From presentations by
M Safronova, Delaware

Quantum Simulation and

Quantum Computing with Neutral Atoms

How does one produce optical lattices with one atom per site ?

Cooling strategies

Laser cooling of atomic beams

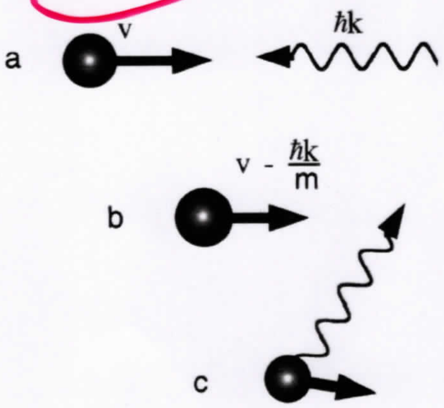
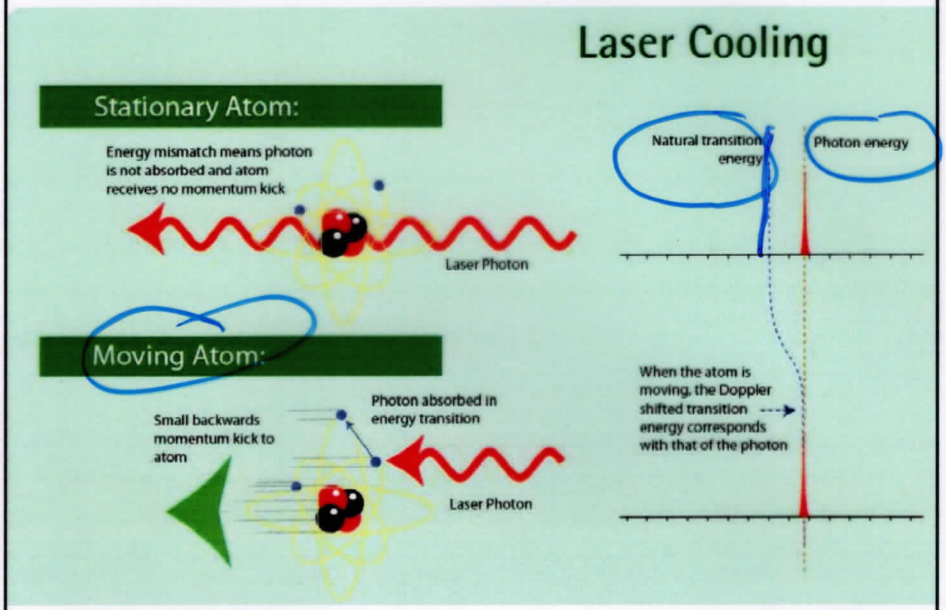


FIG. 1. (a) An atom with velocity v encounters a photon with momentum $\hbar k = h/\lambda$; (b) after absorbing the photon, the atom is slowed by $\hbar k/m$; (c) after re-radiation in a random direction, on average the atom is slower than in (a).

Laser Cooling



sciencewise.anu.edu.au

Another problem: Doppler shift

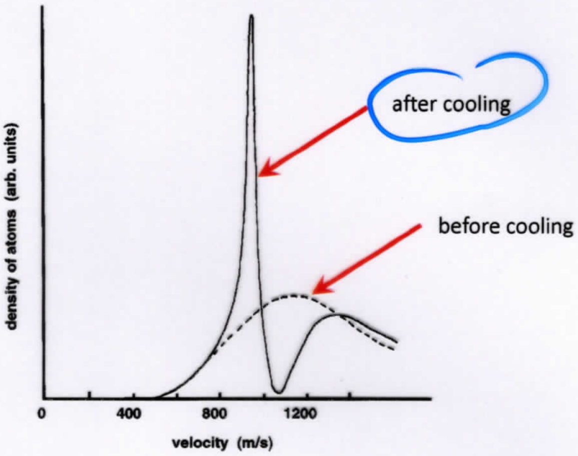
In order for the laser light to be resonantly absorbed by a counterpropagating atom moving with velocity v, the frequency ϖ of the light must be kv lower than the resonant frequency for an atom at rest.

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.

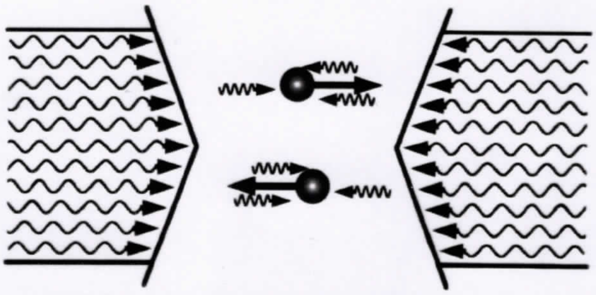
The result is that only atoms with the "proper" velocity to be resonant with the laser are slowed, and they are only slowed by a small amount.

Cooling an atomic beam with a fixed frequency laser



The dotted curve is the velocity distribution before cooling, and the solid curve is after cooling. Atoms from a narrow velocity range are transferred to a slightly narrower range centered on a lower velocity.

Doppler cooling in one dimension



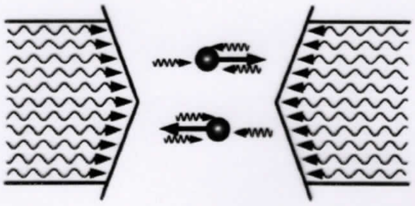
Laser beams are tuned slightly below the atomic resonance frequency.

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.

Doppler cooling limit



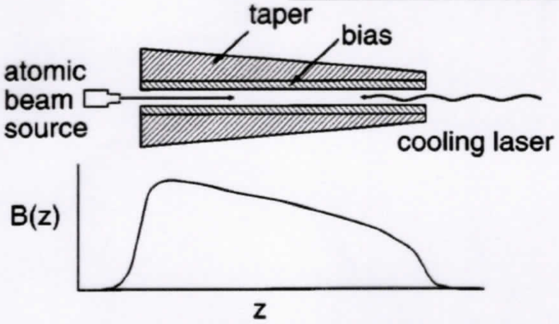
Doppler cooling limit

$$k_B T_{\text{Dopp}} = \frac{\hbar\Gamma}{2}.$$

This cooling process leads to a temperature whose lower limit is on the order of ħΓ, where Γ is the rate of spontaneous emission of the excited state (Γ^{-1} is the excited state lifetime). The temperature results from an equilibrium between laser cooling and the heating process arising from the random nature of both the absorption and emission of photons.

The random addition to the average momentum transfer produces a random walk of the atomic momentum and an increase in the mean square atomic momentum.
This heating is countered by the cooling force *F* opposing atomic motion.

Zeeman slower

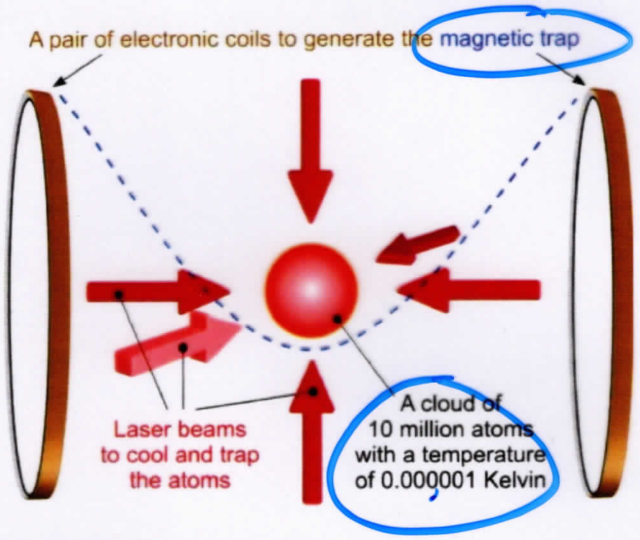


The laser is tuned so that, given the field induced Zeeman shift and the velocity-induced Doppler shift of the atomic transition frequency, atoms with velocity v_0 are resonant with the laser when they reach the point where the field is maximum.

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.

Magneto-optical trapping (MOT)



A pair of electronic coils to generate the magnetic trap

Laser beams to cool and trap the atoms

A cloud of 10 million atoms with a temperature of 0.000001 Kelvin

"Harmonic trap"

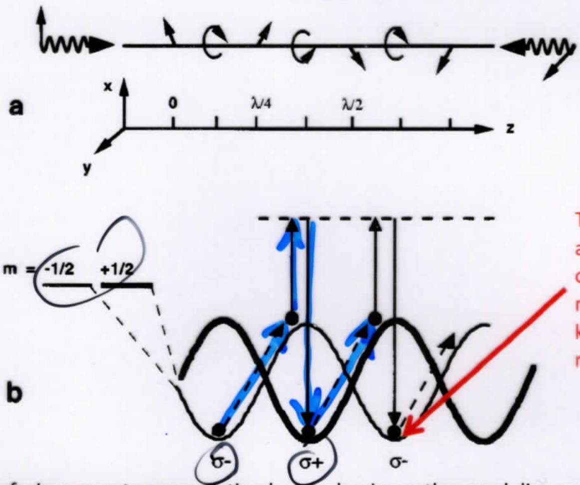
Optical molasses

A sodium atom cooled to the Doppler limit has a "mean free path" (the mean distance it moves before its initial velocity is damped out and the atom is moving with a different, random velocity) of only 20 mm, while the size of the laser beams doing the cooling might easily be one centimeter.

Thus, the atom undergoes diffusive, Brownian-like motion, and the time for a laser cooled atom to escape from the region where it is being cooled is much longer than the ballistic transit time across that region.

This means that an atom is effectively "stuck" in the laser beams that cool it. This stickiness, and the similarity of laser cooling to viscous friction, prompted the Bell Labs group (Chu *et al.*, 1985) to name the intersecting laser beams "optical molasses."

"Sisyphus" cooling

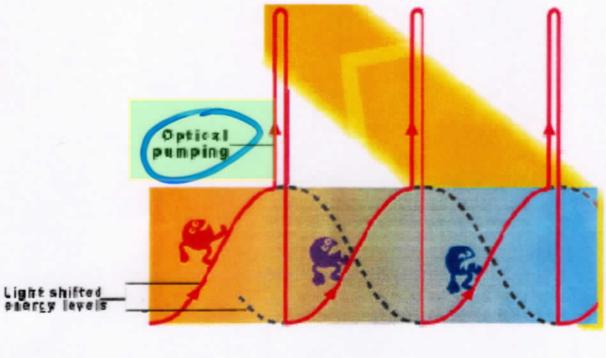


The atom is now again at the bottom of a hill, and it again must climb, losing kinetic energy, as it moves.

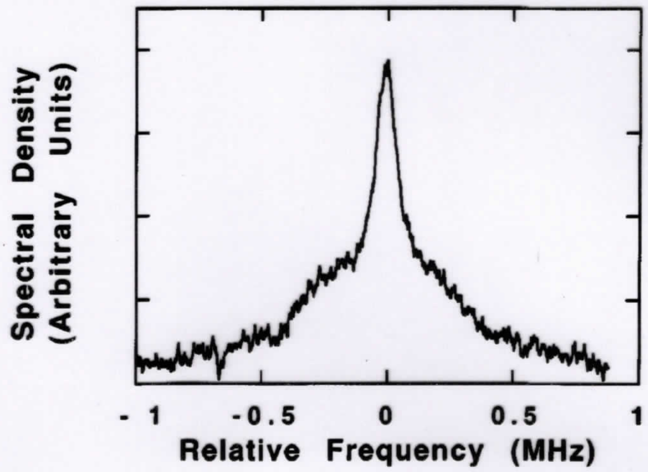
(a) Interfering, counterpropagating beams having orthogonal, linear polarizations create a polarization gradient.

(b) The different Zeeman sublevels are shifted differently in light fields with different polarizations; optical pumping tends to put atomic population on the lowest energy level, but nonadiabatic motion results in "Sisyphus" cooling.

"Sisyphus" cooling



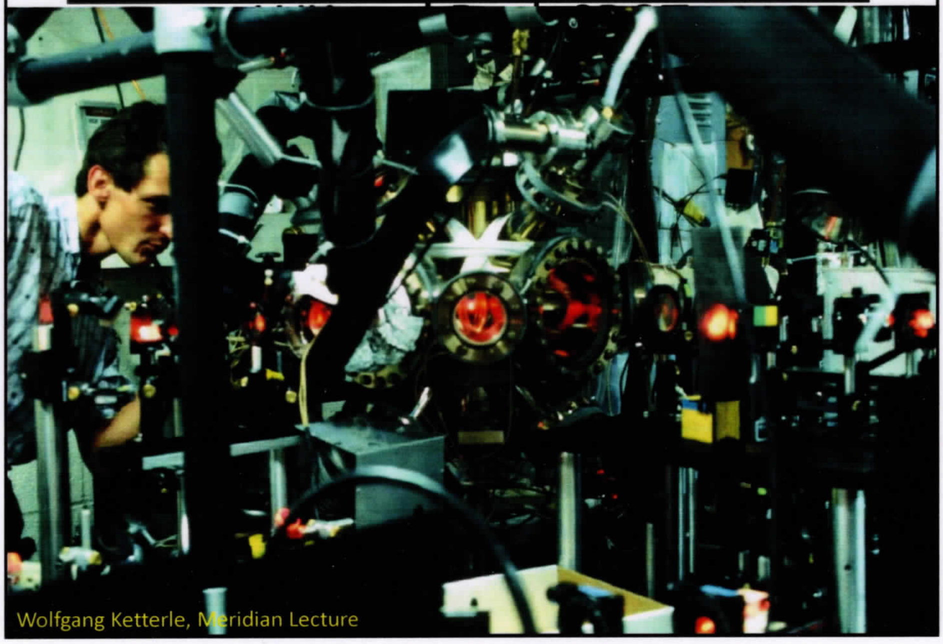
http://www.nobelprize.org/nobel_prizes/physics/laureates/1997/illpres/doppler.html



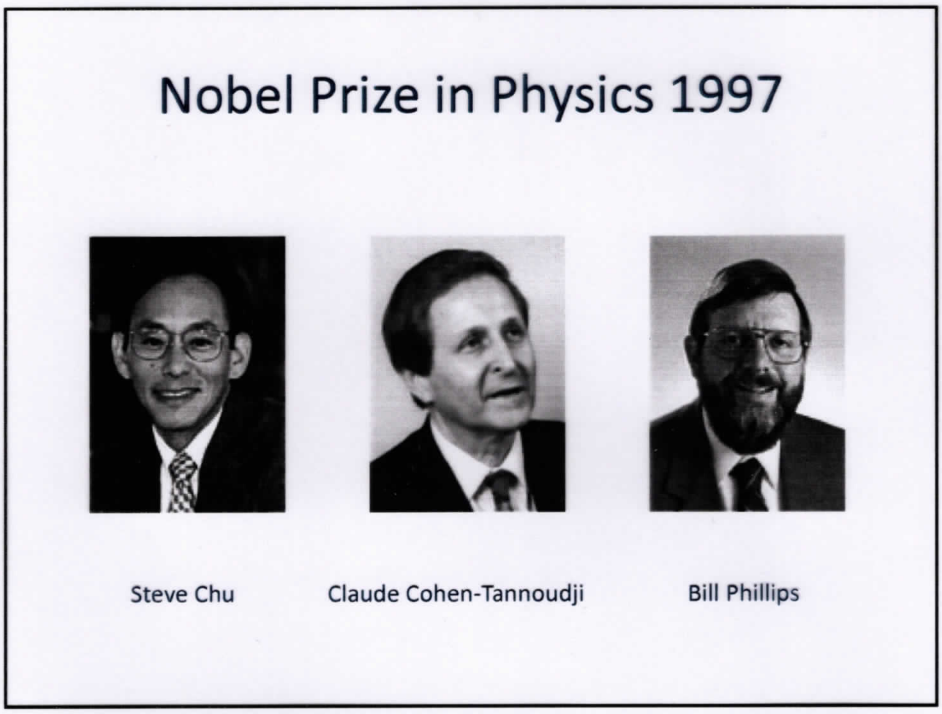
Heterodyne spectrum of fluorescence from Na atoms in optical molasses. The broad component corresponds to a temperature of 84 μK, which compares well with the temperature of 87 μK measured by time-of-flight measurement . The narrow component indicates a sub-wavelength localization of the atoms.

μK

Sodium laser cooling experiment (1992)



Wolfgang Ketterle, Meridian Lecture

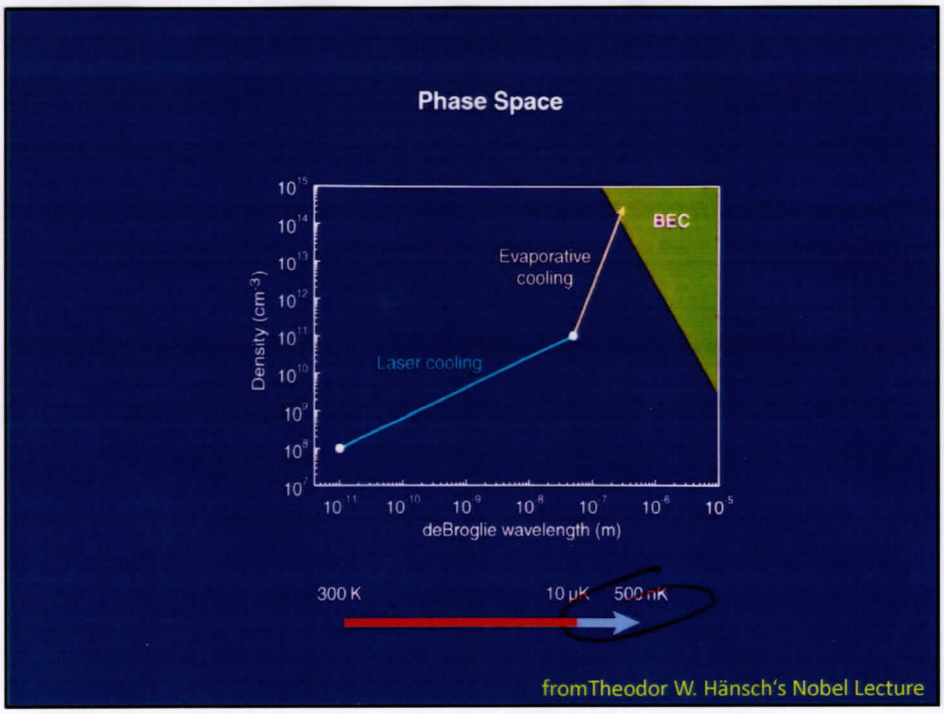


Nobel Prize in Physics 1997

Steve Chu

Claude Cohen-Tannoudji

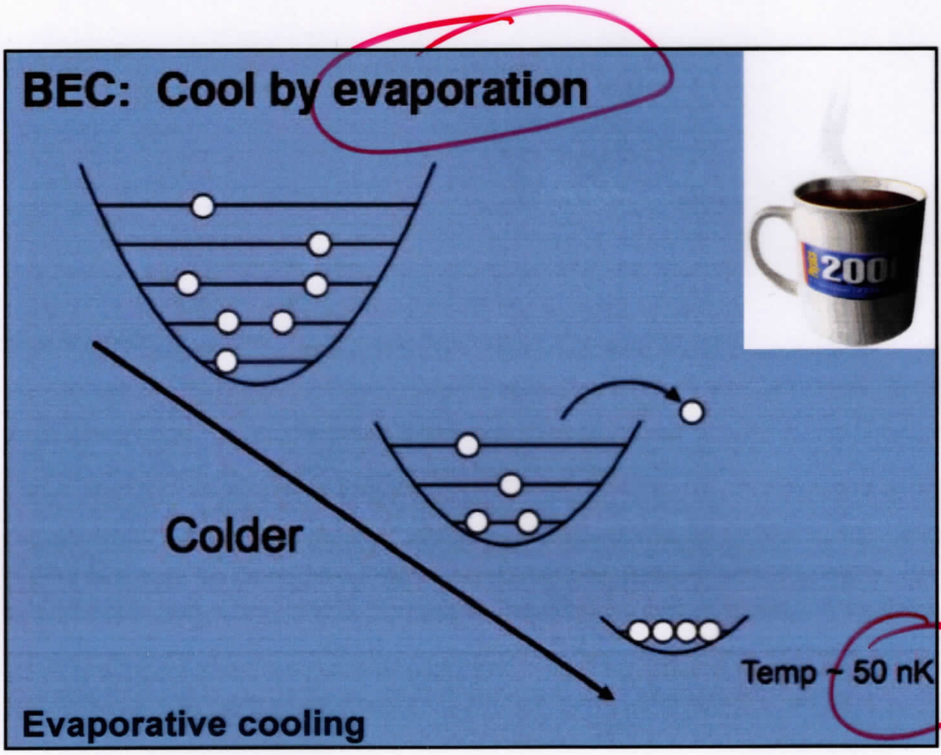
Bill Phillips



Phase Space

fromTheodor W. Hänsch's Nobel Lecture

After Laser Cooling: Need "Evaporative cooling"



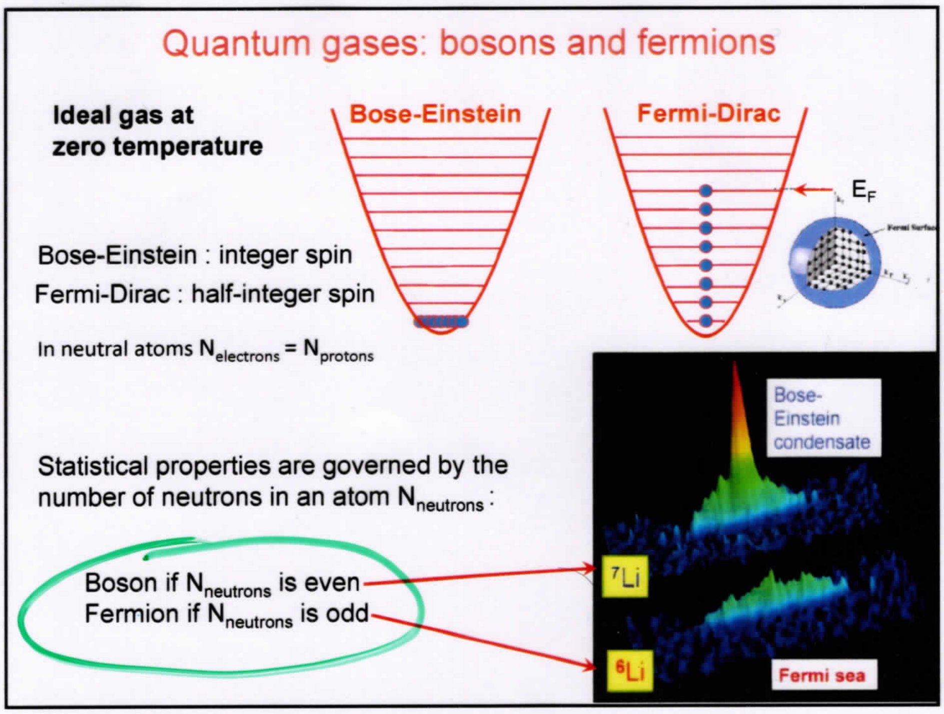
BEC: Cool by evaporation

Colder

Temp ~ 50 nK

Evaporative cooling

!



Quantum gases: bosons and fermions

Ideal gas at zero temperature

Bose-Einstein : integer spin

Fermi-Dirac : half-integer spin

In neutral atoms $N_{electrons} = N_{protons}$

Statistical properties are governed by the number of neutrons in an atom $N_{neutrons}$:

Boson if $N_{neutrons}$ is even

Fermion if $N_{neutrons}$ is odd

!

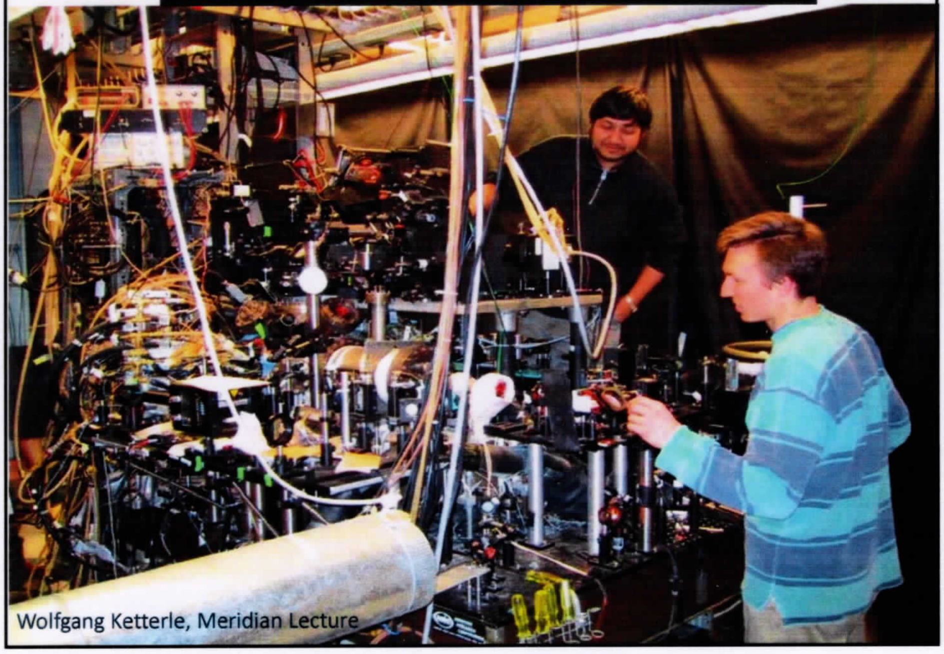
Nobel Prize in Physics 2001

Eric Cornell

Wolfgang Ketterle

Carl Wieman

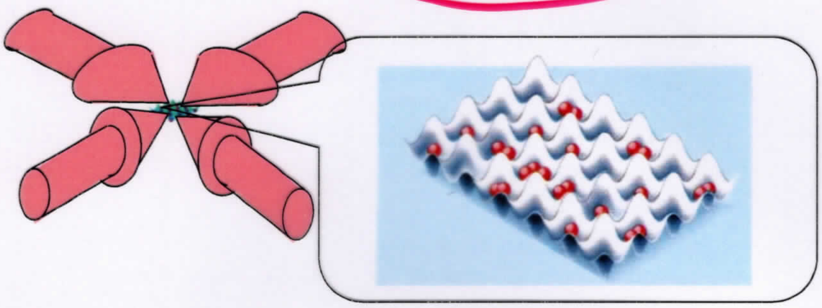
Sodium BEC I experiment (2001)



Wolfgang Ketterle, Meridian Lecture

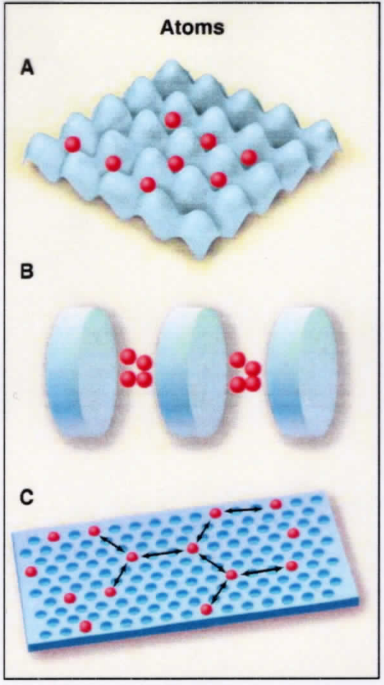
BEC = Bose-Einstein-Condensate

Atoms in optical lattices

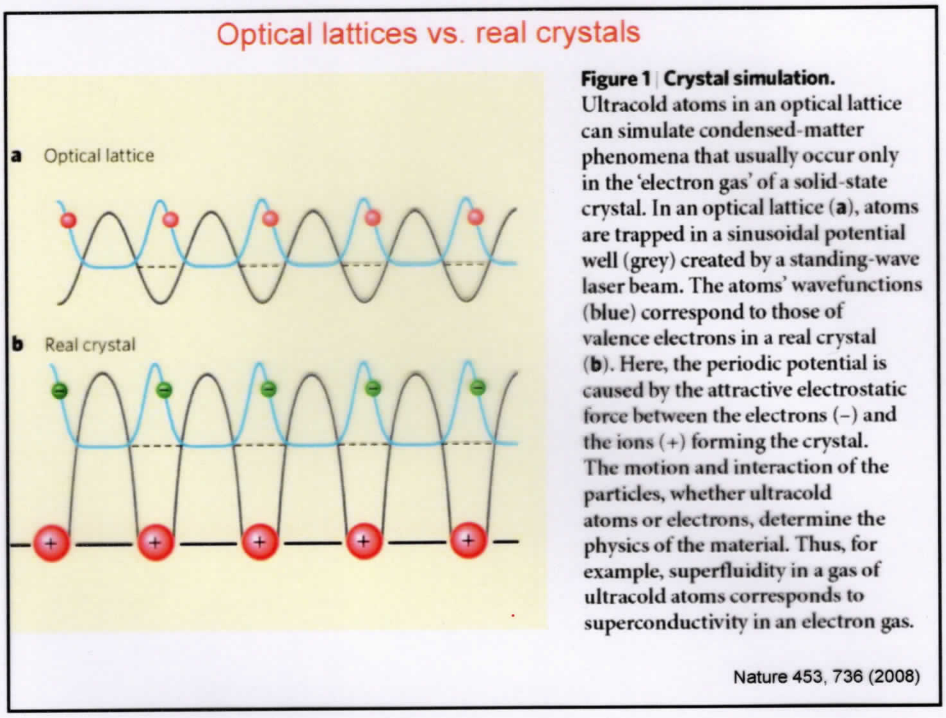


An optical lattice works as follows. When atoms are exposed to a laser field that is not resonant with an atomic optical transition (and thus does not excite the atomic electrons), they experience a conservative potential that is proportional to the laser intensity. With two counterpropagating laser 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



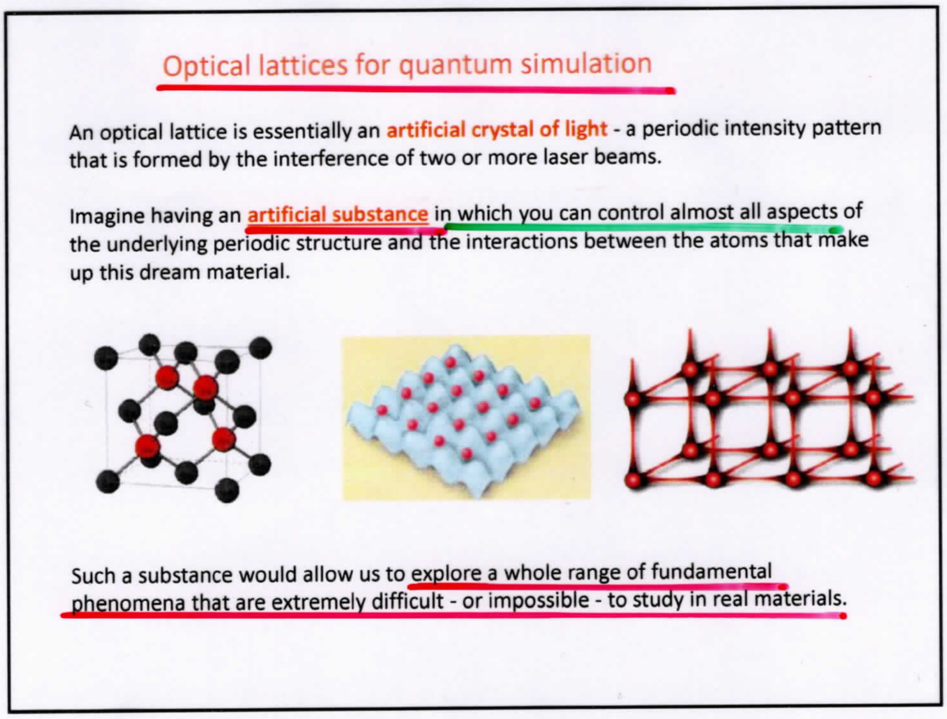
Atoms in optical lattices (**A**) or in
1D (**B**) or
2D (**C**) arrays of cavities.



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)



Optical lattices for quantum simulation

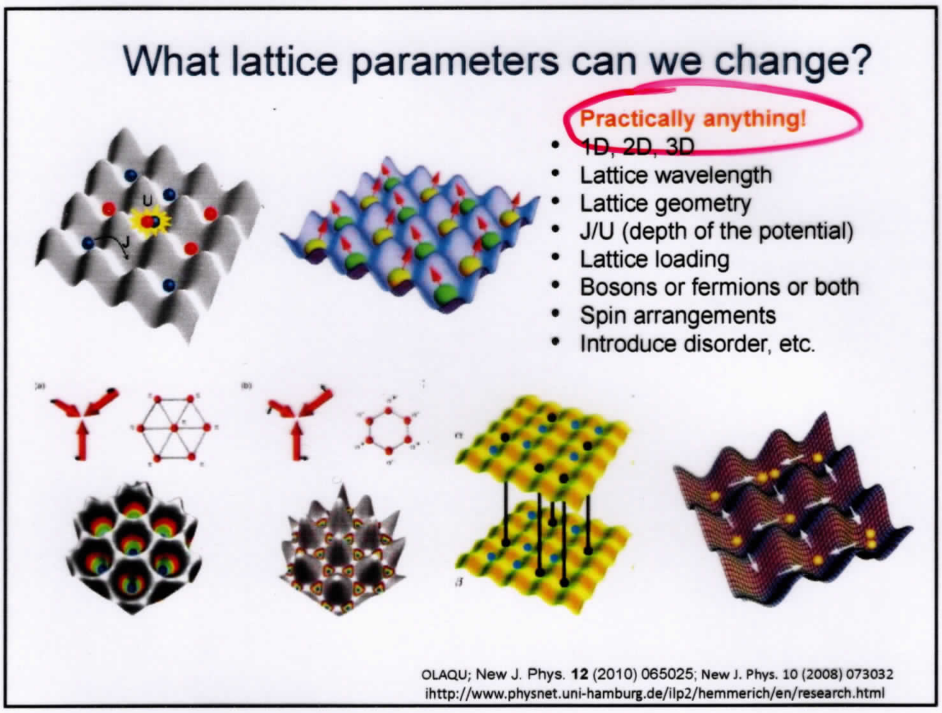
An optical lattice is essentially an **artificial crystal of light** - a periodic intensity pattern that is formed by the interference of two or more laser beams.

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.

Time scales ~μs and distances ~μm
ms

much better accessible than 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

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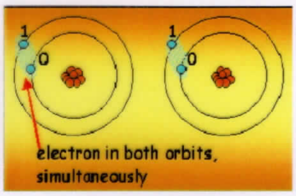
What do we need to build a quantum computer?

- **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

Encoding qubits and 1-qubit operations

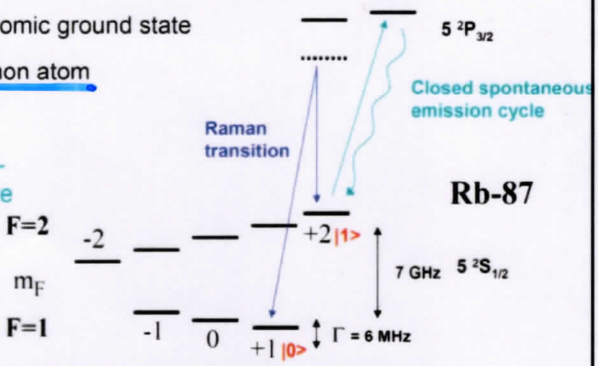
In hyperfine levels of the atomic ground state

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>

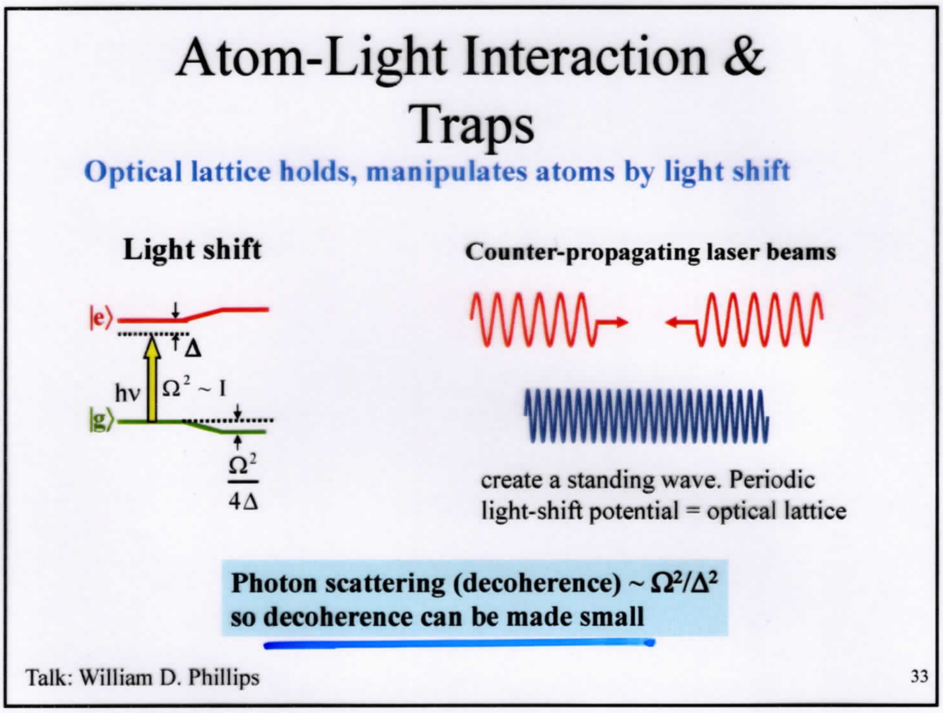
Raman transition performs single qubit rotation selectively on a single qubit

(see later)



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

Talk: M. Shotter



Atom-Light Interaction & Traps

Optical lattice holds, manipulates atoms by light shift

Light shift

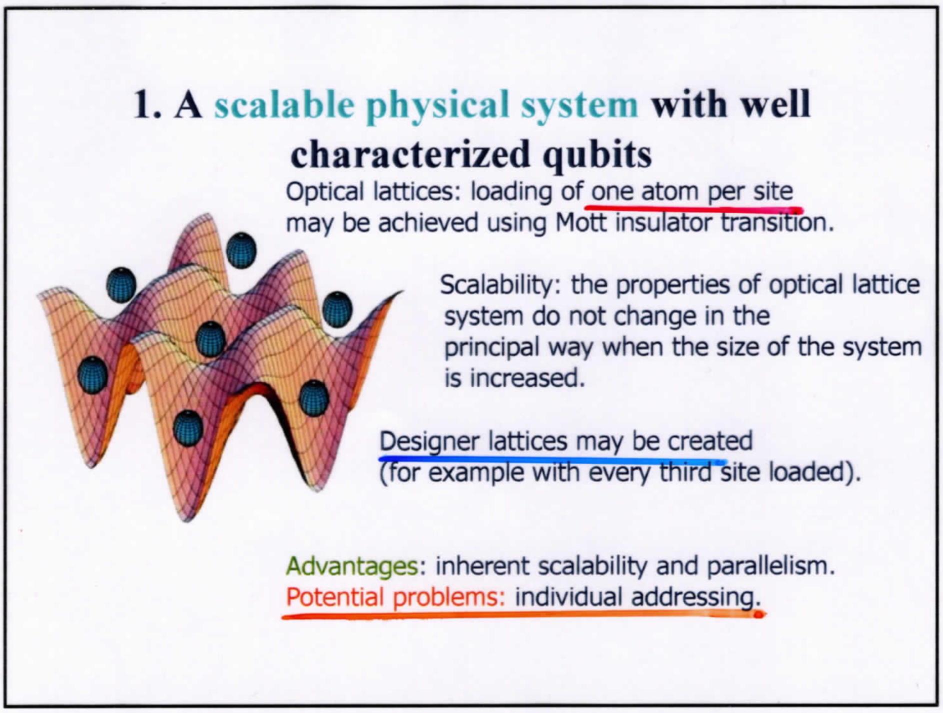
Counter-propagating laser beams

create a standing wave. Periodic light-shift potential = optical lattice

Photon scattering (decoherence) ~ Ω^2/Δ^2 so decoherence can be made small

Talk: William D. Phillips

33



1. A scalable physical system with well characterized qubits

Optical lattices: loading of one atom per site may be achieved using Mott insulator transition.

!

Scalability: the properties of optical lattice system do not change in the principal way when the size of the system is increased.

Designer lattices may be created (for example with every third site loaded).

Advantages: inherent scalability and parallelism.

Potential problems: individual addressing.

→ see below

2: Initialization

Internal state preparation: putting atoms in the ground hyperfine state

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

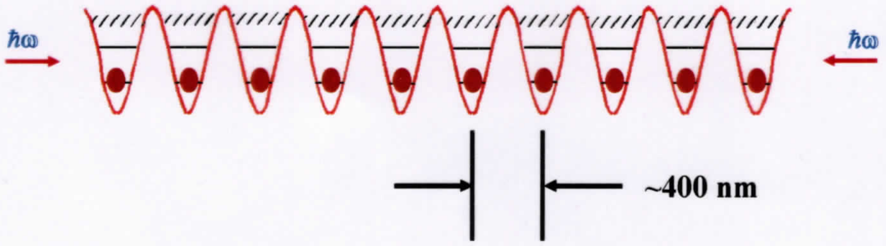
Very reliable (>0.9999 population may be achieved)

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

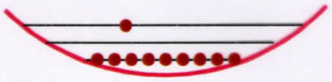


Loading a BEC into a Lattice

1)

Bose-Einstein Condensate:

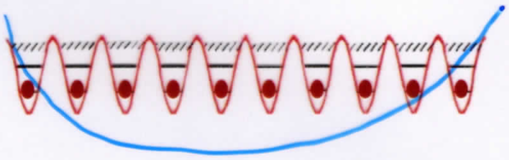
Huge number of atoms in lowest state in a magnetic trap



Bose-Einstein Condensation + Optical Lattice

2)

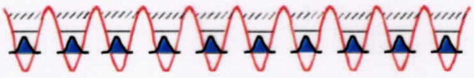
Adiabatic turn-on: All of the BEC in the lowest state.



Non-adiabatic:
superposition of excited states.

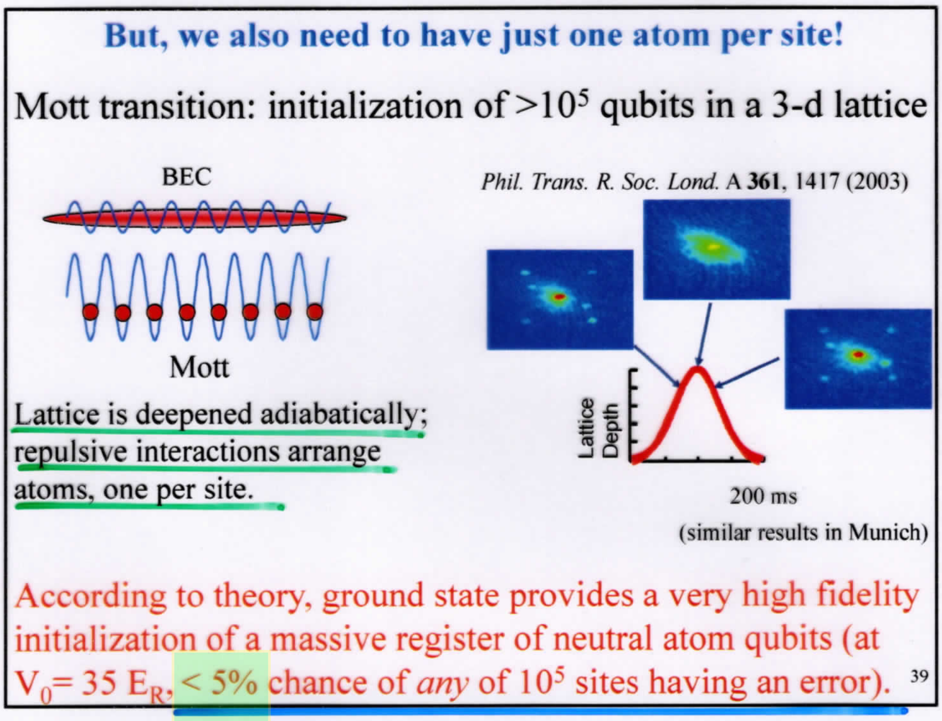
Measuring the loading of a lattice

Suddenly (non-adiabatically) releasing the atoms from the lattice projects the lattice wavefunction into free space.



The periodic wavefunction has momentum components at multiples of the reciprocal lattice momentum-- twice the photon momentum ($2n\hbar k$).

(This is the same as diffraction!)



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

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

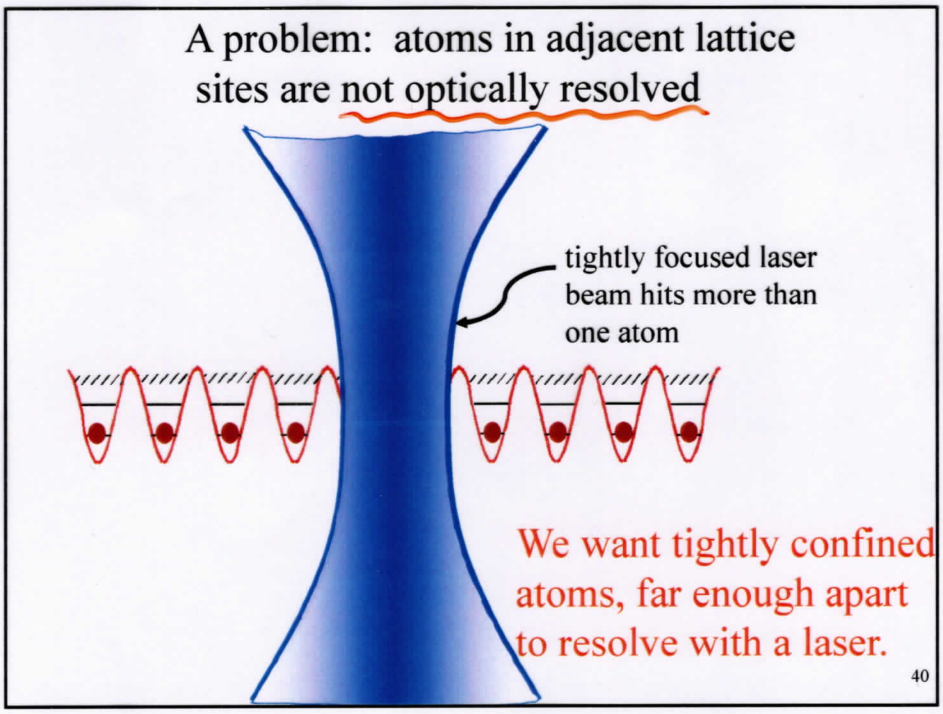
Phil. Trans. R. Soc. Lond. A **361**, 1417 (2003)

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

(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).

!!

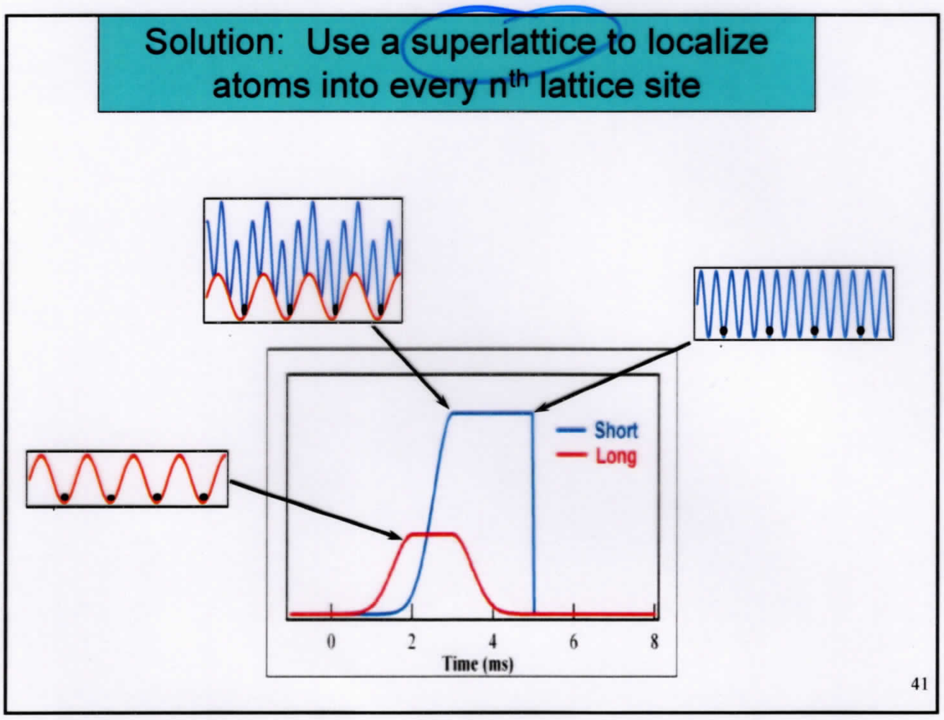


A problem: atoms in adjacent lattice sites are not optically resolved

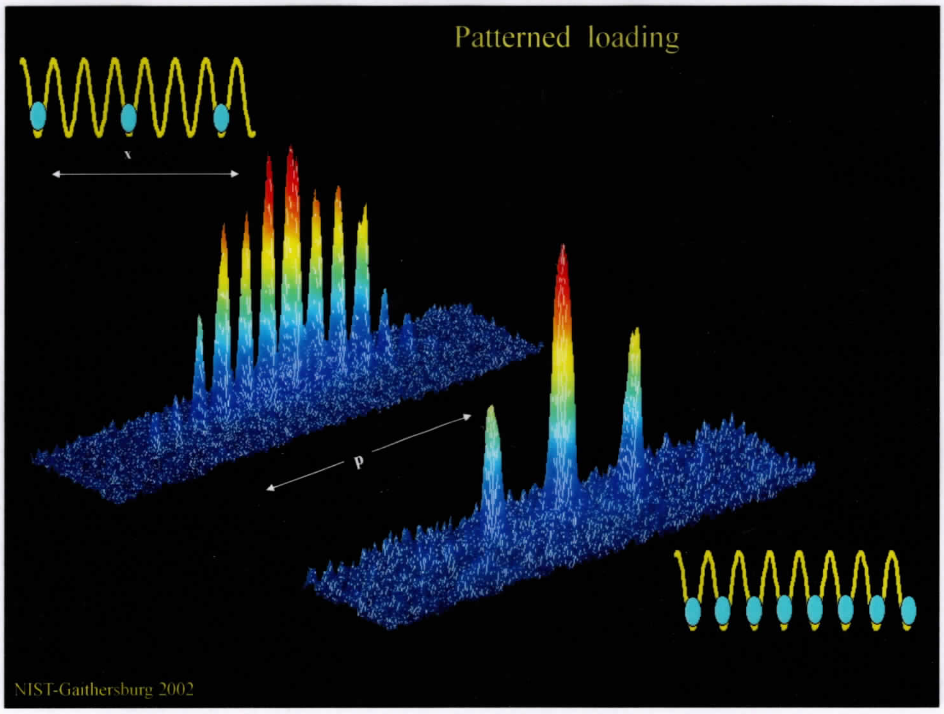
!? !?

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

One solution!



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



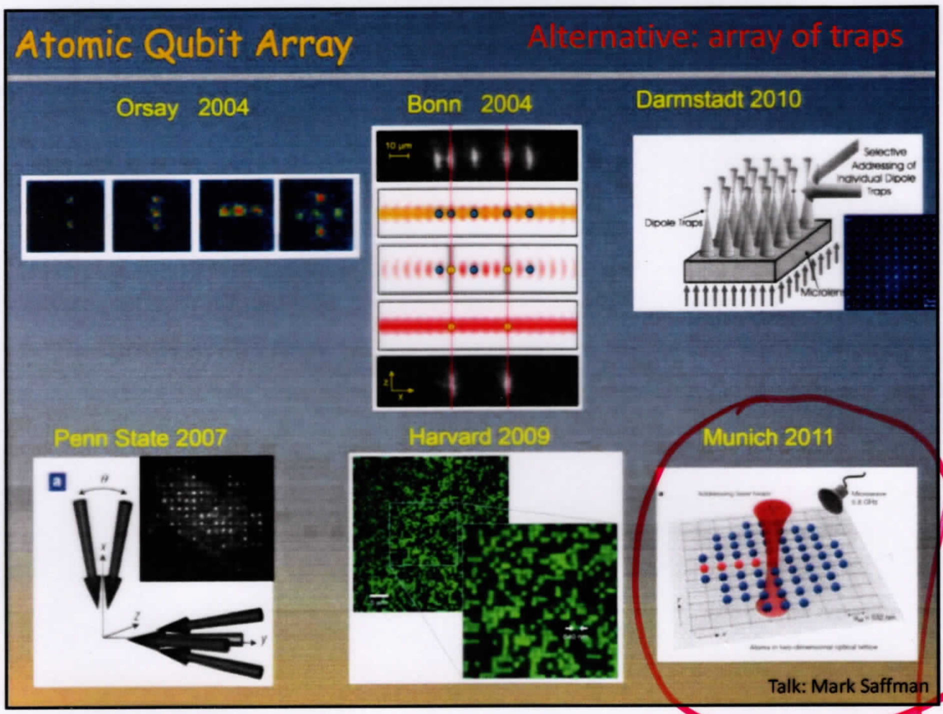
Patterned loading

NIST-Gaithersburg 2002

Atoms can be resolved

Atomic Qubit Array

Alternative: array of traps



Talk: Mark Saffman

Primary lattice (λ_{light})

Yet single atom detection and control !

↳ see next pages

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

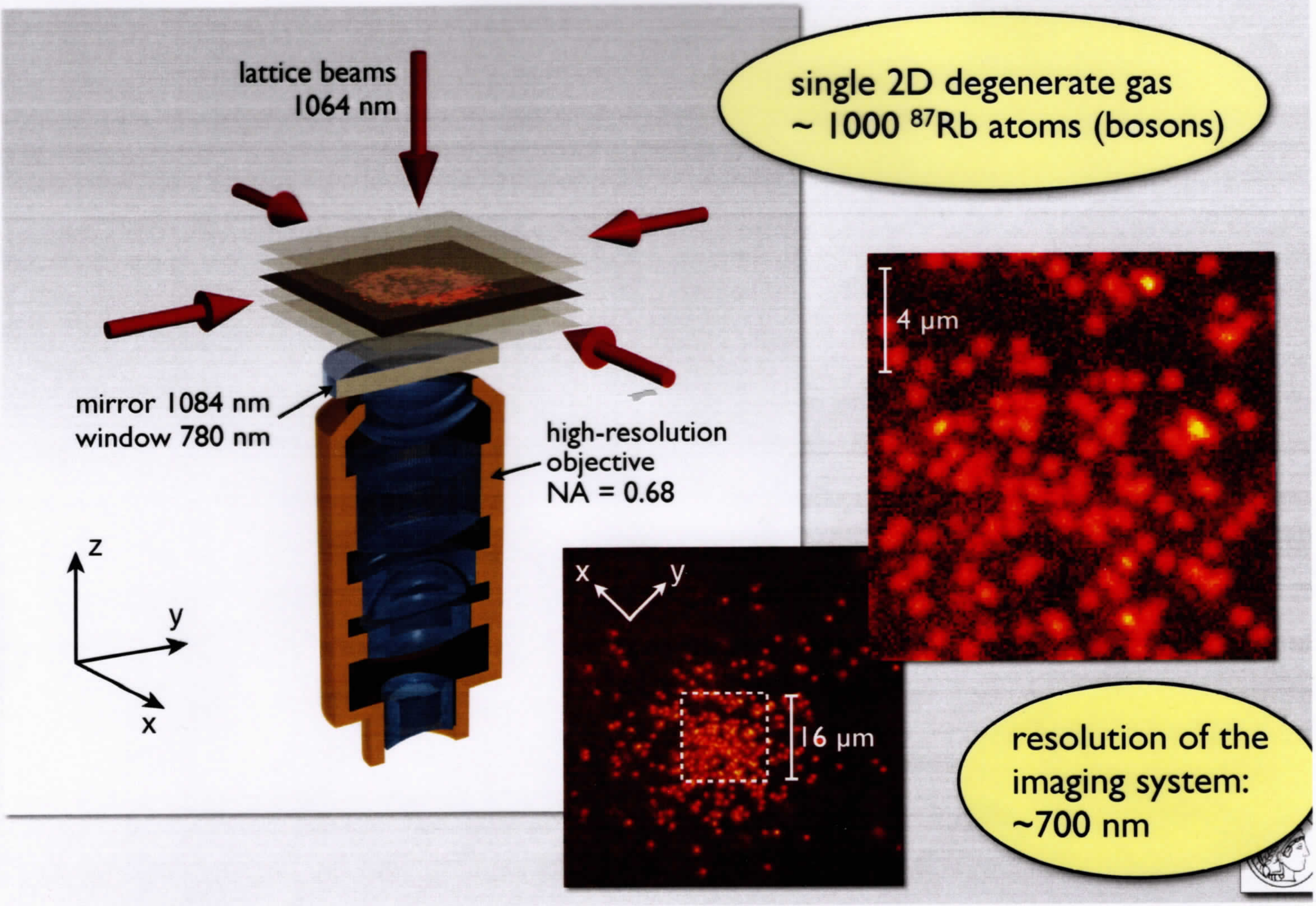
Only one gate proposal does not involve moving atoms (Rydberg gate).

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

we need a lot of optics!

From I. Bloch, Munich

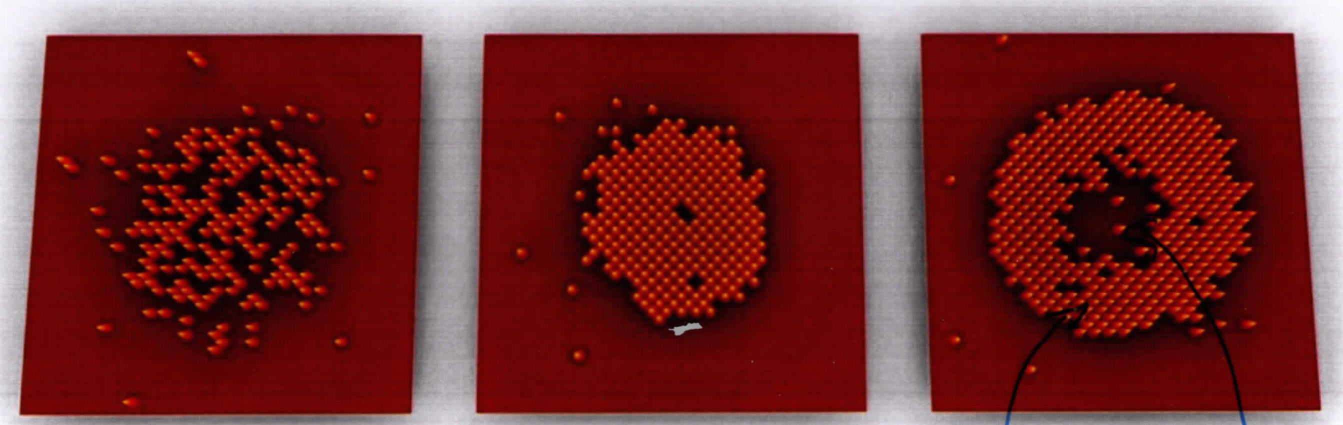
Seeing Single Atoms



single 2D degenerate gas
~ 1000 ^{87}Rb atoms (bosons)

resolution of the
imaging system:
~700 nm

Snapshot of an Atomic Density Distribution



BEC

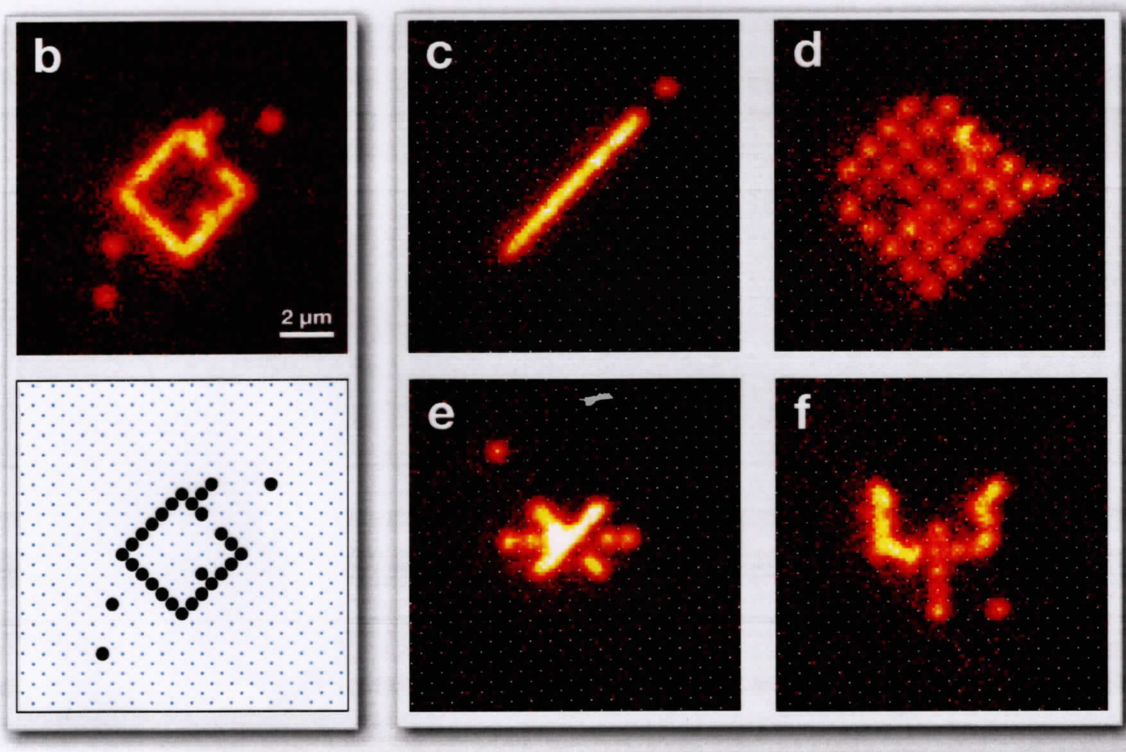
n=1
Mott Insulator

n=1 & n=2
Mott Insulator

J. Sherson *et al.* Nature **467**, 68 (2010)

Addressing

Coherent Spin Flips - Positive Imaging



Subwavelength spatial resolution: 50 nm

Ch. Weitenberg et al., Nature **471**, 319-324 (2011)

($\lambda \approx 700$ nm !)

⇒ • Single atom detection and control !

• Quantum simulation : observe movement of atoms