Laser cooling and trapping

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University of Maryland 1856

Joint
Quantum
Institute

Why Cool and Trap Atoms?

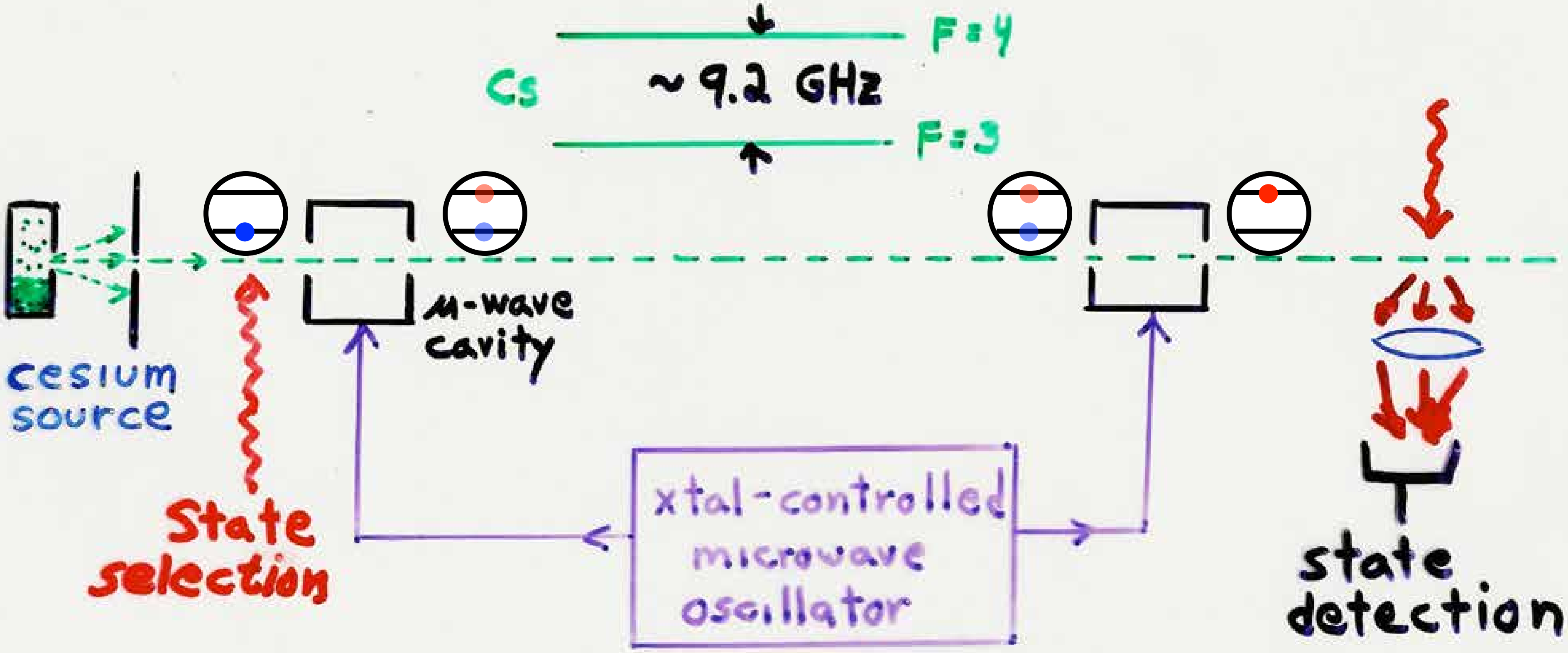
Original motivation and most practical current application:

ATOMIC CLOCKS

Current scientific activity:

A new field of cold-atom physics, including a lot of work in quantum degenerate gases with connections to condensed matter physics, and quantum information Generally, cold atoms provide new quantum systems with new possibilities: Much if not most of current AMO physics uses cold atoms in some way.

Atomic Clock: Ramsey separated oscillatory fields



resonance width $\sim \frac{1}{T_{transit}}$

1st and 2nd-order Doppler effects limit performance

Best clocks (e.g. NIST-7): accuracy $< 10^{-14}$

Motional Effects

Observation time: Ramsey linewidth of $\Delta\nu = 1/2T$ gives about 100 Hz width for a meter between Ramsey zones. 10^{-14} resolution requires splitting the line to 10^{-6}.

1st-order Doppler: $\Delta\nu/\nu = (v/c)$; for typical thermal velocities v of a few 100 m/s, this is about 10^{-6}, a disaster if not compensated. Doppler "free" techniques are essential, but residual effects remain.

2nd-order Doppler: $\Delta\nu/\nu = (1/2)\,(v/c)^2$; this is typically parts in 10^{13}, and there is no "2nd-order Doppler-free" technique--the shift must be evaluated and corrected.

These issues were among those motivating laser cooling for clocks.

Cooling and Trapping Atoms

Laser cooling: reducing the velocity spread of a thermal gas of atoms

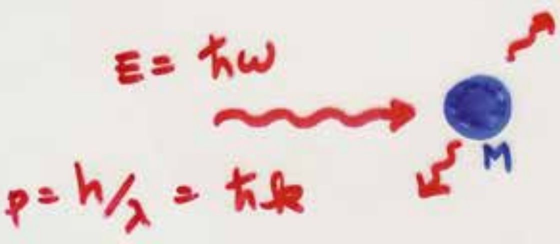
Electromagnetic trapping: confining atoms using laser or other electromagnetic (usually magnetic) fields

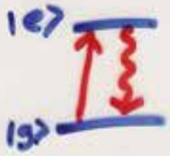
Note that “ordinary cooling” i.e., contact refrigeration, doesn’t generally work because gases condense or stick at temperatures too high to be useful.

Radiative Forces

(Mechanical effects of light)

Scattering force (spontaneous force, radiation pressure, ..)

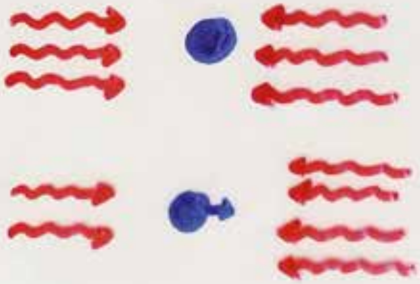




$$\langle \vec{F} \rangle = \hbar \vec{k} \, R_{scatt}$$

(spontaneous emissions average to zero)

Dipole force (stimulated force, gradient force, ...)



Force results from a coherent redistribution of photons among the laser fields

Note:

The division of forces into “scattering” and “dipole” is usually quite clear. Nevertheless, there are some cases that are ambiguous in that they can be viewed as arising from either.

Scattering of light by a 2-level atom:

$\langle \vec{F} \rangle = R \hbar \vec{k}$

photon scattering rate

Power-broadened, Lorentz line shape

$$\mathcal{R} = \frac{\Gamma}{2} \frac{I/I_0}{1 + I/I_0 + \left(2\delta/\Gamma\right)^2}$$

Γ = decay rate of excited atom = ***FWHM***

$\delta = \omega - \omega_0$, detuning from resonance

$\omega_0 = (E_e - E_g)/\hbar$

I_0 = saturation intensity of incident light

$$I/I_0 = \frac{2\Omega^2}{\Gamma^2}$$

Ω = Rabi frequency

Rabi frequency = rate of oscillation between ground and excited states when $\delta = 0$, $\Gamma \rightarrow 0$.

An aside:

There are more than one definition of "saturation intensity." Our choice:

$$I/I_0 = 2\Omega^2/\Gamma^2$$

takes it to be the intensity at which the natural decay and the power broadening contribute equally to the linewidth. Another common choice is:

$$I/I_{sat} = \Omega^2/\Gamma^2$$

One view of the Dipole Force:

Dipole Energy

$$W = -\vec{\mu} \cdot \vec{E}$$

$$\vec{E} = \vec{E}_0(\vec{r}) \cos(\omega t)$$

$$\vec{\mu}(t) = e x(t)$$

Assume a harmonically bound charge:

$$\ddot{x} + \omega_0^2 x = \frac{e}{m} E_0 \cos(\omega t)$$

soln: $$x(t) \propto \frac{E_0}{\omega_0^2 - \omega^2} \cos(\omega t)$$

For $\omega < \omega_0$ $W \sim -E_0^2$

(attraction to high intensity)

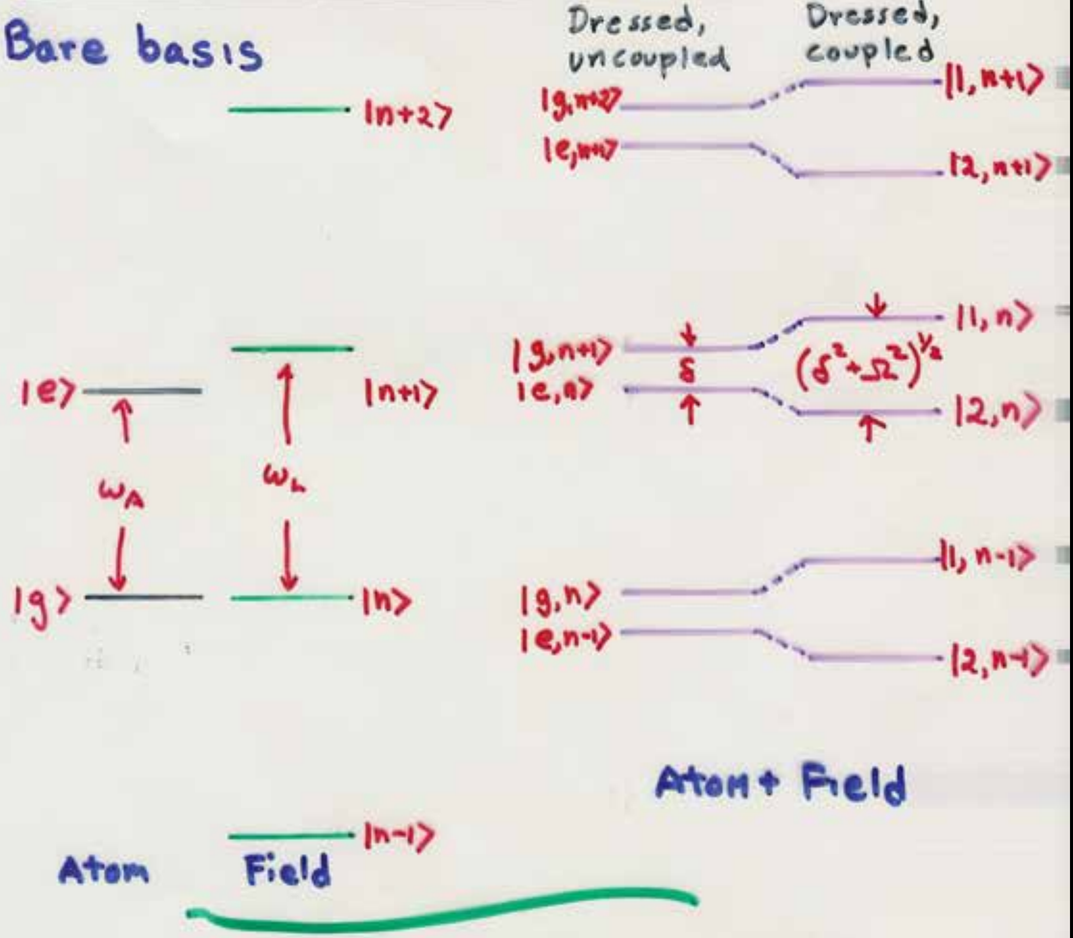
For $\omega > \omega_0$ $W \sim E_0^2$

(repulsion from high intensity)

(see Dalibard + Cohen-Tannoudji - JOSA B 1985)

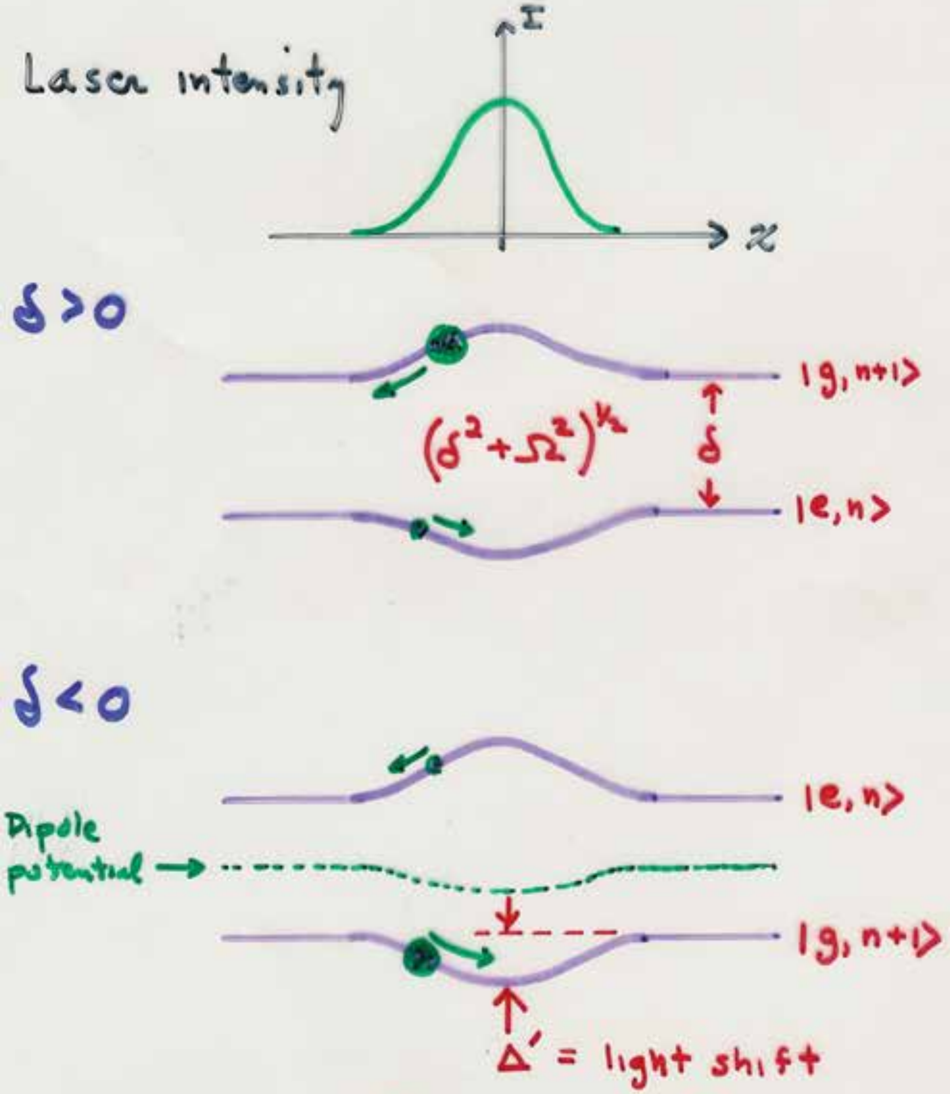
2-level dipole forces in the dressed atom picture I

$\delta = \omega_L - \omega_A$ Ω = Rabi frequency



Spont. emission establishes equilibrium population of the dressed states

Dressed atom dipole forces
II



$$\Delta' = \frac{(\delta^2+\Omega^2)^{1/2}-\delta}{2} \approx \frac{\Omega^2}{4\delta} \quad \text{for } \delta \gg \Omega$$

For $\delta \gg \Omega, \Gamma$

the dressed states are only slightly perturbed from the bare states :

almost all the population is in the state that is almost all |g>

The potential depth is $U = \frac{\hbar\Omega^2}{4\delta}$

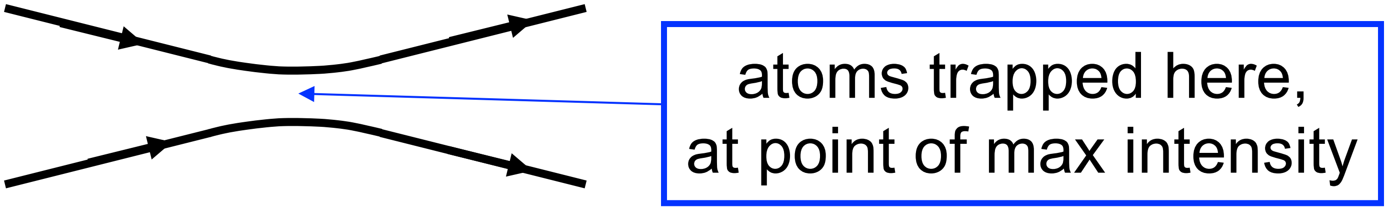
and the potential is conservative for times

$$t \ll \left[\Gamma \cdot \frac{\Omega^2}{\delta^2}\right]^{-1}$$

order of the scattering rate

Optical dipole traps for neutral atoms

A single laser beam, tightly focussed, tuned below resonance, makes a simple and commonly used trap for neutral atoms.



atoms trapped here,
at point of max intensity

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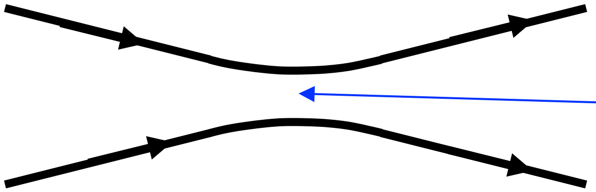

atoms trapped here,
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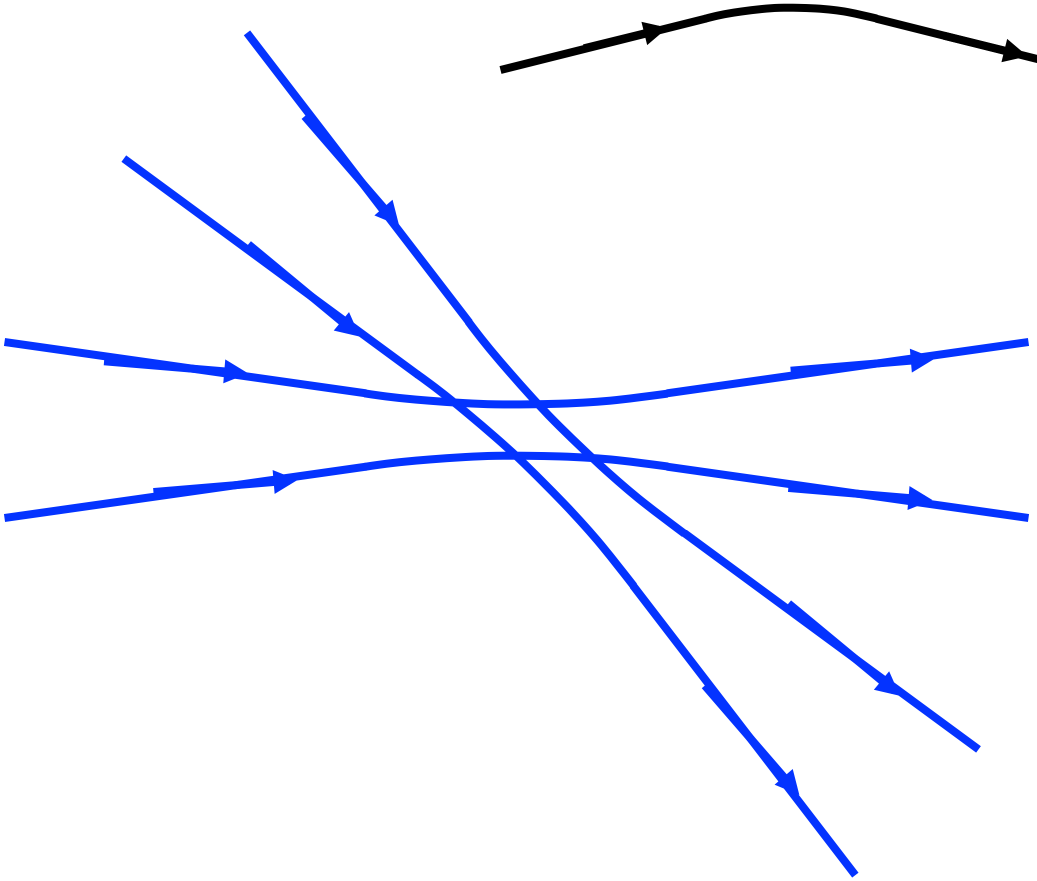


Crossed dipole traps
improve restoring
force in all directions.

Far Off Resonance Trap
(FORT)

An aside:

In the early days of optical forces on atoms, it was typical for detunings to be not very large compared to Ω, Γ. This was probably due in part to lack of laser power sufficient to have a big enough effect at large detuning (both because the lasers were weak and the atoms were hot). Today, it is more common to tune far from resonance, so the dipole potential is conservative, and is given by just one of the dressed state potentials.

This is possible because scattering goes as $1/\delta^2$ while dipole potential goes as $1/\delta^2$.

Aside:

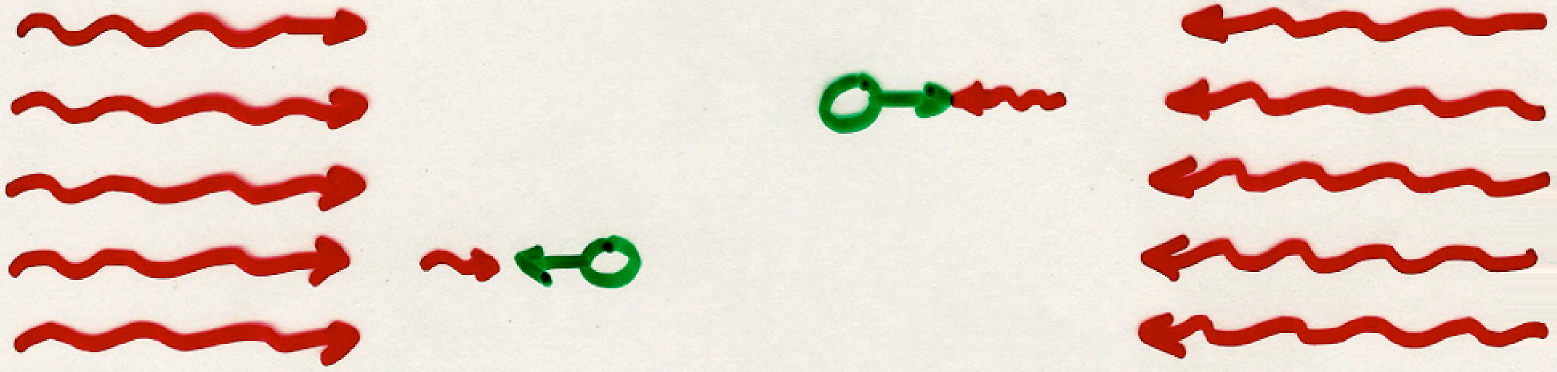
We have been working in the rotating wave approximation. This is fine as long as $\delta << \omega_0$. Otherwise, one needs to consider the effect of the counter-rotating term. There are effects both on the spontaneous emission and on the dipole force. For example, as the applied frequency goes to DC, the spontaneous emission goes to zero, but the dipole force does not.

Questions?

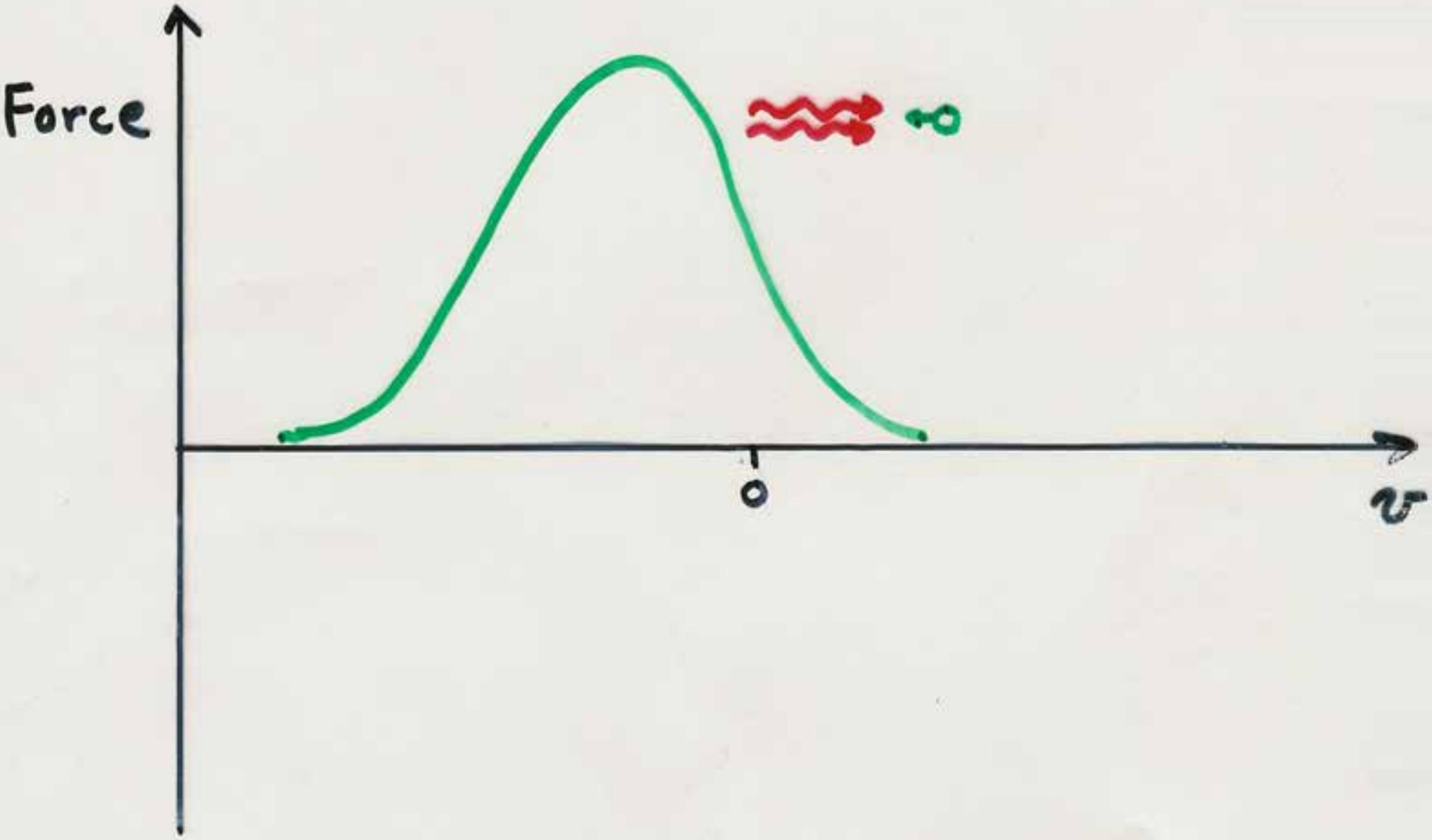
- Clocks—Ramsey method, 1st and 2nd Doppler
- Radiative forces: dipole and scattering
- Dressed Atom
- Rotating wave approximation

Optical Molasses

AT&T
NBS
1985



$\delta = \omega - \omega_0 < 0$



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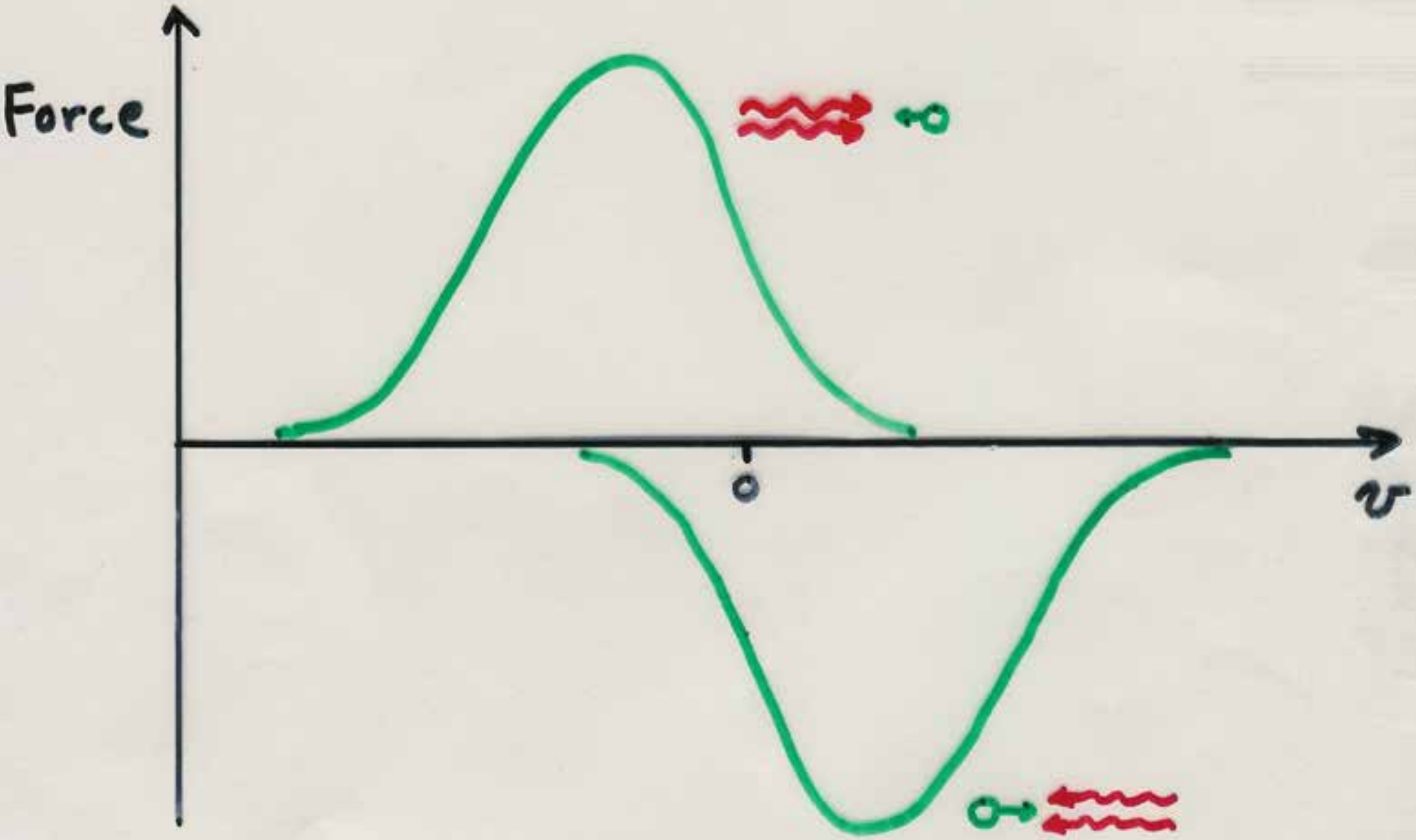

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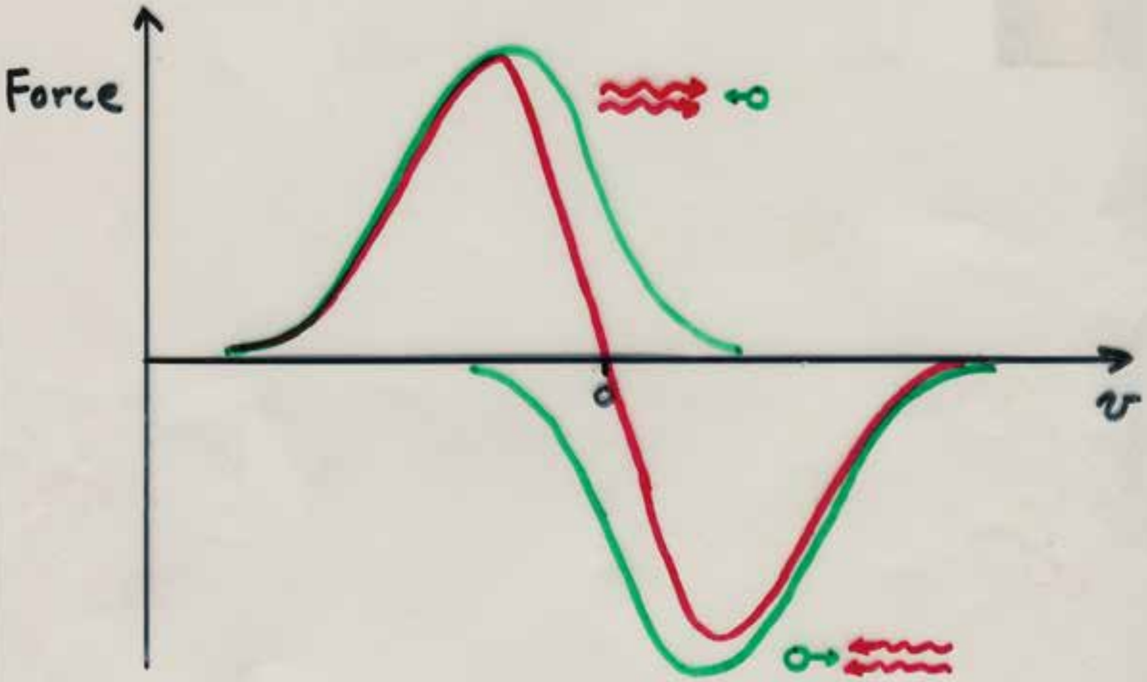
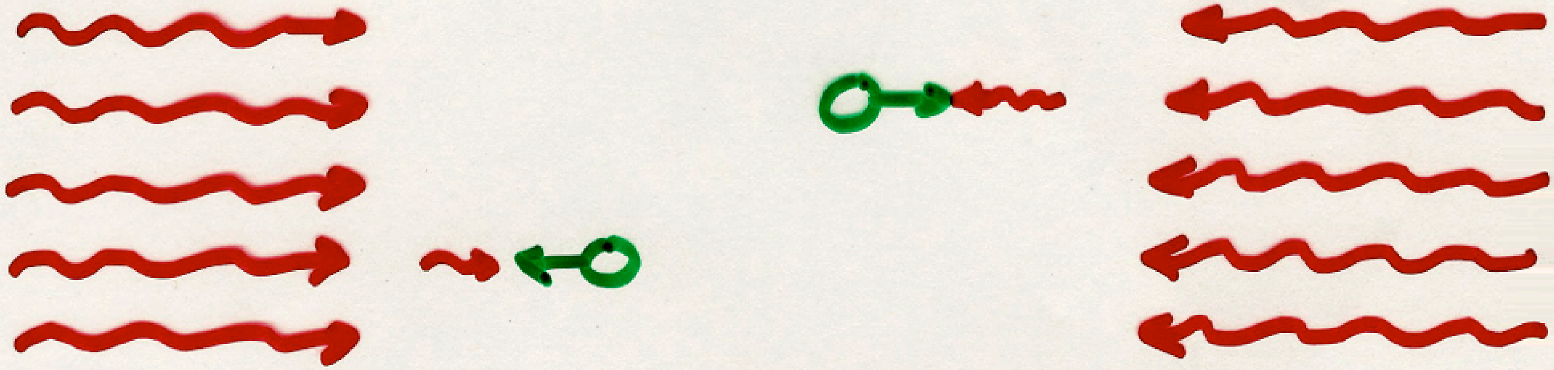


Force has opposite sign as velocity : damping. Near $v = 0$ $\vec{F} = -\alpha\vec{v}$ (like viscosity)

AT+T 1985
NBS

Optical Molasses



substitute δ → δ -/+ *kv*

$$F_\pm = \pm \hbar k \frac{\Gamma}{2} \frac{I/I_0}{1 + I/I_0 + \left[\frac{2(\delta \mp kv)}{\Gamma}\right]^2}$$

$$F_{\pm} = \pm\left(\hbar k\Gamma/2\right)\frac{I/I_o}{1+I/I_o+\left(\dfrac{2\left[\delta \mp kv\right]}{\Gamma}\right)^2}$$

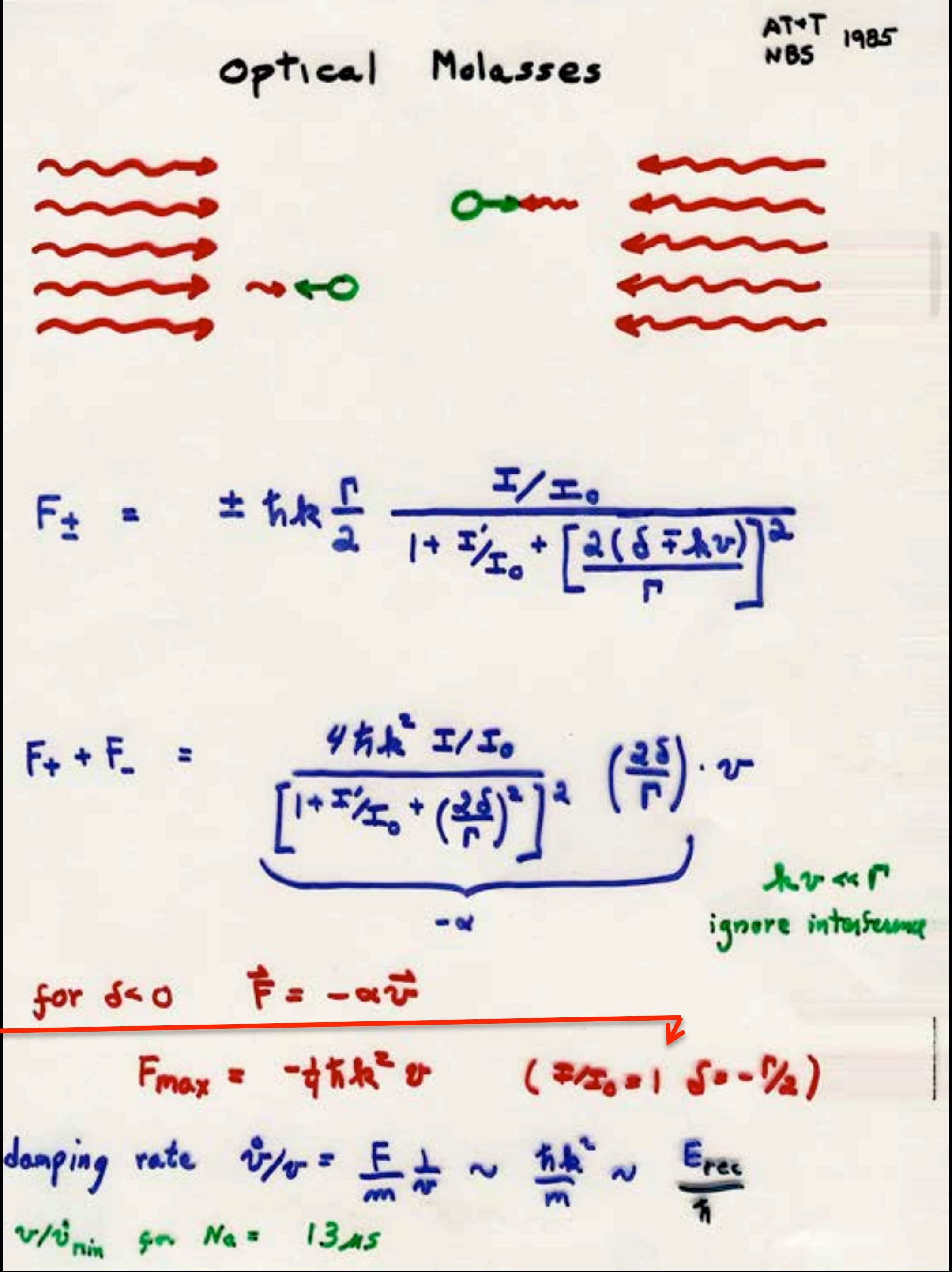
$$F = F_+ + F_- =$$

$$\left(\hbar k\Gamma/2\right)\left(I/I_o\right)\frac{1+I'/I_o+(4\delta^2+8k\delta v+4k^2v^2)/\Gamma^2-\left(1+I'/I_o+(4\delta^2-8k\delta v+4k^2v^2)/\Gamma^2\right)}{\left(1+I'/I_o+\left(\dfrac{2\left[\delta-kv\right]}{\Gamma}\right)^2\right)\left(1+I'/I_o+\left(\dfrac{2\left[\delta+kv\right]}{\Gamma}\right)^2\right)}$$

I'/I_0 accounts for cross saturation

$$F = \frac{4\hbar k^2\left(I/I_o\right)}{\left(1+I'/I_o+\left[\dfrac{2\delta}{\Gamma}\right]^2\right)^2}\frac{2\delta}{\Gamma}v$$

assume
$kv << \delta, \Gamma$



AT+T 1985
NBS

Optical Molasses

$$F_{\pm} = \pm \hbar k \frac{\Gamma}{2} \frac{I/I_0}{1 + I'/I_0 + \left[\frac{2(\delta \mp kv)}{\Gamma}\right]^2}$$

$$F_+ + F_- = \underbrace{\frac{4\hbar k^2\, I/I_0}{\left[1 + I'/I_0 + \left(\frac{2\delta}{\Gamma}\right)^2\right]^2} \left(\frac{2\delta}{\Gamma}\right)}_{-\alpha} \cdot v$$

$kv \ll \Gamma$
ignore interference

for $\delta < 0$ $\quad \vec{F} = -\alpha \vec{v}$

$$F_{max} = -\tfrac{1}{4}\hbar k^2 v \qquad (I/I_0 = 1 \quad \delta = -\Gamma/2)$$

damping rate $\dot{v}/v = \frac{F}{m}\frac{1}{v} \sim \frac{\hbar k^2}{m} \sim \frac{E_{rec}}{\hbar}$

$v/\dot{v}_{min}$ for Na = 13 μs

I′ = 2I, meaning alternating beams or no cross-saturation

Fluctuations of the Scattering Force

1. Fluctuations of the number of photons absorbed per unit time.

2. Fluctuations in the direction of spontaneously emitted photons.

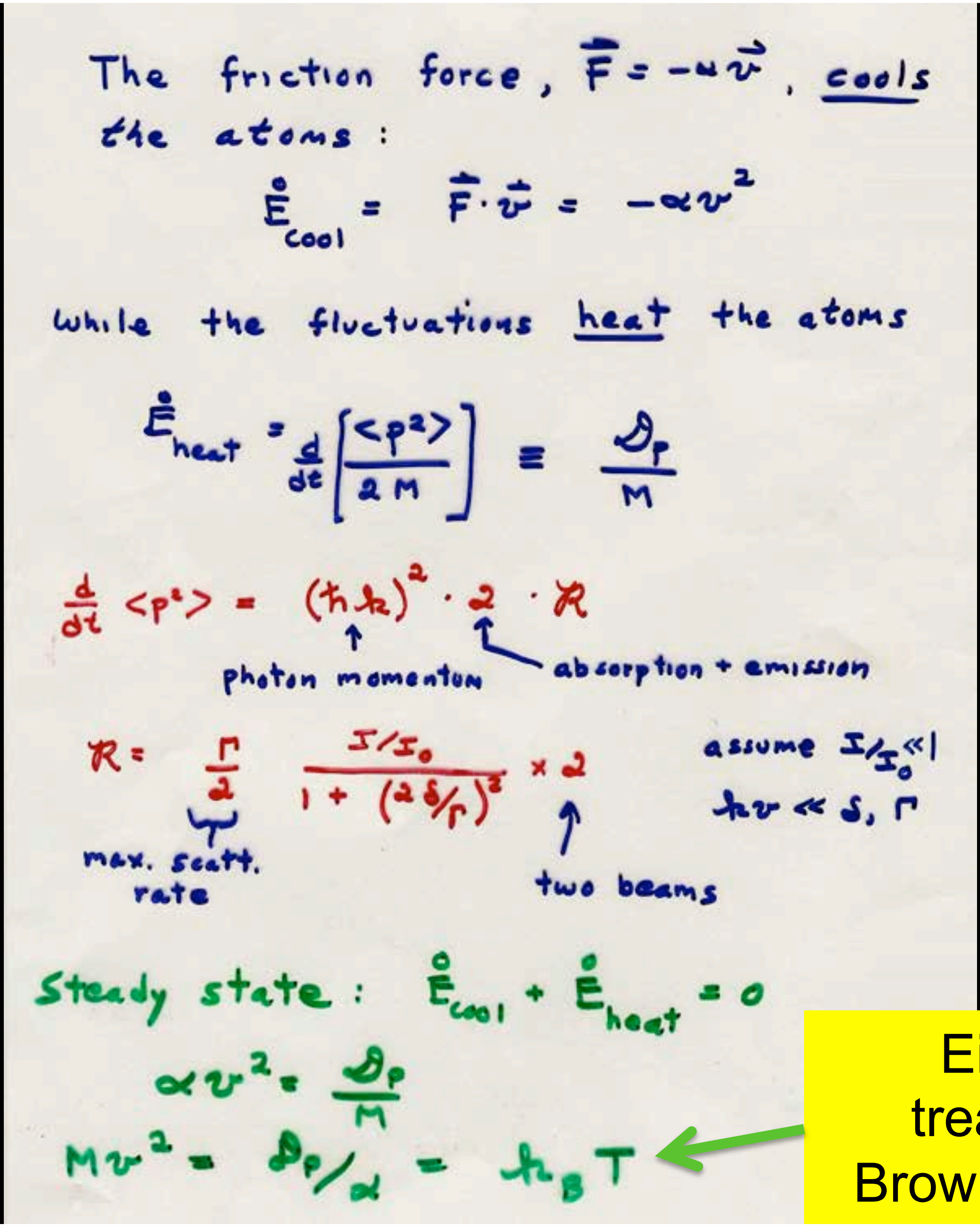
   (here, assume a 1-D universe)

NOTE: Both of these effects arise from the randomness of Spontaneous emission.

The fluctuations represent a random walk, of step $\hbar k$, around the momentum change produced by the average force.

$$d/dt <\Delta p^2> = \underset{\substack{\uparrow \\ \text{Two recoils/scattering}}}{2}\ \underset{\substack{\uparrow \\ \text{Scattering rate}}}{R}\ (\hbar k)^2$$

(assumed Poisson)



The friction force, $\vec{F} = -\alpha\vec{v}$, cools the atoms:

$$\dot{E}_{cool} = \vec{F}\cdot\vec{v} = -\alpha v^2$$

while the fluctuations heat the atoms

$$\dot{E}_{heat} = \frac{d}{dt}\left[\frac{\langle p^2\rangle}{2M}\right] \equiv \frac{\mathcal{D}_p}{M}$$

$$\frac{d}{dt}\langle p^2\rangle = \underset{\substack{\uparrow \\ \text{photon momentum}}}{(\hbar k)^2}\cdot \underset{\substack{\uparrow \\ \text{absorption + emission}}}{2}\cdot \mathcal{R}$$

$$\mathcal{R} = \underbrace{\frac{\Gamma}{2}}_{\text{max. scatt. rate}} \frac{I/I_0}{1+(2\delta/\Gamma)^2} \times \underset{\substack{\uparrow \\ \text{two beams}}}{2}$$

assume $I/I_0 \ll 1$

$kv \ll \delta, \Gamma$

Steady state: $\dot{E}_{cool} + \dot{E}_{heat} = 0$

$$\alpha v^2 = \frac{\mathcal{D}_p}{M}$$

$$Mv^2 = \mathcal{D}_p/\alpha = k_B T$$

Einstein's treatment of Brownian motion

The Doppler Cooling Limit

$$k_B T = \frac{\mathcal{D}_p}{\alpha}$$

$$\mathcal{D}_p = \hbar^2 k^2 \, \Gamma \, \frac{I/I_0}{1 + (2\delta/\Gamma)^2} = \frac{\langle \dot{p^2} \rangle}{2}$$

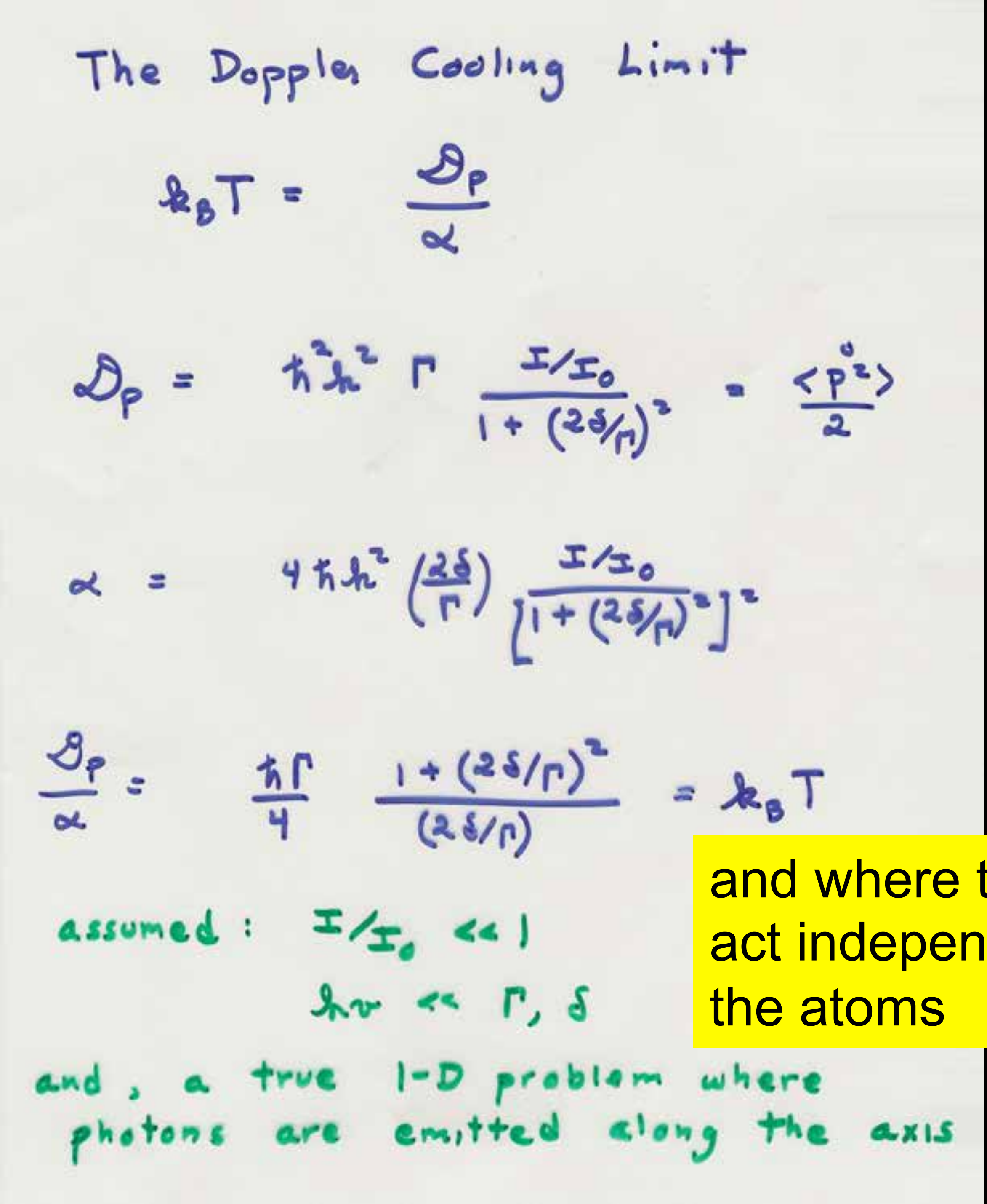
$$\alpha = 4 \hbar k^2 \left(\frac{2\delta}{\Gamma}\right) \frac{I/I_0}{\left[1 + (2\delta/\Gamma)^2\right]^2}$$

$$\frac{\mathcal{D}_p}{\alpha} = \frac{\hbar \Gamma}{4} \, \frac{1 + (2\delta/\Gamma)^2}{(2\delta/\Gamma)} = k_B T$$

assumed : $I/I_0 \ll 1$

$kv \ll \Gamma, \delta$

and , a true 1-D problem where photons are emitted along the axis



The Doppler Cooling Limit

$$k_B T = \frac{D_p}{\alpha}$$

$$D_p = \hbar^2 k^2 \Gamma \frac{I/I_0}{1 + (2\delta/\Gamma)^2} = \frac{\langle \dot{p}^2 \rangle}{2}$$

$$\alpha = 4 \hbar k^2 \left(\frac{2\delta}{\Gamma}\right) \frac{I/I_0}{\left[1 + (2\delta/\Gamma)^2\right]^2}$$

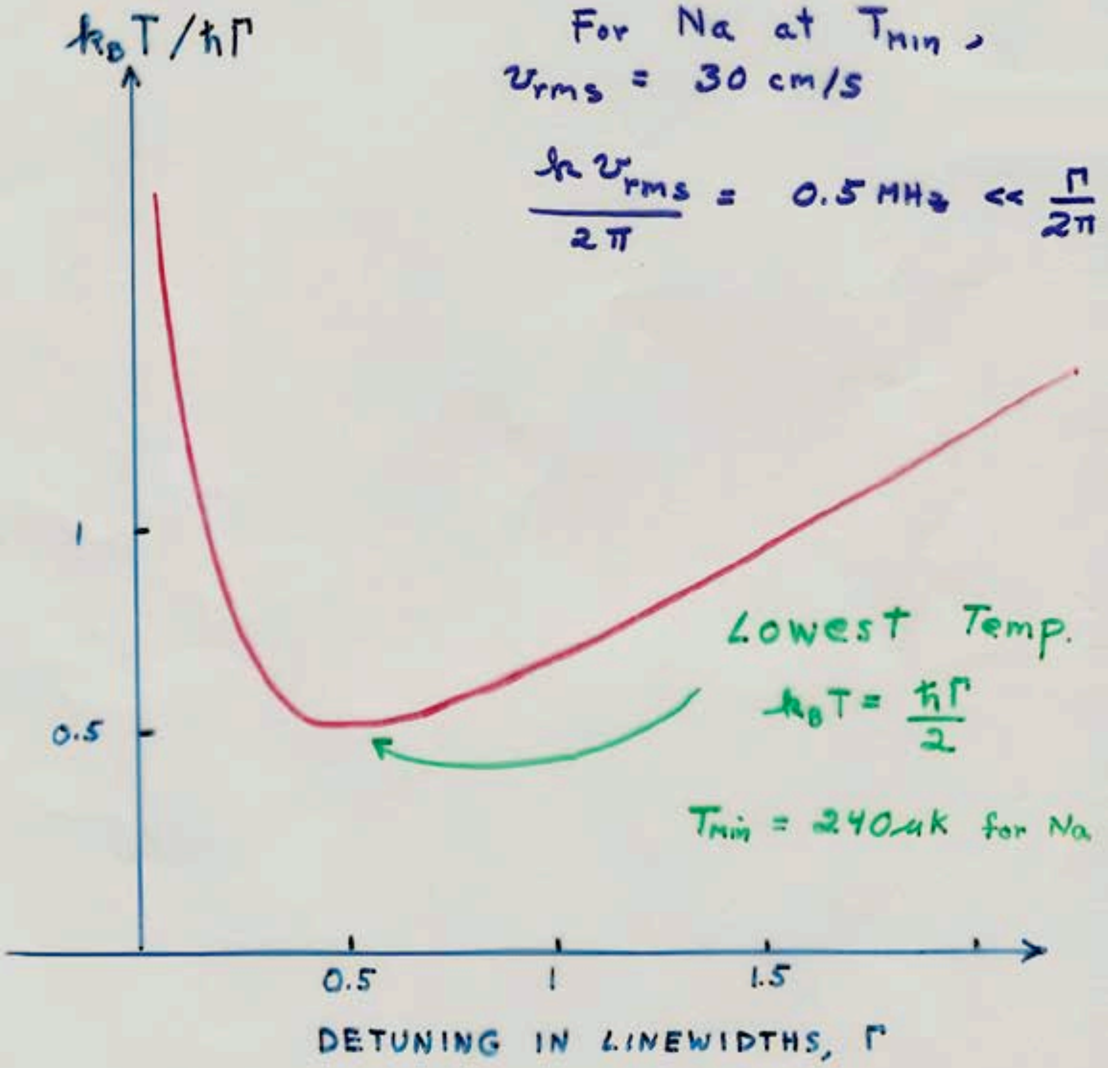
$$\frac{D_p}{\alpha} = \frac{\hbar\Gamma}{4} \frac{1 + (2\delta/\Gamma)^2}{(2\delta/\Gamma)} = k_B T$$

assumed : $I/I_0 \ll 1$

$kv \ll \Gamma, \delta$

and , a true 1-D problem where photons are emitted along the axis

and where the beams act independently on the atoms



For Na at T_{min},
$v_{rms} = 30$ cm/s

$$\frac{k v_{rms}}{2\pi} = 0.5 \text{ MHz} \ll \frac{\Gamma}{2\pi}$$

Lowest Temp.
$k_B T = \frac{\hbar\Gamma}{2}$

$T_{min} = 240 \mu K$ for Na

Also valid for Doppler cooling at low intensity in 3-D.

Aside:

The result $\hbar(kv_{\text{rms}})_{\text{limit}} \ll \hbar\Gamma$ justifies the assumptions we made about the linearity of $F = -\alpha v$. In order for our expressions for the average force to be meaningful, we must also have $E_{\text{rec}} \ll \hbar\Gamma$. Satisfying this latter condition guarantees that the cooling limit will also satisfy *its* condition, although less strongly. That is:

$$E_{\text{rec}} < \hbar(kv_{\text{rms}})_{\text{limit}} < \hbar\Gamma$$

is the usual situation.

The Doppler shift of atoms moving at the rms Doppler cooling limit velocity is the geometric mean of the recoil shift ($E_{\mathrm{rec}}/\hbar$) and the natural linewidth.

Questions?

Doppler cooling

Momentum diffusion—due to both absorption and emission

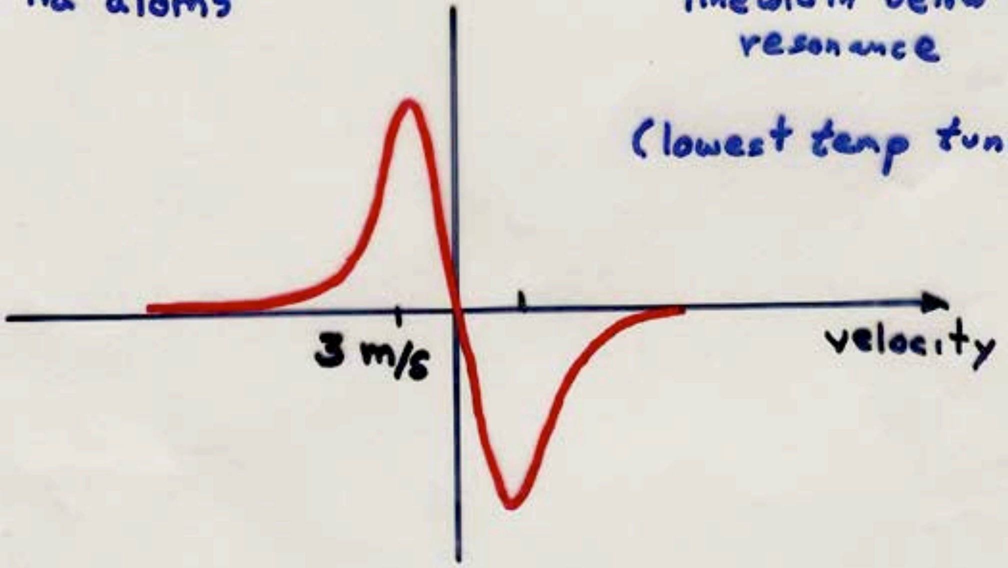
Equilibrium temperature

Cooling Force vs. Velocity

Na atoms

laser tuned a half
linewidth below
resonance

(lowest temp tuning)

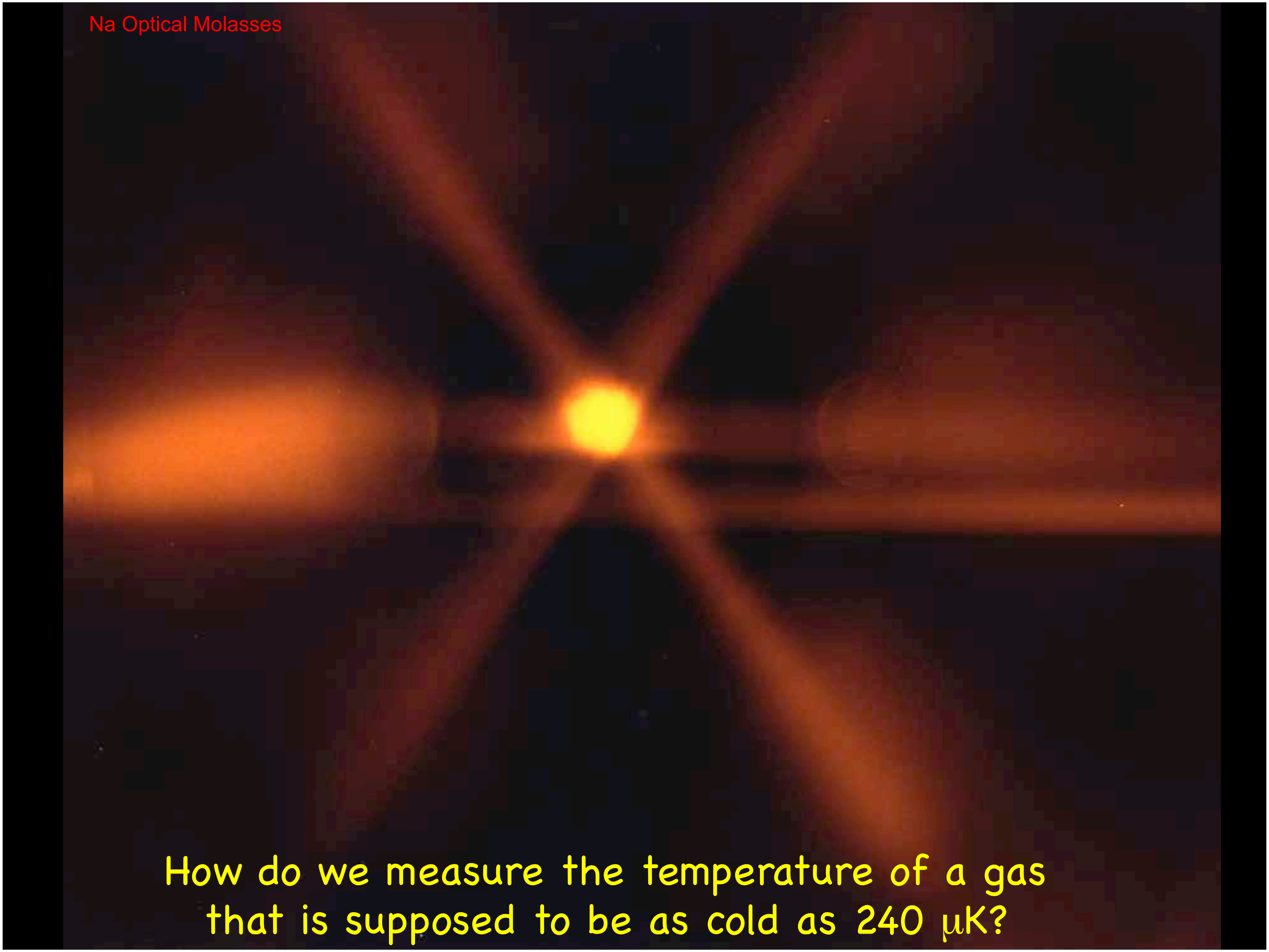


Problem: typical atoms have

$v = 500 - 1000$ m/s

Need to slow these atoms down
before laser cooling can work

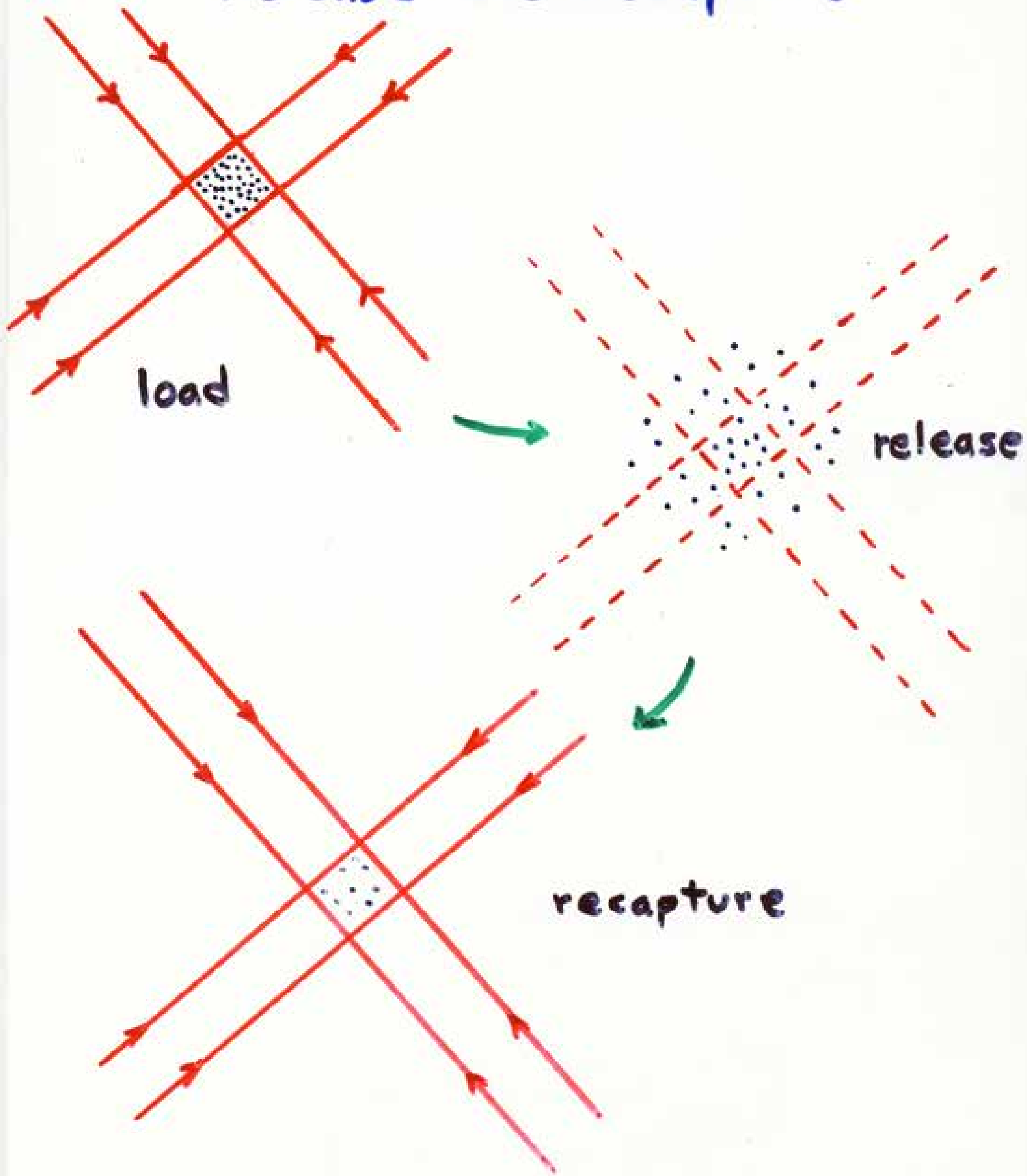
various techniques exist—beyond scope of this lecture



Na Optical Molasses

How do we measure the temperature of a gas that is supposed to be as cold as 240 μK?

Temperature measurement by Release and Recapture



Release and recapture

Laser-Cooling Temperatures
by Release-and-Recapture

Bell Labs (1985):

S. Chu, L. Hollberg, J. Bjorkholm,
A. Cable, Art Ashkin

$$T = 240^{+200}_{-60}\ \mu K$$

NBS-Gaithersburg (1987)

$$T \approx 240\ \mu K$$

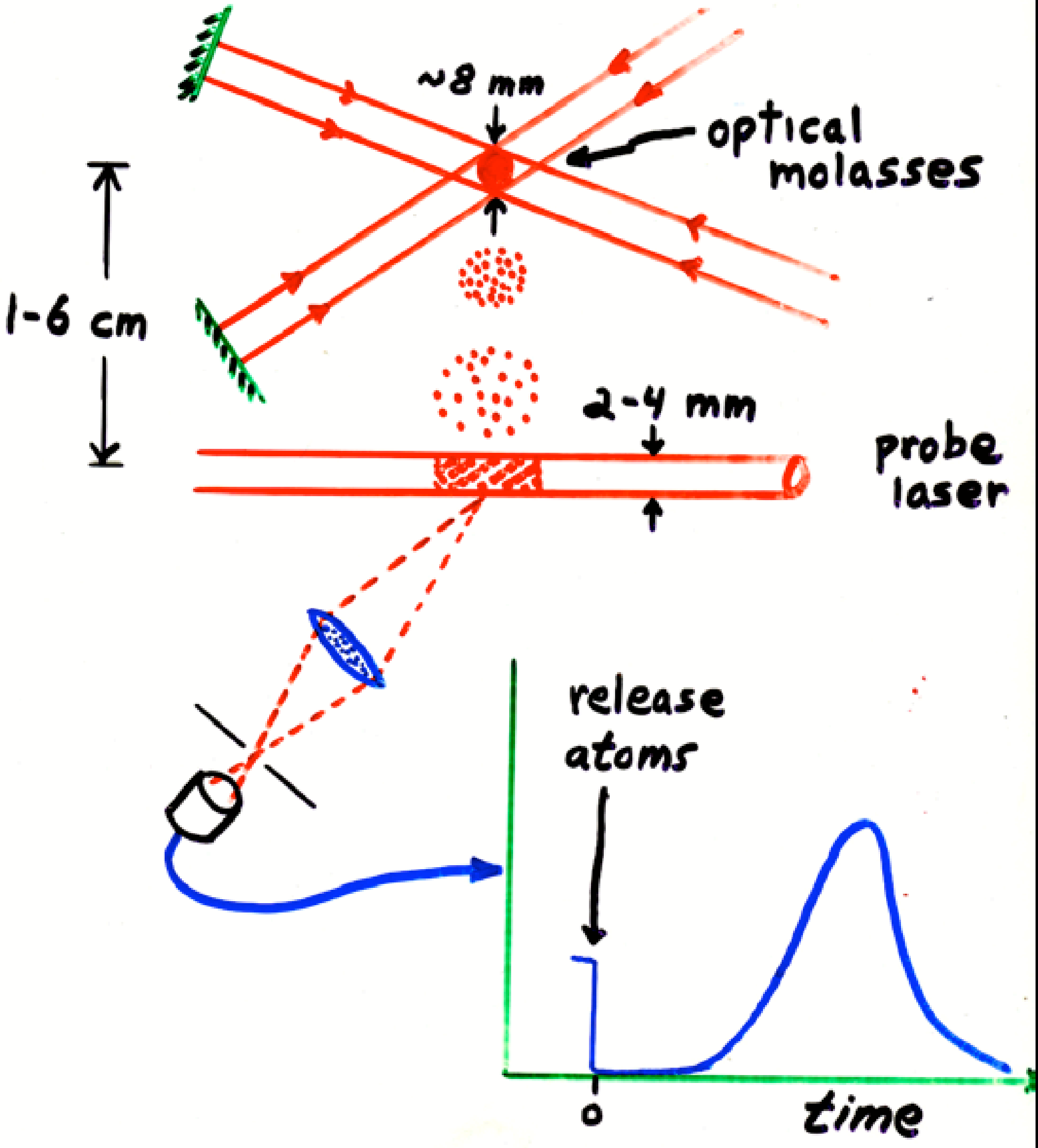
other measurements were consistent with Doppler-cooling theory....

until ...

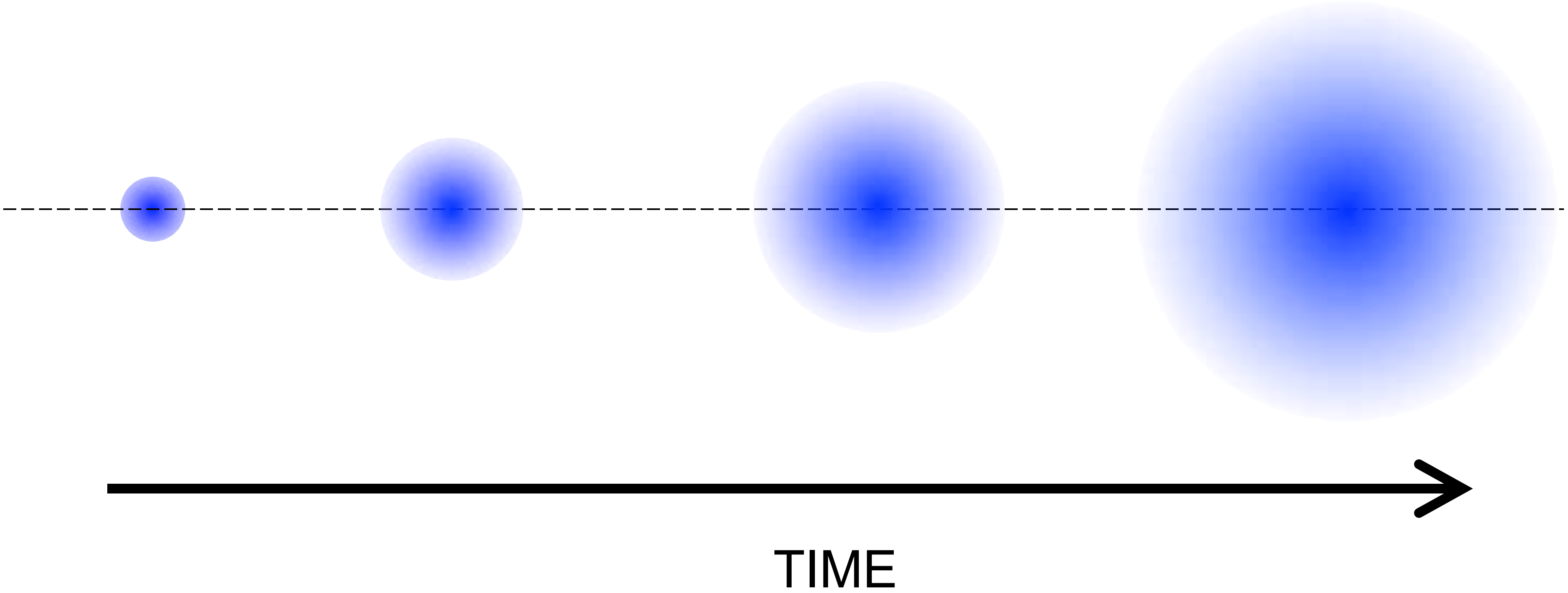
TOF expt.

Lett, Watts, Westbrook, Phillips,
Gould, and Metcalf - 1988

Temperature by Time-of-Flight



Aside: Today, temperatures are measured by imaging the cloud after free expansion.

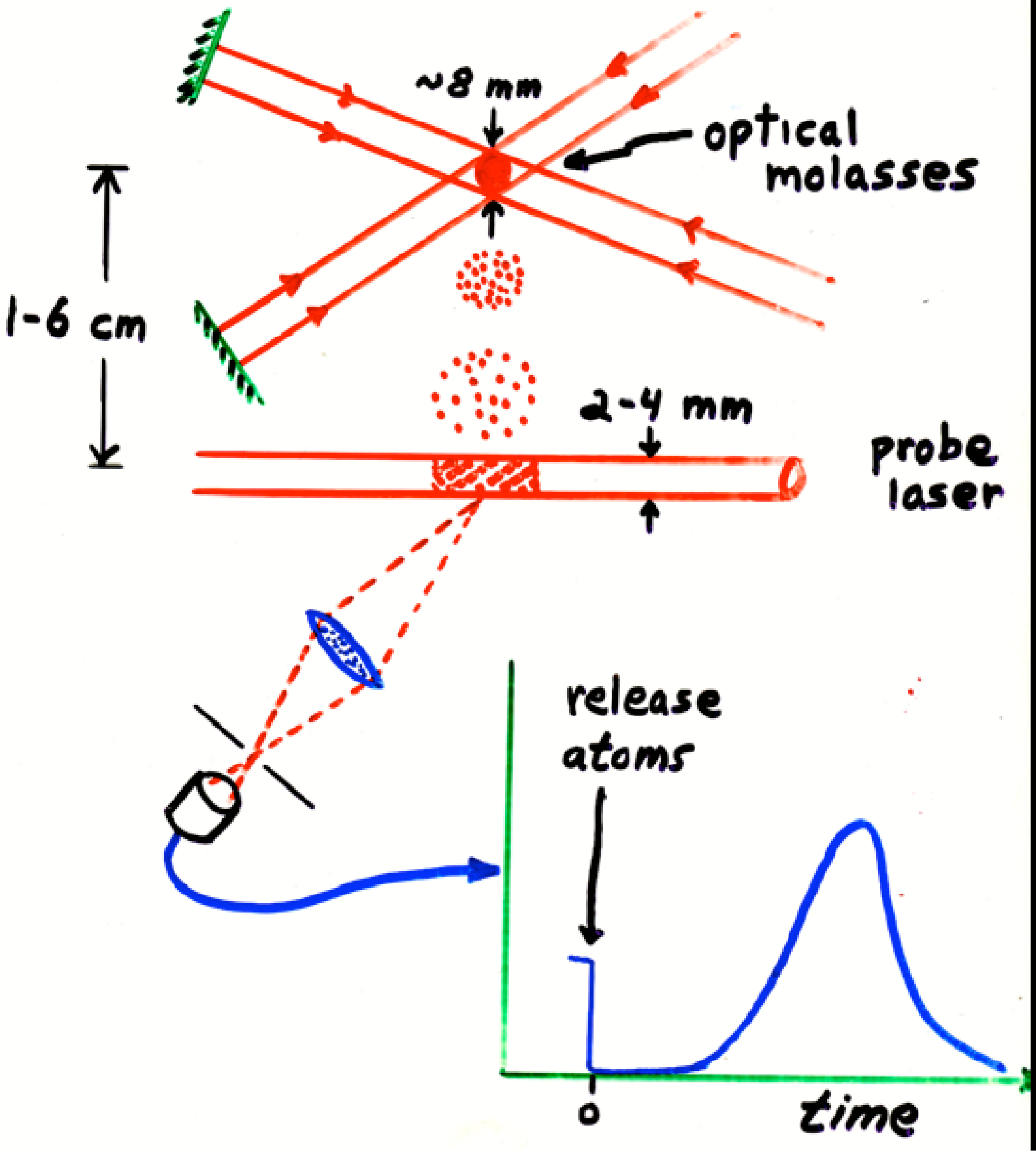


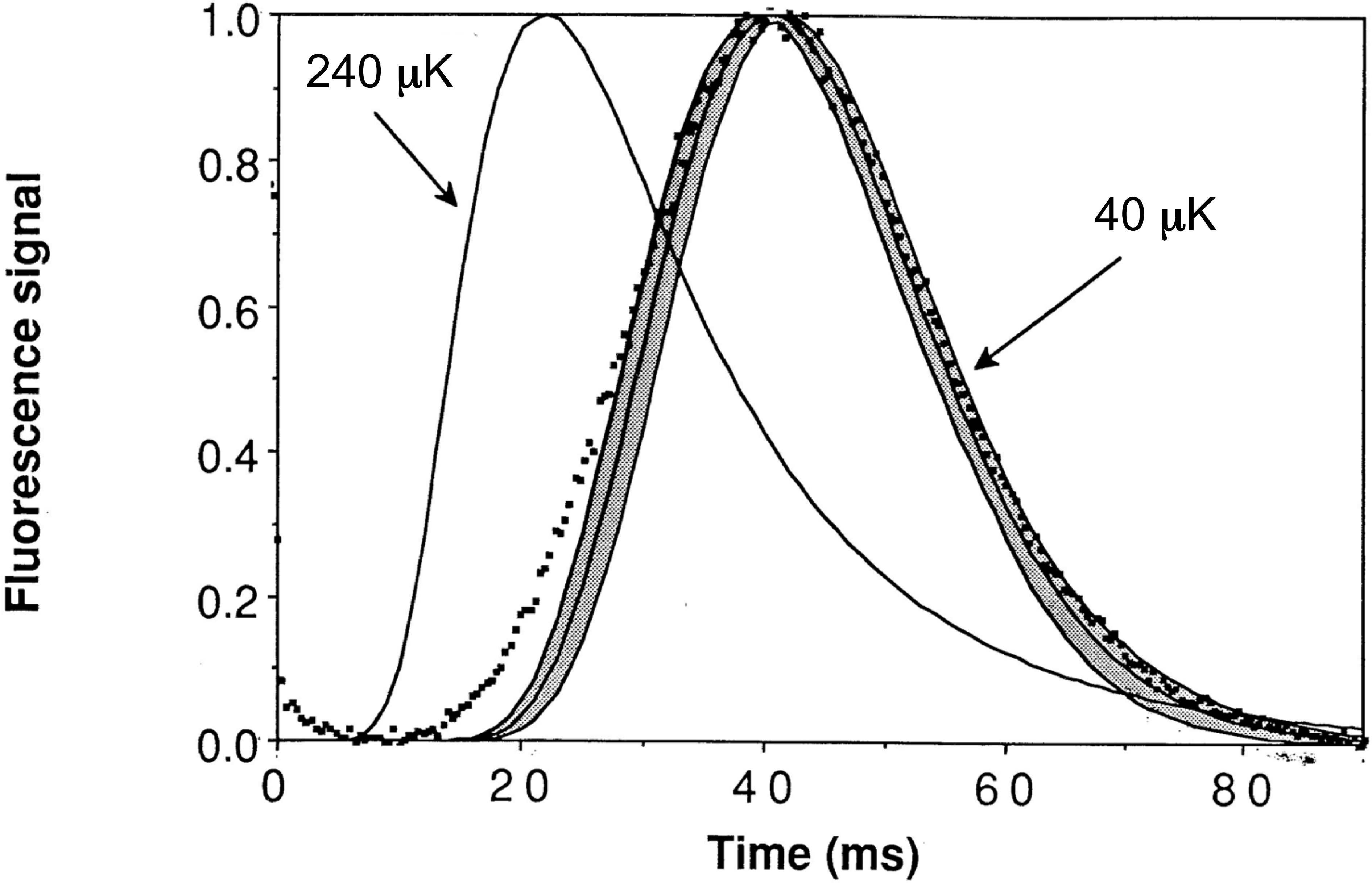
This is the current usual meaning of “time-of-flight” (TOF)

TOF expt.

Lett, Watts, Westbrook, Phillips,
Gould, and Metcalf - 1988

Temperature by Time-of-Flight




240 µK
40 µK
Fluorescence signal
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
Time (ms)

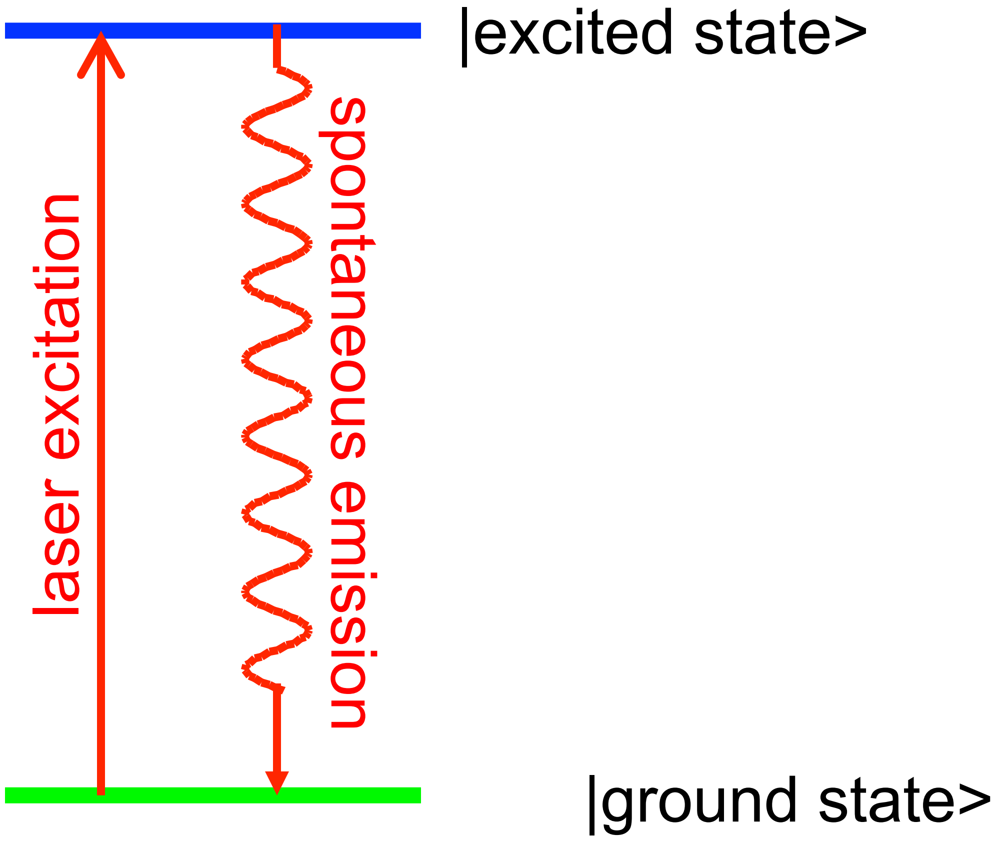
Soon,
Dalibard & Cohen-Tannoudji at ENS
and
Chu and colleagues at Stanford
Discovered a new explanation for laser cooling, involving:

- Multi-state atoms
- Polarization gradients
- Light shifts
- Optical pumping

We follow the Dalibard and Cohen-Tannoudji model

Multi-level Atoms

(The old theory was not really wrong;
it only applied to 2-level atoms.)



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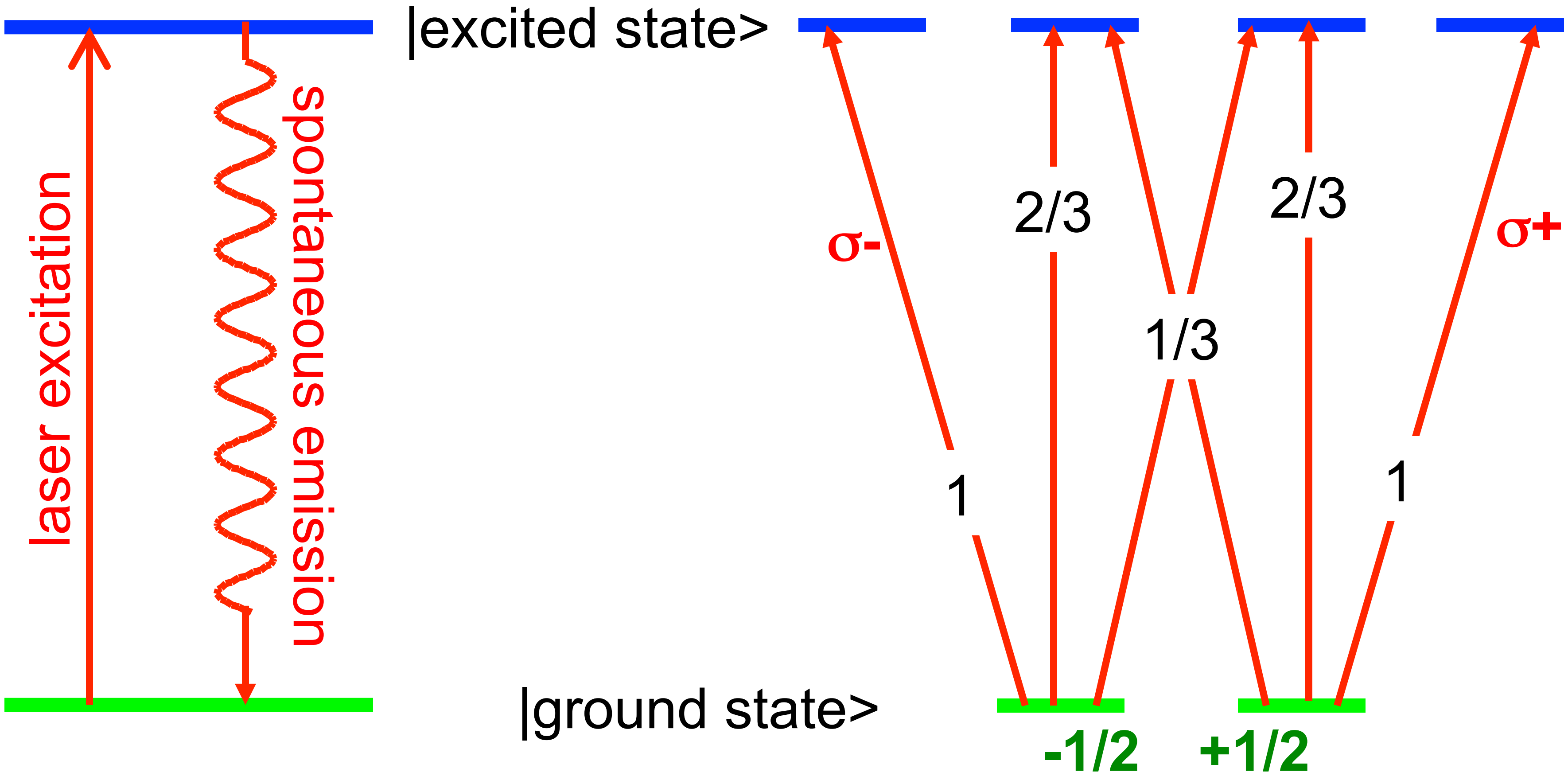
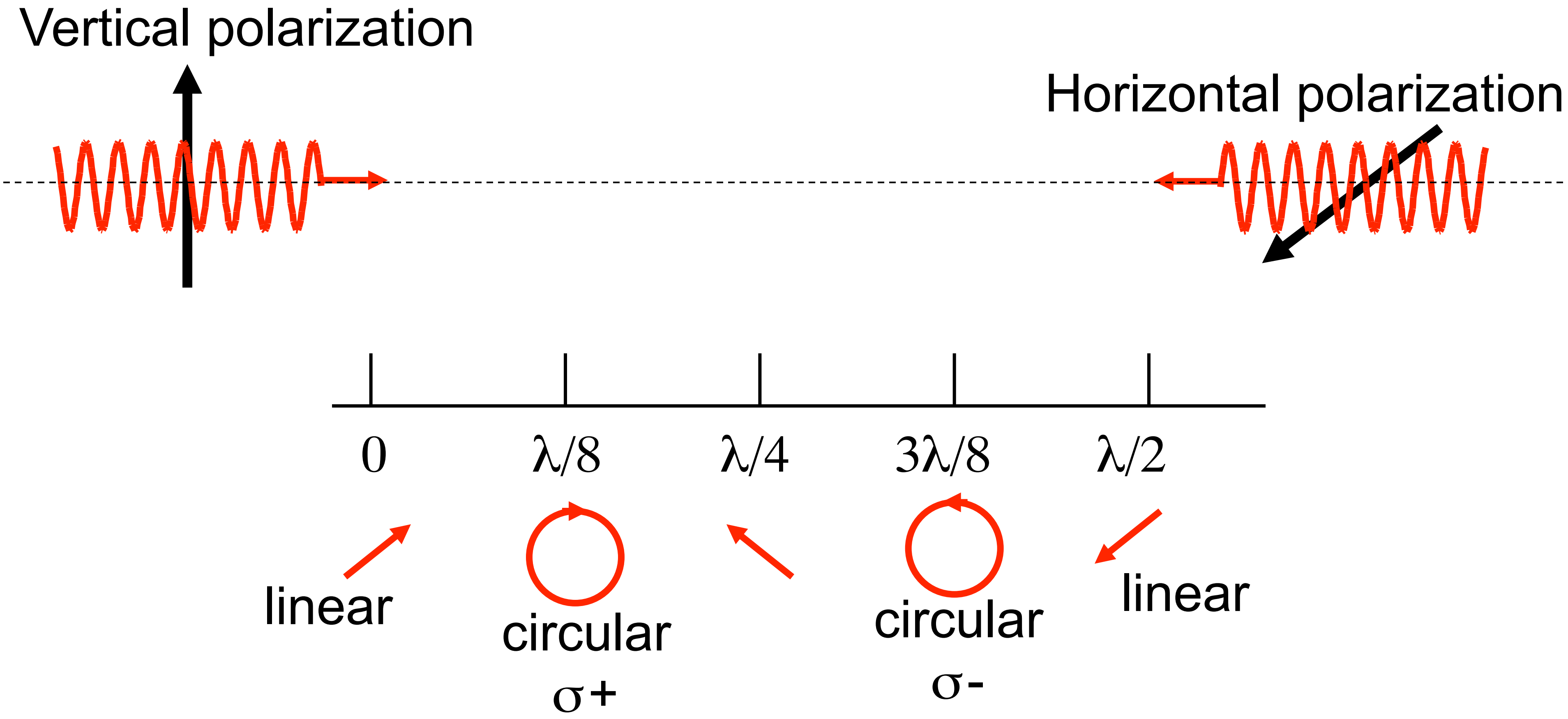


Polarization gradients

Orthogonally polarized, counter-propagating laser beams



Vertical polarization

Horizontal polarization

0 $\lambda/8$ $\lambda/4$ $3\lambda/8$ $\lambda/2$

linear

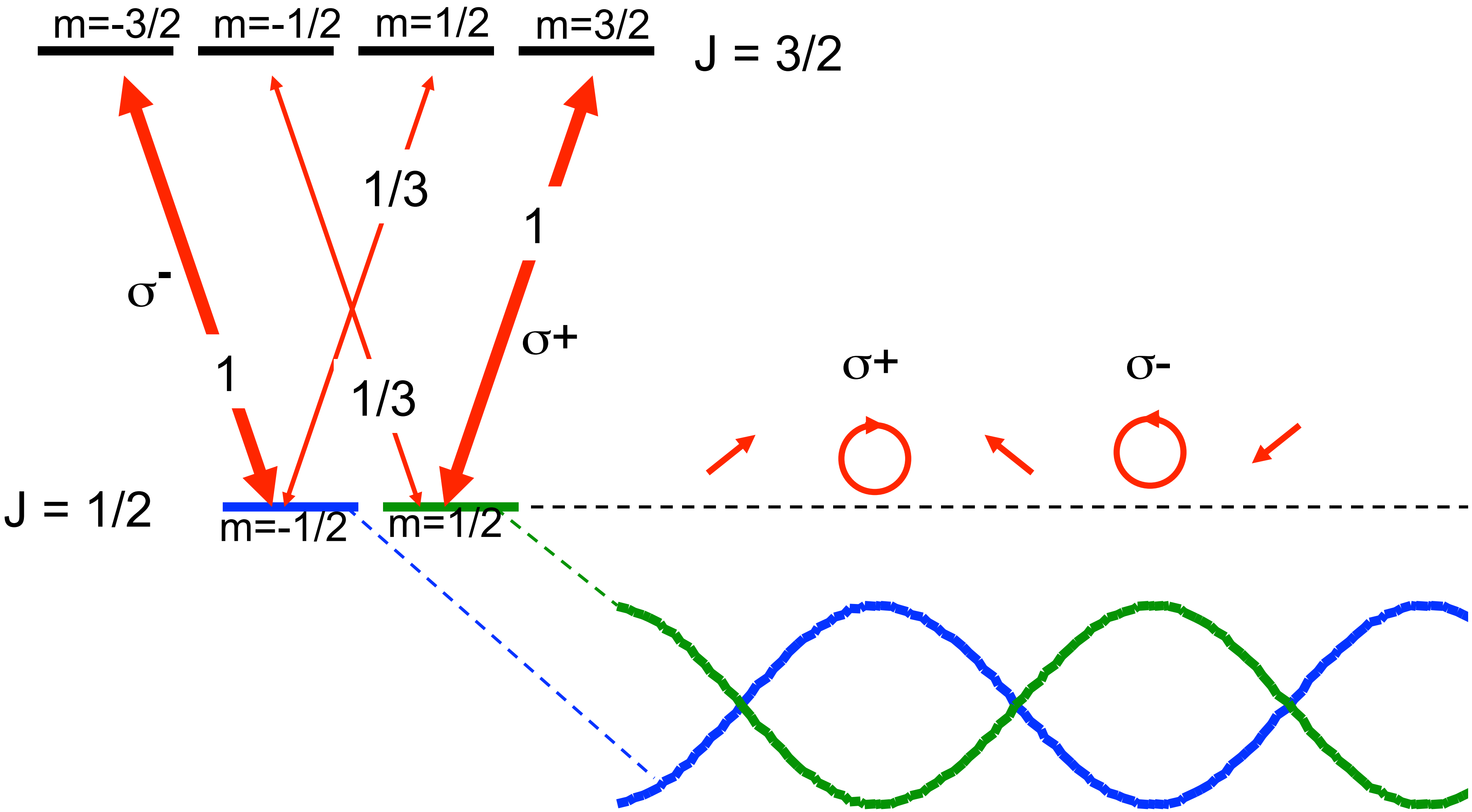
circular $\sigma+$

circular $\sigma-$

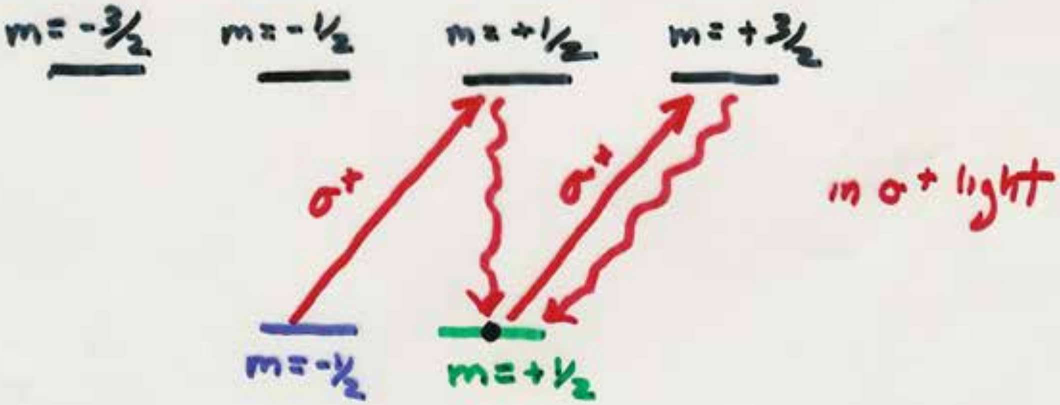
linear

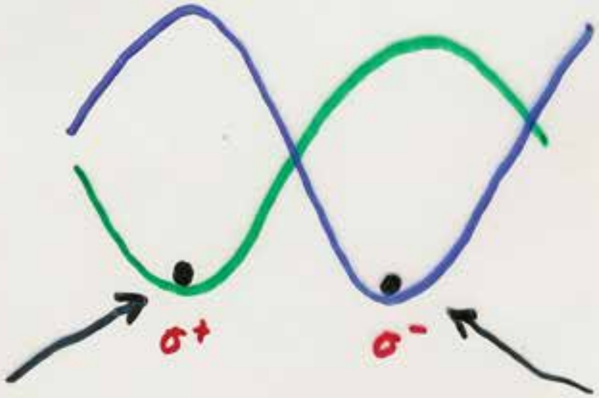
The atom experiences a polarization gradient as it moves

Light Shifts



Optical Pumping





when light is σ+, atom goes here

when light is σ−, atom goes here

always to the lower energy level **(*when δ < 0*)**

Questions?

TOF and temperature measurements

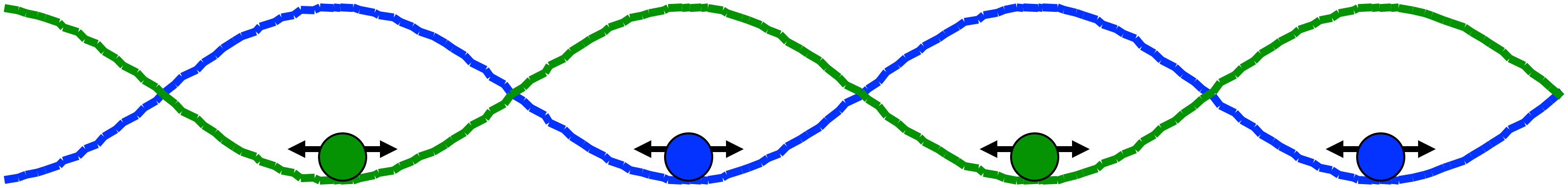
Sub-Doppler cooling

- polarization gradients
- optical pumping
- differential light shift
- lag in population adjustment

Sisyphus temperatures

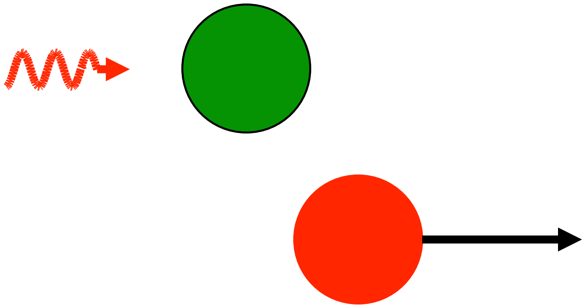
The rate for Sisyphus cooling is typically much faster than for Doppler cooling, so the temperature is lower.

The temperature gets colder for lower laser intensity greater laser detuning (contrary to the case for Doppler cooling) and is low enough that the atoms are trapped in the standing wave.



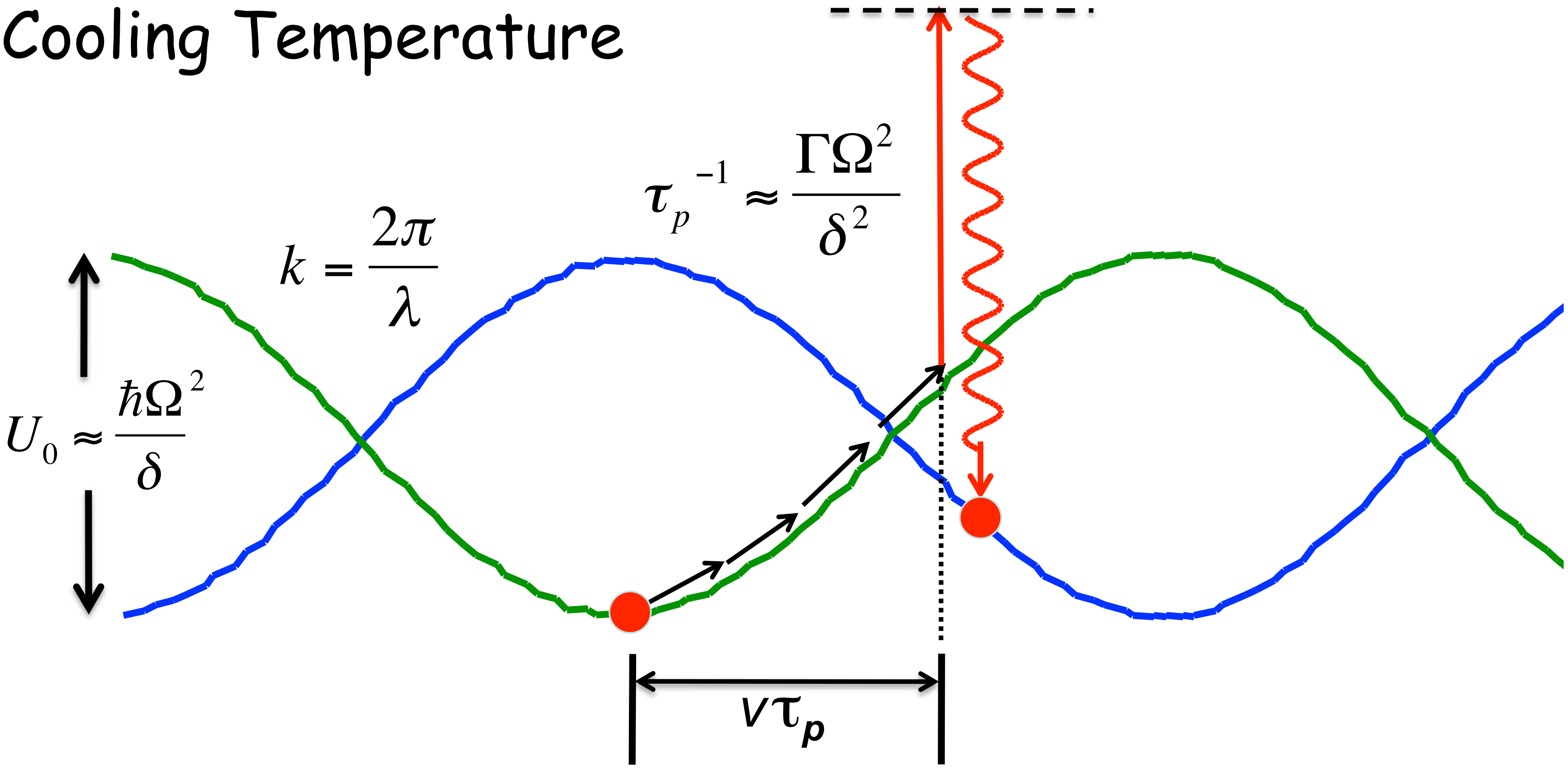
The lowest temperature achievable is limited to a few times the recoil temperature:

$$k_B T_{rec} = m v^2_{rec}$$



$$V_{rec} = \hbar k / M$$

Estimating the Sisyphus Cooling Temperature



$$\langle F \rangle \approx \underbrace{U_0\, k}_{\text{energy/distance}}\, \underbrace{v\tau_p}_{\text{fraction of potential used}} k \approx \frac{\hbar\Omega^2}{\delta} k^2 v \frac{1}{\Omega^2\,\Gamma/\delta^2} \approx \hbar k^2 \frac{\delta}{\Gamma} v$$

$$\alpha \approx \hbar k^2 \frac{\delta}{\Gamma}$$

Estimating the Sisyphus Cooling Temperature

A careful calculation gives: $\langle F \rangle_{\text{sisyphys}} = 3\hbar k^2 \frac{\delta}{\Gamma} v$ $\langle F \rangle_{\text{Dop max}} = \frac{\hbar k^2 v}{4}$

Compare to Doppler cooling in the low-intensity, large-detuning limit:

$$\langle F \rangle = \frac{4\hbar k^2 (I/I_o)}{\left[\frac{2\delta}{\Gamma}\right]^4} \frac{2\delta}{\Gamma} v$$

Force is independent of intensity; increases with detuning (because less optical pumping means more energy loss).

Estimating the Sisyphus Cooling Temperature

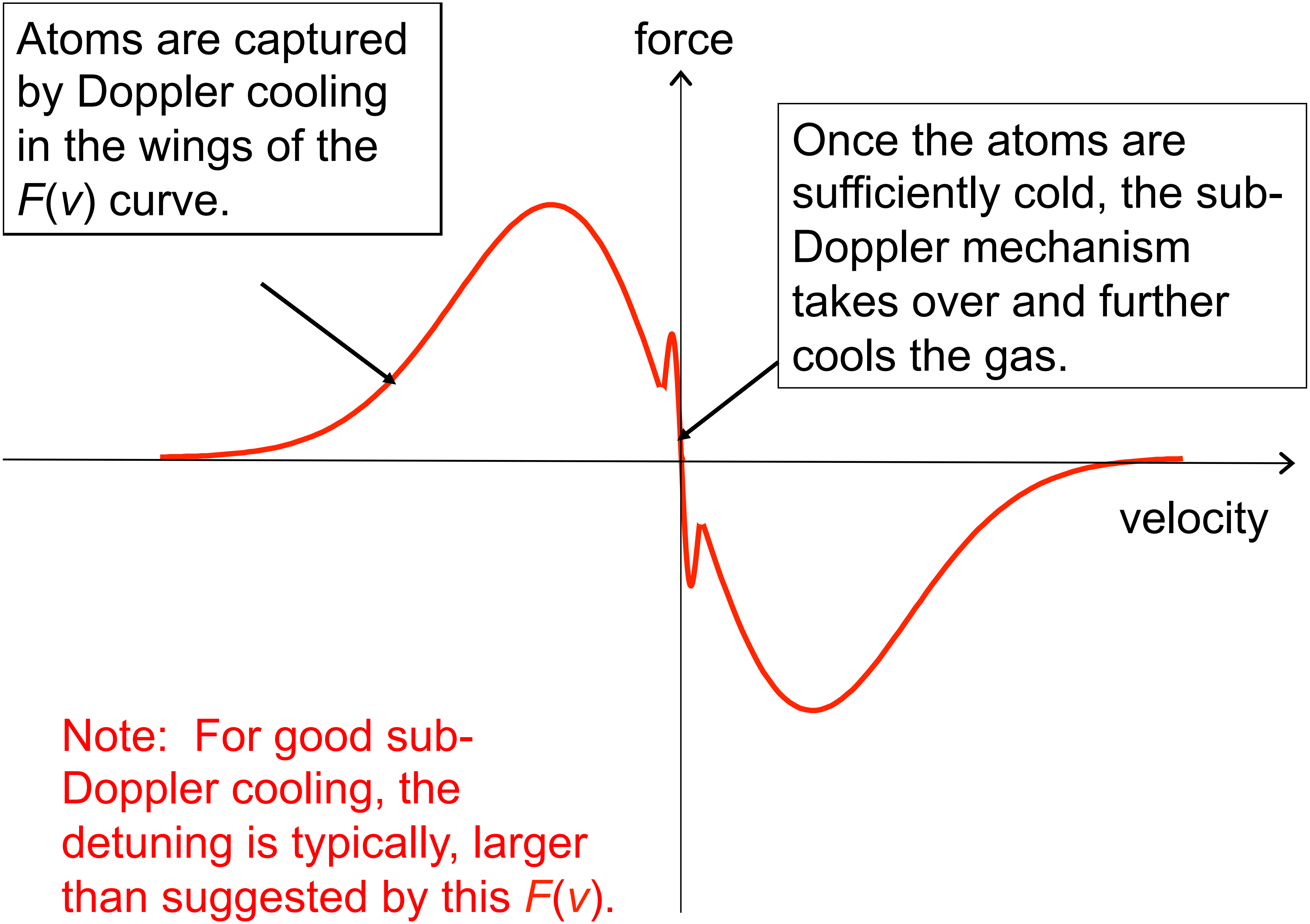
The momentum diffusion coefficient

$$2D_p = \frac{d}{dt}p^2 \approx \left(F\tau_p\right)^2 \frac{1}{\tau_p} \approx \underbrace{\left(\frac{\hbar\Omega^2}{\delta}k\right)}_{\boxed{kU_0}}^2 \frac{1}{\Gamma\Omega^2/\delta^2} \approx \frac{\hbar^2k^2\Omega^2}{\Gamma}$$

$$k_\mathbf{B}T = \frac{D_p}{\alpha} \approx \frac{\dfrac{\hbar^2k^2\Omega^2}{\Gamma}}{\hbar k^2\dfrac{\delta}{\Gamma}} \approx \frac{\hbar\Omega^2}{\delta} \approx U_0$$

What happens as $U_0 \Rightarrow 0$?

The thermal energy is about equal to (in fact, less than) the potential depth, so the atoms are typically trapped.



Atoms are captured by Doppler cooling in the wings of the *F*(*v*) curve.

Once the atoms are sufficiently cold, the sub-Doppler mechanism takes over and further cools the gas.

Note: For good sub-Doppler cooling, the detuning is typically, larger than suggested by this *F*(*v*).

How low ?

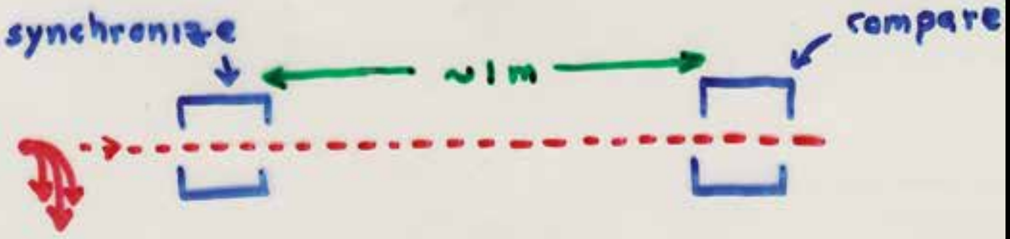
Typical lowest thermal velocities are a few times the recoil velocity.

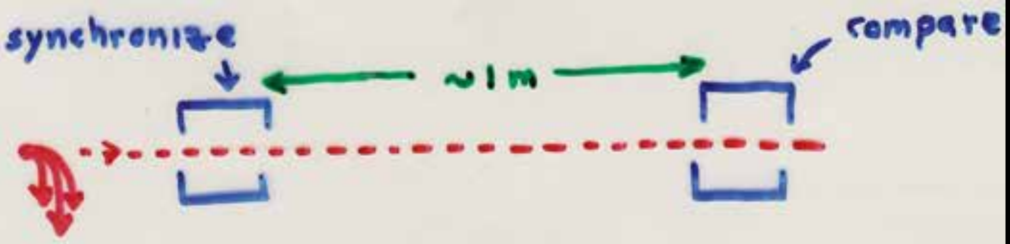
v_{rec} for Cs is 3.5 mm/s

By adiabatically releasing atoms trapped in the standing waves, we have achieved cesium temperatures below 1 microkelvin, $v < 1$ cm/s.

This cooling has become standard procedure for atomic clocks.


synchronize
~1m
compare


synchronize
~1m
compare



Idea of Zacharias ca 1953

"Atomic Fountain"

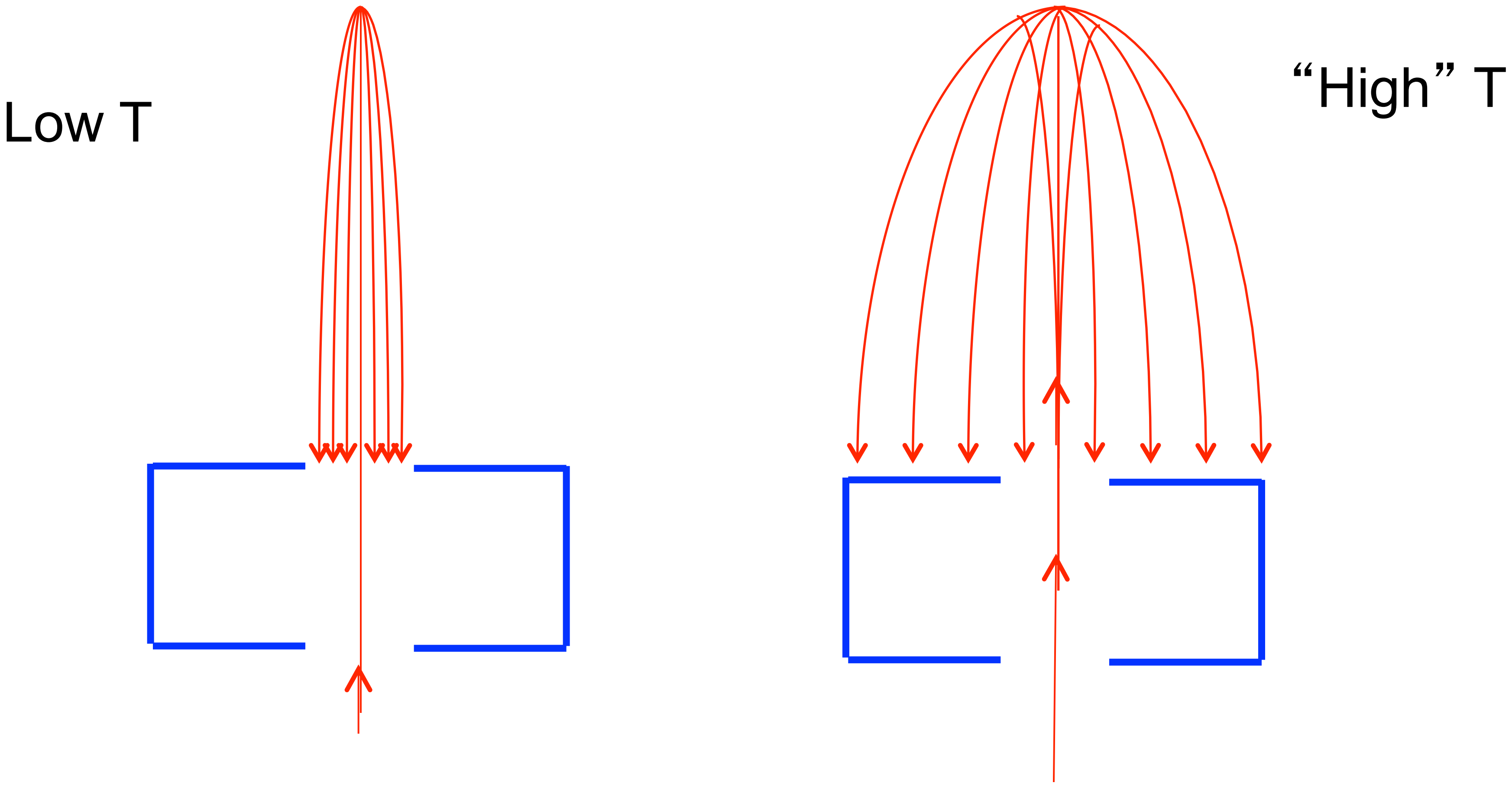
Synchronize on the way up

Compare on the way down

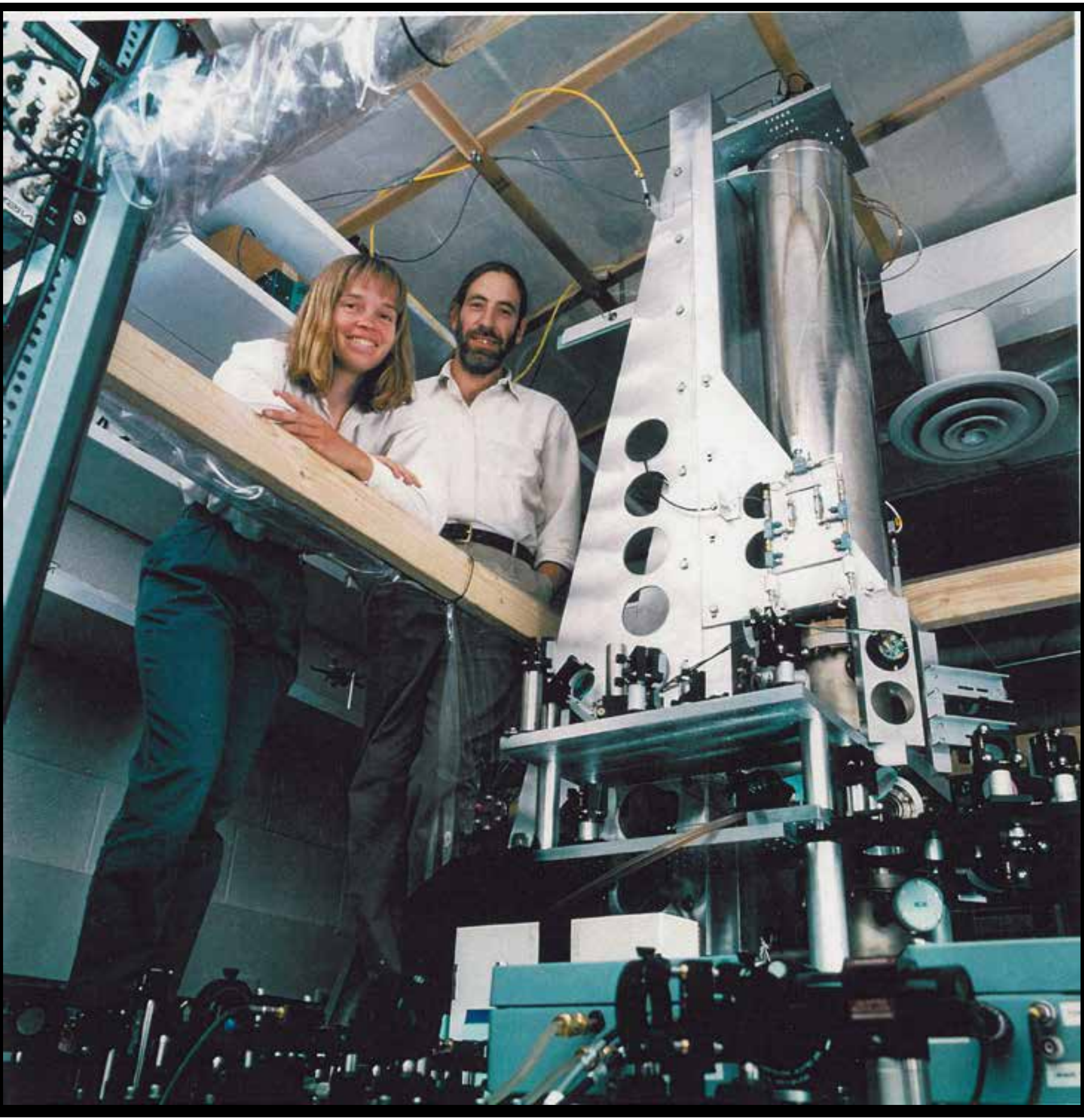
Early Fountain: Stanford 1989

"Zacharias" Fountain: Paris 1991

The importance of low temperature



NIST F-1



Atomic Fountain Clocks Today

Fountain clocks using Cs and Rb operate in standards labs around the world. The best of these have accuracies of about 1 x 10^{-16} or less, and together the Cs fountains determine the rate of international atomic time.

The accuracy of Cs fountains is in part limited by collisional frequency shifts. Rb has a smaller collisional shift. Blackbody shifts have also proved to be important.

Laser-cooled, trapped ion clocks and optical lattice clocks are now exceeding the performance of neutral atom fountains.

A single, trapped ion at NIST gives an accuracy of better than 8 x 10^{-18}.

Neutral atoms (Sr) in optical lattices are at 2.4 x 10^{-18} *accuracy* at NIST/JILA.

This is equivalent to about one second in the age of the universe!

Questions?

Sub-Doppler cooling limit—trapping in lattice

Fountain clocks

Lattice clocks

A benign trap (no light to heat the atoms) is a magneto-static trap.