

The amazing story of Laser Cooling and Trapping

following Bill Phillips' Nobel Lecture

[http://www.nobelprize.org/nobel_prizes/physics/
laureates/1997/phillips-lecture.pdf](http://www.nobelprize.org/nobel_prizes/physics/laureates/1997/phillips-lecture.pdf)

Laser cooling of atomic beams

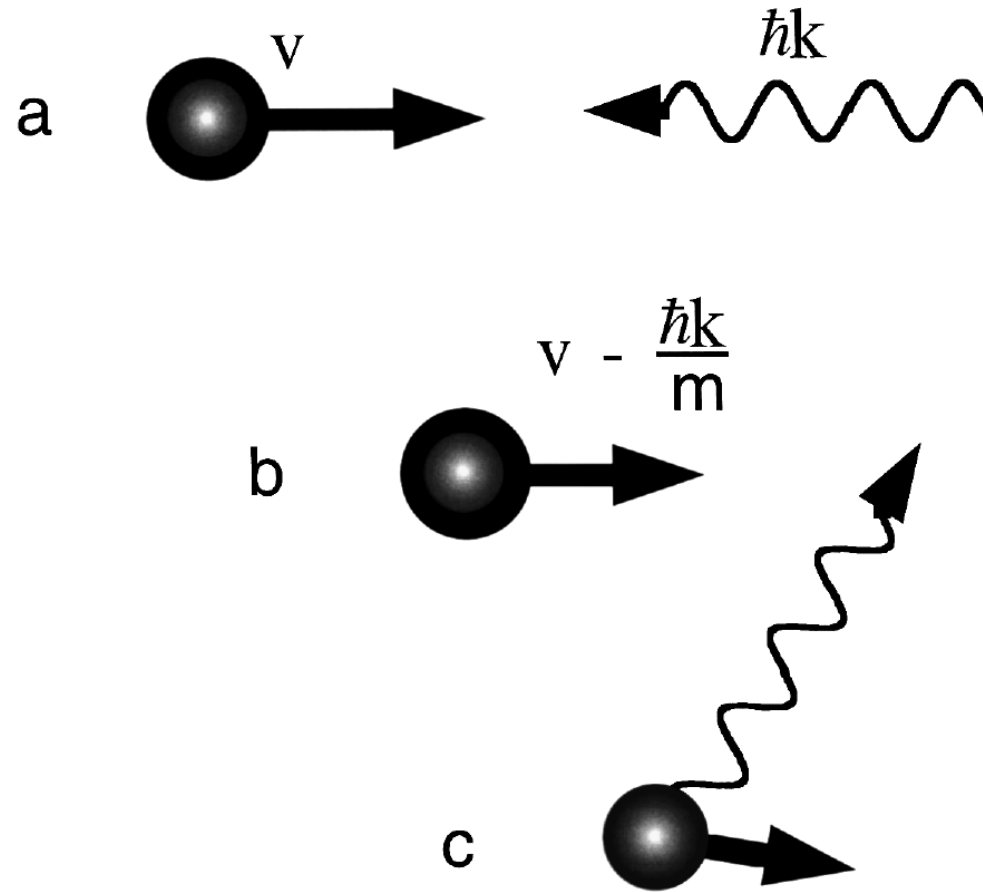
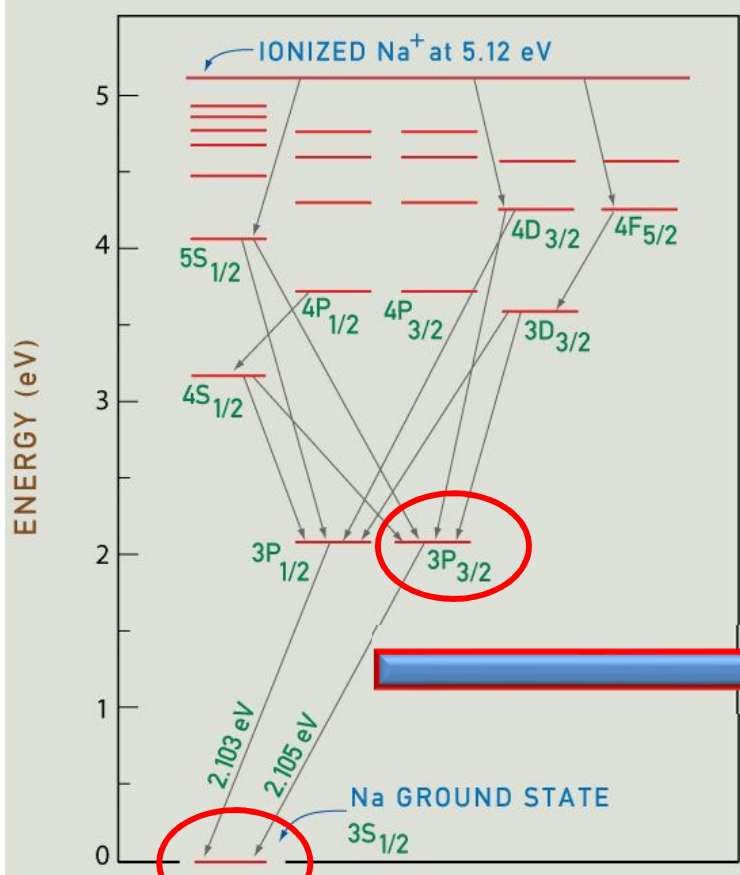
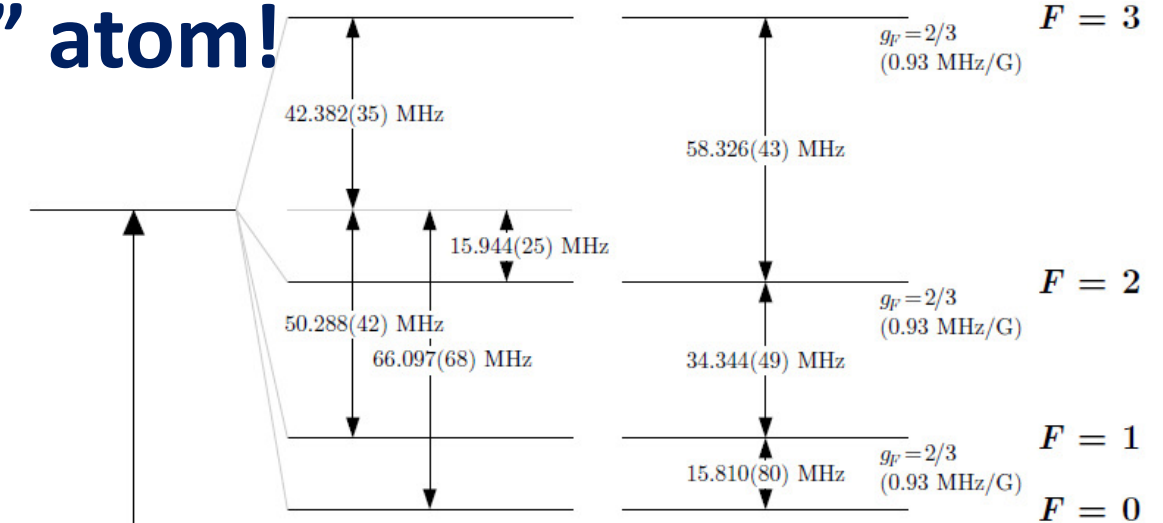


FIG. 1. (a) An atom with velocity v encounters a photon with momentum $\hbar k = h/\lambda$; (b) after absorbing the photon, the atom is slowed by $\hbar k/m$; (c) after re-radiation in a random direction, on average the atom is slower than in (a).

Na is not a "two-level" atom!

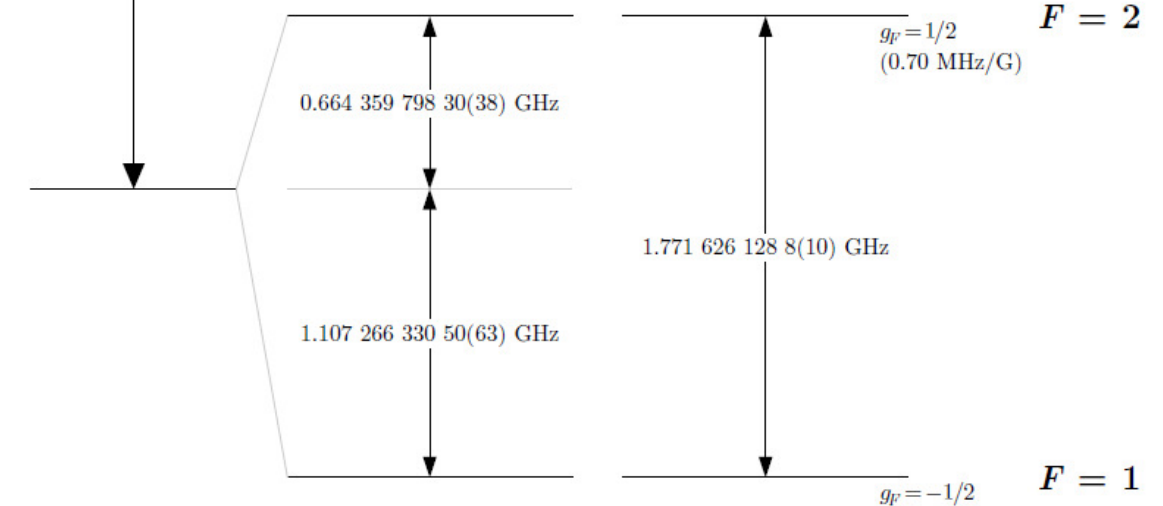


$3^2P_{3/2}$



589.158 326 4(15) nm
 508.848 716 2(13) THz
 16 973.366 160(43) cm⁻¹
 2.104 429 011(51) eV

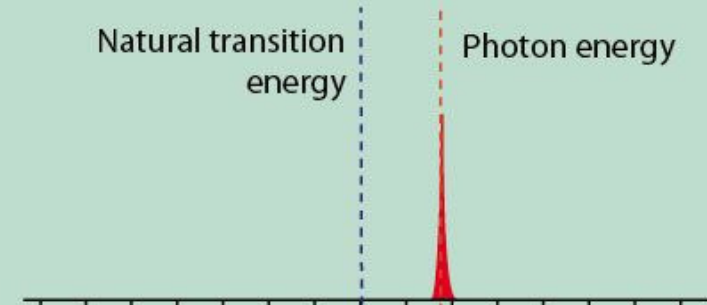
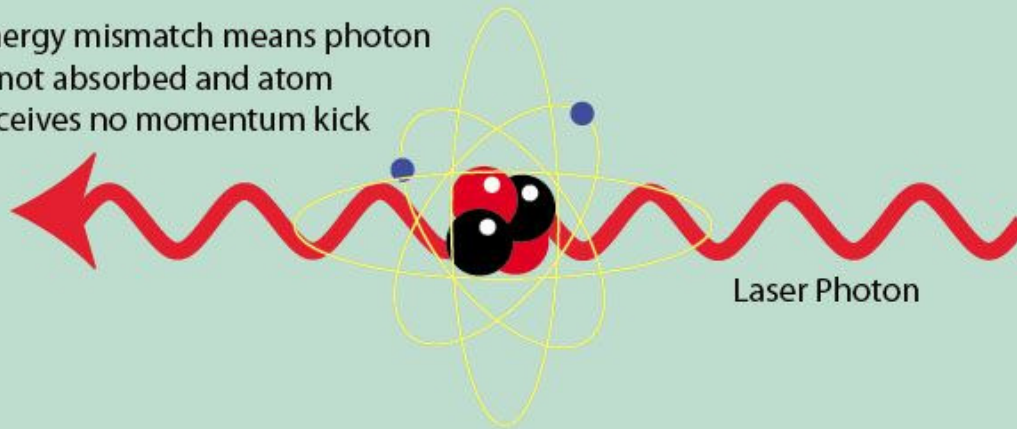
$3^2S_{1/2}$



Laser Cooling

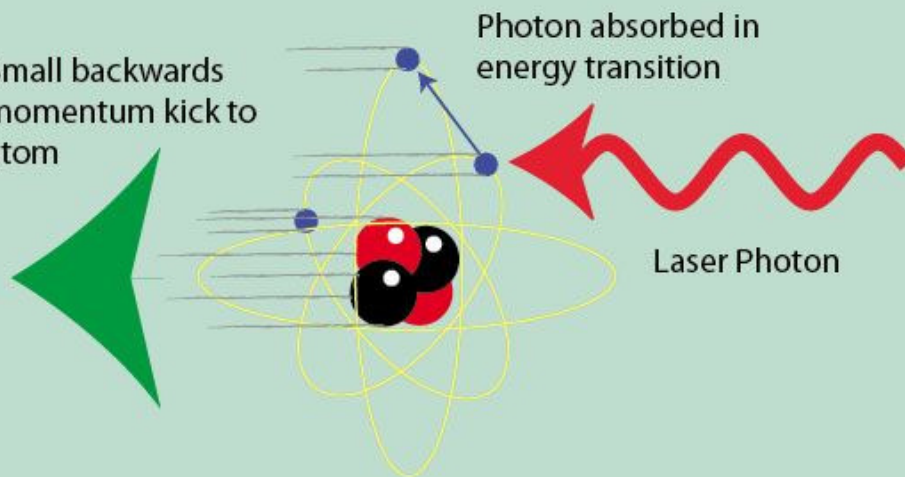
Stationary Atom:

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

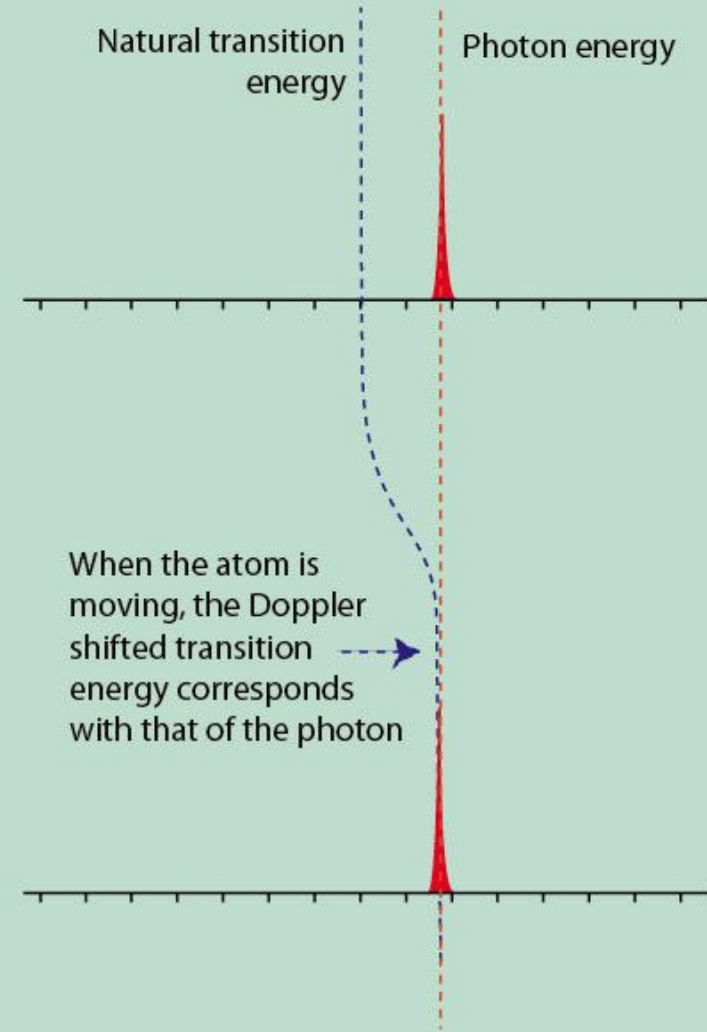


Moving Atom:

Small backwards momentum kick to atom



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



Another problem: Doppler shift

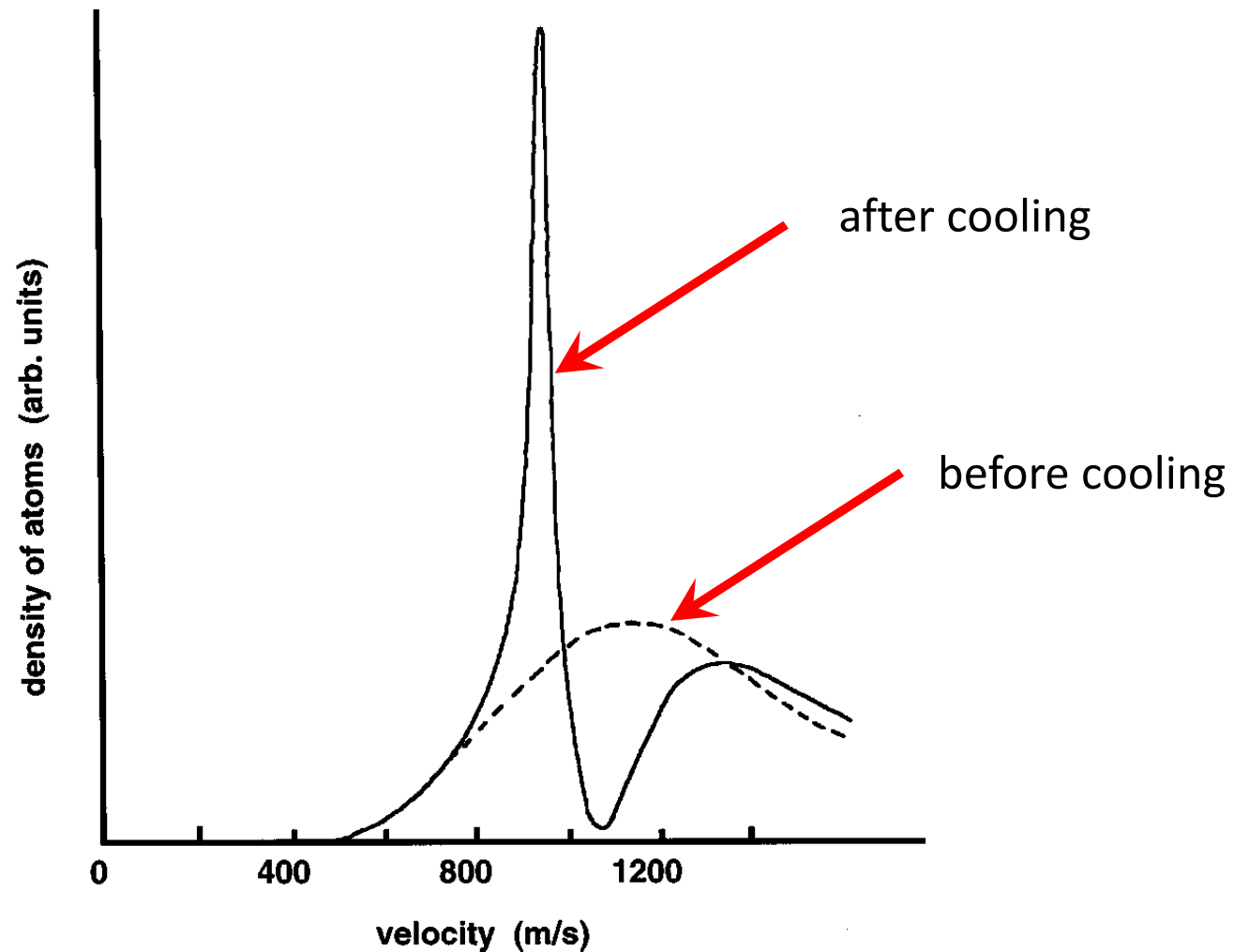
In order for the laser light to be resonantly absorbed by a counterpropagating atom moving with velocity v , the frequency ω of the light must be kv lower than the resonant frequency for an atom at rest.

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.

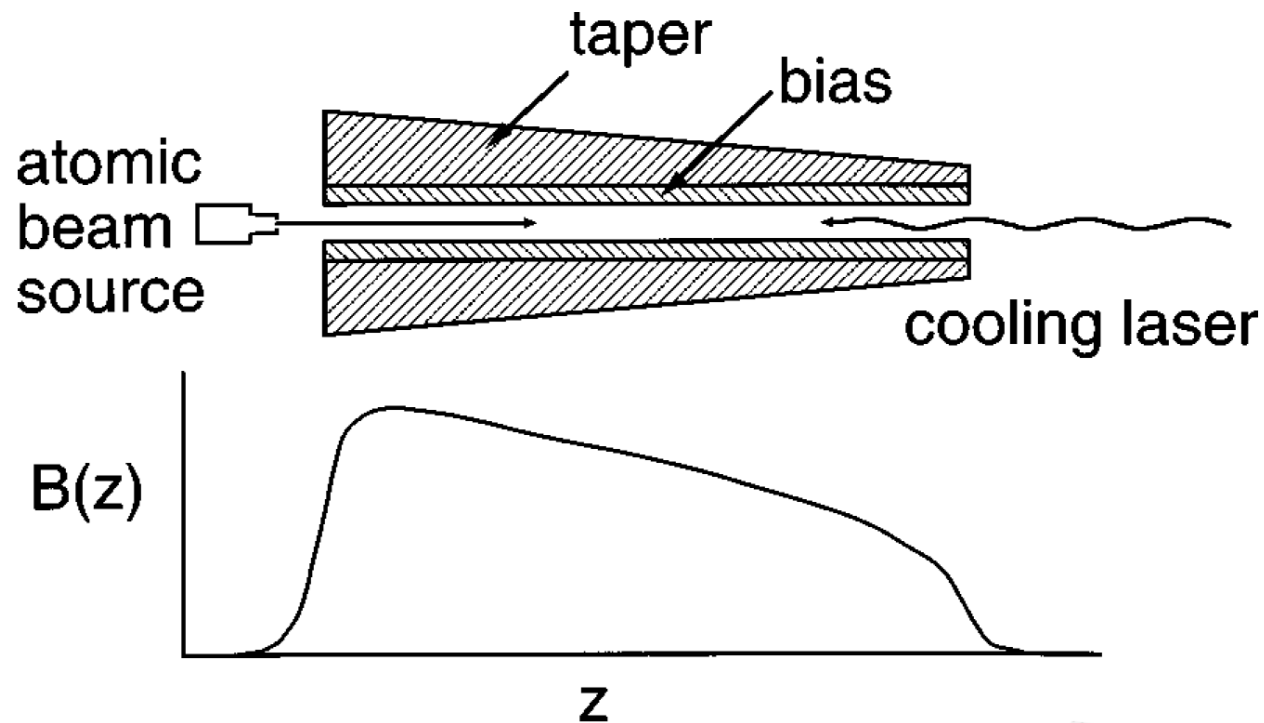
The result is that only atoms with the “proper” velocity to be resonant with the laser are slowed, and they are only slowed by a small amount.

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.

Zeeman slower

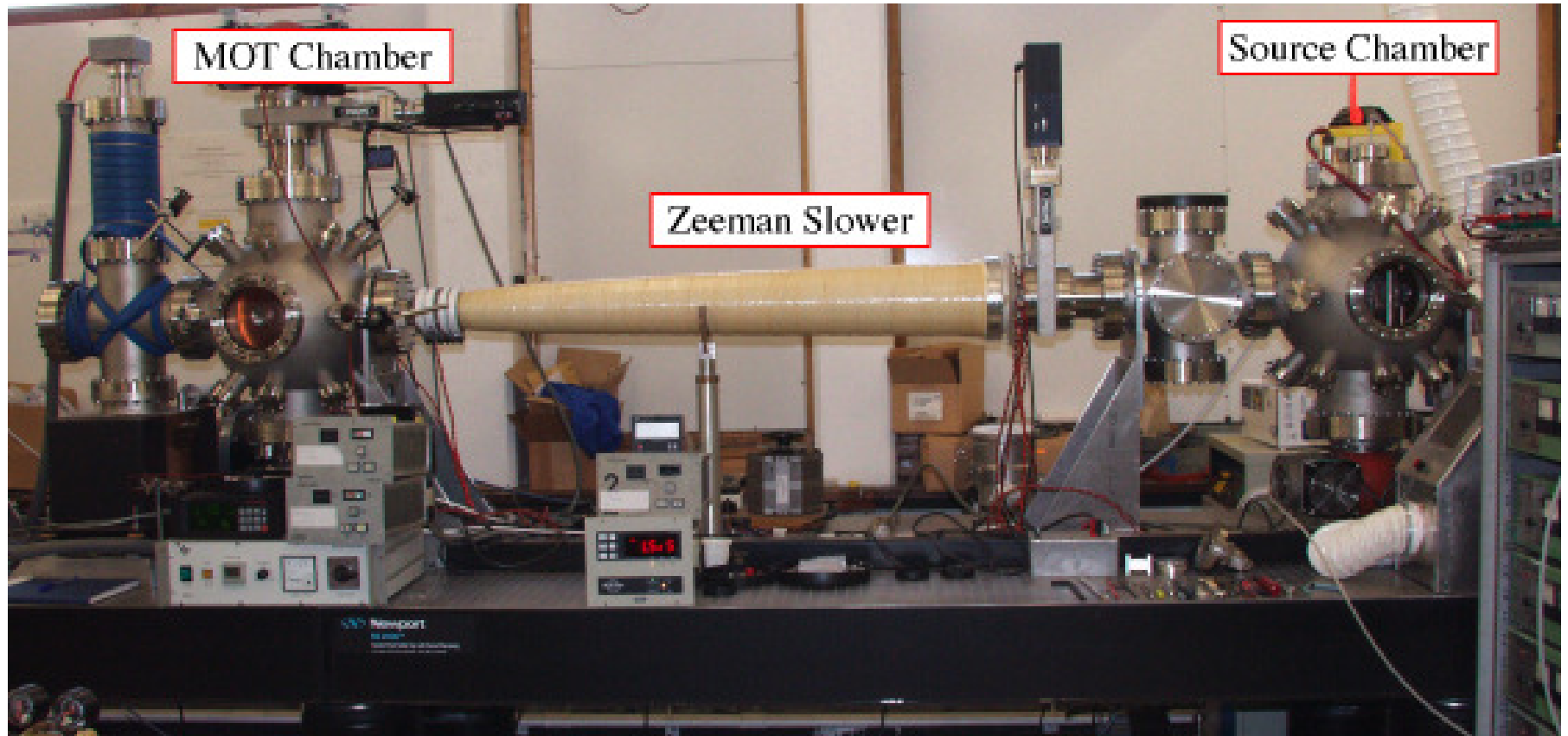


The laser is tuned so that, given the field induced Zeeman shift and the velocity-induced Doppler shift of the atomic transition frequency, atoms with velocity v_0 are resonant with the laser when they reach the point where the field is maximum.

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.

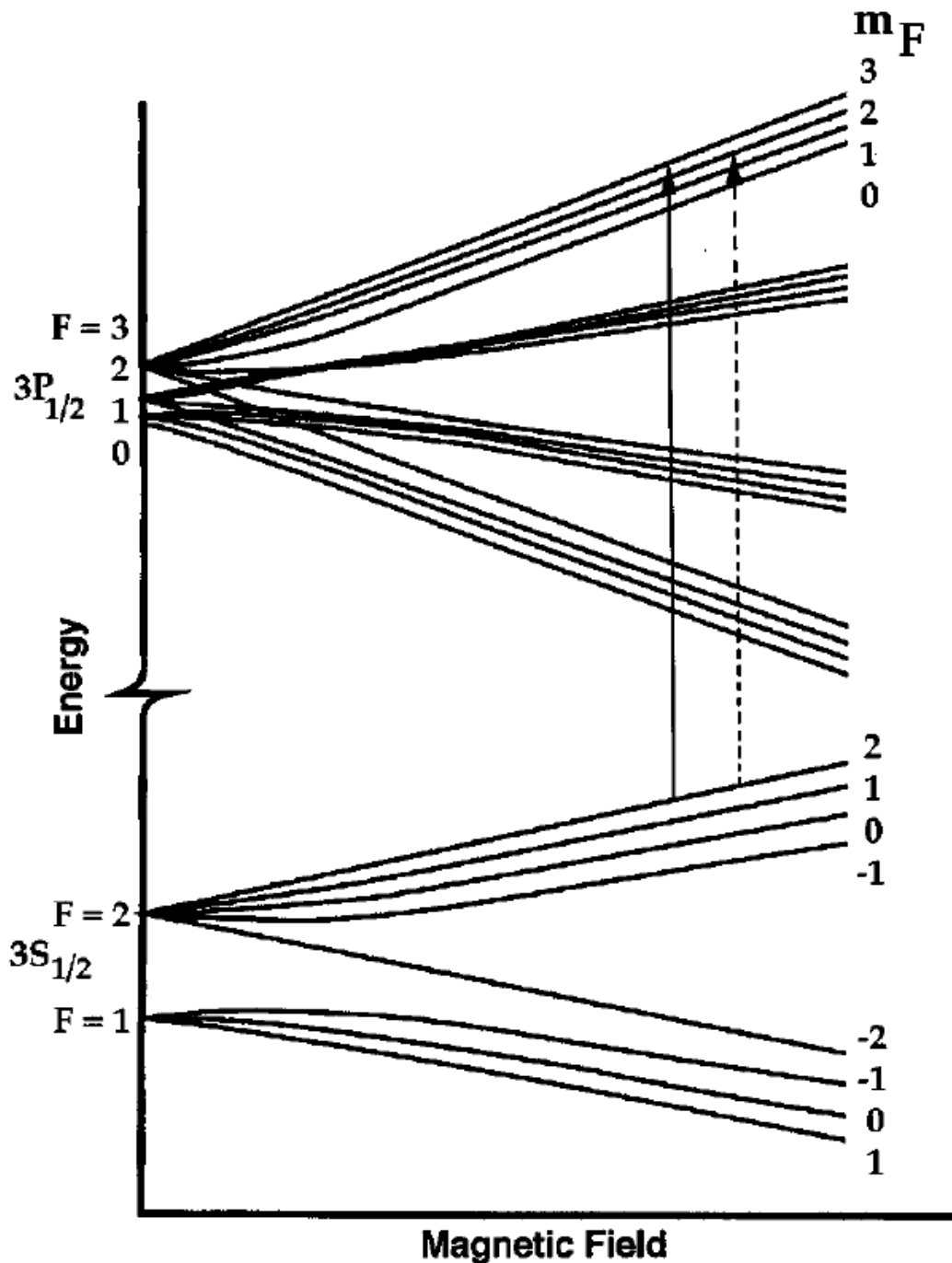
The process continues with the initially fast atoms decelerating and staying in resonance while initially slower atoms come into resonance and begin to be slowed as they move further down the solenoid.

Zeeman Cooling



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

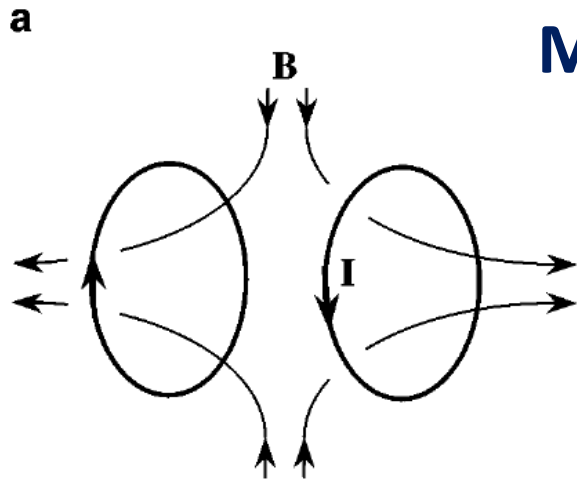
Note: optical pumping problem is avoided



By shutting off the cooling laser beam and delaying observation until the slow atoms arrived in the observation region, Prodan, Phillips, and Metcalf (1982) were able to detect atoms as slow as 40 m/s with a spread of 10 m/s, corresponding to a temperature (in the atoms' rest frame) of 70 mK.

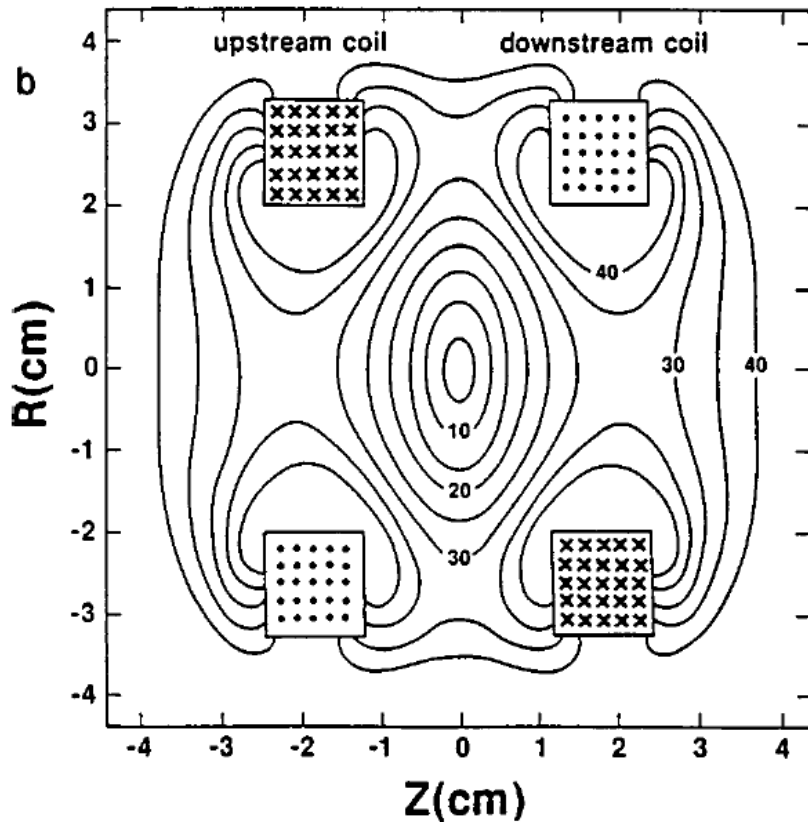
The next step was to get these atoms to come to rest in the observation region.

Magnetic trapping



The idea of magnetic trapping is that in a magnetic field, an atom with a magnetic moment will have quantum states whose magnetic or Zeeman energy increases with increasing field and states whose energy decreases, depending on the orientation of the moment compared to the field.

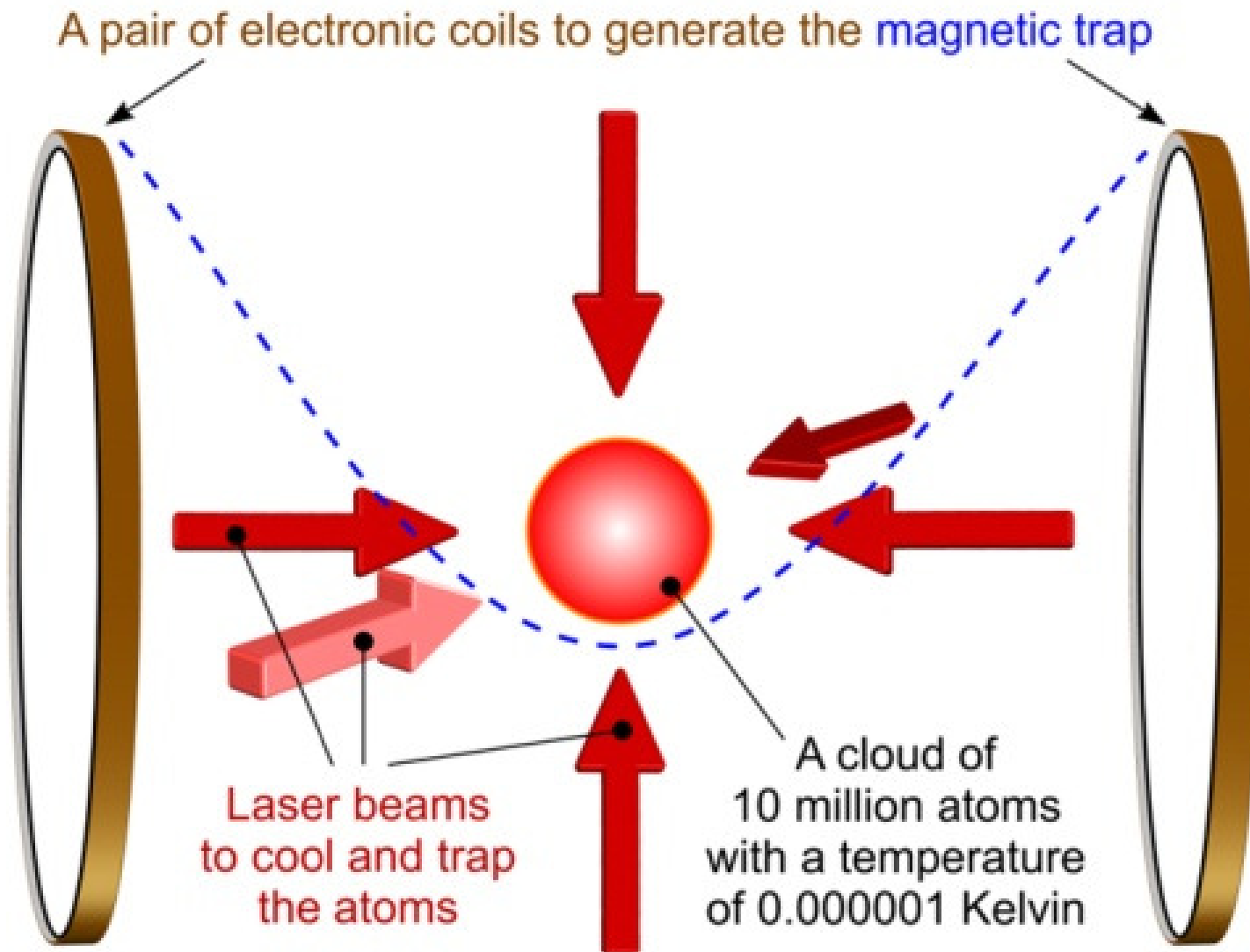
The increasing-energy states, or low-field seekers, can be trapped in a magnetic field configuration having a point where the magnitude of the field is a relative minimum.



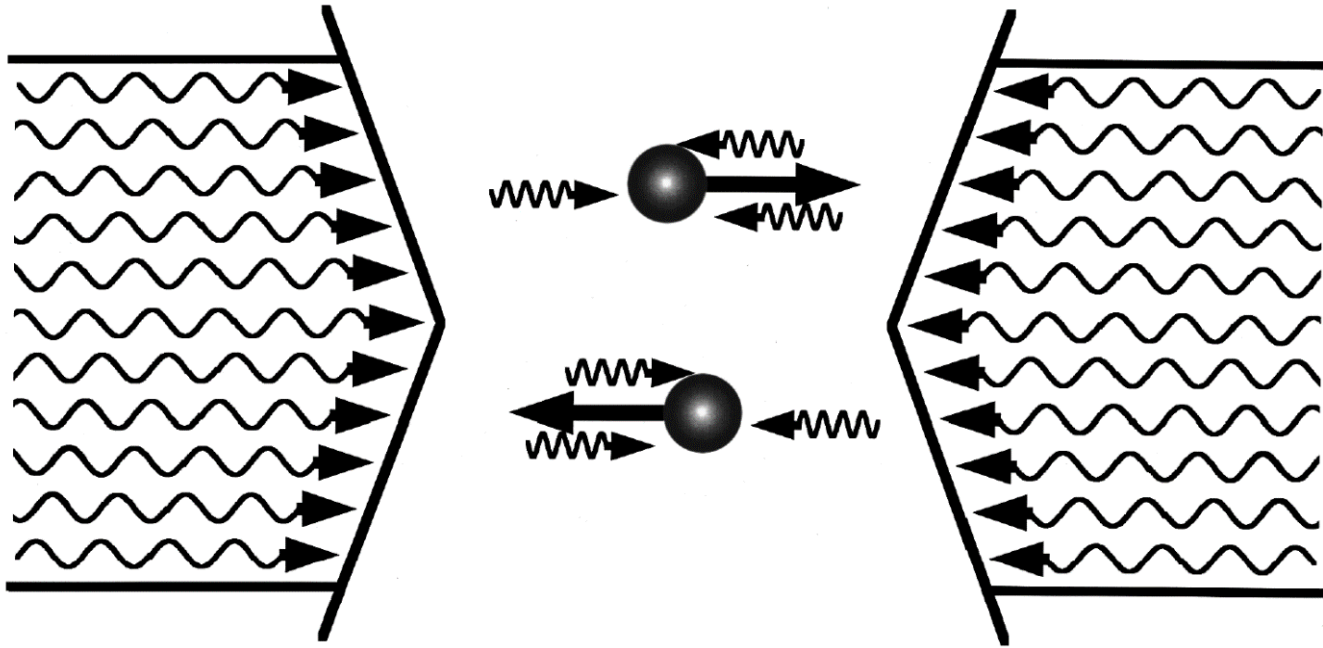
(a) Spherical quadrupole trap with lines of B -field.

(b) Equipotentials of our trap (equal field magnitudes in millitesla), in a plane containing the symmetry (z) axis.

Magneto-optical trapping (MOT)



Doppler cooling in one dimension



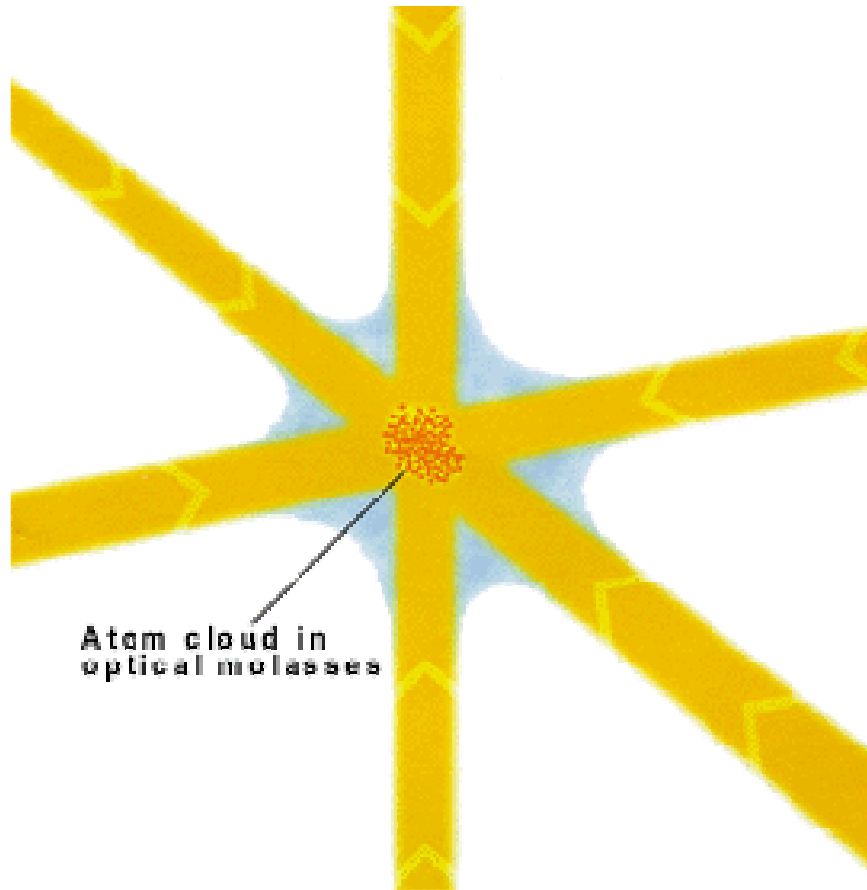
Laser beams are tuned slightly below the atomic resonance frequency.

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.

Optical molasses

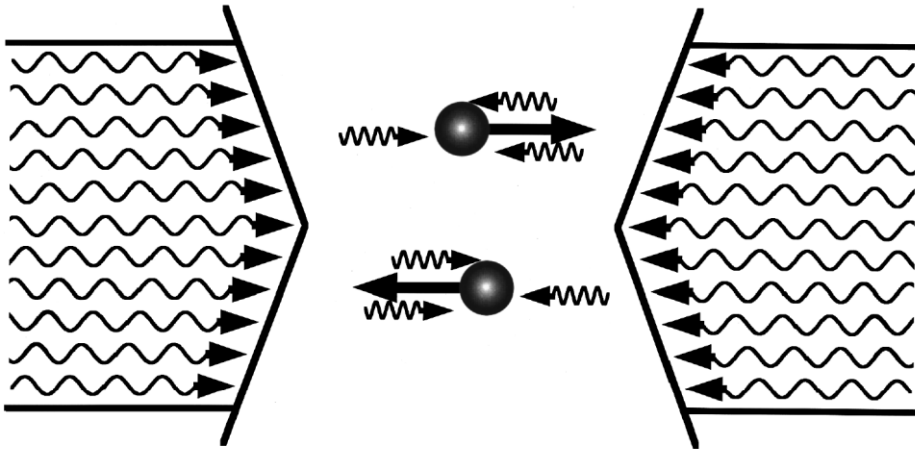


A sodium atom cooled to the Doppler limit has a “mean free path” (the mean distance it moves before its initial velocity is damped out and the atom is moving with a different, random velocity) of only 20 nm, while the size of the laser beams doing the cooling might easily be one centimeter.

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.”

Doppler cooling limit



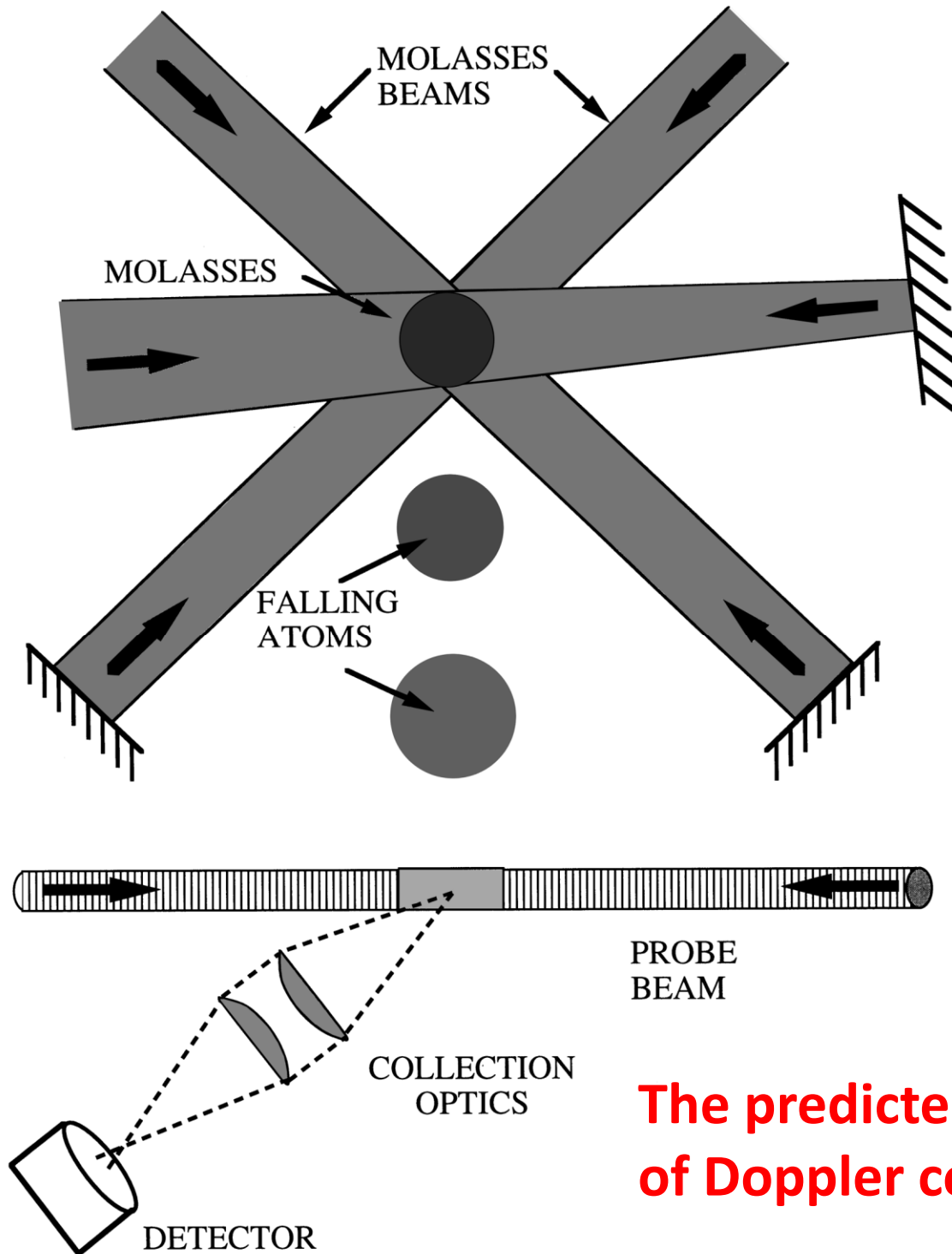
Doppler cooling limit.

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

This cooling process leads to a temperature whose lower limit is on the order of $\hbar \Gamma$, 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.

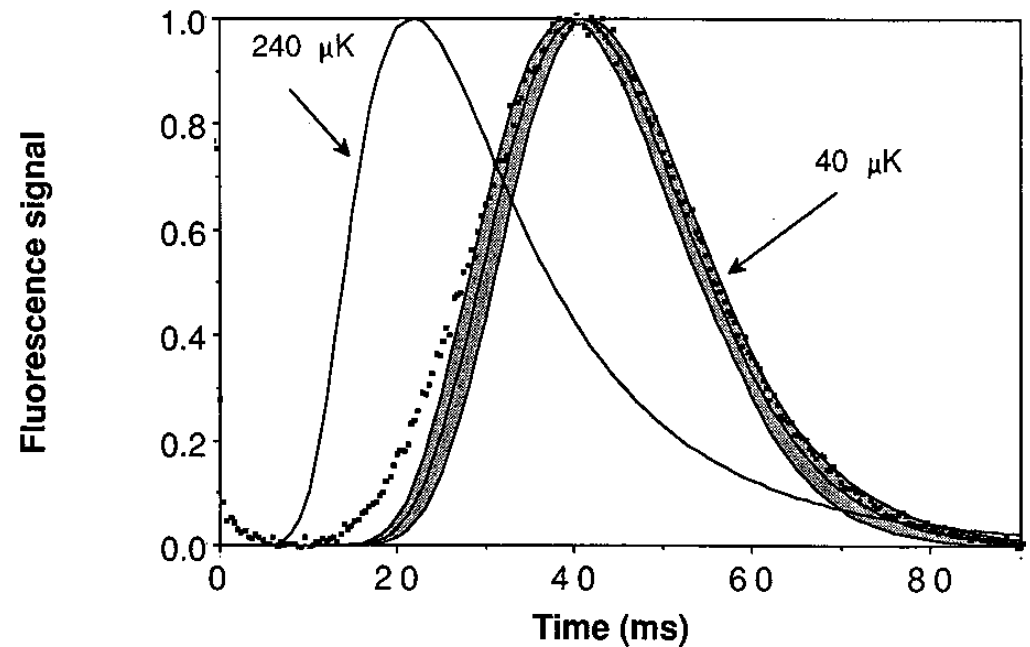
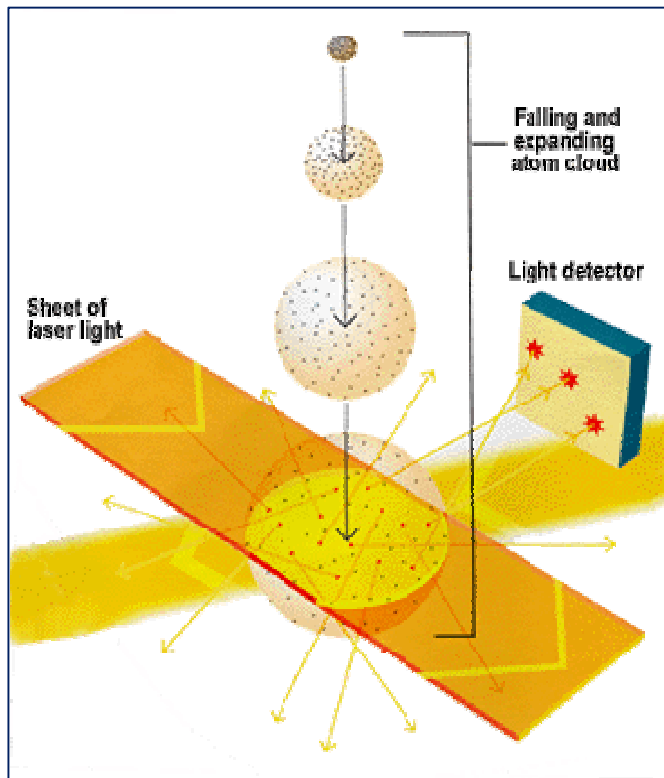
The random addition to the average momentum transfer produces a random walk of the atomic momentum and an increase in the mean square atomic momentum. This heating is countered by the cooling force F opposing atomic motion.

Time-of-flight method for measuring laser cooling temperatures



The predicted lower limit of Doppler cooling: 240 mK

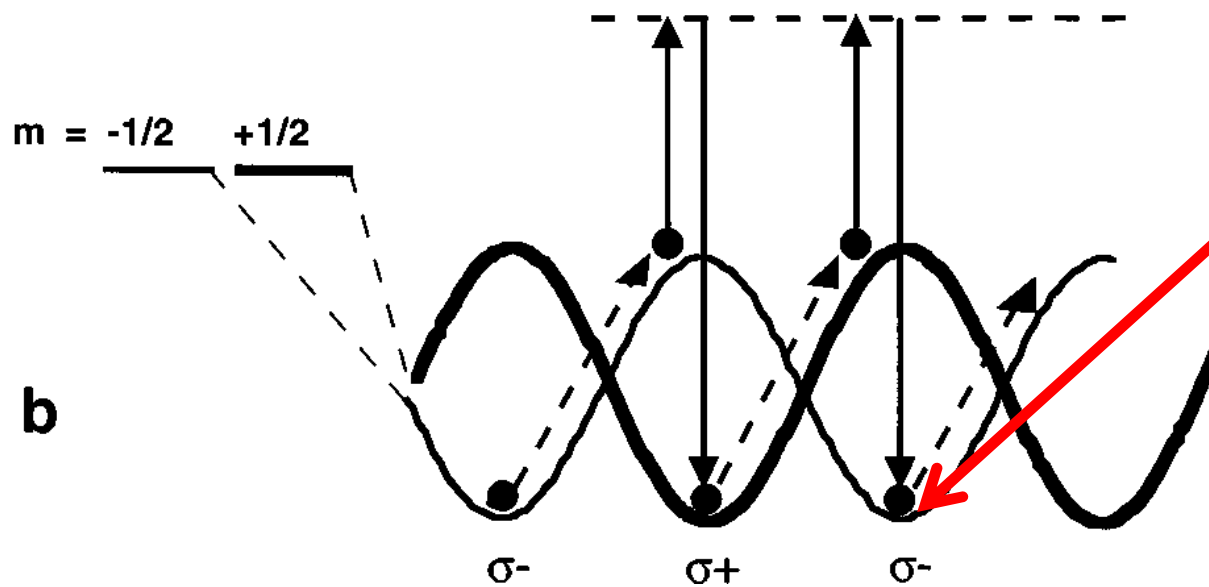
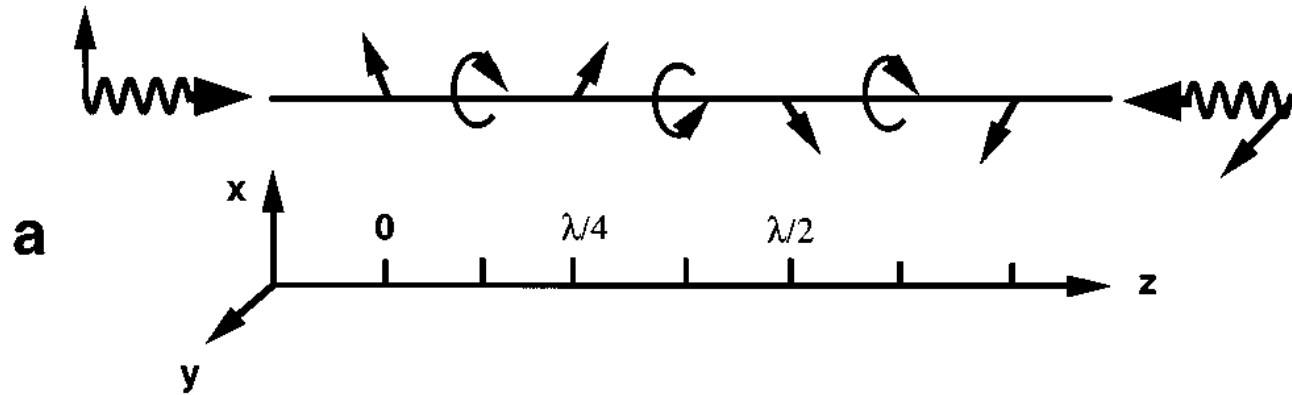
Time-of-flight method for measuring laser cooling temperatures



The experimental TOF distribution (points) and the predicted distribution curves for 40 mK and 240 mK (the predicted lower limit of Doppler cooling).

Conclusion: atoms were much colder than the Doppler limit!

“Sisyphus” cooling

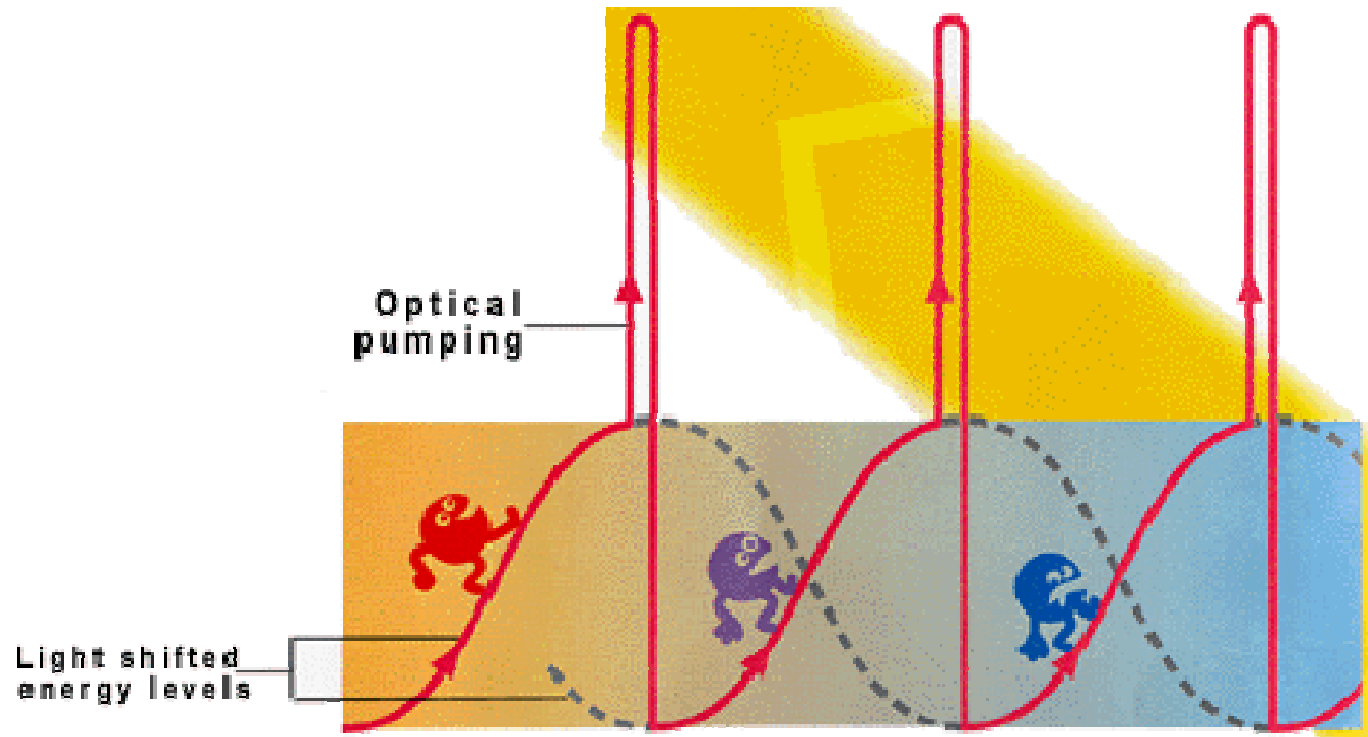


The atom is now again at the bottom of a hill, and it again must climb, losing kinetic energy, as it moves.

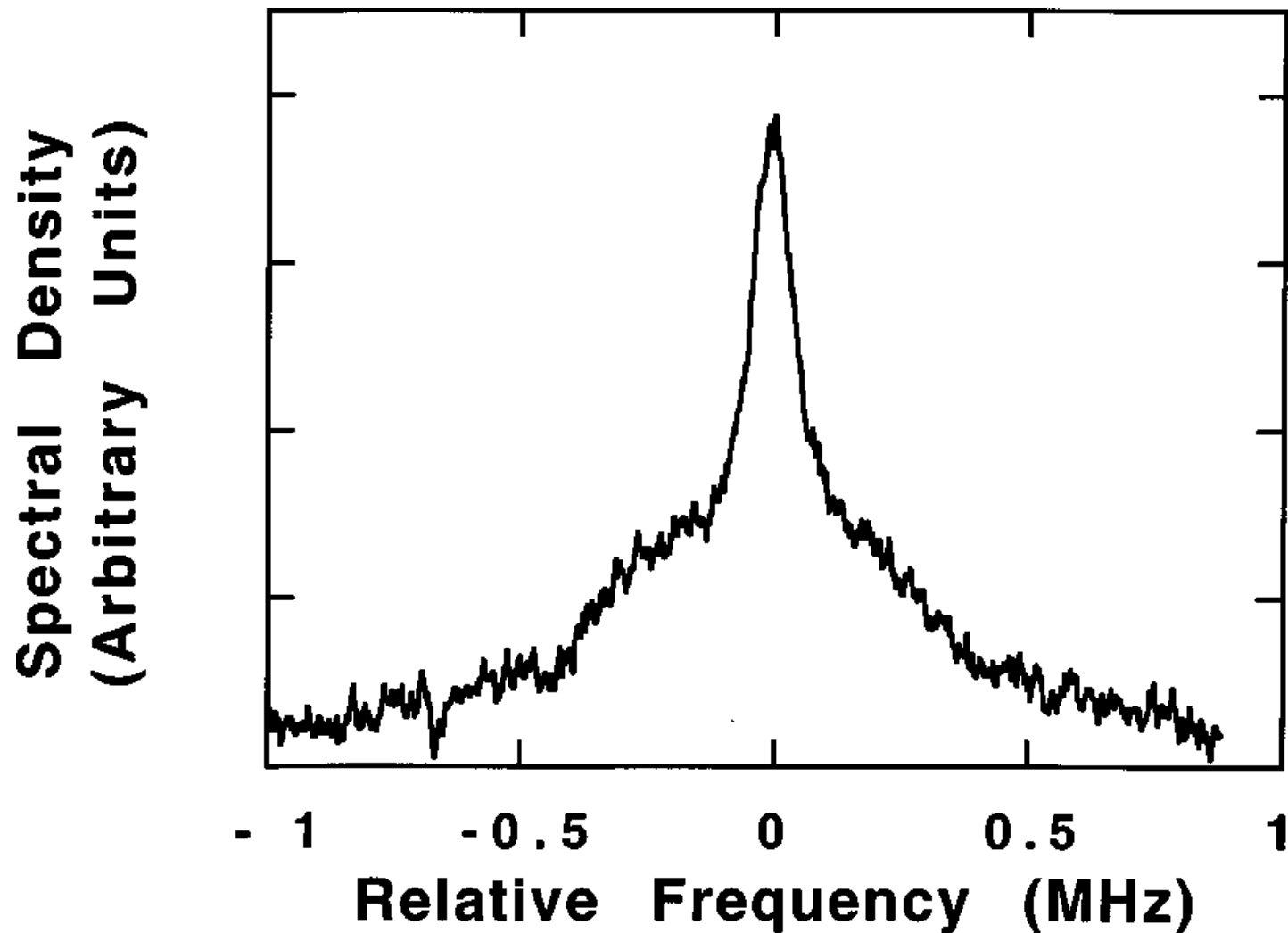
(a) Interfering, counterpropagating beams having orthogonal, linear polarizations create a polarization gradient.

(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

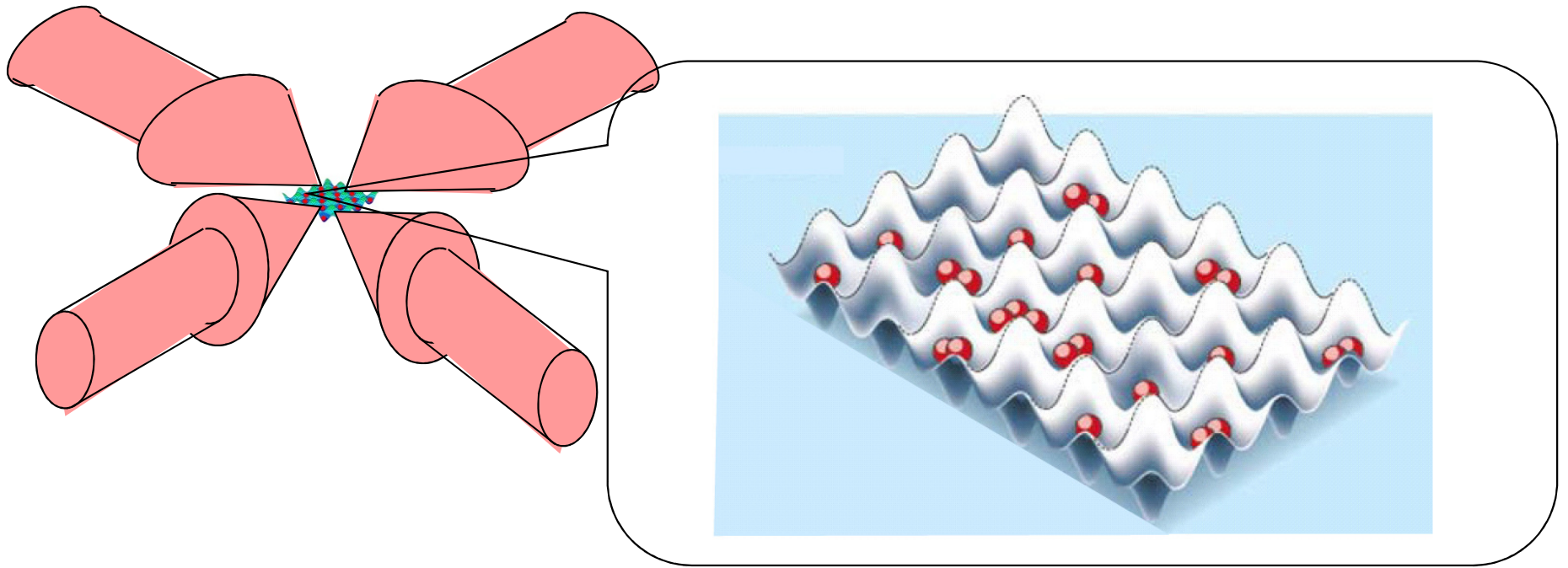


http://www.nobelprize.org/nobel_prizes/physics/laureates/1997/illpres/doppler.html



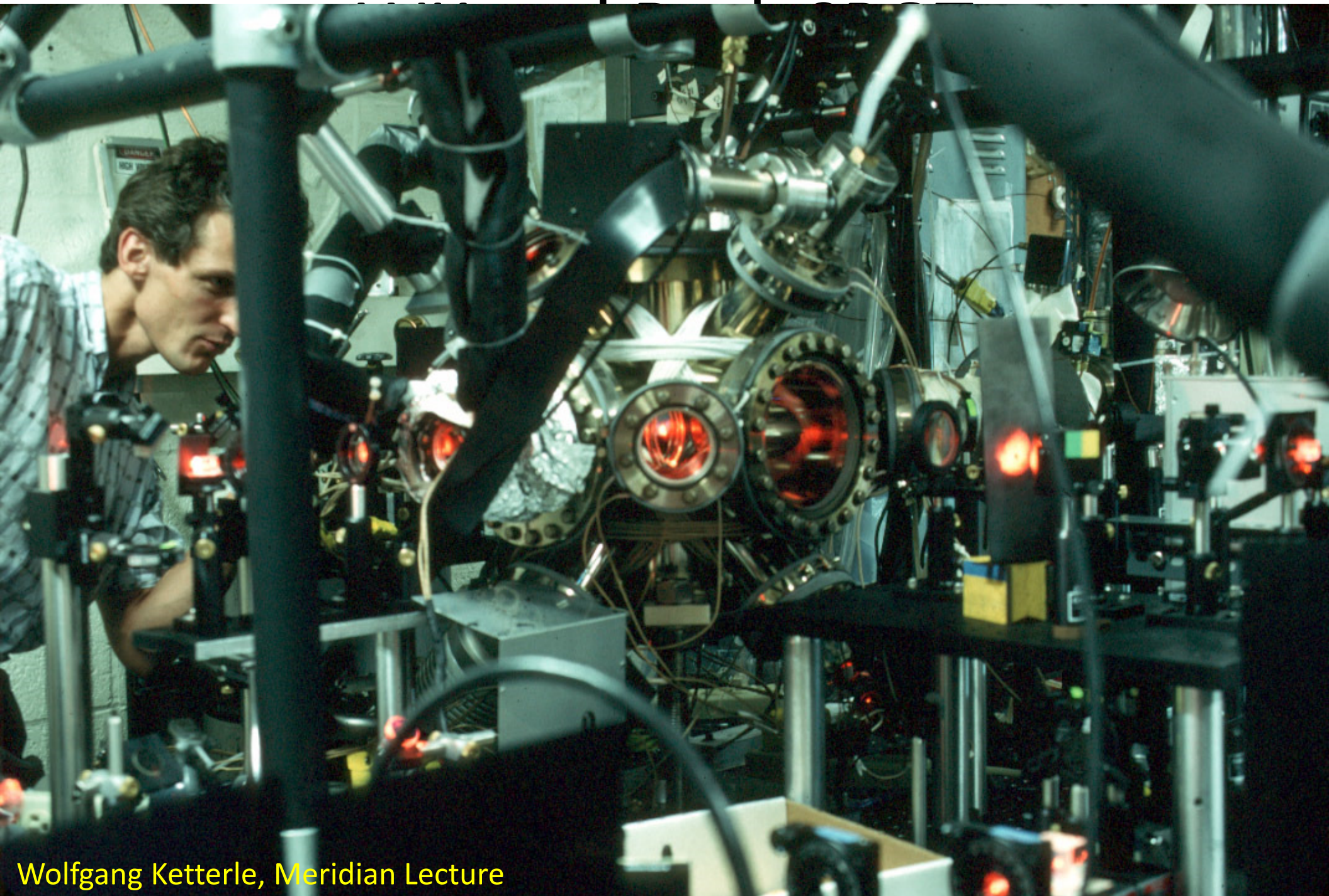
Heterodyne spectrum of fluorescence from Na atoms in optical molasses. The broad component corresponds to a temperature of $84 \mu\text{K}$, which compares well with the temperature of $87 \mu\text{K}$ measured by time-of-flight measurement. The narrow component indicates a sub-wavelength localization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

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.

Sodium laser cooling experiment (1992)



Nobel Prize in Physics 1997



Steve Chu

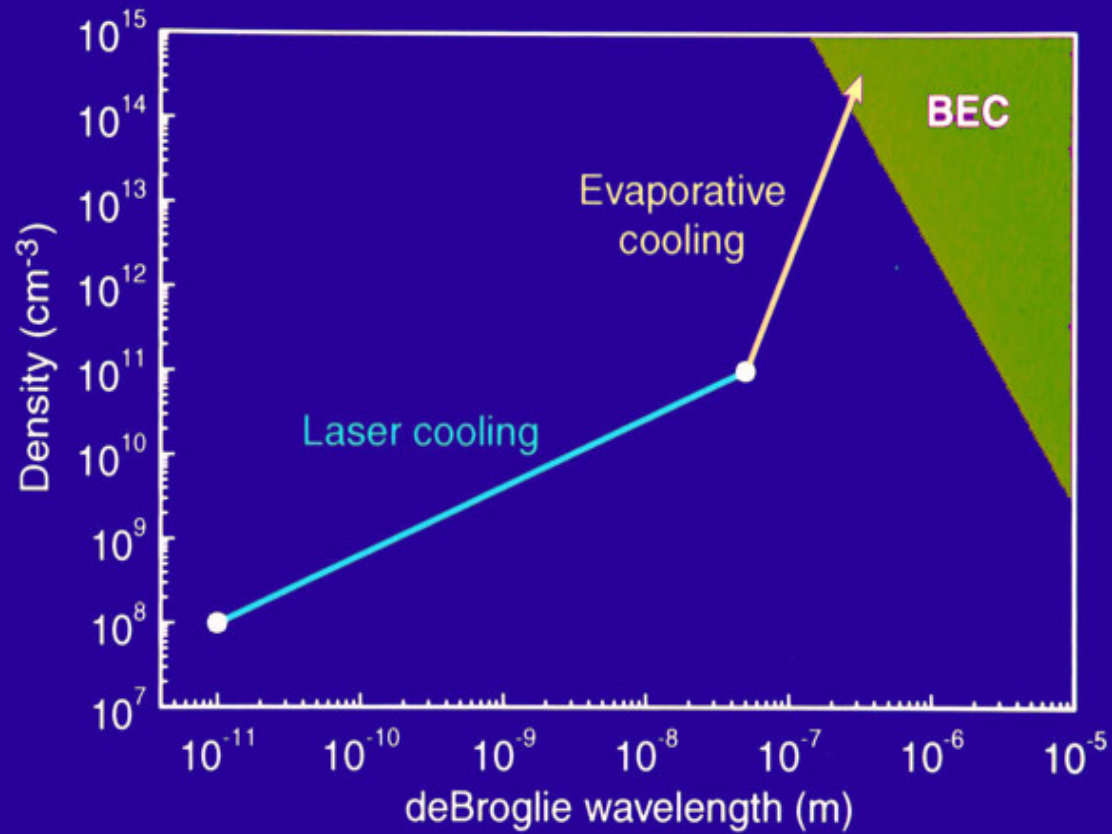


Claude Cohen-Tannoudji



Bill Phillips

Phase Space



300 K

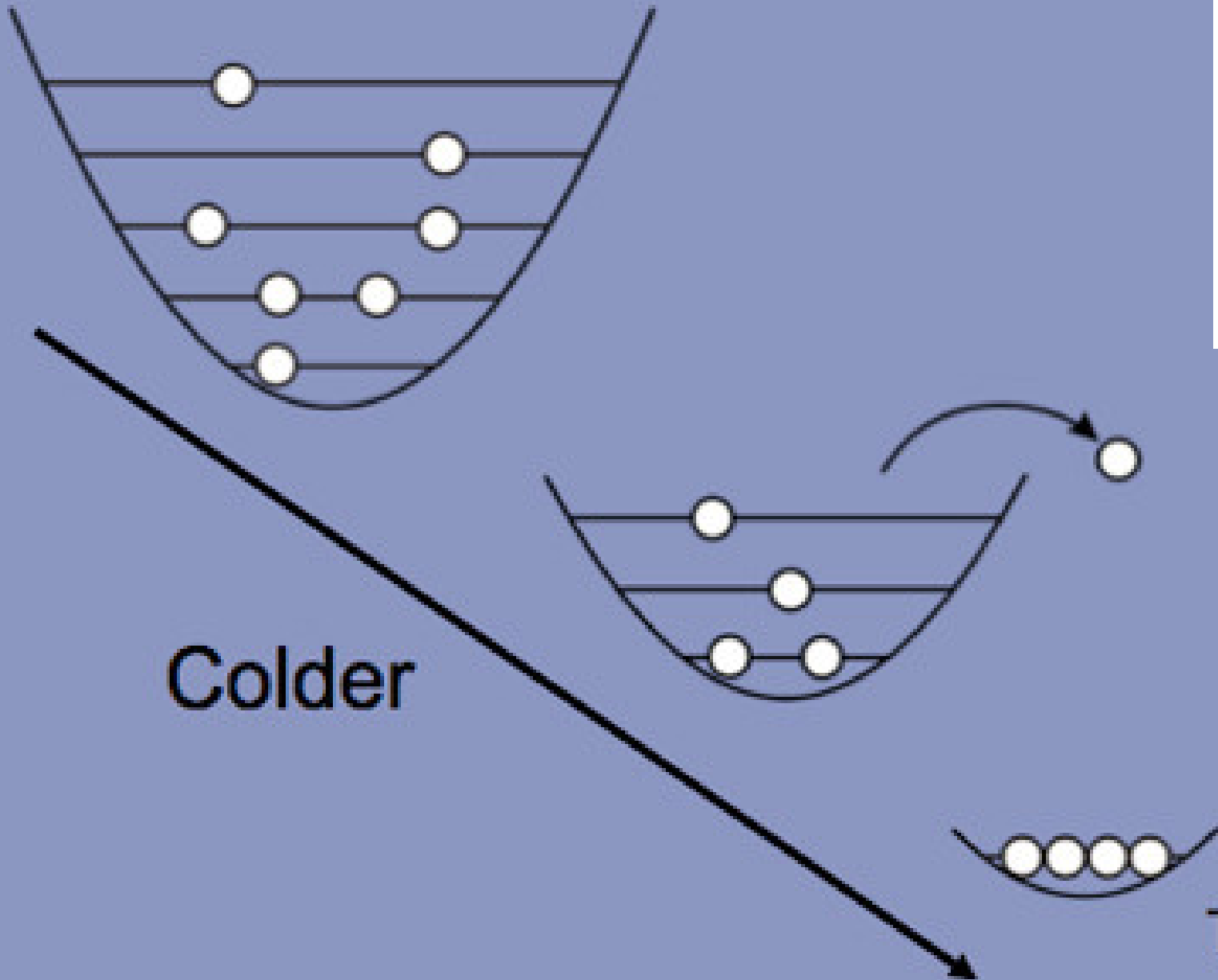
10 μK

500 nK



from Theodor W. Hänsch's Nobel Lecture

BEC: Cool by evaporation



Colder

Temp ~ 50 nK

Evaporative cooling

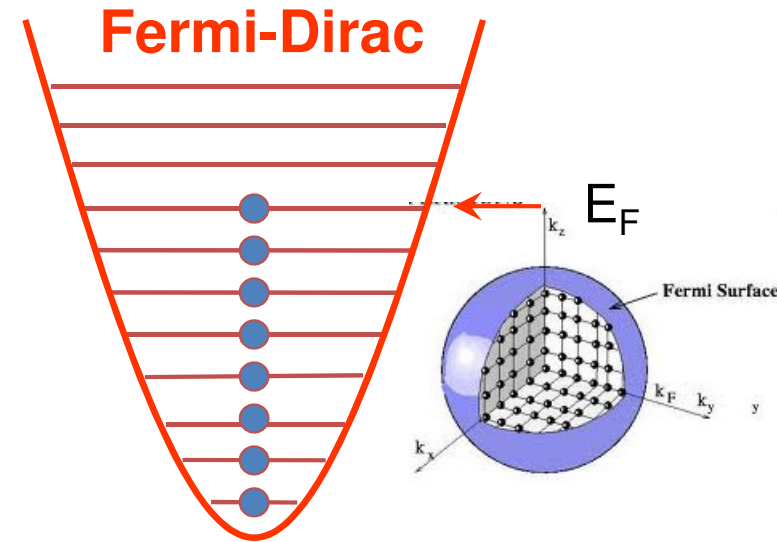
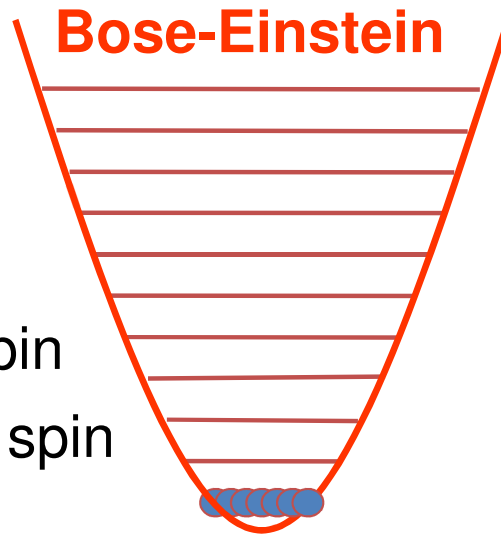
Quantum gases: bosons and fermions

Ideal gas at zero temperature

Bose-Einstein : integer spin

Fermi-Dirac : half-integer spin

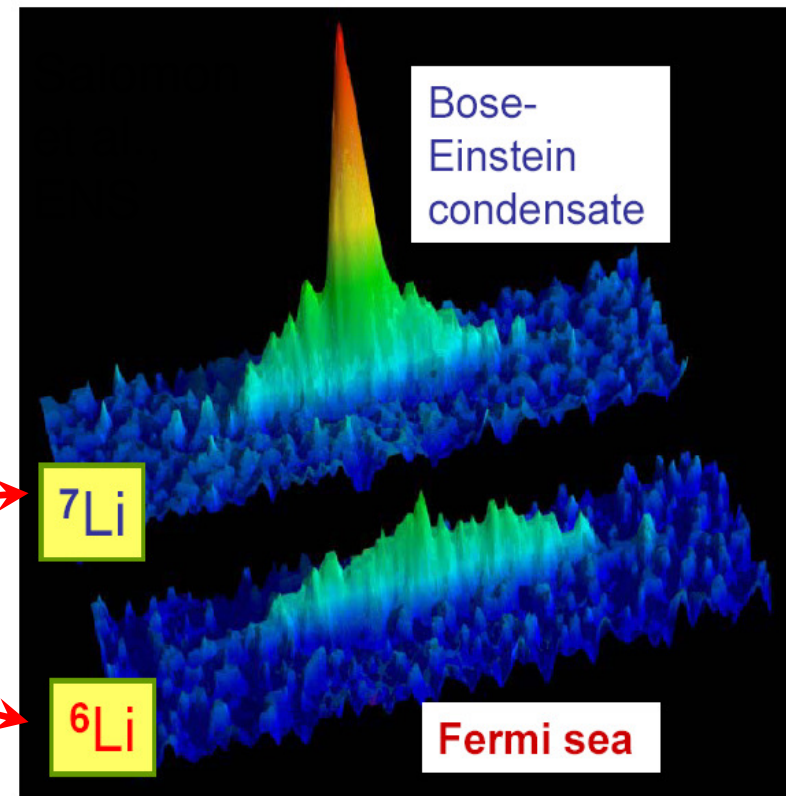
In neutral atoms $N_{\text{electrons}} = N_{\text{protons}}$



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

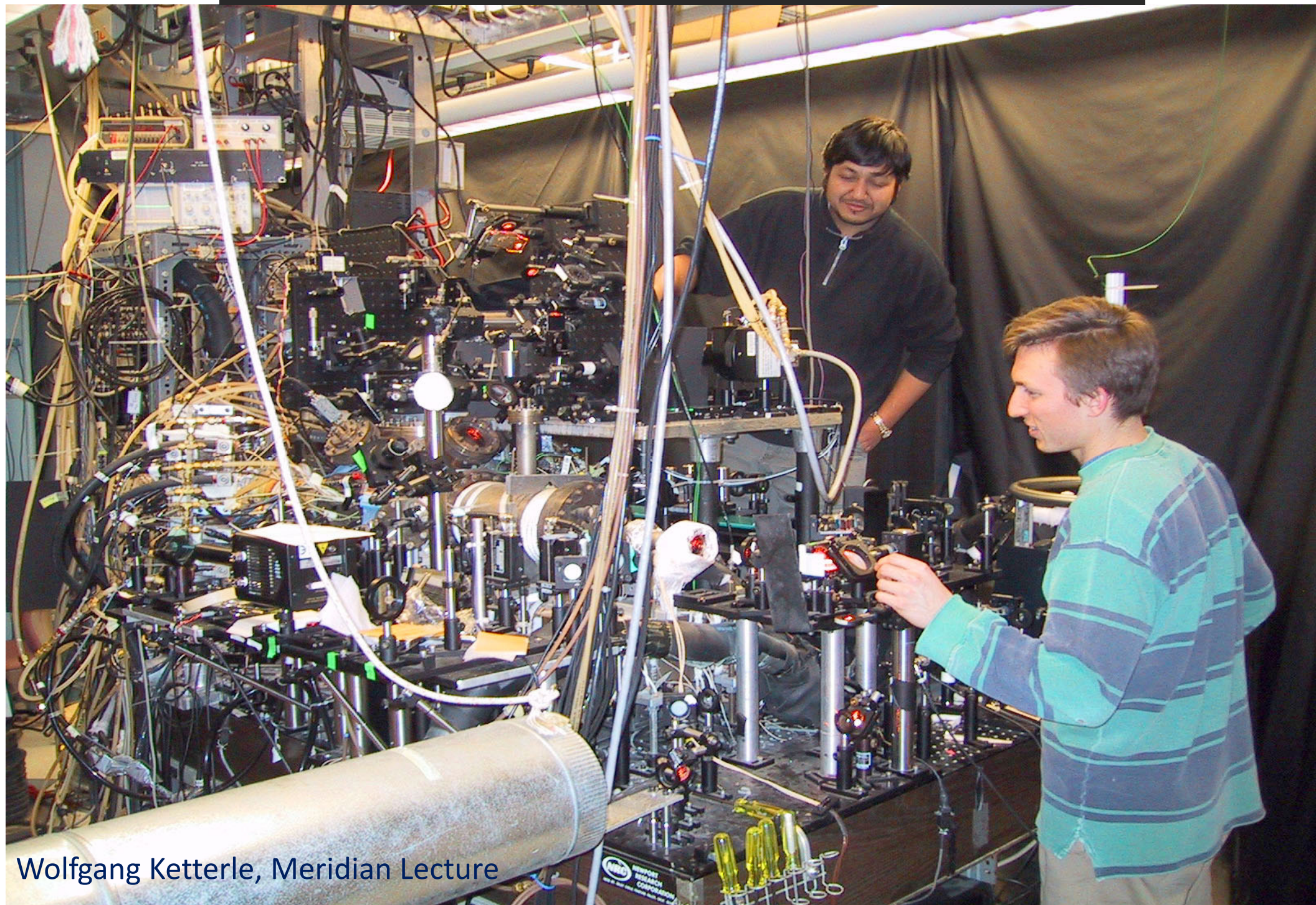


Wolfgang Ketterle



Carl Wieman

Sodium BEC I experiment (2001)



Wolfgang Ketterle, Meridian Lecture