Scalable quantum computing with neutral atom qubits

Mark Saffman

THE UNIVERSITY of WISCONSIN MADISON

- Neutral atom qubits
- Efficient quantum search
- Experimental status

NSF

I A R P A BE THE FUTURE

BRIDGING THE GAP DARPA POWERED BY IDEAS

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Sandia National Laboratories

W A R F Wisconsin Alumni Research Foundation

The challenge of quantum computing

qubit 1

qubit 2

The challenge of quantum computing

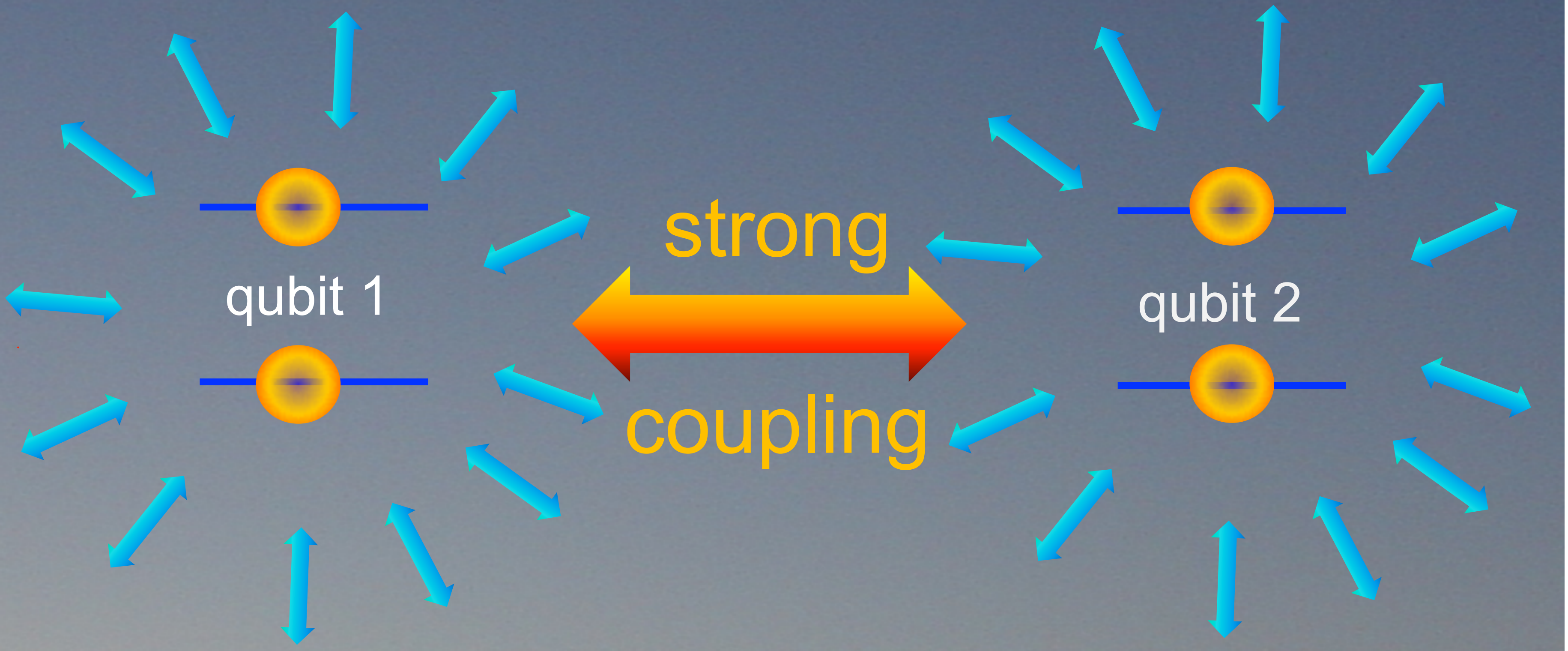
qubit 1

qubit 2

weak coupling to environment

weak coupling to environment

The challenge of quantum computing



qubit 1

strong

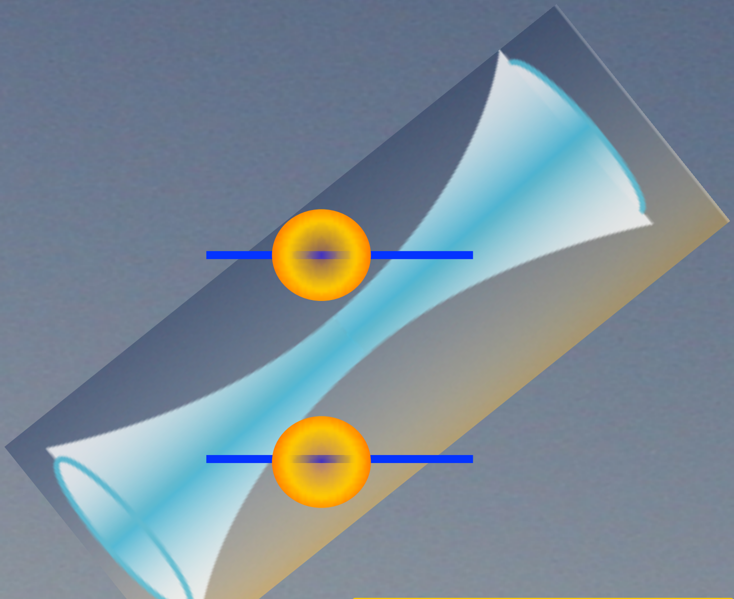
coupling

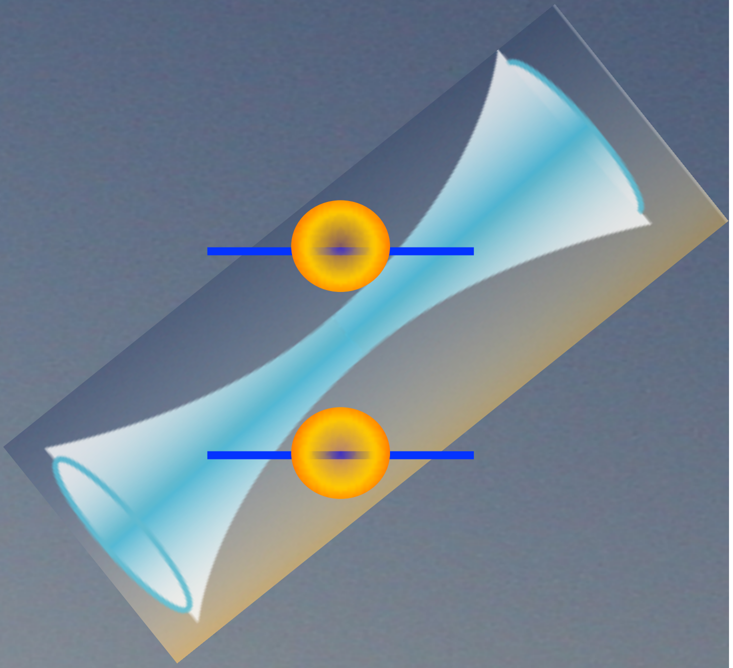
qubit 2

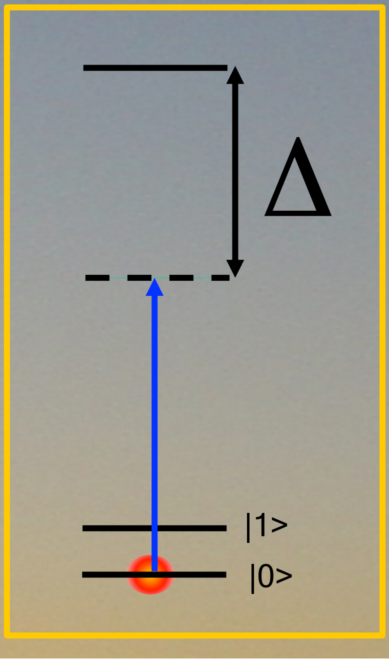
weak coupling to
environment

weak coupling to
environment

Neutral atoms in optical traps



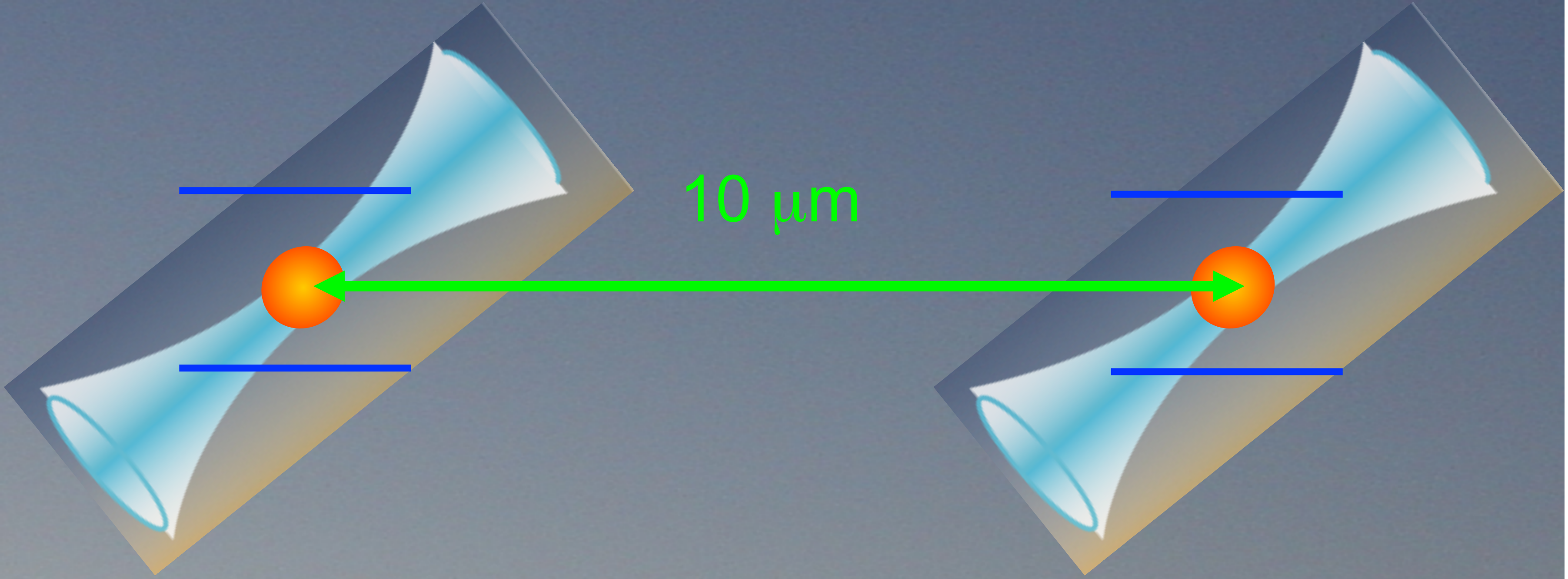




Trap depth ~ $1/\Delta$

Decoherence rate ~ $1/\Delta^2$

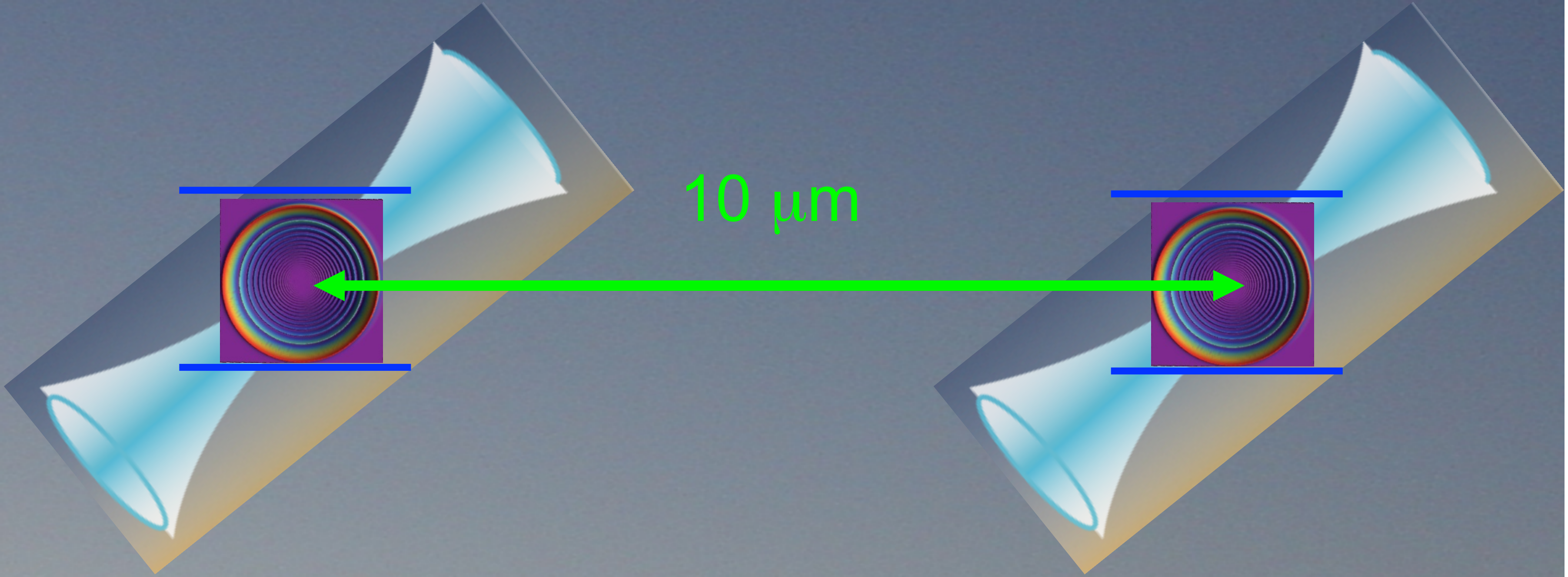
Long range interactions



Rb-Rb ground state
magnetostatic interaction

$$\Delta E \sim 100\ \mu\text{Hz}$$

Long range interactions



Rb-Rb ground state
magnetostatic interaction

$$\Delta E \sim 100\ \mu\mathrm{Hz}$$

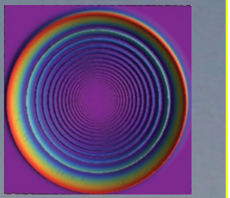
Rydberg n=100
van der Waals interaction

$$\Delta E \sim 100\,\mathrm{MHz}$$

12 orders of magnitude!

Rydberg atoms

Highly excited atoms with exaggerated properties.

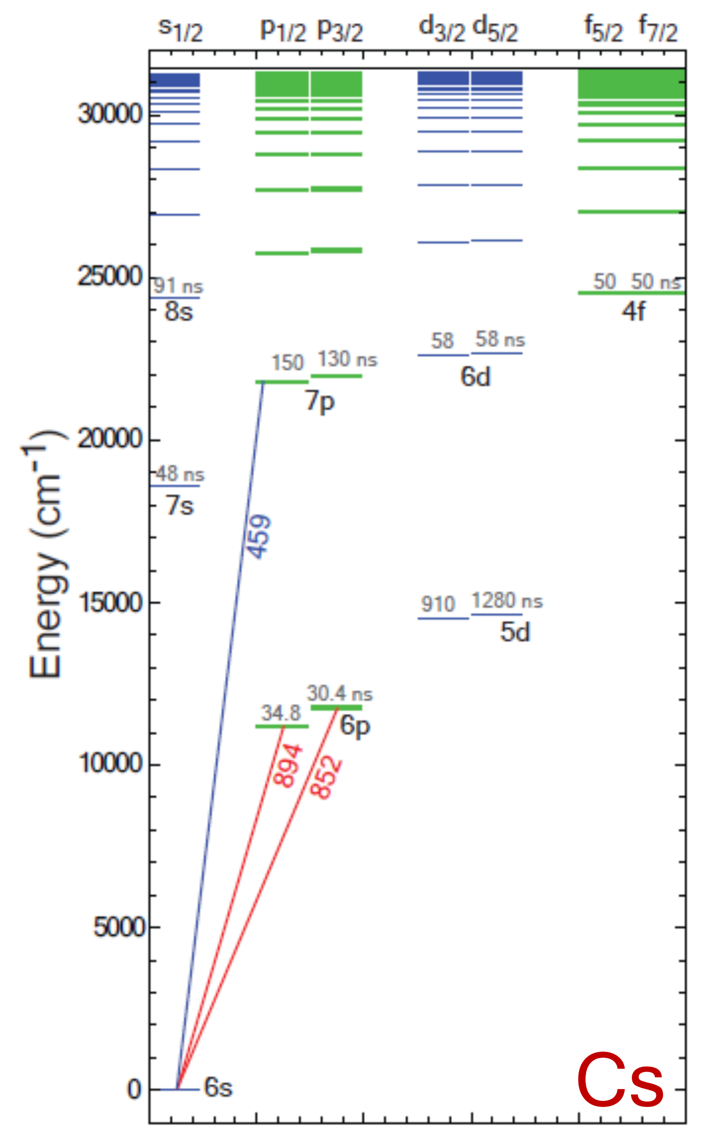


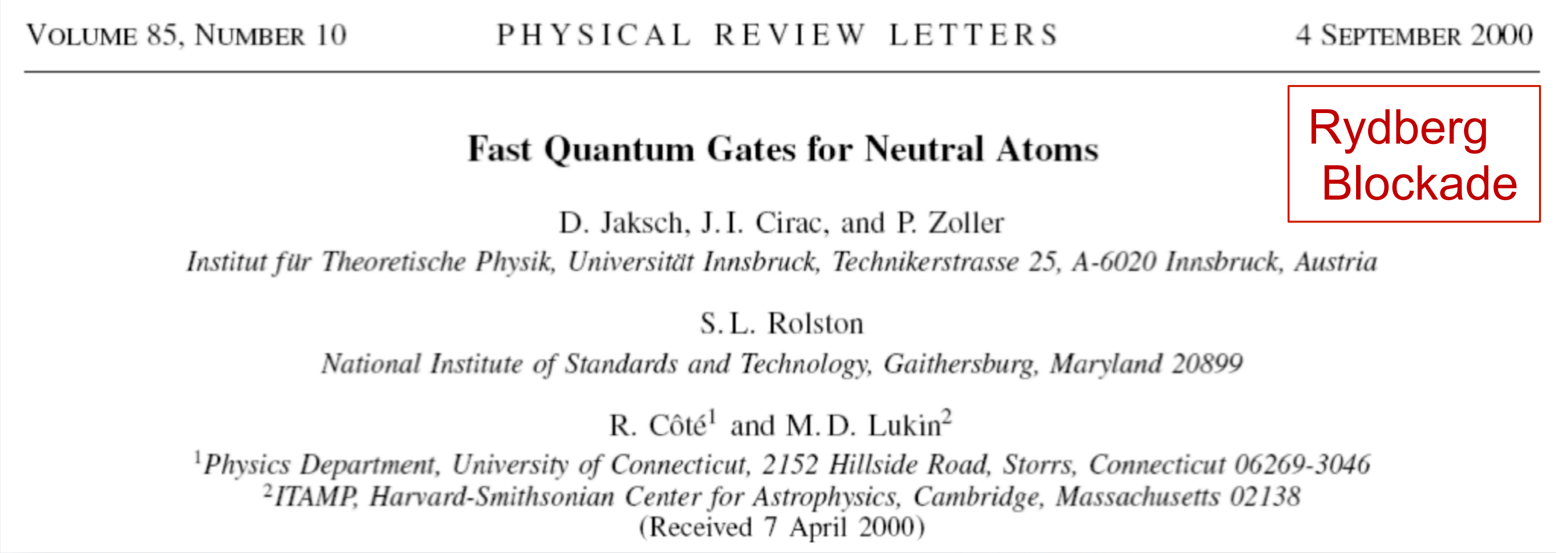
$$< r > \sim a_0 n^2$$

$$V_{vdw} \sim n^{12}$$

$$\tau \sim n^3$$

$$Fidelity\ of\ C_Z \sim 1 - \frac{a}{(V\tau)^{2/3}}$$





VOLUME 85, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 2000

Fast Quantum Gates for Neutral Atoms

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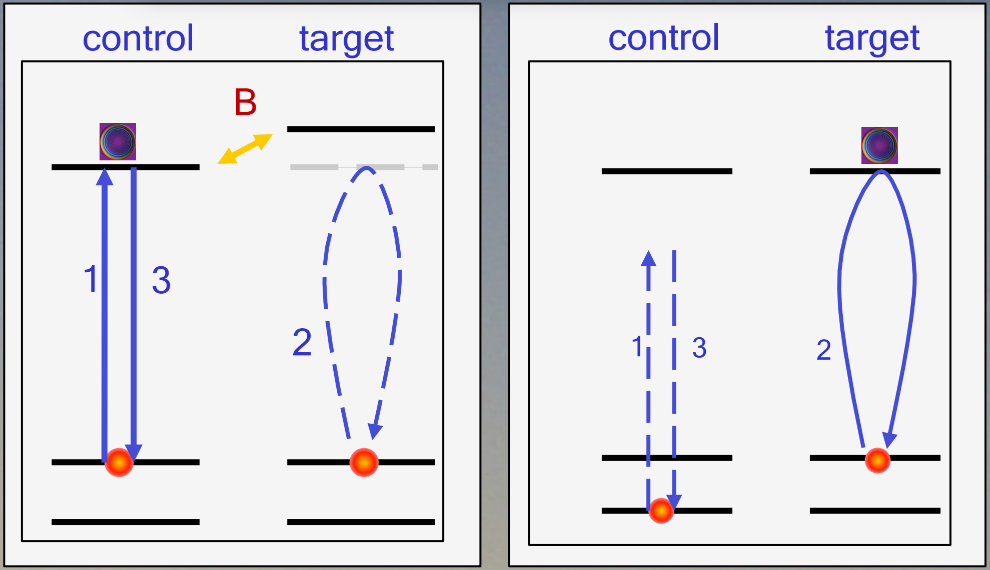
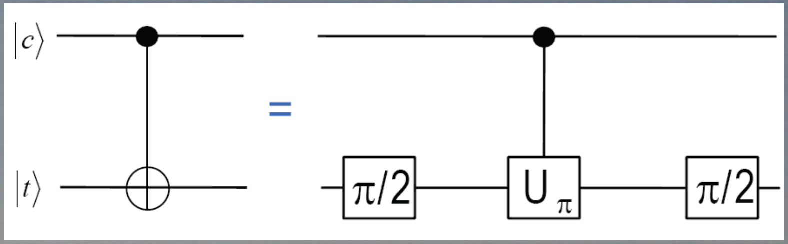
(Received 7 April 2000)

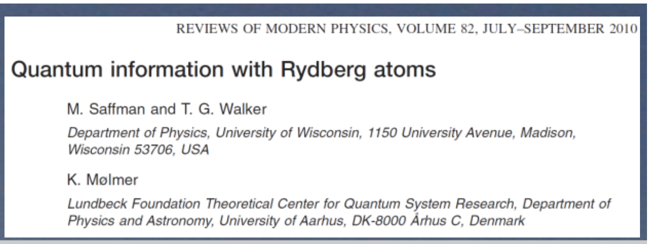
Rydberg Blockade





conditional phase of π on target

Rydberg atom quantum information related experiments


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

Quantum information with Rydberg atoms

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- University of Connecticut
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- University of Virginia
- University of Oklahoma
- Penn State
- MIT
- Georgia Tech
- Sandia National Lab

- Waterloo

- University of Heidelberg
- University of Stuttgart
- Max Planck Institute for Quantum Optics, Garching
- Technical University of Darmstadt

- ENS Paris
- Institut d’Optique, Palaiseau
- Laboratoire Aimé Cotton, Université Paris Sud

- ETH, Zurich

- University of Durham
- Open University, Milton Keynes

- University of Amsterdam

- University of Pisa

- RAS Novosibirsk

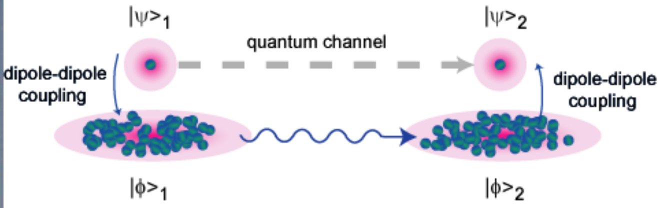
- University of Electro-Communications

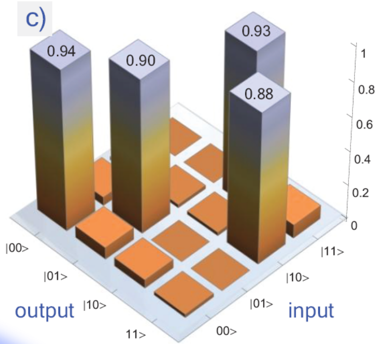
- Shanxi University

- São Paulo

Quantum Information with Rydberg atoms

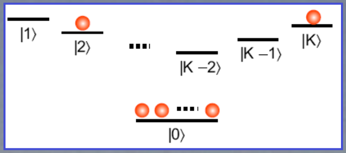
Ensembles for quantum networking

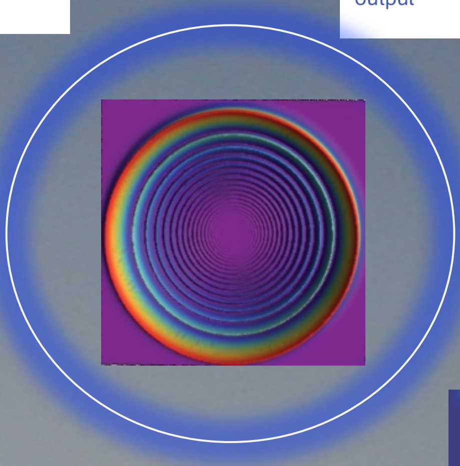




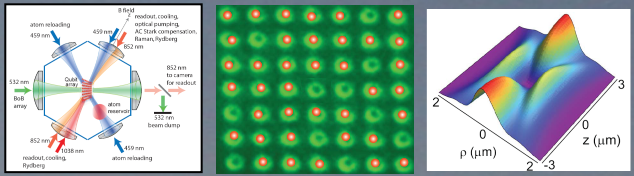
Quantum gates, entanglement

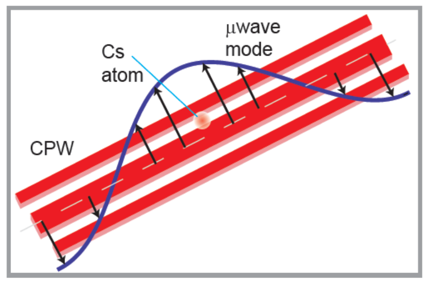
Ho collective encoding



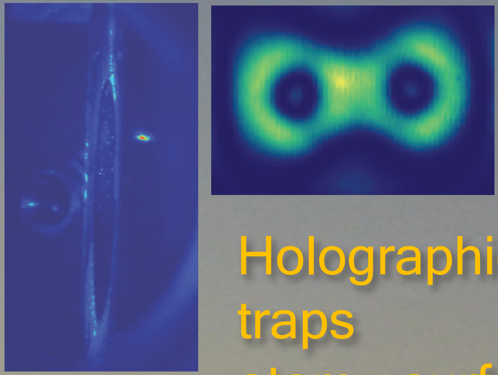


AQuA - atomic Qubit array





hybrid interfaces

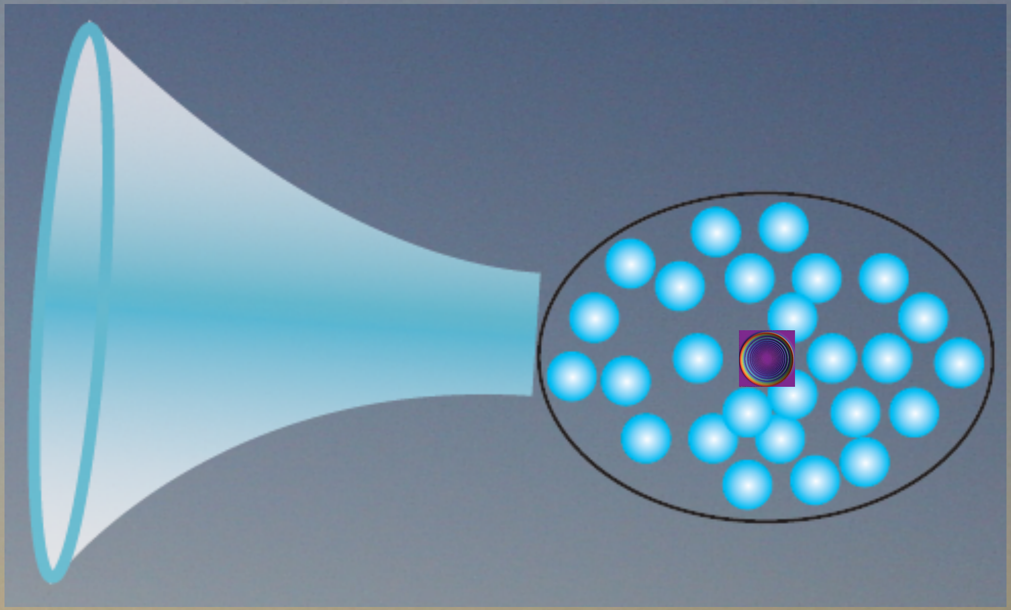


Holographic chip traps

atom - surface interactions

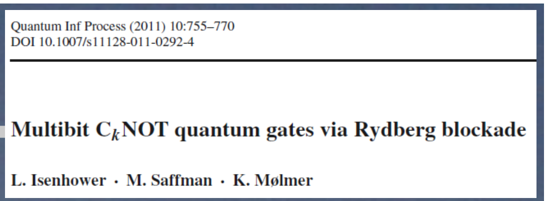
Efficient quantum search

- As with classical computing we can use universal quantum hardware to run generic algorithms.
- Nevertheless some hardware is better suited for certain tasks,   (e.g. graphics accelerators,..).
- Rydberg blockade enables significant speedup for the quantum search algorithm.
- Ensemble blockade



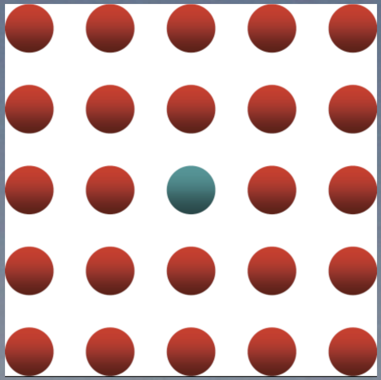
One atom can control the state of N other atoms inside a blockade sphere.

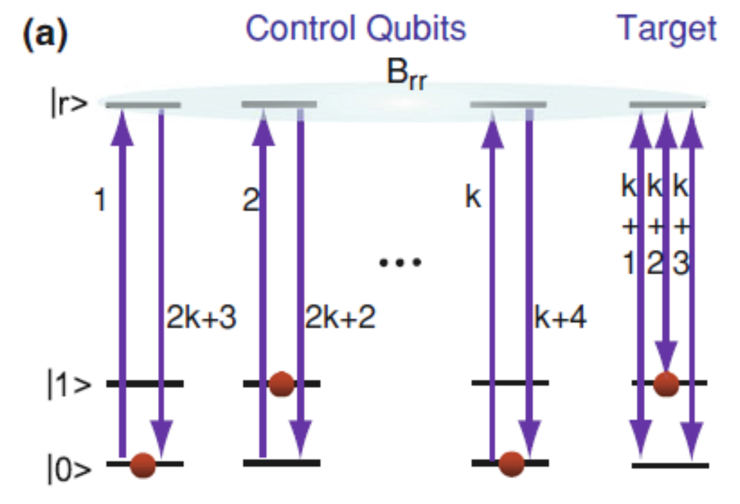
Blockade and multi-bit gates


Quantum Inf Process (2011) 10:755–770
DOI 10.1007/s11128-011-0292-4

Multibit C_kNOT quantum gates via Rydberg blockade

L. Isenhower · M. Saffman · K. Mølmer





- k control atoms and 1 target atom
- If one or more control atoms is in state 0, there will be a Rydberg excitation which blocks target atom pulses
- C_kNOT gate needs only 2k+3 laser pulses
- Best known qu. circuit: 32k-120 gates, k>= 5.

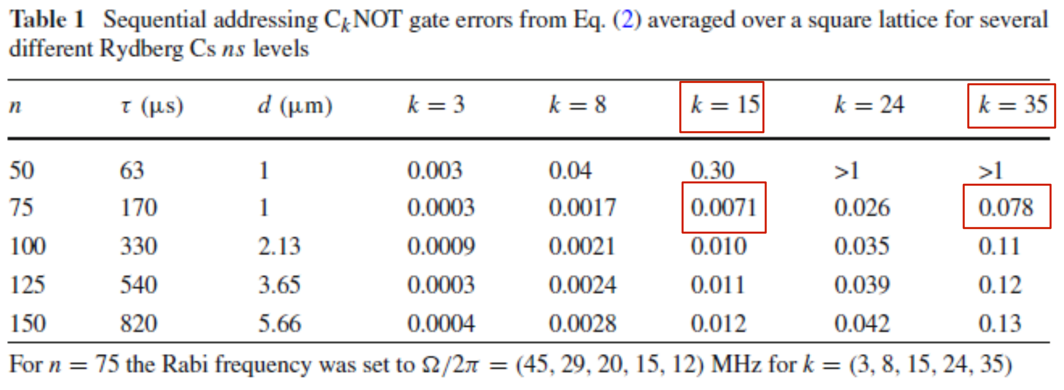


Table 1 Sequential addressing C_kNOT gate errors from Eq. (2) averaged over a square lattice for several different Rydberg Cs *ns* levels

n	τ (μs)	d (μm)	$k = 3$	$k = 8$	$k = 15$	$k = 24$	$k = 35$
50	63	1	0.003	0.04	0.30	>1	>1
75	170	1	0.0003	0.0017	0.0071	0.026	0.078
100	330	2.13	0.0009	0.0021	0.010	0.035	0.11
125	540	3.65	0.0003	0.0024	0.011	0.039	0.12
150	820	5.66	0.0004	0.0028	0.012	0.042	0.13

For $n = 75$ the Rabi frequency was set to $\Omega/2\pi = (45, 29, 20, 15, 12)$ MHz for $k = (3, 8, 15, 24, 35)$

2^{35} ~ 34 billion

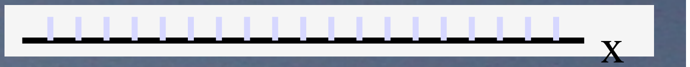
Grover search

Quantum Mechanics Helps in Searching for a Needle in a Haystack

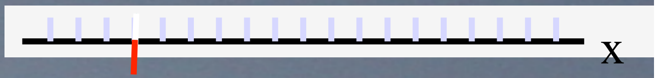
Lov K. Grover*

VOLUME 79, NUMBER 2 PHYSICAL REVIEW LETTERS

- Register $\sum_x c_x |x\rangle$

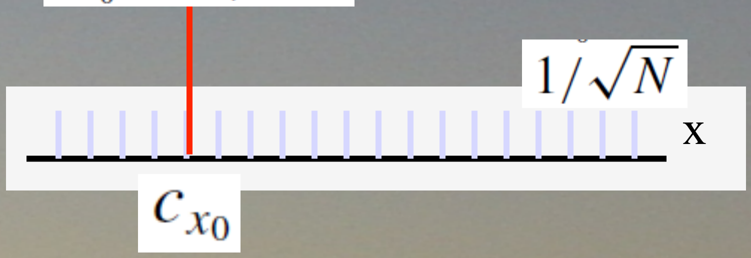


- Wish to find marked element $|x_0\rangle$
- 1) Sign change $c_{x_0} \;\rightarrow\; -c_{x_0}$



- 2) Inversion about mean $\overline{c} = \frac{1}{N} \sum_x c_x$ $\quad c_x \rightarrow \frac{1}{N} \sum_{x'} c_{x'} - (c_x - c_{x'})$
- Factor 3 enhancement after first step.
- Succeeds with high probability after $N^{1/2}$ steps vs. N/2 for classical search.

$c_{x_0} \sim 3/\sqrt{N}$



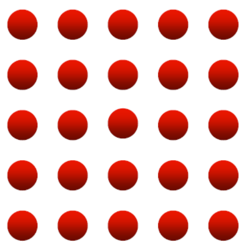
Multi-bit gates and Grover search

J. Phys. B: At. Mol. Opt. Phys. **44** (2011) 184016 (8pp)

Efficient Grover search with Rydberg blockade

Klaus Mølmer[1,3], Larry Isenhower[2] and Mark Saffman[2]

k=$\log_2(N)$ qubits



sign change $c_{x_0} \rightarrow -c_{x_0}$

inversion about mean $c_x \rightarrow \frac{1}{N}\sum_{x'} c_{x'} - (c_x - c_{x'})$

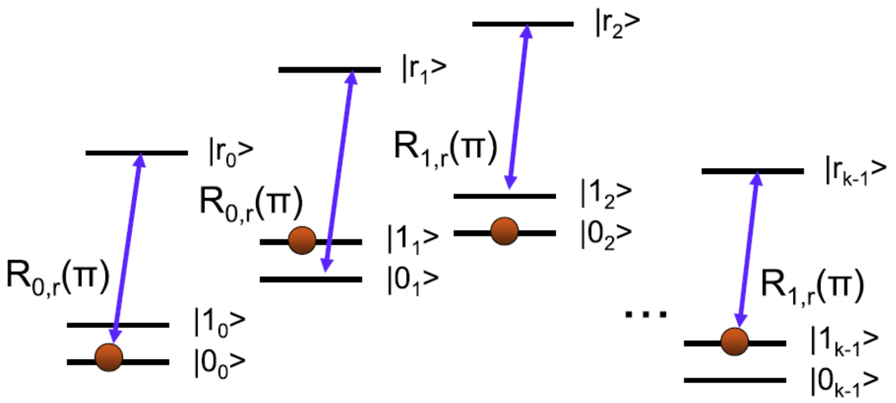


Figure 2. Grover conditional phase: successive π-pulse excitation transfer of all atoms from one of their qubit states to the Rydberg state. The lasers couple the states $|1-b_i\rangle$, complementary to the bit values of the marked element x_0, to the Rydberg states. If one atom is already excited, no further excitation occurs, and hence quantum register components with more atoms populating the states coupled to the laser field will only be excited once, while the state with no atoms coupled to the laser fields will not be excited at all. A second set of π-pulses, applied to the atoms in reverse order, returns all population to the initial states, but a relative change of sign has been accumulated between the state $|x_0\rangle$ and all other components.

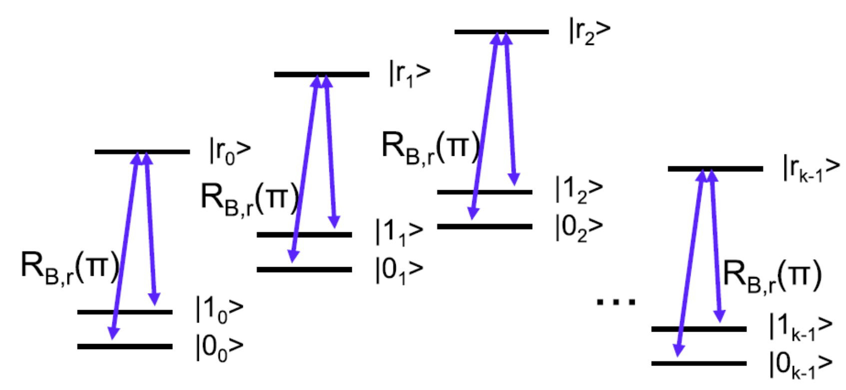


Figure 3. Grover inversion-about-the-mean: with the Λ-transition laser excitation scheme shown, the $(|0_i\rangle + |1_i\rangle)/\sqrt{2}$ dark state in each atom is uncoupled while a π-pulse excitation transfers the bright superposition qubit state $|B_i\rangle = (|0_i\rangle - |1_i\rangle)/\sqrt{2}$ to the Rydberg state. In a succession of such excitation pulses, if one atom is already excited, no further excitation occurs, and hence quantum register components with more atoms populating the bright states will only be excited once, while the state $|\Psi_0\rangle$ with no bright state atoms will not be excited at all. A second set of π-pulses, applied to the atoms in reverse order, returns all population to the initial states, and a relative change of sign has been accumulated between the state $|\Psi_0\rangle$ and all other components.

$$|\Psi\rangle \rightarrow U_G|\Psi\rangle$$

$$U_G = P - (I - P) = P - Q$$

$$P = |\Psi_0\rangle\langle\Psi_0| \qquad |\Psi_0\rangle \equiv \sum_x \frac{1}{\sqrt{N}}|x\rangle$$

inversion about mean is equivalent to sign change conditioned on all bits being in $(|0\rangle + |1\rangle)/\sqrt{2}$

Wang, Sørensen, Mølmer, PRL **86**, 3907 (2001)

Scaling

- Grover iteration can be performed with 4k laser pulses, each of area π
- Alternative, simultaneous addressing scheme requires only 8 pulses/iteration
- Best known quantum circuit: 49k-149 gates, k>3.
- Error estimates:

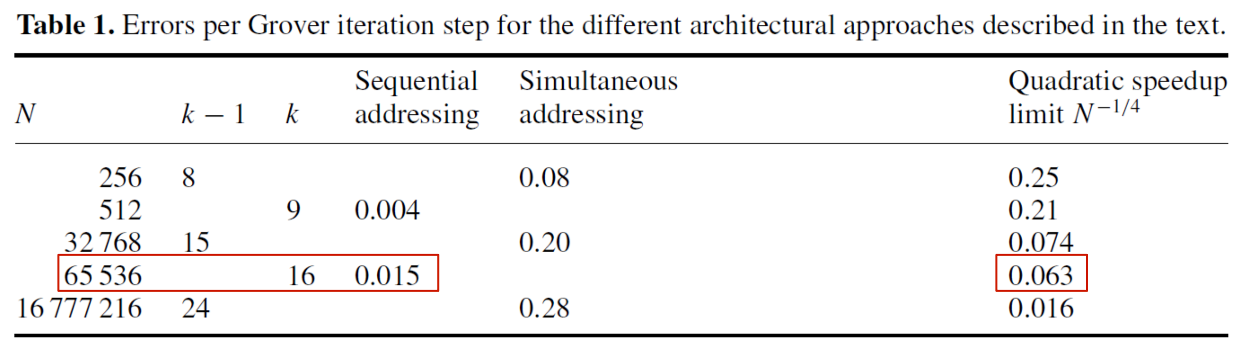


Table 1. Errors per Grover iteration step for the different architectural approaches described in the text.

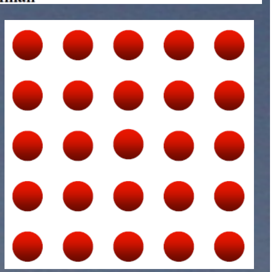
N	$k-1$	k	Sequential addressing	Simultaneous addressing	Quadratic speedup limit $N^{-1/4}$
256	8			0.08	0.25
512		9	0.004		0.21
32 768	15			0.20	0.074
65 536		16	0.015		0.063
16 777 216	24			0.28	0.016

J. Phys. B: At. Mol. Opt. Phys. **44** (2011) 184016 (8pp)

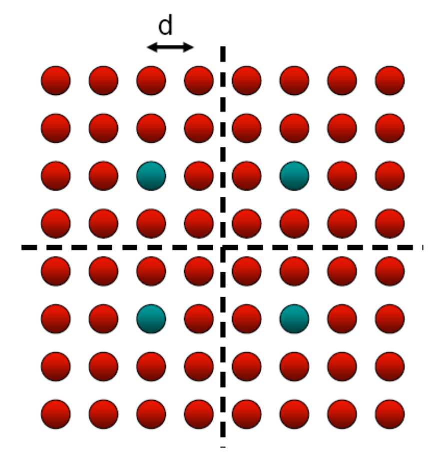
Efficient Grover search with Rydberg blockade

Klaus Mølmer[1,3], Larry Isenhower[2] and Mark Saffman[2]

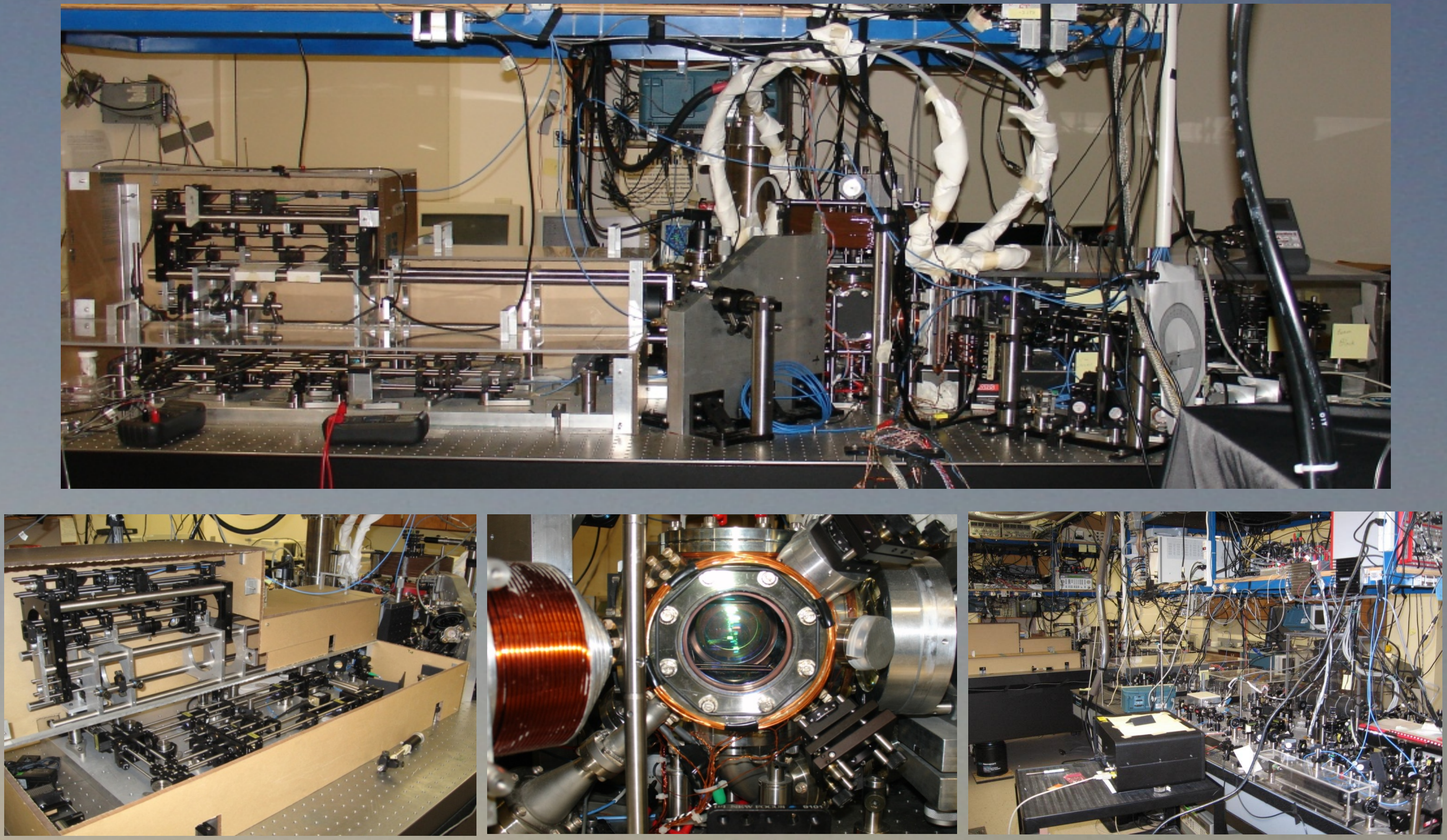
k=$\log_2(N)$ qubits



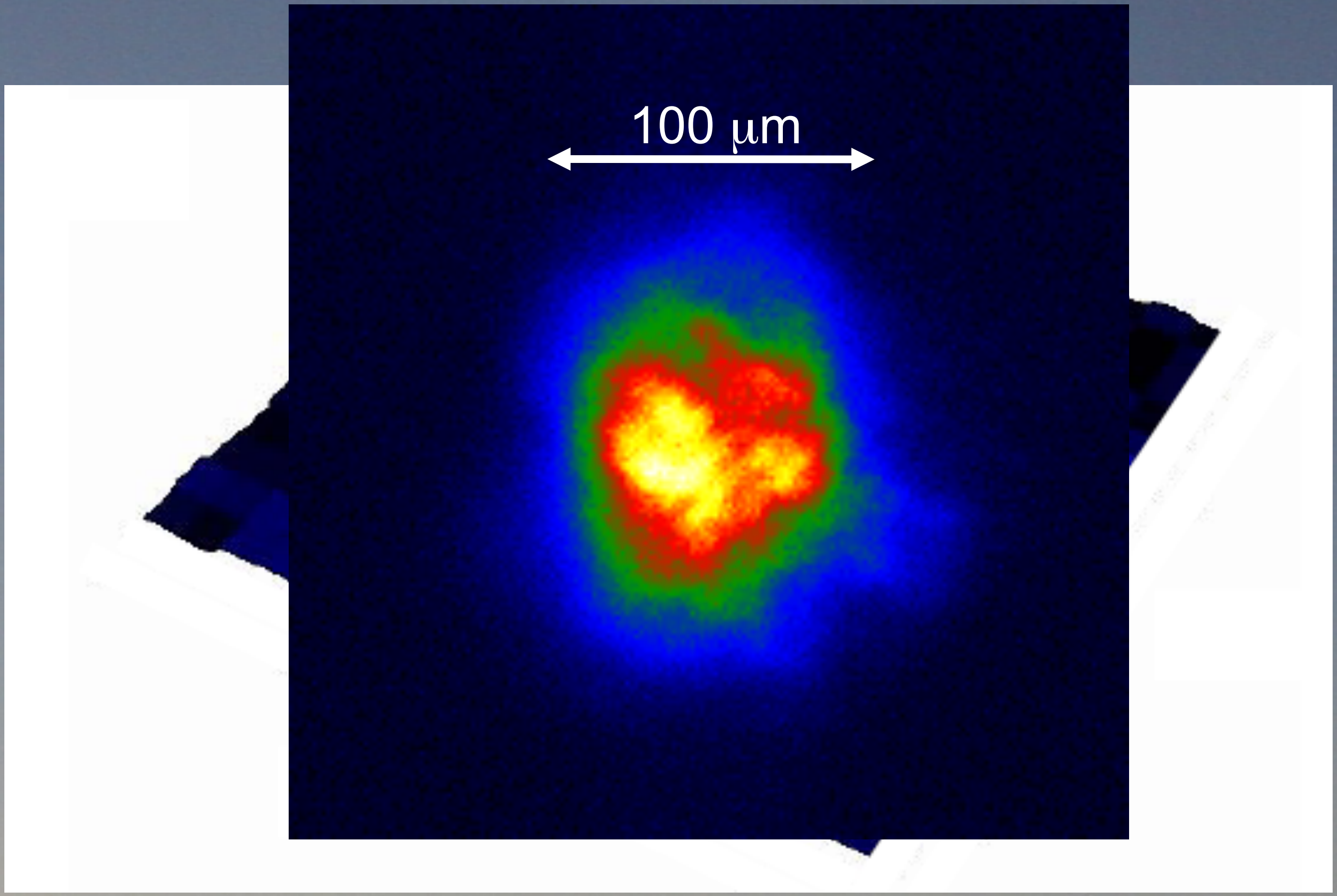
sub-register architecture



Experimental Status

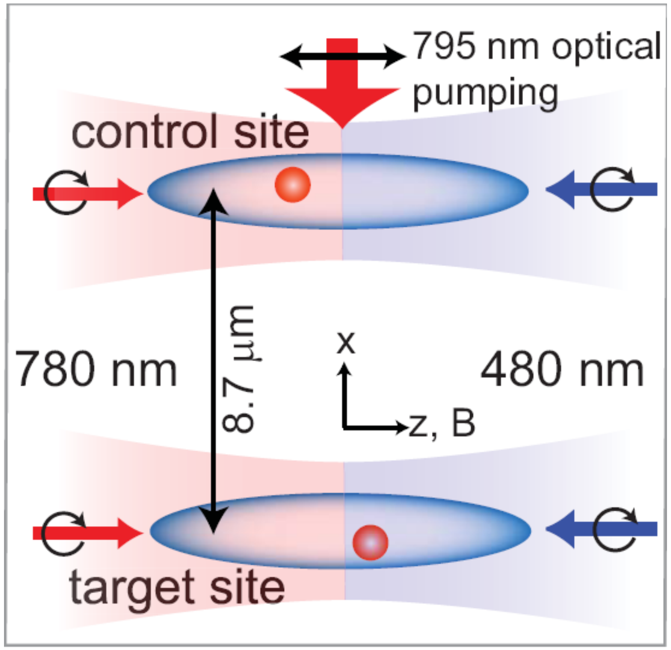


CNOT implementation - two site experiment

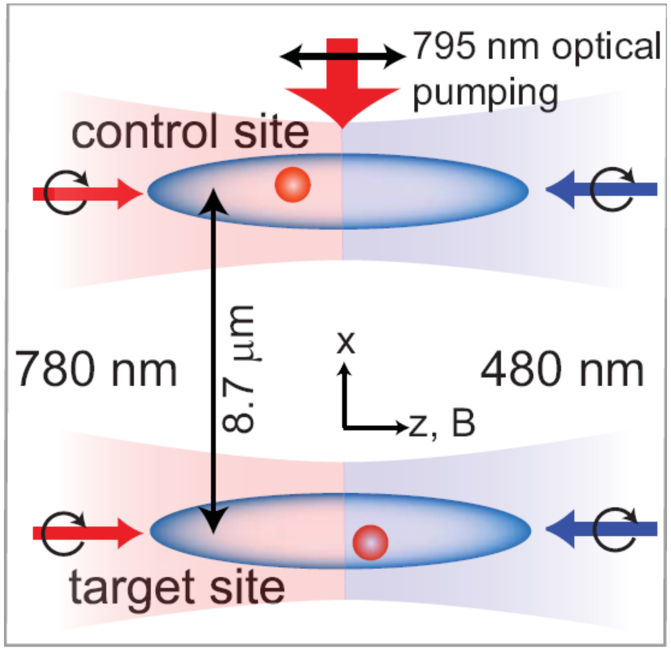


Average of 146 shots.
Probability of one atom in both sites about 10%.

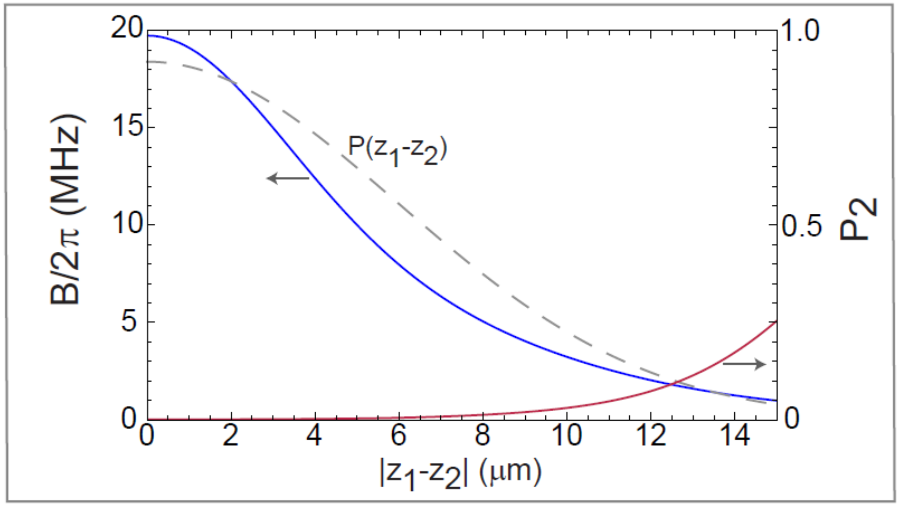
CNOT implementation



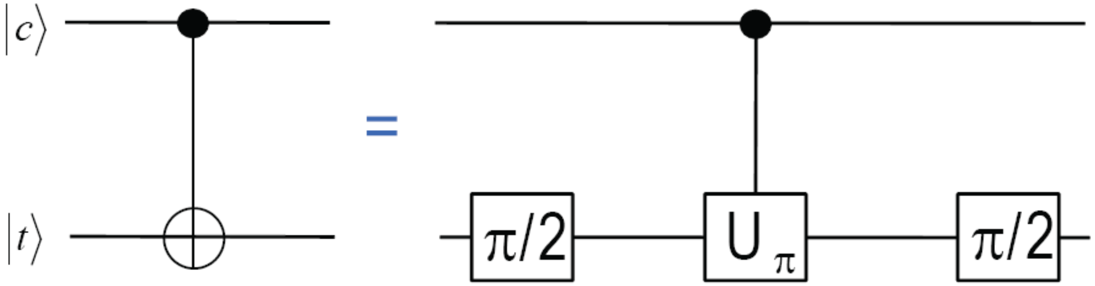
CNOT implementation



$97d_{5/2}$

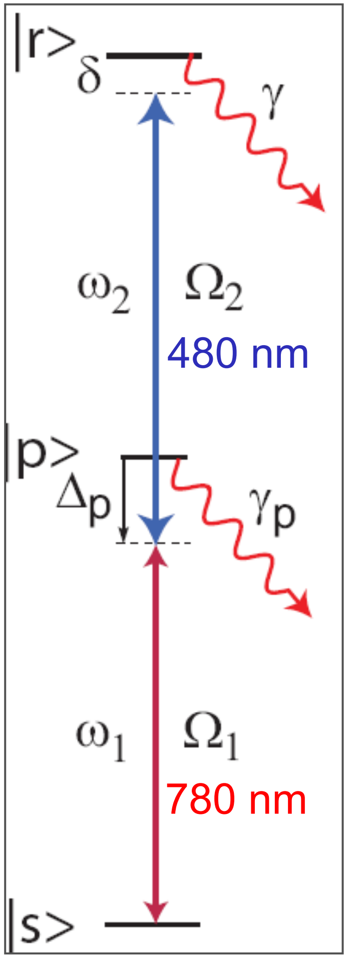


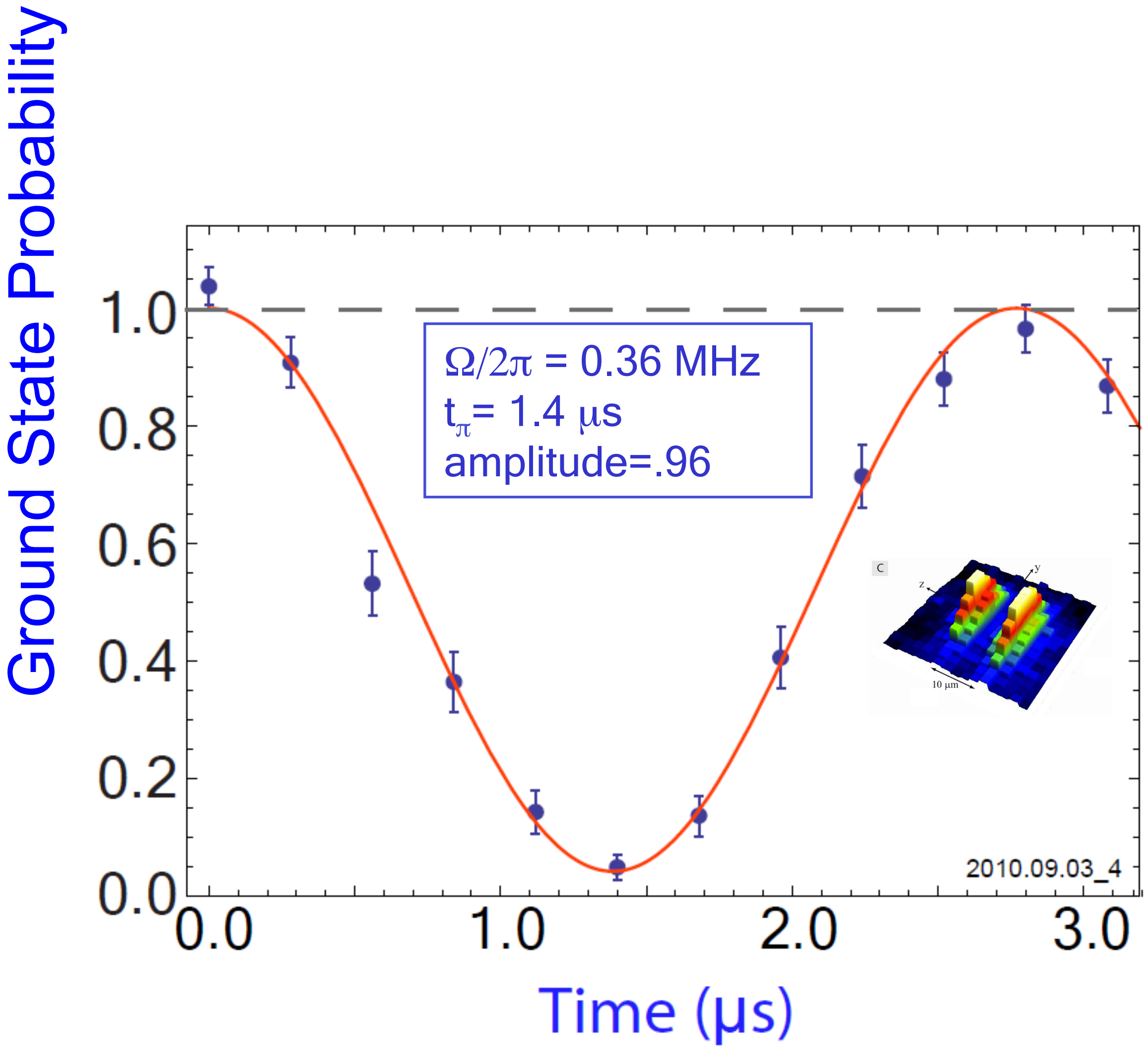
CNOT



Rydberg state Rabi oscillations

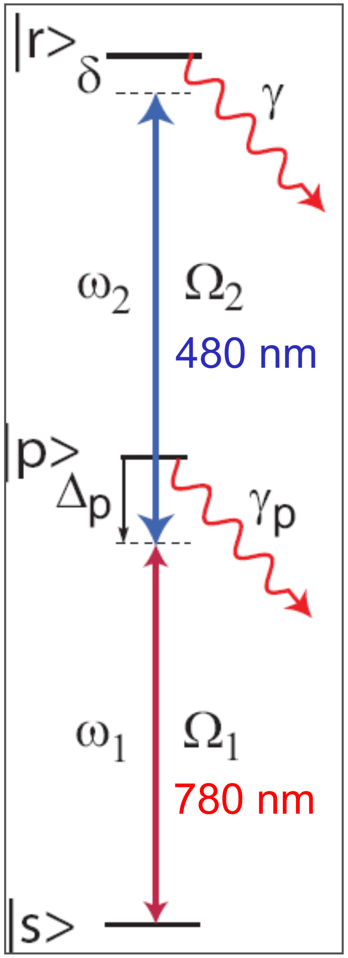
$5s_{1/2}$ - $5p_{3/2}$ - $97d_{5/2}$, m=5/2

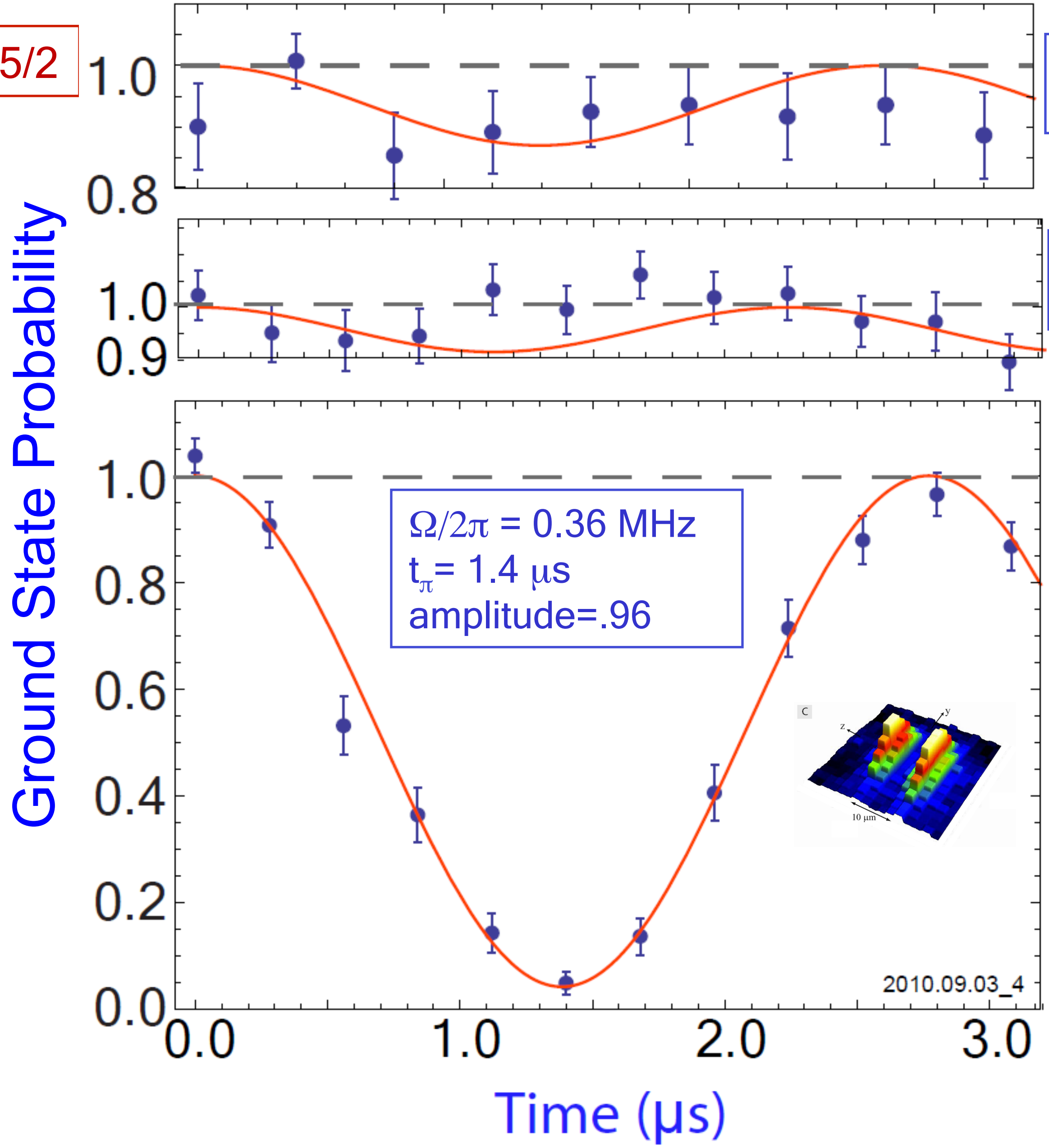




Rydberg state Rabi oscillations

$5s_{1/2}$ - $5p_{3/2}$ - $97d_{5/2}$, m=5/2





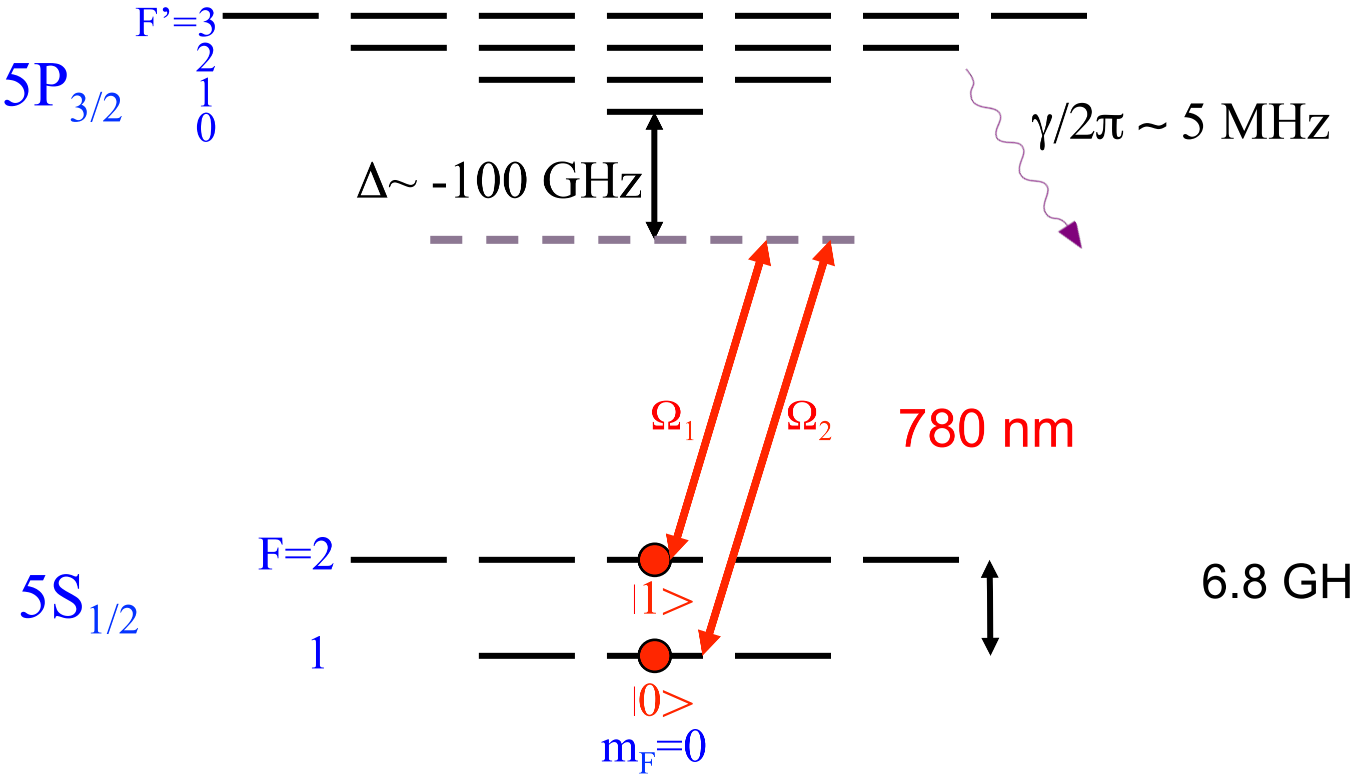
$\Omega/2\pi$ = 0.36 MHz
t_π= 1.4 µs
amplitude=.96

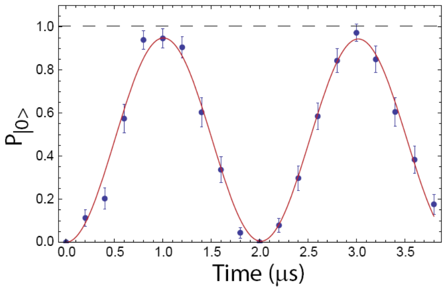
blockaded excitation

other site crosstalk

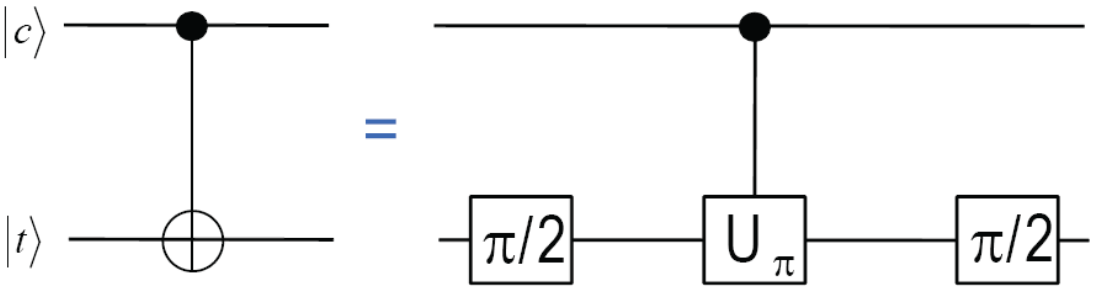
Single qubit rotations

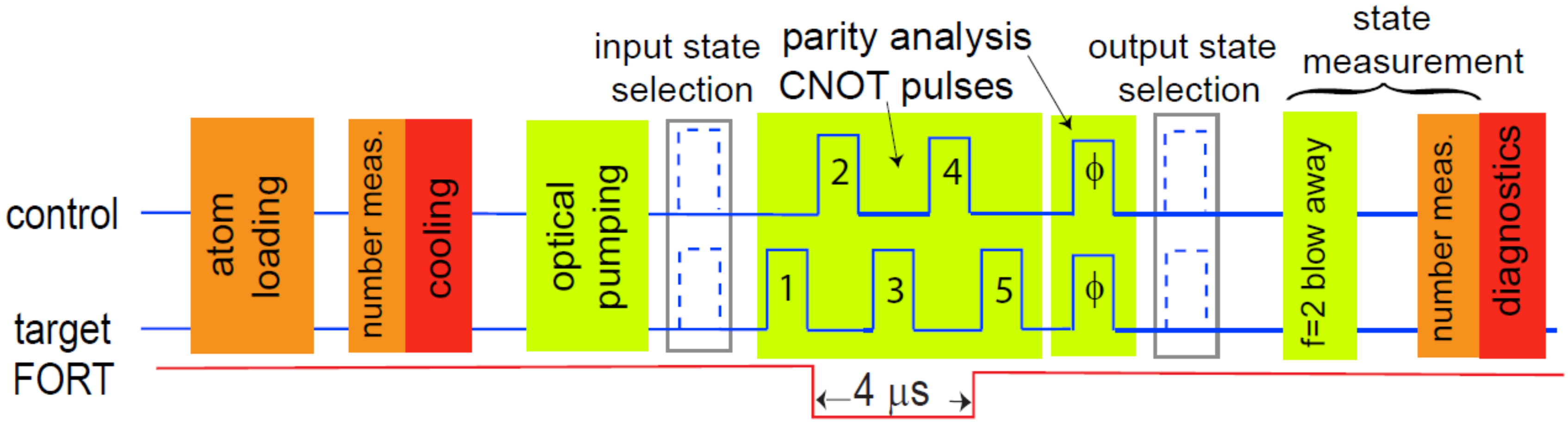
single qubit rotations by 2 photon stimulated Raman





CNOT implementation

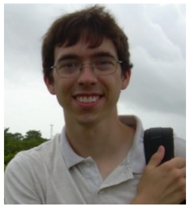




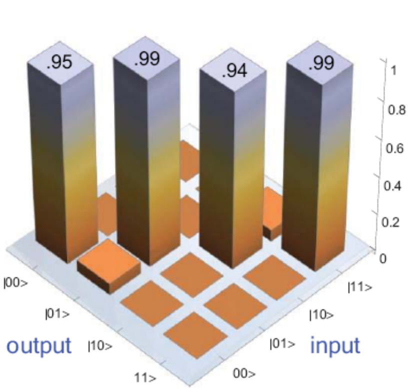
Rydberg blockade experiment - collaboration with Thad Walker

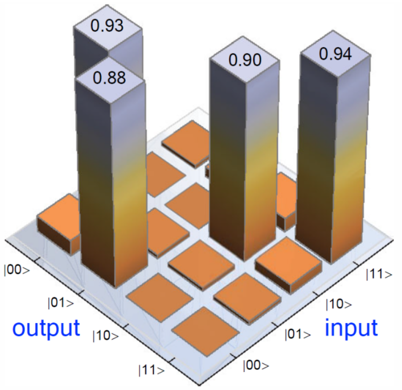
Xianli Zhang

Larry Isenhower



Alex Gill



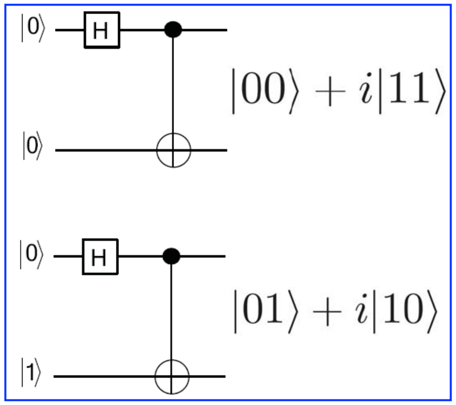


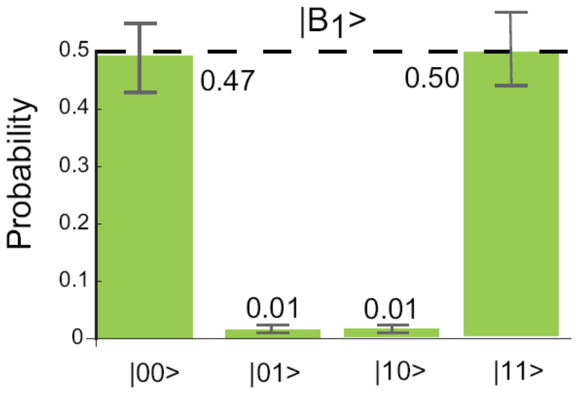
CNOT truth table

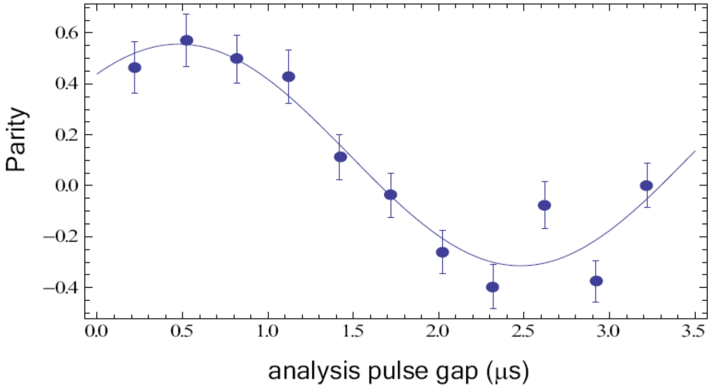
Fidelity: raw $(1/4)Tr(U_{ideal}^{T}U_{\exp}) = .74 \pm .05$

loss corrected $(1/4)Tr(U_{ideal}^{T}U_{\exp}) = .92 \pm .06$

Entanglement





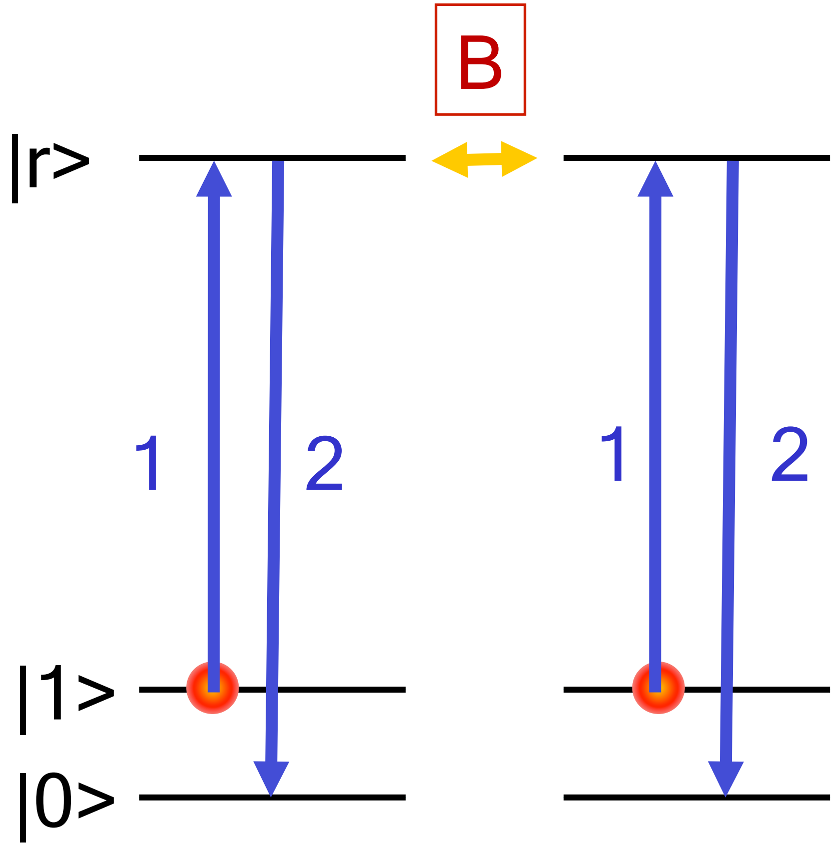


Fidelity: raw 0.58+/-0.04

loss corrected 0.71+/-0.05

Isenhower et al. PRL 2010
Zhang, et al. PRA 2010

Entanglement by global addressing



$$|\psi\rangle = |11\rangle$$

Inst. d'Opt.: Wilk, et al. PRL (2010)

Summary: Rydberg mediated quantum logic experiments

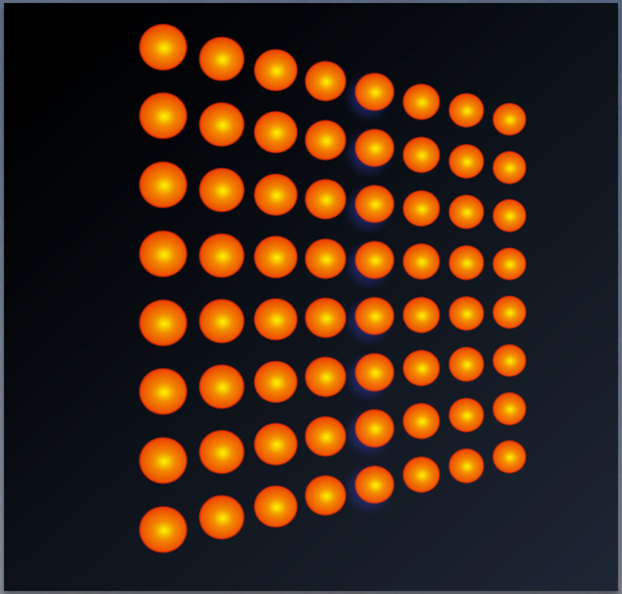
Results with two qubits:

Single qubit operation	F ~ 0.95
CNOT truth table	F ~ 0.9
Entanglement fidelity	F ~ 0.7
Gate time	~ 5 μs
Coherence time	~ 40 ms
Theoretical fidelity limit	~0.001
Fault tolerance threshold (architecture dependent)	.01 - .0001

Atomic Qubit Array wishlist

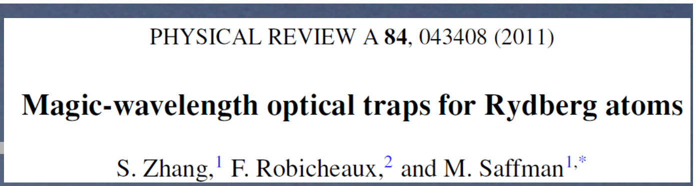
Single site operations without crosstalk:

- atom loading (reloading)
- fiducial state preparation
- single and two qubit gates with high fidelity
- QND Measurements (free space QND Browaeys, Chapman)
- recooling
- long coherence time
- parallel operations



special requirement – trapping of both ground and Rydberg states

Ground-Rydberg magic trapping



PHYSICAL REVIEW A **84**, 043408 (2011)

Magic-wavelength optical traps for Rydberg atoms

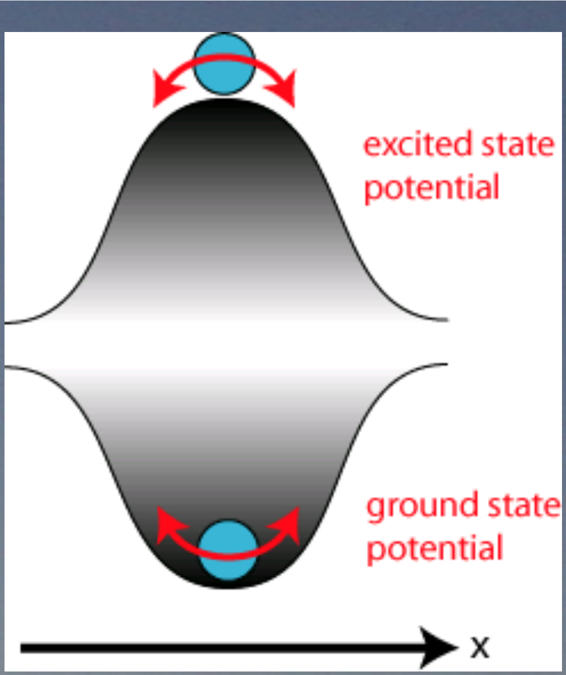
S. Zhang,[1] F. Robicheaux,[2] and M. Saffman[1,*]

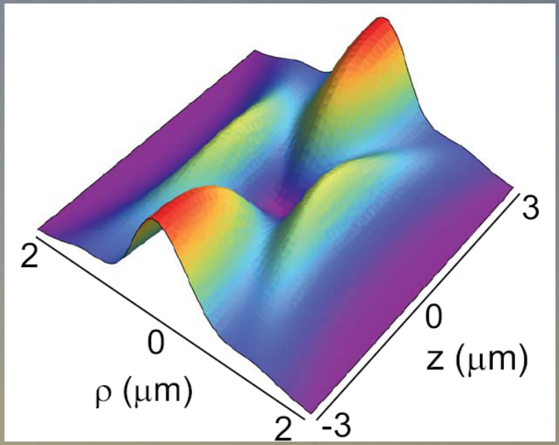
Rydberg state has negative polarizability (free electron, ponderomotive potential, Raithel)

Ground state has positive polarizability for 1 micron wavelength light

Choose wavelength so also ground state has negative polarizability

Blue detuned trap with same potential for ground and Rydberg states

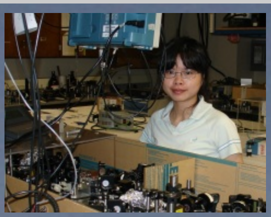




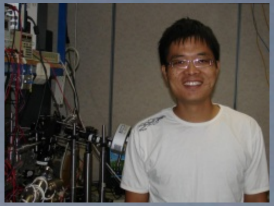
Single atom in BoB trap

A crossed vortex bottle beam trap for single-atom qubits

G. Li, S. Zhang, L. Isenhower, K. Maller, and M. Saffman*

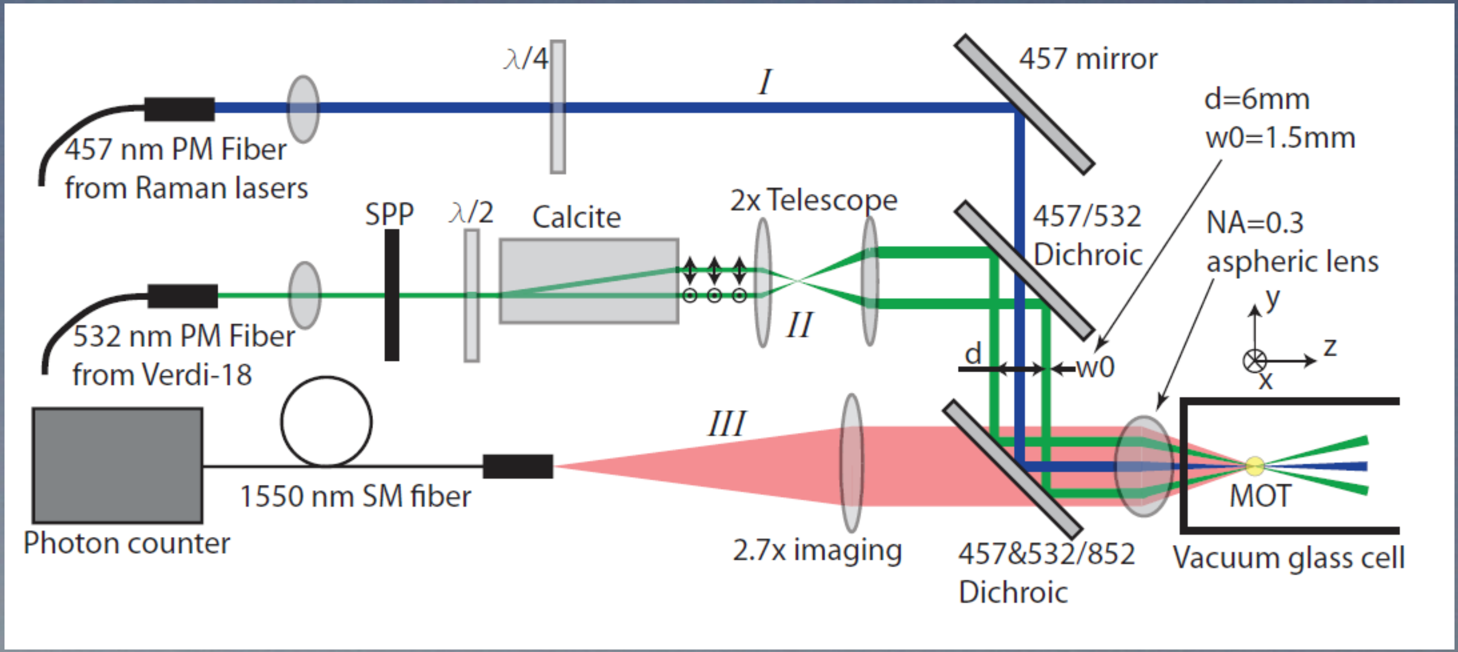


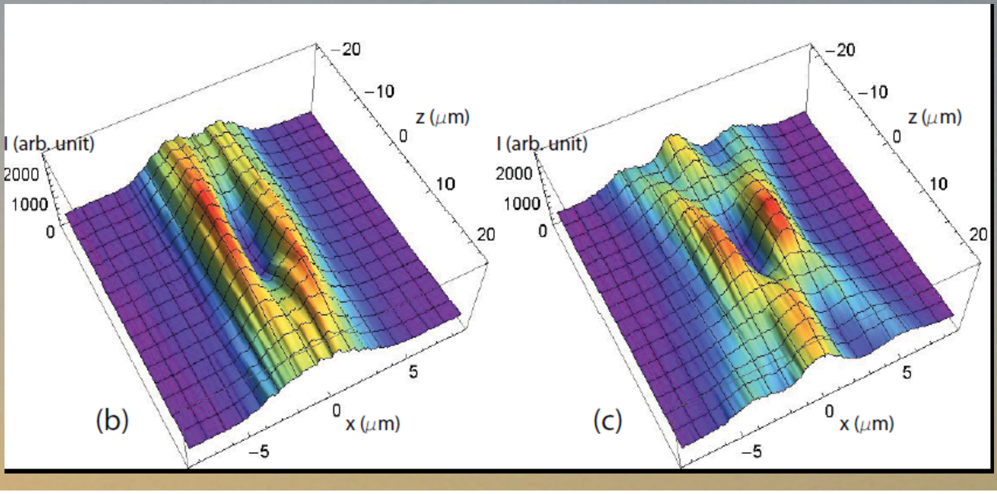
Siyuan Zhang

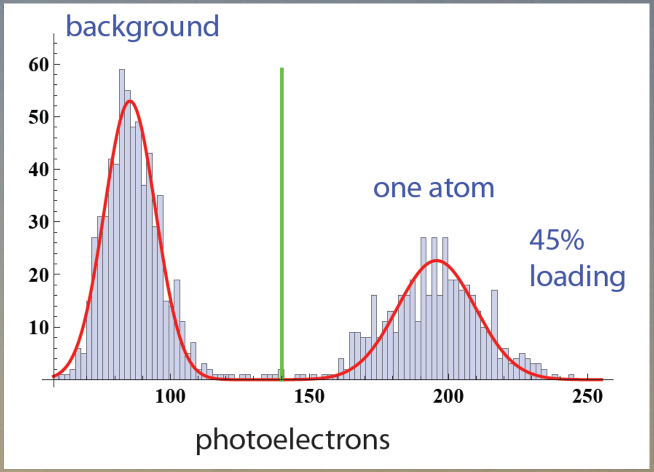


Gang Li

Kara Maller

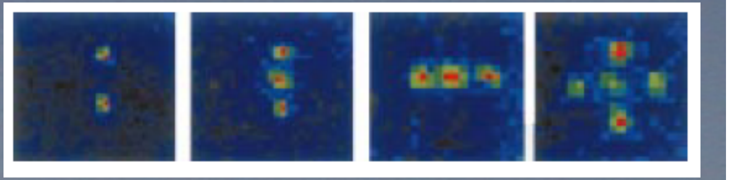




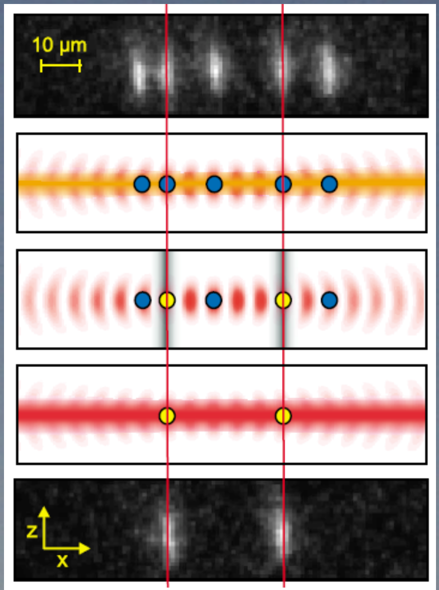


Atomic Qubit Array

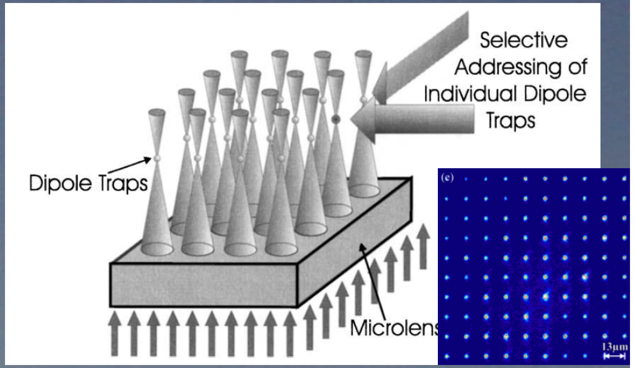
Orsay 2004



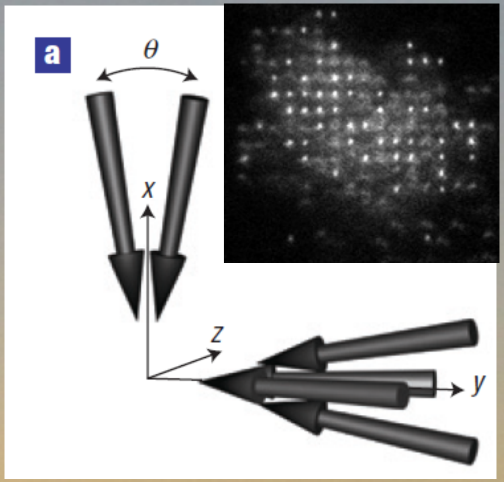
Bonn 2004



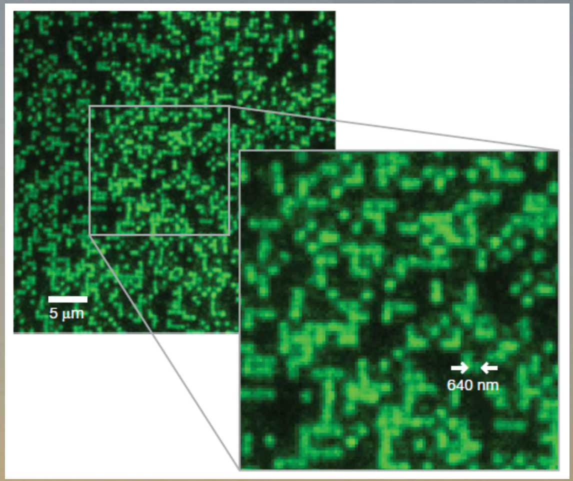
Darmstadt 2010



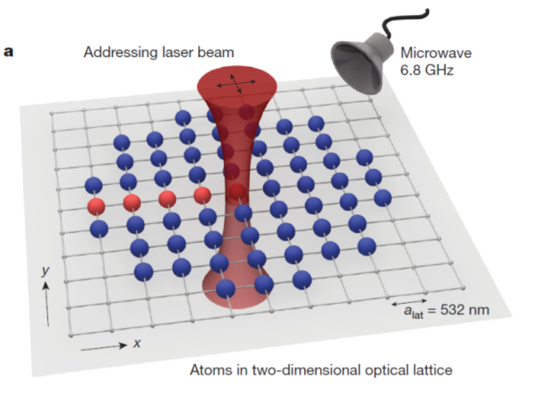
Penn State 2007



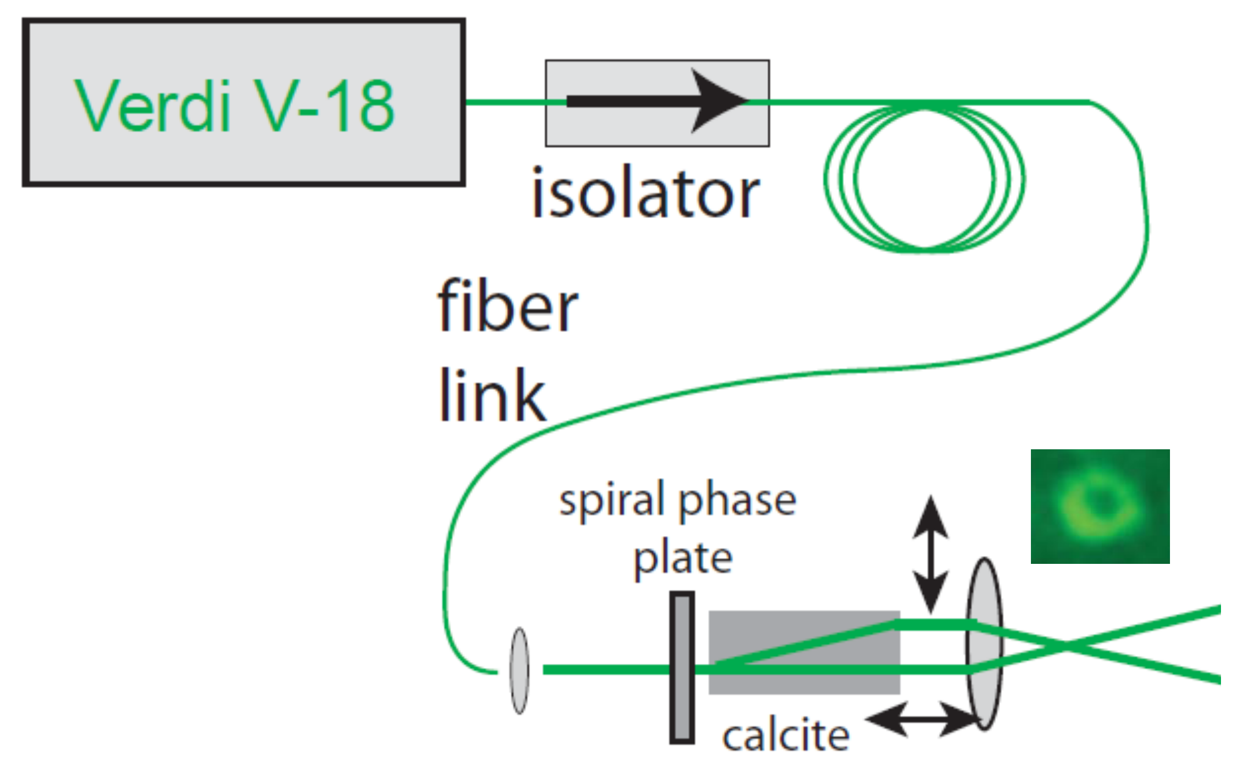
Harvard 2009



Munich 2011



Array of bottle traps



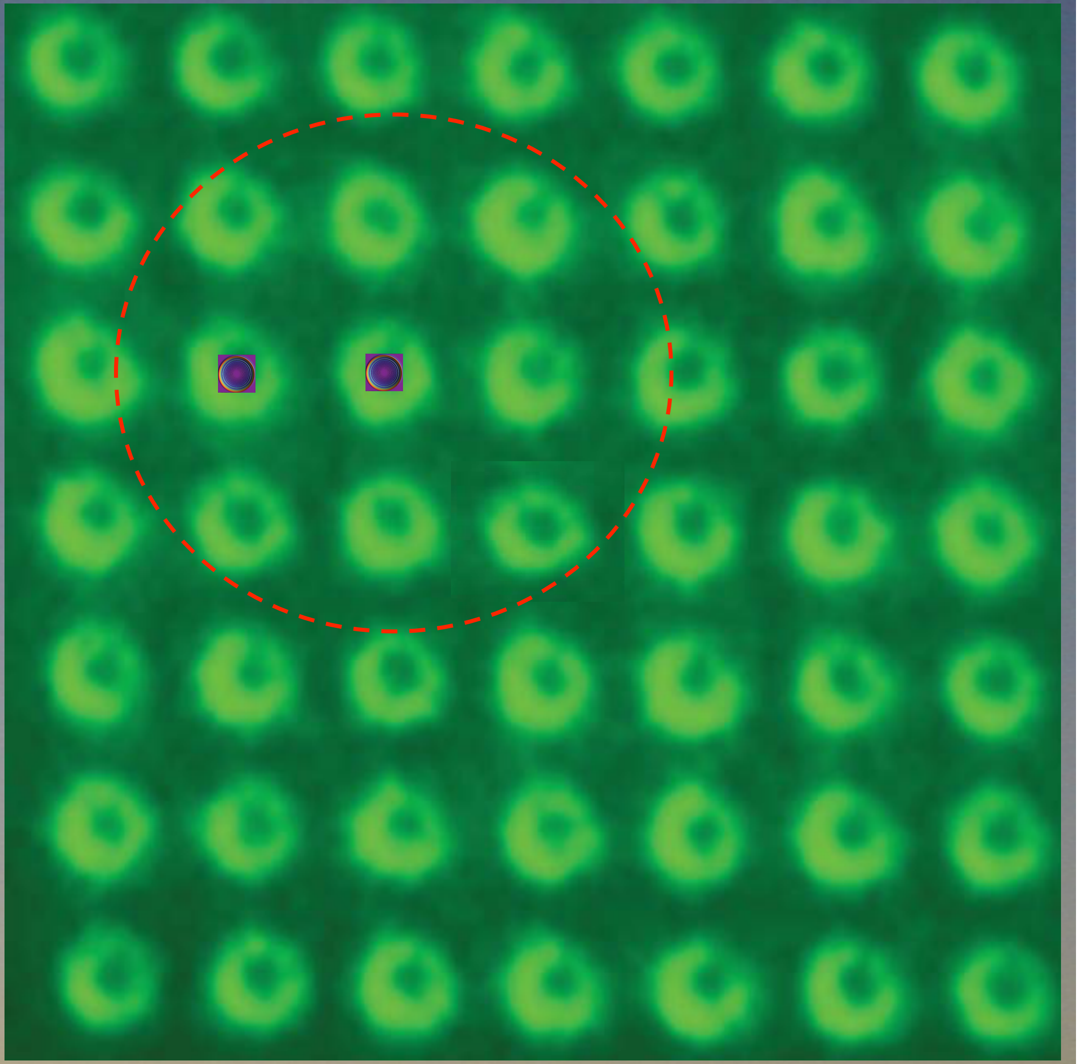
Array of bottle traps

Two walls between each trap

N=100 -> spacing~8 μm

Blockade distance~30 μm

9 coupled qubits

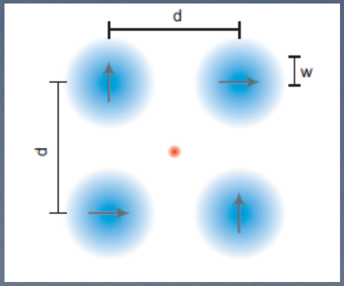


2D array of traps

One wall between each trap

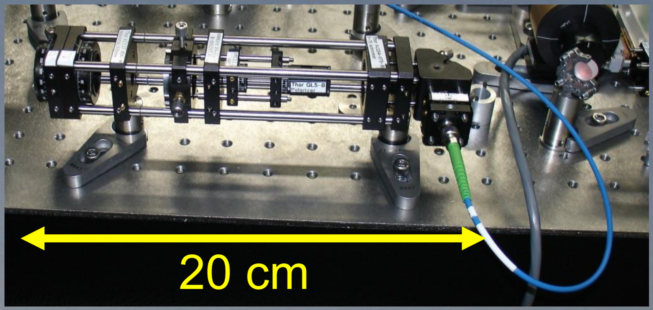
N=100 -> spacing~4 μm

40 coupled qubits



Michal

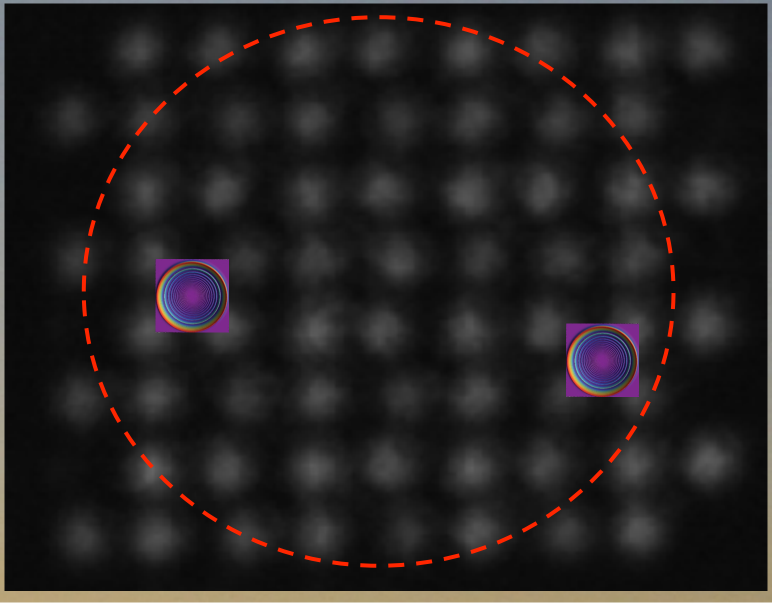
Piotrowicz



projected lattice, 42 sites

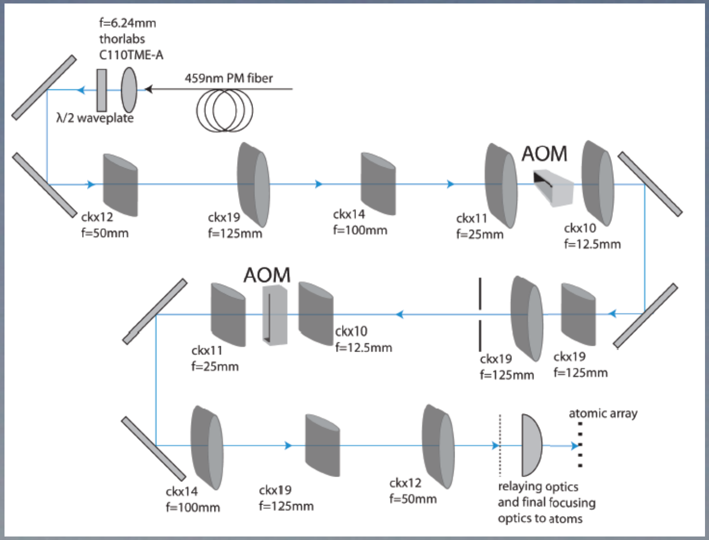
no sensitivity to phase drifts

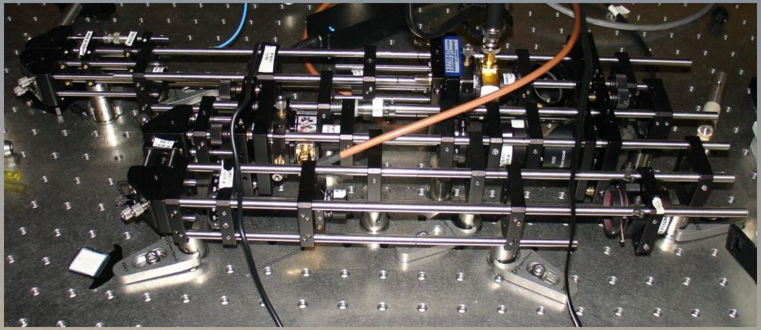
long term stability



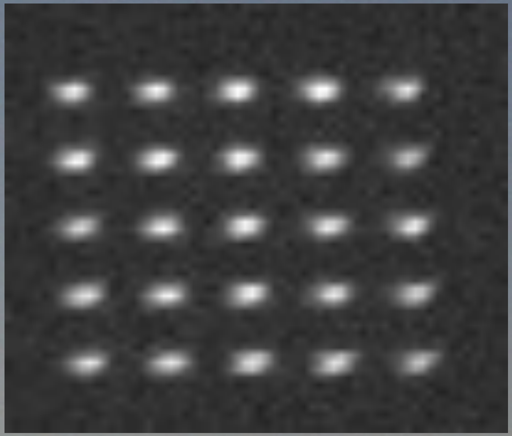
Qubit addressing

2D acousto-optic beam scanners





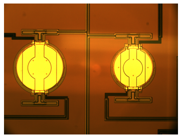
Kara Maller

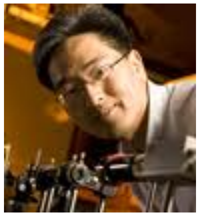


25 scanned spots,
sub μs addressing

Using MEMS for atomic QIP

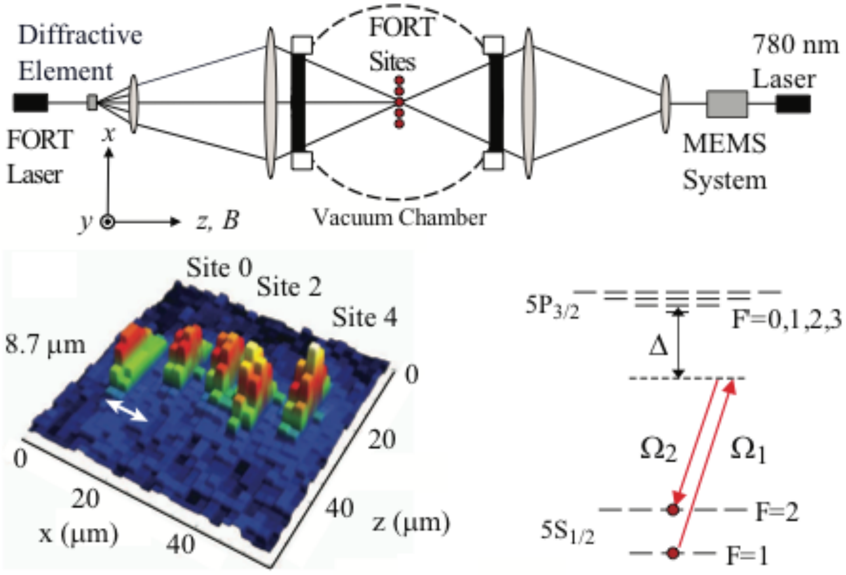
- Addressing individual Rb atoms

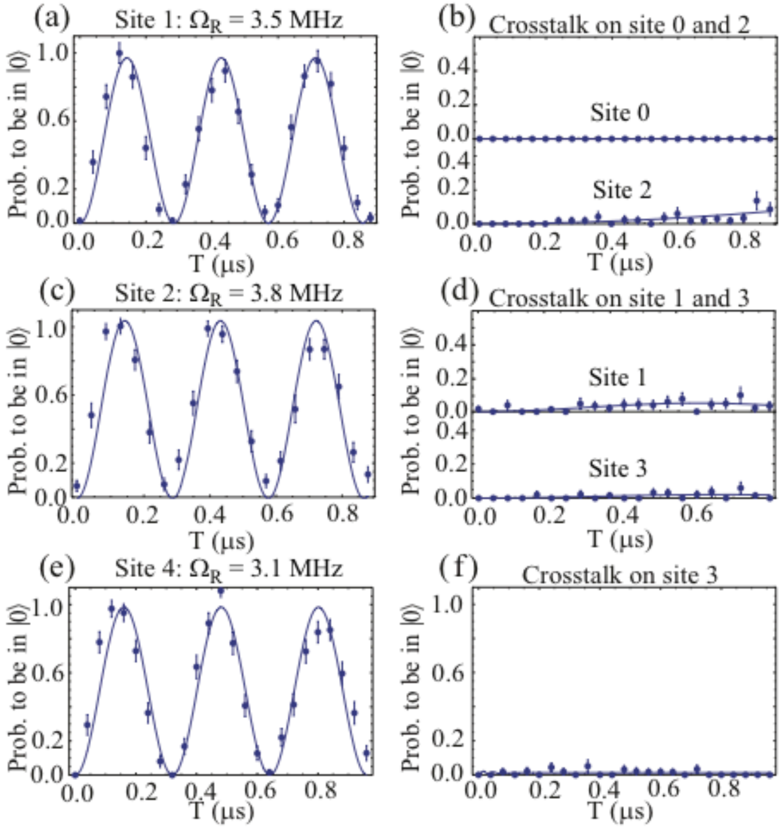




Jungsang Kim

Felix Lu

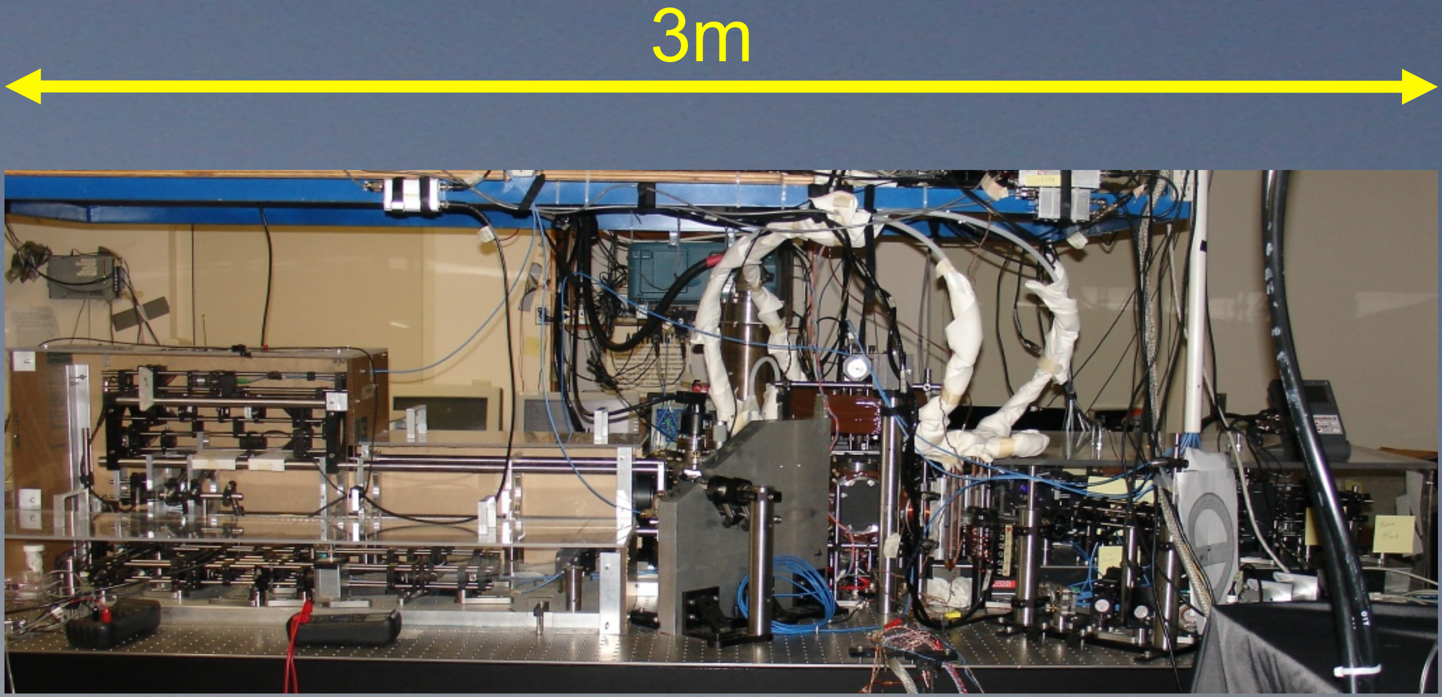




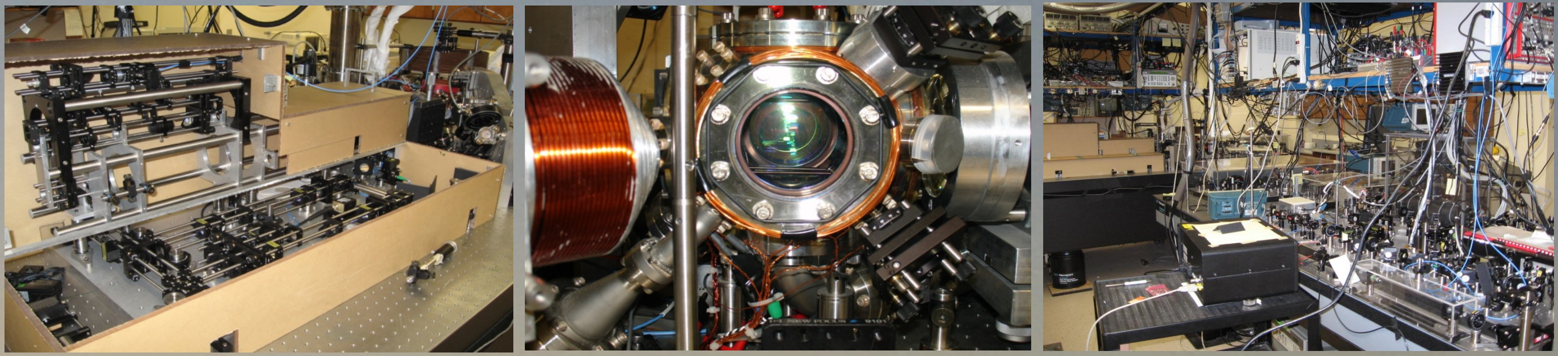
(U. Wisconsin, Duke, AQT)

C. Knoernschild et al., Appl. Phys. Lett. (2010)

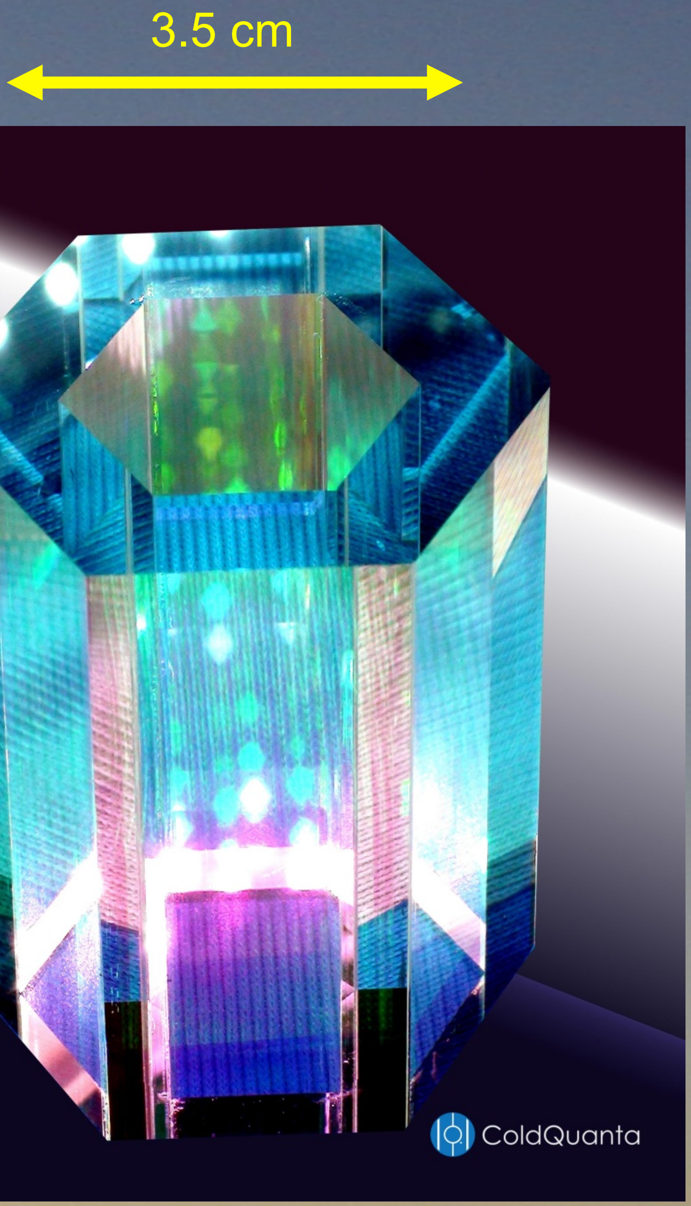
Footprint: Rb experiment 2001-2011

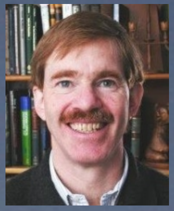


Rb



Next generation





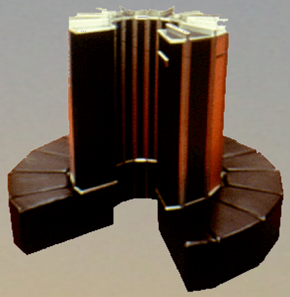
Dana Anderson

JILA NIST CU

ColdQuanta

SRI International
SARNOFF

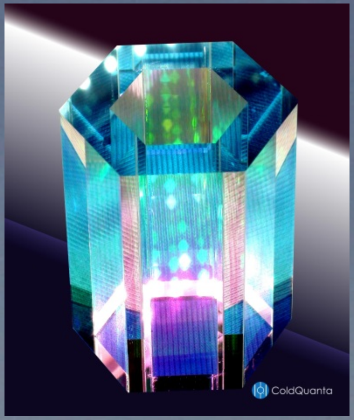
IARPA
BE THE FUTURE

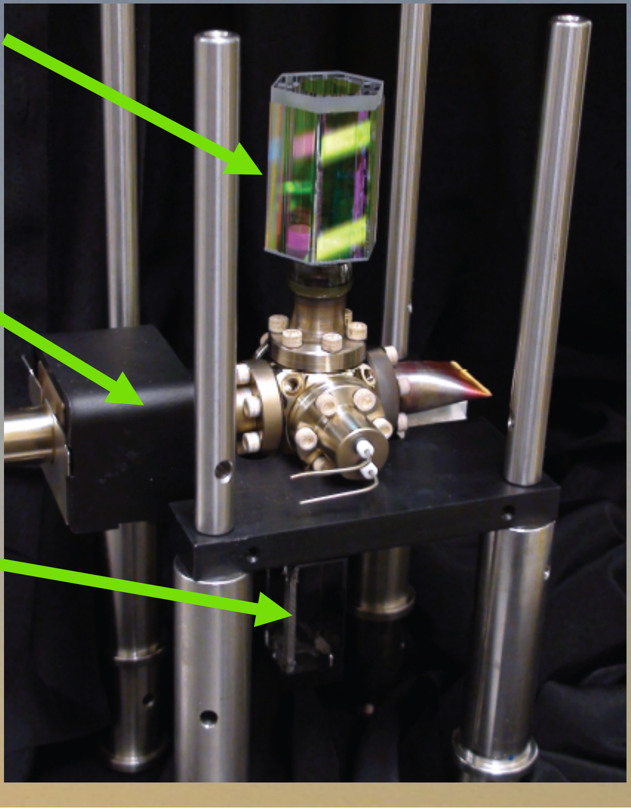


Next generation

small pyrex cells

6 sides $\Omega/4\pi$=40%



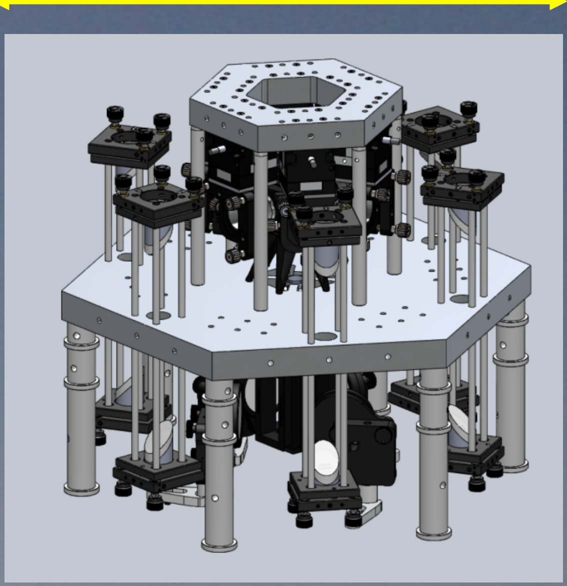


science cell

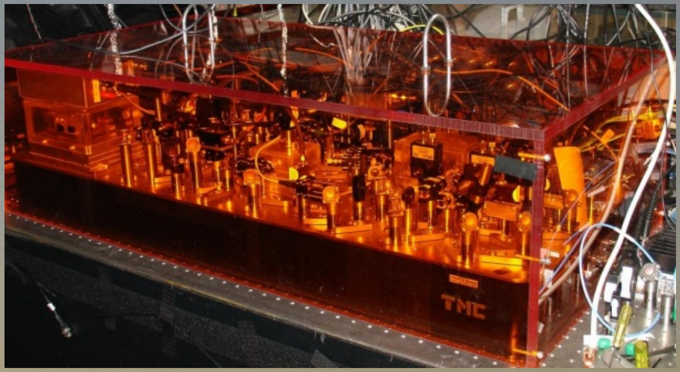
ion pump

2D MOT source

addressing optics, ~ 25 cm



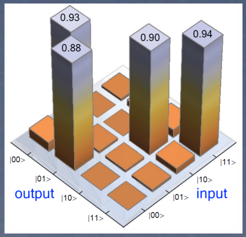
new lasers, referenced to frequency comb



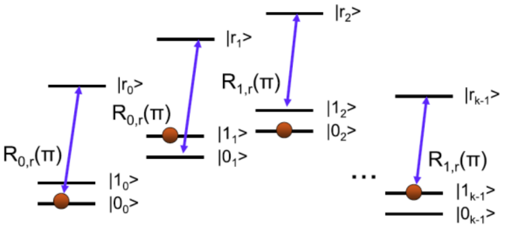
Quantum Information with Rydberg atoms

THE UNIVERSITY of WISCONSIN MADISON

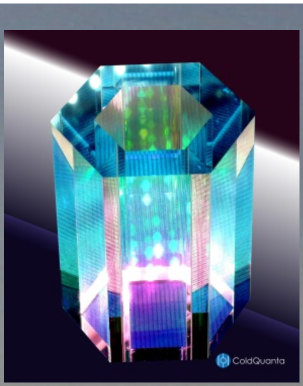
Neutral atoms are excellent candidates for scalable QIP



Multi-bit Rydberg interactions for efficient Implementation of algorithms



New technology for multi-qubit experiments



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