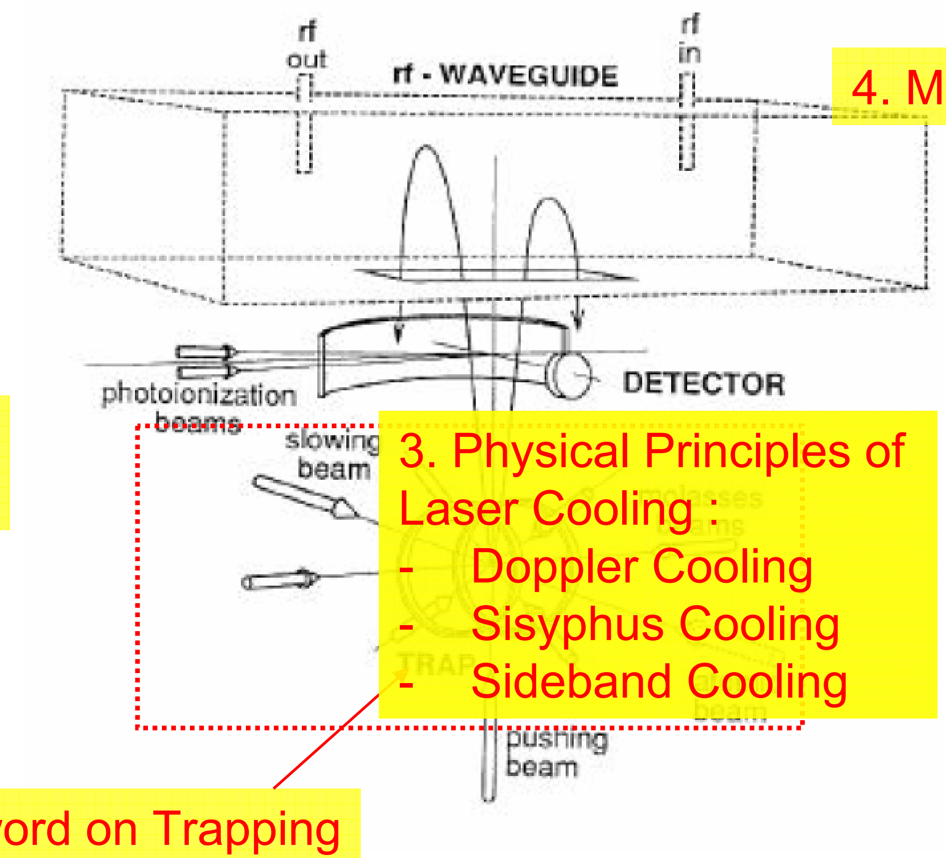
The Physics of Laser Cooling

Seminar Moderne Optik
HU-Berlin, WS 07-08
Geert Van Hout

Laser cooling & trapping in action

The cold-atom fountain



4. More applications

1. Laser Cooling :
   What? Why?

3. Physical Principles of Laser Cooling :
- Doppler Cooling
- Sisyphus Cooling
- Sideband Cooling

2. A word on Trapping

massey.dur.ac.uk/articles/newoptics.pdf

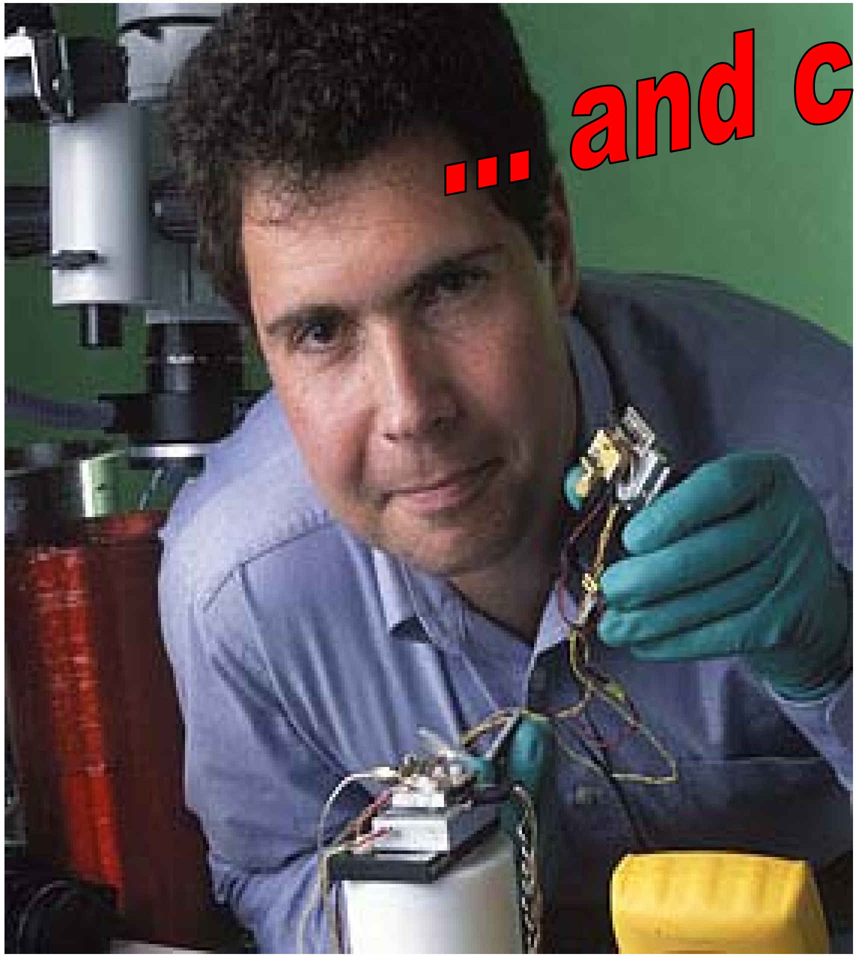
Atomic (fountain) clock

Large ...

NIST F-1
Accurate to 1 second
in 60 million years (2005)

http://encarta.msn.com/

Atomic (fountain) clock



... and chip-scale

http://www.nist.gov/public_affairs/releases/miniclock.htm

What is laser cooling?

Cool, trap and manipulate atoms, ions, micro-particles using laser light

– Isolate particles from environment
– Virtually no Doppler shifts
– Extremely long interaction times
– BEC, superfluidity

It all started in 1975…

- **1975 Hänsch/Schawlow** and **Wineland/Dehmelt** : possibility of laser cooling
- **1978 First demonstration of laser cooling** for trapped ions (Neuhauser et al.; Wineland et al.)
- 1982 First stopping of a thermal beam (Philips & Metcalf)
- **1985 First 3-D cooling (Chu, Hollberg et al.)** → 240 μK
- 1987 theory of magneto-optical trap (MOT) (Dalibard et al.)
- 1988 Sub-Doppler cooling (Cohen-Tannoudji et al.) → 40 nK
- 1995 Laser + evaporative cooling (Anderson, Cornell et al.) → 20 nK
- Nobel Prizes

1989	Paul	ion-trap
1997	Chu, Cohen-Tannoudji, Philips	laser cooling & trapping
2001	Cornell, Ketterle, Wieman	BEC
2005	Glauber, Hall, Hänsch	laser-based precision spectroscopy

Laser cooling: what?
Why?

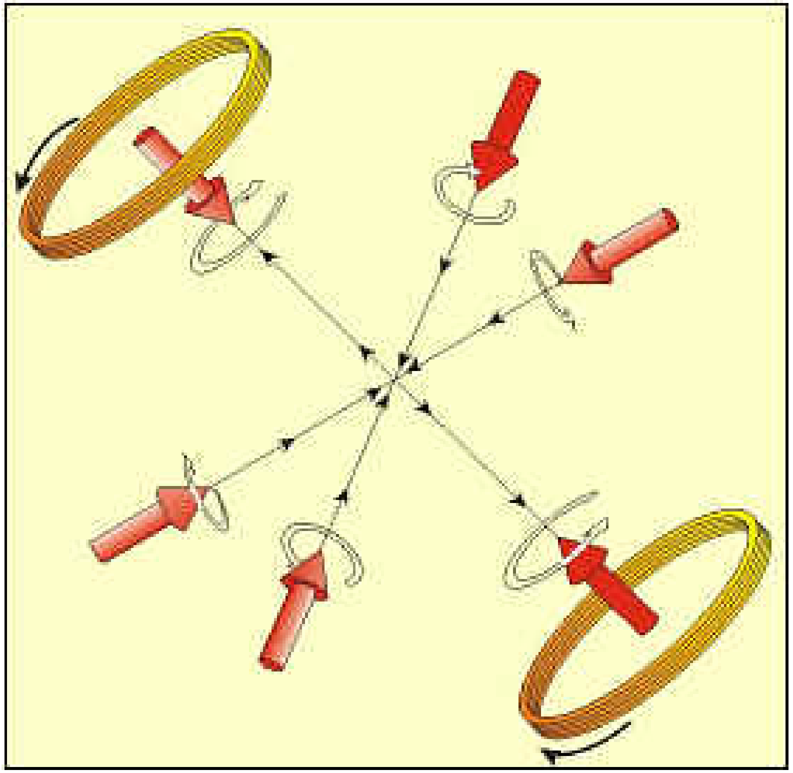
A word on Trapping

Laser cooling

Applications

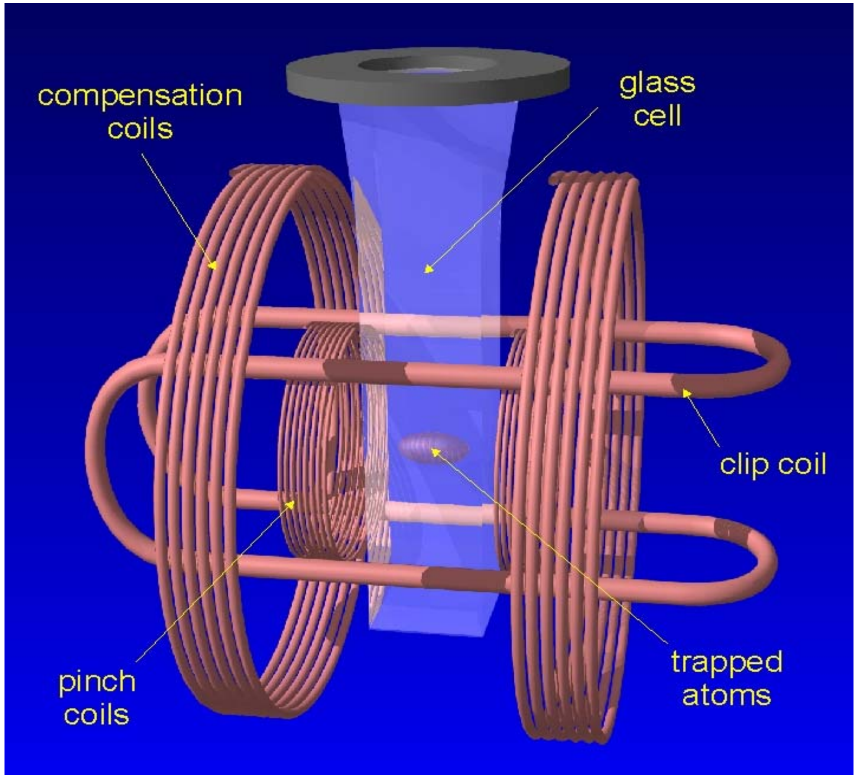
Trapping of neutral particles

Magneto-optical trap (MOT)



massey.dur.ac.uk/articles/newoptics.pdf

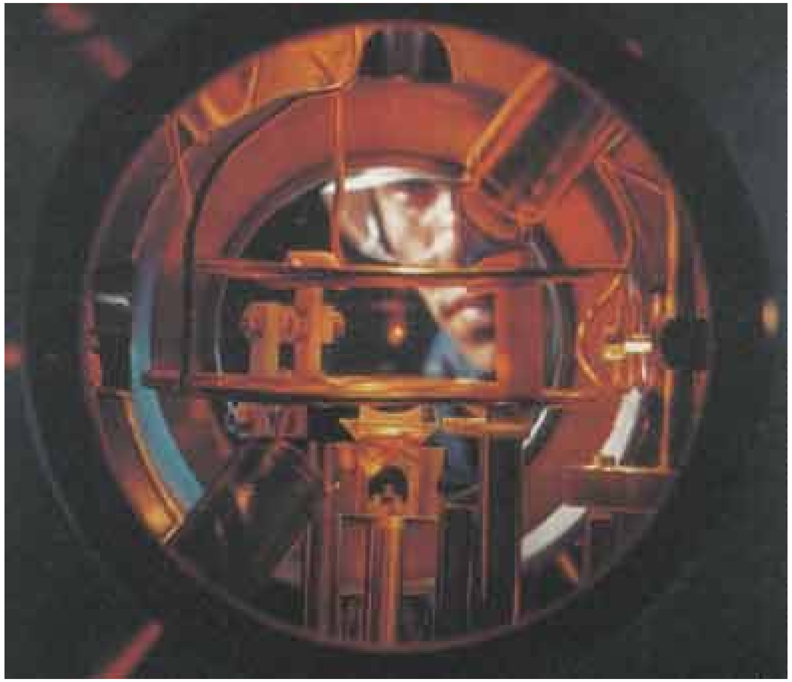
Ioffe-Pritchard Trap



www.mpq.mpg.de/qdynamics/projects/bec/BECtrap.html

Trapping of neutral particles

Magneto-optical trap (MOT)



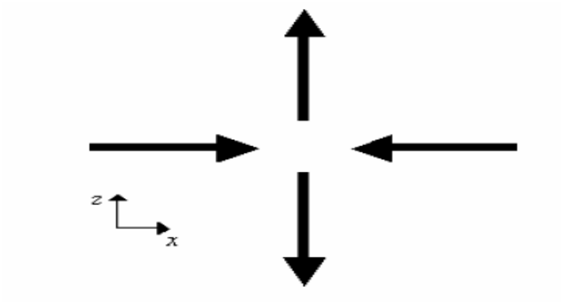
http://www.weltderphysik.de/de/1054.php

Trapping of charged particles

Earnshaw's Theorem

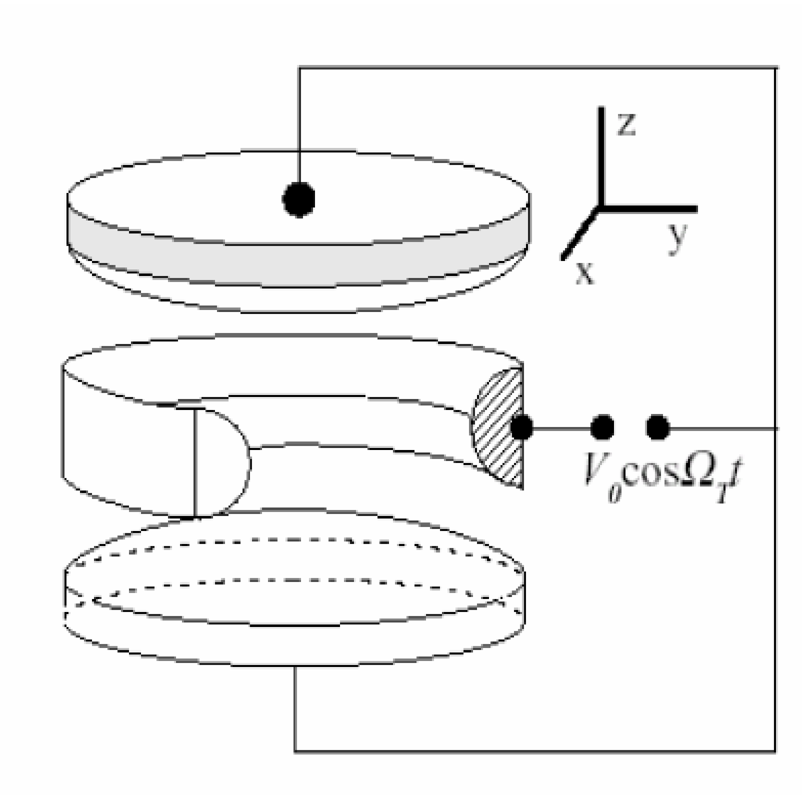
A collection of point charges cannot be maintained in a stable stationary equilibrium configuration solely by the electrostatic interaction of the charges

$$\nabla \cdot \vec{E} = 0$$



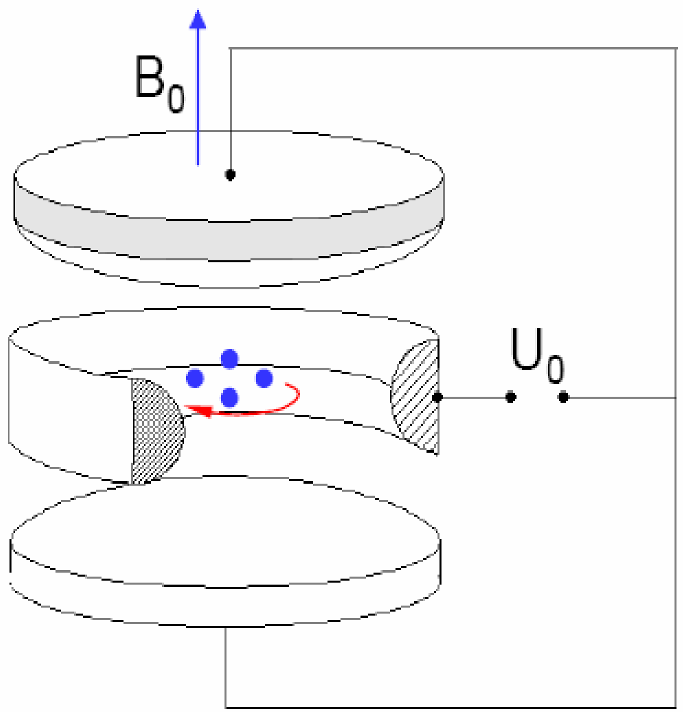
Trapping of charged particles

Paul Trap



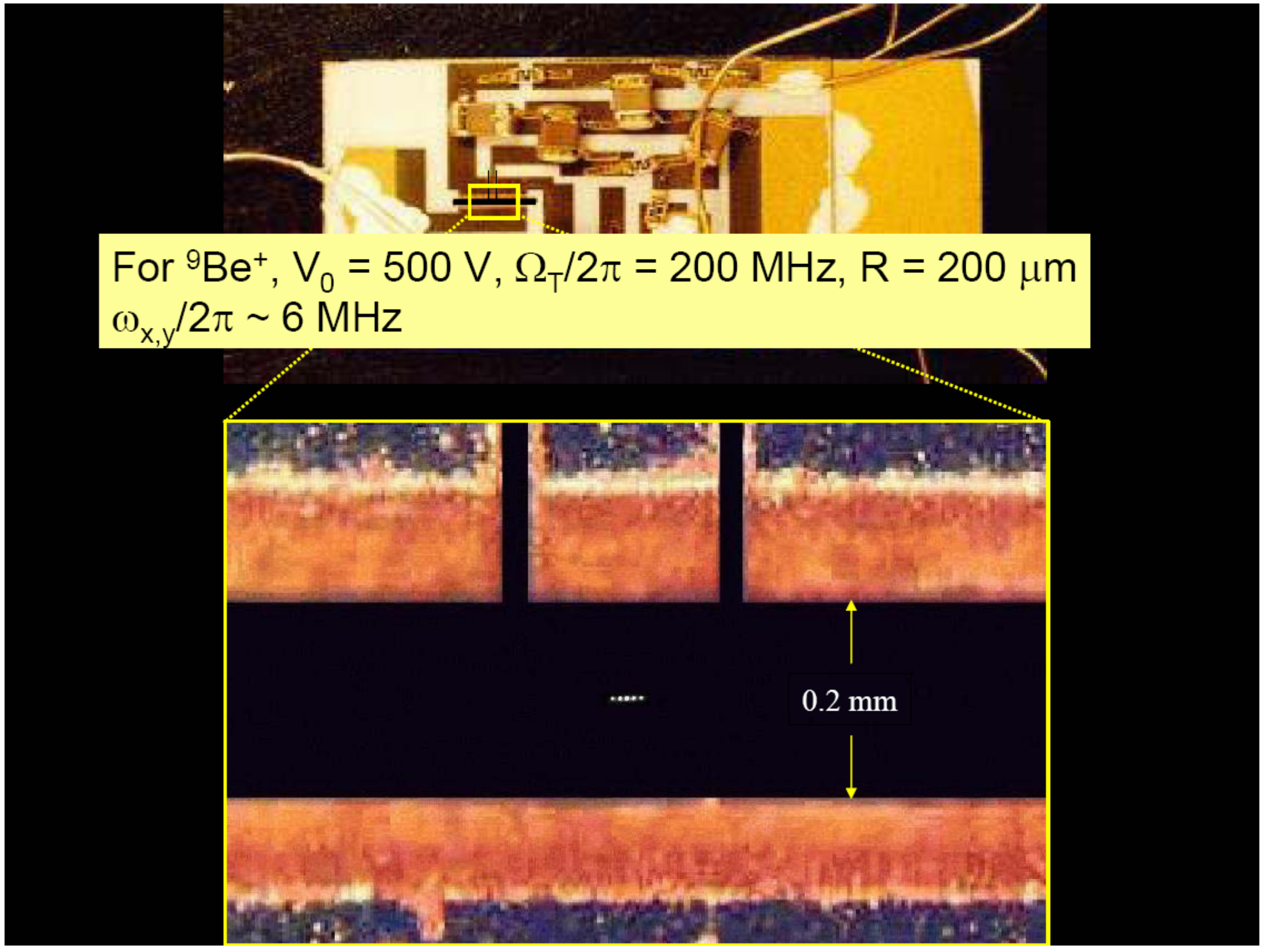
http://www.physics.mcmaster.ca/people/faculty/King/ion_traps.html

Penning Trap



Wineland, Quantum Information Processing in Ion Traps II (Les Houches Summer School, 2003)

Particles in a linear Paul trap



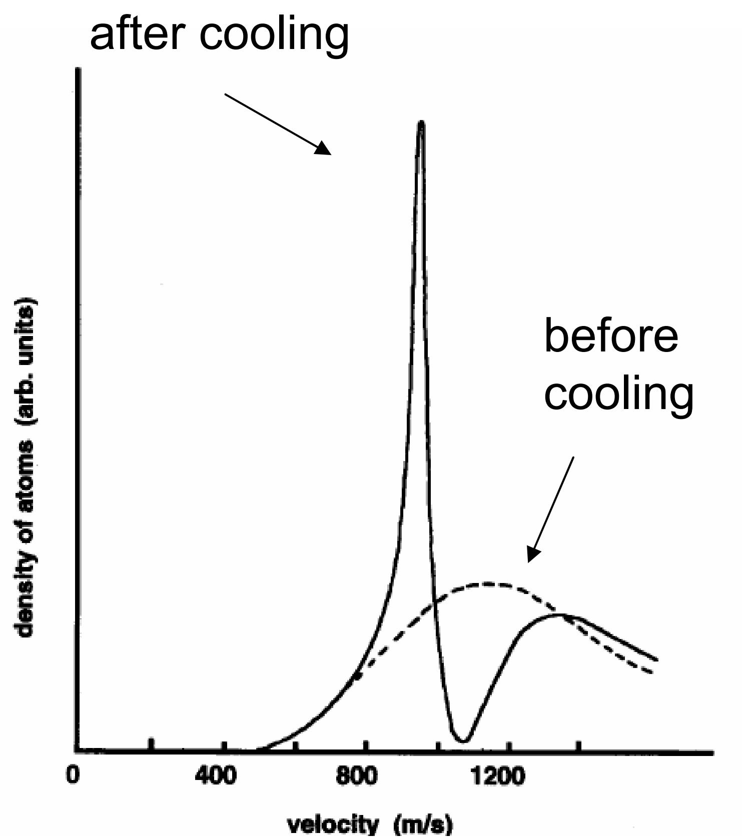
1. Introduction

2. Trapping

3. Laser cooling

4. Applications

Slowing ≠ Cooling



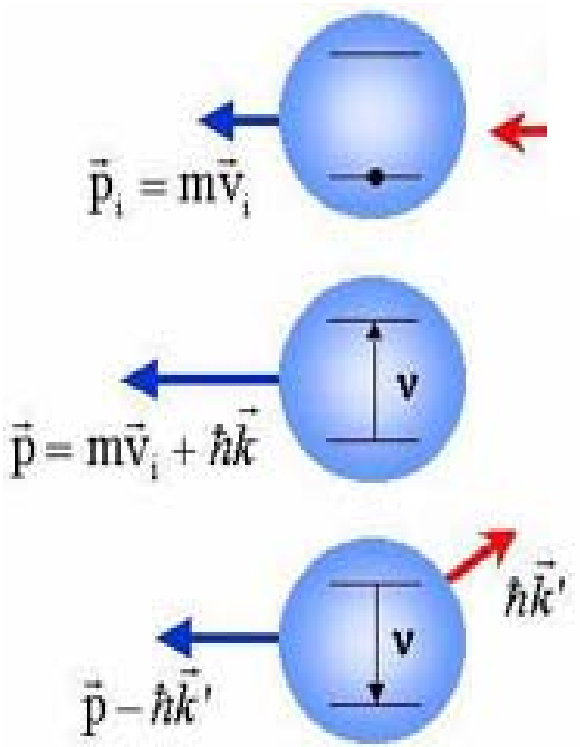
W.D. Philips, Laser Cooling and Trapping of Neutral Atoms (Nobel Lecture), 1997

What happens when a moving atom is excited by laser light?

A simple 2-level model
(model for a closed transition)

Radiation-pressure force

A two-level model



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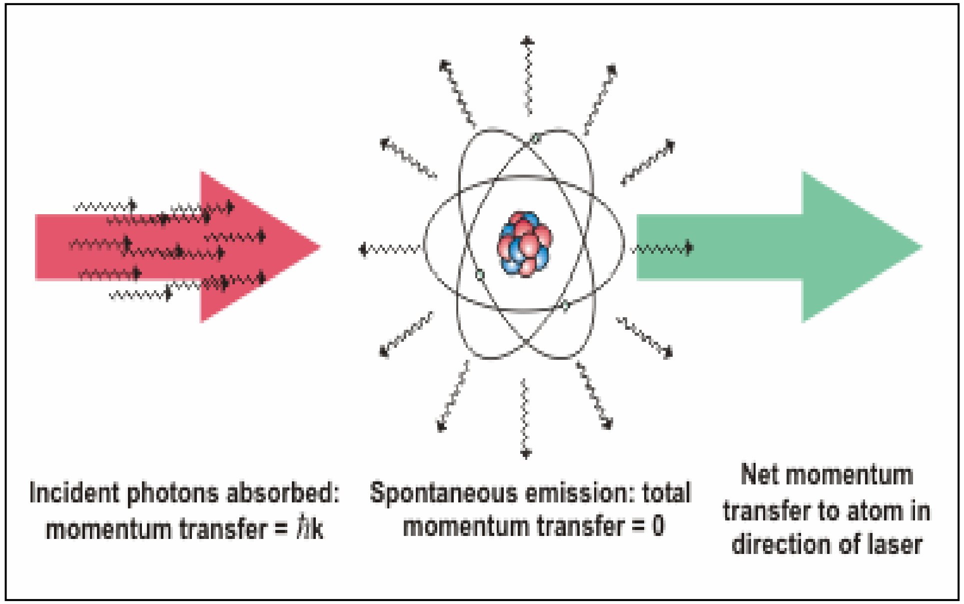


users.york.ac.uk

http://inms-ienm.nrc-cnrc.gc.ca/research/cesium_clock_e.html

Not included in model :

Change of Doppler shift

Zeeman slower

Changes resonant frequency of atoms

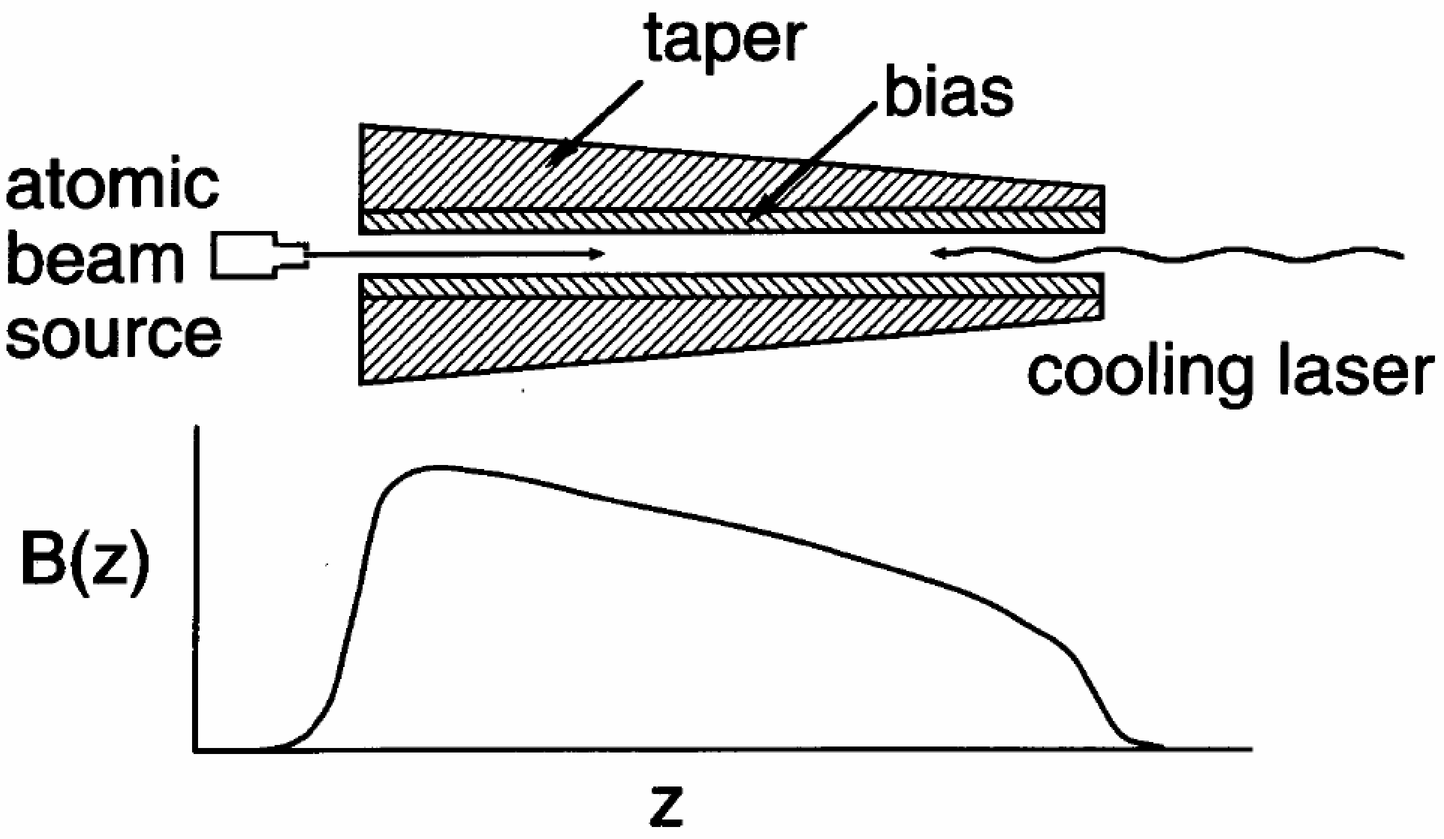
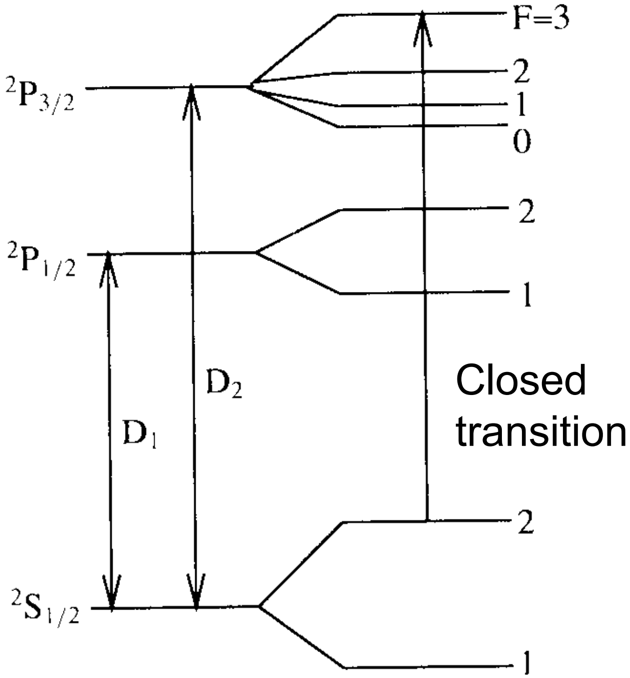


Figure 4. Upper: Schematic representation of a Zeeman slower. Lower: Variation of the axial field with position.

W.D. Philips, Laser Cooling and Trapping of Neutral Atoms (Nobel Lecture), 1997

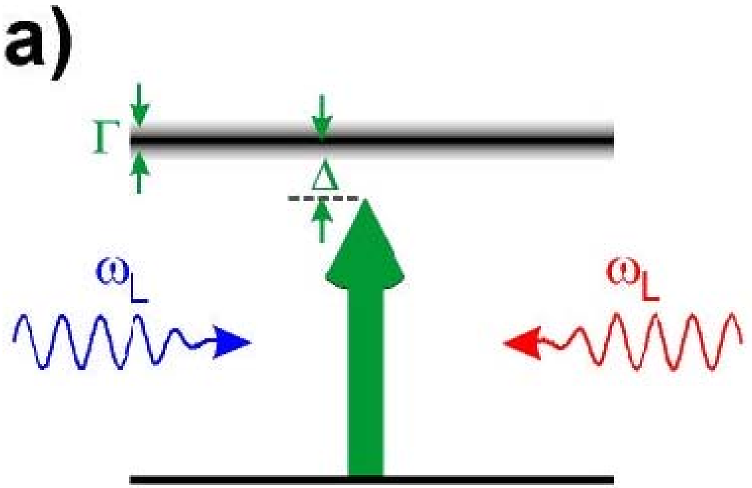
Example: Na atom beam

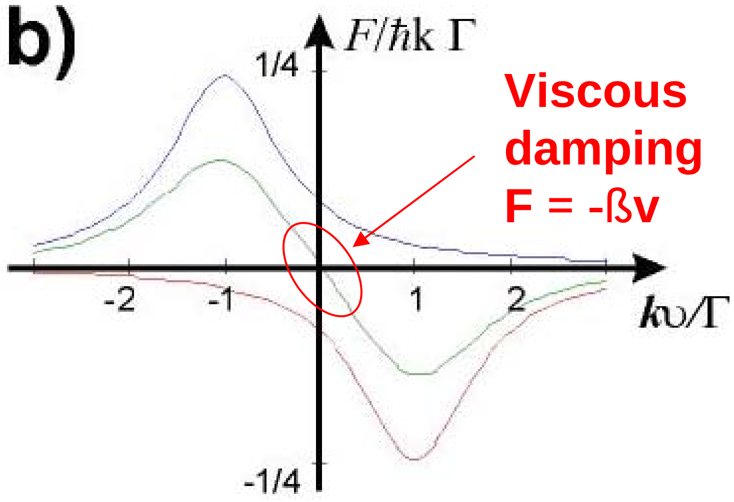


- λ_L = 589 nm
- $v_{rec} = \hbar k/M \sim 1$ cm/s
  $\tau_R \sim 10^{-8}$ s => 10^8 cycles/s
  $\Delta v_{tot} \sim 10^6$ m/s² = 10^5 x g
- A Na atomic beam from an oven (500 K, <v> ~ 1 km/s) is brought to rest in 1 ms, after 50 cm
- Atoms may return in opposite direction => use 2 beams ('Doppler cooling')

H.J. Metcalf, P. van der Straten, Laser Cooling and Trapping, Springer, 1999

Doppler Cooling in 1D





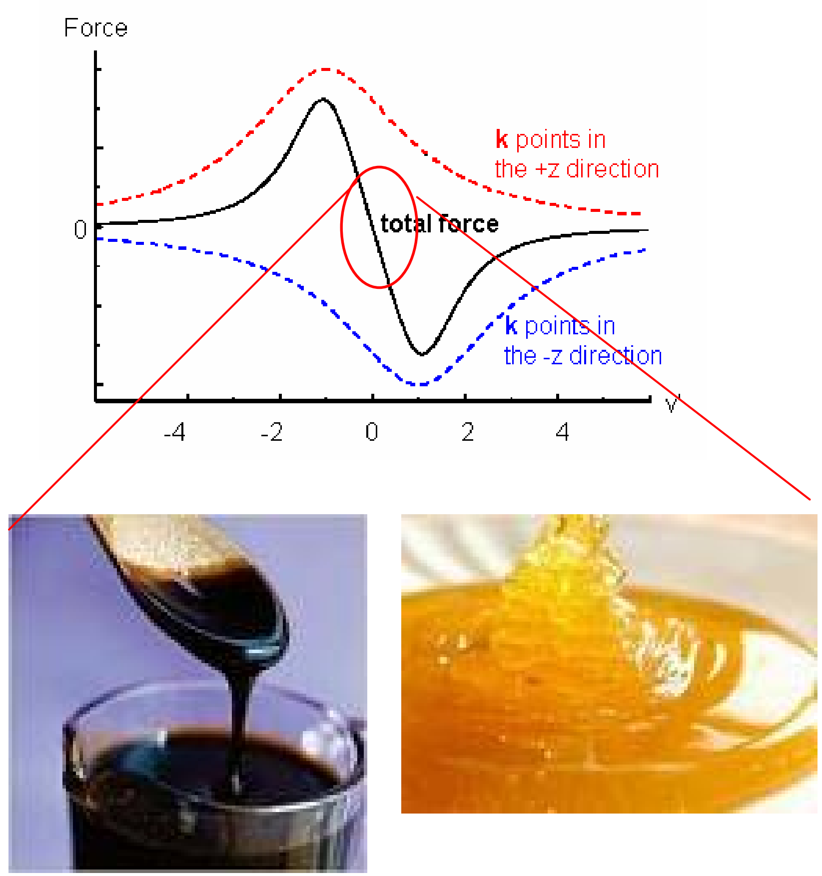
massey.dur.ac.uk/articles/newoptics.pdf

Optical Molasses

- F = -ßv for small v
  (ß : friction coefficient)

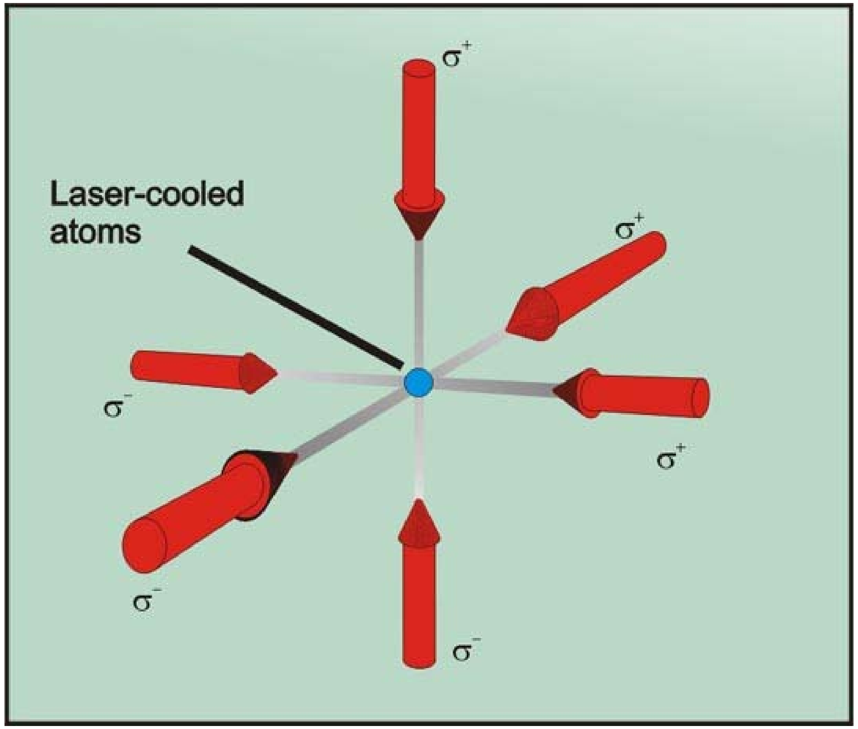
- ‘Optical molasses’
  ≠ trap!

- Very slow atom diffusion
  (random walk)



3D optical molasses

An ingeneous idea :



http://www.ptb.de/en/org/4/44/443/kuehl_e.htm

- Limiting process = momentum diffusion from fluorescence ('heating' from random walk)
- $T_{D,theo}$ ~ 100 μK (alkali)
- But first experiments :

  T ~ 10 μK
  longer lifetimes
  better stability

  than predicted by Doppler-cooling model

=> Search for new model !

Doppler Cooling

↓

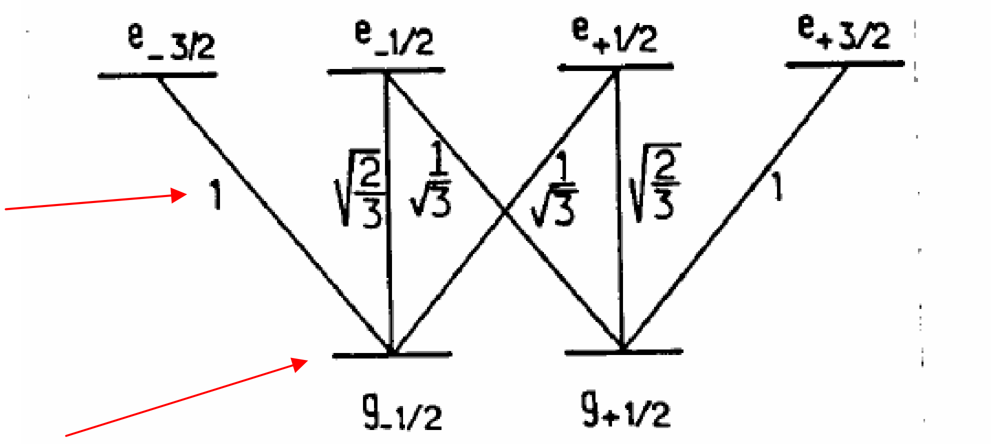
Sub-Doppler Cooling :

Sisyphus Cooling

1. Multi-level atom

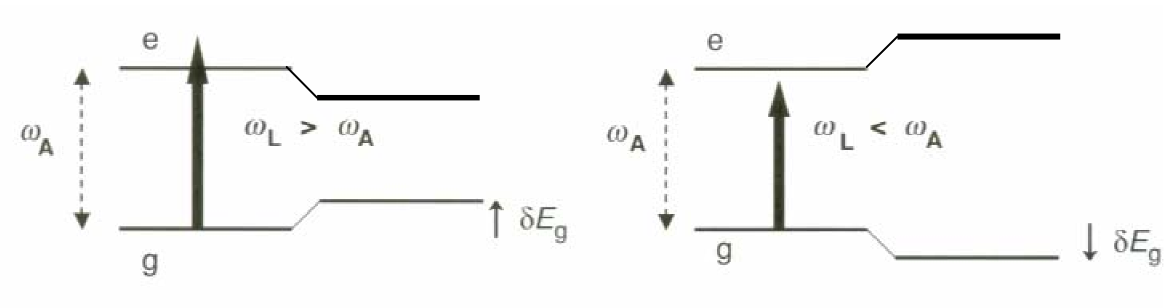
- Zeeman sublevels of atomic ground state
- Simplest model : 2-fold degenerate ground-state

CG coefficients



Zeeman structure
of ground state

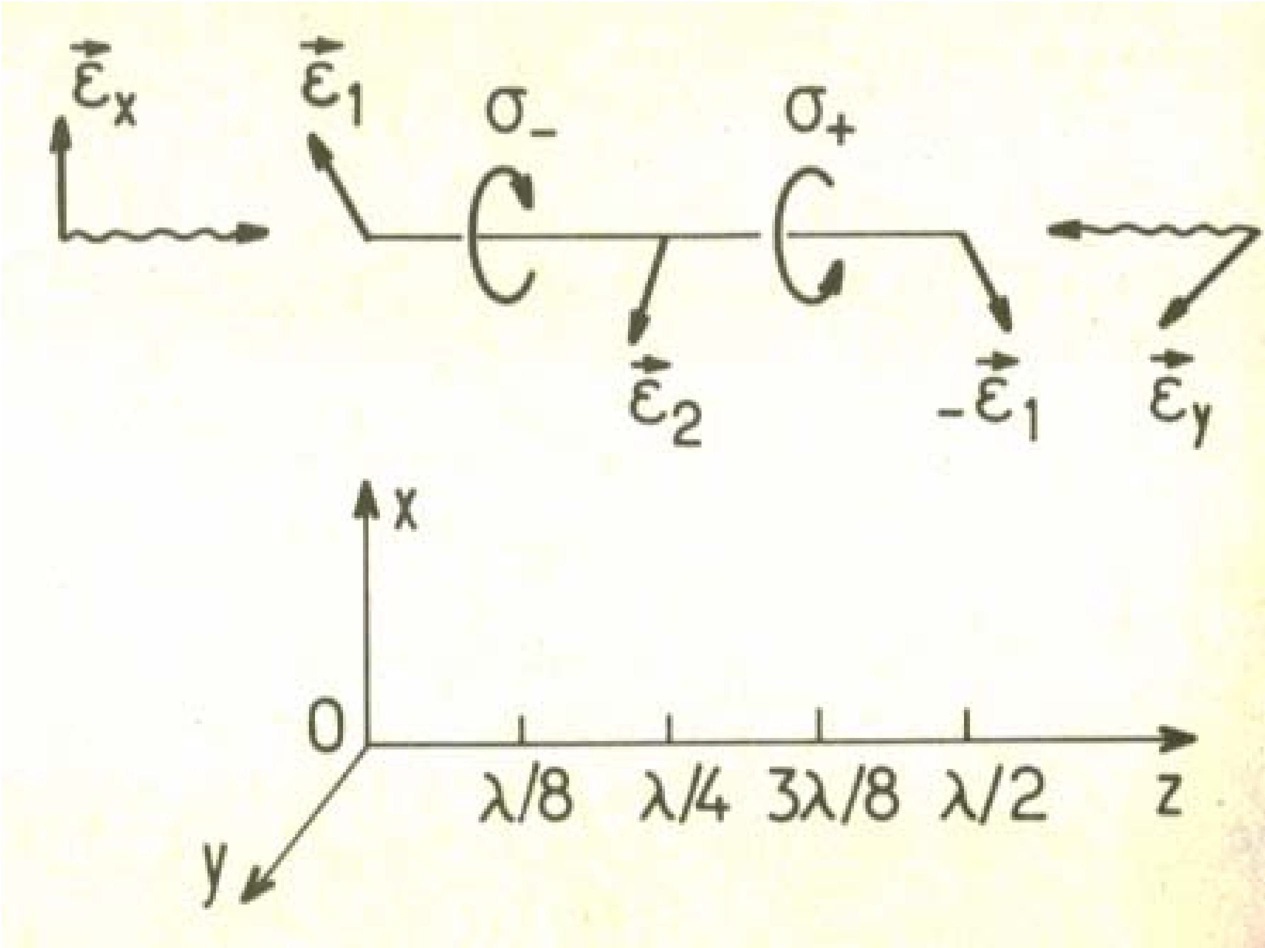
2. Light Shift (ac Stark Shift)



Nearly resonant light causes energy shift of atomic levels

- δE_g in the direction of the detuning $\Delta = \omega_L - \omega_A$
- $\delta E_g = 0$ for $\Delta = 0$
- $\delta E_g \sim C^2_{ge}$ => δE_g depends on:
  - magnetic quantum numbers of atom
  - polarization of light field

3. Polarization Gradient



Dalibard, Cohen-Tannoudji, J. Opt. Ph (B), 1989(11)

4. Selection rules

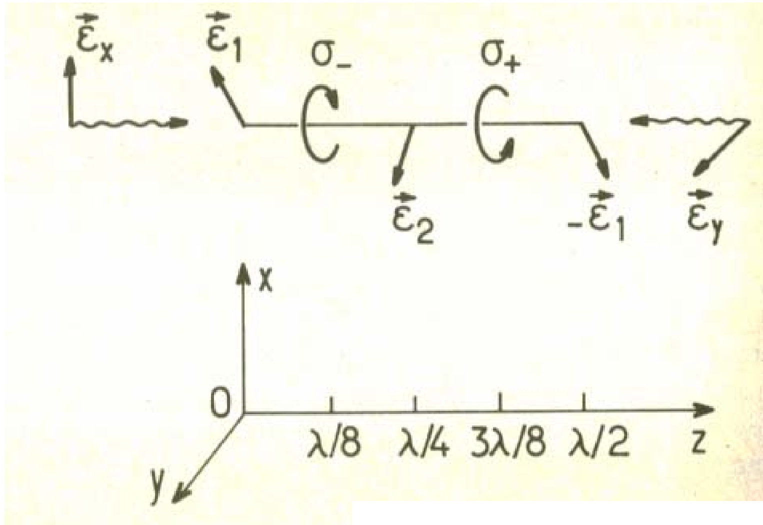
Selection rules are polarization-dependent

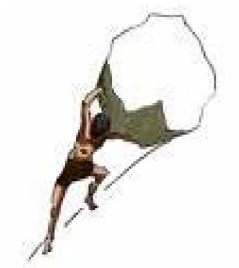
$$\sigma_+ : \Delta M = +1$$
$$\sigma_- : \Delta M = -1$$
$$\pi : \Delta M = 0$$

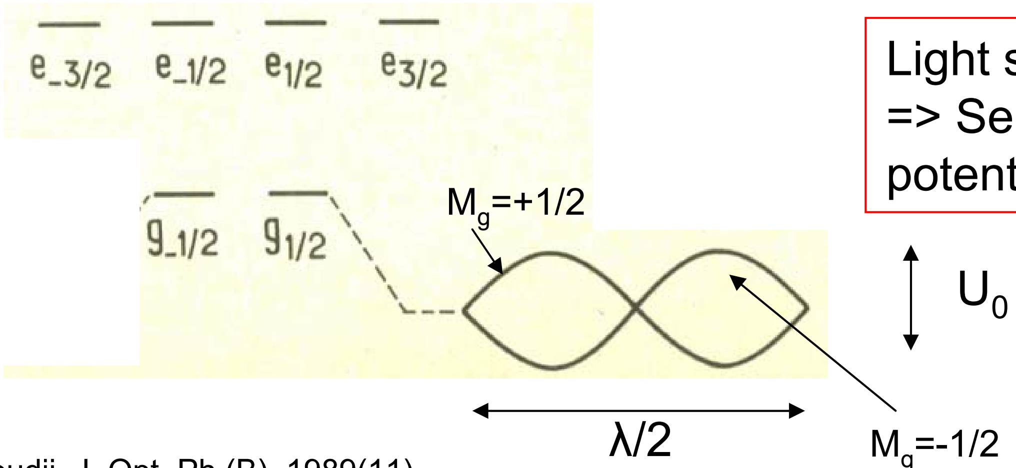
1. Multi-level atom
2. Light shift
3. Polarization gradient
4. Selection rules

Sisyphus Cooling
('Polarization Gradient Cooling')

Light shift of ground state levels



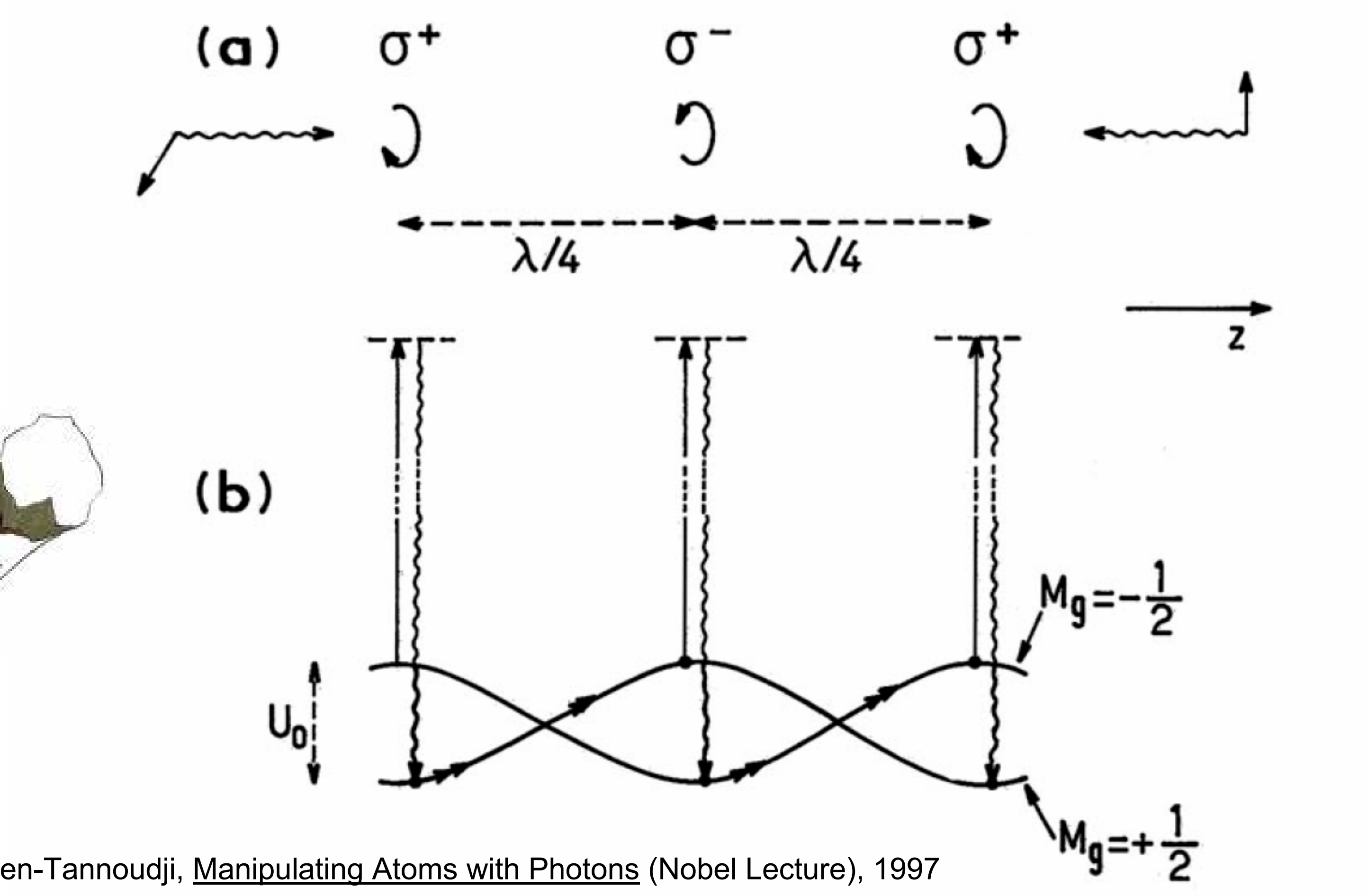




Light shift oscillates!
=> Series of
potential hills/valleys

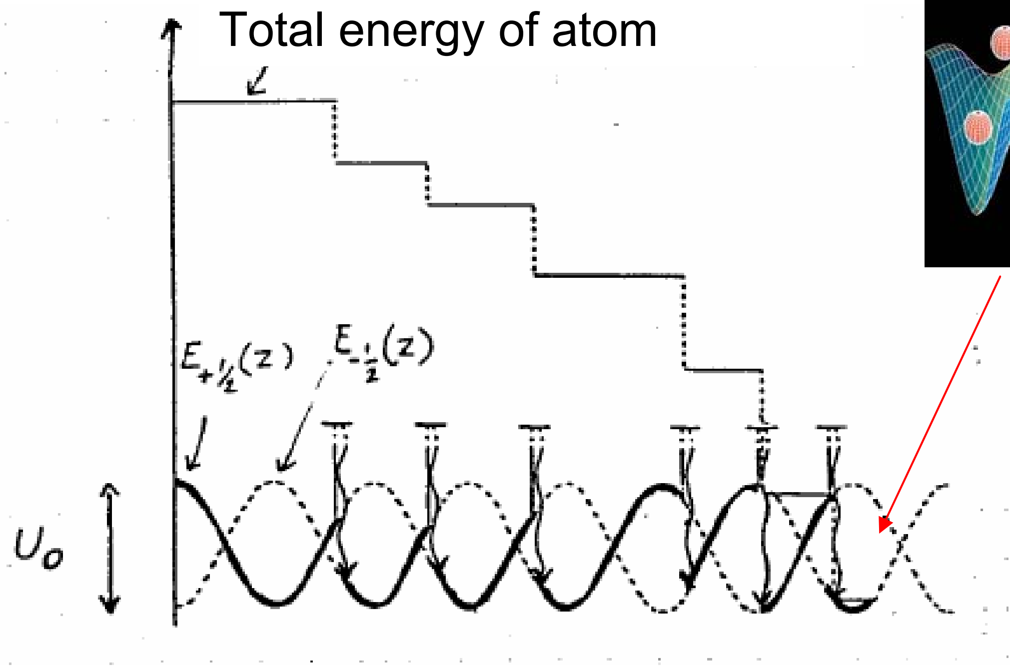
Dalibard, Cohen-Tannoudji, J. Opt. Ph (B), 1989(11)

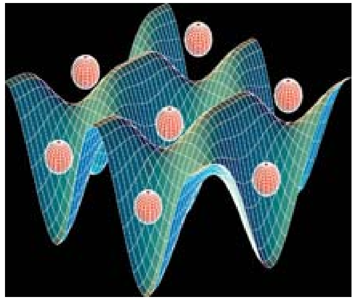
Sisyphus Cooling



Cohen-Tannoudji, Manipulating Atoms with Photons (Nobel Lecture), 1997

Sisyphus Cooling

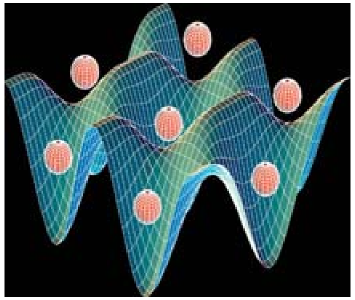


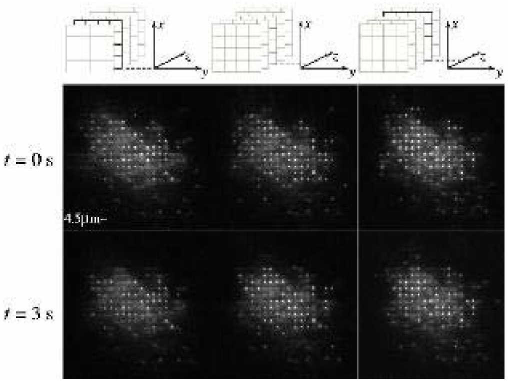


Temp limit:
$k_B T_{sis} \approx U_0$
(= a few μK)

http://www.phys.ens.fr/cours/college-de-france/1990-91/1990-91.htm

Optical lattices



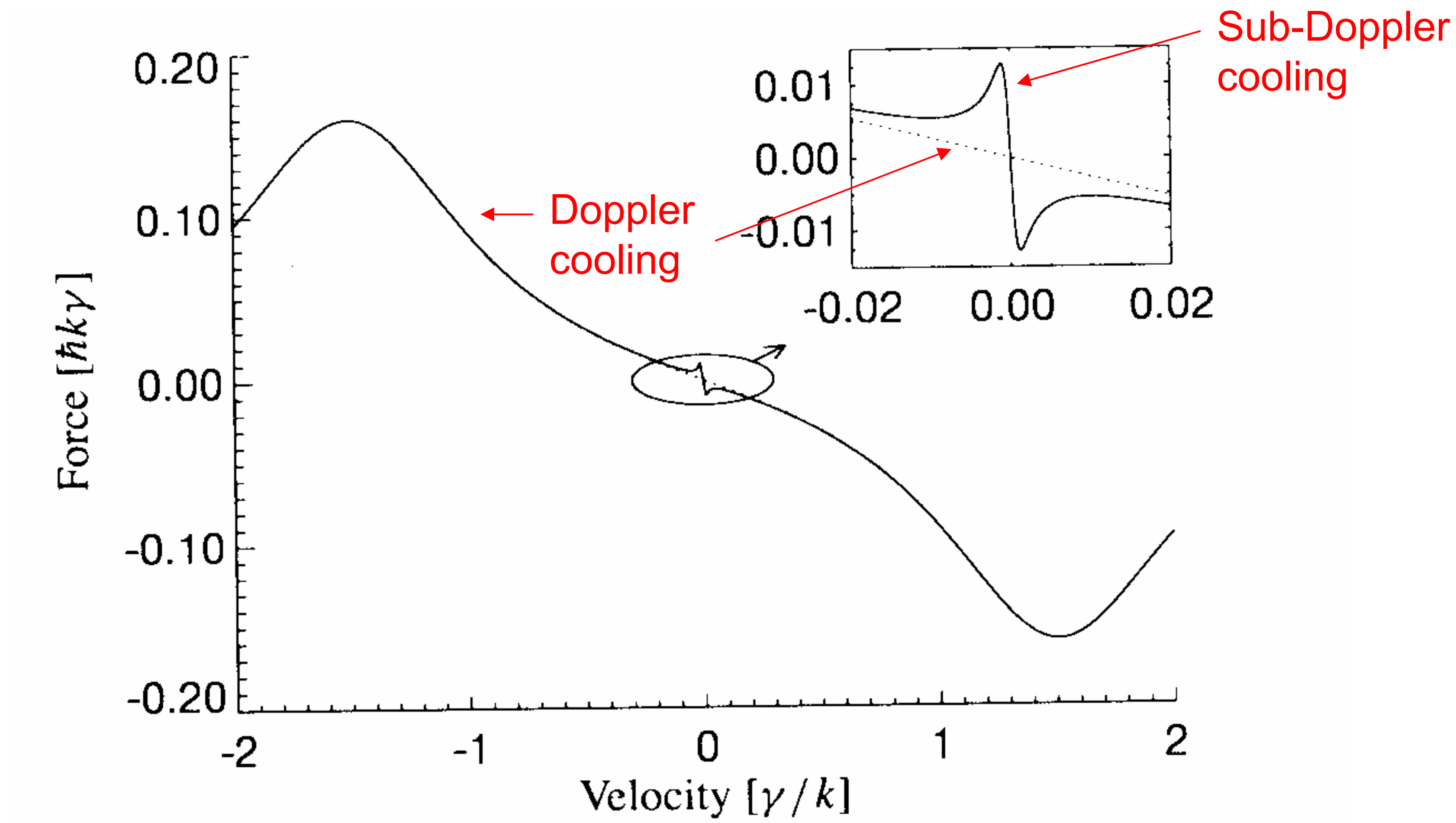


- Study of quantum transport in a periodic potential (tunneling)

- Applications in theoretical solid state physics

- Holy Grail for quantum computing?
  (qubit register)

Polarization gradient cooling force



H.J. Metcalf, P. van der Straten, Laser Cooling and Trapping, Springer, 1999

Doppler Cooling

~ 100 µK

↓

Sub-Doppler Cooling

~ few µK

↓

Sub-Recoil Cooling

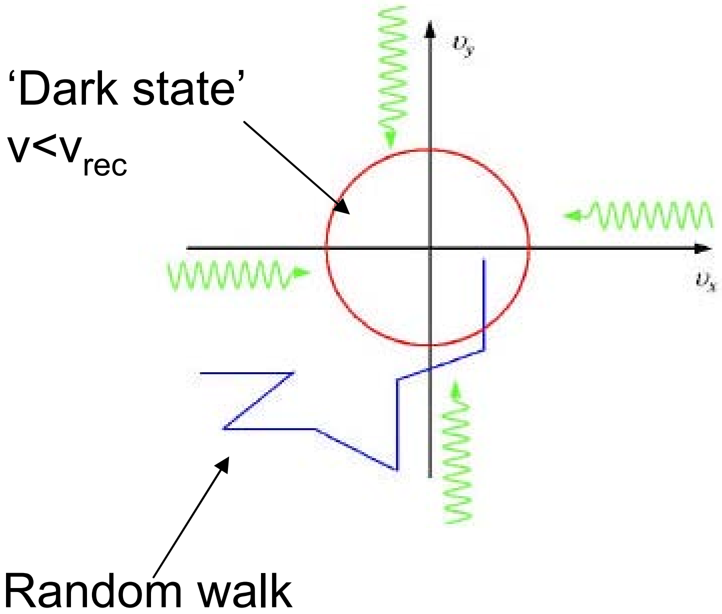
~ nK ?

~ 100 nK

Sub-recoil Cooling

single-photon recoil
from fluorescence cycle

$$\delta p = \hbar k$$



massey.dur.ac.uk/articles/newoptics.pdf

- quench absorption of light for atoms with $v \approx 0$
- 'velocity space optical pumping'

- 3 techniques :

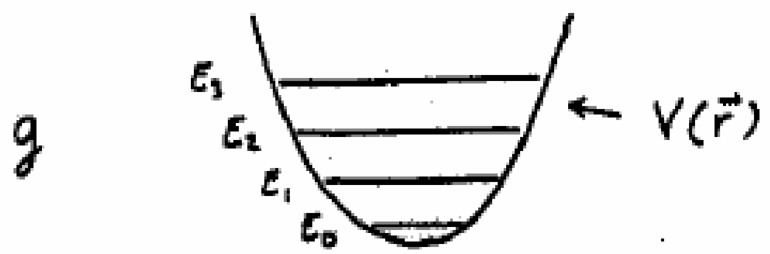
Random walk-related

1. Velocity Selective Coherent Population Trapping (VSCPT)
2. Raman cooling

Not random walk-related

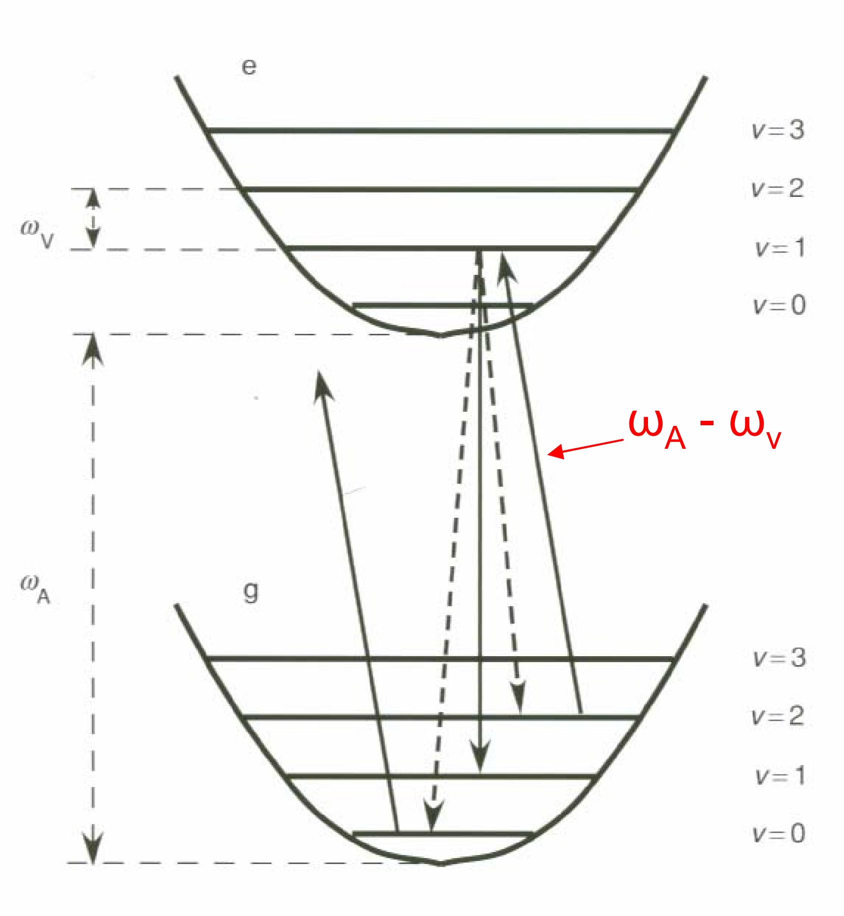
3. Trapped ions: Sideband cooling

Sideband cooling



- = dark-state cooling for trapped ions
- Very convenient for preparing a single ion in vibrational ground state
- Single ion in 1-D parabolic potential well (eg. Paul trap)
- The vibrational motion of the ion's center of mass is quantized (vibrational quantum number ε)

Sideband Cooling



2 conditions

1. Trap frequency ω_v >> recoil frequency of optical transition ('Lamb-Dicke regime')

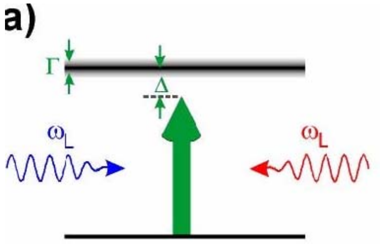
   => recoil absorbed by total system ion + trap (analogy : Mössbauer effect)

2. Trap frequency ω_v > radiative linewidth Γ

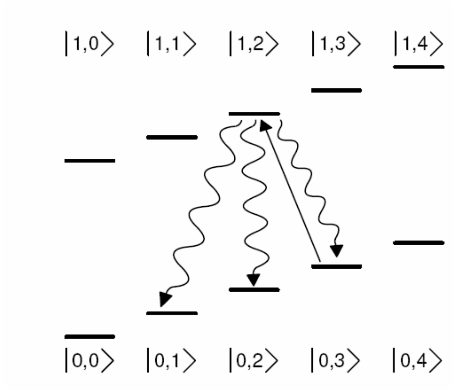
   => motional sidebands can be selectively excited

[G. Fraser (ed.), The New Physics for the Twenty-First Century, Cambridge University Press, 2006

Doppler-cooling



Sisyphus cooling



Sideband cooling

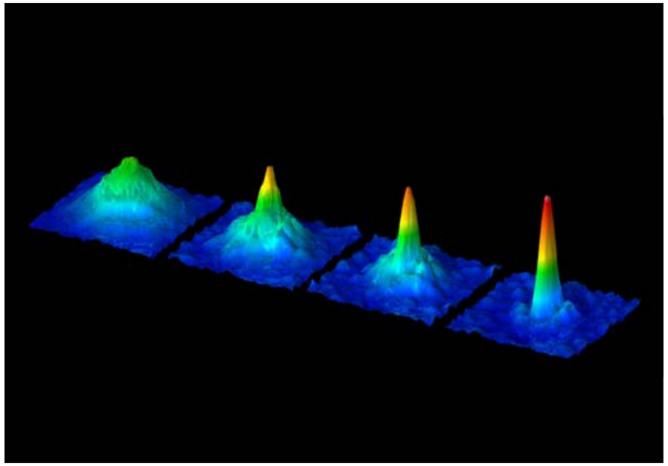
Finally,

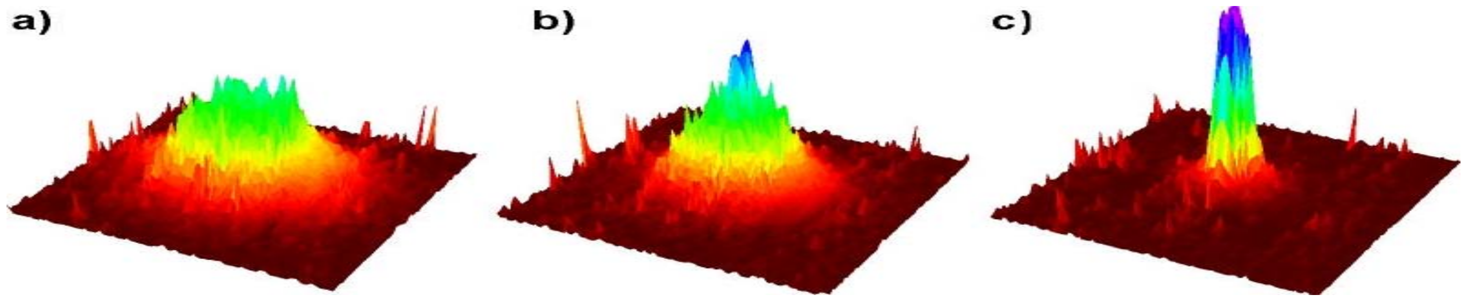
some more applications…

(slide show, 5 x 9 seconds)

BEC

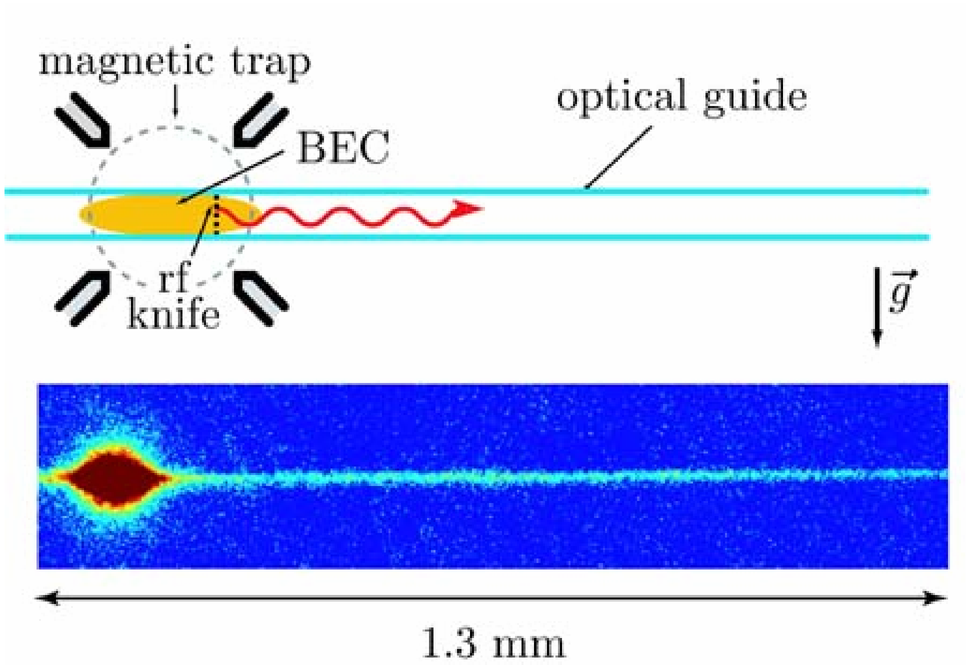
Requires
laser cooling +
'evaporative cooling'
(non-optical cooling
mechanism)





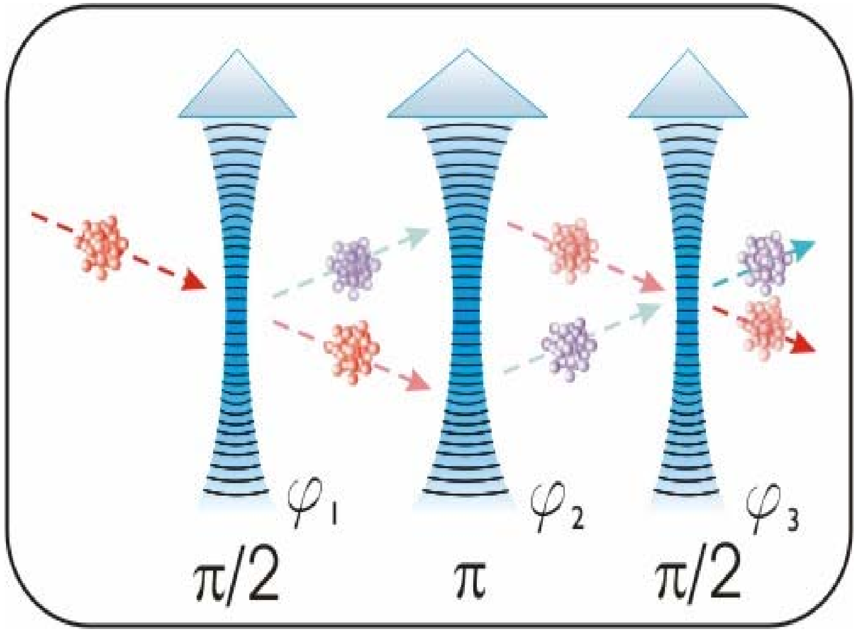
massey.dur.ac.uk/articles/newoptics.pdf

Guided atom laser

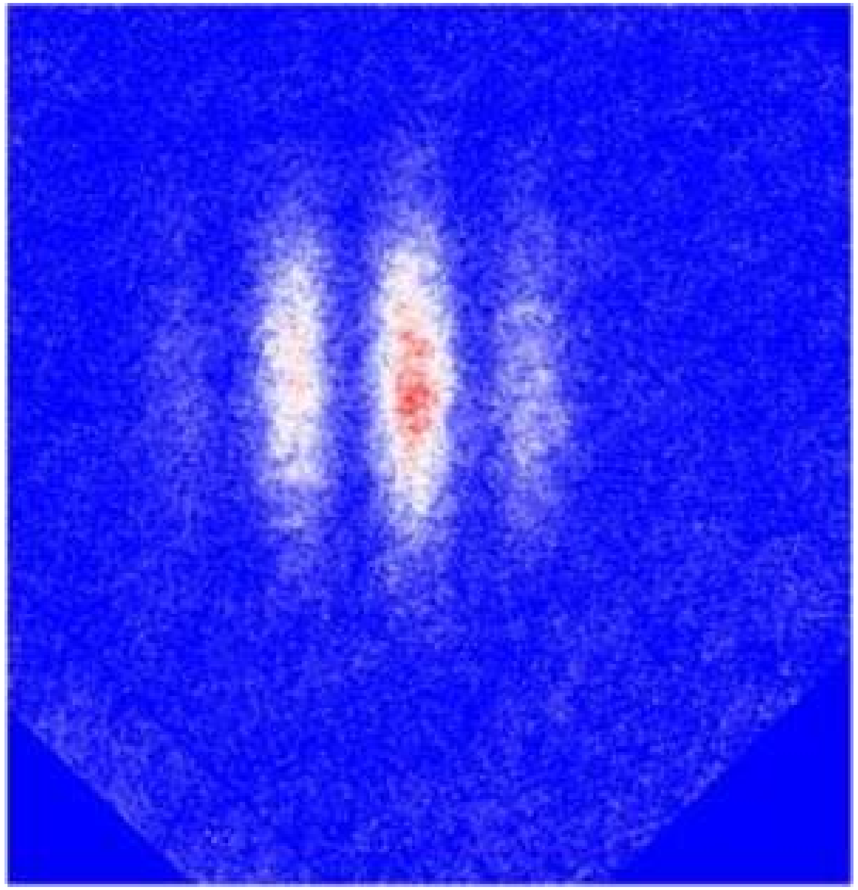


http://www.aip.org/png/2006/273.htm

Atom Interferometry

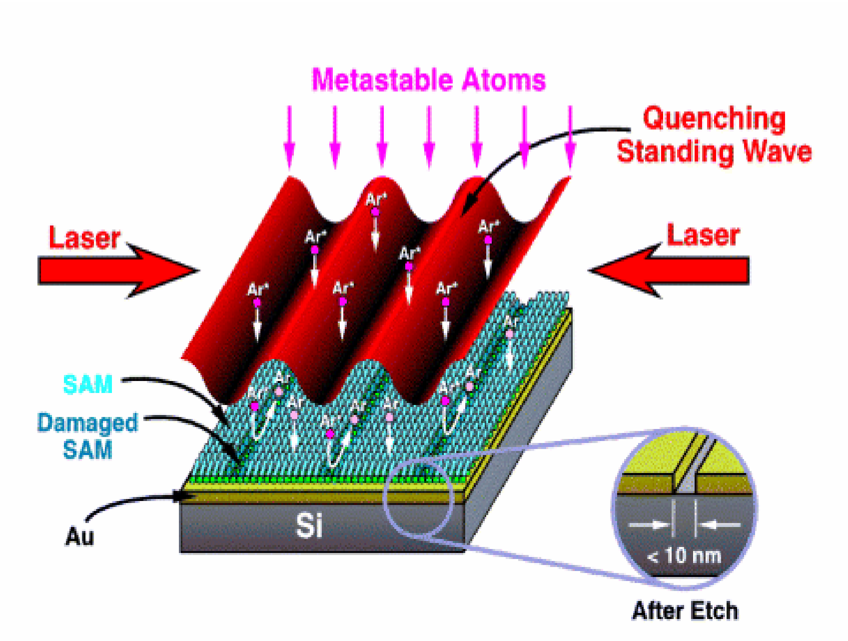


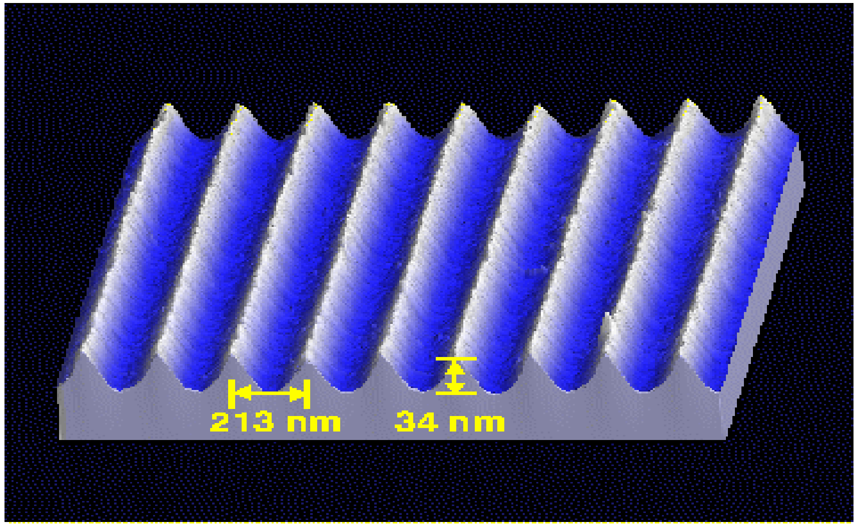
http://www.iqo.uni-hannover.de/ertmer/casiindex/



www.sciencedaily.com/gallery/computers_math/information_
technology/9/

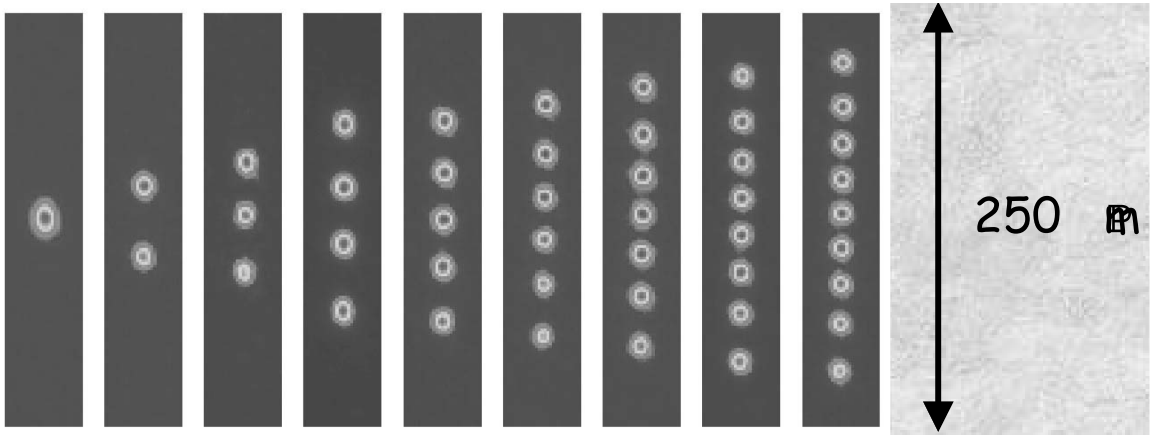
Atom Lithography

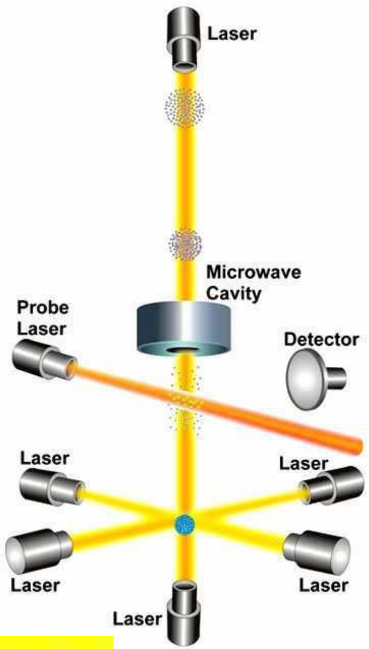


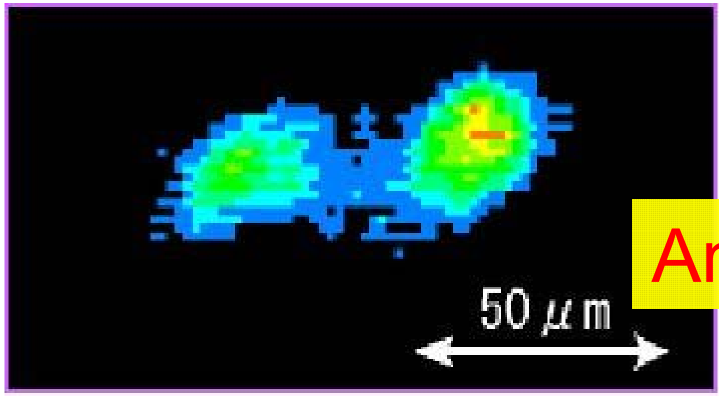


AFM image of Cr lines on a Si substrate

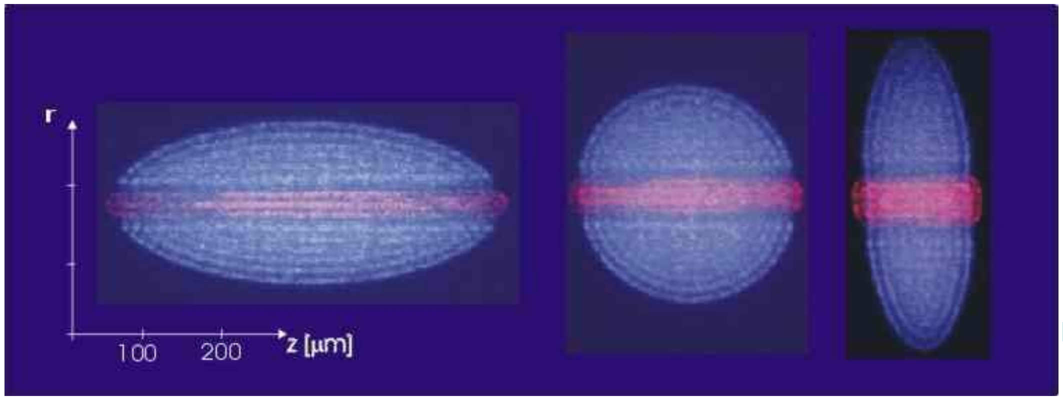
http://cnst.nist.gov/epg/Projects/Atom/metasam_proj.html

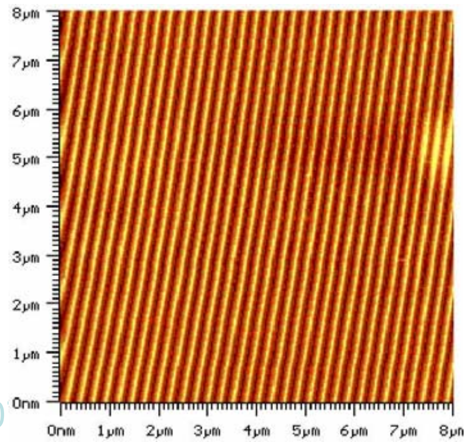






And so much more…





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- Cohen-Tannoudji, Manipulating Atoms with Photons (Nobel Lecture), 1997, http://nobelprize.org.
- C. Cohen-Tannoudji & J. Dalibard, Manipulating atoms with photons, in: G. Fraser (ed.), The New Physics for the Twenty-First Century, Cambridge University Press, 2006.
- W. Paul, Electromagnetic Traps for Charged and Neutral Particles (Nobel Lecture), 1989, http://nobelprize.org.
- W.D. Philips, Laser Cooling and Trapping of Neutral Atoms (Nobel Lecture), 1997, http://nobelprize.org.
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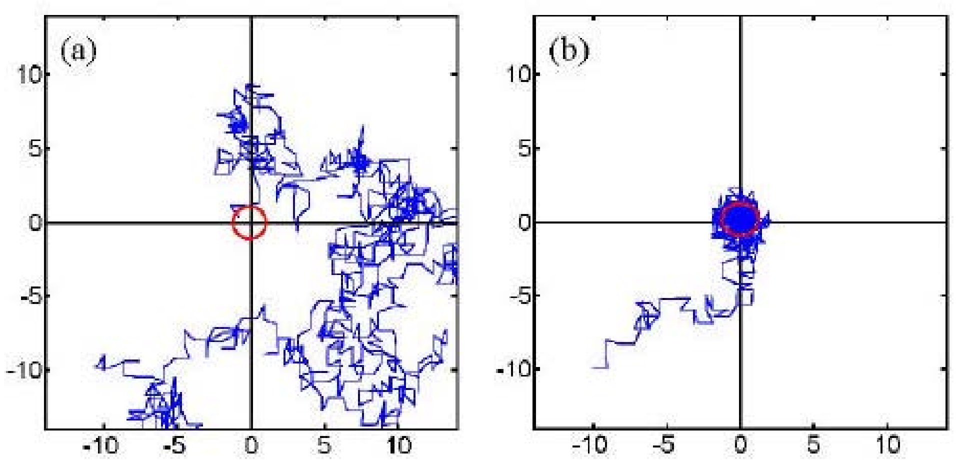
- S. Haroche, J-M. Raimond, Exploring the Qunatum. Atoms, Cavities and Photons, Oxford University Press, 2006.
- Diedrich, Wineland et al., Laser Cooling to the Zero-Point Energy of Motion, PRL 1989(4).
- Wineland, Itano et al., Laser-cooling limites and single ion spectroscopy, PR(A) 1987(5).

Internet:

- Adams, Riis, Laser Cooling and Manipulating of Neutral Atoms, massey.dur.ac.uk/articles/newoptics.pdf
- Particles in a Paul trap (video) http://www.pi5.uni-stuttgart.de/institut/fallenkoffer.html
- Playful introduction to laser cooling http://www.colorado.edu/physics/2000/bec/lascool1.html
- Cohen-Tannoudji's courses on LC (lecture notes & mp3 audio, in French) http://www.phys.ens.fr/cours/college-de-france/index.html
- 'Atomic Clocks Meet Laser Cooling' (Buell, Jaduszliwer) http://www.aero.org/publications/crosslink/winter2000/02.html

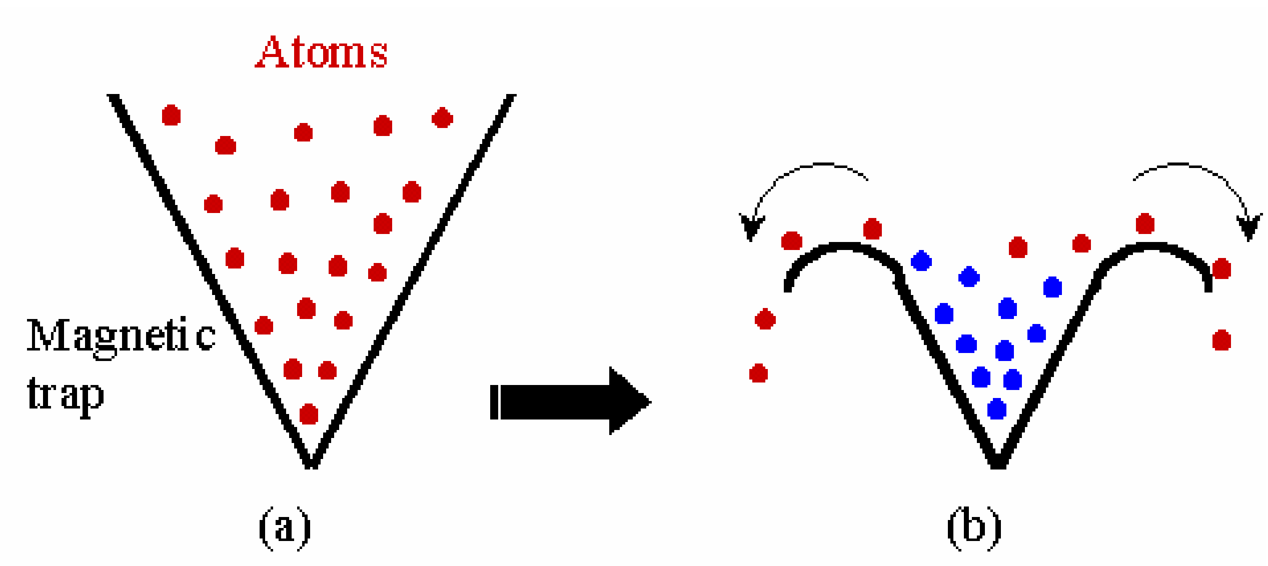
Sub-recoil Cooling



massey.dur.ac.uk/art

- In principle : no minimum T°
  but random walk takes longer and longer to reach lower T°
- 3 techniques :
  1. Velocity Selective Coherent Population Trapping (VSCPT)
  2. Raman cooling
  3. Trapped ions: Sideband cooling

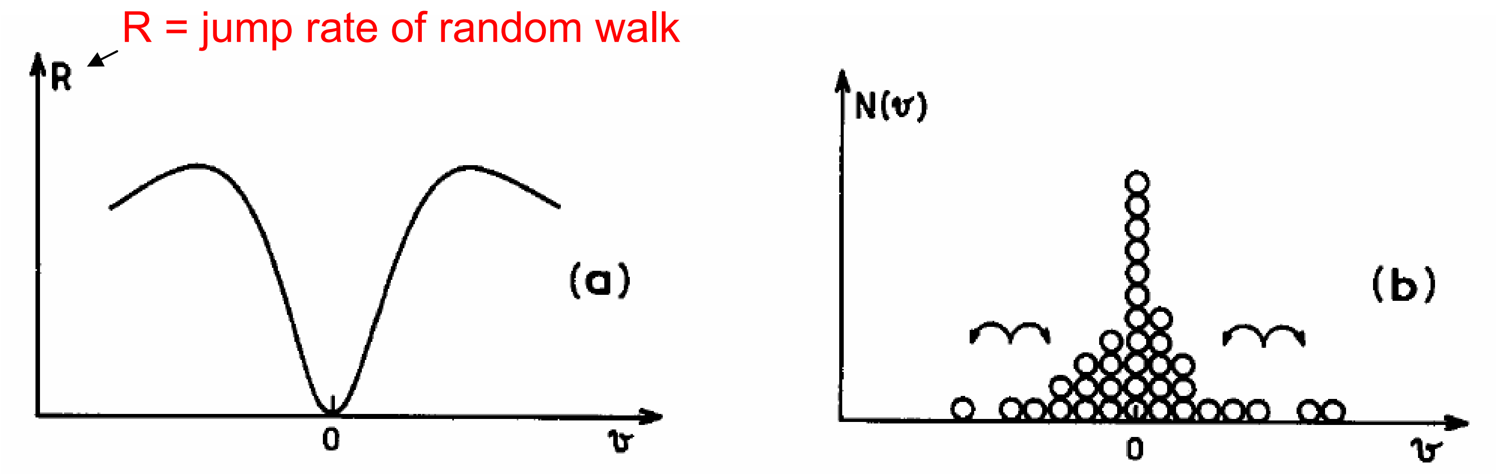
Evaporative Cooling



T ~ 20 nK

www.physics.otago.ac.nz/research/uca/resources

Sub-recoil Cooling

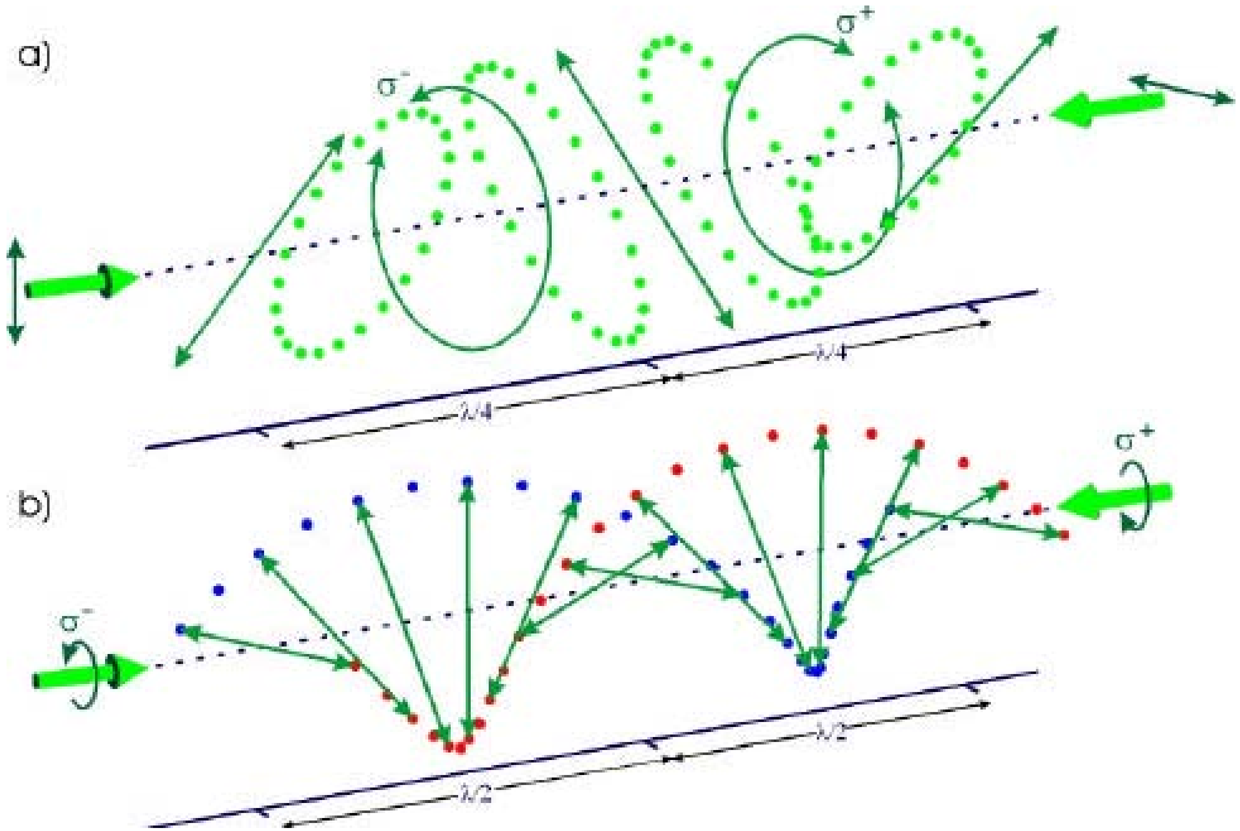


[COH1]

1. Polarization Gradient

Lin-Lin

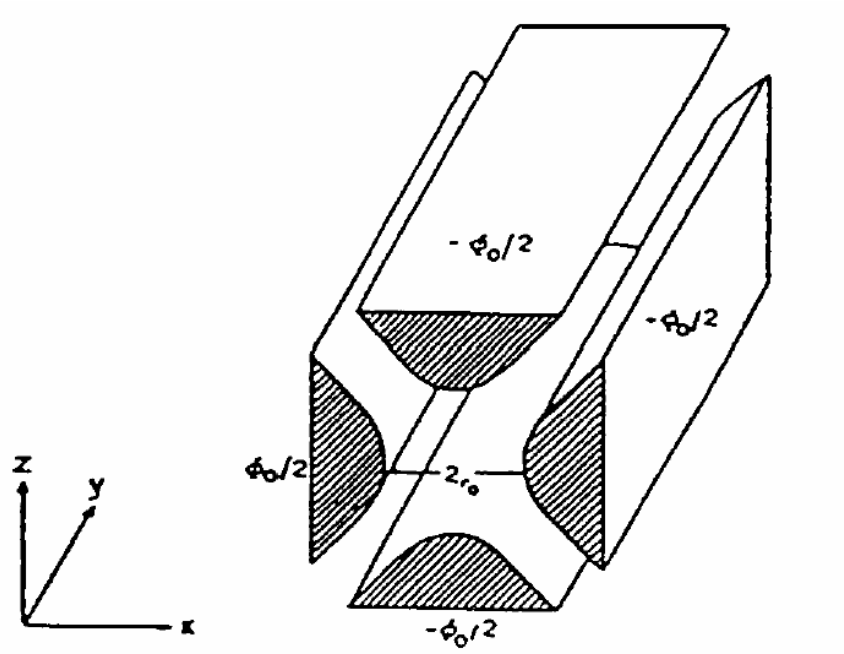
σ⁺ σ ⁻



massey.dur.ac.uk/articles/newoptics.pdf

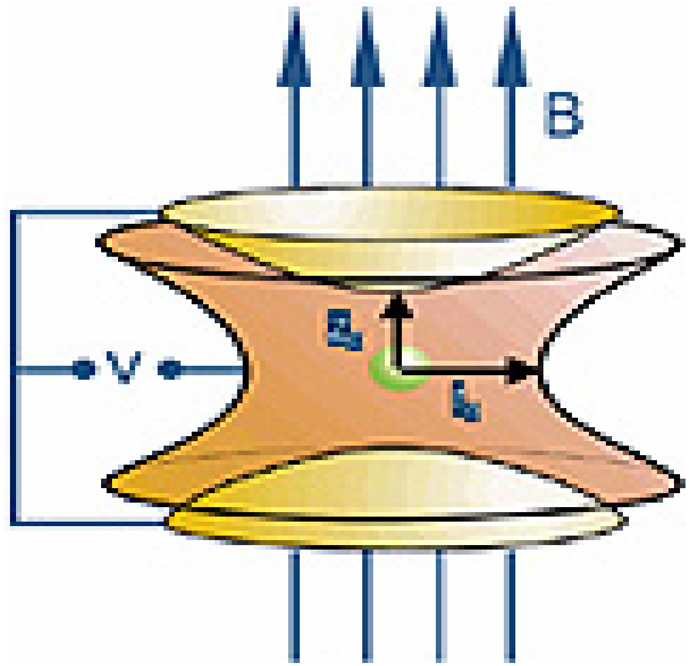
Trapping of charged particles

Linear Paul Trap



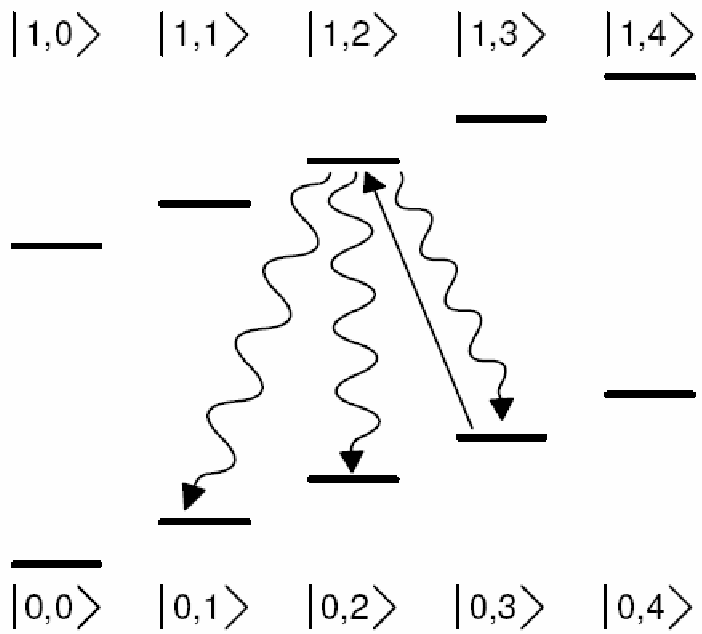
W. Paul, Electromagnetic Traps for Charged and Neutral Particles (Nobel Lecture), 1989

Penning Trap

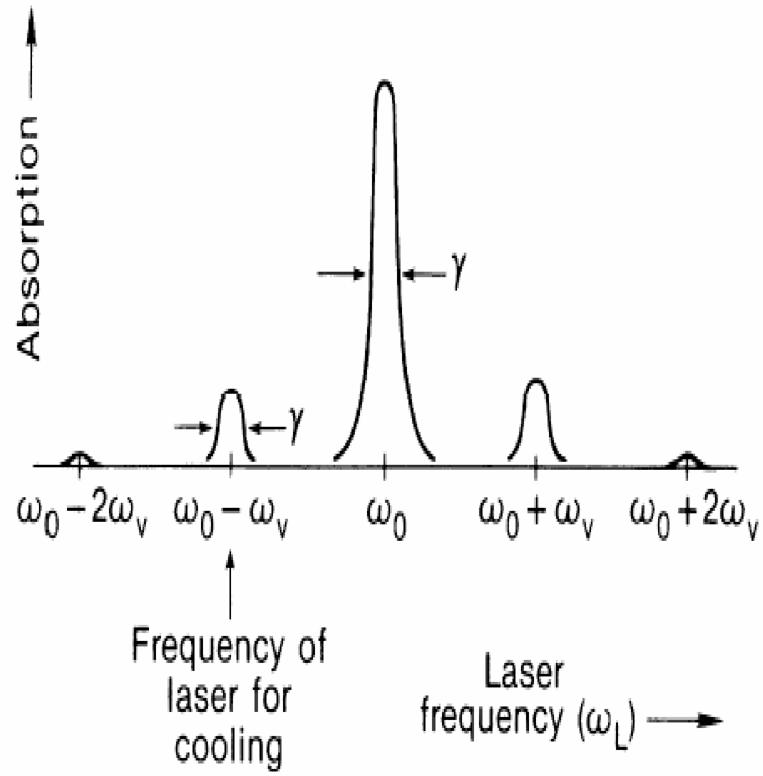


www.physics.mcmaster.ca/people/faculty/King/ion_traps.html

Sideband cooling



Resolved fm sidebands



obelix.physik.uni-osnabrueck.de/~nroseman/quantum.pdf

Wineland, Itano et al., Laser-cooling limites and single ion spectroscopy, PR(A) 1987(5)