

Rydberg atoms in optical tweezers

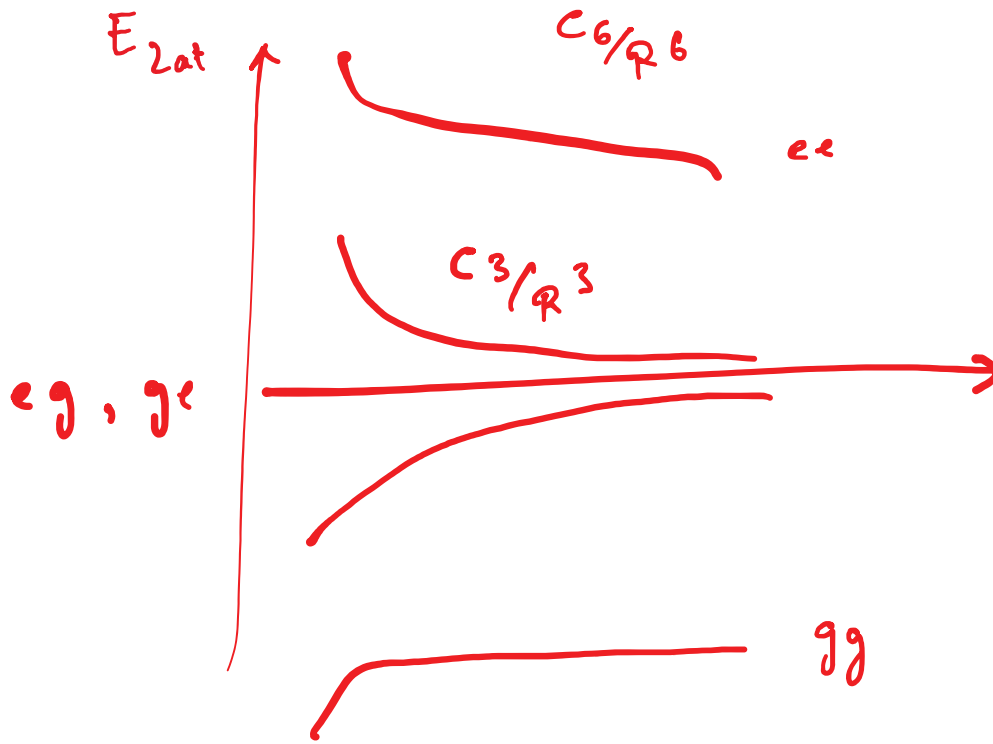
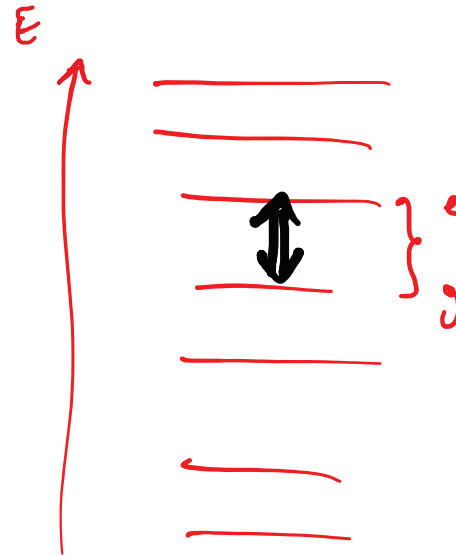
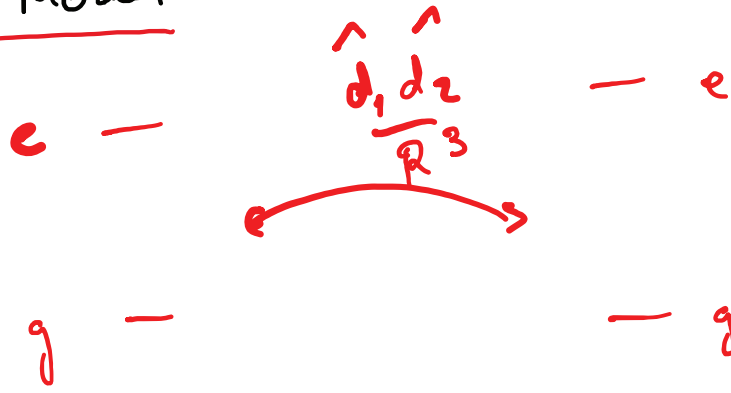
Lecture 1: Dipolar interactions between atoms

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

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

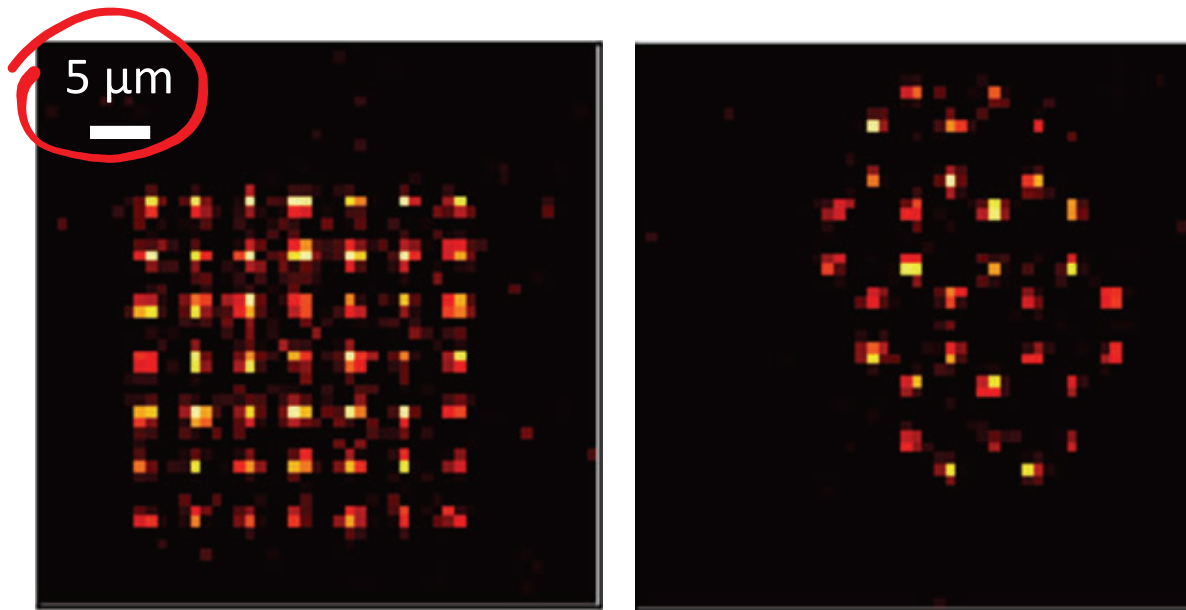


$$|\tilde{s}\rangle = |s\rangle + \frac{dE_0}{2\omega_0} |p\rangle$$

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

Stark

Goal: many-body physics and QIP with individual atoms

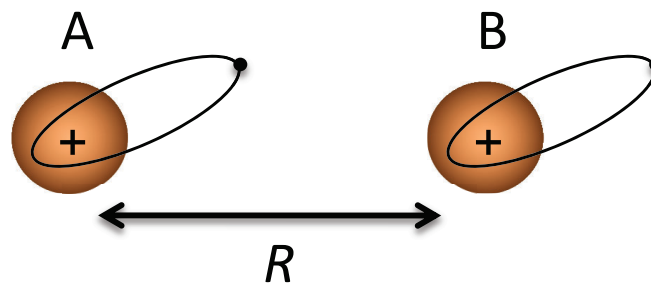


Addressable!!

$$n \sim 50$$

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

Rydberg interactions



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

2 Rb. (55)

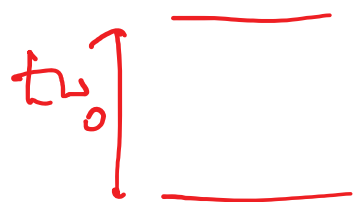
$\sim 5 \mu\text{m}$

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

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

Vander Waals vs Resonant interaction

$\frac{e^2}{R^3} \sim \text{few Hz}$
 $1 \text{ eV} \sim 400 \text{ THz}$



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

$\sim$

$$\left(\frac{d^2}{R^3} \right)^2$$

$$\frac{1}{2\hbar\omega_0}$$

$=$

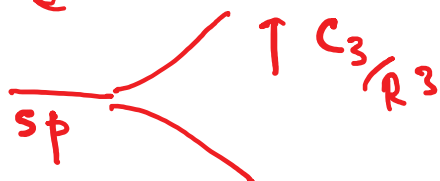
$$\frac{C_3}{R^3}$$

$$\frac{\frac{C_3}{R^3}}{\hbar\omega_0} \ll 1$$

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

$\sim$

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



Note: Alkali also have magnetic
 dipole interaction
 But: $\frac{\mu_B^2}{R^3} \ll \frac{C_6}{r^6}$

Outline

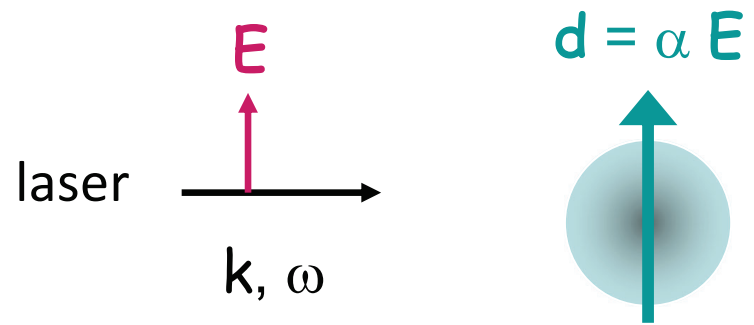
1. Experimental considerations: arrays of individual atoms
2. “Rydbergology”: scalings, interactions, blockade...
3. Measurement of interactions between Rydberg atoms: towards many-body physics
4. Application of Rydberg blockade to QIP

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

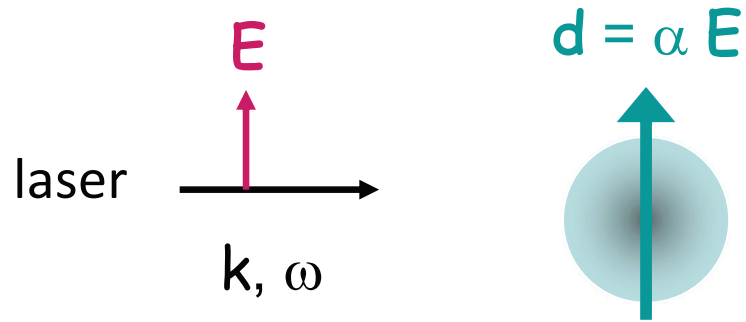
Optical dipole trap

Classical

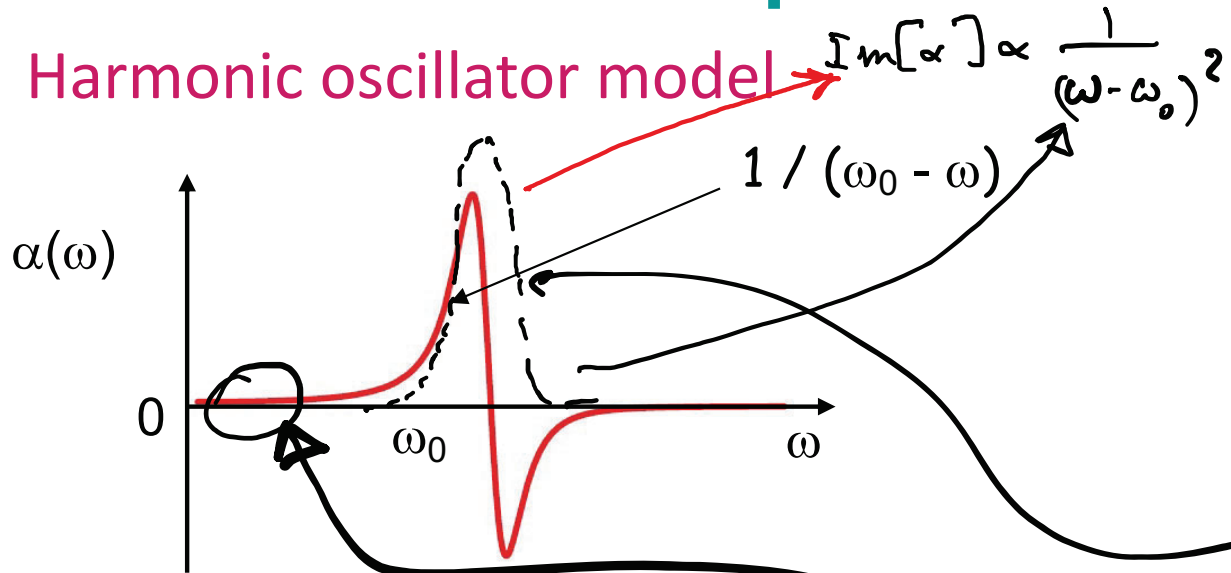


Optical dipole trap

Classical



Harmonic oscillator model

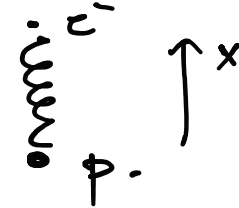


Interaction atom - light

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

⇒ Conservative POTENTIAL

Elastically bound e^- model:



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

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

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

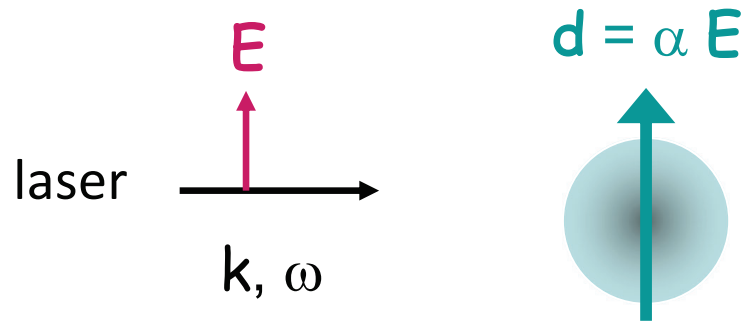
$$\alpha \sim \frac{1}{\omega_0^2 - \omega^2}$$

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

$$\left[\begin{array}{l} \alpha > 0 \rightarrow U_{\min} \quad E^2_{\max} \\ \alpha < 0 \rightarrow U_{\min} \quad E^2_{\min} \end{array} \right.$$

Optical dipole trap

Classical

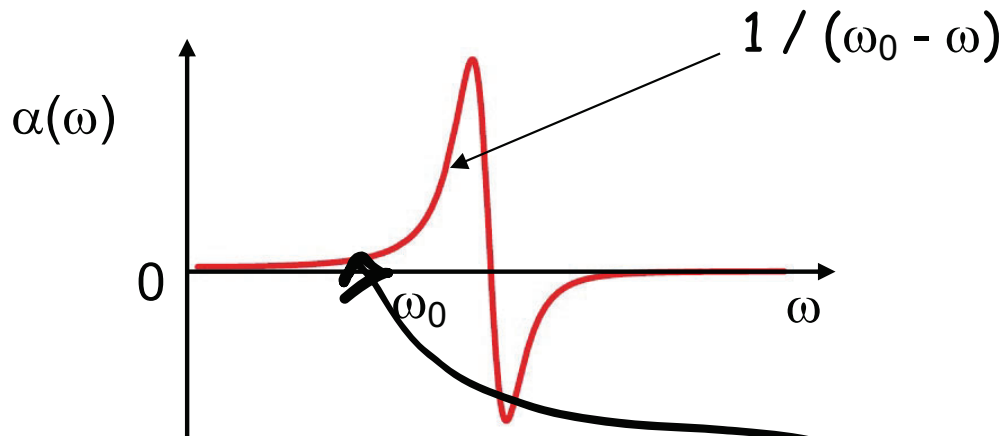


Quantum

$$\hbar\Omega = d \cdot E$$

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

Harmonic oscillator model

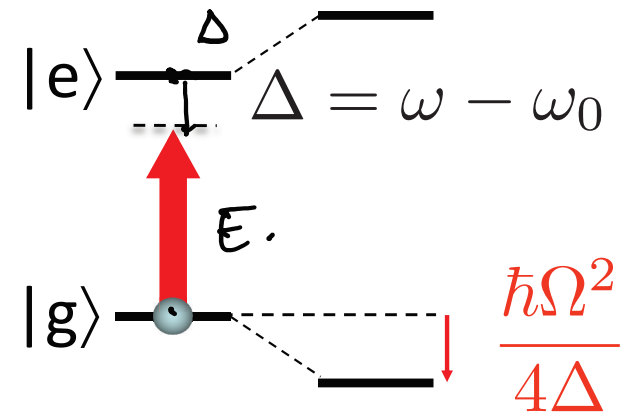


Interaction atom - light

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

$\Rightarrow$ Conservative POTENTIAL

$$\omega_0 > \omega$$

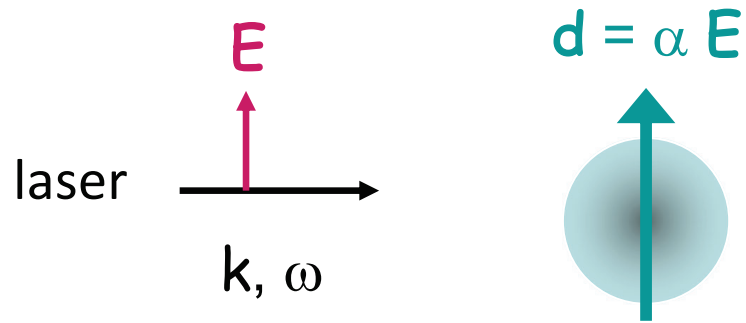


$$H = \begin{pmatrix} 0 & \Omega/2 \\ \Omega/2 & -\Delta \end{pmatrix}$$

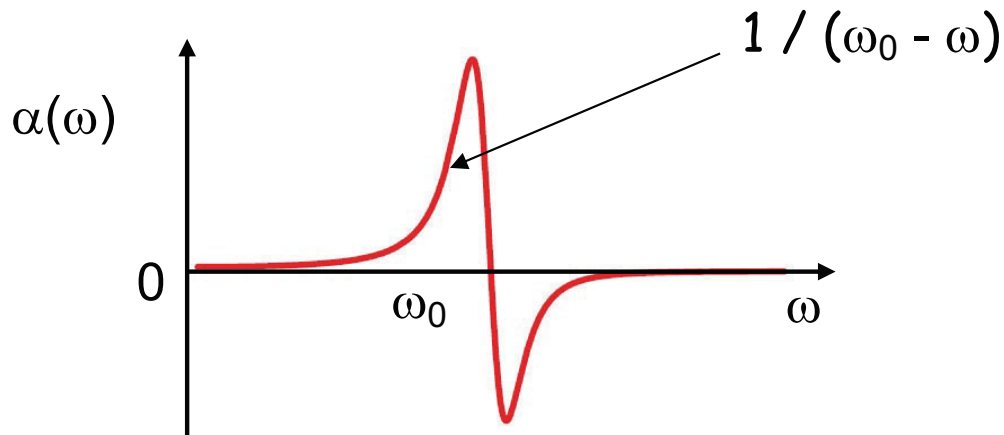
$$\Delta E_g \sim \frac{(\Omega/2)^2}{\Delta} = \frac{(\omega E)^2}{\omega - \omega_0}$$

Optical dipole trap

Classical



Harmonic oscillator model



Interaction atom - light

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

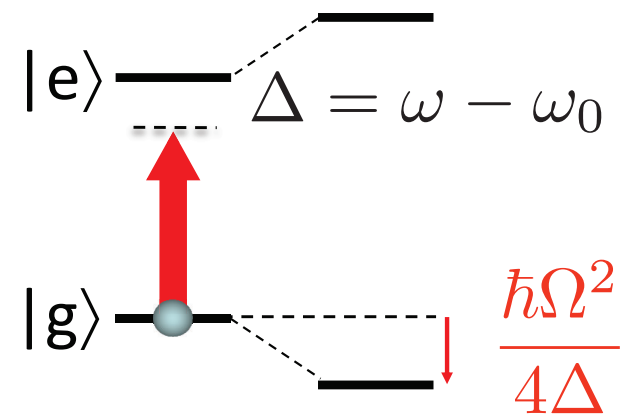
$\Rightarrow$ Conservative POTENTIAL

Quantum

$$\hbar\Omega = d \cdot E$$

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

$$\omega_0 > \omega$$



Trap depth $\sim 100 \mu\text{K} - 1 \text{ mK}$

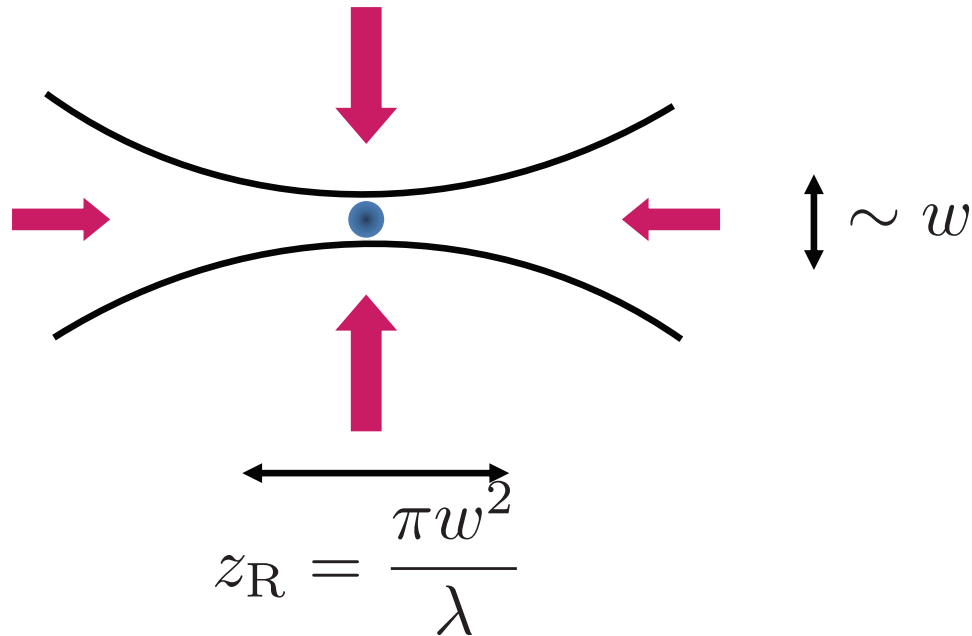
$\Rightarrow$ cold atoms

$P \sim 1 \text{ W} \quad \sim 100 \mu\text{m}$

Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

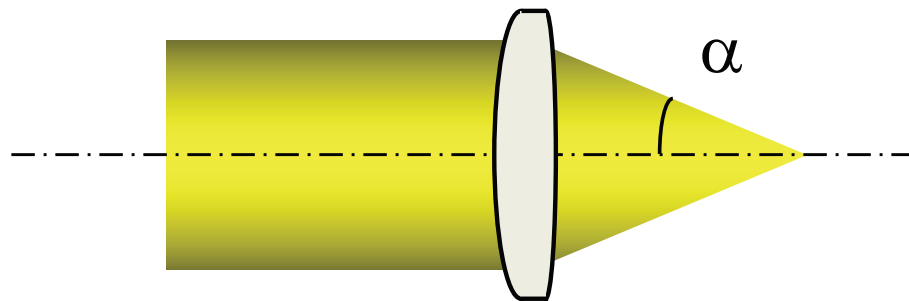
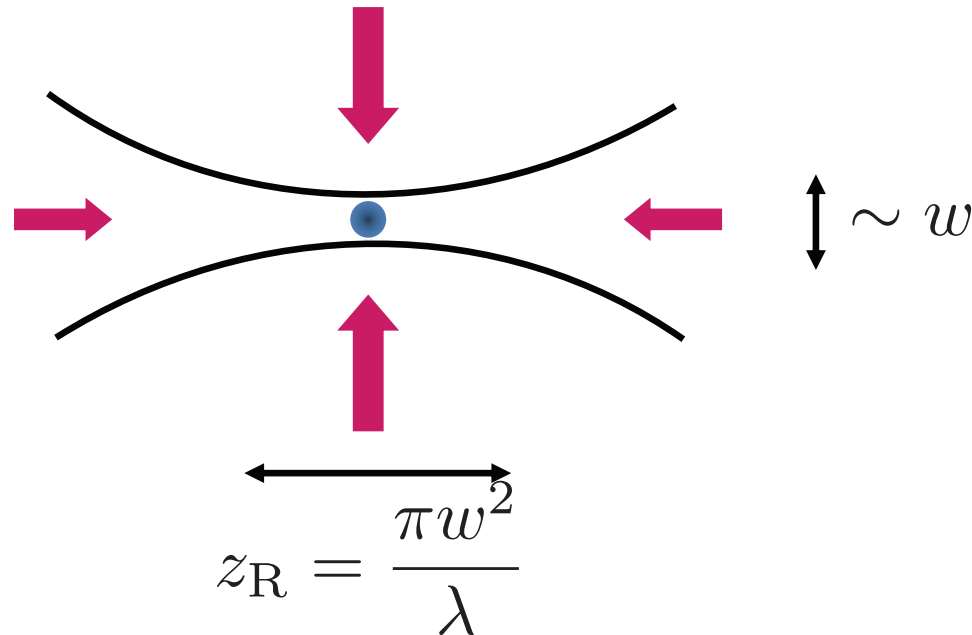
Gaussian beam



Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

Gaussian beam



$$\text{NA} = \sin \alpha$$
$$w \sim \lambda / \text{NA}$$

Diffraction limited optics $w \sim \lambda$

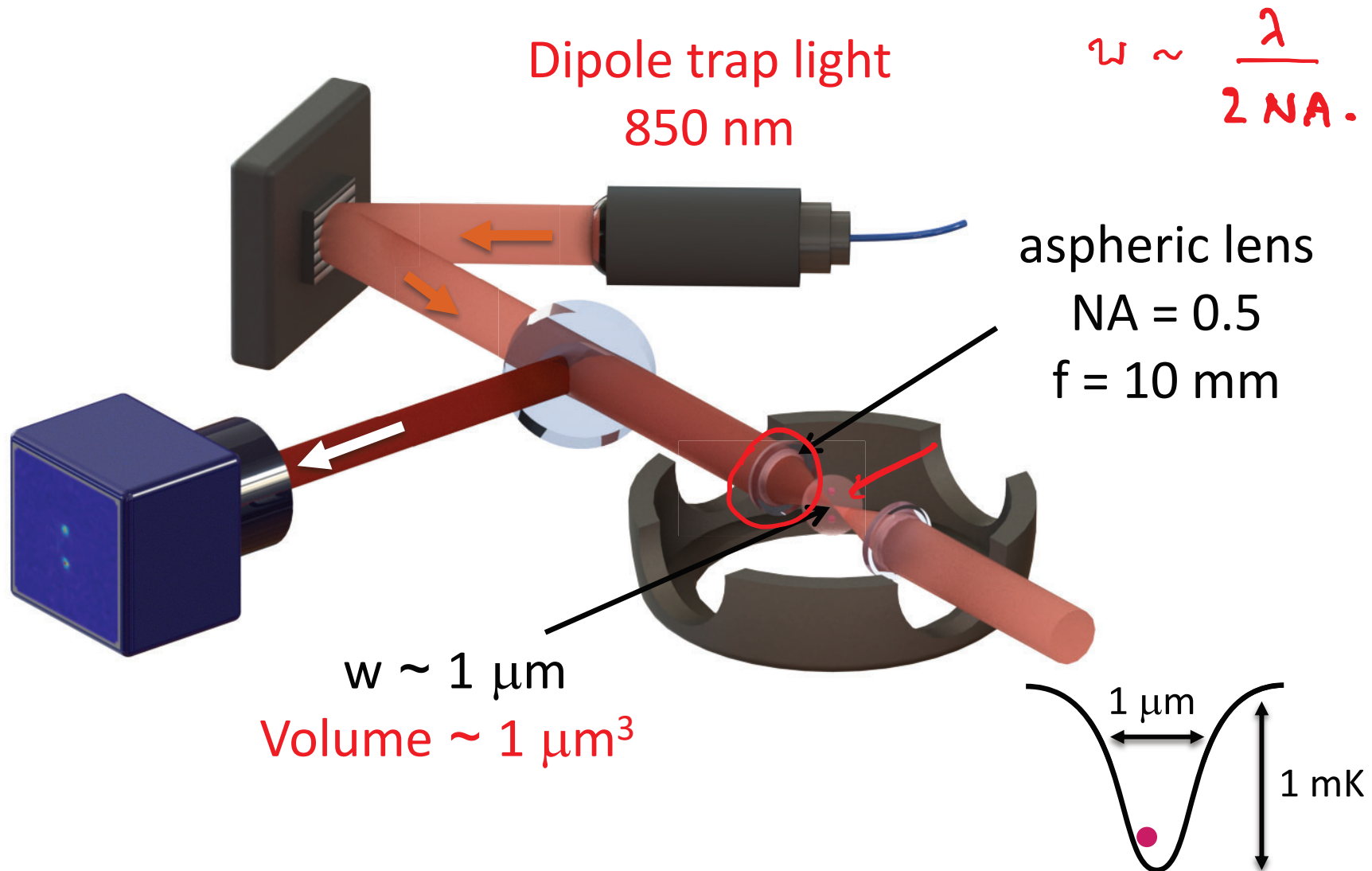
Trapping volume $\sim \pi \lambda^3$

Ex: 1 mW on 1 μm

Trap depth = 1 mK

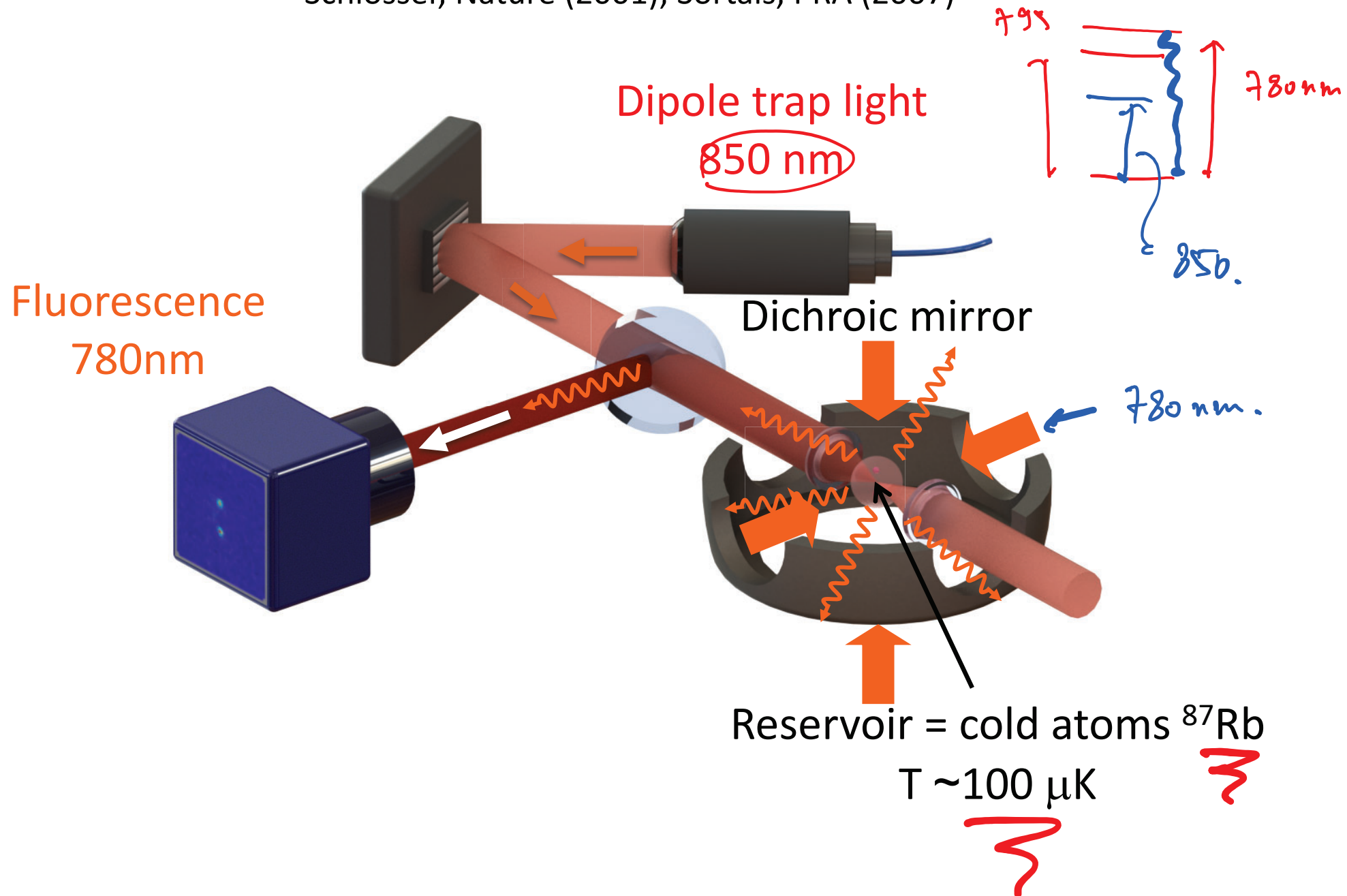
Optical tweezers: trapping in 3D

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



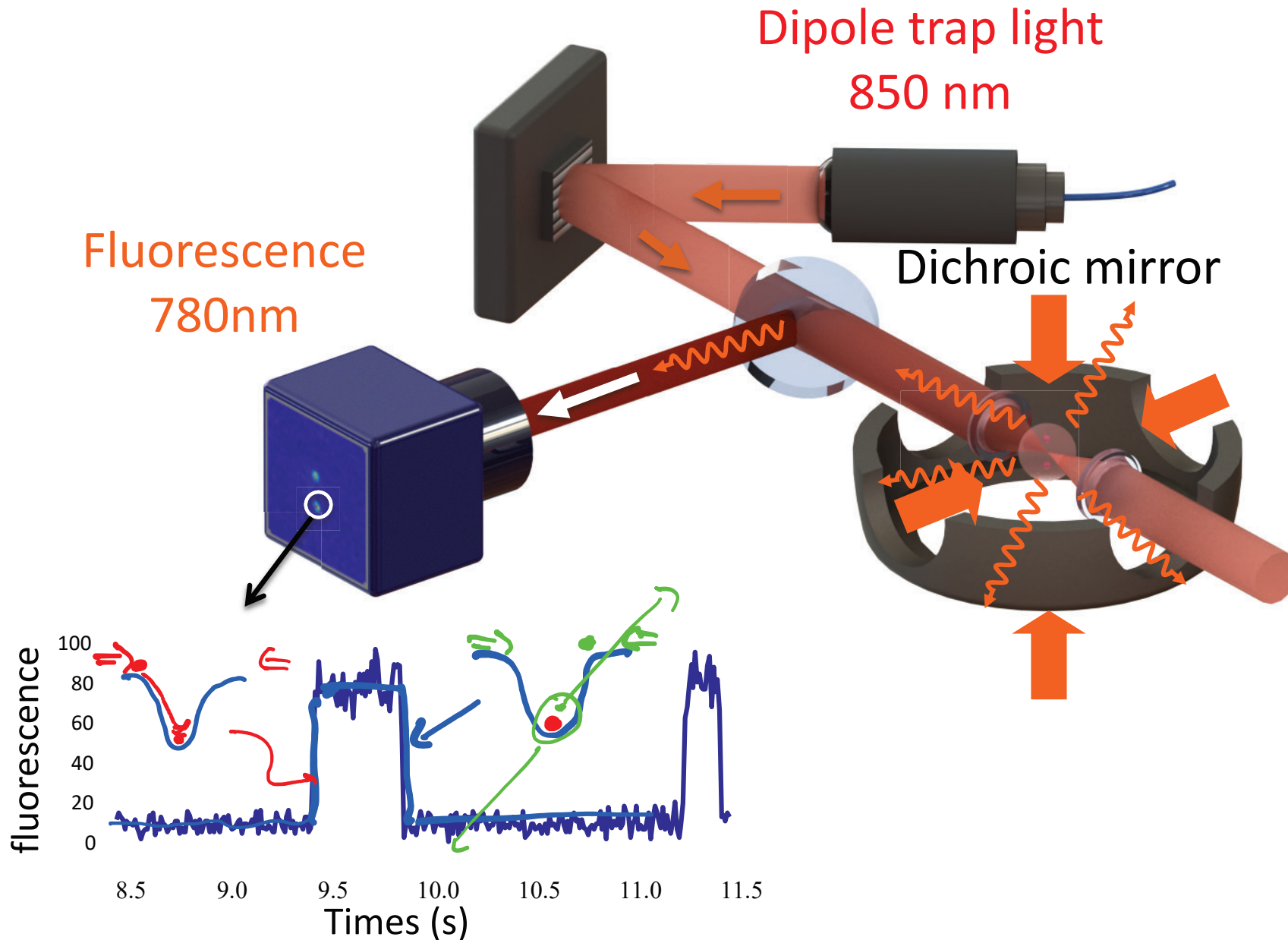
Single atoms in optical tweezers

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



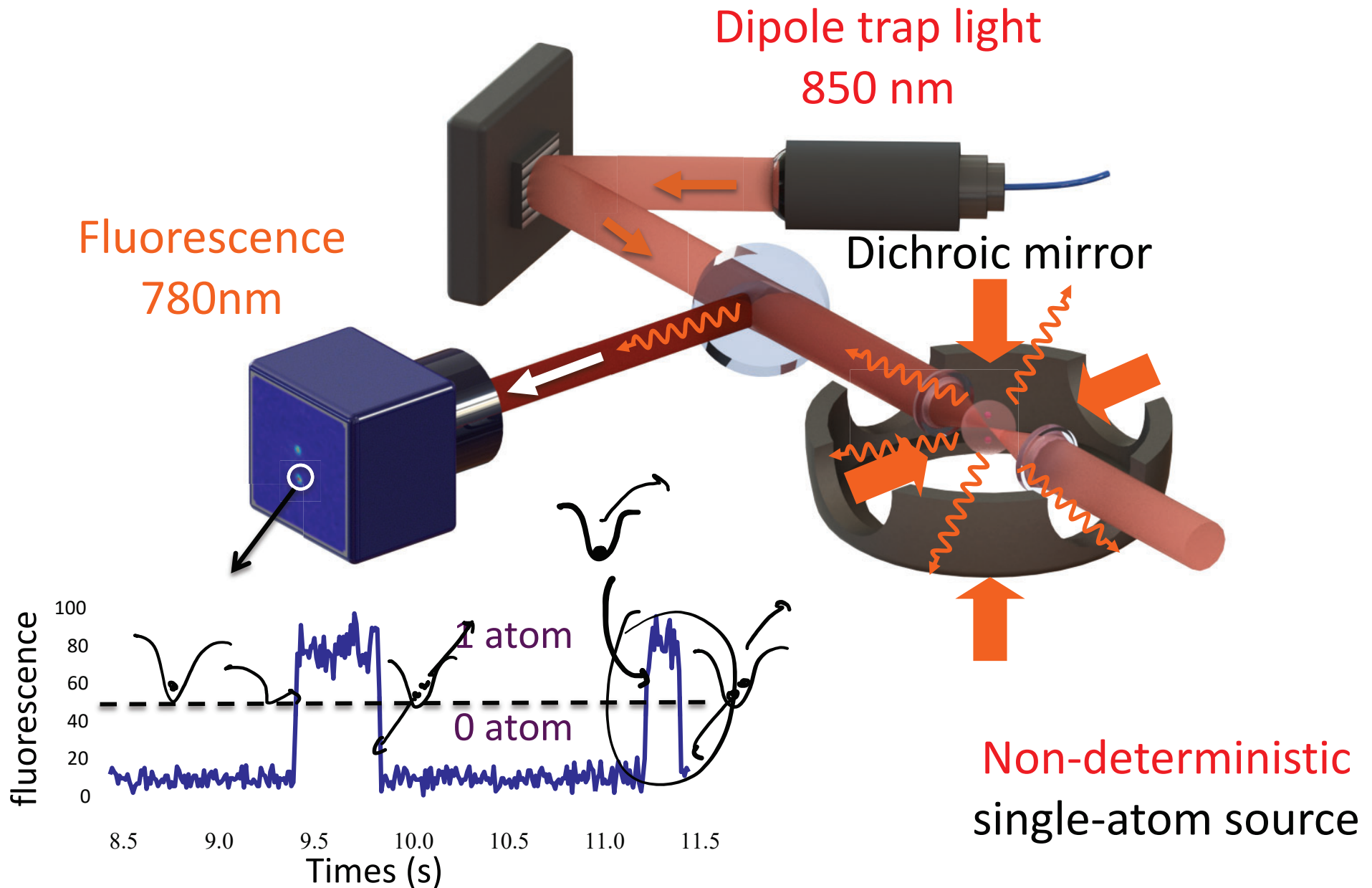
Single atoms in optical tweezers

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



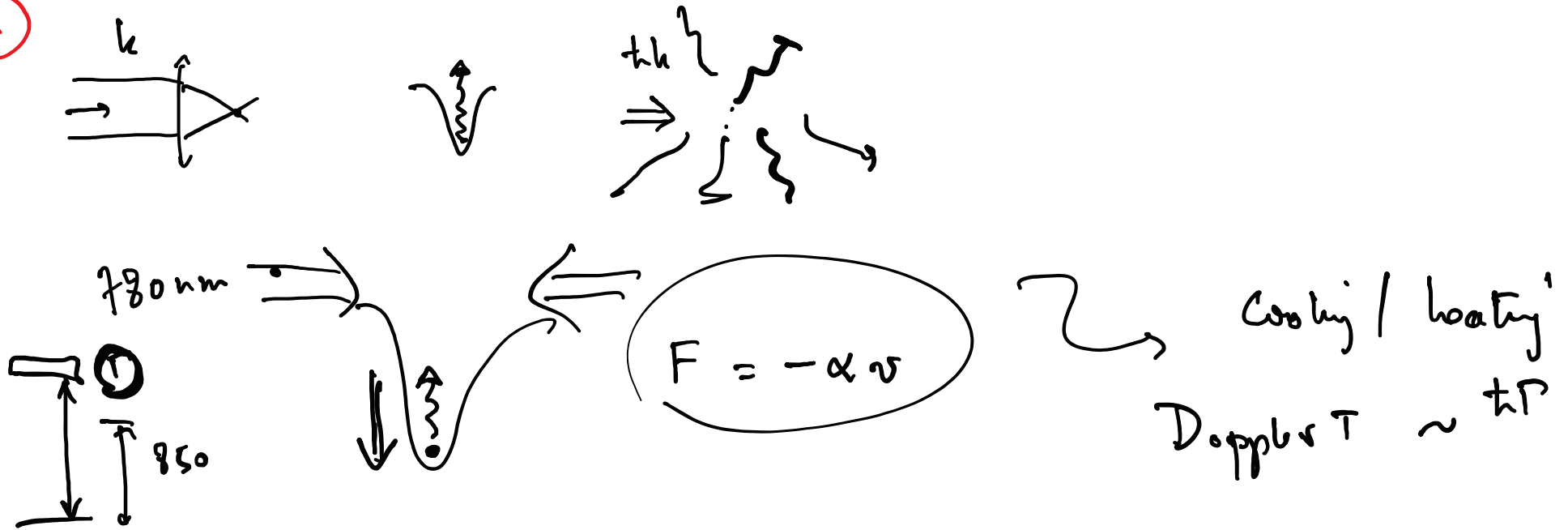
Single atoms in optical tweezers

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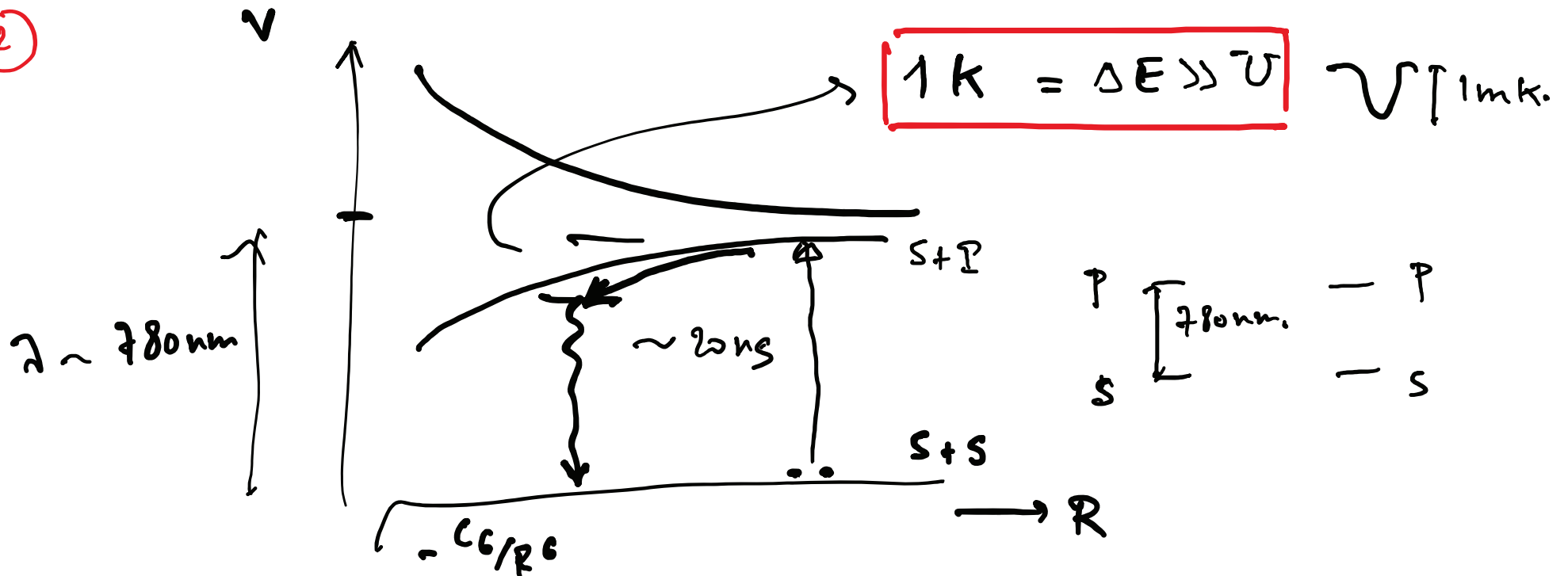


Light-assisted collisions prevents 2 atoms...

①



2



Which atoms?

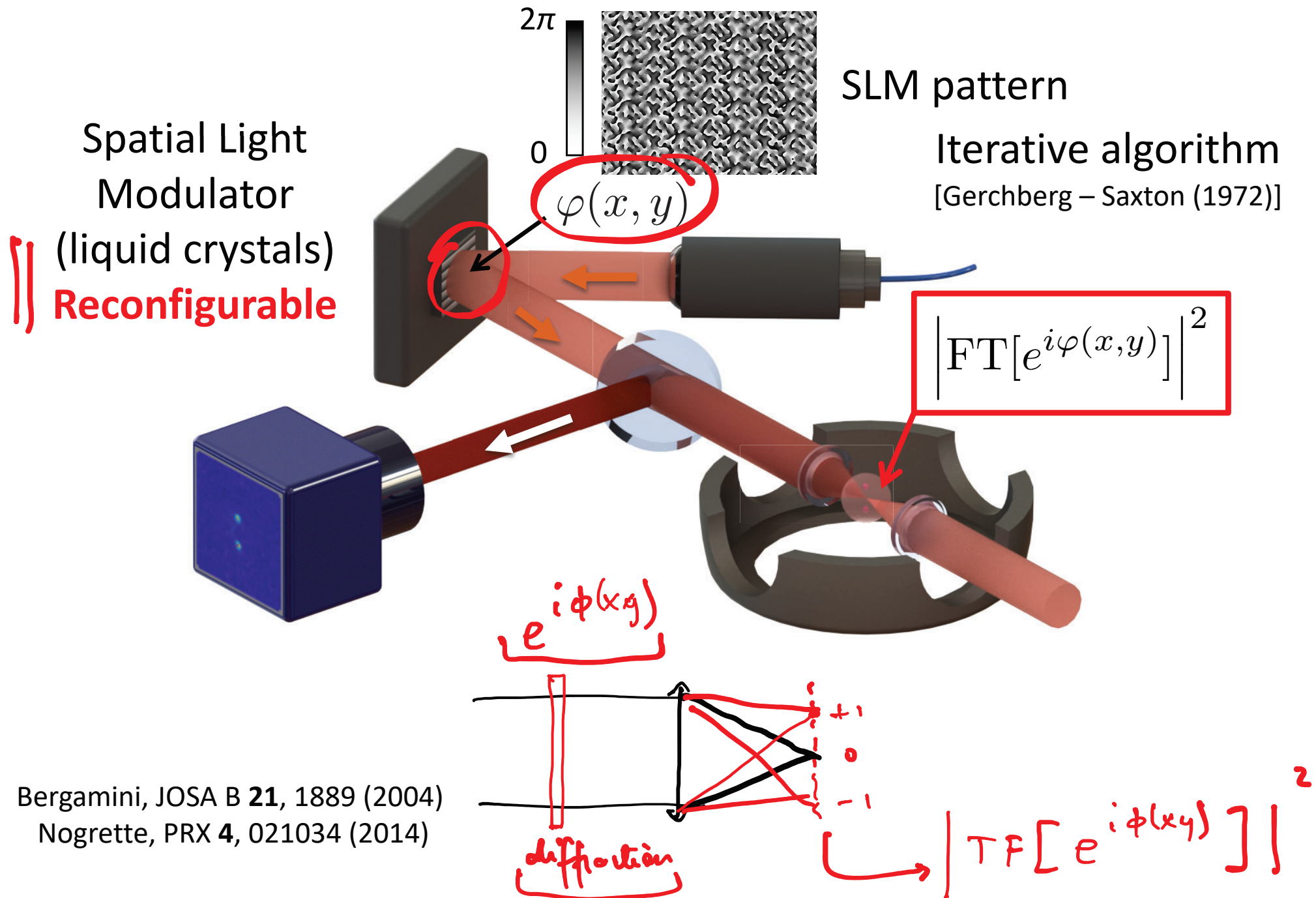
○ Laser cooled

○ Single atom

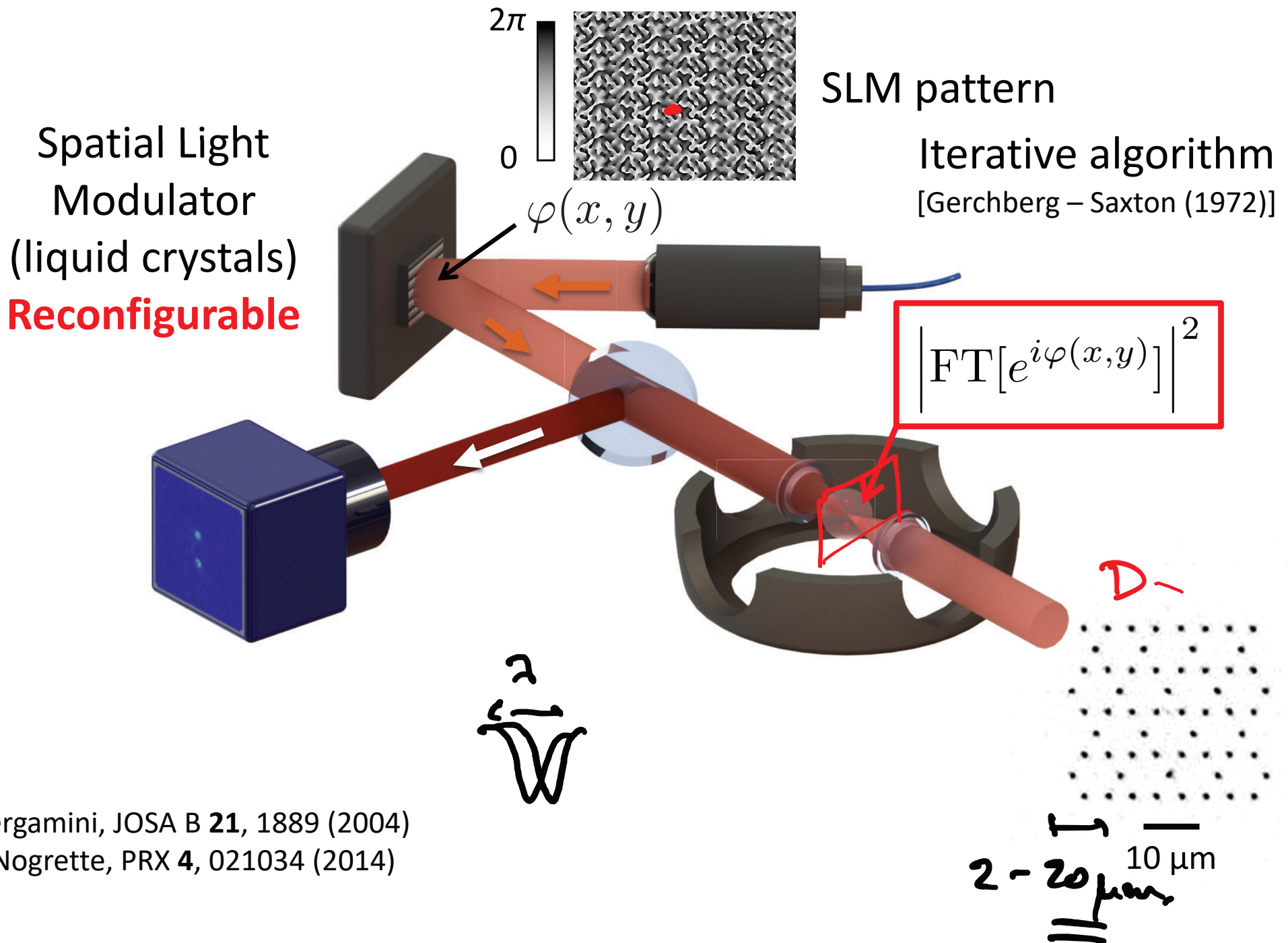
1	1 H 1.0079	2																4 He 4.0026
2	3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.065	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57-71 La-Lu	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89-103 Ac-Lr	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Uun (281)	111 Uuu (272)	112 Uub (285)		114 Uuq (289)				

Lanthanides	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinides	89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Holographic 2D arrays of tweezers



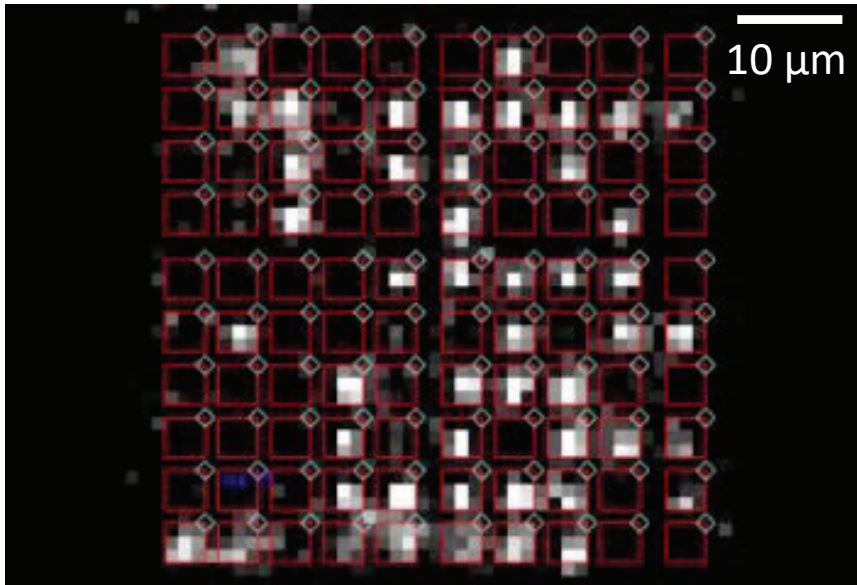
Holographic 2D arrays of tweezers



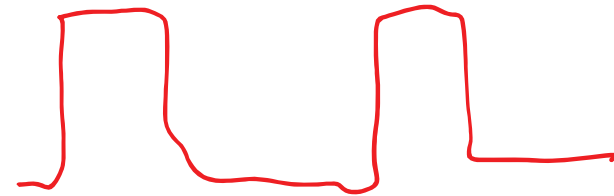
Bergamini, JOSA B **21**, 1889 (2004)

Nogrette, PRX **4**, 021034 (2014)

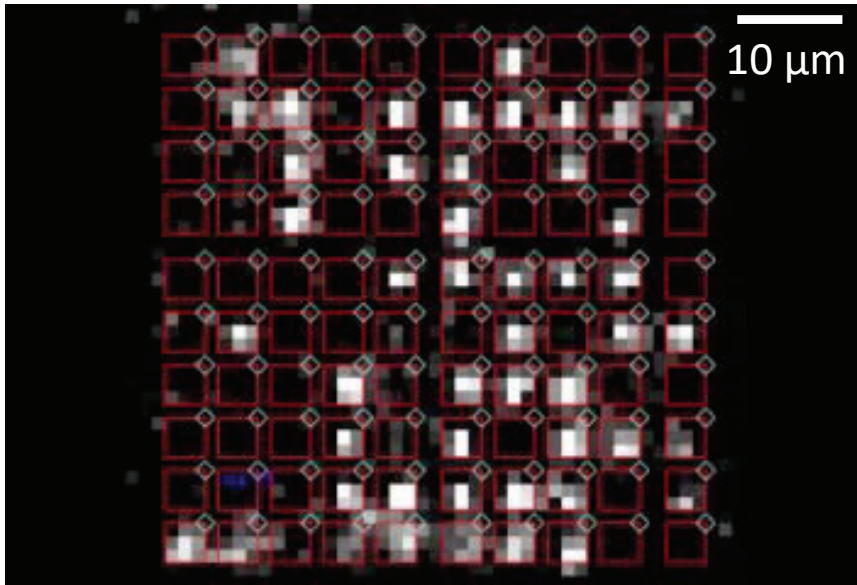
Atom-by-atom assembling of 2D arrays



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



Atom-by-atom assembling of 2D arrays



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

Solution: **sort atoms in arrays**

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

Atom-by-atom assembling of 2D arrays

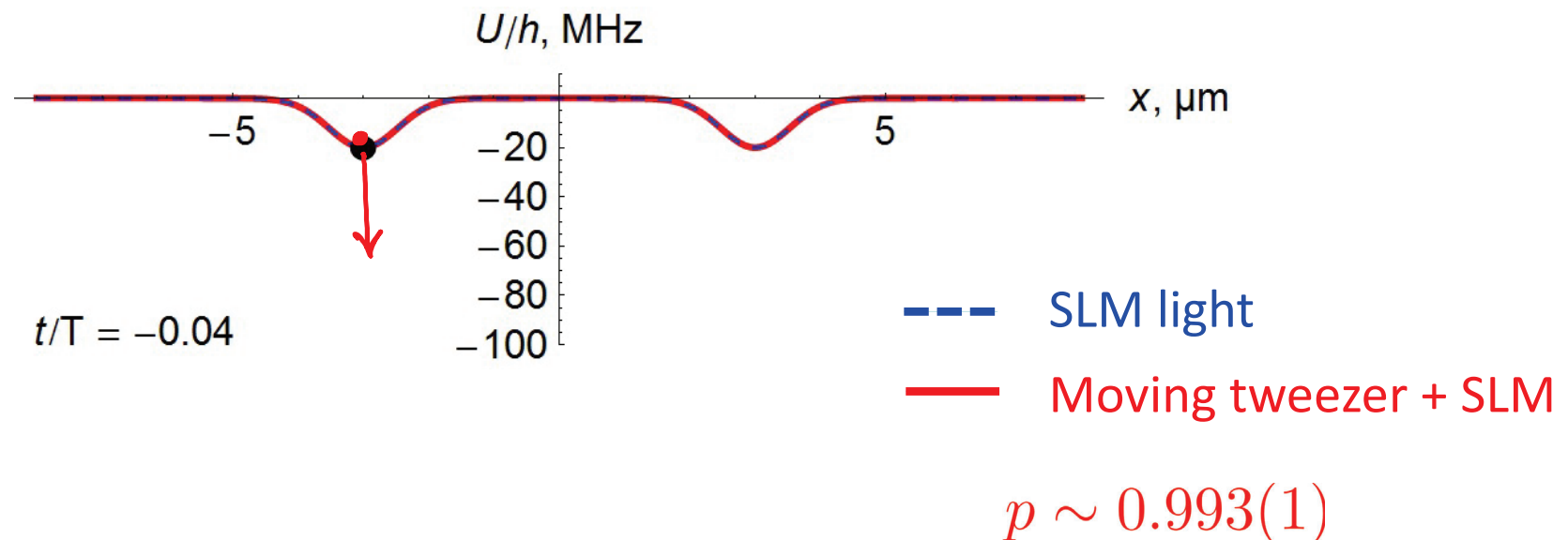


Problem: stochastic loading ($p \sim 0.5$)

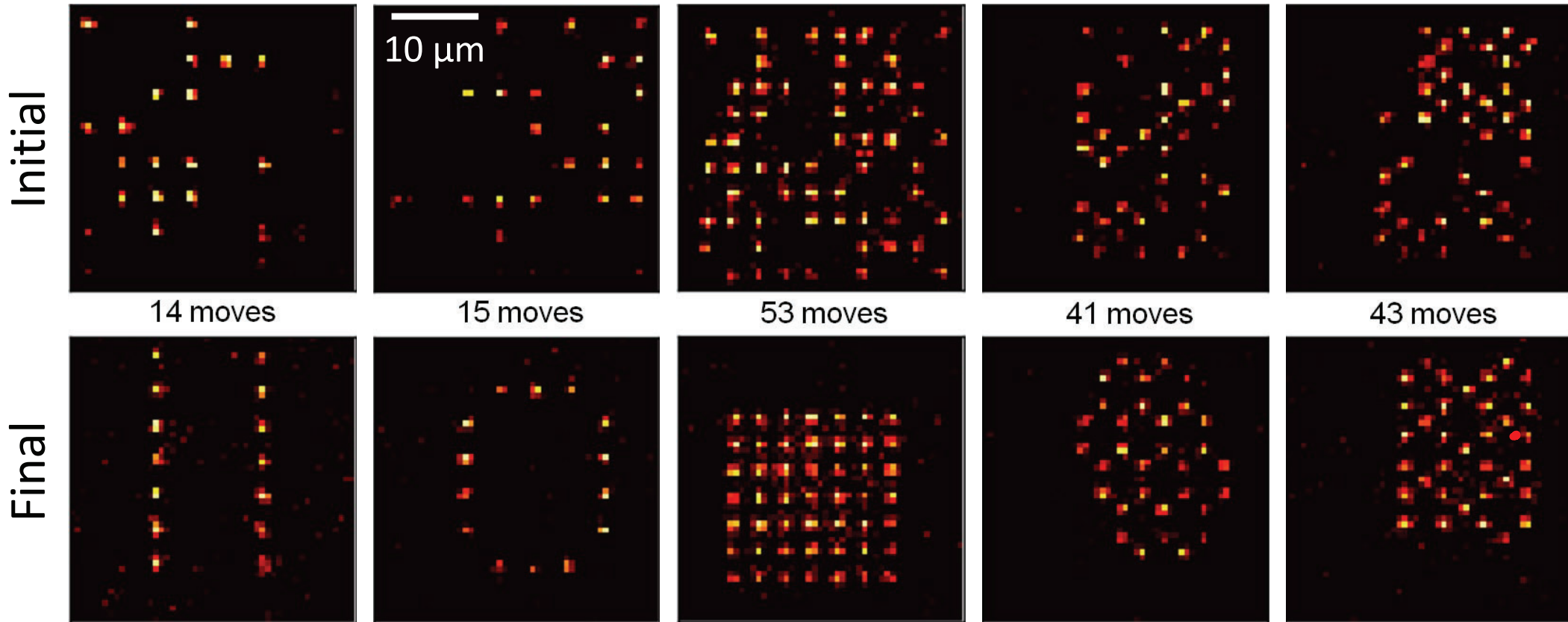
Solution: **sort atoms in arrays**

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

Moving atoms with a tweezers

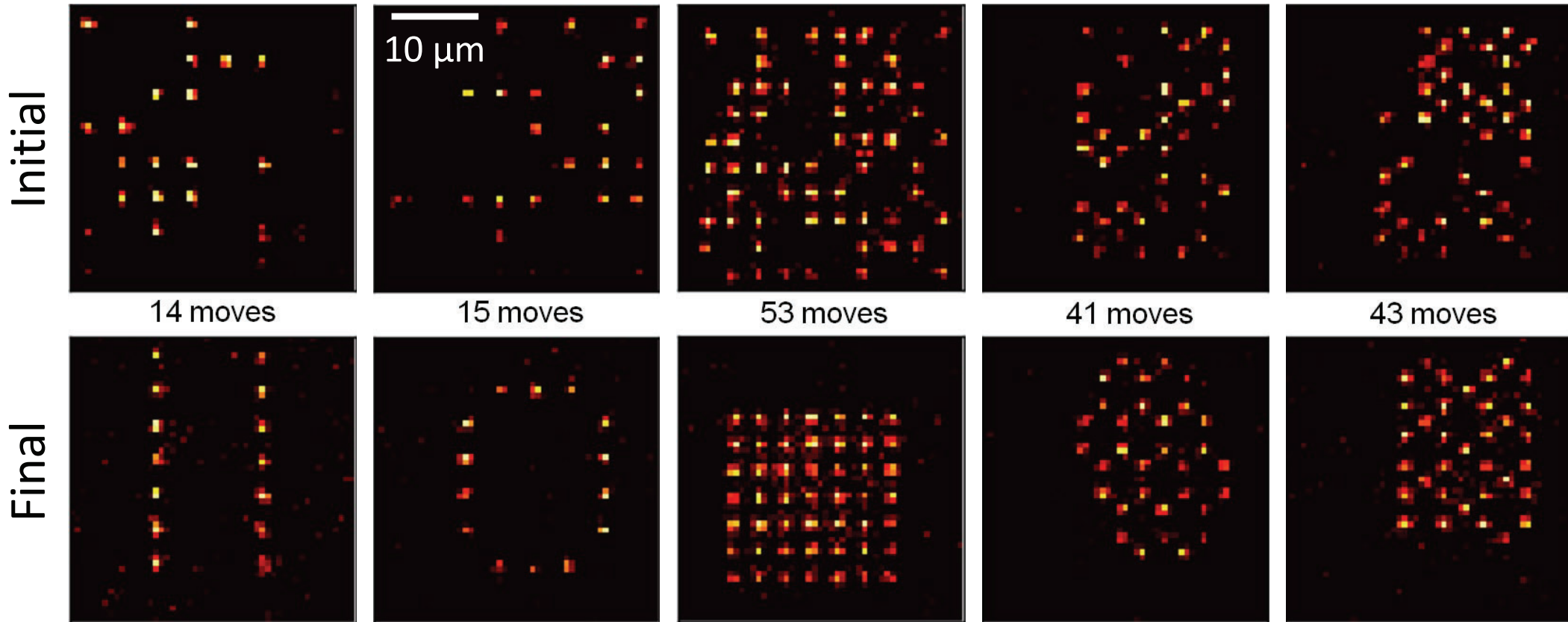


Gallery of assembled 2D arrays... (single-shot images...)

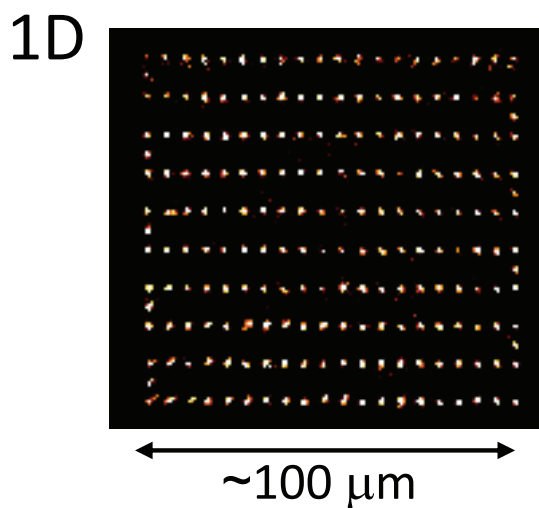


Barredo, de Léséleuc, *et al.*, Science **354**, 1021 (2016)

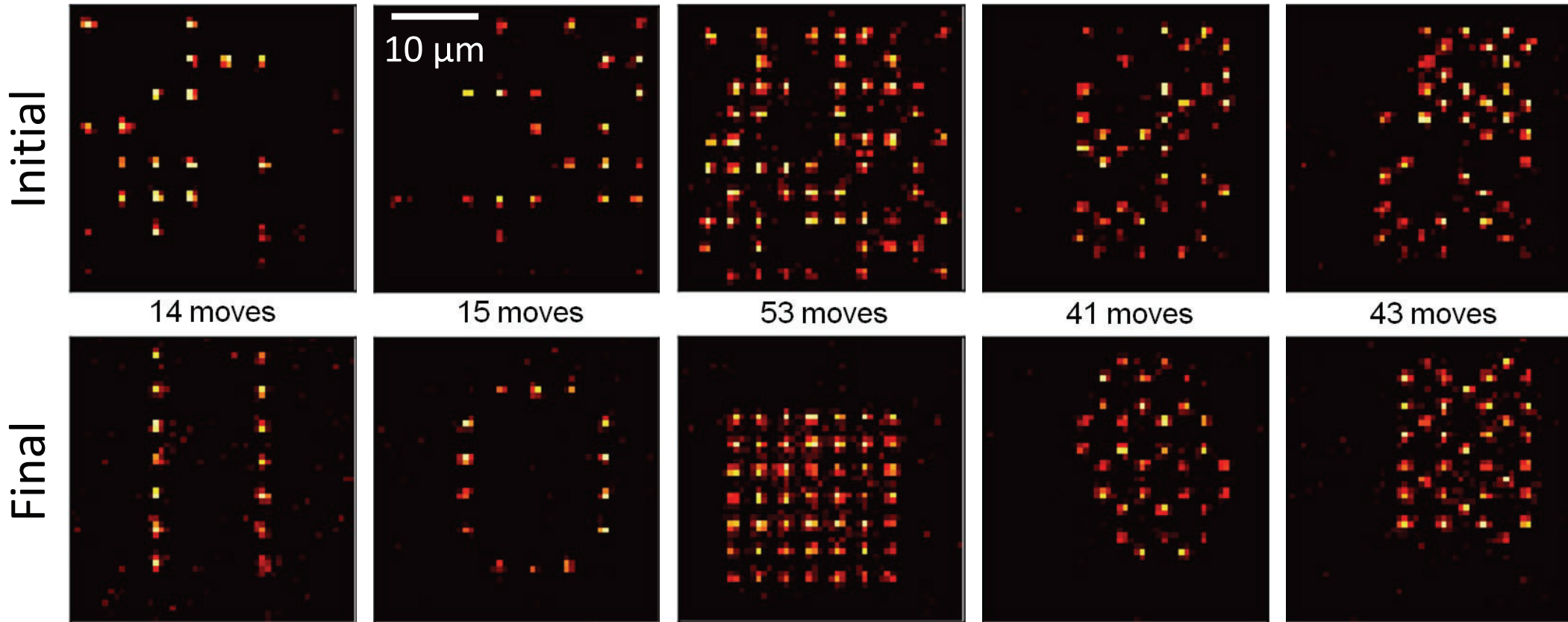
Gallery of assembled 2D arrays... (single-shot images...)



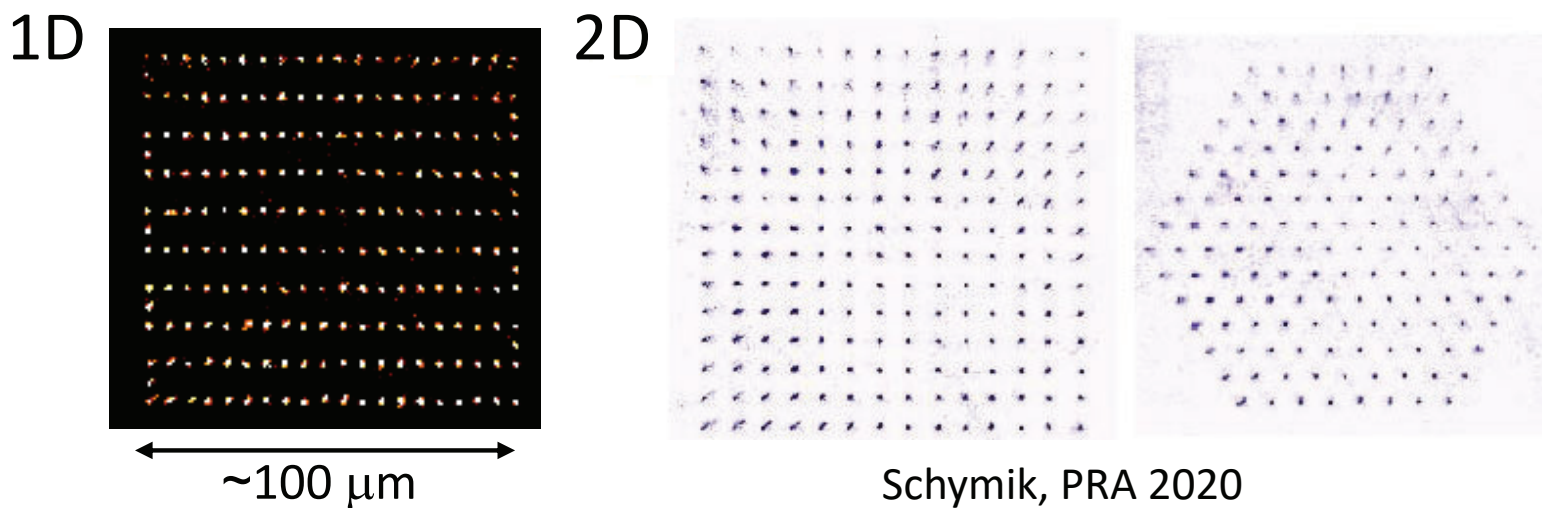
Now ~ 200 atoms



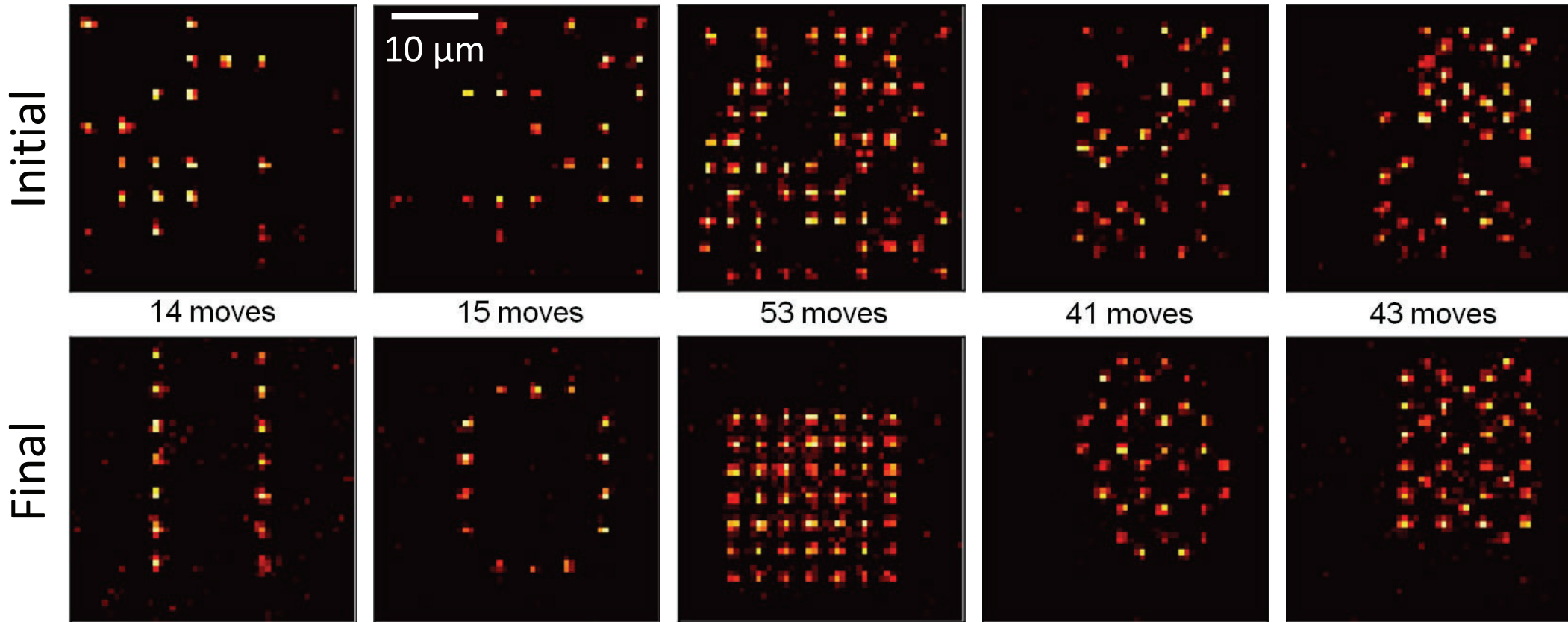
Gallery of assembled 2D arrays... (single-shot images...)



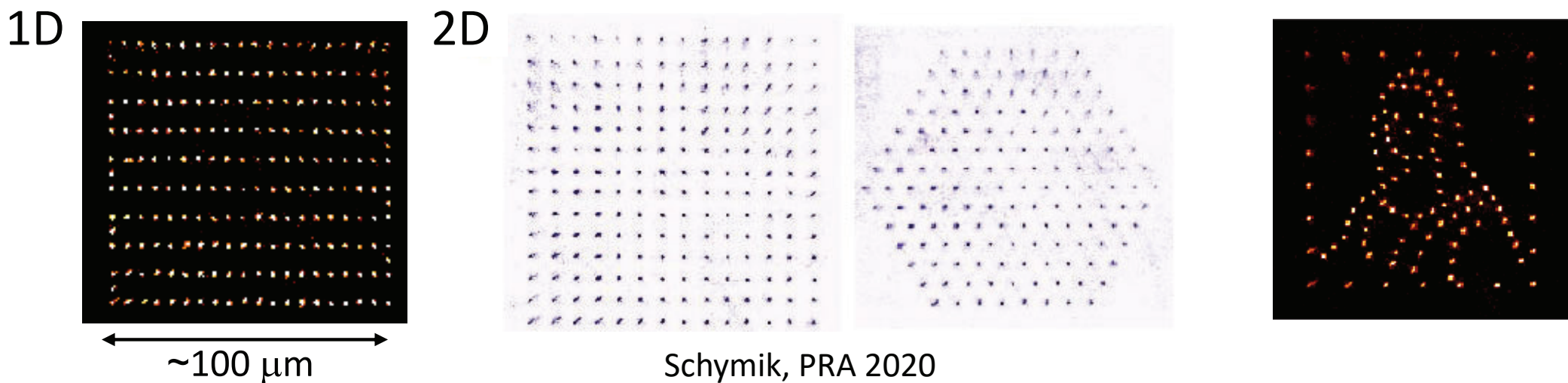
Now ~ 200 atoms



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

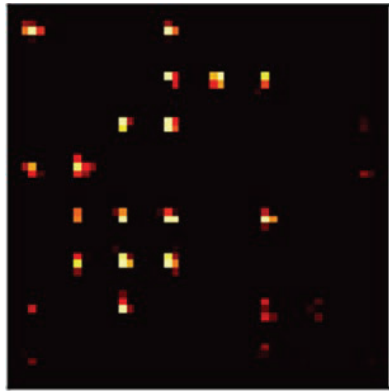


Now ~ 200 atoms

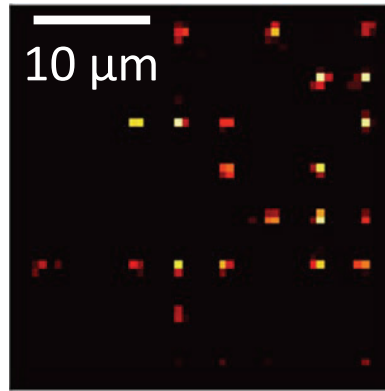


Gallery of assembled 2D arrays... (single-shot images...)

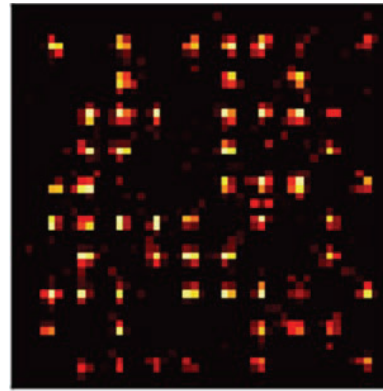
Initial



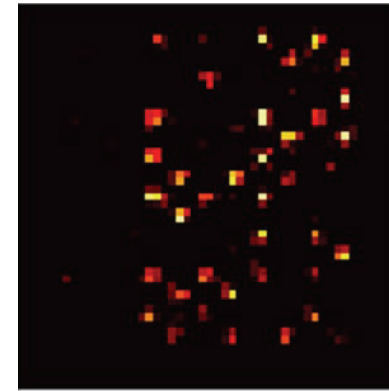
14 moves



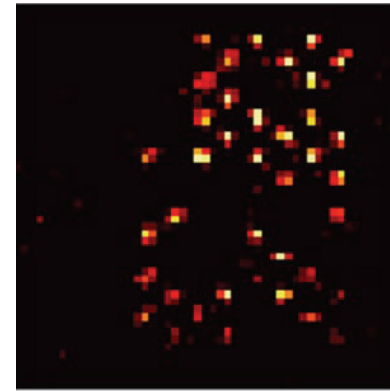
15 moves



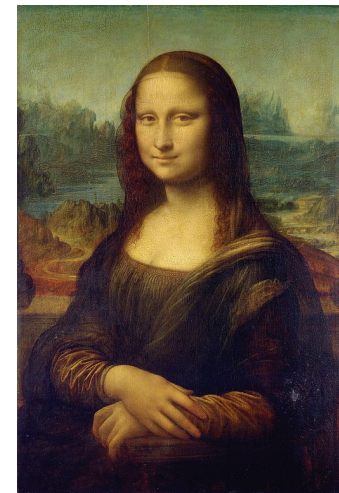
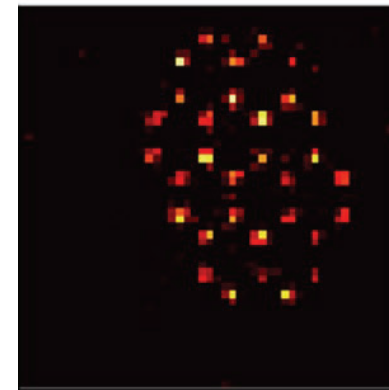
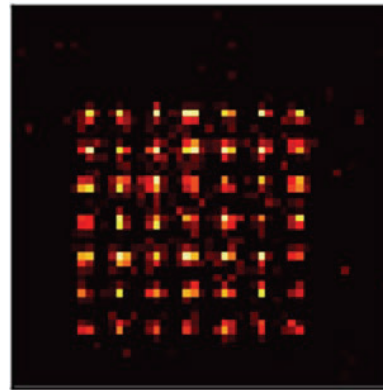
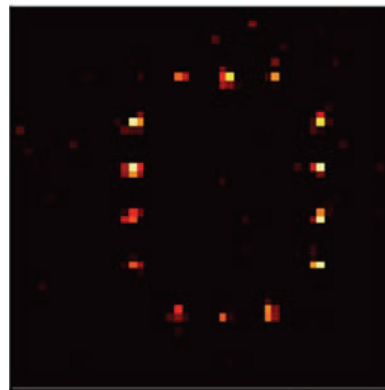
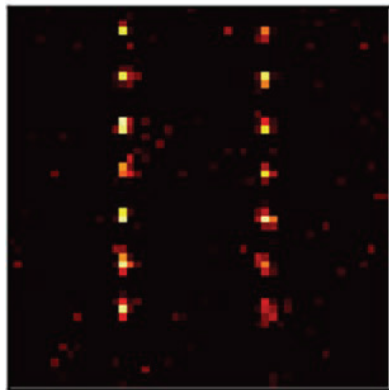
53 moves



41 moves



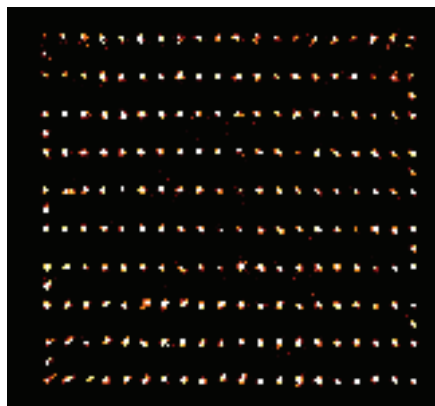
Final



L. da Vinci

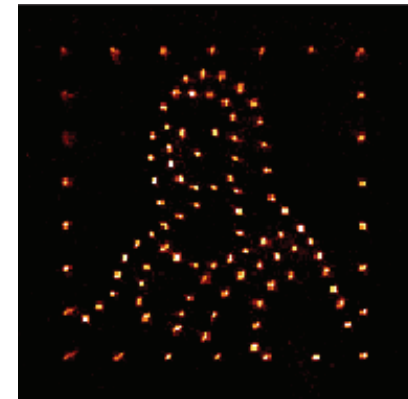
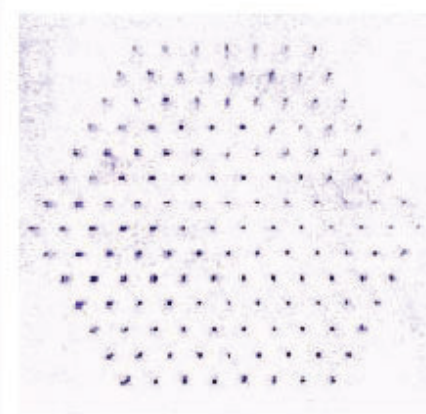
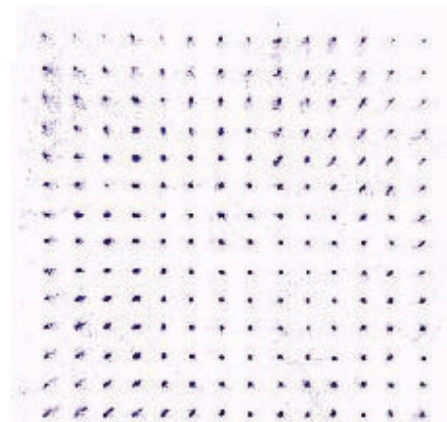
Now ~ 200 atoms

1D



$\sim 100 \mu\text{m}$

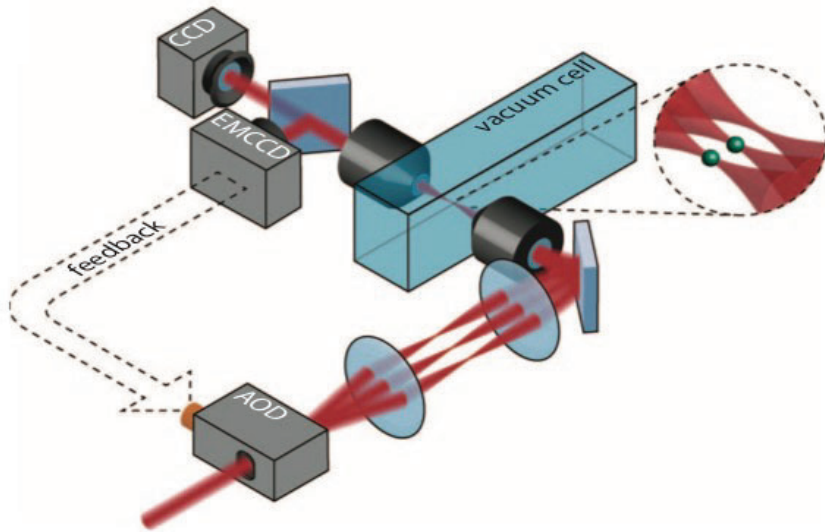
2D



Schymik, PRA 2020

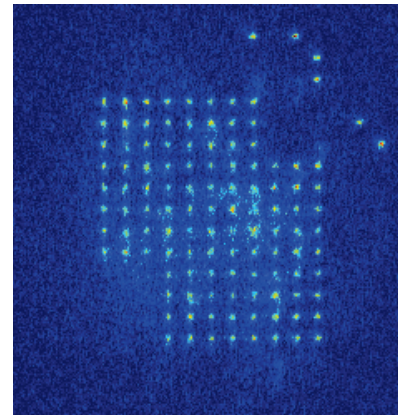
Now widely used,... with variants (1D, 2D & 3D)

Lukin (Harvard), 2016



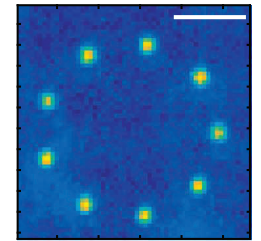
Rb Birkel (Germany)

2D

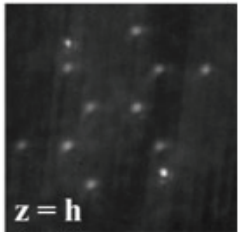
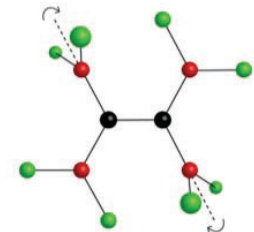


Ahn (Korea)

2D

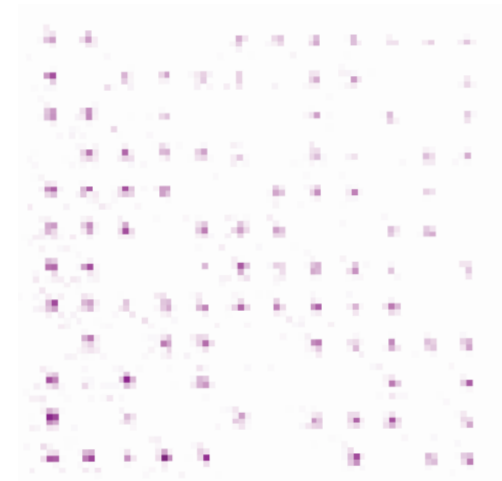
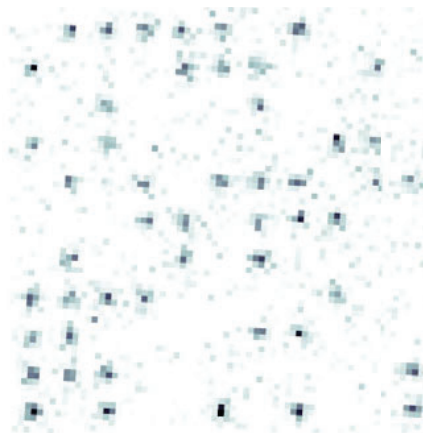


3D



Sr

Yb

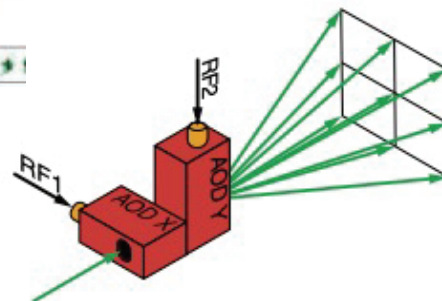


Endres (Caltech)
Kauffman (JILA)
2018

Thompson (Princeton)
2018

~300 atoms

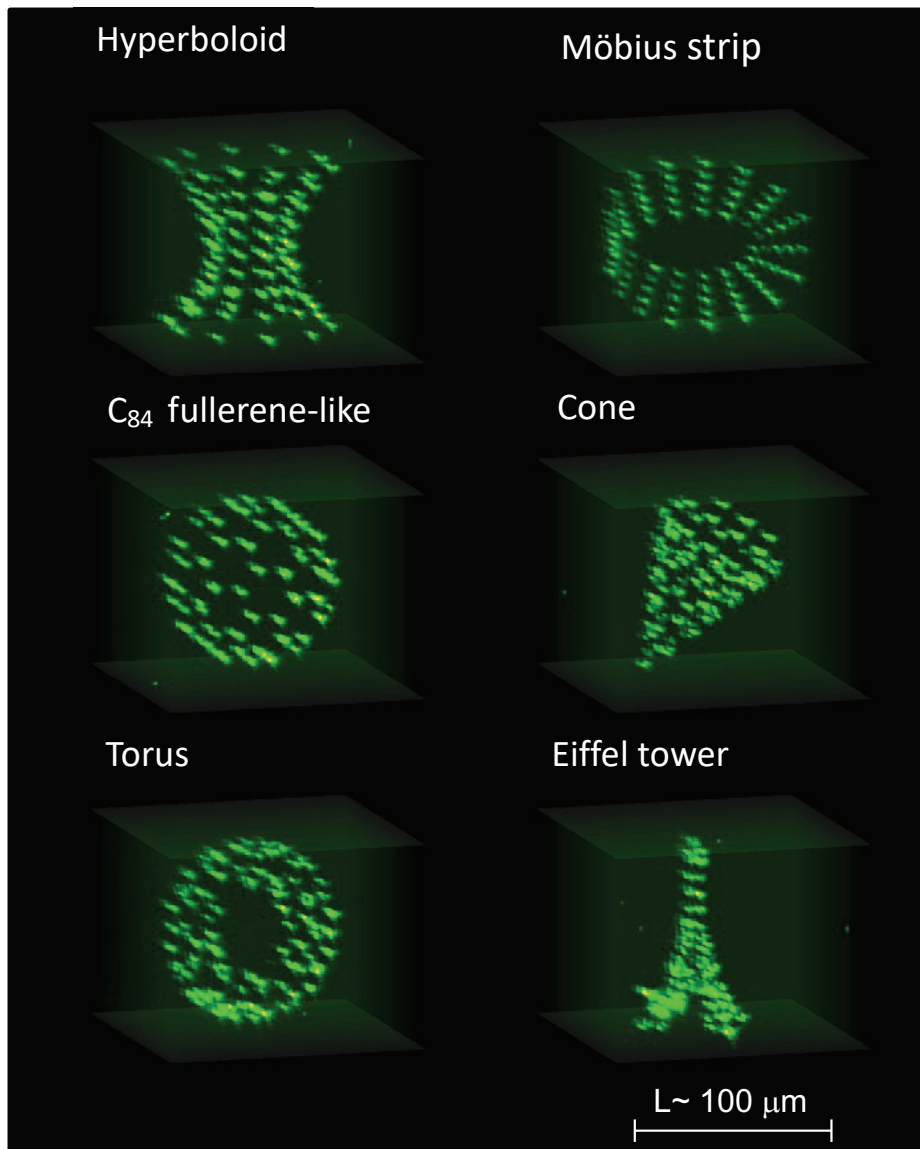
arXiv:2012.12281



It also works in 3d!

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

Averaged fluorescence
imaged “slice-by-slice”



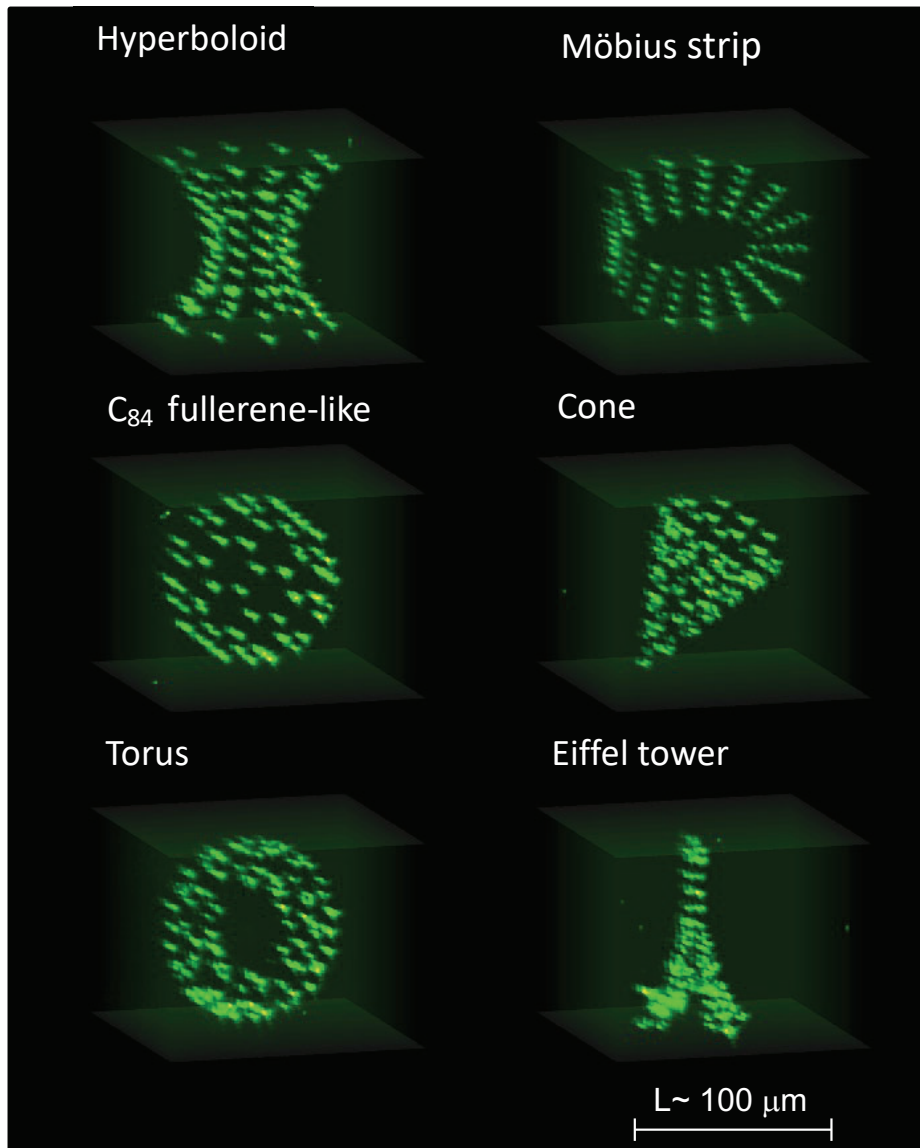
Barredo, Nature (2018)

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

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

Averaged fluorescence
imaged “slice-by-slice”

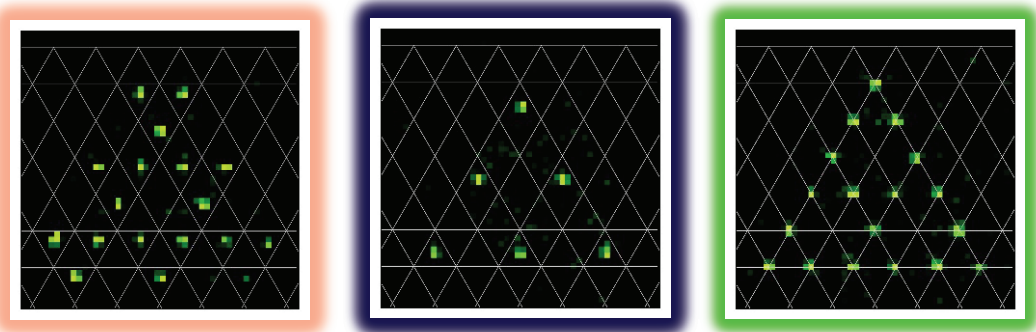


Assembled Pyrochlore lattice

Plane 1

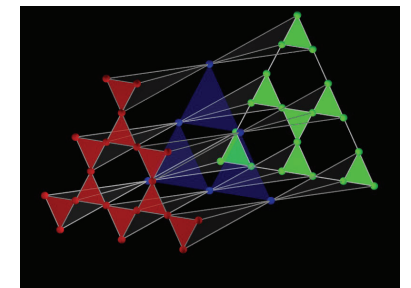
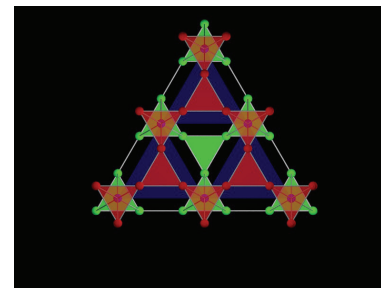
Plane 2

Plane 3



Front view

Side view



Barredo, *Nature* (2018)

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

V

- $T \sim 20 \text{ s.}$ lifetime of an atom in a tweezers
- N atoms $\rightarrow T/N$: lifetime of a config.
 $\hookrightarrow \sim N \text{ moves } \Delta t.$

$$N \sim 1000$$

Questions ?

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



Johannes Rydberg
1854-1919

References:

“Rydberg atoms”, T. Gallagher, Cambridge (1994)

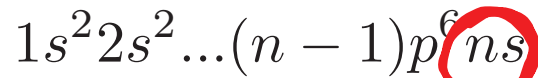
“An experimental and theoretical guide to strongly interacting Rydberg gases”, R. Loew, J. Phys. B **45**, 113001(2012)

“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

Periodic Table of the Elements

Alkali: 1 external electron



Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Alkali: 1 external electron

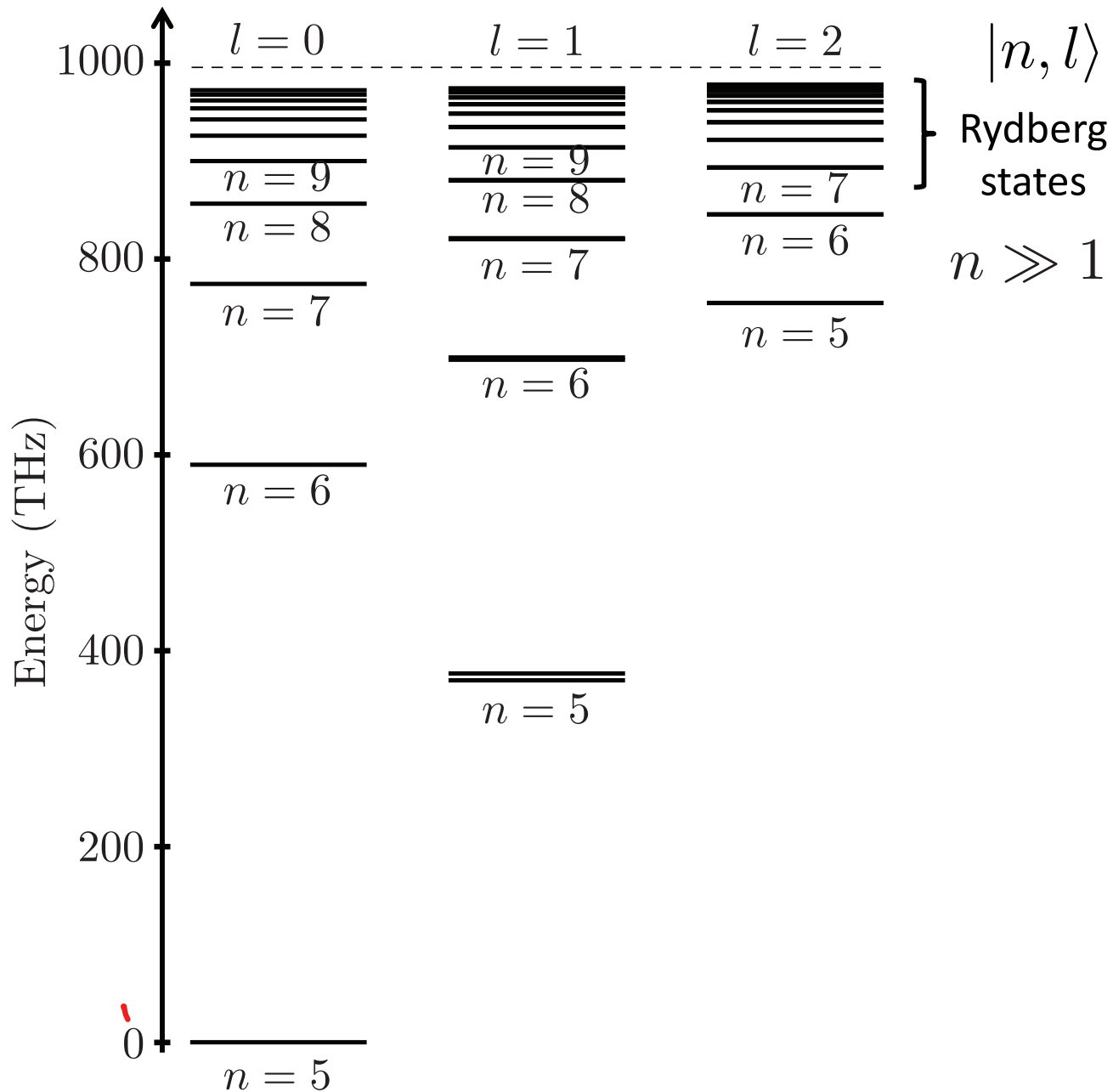
$$1s^2 2s^2 \dots (n-1)p^6 ns^1$$

$$e^-$$

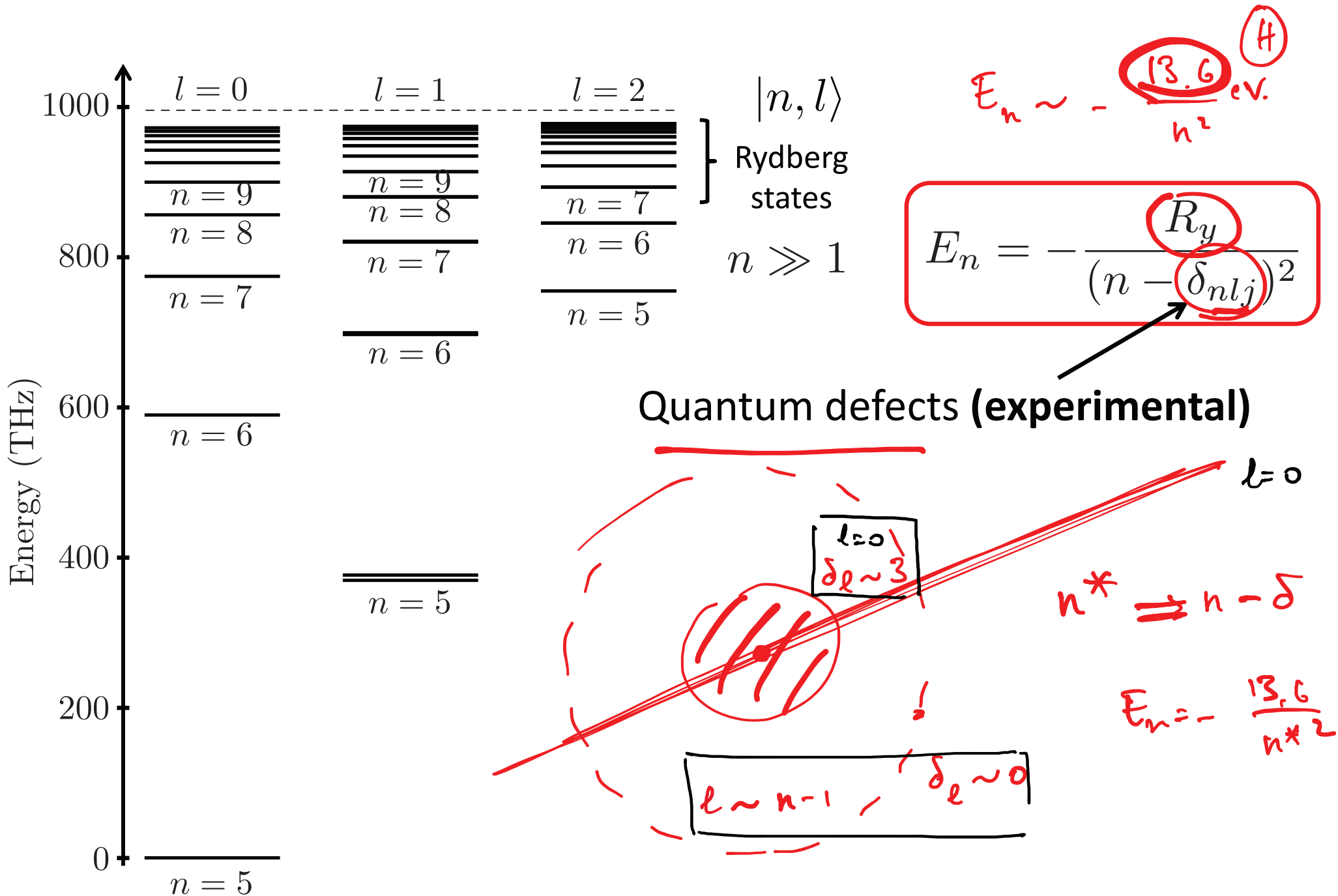
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide
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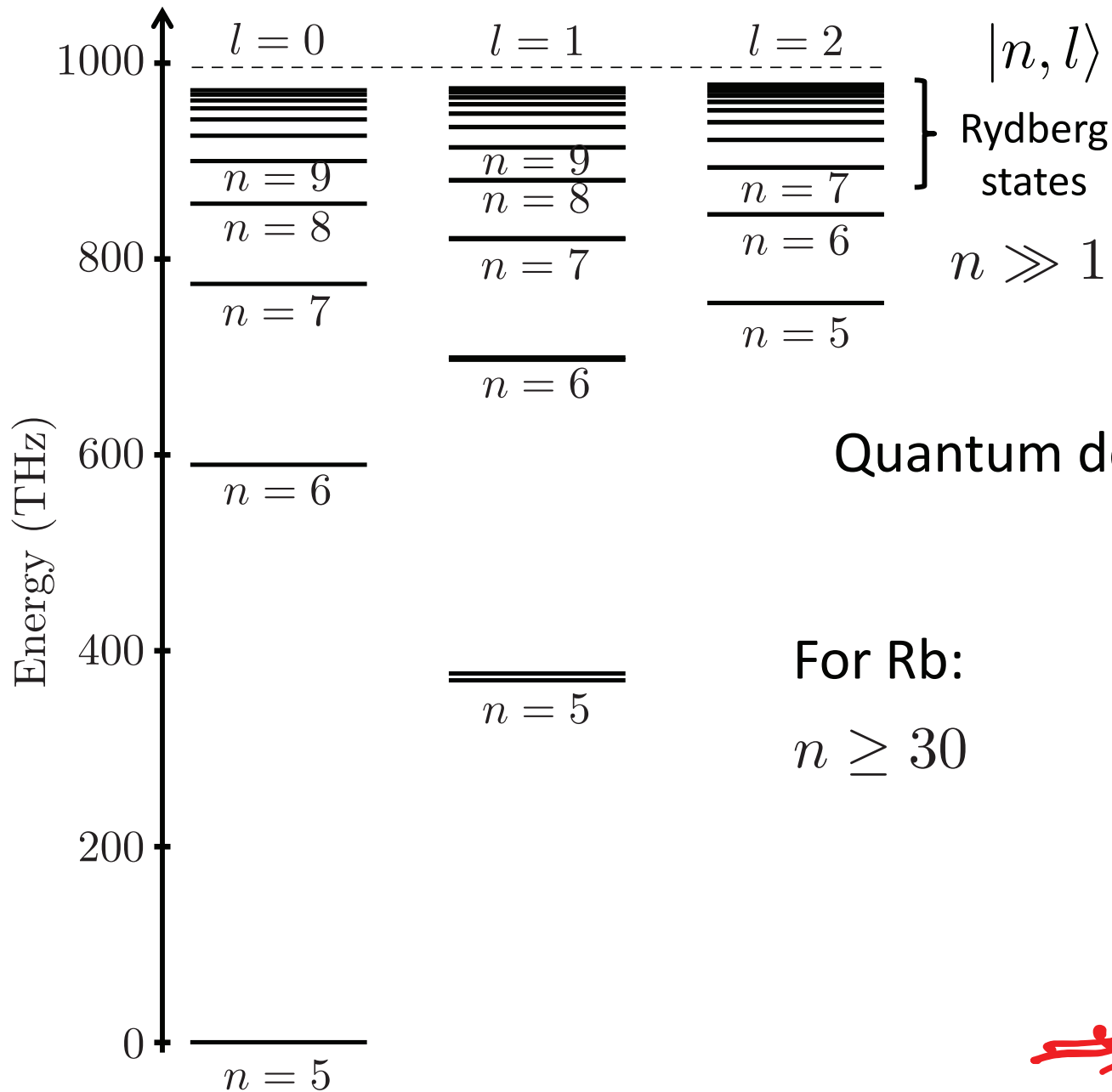
“Rydberg atom” = a highly excited atom (e.g. Rb)



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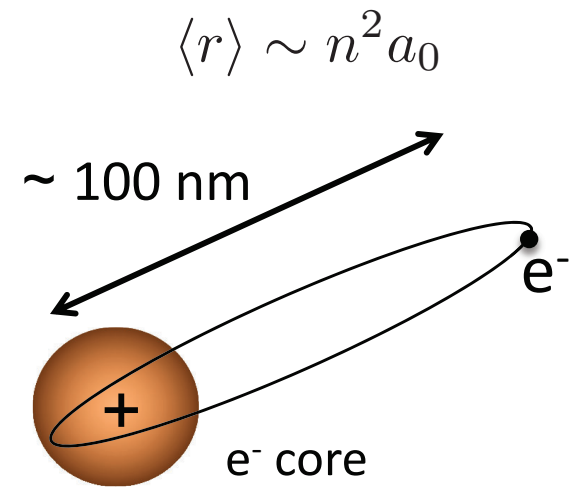
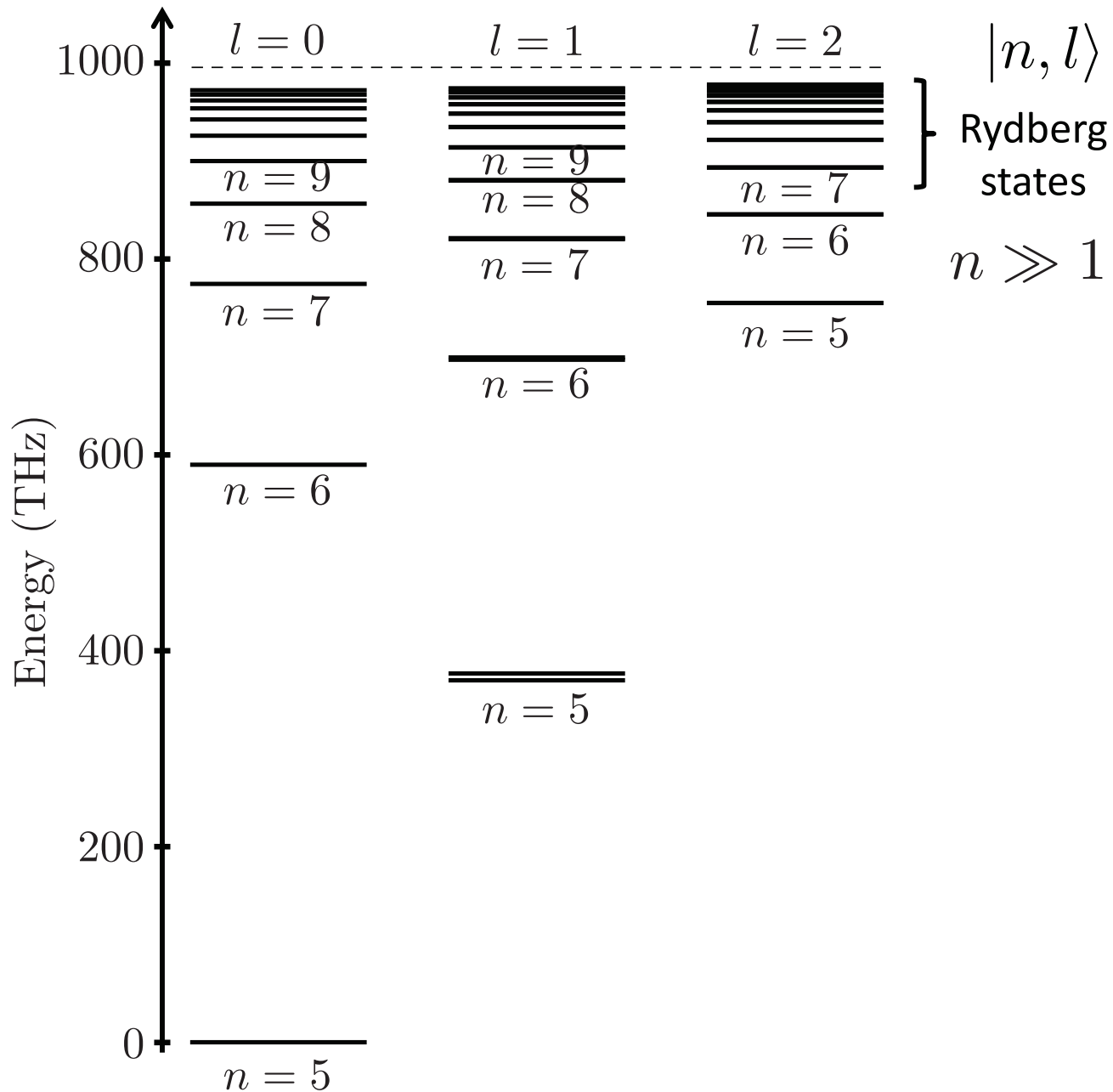
$$E_n = -\frac{R_y}{(n - \delta_{nlj})^2}$$

Quantum defects (**experimental**)

For Rb:
 $n \geq 30$

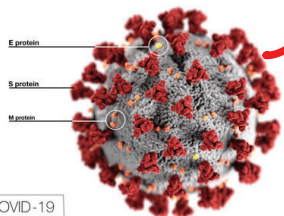
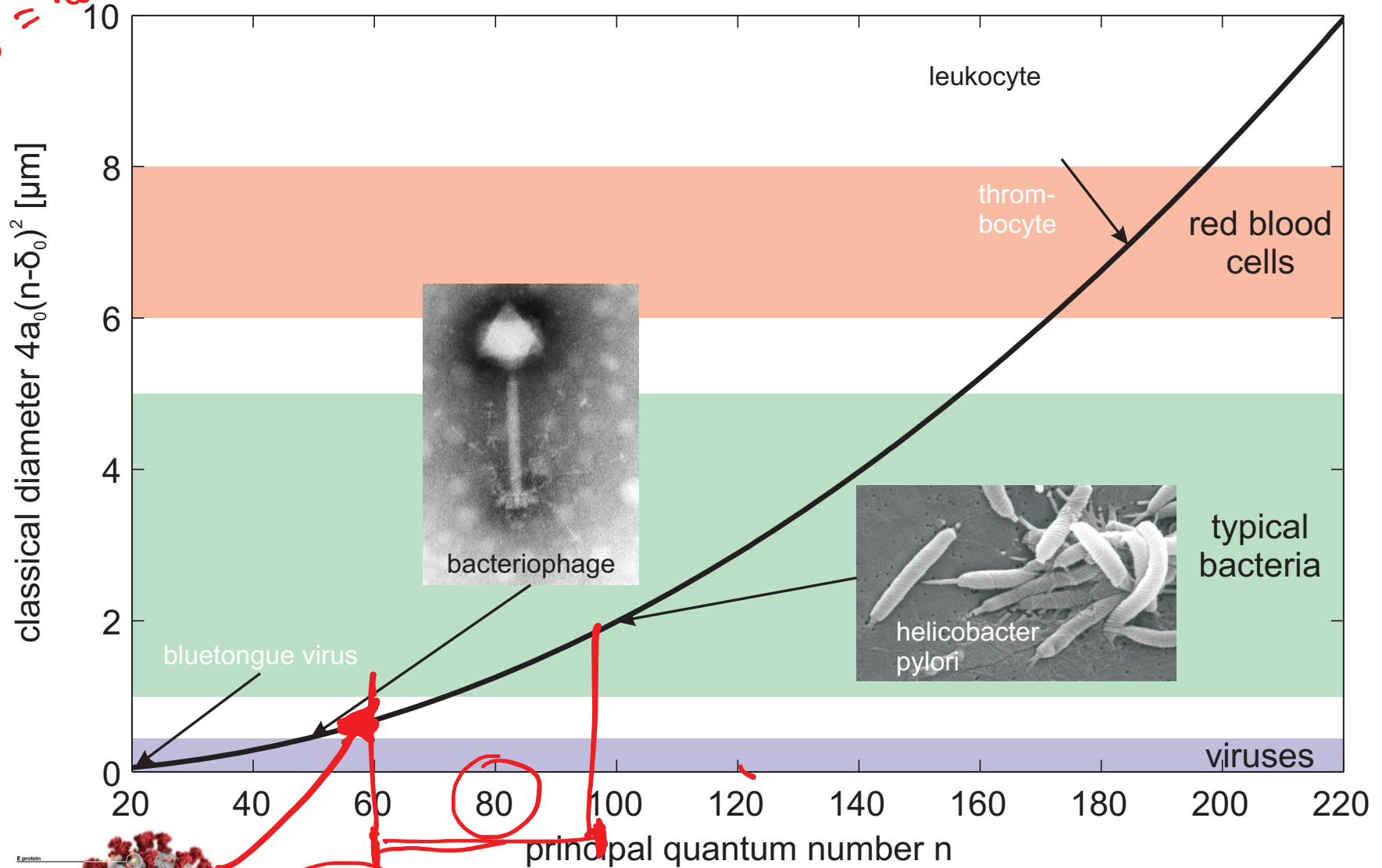
L	J	$\delta_{L,J}$
0	1/2	3.131
1	1/2	2.654
	3/2	2.641
2	3/2	1.348
	5/2	1.346
3	5/2	0.016
	7/2	0.016

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



Rydberg atoms are huge...

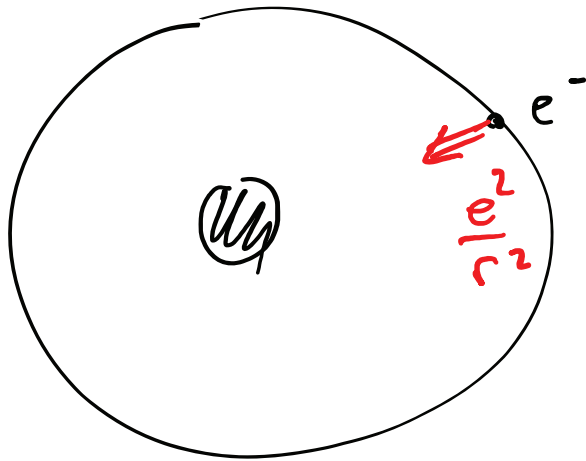
$n^2 a_0 \approx \text{radius}$



125 nm

$n \approx 60$

The Bohr model to recover quickly the scalings...

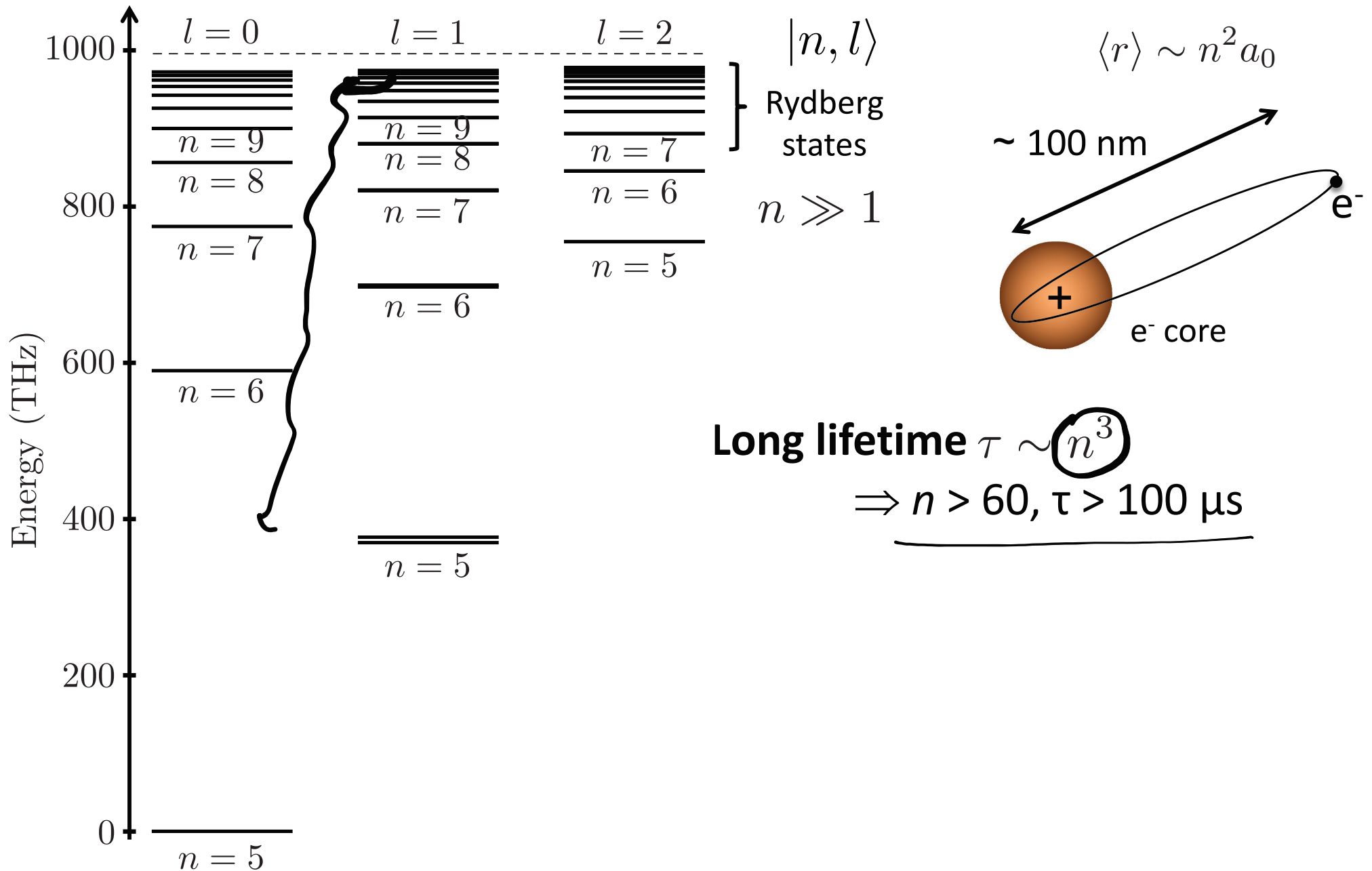


$$\left\{ \begin{array}{l} m \frac{v^2}{r} = \frac{e^2}{r^2} \\ m v r = n \hbar \end{array} \right. \quad \text{Bohr}$$

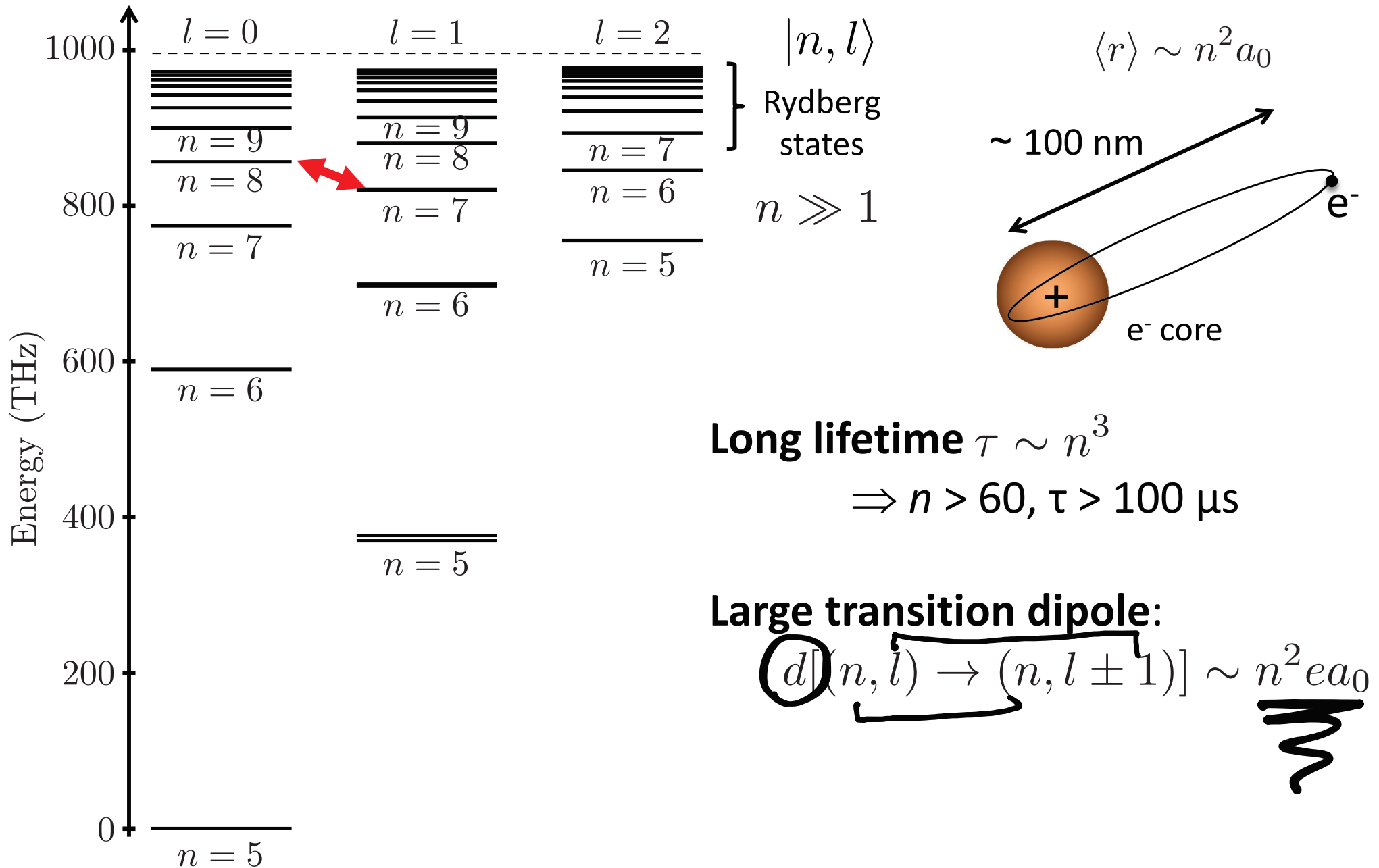
$\hookrightarrow n=1,2,\dots$

$$\Rightarrow \quad r = \left[\frac{n^2}{e^2} \frac{m \hbar^2}{e^2} \right] \quad \left(e^2 = \frac{q^2}{4\pi\epsilon_0} \right)$$

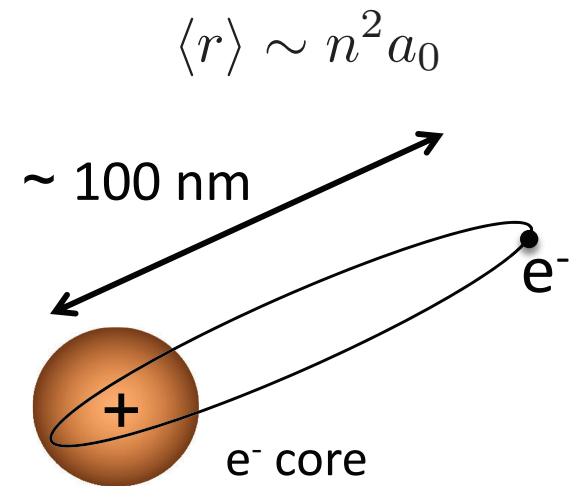
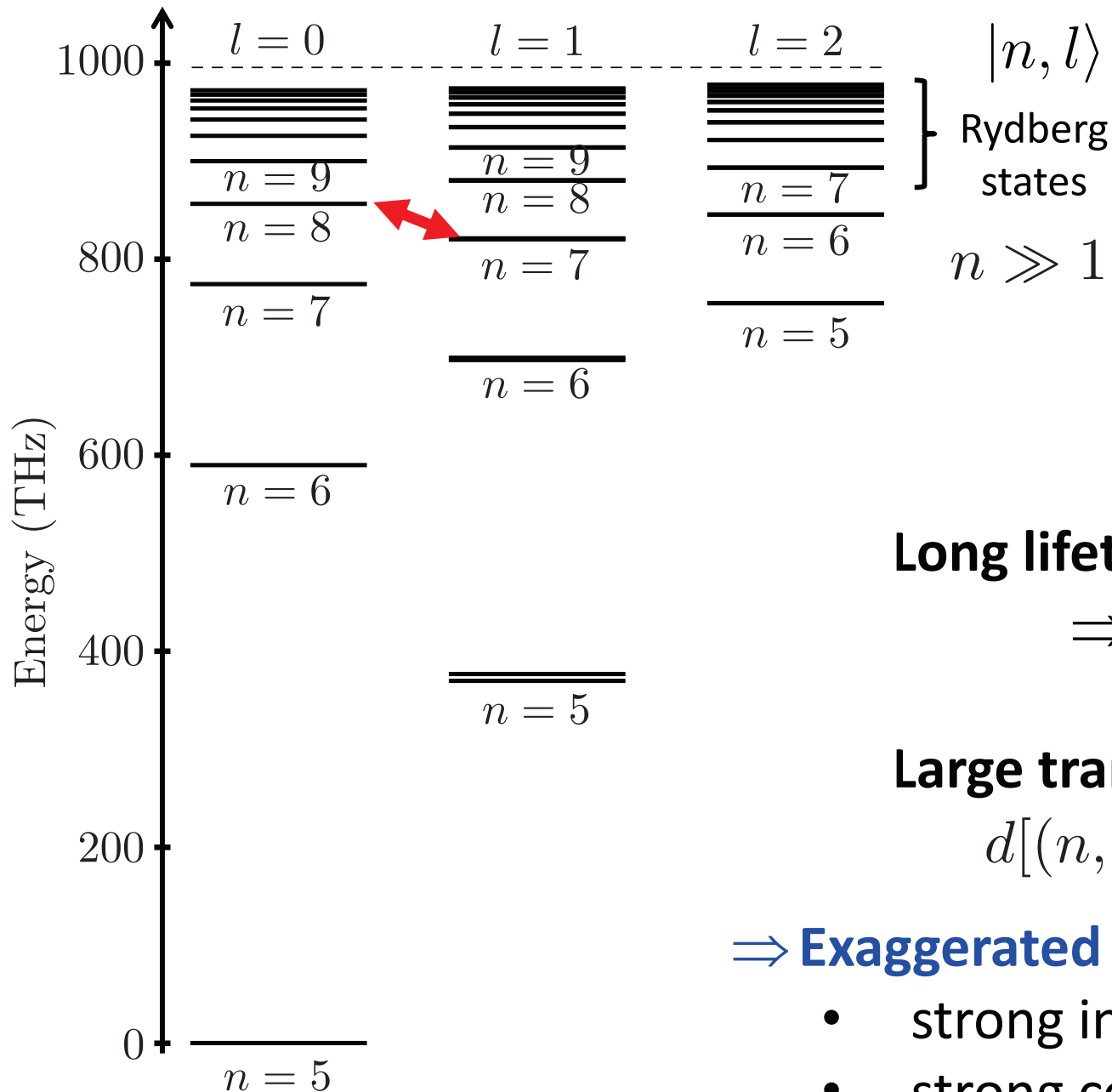
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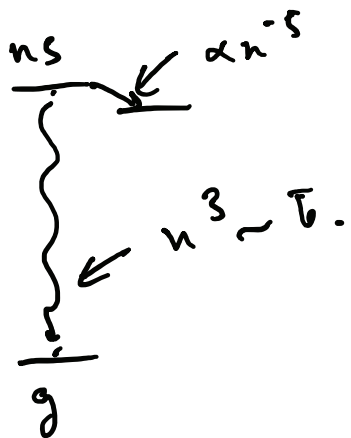


Long lifetime $\tau \sim n^3$
 $\Rightarrow n > 60, \tau > 100 \mu\text{s}$

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)



Rydberg's have exaggerated properties

Do it as a problem.

Table 1. Properties of Rydberg states.

Property	<i>n</i> -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 μ s
Polarizability α	n^7	−1.8 GHz/(V/cm) ²
van der Waals coefficient C_6	n^{11}	4 THz · μ m ⁶

$$\Gamma = d_{1g}^2 \omega^3$$

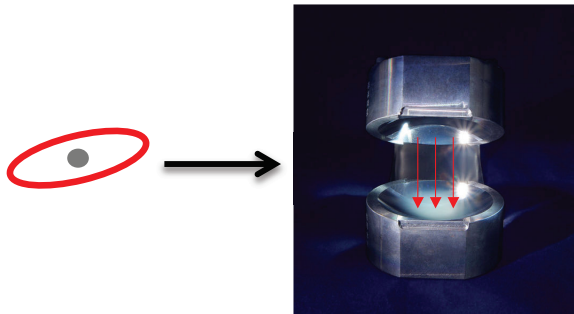
$$\approx 12 \left(\frac{1}{n^3} \right)^3 n^4$$

$$C_6 \sim n^{11}$$

Rydberg atoms: a few historical landmarks

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

1980 – 2000 Cavity Quantum Electrodynamics using Rydbergs

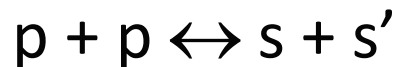
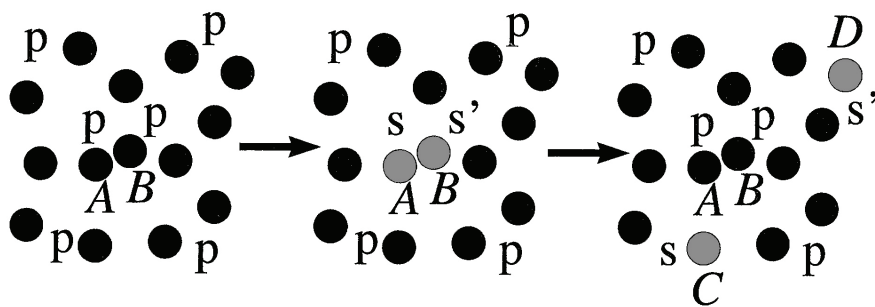


High Q cavity: photon lifetime $> 1\text{ms}$
 + large dipole $\Rightarrow$
1 Rydberg interacts with 1 photon!

Haroche, Walther...



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



"Frozen" gas

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

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

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

$k_B T \ll$ Interaction energy

$\Rightarrow T < 1 \text{ mK}$

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

National Institute of Standards and Technology, Gaithersburg, Maryland 20899

R. Côté¹ and M. D. Lukin²

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. Cote³

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²*Fachbereich Physik, Universität Kaiserslautern, D-67663 Kaiserslautern, Germany*

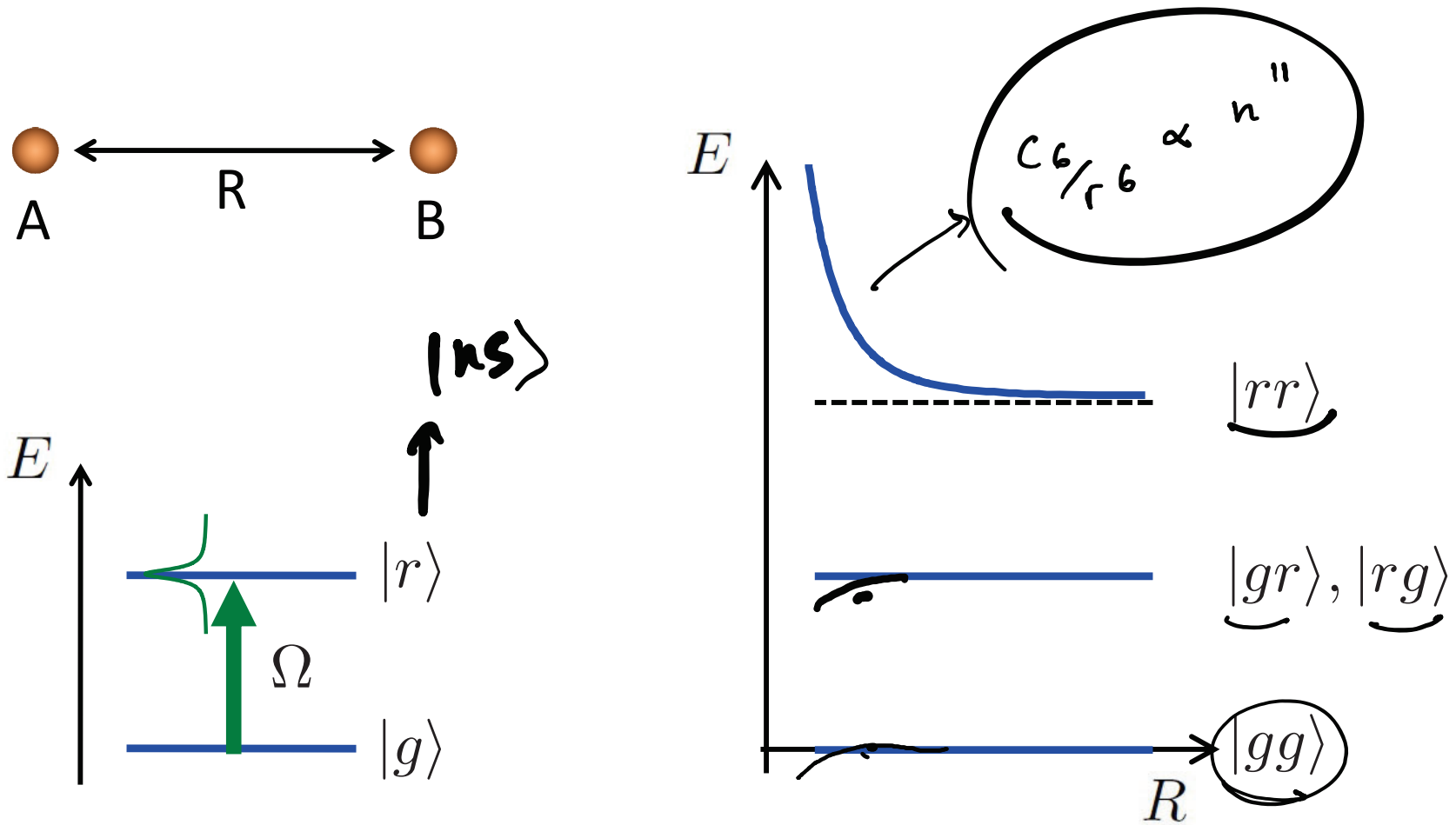
³*Physics Department, University of Connecticut, Storrs, Connecticut 06269*

L. M. Duan, D. Jaksch, J. I. Cirac, and P. Zoller

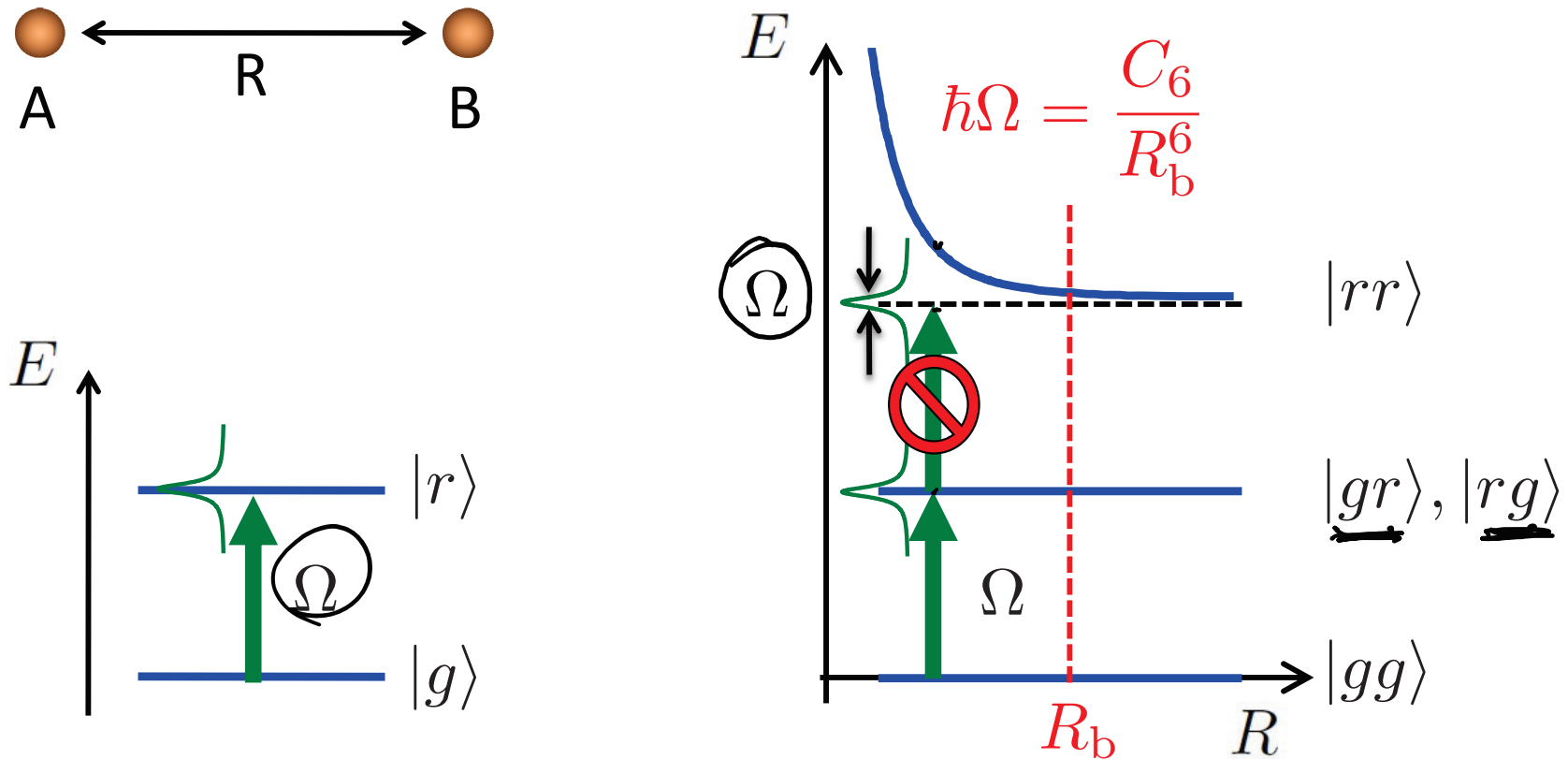
Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria

(Received 7 November 2000; published 26 June 2001)

A new era: the Rydberg Blockade idea

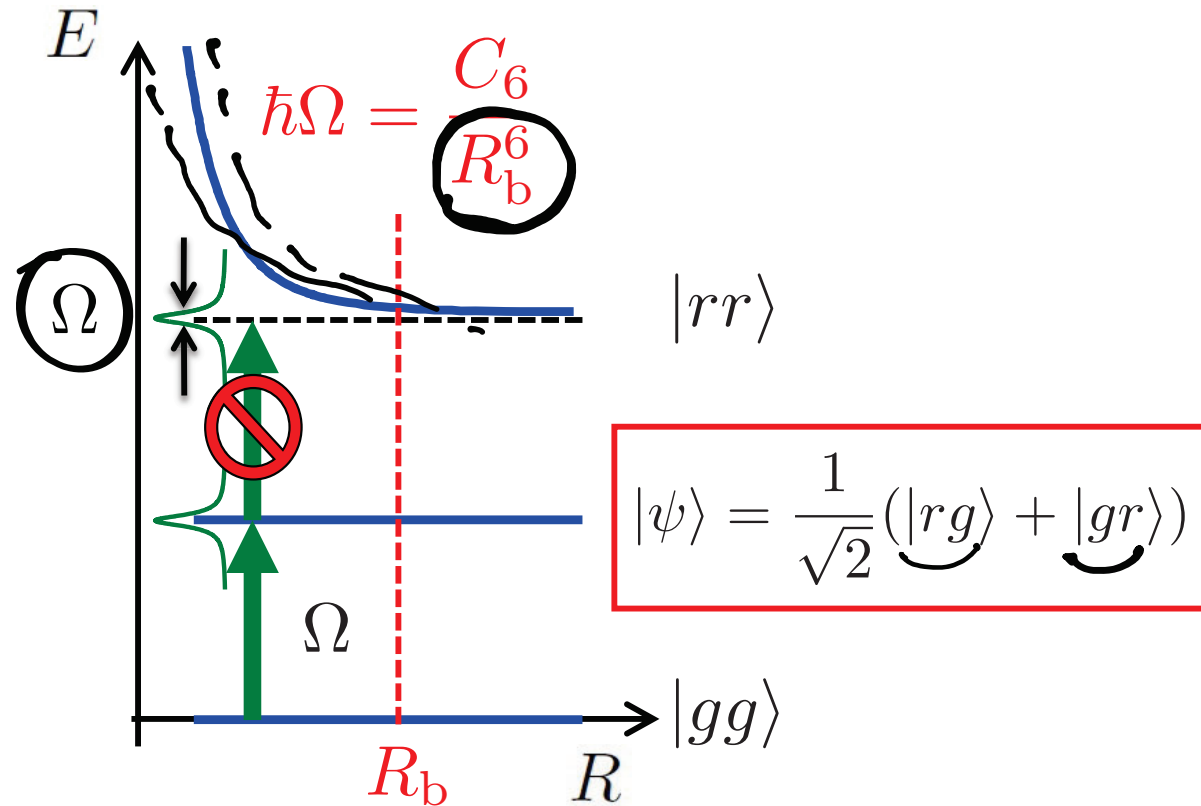
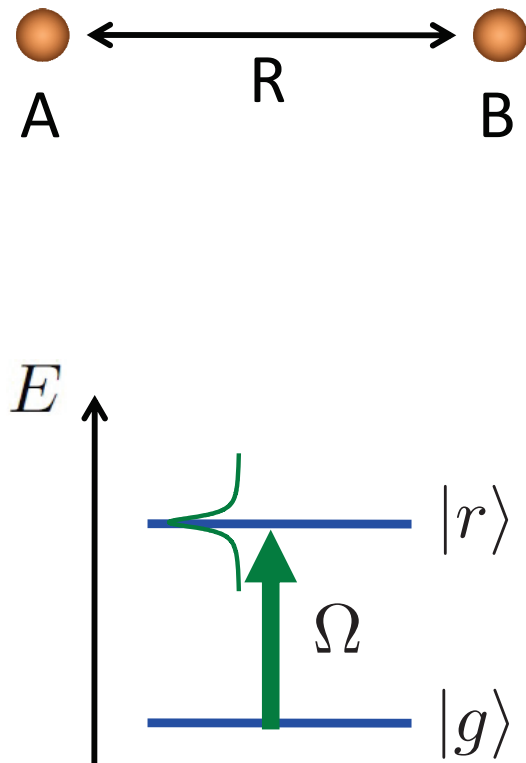


A new era: the Rydberg Blockade idea



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

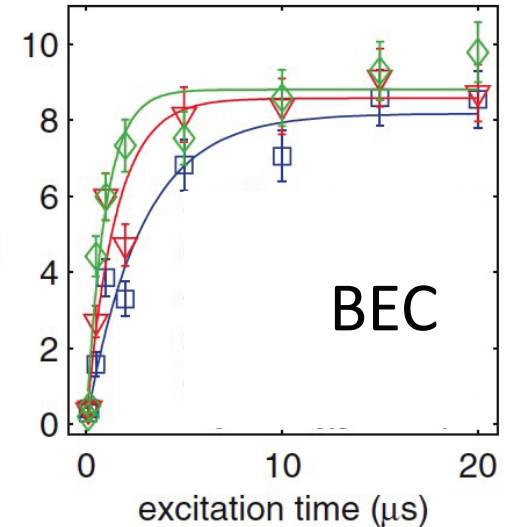
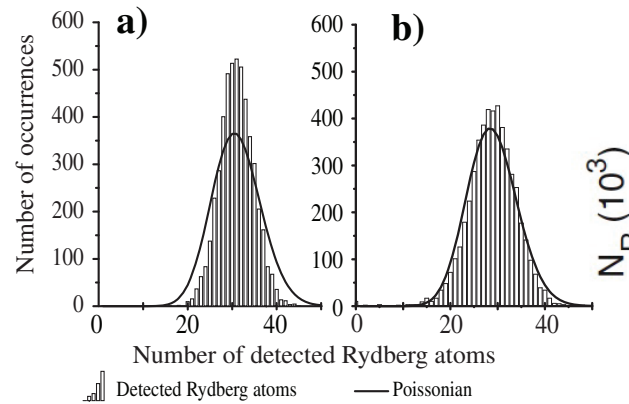
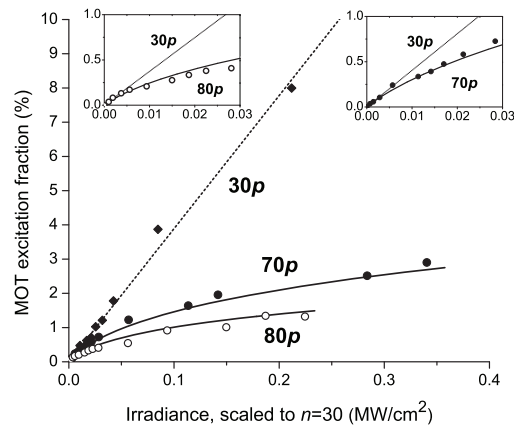
A new era: the Rydberg Blockade idea



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

The first blockade experiments

Atomic ensembles



Pfau, PRL 2007

Gould, PRL 2004
Weidemuller, PRL 2004

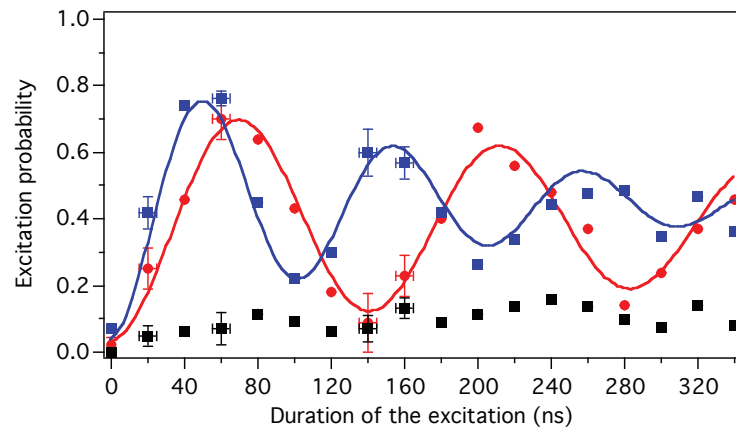
Martin, PRL 2004

Pillet, PRL 2006

Raithel, PRL 2005

Individual atoms

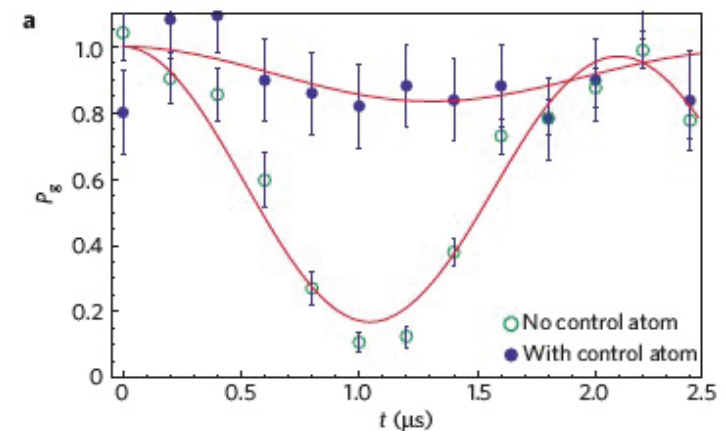
IO Palaiseau



Blockade + collective excitation $\sqrt{2}$

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

U. Wisconsin

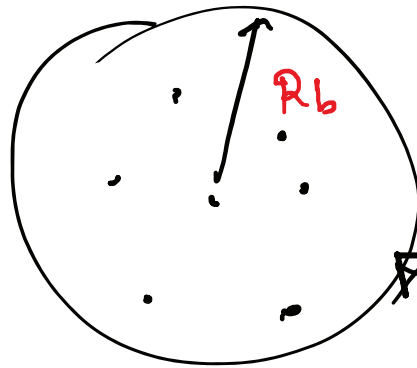


Blockade

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

①

Blockade for N atoms:

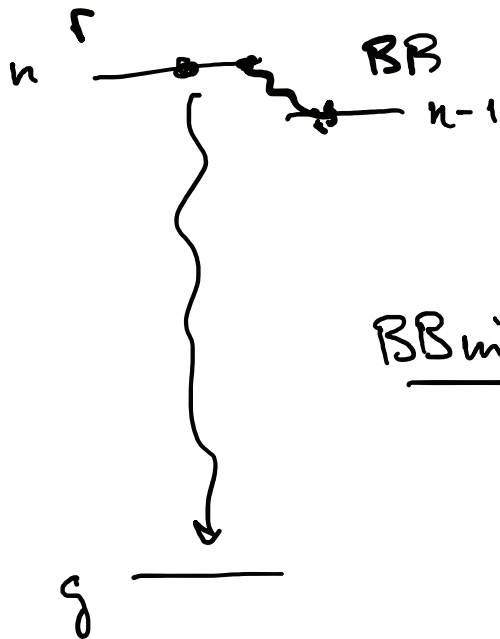


$$\frac{1}{\sqrt{N}}$$

$$\left(\langle r_g \dots r_g \rangle + \langle r_g g \dots \rangle e^{i\vec{k} \cdot \vec{r}_i} \right)$$

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

Questions ?



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

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

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)

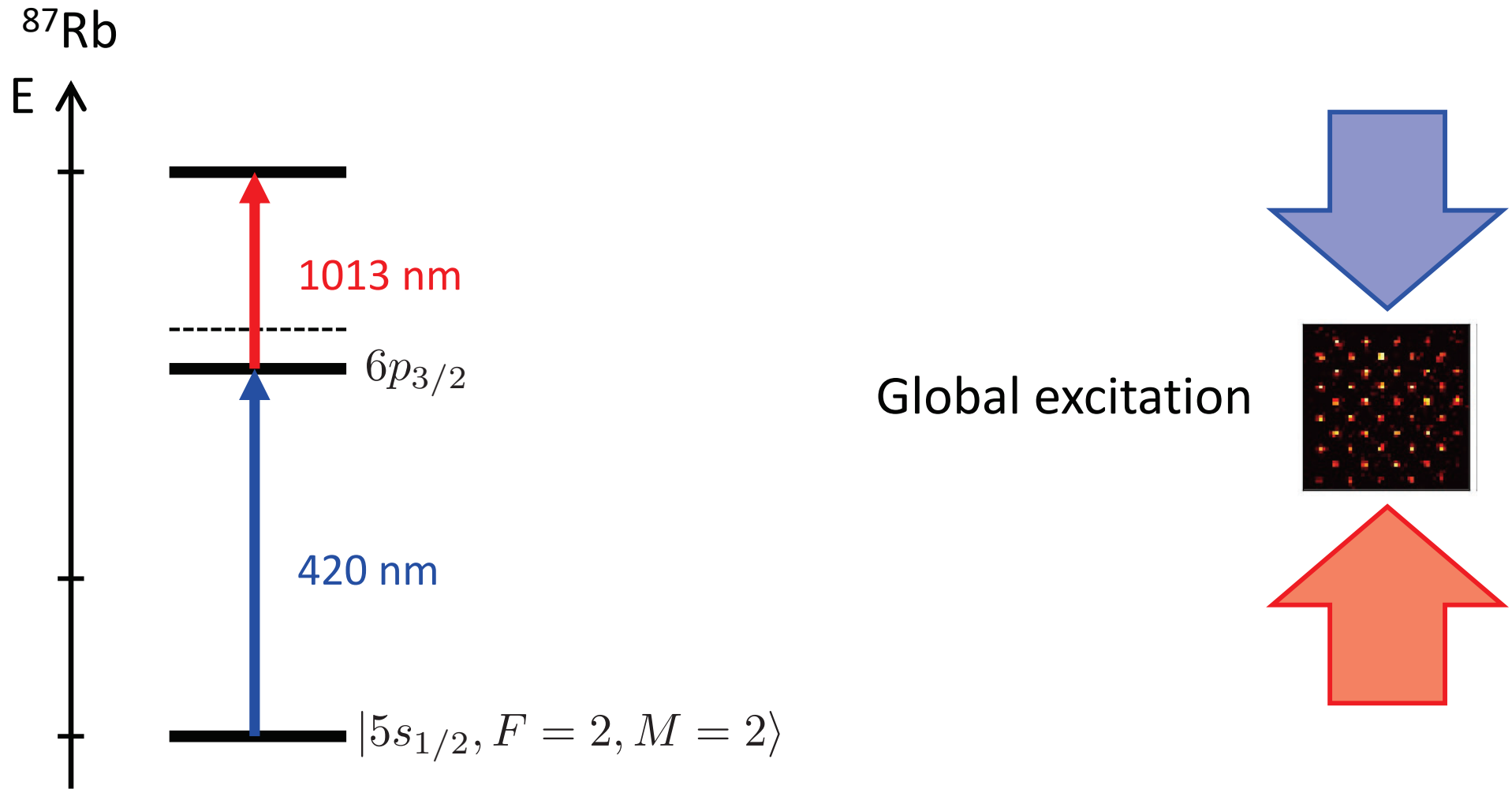
“Calculation of Rydberg interaction potentials”, S. Weber *et al.*, J. Phys. B **50**, 133001 (2017)

Softwares to calculate interaction energies

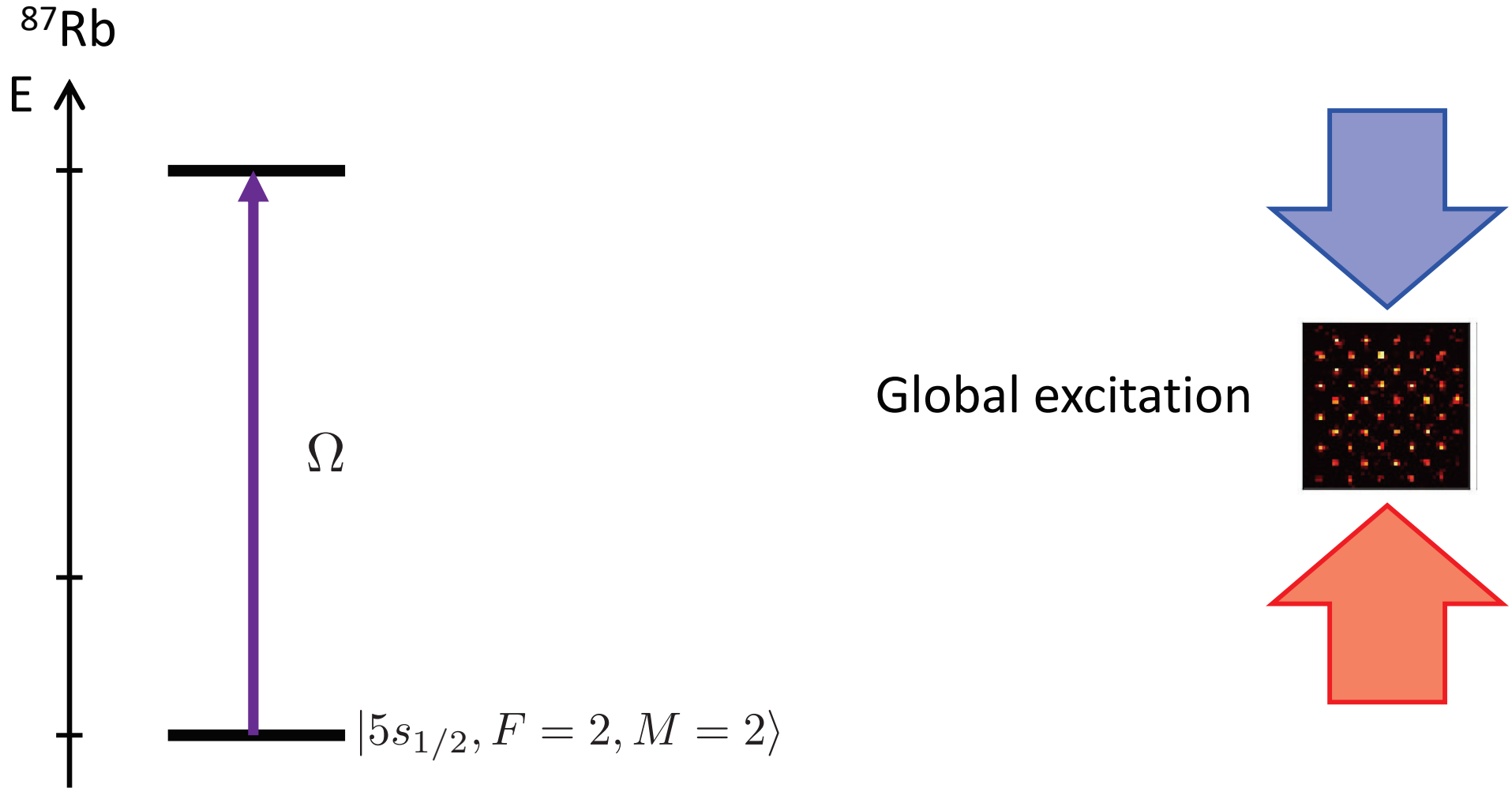
S. Weber *et al.*, [arXiv:1612.08053](https://arxiv.org/abs/1612.08053), <https://pairinteraction.github.io>

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

Coherent optical Rydberg excitation ($n = 50 - 100$)



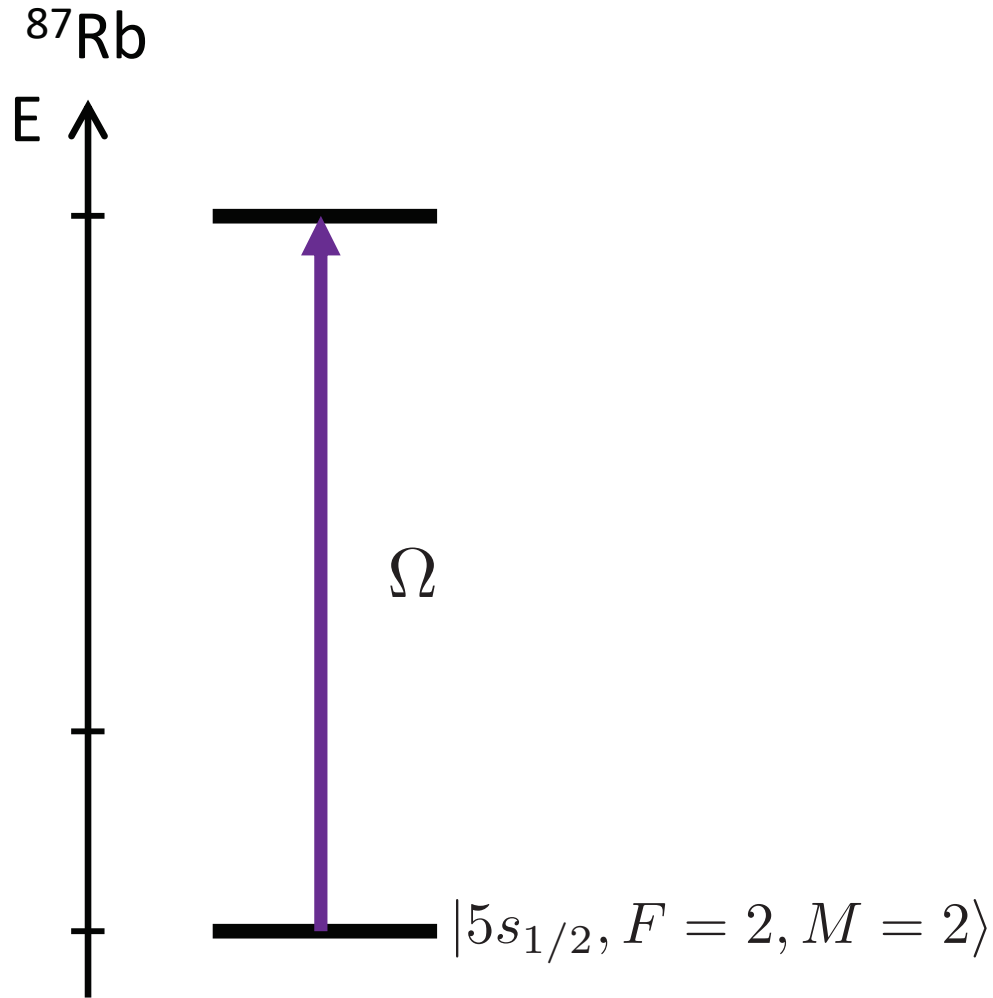
Coherent optical Rydberg excitation ($n = 50 - 100$)



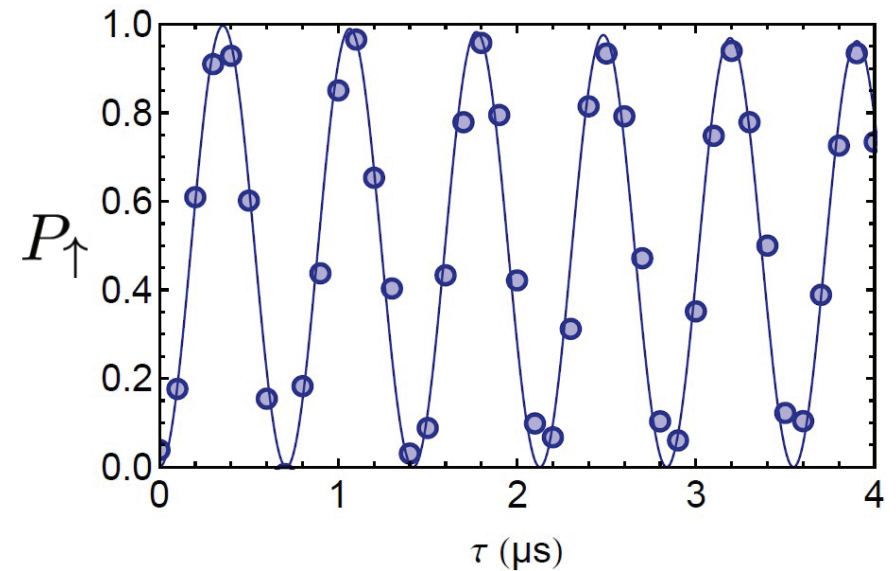
Effective Rabi frequency:

Light-shift:

Coherent optical Rydberg excitation ($n = 50 - 100$)



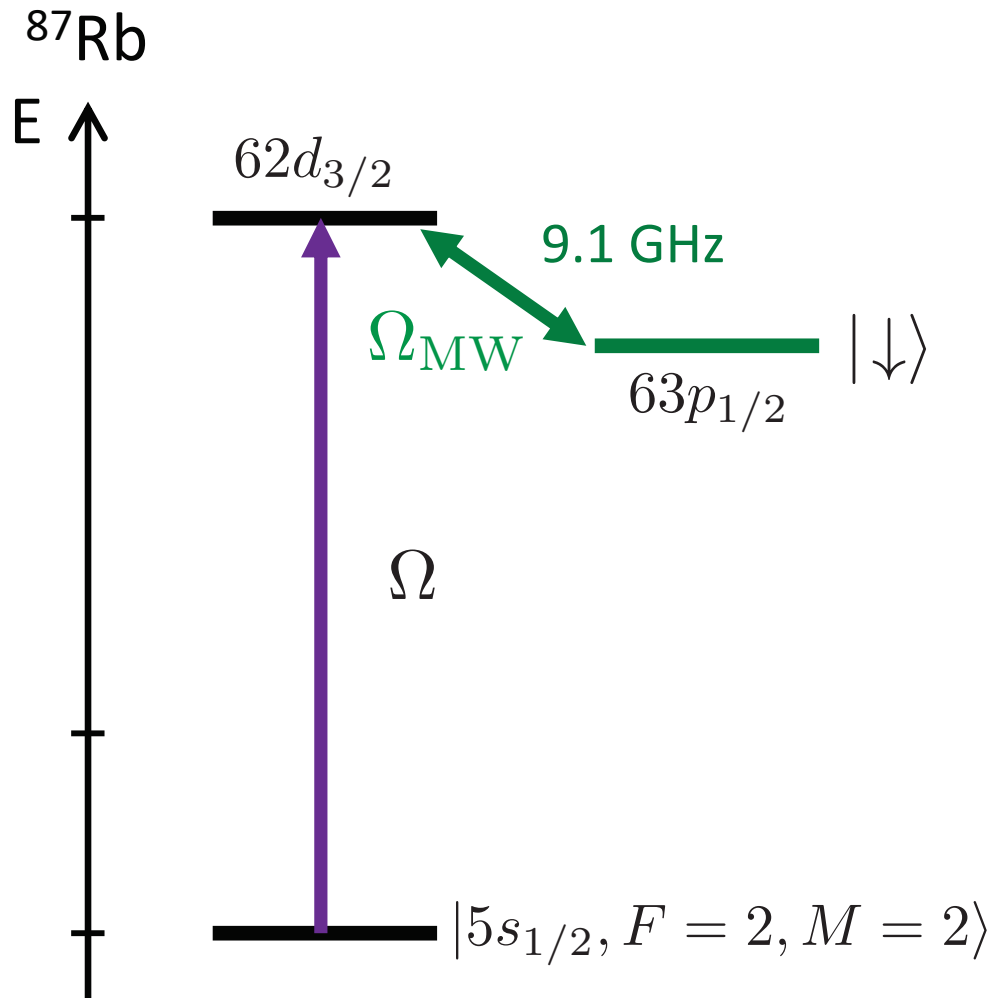
Optical excitation ($\Omega = 0.5 - 5$ MHz)



Effective Rabi frequency:

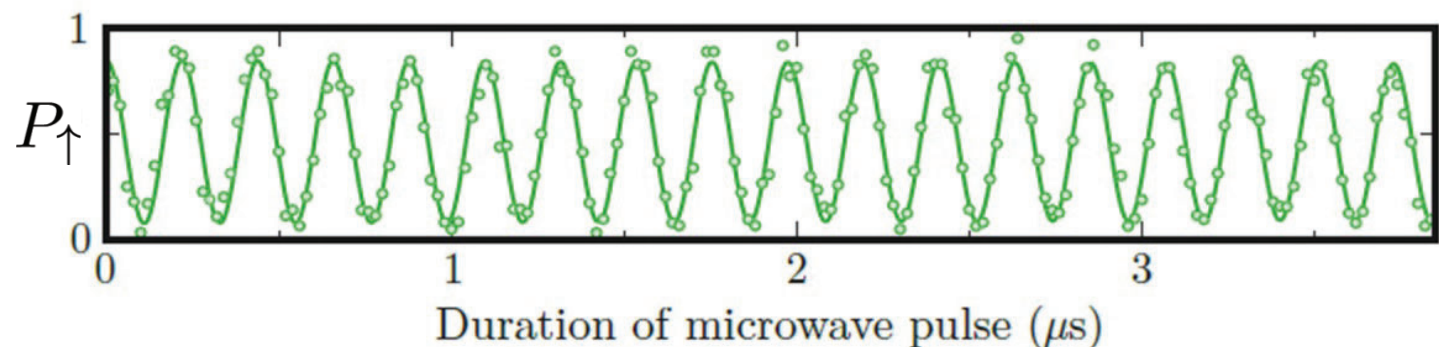
Light-shift:

Microwave manipulations ($n = 50 - 100$)



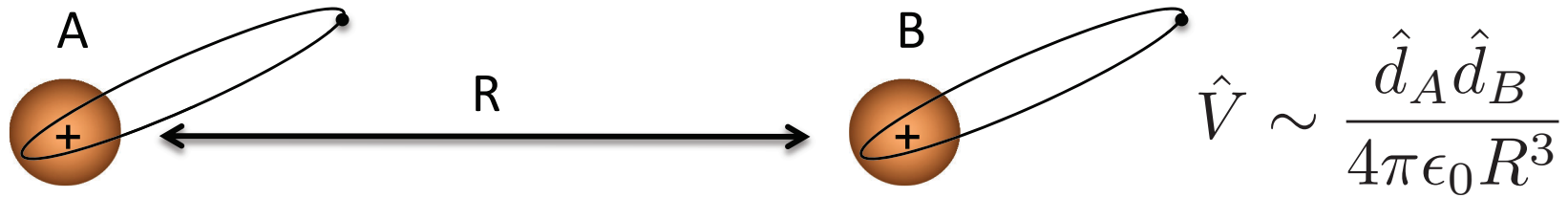
Microwave Rabi oscillation

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

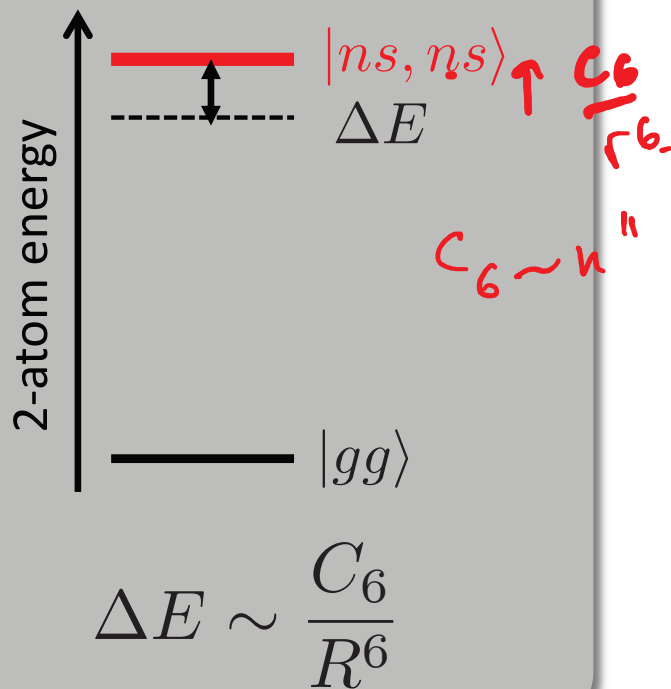


Questions ?

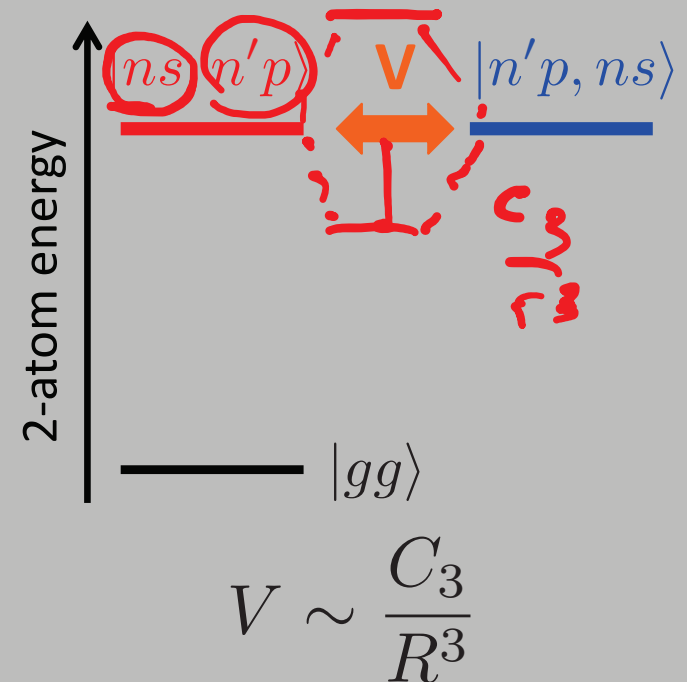
Interactions between Rydberg atoms



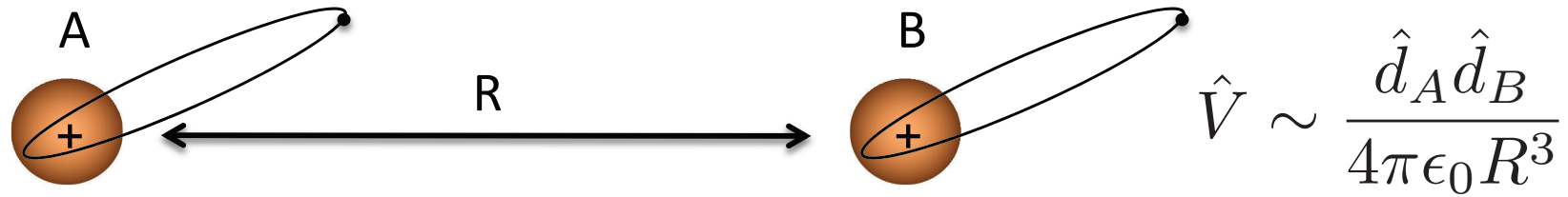
van der Waals



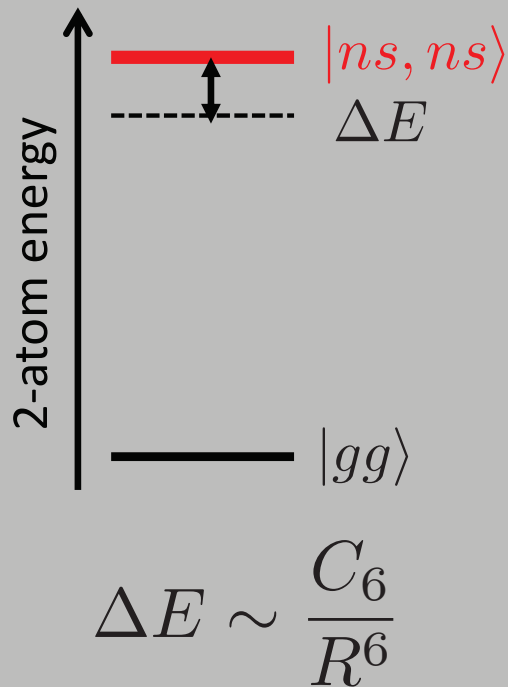
Resonant interaction



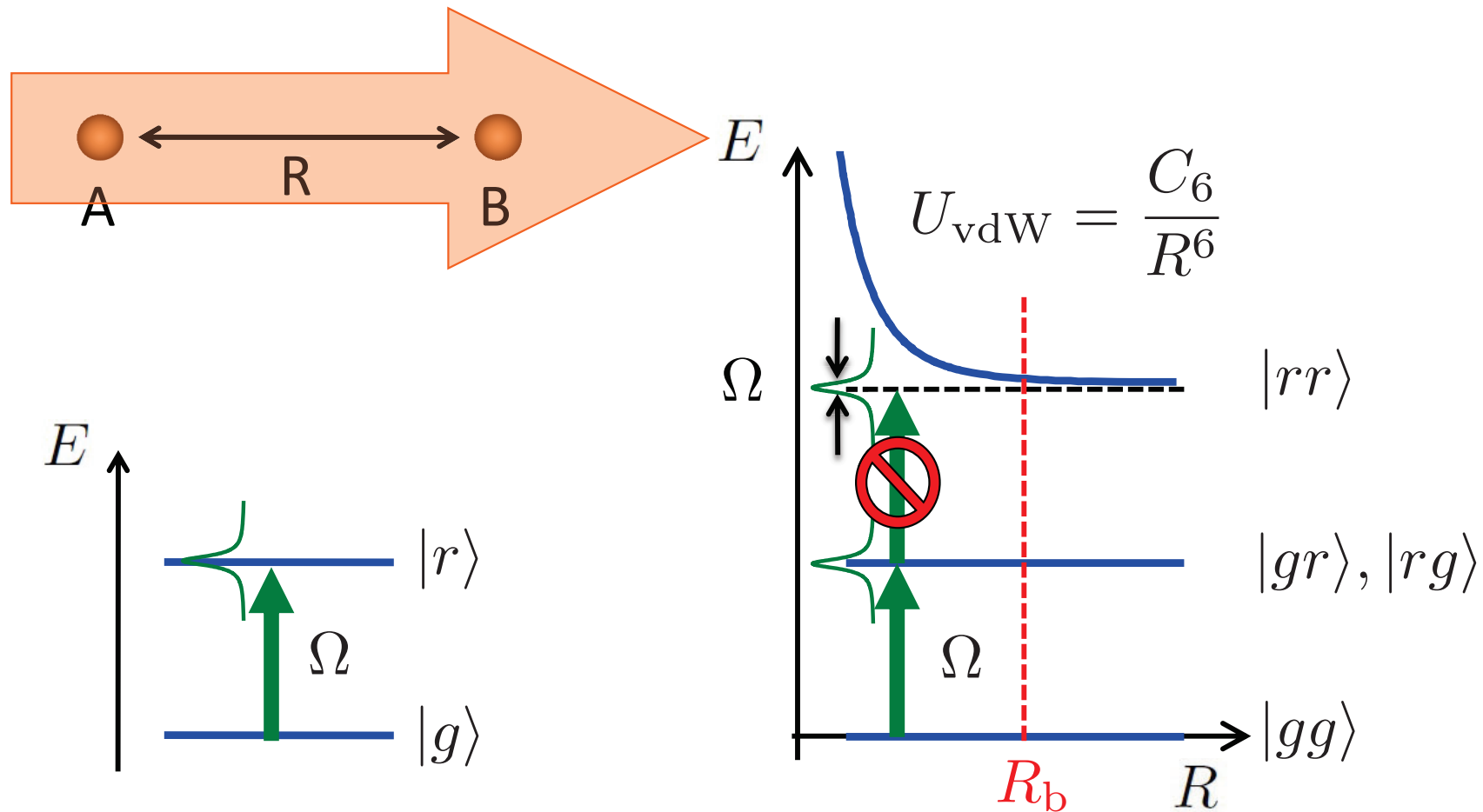
Interactions between Rydberg atoms



van der Waals



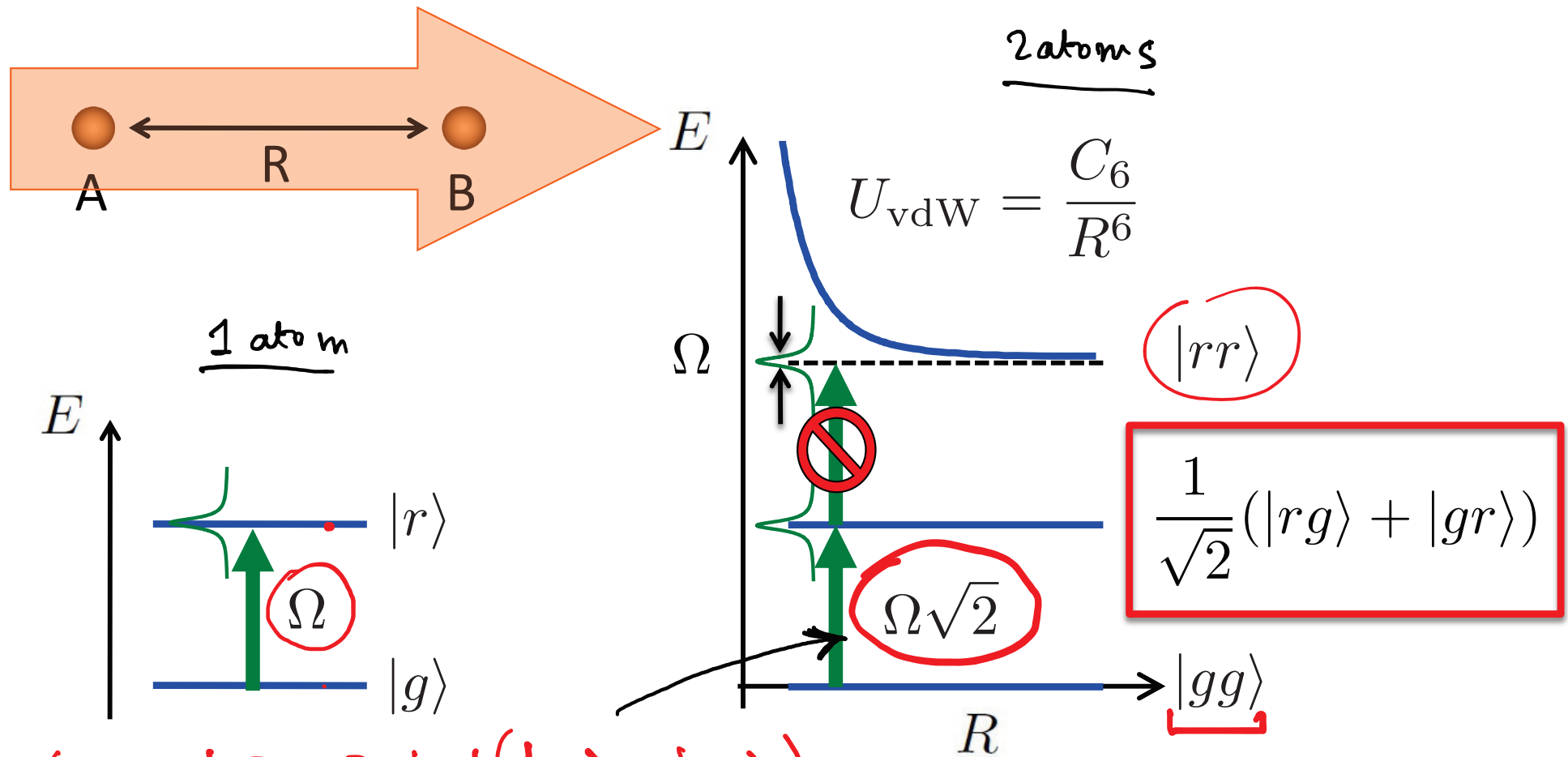
Collective excitation of two interacting Rydberg atoms



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

Dynamics governed by Ω **only**

Collective excitation of two interacting Rydberg atoms



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

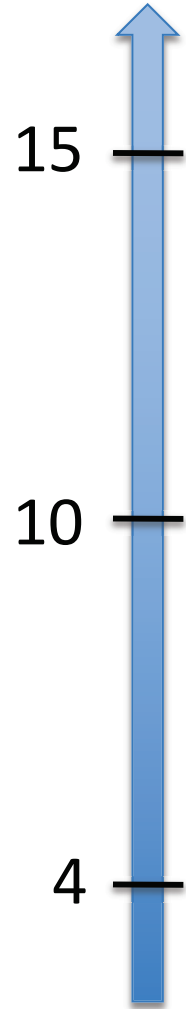
Collective oscillation between $|gg\rangle$ and $\frac{1}{\sqrt{2}}(|rg\rangle + |gr\rangle)$

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

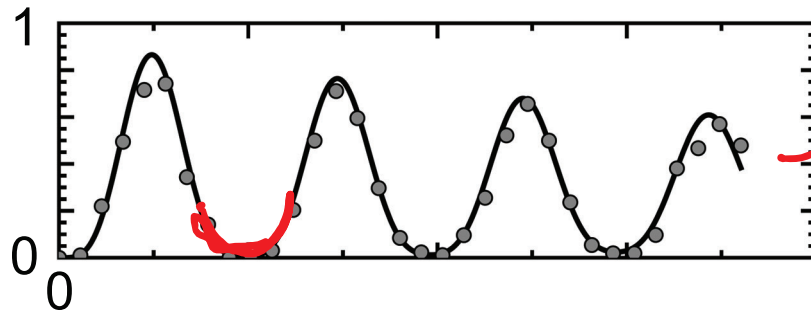
with coupling $\Omega\sqrt{2}$ (N atoms $\Rightarrow \Omega\sqrt{N}$)

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

R (μm)



P_{rr}



t

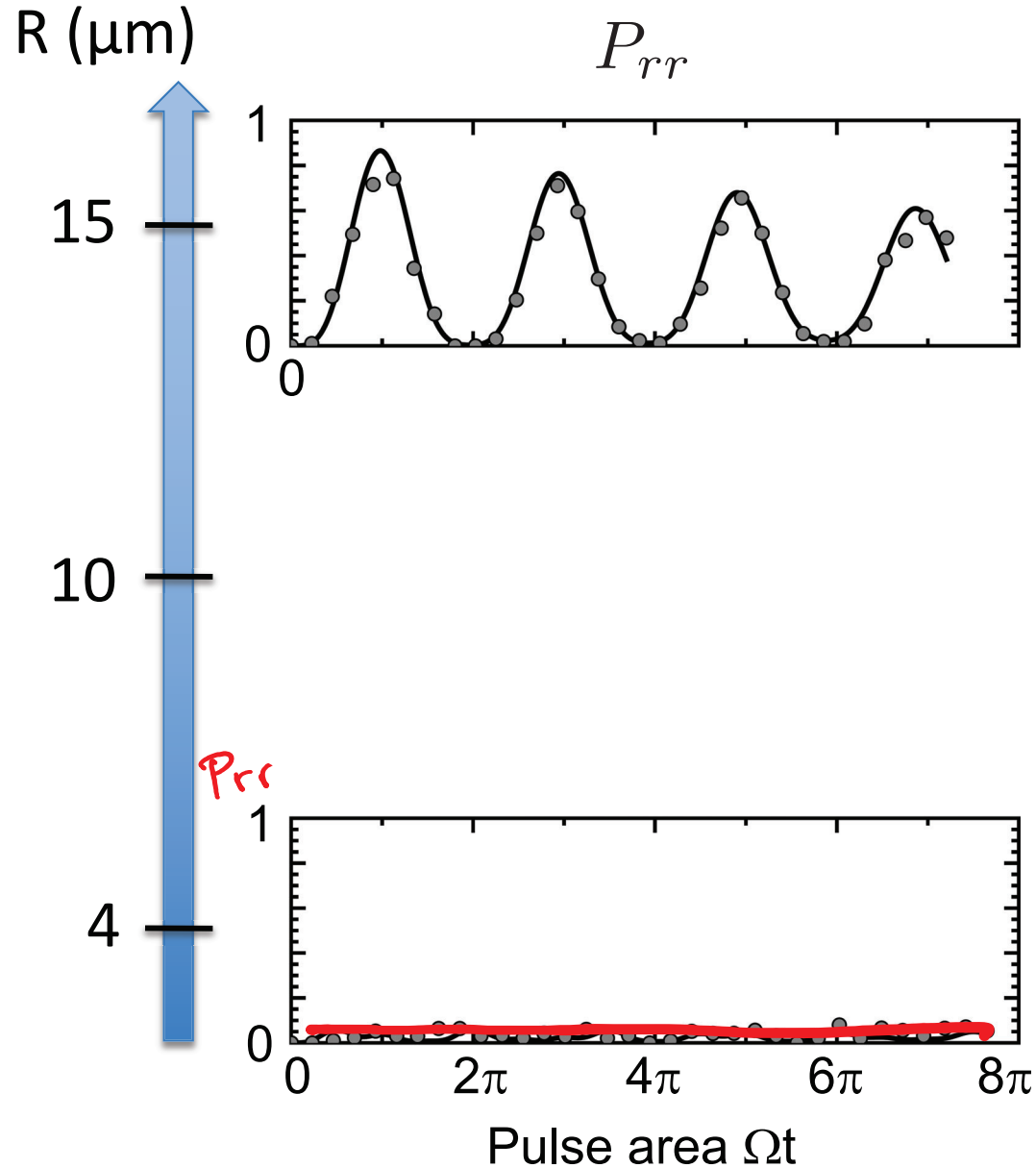
$$\left[\sin^2 \frac{\Omega t}{2} \right]^2 = P_{rr}$$

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

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

Pulse area Ωt

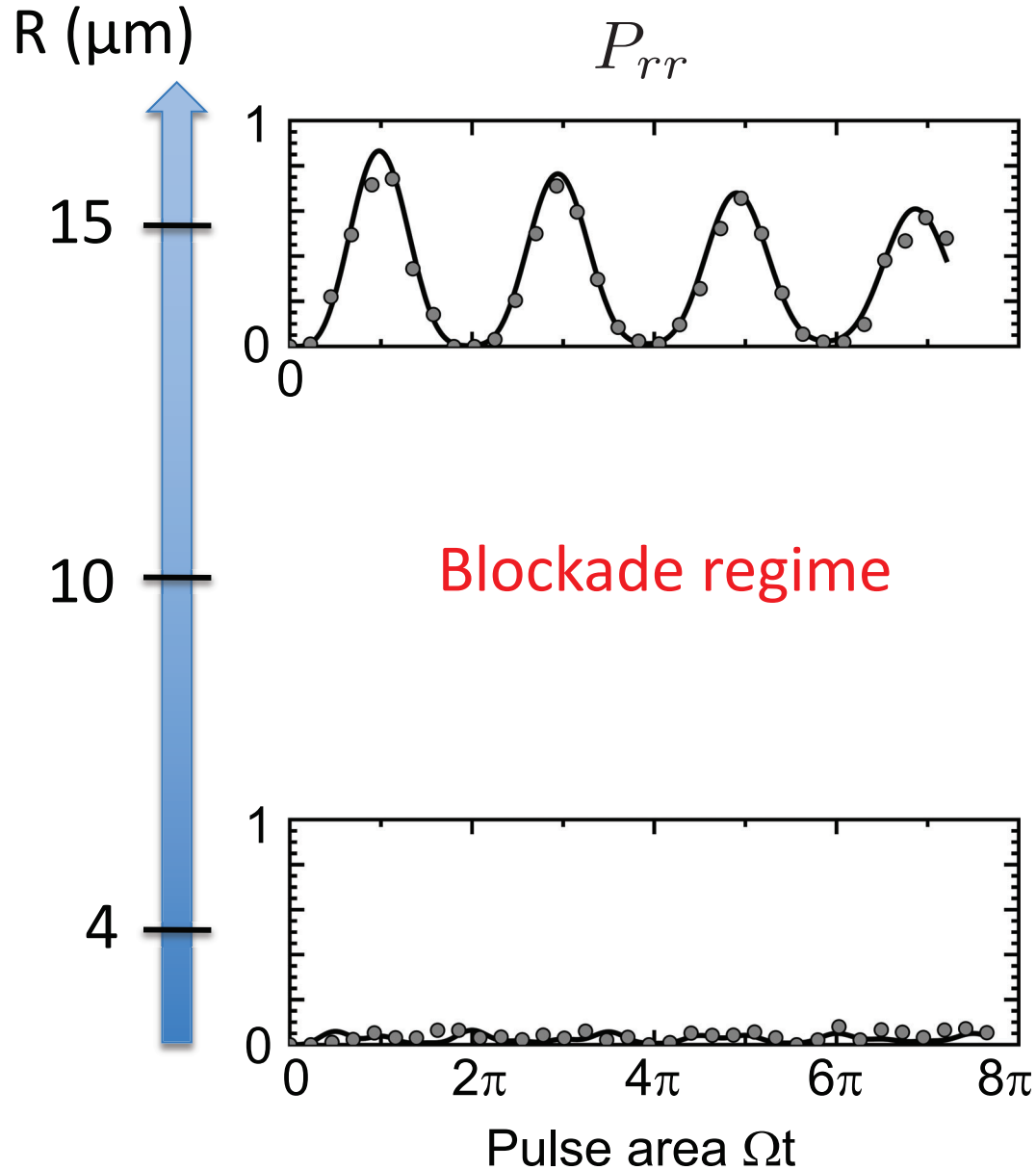
From independent atoms to blockade ($62d_{3/2}$)



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

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

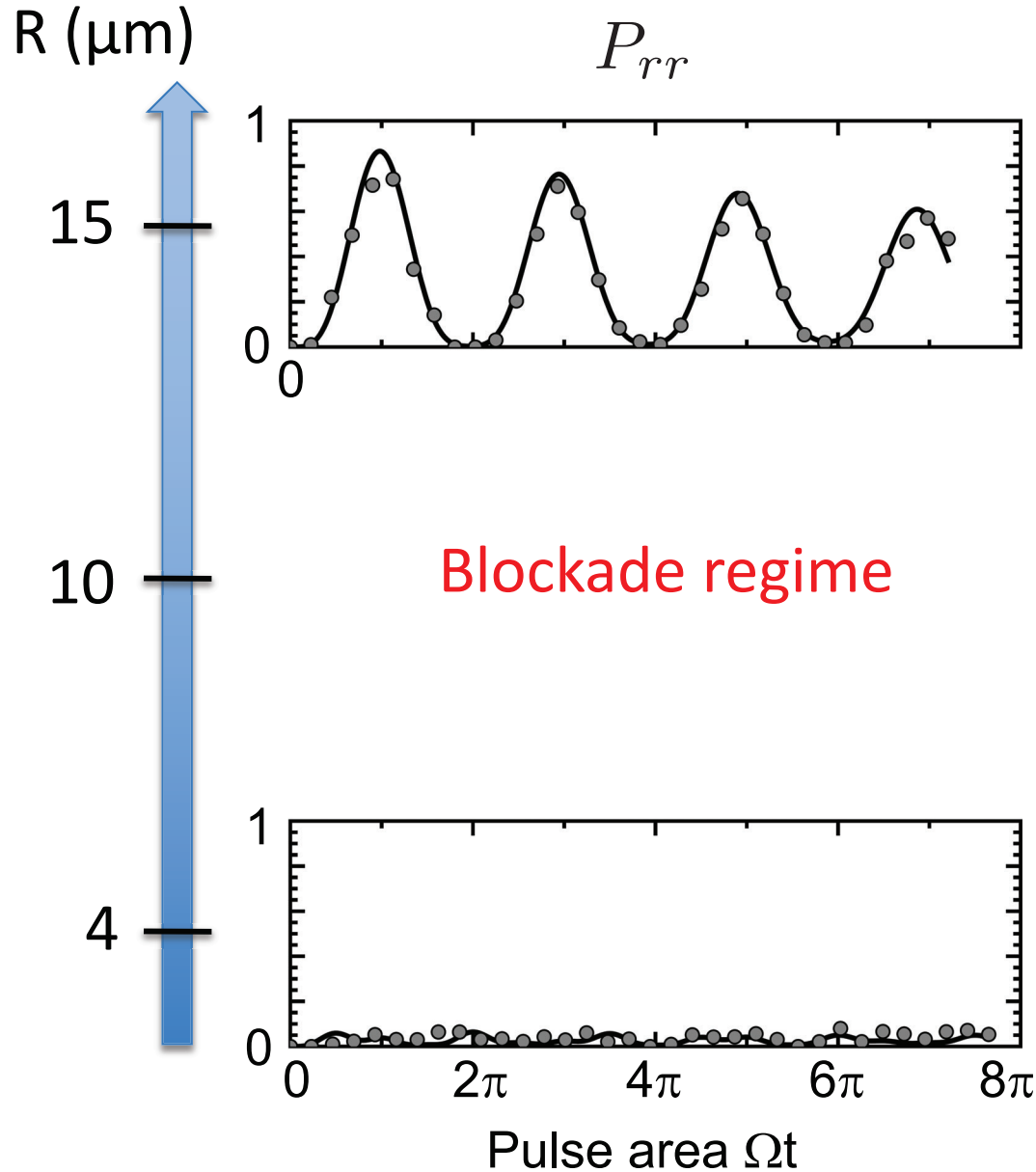
From independent atoms to blockade ($62d_{3/2}$)



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

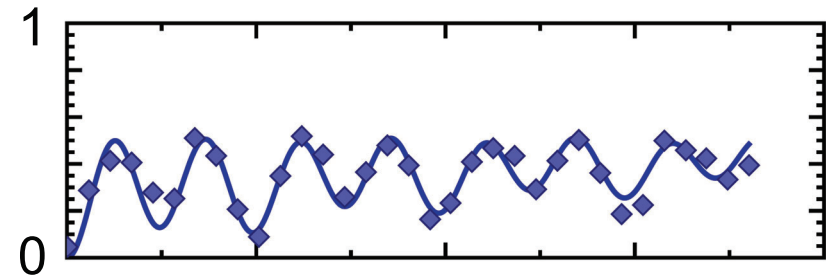
$$\hbar\Omega \ll U_{\text{vdW}}$$

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

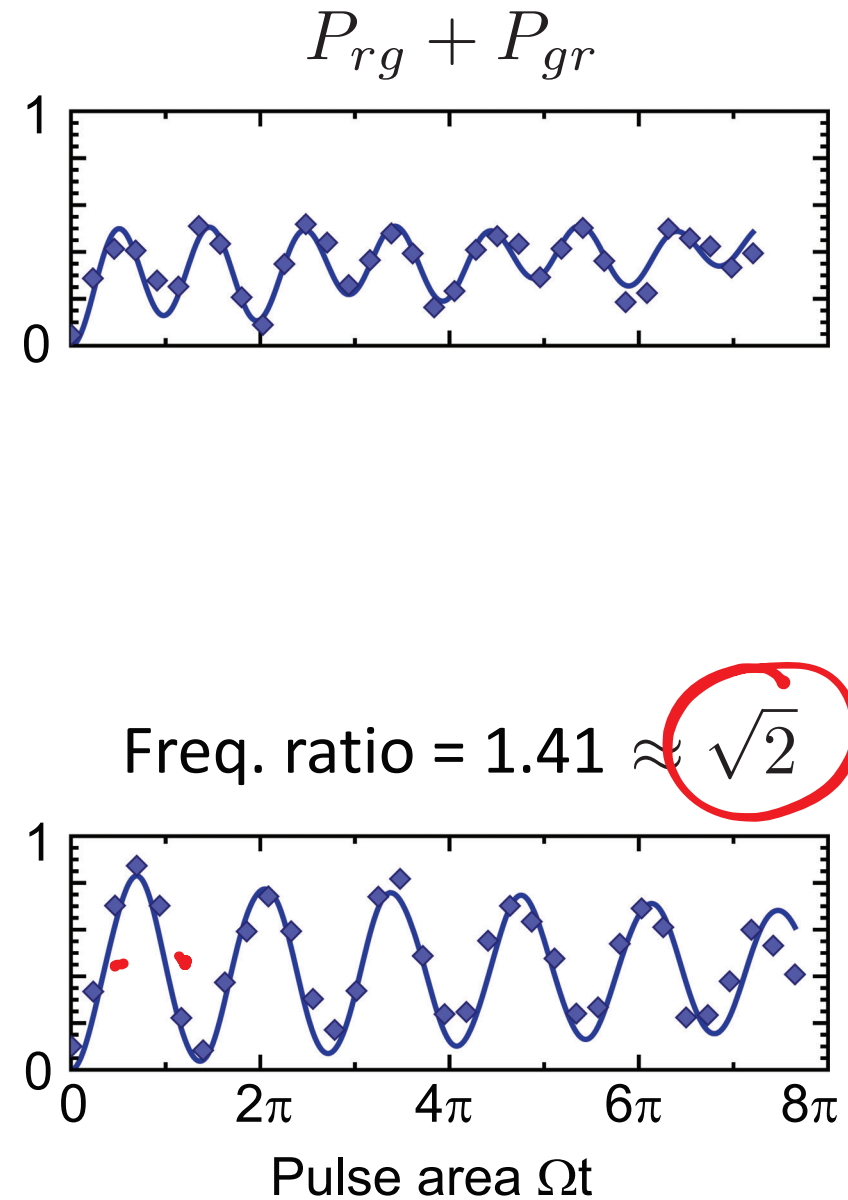
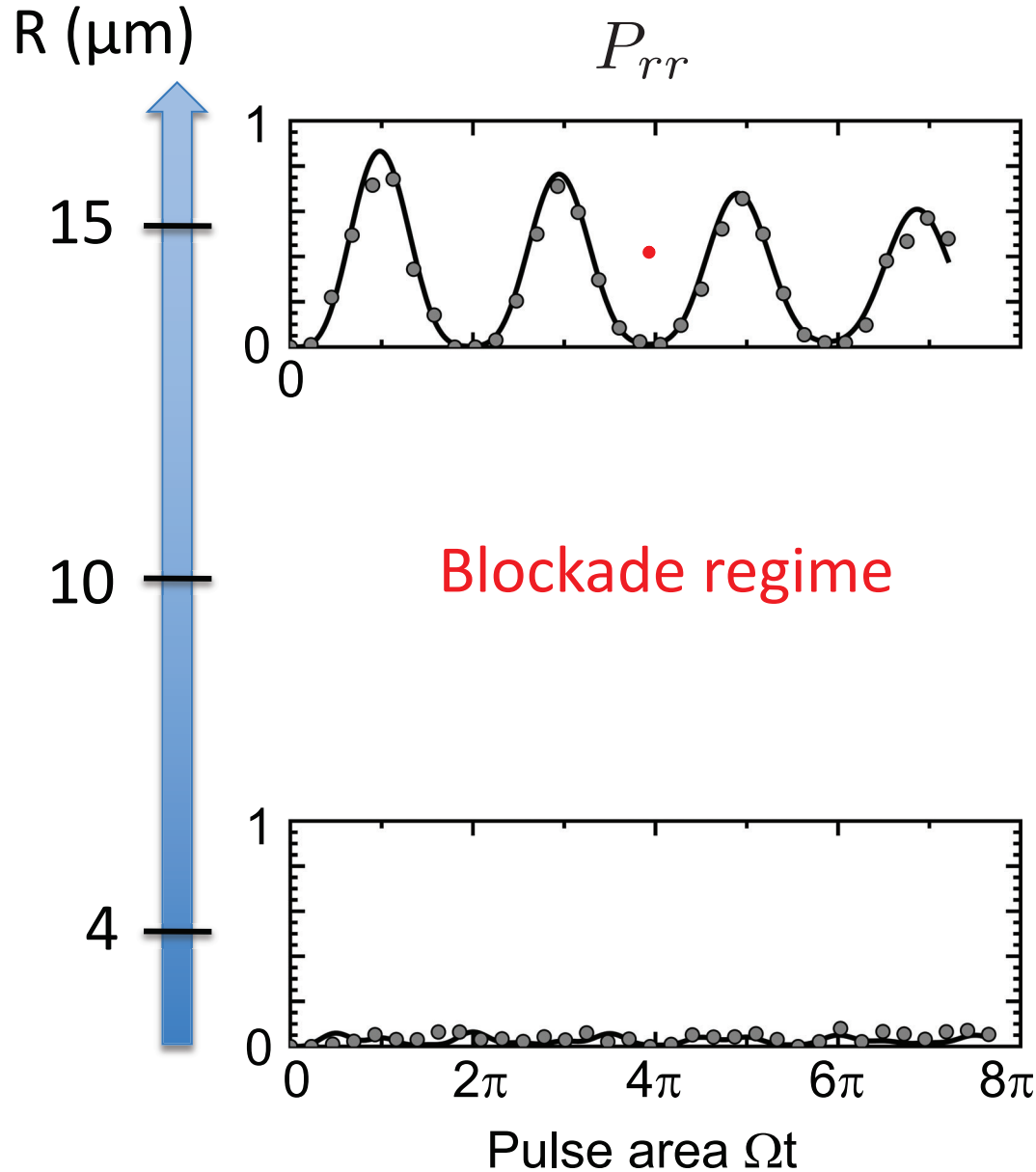


$$= p_r(1-p_c) + 2$$

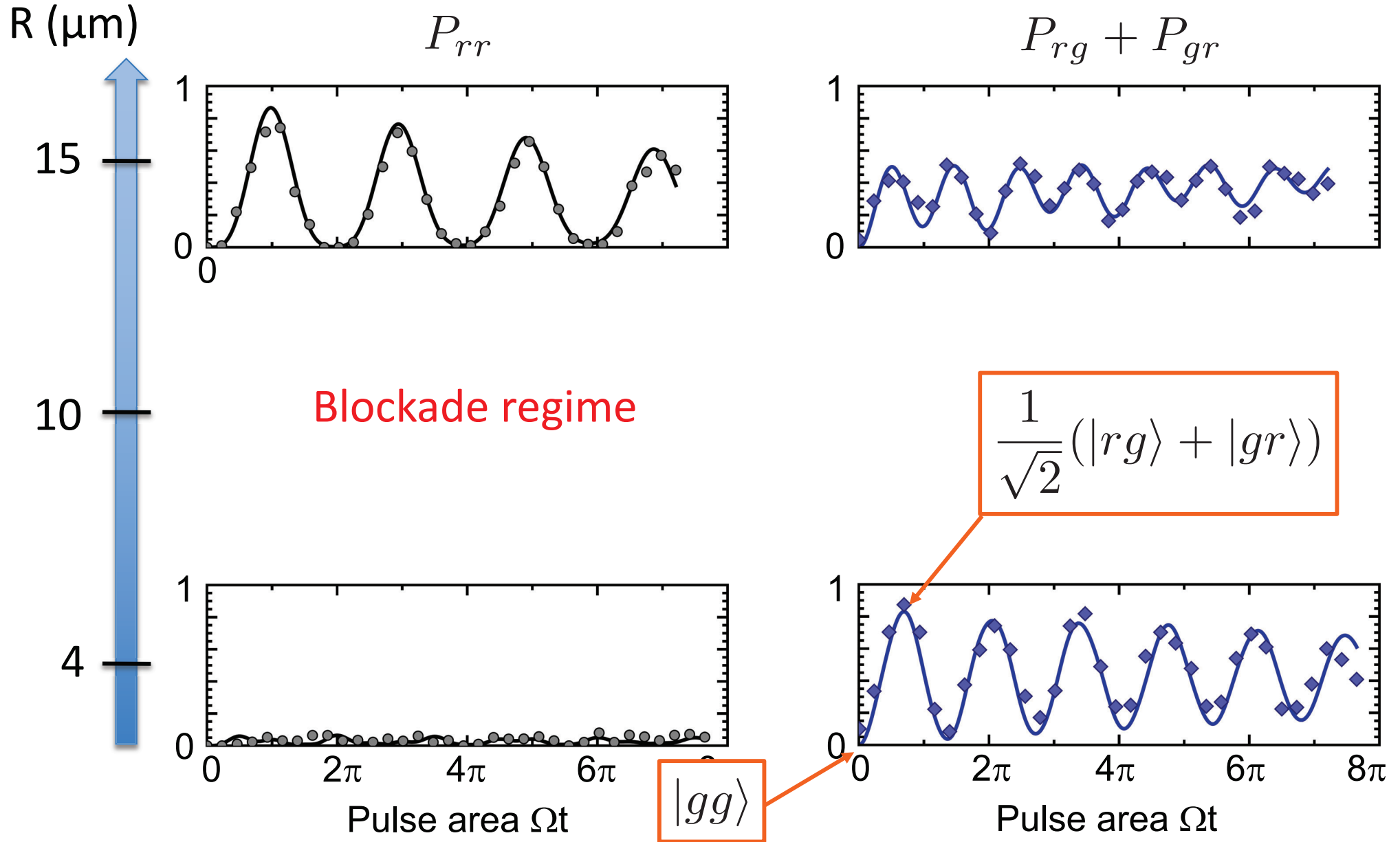
$$P_{rg} + P_{gr}$$



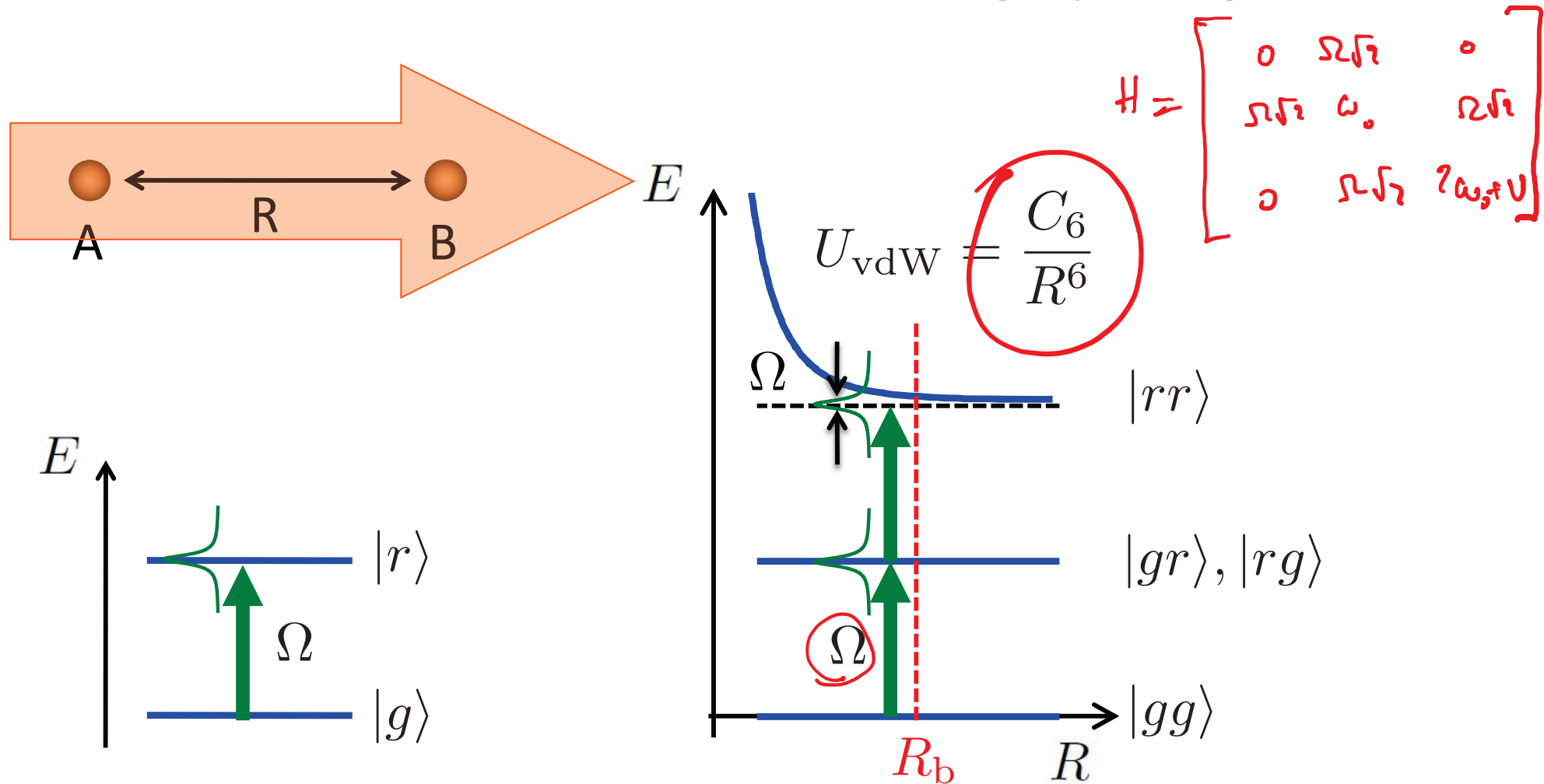
From independent atoms to blockade ($62d_{3/2}$)



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



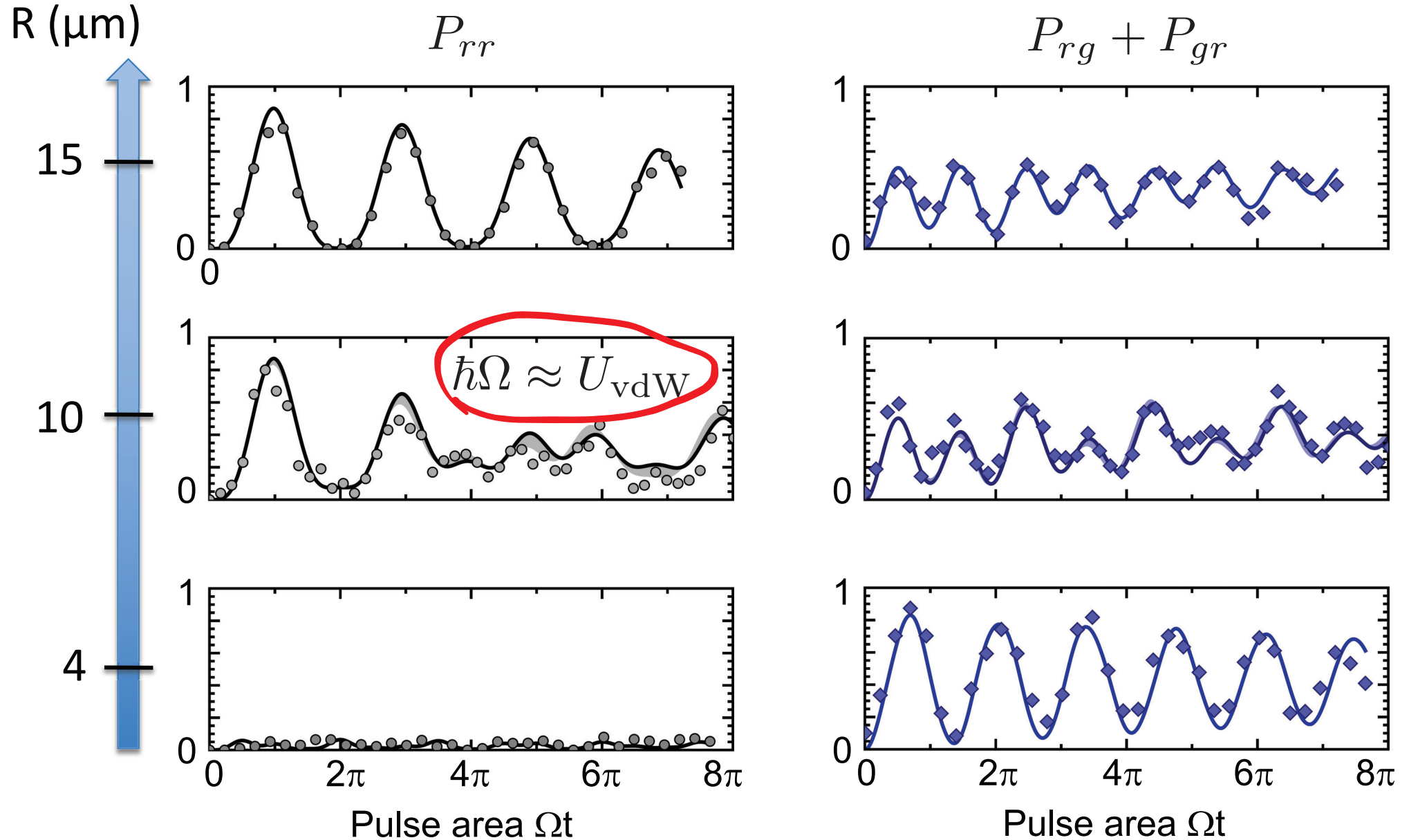
Collective excitation of two interacting Rydberg atoms



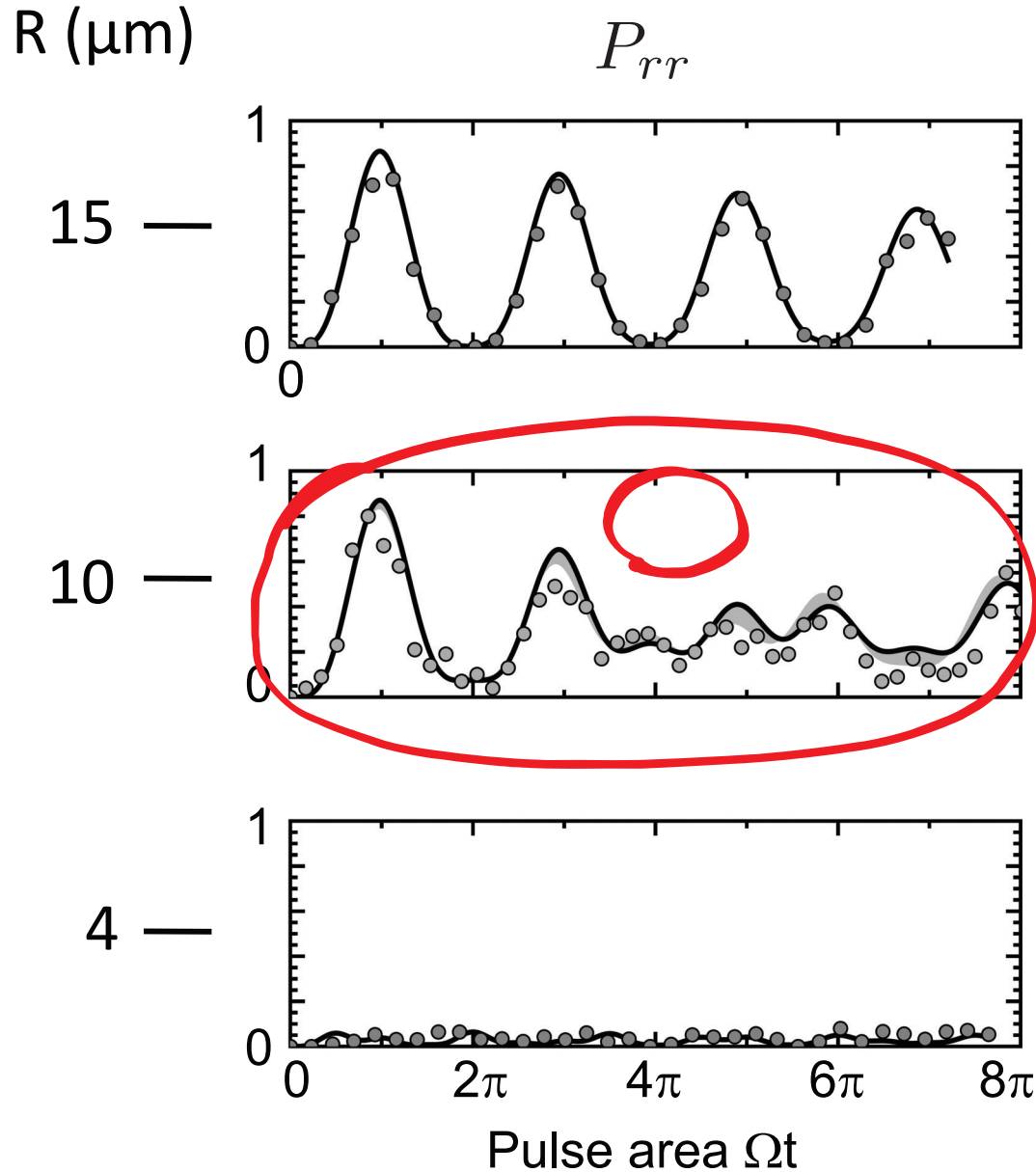
If $\hbar\Omega \approx U_{\text{vdW}}$: dynamics governed by Ω **and** U_{vdW}

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

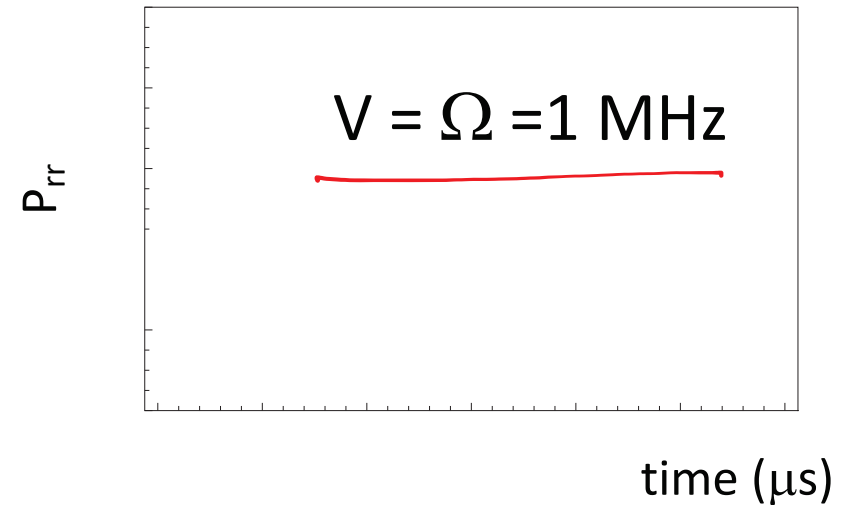
From independent atoms to blockade ($62d_{3/2}$)



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

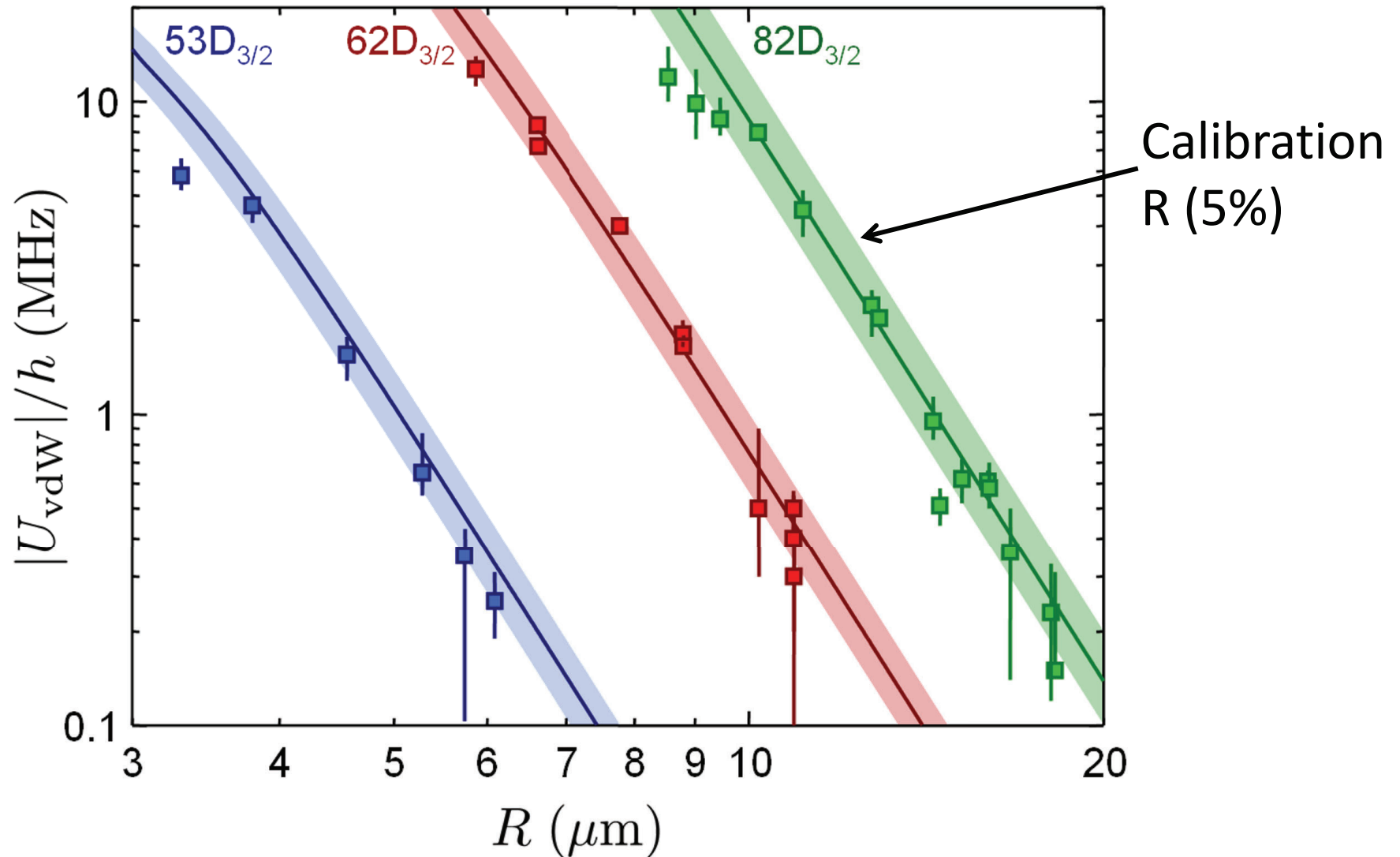


Theory (Schrödinger eq.)



Fit $\Rightarrow$ 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