Quantum information processing with individual neutral atoms in optical tweezers

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Outline

Yesterday's lectures :

1. Trapping and exciting single atoms in optical tweezers

2. Driving, manipulating and moving individual atomic qubits

Today's lecture :

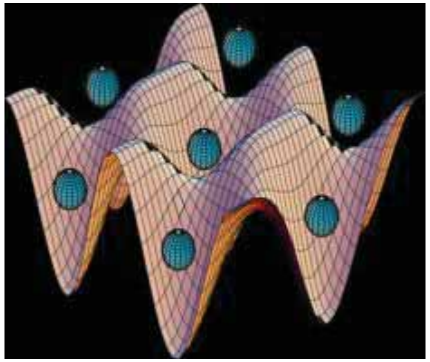
3. Entanglement and two-qubit gates

   - Rydberg blockade as a way to entangle two atoms
   - Observation of Rydberg blockade between two atoms
   - Observation of the collective oscillation of two atoms
   - Entanglement of two atoms in the ground state

A possible architecture for a neutral atom-based QC

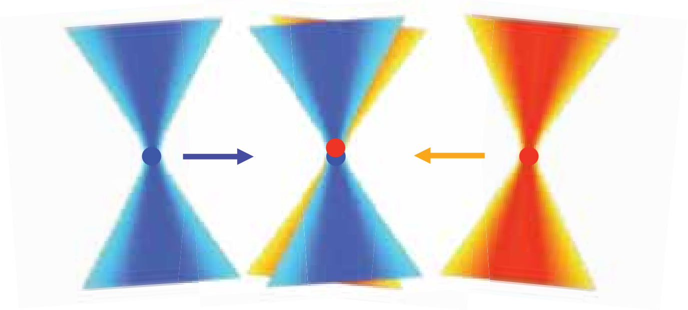
(DTO / IARPA coll. with Bill Phillips, Trey Porto, Ivan Deutsch, Poul Jessen...)

Storage



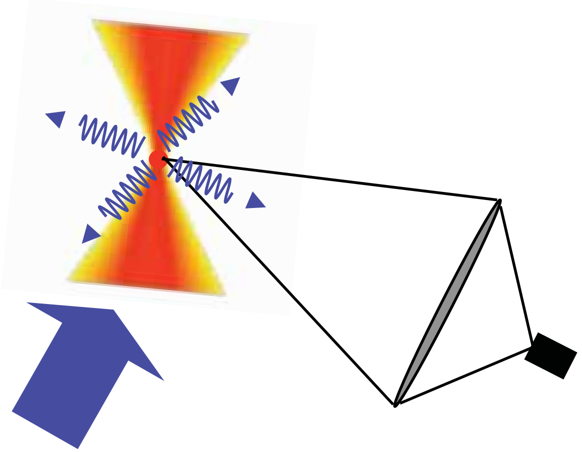
Lattices
Array of dipole traps
(hologram, micro-lenses)

2-qubit gates

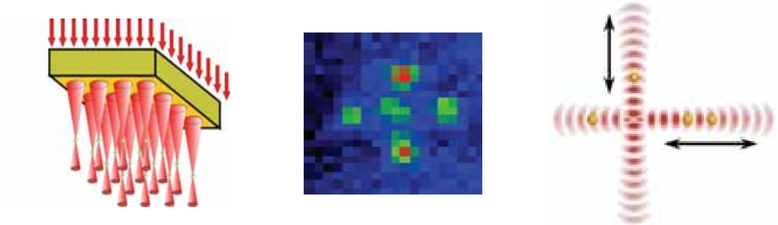


Tweezer / lattices

Quantum measurement



(optical cavity)

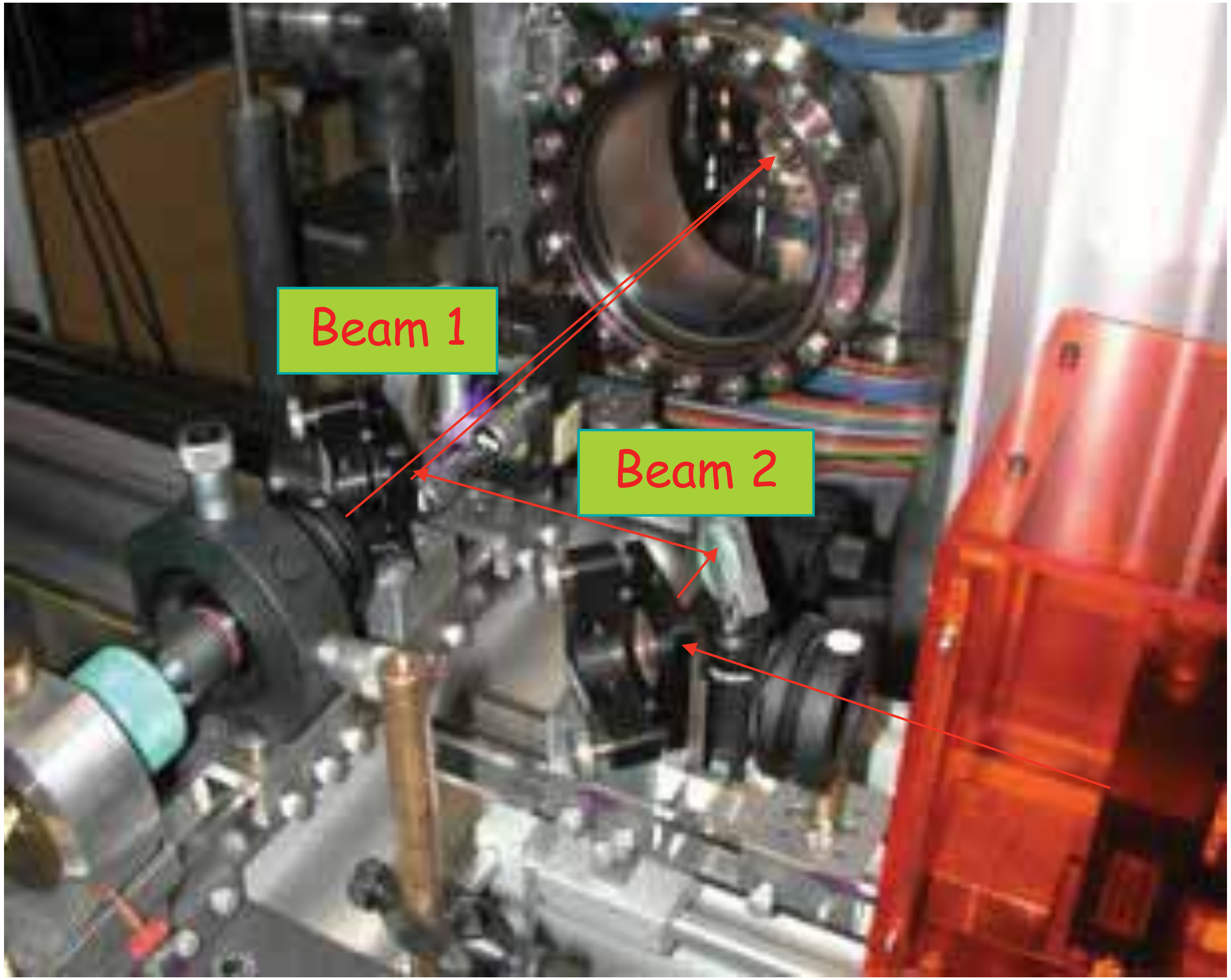


Natural link = moving optical tweezer

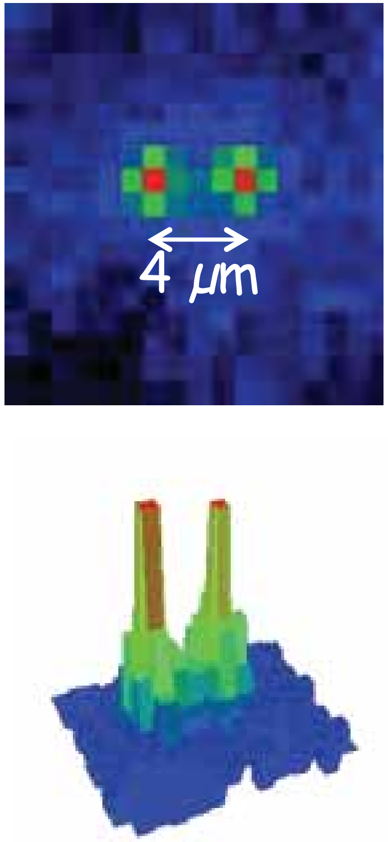
Requires « long » coherence time of a qubit in a moving tweezer, and a good way to perform two-qubit gate

Two atoms at your fingertips

N. Schlosser et al, Nature 411, 1024 (2001)
PRL 89, 023005 (2002)



Resolution of the imaging system:
1 micron / pixel



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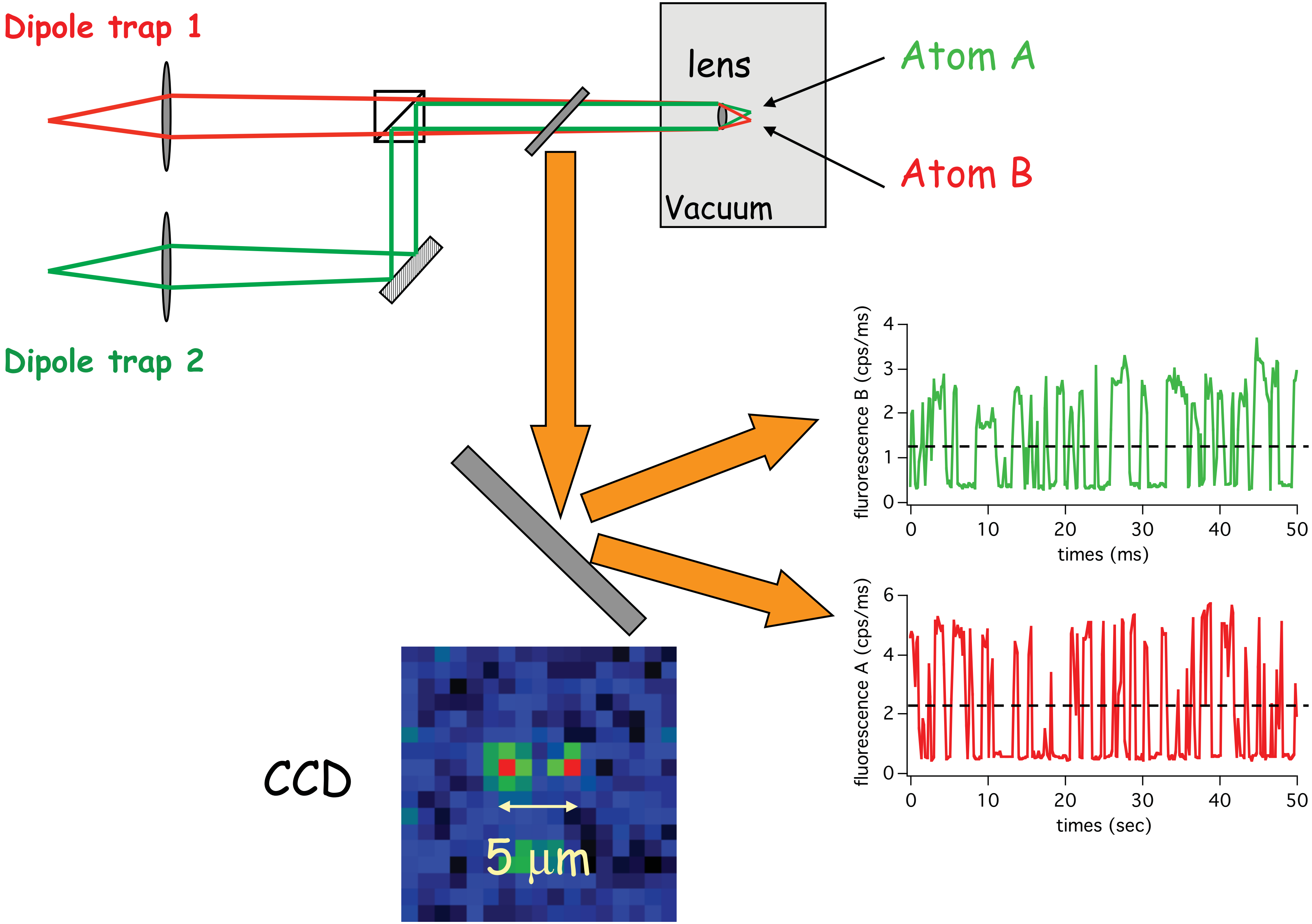
Detecting and "heralding" two single trapped atoms



Dipole trap 1

Dipole trap 2

lens

Vacuum

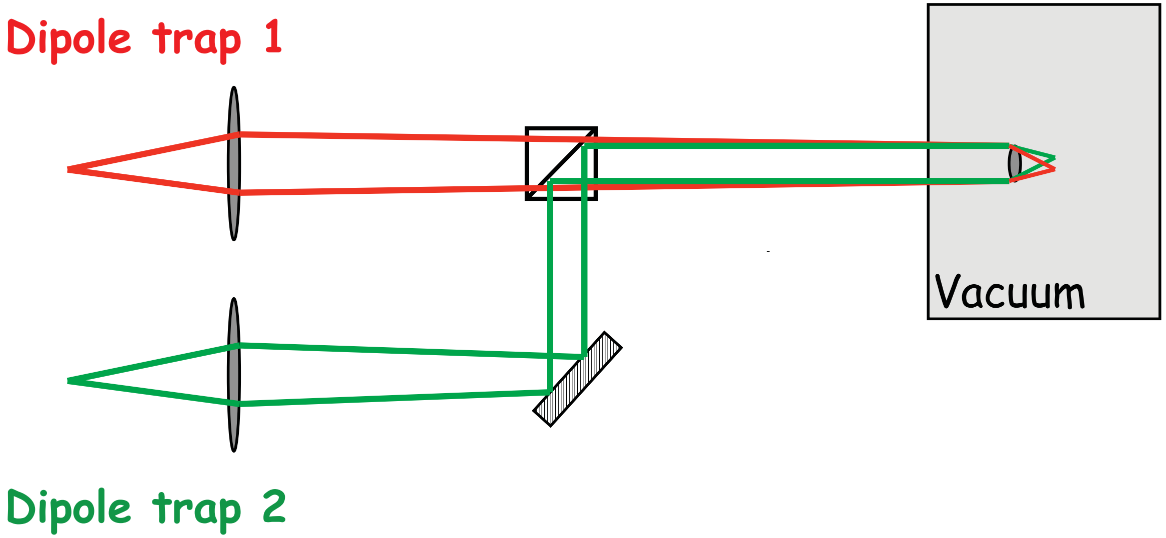
Atom A

Atom B

CCD

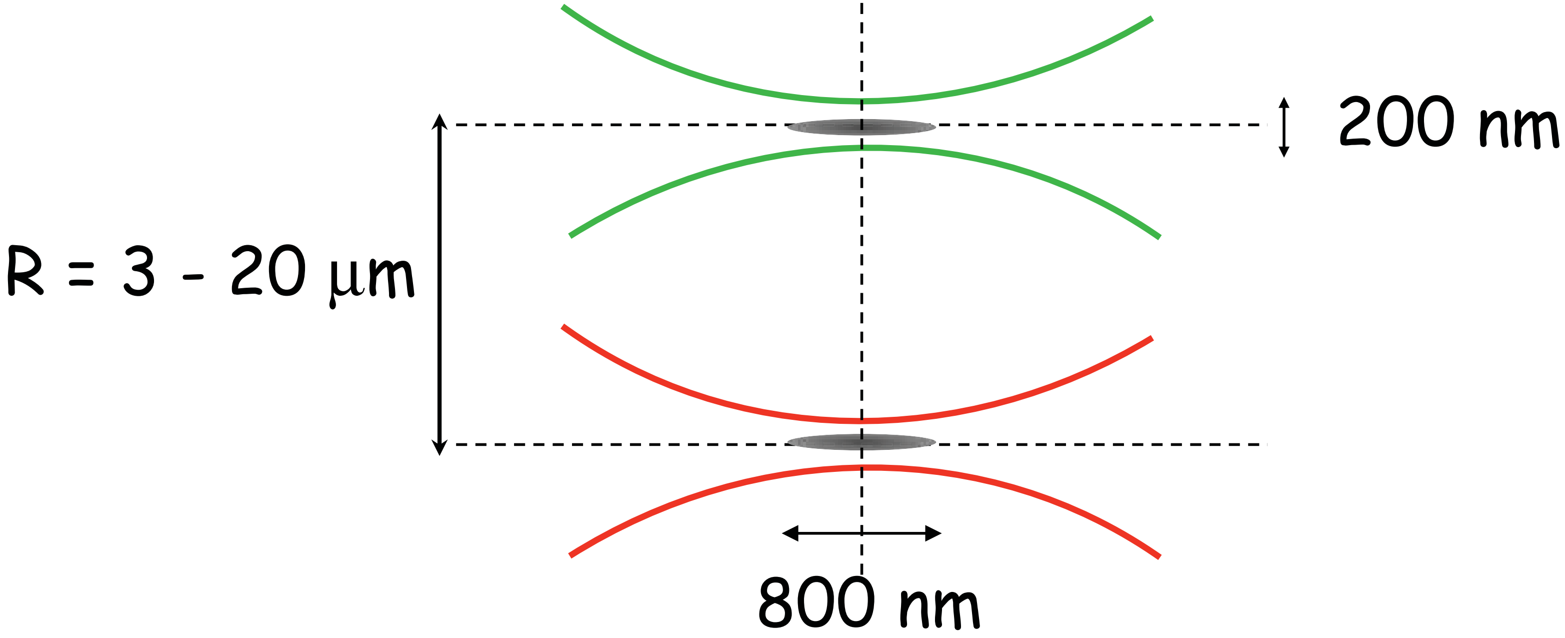
5 µm

Distance and size of the "single atom clouds"

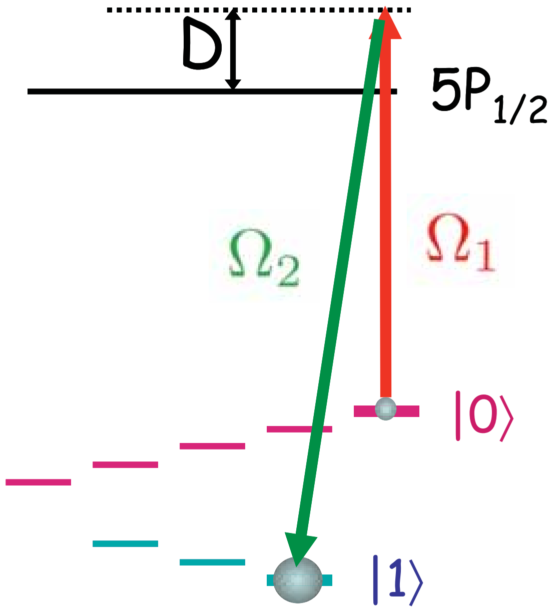


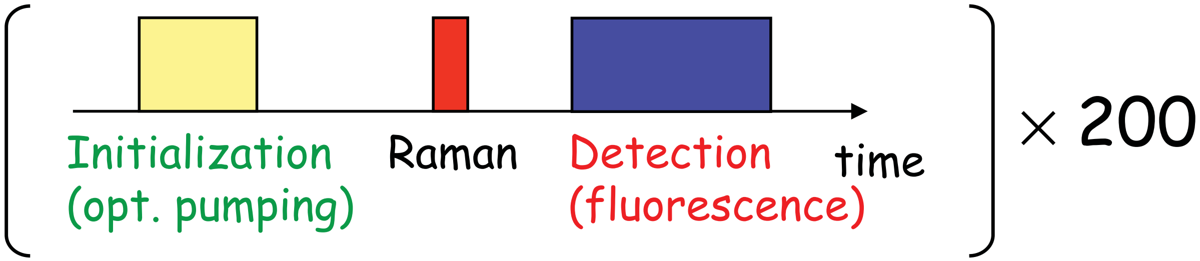
Depth = 0.5 mK
T = 70 µK

f_r = 80 kHz
f_z = 16 kHz



Coherent driving of the qubit





Initialization (opt. pumping)

Raman

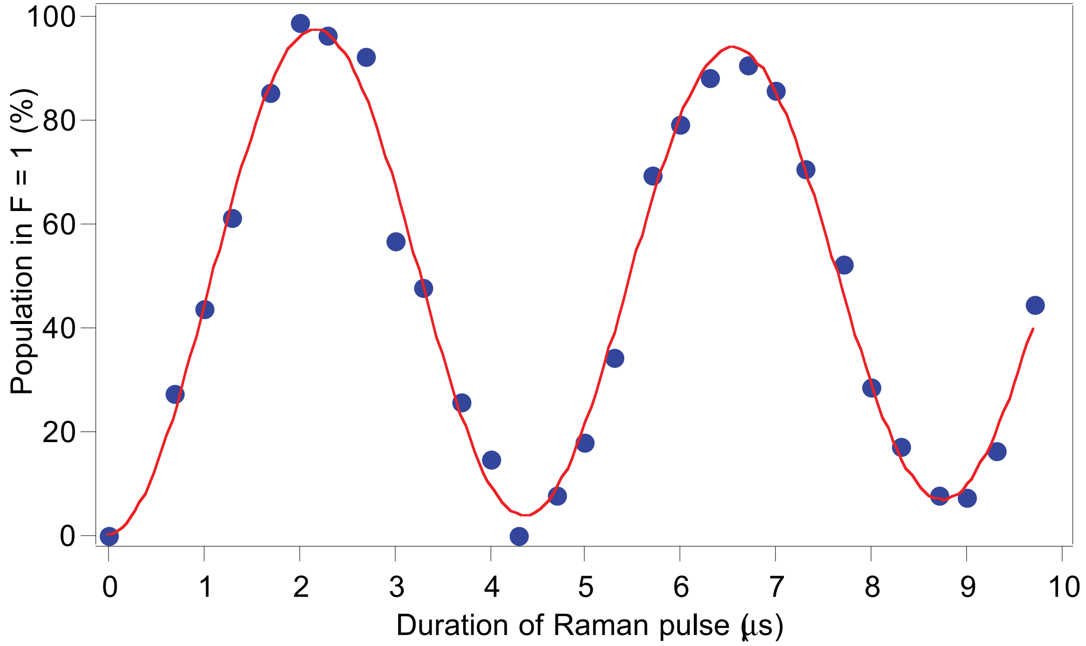
Detection (fluorescence)

time

× 200

Results : $|0\rangle$, $|1\rangle$, $|1\rangle$, $|0\rangle$, …, $|1\rangle$, $|0\rangle$, $|0\rangle$

⇒ Probability P(1) :



$$\Omega_{\text{Raman}} = \frac{\Omega_1 \Omega_2}{2\Delta}$$

Raman transition :
Rabi oscillation

π Pulse = 99% efficiency

Creating entanglement...

$$(|0_A\rangle + |1_A\rangle) \otimes (|0_B\rangle + |1_B\rangle)$$

$$= |0_A,0_B\rangle + |0_A,1_B\rangle + |1_A,0_B\rangle + |1_A,1_B\rangle$$

State-dependent operation

$$|0_A,0_B\rangle + |0_A,1_B\rangle + |1_A,0_B\rangle - |1_A,1_B\rangle$$

Measurement Filtering

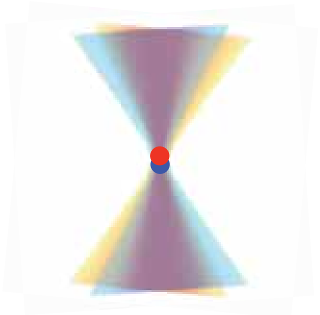
$$|0_A,1_B\rangle + |1_A,0_B\rangle$$

Proposals for creating entanglement / gates

Several protocols adapted to single atoms in tweezers

« Deterministic » entanglement

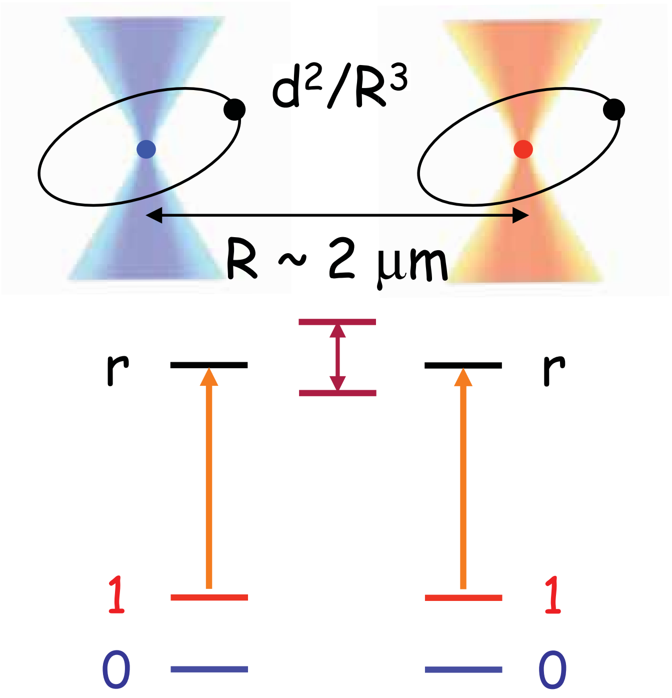
s-wave collision (also in optical lattices)



Mainz, NIST, …

Slow, sensitive to motional state (OK for BEC !)

Dipole-dipole (Rydberg blockade)

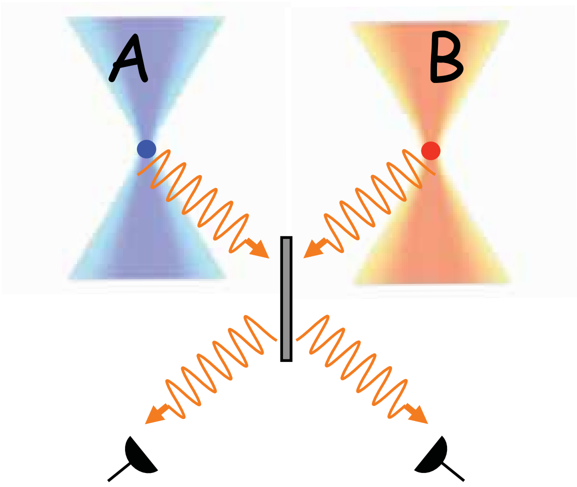


U. Wisconsin, Palaiseau

Fast, insensitive in ΔR

« Conditional » entanglement

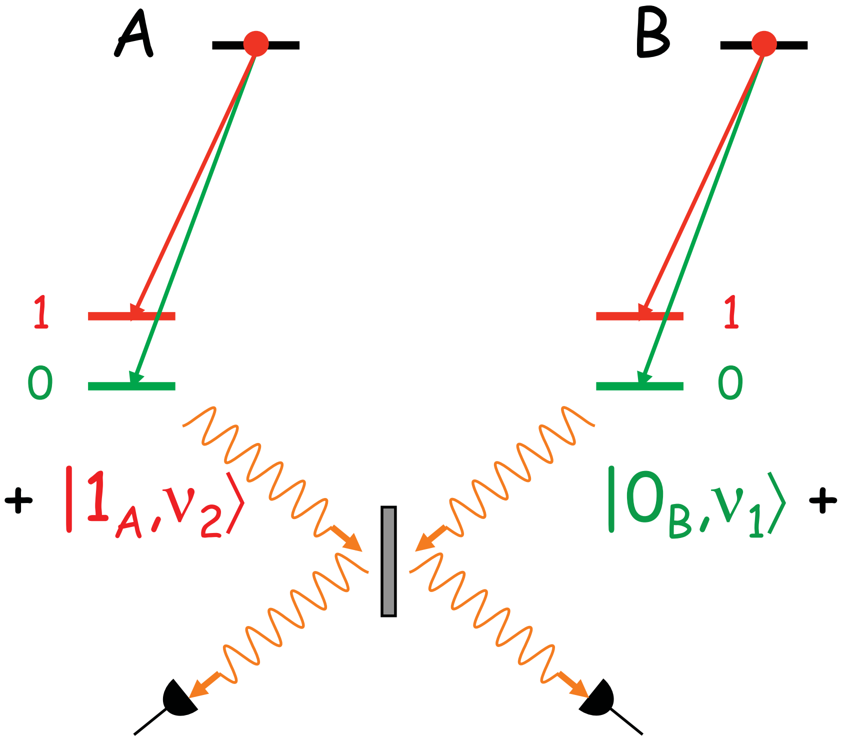
Entanglement induced by a Bell measurement



JQI, Munich, Barcelona…

No « direct » coupling, but hard to scale

Perspective for conditional entanglement



$|0_A,\nu_1\rangle + |1_A,\nu_2\rangle$

$|0_B,\nu_1\rangle + |1_B,\nu_2\rangle$

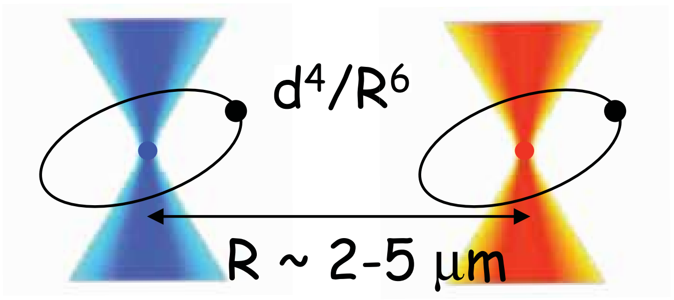
Entanglement swapping
projects onto
$|0_A,1_B\rangle - |1_A,0_B\rangle$

PRA **73**, 062324 (2006)

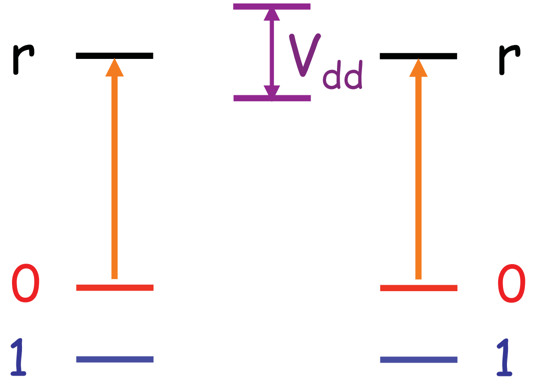
Requires
- Triggered emission of single photons
- Two photon interferences
- Excellent stability of the expt (very low production rate)

Implemented with trapped ions (Chris Monroe et al.)

Deterministic entanglement using Rydberg excitation

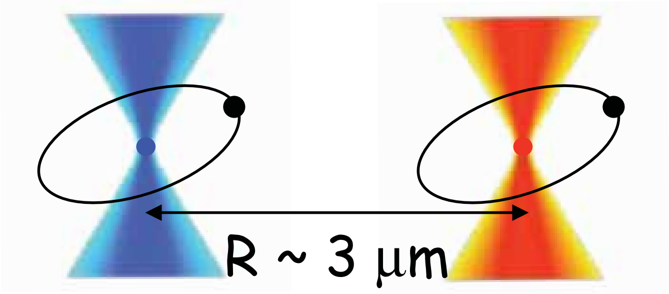


D. Jaksch, J. I. Cirac,
P. Zoller, S. L. Rolston,
R.Côté, and M. D. Lukin
PRL **85**, 2208 (2000)



- Two atoms separated by few microns and excited to Rydberg states will interact very strongly (dipole-dipole coupling)
- This strong interaction may inhibit to excite both atoms : « Rydberg blockade »
- The blockade effect can be used to entangle the atoms, and to design very fast (sub-μs) quantum gates

Interaction between Rydberg atoms



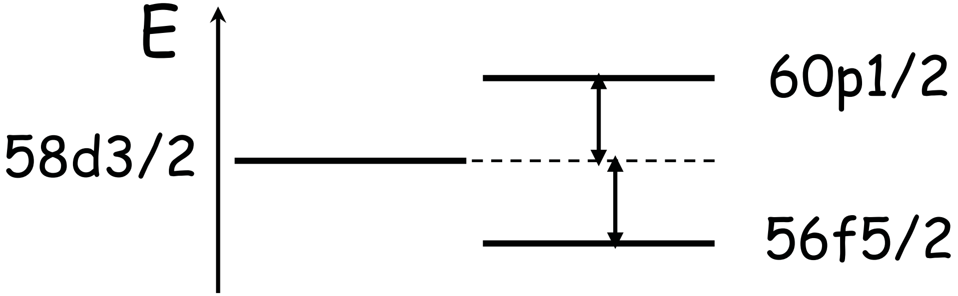
In general (no electric field) : van der Waals interaction

$$\Delta E \propto \frac{(ea_0)^4}{R^6} n^{11}$$

e.g.: n = 58, R = 3 μm

⇒ ΔE ≈ 5 MHz

« Accidental » degeneracy (Förster interaction)



⇒ dipole-dipole interaction

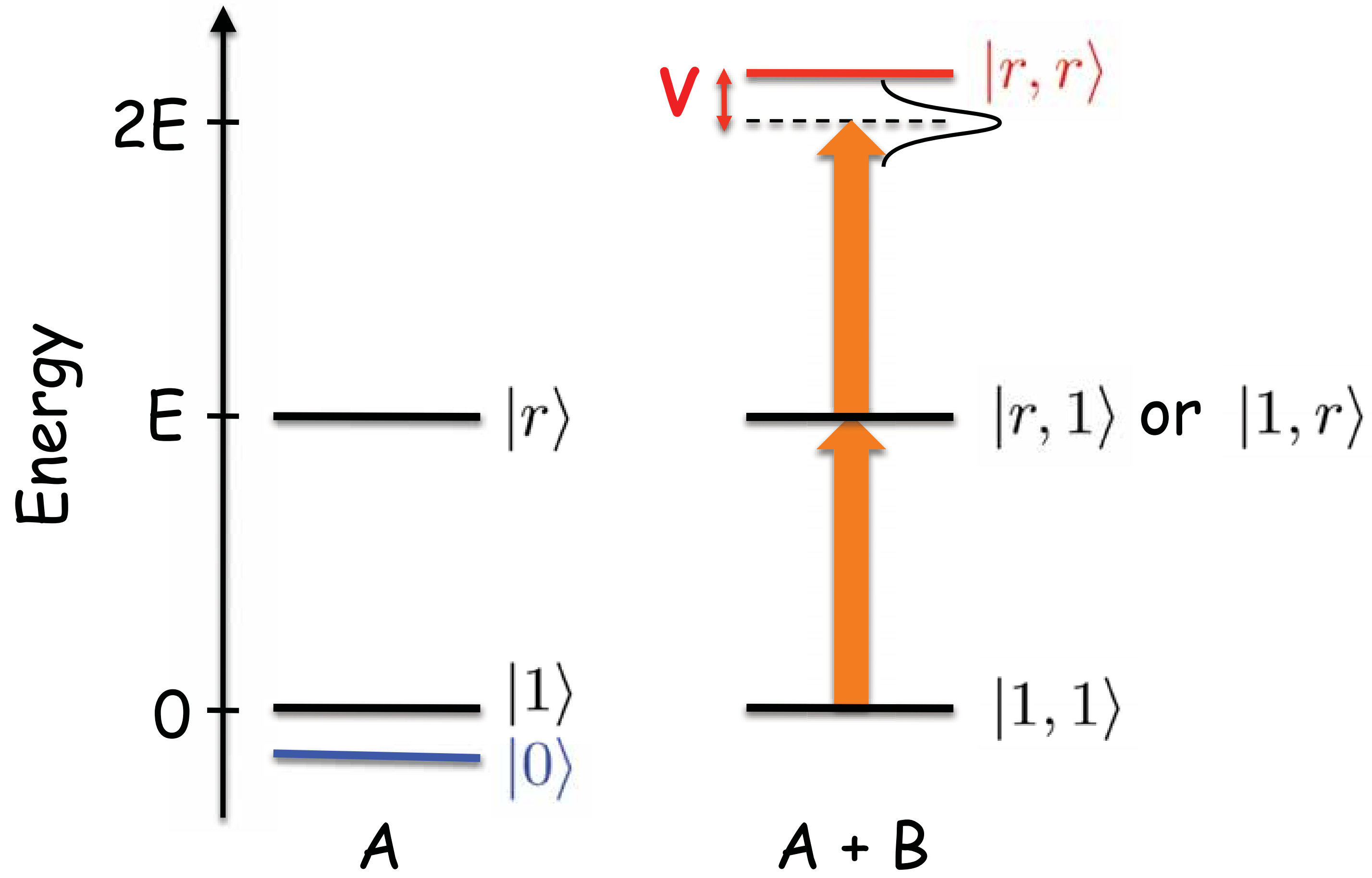
$$\Delta E \sim \frac{1}{4\pi\epsilon_0} \frac{(ea_0)^2}{R^3} n^4$$

n = 58, R = 3 μm

⇒ ΔE ≈ 100 MHz

T. G. Walker and M. Saffman
Phys. Rev. A **77**, 032723 (2008)

« Rydberg blockade »



Insensitive to exact V, i.e. **distance** between atoms!

Observations of Rydberg blockade in atomic ensembles

Tong et al. PRL 93, p. 063001 (2004)	MOT
Singer et al. PRL 93, p. 163001 (2004)	
Afrousheh et al. PRL 93, p. 233001 (2004)	
Cubel Liebisch et al. PRL 95, p. 253002 (2005)	
Vogt et al. PRL 97, p. 083003 (2006)	
Vogt et al. PRL 99, p. 073002 (2007)	
Heidemann et al. PRL 99, p. 163601 (2007)	BEC

In these experiments many atoms in the sample :
sensitive to $\langle V_{int} \rangle$ over random inter-atomic distances

Two individual atoms in dipole traps :

E. Urban et al, Nature Physics **5**, 110 (2009) [U. Wisconsin]
A. Gaëtan et al , Nature Physics **5**, 115 (2009) [Paris Sud]

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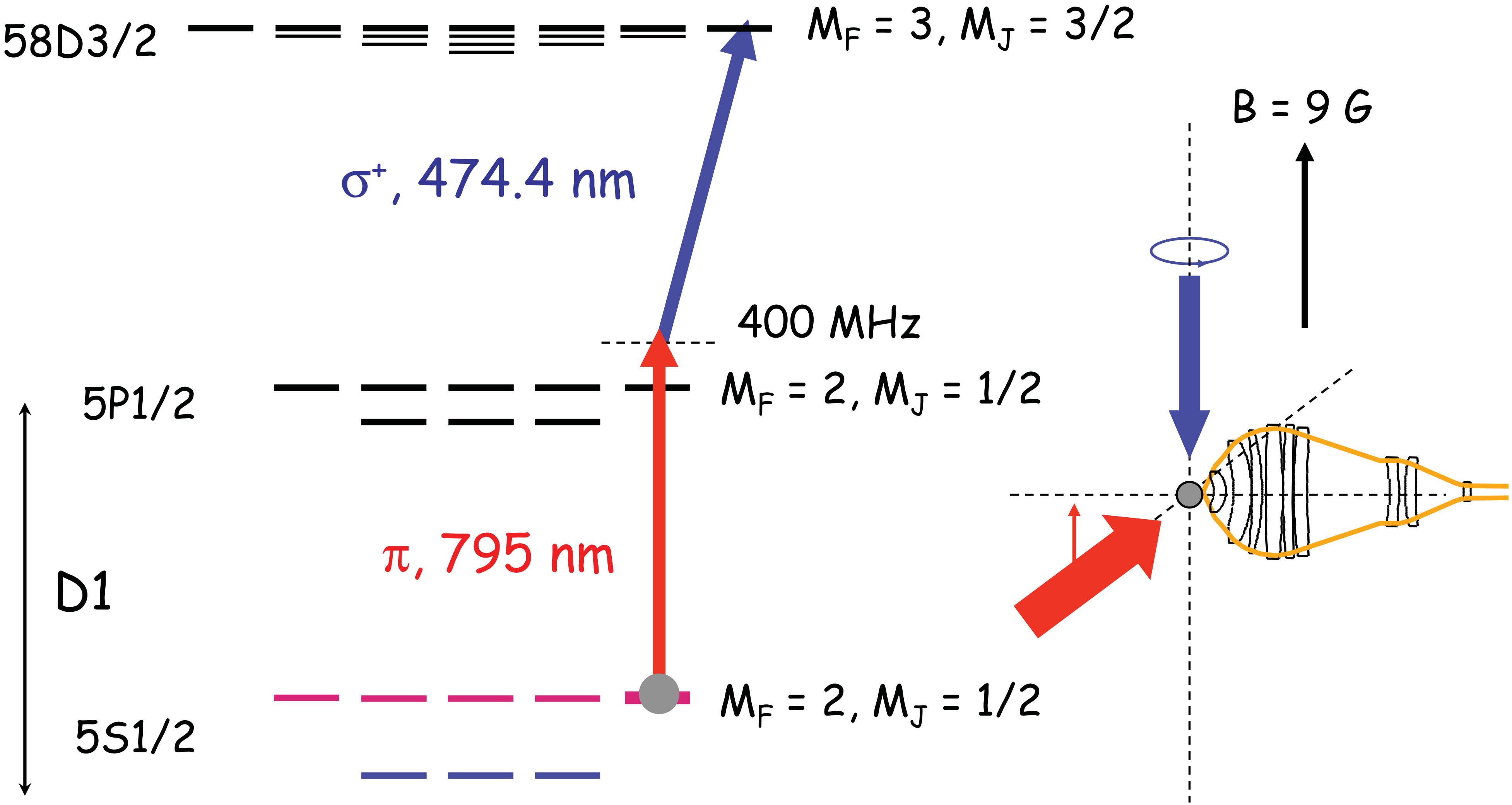
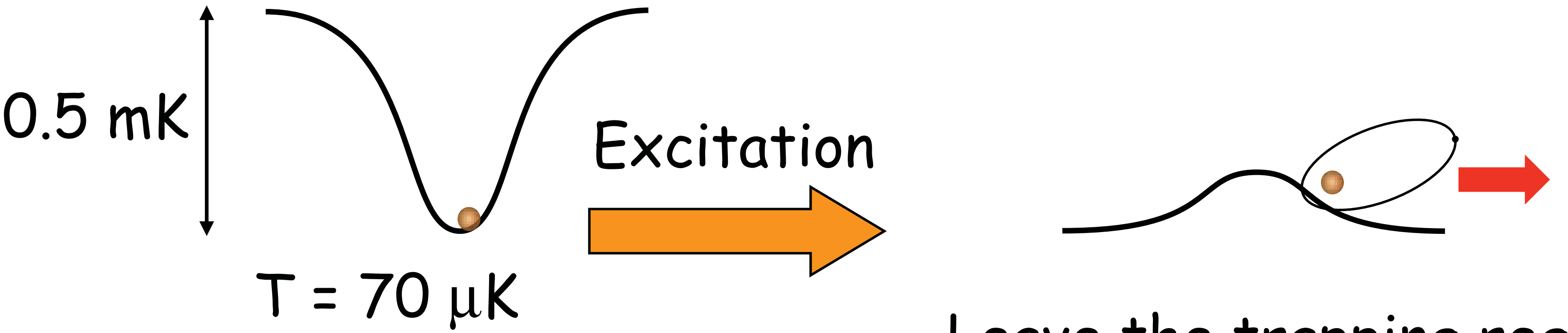
Deterministic Rydberg excitation



Detection of Rydberg excitation

Through loss of the atom



Leave the trapping region
(1 µm) in < 5 µsec

Before

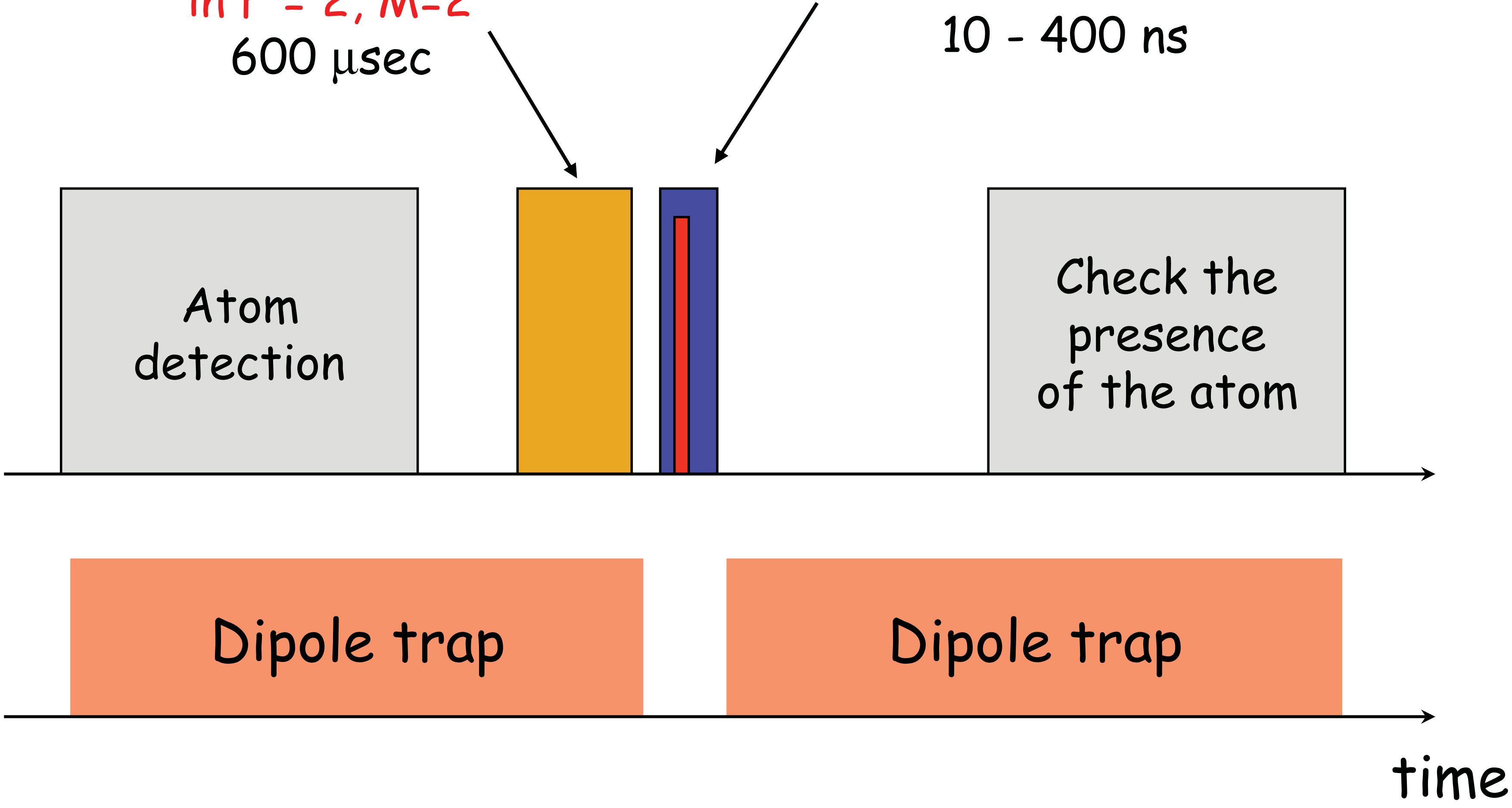
Photo-ionization by dipole trap (810 nm) = 500 µsec

Radiative decay to $5P_{1/2}$ = 500 µsec

Black-Body = 50 µsec

Deterministic Rydberg excitation

Repeat 100 times the sequence



Zeeman pumping
in F = 2, M=2
600 μsec

Excitation red + blue
10 - 400 ns

Atom detection

Check the presence of the atom

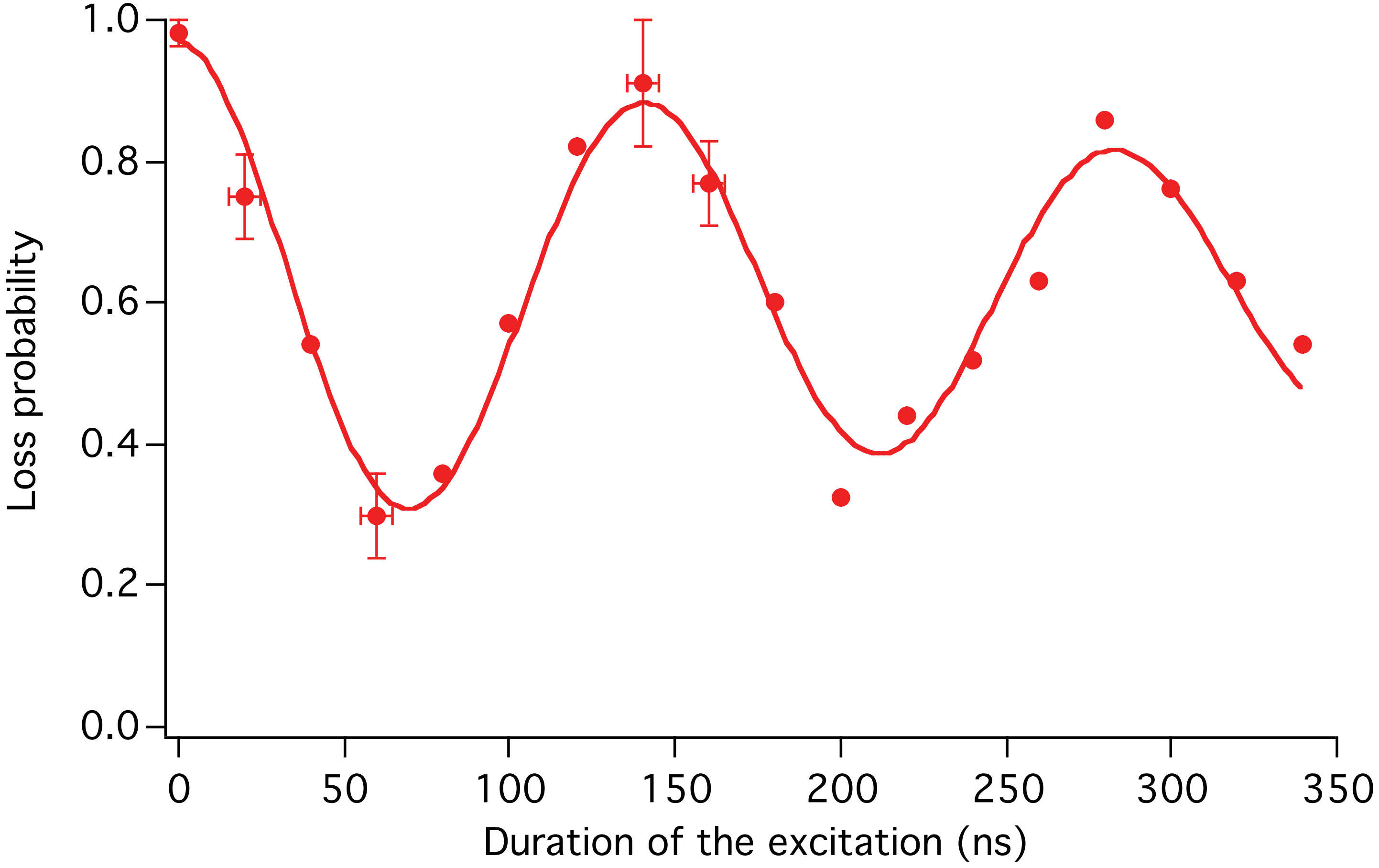
Dipole trap

Dipole trap

time

Rabi oscillations on a single atom

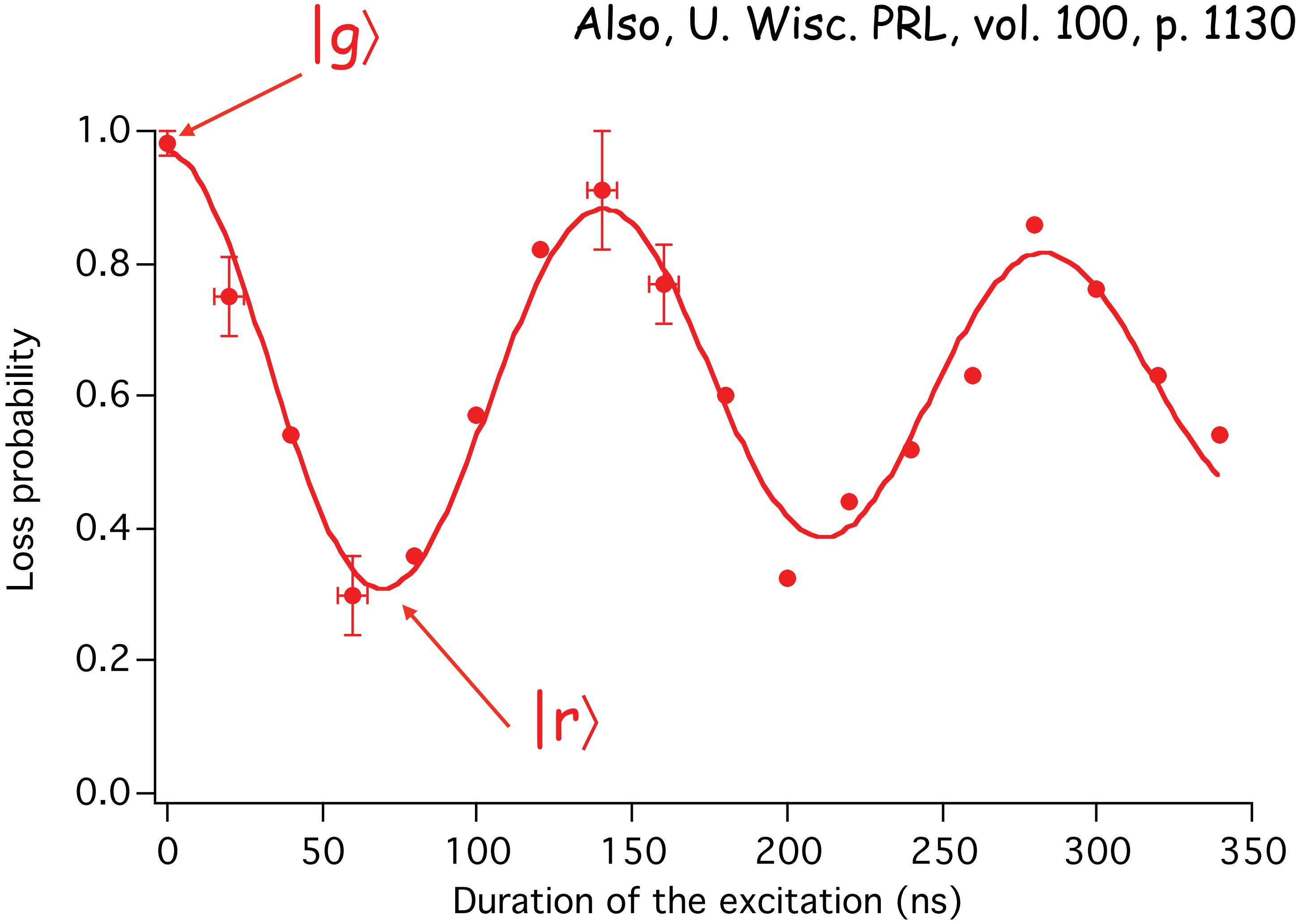
Also, U. Wisc. PRL, vol. 100, p. 113003 (2008)



Two-photon Rabi oscillation between the ground and Rydberg state (58d 3/2)

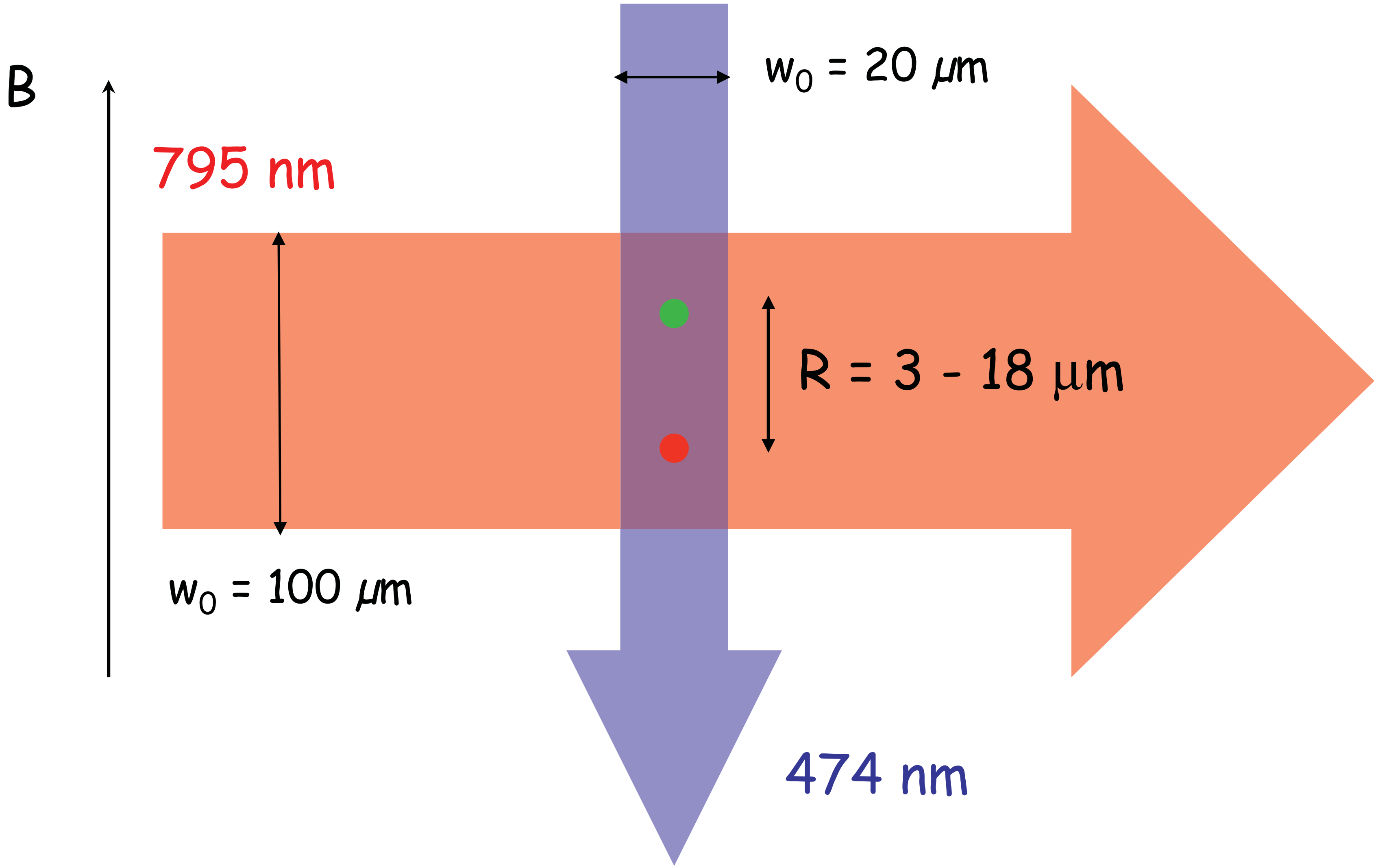
Rabi oscillations on a single atom

Also, U. Wisc. PRL, vol. 100, p. 113003 (2008)



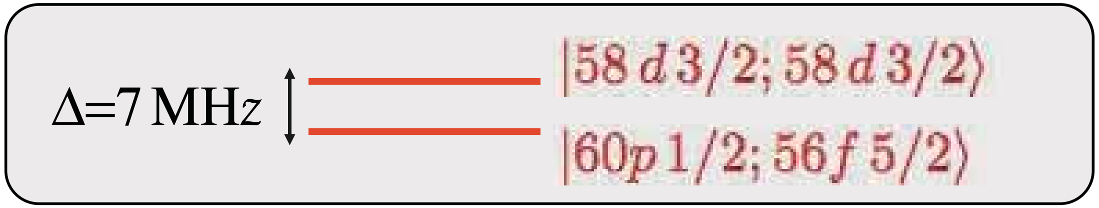
$$\Omega = \frac{\Omega_R \Omega_B}{2\Delta} \approx 2\pi \times 7\ \mathrm{MHz}$$

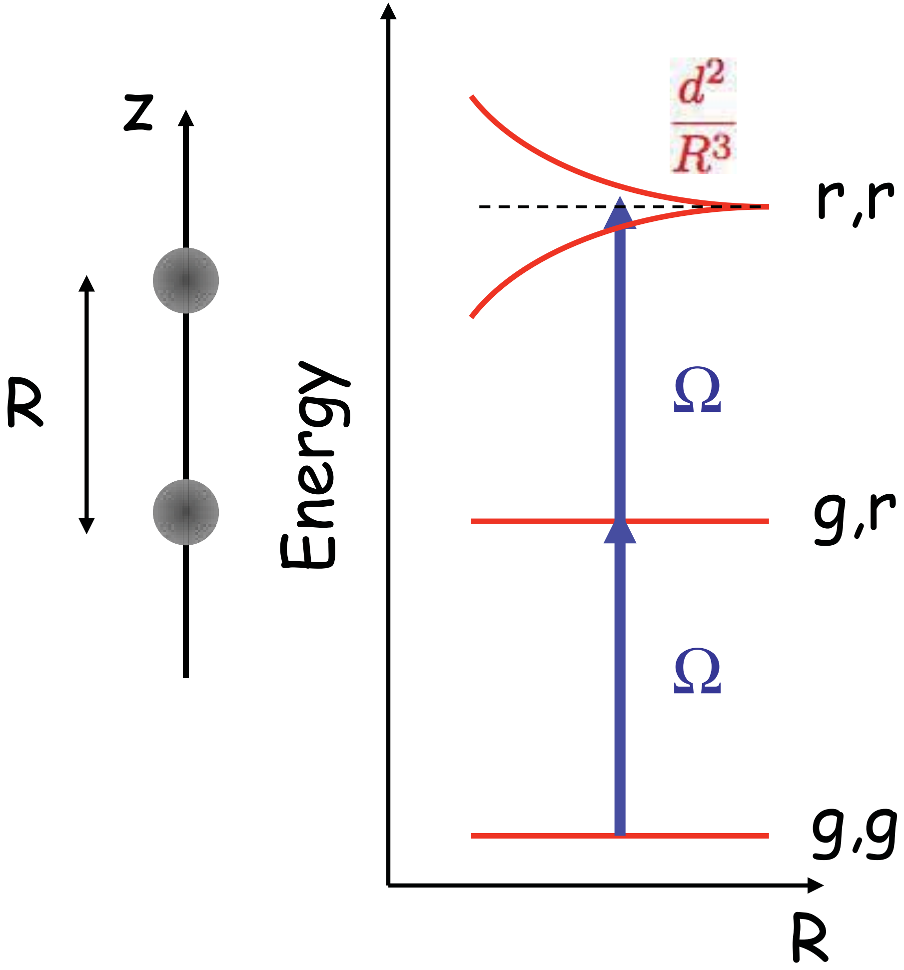
Excitation of two atoms



« Blockade » range

Two atoms excited to
$|58d_{3/2}\,;\,M_J = 3/2\rangle$





Blockade stops when

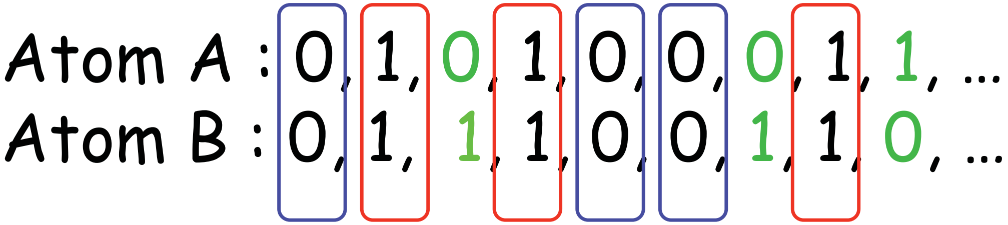
$$\hbar\Omega \approx \frac{d^2}{R^3}$$

Ω = 2π× 7 MHz
⇒ Rmax = 8 μm

Experimental protocol

1. Trap 2 atoms in 2 tweezers and optically pump them
2. Excite the two atoms
3. Measure if they are still trapped after the excitation

Repeat 100 times

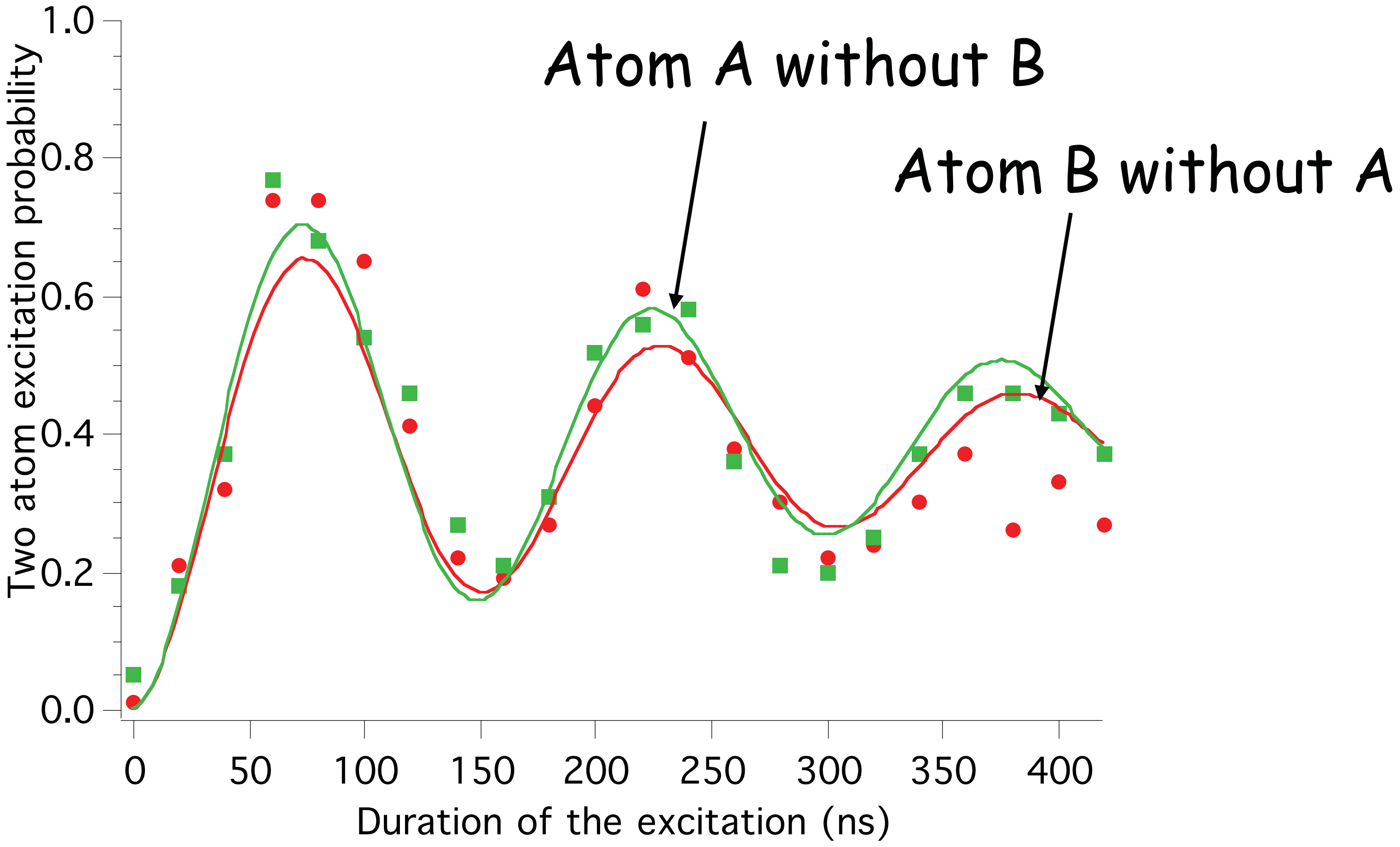


Atom A : 0, 1, 0, 1, 0, 0, 0, 1, 1, …
Atom B : 0, 1, 1, 1, 0, 0, 1, 1, 0, …

Extract

P to excite no Rydberg's
P of exciting two Rydberg's simultaneously
P to excite only one Rydberg

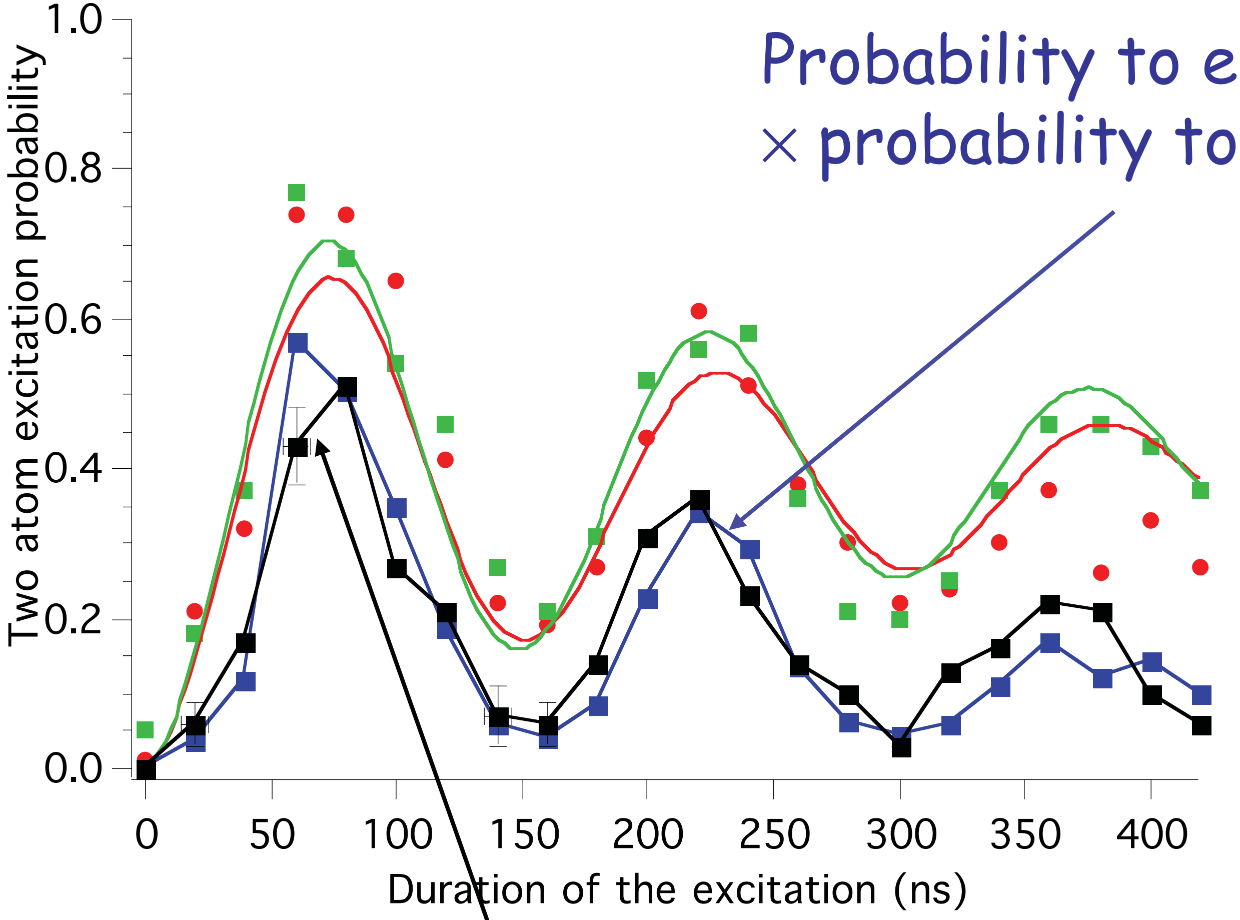
Excitation of two atoms at R = 18 µm



Single atom Rabi oscillation
between ground and Rydberg state

Excitation of two atoms at R = 18 µm

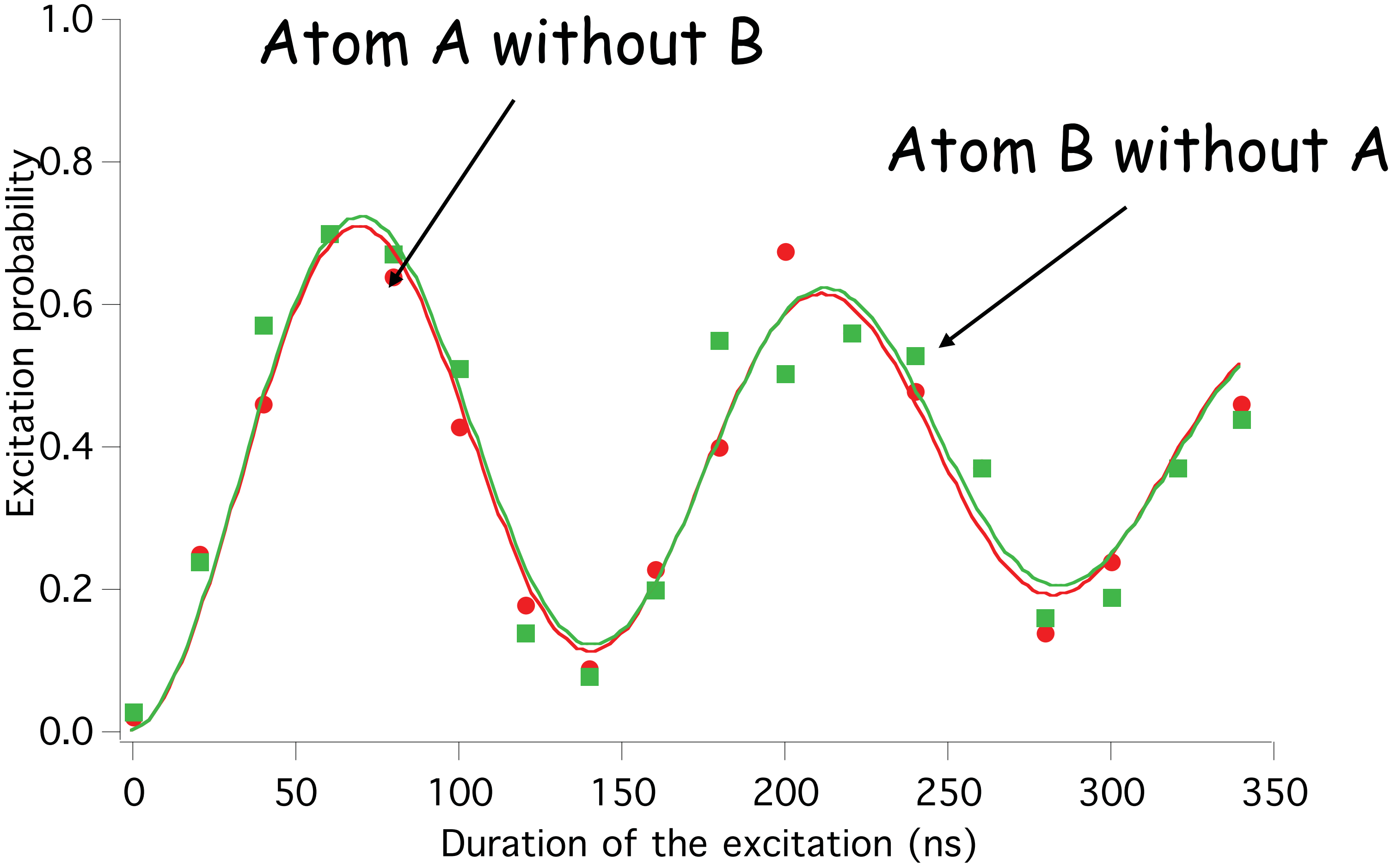
The atoms are « independent »



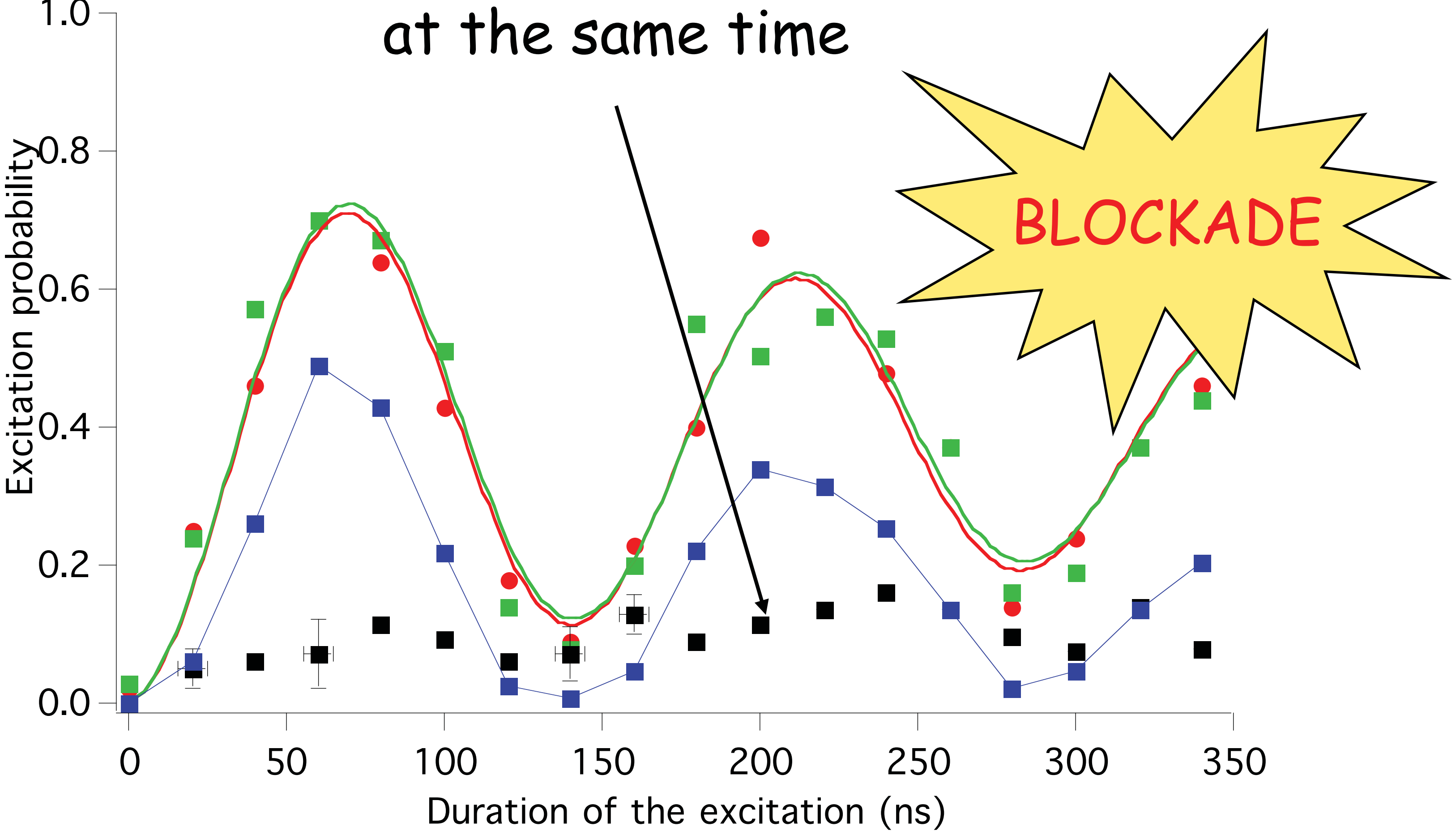
Probability to excite A
× probability to excite B

Measured probability to excite the two atoms

Excitation of two atoms at R = 3.6 µm



Excitation of two atoms at R = 3.6 μm



Probability to excite 2 atoms
at the same time

BLOCKADE

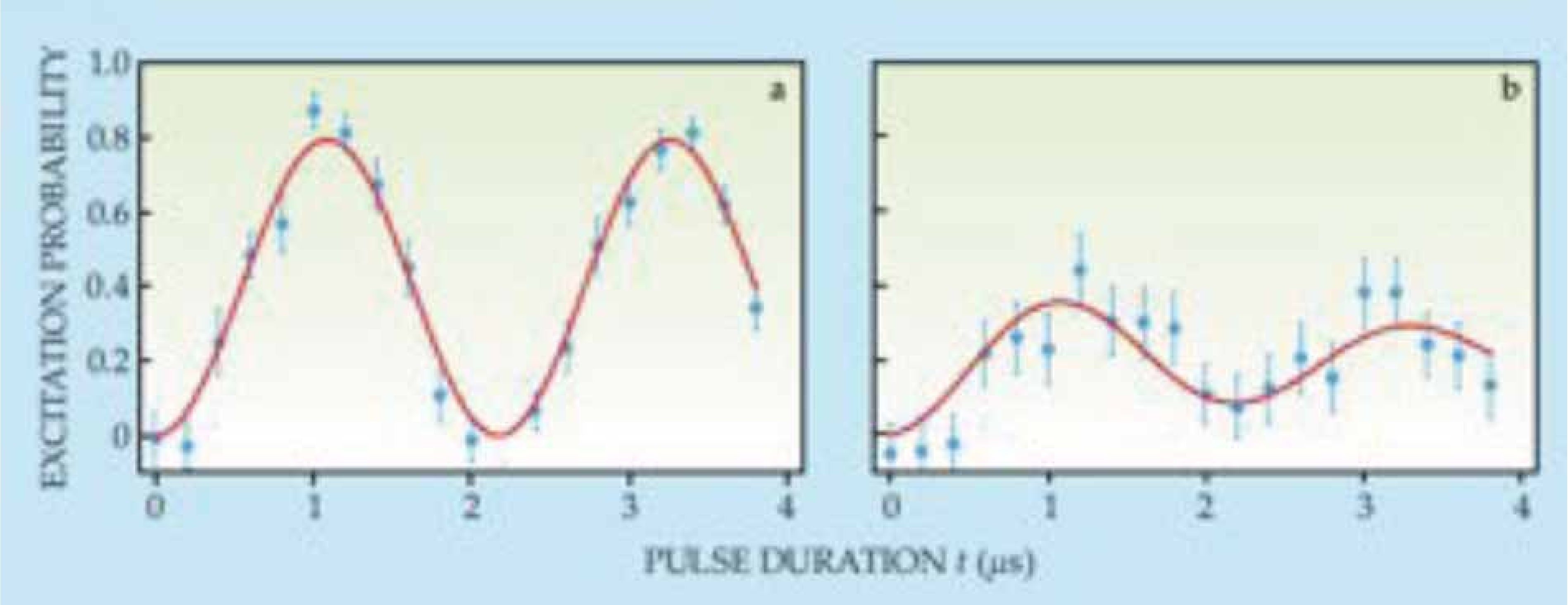
« Observation of collective excitation of two individual atoms in the Rydberg blockade regime », A. Gaëtan, Y. Miroshnychenko, T. Wilk, A. Chotia, M. Viteau, D. Comparat, P. Pillet, A. Browaeys, and P. Grangier, Nature Physics **5**, 115 (2009).

Blockade at U. Wisconsin (M. Saffman)

Two atoms only, Rydberg level n = 79, distance 10 μm

Rabi oscillation for atom 1,
atom 2 in ground state

Rabi oscillation for atom 1,
atom 2 in Rydberg state



« Observation of Rydberg blockade between two individual atoms », E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, M. Saffman, Nature Physics **5**, 110 - 114 (2009).

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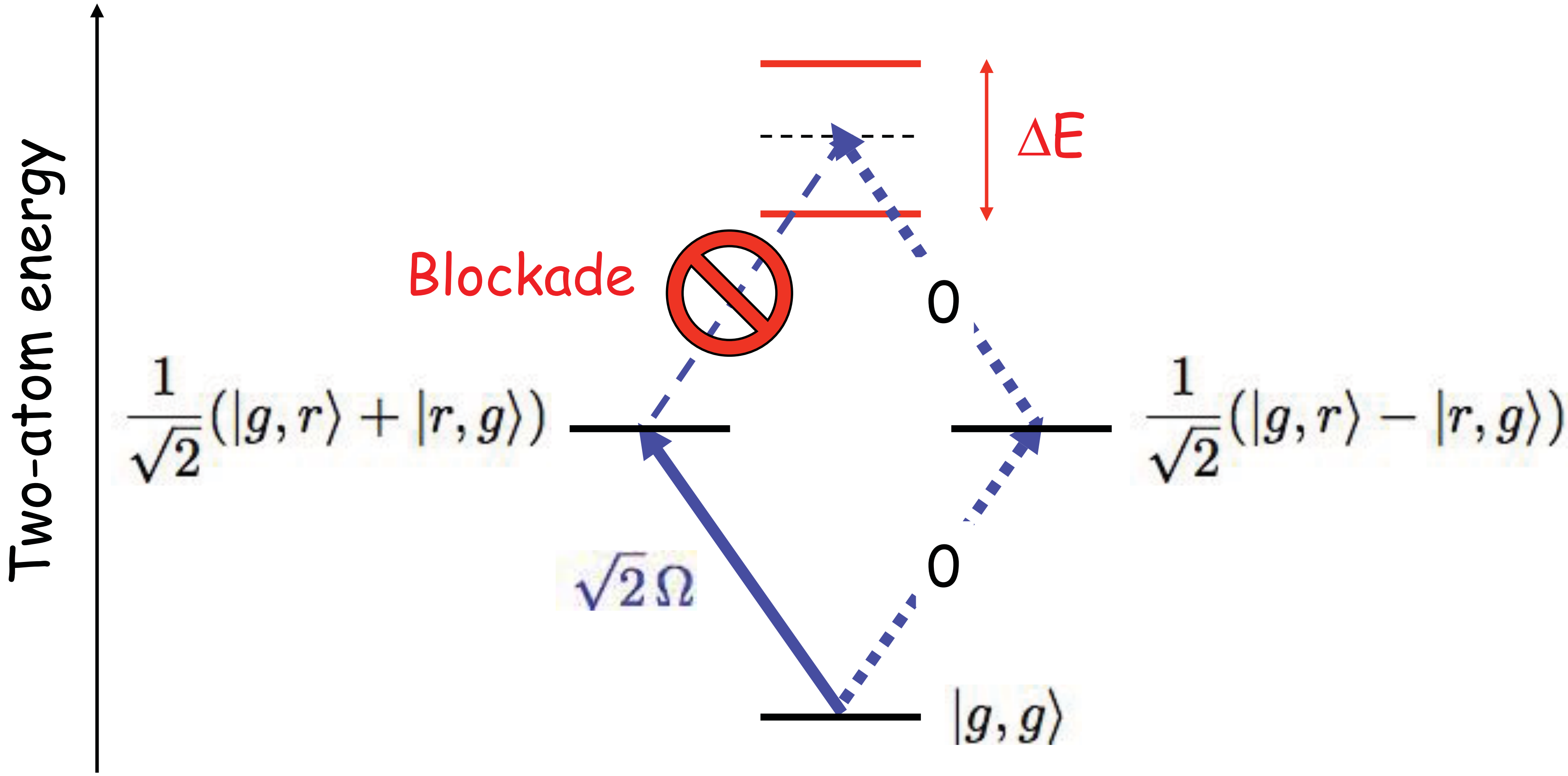
« Collective » Rabi oscillations



The probability to excite one atom in the blockade regime should oscillate √2 faster than the initial single atom Rabi frequency !

« Collective » Rabi oscillations

One atom only : usual Rabi oscillations $p_r = \sin^2(\Omega T/2)$,

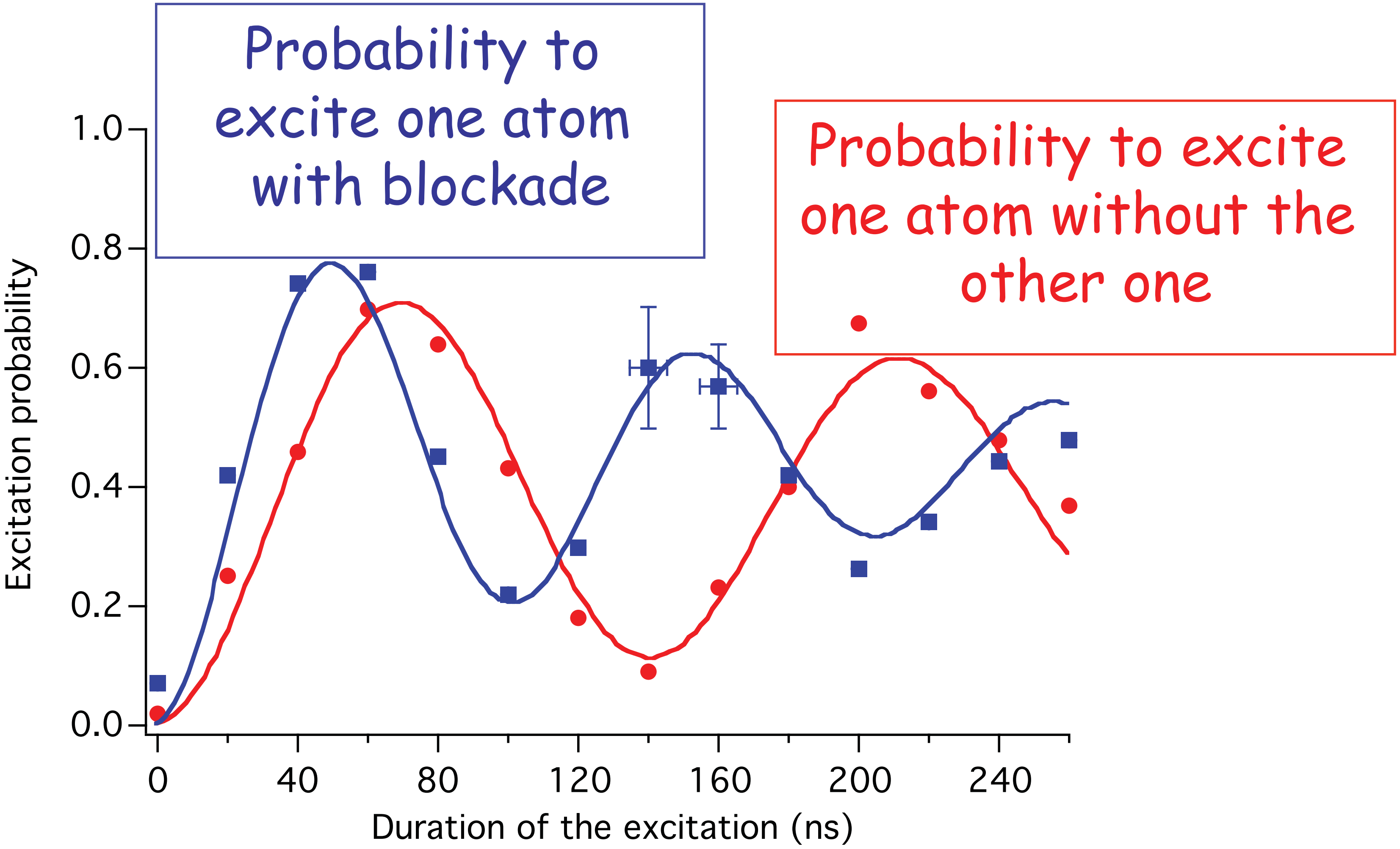
Two atoms, basis $|0\rangle = |g, g\rangle$, $|1\rangle = (|g, r\rangle + |r, g\rangle)/\sqrt{2}$, $|2\rangle = |rr\rangle$

$$H_{\text{indépend.}} = \hbar\Omega \begin{pmatrix} 0 & \sqrt{2} & 0 \\ \sqrt{2} & 0 & \sqrt{2} \\ 0 & \sqrt{2} & 0 \end{pmatrix} \Rightarrow \begin{array}{l} p(0) = \cos^4(\Omega T/2) \\ p(1) = 2\sin^2(\Omega T/2)\cos^2(\Omega T/2) \\ p(2) = \sin^4(\Omega T/2) = p_r^2 \end{array}$$

$$H_{\text{blockade}} = \hbar\Omega \begin{pmatrix} 0 & \sqrt{2} & 0 \\ \sqrt{2} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow \begin{array}{l} p(0) = \cos^2(\sqrt{2}\,\Omega T/2) \\ p(1) = \sin^2(\sqrt{2}\,\Omega T/2) \\ p(2) = 0 \end{array}$$

With two atoms the probability $p(1) = \sin^2(\sqrt{2}\,\Omega T/2)$ oscillates $\sqrt{2}$ faster than the single atom value $p_r = \sin^2(\Omega T/2)$!

Probability to excite only one atom (R = 3.6 μm)



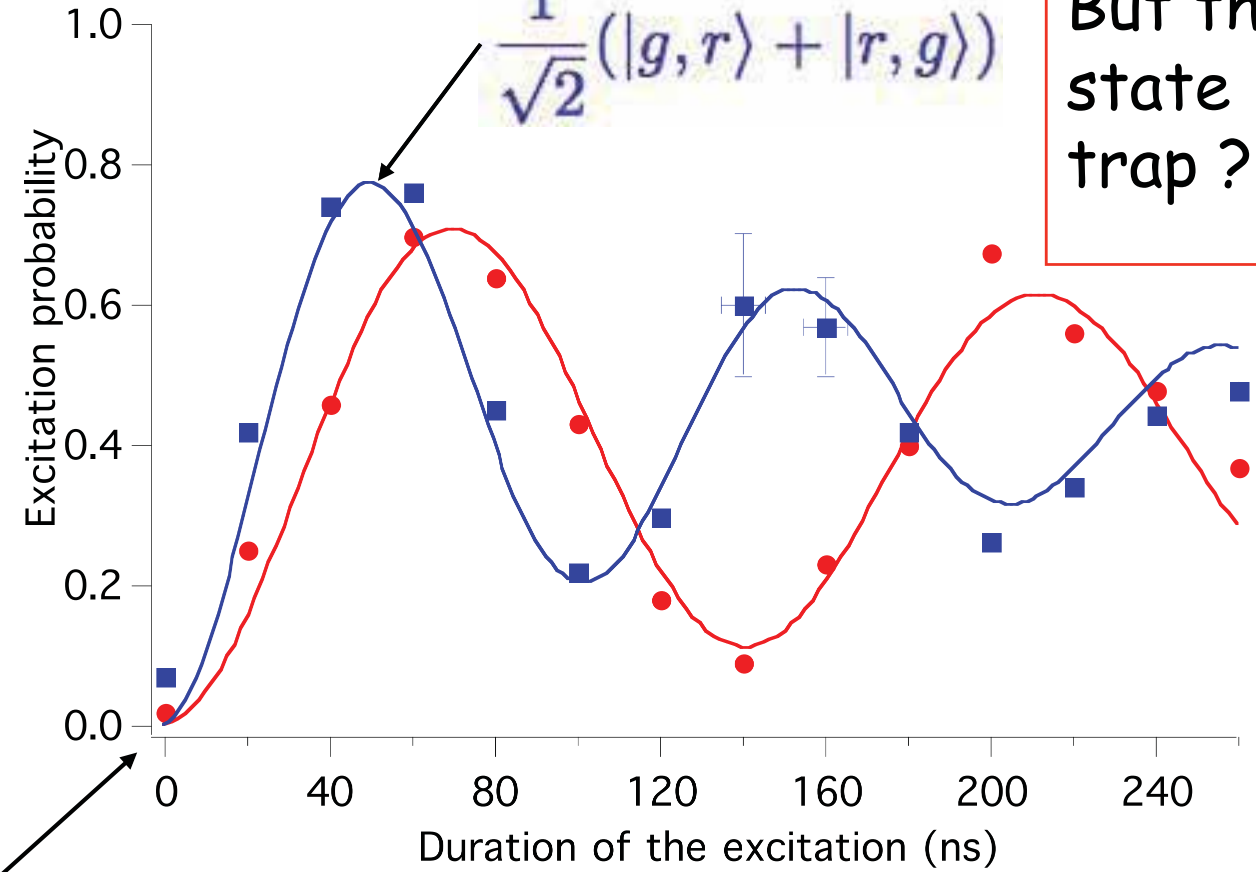
Probability to excite one atom with blockade

Probability to excite one atom without the other one

Frequency ratio = 1.38 ≈ √2

Also Heidemann, et al. PRL 99, p. 163601 (2007)

Probability to excite only one atom (R = 3.6 μm)



$$\frac{1}{\sqrt{2}}(|g,r\rangle + |r,g\rangle)$$

$$|g,g\rangle$$

Entangled state !
But the Rydberg state leaves the trap ?

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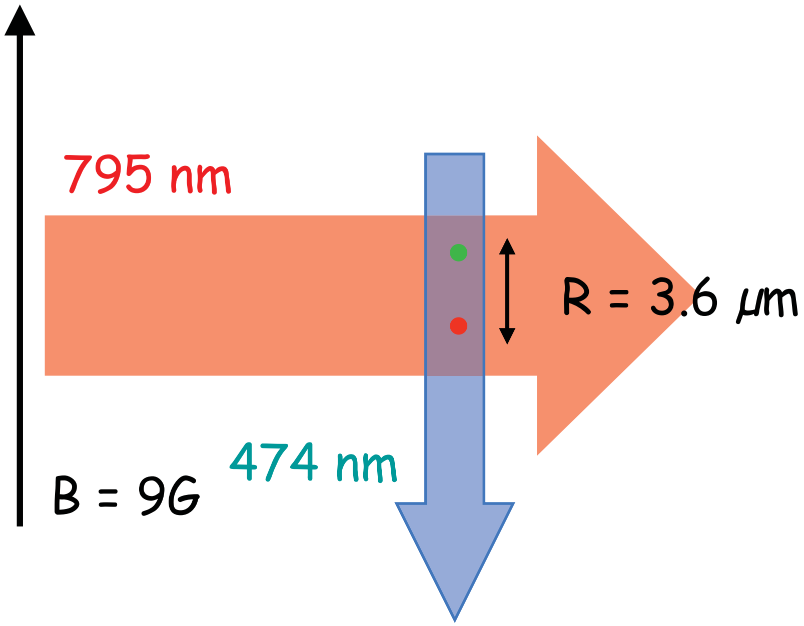
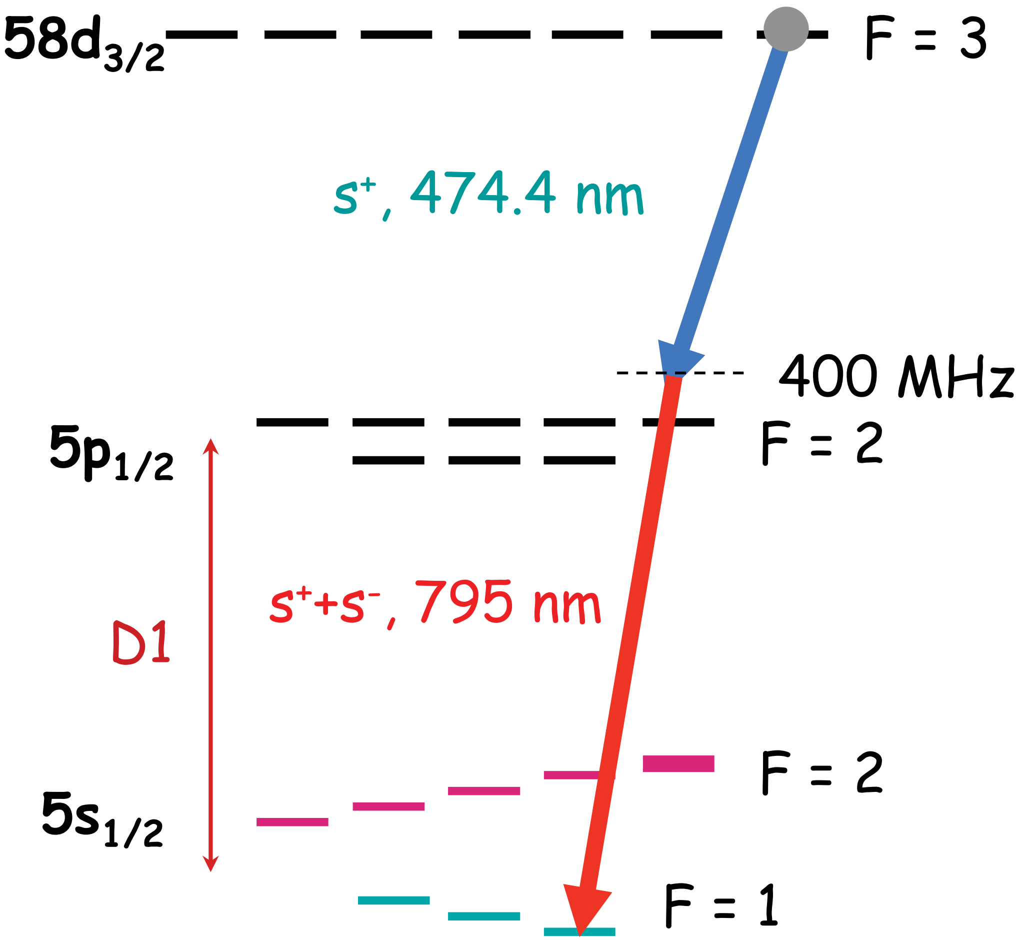
Mapping Rydberg state to the other ground state



$$\frac{1}{\sqrt{2}}(|r,1\rangle + |1,r\rangle)$$

$$\rightarrow \left|\psi_B\right\rangle = \frac{1}{\sqrt{2}}\left(\left|1,0\right\rangle + \left|0,1\right\rangle\right)$$



Analyzing entanglement : general idea

Global Raman rotation on the two atoms ($|0\rangle \leftrightarrow |1\rangle$, Ω)

$$|\psi_B\rangle = \frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right) \quad \Longleftrightarrow \quad |\psi_C\rangle = \frac{1}{\sqrt{2}}\left(|0,0\rangle - |1,1\rangle\right)$$

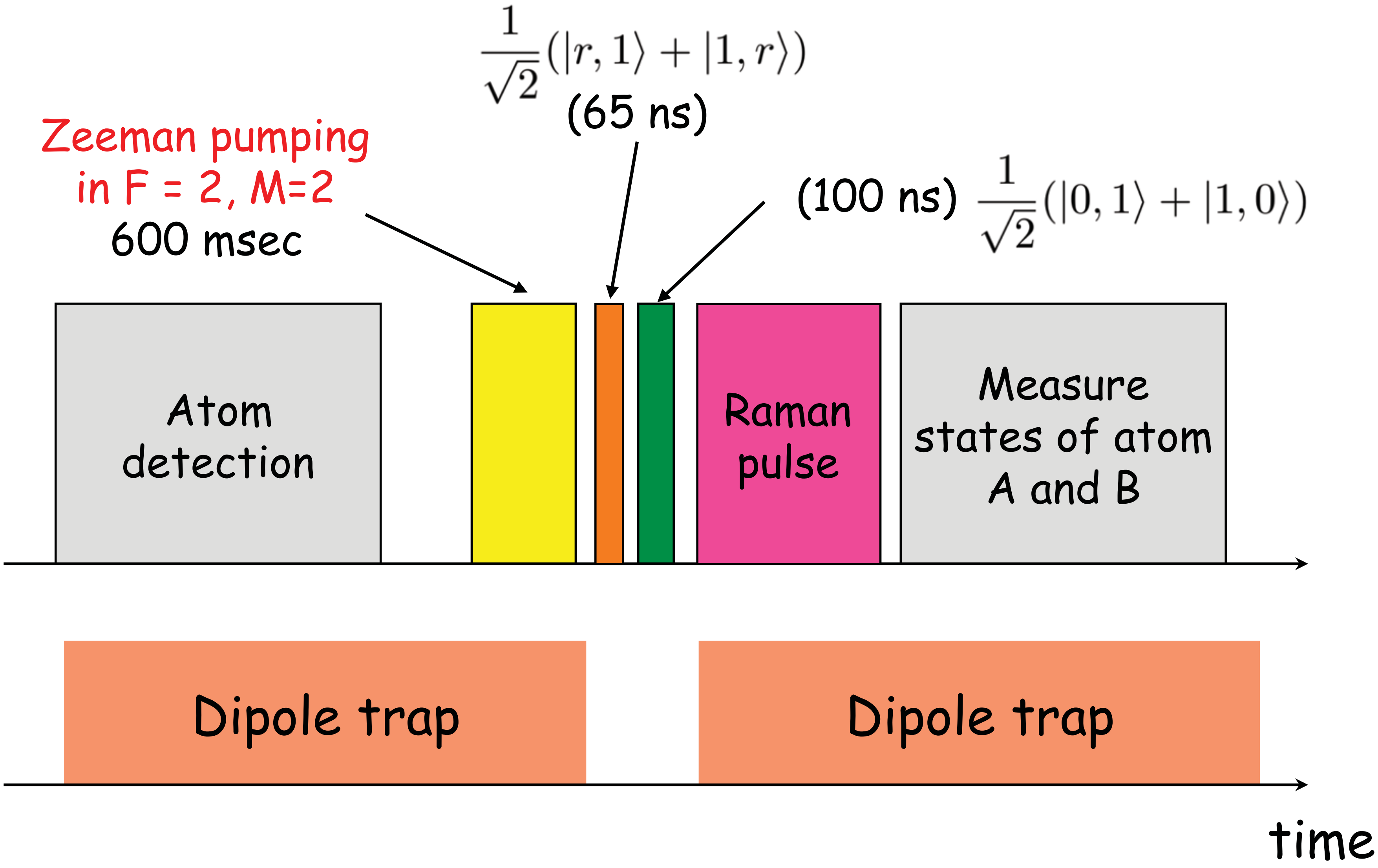
Raman oscillation at frequency **2 x Ω**

The visibility (contrast) of this oscillation tells how close the state is (« fidelity ») from the desired Bell state !

Q. A. Turchette, D. Wineland et al., **Phys. Rev. Lett. 81**, 3631 (1998).

Time sequence of the experiment…

Repeat 100 times the sequence



$\frac{1}{\sqrt{2}}(|r,1\rangle + |1,r\rangle)$

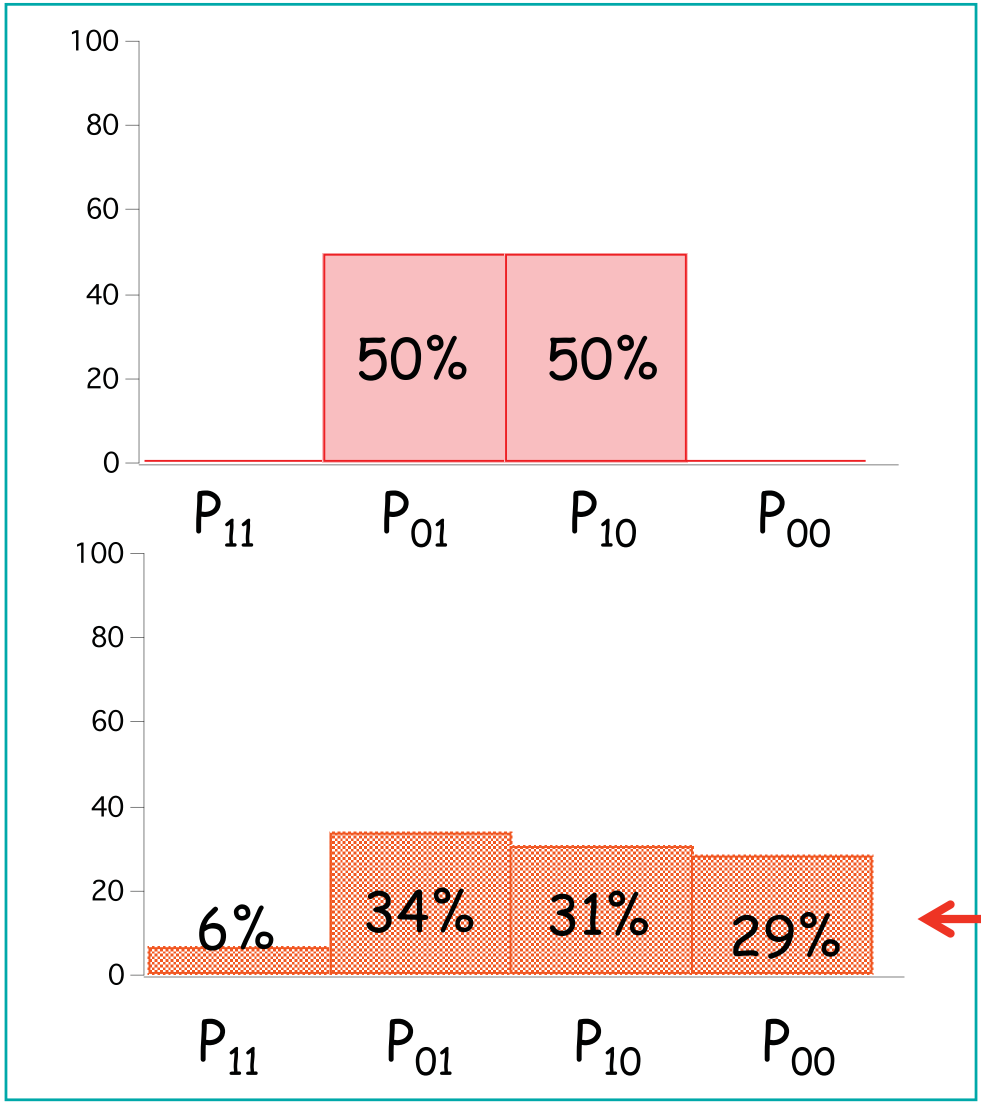
(65 ns)

Zeeman pumping
in F = 2, M=2
600 msec

(100 ns) $\frac{1}{\sqrt{2}}(|0,1\rangle + |1,0\rangle)$

Analyzing entanglement…

$$|\psi_B\rangle = \frac{1}{\sqrt{2}}(|0,1\rangle + |1,0\rangle)$$



Theory

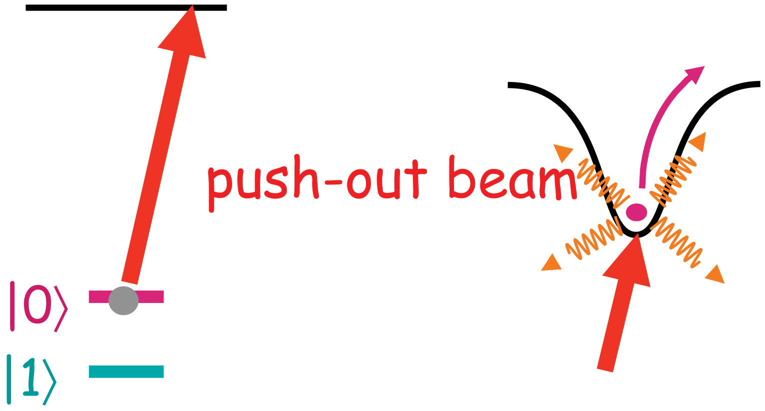
Experiment

oops …

Why is P_{00} so high ?

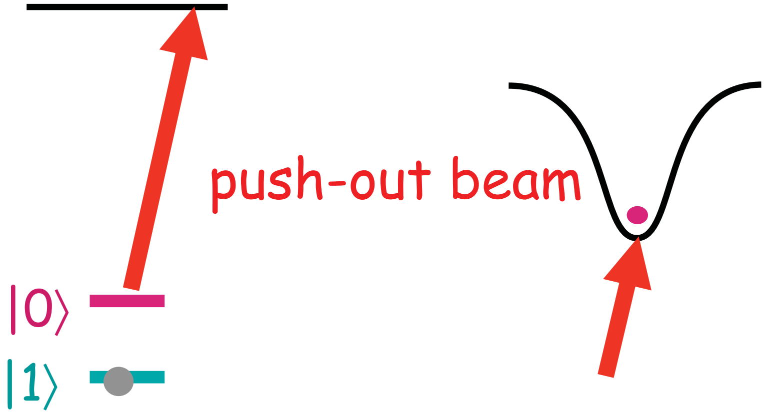
Push-out beam

Check presence of the atom



atom lost $\Rightarrow |\,0\,\rangle$

Result « 0 » each time the atom is lost (including before the push-out sequence…)



atom still there $\Rightarrow |\,1\,\rangle$

Taking into account the atom loss...

2 atoms there 1 atom lost 2 atoms lost

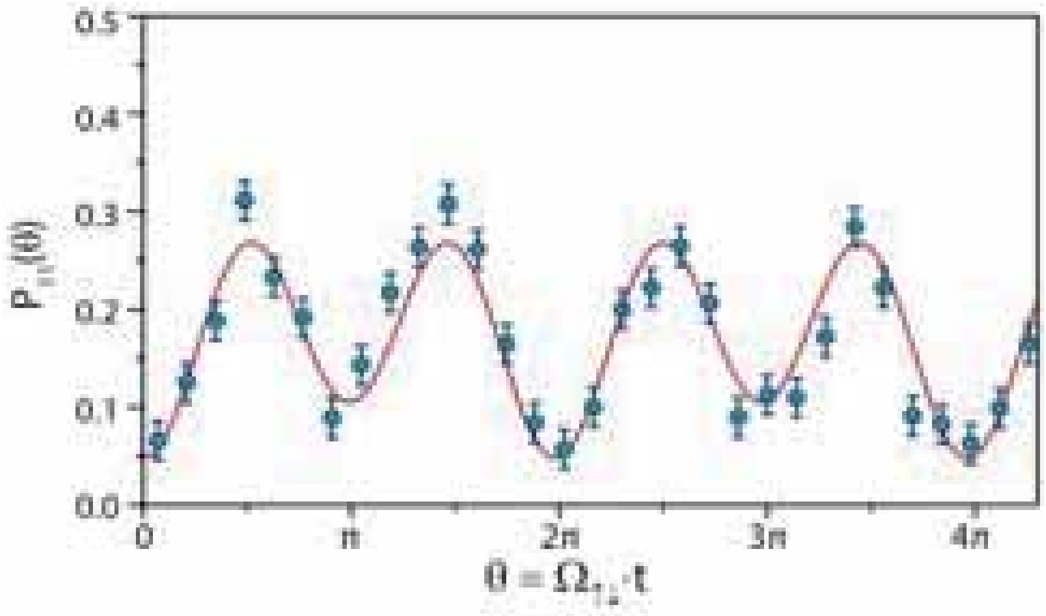
$$\rho = \begin{array}{c} \begin{array}{ccccccccc} 11 & 10 & 01 & 00 & 1x & 0x & x1 & x0 & xx \end{array} \\ \left(\begin{array}{ccccccccc} a11 & a12 & a13 & a14 & 0 & 0 & 0 & 0 & 0 \\ a21 & a22 & a23 & a24 & 0 & 0 & 0 & 0 & 0 \\ a31 & a32 & a33 & a34 & 0 & 0 & 0 & 0 & 0 \\ a41 & a42 & a43 & a44 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c11 & c12 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c21 & c22 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & c33 & c34 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & c43 & c44 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boxed{c55} \end{array}\right) \end{array}$$

$Fm = \langle \Phi | \rho | \Phi \rangle$ with $| \Phi \rangle = (| 10 \rangle + |01 \rangle)/\sqrt{2}$

$Fm = (a22 + a33 + a23 + a32)/2$

$P(2\ \text{atoms}) = a11 + a22 + a33 + a44$

Extracting the result from the data…



It can be shown that

$P_{11}(\theta)$ = A + B cos($\theta/2$) + C cos(θ)

where A, B, C can be obtained from the fit !

Ideally B = 0, A = - C =1/4 :

$P_{11}(\theta)$ = (1 + cosθ)/4

Result of the analysis :

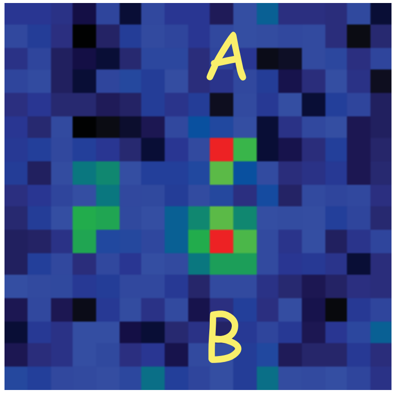
* Probability to still have both atoms in the 2 qubits space at the end of the complete sequence = 61%

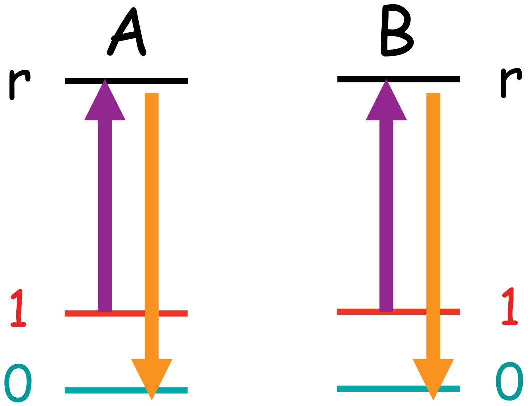
*** If both atoms are there, fidelity vs Bell state = 75%**

T. Wilk et al, Phys. Rev. Lett. **104,** 010502 (2010)

L. Isenhower et al, Phys. Rev. Lett. 104, 010503 (2010)

Motion of the atoms and fidelity (1)





$|1,1\rangle$ ➡ $$\frac{1}{\sqrt{2}}\left(e^{ik\cdot r_1}|r,1\rangle + e^{ik\cdot r_2}|1,r\rangle\right)$$ $k = k_{\mathrm{R}} + k_{\mathrm{B}}$

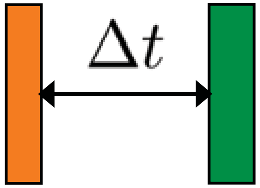
➡ $$\frac{1}{\sqrt{2}}\left(e^{i(k\cdot r_1 - k\cdot r_1')}|0,1\rangle + e^{i(k\cdot r_2 - k\cdot r_2')}|1,0\rangle\right)$$

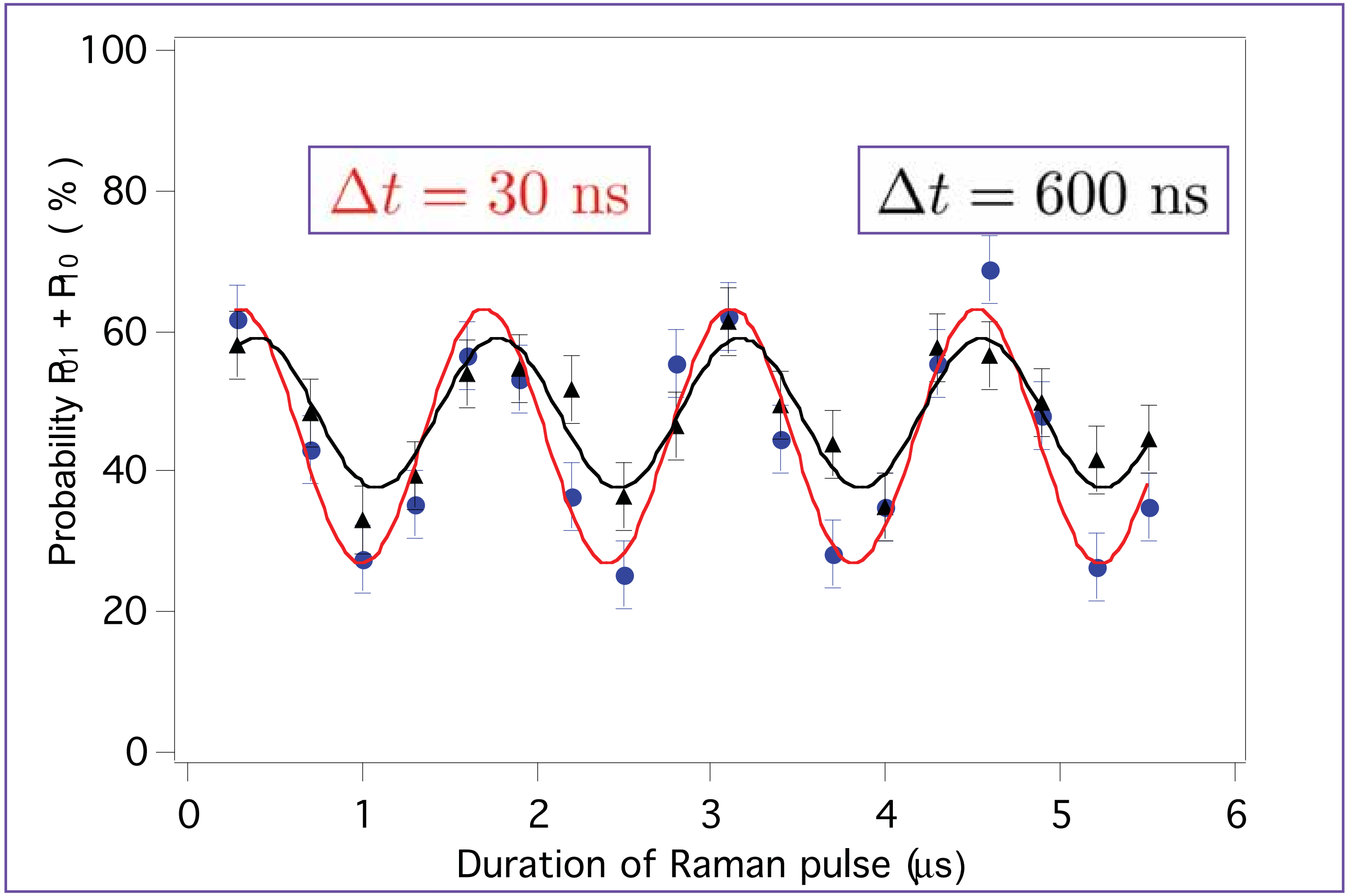
$$\Rightarrow \boxed{\frac{1}{\sqrt{2}}\left(|0,1\rangle + e^{i\phi}|1,0\rangle\right)}$$

with ϕ = **k** ($\Delta r_2 - \Delta r_1$)
and **k = kR + kB**

If pulses are short enough, atomic motion is frozen ⇒ $\Delta r_n \approx 0$

Motion of the atoms and fidelity (2)





$$\rho = p\,|\psi_{\mathrm{B}}\rangle\langle\psi_{\mathrm{B}}| + (1-p)\,\rho_{\mathrm{m}}$$

$$p \approx 0.44$$

$$p' \approx 0.25$$

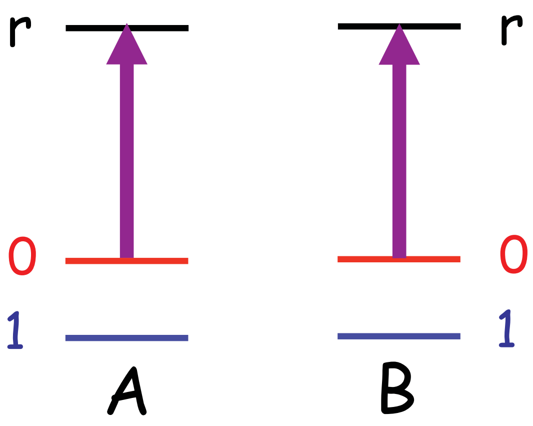
$$\Rightarrow \quad p'/p \approx 0.57$$

Theory $\langle e^{i\phi}\rangle \approx 0.6$

This gate IS fast ! (PZ, 2000…)

Towards a phase gate

Jaksch, **et al.**
PRL **85**, 2208 (2000)



$$\begin{matrix} |1\,1\rangle \\ |0\,1\rangle \\ |1\,0\rangle \\ |0\,0\rangle \end{matrix} \xrightarrow{\text{Phase}} \begin{matrix} |1\,1\rangle \\ -|0\,1\rangle \\ -|1\,0\rangle \\ -|0\,0\rangle \end{matrix}$$

Blockade

π - excitation on A
2π - excitation on B
π - excitation on A

* Requires « adressability ». Very fast gate
* Can (easily ?) be turned into a CNOT gate

Full gate realized at U. Wisconsin :

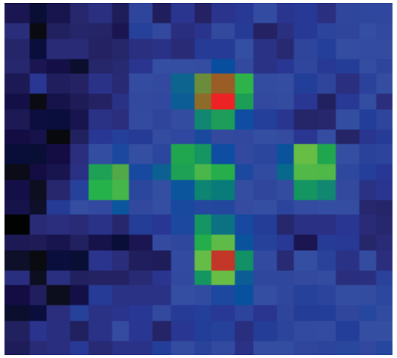
L. Isenhower et al, Phys. Rev. Lett. 104, 010503 (2010)

Conclusion

- single qubit operations with trapped neutral atoms (99 % Fidelity)
- observation of Rydberg blockade
- "collective" Rabi oscillations of an atom pair : entanglement !
- deterministic entanglement between neutral atoms in their ground state (Fcorrected = 75 %)

What next ?

- do full two-qubit gates (phase gate and C-NOT gate)
- extend to small arrays (W states, « Schrödinger cat » states…)



blockade over all the sample : W state ⇒

$$|W\rangle = \frac{1}{\sqrt{5}}(|10000\rangle + |01000\rangle + ...|00001\rangle)$$

decoherence control… ?

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The Rydberg Team at Institut Optique

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