Rydberg atoms in optical tweezers

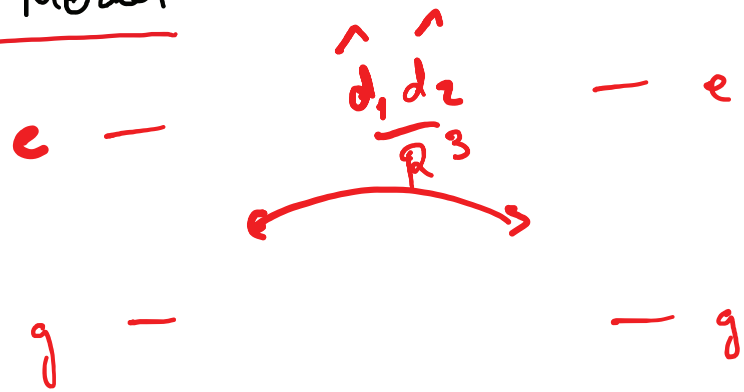
Lecture 1: Dipolar interactions between atoms

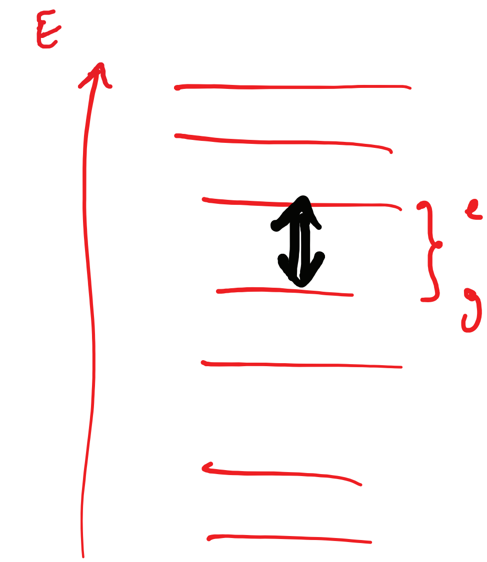
Lecture 2: Arrays of atoms. Basics of Rydberg physics. Rydberg blockade (2-body physics) & gates

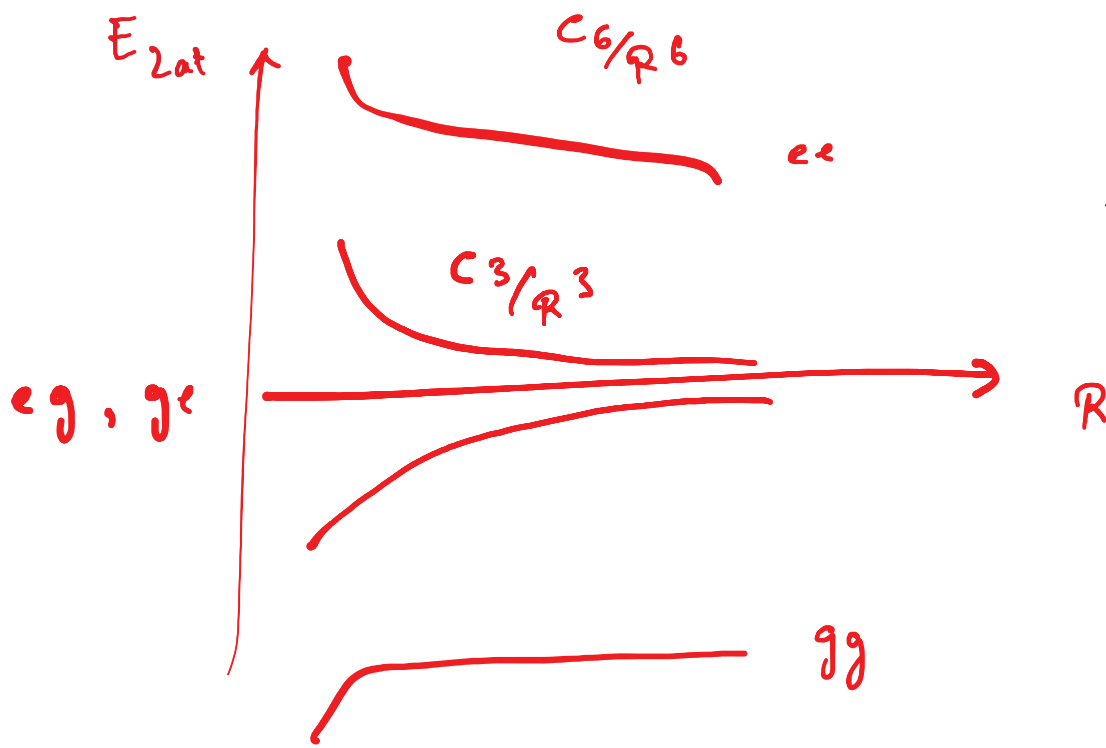
Lecture 3: Many-body physics with Rydberg atoms: spin models and transport

Recap of Lecture 1

Toy Model

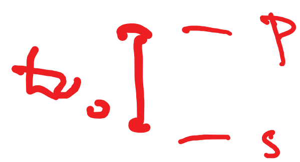






Note: induced dipole by E_0 DC field

$$\Rightarrow H \sim \hat{d} \cdot E_0$$

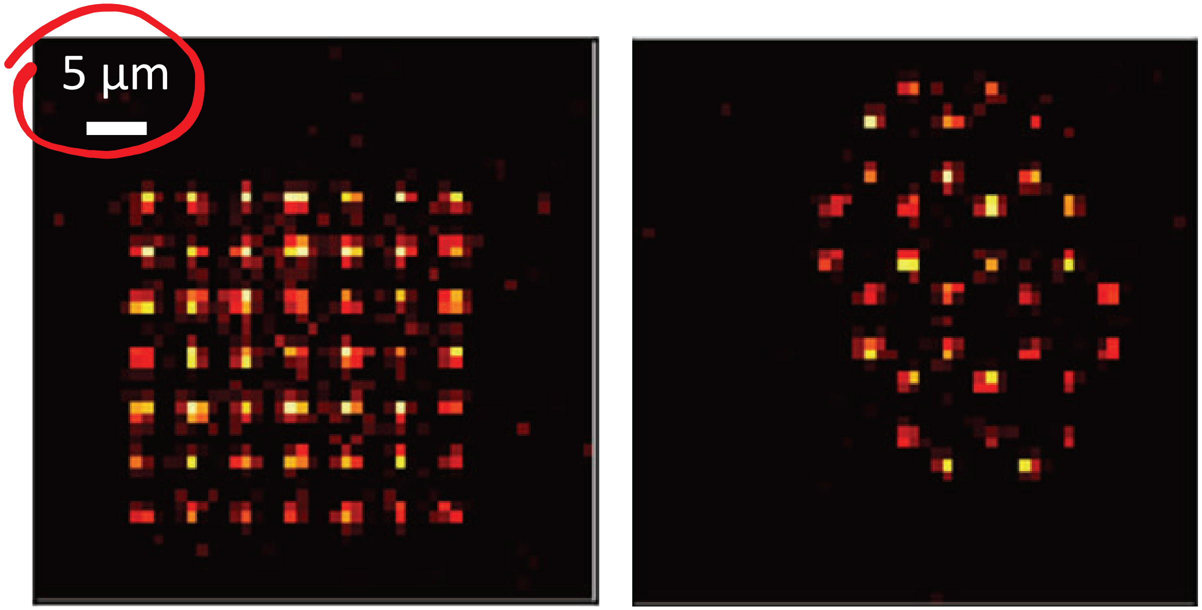


$$|\tilde{s}\rangle = |s\rangle + \frac{d E_0}{\hbar \omega_0} |p\rangle$$

$$\langle \tilde{s} | d | \hat{s} \rangle \neq 0$$

Stark

Goal: many-body physics and QIP with individual atoms



Addressable!!

2 Rb. (5s)

~5 μm

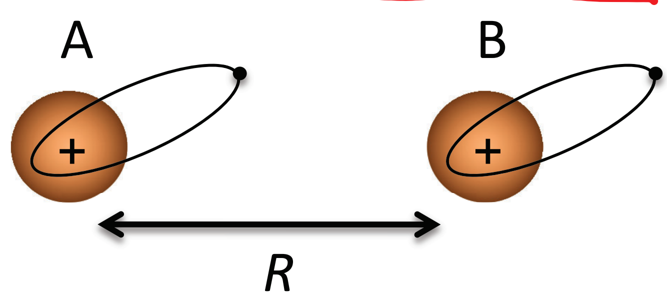
$n \sim 50$

$10\,\text{MHz} = \frac{C_6}{R^6}$

$\frac{C_6}{R^6} \sim 0.1\,\text{Hz}$

$\frac{C_3}{R^3}$ s p ~

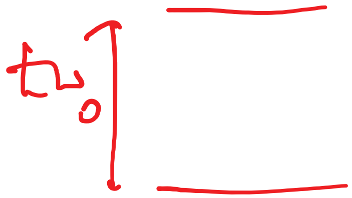
Rydberg interactions



1. Van der Waals $\frac{C_6}{R^6}$
2. resonant $\frac{C_3}{R^3}$

Van der Waals vs Resonant interaction

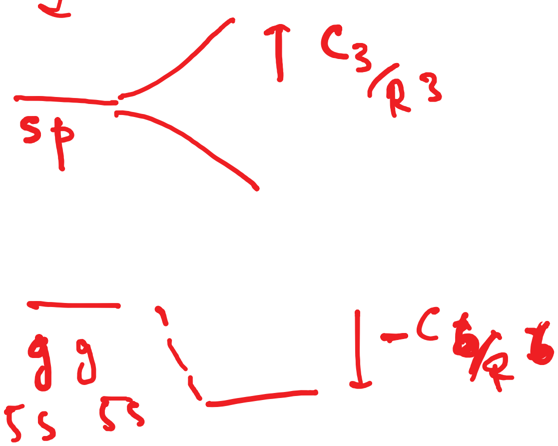
$\frac{C_3}{R^3} \sim$ few Hz



$1\,\text{eV} \sim 400\,\text{THz}$

$$\frac{C_6}{r^6} \sim \left(\frac{d^2}{R^3}\right)^2 \frac{1}{2\hbar\omega_0} = \frac{C_3}{R^3} \underbrace{\left(\frac{C_3/R^3}{\hbar\omega_0}\right)}_{\ll 1}$$

$$\frac{C_3}{R^3} \sim \frac{d^2}{R^3}$$



Note: Alkali also have magnetic dipole interaction

But: $\frac{\mu_B^2}{R^3} \ll \frac{C_6}{r^6}$

Outline

1. Experimental considerations: arrays of individual atoms
2. "Rydbergology": scalings, interactions, blockade…
3. Measurement of interactions between Rydberg atoms: towards many-body physics
4. Application of Rydberg blockade to QIP

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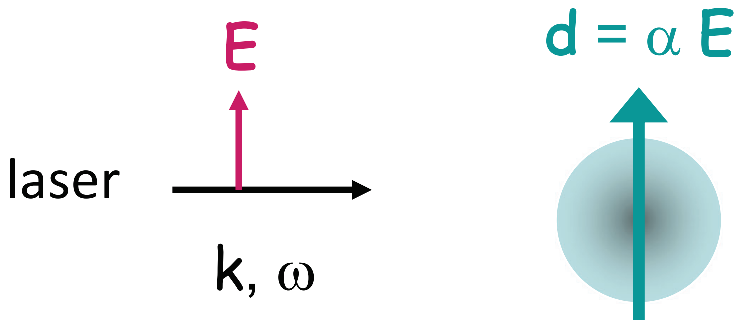
Optical dipole trap

Classical



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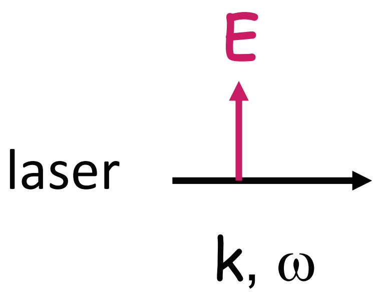
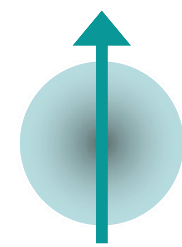
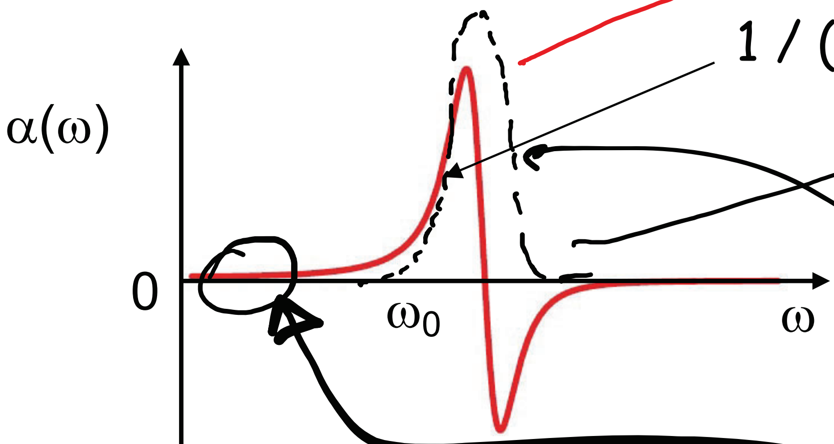




Harmonic oscillator model



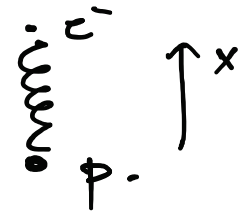
$\mathrm{Im}[\alpha] \propto \frac{1}{(\omega-\omega_0)^2}$

Interaction atom - light

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

⇒ Conservative POTENTIAL

Elastically bound e^- model:



$$m\ddot{x} = -m\omega_0^2 x - (\ )\dot{x} + qE_L$$

$$\Downarrow$$

$$\alpha \sim \frac{q^2}{m} \frac{1}{\omega_0^2 - \omega^2 - i\omega\Gamma}$$

$|\omega - \omega_0| \gg \Gamma$.

$$\alpha \sim \frac{1}{\omega_0^2 - \omega^2}$$

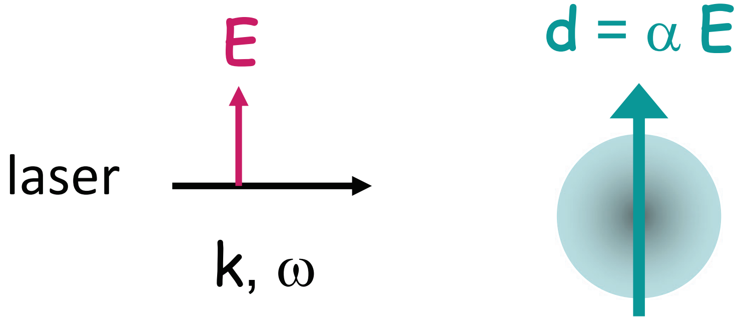
$$U \sim -\frac{1}{2}\vec{d}\cdot\vec{E} = -\frac{1}{2}\alpha E^2$$

- $\alpha > 0 \rightarrow U_{min}$ E^2 max.
- $\alpha < 0 \rightarrow U_{min}$ E^2 min.

Optical dipole trap

Classical

$d = \alpha E$



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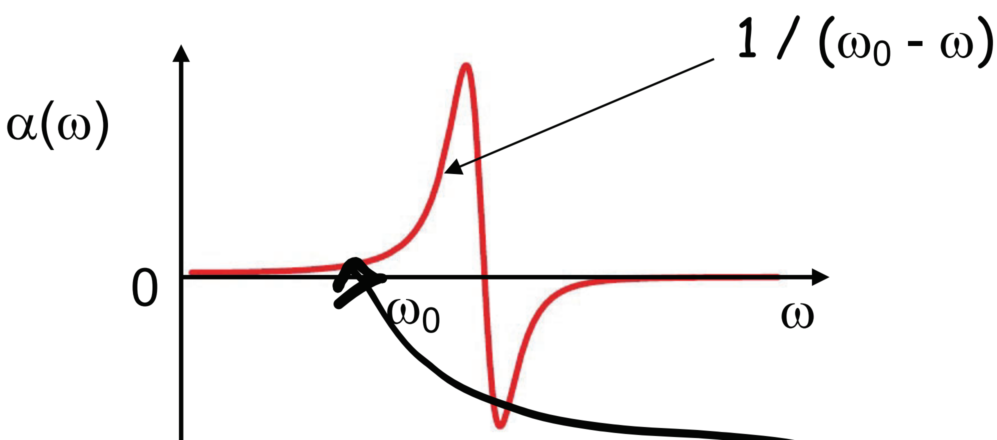

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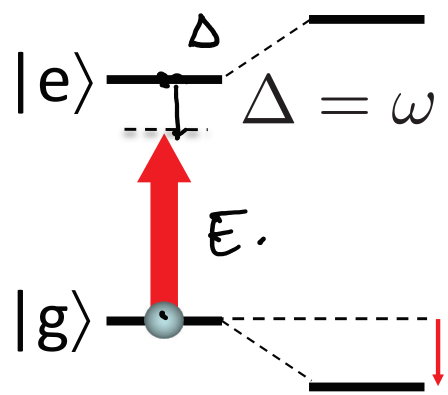
Quantum

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

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

$\omega_0 > \omega$



$$\Delta = \omega - \omega_0$$

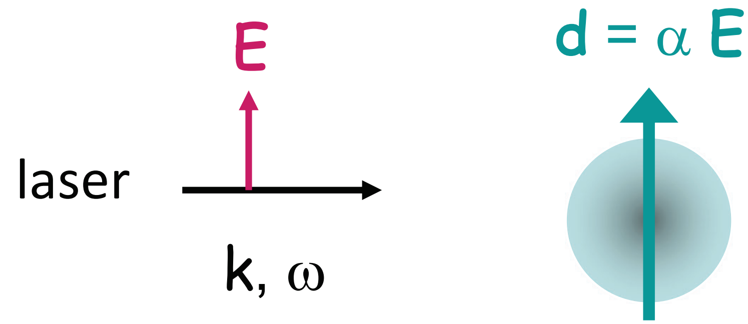
$$\frac{\hbar\Omega^2}{4\Delta}$$

$$H = \begin{pmatrix} 0 & \Omega/2 \\ \Omega/2 & -\Delta \end{pmatrix}$$

$$\Delta E_g \sim \frac{(\Omega/2)^2}{\Delta} = \frac{(dE)^2}{\omega - \omega_0}$$

Optical dipole trap

Classical



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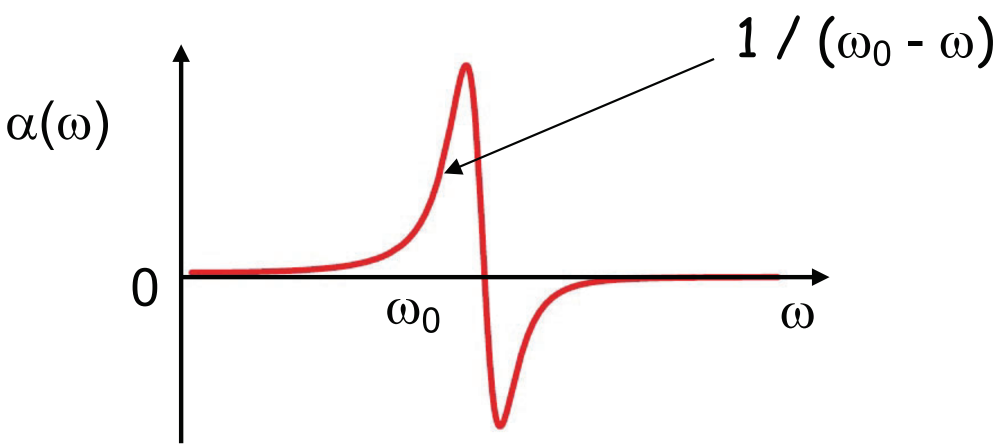

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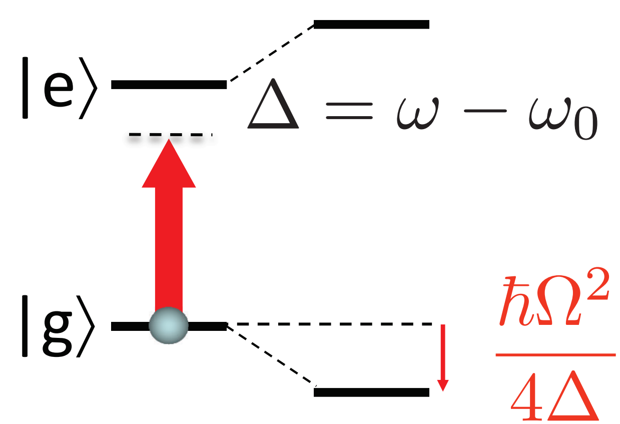


Trap depth ~ 100 μK – 1 mK

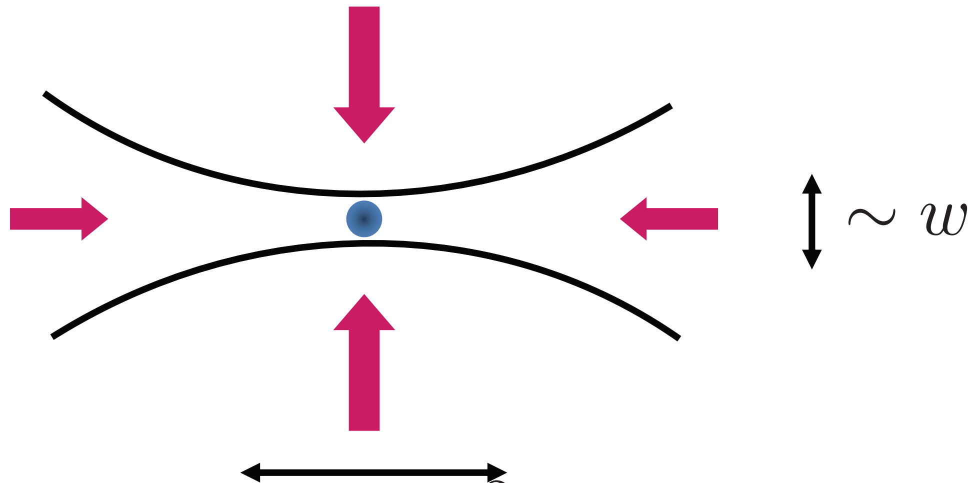
$\Rightarrow$ cold atoms

P ~ 1W ~ 100 μm

Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

Gaussian beam



$$z_R = \frac{\pi w^2}{\lambda}$$

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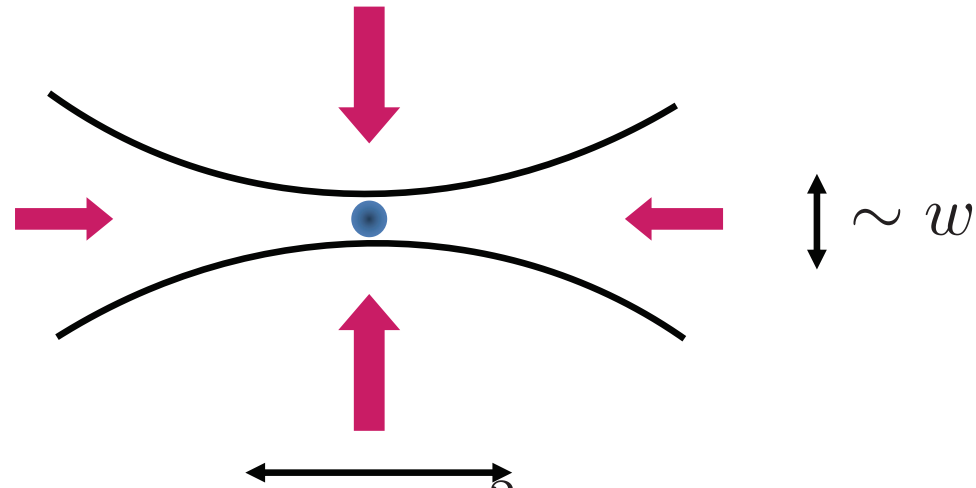
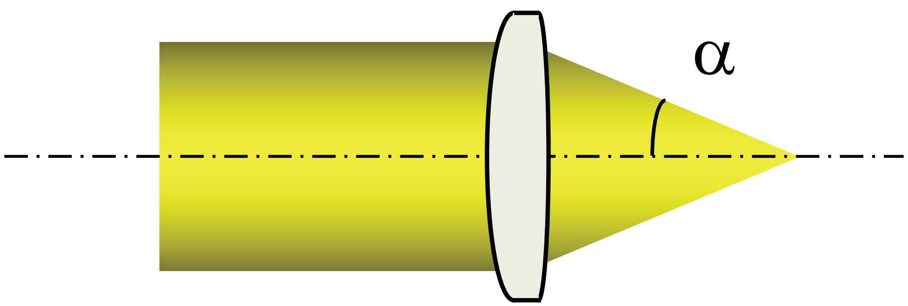


$$z_{\mathrm{R}} = \frac{\pi w^2}{\lambda}$$



NA = sin α

w ~ **λ**/**NA**

Diffraction limited optics $w \sim \lambda$

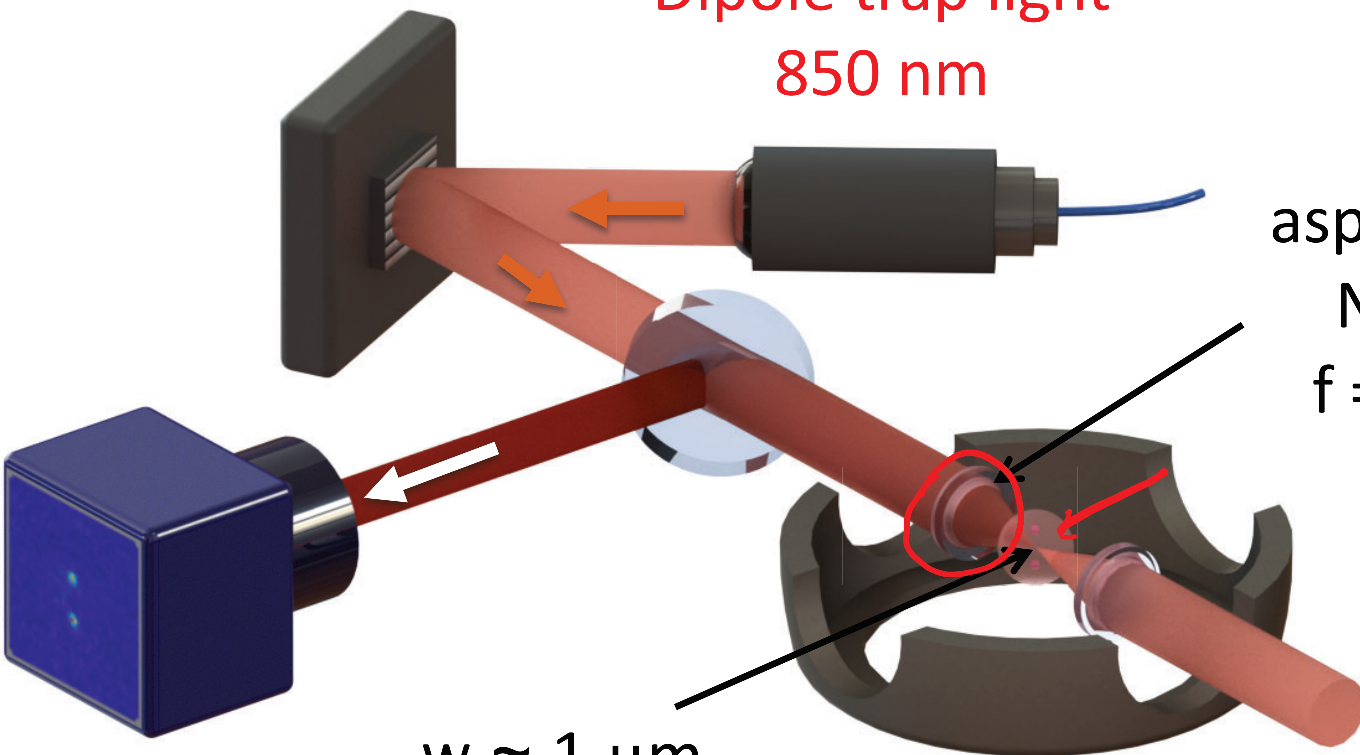
Trapping volume $\sim \pi\lambda^3$

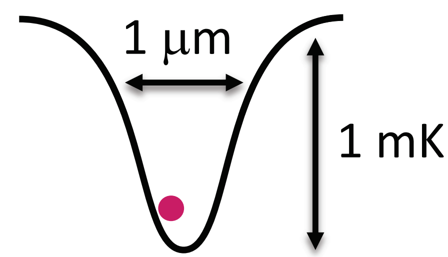
Ex: 1 mW on 1 µm

Trap depth = 1 mK

Optical tweezers: trapping in 3D

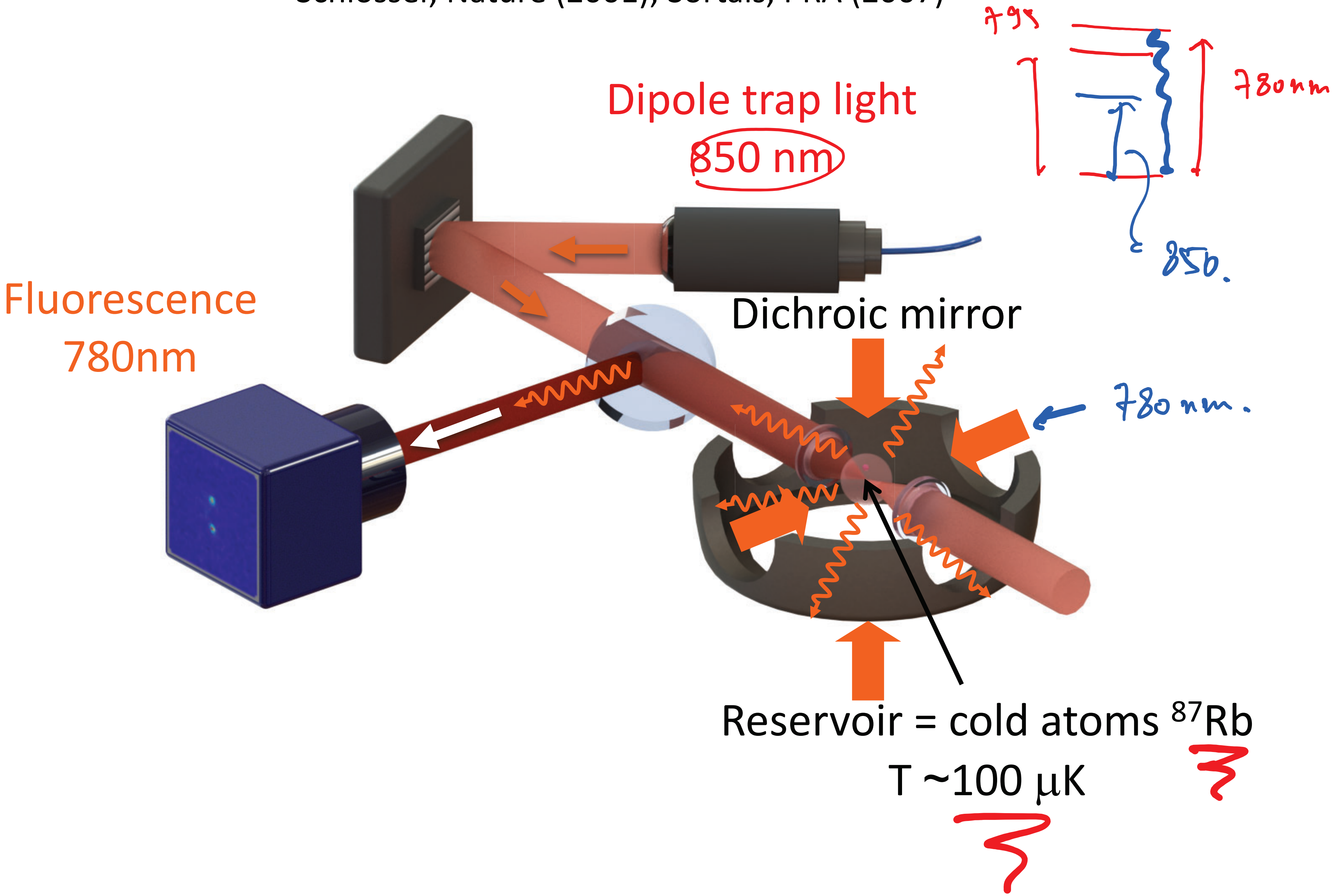
Schlosser, Nature (2001); Sortais, PRA (2007)





Single atoms in optical tweezers

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



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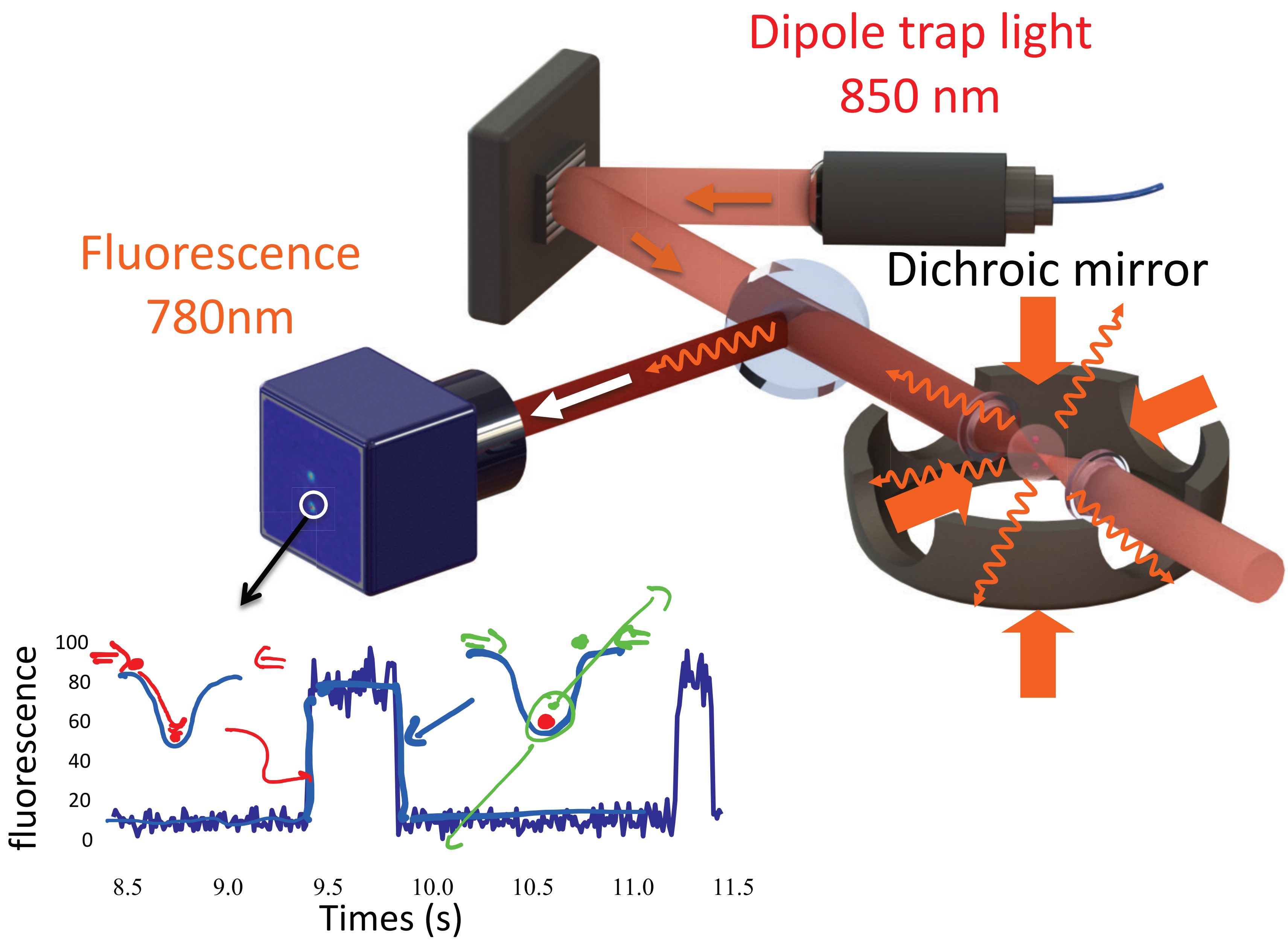

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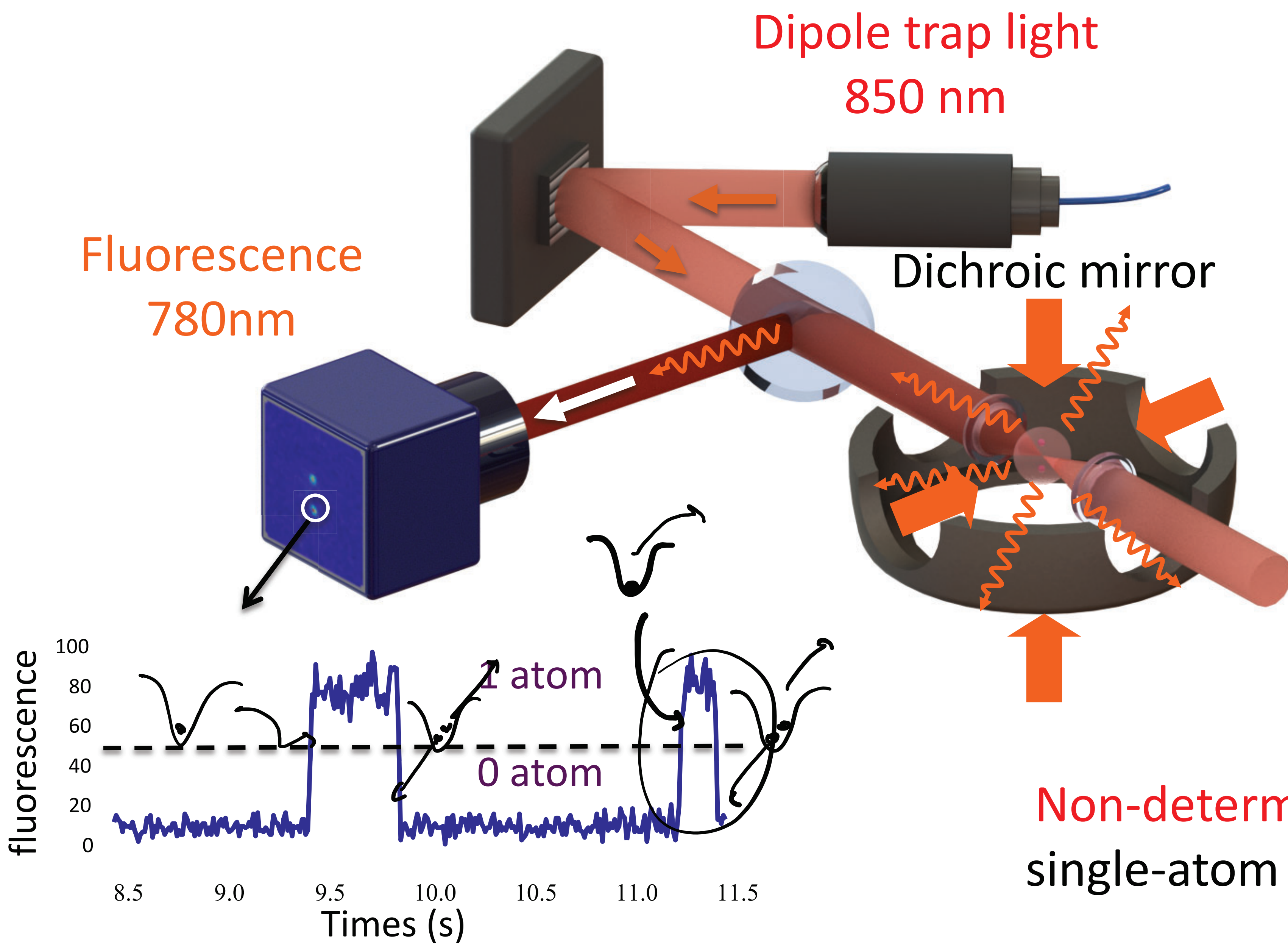
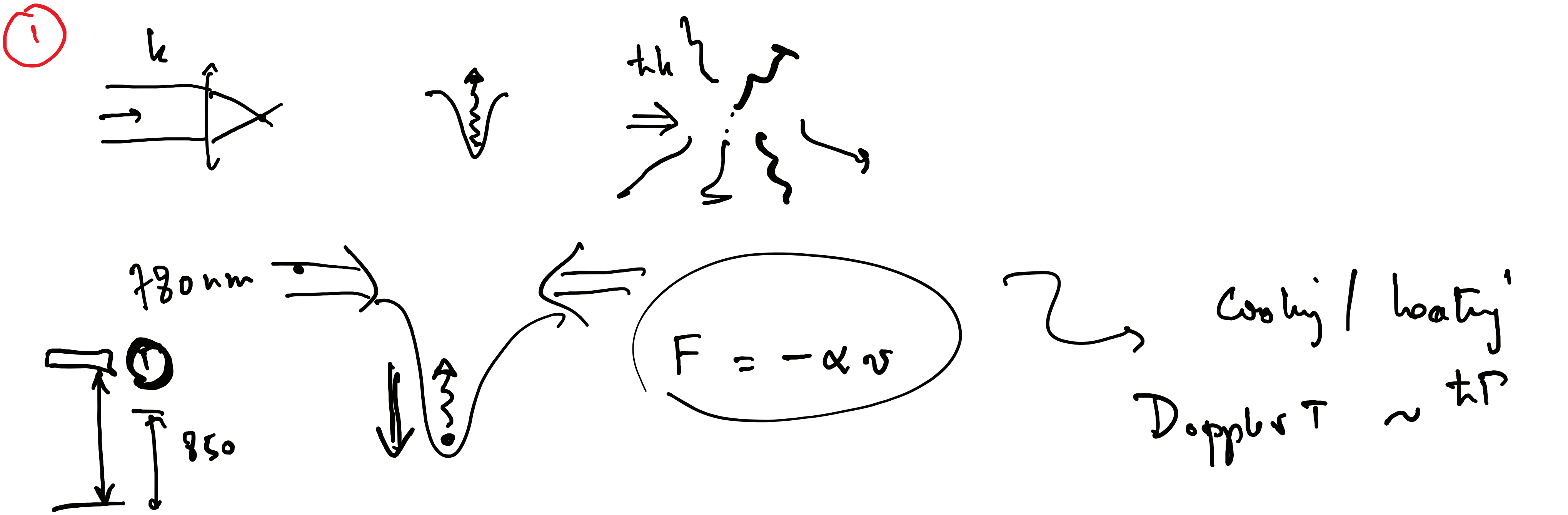
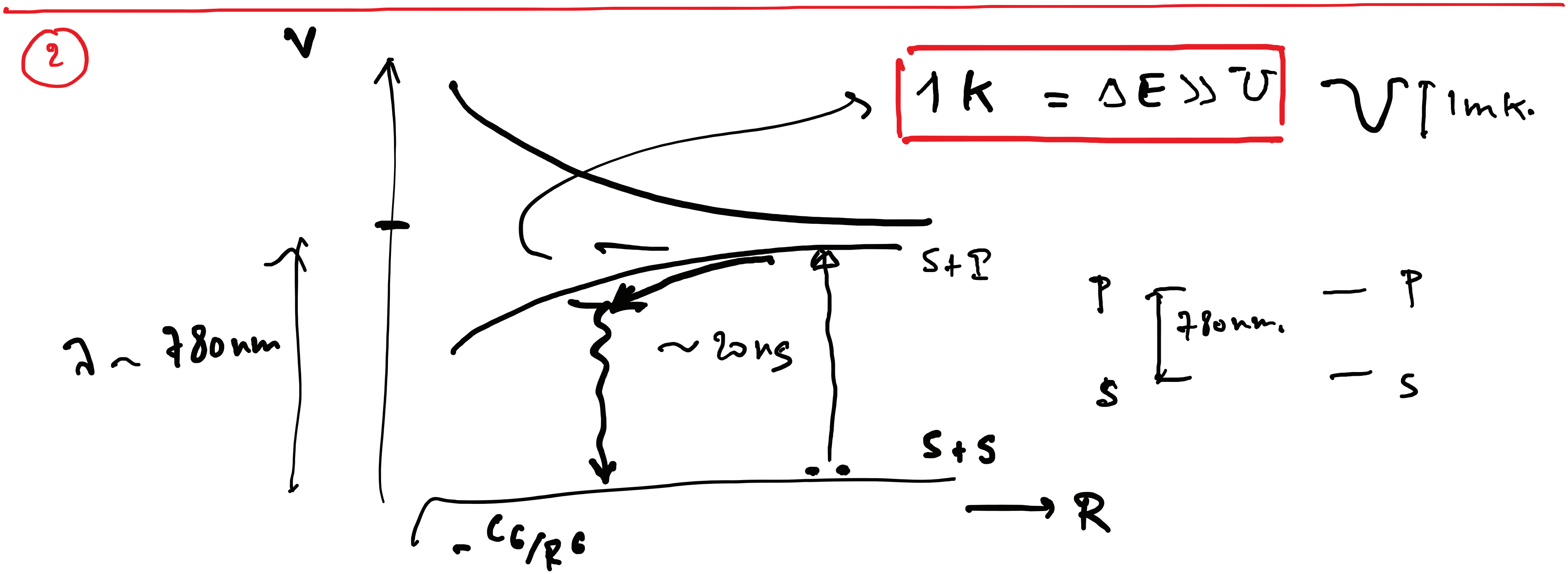
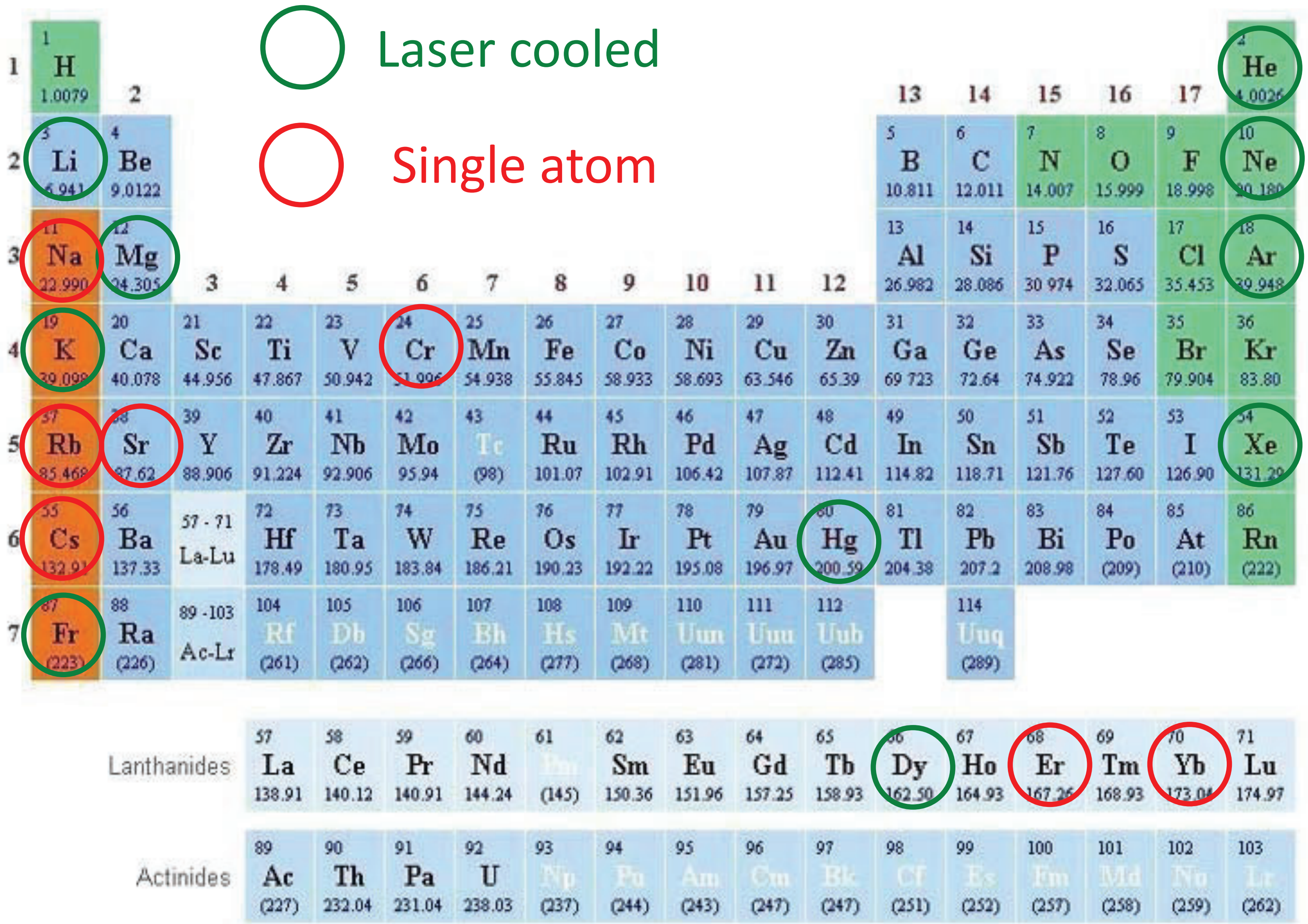


Light-assisted collisions prevents 2 atoms...



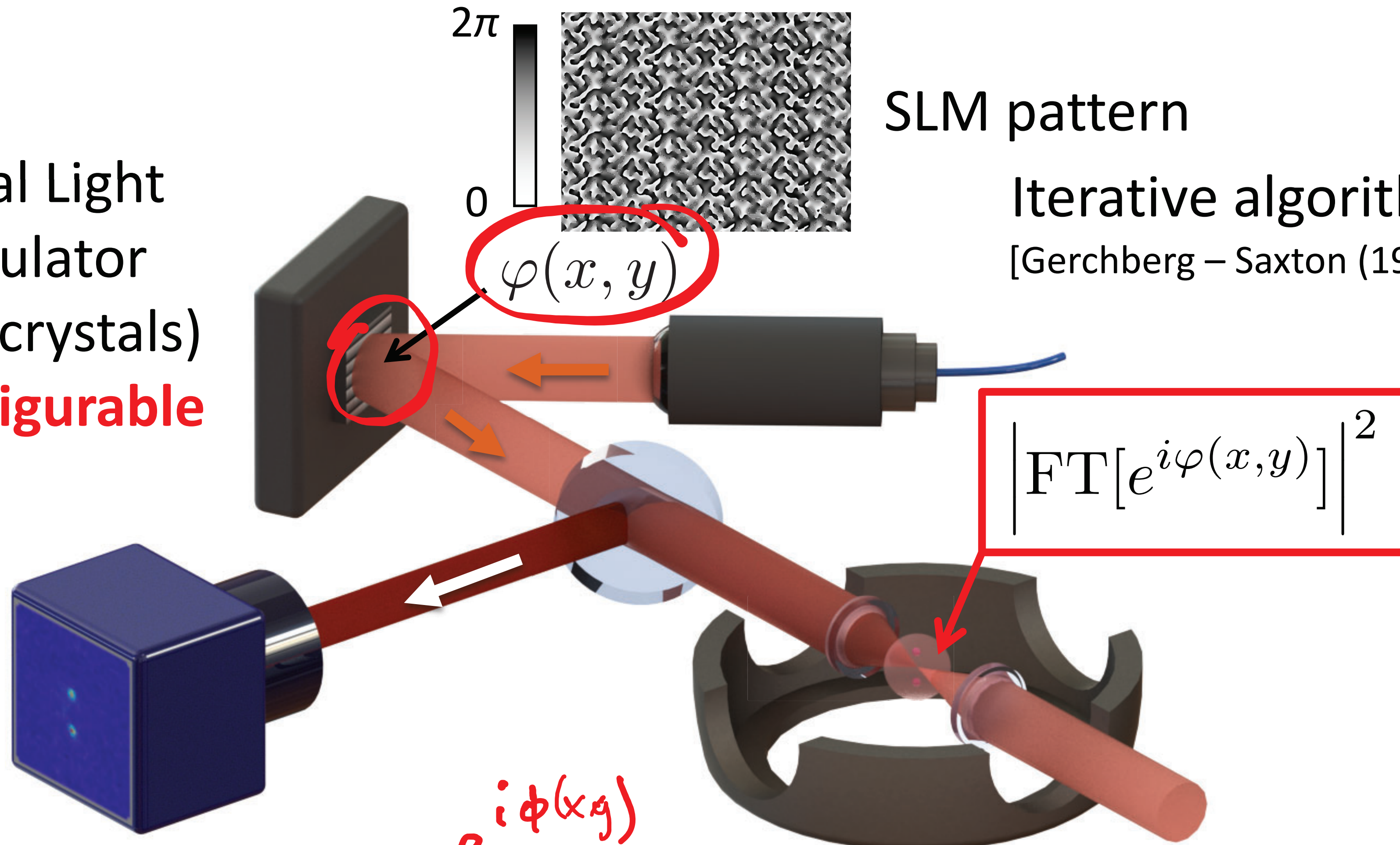


Which atoms?

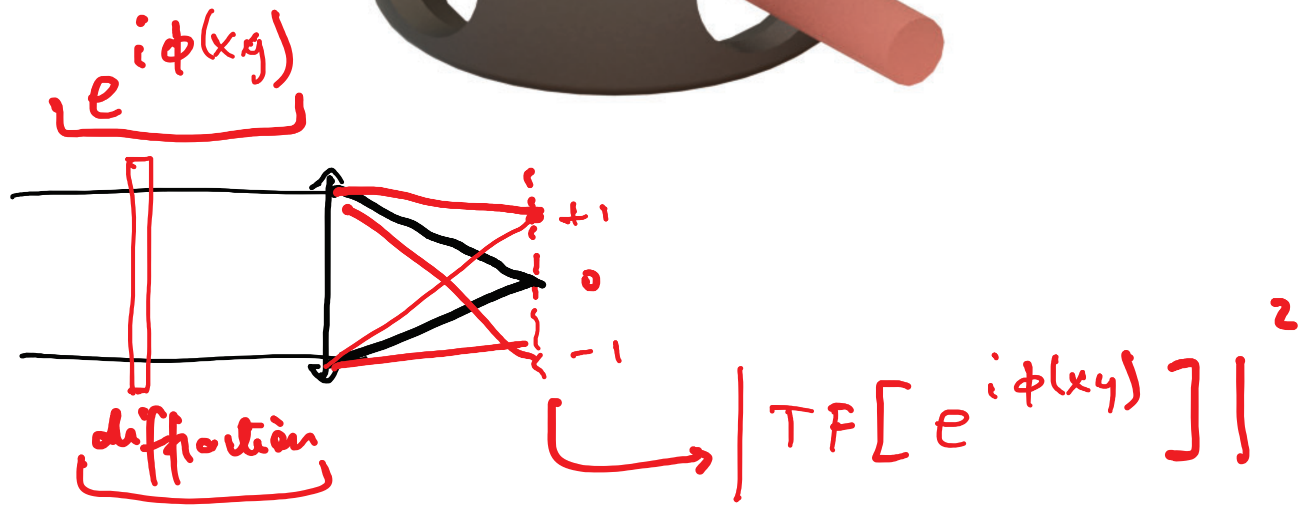


Holographic 2D arrays of tweezers

Spatial Light
Modulator
(liquid crystals)
Reconfigurable



Iterative algorithm
[Gerchberg – Saxton (1972)]



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

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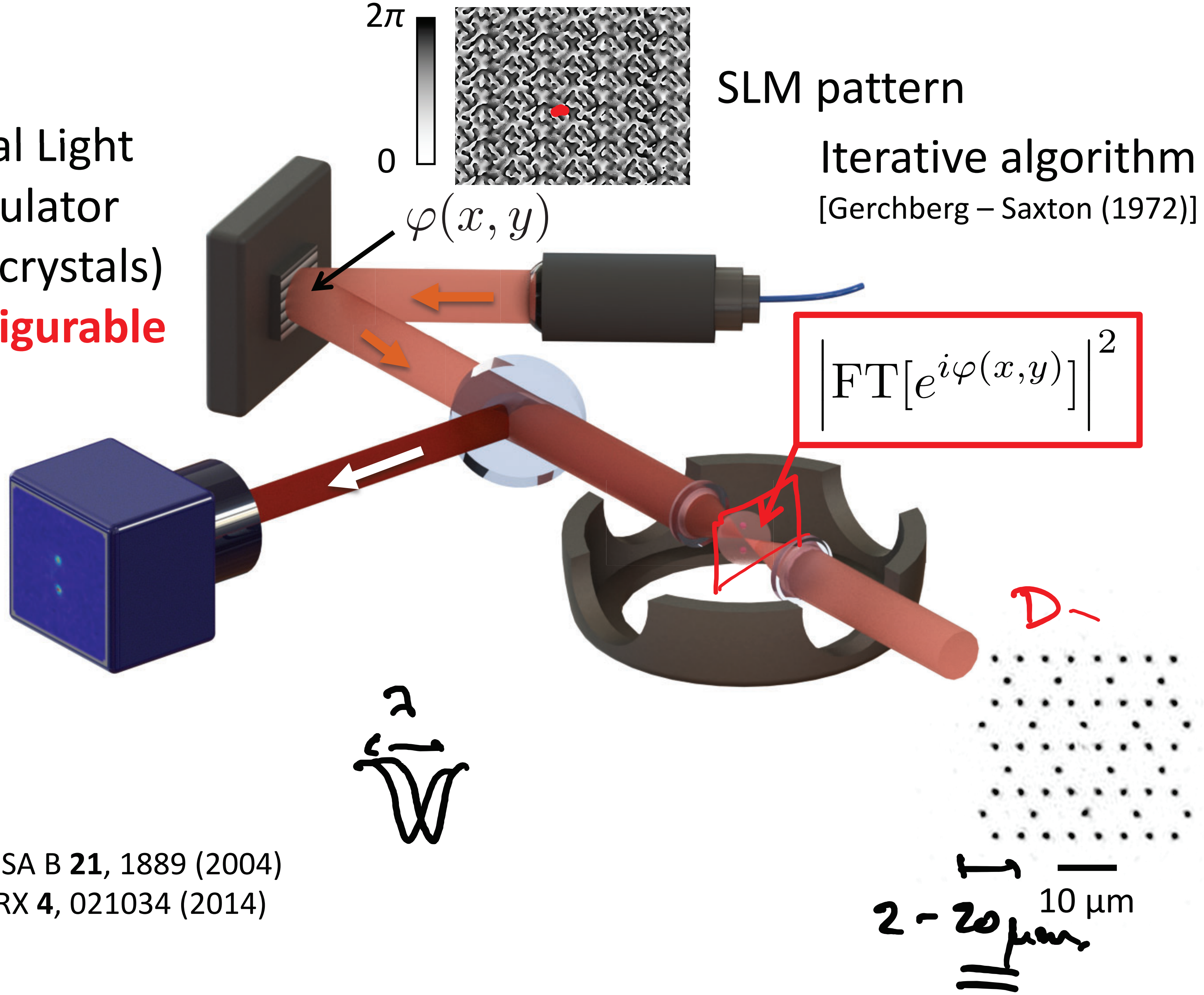

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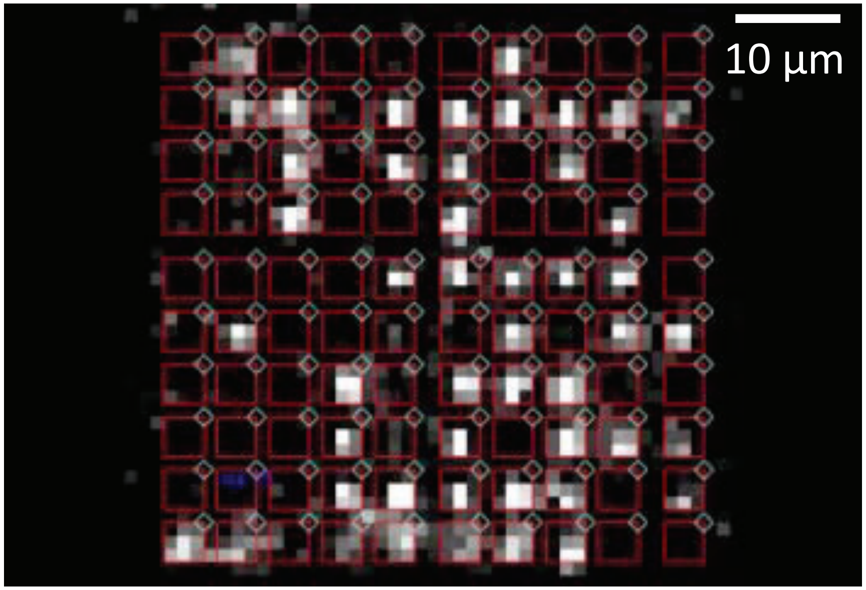
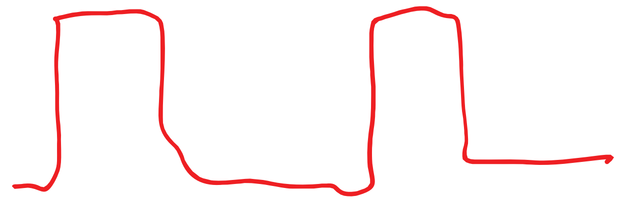
Atom-by-atom assembling of 2D arrays



Problem: stochastic loading ($p \sim 0.5$)



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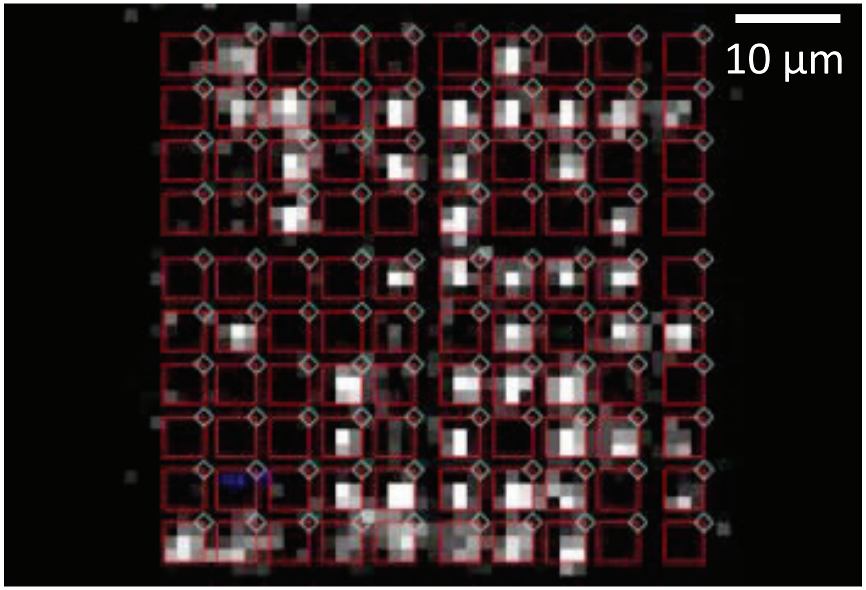

Problem: stochastic loading (*p* ~ 0.5)

Solution: **sort atoms in arrays**

Miroshnychenko, Nature **442**, 151 (2006)

Atom-by-atom assembling of 2D arrays

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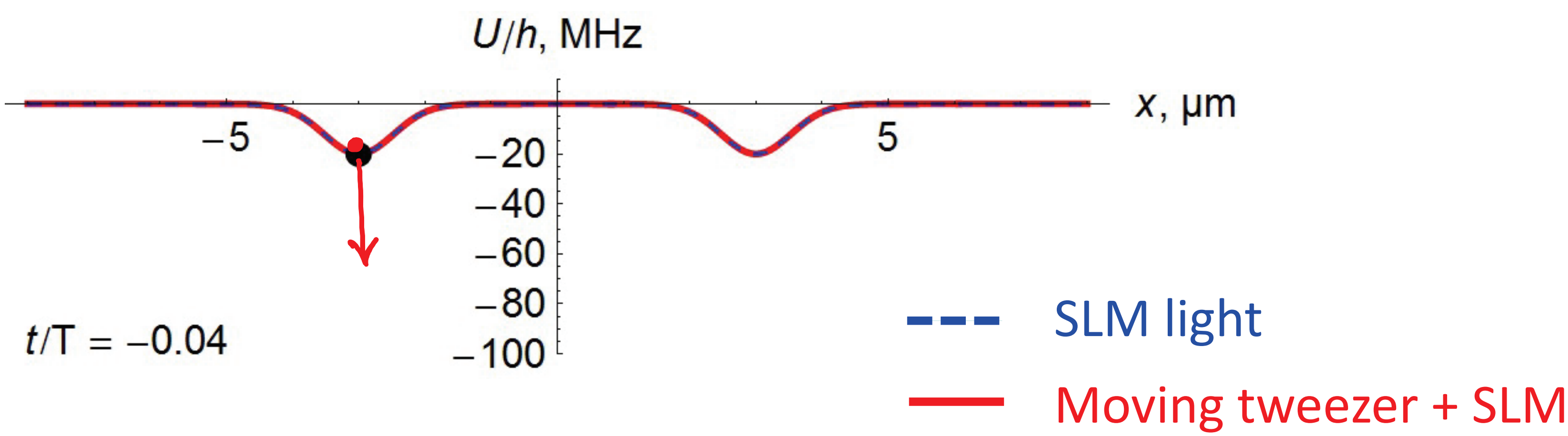
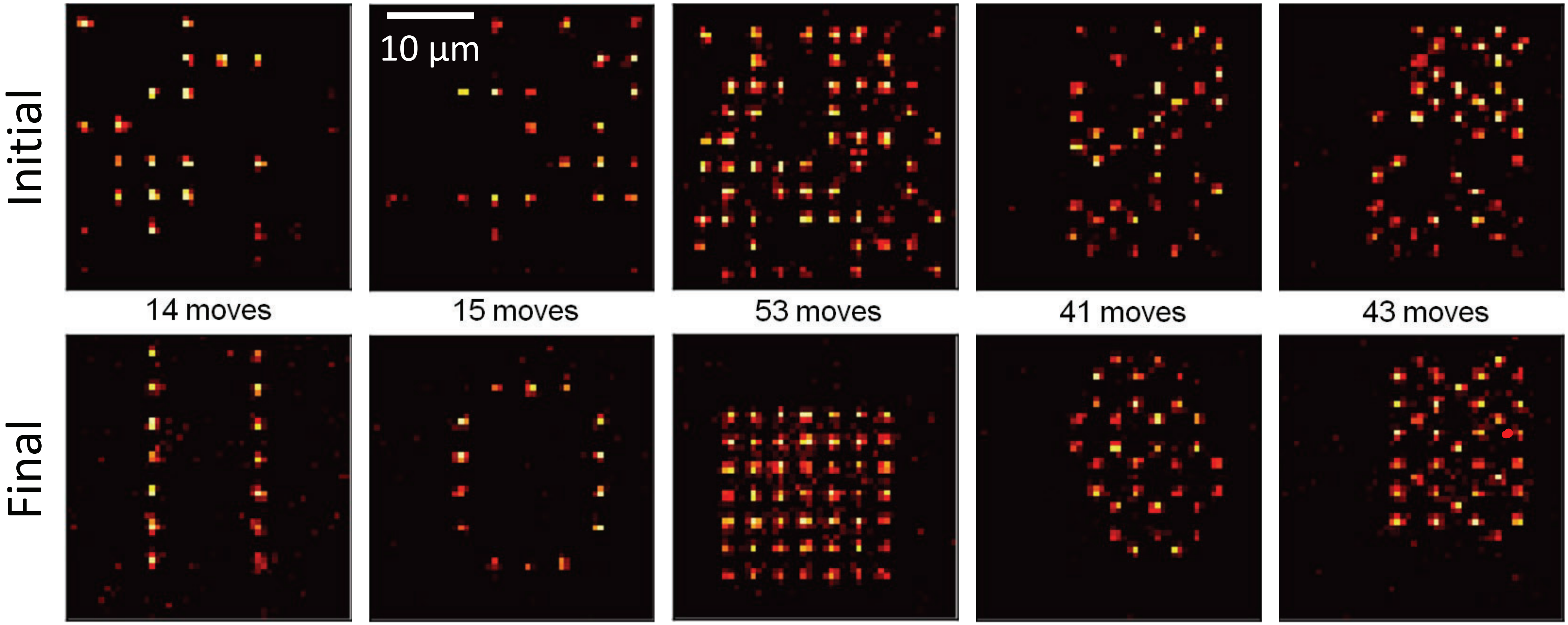
Miroshnychenko, Nature **442**, 151 (2006)

Moving atoms with a tweezers



$p \sim 0.993(1)$

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



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

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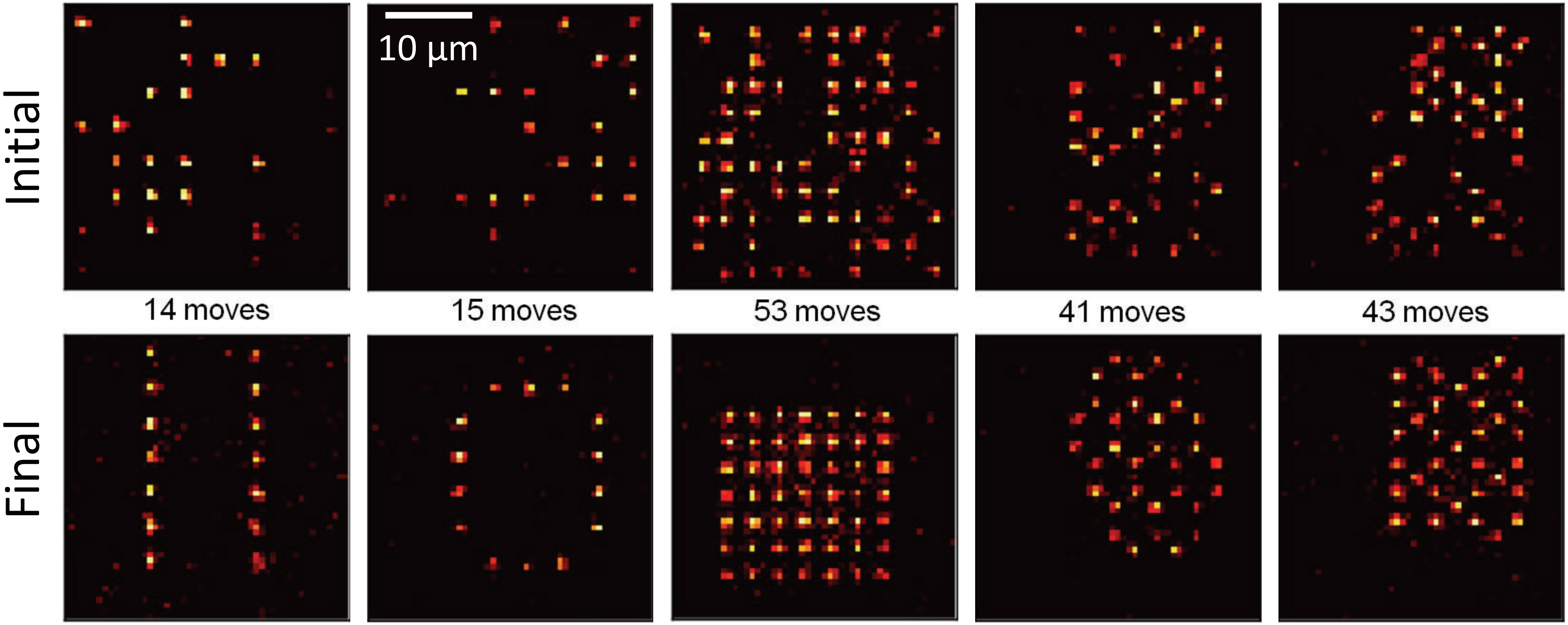
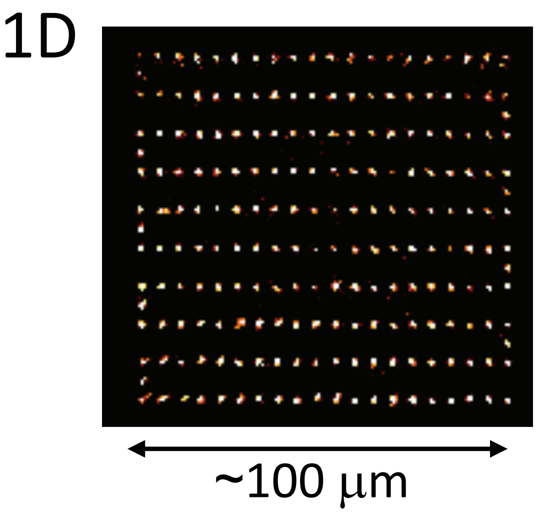


Now ~ 200 atoms



Schymik, PRA 2020

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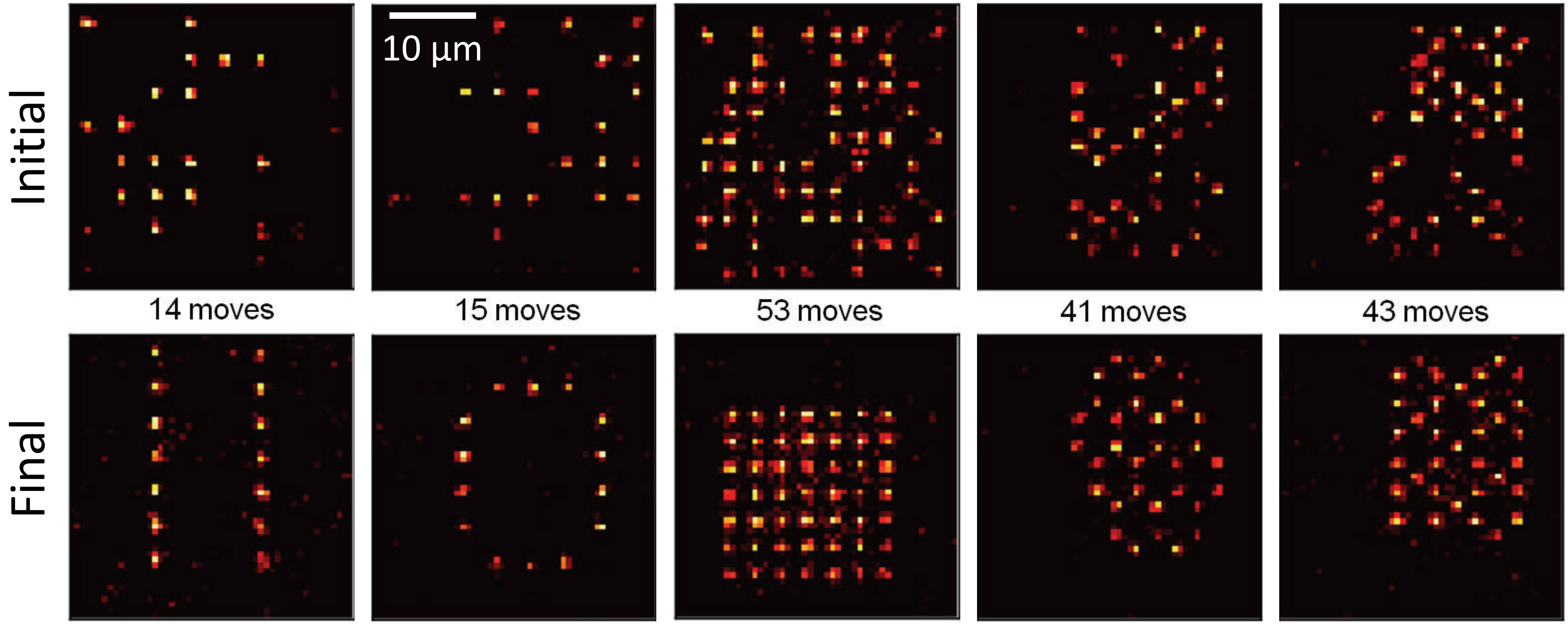

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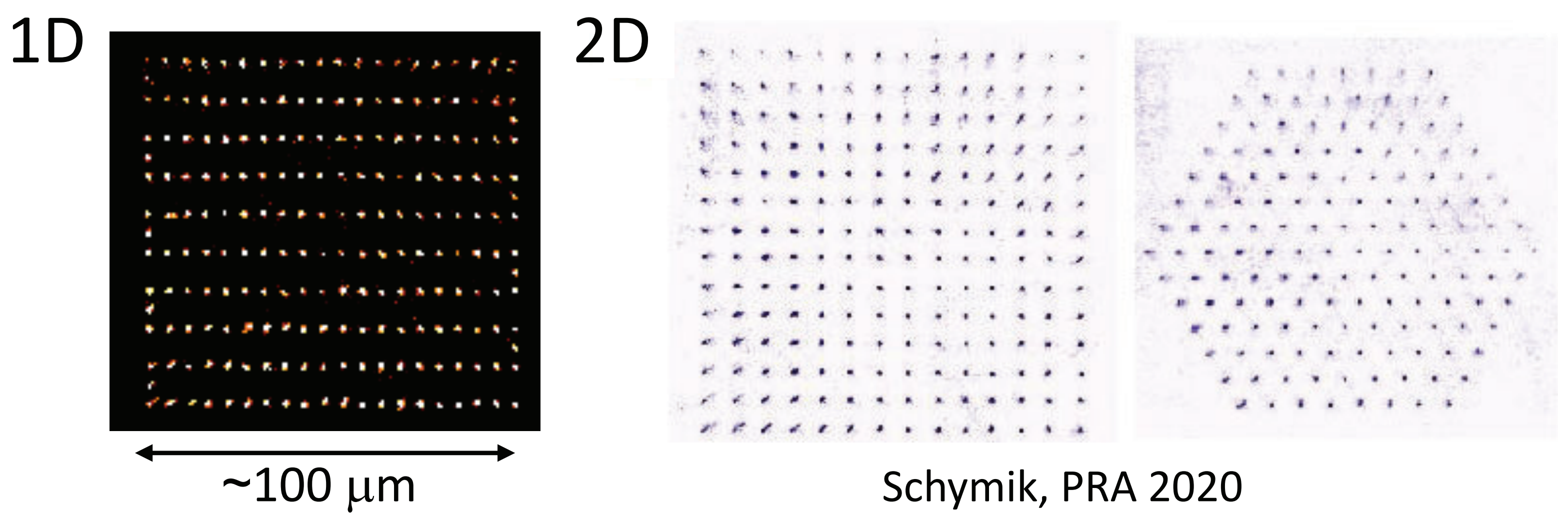

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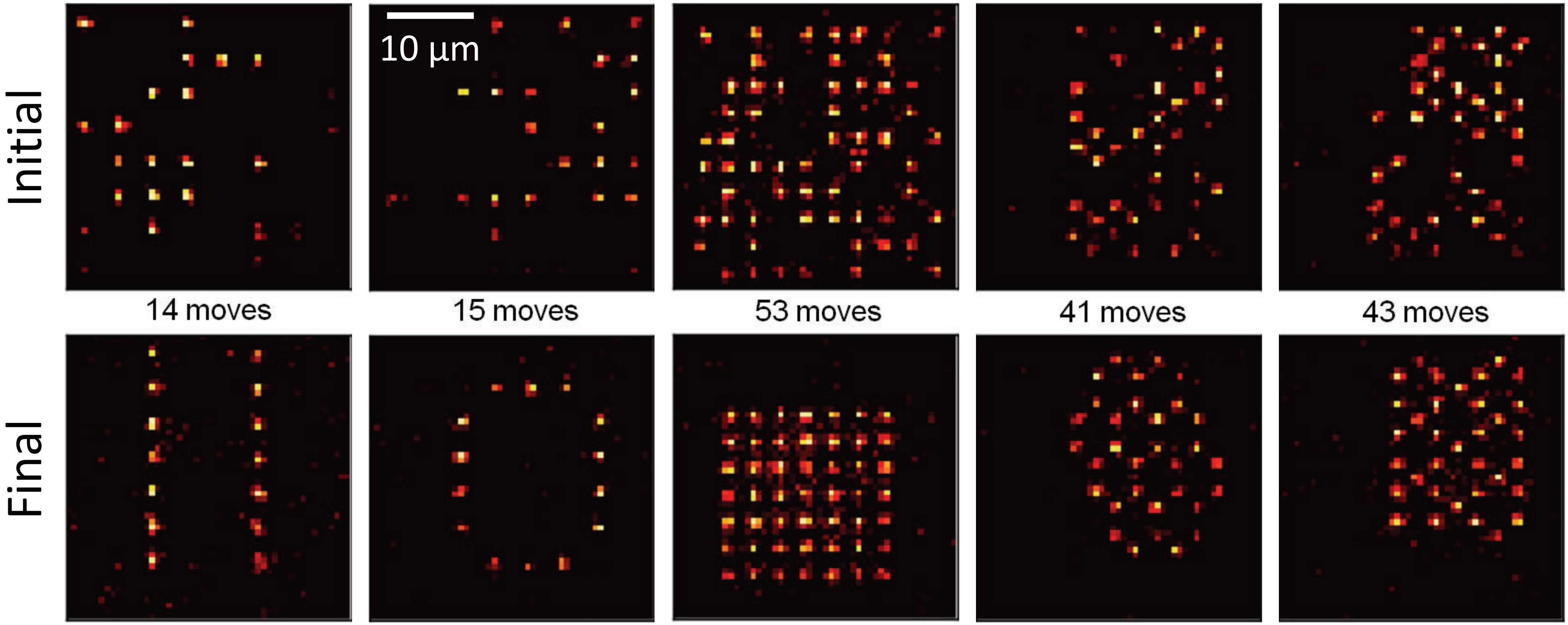
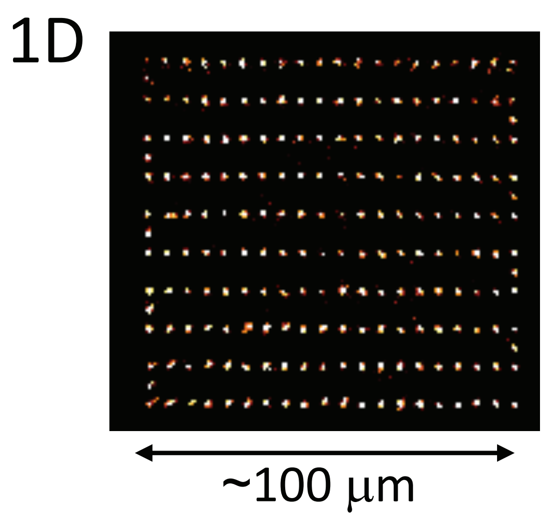
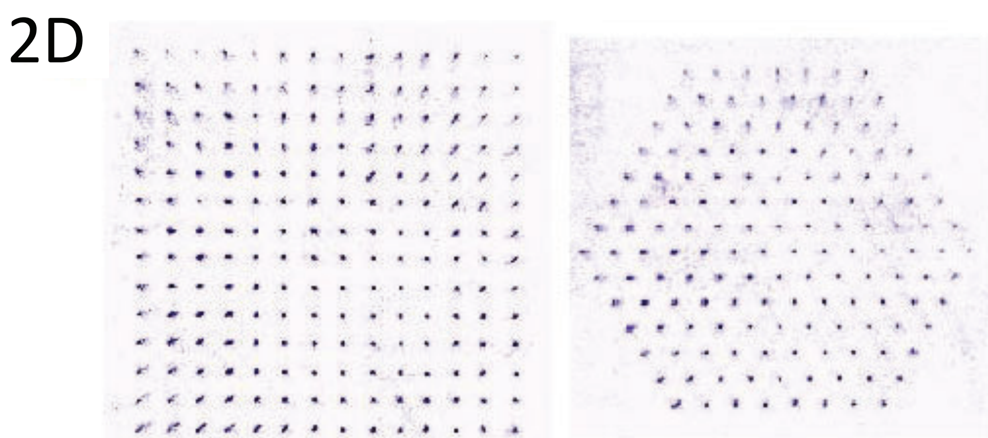
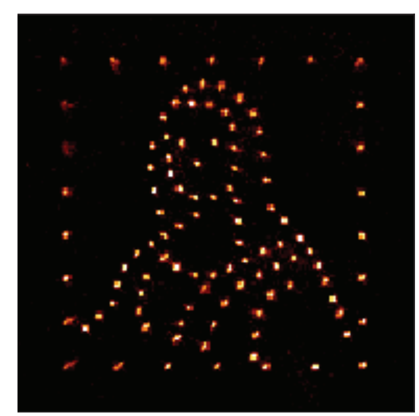


Now ~ 200 atoms







Schymik, PRA 2020

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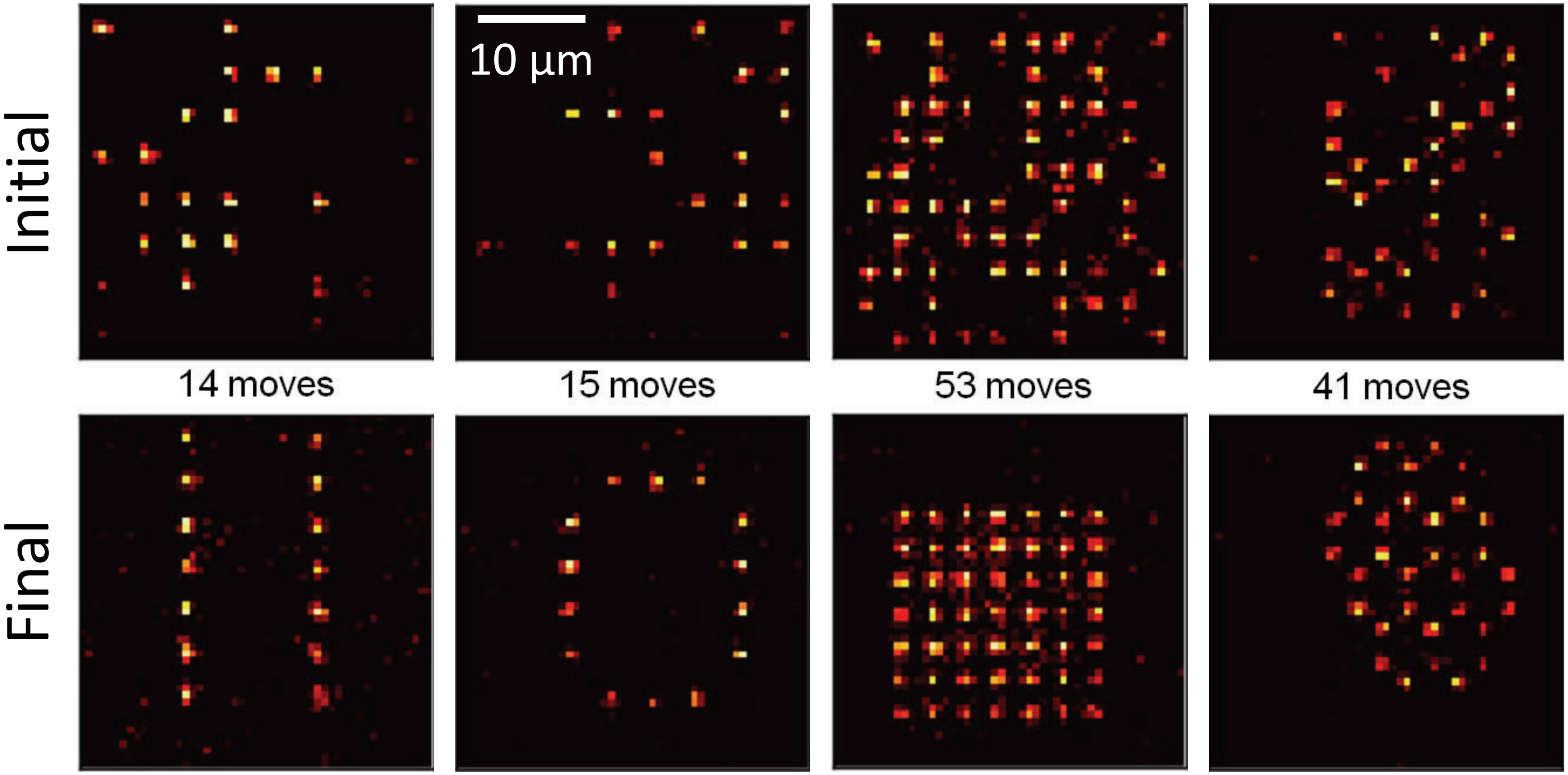
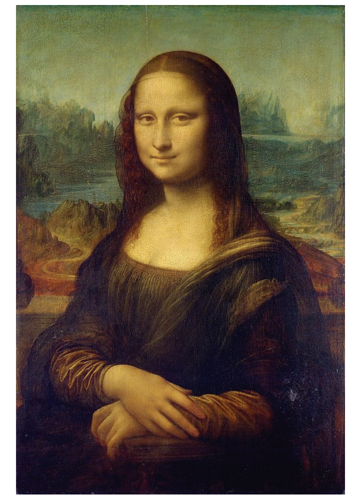
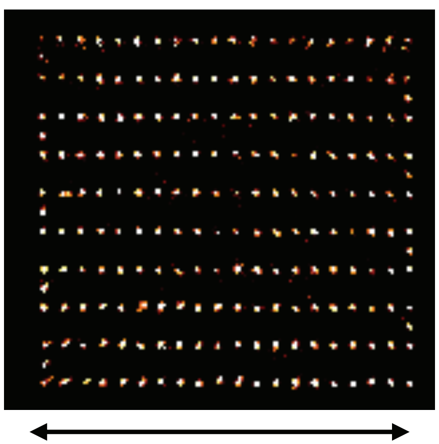




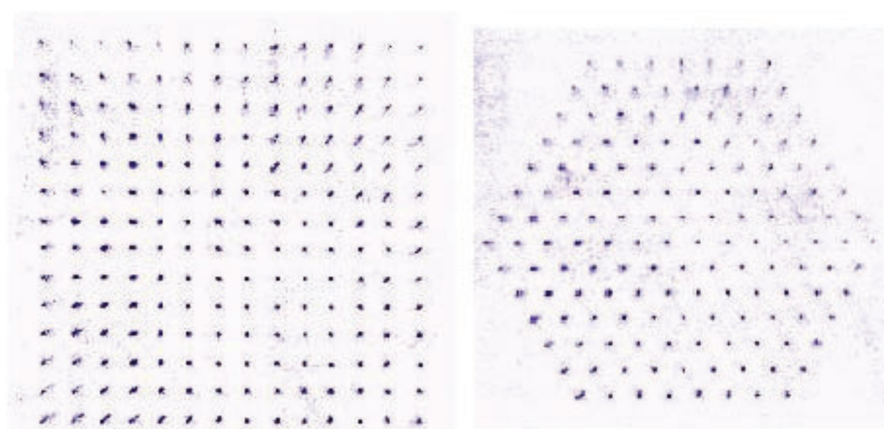
L. da Vinci

Now ~ 200 atoms

1D



2D



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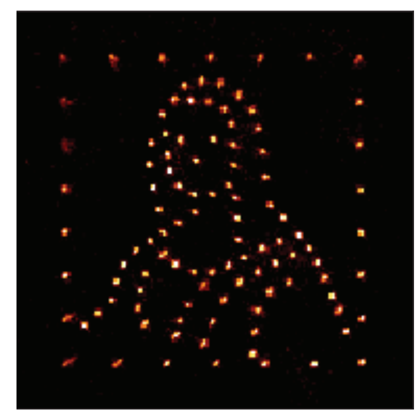
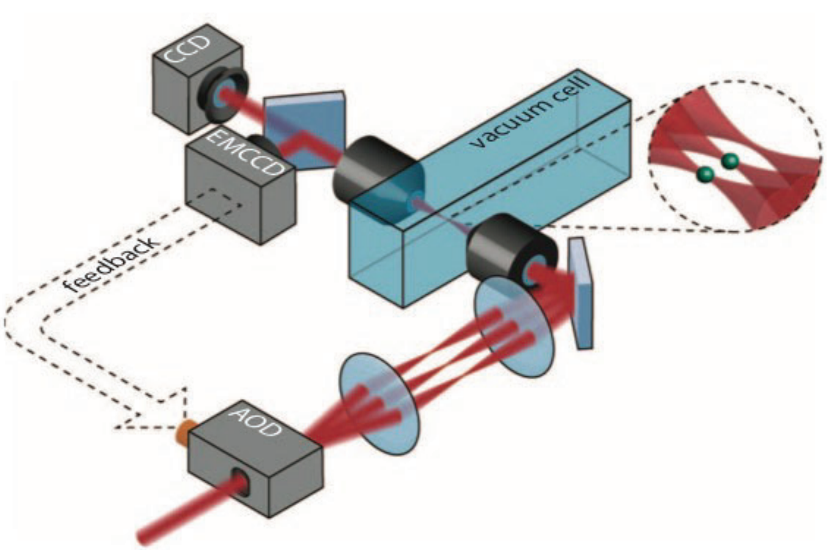


Now widely used,… with variants (1D, 2D & 3D)

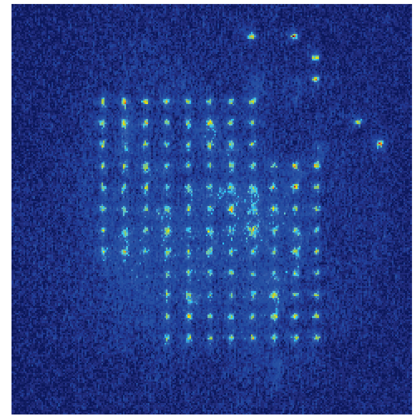
Lukin (Harvard), 2016



Rb

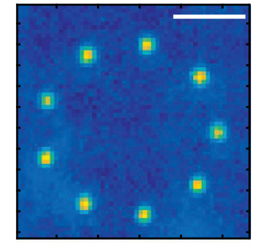
Birkl (Germany)

2D

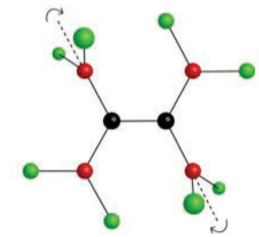


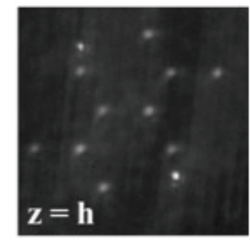
Ahn (Korea)

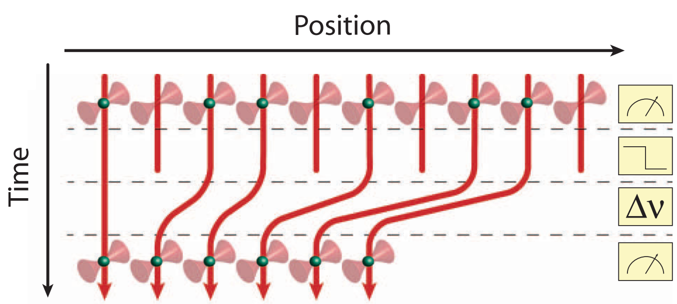
2D



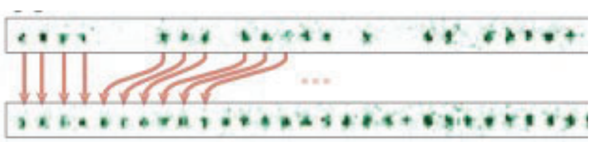
3D





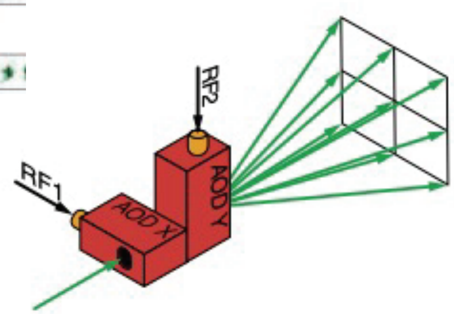


Rb

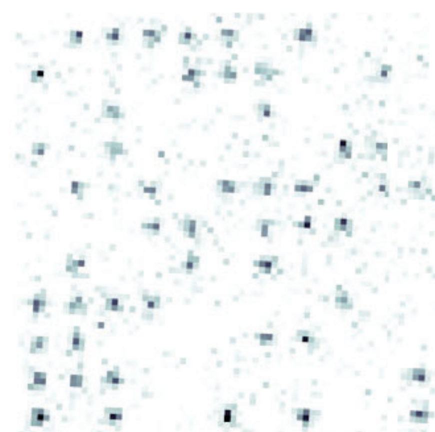


~300 atoms

arXiv:2012.12281

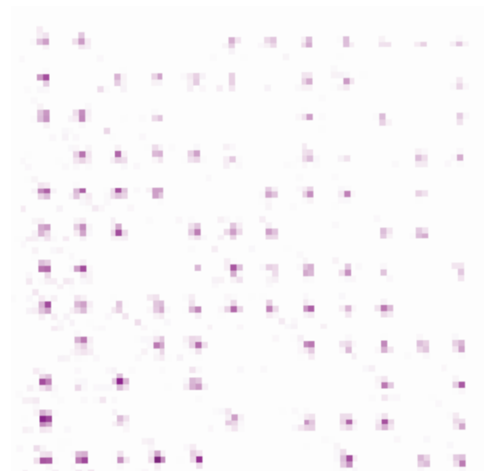


Sr



Endres (Caltech)
Kauffman (JILA)
2018

Yb

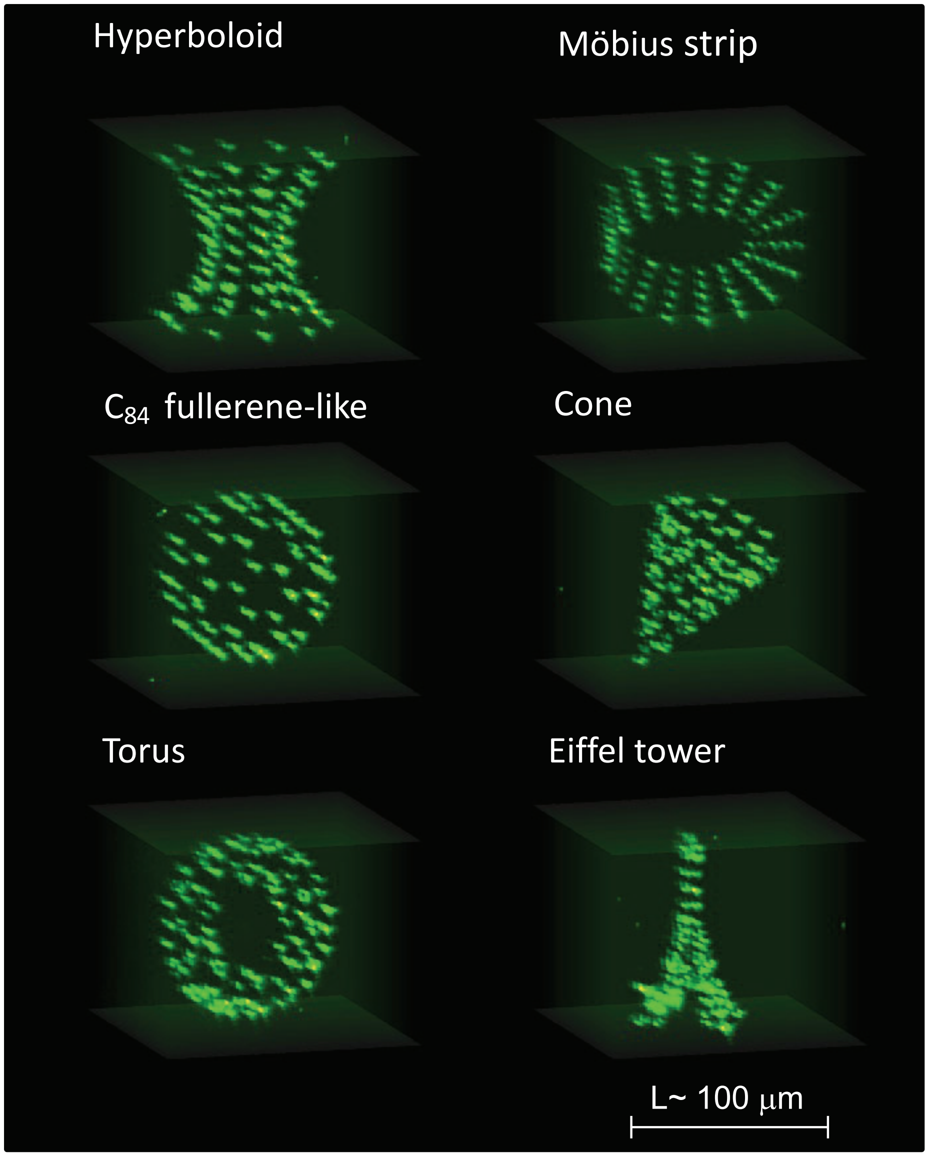


Thompson (Princeton)
2018

It also works in 3d!

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

Averaged fluorescence
imaged "slice-by-slice"



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

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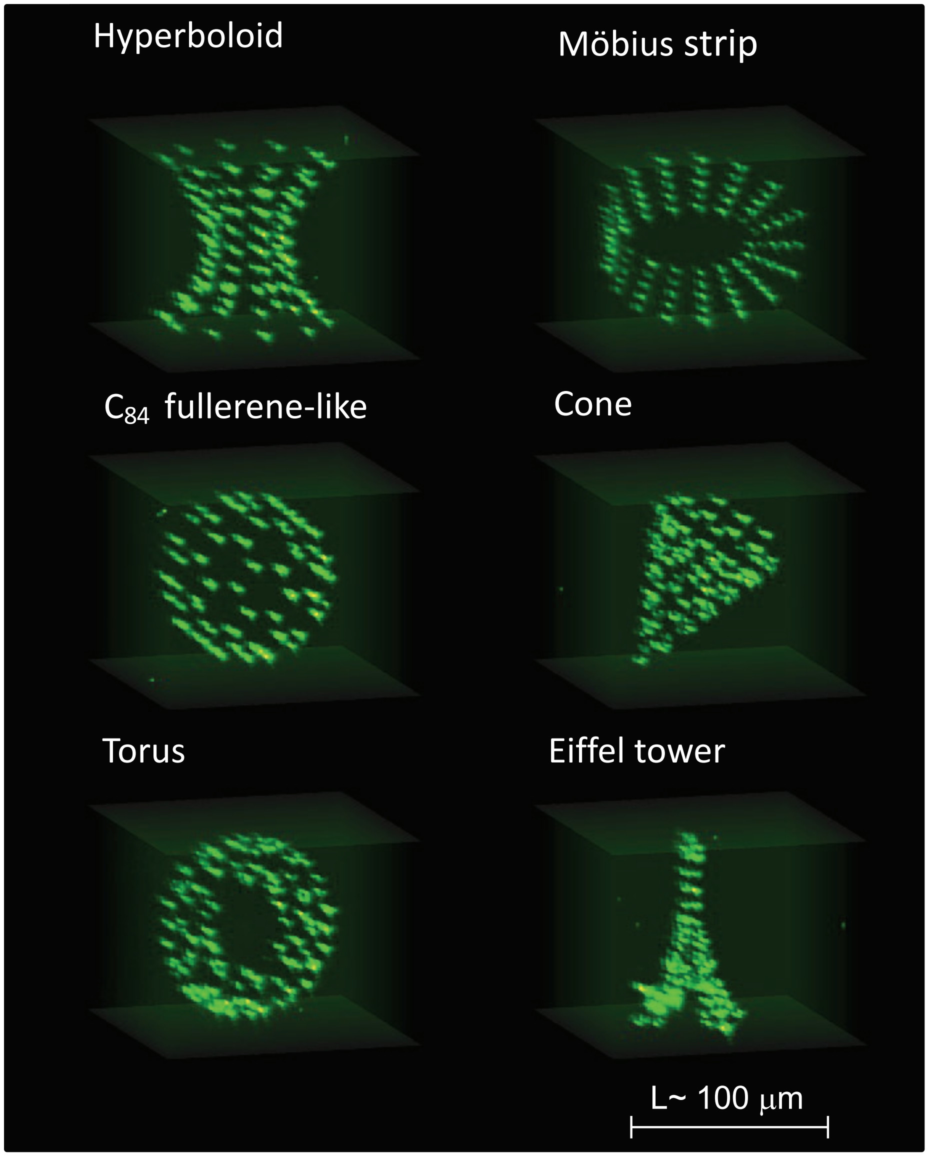
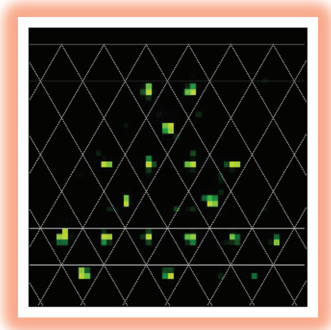
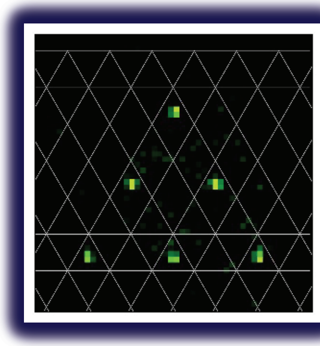


Assembled Pyrochlore lattice

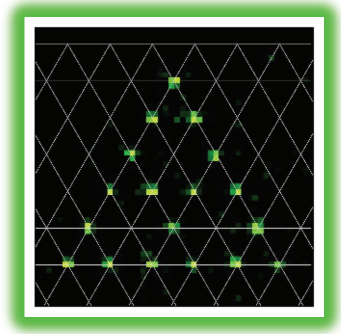
Plane 1



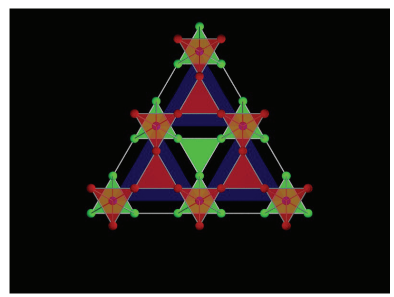
Plane 2



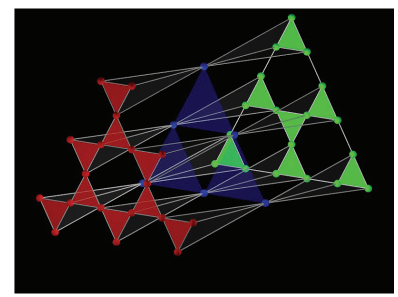
Plane 3



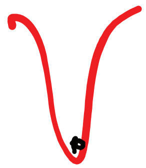
Front view



Side view



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



- $\tau \sim 20\,s.$ lifetime of an atom in a tweezers
- N atoms $\longrightarrow$ τ/N : lifetime of a config.
  - ↳ $\sim$ N moves Δt.

$N \sim 1000$

Questions ?

Outline

1. Experimental considerations: arrays of individual atoms

2. "Rydbergology": scalings, interactions, blockade…

Johannes Rydberg
1854-1919

3. Measurement of interactions between Rydberg atoms: towards many-body physics

4. Application of Rydberg blockade to QIP

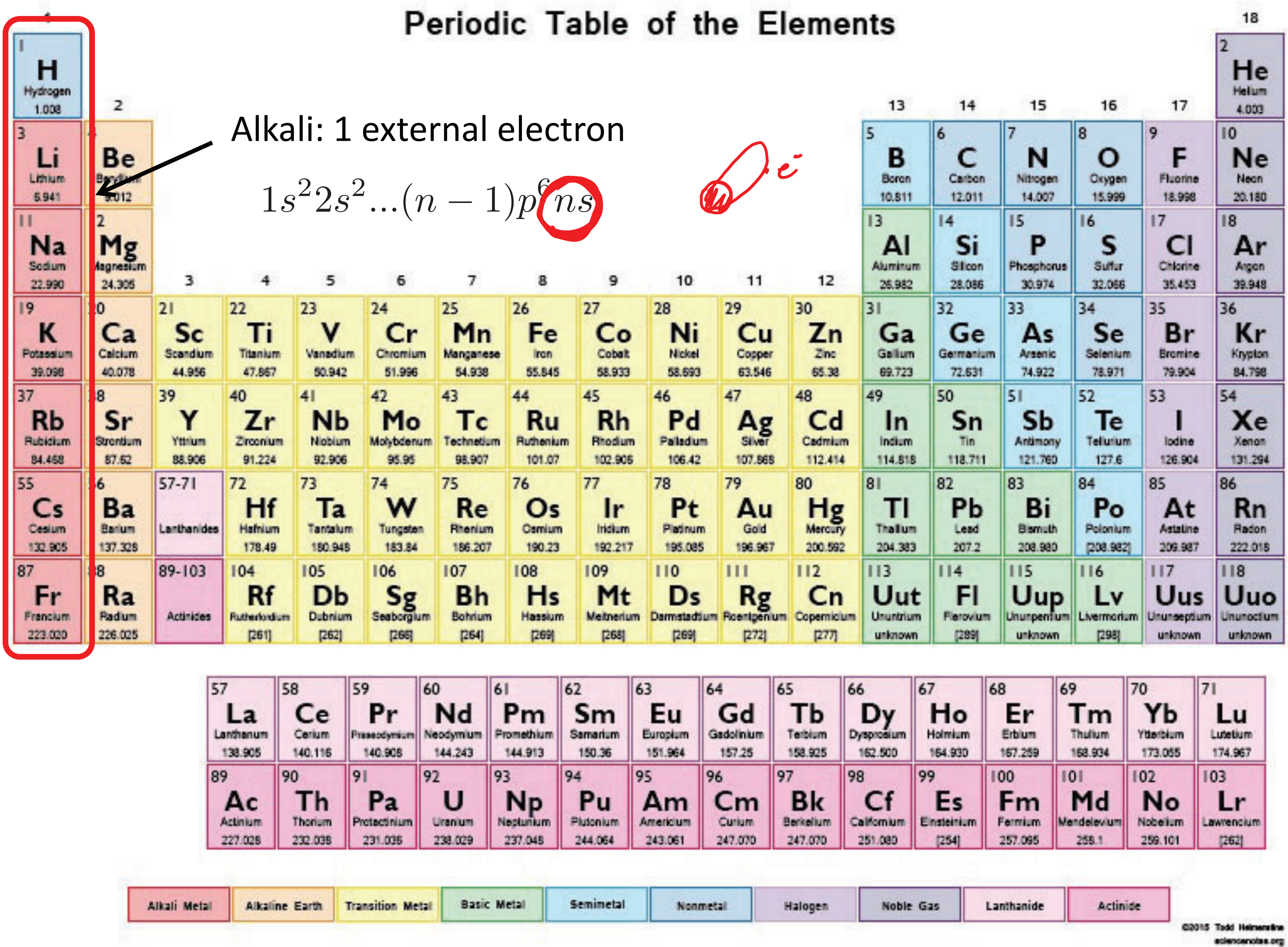
References:

"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

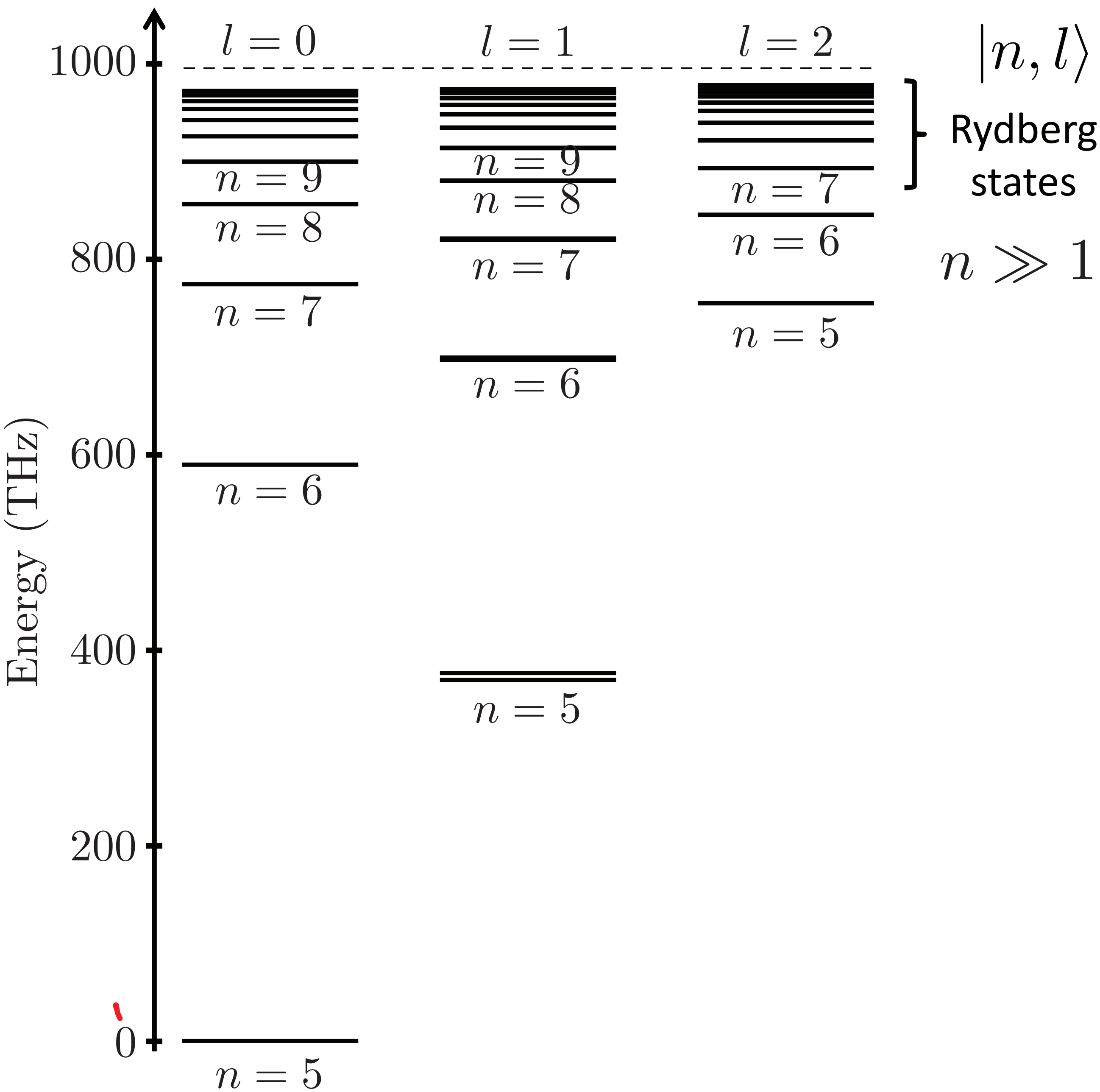


Alkali: 1 external electron

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

e^-

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



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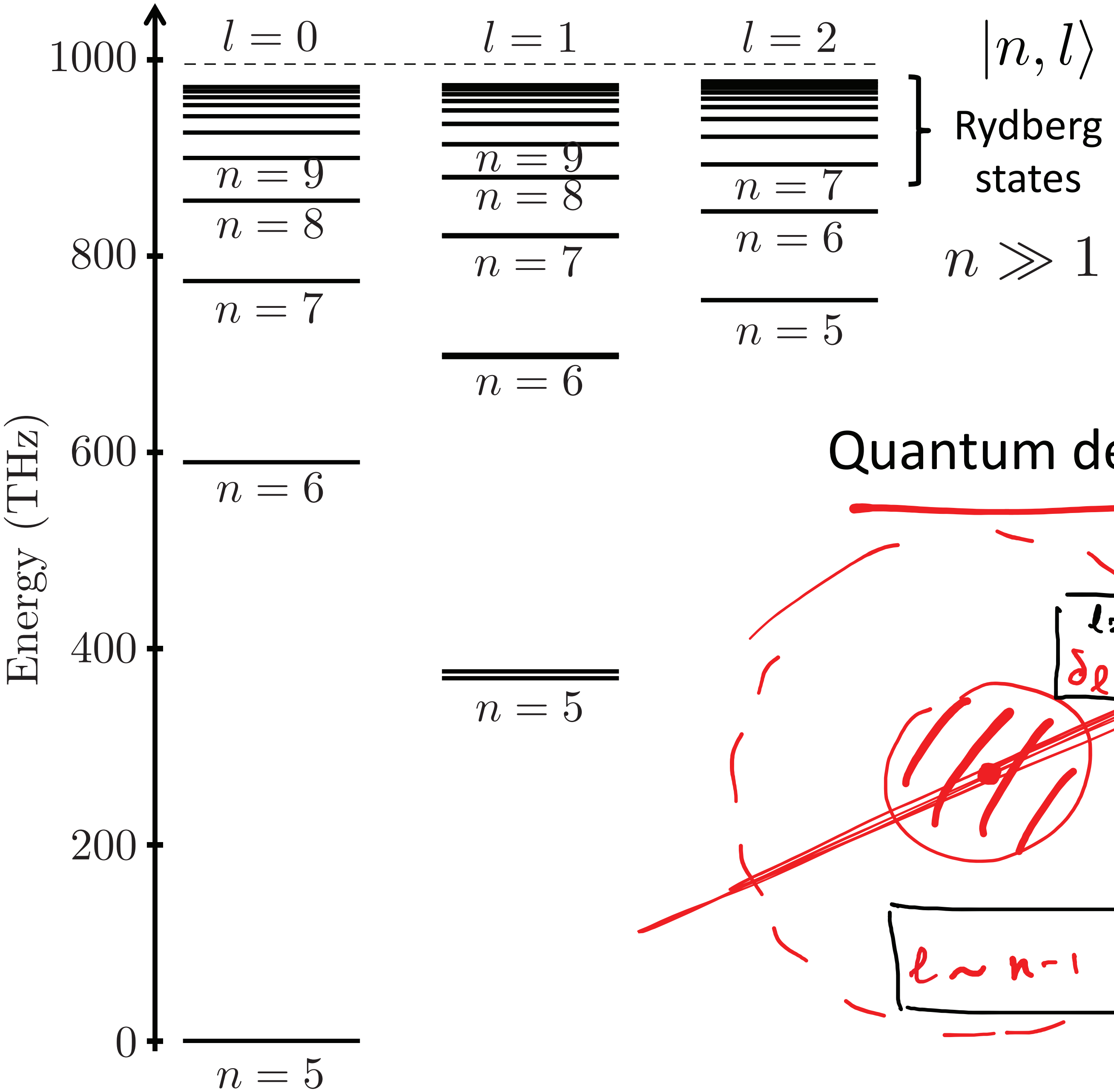
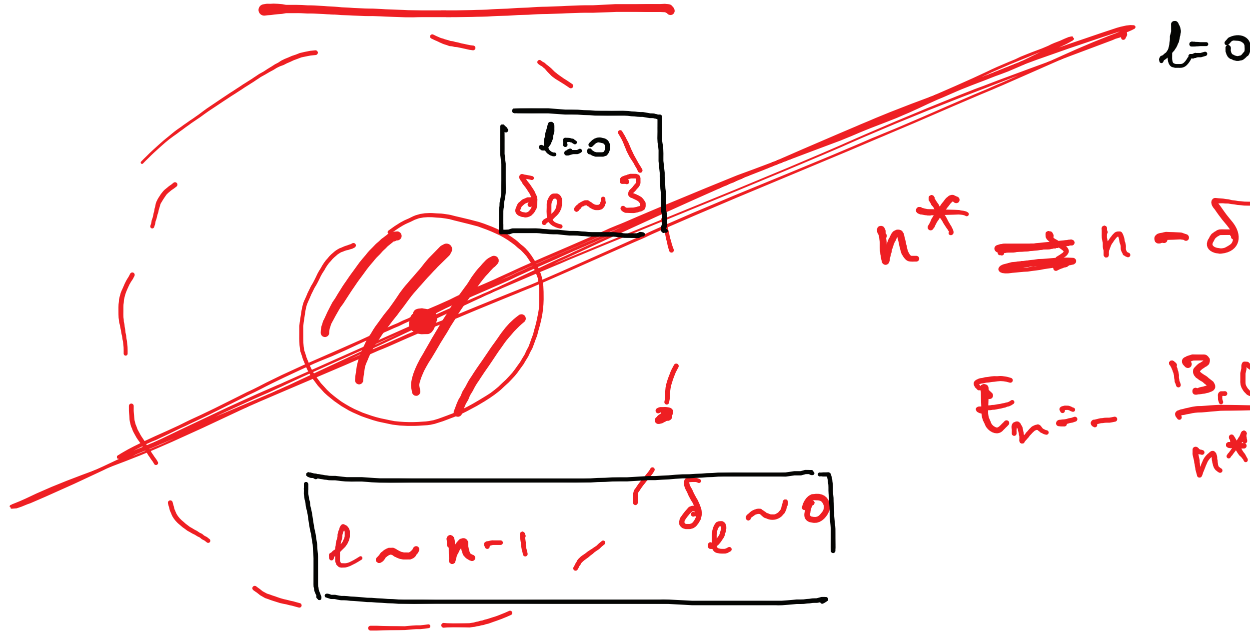


$E_n \sim -\frac{13.6}{n^2}$ eV. (H)

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

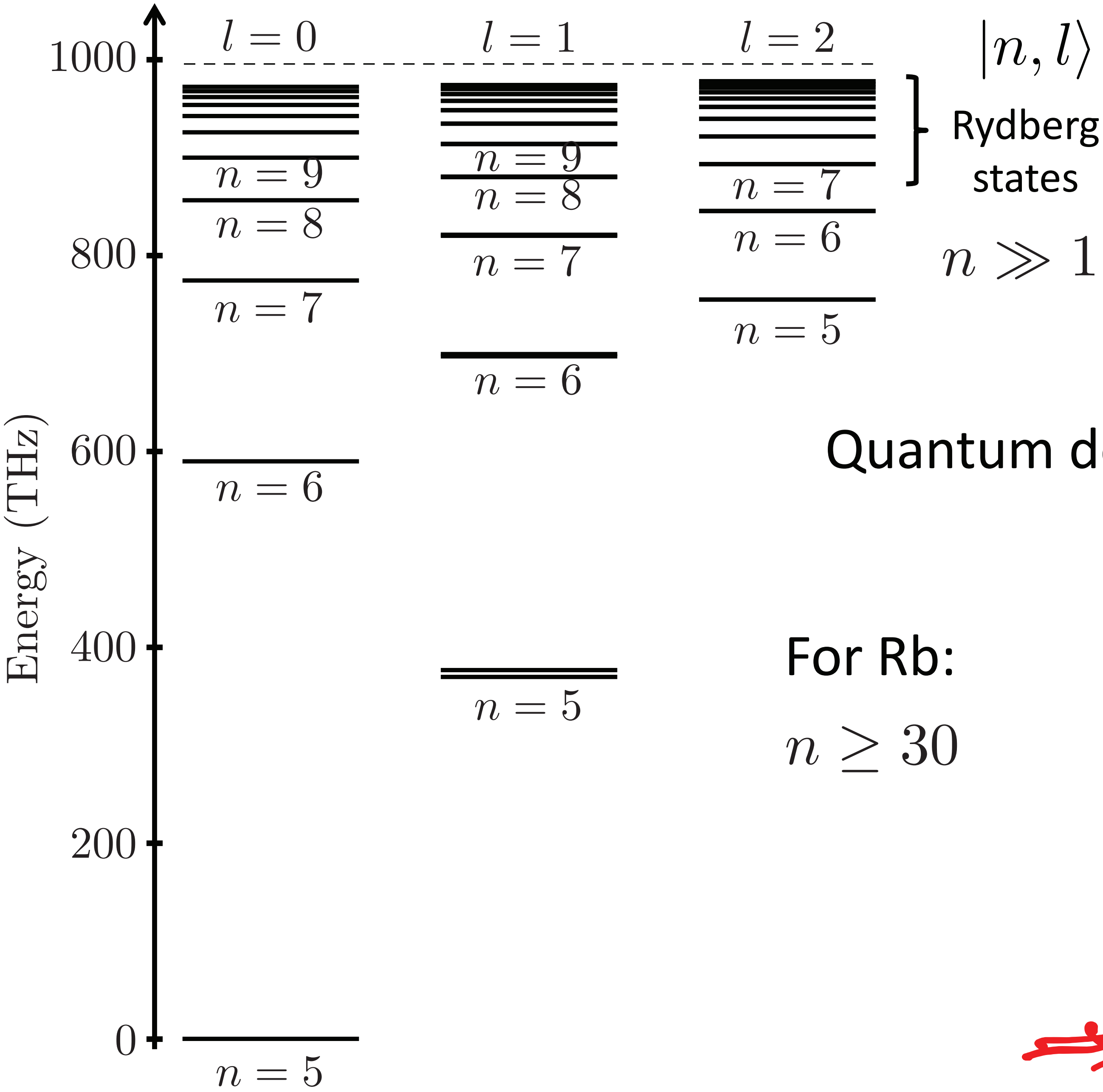
Quantum defects **(experimental)**



$n^* \Rightarrow n - \delta$

$E_n = -\frac{13.6}{n^{*2}}$

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



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

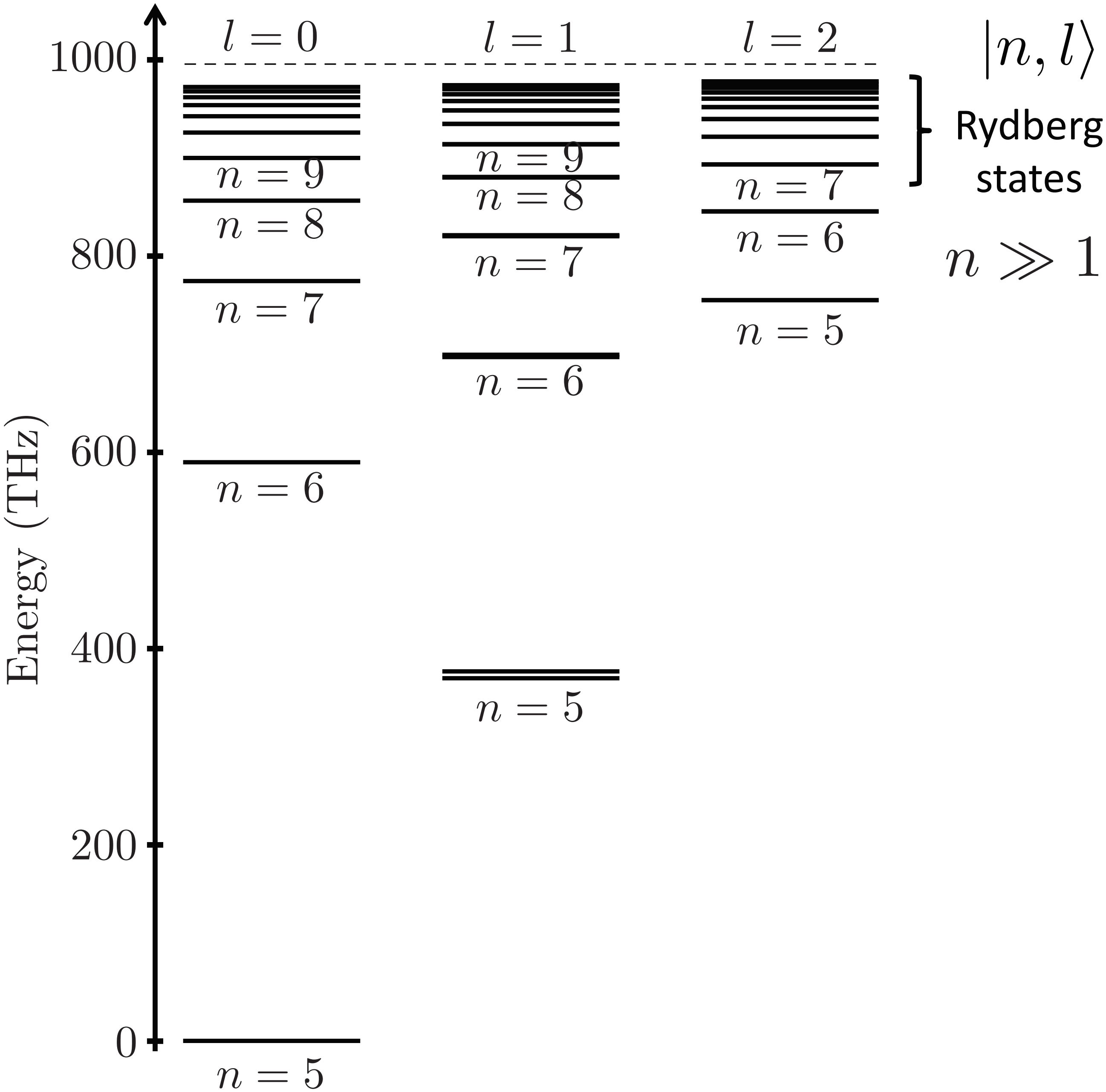
Quantum defects **(experimental)**

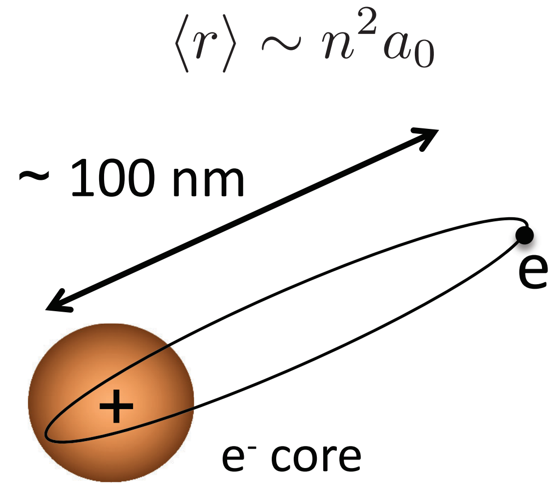
For Rb:

$n \geq 30$

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

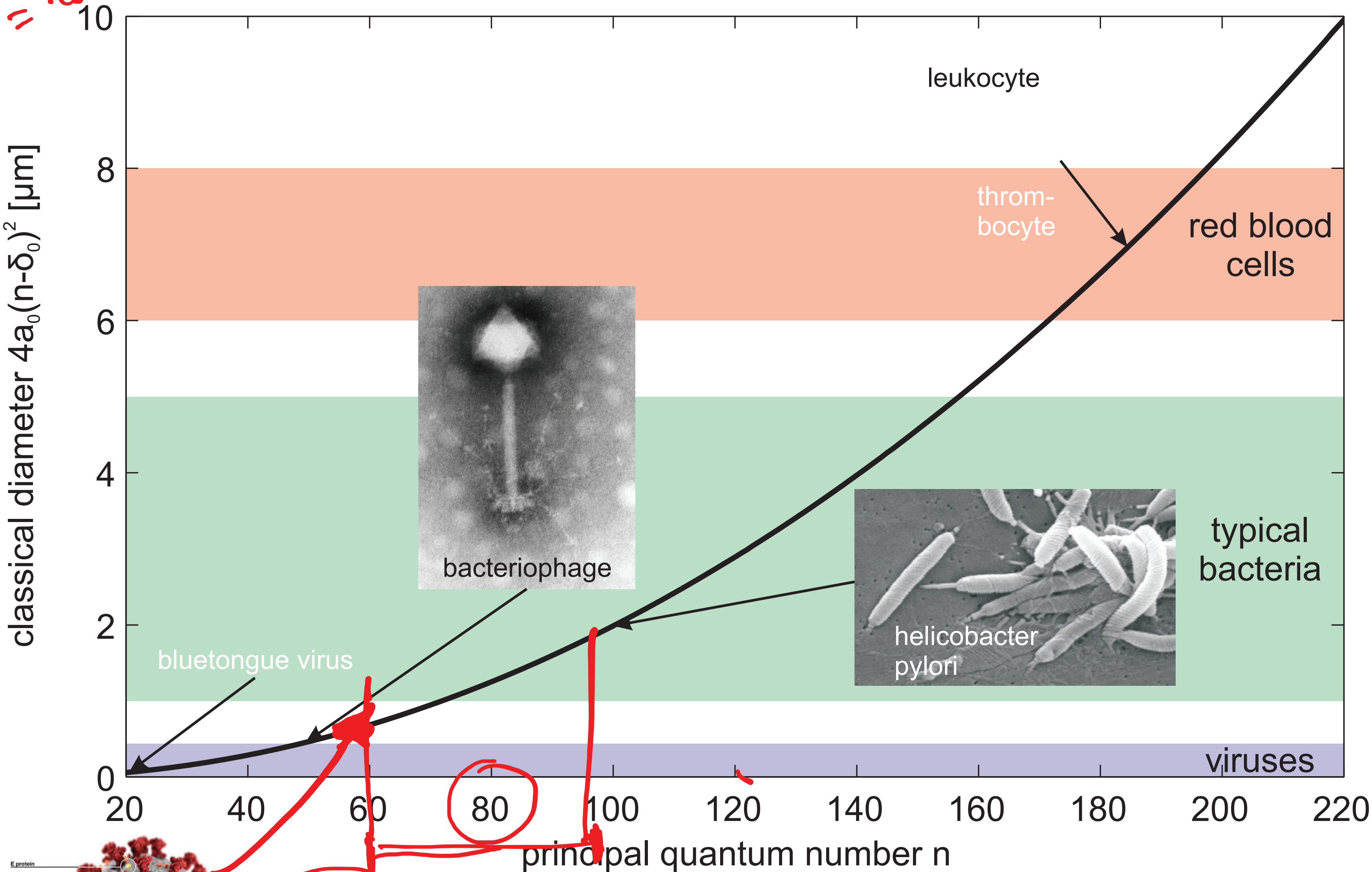
"Rydberg atom" = a highly excited atom (e.g. Rb)

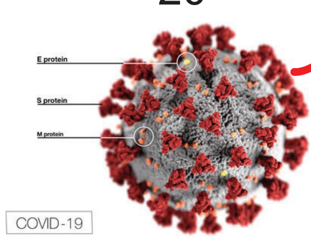




Rydberg atoms are huge...

$n^2 a_0$ = "radius"



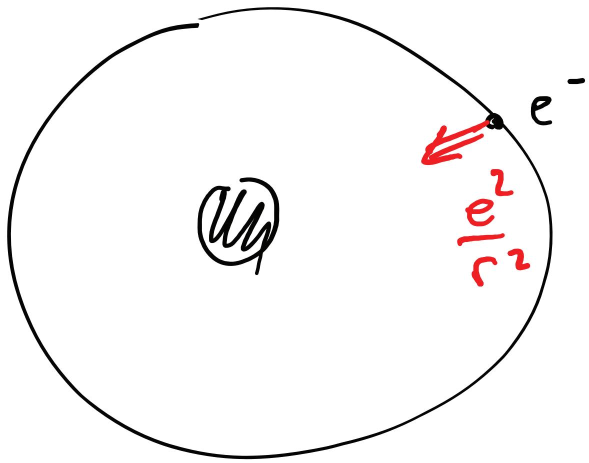


125 nm

$n \simeq 60$

J. Balewski, PhD thesis

The Bohr model to recover quickly the scalings…



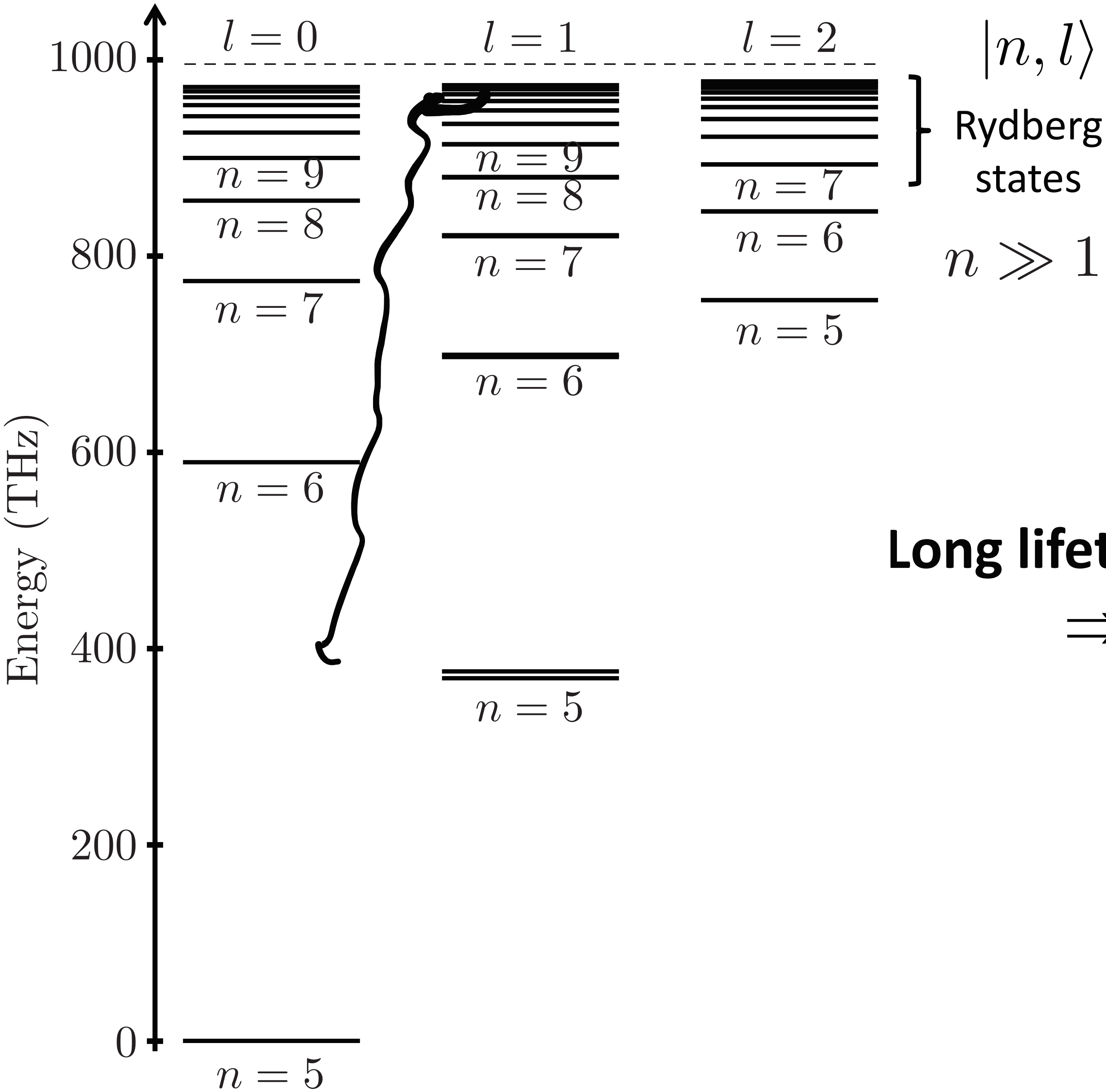
$$\begin{cases} m\frac{v^2}{r} = \frac{e^2}{r^2} \\ m v r = n\hbar \end{cases}$$

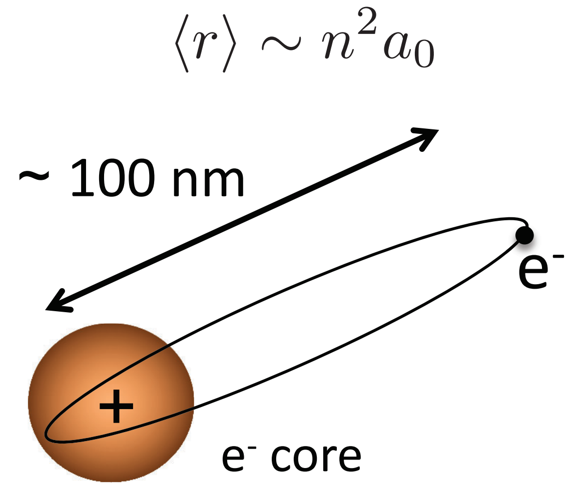
Bohr

$\hookrightarrow n = 1, 2, \ldots$

$$\Rightarrow \quad r = \underbrace{n^2} \frac{m\hbar^2}{e^2} \qquad \left(e^2 = \frac{q^2}{4\pi\varepsilon_0}\right)$$

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

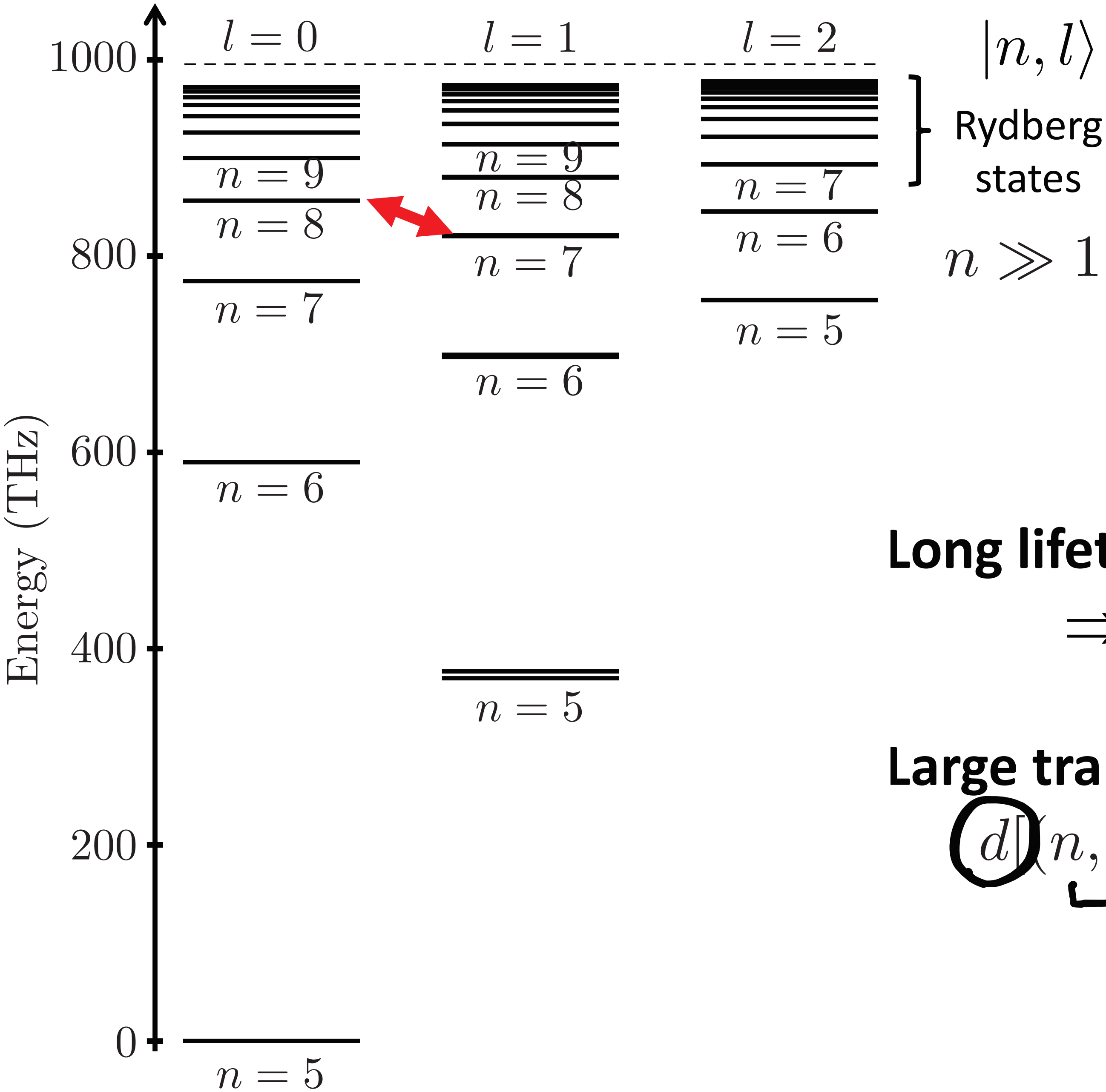


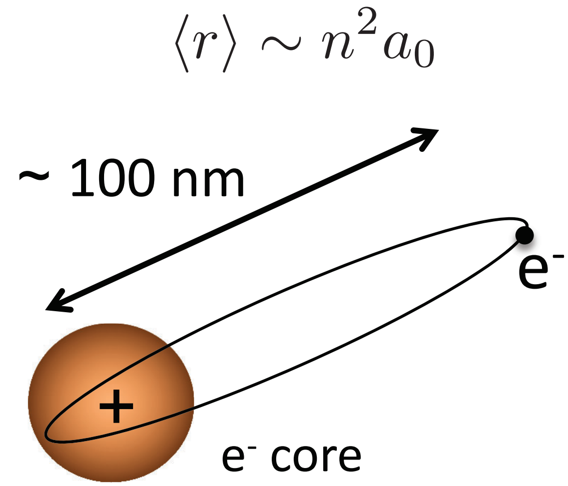


Long lifetime $\tau \sim n^3$

$\Rightarrow$ $n > 60$, $\tau > 100$ μs

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





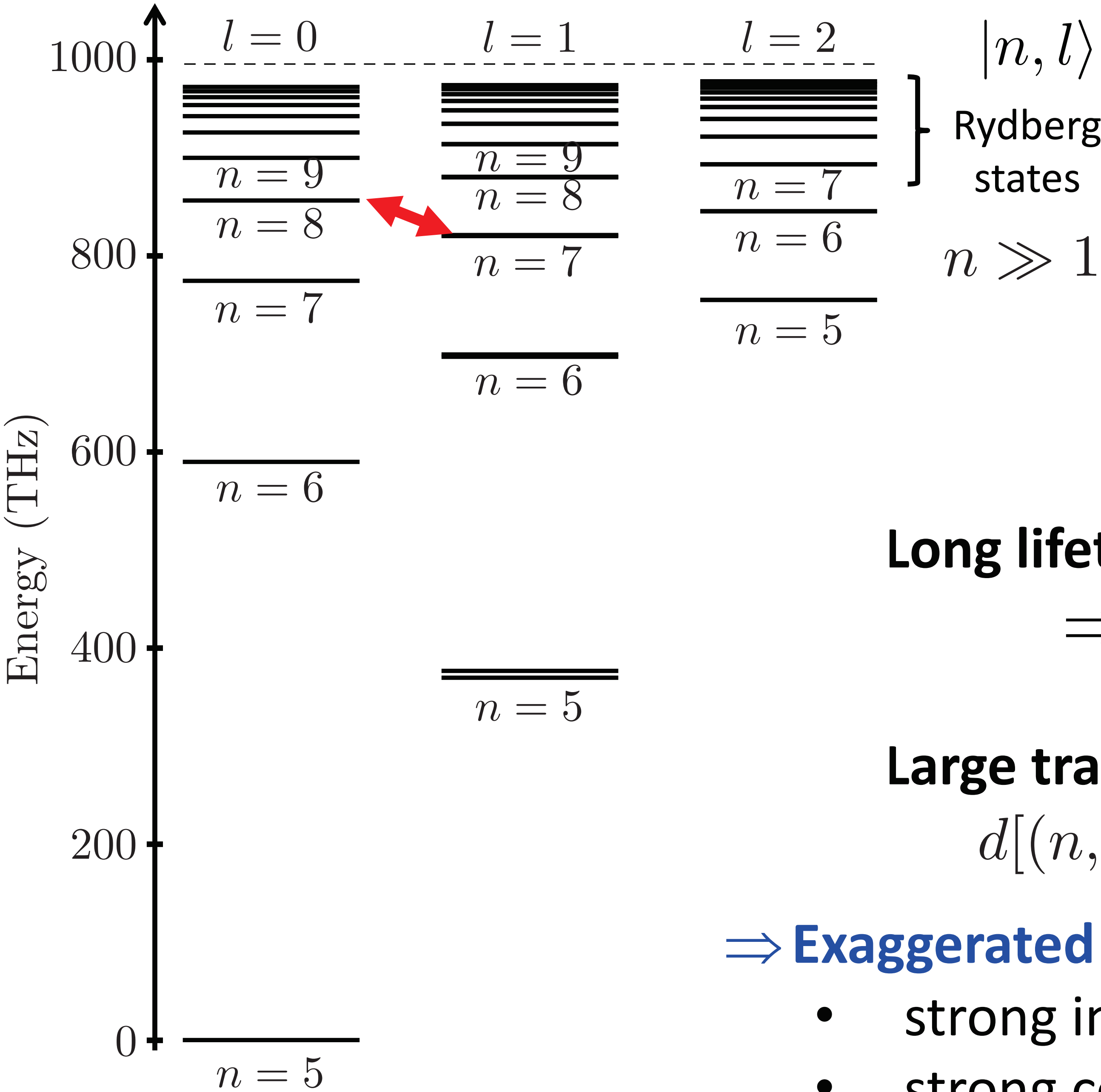
Long lifetime $\tau \sim n^3$

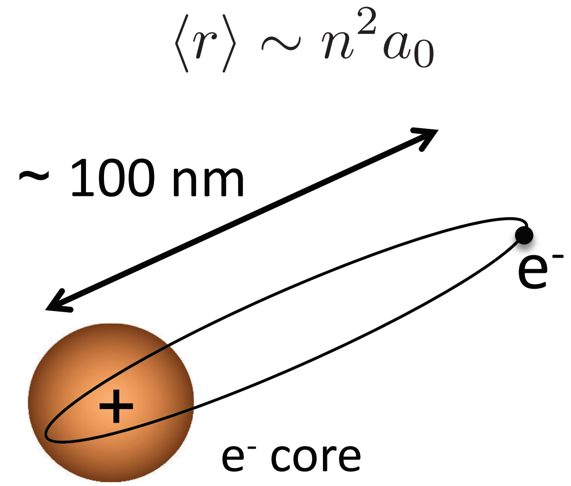
$\Rightarrow$ *n* > 60, τ > 100 µs

Large transition dipole:

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

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





Long lifetime $\tau \sim n^3$

$\Rightarrow$ *n* > 60, τ > 100 μs

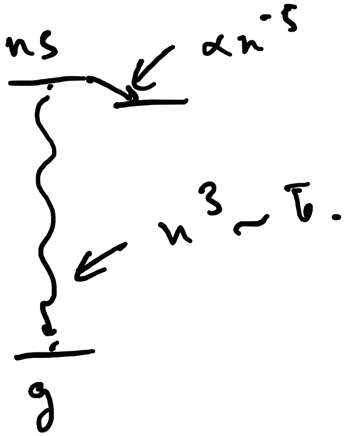
Large transition dipole:

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

$\Rightarrow$ **Exaggerated properties:**

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

Rydberg's have exaggerated properties



Do it as a problem.

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

$\Gamma = d_{ig}^2 \, \omega^3$

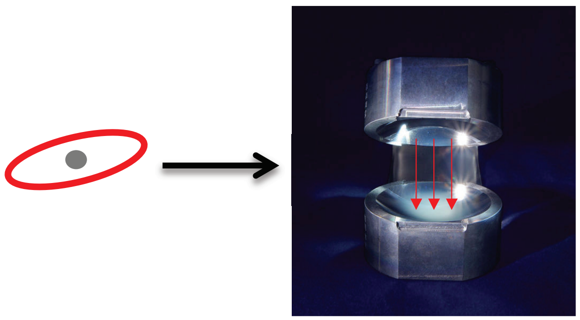
$= \Gamma \propto \left(\frac{1}{n^3}\right)^3 n^4$

$C_6 \sim n^{11}$

Rydberg atoms: a few historical landmarks

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

1980 – 2000 Cavity Quantum Electrodynamics using Rydbergs



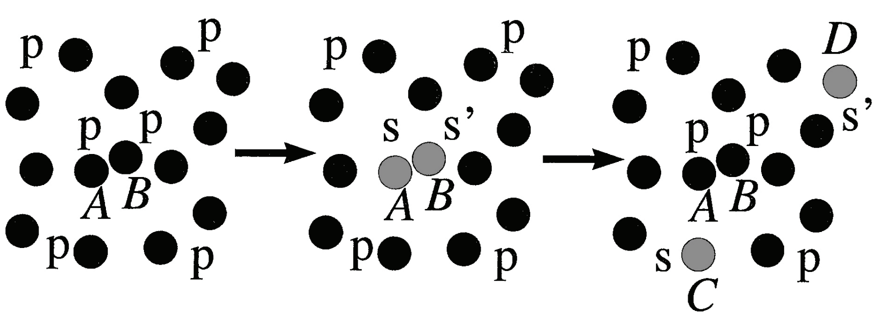
High Q cavity: photon lifetime > 1ms

+ large dipole $\Rightarrow$

1 Rydberg interacts with 1 photon!

Haroche, Walther…

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



$p + p \leftrightarrow s + s'$

$p + s \leftrightarrow s + p$

"Frozen" gas

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

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

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

$k_B T$ << Interaction energy

$\Rightarrow T < 1$ mK

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
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

S. L. Rolston
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R. Côté[1] and M. D. Lukin[2]

VOLUME 87, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JULY 2001

Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles

M. D. Lukin,[1] M. Fleischhauer,[1,2] and R. Cote[3]
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[2]*Fachbereich Physik, Universität Kaiserslautern, D-67663 Kaiserslautern, Germany*
[3]*Physics Department, University of Connecticut, Storrs, Connecticut 06269*

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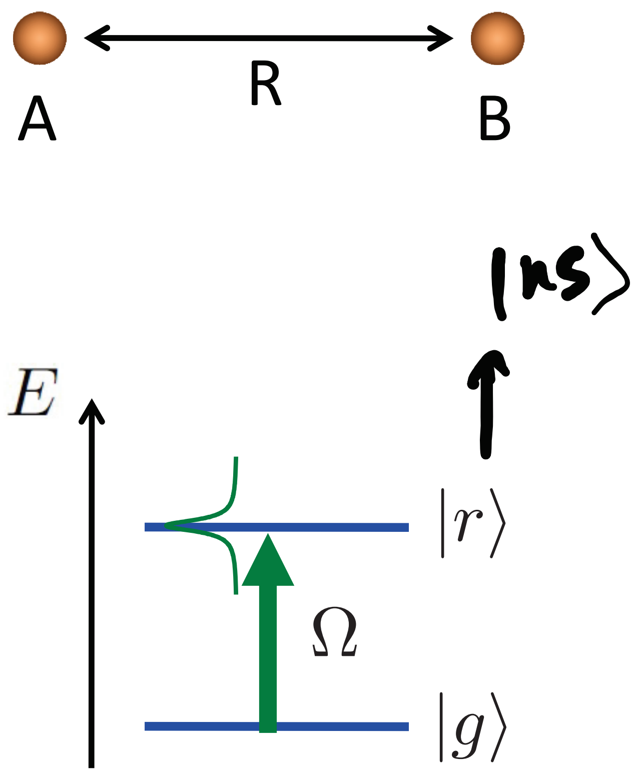
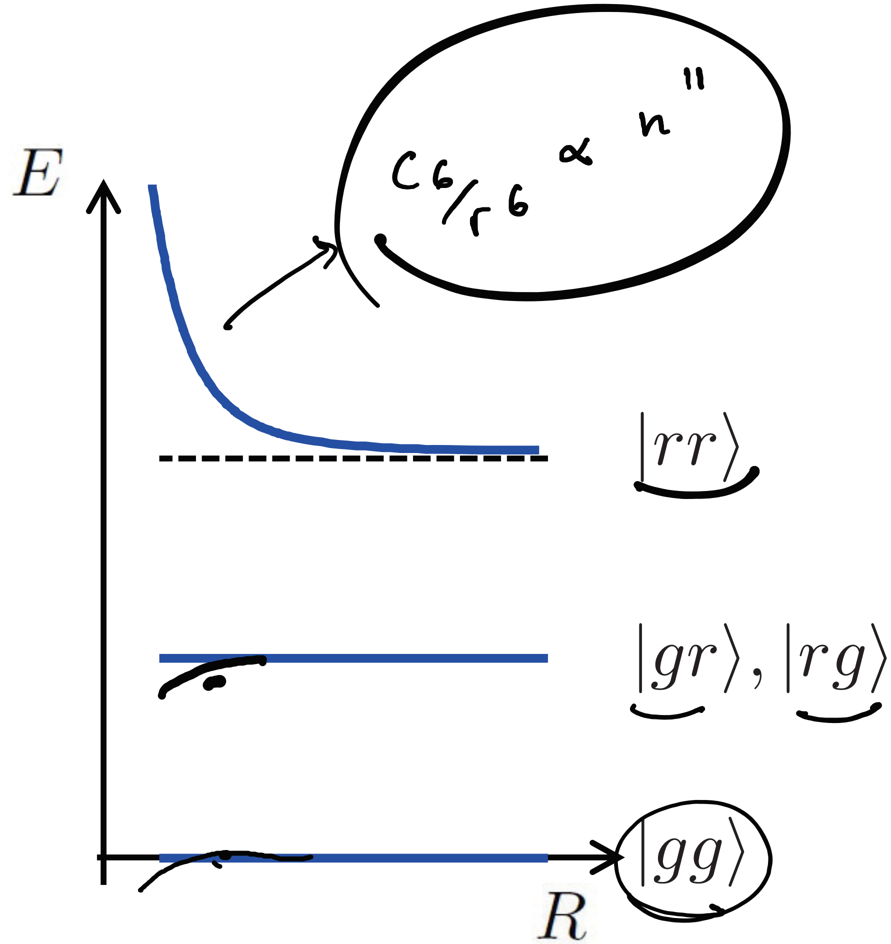
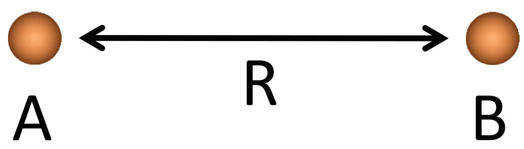
(Received 7 November 2000; published 26 June 2001)

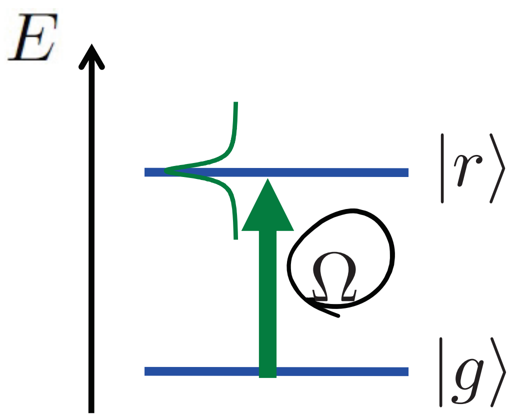
A new era: the Rydberg Blockade idea

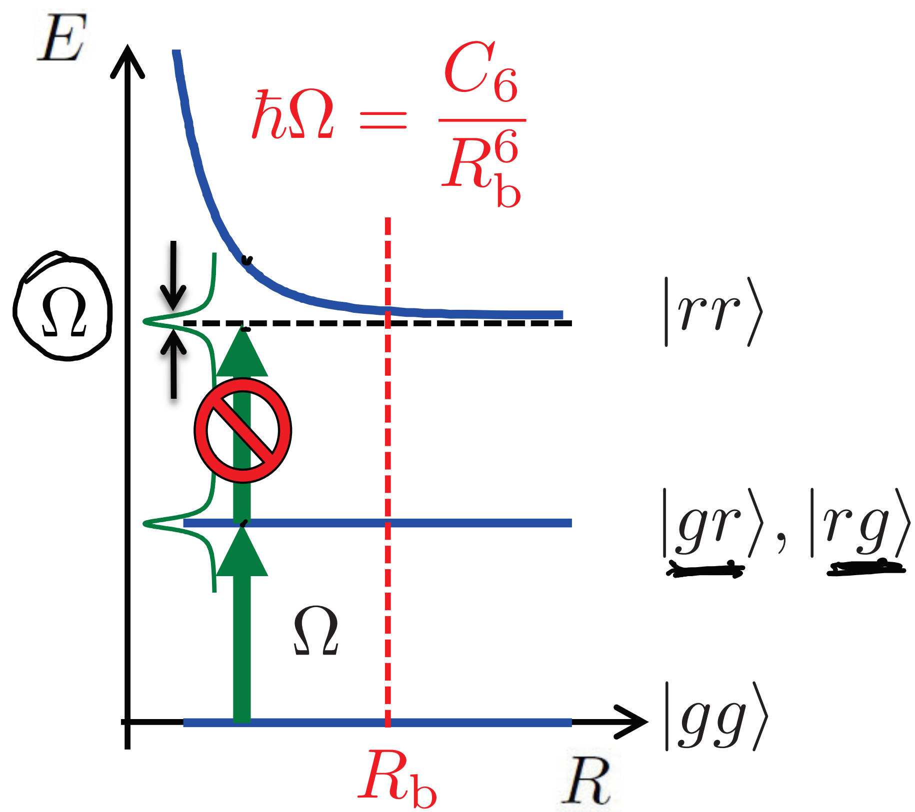




A new era: the Rydberg Blockade idea

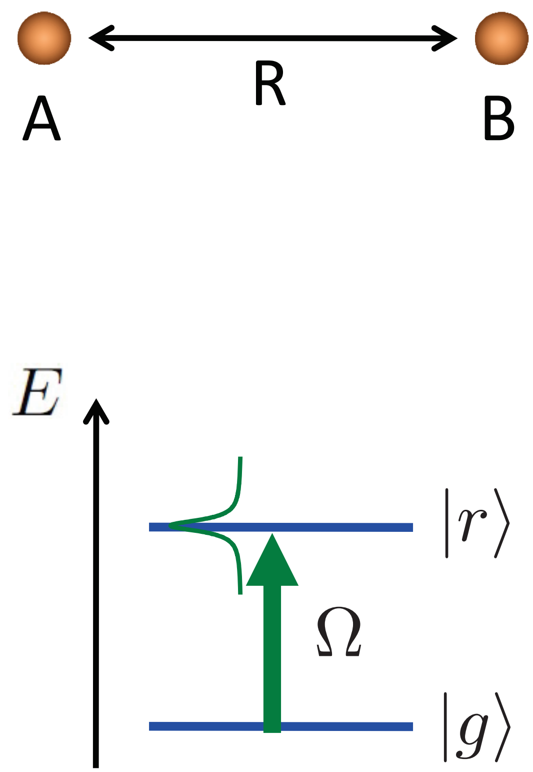


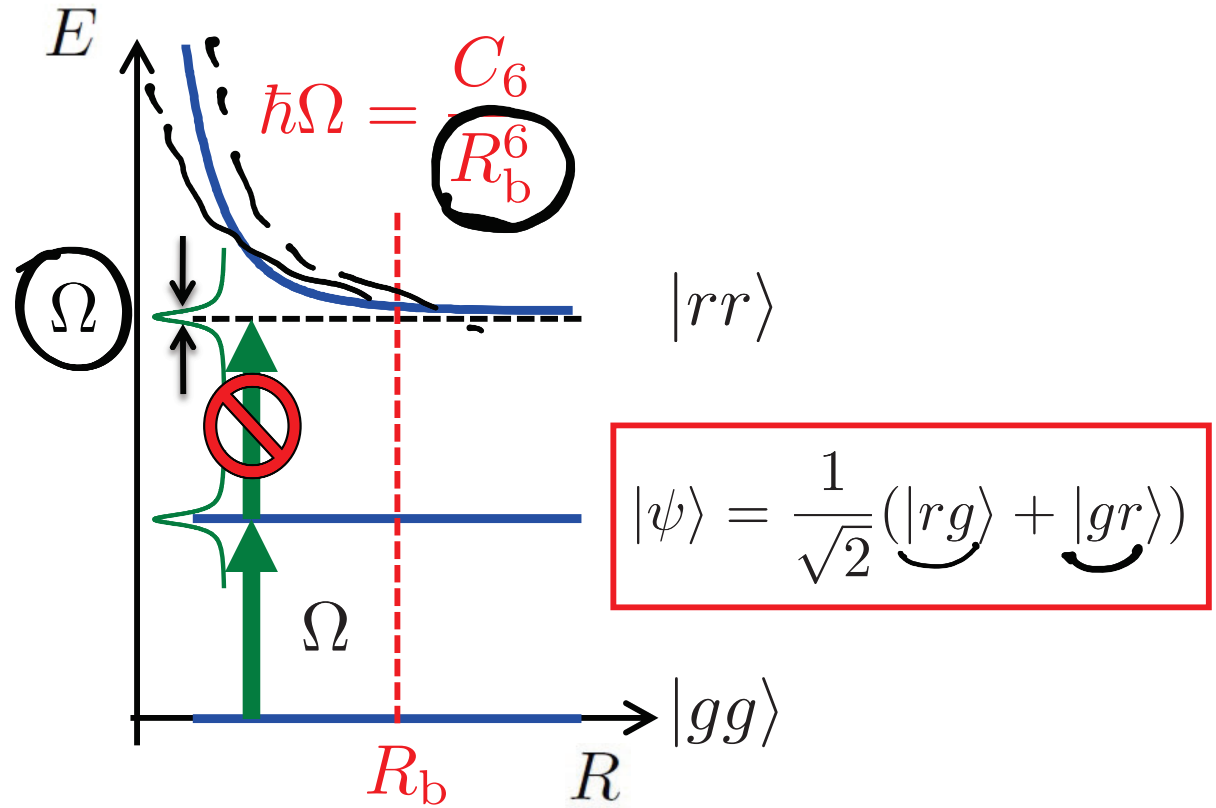




If $\hbar\Omega \ll U_{\mathrm{vdW}}$: no excitation of $|rr\rangle \Rightarrow$ **blockade**

A new era: the Rydberg Blockade idea

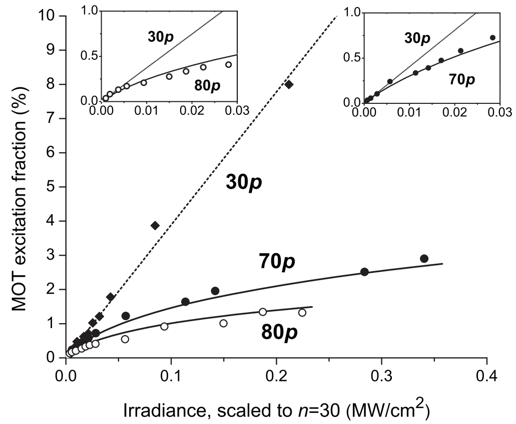


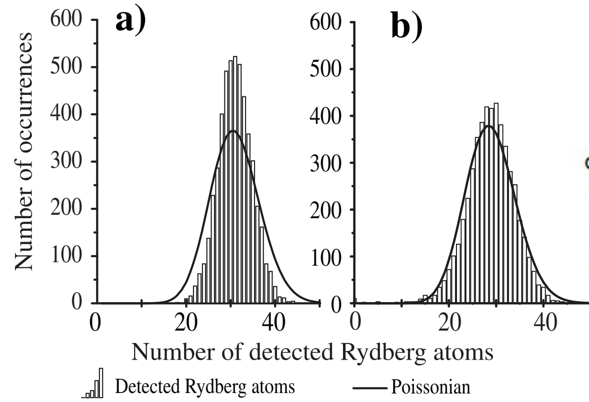


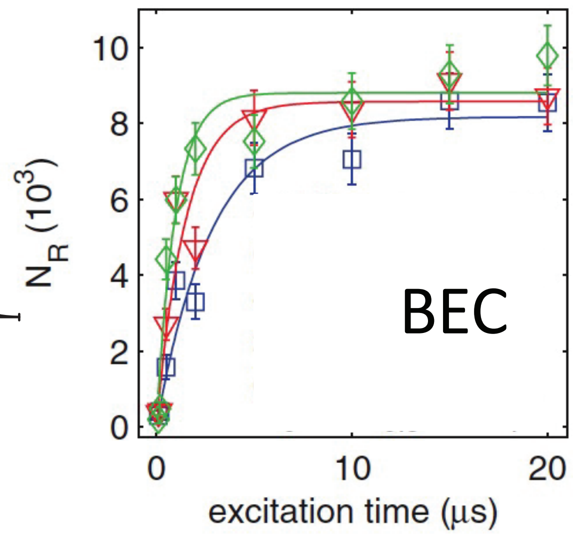
Blockade $\Rightarrow$ **entanglement and gates!!**

The first blockade experiments

Atomic ensembles







Gould, PRL 2004

Weidemuller, PRL 2004

Martin, PRL 2004

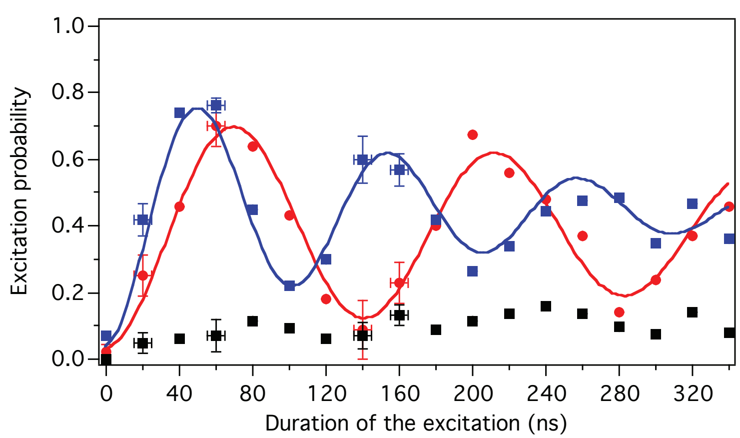
Pillet, PRL 2006

Raithel, PRL 2005

Pfau, PRL 2007

Individual atoms

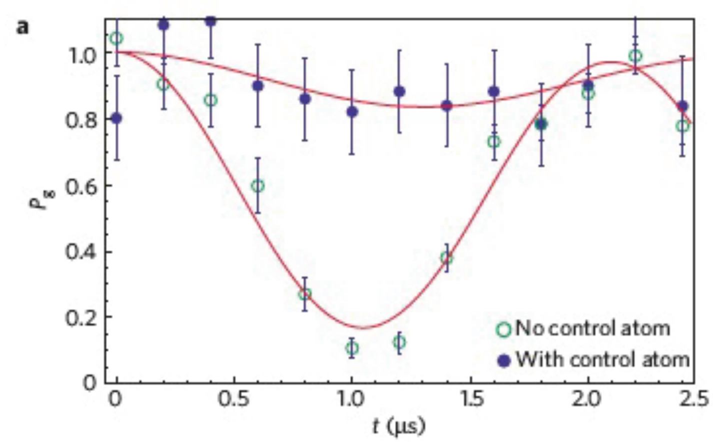
IO Palaiseau



Blockade + collective excitation √2

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

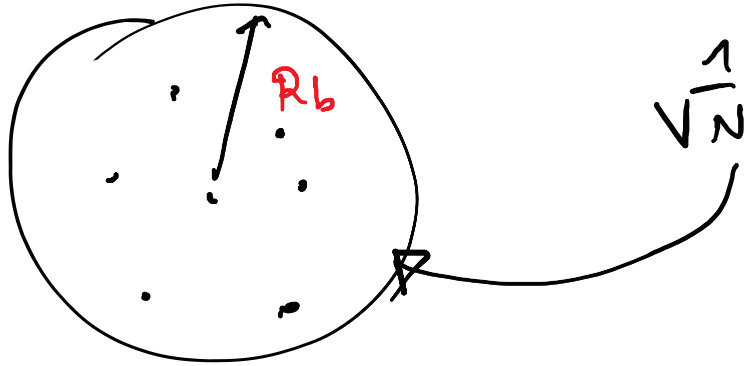
U. Wisconsin



Blockade

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

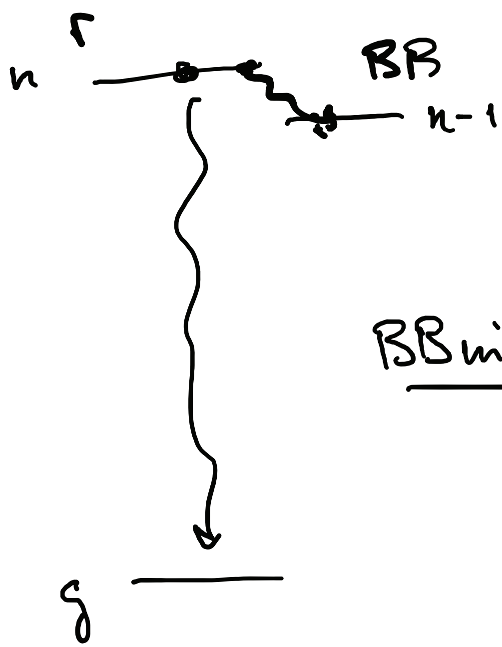
① Blockade for N atoms:



$$\frac{1}{\sqrt{N}}\left(|rg\ldots g\rangle e^{i\vec{k}\cdot\vec{r}_1} + |grg\ldots\rangle e^{i\vec{k}\cdot\vec{r}_2}\right)$$

② Influence of Black-Body radiation on lifetime of Rydb. state.

Questions ?



- $\Gamma_{n\to n-1} \sim n^5$

BB induced: $\Gamma_{n\to n-1} \times \bar{n}_{ph\,BB} \to \sim 100\,\mu s.$

Outline

1. Experimental considerations: arrays of individual atoms
2. "Rydbergology": scalings, interactions, blockade…
3. Measurement of interactions between Rydberg atoms: towards many-body physics
4. Application of Rydberg blockade to QIP

References:

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

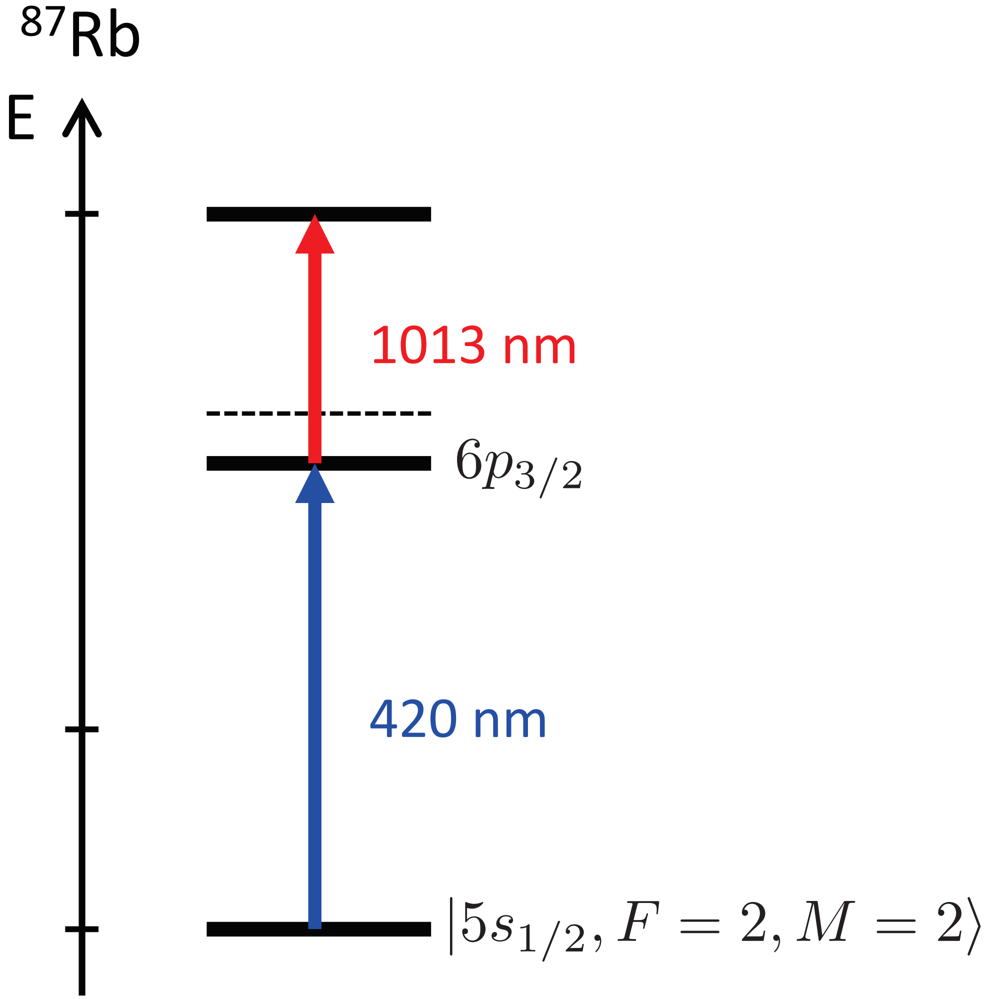
“Calculation of Rydberg interaction potentials”, S. Weber *et al.*, J. Phys. B **50**, 133001 (2017)

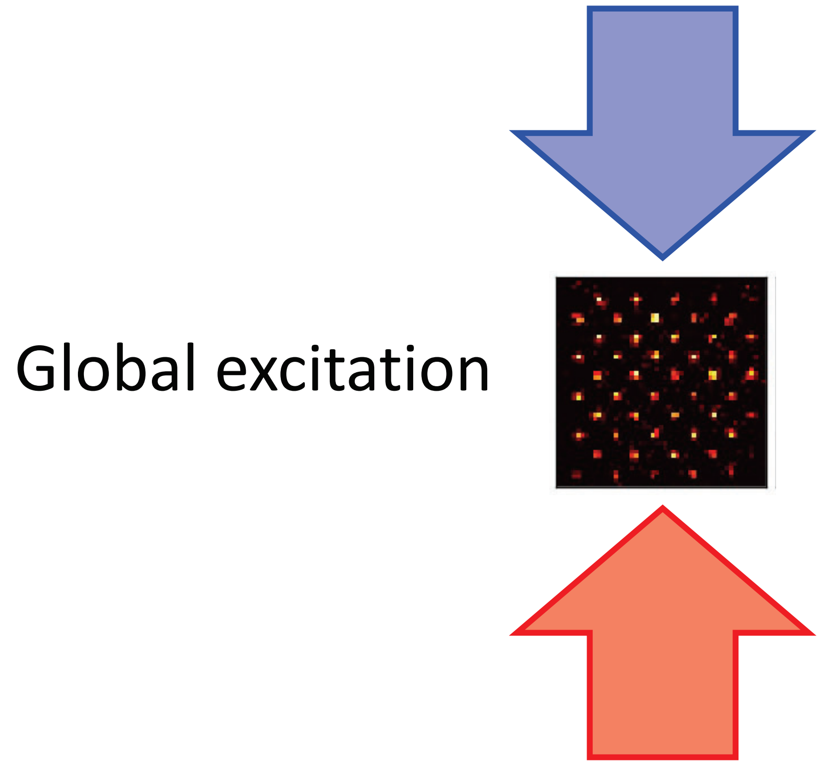
Softwares to calculate interaction energies

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

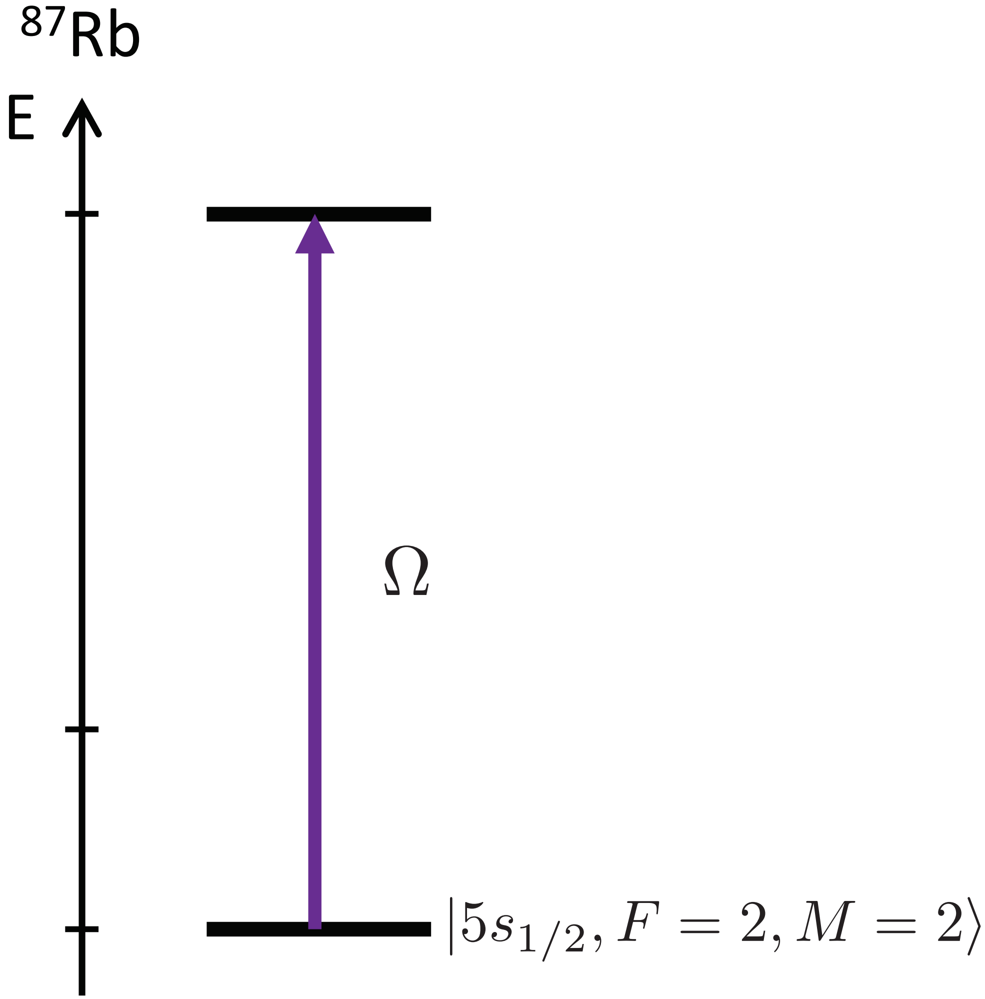
ARC: An open-source library for calculating properties of alkali Rydberg atoms, N. Sibalic *et al.,* arXiv:1612.05529 (2016)

Coherent optical Rydberg excitation (n = 50 – 100)

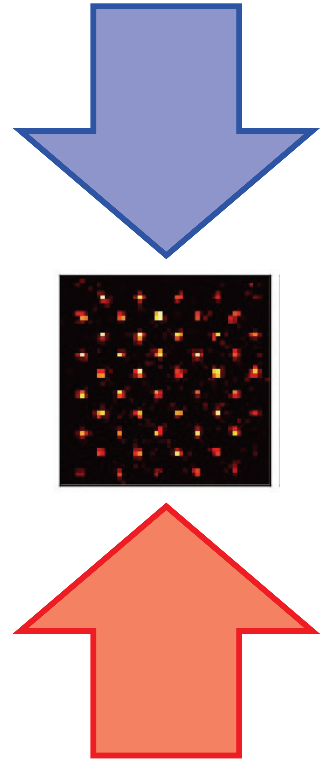




Coherent optical Rydberg excitation (n = 50 – 100)



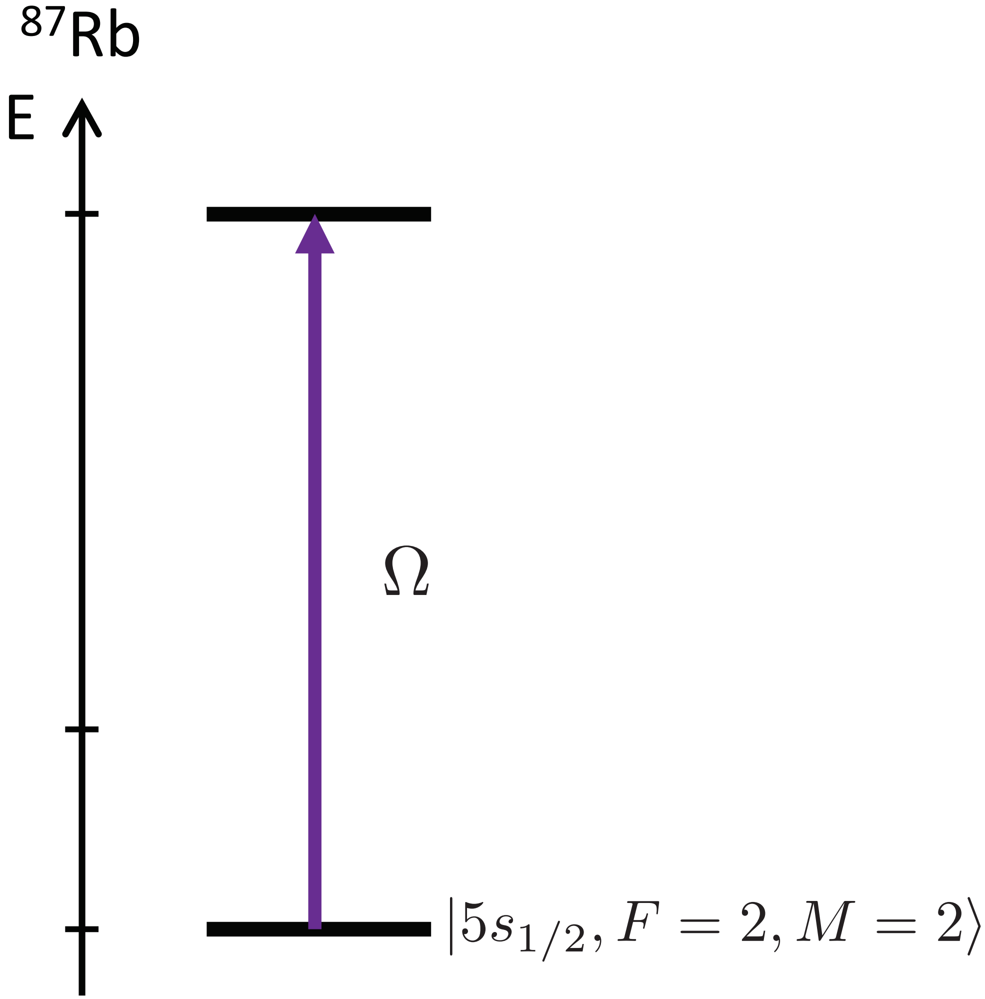
Global excitation



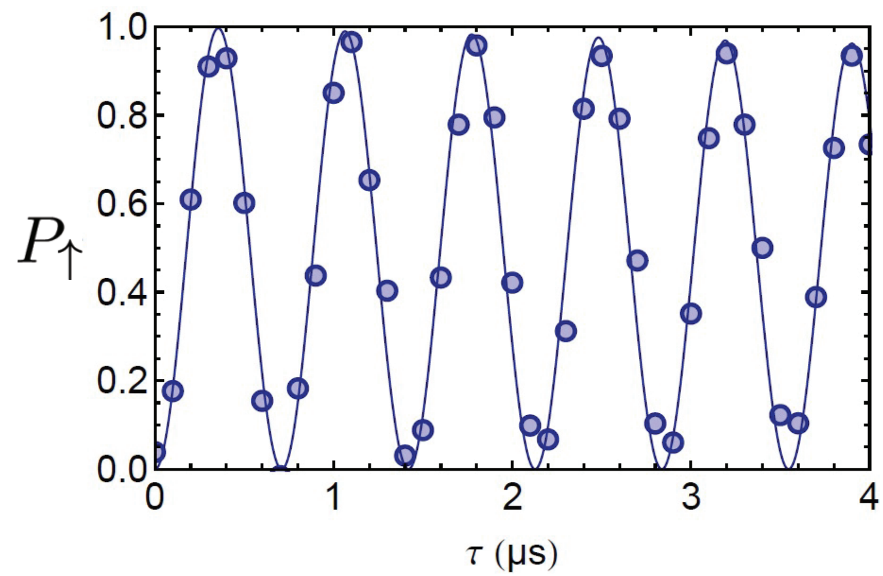
Effective Rabi frequency:

Light-shift:

Coherent optical Rydberg excitation (n = 50 – 100)



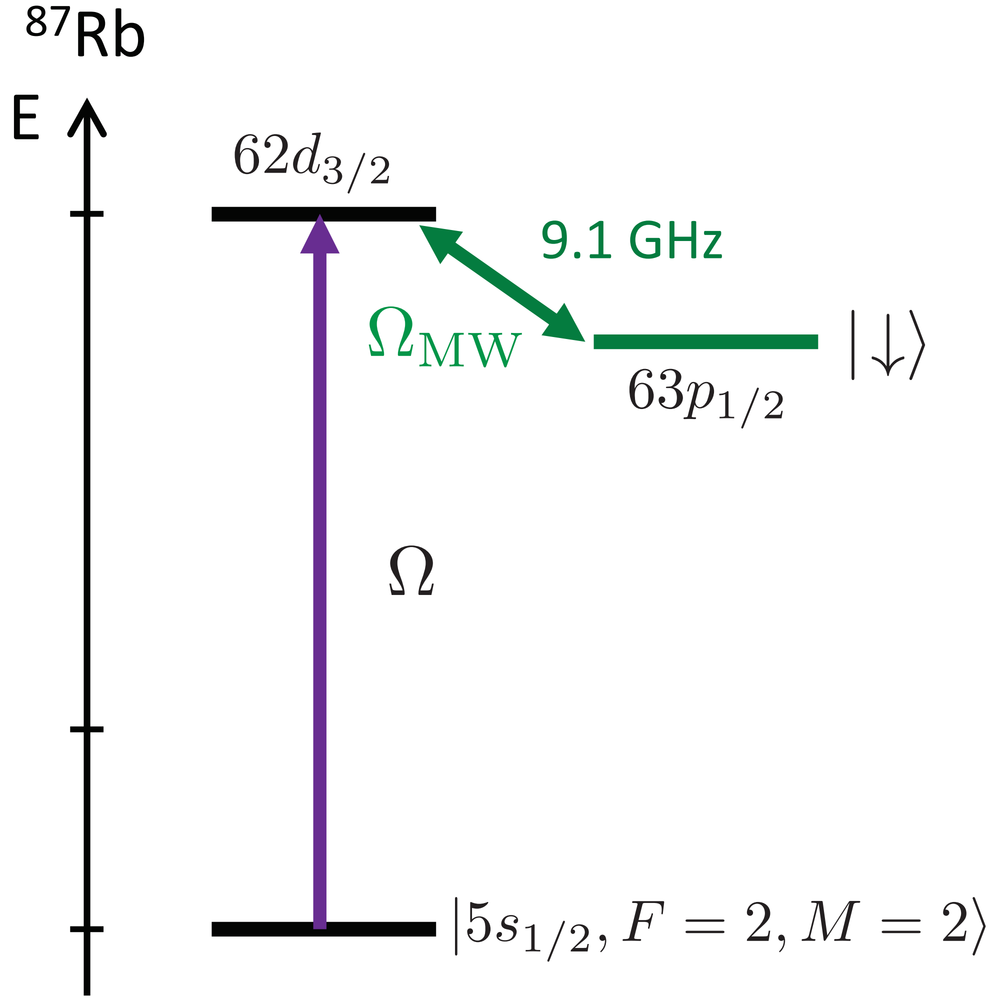
Optical excitation (Ω = 0.5 – 5 MHz)



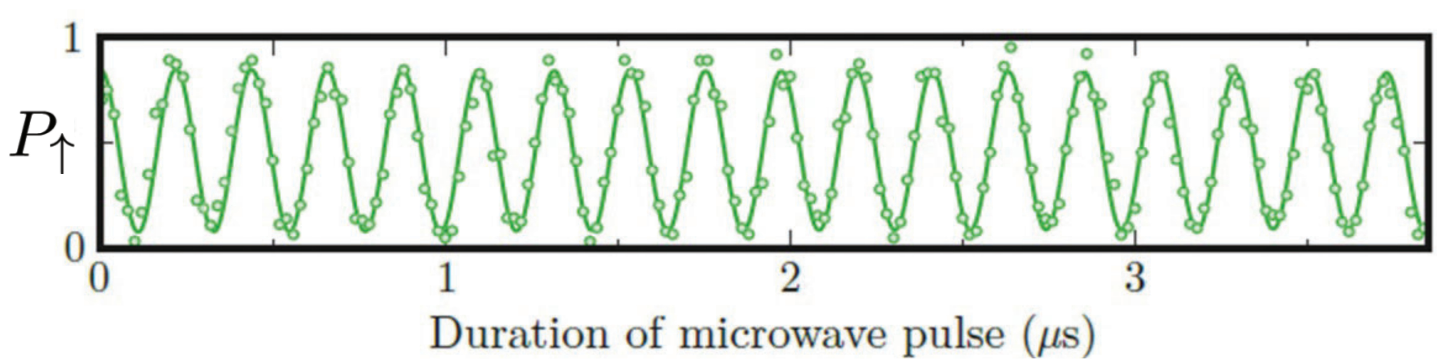
Effective Rabi frequency:

Light-shift:

Microwave manipulations (n = 50 – 100)



Microwave Rabi oscillation



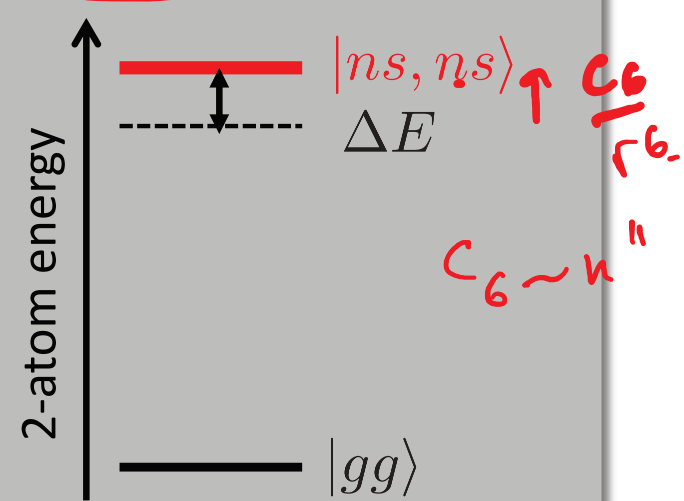
D. Barredo *et al.*,
PRL **114**, 113002 (2015)

Questions ?

Interactions between Rydberg atoms

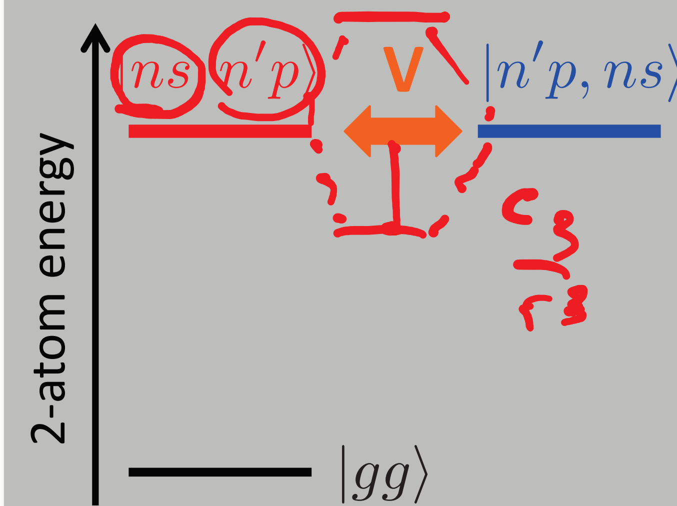
$$\hat{V} \sim \frac{\hat{d}_A \hat{d}_B}{4\pi\epsilon_0 R^3}$$

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)

Interactions between Rydberg atoms

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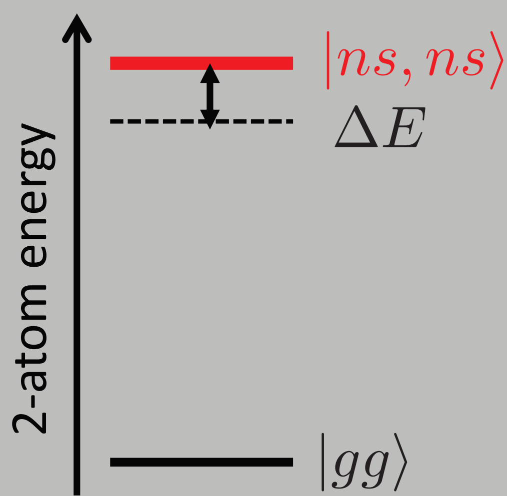

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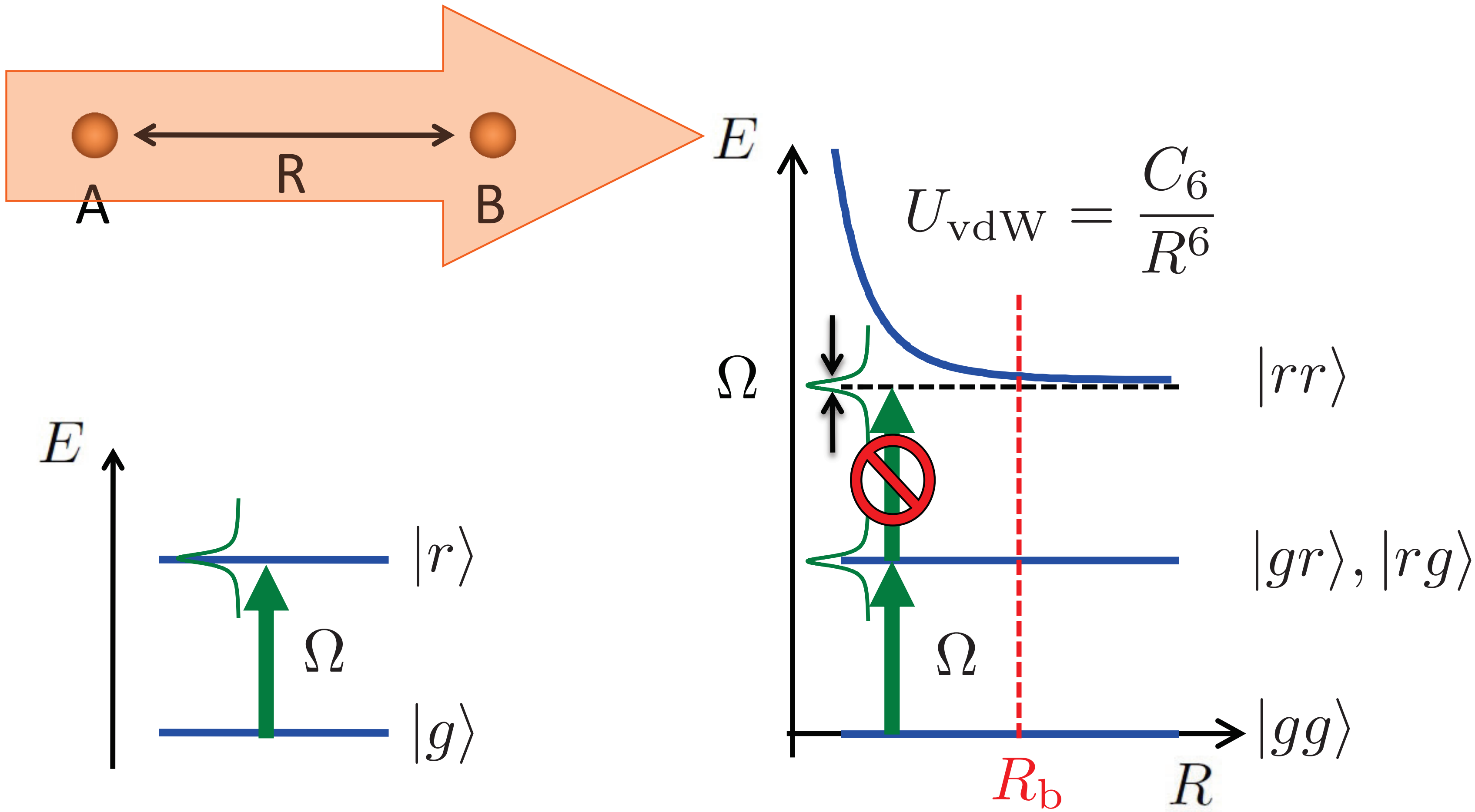
Review: Browaeys *et al.*, J. Phys. B **49**, 152001 (2016)

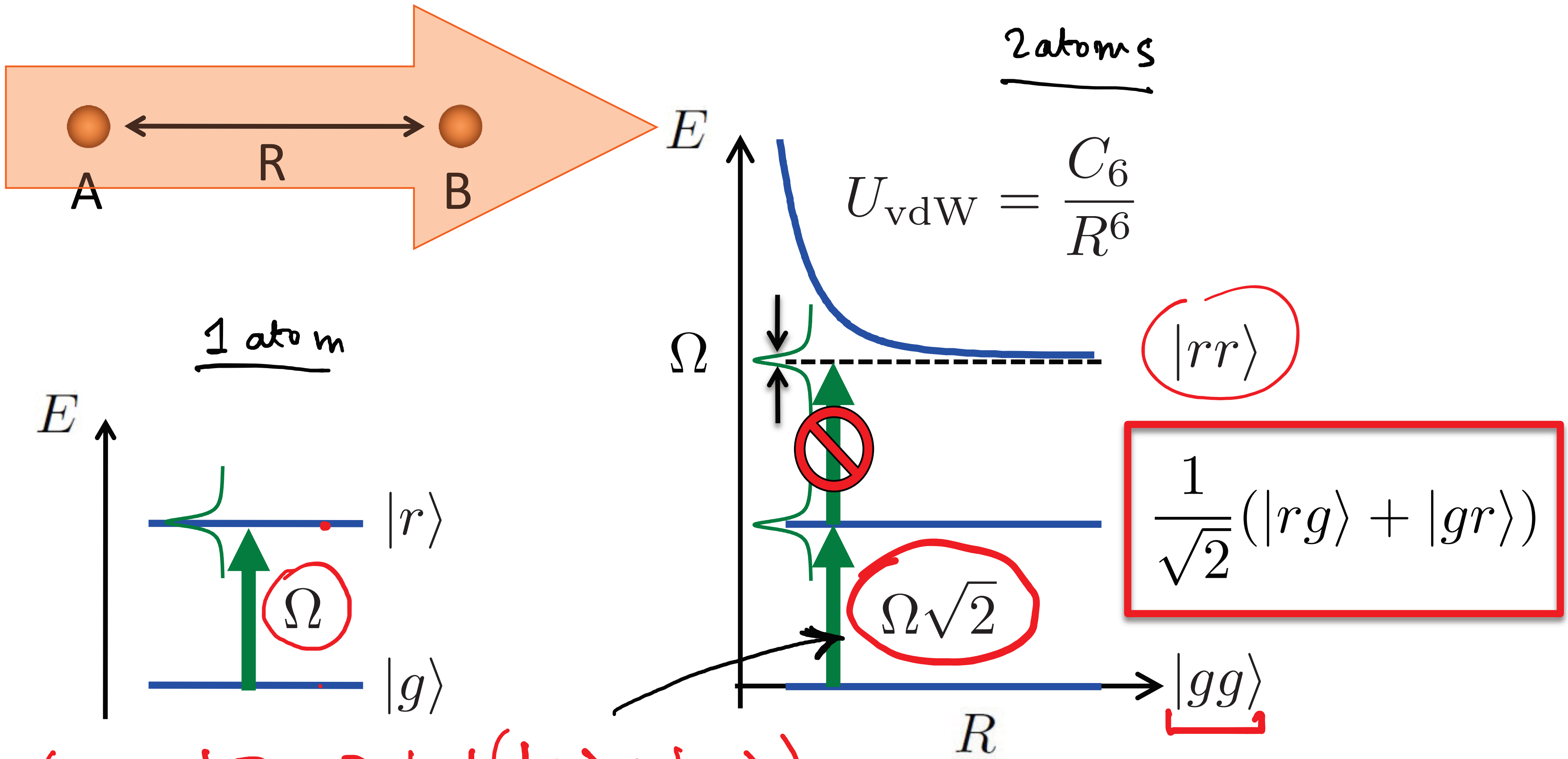
Collective excitation of two interacting Rydberg atoms



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



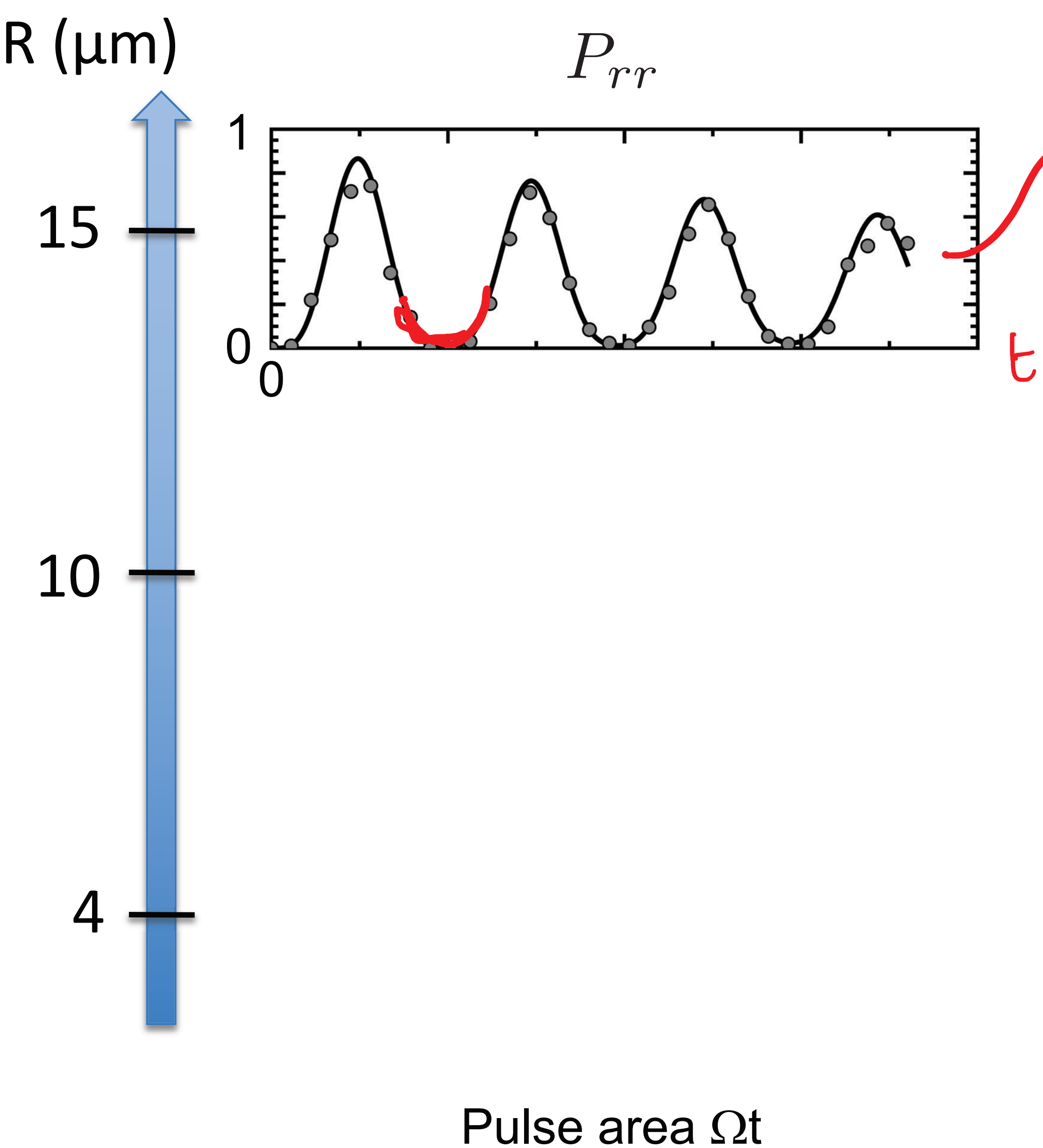
$\langle gg | D_1 + D_2 | \frac{1}{\sqrt{2}}(|rg\rangle + |gr\rangle)$

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

$= \frac{1}{\sqrt{2}}(\langle g | D_1 | r\rangle + \langle g | D_2 | r \rangle) = 2\Omega/\sqrt{2}$

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

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

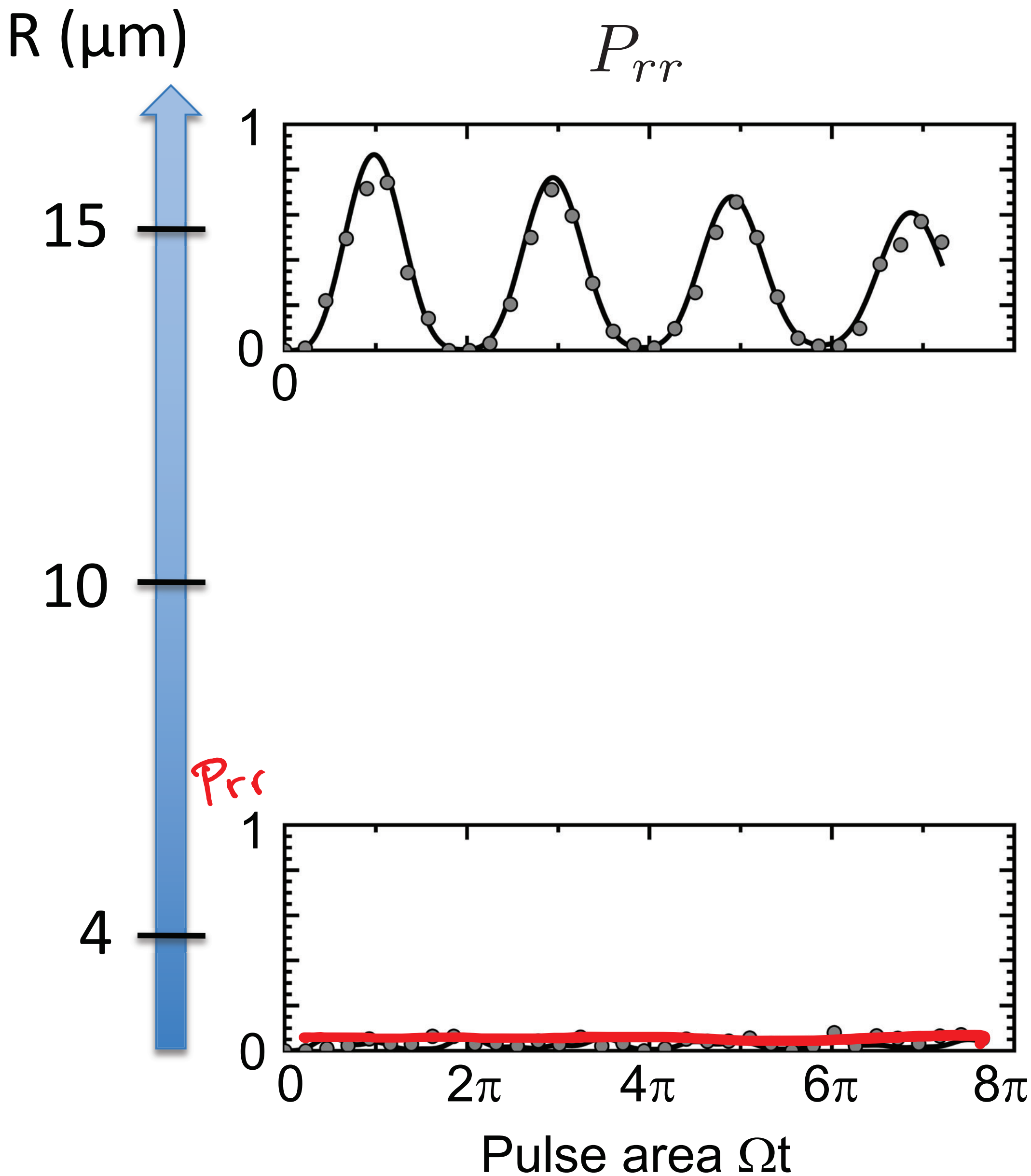


$$\left[\sin^2 \frac{\Omega t}{2}\right]^2 = P_{rr}$$

$$P_{r_1} \cdot P_{r_2}$$

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

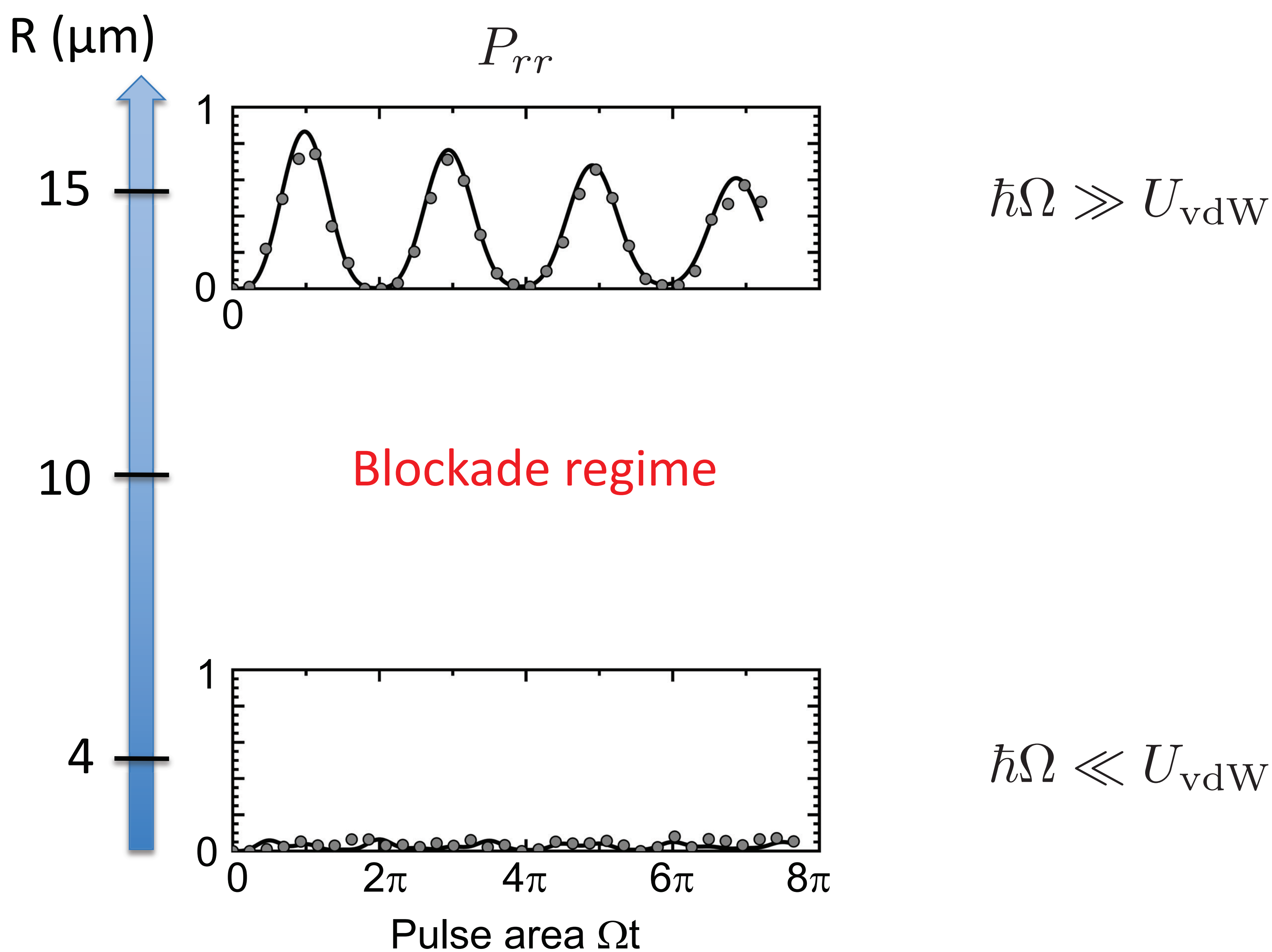
From independent atoms to blockade ($62d_{3/2}$)



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

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

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



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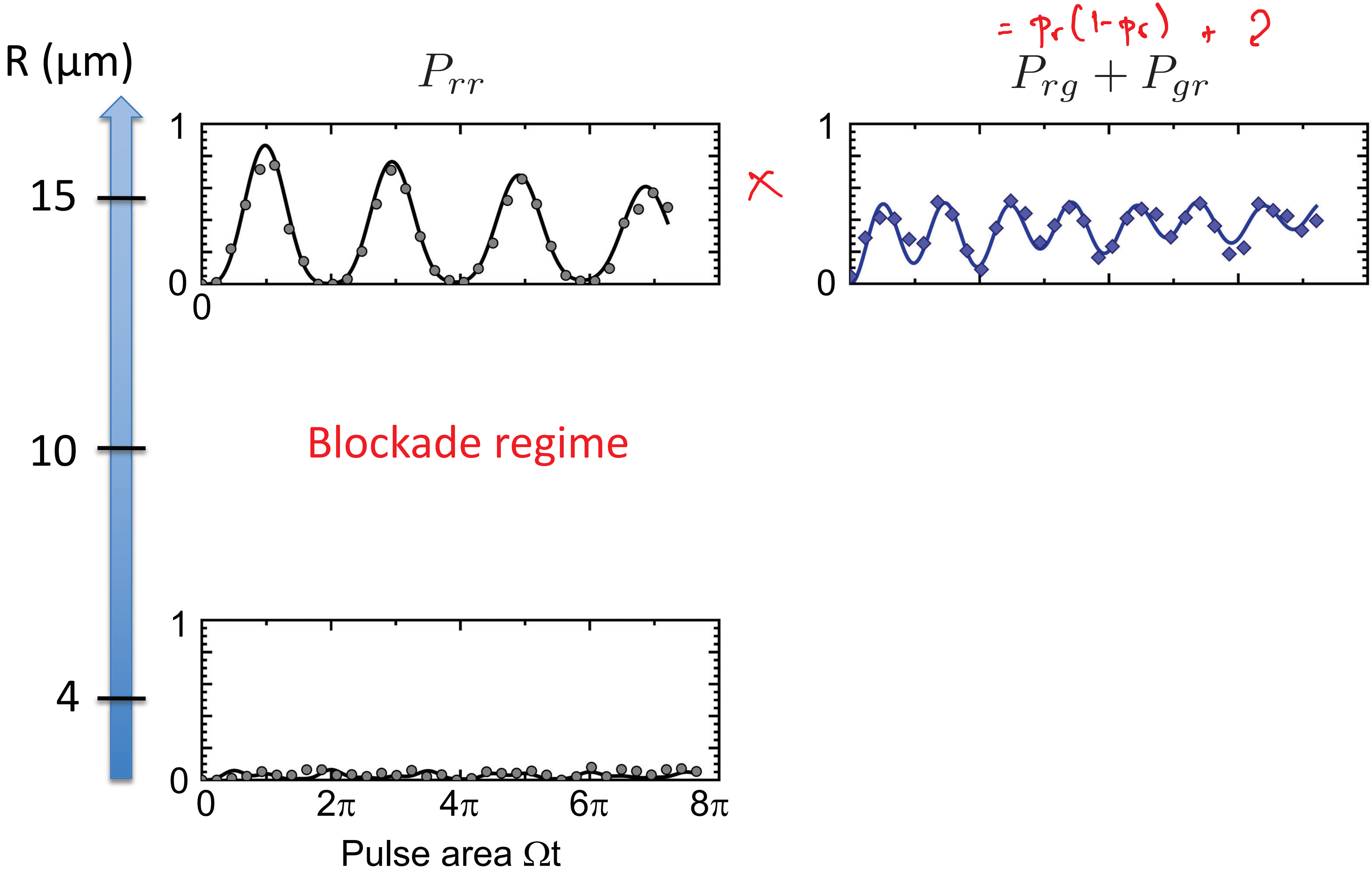

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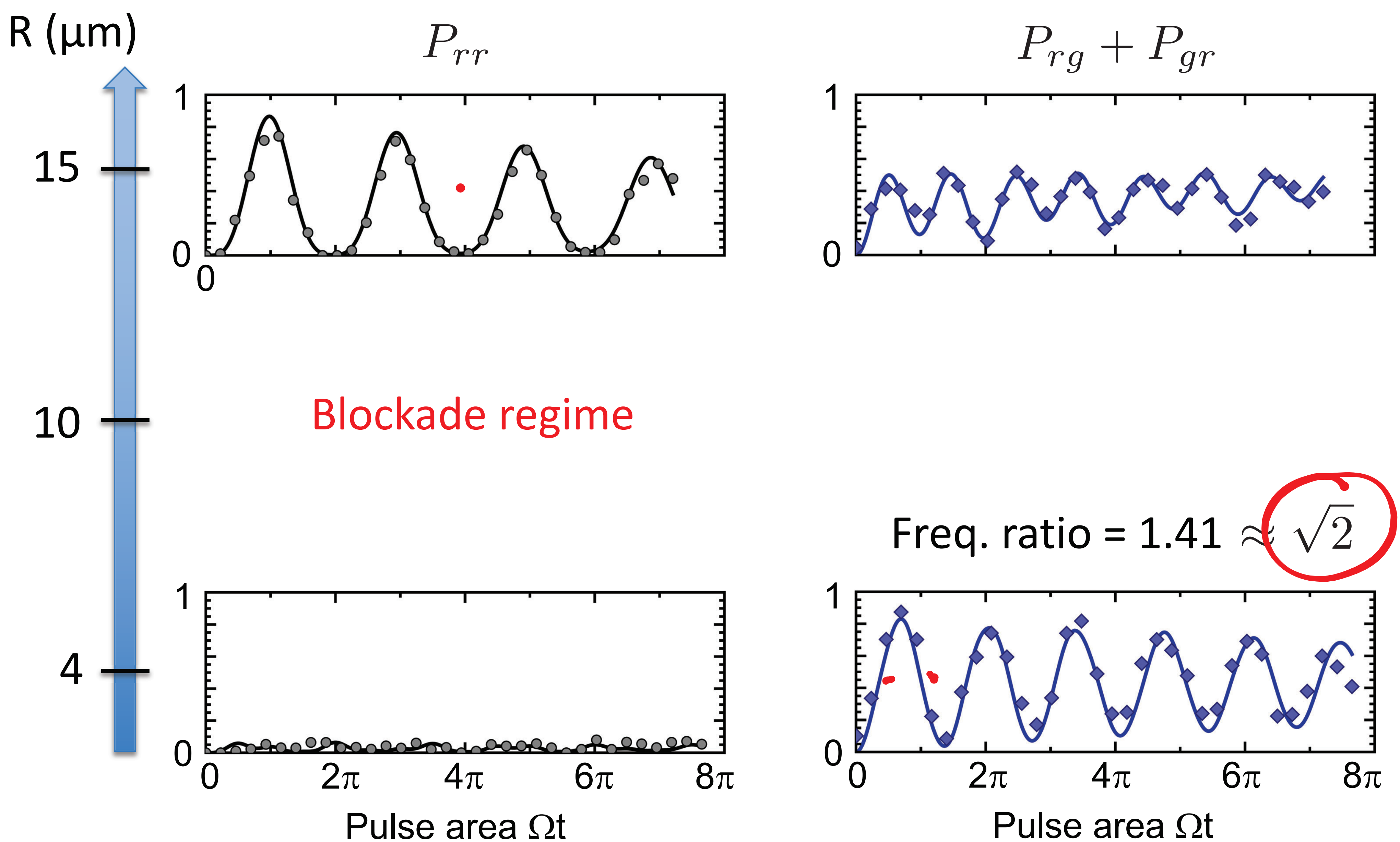

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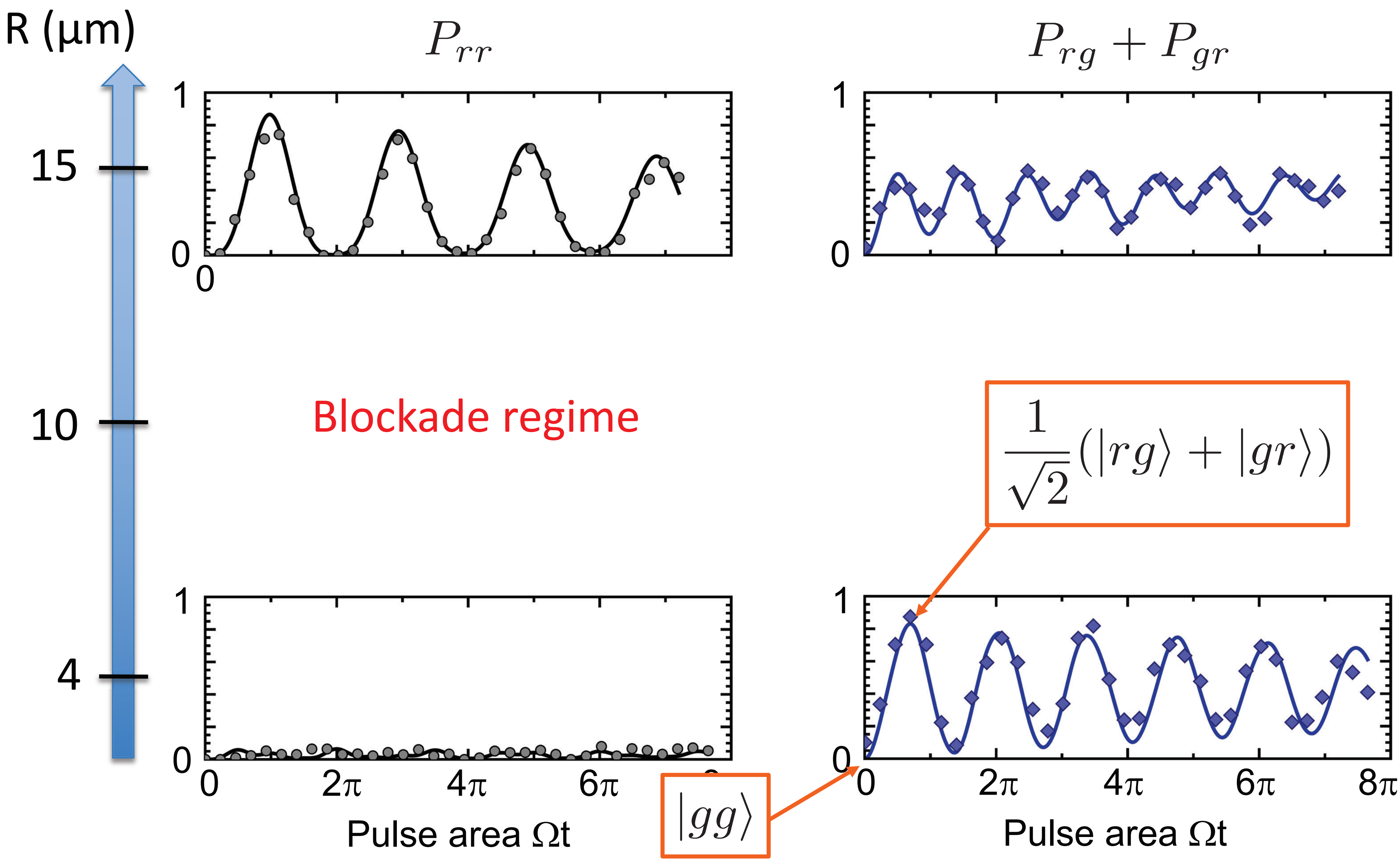
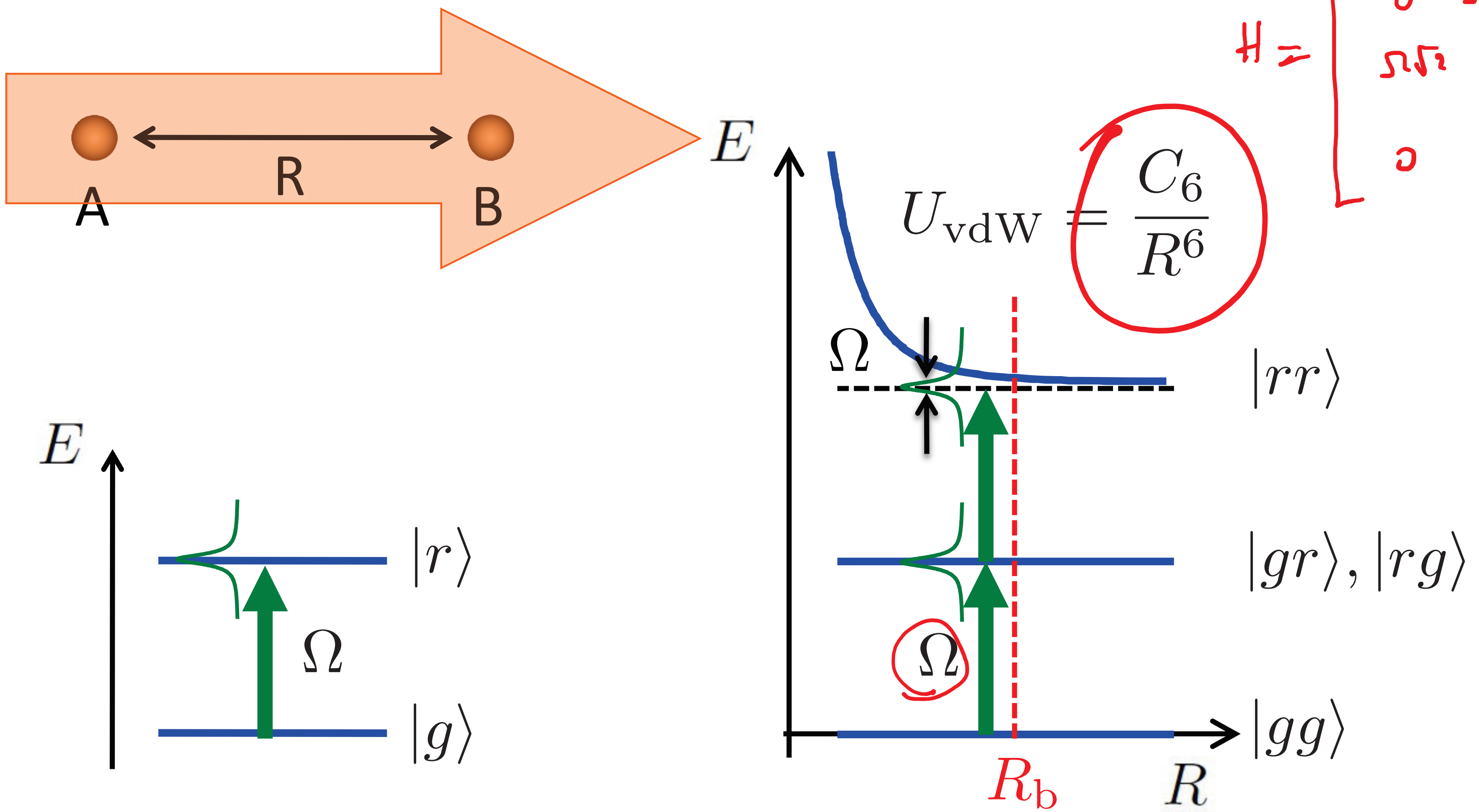


Collective excitation of two interacting Rydberg atoms

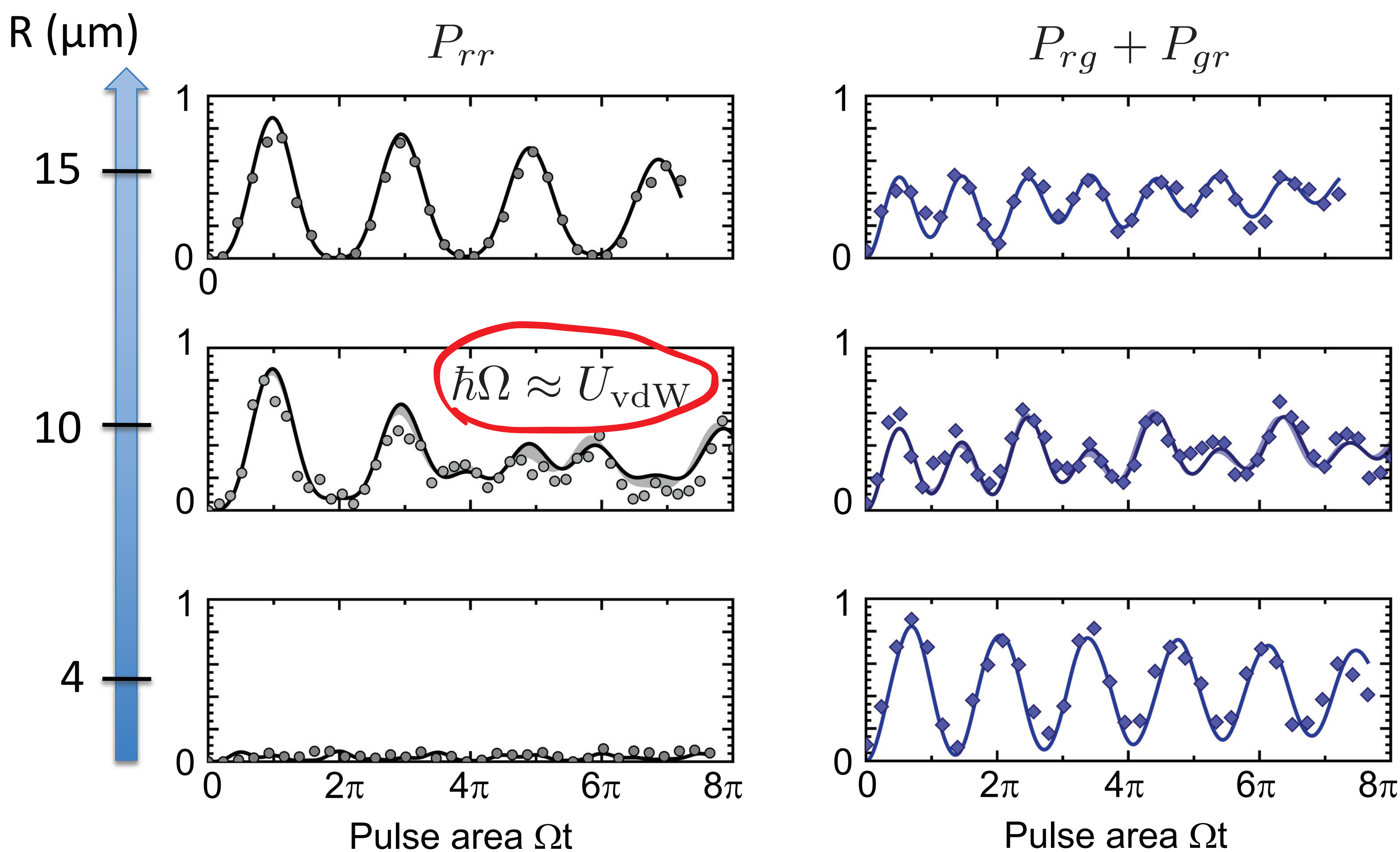
$$H = \begin{bmatrix} 0 & \Omega\sqrt{2} & 0 \\ \Omega\sqrt{2} & \omega_0 & \Omega\sqrt{2} \\ 0 & \Omega\sqrt{2} & 2\omega_0 + U \end{bmatrix}$$



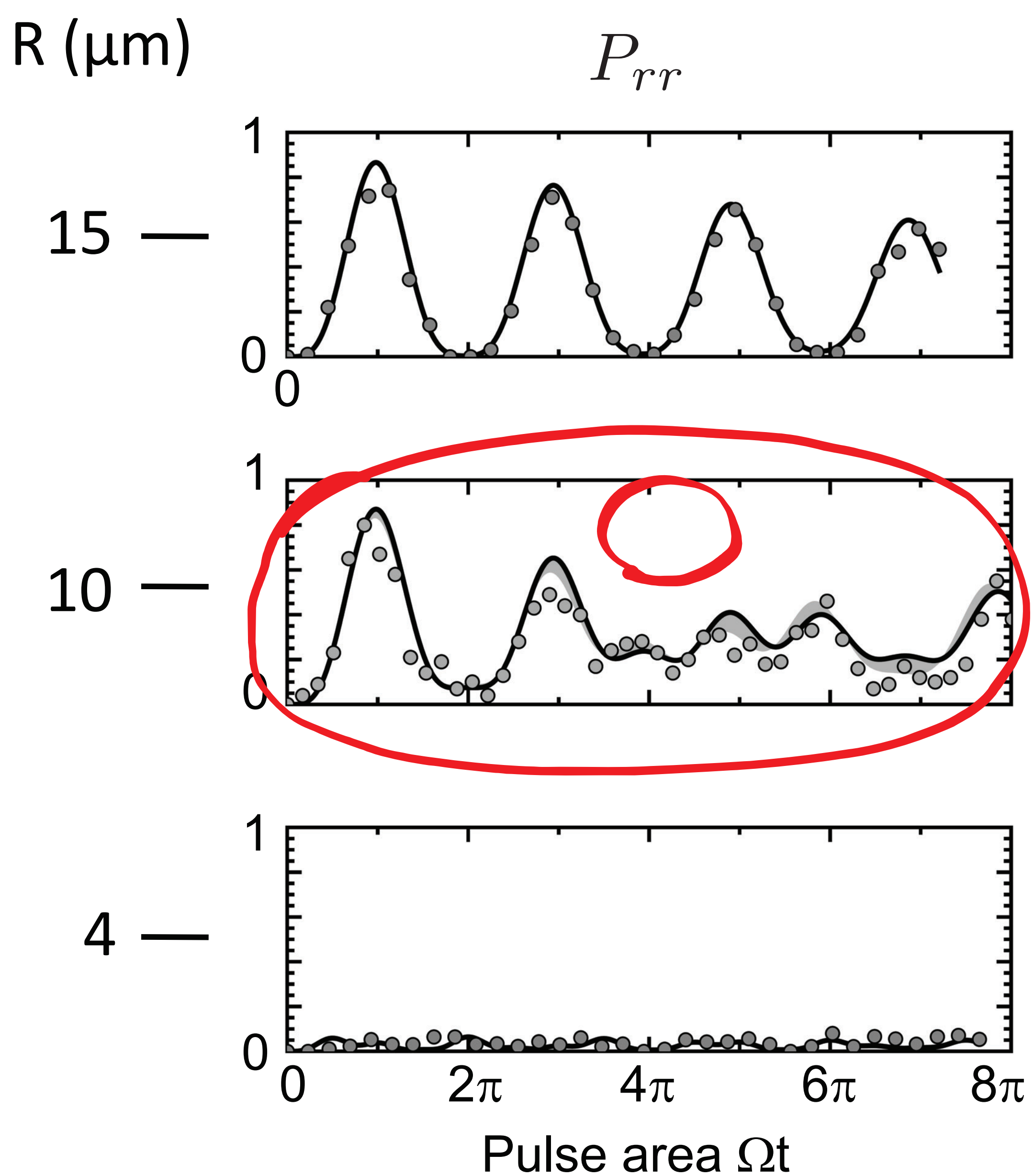
If $\hbar\Omega \approx U_{\mathrm{vdW}}$: dynamics governed by Ω **and** U_{vdW}

$$|\psi(t)\rangle = \alpha|gg\rangle + \beta \frac{1}{\sqrt{2}}\left(|gr\rangle + |rg\rangle\right) + \gamma |rr\rangle$$

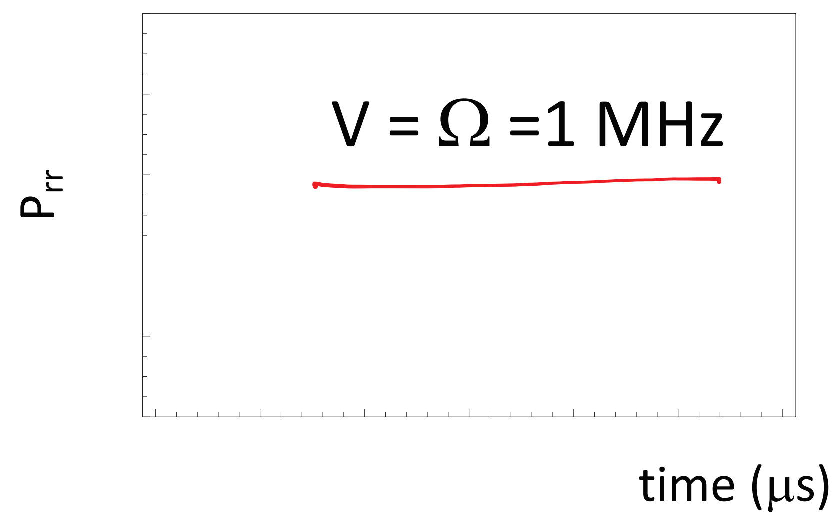
From independent atoms to blockade ($62d_{3/2}$)



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

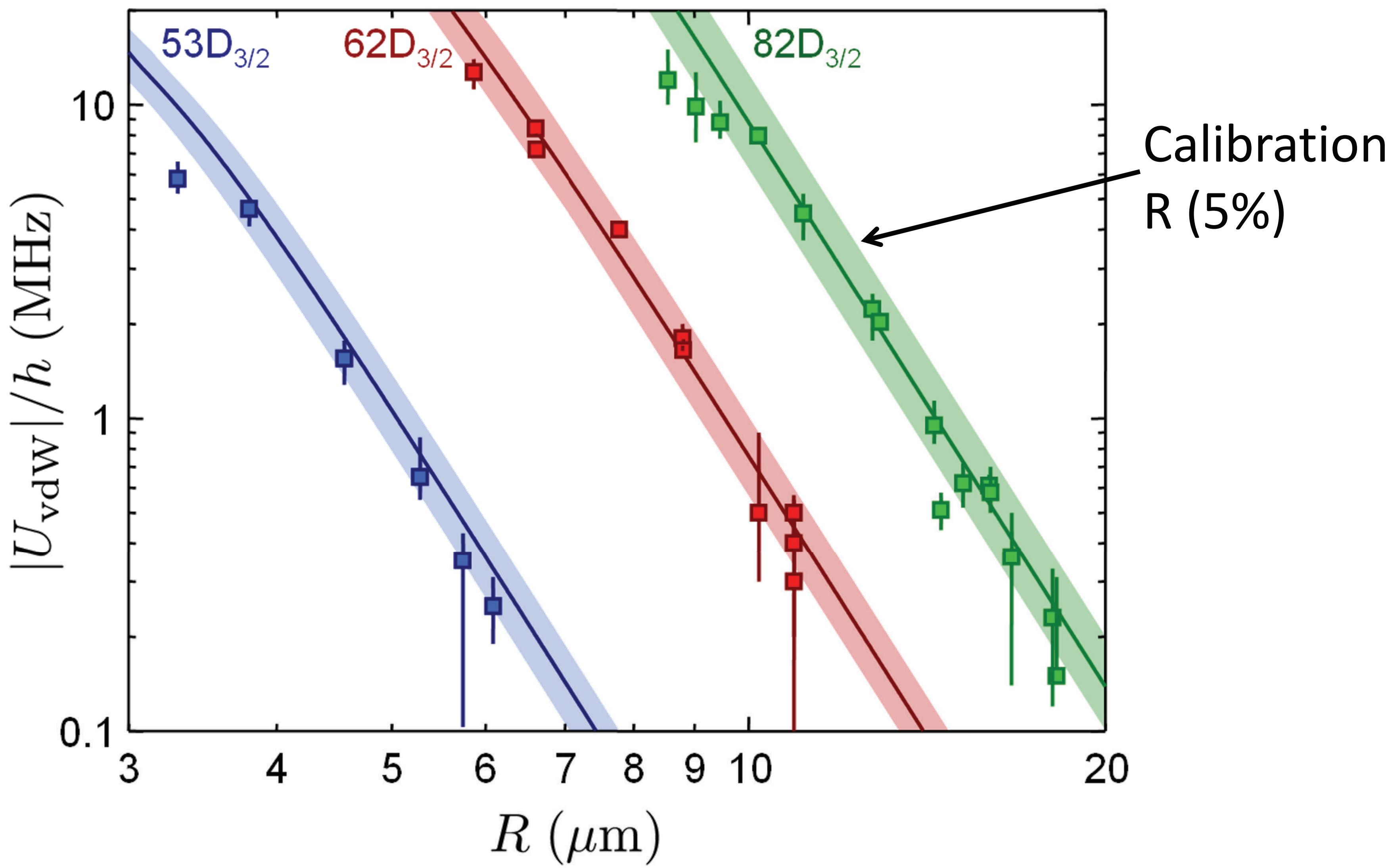


Theory (Schrödinger eq.)



Fit ⇒ extract U_{vdW}

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)

Many-body physics with arrays of atoms

Lecture 1: Dipolar interactions between atoms

Lecture 2: Arrays of atoms. Basics of Rydberg physics. Rydberg blockade (2-body physics)

Lecture 3: Many-body physics with Rydberg atoms: spin models and transport