



UNIVERSITÉ
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CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

Manipulation of individual atoms for quantum information

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I A R P A
BE THE FUTURE



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RECHERCHE



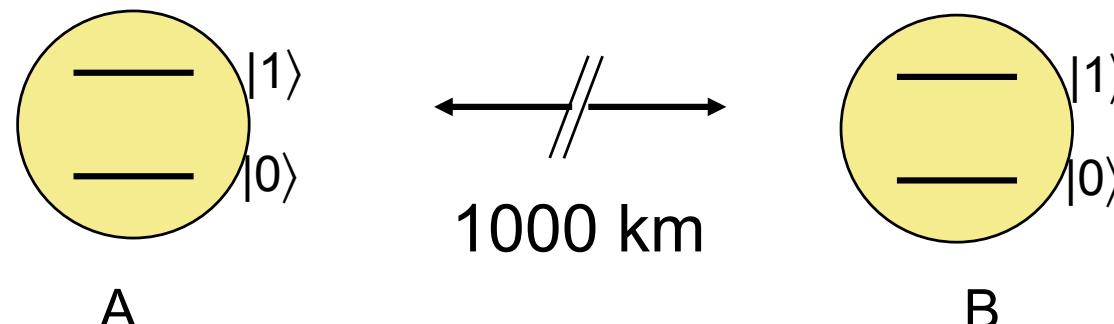
Manipulation of single quantum systems

Ion, atom, superconducting circuit, photon...

One single quantum object

Isolate the quantum system
Coherent manipulation of the state
(quantum bit): $\alpha|0\rangle + \beta|1\rangle$

More than two \Rightarrow entanglement



$$\frac{1}{\sqrt{2}}(|0_A, 1_B\rangle + |1_A, 0_B\rangle)$$

Why is it interesting?

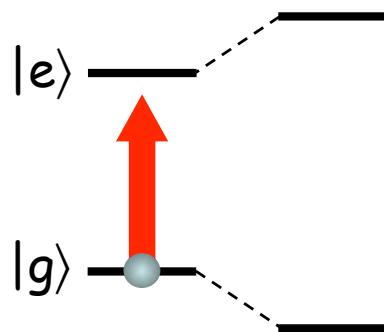
Quantum information and computing

Quantum metrology

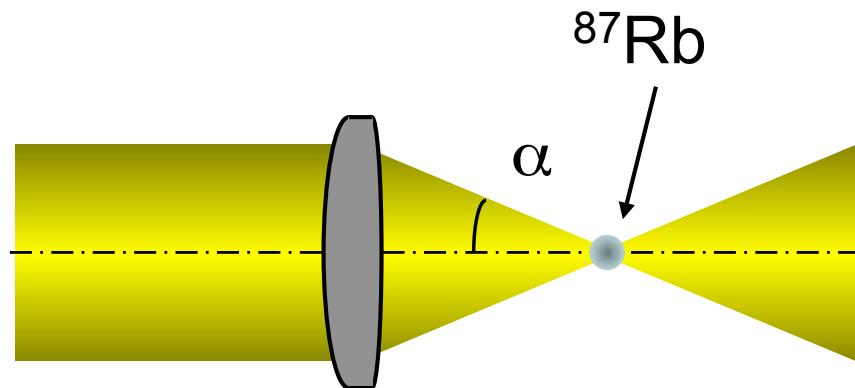
Explore the weirdness of quantum physics:
measurement, quantum jumps,
entanglement, interference...

Our system: single atoms in optical tweezers

Interaction atom – laser \Rightarrow lightshift



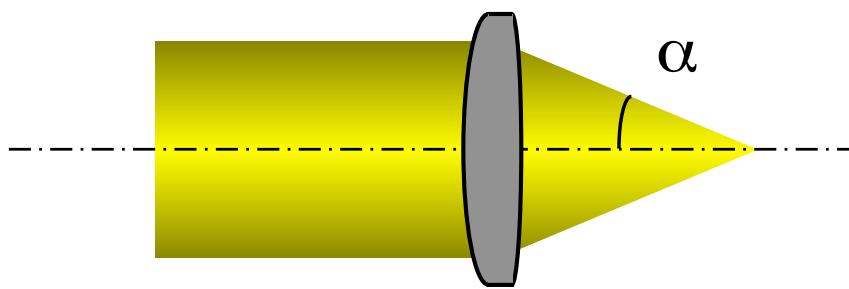
Tweezer = tightly focused far-off resonance dipole trap



Trap depth = 1 mK
 \Rightarrow cold atoms

(also Madison, Barcelona,
Munich, Bonn, Darmstadt, Oxford...)

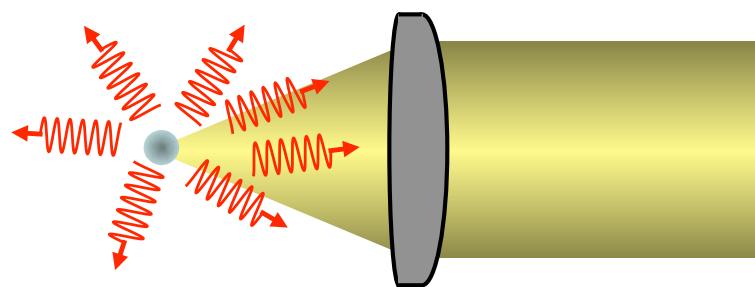
Strong focalisation \Rightarrow strong confinement (+ 3D trapping)



$$\text{NA} = \sin \alpha$$

$$w \sim \lambda / \text{NA}$$

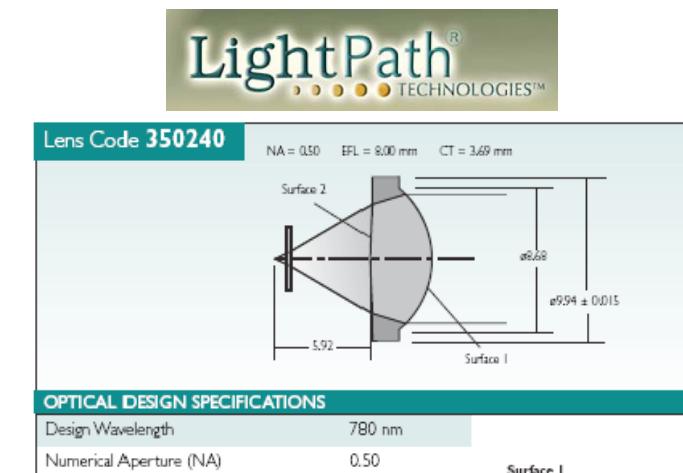
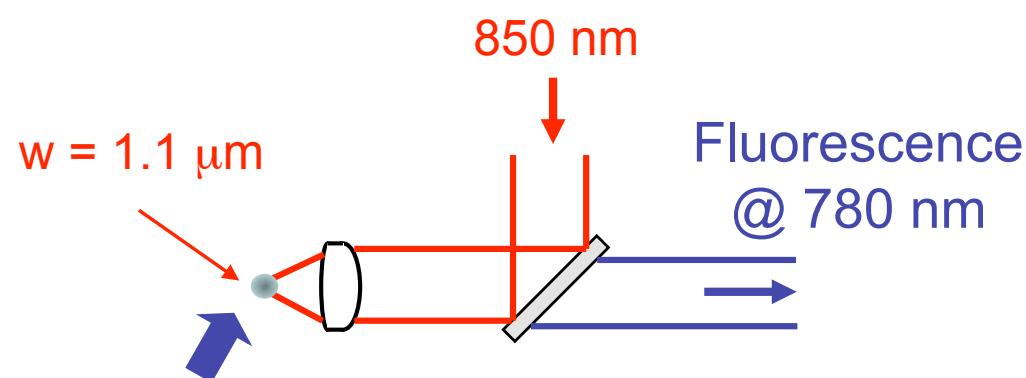
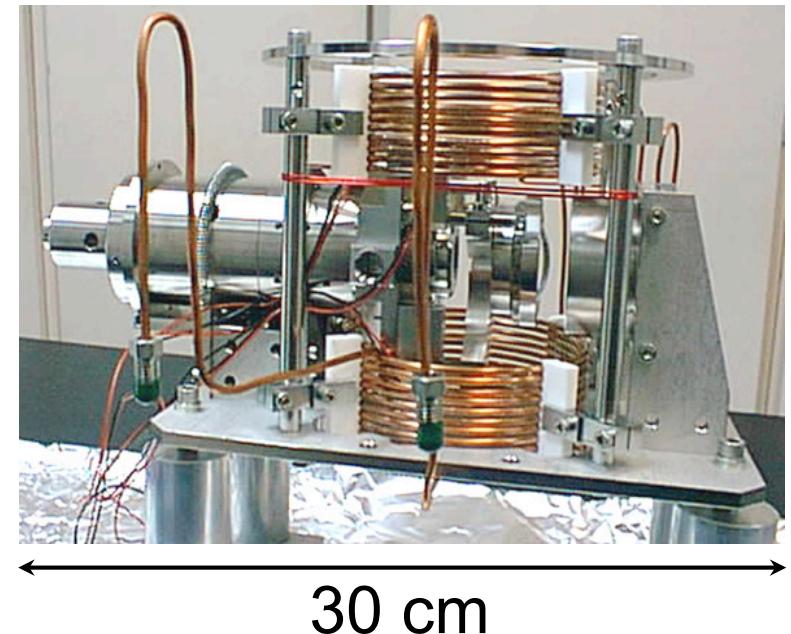
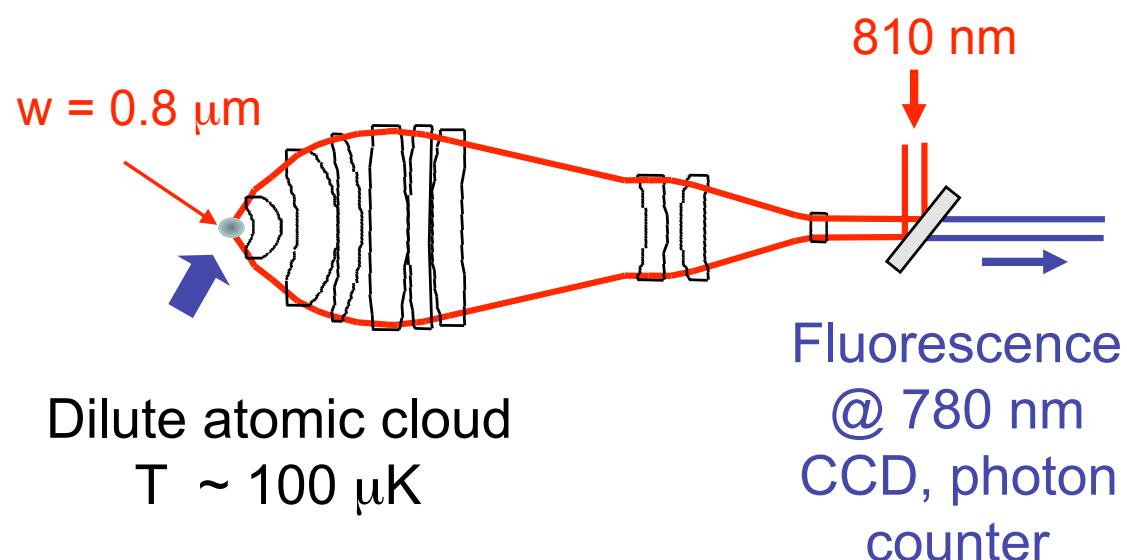
Large collection efficiency (fluorescence)



$$\Omega / 4\pi \sim \text{NA}^2$$

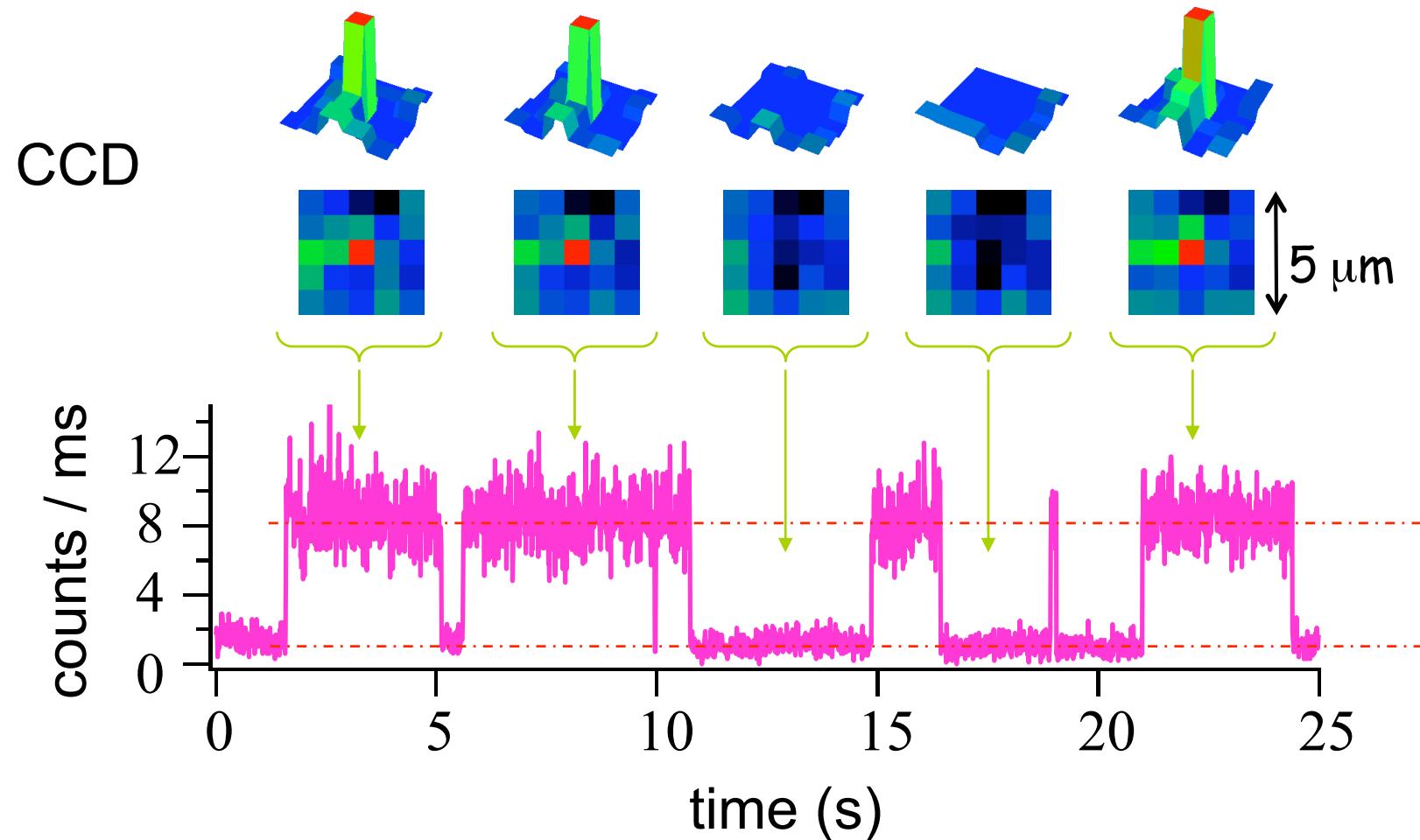
\Rightarrow Large numerical aperture lens

Tweezer: focusing optical systems with large N.A.



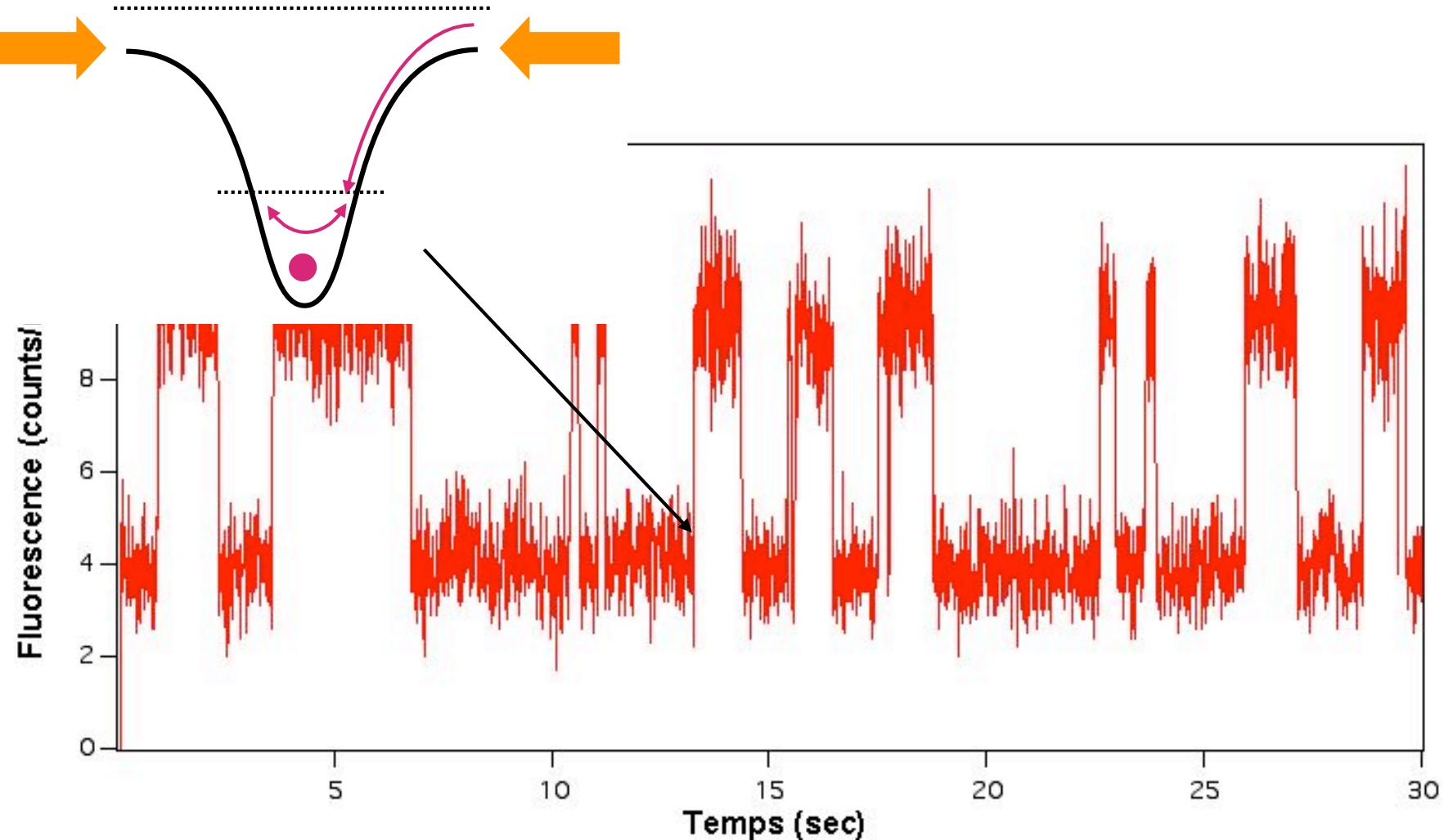
Sortais *et al.* PRA 75, 013406 (2007)

Single atom trapping

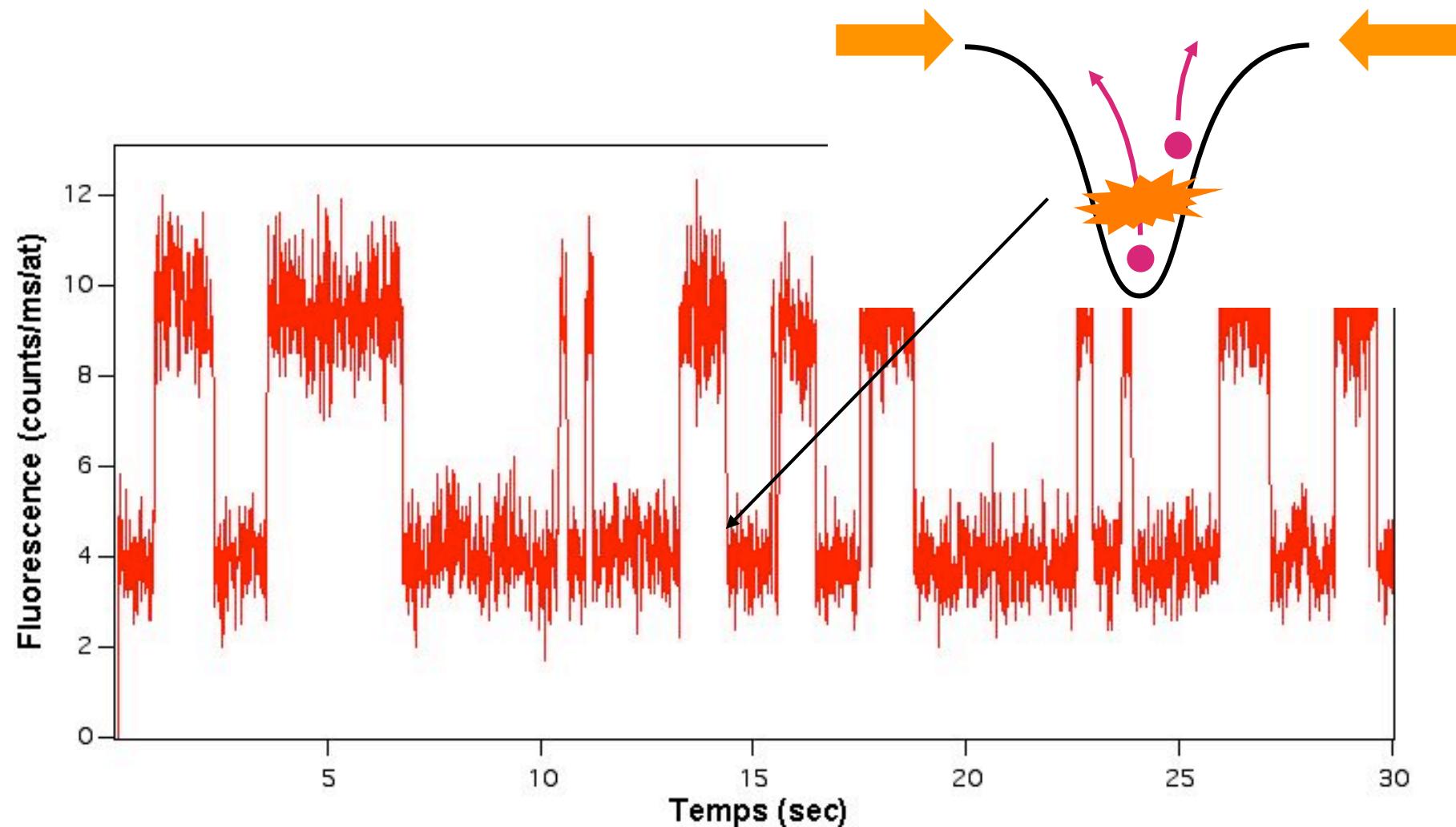


Fluorescence (780 nm) induced by the molasses beams

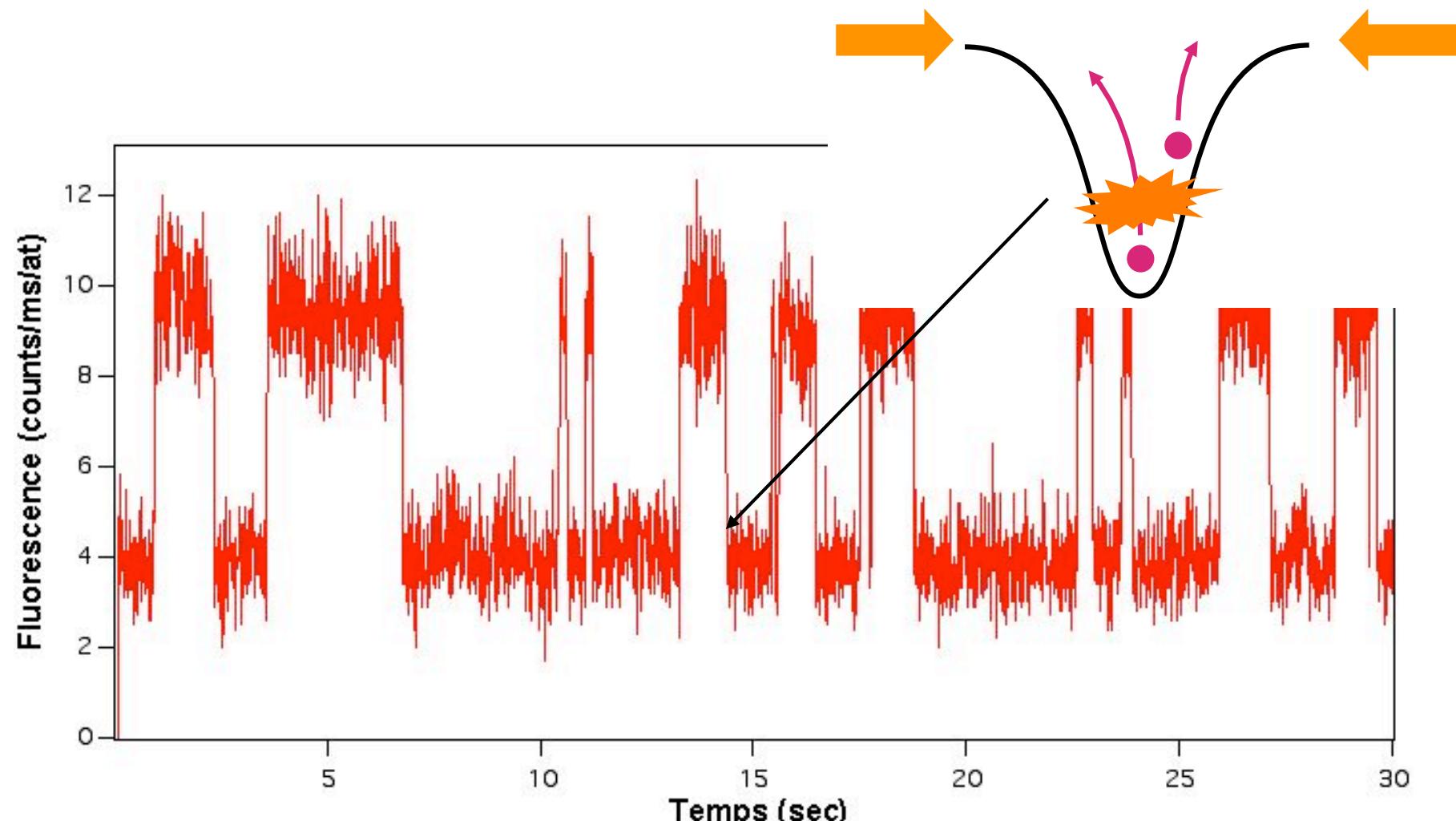
Single atom trapping



Single atom trapping

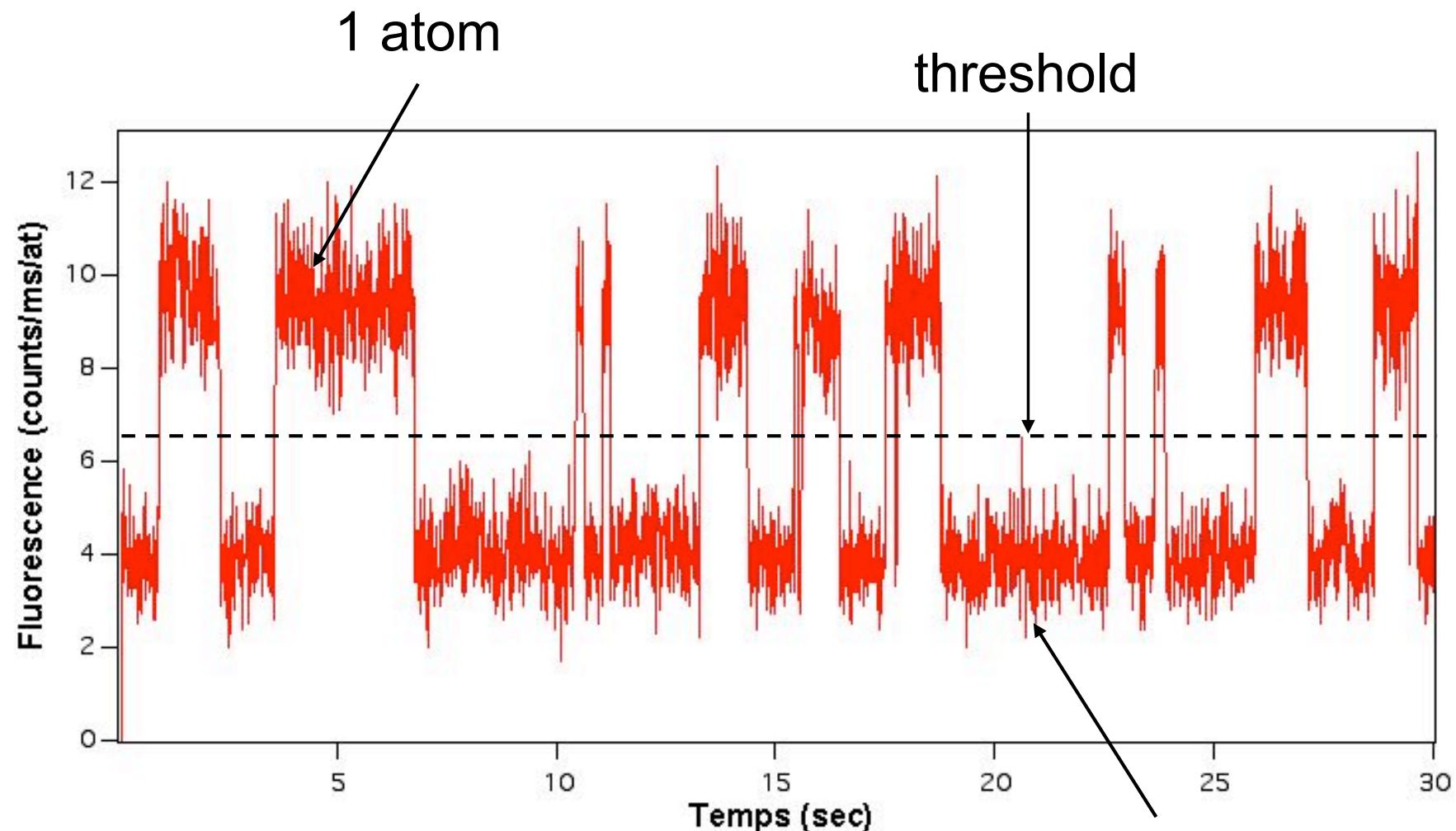


Single atom trapping



Requires trap size < few μm

Single atom trapping



Trapping time
in the dark ~ 10 s

Sortais *et al.*, PRA 75, 013406 (2007)

Outline

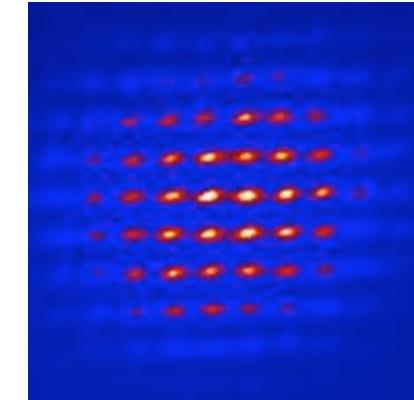
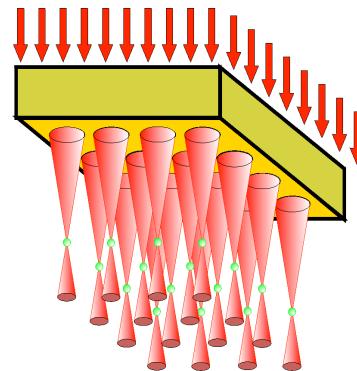
1. Arrays of optical tweezers
2. Single qubit manipulations
3. Rydberg interaction for entanglement
4. Deterministic excitation to a Rydberg state
5. Demonstration of Rydberg blockade
6. Collective excitation in the blockade regime

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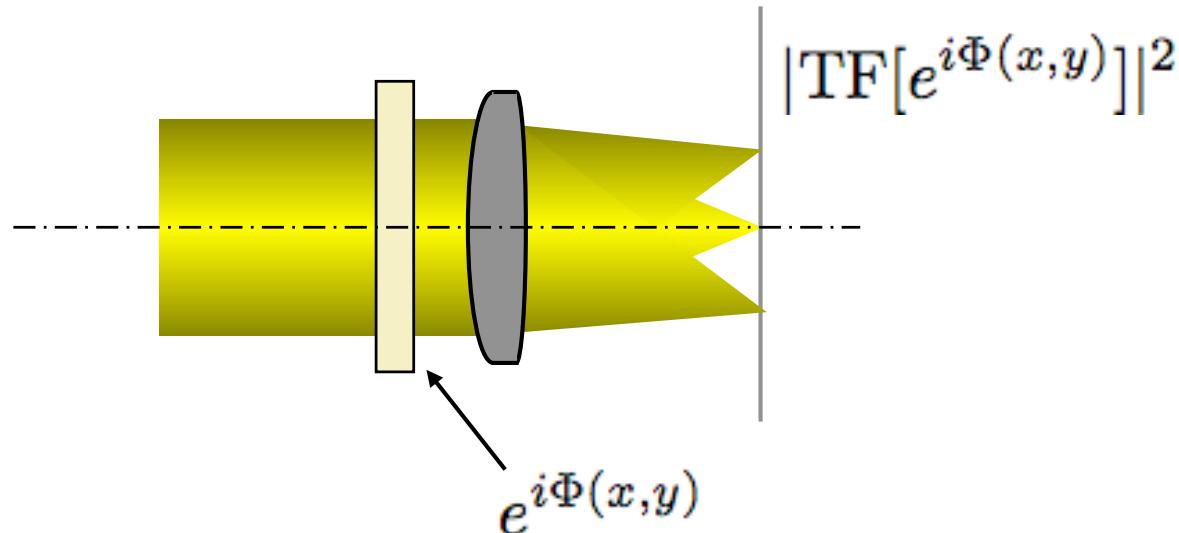
2D arrays of optical tweezers

Array of microlenses

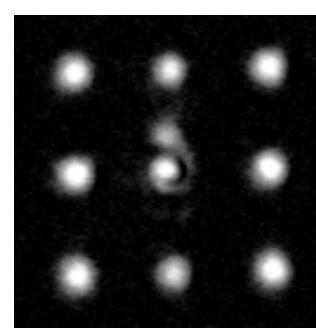
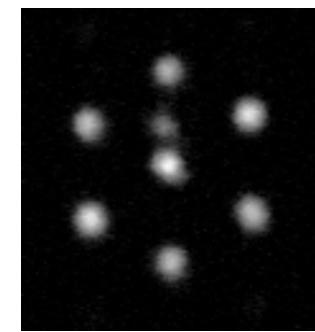
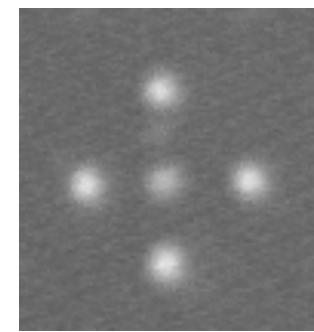
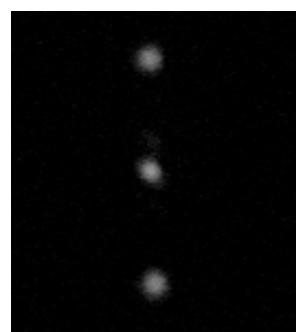
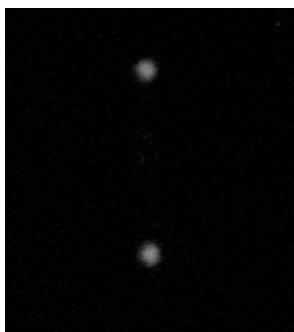
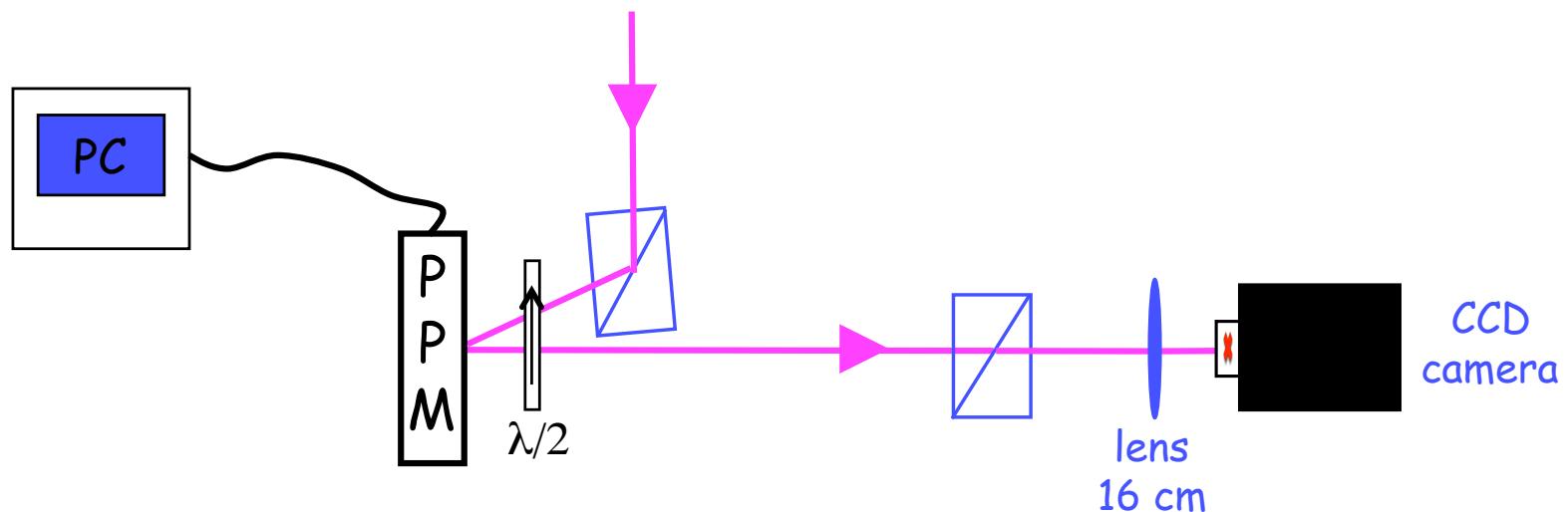


Dumke *et al*, PRL **89**, 097903 (2002)

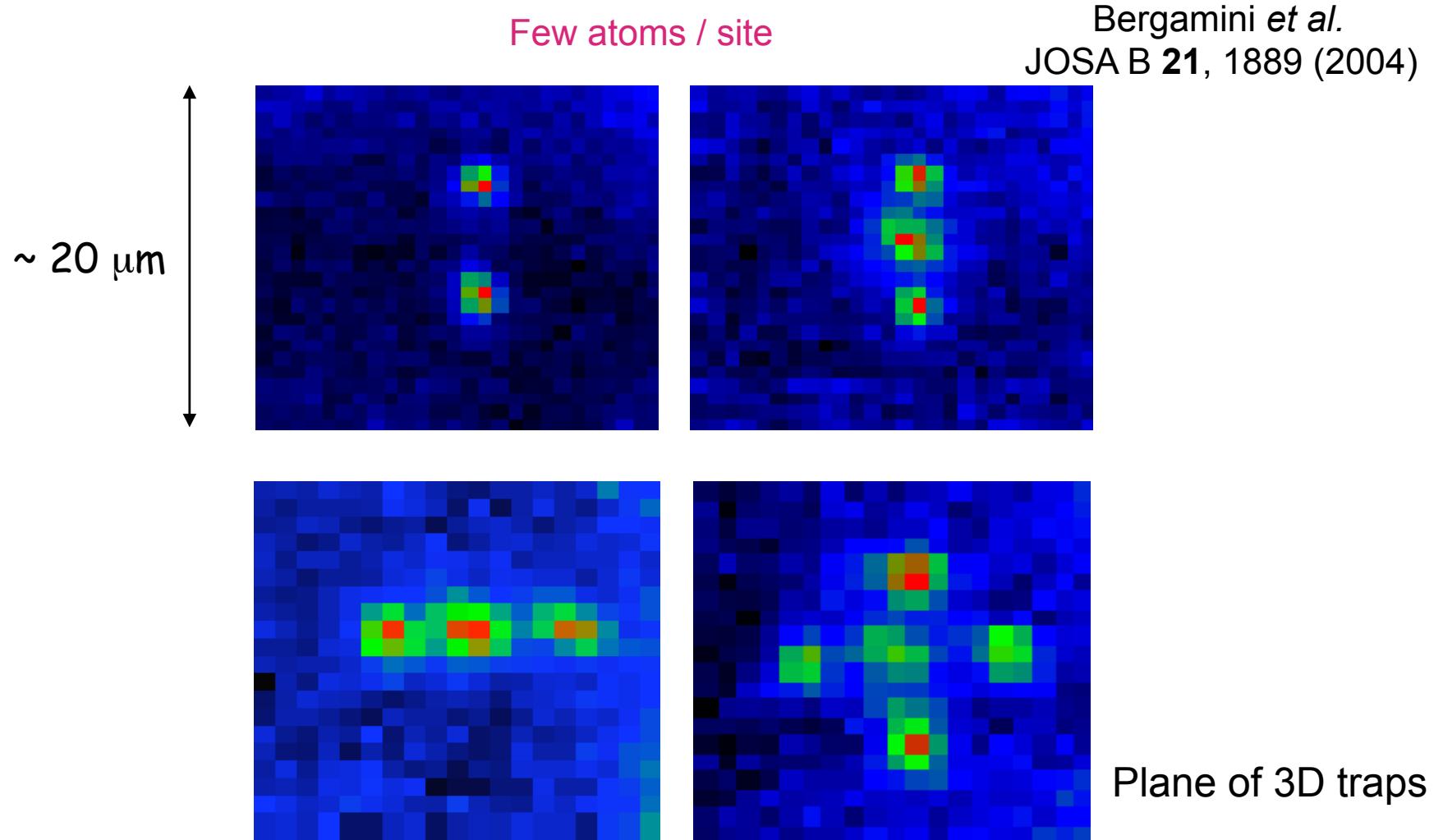
Spatial light modulator



Various geometries of 2D arrays



Arrays of trapped atoms

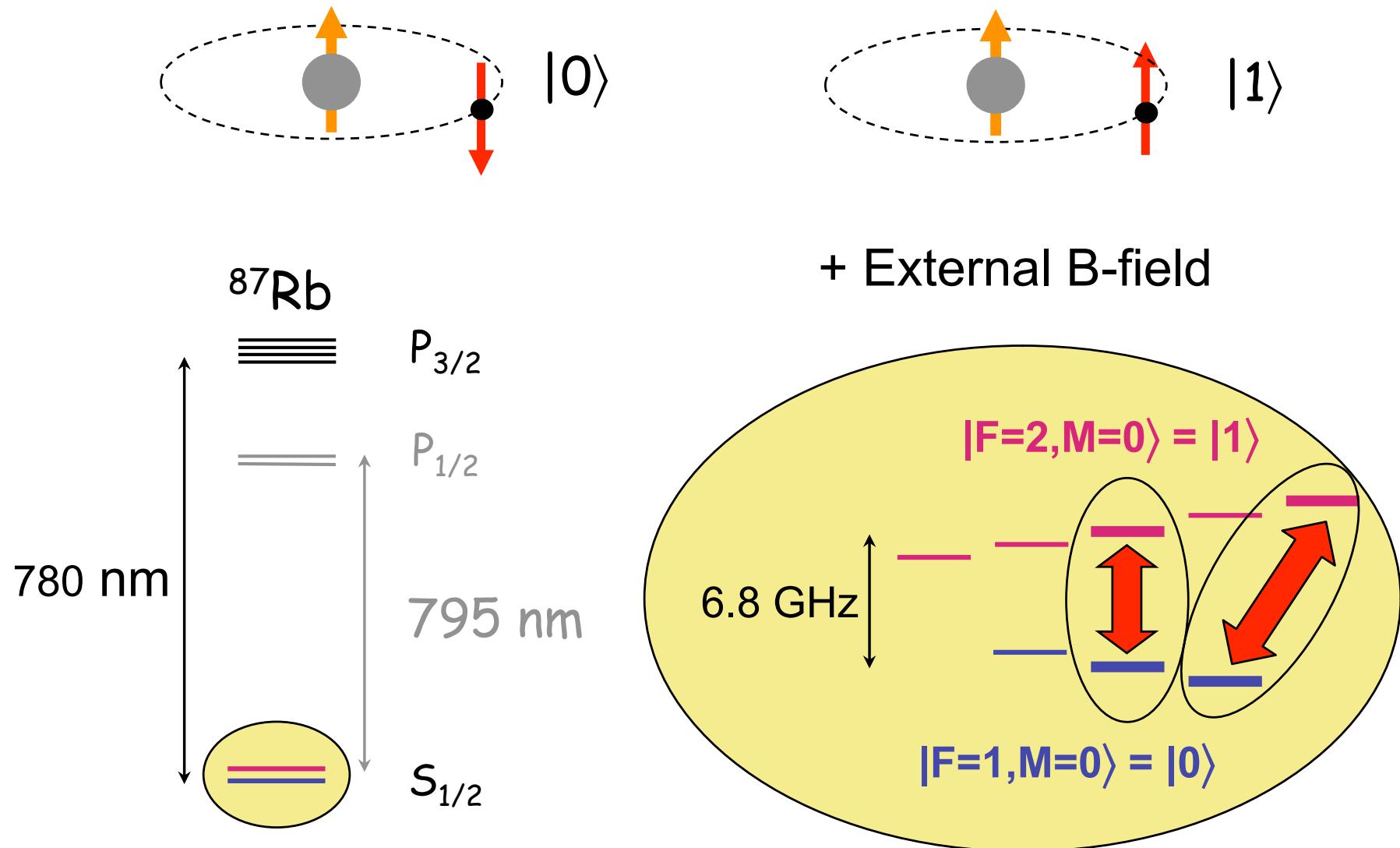


Non deterministic loading = probability to fill N traps
 $= 1 / 2^N$

Outline

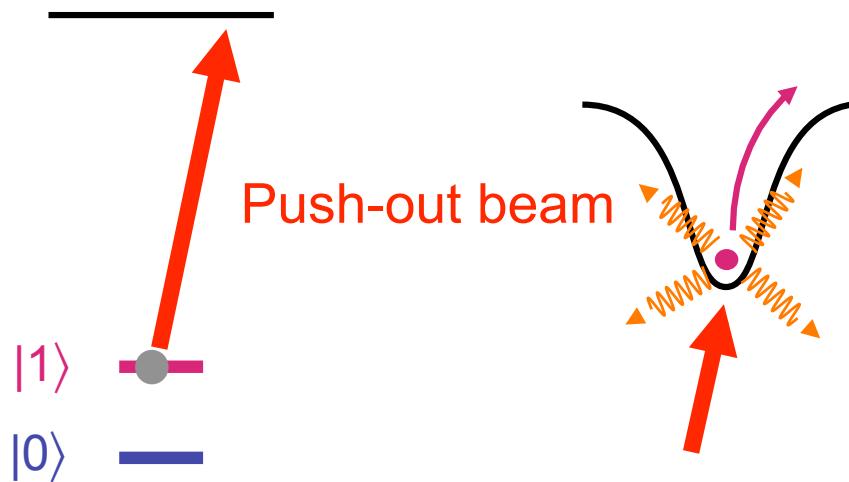
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The two-level system (${}^{87}\text{Rb}$)



Readout of the state of the qubit

State-selective detection (destructive)

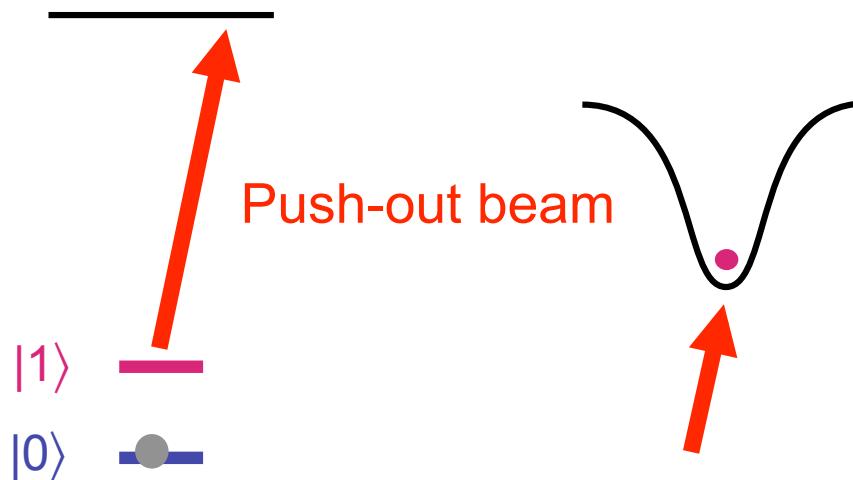


Check for the presence
of the atom

No atom $\Rightarrow |1\rangle$

Readout of the state of the qubit

State-selective detection (destructive)

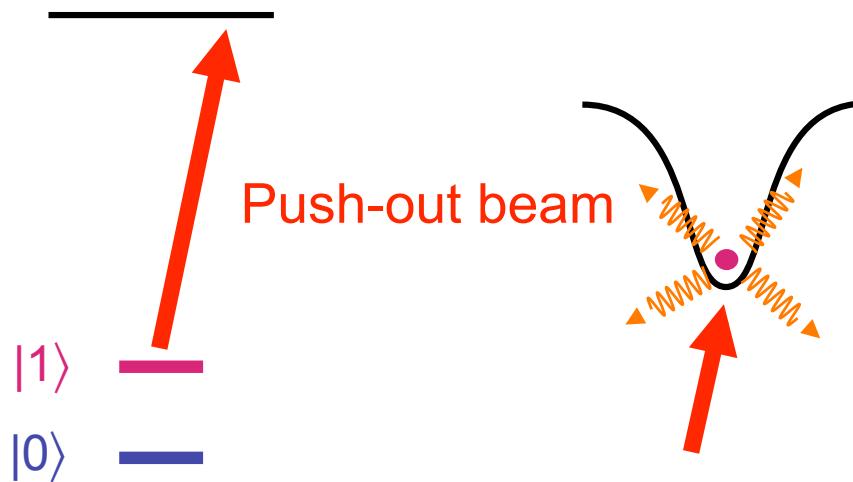


Check for the presence
of the atom

Atom $\Rightarrow |0\rangle$

Readout of the state of the qubit

State-selective detection (destructive)

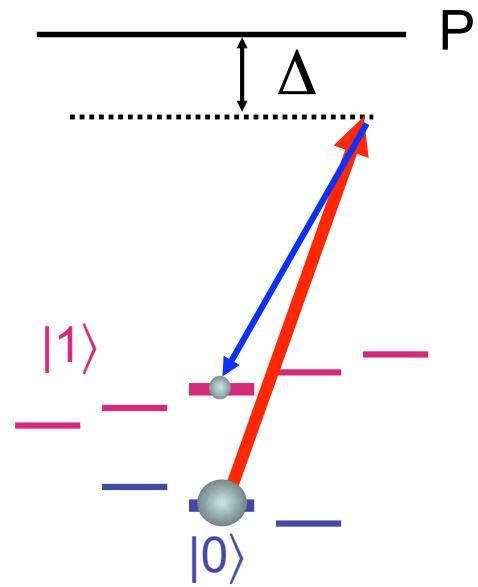


Check for the presence
of the atom

No atom $\Rightarrow |1\rangle$
Atom $\Rightarrow |0\rangle$

98% efficiency + quantum
projection noise limited

Single-atom qubit rotation



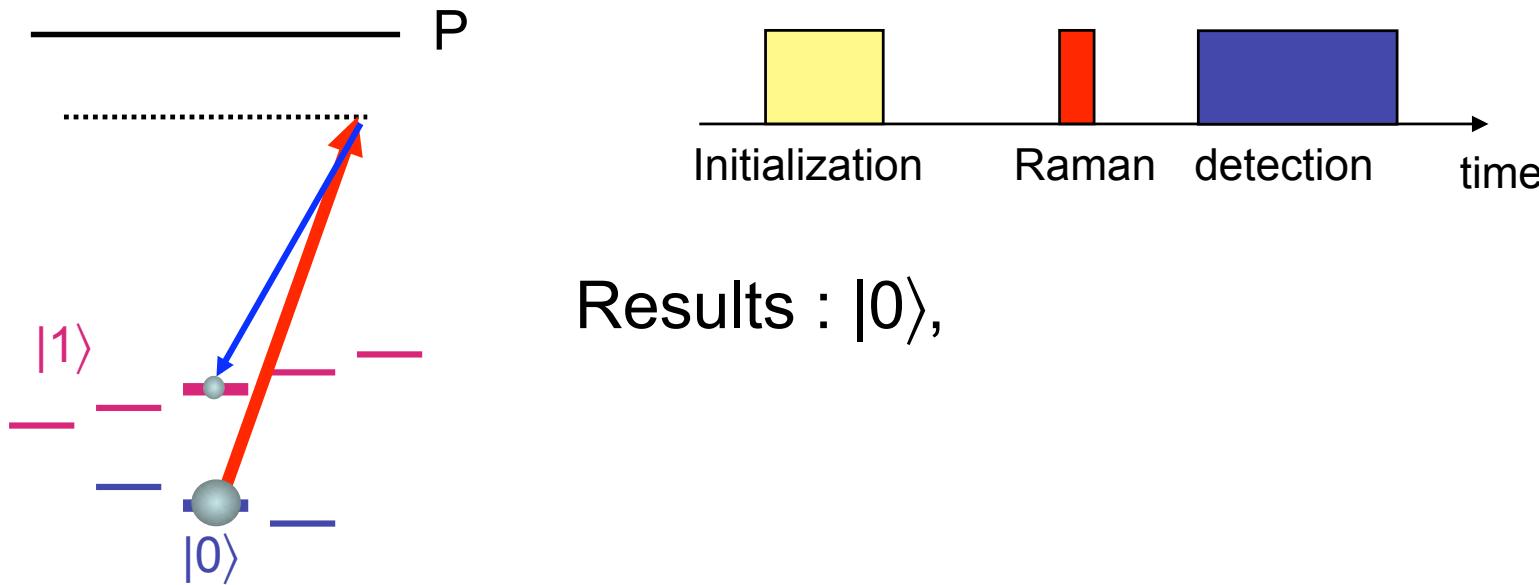
Raman transition $\Omega_R = \frac{\Omega_1 \Omega_2}{2\Delta}$

Realizes the rotation $R(\theta, \varphi)$

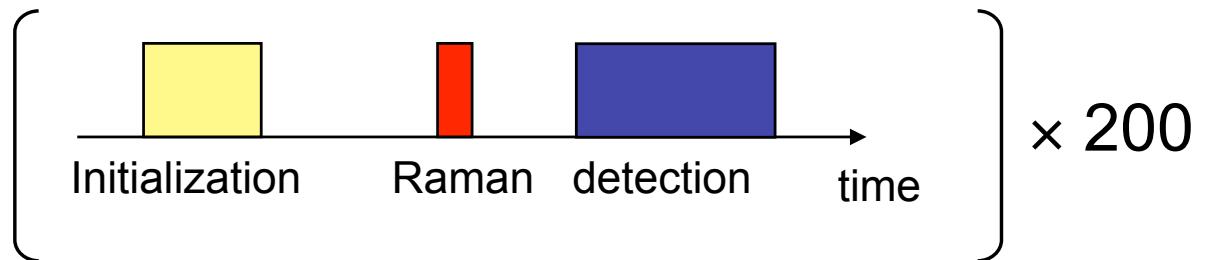
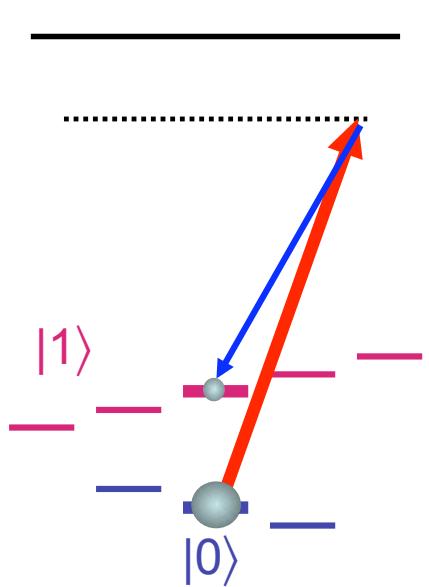
$$|0\rangle \rightarrow \cos \frac{\theta}{2} |0\rangle + \sin \frac{\theta}{2} e^{i\varphi} |1\rangle$$

$$|1\rangle \rightarrow -\sin \frac{\theta}{2} e^{i\varphi} |0\rangle + \cos \frac{\theta}{2} |1\rangle$$

Single-atom qubit rotation

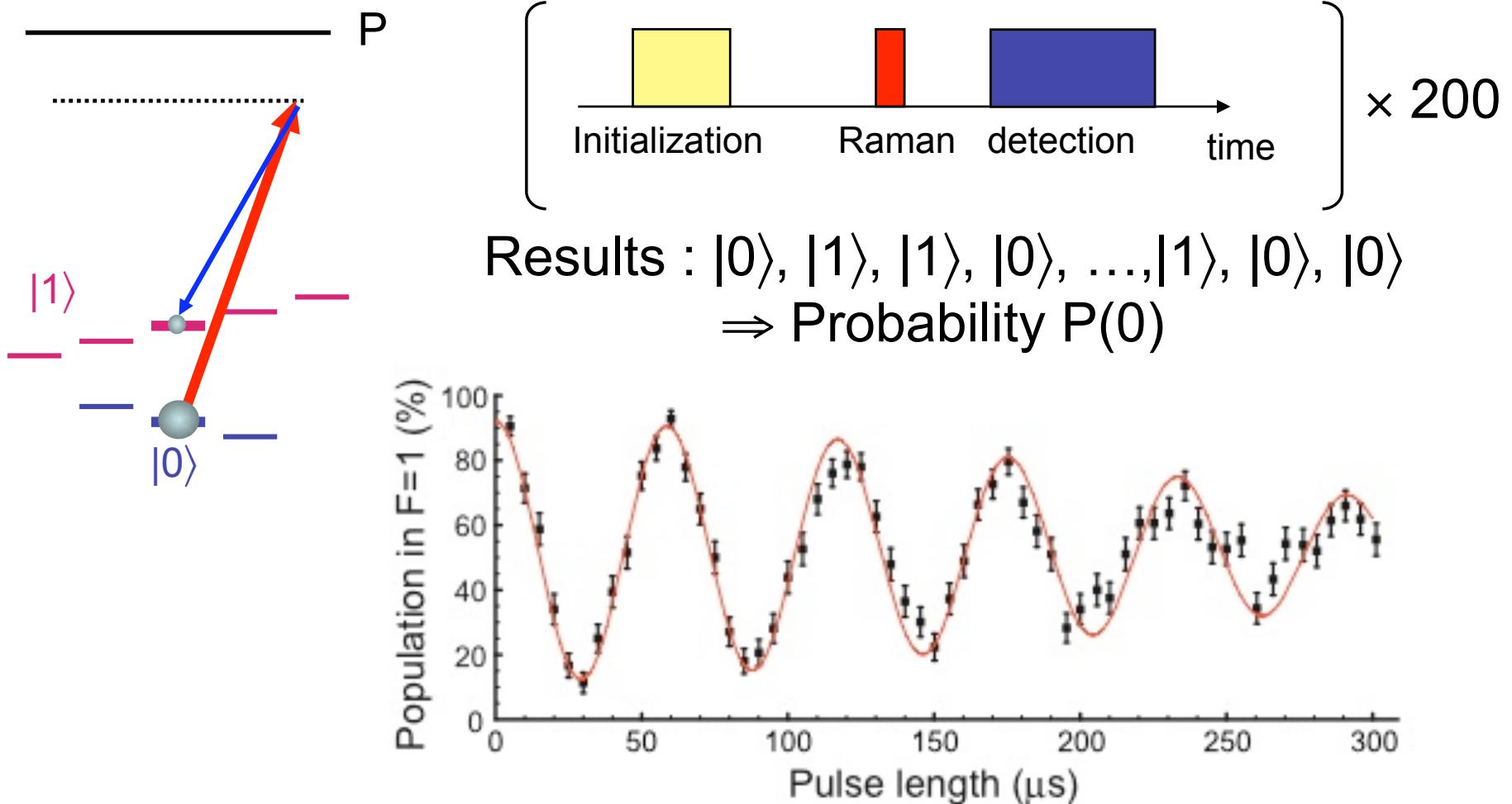


Single-atom qubit rotation



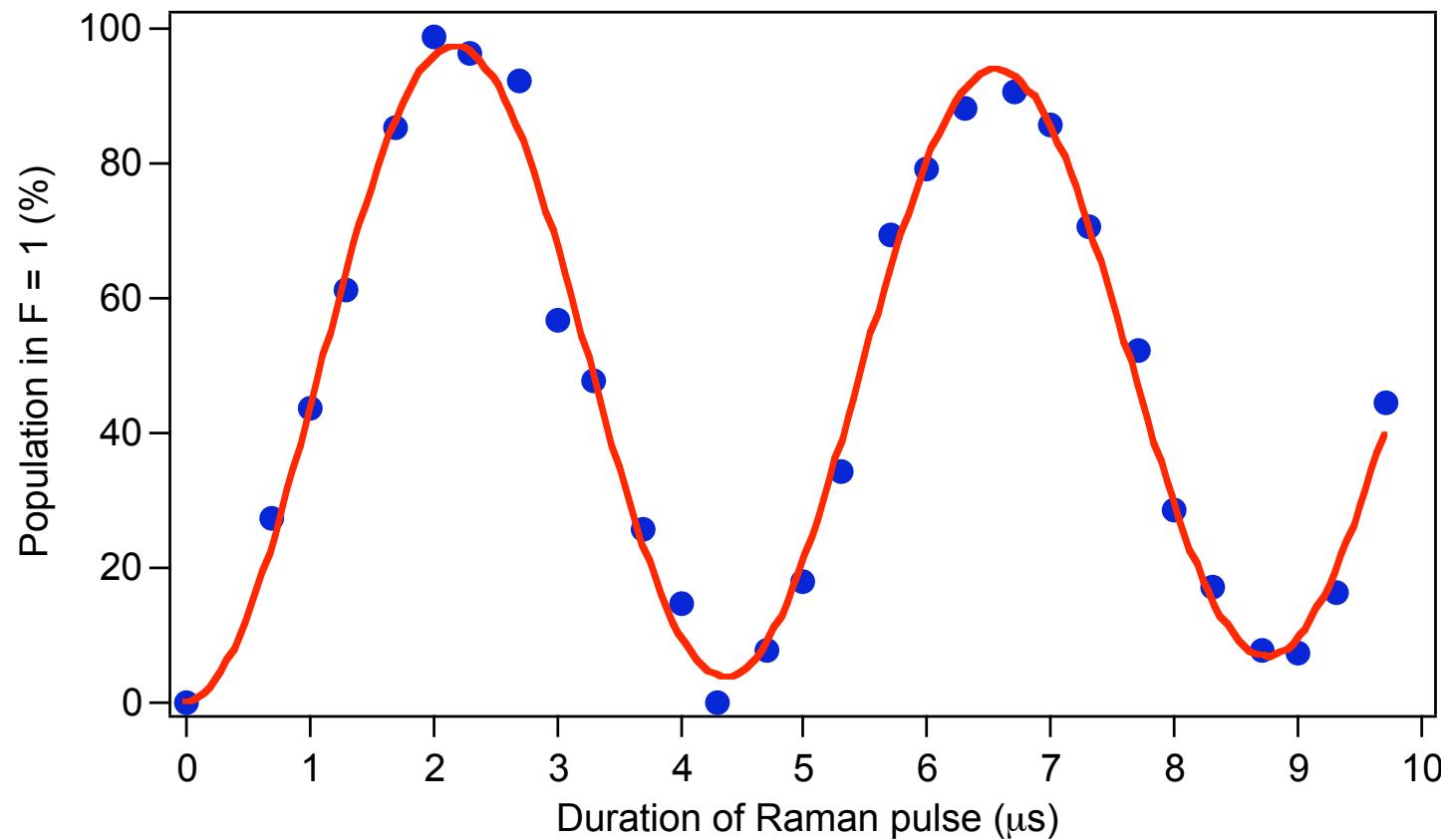
Results : $|0\rangle, |1\rangle, |1\rangle, |0\rangle, \dots, |1\rangle, |0\rangle, |0\rangle$
⇒ Probability $P(0)$

Single-atom qubit rotation



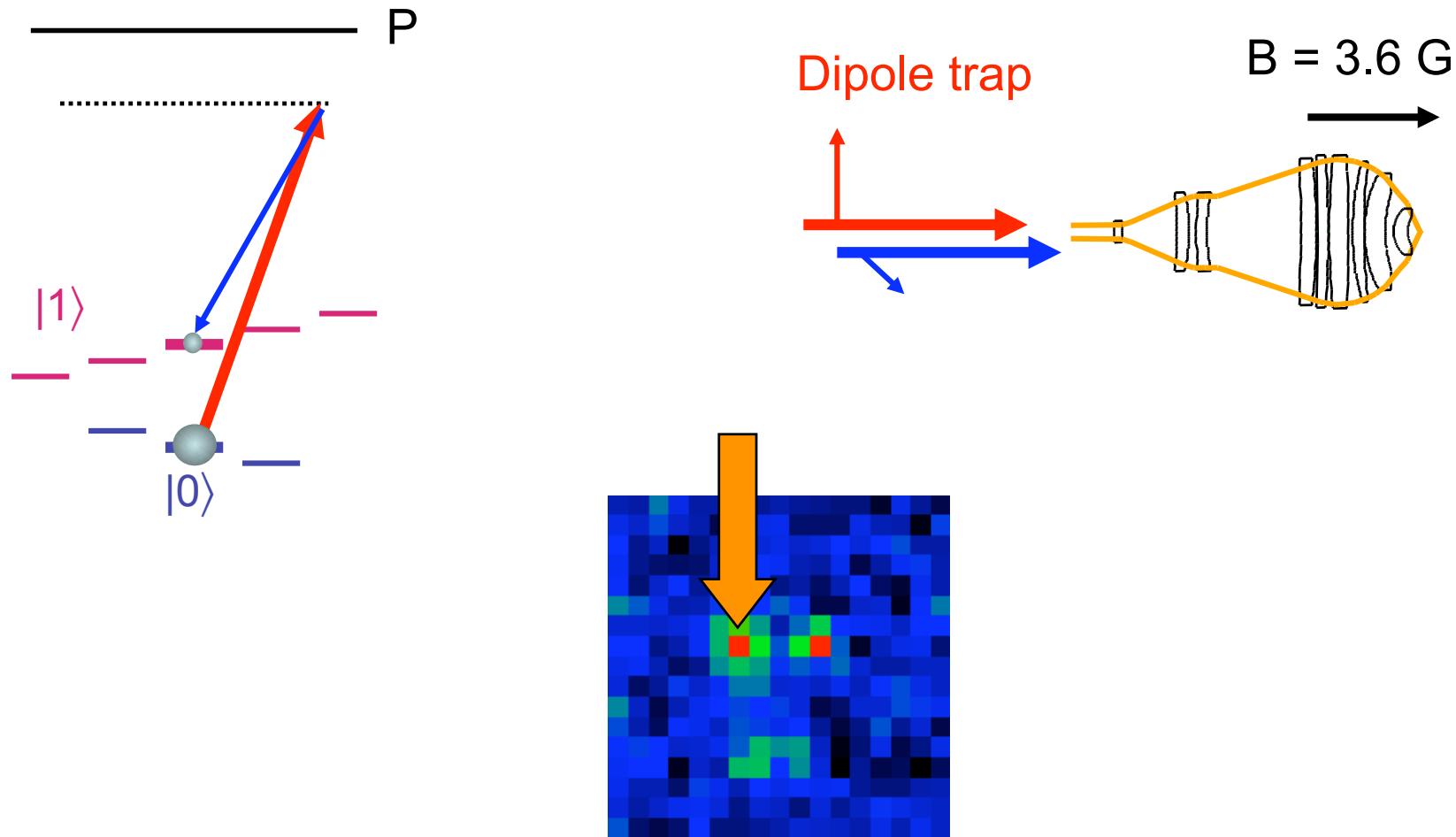
M.P.A. Jones *et al.*, PRA 75, 040301 (2007)

Rabi oscillations $|F = 1, M = 1\rangle \leftrightarrow |F = 2, M = 2\rangle$



Pulse $\pi = 99\%$

Adressability?



$$\text{distance} = 2 \text{ } \mu\text{m}, P_{\text{at } 1} = 100\% \Rightarrow P_{\text{at } 2} = 1\%$$

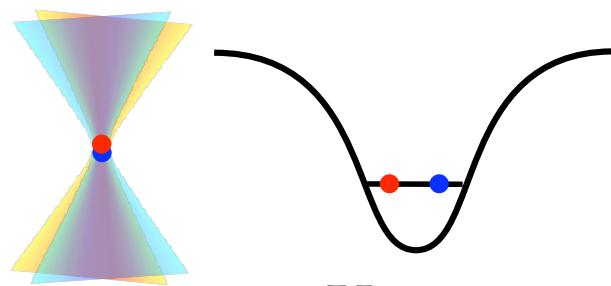
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Perspectives for creating entanglement

State-dependent interaction

s-wave collision



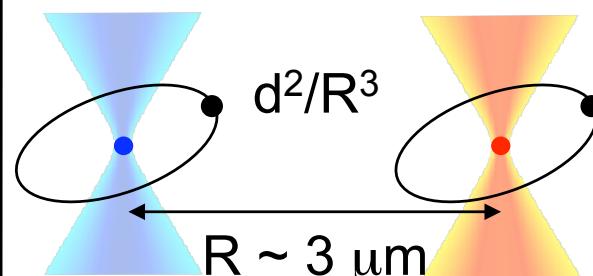
$$\Phi = \frac{U t}{\hbar}$$

$$U \approx \hbar \times 1 \text{ kHz}$$

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

$$\rightarrow |0_A, 0_B\rangle + |0_A, 1_B\rangle + \\ |1_A, 0_B\rangle + e^{i\Phi} |1_A, 1_B\rangle$$

dipole-dipole (Rydberg)



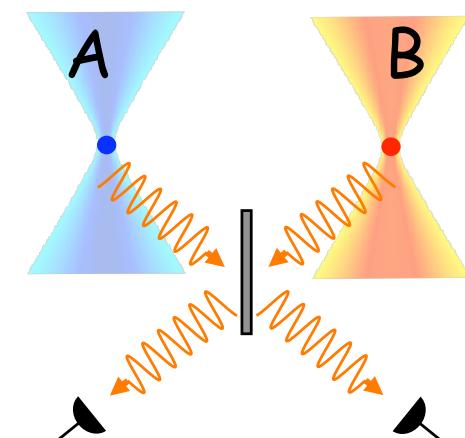
$$U \sim \hbar \times 1 - 100 \text{ MHz}$$

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



$$\frac{1}{\sqrt{2}}(|0_A, 1_B\rangle + |1_A, 0_B\rangle)$$

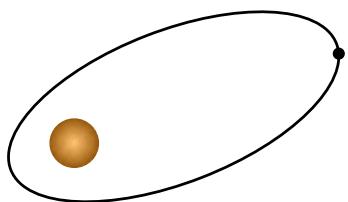
Conditional entanglement



Entanglement induced by a measurement

Slow and hard to scale

« Rydberg blockade »

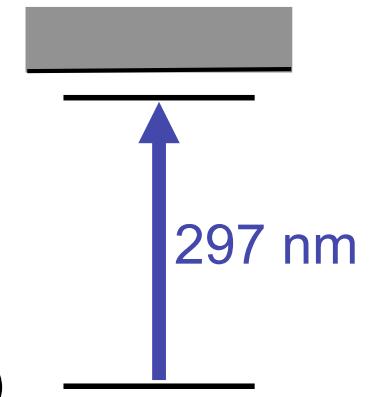


$n \gg 1$

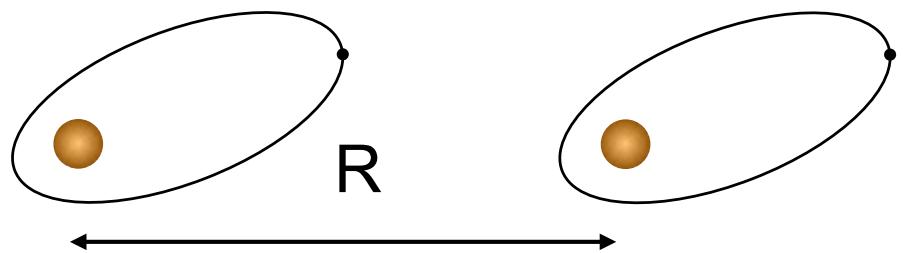
Long lifetime ($>100 \mu\text{s}$)

$r(n,l)$

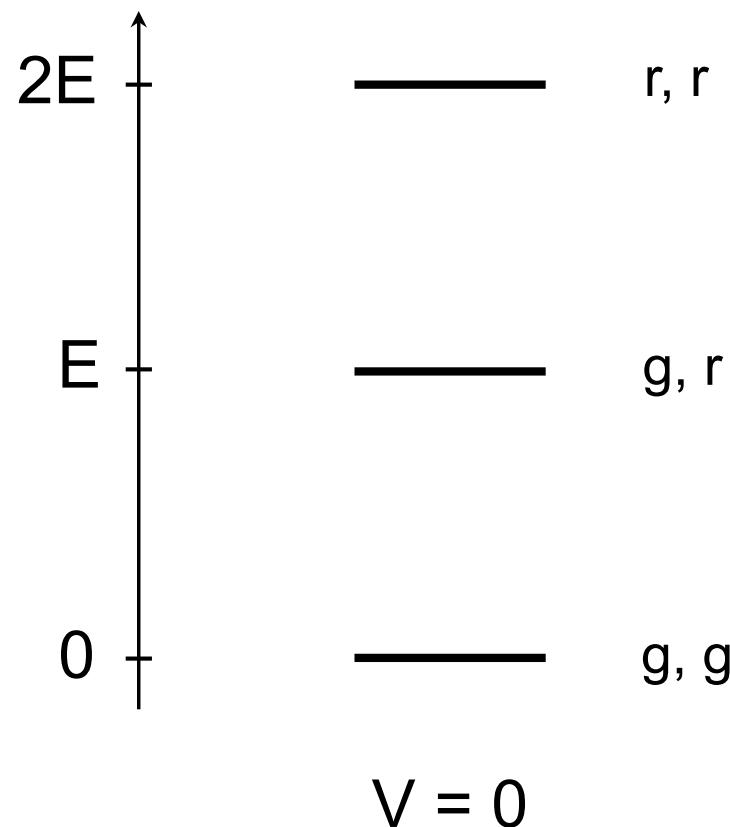
$g(5,s)$



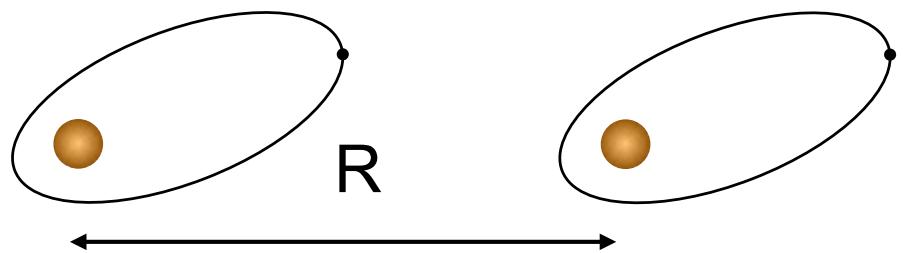
« Rydberg blockade »



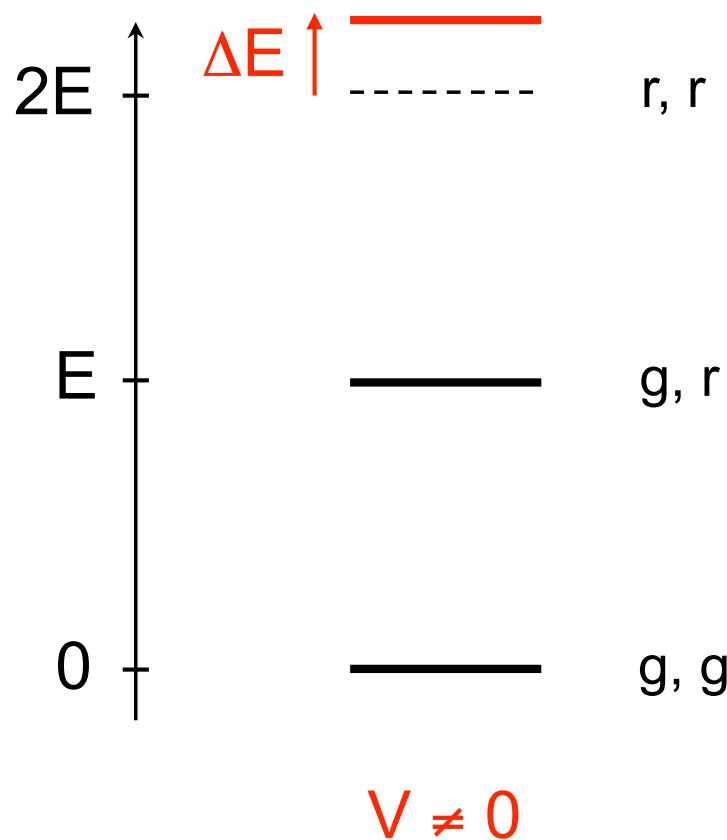
$$V \sim \frac{1}{4\pi\epsilon_0} \frac{\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{d}}_2}{R^3}$$



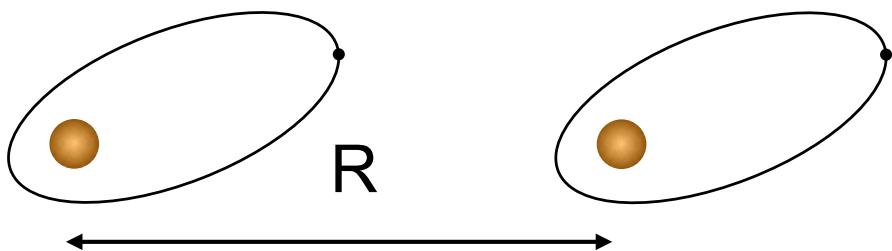
« Rydberg blockade »



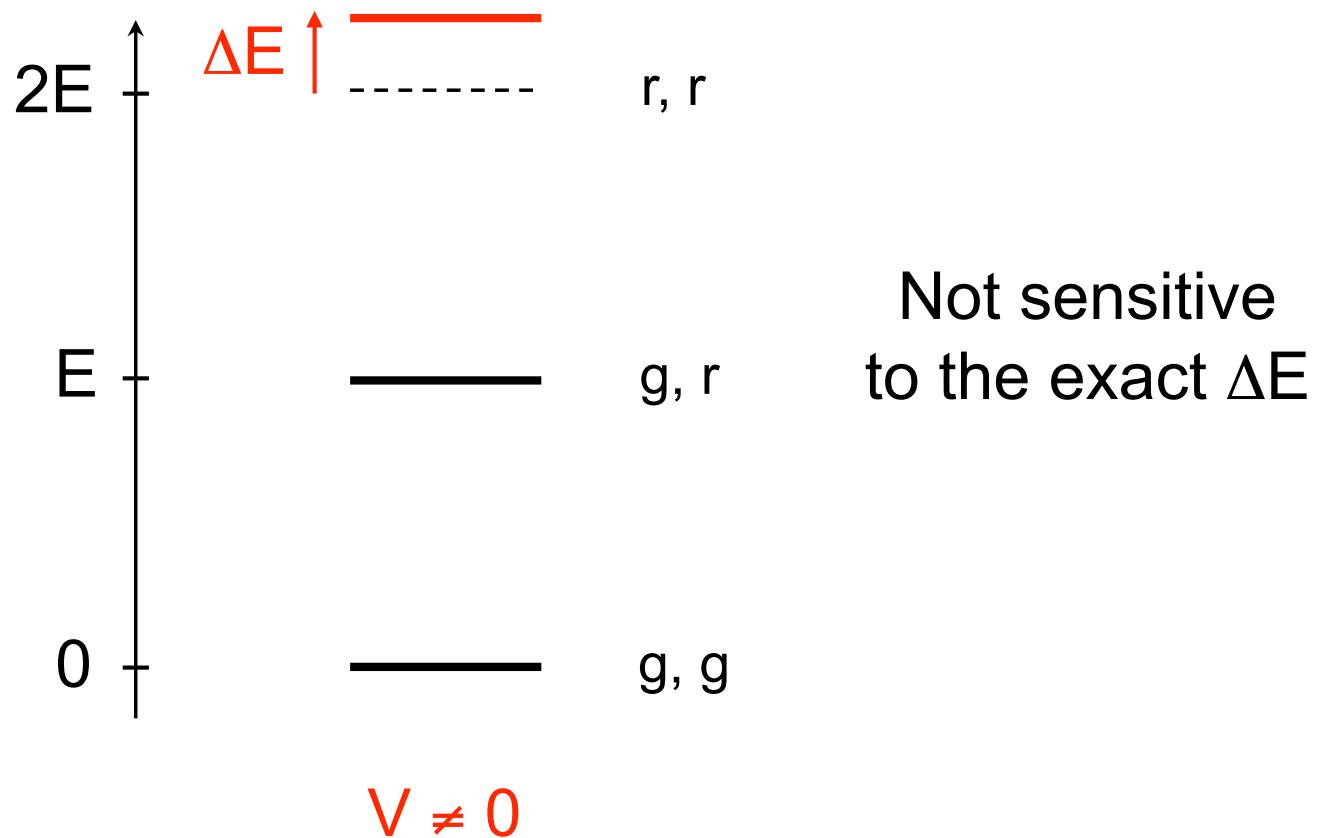
$$V \sim \frac{1}{4\pi\epsilon_0} \frac{\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{d}}_2}{R^3}$$



« Rydberg blockade »



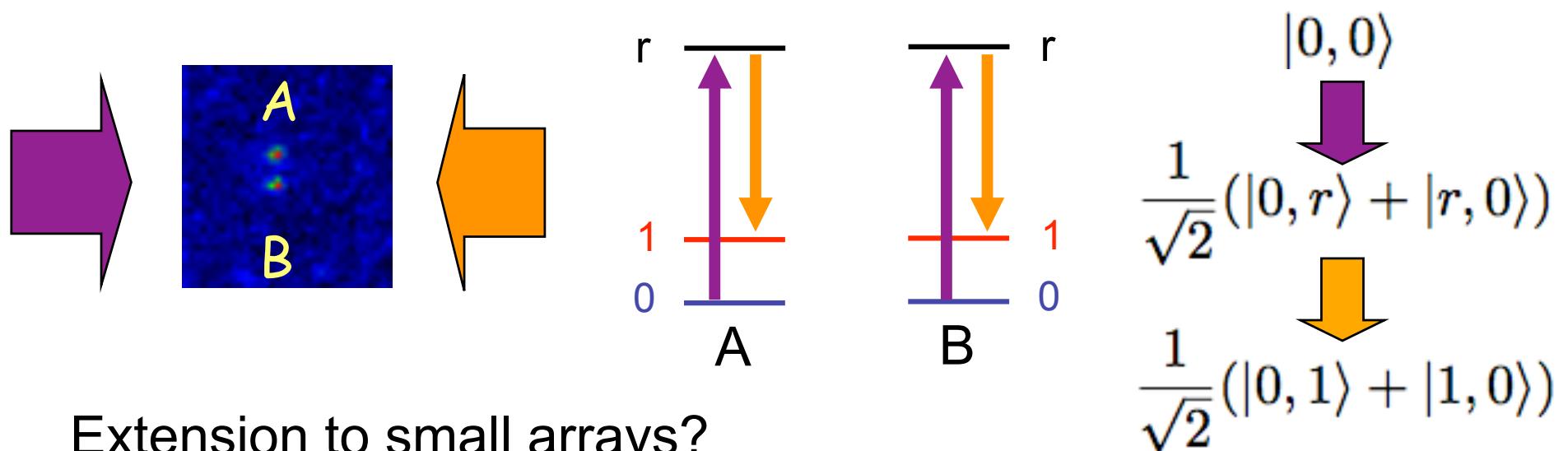
$$V \sim \frac{1}{4\pi\epsilon_0} \frac{\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{d}}_2}{R^3}$$



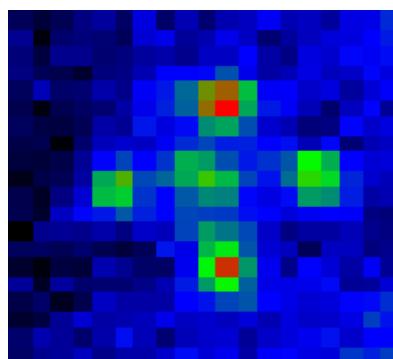
Deterministic entanglement using Rydberg excitation

Entanglement of 2 atoms: prepare

$$\frac{1}{\sqrt{2}}(|0_A, 1_B\rangle + |1_A, 0_B\rangle)$$



Extension to small arrays?



Blockade over all the sample \Rightarrow

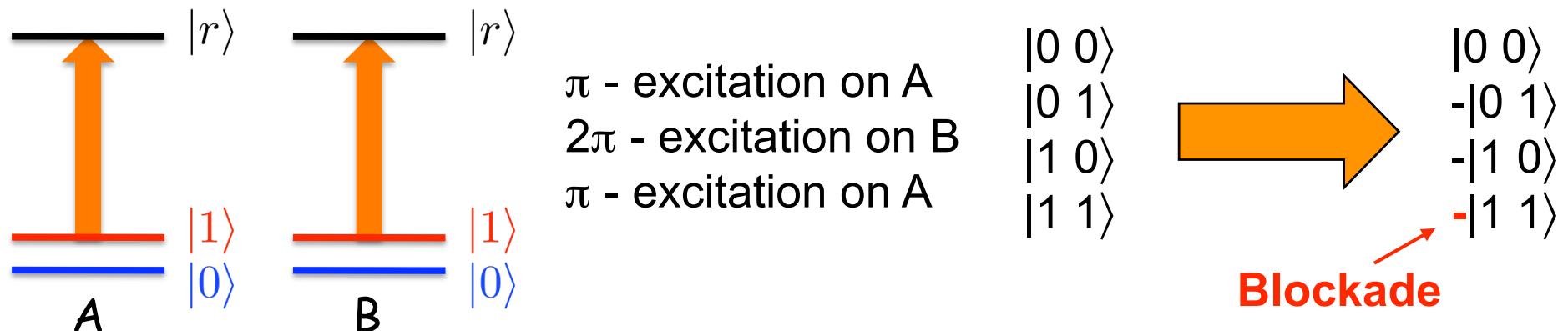
$$|W\rangle = \frac{1}{\sqrt{5}}(|10000\rangle + |01000\rangle + \dots + |00001\rangle)$$

Jaksch, et al. PRL, vol. 85, p. 2208 (2000)

Qubit gates (addressability required)

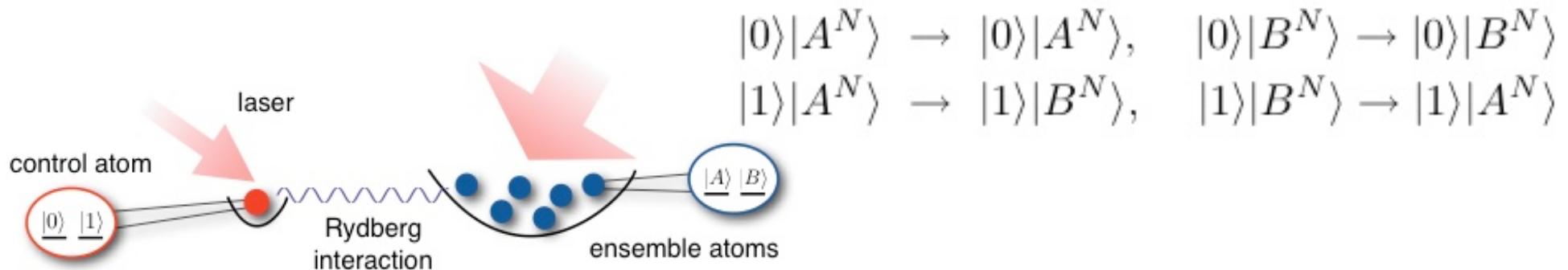
Control - phase gate

D. Jaksch, PRL 85, 2208 (2000)



Control - Not gate

M. Müller, arXiv:0811.1155 (2008)

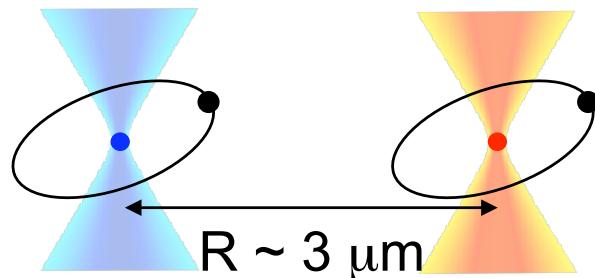


Implements N-spin interaction

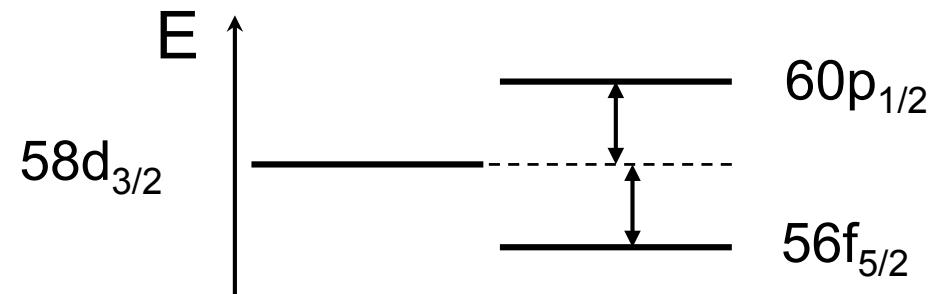
$$H = |0\rangle\langle 0| \otimes \hat{1} + |1\rangle\langle 1| \otimes J\hat{\sigma}_x^{(1)}\hat{\sigma}_x^{(2)}\hat{\sigma}_x^{(3)} \dots$$

Interaction between two Rydberg atoms

No electric field: **dipole of transition**



« Accidental » degeneracy



In general: vdW interaction

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

e.g.: $n = 60$, $R = 3 \mu\text{m}$
 $\Rightarrow \Delta E \approx 5 \text{ MHz}$

\Rightarrow dipole-dipole interaction

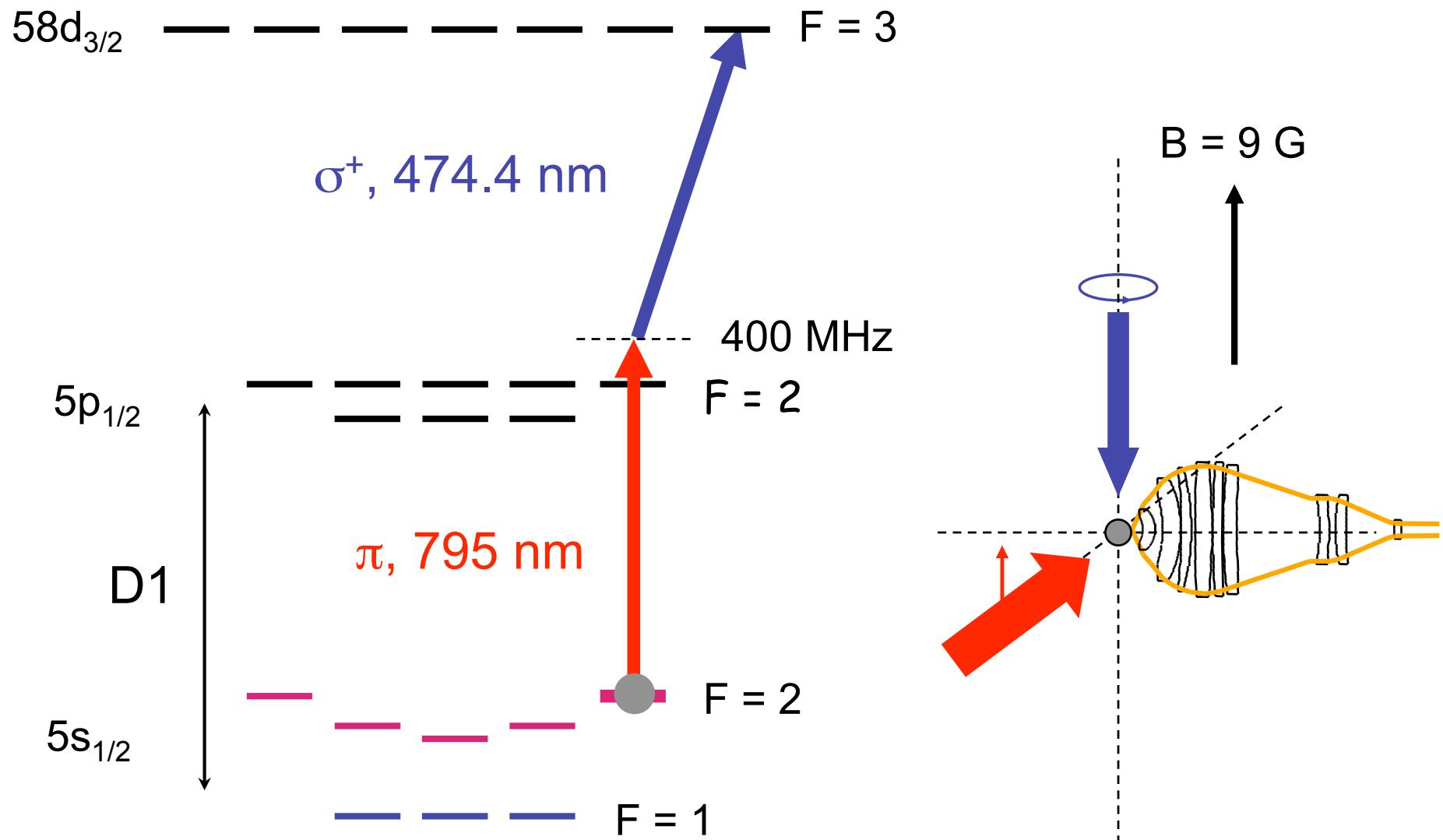
$$\Delta E \sim \frac{1}{4\pi\epsilon_0} \frac{(ea_0)^2}{R^3} n^4$$

$n = 58$, $R = 3 \mu\text{m}$
 $\Rightarrow \Delta E \approx 120 \text{ MHz}$

Outline

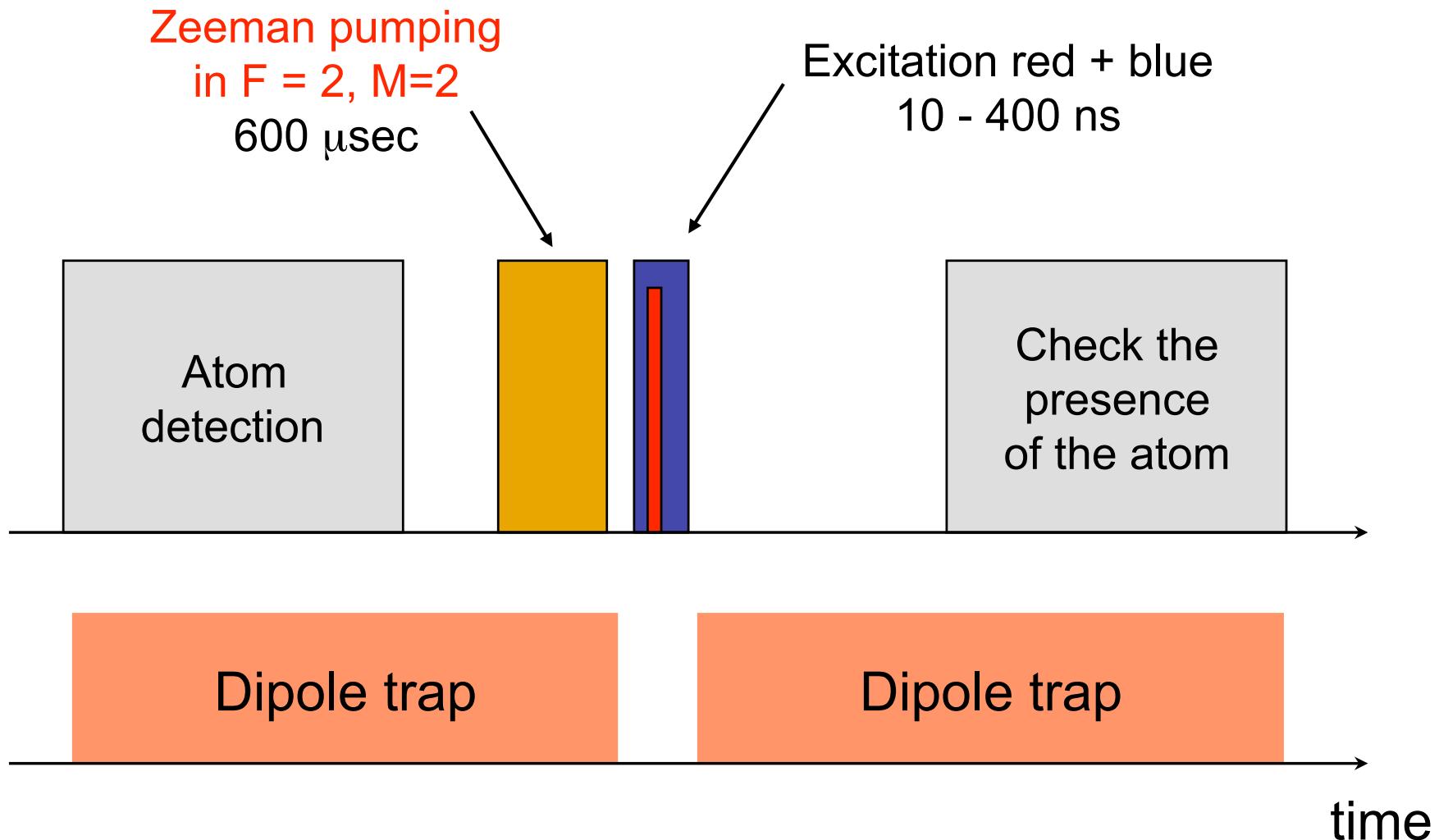
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Deterministic Rydberg excitation



Deterministic Rydberg excitation

Repeat 100 times the sequence



Detection of Rydbergs

Through loss of the atom

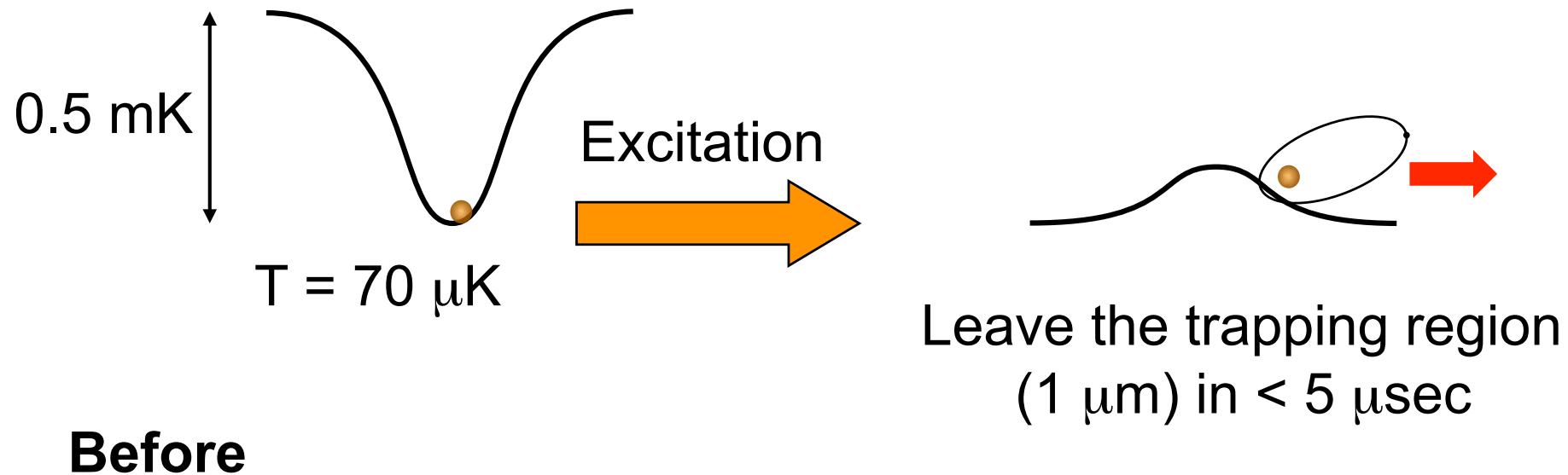
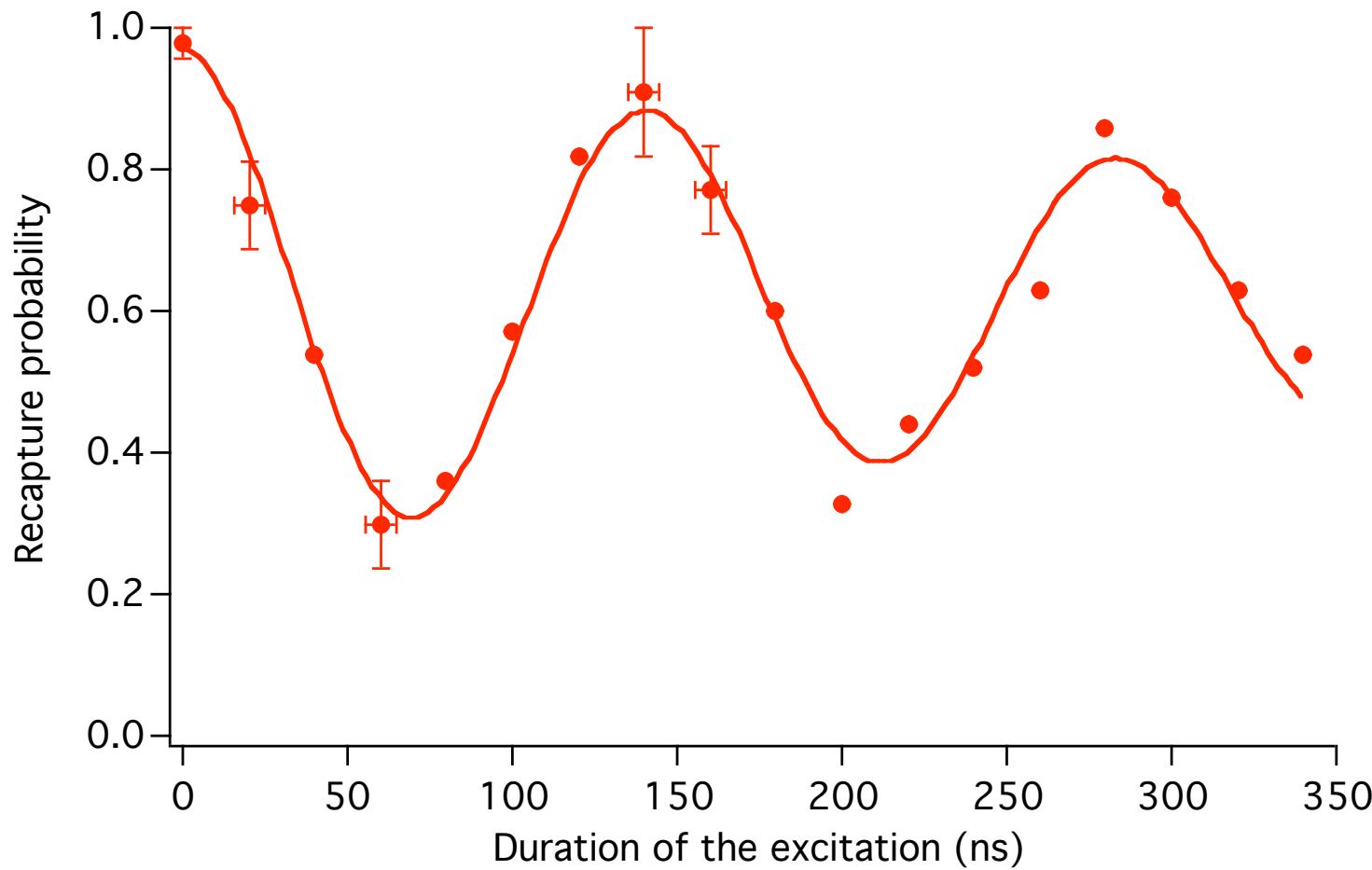


Photo-ionization by dipole trap (810 nm) = $500 \mu\text{sec}$

Radiative decay to $5P_{1/2}$ = $500 \mu\text{sec}$
Black-Body = $50 \mu\text{sec}$

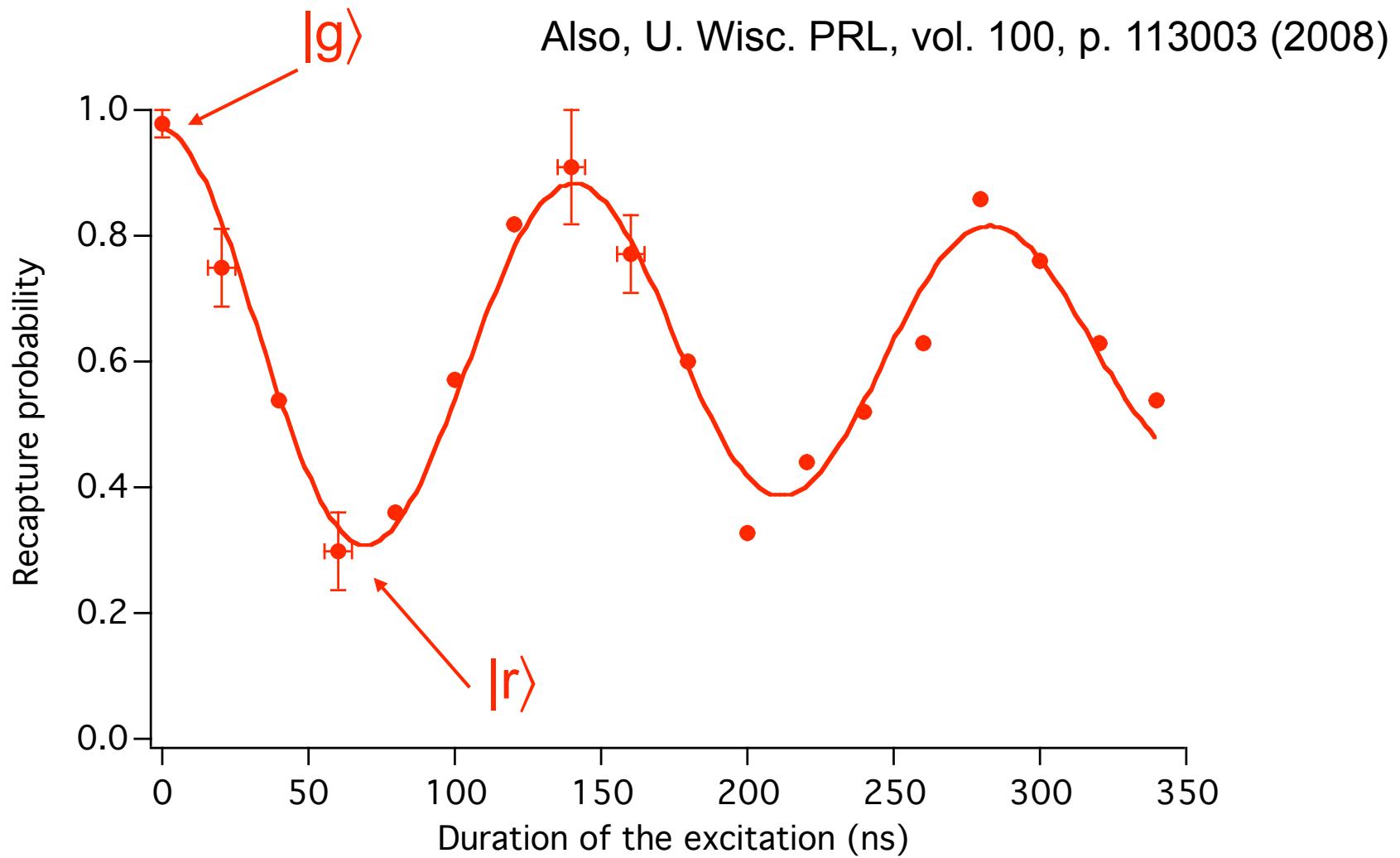
Rabi oscillations on a single atom

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



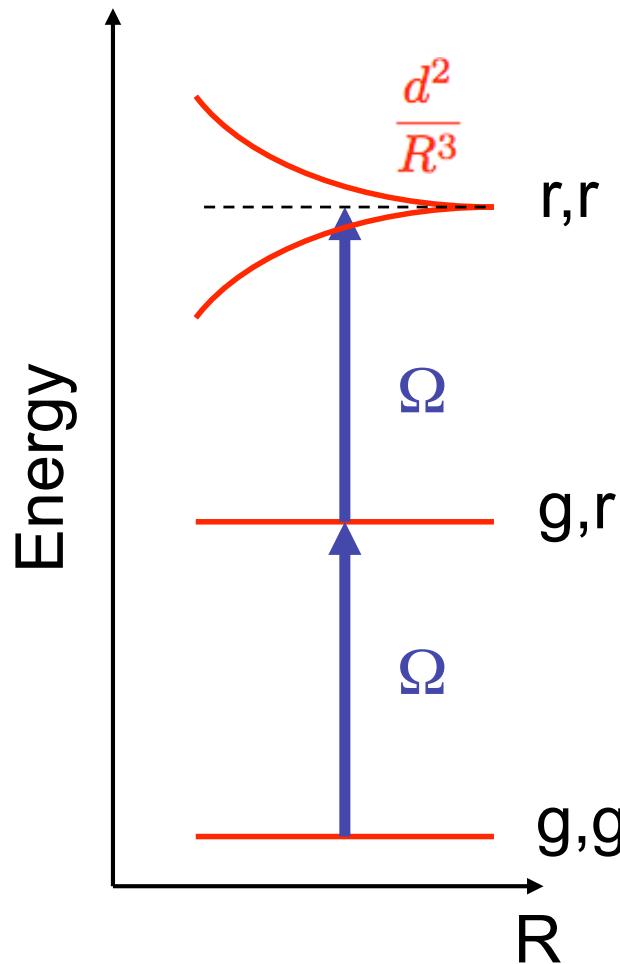
A. Gaëtan, et al., Nat. Phys. 5, 115, (2009)

Rabi oscillations on a single atom



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

« Blockade » range



Blockade stops when

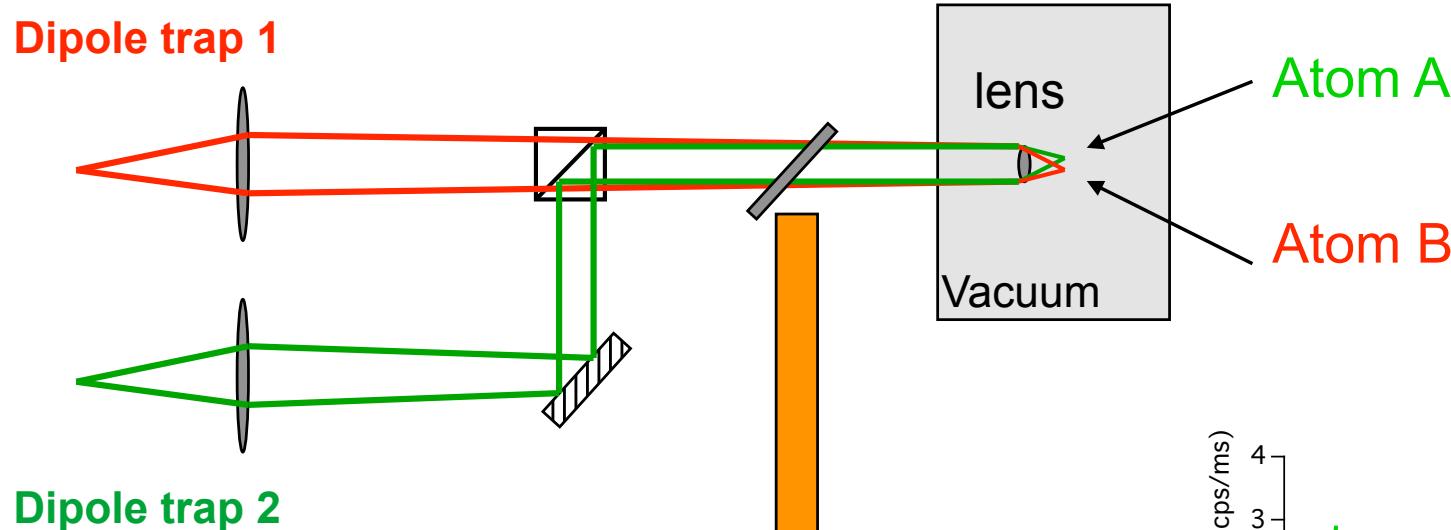
$$\hbar\Omega \approx \frac{d^2}{R^3}$$

$$\Omega = 2\pi \times 7 \text{ MHz} \Rightarrow R = 8 \text{ } \mu\text{m}$$

Outline

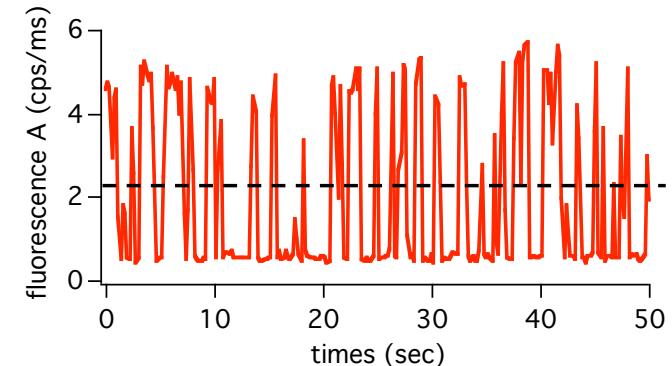
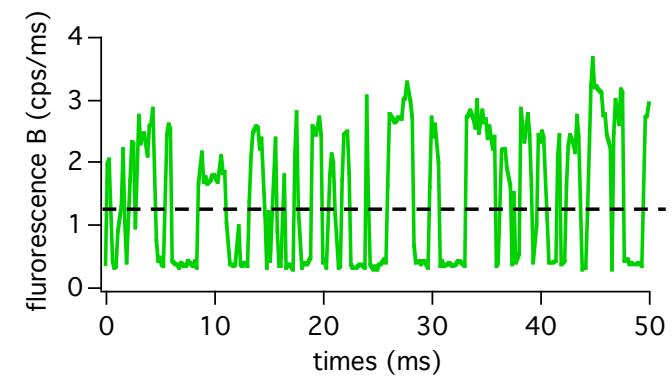
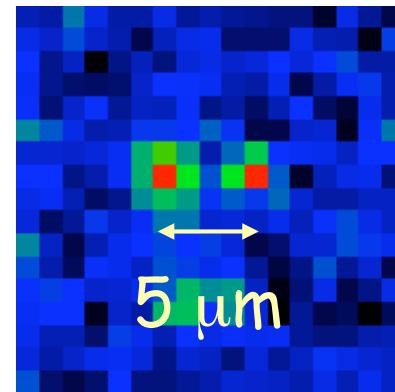
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Detecting and “heralding” two single trapped atom



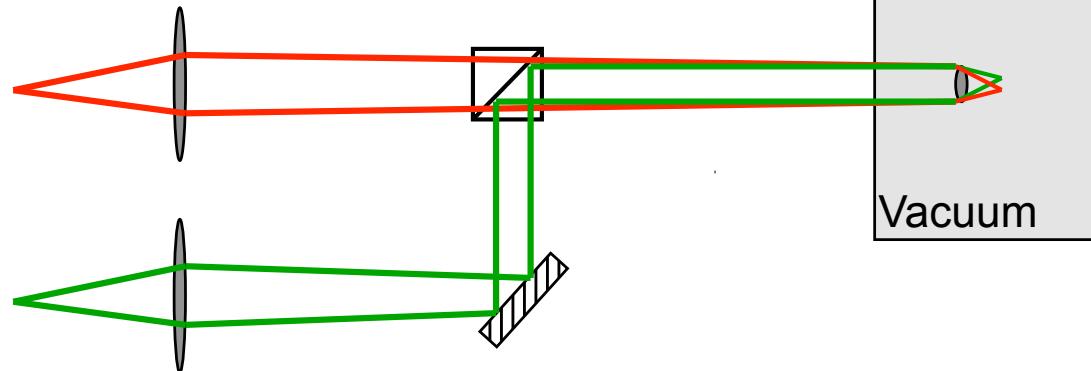
Dipole trap 2

CCD



Distance between the atoms

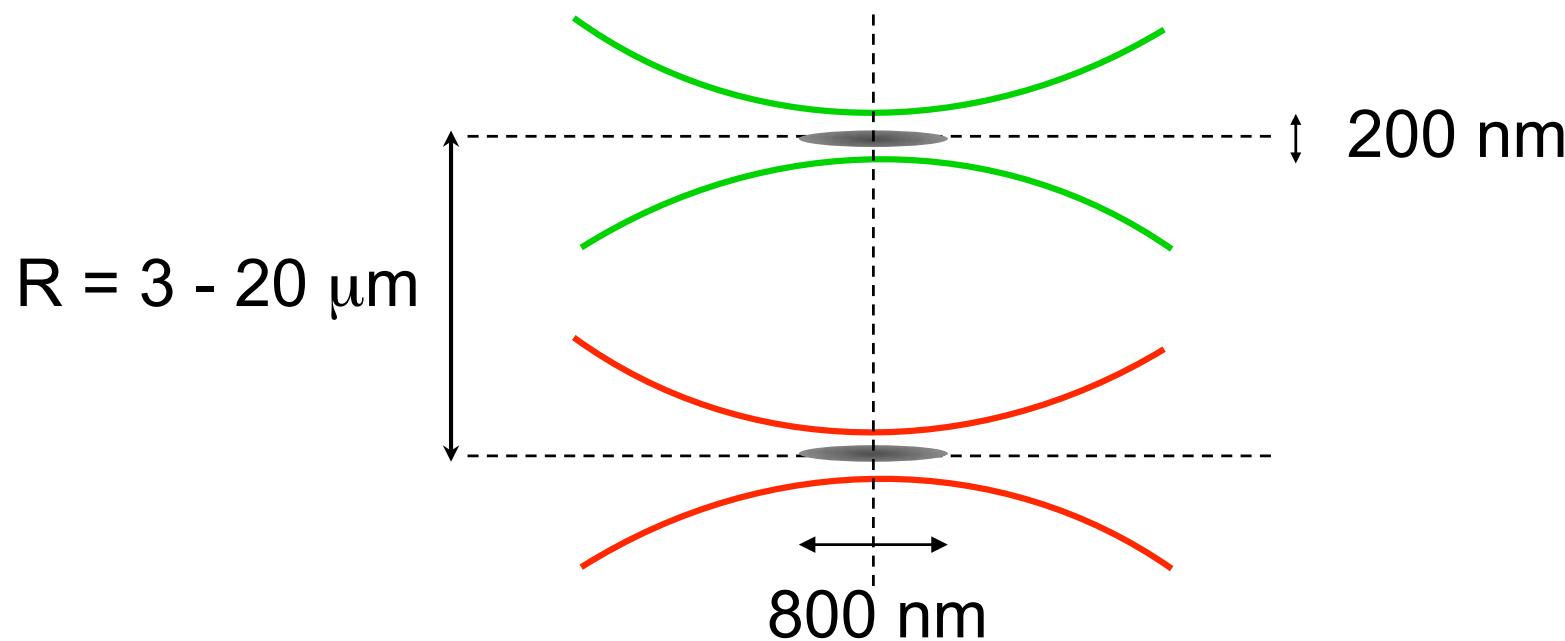
Dipole trap 1



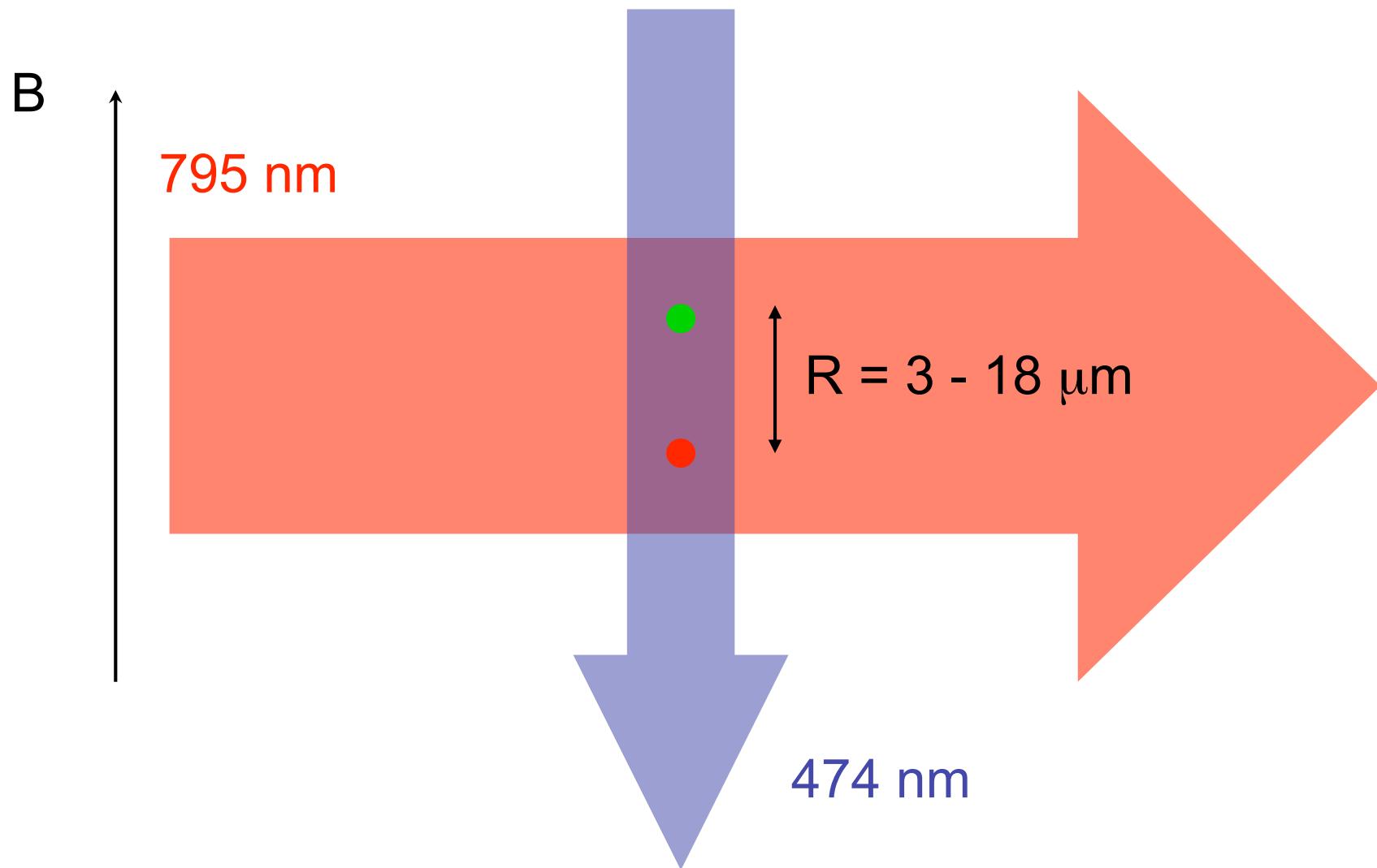
Depth = 0.5 mK
T = 70 μ K

$f_r = 80$ kHz
 $f_z = 16$ kHz

Dipole trap 2



Excitation of two atoms



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, ...

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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, ...

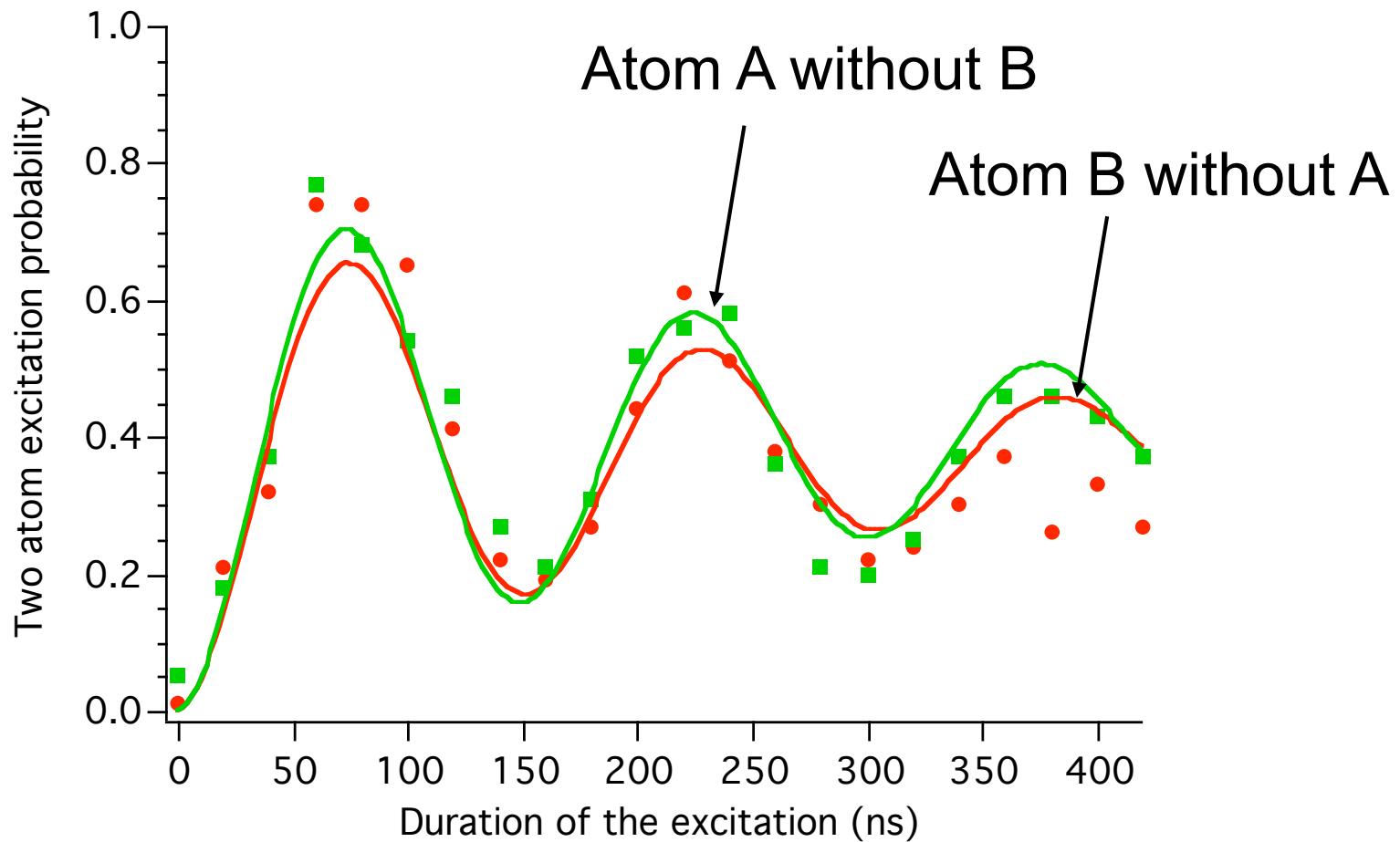
Extract

P to excite no Rydberg's

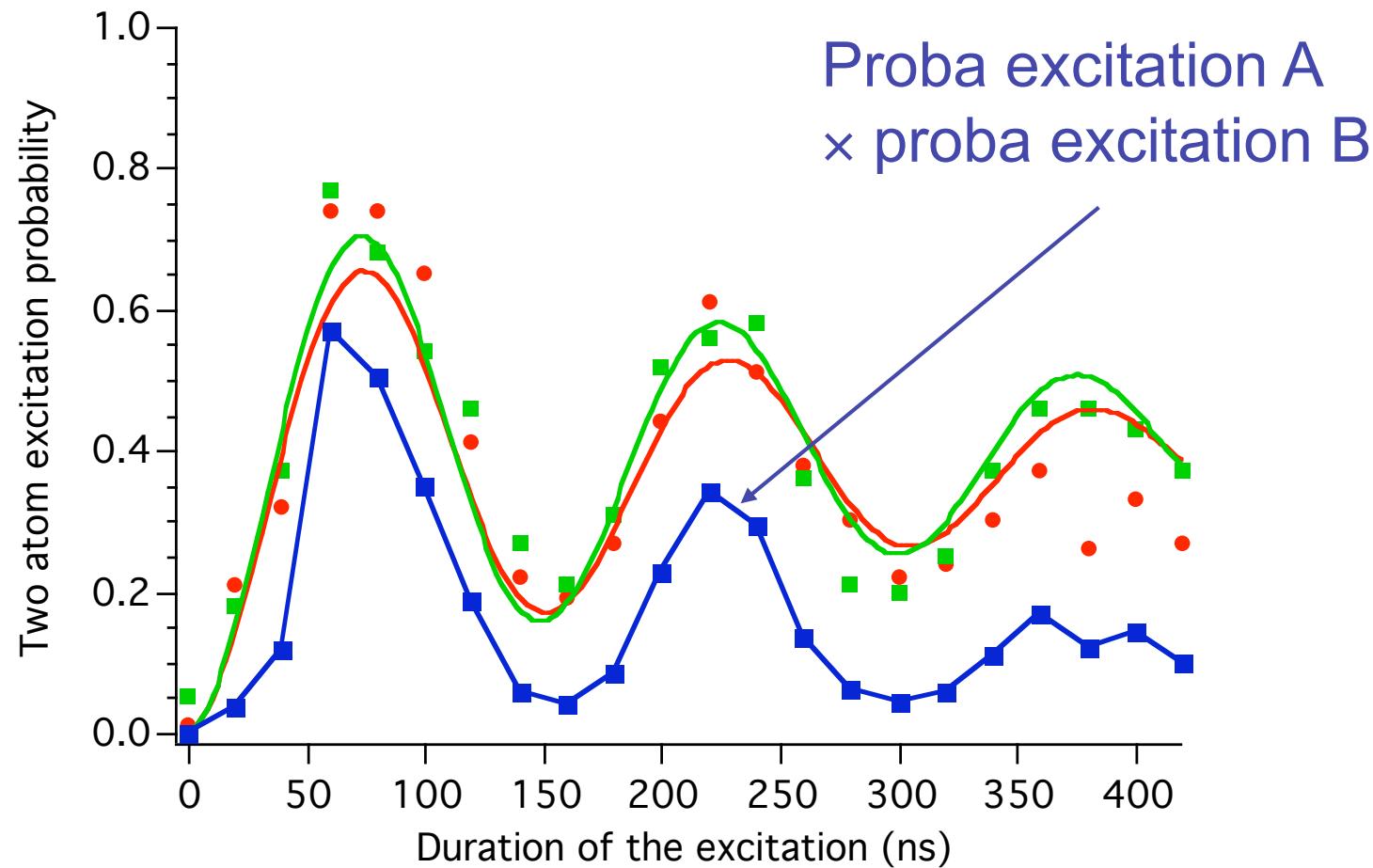
P of exciting two Rydberg's simultaneously

P to excite only one Rydberg

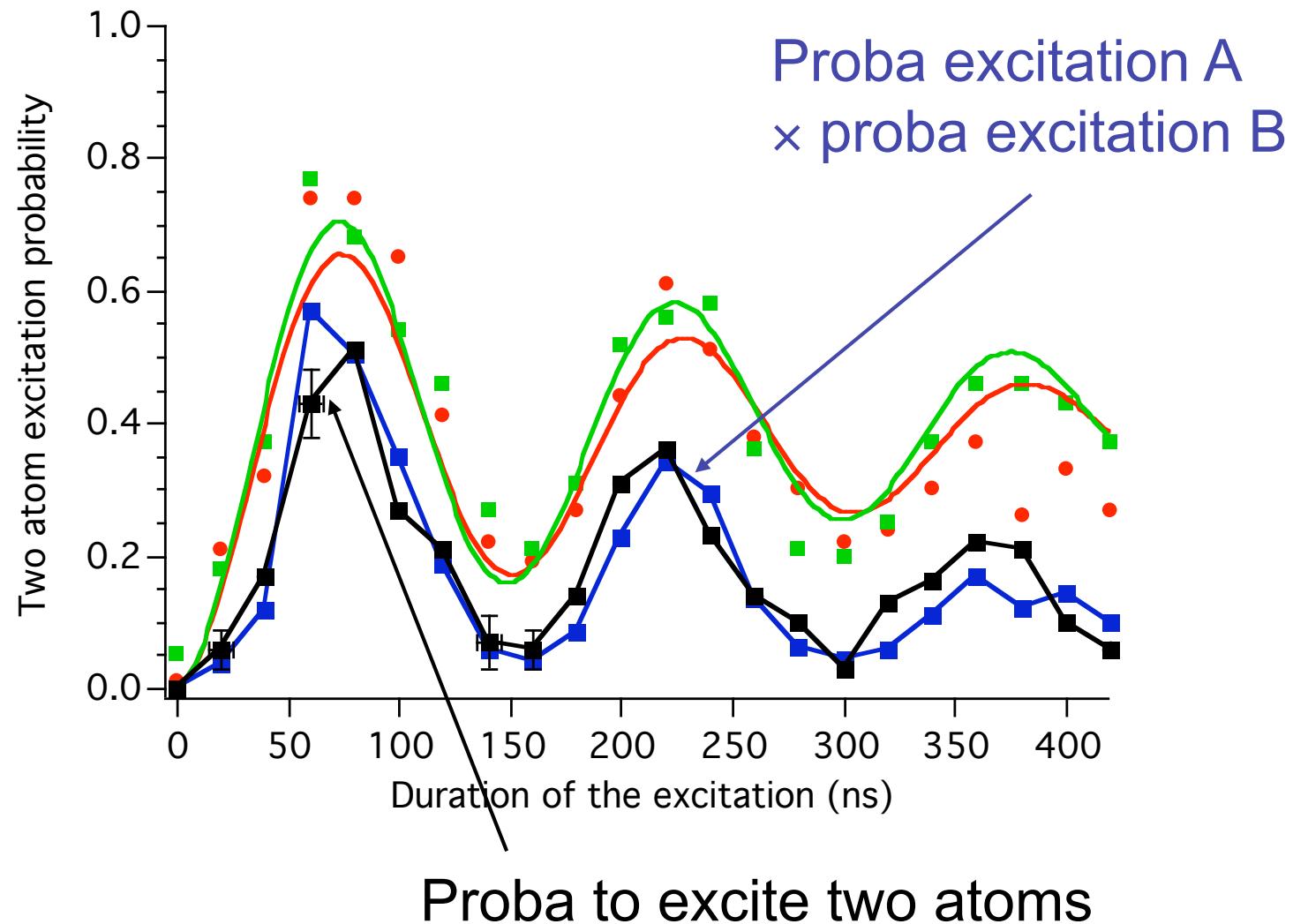
Excitation of two atoms at R = 18 mm



Excitation of two atoms at R = 18 mm

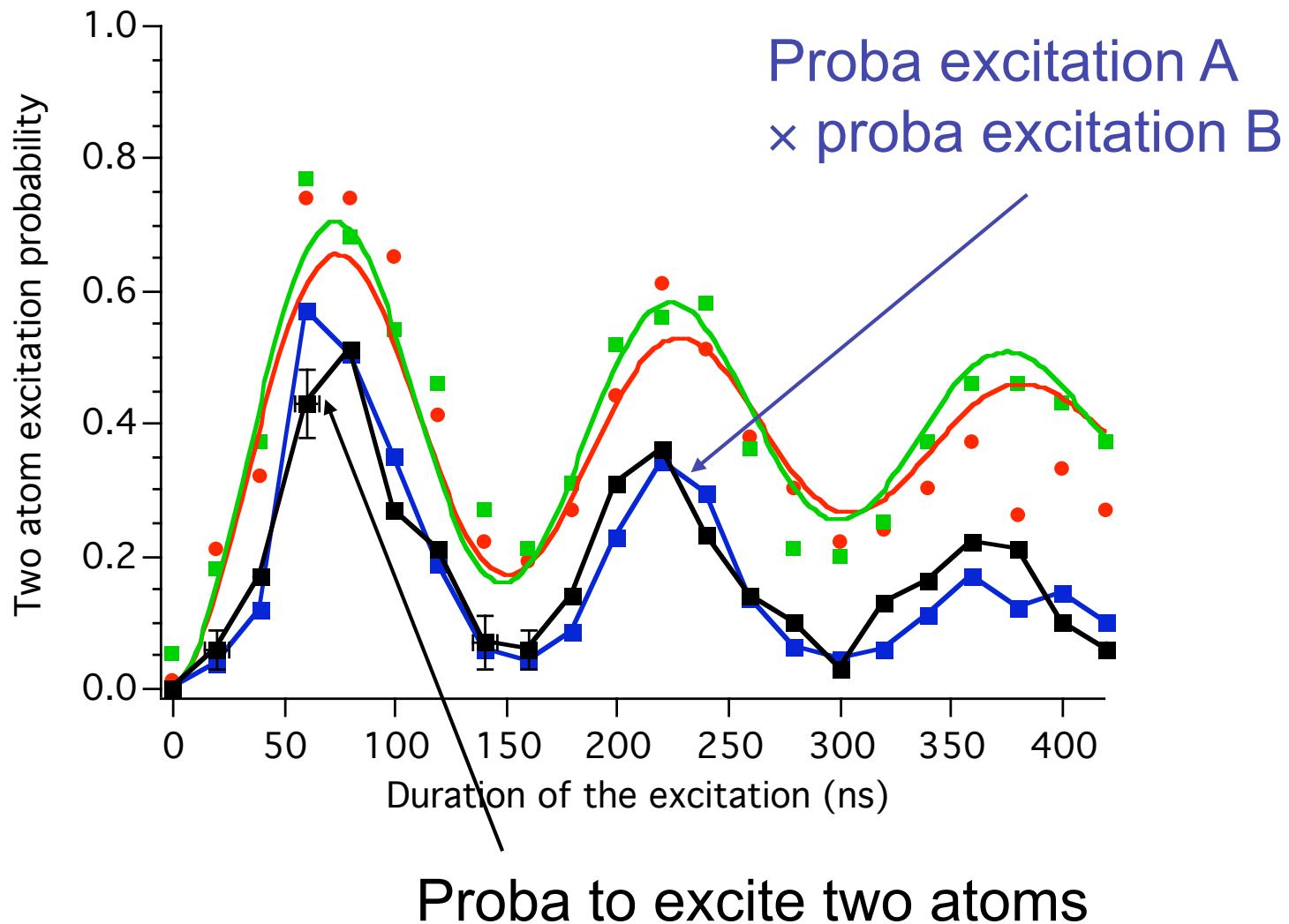


Excitation of two atoms at R = 18 mm

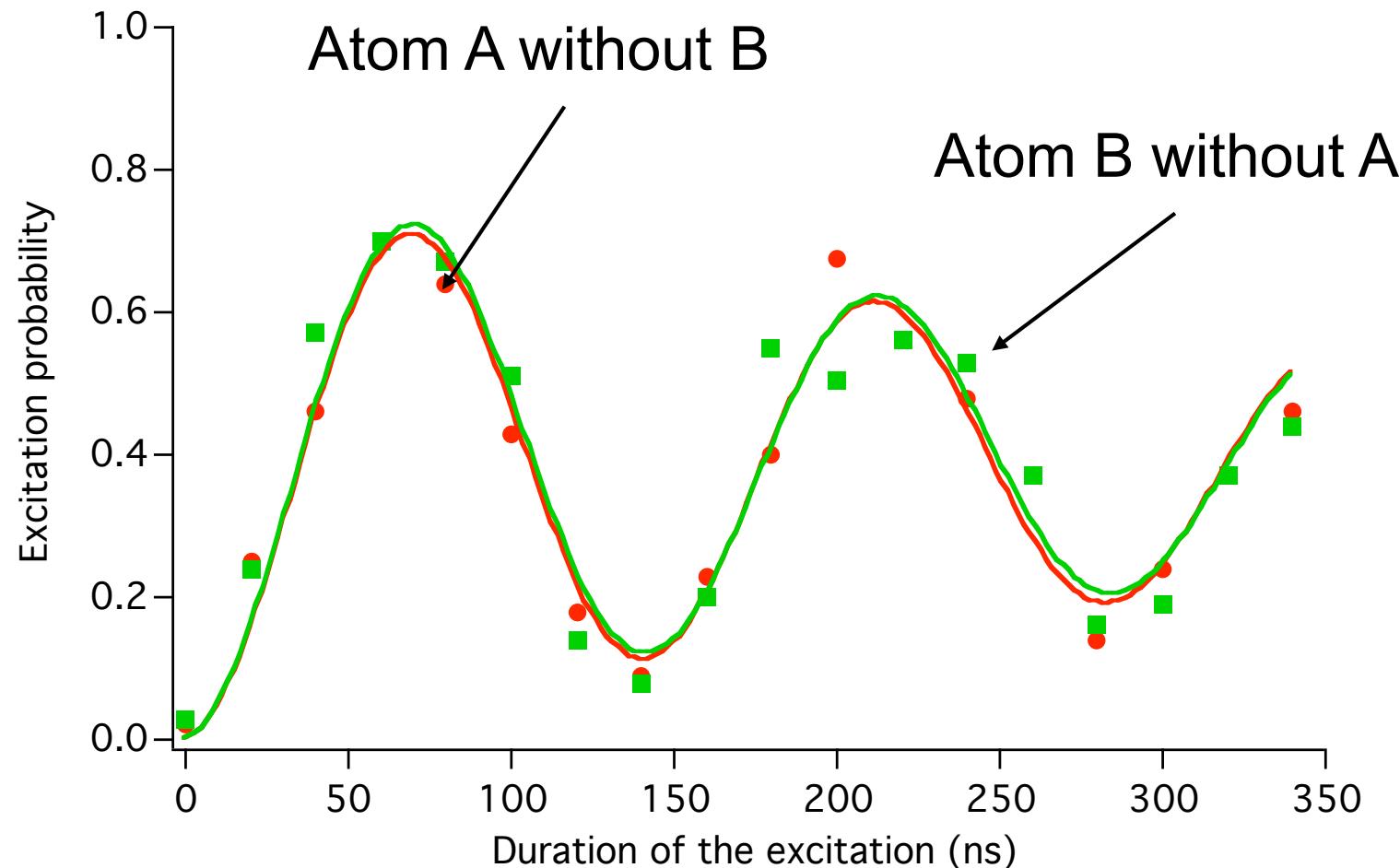


Excitation of two atoms at R = 18 mm

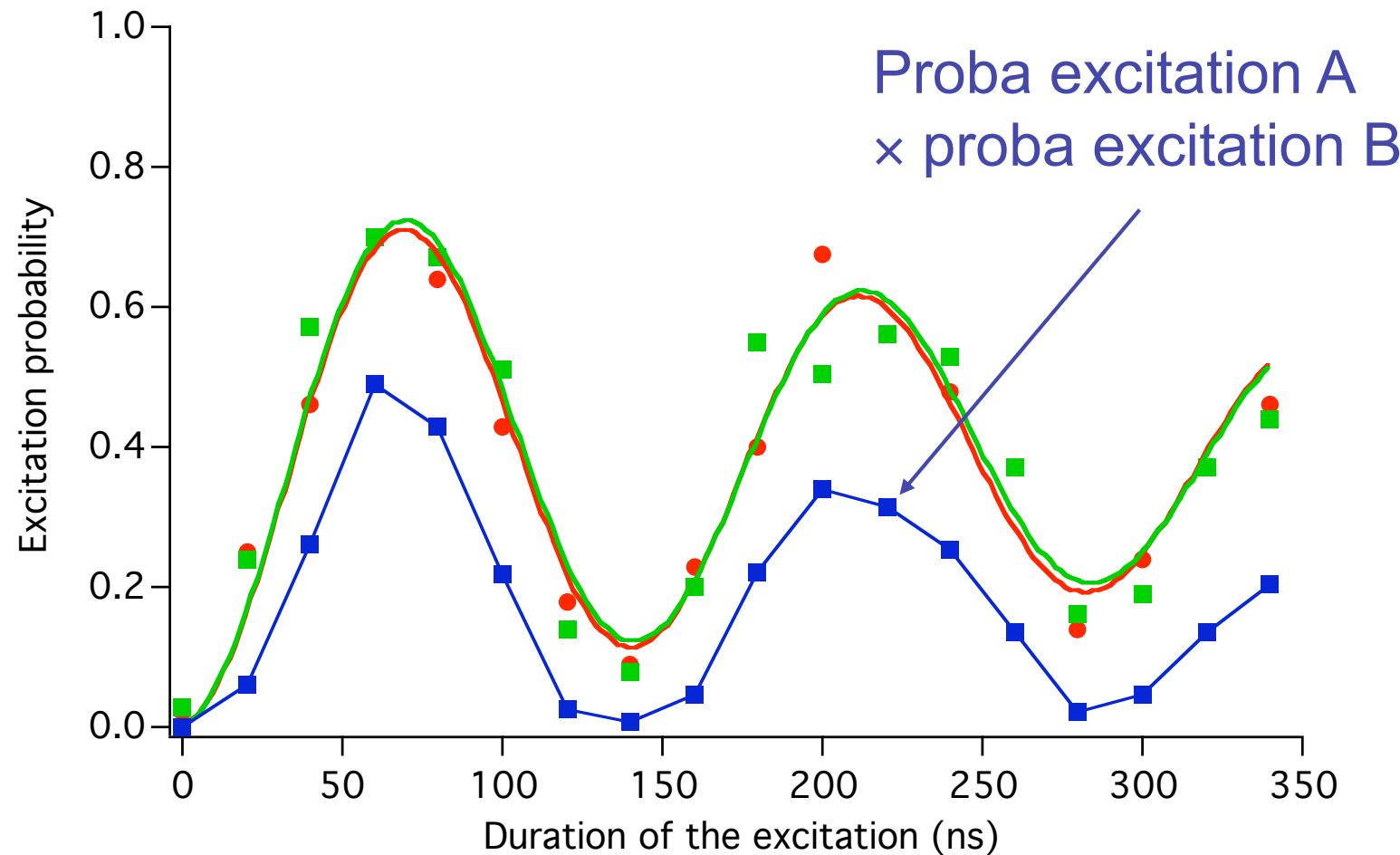
Atoms are « independent »



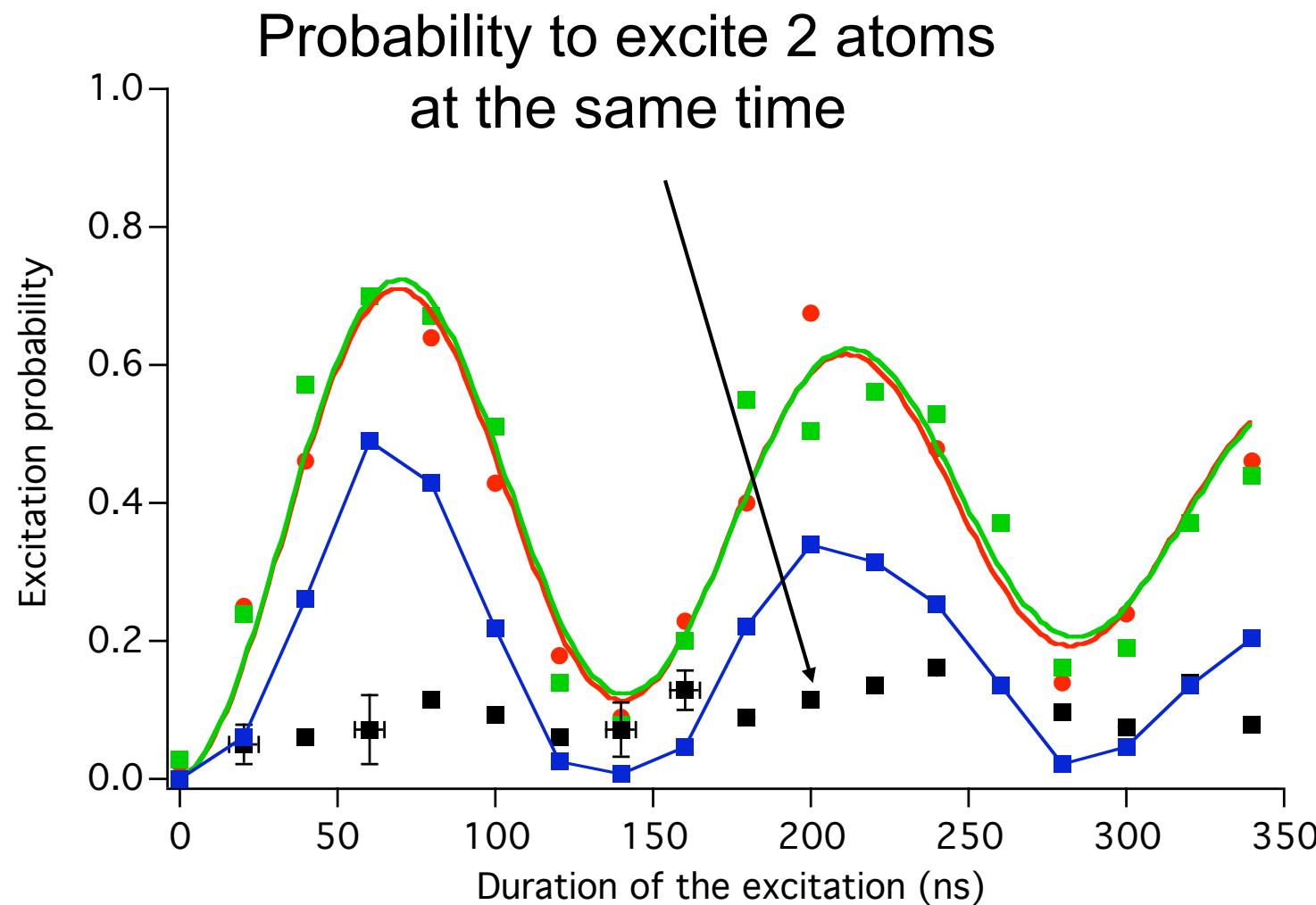
Excitation of two atoms at $R = 4 \mu\text{m}$



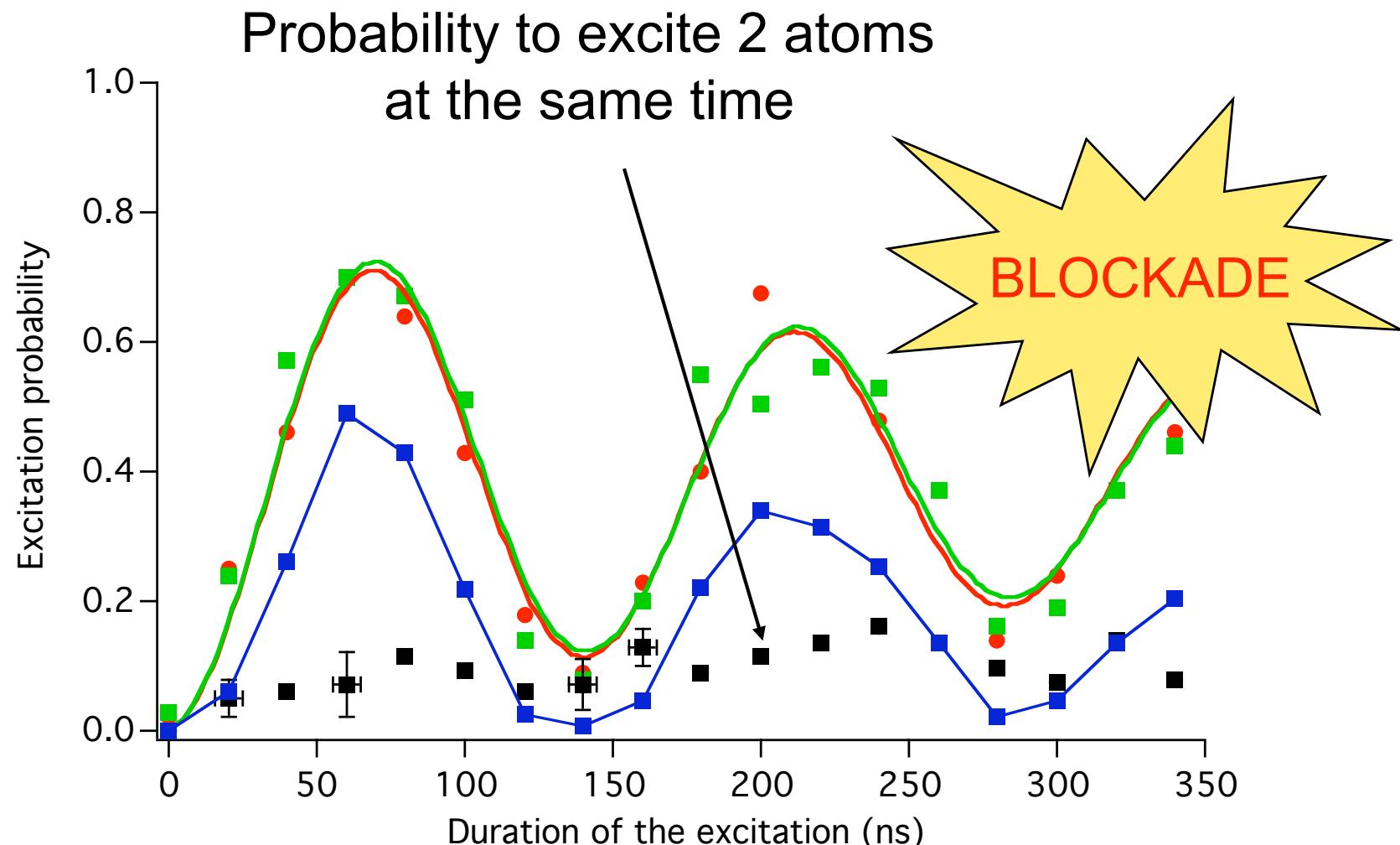
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Excitation of two atoms at $R = 4 \mu\text{m}$

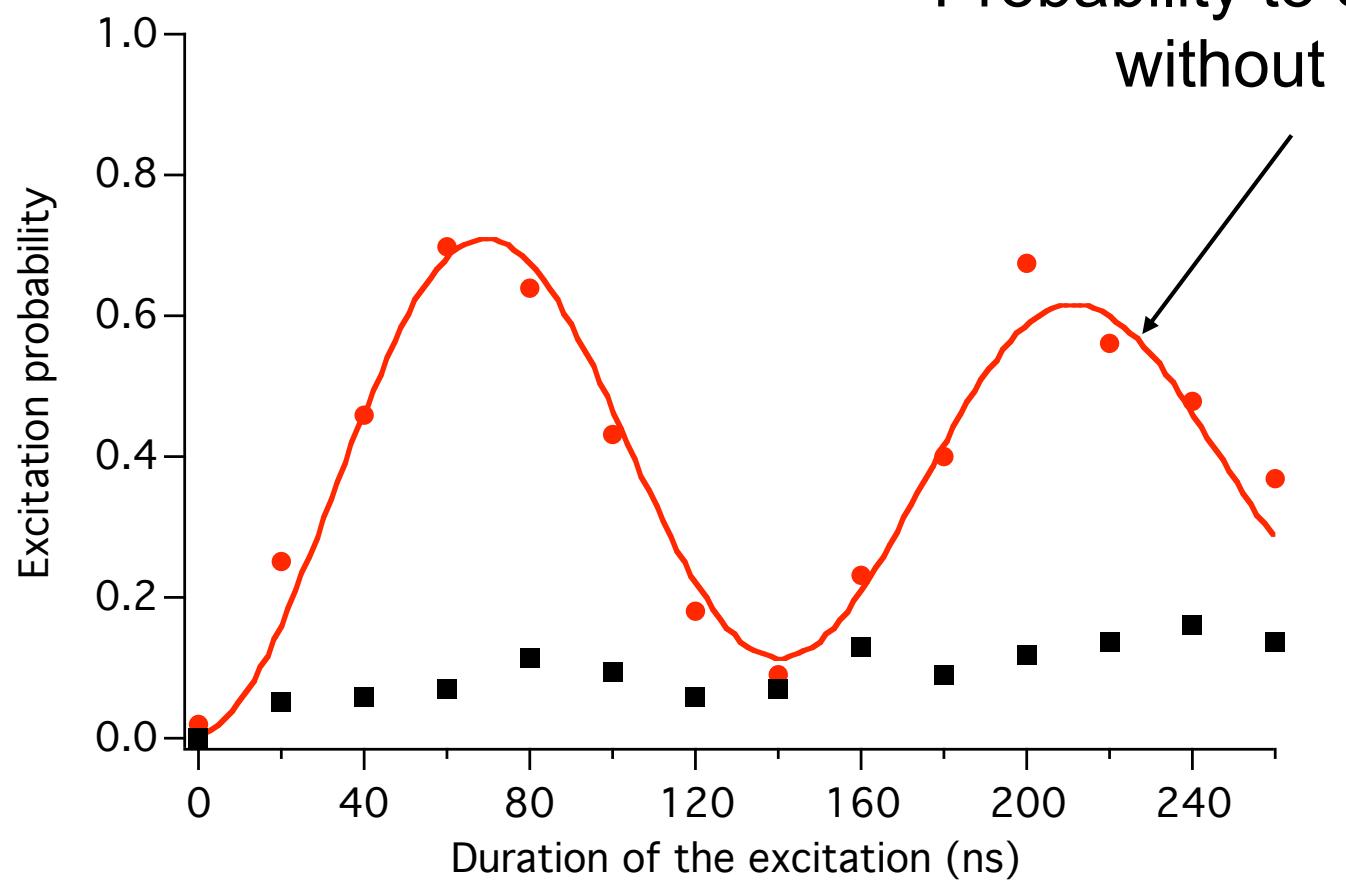


Excitation of two atoms at $R = 4 \mu\text{m}$

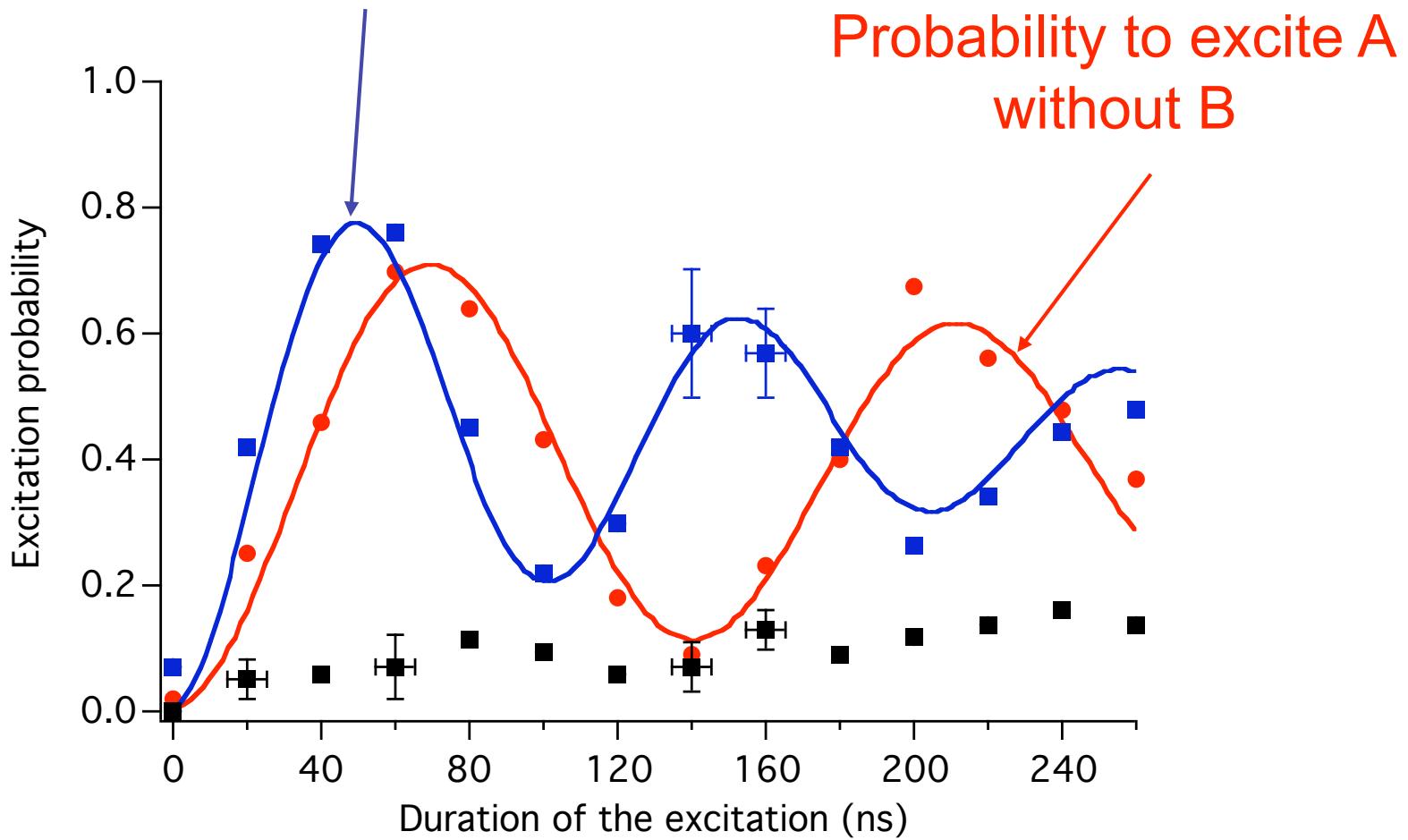


The atoms interact

Probability to excite A
without B



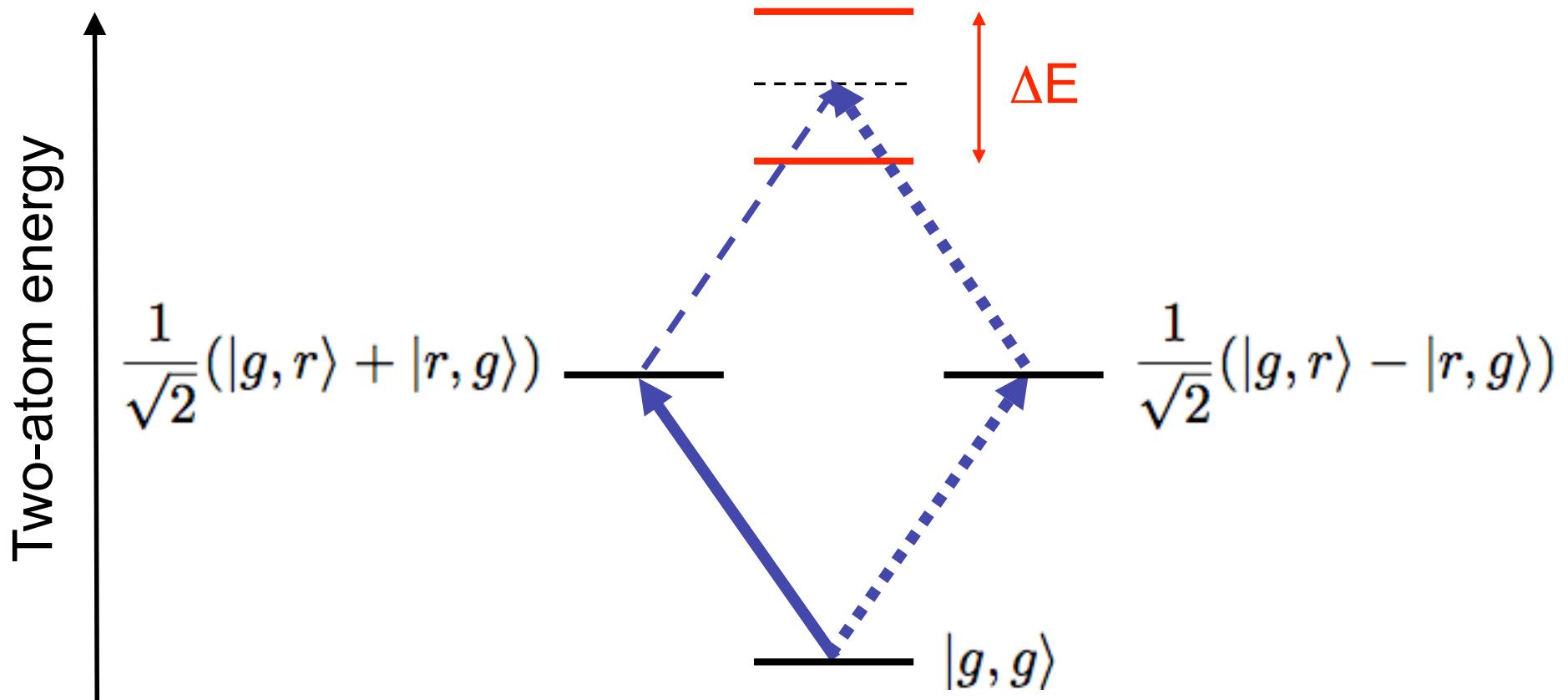
Probability to excite only one atom ($R = 4 \mu\text{m}$)



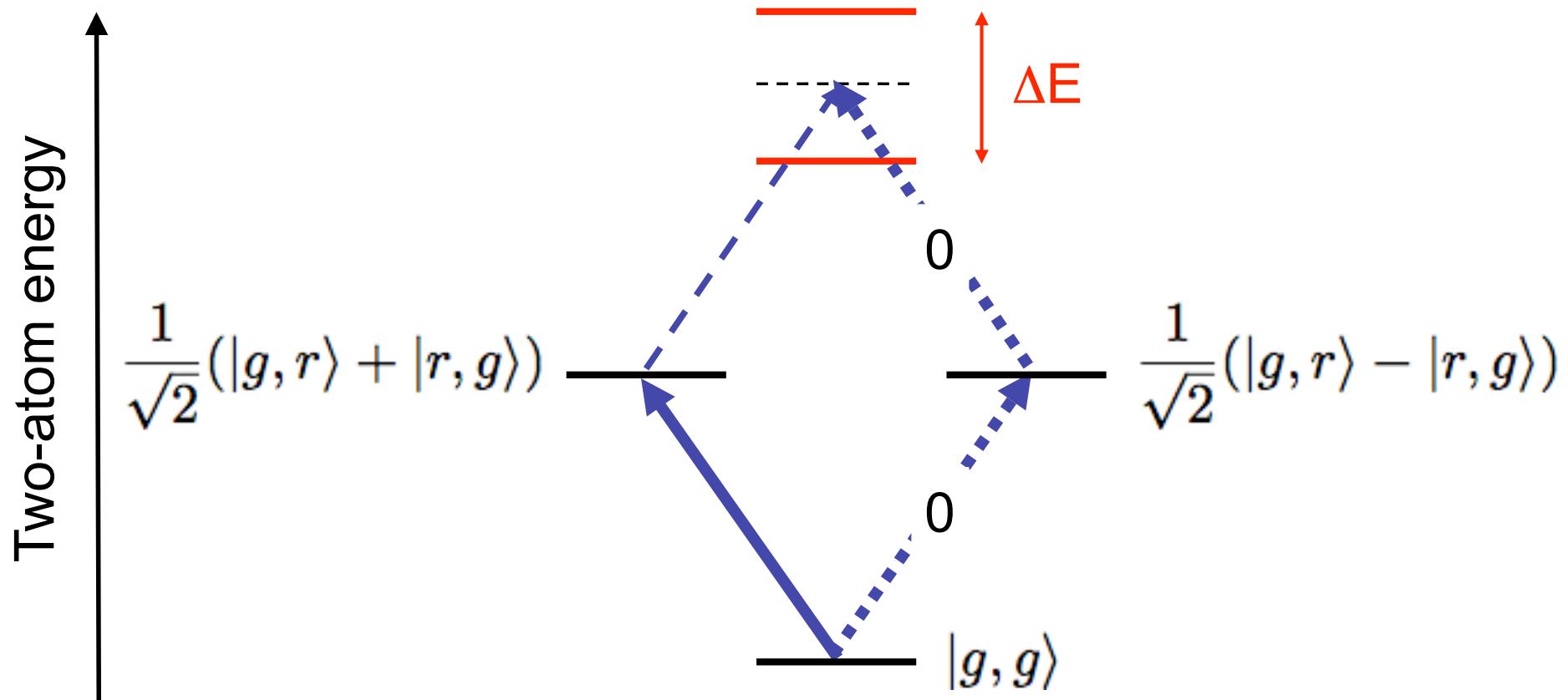
Outline

1. Arrays of optical tweezers
2. Single qubit manipulations
3. Rydberg interaction for entanglement
4. Deterministic excitation to a Rydberg state
5. Demonstration of Rydberg blockade
6. Collective excitation in the blockade regime

« Collective » Rabi oscillations



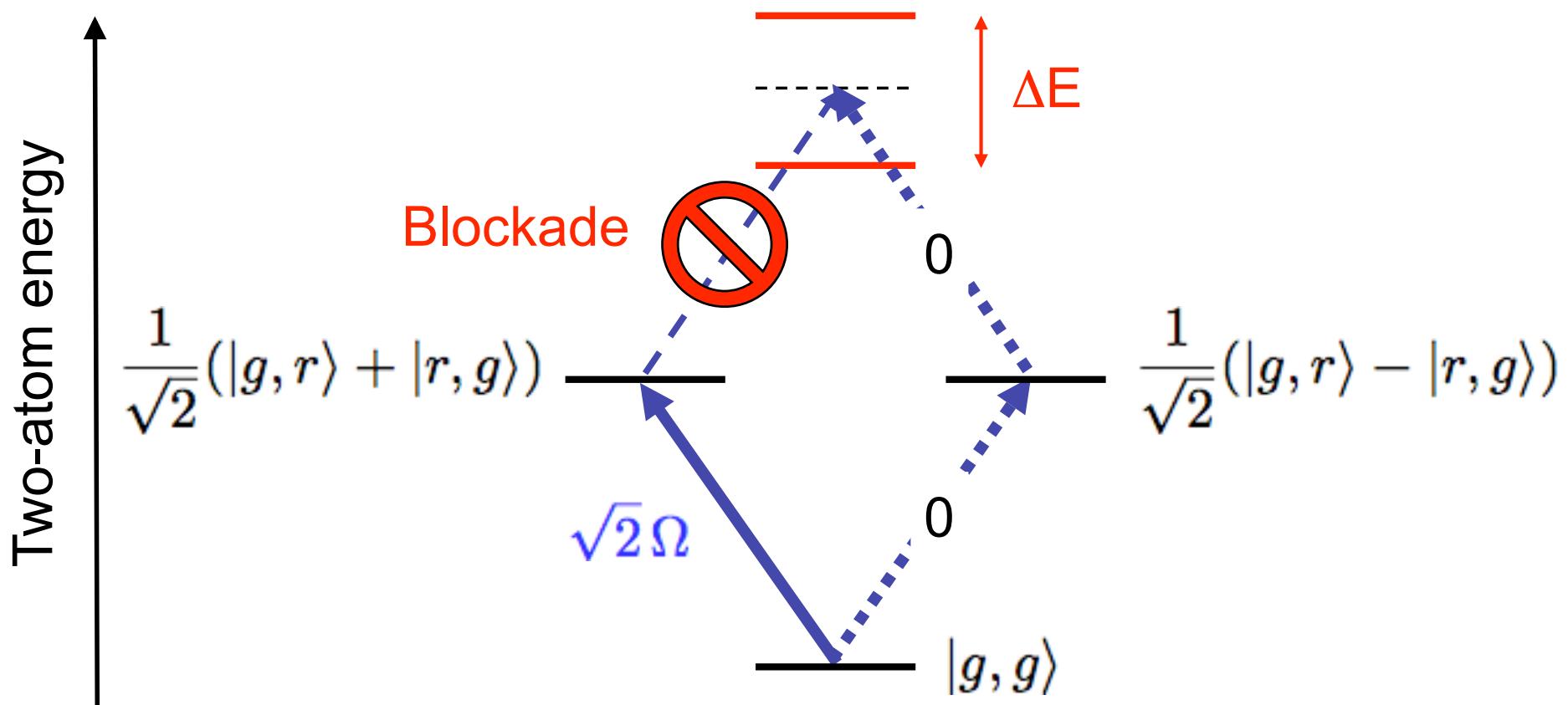
« Collective » Rabi oscillations



« Collective » dipole:

$$\langle g, g | \hat{d}_A + \hat{d}_B | \frac{1}{\sqrt{2}}(|g, r\rangle - |r, g\rangle) = 0$$

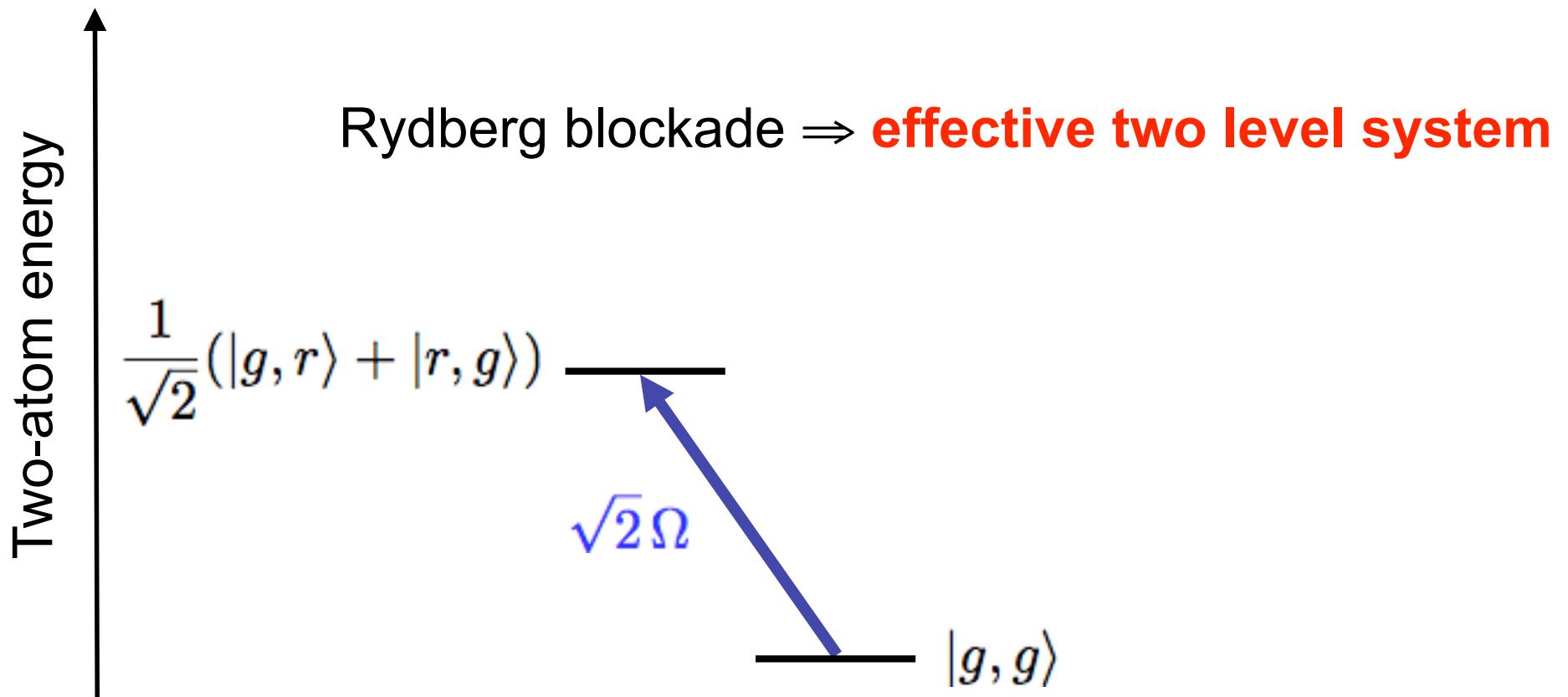
« Collective » Rabi oscillations



« Collective » dipole:

$$\langle g,g | \hat{d}_A + \hat{d}_B | \frac{1}{\sqrt{2}}(|g,r\rangle + |r,g\rangle) \rangle = \sqrt{2} d$$

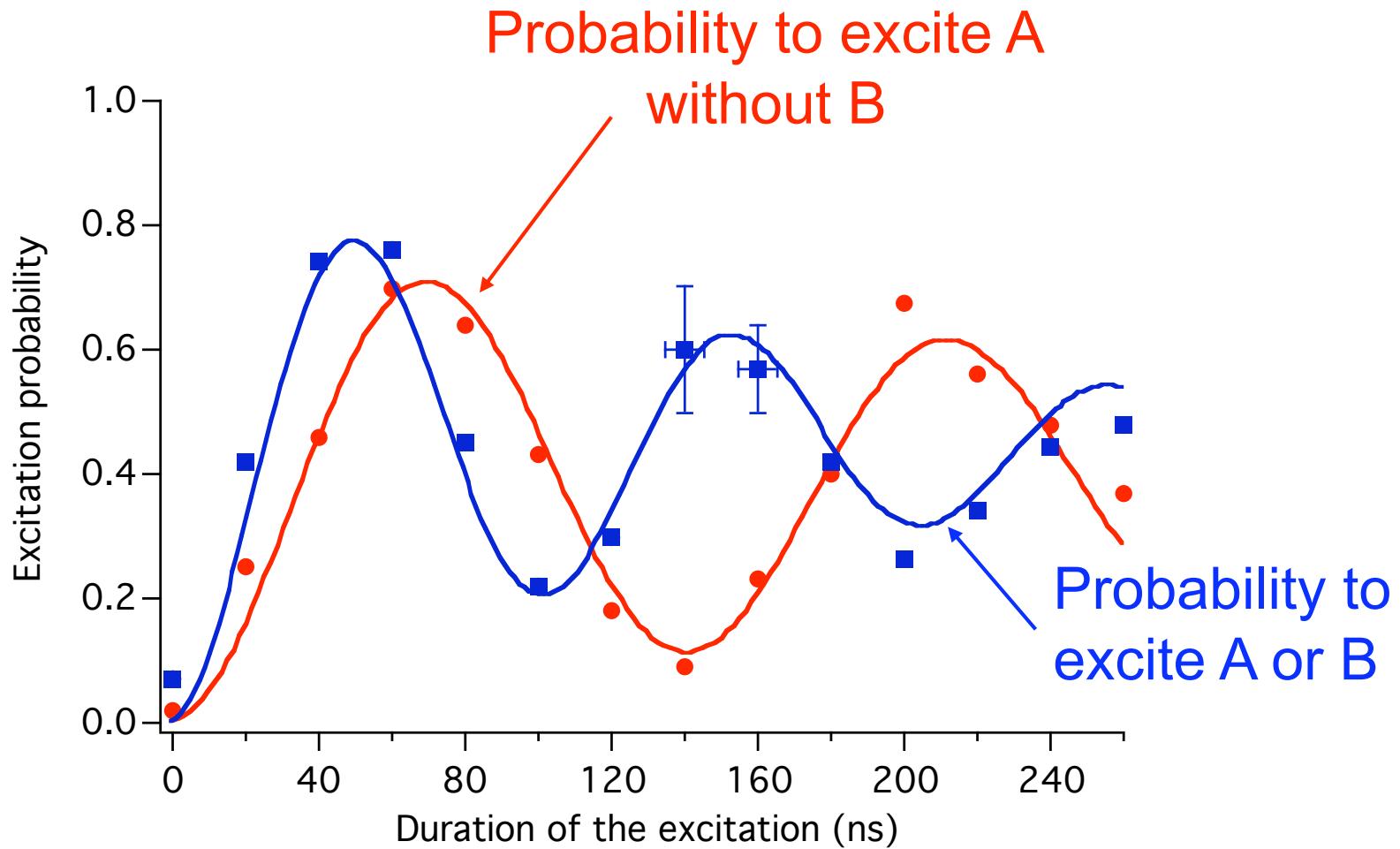
« Collective » Rabi oscillations



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$$\langle g, g | \hat{d}_A + \hat{d}_B | \frac{1}{\sqrt{2}}(|g, r\rangle + |r, g\rangle) \rangle = \sqrt{2} d$$

Probability to excite only one atom ($R = 4 \mu\text{m}$)

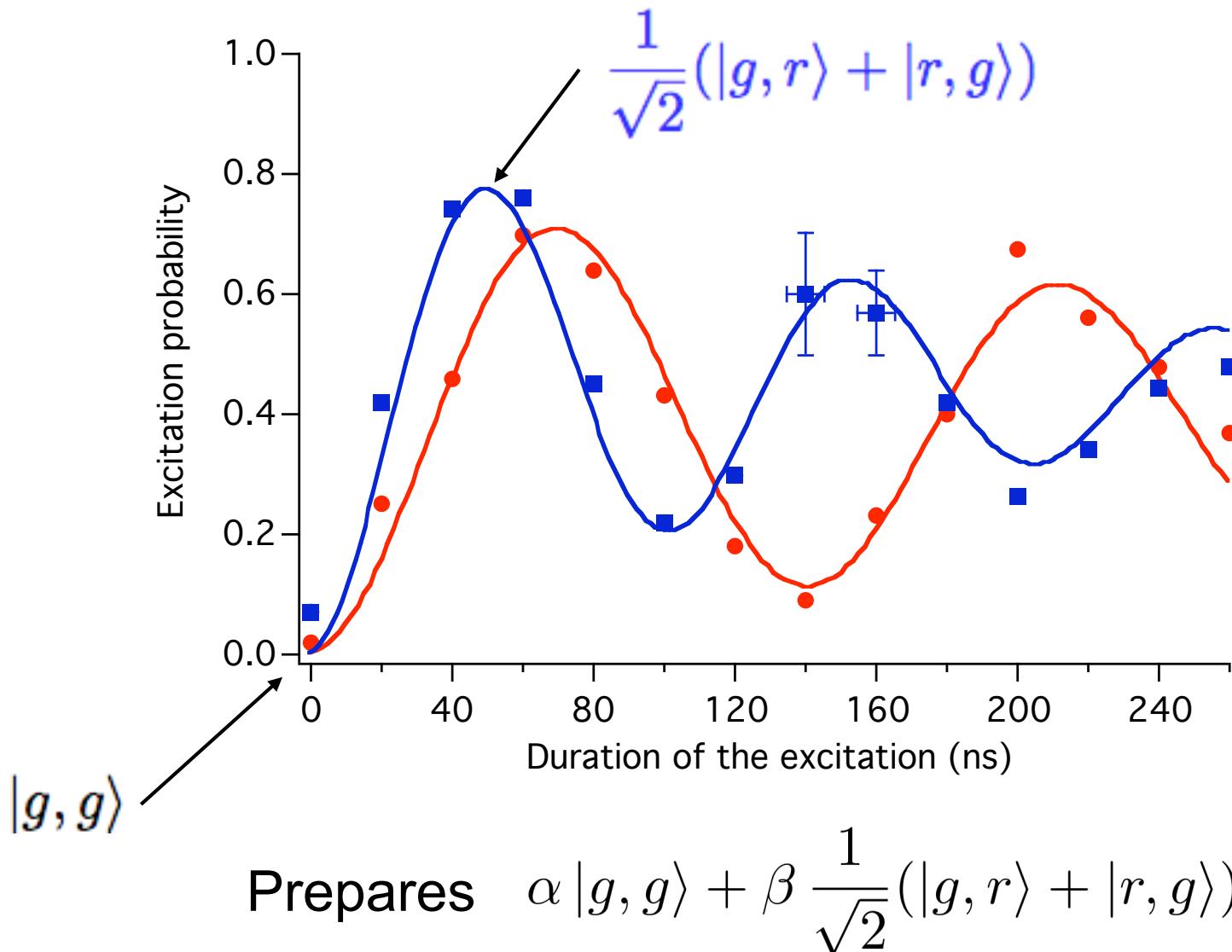


Frequency ratio = $1.38 \approx \sqrt{2}$

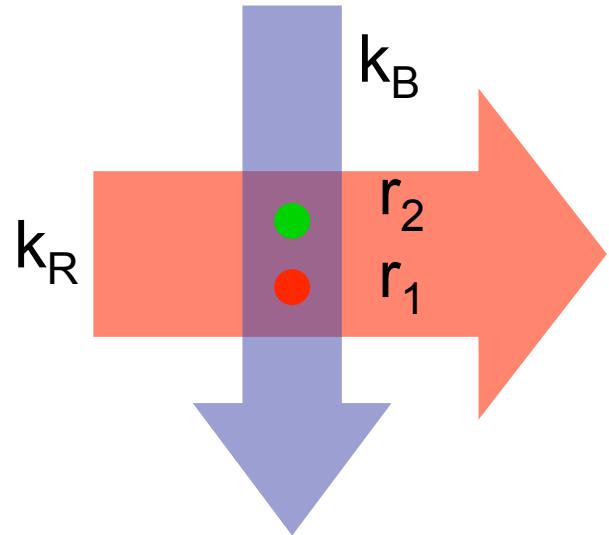
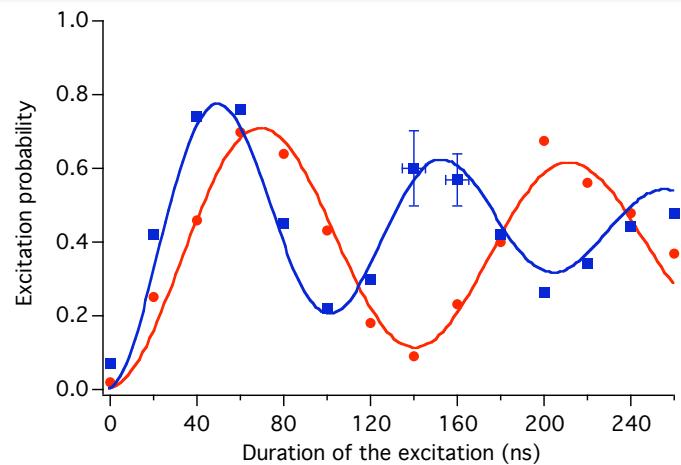
Also Heidemann, et al. PRL 99, p. 163601 (2007)

Probability to excite only one atom ($R = 4 \mu\text{m}$)

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



Useful entanglement?



Oscillation compatible
with the excitation of

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

Position of the atoms \Rightarrow

$$\frac{1}{\sqrt{2}}(e^{ik \cdot r_1} |g, r\rangle + e^{ik \cdot r_2} |r, g\rangle)$$
$$k = k_A + k_B$$

Motion of the atoms frozen during excitation
Random shot-to-shot r_1 and r_2 : $k(\delta r_1 - \delta r_2) \gg 1$

\Rightarrow Mixed states

Conclusion

2D arrays of optical tweezers (~ 10)

Single qubit operations

Observation of the blockade of the excitation of two atoms

“Collective” Rabi oscillations of the pair of atoms

Next:

Entanglement in the ground state

Gates + extend to a larger number of atoms (3 - 4)