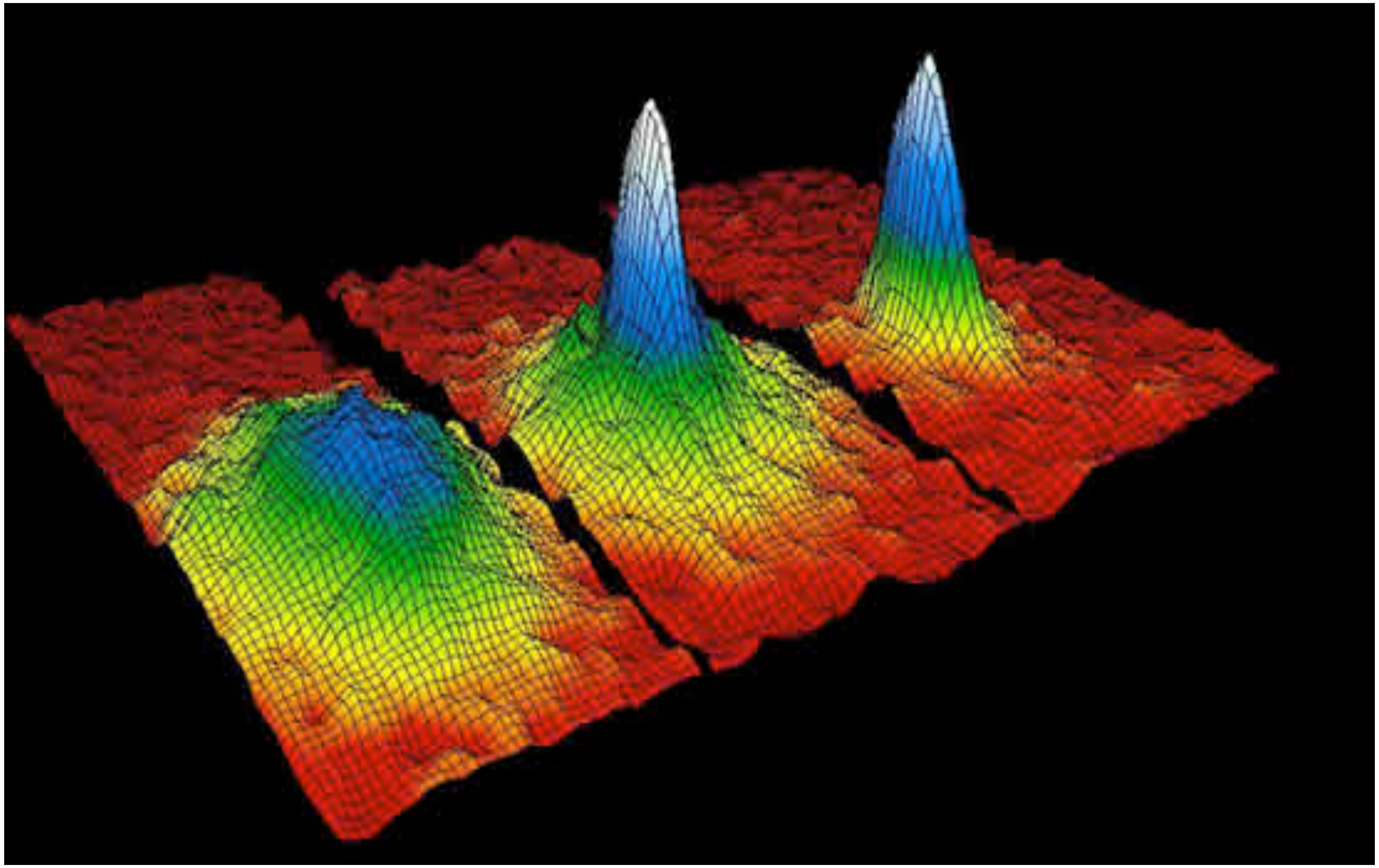
Production of BECs



BEC @ JILA June 1995 (Rubidium)

Defining the Goal: How cold is „ultracold“?

T

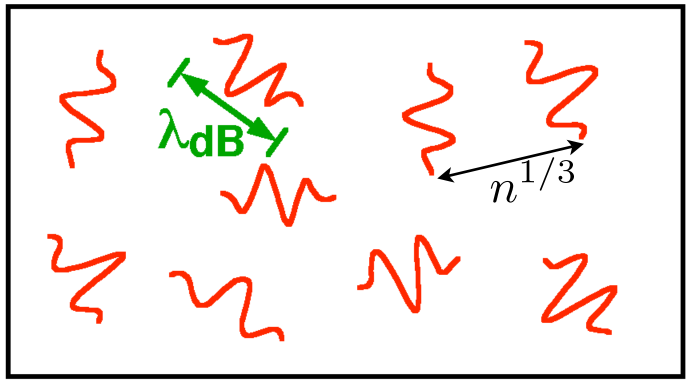
300 K	Room Temperature
2.7 K	CMB Temperature
~ 1 mK	^{3}He becomes superfluid
~10 µK	Photon Recoil
~100 nK	Occurance of BEC

Production of BECs

- Defining the Goal: BEC
- Atom Sources
- Laser Cooling
- Evaporative Cooling and Optical Traps
- Observing a BEC

Condition of Degeneracy

interparticle distance ~ extension of the wavefunction



required background pressure for lifetimes of ~ 1s: p ≈ 10^{-9} mbar

mean free path: 10^2 km

BEC condition: $$n\lambda_{dB}^3 = n\sqrt{\frac{2\pi\hbar^2}{mk_BT}}^{\,3} = 2.612$$

assume $n = 10^{12}$ cm^{-3} ⟶ $T_c \approx 100$ nK

Ideal Bose gas in a Trap

mean occupation number: $$\langle n_i \rangle = \frac{1}{\exp[\beta(\epsilon_i - \mu)] - 1}$$

h.o. trapping potential: $$V = \frac{1}{2} m \left(\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2\right)$$

critical Temperature T_c: $$\begin{aligned} \mu &= \epsilon_0 \\ \Rightarrow k_B T_c &= \hbar\overline{\omega} \left(\frac{N}{\zeta(3)}\right)^{1/3} \approx 0.94 \hbar\overline{\omega} N^{1/3} \end{aligned} \qquad \text{with} \quad \overline{\omega}^3 = \omega_x \omega_y \omega_z$$

condensate fraction: $$N_0 = N \left(1 - \left(\frac{T}{T_c}\right)^3\right)$$

Atom Sources

several types of sources for cold atom experiments:

• loading a MOT from the background gas and transferring the atoms to the UHV part

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2D+ MOT / 3D MOT configuration

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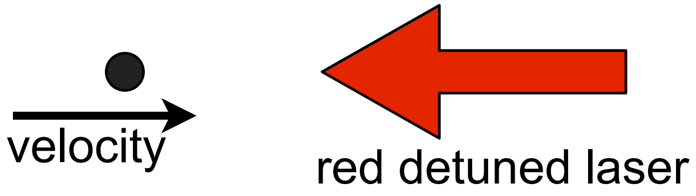
• Oven & Zeeman Slower to feed the 3D MOT

Laser Cooling

- Slowing a hot atomic beam
- Atom-Light Interaction
- optical Molasses
- Magneto-Optical Trap (MOT)
- Limits of laser cooling

Slowing a hot atomic beam



Doppler shift: $\Delta\omega_{\text{Doppler}} = \vec{k}\vec{v}$

Zeeman shift: $\Delta\omega_{\text{Zeeman}} = \frac{\mu_B}{\hbar}\left(m_{je}g_{je} - m_{jg}g_{jg}\right)B$

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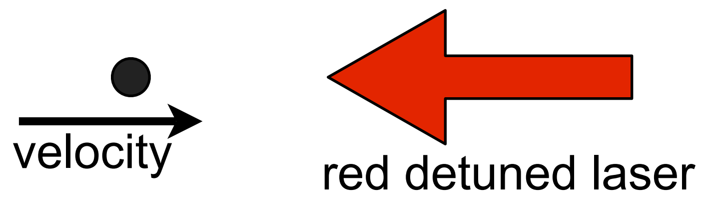

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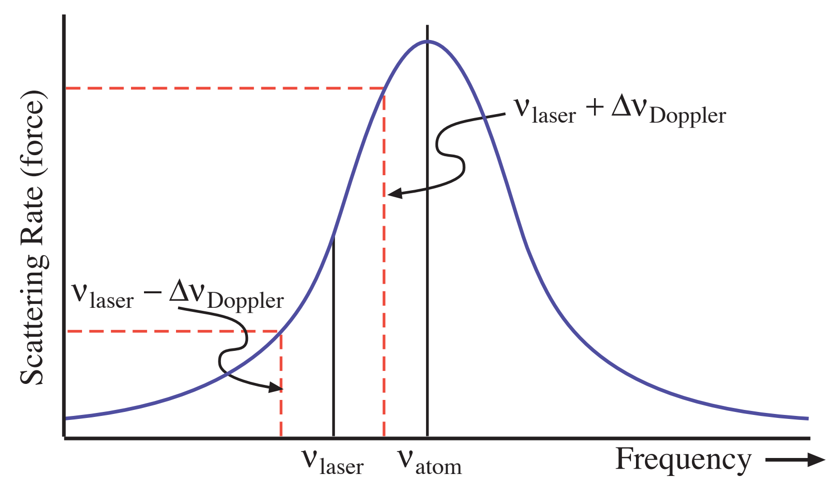
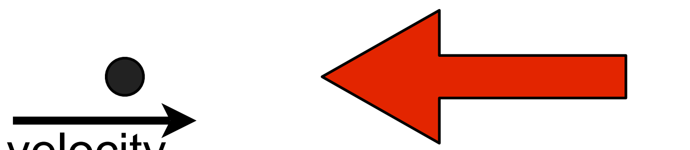


Figure 1. Atomic scattering rate versus laser frequency.

Slowing a hot atomic beam



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Resonance Condition: The decreasing Doppler shift due to the decelerated atom must be compensated by an inhomogeneous magnetic field to keep the atom in resonance with the incident laser.

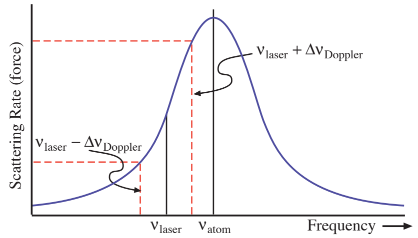
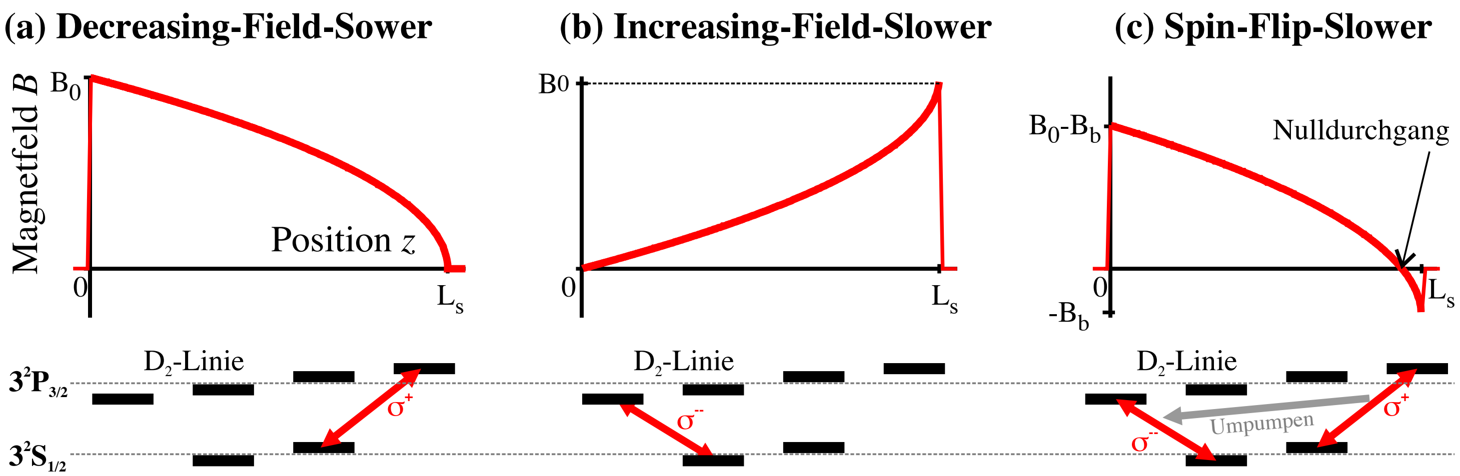


Figure 1. Atomic scattering rate versus laser frequency.

$$0 = \Delta_0 + \Delta\omega_{\mathrm{Doppler}}(\nu) - \Delta\omega_{\mathrm{Zeeman}}(r)$$

Slowing a hot atomic beam

different configurations possible & used



Slowing down a hot atomic beam:

$$v_{initial} = 700\frac{m}{s}$$

$$v_{final} = 30\frac{m}{s}$$

Atom-Light Interaction

resonant

with the atomic transition

off-resonant

Atom-Light Interaction

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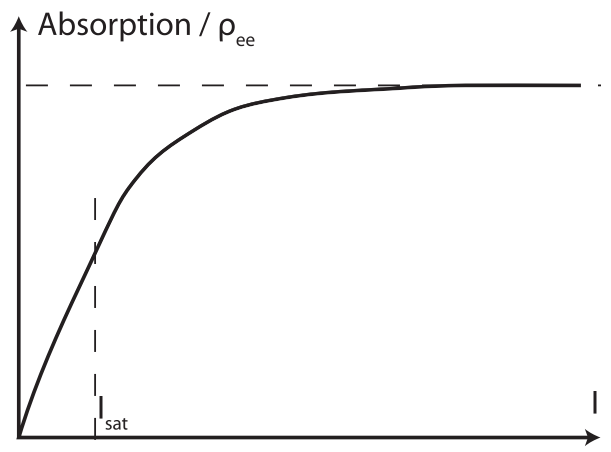


probability to find an atom in the excited state:

$$\rho_{ee} = \frac{s_0/2}{1 + s_0 + (2\Delta/\Gamma)^2}$$

$$s_0 = I/I_{\mathrm{sat}}$$

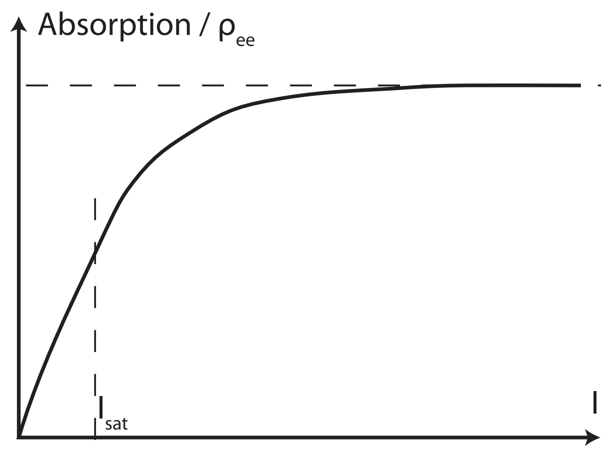
Γ linewidth

typical numbers: ^{87}Rb I_{sat} = 1.7 mW cm^{-2}

^{23}Na I_{sat} = 6.3 mW cm^{-2}

Atom-Light Interaction

resonant with the atomic transition off-resonant



→ photon scattering rate $R = \Gamma \rho_{ee}$

→ deceleration up to ~ 10^5 g

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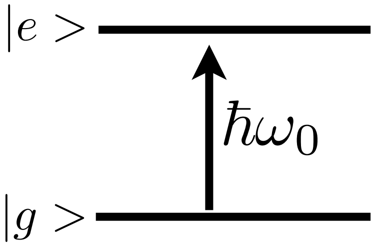

bare states

two-level atom & classical light field described by Jaynes-Cummings Model

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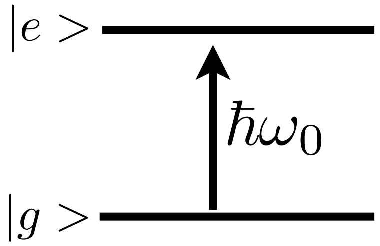

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two-level atom & classical light field described by Jaynes-Cummings Model

Assumptions:

- two level atom (good for most Alkalis)
- dipole approximation ($\lambda \gg r_{\text{Atom}}$)
- rotating wave approximation ($|\omega_0 - \omega_L| \ll \omega_0$)

Atom-Light Interaction

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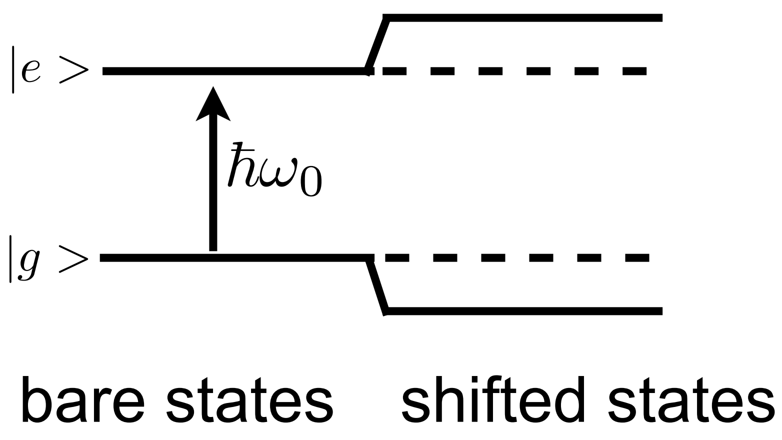

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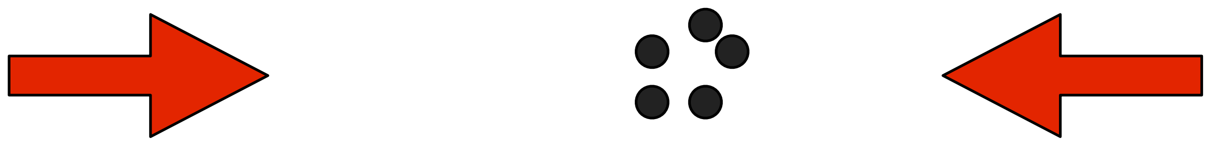
- rotating wave approximation ($|\omega_0 - \omega_L| \ll \omega_0$)

due to the atom-light interaction, the energies of the levels are shifted by

$$\Delta E_{e/g} = \pm \frac{\hbar \Omega^2}{4\Delta} \quad \text{for } \Omega \ll |\Delta| \equiv |\omega_L - \omega_0|$$

Optical Molasses

starting point: resonant atom-light interaction



$$\vec{F}(v) = \hbar\vec{k}(R(v) - R(-v)) = \hbar\vec{k}\frac{\Gamma}{2}\left(\frac{s_0}{1+s_0+\left(\frac{2(\Delta-kv)}{\Gamma}\right)^2} - \frac{s_0}{1+s_0+\left(\frac{2(\Delta+kv)}{\Gamma}\right)^2}\right)$$

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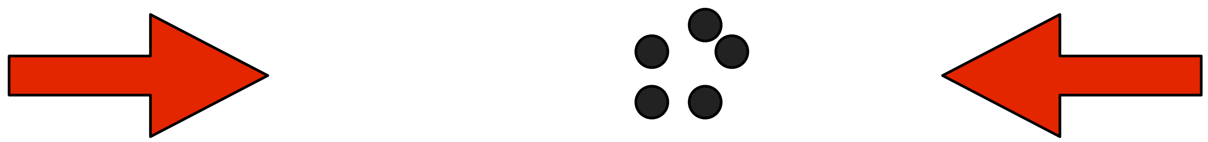

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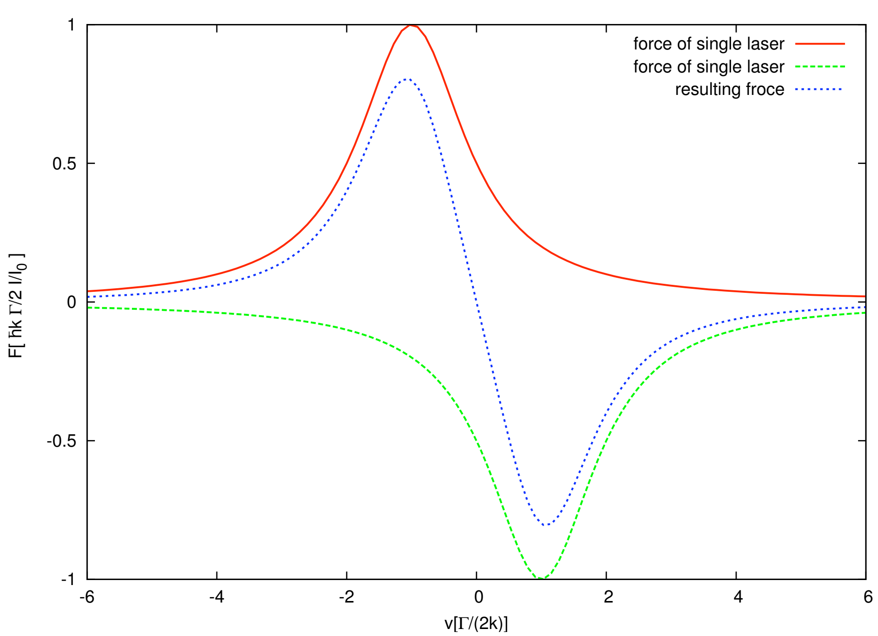

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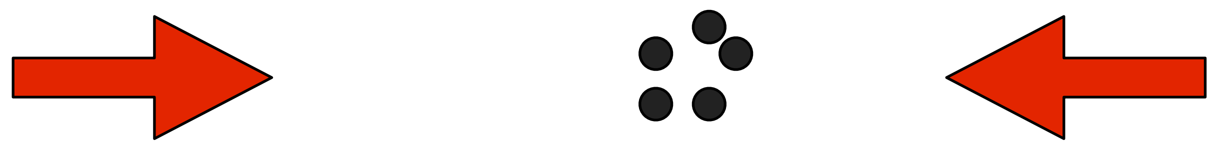

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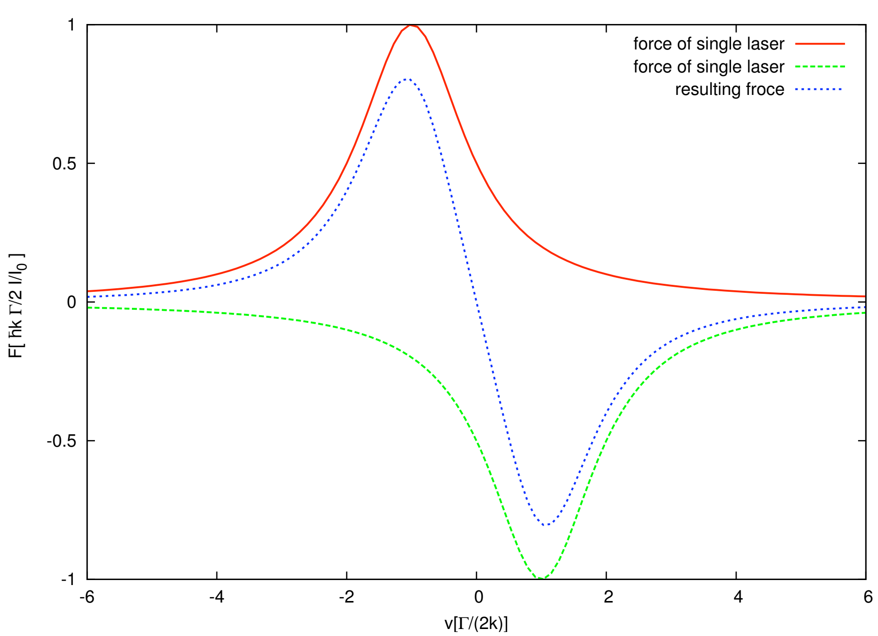

Taylor series arround v = 0

$$F = -\alpha v$$

strong damping term due to many scattered photons from one direction

Magneto-Optical Trap

add a position dependent term to obtain a confinement in real space

$$F = -\alpha v - Dx$$

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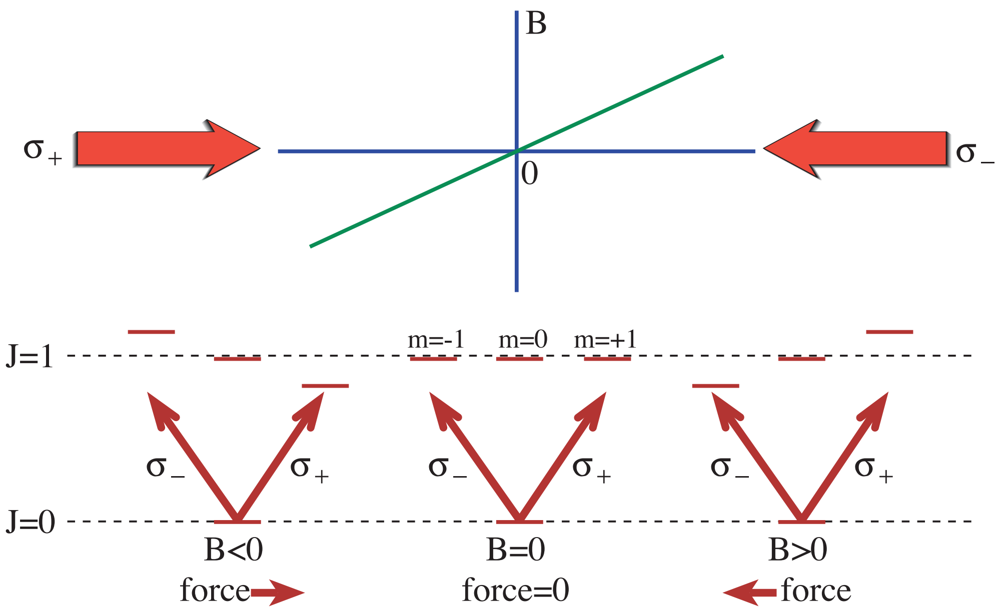
inhomogeneous magnetic field leads to an inhomogeneous Zeeman splitting



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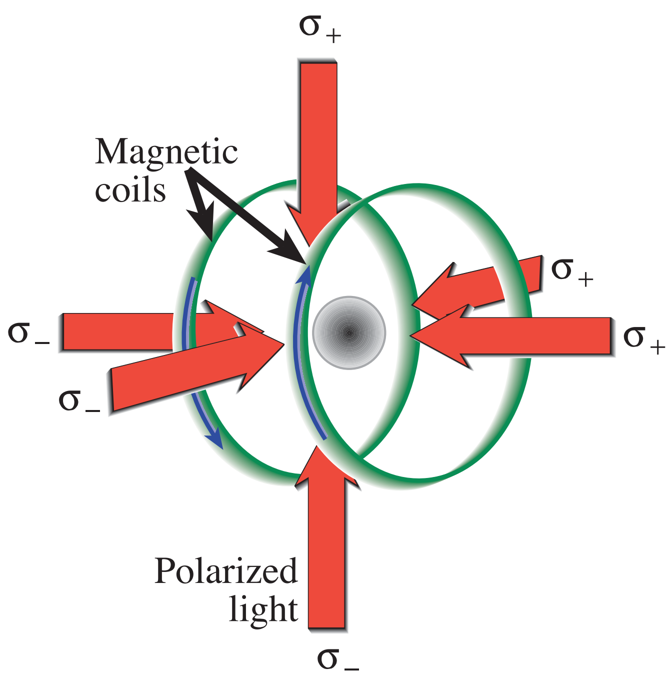

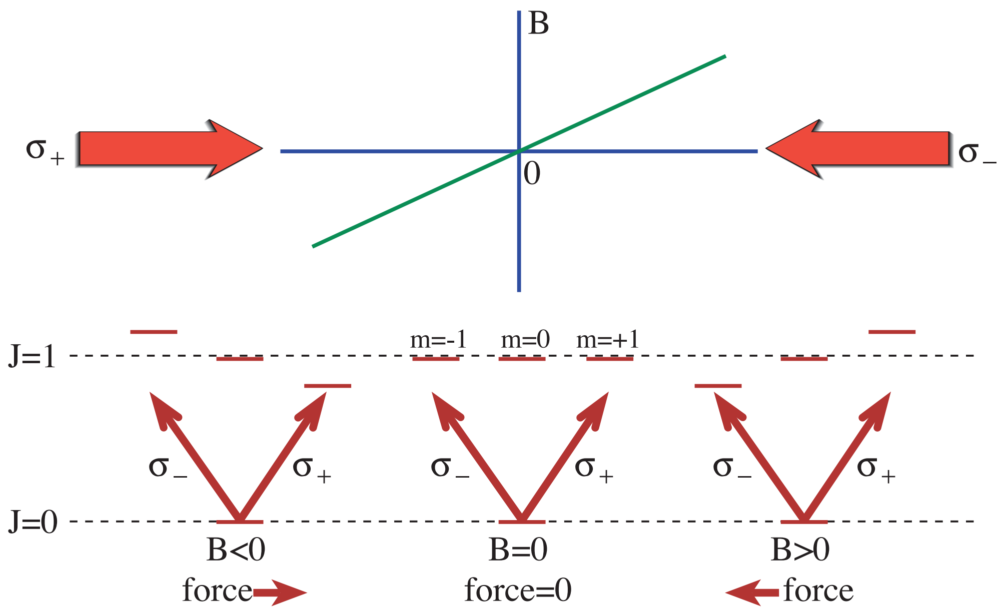

Magneto-Optical Trap

Temperature Limit:

max. scatt. Rate = Γ/2

$$k_B T_D = \hbar \frac{\Gamma}{2}$$

Doppler Temperature

Na: 235 μK

typical numbers:

$n = 10^{11}\ \mathrm{cm}^{-3}$

$n\lambda_{dB} = 10^{-6}$

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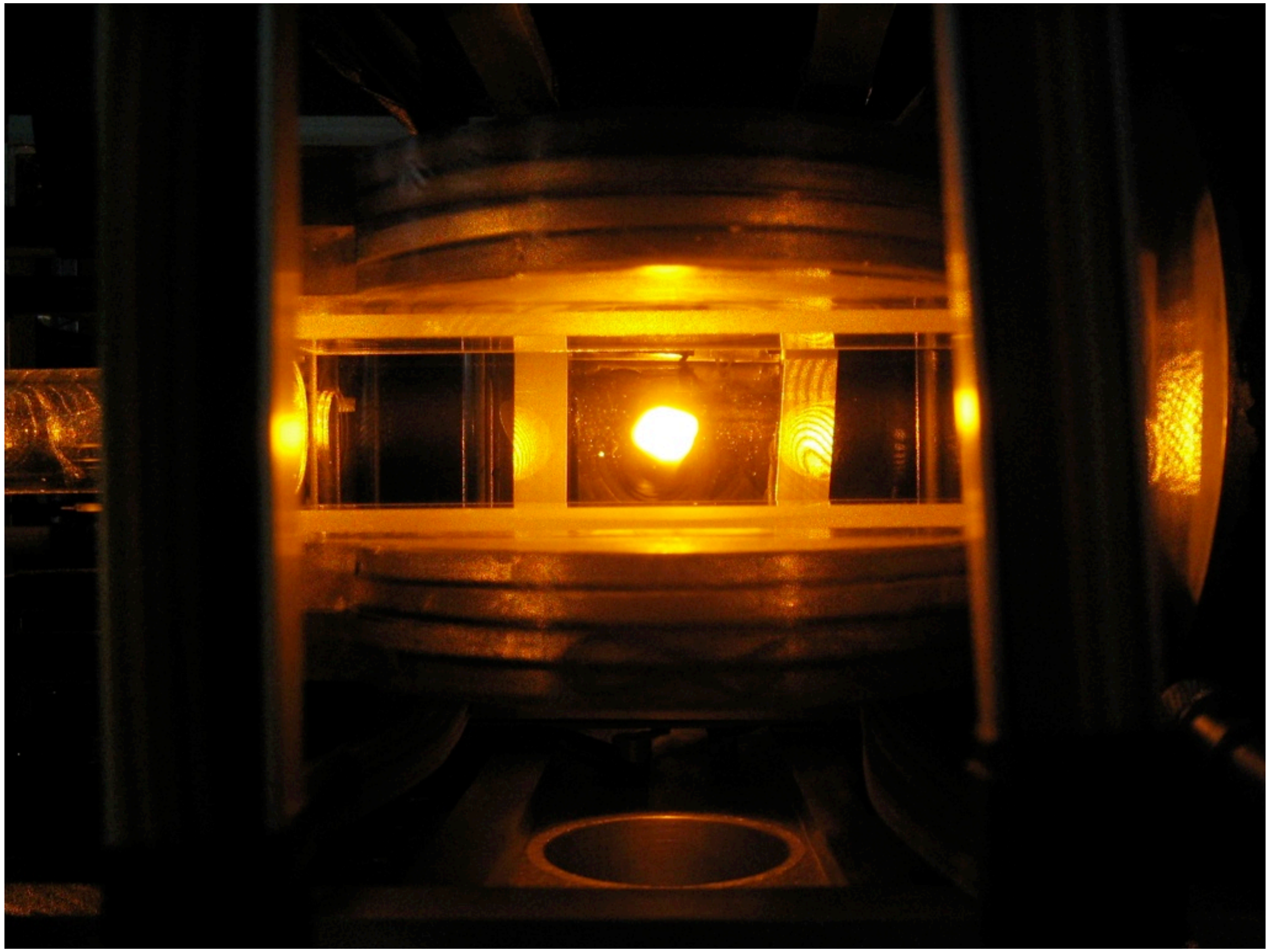

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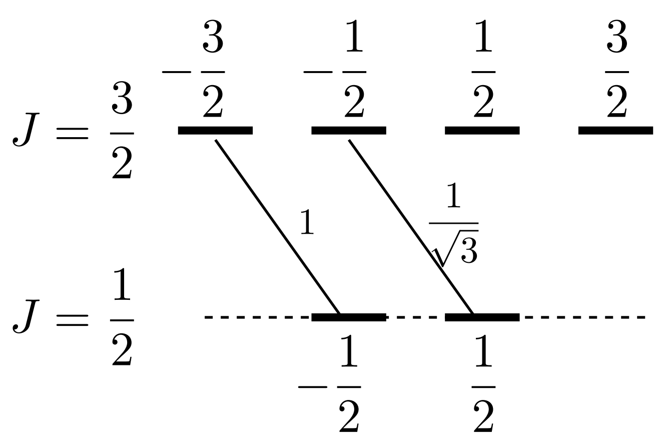
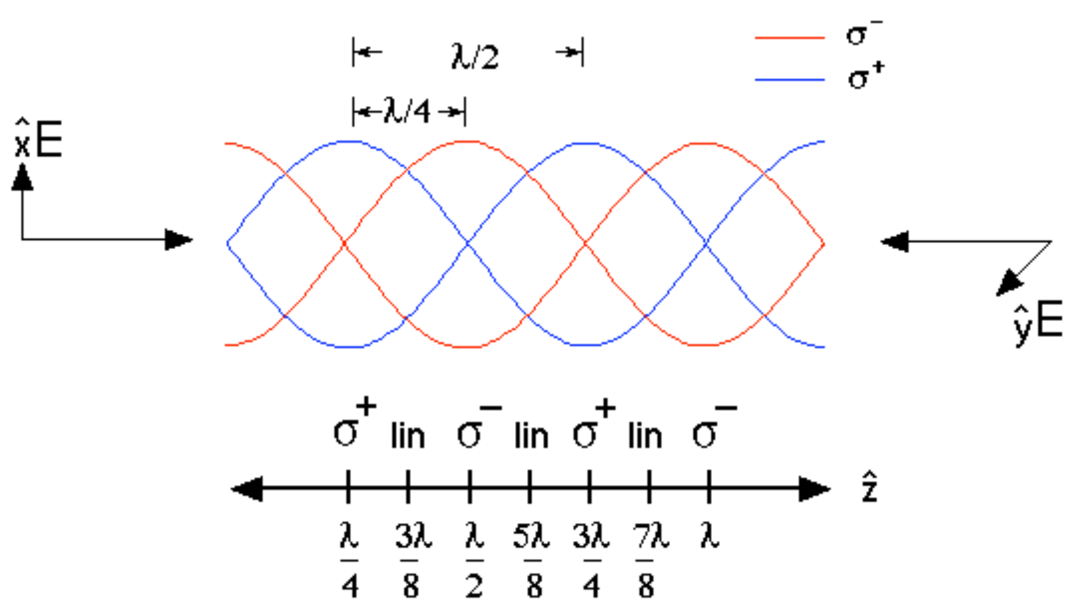
Sub-Doppler Cooling
lin ⊥ lin

no external magn. field ⟶ degenerate Zeeman levels, even in the ground state





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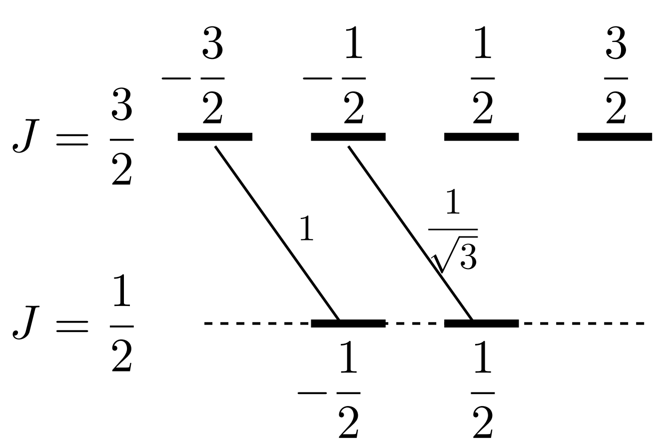

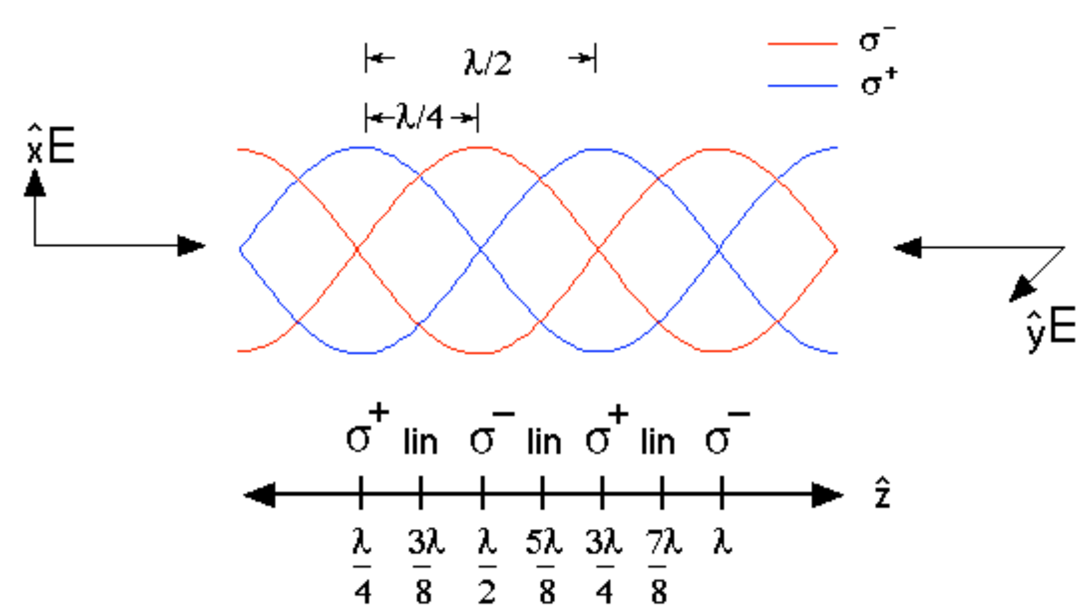

Suppose σ⁻:

ground state population: -1/2

light shifts:

$$\Delta E_{-1/2} = \frac{\hbar\Omega^2}{4\Delta}$$

$$\Delta E_{1/2} = \frac{1}{3}\frac{\hbar\Omega^2}{4\Delta}$$

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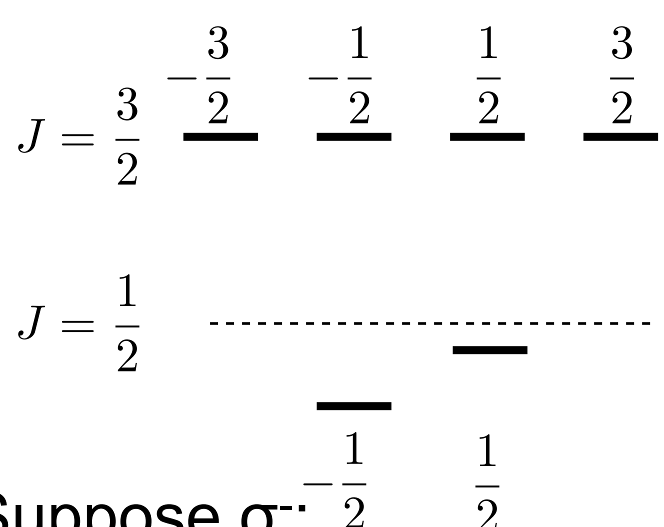

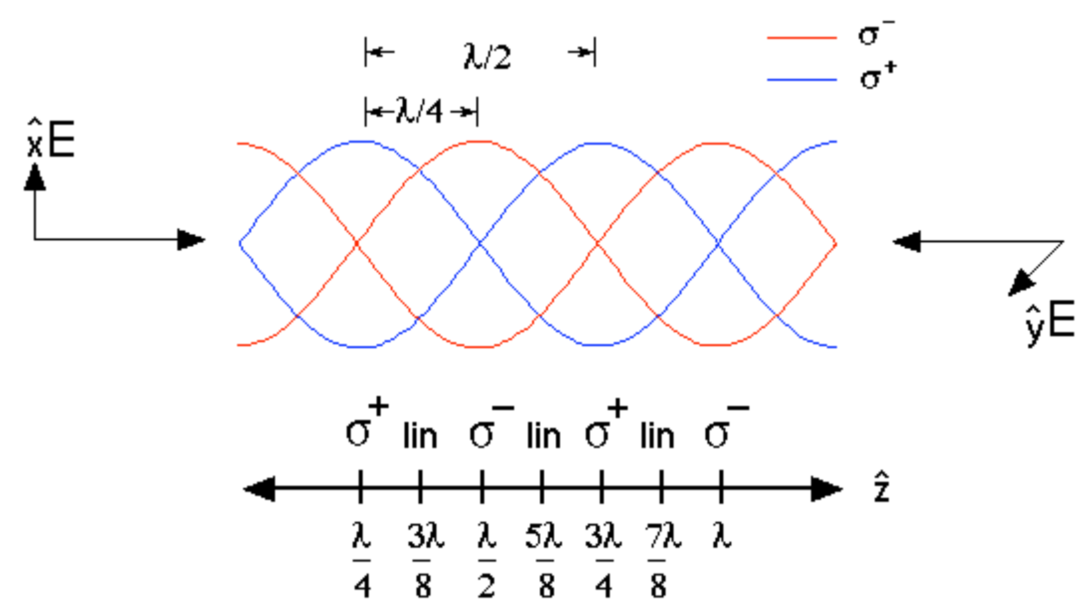

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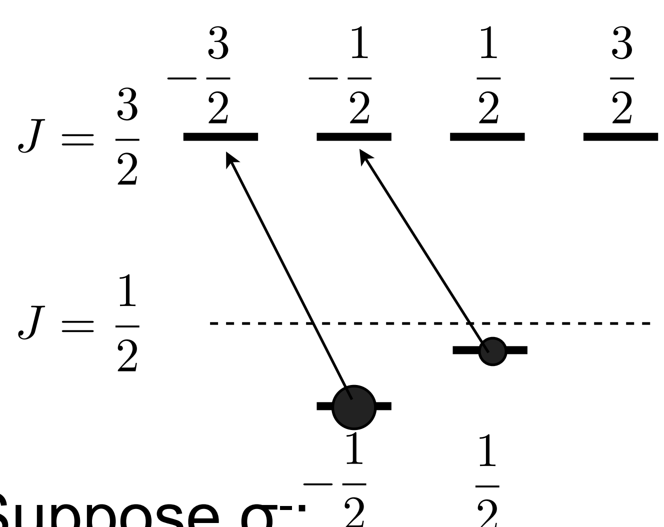

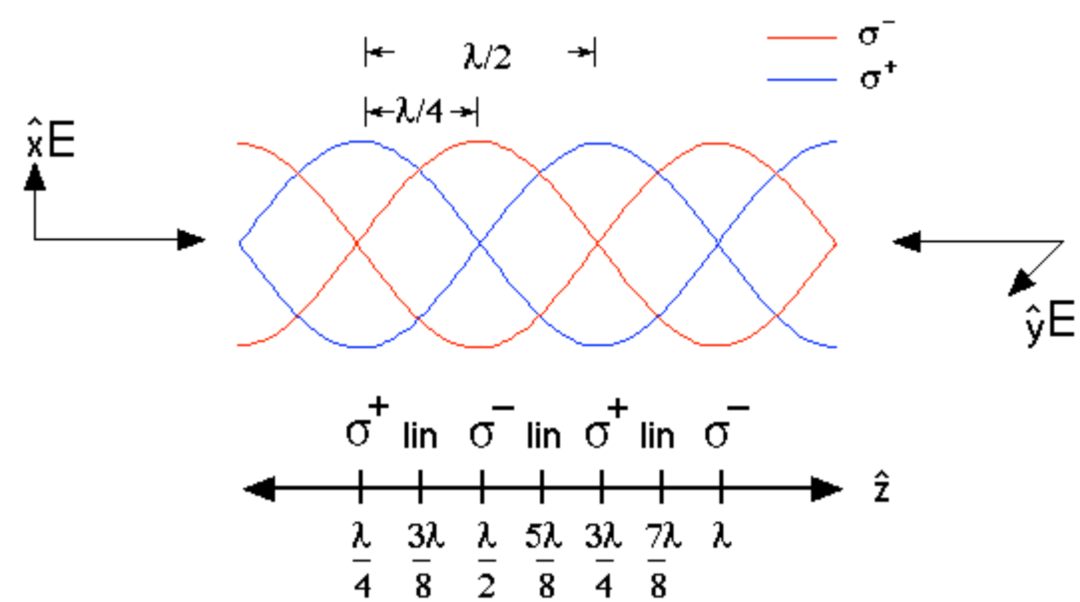

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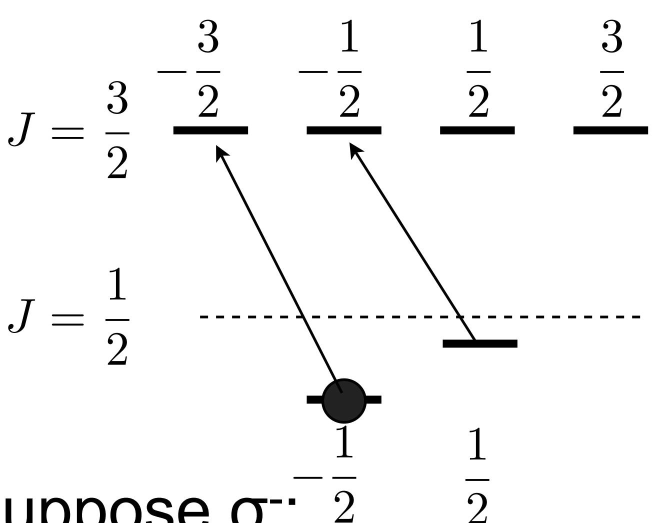

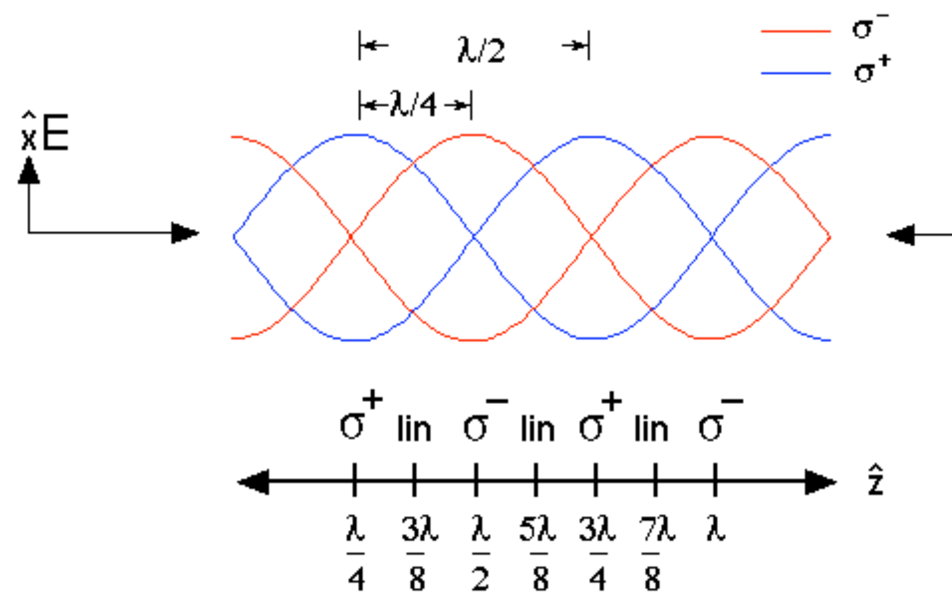

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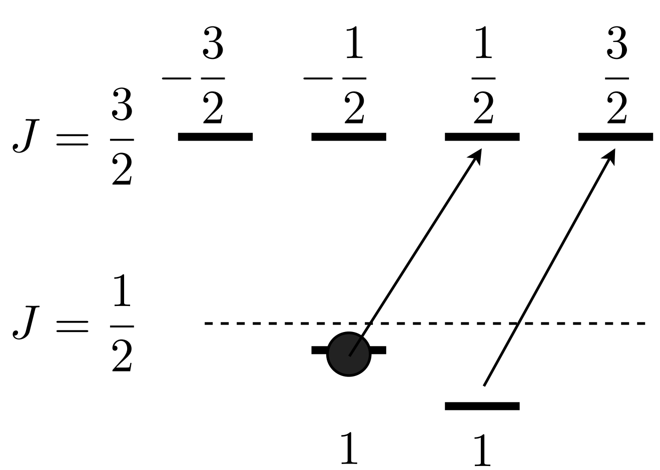

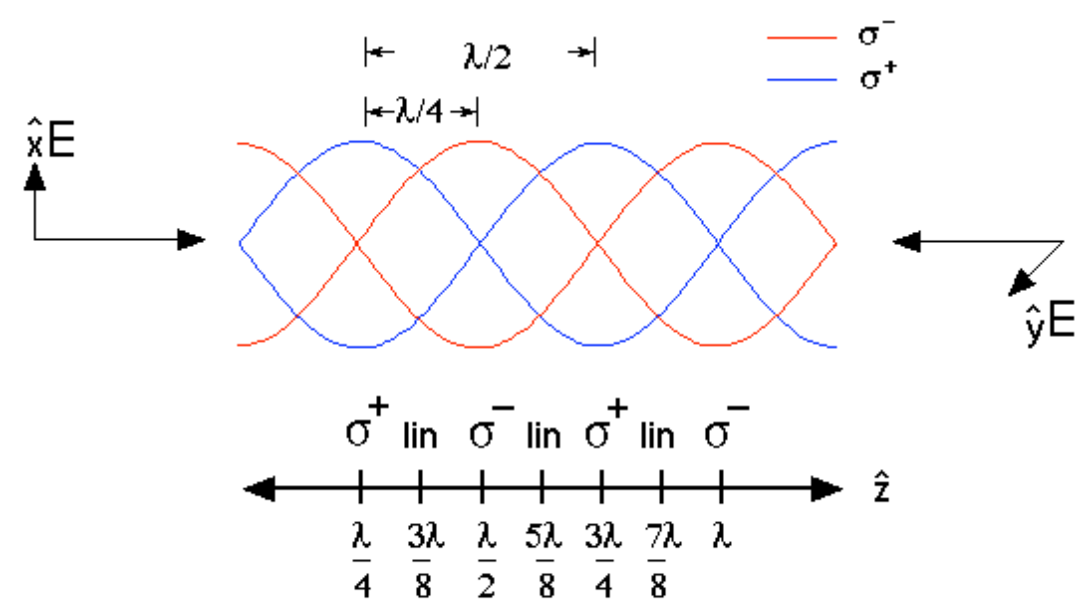

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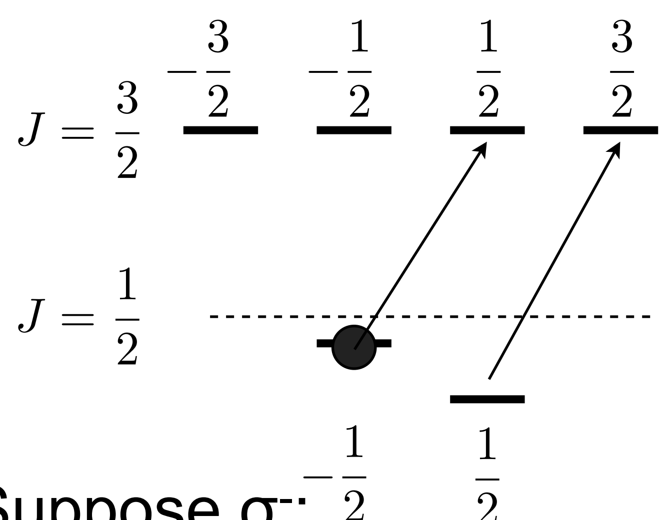

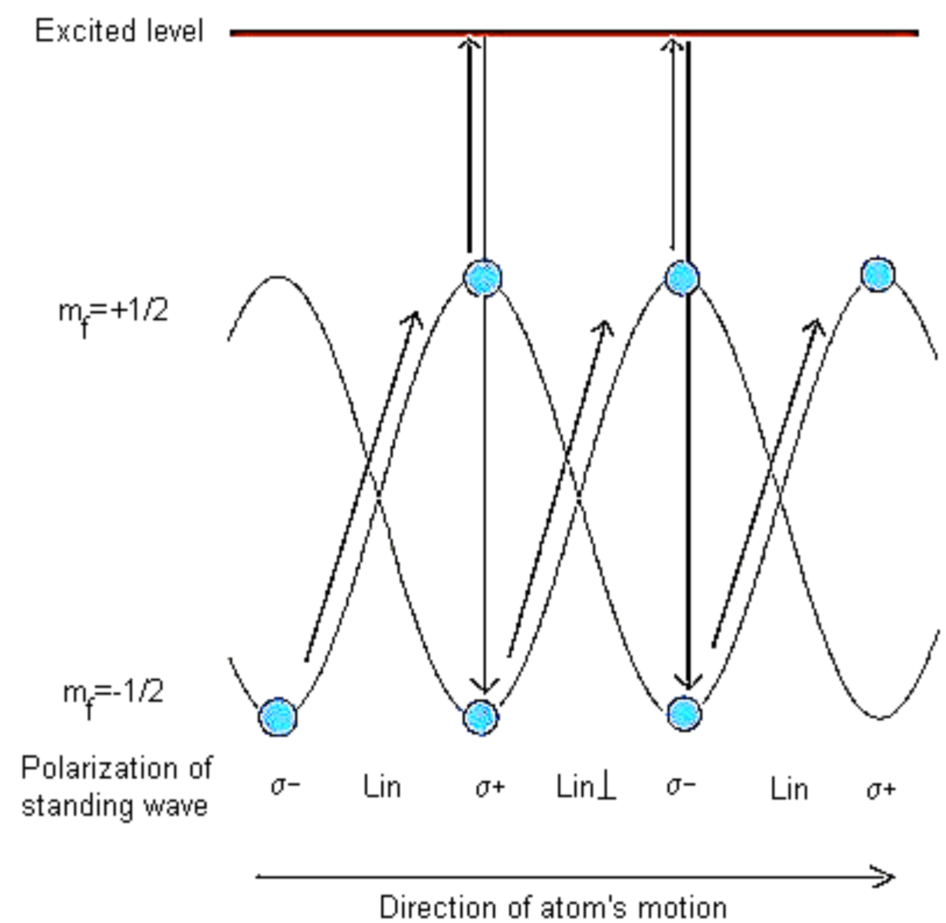

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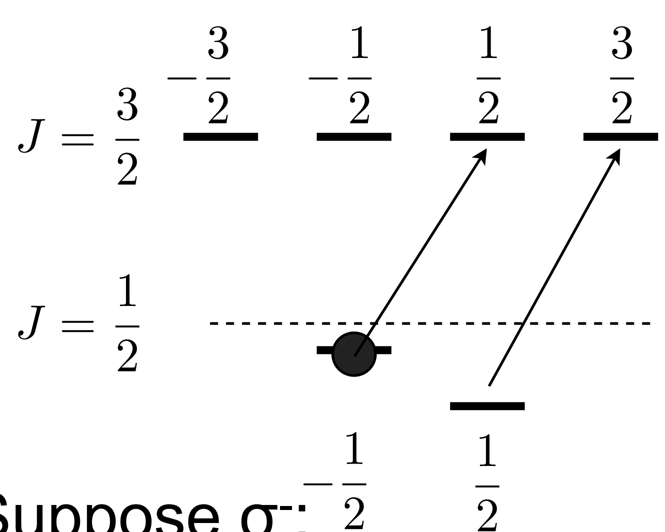

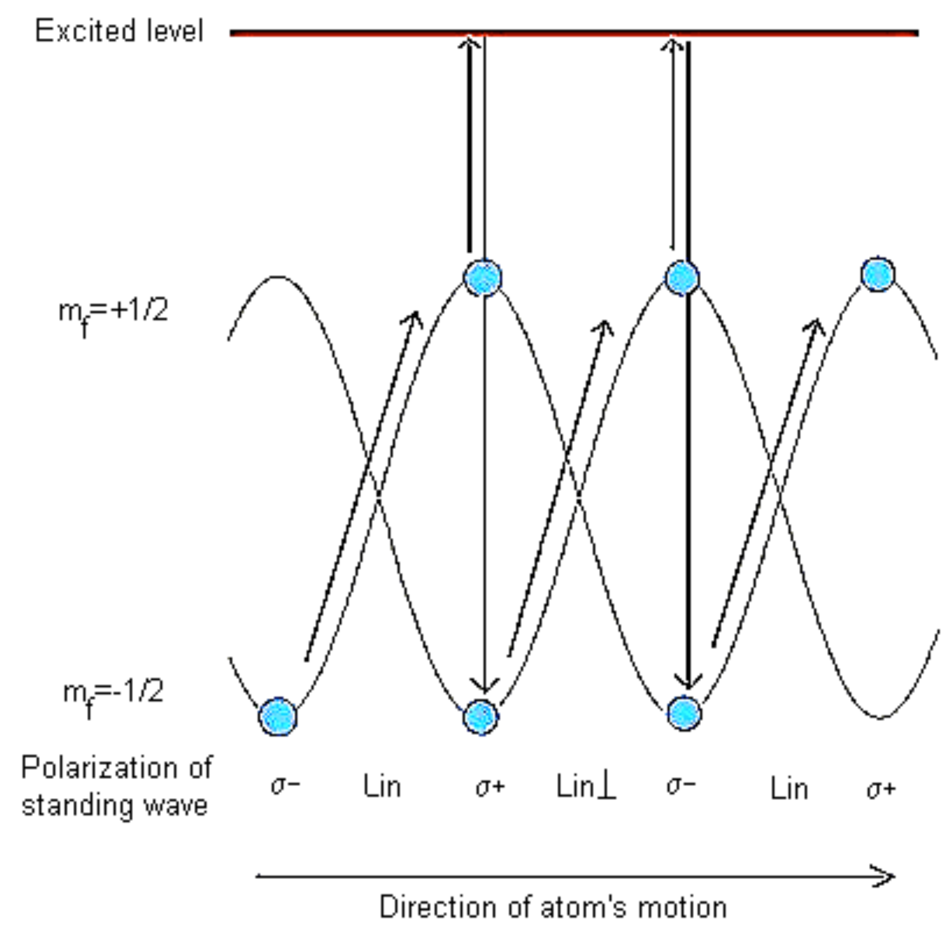

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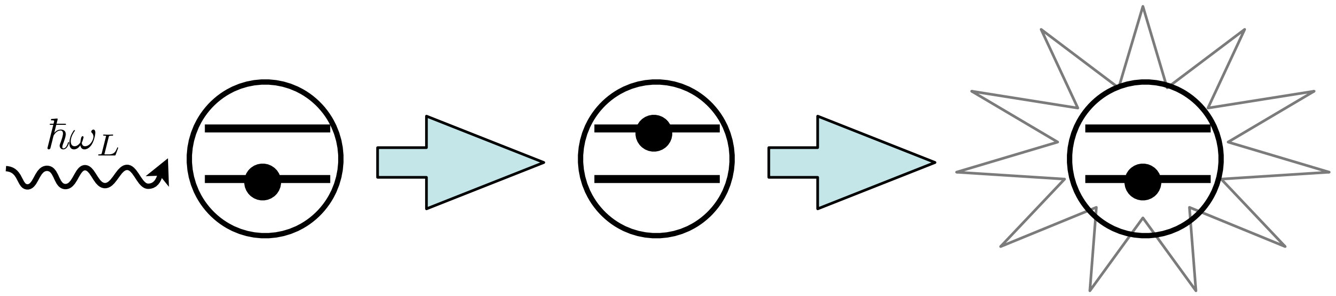
pumping process takes a finite time τ_p ⟶ Sisyphus cooling

Sub-Doppler Cooling
Recoil Limit



emission in a random direction

Limit:
Absorption of 1 Photon ⟶ Atom in Rest ⟶ Acceleration due to reemission

Recoil Temperature: ~$3\ \mu K$ for ^{23}Na

Limits of Laser Cooling

Atomic Level structure

degenerate	non-degenerate
sub-doppler cooling	doppler cooling in a MOT
limited by 1 photon recoil	limited by finite scattering rate

$$k_B T_r = \frac{\hbar^2 k^2}{2m}$$

$$k_B T_D = \hbar \frac{\Gamma}{2}$$

$T_r \approx 3\ \mu K$	^{23}Na	$T_D \approx 235\ \mu K$
$T_r \approx 350\ nK$	^{87}Rb	$T_D \approx 146\ \mu K$

phase space density: ~ 10^{-5} - 10^{-6}

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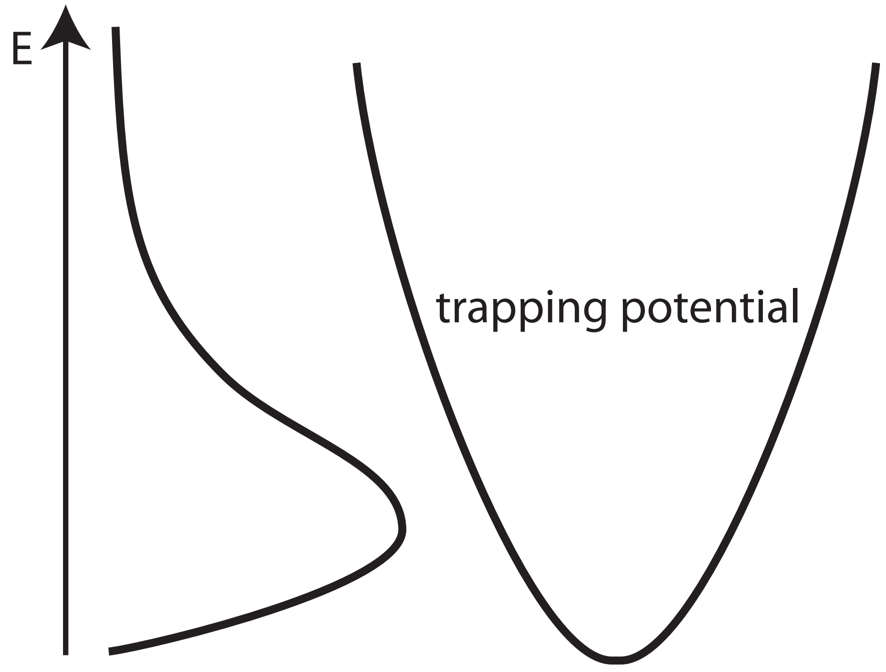
further cooling schemes needed to reach BEC

Evaporative Cooling and Optical Dipole Traps

- Cooling scheme
- Commonly used trap configurations
  - magnetic traps
  - optical dipole traps & lattice potentials

Evaporative Cooling

remove hottest atoms from the trap



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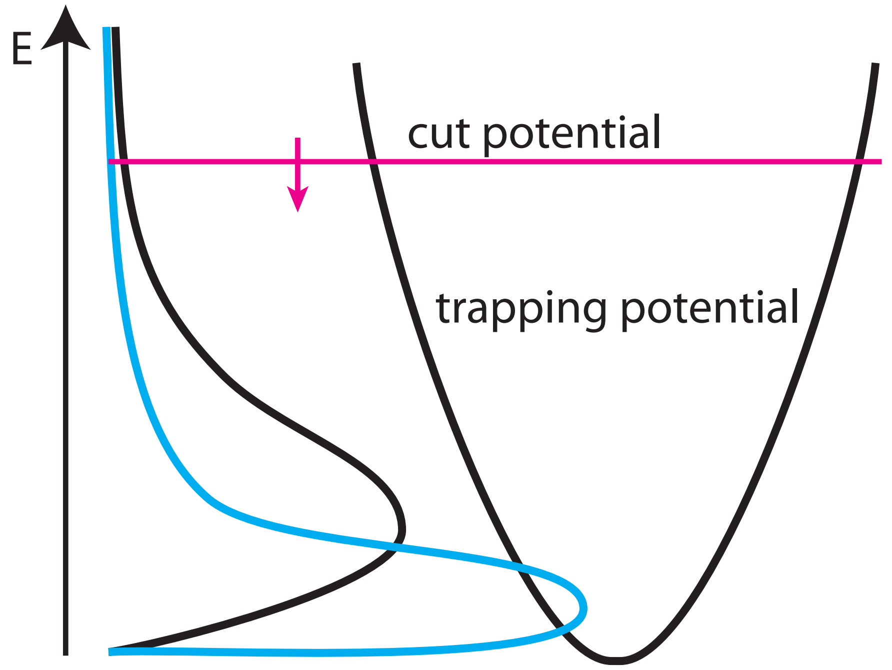

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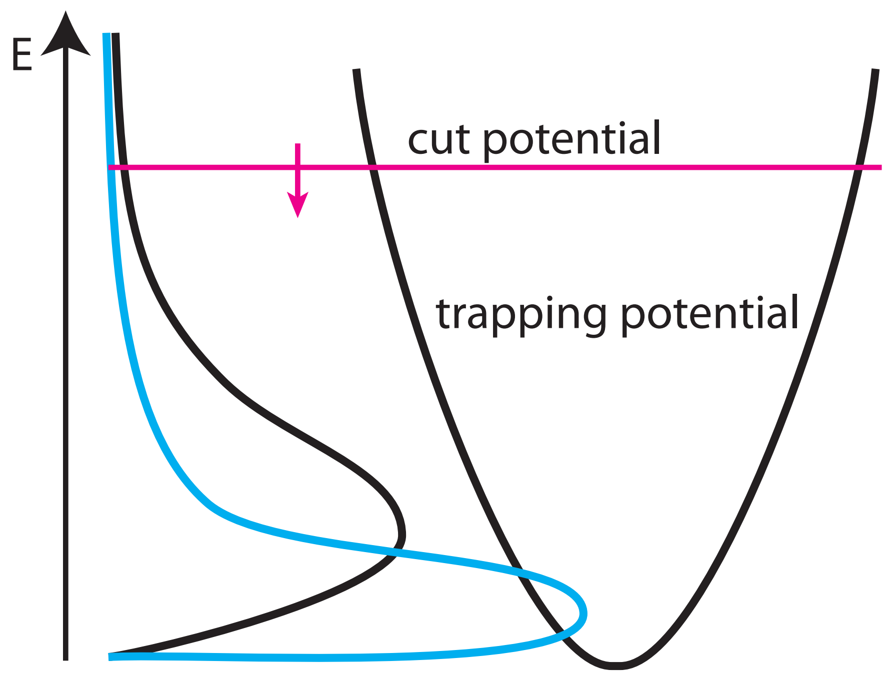

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i.e. temperature decrease due to atom loss leads to an increasing atom density

⟶ gain in phase space density

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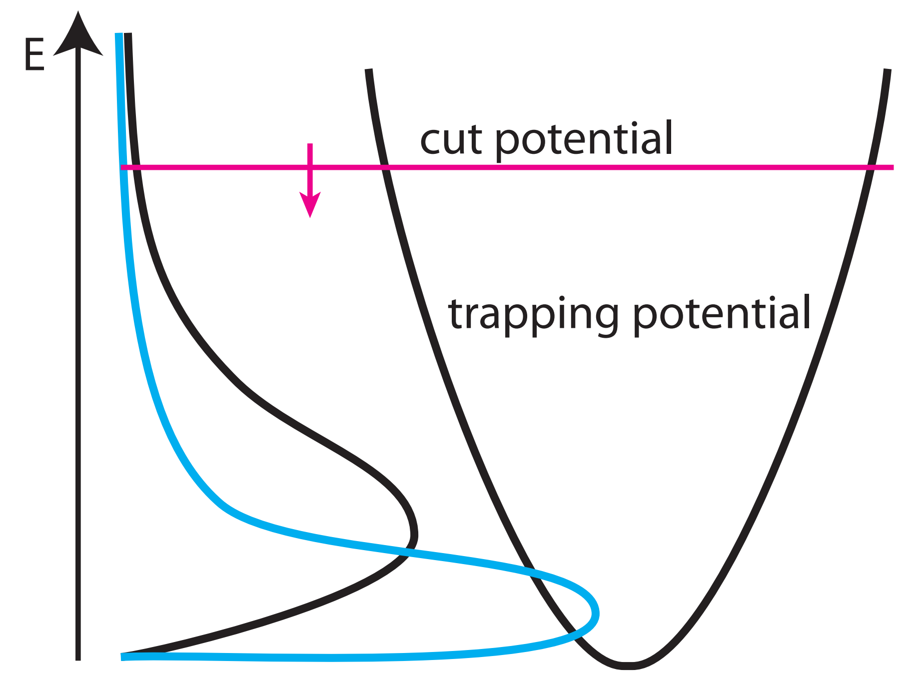

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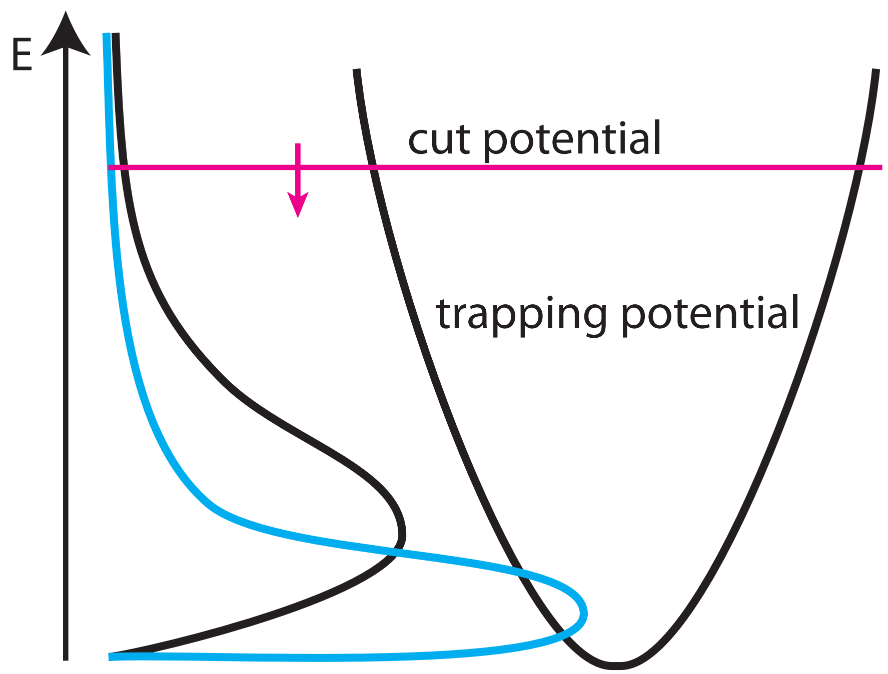

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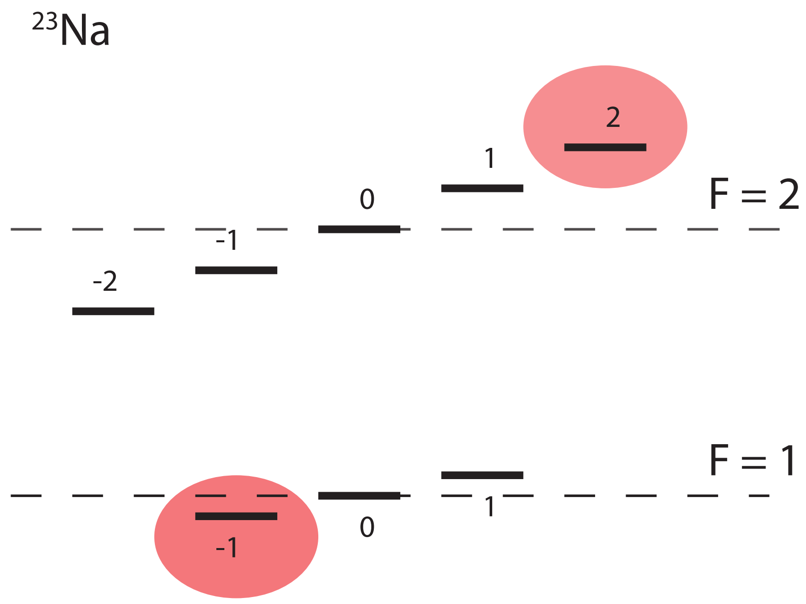
BEC occures

Magnetic Traps

$$V = m_F g_F \mu_B |B|$$

magnetic field maximum in free space forbidden by Maxwells laws

⟶ need low field seeking states ($m_F g_F > 0$)



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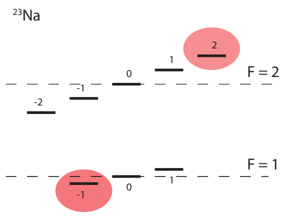

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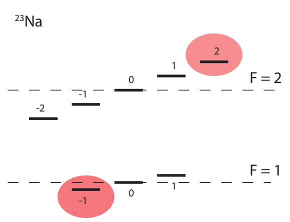

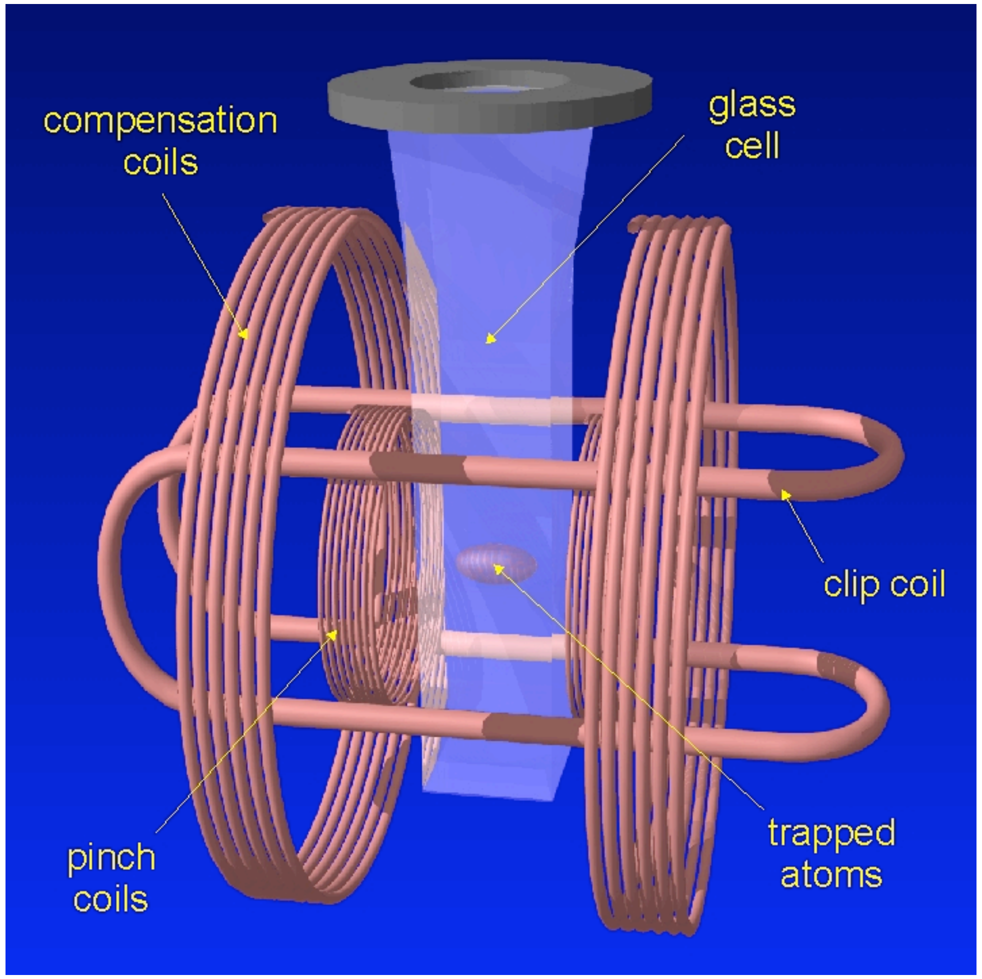

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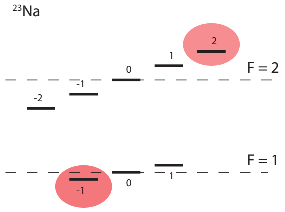

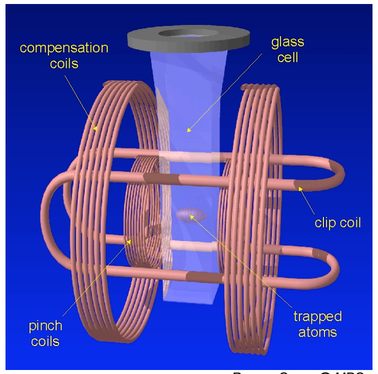

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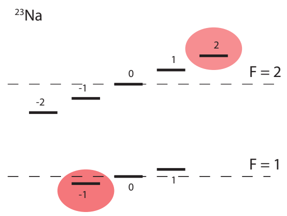
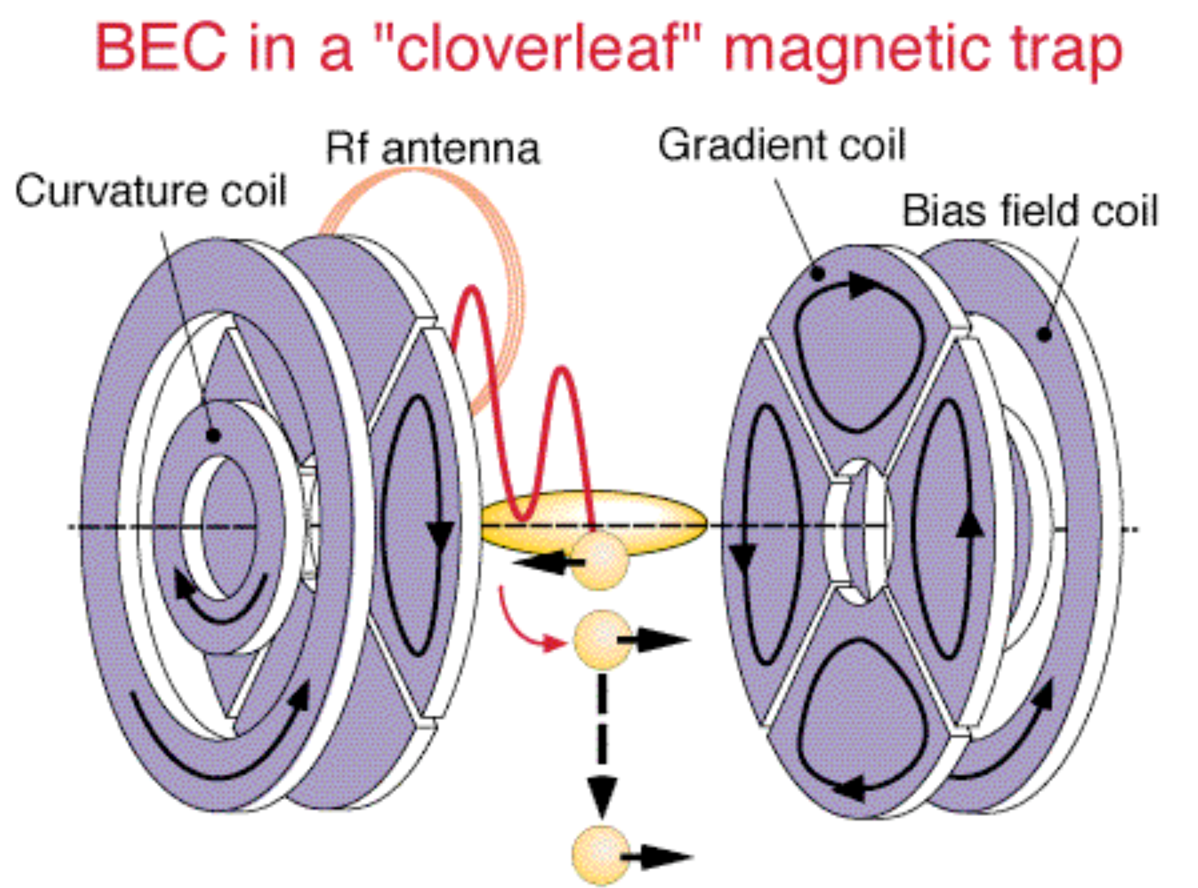
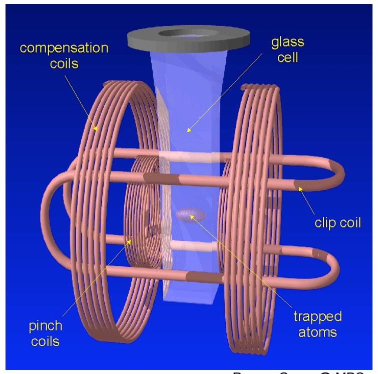




MIT, March '96 [M.-O. Mewes et al., PRL 77, 416 (1996)]



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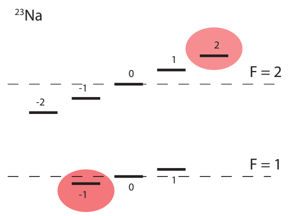

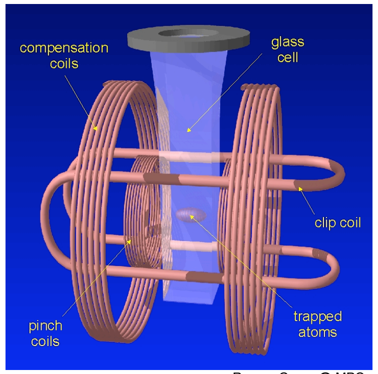

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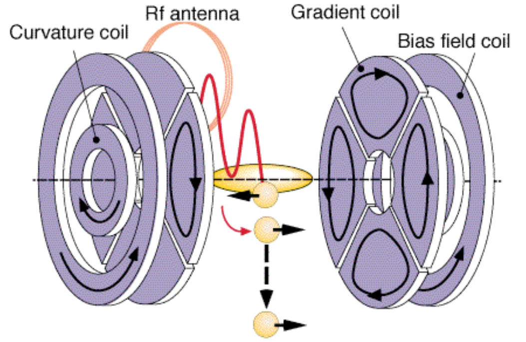
BEC in a "cloverleaf" magnetic trap



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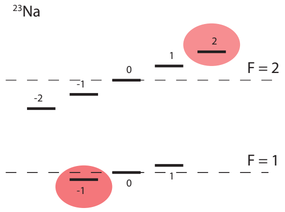

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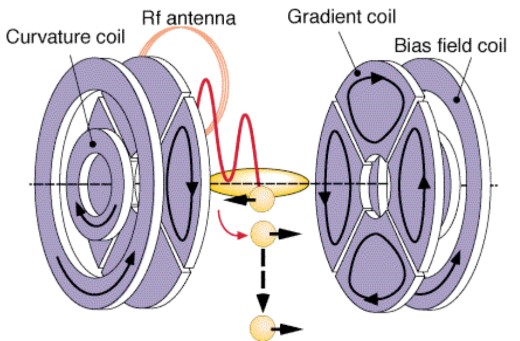

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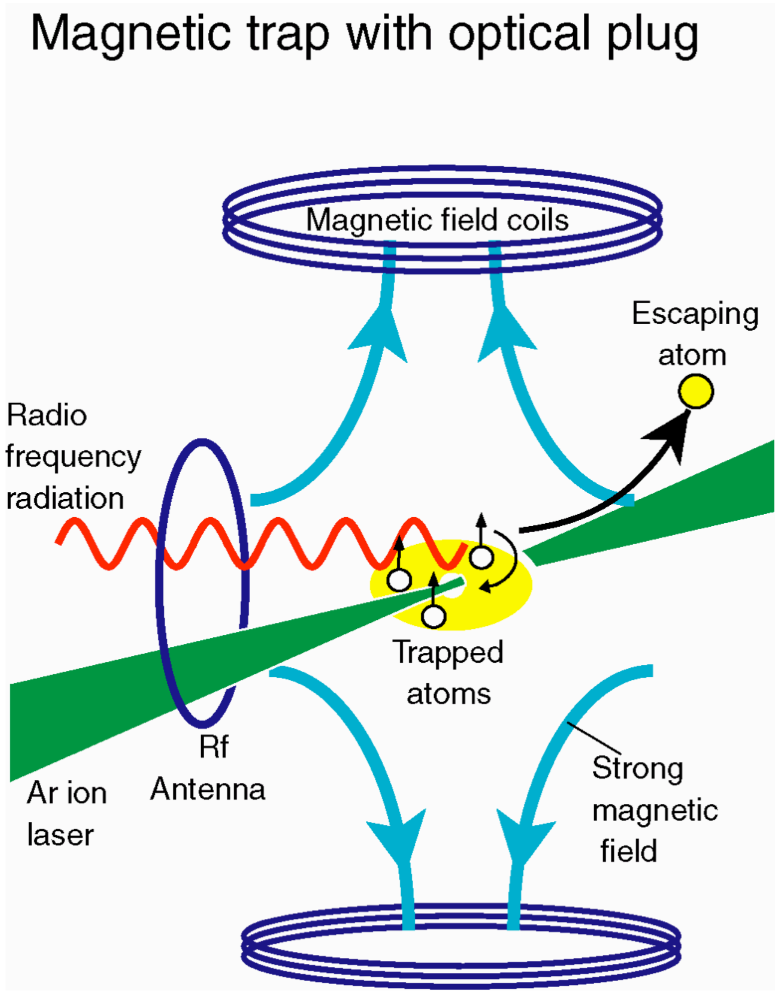

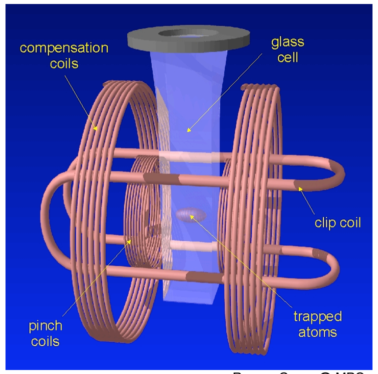

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Far-Off-Resonance Traps

light shift of the atomic levels due to laser light:

$$E = \frac{\hbar\Omega^2}{4\Delta} \qquad |\Omega|^2 = \frac{\Gamma^2 I(r)}{2I_{\mathrm{sat}}}$$

inhomogeneous intensity profile creates (trapping) potential for the atom

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Two cases:

- blue detuned light (i.e. $\Delta = \omega_L - \omega_0 > 0$):

  repulsive potential, repell atoms from intensity maximum

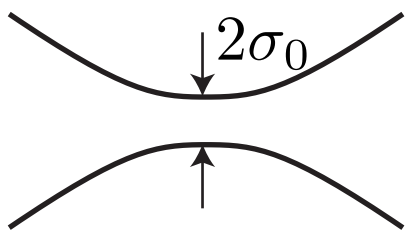
- red detuned light (i.e. $\Delta = \omega_L - \omega_0 < 0$):

  attractive potential, single beam acts as a trap

Far-Off-Resonance Traps

Single Beam Trap:

use a focused beam to trap atoms



$$I(r) = I_0 \frac{\sigma(z)}{\sigma_0} \exp[\frac{-2(x^2+y^2)}{\sigma(z)^2}]$$

$$\sigma(z) = \sigma_0 \sqrt{1+\frac{z^2}{z_R^2}}$$

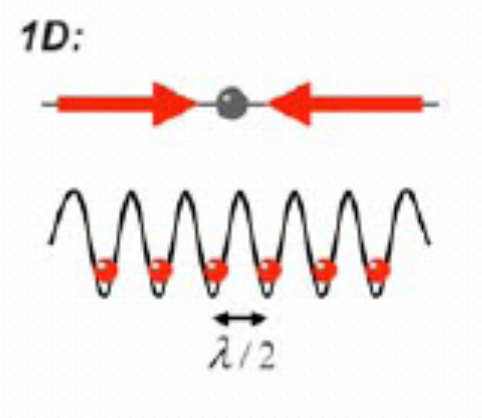
$$z_R = \frac{\pi \sigma_0^2}{\lambda} \text{ Rayleigh range}$$

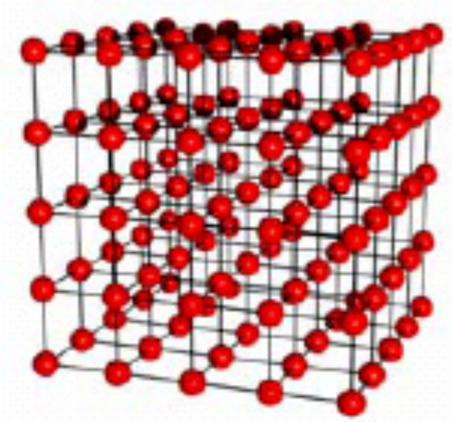
trapping frequencies in radial and longitudinal direction:

$$\omega_\perp = \sqrt{\frac{4|V|}{m\sigma_0^2}} \qquad \omega_\parallel = \sqrt{\frac{2|V|}{m z_R^2}}$$

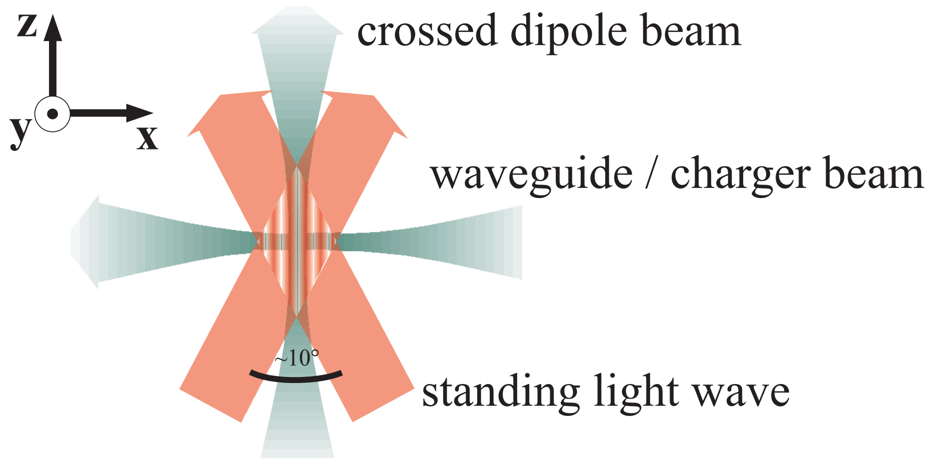
Optical Potentials

Creation of Lattice Potentials by interfering trapping beams





tight confinement, single site addressability, variable lattice depth



Observing a BEC

- density distirbution of a thermal cloud in the harmonic trap given by Boltzmann distribution
- during TOF the cloud expands due to its velocity distriburion governed by the Maxwell-Boltzmann distribution, i.e. homogeneous expansion in free space

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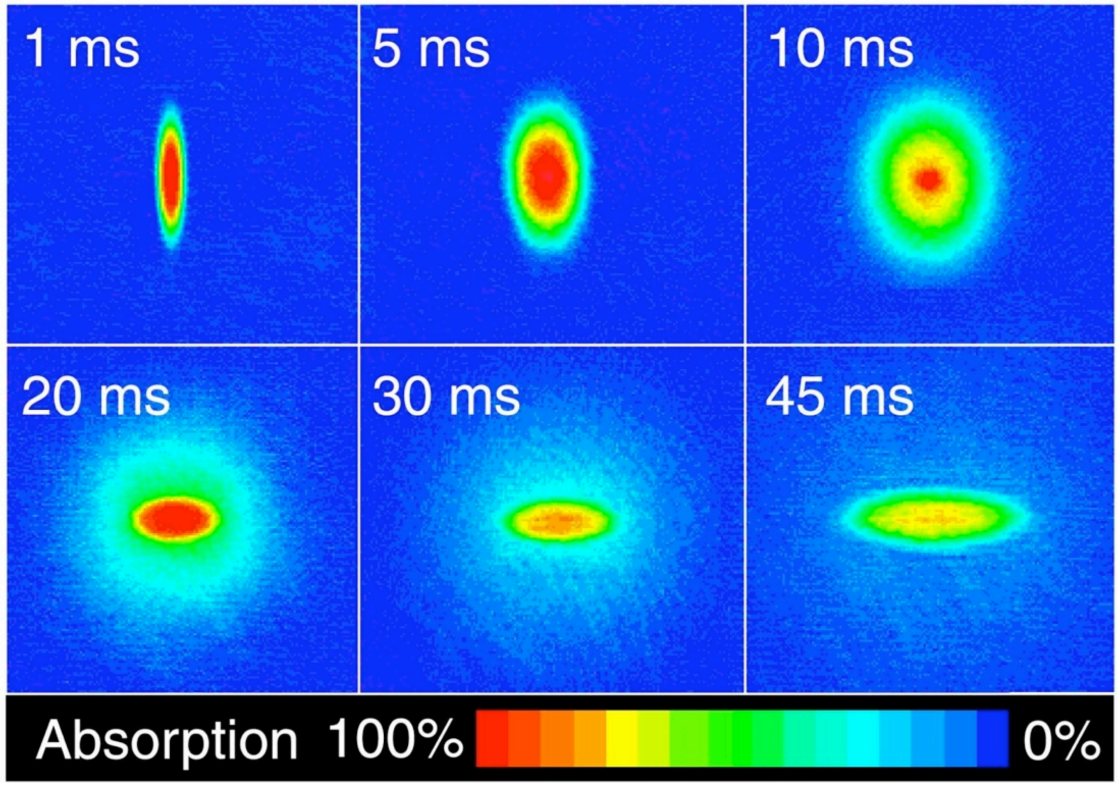
BEC:

additional interaction energy adds during expansion



MIT, Ketterle group

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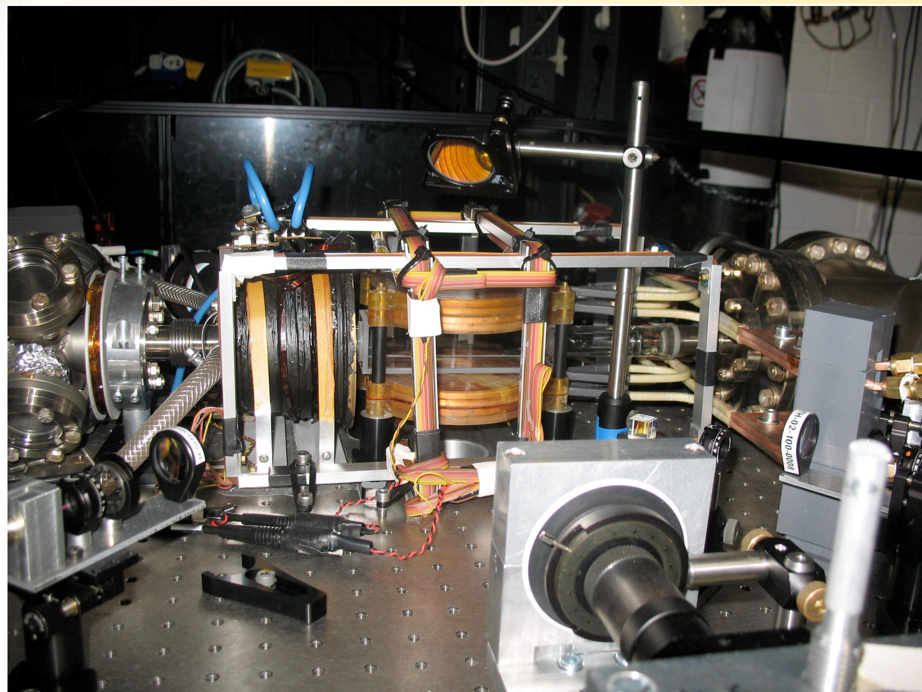

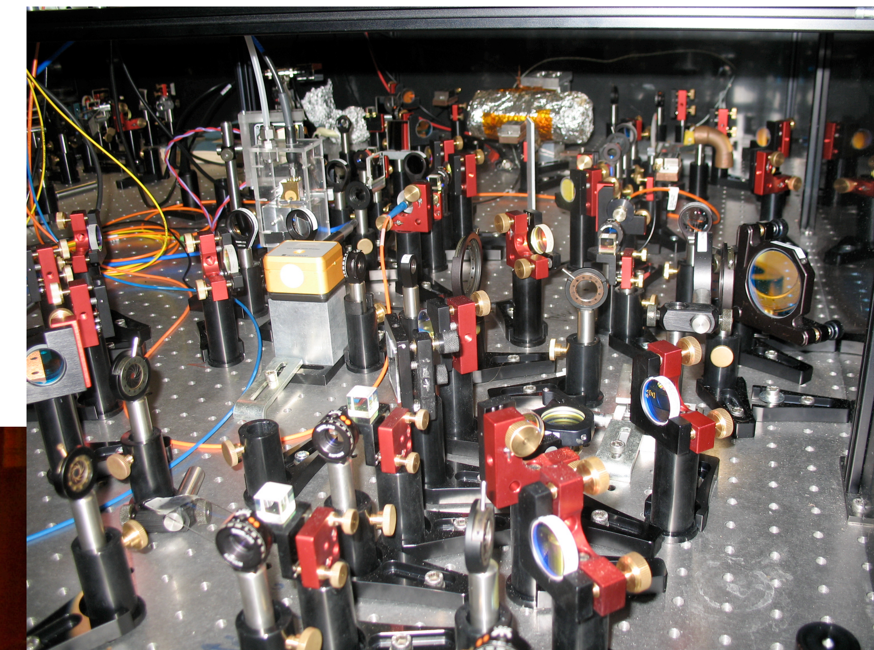

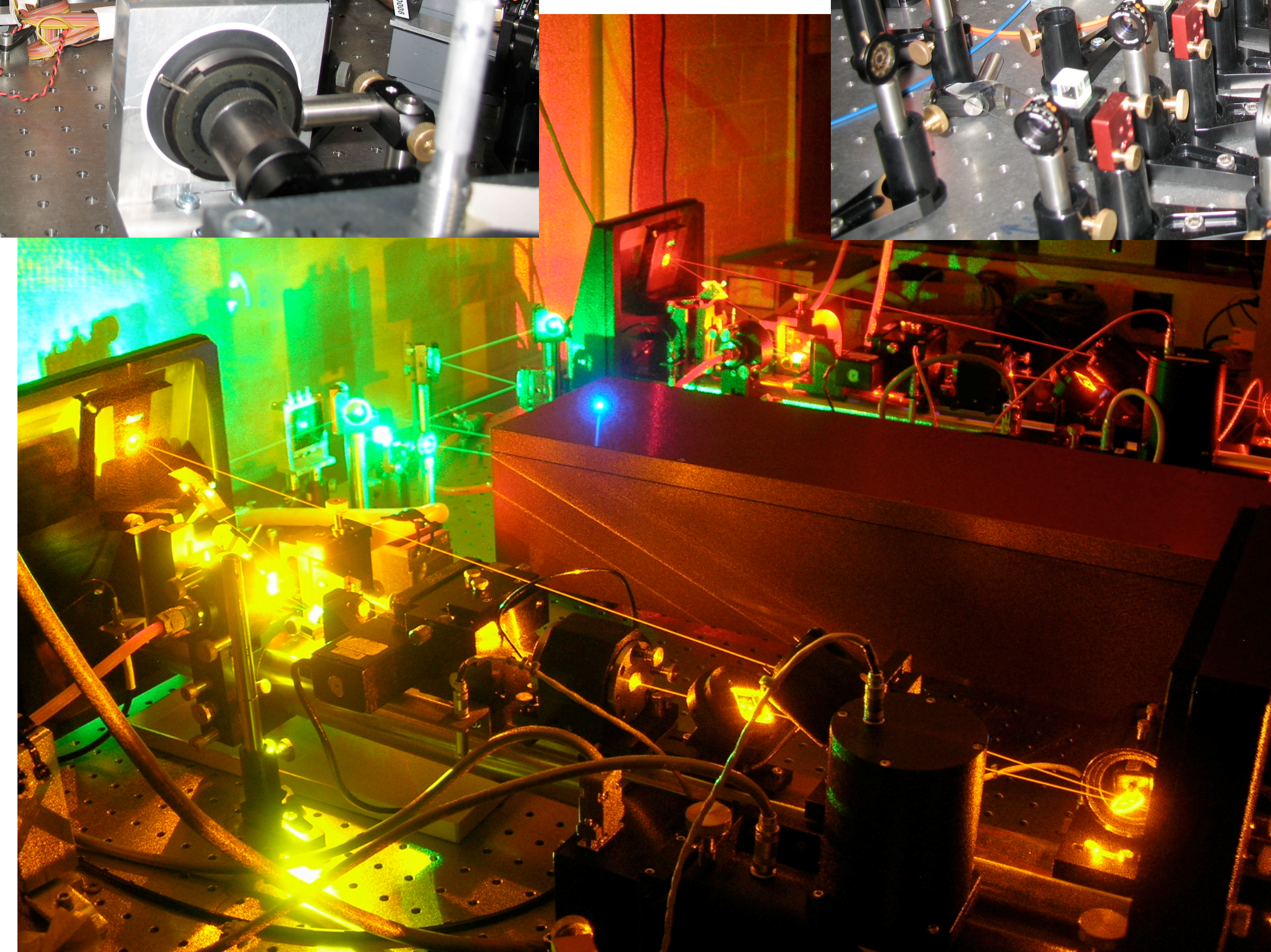

Jens Appmeier

Fabienne Haupert

Jan Krieger

Peter Krüger

Anton Piccardo-Selg

Valentin Volchov

Markus K. Oberthaler

former members: Elisabeth Brama Marc Repp Stefan Weis