

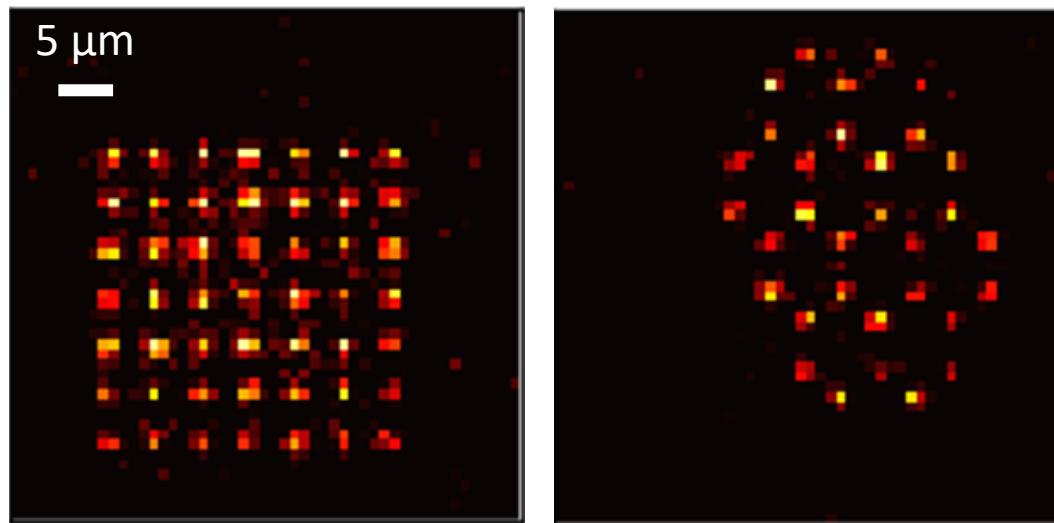
Dipole-dipole interactions between atoms for many-body physics and quantum information

Lecture 1: Dipole-dipole interaction between atoms

Lecture 2: Basics of Rydberg physics. Arrays of cold atoms. Rydberg blockade & QIP

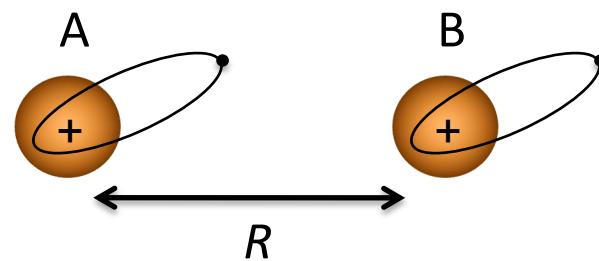
Lecture 3: Many-body physics with Rydberg atoms

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

Rydberg atoms: a few historical landmarks

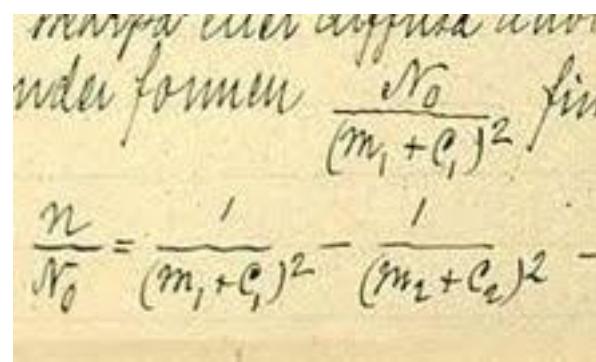
1814 Joseph von Fraunhofer



observation of dark lines in spectrum of the sun

1888 “Rydberg formula”





maniga ena annan unni
nder formen $\frac{N_0}{(m_i + c_i)^2}$ fin

$$\frac{n}{N_0} = \frac{1}{(m_1 + c_1)^2} - \frac{1}{(m_2 + c_2)^2} - \dots$$

Johannes Rydberg
1854-1919

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

Idea of an infinite series
⇒ **highly excited** states

Periodic Table of the Elements

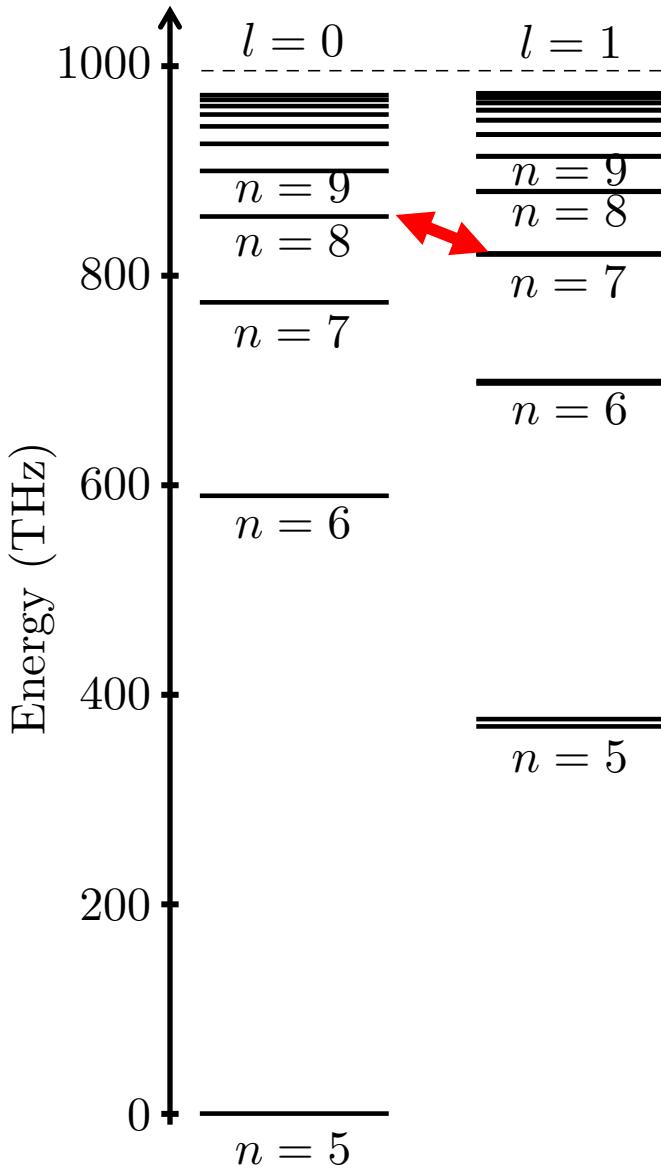
1 H Hydrogen 1.008	2 Be Boron 9.012	3 Li Lithium 6.941	4 Mg Magnesium 24.306	5	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180								
11 Na Sodium 22.990	12	13 B Boron 10.811	14 C Carbon 12.011	15 N Nitrogen 14.007	16 O Oxygen 15.999	17 F Fluorine 18.998	18 Ne Neon 20.180										
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								
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 102.906	46 Pd Palladium 106.42								
55 Cs Cesium 132.905	56 Ba Barium 137.326	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								
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [263]	107 Bh Bohrium [264]	108 Hs Hassium [265]	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 [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
			57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.905	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]	101 Md Mendelevium [258.1]	102 No Nobelium [259.101]	103 Lr Lawrencium [262]

Alkali: 1 external electron

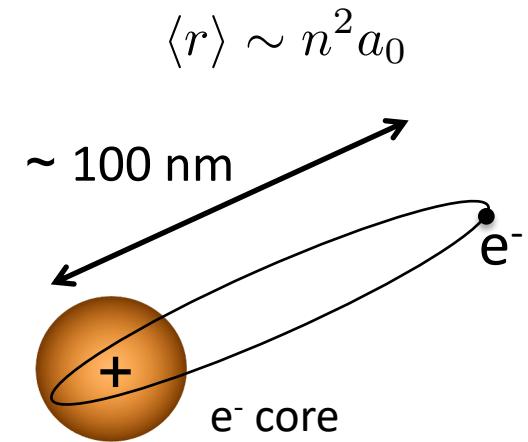
$$1s^2 2s^2 \dots (n - 1)p^6 ns$$

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)



$|n, l\rangle$
Rydberg states
 $n \gg 1$



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

Large transition dipole:

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

⇒ Exaggerated properties:

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

Quantum defects for alkali atoms

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

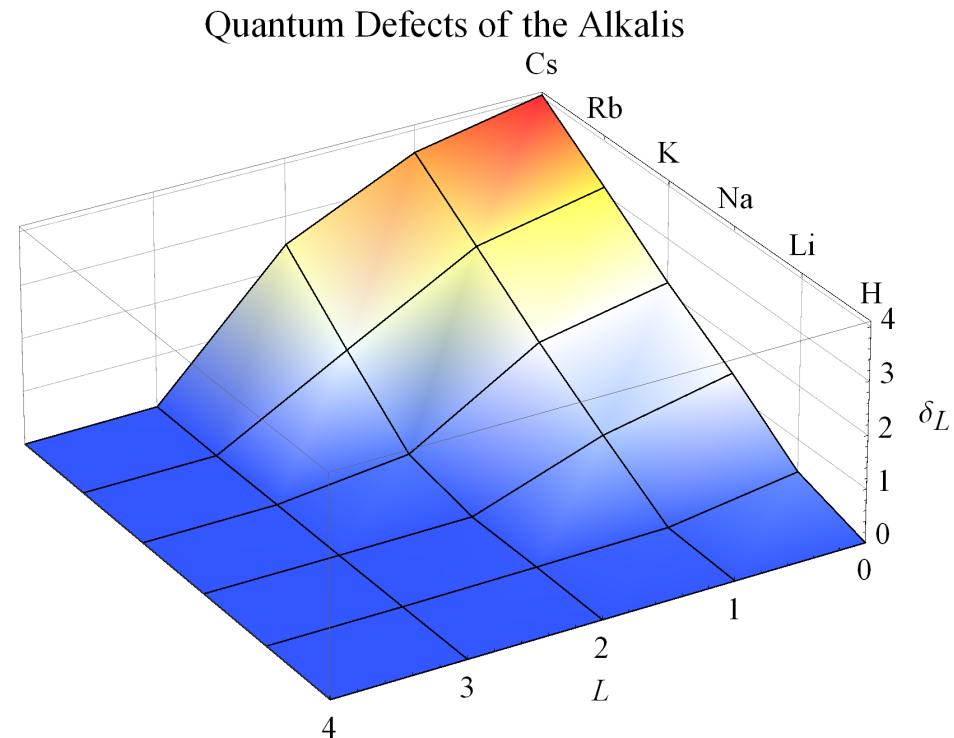
$$R_y^\infty = 10\ 973\ 371.568\ 539\ \text{m}^{-1}$$

Quantum defects (**Experimental**)

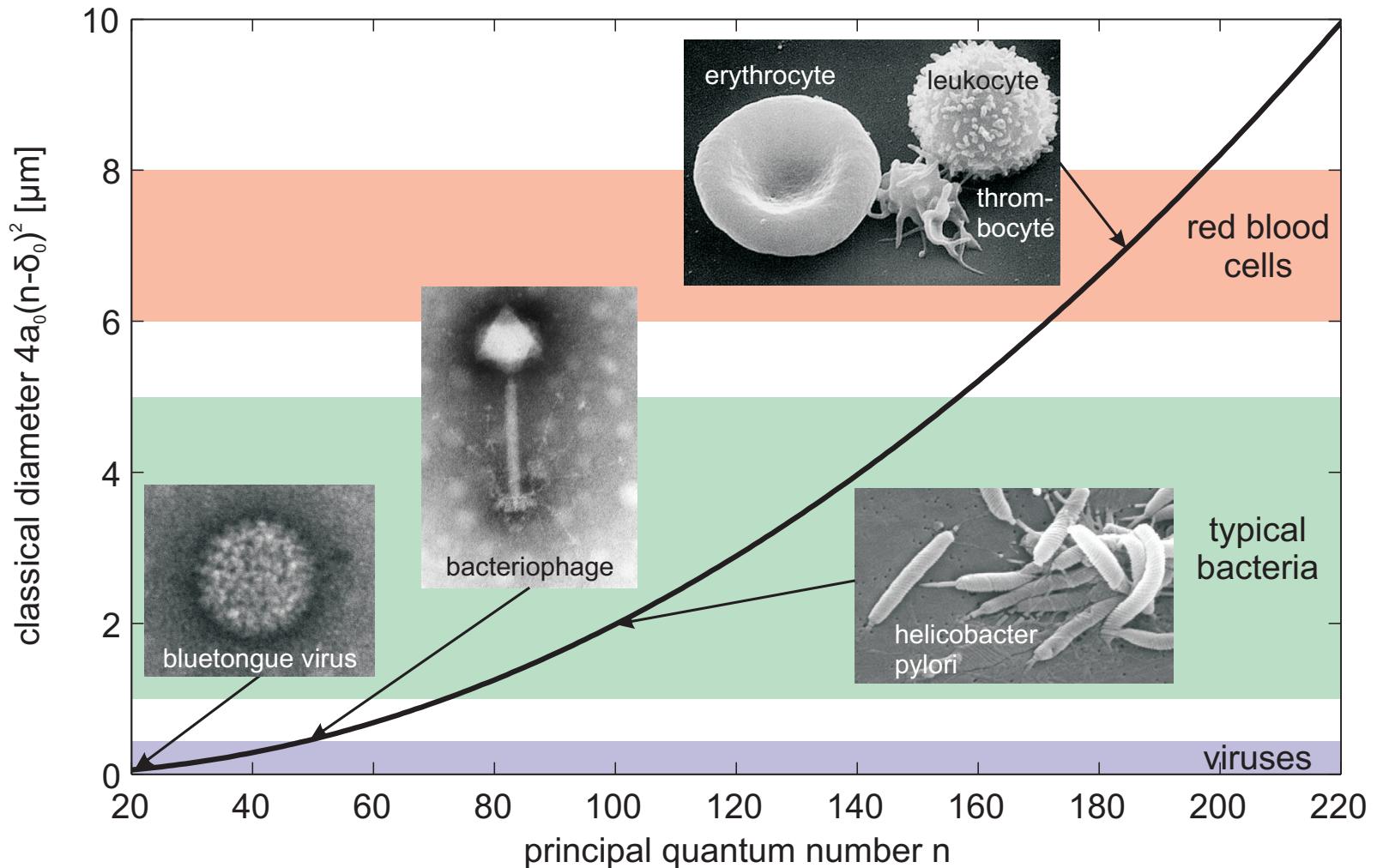
For Rb:

$n \geq 30$

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...



Rydberg's have exaggerated properties

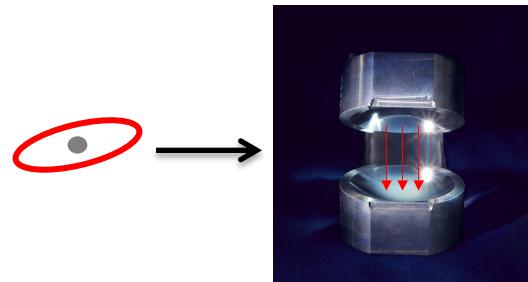
Table 1. Properties of Rydberg states.

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 μ s
Polarizability α	n^7	-1.8 GHz/(V/cm) ²
van der Waals coefficient C_6	n^{11}	4 THz \cdot μ m ⁶

Back to history...

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!

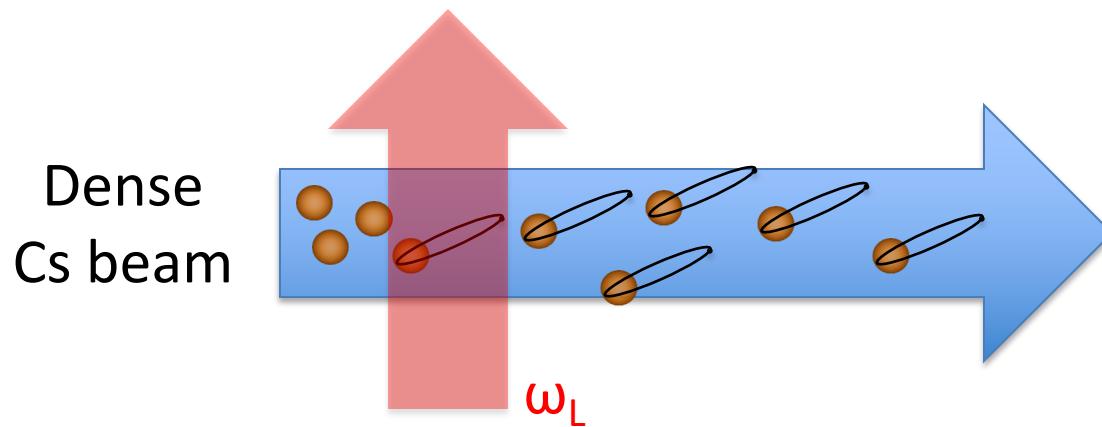
Haroche, Walther...



Back to history...: Rydberg interactions

The “dense Rydberg gas”

J-M Raimond, J. Phys. B **14**, L655 (1981)

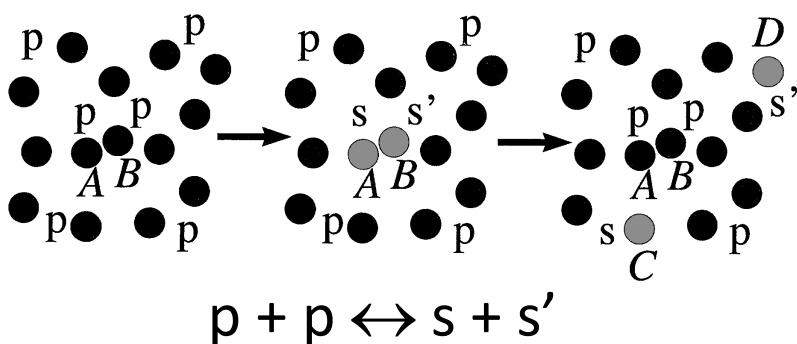


Broadening of excitation

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

$k_B T \ll \text{Interaction energy} \Rightarrow T < 1 \text{ mK} \Rightarrow \text{cold atoms}$

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

$k_B T \ll \text{Interaction energy}$
 $\Rightarrow T < 1 \text{ mK}$

Interactions between Rydberg atoms

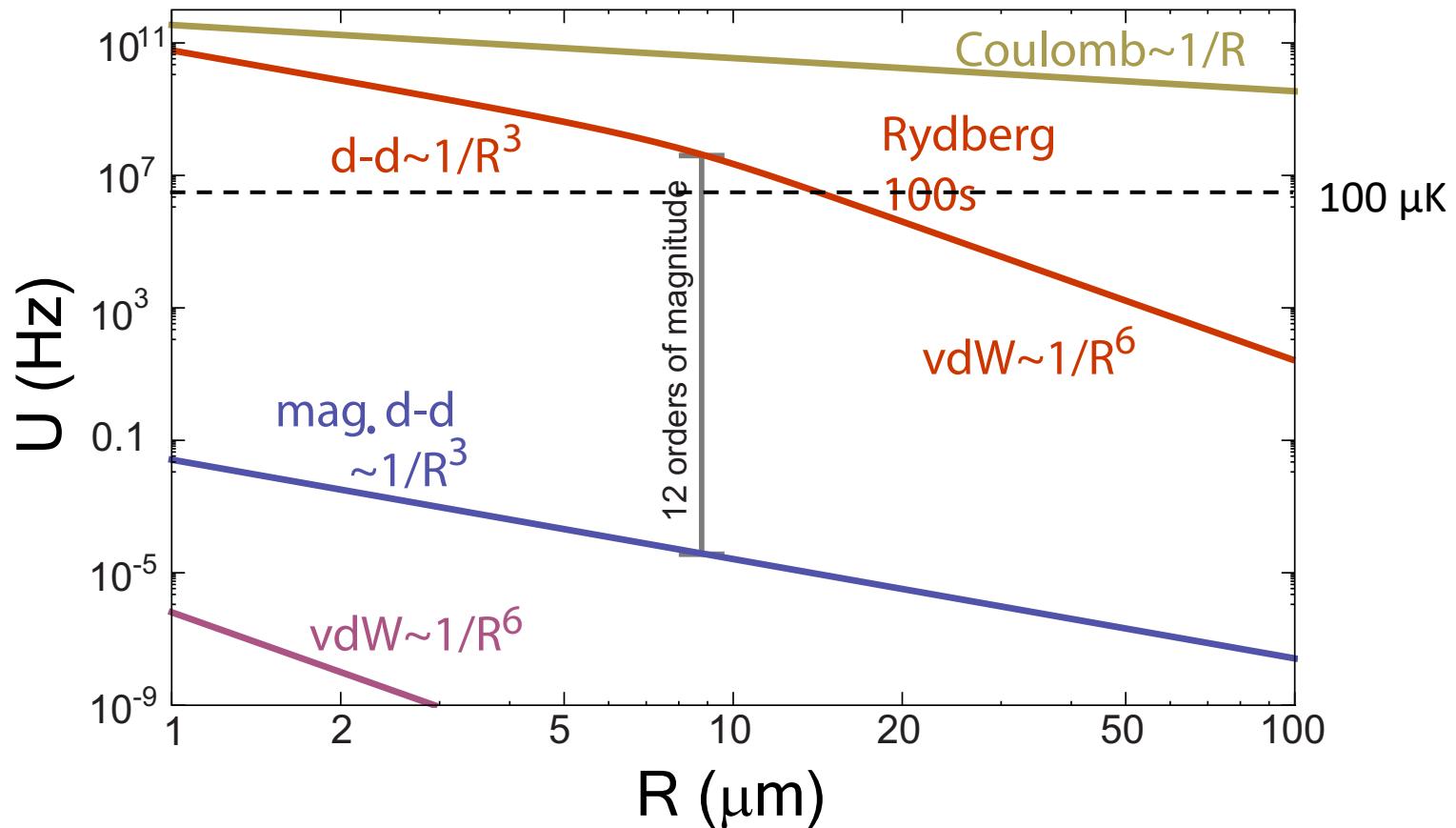
REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010

Quantum information with Rydberg atoms

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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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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

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

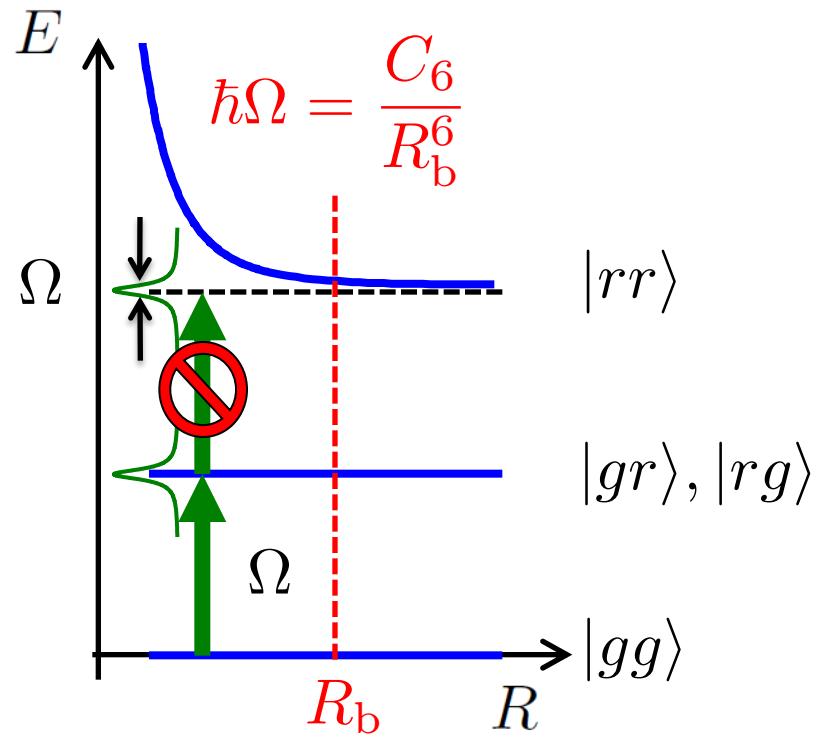
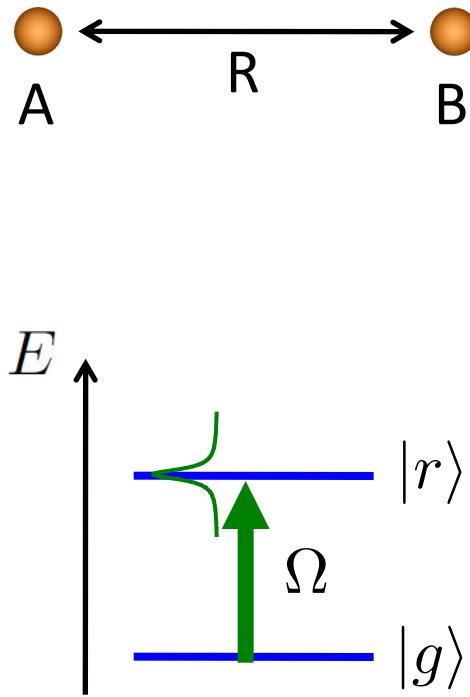
³*Physics Department, University of Connecticut, Storrs, Connecticut 06269*

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

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

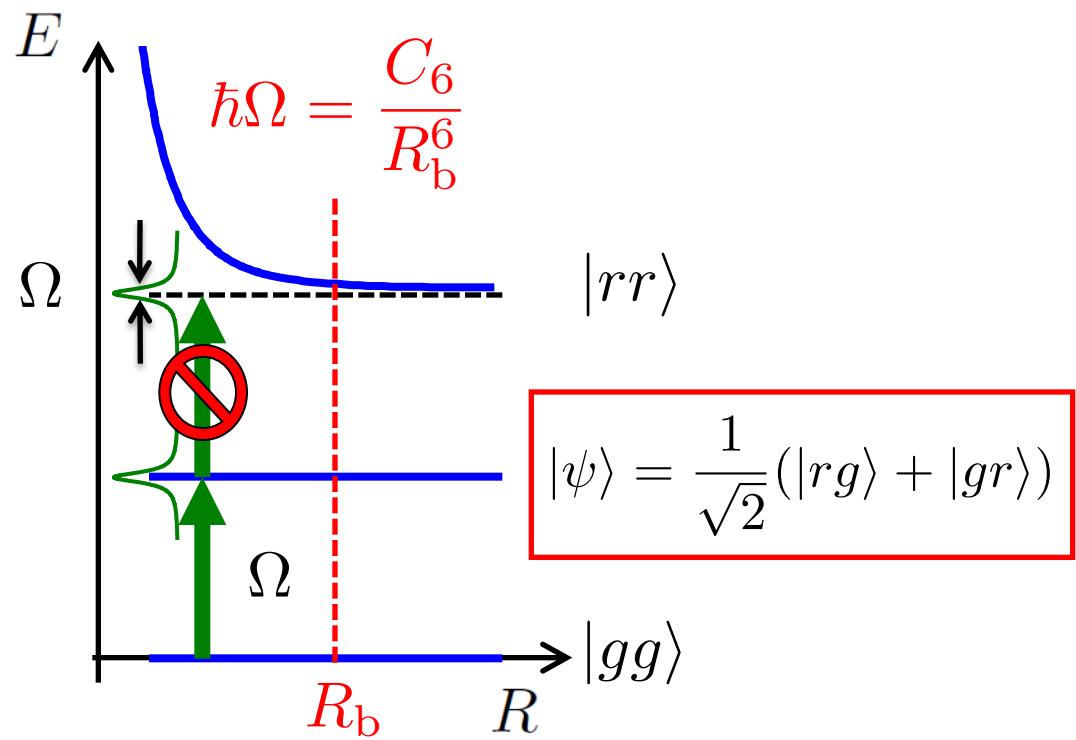
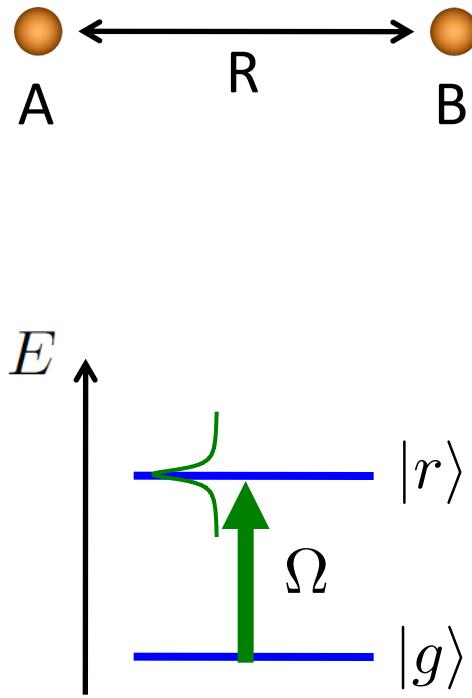
(Received 7 November 2000; published 26 June 2001)

A new era: the Rydberg Blockade idea



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

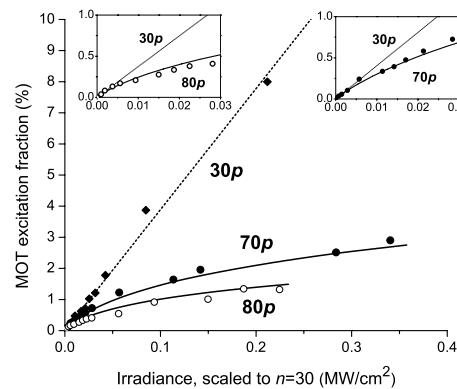
A new era: the Rydberg Blockade idea



Blockade \Rightarrow entanglement and gates!!

The first blockade experiments

Atomic ensembles



Gould, PRL 2004

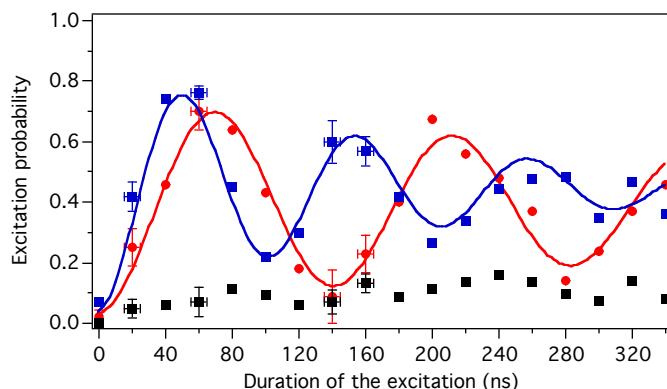
Weidemuller, PRL 2004

Martin, PRL 2004

Pillet, PRL 2006

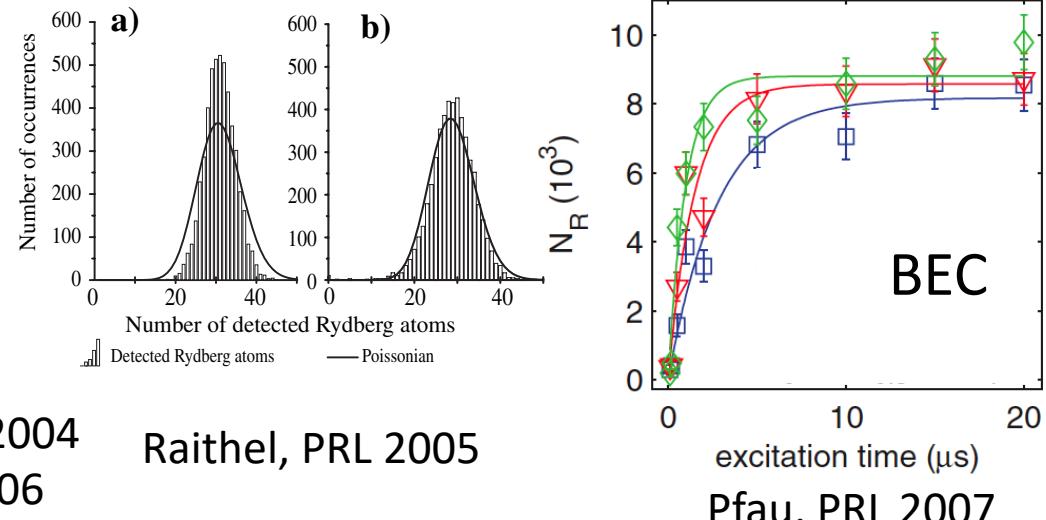
Individual atoms

IO Palaiseau



Blockade + collective excitation $\sqrt{2}$

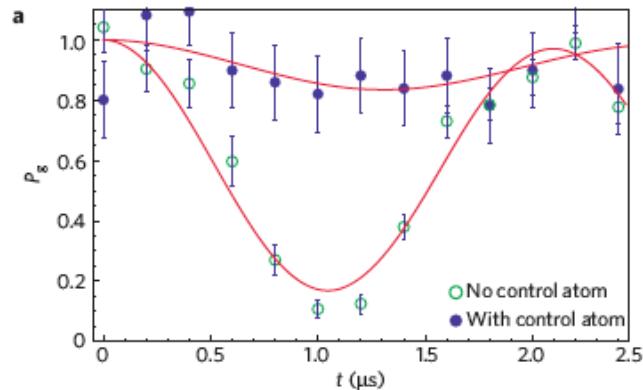
Gaétan *et al.*, Nat. Phys. 5, 115 (2009)



Raithel, PRL 2005

Pfau, PRL 2007

U. Wisconsin

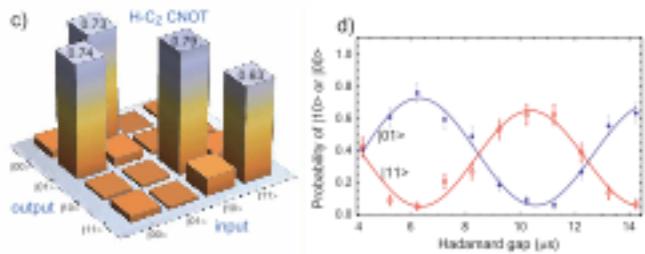


Blockade

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

And now (2019)... a few examples

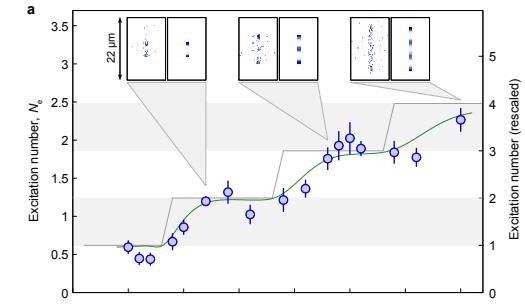
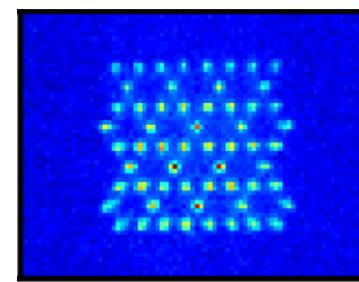
QIP: entanglement and gates



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

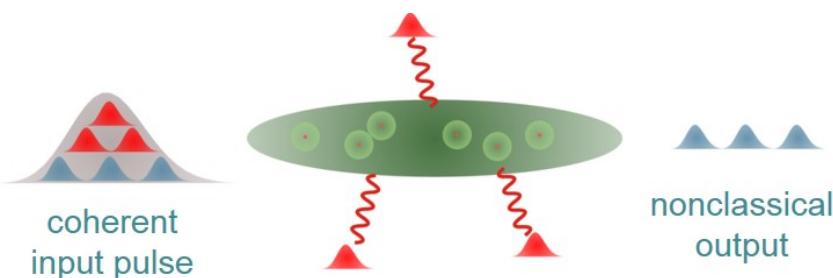
Saffman, Biedermann...

Many-body physics Quantum simulation



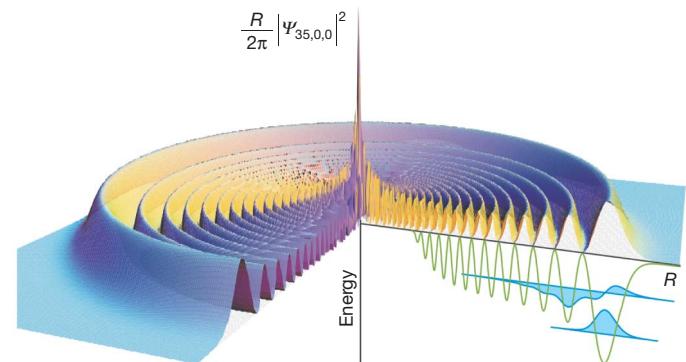
Browaeys, Lukin, Bloch, Pillet, Weidemuller, Morsch...

Non-linear classical & quantum optics



Adams, Hofferbert, Firstenberg, Lukin, Vuletic...

Exotic long-range molecules



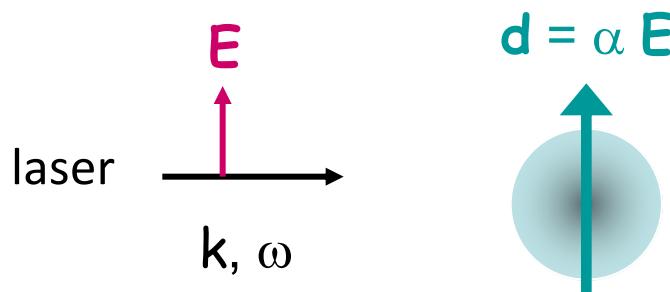
Pfau-Löw, Ott, Shaeffer ...

Outline

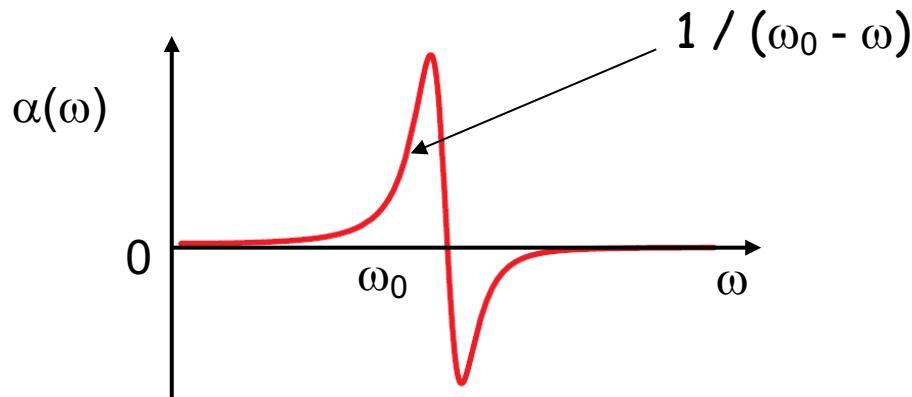
1. “Rydbergology”: scalings, interactions...
2. Experimental considerations: arrays of individual atoms
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Optical dipole trap

Classical



Harmonic oscillator model



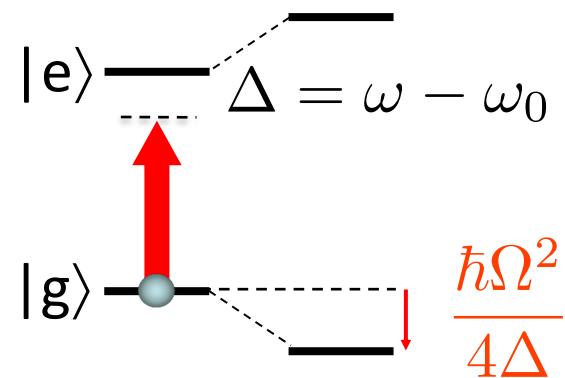
Interaction atom - light

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

Quantum

$$\hbar\Omega = d \cdot E$$
$$d = \langle e | \hat{D} | g \rangle$$

$$\omega_0 > \omega$$



\Rightarrow Conservative POTENTIAL

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

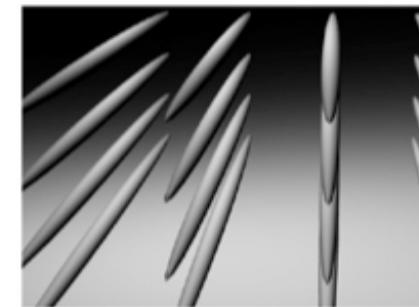
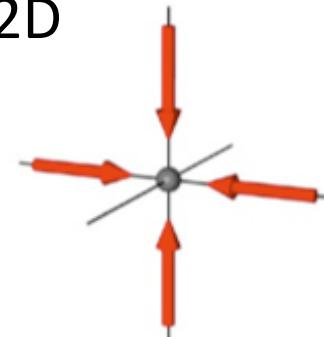
Optical lattices

1D

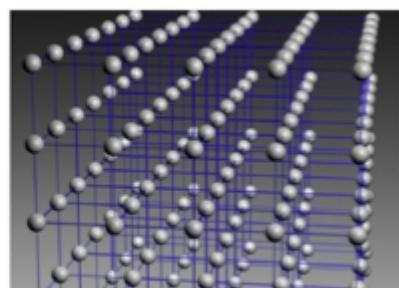
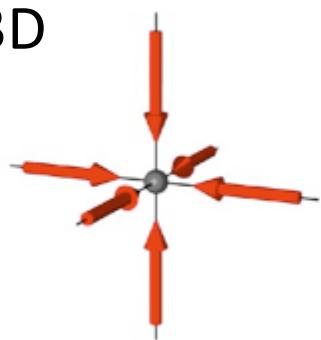


$$I(x) = 2E_0^2(1 + \cos 2kx)$$

2D



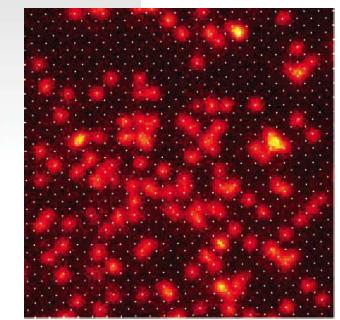
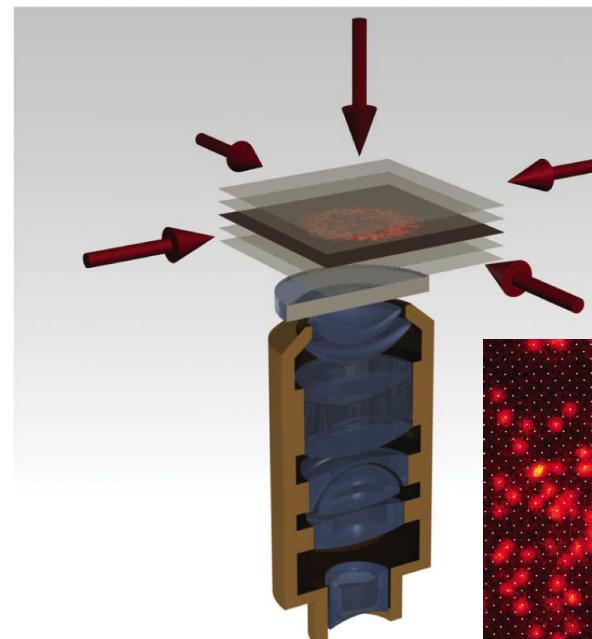
3D



(M. Greiner thesis)

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

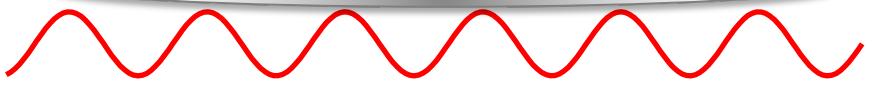
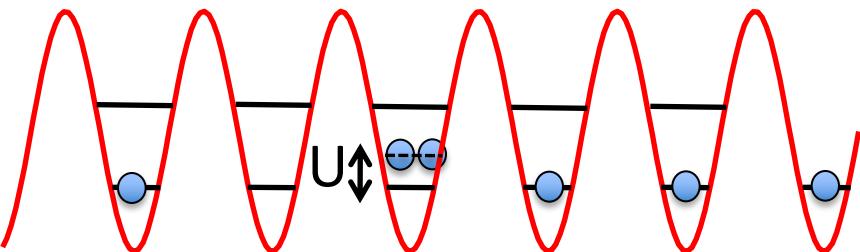
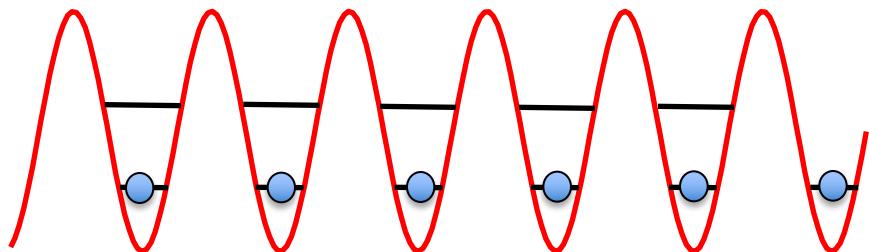
Single site resolution (< 1 μm)



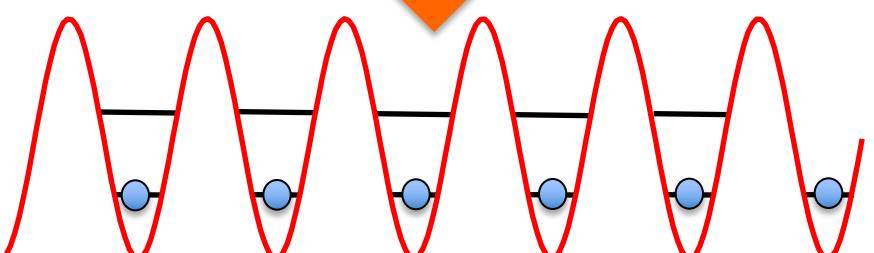
Bakr *et al.*, Nature **462**, 74 (2009)
Sherson *et al.*, Nature **467**, 68 (2010)

Preparation of individual atoms in optical lattices

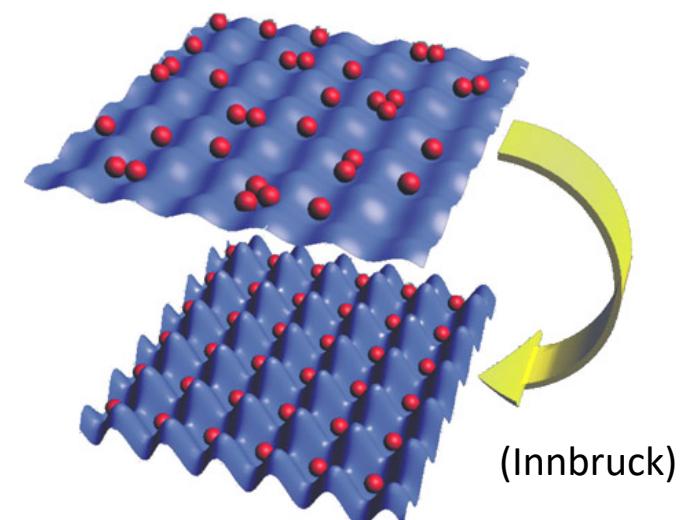
Superfluid - Mott insulator transition Greiner *et al.*, Nature **415**, 39 (2002)



Adiabatic increase:
connects ground-states



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

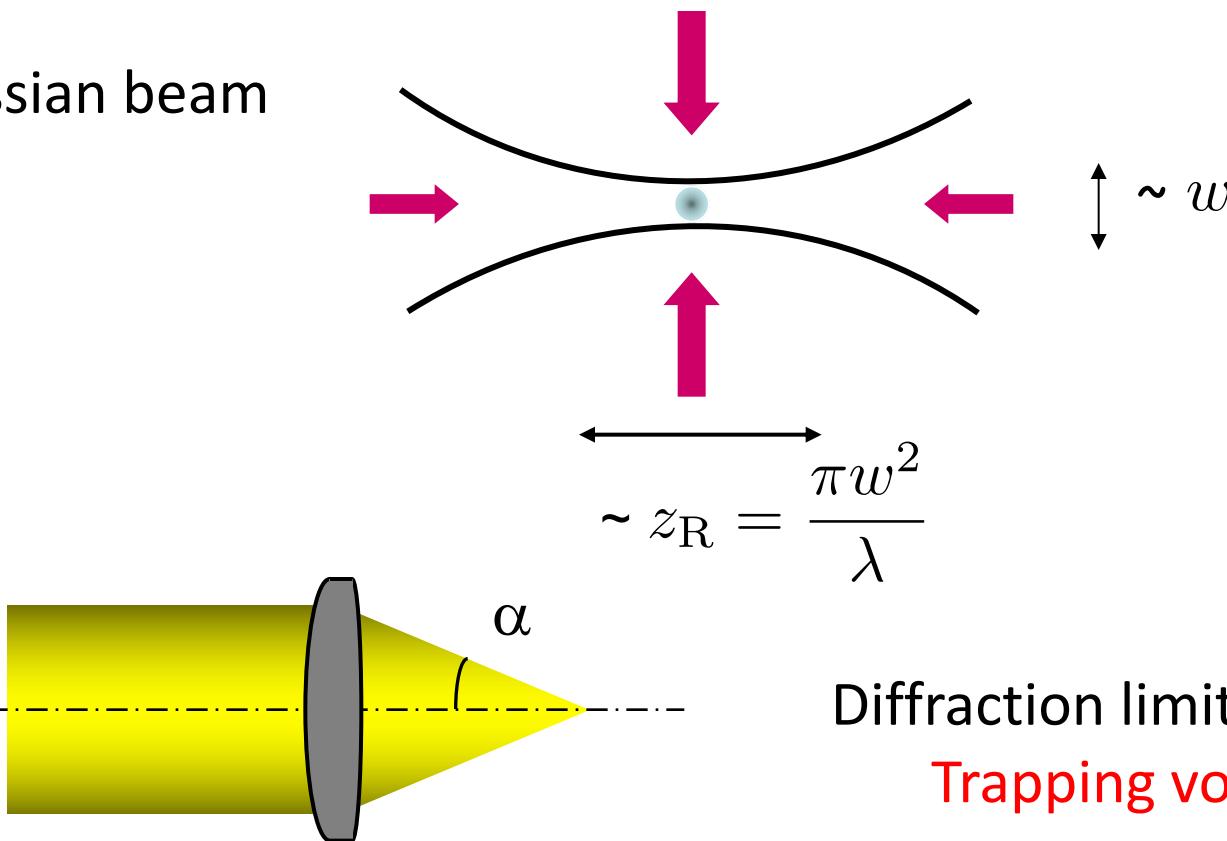


Works in 2D and 3D

Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

Gaussian beam



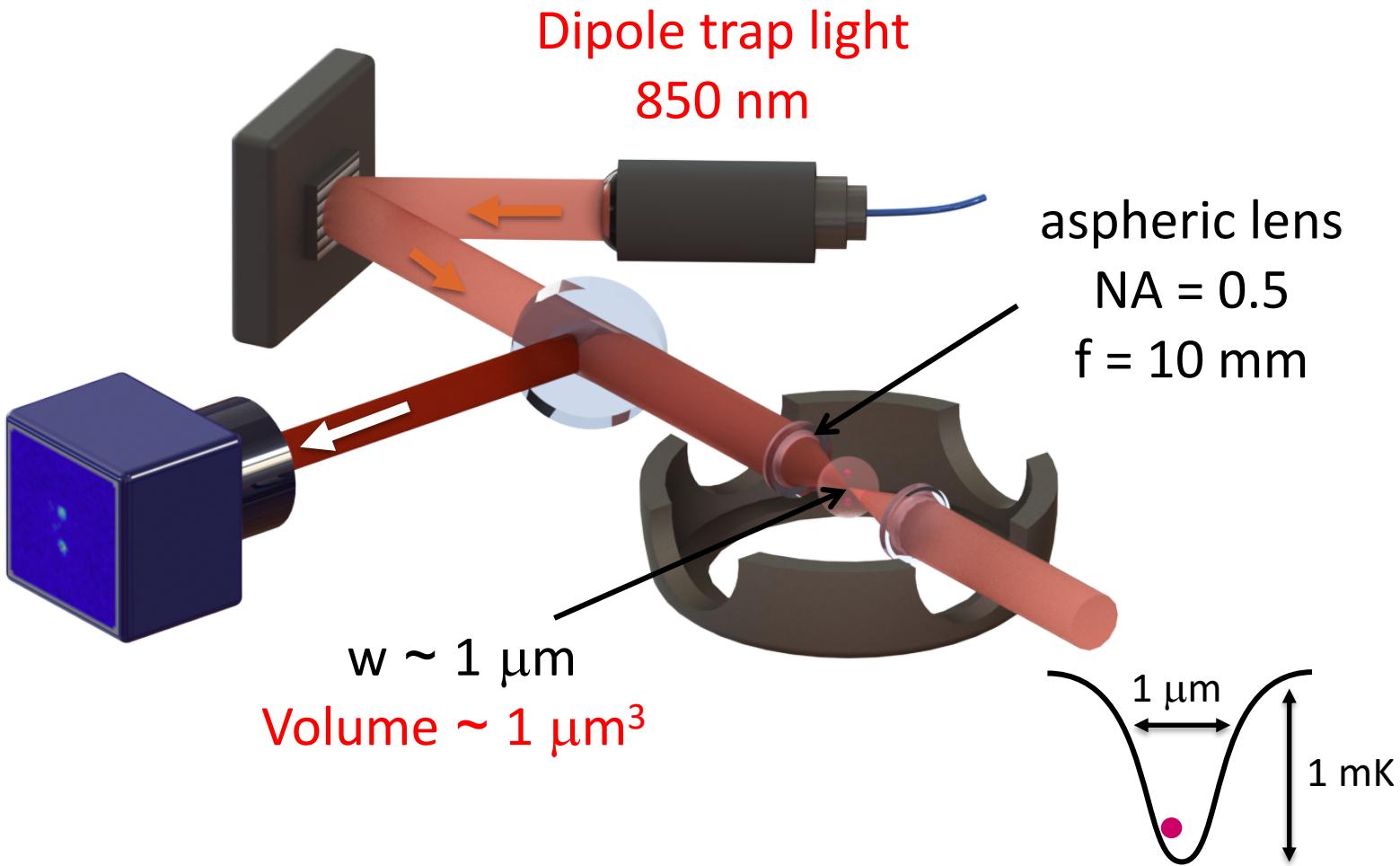
$$\text{NA} = \sin \alpha$$
$$w \sim \lambda / \text{NA}$$

Diffraction limited optics $w \sim \lambda$
Trapping volume $\sim \pi \lambda^3$

Ex: 1 mW on 1 μm
Trap depth = 1 mK

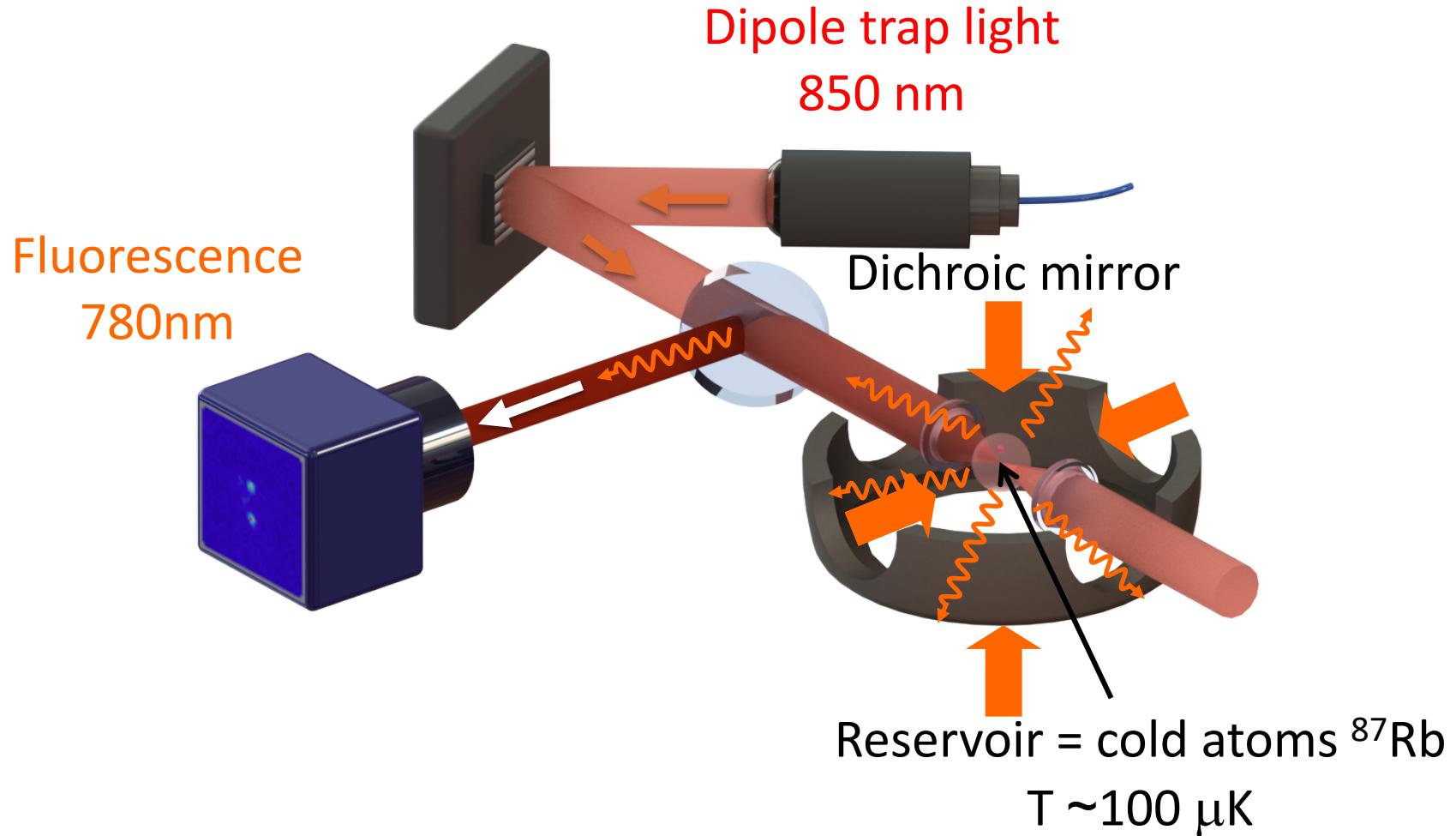
Single atoms in optical tweezers

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



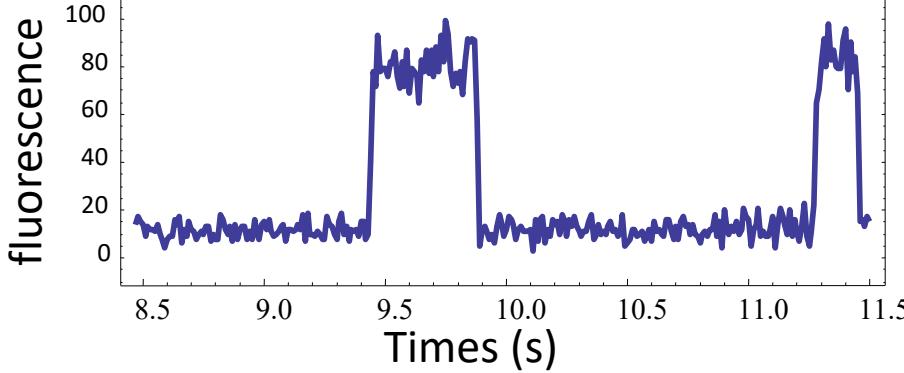
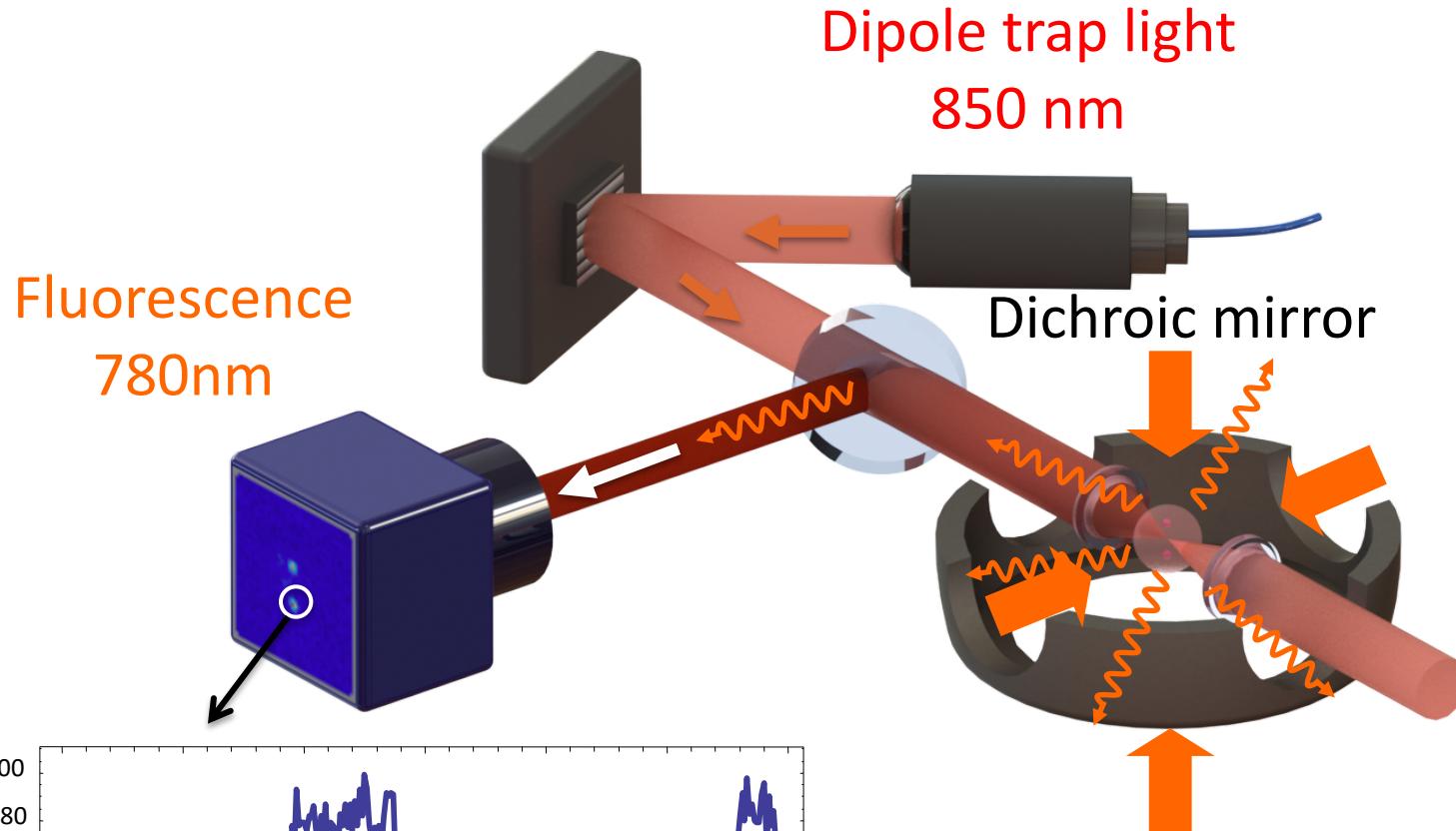
Single atoms in optical tweezers

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



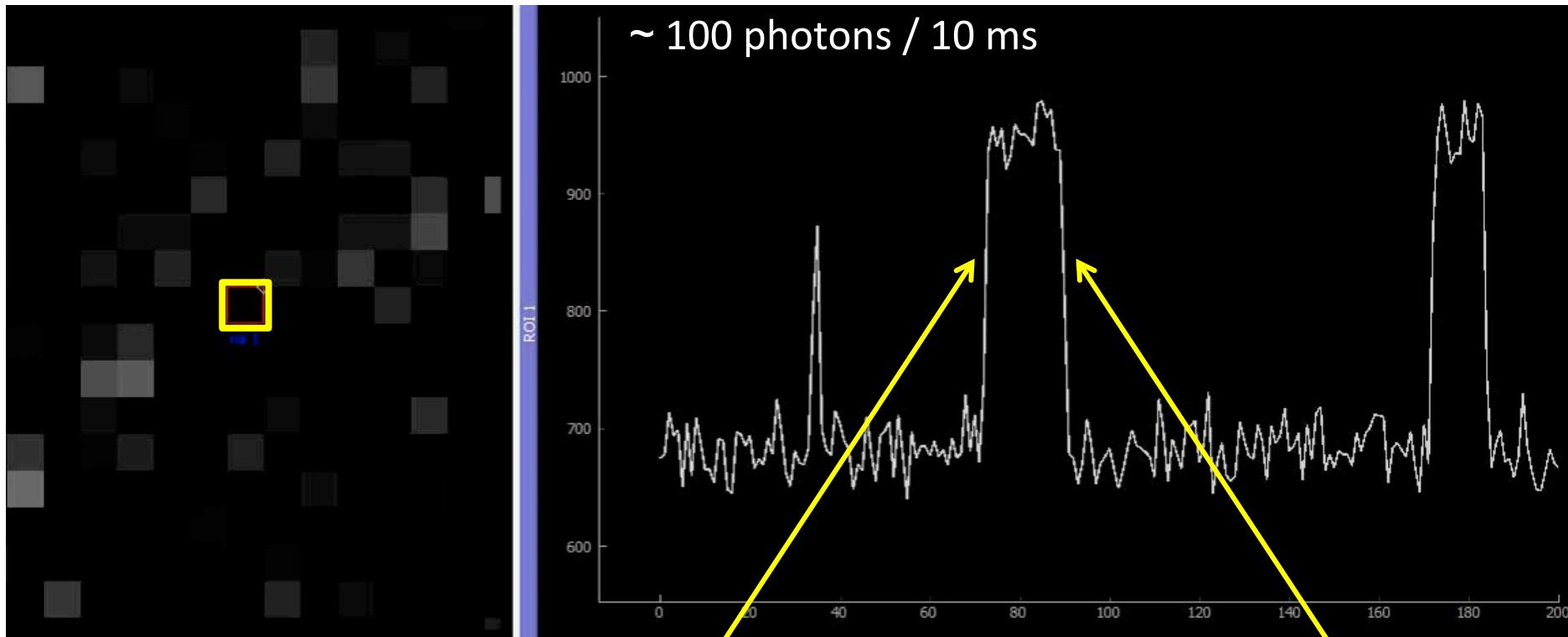
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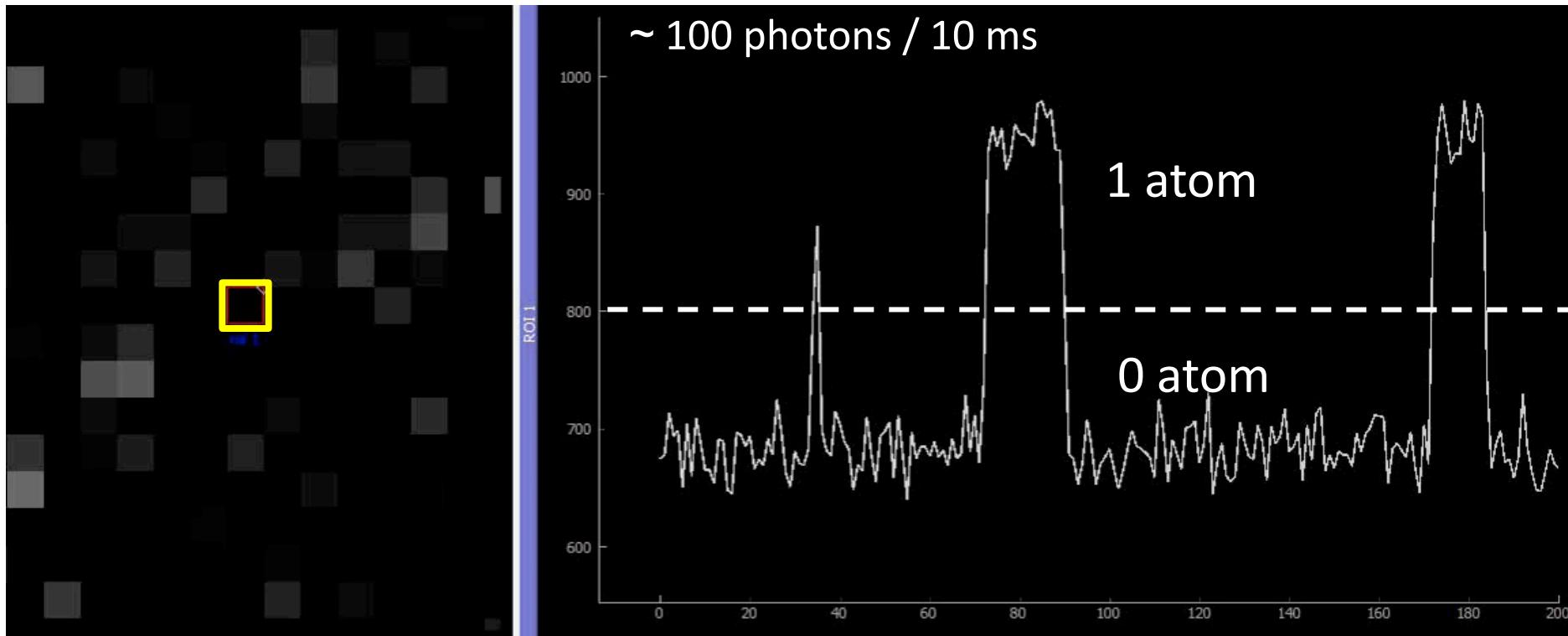
Fast light-assisted collision prevents 2 atoms ...

Fluorescence @ 780 nm induced by the cooling lasers



Fast light-assisted collision prevents 2 atoms ...

Fluorescence @ 780 nm induced by the cooling lasers



A single Rb atom ($20 \mu\text{K}$)!

Non deterministic



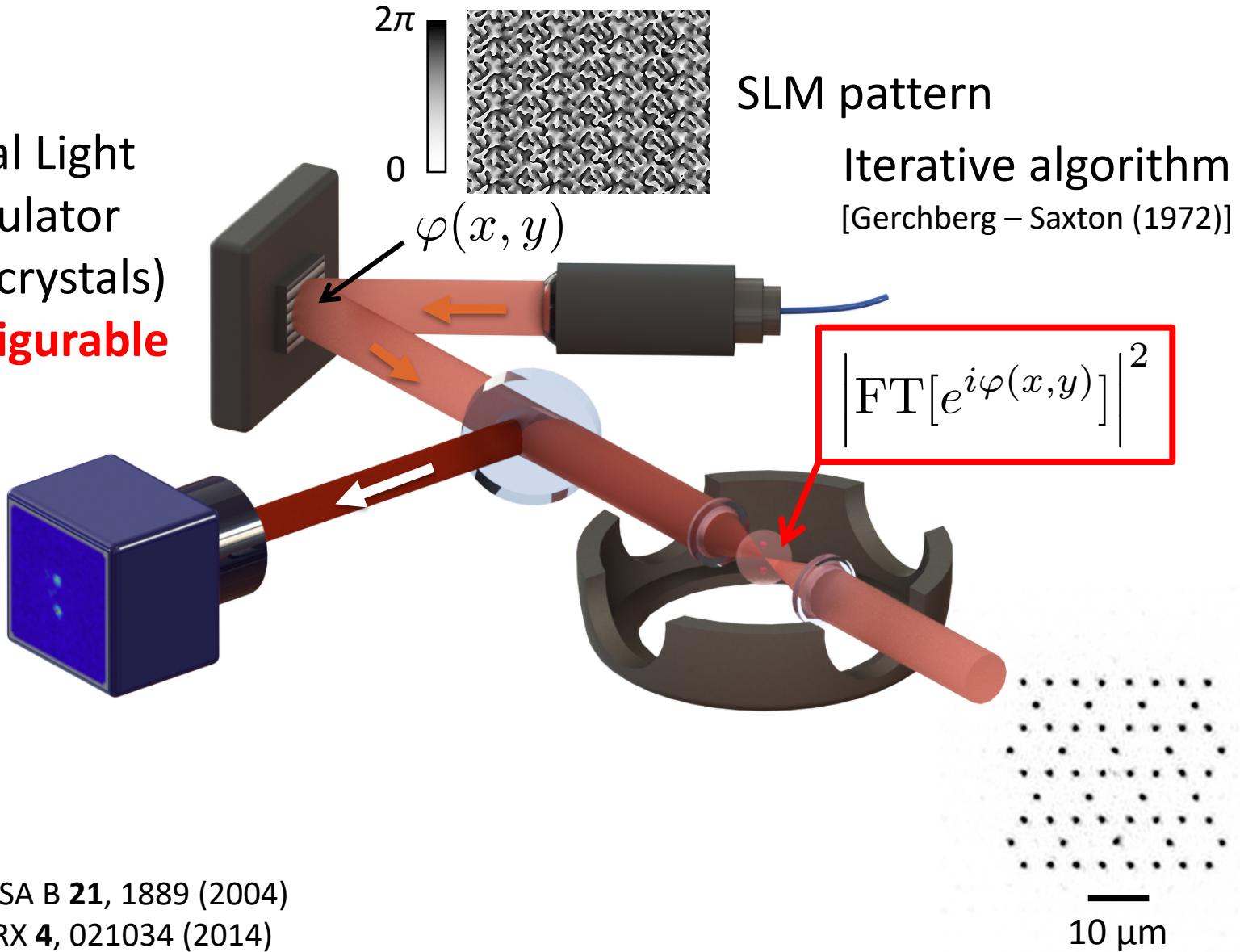
Which atoms?

Lanthanides	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	138.91	140.12	140.91	144.24	(145)	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04	174.97

	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Actinides	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
	(227)	232.04	231.04	238.03	(237)	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(262)

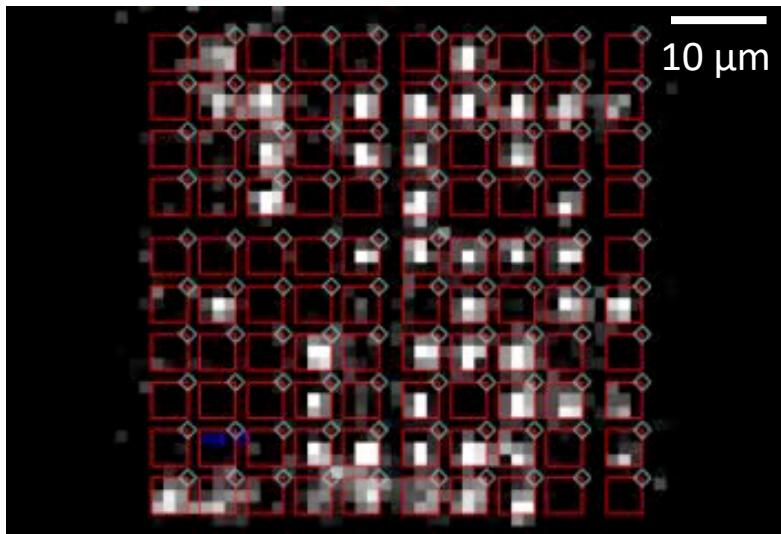
Holographic 2D arrays of tweezers

Spatial Light
Modulator
(liquid crystals)
Reconfigurable



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

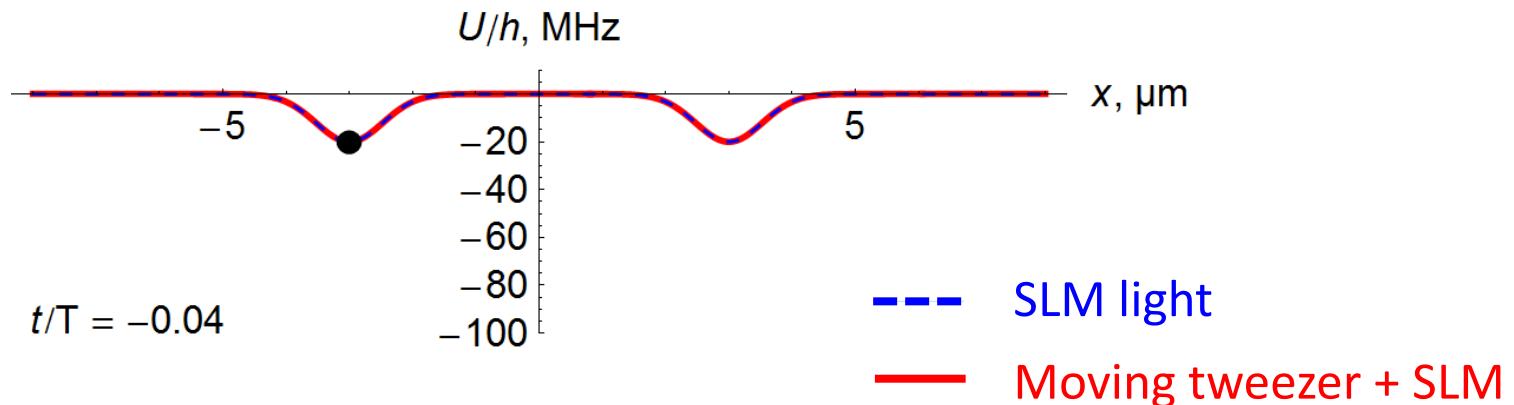
Atom-by-atom assembling of 2D arrays



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

Solution: sort atoms in arrays

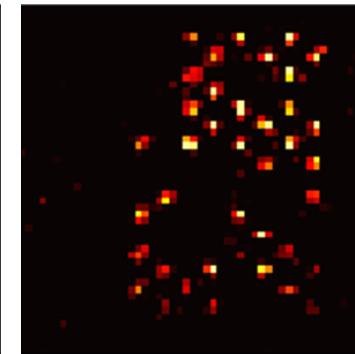
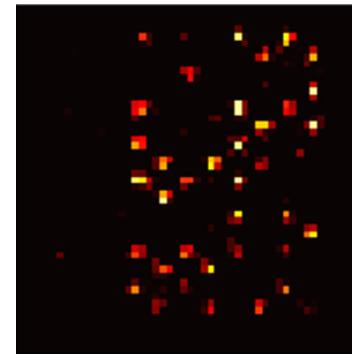
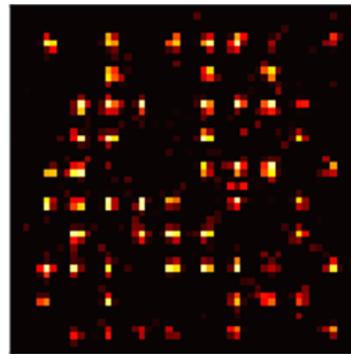
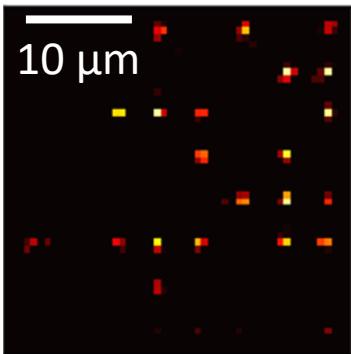
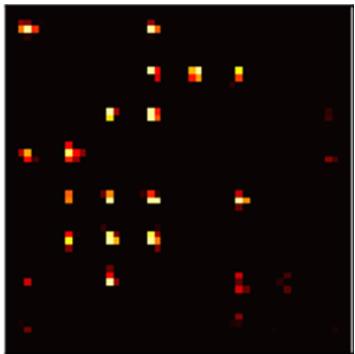
Moving atoms with a tweezers



$$p \sim 0.993(1)$$

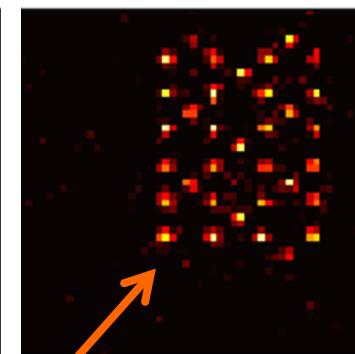
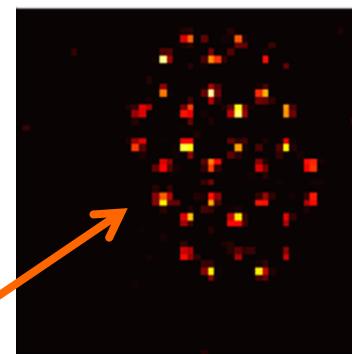
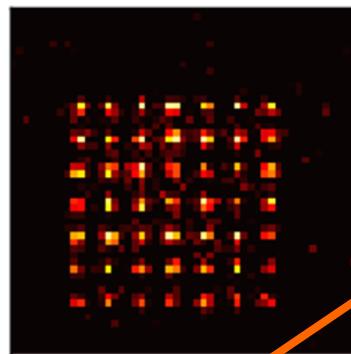
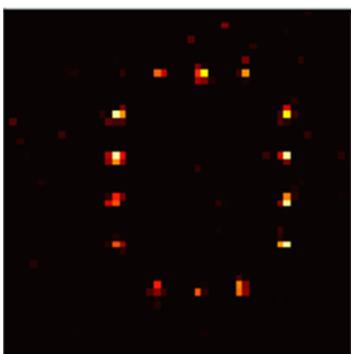
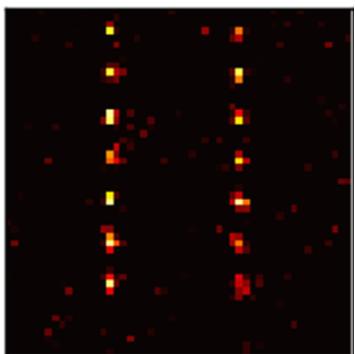
Gallery of assembled 2D arrays... (single-shot images...)

Initial

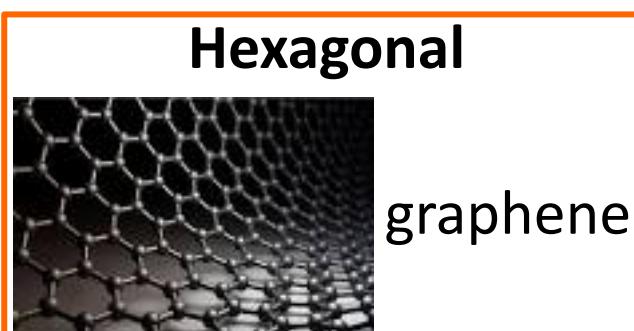


43 moves

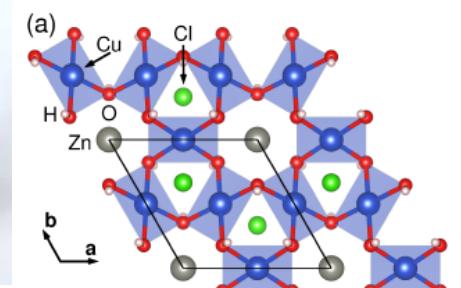
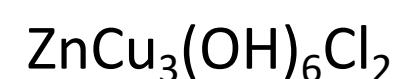
Final



43 moves

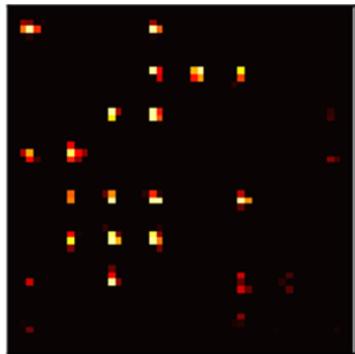


Kagome: Herbertsmithite

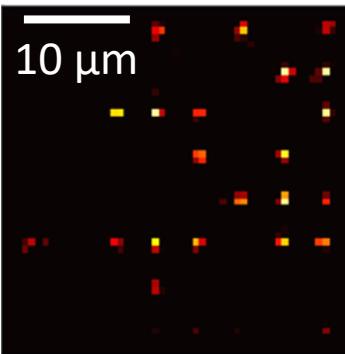


Gallery of assembled 2D arrays... (single-shot images...)

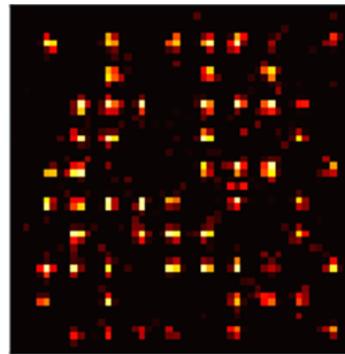
Initial



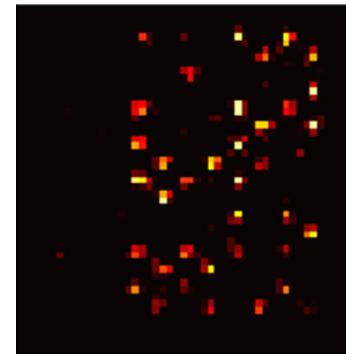
14 moves



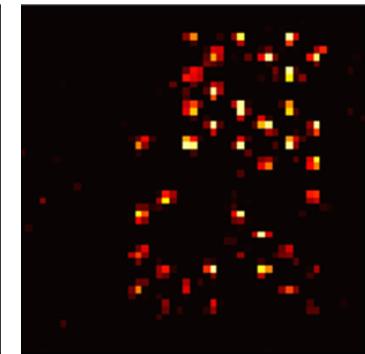
15 moves



53 moves

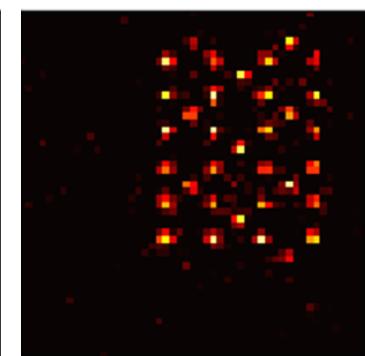
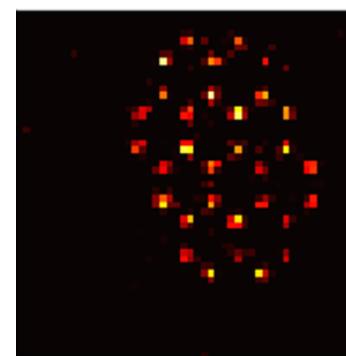
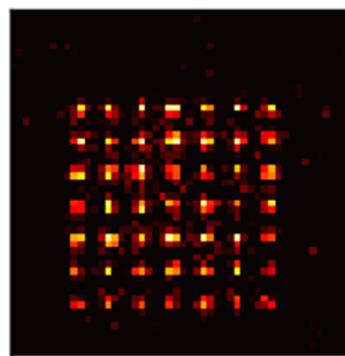
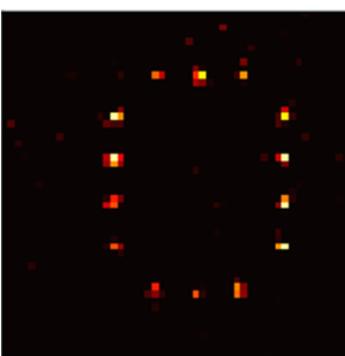
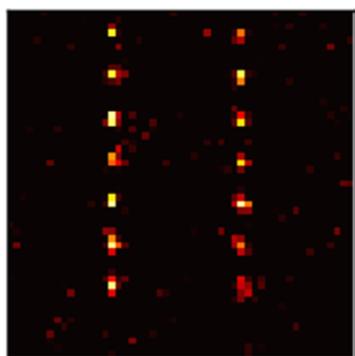


41 moves



43 moves

Final



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

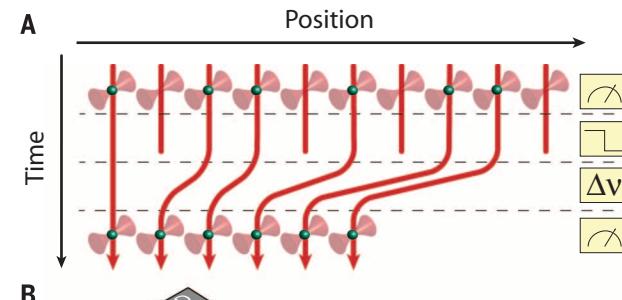
- Fully loaded arrays up to 50 atoms
- 98% filling fraction **@ 5 Hz**
- 100% filling every ~ 2-5 sec

Related works

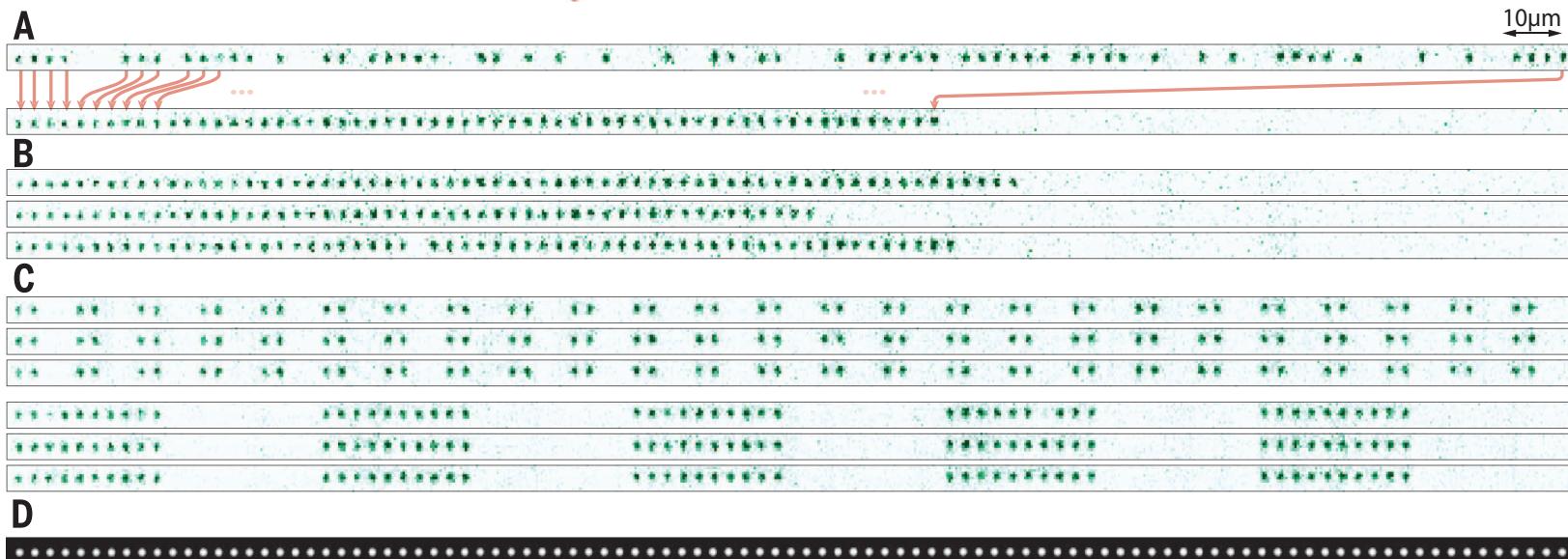
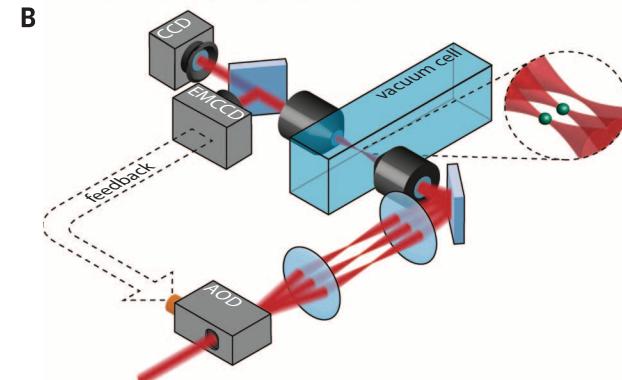
Harvard (1D) Science **354**, 1024 (2016)

Korea (2D) Nat. Comm. **7**, 13317 (2016)

Sorting in 1D (Harvard)



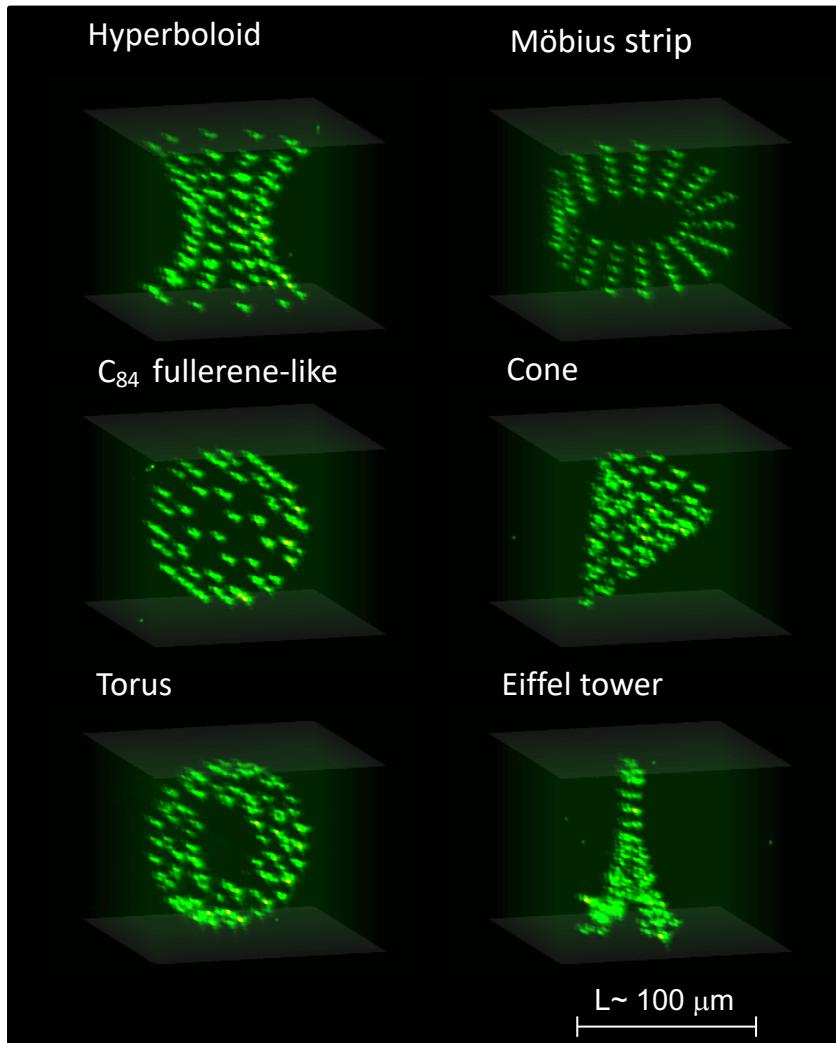
Science 354, 1024 (2016)



It also works in 3d!

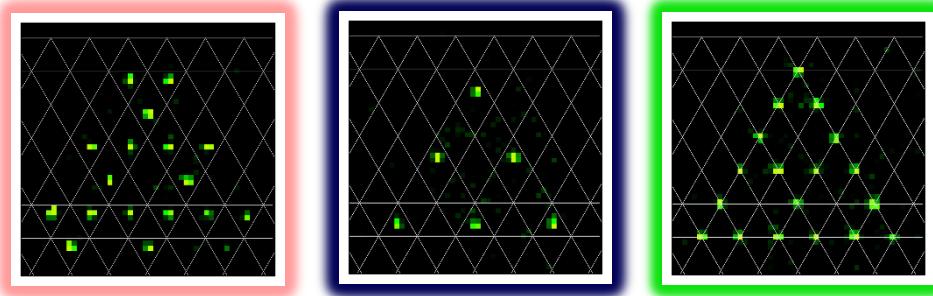
Di Leonardo, Optics Express **15**, 1913 (2007)

Averaged fluorescence
imaged “slice-by-slice”



Assembled Pyrochlore lattice

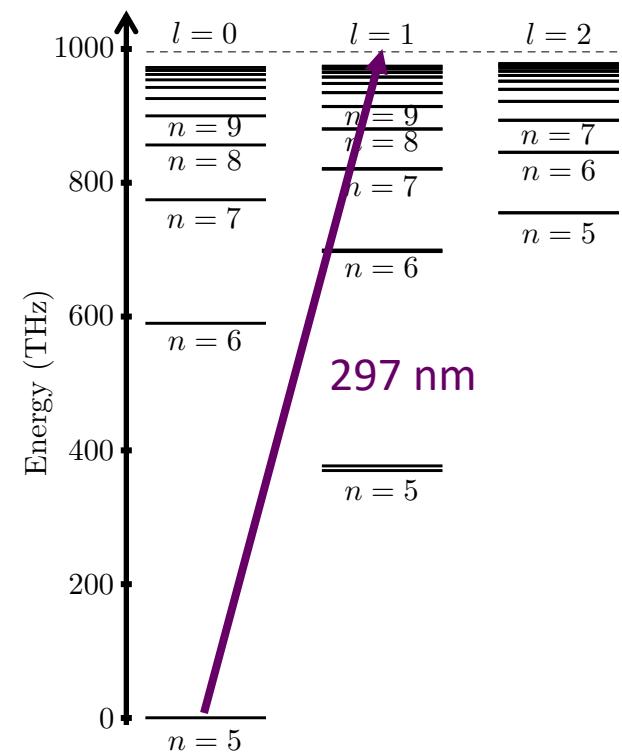
Plane 1 Plane 2 Plane 3



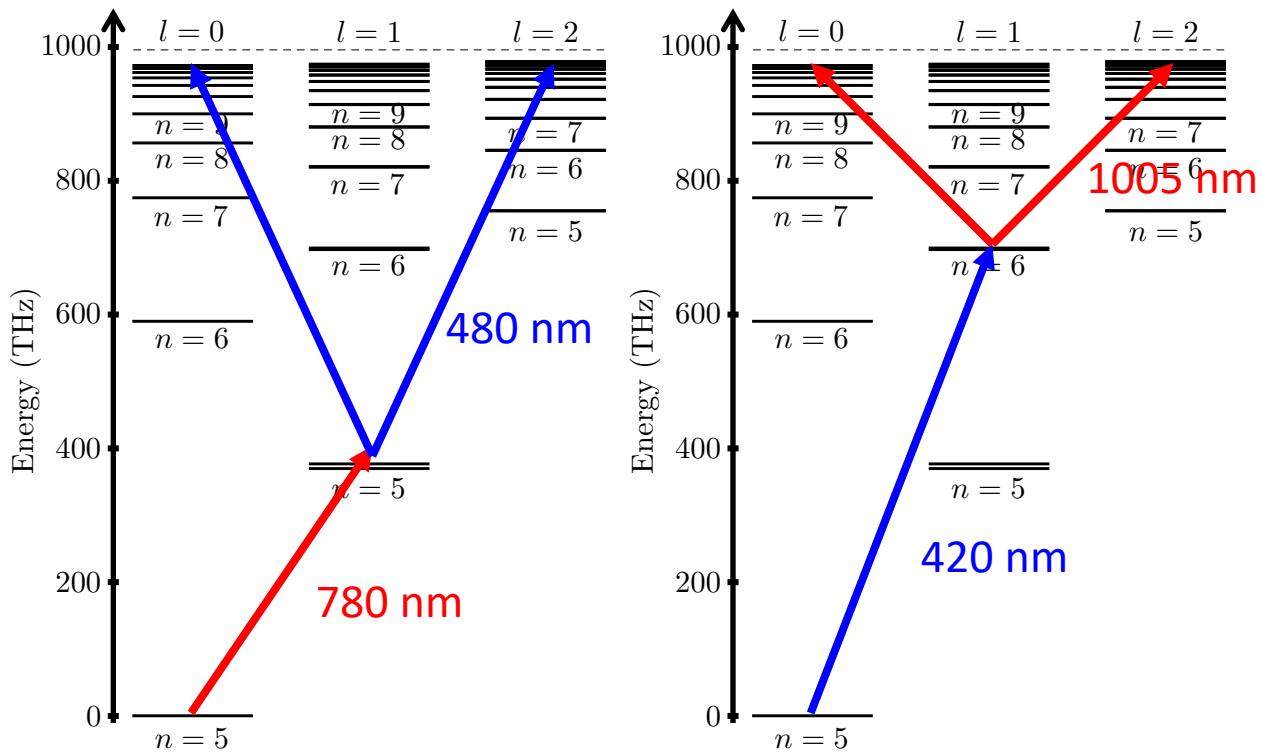
Barredo, Nature (2018)
Also: Weiss, Nature (2018); Ahn, Opt. Exp (2016)

Coherent Rydberg excitation (rubidium)

Single photon (UV)



Two-photon

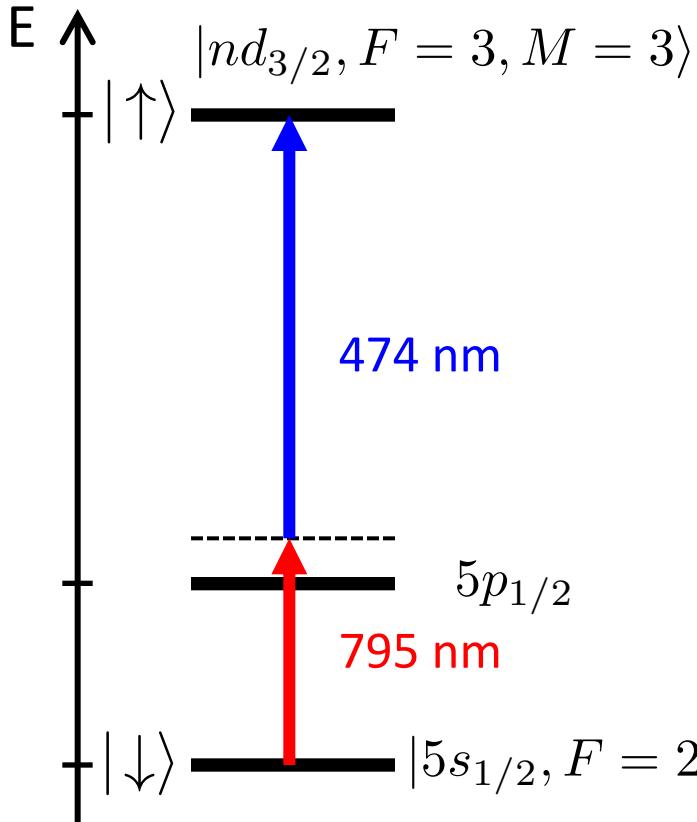


$$\Omega = \frac{\Omega_1 \Omega_2}{2\Delta}$$

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

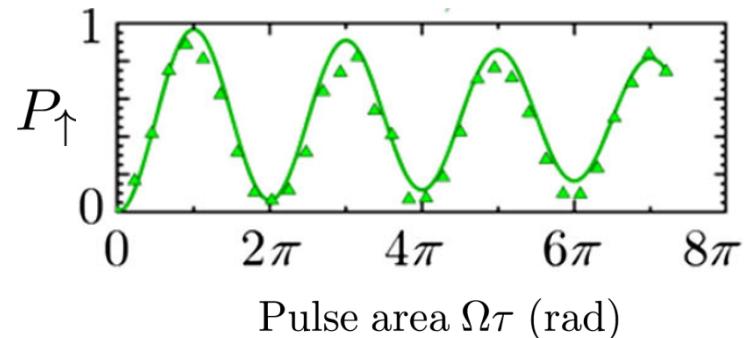
Coherent optical Rydberg excitation ($n = 50 - 100$)

^{87}Rb



Single atom \Rightarrow repeat 100 times

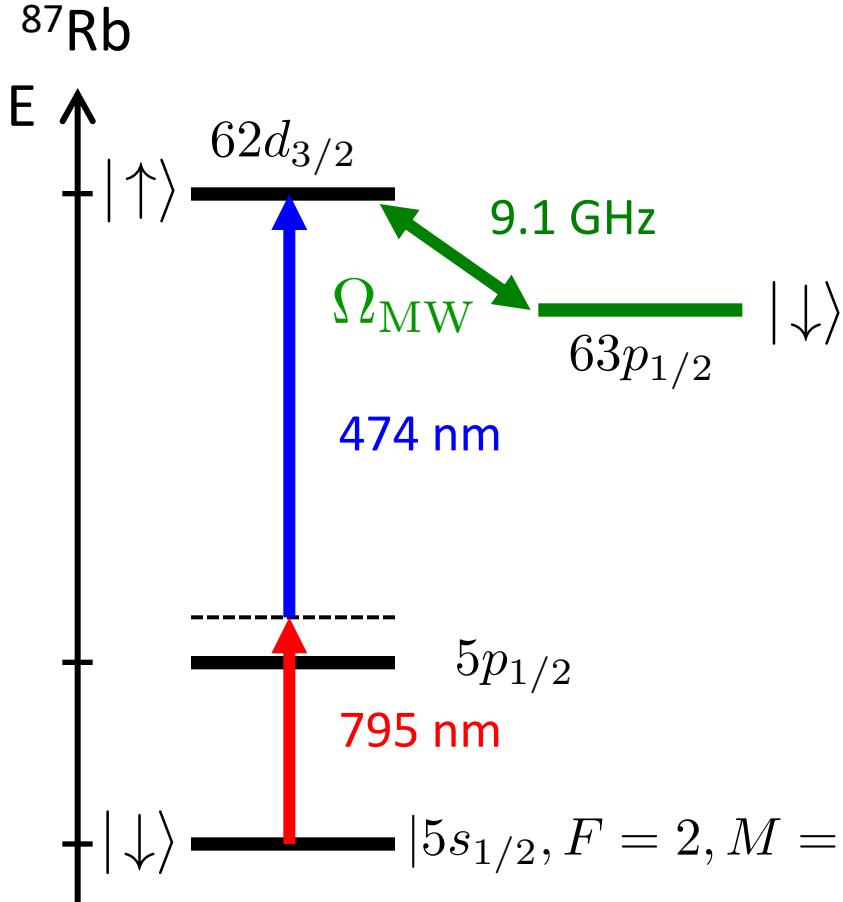
Optical excitation ($\Omega = 0.5 - 5 \text{ MHz}$)



T. A. Johnson *et al.*, PRL **100**, 113003 (2008)

Miroshnychenko, PRA **82**, 023623 (2010)

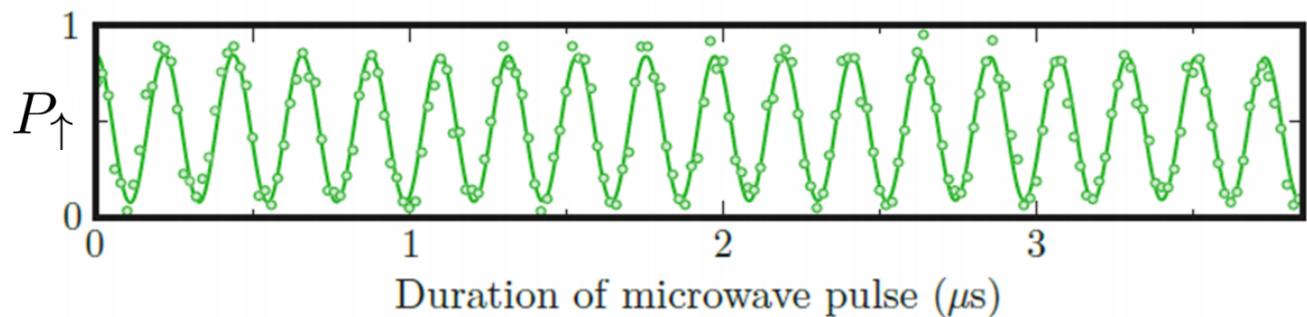
Microwave manipulations ($n = 50 - 100$)



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)

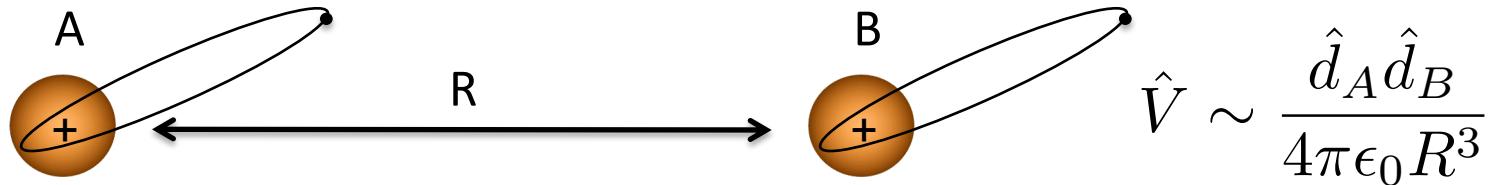
“Calculation of Rydberg interaction potentials”, S. Weber *et al.*, J. Phys. B **50**, 133001 (2017)

Softwares to calculate interaction energies

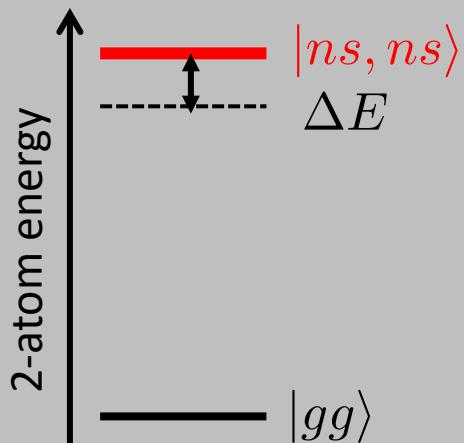
S. Weber *et al.*, arXiv:1612.08053, <https://pairinteraction.github.io>

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

Interactions between Rydberg atoms

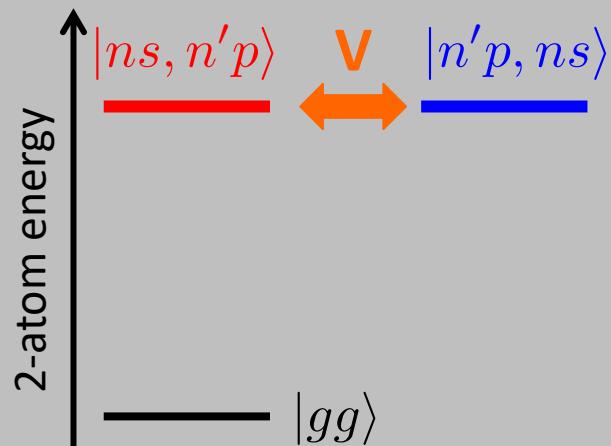


van der Waals



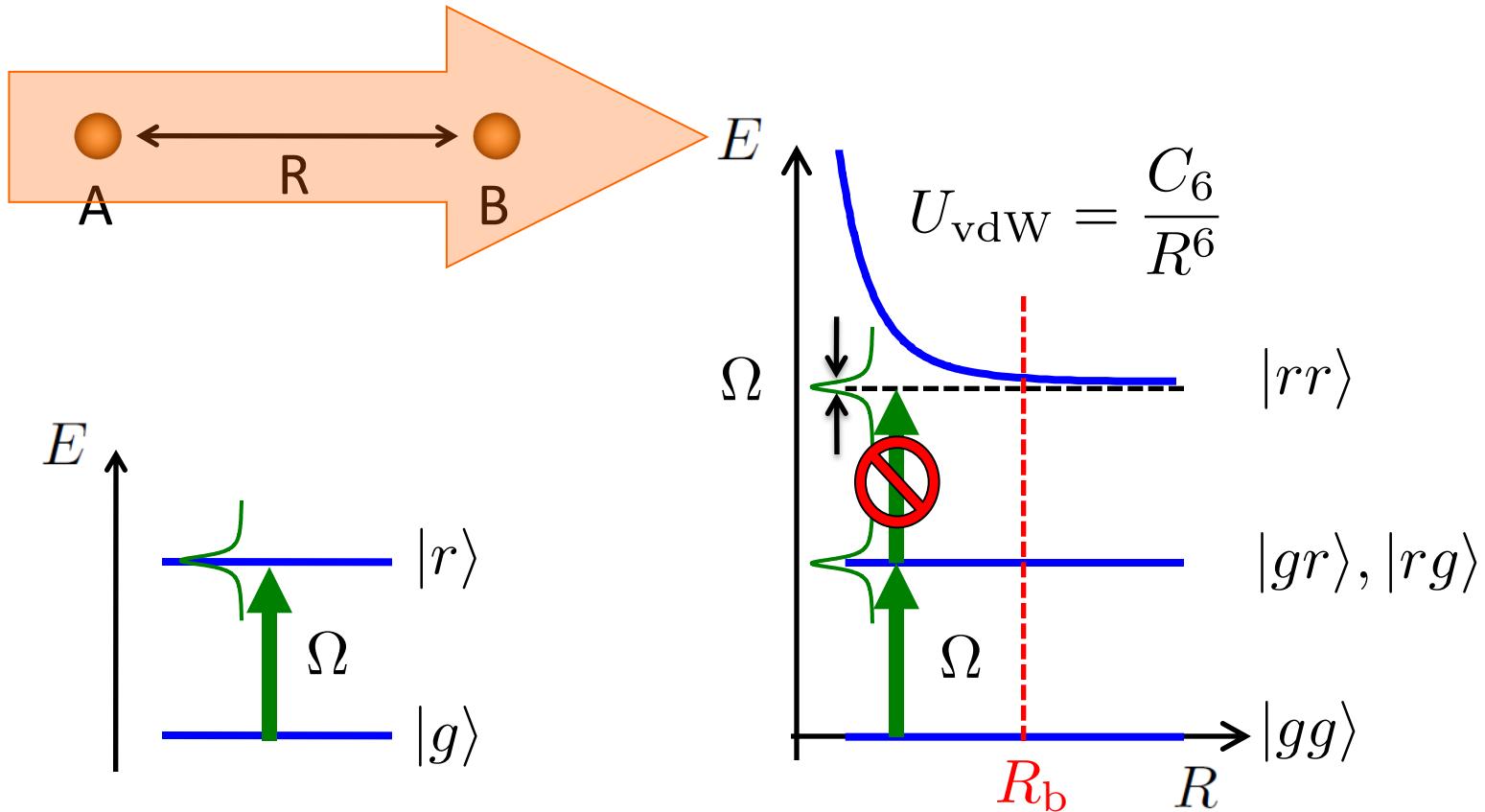
$$\Delta E \sim \frac{C_6}{R^6}$$

Resonant interaction



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

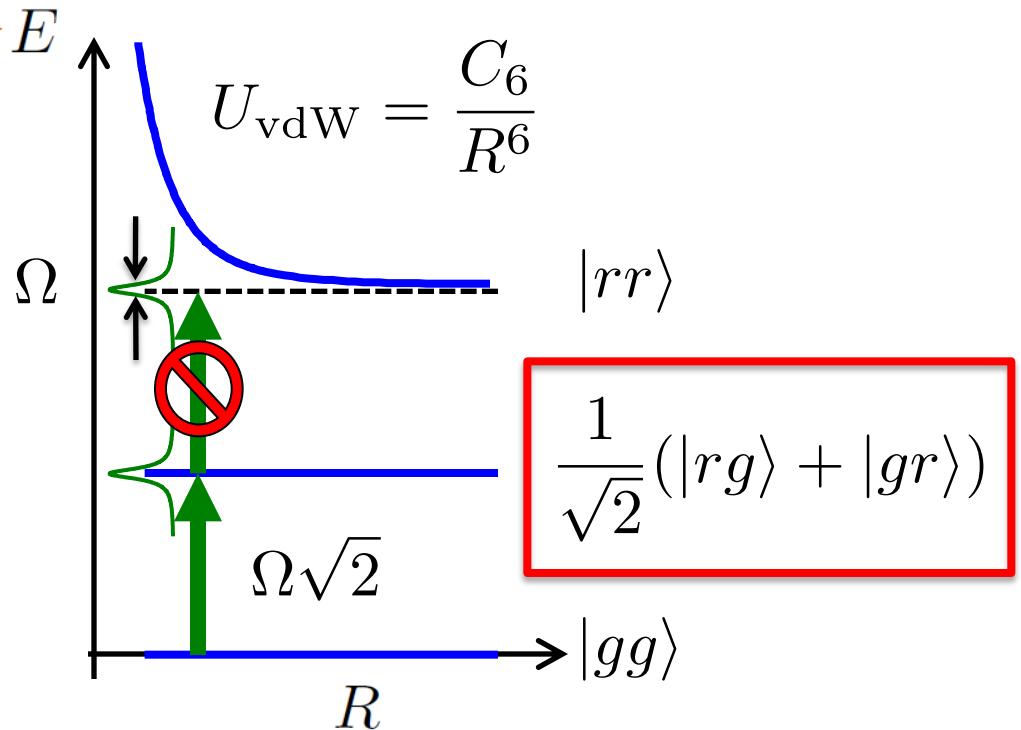
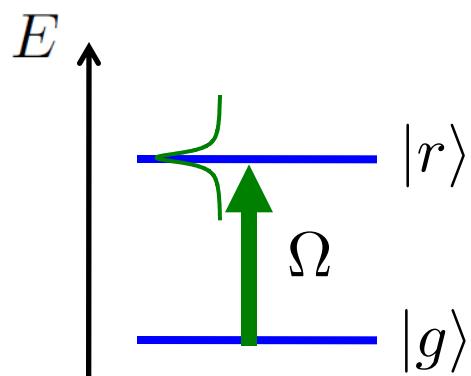
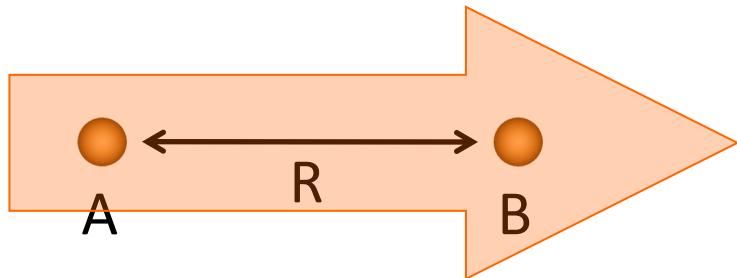
Collective excitation of two interacting Rydberg atoms



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

Dynamics governed by Ω **only**

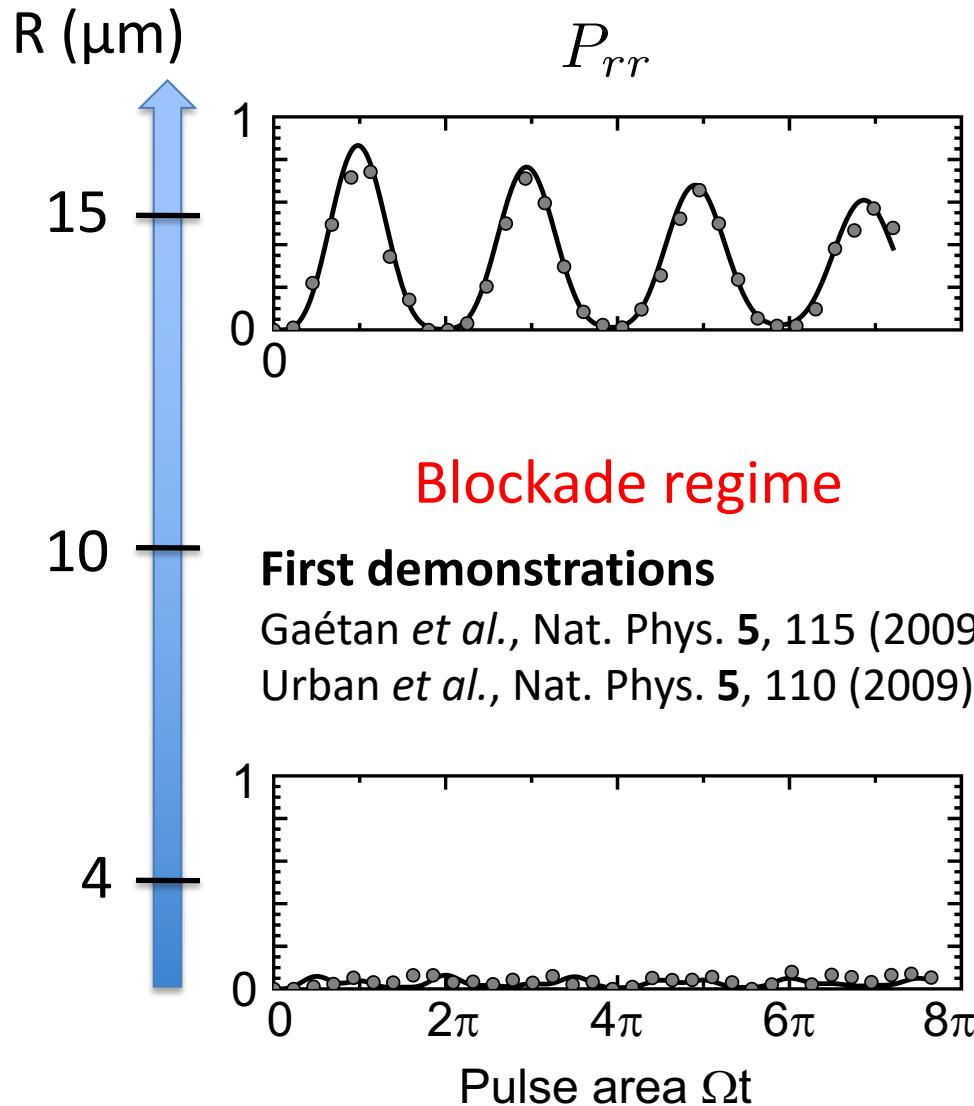
Collective excitation of two interacting Rydberg atoms



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

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

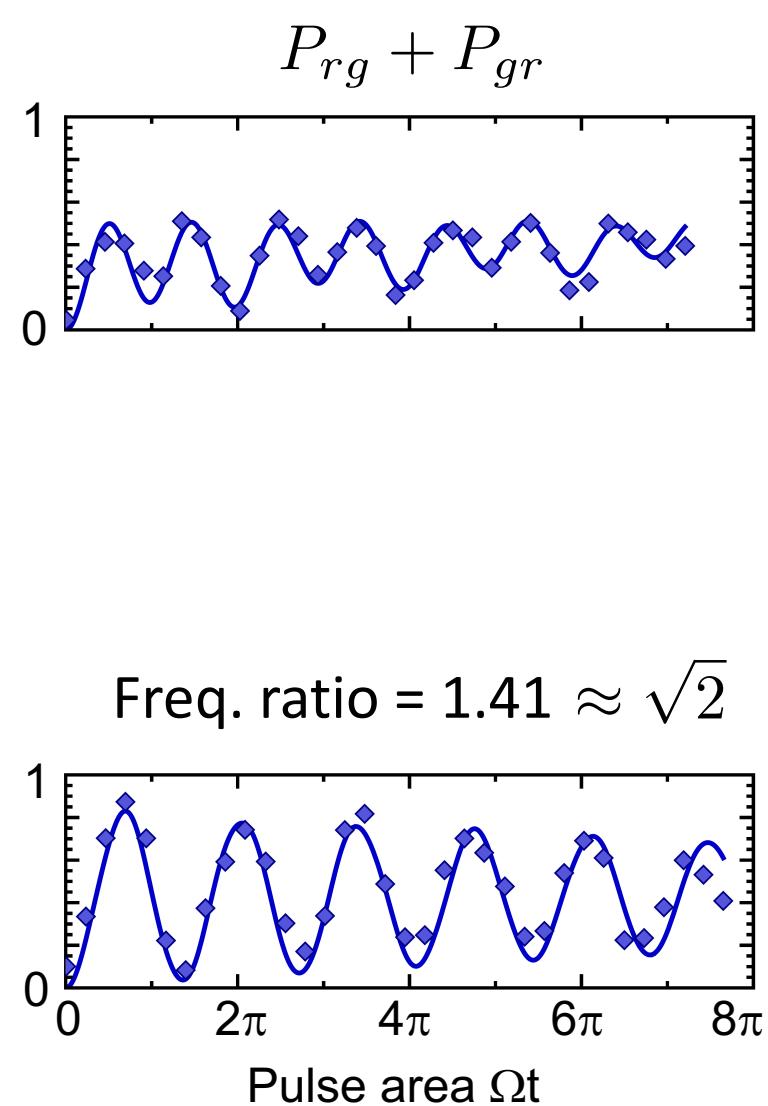
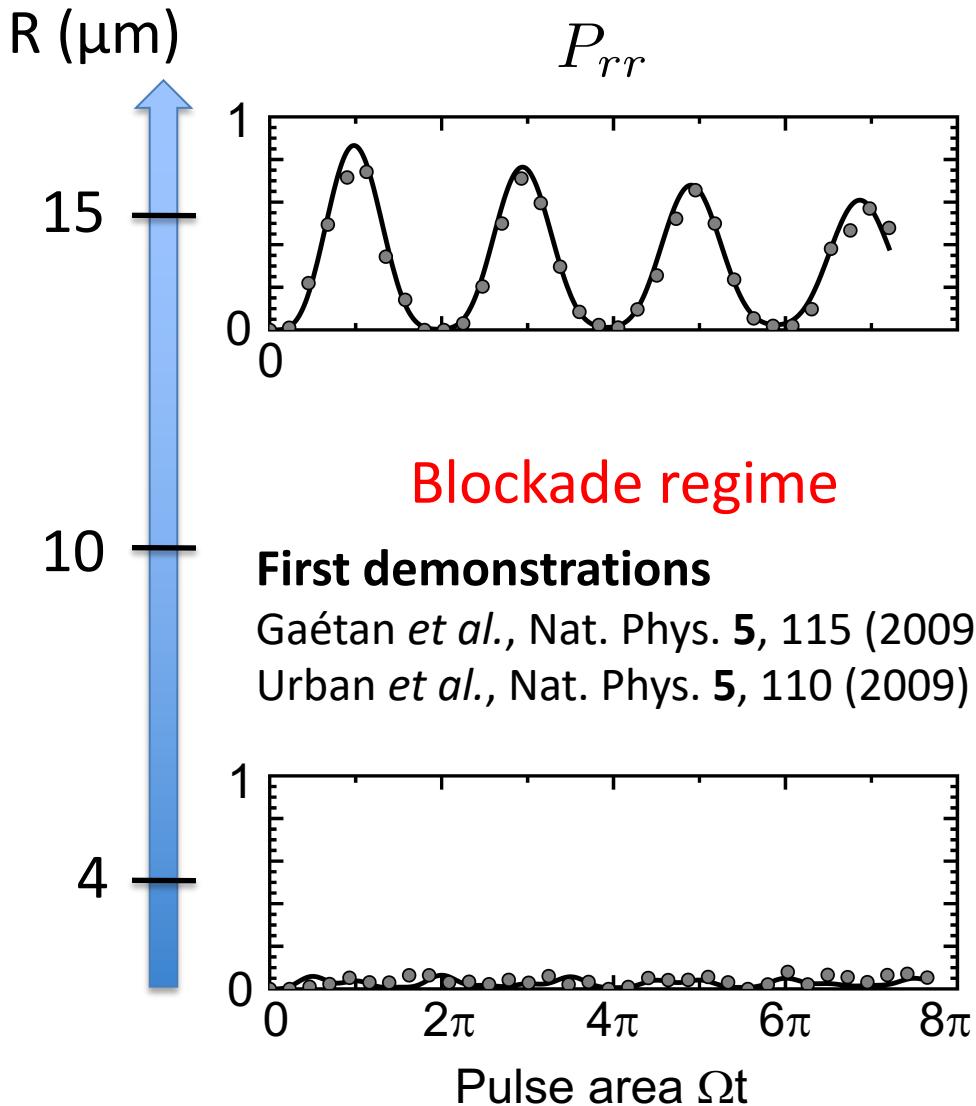
From independent atoms to blockade ($62\text{d}_{3/2}$)



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

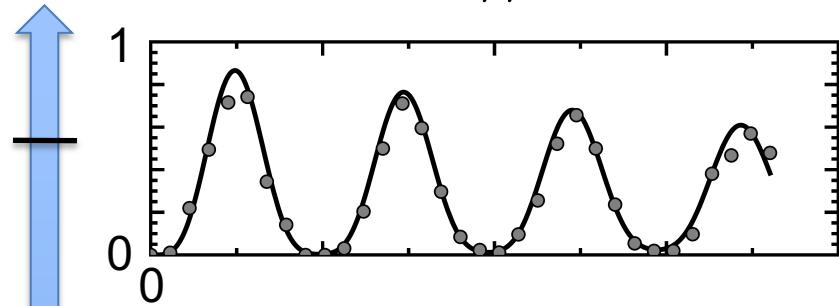
$\hbar\Omega \ll U_{\text{vdW}}$

From independent atoms to blockade ($62\text{d}_{3/2}$)



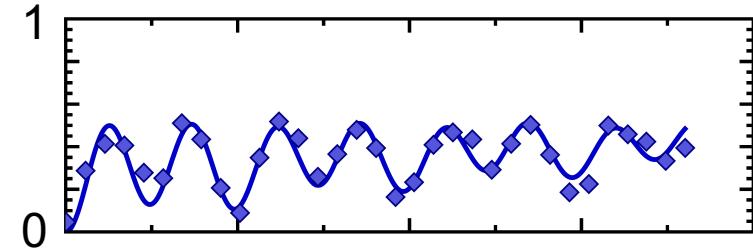
From independent atoms to blockade ($62d_{3/2}$)

R (μm)



P_{rr}

$P_{rg} + P_{gr}$

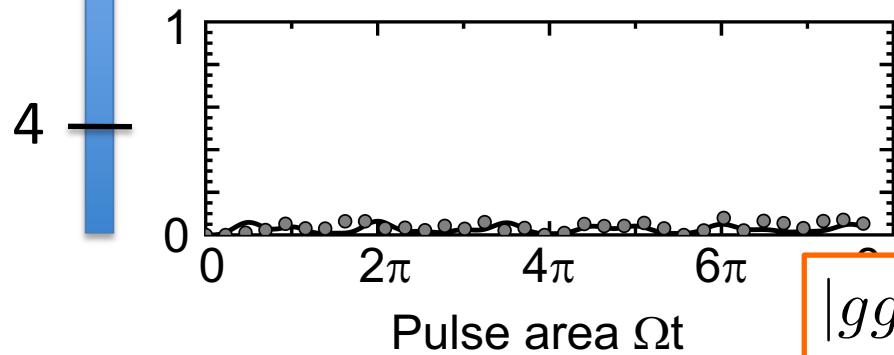


Blockade regime

First demonstrations

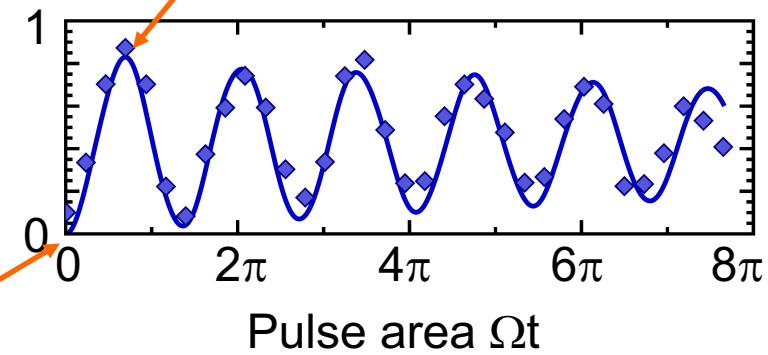
Gaétan *et al.*, Nat. Phys. 5, 115 (2009)

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

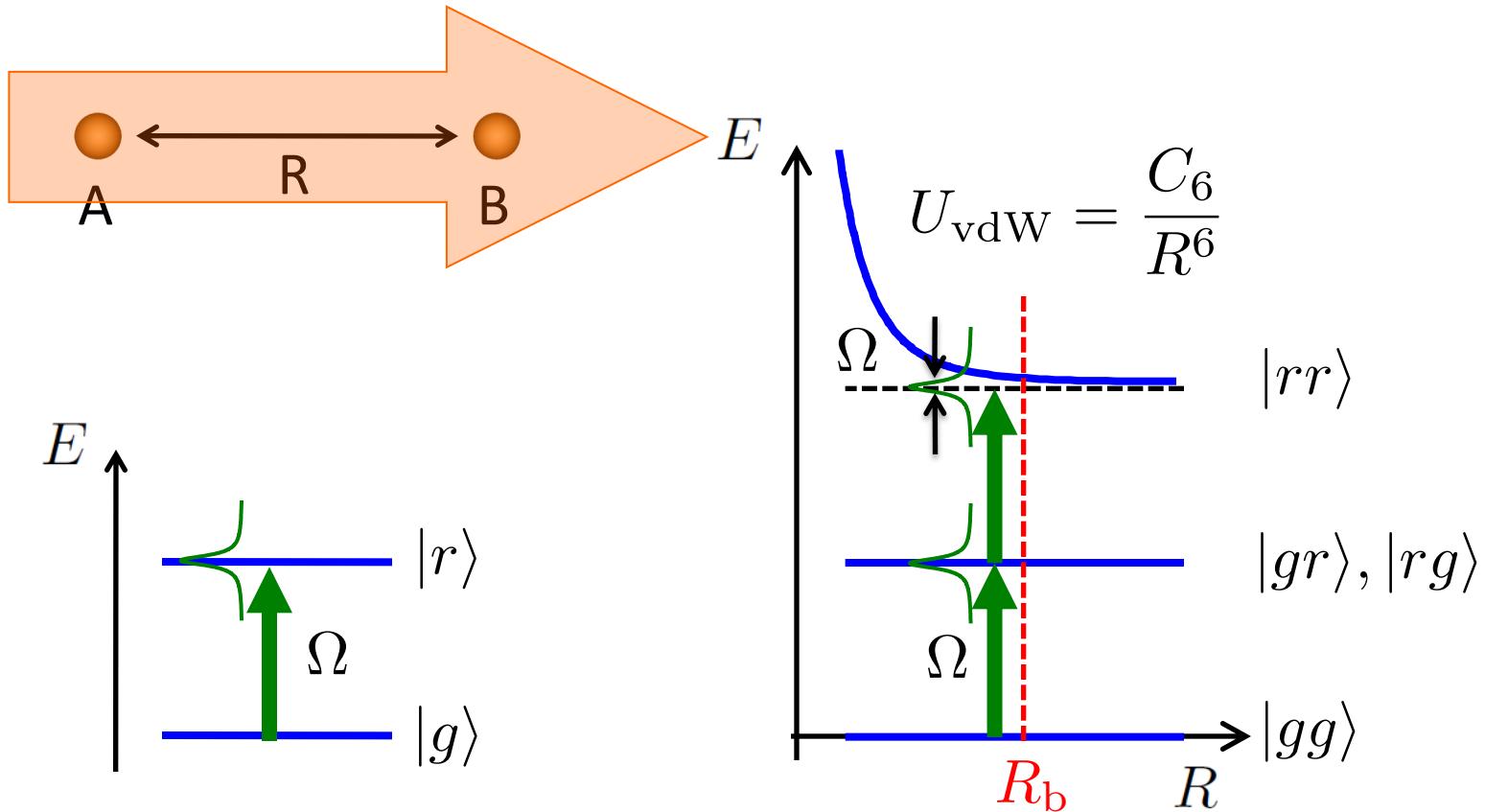


$|gg\rangle$

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

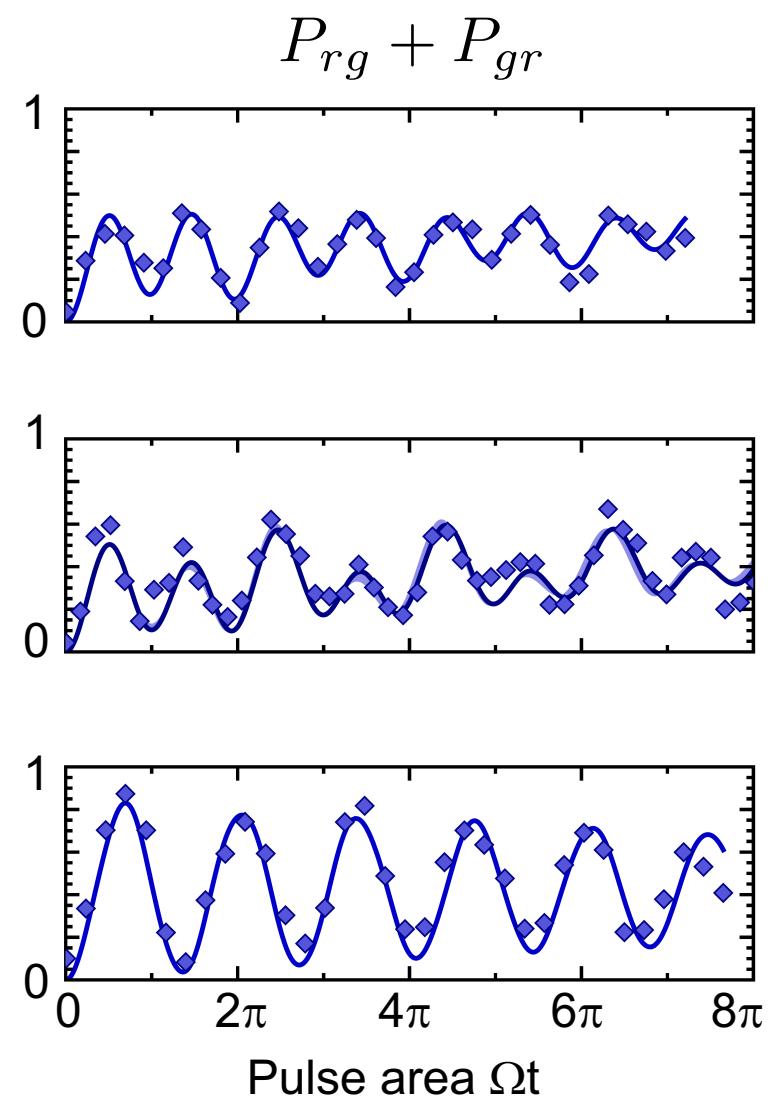
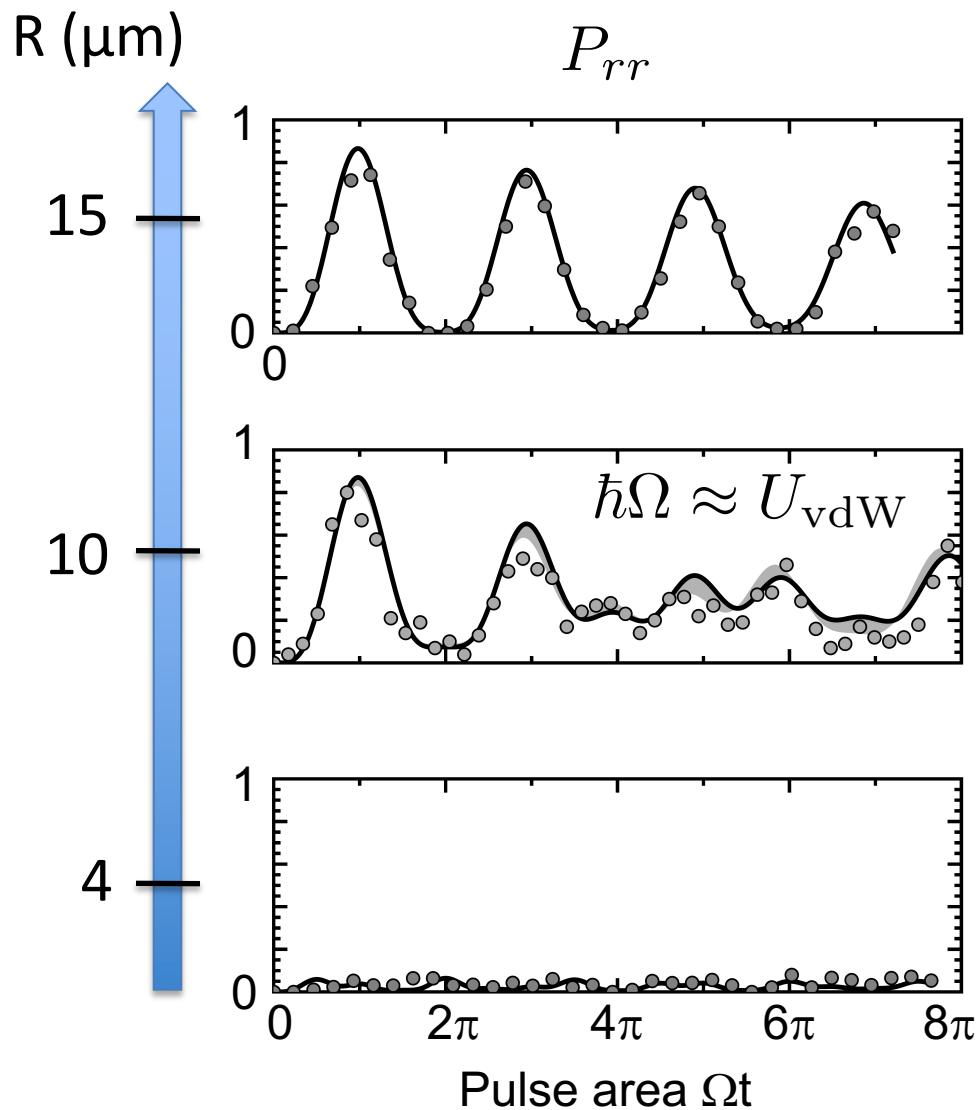


Collective excitation of two interacting Rydberg atoms

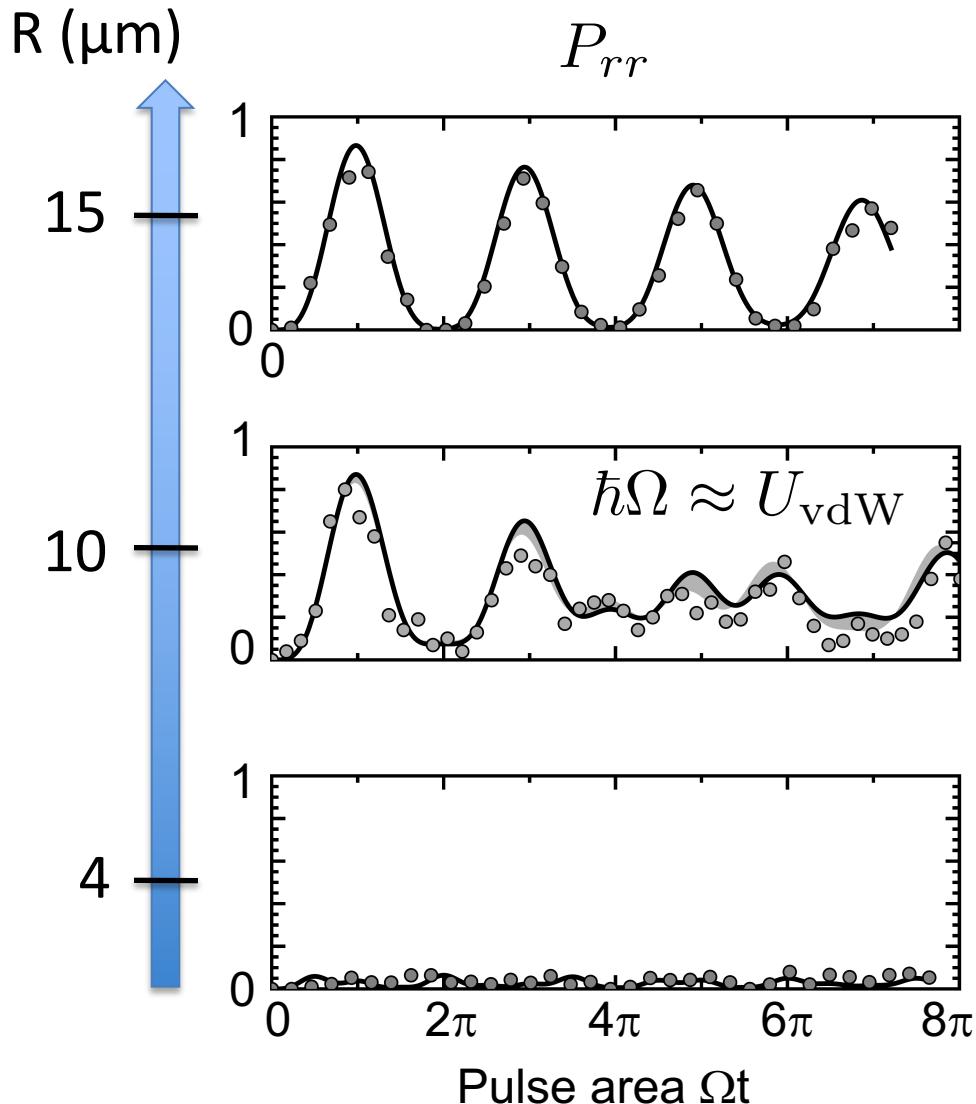


If $\hbar\Omega \approx U_{\text{vdW}}$: dynamics governed by Ω **and** U_{vdW}

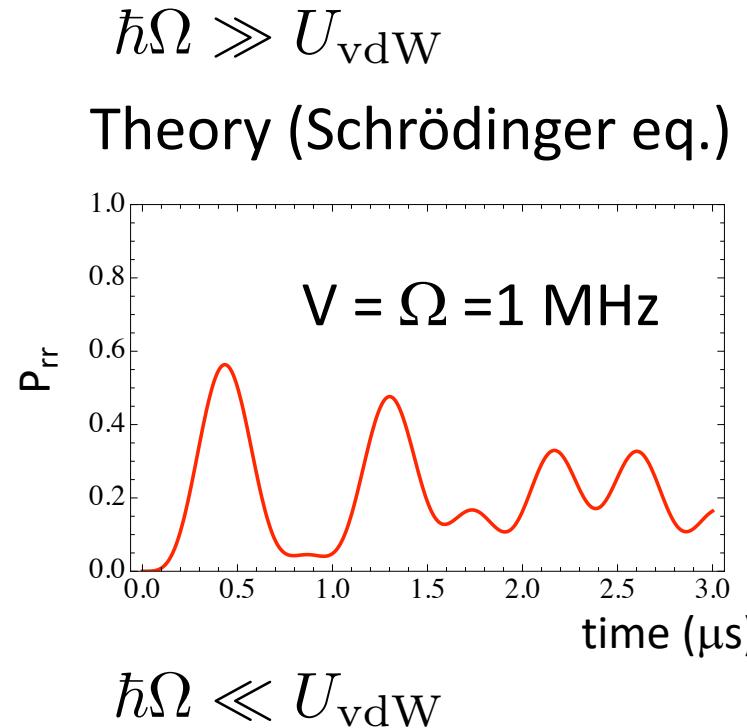
From independent atoms to blockade ($62d_{3/2}$)



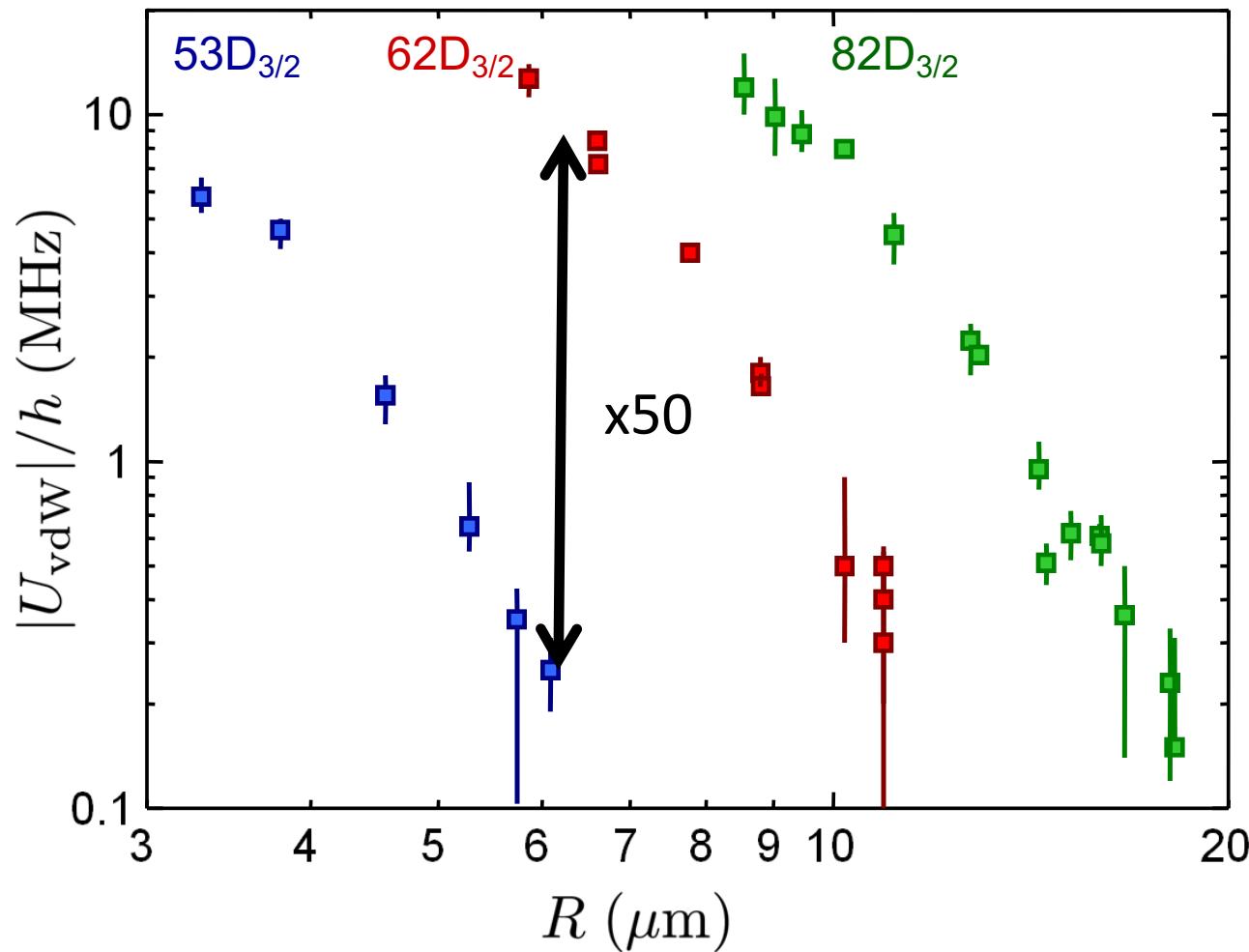
From independent atoms to blockade ($62\text{d}_{3/2}$)



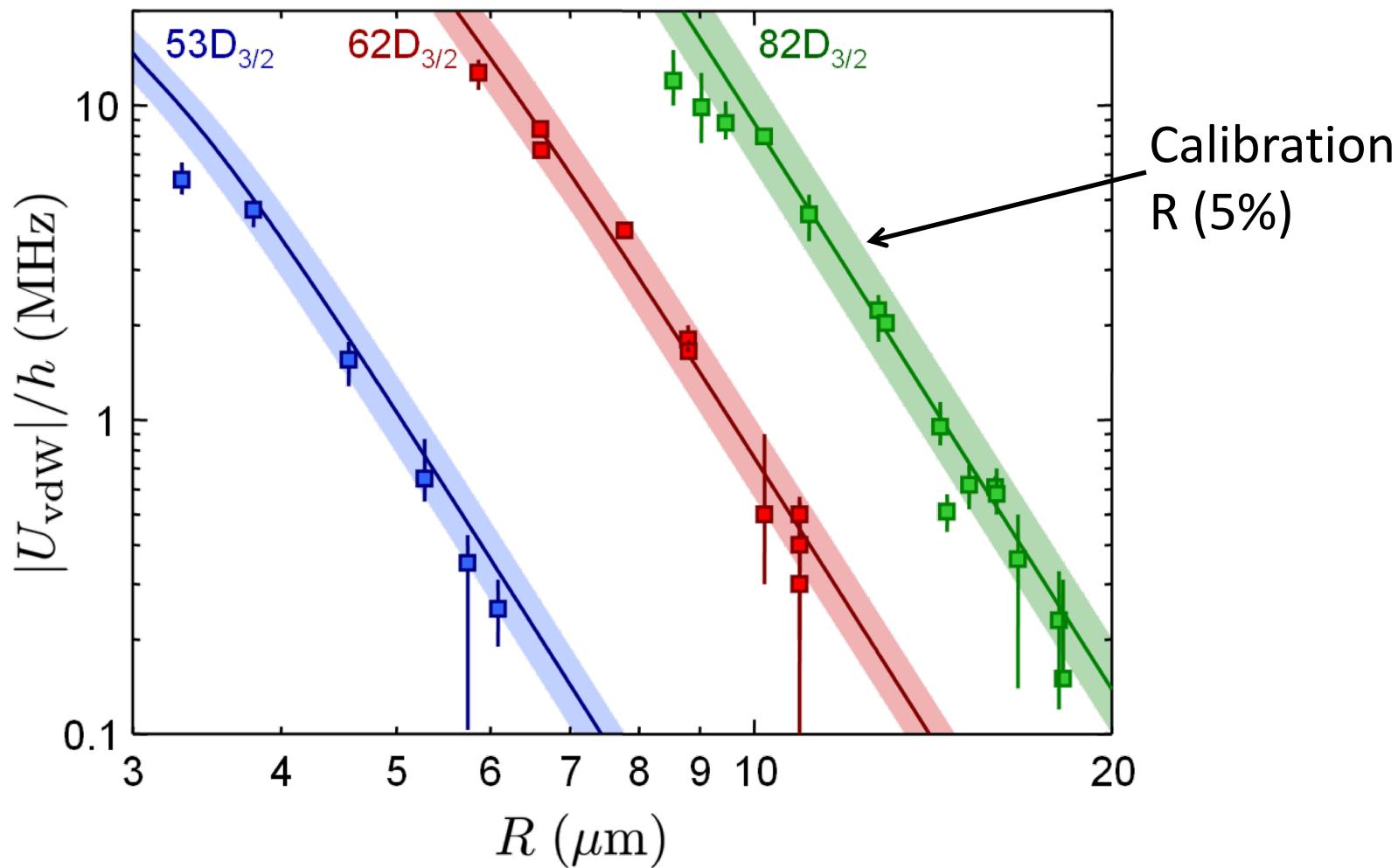
Fit \Rightarrow extract U_{vdW}



Measurement of vdW interaction between 2 atoms



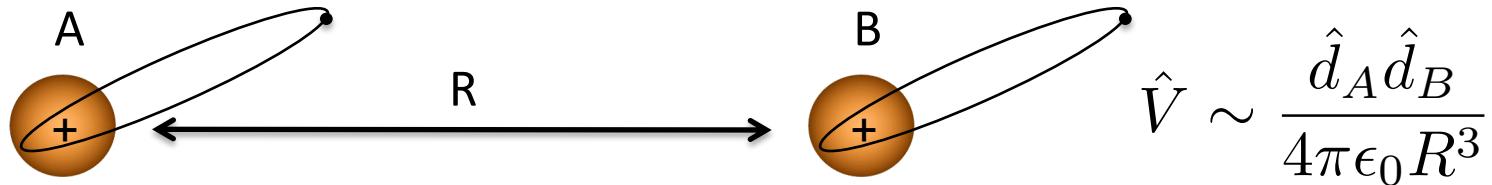
Measurement of vdW interaction between 2 atoms



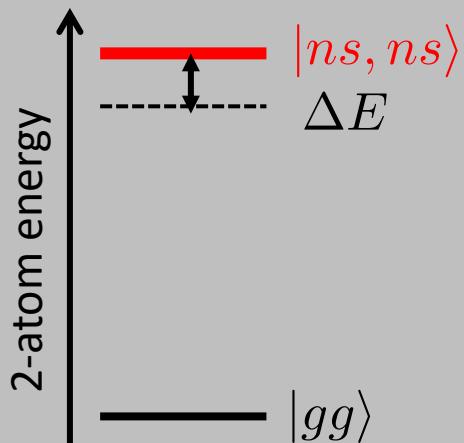
Theory curves: direct diagonalization (dipole-dipole interaction)
No adjustable parameter!

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

Interactions between Rydberg atoms

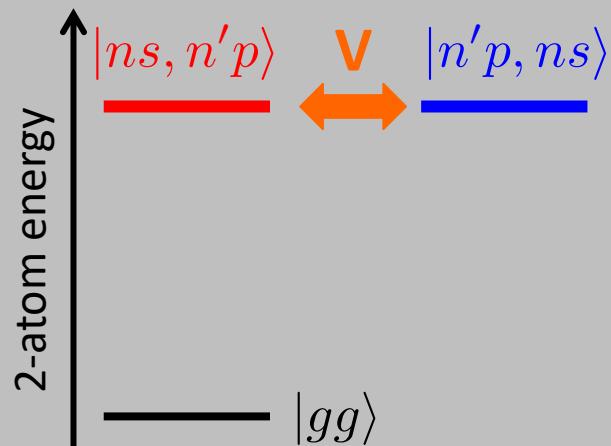


van der Waals



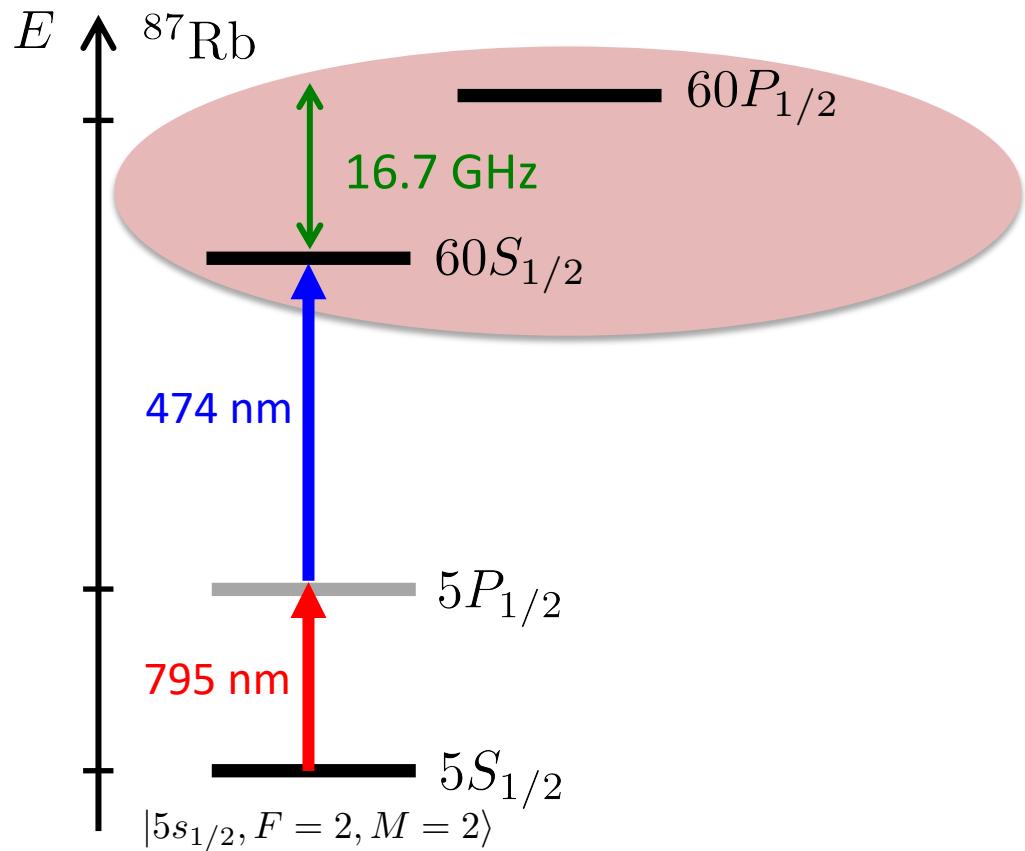
$$\Delta E \sim \frac{C_6}{R^6}$$

Resonant interaction

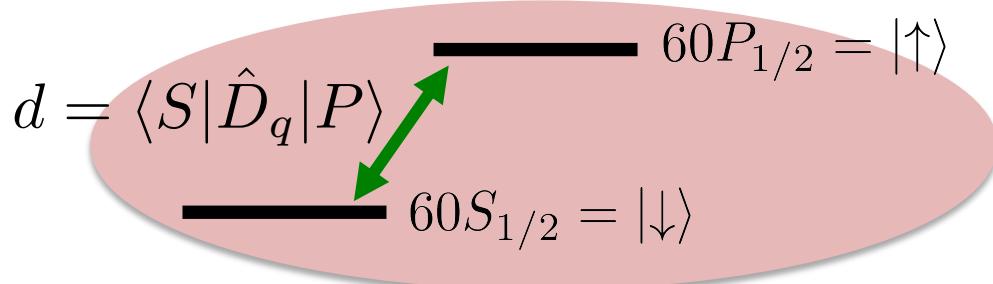


$$V \sim \frac{C_3}{R^3}$$

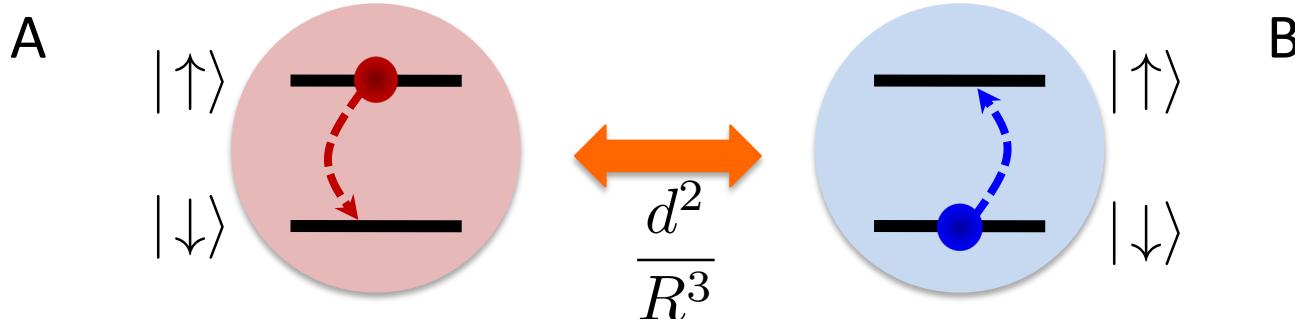
Resonant dipole-dipole interaction between Rydberg atoms



Resonant dipole-dipole interaction between Rydberg atoms



Mapping on
spin ½ system



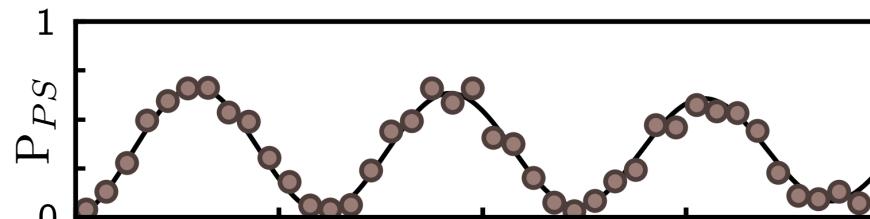
$$\hat{H} = \frac{d^2}{4\pi\epsilon_0 R^3} (\hat{\sigma}_A^+ \hat{\sigma}_B^- + \hat{\sigma}_A^- \hat{\sigma}_B^+)$$

Non radiative “exchange” of excitation

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

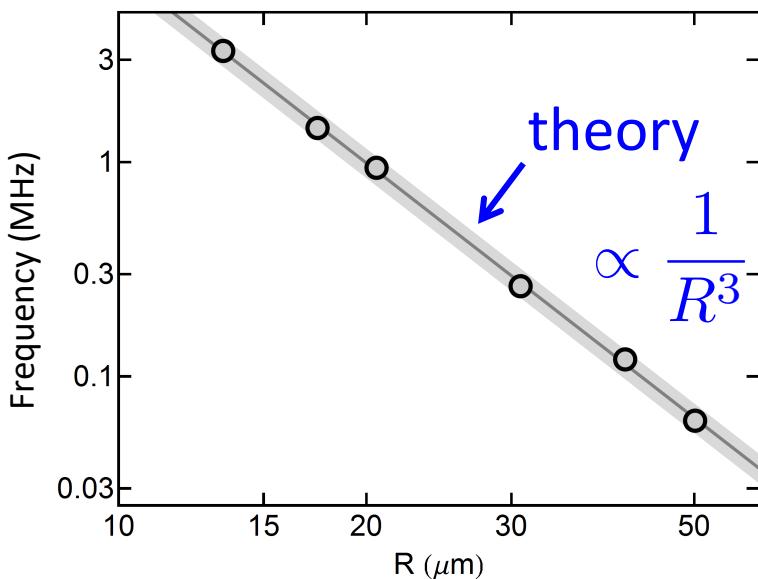
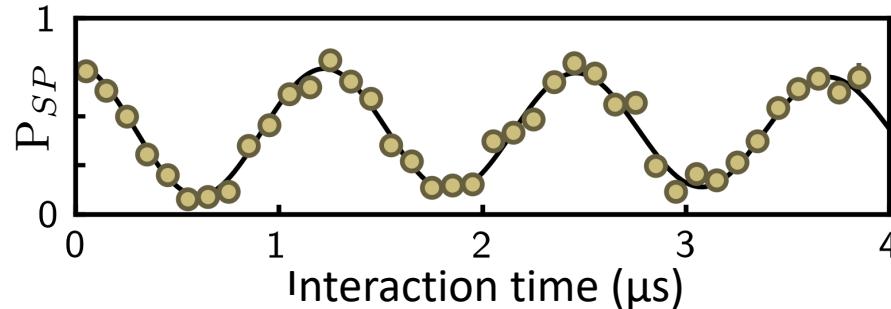
Prepare $|\uparrow\downarrow\rangle$ using microwaves + addressing beam

$$R = 30 \mu\text{m}$$



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

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



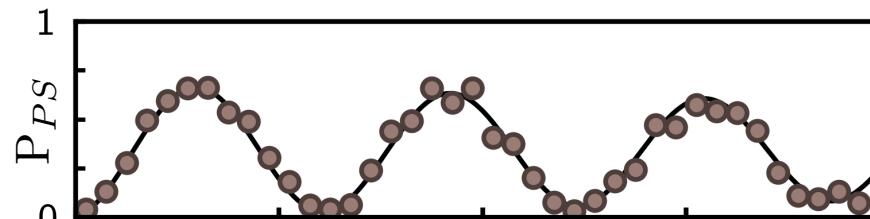
Thickness:

Paper sheet $\sim 100 \mu\text{m}$
Hair $\sim 50 - 100 \mu\text{m}$

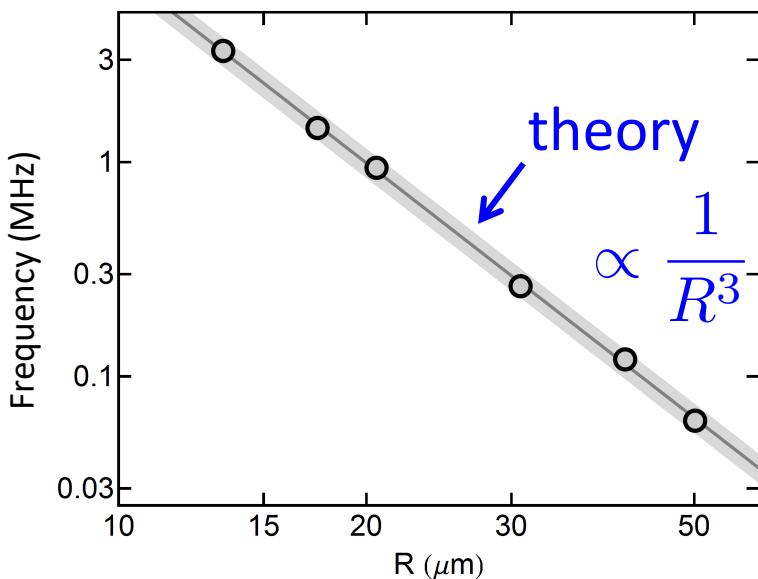
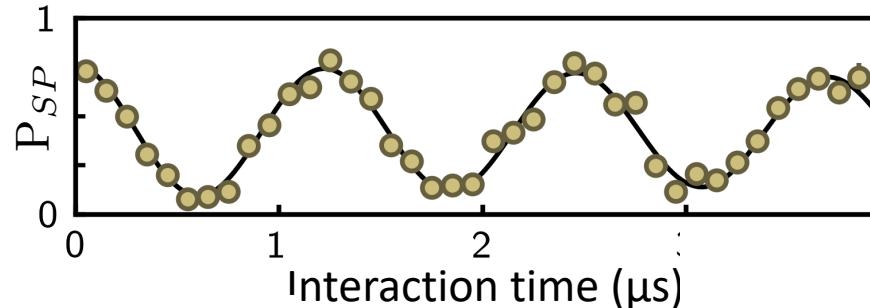
Observation of resonant dip.-dip. interaction with 2 atoms

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

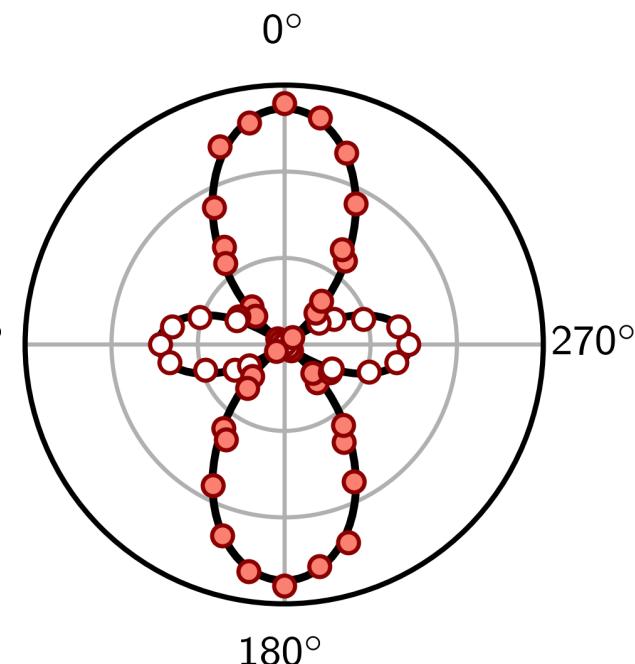
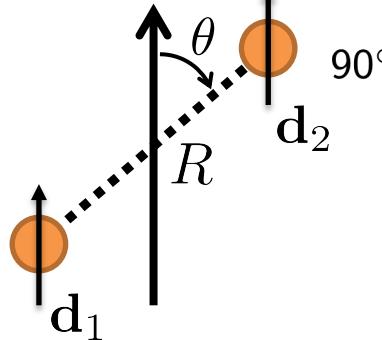
$$R = 30 \mu\text{m}$$



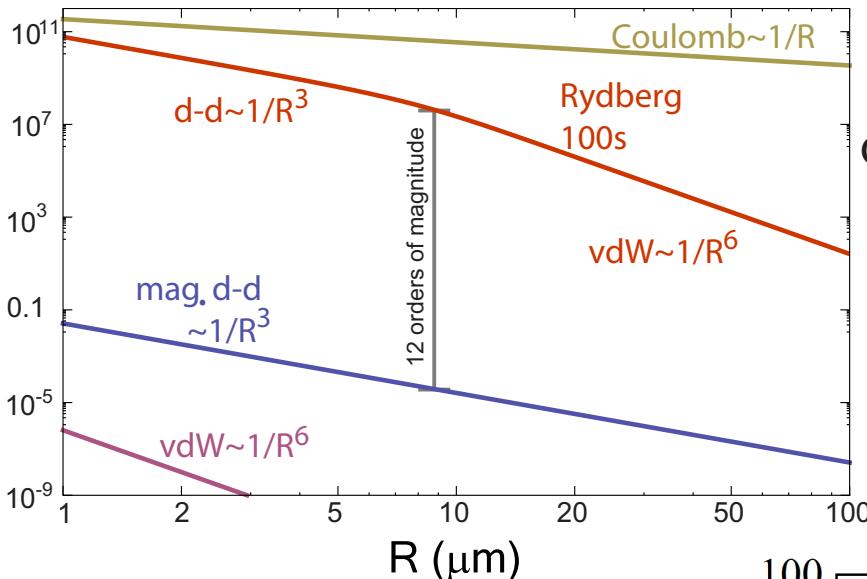
$$\text{Frequency: } \frac{2C_3}{R^3}$$



Quantization
axis (B)



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

