Victorian Summer School on Ultracold Atoms

Course: Laser Cooling and Trapping of Atoms

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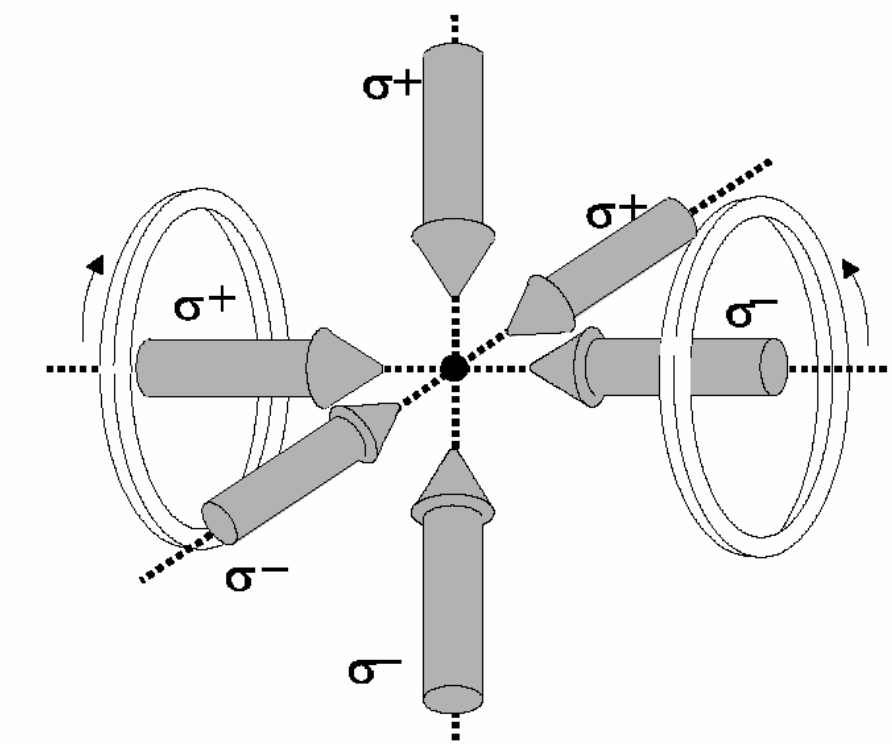
1. Magneto-optical trap
2. Sub-Doppler temperatures
3. Polarisation-gradient cooling
4. Laser cooling and BEC on atom chip

Magneto-optical trap

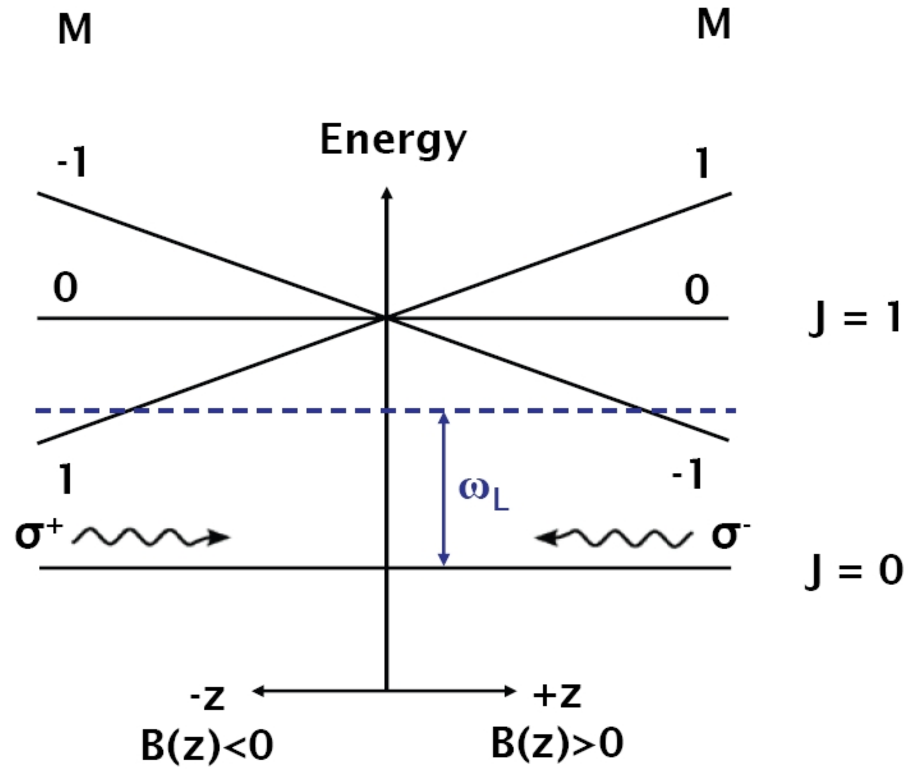


• Three pairs of counterpropagating σ+-σ- laser beams (power 5 mW – 50 mW per beam),

• Quadrupole magnetic field provided by a pair coils in anti-Helmholtz configuration (optimal gradient ~ 10 G/cm)

• Idea proposed by Jean Dalibard in 1987

• Realised by Raab, Prentiss, Cable, Chu and Pritchard in 1987 (Bell labs/ MIT collaboration)



Consider low intensity limit: $\Omega << \Gamma$

$$b = \nabla B$$

$$F = F_{\sigma^+} - F_{\sigma^-}$$

$$= \frac{\hbar k \Gamma}{2} \left[\frac{\Omega^2/2}{(\delta - kv - bz)^2 + (\Gamma/2)^2} - \frac{\Omega^2/2}{(\delta + kv + bz)^2 + (\Gamma/2)^2} \right]$$

$$F(v,z) = -\hbar k \Omega^2 \frac{\delta \Gamma}{\left(\delta^2 + \Gamma^2/4\right)^2} \left(kv + bz\right)$$

Damped harmonic oscillator $$\ddot{z} + \beta\dot{z} + \omega^2 z = 0$$

$$\beta = \frac{\hbar k^2 \Omega^2 \delta\Gamma}{M\left[\delta^2 + \Gamma^2/4\right]^2} \qquad \omega^2 = \frac{\hbar k \Omega^2 \delta\Gamma}{M\left[\delta^2 + \Gamma^2/4\right]^2} b$$

$$\frac{\beta^2}{\omega^2} = \frac{\hbar k^3 \Omega^2 \delta\Gamma}{bM\left[\delta^2 + \Gamma^2/4\right]^2}$$

In optimal conditions for cooling (damping) $2\delta/\Gamma = -1$ and $4\Omega^2/\Gamma^2 = 1$

$$\frac{\gamma^2}{4\omega^2} = \frac{\pi E_{rec}}{4\hbar\beta\lambda}$$

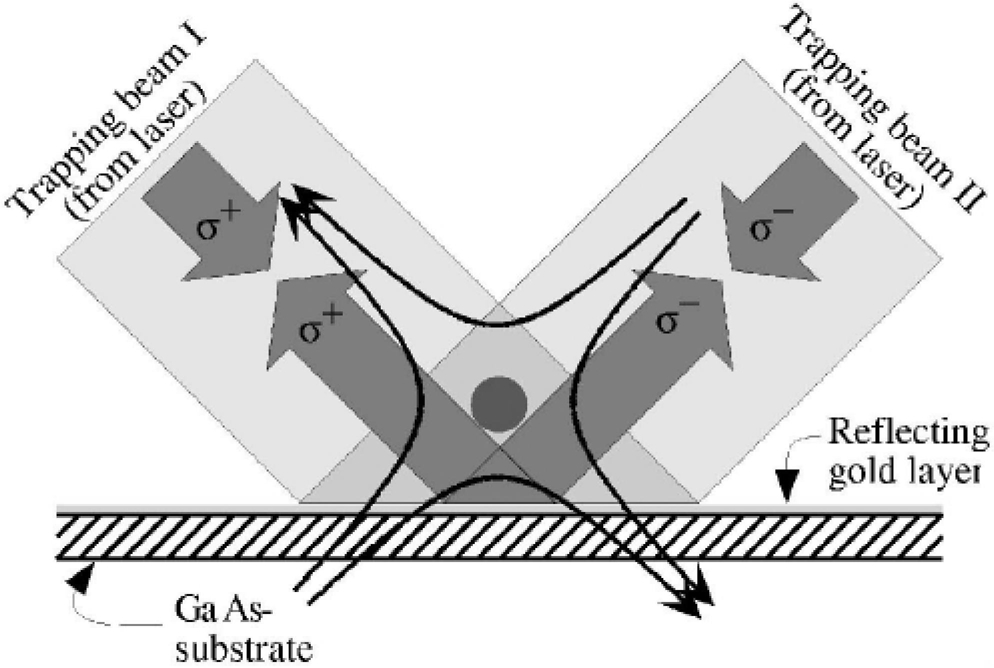
= 25 for Na

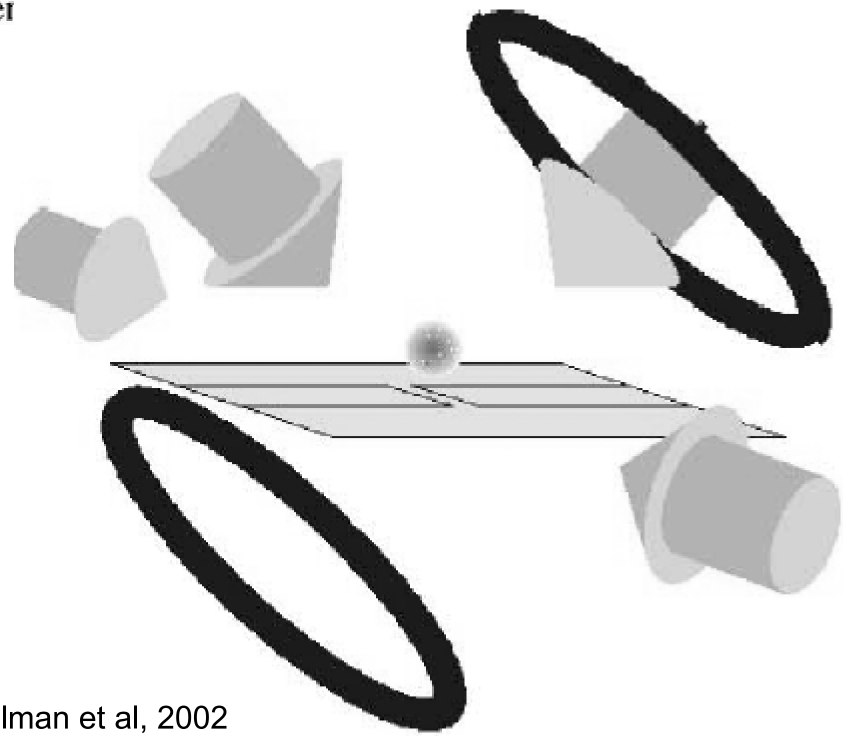
= 2.5 for Cs

$$U_{tr} \approx k_B \times 2K$$

Doppler limit for Rb $$k_B T_{Dop} = \hbar\Gamma/2 = k_B \times 140\,\mu K$$

Mirror MOT (Reichel, Munich, 2001)





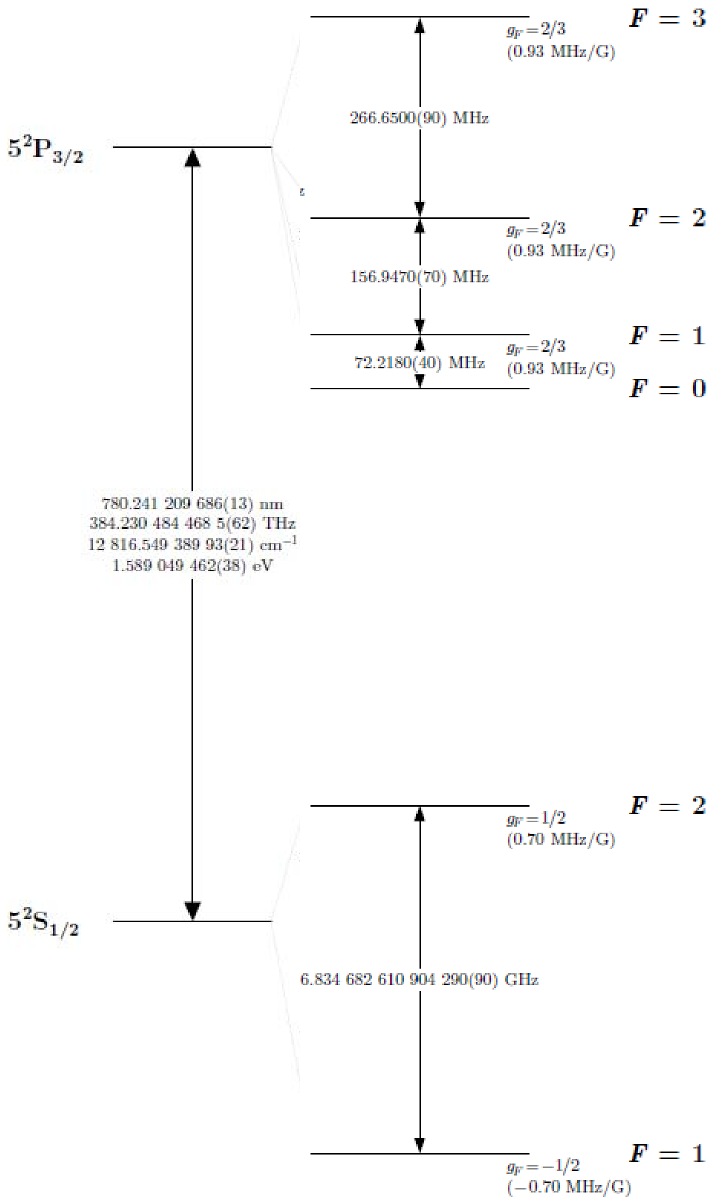
R. Folman et al, 2002

Cooling parameters

	^{7}Li	^{23}Na	^{87}Rb	^{133}Cs
$\lambda_0\,(nm)$	671	589	780	852
$\Gamma/2\pi \quad (MHz)$	5.9	9.9	5.9	5.3
$I_0 = \frac{\hbar\omega\Gamma k^2}{12\pi} \quad (mW/cm^2)$	2.5	6.3	1.6	1.1
$T_{Dop} = \frac{\hbar\Gamma}{2k_B} \quad (\mu K)$	140	240	140	120
$\frac{E_{rec}}{k_B} = \frac{\hbar^2 k^2}{2Mk_B} \quad (\mu K)$	3	1.2	0.18	0.1

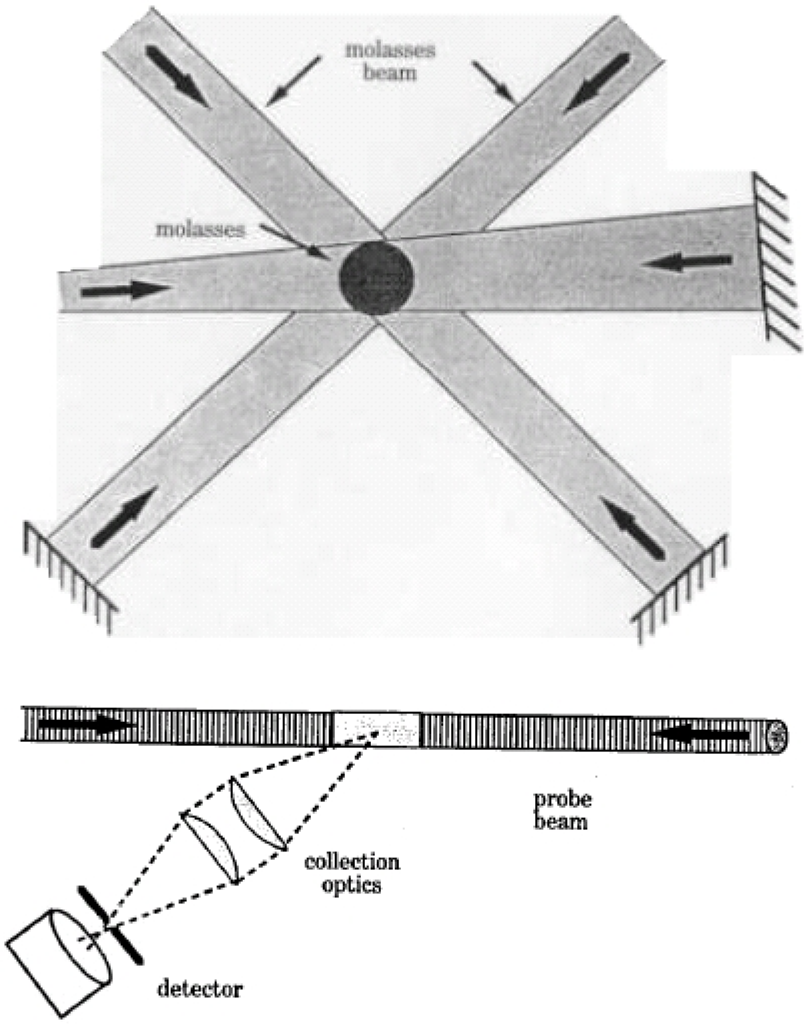
For Na: $v_\Gamma = \frac{\Gamma}{k} = 6\,m/s \qquad v_{rec} = 3cm/s$

Quantum level diagram in ^{87}Rb



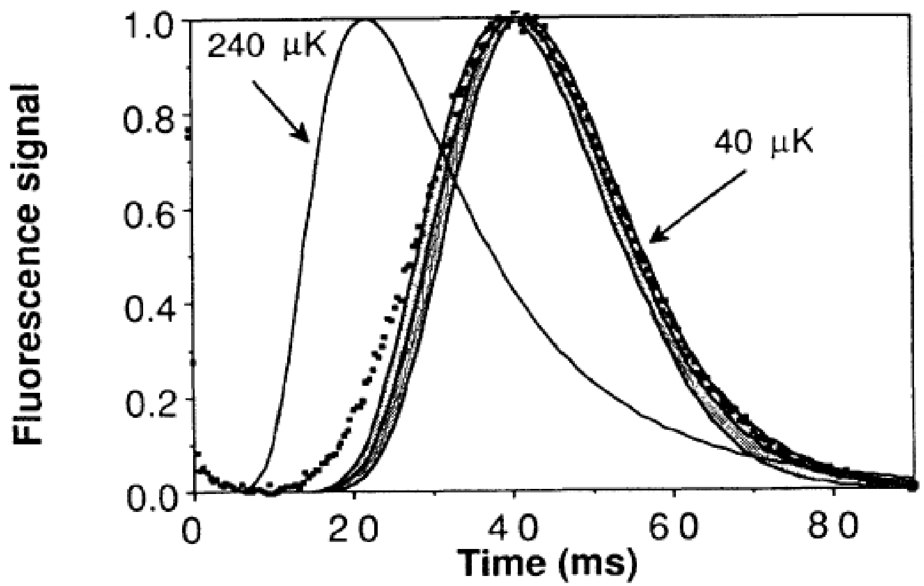
D. Steck, 2003

Sub-Doppler temperature in optical molasses (W. Phillips et al, 1988)

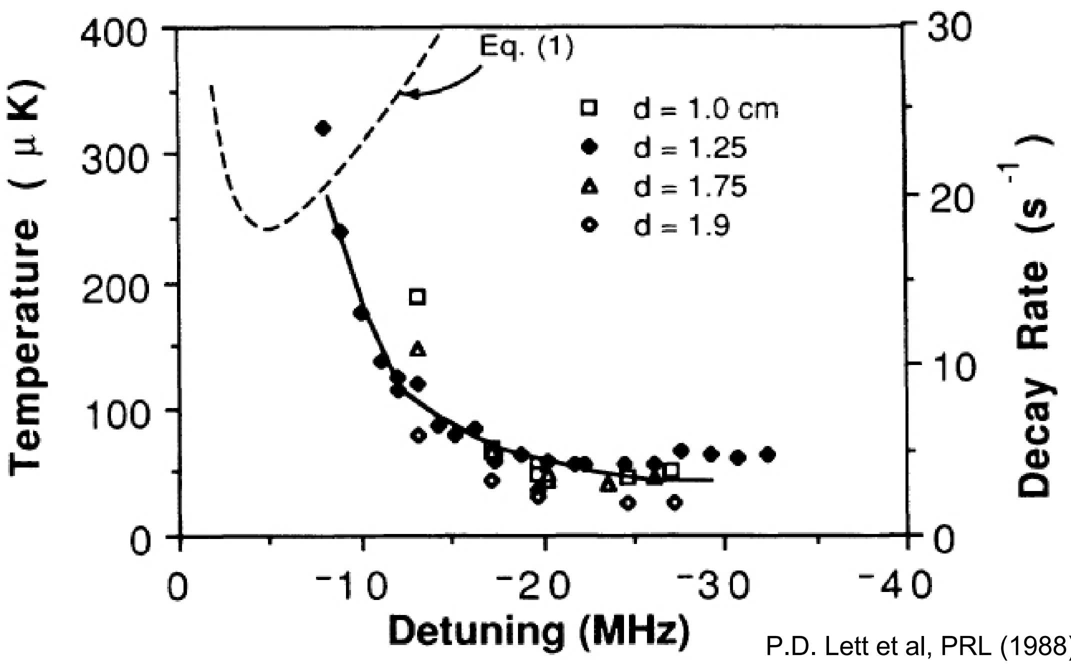


P.D. Lett et al, PRL (1988)

1) Time-of-flight



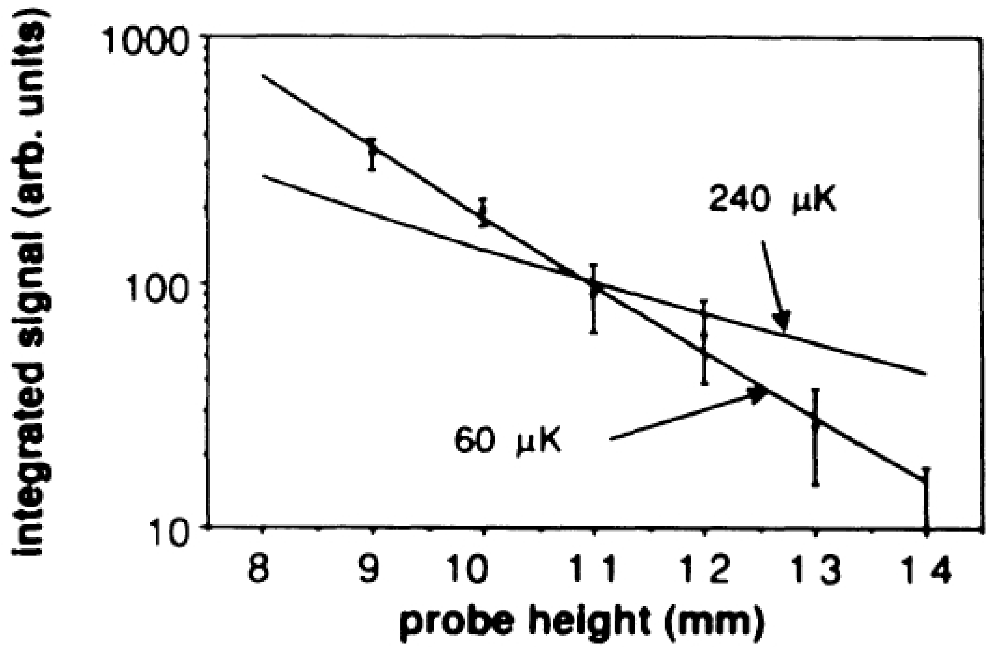
2) Dependence on detuning



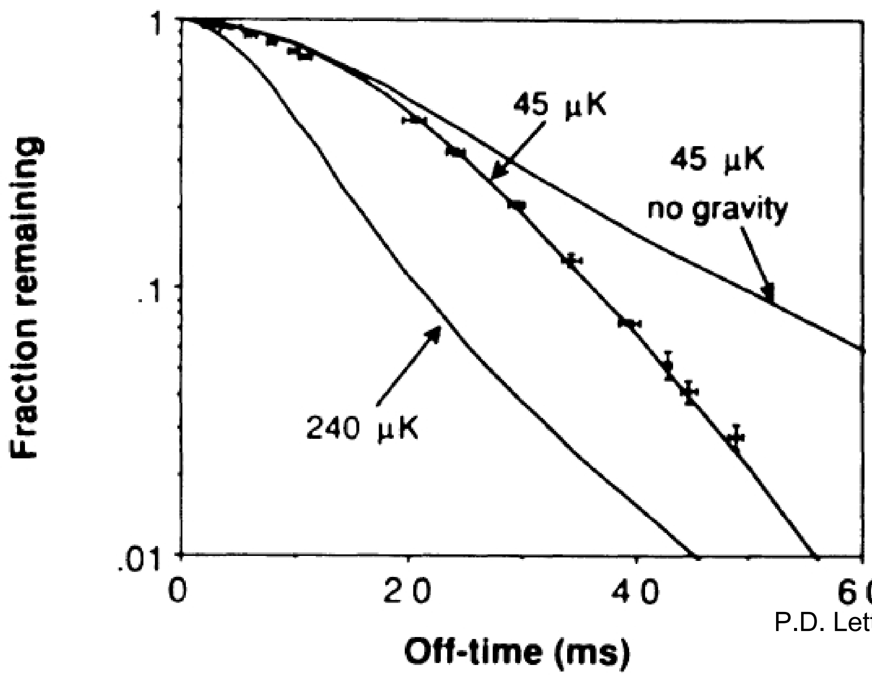
P.D. Lett et al, PRL (1988)

$$k_B T = \frac{D}{\alpha} = \frac{\hbar\Gamma}{4}\left(\frac{\Gamma}{2\delta} + \frac{2\delta}{\Gamma}\right)$$

3) Fountain



4) Release and recapture



P.D. Lett et al, PRL (1988)

J. Dalibard and C. Cohen-Tannoudji
Vol. 6, No. 11/November 1989/J. Opt. Soc. Am. B

Laser cooling below the Doppler limit by polarization gradients: simple theoretical models

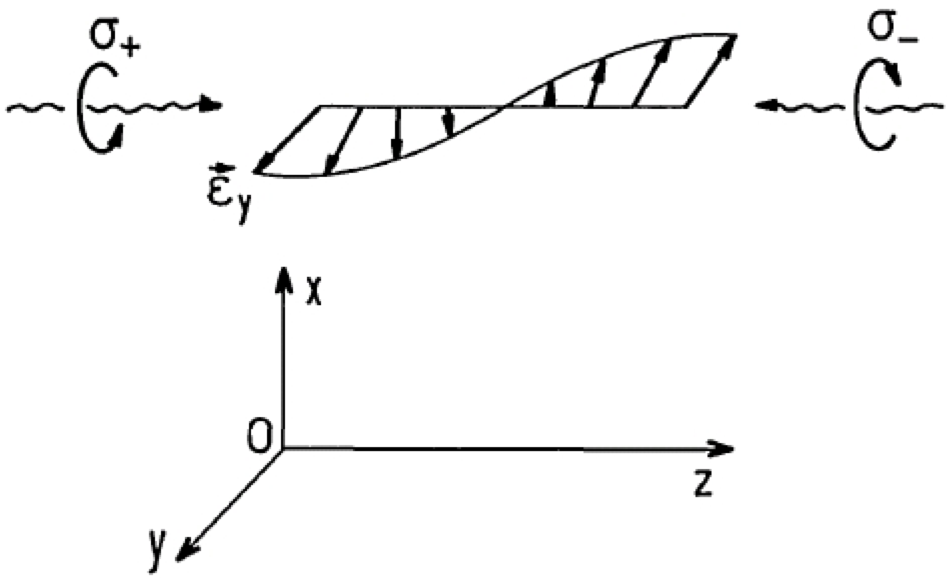
J. Dalibard and C. Cohen-Tannoudji

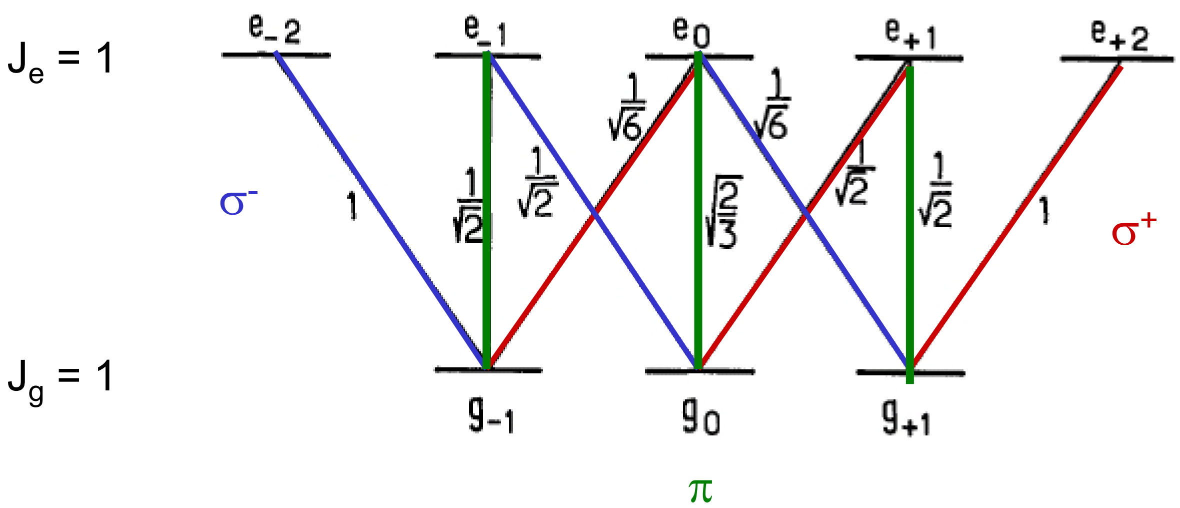
σ^+ - σ^- configuration

$$\mathbf{E}(z,t) = \mathbf{E}^+(z)e^{-i\omega_l t} + c.c. \qquad \mathbf{E}^+(z) = \mathbf{e}_+ E_0 e^{ikz} + \mathbf{e}_- E_0 e^{-ikz}$$

$$\mathbf{e}_+ = -\frac{1}{\sqrt{2}}(\mathbf{e}_x + i\mathbf{e}_y) \qquad \mathbf{e}_- = \frac{1}{\sqrt{2}}(\mathbf{e}_x - i\mathbf{e}_y)$$

$$\mathbf{E}^+(z) = -i\sqrt{2}E_0\left(\mathbf{e}_x \sin kz + \mathbf{e}_y \cos kz\right)$$





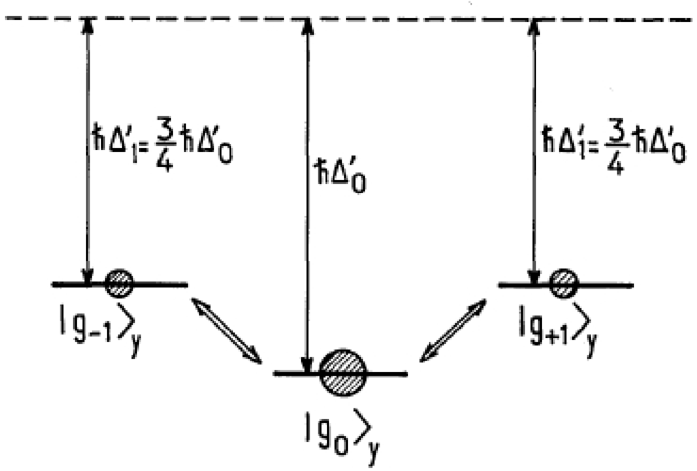
<u>Atom at rest</u> (z = 0)

π polarization leads to accumulation of atoms in g_0 (pumping rates ¼ and 1/9).

Steady state populations 4/17, 9/17, 4/17.

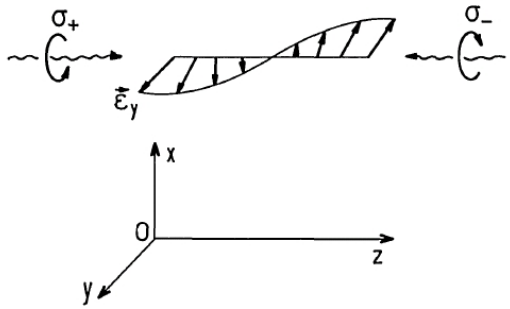
Stronger coupling leads to the light shift

$$\Delta_0' = \frac{4}{3}\Delta_1'$$



J. Dalibard et al, JOSA (1989)

Moving atom and motion-induced orientation



$$z = vt \longrightarrow \varphi = -kz = kvt$$

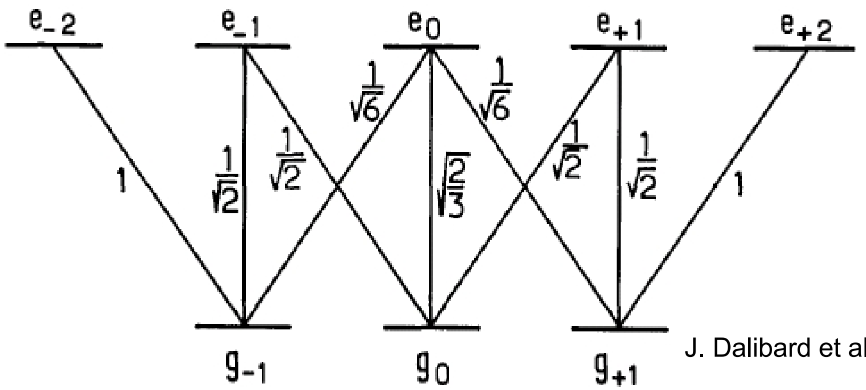
In the rotating frame the new $|g_0\rangle$ is contaminated by $|g_1\rangle$ and $|g_{-1}\rangle$

$$|g_0\rangle_{rot} = |g_0\rangle + \frac{kv}{\sqrt{2}\left(\Delta_0' - \Delta_1'\right)}|g_{+1}\rangle + \frac{kv}{\sqrt{2}\left(\Delta_0' - \Delta_1'\right)}|g_{-1}\rangle$$

$$\langle J_z\rangle_{st} = \frac{40}{17}\frac{\hbar kv}{\Delta_0'} \longrightarrow \Pi_{+1} - \Pi_{-1} = \frac{40}{17}\frac{kv}{\Delta_0'}$$

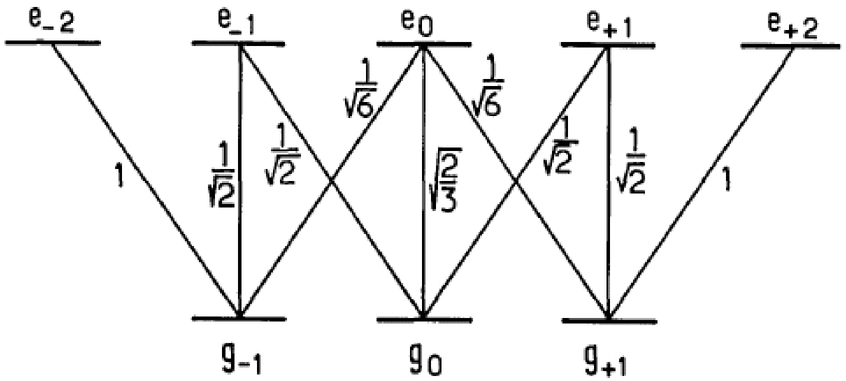
For v > 0 and $\delta < 0$ $\longrightarrow$ $\Pi_{-1} > \Pi_{+1}$

Different populations lead to unbalanced radiation pressure, eg for v >0 an atom will scatter more counter-propagating σ- photons than co-propagating σ+ photons.



J. Dalibard et al, JOSA (1989)

Does not work for $J_g = 1/2$



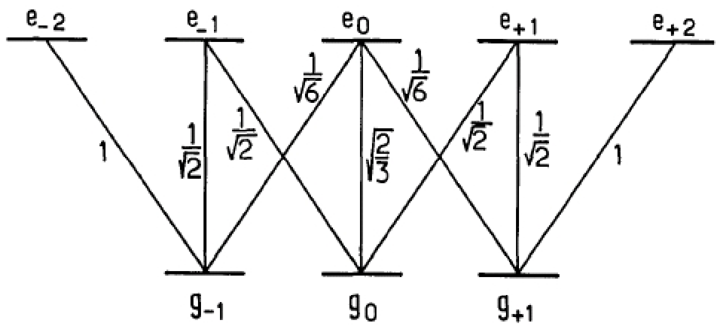
$$\hat{V} = -\frac{\hbar\Omega}{2}\left(|g_1\rangle\langle e_2| + \frac{1}{\sqrt{2}}|g_0\rangle\langle e_1| + \frac{1}{\sqrt{6}}|g_{-1}\rangle\langle e_0|\right)e^{i(\omega_- t - kz)} \qquad \Omega = \frac{2dE_0}{\hbar}$$

$$-\frac{\hbar\Omega}{2}\left(|g_{-1}\rangle\langle e_{-2}| + \frac{1}{\sqrt{2}}|g_0\rangle\langle e_{-1}| + \frac{1}{\sqrt{6}}|g_1\rangle\langle e_0|\right)e^{i(\omega_+ t - kz)} + h.c. \qquad \omega_\pm = \omega_l \pm kv$$

$$\mathbf{F}_\sigma = \left\langle -\frac{dV}{dz}\right\rangle = -i\hbar\mathbf{k}\Omega\left[\rho(e_2, g_1) + \frac{1}{\sqrt{2}}\rho(e_1, g_0) + \frac{1}{\sqrt{6}}\rho(e_0, g_{-1})\right]$$

$$i\hbar\mathbf{k}\Omega\left[\rho(e_{-2}, g_{-1}) + \frac{1}{\sqrt{2}}\rho(e_{-1}, g_0) + \frac{1}{\sqrt{6}}\rho(e_0, g_1)\right] + c.c.$$

$$
\begin{aligned}
\mathbf{F}_\sigma &= \frac{\hbar \mathbf{k}\Gamma}{2}\left[\Pi_1\left(s_+ - \frac{s_-}{6}\right) + \Pi_0\left(\frac{s_+ - s_-}{2}\right) + \Pi_{-1}\left(\frac{s_+}{6} - s_-\right)\right] \\
&\quad + C_r\left(\frac{s_+ - s_-}{6}\right) - \frac{1}{3}C_i\left(s_+\frac{\delta - kv}{\Gamma} + s_-\frac{\delta + kv}{\Gamma}\right)]
\end{aligned}
$$

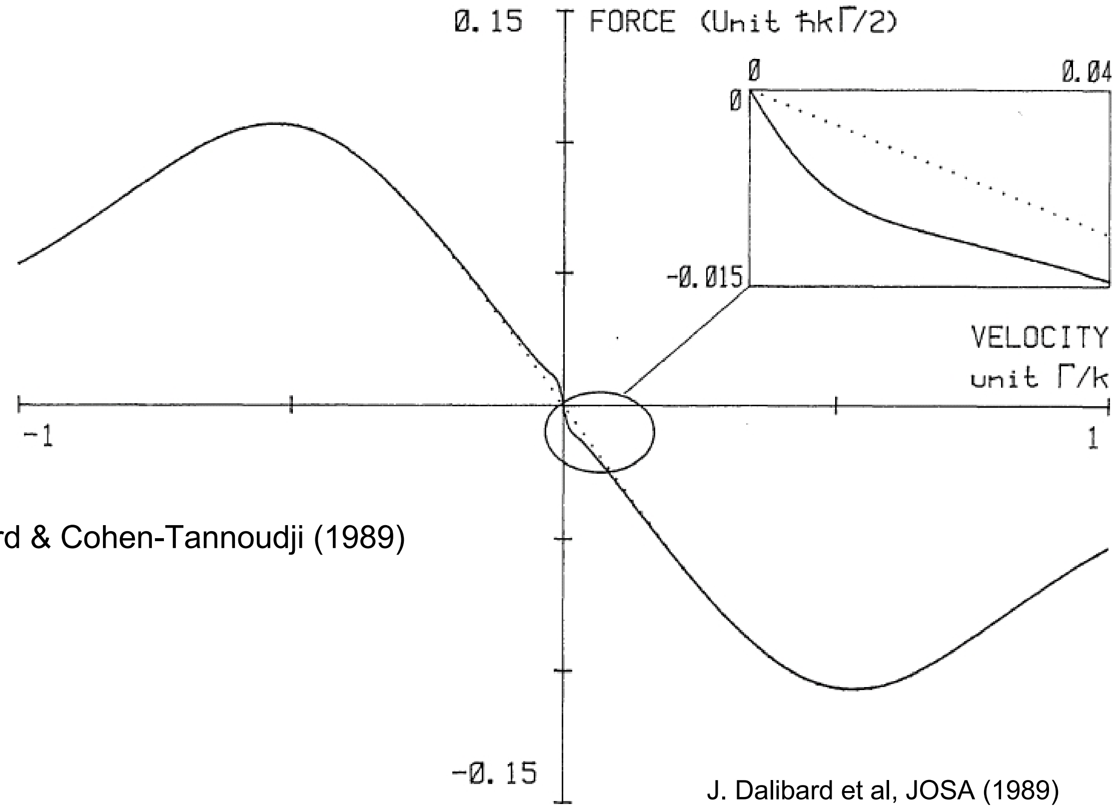


$$C_r = \mathrm{Re}\left[\langle g_1|\rho|g_{-1}\rangle e^{-2ikvt}\right]$$

$$C_i = \mathrm{Im}\left[\langle g_1|\rho|g_{-1}\rangle e^{-2ikvt}\right]$$

$$s_\pm = \frac{\Omega^2/2}{(\delta \mp kv)^2 + \Gamma^2/4}$$

Evaluation of Π_i and C_i is given in Dalibard & Cohen-Tannoudji (1989)



J. Dalibard et al, JOSA (1989)

In the low velocity domain

$$F_\sigma = \frac{\hbar k \Gamma}{2} s_0 \left[\frac{5}{6}(\Pi_1 - \Pi_{-1}) - \frac{2}{3}\frac{\delta}{\Gamma} C_i \right] \qquad s_0 = \frac{\Omega^2/2}{\delta^2 + \Gamma^2/4}$$

$$\mathbf{F}_\sigma \cong -\alpha v \qquad \alpha = \frac{120}{17} \frac{-\delta\Gamma}{5\Gamma^2 + 4\delta^2} \hbar k^2$$

← Independent on Ω!!!

$$D = \left[\frac{18}{170} + \frac{4}{17} + \frac{36}{17} \frac{1}{1 + 4\delta^2/5\Gamma^2} \right] \hbar^2 k^2 \Gamma s_0$$

$$\boxed{k_B T = \frac{\hbar \Omega^2}{|\delta|} \left[\frac{29}{300} + \frac{254}{75} \frac{\Gamma^2/4}{\delta^2 + \Gamma^2/4} \right]}$$

J = 1 → J = 2 atom

$$\boxed{k_B T = \frac{D}{\alpha} = \frac{\hbar \Gamma}{4} \left(\frac{\Gamma}{2\delta} + \frac{2\delta}{\Gamma} \right)}$$

compare to J = 0 → J = 1 atom

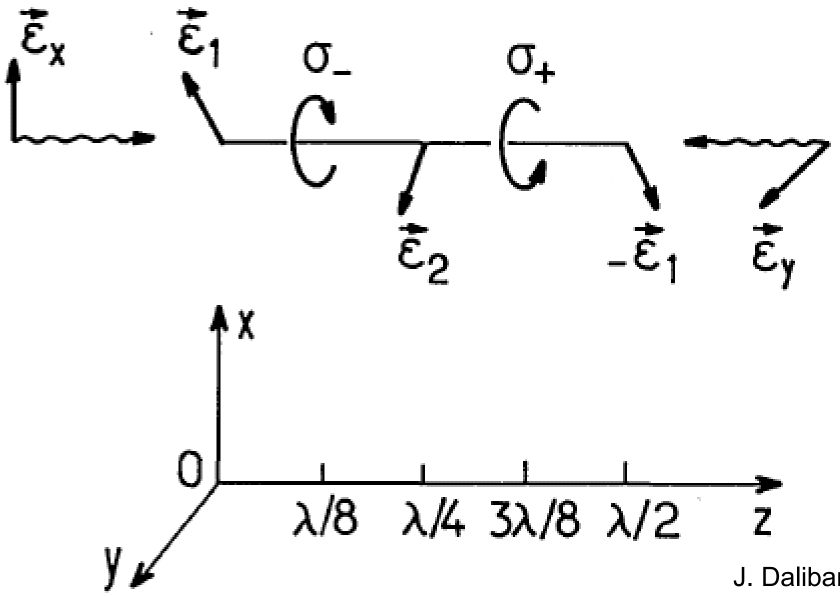
Lin ⊥ Lin laser configuration

Again follow J. Dalibard and C. Cohen-Tannoudji, JOSA B **6**, 2025 (1989)

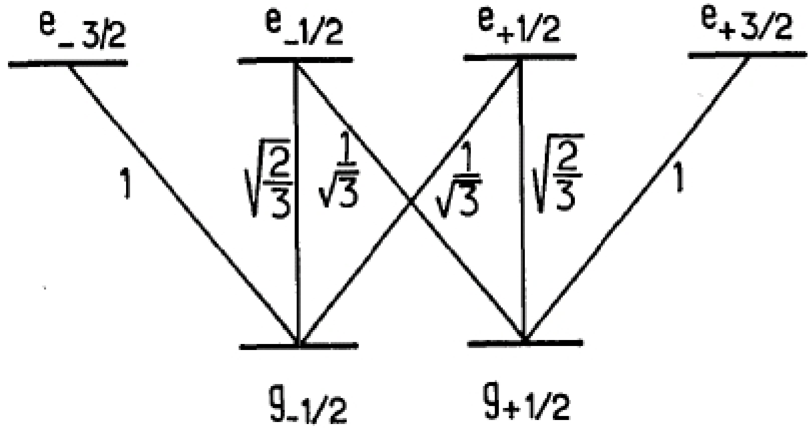
$$\mathbf{E}(z,t) = \mathbf{E}^{+}(z)e^{-i\omega_l t} + c.c.$$

$$\mathbf{E}^{+}(z) = \mathbf{e}_x E_0 e^{ikz} + \mathbf{e}_y E_0 e^{-ikz}$$

$$= E_0\sqrt{2}\left(\cos kz \frac{\mathbf{e}_x + \mathbf{e}_y}{\sqrt{2}} - i \sin kz \frac{\mathbf{e}_x - \mathbf{e}_y}{\sqrt{2}}\right)$$



J. Dalibard et al, JOSA (1989)



J. Dalibard et al, JOSA (1989)

$$\hat{V} = -\frac{\hbar\Omega}{\sqrt{2}}\sin kz\left(|e_{3/2}\rangle\langle g_{1/2}| + \frac{1}{\sqrt{3}}|e_{1/2}\rangle\langle g_{-1/2}|\right)e^{-i\omega_l t}$$

$$- \frac{\hbar\Omega}{\sqrt{2}}\cos kz\left(|e_{-3/2}\rangle\langle g_{-1/2}| + \frac{1}{\sqrt{3}}|e_{-1/2}\rangle\langle g_{1/2}|\right)e^{-i\omega_l t} \quad + h.c.$$

$$\Omega = \frac{2dE_0}{\hbar}$$

$$F_\perp = \left\langle -\frac{d\hat{V}}{dz}\right\rangle$$

$$= \frac{\hbar k\Omega}{\sqrt{2}}\cos kz\left[\rho(g_{1/2}, e_{3/2}) + \frac{1}{\sqrt{3}}\rho(g_{-1/2}, e_{1/2}) + c.c.\right]$$

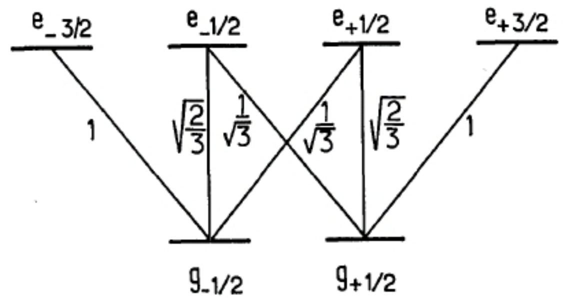
$$- \frac{\hbar k\Omega}{\sqrt{2}}\sin kz\left[\rho(g_{-1/2}, e_{-3/2}) + \frac{1}{\sqrt{3}}\rho(g_{1/2}, e_{-1/2}) + c.c.\right]$$

In the limits of low intensity ($\Omega \ll \Gamma$) and low velocities ($kv \ll \Gamma$)

The optical coherence adiabatically follows the ground-state population

$$\tilde{\rho}(g_{1/2}, e_{3/2}) = \frac{\Omega/\sqrt{2}}{\delta - i\Gamma/2}\Pi_{1/2}\sin kz$$

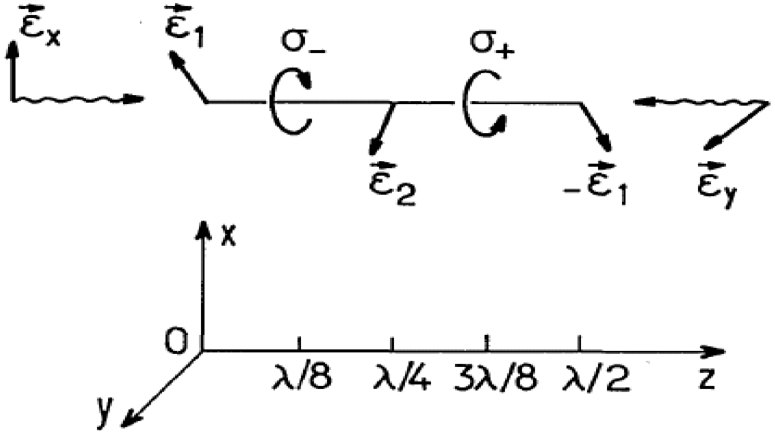
$$F_{\perp} = -\frac{2}{3}\hbar k \delta s_0 \left(\Pi_{1/2} - \Pi_{-1/2}\right)\sin 2kz$$



$$\Delta E_{1/2} = \hbar\Delta'_{+} = E_0 - \frac{\hbar\delta s_0}{3}\cos 2kz$$

$$\Delta E_{-1/2} = \hbar\Delta'_{-} = E_0 + \frac{\hbar\delta s_0}{3}\cos 2kz$$

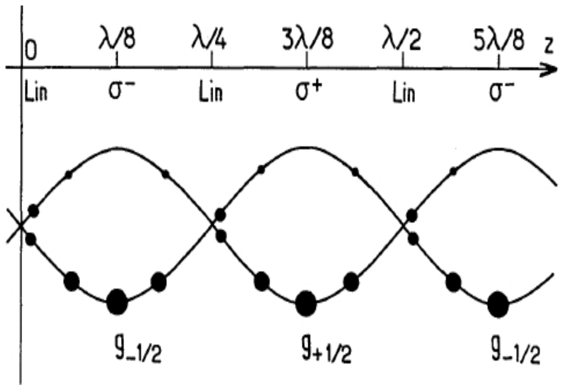
$$E_0 = \frac{2}{3}\hbar\delta s_0$$



$$f_{\pm 1/2} = -\frac{d}{dz}\Delta E_{\pm 1/2}$$

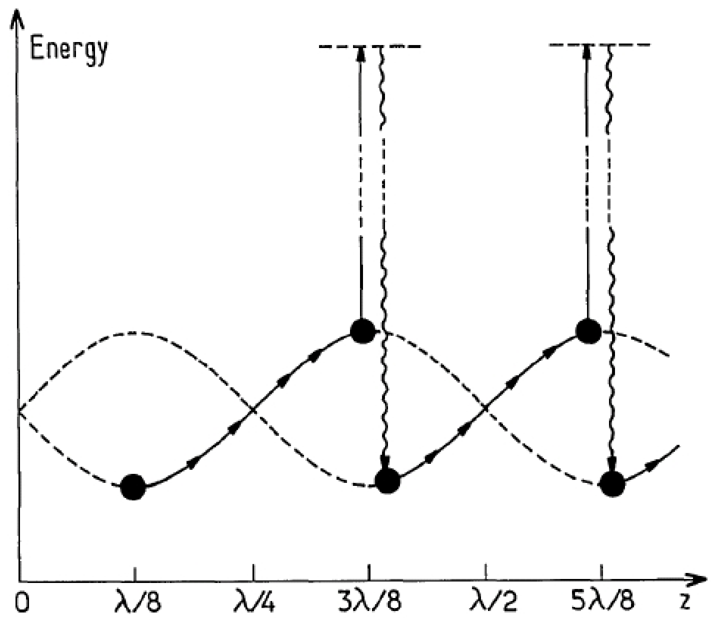
$$F_{\perp} = f_{1/2}\Pi_{1/2} + f_{-1/2}\Pi_{-1/2}$$

light shift



J. Dalibard et al, JOSA (1989)

Sisyphus cooling



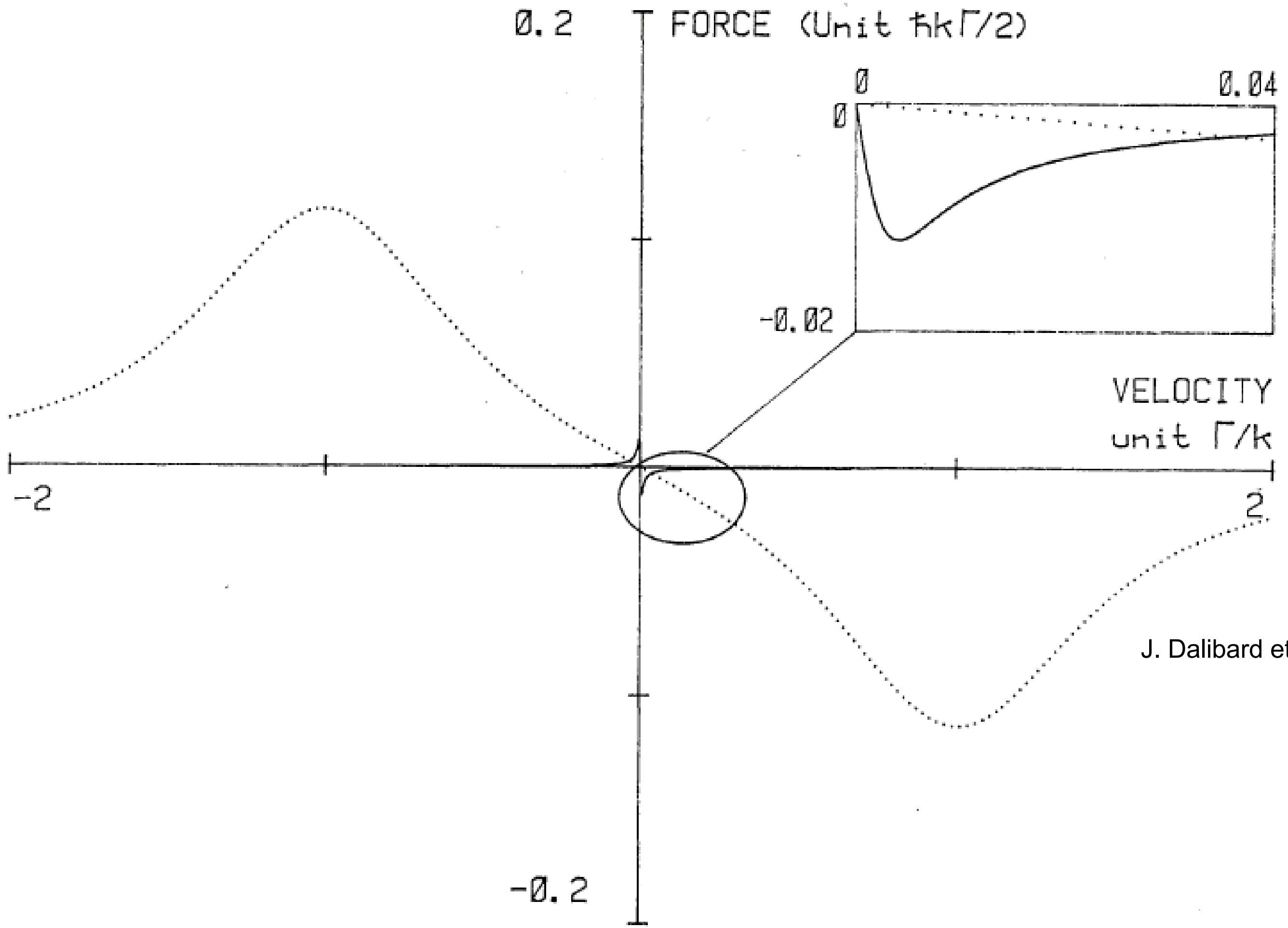
J. Dalibard et al, JOSA (1989)

Optical pumping time τ_p

$$\langle F_\perp \rangle_\lambda = \frac{-\alpha v}{1+v^2/v_{cr}^2} \qquad k v_{cr} = 1/2\tau_p \qquad \alpha = -3\hbar k^2 \frac{\delta}{\Gamma}$$

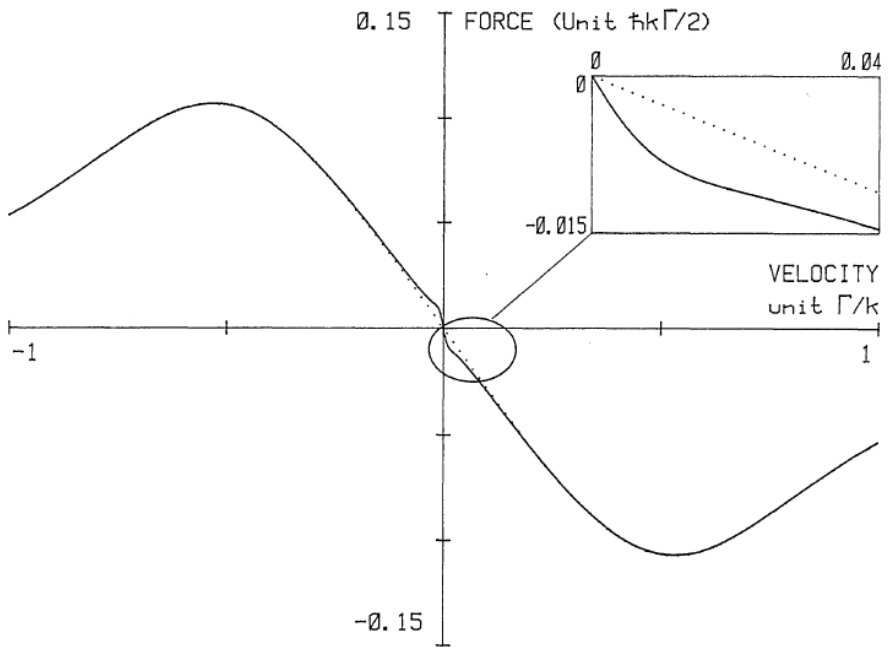
Independent on Ω!!!

$$D = \frac{3}{4}\hbar^2 k^2 \frac{\delta^2}{\Gamma} s_0 \qquad k_B T = \frac{D}{\alpha} \approx \frac{\hbar \Omega^2}{8|\delta|}$$

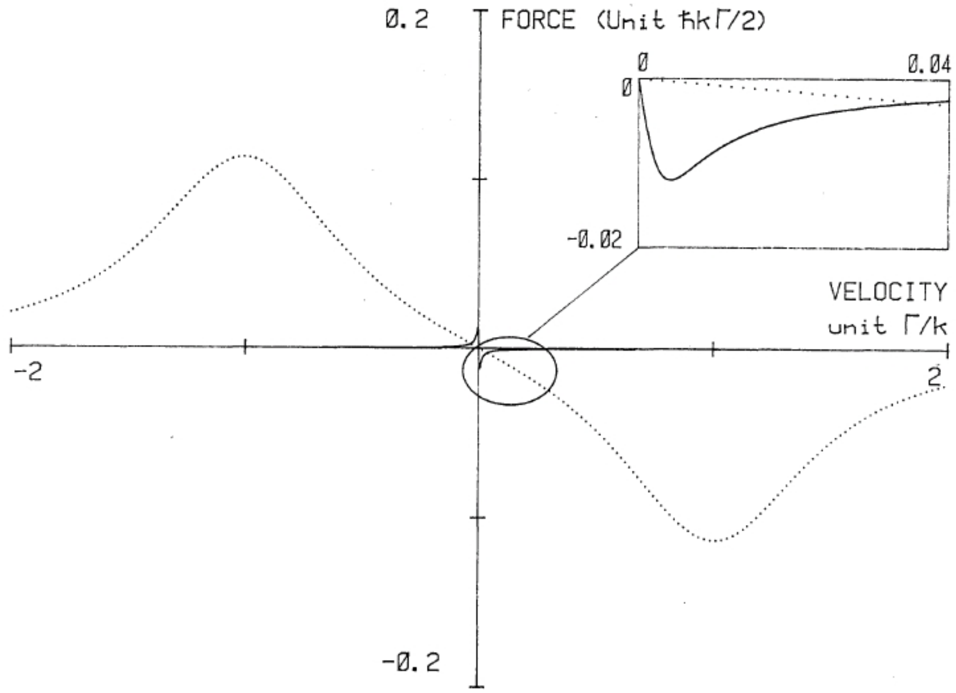


J. Dalibard et al, JOSA (1989)

σ+ - σ-

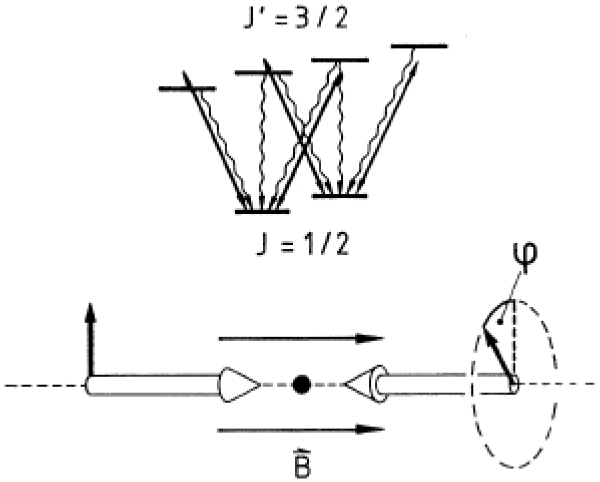


Lin ⊥ lin



J. Dalibard et al, JOSA (1989)

"Lin – 45^0 lin" magneto-optical force (Grimm, Sidorov et al, 1992-93)



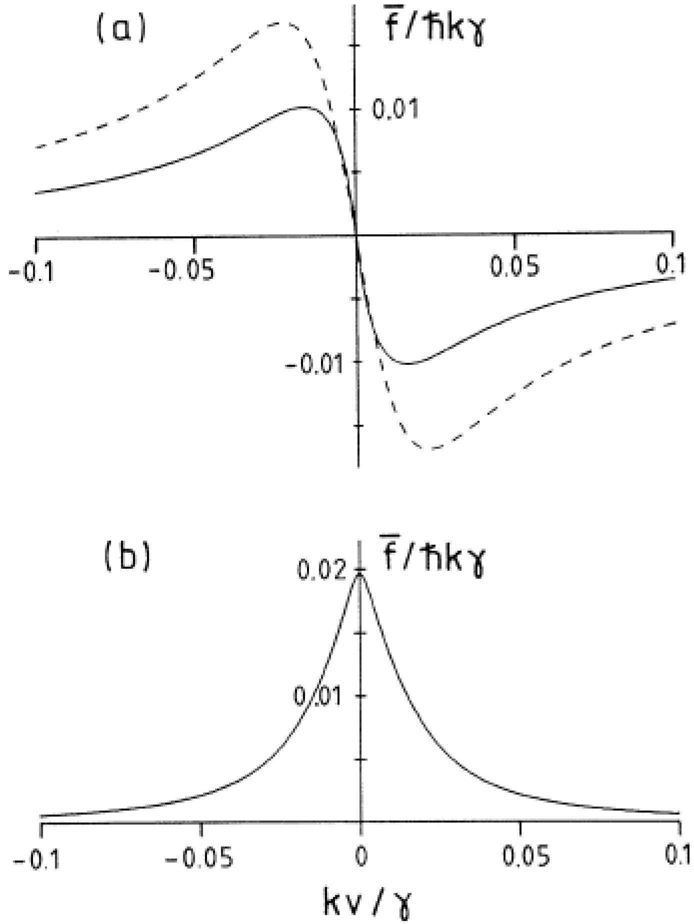


Fig. 2. Two elementary cases of the sub-Doppler radiation force $\bar{f}(v)$. (a) The pure polarization gradient cooling force at $\omega_L=0$, $\Delta=-\gamma$, and $G_0=0.2$ for $\varphi=90°$ (dashed curve) and $\varphi=45°$ (solid curve). (b) The pure sub-Doppler magneto-optical force at $\omega_L=\gamma$, $\Delta_0=0$, $G_0=0.2$, and $\varphi=45°$.

“Lin – 45^0 lin” magneto-optical trap (Salomon et al, 1992)

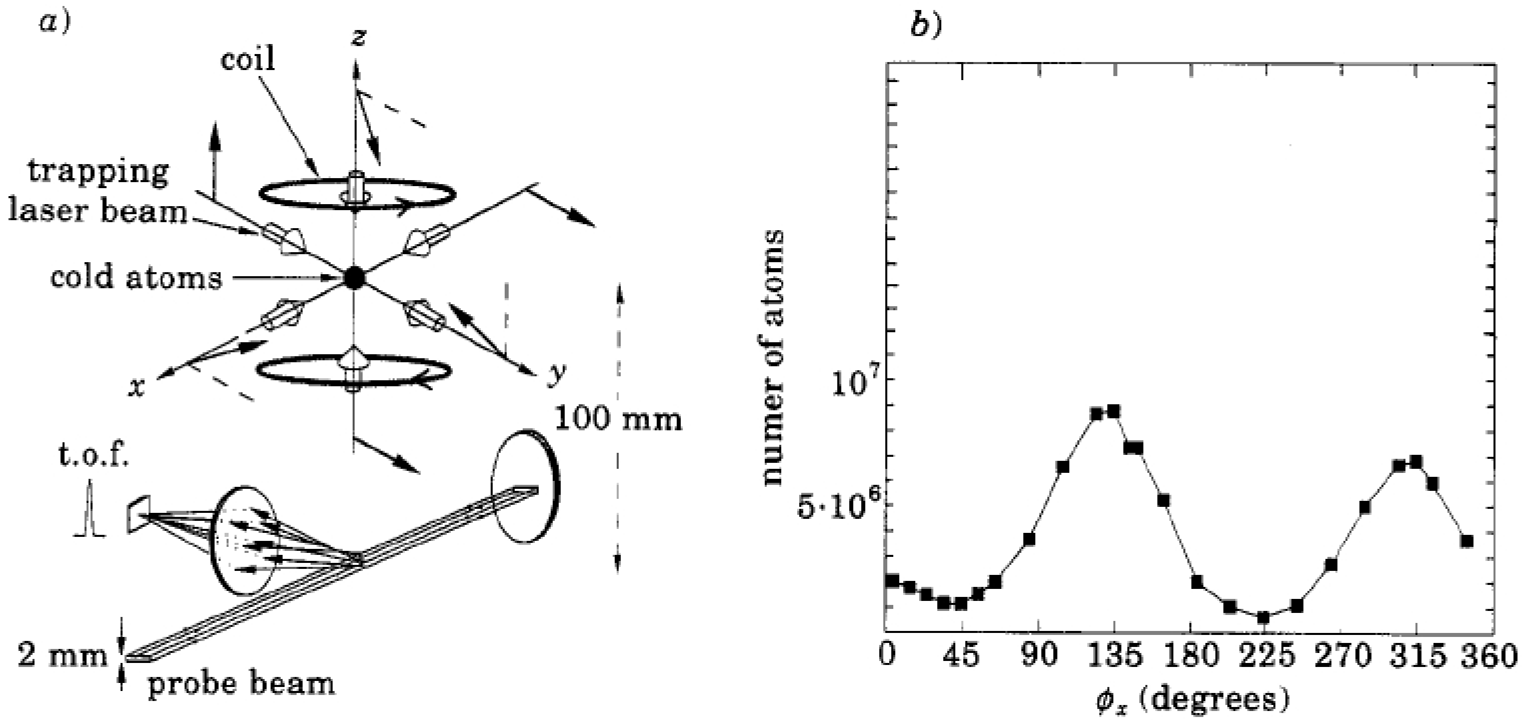
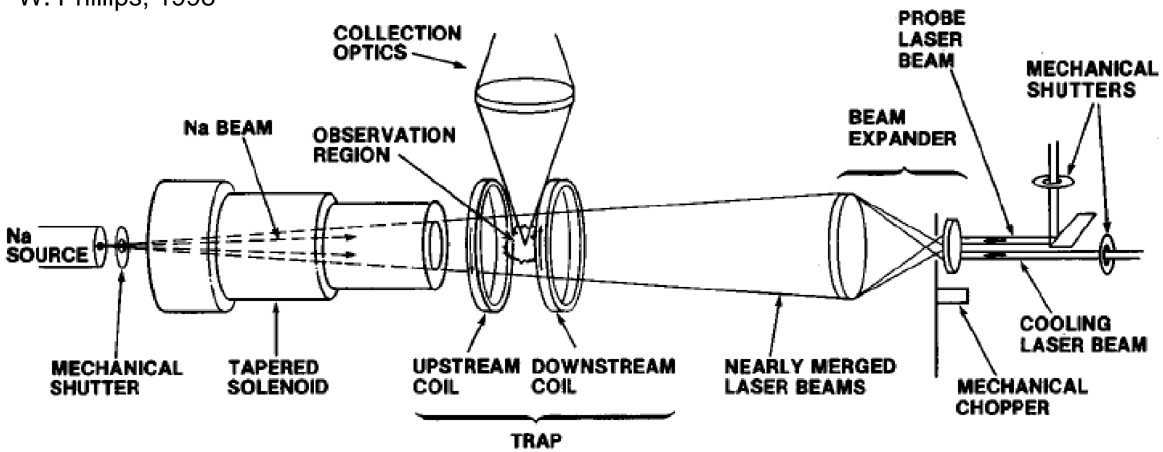


Fig. 1. – *a*) Experimental set-up and polarization configuration. The temperature of the trapped atoms is measured by a time-of-flight technique. *b*) Number of trapped atoms as a function of the angle ϕ_x between the polarization vectors in the Ox-arm of the trap. The locations of the minima and extrema demonstrate the role of the new magneto-optical force of ref. [4] in this trap.

W. Phillips, 1998



$$N_{tr} = \frac{d^2}{\sigma_c}\left(\frac{v_c}{v_{mp}}\right)^4$$

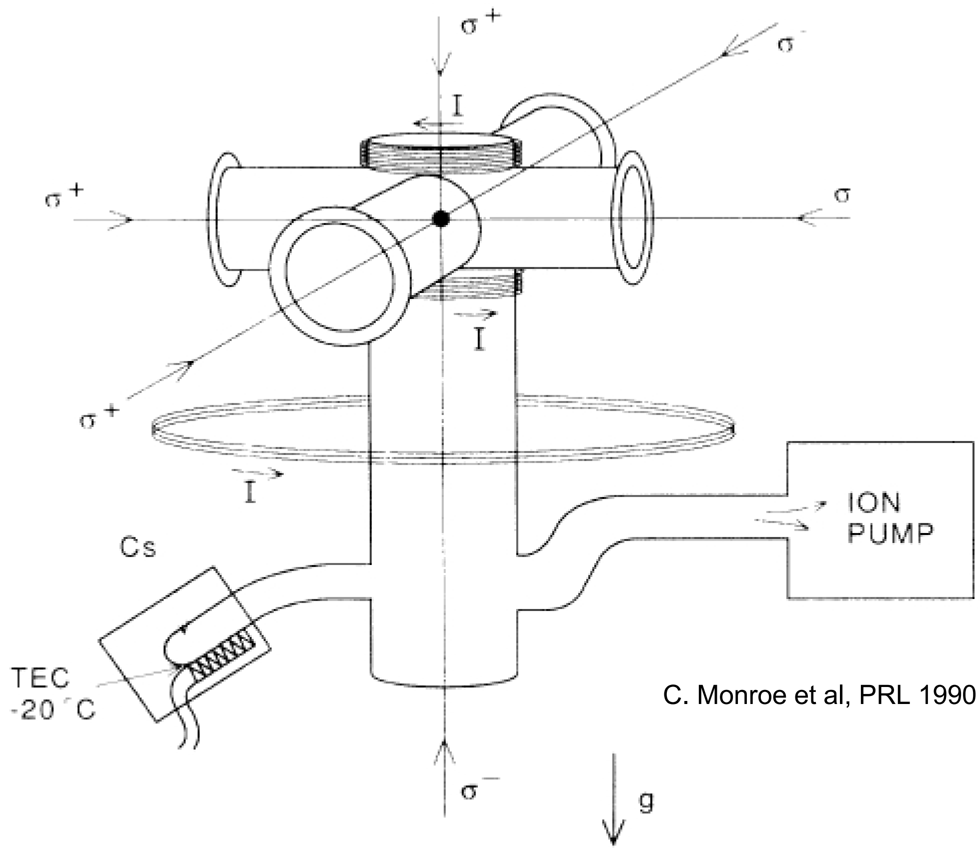
σ – collision rate, d - diameter

$$v_{cr}^2 \sim d$$

$$N_{tr} \sim d^4$$

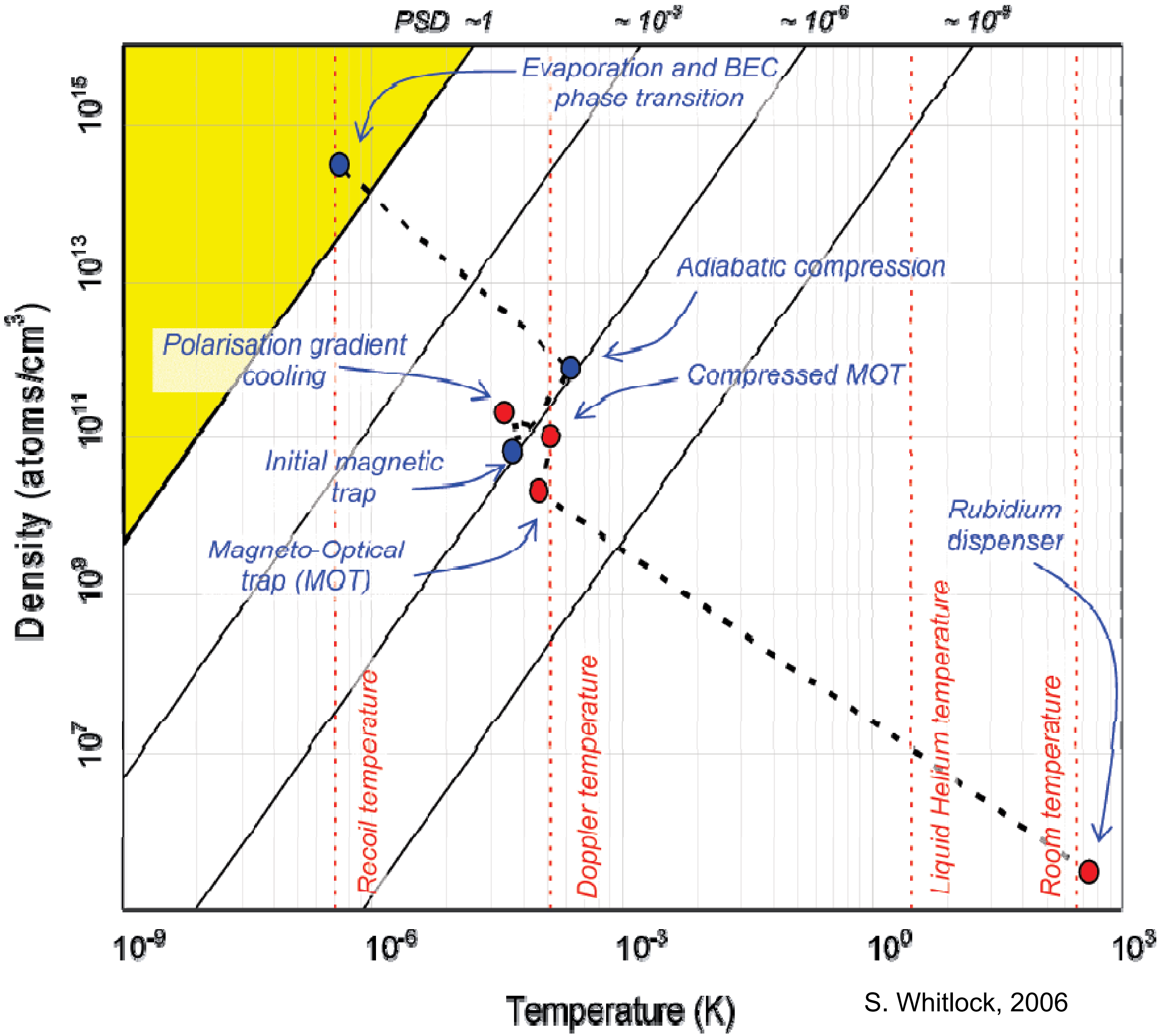
Gibble et al, 1992:

d = 5.5 cm Ntr = 3.6×10^{10} atoms

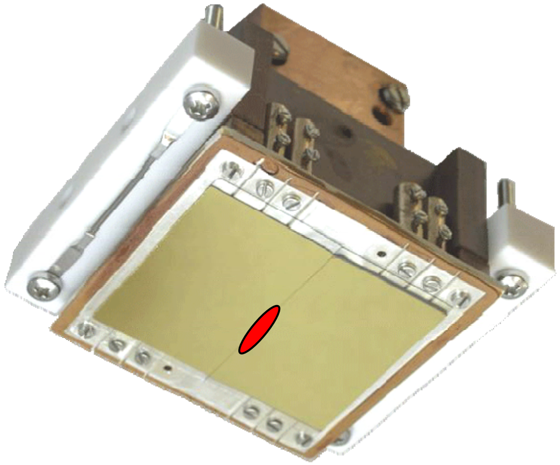


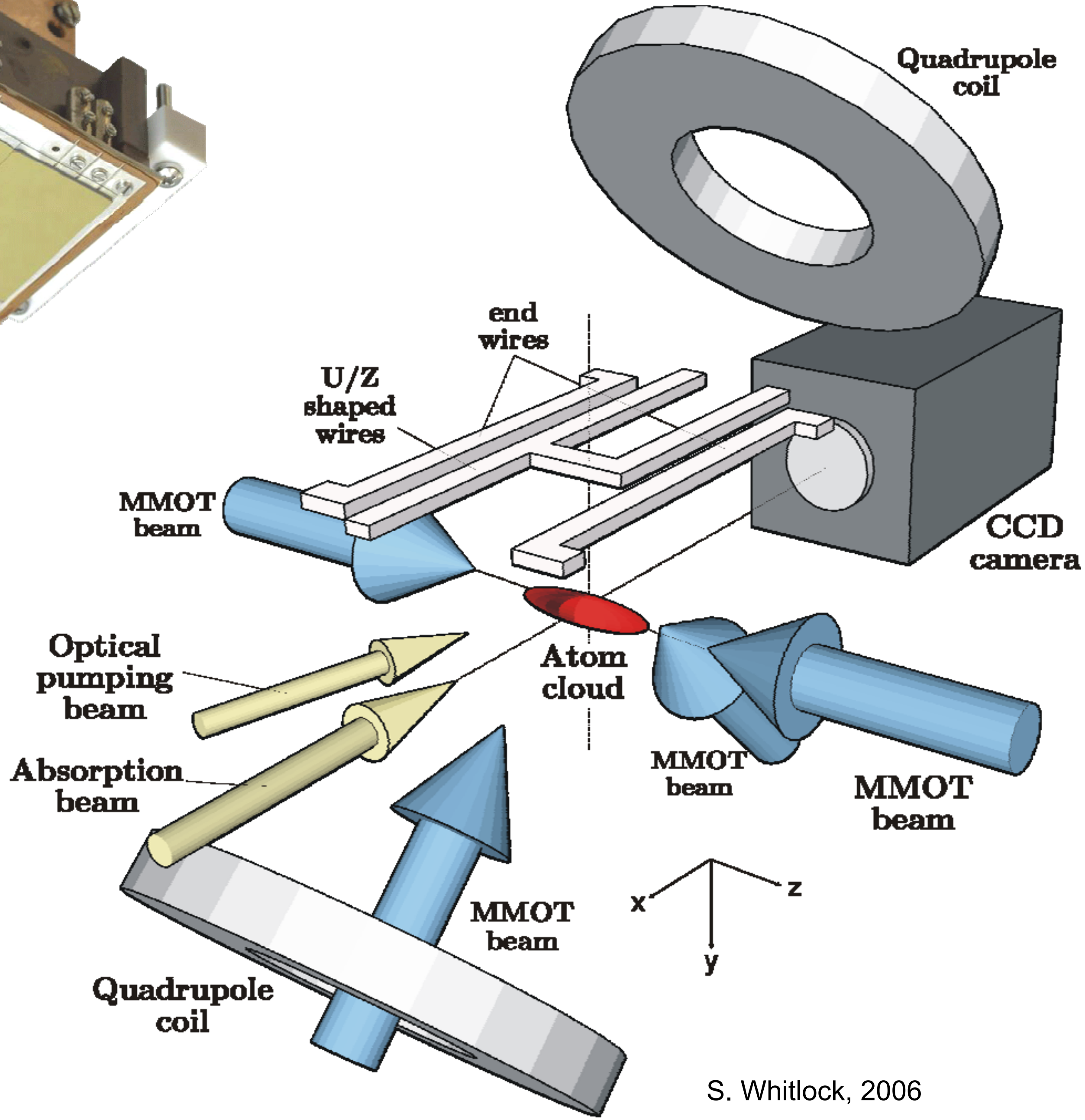
C. Monroe et al, PRL 1990

Bose-Einstein condensation on atom chip

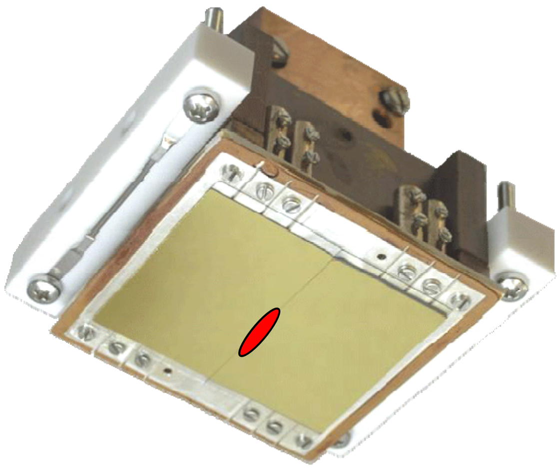


S. Whitlock, 2006





S. Whitlock, 2006



Laser cooling of atoms on atom chip

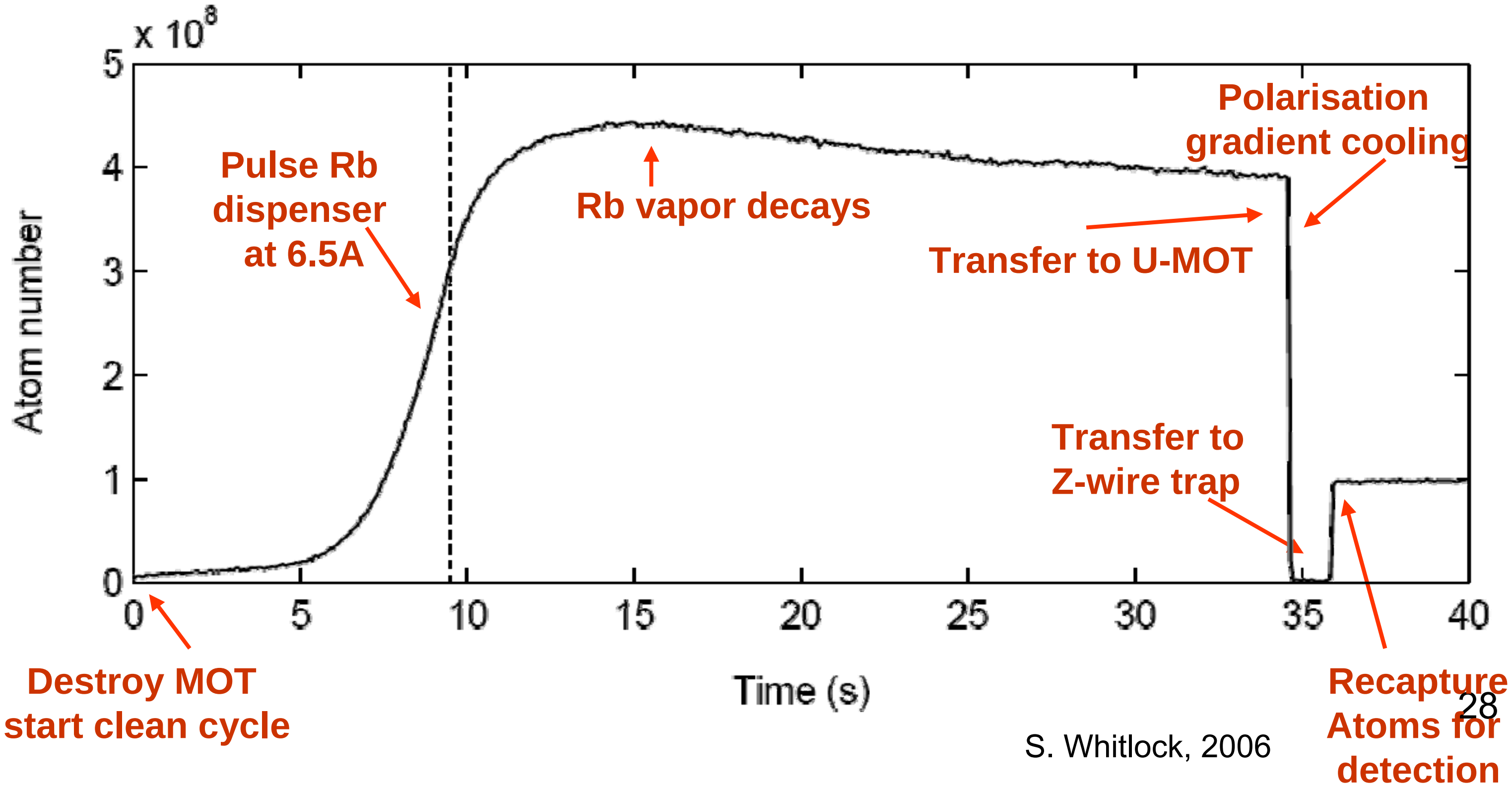
0 s – MMOT, 2×10^6 atoms

0-10 s – Rb dispenser on 6.5 A

10 - 35 s – Wait for vacuum 1×10^{-11} Torr

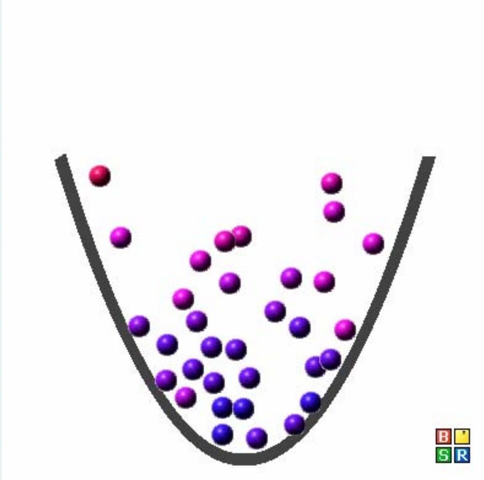
35 s – Compressed U-wire MMOT

35 s – Z-wire magnetic trap



S. Whitlock, 2006

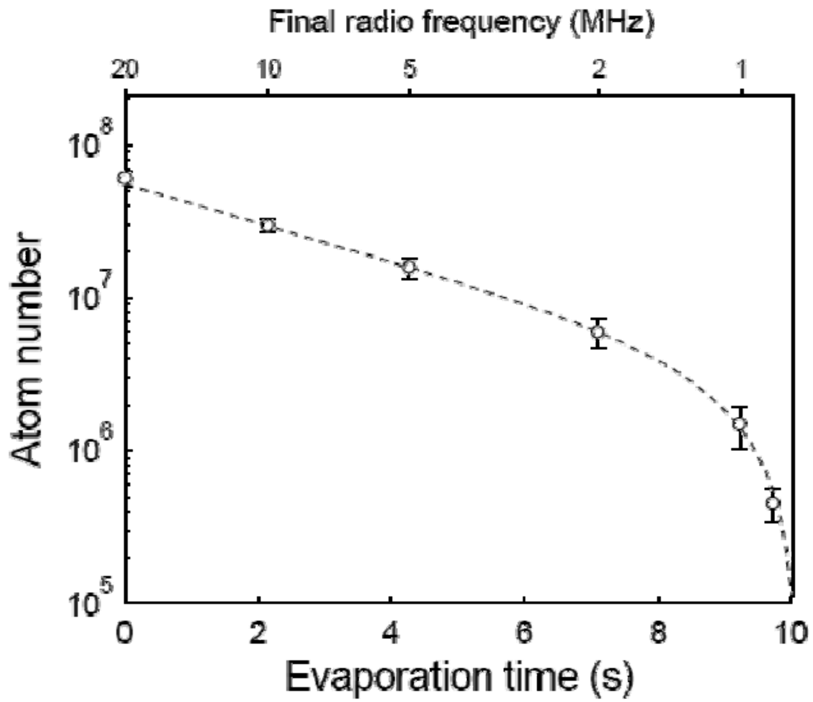
Evaporative cooling of atoms

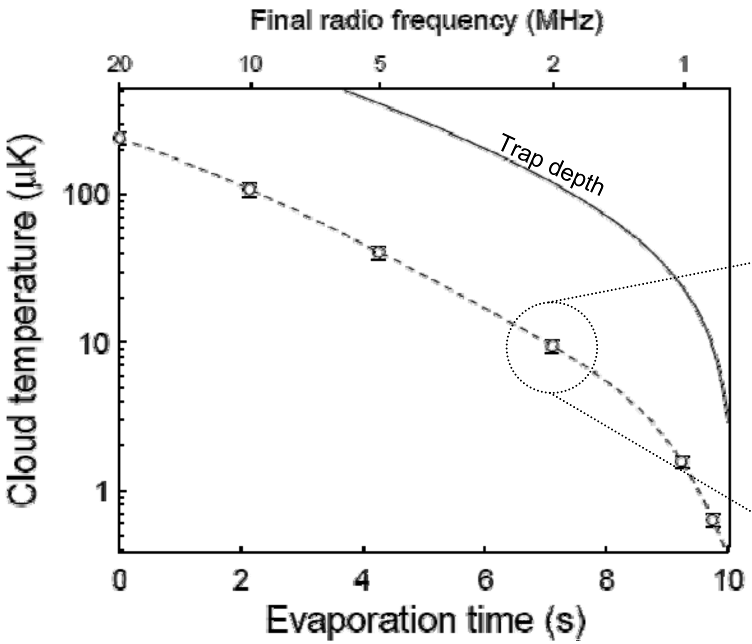


Physics 2000 website
http://www.colorado.edu/physics/2000/index.pl

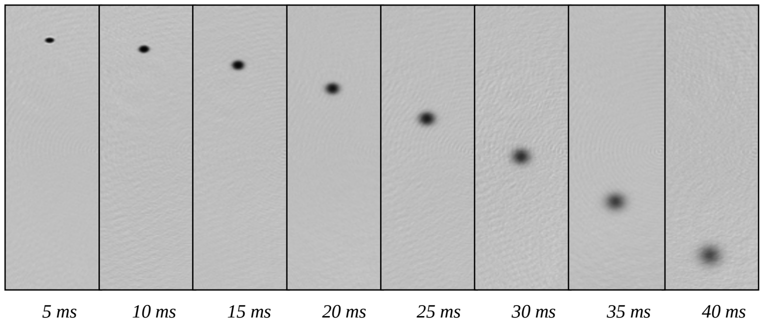
Red – high energy

Blue – low energy



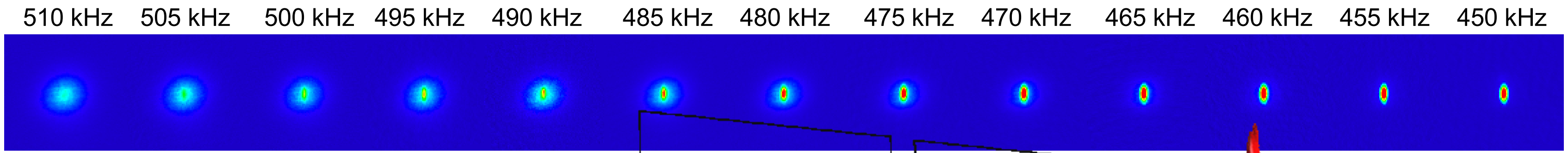


Ballistic expansion



S. Whitlock, 2006

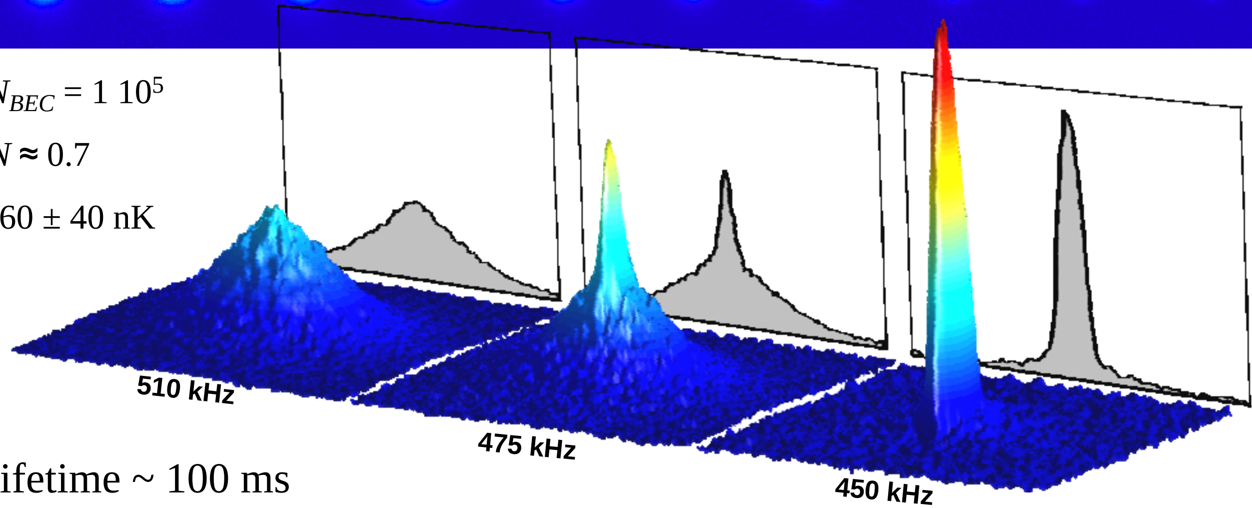
Bose-Einstein condensation



Number of atoms in BEC, $N_{BEC} = 1\ 10^5$

Condensate fraction, $N_{BEC}/N \approx 0.7$

Critical temperature, $Tc = 460 \pm 40$ nK



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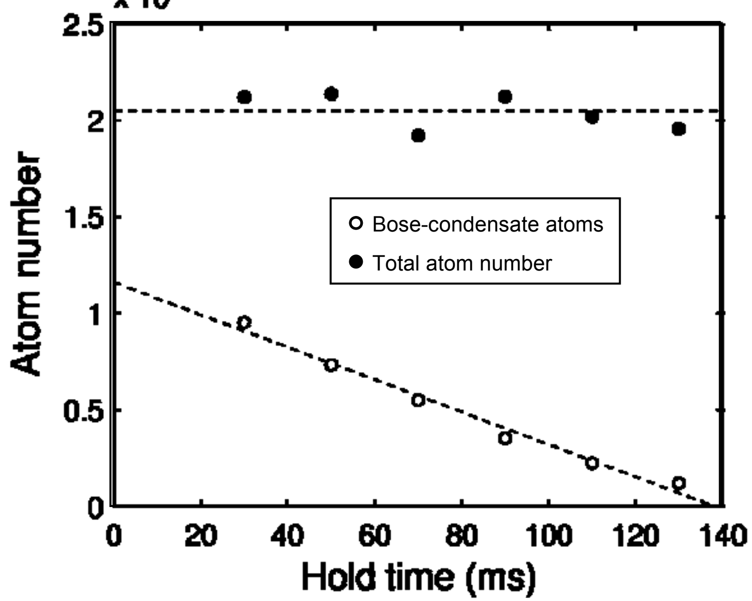
BEC lifetime ~ 100 ms

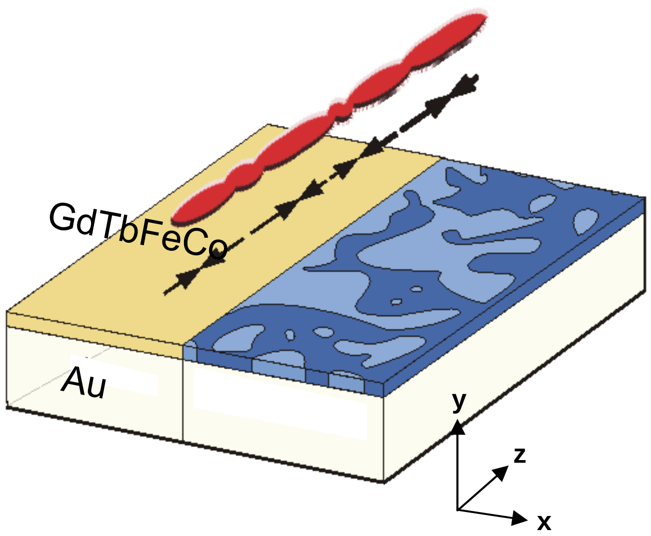


The BEC decays over 100 ms, while the total atom number remains approximately constant.

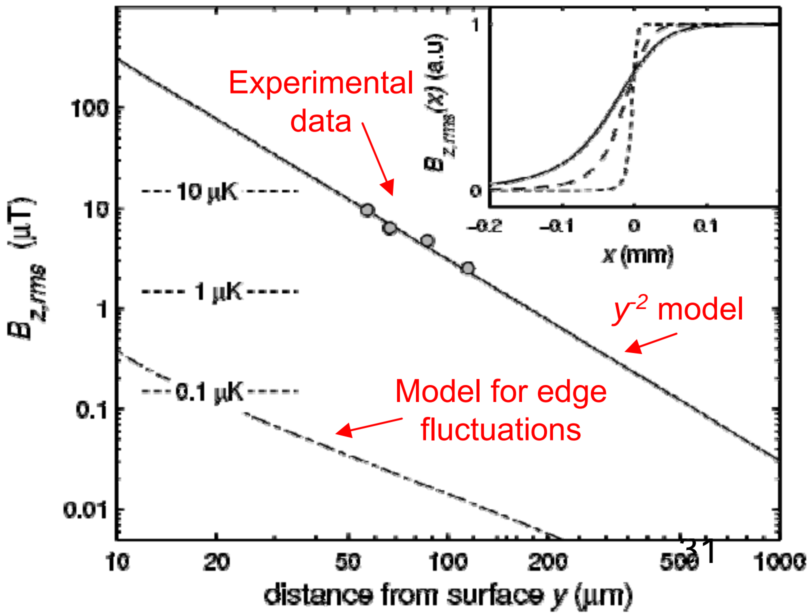
Lifetime limited by in-trap heating?

Can be extended to ~1 s by using a 'RF shield'

Fragmentation of cold cloud above magnetic film



S. Whitlock, 2006



Radiofrequency spectroscopy

Relax axial confinement. The thermal cloud spans 5 mm.

Sweep RF from 2 MHz to the final cut-off frequency, ν_f,

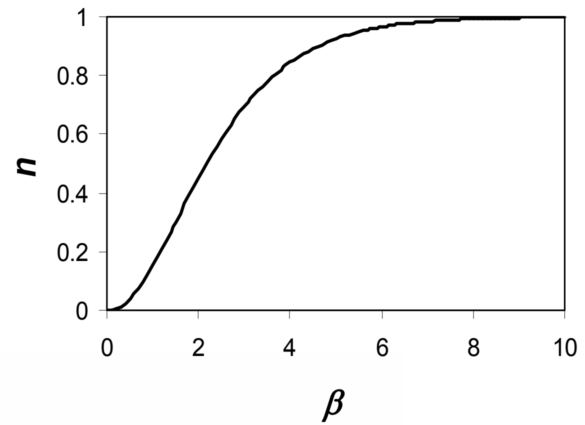
Fit cloud density to the truncated Boltzmann distribution.

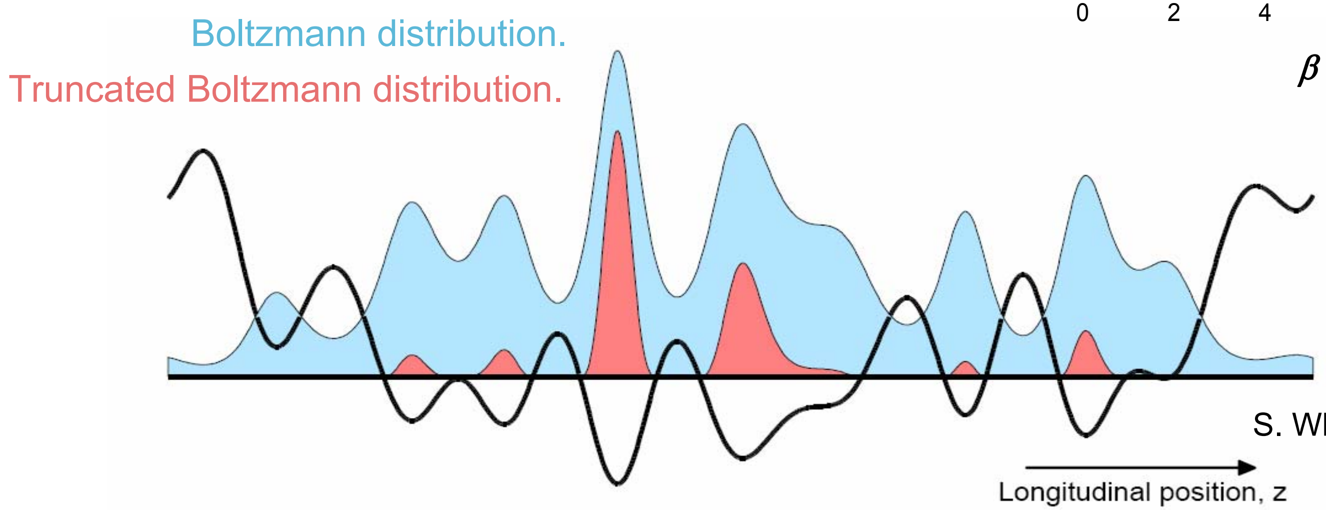
Truncated Boltzmann distribution

$$n(z,\beta) = n_\infty(z)[\mathrm{erf}(\sqrt{\beta}) - 2\sqrt{\beta/\pi}\mathrm{e}^{-\beta}(1+2\beta/3)],$$

Spatially dependent truncation parameter

$$\beta(z,\nu_f) = (h\nu_f - g_F\mu_B|B_z(z)|)/k_BT,$$





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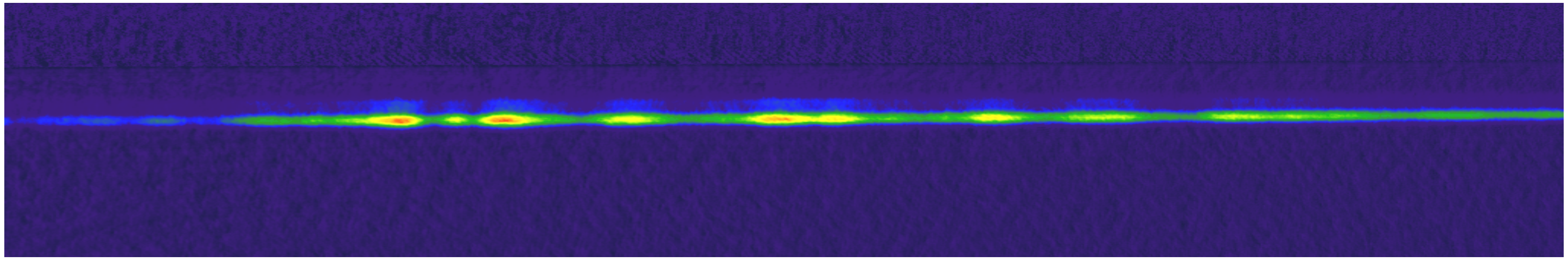
Radiofrequency spectroscopy



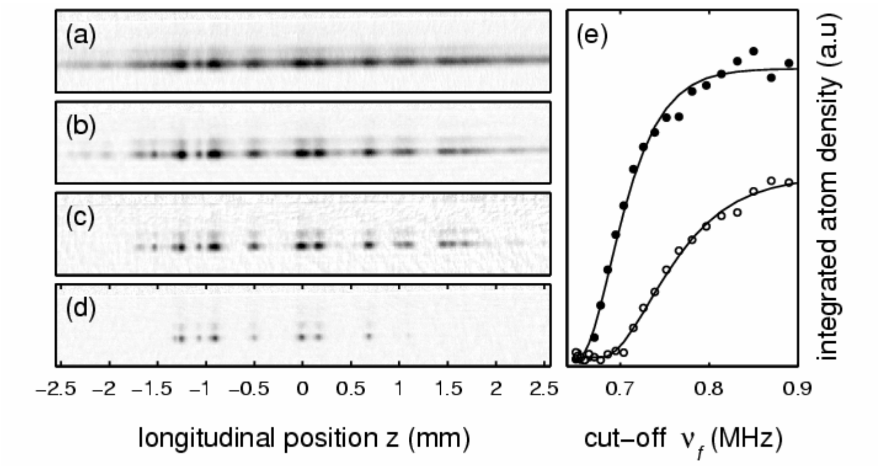


FIG. 2: Absorption images of the atomic density in the magnetic film microtrap located $y_0 = 67$ µm from the surface. As the RF cut-off ν_f is decreased, the structure of the potential is revealed. (a) ν_f=1238 kHz, (b) ν_f=890 kHz, (c) ν_f=766 kHz, (d) ν_f=695 kHz and (e) integrated atomic density vs. ν_f for two longitudinal positions, z = 0.69 mm (solid circles) and z = 1.00 mm (open circles), fitted to the truncated thermal distribution function (Eq. 1).

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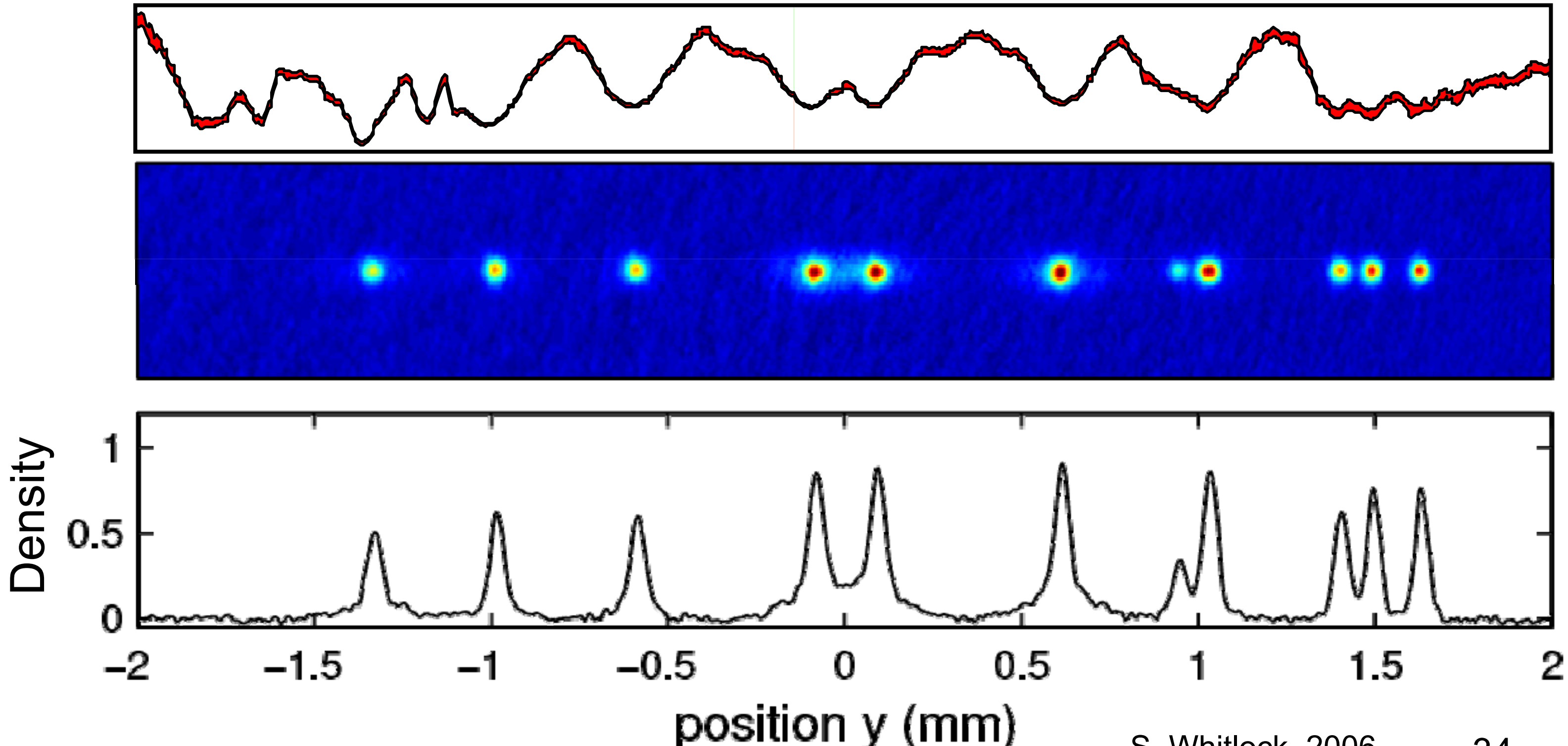
Multiple Bose-Einstein condensates

Independently tune end wire currents to remove linear and quadratic components of the longitudinal trap potential - minimise the energy difference between each potential well.

RF evaporatively cool the elongated thermal cloud to the BEC transition to simultaneously produce 11 spatially separated Bose-Einstein condensates



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Summary

1. Laser cooling allow to produce large ensembles of ultracold atoms
2. Cooling is done by the dissipative, radiation pressure force (spontaneous emission plays a major role)
3. Doppler limit (100÷200 μK) for a two (or J=0→J=1) atom
4. Sub-Doppler temperatures via the polarisation-gradient cooling (recoil energy – ultimate limit)
5. Magneto-optical trap
6. Laser and evaporative cooling on atom chip