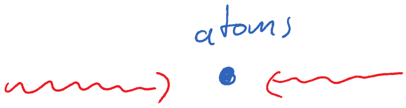
Trapping of cold atoms

Donnerstag, 13. Januar 2022 12:19

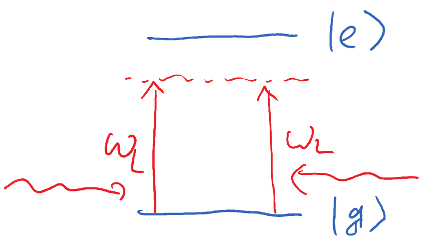
Optical Molasses

↳ "Honey"

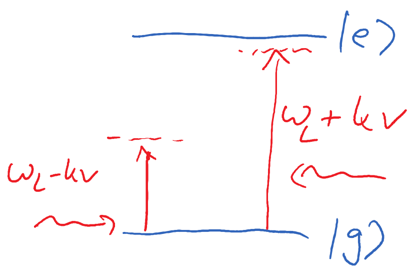


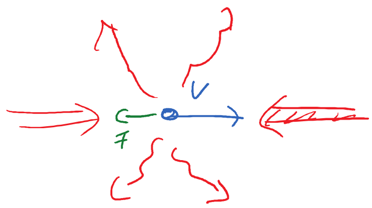
2 counterpropagating lasers, red-detuned

atom at rest



atom moves ⟶





$$\vec{F} = -\beta \cdot \vec{v}$$

force = opposing atom's velocity

total force on atom in O.M.

$$\vec{F}_{OM} = \vec{F}_+ + \vec{F}_-$$

2 lasers in $\pm z$ direction

$$\vec{F}_\pm = \pm \frac{\hbar \vec{k} \Gamma}{2} \frac{S_0}{1 + S_0 + \left[2\left(\delta \pm |\omega_D|/\Gamma\right)\right]^2}$$

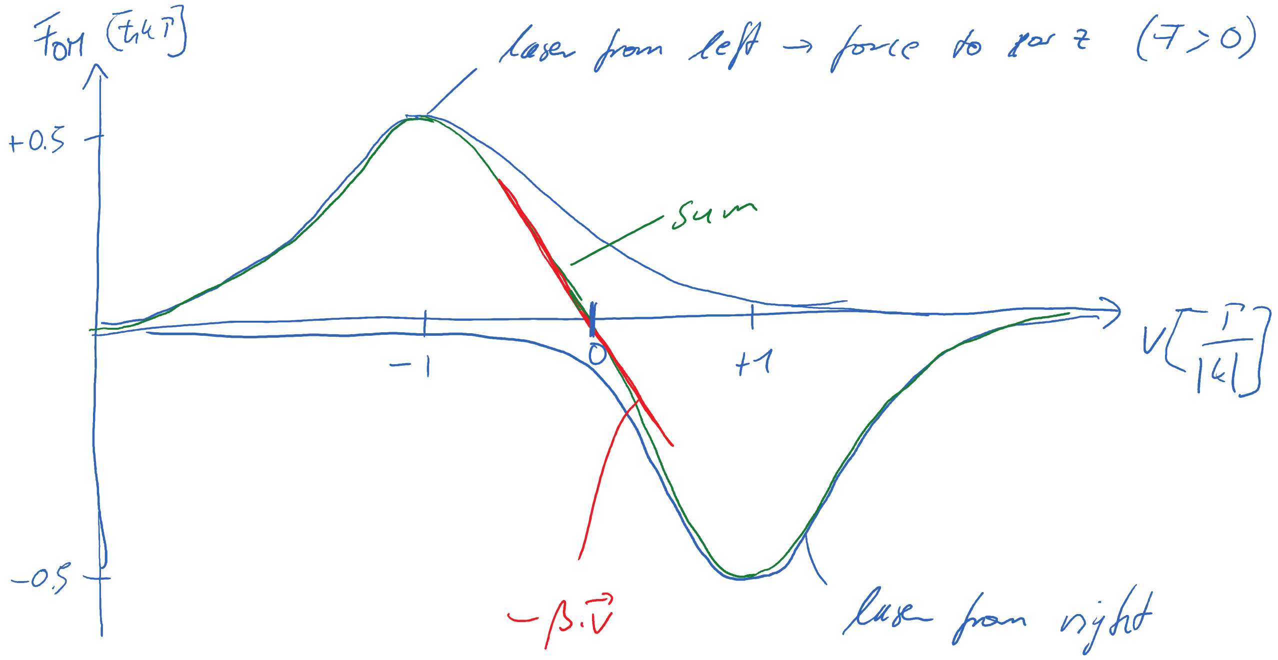
ignore stuff $O\left(\left(\frac{kv}{\Gamma}\right)^4\right)$

$$\vec{F}_{OM} \simeq \frac{8\hbar k^2 \delta S_0 \vec{v}}{\ldots} = -\beta \cdot \vec{v}$$

$$\vec{F}_{OM} \simeq \frac{8\hbar k^2 \delta s_0 \vec{v}}{\Gamma\left(1+s_0+\left(\frac{2\delta}{\Gamma}\right)^2\right)^2} = -\beta\cdot\vec{v}$$

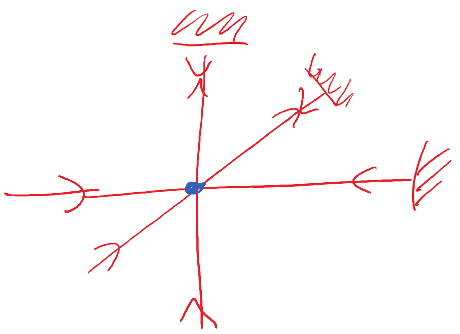
$\delta < 0$ viscous friction $\rightarrow$ Chu et al : Molasses

↑ red-detuned laser



1D cooling

3D:



6 lasers
(3 + mirrors)

kin.e: $E = \frac{1}{2}M\left(v_x^2 + v_y^2 + v_z^2\right)$

$$\frac{dE}{dt} = -\frac{2\beta}{M}E = -\frac{E}{\tau_{cool}}$$

$$\tau_{cool} \sim O(\mu s)$$

$E = 0$ is impossible

atom is <u>heated</u>

↳ Doppler cooling limit

Doppler cooling limit

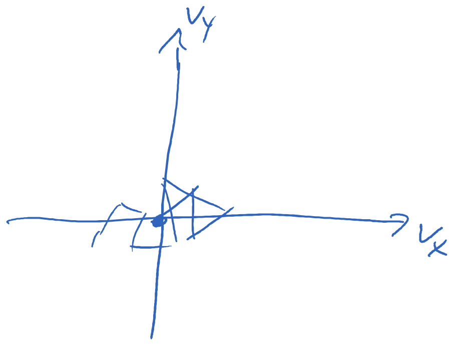
$$F = F_{abs} + \delta F_{abs} + F_{spont} + \delta F_{spont}$$

↑ ↑

fluctuations → heating

- $\overline{F_{abs}} = F_{scatt} = \hbar k R_{scatt} = \hbar k \frac{\Gamma}{2} \frac{S_0}{1 + S_0 + \frac{4\delta^2}{\Gamma^2}}$
- $\overline{F_{spont}} = 0$ → isotropic emission
- δS_{pont} → random kicks

random walk



N steps, individual length $= \hbar k$

σ of avg. momentum change $\sqrt{N} \cdot \hbar k$

time t: $N = R_{scatt} \cdot t$

spont. emission increses $(v_{avg})^2$

$\overline{v^2} = R_{scatt} \cdot t \cdot v_r^2$ → heating

recoil velocity

projection along z direction

$$(\overline{v_z^2})_{spont} = \eta \cdot v_r^2 \cdot R_{scatt} \cdot t$$

$\eta = \langle \cos^2\theta \rangle = \frac{1}{2}$ projection onto z axis

• δF_{abs} within time t: atom scatters $N \pm \sqrt{N}$ photons (Poisson)

similar random walk

$(\overline{v_z^2})_{abs} = v_r^2 \, R_{scatt} \cdot t$ 1 laser

2 lasers: fluctuations add

$$\frac{1}{2} M \frac{d\overline{v_z^2}}{dt} = (1+\eta) \underbrace{E_r}_{\text{recoil energy}} \cdot 2 \cdot R_{scatt} - \beta \overline{v_z}^2$$

6 lasers in 3D

$$1+\eta \rightarrow 1+3\eta = 2$$

equilibrium temperature

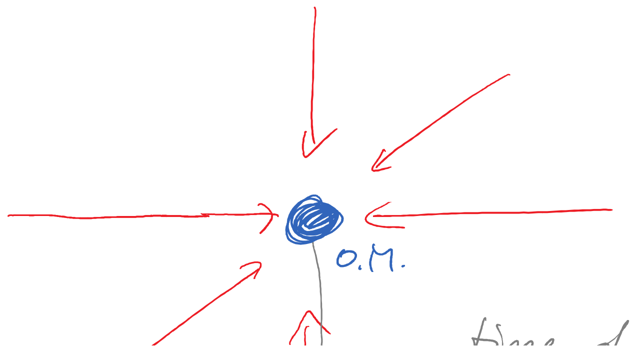
$$k_B T = \frac{\hbar\Gamma}{4} \frac{1 + \left(\frac{2\delta}{\Gamma}\right)^2}{-2\delta/\Gamma}$$

has a minimum at $\boxed{\delta = -\frac{\Gamma}{2}}$ optimal detuning

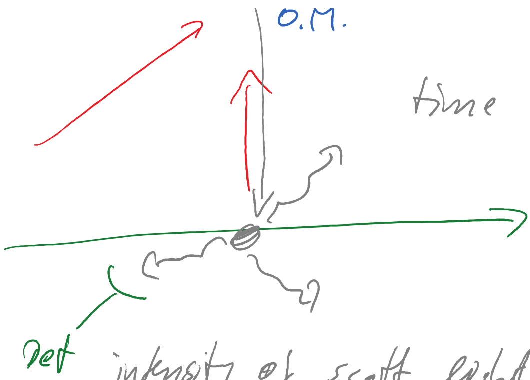
$\Rightarrow k_B \cdot T_{Doppler} = \frac{\hbar\Gamma}{2}$ Doppler cooling limit

minimal expected temperature in optical molasses

e.g. Na $T_D = 240 \mu K \hat{=} v \approx 0.5 \frac{m}{s}$



time of flight



time of flight

intensity of scatt. light
↳ velocity distribution

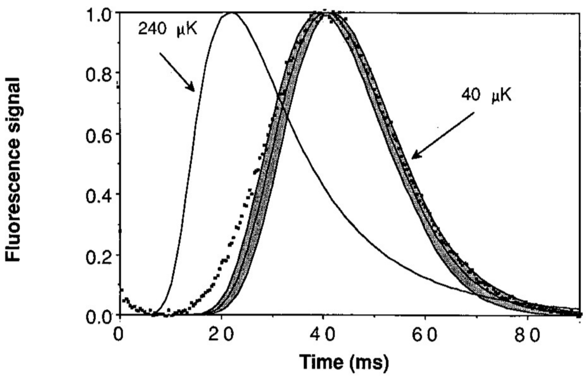


FIG. 16. The experimental TOF distribution (points) and the predicted distribution curves for 40 μK and 240 μK (the predicted lower limit of Doppler cooling). The band around the 40 μK curve reflects the uncertainty in the measurement of the geometry of the molasses and probe.

Bill Philips
Nobel lecture

Sub-Doppler Cooling

(Sisyphus cooling)

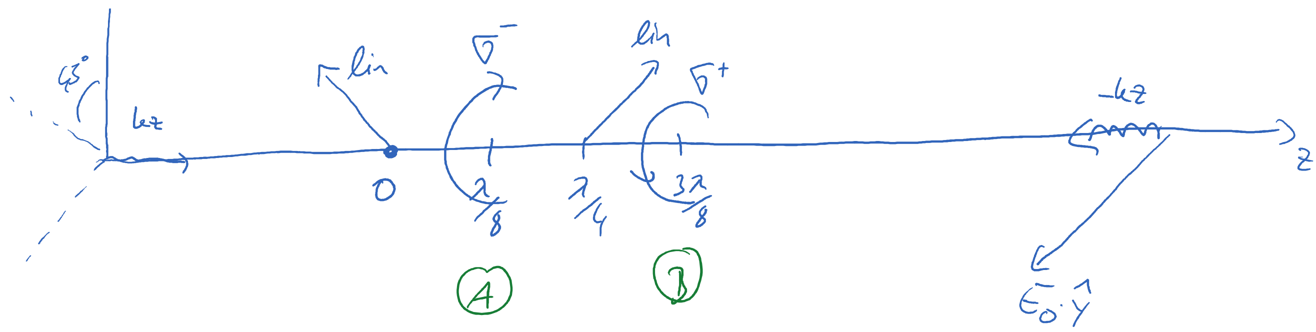
Dalibard, Cohen Tannoudji
J. Opt. Soc. Am. B6, 2023 (1989)

"lin - perp - lin"

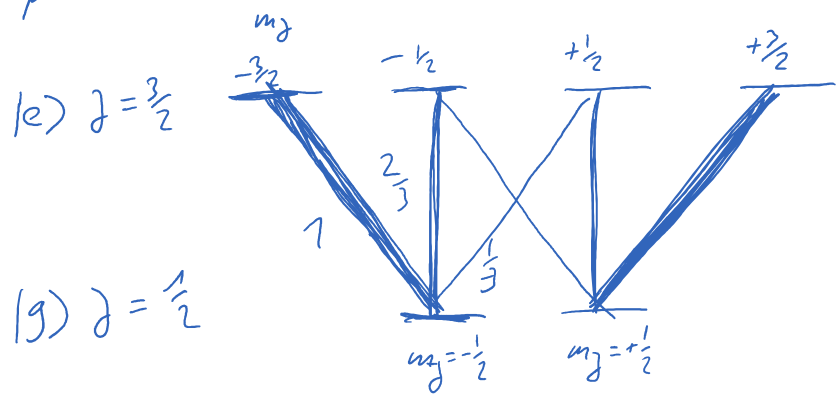
lin ⊥ lin polarization gradient cooling

2 lasers lin pol ⊥ to each other

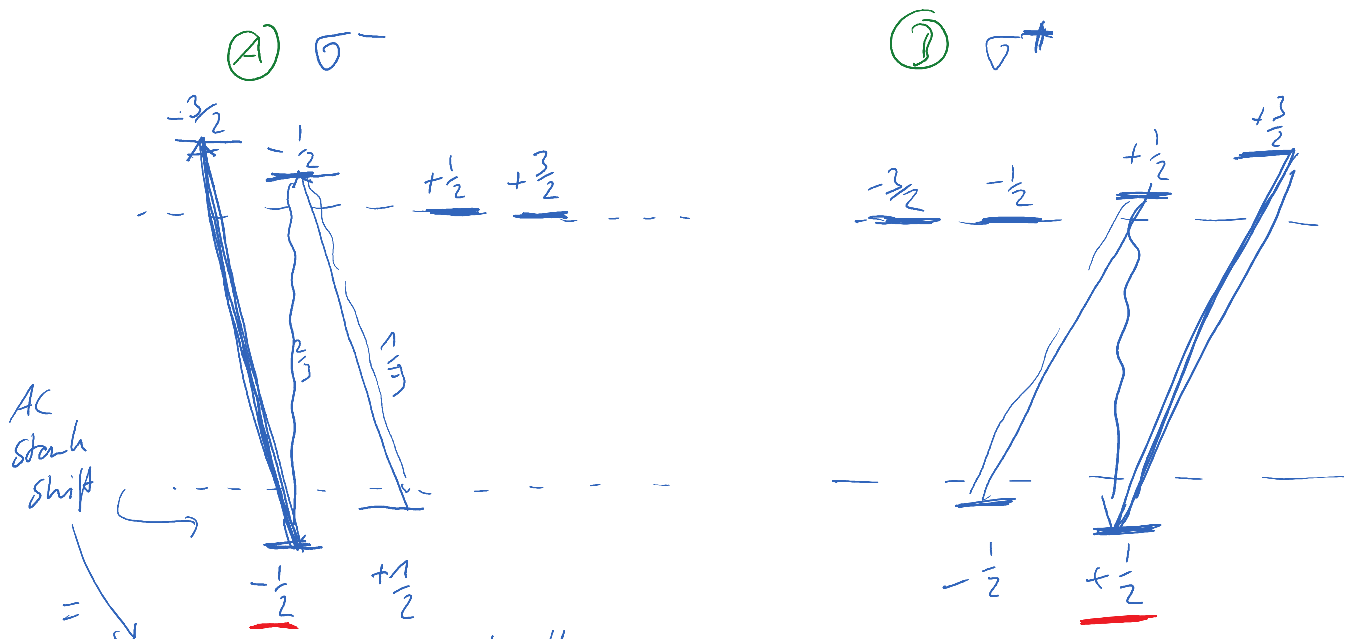
$$\vec{E} = E_0 \hat{x} \cos(\omega_L t - kz) + E_0 \hat{y} \cos(\omega_L t + kz)$$



example atom

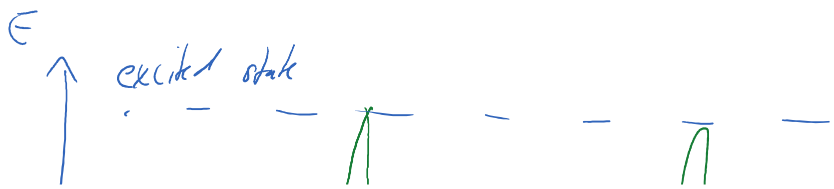


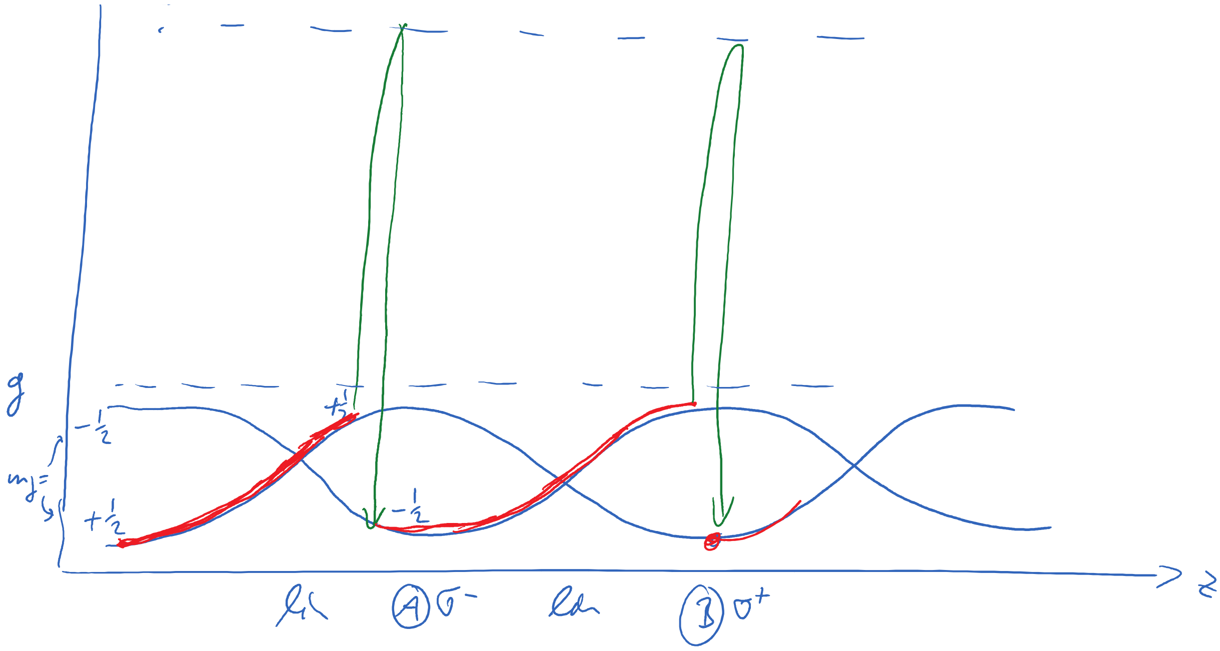
rel. line strengths (Clebsch-Gordan)



= light shift ∝ osc. strength
= 1:3

fluorescence always to the lower state (optical pumping)





atom moves "uphill" Sisyphus → loses kin. energy

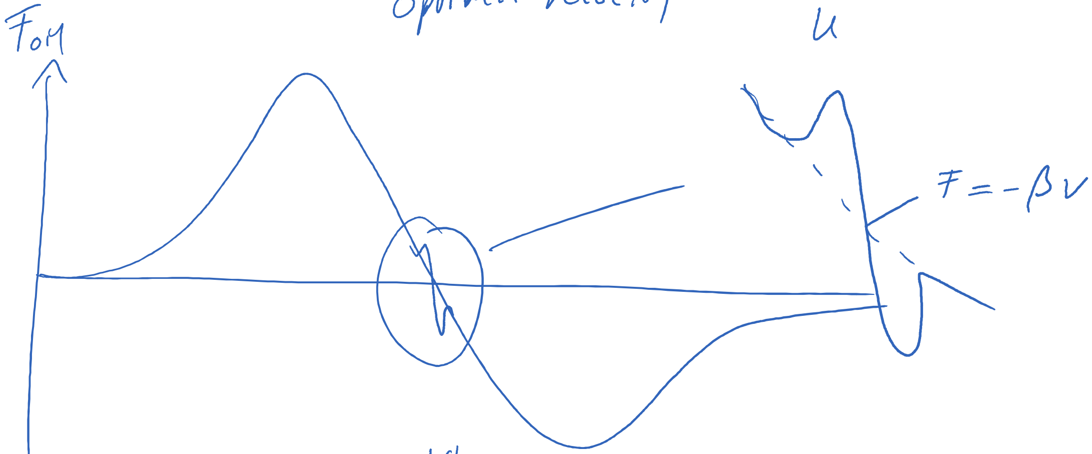
deexcitation mainly to other m_J state

works best for 1 velocity class

"1 hill per scattering"

$\tau_p = \frac{1}{\gamma_p}$

optimal velocity $\sim \frac{\gamma_p}{k}$



$\beta_{sys} = 2 \frac{|\delta|}{\Gamma}$ larger than $\beta_{Doppler}$

optical molasses : Force $\propto -\vec{v}$

not a trap!

No Force $\propto -\vec{v}$

trap needs a position dependent restoring force

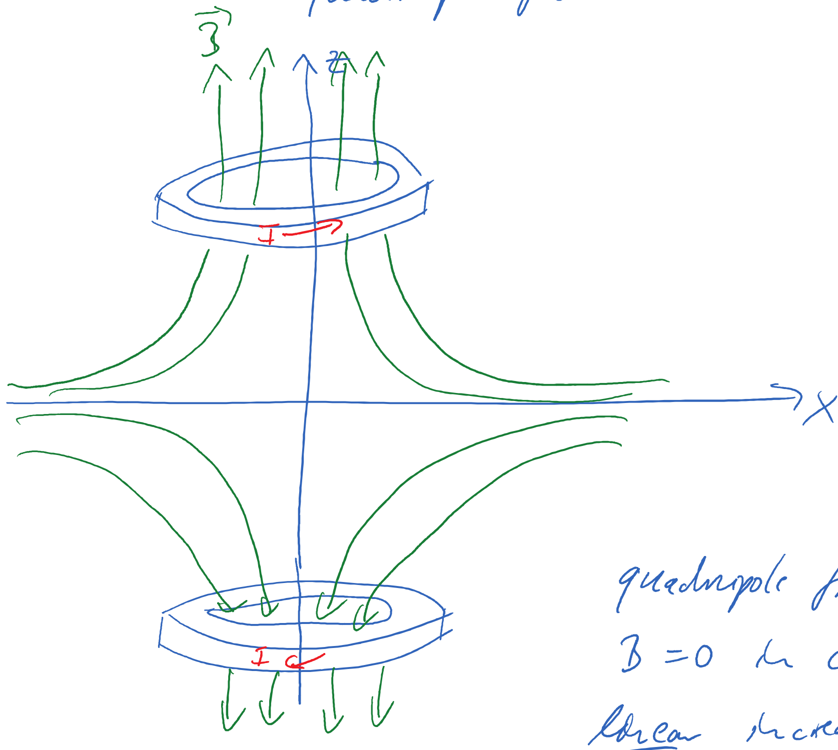
MOT: Magneto-optical trap

Pritchard, Chu PRL 59, 2631 (1987)

6 Lasers

+ 2 coils in anti-Helmholtz configuration

↳ quadrupole field



quadrupole field

B = 0 in center

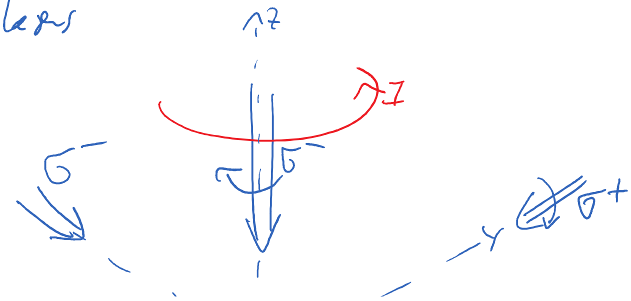
linear increase in all directions

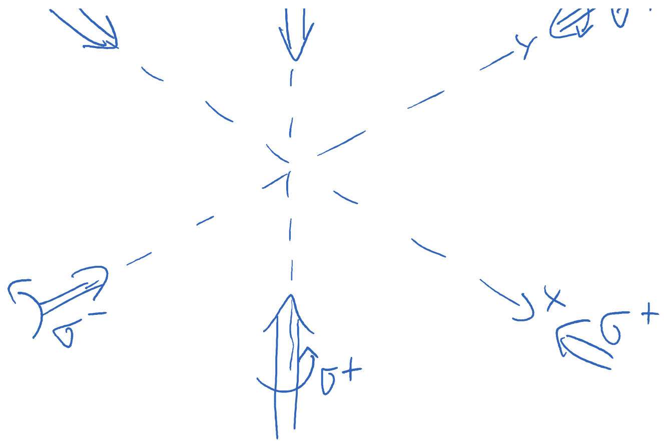
Maxwell: $\operatorname{div} \vec{B} = 0$

$$\frac{dB_x}{dx} = \frac{dB_y}{dy} = -\frac{1}{2}\frac{dB_z}{dz}$$

gradient in x, y = $\frac{1}{2}$ gradient in z

+ 6 lasers





example atom, 1D ($\hat{z}$)

$|g\rangle$ $J=0$ 1 m_J

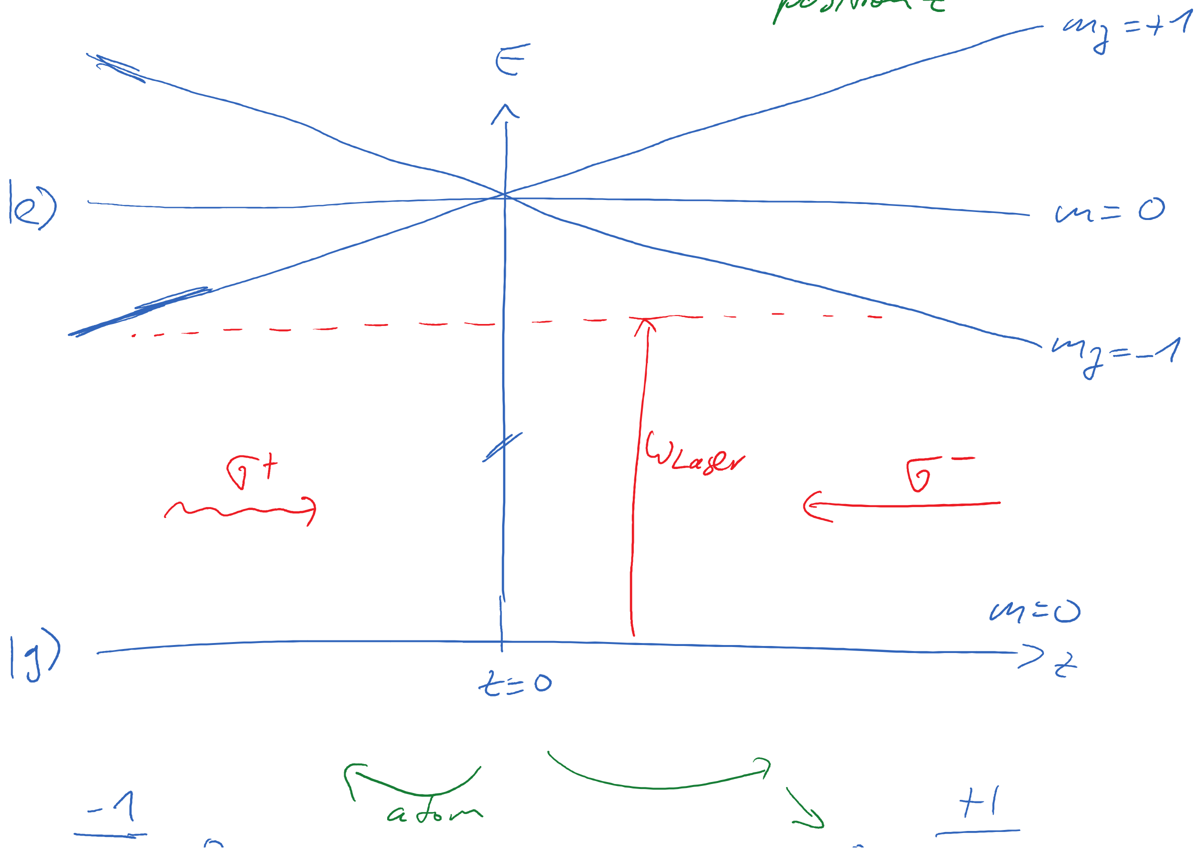
$|e\rangle$ $J=1$ 3 m_J s

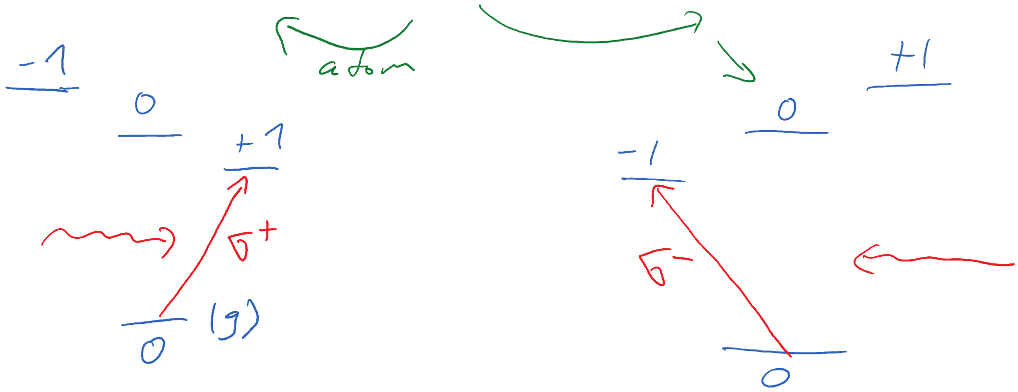
$B(z) = b \cdot z$ linear in z

Zeeman splitting $\Delta E = \mu_B \cdot m_J \cdot B$

$= \mu_B \cdot m_J \cdot b \cdot z$

level position depends on position z



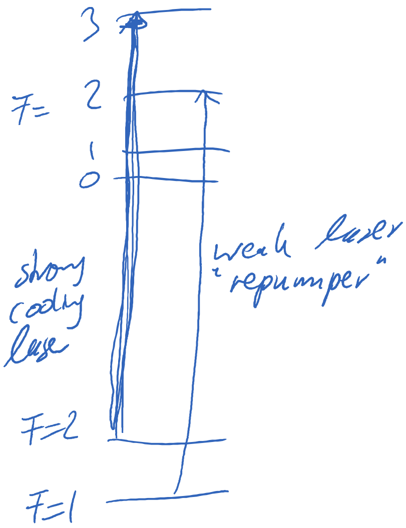


atoms trying to "escape" will have their levels Zeeman shifted such that the opposite laser will become resonant

→ position dependent force

⇒ Trap

^{87}Rb



lasers mW

detuning ~ 10 MHz

~ $10^6 \dots 10^{10}$ atoms trapped

~ Ø mm ... cm

$\rho \lesssim 10^{11}/\mathrm{cm}^3$

$T = T_{Doppler} \sim 100\,\mu K$

lifetimes sec ... hours

↑

10^{-12} mbar vacuum