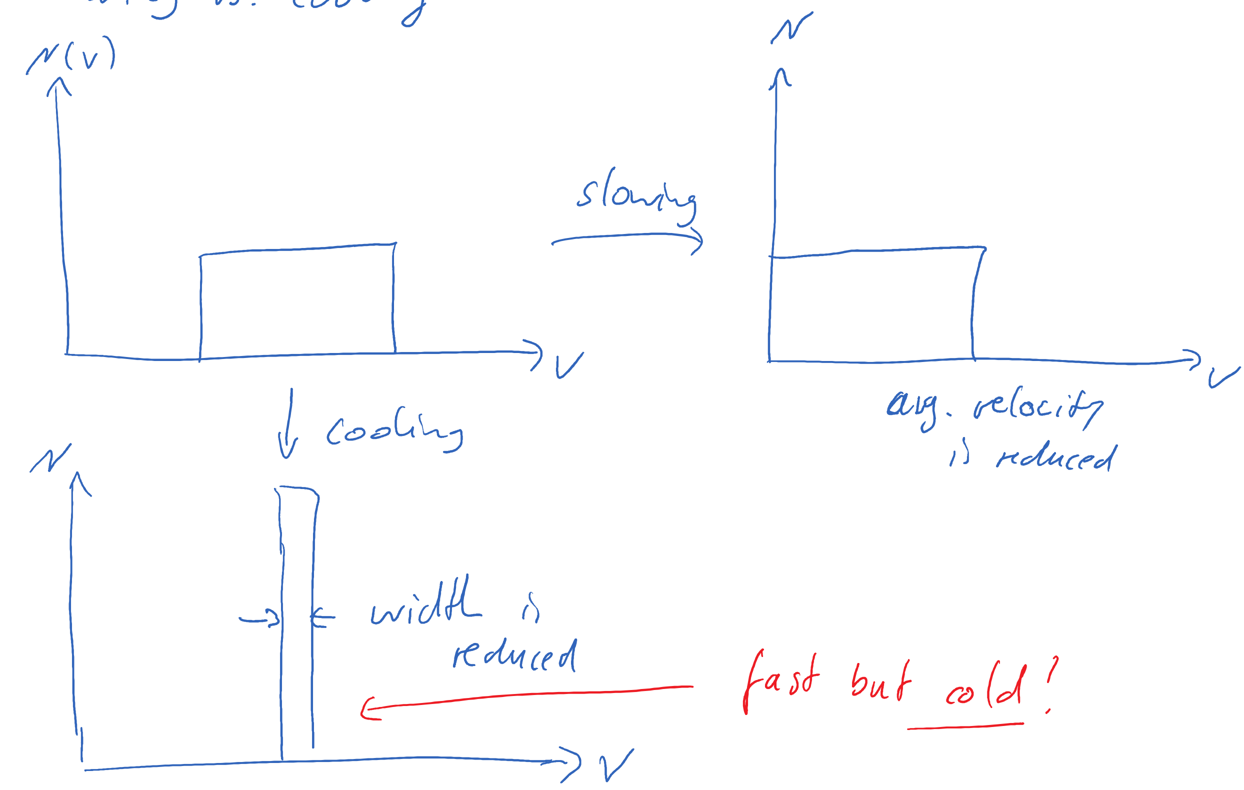
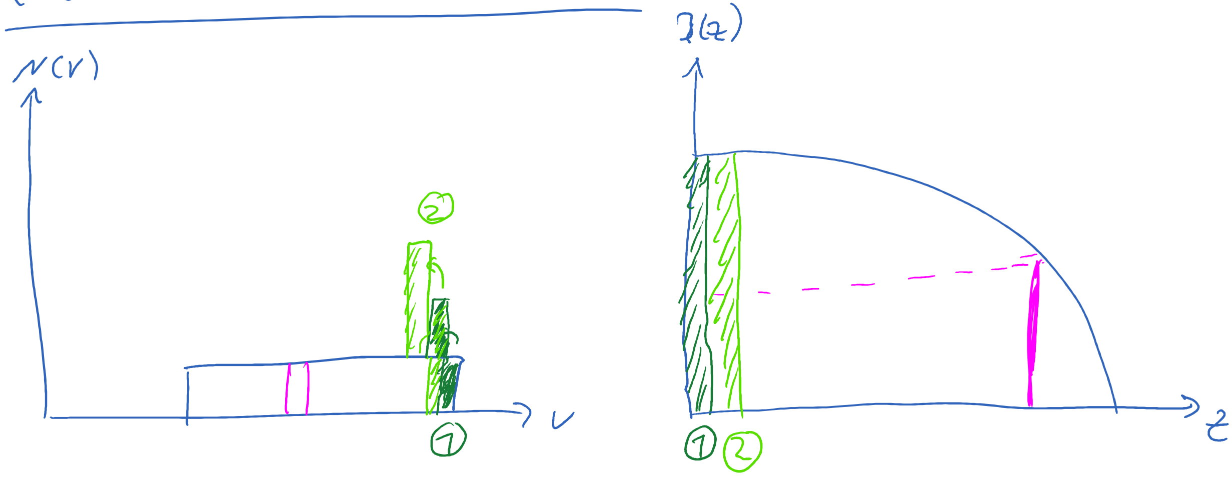
Slowing vs. cooling

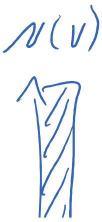


Zeeman slower does both



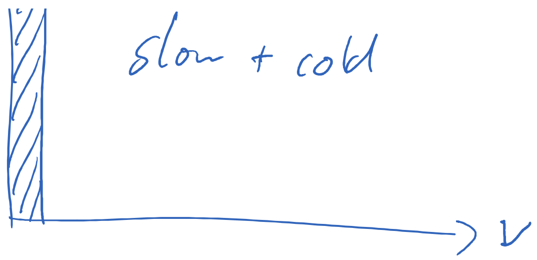
1 fastest atoms + largest B-field → on resonance
→ slowing

⇒ finally



slow + cold

$\Rightarrow$ finally



Temp. defined for closed system in equilibrium

$\neq$ atom + laser

we just <u>claim</u> $\frac{1}{2} k_B T = \langle E_{kin} \rangle$ avg. E_{kin} in 1D

- critical temp.

  Doppler shift small enough for interaction with laser

  $$v_c = \frac{\Gamma}{k} \sim 1\,\mathrm{m/s} \qquad \text{few mK}$$

- Doppler temperature

  1D velocity $v_D = \sqrt{\frac{k_B T}{M}} \sim 30\,\mathrm{cm/s}$

  $\hat{=}$ nat. line width $\qquad k_B T = \frac{\hbar \Gamma}{2}$

- recoil temperature

  1 photon recoil

  $$v_r = \frac{\hbar k}{M} \sim 1\,\mathrm{cm/s}$$

  $$k_B T_r = \frac{\hbar^2 k^2}{M} \sim \mu\mathrm{K}$$

<u>Trapping of cold atoms</u>

<u>Optical Molasses</u>

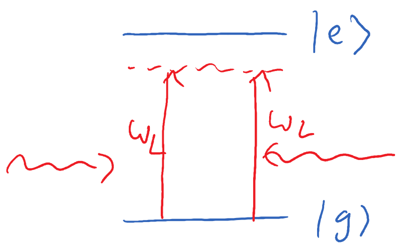
Optical Molasses

↪ "Honey"

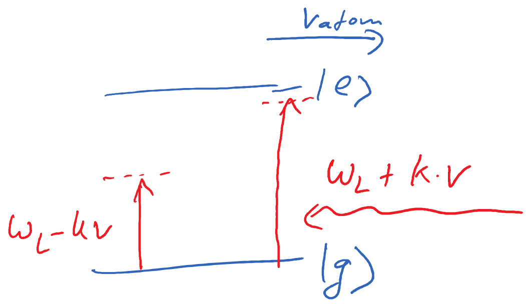
2 counterpropagating lasers

red-detuned

atom at rest



atom moves



even further detuned

Doppler-shifted onto resonance

atom scatters laser photons from 1 laser against the velocity

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

total force in O.M.

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

2 lasers in $\pm z$ direction

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

2 direction

2 direction

saturated | Lorentzian

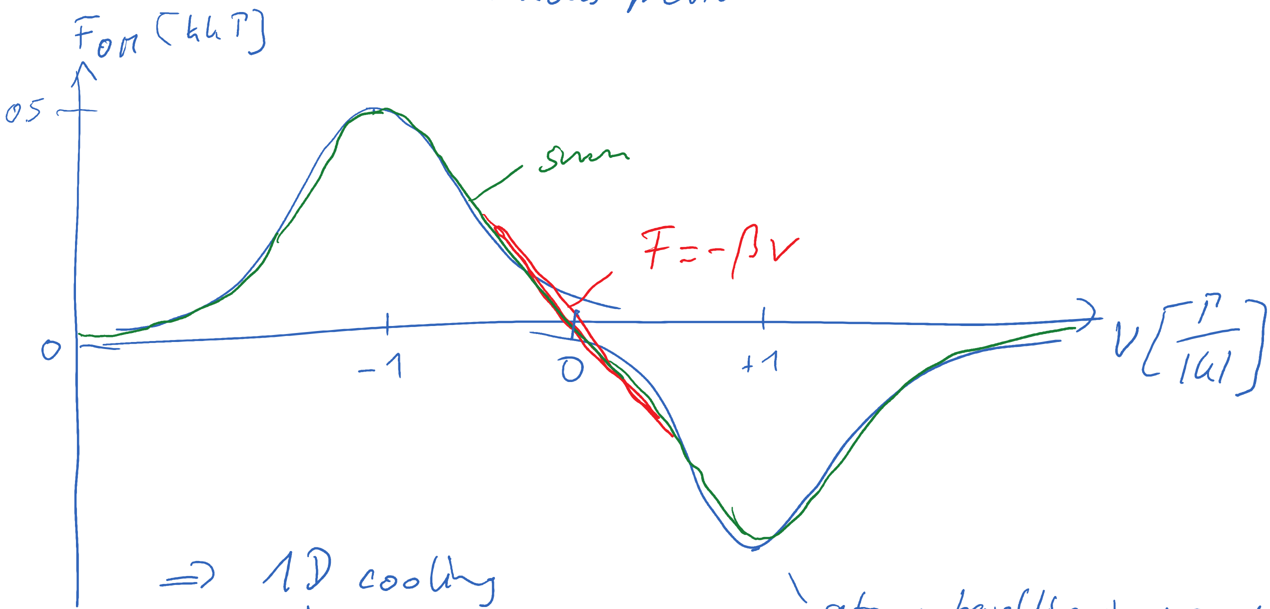
Doppler-shifted

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

$$\vec{F}_{OM} \approx \frac{8\hbar k^2 \delta S_0 \vec{v}}{\Gamma\left(1+S_0+\left(\frac{2\delta}{\Gamma}\right)^2\right)^2} = -\beta\cdot\vec{v}$$

for $\delta < 0$
red-detuned

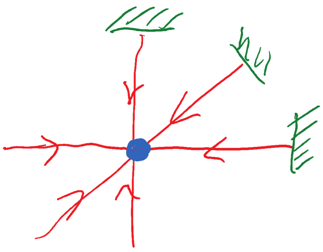
$\hat{=}$ viscous friction



$\Rightarrow$ 1D cooling with 2 lasers

atoms travelling in +z direction feel force in −z direction

3D



6 lasers or
3+ mirrors

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

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

$dT \quad\quad \Gamma \quad\quad\quad \tau_{cool}$

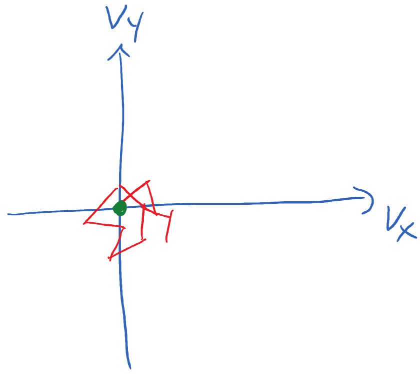
$\hookrightarrow O(ms)$

leads to $E = 0$ unphysical !

Heating processes $\rightarrow$ Doppler cooling limit

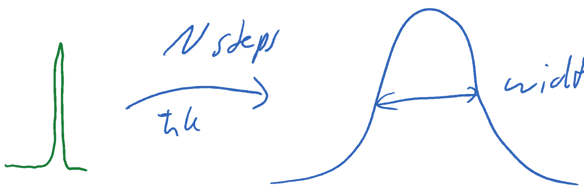
photon scattering is a stochastic process
+ discrete momentum kicks
$\rightarrow$ scattering force fluctuates

e.g. 2D



N steps, each $\hbar k$ long

Random walk



width $\propto \sqrt{N} \cdot \hbar k$

$\vdots$

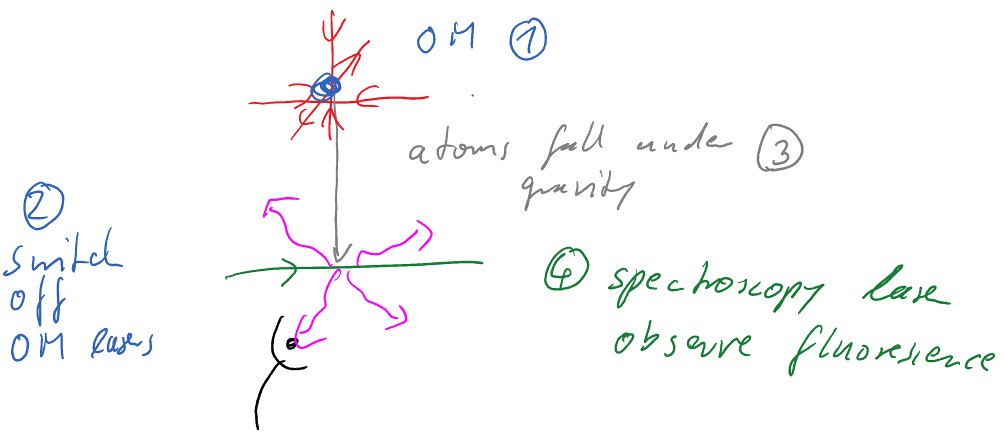
equilibrium temperature

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

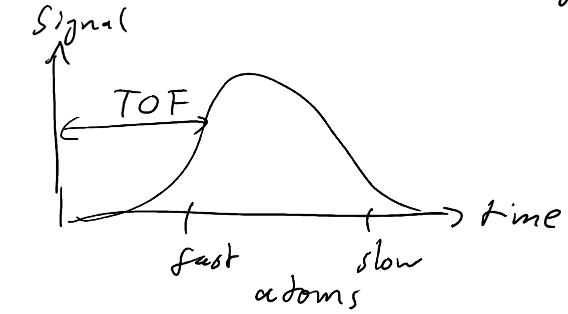
has a minimum at $\boxed{\delta = -\frac{\Gamma}{2}}$ optimal detuning

$$\Rightarrow k_B T_{Doppler} = \frac{\hbar k}{2} \quad \text{Doppler cooling limit}$$

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



Detector observes Time-of-flight TOF



Cooling of this order could be achieved quite quickly. When a photon of momentum $h\nu/c$ is scattered by an atom of mass M, moving towards it with a velocity v, the average change in velocity is

$$\Delta V = \frac{\Delta(Mv)}{M} = \frac{h\nu}{Mc}.$$

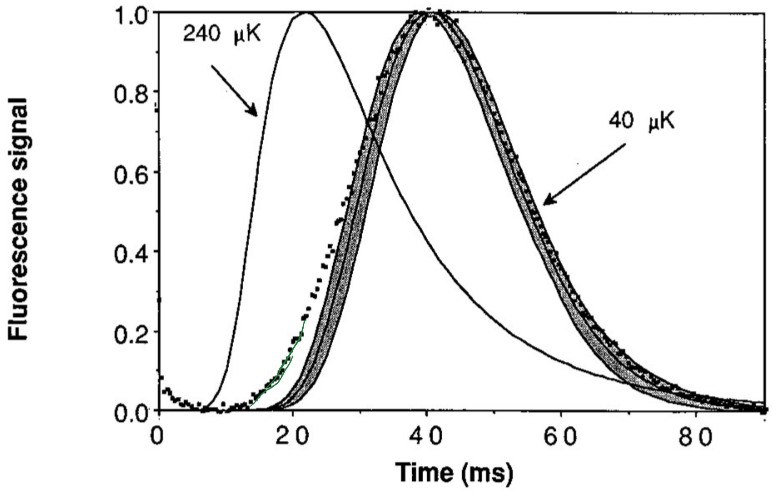


FIG. 16. The experimental TOF distribution (points) and the predicted distribution curves for 40 μK and 240 μK (the predicted lower limit of Doppler cooling). The band around the 40 μK curve reflects the uncertainty in the measurement of the geometry of the molasses and probe.

atoms are colder than expected

Sub-Doppler cooling

(Sisyphus cooling)

Dalibard, Cohen-Tannoudji J. Opt. Soc. Am. B6, 2023

(1989)

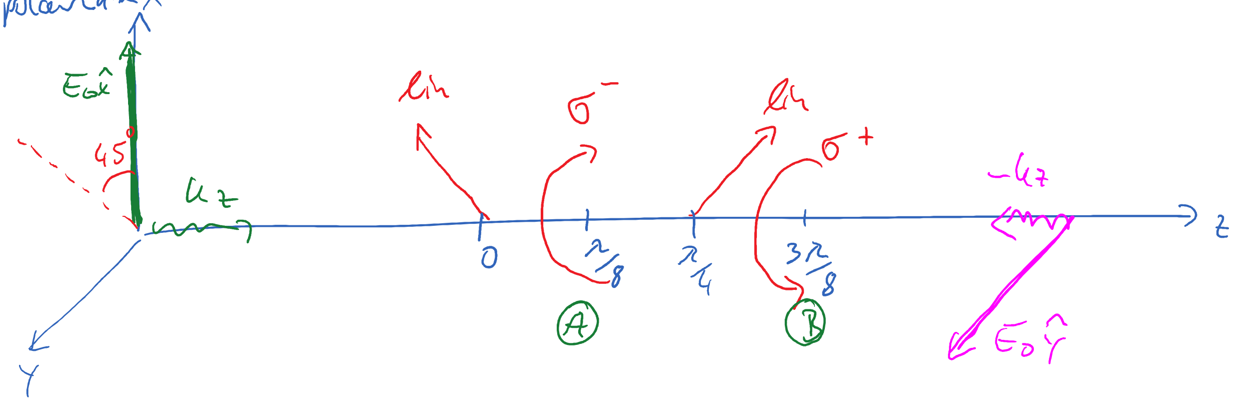
"lin perp. lin"

lin ⊥ lin polarization gradient cooling

2 lasers ↑↓, lin. pol., ⊥ to each other

$$\vec{E} = \underbrace{E_0 \hat{x} \cos(\omega_L t - k z)}_{\text{runs pos. z-direction}} + \underbrace{E_0 \hat{y} \cos(\omega_L t + k z)}_{\text{neg. z. dir.}}$$

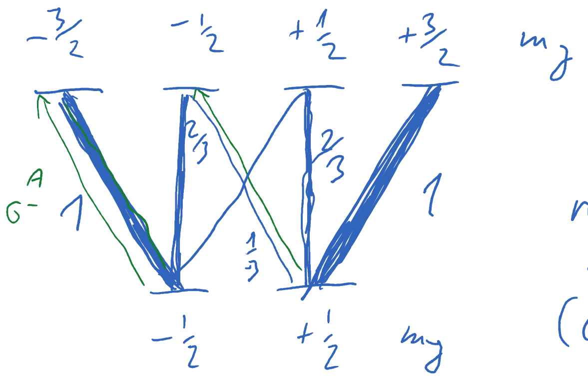
① standing wave & polarization



② atom (example)

$|e\rangle$ $J = \frac{3}{2}$

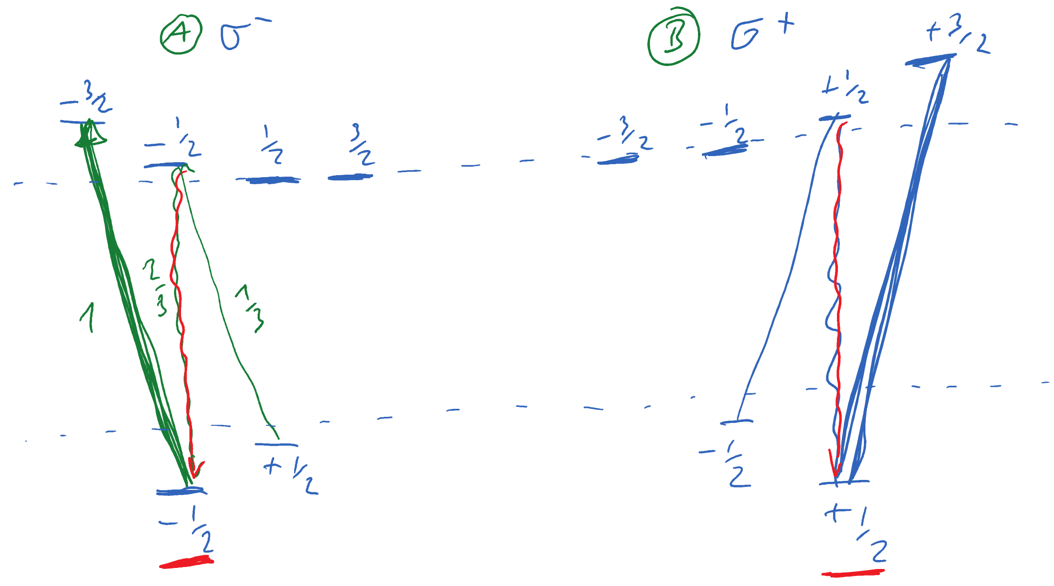
$|g\rangle$ $J = \frac{1}{2}$



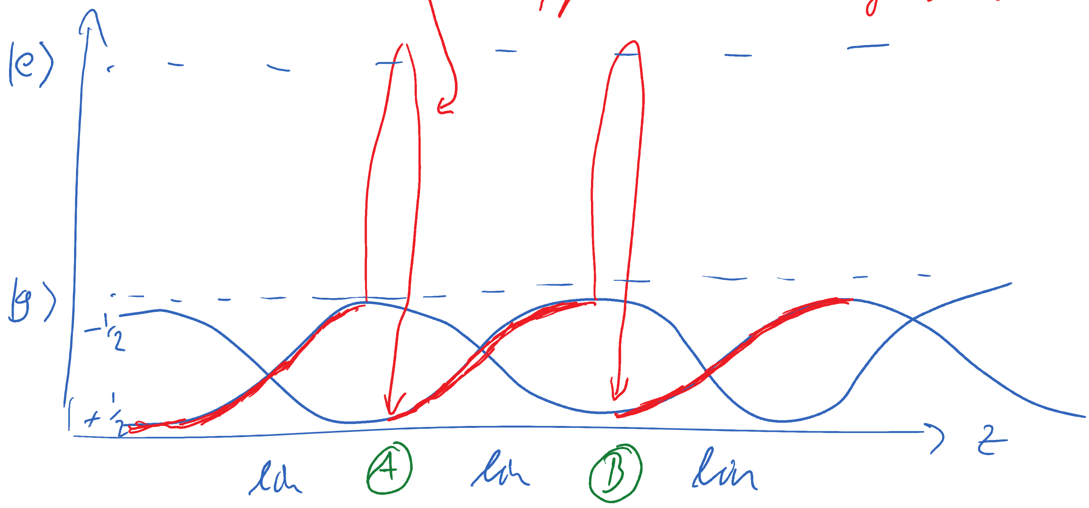
rel. line strengths (Clebsch-Gordan)

③ AC Stark shift

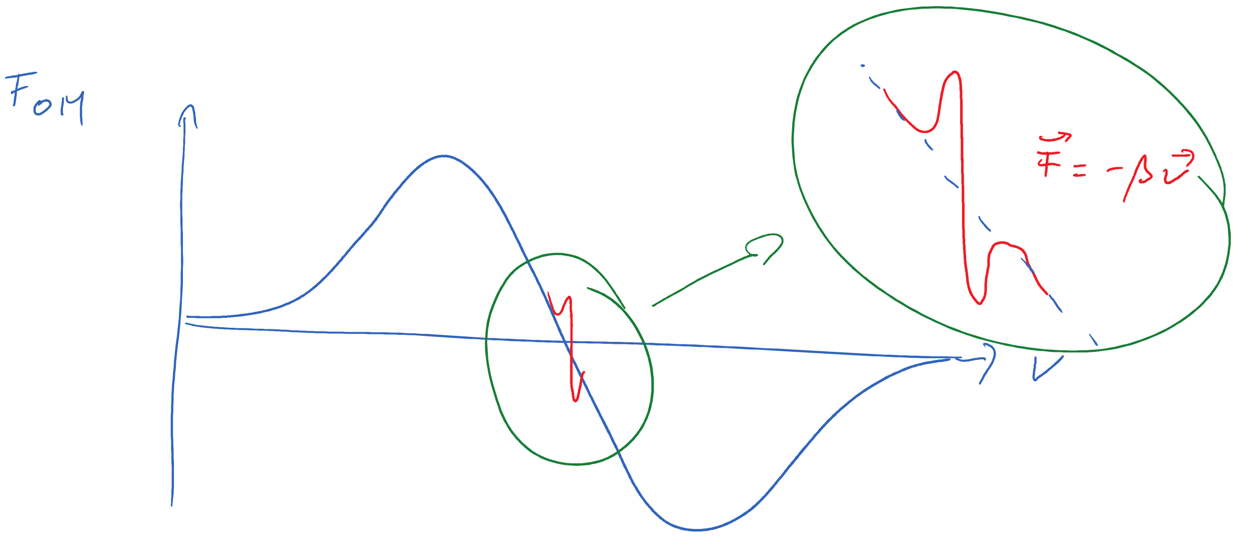
∝ line strength



Fluorescence always goes to the lower state
Sisyphos' rock → falls down



atoms are always moving uphill
→ loss of k.e.



None of this is a trap!
$\vec{\text{Force}} = -\beta \vec{v}$

no restoring force $\propto -r$ pos. dependent
↳ this is what you need to trap

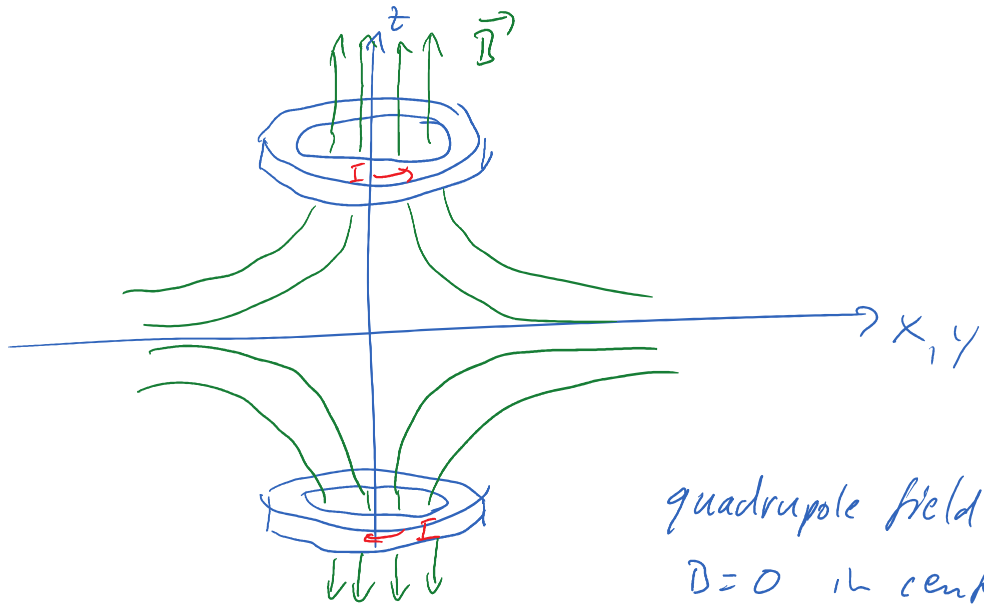
MOT: Magneto-optical trap

Pritchard, Chu PRL 59, 2631 (1987)

6 lasers (OM, Sisyphos)

\+ 2 coils in <u>anti</u> Helmholtz configuration

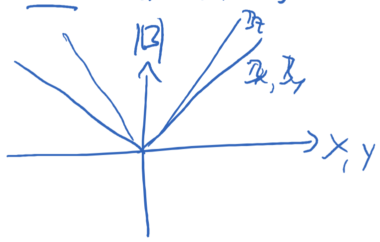
↳ quadrupole field



quadrupole field

$B = 0$ in center

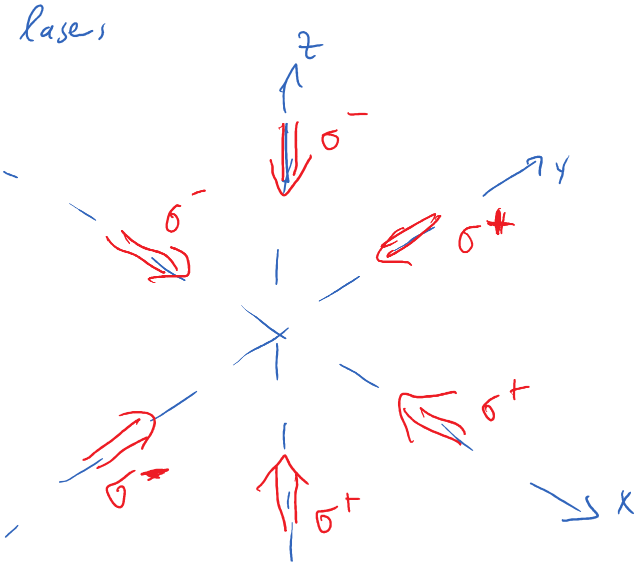
linear increase in <u>all</u> directions



Maxwell $\mathrm{div}\,\vec{B} = 0$

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

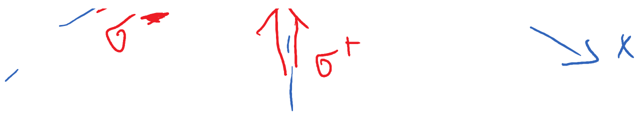
\+ 6 lasers



6 lasers

red detuned

opposite circular polarization



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

$|e\rangle\ J=1 \qquad 3:\ m_J = -1, 0, +1$

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

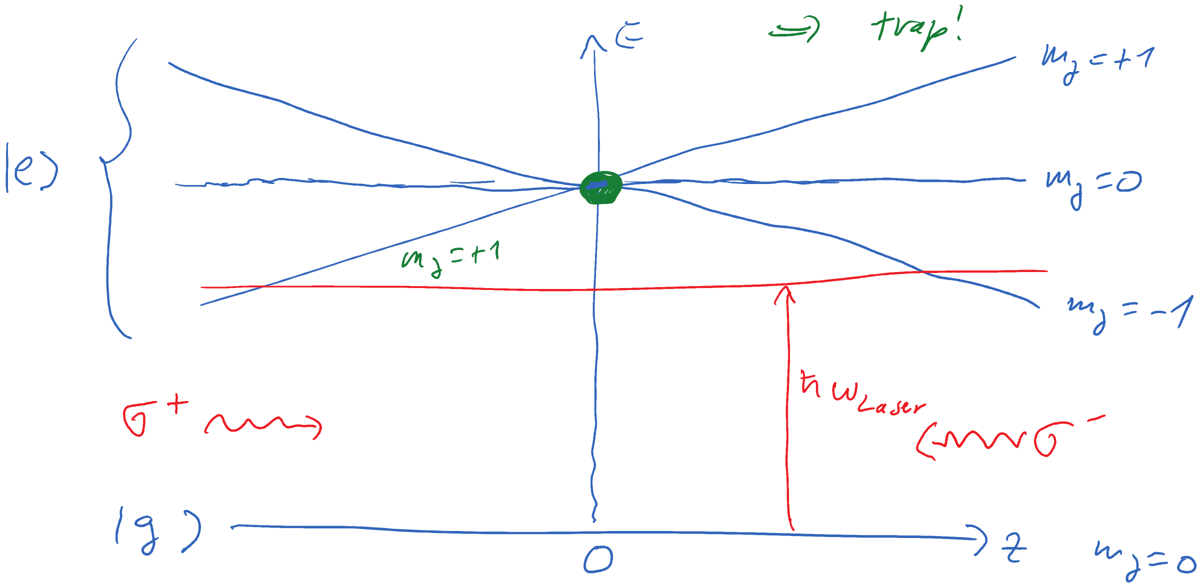
$\underline{B(z) = b \cdot z}$ linear in z

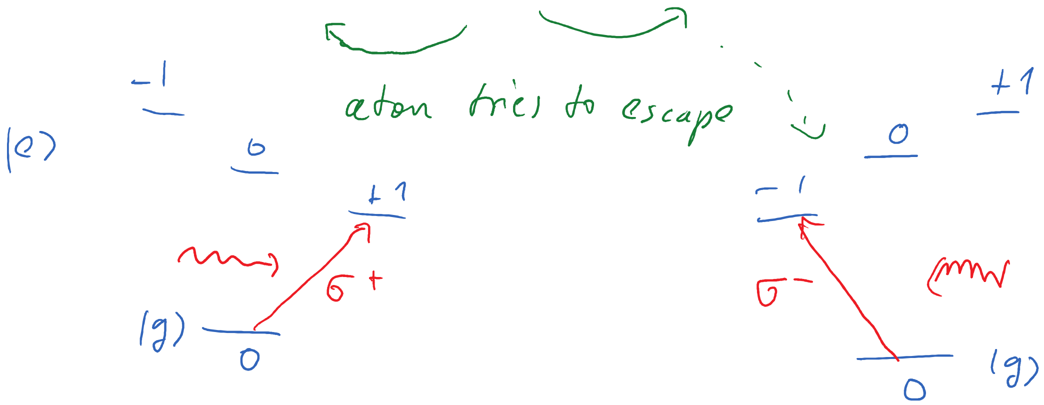
Zeeman splitting $\quad \underline{\Delta E} \propto \mu_B \cdot m_J \cdot \underline{B}$

$= \mu_B \cdot m_J \cdot \underline{b \cdot z}$

level position depends on z position

$\Rightarrow$ trap!





position-dependent restoring force

$\Rightarrow$ trap!

Reality

^{87}Rb