Cold Rydberg atoms

Applications to QIP, many-body physics

and quantum optics

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The "Quantum Optics – Atom" team at Institut d'Optique

https://atom-tweezers-io.org

2 projects:

Many-body physics with arrays of individual Rydberg atoms

Light scattering in dense, small cold atomic clouds

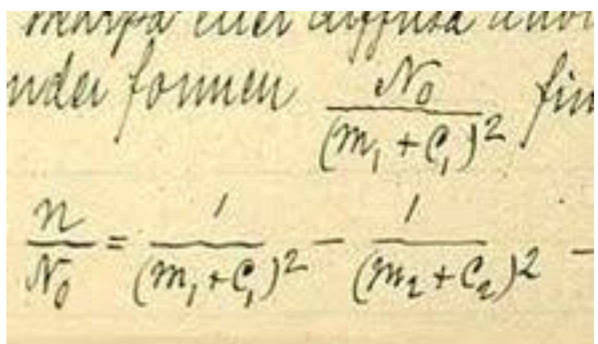
A few historical landmarks

1814 Joseph von Fraunhofer

observation of dark lines in spectrum of the sun

1888 "Rydberg formula"

Johannes Rydberg
1854-1919

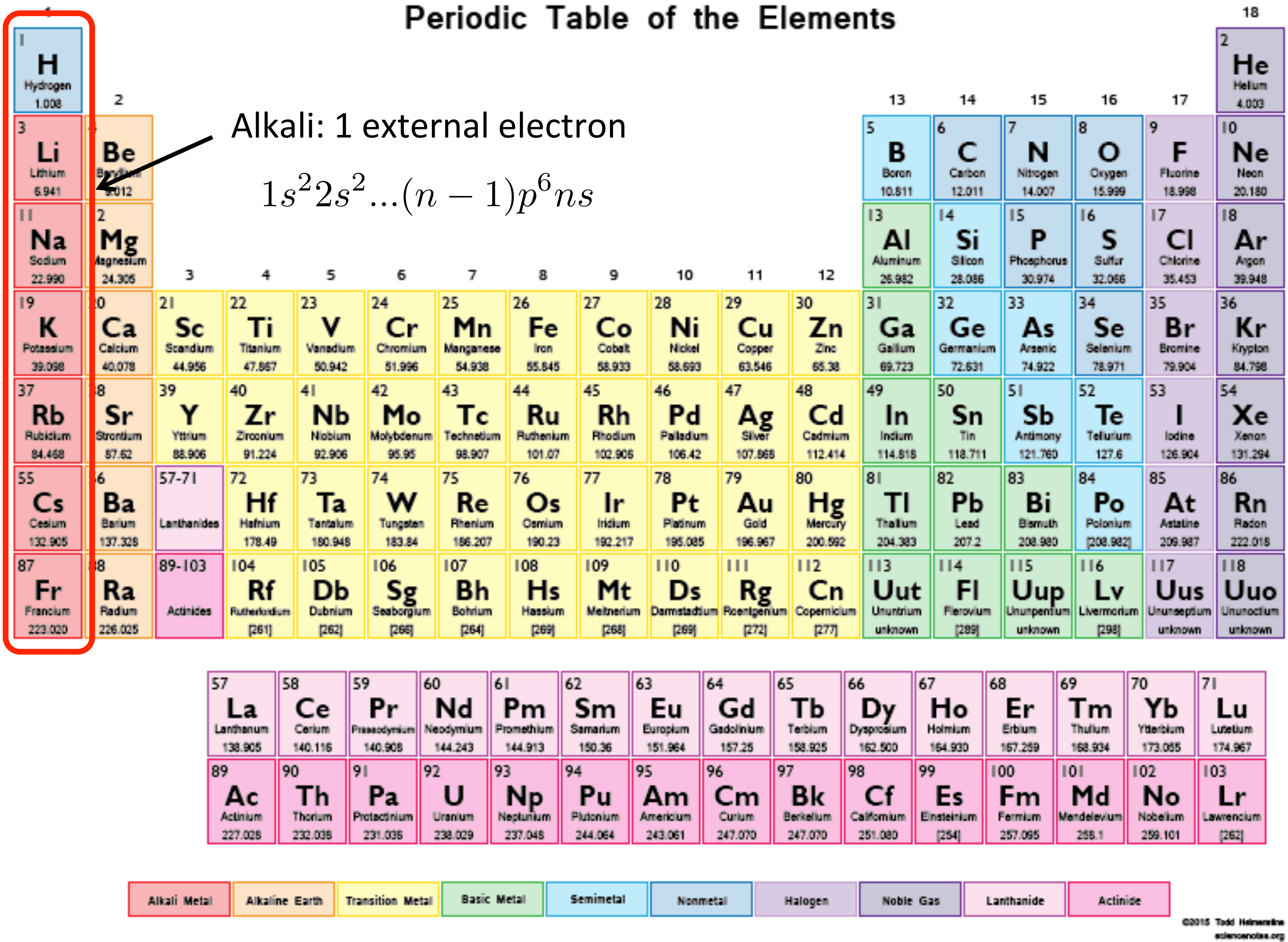


$$\frac{1}{\lambda_{nm}} = R_{\mathrm{H}} \left(\frac{1}{n^2} - \frac{1}{m^2} \right)$$

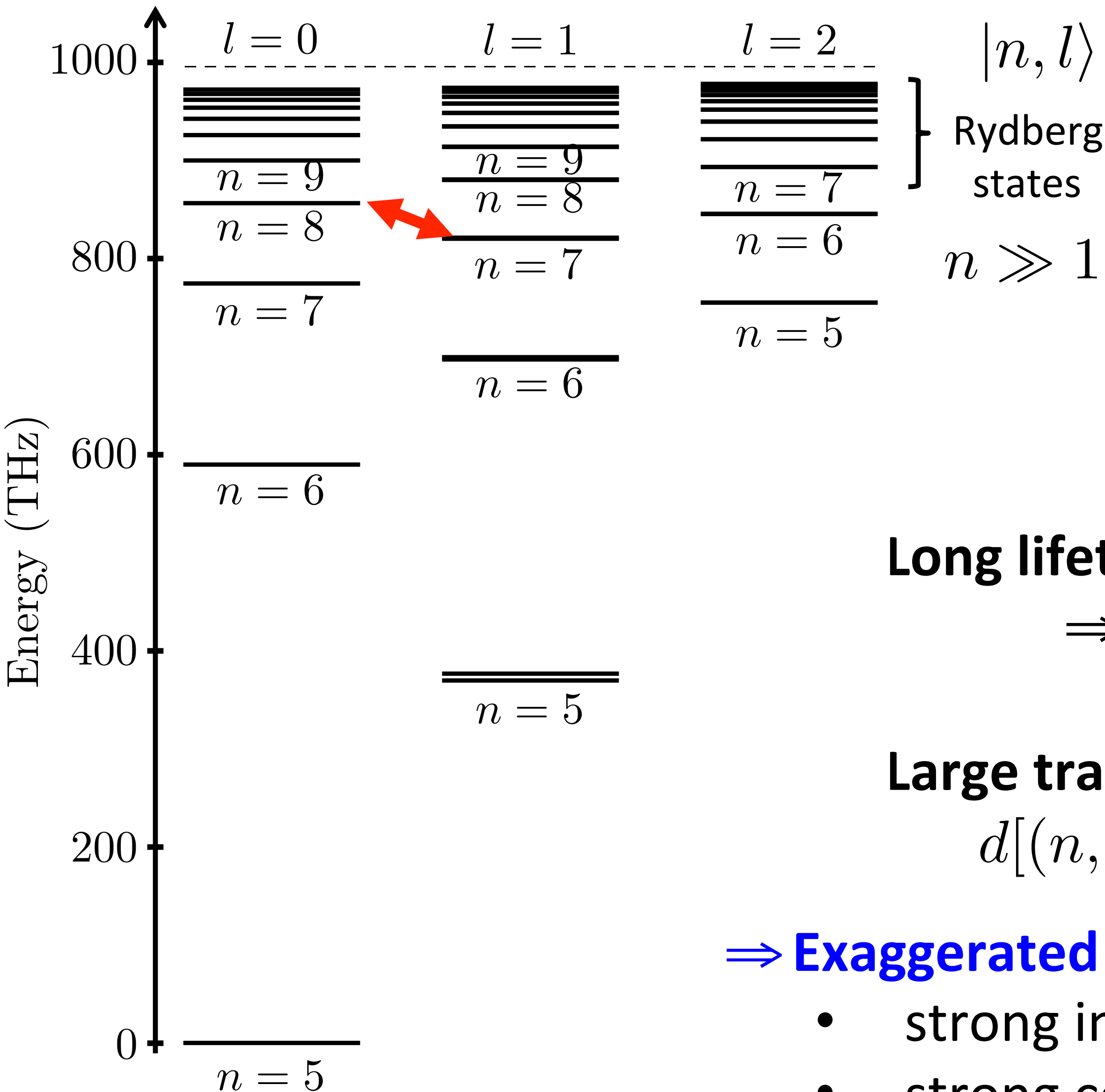
Idea of an infinite series
⇒ highly excited states

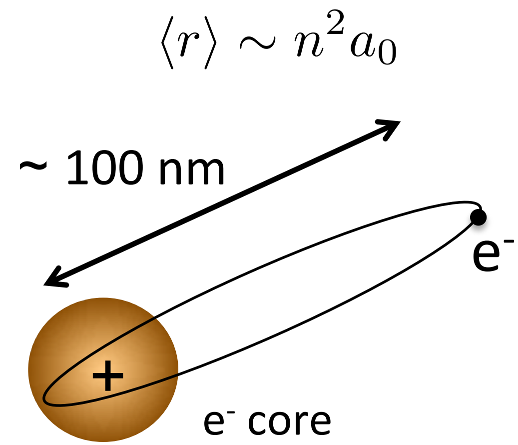
Alkali: 1 external electron

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



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





Long lifetime $\tau \sim n^3$

$\Rightarrow$ *n* > 60, τ > 100 μs

Large transition dipole:

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

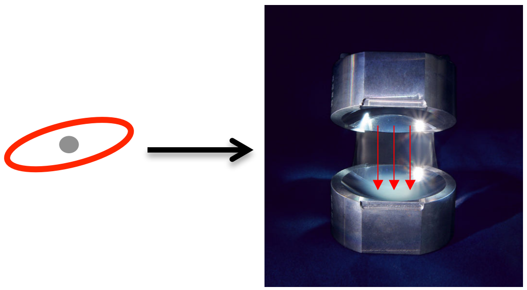
$\Rightarrow$ Exaggerated properties:

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

Back to history…

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

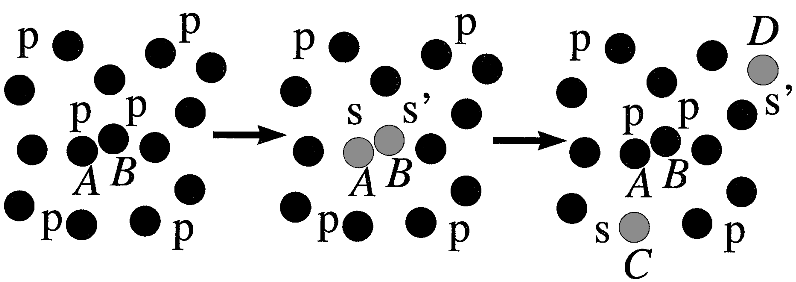
1980 – 2000 Cavity Quantum Electrodynamics using Rydbergs



High Q cavity: photon lifetime > 1ms
+ large dipole ⇒
1 Rydberg interacts with 1 photon!

Haroche, Walther…

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



p + p ⇔ s + s'
p + s ⇔ s + p

"Frozen" gas

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

Diffusion of excitation faster than motion ⇒ correlations between all atoms

$k_B T$ << Interaction energy
⇒ T < 1 mK

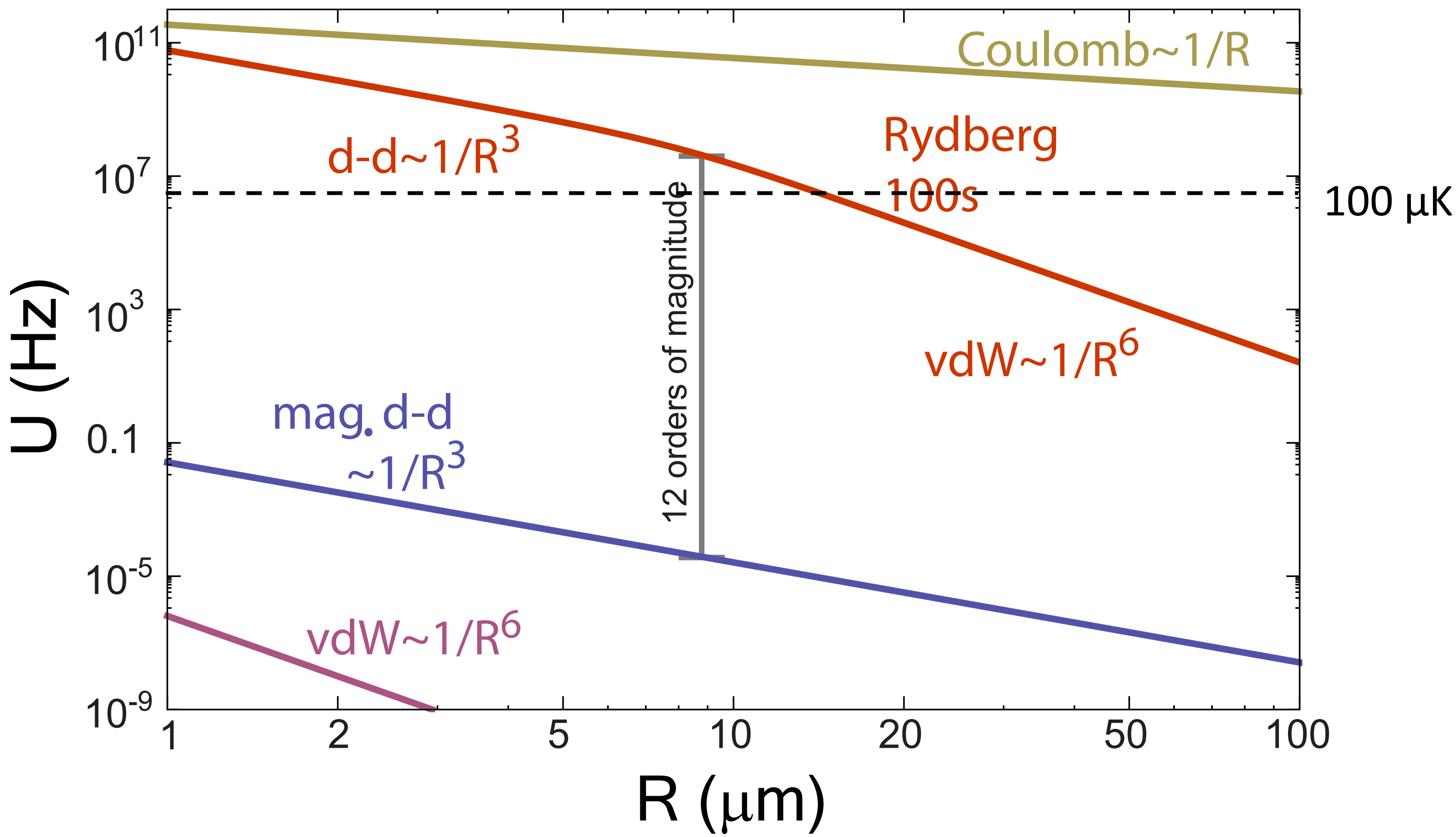
Interactions between Rydberg atoms

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

Quantum information with Rydberg atoms

M. Saffman and T. G. Walker
Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, Wisconsin 53706, USA

K. Mølmer



A new era: the Rydberg Blockade idea

VOLUME 85, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 2000

Fast Quantum Gates for Neutral Atoms

D. Jaksch, J. I. Cirac, and P. Zoller
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. 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]
[1]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
[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
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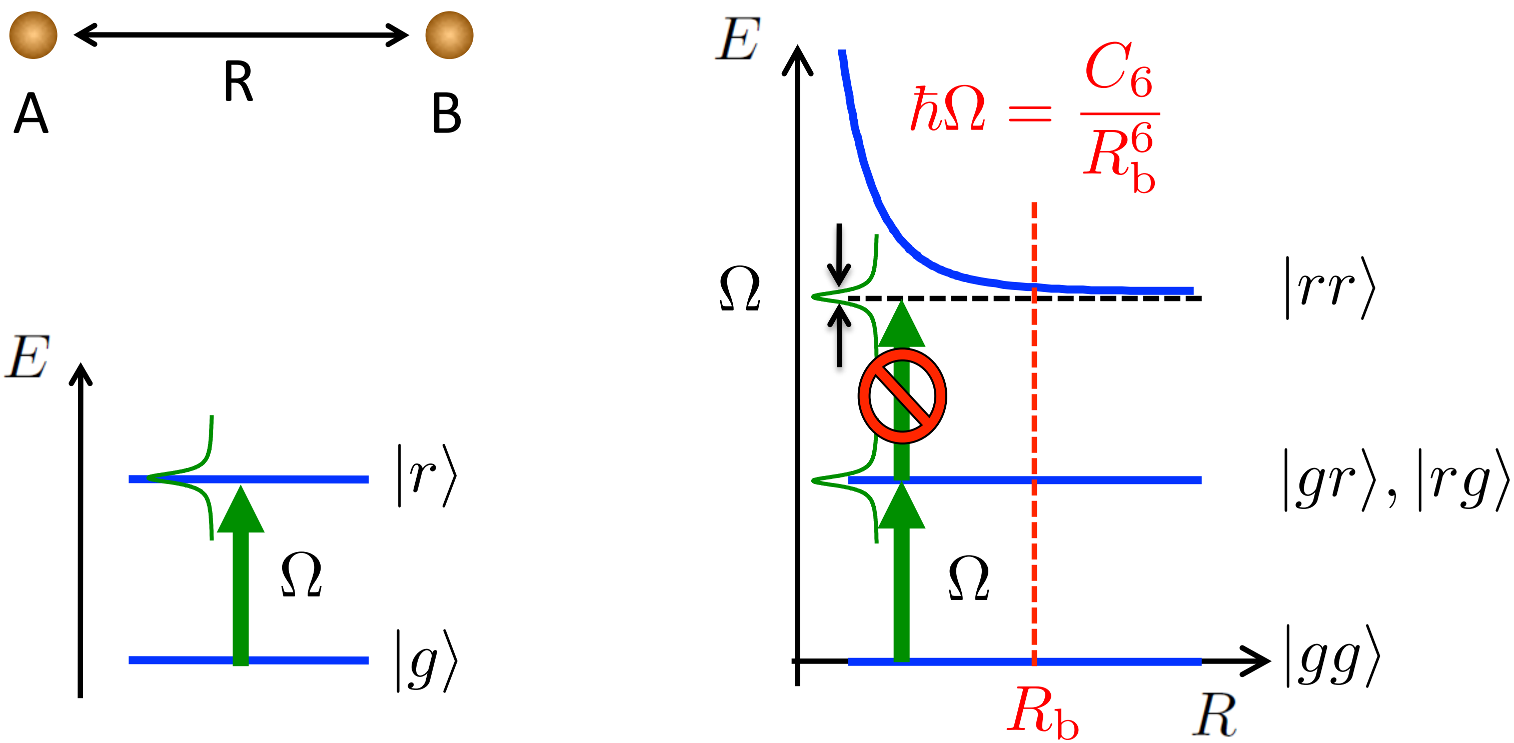
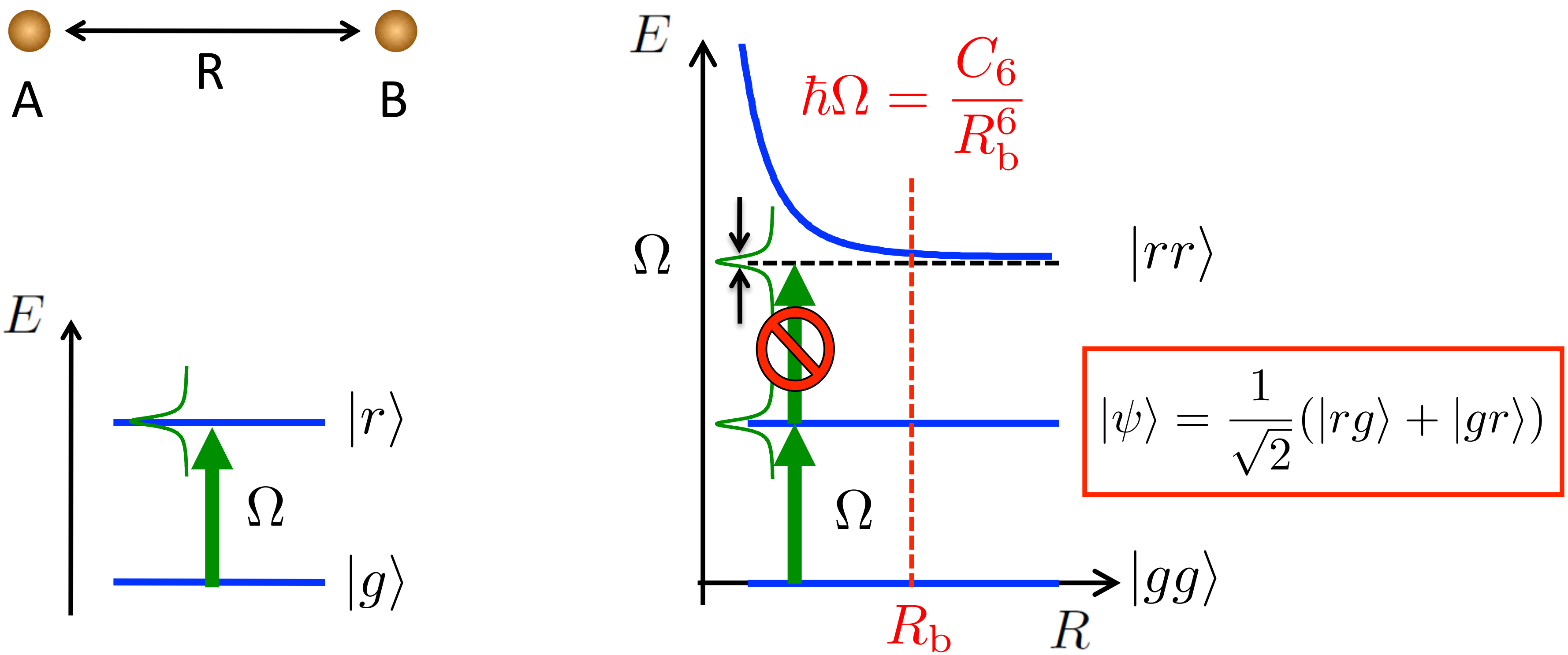
(Received 7 November 2000; published 26 June 2001)

A new era: the Rydberg Blockade idea



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

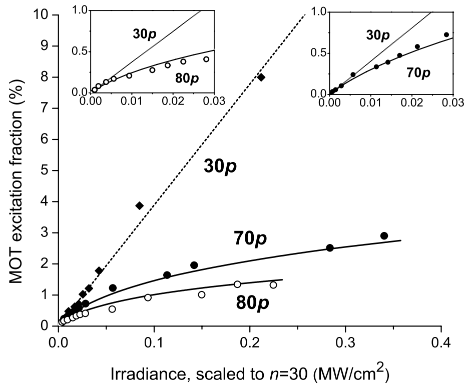
A new era: the Rydberg Blockade idea

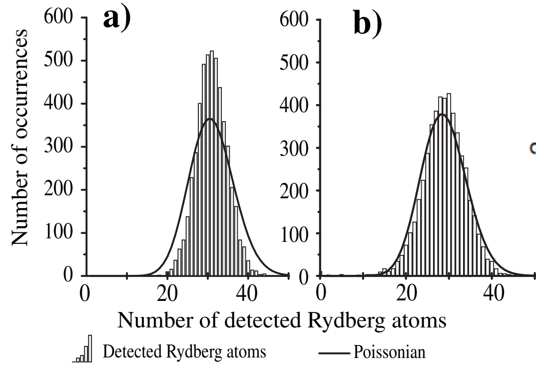


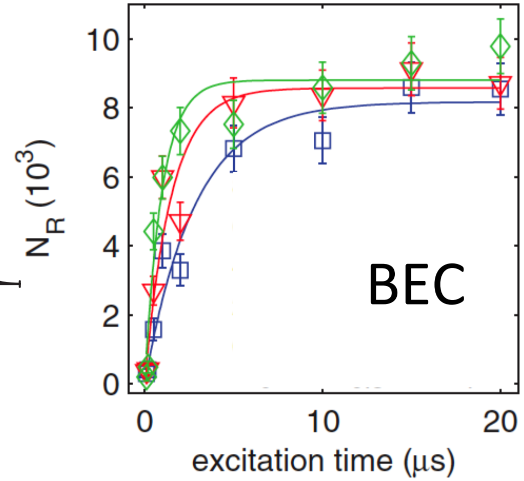
Blockade $\Rightarrow$ **entanglement and gates!!**

The first blockade experiments

Atomic ensembles







Gould, PRL 2004
Weidemuller, PRL 2004

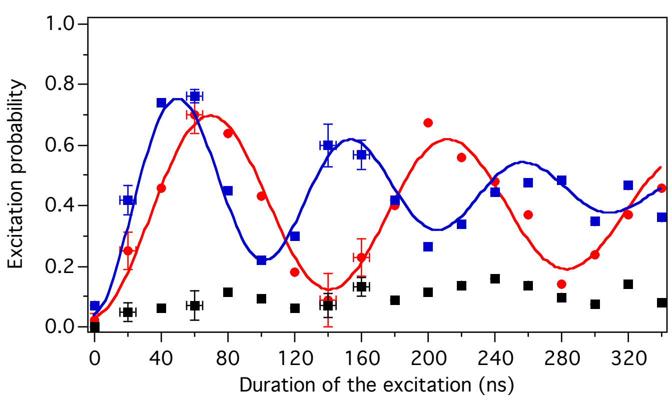
Martin, PRL 2004
Pillet, PRL 2006

Raithel, PRL 2005

Pfau, PRL 2007

Individual atoms

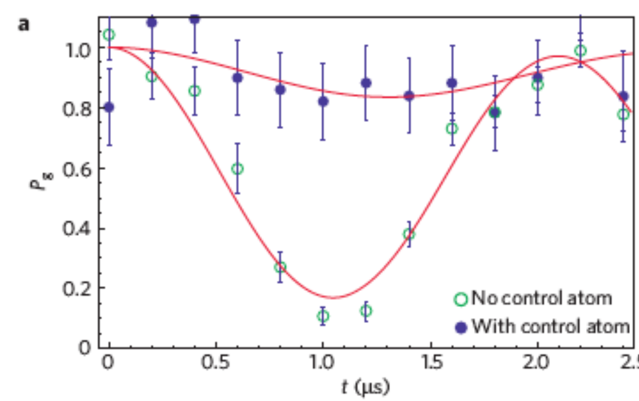
IO Palaiseau



Blockade + collective excitation √2

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

U. Wisconsin

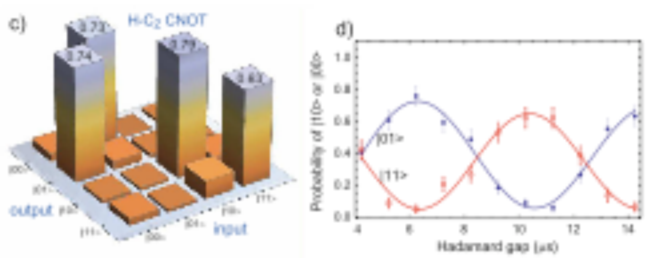


Blockade

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

And now (2017)… a few examples

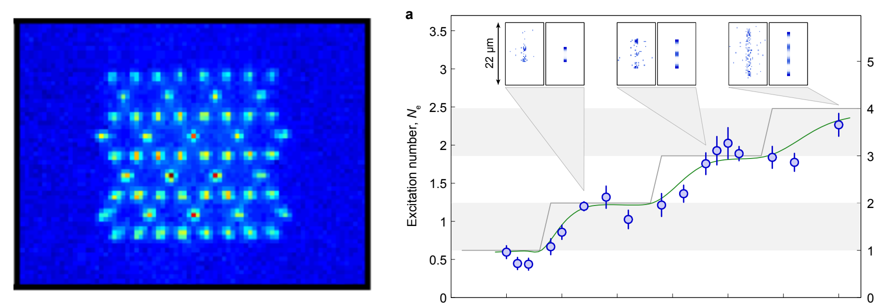
QIP: entanglement and gates



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

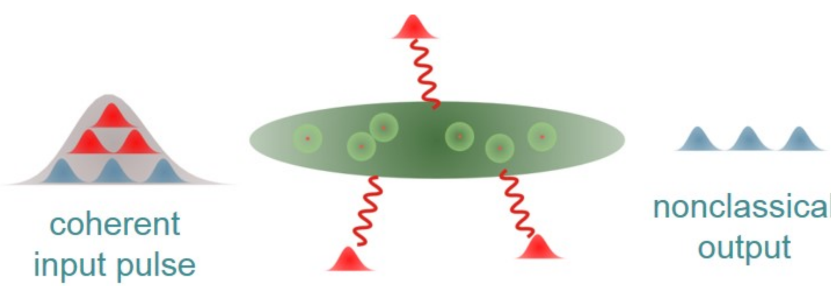
Saffman, Biedermann…

Many-body physics Quantum simulation



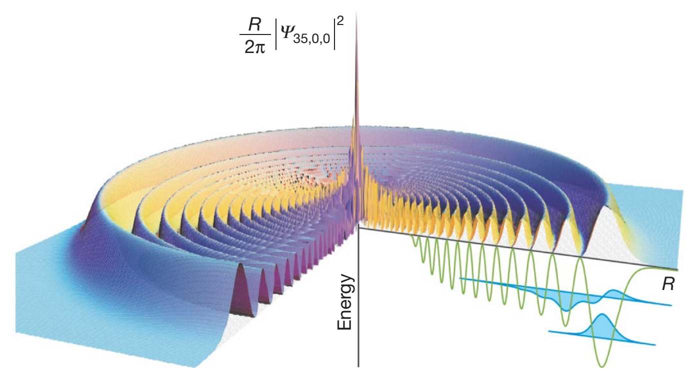
Browaeys, Lukin, Bloch, Pillet, Weidemuller, Morsch…

Non-linear classical & quantum optics



Adams, Hofferbert, Firstenberg, Lukin, Vuletic…

Exotic long-range molecules



Pfau-Löw, Ott, Shaeffer …

Outline

Lecture 1: Rydberg atoms and their interactions (~2h)

Lecture 2: Rydberg blockade and application to QIP (~1h)

Lecture 3: Quantum simulation & Quantum Optics with Rydbergs (~1h)

Properties of Rydberg atoms

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

Quantum defects for alkali atoms

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

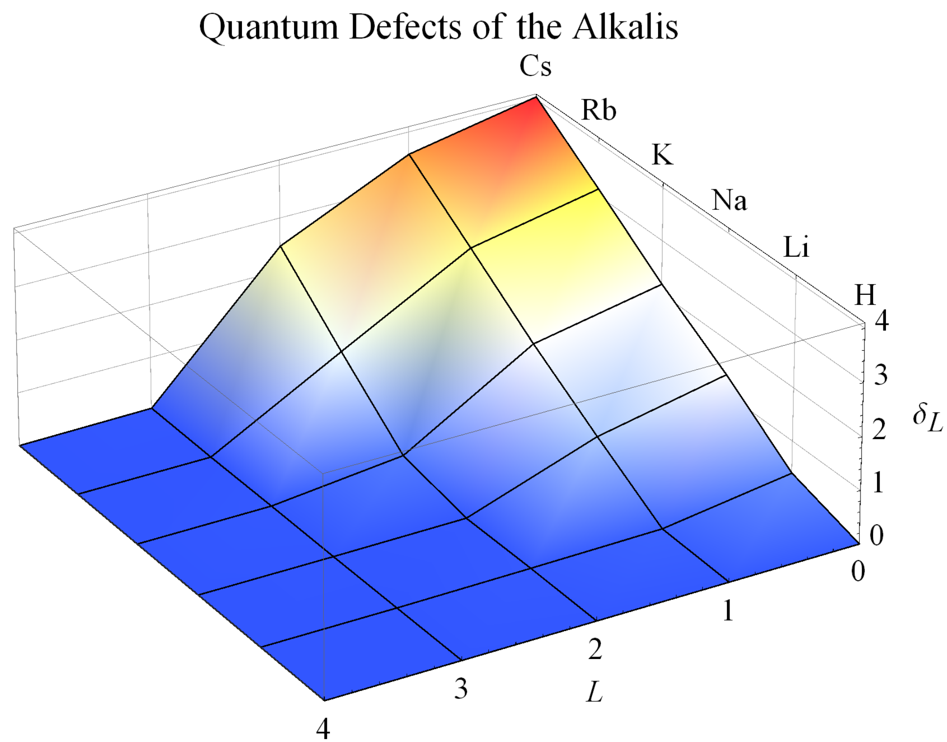
$$R_y^\infty = 10\ 973\ 371.568\ 539\ \mathrm{m}^{-1}$$

Quantum defects **(Experimental)**

For Rb:

$n \geq 30$

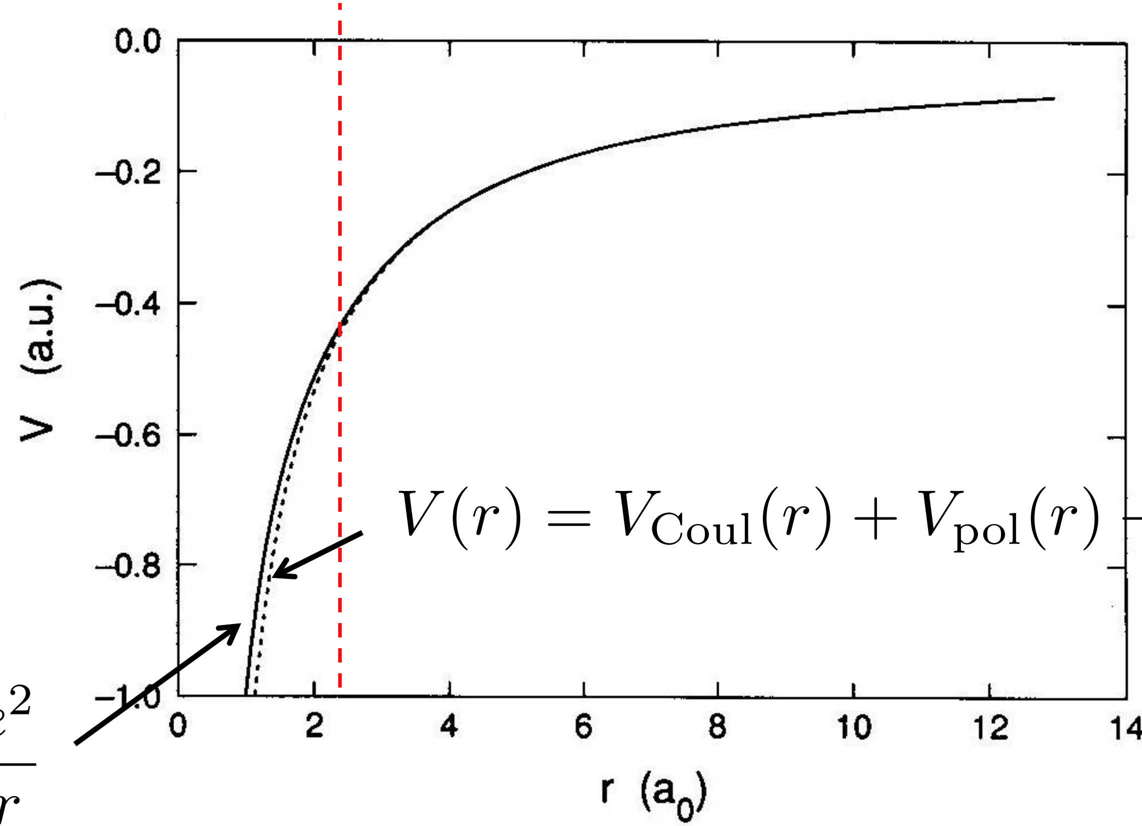
L	J	$\delta_{L,J}$
0	1/2	3.131
1	1/2	2.654
	3/2	2.641
2	3/2	1.348
	5/2	1.346
3	5/2	0.016
	7/2	0.016



The "effective" potential

$r > r_c \Rightarrow$ Coulomb potential

Na



$$V(r) = V_{\mathrm{Coul}}(r) + V_{\mathrm{pol}}(r) + V_{\mathrm{SO}}(r)$$

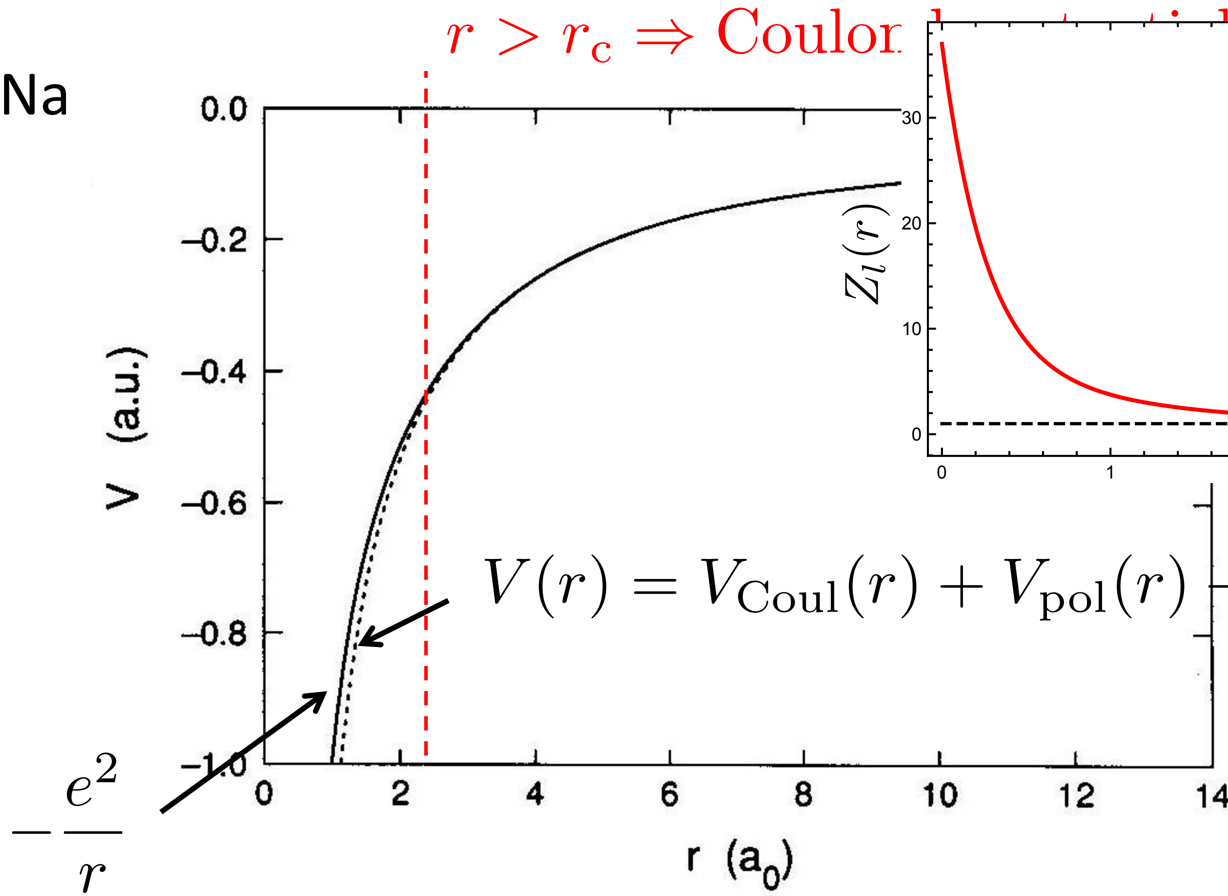
$$-\frac{e^2}{r}$$

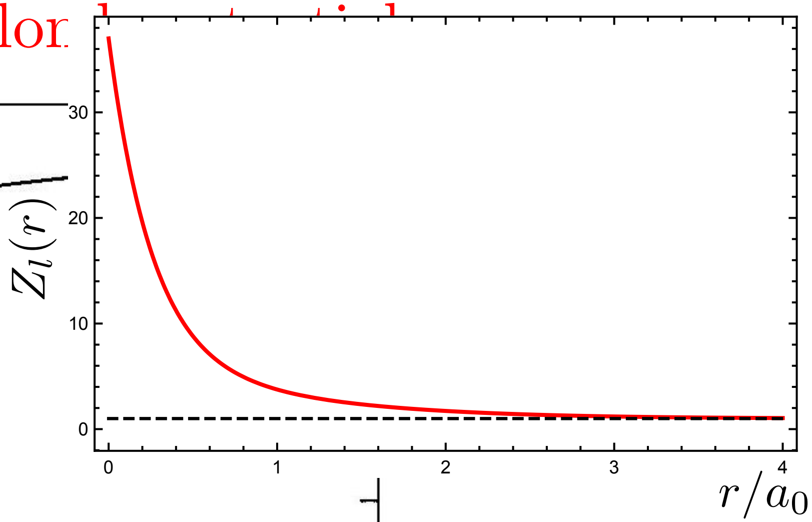
$$V_{\mathrm{Coul}}(r) = -\frac{Z_l(r)e^2}{r} \qquad V_{\mathrm{pol}}(r) = -\frac{\alpha_{\mathrm{D}}}{2r^4} \qquad V_{\mathrm{SO}}(r) = \frac{\alpha^2}{2r^3}\mathbf{L}\cdot\mathbf{S}$$

Marinescu, PRA **49**, 982 (1994)

The "effective" potential

Na



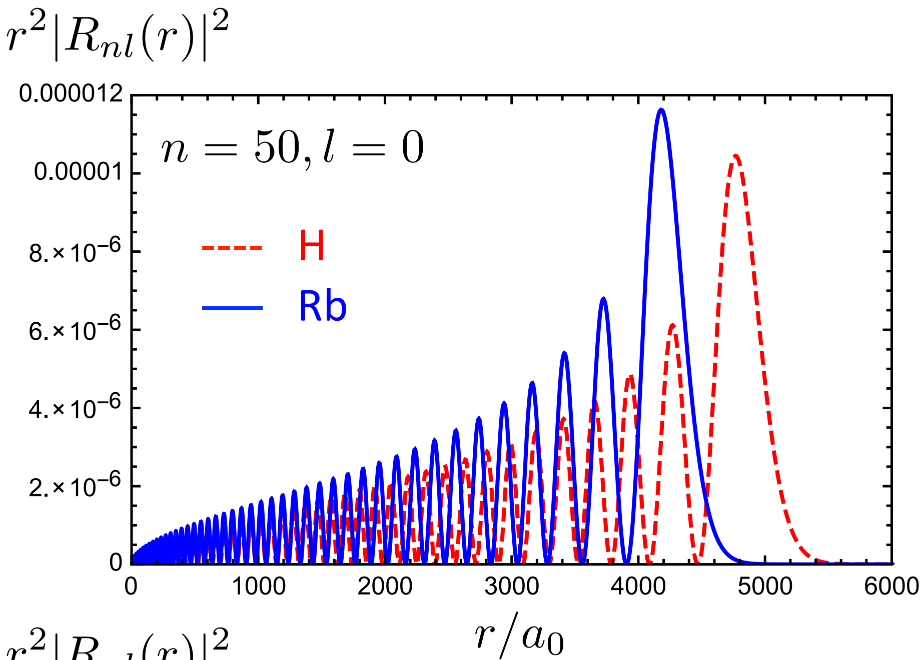


$$V(r) = V_{\mathrm{Coul}}(r) + V_{\mathrm{pol}}(r) + V_{\mathrm{SO}}(r)$$

$$V_{\mathrm{Coul}}(r) = -\frac{Z_l(r)e^2}{r} \qquad V_{\mathrm{pol}}(r) = -\frac{\alpha_{\mathrm{D}}}{2r^4} \qquad V_{\mathrm{SO}}(r) = \frac{\alpha^2}{2r^3}\mathbf{L}\cdot\mathbf{S}$$

Marinescu, PRA **49**, 982 (1994)

Radial wave-function for rubidium

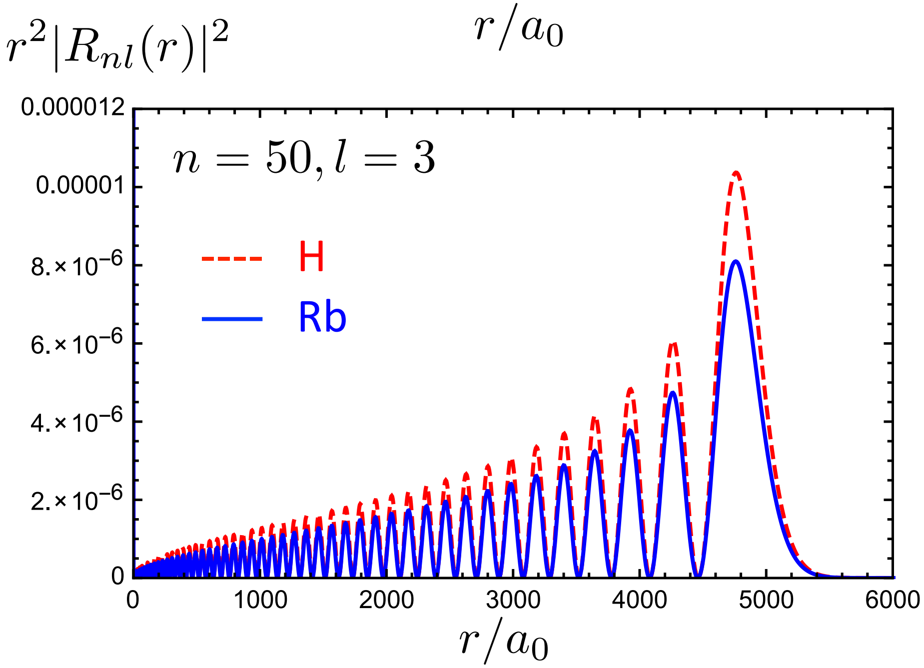


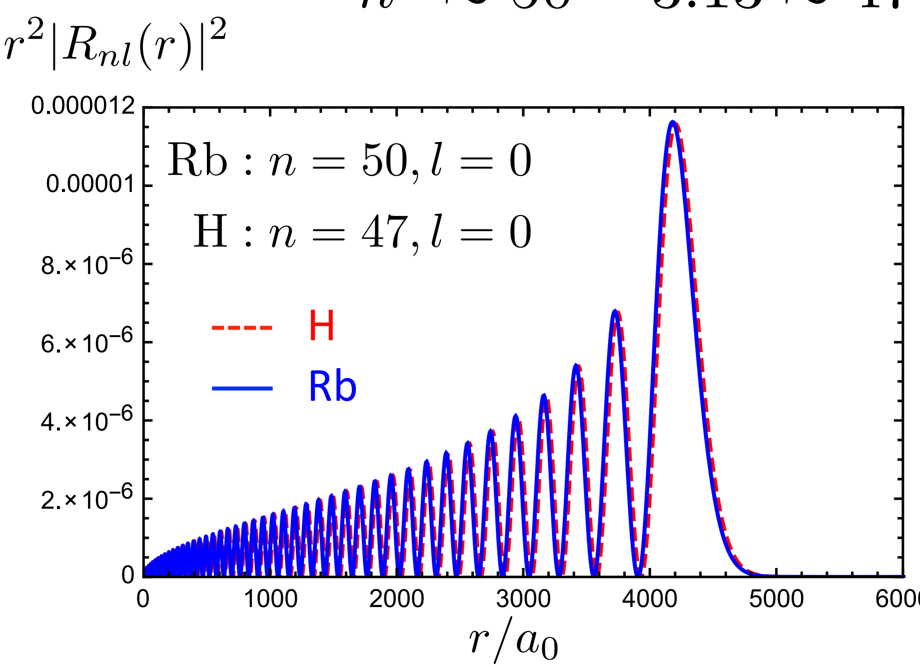
Numerov algorithm

Zimmerman, PRA 20, 2251 (1978)

$$n = 50 \Rightarrow n^* = n - \delta_0$$

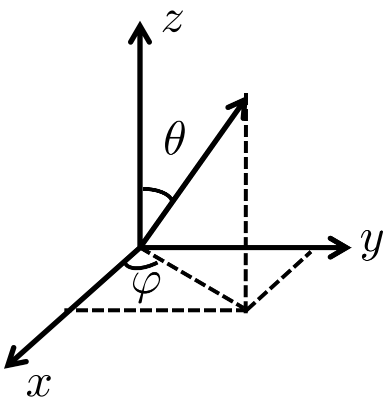
$$n^* \approx 50 - 3.13 \approx 47$$

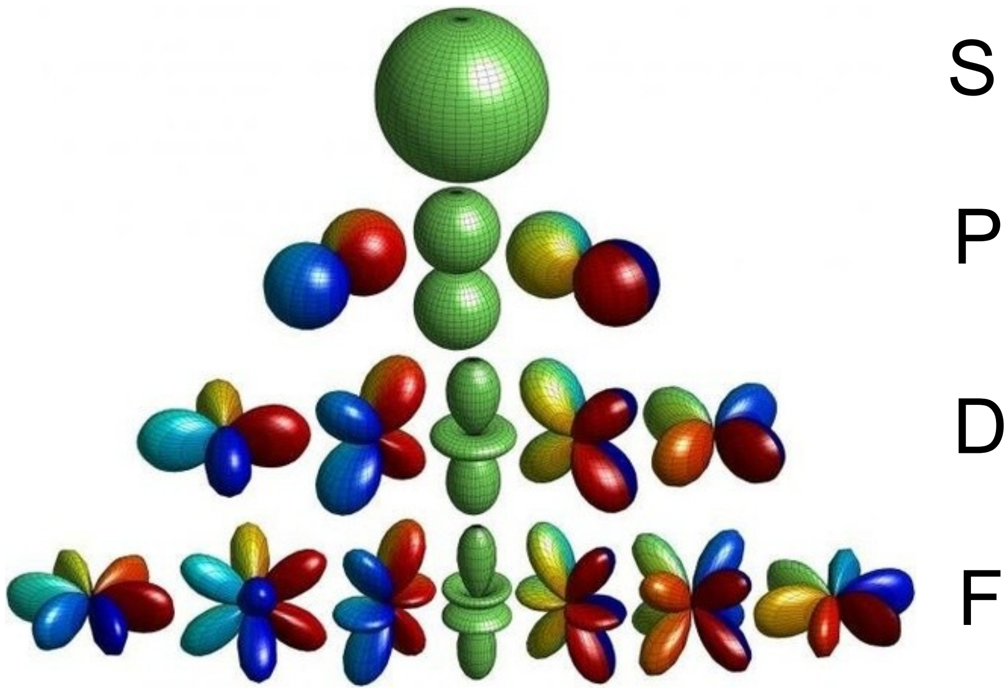




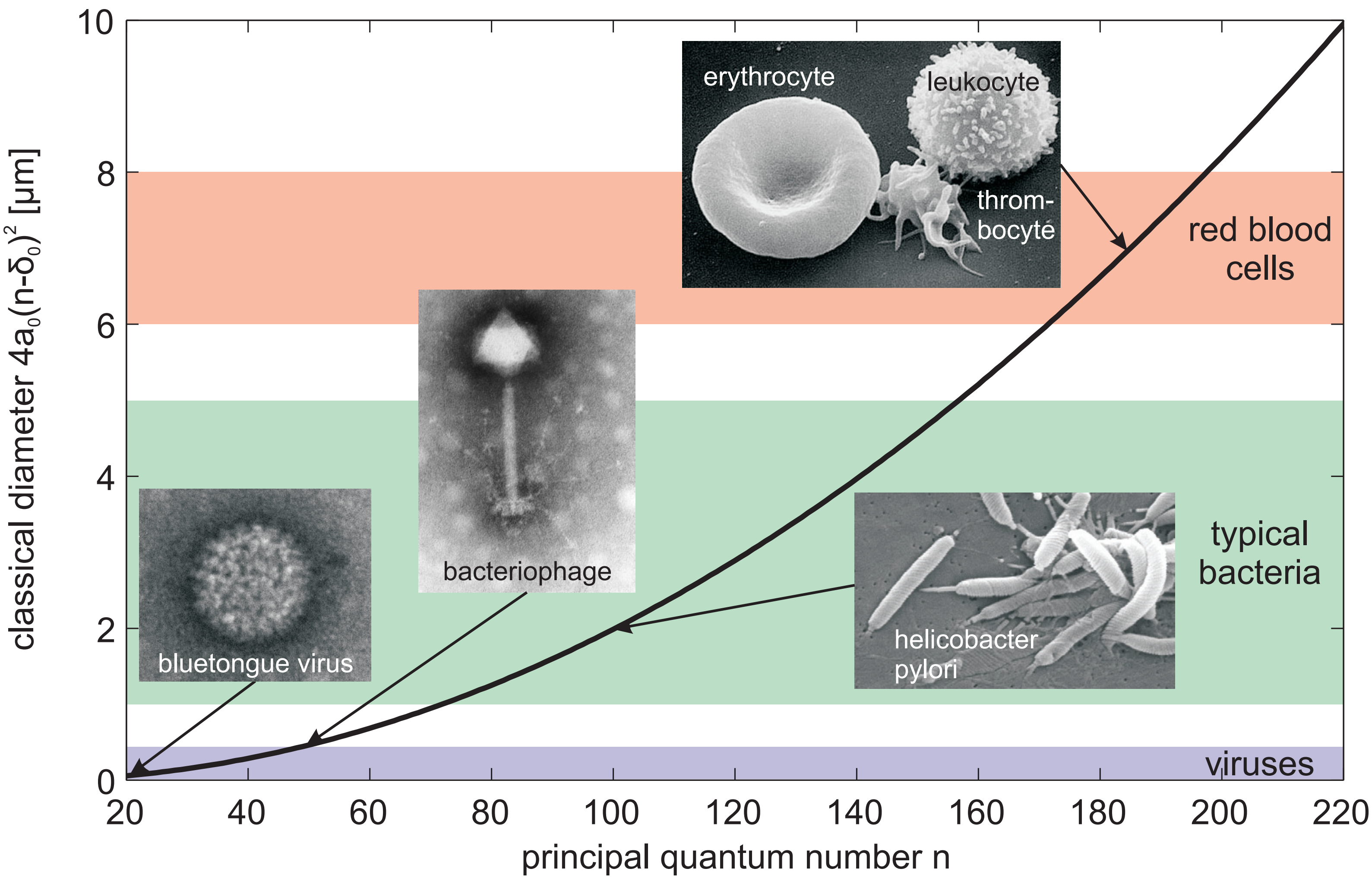
Angular wave-function

$$|Y_{lm}(\theta, \varphi)|^2$$



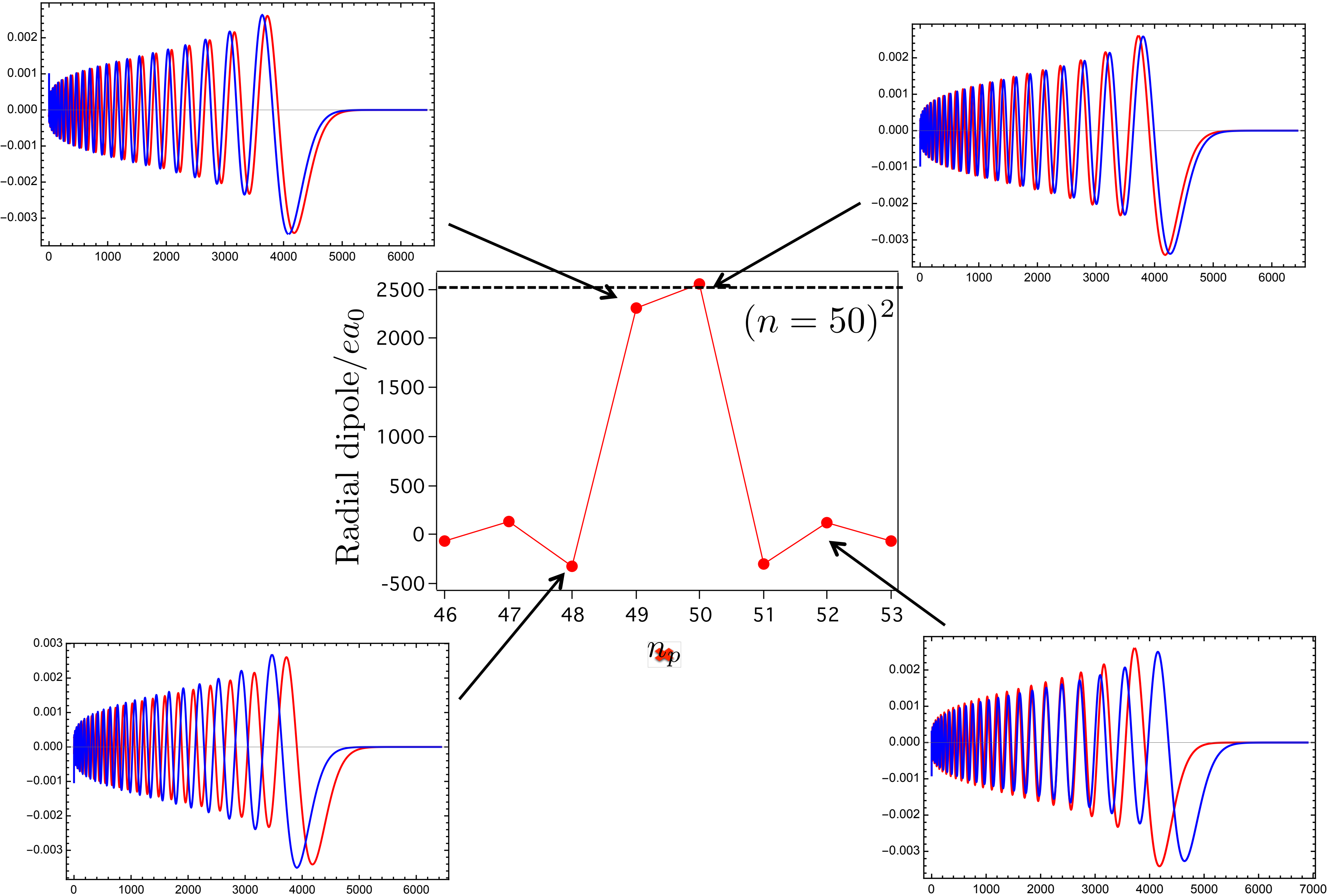


Rydberg atoms are huge…

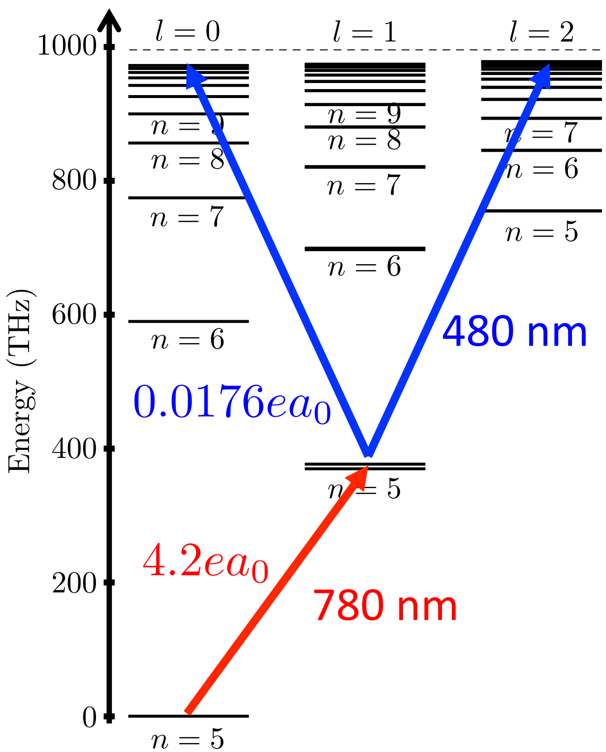


J. Balewski, PhD thesis

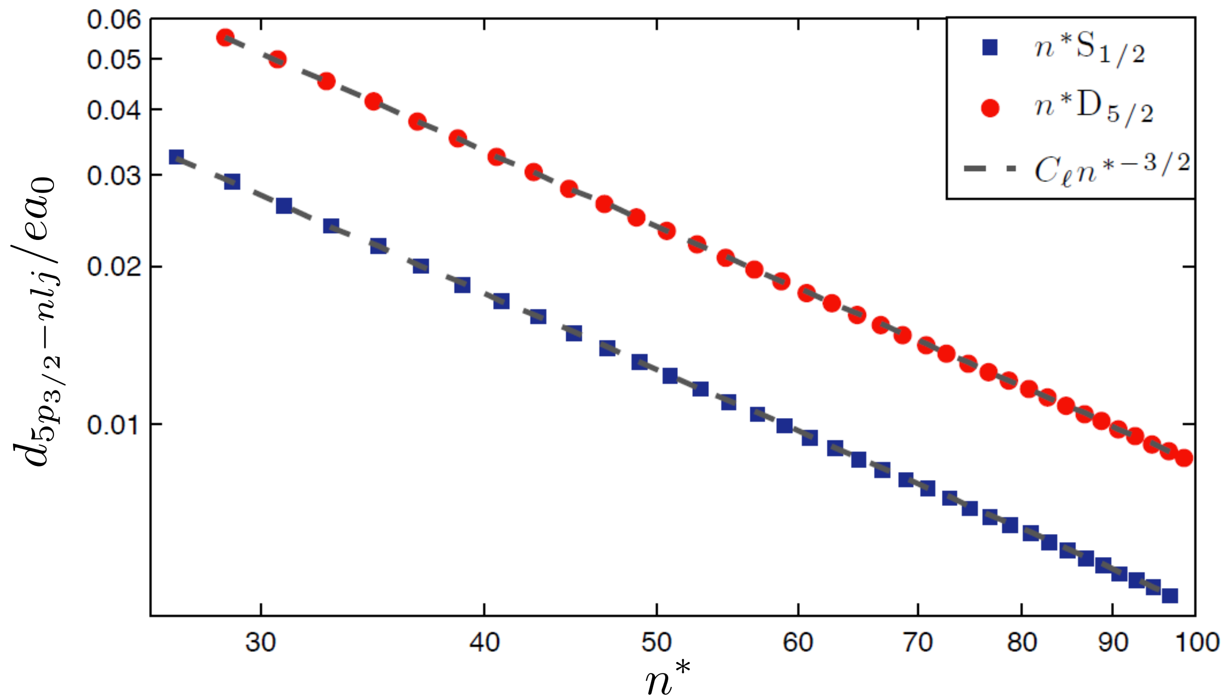
Dipole matrix element from 50*s* (radial part)



Dipole matrix element from low lying states



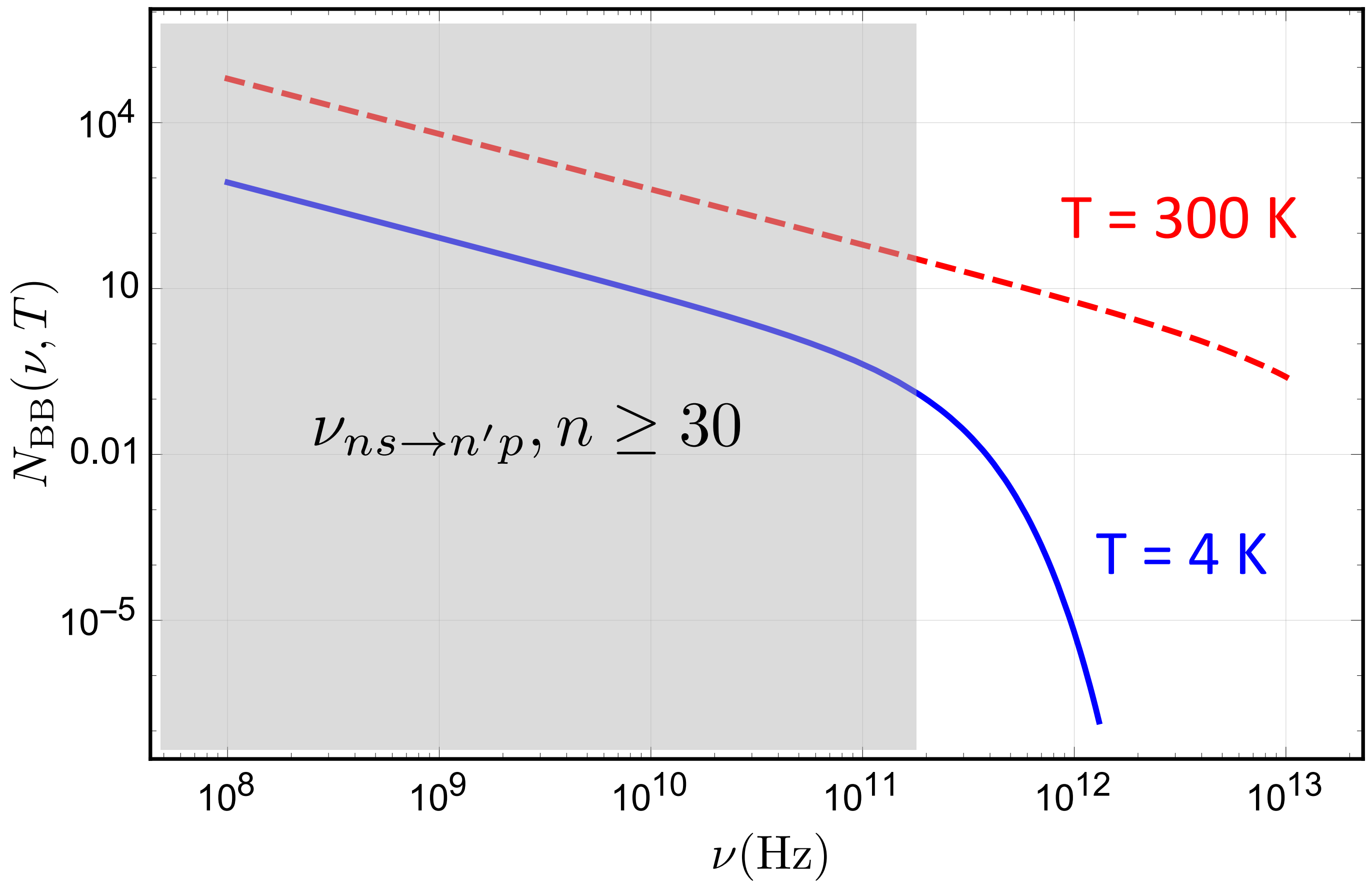
$$d_{5p_{3/2}-nlj} \propto \frac{ea_0}{(n^*)^{\frac{3}{2}}}$$



S. Hofferberth

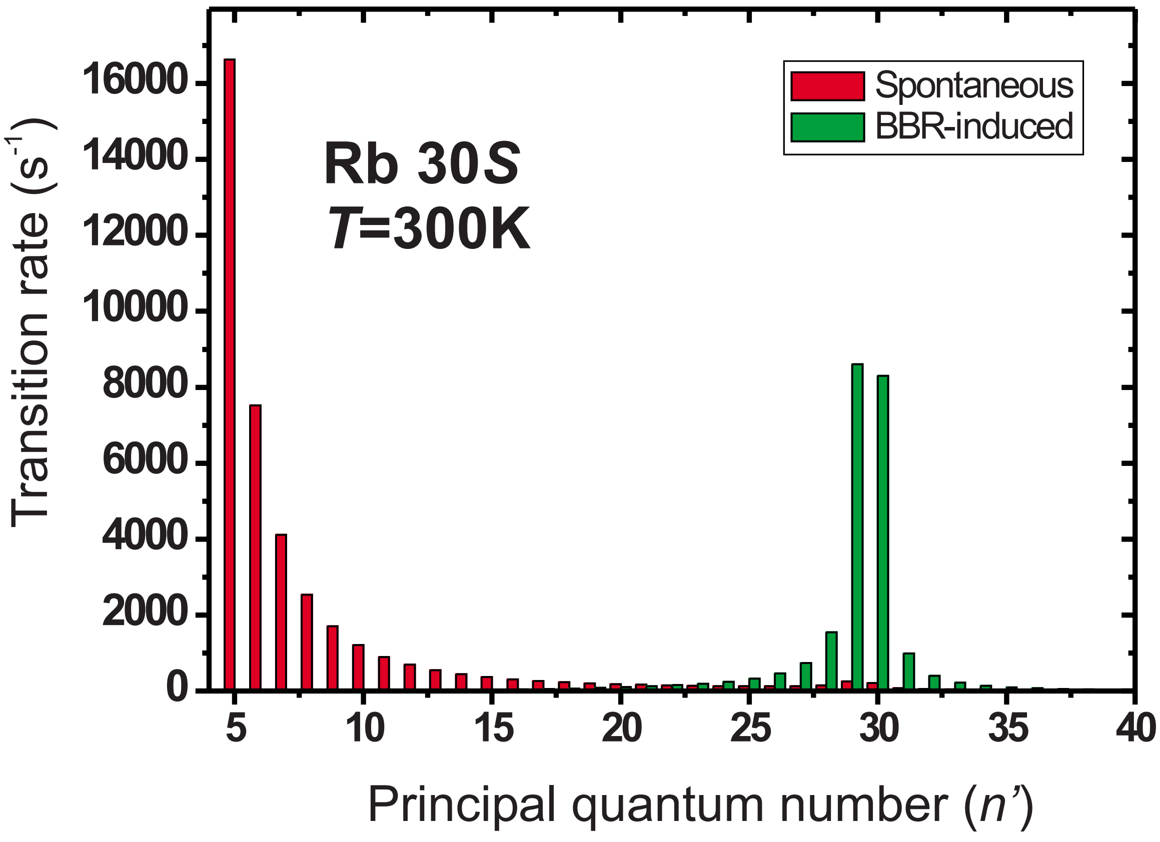
Black-Body radiation

Number of photons / mode: $$N_{\mathrm{BB}}(\nu,T)=\frac{1}{e^{\frac{h\nu}{k_{\mathrm{B}}T}}-1}$$



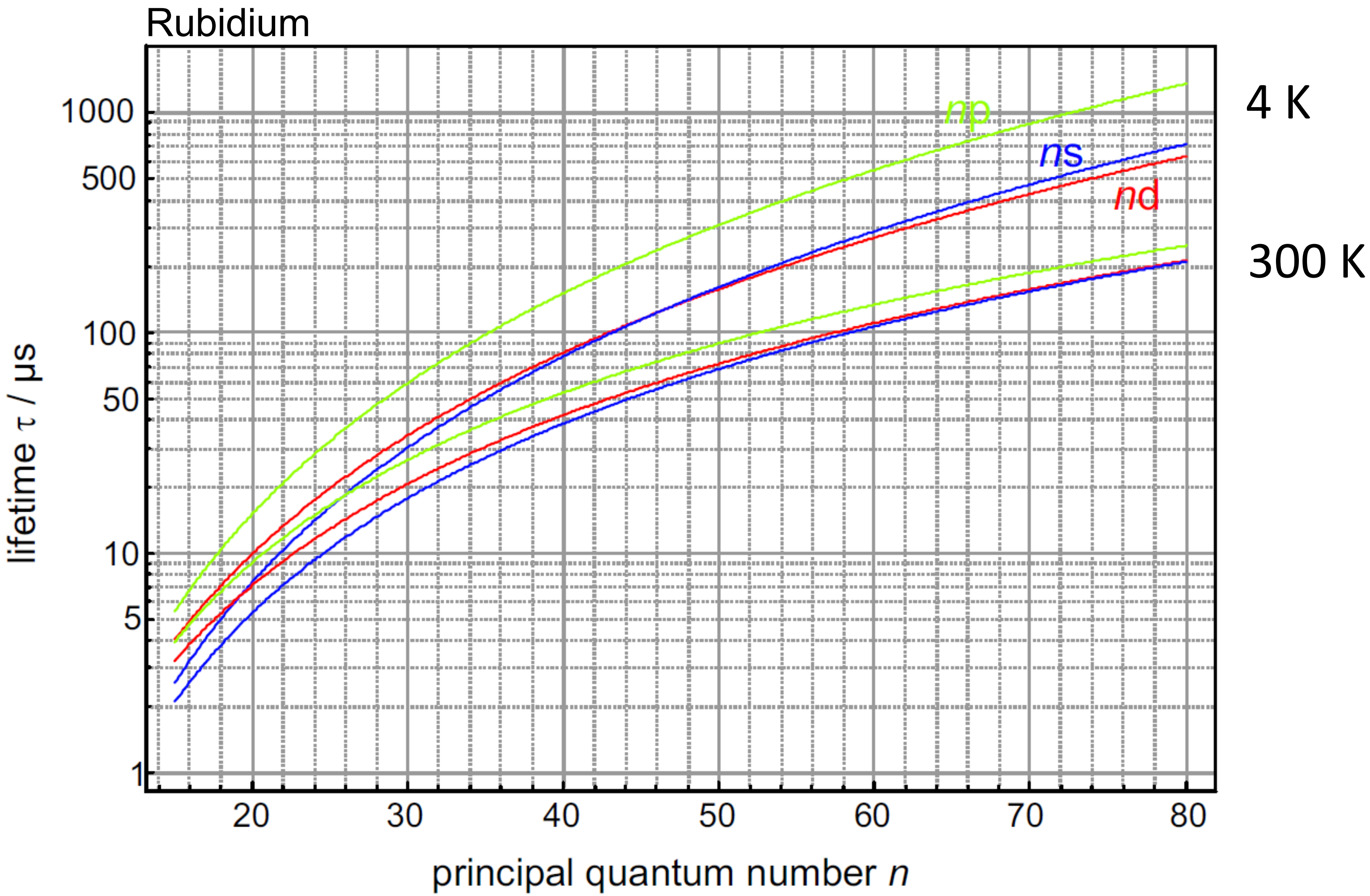
Stimulated rate: $\Gamma^{\mathrm{stim,BB}}_{n\to n'}=\Gamma^{\mathrm{rad}}_{n\to n'}N_{\mathrm{BB}}(\nu,T)$

Rydberg lifetimes



Beterov *et al.*, Phys. Rev. A **79**, 052504 (2009)

Rydberg lifetimes



S. Hofferberth

Stark map without fine structure (Li)

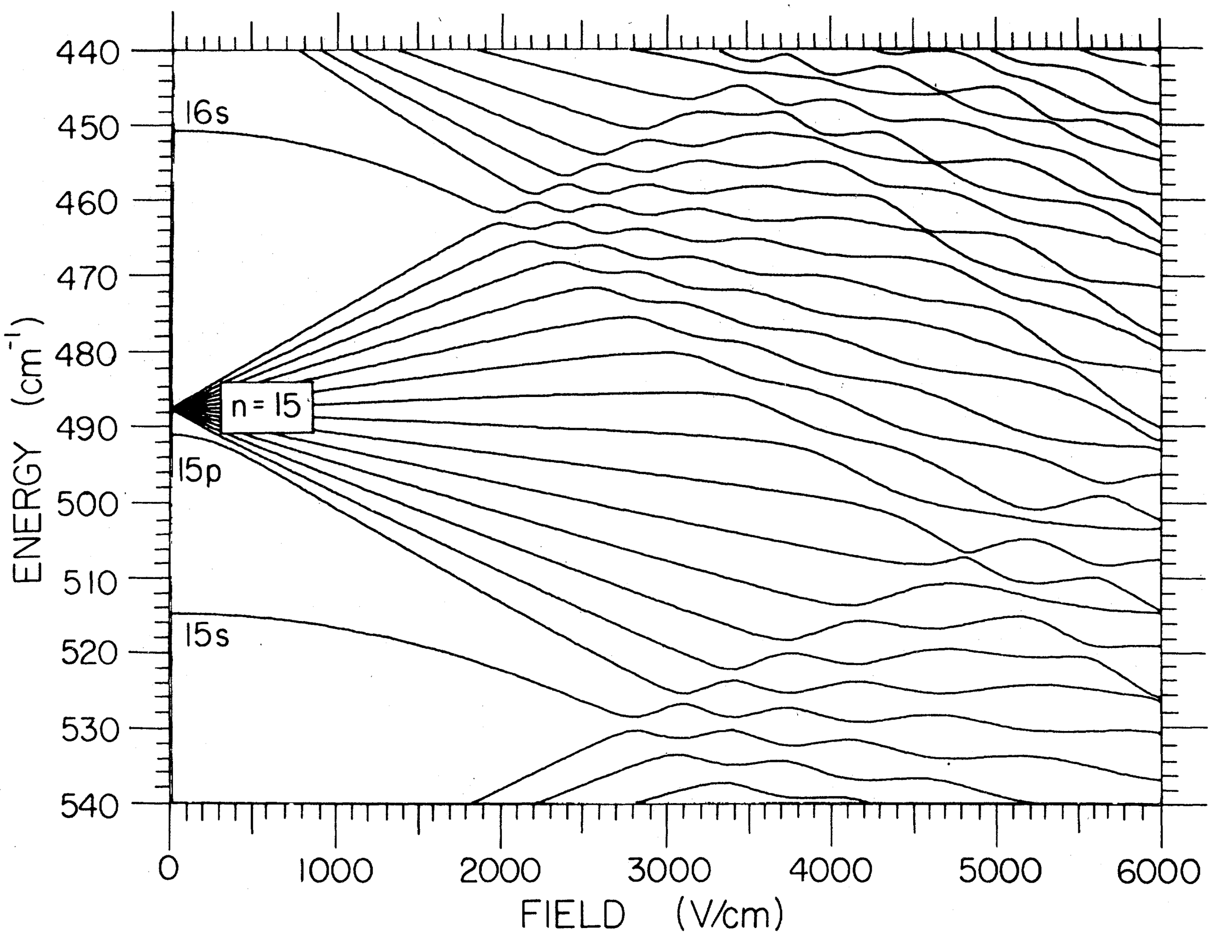


FIG. 6. Lithium, $m = 0$.

Zimmerman, PRA 20, 2251 (1978)

Summary: Rydberg have exaggerated properties

Table 1. Properties of Rydberg states.

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

A few experimental considerations

References:

Laser cooling and trapping, Nobel Lectures Phillips, Chu, Cohen-Tannoudji, Rev. Mod. Phys. **70**, july 1998

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

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

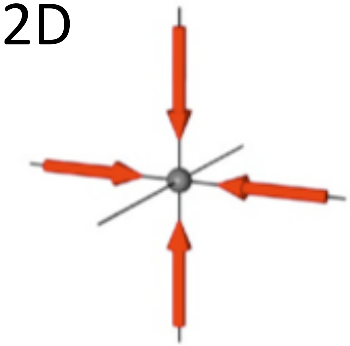
Optical lattices

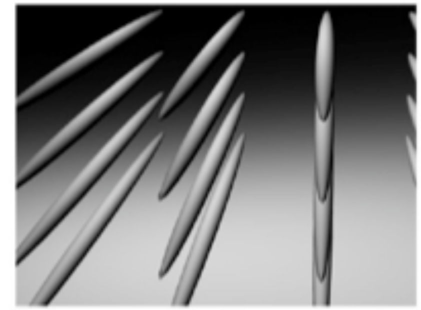
1D

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

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

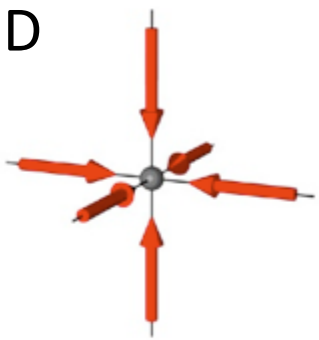
2D

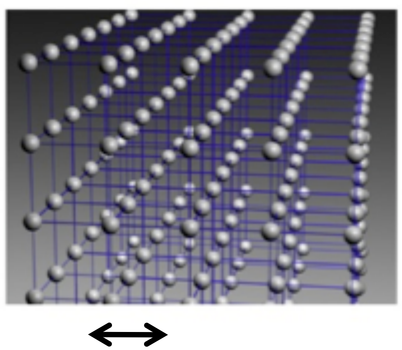




Single site resolution (< 1 μm)

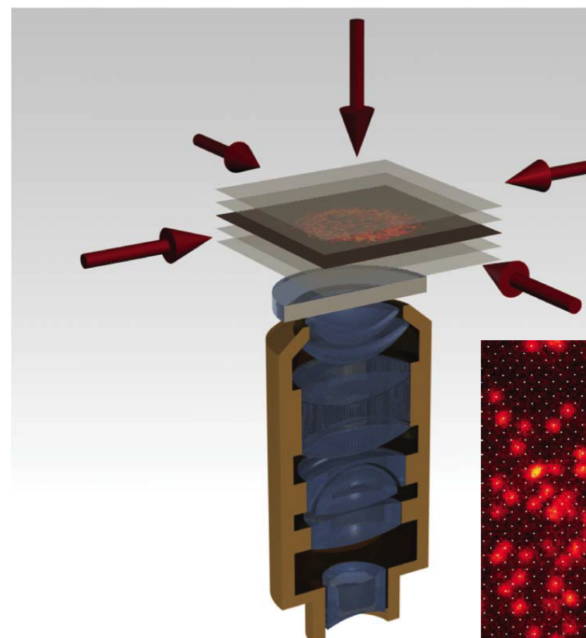
3D

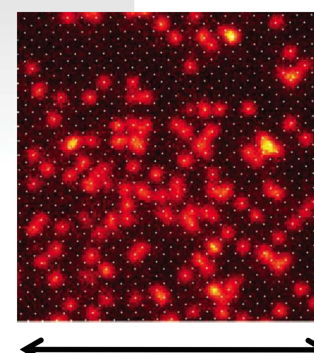




$\lambda/2 = 0.5\ \mu m$

(M. Greiner thesis)



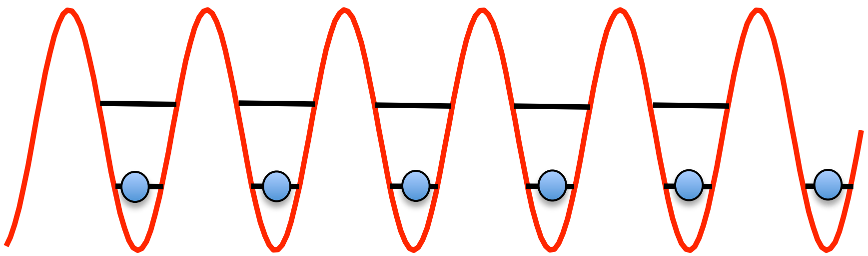


16 μm

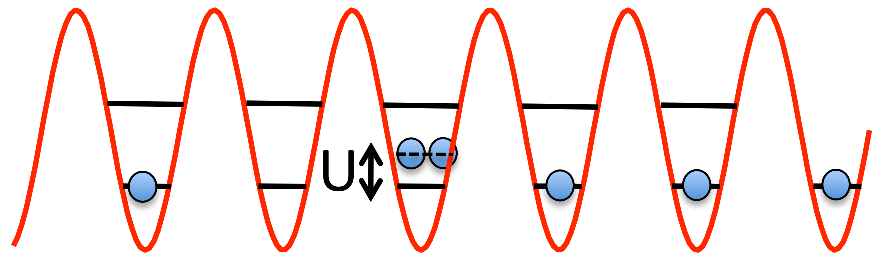
Bakr *et al.*, Nature **462**, 74 (2009)
Sherson *et al.*, Nature **467**, 68 (2010)

Preparation of individual atoms in optical lattices

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



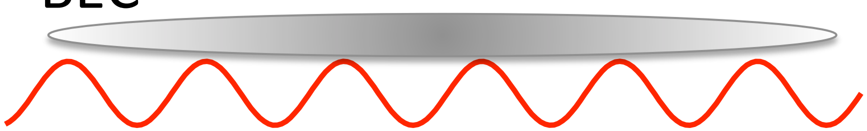
$6E_0$

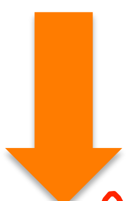


$6E_0 + U$ (~1kHz)

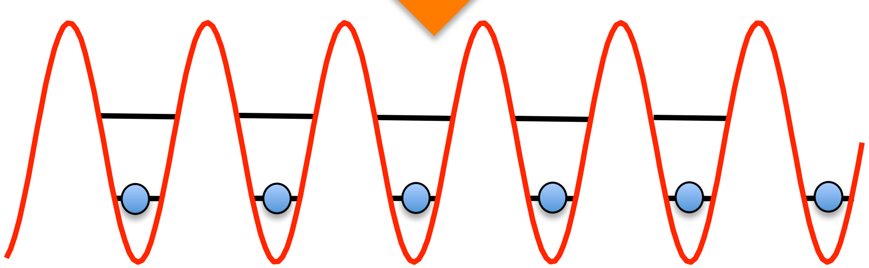
$$U = \frac{4\pi\hbar^2 a}{m}\int |\phi(\mathbf{r})|^4 d^3\mathbf{r}$$

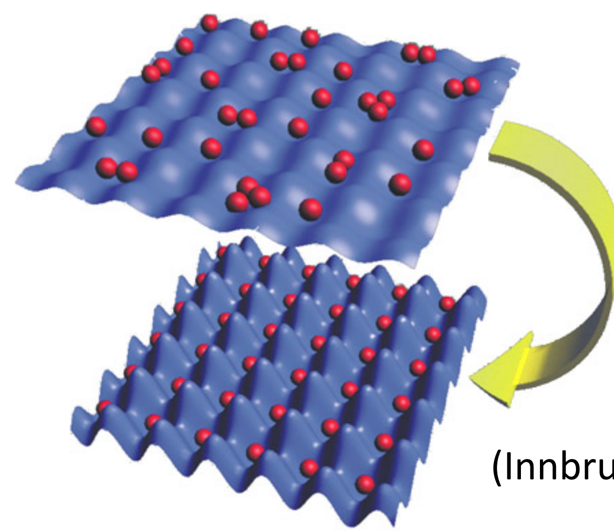
BEC





Adiabatic increase:
connects ground-states



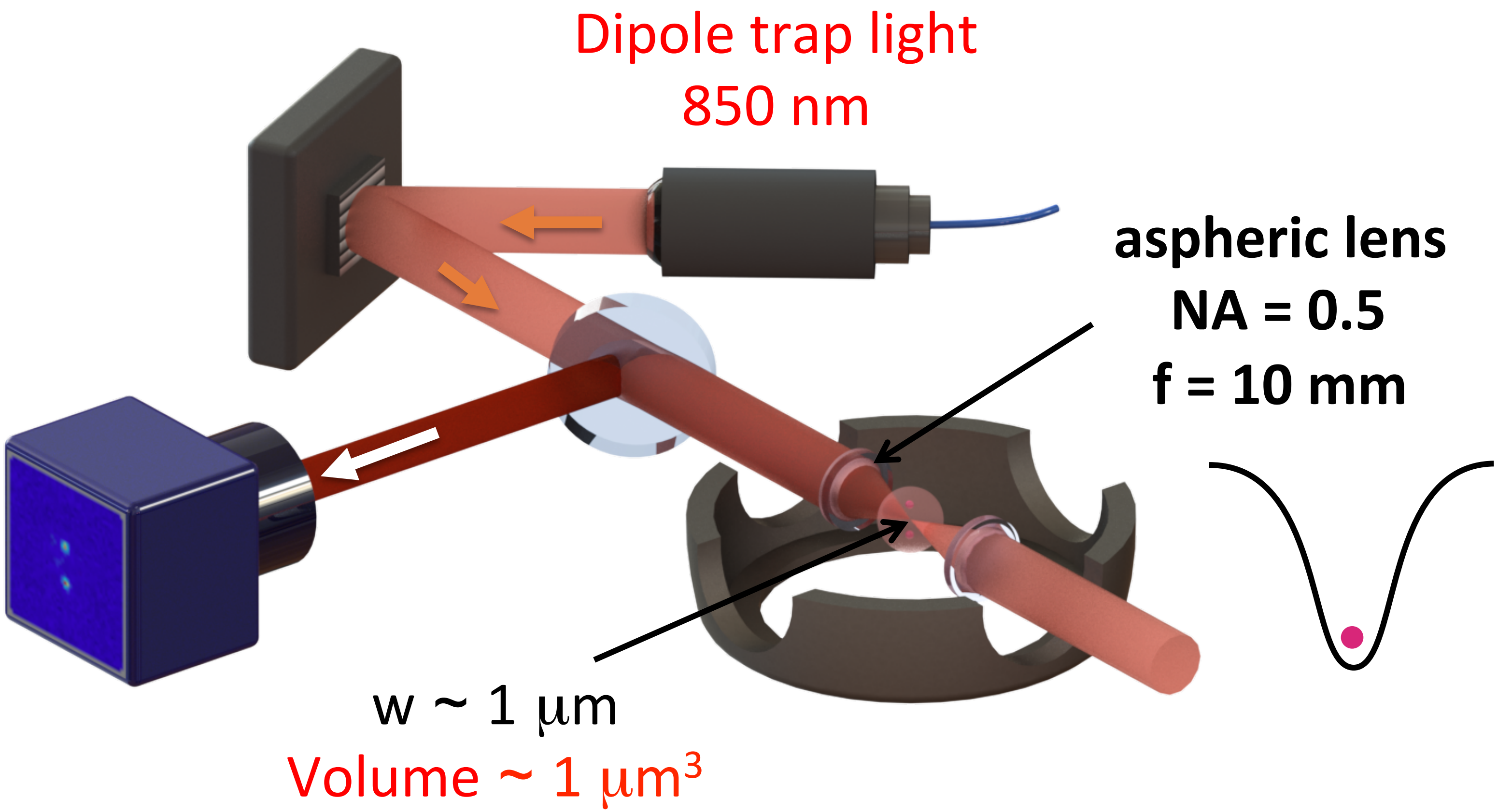


(Innbruck)

Works in 2D and 3D

Microscopic dipole traps (tweezers) for single atoms

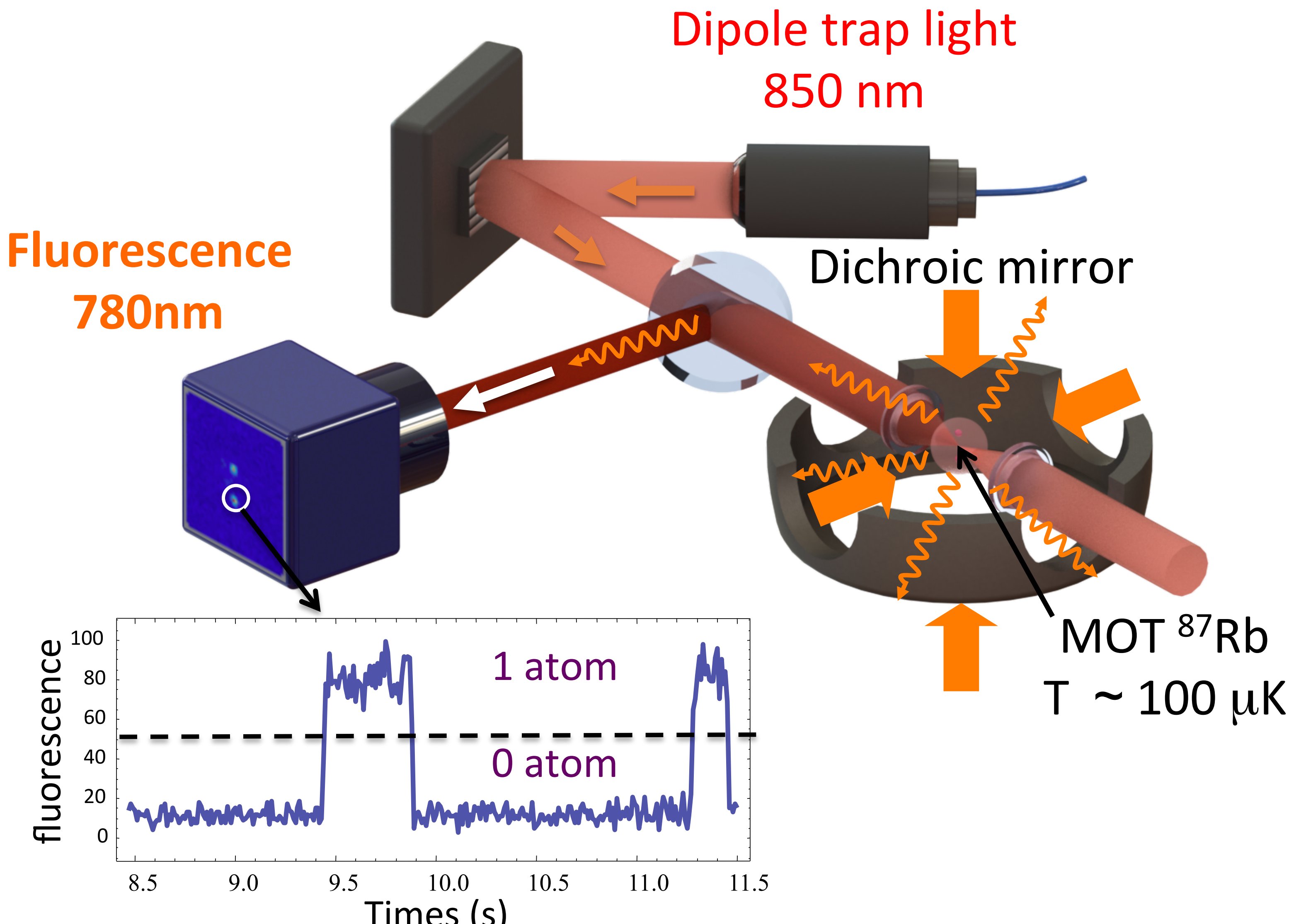
Schlosser, Nature (2001); Sortais, PRA (2007); Nogrette, PRX (2014)



Related works: Darmstadt, Amsterdam, Wisconsin, Harvard, Otago…

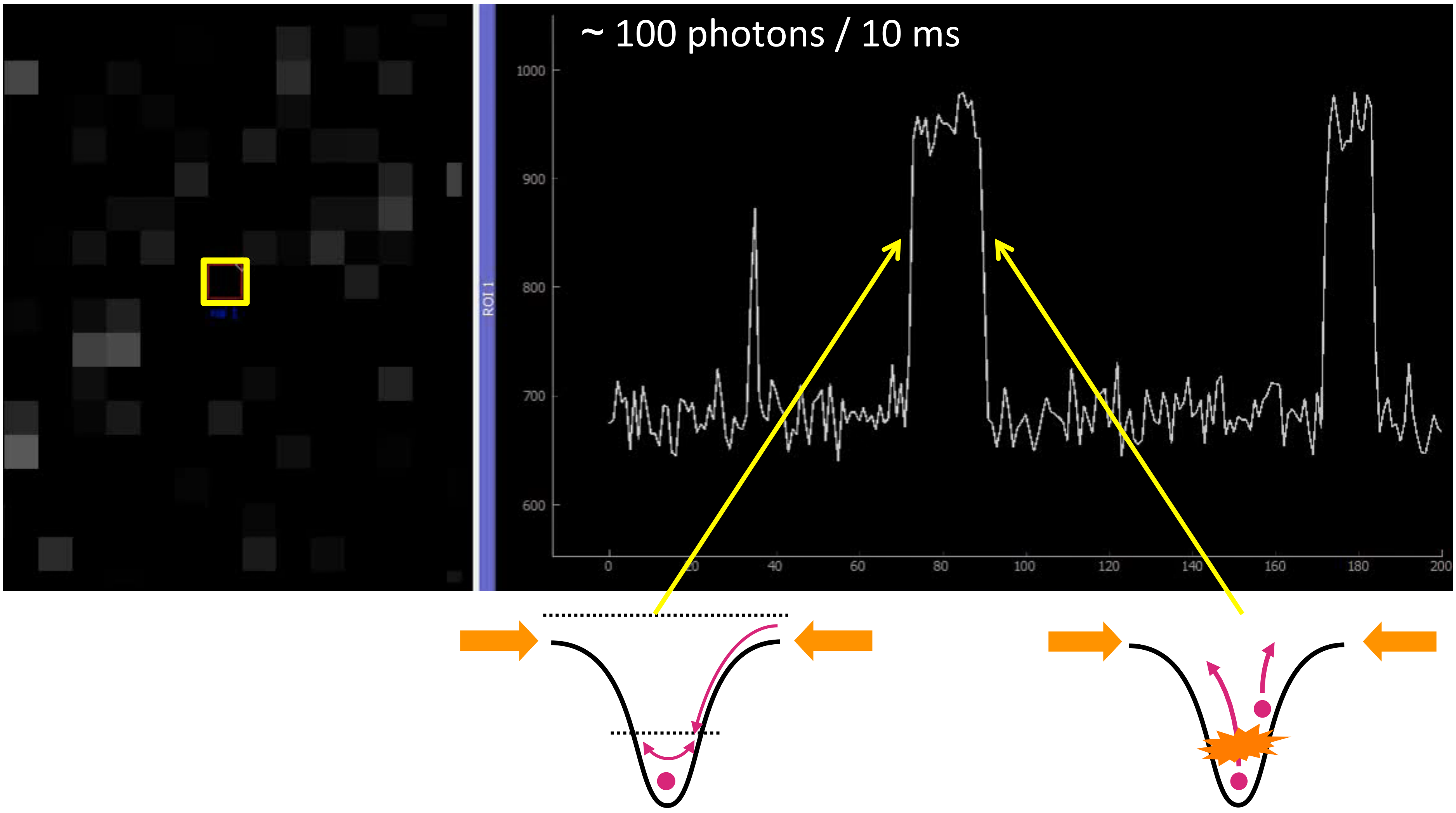
Microscopic dipole traps (tweezers) for single atoms

Schlosser, Nature (2001); Sortais, PRA (2007); Nogrette, PRX (2014)



Fast light-assisted collision prevents two atoms at the same time…

Fluorescence @ 780 nm induced by the cooling lasers



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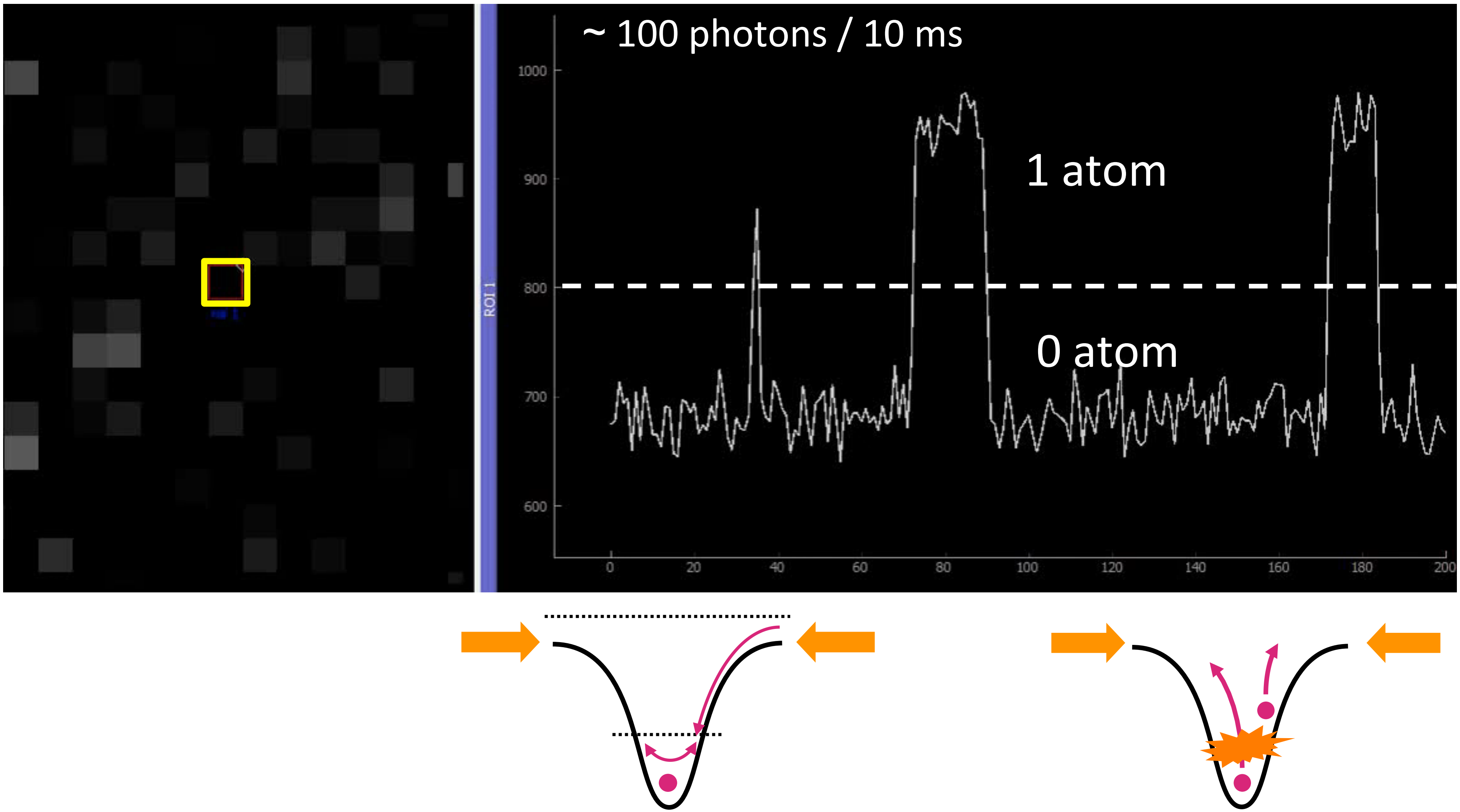
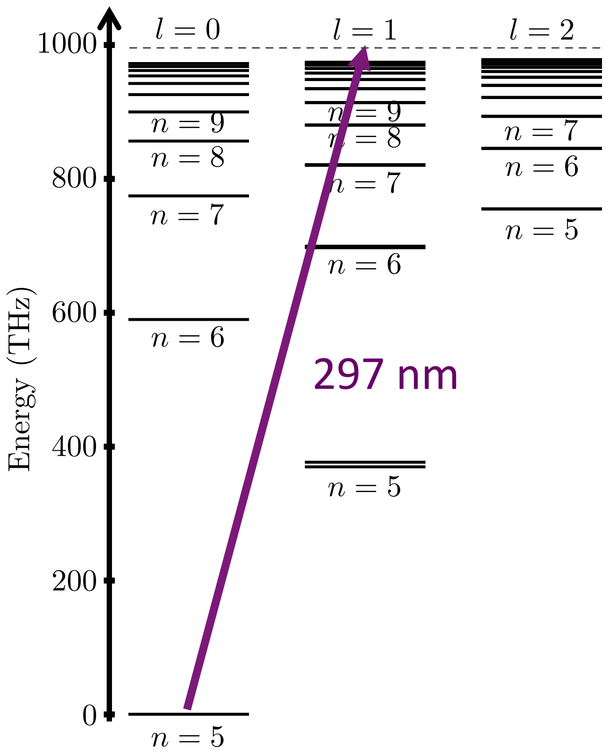
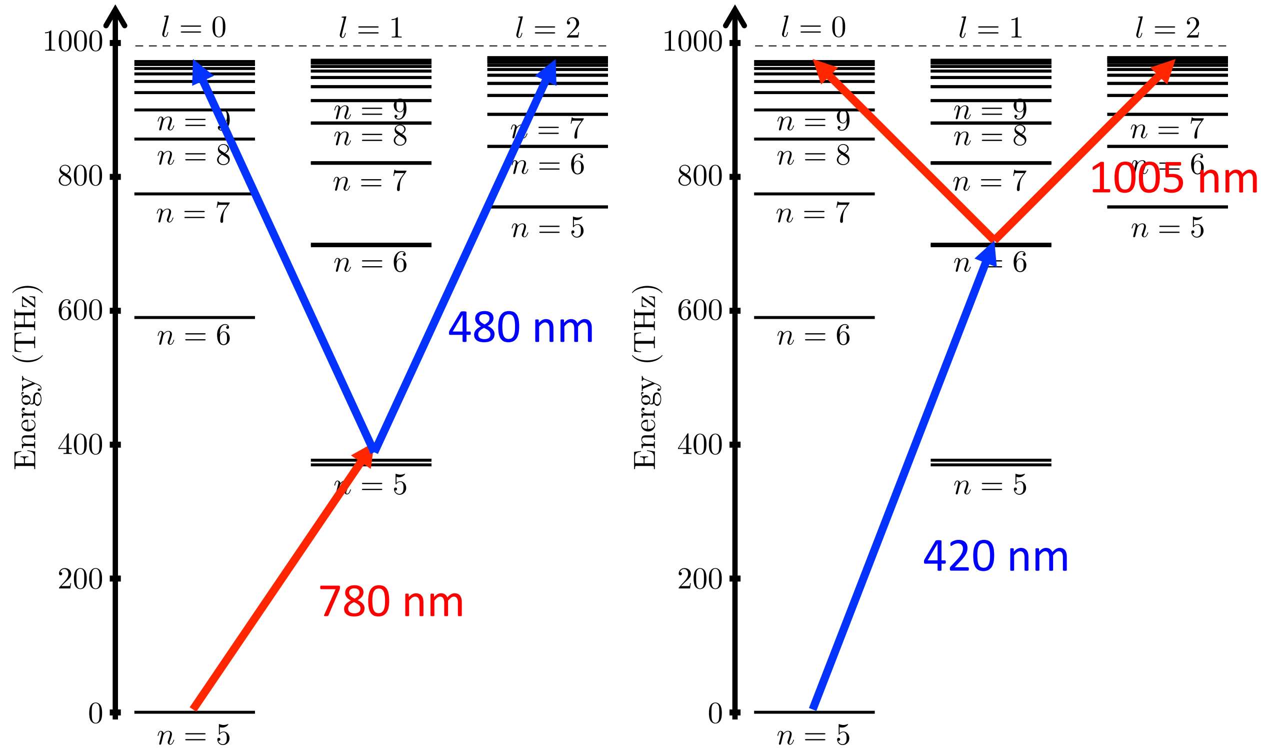


Coherent Rydberg excitation (rubidium)

Single photon (UV)



Two-photon

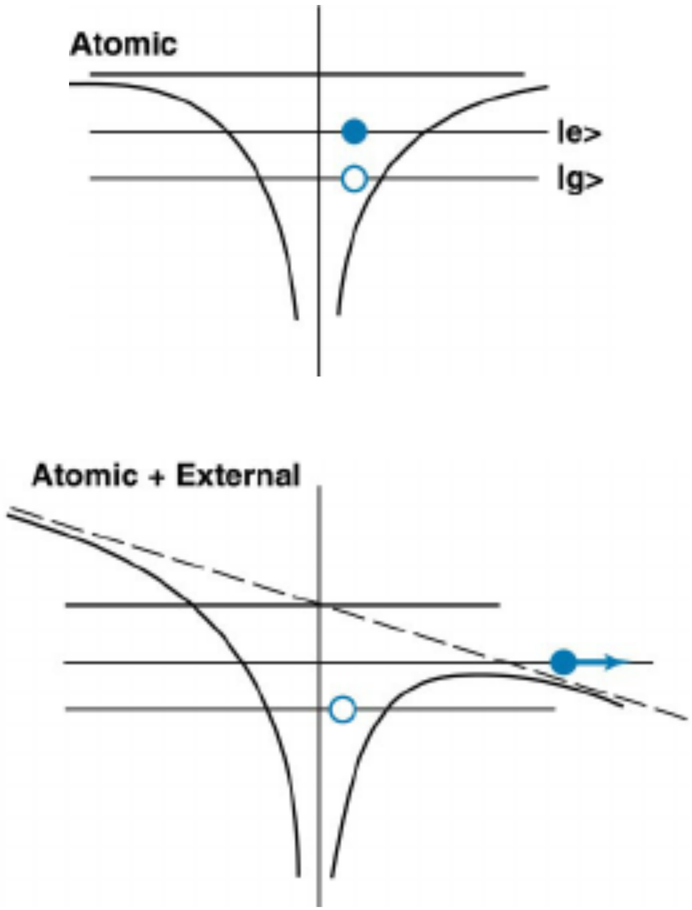


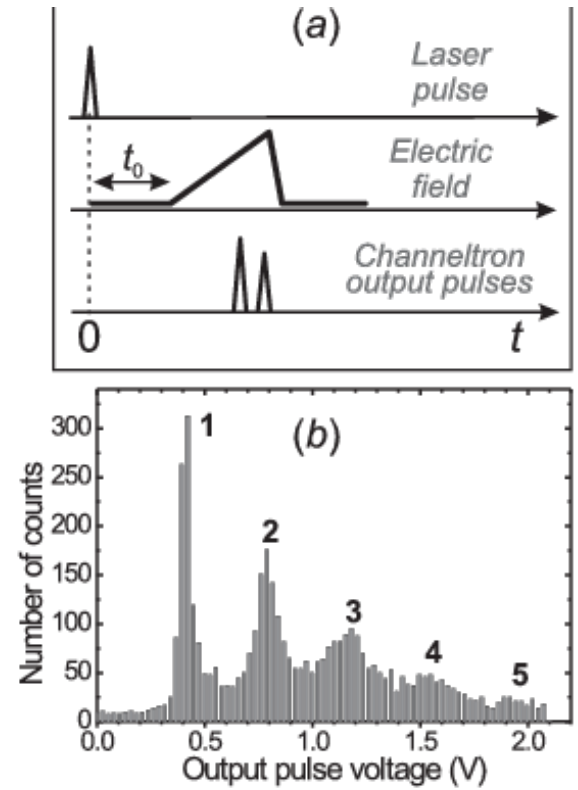
$$\Omega = \frac{\Omega_1 \Omega_2}{2\Delta}$$

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

Electronic detection of Rydberg atoms

Field ionization

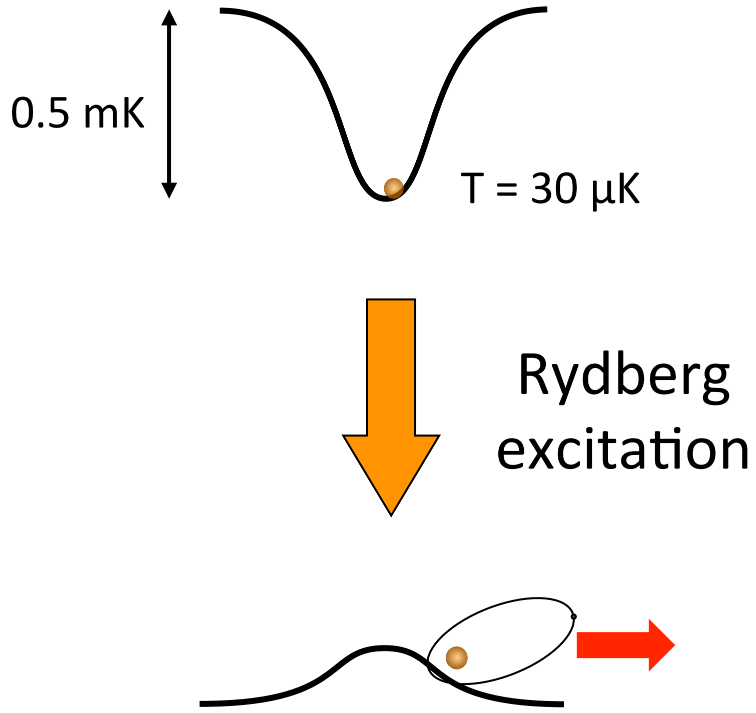




I. Beterov

Detection of Rydberg atoms

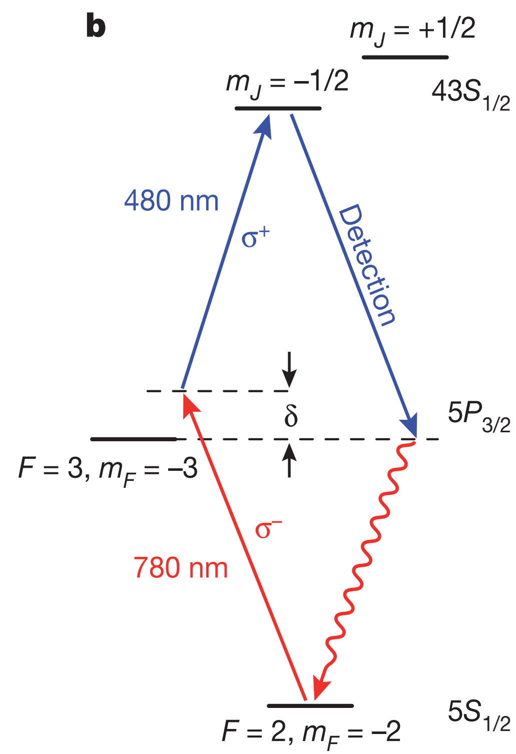
Atom loss



Leave trapping region (1 μm) in < 5 μsec

Efficiency > 95%

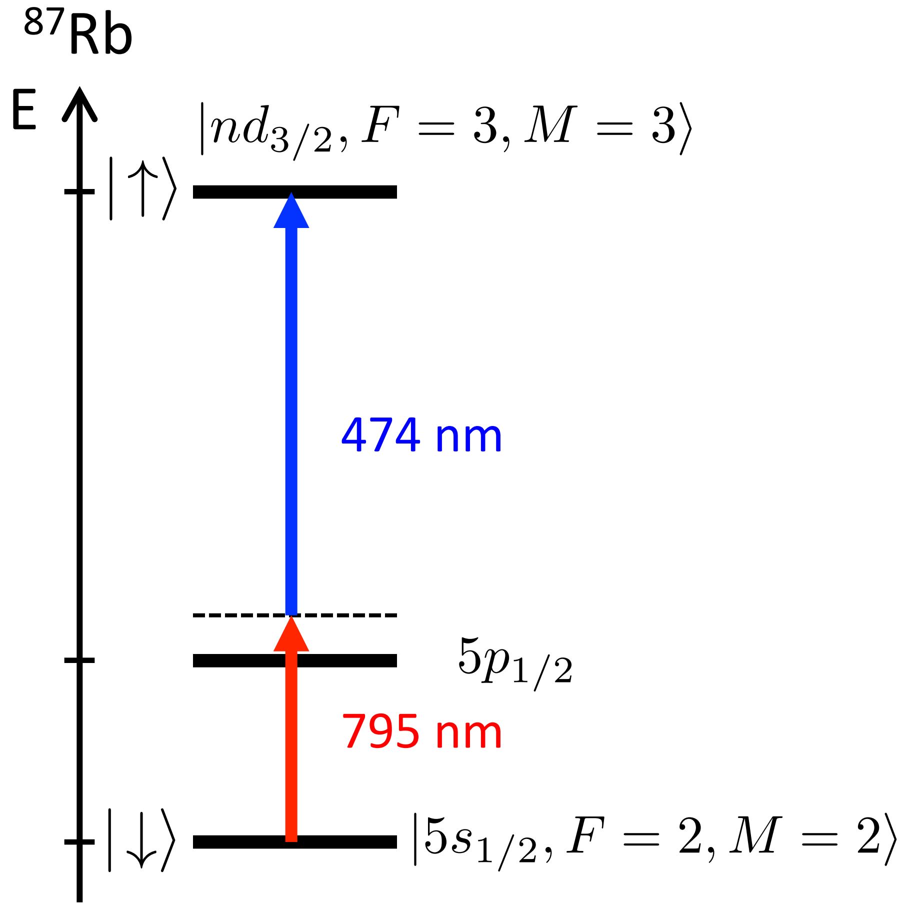
"Optical" detection



Schauss, Nature **491**, 87 (2012)

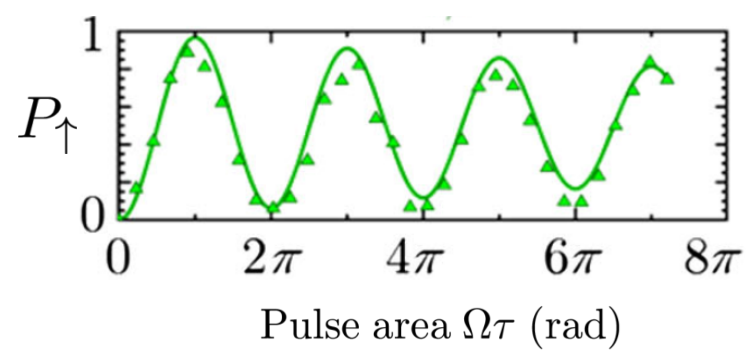
Efficiency ~ 80%

Coherent optical Rydberg excitation (n = 50 – 100)



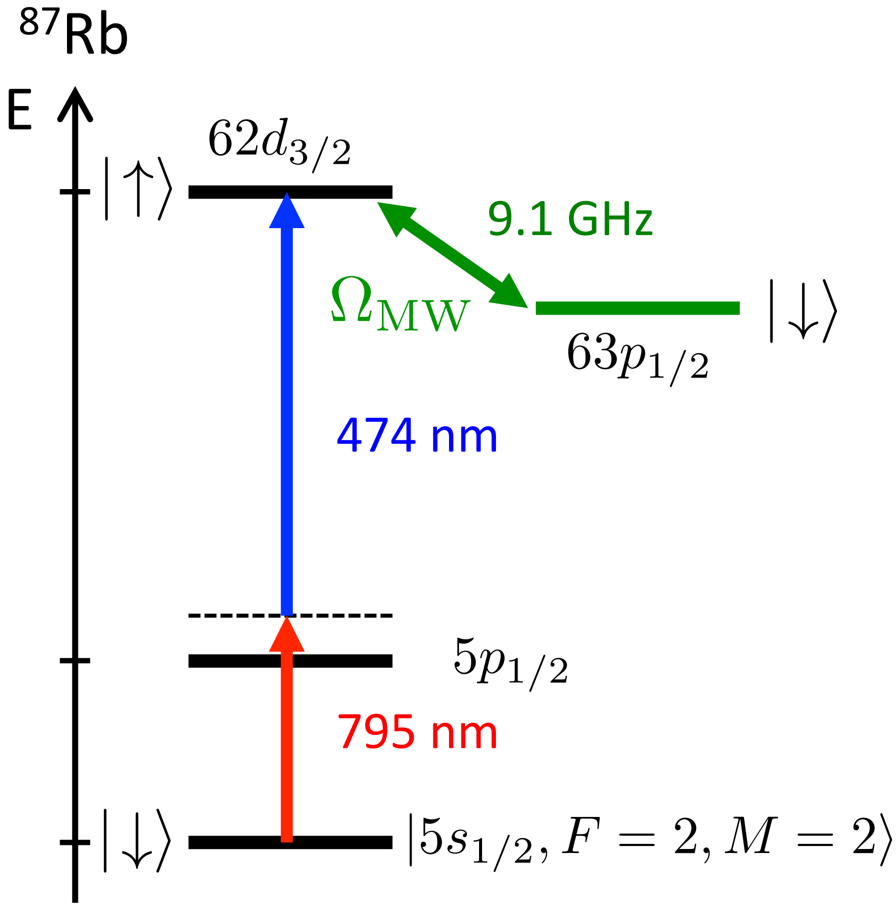
Single atom ⇒ repeat 100 times

Optical excitation (Ω = 0.5 – 5 MHz)



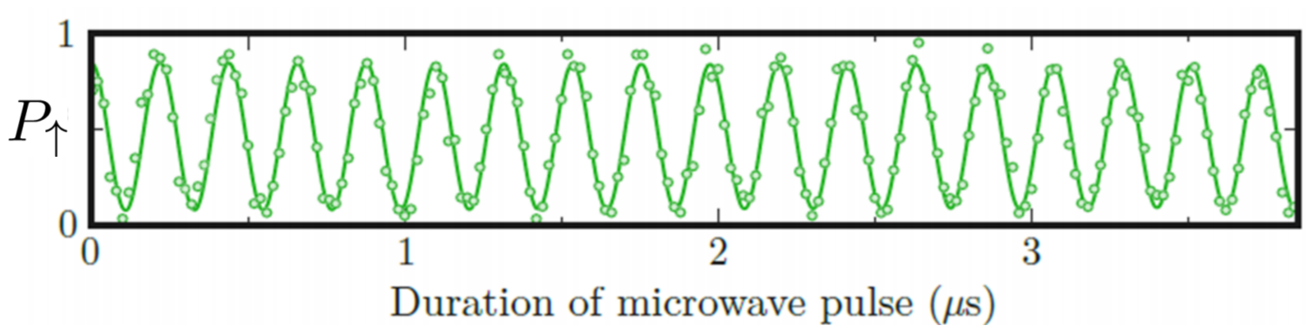
T. A. Johnson *et al.*, PRL **100**, 113003 (2008)
Miroshnychenko, PRA **82**, 023623 (2010)

Microwave manipulations (n = 50 – 100)



Single atom ⇒ repeat 100 times

Microwave transfer



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

Interactions between Rydberg atoms

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)

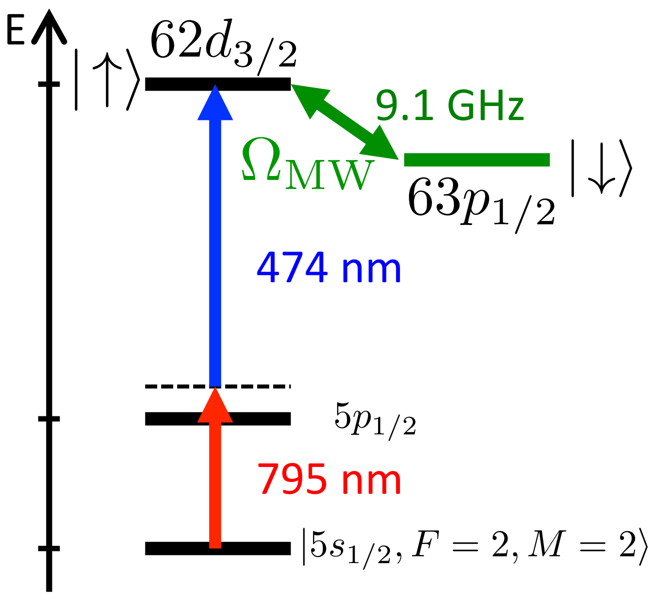
Softwares to calculate interaction energies

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

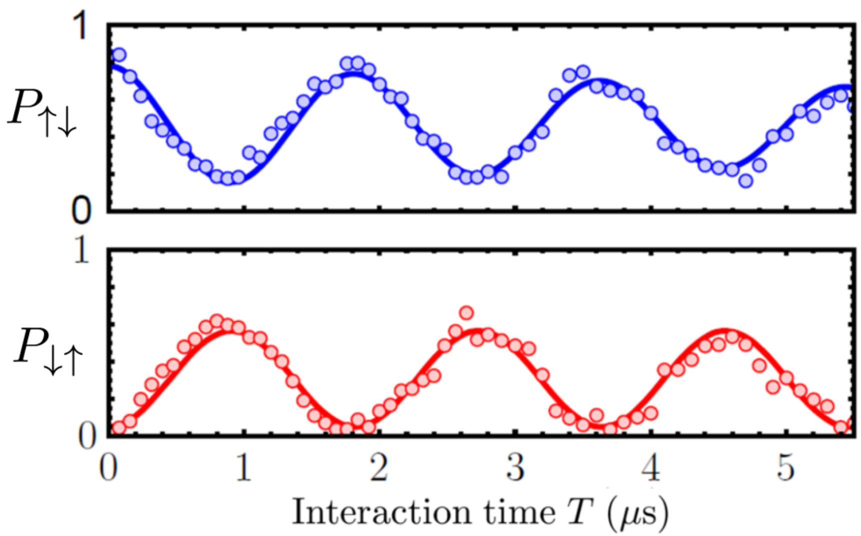
ARC: An open-source library for calculating properties of alkali Rydberg atoms, N. Sibalic *et al.,* arXiv:1612.05529 (2016)

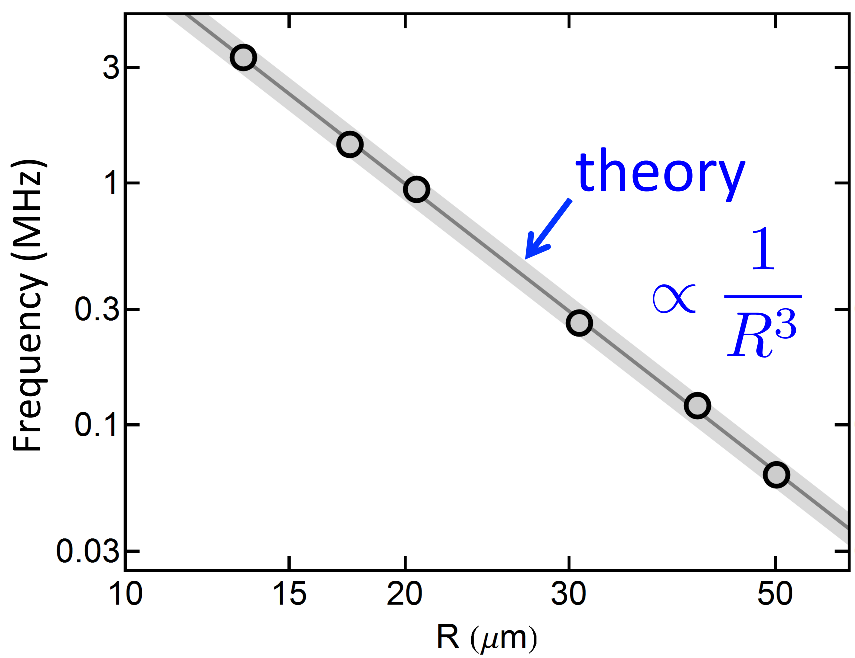
Observation of spin exchange between 2 atoms (R = 30 µm)

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

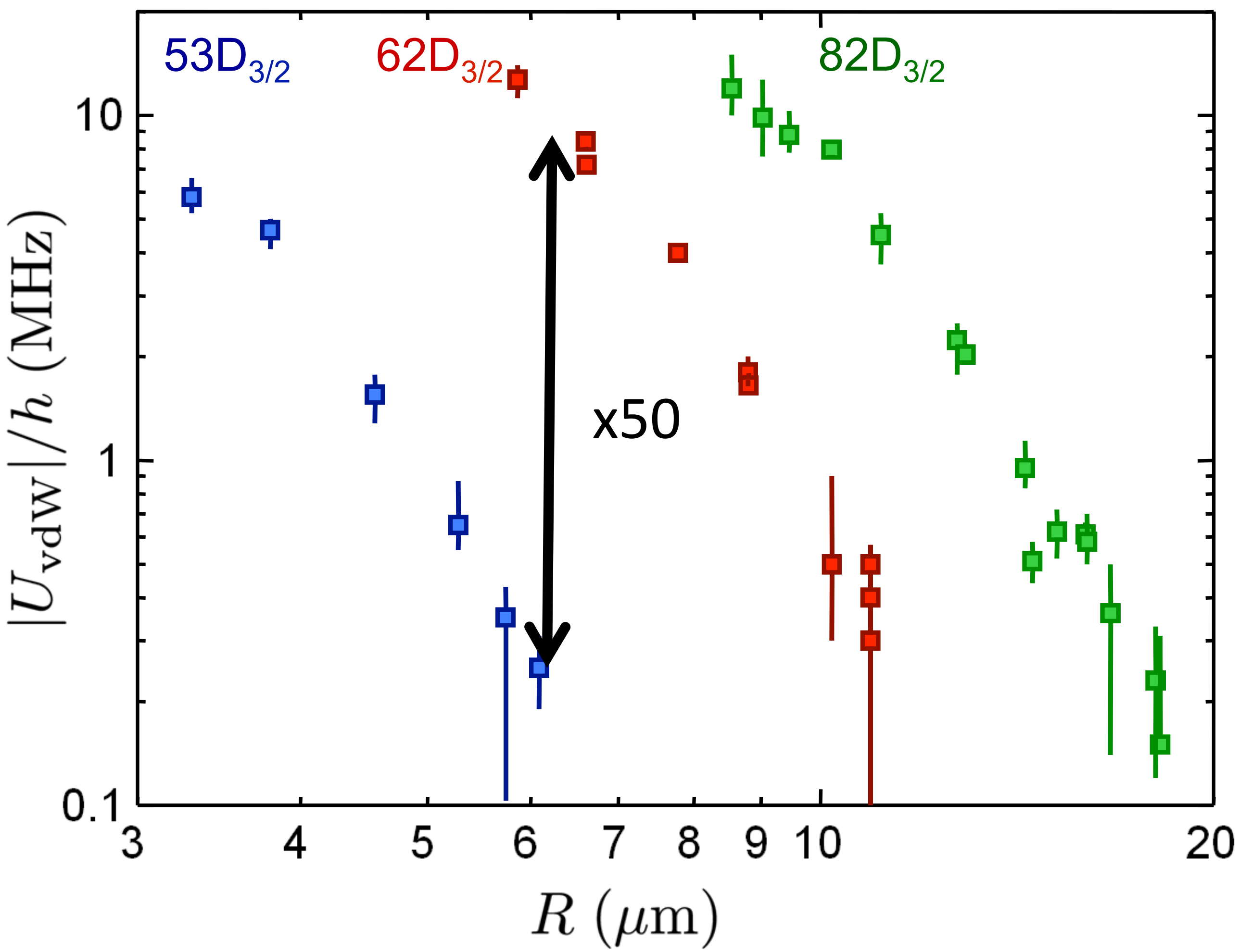


Prepare $|\uparrow\downarrow\rangle$ using microwaves + addressing beam [Labuhn, PRA **90**, 023415 (2014)]

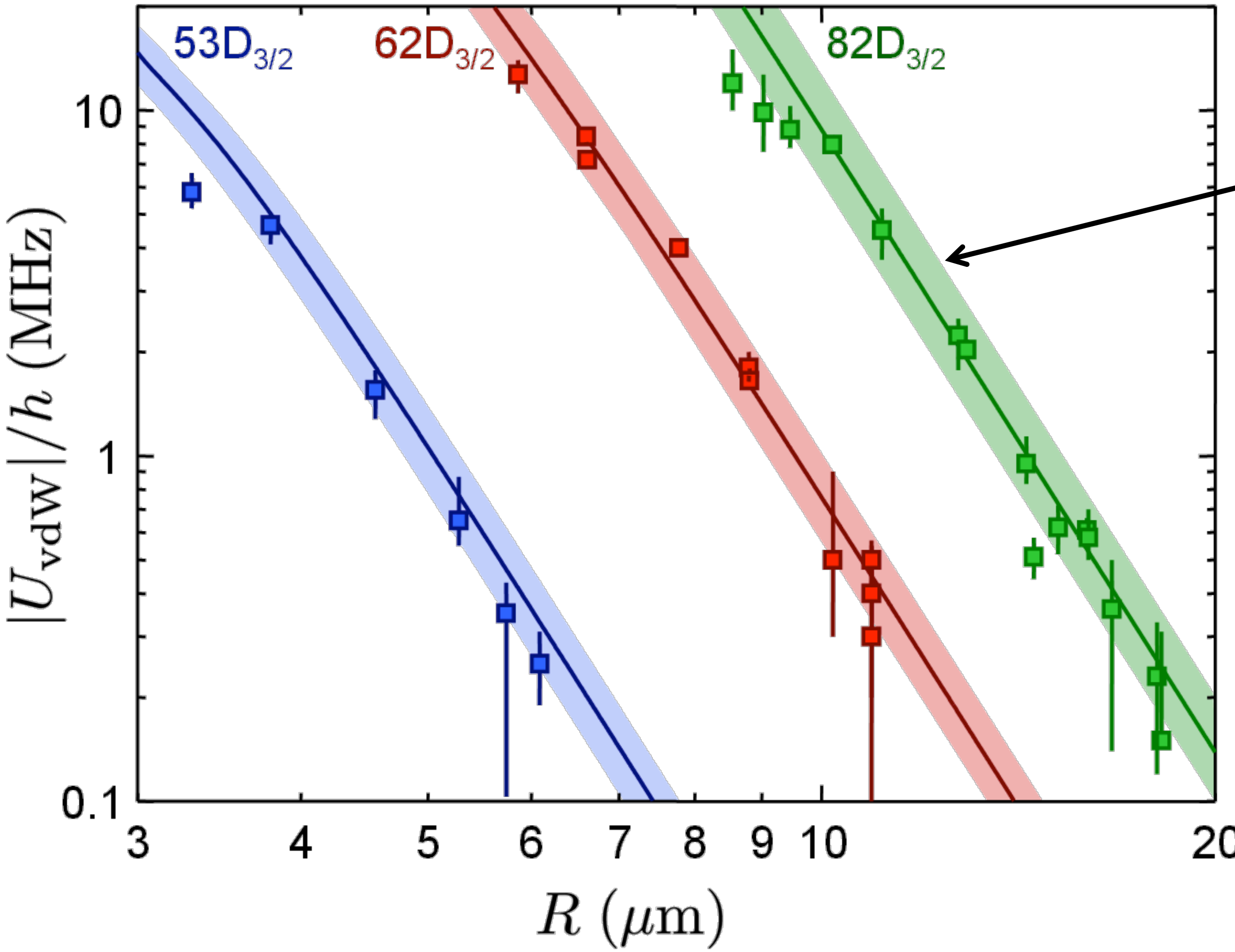




Measurement of the Van der Waals energy between 2 atoms



Measurement of the Van der Waals energy between 2 atoms



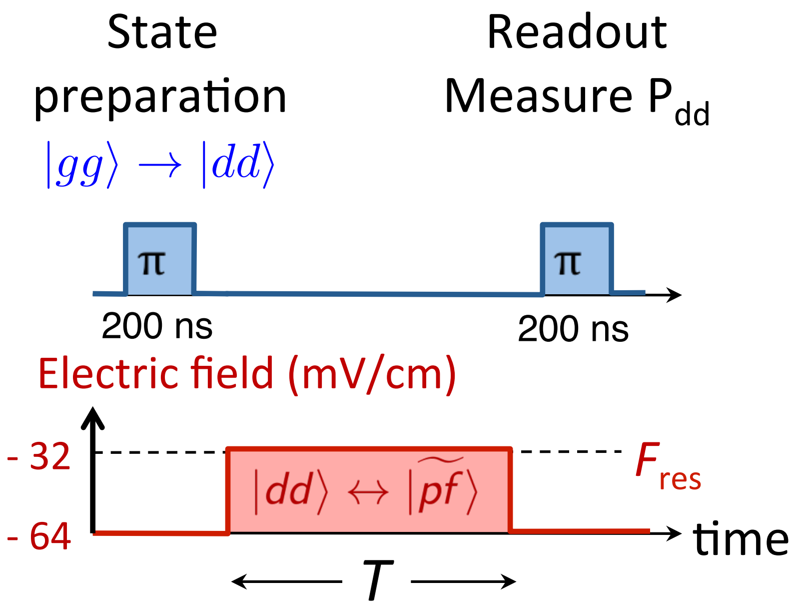
Calibration R (5%)

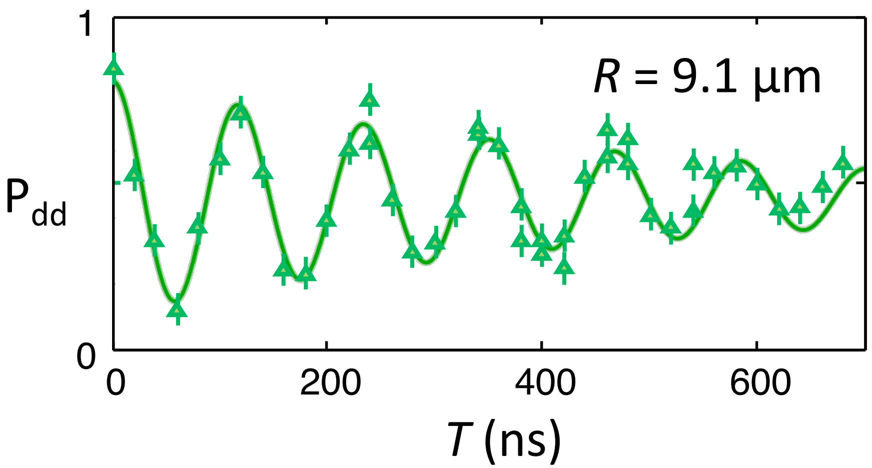
Theory curves: direct diagonalization (dipole-dipole interaction)

No adjustable parameter!

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

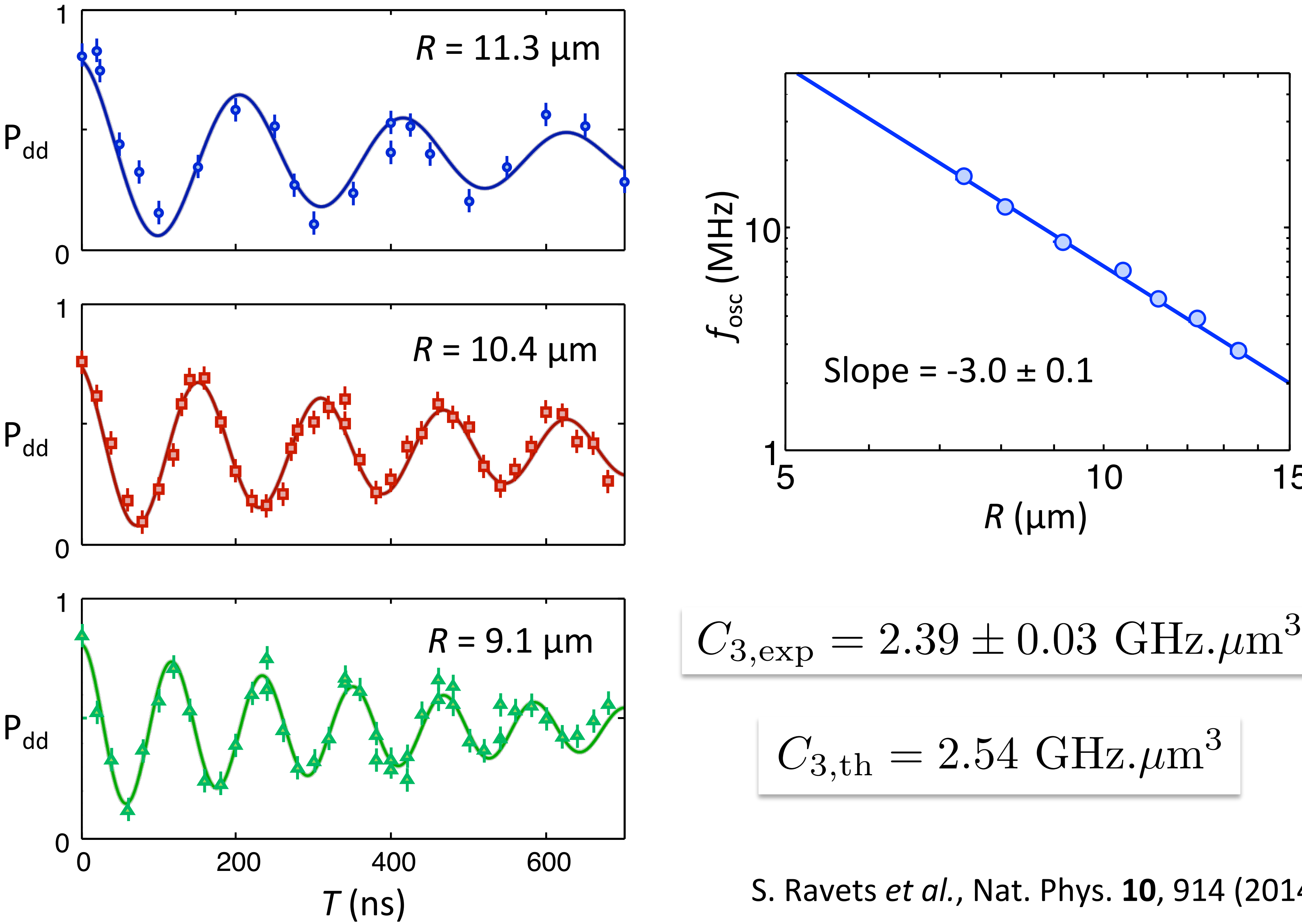
Förster resonance: electrically-tuned interaction





S. Ravets *et al.*, Nat. Phys. **10**, 914 (2014)

Förster resonance: electrically-tuned interaction

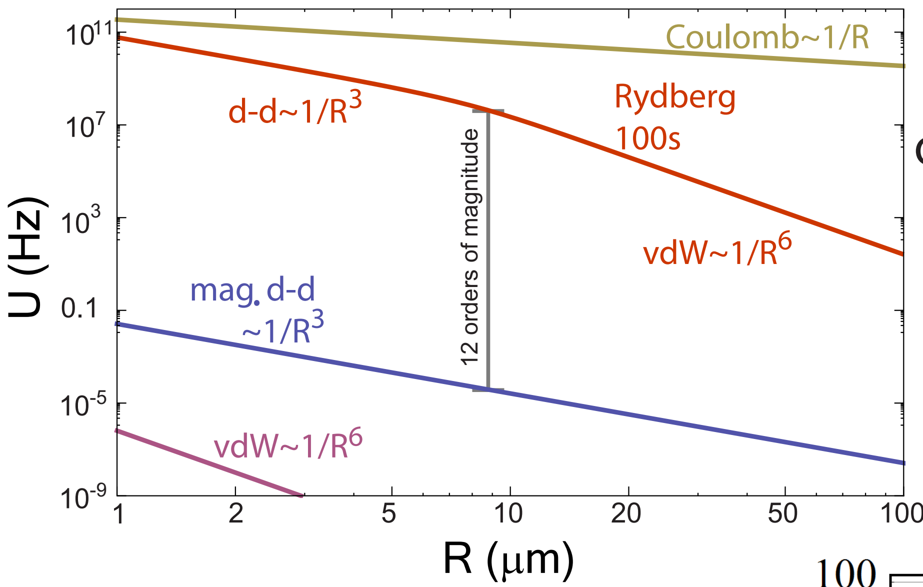


$$C_{3,\mathrm{exp}} = 2.39 \pm 0.03\ \mathrm{GHz}.\mu\mathrm{m}^3$$

$$C_{3,\mathrm{th}} = 2.54\ \mathrm{GHz}.\mu\mathrm{m}^3$$

S. Ravets *et al.*, Nat. Phys. **10**, 914 (2014)

Summary of interaction between Rydberg atoms



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

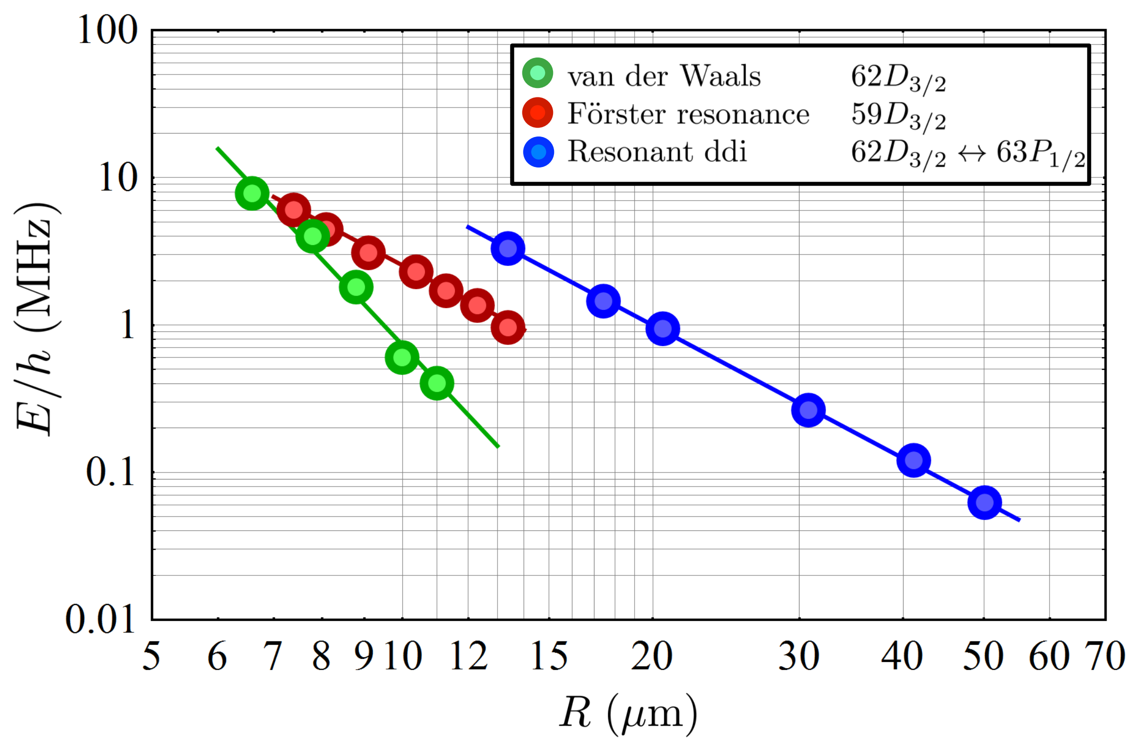
Quantum information with Rydberg atoms

M. Saffman and T. G. Walker

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

K. Mølmer

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



Outline

Lecture 1: Rydberg atoms and their interaction

Lecture 2: Rydberg Blockade and application to QIP

Lecture 3: Quantum simulation & Quantum Optics with Rydbergs

Blockade with 2 individual atoms

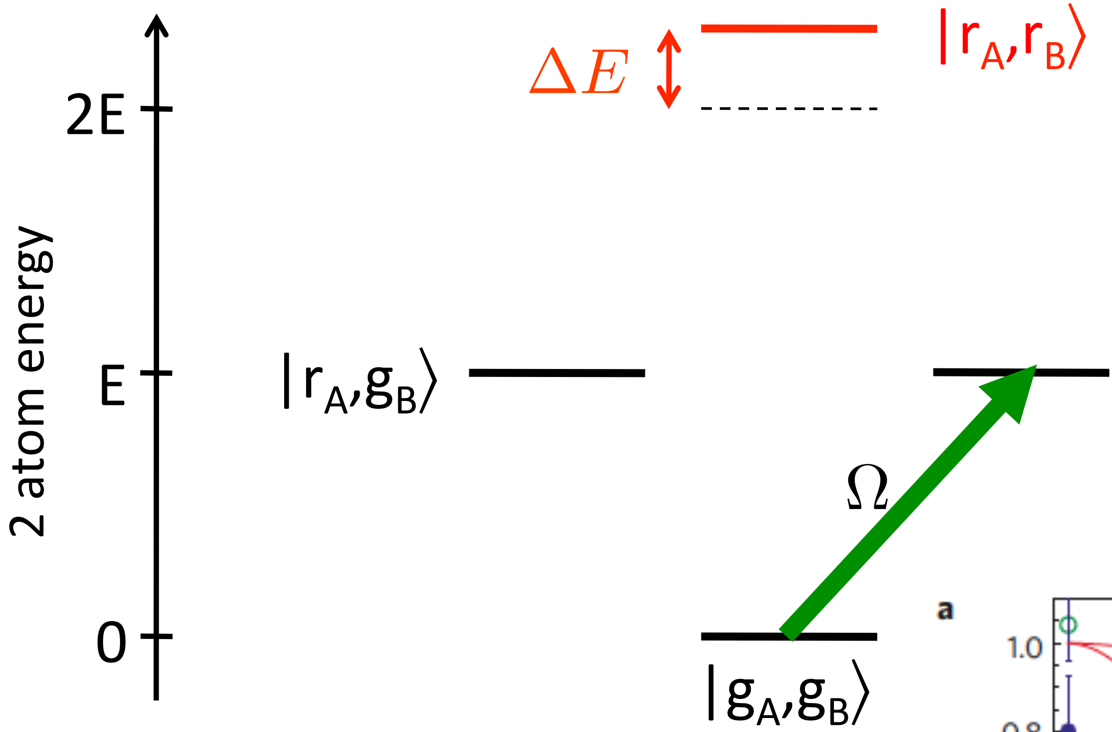
Application to gates and entanglement

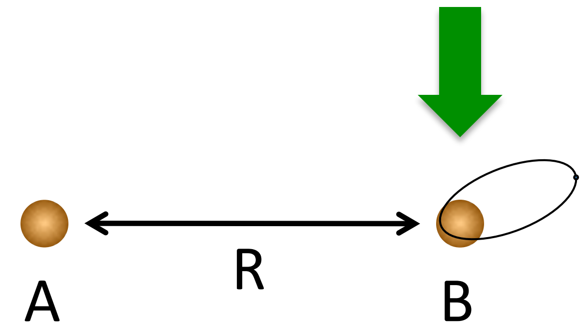
References:

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

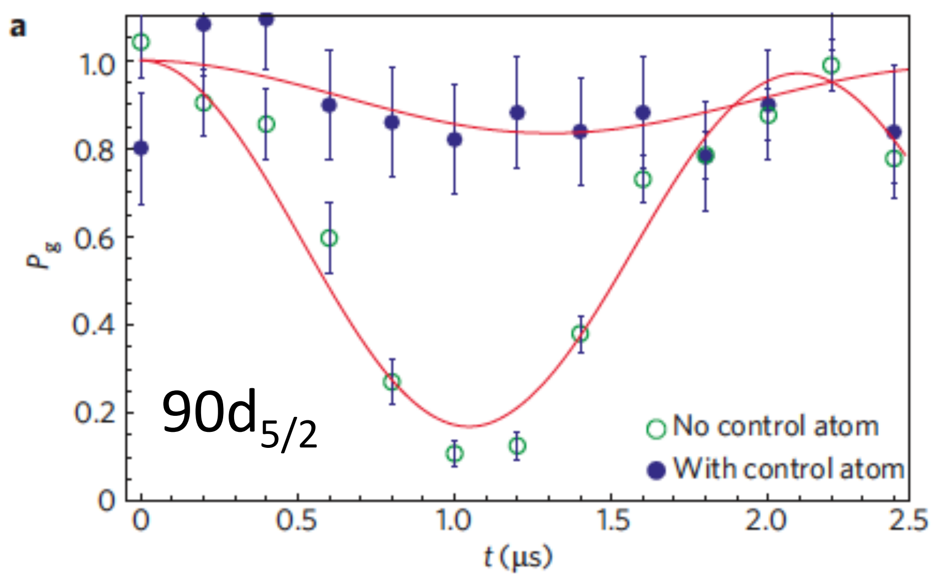
"Quantum computing with atomic qubits and Rydberg interactions: progress and challenges", M. Saffmann., J. Phys. B **49**, 202001 (2017)

Rydberg blockade: "addressable" version (U. Wisconsin)





Oscillation of atom B



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

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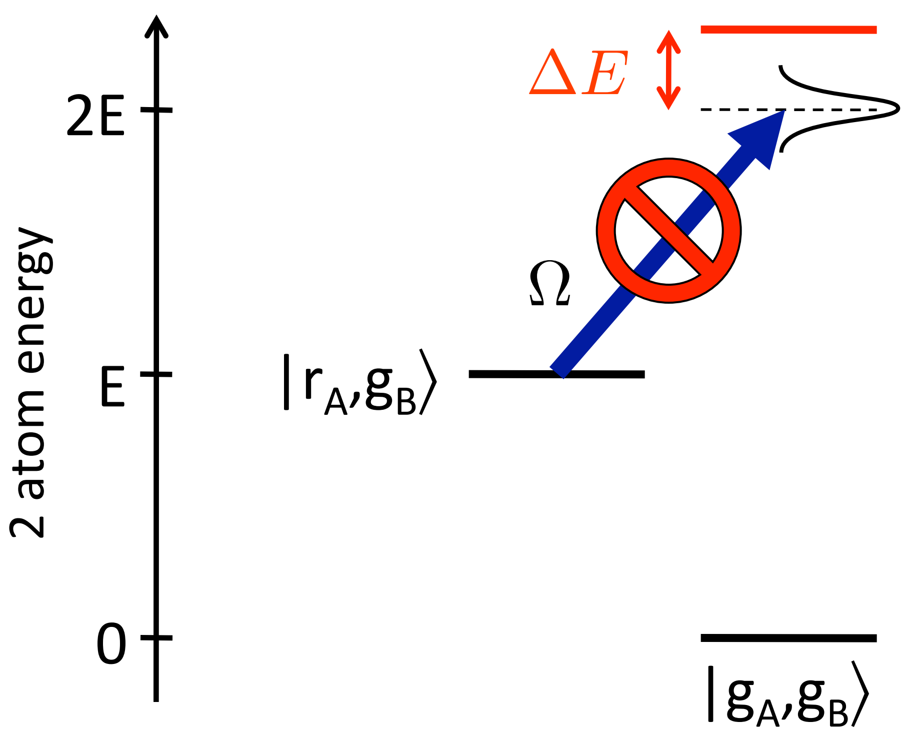
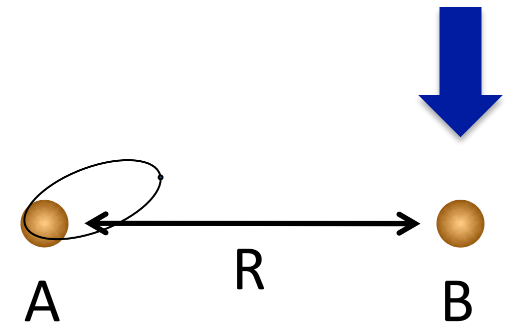
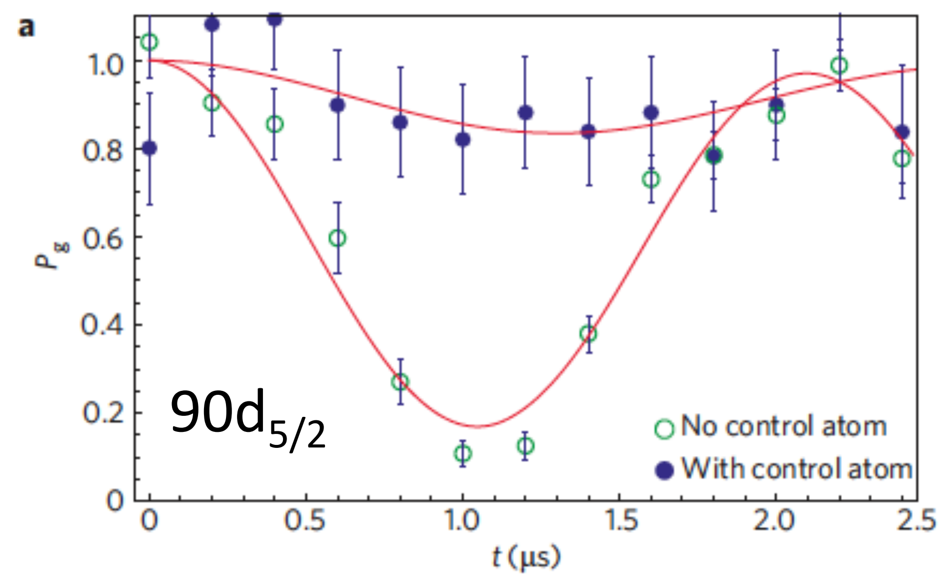


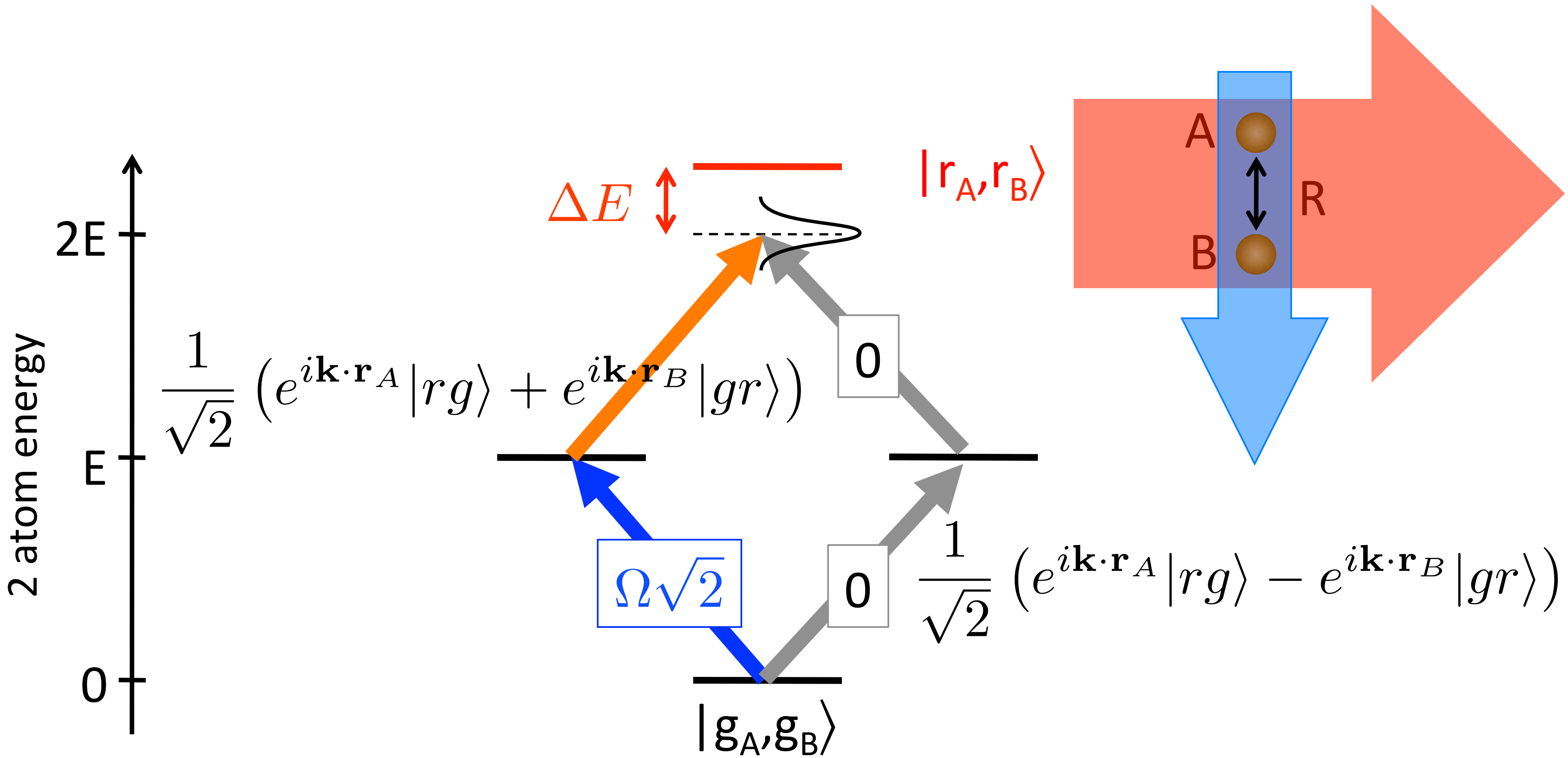


Oscillation of atom B



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

Rydberg blockade: collective excitation (IO Palaiseau)



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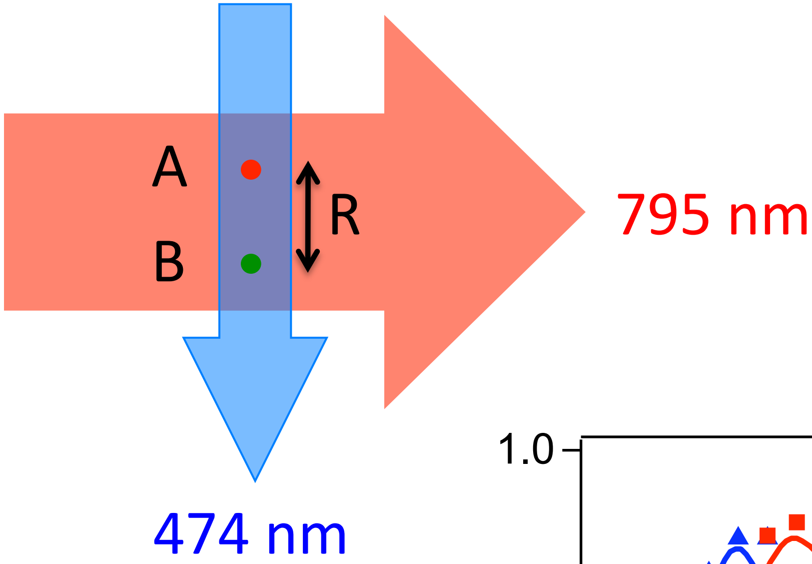


Exc. proba atom A only

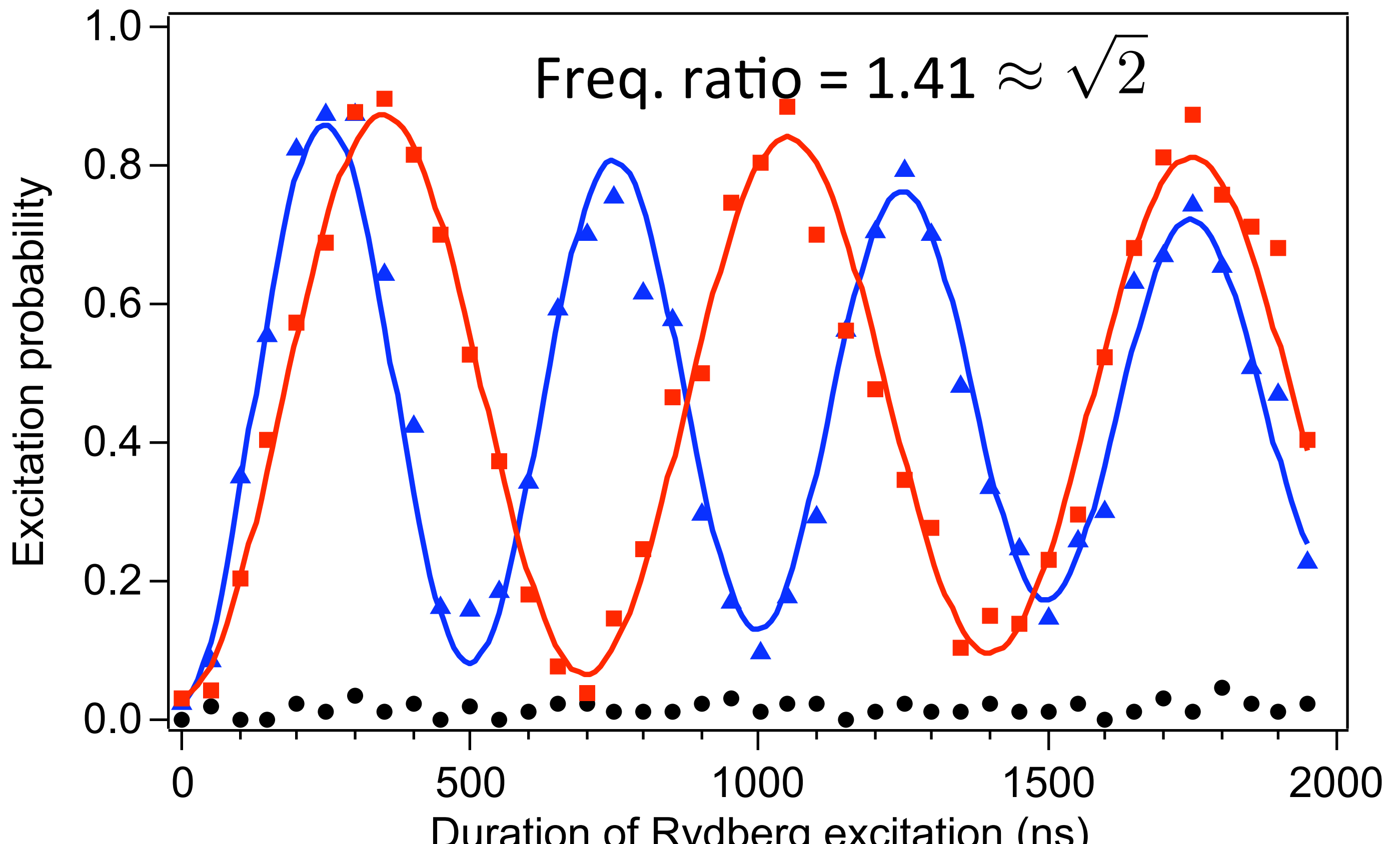
Exc. proba atom A & B

Exc. proba atom A **OR** B

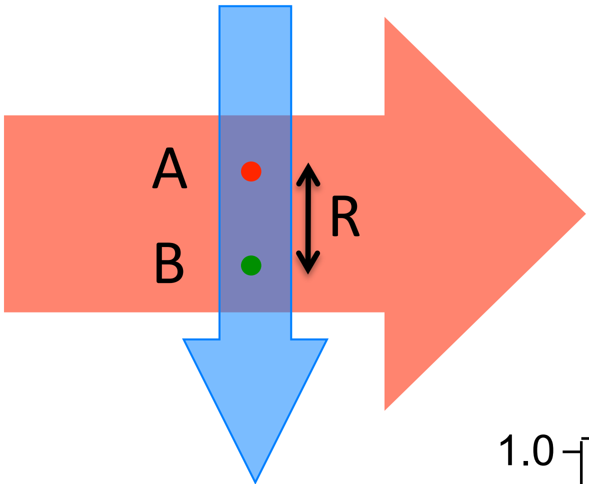
$58d_{3/2}$

R = 5 μm

ΔE_{theo} = 25 MHz



Rydberg blockade: collective excitation (IO Palaiseau)

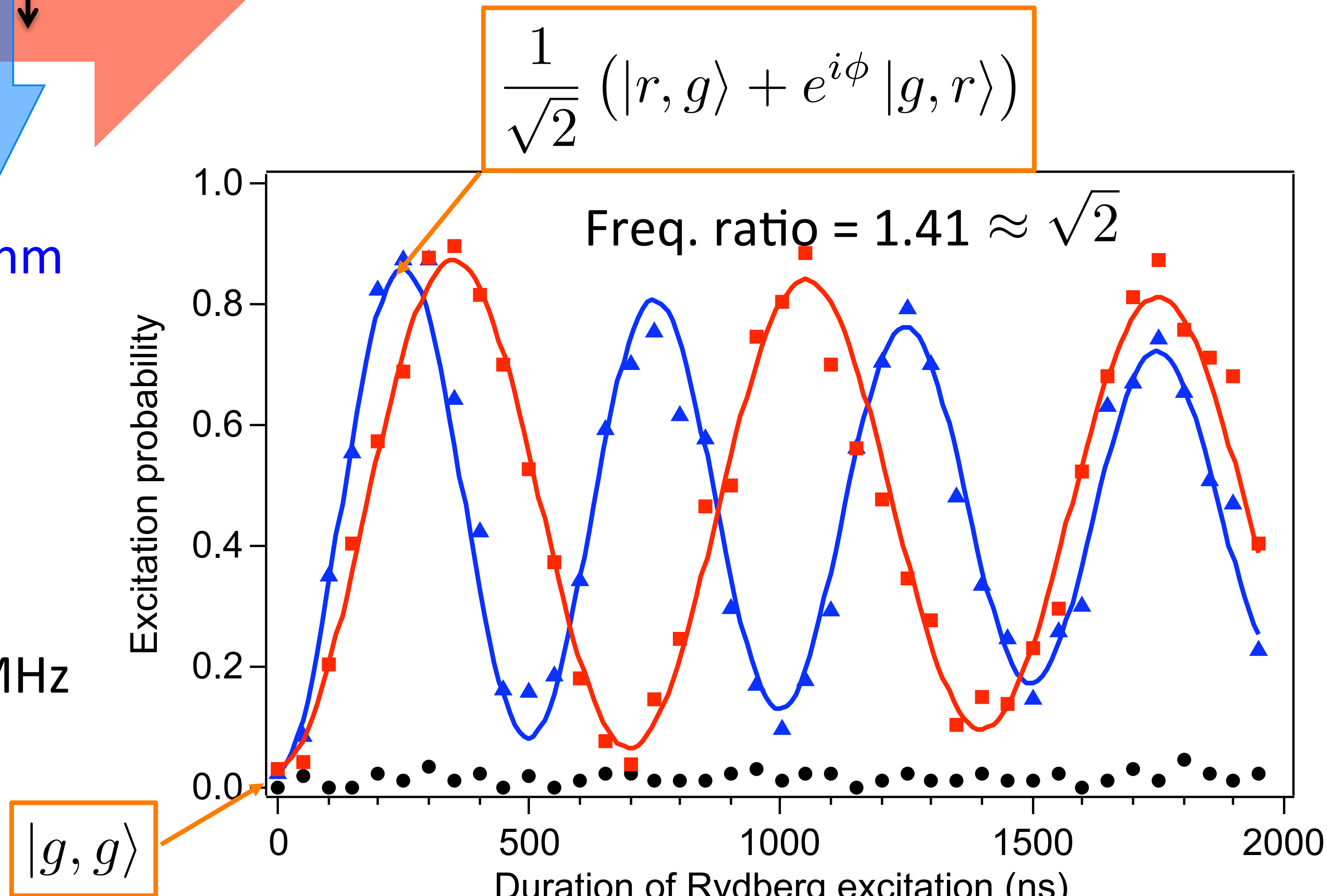


Note: $\phi = \mathbf{k}_{\text{exc}} \cdot (\mathbf{r}_A - \mathbf{r}_B)$

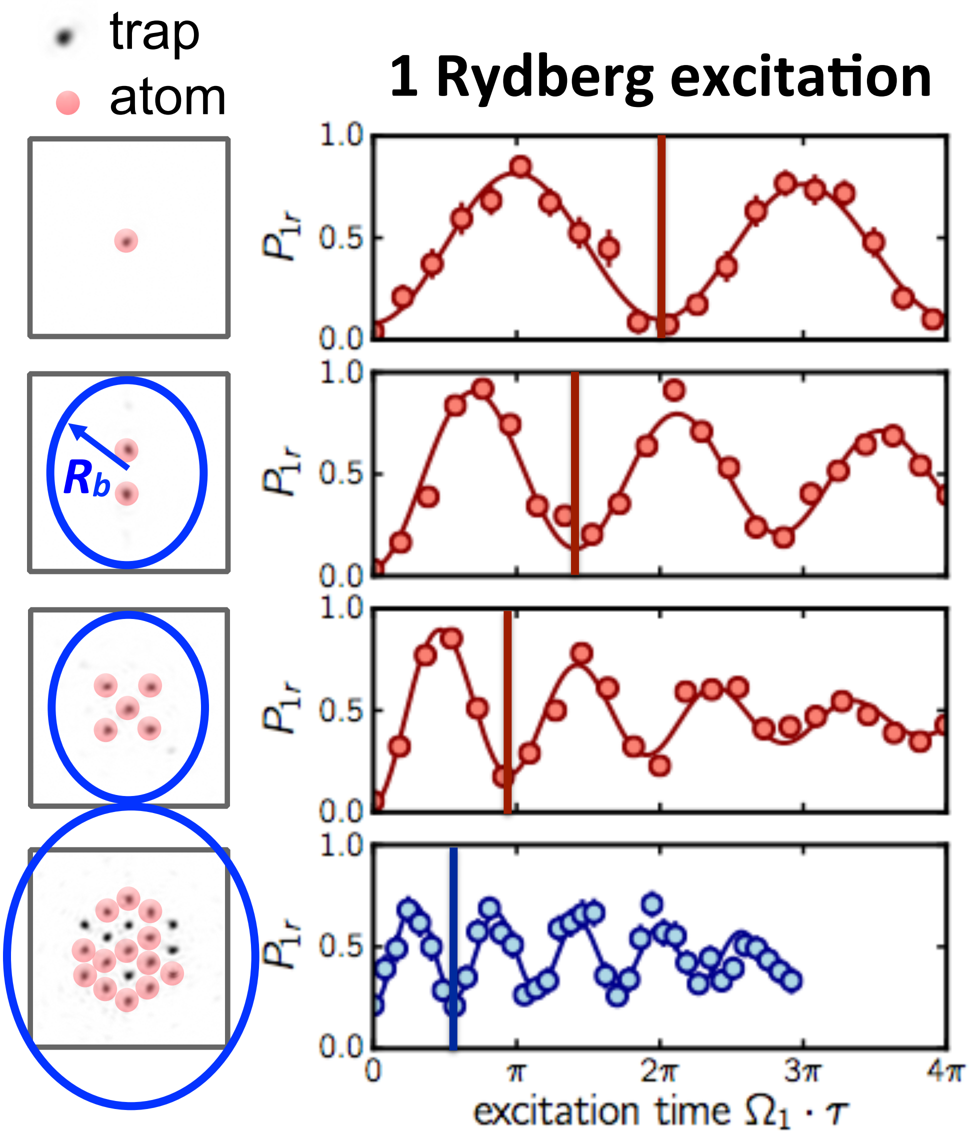
$58d_{3/2}$

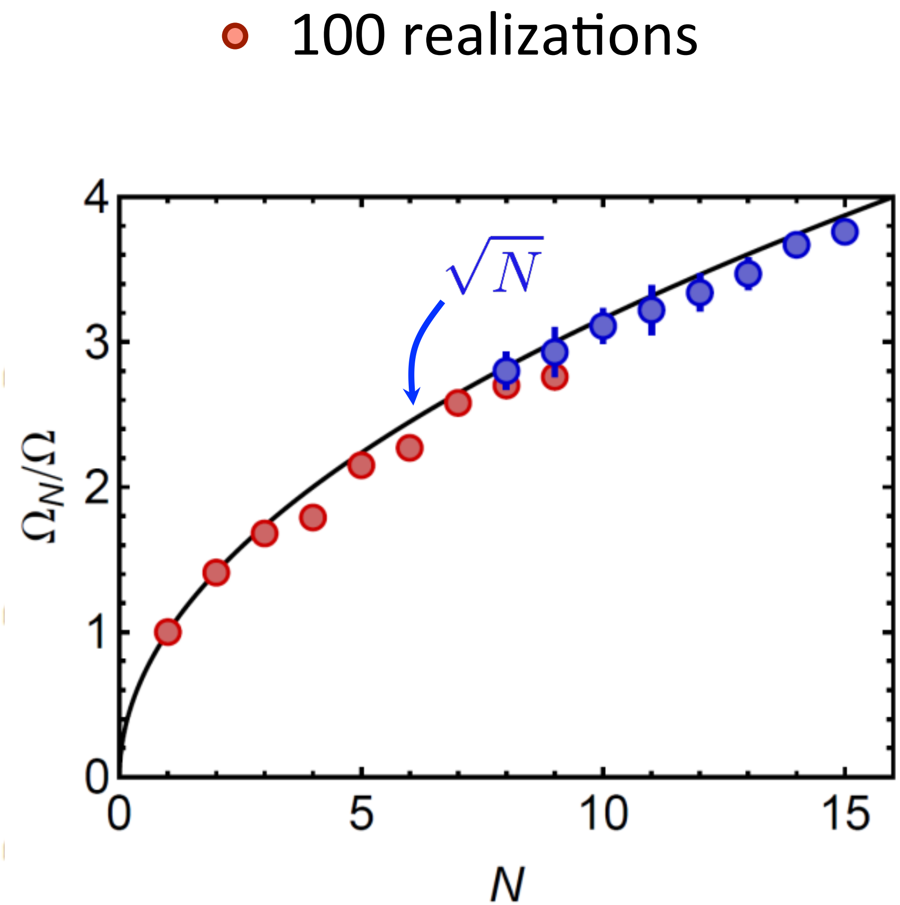
R = 5 µm

ΔE_{theo} = 25 MHz



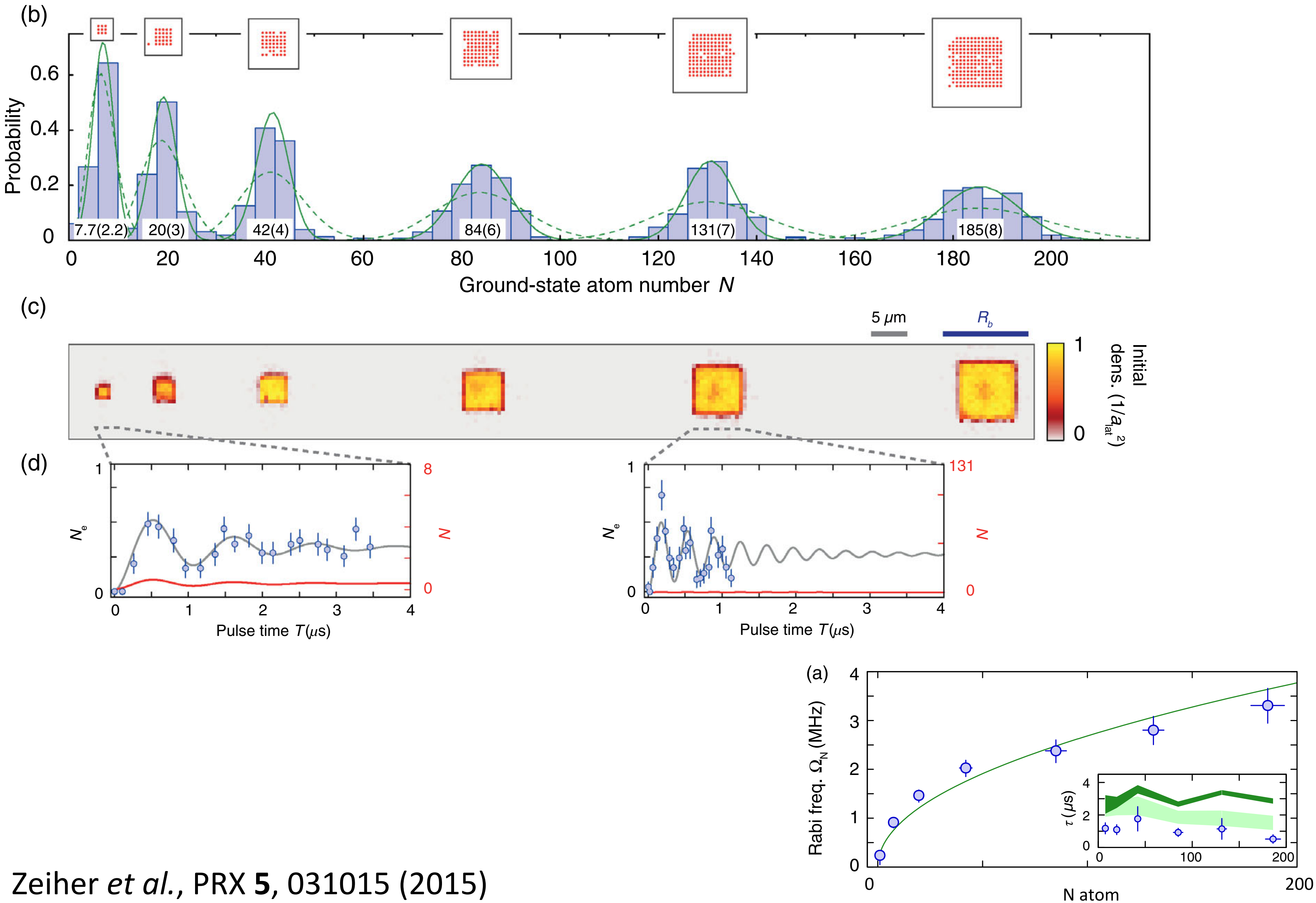
Collective excitation and Rydberg blockade





Labuhn *et al.*, Nature (2016)

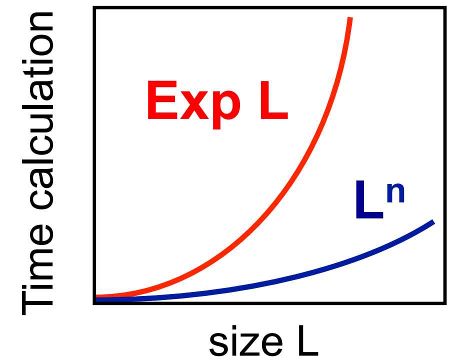
Collective excitation in sub-poissonian ensemble (MPQ, Garching)



Zeiher *et al.*, PRX **5**, 031015 (2015)

Entanglement = resource for quantum computation

Help solving "hard" problems: factoring (Shor)
searching (Grover)



Encode information on a **qubit**: $|0\rangle$, $|1\rangle$

Elementary bricks ("circuit" approach):

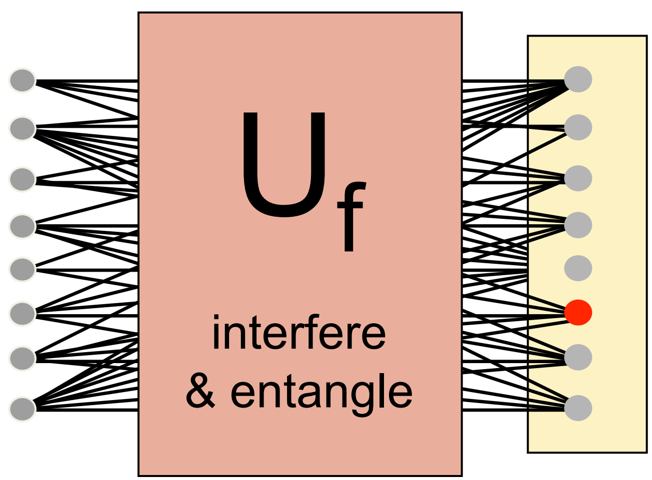
One-qubit gate $|0\rangle$ — U_1 — $\alpha|0\rangle + \beta|1\rangle$

Two-qubit gate c, t — U_2 — $|0\rangle\langle 0| \otimes \hat{\mathrm{Id}} + |1\rangle\langle 1| \otimes \sigma_x$

C-NOT

$|0\rangle \otimes |0\rangle \otimes |0\rangle \ldots$

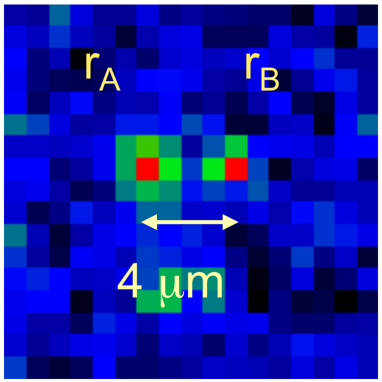
N qubits

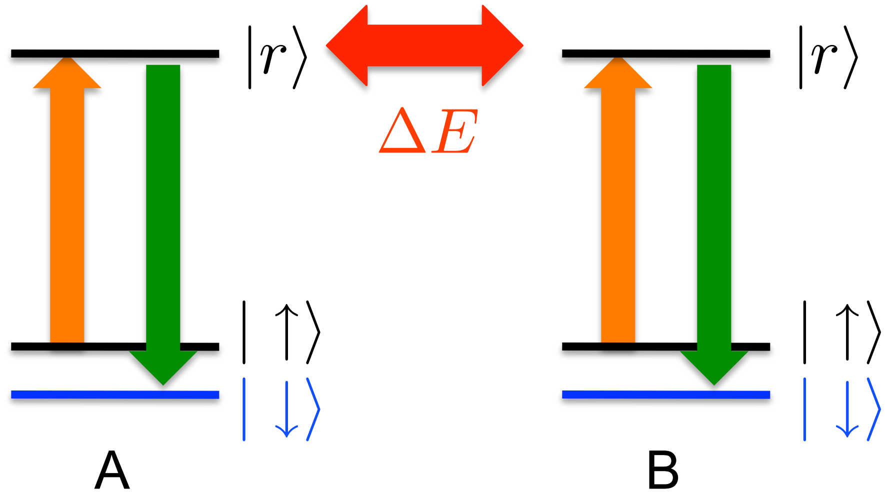


$|\Psi_f\rangle$ Highly entangled

Entanglement of two atoms using the Rydberg blockade

Collective excitation version





$$|\uparrow,\uparrow\rangle \;\Rightarrow\; \frac{1}{\sqrt{2}}\left(e^{i\mathbf{k}\cdot\mathbf{r}_A}|r,\uparrow\rangle + e^{i\mathbf{k}\cdot\mathbf{r}_B}|\uparrow,r\rangle\right) \quad k = k_{\mathrm{R}} + k_{\mathrm{B}}$$

$$\Rightarrow \frac{1}{\sqrt{2}}\left(e^{i(\mathbf{k}\cdot\mathbf{r}_A - \mathbf{k}'\cdot\mathbf{r}'_A)}|\downarrow,\uparrow\rangle + e^{i(\mathbf{k}\cdot\mathbf{r}_B - \mathbf{k}'\cdot\mathbf{r}'_B)}|\uparrow,\downarrow\rangle\right)$$

$$\Rightarrow \frac{1}{\sqrt{2}}(|\downarrow,\uparrow\rangle + e^{i\phi}|\uparrow,\downarrow\rangle) \text{ with } \phi = \mathbf{k}\cdot(\delta\mathbf{r}_A - \delta\mathbf{r}_B) \quad (k \approx k')$$

If atomic motion frozen $\Rightarrow \delta r_A \approx \delta r_B \approx 0$

Wilk *et al.*, PRL **104,** 010502 (2010)

Analyzing entanglement

$$|\psi_+\rangle = \frac{1}{\sqrt{2}}(|\downarrow,\uparrow\rangle + |\uparrow,\downarrow\rangle)$$

Measure the density matrix: $\rho_{\mathrm{exp}} = F|\psi_+\rangle\langle\psi_+| + \rho_{\mathrm{junk}}$

$$\hat{\rho} = \begin{pmatrix} P_{\downarrow\downarrow} & a & b & c \\ a^* & P_{\downarrow\uparrow} & \rho_{\uparrow\downarrow,\downarrow\uparrow} & d \\ b^* & \rho^*_{\uparrow\downarrow,\downarrow\uparrow} & P_{\uparrow\downarrow} & e \\ c^* & d^* & e^* & P_{\uparrow\uparrow} \end{pmatrix}_{|\downarrow\downarrow\rangle,|\downarrow\uparrow\rangle,|\uparrow\downarrow\rangle|,\uparrow\uparrow\rangle}$$

Extract the fidelity: $F = \langle\psi_+|\hat{\rho}|\psi_+\rangle$

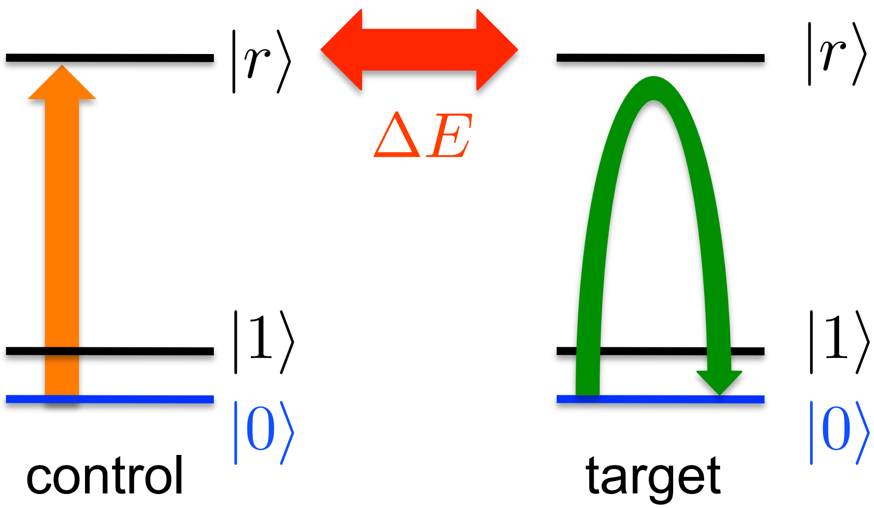
$$F = \frac{1}{2}(P_{\downarrow\uparrow} + P_{\uparrow\downarrow} + 2\,\Re(\rho_{\downarrow\uparrow,\uparrow\downarrow}))$$

$F_{\mathrm{pairs}} = 0.75 \pm 0.07$

Details in Gaëtan *et al.*, NJP **12**, 065040 (2010)

Quantum gate using Rydberg blockade

D. Jacksch *et al.*, PRL **85**, 2208 (2000)



Sequence:

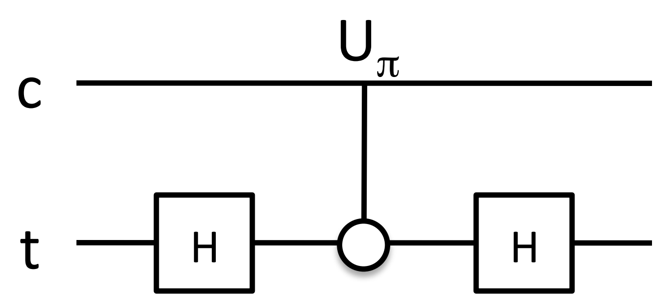
$\pi_A - 2\pi_B - \pi_A$

Table of truth:

11	→	11	→	11	→	11
10	→	10	→	-10	→	-10
01	→	r1	→	r1	→	-01
00	→	r0	→	r0	→	-00

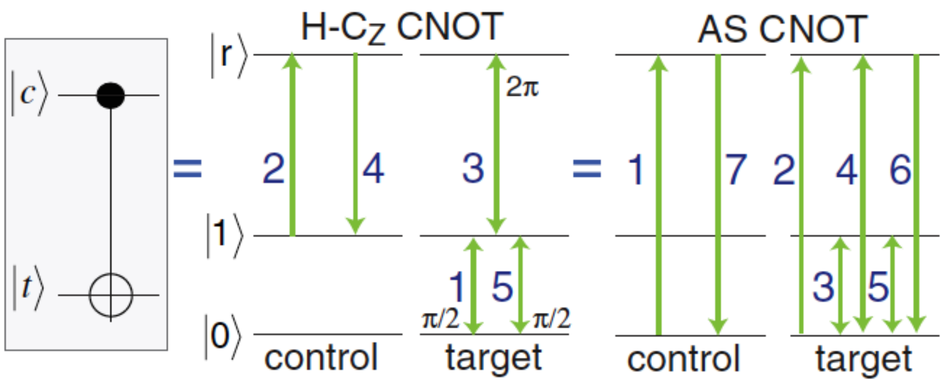
Blockade

From π-gate to CNOT



11	→	10
10	→	11
01	→	01
00	→	00

The CNOT gate at uni. Wisconsin (1)



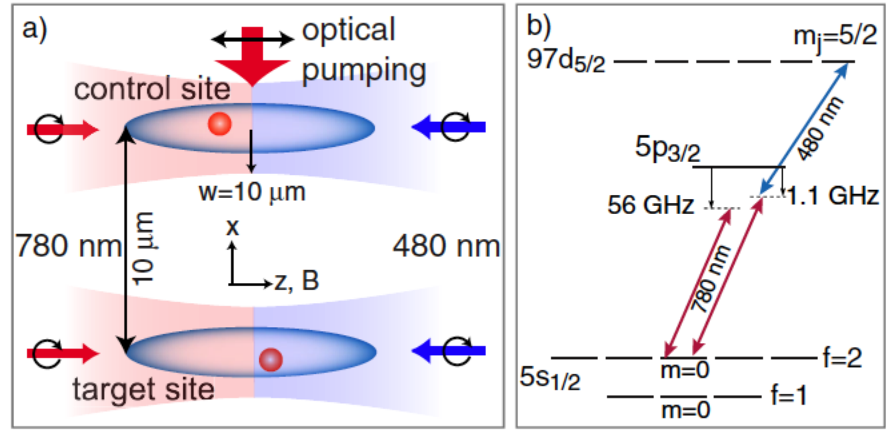
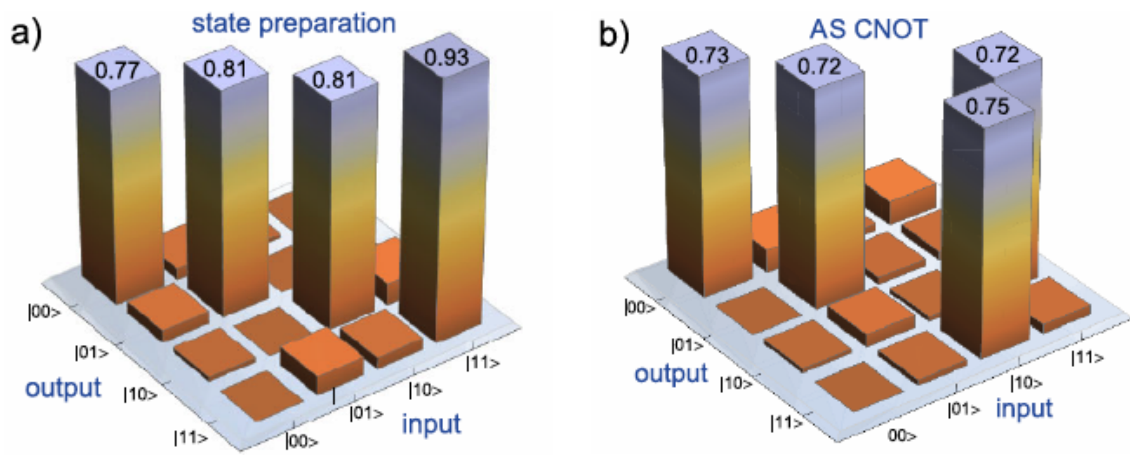


Table of truth: check blockade



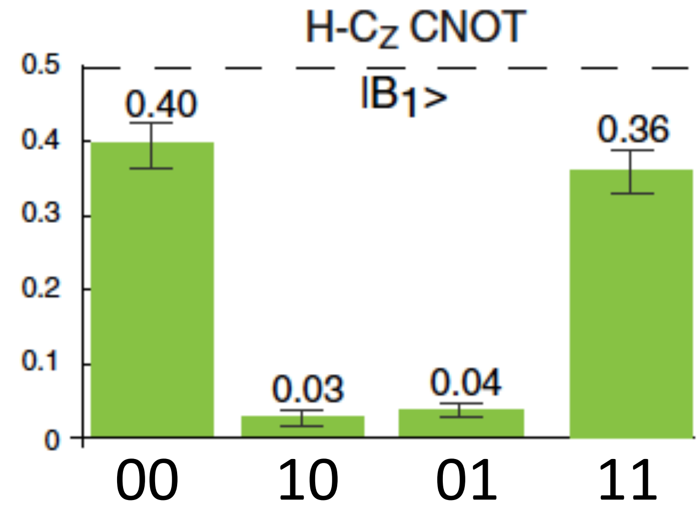
F = 0.73

Isenhower *et al.*, PRL **104**, 010503 (2010)

The CNOT gate at uni. Wisconsin (2)

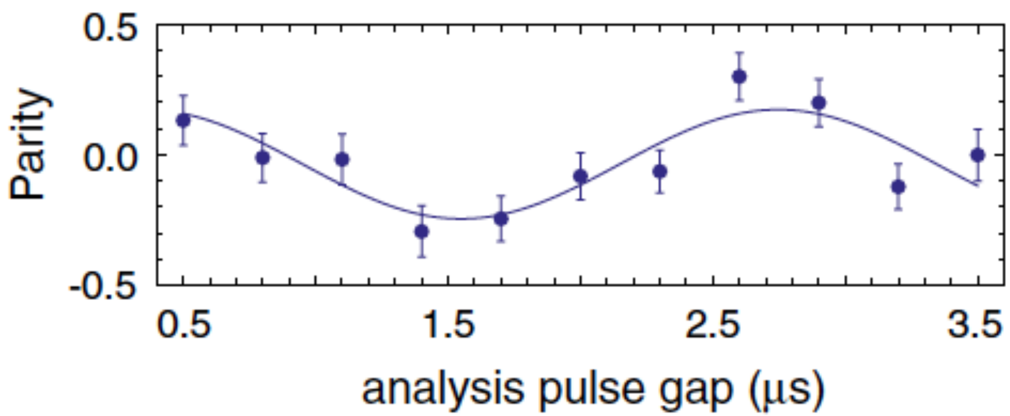
Prepare entangled states

Prepare (|0⟩+|1⟩)|0⟩ → gate



Check coherence: global Raman rotation

$$\Pi = P_{00} + P_{11} - P_{01} - P_{10}$$



Amplitude

$\Rightarrow \Re(\rho_{0011})$

$$\mathcal{F} = \frac{1}{2}(P_{00} + P_{11}) + \Re(\rho_{0011})$$

F = 0.58
(with loss correction)

See also: Zhang *et al.*, PRA **82**, 030306(R) (2010)

Tailoring the interaction: the dressed interaction picture

PHYSICAL REVIEW A, VOLUME 65, 041803(R)

Spin squeezing of atoms by the dipole interaction in virtually excited Rydberg states

Isabelle Bouchoule and Klaus Mølmer

PRL **104,** 223002 (2010) PHYSICAL REVIEW LETTERS week ending 4 JUNE 2010

Strongly Correlated Gases of Rydberg-Dressed Atoms: Quantum and Classical Dynamics

G. Pupillo,[1] A. Micheli,[1] M. Boninsegni,[2,1] I. Lesanovsky,[3] and P. Zoller[1]

PHYSICAL REVIEW A **82**, 033412 (2010)

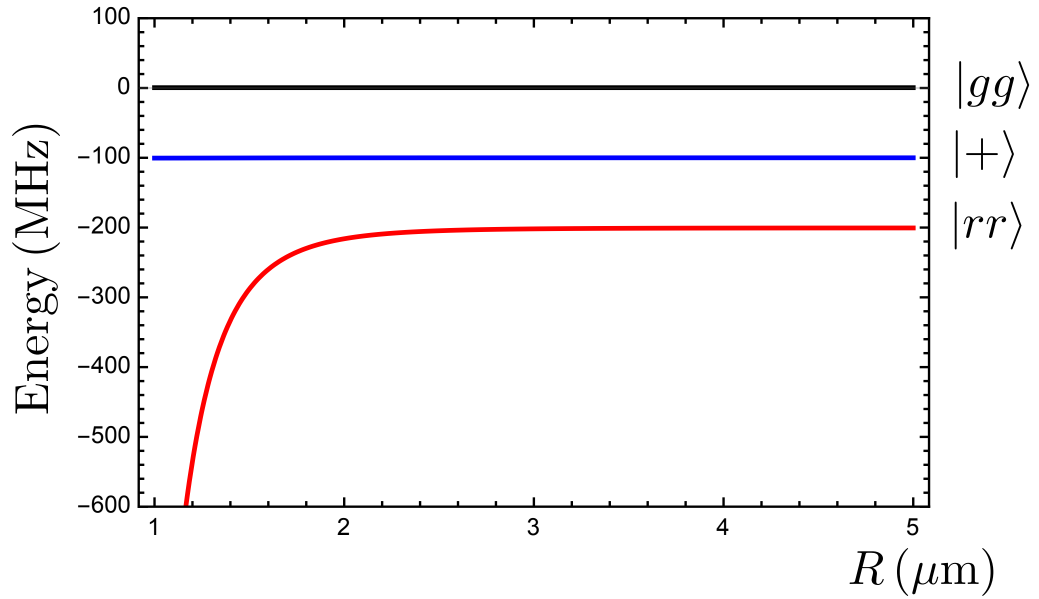
Interactions between Rydberg-dressed atoms

J. E. Johnson and S. L. Rolston

$$H = \hbar \begin{pmatrix} 0 & \frac{\Omega}{\sqrt{2}} & 0 \\ \frac{\Omega}{\sqrt{2}} & \delta & \frac{\Omega}{\sqrt{2}} \\ 0 & \frac{\Omega}{\sqrt{2}} & 2\delta + U_{dd} \end{pmatrix}.$$

$$U_{dd} = -\frac{1000(\mathrm{MHz})}{R(\mu\mathrm{m})^6}$$

$$\delta = -100\,(\mathrm{MHz})\ ;\ \Omega = 10\,(\mathrm{MHz})$$



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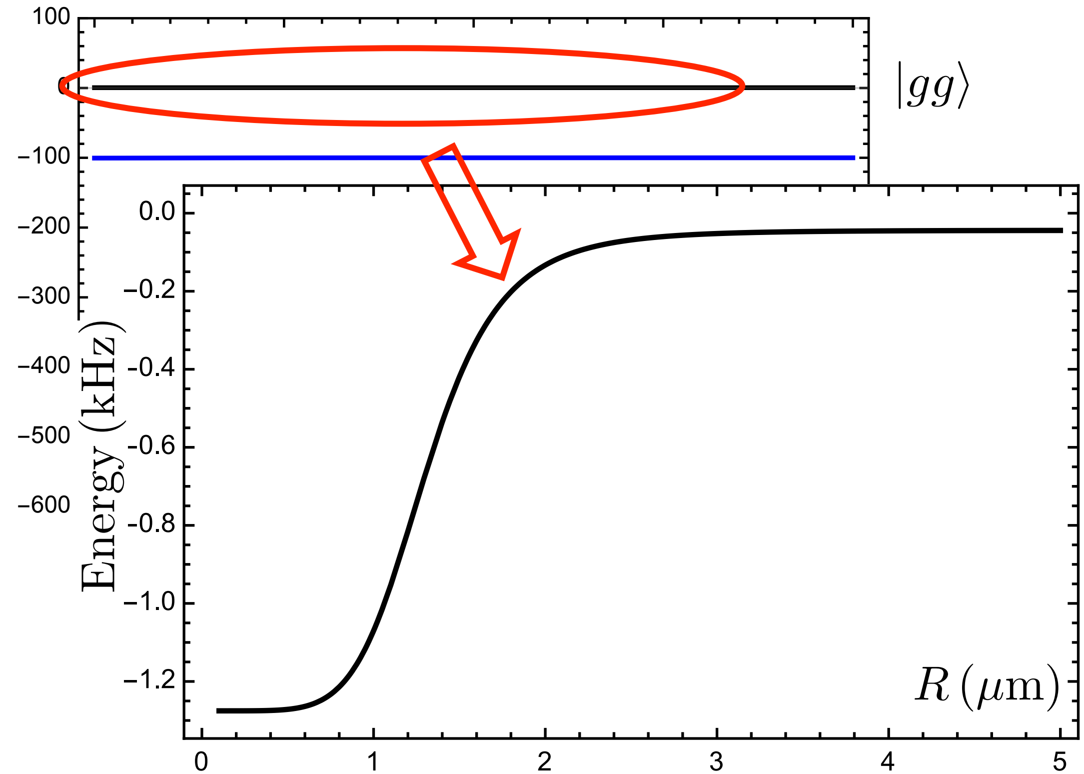
$$H = \hbar \begin{pmatrix} 0 & \frac{\Omega}{\sqrt{2}} & 0 \\ \frac{\Omega}{\sqrt{2}} & \delta & \frac{\Omega}{\sqrt{2}} \\ 0 & \frac{\Omega}{\sqrt{2}} & 2\delta + U_{dd} \end{pmatrix}.$$

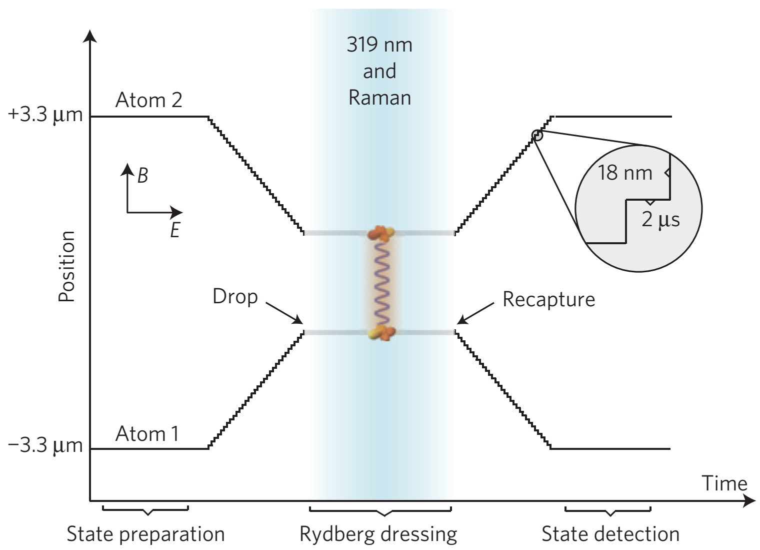
$$U_{dd} = -\frac{1000(\mathrm{MHz})}{R(\mu\mathrm{m})^6}$$

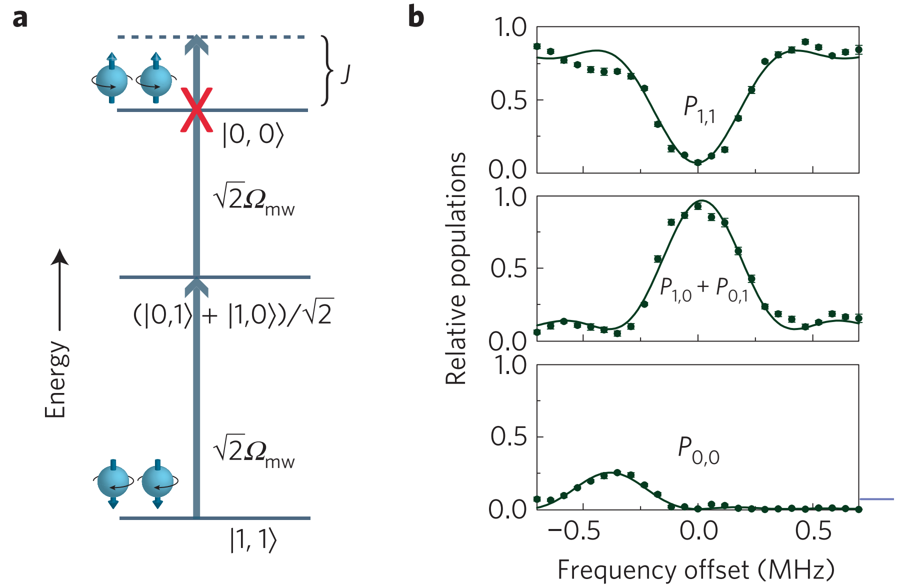
$$\delta = -100\,(\mathrm{MHz})\ ;\ \ \Omega = 10\,(\mathrm{MHz})$$

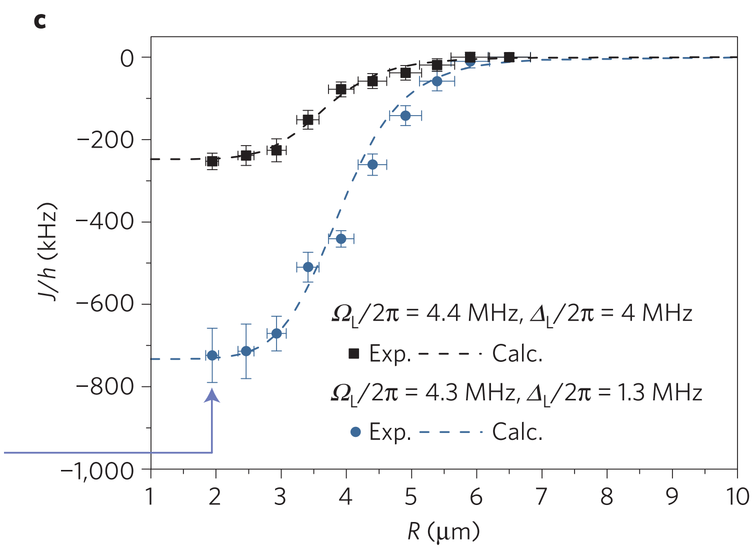


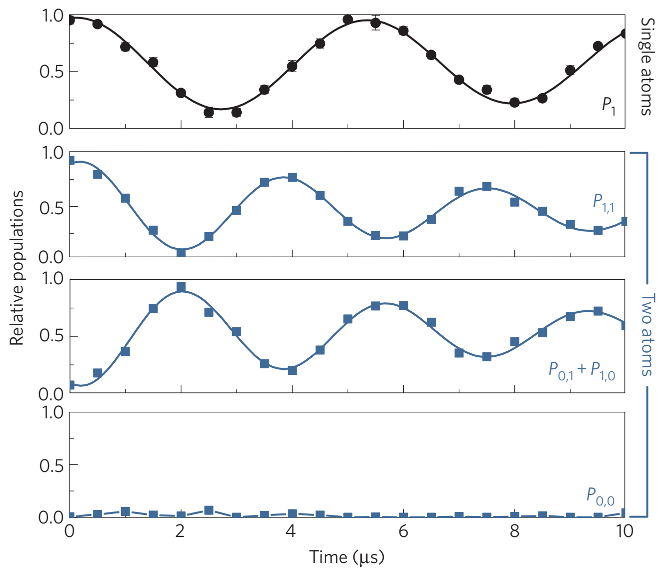
Tailoring the interaction: Rydberg “dressing” with two atoms

Jau *et al.*, Nat. Phys. **12**, 71 (2015)







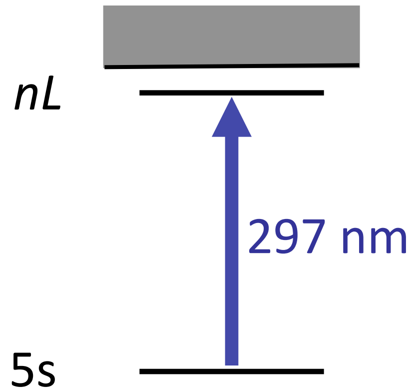


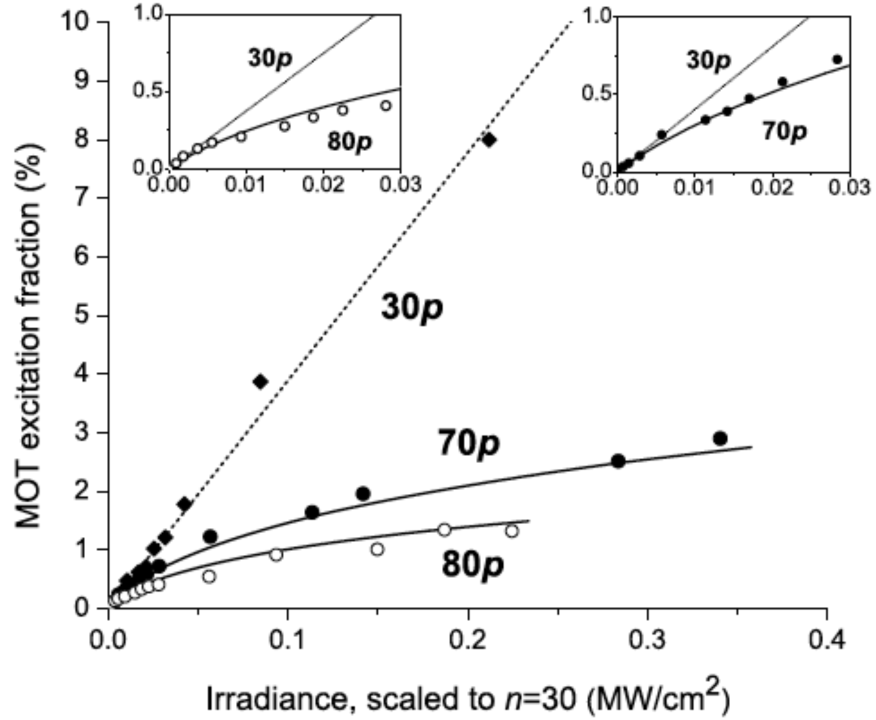
Blockade in atomic ensembles

Applications to single-photon and single-atom source

Rydberg blockade in cold atomic cloud: the U. Connecticut exp[t].

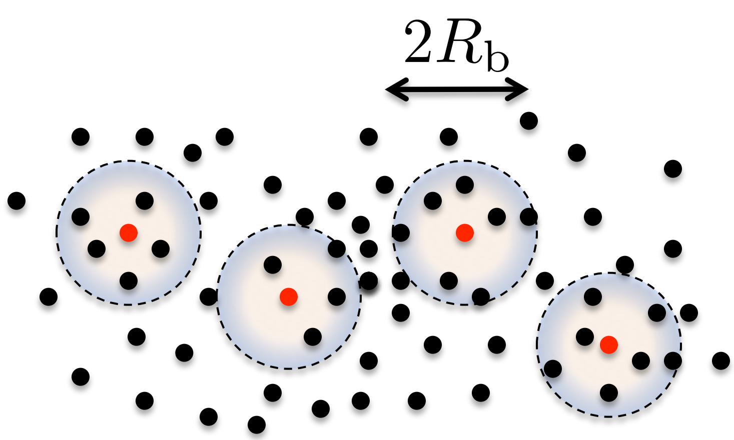
D. Tong *et al.*, PRL **93**, 063001 (2004)





Pulsed, incoherent laser excitation of a MOT

⇒ expect $N_{Ryd} \propto$ Intensity



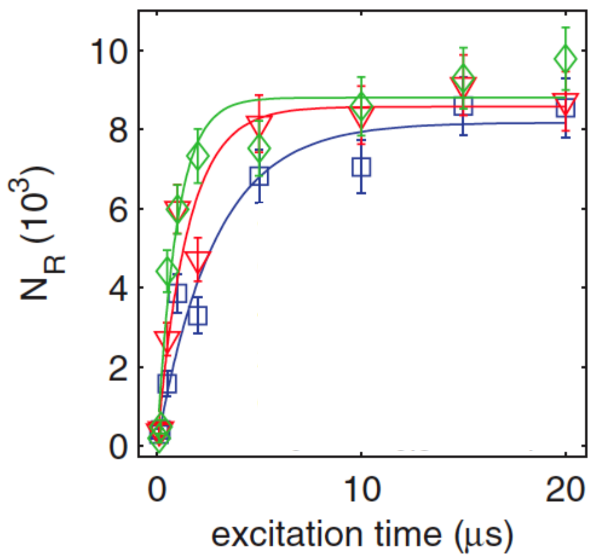
Increase n ⇒ increase C_6

⇒ increase R_b

$$N_{\mathrm{Ryd}}^{\mathrm{max}} \approx \frac{\mathrm{Volume}}{\frac{4\pi R_\mathrm{b}^3}{3}}$$

Rydberg blockade in dense cold atomic cloud: the Stuttgart expt.

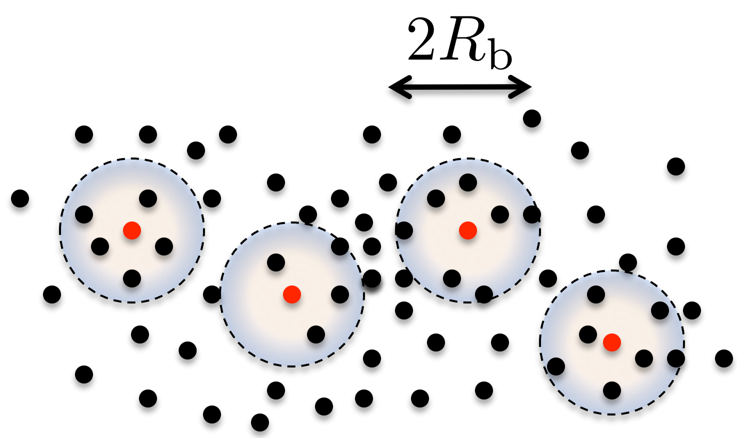
Use a dense ultracold cloud of ^{87}Rb + coherent 2-ph. excitation

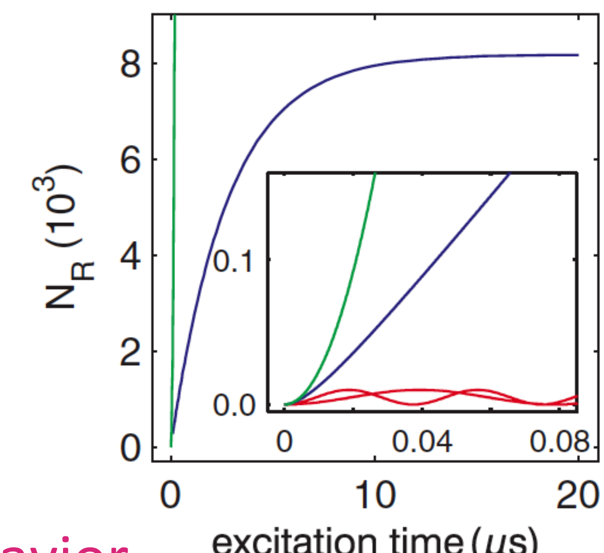


⇒ reach saturation

H. Heidemann *et al.*,
PRL **99**, 163601 (2007)

Inhomogeneous distribution of *N*





$$N_{\mathrm{Ryd}}(t) = \sum_{\{N\}} C_N \sin^2 \frac{\Omega_0 \sqrt{N} t}{2}$$

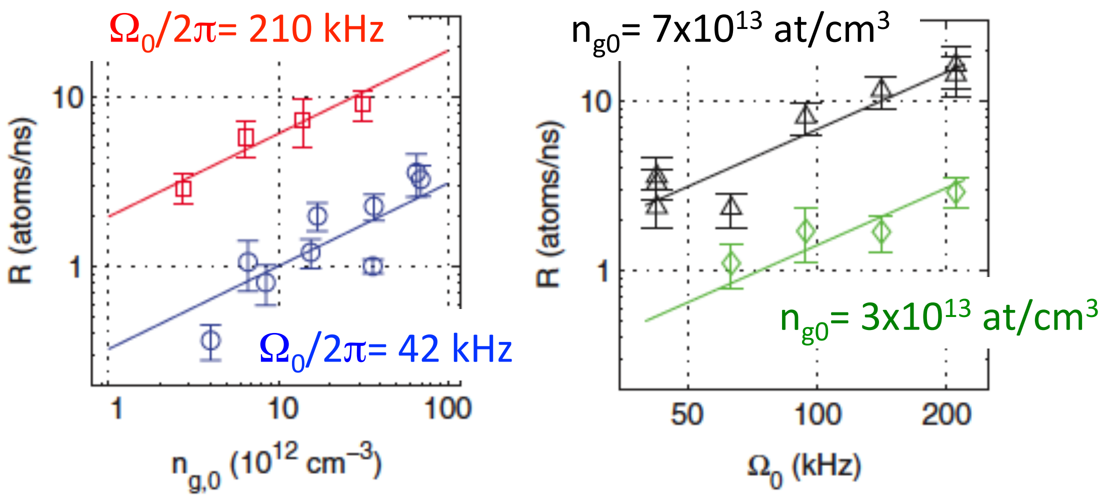
⇒ Incoherent behavior

Rydberg blockade in dense cold atomic cloud: the Stuttgart exp^t.

Check scaling laws

Expect rate of Rydberg production $R \propto \Omega_0 \sqrt{\langle N \rangle}$ with $\langle N \rangle \propto n_{g0}$

Find:



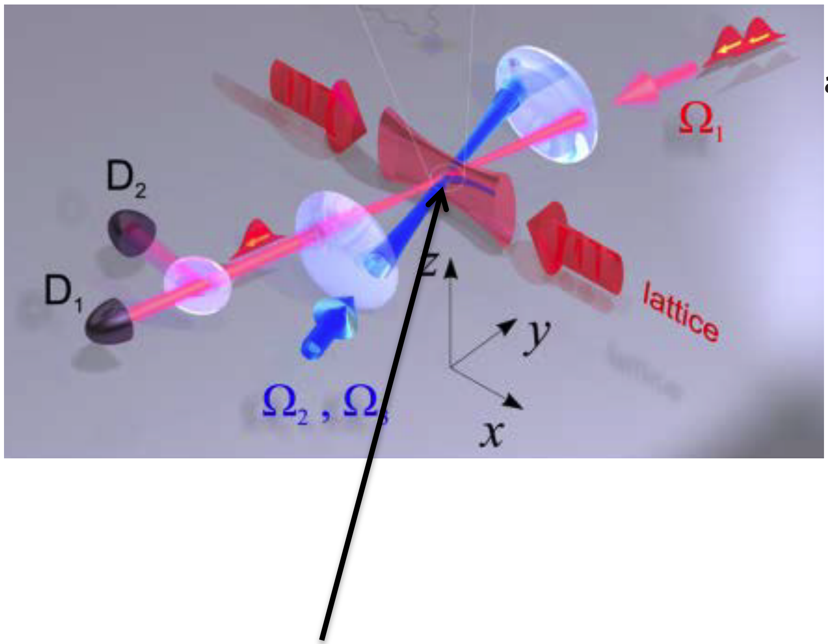
$R \propto n_{g0}^{0.49} \Omega^{1.1}$

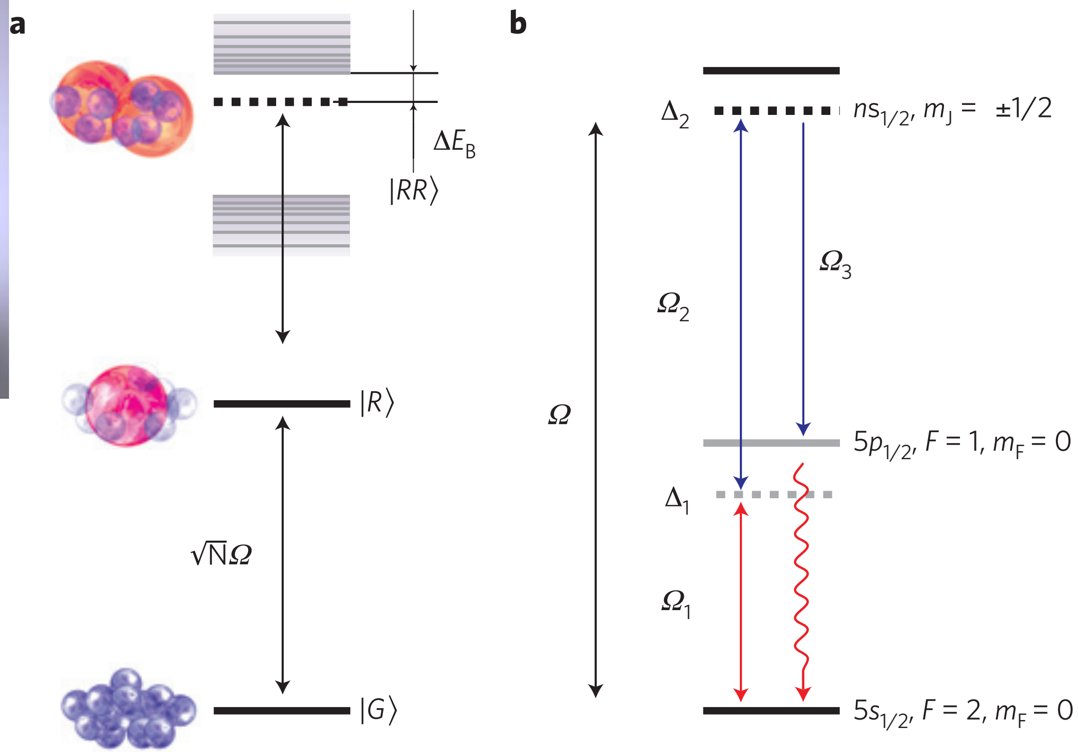
Also, expect: $N_{\rm Ryd}^{\rm max} \propto \dfrac{1}{R_{\rm b}^3} \propto \Omega_0^{1/2}$ and find: $\Omega_0^{0.38}$

H. Heidemann *et al.*, PRL **99**, 163601 (2007)

Collective Rabi oscillations in ensemble

Y.O. Dudin *et al.*, Nat. Phys. **8**, 790 (2012)



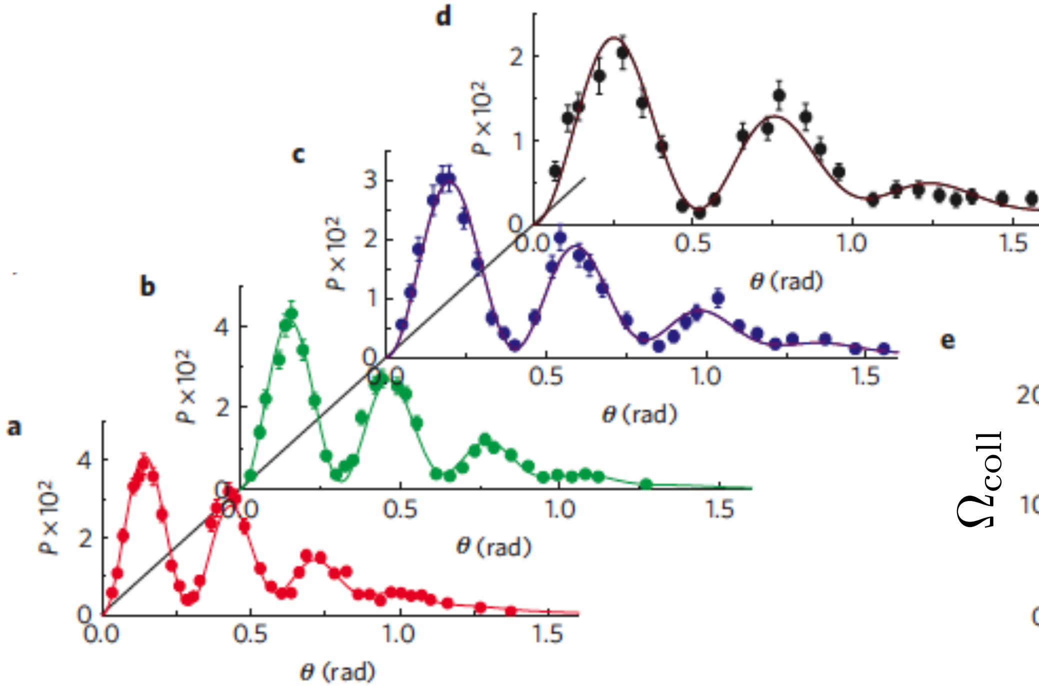


Excitation volume < R_b^3

102s, R_b = 15 μm

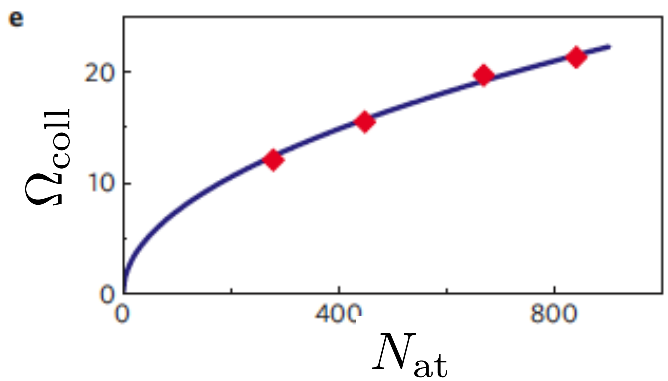
Collective Rabi oscillations in ensemble

Y.O. Dudin *et al.*, Nat. Phys. **8**, 790 (2012)



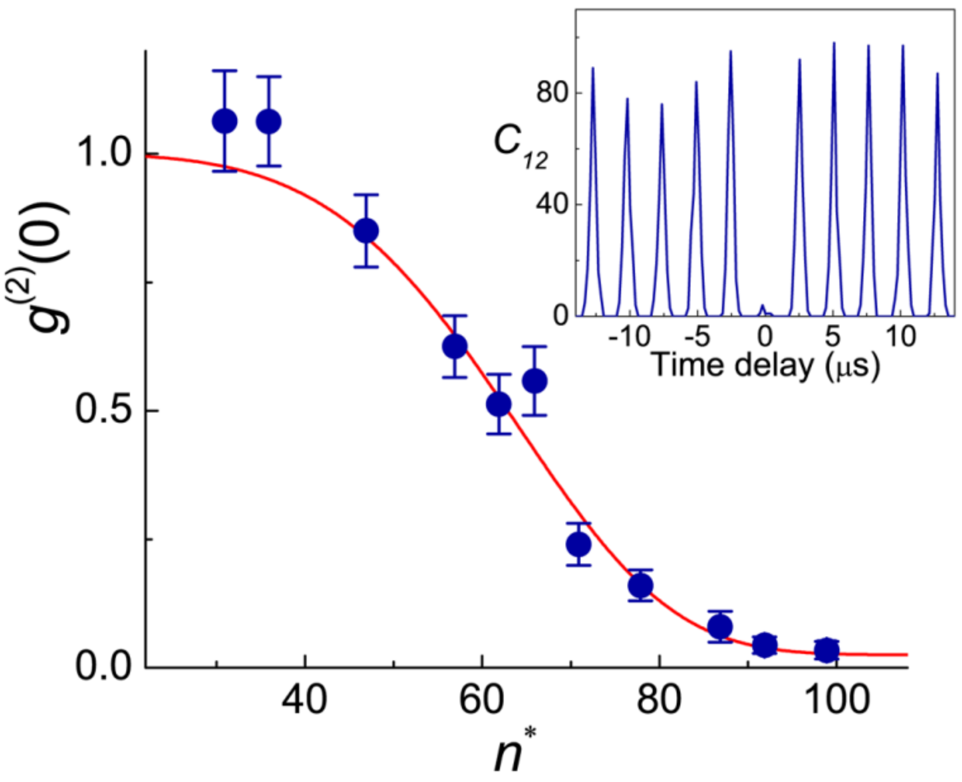
Expect:

$$\Omega_{\rm coll} \propto \sqrt{N_{\rm at}}$$

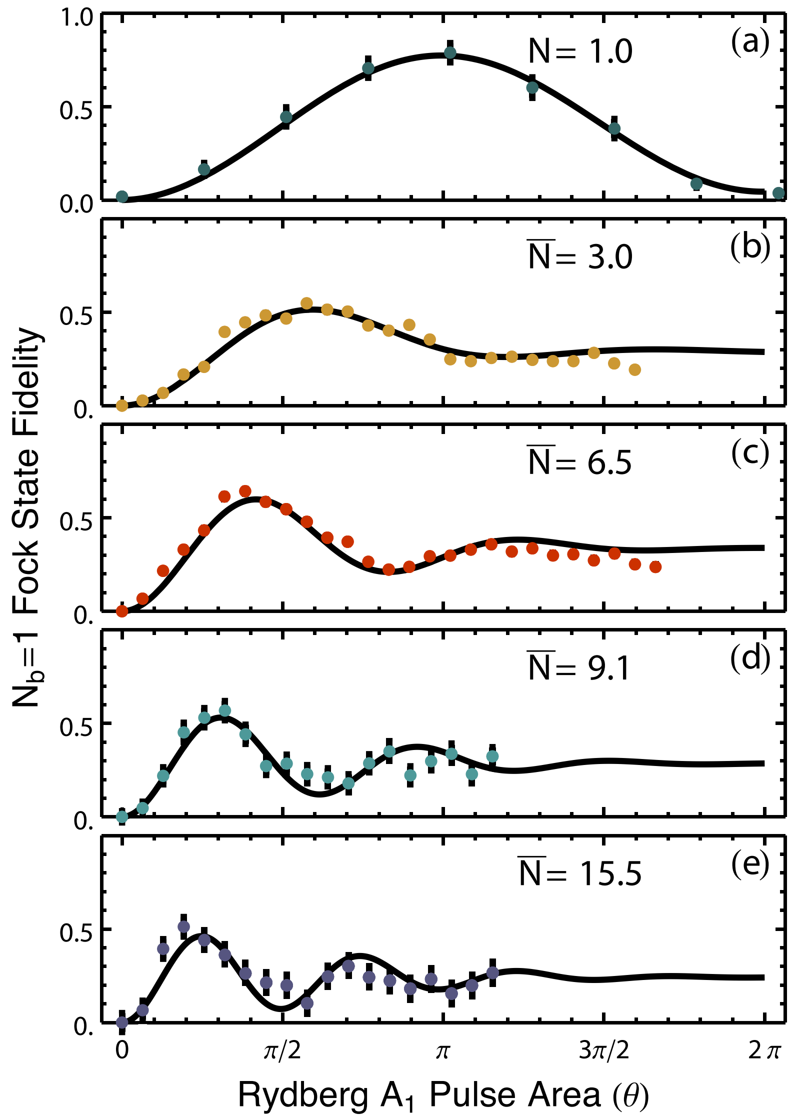


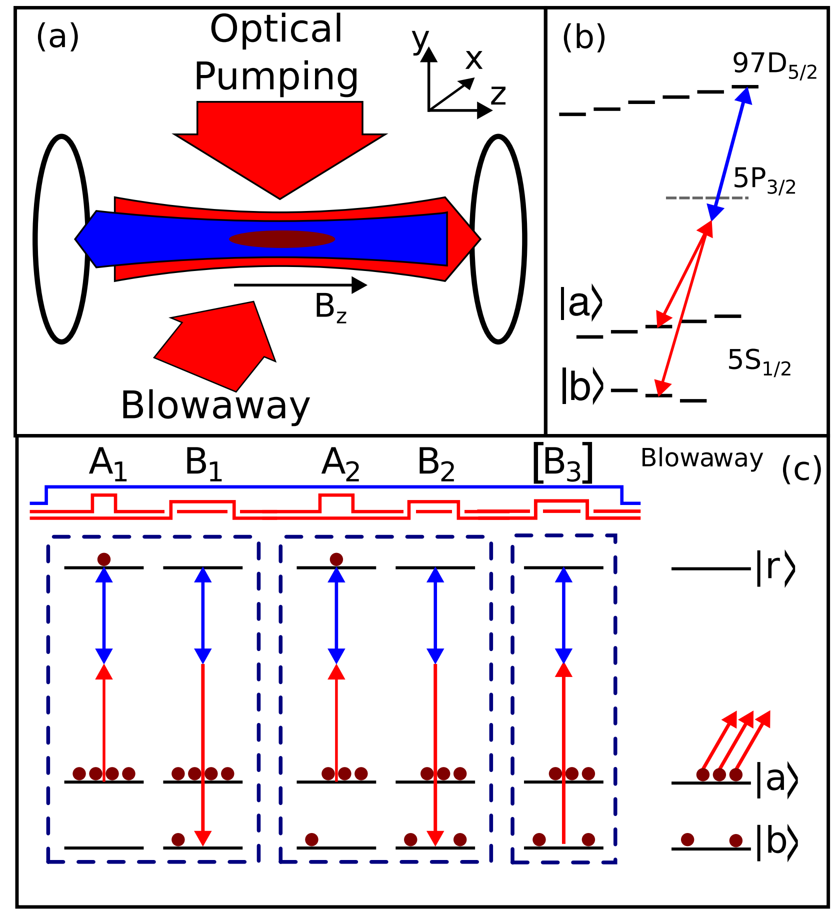
Application of blockade: a single photon source

Y.O. Dudin *et al.*, Science **336**, 887 (2012)



Atom Fock state preparation using blockade





Ebert *et al.*, PRL **112**, 043602 (2014)

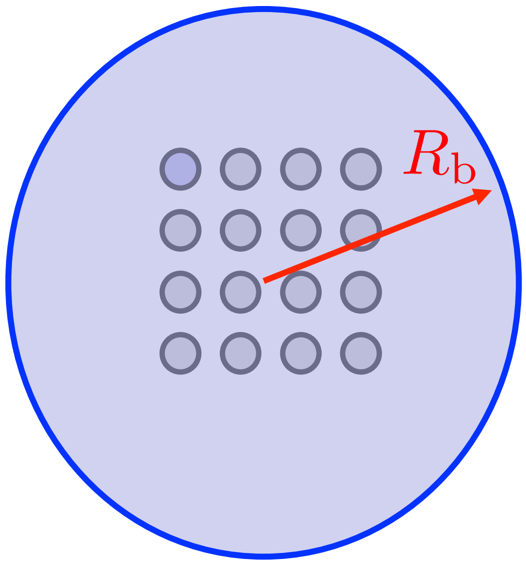
Outline

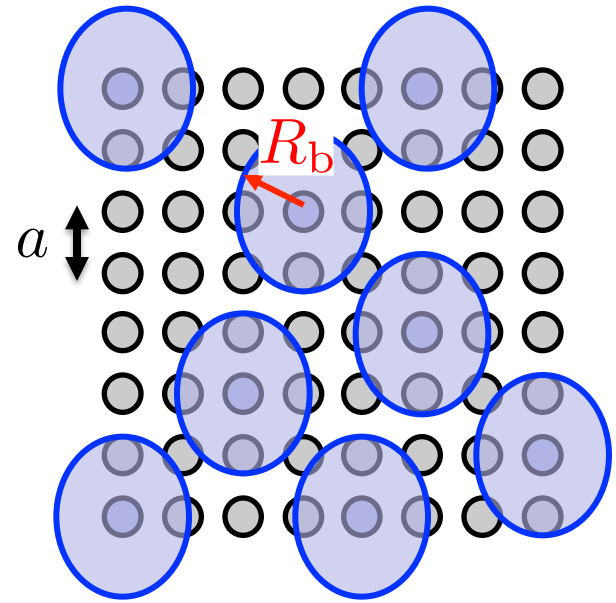
Lecture 1: Rydberg atoms and their interaction

Lecture 2: Rydberg Blockade and application to QIP

Lecture 3: Quantum simulation & Quantum Optics with Rydbergs

From blockade to many-body physics





dim H = 2

dim $H \sim 2^N$

Two (collective) states

$$|ggg...\rangle \Longleftrightarrow \frac{1}{\sqrt{N}} \sum_i |g...r_i g...\rangle$$

Also: Saffman, Kuzmich, Bloch, Pfau, Ott…

Strongly correlated many-body system!

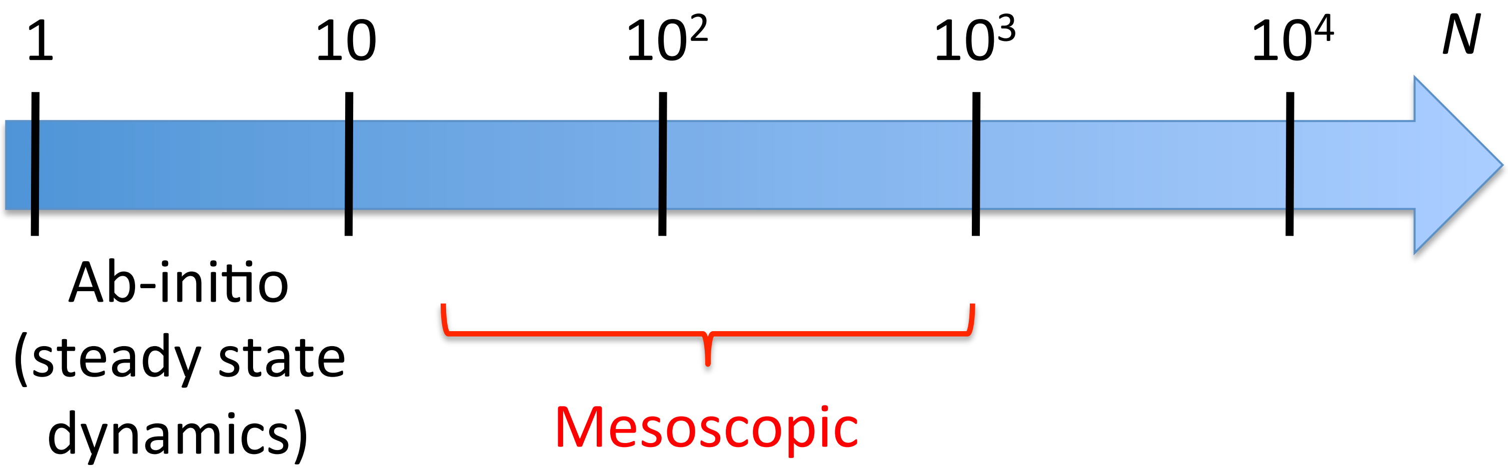
Experimentally :

tune $\frac{R_b}{a}$ = 1-20

Many - body systems and complexity

Complexity: for N > 30 – 40, ab-initio calculations impossible!!

Ex: spin 1/2 ⇒ size of Hilbert space $\sim 2^N$ too large



Approximate methods ($10^2 < N < 10^5$): DMRG, Monte Carlo, density functionnal, mean field…

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

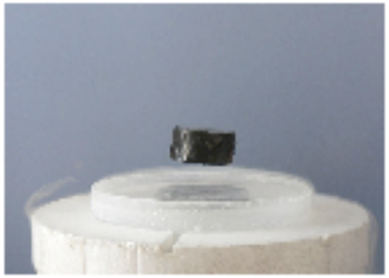
Simulating Physics with Computers

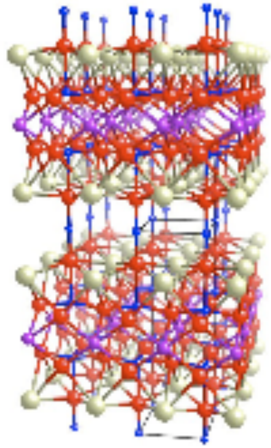
Richard P. Feynman

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

with it, with quantum-mechanical rules). For example, the spin waves in a spin lattice imitating Bose-particles in the field theory. I therefore believe it's true that with a suitable class of quantum machines you could imitate any quantum system, including the physical world. But I don't know whether the general theory of this intersimulation of quantum systems has ever been worked out, and so I present that as another interesting problem: to work out the classes of different kinds of quantum mechanical systems which are really intersimulatable—which are equivalent—as has been done in the case of classical computers. It has been found that there is a kind of

Quantum simulation: an example





Ex: high-T_c superconductivity

simplify

Experience on the real system

Model Hamiltonian

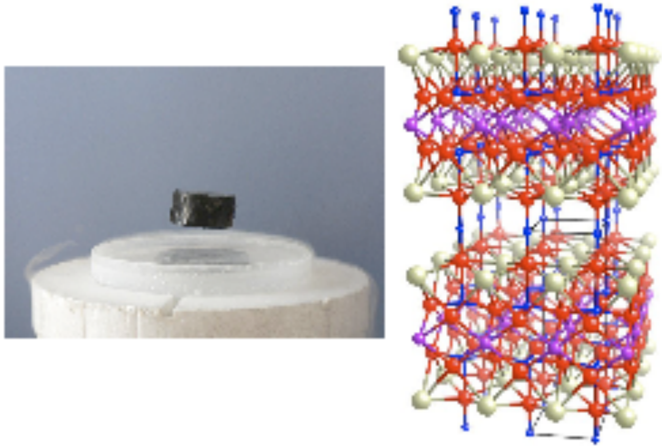
$$H_{\mathrm{model}} = -\sum_{i,j} J_{ij} a_i^\dagger a_j + \sum_i g(a_i^\dagger)^2 (a_i)^2$$

Calcul ... H_{model}

$\Rightarrow$ super ... luctivty ?

Calculation too hard…

Quantum simulation: an example



Ex: high-T_c superconductivity

Experience on the real system

simplify →

Model Hamiltonian

$$H_{\text{model}} = -\sum_{i,j} J_{ij} a_i^\dagger a_j + \sum_i g(a_i^\dagger)^2 (a_i)^2$$

Lab...

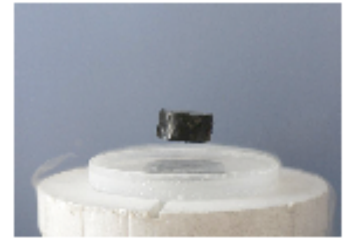
Quantum simulator = engineer ensemble of atoms ruled by H_{model}

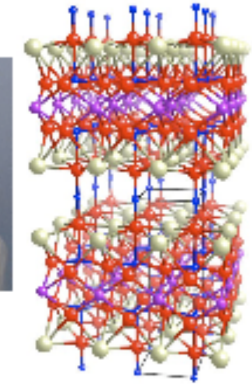
$$|\psi(t)\rangle = e^{-\frac{i}{\hbar} H_{\text{model}} t} |\psi(0)\rangle$$

"Preparable"

Mesure outcome of simulator: **ground state = supercond.?**

What can you simulate = N-body problem?



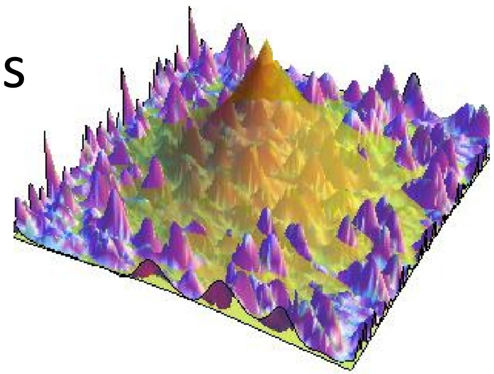


High-Tc superconductivity

Fermi-Hubbard: $\hat{H} = -t \sum_{\sigma,\langle i,j\rangle\in\Omega} (\hat{c}^\dagger_{i,\sigma}\hat{c}_{j,\sigma} + h.c.) + U \sum_{i\in\Omega} \hat{n}_{i,\downarrow}\hat{n}_{i,\uparrow},$

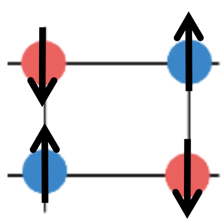
Conduction properties of metal:
Influence of disorder and interactions

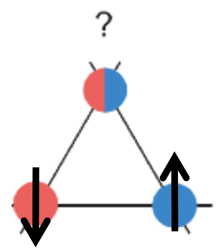
Anderson localization



Quantum magnetism: ferro & anti-ferromagnetic order

Néel order





frustration

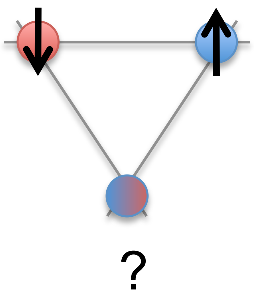
Phase diagram, dynamics…

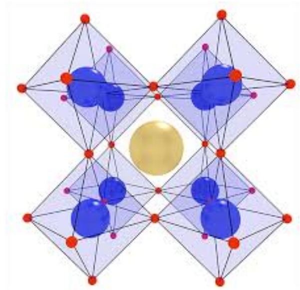
+ Dirac equation, cosmology, gauge theory, quantum chemistry…

Georgescu *et al.* Rev. Mod. Phys. **86**, 153 (2014)

Spin models in condensed matter systems: a few examples

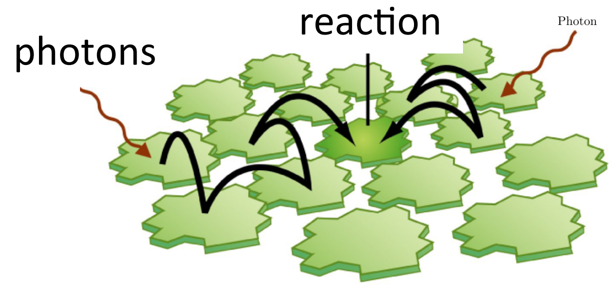
Quantum magnetism



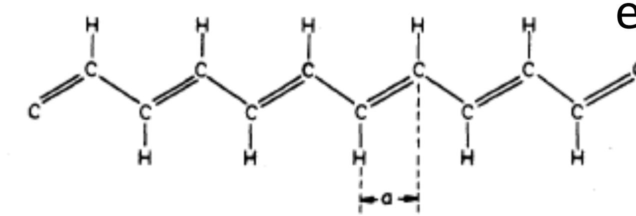


Perovskite
$Y_2Ti_2O_7$

Transport of excitations

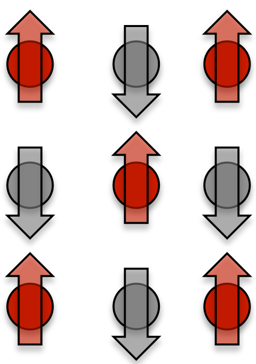


photosynthesis



excitons

"Simplest" system: interacting spin ½ particles on a lattice:



Ising $$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}$$

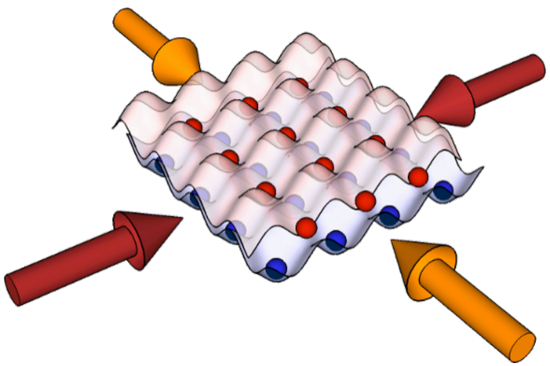
XY model $$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+ \right)$$

Open questions (long-range interaction) for N > 30:
phase diagram, dynamics, role anisotropy, geometry (frustration) …

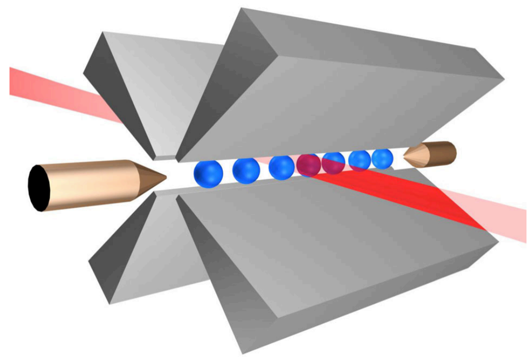
Quantum state engineering

Current status

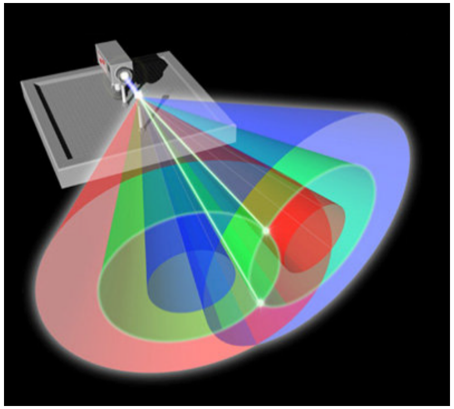
☑ Isolate and control ≤ 10 individual quantum systems



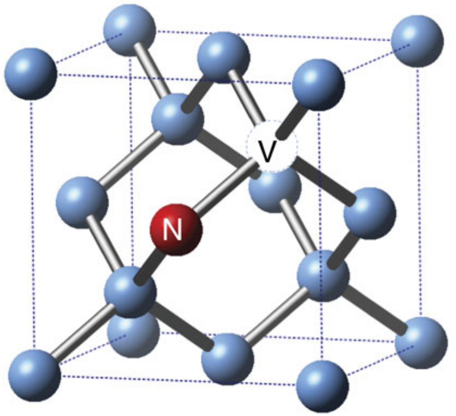
Neutral atoms



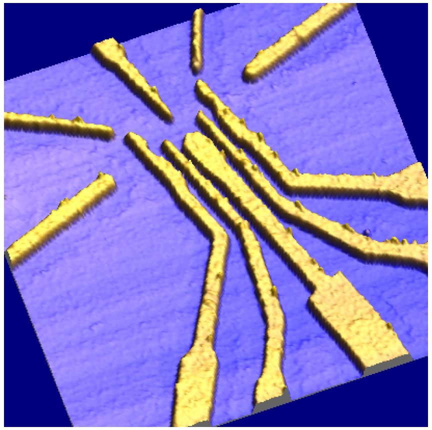
Trapped ions



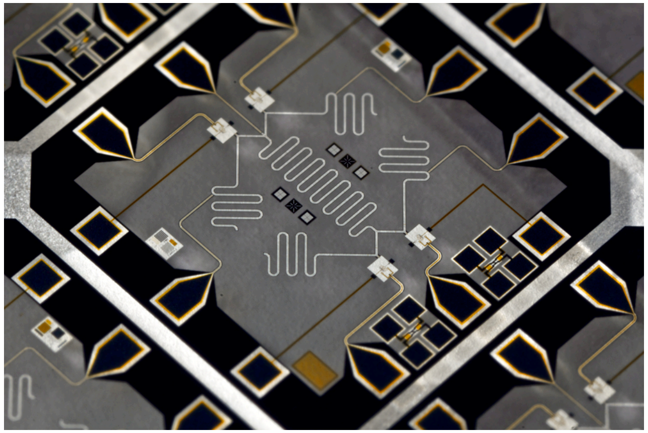
Photons



NV centers



Quantum dots

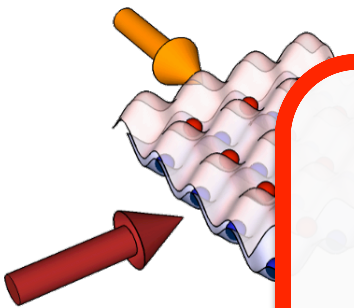


Superconducting qubits

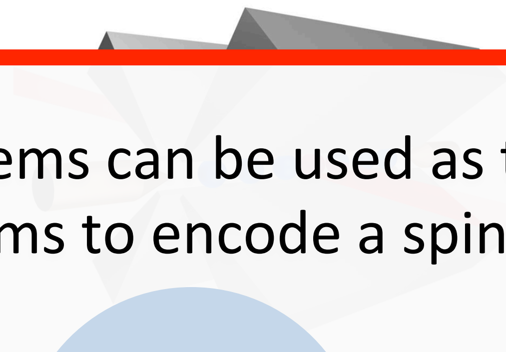
Quantum state engineering

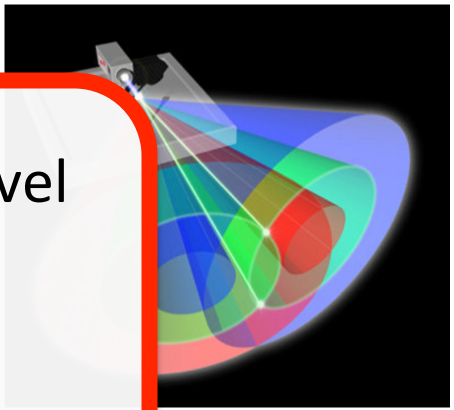
Current status

☑ Isolate and control ≤ 10 individual quantum systems



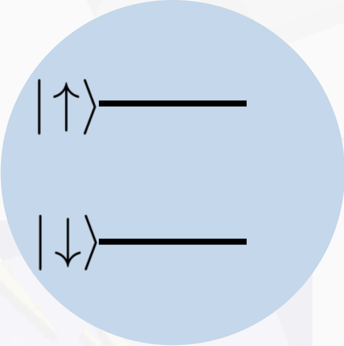
Neutral atoms

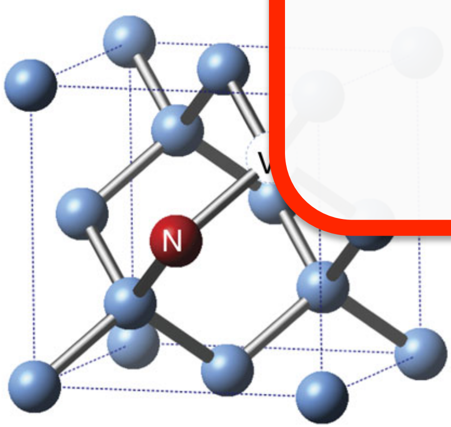




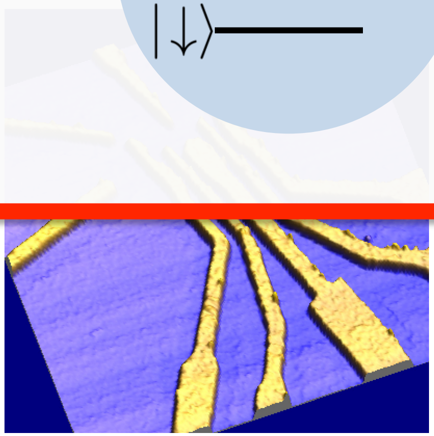
Photons

All those systems can be used as two-level systems to encode a spin:

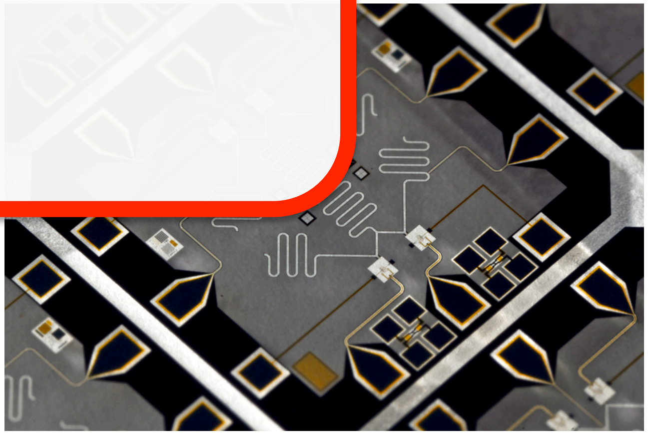




NV centers



Quantum dots



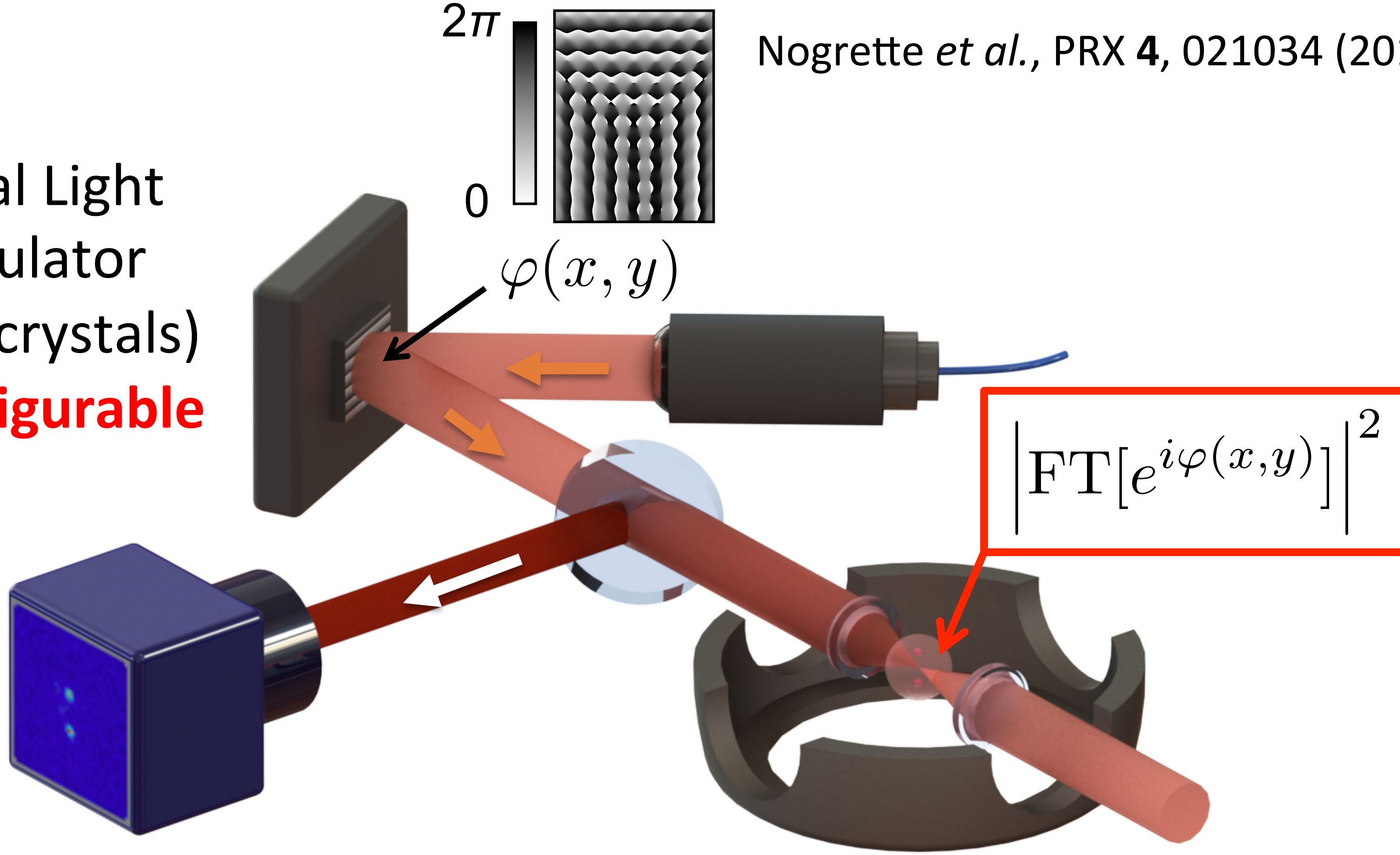
Superconducting qubits

Holographic 2D arrays of tweezers

Nogrette *et al.*, PRX **4**, 021034 (2014)

Spatial Light Modulator (liquid crystals)

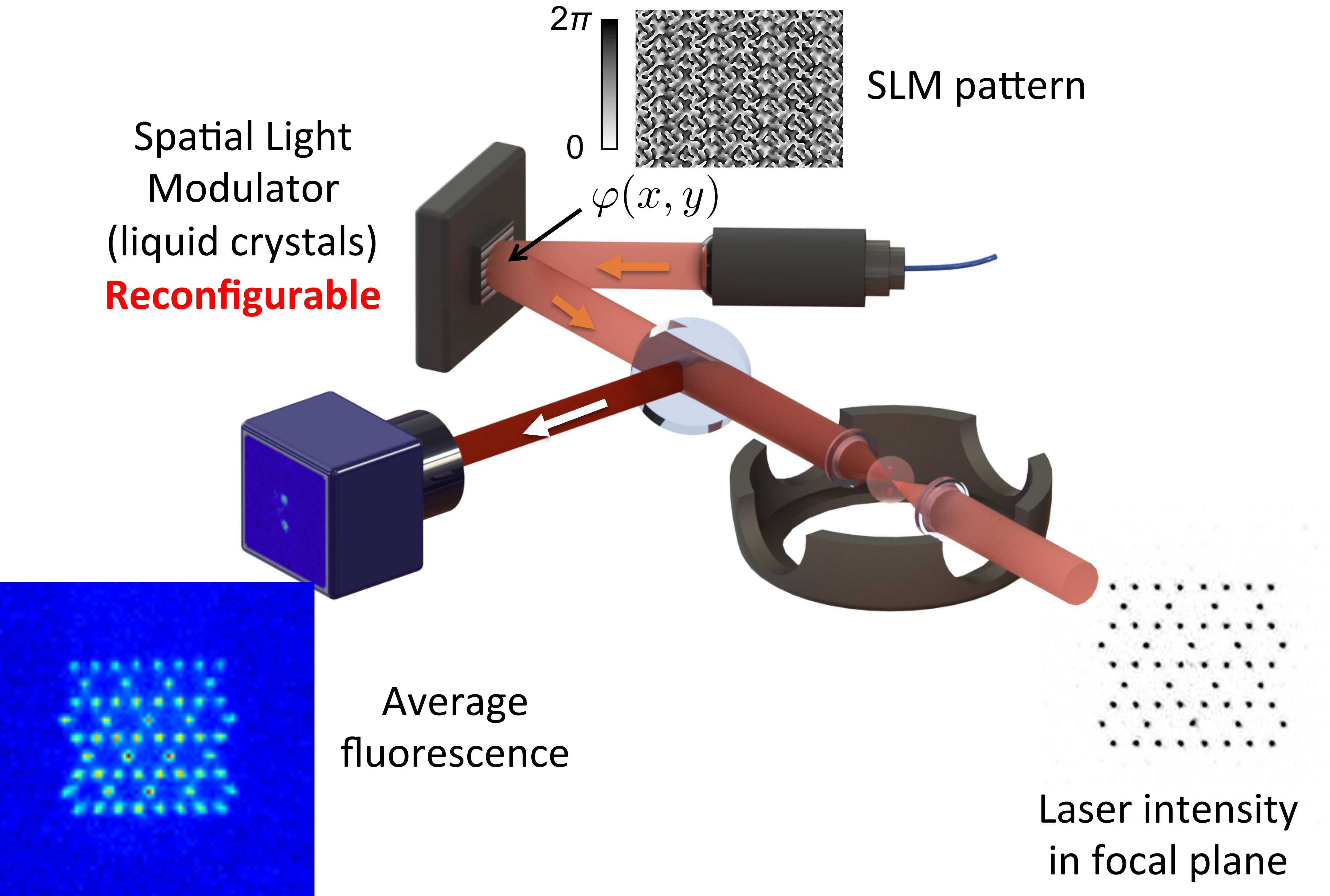
Reconfigurable



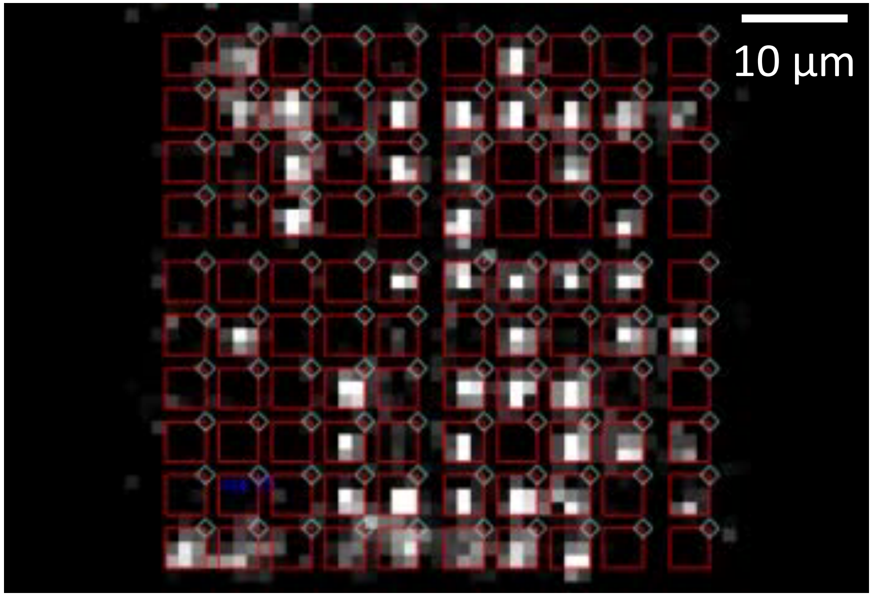
Phase calculation: iterative algorithm [Gerchberg – Saxton, Optik **35**, 237 (1972)]

Related works: Darmstadt, Amsterdam, Wisconsin, Harvard, Albuquerque, Chofu, Otago…

Holographic 2D arrays of tweezers



Arrays of optical tweezers with individual atoms

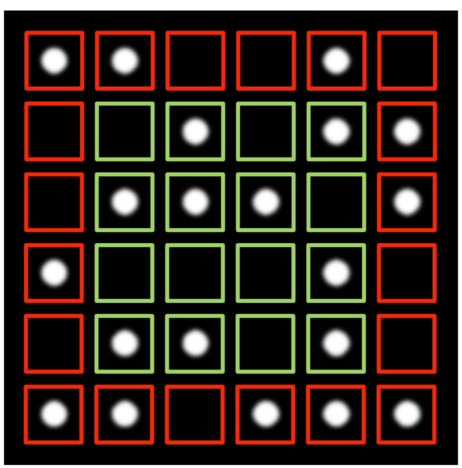


Problem: stochastic loading ($p \sim 0.5$)

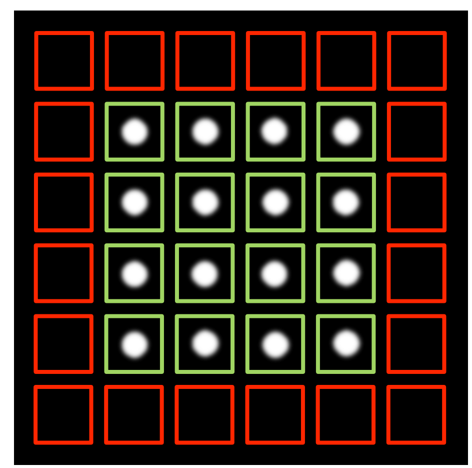
One solution: sort atoms in arrays

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

Initial atom distribution
(stochastically filled)

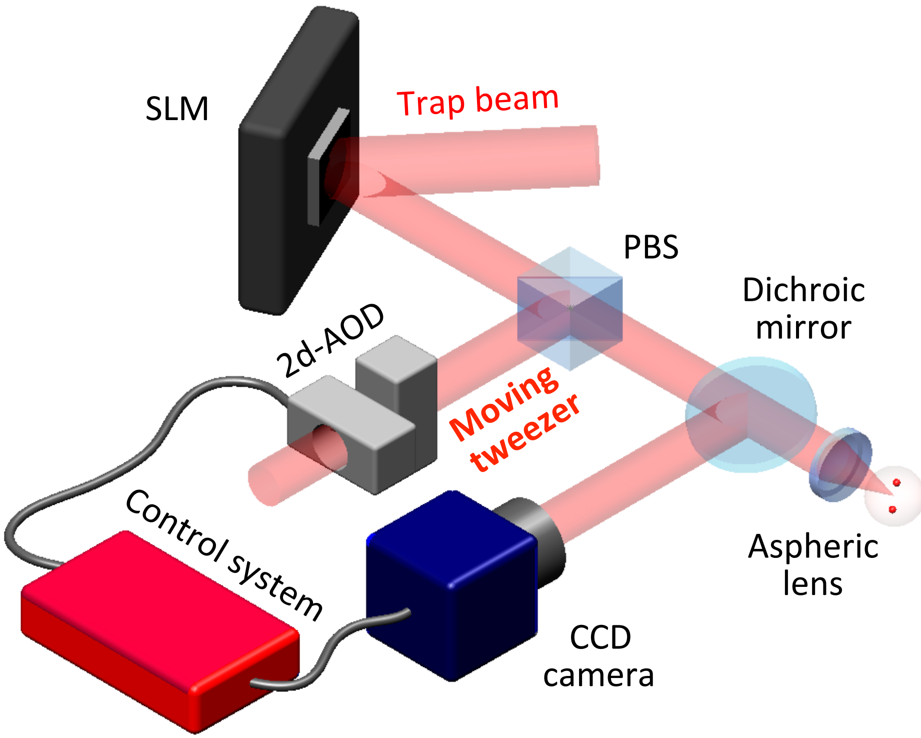


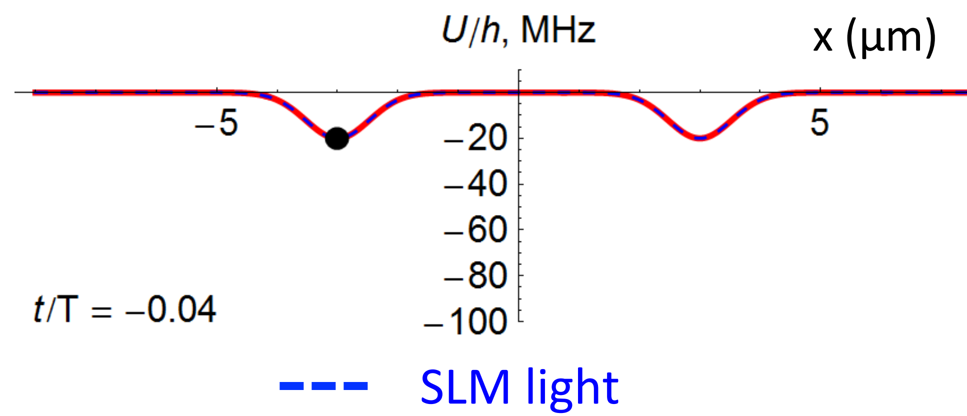
Target atom distribution
(ordered array)



Moving optical tweezers for atom assembling

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

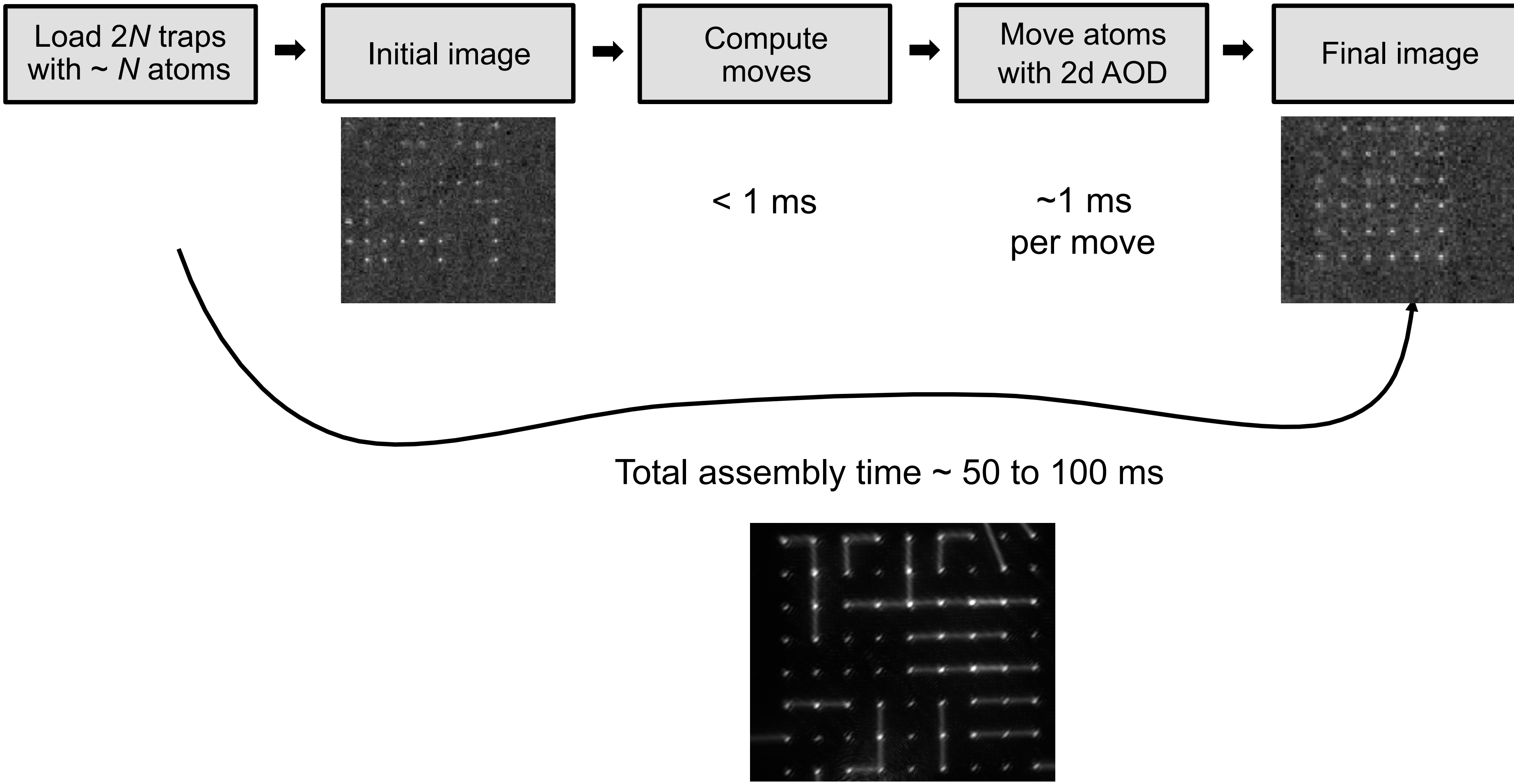




$p \sim 0.993(1)$

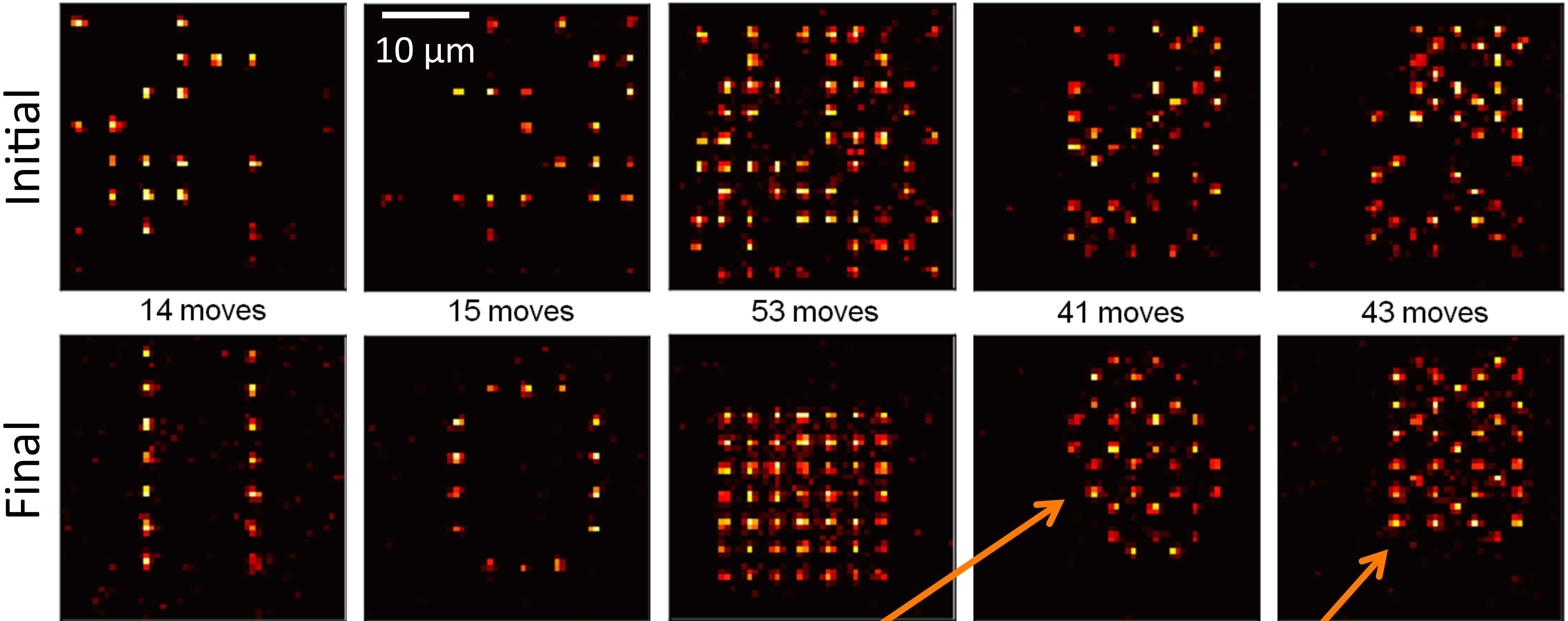
Labuhn, PRA **90**, 023415 (2014)

Atom assembler sequence

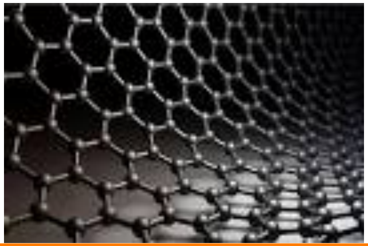


Barredo, de Léséleuc, *et al.*, Science **354**, 1021 (2016)

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



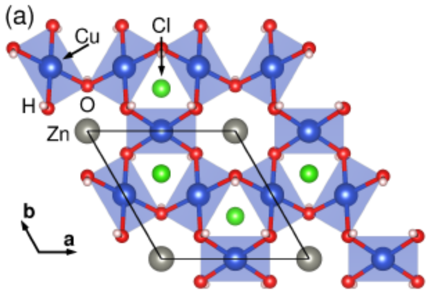
Hexagonal



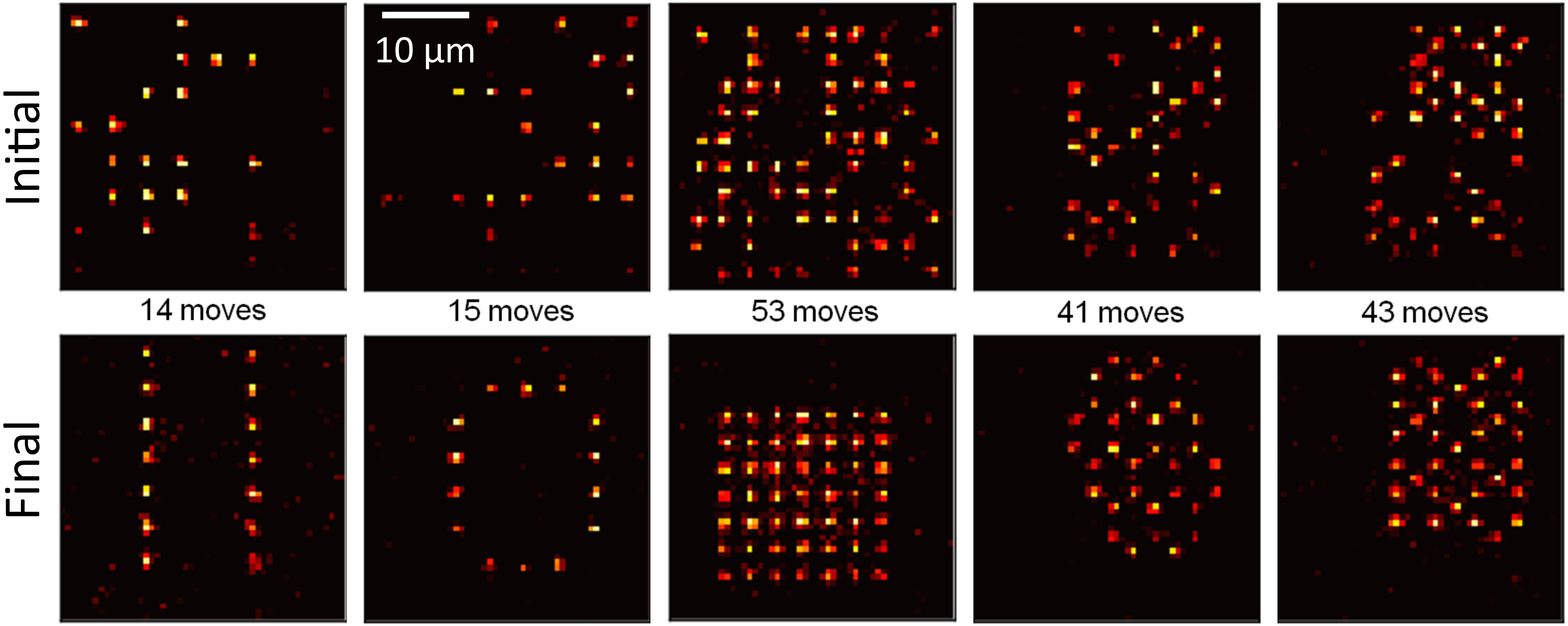
graphene

Kagome: Herbertsmithite

$ZnCu_3(OH)_6Cl_2$



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



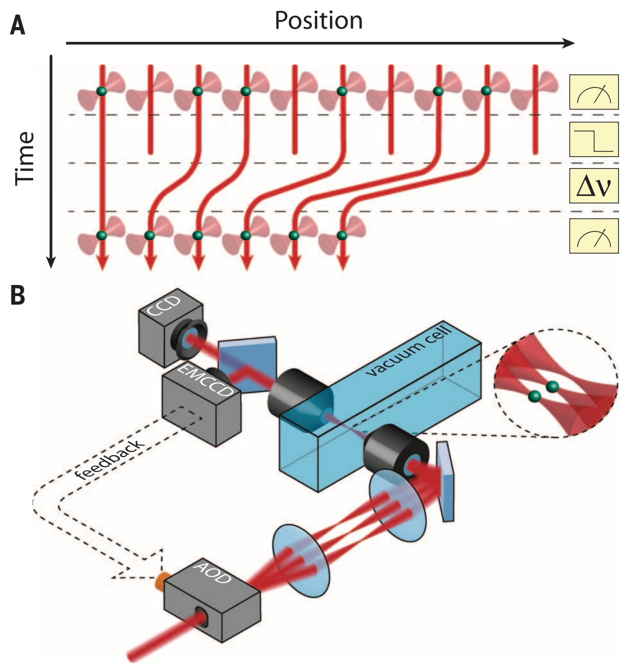
Barredo, de Léséleuc, *et al.*, Science **354**, 1021 (2016)

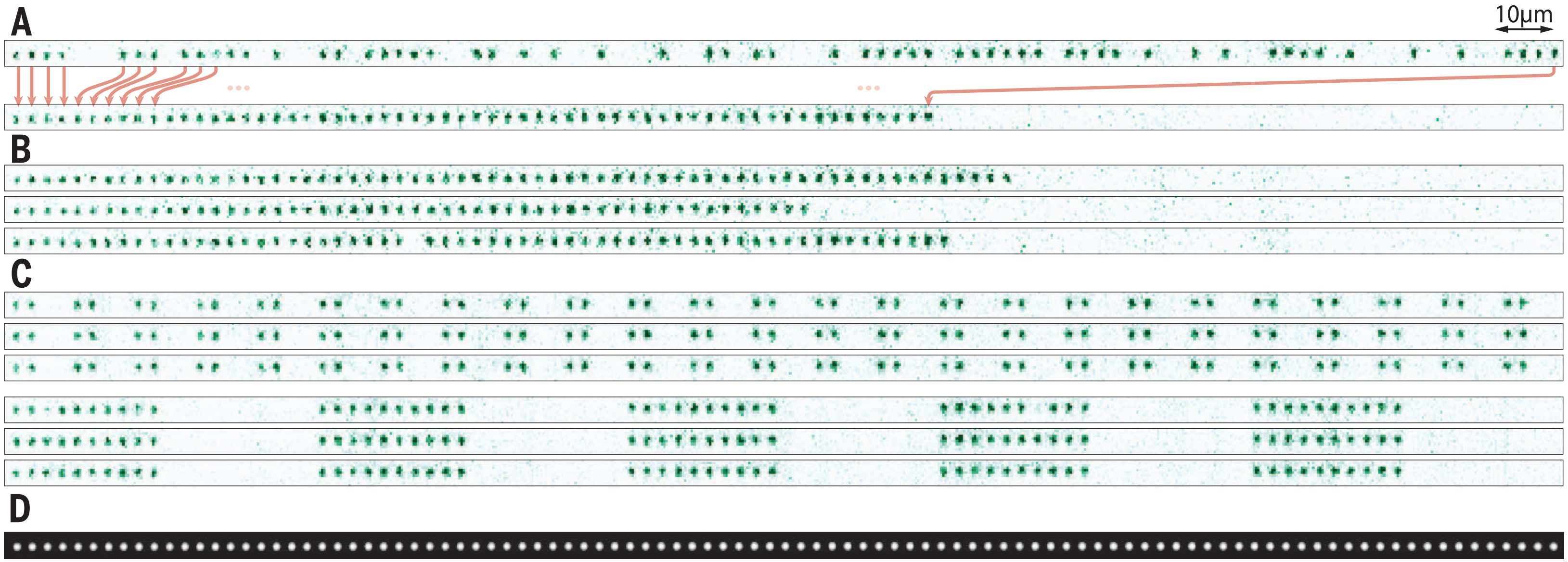
- Fully loaded arrays up to 50 atoms
- 98% filling fraction ~ 1 / sec rep. rate
- 100% filling every ~ 2-5 sec

Related work in Harvard (1D), Science **354**,1024 (2016)

Sorting in 1D (Harvard)

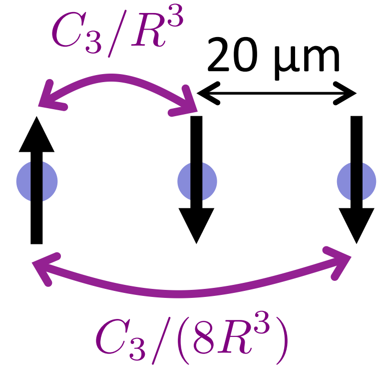
Science **354**,1024 (2016)



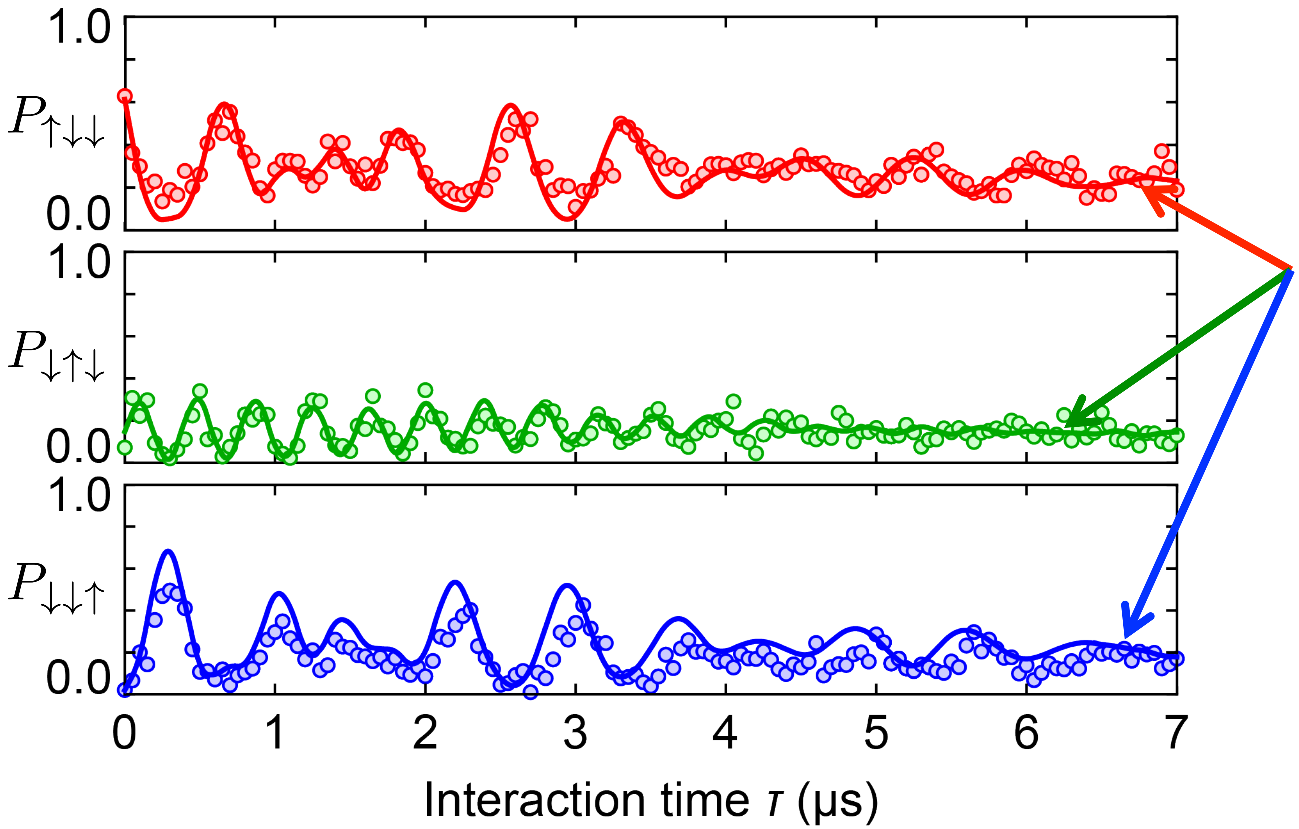


Observation of spin exchange in a 3-atom chain

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



Prepare $|\uparrow\downarrow\downarrow\rangle$ at $t = 0$, and let the system evolve

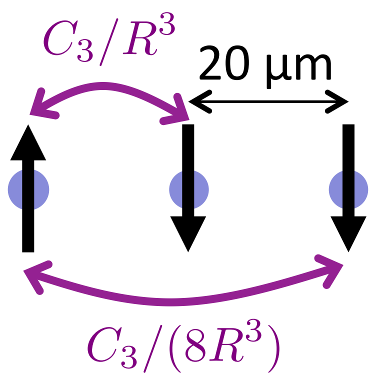


XY model (Schrödinger) + imperfections

No adjustable parameter

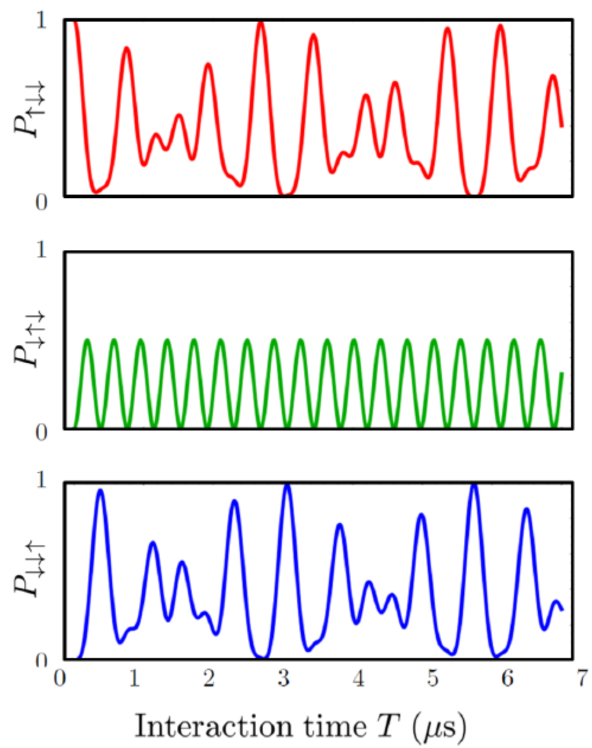
Optical lattices Nat. Phys. **9**, 235 (2013) ; trapped ions Nature, **511**, 198 & 202 (2014)

Three-atom "spin-chain": what to expect (theory) ?



Prepare $|\uparrow\downarrow\downarrow\rangle$ at $t = 0$,
and let the system evolve

$1/R^3$ interaction



2 off-diagonal couplings: V & V / 8

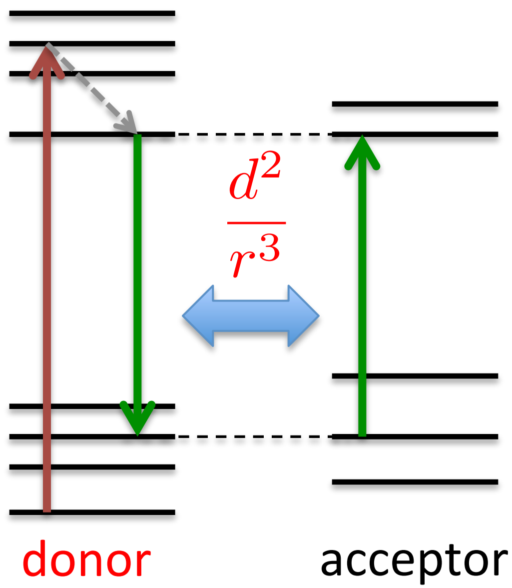
⇒ eigenvalues (incommensurate):

$$\frac{V}{16}\left(1+3\sqrt{57}\right)\ ,\ \frac{V}{16}\left(1-3\sqrt{57}\right)\ ,\ -\frac{V}{8}$$

Resonant energy exchange around us…

Energy transport in biological systems

FRET



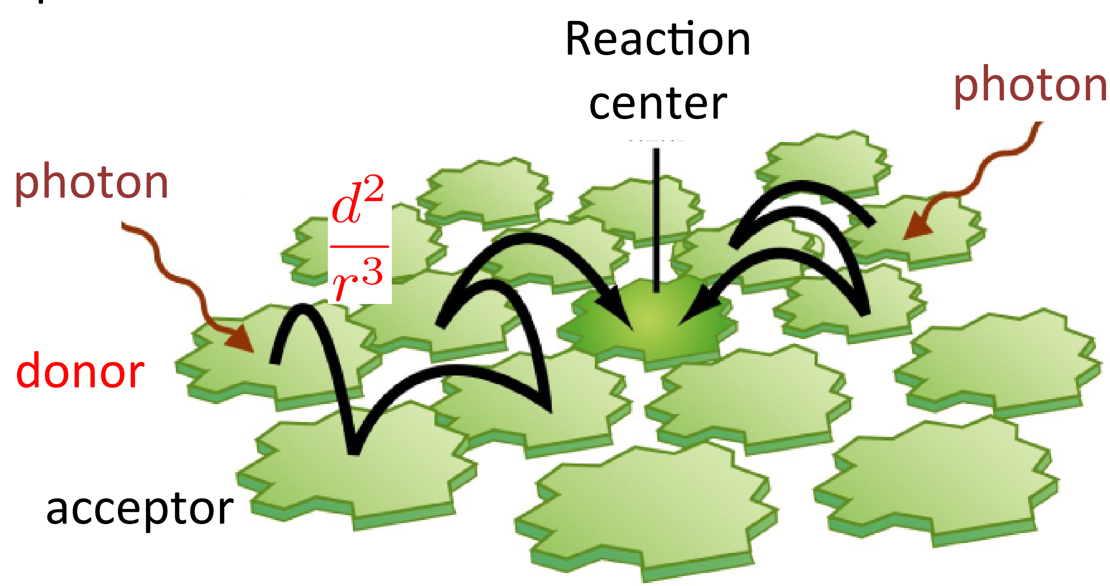
$$k_{tr} = \frac{1}{\tau}\left(\frac{R_0}{r}\right)^6 \propto \left(\frac{d^2}{r^3}\right)^2$$

F. Perrin (1933), Oppenheimer (1941)
Th. Förster (1946)

Clegg, *The History of FRET* (2006)

Photosynthesis:

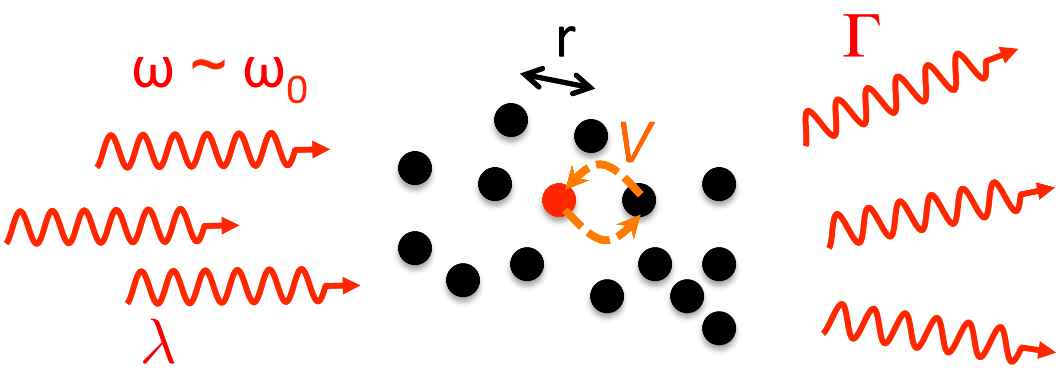
QE > 90%

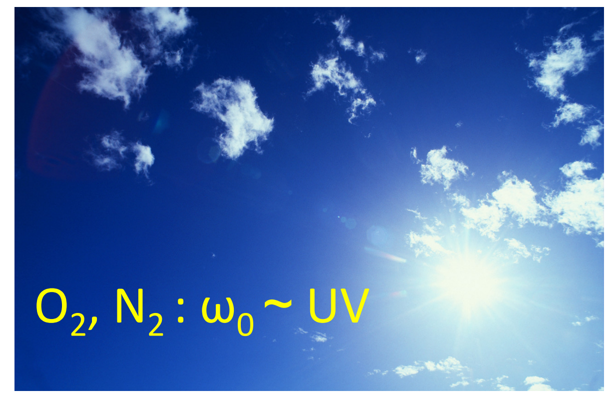


Resonant interaction and light scattering...

Near-resonance light scattering in dense media

Ensemble of two level-atoms (frequency ω_0, linewidth Γ)

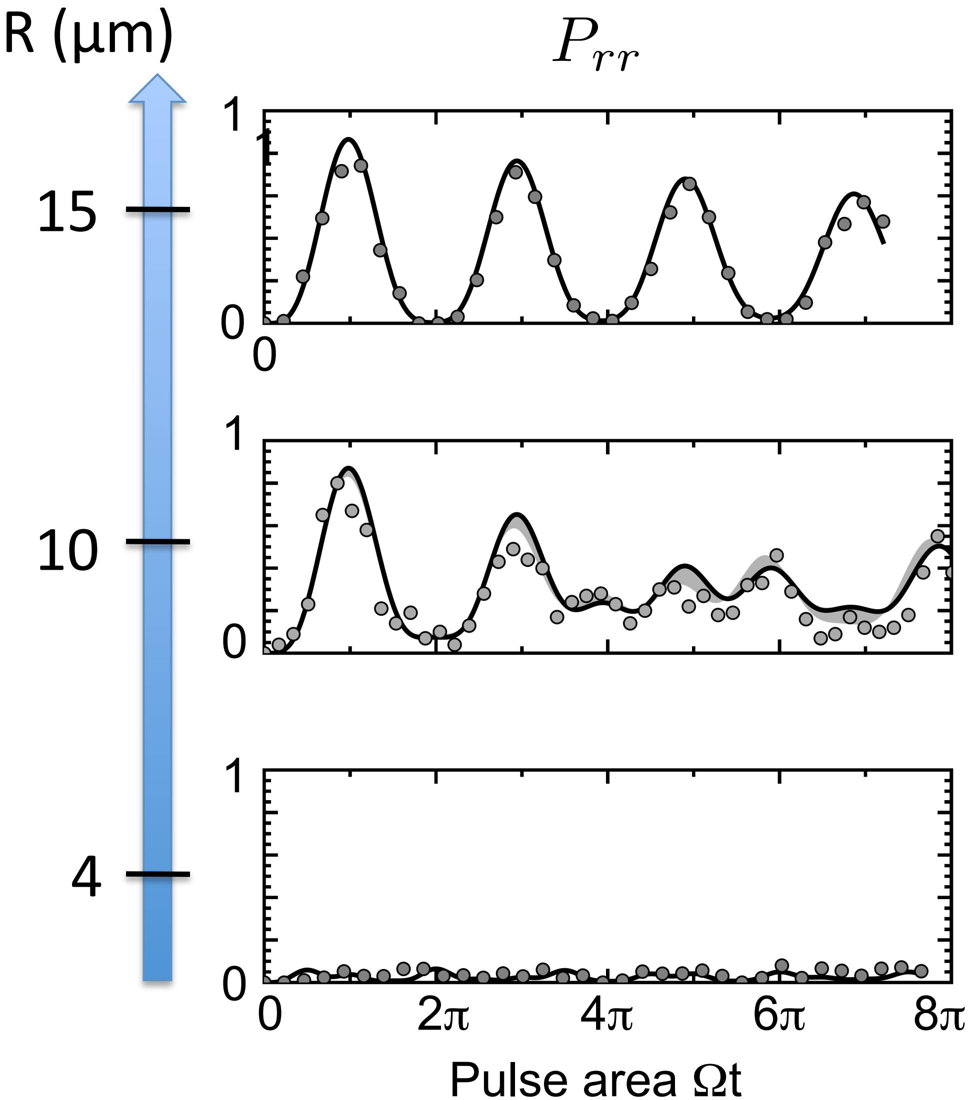




Non-radiative energy redistribution. Rate: $\frac{V}{\hbar} \Rightarrow$ modifies scattering

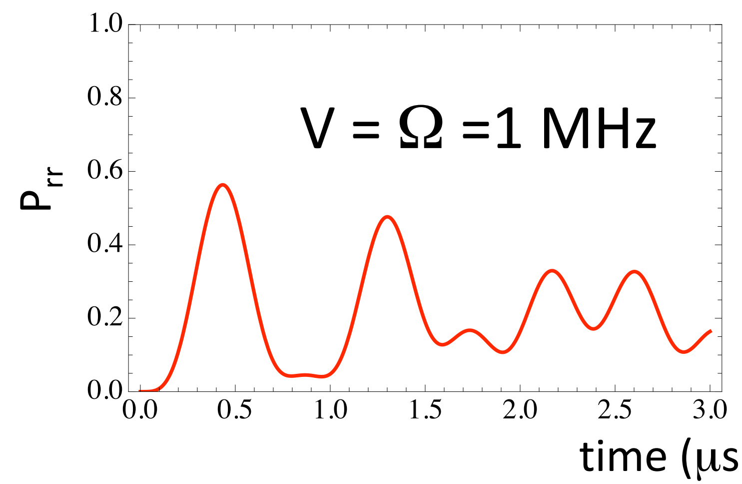
Pellegrino, PRL **113**, 133602 (2014)
Jennewein, PRL **116**, 233601 (2016)
Schilder, PRA **93**, 063835 (2016)
Schilder, PRA **96**, 013825 (2017)

From blockade to many-body physics with 2 atoms ($62d_{3/2}$)



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

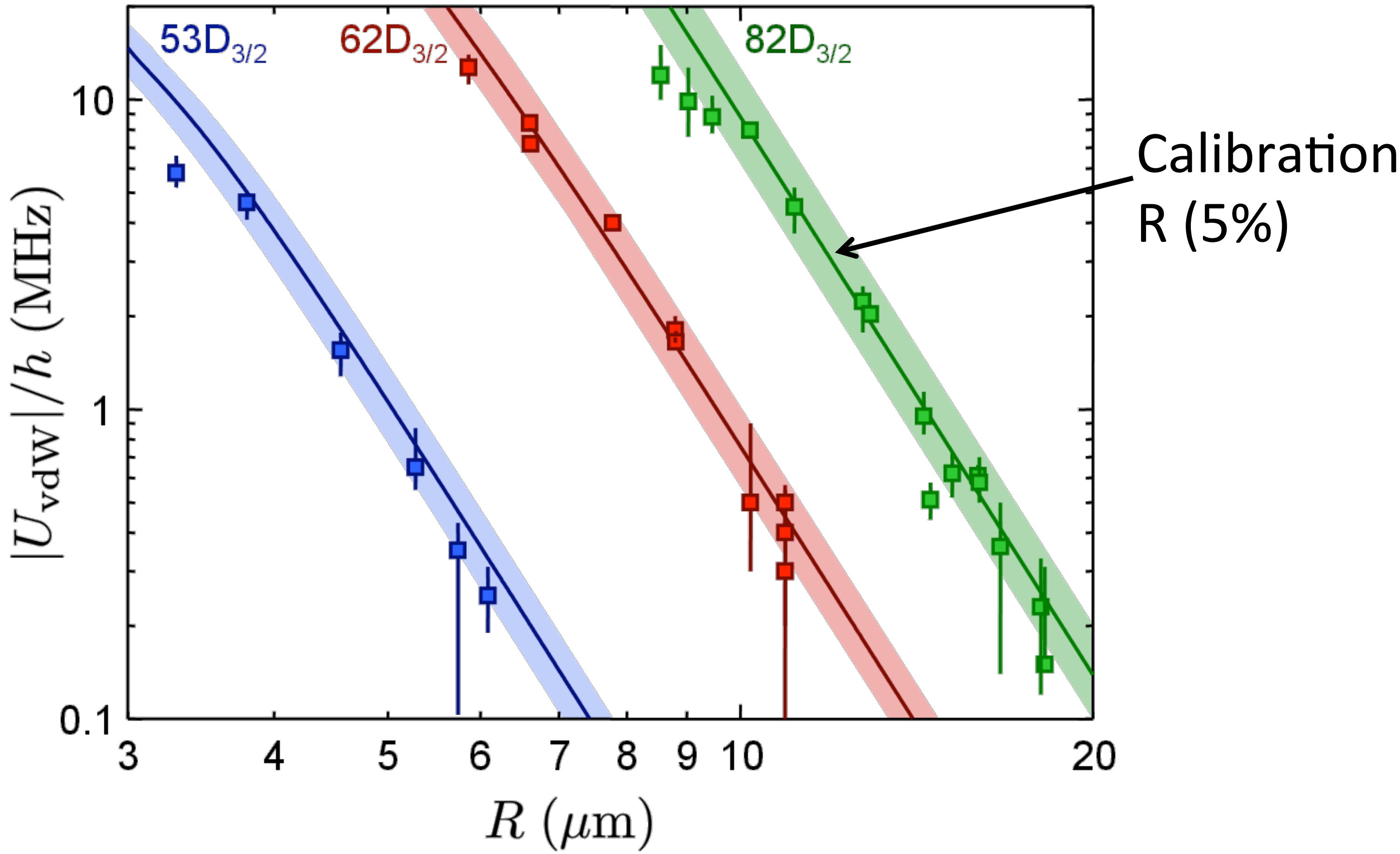
Theory (Schrödinger eq.)



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

Fit ⇒ extract U_{vdW}

Measurement of vdW interaction between 2 atoms



Theory curves: direct diagonalization (dipole-dipole interaction)

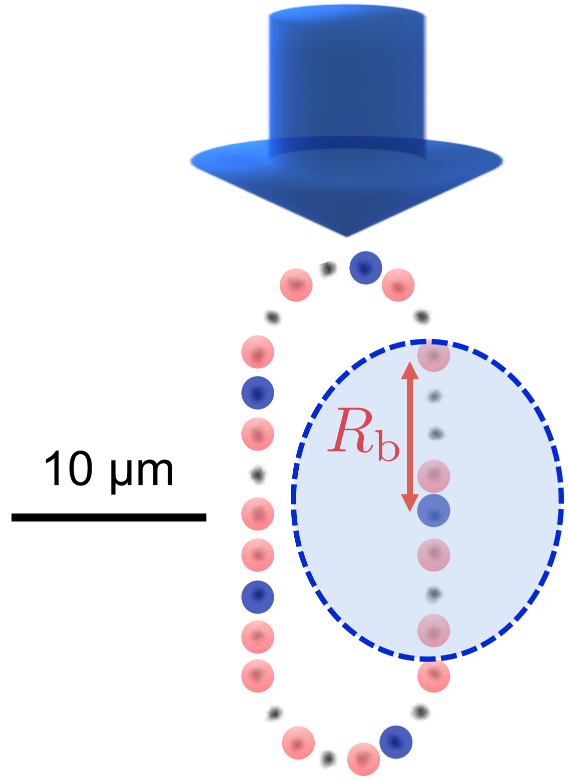
No adjustable parameter

Béguin *et al.,* PRL **110,** 263201 (2013).

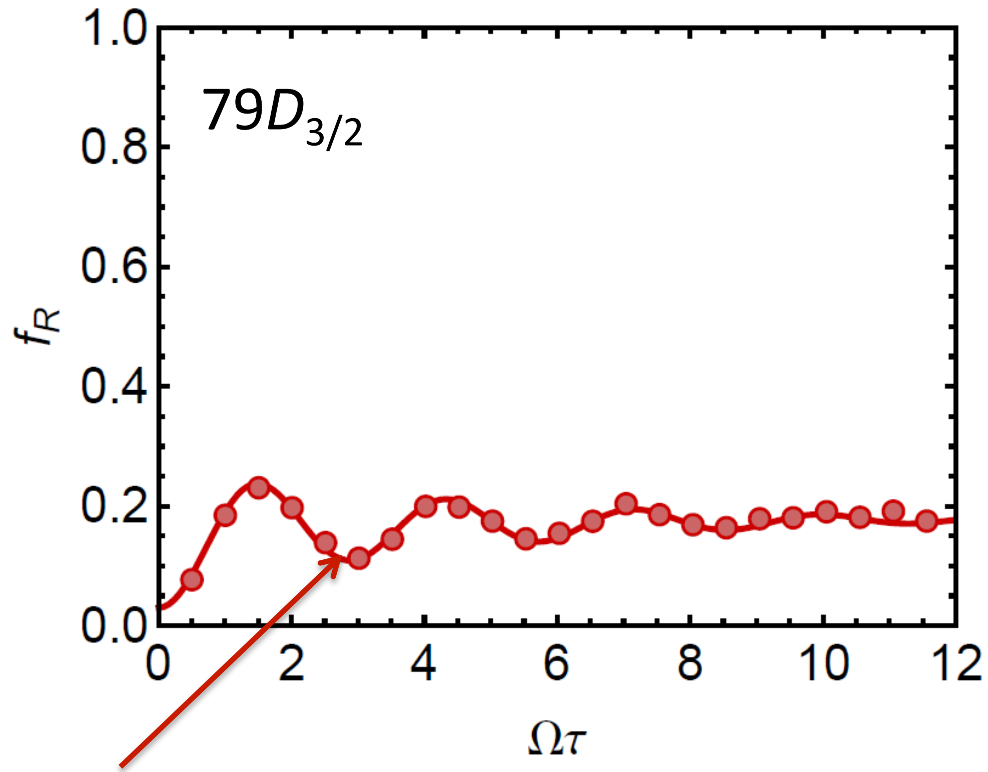
A 1D Ising chain (periodic cond.): mean number of Rydberg excitations

Labuhn *et al.*, Nature **534**, 667 (2016)

Partially loaded 1D ring (30 traps, 20 atoms)



Rydberg fraction: $f_r = \frac{\langle N_r \rangle}{N}$ ~ magnetization



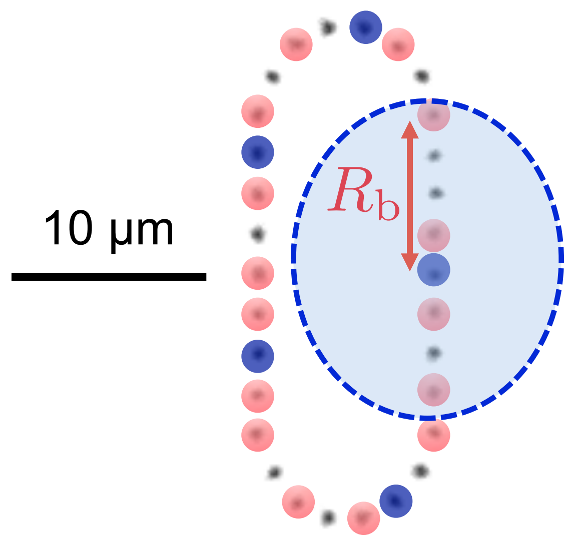
Theory (Schrödinger), no adjustable parameter…!

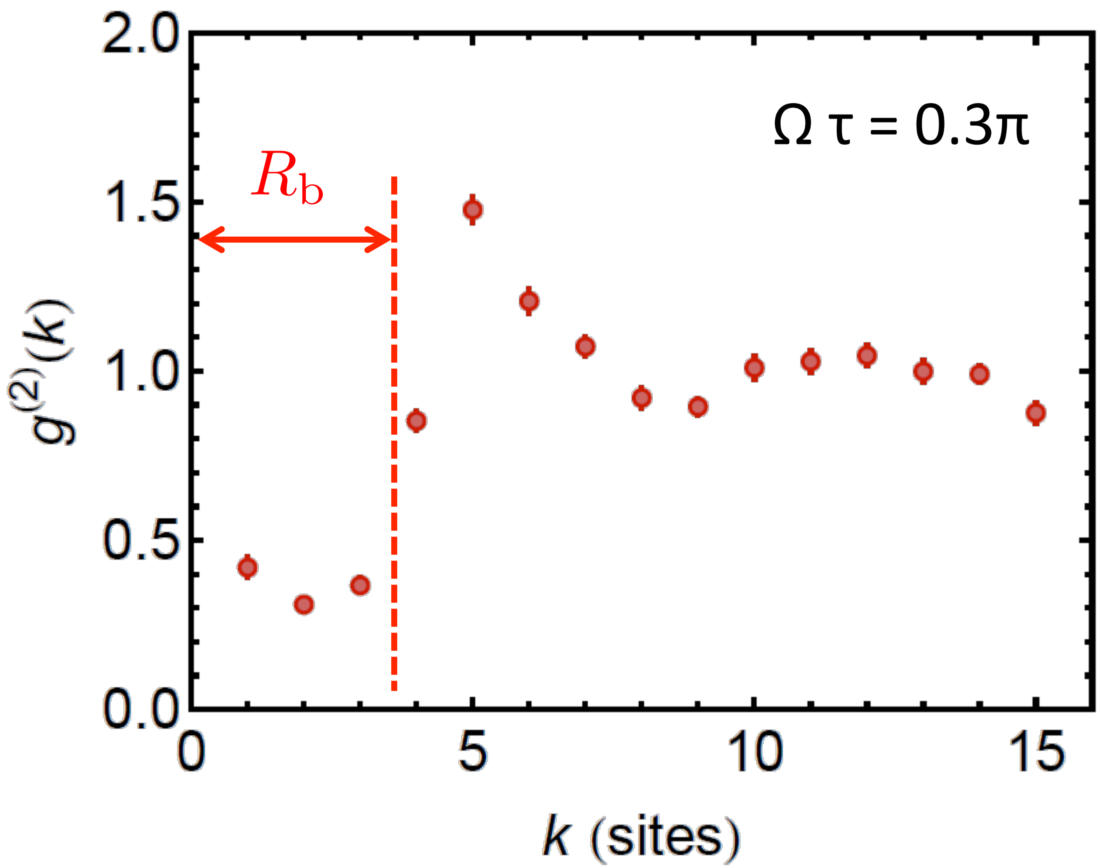
Includes detection efficiency (T. Macri)

A 1D Ising chain (periodic cond.): pair correlation function

Labuhn *et al.*, Nature **534**, 667 (2016)

Partially loaded 1D ring (30 traps, 20 atoms)

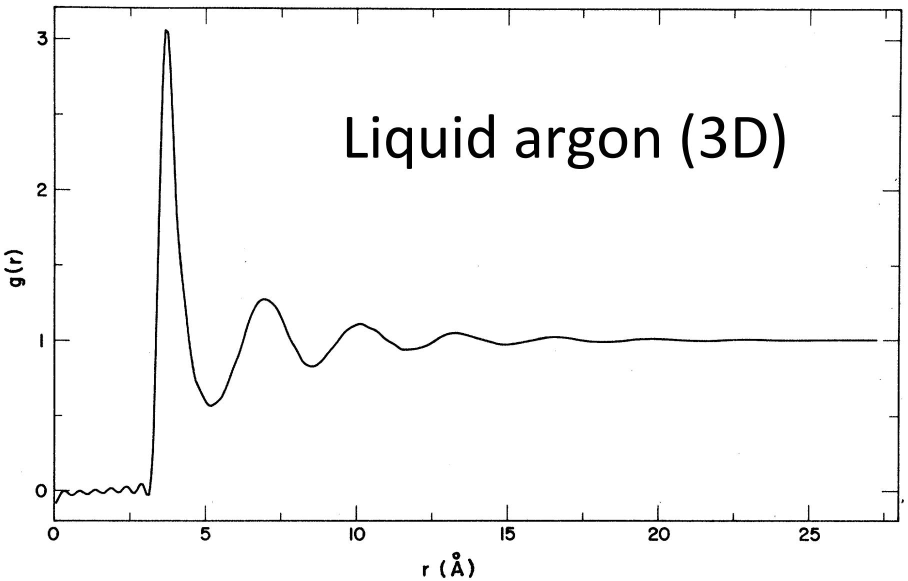




Pair correlation function:

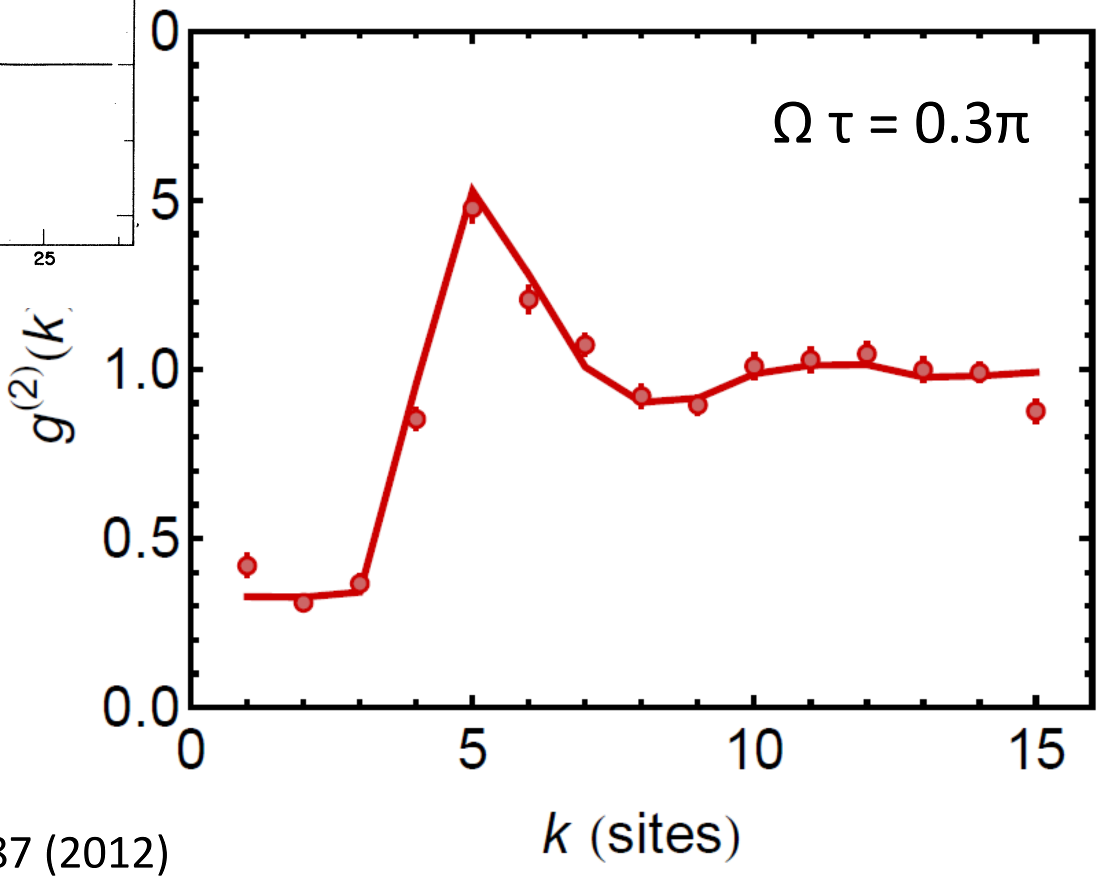
$$g^{(2)}(k) = \frac{1}{N_{\mathrm{tot}}} \sum_i \frac{\langle n_i n_{i+k} \rangle}{\langle n_i \rangle \langle n_{i+k} \rangle}$$

A 1D Ising chain (periodic cond.) = 1D liquid!



PRA **7**, 2130 (1973)

Labuhn *et al.*, Nature **534**, 667 (2016)

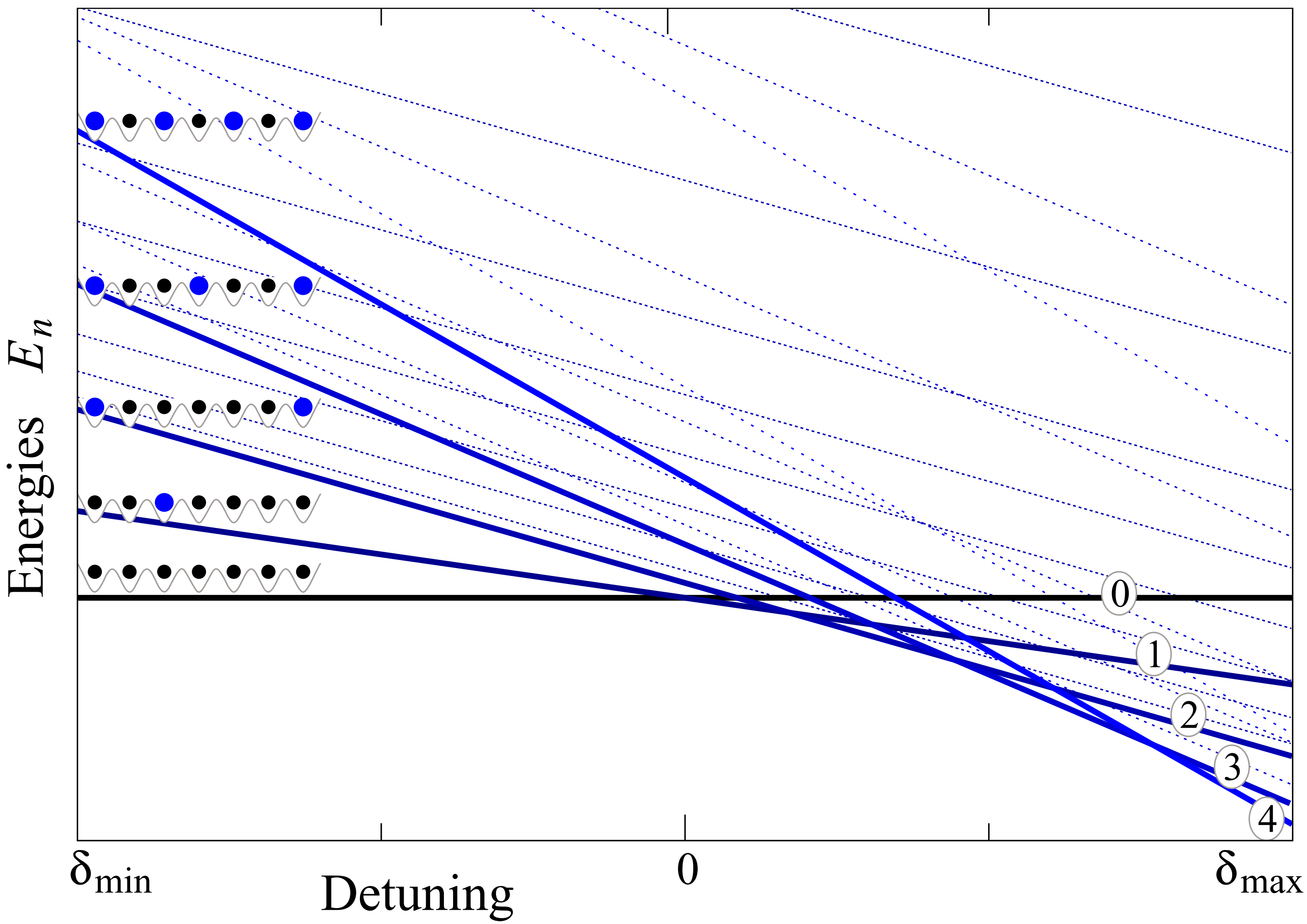


Analogous to 1D liquid:

hard sphere R_b

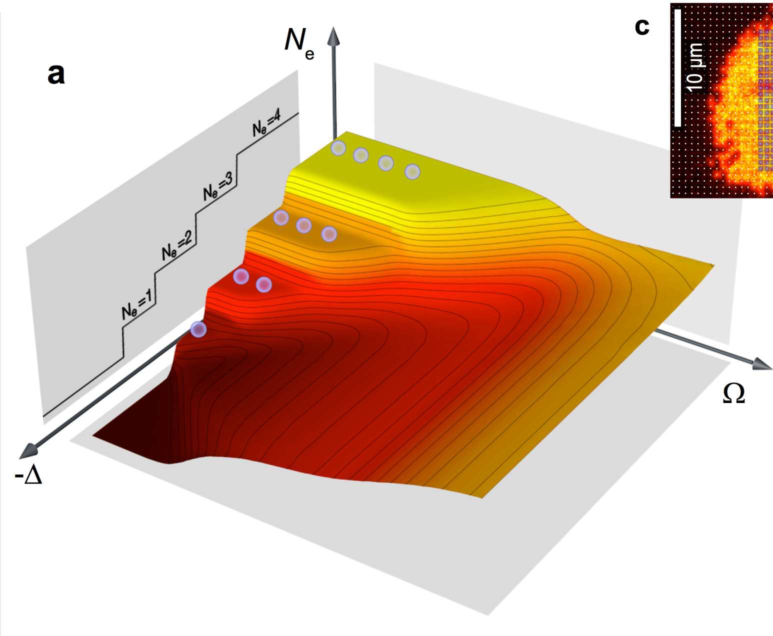
Also in Munich (2D), Nature **491**, 87 (2012)
Ates & Lesanovsky, PRA **86**, 013408 (2012)
Petrosyan, PRA **87** 053414 (2013)

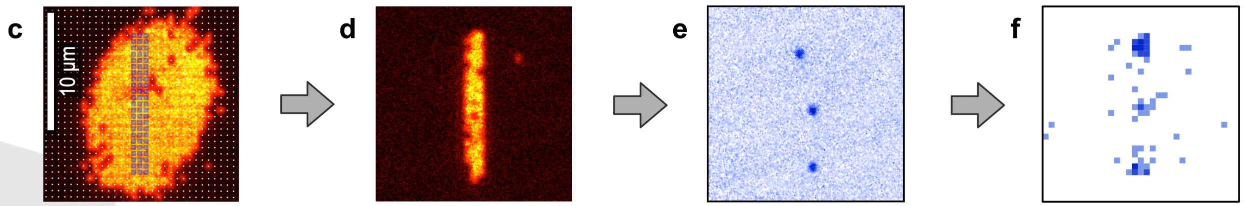
Adiabatic preparation of spatially-ordered 1D Rydberg chains

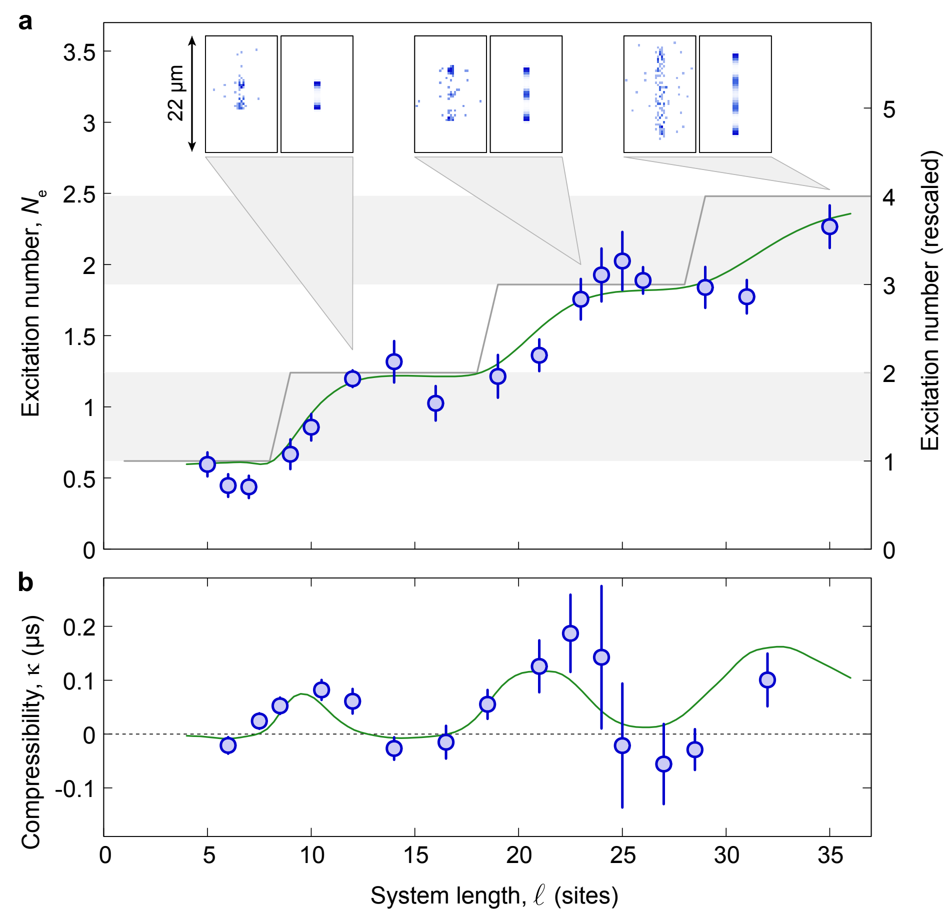


Petrosyan *et al.*, J. Phys. B **49**, 084003 (2016)

Dynamical crystallization in 1D (MPQ)







$$R_b \gg a$$

Schauss *et al.*, Science (2015)

A 51-atom “quantum simulator” (Harvard-MIT)

$$R_b \sim a$$

H. Bernien, arXiv:1707.04344