrow$ 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



Grangier (2001)
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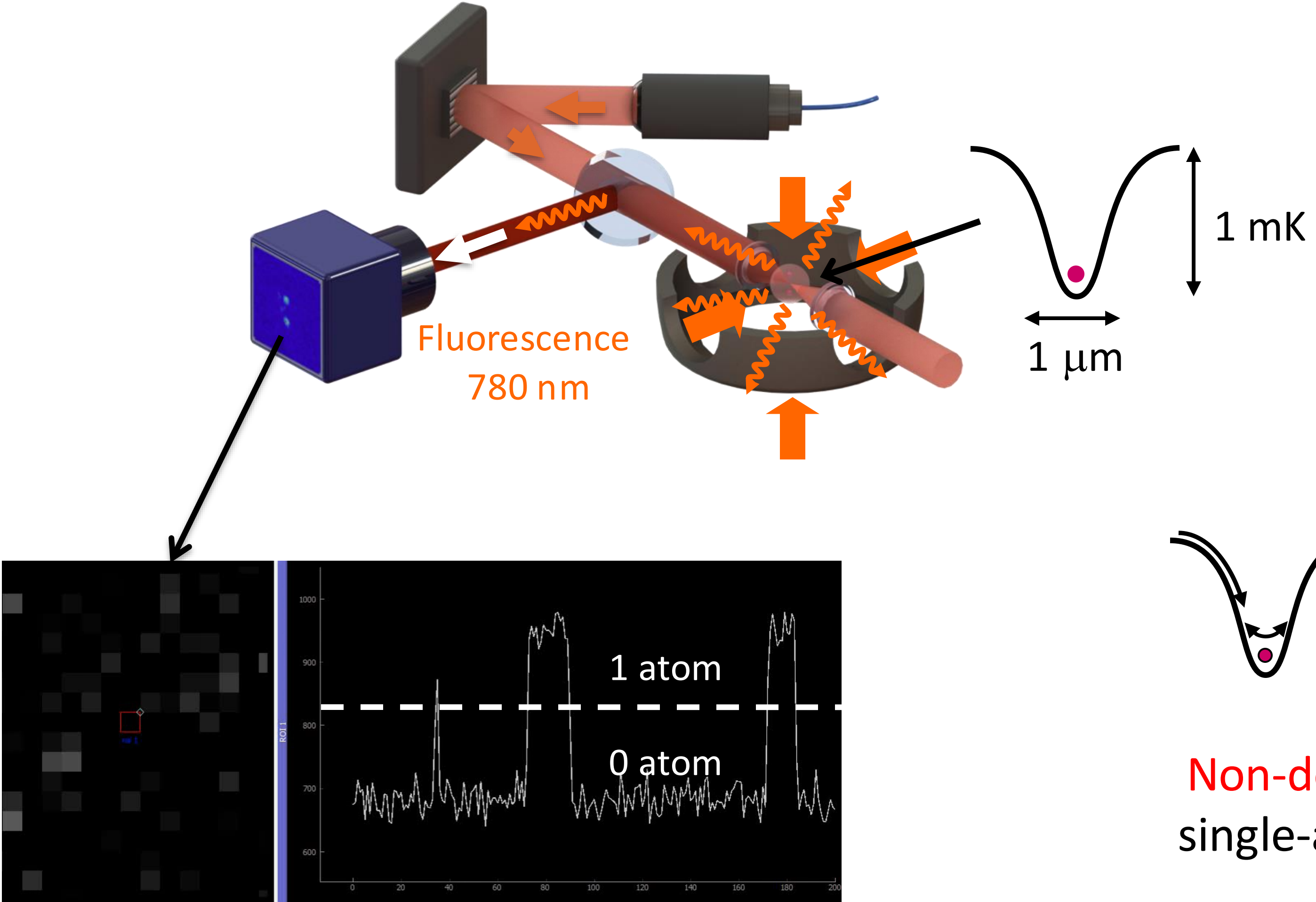
Reservoir = laser-cooled Rb atoms
T ~ 100 μK

A single Rb atom in an optical tweezer



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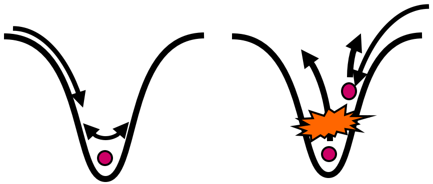
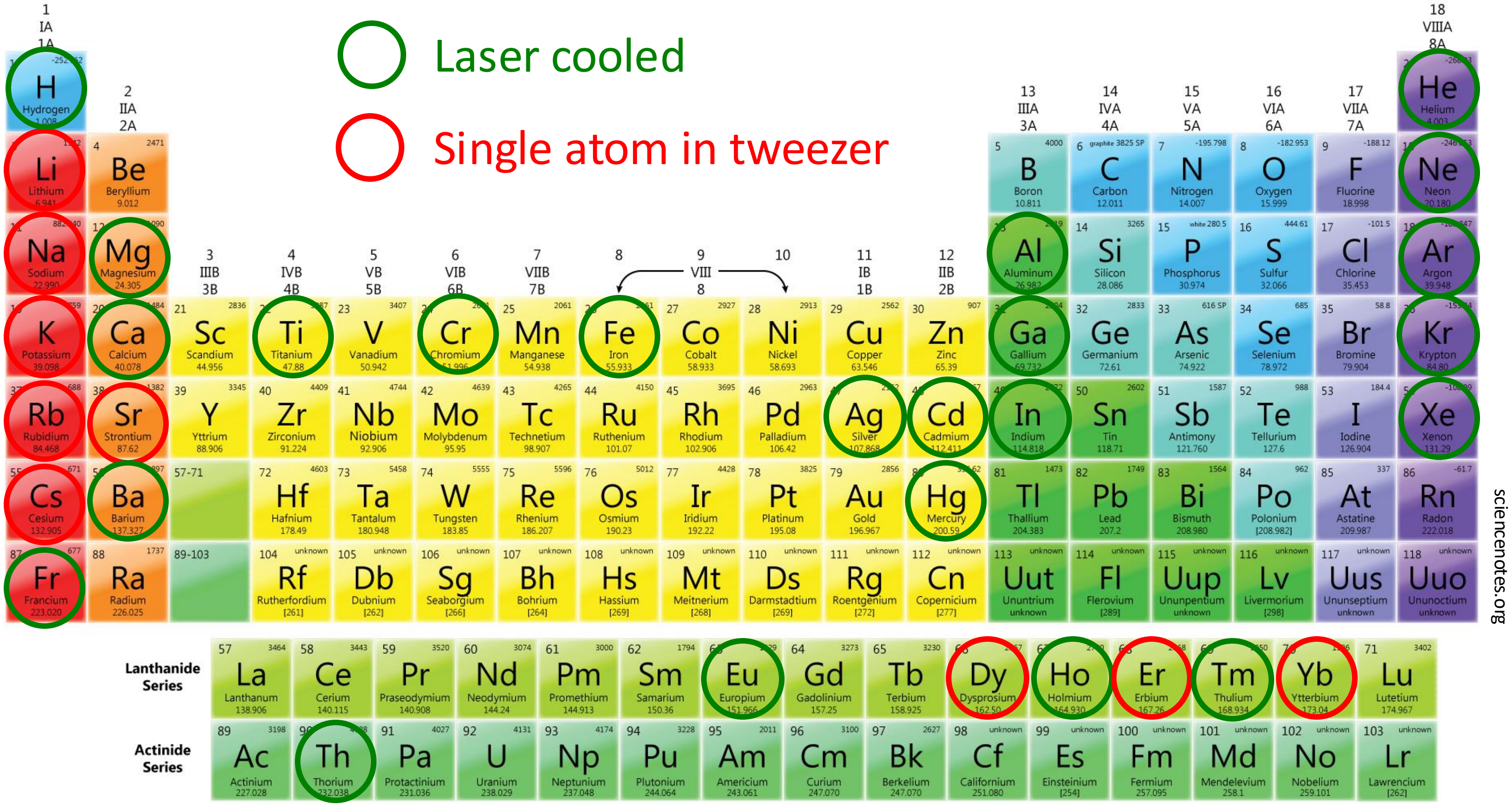


Non-deterministic
single-atom source

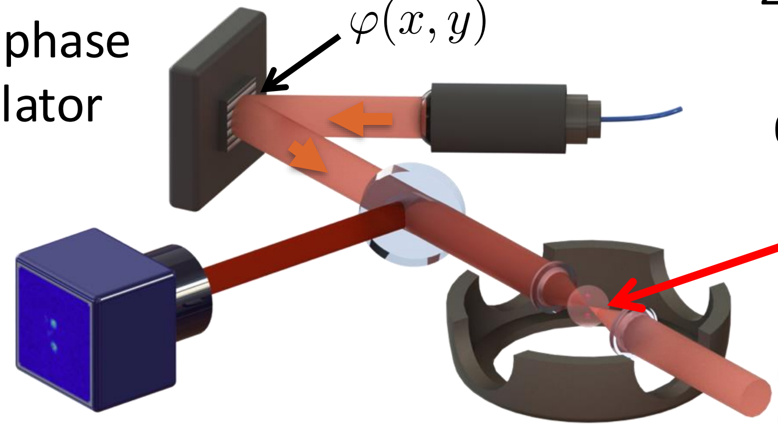
Single-atom trapping zoo (2024)

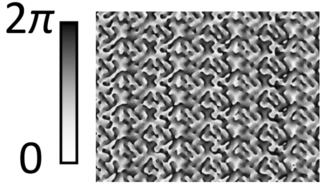


Atoms in arrays of optical tweezers

Spatial phase modulator

$\varphi(x,y)$

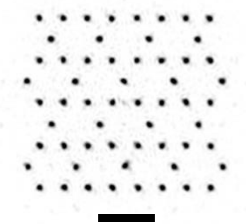




Phase mask

Nogrette, PRX (2014)

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



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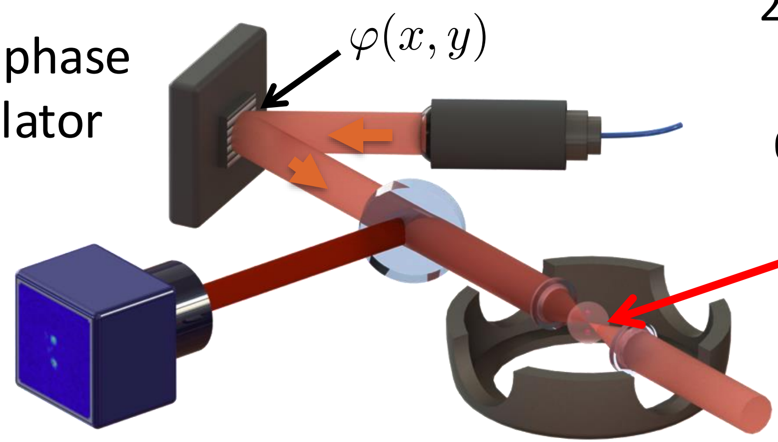
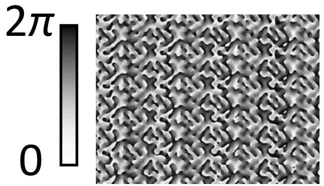




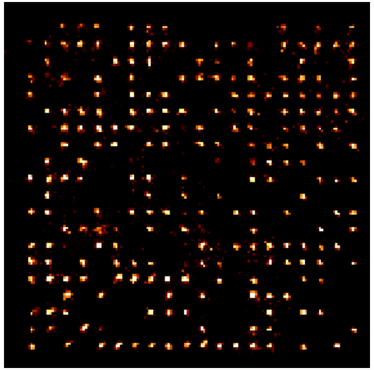
Phase mask

Nogrette, PRX (2014)

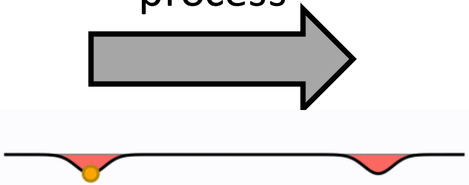
$$\left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$

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

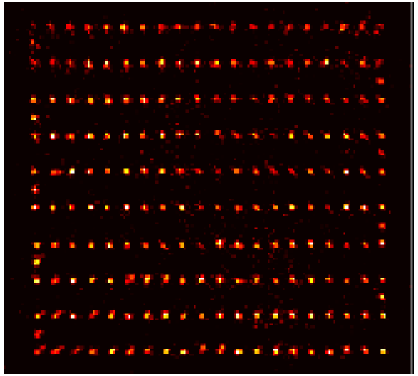
Initial configuration



Assembling process

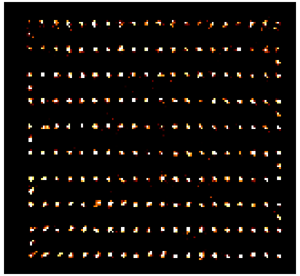


Assembled configuration



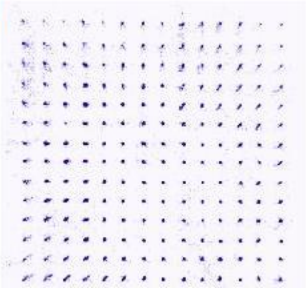
Atoms in arrays of optical tweezers (single-shot images)

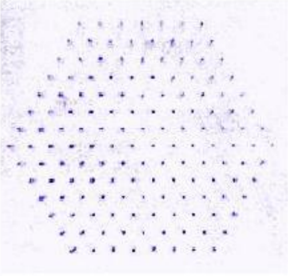
1D

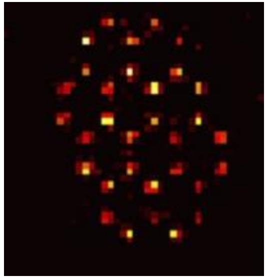


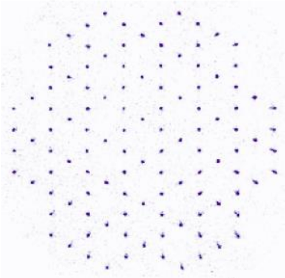
$\sim 100\ \mu m$

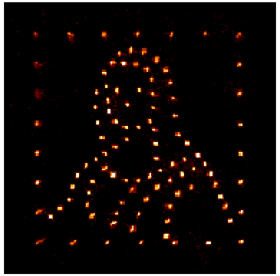
2D









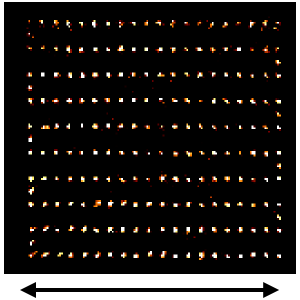


L. da Vinci

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

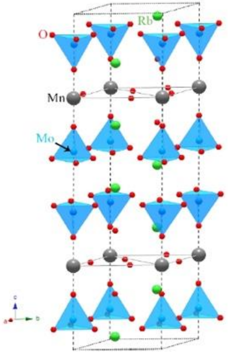
Atoms in arrays of optical tweezers (single-shot images)

1D



~100 μm

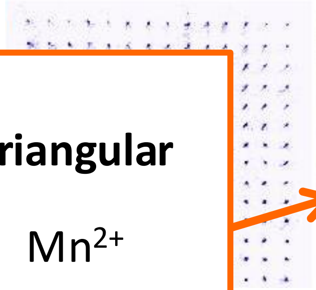
2D

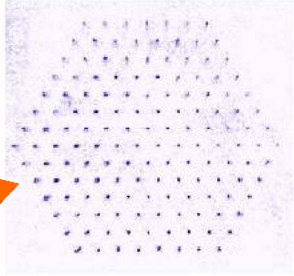


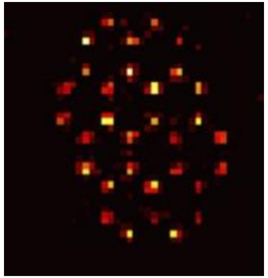
Triangular

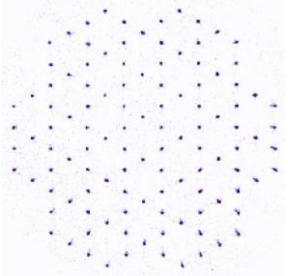
Mn^{2+}

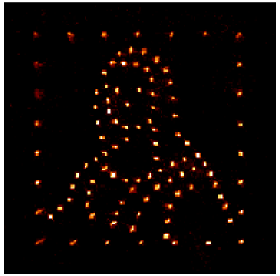
$Rb_4Mn(MoO_4)_3$





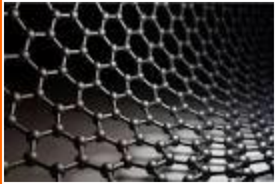






L. da Vinci

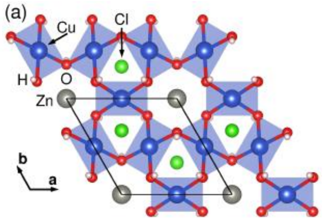
Hexagonal



graphene

Kagome: Herbertsmithite

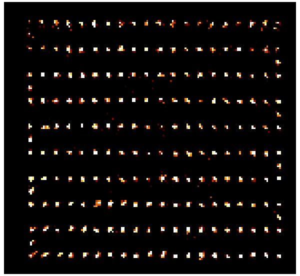
$ZnCu_3(OH)_6Cl_2$



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

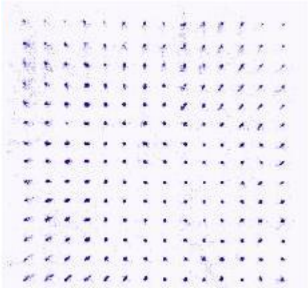
Atoms in arrays of optical tweezers (single-shot images)

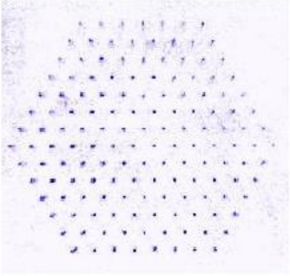
1D



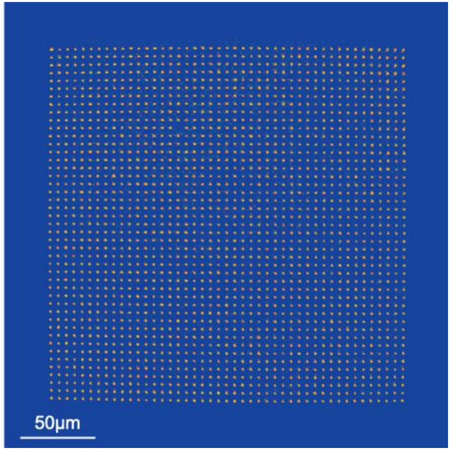
~100 μm

2D





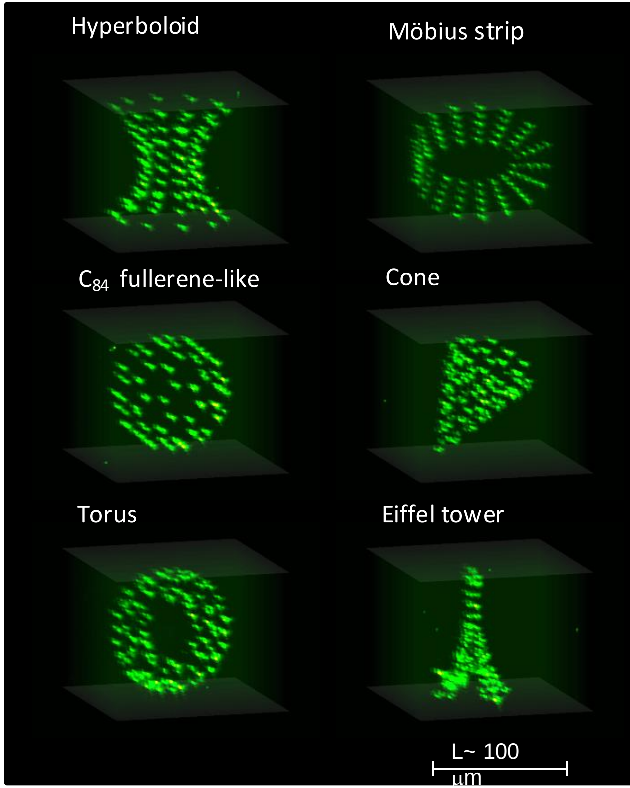
2024 atoms (AI + fast SLM)

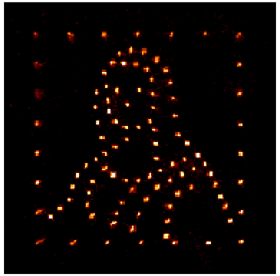


arXiv:2412.14647

3D

Barredo, Nature (2018)





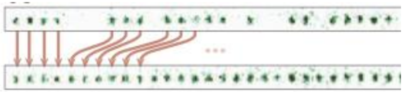
L. da Vinci

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

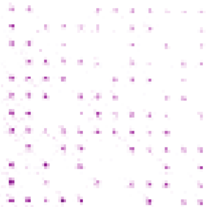
Also: Weiss, Nature (2018); Ahn, Opt. Exp (2016)

Now a popular platform…with many developments

Variants & new species



Lukin Science 2016

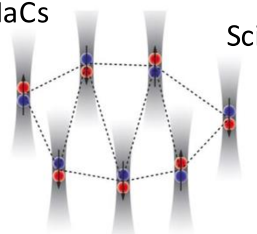


Yb, Sr

Endres, Kaufman, Thompson…

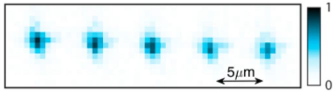
Trapping molecules

NaCs



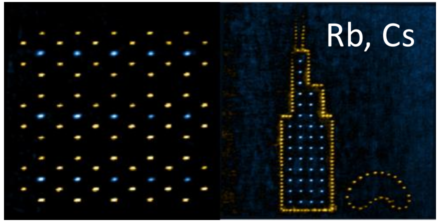
K-K Ni
Science 2018,
PRX 2019

CaF

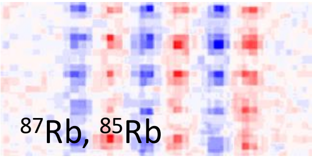


Ni, Doyle, Science 2019

Dual species arrays

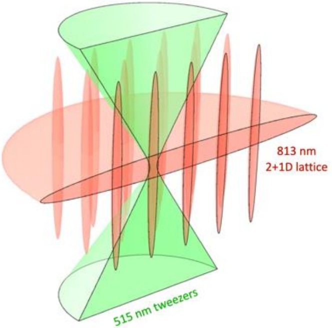


H. Bernien PRX 2022

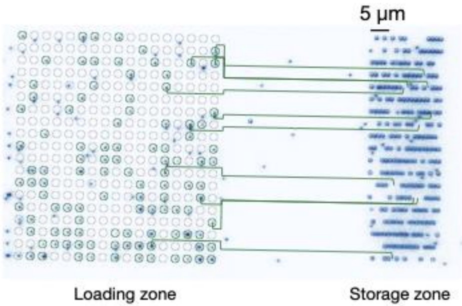


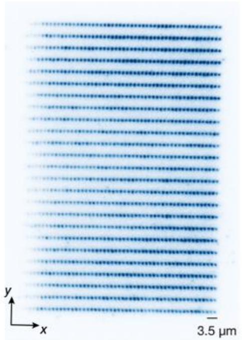
Zhan
PRL 2022

Combining optical lattices + tweezer array



A. Kaufman Science 2022

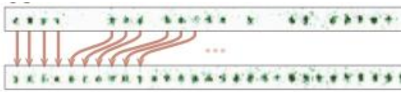




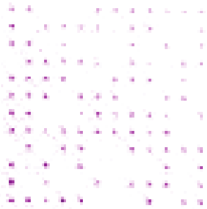
arXiv:2402.04994

Now a popular platform…with many developments

Variants & new species



Lukin Science 2016



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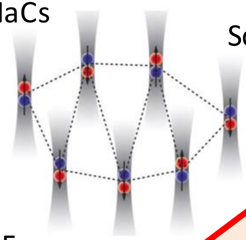

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…2019

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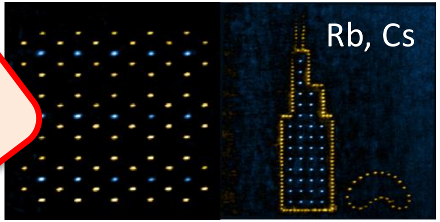
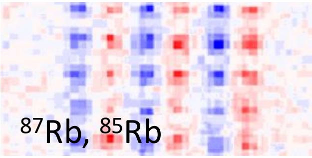


H. Bernien PRX 2022

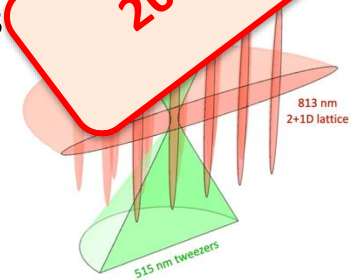


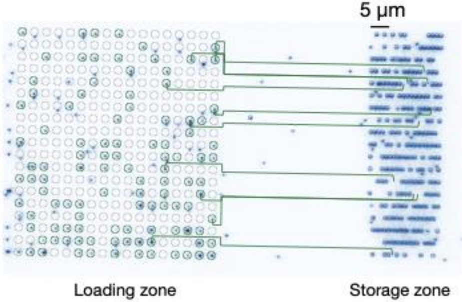
Zhan
PRL 2022

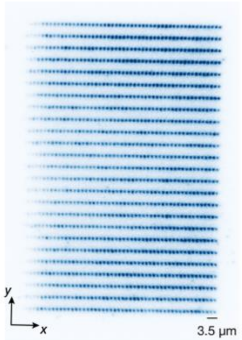
200+ in construction worldwide…

Combining optical lattices + tweezer array

A. Kaufman Science 2022







arXiv:2402.04994

Outline – Lecture 1

1. Many-body physics and synthetic quantum systems

2. Arrays of individual atoms: lattices and tweezers

3. Basics of Rydberg physics

4. Interaction between Rydberg atoms

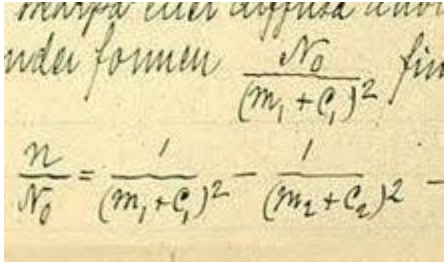
Rydberg atoms: the discovery

1814 Joseph von Fraunhofer

observation of dark lines in spectrum of the sun

1888 "Rydberg formula"

Johannes Rydberg
1854-1919



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

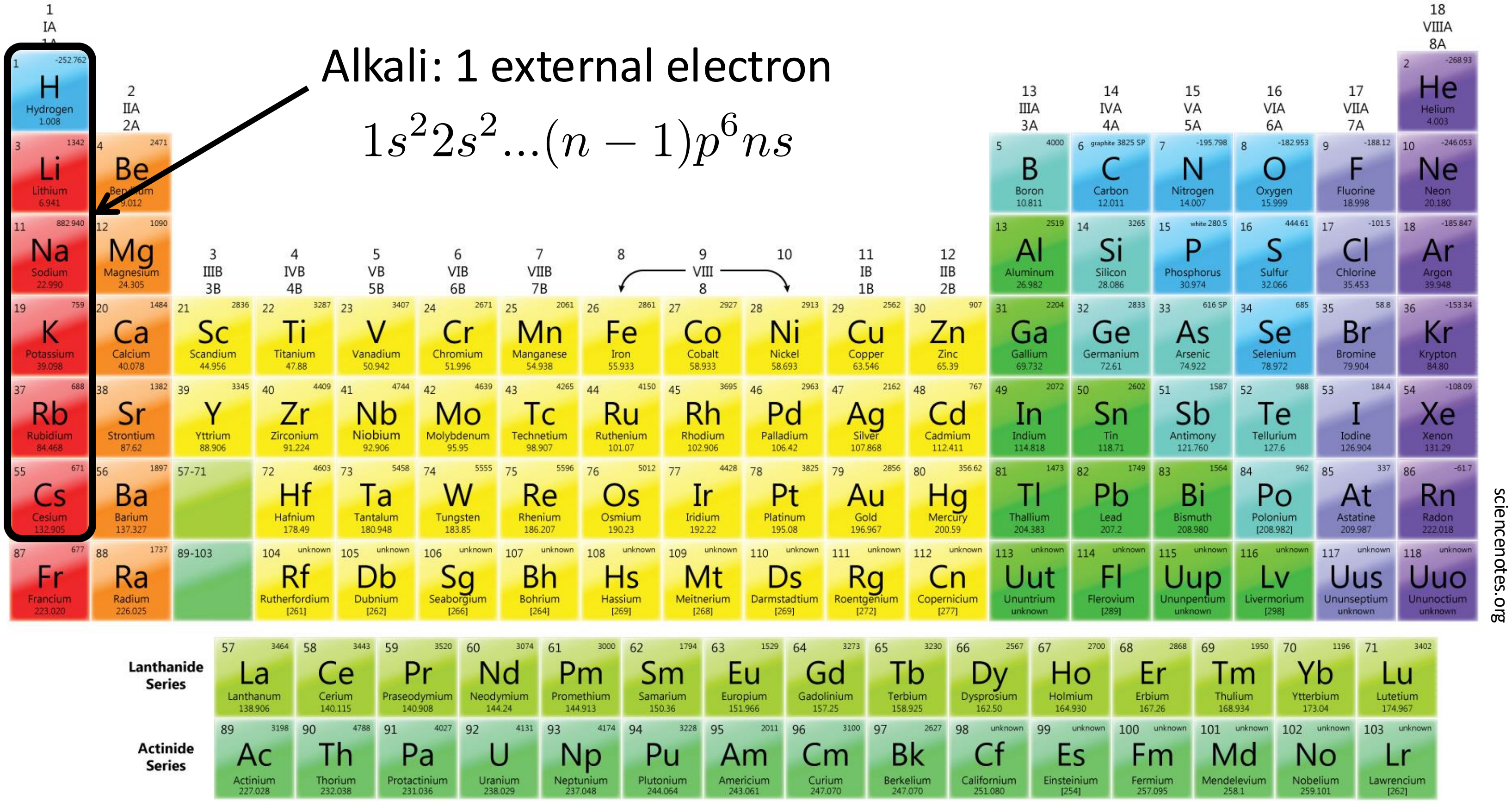
Idea of an infinite series

$\Rightarrow$ highly excited states

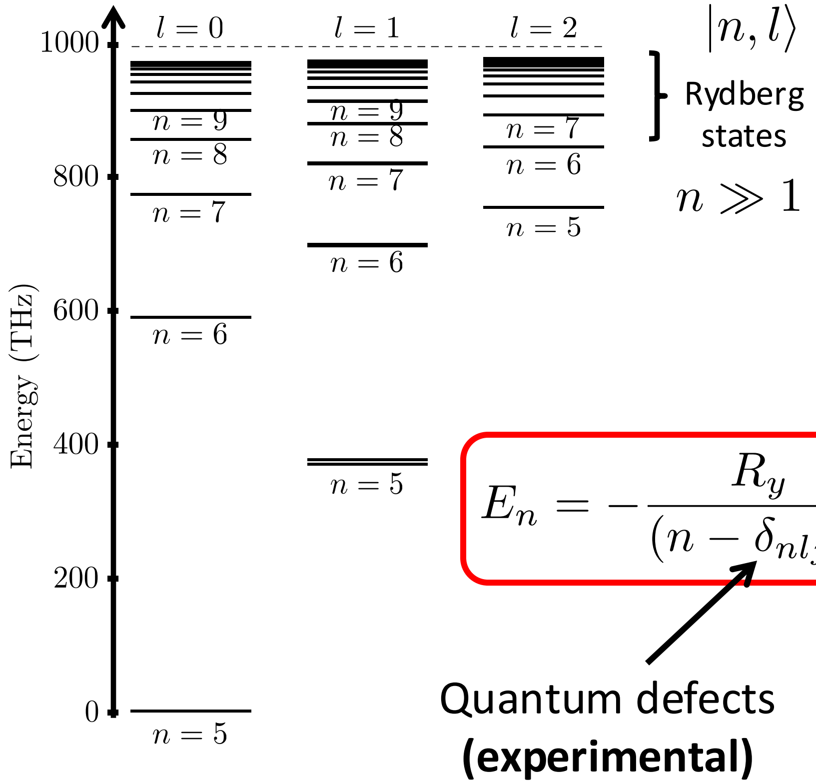
Examples: alkali atoms

Alkali: 1 external electron

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

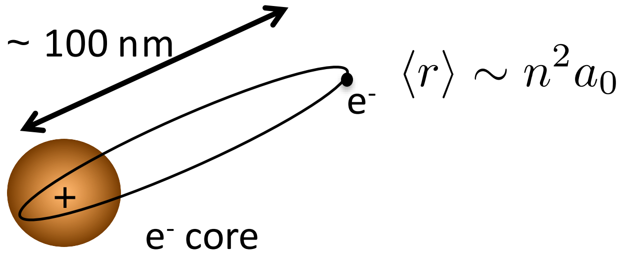


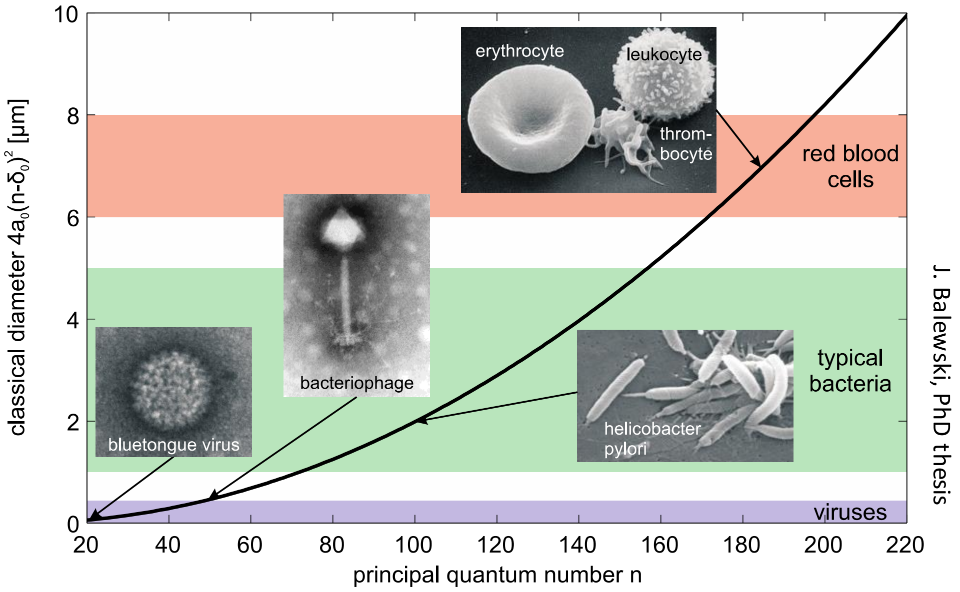
"Rydberg atom" = a highly excited atom (e.g. Rb)



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

Quantum defects **(experimental)**





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

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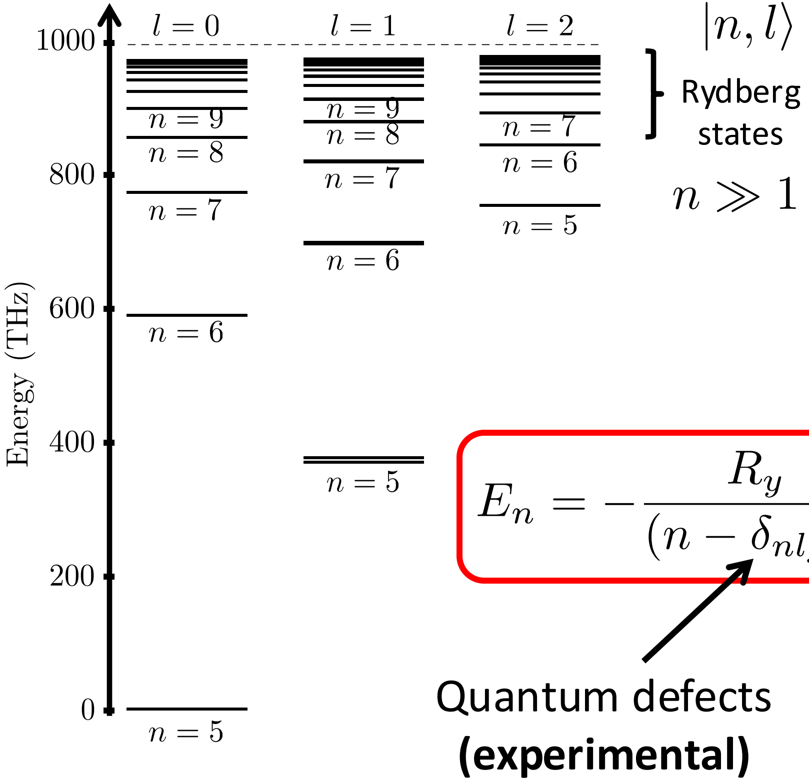

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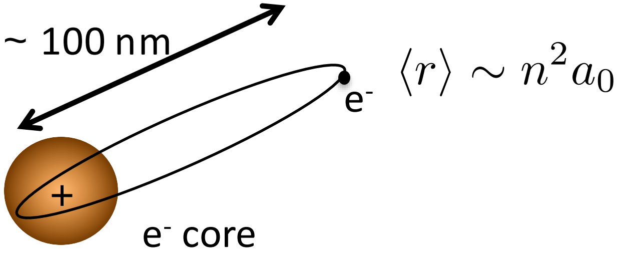
Quantum defects **(experimental)**

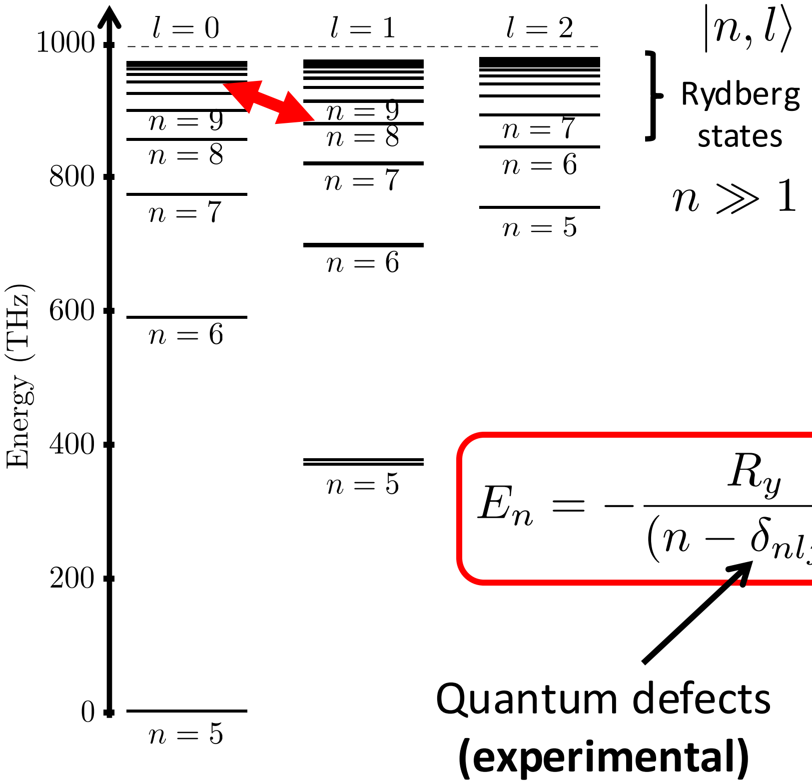


For Rb:
$n \geq 30$

L	J	$\delta_{L,J}$
0	1/2	3.131
1	1/2	2.654
	3/2	2.641
2	3/2	1.348
	5/2	1.346
3	5/2	0.016
	7/2	0.016

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

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



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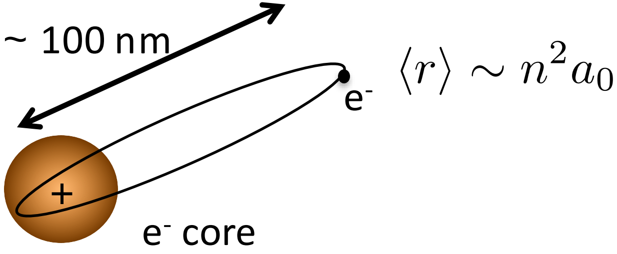

Long lifetime: $\tau \sim n^3$

$\Rightarrow$ 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

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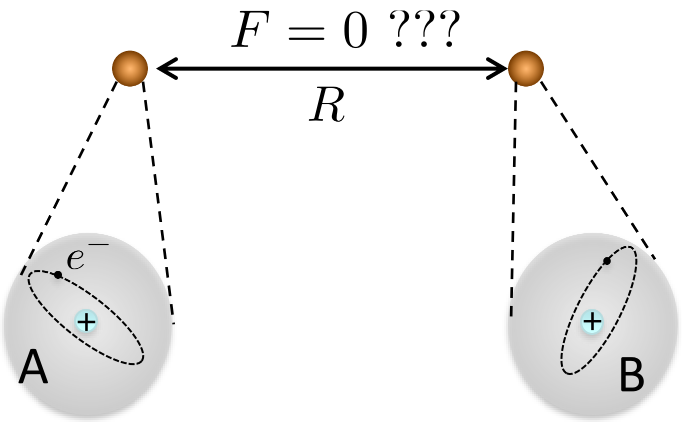
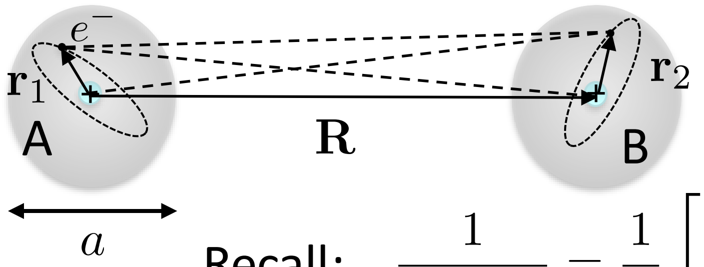
Dipolar Interaction between atoms



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

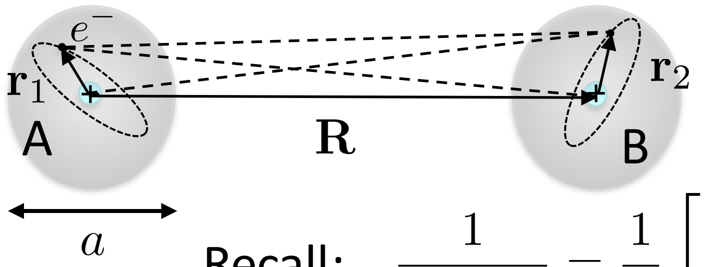
$a \ll R$

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

Dipolar Interaction between atoms

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

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



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

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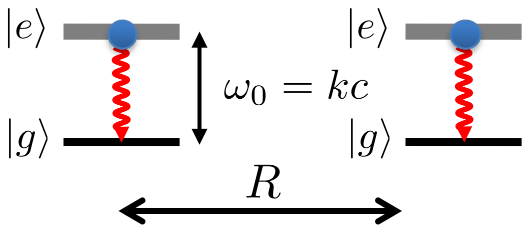
with dipoles: $$\hat{\mathbf{d}}_{1,2} = q\,\hat{\mathbf{r}}_{1,2}$$

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

Interaction between atoms: A toy model

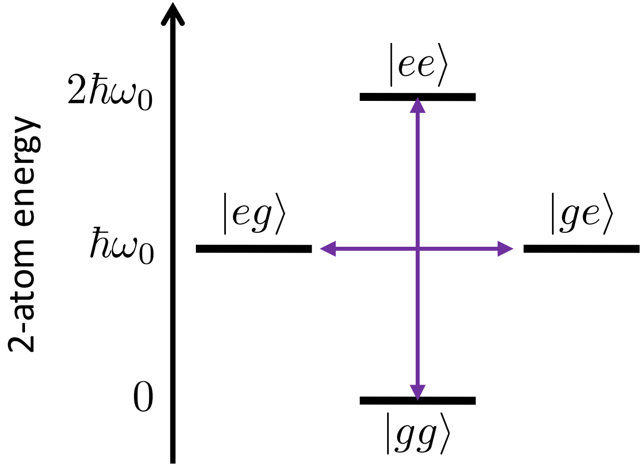


$$\Gamma = \frac{d_{eg}^2 k^3}{3\pi\epsilon_0}$$

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

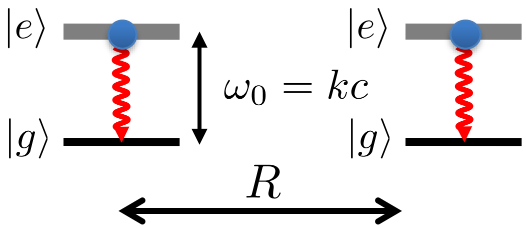
$$d_{eg} = \langle e|\hat{d}_{Az}|g\rangle = \langle e|\hat{d}_{Bz}|g\rangle$$

$$\hat{H}_{\mathrm{dd}} = \begin{pmatrix} 0 & d_{eg}^2/R^3 & 0 & 0 \\ d_{eg}^2/R^3 & 2\hbar\omega_0 & 0 & 0 \\ 0 & 0 & \hbar\omega_0 & d_{eg}^2/R^3 \\ 0 & 0 & d_{eg}^2/R^3 & \hbar\omega_0 \end{pmatrix}_{|gg\rangle,|ee\rangle,|eg\rangle,|ge\rangle}$$



$$\frac{d_{eg}^2}{R^3} \ll \hbar\omega_0$$

Interaction between atoms: A toy model



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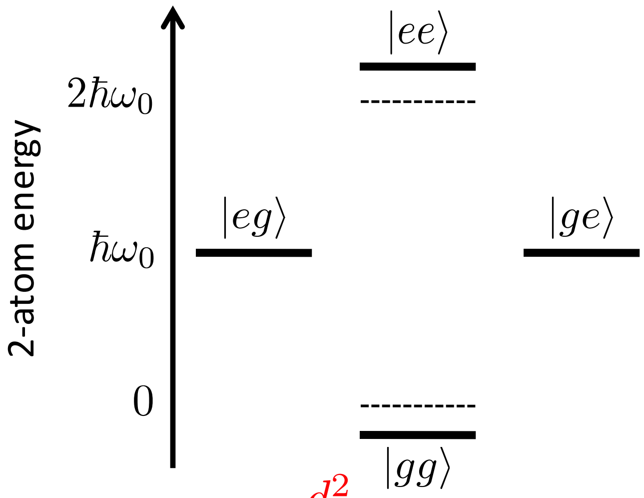


$$\frac{d_{eg}^2}{R^3} \ll \hbar\omega_0$$

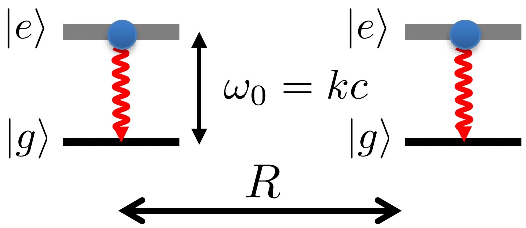
$$\Delta E_{gg}^{(2)} = -\Delta E_{ee}^{(2)}$$

$$\approx -\frac{1}{2\hbar\omega_0}\left(\frac{d_{eg}^2}{R^3}\right)^2$$

$$= -\frac{9}{32}\frac{\Gamma}{\omega_0}\frac{\hbar\Gamma}{(kR)^6}$$

Van der Waals

Interaction between atoms: A toy model



$$\Gamma = \frac{d_{eg}^2 k^3}{3\pi\epsilon_0}$$

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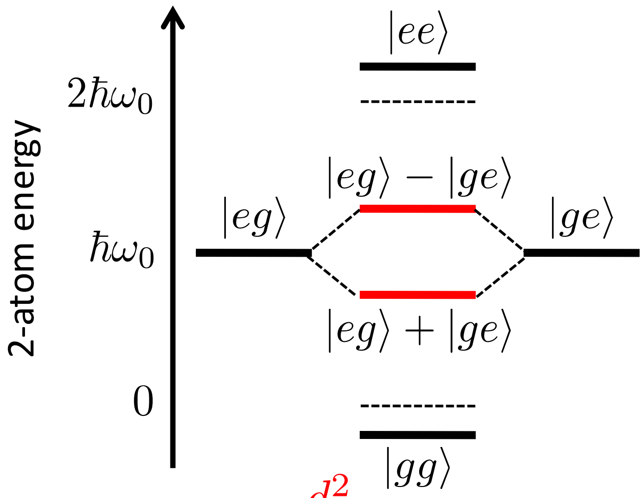
$$d_{eg} = \langle e|\hat{d}_{Az}|g\rangle = \langle e|\hat{d}_{Bz}|g\rangle$$

$$\hat{H}_{\rm dd} = \begin{pmatrix} 0 & d_{eg}^2/R^3 & 0 & 0 \\ d_{eg}^2/R^3 & 2\hbar\omega_0 & 0 & 0 \\ 0 & 0 & \hbar\omega_0 & d_{eg}^2/R^3 \\ 0 & 0 & d_{eg}^2/R^3 & \hbar\omega_0 \end{pmatrix}$$

$|gg\rangle, |ee\rangle, |eg\rangle, |ge\rangle$



$$\frac{d_{eg}^2}{R^3} \ll \hbar\omega_0$$

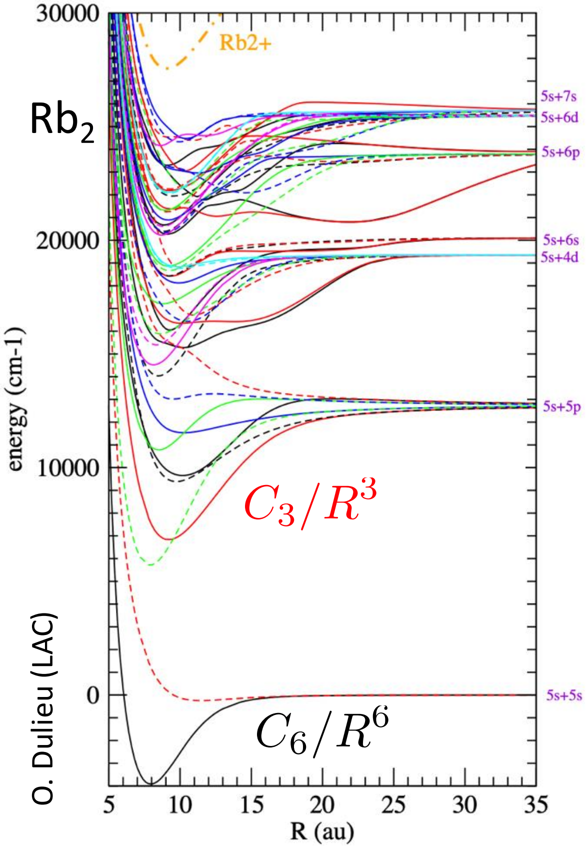
$$\Delta E_{gg}^{(2)} = -\Delta E_{ee}^{(2)} \approx -\frac{1}{2\hbar\omega_0}\left(\frac{d_{eg}^2}{R^3}\right)^2 = -\frac{9}{32}\frac{\Gamma}{\omega_0}\frac{\hbar\Gamma}{(kR)^6}$$

Van der Waals

$$E_\pm = \pm\frac{1}{4\pi\epsilon_0}\frac{d_{eg}^2}{R^3} = \pm\frac{3}{4}\frac{\hbar\Gamma}{(kR)^3}$$

Resonant

Long-range interaction between *real* atoms



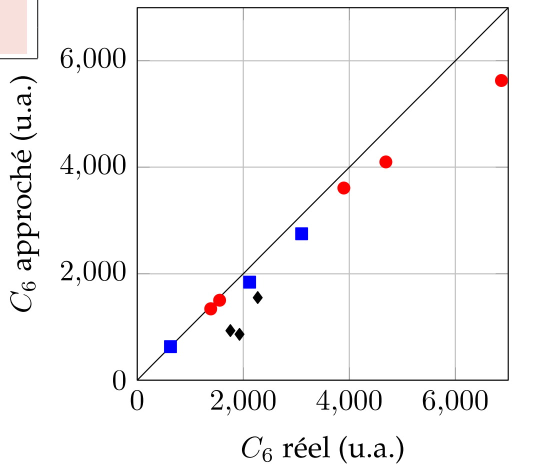
Expt[t] — Theory

système	C_6 [u.a.]	$\Gamma/2\pi$ [MHz]	λ [nm]	C_6 approché [u.a.]
Li-Li	1389	5.87	671	1340
Na-Na	1556	9.80	589	1500
K-K	3897	6.04	767	3610
Rb-Rb	4691	6.07	780	4100
Cs-Cs	6870	5.22	852	5629
Mg-Mg	627	80.9	235	630
Ca-Ca	2121	34.6	423	1840
Sr-Sr	3103	32.0	461	2750
Er-Er	1760	29.7	401	930
Dy-Dy	2275	32.2	421	1550
Yb-Yb	1929	29	399	860

J. Dalibard, Collège de France, 2021

Van der Waals: C_6/R^6

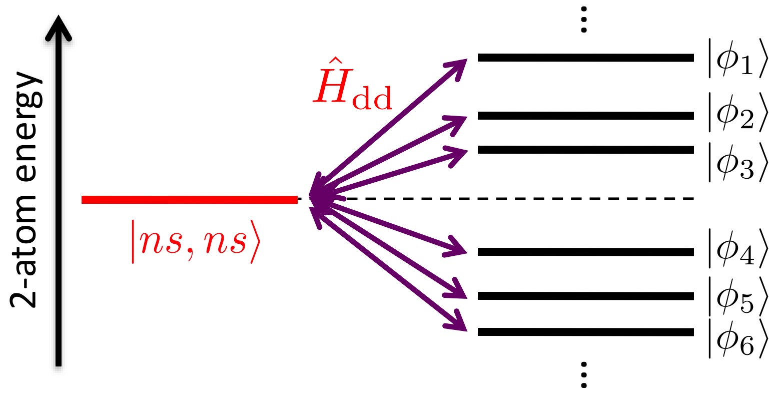
$$C_6 = -\frac{27}{16}\frac{\hbar\Gamma}{k^6}\frac{\Gamma}{\omega_0}$$



Useful for: scattering length (quantum gases), Rydberg physics…

Interactions between Rydberg atoms

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



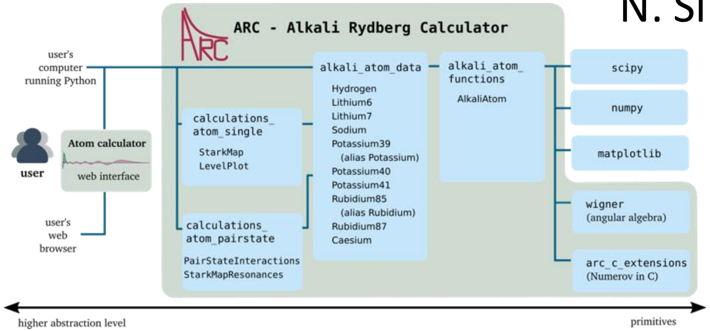
Van der Waals regime:

$$\Delta E_{ss}^{(2)} = \sum_{|\phi\rangle} \frac{|\langle\phi|\hat{H}_{\rm dd}|ss\rangle|^2}{E_{ss}-E_\phi} = \frac{C_6}{R^6}\,, \quad C_6 \propto n^{11}$$

Resonant regime:

$$E_\pm = \pm\langle sp|\hat{H}_{\rm dd}|ps\rangle = \pm\frac{1}{4\pi\epsilon_0}\frac{d_{sp}^2}{R^3} \propto n^4$$

N. Sibalic



https://arc-alkali-rydberg-calculator.readthedocs.io/en/latest/

Docs » Pairinteraction - A Rydberg Interaction Calculator

S. Weber

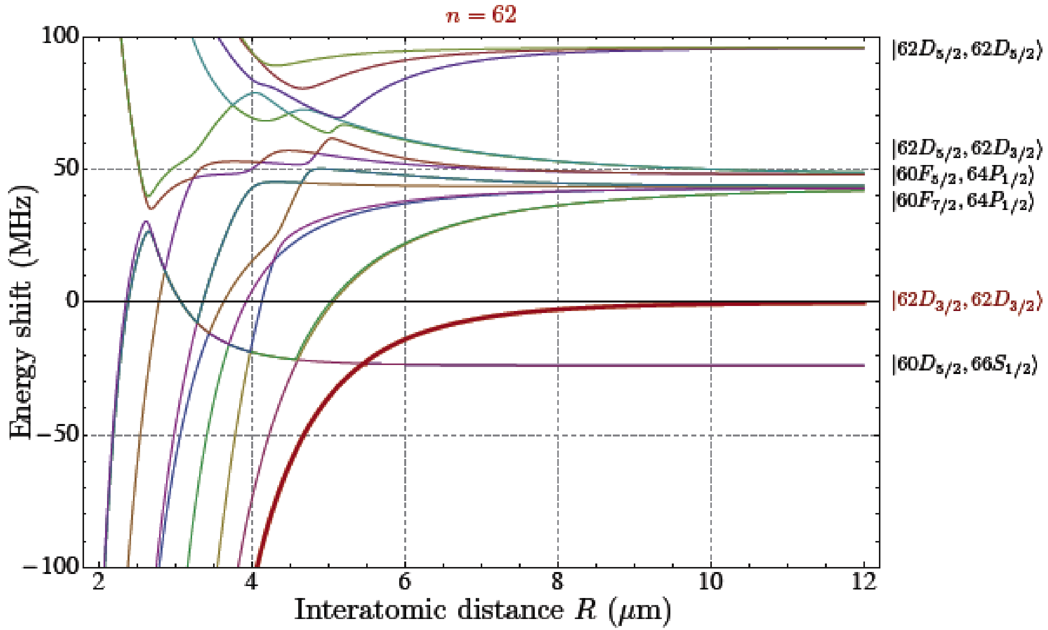
Pairinteraction - A Rydberg Interaction Calculator

build passing | build passing | codecov 67% | pypi v0.9.5a0 | arXiv 1612.08053 | License GPLv3

The *pairinteraction* software calculates properties of Rydberg systems. The software consists of a C++/Python library and a graphical user interface for pair potential calculations. For usage examples visit the tutorials section of the documentation. Stay tuned by signing up for the newsletter so whenever there are updates to the software or new publications about pairinteraction we can contact you. If you have a question that is related to problems, bugs, or suggests an improvement, consider raising an issue on GitHub.

https://pairinteraction.github.io/pairinteraction/sphinx/html/index.html

Interactions between "real" Rydberg atoms



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

The program

Lecture 1: Many-body problem and quantum simulation
Arrays of atoms & “Rydbergology”
Interactions between atoms

Lecture 2: Rydberg Interactions and spin models
Engineering many-body Hamiltonians

Lecture 3: Examples of quantum simulations in
and out-of-equilibrium: quantum magnetism