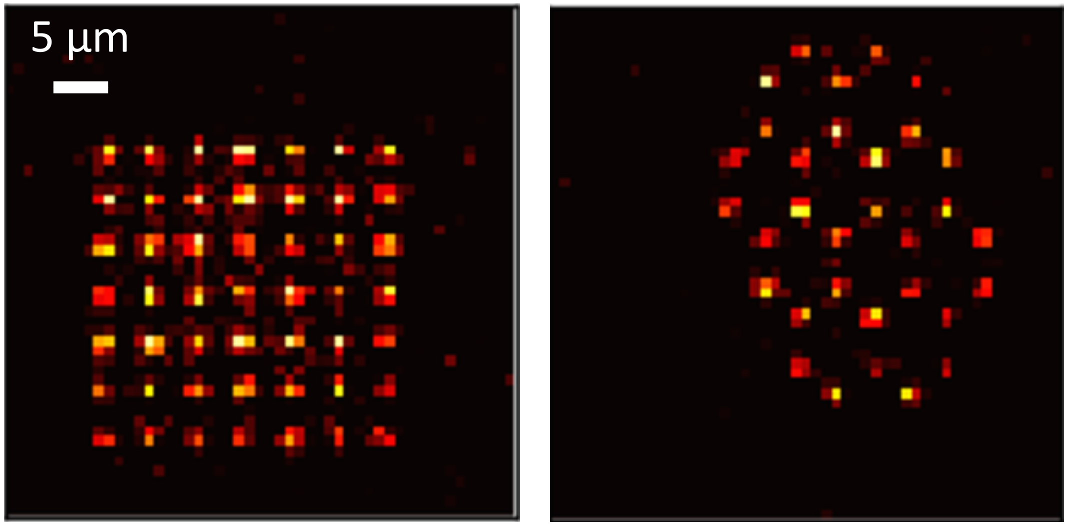
Dipole-dipole interactions between atoms for many-body physics and quantum information

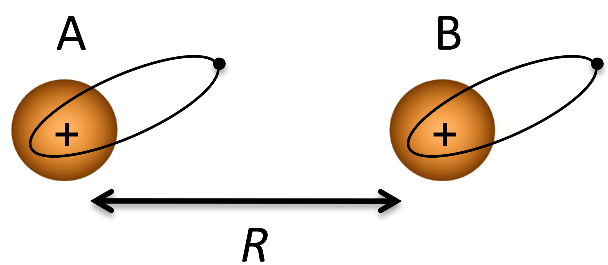
Lecture 1:	Dipole-dipole interaction between atoms
Lecture 2:	Basics of Rydberg physics. Arrays of cold atoms. Rydberg blockade & QIP
Lecture 3:	Many-body physics with Rydberg atoms

Goal: many-body physics and QIP with individual atoms



Addressable!!

Rydberg interactions



Van der Waals

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

resonant

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

Outline

1. “Rydbergology”: scalings, interactions…
2. Experimental considerations: arrays of individual atoms
3. Measurement of interactions between Rydberg atoms
4. Rydberg blockade with individual atoms. Applications to quantum information
5. Rydberg blockade in atomic ensembles. Applications to quantum optics

References:

"Rydberg atoms", T. Gallagher, Cambridge (1994)

"An experimental and theoretical guide to strongly interacting Rydberg gases", R. Loew, J. Phys. B **45**, 113001(2012)

"Quantum Information with Rydberg atoms", M. Saffman, T. Walker, K. Moelmer, Rev. Mod. Phys. **82**, 2313 (2010)

Special Issue on Rydberg Atomic Physics, J. Phys. B (2016) contains many reviews

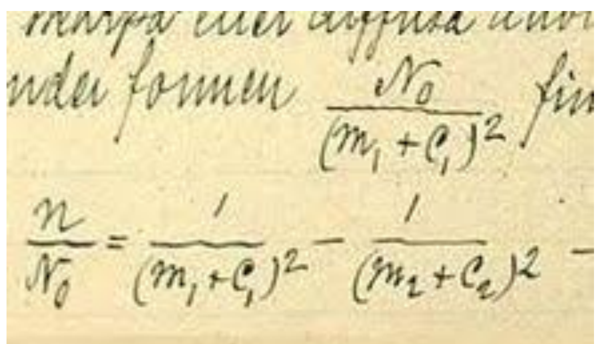
Rybderg atoms: a few historical landmarks

1814 Joseph von Fraunhofer

observation of dark lines in spectrum of the sun

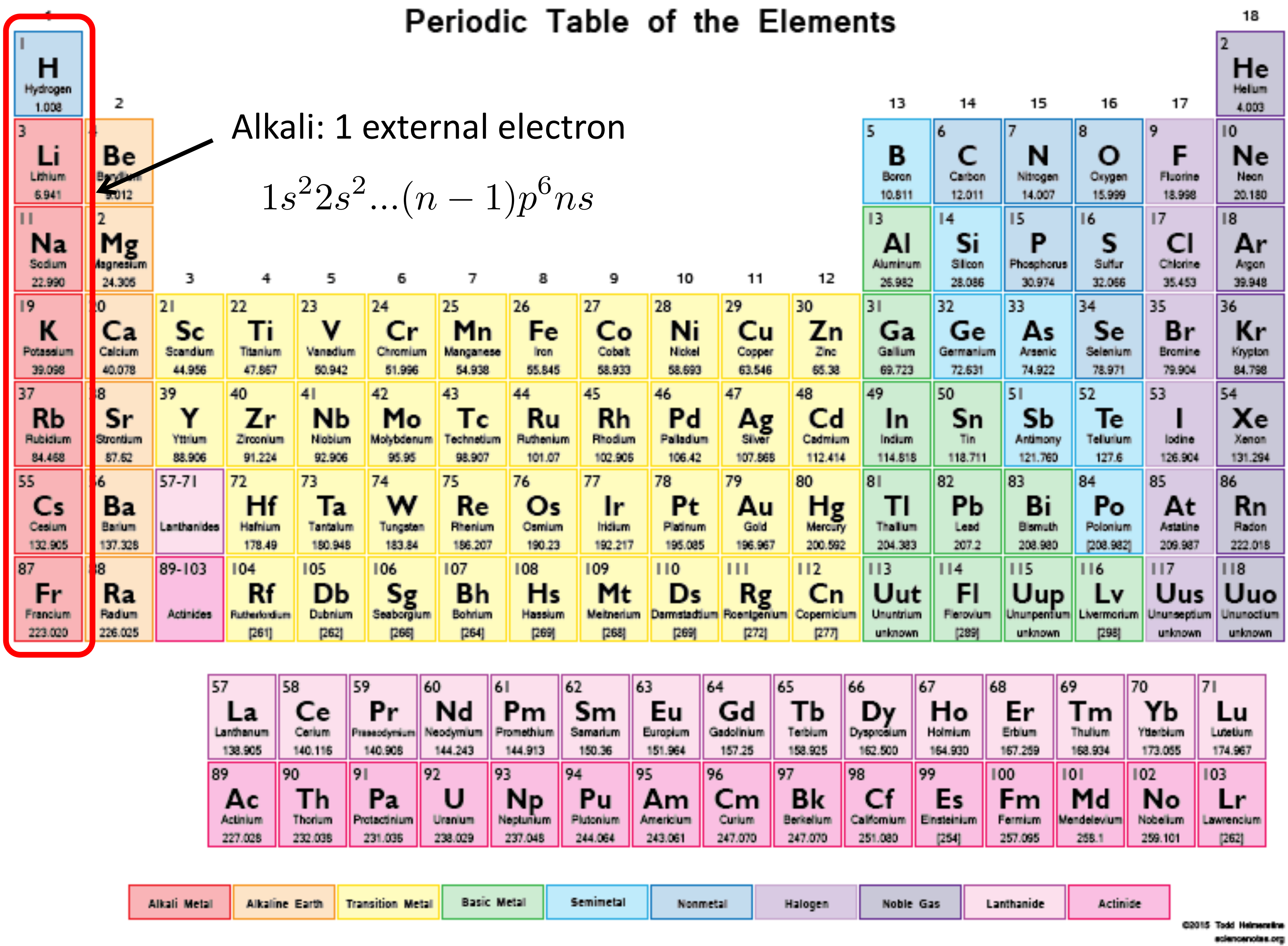
1888 “Rydberg formula”

Johannes Rydberg
1854-1919



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

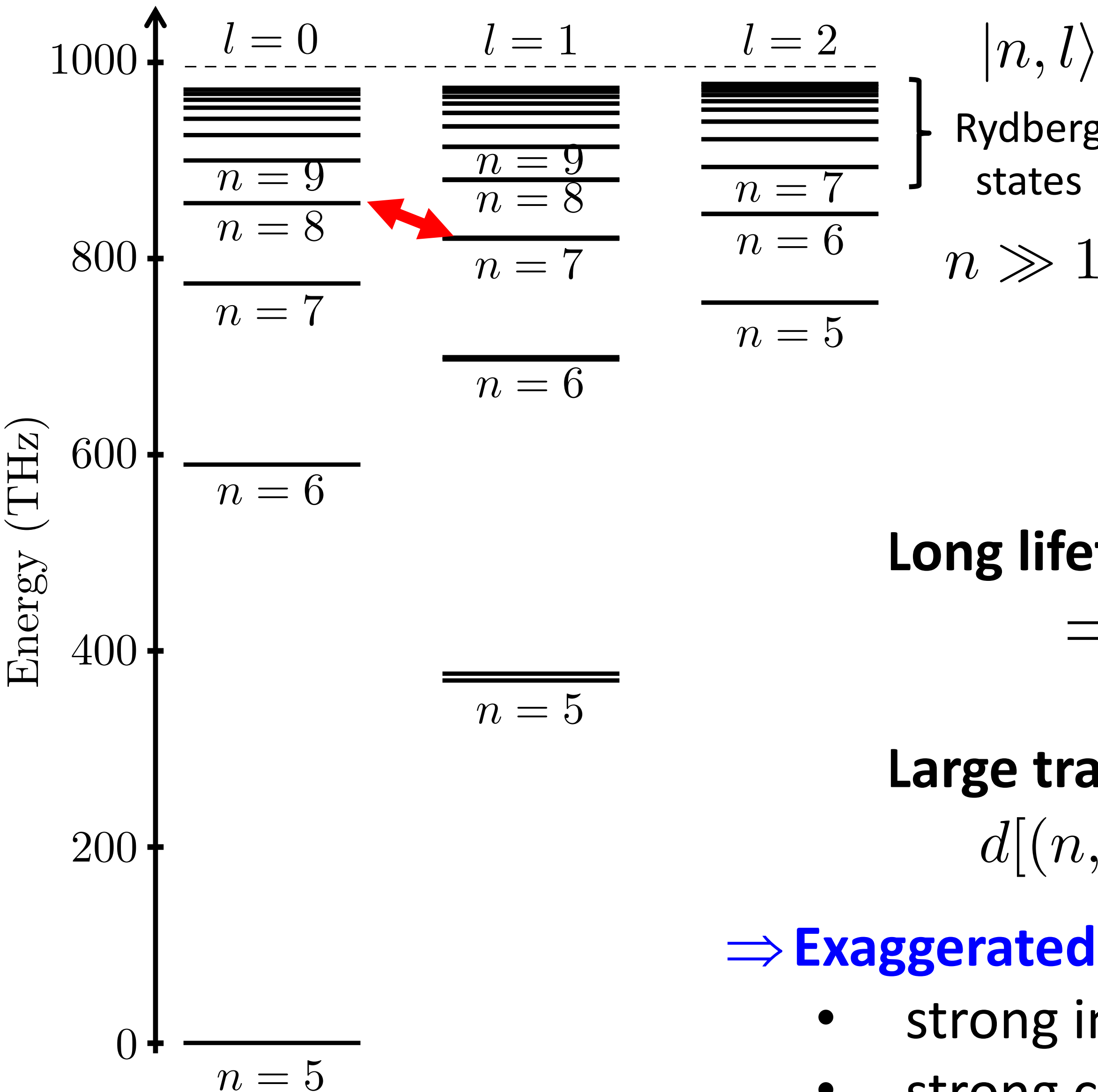
Idea of an infinite series
$\Rightarrow$ highly excited states

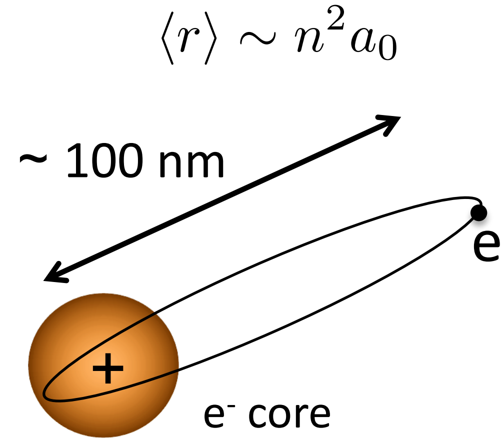


Alkali: 1 external electron

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

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





Long lifetime $\tau \sim n^3$

$\Rightarrow$ *n* > 60, τ > 100 μs

Large transition dipole:

$$d[(n,l) \rightarrow (n, l \pm 1)] \sim n^2 e a_0$$

$\Rightarrow$ **Exaggerated properties:**

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

Quantum defects for alkali atoms

Experiments $\Rightarrow$ $$E_n = -\frac{R_y}{(n-\delta_{nlj})^2} \qquad R_y = R_y^{\infty}\left(1+\frac{m_e}{M}\right)^{-1}$$

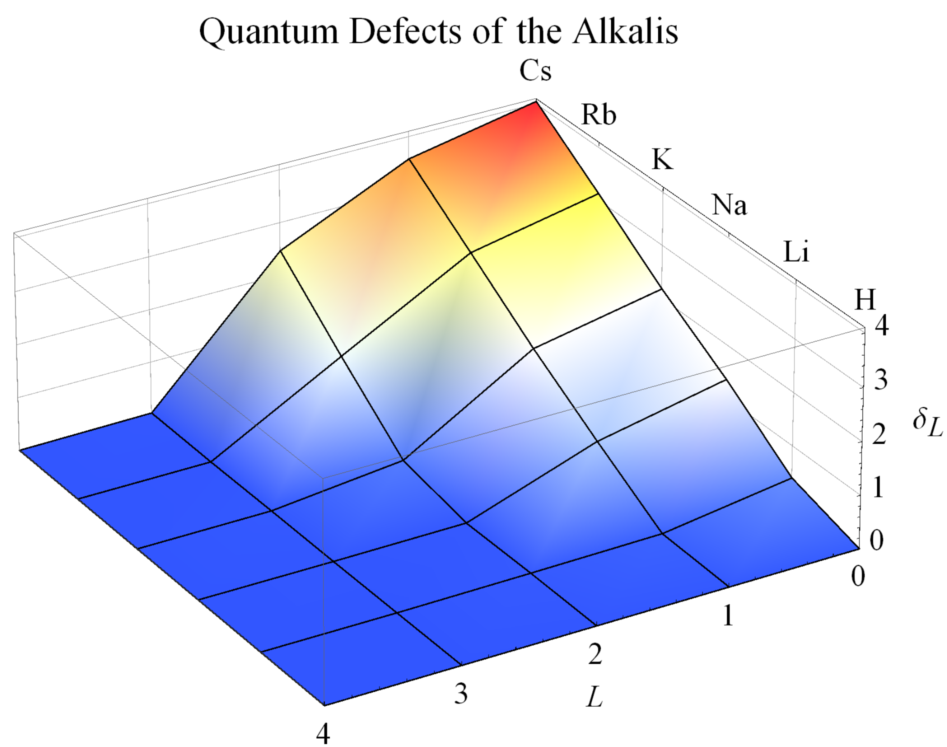
$$R_y^{\infty} = 10\ 973\ 371.568\ 539\ \mathrm{m}^{-1}$$

Quantum defects **(Experimental)**

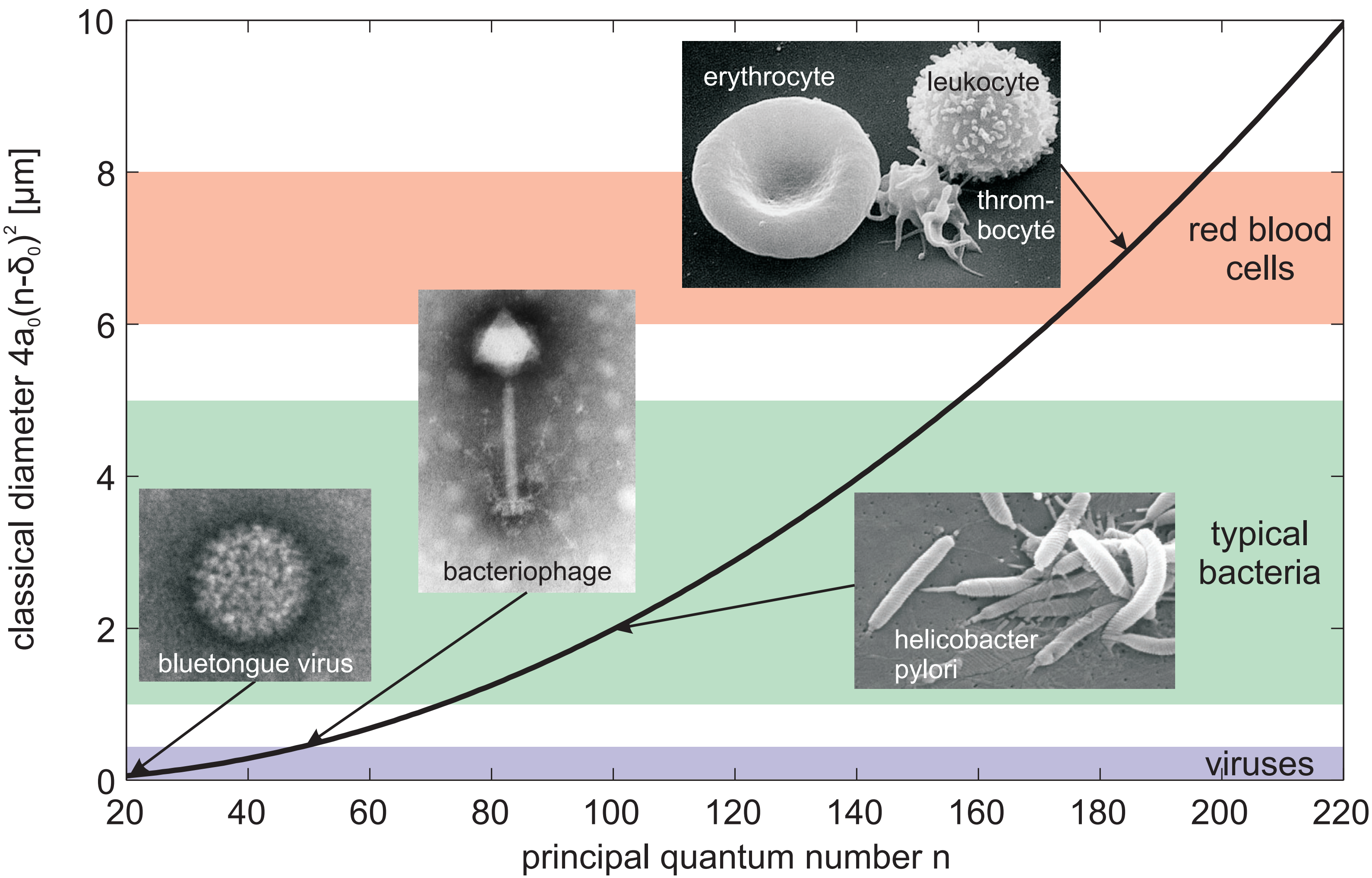
For Rb:

$n \geq 30$

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



Rydberg atoms are huge…



J. Balewski, PhD thesis

Rydberg's have exaggerated properties

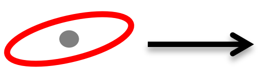
Table 1. Properties of Rydberg states.

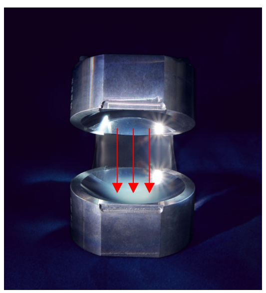
Property	n−scaling	Value for $80S_{1/2}$ of Rb
Binding energy E_n	n^{-2}	-500 GHz
Level spacing $E_{n+1} - E_n$	n^{-3}	13 GHz
Size of wavefunction $\langle r \rangle$	n^2	500 nm
Lifetime τ	n^3	200 μs
Polarizability α	n^7	-1.8 GHz/(V/cm)^2
van der Waals coefficient C_6	n^{11}	4 THz $\cdot$ μm^6

Back to history…

1975 Spectroscopy using lasers (Gallagher, Kleppner, Haroche…)

1980 – 2000 Cavity Quantum Electrodynamics using Rydbergs





High Q cavity: photon lifetime > 1ms

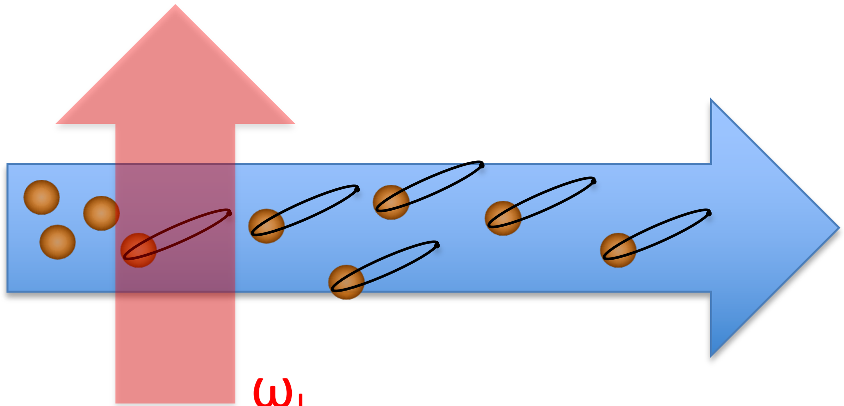
+ large dipole $\Rightarrow$

1 Rydberg interacts with 1 photon!

Haroche, Walther…

Back to history...: Rydberg interactions

The "dense Rydberg gas" J-M Raimond, J. Phys. B **14**, L655 (1981)



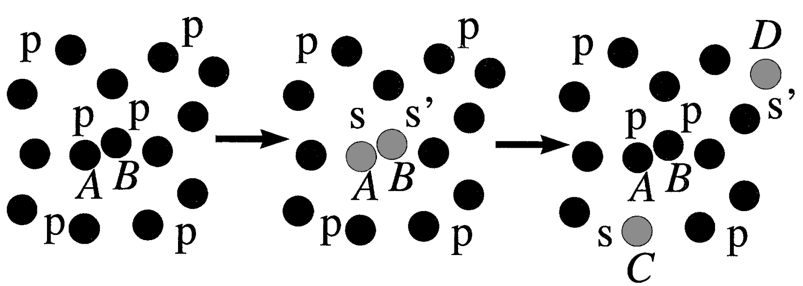
Broadening of excitation

$$\Delta\omega \sim \frac{d^2}{R^3} \sim 10\ \text{GHz}$$

k_BT << Interaction energy $\Rightarrow$ T < 1 mK $\Rightarrow$ **cold atoms**

1998 Rydbergs meet cold atoms P. Pillet and T. Gallagher

Anderson, PRL **80**, 249 (1998)
Mourachko, PRL **80**, 253 (1998)



p + p $\leftrightarrow$ s + s'

p + s $\leftrightarrow$ s + p

"Frozen" gas

Diffusion of excitation faster than motion $\Rightarrow$ correlations between all atoms

k_BT << Interaction energy

$\Rightarrow$ T < 1 mK

Interactions between Rydberg atoms

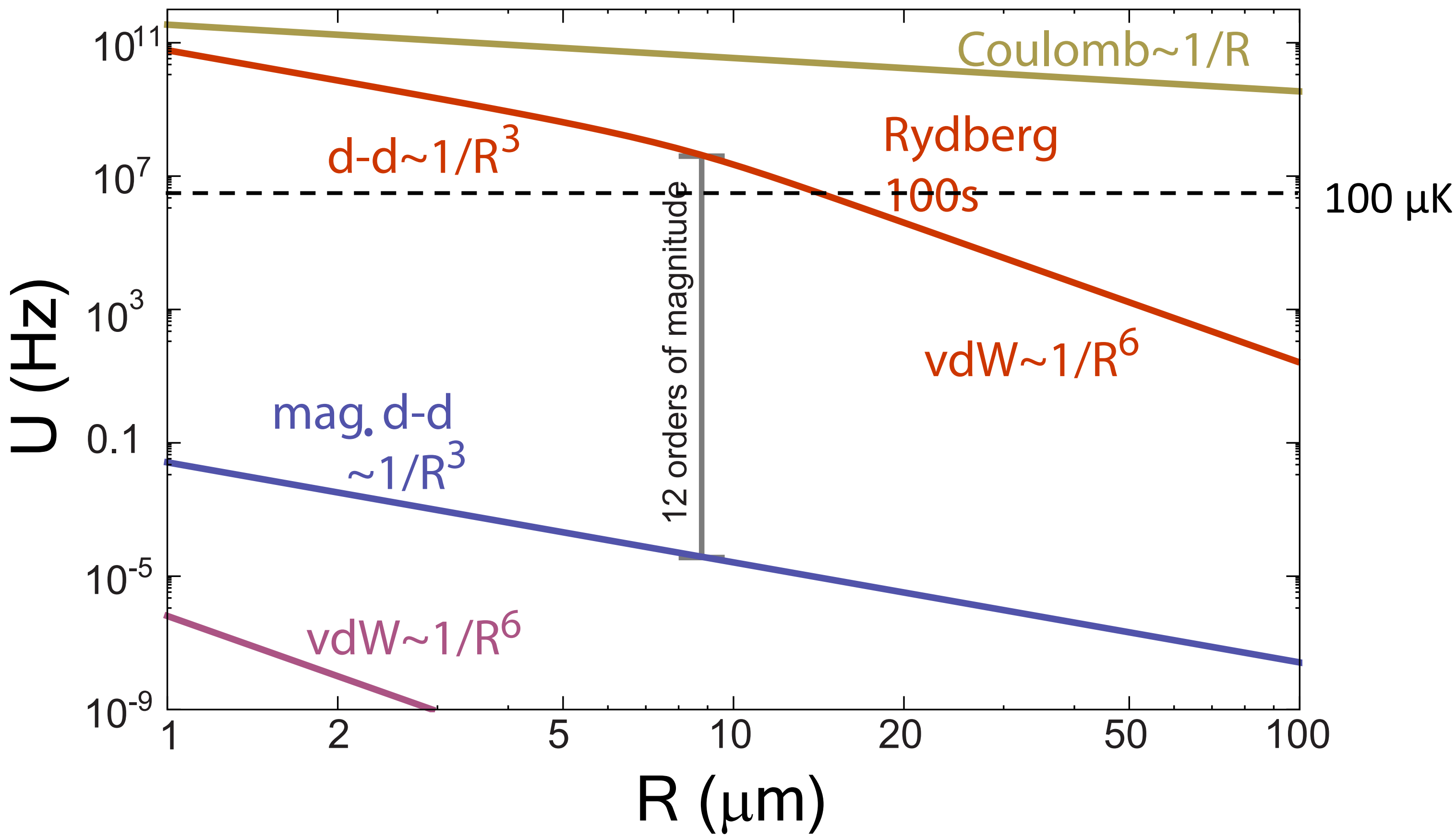
REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010

Quantum information with Rydberg atoms

M. Saffman and T. G. Walker

Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, Wisconsin 53706, USA

K. Mølmer



A new era: the Rydberg Blockade idea

VOLUME 85, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 2000

Fast Quantum Gates for Neutral Atoms

D. Jaksch, J. I. Cirac, and P. Zoller
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VOLUME 87, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JULY 2001

Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles

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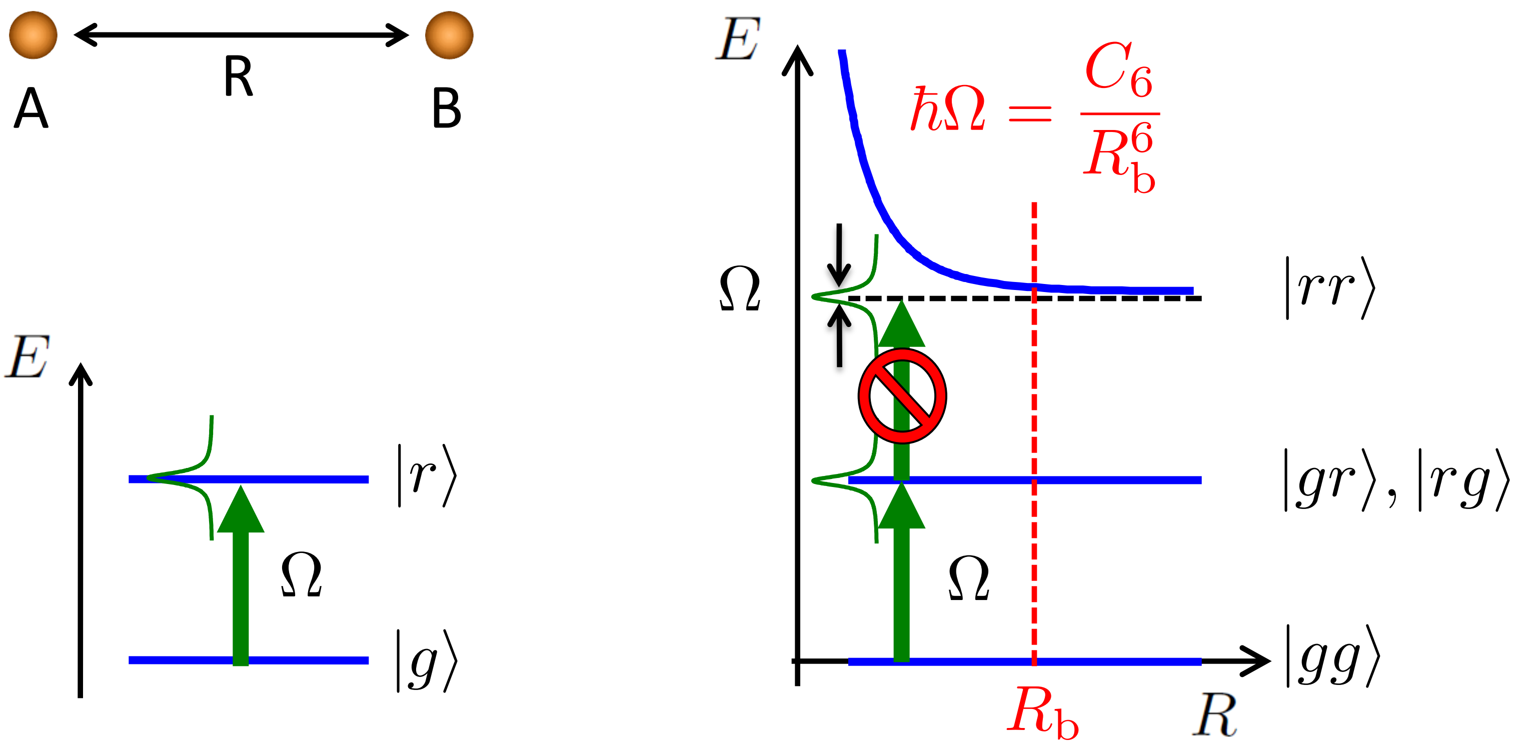
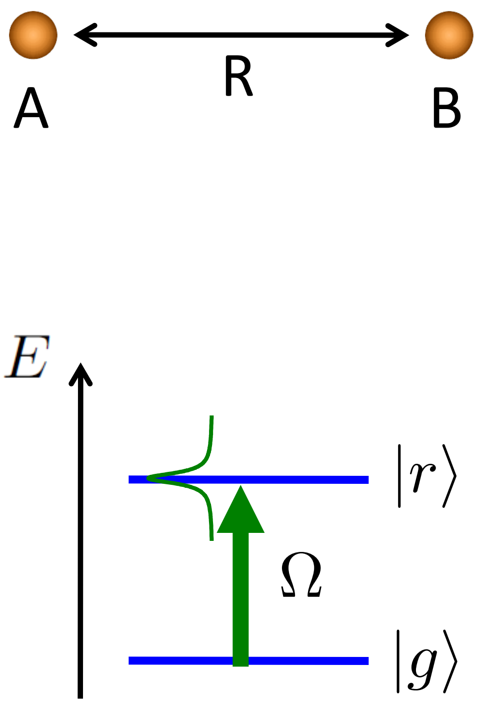
(Received 7 November 2000; published 26 June 2001)

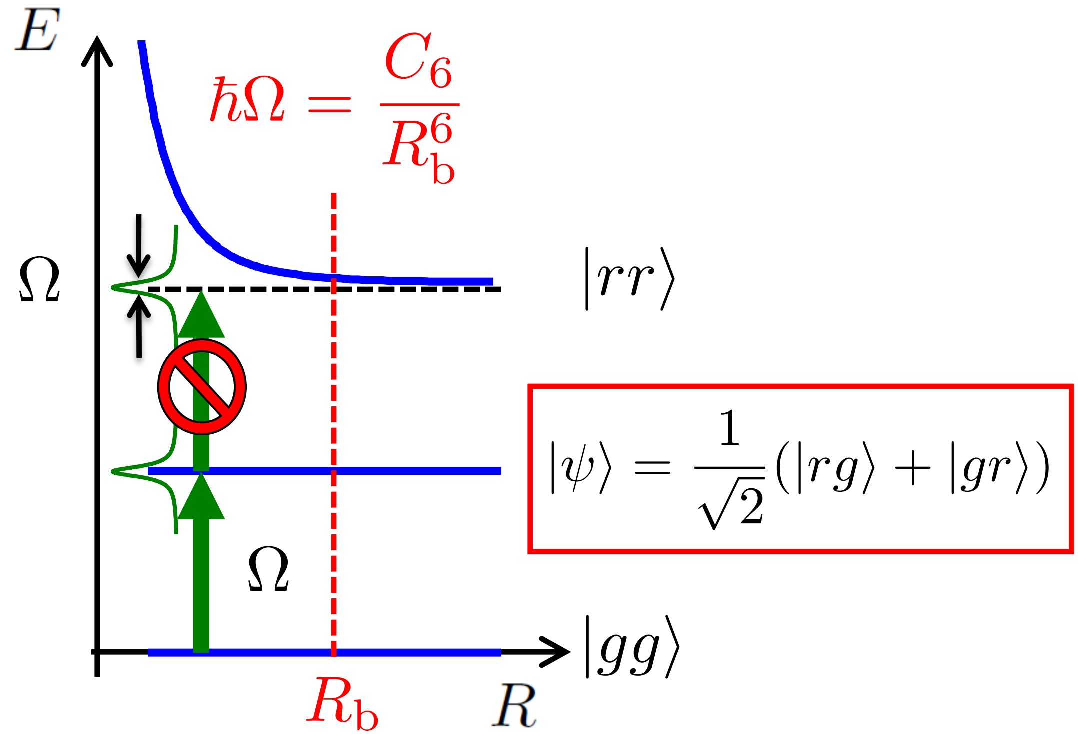
A new era: the Rydberg Blockade idea



If $\hbar\Omega \ll U_{vdW}$: no excitation of $|rr\rangle \Rightarrow$ **blockade**

A new era: the Rydberg Blockade idea

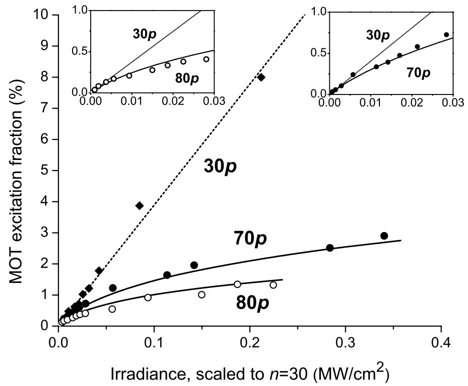




Blockade $\Rightarrow$ **entanglement and gates!!**

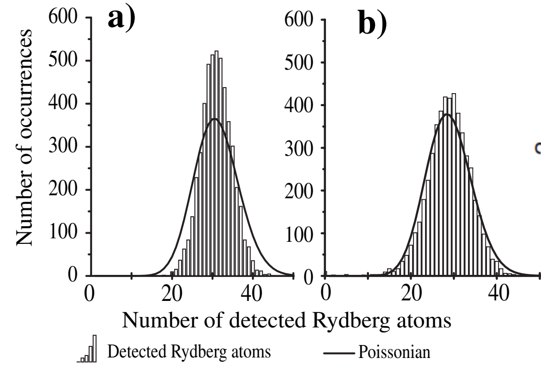
The first blockade experiments

Atomic ensembles

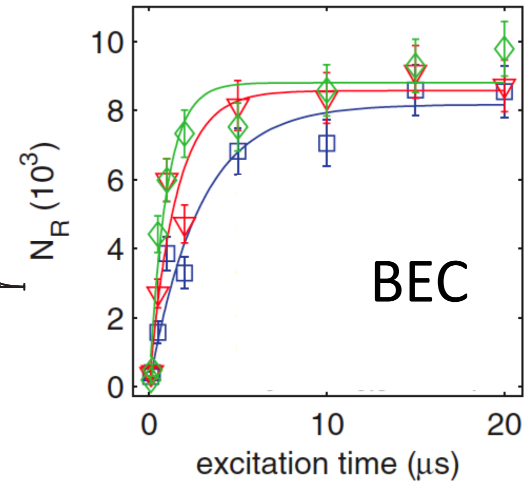


Gould, PRL 2004
Weidemuller, PRL 2004

Martin, PRL 2004
Pillet, PRL 2006



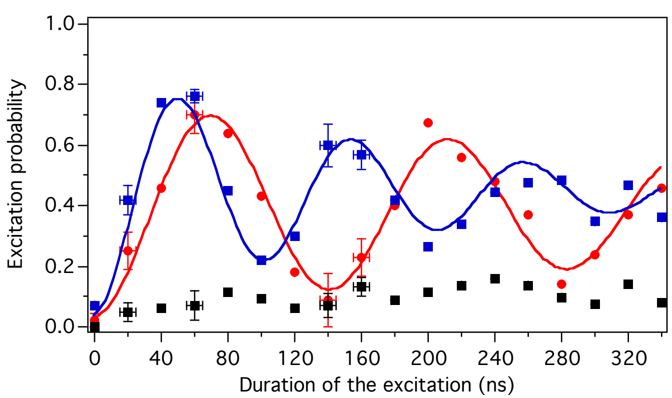
Raithel, PRL 2005



Pfau, PRL 2007

Individual atoms

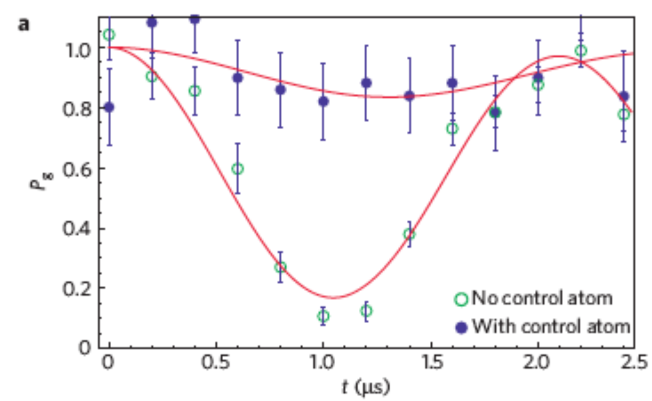
IO Palaiseau



Blockade + collective excitation √2

Gaétan *et al.*, Nat. Phys. **5**, 115 (2009)

U. Wisconsin

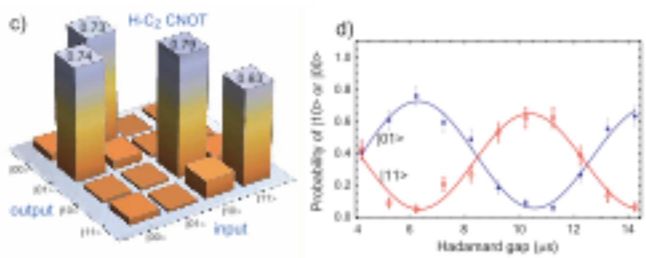


Blockade

Urban *et al.*, Nat. Phys. **5**, 110 (2009)

And now (2019)… a few examples

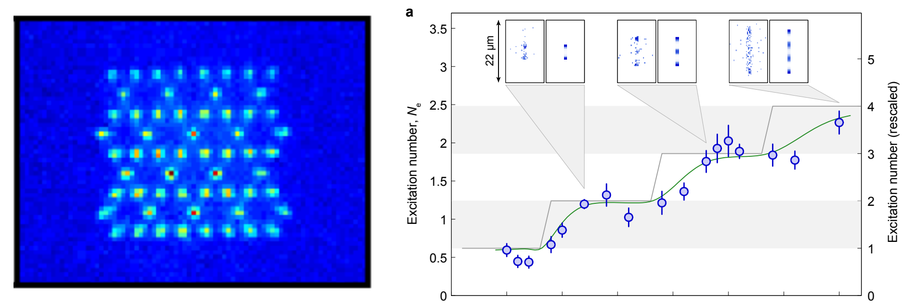
QIP: entanglement and gates



Saffman RMP **82**, 2313 (2010)

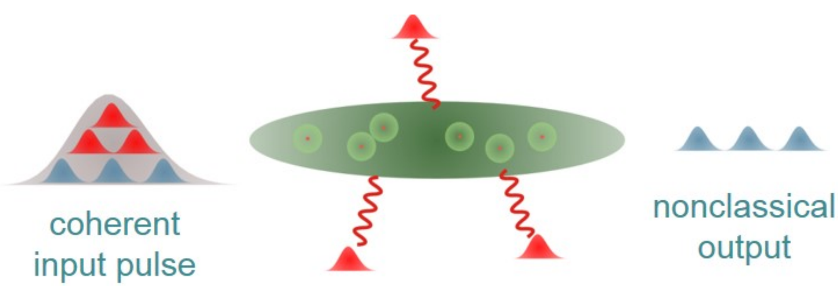
Saffman, Biedermann…

Many-body physics Quantum simulation



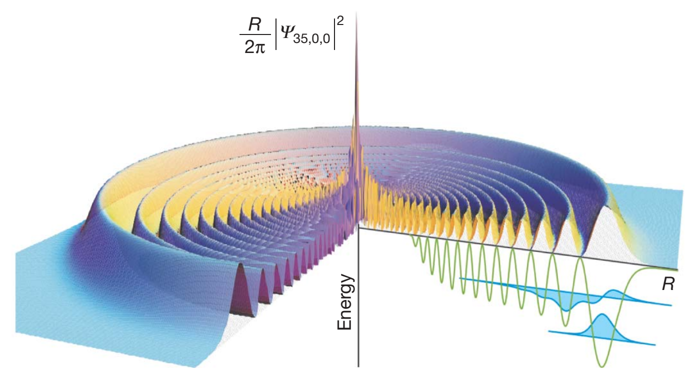
Browaeys, Lukin, Bloch, Pillet, Weidemuller, Morsch…

Non-linear classical & quantum optics



Adams, Hofferbert, Firstenberg, Lukin, Vuletic…

Exotic long-range molecules



Pfau-Löw, Ott, Shaeffer …

Outline

1. “Rydbergology”: scalings, interactions…
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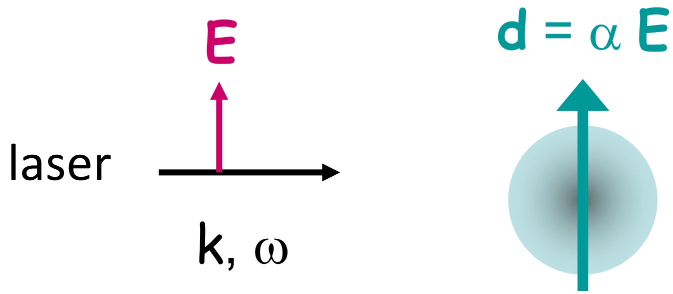
Optical dipole trap

Classical

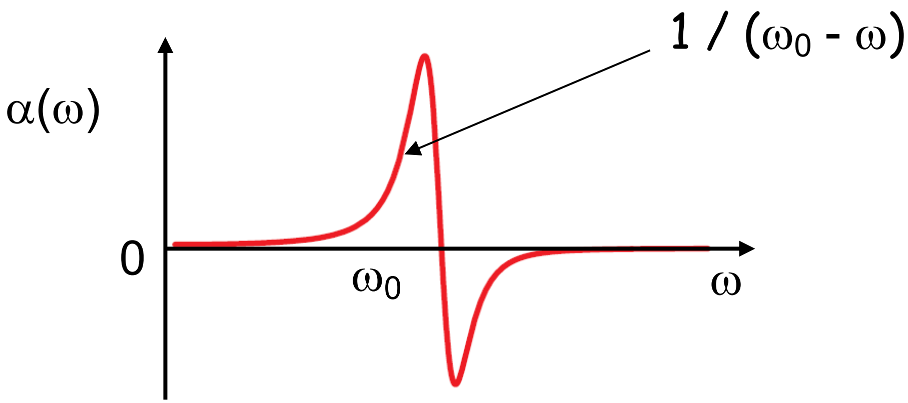


Quantum

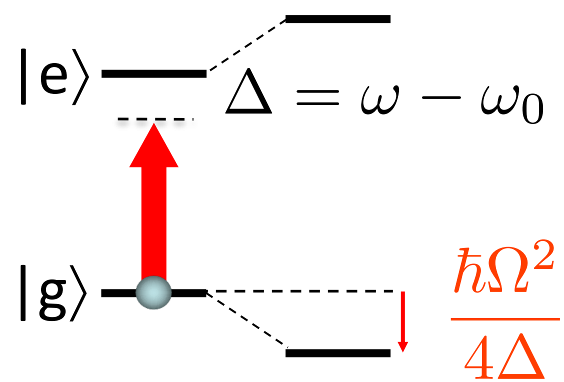
$$\hbar\Omega = d.E$$

$$d = \langle e|\hat{D}|g\rangle$$

Harmonic oscillator model



$\omega_0 > \omega$



Interaction atom - light

$U(\mathbf{x}) \sim -\alpha E(\mathbf{x})^2$

⇒ Conservative POTENTIAL

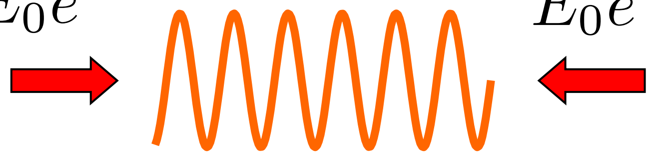
Trap depth ~ 100 μK – 1 mK

⇒ cold atoms

Optical lattices

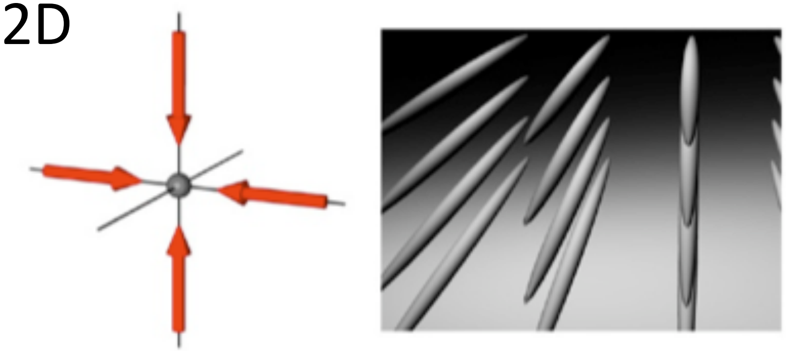
1D

$E_0 e^{ikx}$ $E_0 e^{-ikx}$

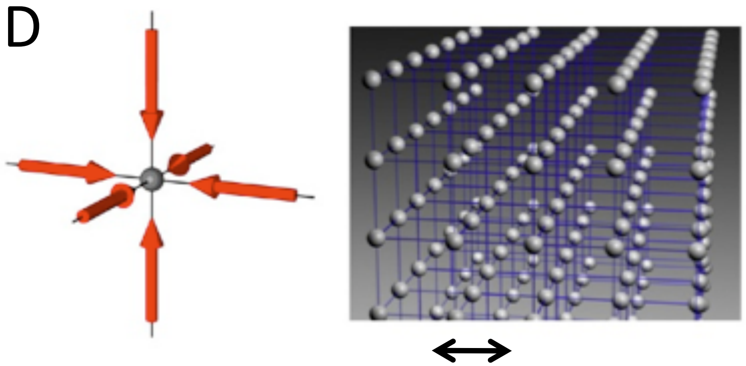


$$I(x) = 2E_0^2(1 + \cos 2kx)$$

2D



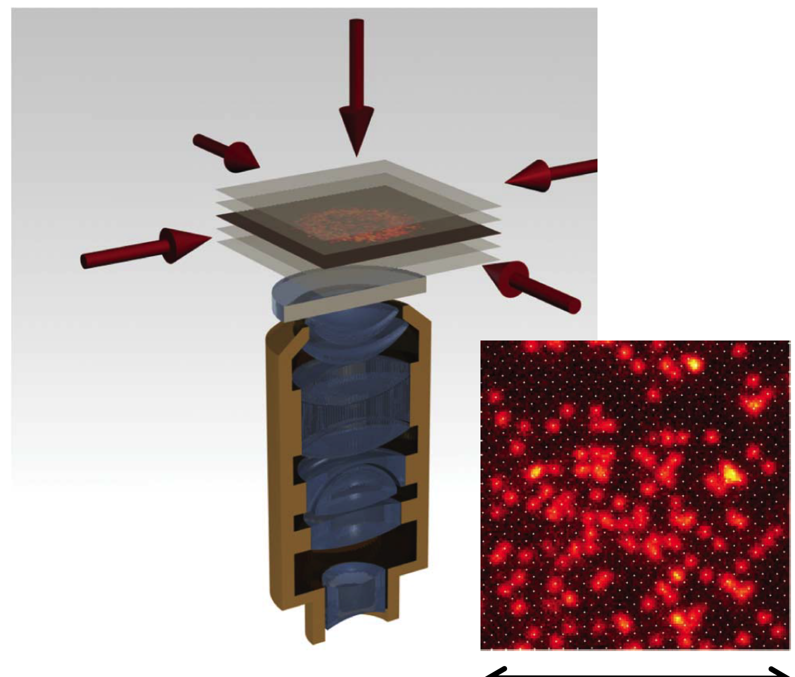
3D



$\lambda/2 = 0.5\ \mu\text{m}$

(M. Greiner thesis)

Single site resolution (< 1 μm)

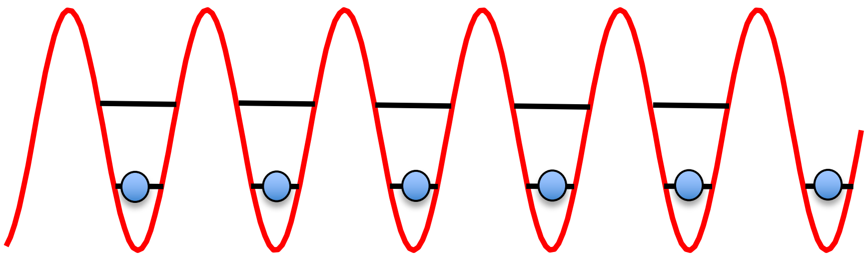


16 μm

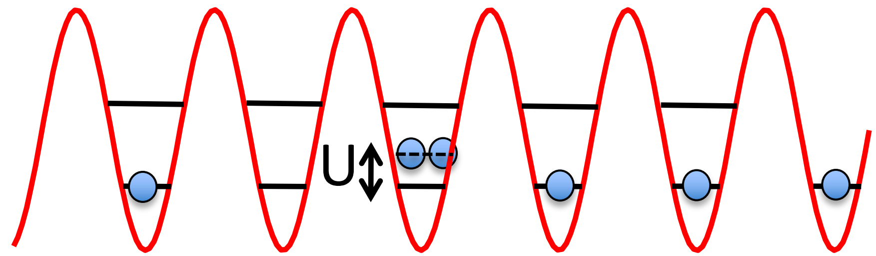
Bakr *et al.*, Nature **462**, 74 (2009)
Sherson *et al.*, Nature **467**, 68 (2010)

Preparation of individual atoms in optical lattices

Superfluid - Mott insulator transition Greiner *et al.*, Nature **415**, 39 (2002)



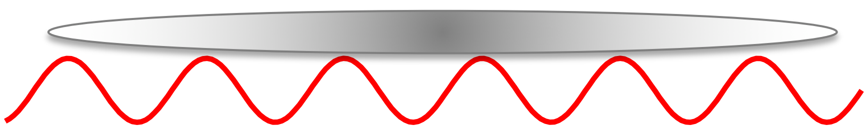
$6E_0$



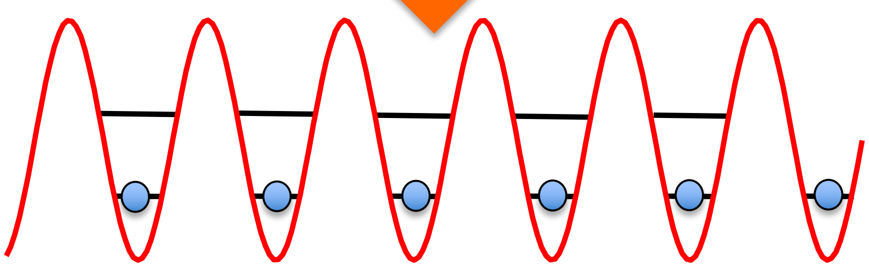
$6E_0 + U$ (~1kHz)

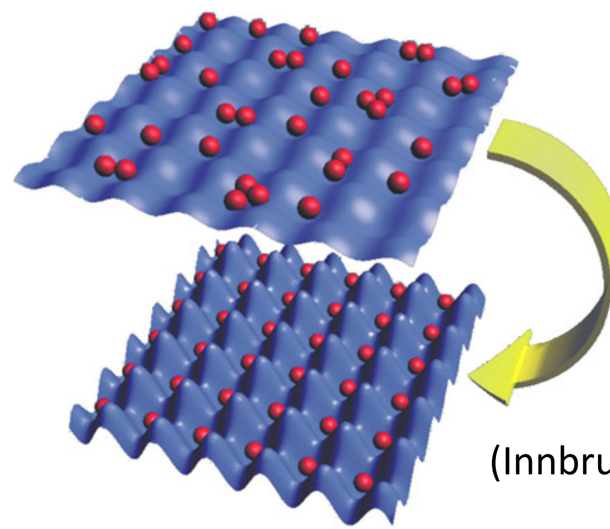
$$U = \frac{4\pi\hbar^2 a}{m} \int |\phi(\mathbf{r})|^4 d^3\mathbf{r}$$

BEC



Adiabatic increase:
connects ground-states





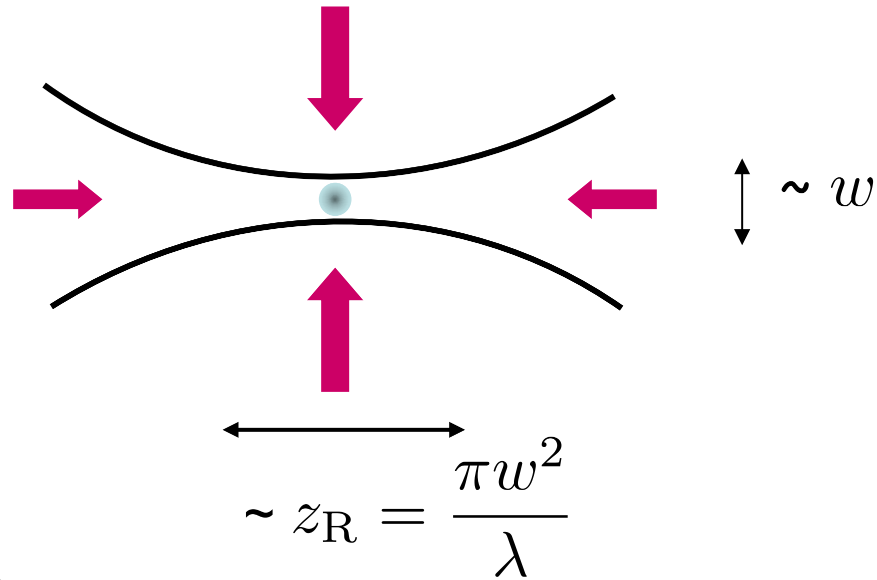
(Innbruck)

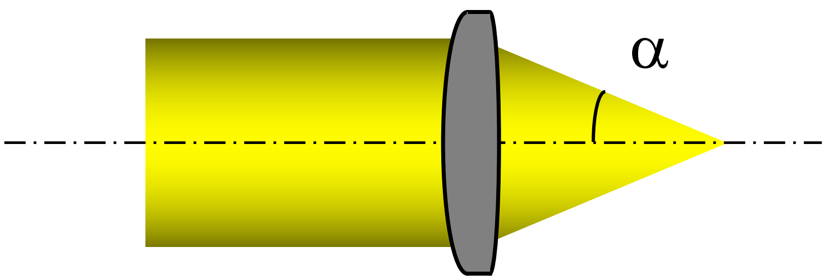
Works in 2D and 3D

Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

Gaussian beam





NA = sin α
w ~ **λ**/**NA**

Diffraction limited optics $w \sim \lambda$

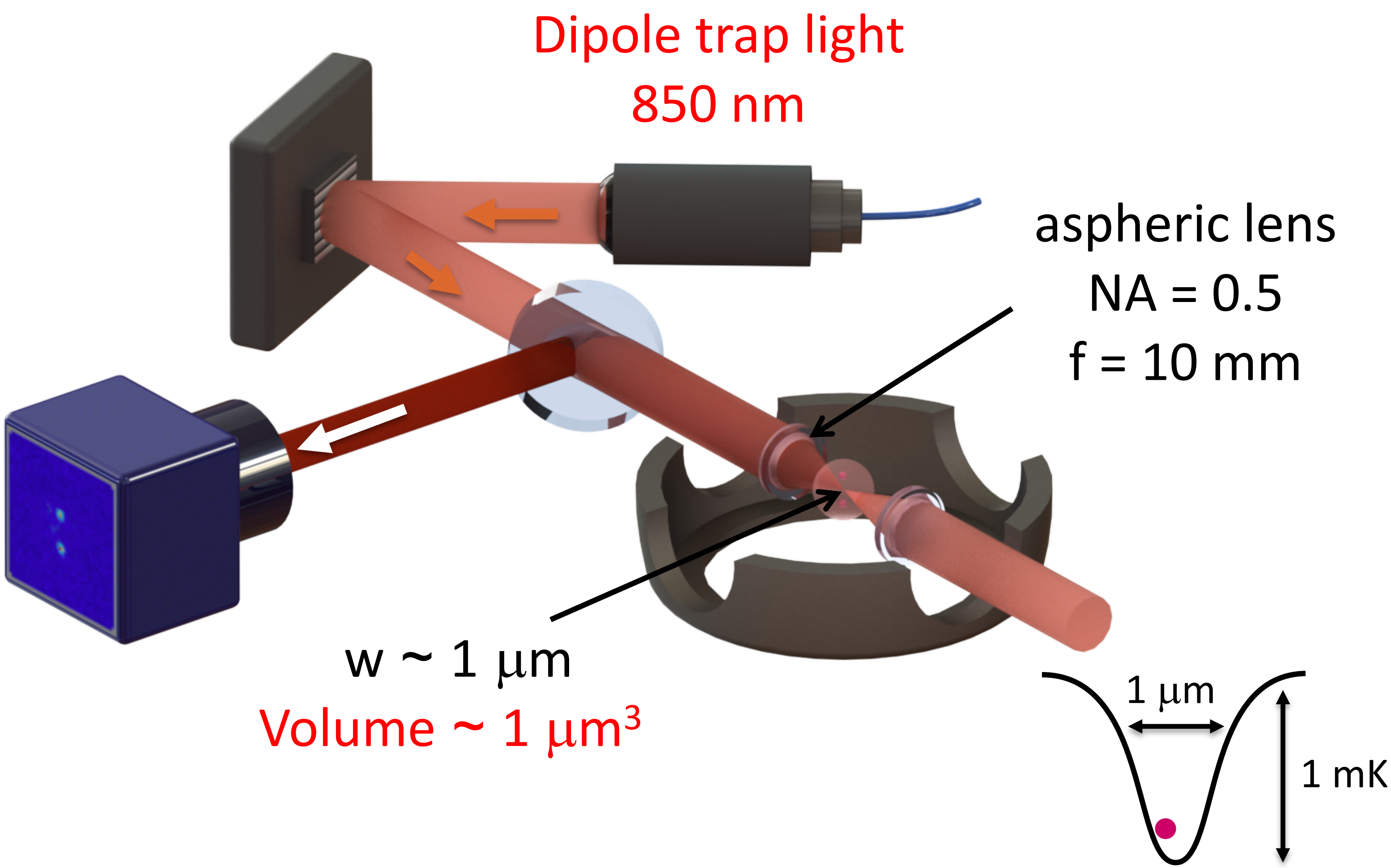
Trapping volume $\sim \pi\lambda^3$

Ex: 1 mW on 1 μm

Trap depth = 1 mK

Single atoms in optical tweezers

Schlosser, Nature (2001); Sortais, PRA (2007)



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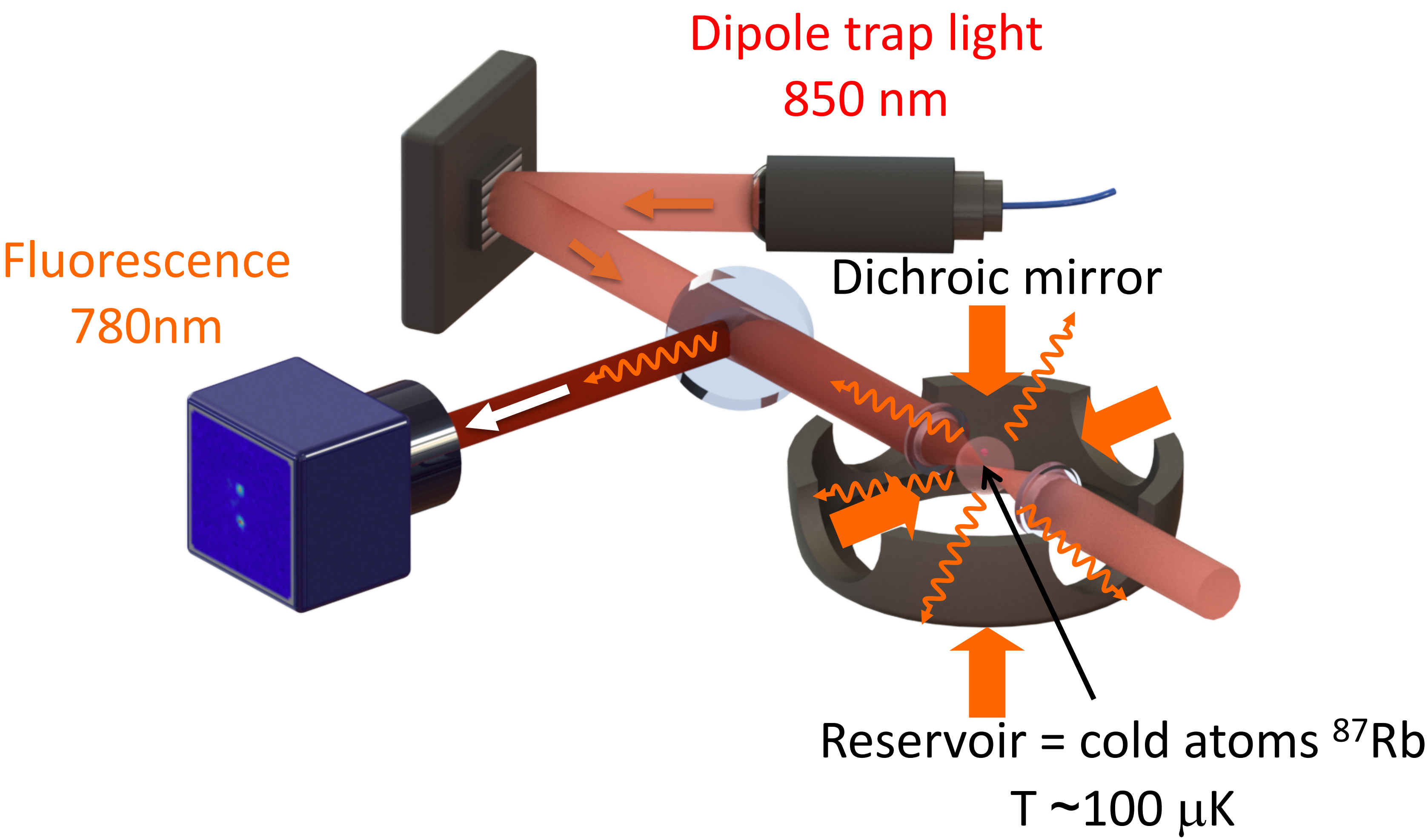
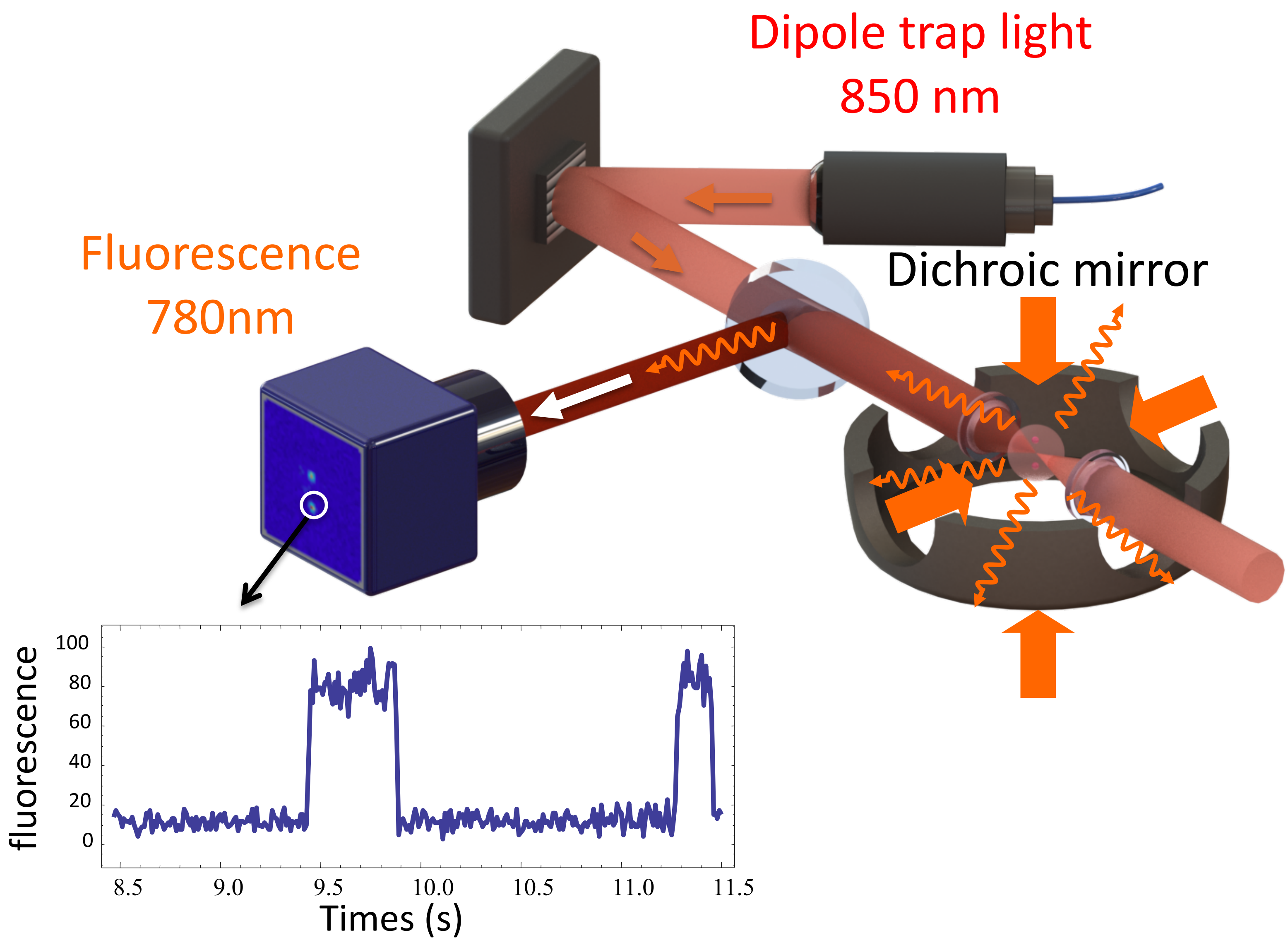
Schlosser, Nature (2001); Sortais, PRA (2007)



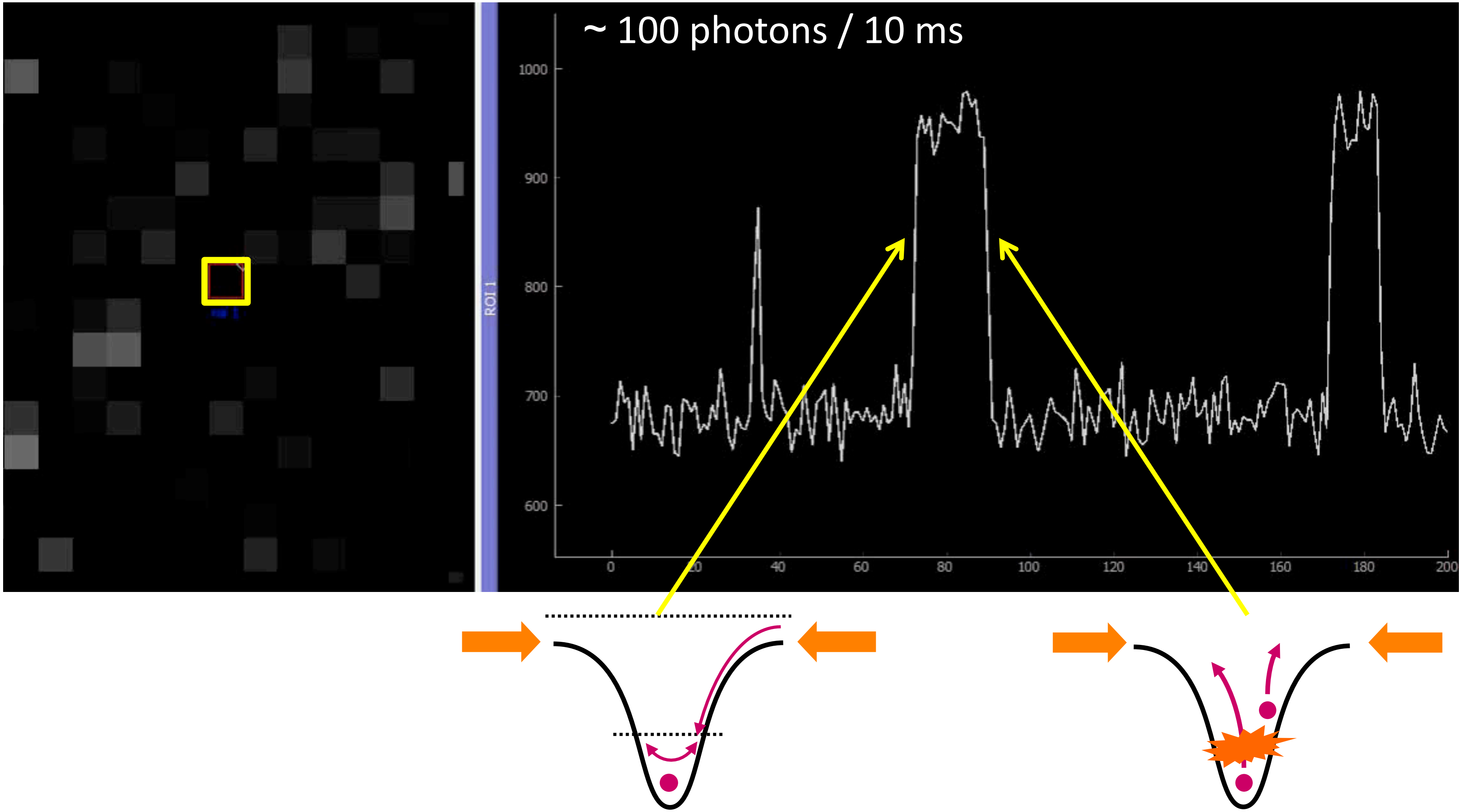
Single atoms in optical tweezers

Schlosser, Nature (2001); Sortais, PRA (2007)



Fast light-assisted collision prevents 2 atoms ...

Fluorescence @ 780 nm induced by the cooling lasers



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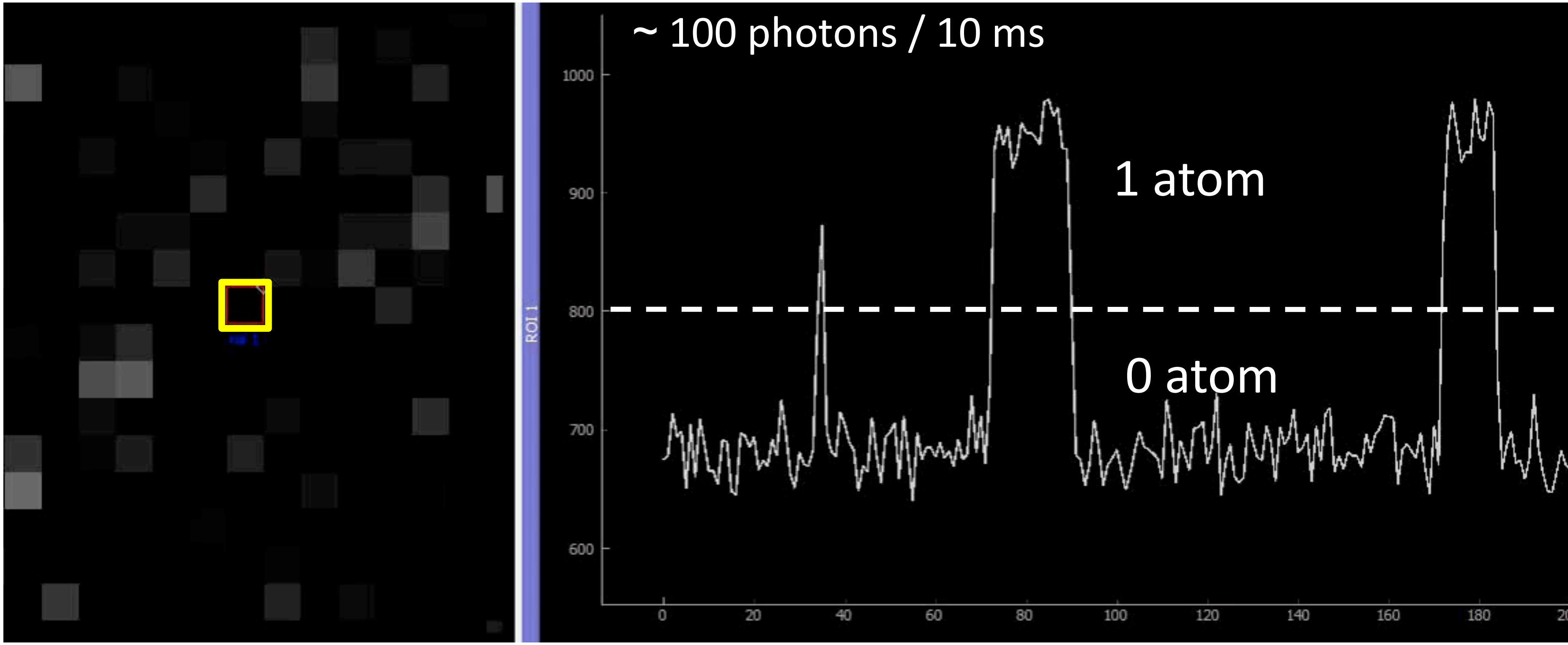
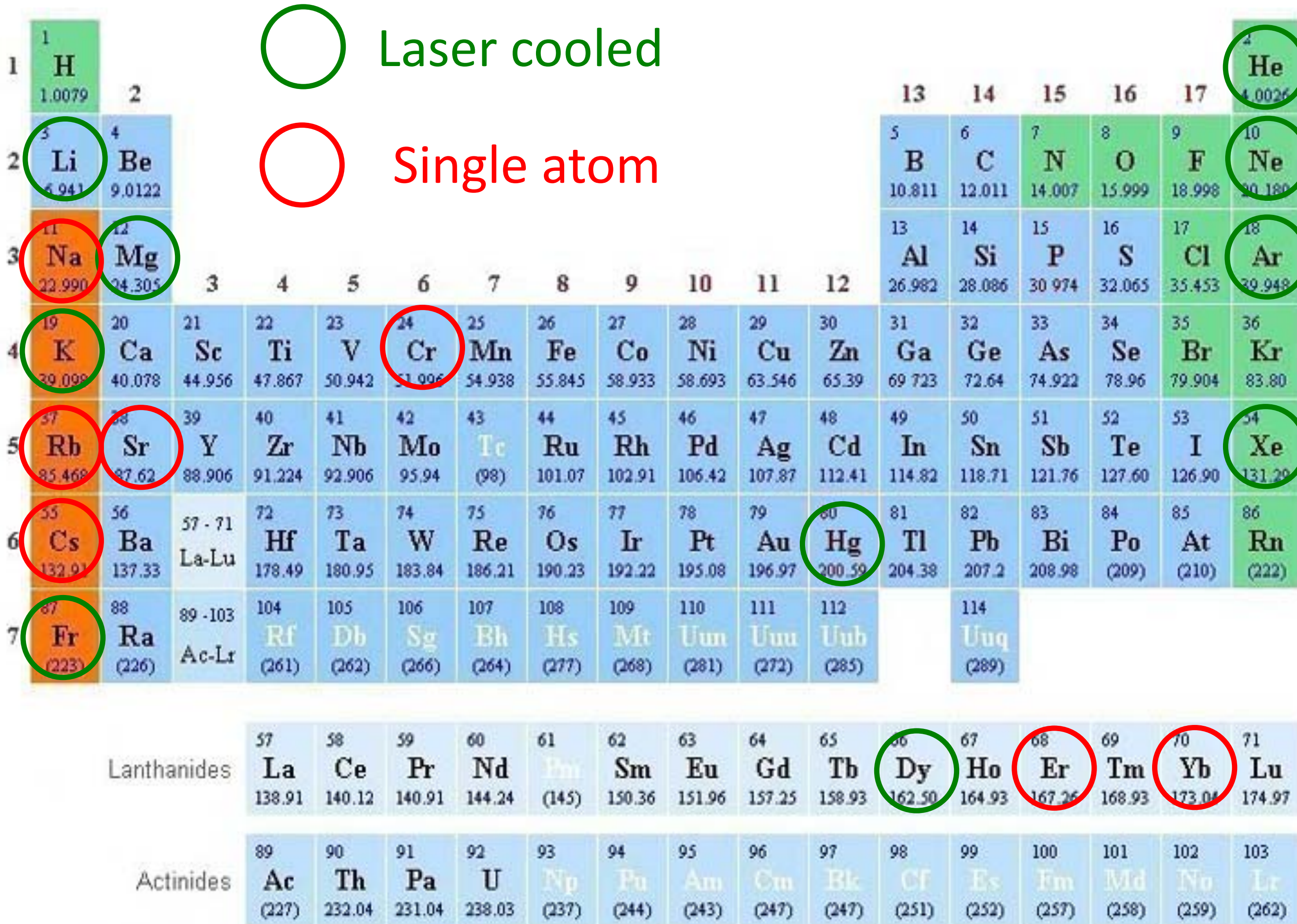


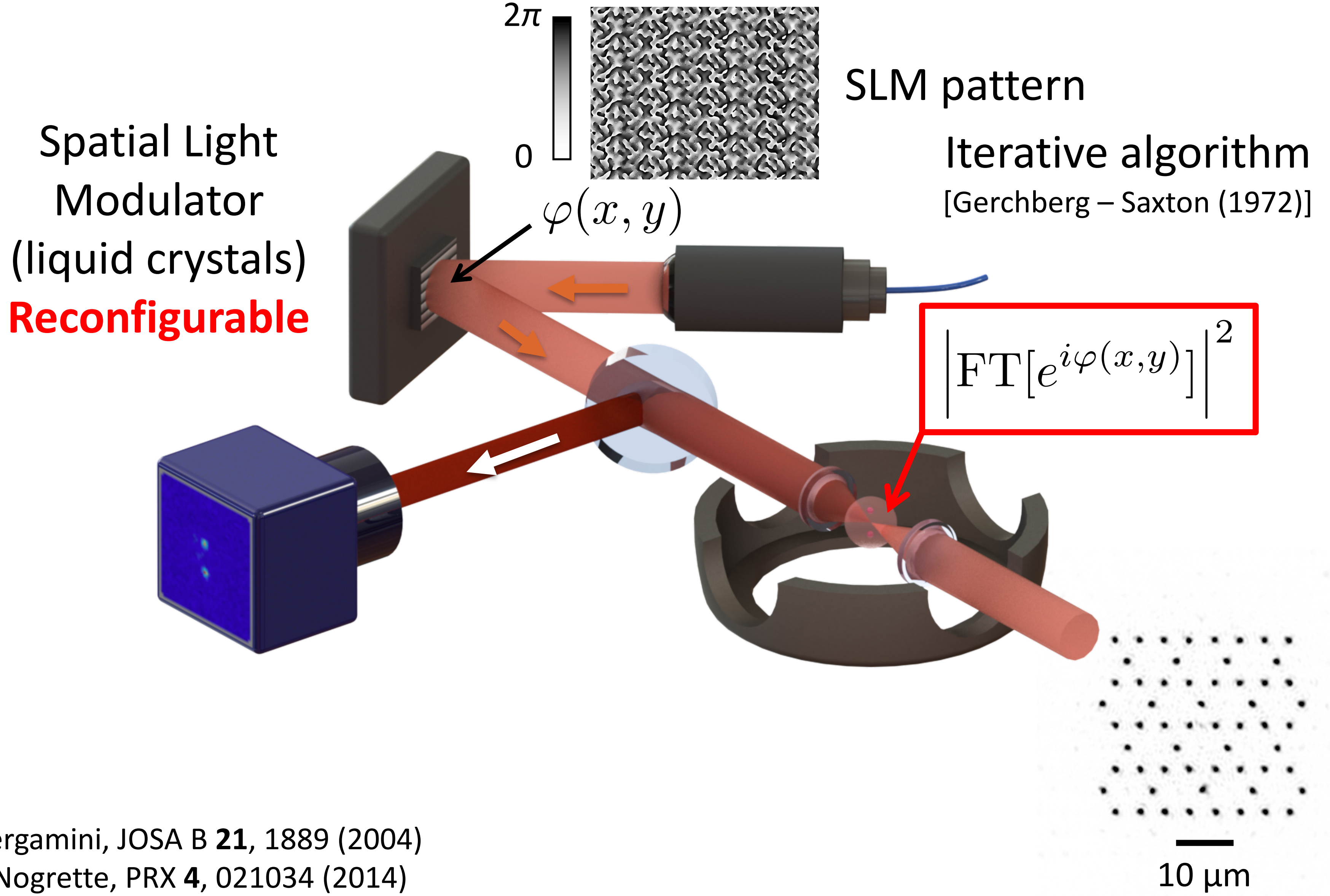
A single Rb atom (20 μK)!

Non deterministic

Which atoms?

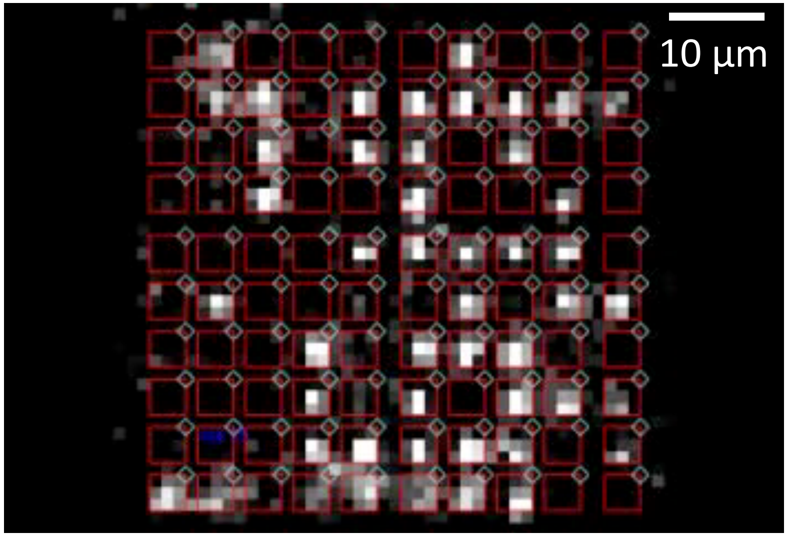


Holographic 2D arrays of tweezers



Bergamini, JOSA B **21**, 1889 (2004)
Nogrette, PRX **4**, 021034 (2014)

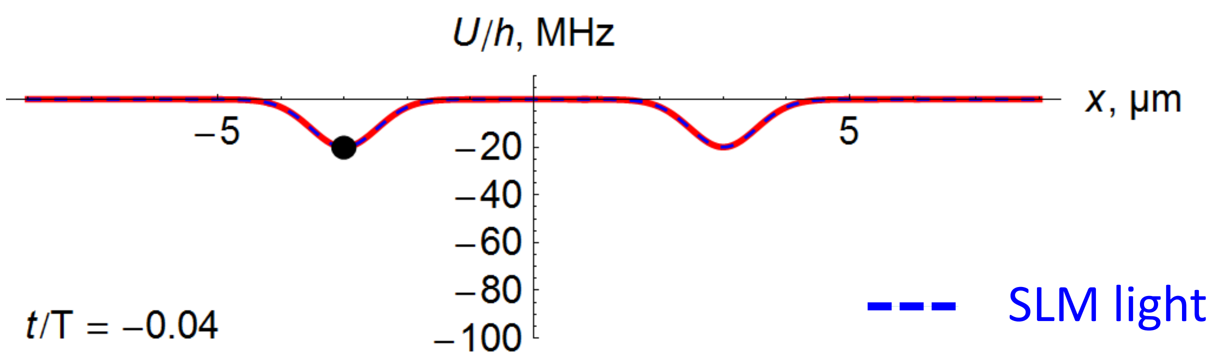
Atom-by-atom assembling of 2D arrays



Problem: stochastic loading (p ~ 0.5)

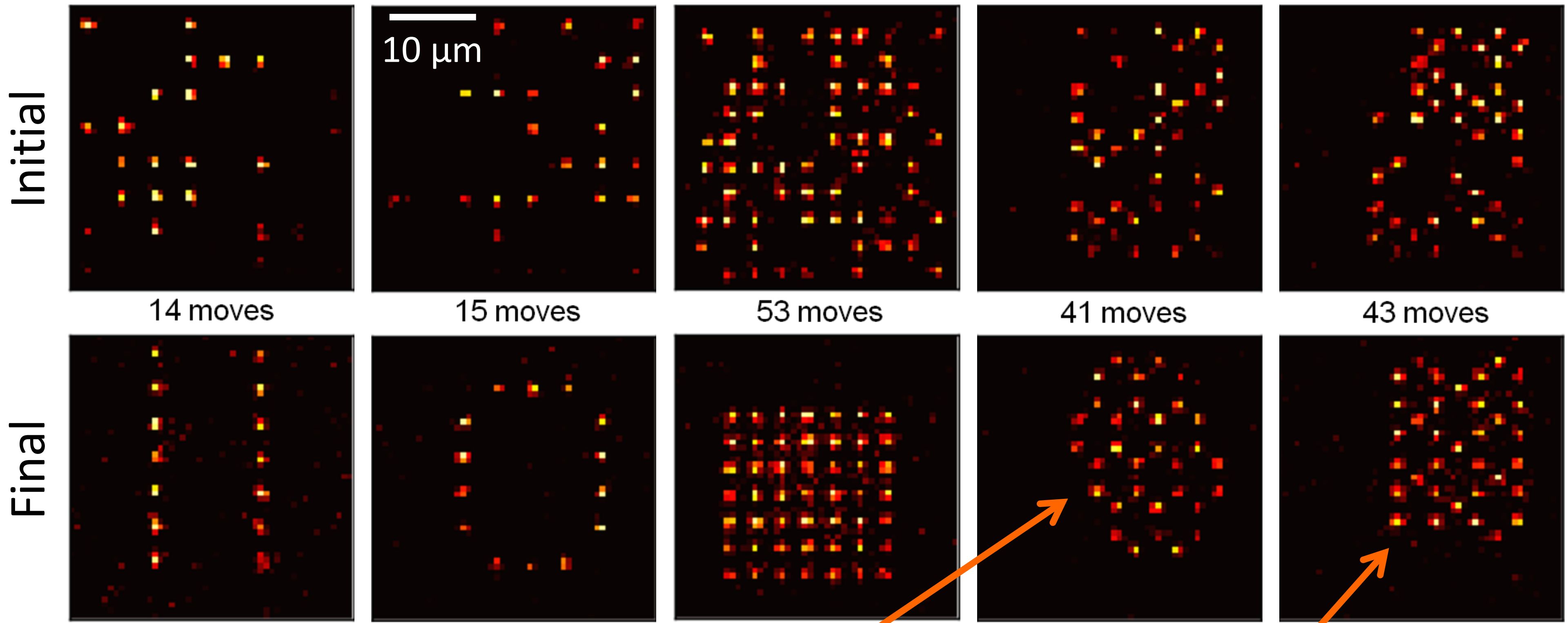
Solution: sort atoms in arrays

Moving atoms with a tweezers

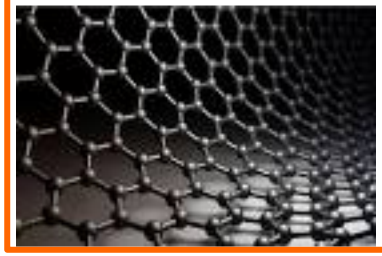


$$p \sim 0.993(1)$$

Gallery of assembled 2D arrays… (single-shot images…)



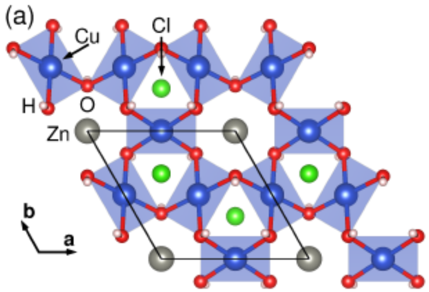
Hexagonal



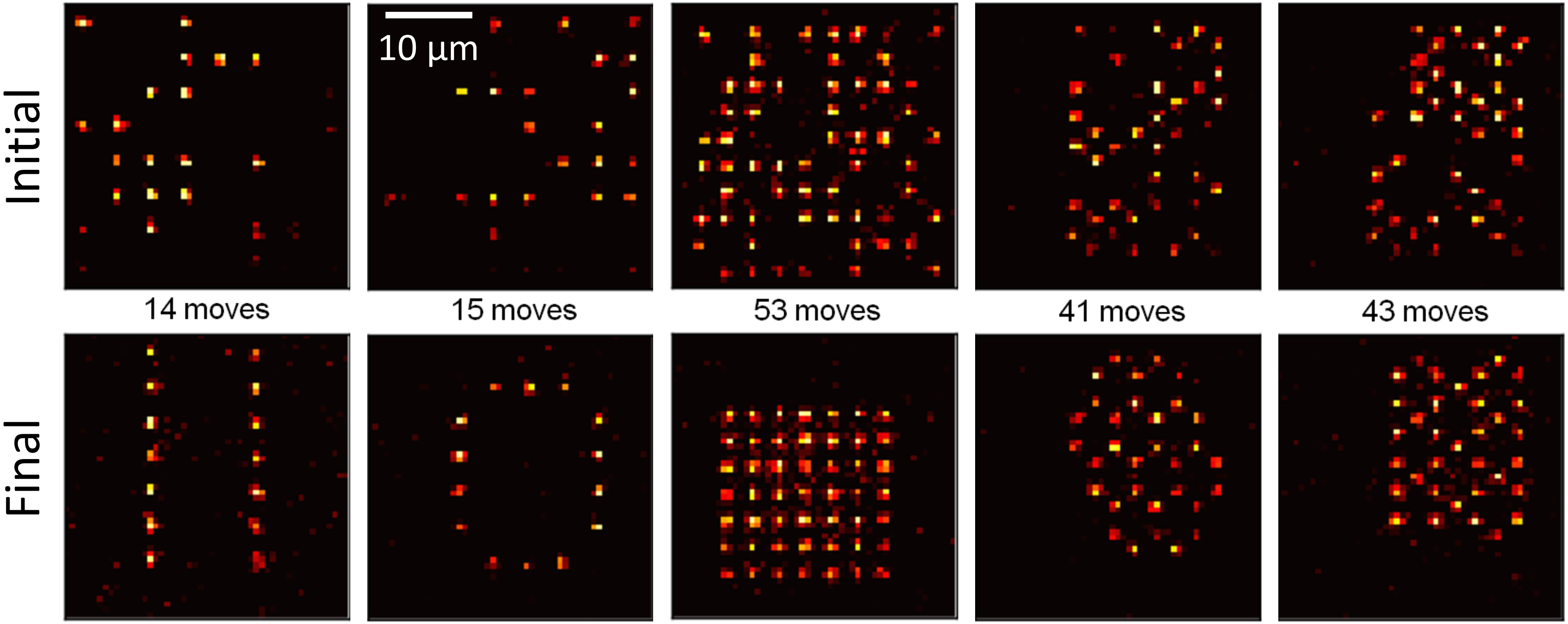
graphene

Kagome: Herbertsmithite

$ZnCu_3(OH)_6Cl_2$



Gallery of assembled 2D arrays... (single-shot images...)



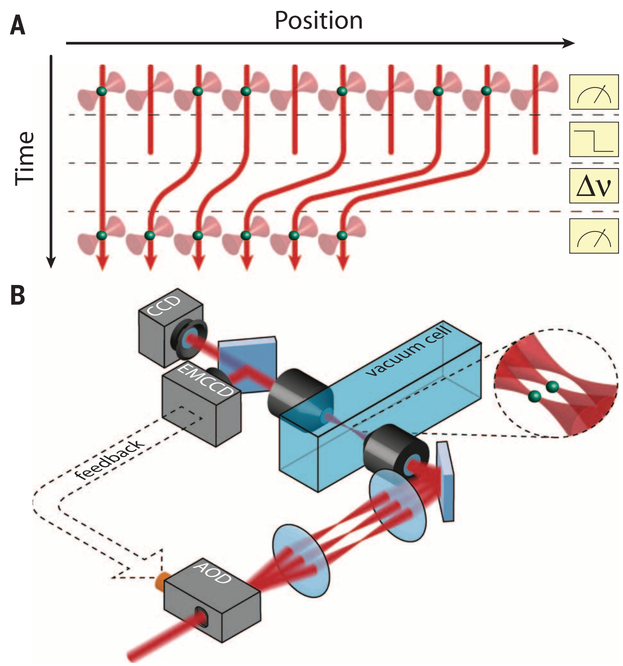
Barredo, de Léséleuc, *et al.*, Science **354**, 1021 (2016)

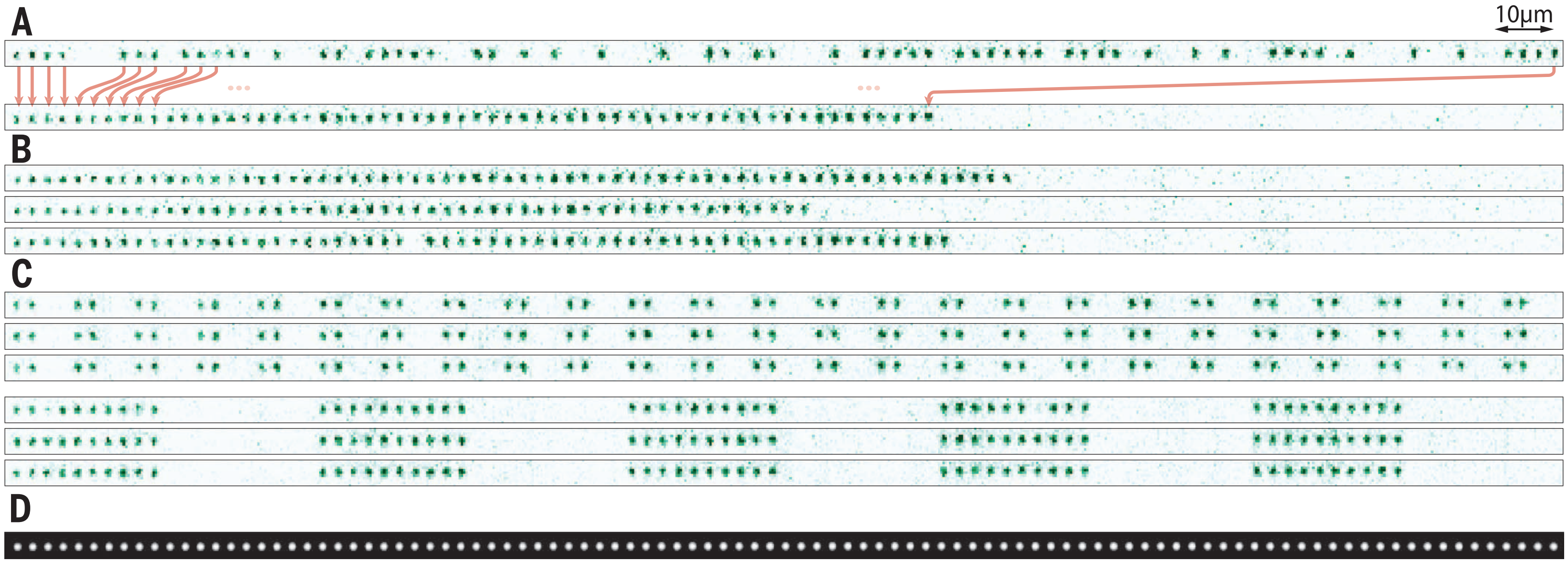
- Fully loaded arrays up to 50 atoms
- 98% filling fraction **@ 5 Hz**
- 100% filling every ~ 2-5 sec

Related works Harvard (1D) Science **354**,1024 (2016)
Korea (2D) Nat. Comm. **7**, 13317 (2016)

Sorting in 1D (Harvard)

Science **354**,1024 (2016)



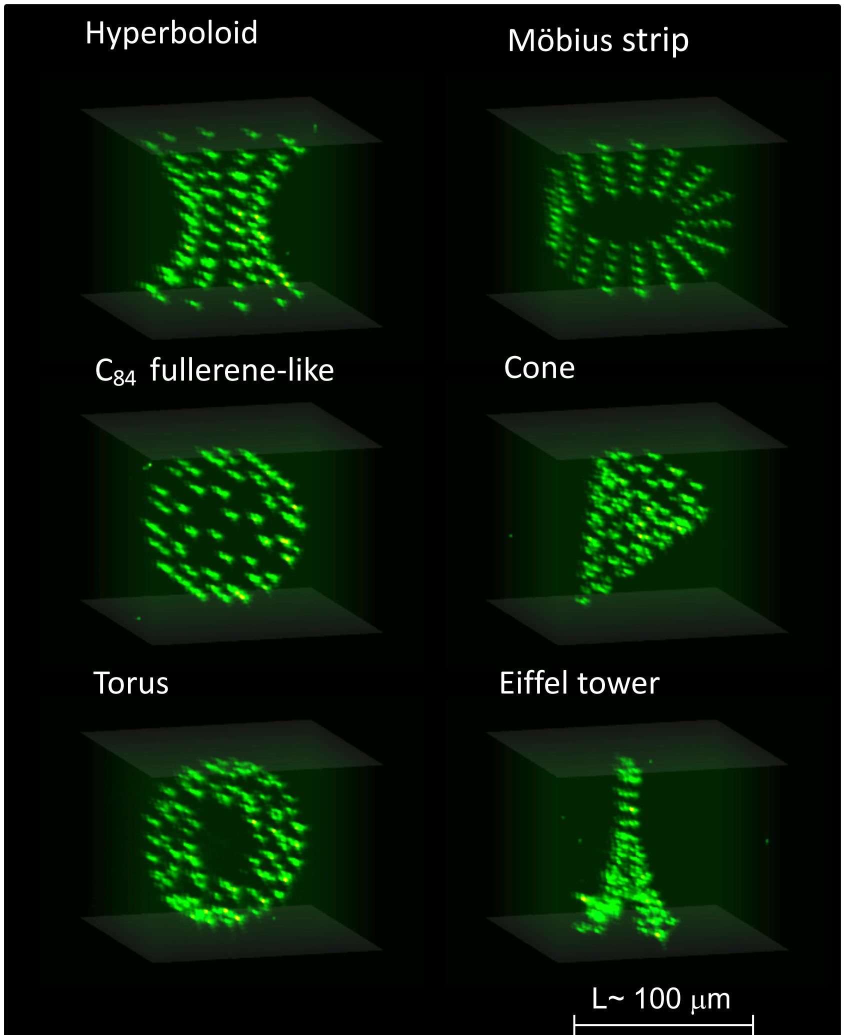


It also works in 3d!

Di Leonardo, Optics Express **15**, 1913 (2007)

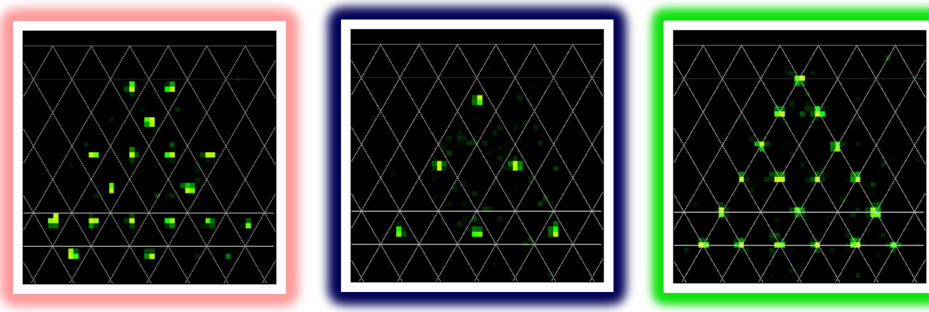
Averaged fluorescence

imaged "slice-by-slice"

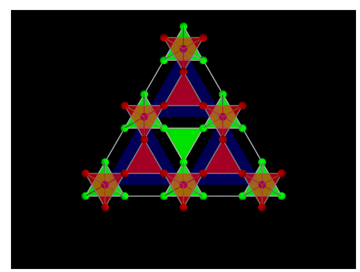


Assembled Pyrochlore lattice

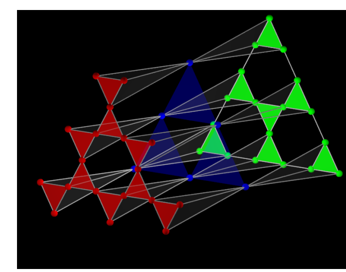
Plane 1 Plane 2 Plane 3



Front view



Side view

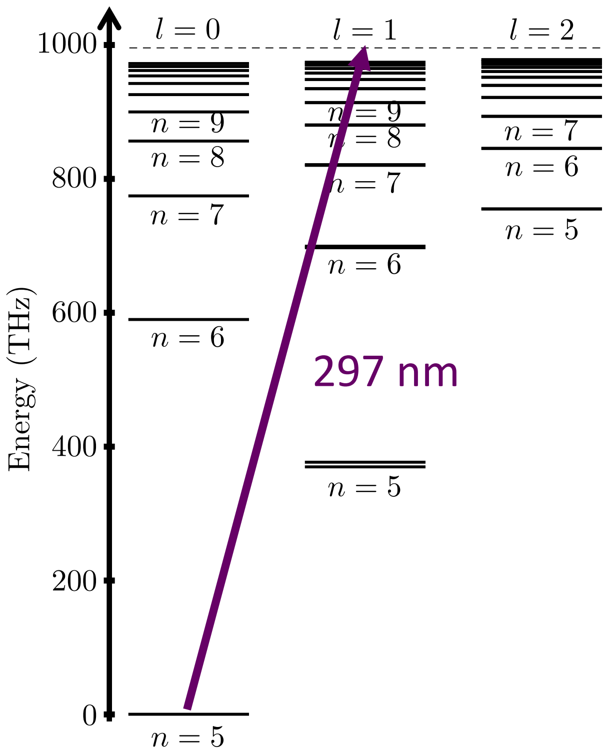


Barredo, Nature (2018)

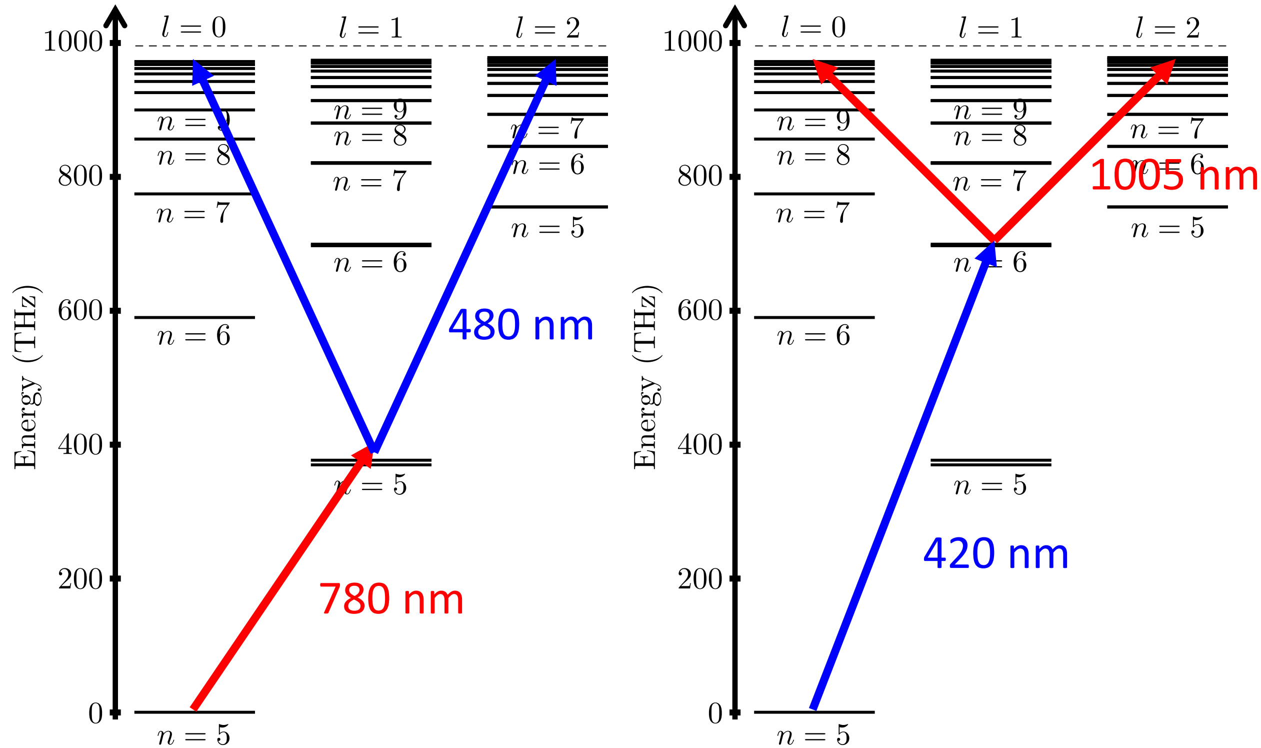
Also: Weiss, Nature (2018); Ahn, Opt. Exp (2016)

Coherent Rydberg excitation (rubidium)

Single photon (UV)



Two-photon

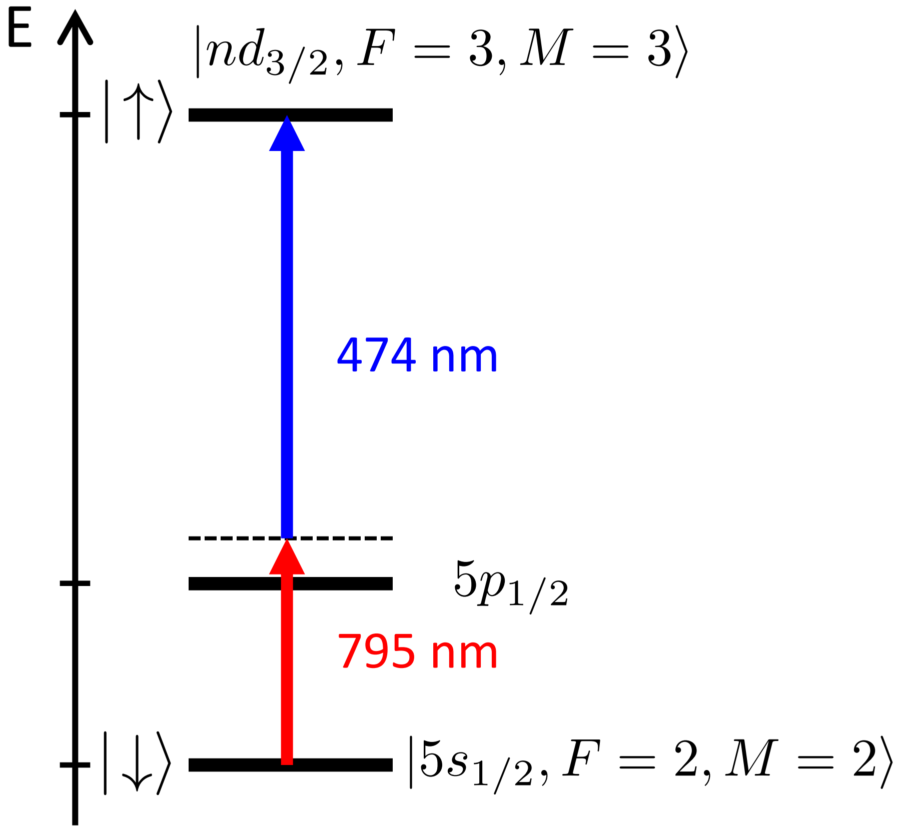


$$\Omega = \frac{\Omega_1 \Omega_2}{2\Delta}$$

Light-shift: $\delta_{\text{eff}} = \delta - \left(\frac{|\Omega_R|^2}{4\Delta} - \frac{|\Omega_B|^2}{4\Delta} \right)$

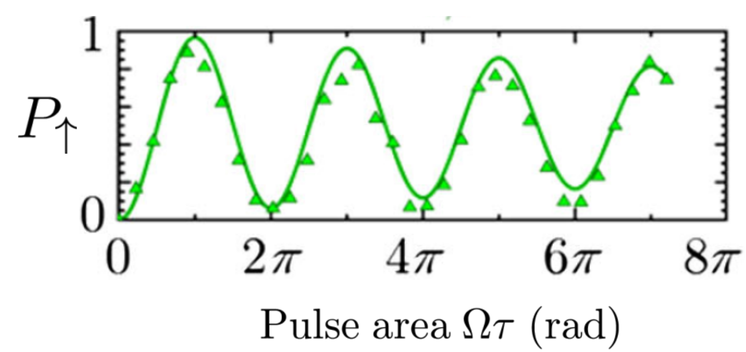
Coherent optical Rydberg excitation (n = 50 – 100)

^{87}Rb



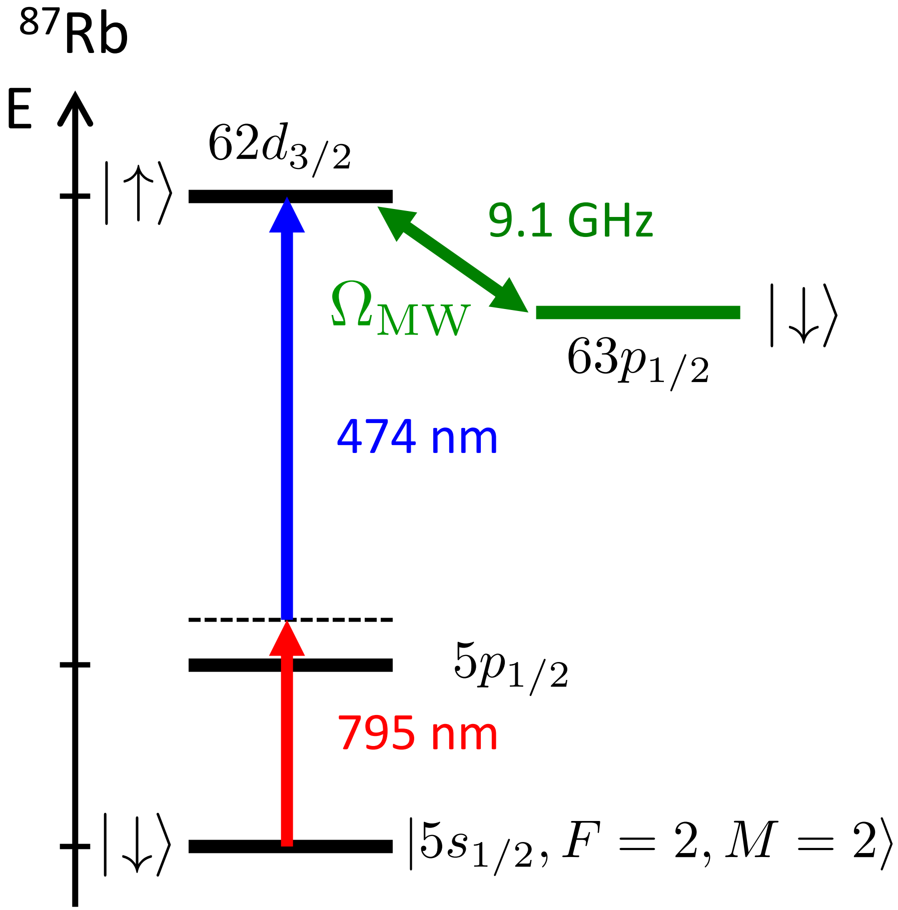
Single atom ⇒ repeat 100 times

Optical excitation (Ω = 0.5 – 5 MHz)



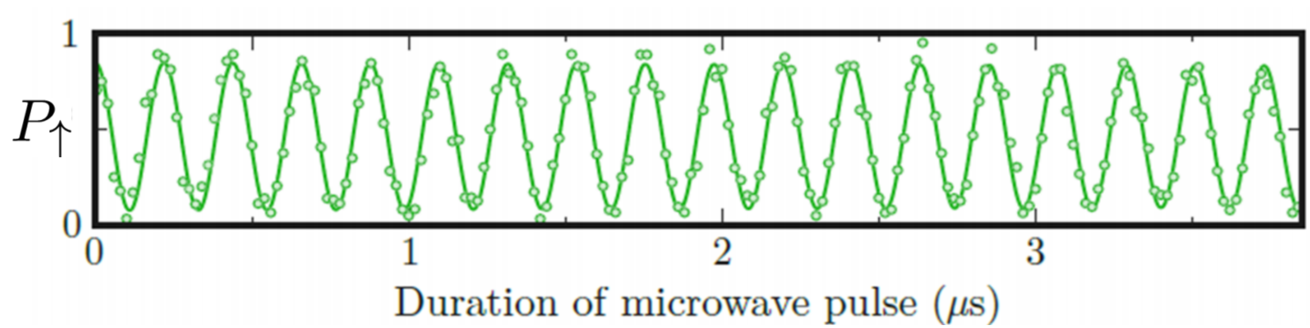
T. A. Johnson *et al.*, PRL **100**, 113003 (2008)
Miroshnychenko, PRA **82**, 023623 (2010)

Microwave manipulations (n = 50 – 100)



Single atom $\Rightarrow$ repeat 100 times

Microwave transfer



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

Outline

1. “Rydbergology”: scalings, interactions…
2. Experimental considerations: arrays of individual atoms
3. Measurement of interactions between Rydberg atoms
4. Rydberg blockade with individual atoms. Applications to quantum information
5. Rydberg blockade in atomic ensembles. Applications to quantum optics

References:

“Experimental investigations of dipole–dipole interactions between a few Rydberg atoms”, A. Browaeys *et al.*, J. Phys. B 49, 152001 (2016)

“Calculation of Rydberg interaction potentials”, S. Weber *et al.*, J. Phys. B **50**, 133001 (2017)

Softwares to calculate interaction energies

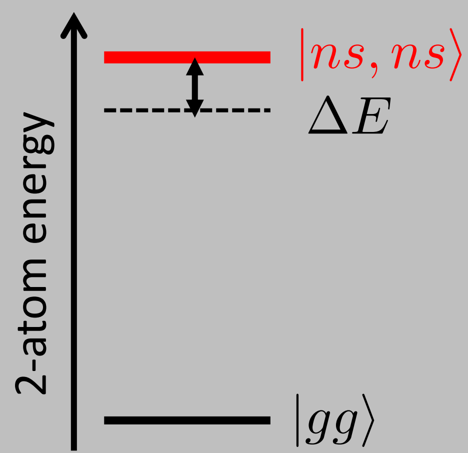
S. Weber *et al.*, arXiv:1612.08053, https://pairinteraction.github.io

ARC: An open-source library for calculating properties of alkali Rydberg atoms, N. Sibalic *et al.,* arXiv:1612.05529 (2016)

Interactions between Rydberg atoms

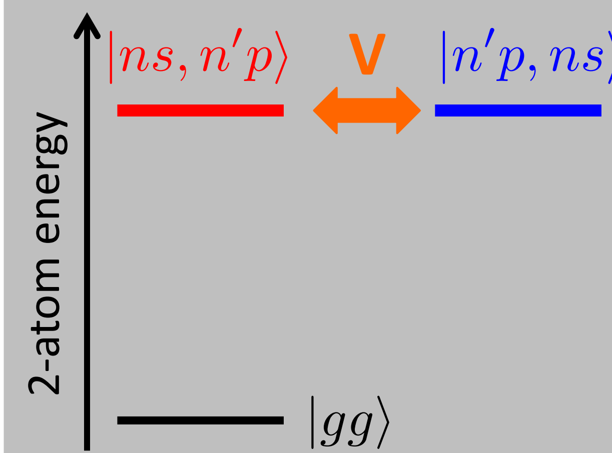
$$\hat{V} \sim \frac{\hat{d}_A \hat{d}_B}{4\pi\epsilon_0 R^3}$$

van der Waals



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

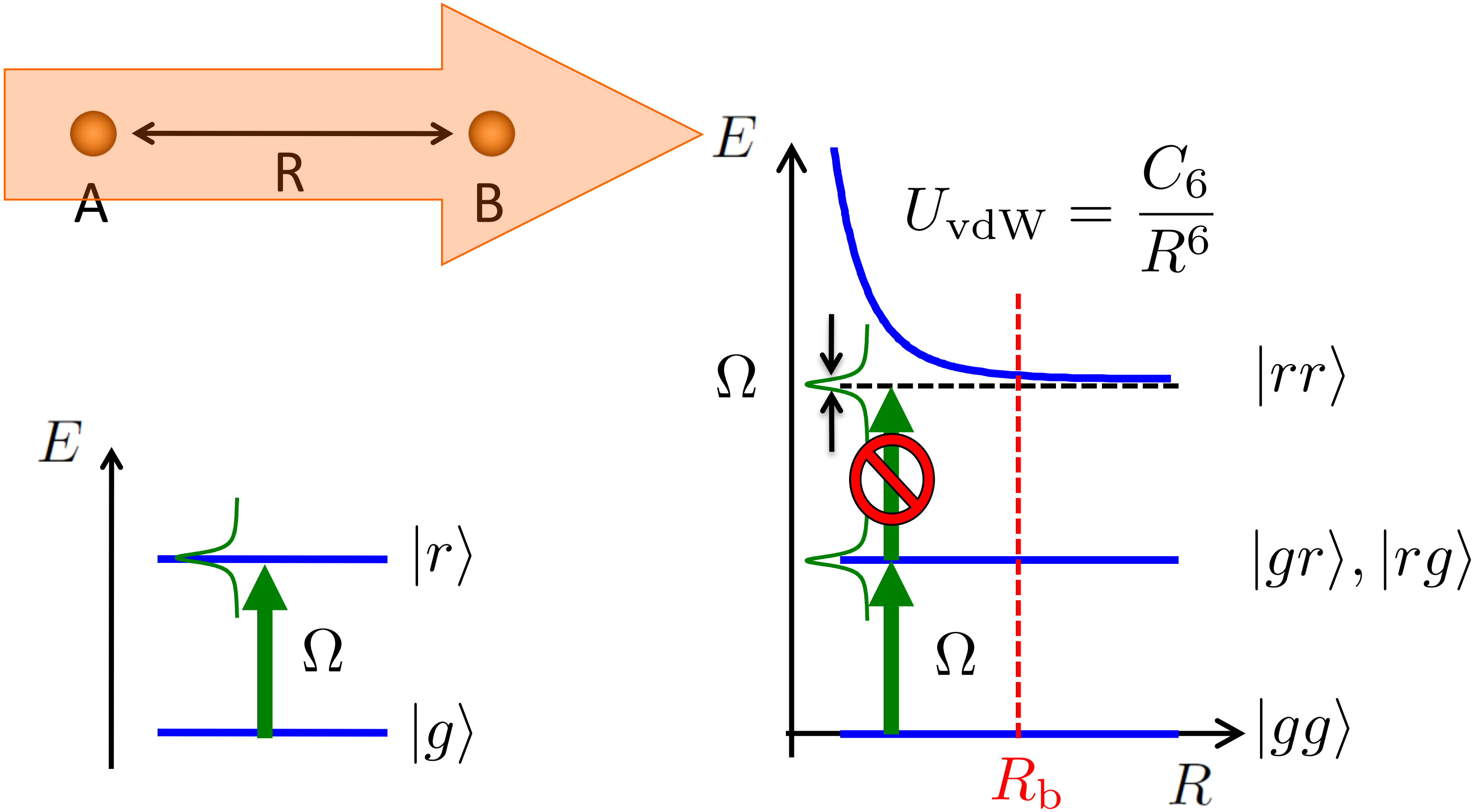
Resonant interaction



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

Review: Browaeys *et al.*, J. Phys. B **49**, 152001 (2016)

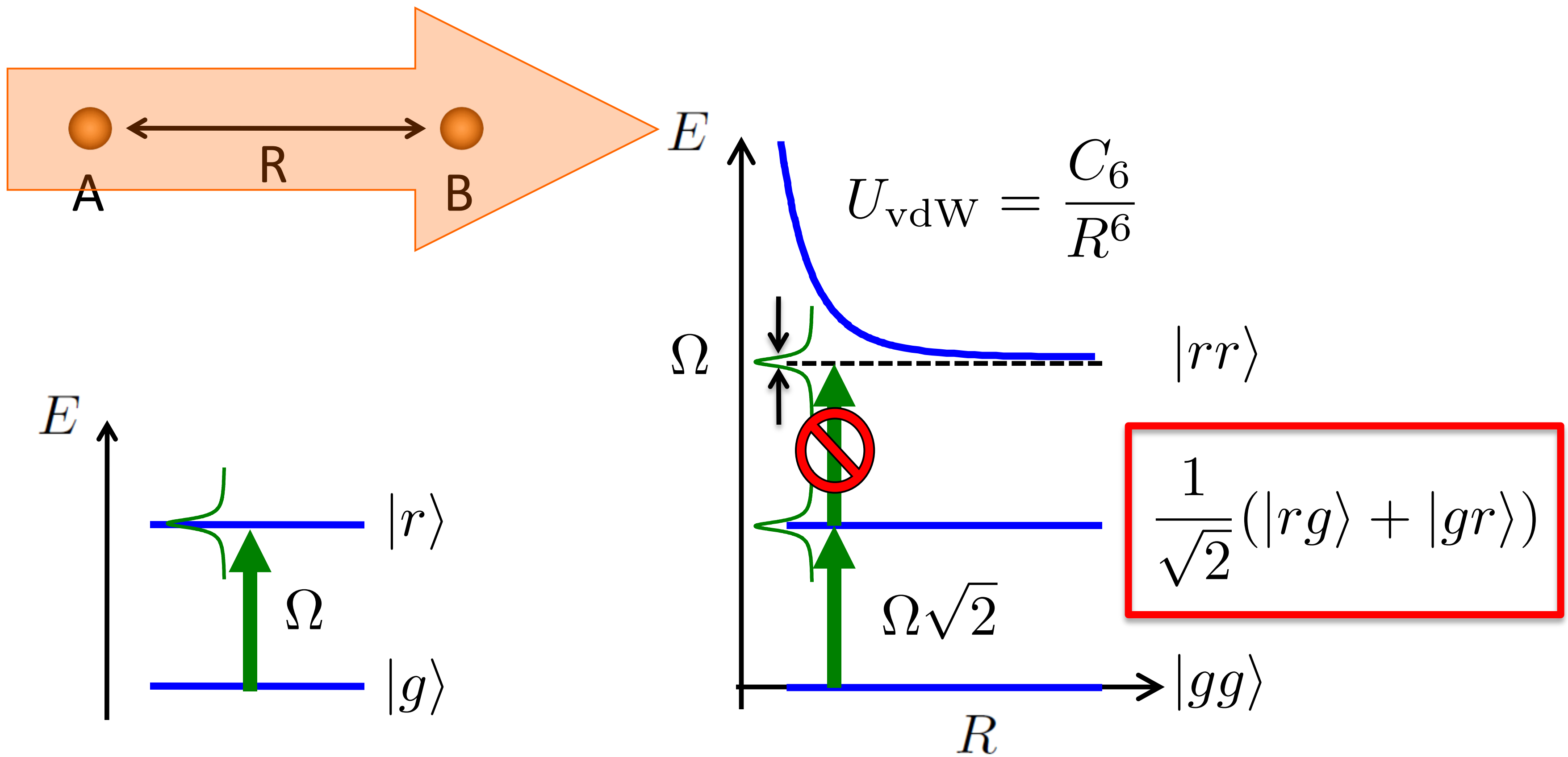
Collective excitation of two interacting Rydberg atoms



If $\hbar\Omega \ll U_{\mathrm{vdW}}$: no excitation of $|rr\rangle \Rightarrow$ **blockade**

Dynamics governed by Ω **only**

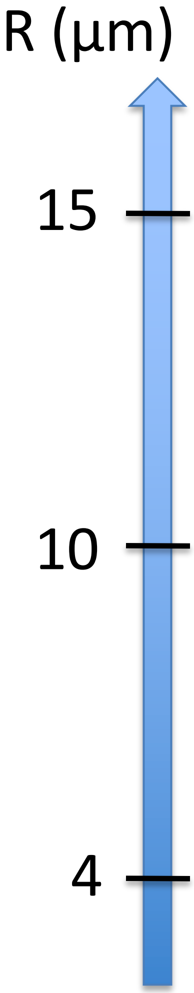
Collective excitation of two interacting Rydberg atoms

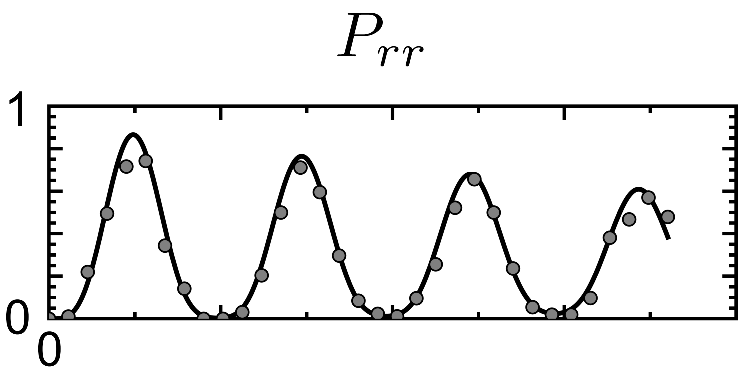


Collective oscillation between $|gg\rangle$ and $\frac{1}{\sqrt{2}}(|rg\rangle + |gr\rangle)$

with coupling $\Omega\sqrt{2}$ (N atoms $\Rightarrow$ $\Omega\sqrt{N}$)

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





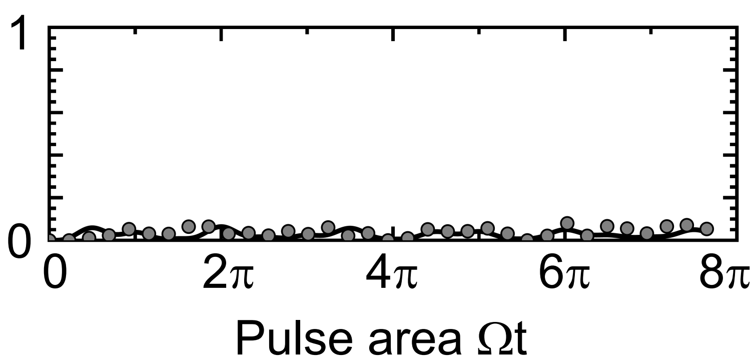
$$\hbar\Omega \gg U_{\mathrm{vdW}}$$

Blockade regime

First demonstrations

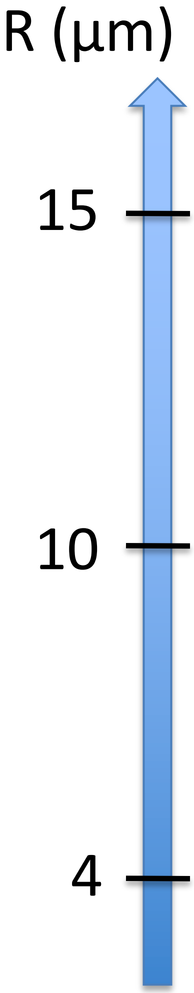
Gaétan *et al.*, Nat. Phys. **5**, 115 (2009)

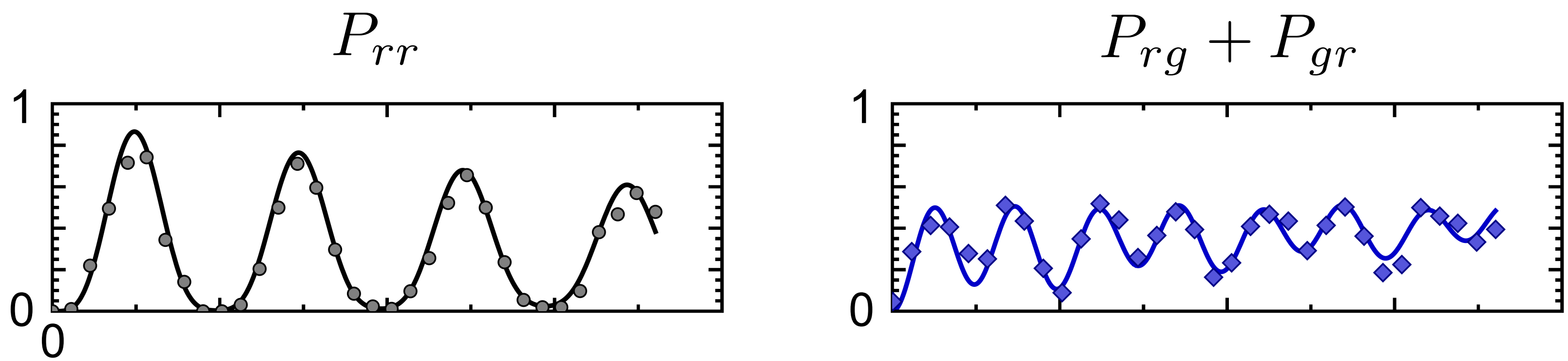
Urban *et al.*, Nat. Phys. **5**, 110 (2009)



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

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





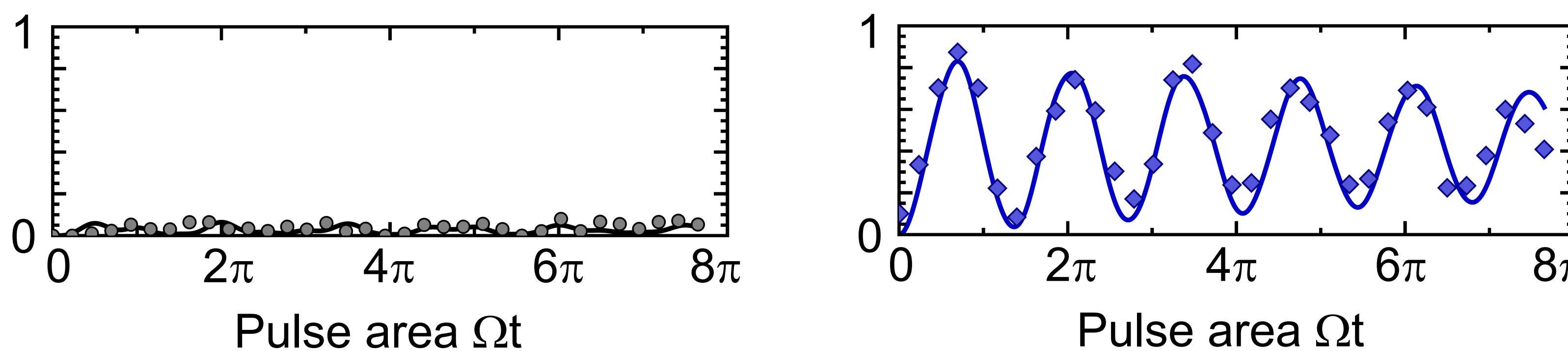
Blockade regime

First demonstrations

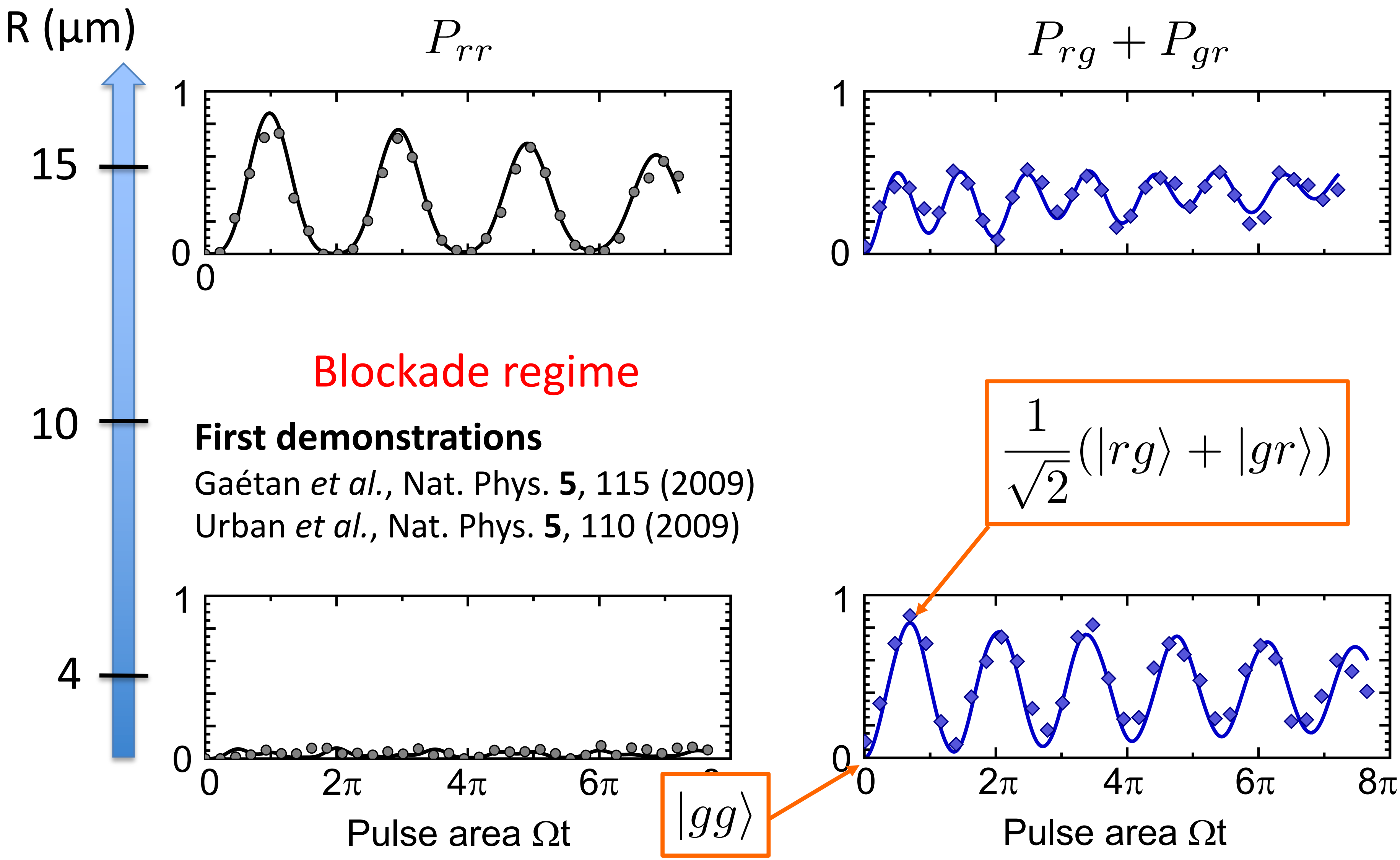
Gaétan *et al.*, Nat. Phys. **5**, 115 (2009)

Urban *et al.*, Nat. Phys. **5**, 110 (2009)

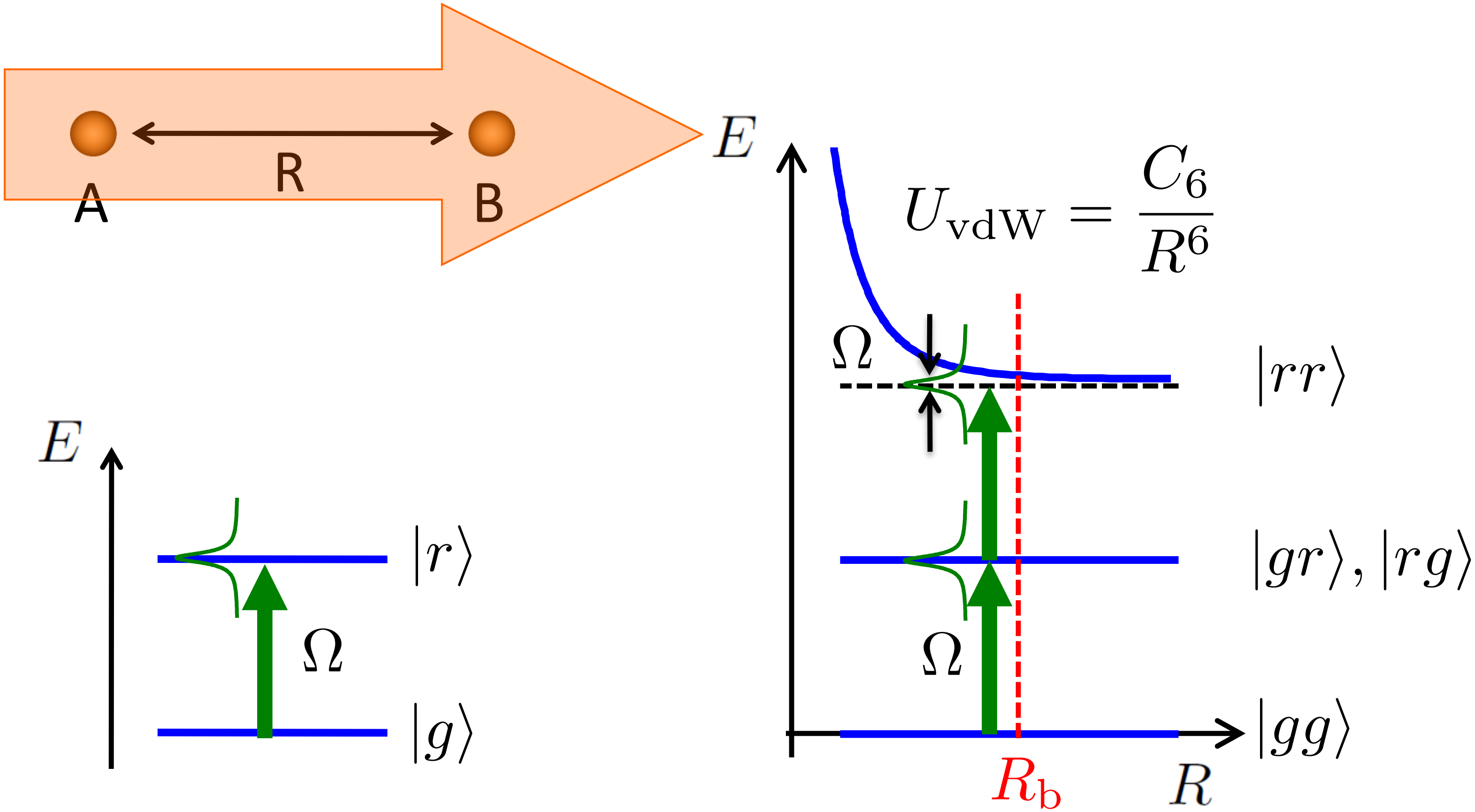
Freq. ratio = 1.41 $\approx \sqrt{2}$



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

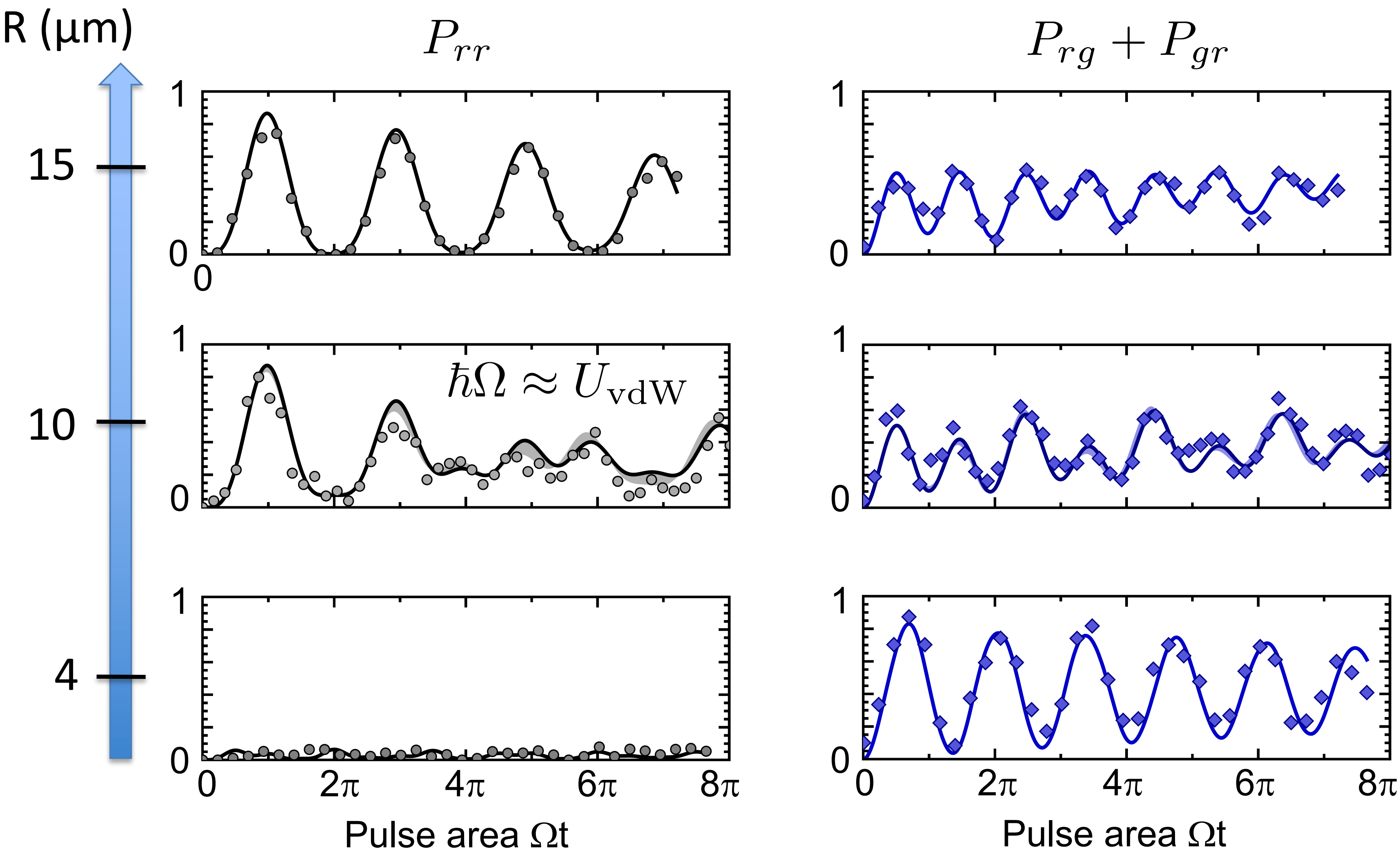


Collective excitation of two interacting Rydberg atoms

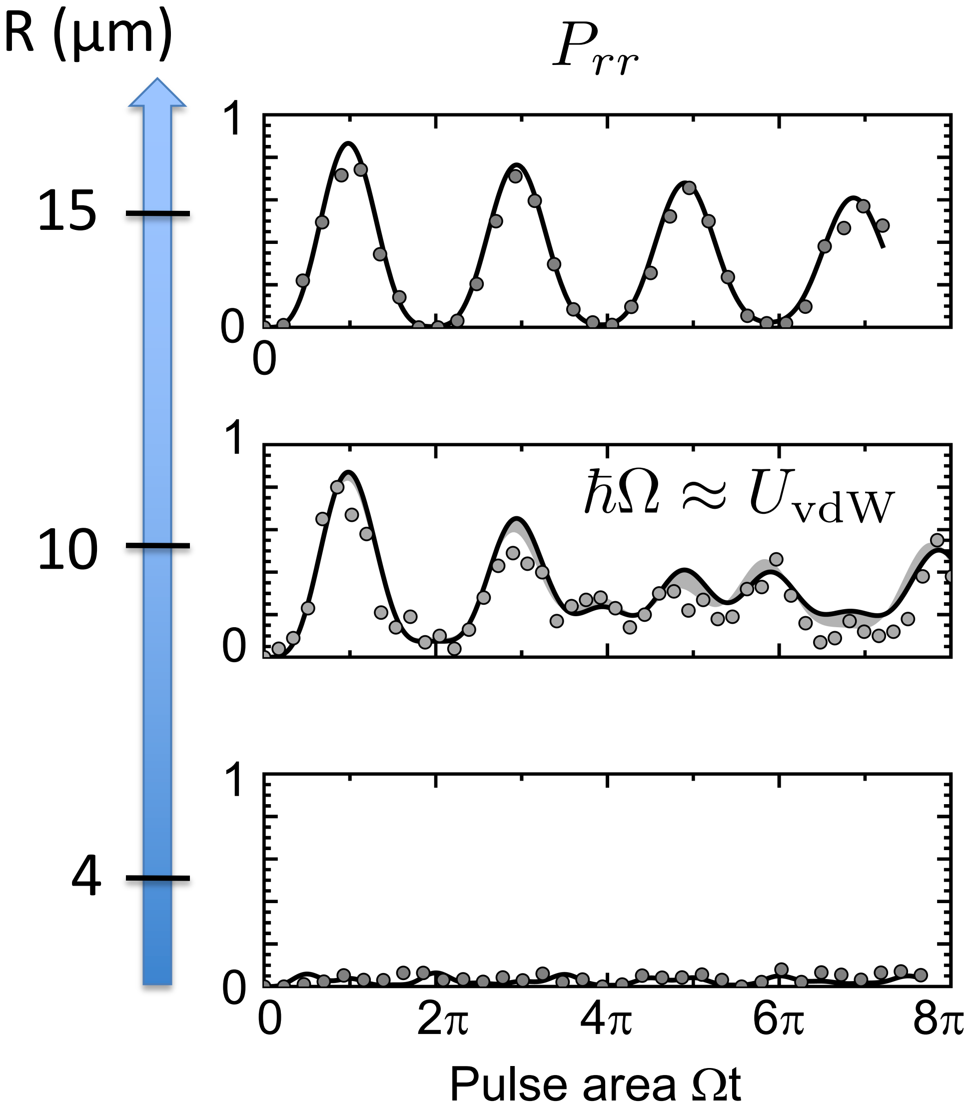


If $\hbar\Omega \approx U_{\mathrm{vdW}}$: dynamics governed by Ω **and** U_{vdW}

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

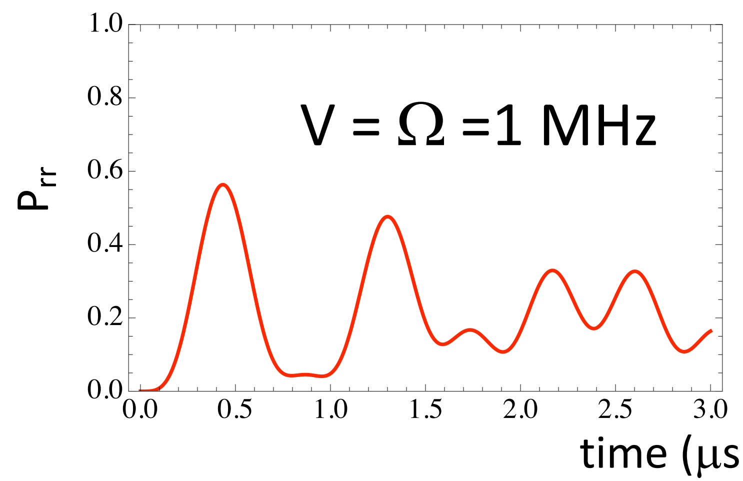


From independent atoms to blockade ($62d_{3/2}$)



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

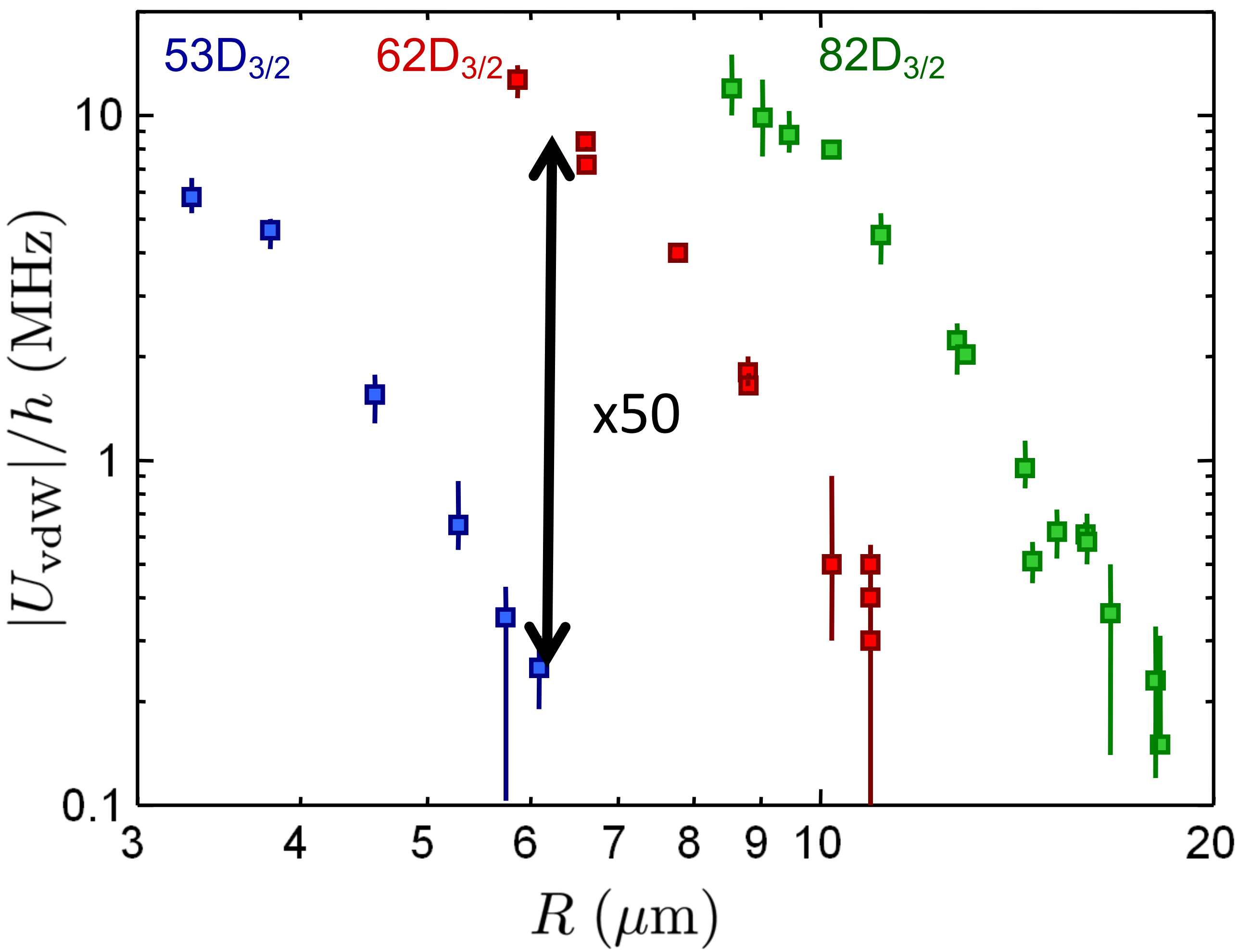
Theory (Schrödinger eq.)



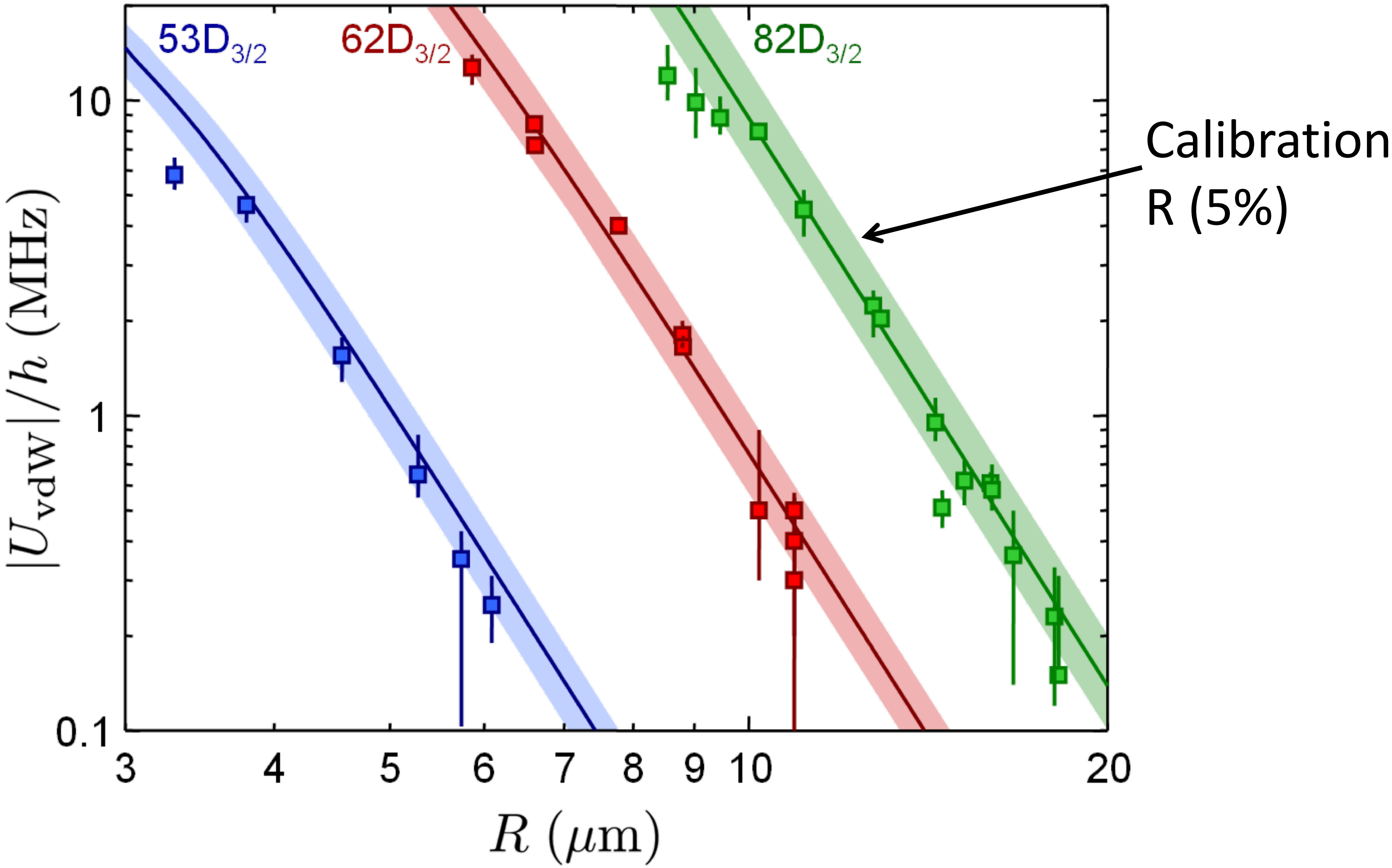
$\hbar\Omega \ll U_{\mathrm{vdW}}$

Fit ⇒ extract U_{vdW}

Measurement of vdW interaction between 2 atoms



Measurement of vdW interaction between 2 atoms



Theory curves: direct diagonalization (dipole-dipole interaction)

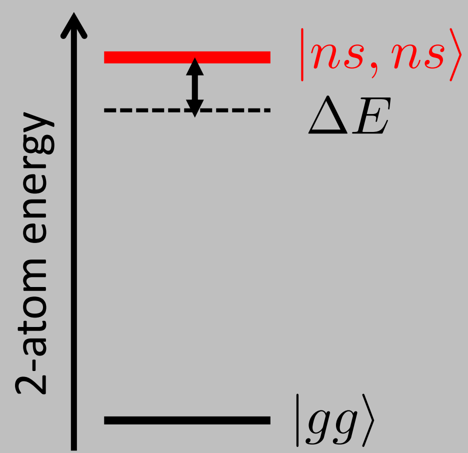
No adjustable parameter!

Béguin *et al.*, Phys. Rev. Lett. **110** 263201 (2013)

Interactions between Rydberg atoms

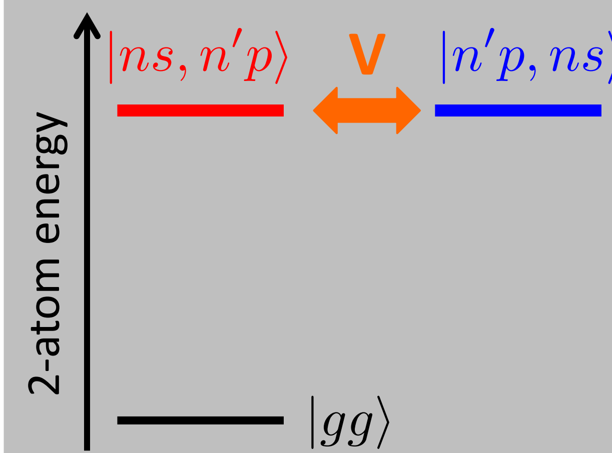
$$\hat{V} \sim \frac{\hat{d}_A \hat{d}_B}{4\pi\epsilon_0 R^3}$$

van der Waals



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

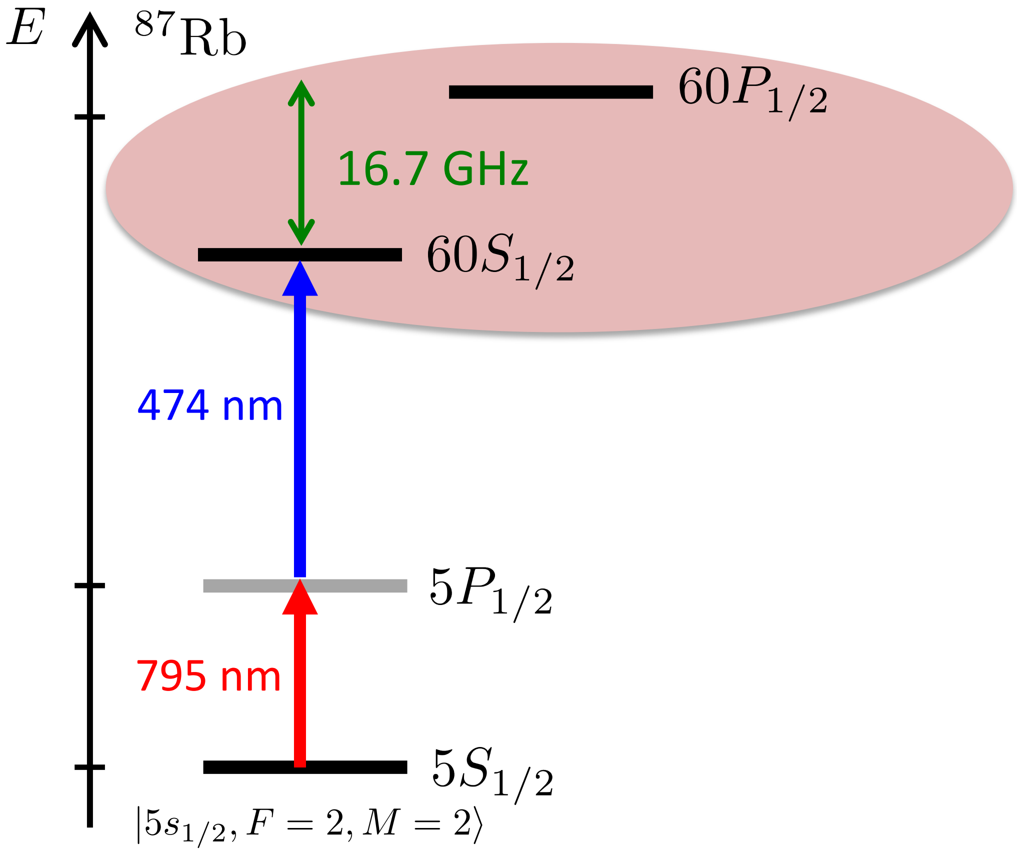
Resonant interaction



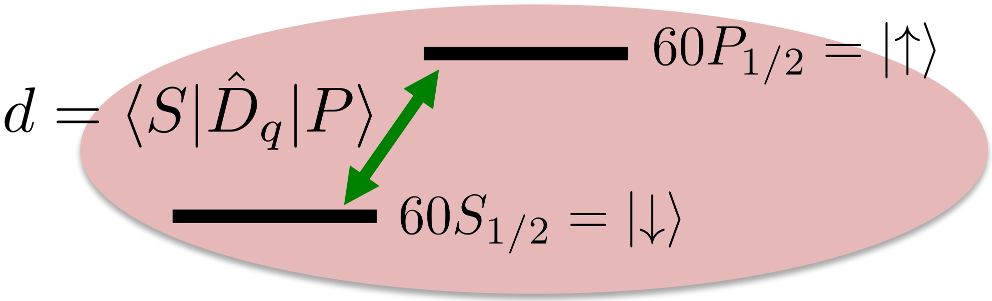
$$V \sim \frac{C_3}{R^3}$$

Review: Browaeys *et al.*, J. Phys. B **49**, 152001 (2016)

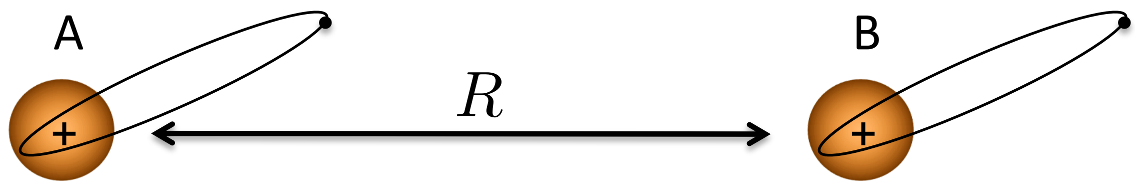
Resonant dipole-dipole interaction between Rydberg atoms

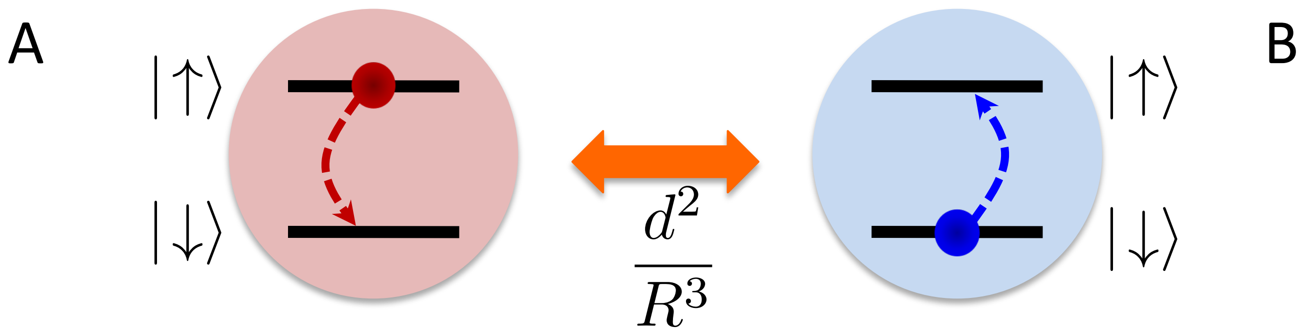


Resonant dipole-dipole interaction between Rydberg atoms



Mapping on spin ½ system





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

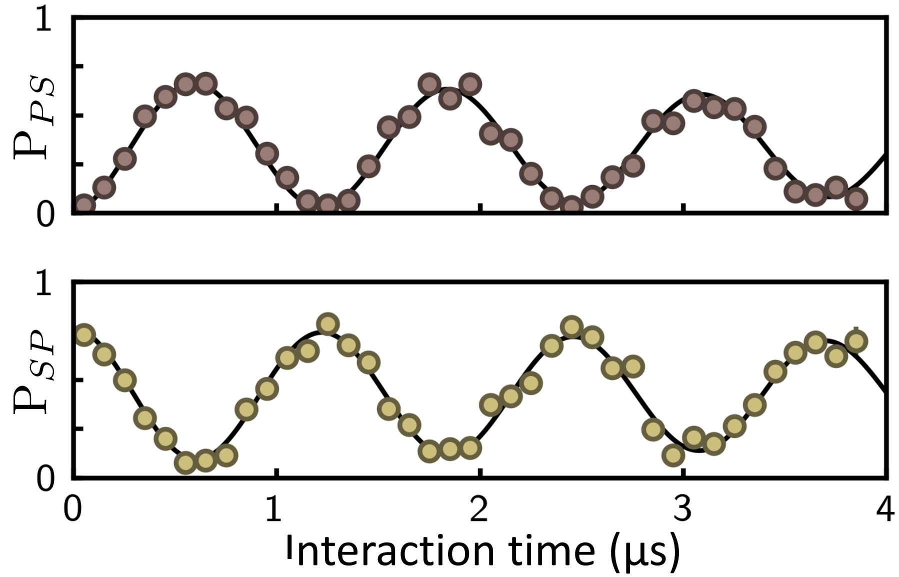
Non radiative “exchange” of excitation

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

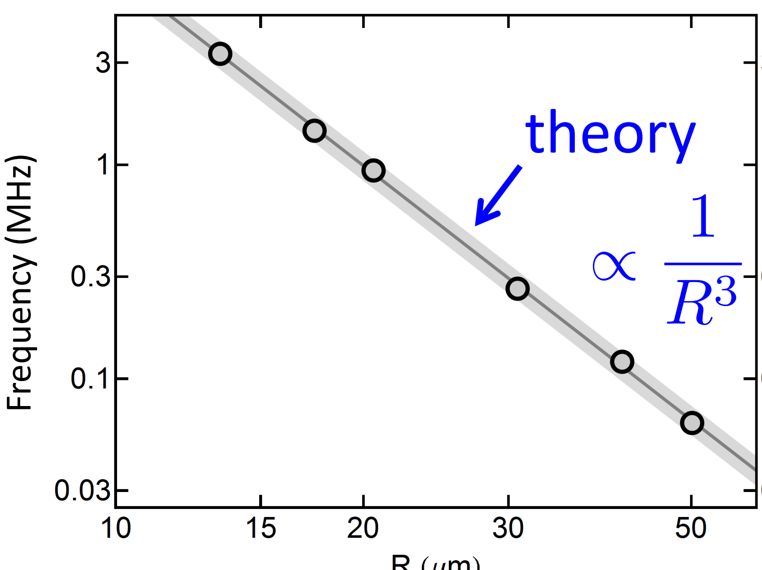
Prepare $|\uparrow\downarrow\rangle$ using microwaves + addressing beam

R = 30 µm

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



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



Thickness:

Paper sheet ~ 100 µm

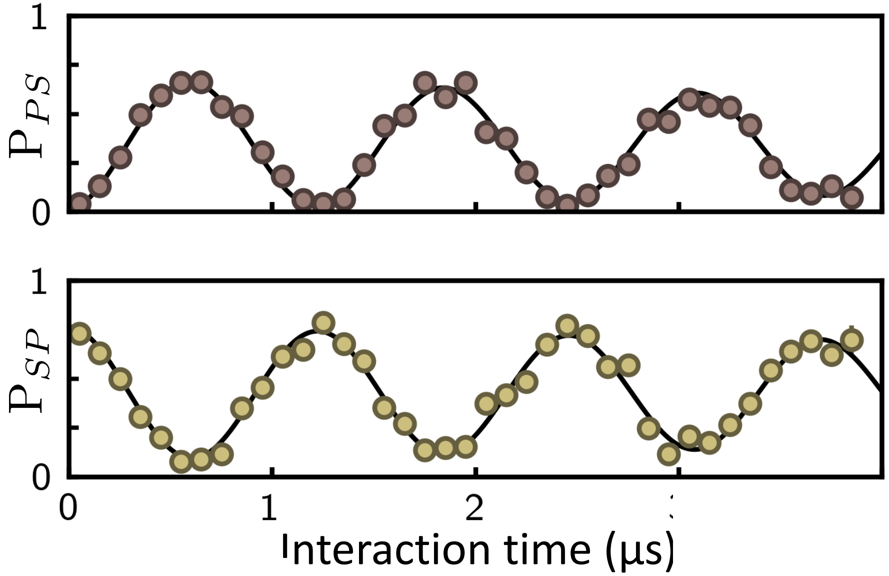
Hair ~ 50 – 100 µm

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

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

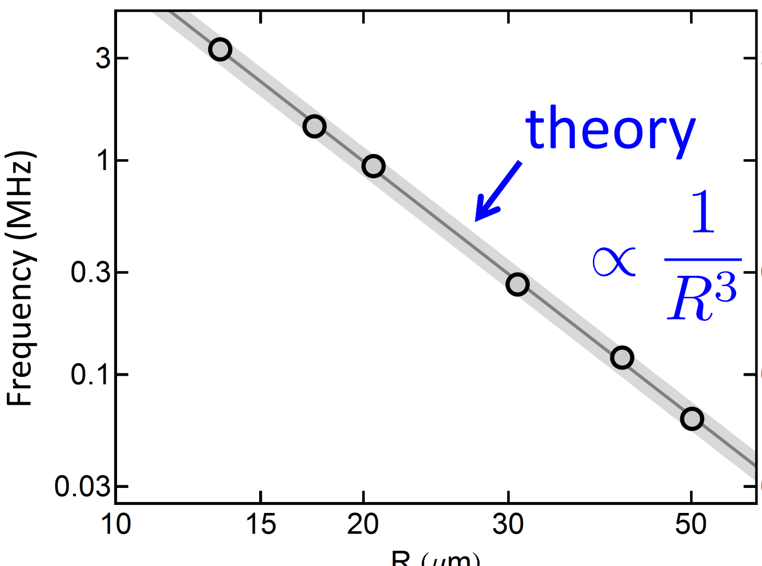
R = 30 µm

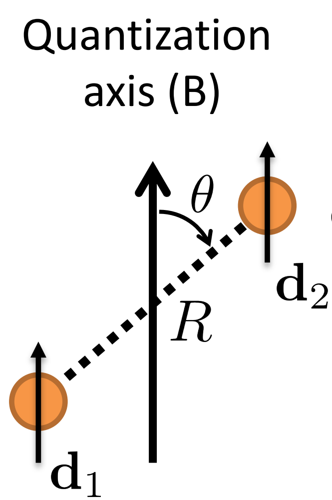
Frequency: $\frac{2C_3}{R^3}$

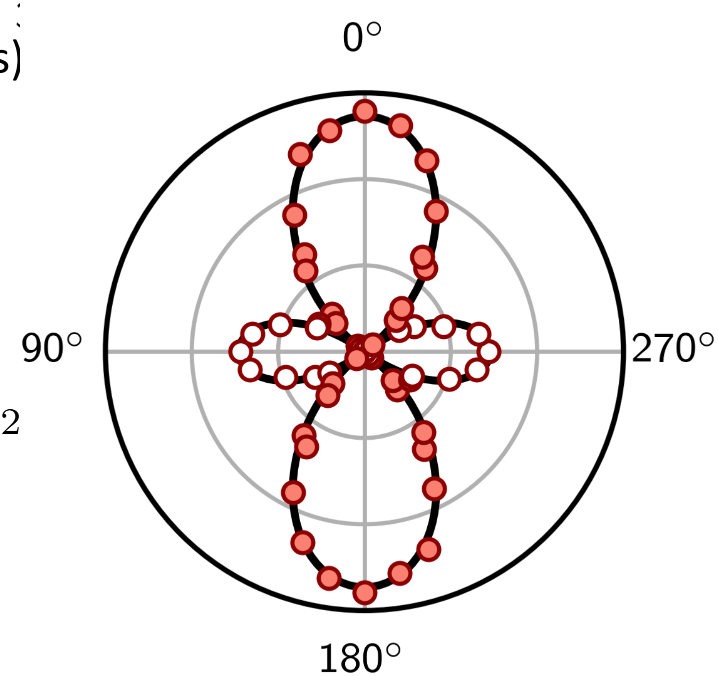


Barredo PRL (2015)
de Léséleuc, PRL (2017)

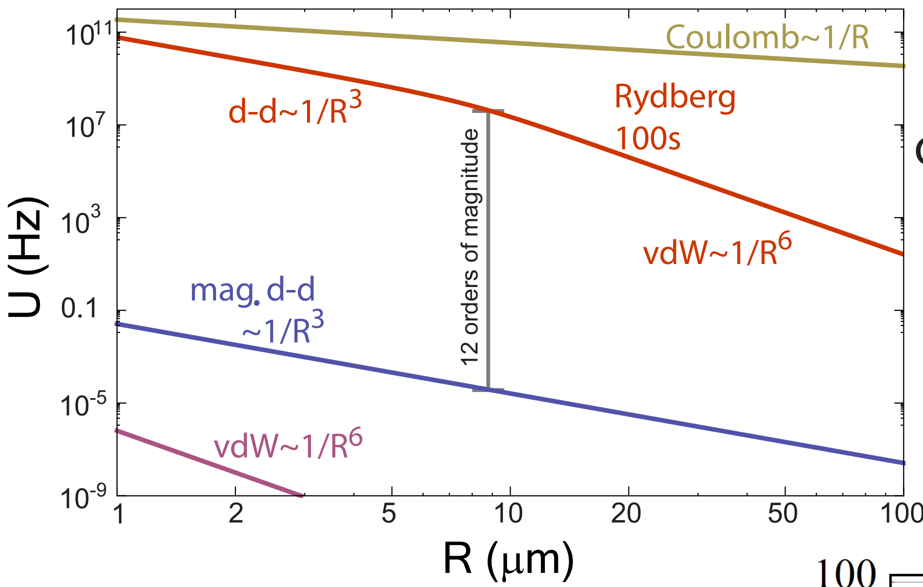
$C_3(\theta) \propto 1 - 3\cos^2\theta$







Summary of interactions between Rydberg atoms



REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010

Quantum information with Rydberg atoms

M. Saffman and T. G. Walker

Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, Wisconsin 53706, USA

K. Mølmer

Summary of Palaiseau's experiments (2013-2015) using **individual** atoms