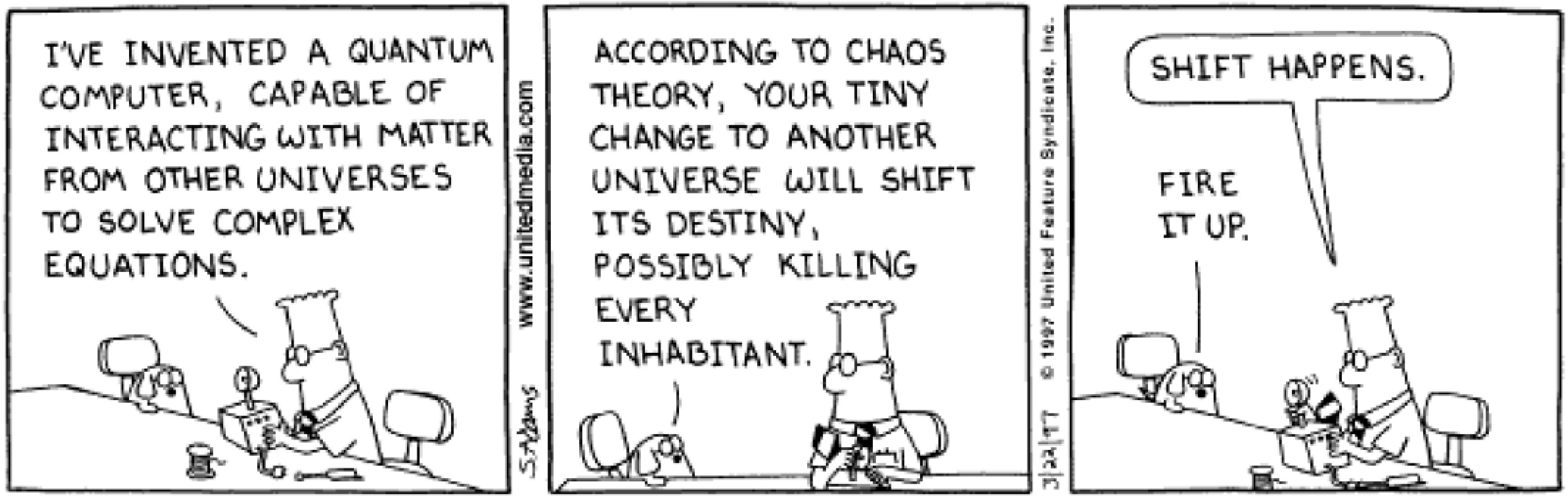
Quantum Information with Rydberg atoms: Experiments

Oliver Morsch
INO-CNR, Pisa
Coherence School Pisa, September 2012



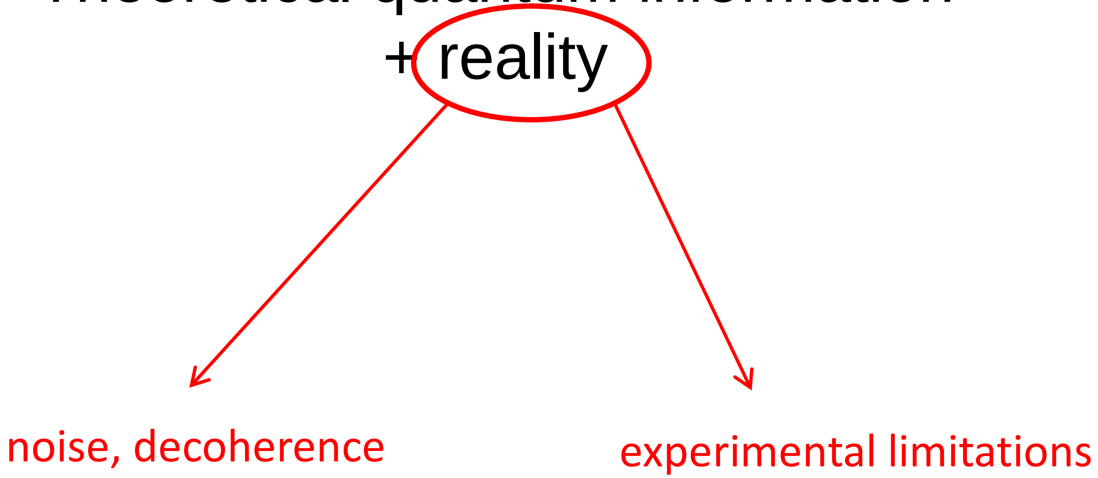
http://qso.lanl.gov/qc

Experimental quantum information =

Theoretical quantum information
+ reality

Experimental quantum information =

Theoretical quantum information
+ reality



noise, decoherence

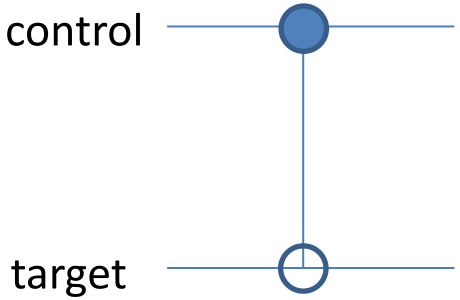
experimental limitations

Overview

- Lecture 1: Experimental quantum information – systems, successes and pitfalls
- Lecture 2: Quantum information with Rydberg atoms – The ingredients
- Lecture 3: The state of the art - and beyond

Quantum Computers

Set of universal quantum gates: cNOT plus single qubit gate



cNOT gate

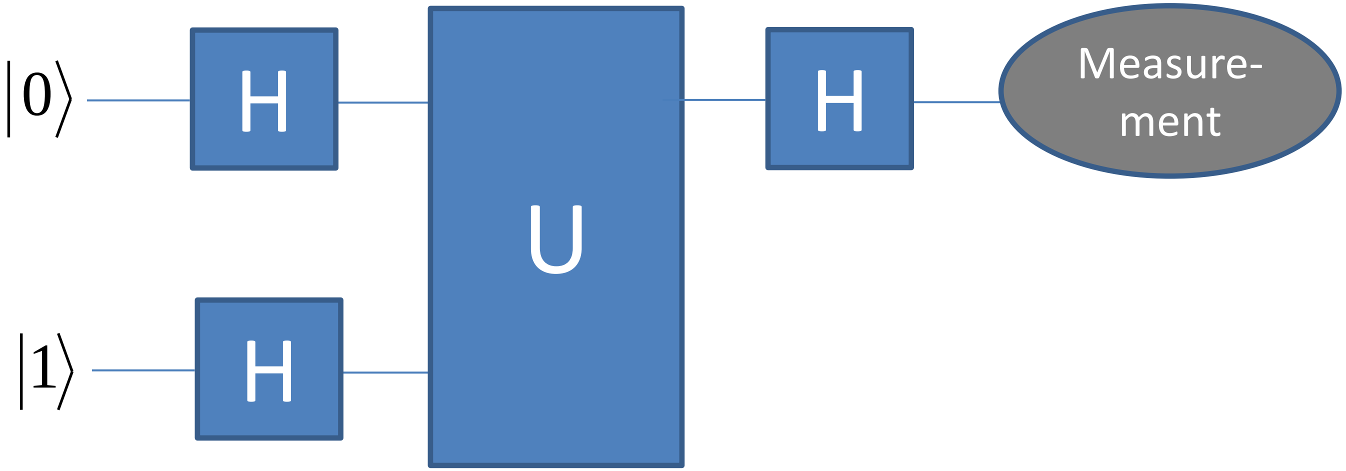
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} = \begin{pmatrix} I & 0 \\ 0 & \sigma_x \end{pmatrix}$$

Single qubit gate, e.g.
Hadamard gate H

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

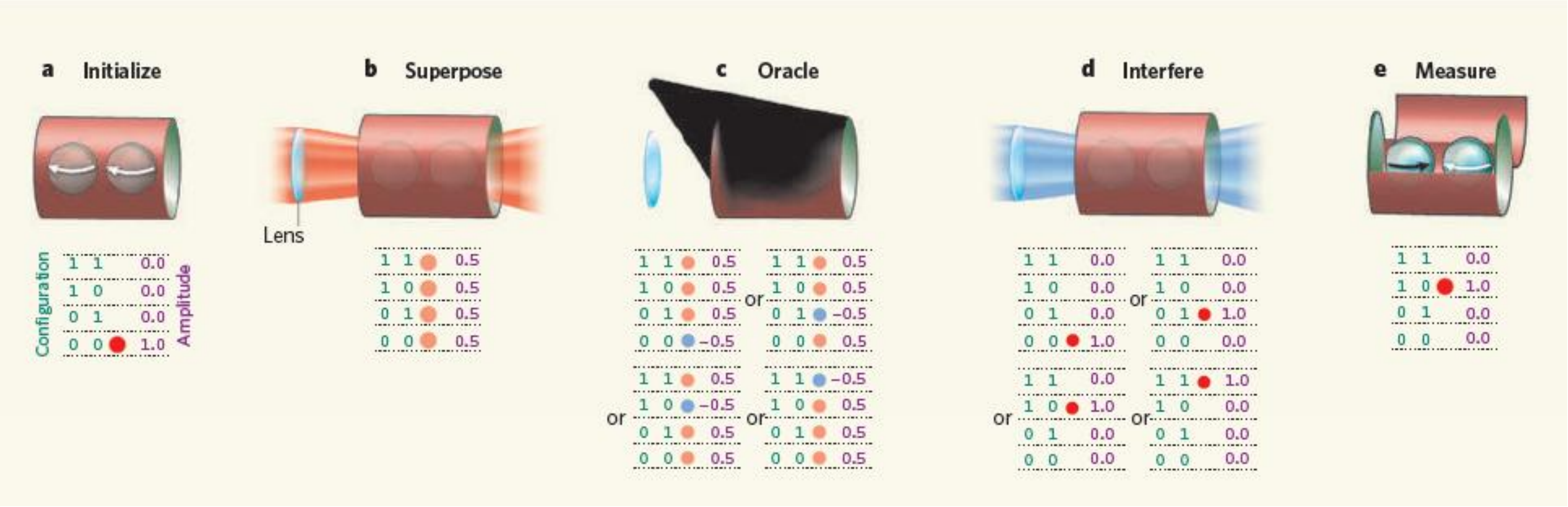
Takes |0> and |1> into superposition states

Quantum Computers

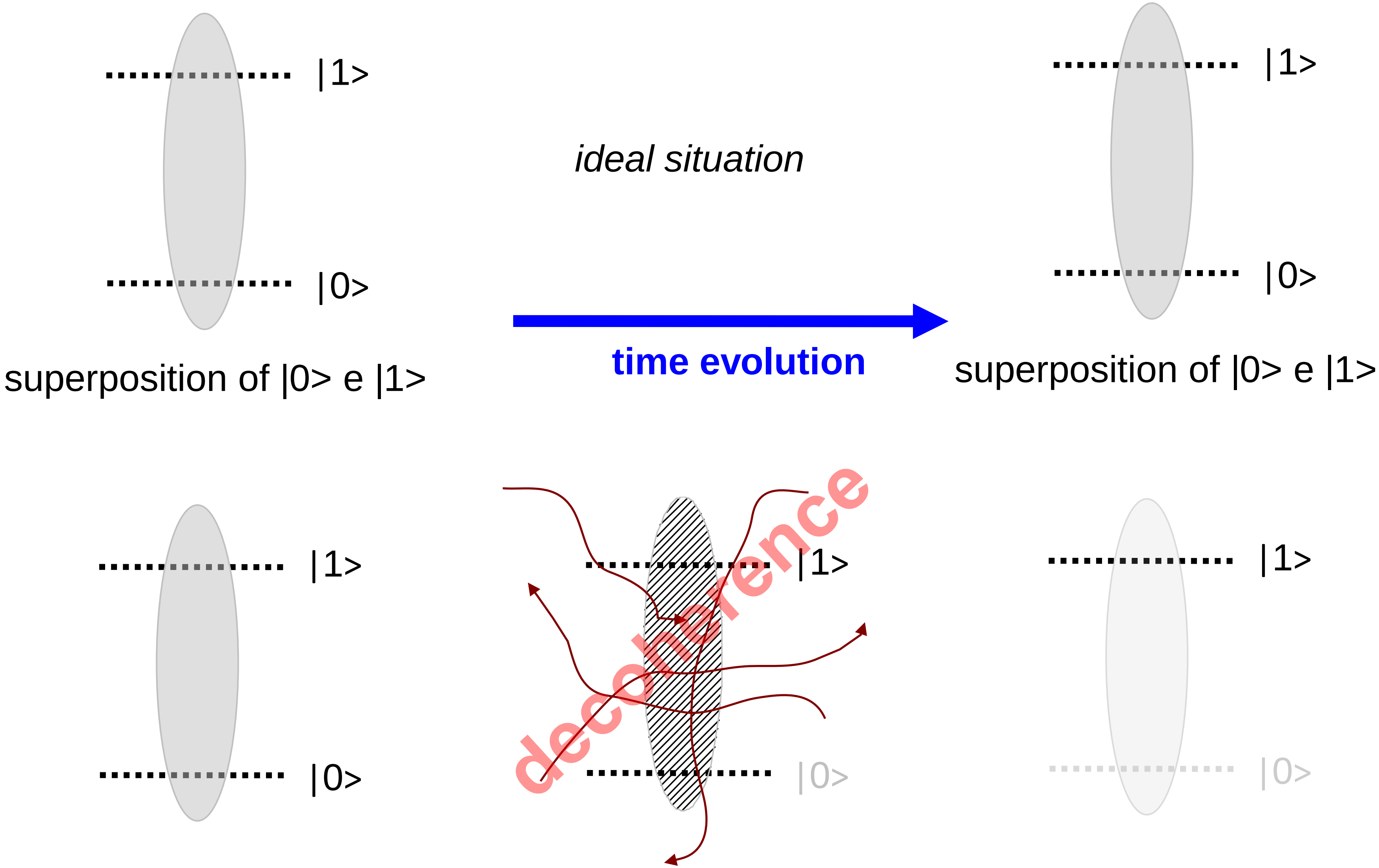


Deutsch algorithm (checks whether a function is constant or balanced)

Working principle of a quantum computer



Decoherence



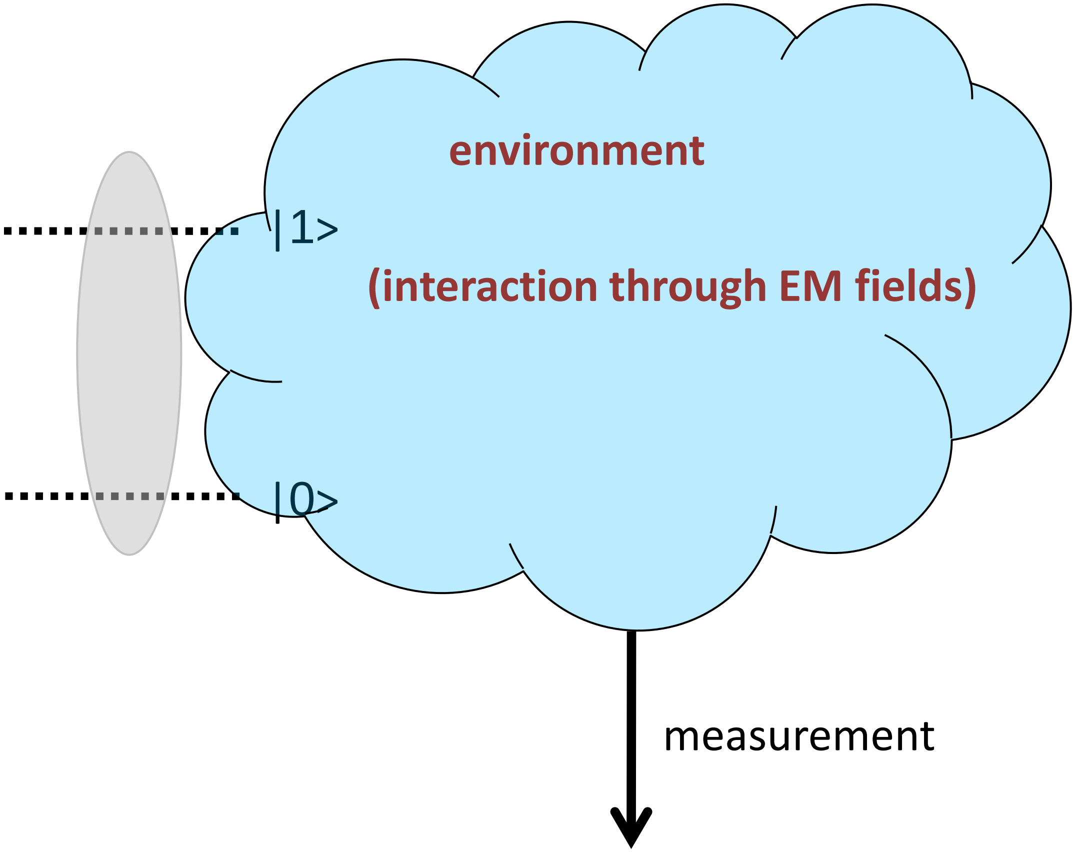
superposition of |0> e |1>

ideal situation

time evolution

superposition of |0> e |1>

Decoherence



environment

|1>

(interaction through EM fields)

|0>

measurement

trace over the environment-> coherence vanishes, the system becomes a mixed state

Quantum Computers

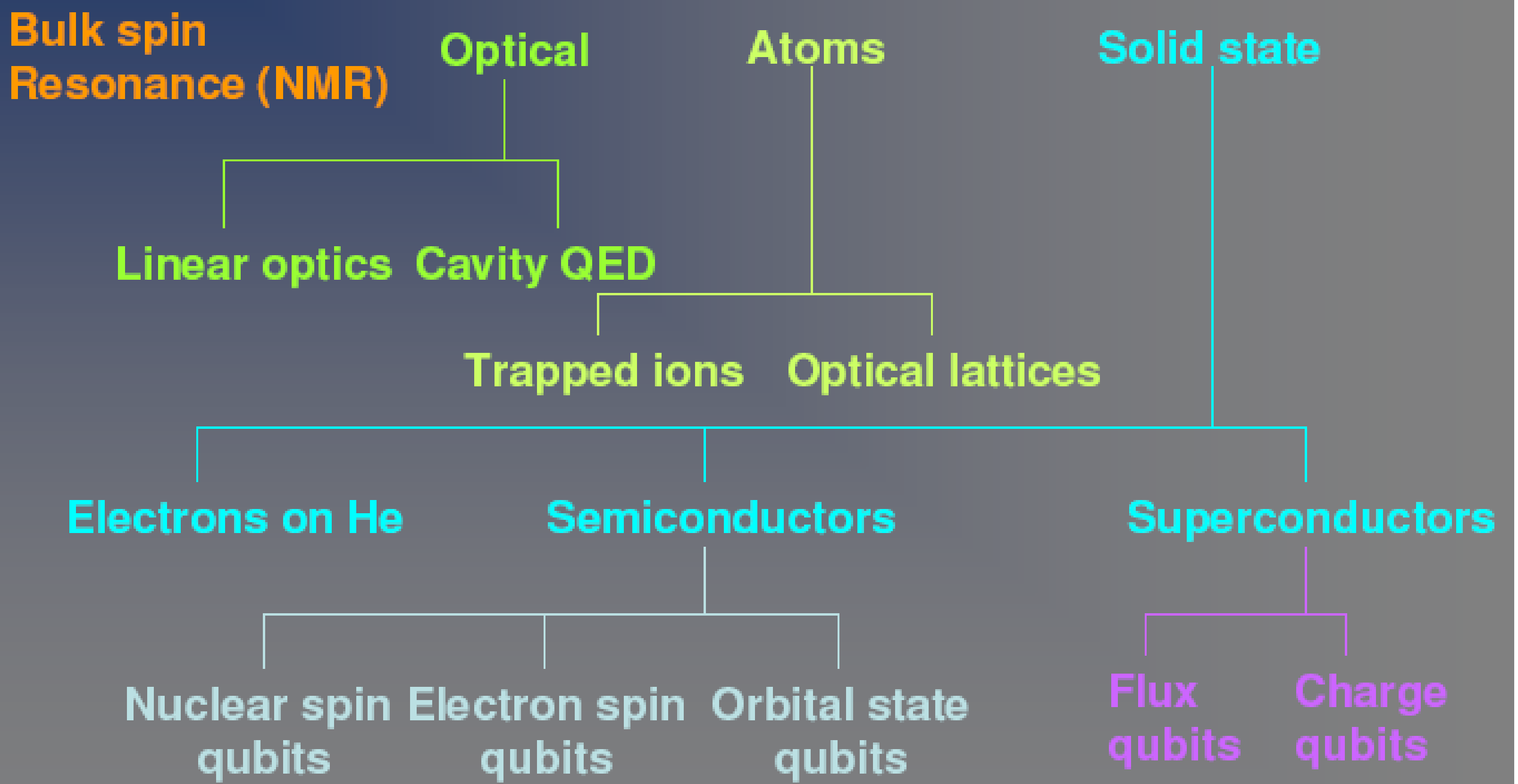
The DiVincenzo criteria

For a system to be a possible candidate for the implementation of a quantum computer, it must:

- Be a scalable physical system with well-defined qubits
- Be initializable to a simple fiducial state such as |000...>
- Have decoherence times that are much longer than the gate times
- Have a universal set of quantum gates
- Permit high quantum efficiency, qubit-specific measurements

Can we satisfy these criteria using ultra-cold atoms?

QC implementation proposals



Bulk spin Resonance (NMR)

Optical

Atoms

Solid state

Linear optics

Cavity QED

Trapped ions

Optical lattices

Electrons on He

Semiconductors

Superconductors

Nuclear spin qubits

Electron spin qubits

Orbital state qubits

Flux qubits

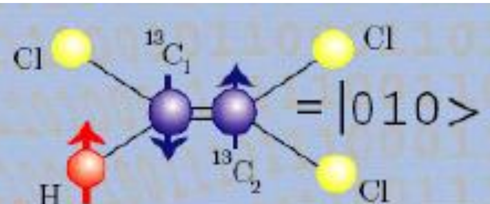
Charge qubits

http://courses.washington.edu/bbbteach/576/

Liquid State NMR

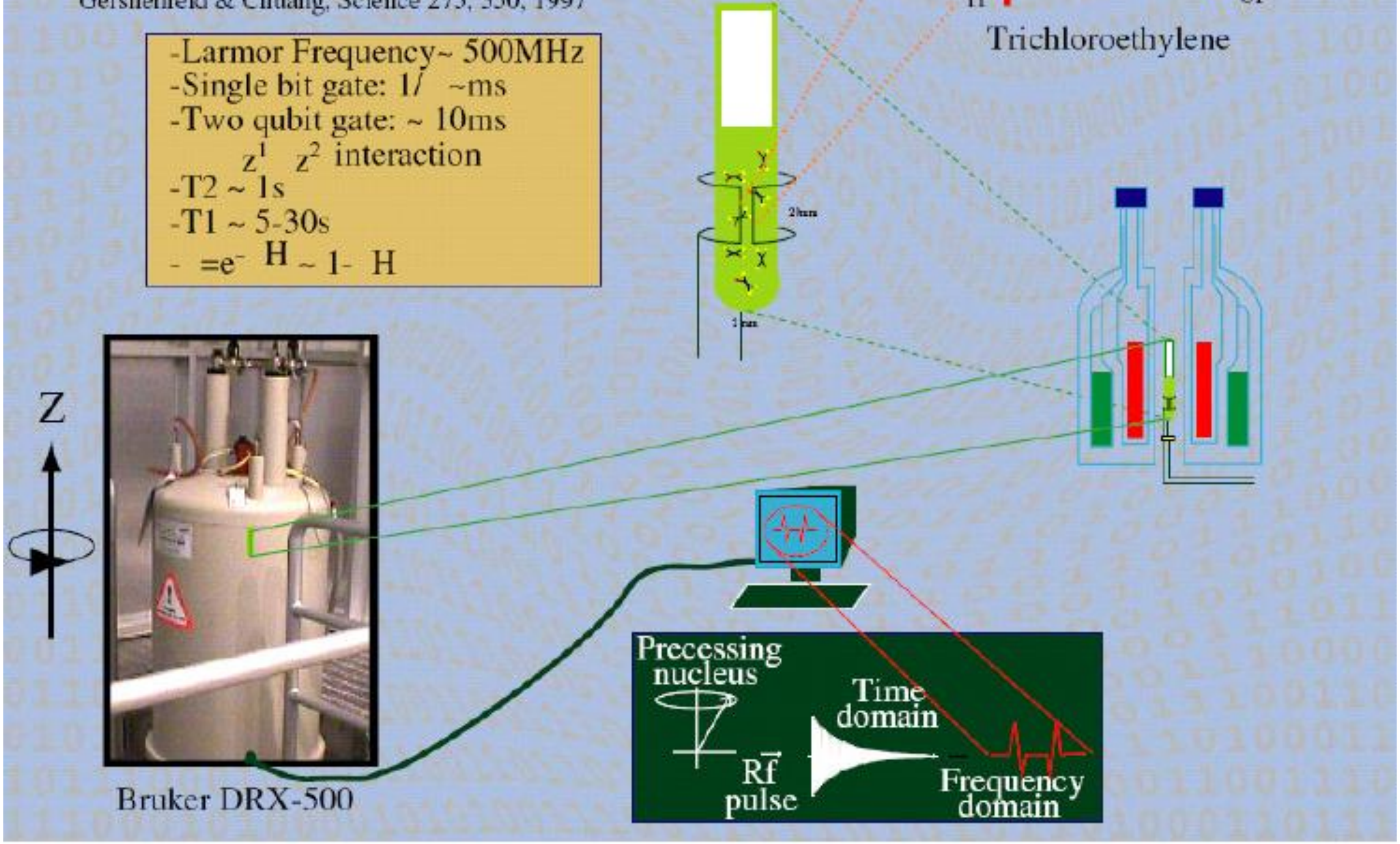
Cory & Havel PNAS, 64, 1634, 1997

Gershenfeld & Chuang, Science 275, 350, 1997



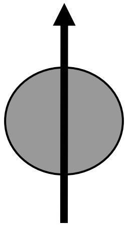
Trichloroethylene

- -Larmor Frequency~ 500MHz
- -Single bit gate: 1/ ~ms
- -Two qubit gate: ~ 10ms
  - z^1 z^2 interaction
- -T2 ~ 1s
- -T1 ~ 5-30s
- - $=e^{-}$ H ~ 1- H

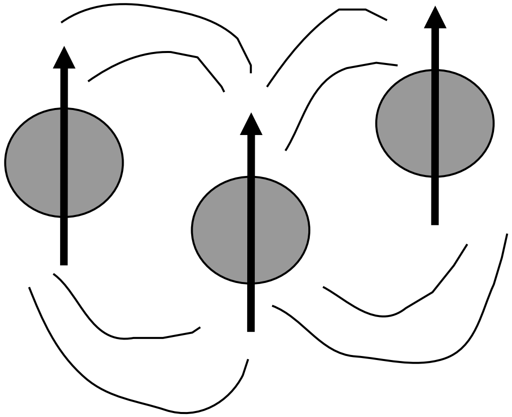


Bruker DRX-500

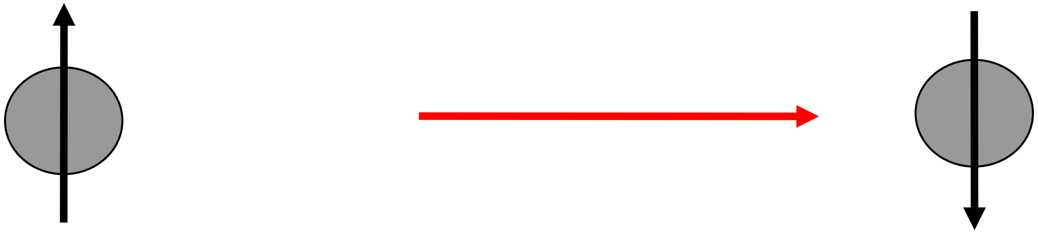
NMR quantum computer



nuclear spin/
magnetic moment



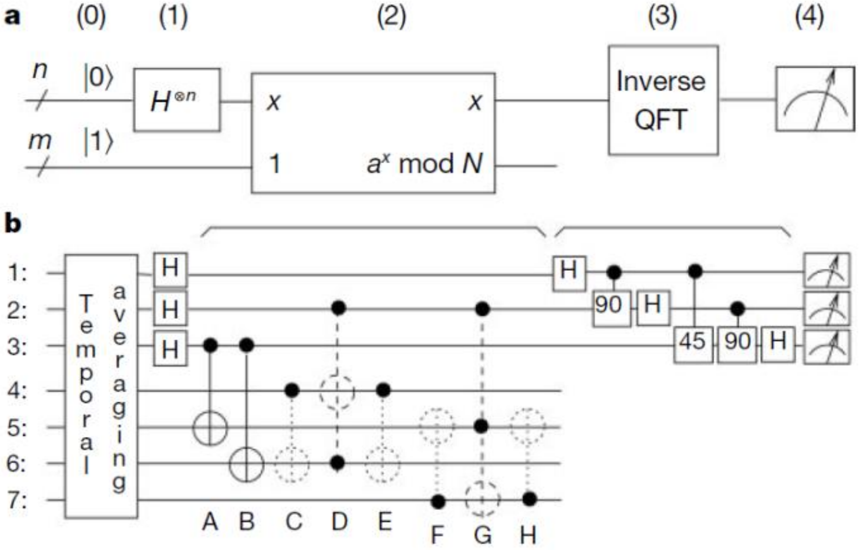
EM field

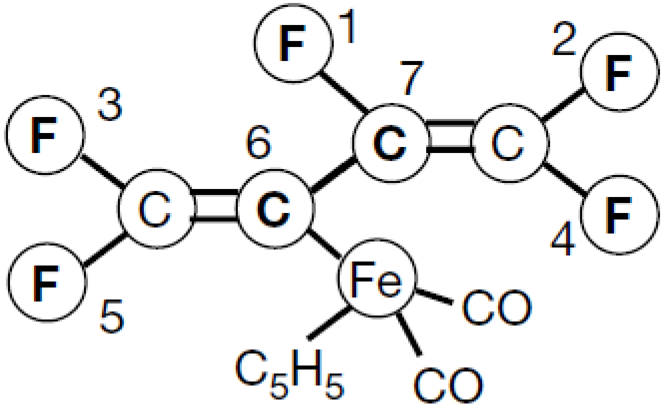


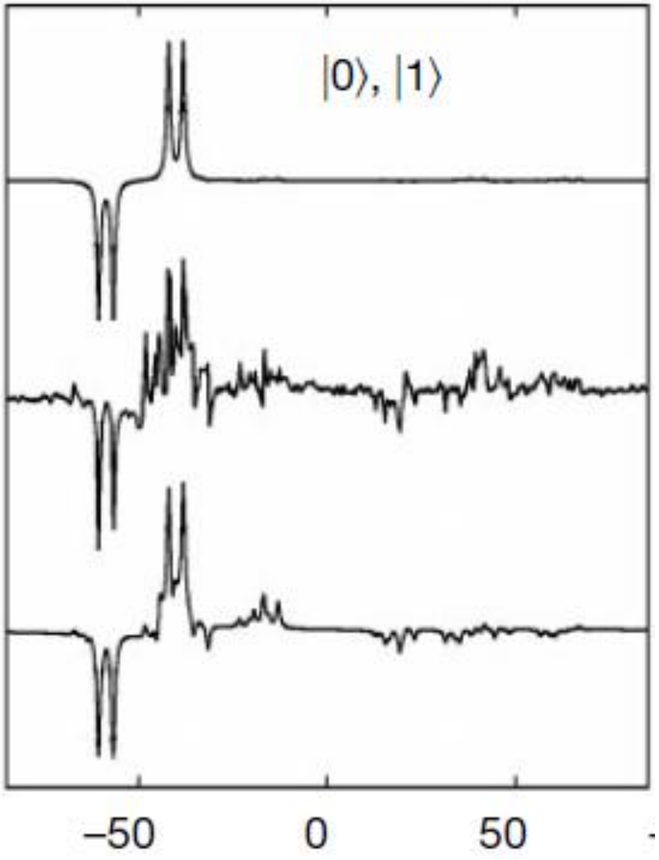
resonance frequency depends on interactions with nearby nuclei

spin flips for a well-defined resonant frequency

Shor’s algorithm on an NMR QC

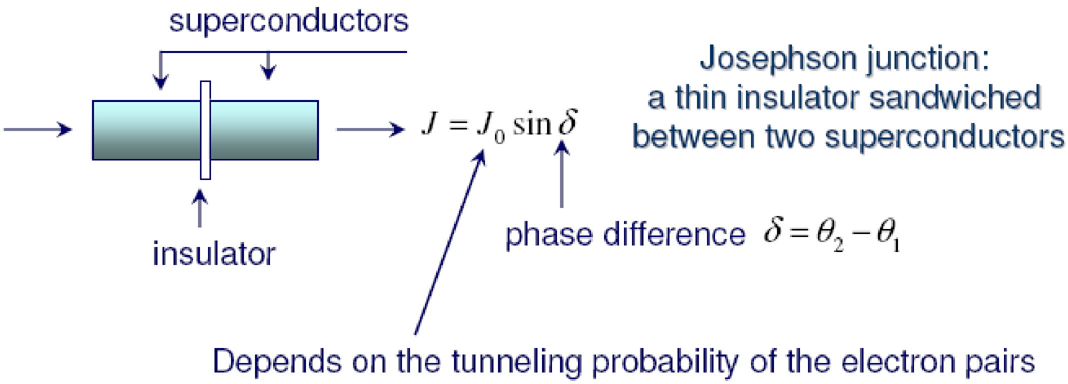






NATURE | VOL 414 | 20/27 DECEMBER 2001 | www.nature.com

Solid state quantum computers



superconductors

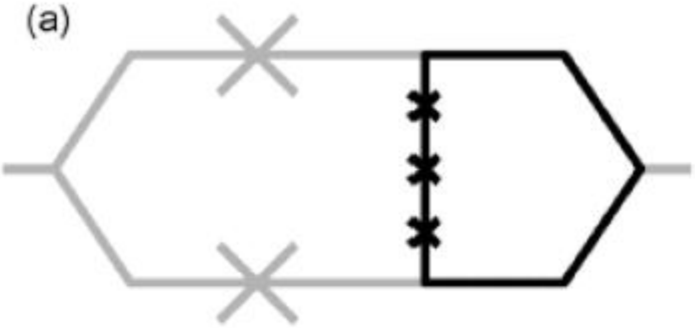
insulator

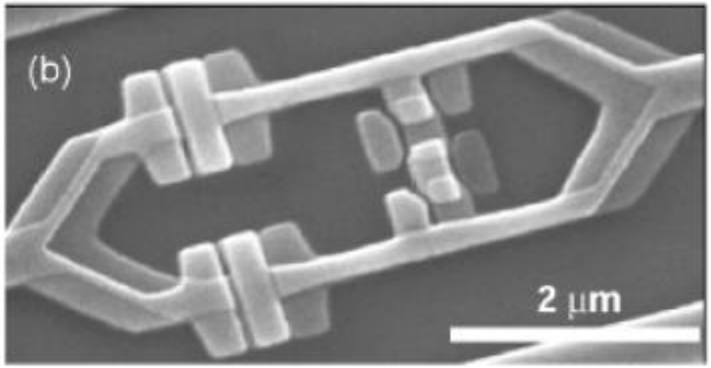
$J = J_0 \sin\delta$

Josephson junction:
a thin insulator sandwiched
between two superconductors

phase difference $\delta = \theta_2 - \theta_1$

Depends on the tunneling probability of the electron pairs





- can exploit current technology (lithography)
- easy to scale
- problem: coherence times

Ion trap quantum computers

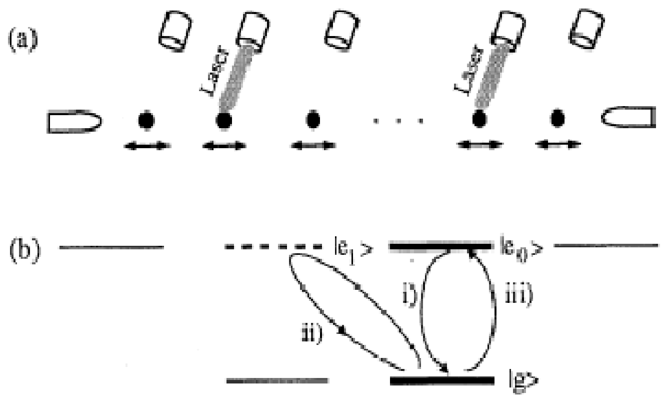


FIG. 1. (a) N ions in a linear trap interacting with N different laser beams; (b) atomic level scheme.

In this Letter we show that a set of N cold ions interacting with laser light and moving in a linear trap [7] provides a realistic physical system to implement a quantum computer. The distinctive features of this system are (i) it allows the implementation of n-bit quantum gates between any set of (not necessarily neighboring) ions, (ii) decoherence can be made negligible during the whole computation, and (iii) the final readout can be performed with unit efficiency.

Phys. Rev. Lett. 74, 4091 (1995)

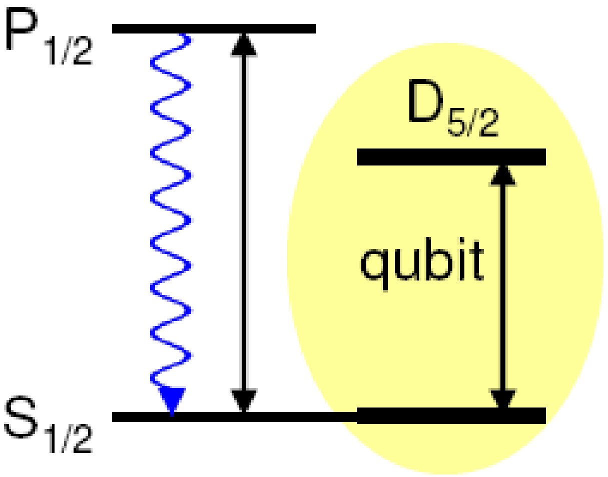
Ion trap quantum computers

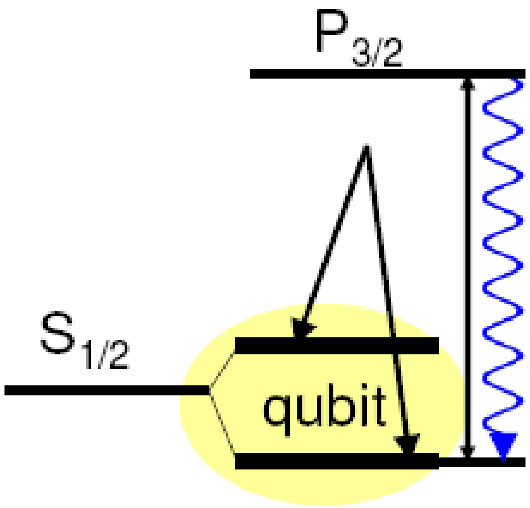
- optical transitions

Ca^+, Sr^+, Ba^+, Ra^+, Yb^+, Hg^+ etc.

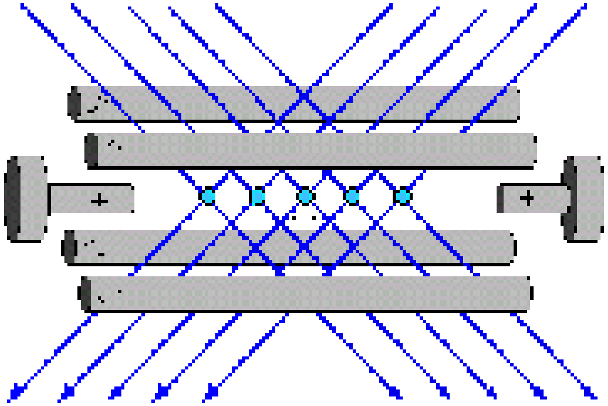
- microwave transitions

$^{9}\mathrm{Be}^+$, $^{25}\mathrm{Mg}^+$, $^{43}\mathrm{Ca}^+$, $^{87}\mathrm{Sr}^+$, $^{137}\mathrm{Ba}^+$, $^{111}\mathrm{Cd}^+$, $^{171}\mathrm{Yb}^+$

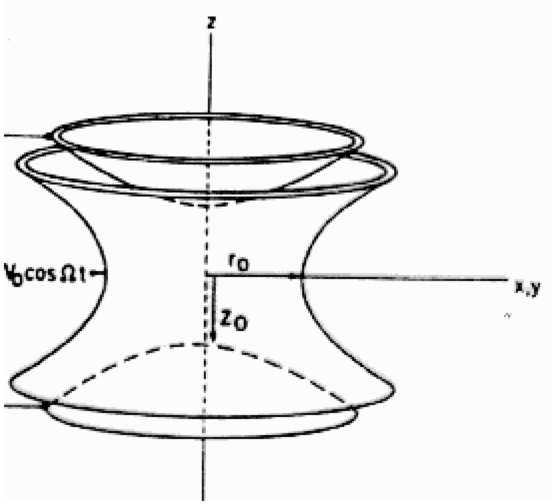


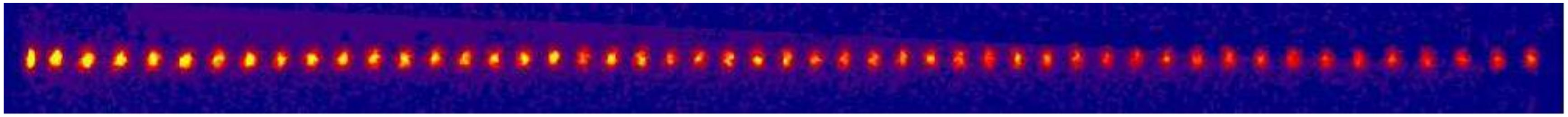


Ion trap quantum computers



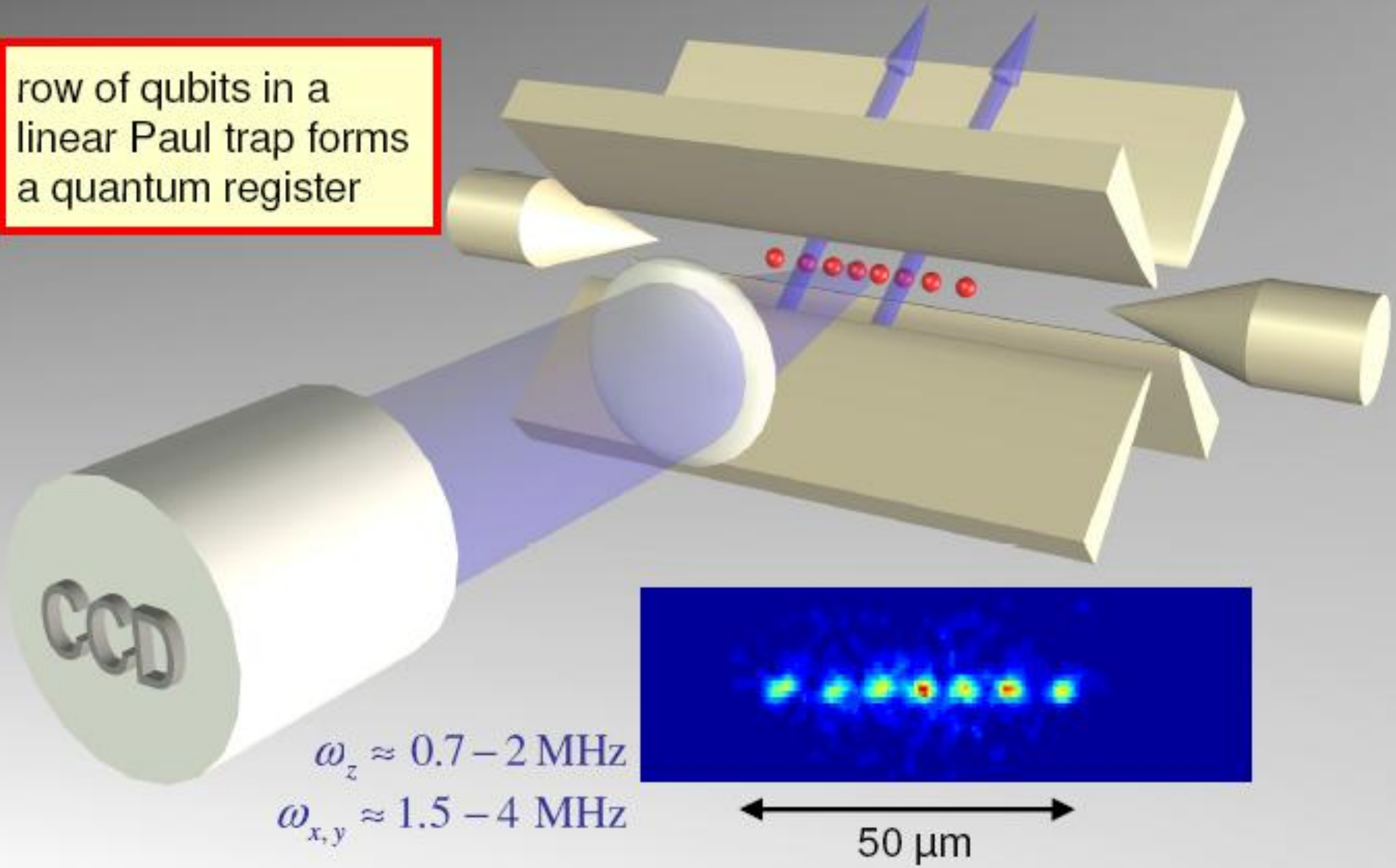
Paul traps





String of Ca+ ions in linear Paul trap

row of qubits in a linear Paul trap forms a quantum register

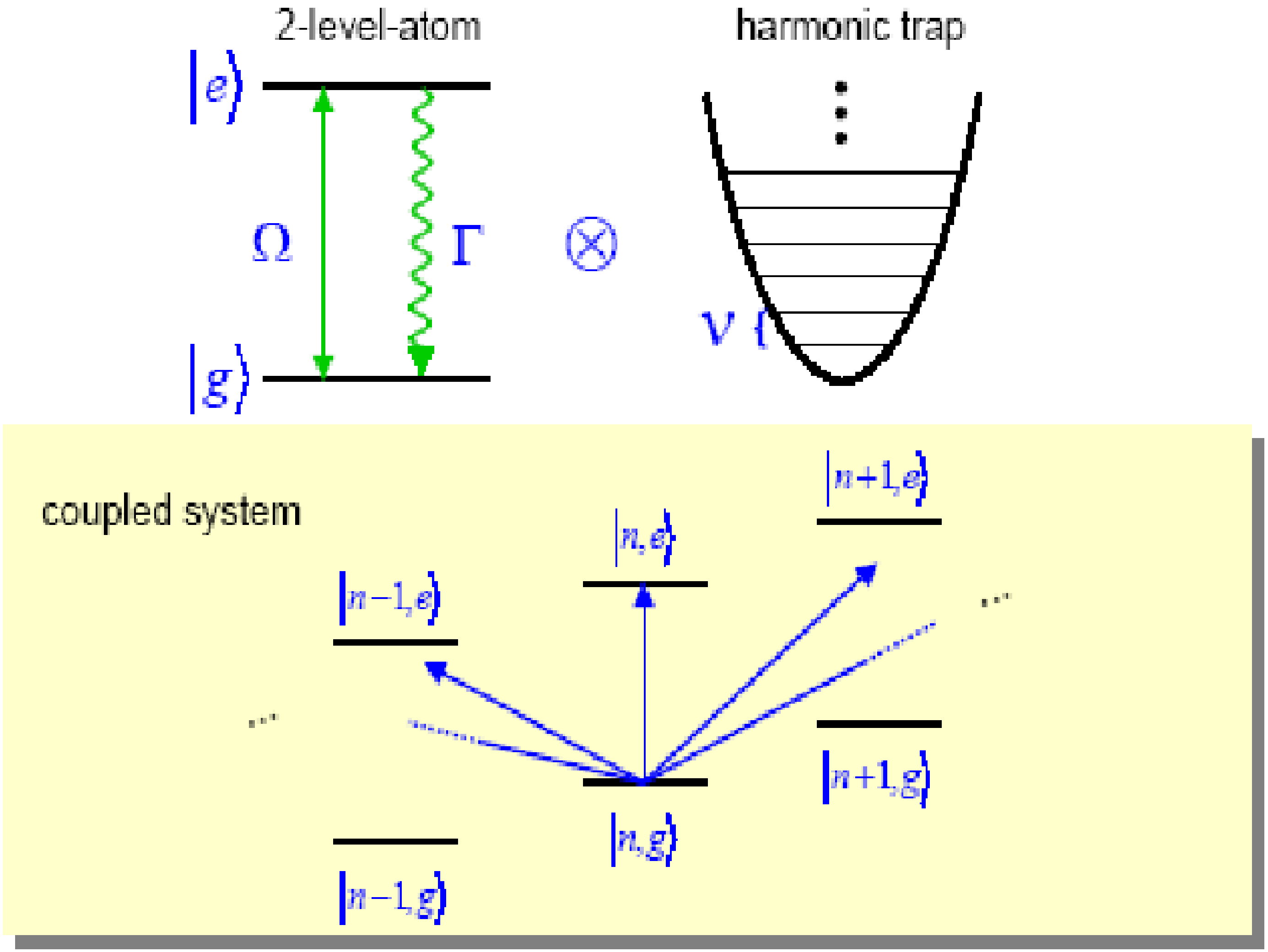


$\omega_z \approx 0.7 - 2\,\text{MHz}$

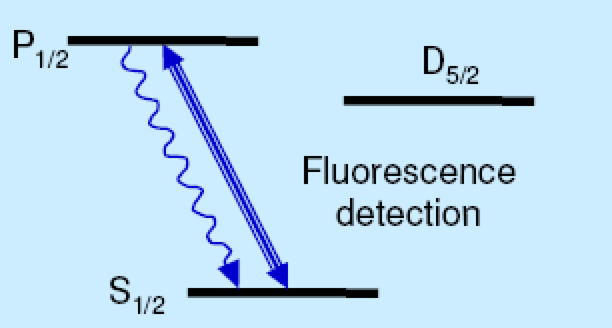
$\omega_{x,y} \approx 1.5 - 4\ \text{MHz}$

50 µm

Ion trap quantum computers



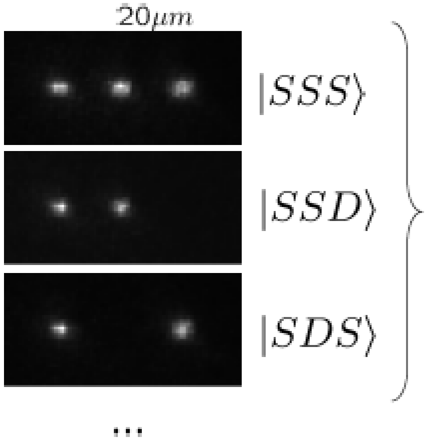
Ion trap quantum computers



1. Initialization in a pure quantum state: Laser sideband cooling
2. Quantum state manipulation on $S_{1/2} – D_{5/2}$ transition
3. **Quantum state measurement by fluorescence detection**

Multiple ions:

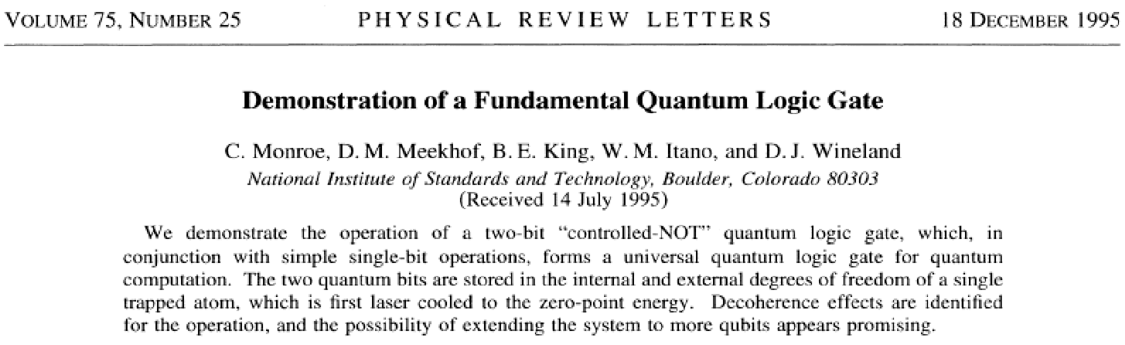
Spatially resolved detection with CCD camera:



50 experiments / s

Repeat experiments 100-200 times

Ion trap quantum computers



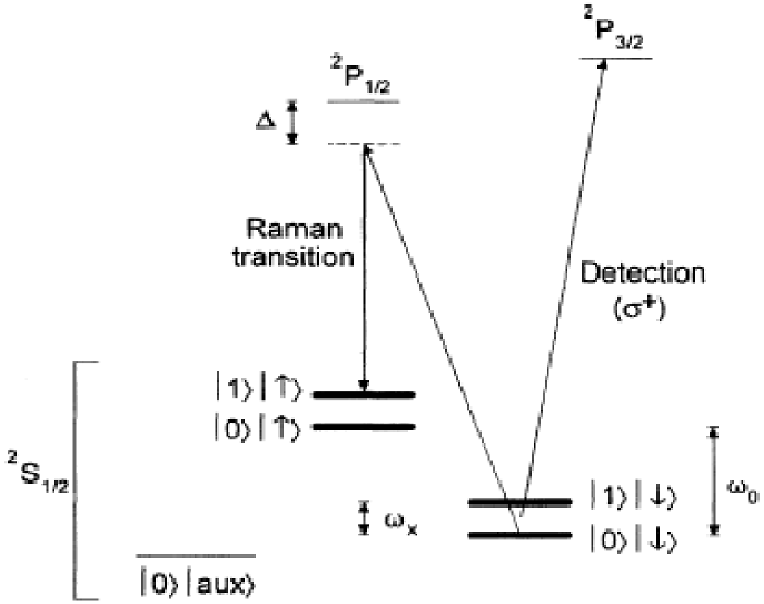
VOLUME 75, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1995

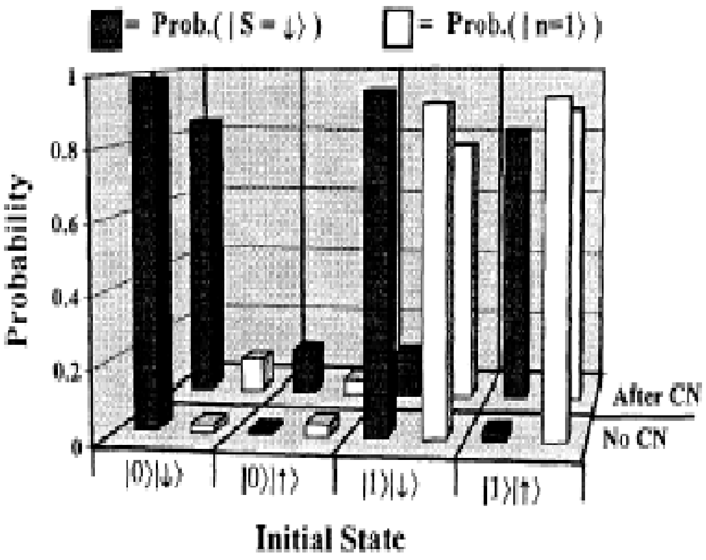
Demonstration of a Fundamental Quantum Logic Gate

C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland
National Institute of Standards and Technology, Boulder, Colorado 80303

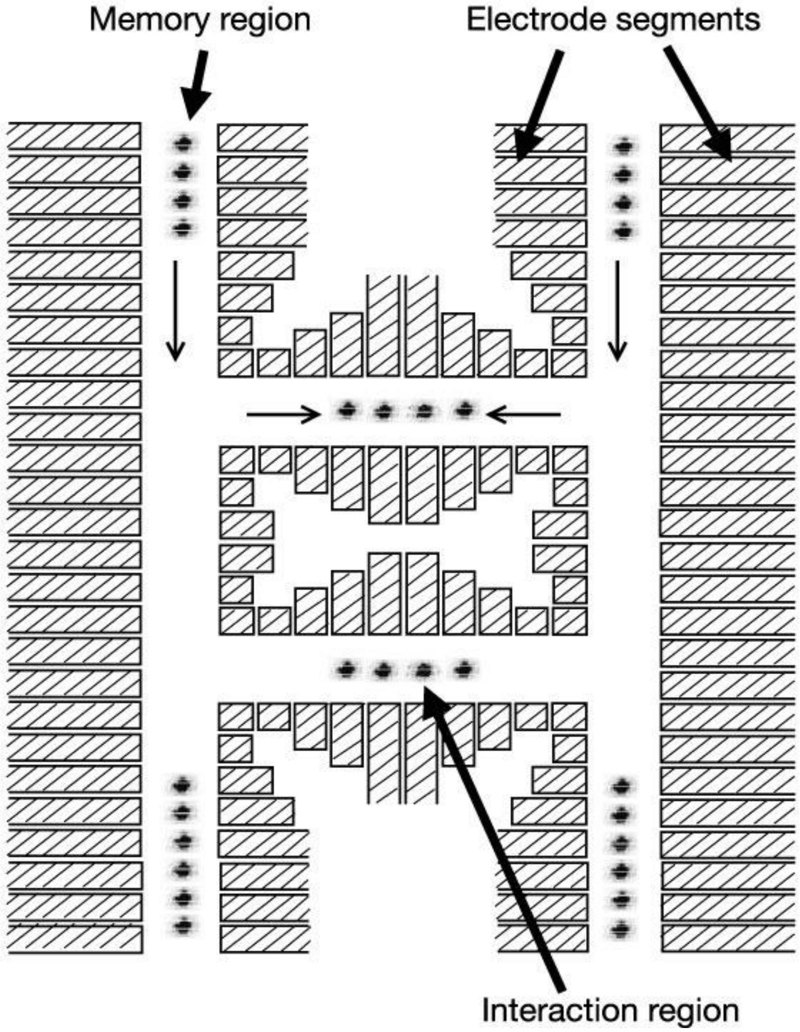
(Received 14 July 1995)

We demonstrate the operation of a two-bit "controlled-NOT" quantum logic gate, which, in conjunction with simple single-bit operations, forms a universal quantum logic gate for quantum computation. The two quantum bits are stored in the internal and external degrees of freedom of a single trapped atom, which is first laser cooled to the zero-point energy. Decoherence effects are identified for the operation, and the possibility of extending the system to more qubits appears promising.





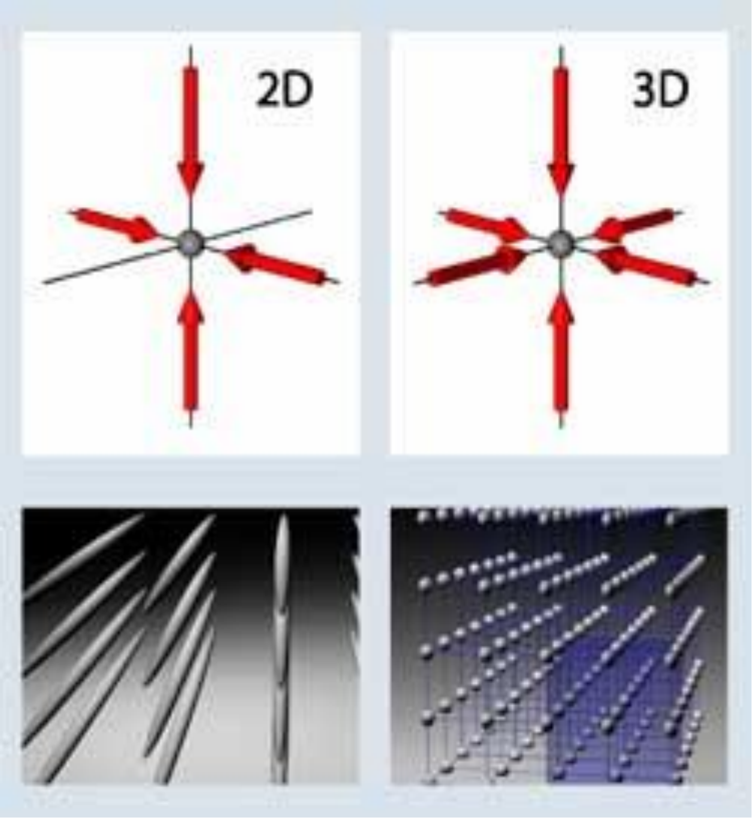
Multi-region ion traps



Nature **417**, 709

Neutral atom quantum computers

Optical lattices



- easy to trap an manipulate atoms, geometry can be freely chosen

- neutral atoms interact very weakly with the environment – long coherence times

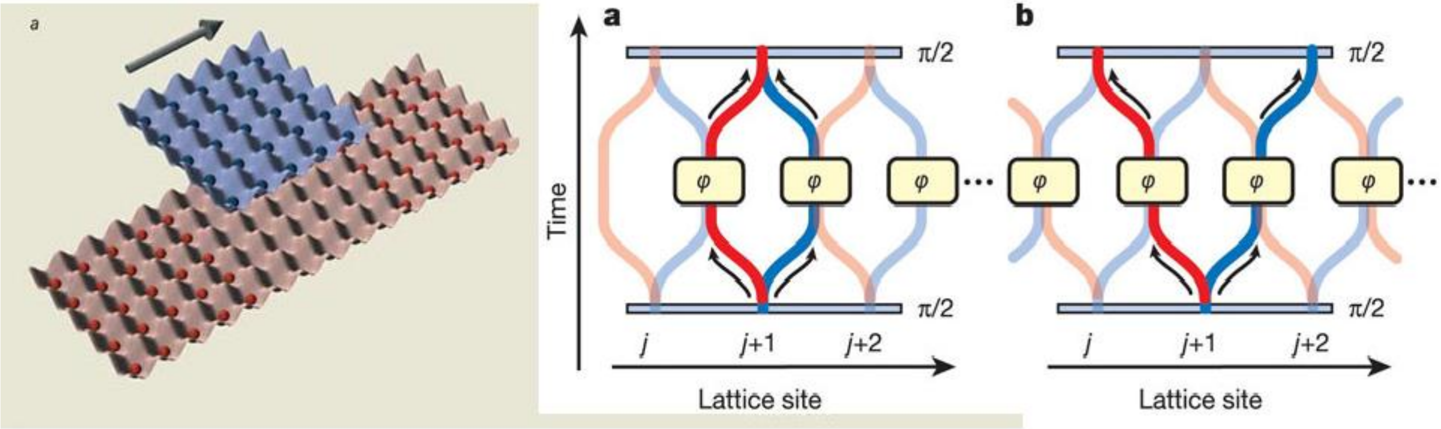
- but: not easy to address single atoms (although lots of progress recently!)

- atom-atom interactions are weak, so gate times are long (you can guess where this is going…!)

Neutral atom quantum computers

Collisional phase gate

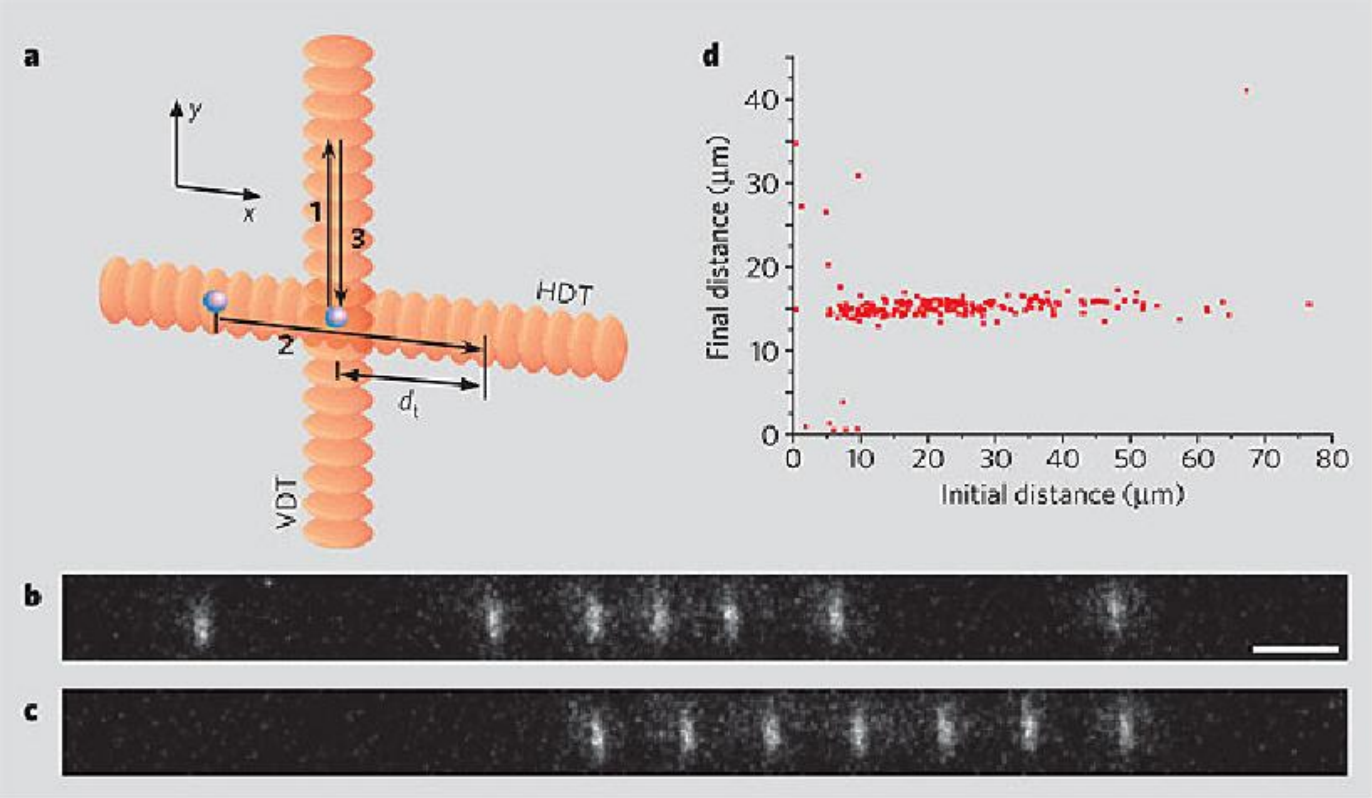
Entanglement is generated by coherently splitting the atomic wavefunction and them making the atoms in neigbouring sites collide by shifting the two lattices



Nature **425**, 937

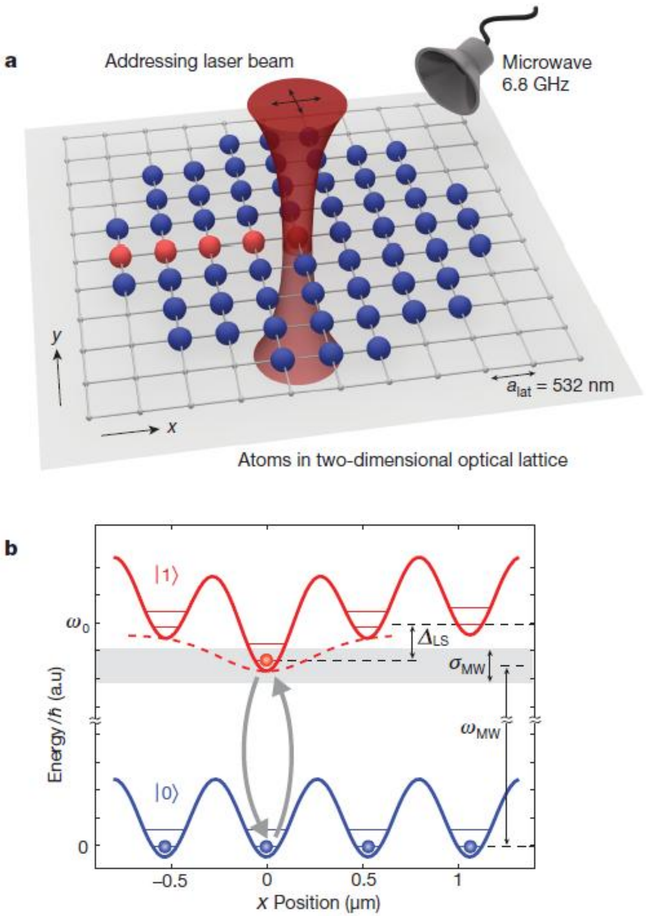
Neutral atom quantum computers

Atom conveyor belt



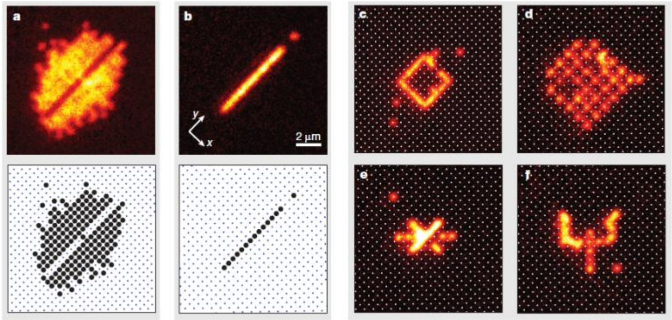
Miroshnychenko et al., Nature **442**, 151 (2006)

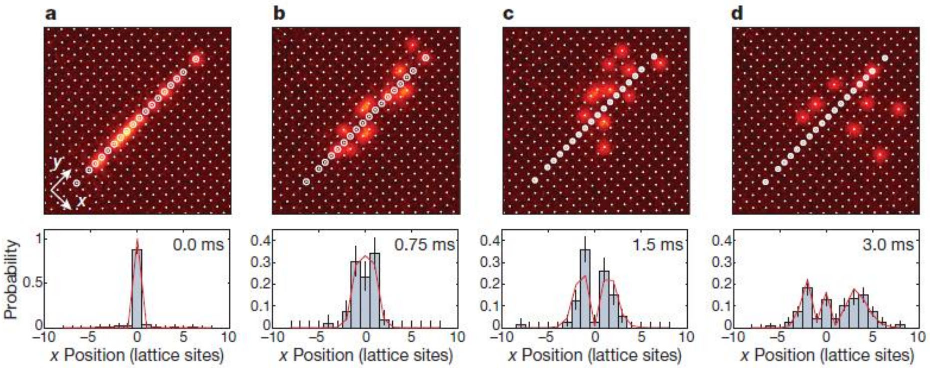
Neutral atom quantum computers



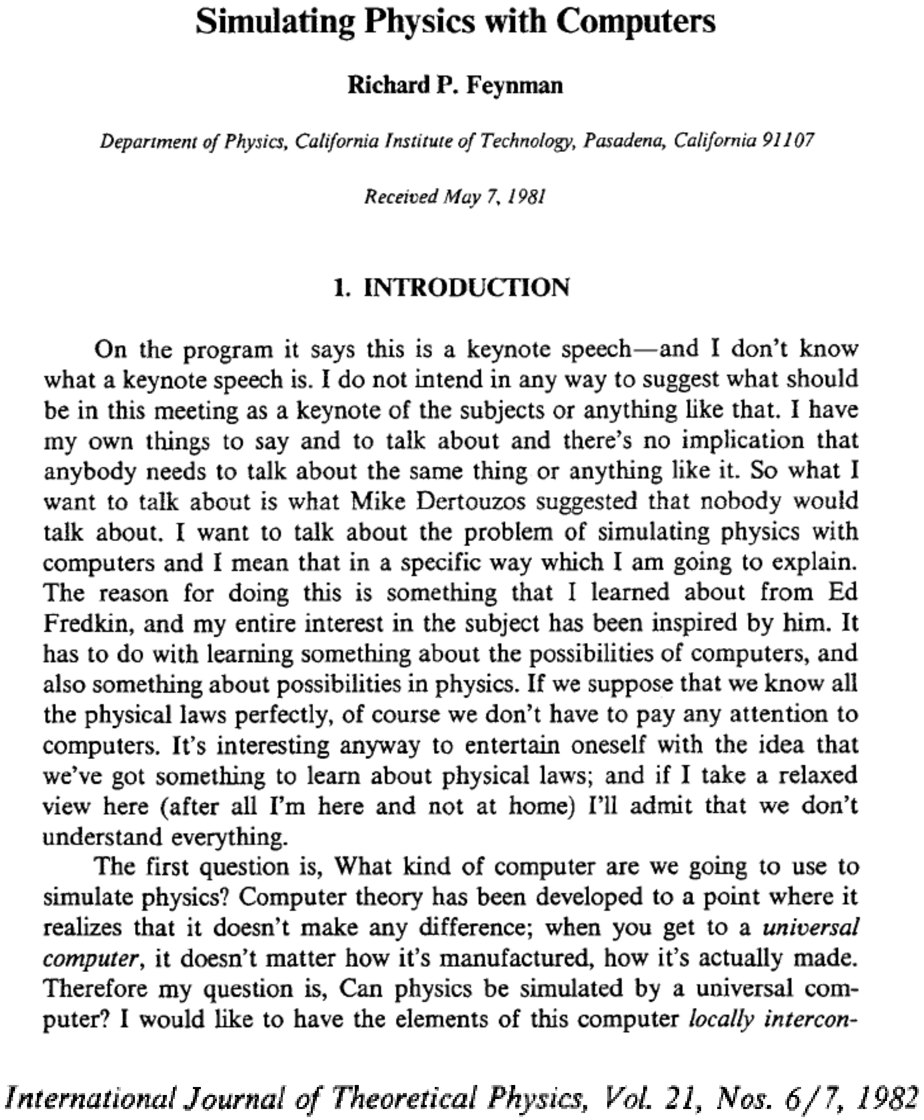
Single-spin addressing in an atomic Mott insulator

Christof Weitenberg[1], Manuel Endres[1], Jacob F. Sherson[1]†, Marc Cheneau[1], Peter Schauß[1], Takeshi Fukuhara[1], Immanuel Bloch[1,2] & Stefan Kuhr[1]





Quantum Simulators



Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

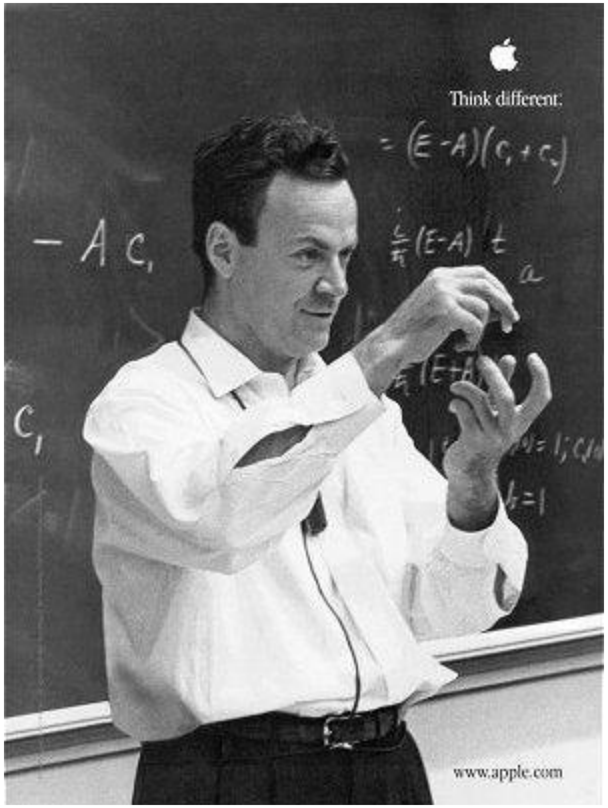
Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don't have to pay any attention to computers. It's interesting anyway to entertain oneself with the idea that we've got something to learn about physical laws; and if I take a relaxed view here (after all I'm here and not at home) I'll admit that we don't understand everything.

The first question is, What kind of computer are we going to use to simulate physics? Computer theory has been developed to a point where it realizes that it doesn't make any difference; when you get to a *universal computer*, it doesn't matter how it's manufactured, how it's actually made. Therefore my question is, Can physics be simulated by a universal computer? I would like to have the elements of this computer *locally intercon-*

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982



Quantum simulators

Quantum Computer

- multi-purpose
- quantum gates
- algorithms

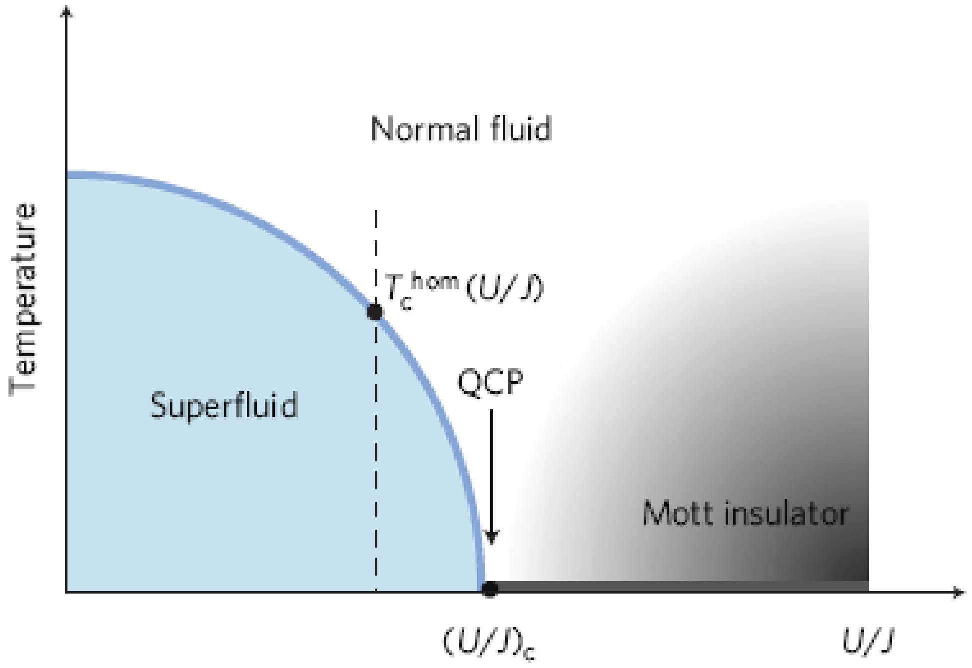
Quantum Simulator

- single-purpose
- implements a Hamiltonian
- computer calculation intractable
- analogue or digital

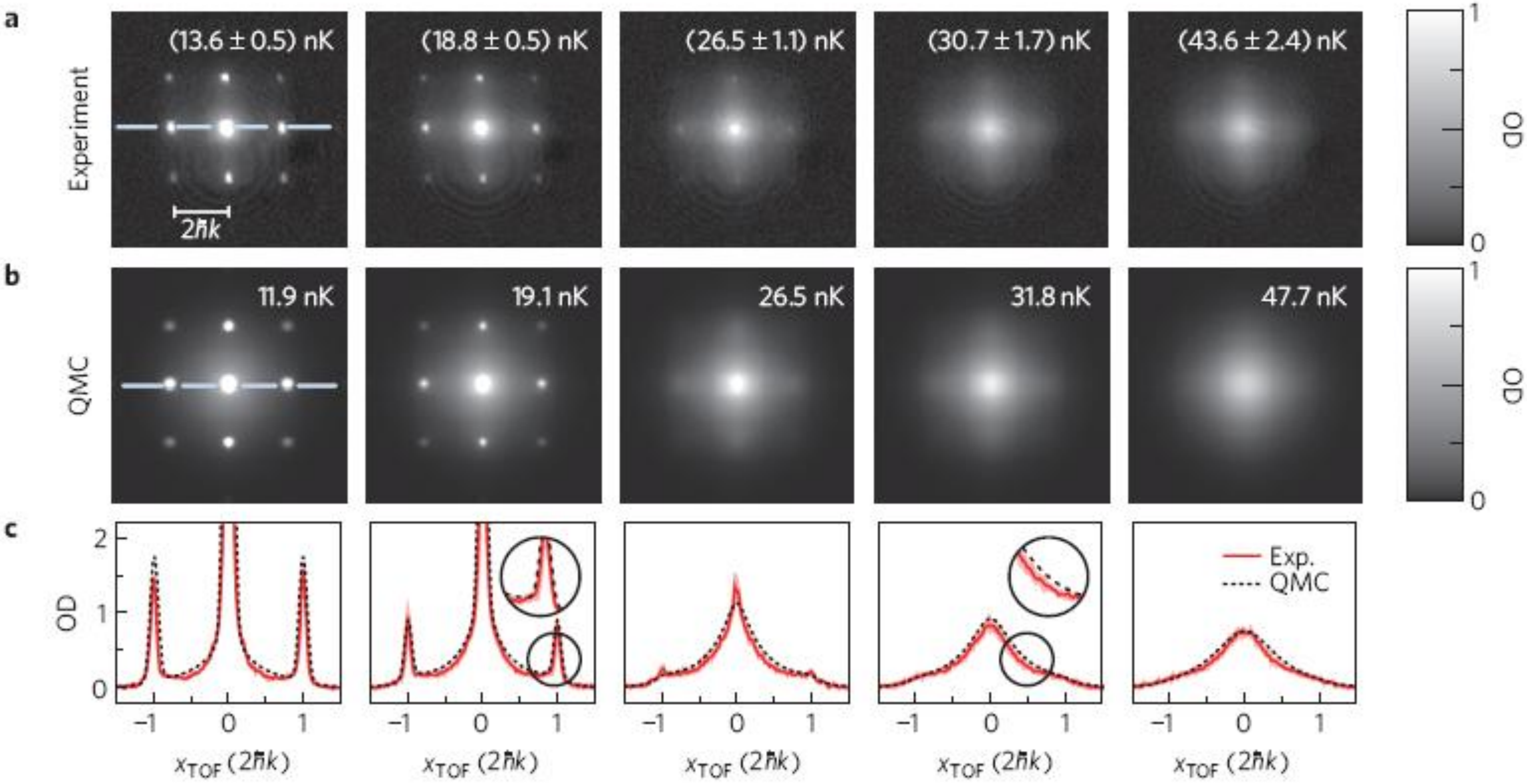
Quantum simulators

Finite-temperature Mott insulator transition

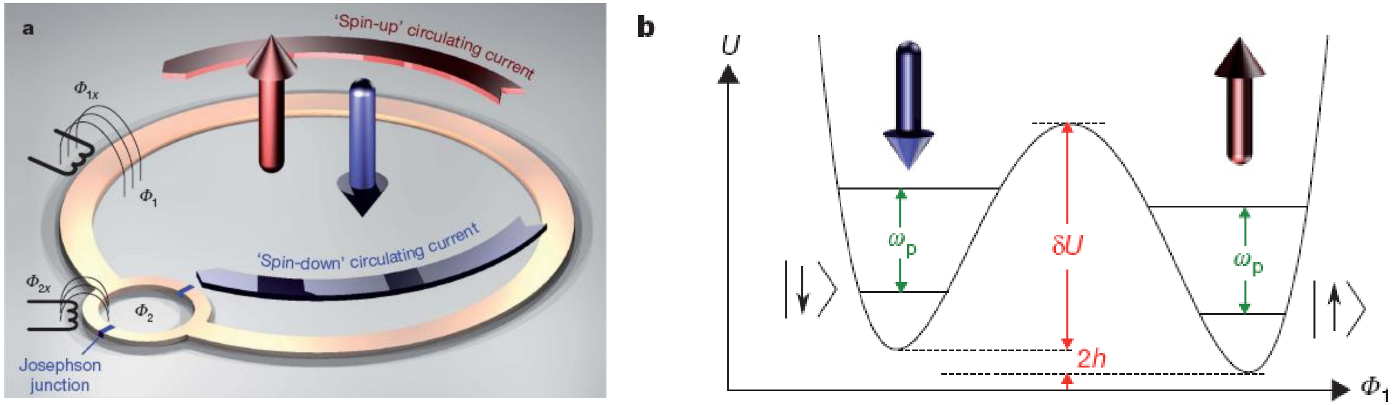
Use Quantum Monte Carlo simulation to “benchmark” the quantum simulator

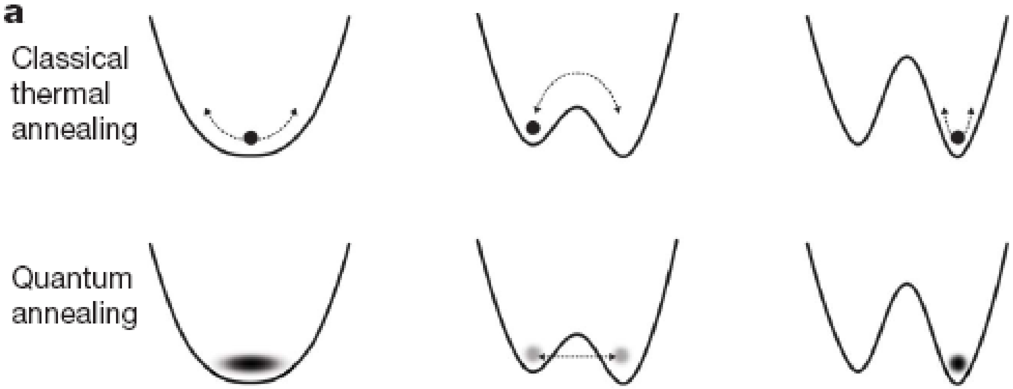


Quantum simulators

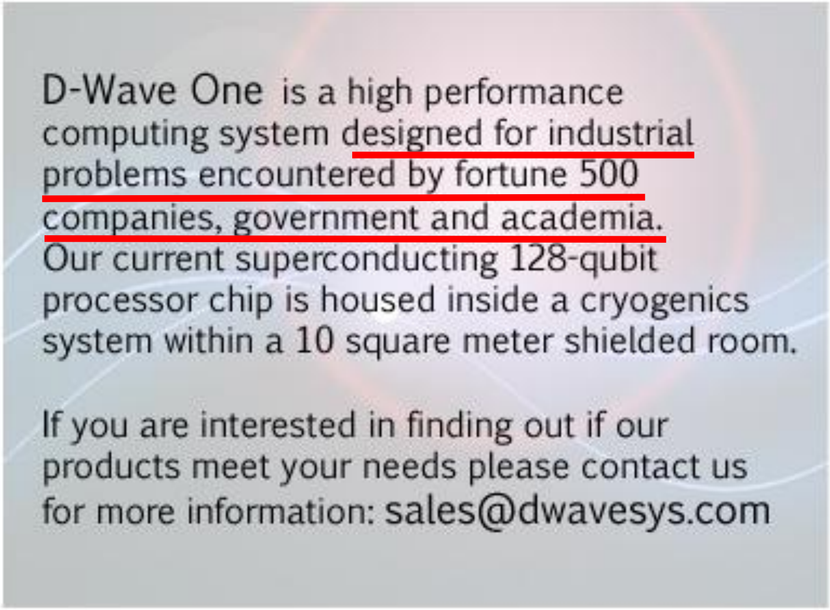


Quantum computing by “annealing”





D-Wave: The first commercial quantum computer?



D-Wave One is a high performance computing system designed for industrial problems encountered by fortune 500 companies, government and academia. Our current superconducting 128-qubit processor chip is housed inside a cryogenics system within a 10 square meter shielded room.

If you are interested in finding out if our products meet your needs please contact us for more information: sales@dwavesys.com

http://www.dwavesys.com/

D-Wave uses quantum method to solve protein folding problem

August 21, 2012 by Lisa Zyga report

D-Wave One and CEO Geordie Rose. Image credit: D-Wave Systems, Inc.

Enlarge

(Phys.org) -- While there has been some skepticism as to whether the Canadian company D-Wave's quantum computing system, the D-Wave One, truly involves quantum computing, the company is intent on proving that the system is both a quantum device as well as a useful one. In a new study, D-Wave CEO Geordie Rose and other D-Wave researchers have teamed up with Harvard quantum physicist Alán Aspuru-Guzik and post-doc Alejandro Perdomo-Ortiz to demonstrate that the D-Wave One system can solve the challenging task of finding the lowest-energy configuration of a folded protein.

The study, "Finding low-energy conformations of lattice protein models by quantum annealing," is published in a recent issue of Nature's *Scientific Reports*.

The computer used quantum annealing to find the lowest-energy protein configuration by solving for the configuration as an optimization problem, where the optimal state was the lowest-energy state. Proteins can be folded in a large number of ways because they're made up of many chains of amino acids. Yet somehow, proteins almost always manage to fold themselves in the correct configuration (when they don't fold correctly, they can cause misfolded-protein diseases such as Alzheimer's, Huntington's, and Parkinson's). Scientists think that proteins fold themselves correctly because the correct configuration is also the state of lowest energy, the state at which the protein becomes stable.

In quantum annealing, the system starts by randomly picking a starting state, and then selecting random neighbor states to see if they have lower energies than the starting state. If they do, the computer replaces the original state with the lower-energy state.

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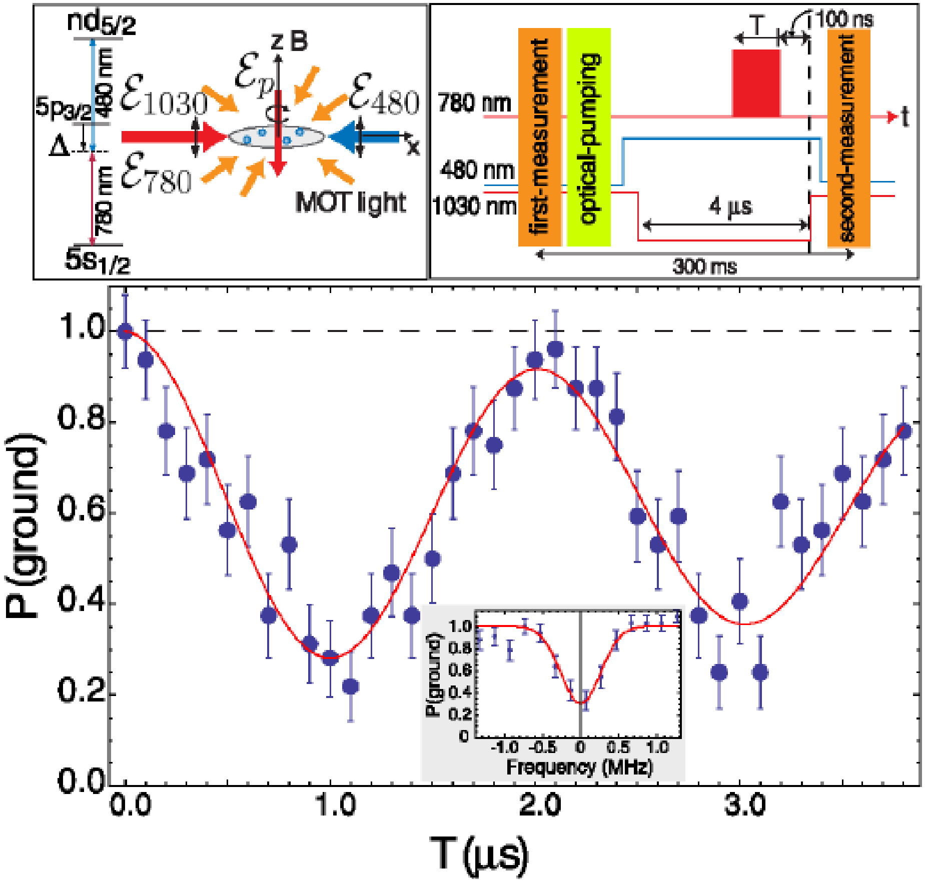
Lecture 2: Quantum information with Rydberg atoms: The ingredients

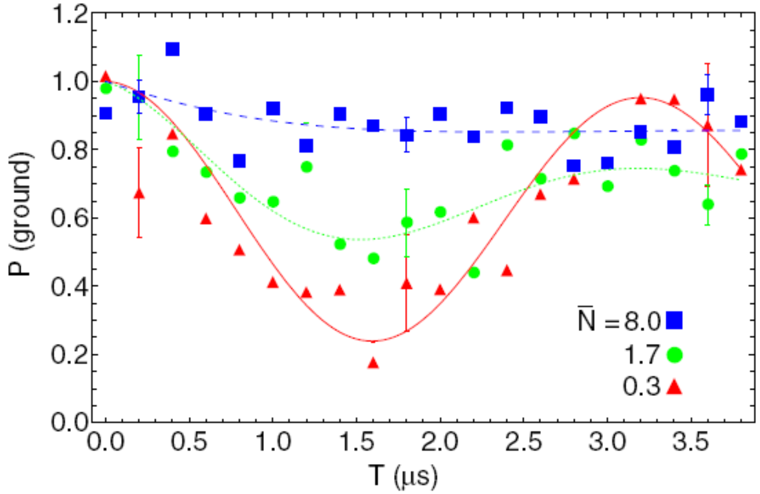
- Quantum control of a single Rydberg excitation: Rabi oscillations

- Interactions between Rydberg atoms: The dipole blockade

- Quantum control of collective excitations

Rabi oscillations

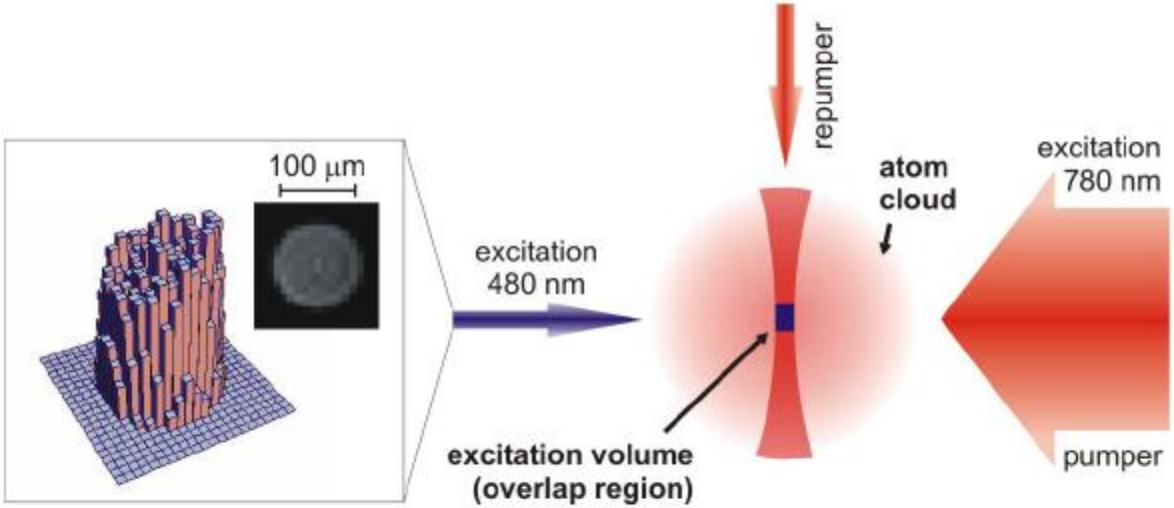


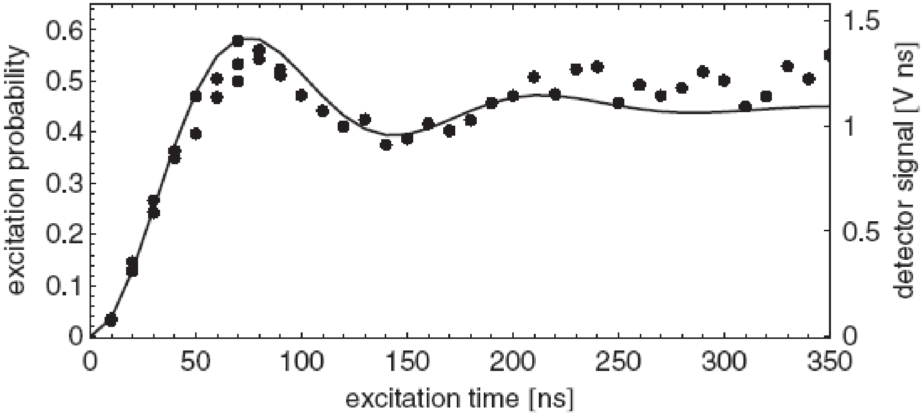


- single atoms trapped in FORT @ 1030 nm
- optically pumped into |f=2,m$_f$=2>
- excite with FORT off, then turn FORT back on and measure ground state population
- presence of further atoms leads to dephasing (but interactions not strong enough to cause collective excitations)

PRL **100**, 113003 (2008)

Rabi oscillations

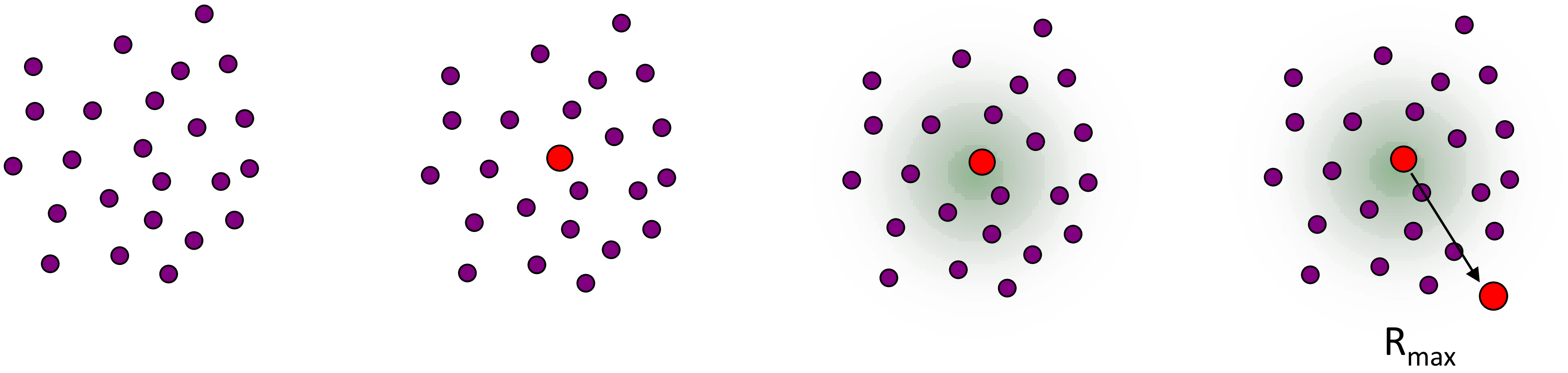


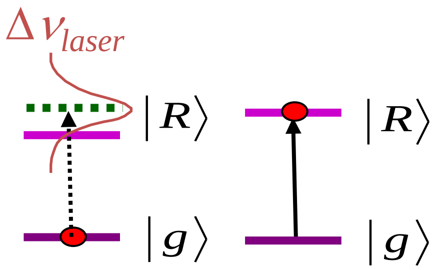


- simultaneous Rabi oscillations of around 100 atoms
- flat-top beam ensures homogeneous Rabi frequency
- damping of oscillations due to admixture of intermediate state, laser linewidth and intensity distribution

PRL **100**, 253001 (2008)

The dipole blockade

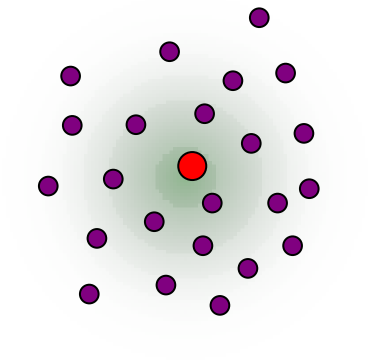




$$V = C_6 / R_{max}^6 \sim \Delta\nu_{laser}$$

Blockade radius up to tens of microns for our parameters

The dipole blockade

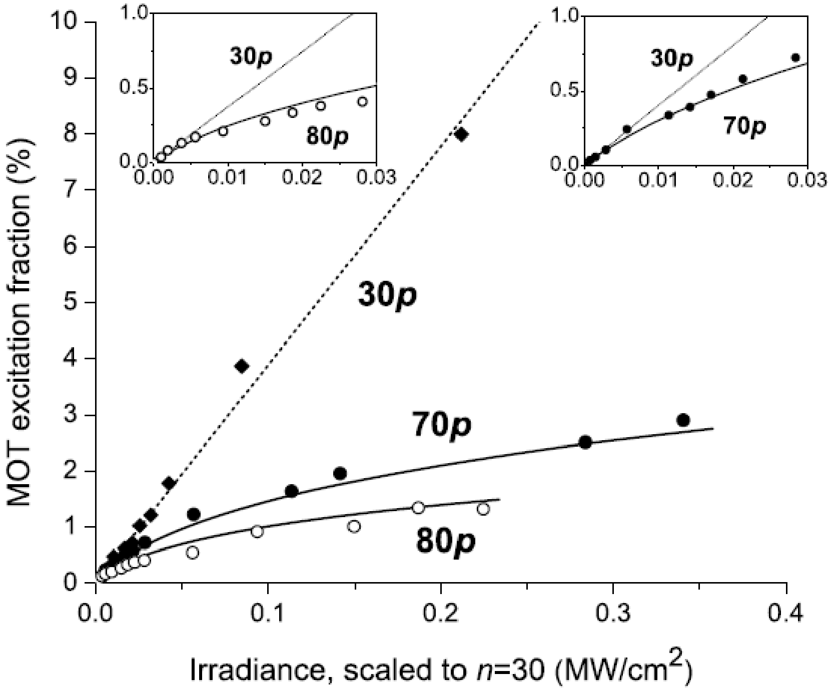


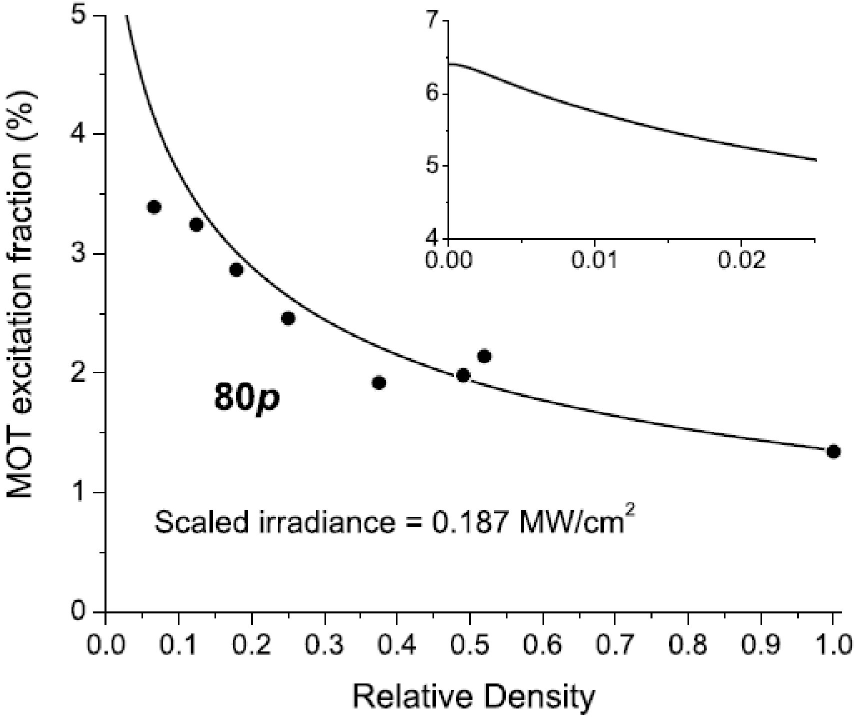
collective excitation (“super-atom”) with Rabi frequency

$$\Omega_{coll} = \sqrt{N}\Omega_0$$

$$\left|\Psi_{coll}\right\rangle = \frac{1}{\sqrt{N}}\left(\left|rgg\ldots g\right\rangle + \left|grg\ldots g\right\rangle + \ldots + \left|ggg\ldots r\right\rangle\right)$$

The dipole blockade

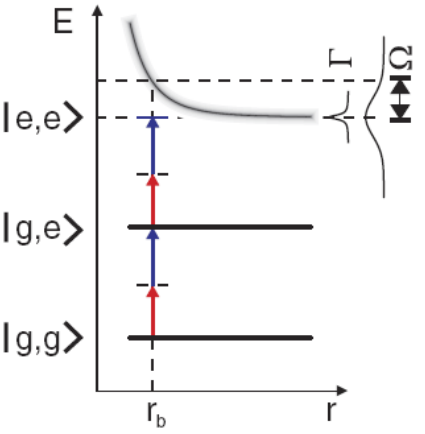


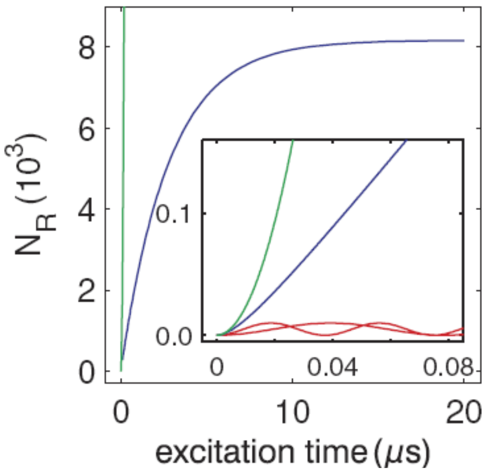


- single-step excitation of p-state using UV laser
- scaling data with $(30^*/n^*)^3$ (transition matrix element) reveals effect of blockade (inset in LH figure)
- blockade effect increases with density (=with decreasing inter-particle spacing)

VOLUME 93, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 6 AUGUST 2004

The dipole blockade



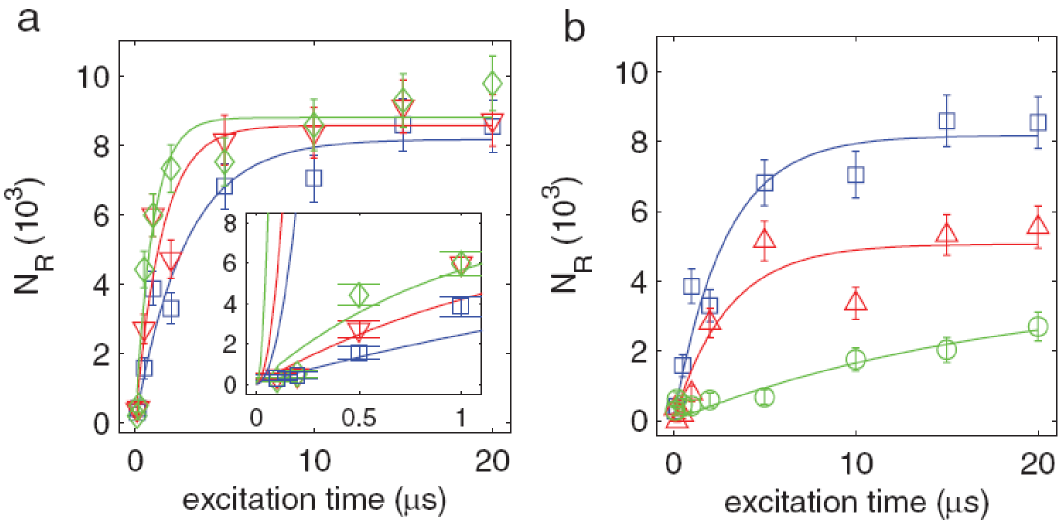


- strong blockade regime: N>>1 in a single blockade radius

- characteristic saturation of Rydberg number

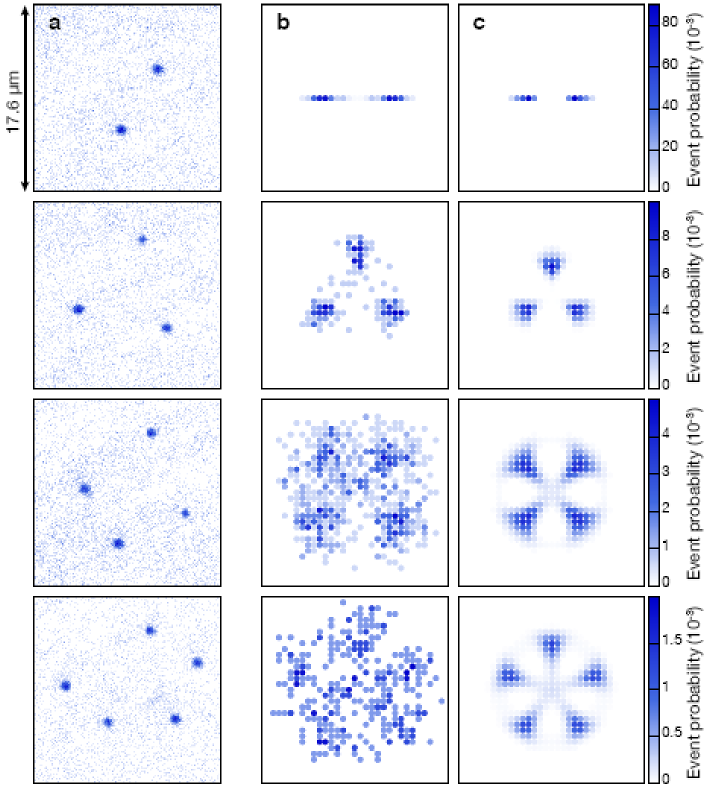
- scaling of excitation timescale with $\sqrt{N}$

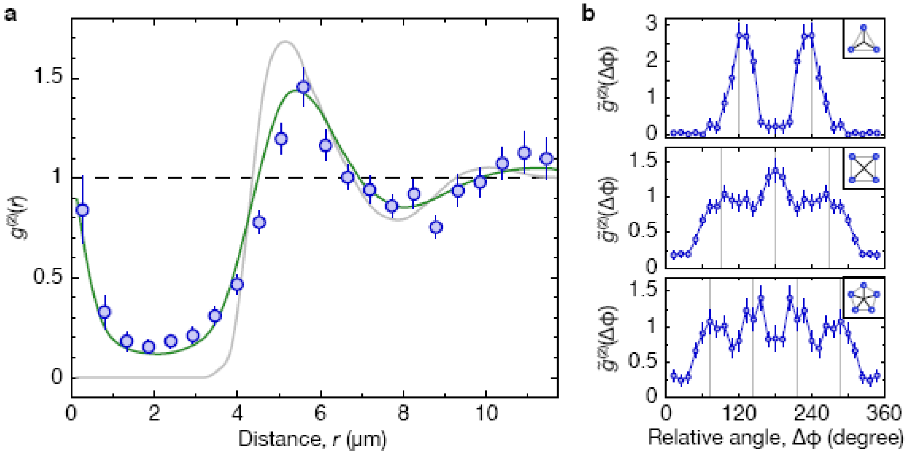
- observe universal scaling



PRL **99**, 163601 (2007)

The dipole blockade

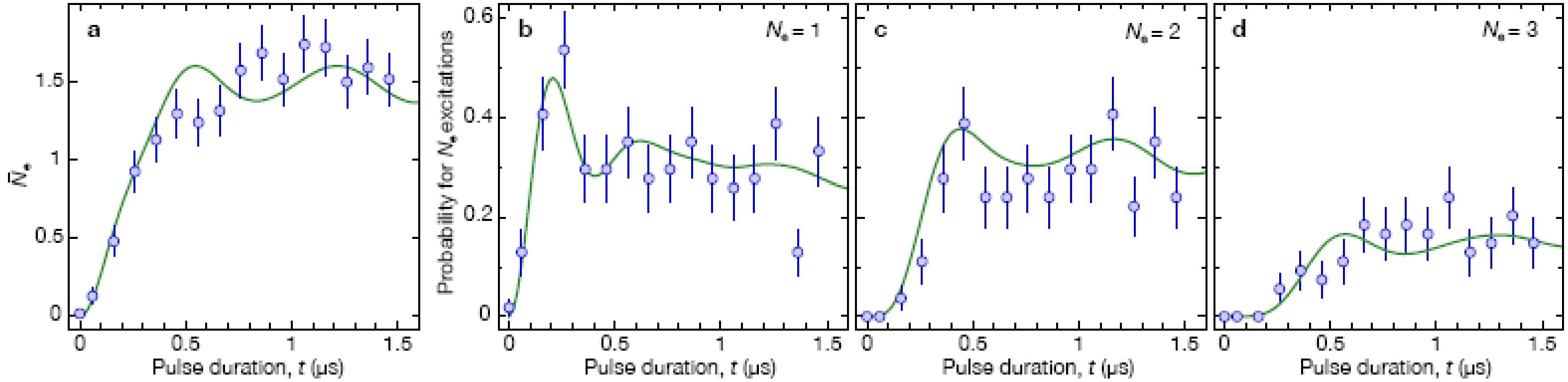


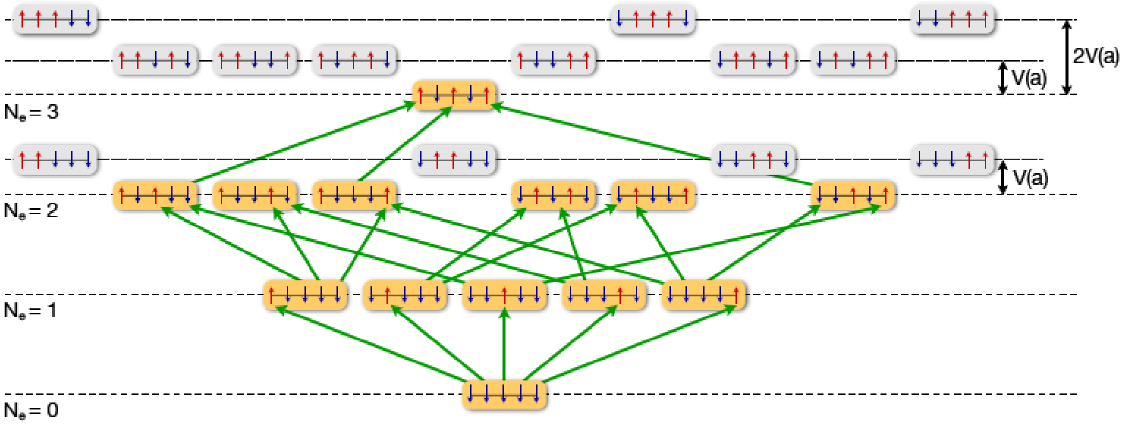


- in a 2D Mott insulator in an optical lattice, crystalline structures of Rydberg excitations are observed
- the inter-particle correlation function shows a clear suppression below the blockade radius

arXiv:1209.0944

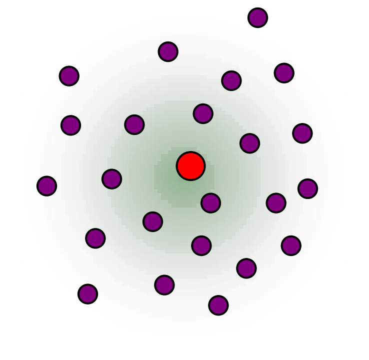
The dipole blockade





- dynamics reproduced by numerical model taking into account a limited number of possible excitations

The dipole blockade

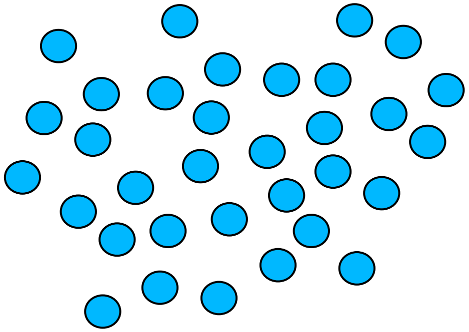


$$\left|\Psi_{coll}\right\rangle = \frac{1}{\sqrt{N}}\left(\left|egg....g\right\rangle + \left|geg....g\right\rangle + ... + \left|ggg....e\right\rangle\right)$$

Counting statistics:
Mandel Q-Parameter,
Sub-Poissonian counting statistics

1D excitation geometry:
number of Rydberg excitations as
a function of length of cloud

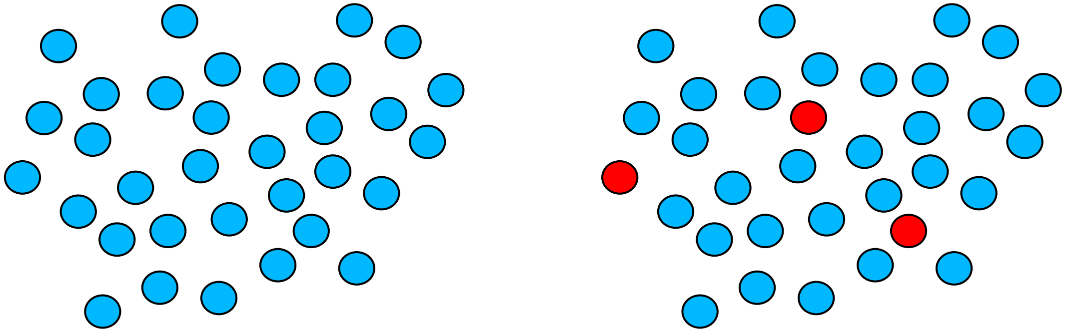
The dipole blockade



$$Q = \frac{\langle N_e^2 \rangle - \langle N_e \rangle^2}{\langle N_e \rangle} - 1$$

$Q = 0$: Poissonian counting statistics

The dipole blockade

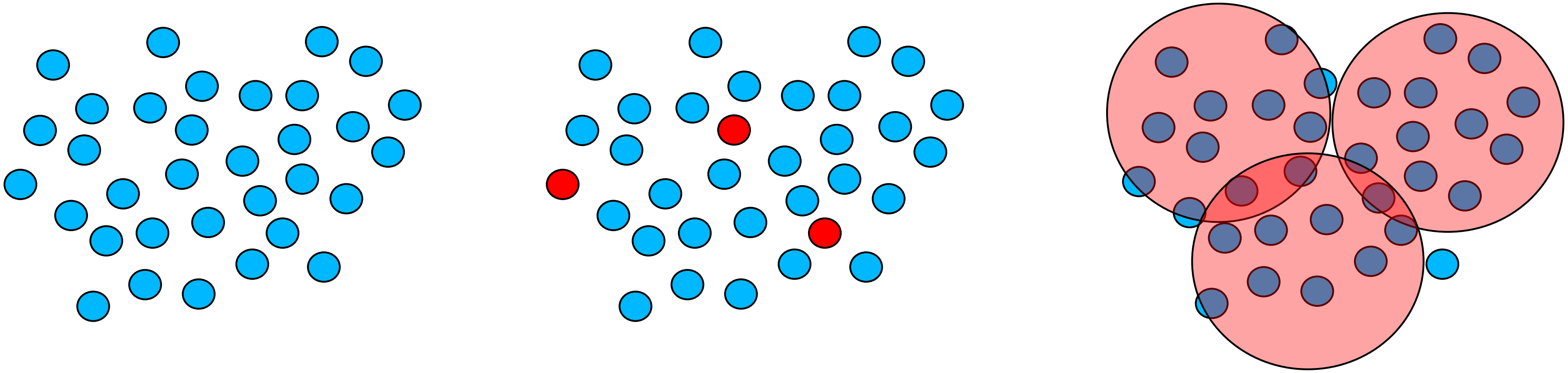


$$Q = \frac{\left\langle N_e^2 \right\rangle - \left\langle N_e \right\rangle^2}{\left\langle N_e \right\rangle} - 1$$

$$Q = -P_e \approx -0.1$$

$Q = 0$: Poissonian counting statistics

The dipole blockade



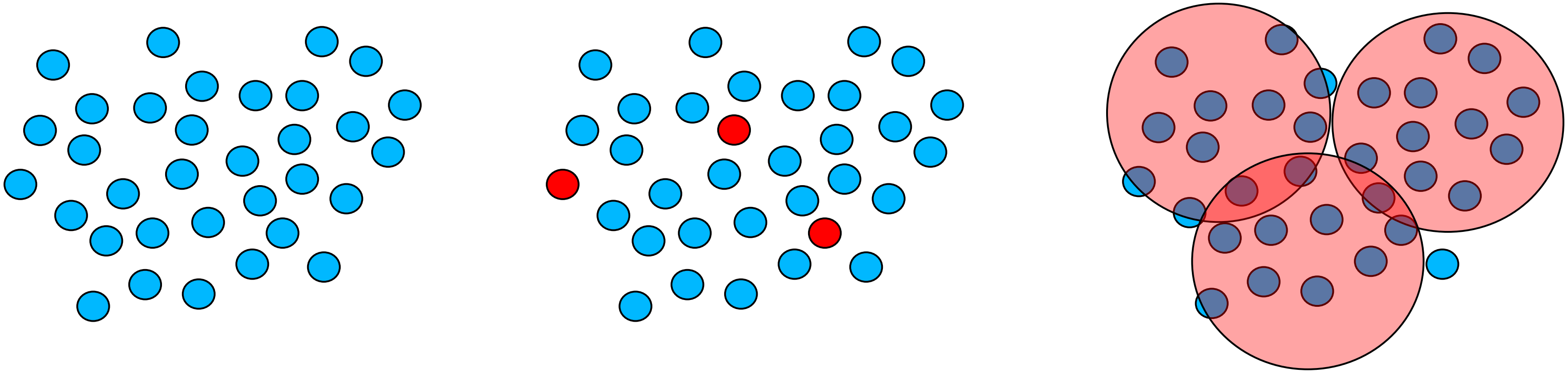
$$Q = \frac{\langle N_e^2 \rangle - \langle N_e \rangle^2}{\langle N_e \rangle} - 1$$

$$Q = -P_e \approx -0.1$$

$$Q = -P_e^{coll} \approx -1$$

$Q = 0$: Poissonian counting statistics

The dipole blockade



$$Q=\frac{\left\langle N_e^2\right\rangle-\left\langle N_e\right\rangle^2}{\left\langle N_e\right\rangle}-1$$

$$Q=-P_e\approx-0.1$$

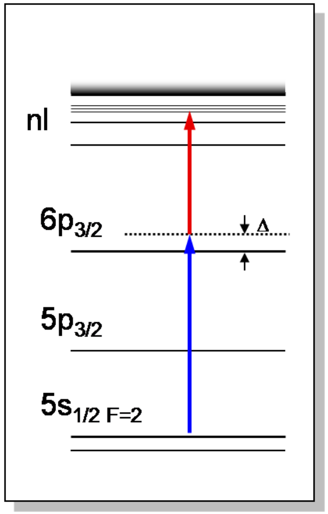
$$Q=-P_e^{coll}\approx-1$$

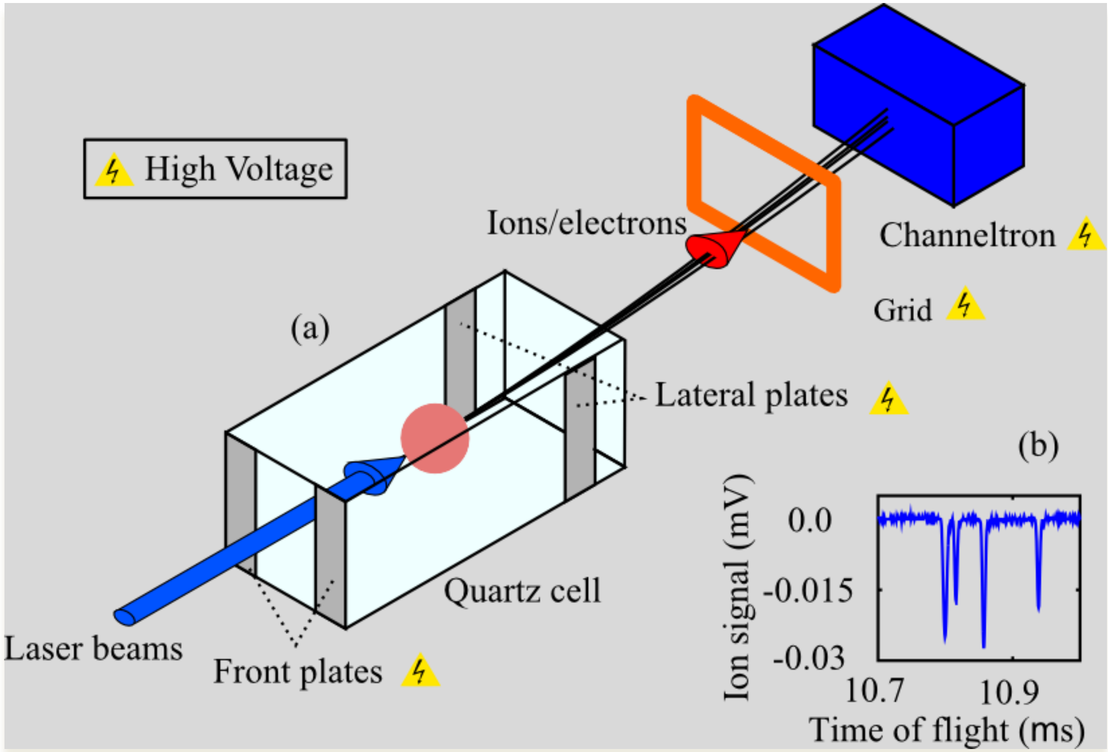
$Q=0$: Poissonian counting statistics

- in MOT, interparticle spacing around 2-5 microns; blockade radius 10 microns

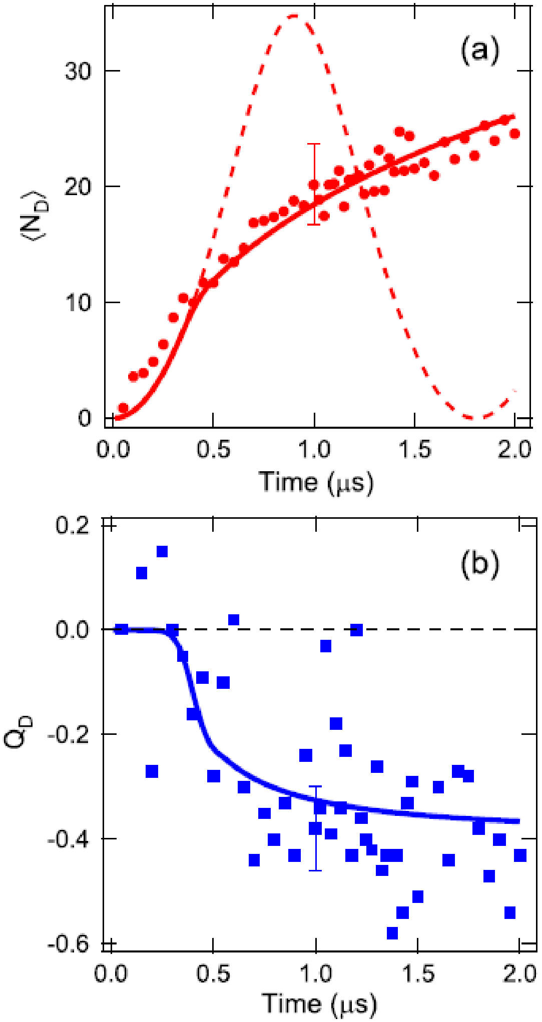
The dipole blockade

- Rb MOT; atom numbers between 10^3 and 10^6
- TOP-trap and dipole trap to reach BEC
- two-step Rydberg excitation ($40<n<80$)
- field ionization and detection using channeltron

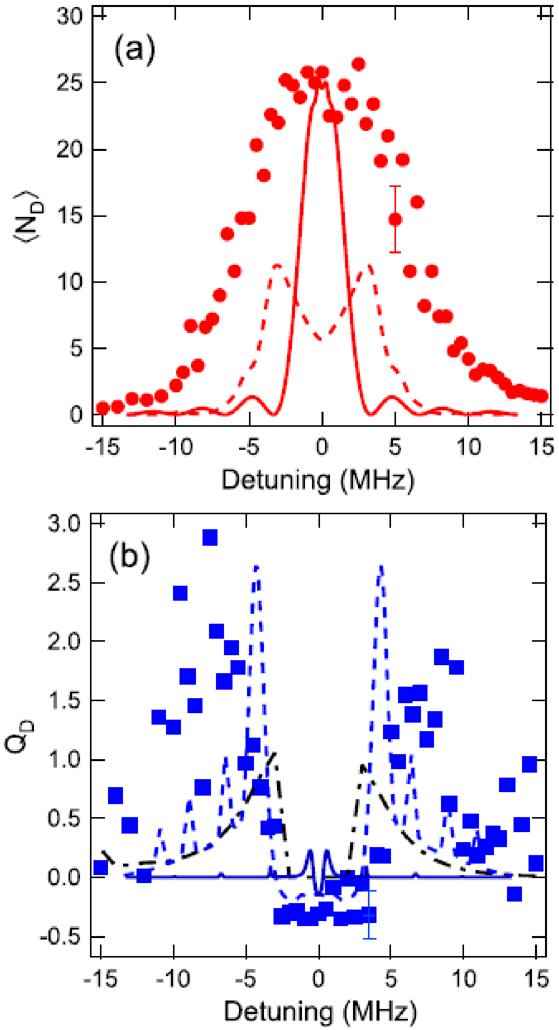




The dipole blockade

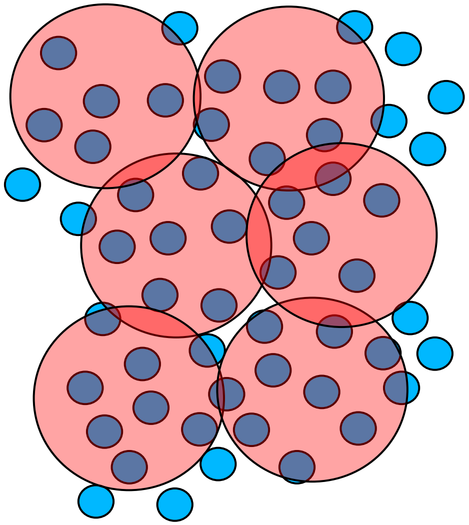


- as expected, the strong correlations due to the dipole blockade lead to a suppression of fluctuations
- off-resonance, enhanced fluctuations are observed (super-Poissonian statistics)
- well reproduced by a Dicke-type model

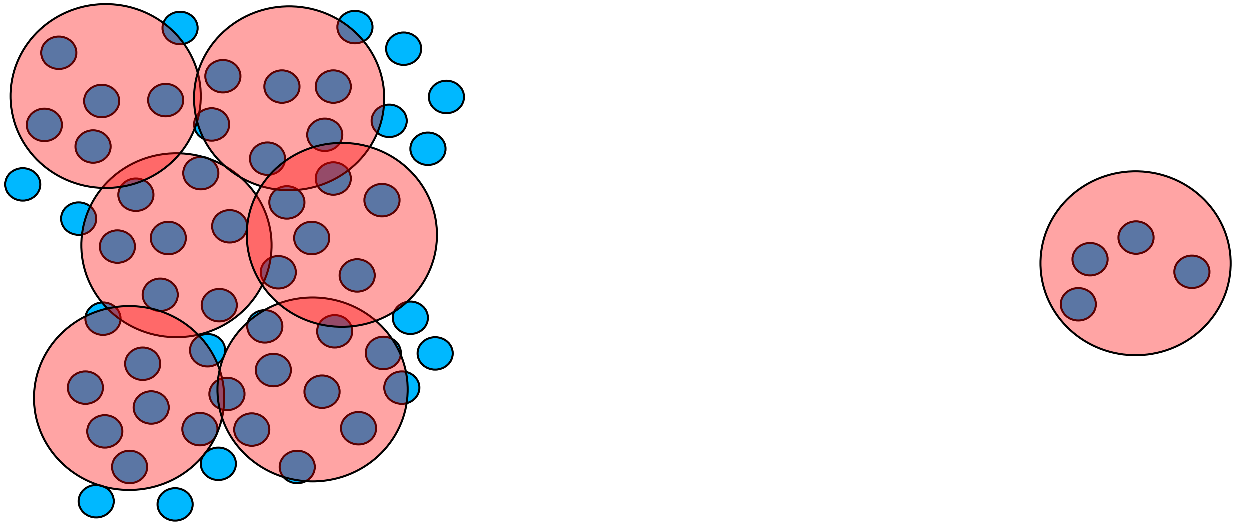


PRL **109**, 053002 (2012)

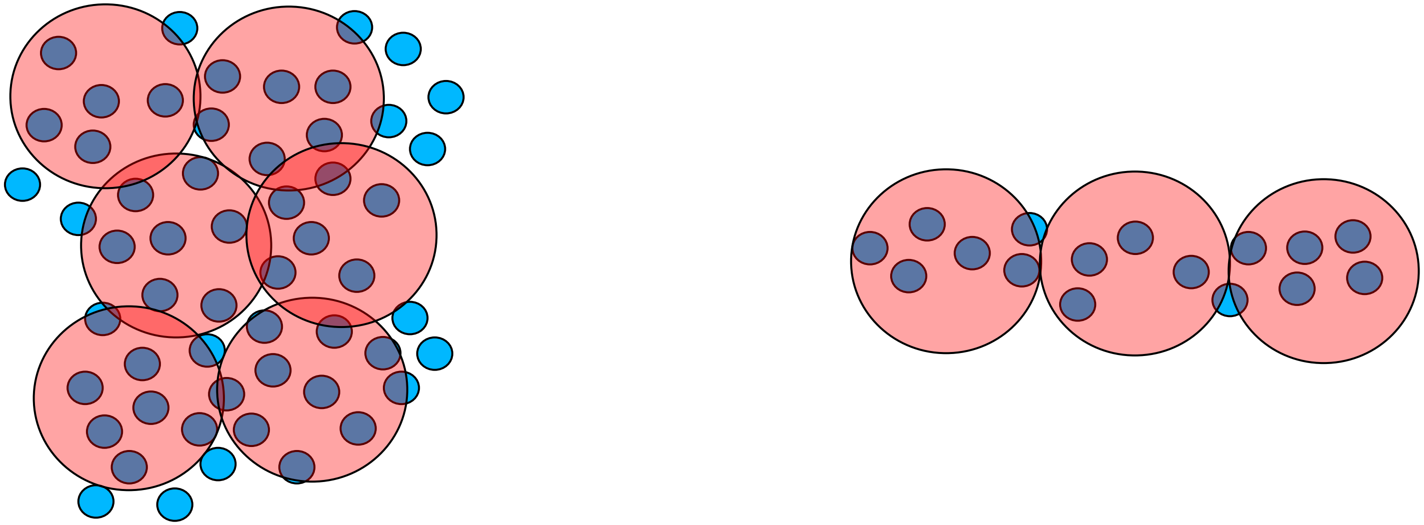
Dipole blockade in 1D geometries



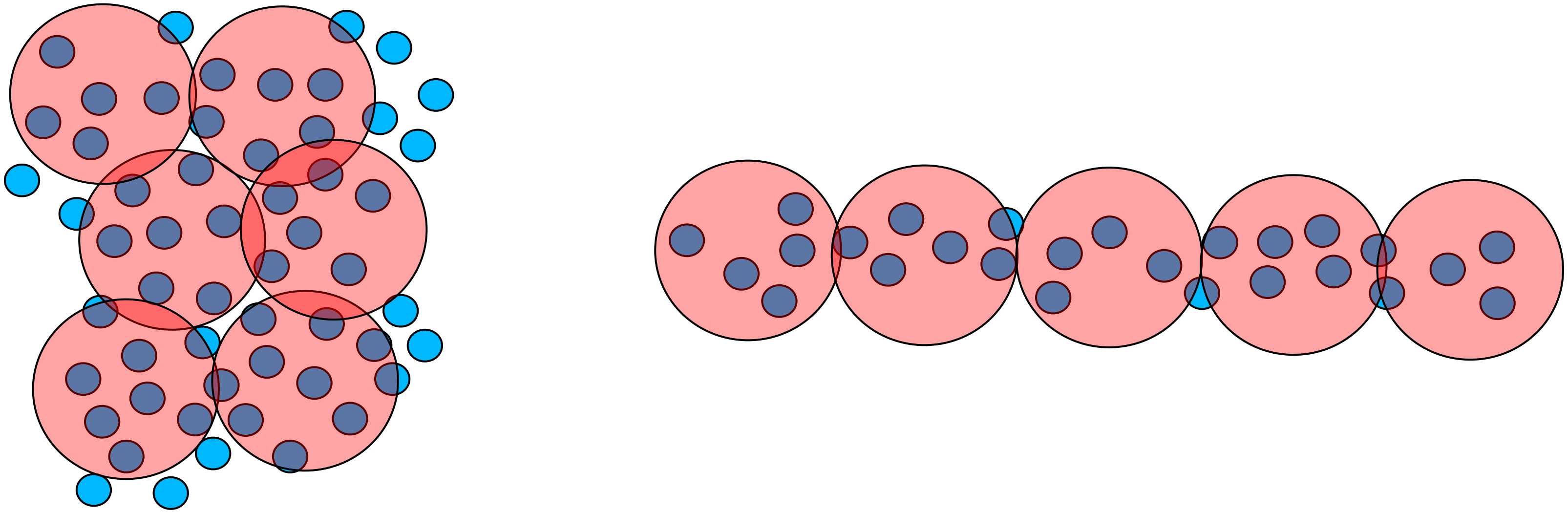
Dipole blockade in 1D geometries



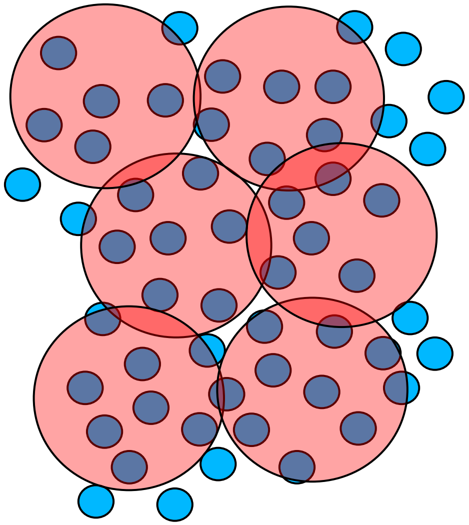
Dipole blockade in 1D geometries

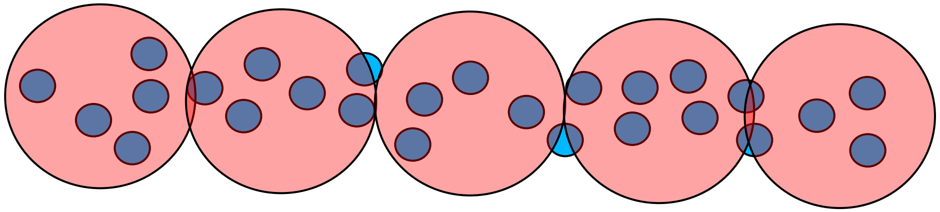


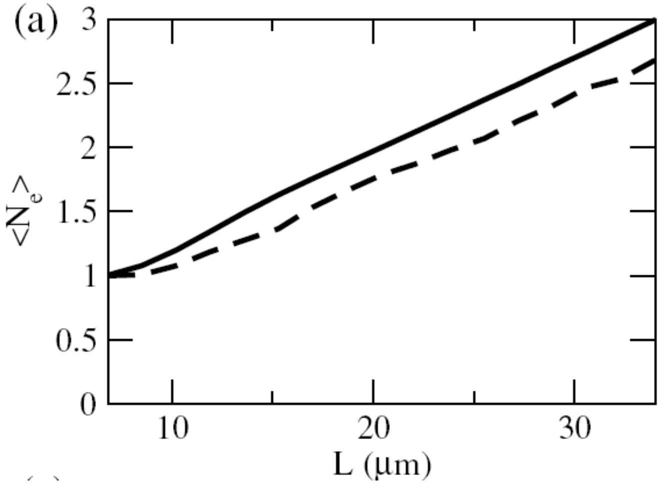
Dipole blockade in 1D geometries



Dipole blockade in 1D geometries

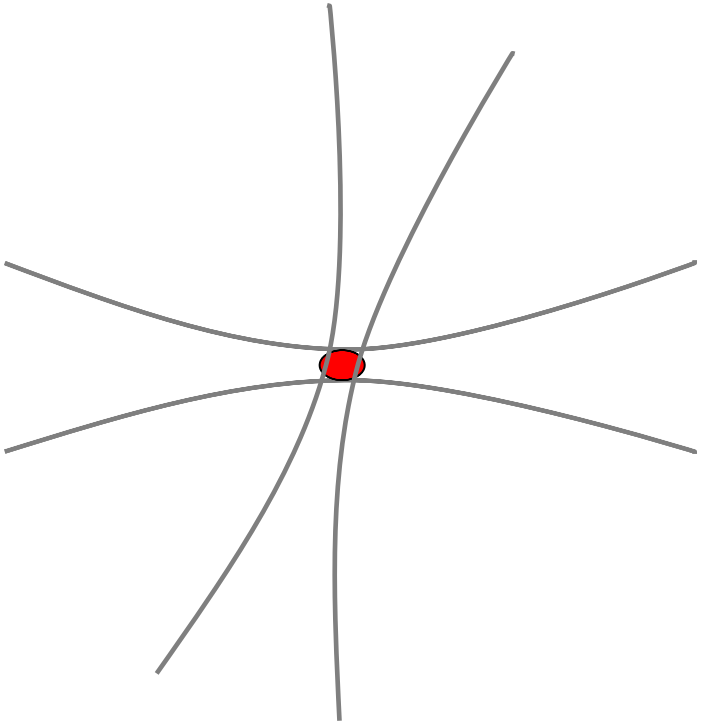




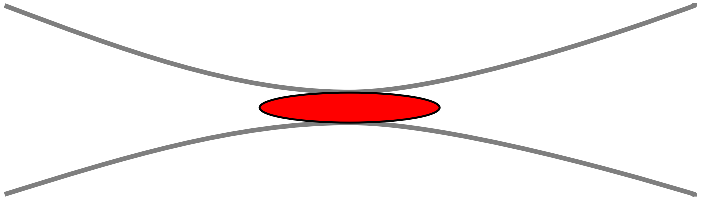


J.V. Hernandez and F. Robicheaux, J.Phys. B **39**, 4883 (2006);

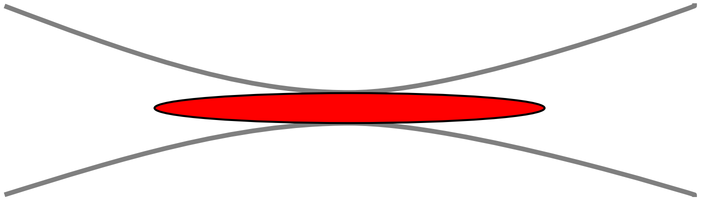
Dipole blockade in 1D geometries



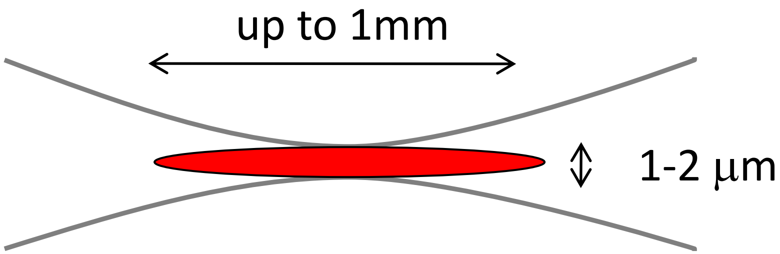
Dipole blockade in 1D geometries



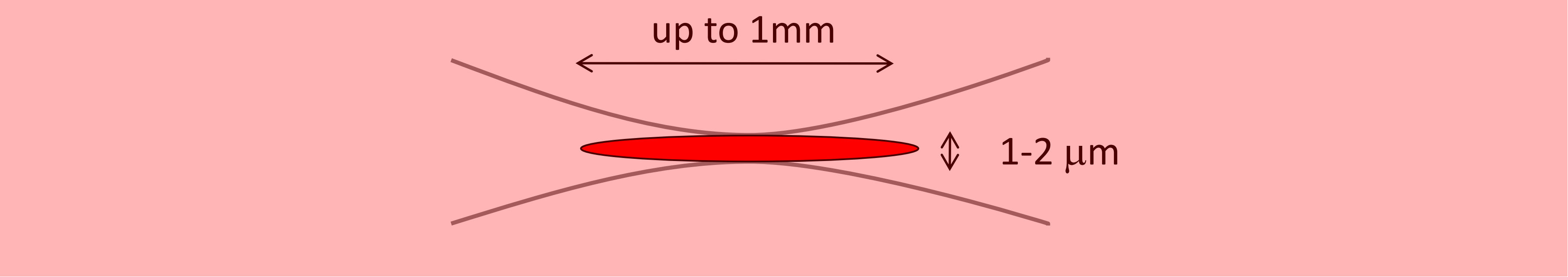
Dipole blockade in 1D geometries



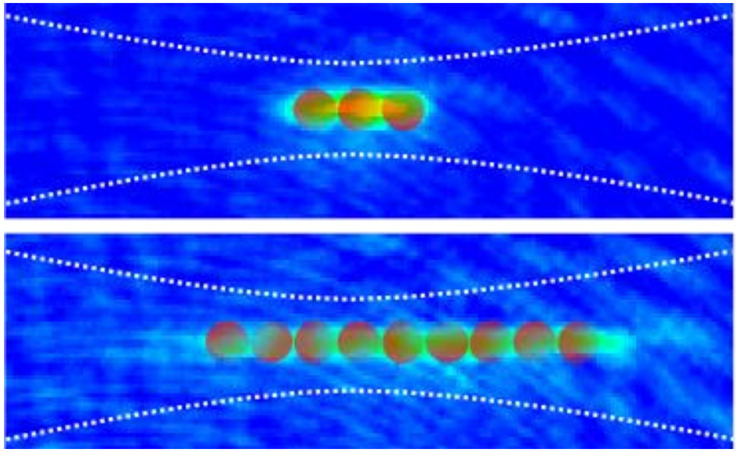
Dipole blockade in 1D geometries

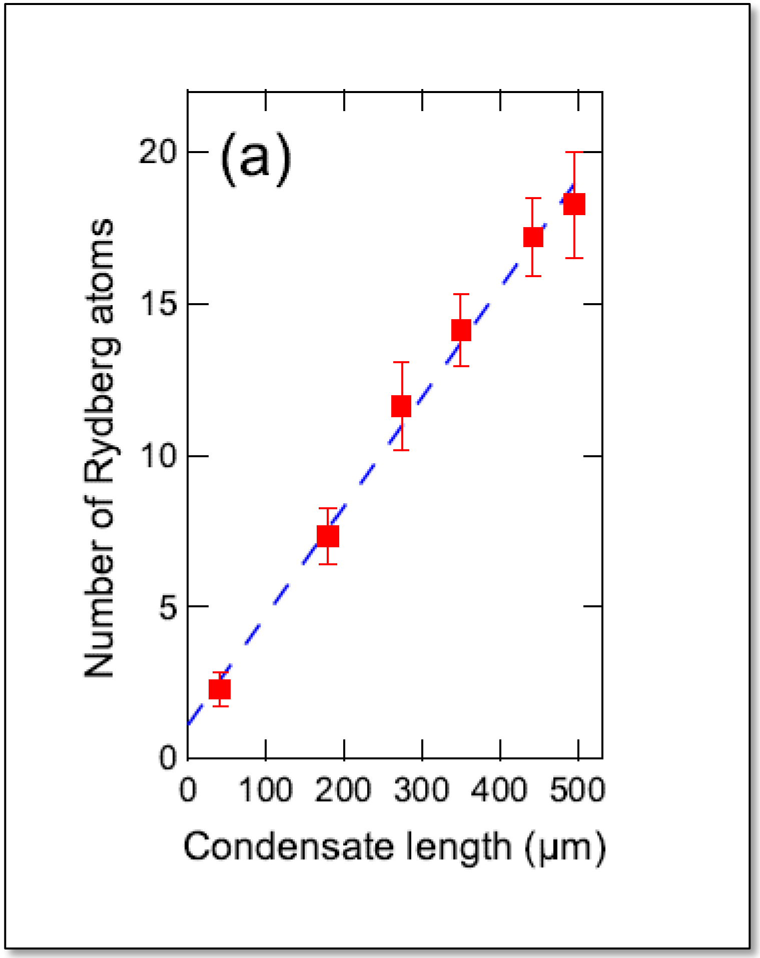


Dipole blockade in 1D geometries



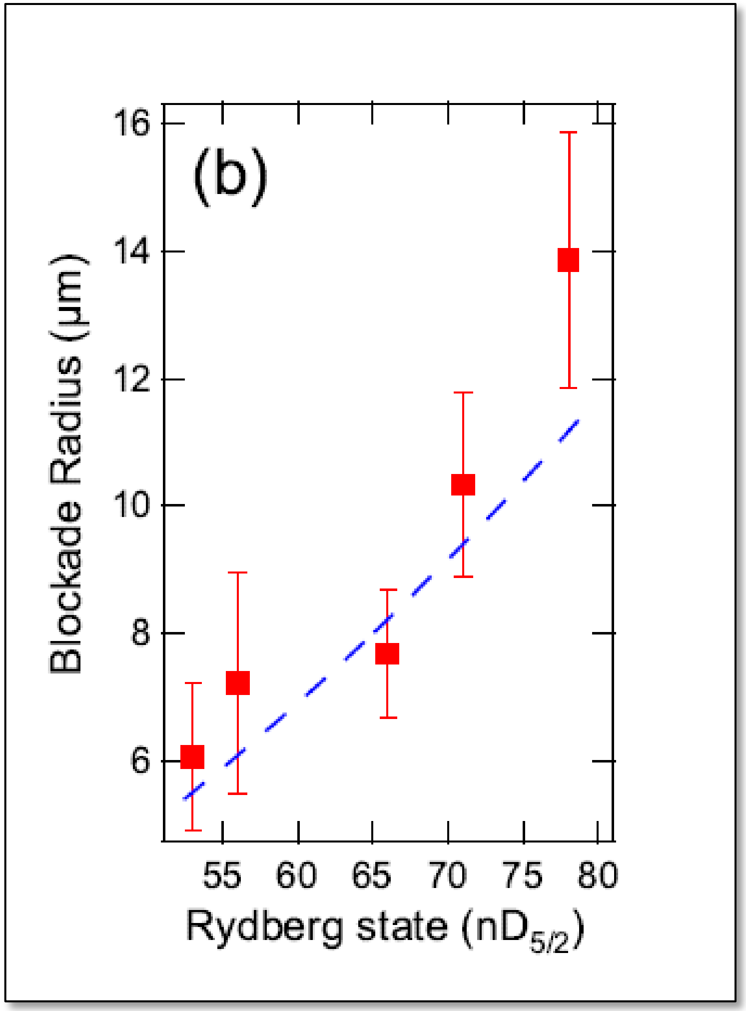
Dipole blockade in 1D geometries





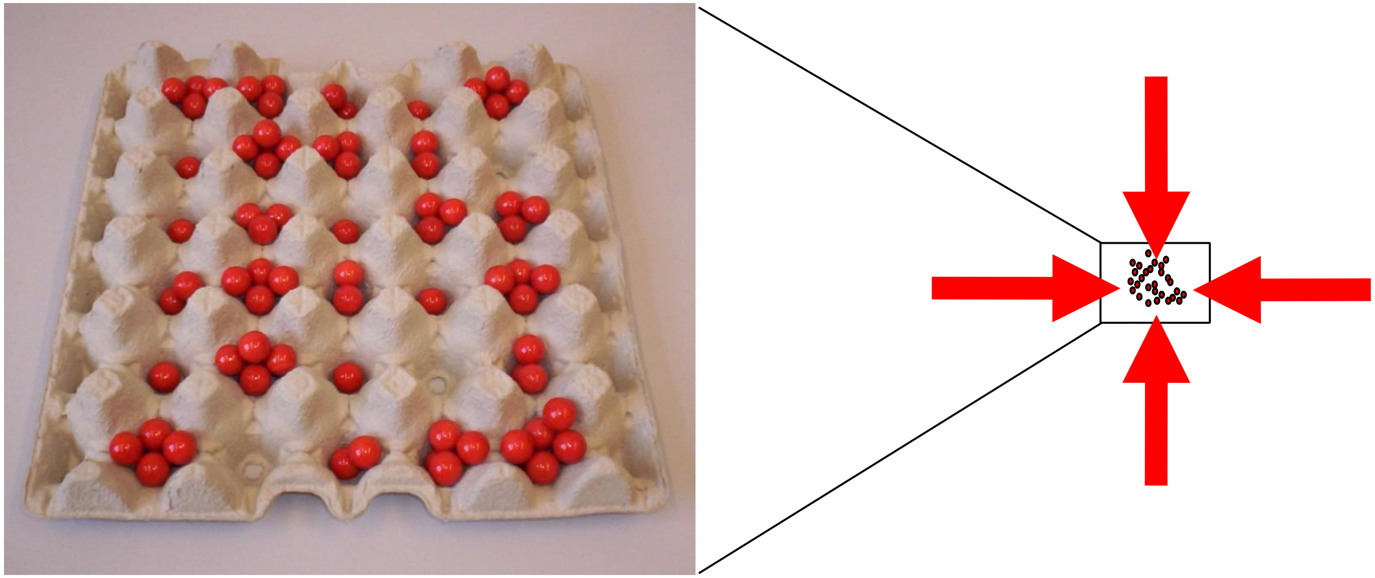
- number of Rydberg excitations grows linearly with the size of the condensate
- 1D “lattice” of excitations?
- can extract blockade radius from slope of linear fit

Dipole blockade in 1D geometries

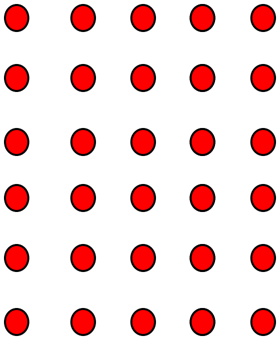


- extracted blockade radius agrees well with theoretical prediction assuming a reasonable laser linewidth (around 300 kHz)

Rydberg atoms in optical lattices



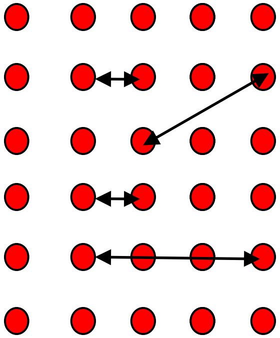
Rydberg atoms in optical lattices



Ultra-cold atoms in optical lattices:

- spatial order
- “artificial crystal”
- possibility of simulating solid state systems (Bose-Hubbard model, Mott insulator)

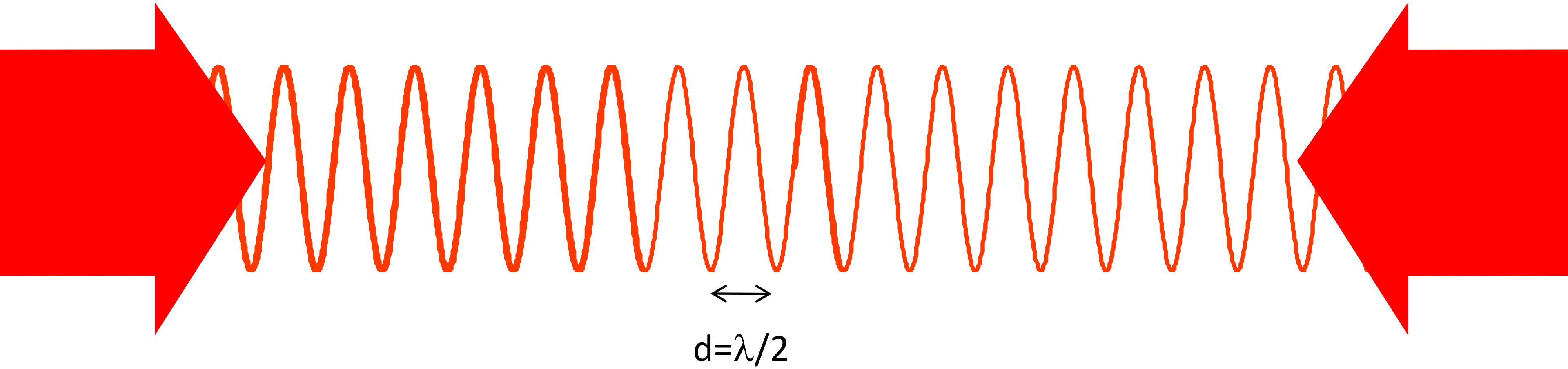
Rydberg atoms in optical lattices



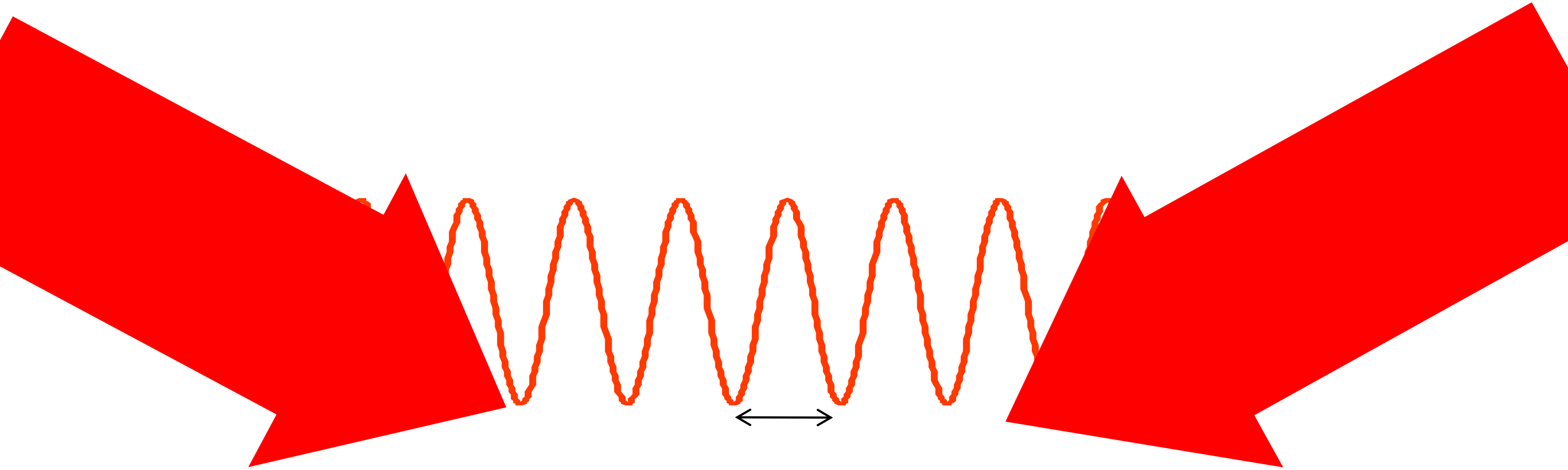
Ultra-cold atoms in optical lattices plus long-range interactions:

- quantum simulation of more sophisticated Hamiltonians
- quantum control
- quantum computation

Rydberg atoms in optical lattices



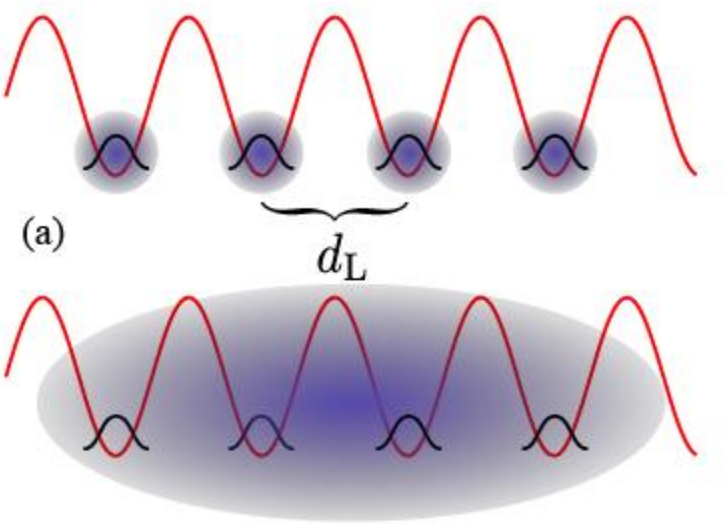
Rydberg atoms in optical lattices



$d=\lambda/2\sin(\theta/2)$

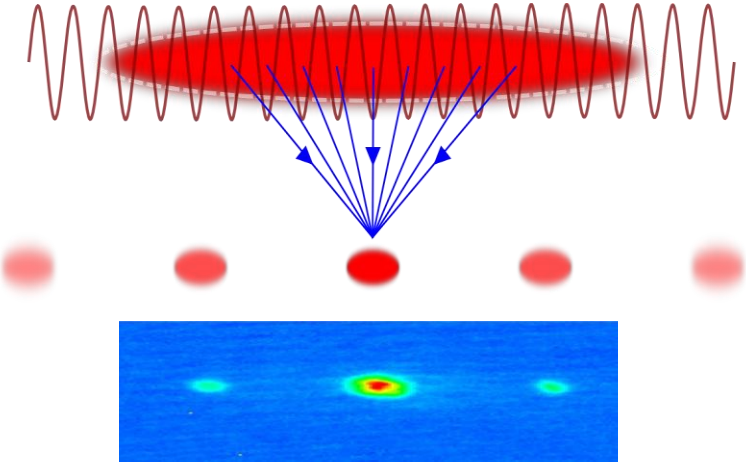
i.e., can realize d between 0.5 μm and 30 μm

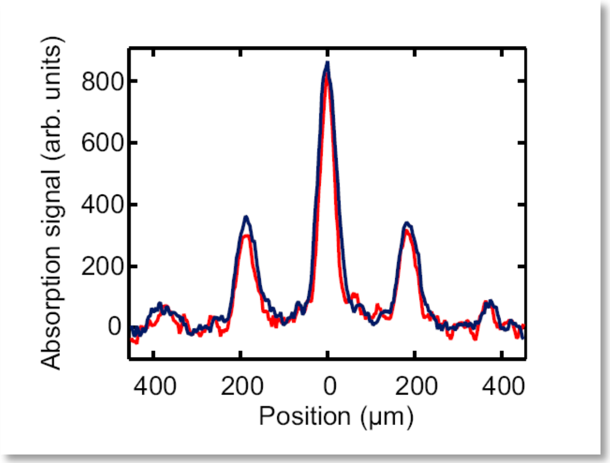
Rydberg atoms in optical lattices



- possibility to interpolate between extreme cases of **blockade radius << lattice spacing** and **blockade radius >> lattice spacing**

Rydberg atoms in optical lattices

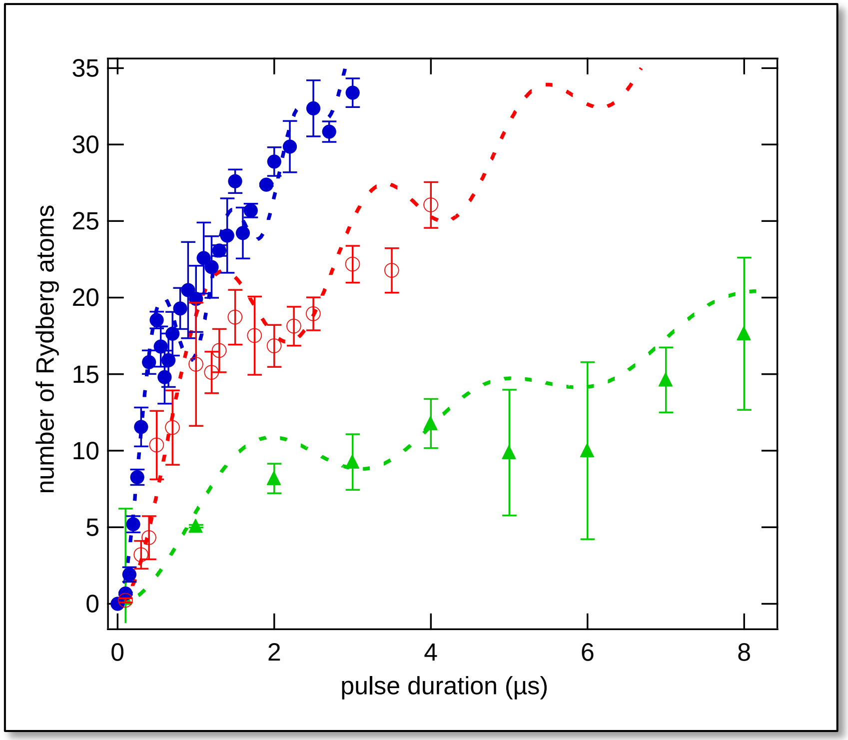


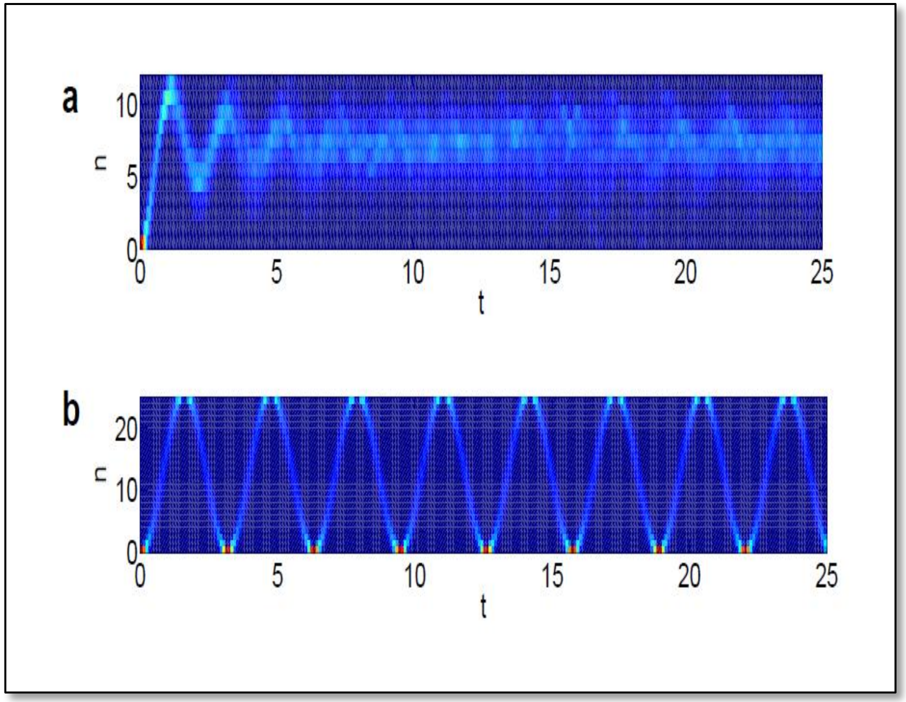


- can measure phase coherence of condensate using time-of-flight images of interferece pattern

- detect practically no decrease in coherence after up to 10 excitation/detection cycles

Rydberg atoms in optical lattices

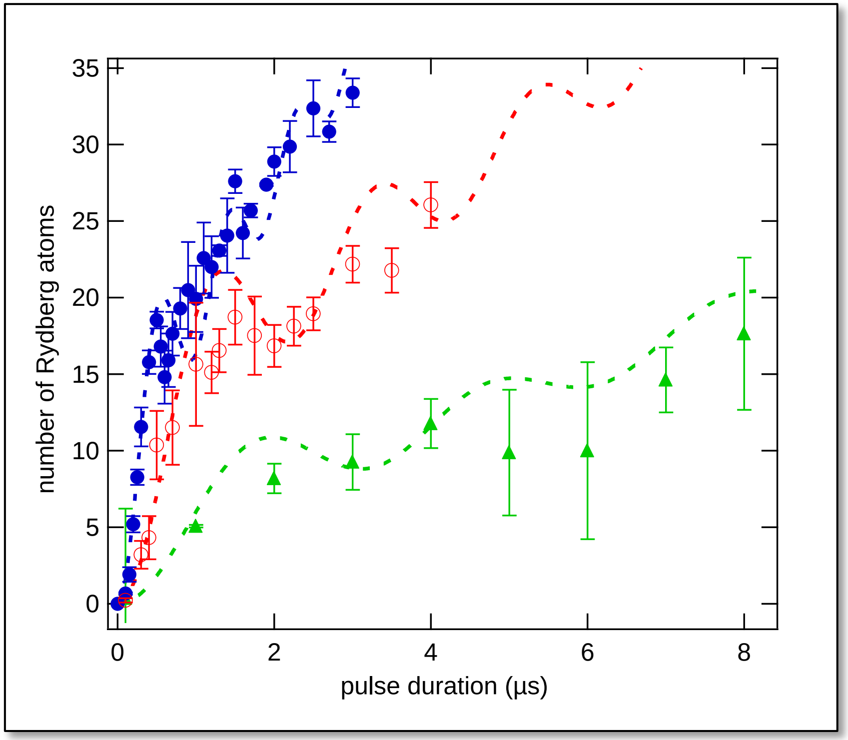


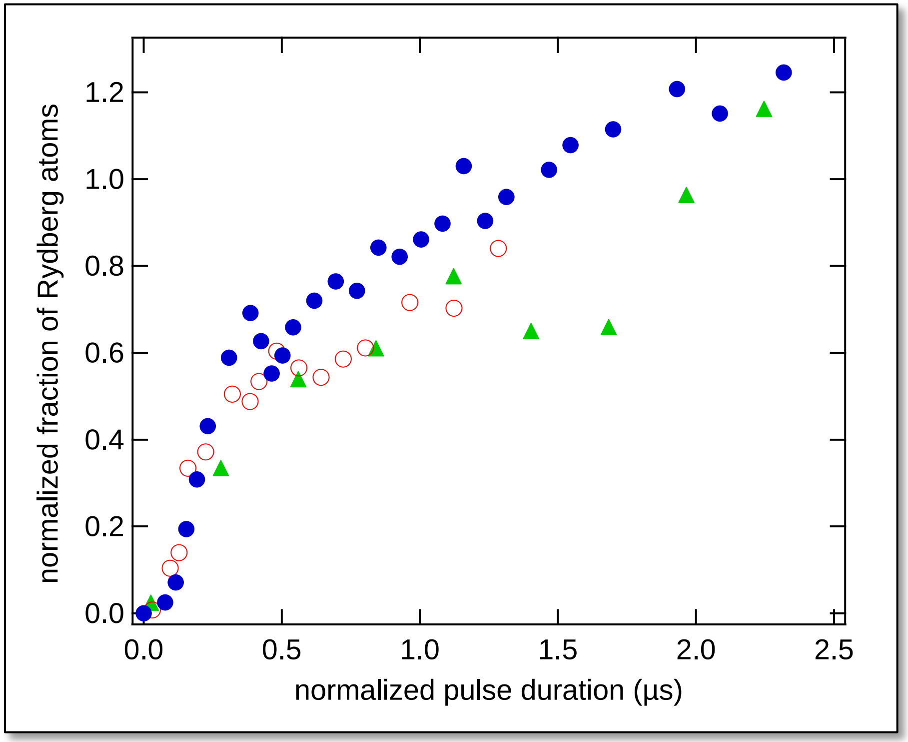


I. Lesanovsky and B. Olmos

$53D_{5/2}$, between $6x10^3$ and $8x10^4$ atoms, lattice spacing 2.6 microns, 30-50 wells occupied

Rydberg atoms in optical lattices

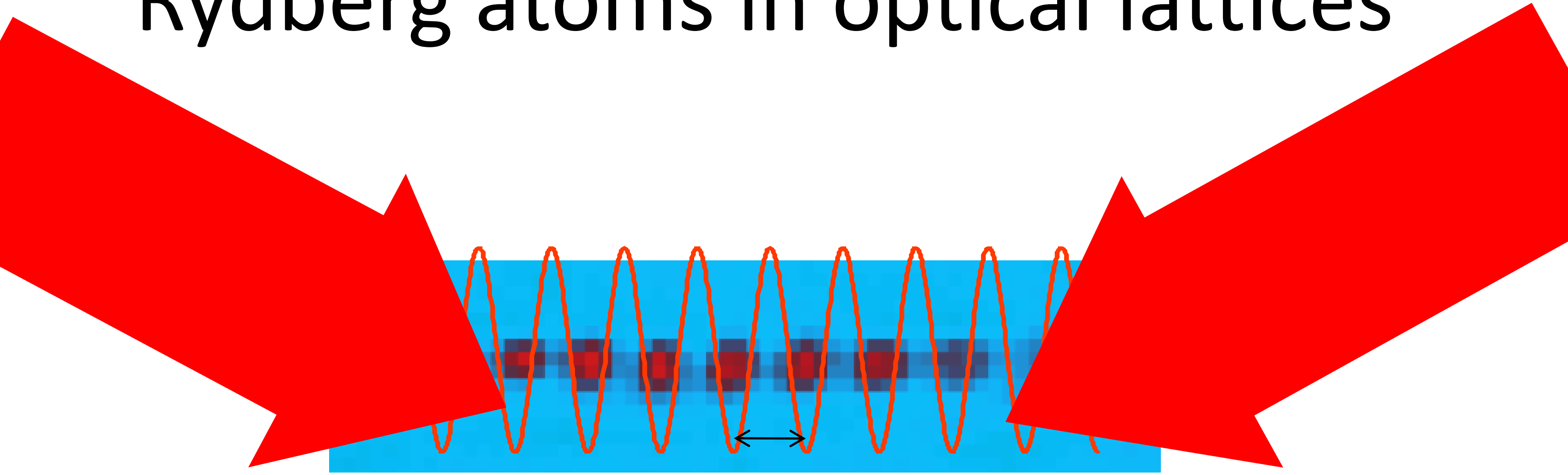




$53D_{5/2}$, between $6x10^3$ and $8x10^4$ atoms, lattice spacing 2.6 microns, 30-50 wells occupied

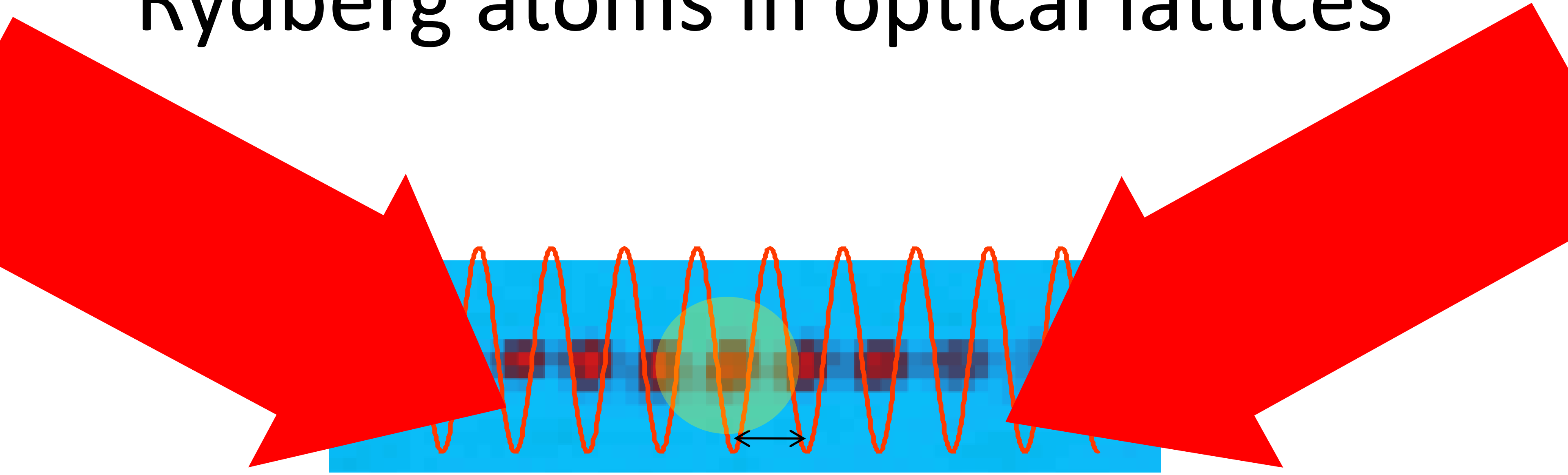
- excitation dynamics agrees well with simple theoretical model
- (approximately) uniform distribution achieved by “cutting” into expanded condensate
- for different atom numbers per lattice well scaling with $\sqrt{N}$ observed

Rydberg atoms in optical lattices

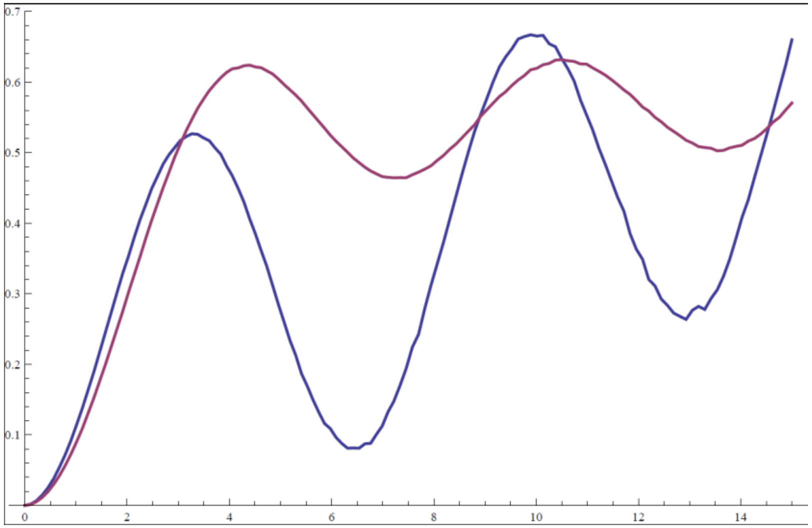


d = 26.7 μm

Rydberg atoms in optical lattices

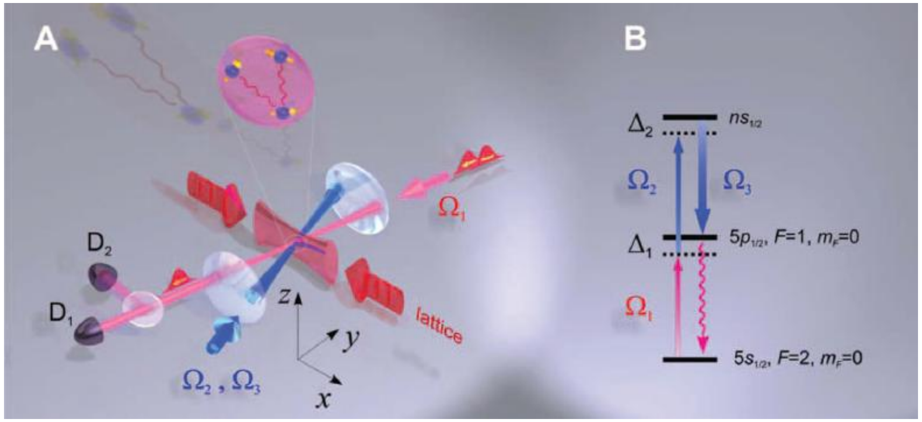


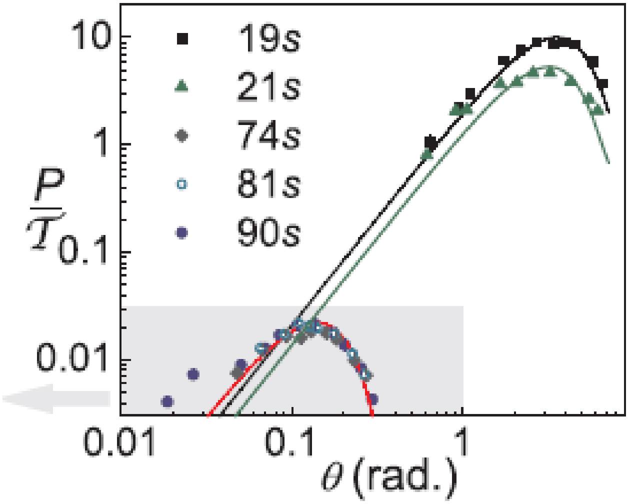
d = 26.7 μm

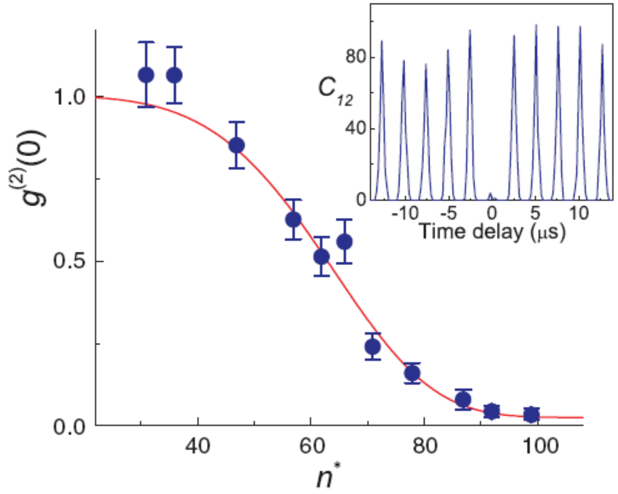


- **around 100-400 atoms per lattice site**
- **size of excitation beam 12 microns (effectively 17 microns due to angle)**
- **position of lattice stable to within 1 micron**

Collective Rabi oscillations







- for large enough n, only a single excitation fits into the volume

- single-excitation character reflected in correlation function of the detection photons

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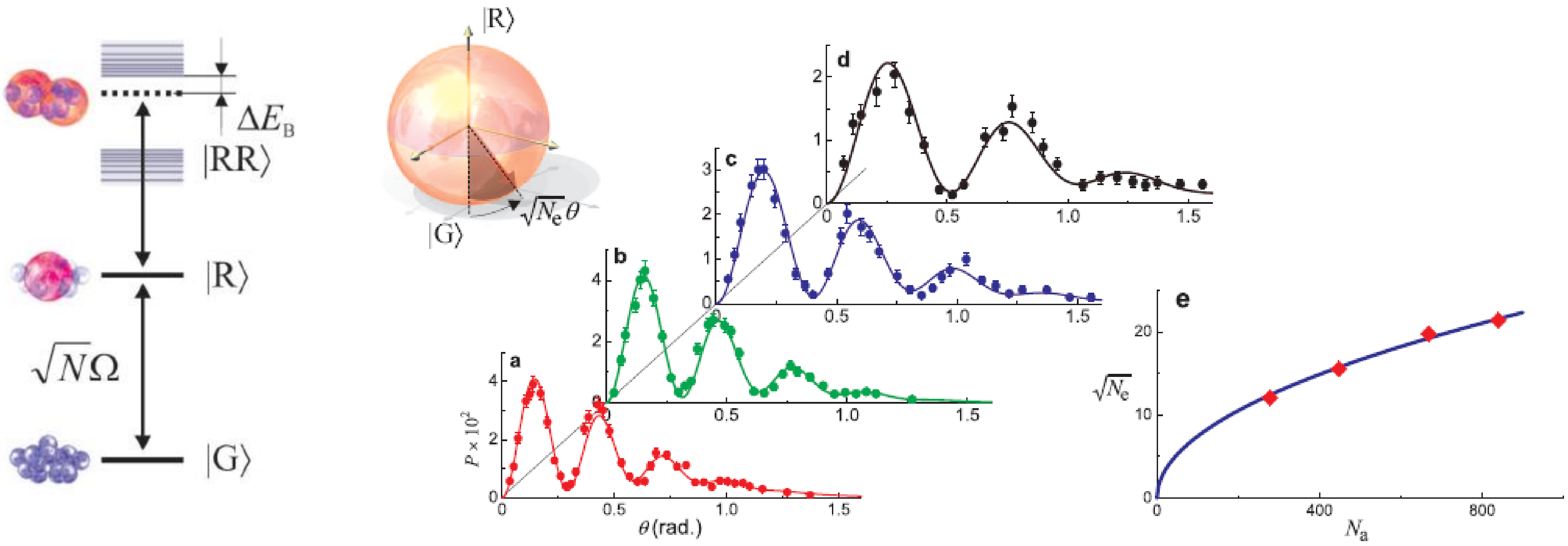
Collective Rabi oscillations



- several Rabi cycles observed
- collective enhancement of Rabi frequency

doi:10.1038/nphys2413

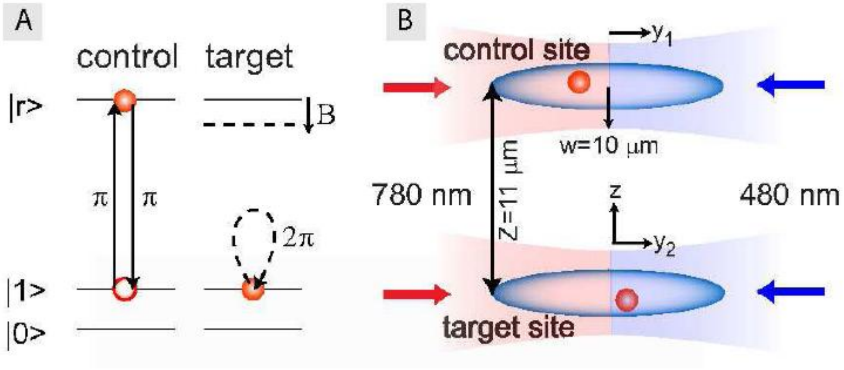
Lecture 3: The state of the art – and beyond

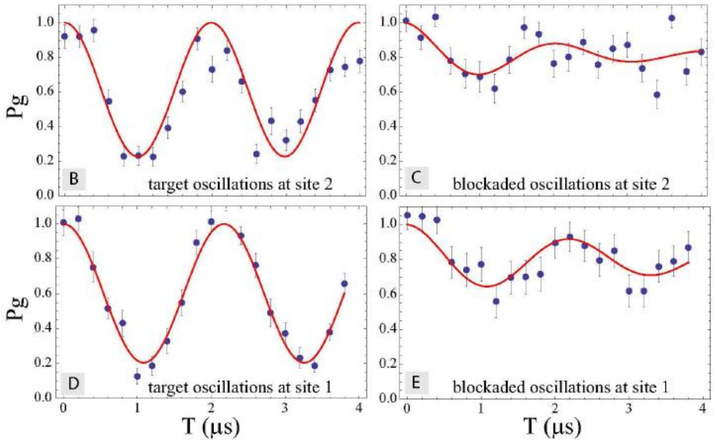
Attractive features of ultracold Rydberg atoms:

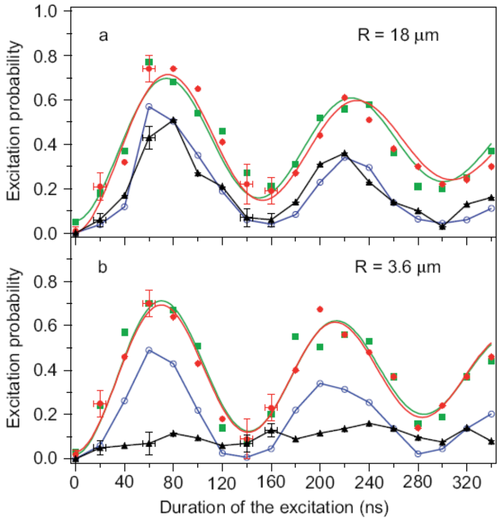
- can use cold atom techniques, including manipulation with optical lattices
- long decoherence times in the ground state
- strong interactions between Rydberg states – fast gates possible!

REVIEWS OF MODERN PHYSICS, VOLUME 82, 2313

Dipole blockade and Rydberg gates

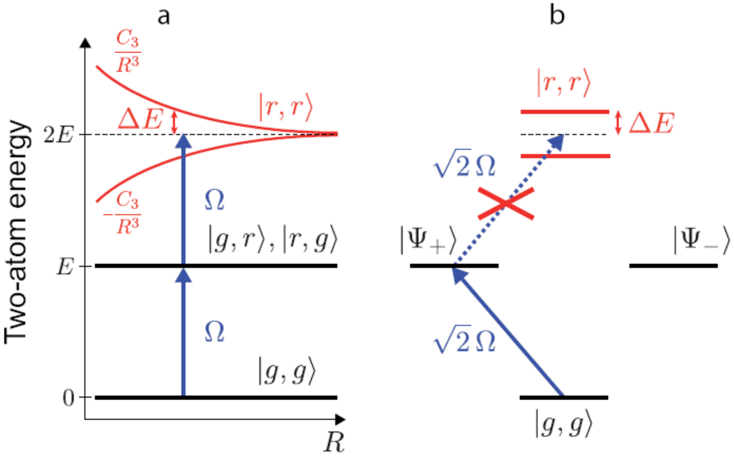


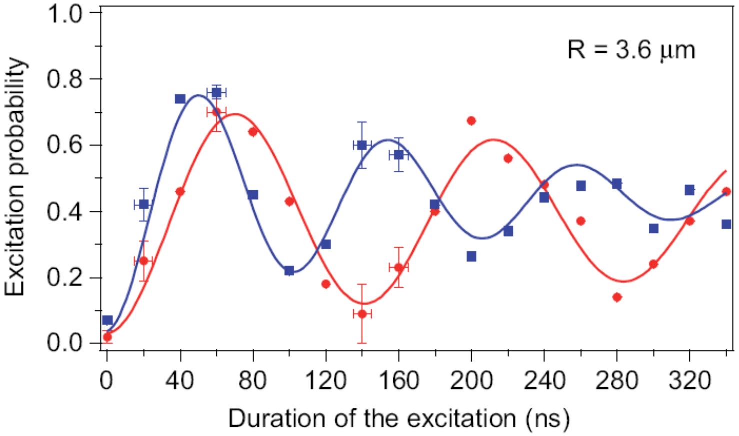




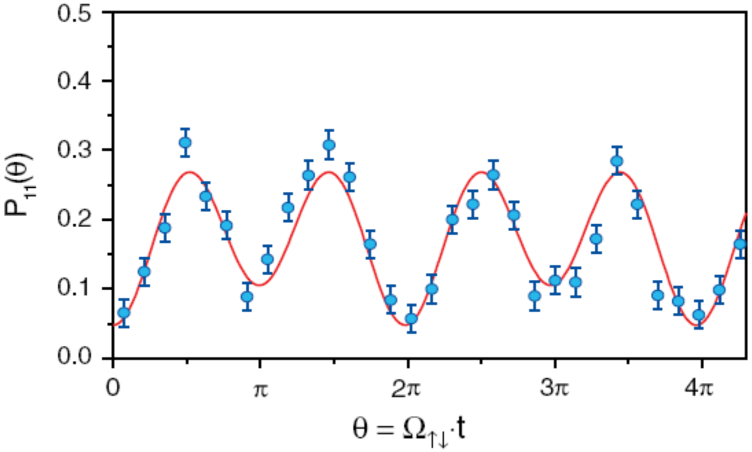
- Rydberg excitation of atom in control site blocks excitation of target atom

Dipole blockade and Rydberg gates



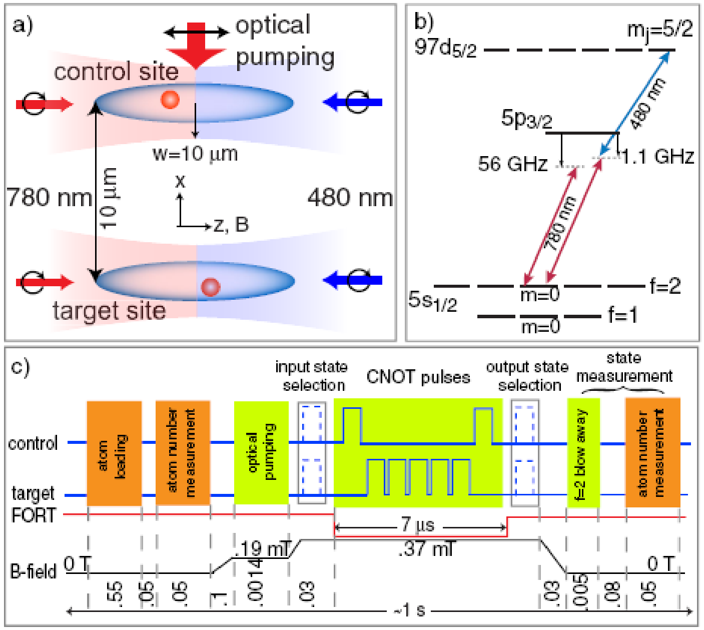


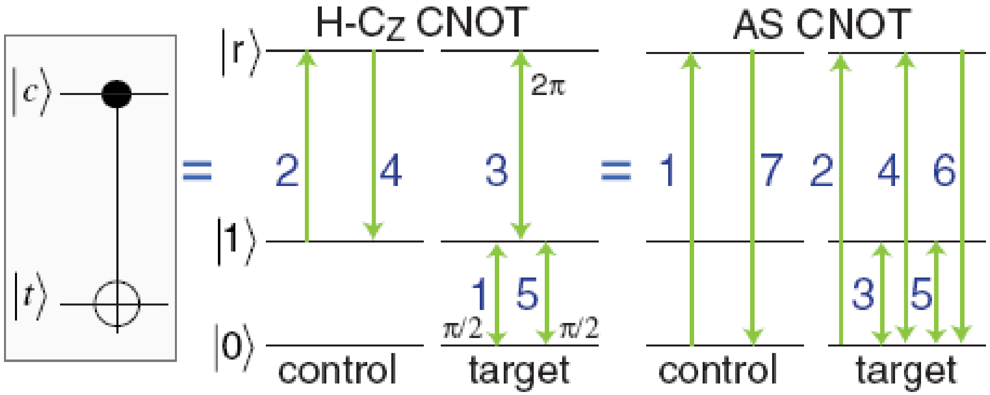
- when trying to excite both atoms simultaneously, $\sqrt{2}$ enhancement of Rabi frequency is observed
- collectively excited state is entangled

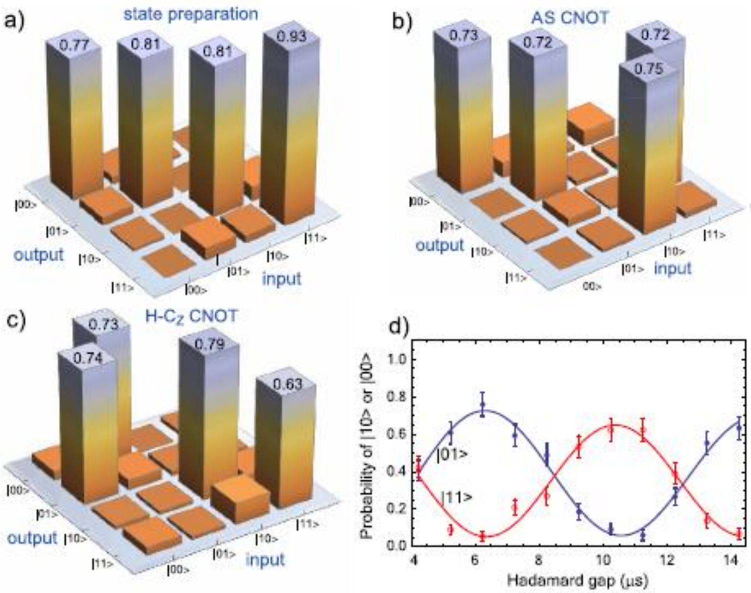


PRL **104,** 010502 (2010)

Dipole blockade and Rydberg gates







- CNOT gate was implemented using the dipole blockade
- fast gate: microsecond timescale!
- limited fidelity due to thermal motion, atom loss, imperfect pulses

PRL **104**, 010503 (2010)

QC with Rydberg atoms: checklist

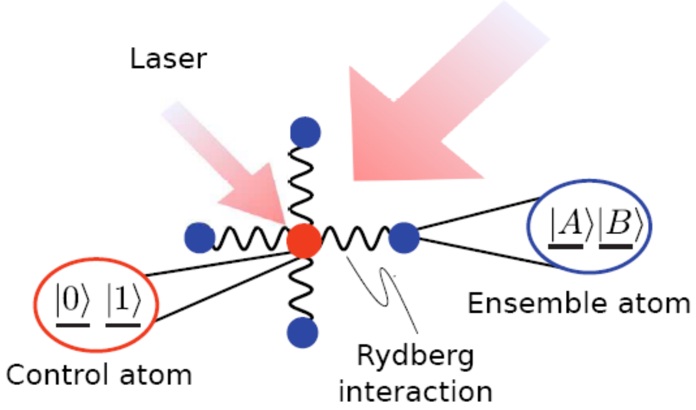
The DiVincenzo criteria

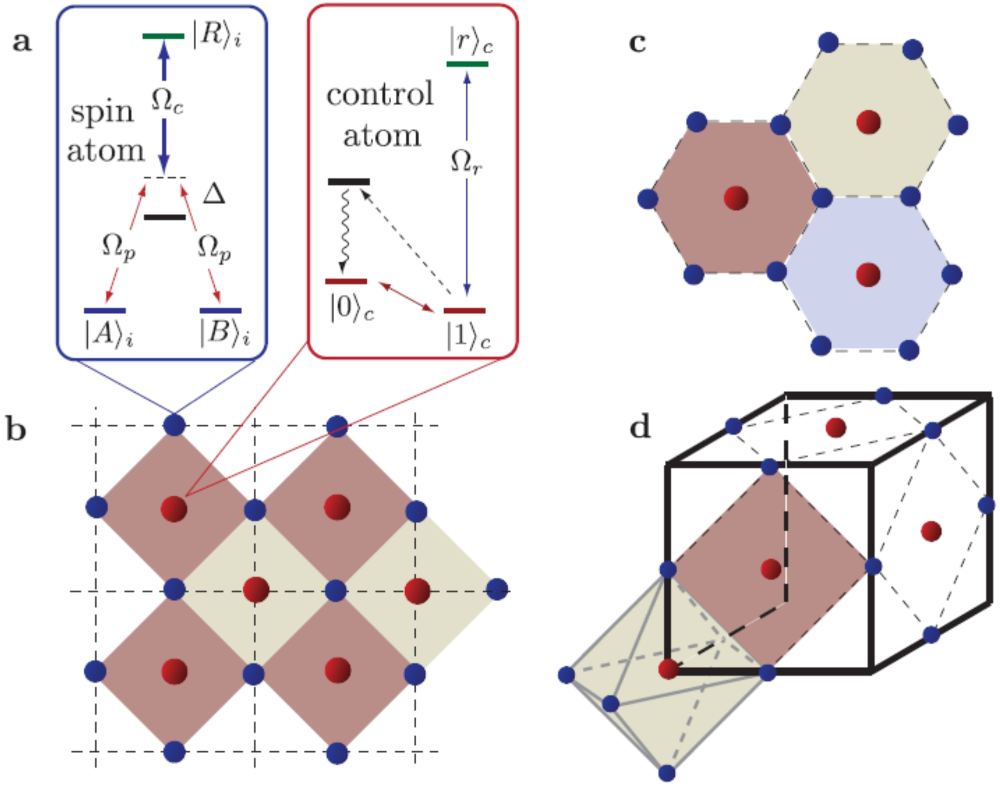
For a system to be a possible candidate for the implementation of a quantum computer, it must:

- Be a scalable physical system with well-defined qubits
- Be initializable to a simple fiducial state such as |000...>
- Have decoherence times that are much longer than the gate times
- Have a universal set of quantum gates
- Permit high quantum efficiency, qubit-specific measurements

Looks like it might not be completely impossible!

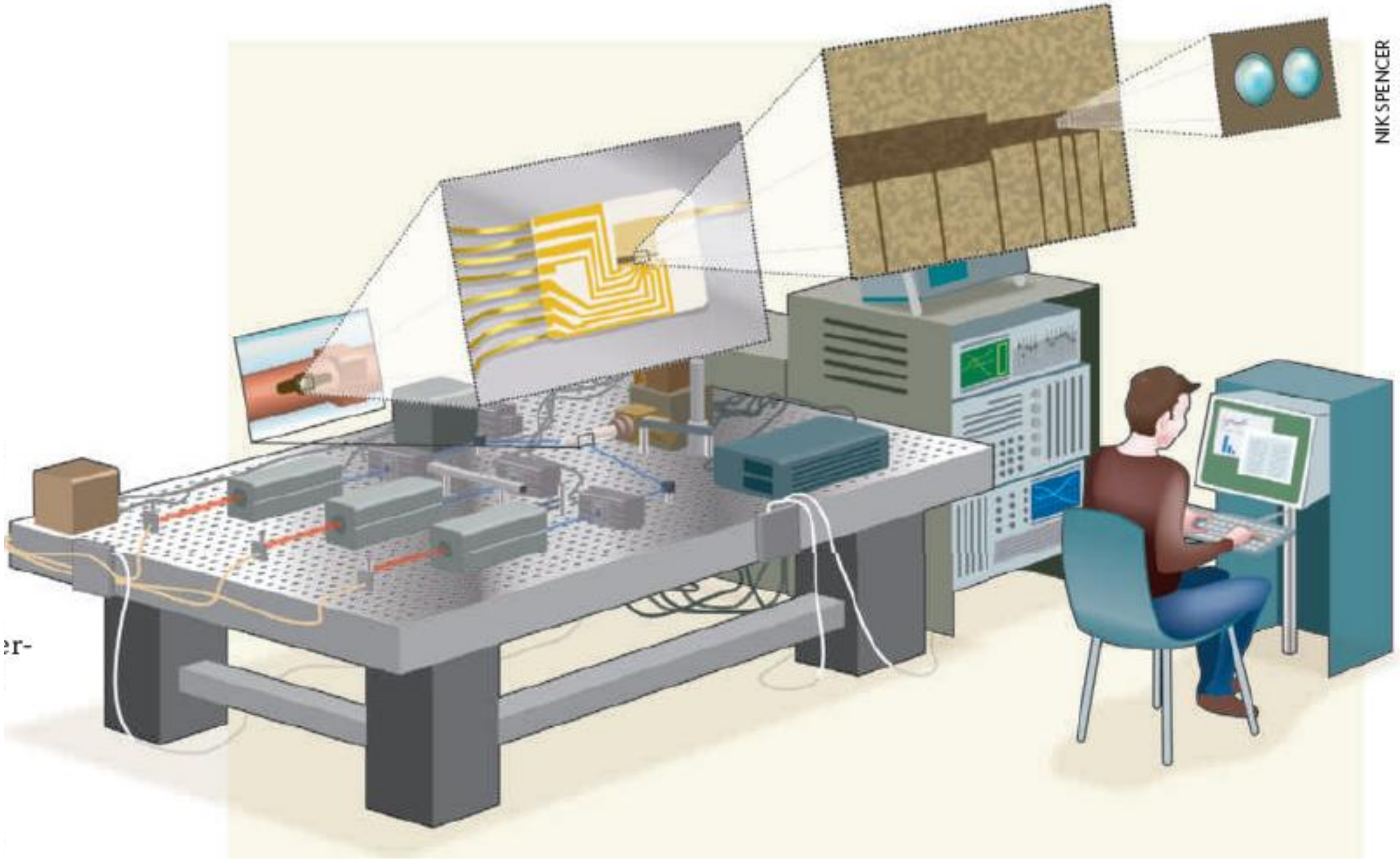
Rydberg quantum simulator





H. Weimer et al., Nature Phys. **6**, 382–388 (2010).

The “real world” quantum computer



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Summary

- Several systems are under investigation for the realization of a useful quantum computer
- Rydberg atoms have a number of attractive features for quantum computing: long decoherence times in the ground state, strong interactions (=fast gates) in the excited state, easy to manipulate
- Coherent excitation of Rydberg states and interaction effects (dipole blockade) have been studied extensively in recent years, and coherent control of collective excitations has just been demonstrated
- CNOT gate and entanglement of two atoms using the dipole blockade has been realized
- Many proposals (gates using collective excitations, collective qubit encoding) are waiting to be realized – plus many more to be developed by you!