Building Quantum Computers

Real qubits and quantum gates
Example of Neutral Atoms

Atoms as qubits

- Which atoms will make good qubits?
- How to initialize the qubits - how to cool and trap atoms?
- How to manipulate atomic states (i.e. qubits)?
- How to perform two-qubits gates - which physical processes can we use?
- How to read out the result?
- What are the error sources?
- How large are the errors?
- How can we minimize errors?

Terminology:

Atom is neutral (all electrons are present)
Ion has one or more electrons removed - therefore it is charged. In quantum information, we use either neutral atoms or singly-charged ions that have one electron removed.

The qubit representations are the same in atoms and ions but trapping and logic gate technologies are completely different. Therefore, we first discuss what make a good qubit for atom/ion and then separately consider using atoms and ions for quantum information.

In the discussion below, I will use "atom" for either atom or ion unless we discuss a specific system.

Main info about atoms:

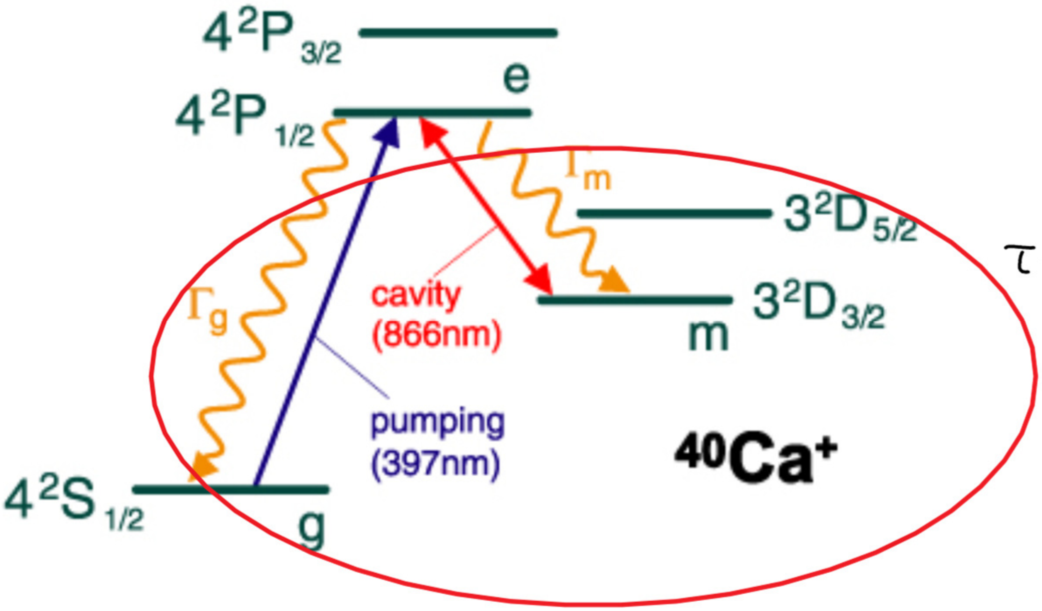
(1) Atom have different "energy levels"

(2) This energy levels are discrete by the rules of quantum mechanics.

(3) The levels are described by "quantum numbers"

(4) The lowest energy level is called the ground state

(5) Higher energy levels are called excited states



$\tau \approx 1s$

Qubit

Main info about atoms contd.:

(6) The atoms can absorb photons of only specific wavelengths given by the difference of two these discrete energy levels.

(5) There are vastly different separation between different energy levels - some can be in microwave region and some in ultraviolet or even X-ray (for ions)

(6) When the atom emits a photon and jumps to lower energy level it is called spontaneous emission.

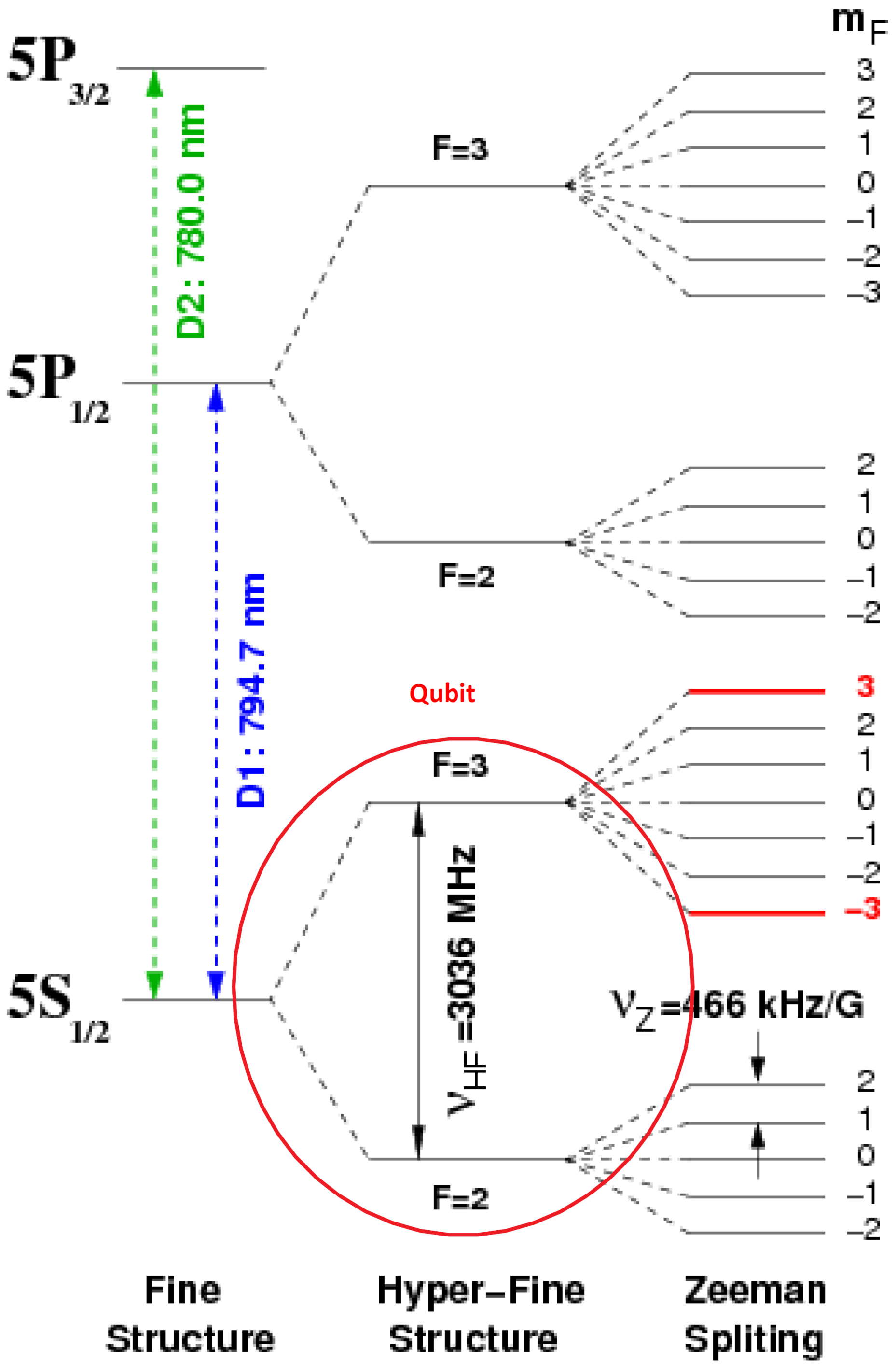
There are also vastly different "lifetimes" of the excited states defined by their electronic structure. Some can live for years and some will decay in nanoseconds.

(7) Table-top lasers can be built from VUV (not too deep in VUV) to infrared run (generally under 2000 nm except 10.6 micron case)

Atoms are not “two-level system”

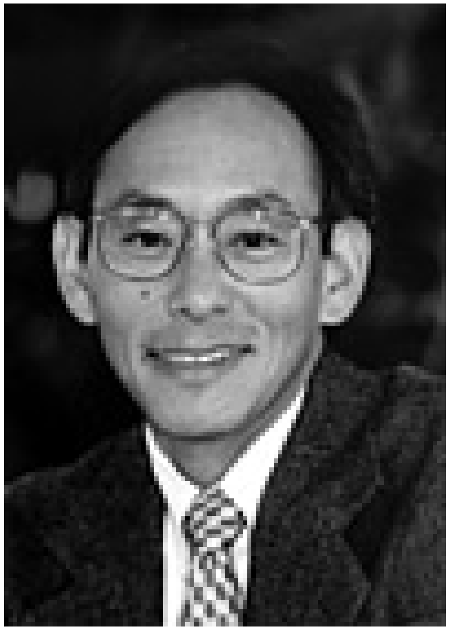
Here are first 3 lowest states in Rb

However, we can put atoms in a specific state with very high accuracy “fidelity”



Atoms have to be ultracold and trapped

Nobel Prize in Physics 1997 for laser cooling of atoms



Steve Chu

Claude Cohen-Tannoudji

Bill Phillips

Laser cooling of atomic beams

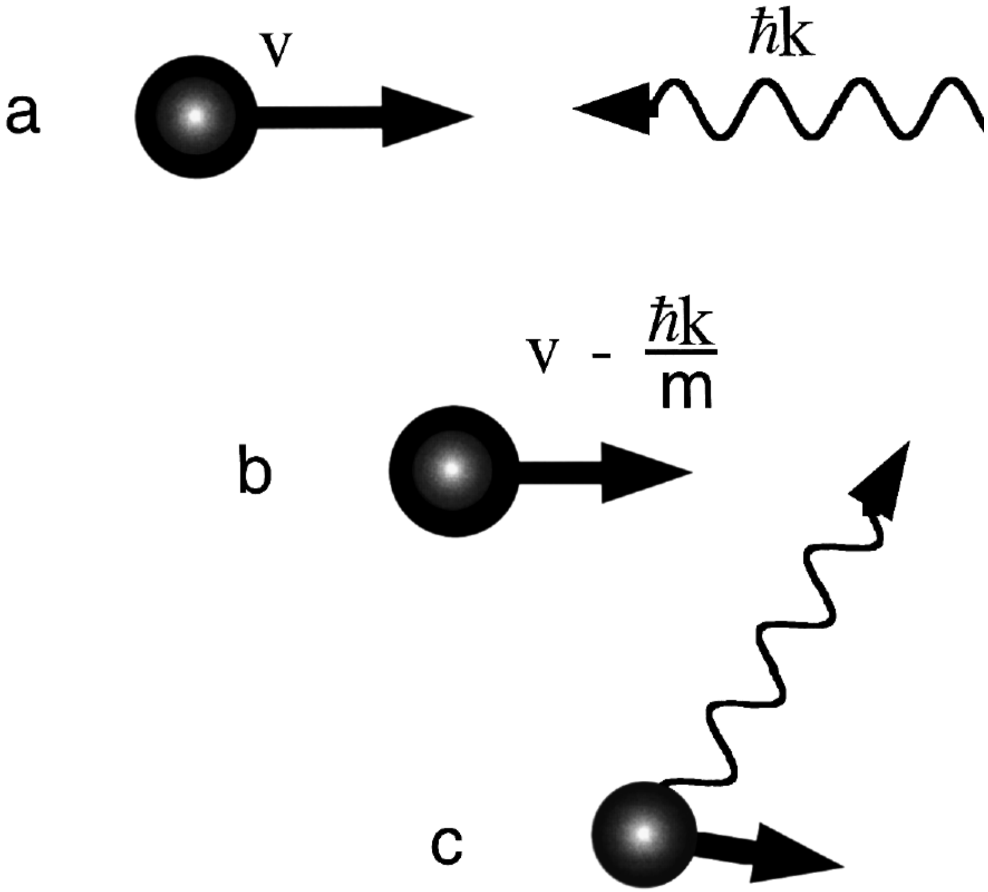
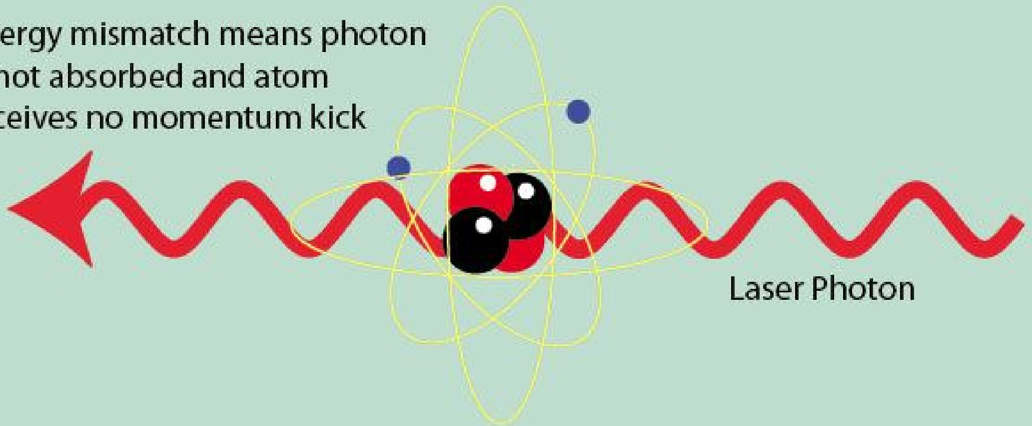


FIG. 1. (a) An atom with velocity v encounters a photon with momentum $\hbar k = h/\lambda$; (b) after absorbing the photon, the atom is slowed by $\hbar k/m$; (c) after re-radiation in a random direction, on average the atom is slower than in (a).

Laser Cooling

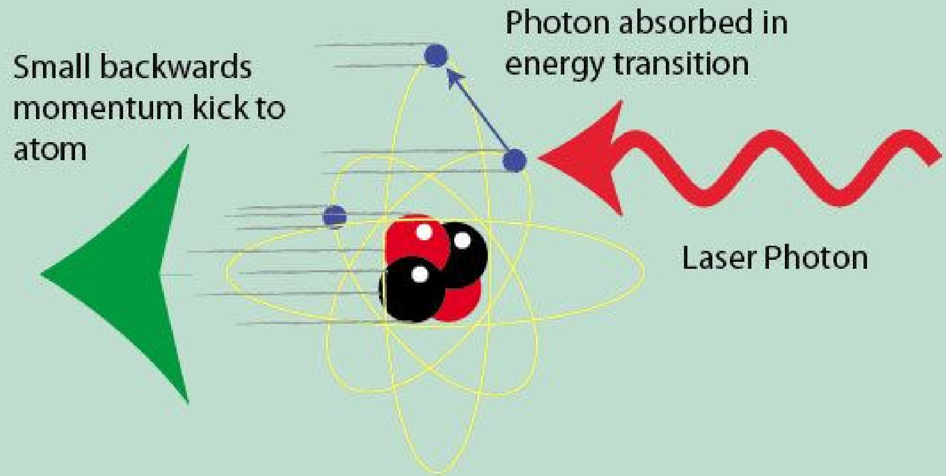
Stationary Atom:



Energy mismatch means photon is not absorbed and atom receives no momentum kick

Laser Photon

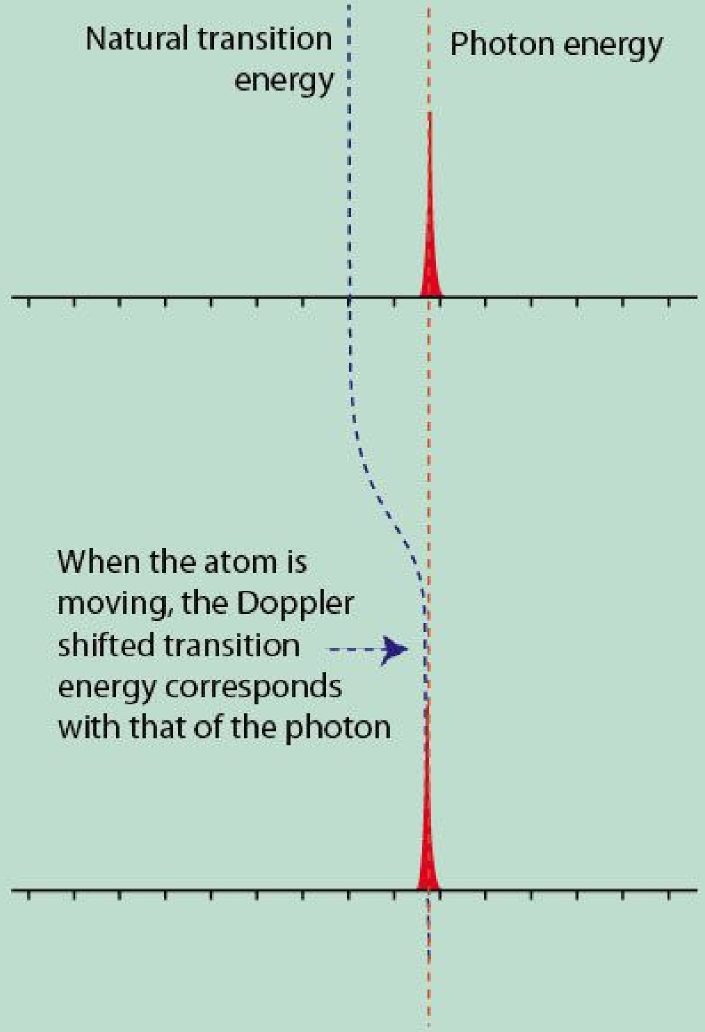
Moving Atom:



Small backwards momentum kick to atom

Photon absorbed in energy transition

Laser Photon



Natural transition energy

Photon energy

When the atom is moving, the Doppler shifted transition energy corresponds with that of the photon

sciencewise.anu.edu.au

Another problem: Doppler shift

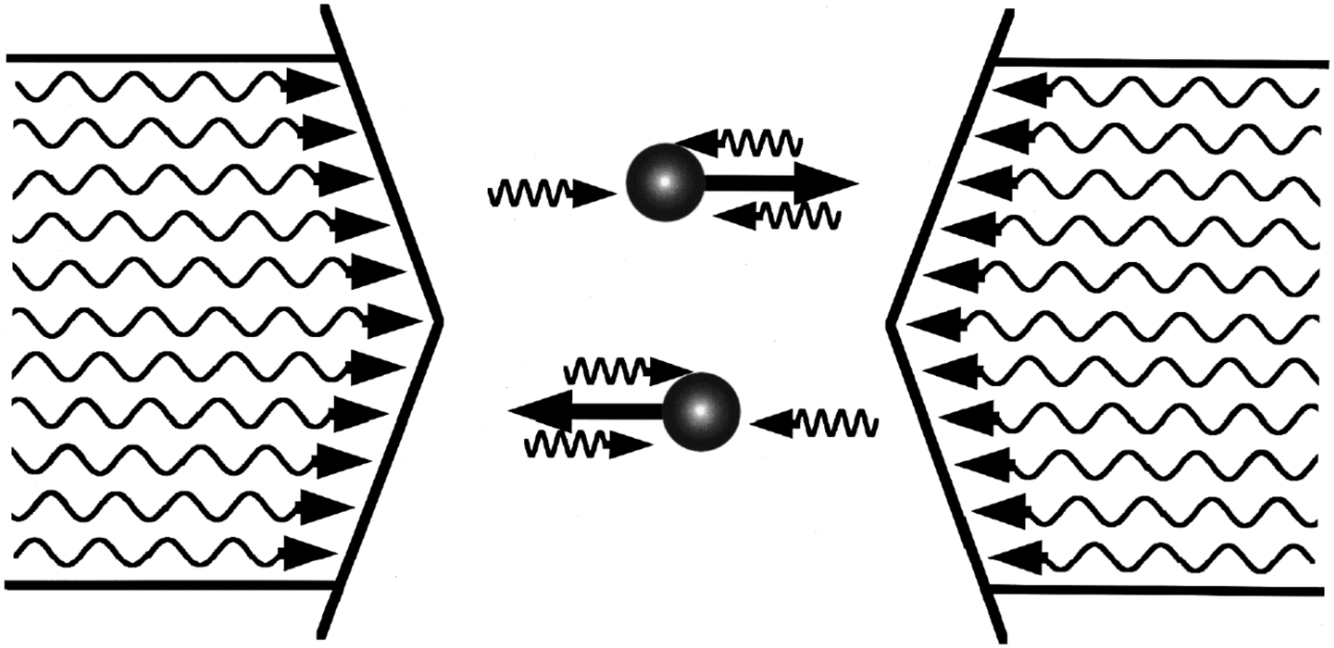
In order for the laser light to be resonantly absorbed by a counterpropagating atom moving with velocity v, the frequency ϖ of the light must be kv lower than the resonant frequency for an atom at rest.

As the atom repeatedly absorbs photons, slowing down as desired, the Doppler shift changes and the atom goes out of resonance with the light.

The natural linewidth $\Gamma/2\pi$ of the optical transition in Na is 10MHz (full width at half maximum). A change in velocity of 6 m/s gives a Doppler shift this large, so after absorbing only 200 photons, the atom is far enough off resonance that the rate of absorption is significantly reduced.

The result is that only atoms with the ‘‘proper’’ velocity to be resonant with the laser are slowed, and they are only slowed by a small amount.

Doppler cooling in one dimension



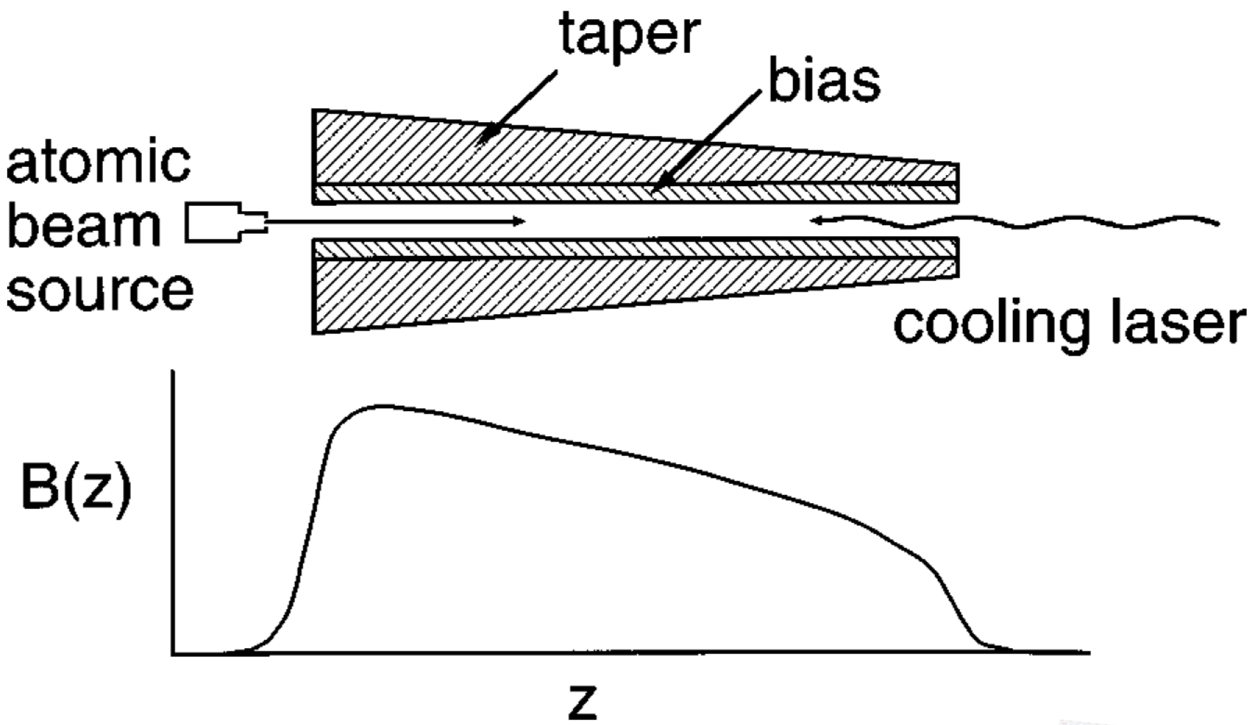
Laser beams are tuned slightly below the atomic resonance frequency.

An atom moving toward the left sees that the laser beam opposing its motion is Doppler shifted toward the atomic resonance frequency.

It sees that the laser beam directed along its motion is Doppler shifted further from its resonance. The atom therefore absorbs more strongly from the laser beam that opposes its motion, and it slows down.

The same thing happens to an atom moving to the right, so all atoms are slowed by this arrangement of laser beams.

Zeeman slower

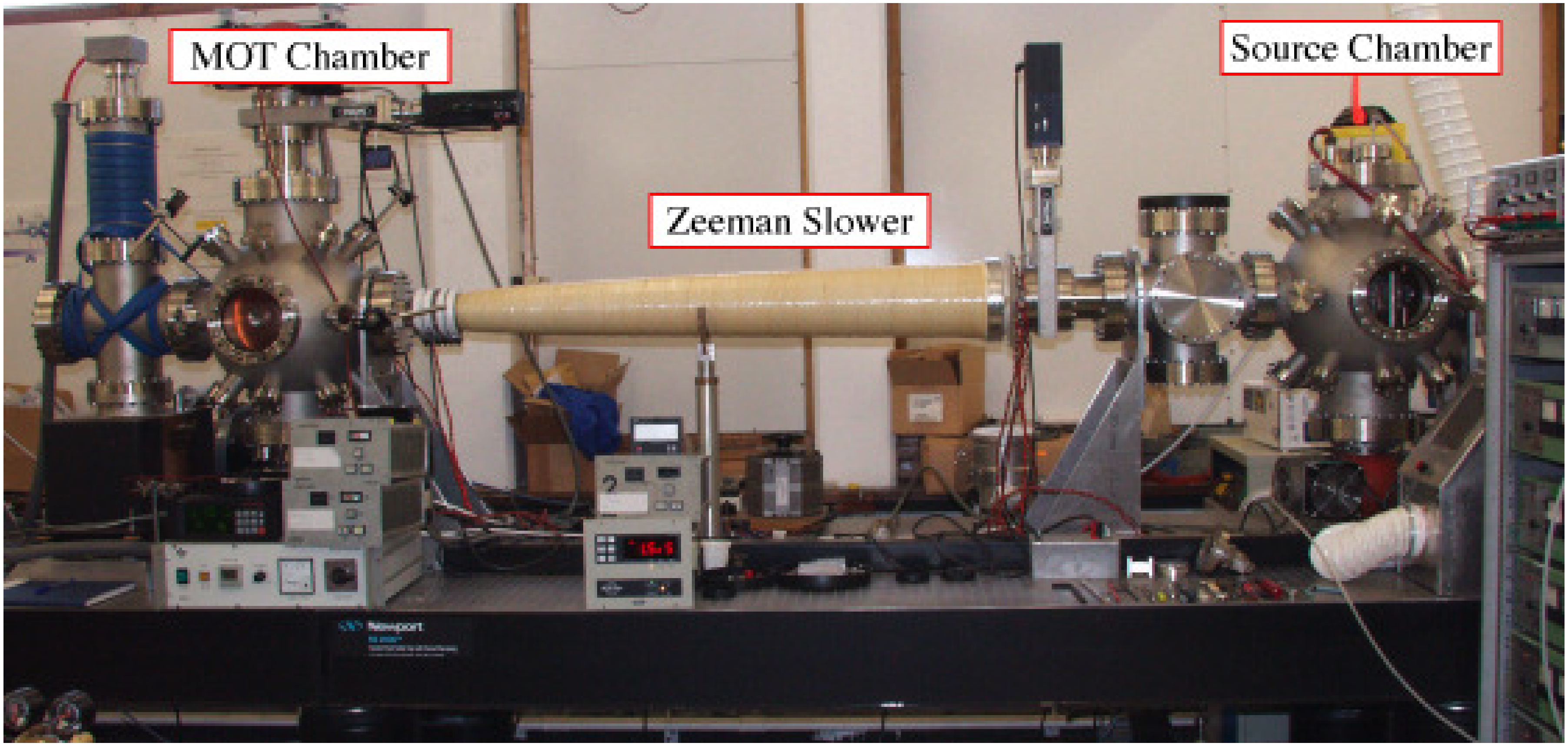


The laser is tuned so that, given the field induced Zeeman shift and the velocity-induced Doppler shift of the atomic transition frequency, atoms with velocity v_0 are resonant with the laser when they reach the point where the field is maximum.

Those atoms then absorb light and begin to slow down. As their velocity changes, their Doppler shift changes, but is compensated by the change in Zeeman shift as the atoms move to a point where the field is weaker. At this point, atoms with initial velocities slightly lower than v_0 come into resonance and begin to slow down.

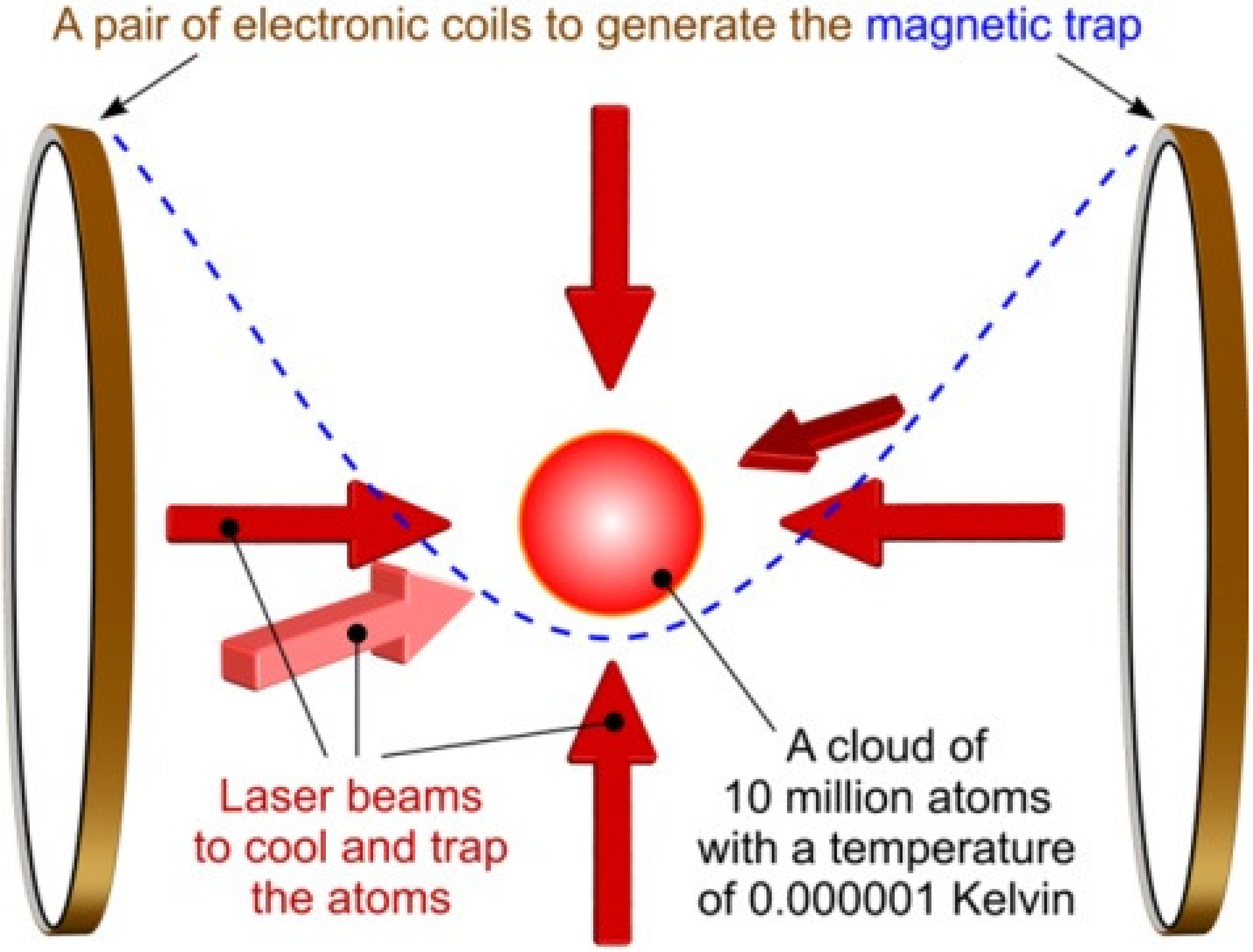
The process continues with the initially fast atoms decelerating and staying in resonance while initially slower atoms come into resonance and begin to be slowed as they move further down the solenoid.

Zeeman Cooling

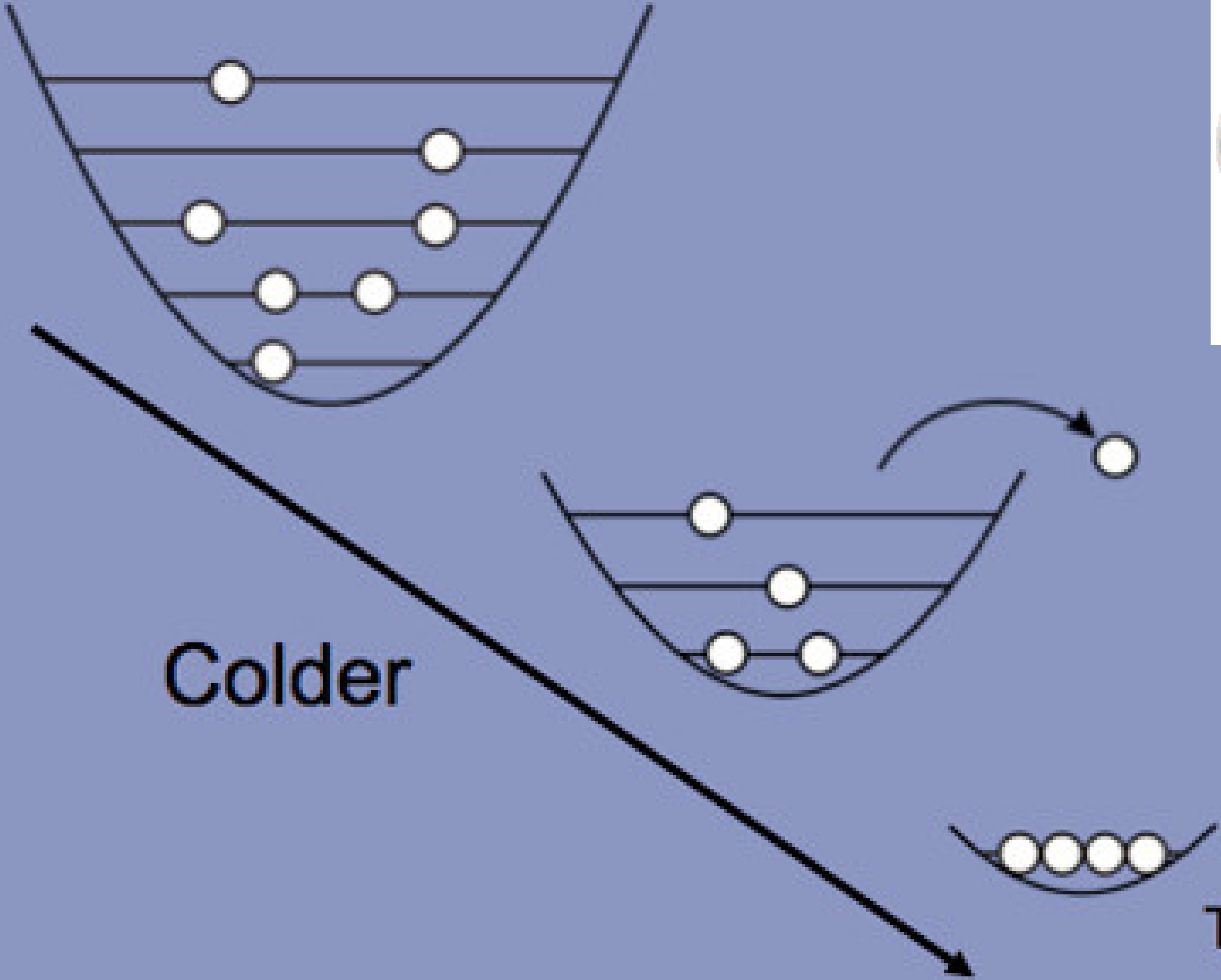


http://es1.ph.man.ac.uk/AJM2/Atomtrapping/Atomtrapping.htm

Magneto-optical trapping (MOT)



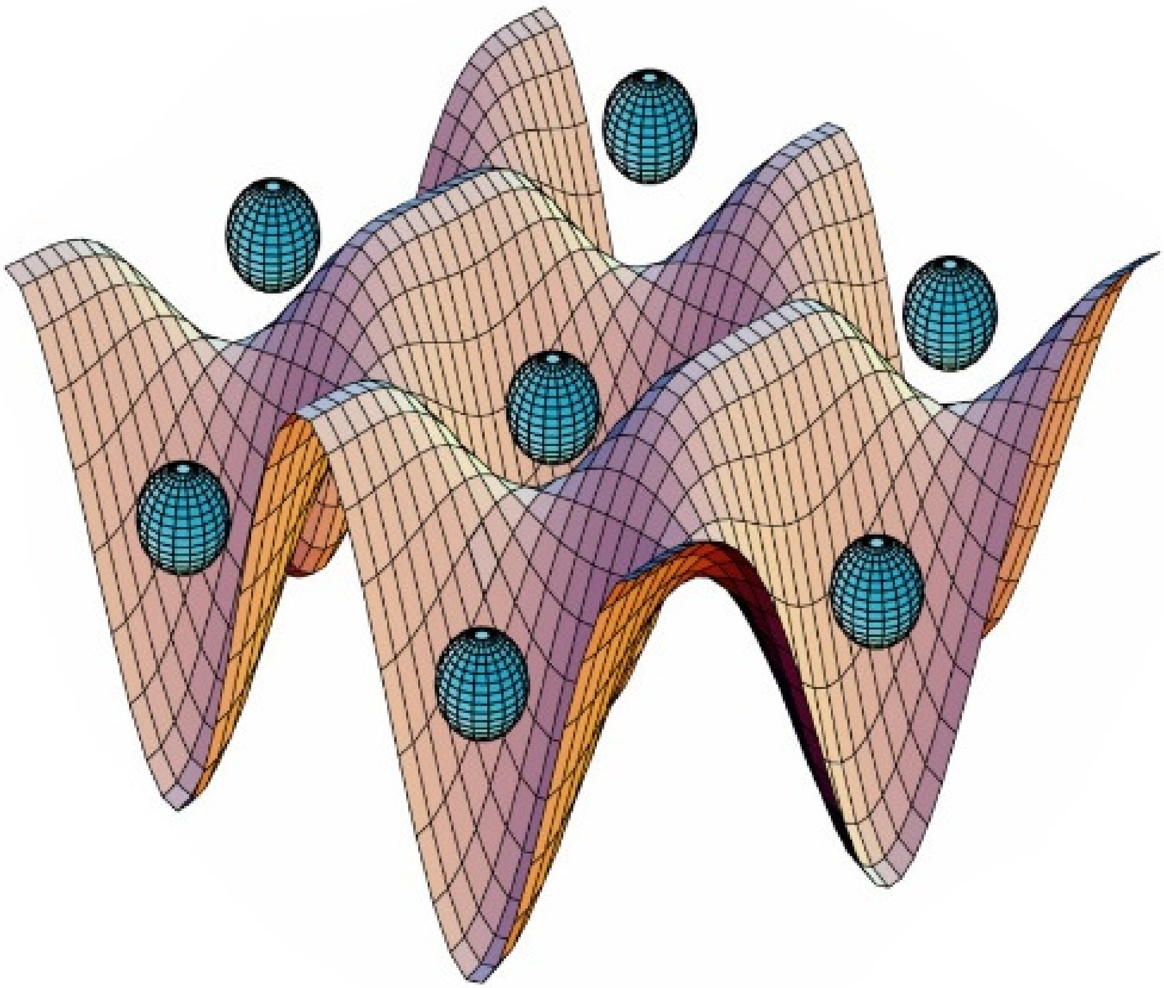
BEC: Cool by evaporation



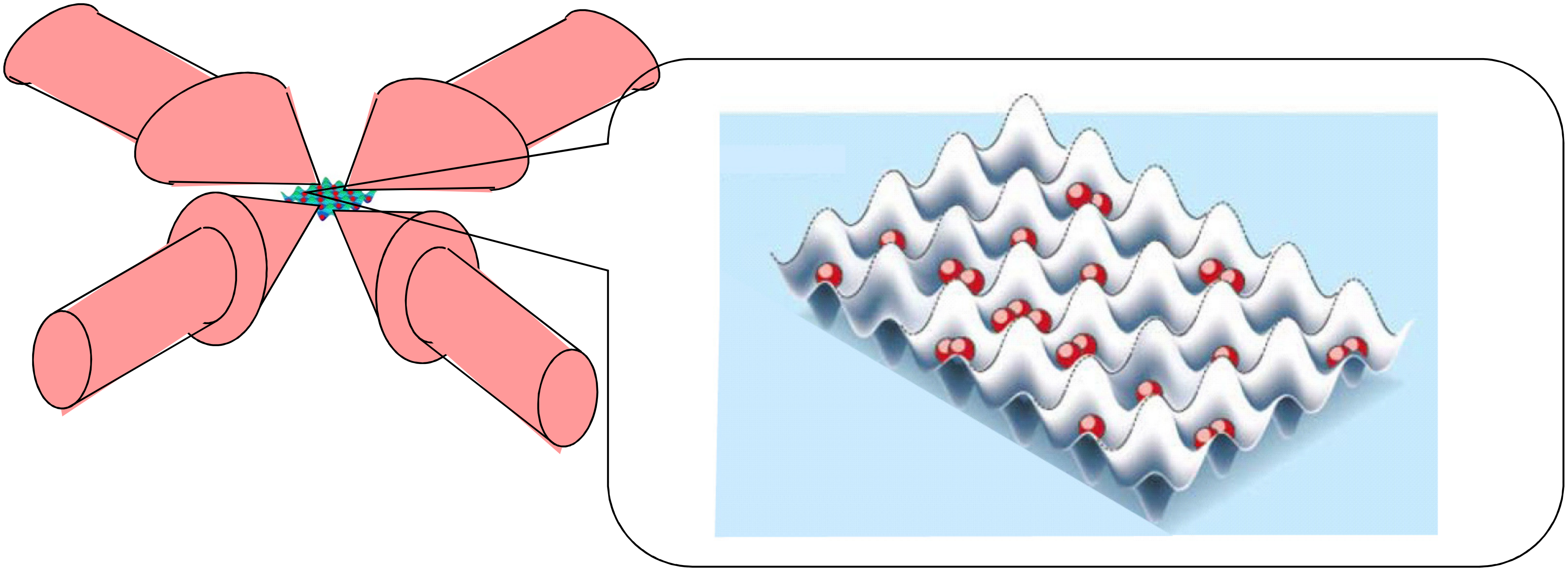
Temp ~ 50 nK

Evaporative cooling

Optical lattice trap



Atoms in optical lattices



An optical lattice works as follows. When atoms are exposed to a laser field that is not resonant with an atomic optical transition (and thus does not excite the atomic electrons), they experience a conservative potential that is proportional to the laser intensity. With two counterpropagating laser fields, a standing wave is created and the atoms feel a periodic potential. With three such standing waves along three orthogonal spatial directions, one obtains a three-dimensional optical lattice. The atoms are trapped at the minima of the corresponding potential wells.

Adapted from: Eugene Demler

Optical lattices vs. real crystals

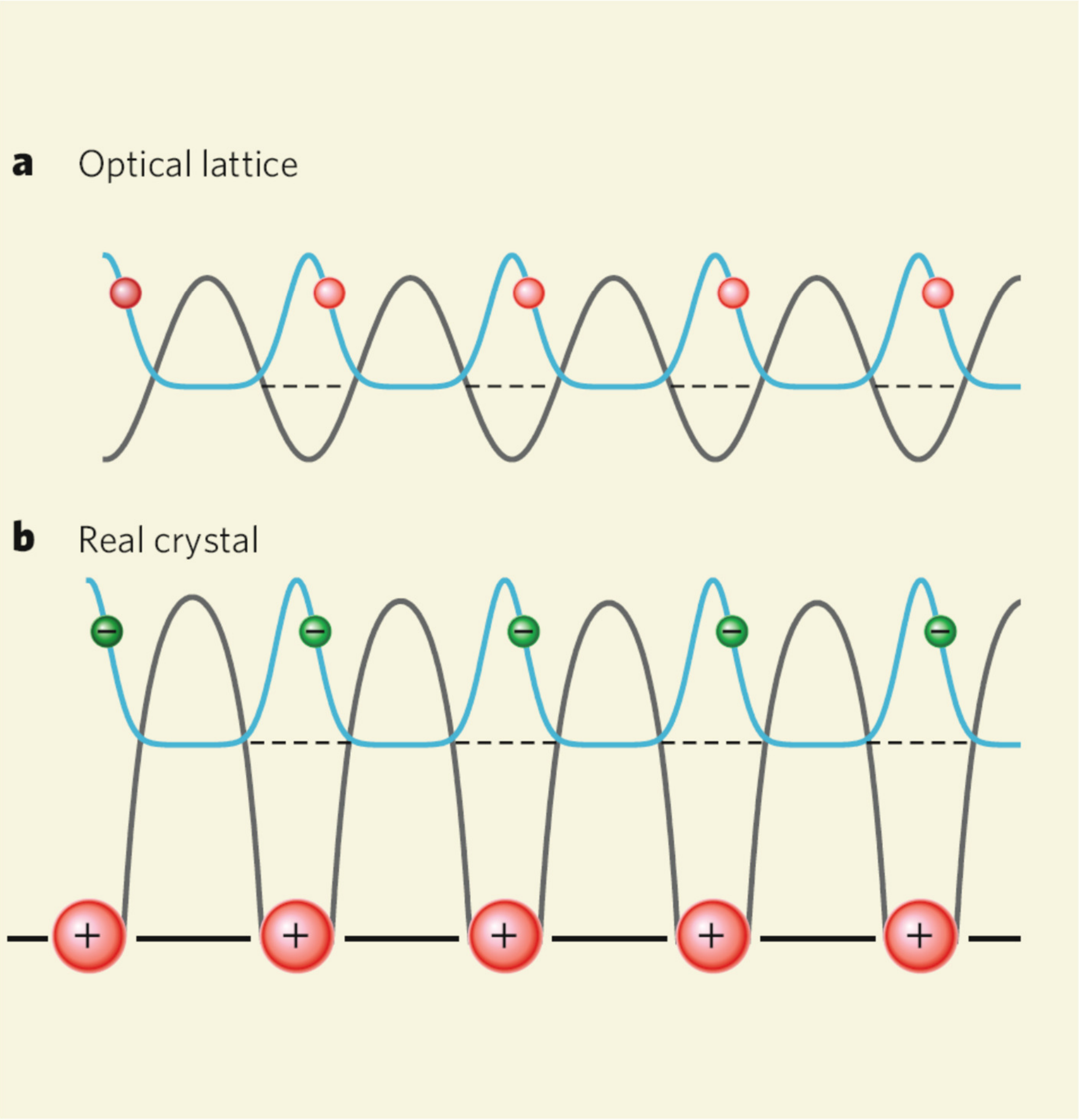
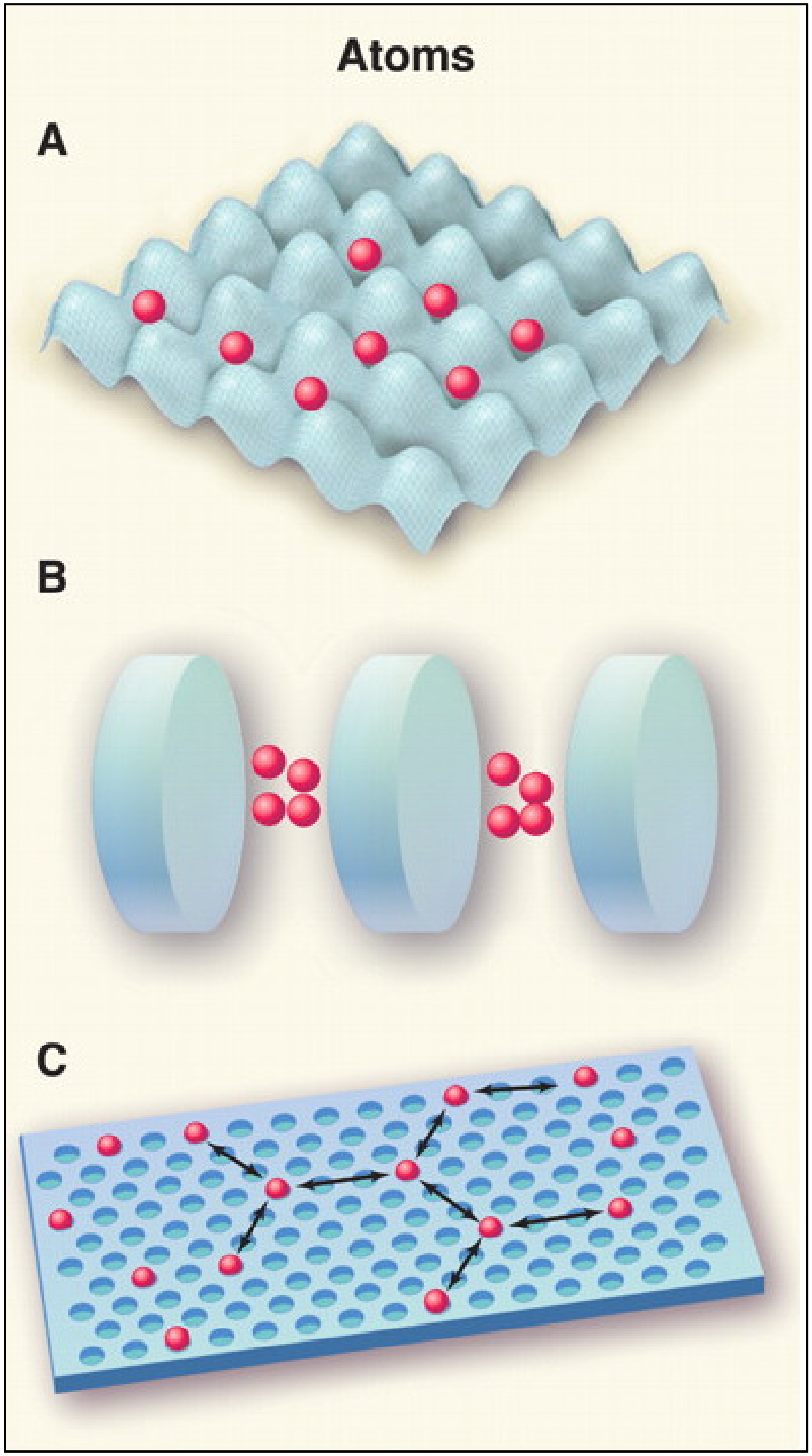


Figure 1 | Crystal simulation. Ultracold atoms in an optical lattice can simulate condensed-matter phenomena that usually occur only in the 'electron gas' of a solid-state crystal. In an optical lattice (**a**), atoms are trapped in a sinusoidal potential well (grey) created by a standing-wave laser beam. The atoms' wavefunctions (blue) correspond to those of valence electrons in a real crystal (**b**). Here, the periodic potential is caused by the attractive electrostatic force between the electrons (–) and the ions (+) forming the crystal. The motion and interaction of the particles, whether ultracold atoms or electrons, determine the physics of the material. Thus, for example, superfluidity in a gas of ultracold atoms corresponds to superconductivity in an electron gas.

Nature 453, 736 (2008)

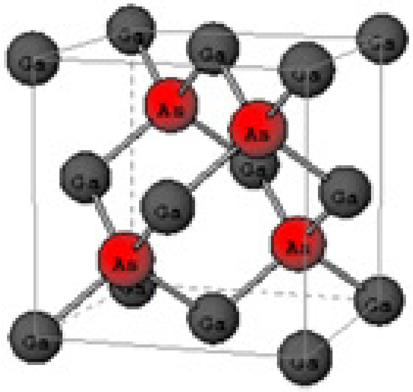


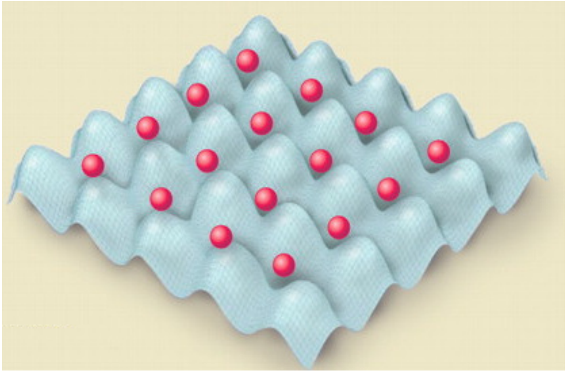
Atoms in optical lattices (**A**) or in
1D (**B**) or
2D (**C**) arrays of cavities.

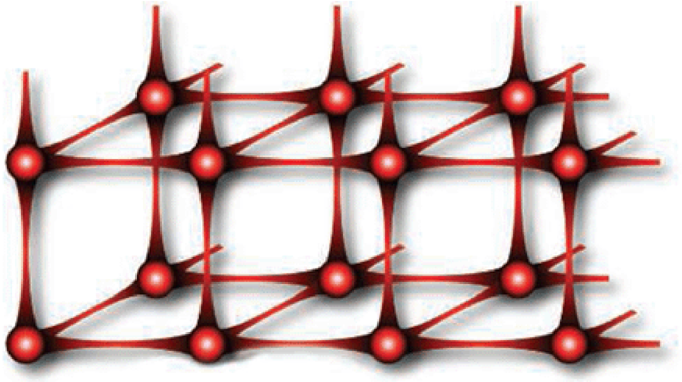
Optical lattices for quantum simulation

An optical lattice is essentially an **artificial crystal of light** - a periodic intensity pattern that is formed by the interference of two or more laser beams.

Imagine having an **artificial substance** in which you can control almost all aspects of the underlying periodic structure and the interactions between the atoms that make up this dream material.

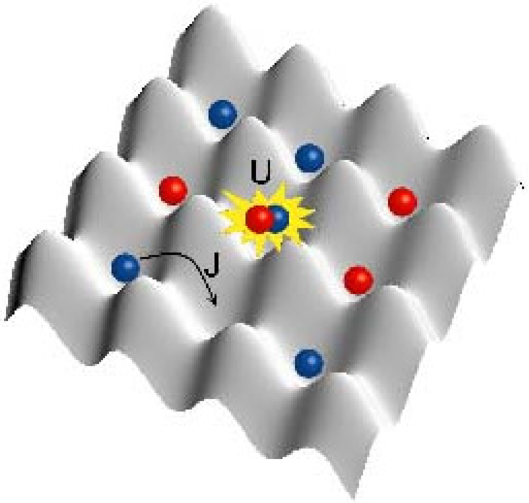


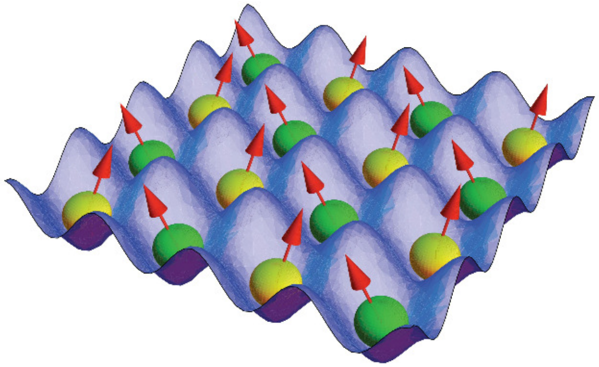




Such a substance would allow us to explore a whole range of fundamental phenomena that are extremely difficult - or impossible - to study in real materials.

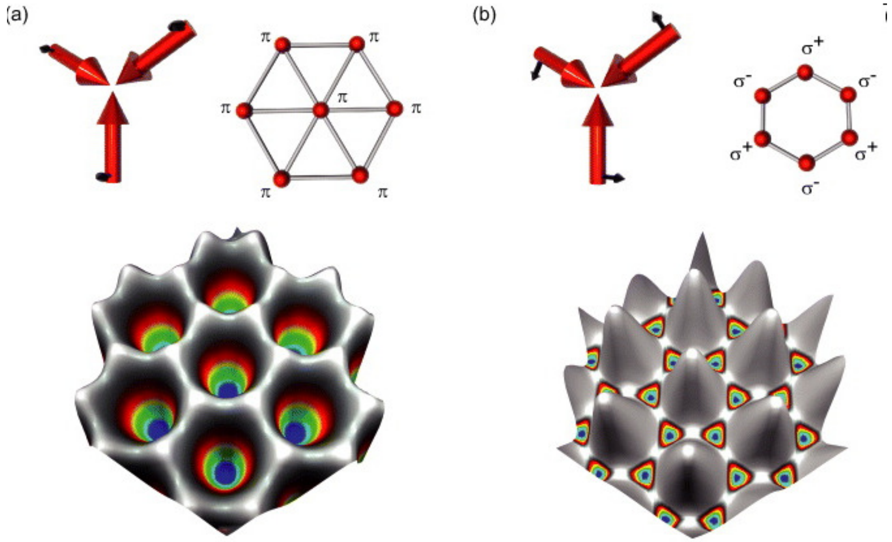
What lattice parameters can we change?

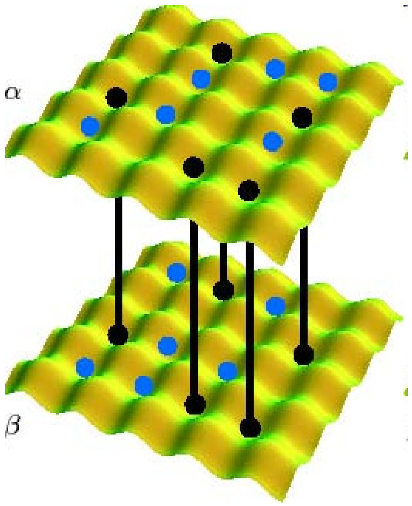


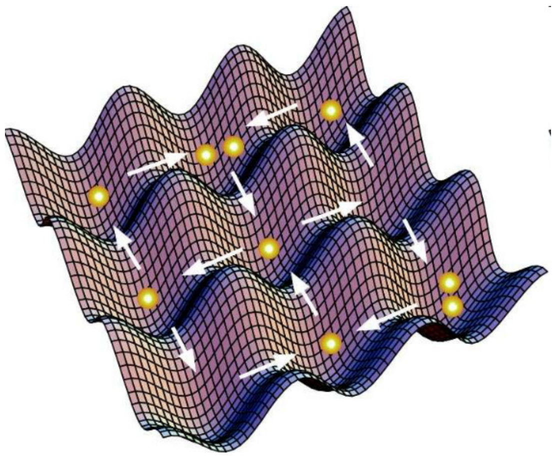


Practically anything!

- 1D, 2D, 3D
- Lattice wavelength
- Lattice geometry
- J/U (depth of the potential)
- Lattice loading
- Bosons or fermions or both
- Spin arrangements
- Introduce disorder, etc.







OLAQU; New J. Phys. **12** (2010) 065025; New J. Phys. 10 (2008) 073032
ihttp://www.physnet.uni-hamburg.de/ilp2/hemmerich/en/research.html

What do we need to build a quantum computer?

- **Qubits** which retain their properties.
  Scalable array of qubits.
- **Initialization:** ability to prepare one certain state repeatedly on demand. Need continuous supply of $|0\rangle$.
- **Universal set of quantum gates.** A system in which qubits can be made to evolve as desired.
- **Long relevant decoherence times.**
- Ability to efficiently **read out the result.**

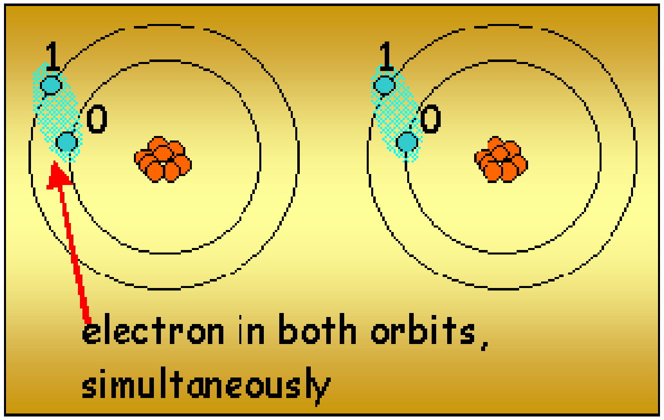
1. A scalable physical system with well characterized qubits: memory

Internal atomic state qubits:

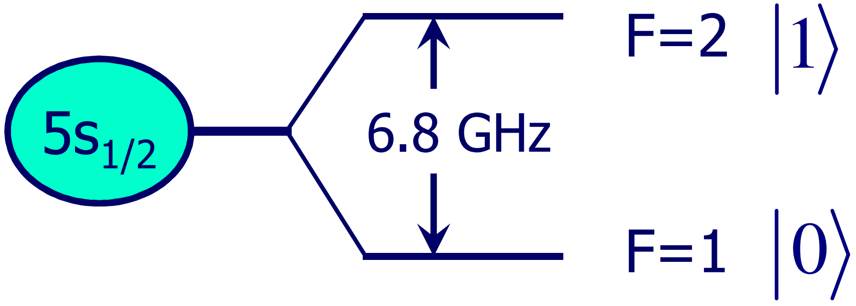
ground hyperfine states of neutral trapped atoms

well characterized

Very long lived!



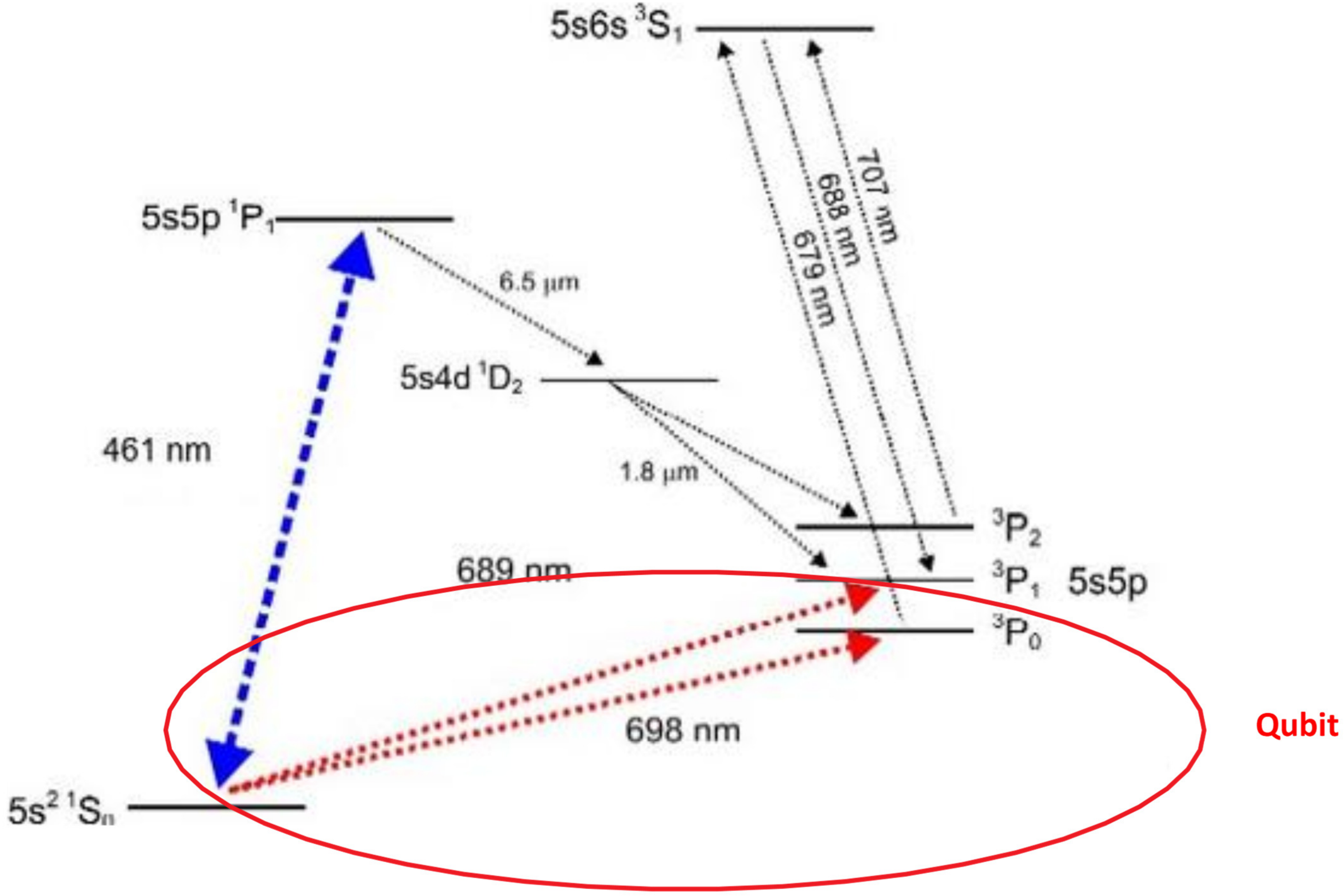
M_F=-2,-1,0,1,2



^{87}Rb: Nuclear spin I=3/2

M_F=-1,0,1

Alkaline-earth metal atoms: lowest excited level is also metastable.



Strontium energy level diagram

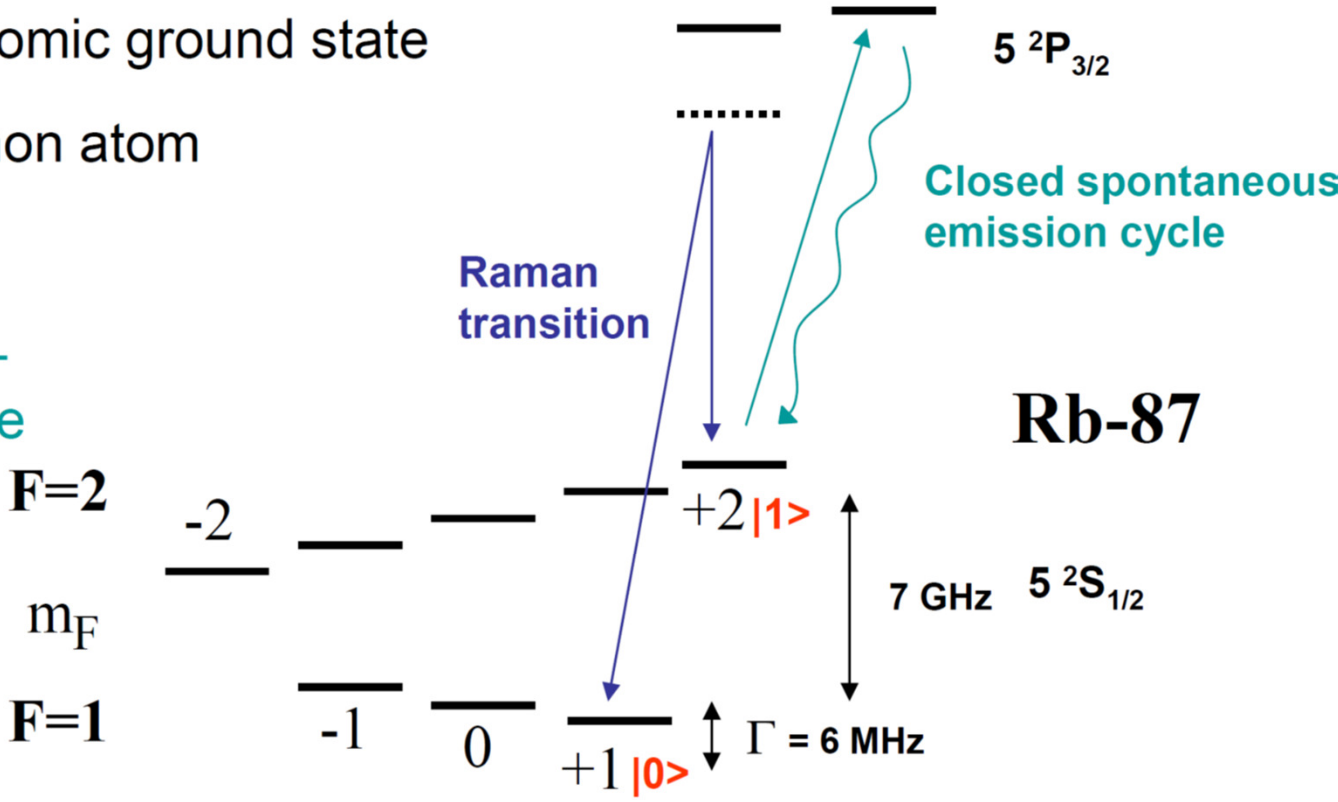
Encoding qubits and 1-qubit operations

In hyperfine levels of the atomic ground state

Rb-87 is the most common atom
to use for laser cooling

Uses of Closed transition –
1) Optical pumping for state preparation
2) Readout of qubit |1>

Raman transition performs single qubit rotation selectively on a single qubit



Choice of magnetic sublevels may depend on details of 2-qubit gate

Talk: M. Shotter

2: Initialization

Internal state preparation: putting atoms in the ground hyperfine state

Very well understood (optical pumping technique is in use since 1950)

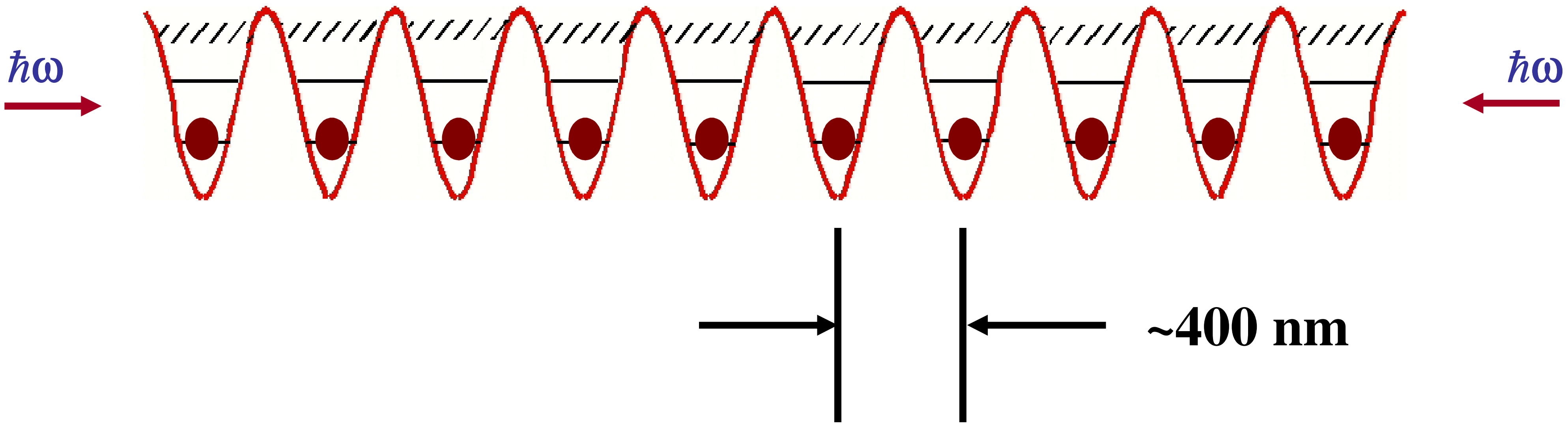
Very reliable (>0.9999 population may be achieved)

Motional states may be cooled to motional ground states (>95%)

Loading with one atom per site: Mott insulator transition and other schemes.

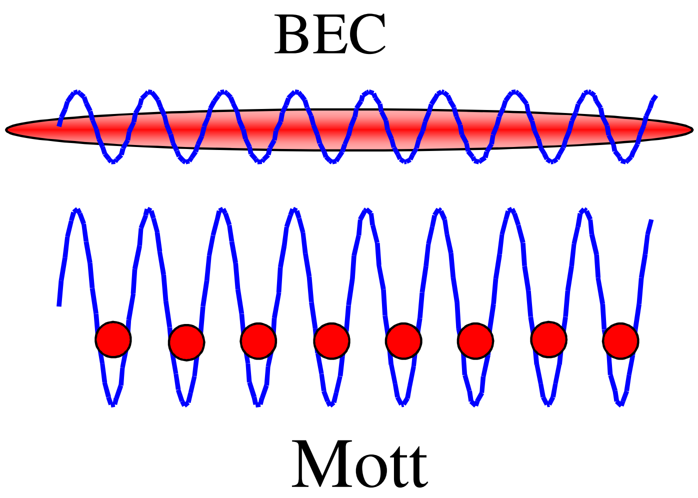
Zero's may be supplied during the computation (providing individual or array addressing).

The periodic potential of an optical lattice is a natural, nanoscale register for atomic qubits



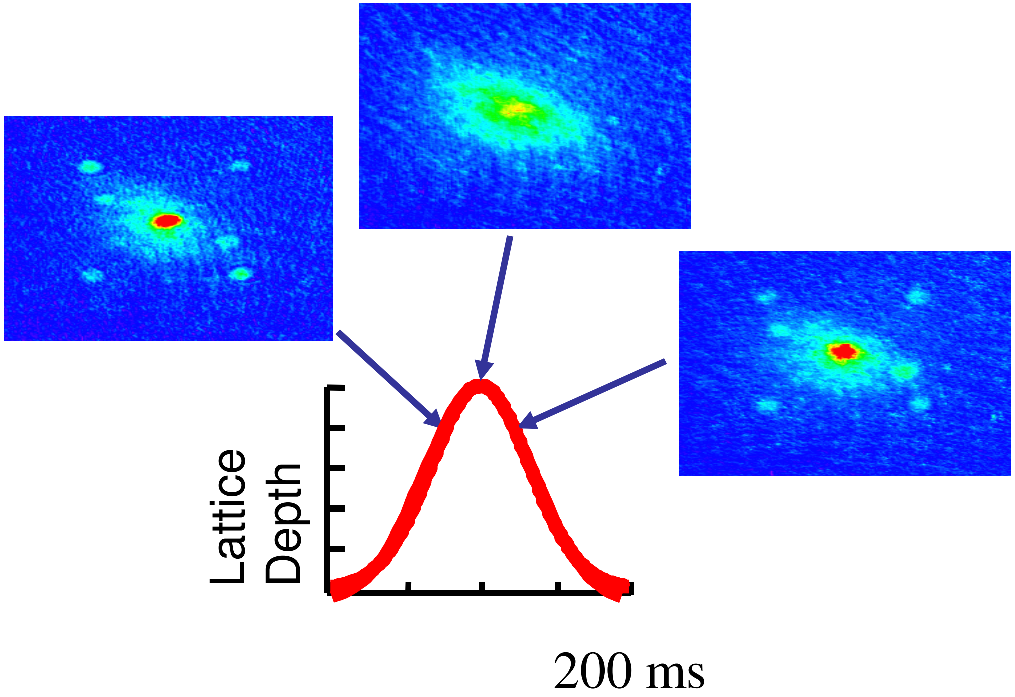
But, we also need to have just one atom per site!

Mott transition: initialization of >10^5 qubits in a 3-d lattice



Lattice is deepened adiabatically; repulsive interactions arrange atoms, one per site.

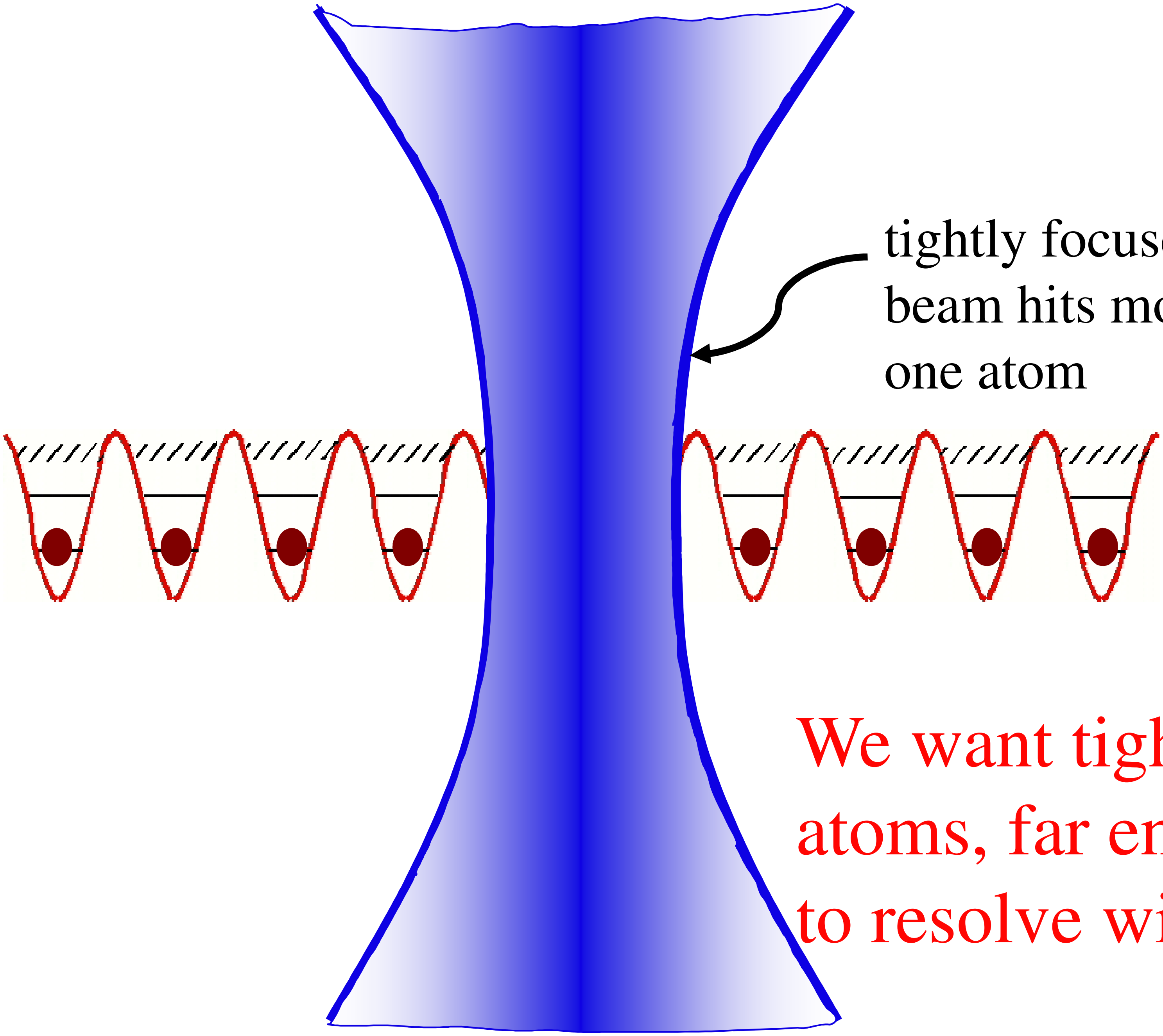
Phil. Trans. R. Soc. Lond. A **361**, 1417 (2003)



(similar results in Munich)

According to theory, ground state provides a very high fidelity initialization of a massive register of neutral atom qubits (at $V_0 = 35\ E_R$, < 5% chance of *any* of 10^5 sites having an error).

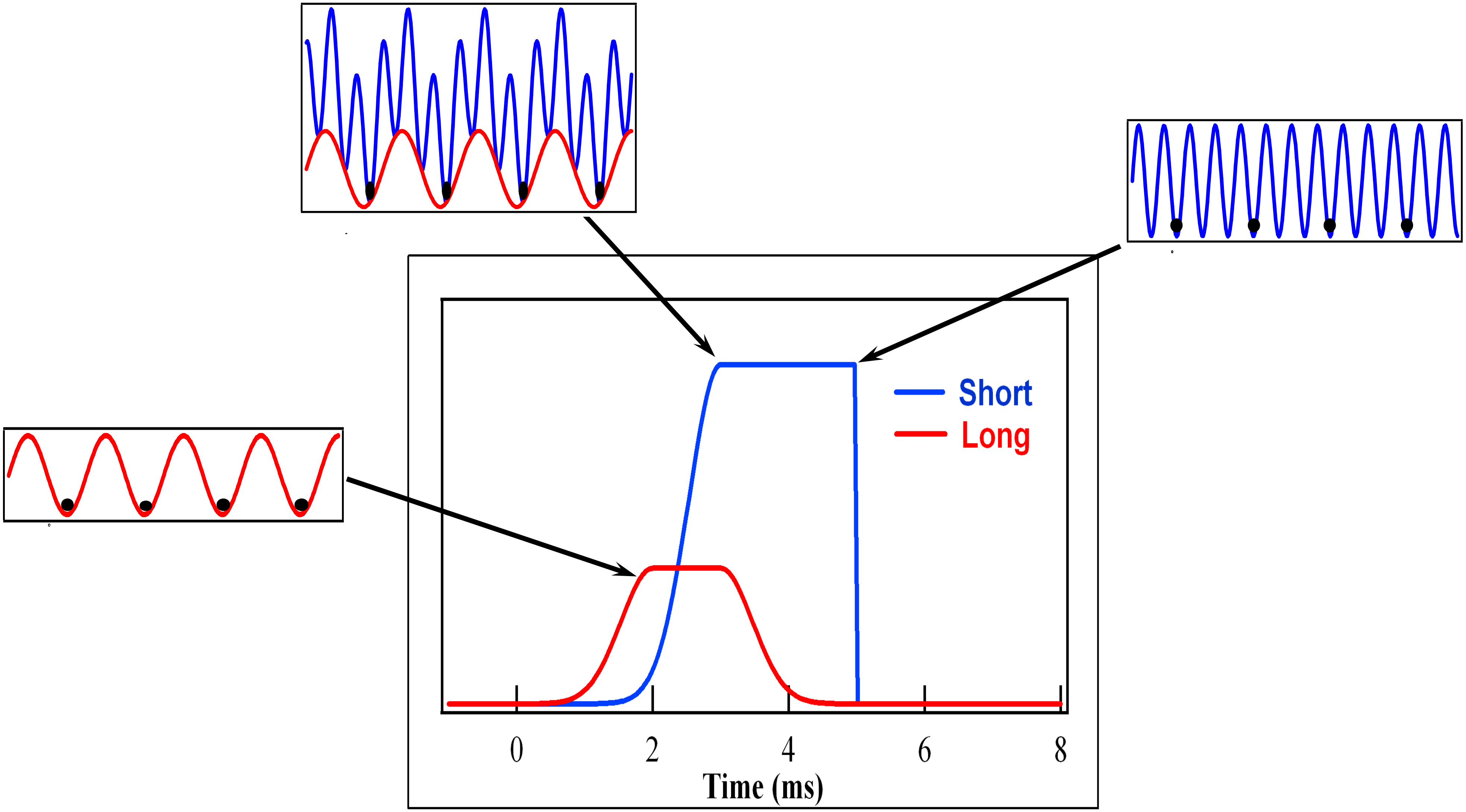
A problem: atoms in adjacent lattice sites are not optically resolved



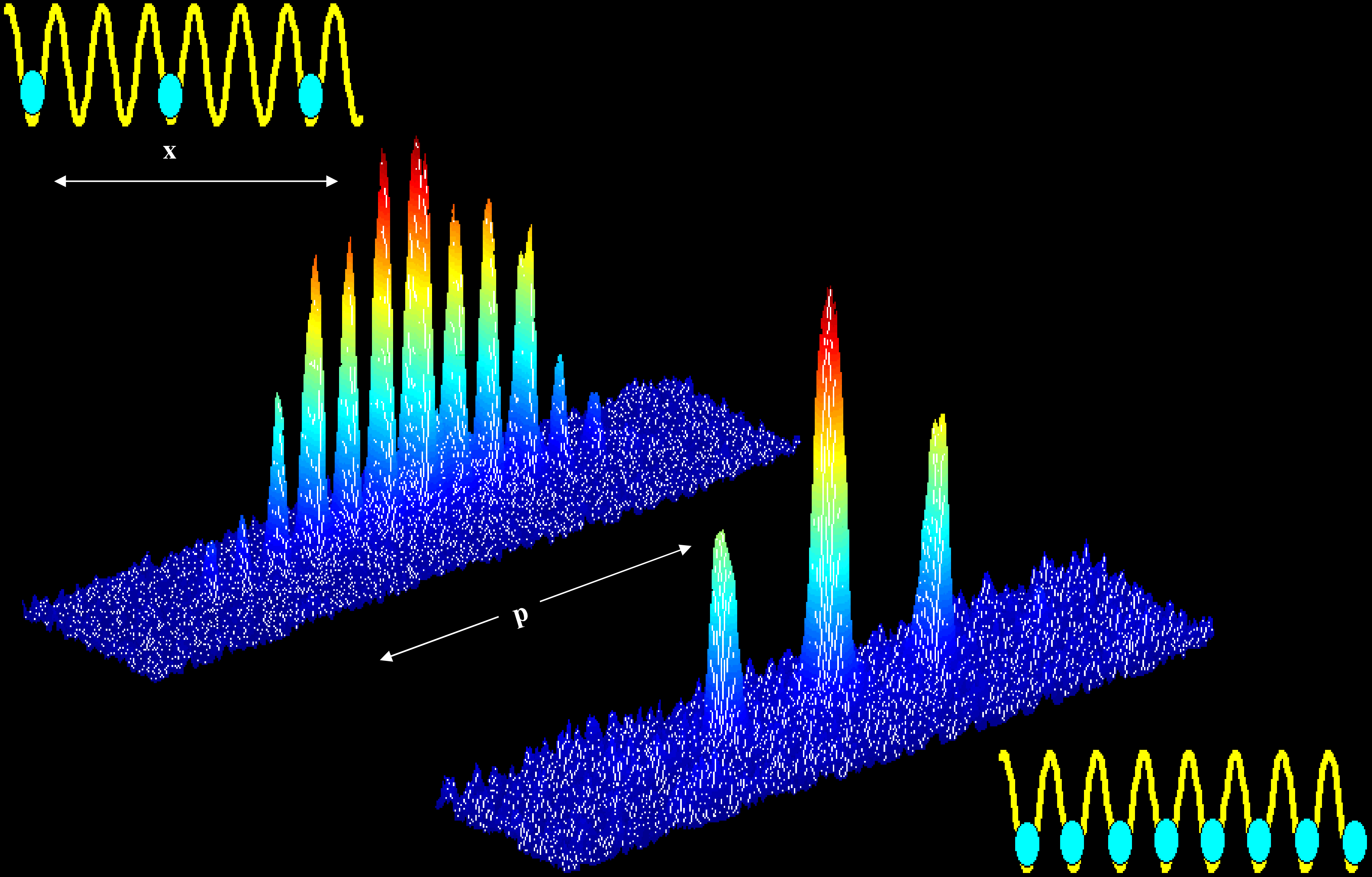
tightly focused laser beam hits more than one atom

We want tightly confined atoms, far enough apart to resolve with a laser.

Solution: Use a superlattice to localize atoms into every n^{th} lattice site



Patterned loading

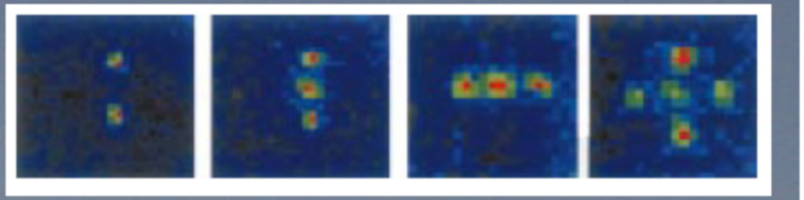


NIST-Gaithersburg 2002

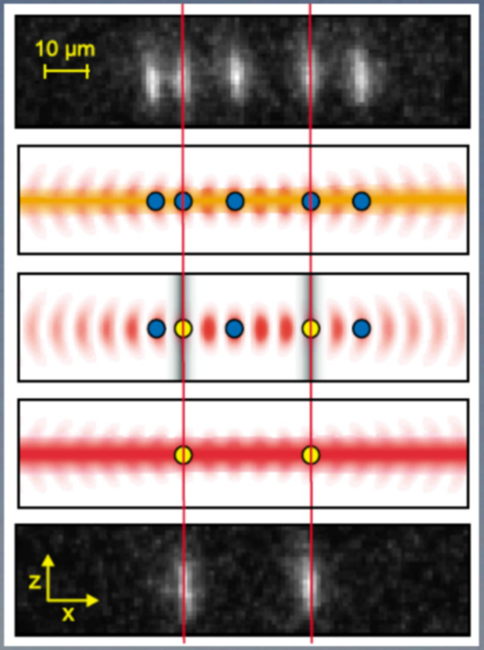
Atomic Qubit Array

Alternative: array of traps

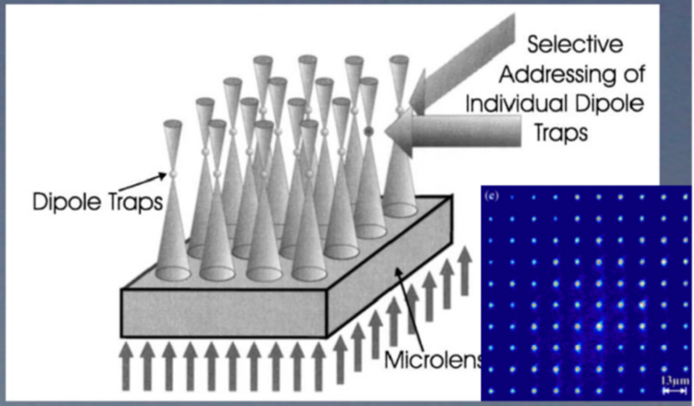
Orsay 2004



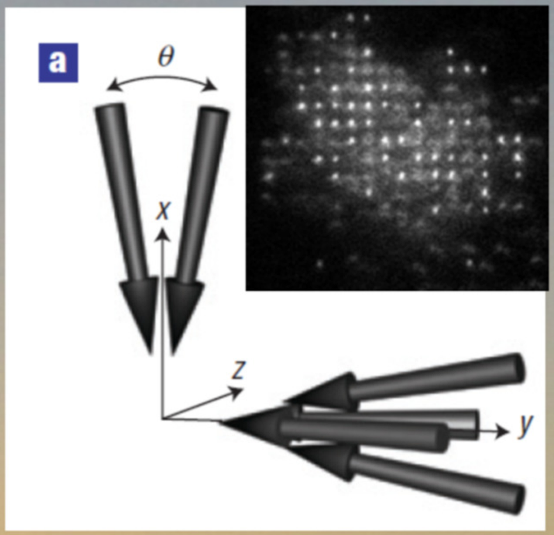
Bonn 2004



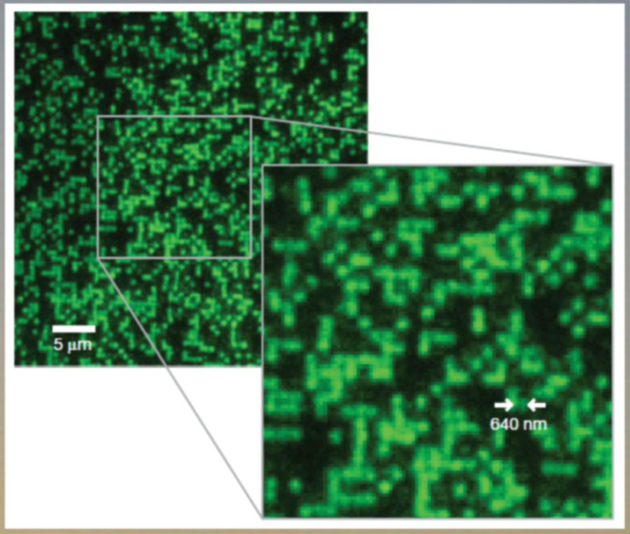
Darmstadt 2010



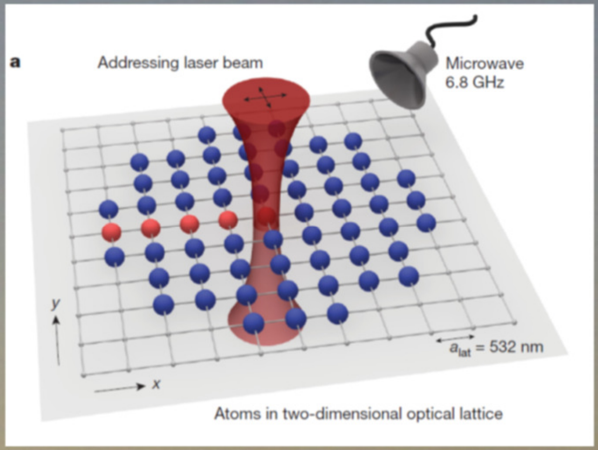
Penn State 2007



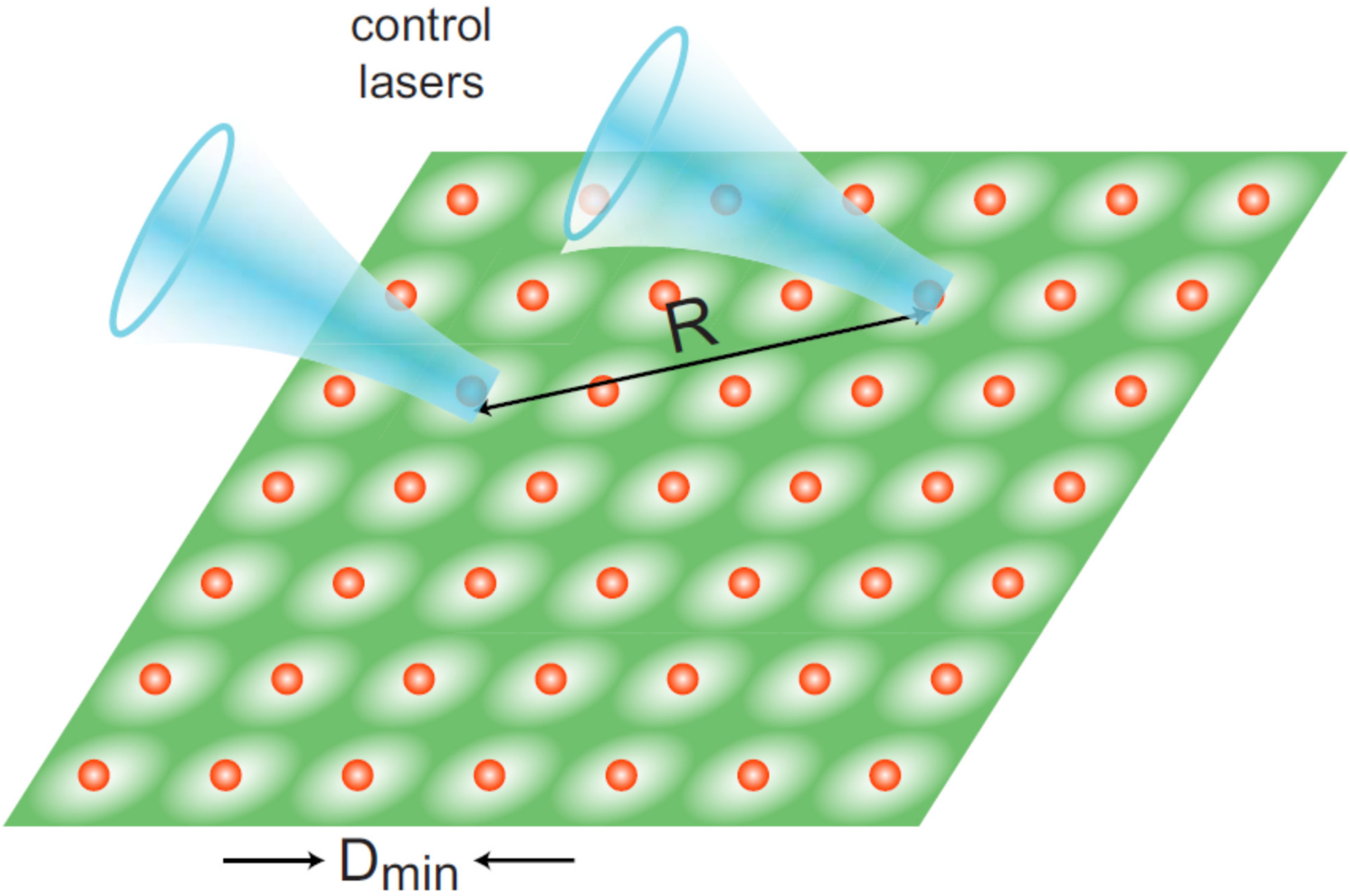
Harvard 2009



Munich 2011



Talk: Mark Saffman



Neutral-atom qubit array in an optical lattice with period D_{min}. A two-qubit gate between sites separated by R is implemented with focused laser beams.

Rev. Mod. Phys., Vol. 82, 2010

3: A universal set of quantum gates

1. Single-qubit rotations: well understood and had been carried out in atomic spectroscopy since 1940's.

2. Two-qubit gates: none currently implemented (conditional logic was demonstrated)

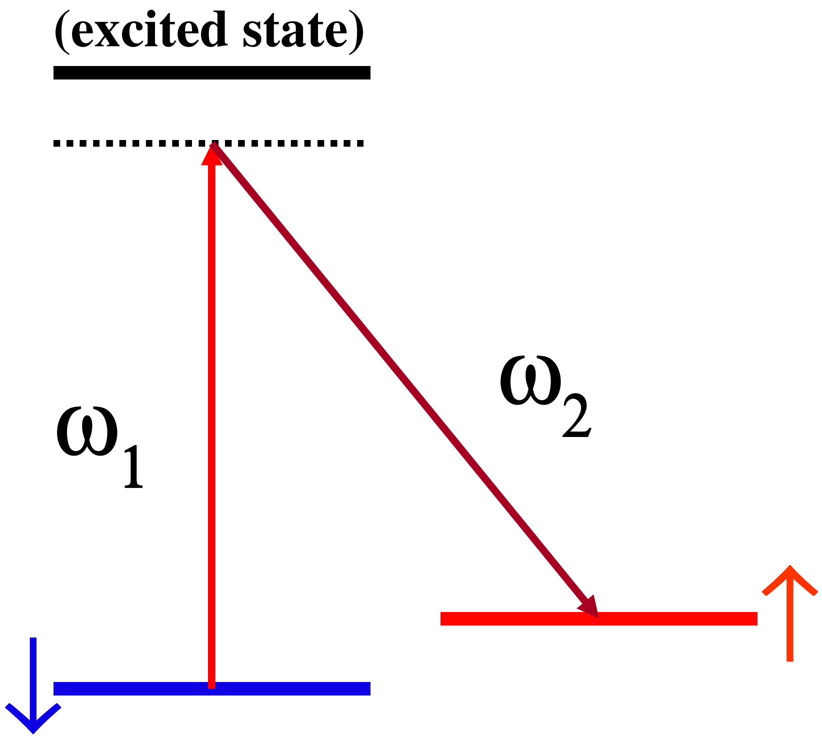
Proposed interactions for two-qubit gates:

(a) Electric-dipole interactions between atoms
(b) Ground-state elastic collisions
(c) Magnetic dipole interactions

Only one gate proposal does not involve moving atoms (Rydberg gate).

Advantages: possible parallel operations
Disadvantages: decoherence issues during gate operations

Quantum Processing: single bit operations



Raman transitions: two laser beams induce transitions between the atomic qubit states.

Rydberg gate scheme

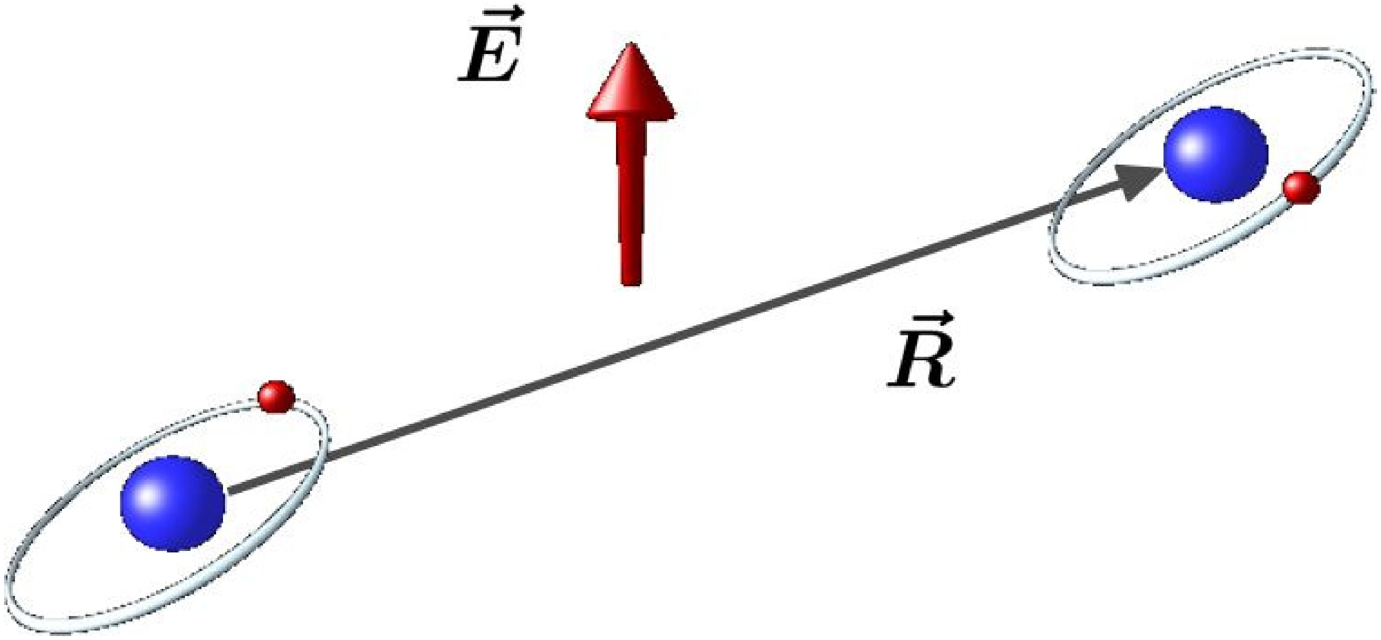
Gate operations are mediated by excitation of Rydberg states
Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)

Do not need to move atoms!

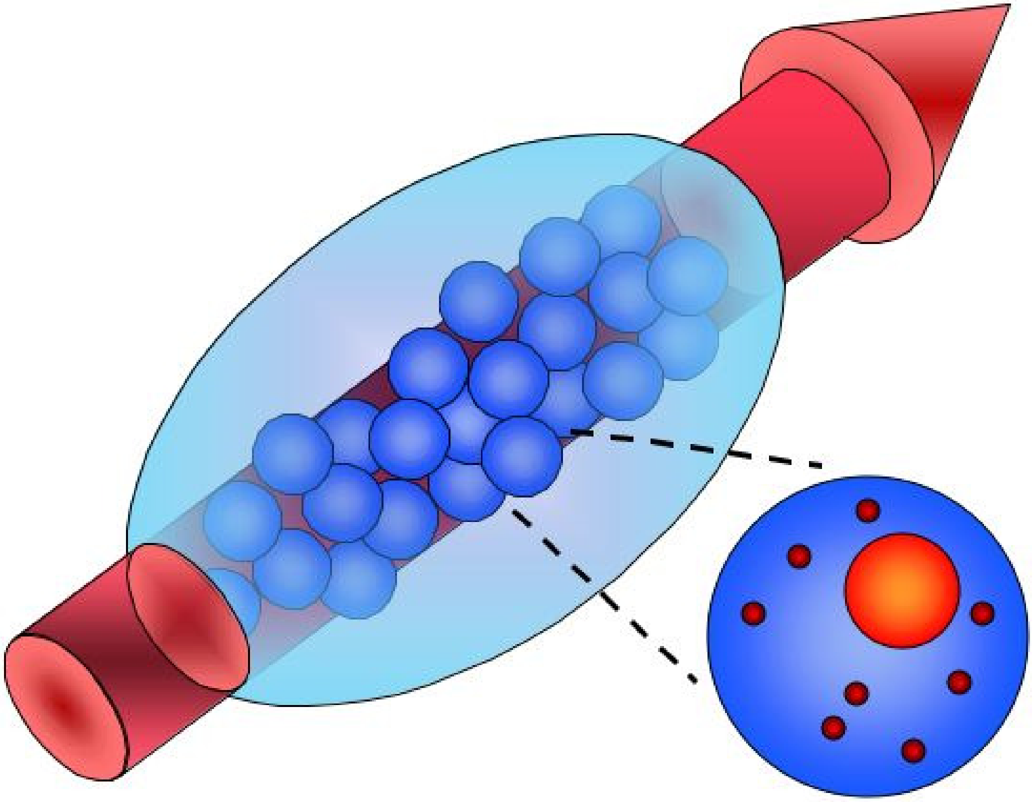
FAST!

Rydberg atoms: atoms is highly-excited states (principal quantum number n is large, n>30)

Rydberg atoms strongly interact with each other



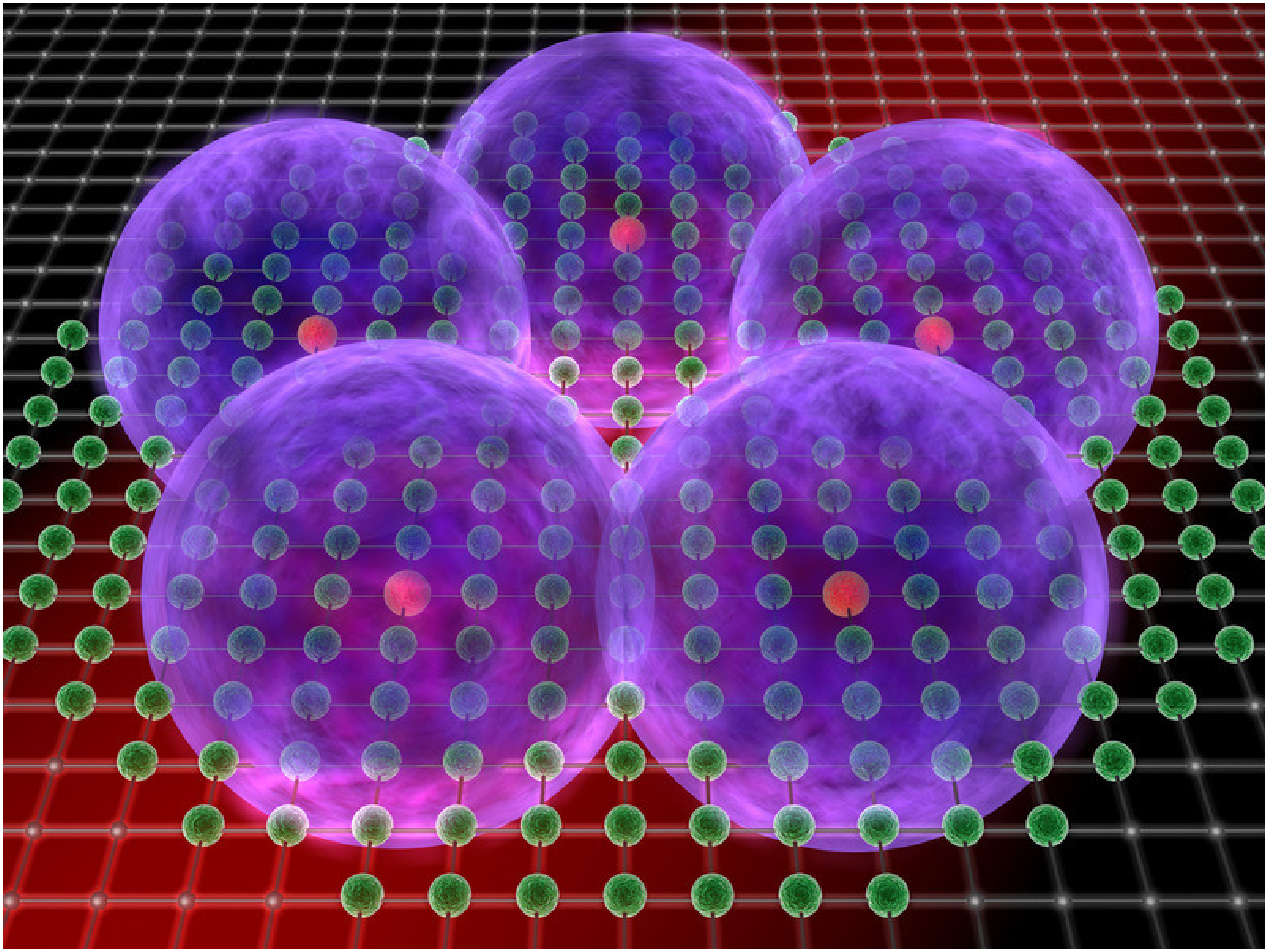
Local blockade of Rydberg excitations



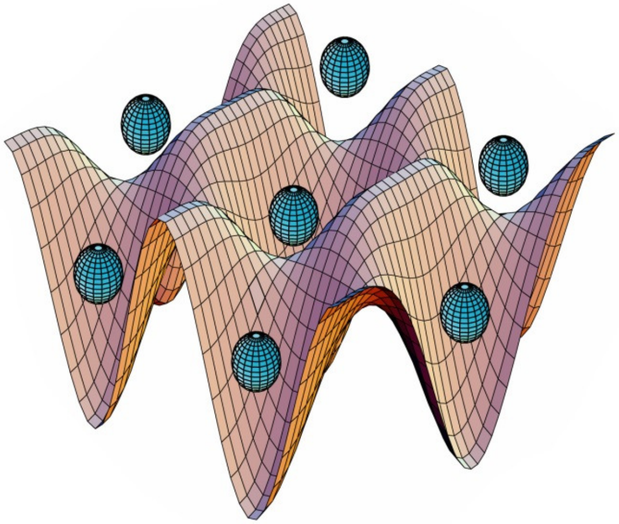
Excitations to Rydberg states are suppressed due to a dipole-dipole interaction or van der Waals interaction

http://www.physics.uconn.edu/~rcote/

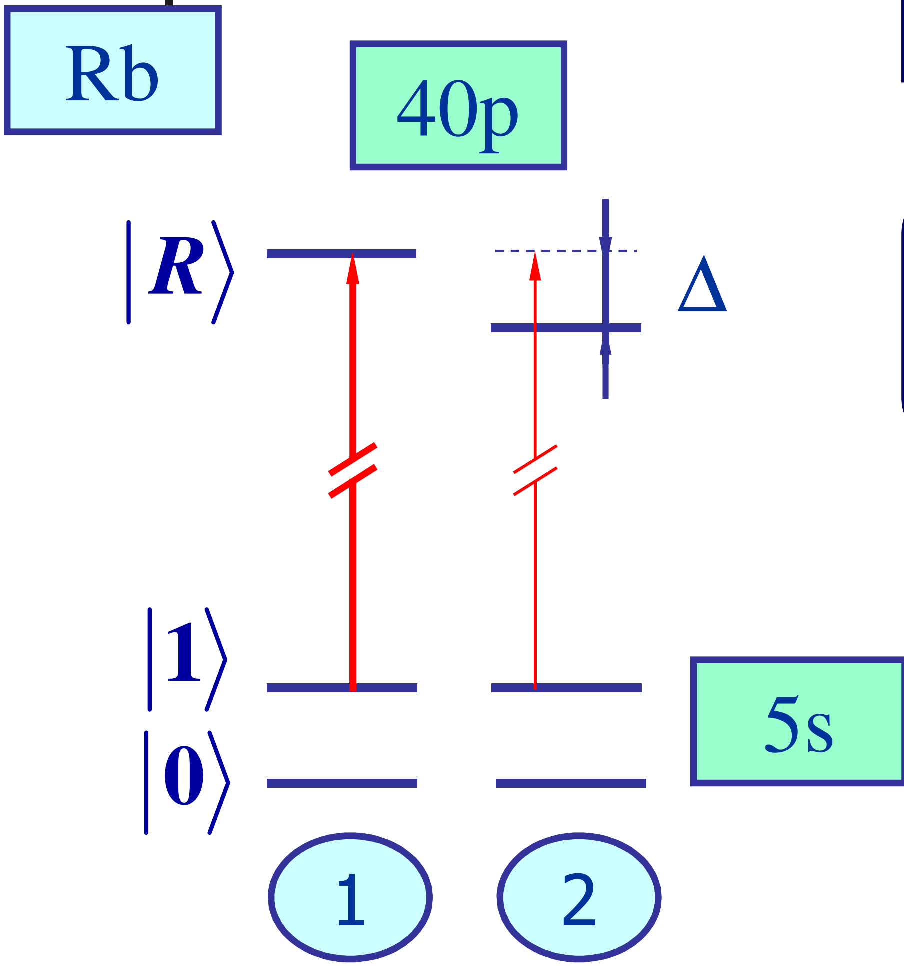
Rydberg “super-atoms” - atoms around them can not be excited into a Rydberg state



Rydberg gate scheme



FAST!



Apply a series of laser pulses to realize the following logic gate:

$$\begin{aligned} |00\rangle &\rightarrow |00\rangle \\ |10\rangle &\rightarrow |01\rangle \\ |01\rangle &\rightarrow |10\rangle \\ |11\rangle &\rightarrow -|11\rangle \end{aligned}$$

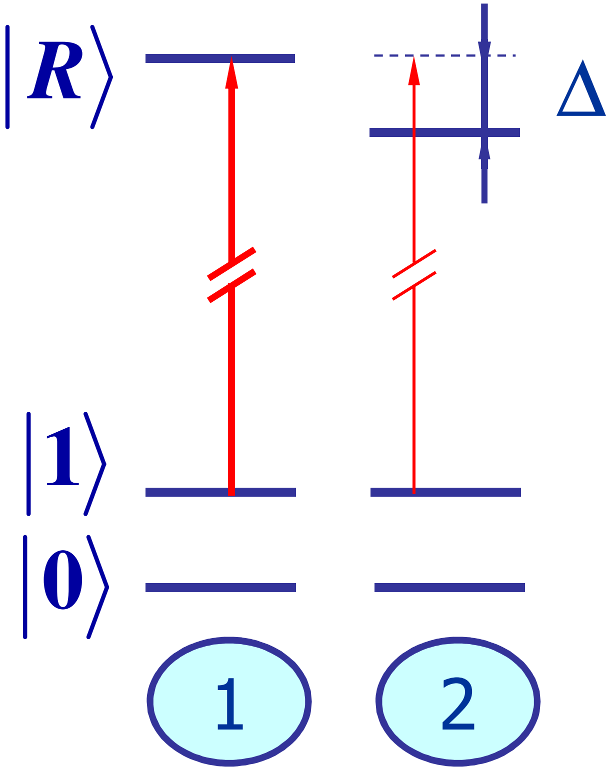
Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)

Rb

5s

Rydberg gate scheme

40p



$$\begin{array}{ccccccc} & \pi[1] & & 2\pi[2] & & \pi[1] & \\ |00\rangle & \to & |00\rangle & \to & |00\rangle & \to & |00\rangle \\ |01\rangle & \to & |01\rangle & \to & -|01\rangle & \to & -|01\rangle \\ |10\rangle & \to & |R0\rangle & \to & |R0\rangle & \to & -|10\rangle \\ |11\rangle & \to & |R1\rangle & \to & |R1\rangle & \to & -|11\rangle \end{array}$$

Decoherence

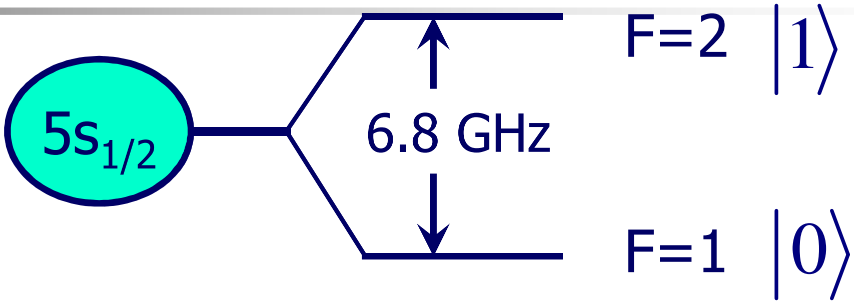
- One of the decoherence sources: motional heating. Results from atom “seeing” different lattice in ground and Rydberg states.
- Solution: choose the lattice photon frequency ω to match frequency-dependent polarizability $\alpha(\omega)$ of the ground and Rydberg states.
- Error correction: possible but error rate has to be really small ($< 10^{-4}$).

Other decoherence sources

- Photoionization
- Spontaneous emission
- Transitions induced by black-body radiation
- Laser beam intensity stability
- Pulse timing stability
- Individual addressing accuracy

4. Long relevant decoherence times

Memory: long-lived states.



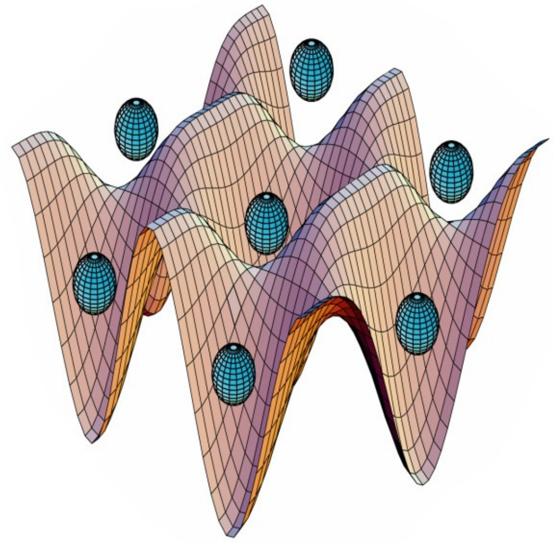
$5s_{1/2}$

6.8 GHz

F=2 $|1\rangle$

F=1 $|0\rangle$

Fundamental decoherence mechanism for optically trapped qubits: photon scattering.



Decoherence during gate operations: a serious issue.

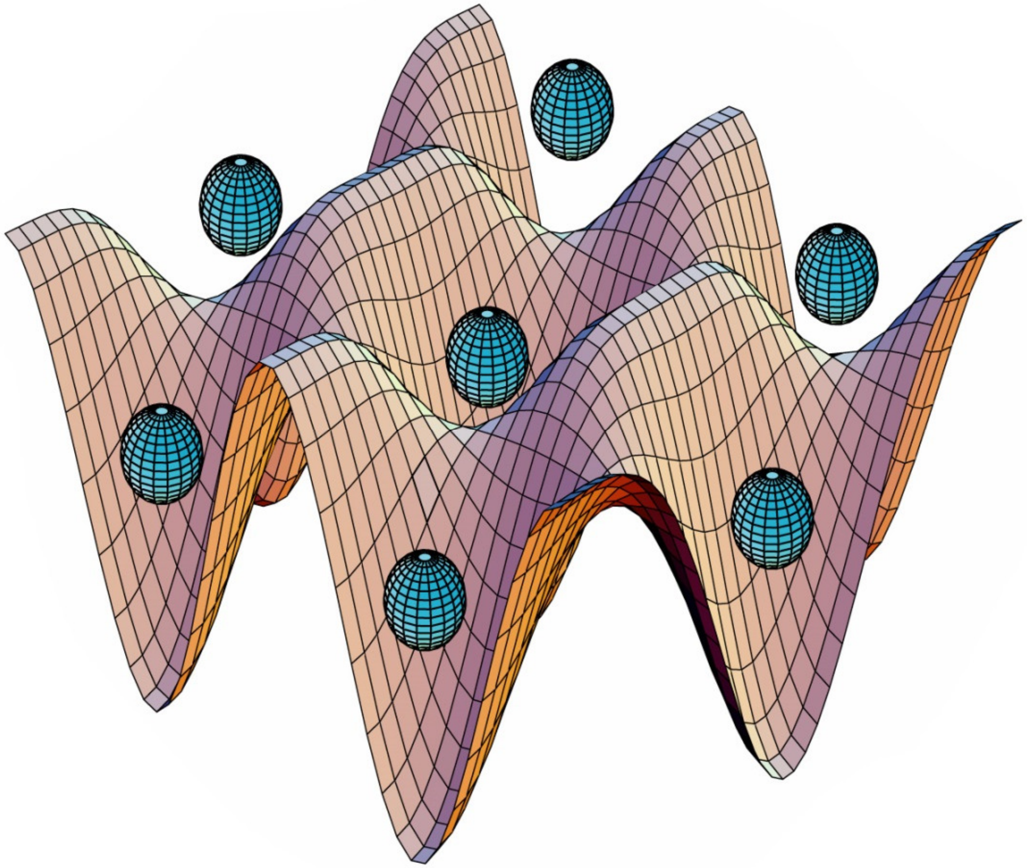
5: Reading out a result

“Quantum jump” method via cycling transitions.

Advantages: standard atomic physics technique, well understood and reliable.

Quantum computation with NEUTRAL ATOMS: ADVANTAGES

Scalability



Possible massive parallelism due to lattice geometry

Long decoherence times (weak coupling to the environment)

Availability of the controlled interactions

Well-developed experimental techniques for initialization, state manipulation, and readout

Accurate theoretical description of the system is possible.

Quantum computation with NEUTRAL ATOMS: PROBLEMS

Decoherence during the gate operations
(various sources)

Reliable lattice loading and individual addressing

QC architecture for lattice geometry:
Error-correcting codes and fault-tolerant computation,
how to run algorithms on neutral atom quantum computer.