Wednesday, September 30, 2020

Laser cooling below the Doppler cooling limit

Sisyphus cooling

A. Review of optical standing waves

1. counterpropagating identical polarizations (and identical freq

$\vec{E}_{left} = E_0 \cos(kx - \omega t)\hat{y}$ $\qquad$ $\vec{E}_{right} = E_0 \cos(kx + \omega t + \phi)\hat{y}$

ignore [physics does not depend on it]

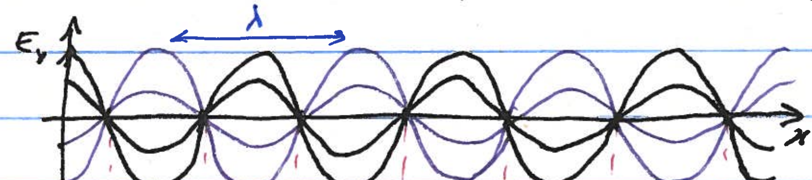
$\vec{E}_{Total} = \vec{E}_{left} + \vec{E}_{right}$

$= E_0 \hat{y} \left[\cos(kx - \omega t) + \cos(kx + \omega t) \right]$

trigonometric identity: $\cos a + \cos b = 2\cos\left(\frac{a+b}{2}\right)\cos\left(\frac{a-b}{2}\right)$

$= E_0 \hat{y} \left[2\cos(kx)\cos(\omega t) \right]$

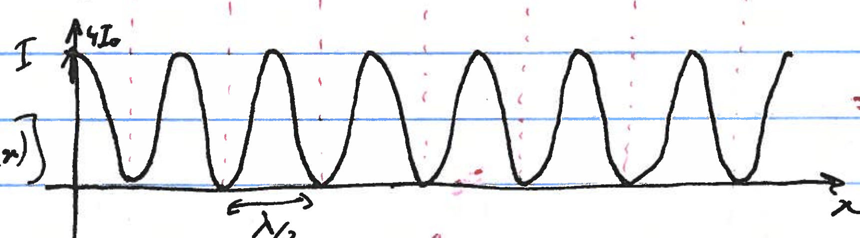
$= 2E_0 \cos(kx)\cos(\omega t)\hat{y} \Rightarrow$ standing wave



$I = 4E_0^2 \epsilon_0 c \cos^2(kx)$

$= 4I_0 \left[\frac{1}{2} + \frac{1}{2}\cos(2kx) \right]$

I_0: intensity of one beam

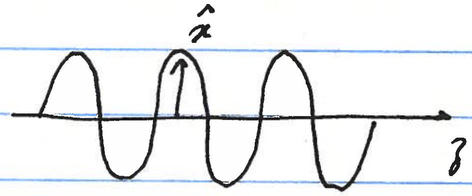


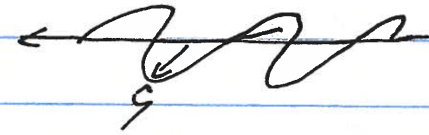
1D optical lattice

$\Rightarrow$ If used as an optical dipole potential, then it is a crystal of light for atoms

2 - Counter propagating perpendicular polarizations

(called "Lin ⊥ Lin" or "Lin-perp-Lin")



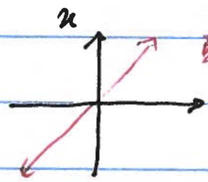


$E_{left} = E_0 \cos(kz - \omega t)\hat{x}$ $E_{right} = E_0 \cos(kz + \omega t \cancel{+ \phi})$ (ignore (again))

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

$$k = \frac{2\pi}{\lambda}$$

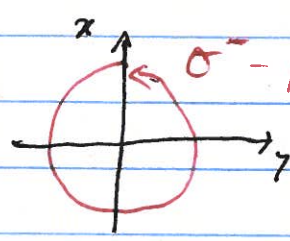
case 1: $kz = 0 \Rightarrow z = 0$ and $\vec{E}_{total} = E_0[\cos(\omega t)\hat{x} + \cos(\omega t)\hat{y}]$



π - polarization at 45°

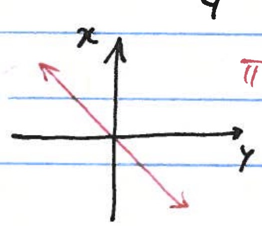
case 2: $kz = \pi/4 \Rightarrow z = \frac{\lambda}{8}$ and $\vec{E}_{Total} = E_0[\cos(\omega t - \pi/4)\hat{x} + \cos(\omega t + \pi/4)\hat{y}]$

time origin shift: $t = t' + \frac{\pi}{4\omega}$ $= E_0[\cos(\omega t')\hat{x} + \cos(\omega t' + \pi/2)\hat{y}]$
$= E_0[\cos(\omega t')\hat{x} - \sin(\omega t')\hat{y}]$



σ^- - polarization

Case 3: $kz = \pi/2 \Rightarrow z = \frac{\lambda}{4}$ and $\vec{E}_{Total} = E_0[\cos(\omega t - \pi/2)\hat{x} + \cos(\omega t + \pi/2)\hat{y}]$
$= E_0[\sin(\omega t)\hat{x} - \sin(\omega t)\hat{y}]$

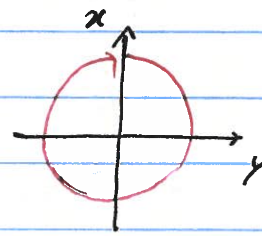


π - polarization at -45°

Case 4: $kz = \frac{3\pi}{4} \Rightarrow z = \frac{3\lambda}{8}$ and $\vec{E}_{total} = E_0\left[\cos(\omega t - 3\pi/4)\hat{x} + \cos(\omega t + 3\pi/4)\hat{y}\right]$

time origin shift: $t = t' + \frac{3\pi}{4\omega}$

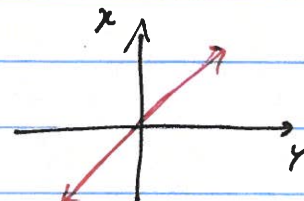
$$= E_0\left[\cos(\omega t')\hat{x} + \cos\left(\omega t' + \frac{3\pi}{2}\right)\hat{y}\right]$$
$$= E_0\left[\cos(\omega t')\hat{x} + \sin(\omega t')\hat{y}\right]$$



σ^+ – polarization

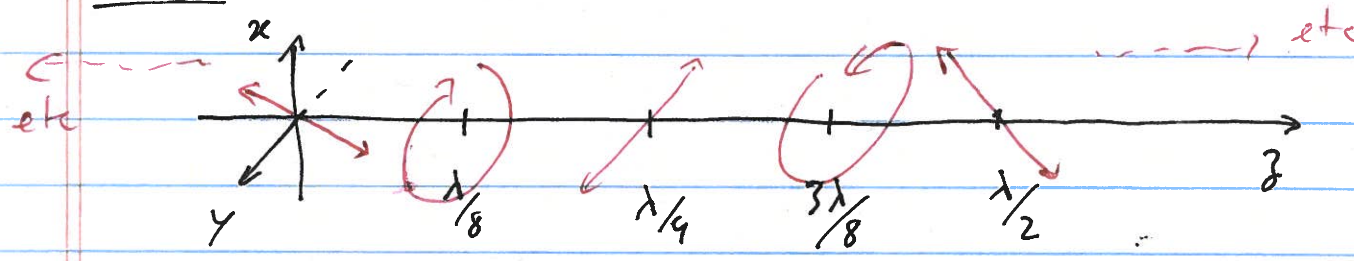
Case 5: $kz = \pi$, $z = \lambda/2$ and $\vec{E}_{Total} = E_0\left[\cos(\omega t - \pi)\hat{x} + \cos(\omega t + \pi)\hat{y}\right]$

$$= -E_0\left[\cos(\omega t)\hat{x} + \cos(\omega t)\hat{y}\right]$$



π – polarization at 45° (or 225°)

Summary:



We get a standing wave but with a periodic gradient in the polarization

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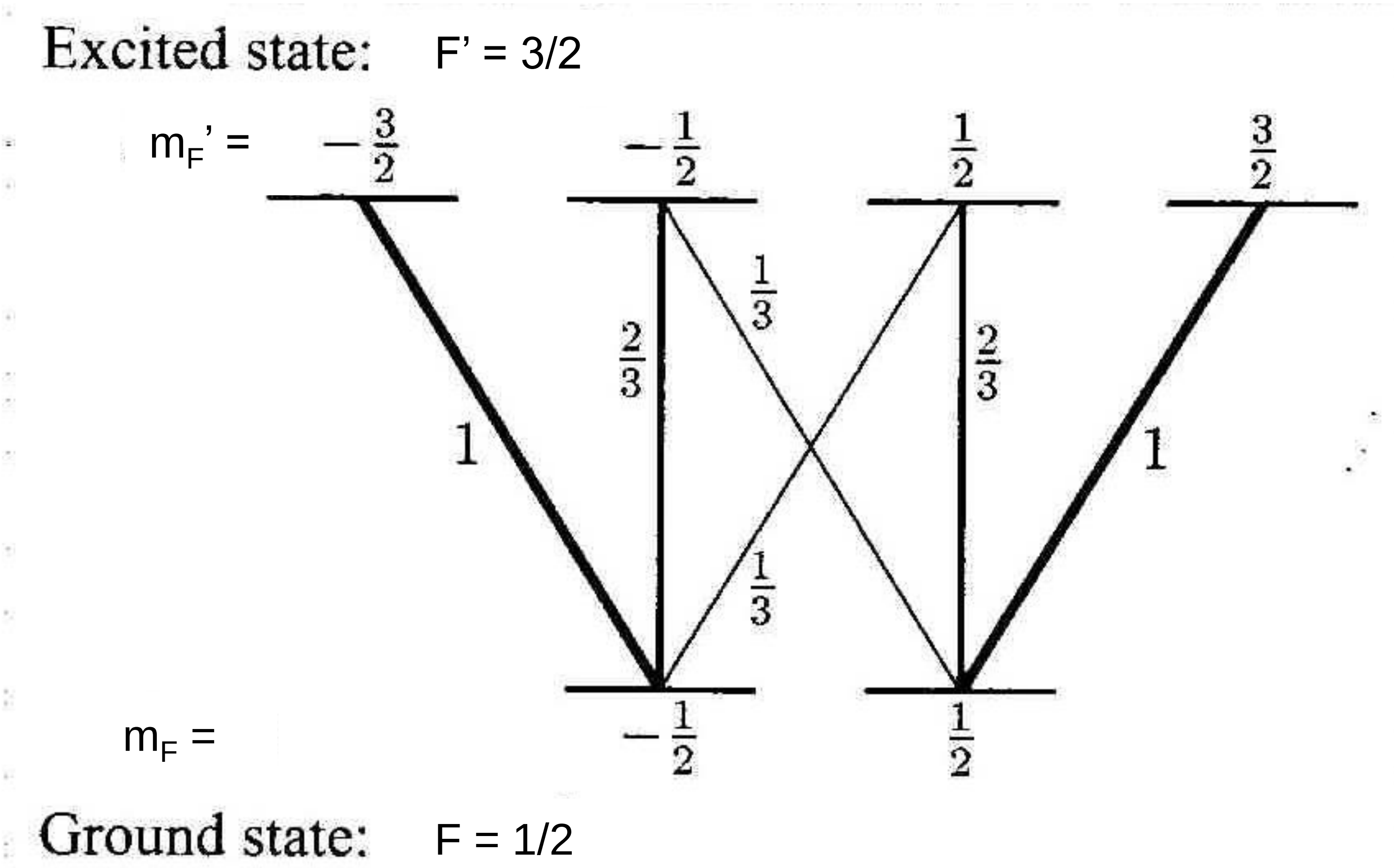
Sysiphus cooling temperature $kT_{sisyphus}\Big|_{theory} \simeq \frac{(\hbar k)^2}{2m} \gtrsim \Delta E_{stark}$

$^{87}Rb \to T = 370\,nK$

$kT_{sisyphus}\Big|_{practical} \simeq 10 \text{ – } 100 \; kT_{sisyphus}\Big|_{theory}$

Multi-level atom

Consider an atom with:
- F=1/2 in ground level.
- F'=3/2 in excited level.



[figure adapted from *Atomic Physics* by C. Foot, Oxford U. Press (2006)]

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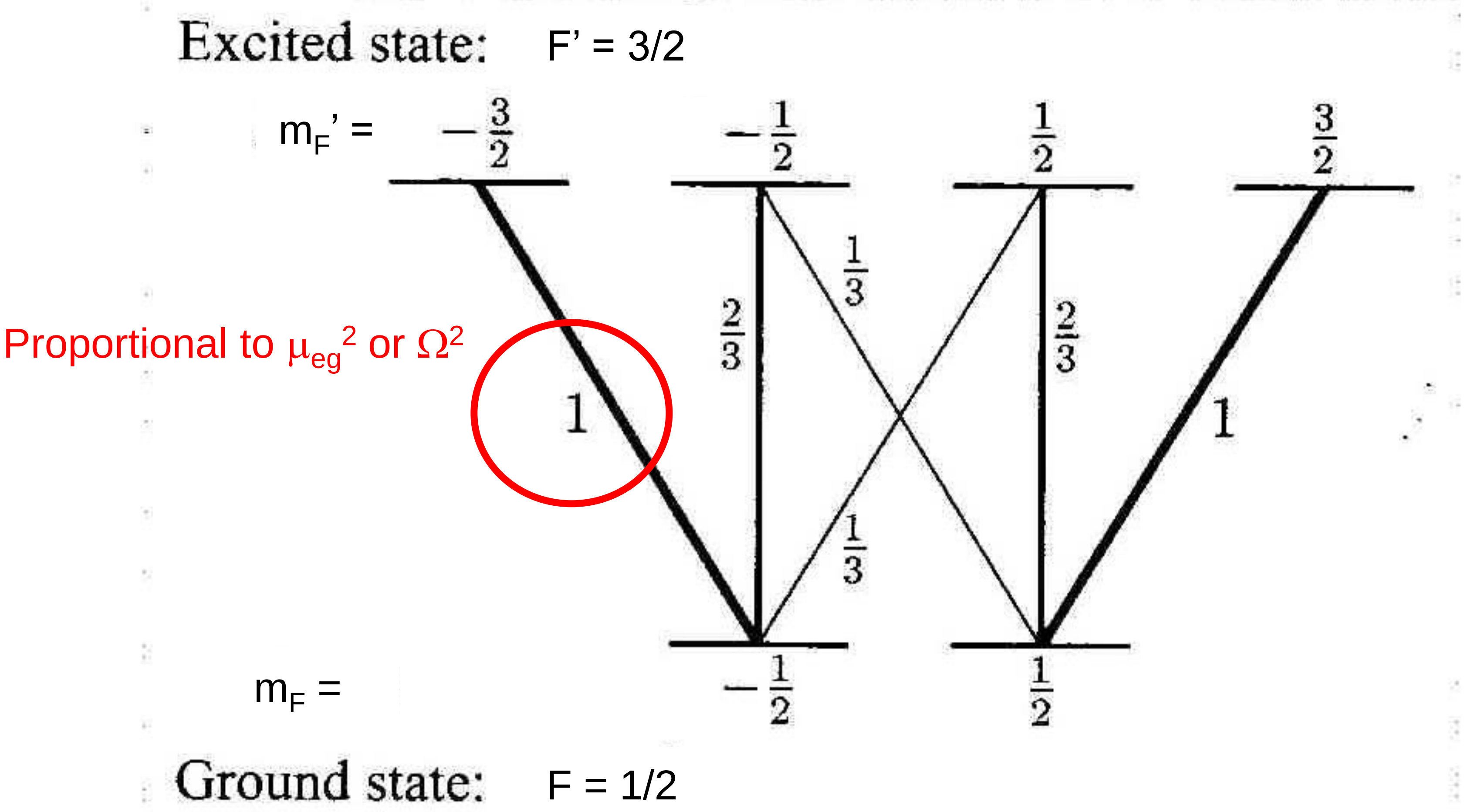

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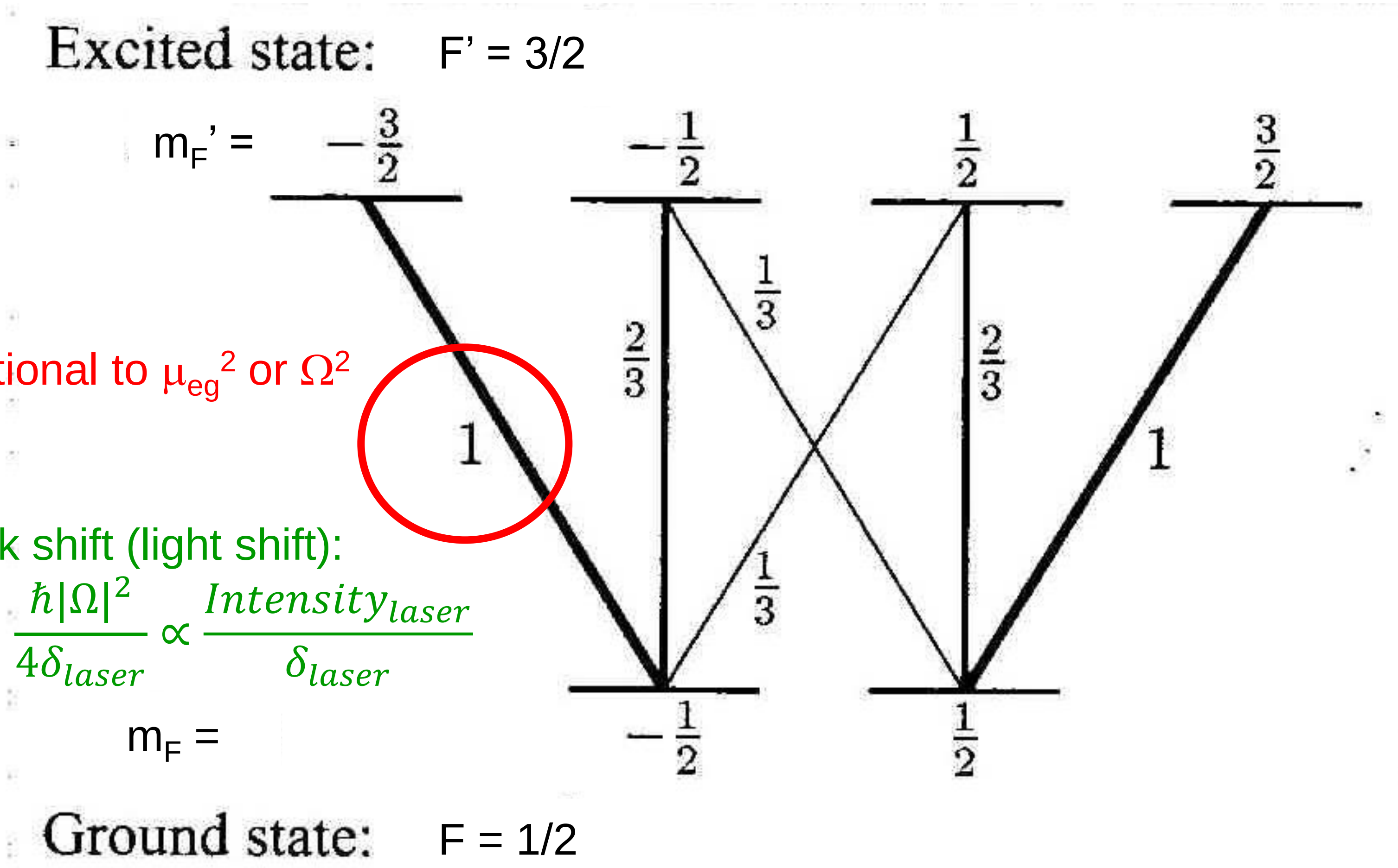
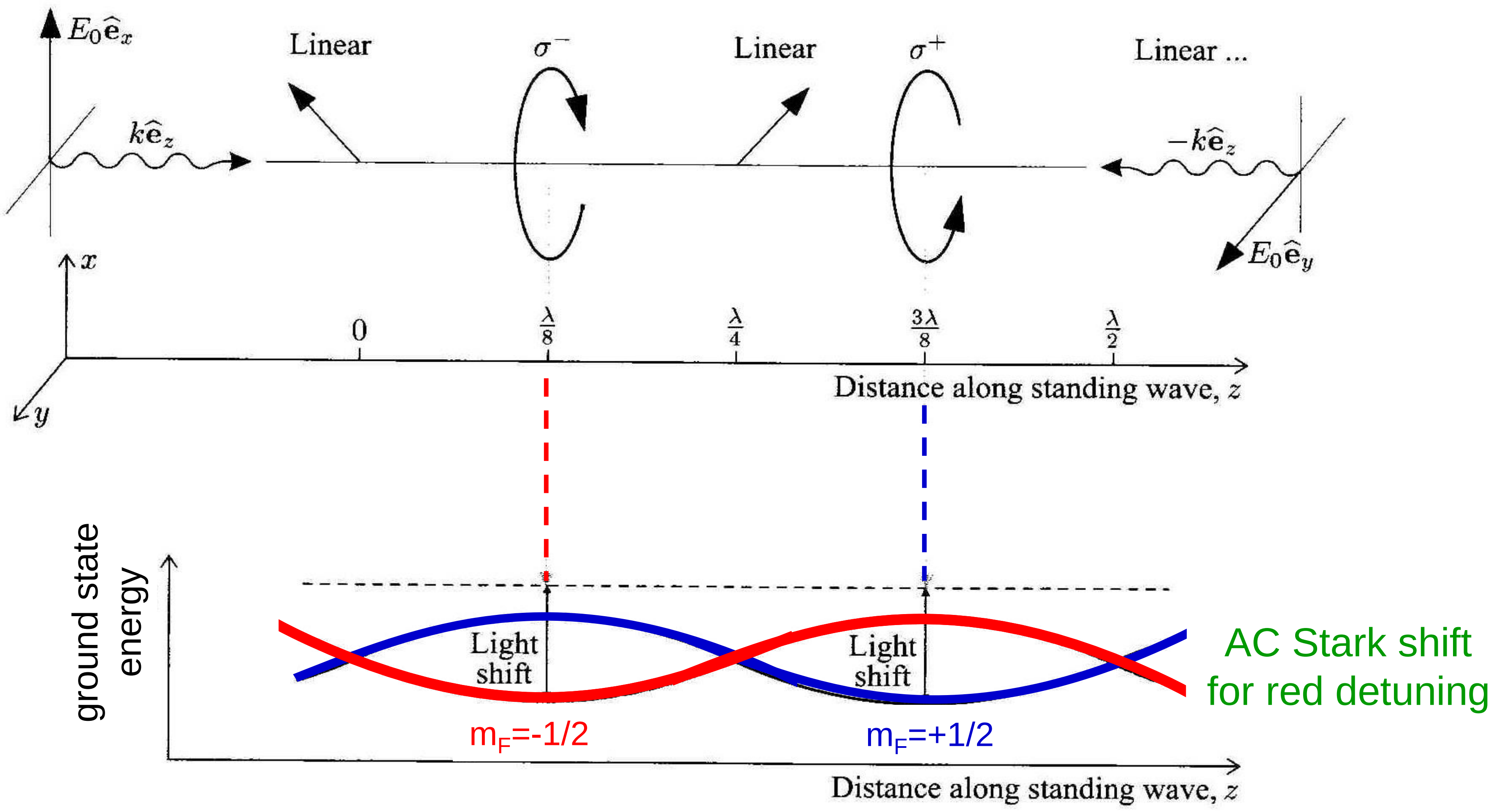


AC Stark shift (light shift):

$$\Delta E_{AC} = \frac{\hbar|\Omega|^2}{4\delta_{laser}} \propto \frac{Intensity_{laser}}{\delta_{laser}}$$

[figure adapted from *Atomic Physics* by C. Foot, Oxford U. Press (2006)]

AC Stark Shift in Polarization Gradient Lattice



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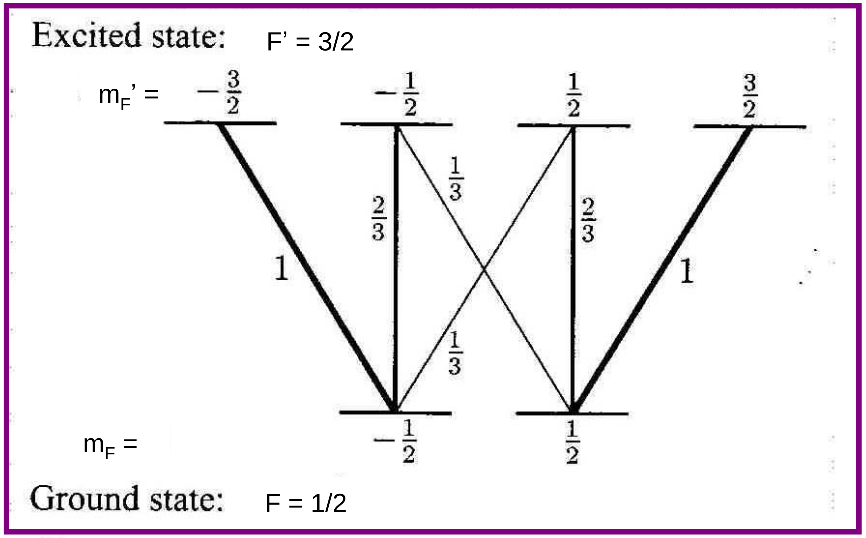
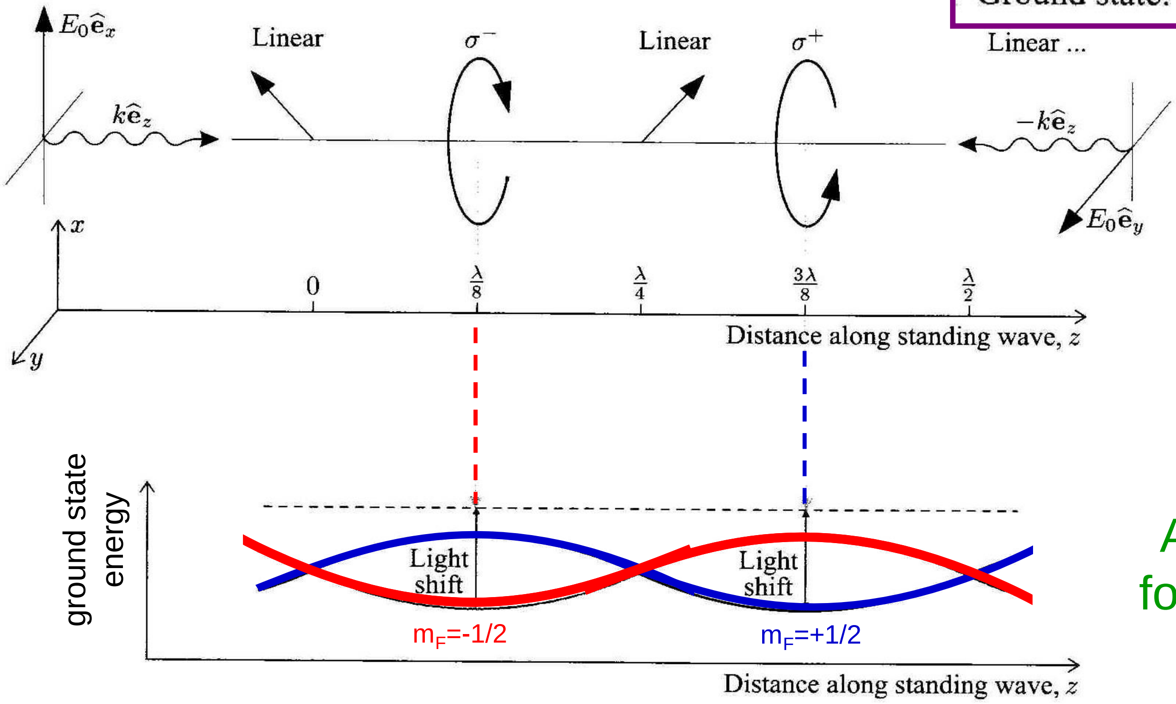
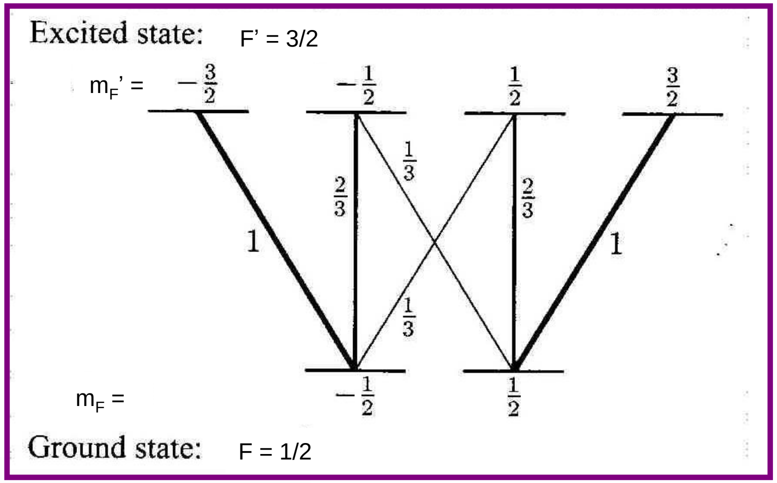


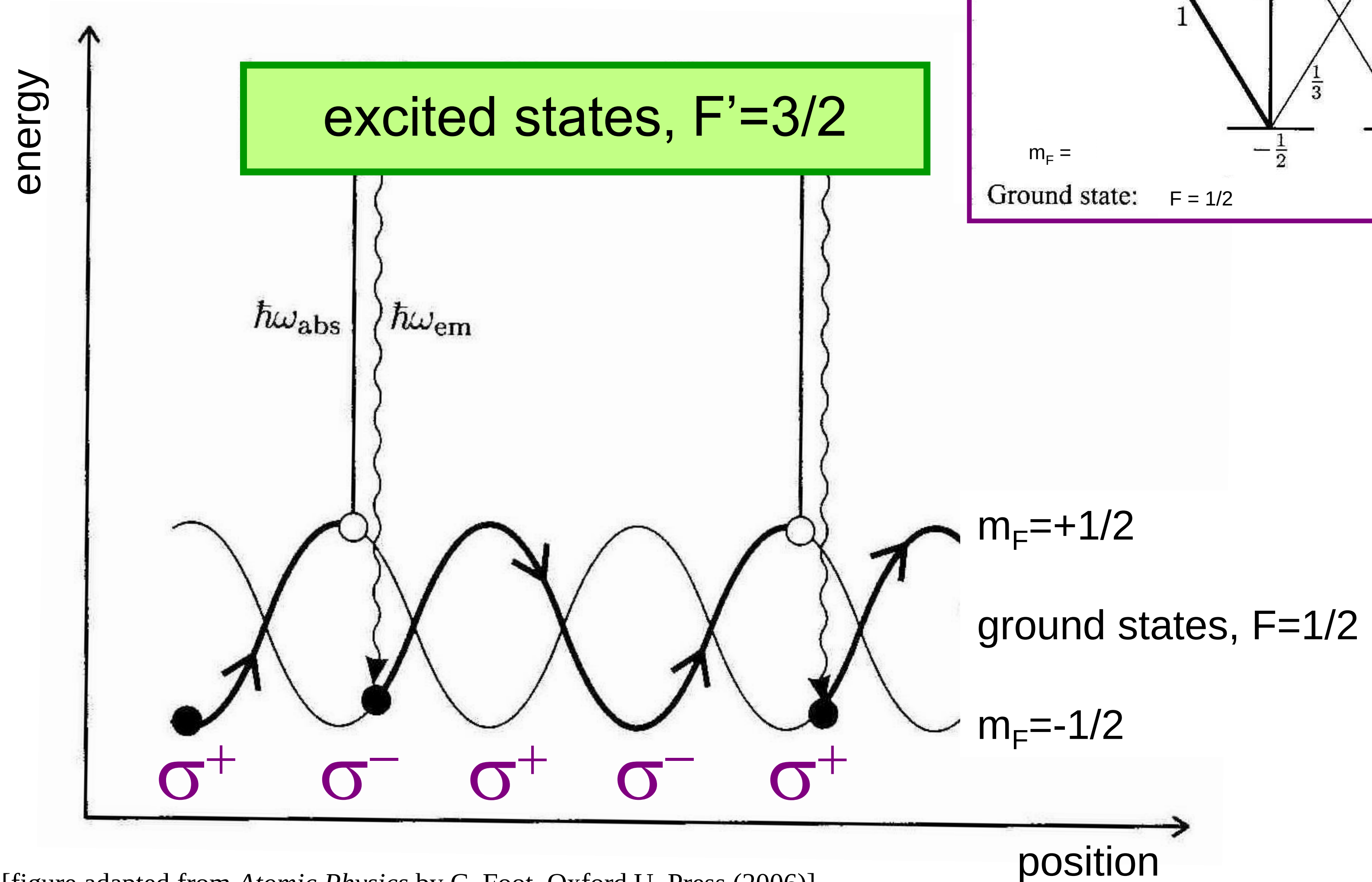


AC Stark shift
for red detuning

[figure adapted from *Atomic Physics* by C. Foot, Oxford U. Press (2006)]

Sisyphus Cooling





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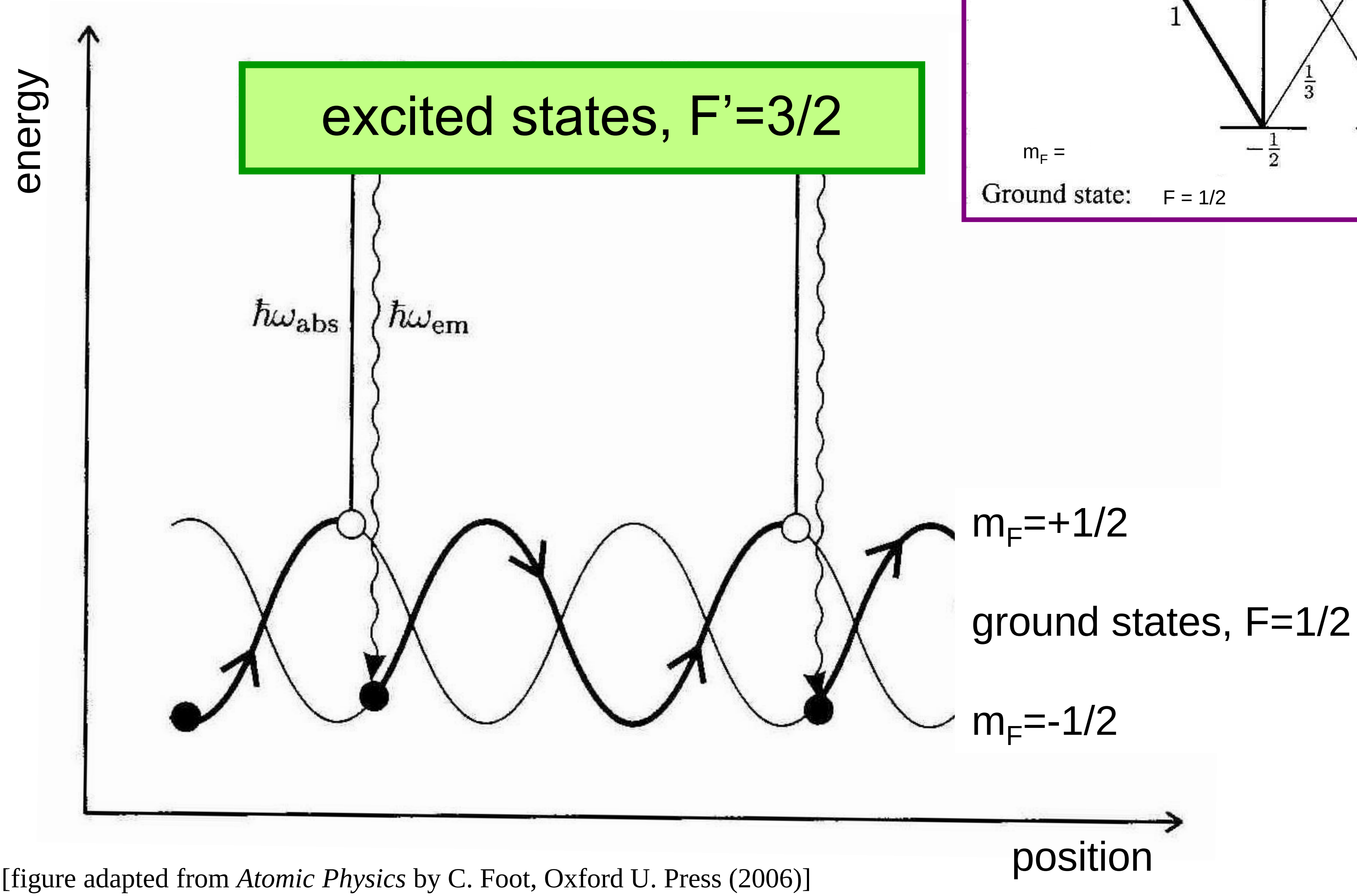
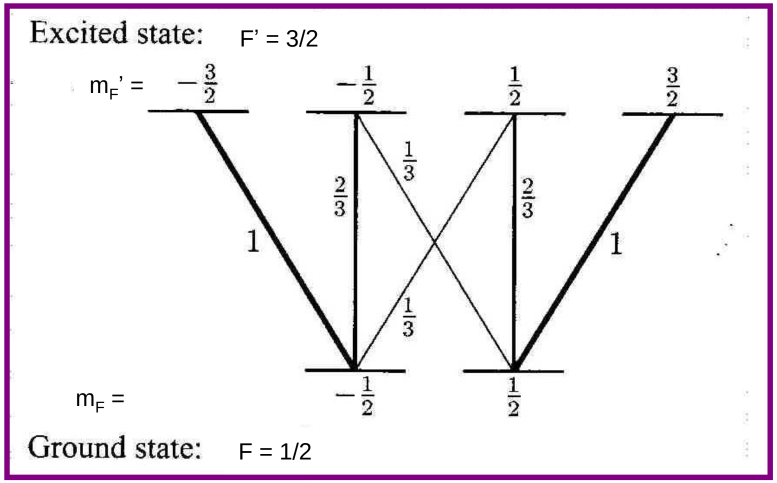
Sisyphus Cooling

Atoms that are excited at the top of a **hill** are most likely to decay to **valley**.





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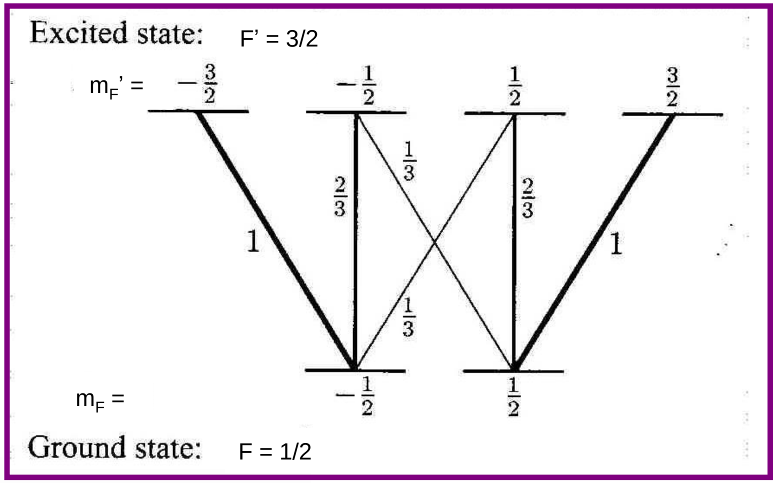
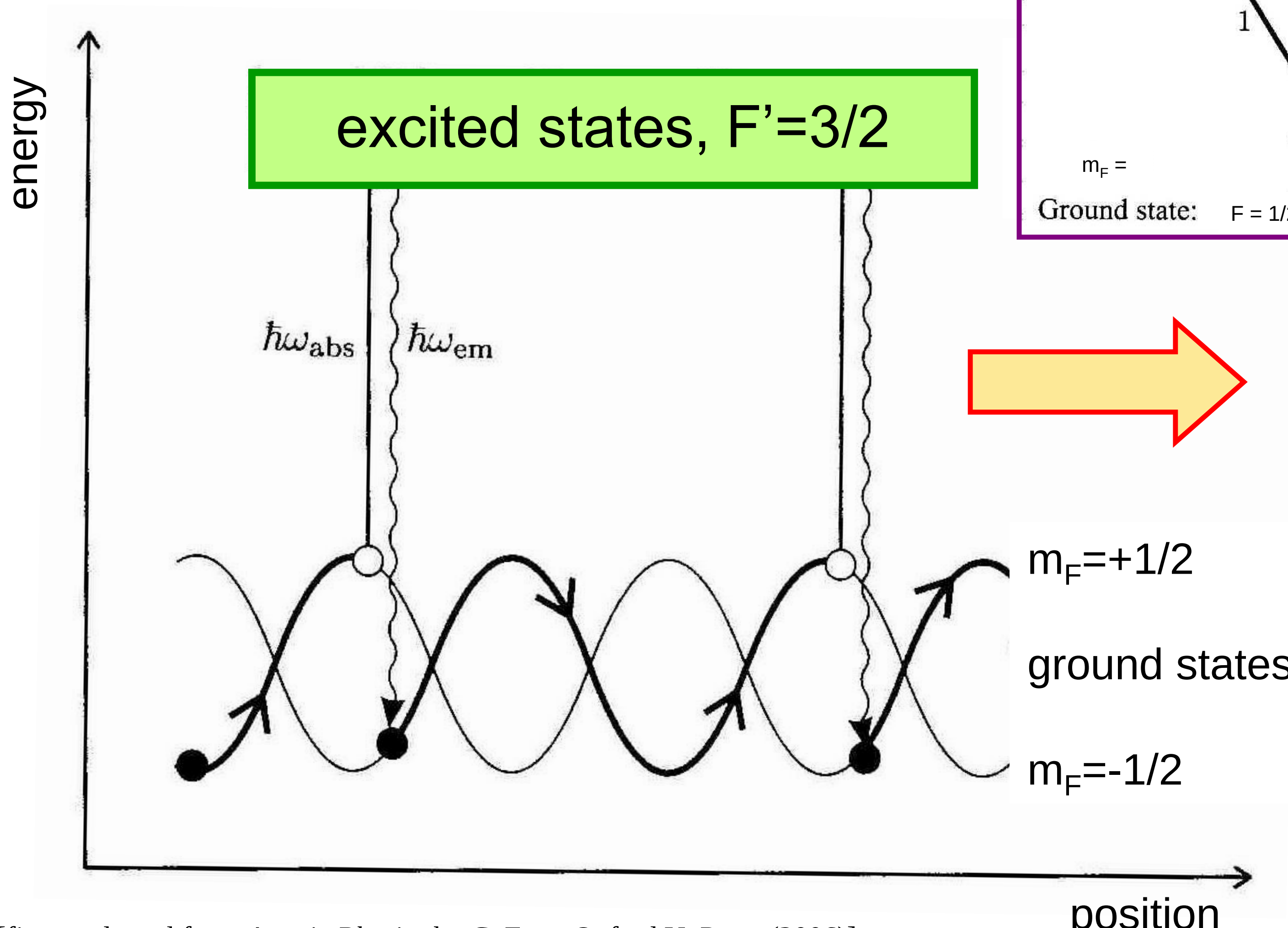


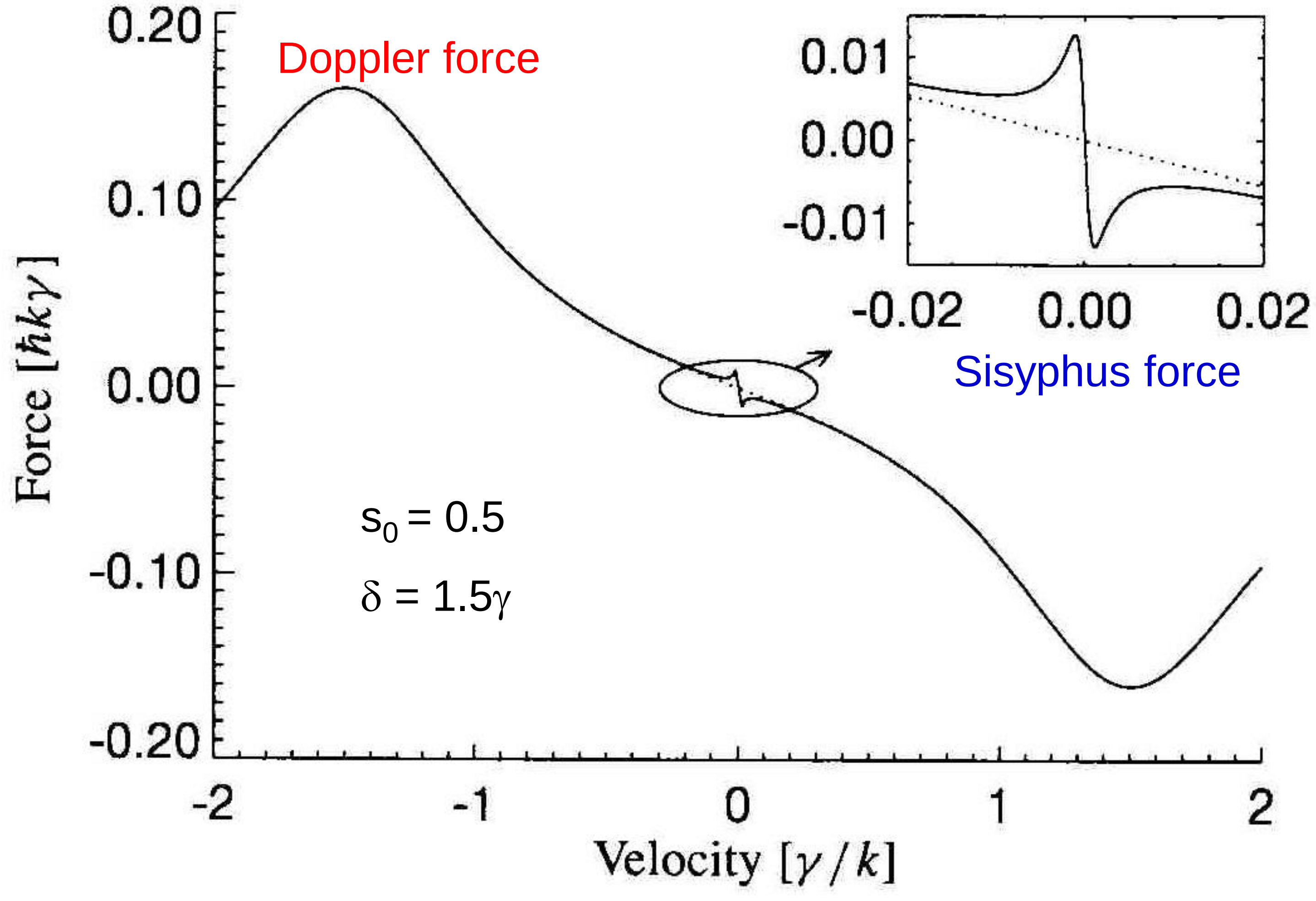


Atoms travel **uphill** most of the time

→ cooling

[figure adapted from *Atomic Physics* by C. Foot, Oxford U. Press (2006)]

Cooling Force (Doppler + Sisyphus)



[figure adapted from *Laser Cooling and Trapping* by H. Metcalf and P. van der Straten, Springer (1999)]

There are no 2-level atoms and cesium isn’t one of them !!!

Attributed to Bill Phillips
Nobel Prize in Physics (1997) for laser cooling

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Take-Home Message

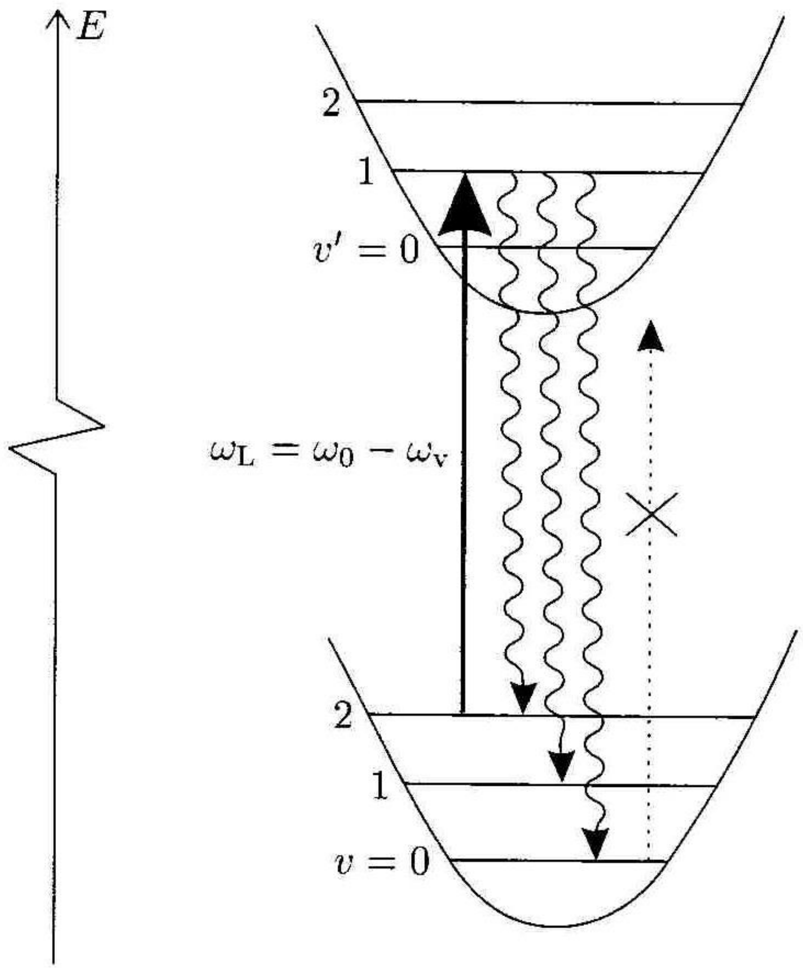
More levels = More complicated

= More ways to get colder

Resolved Sideband Cooling

(or how to use <u>external</u> energy levels to get colder)

Resolved Sideband Cooling



<u>Generally used with ion traps</u>

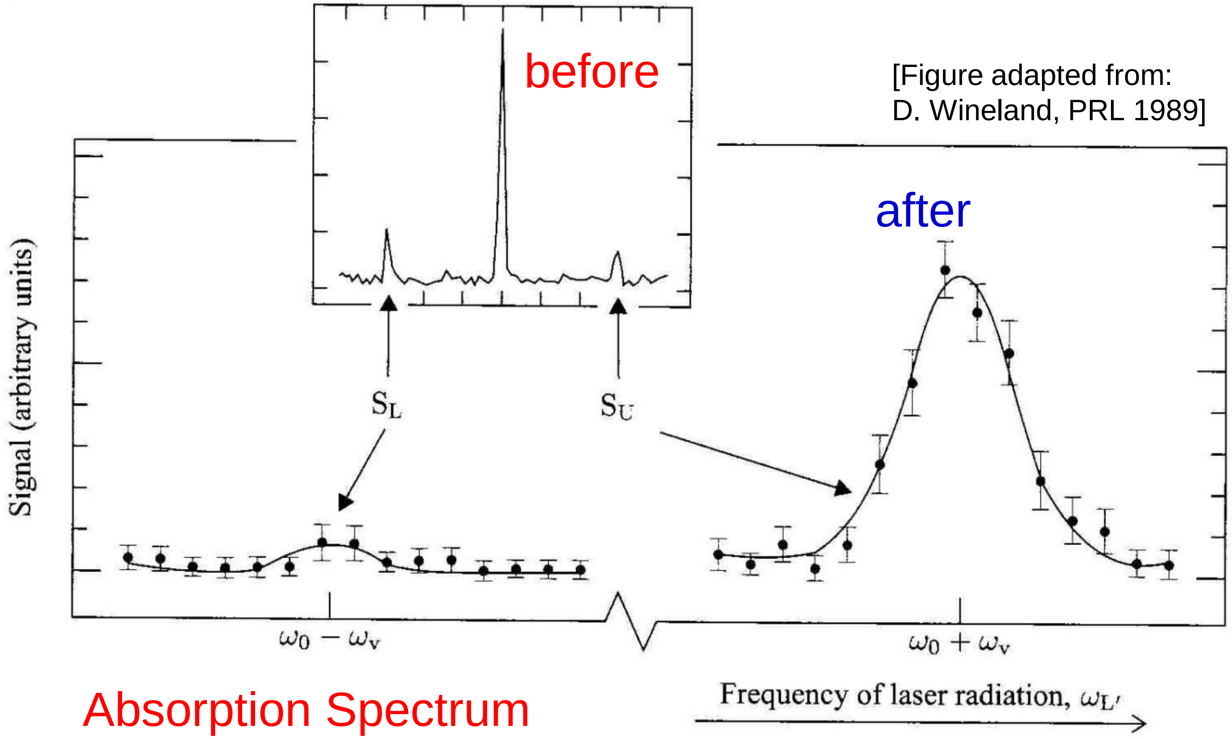
- trapping frequency large (MHz)
- scattering rate small (kHz)
  (i.e. long lifetime)
- i.e. $\omega_v >> \gamma$

[This technique can be implemented with neutral atoms, but it is difficult: *Raman Sideband Cooling.*]

Atoms accumulate in lowest trap vibrational state !!!

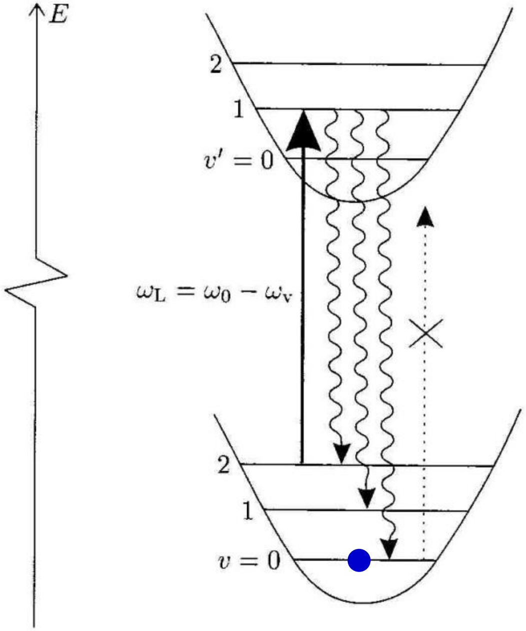
[figure adapted from *Atomic Physics* by C. Foot, Oxford U. Press (2006)]

Resolved Sideband Cooling (Proof)



[Figure adapted from:
D. Wineland, PRL 1989]

Absorption Spectrum



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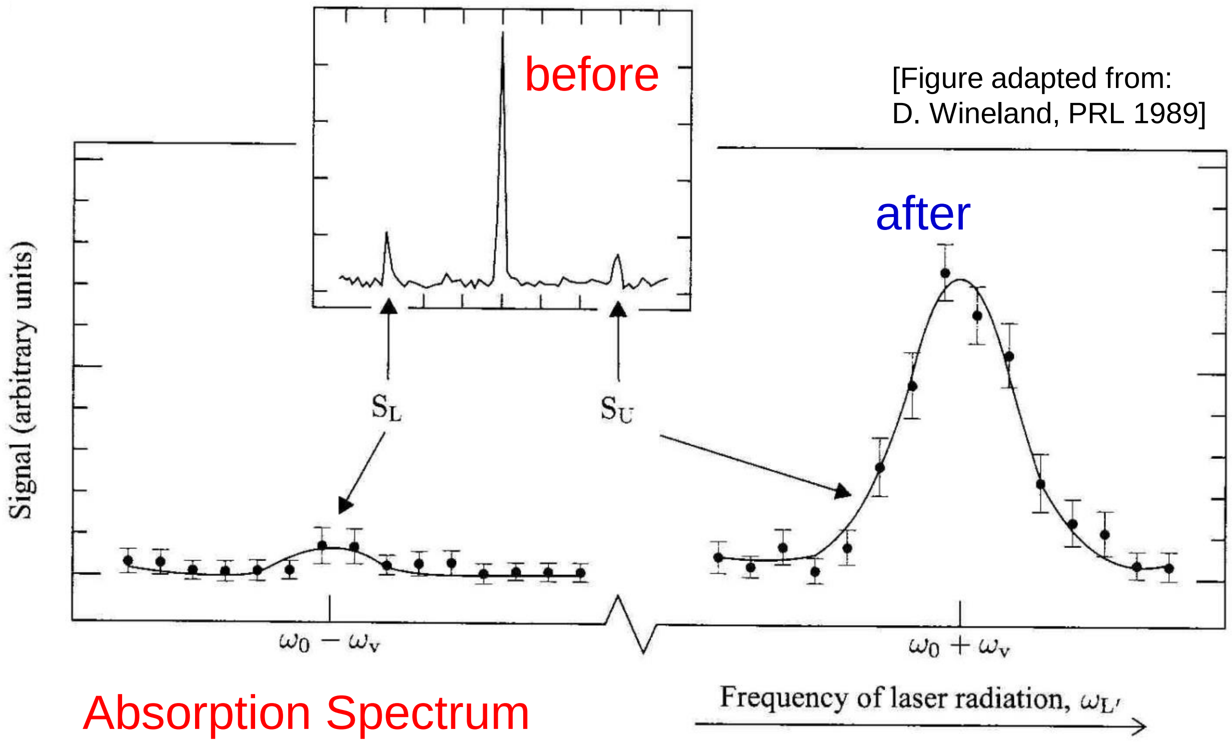

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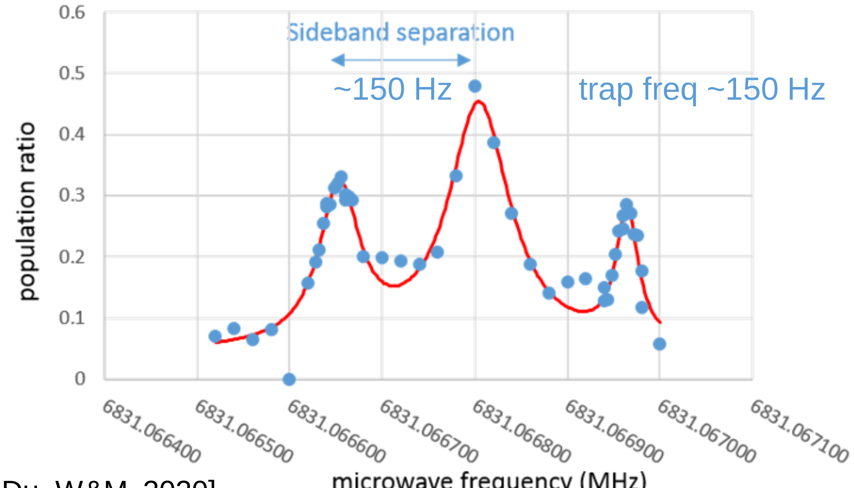

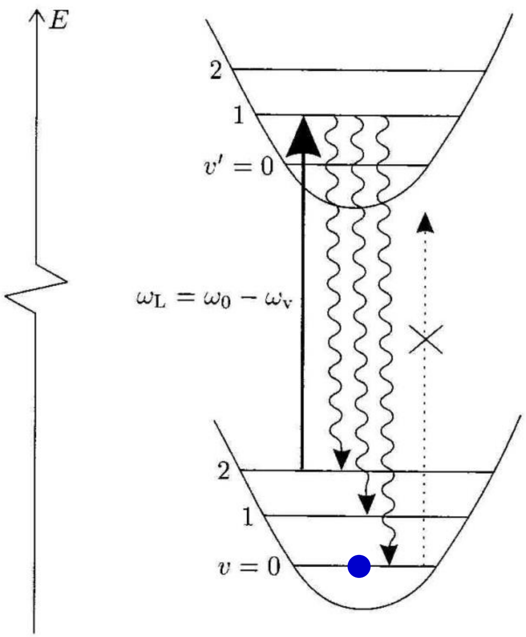

[data: Shuangli Du, W&M, 2020]