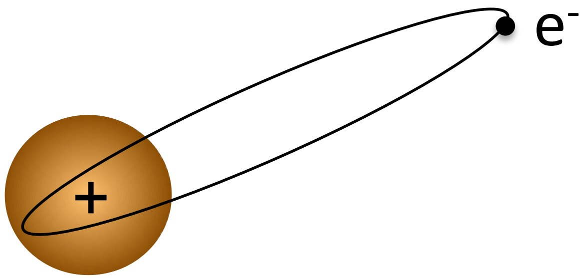


Interacting Cold Rydberg atoms:

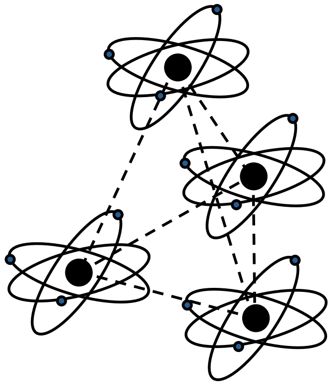
A Toy Many-Body System

Antoine Browaeys
Institut d'Optique, CNRS

Séminaire Poincaré 7 décembre 2013

Many - body systems and complexity

Microscopic



Quantum laws…

Many - body systems and complexity

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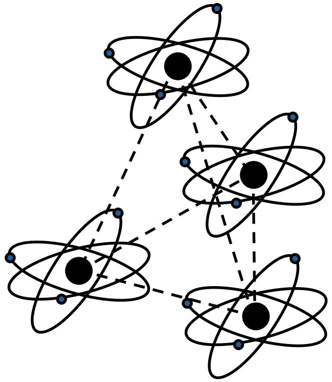

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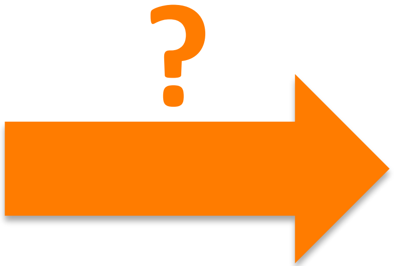
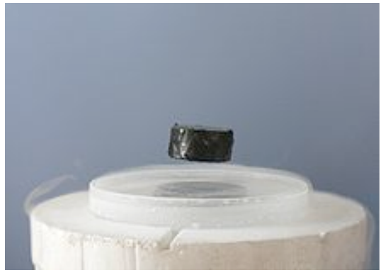


Macroscopic



quantum or classical laws

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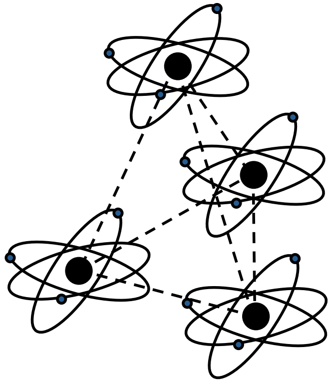

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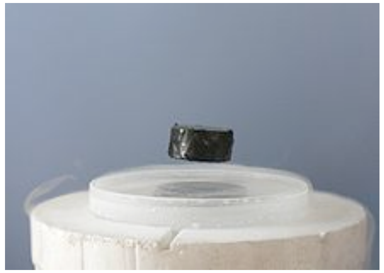


quantum or classical laws

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

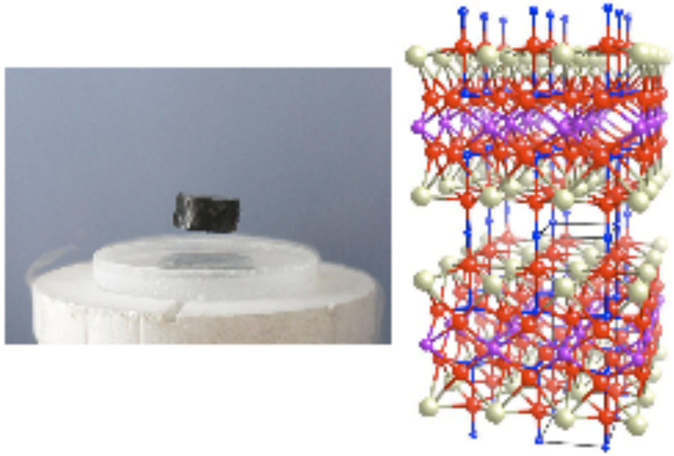
Size of Hilbert space $\sim 2^N$ too large

One idea (Feynman 1982): engineer quantum systems in the lab.

Measure to find properties you can't calculate!

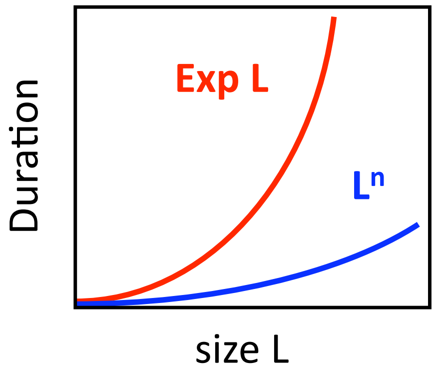
Applications of quantum state engineering

Many-body physics

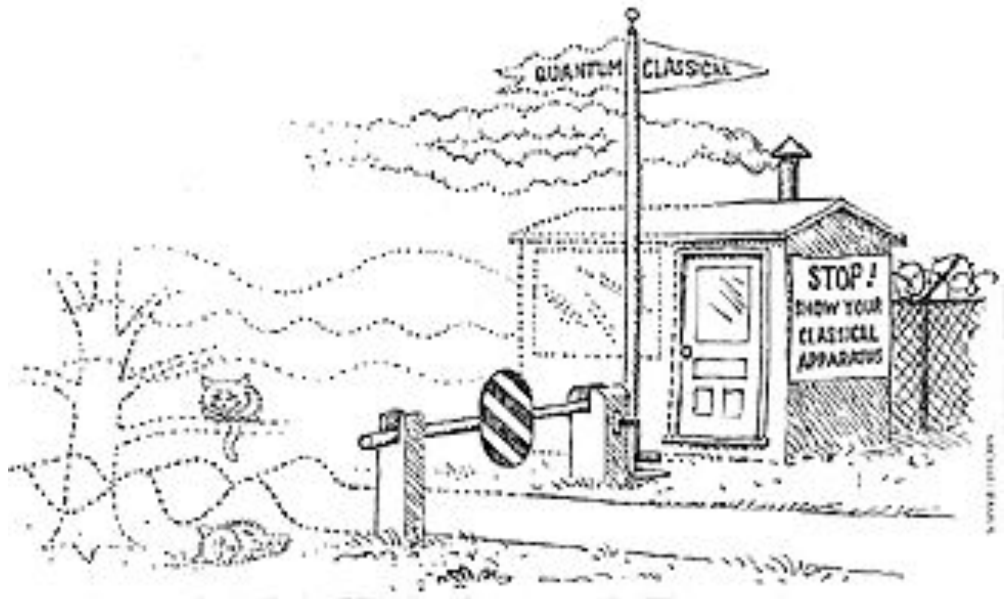


Quantum metrology

Quantum information

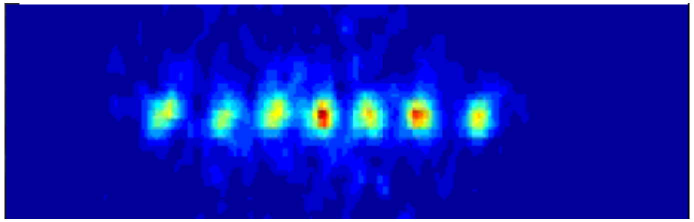


Transition quantum / classical

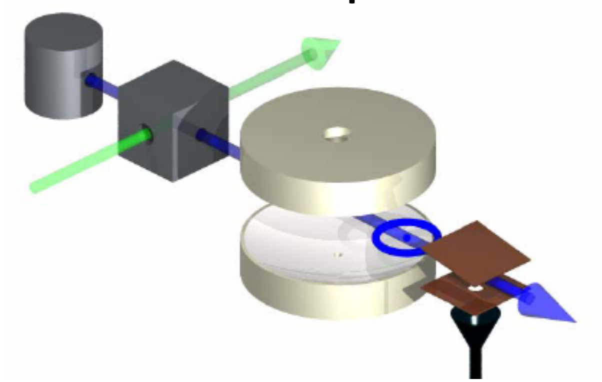


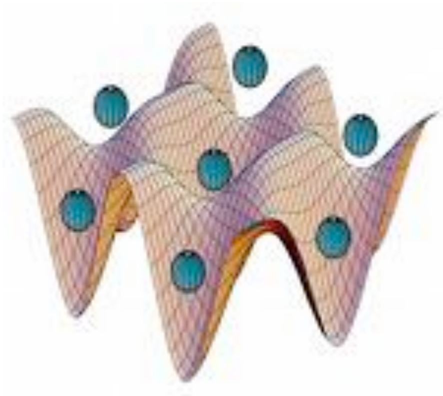
Quantum state engineering = control interactions between particles

Trapped cold ions



Atoms and photons





Cold atoms

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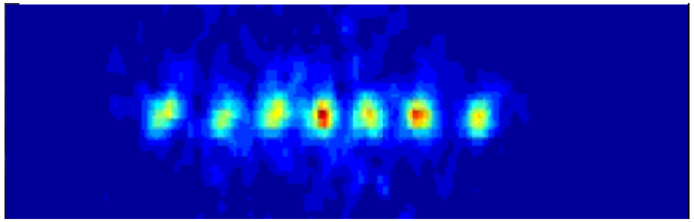

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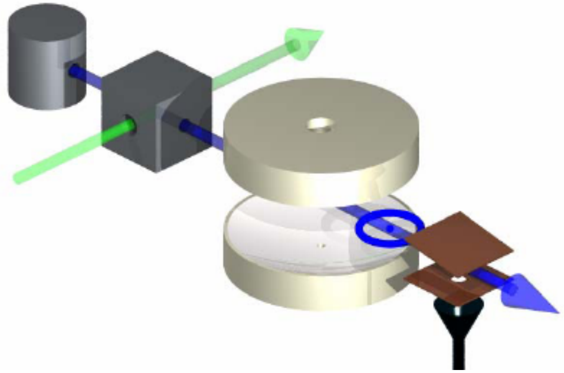
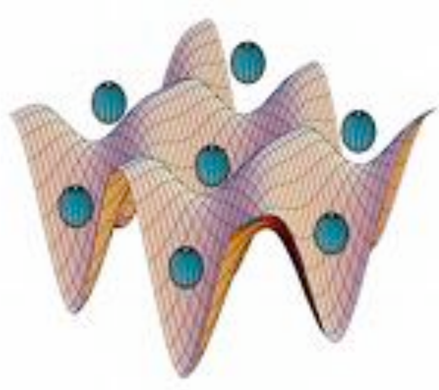
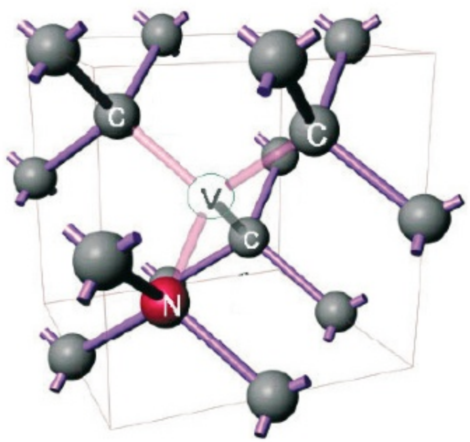


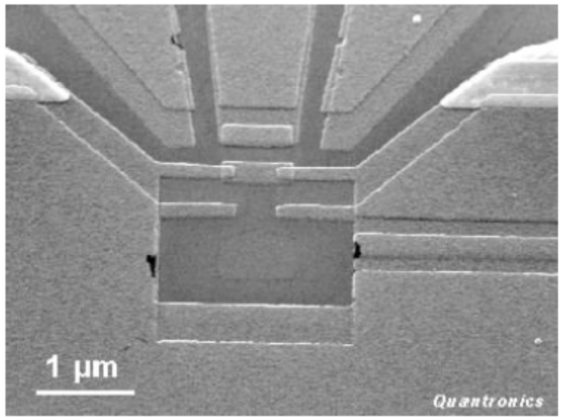


Cold atoms

Artificial atoms



NV center



Supra. circuit

Quantum state engineering = control interactions between particles

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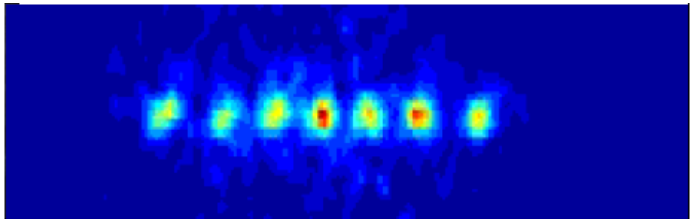

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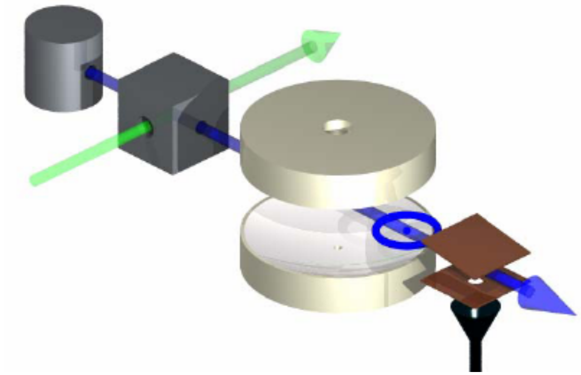

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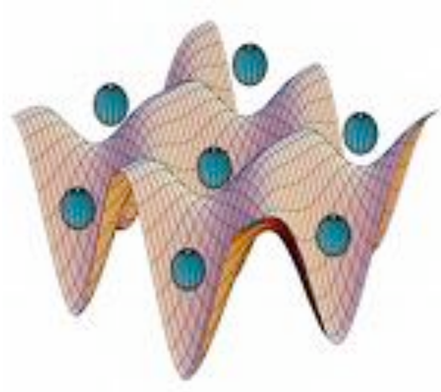

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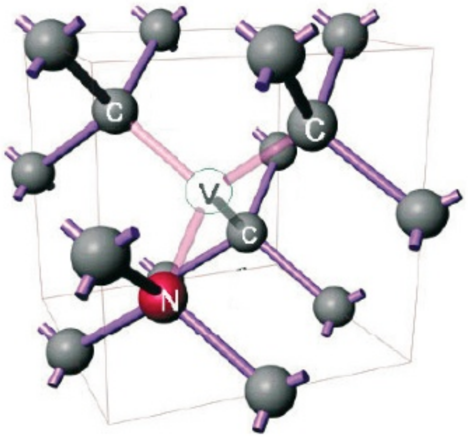

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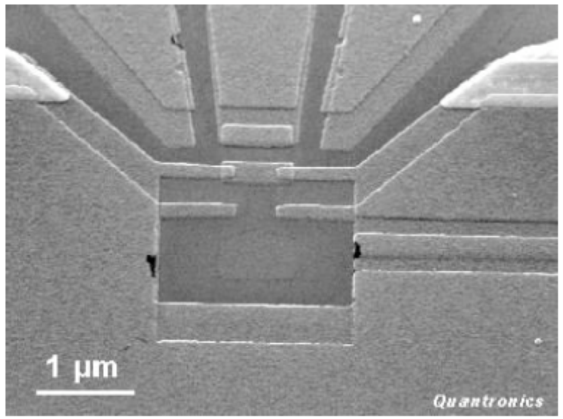

Supra. circuit

Many-body toy systems

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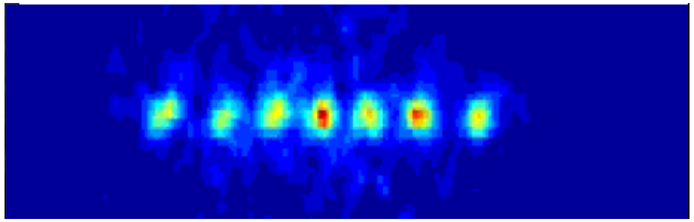

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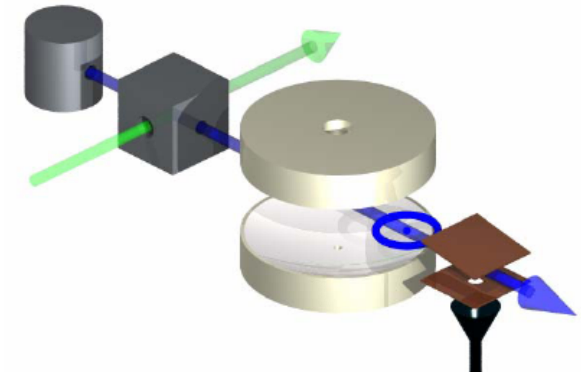

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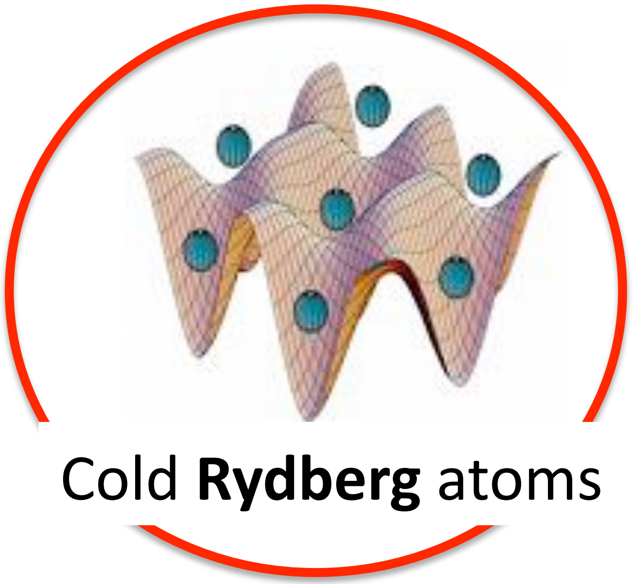
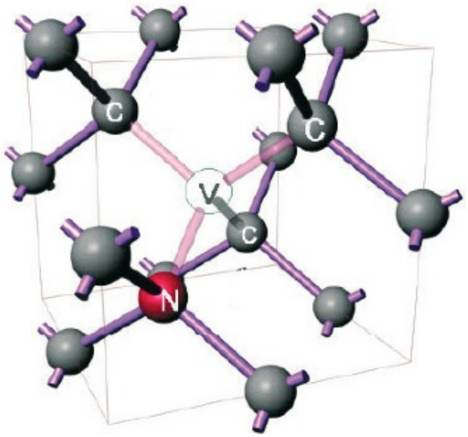


Cold **Rydberg** atoms



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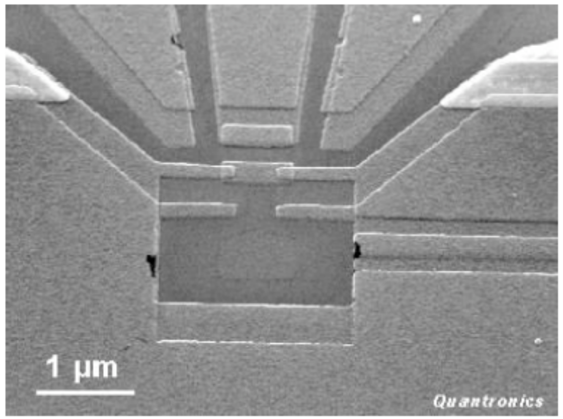

Supra. circuit

Many-body toy systems

Outline

1. Rydberg atoms and their interaction
2. Rydberg blockade: theoretical aspects
3. Observation of the Rydberg blockade and collective excitation for 2 atoms
4. Rydberg blockade in cold atomic ensembles
5. Application of Rydberg blockade in quantum optics

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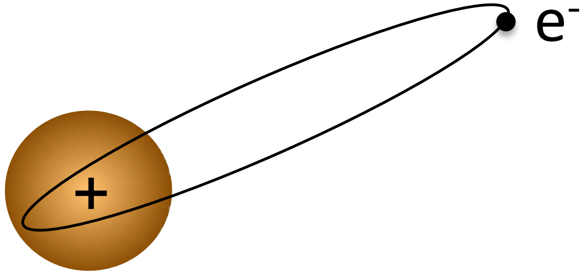
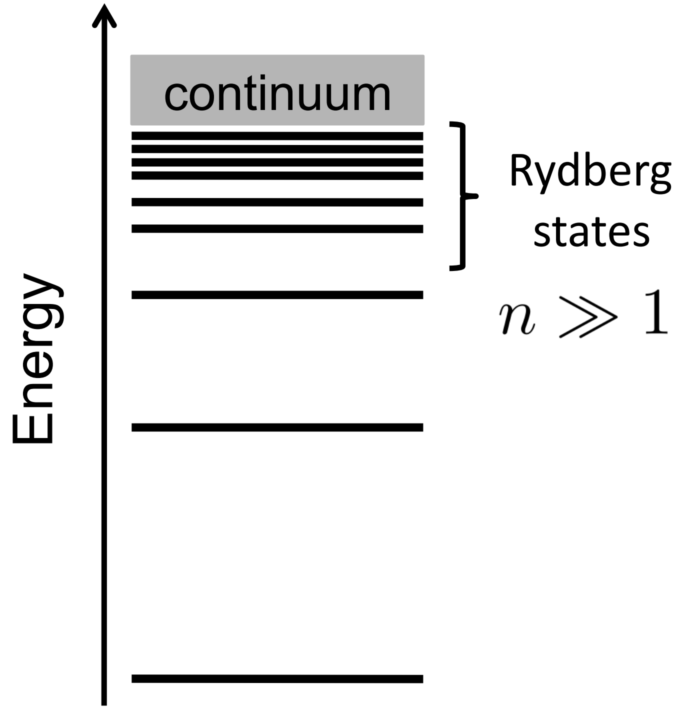
Rydberg atoms (alkali case)

Johannes Rydberg
1854-1919





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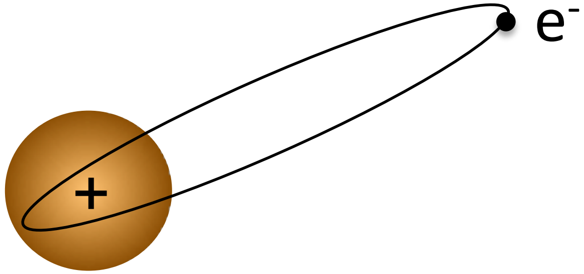

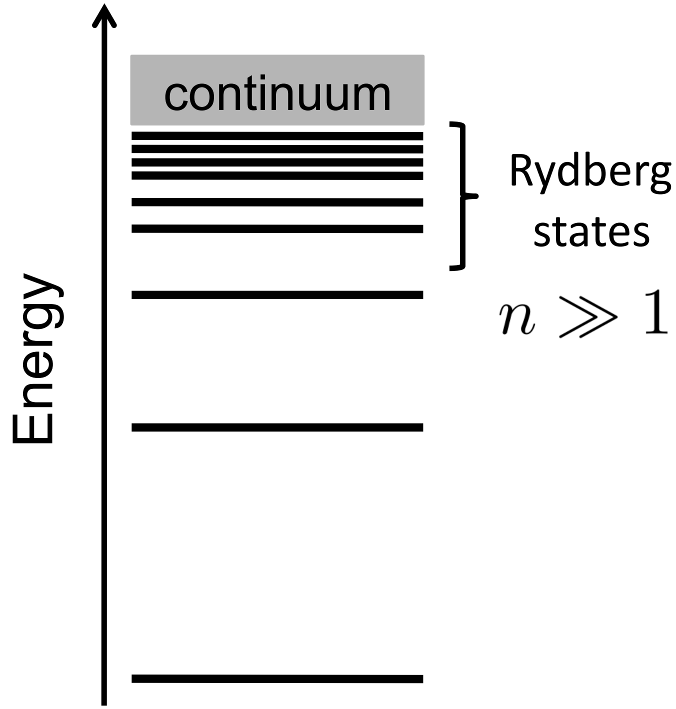

Alkali atoms (Rb, Cs) ⇒ hydrogenoid $|n, l, j, m\rangle$

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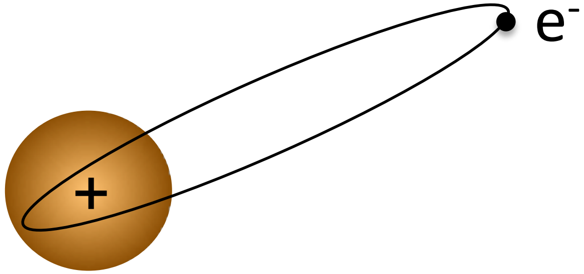

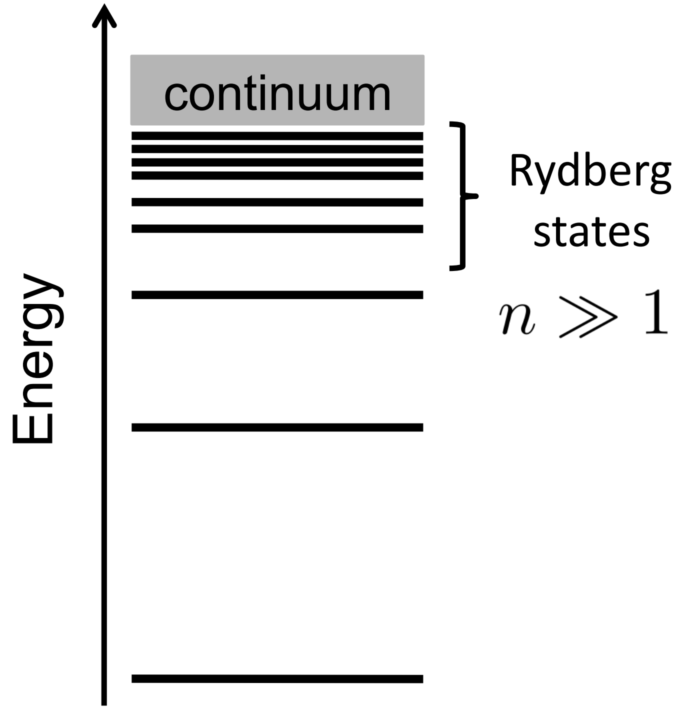

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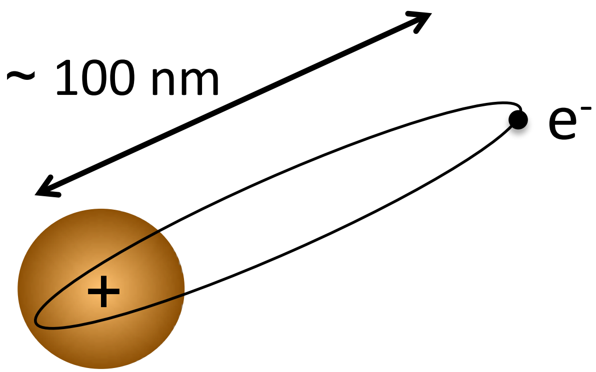
Screening effect of electronic core: $n^* = n - \delta_l$

Quantum defect: $\delta_{l\geq 3} \approx 0$

Properties of Rydberg atoms



Bohr model: size $\sim n^2 a_0$

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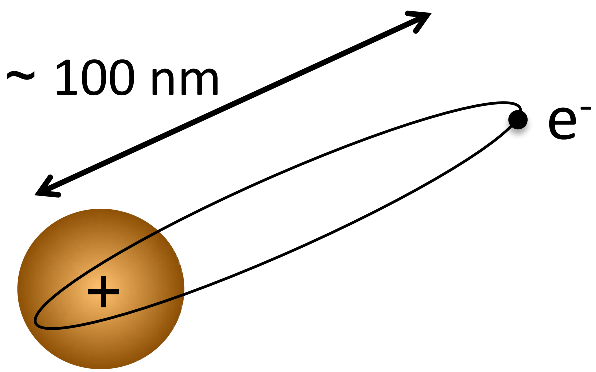

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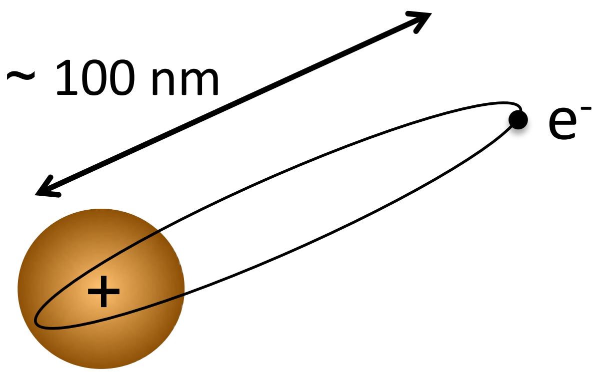

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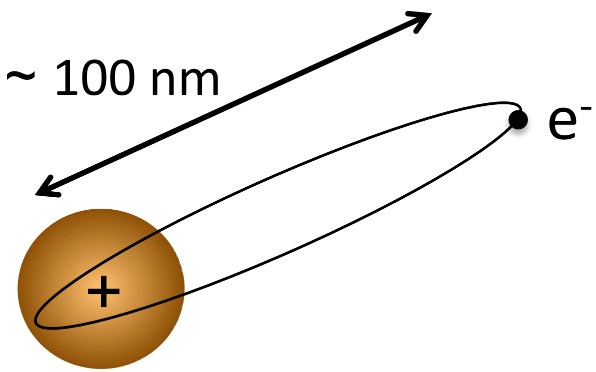

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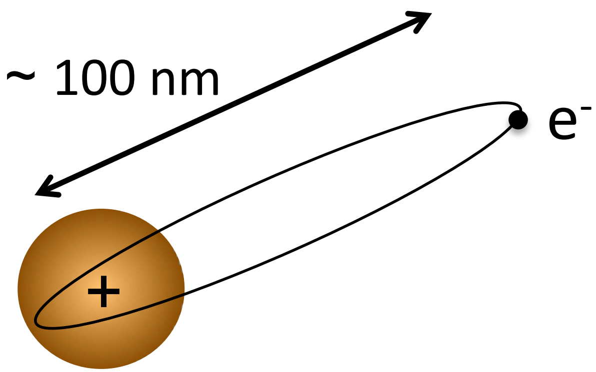

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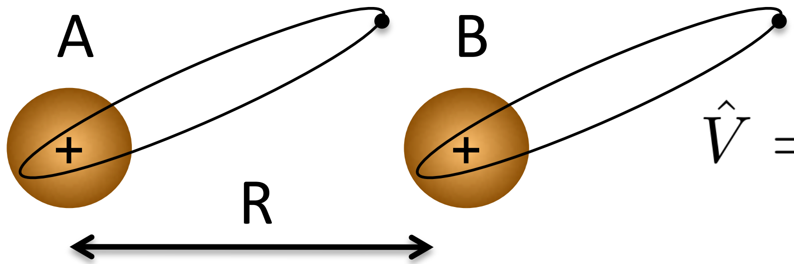
3. Long lifetime $\tau \sim n^3 \Rightarrow n > 60$, $\tau > 100$ µs

Interaction between Rydberg atoms



$$\hat{V} = \frac{1}{4\pi\epsilon_0 R^3}\left(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{d}}_B - 3(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{r}})(\hat{\mathbf{d}}_B \cdot \hat{\mathbf{r}})\right)$$

Two atom basis: $\{|n,l\rangle \otimes |n',l'\rangle\}$

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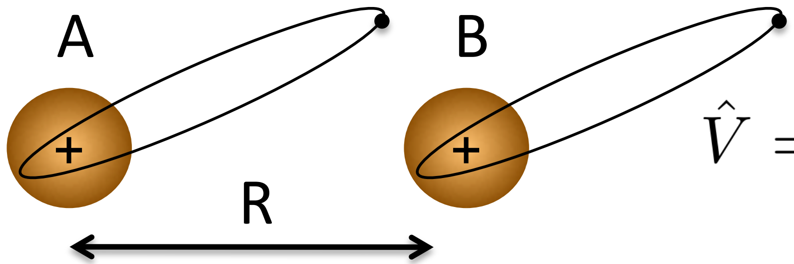

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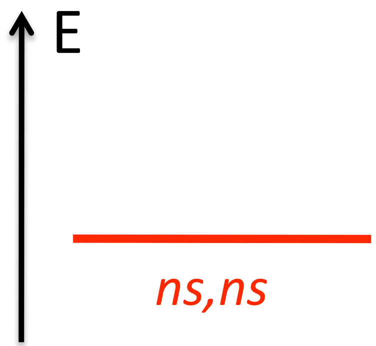

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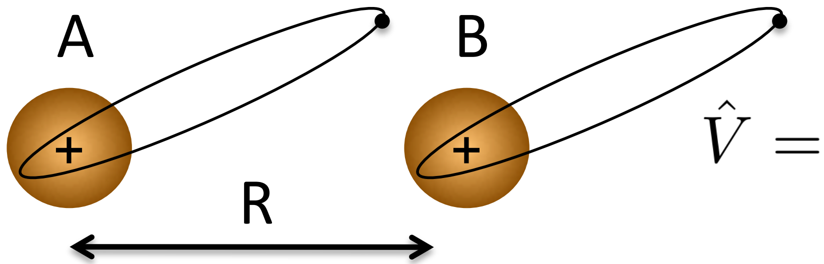

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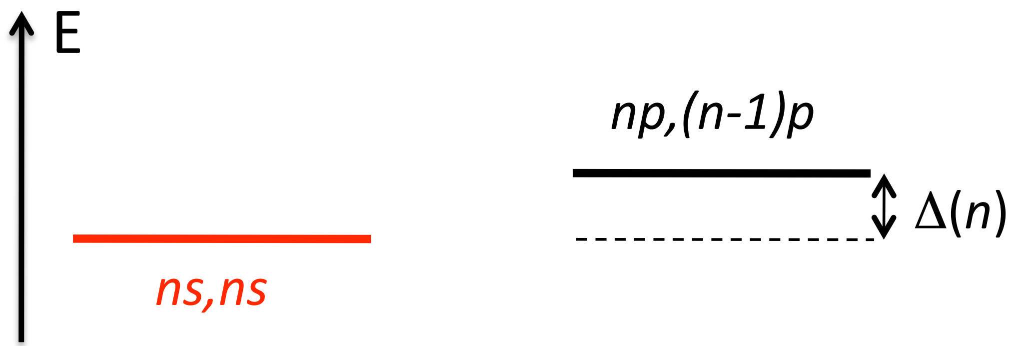

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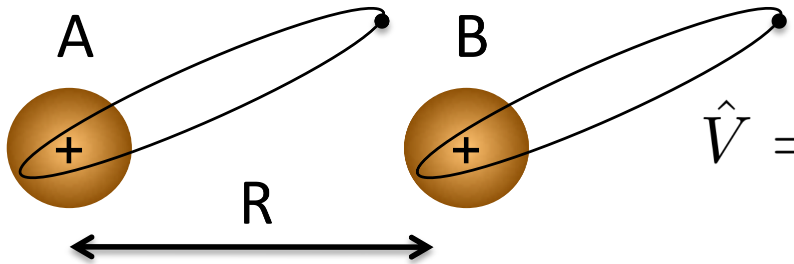

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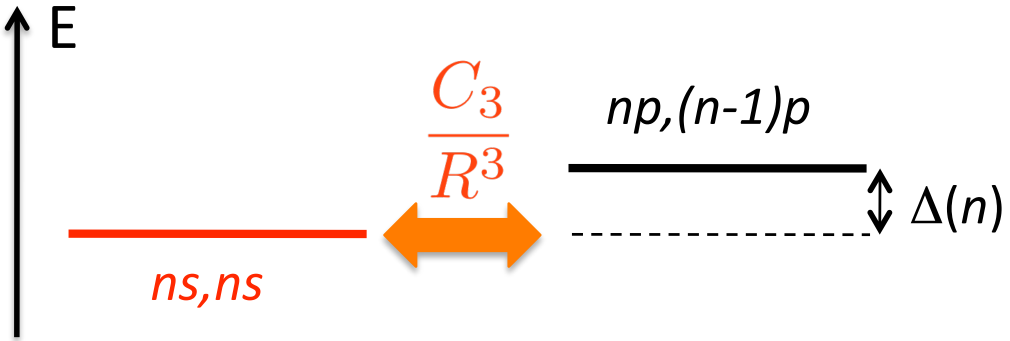

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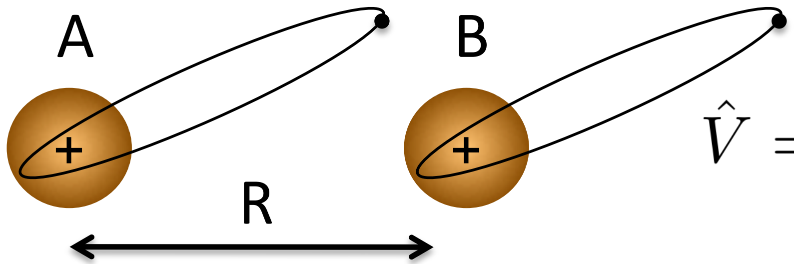

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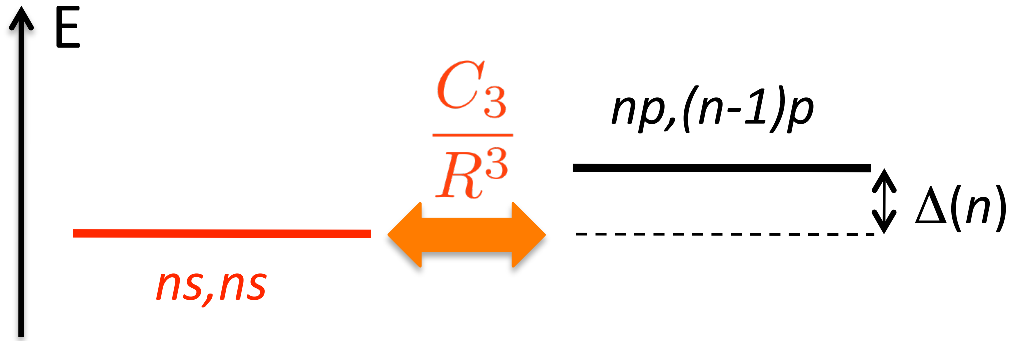
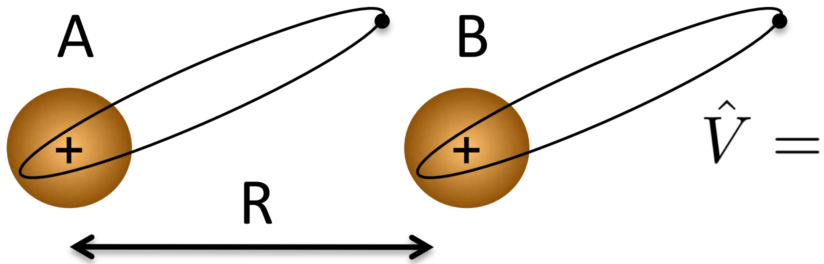


$$\hat{H} = \begin{pmatrix} 0 & \frac{C_3}{R^3} \\ \frac{C_3}{R^3} & \Delta \end{pmatrix}$$

Interaction between Rydberg atoms



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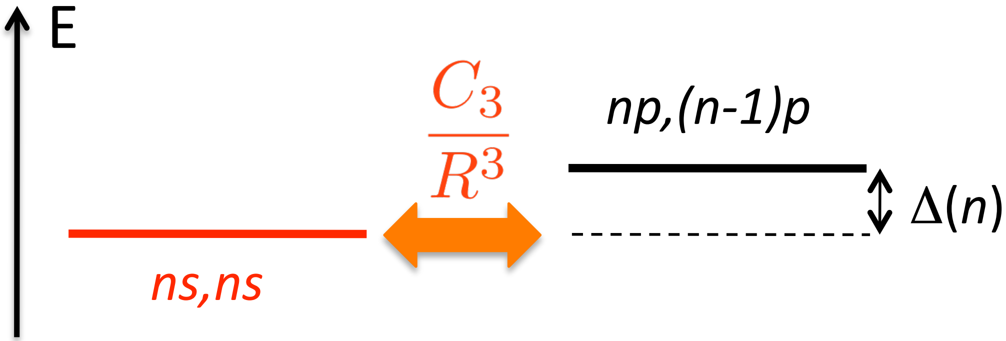

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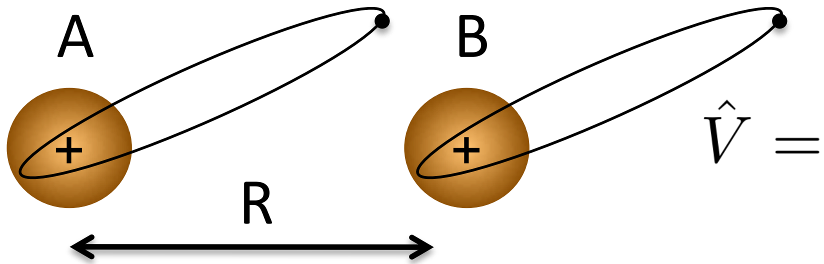

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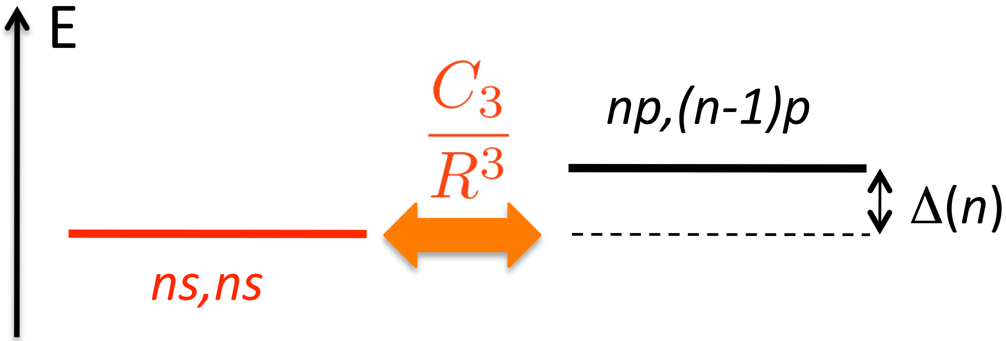

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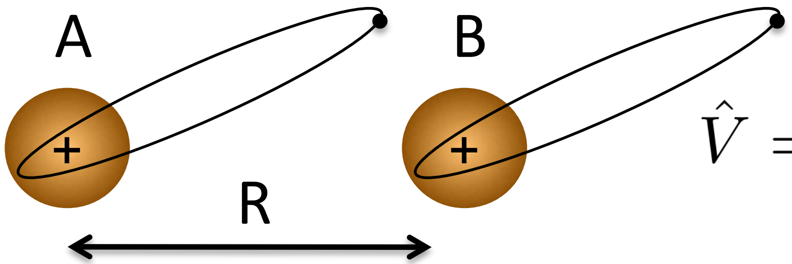

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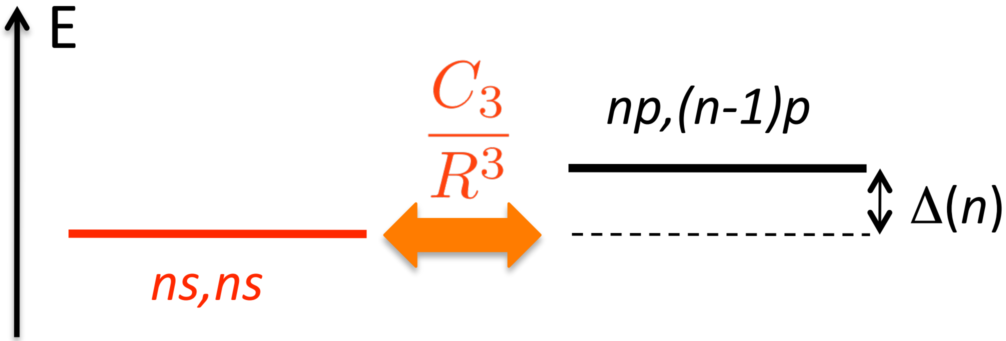

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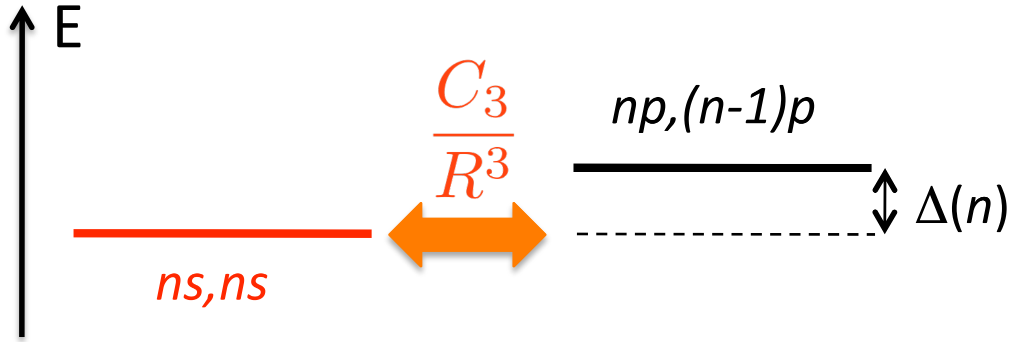
Van der Waals: $\frac{C_3}{R^3} \ll \Delta \;\Rightarrow\; \Delta E_{ss} \approx \frac{1}{2\Delta}\left(\frac{C_3}{R^3}\right)^2 = \frac{C_6}{R^6}$

Scaling: $C_6 \propto n^{11}$

Resonant regime: $\frac{C_3}{R^3} \gg \Delta \Rightarrow \Delta E_{\pm} \approx \pm\frac{C_3}{R^3}$

Tuning the interaction: Förster resonance



Tune $\Delta(n)$: Stark shift

Ex: for ^{87}Rb resonance $59d_{3/2} + 59d_{3/2} \leftrightarrow 57p_{1/2} + 61f_{5/2}$

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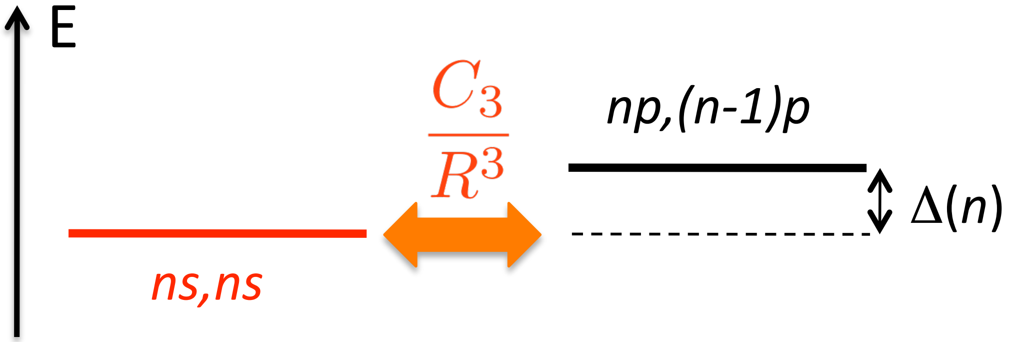

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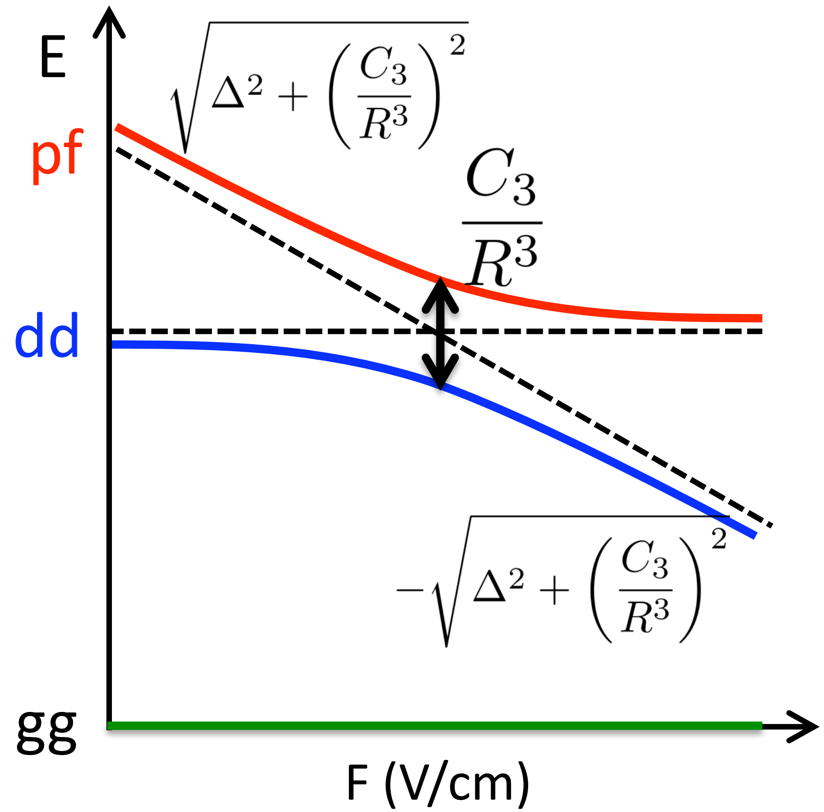
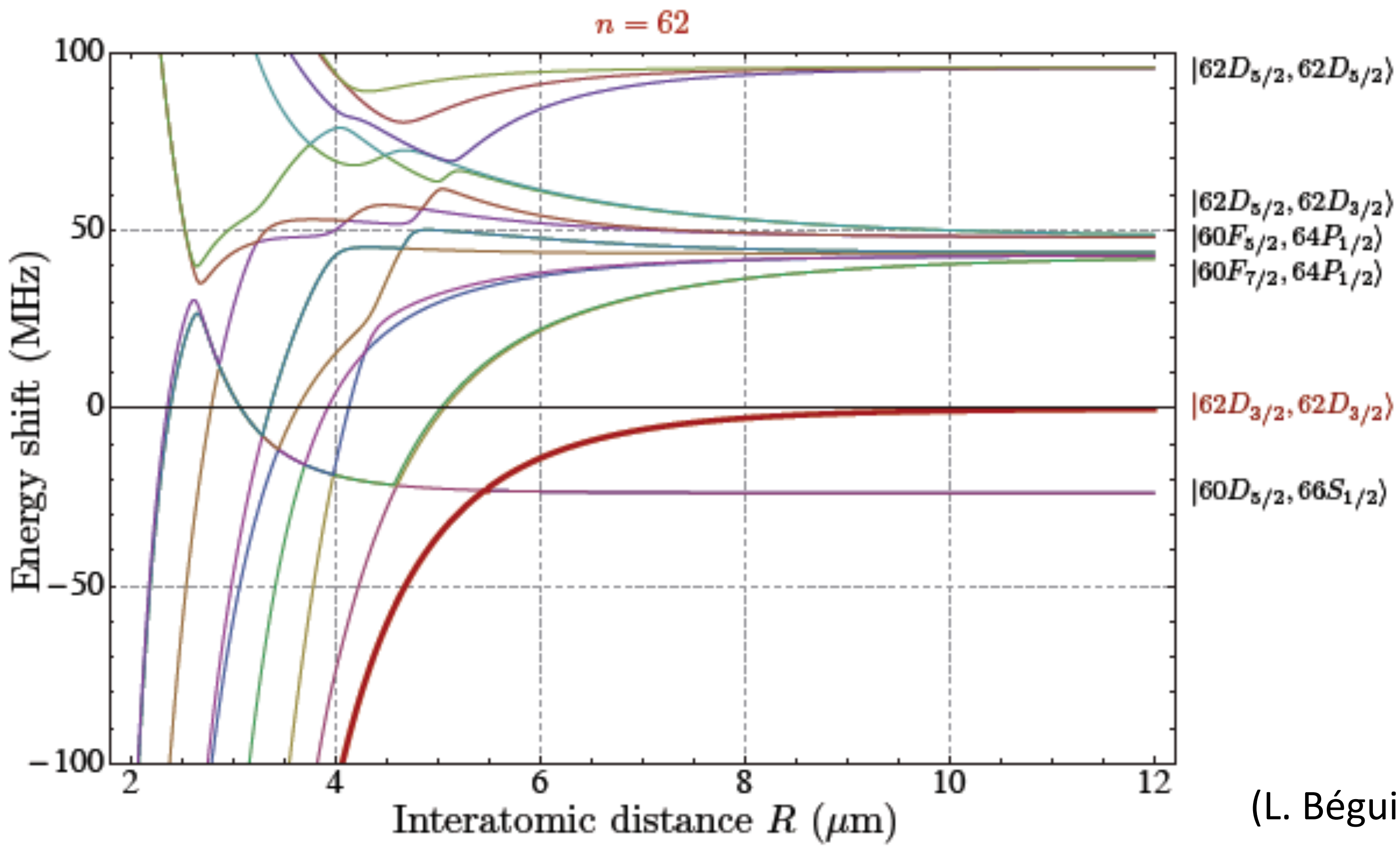


Interaction between "real" Rydberg atoms

Ex: ^{87}Rb atoms in $62d_{3/2}$

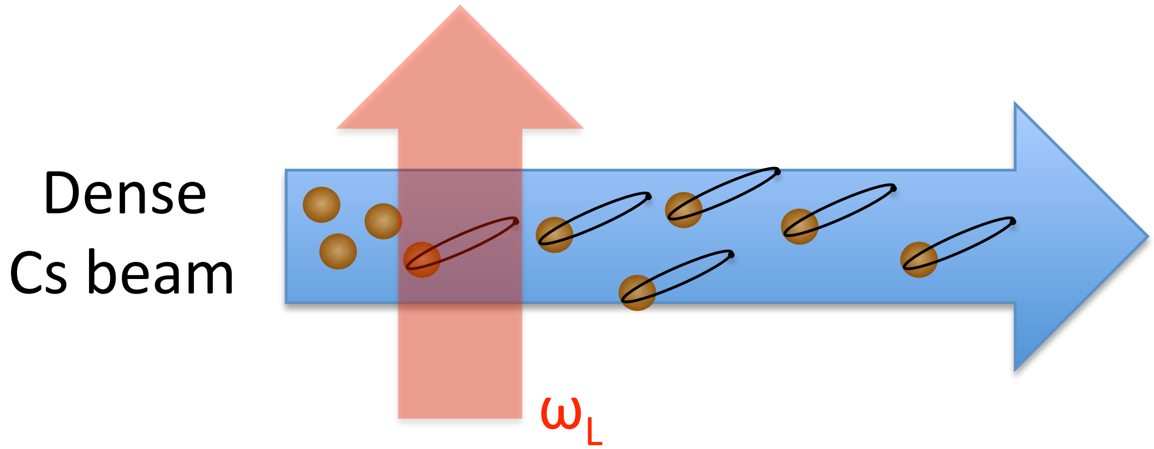


(L. Béguin)

Rydberg interaction: 10^{11} x ground state + **switchable**

”Early” experiments and the “need” for cold atoms

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



Broadening of excitation

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

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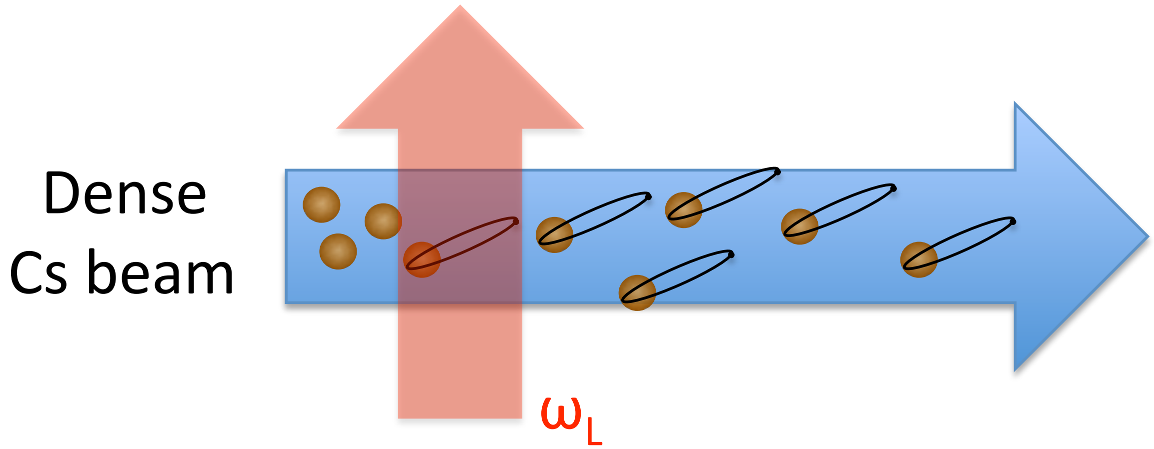

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k_BT << Interaction energy $\Rightarrow T < 1$ mK $\Rightarrow$ cold atoms

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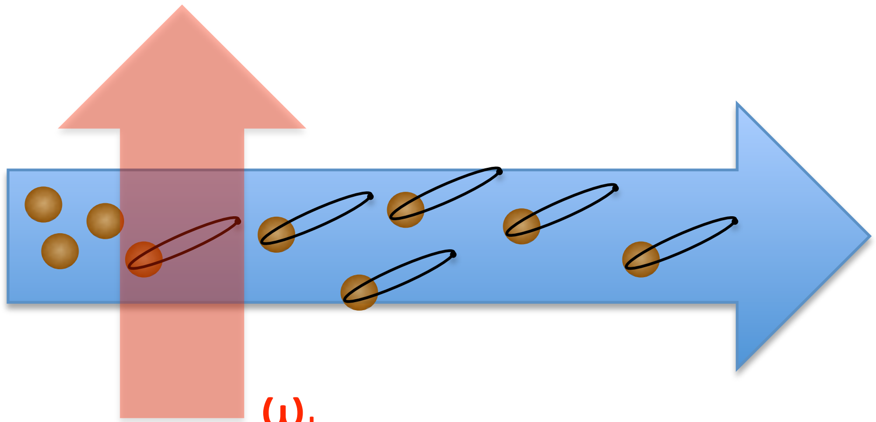

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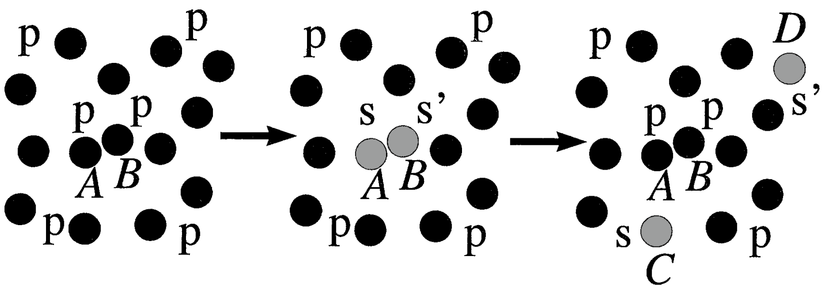
Many body in "frozen gas" Mourachko, PRL **80**, 253 (1998)



p + p ↔ s + s'

p + s ↔ s + p

Diffusion of excitation faster than motion ⇒ correlations between all atoms

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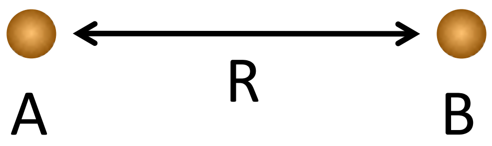
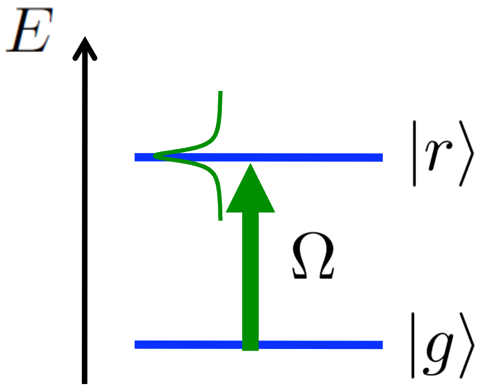
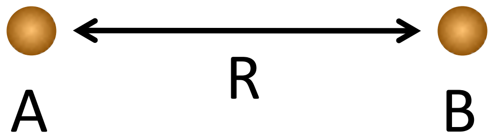
Rydberg blockade and collective excitation

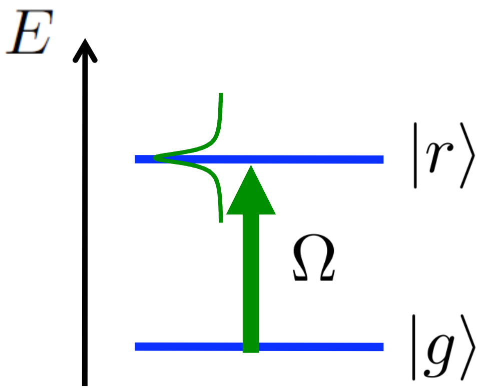


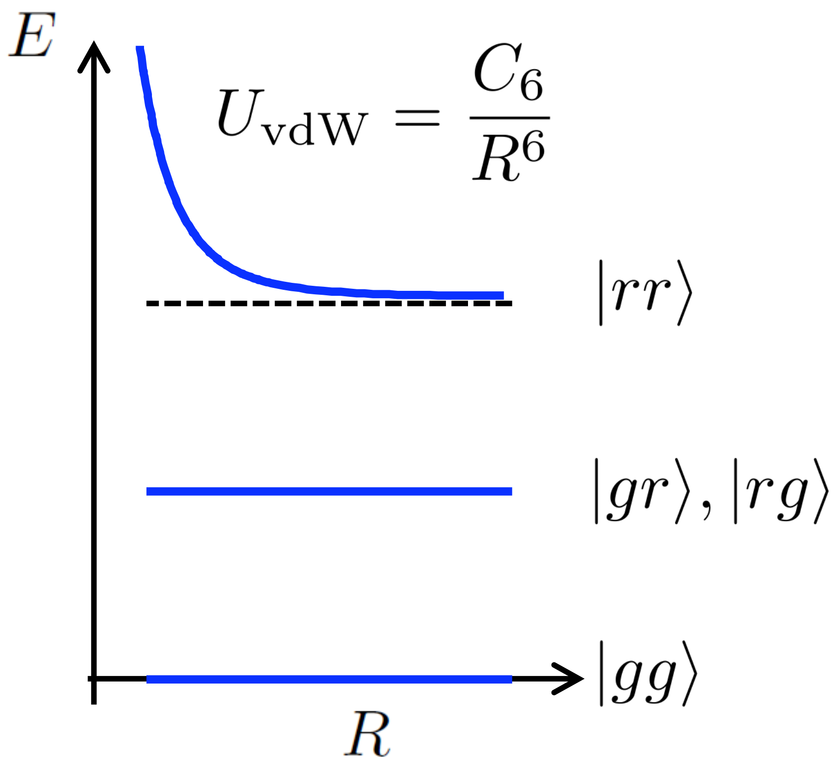


D. Jaksch, *et al.*, PRL **85**, 2208 (2000)
M. D. Lukin, *et al.*, PRL **87**, 037901 (2001)

Rydberg blockade and collective excitation







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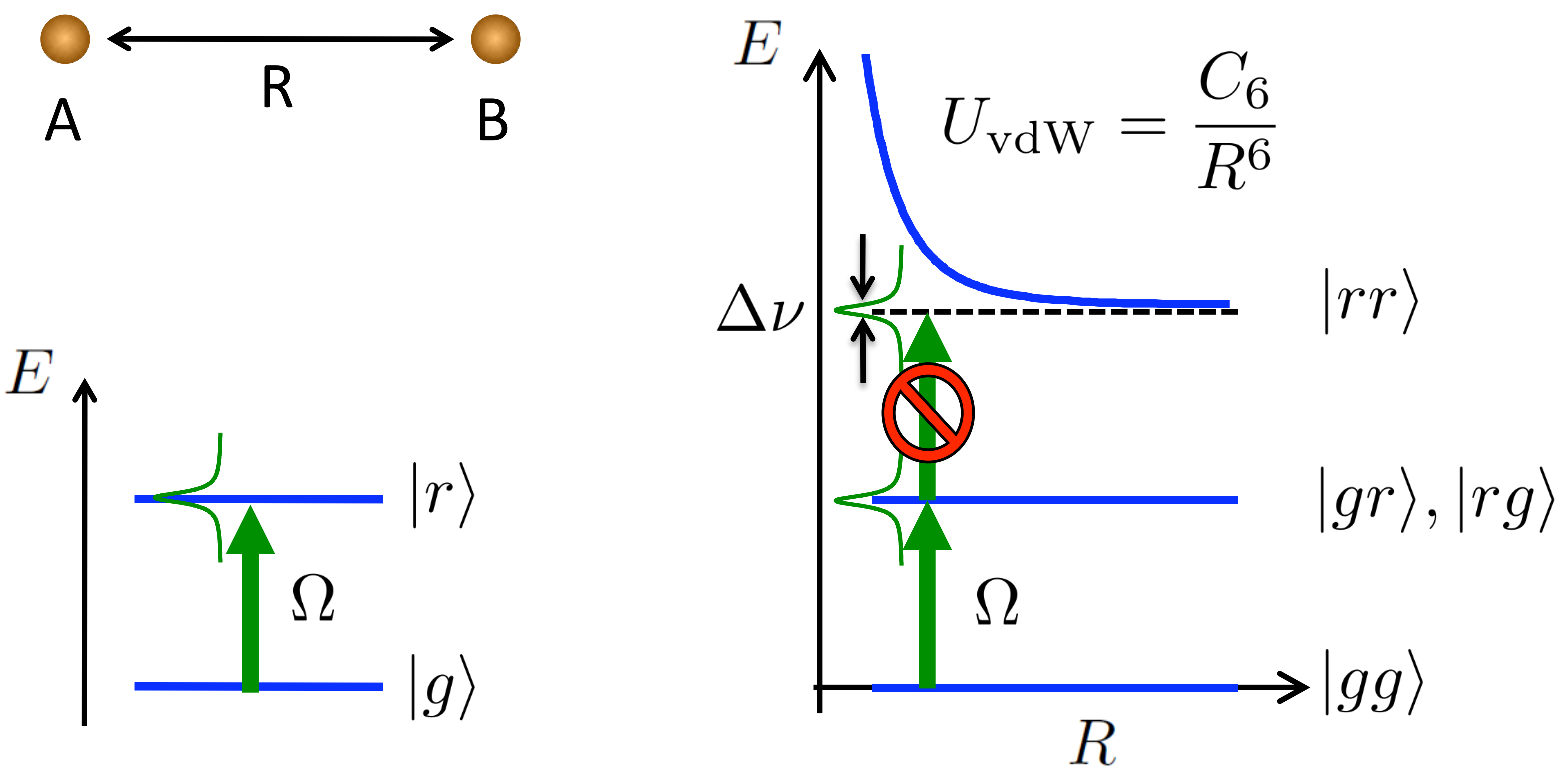
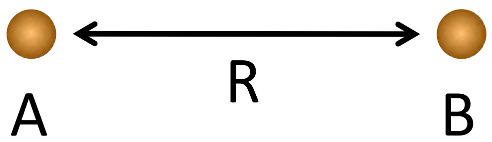
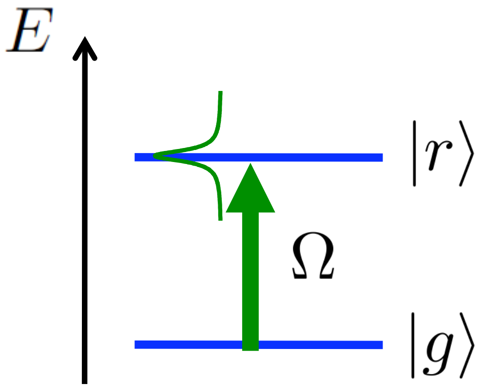


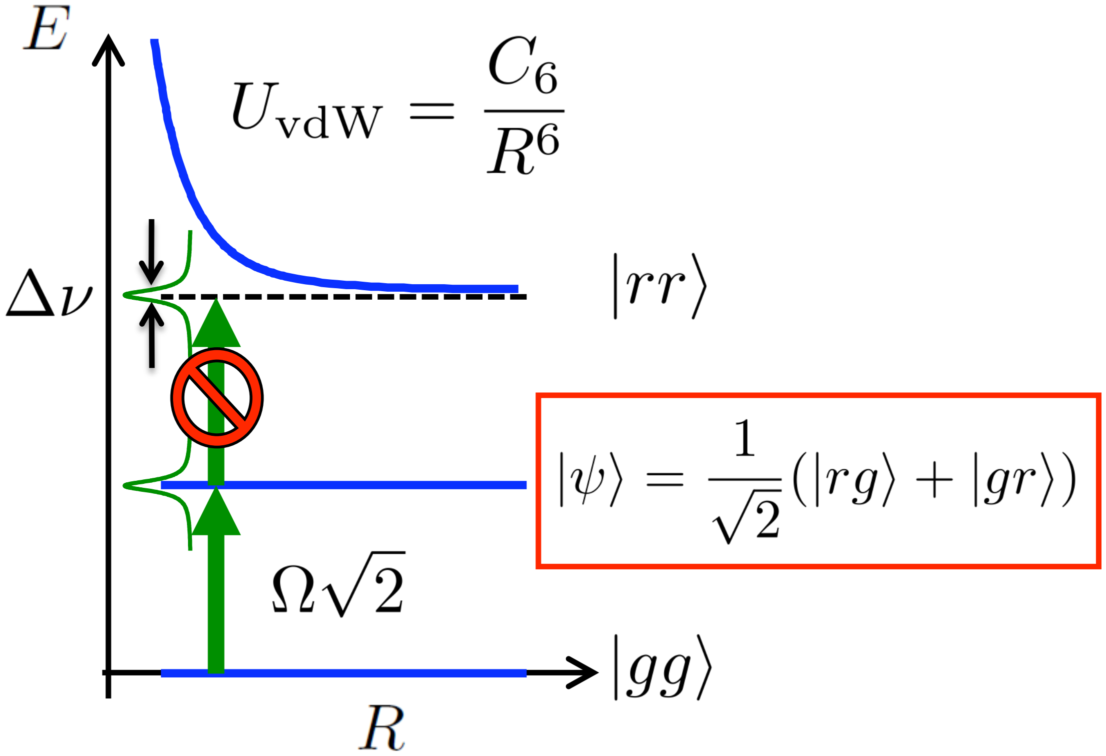
If $\hbar\Delta\nu \ll U_{\mathrm{vdW}}$: no excitation of $|rr\rangle$ $\Rightarrow$ **BLOCKADE**

D. Jaksch, *et al.*, PRL **85**, 2208 (2000)
M. D. Lukin, *et al.*, PRL **87**, 037901 (2001)

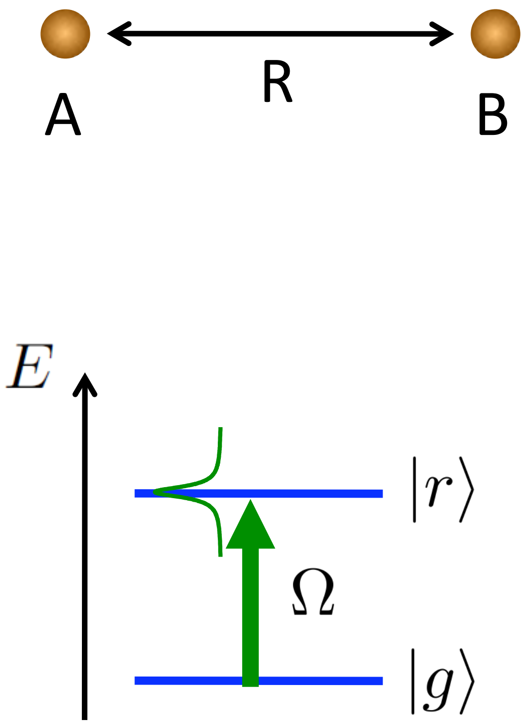
Rydberg blockade and collective excitation

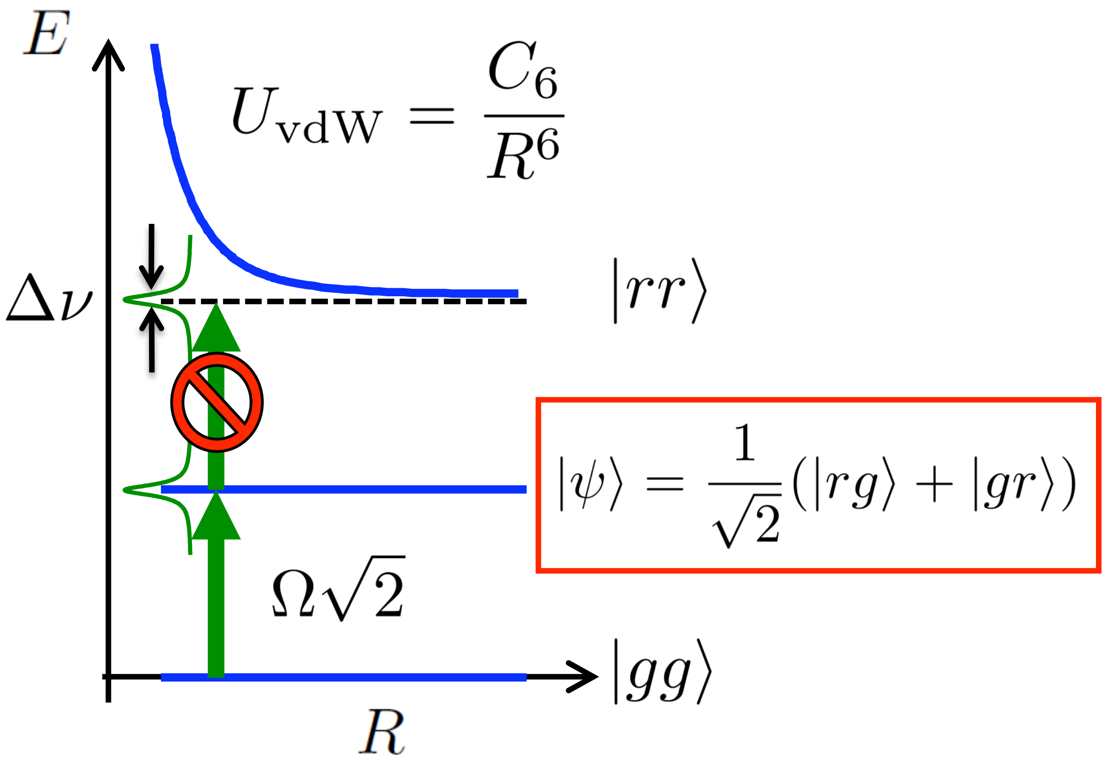






Rydberg blockade and collective excitation



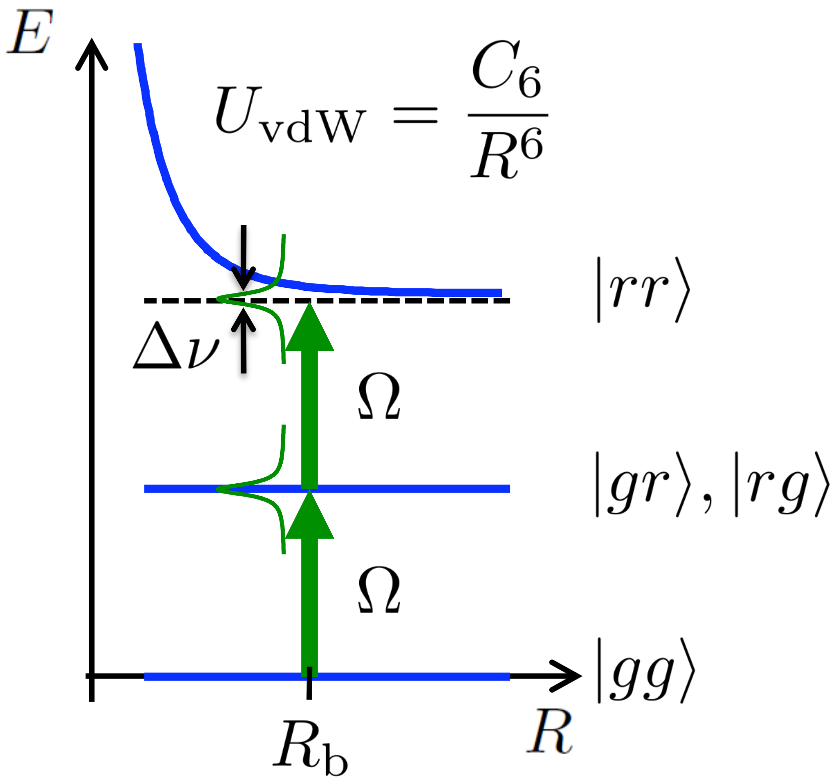


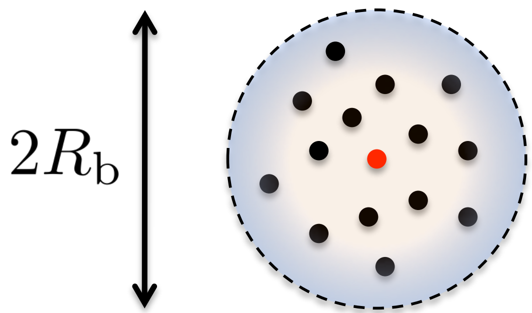
Collective oscillation between $|gg\rangle$ and $|\psi\rangle$ with coupling $\Omega\sqrt{2}$

$$\langle gg|\hat{D}_A + \hat{D}_B|\psi\rangle = \sqrt{2}d \quad \text{with} \quad d = \langle g|\hat{D}_A|r\rangle = \langle g|\hat{D}_B|r\rangle$$

Blockade sphere and N-atom collective excitation

Only one atom excited within a sphere of "blockade" radius R_b





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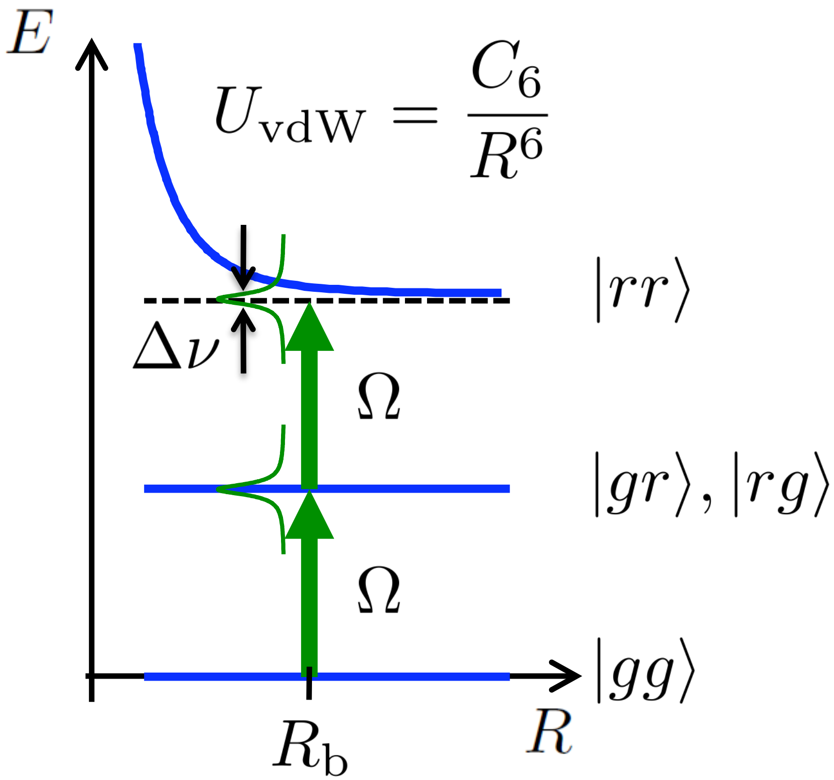

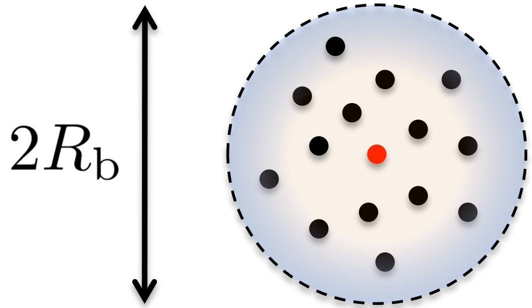

$$\hbar\Delta\nu = \frac{C_6}{R_{\mathrm{b}}^6} \Rightarrow R_{\mathrm{b}} = \left(\frac{\hbar\Delta\nu}{C_6}\right)^{1/6}$$

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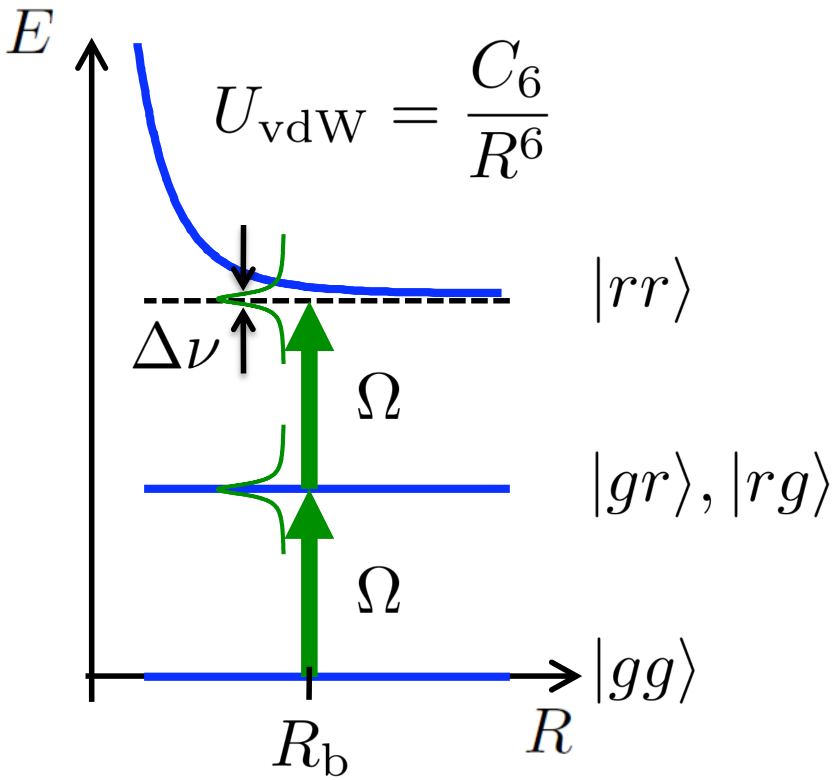

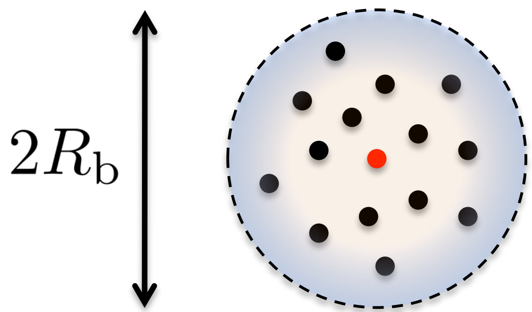

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Coherent excitation: $\Delta\nu = \Omega$

Ex: $62d_{3/2}$, $\Omega / 2\pi = 1$ MHz $\Rightarrow R_b = 10\ \mu m$

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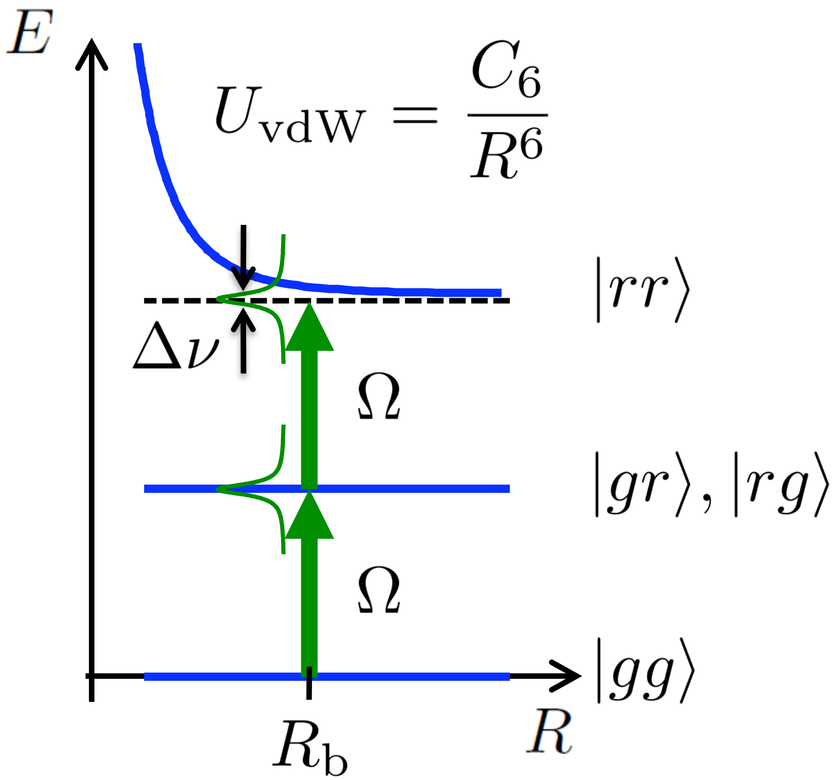

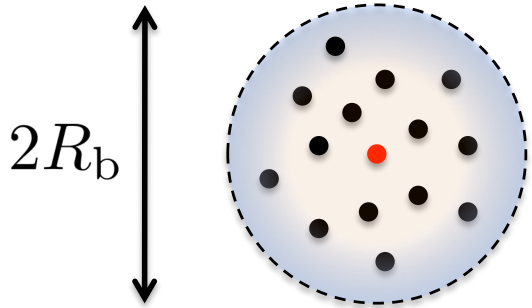

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Ex: $62d_{3/2}$, $\Omega / 2\pi$ = 1 MHz ⇒ R_b= 10 μm

N atoms within the blockade sphere ⇒ collective oscillation

$$|ggg...g\rangle \quad \xleftrightarrow{\Omega\sqrt{N}} \quad |\psi_{\mathrm{c}}\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} |gg...r_j...g\rangle$$

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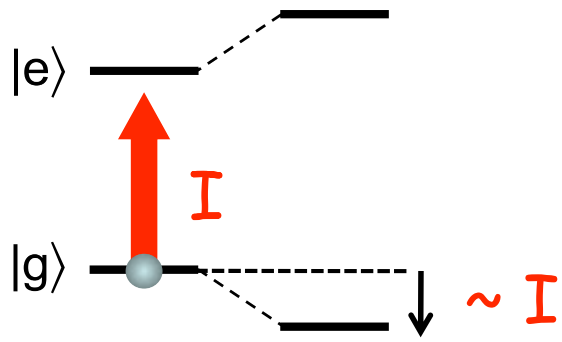
Microscopic optical dipole trap

Non-resonant atom-laser interaction

$\Rightarrow$ **light-shift**



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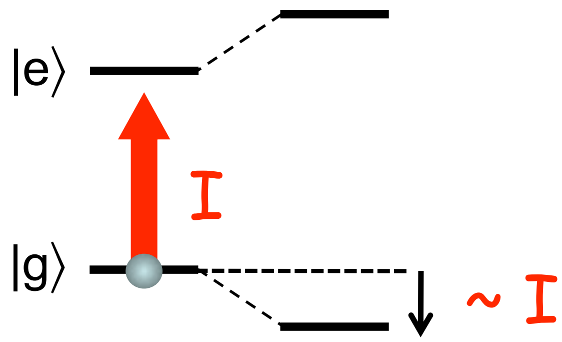
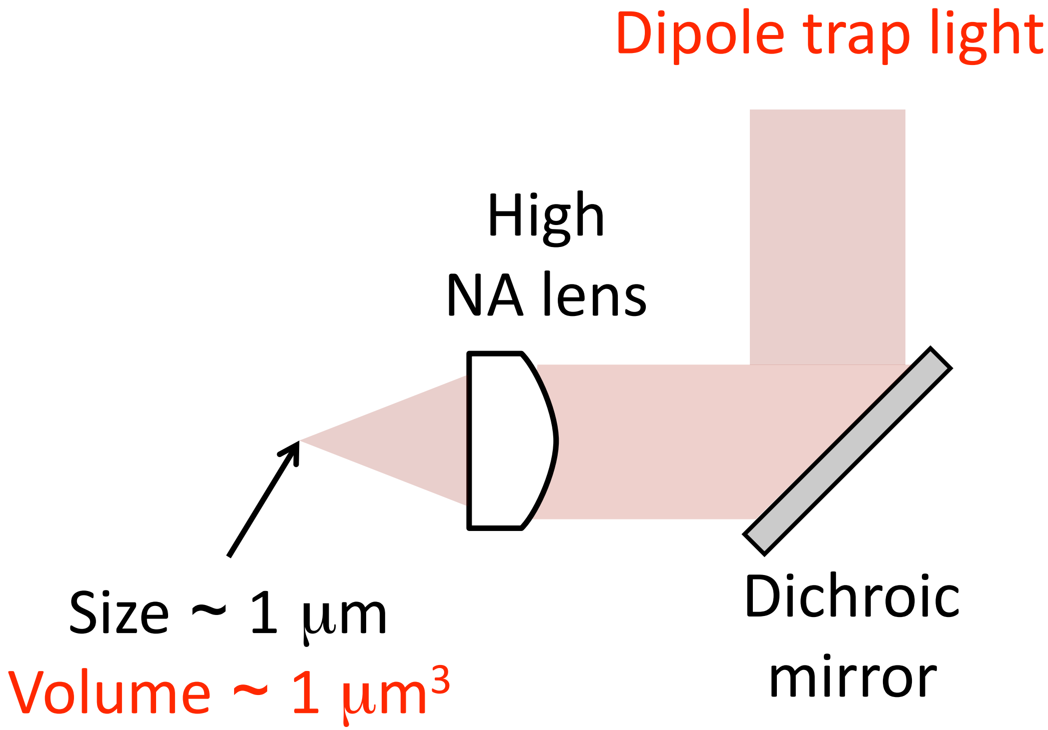
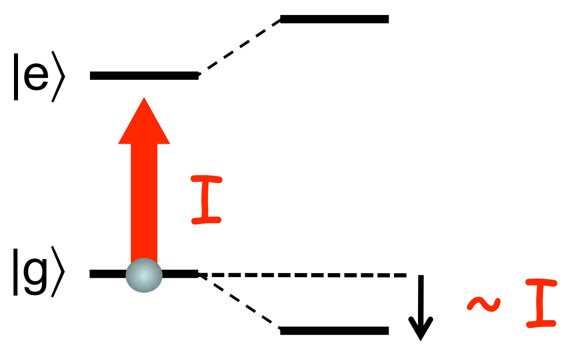


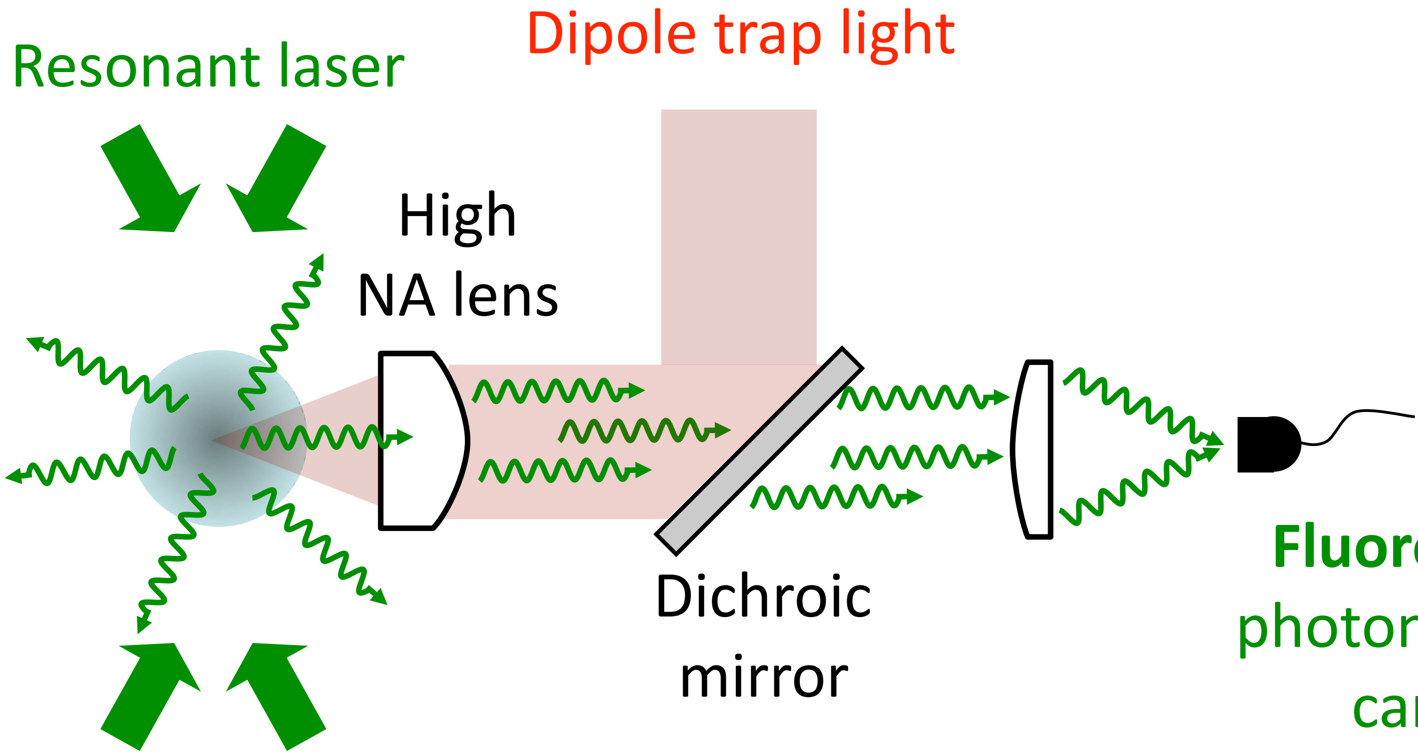


Depth ≈ 1 mK $\Rightarrow$ **laser cooled atoms**

Microscopic optical dipole trap

Non-resonant atom-laser interaction
⇒ **light-shift**

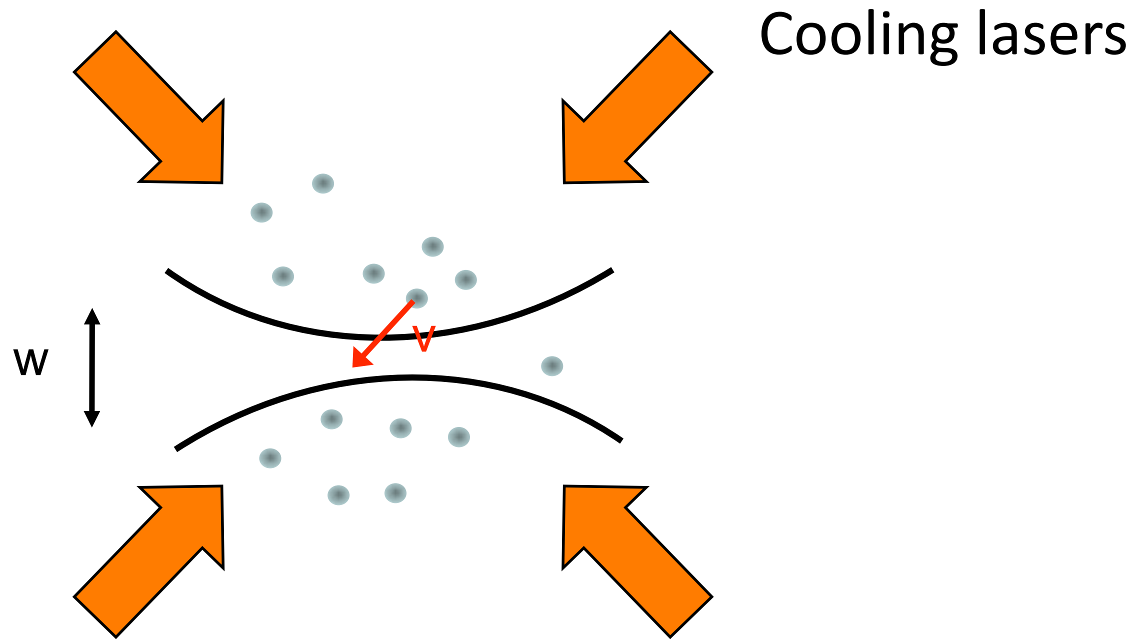




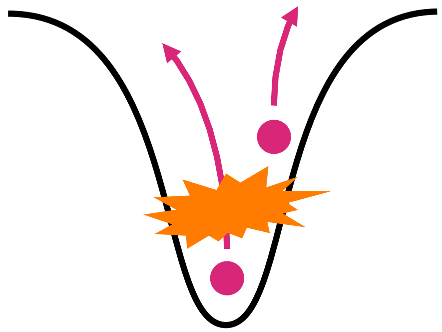
Schlosser *et al.*, Nature **411**, 1024 (2001)
Sortais *et al.*, PRA **75**, 013406 (2007)

Loading the trap with individual atoms

Loading rate



Light-assisted loss in the trap

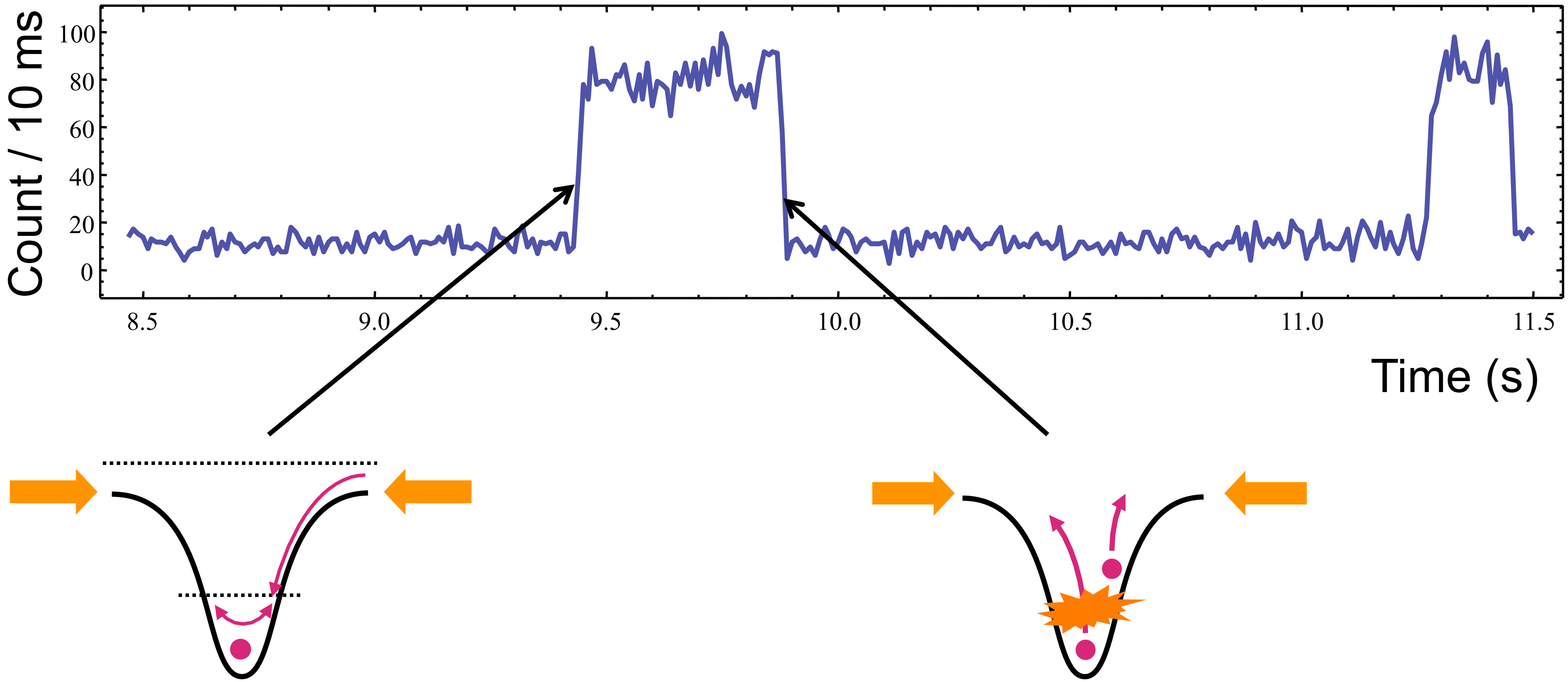


Loss ~ 1/ trap size

Prevents 2 trapped atoms when loss >> loading

Trapping a single (cold) atom

Fluorescence @ 780 nm induced by the cooling lasers



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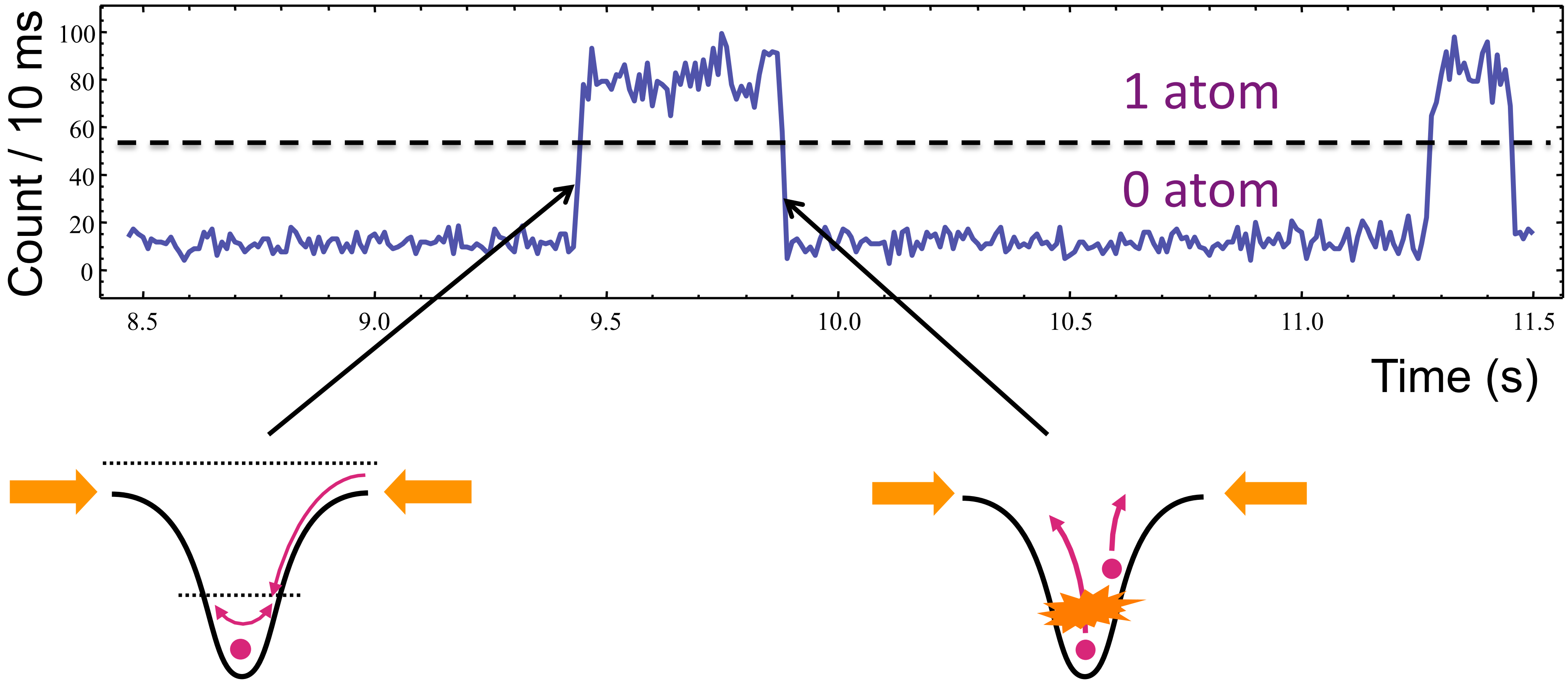
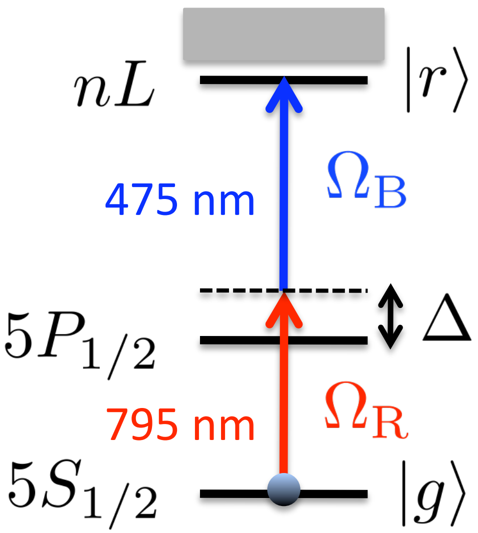


NON deterministic single-atom source

Schlosser *et al.*, Nature **411**, 1024 (2001); Sortais *et al.*, PRA **75**, 013406 (2007)

Coherent excitation of atoms to Rydberg state (ex: ^{87}Rb)



2-photon excitation: $\Omega = \dfrac{\Omega_R \Omega_B}{2\Delta}$

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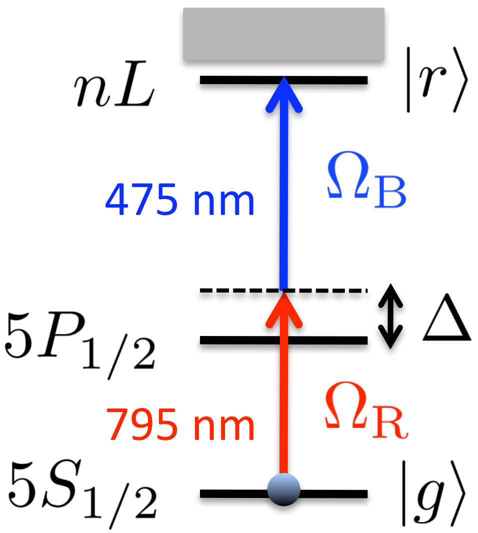

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Prepare: $\cos\dfrac{\Omega t}{2}|g\rangle + \sin\dfrac{\Omega t}{2}|r\rangle$

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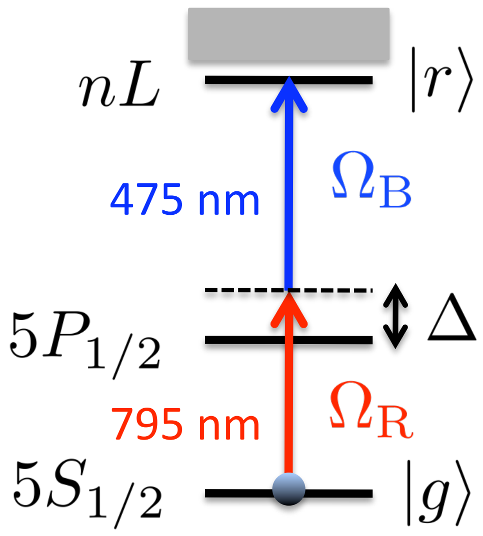

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$\Rightarrow$ must repeat to calculate P_r (x 100)

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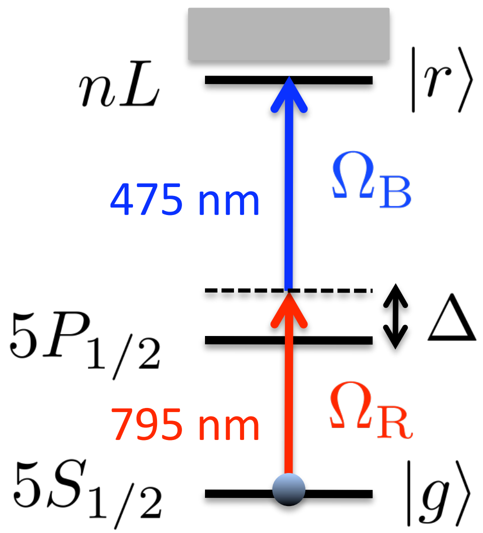

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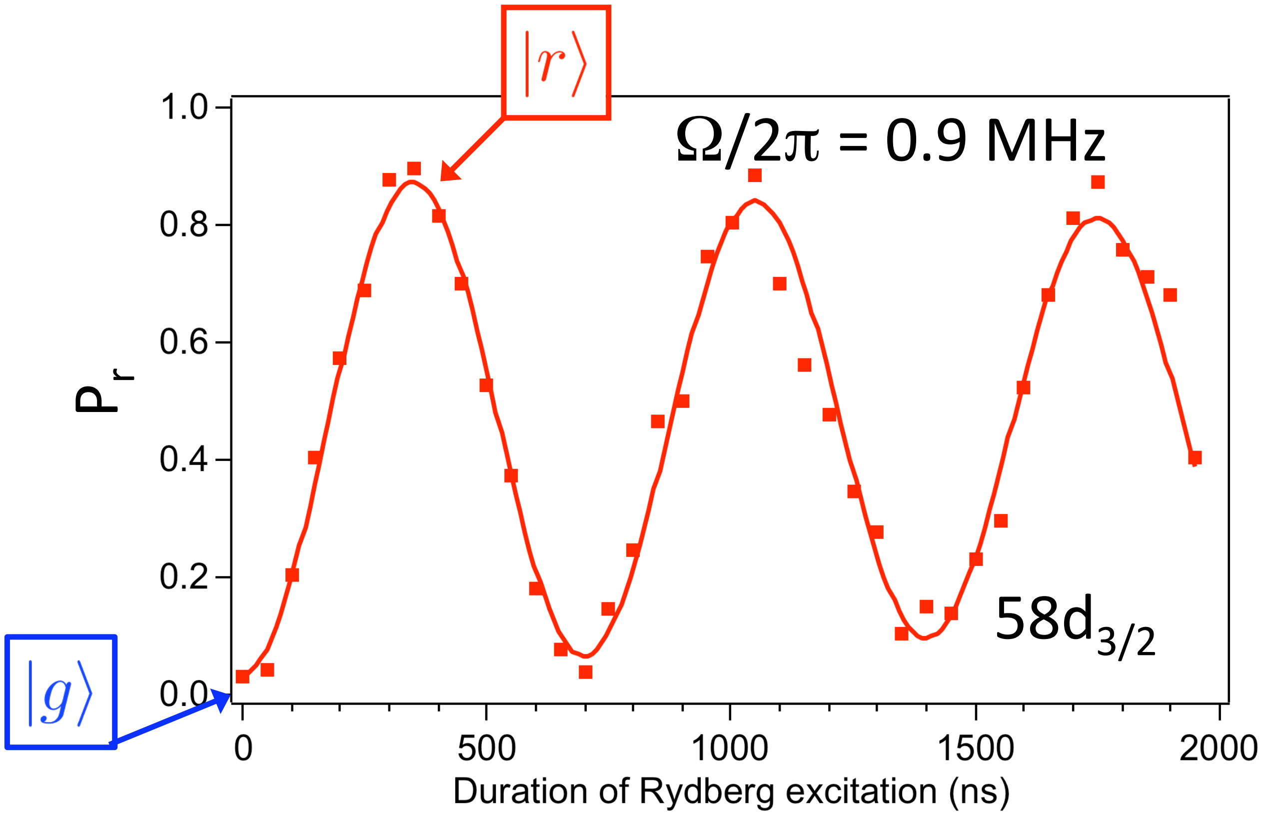
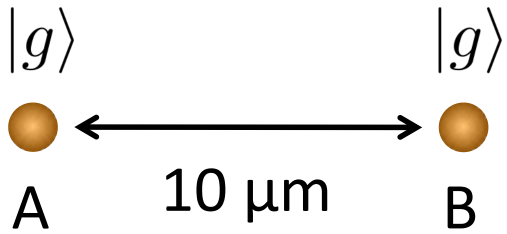


Demonstration of the Rydberg blockade: U. Wisconsin

Addressable excitation



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

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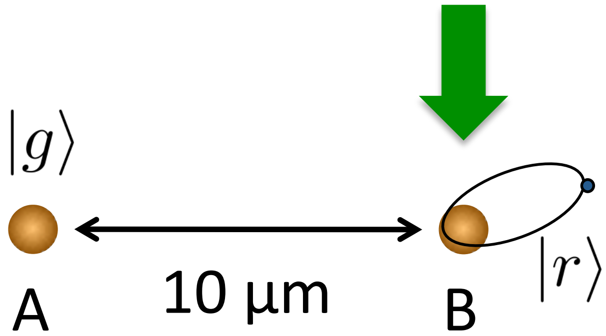
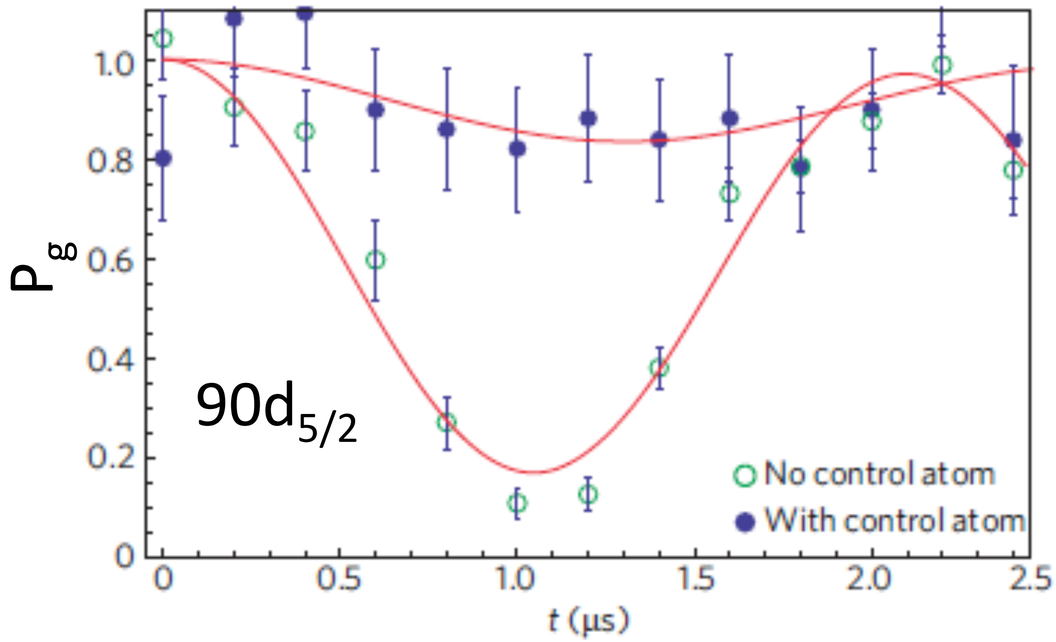


Oscillation of atom B



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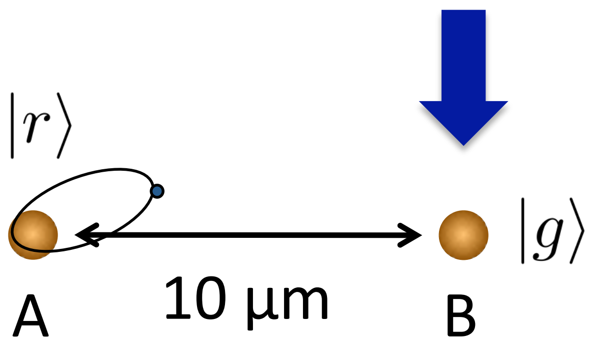

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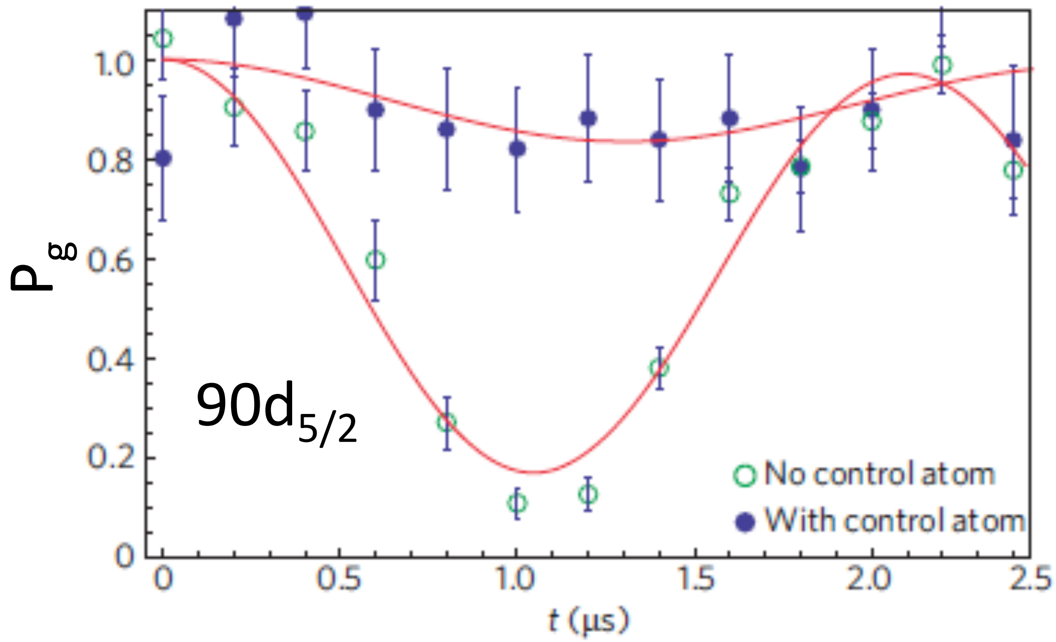
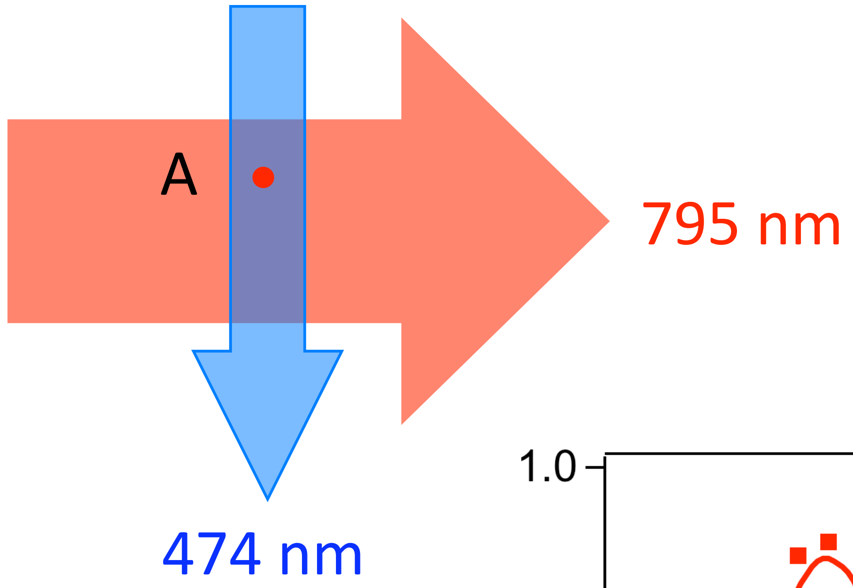


Excitation of atom B conditionned by the state of atom A

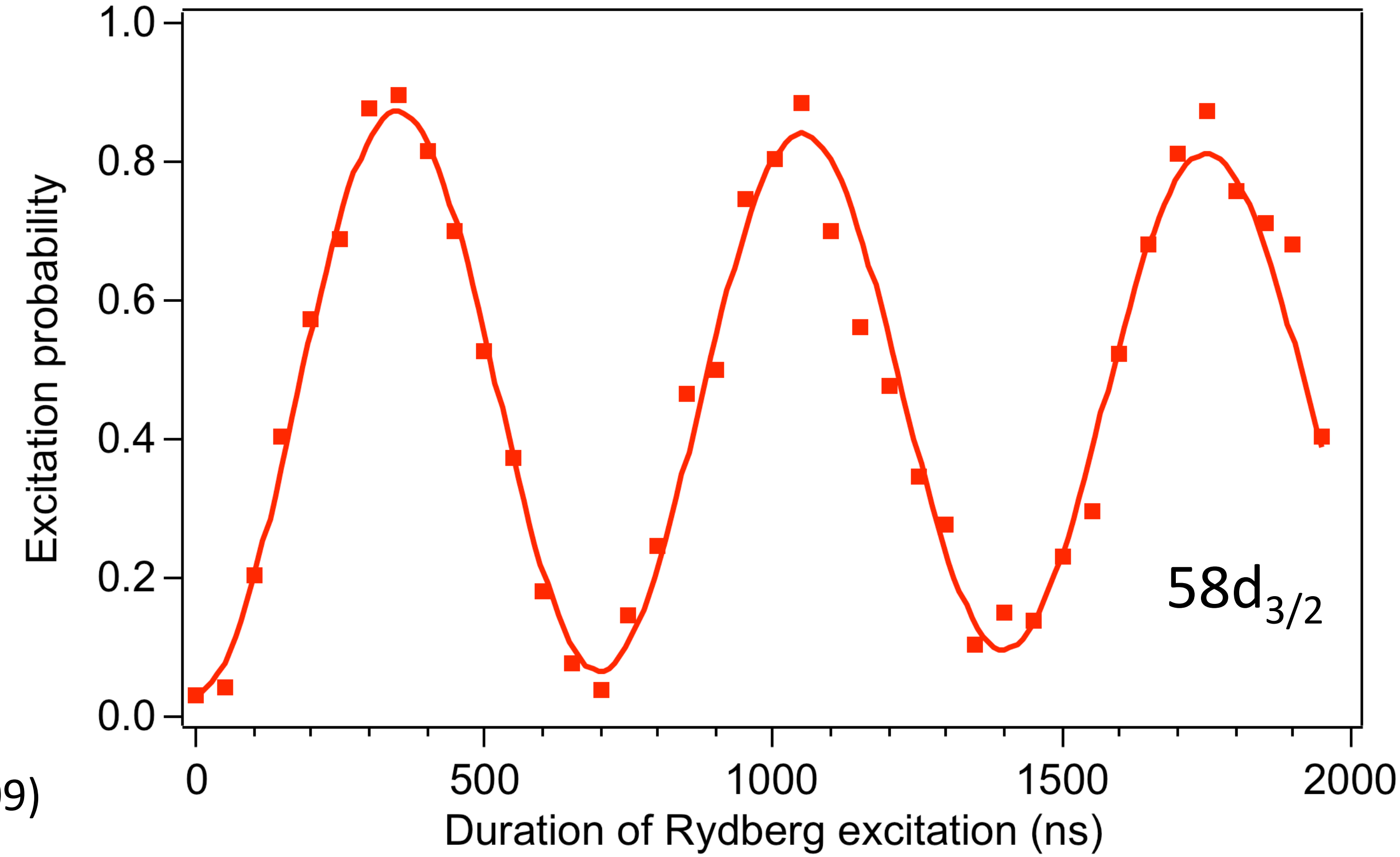
⇒ Demonstration of C-NOT gate and entanglement

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

Rydberg blockade and collective excitation: Institut d'Optique



Exc. proba atom A only



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

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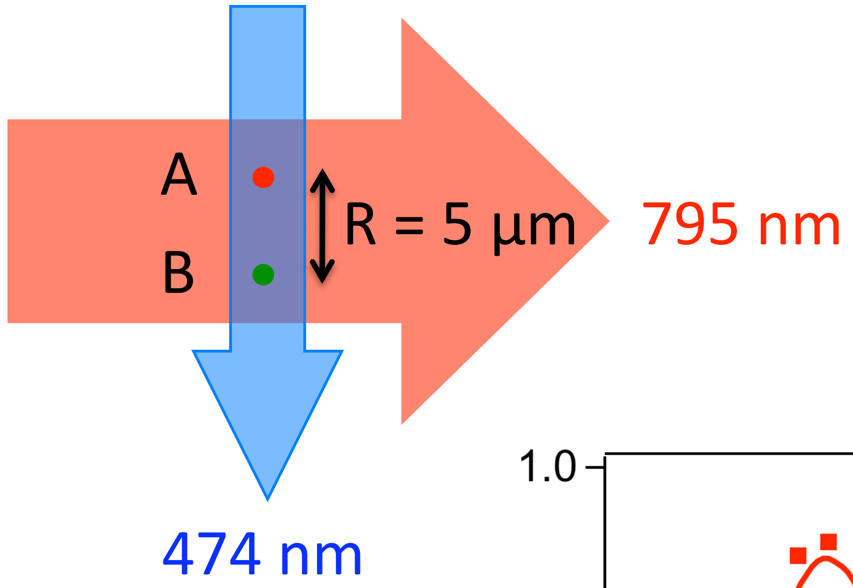

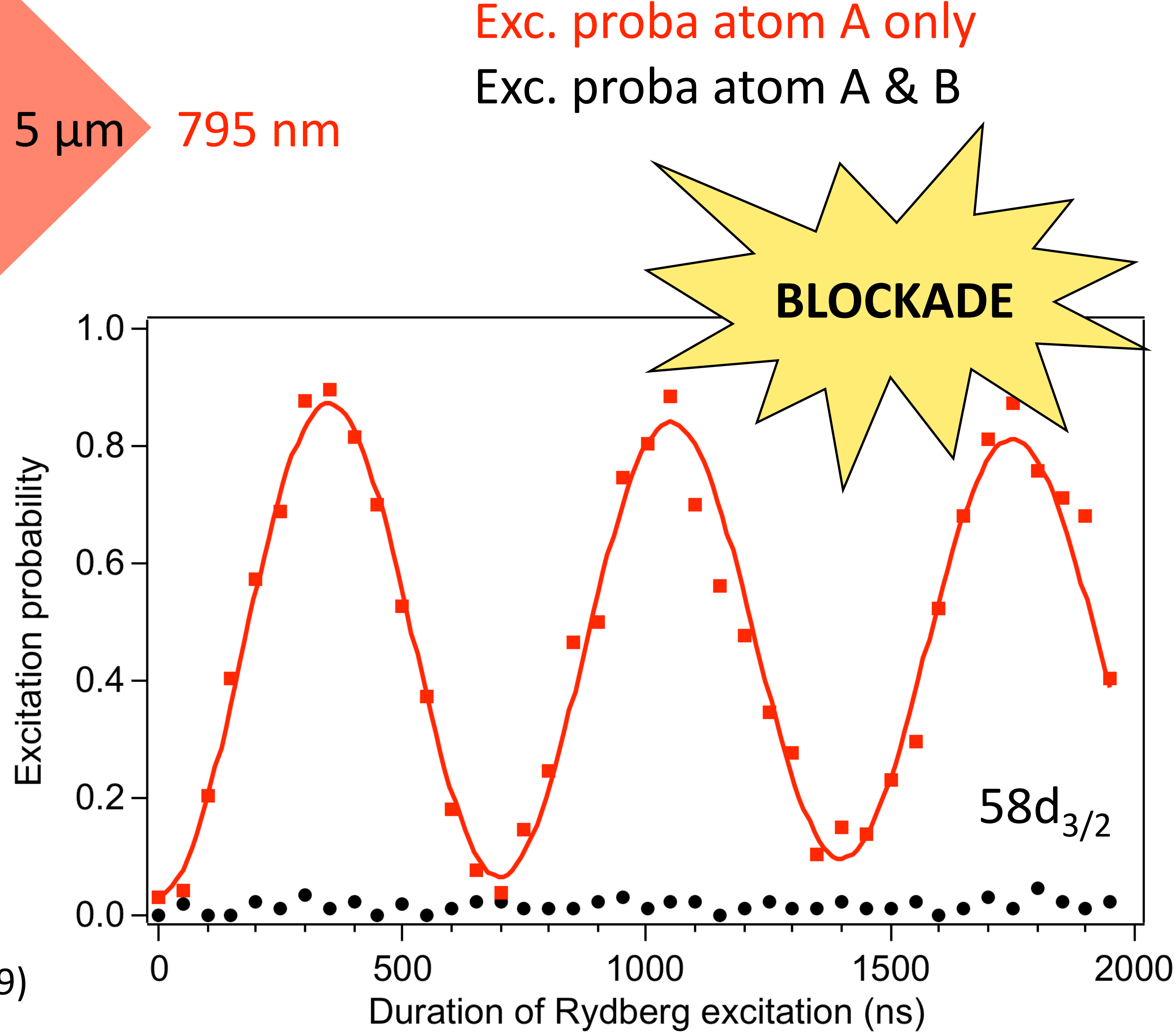

Gaëtan *et al.*,
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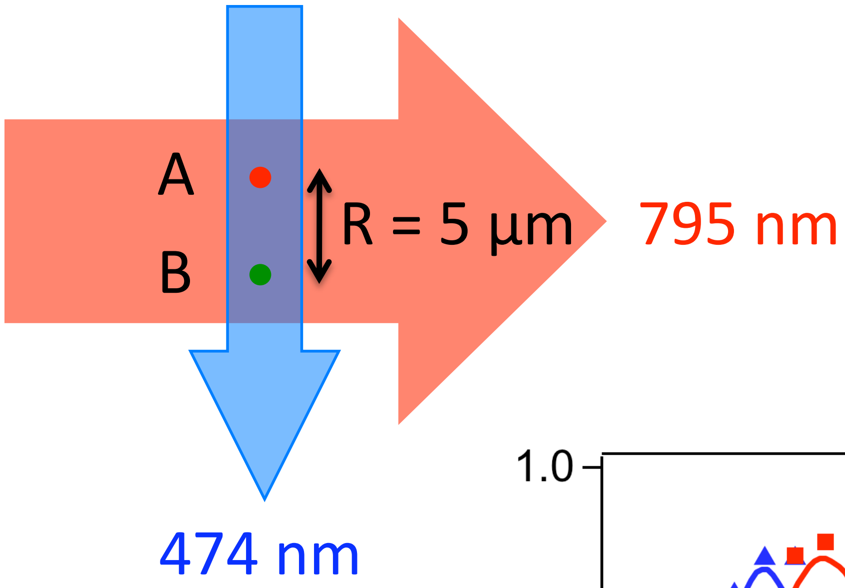
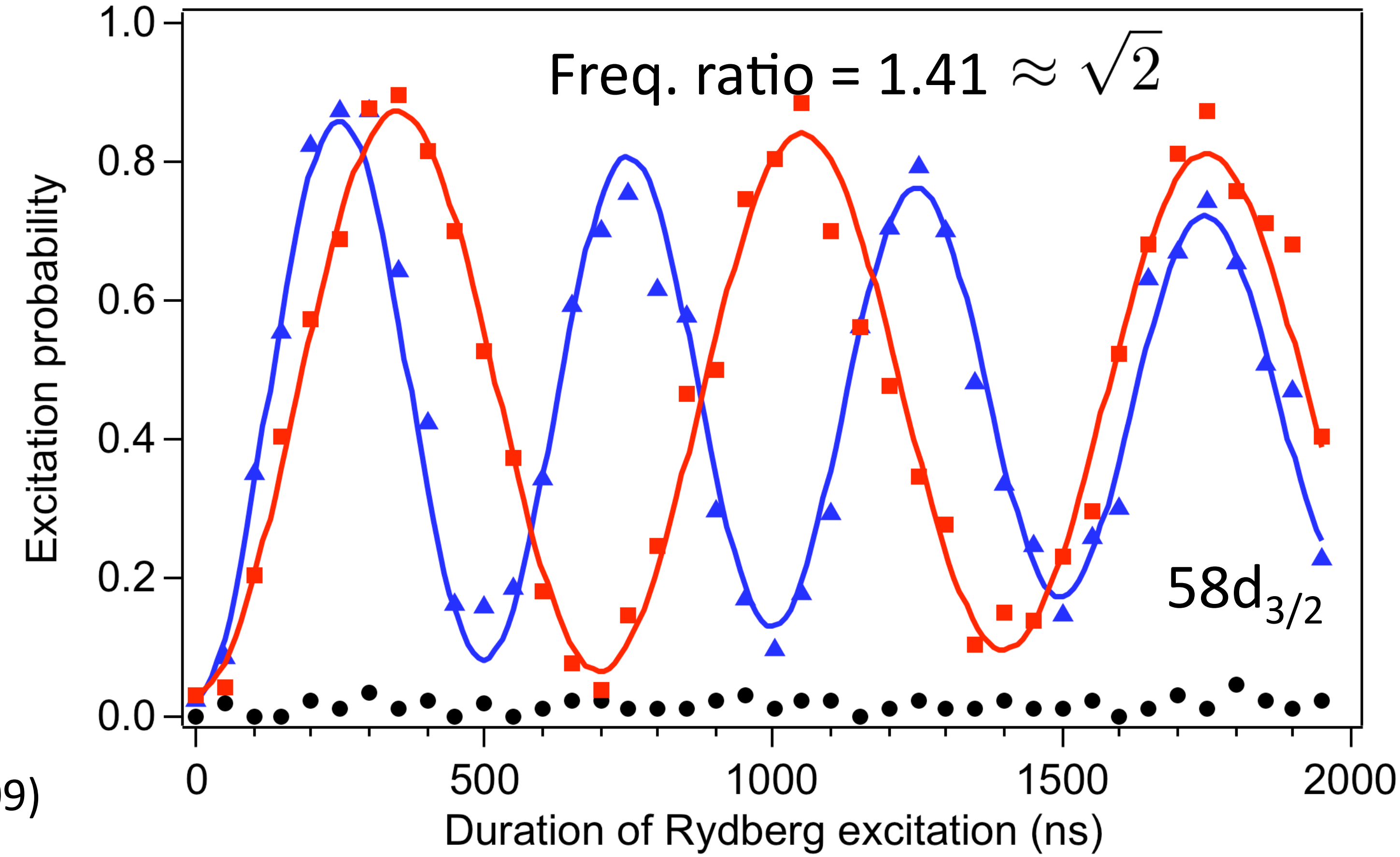
Rydberg blockade and collective excitation: Institut d'Optique



Exc. proba atom A only

Exc. proba atom A & B

Exc. proba atom A **OR** B



Gaëtan *et al.*,
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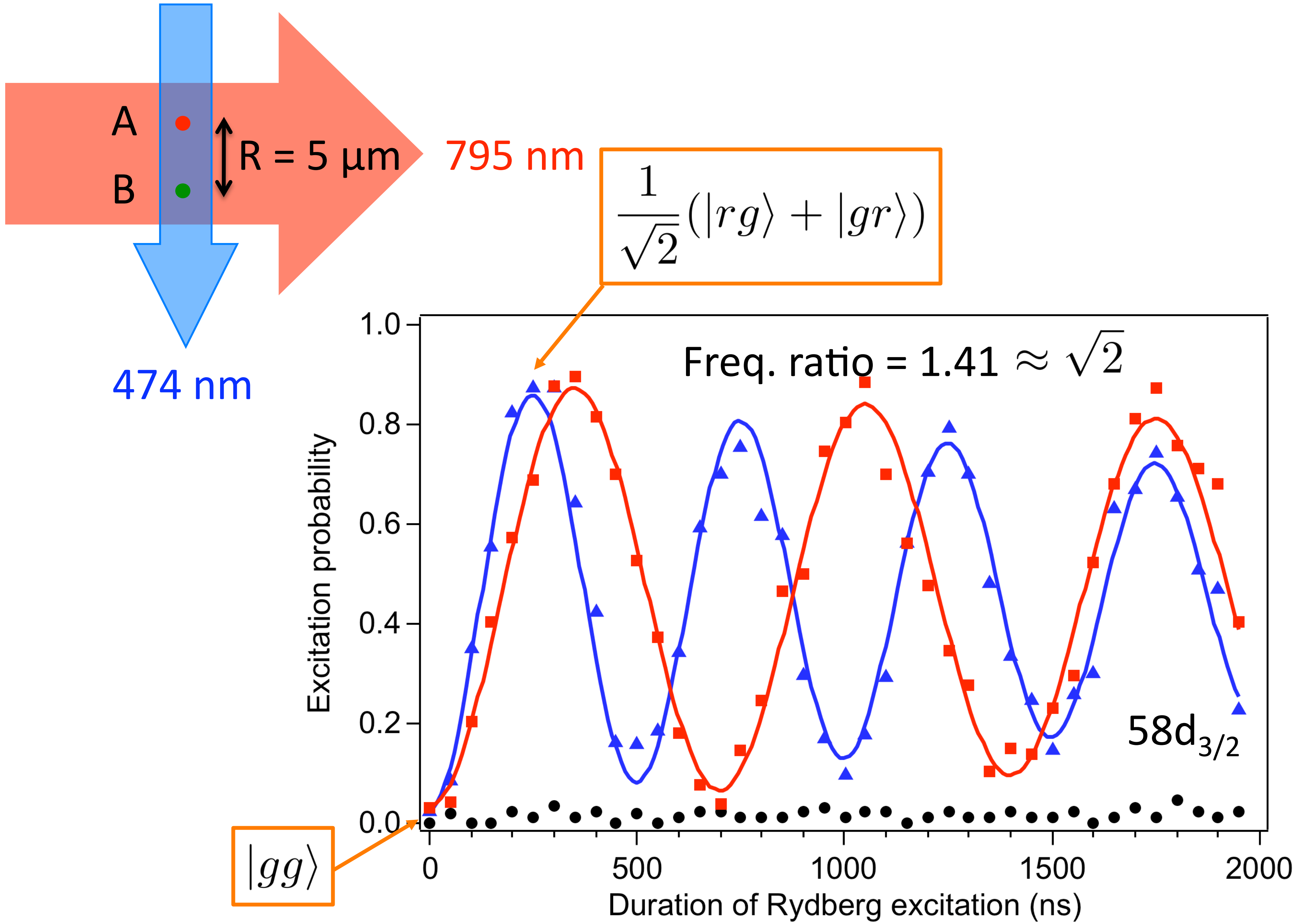
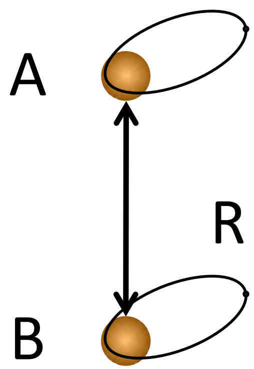
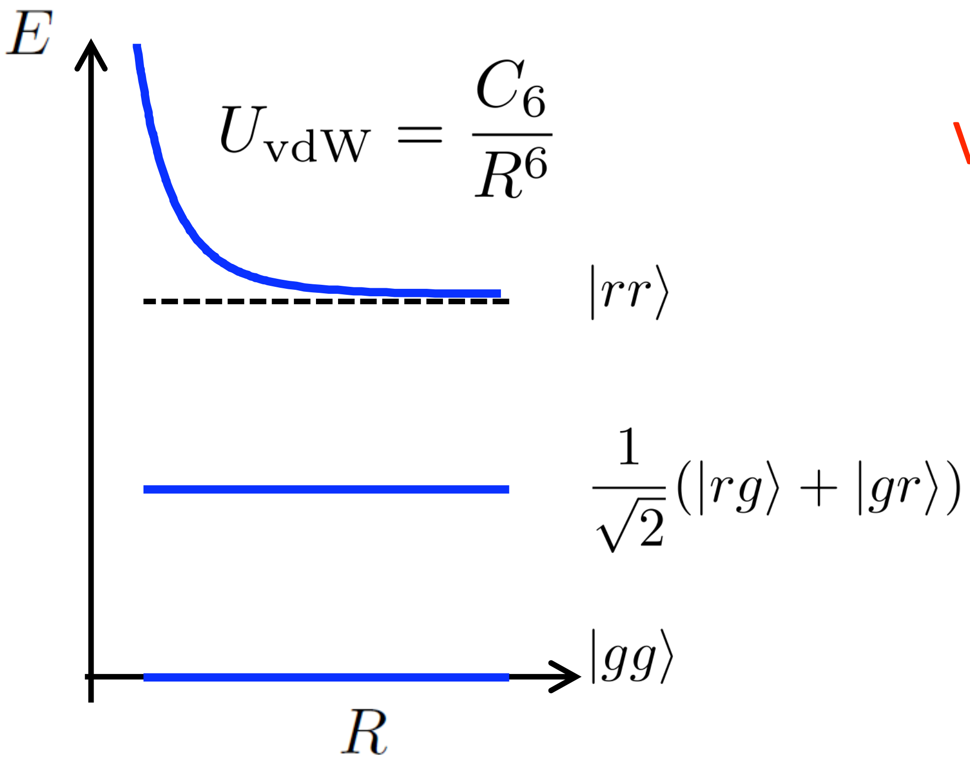


From full blockade to partial blockade…

Non-addressable excitation

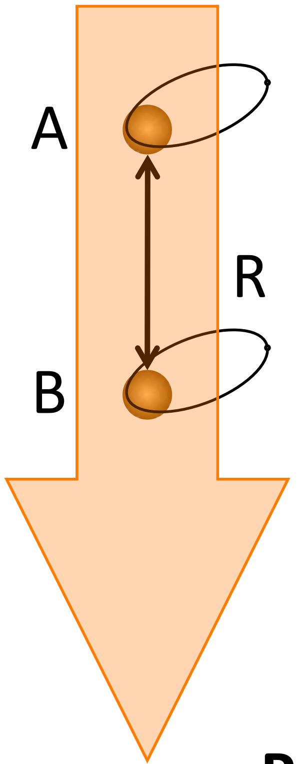


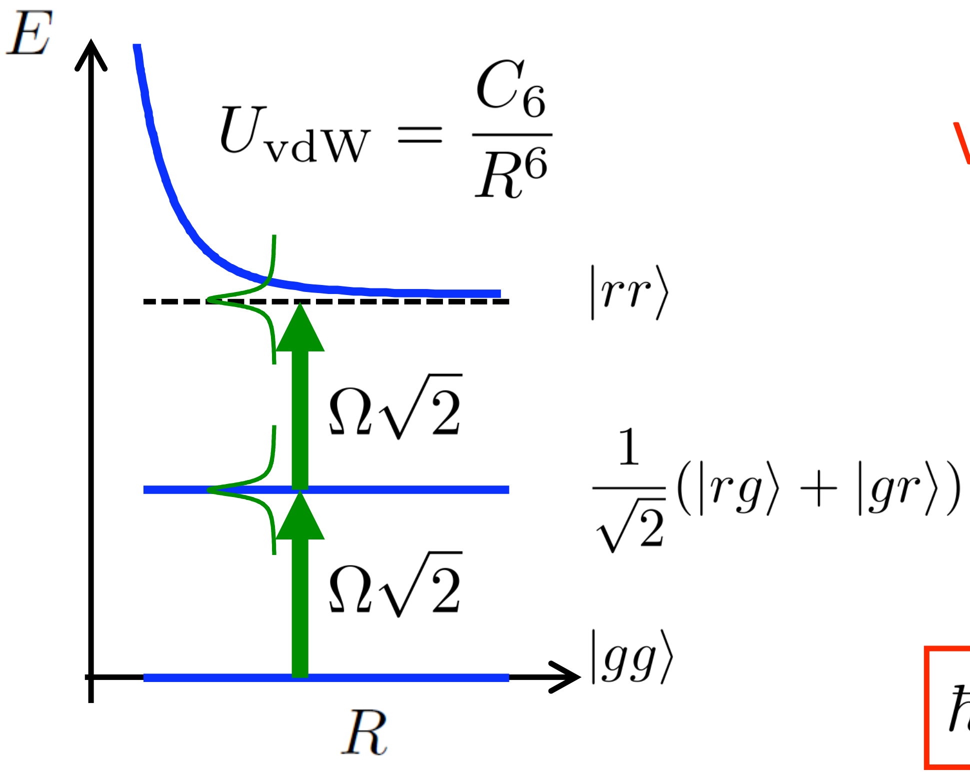


Van der Waals regime

From full blockade to partial blockade…

Non-addressable excitation





Van der Waals regime

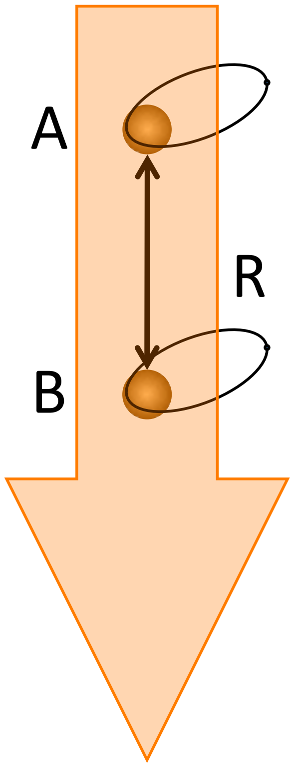
$$\hbar\Omega \approx C_6/R^6$$

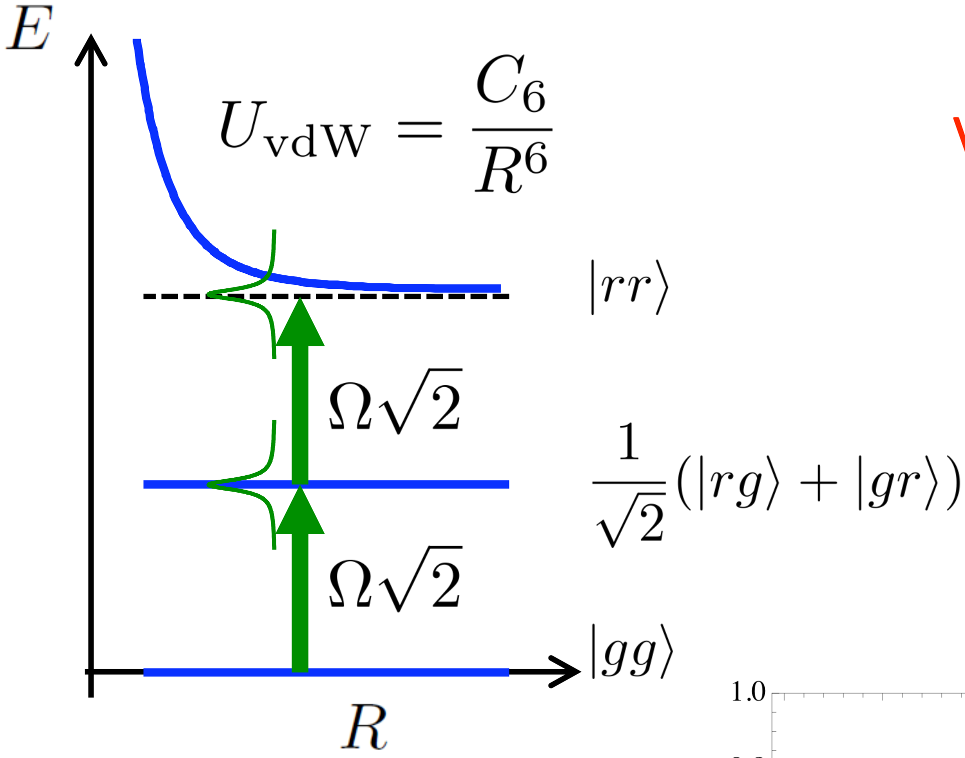
Partial blockade: dynamics involves Ω and U_{vdW}

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

From full blockade to partial blockade…

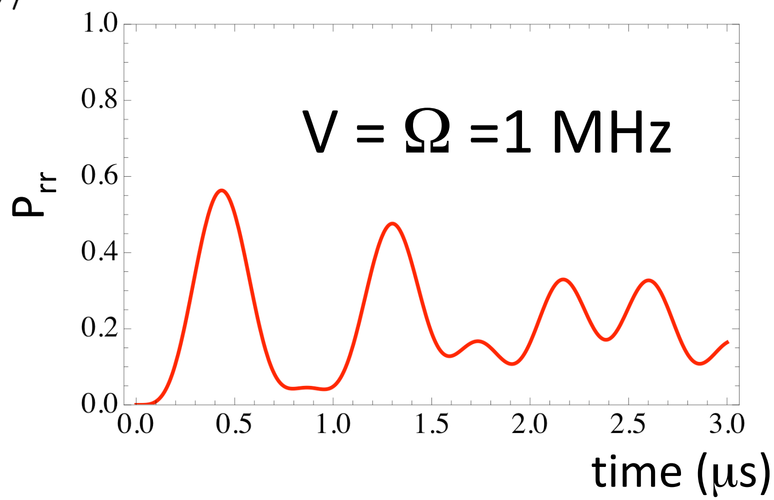
Non-addressable excitation



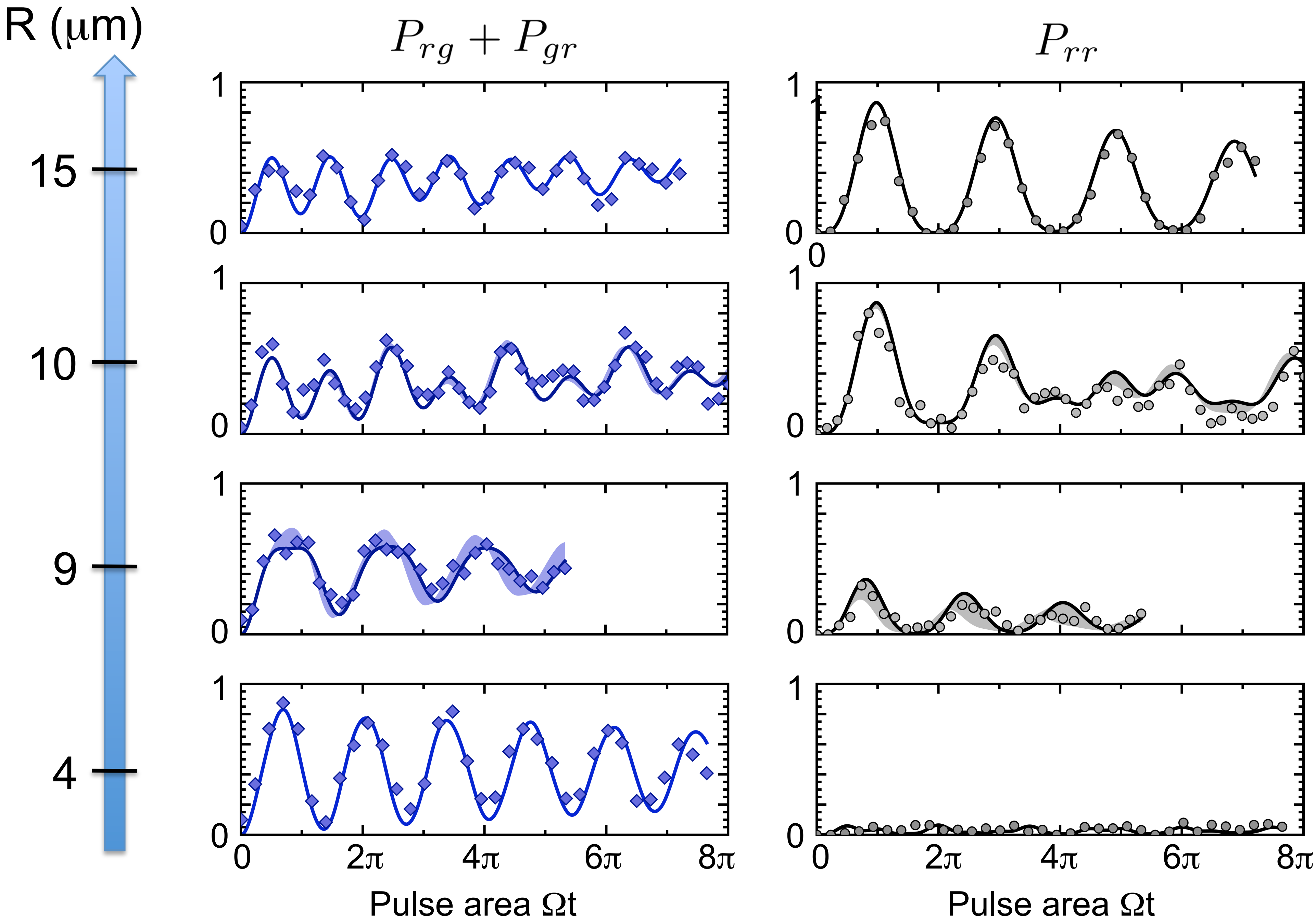


Van der Waals regime

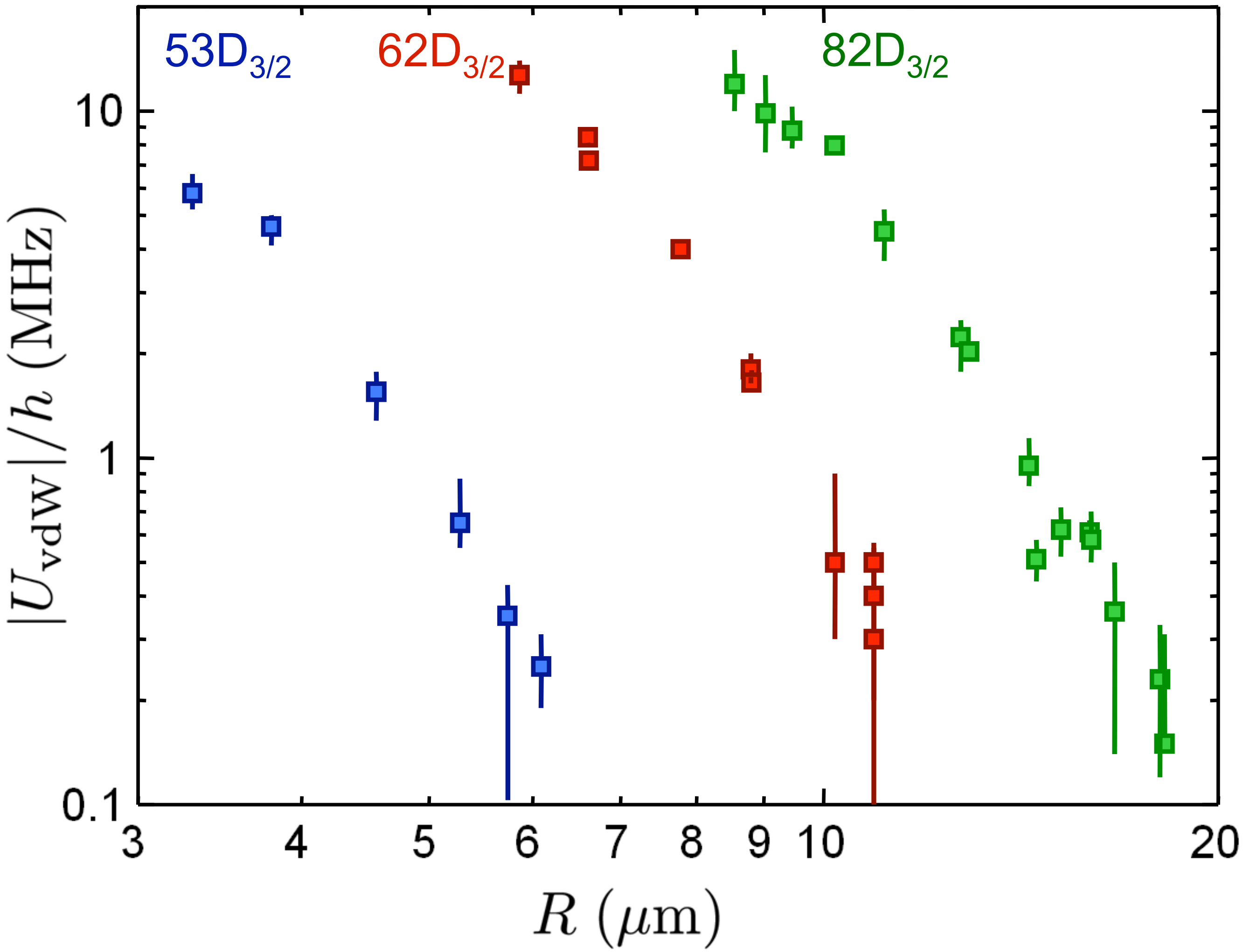
Schrödinger's equation:



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



Measurement of the Van der Waals energy between 2 atoms



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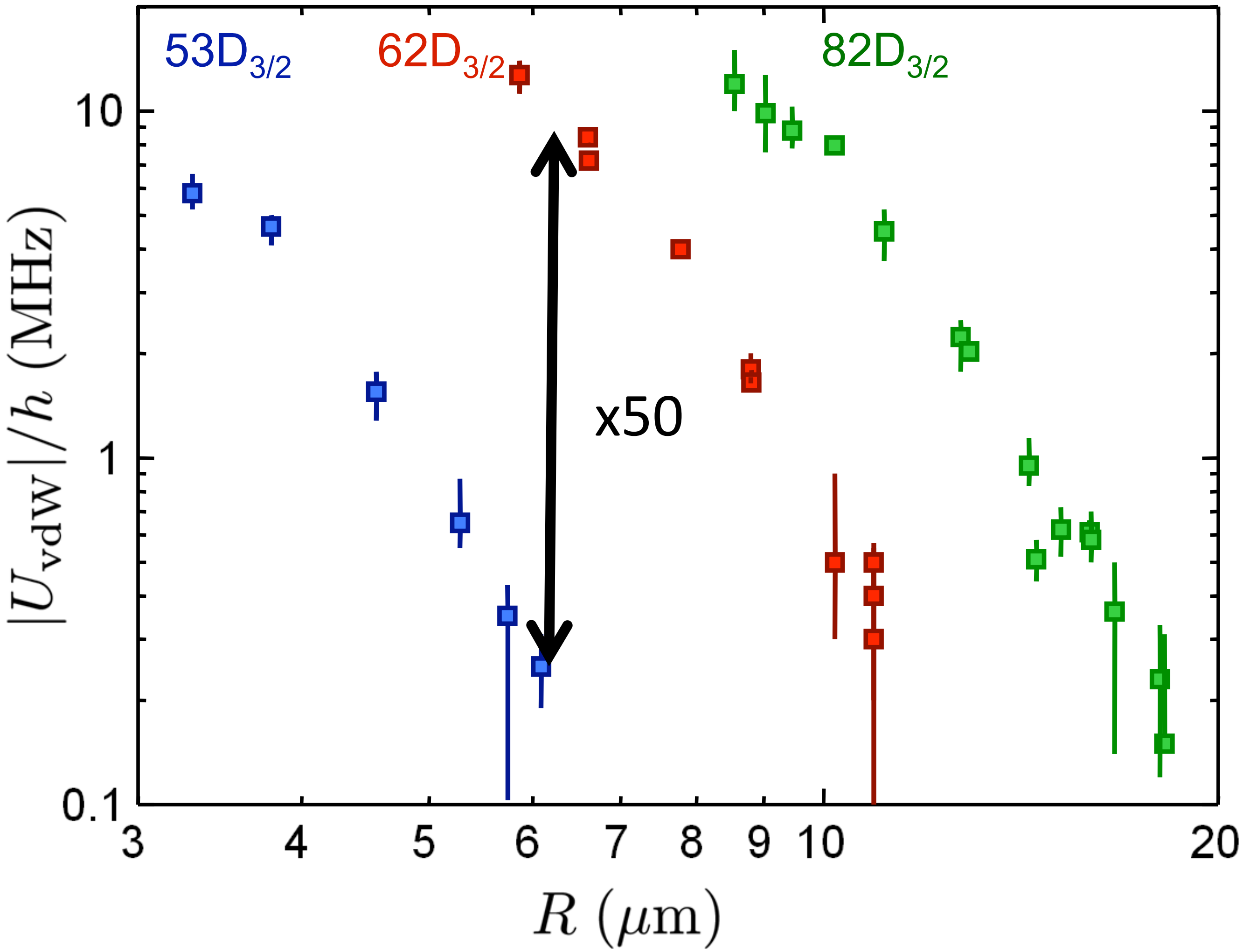

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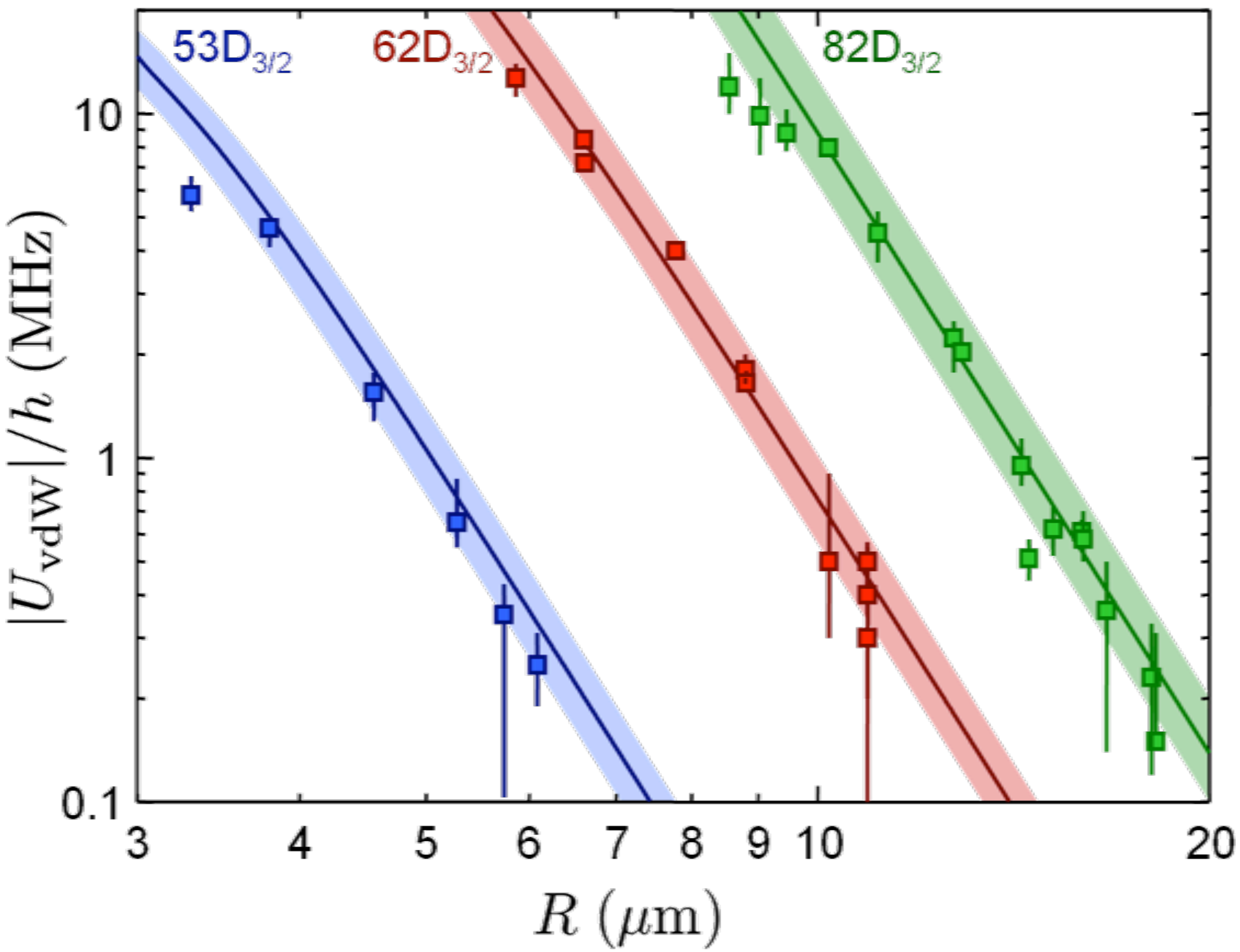

Theory curves: direct diagonalization (dipole-dipole interaction)

No adjustable parameter!

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

Outline

1. Rydberg atoms and their interaction
2. Rydberg blockade: theoretical aspects
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4. Rydberg blockade in cold atomic ensembles
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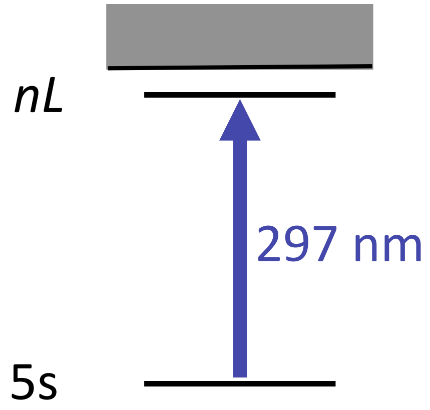
Rydberg blockade in cold atomic cloud: the U. Connecticut expt.

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



Pulsed, incoherent
laser excitation of a MOT
$\Rightarrow$ expect $N_{Ryd} \propto$ Intensity

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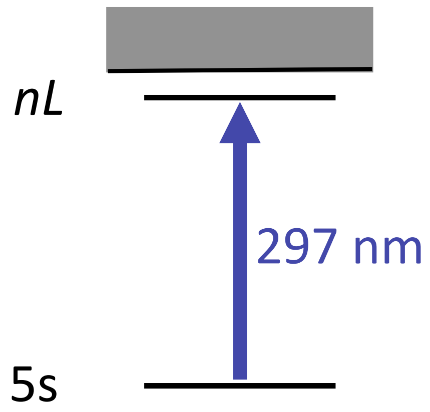

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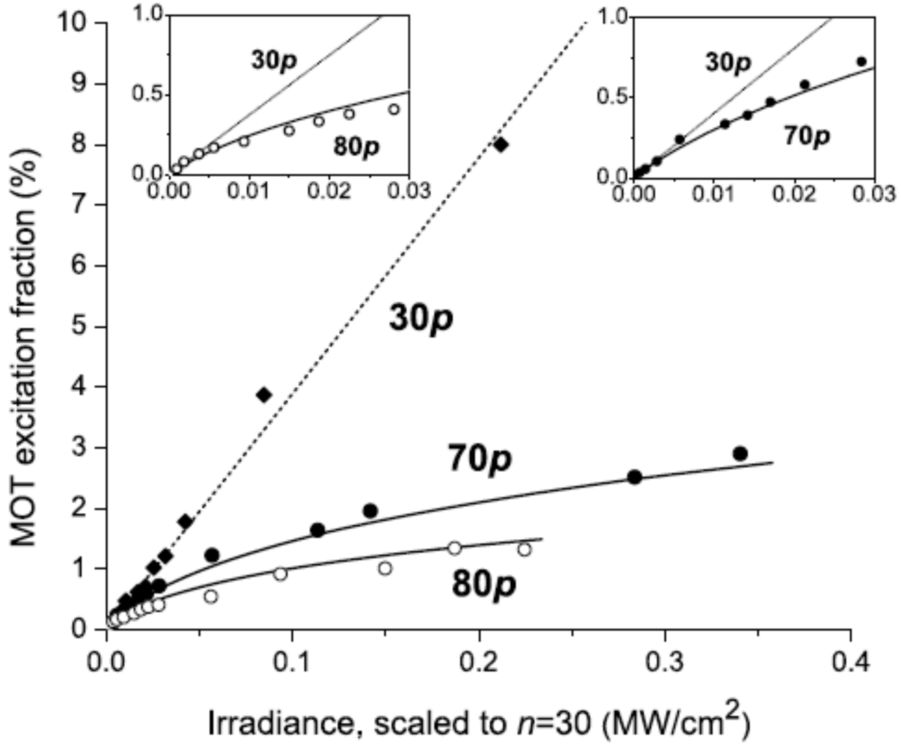
⇒ expect $N_{Ryd} \propto$ Intensity



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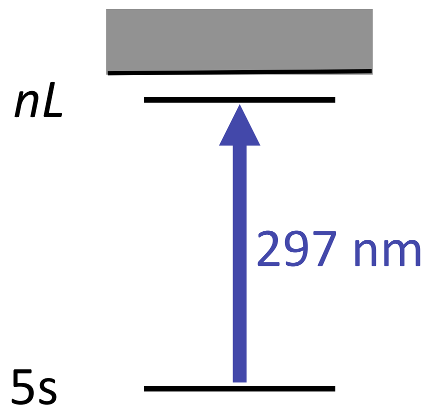

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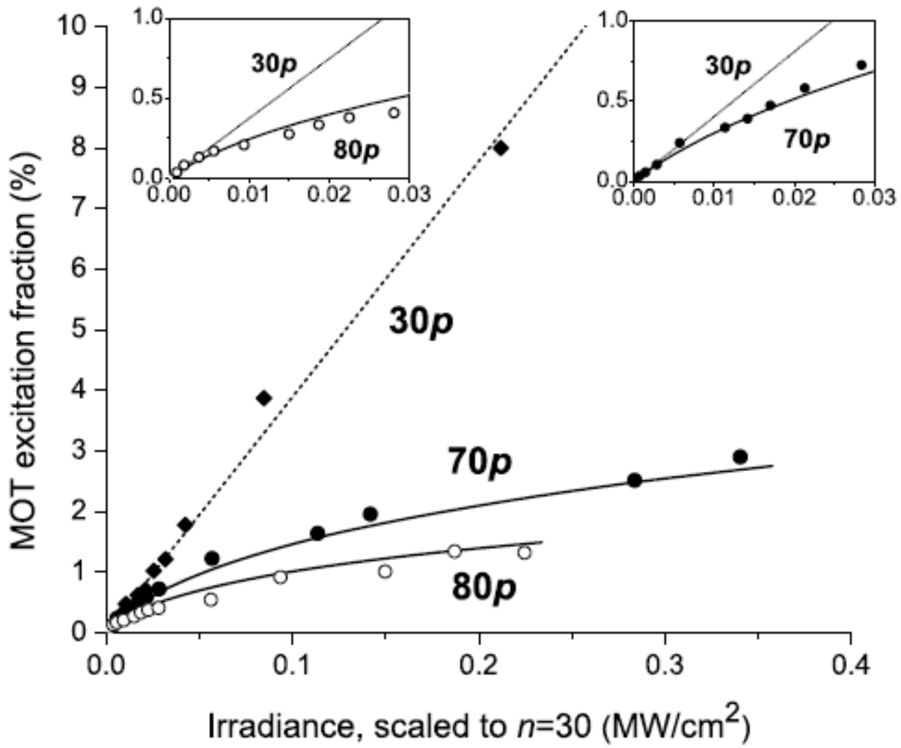
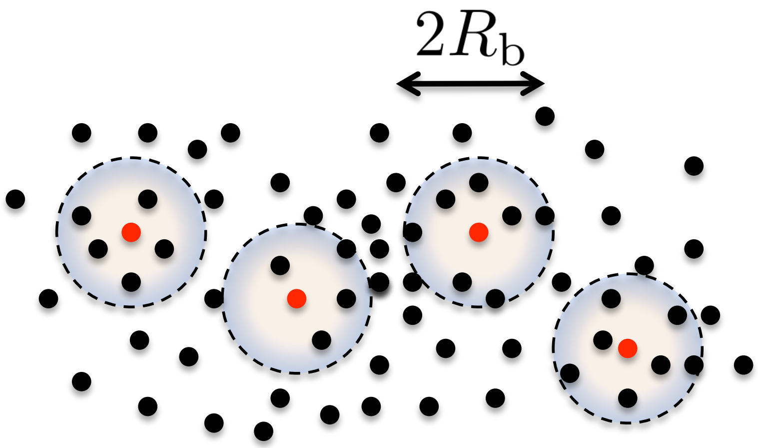


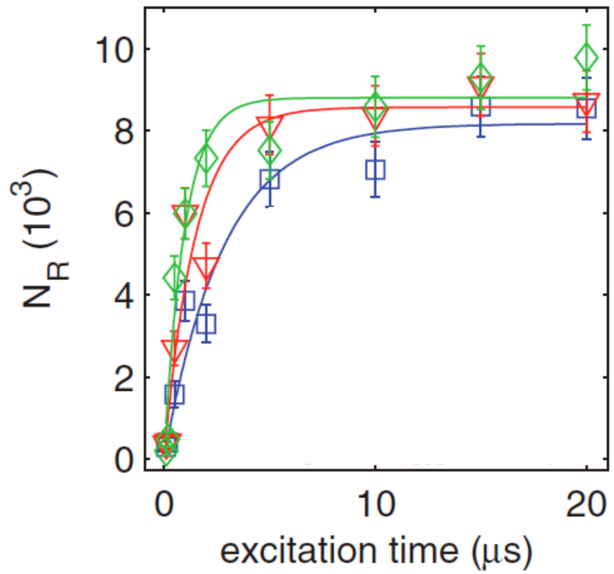


Increase n ⇒ increase C_6
⇒ increase R_b

$$N_{\rm Ryd}^{\rm max} \approx \frac{\rm Volume}{\frac{4\pi R_b^3}{3}}$$

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)

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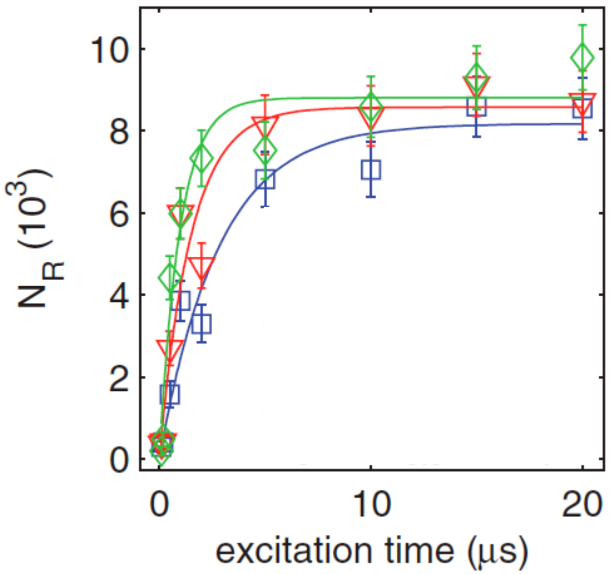

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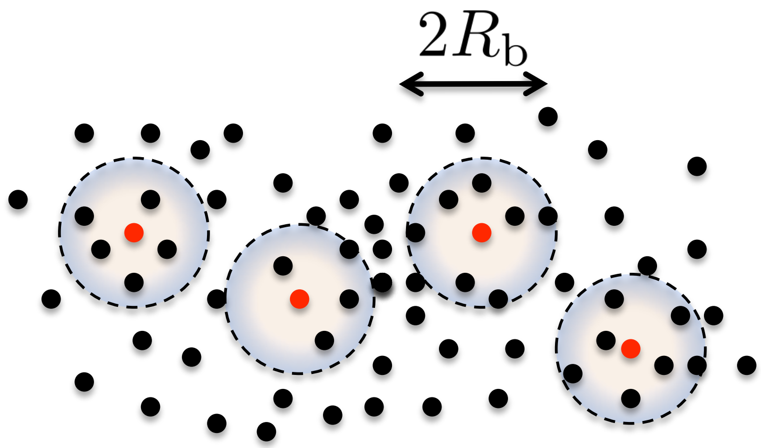
Inhomogeneous distribution of *N*



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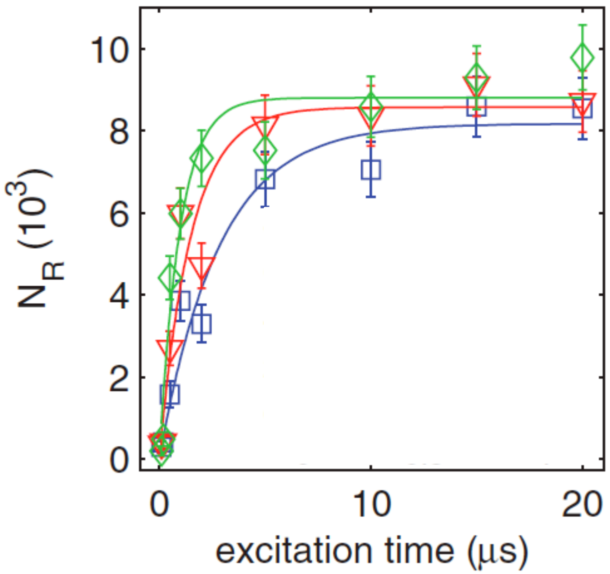

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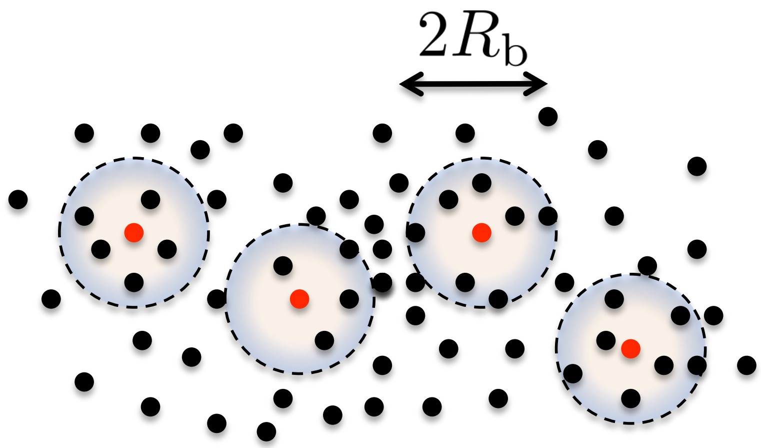
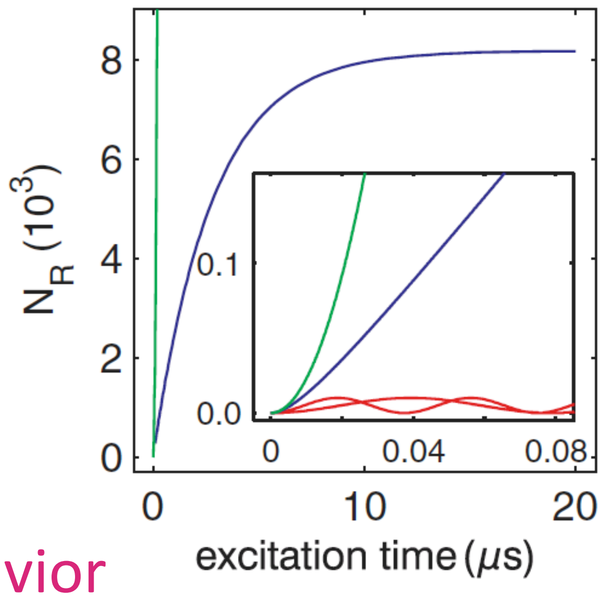
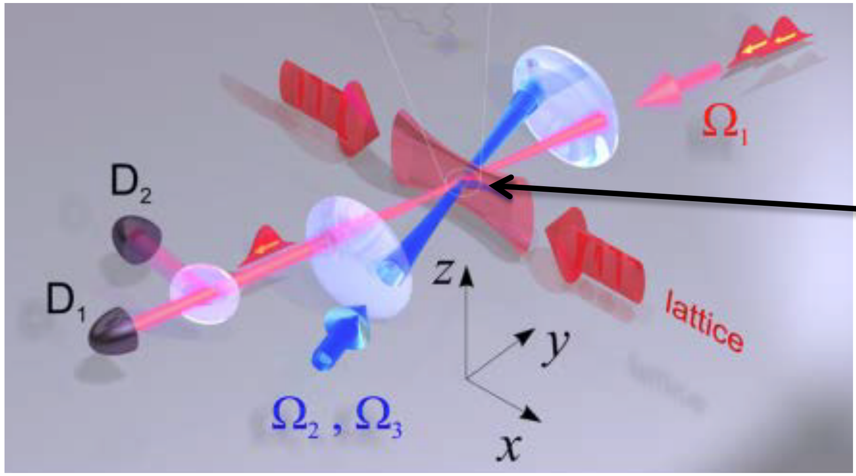




$$N_{\rm Ryd}(t) = \sum_{\{N\}} C_N \sin^2 \frac{\Omega_0 \sqrt{N} t}{2}$$

⇒ Incoherent behavior

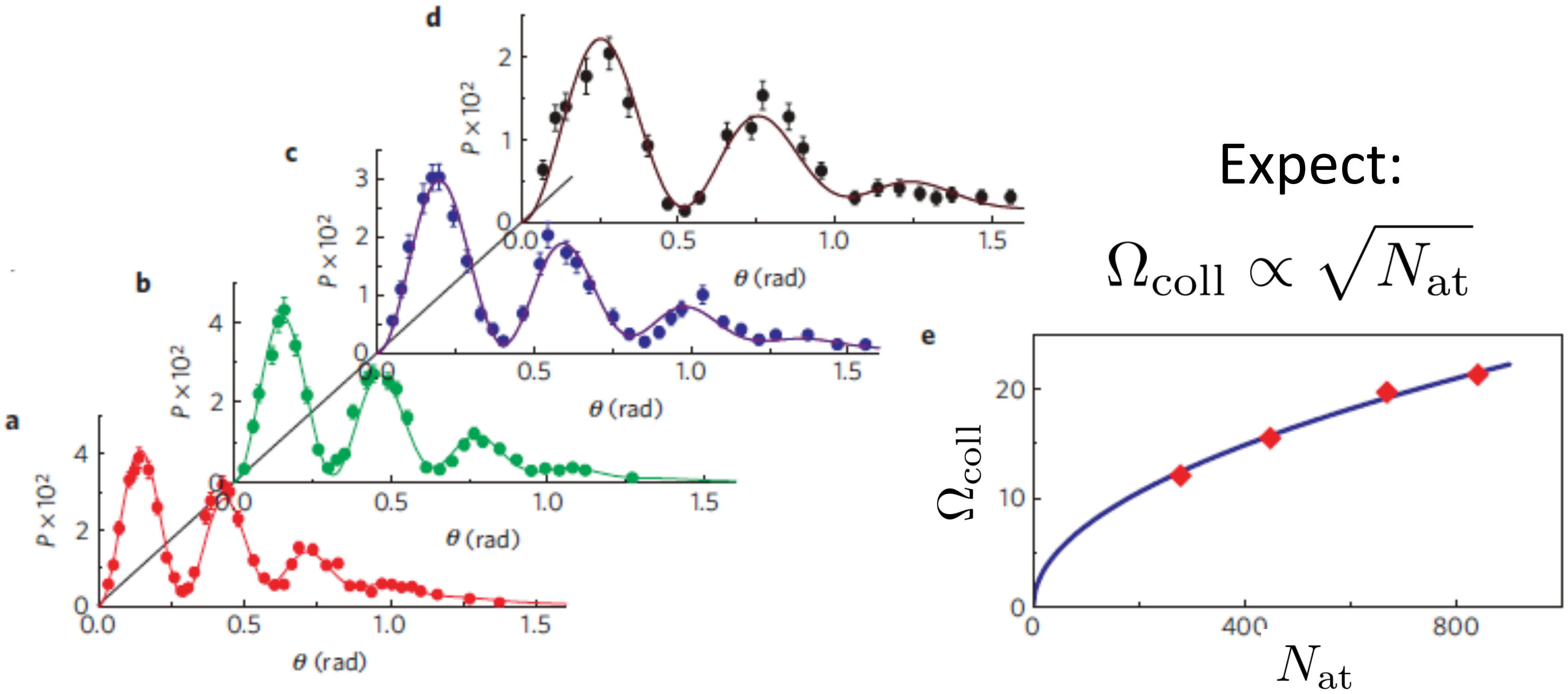
Collective Rabi oscillations in ensemble



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

Excitation volume < R_b^3

102s, R_b = 15 μm



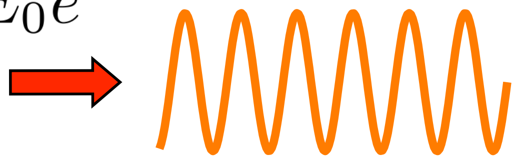
Expect:

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

Optical lattices

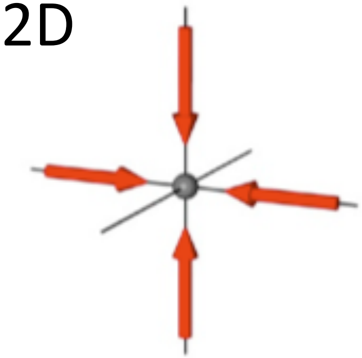
1D

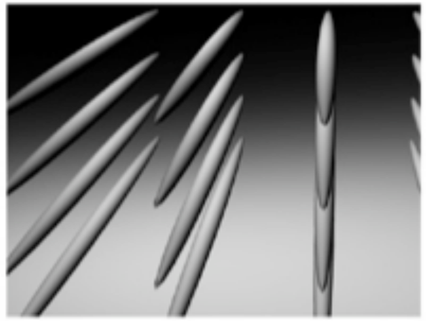
$E_0 e^{ikx}$ $E_0 e^{-ikx}$



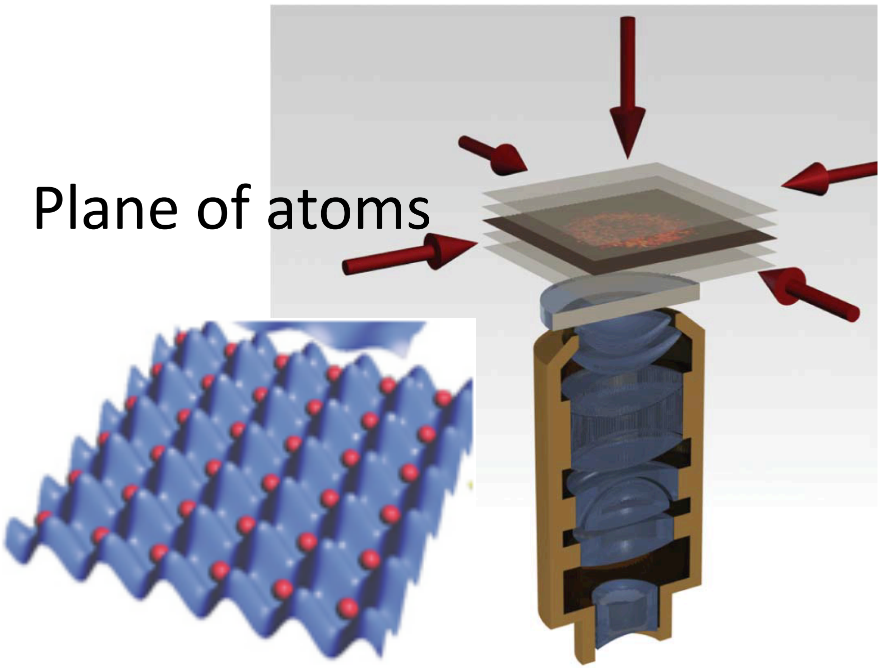
$$I(x) = 2E_0^2(1 + \cos 2kx)$$

2D

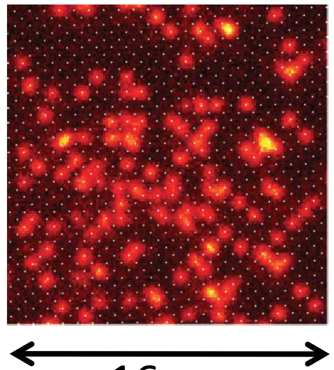




Single site resolution (< 1 μm)



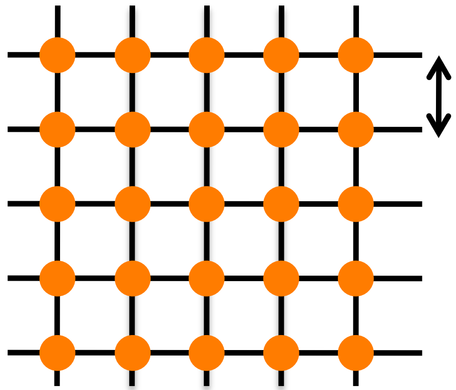
Fluorescence image of individual atoms



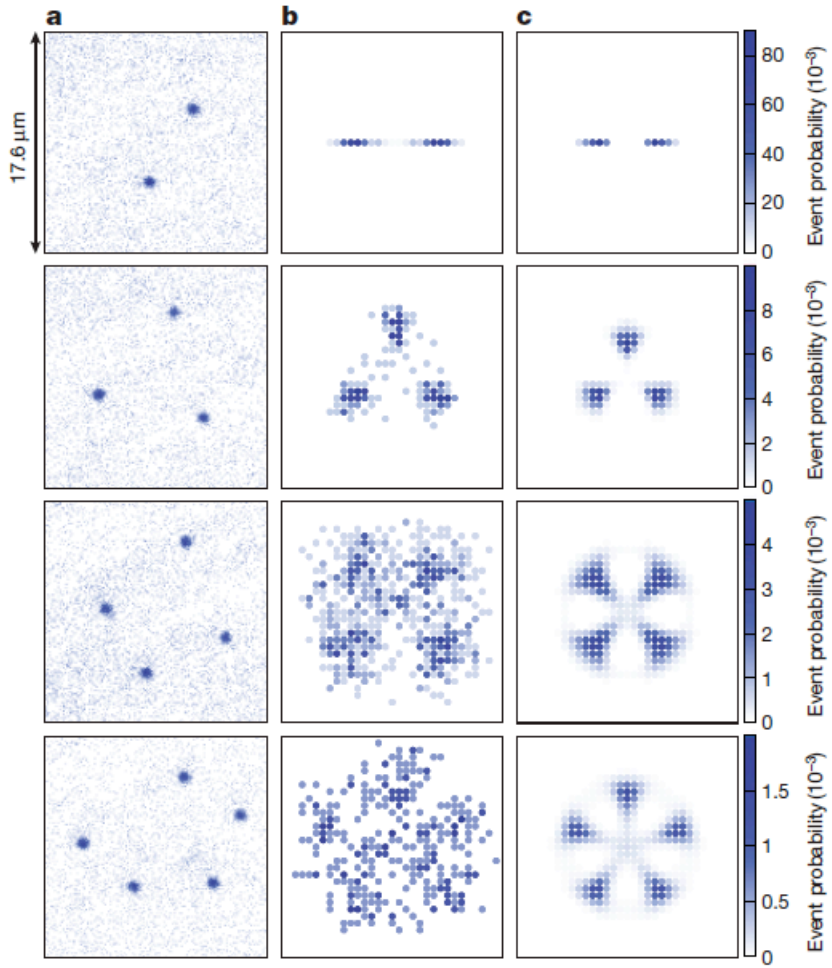
Bakr *et al.*, Nature **462**, 74 (2009)
Sherson *et al.*, Nature **467**, 68 (2010)

Spatial observation of the blockade (MPQ, Garching)

P. Schauss *et al.*, Nature **491**, 87 (2012)



Position resolved detection



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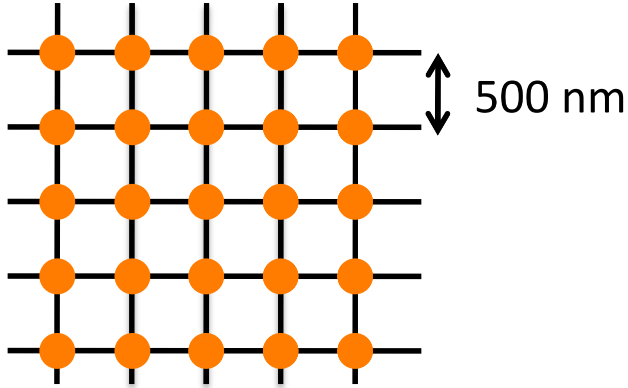

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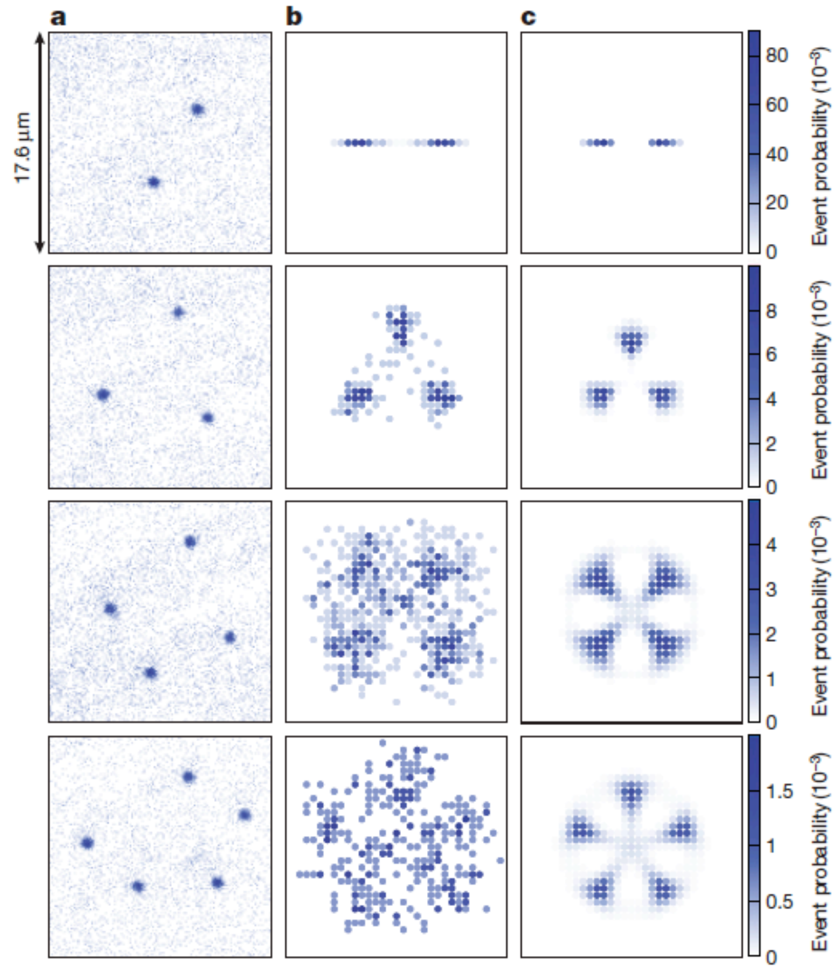
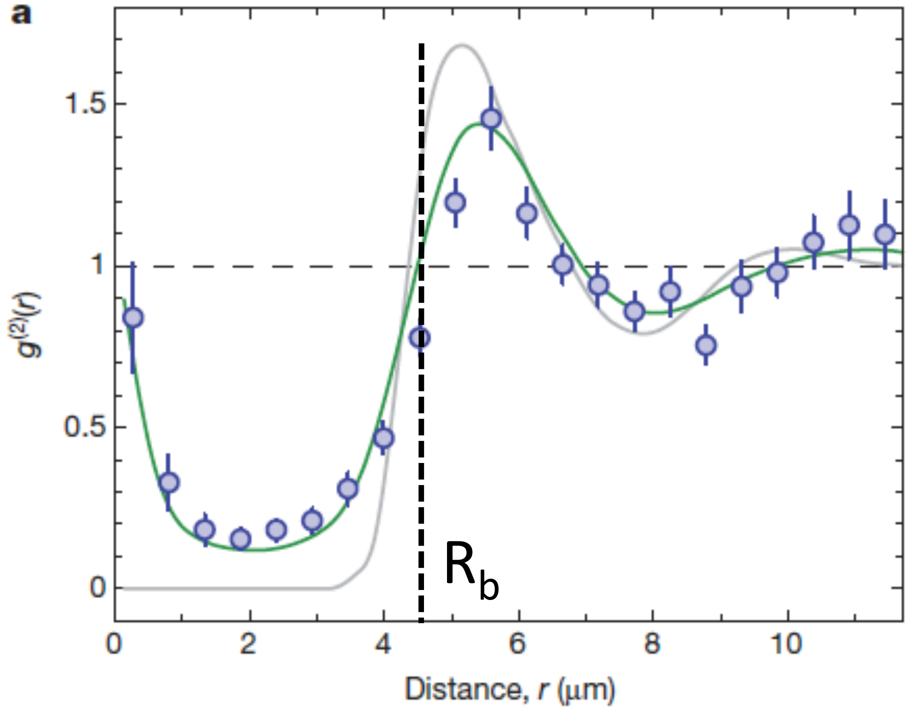


Correlation function



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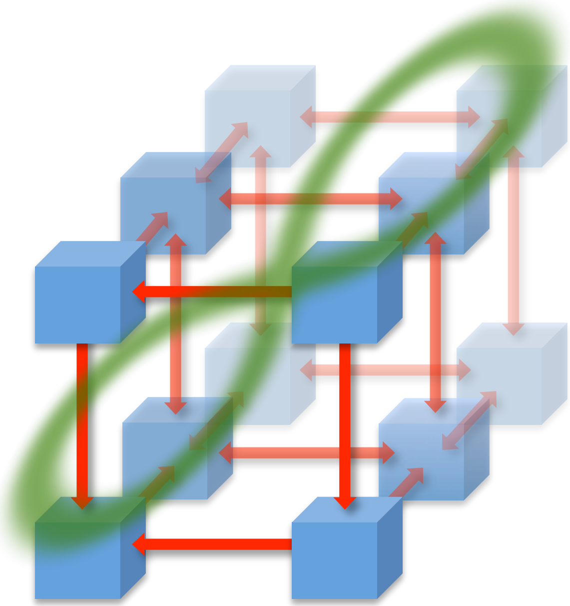
A dream for a “quantum internet”



J.H. Kimble (2005)

Interconnect Q. processor and Q. memory using photons

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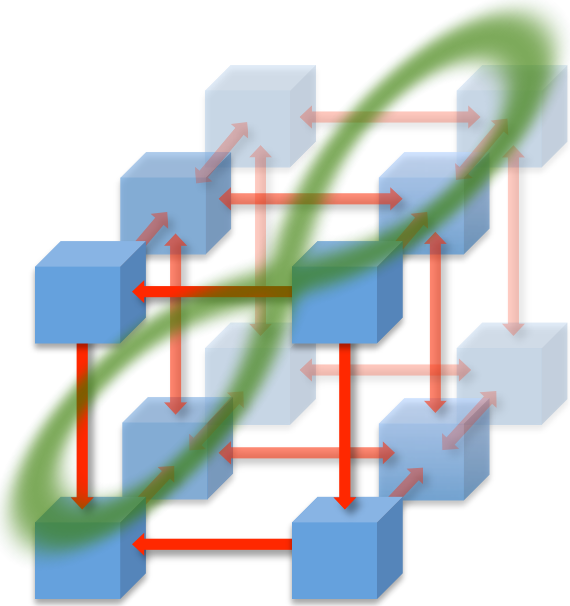
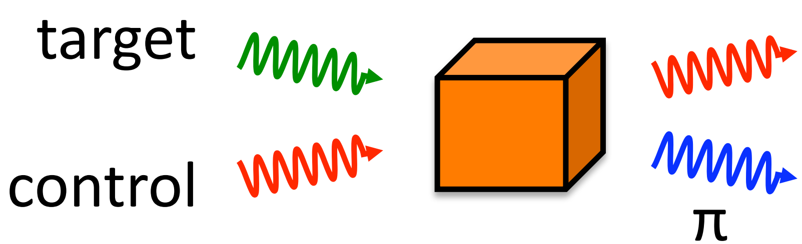


J.H. Kimble (2005)

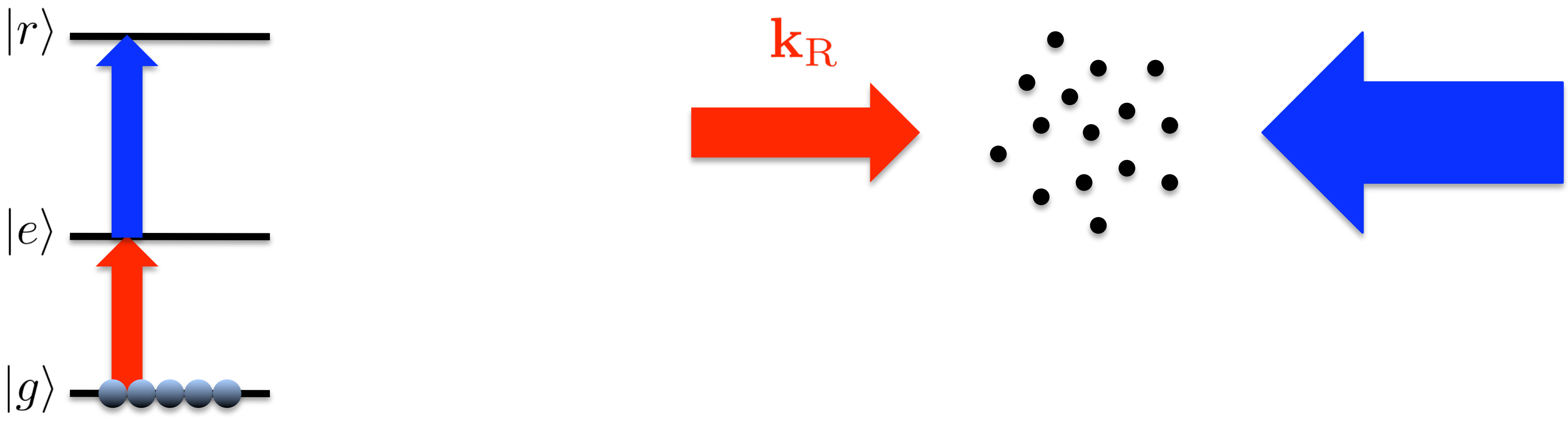
Interconnect Q. processor and Q. memory using photons

Requirements:
1. Single photon on demand
2. Photon storage
3. Photonic gate



Interaction between photons!

Single-photon source and photon storage



D. Maxwell, *et al.*, PRL **110**, 103001 (2013)

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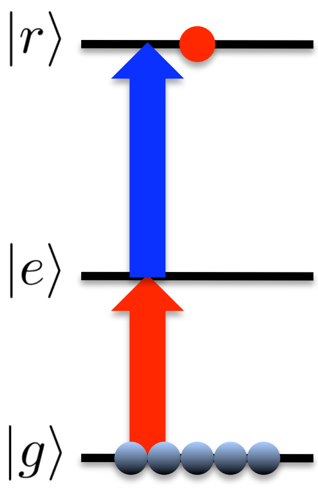

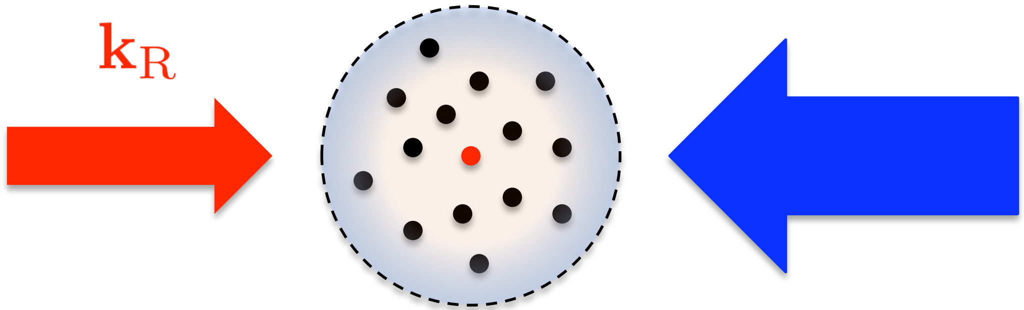

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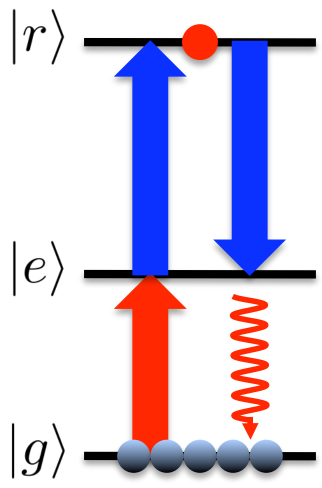

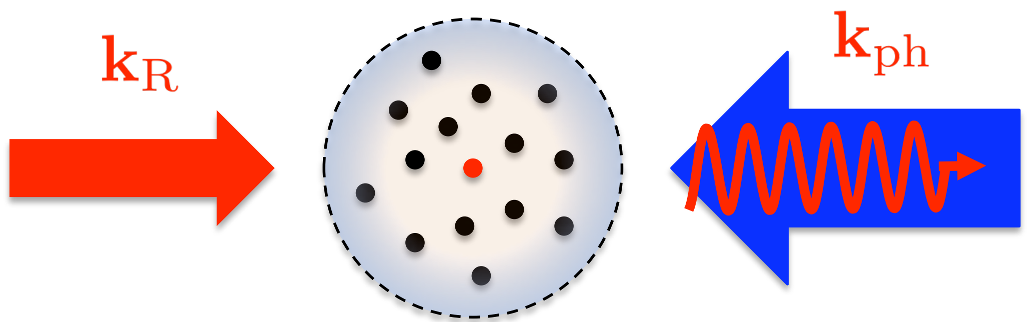

Momentum conservation: $\mathbf{k}_\mathrm{ph} = \mathbf{k}_\mathrm{R}$

D. Maxwell, *et al.*, PRL **110**, 103001 (2013)

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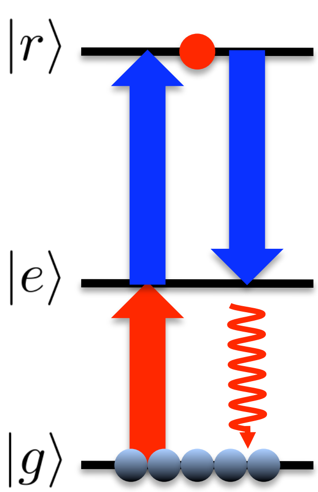

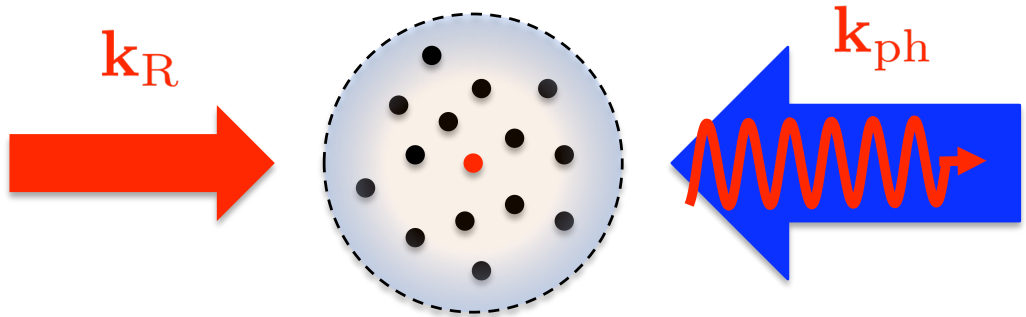

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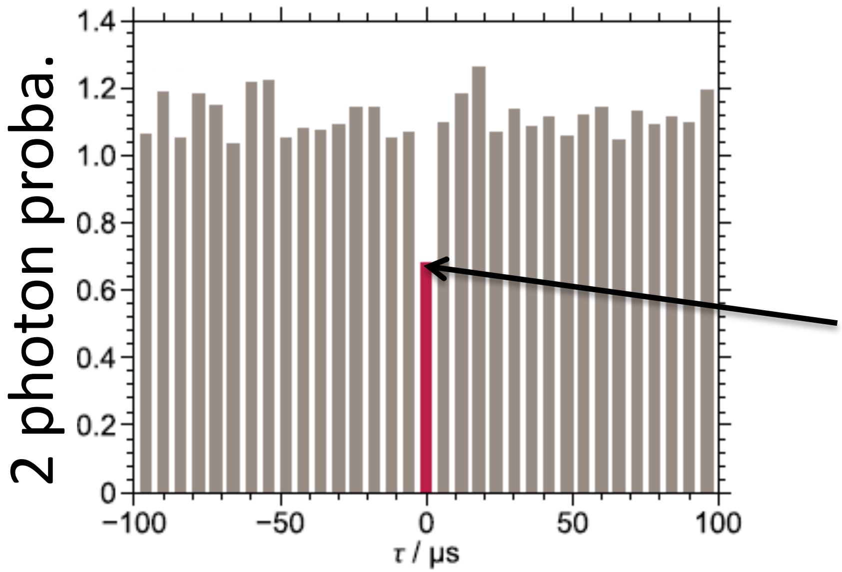
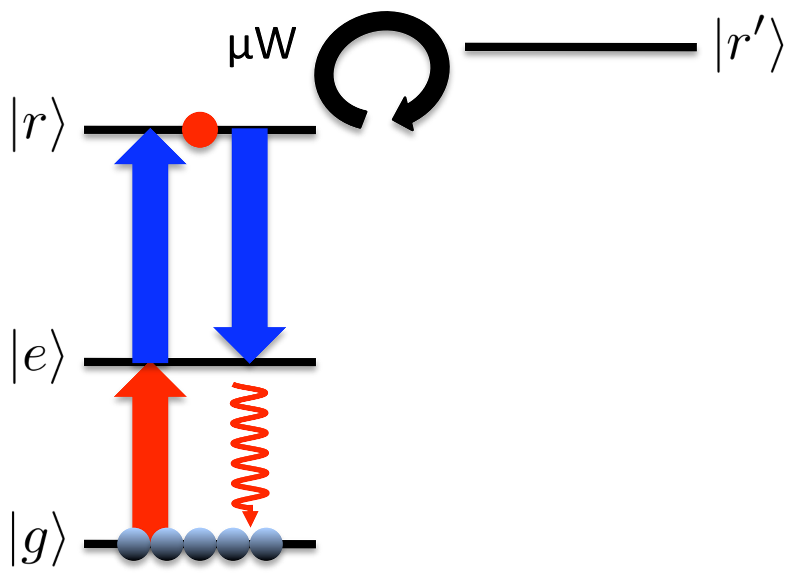
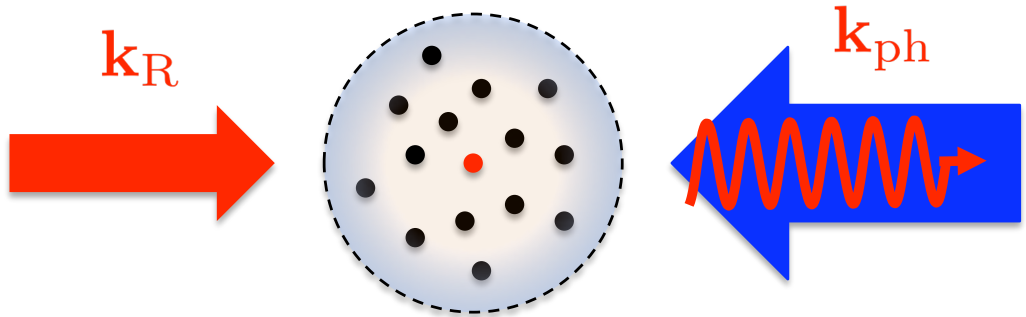


Suppression of 2 photon events

D. Maxwell, *et al.*, PRL **110**, 103001 (2013)

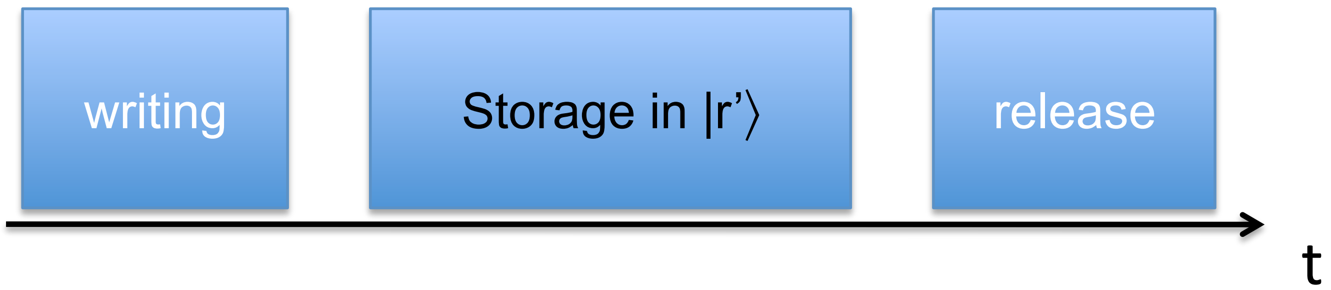
Single-photon source and photon storage





Momentum conservation: $\mathbf{k}_{\mathrm{ph}} = \mathbf{k}_{\mathrm{R}}$

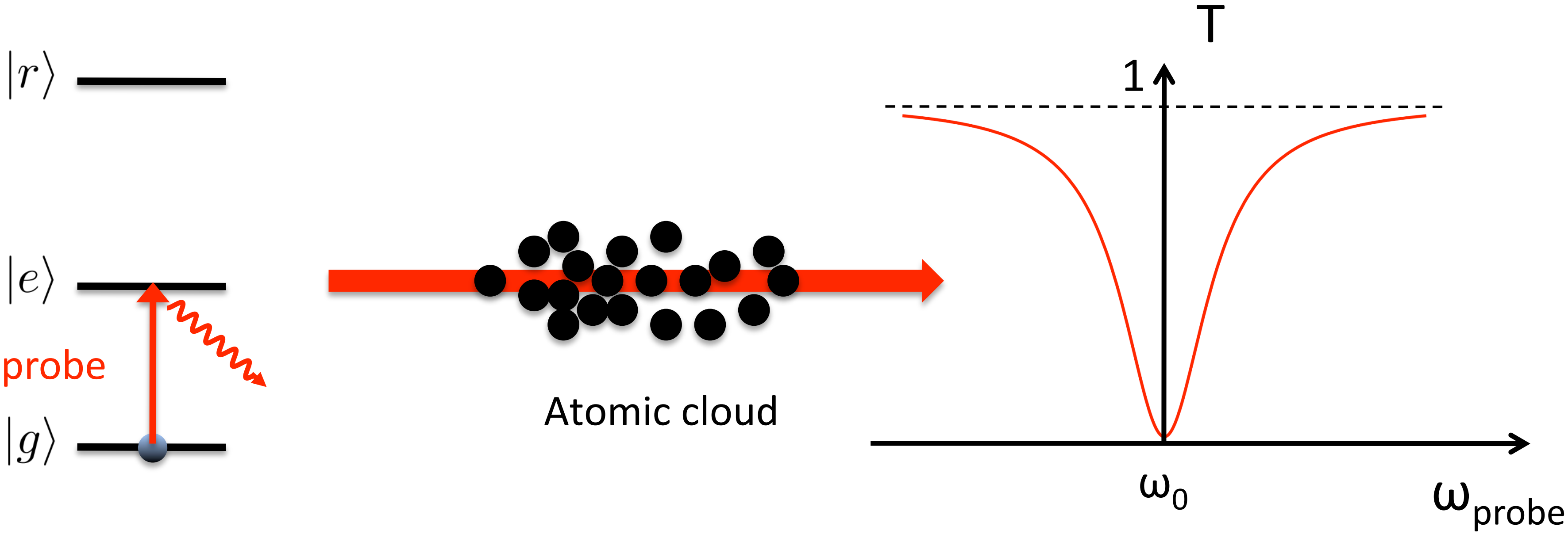
Photon storage using microwave



D. Maxwell, *et al.*, PRL **110**, 103001 (2013)

Non-linearity at the single-photon level

Electromagnetically Induced Transparency (EIT)



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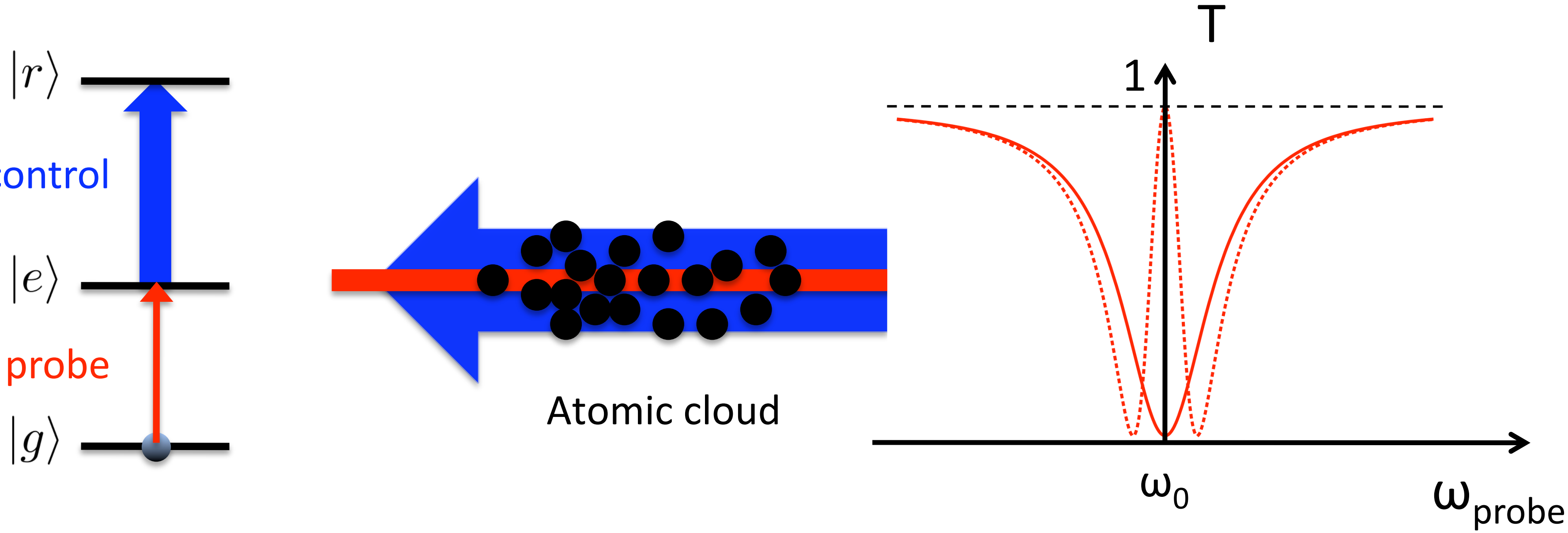

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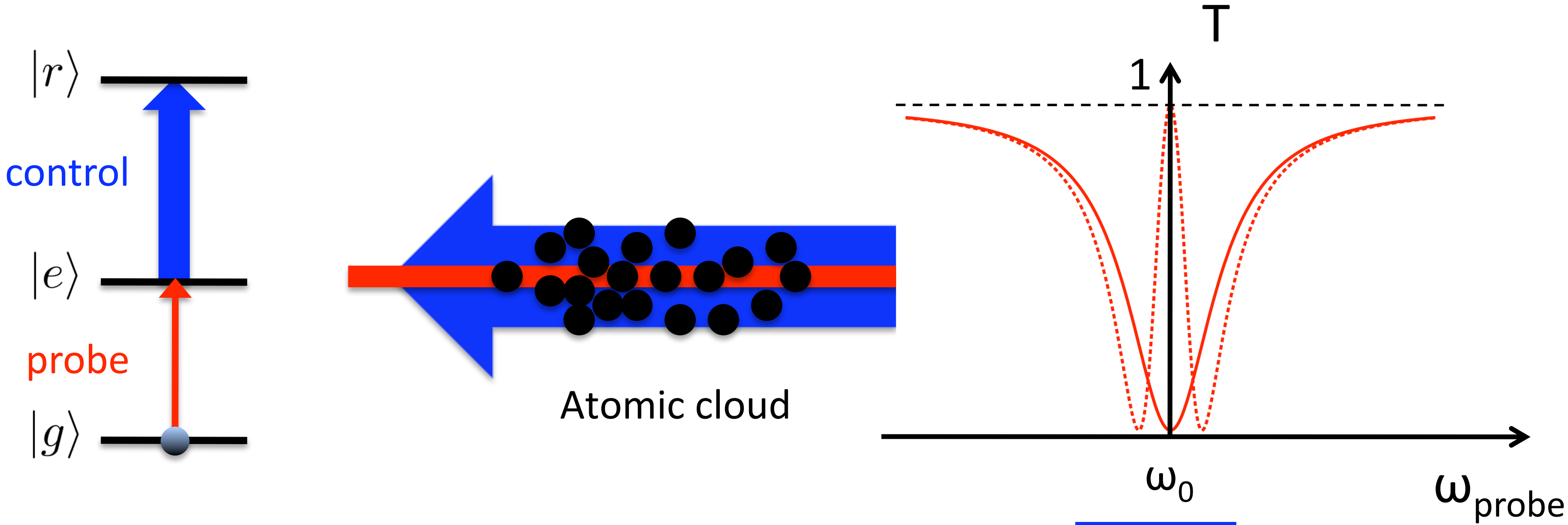
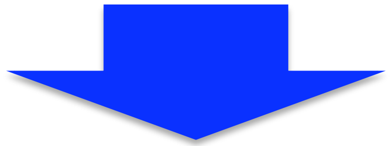
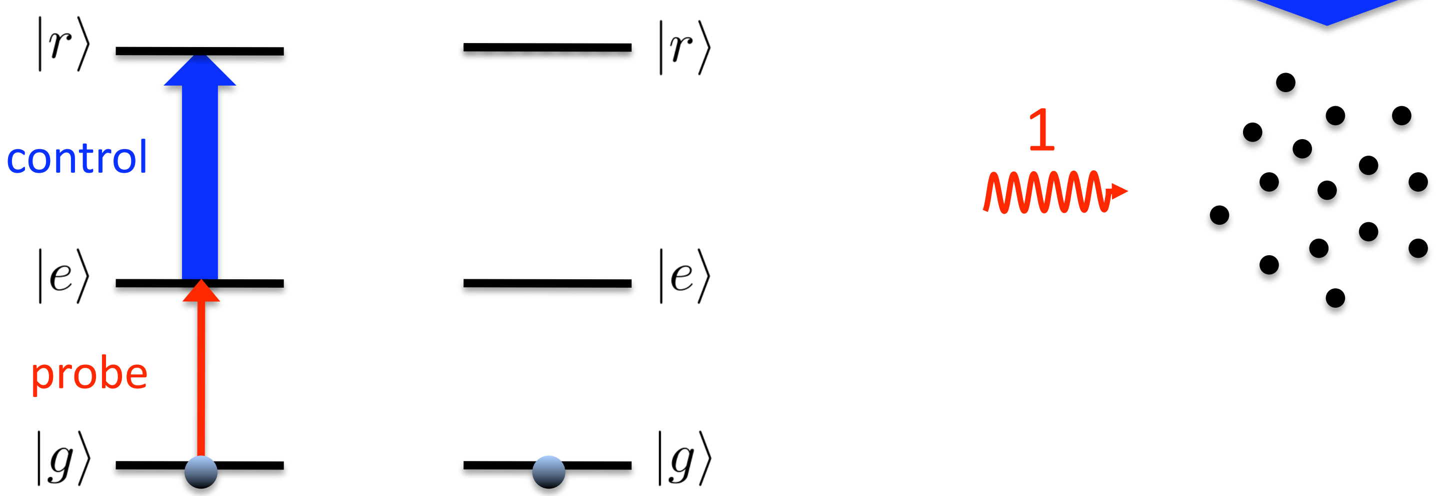




EIT + Rydberg blockade: T controlled by 1 ph.!



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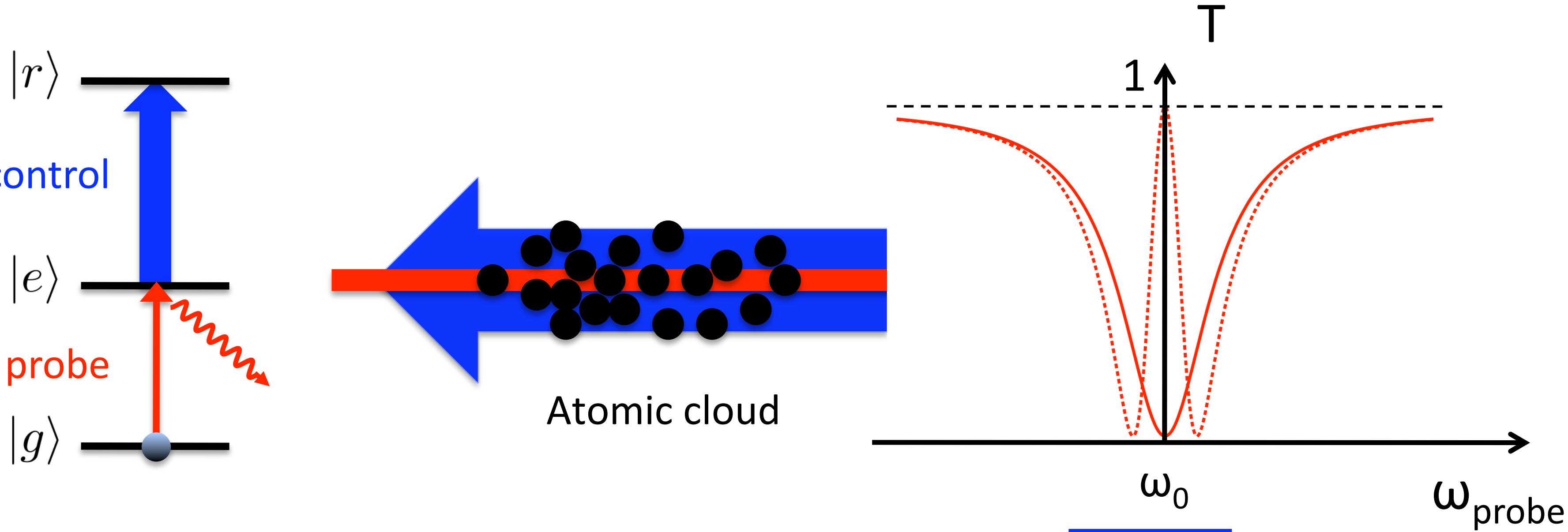

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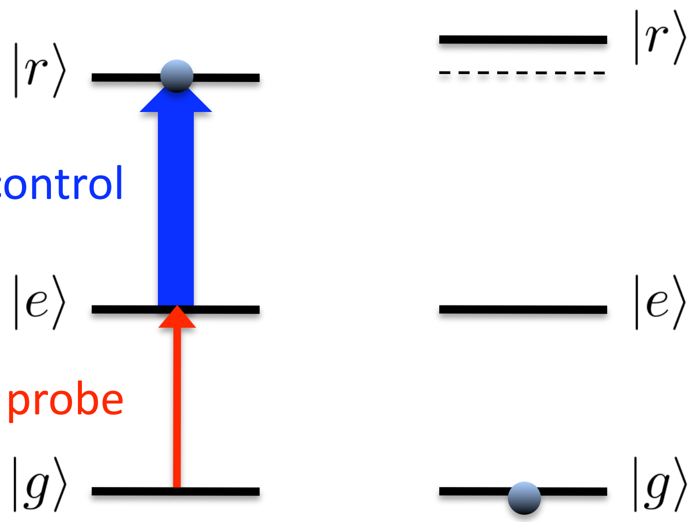

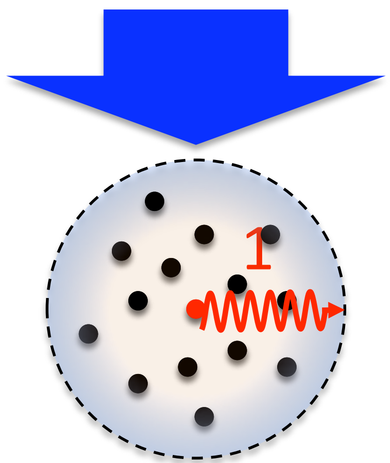

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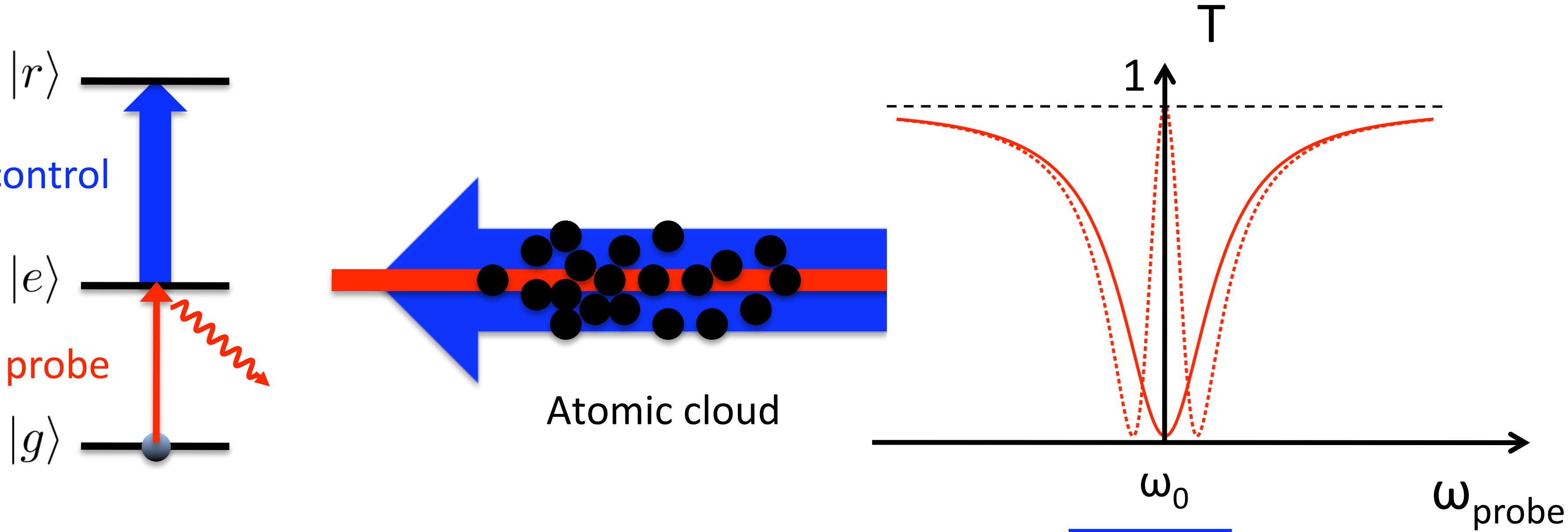

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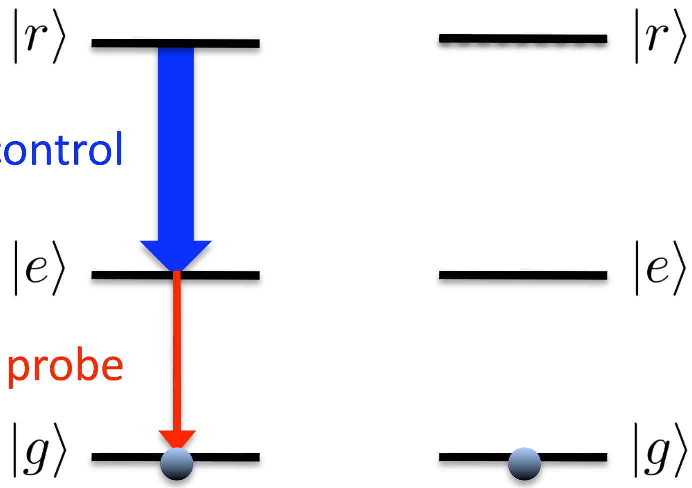

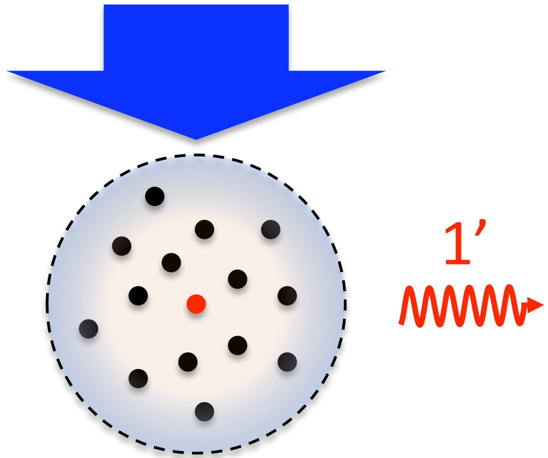

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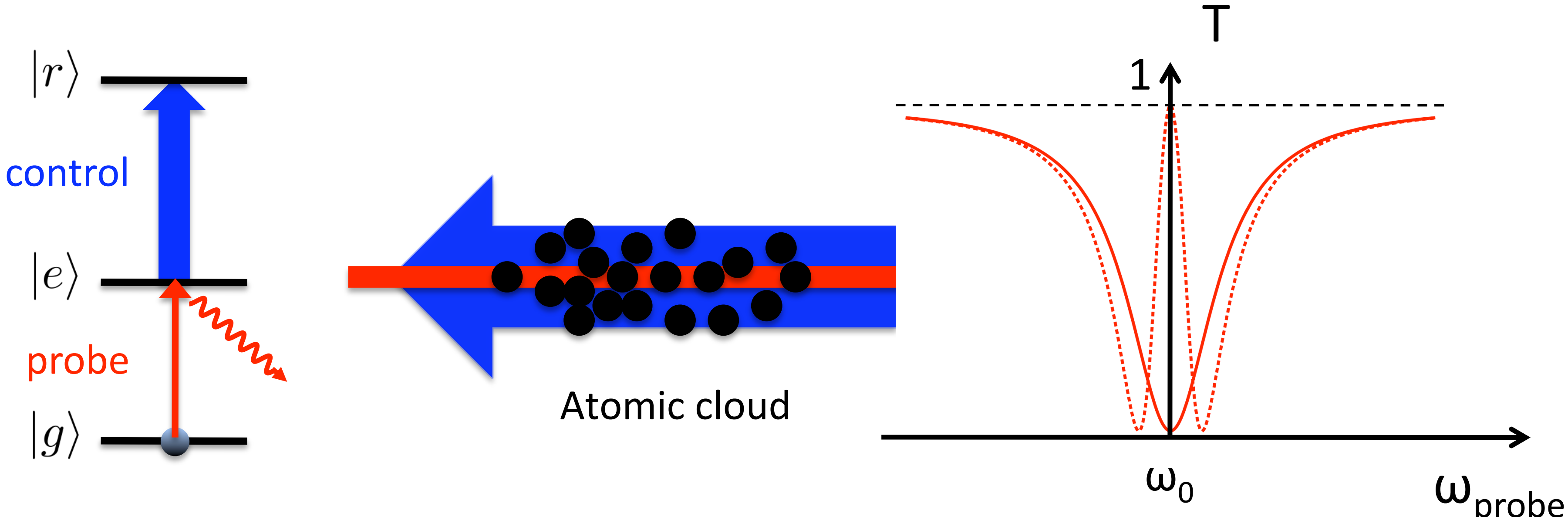
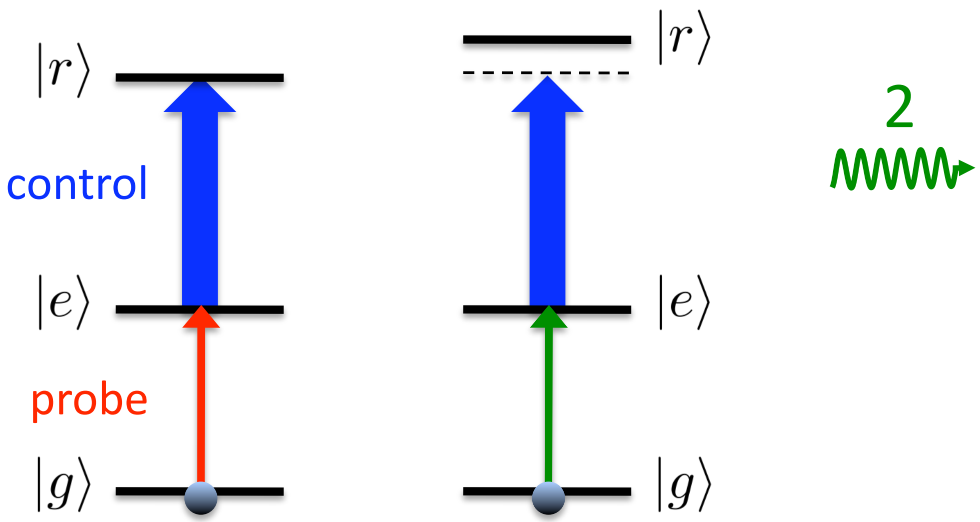
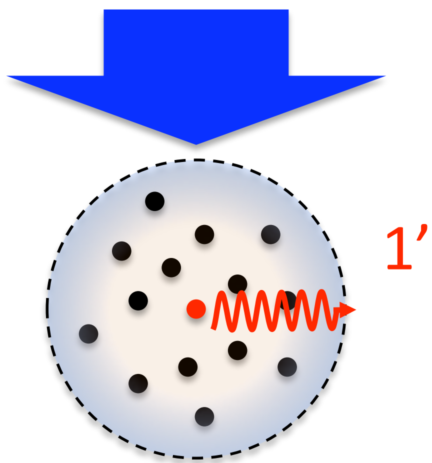


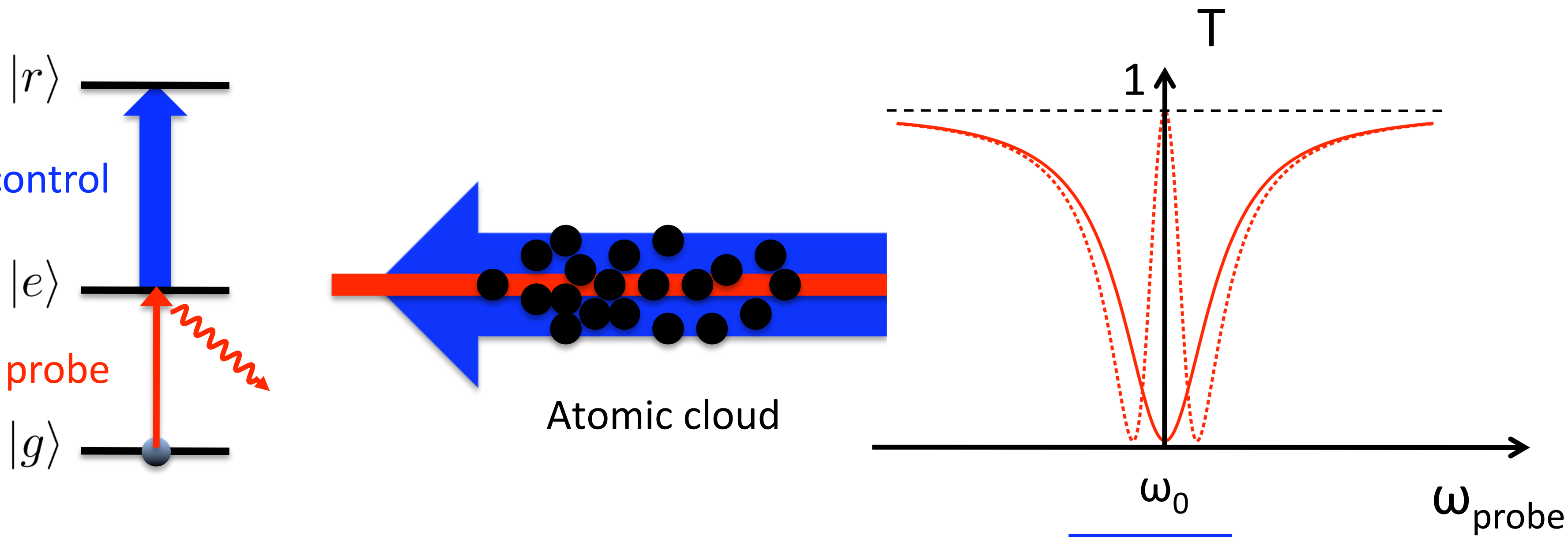
EIT + Rydberg blockade: T controlled by 1 ph.!





Non-linearity at the single-photon level

Electromagnetically Induced Transparency (EIT)



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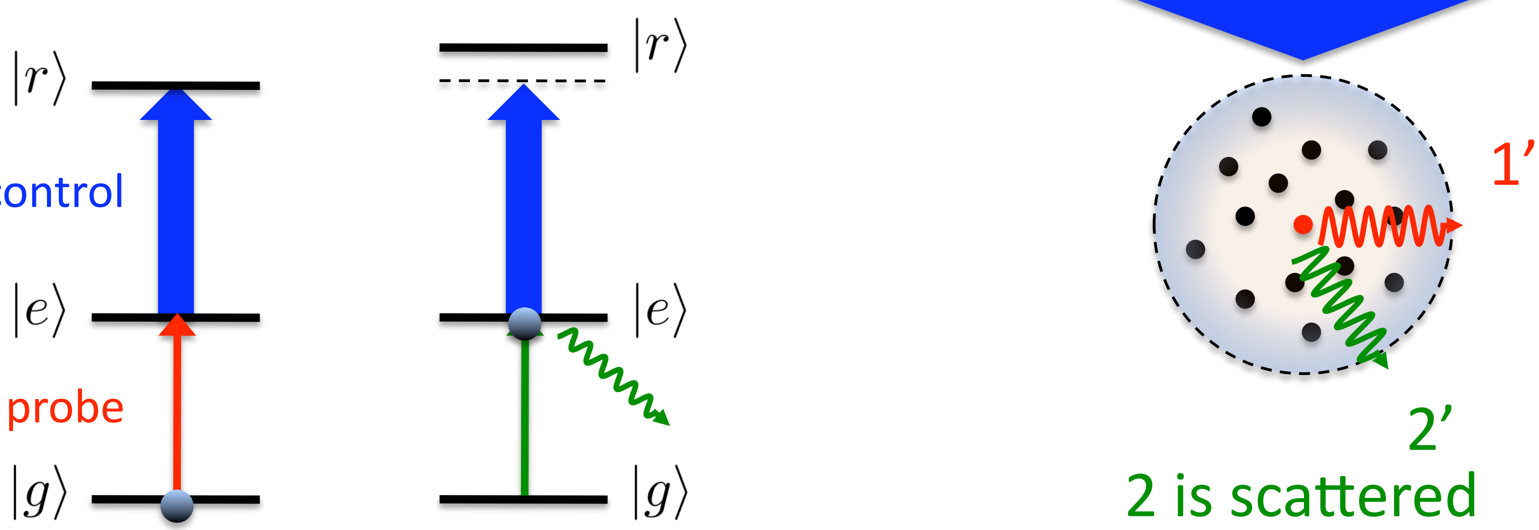
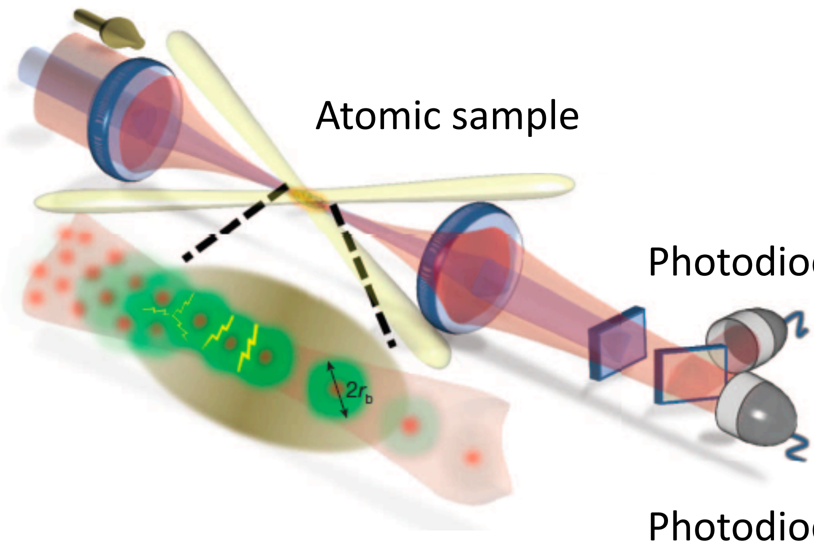
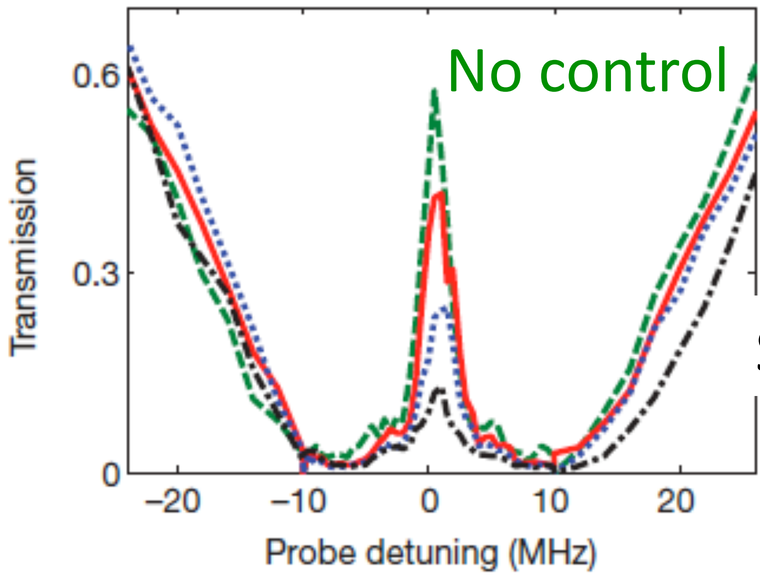


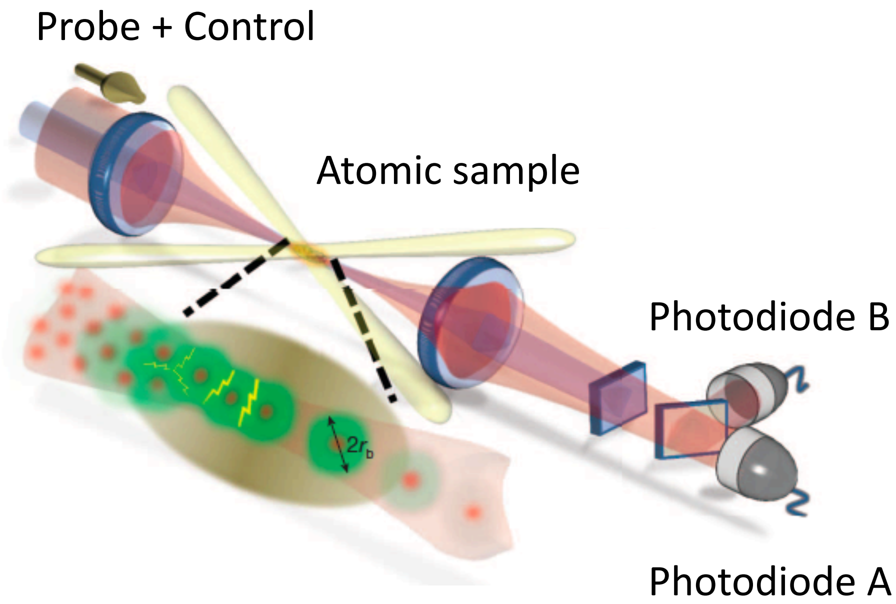
Non-linearity at the single-photon level

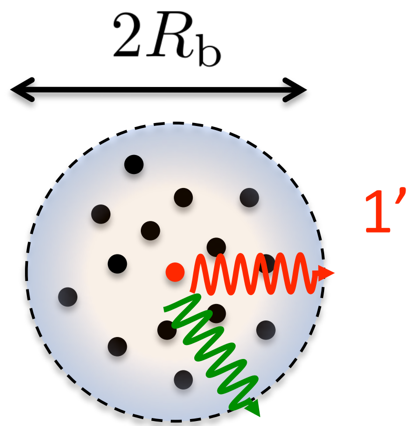
T. Peyronel *et al.*,
Nature **488**, 57 (2012).





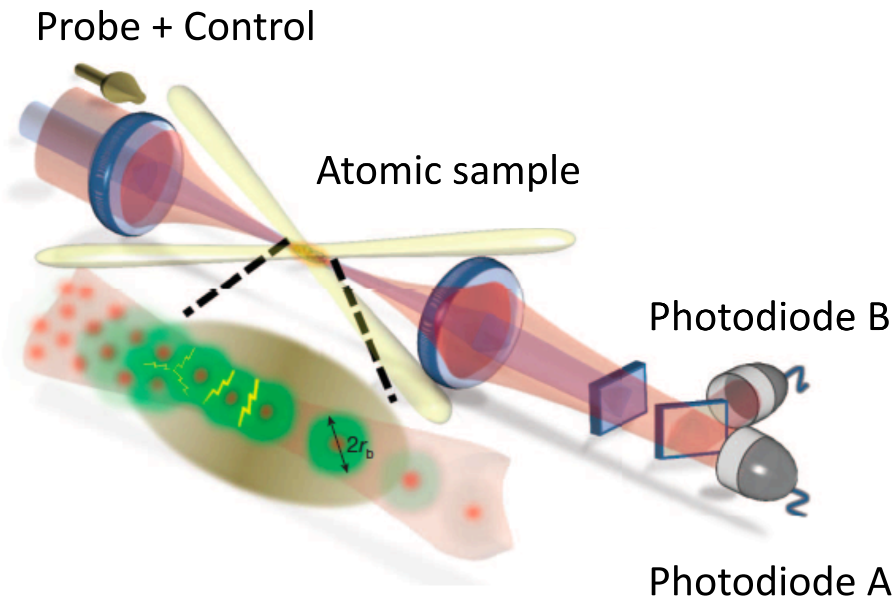
Non-linearity at the single-photon level

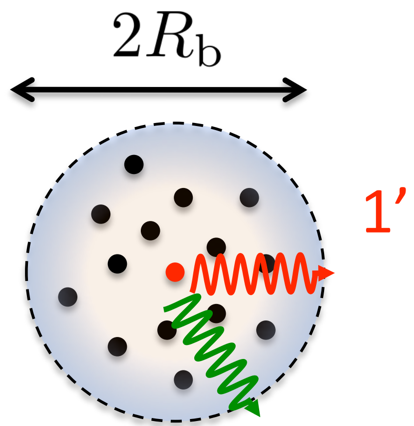




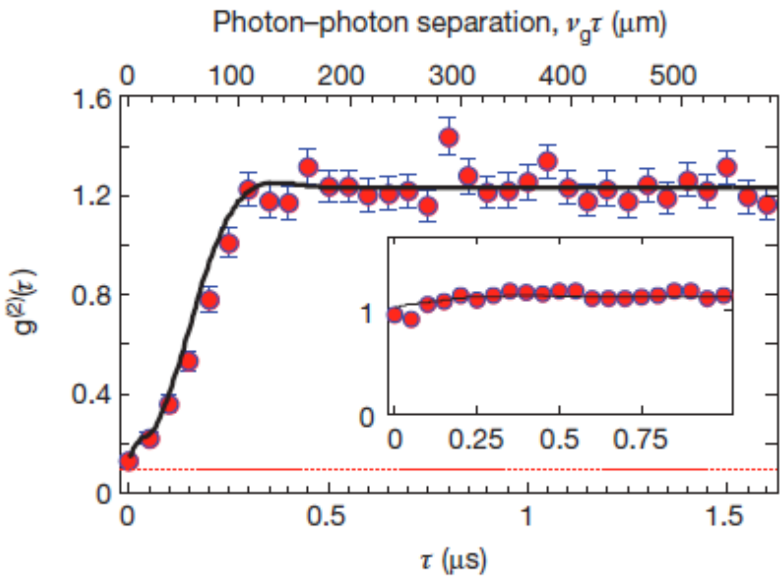
Prevents 2nd ph. during: $\tau_{\rm b} \sim \dfrac{R_{\rm b}}{v_{\rm g}}$

Non-linearity at the single-photon level

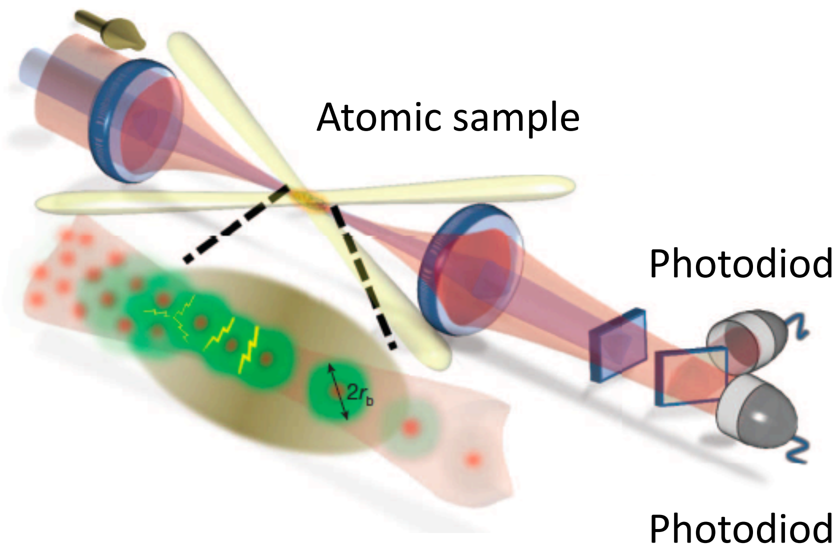


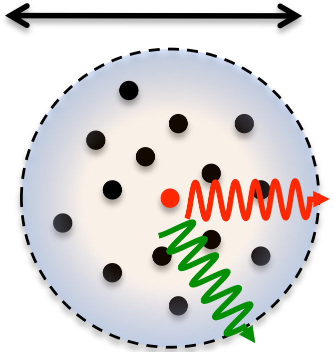


Prevents 2nd ph. during: $\tau_b \sim \dfrac{R_b}{v_g}$



Non-linearity at the single-photon level





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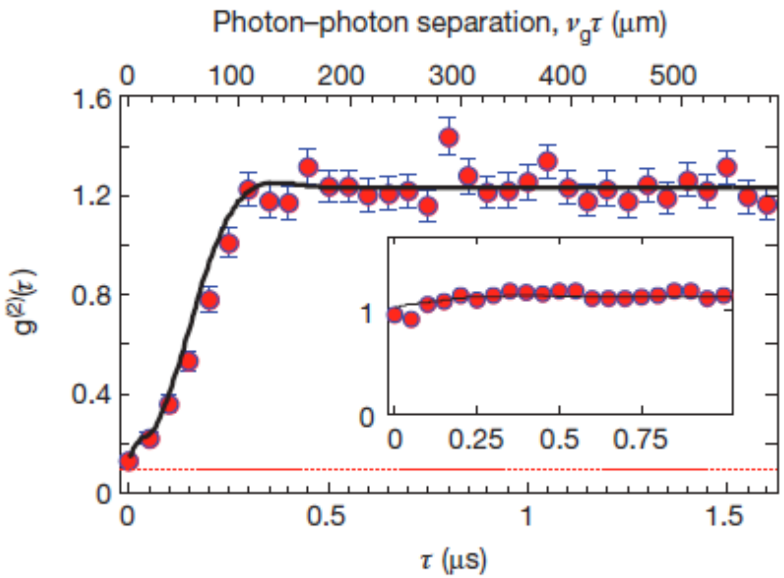
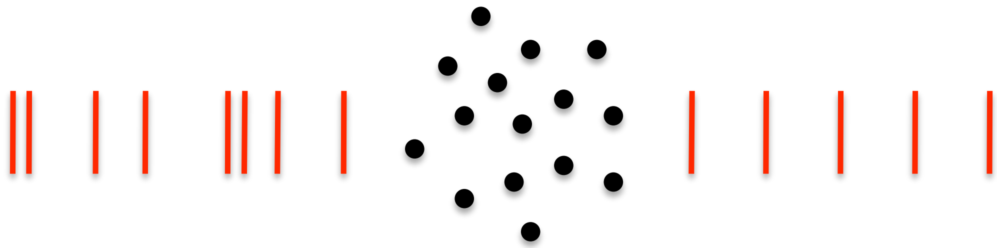


Photon ordering!



Mechanism for photonic gate

Conclusion on interacting Rydberg gases

Playground for semi-classical arguments (Bohr model)

Basic demonstrations OK

Conclusion on interacting Rydberg gases

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Quantum information

Improve fidelity

Simulation of condensed matter Systems

Spin systems, new phases with tailored interactions…

Conclusion on interacting Rydberg gases

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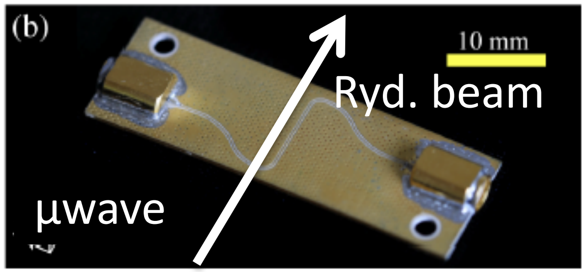
Simulation of condensed matter Systems

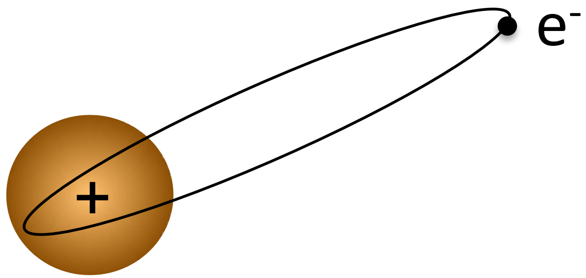
Spin systems, new phases with tailored interactions…

Back to "old" ideas: couple to solid state systems (surface, cavity)

Large α to probe surface field, electrometry



Hogan, PRL **108** 063004 (2012)



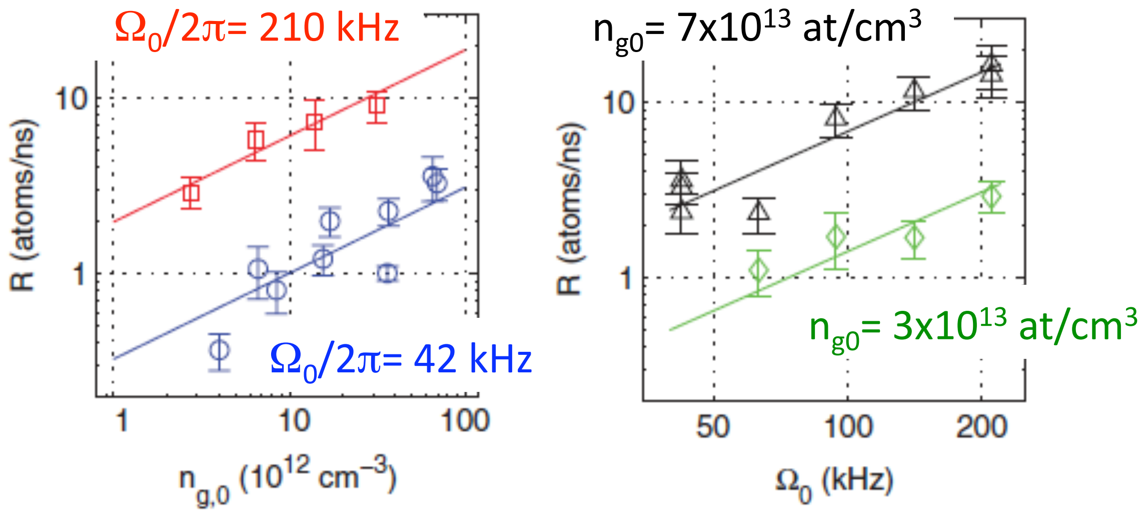
THANK YOU!

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:



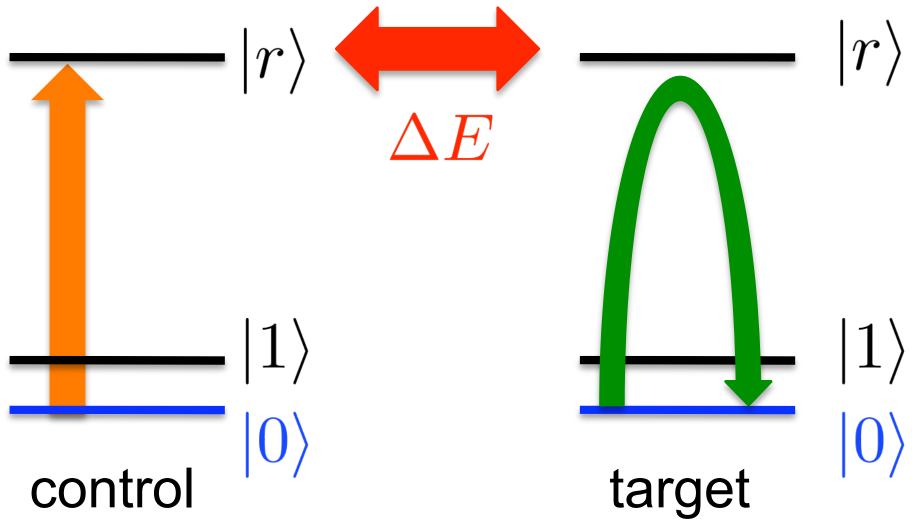
$$R \propto n_{g0}^{0.49} \Omega^{1.1}$$

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

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

Demonstration of a C-NOT gate: U. Wisconsin

Use the conditionnal logic of blockade



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

Sequence:

$\pi_A - 2\pi_B - \pi_A$

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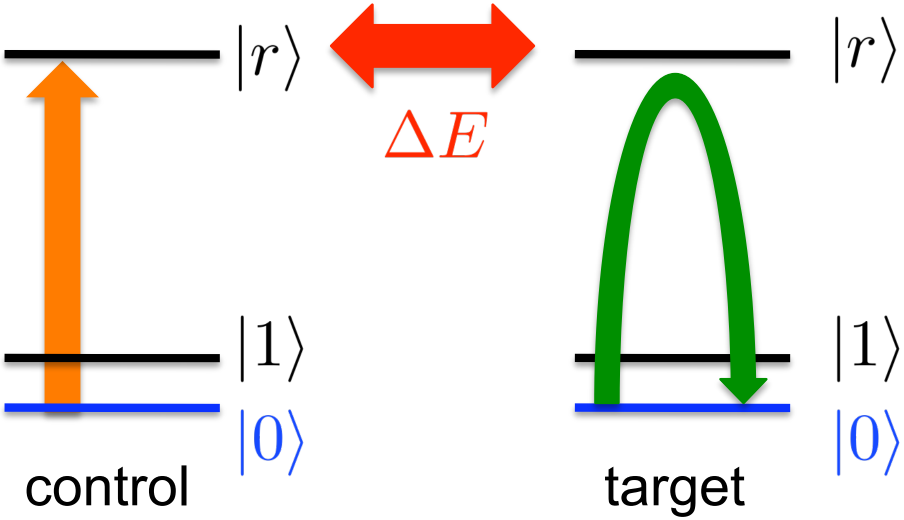


D. Jacksch *et al.*, PRL **85**, 2208 (2000)

Sequence:

$\pi_A - 2\pi_B - \pi_A$

Table of truth:

$11 \rightarrow 10$

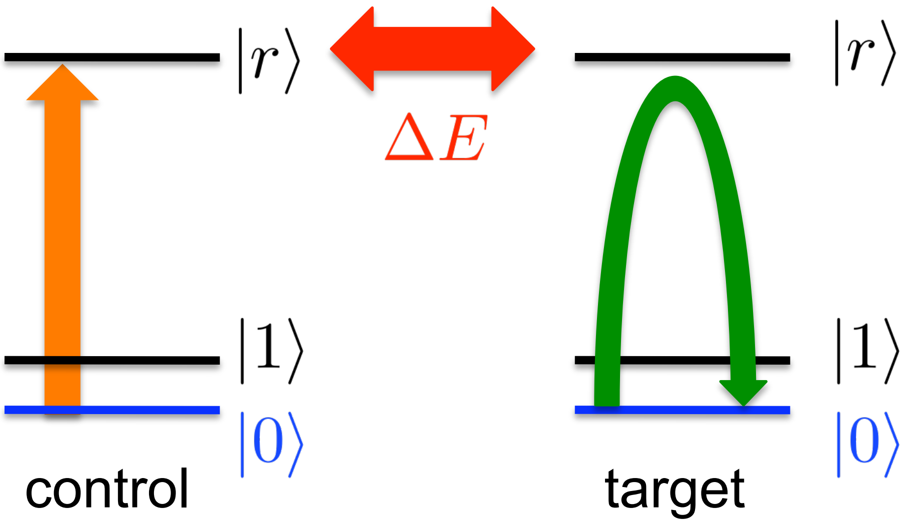
$10 \rightarrow 11$

$01 \rightarrow 01$

$00 \rightarrow 00$

Demonstration of a C-NOT gate: U. Wisconsin

Use the conditionnal logic of blockade



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

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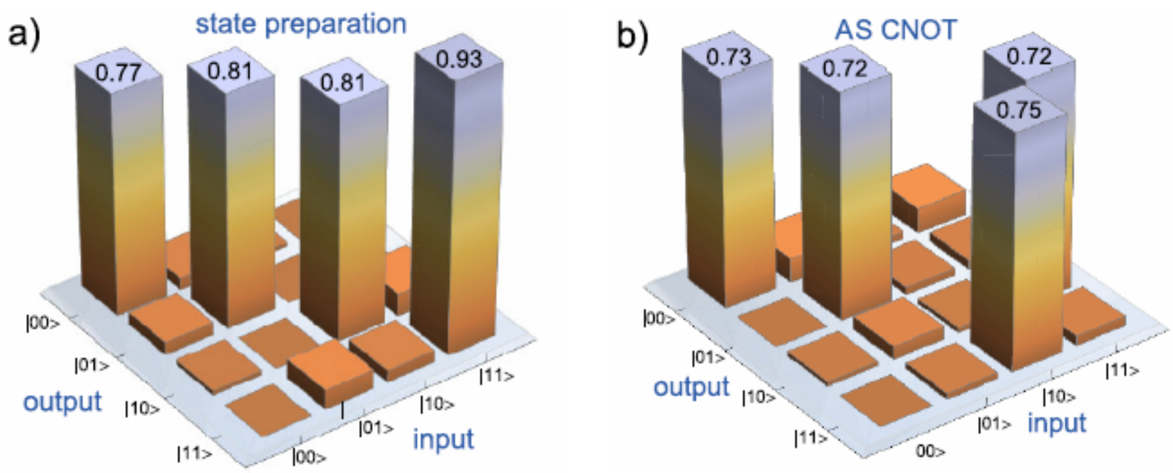
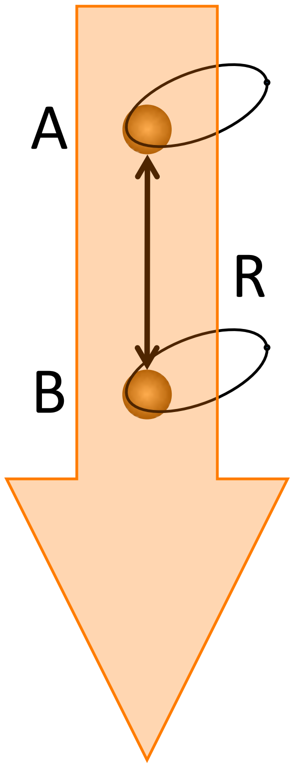
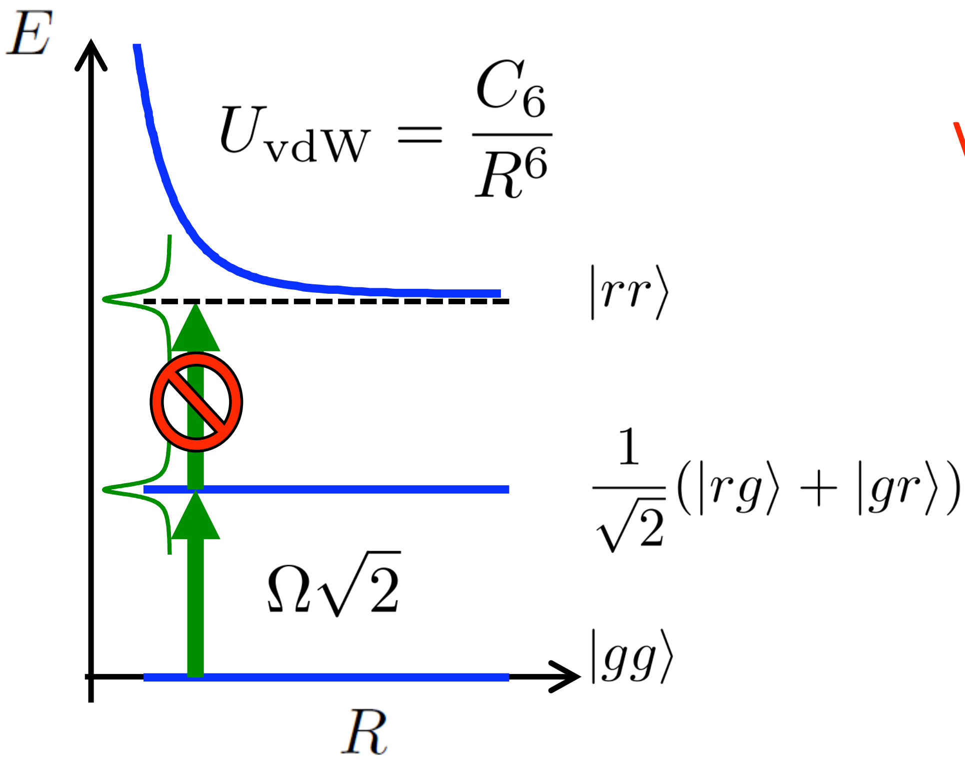


Isenhower *et al.*, PRL **104**, 010503 (2010)

From full blockade to partial blockade…

Non-addressable excitation





Van der Waals regime

Blockade regime: $P_{rr} = 0$ and P_r oscillates √2 faster