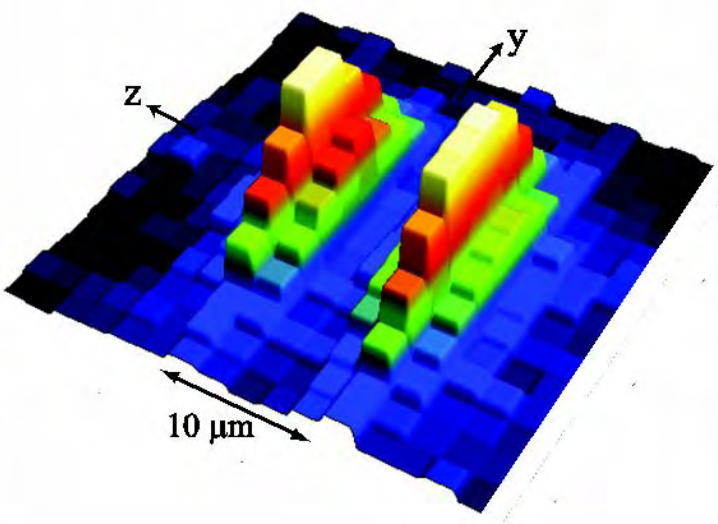
Demonstration of a neutral atom CNOT gate and perspectives for multi-qubit operations

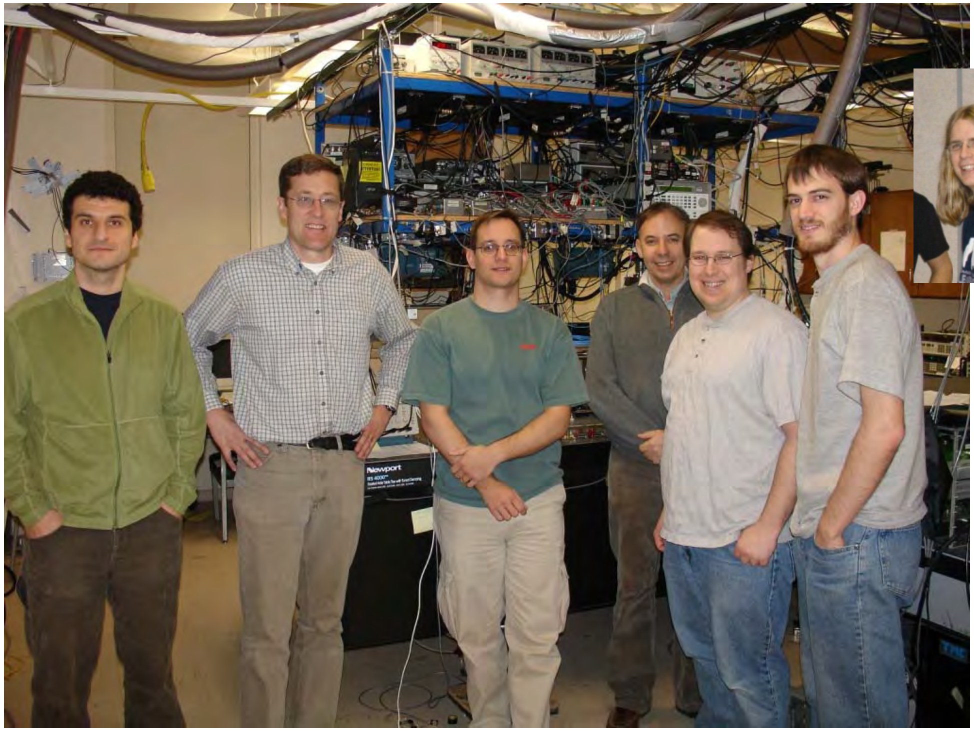
Mark Saffman



two trapped atoms

- Neutral atom quantum gates
- Quantum gates via Rydberg blockade
- Scalability
- Preparation of single atom states
- Collective encoding

People



Deniz Yavuz   Thad Walker   Erich Urban   MS   Thomas Henage   Larry Isenhower

Todd Johnson -> Boulder

Alumni

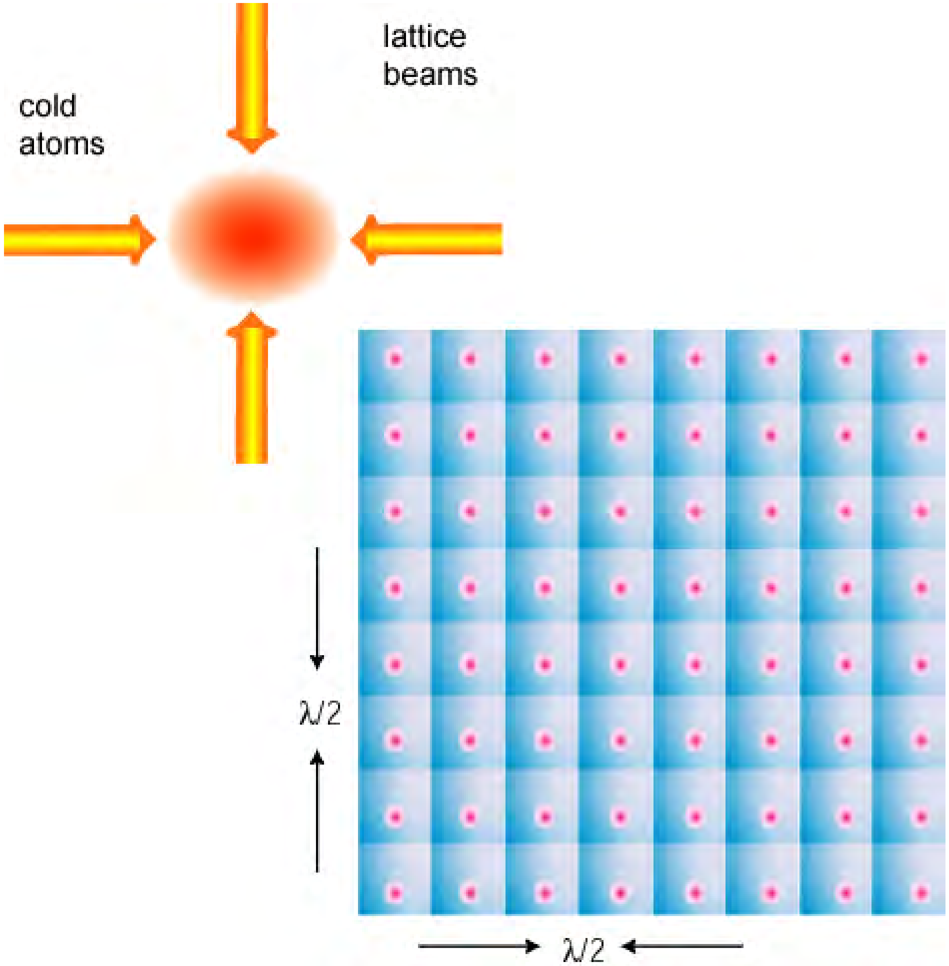
Marie Delaney   Precision Photonics, Boulder
Pasad Kulatunga   Hobart & William Smith Colleges, faculty
Deniz Yavuz   UW Madison, faculty
Todd Johnson   NIST, Boulder

Collaborations

Kelvin Wagner   UC Boulder – qubit addressing optics
Jungsang Kim   Duke – qubit addressing optics
Klaus Mølmer   Aarhus - theory

Also
Alex Gill (PhD)
Jon Sedlacek, Jake Covey, Adam Beardsley (undergrads)

Neutral atoms in optical lattices



Say λ = 1 μm.

4 million lattice sites per mm^2

8 billion lattice sites per mm^3

Critical issues:

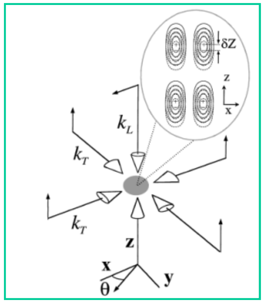
- loading
- addressability
- interconnects

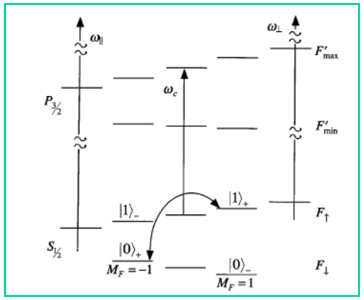
Neutral atom quantum gates

VOLUME 82, NUMBER 5 PHYSICAL REVIEW LETTERS 1 FEBRUARY 1999

Quantum Logic Gates in Optical Lattices

Gavin K. Brennen,[1] Carlton M. Caves,[1] Poul S. Jessen,[2] and Ivan H. Deutsch[1]
[1] *Center for Advanced Studies, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131*
[2] *Optical Sciences Center, University of Arizona, Tucson, Arizona 85721*
(Received 29 May 1998)





VOLUME 82, NUMBER 9 PHYSICAL REVIEW LETTERS 1 MARCH 1999

Entanglement of Atoms via Cold Controlled Collisions

D. Jaksch,[1] H.-J. Briegel,[1] J. I. Cirac,[1] C. W. Gardiner,[2] and P. Zoller[1]
[1] *Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria*
[2] *School of Chemical and Physical Sciences, Victoria University, Wellington, New Zealand*
(Received 28 October 1998)

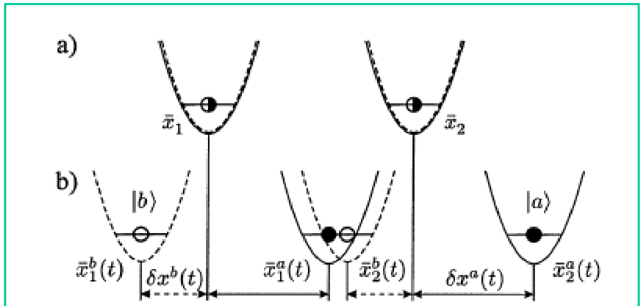


FIG. 1. Configurations at times $\pm\tau$ (a) and at t (b). The solid (dashed) curves show the potentials for particles in the internal state $|a\rangle$ ($|b\rangle$), respectively. Center positions $\bar{x}_j^\beta(t)$ and displacements $\delta x^\beta(t)$ are as defined in the text.

Many body collisional entanglement

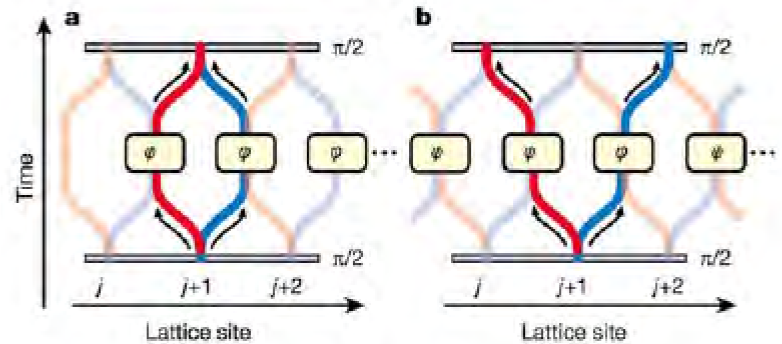
Signatures of entanglement have been demonstrated in lattices, but not at the two-atom level:

NATURE | VOL 425 | 30 OCTOBER 2003

letters to nature

Controlled collisions for multi-particle entanglement of optically trapped atoms

Olaf Mandel, Markus Greiner, Artur Widera, Tim Rom, Theodor W. Hänsch & Immanuel Bloch

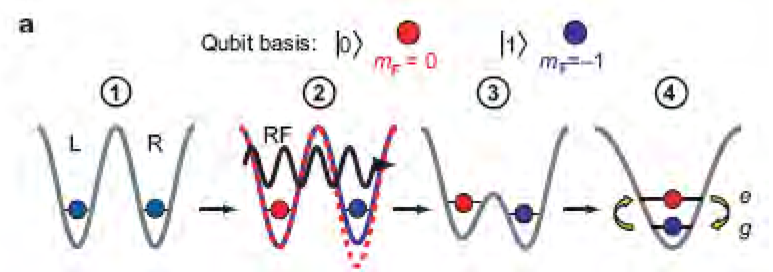


nature Vol 448 | 26 July 2007 | doi:10.1038/nature06011

LETTERS

Controlled exchange interaction between pairs of neutral atoms in an optical lattice

Marco Anderlini[1]†, Patricia J. Lee[1], Benjamin L. Brown[1], Jennifer Sebby-Strabley[1]†, William D. Phillips[1] & J. V. Porto[1]

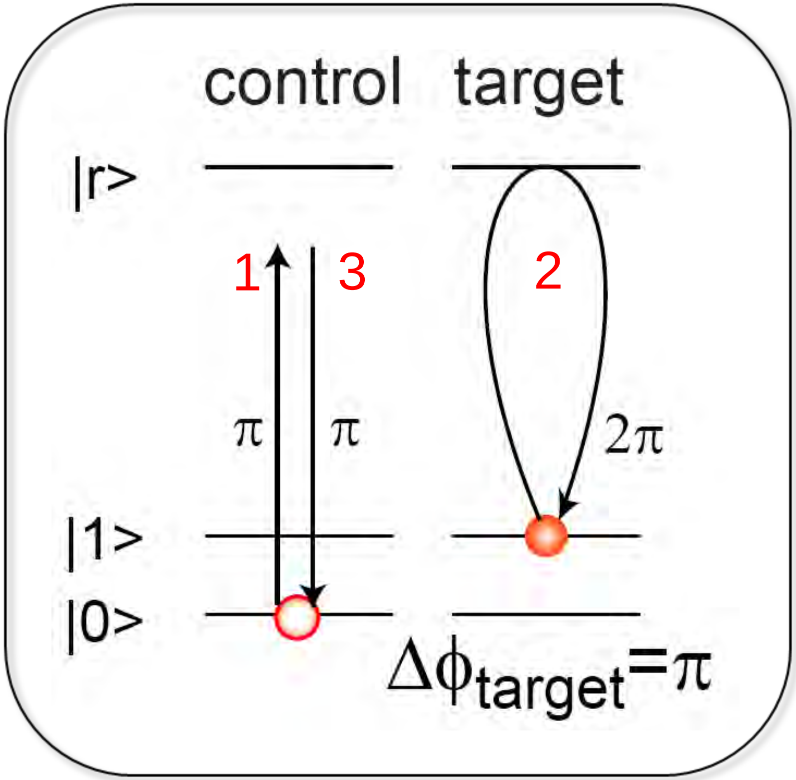


Fast Quantum Gates for Neutral Atoms

D. Jaksch, J.I. Cirac, and P. Zoller
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

S.L. Rolston
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

R. Côté[1] and M.D. Lukin[2]
[1]*Physics Department, University of Connecticut, 2152 Hillside Road, Storrs, Connecticut 06269-3046*
[2]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
(Received 7 April 2000)

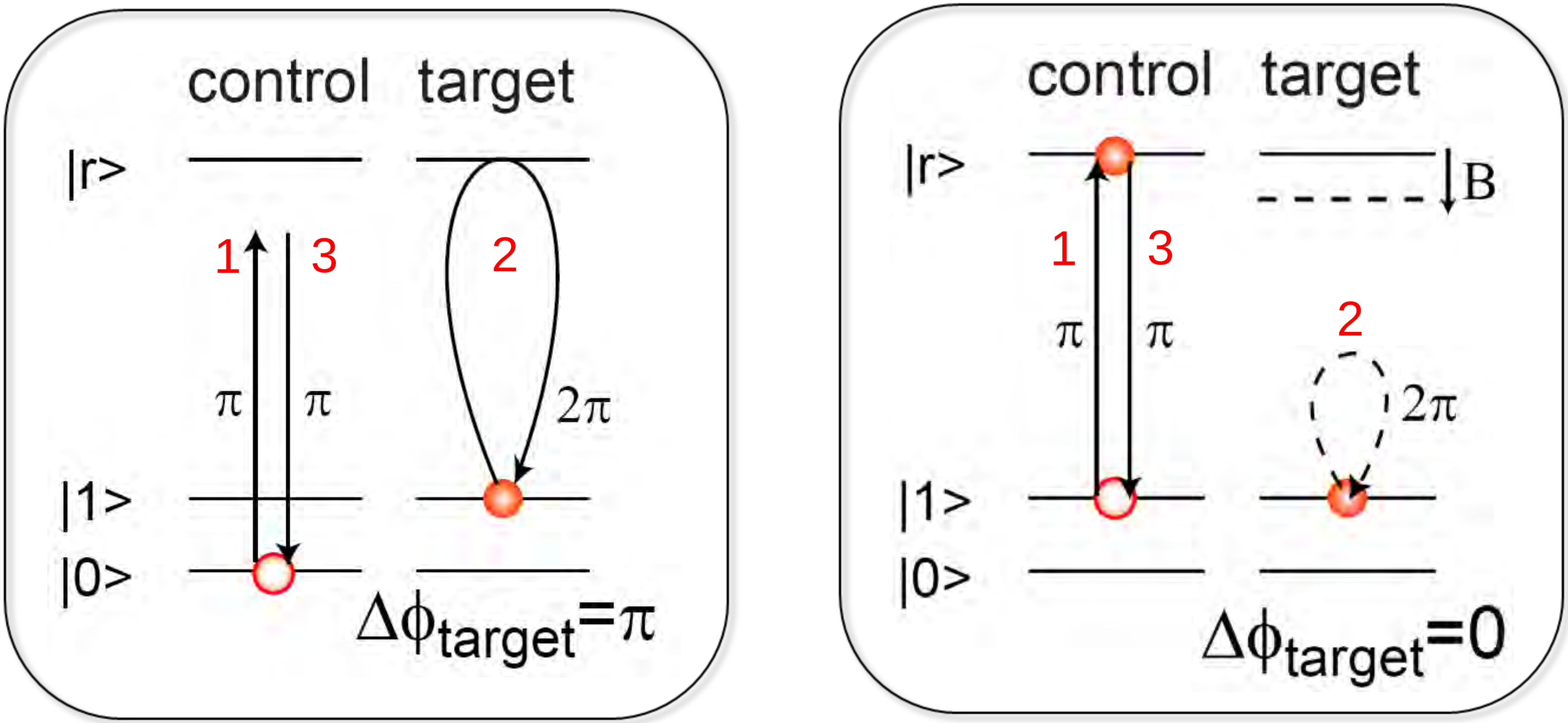


Fast Quantum Gates for Neutral Atoms

D. Jaksch, J.I. Cirac, and P. Zoller
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

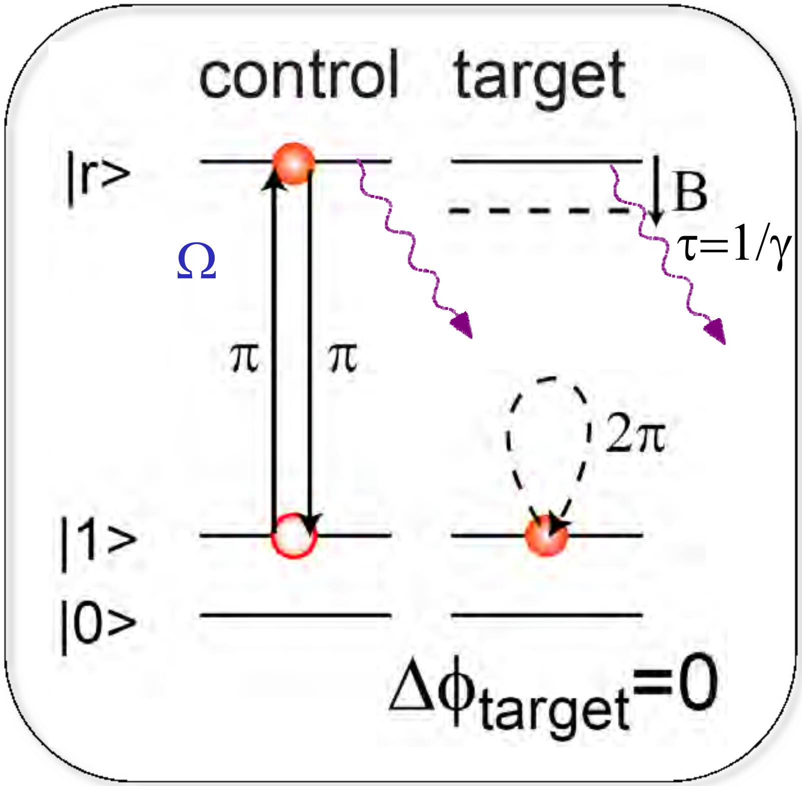
S.L. Rolston
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

R. Côté[1] and M.D. Lukin[2]
[1]*Physics Department, University of Connecticut, 2152 Hillside Road, Storrs, Connecticut 06269-3046*
[2]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
(Received 7 April 2000)



C-phase gate = U_π

Error scaling of Rydberg gate



residual excitation error ~Ω^2/B^2

Rydberg lifetime τ gives error ~$1/\Omega\tau$

optimum Rabi frequency $\Omega \sim B^{2/3}/\tau^{1/3}$

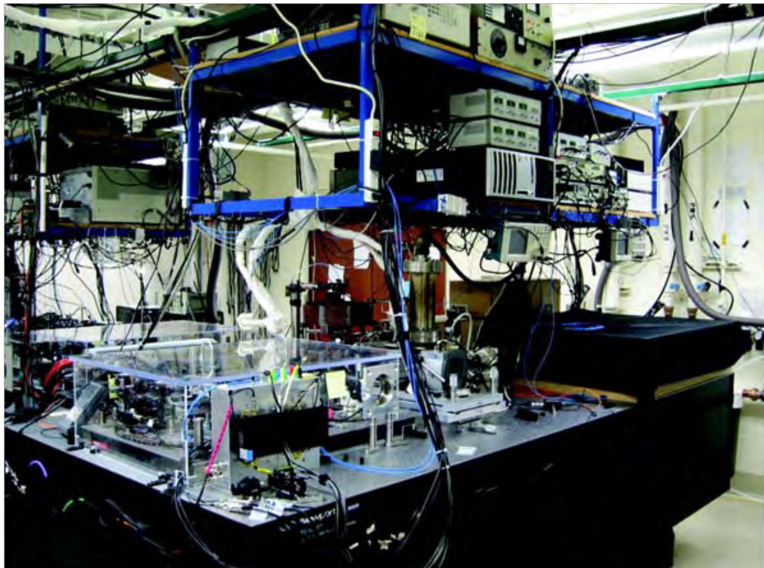
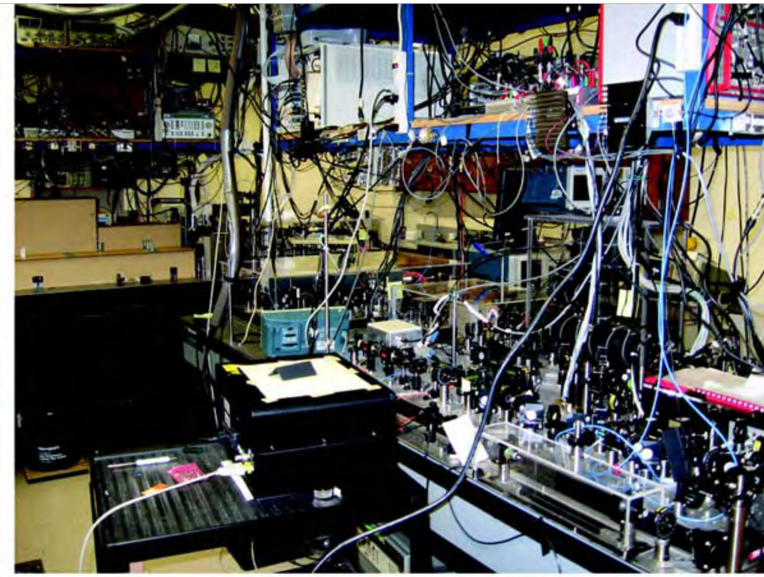
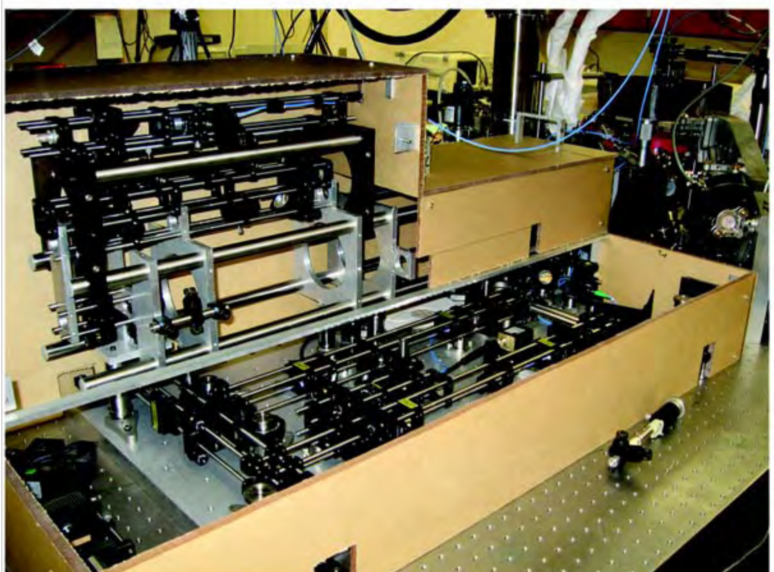
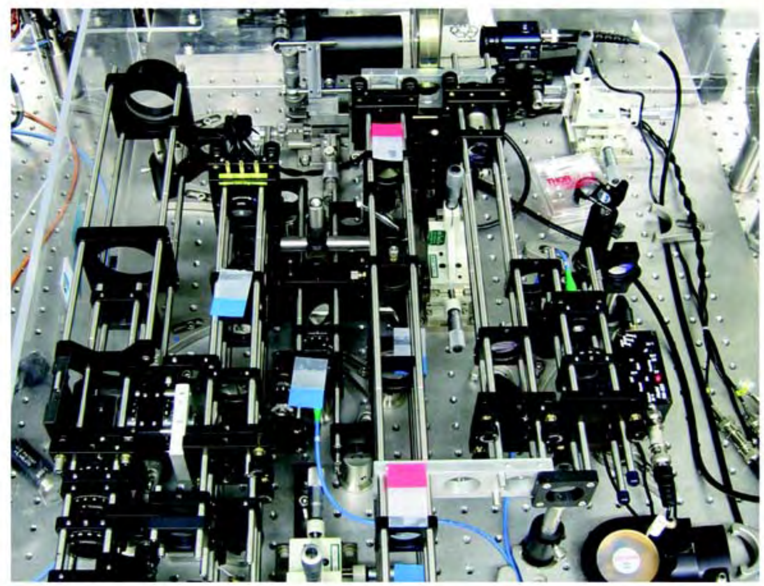
minimum error~ $1/(B\tau)^{2/3}$

Rb atoms, n=100 and R=10 μm
B~25 MHz, τ~300 μs

Error ~ 0.003

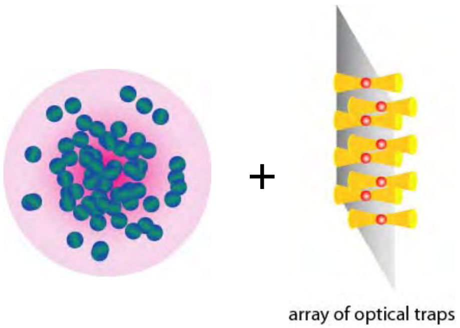
Saffman & Walker PRA (2005)

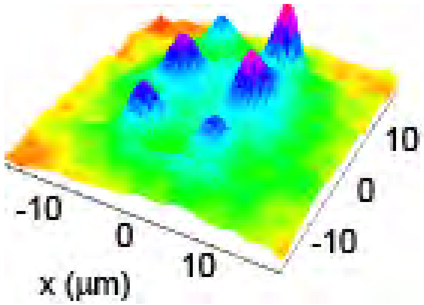
Experiment

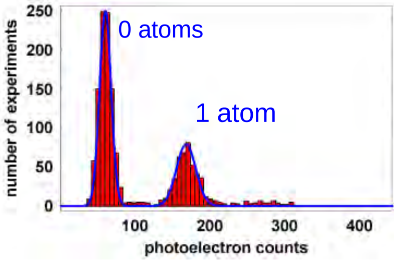
Experimental approach

MOT + Optical traps (FORT)



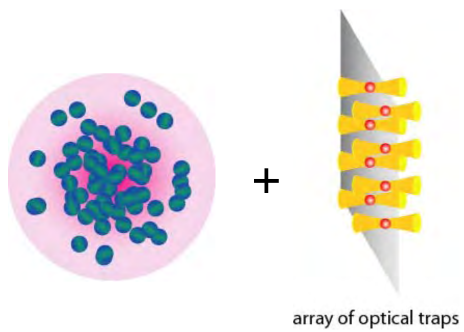


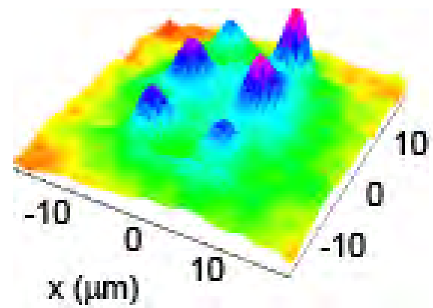
Single atom detection



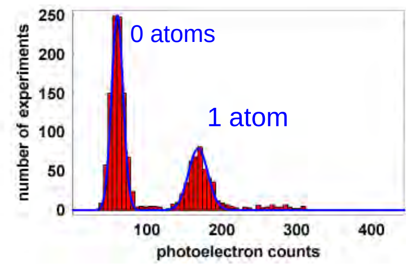
Experimental approach

MOT + Optical traps (FORT)

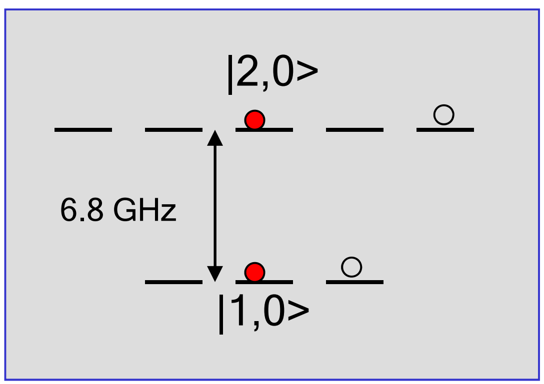




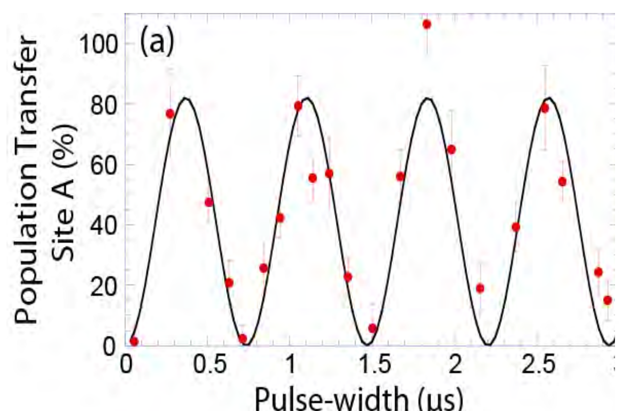
Single atom detection

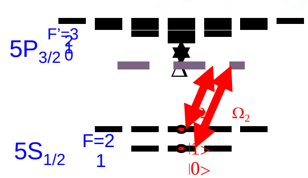


^{87}Rb hyperfine qubit

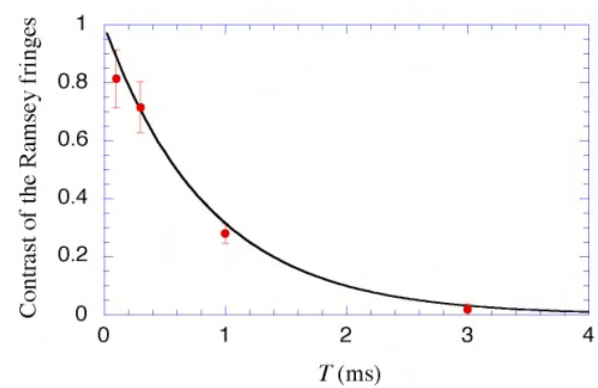


Ground Rabi flopping
$\Omega/2\pi$=1.4 MHz





Ramsey measurement
T2 ~ 1. ms

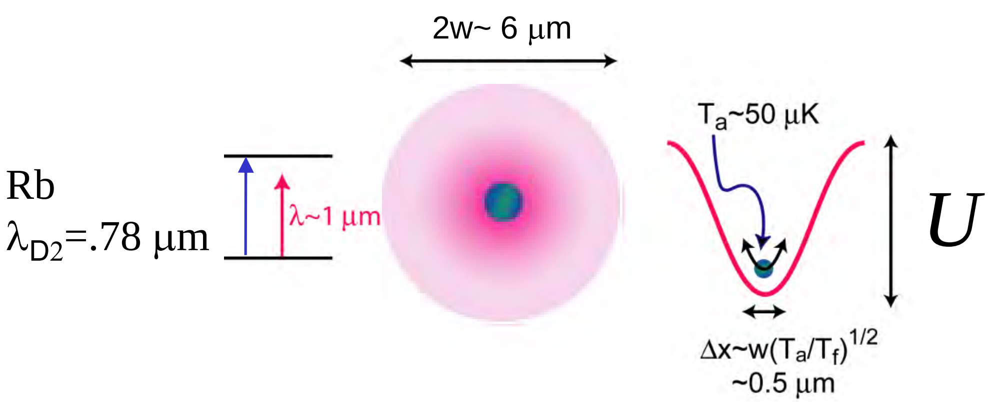


Yavuz, et al. PRL (2006)

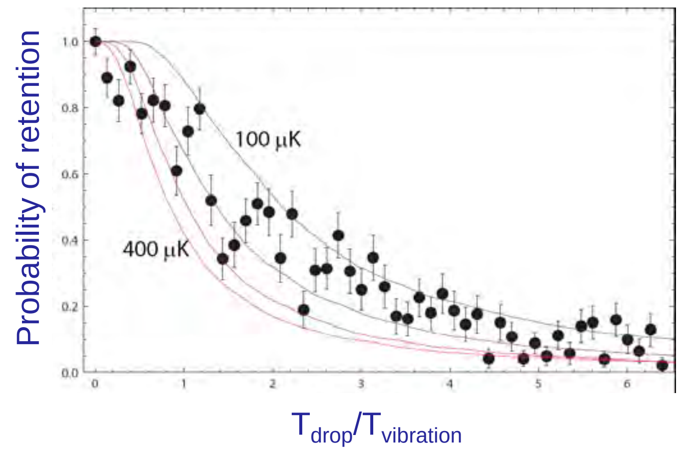
Microscopic optical trap

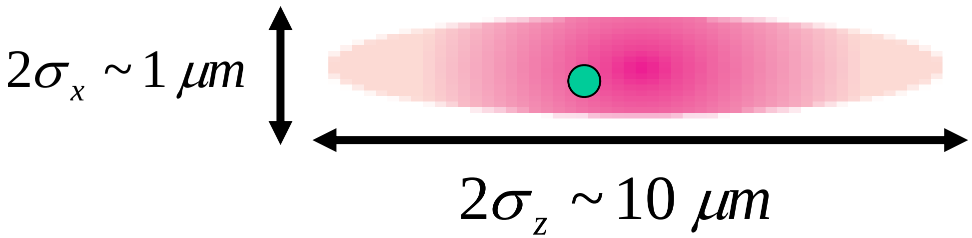
Single beam dipole trap -U ~ Intensity

Pioneering experiments by
Grangier,
Meschede, groups



Atom temperature measured by drop and recapture. Typically T~200 μK

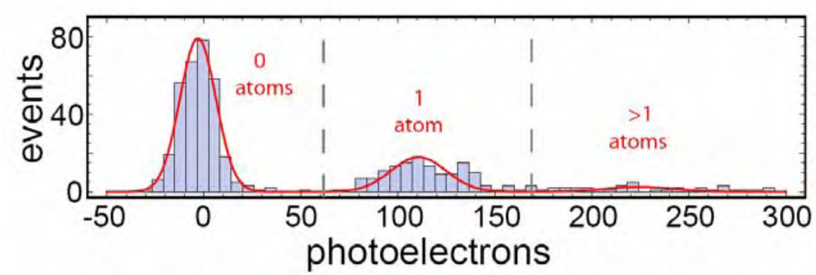




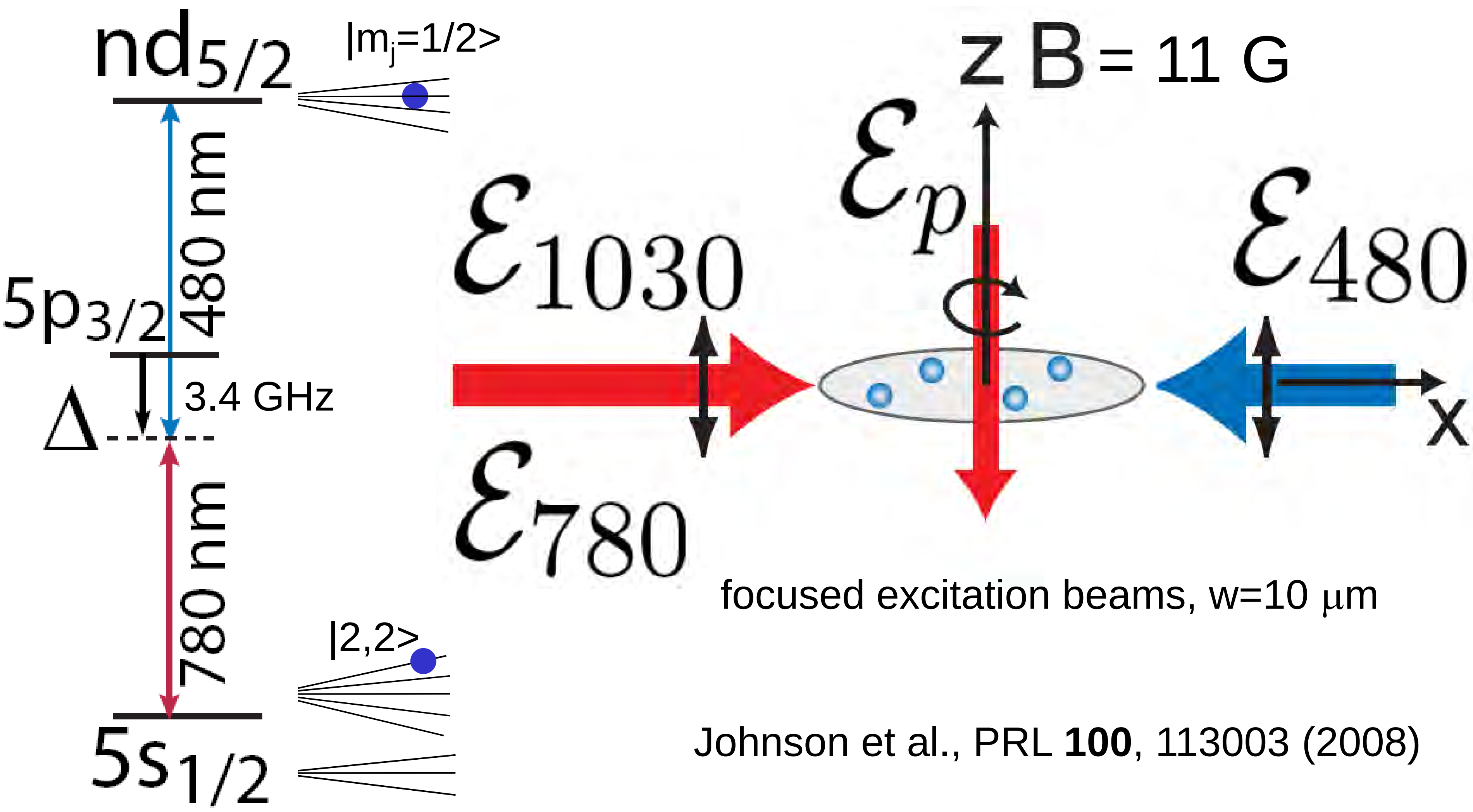
$$w = 3.0\ \mu m, \quad \lambda = 1.06\ \mu m$$

$$T_a = 0.1 - 0.5\, mK, U_f / k_B = 5\, mK$$

Single atom readout with 3D molasses



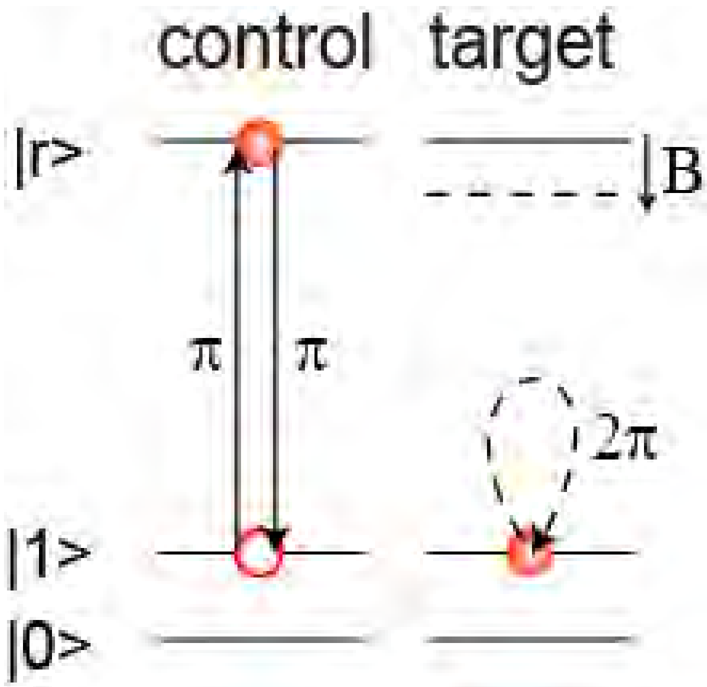
Rydberg excitation geometry



focused excitation beams, w=10 μm

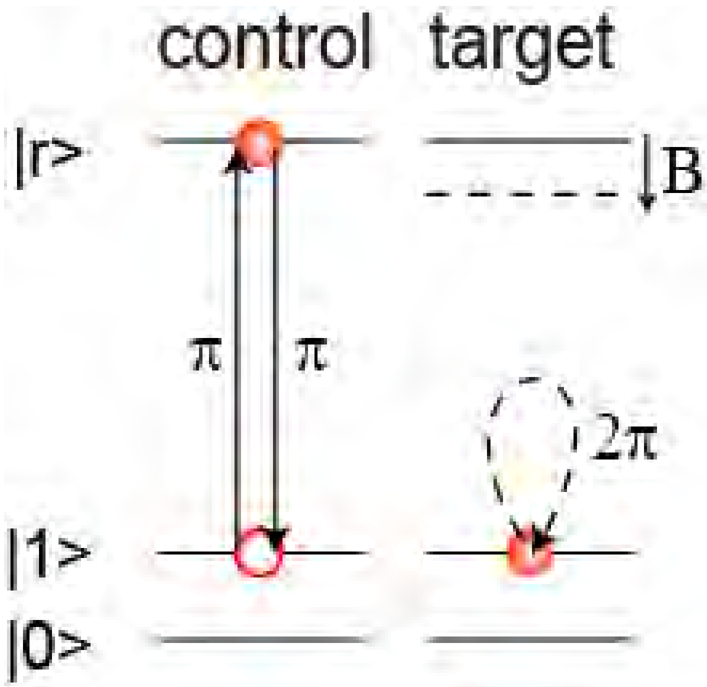
Johnson et al., PRL **100**, 113003 (2008)

Rydberg blockade between two atoms

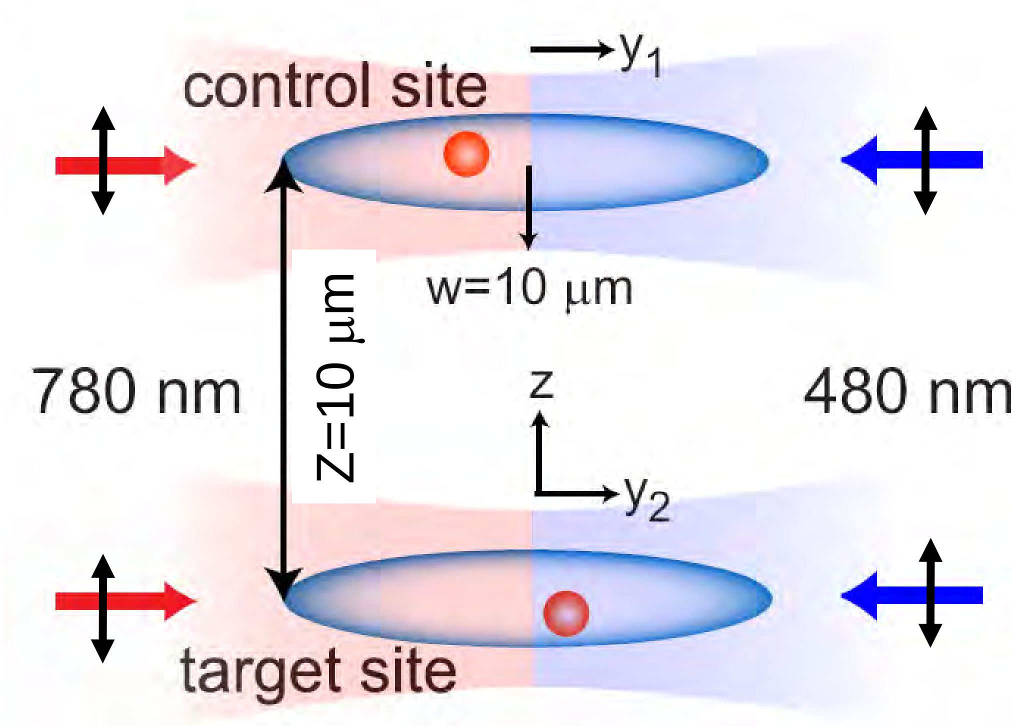


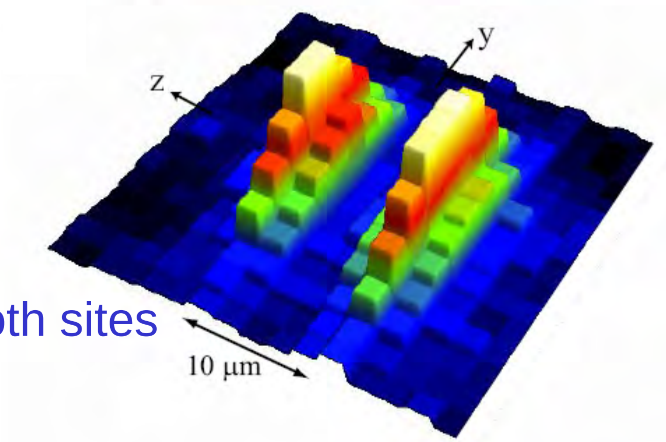
Jaksch, et al. 2000

Rydberg blockade between two atoms



Jaksch, et al. 2000

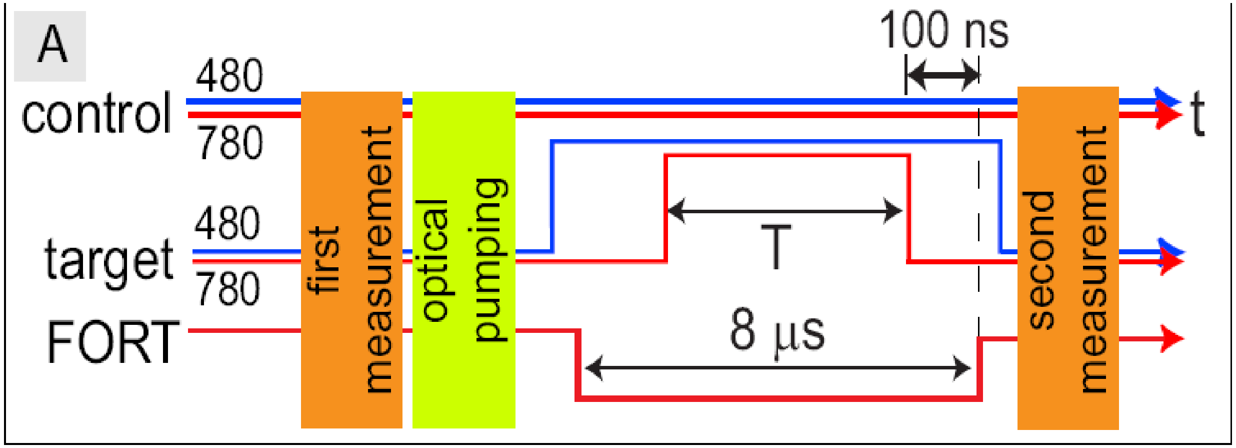




Average of 146 shots.
Probability of one atom in both sites about 5-10%.

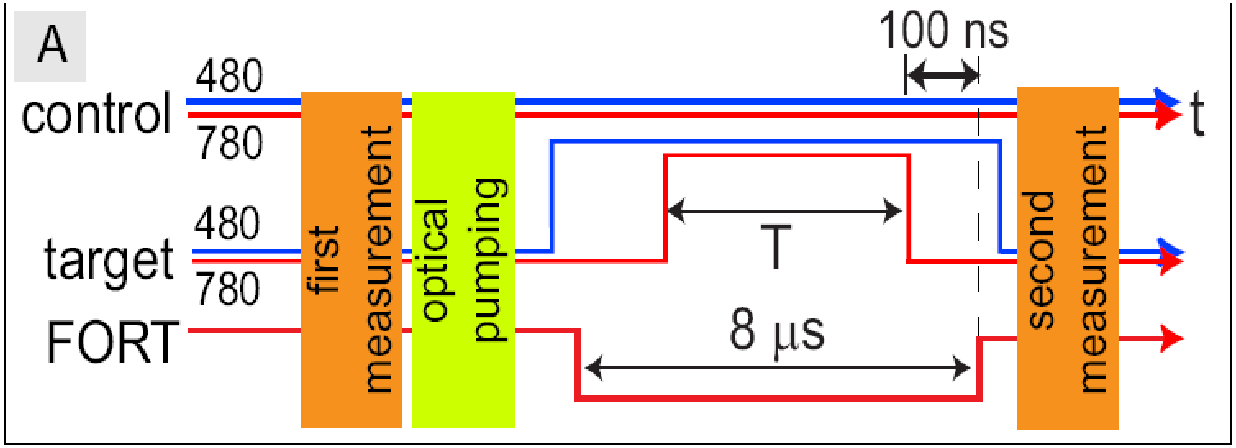
Rabi oscillations

$79d_{5/2}$

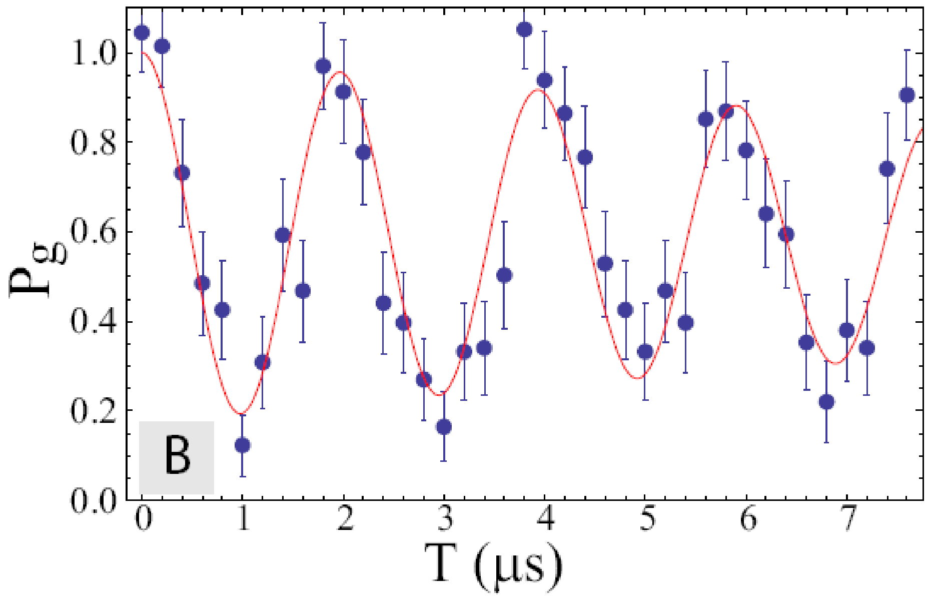


Rabi oscillations

$79d_{5/2}$



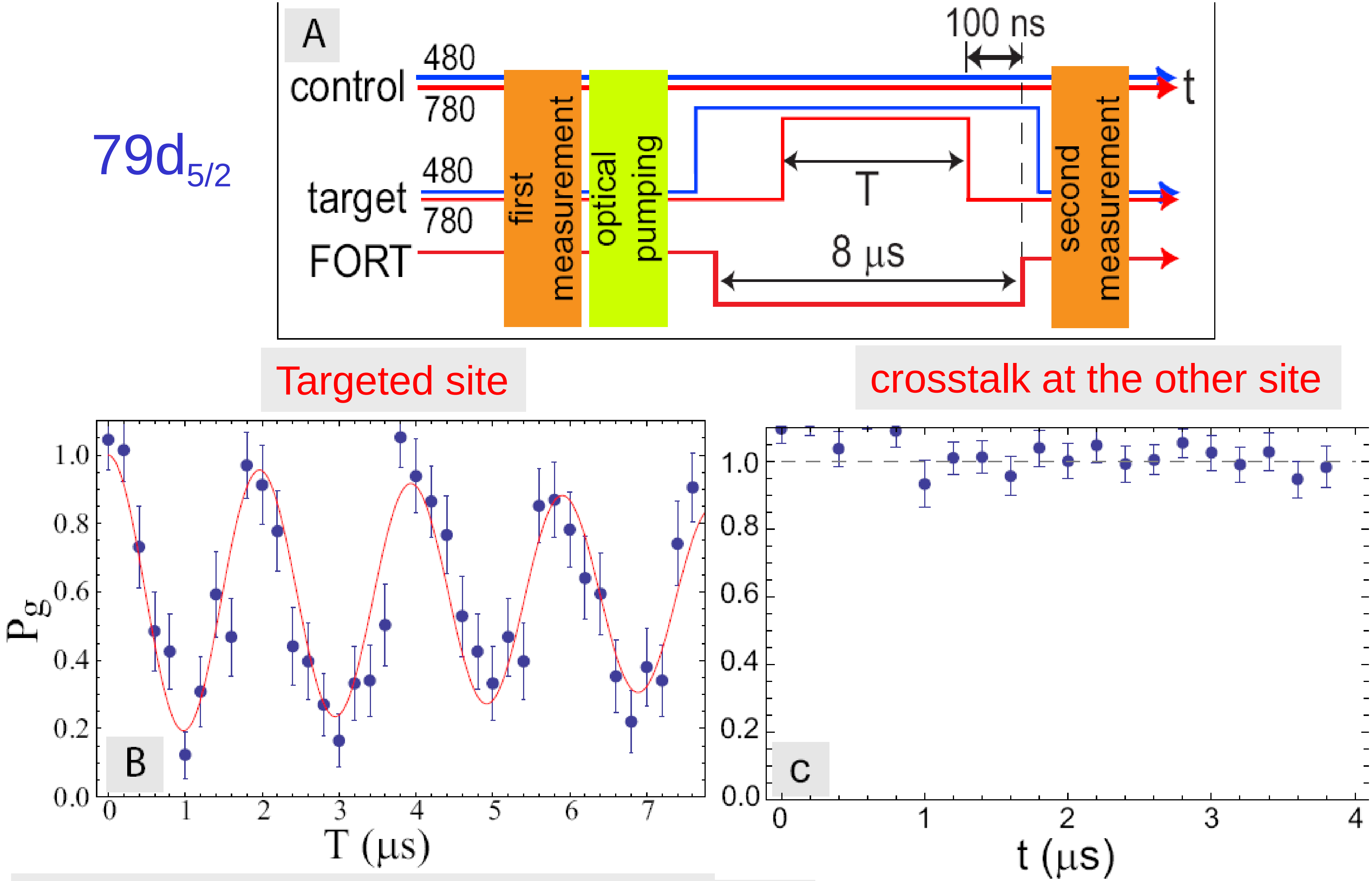
Targeted site



$\Omega/2\pi$= 0.51 MHz (exp.), 0.59 MHz (theory)

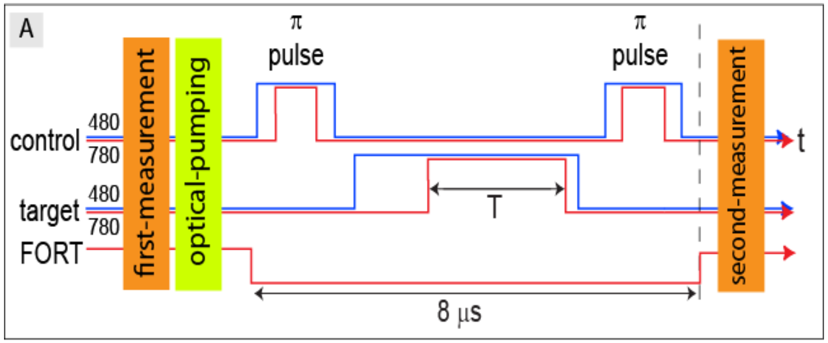
Rabi oscillations

$79d_{5/2}$



$\Omega/2\pi$= 0.51 MHz (exp.), 0.59 MHz (theory)

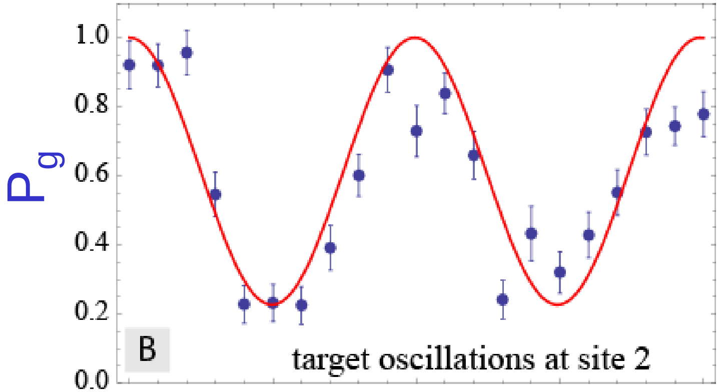
Rydberg Blockade



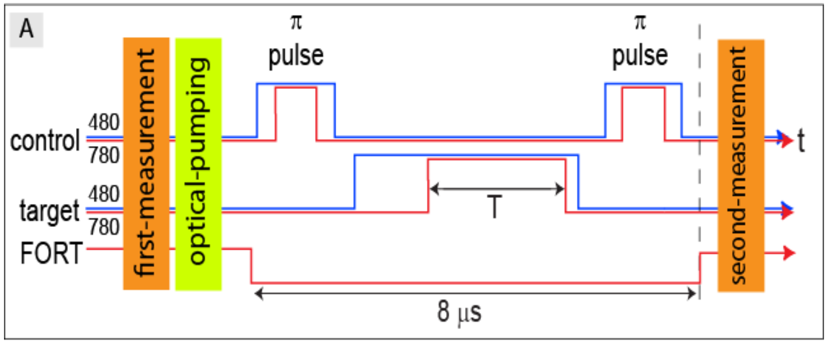
$79d_{5/2}$

no control atom
target oscillations

site
1 -> 2



Rydberg Blockade

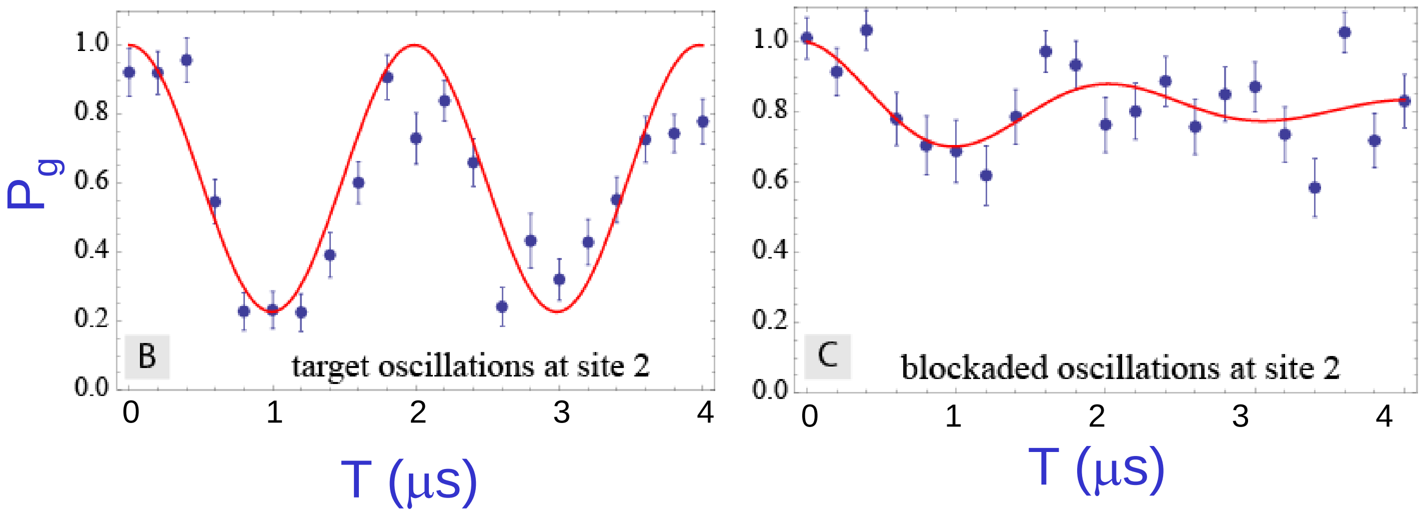


$79d_{5/2}$

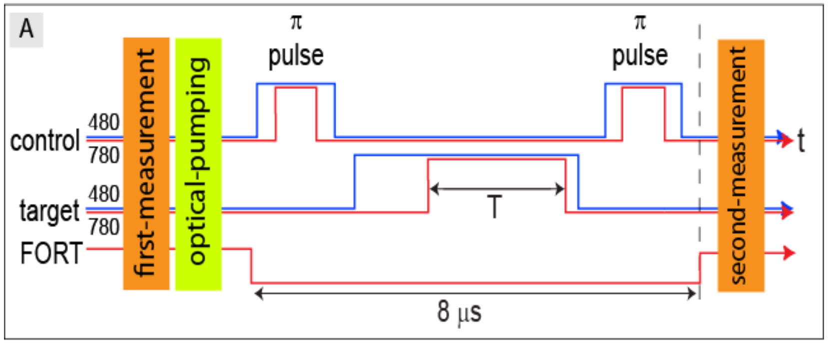
no control atom
target oscillations

with control atom
target blockaded

site
1 -> 2



Rydberg Blockade



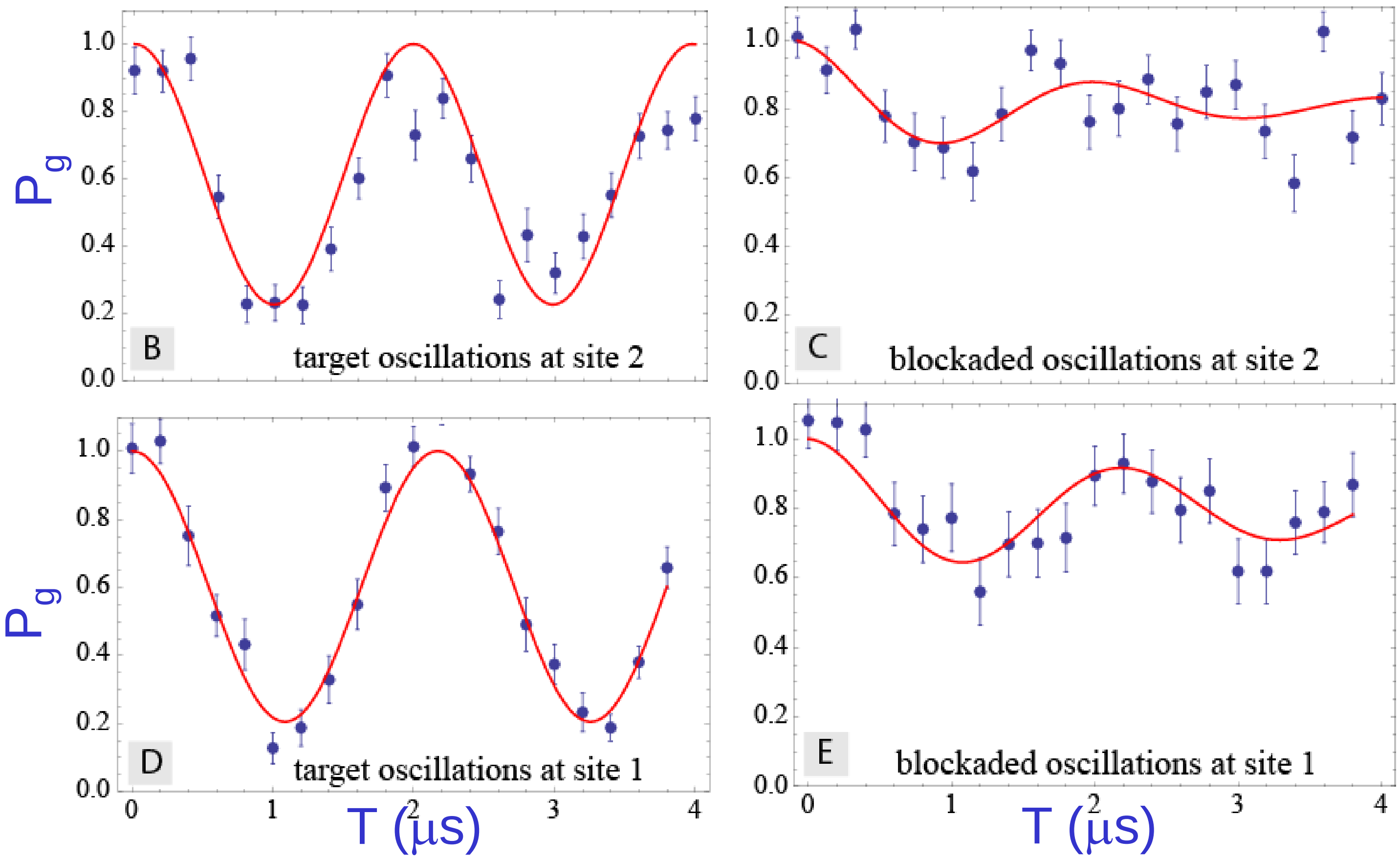
$79d_{5/2}$

no control atom
target oscillations

with control atom
target blockaded

site
1 -> 2

site
2 -> 1

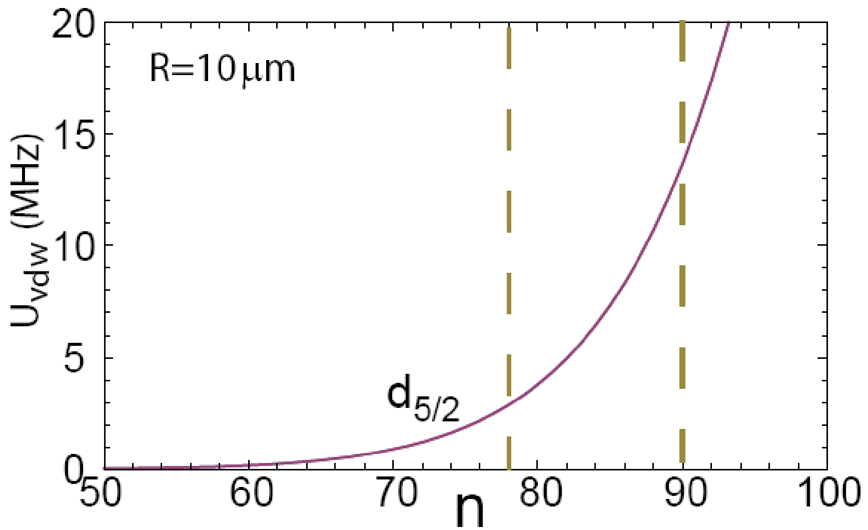


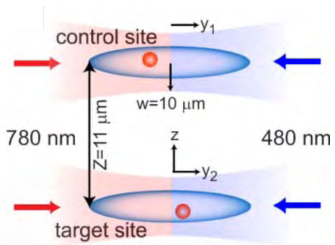
Higher fidelity blockade

We can do better by increasing the interaction strength

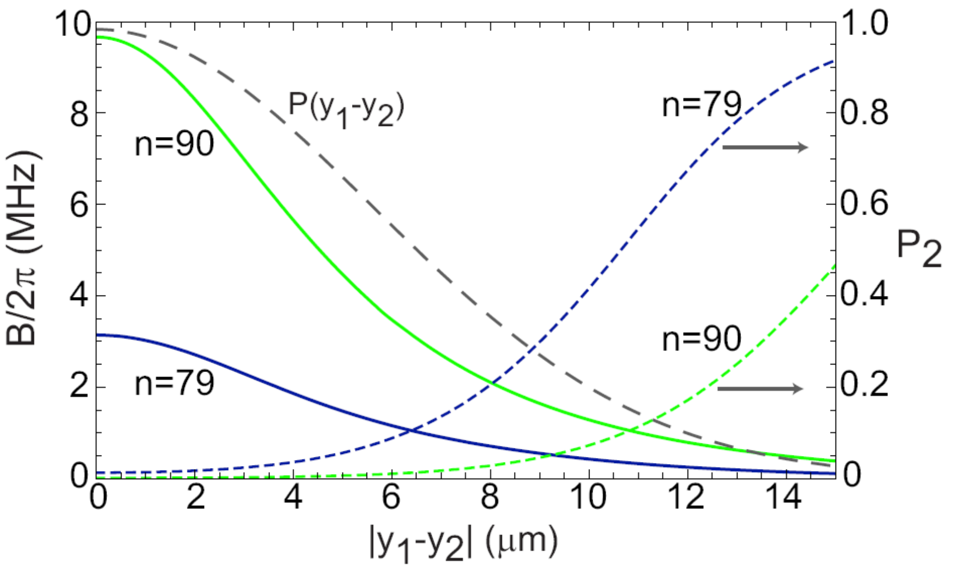
Interaction strength vs. n

$B \sim n^{11} - n^{12}$

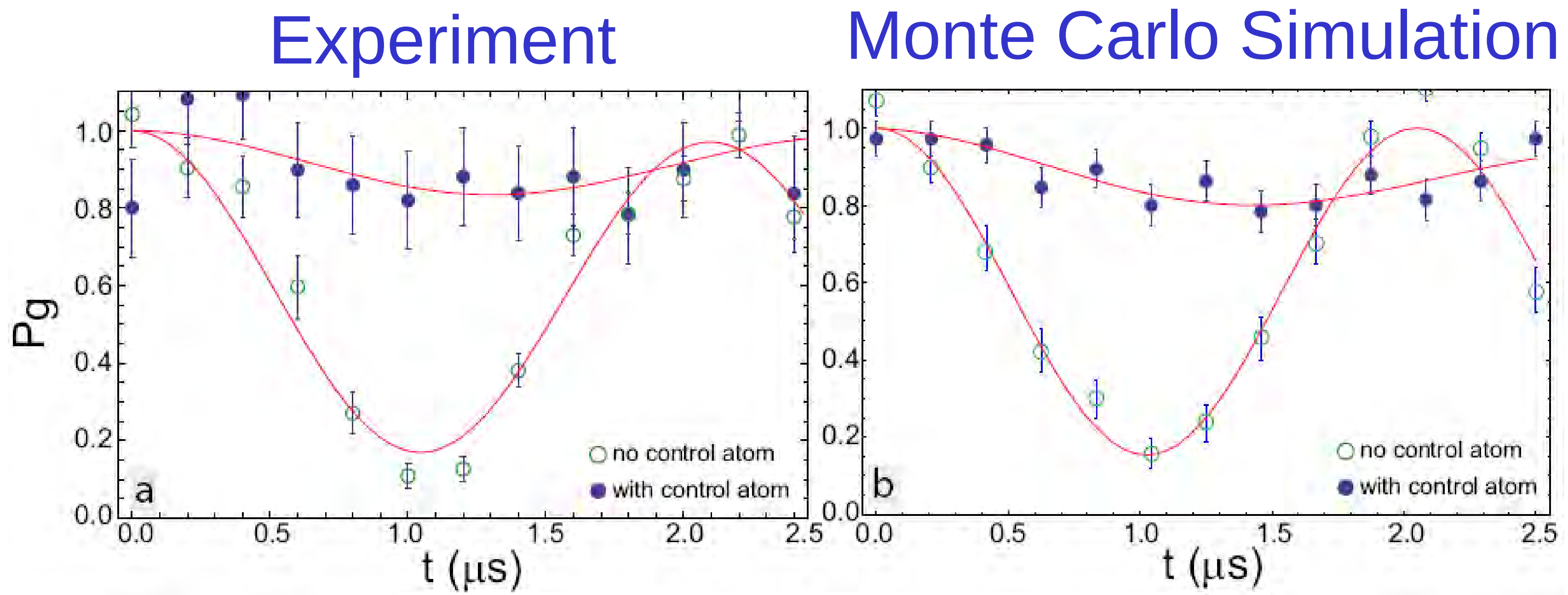




Predicted blockade and P_2 for n=90



Blockade experiment n=90



The data are fit to $$P_g = (1-a) + a\cos(2\pi f t)e^{-t/\tau}$$

With a control atom present we find

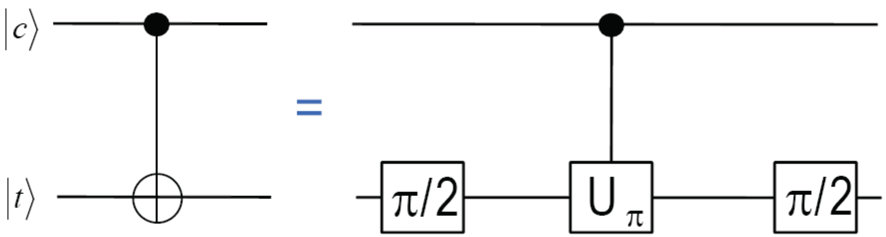
a= 0.09 (experiment) a=0.11 (simulation)

Residual blockade leakage is almost entirely due to state preparation and measurement errors.

Urban, et al. Nature Physics Feb. (2009)
Gaetan, et al. Nature Physics Feb. (2009)

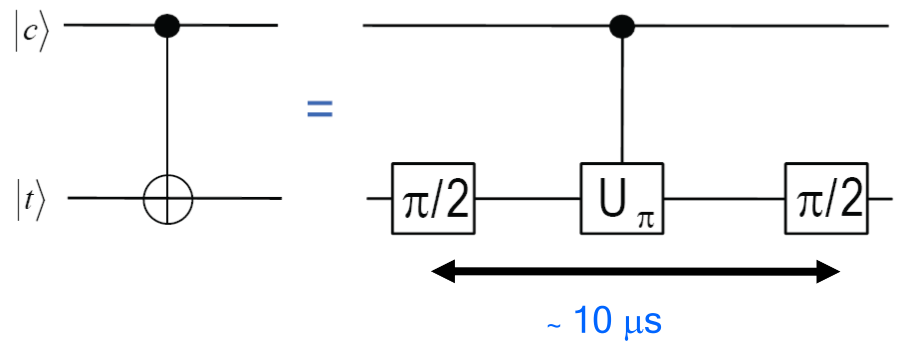
From blockade to quantum gates

The CNOT gate can be realized
with a controlled phase plus Hadamards

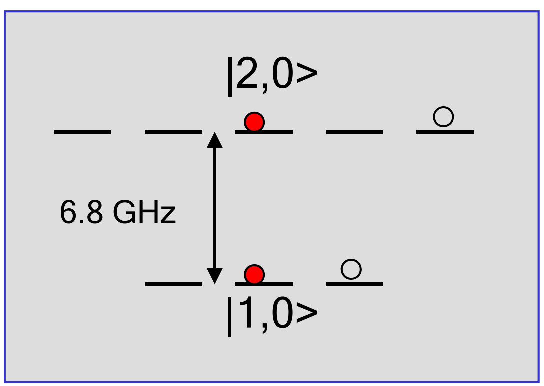


From blockade to quantum gates

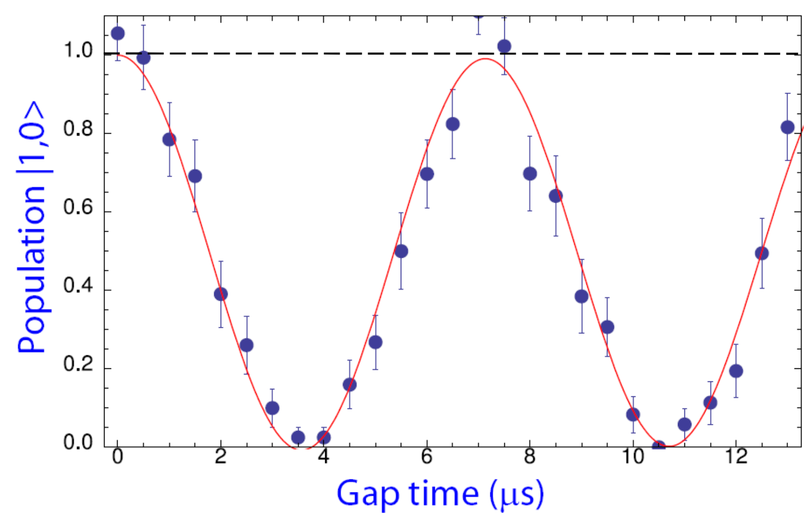
The CNOT gate can be realized
with a controlled phase plus Hadamards



Better ground state
coherence with m=0 states
at B~4 G.



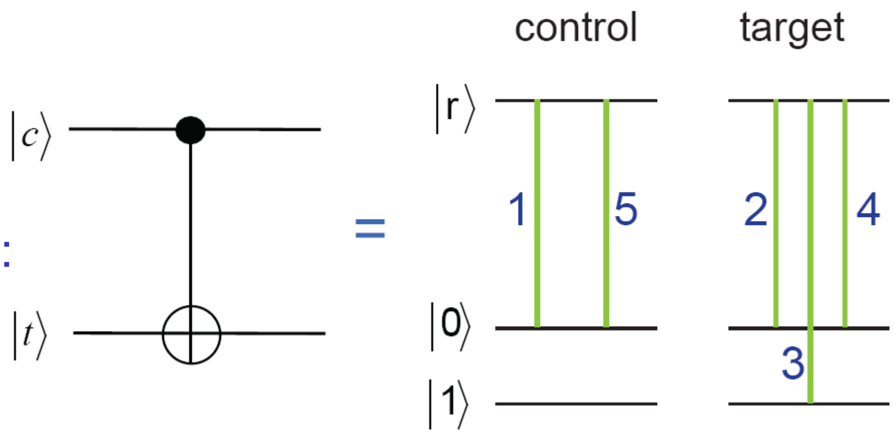
Ground state Ramsey spectroscopy



Other CNOT protocols

It is also possible to perform a CNOT gate using only π pulses and blockade:

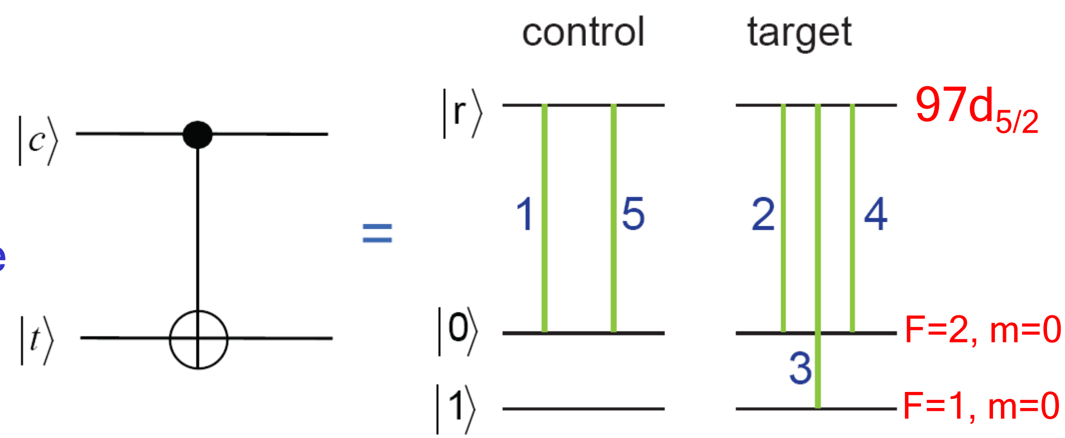
Ohlsson, et al. Opt. Commun. (2002)



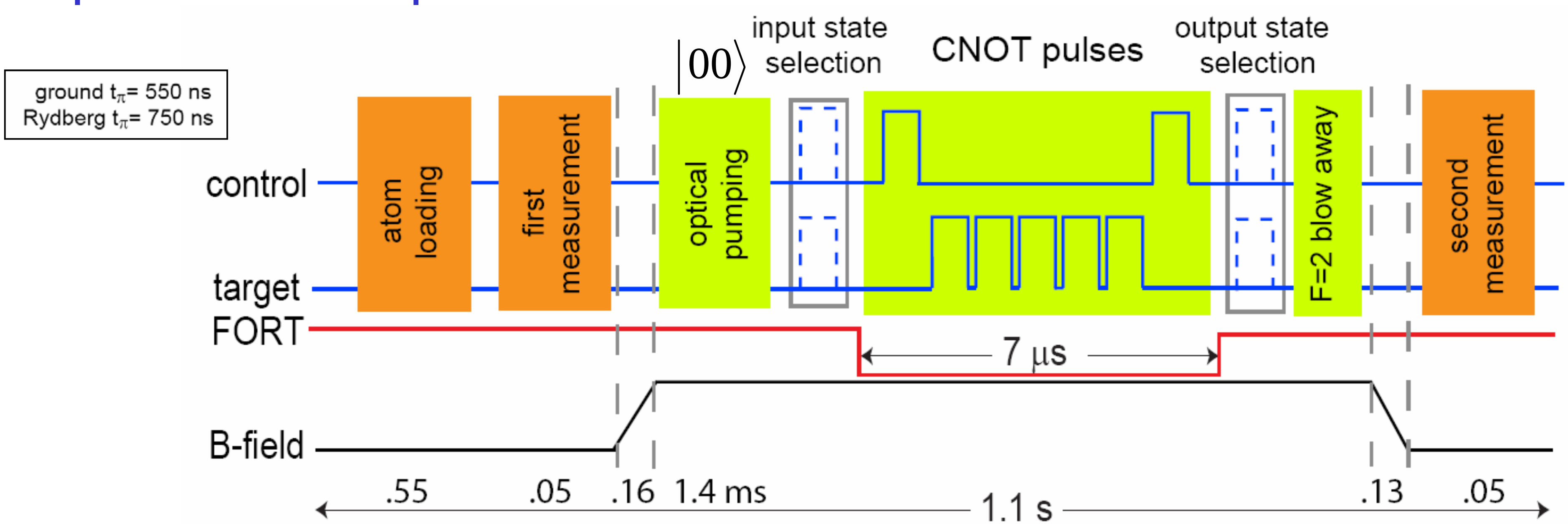
Other CNOT protocols

It is also possible to perform a CNOT gate using only π pulses and blockade

Ohlsson, et al. Opt. Commun. (2002)

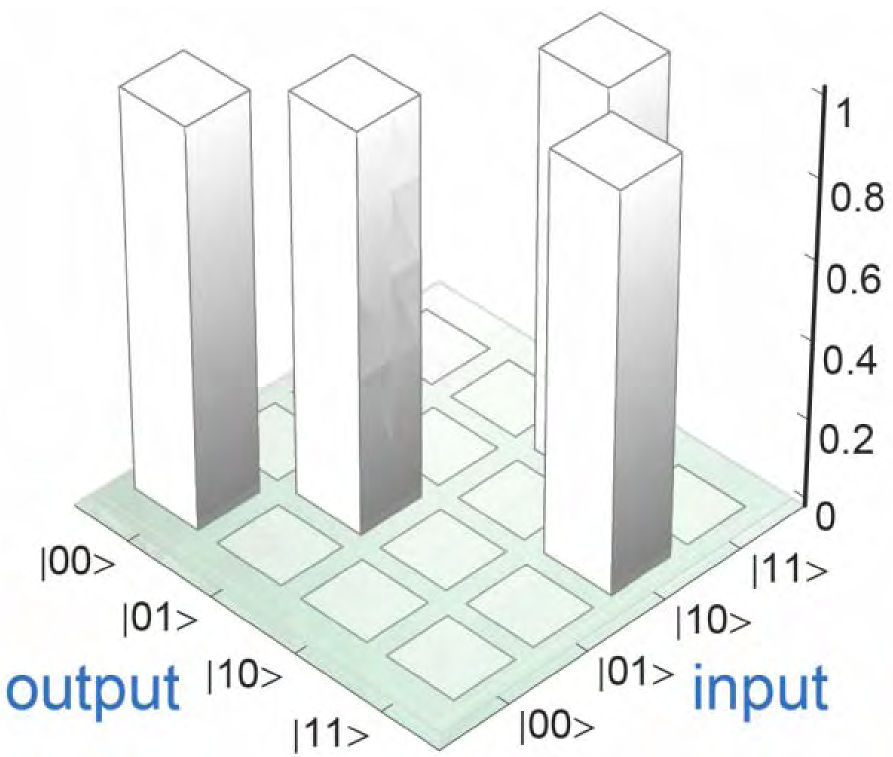


Experimental sequence

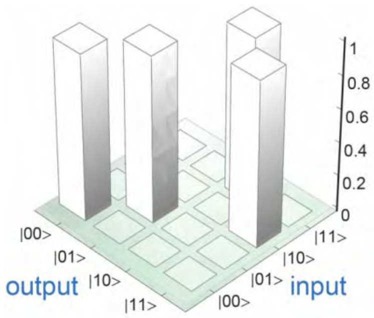


CNOT experiment

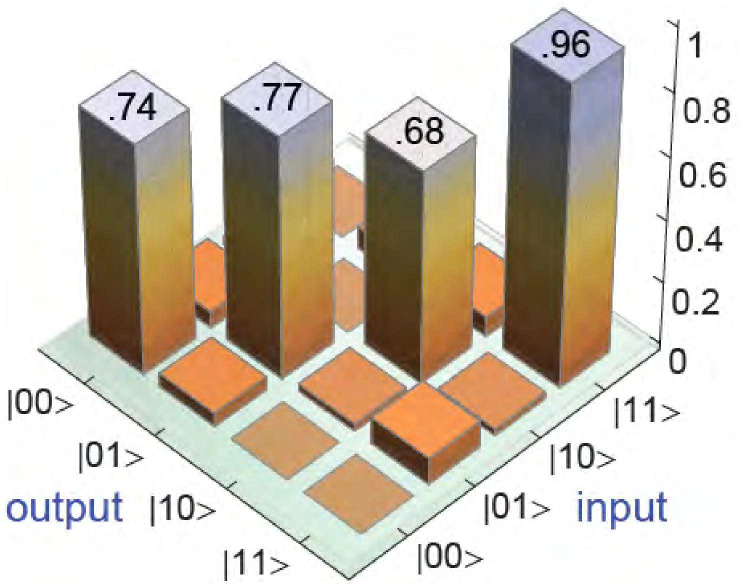
ideal
truth table



CNOT experiment



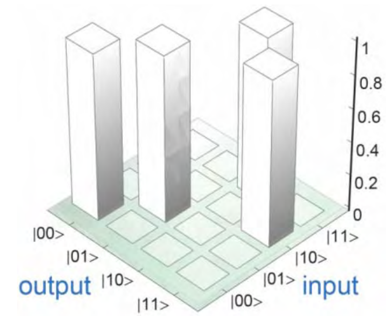
measured
input states

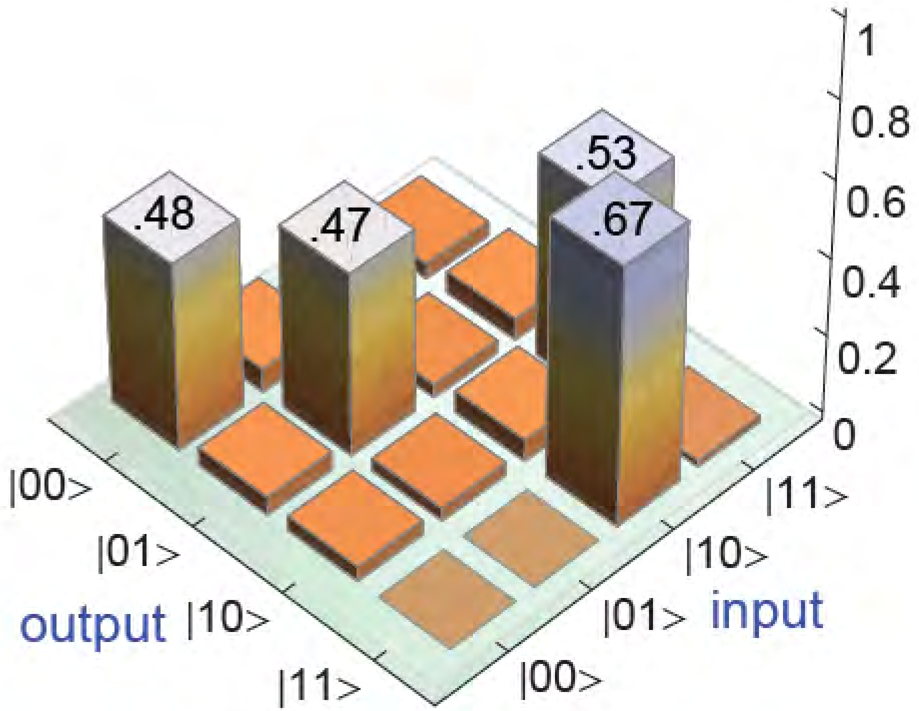


Preliminary data May 2009

CNOT experiment

measured truth table



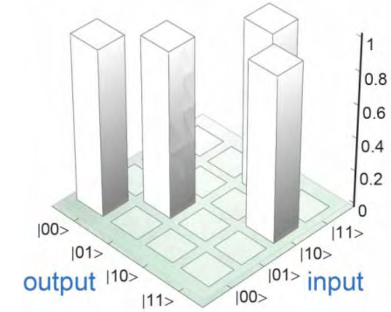


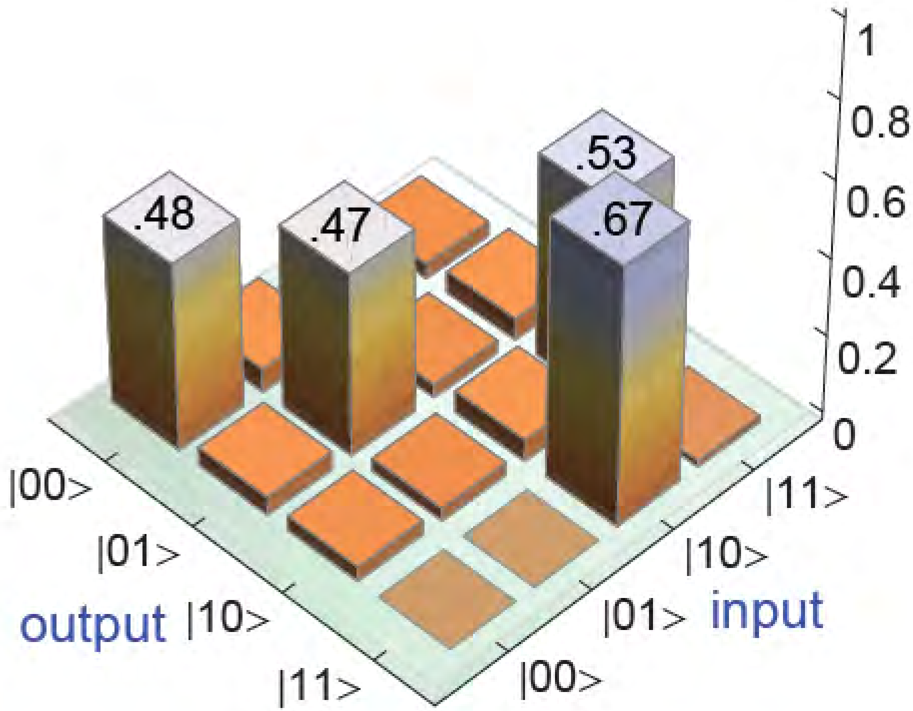
about 75 two-atom trials/ matrix element

Preliminary data May 2009

CNOT experiment

measured truth table





about 75 two-atom trials/ matrix element

Probabilities

0.48	0.06	0	0.04
0.05	0.47	0.03	0.06
0.04	0.03	0.06	0.53
0	0	0.67	0.02

average high/low

$$.54/.03 = 17/1$$

fidelity

$$(1/4)Tr(U_{ideal}^{T} U_{\exp}) = .54$$

Preliminary data May 2009

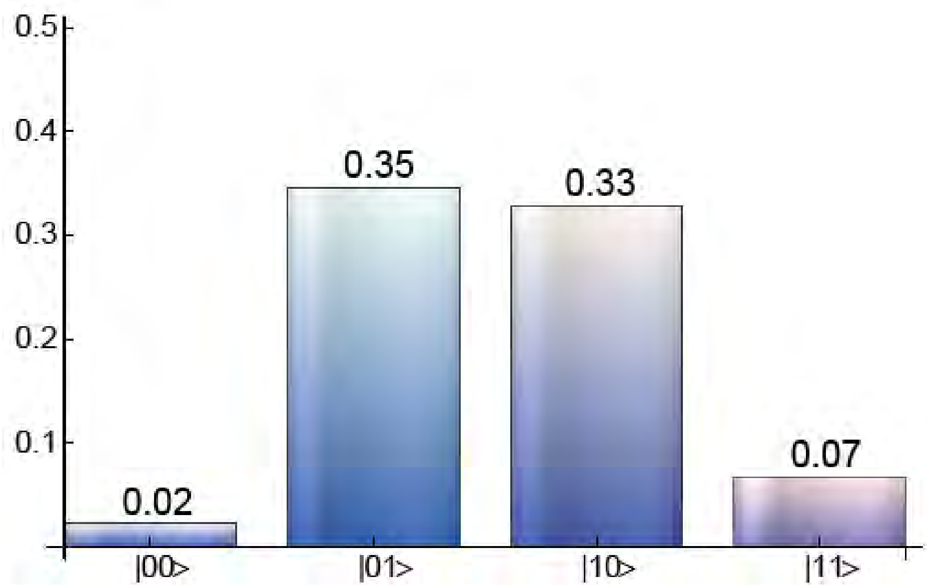
Entanglement on demand

control target

$$\frac{|0> + |1>}{\sqrt{2}} |1> \Rightarrow \frac{|01> + |10>}{\sqrt{2}}$$

input data

ideal output

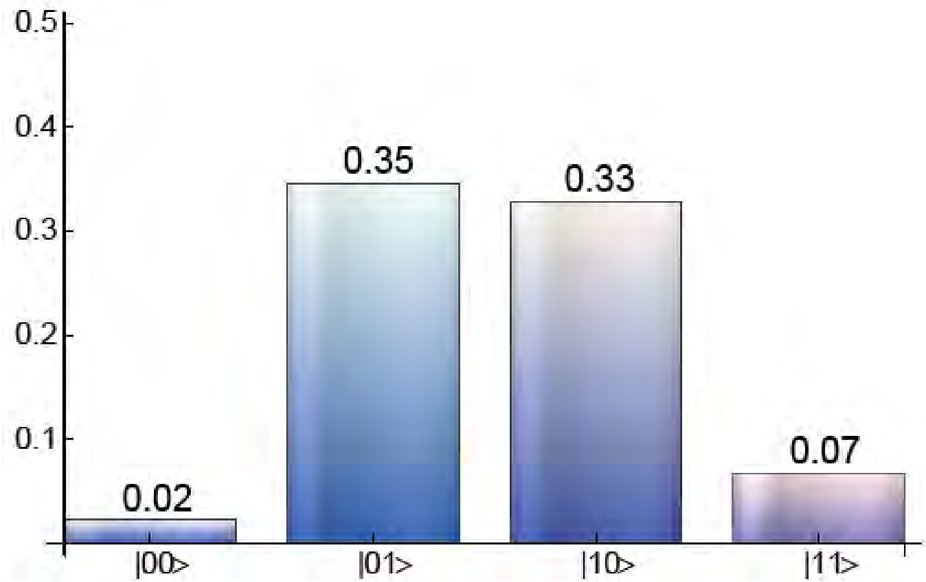


Entanglement on demand

control target

$$\frac{|0>+|1>}{\sqrt{2}}|1>\Rightarrow\frac{|01>+|10>}{\sqrt{2}}$$

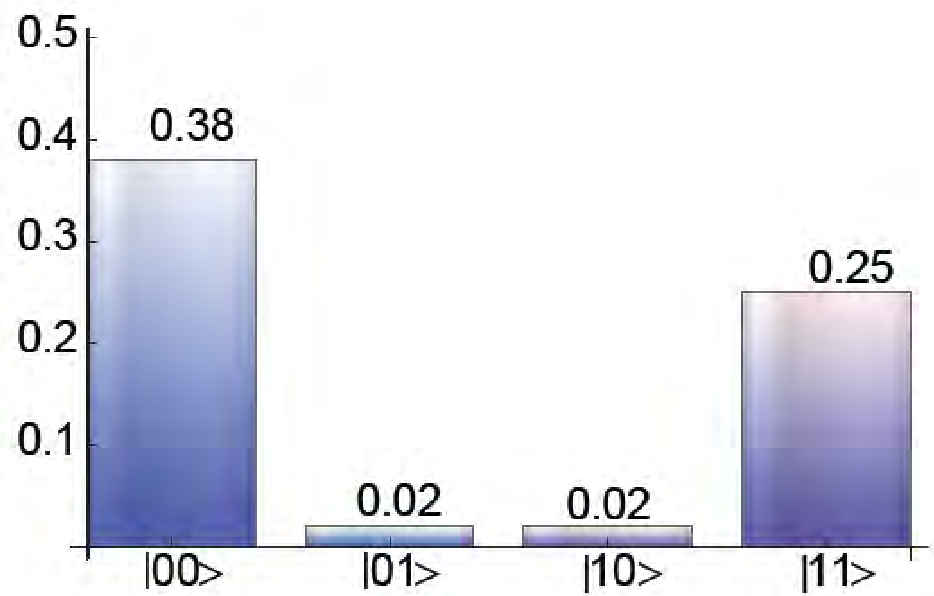
input data ideal output



control target

$$\frac{|0>+|1>}{\sqrt{2}}|0>\Rightarrow\frac{|00>+|11>}{\sqrt{2}}$$

input data ideal output



Publication in preparation

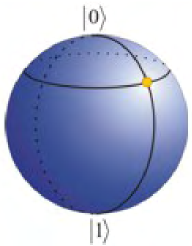
Preliminary data May 2009

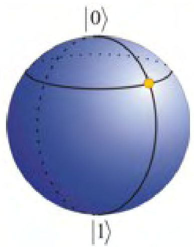
Scalability

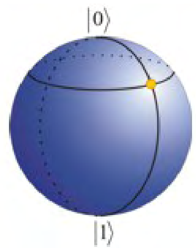


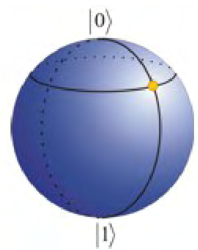


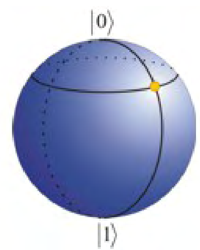
Scalability

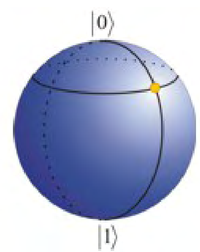


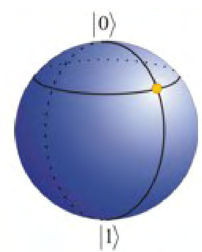


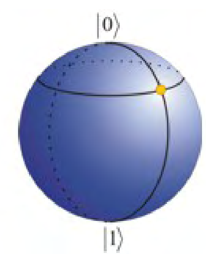












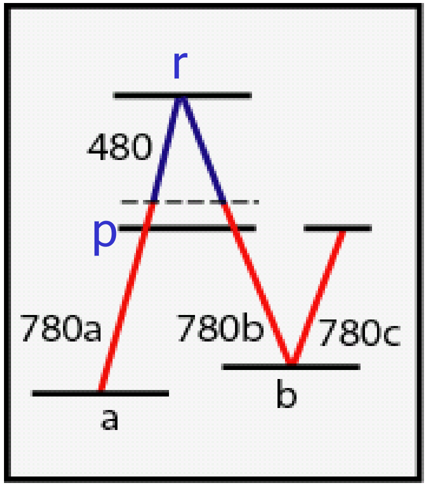
Ion traps N=8 qubits (2005)
Neutral atoms
Superconductors
Semiconductor spins
Photons and linear optics
Nitrogen vacancies
…..

Applications:

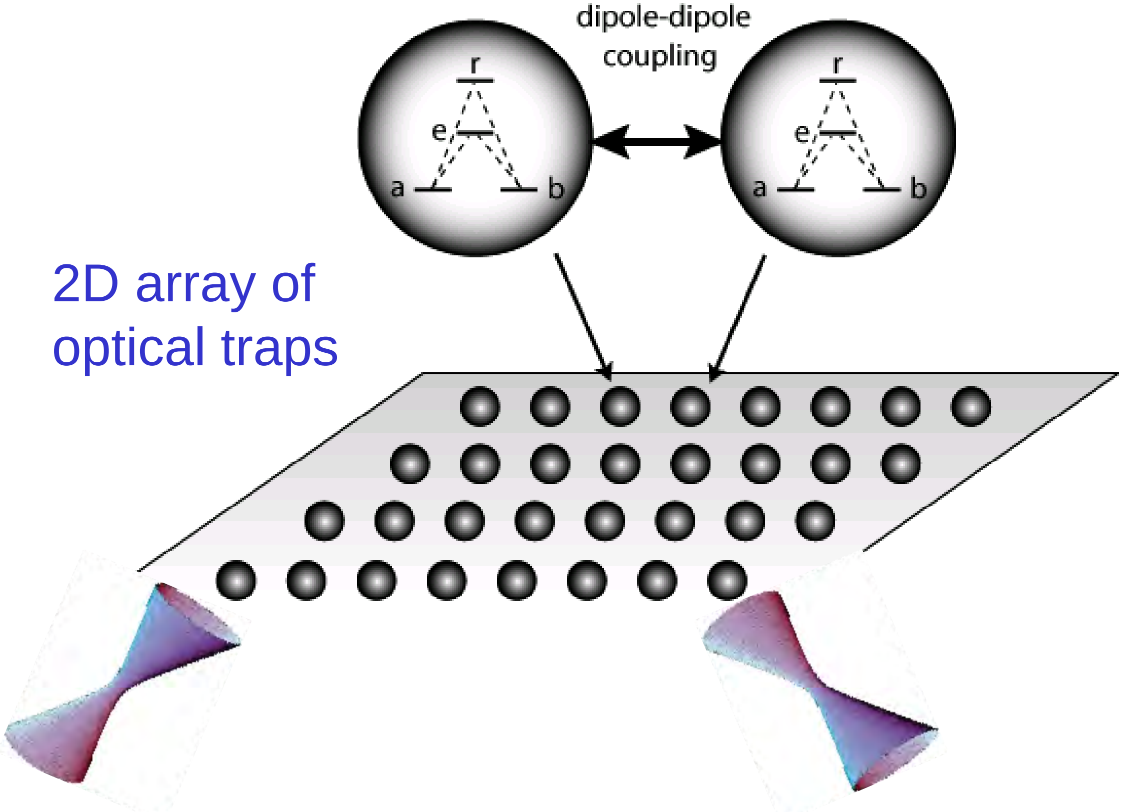
Entanglement and decoherence	N> 2
Quantum simulation	N> 30
Factoring, search, …	N> 10^6

Quantum networks, secure data transmission

Neutral atom Rydberg gate array



hyperfine qubit



2D array of optical traps

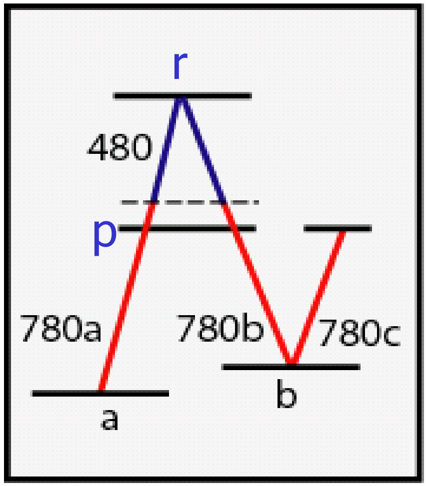
focused laser beams for state preparation, single qubit operations, and measurements

Yavuz, et al. PRL (2006)

focused laser beams for Rydberg excitation and two qubit gates

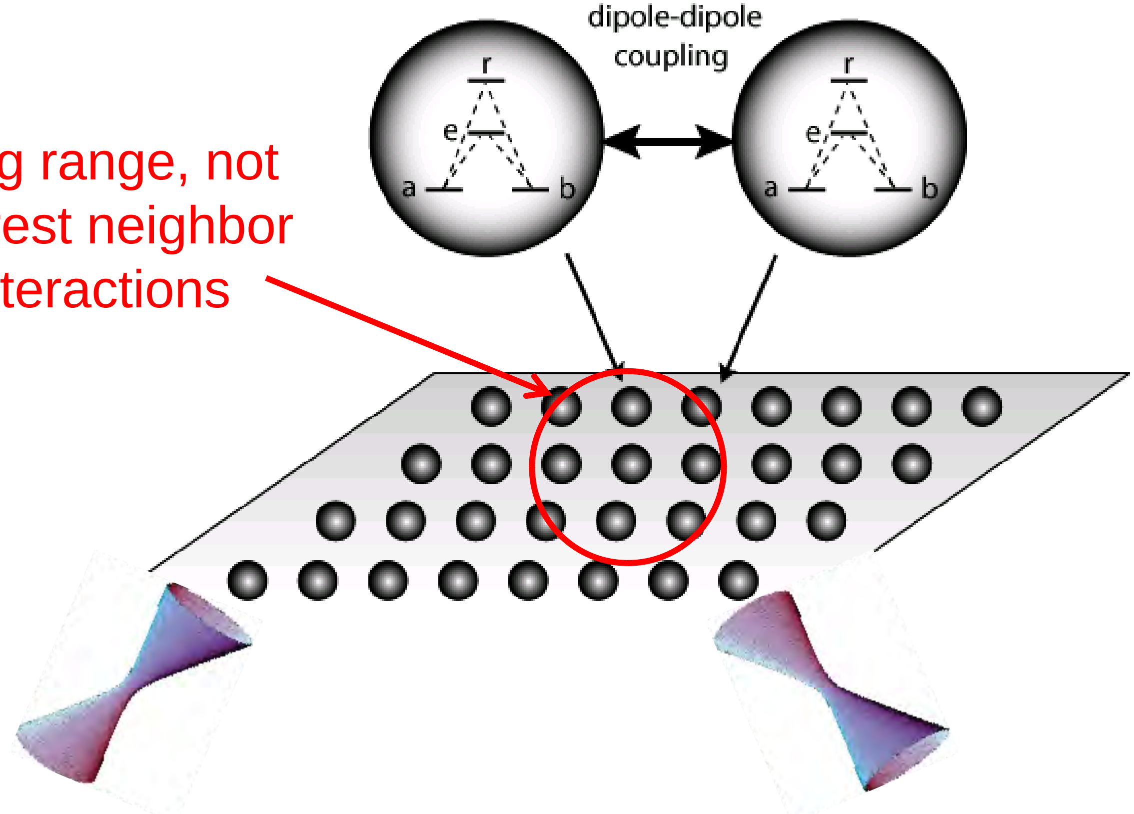
Johnson, et al. PRL (2008)
Urban, et al. NP (2009)

Neutral atom Rydberg gate array concept



hyperfine qubit

long range, not
nearest neighbor
interactions



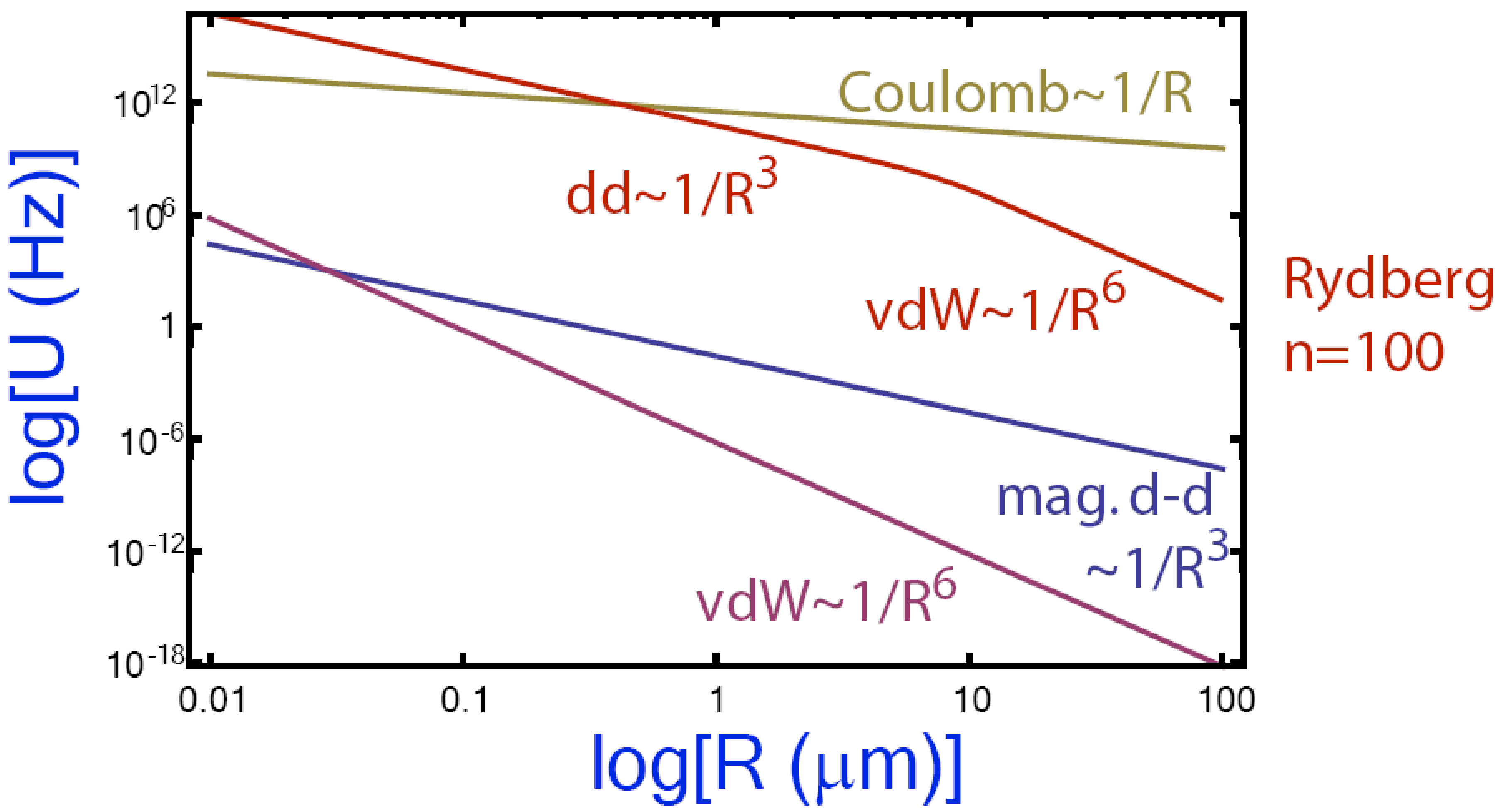
focused laser beams
for state preparation,
single qubit operations,
and measurements

Yavuz, et al. PRL (2006)

focused laser beams
for Rydberg excitation
and two qubit gates

Johnson, et al. PRL (2008)
Urban, et al. NP (2009)

Atomic interactions



Long range interactions between ground state atoms

10 μm

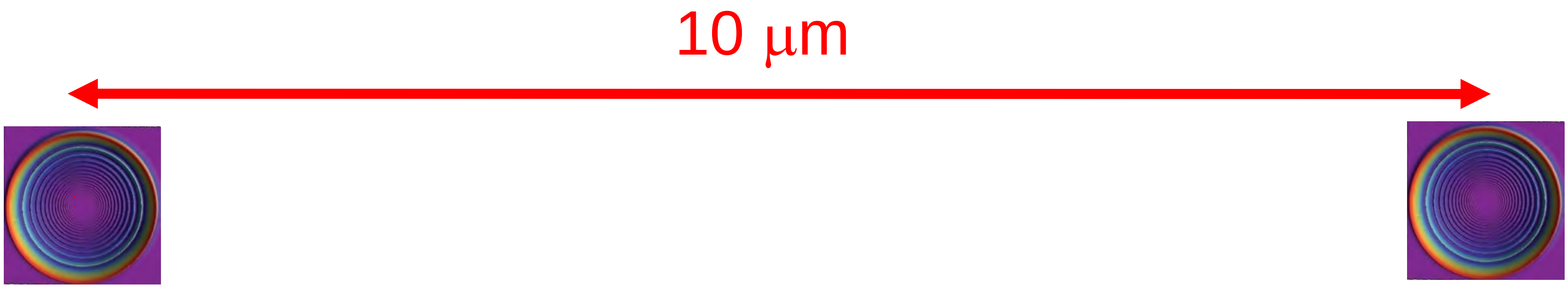
atom 1

atom 2

Rb-Rb magnetic dipole interaction

$$\Delta E \sim 25\,\mu Hz$$

Long range interactions between Rydberg atoms

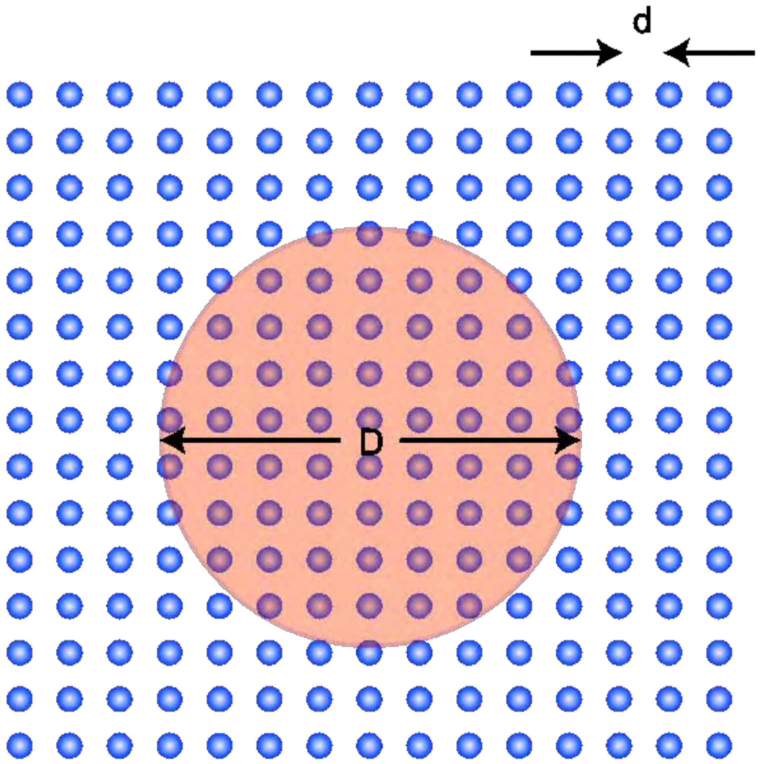


Rydberg n=100 van der Waals interaction

$$\Delta E \sim 25\,MHz$$

We have shown that this interaction can be controlled and used for manipulating quantum states of single atoms.

How many sites can be connected via Rydberg ?



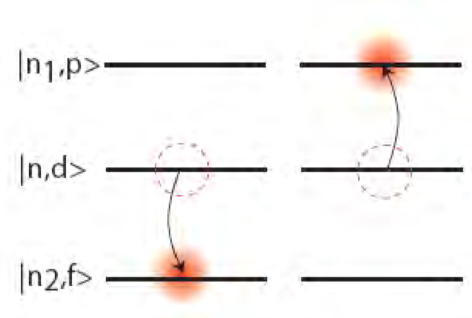
$$N = \frac{\pi}{4} \frac{D^2}{d^2}$$

How large can D be and
how small can d be?

Interaction strength

How large can D be?

$$U_{vdw} = \frac{C_6}{D^6}, \quad C_6 \sim \frac{\langle d\rangle^2 \langle d\rangle^2}{\delta} \sim \frac{n^4 n^4}{1/n^3} \sim n^{11}$$



Numerical calculations for Rb, Cs in the range 50<n<100 show that

$$\delta \sim 1/n^3 \rightarrow \delta \sim k_\delta / n^4$$

due to $|\nu_s - \nu_p| \sim 0.5$.   Also we can tune δ with external fields.

So

$$C_6 \sim n^{12}$$

At constant gate error E, and Rydberg lifetime τ $\tau = \tau_0 n^2 \sim n^2$

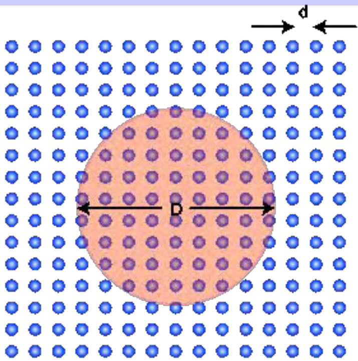
$$D_{\max} \sim (C_6 \tau E)^{1/6} \sim n^{7/3}$$

Saffman and Walker, PRA (2005)

Maximum number of connected sites

The minimum separation is set by the requirement that a Rydberg atom does not collide with a ground state neighbor. So

$$d_{\min} = k_1 a_0 n^2 \sim n^2$$



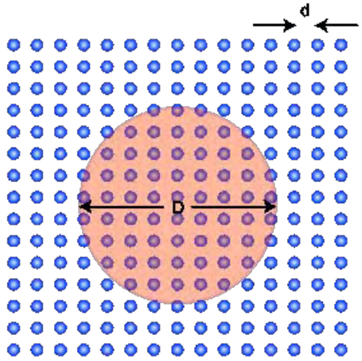
Combining the above we find

$$N_{\max}^{(2D)} = \frac{3\pi^{2/3}}{2^{8/3} k_1^2 k_\delta^{1/3}} \left(\frac{\alpha^2 mc^2 \tau_0}{\hbar} \right)^{1/3} E^{1/3} n^{2/3} \sim n^{2/3}$$

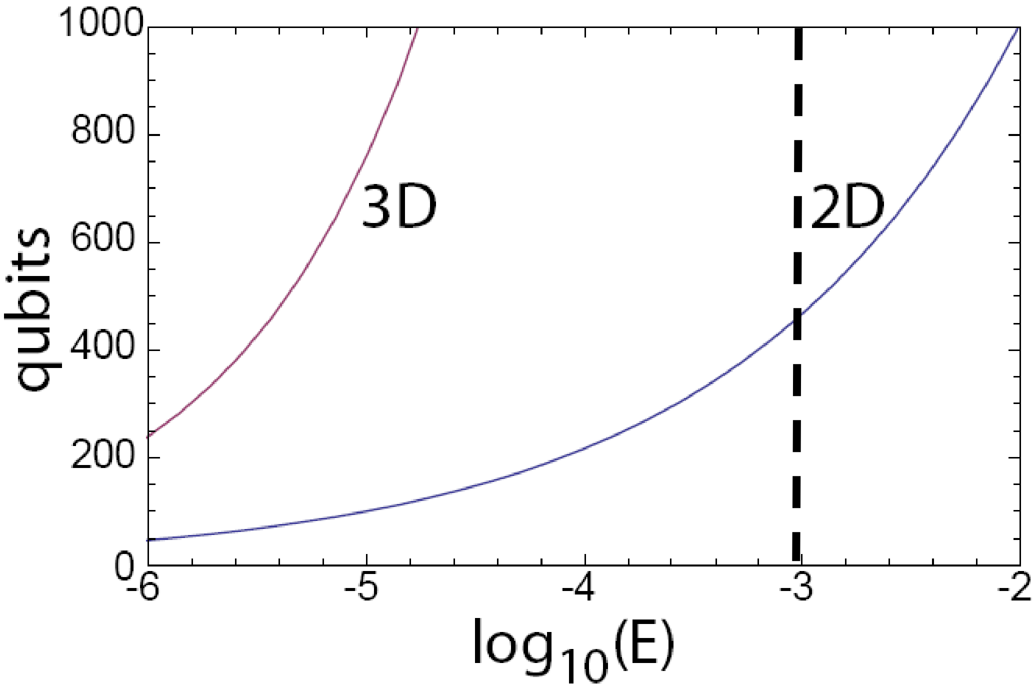
$$N_{\max}^{(3D)} = \frac{3^{1/2} \pi^{1/2}}{4 k_1^3 k_\delta^{1/2}} \left(\frac{\alpha^2 mc^2 \tau_0}{\hbar} \right)^{1/2} E^{1/2} n \sim n$$

Saffman and Mølmer, PRA (2008)

Connected qubits vs. gate error



Rb, n=100, d_{min}=1 μm



At E=0.001

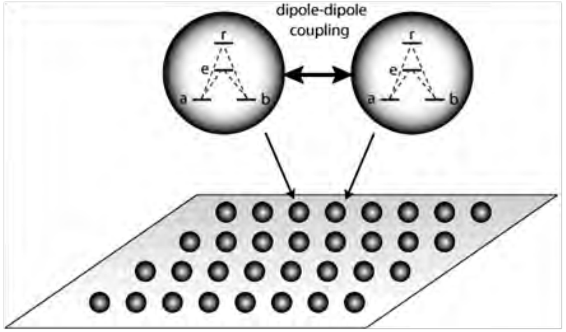
$$N_{\max}^{(2D)} = 470$$

$$N_{\max}^{(3D)} = 7600$$

Challenges: optics, single atom loading,…

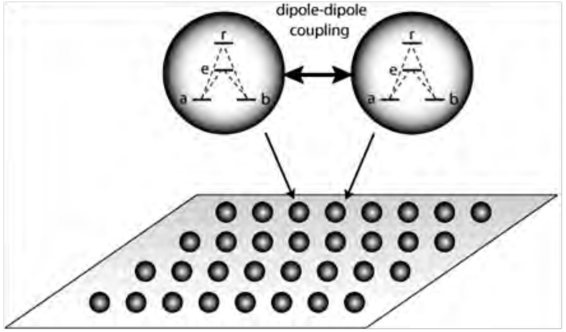
Single atom loading

A primary challenge is preparation of an array of singly occupied sites.



Single atom loading

A primary challenge is preparation of an array of singly occupied sites.



BEC - MI transition + transfer to long period lattice (Phillips, Porto) — adds complexity

Stochastic loading: $P_1 \leq 1/e \sim 0.37$ — does not use all sites

Collisional blockade: $P_1 \leq .5$ (Grangier) — does not use all sites

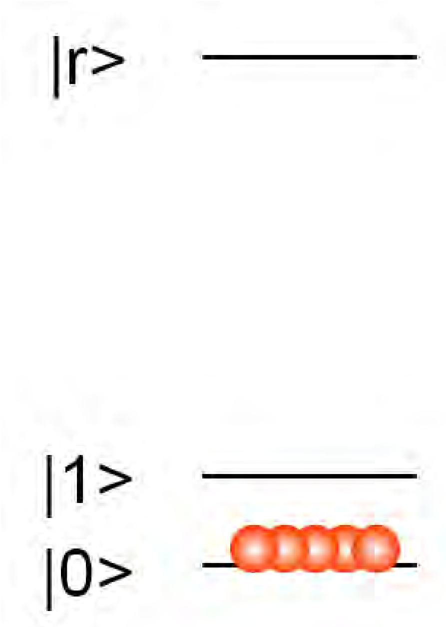
Light assisted collisions in 3D lattice $P_1 \leq .5$ (D. Weiss) — does not use all sites

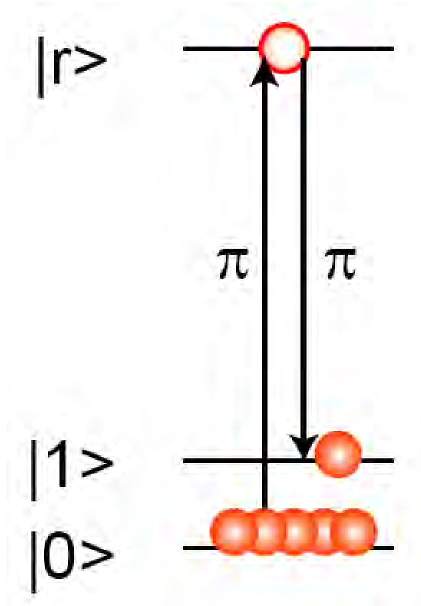
The stochastic loading methods will enable small arrays provided one is willing to throw away half the sites.

Deterministic loading enabled by entanglement: $P_1 \sim 1$ (Saffman, Walker (2002))

Ensemble qubits

Qubits can be represented by single atoms or by ensembles using Rydberg blockade.





Logical 0 $\left|\bar{0}\right\rangle = \left|0_1 .... 0_N\right\rangle$

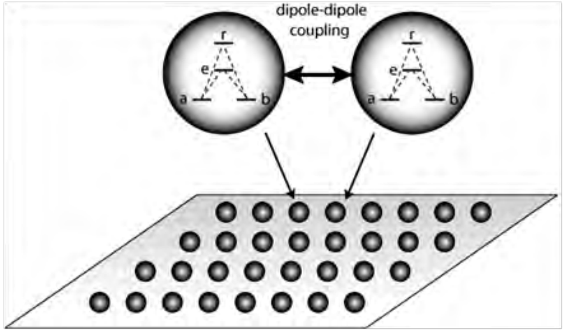
Logical 1 $\left|\bar{1}\right\rangle = \frac{1}{\sqrt{N}} \sum_j \left|0_1 .. 1_j .. 0_N\right\rangle$

“W” state with unit excitation symmetrically shared among all N atoms

Lukin, et al. PRL (2001)

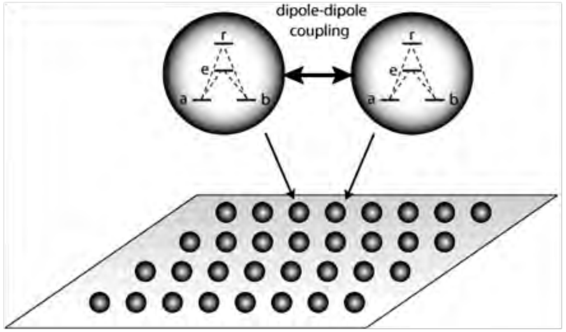
Ensemble qubits and single atom loading

Protocol for deterministic single atom loading.



Ensemble qubits and single atom loading

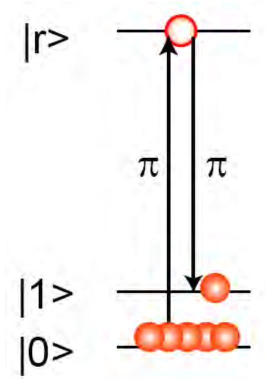
Protocol for deterministic single atom loading.



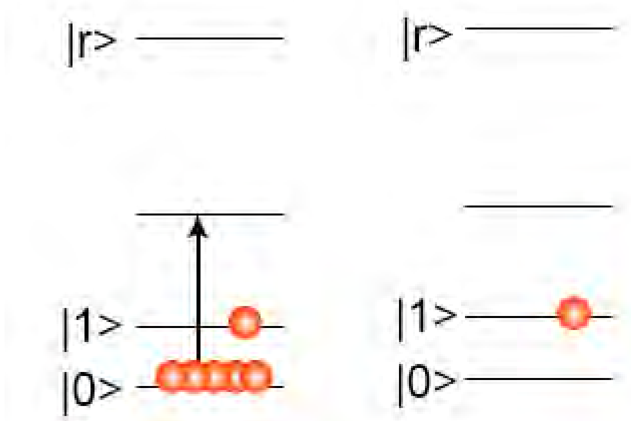
- load N atoms into optical trap
- pump all N atoms to |0>
- transfer “1” atom to |1> via Rydberg
- eject (N-1) atoms in |0> using radiation pressure

$$|\psi\rangle = |0_1....0_N\rangle$$

$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_j |0_1..1_j..0_N\rangle$$



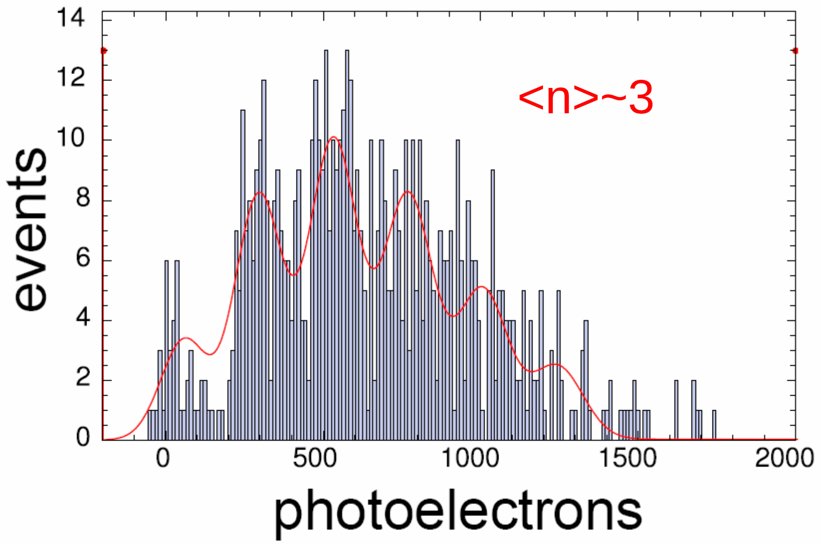
$$|\psi\rangle = |1\rangle$$



Saffman and Walker PRA, (2002)

Ensemble qubits and single atom loading

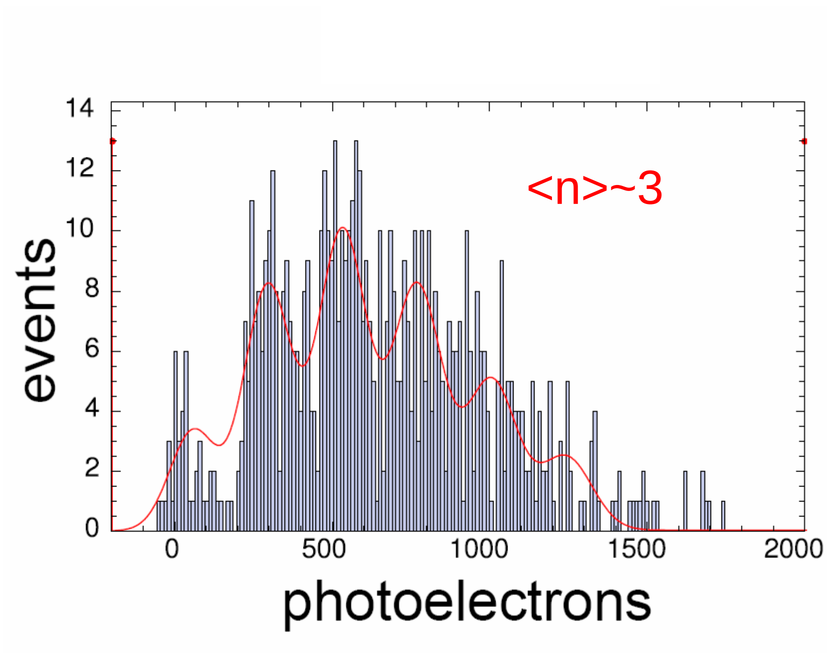
Preliminary results with this loading protocol have produced strongly sub-Poissonian Statistics.



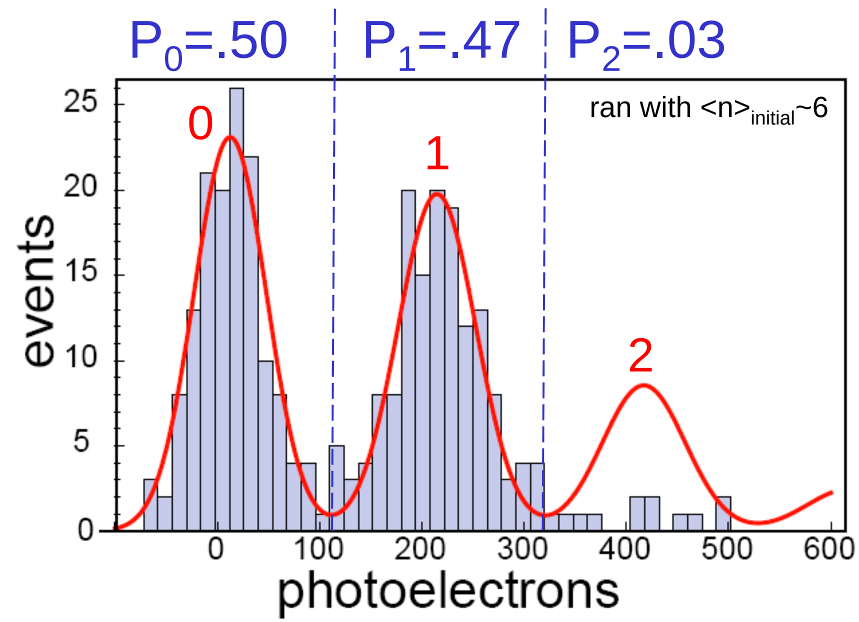
before

Ensemble qubits and single atom loading

Preliminary results with this loading protocol have produced strongly sub-Poissonian Statistics.



before



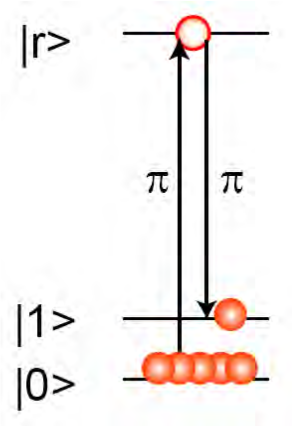
after

Optimization in progress….

N-atom entanglement

The “W” states can be created very naturally with Rydberg blockade

$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_j |0_1..1_j..0_N\rangle$$



“W” states do not have the greatest possible degree of entanglement.
Measuring one atom does not uniquely determine the state of all others.

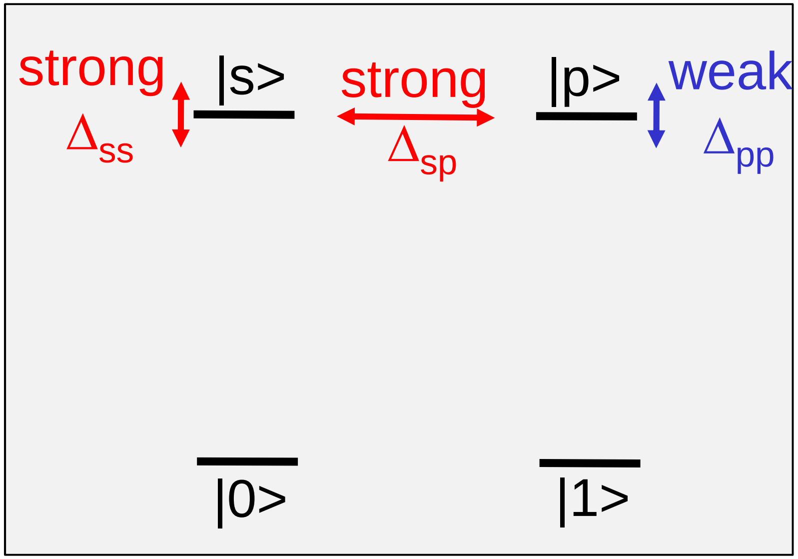
A maximally entangled N atom state is the Schrödinger cat or GHZ state

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left(|000....0_N\rangle + |111....1_N\rangle \right)$$

This can also be efficiently prepared with Rydberg blockade.

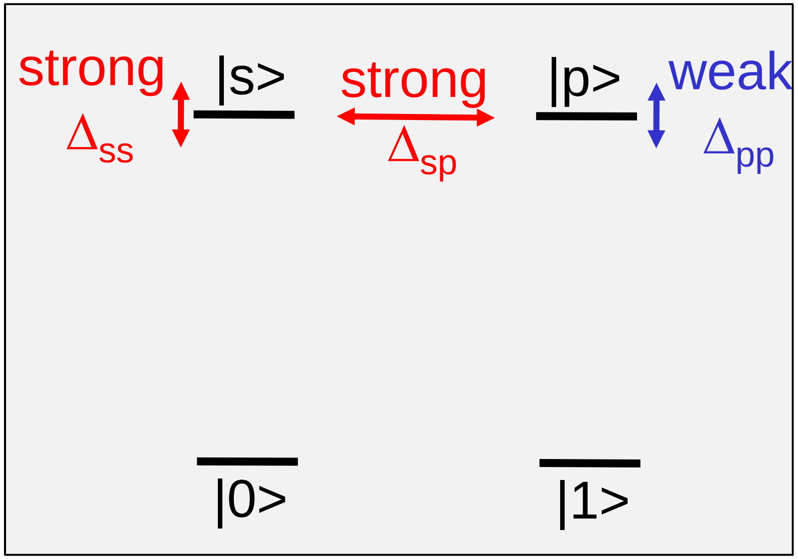
Generation of N-atom Schrödinger Cat states

Basic idea - exploit asymmetric Rydberg interactions:

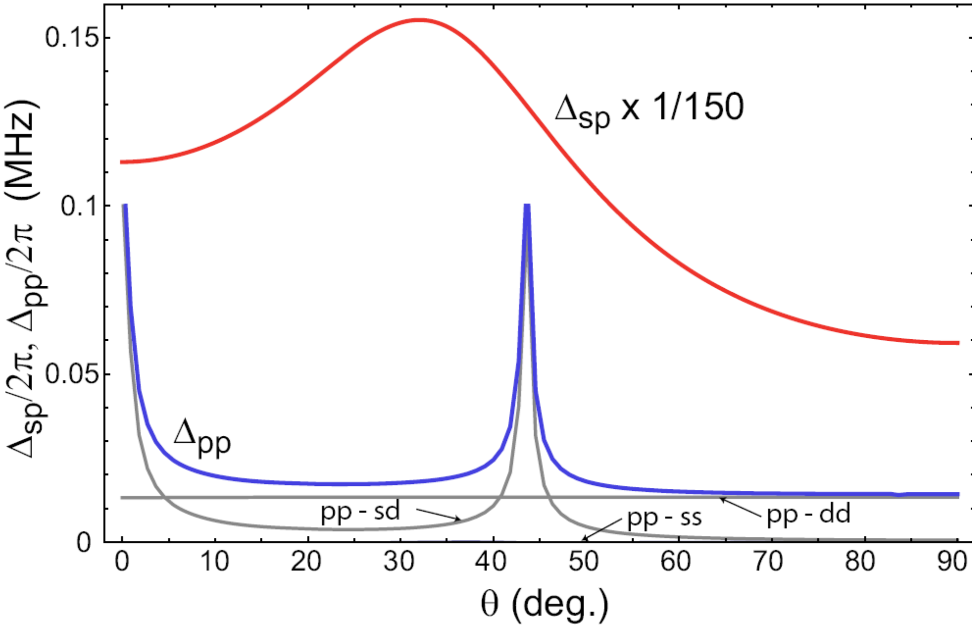


Generation of N-atom Schrödinger Cat states

Basic idea - exploit asymmetric Rydberg interactions:



This is possible with a ratio > 150.

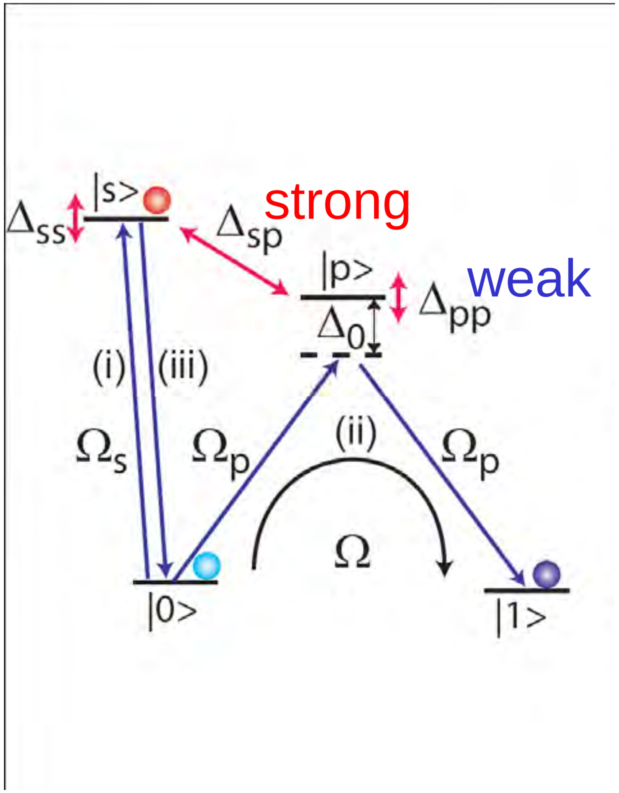


$|s\rangle = 41s_{1/2}$

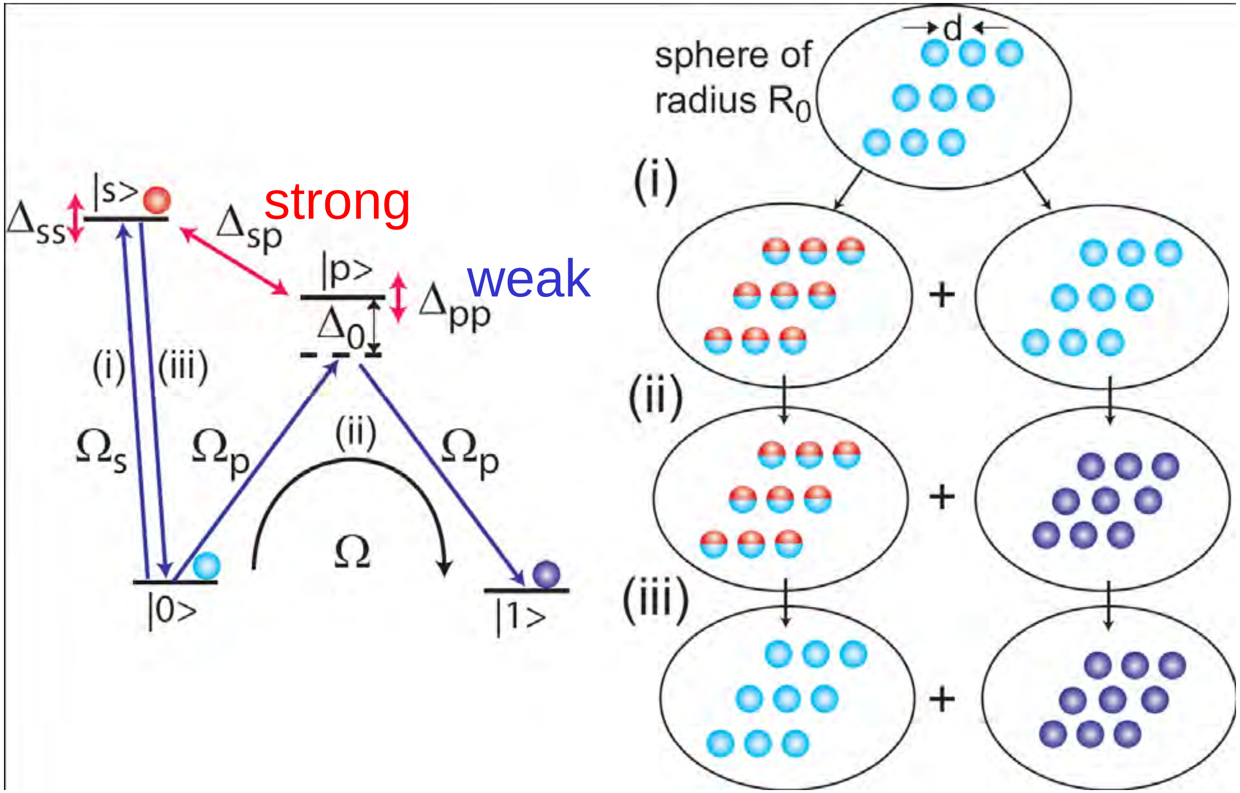
$|p\rangle = 40p_{3/2}$

$R = 3\ \mu m$

Generation of N-atom Schrödinger Cat states



Generation of N-atom Schrödinger Cat states



$$|\psi\rangle = |0, 0, ...0\rangle$$

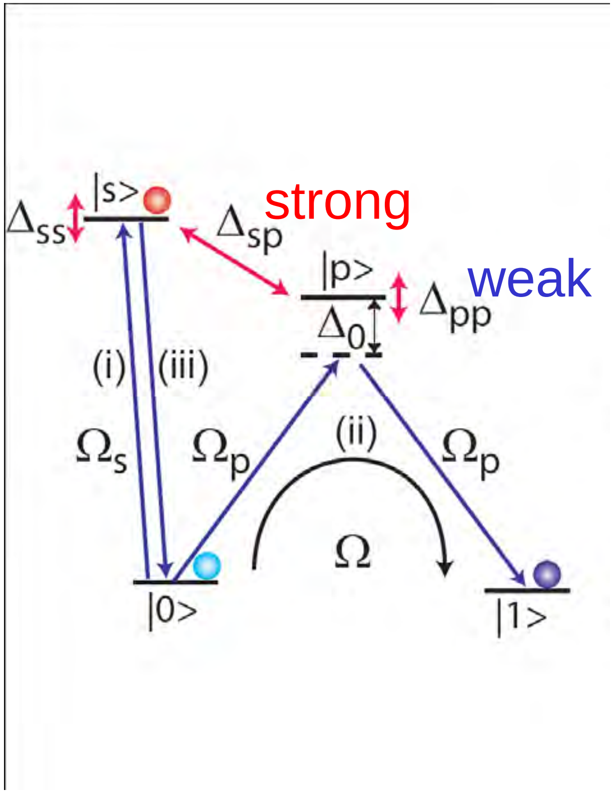
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{N}}\sum_{j=1}^{N}|0, 0, s^{(j)}...0\rangle + |0, 0, ...0\rangle\right)$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{N}}\sum_{j=1}^{N}|0, 0, s^{(j)}...0\rangle + |1, 1, ...1\rangle\right)$$

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

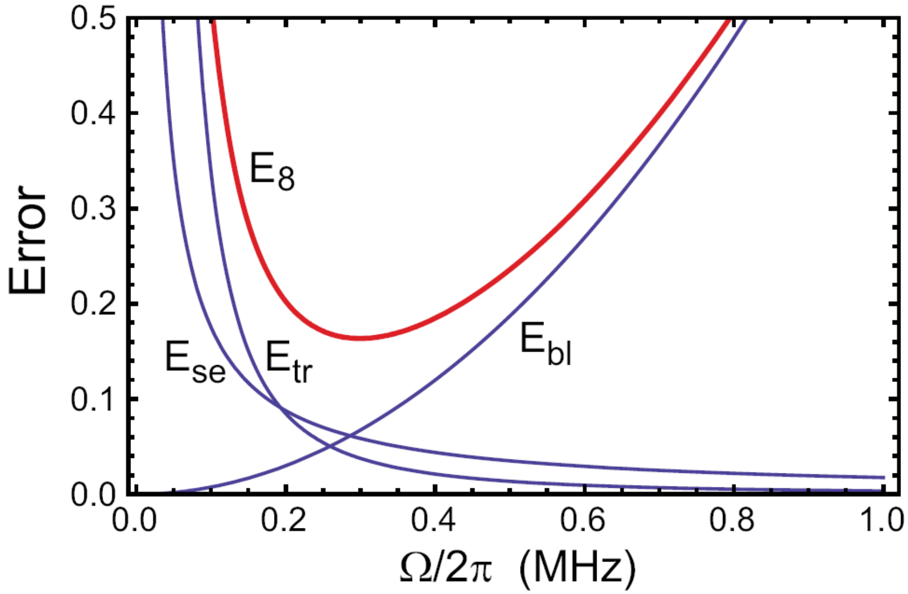
N-atom cat !

Generation of N atom Schrödinger Cat states



Fidelity of 8 atom cat state

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

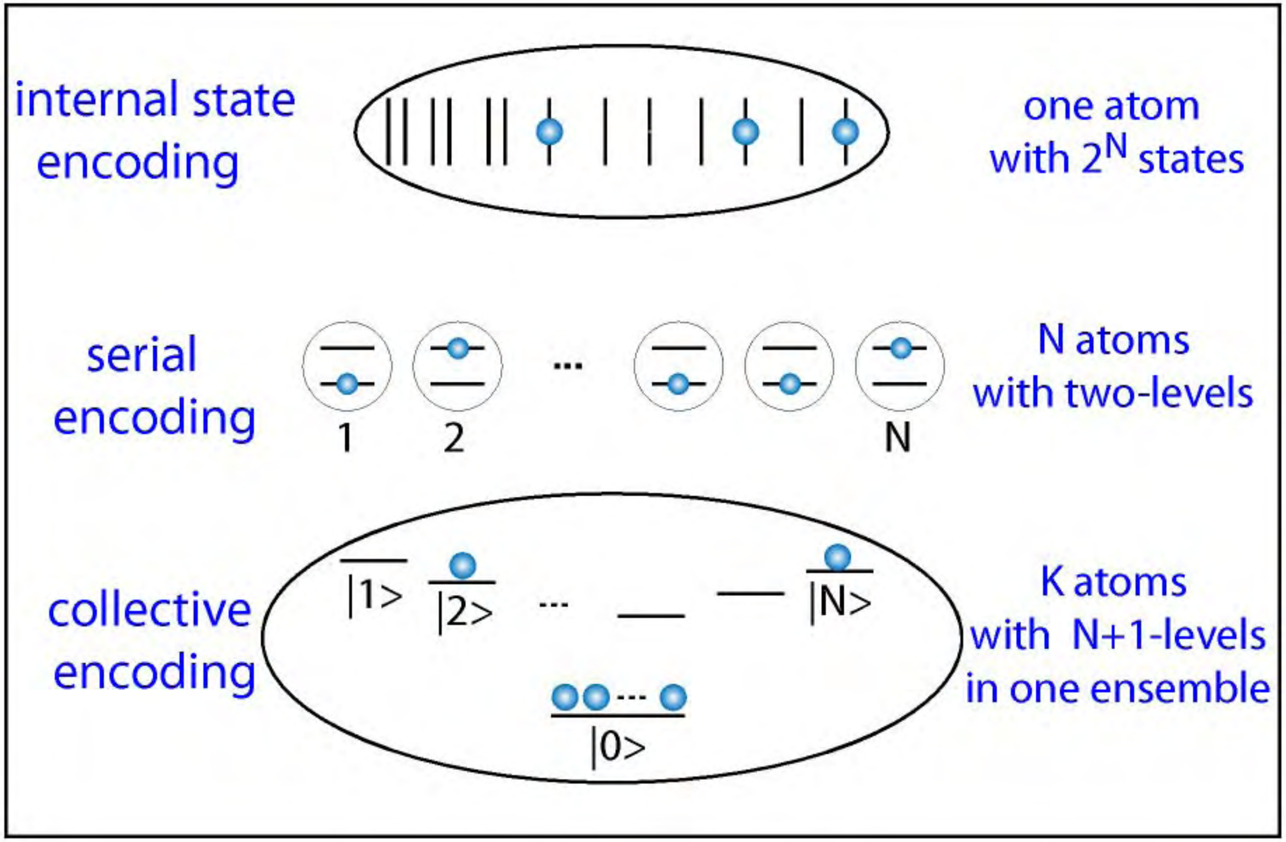


Numerical simulations and perturbation theory show fidelity of 85% for N=8.

Saffman & Mølmer PRL to appear, arXiv:0812.2425

Müller et al., PRL (2009) (N~3)

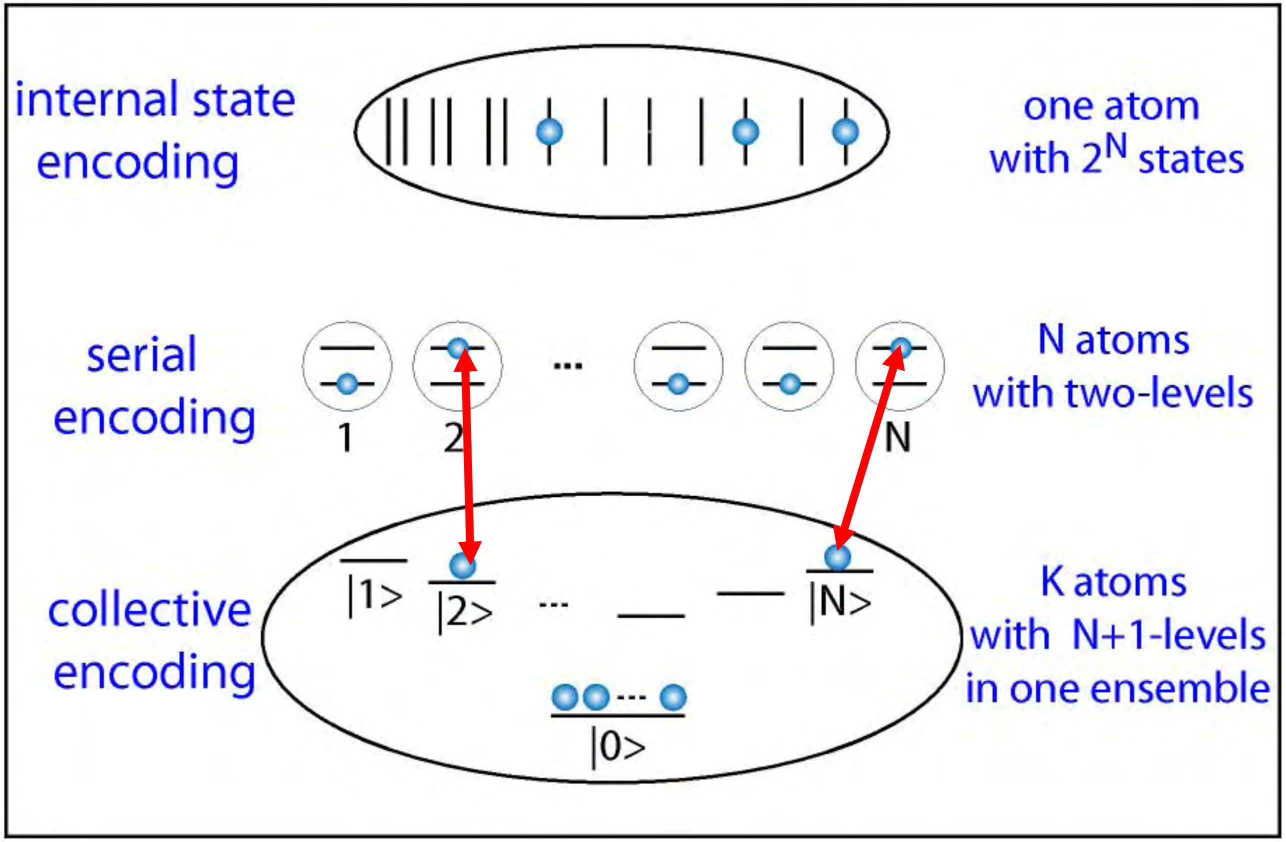
Collective encoding of an N qubit register



K>=N atoms, each with N+1 states all in one site

Less sensitive to atom loss – information is distributed.

Collective encoding of an N qubit register



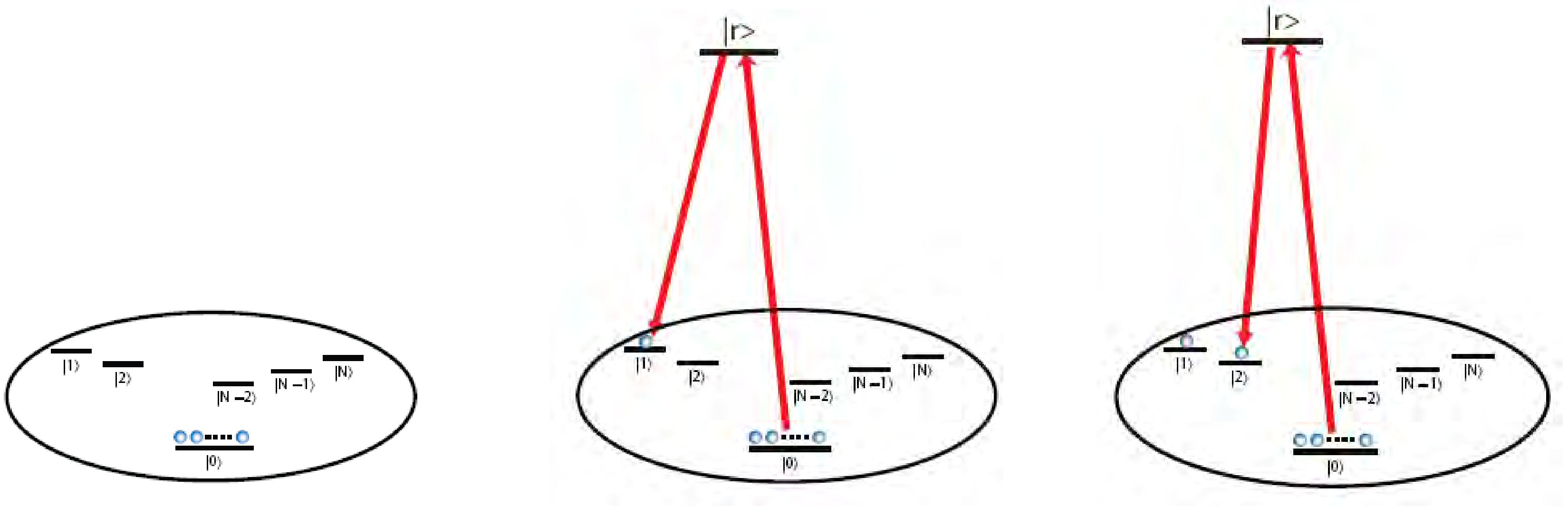
K>=N atoms, each with N+1 states all in one site

Less sensitive to atom loss – information is distributed.

E. Brion, K. Mølmer, and M. Saffman,
Quantum computing with collective ensembles of multi-level systems,
PRL (2007)

Collectively encoded states

Assume K atoms each with N+1 long lived ground states |0>, |1>, |2>, |3>,.... |N>



$$\left|00...0\right\rangle_K \qquad \left|10...0\right\rangle_K \qquad \left|11...0\right\rangle_K$$

Note fiducial register states are now entangled. For example

$$\left|1100\right\rangle_{K=4} = (1/\sqrt{12})(\left|1200\right\rangle + \left|1020\right\rangle + \left|1002\right\rangle + \left|2100\right\rangle + \left|0120\right\rangle + \left|0102\right\rangle$$
$$+ \left|2010\right\rangle + \left|0210\right\rangle + \left|0012\right\rangle + \left|2001\right\rangle + \left|0201\right\rangle + \left|0021\right\rangle)$$

These states can be prepared starting from |0> using ensemble dipole blockade Lukin, et al. (2001).

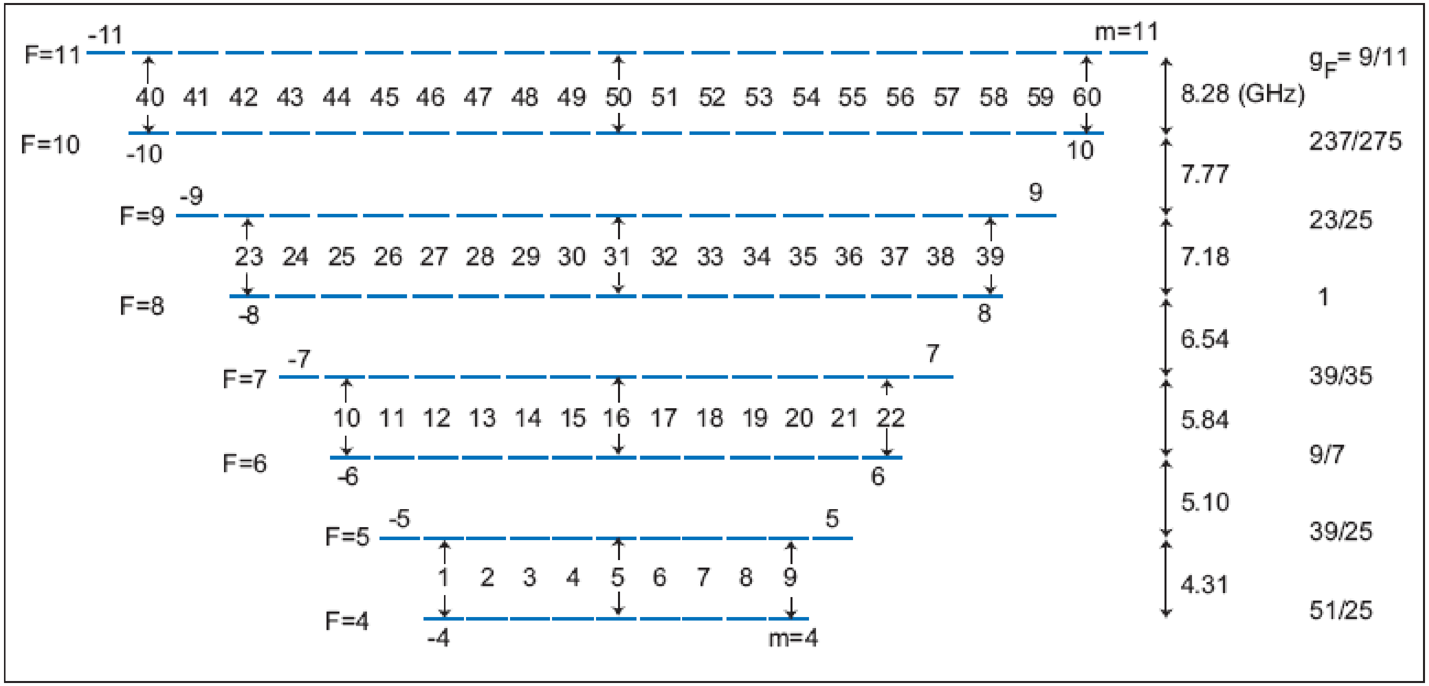
Collective encoding in Ho

With more internal states we can prepare a larger register.

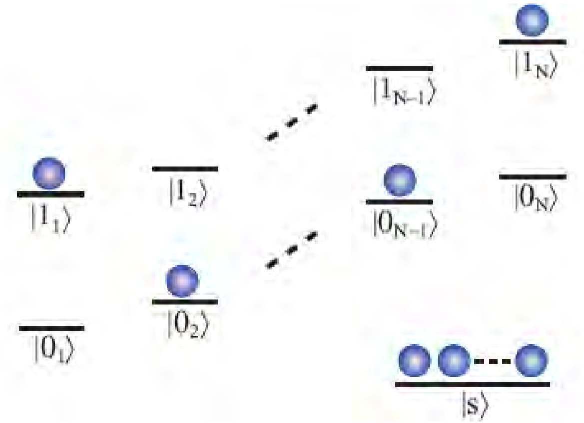
atom	isotope	J	I	ground states	laser cooling demonstrated	BEC demonstrated
Yb	173	0	5/2	6	x	x
Sr	87	0	9/2	10	x	x
Rb	85	1/2	5/2	12	x	x
Al	27	1/2	5/2	12	x	
Cs	133	1/2	7/2	16	x	x
Tm	169	7/2	1/2	16		
Fe	57	4	1/2	18	x	
In	115	1/2	9/2	20	x	
Cr	53	3	3/2	28	x	x
Sc	45	3/2	7/2	32		
Tb	169	15/2	1/2	32		
Ti	49	2	7/2	40		
Mo	95	3	5/2	42		
Pr	141	9/2	5/2	60		
Tb	159	15/2	3/2	64		
Co	59	9/2	7/2	80		
Dy	161	8	5/2	102		
Er	167	6	7/2	104	x	
Ho	165	15/2	7/2	128		

Collective encoding in Ho

Ground state $4f^{11}6s^2$, J=15/2 has 128 hyperfine states

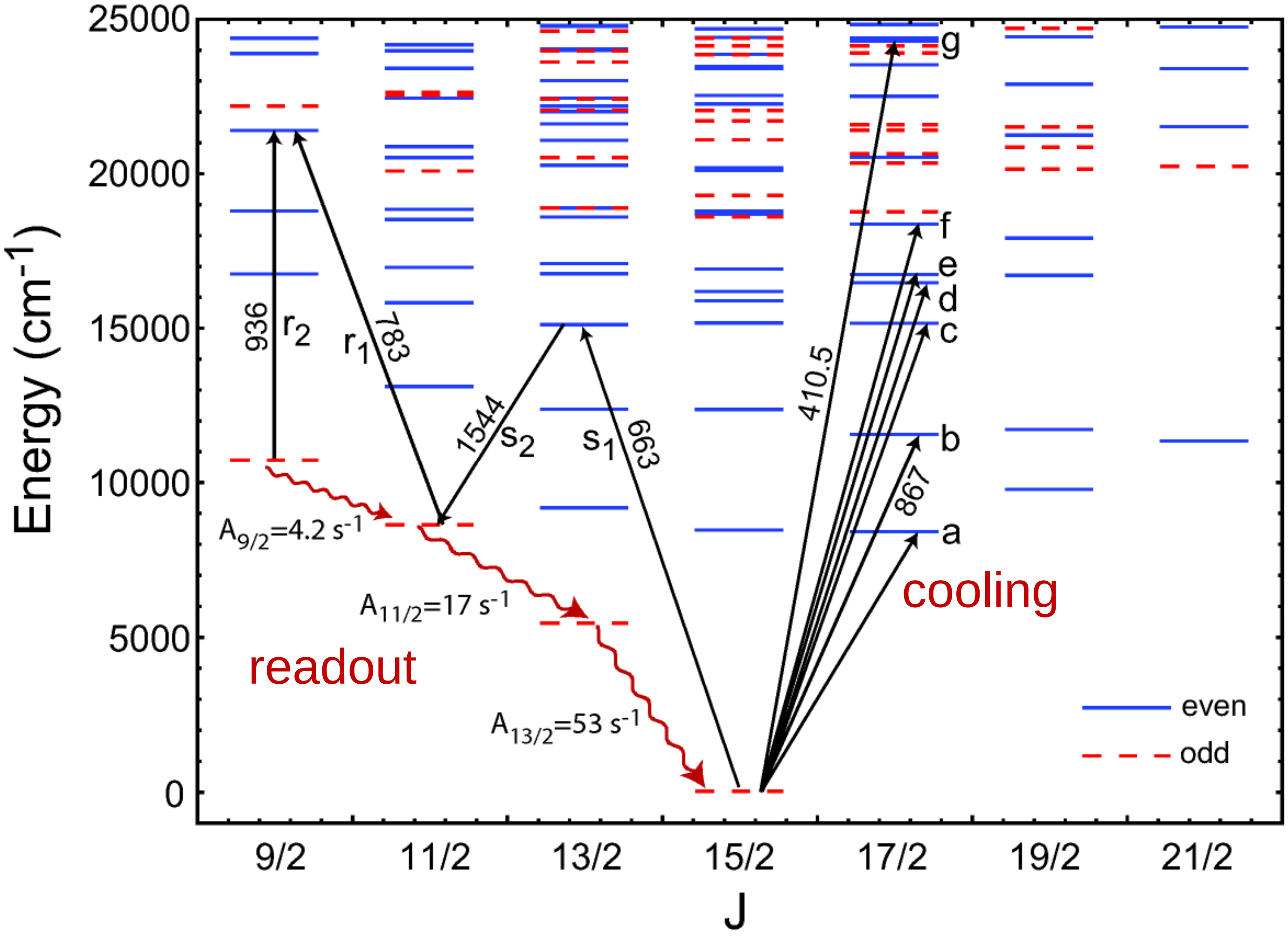


Encoding with two states per qubit gives a 60 qubit register.



E. Brion, K. Mølmer, and M. Saffman, PRL (2008)

Level structure in Ho



a-g cooling and trapping transitions

s1, s2 shelving

r1,r2 readout

Freezing out collisions

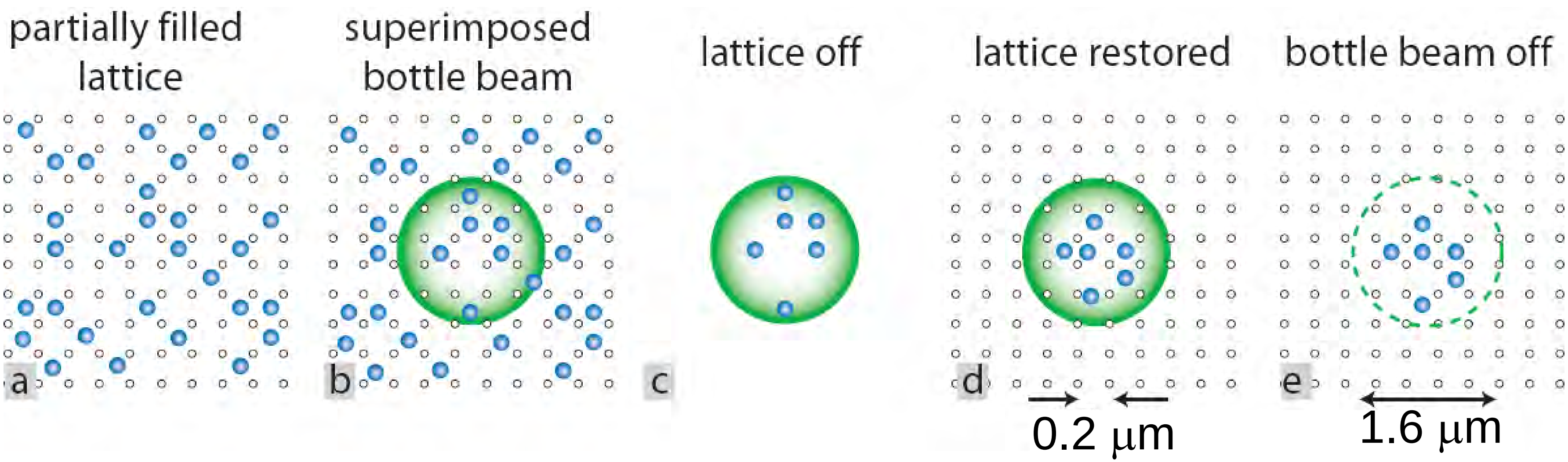


FIG. 6: Protocol for loading small ensembles into a patterned lattice region. The small open circles are the repulsive lattice sites, and the large green circle is the outline of the bottle-beam trap. The lattice is not drawn to scale for clarity. See text for details.

Freezing out collisions

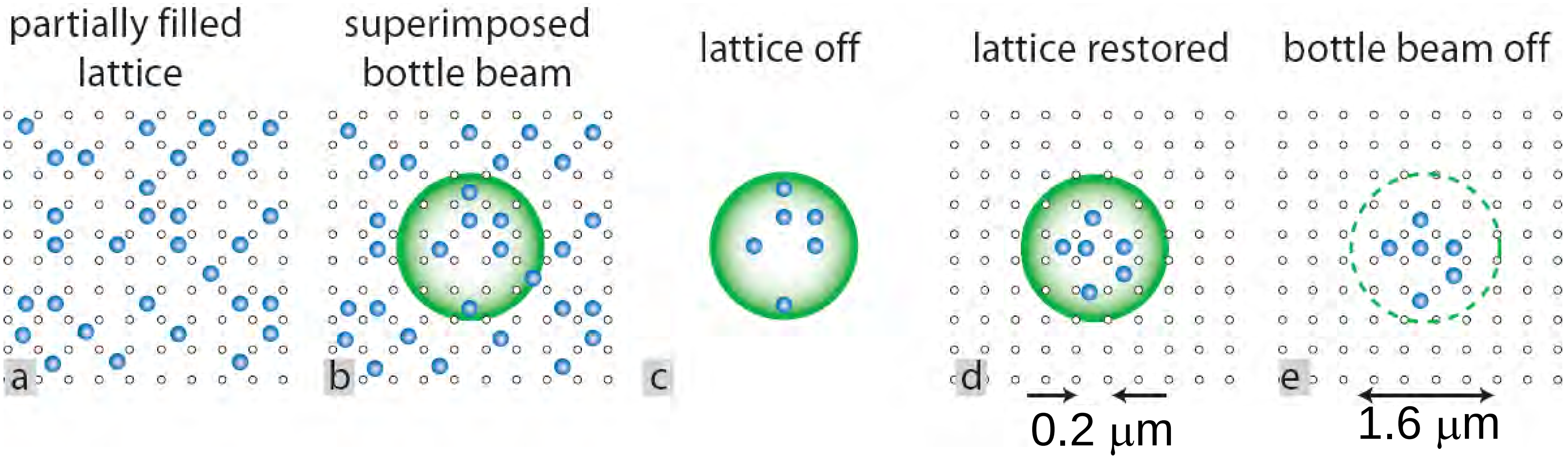
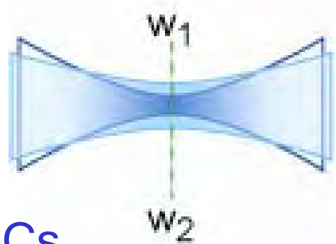
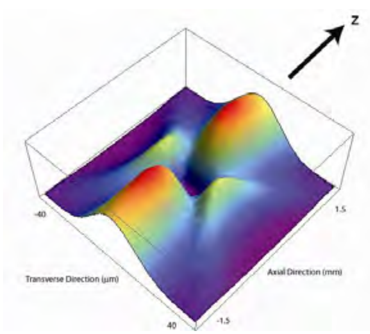


FIG. 6: Protocol for loading small ensembles into a patterned lattice region. The small open circles are the repulsive lattice sites, and the large green circle is the outline of the bottle-beam trap. The lattice is not drawn to scale for clarity. See text for details.





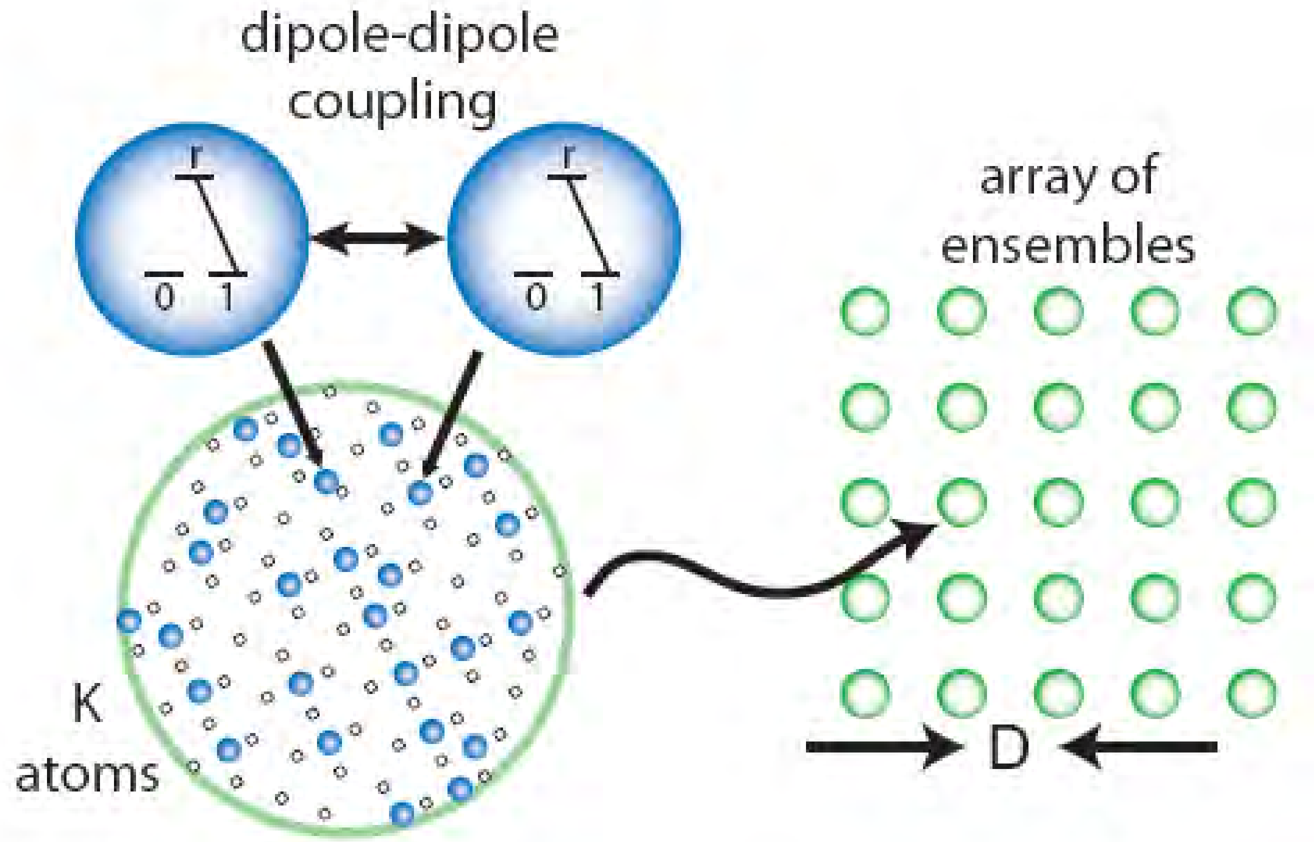
Bottle beam,
demonstrated with Cs

Isenhower, et al. Opt. Lett. 2009

1000 qubit scale processor

1000 qubit register based on:

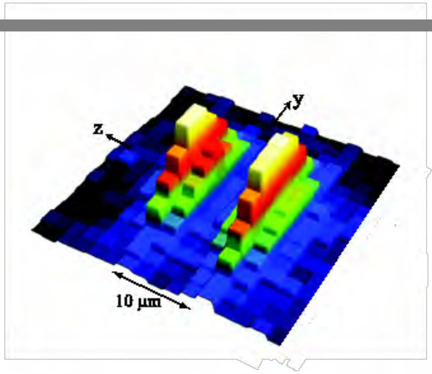
18 sites, each with a 60 qubit ensemble with K~100 atoms/ensemble

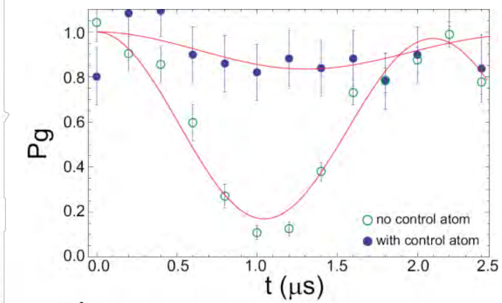


Saffman and Mølmer, PRA (2008)

Summary

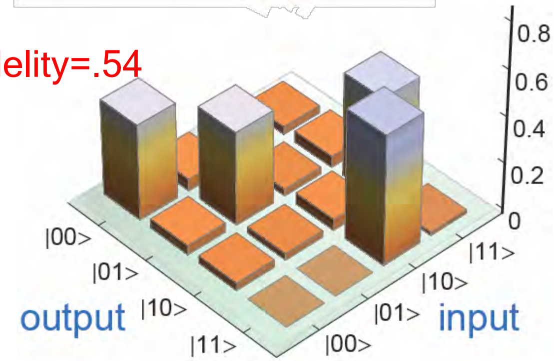
Rydberg blockade at >10 μm

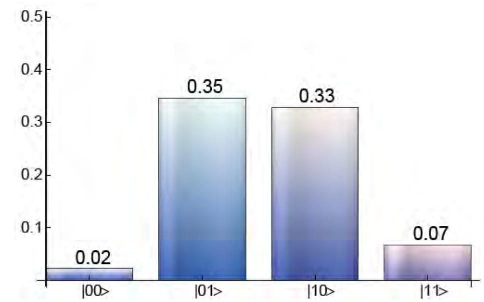




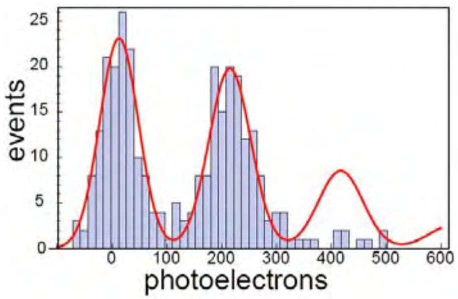
CNOT gate
entanglement

fidelity=.54





Single atom loading



collective encoding