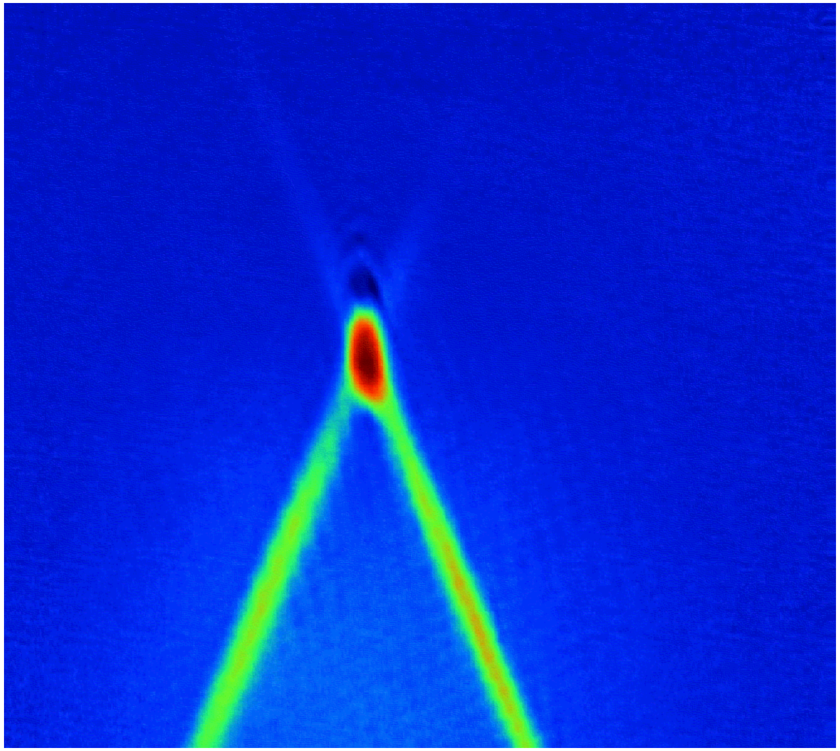
Cold Atoms, Bose–Einstein Condensation Interferometry and Clocks

Institut Francilien de Recherche sur les Atomes Froids

IFRAF



CENTRE NATIONAL
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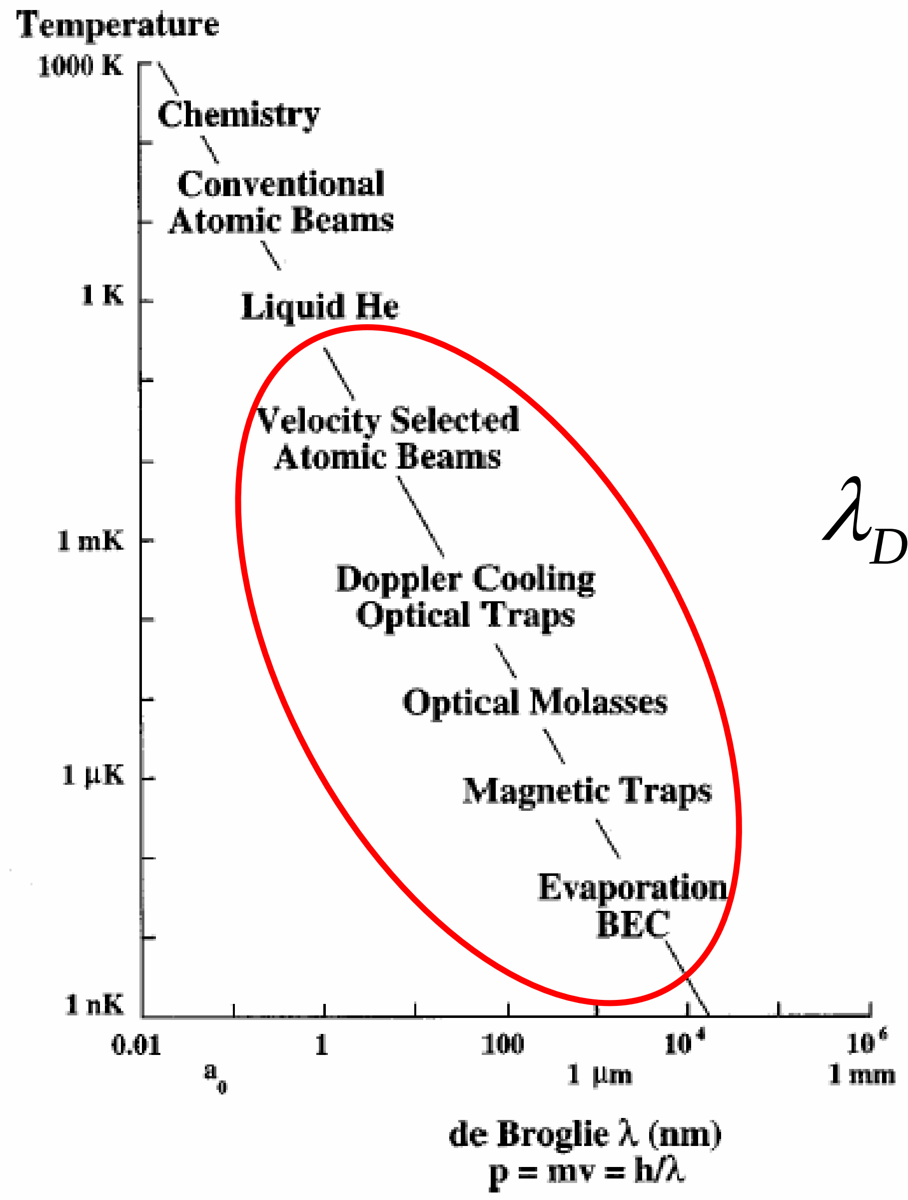
C. Salomon
Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris

SIGRAV School, Firenze, September 2006

Outline of lectures

- Lecture 1
- Laser cooling
- Optical molasses, traps
- Bose-Einstein condensation and applications
- Lecture 2
- Atom interferometry
- Lecture 3
- Atomic clocks: basics
- Lecture 4
- Fundamental tests and space applications

Temperature scale



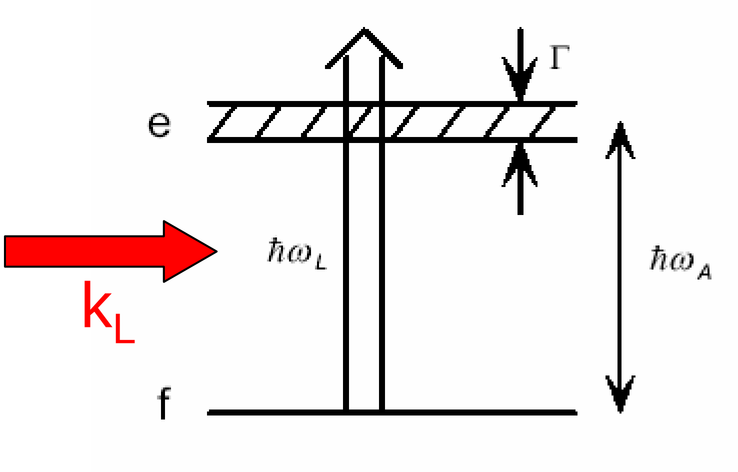
$$\lambda_{DB} = \frac{h}{Mv}$$

Radiation Pressure

Two-level atom

Γ^{-1} lifetime : 32 ns Cesium

$\delta = \omega_L - \omega_A$ detuning



Interaction between atoms and electromagnetic field:
electric **dipole interaction**

Rabi frequency $\hbar\Omega_1(\boldsymbol{r}) = -\left(\boldsymbol{d}\cdot\boldsymbol{\epsilon}_L(\boldsymbol{r})\right)\ \mathcal{E}_L(\boldsymbol{r})$

Change of velocity due to the absorption of a photon:

$$v_{\text{rec}} = \frac{\hbar k_A}{m} = \frac{h}{m\lambda_A}$$

$3{,}5\ \text{mm s}^{-1}$ cesium atoms

<<< thermal velocity

Radiation Pressure

Radiation pressure

$$\boldsymbol{F}_{\mathrm{PR}} = \frac{\hbar \boldsymbol{k}_L \Gamma}{2} \frac{s(\boldsymbol{R})}{1 + s(\boldsymbol{R})} = \hbar \boldsymbol{k}_L \Gamma \sigma_{ee}$$

$\Gamma \sigma_{ee}$ average rate of absorption/spontaneous emission cycles

$$F_{PR} \leq \hbar k_L \Gamma / 2$$

Each cycle transfers a $\hbar \boldsymbol{k}_L$ momentum in average, the contribution of spontaneous emission is zero in average.

Spontaneous emission leads to a diffusion in the velocity space

Atomic beam slowing

Resonance condition

$$\omega_L - k_L V(z) = \omega_A(z)$$

$$V^2(z) = V_0^2 - 2a_{\max} z$$

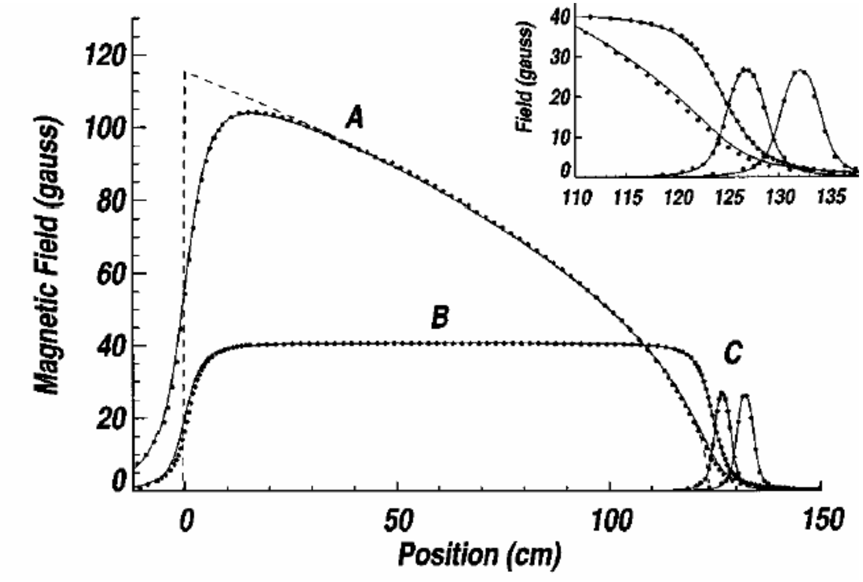
$$z_0 = V_0^2 / (2a_{\max})$$

inhomogeneous magnetic field

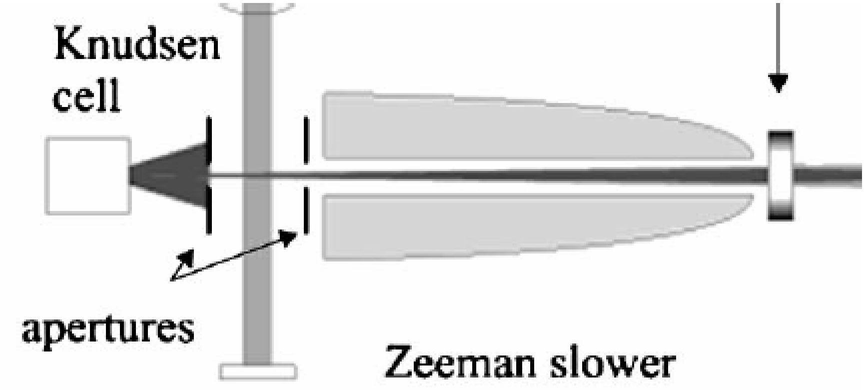
$$s_0 \equiv I/I_0$$

$$F(z,v) = \frac{\hbar k \Gamma}{2} \frac{s_0}{1 + s_0 + 4[\delta + kv - \mu' B(z)/\hbar]^2/\Gamma^2}.$$

$$I_0 = \frac{\Gamma \hbar \omega_0^3}{12\pi c^2}.$$



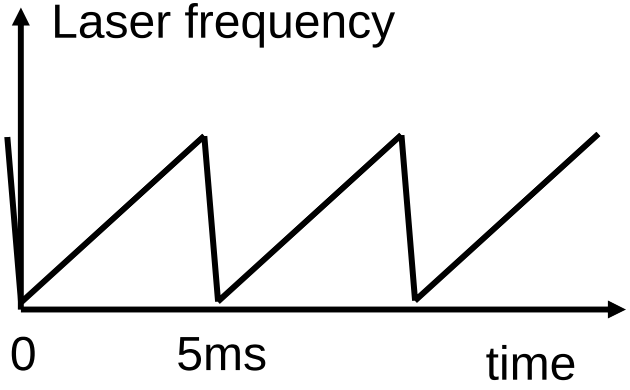
$$B(z) = B_b + B_p \sqrt{1 - z/z_s}.$$



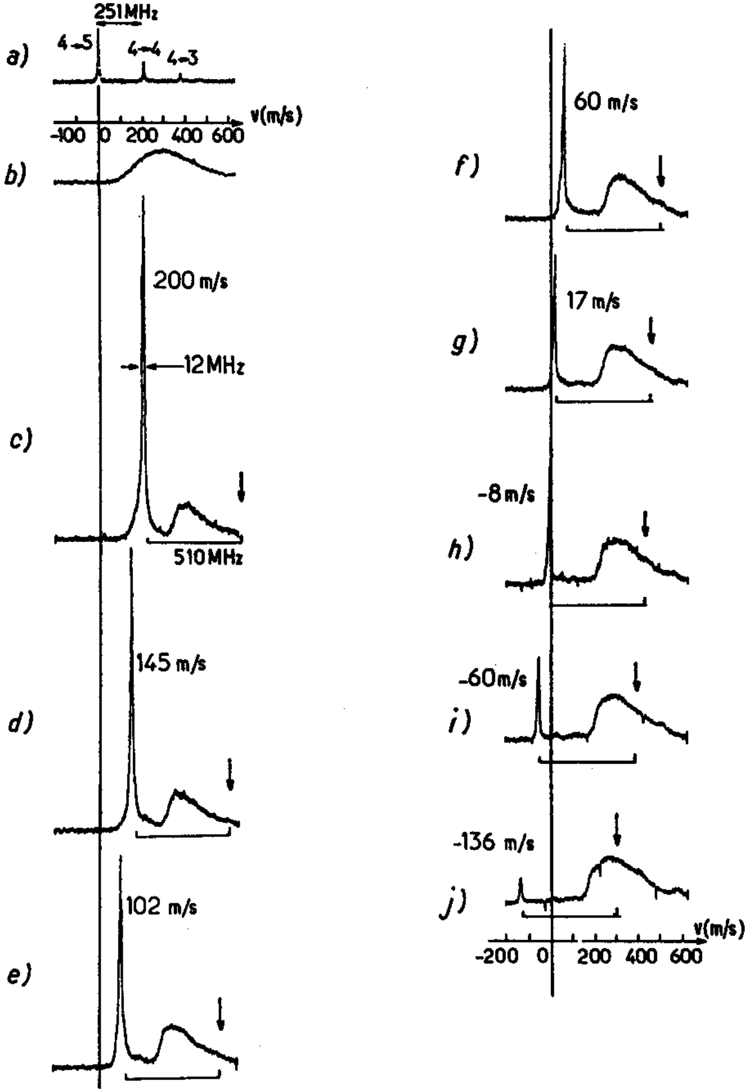
Atomic beam slowing (2)

- Chirped cooling

$$\omega_L(t) - k_L V(t) = \omega_A$$



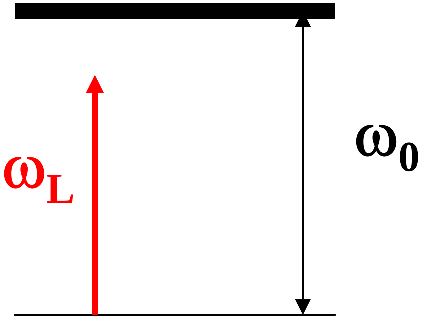
Extremely simple with diode lasers !

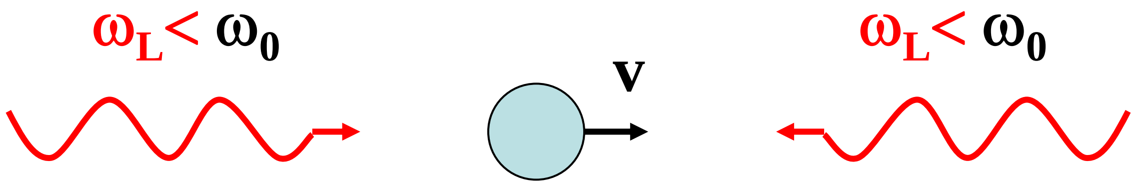


Hänsch, Schawlow
Wineland, Dehmelt
1975

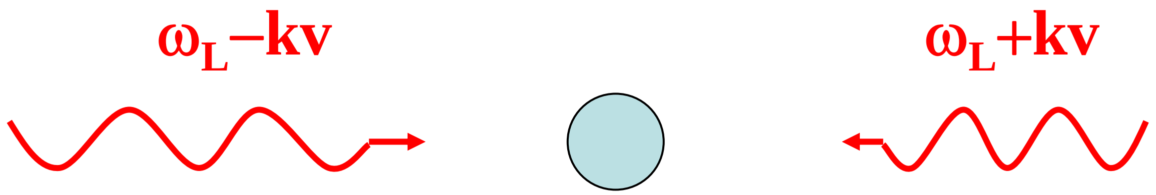
Doppler Cooling

Doppler effect





Laboratory frame



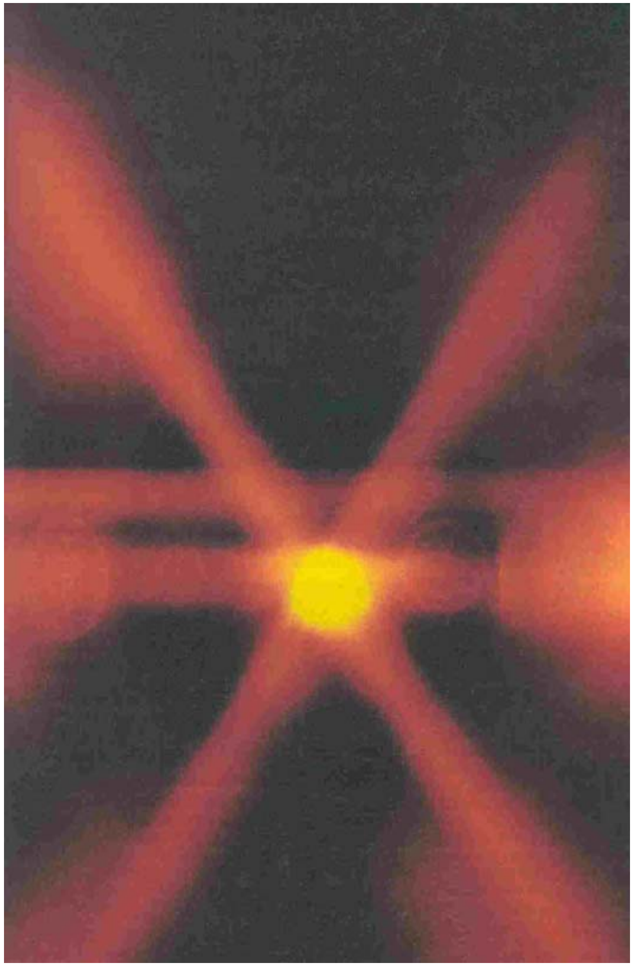
Atom frame

Absorption of the photon $\omega_L + kv$, followed by a spontaneous emission equiprobable in all directions of the space.

Act as: $F = -\alpha v$ (friction force) $= m dv/dt$

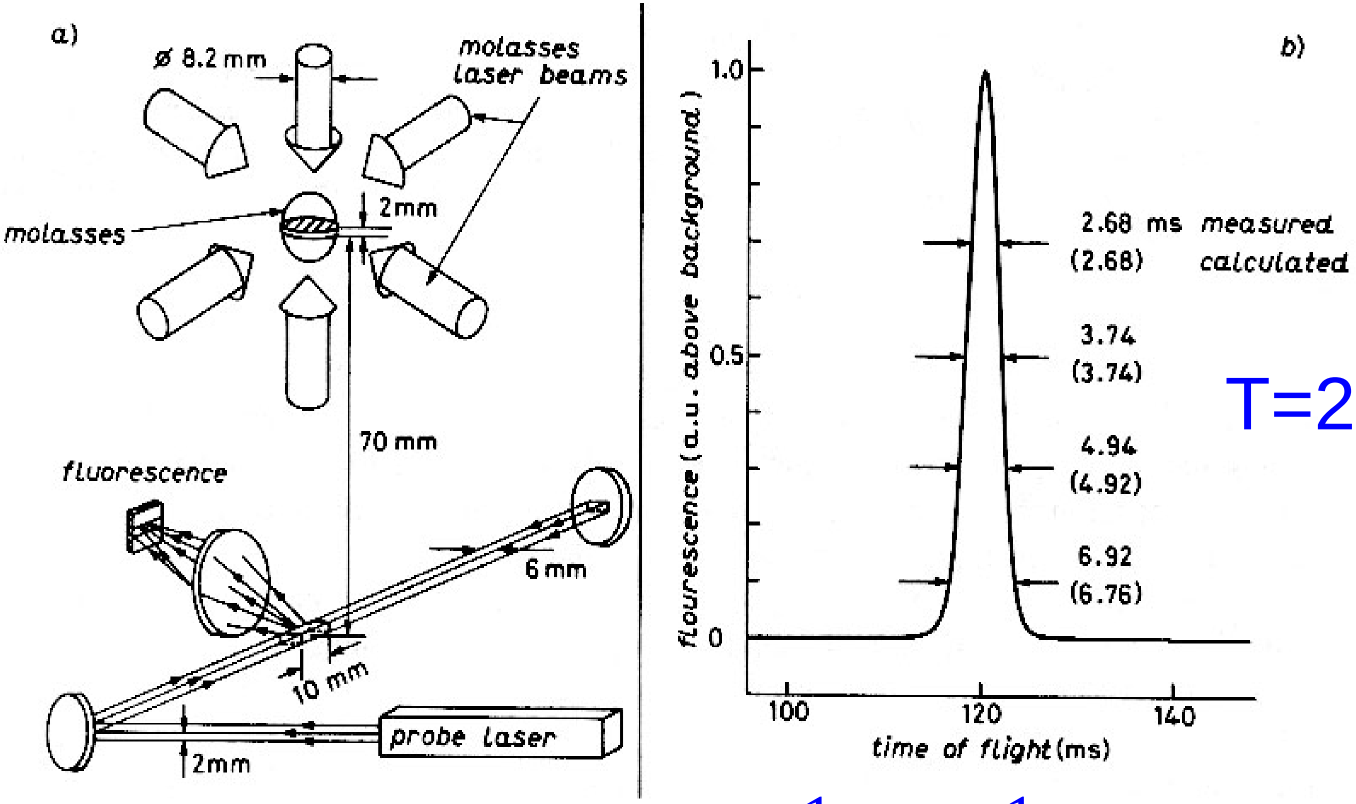
Optical molasses

S. Chu, Scientific American, 174, 1992



Na molasses

Temperature measurement



T=2.5 μK

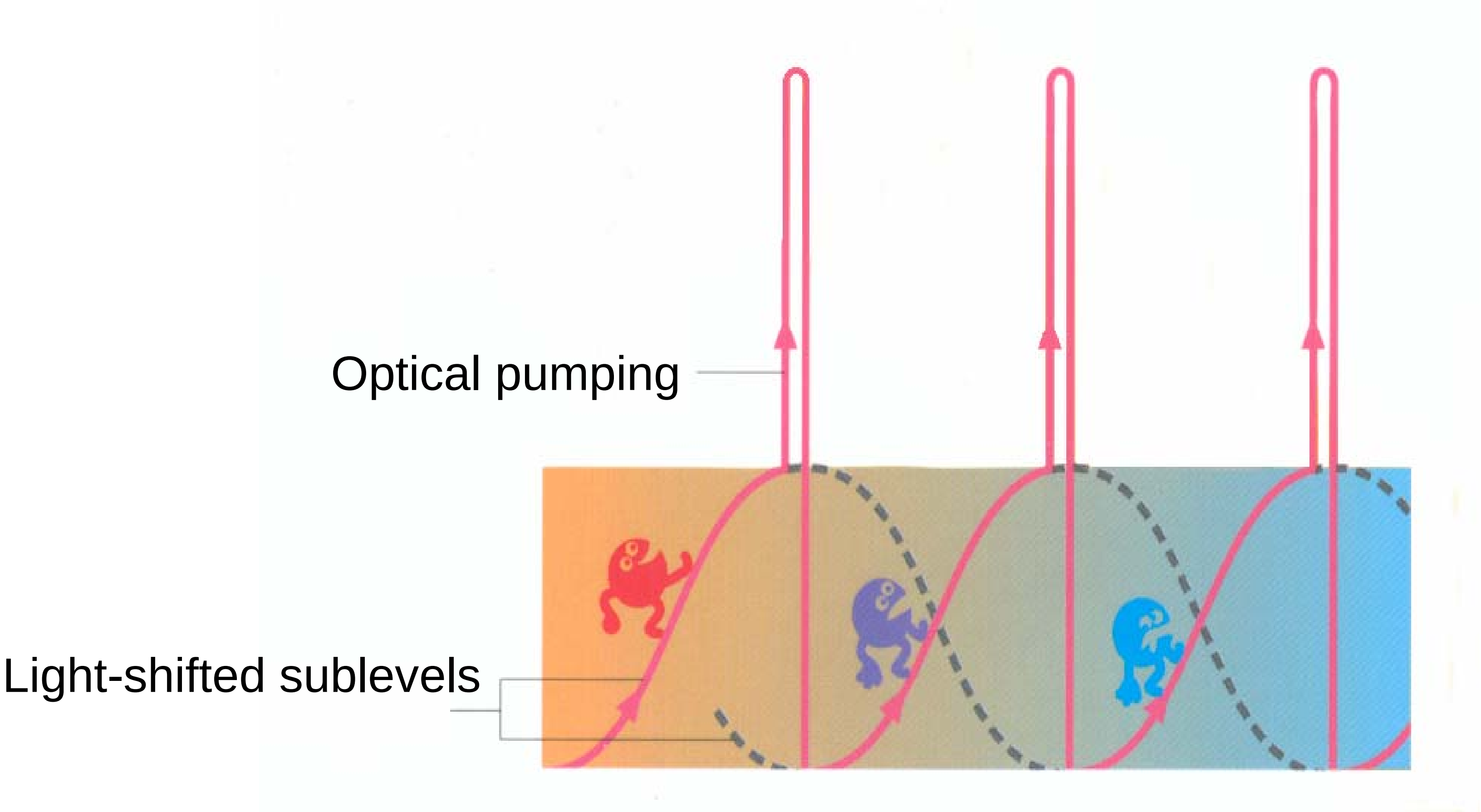
$$\frac{1}{2}k_B T = \frac{1}{2} M V_{rms}^2$$

$$V_{rms} = 12\, mm/s$$

C. Salomon, J. Dalibard, W. Phillips, A. Clairon, S. Guellati, Europhys. Lett., 12, 683, (1990)

Sisyphus cooling

J. Dalibard, C. Cohen-Tannoudji

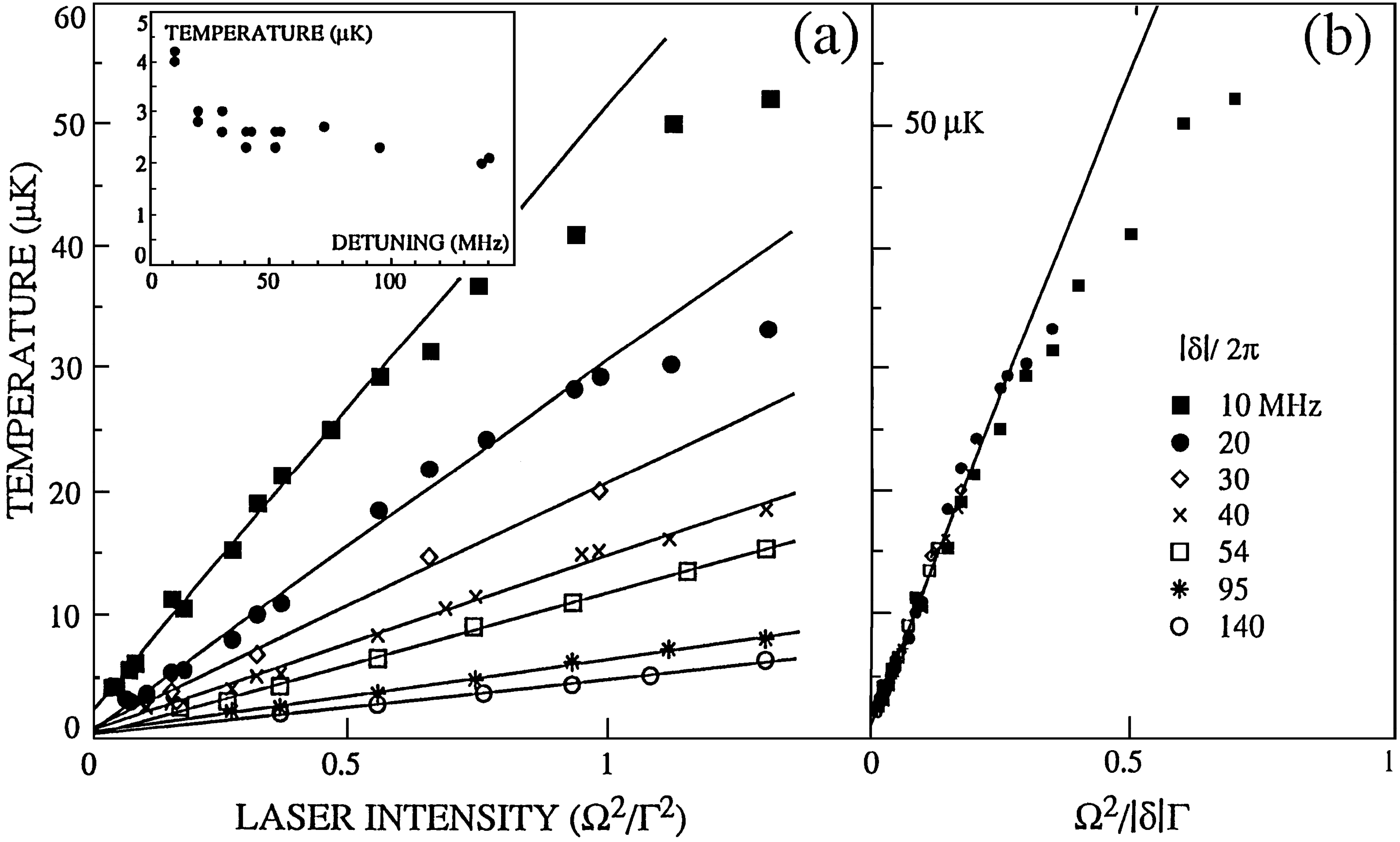


$$k_B T = U_0 / 4$$

Limit Temperature: about 10 times recoil energy

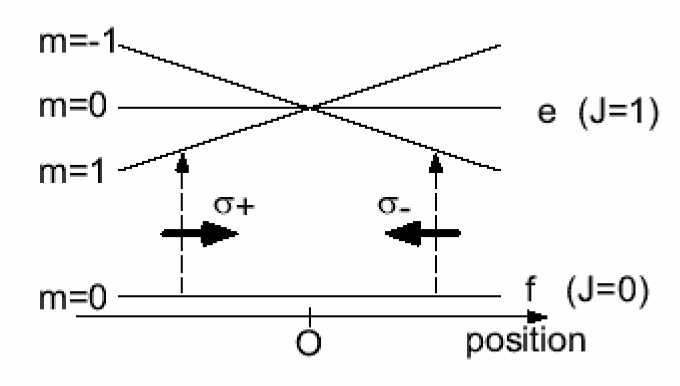
Test of Sisyphus cooling

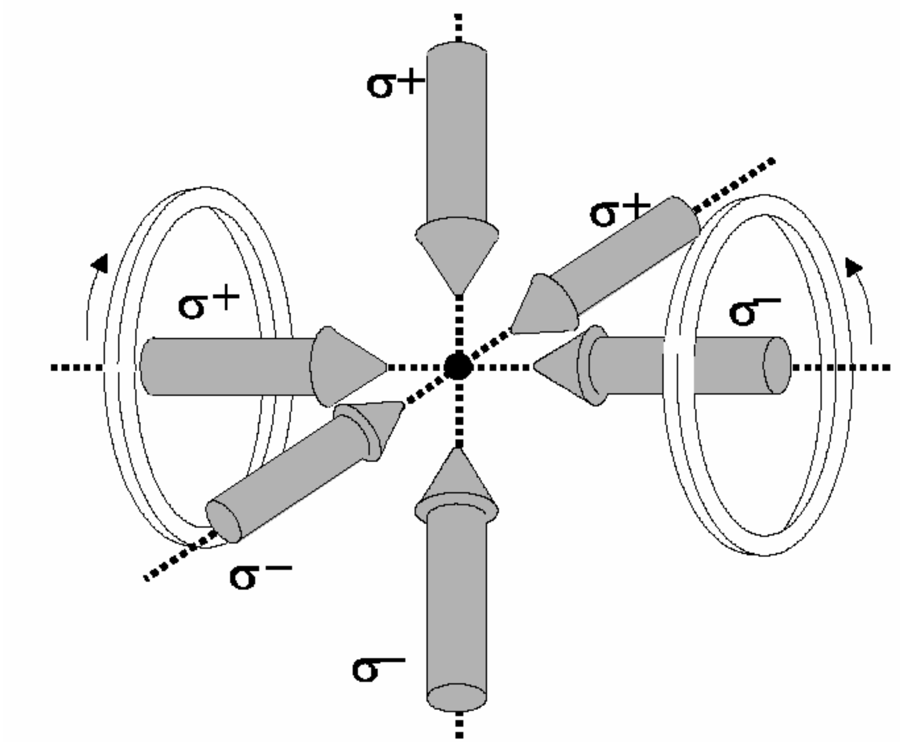
T ~ Laser intensity/Laser detuning



Magneto-optical trap

J. Dalibard - 1987





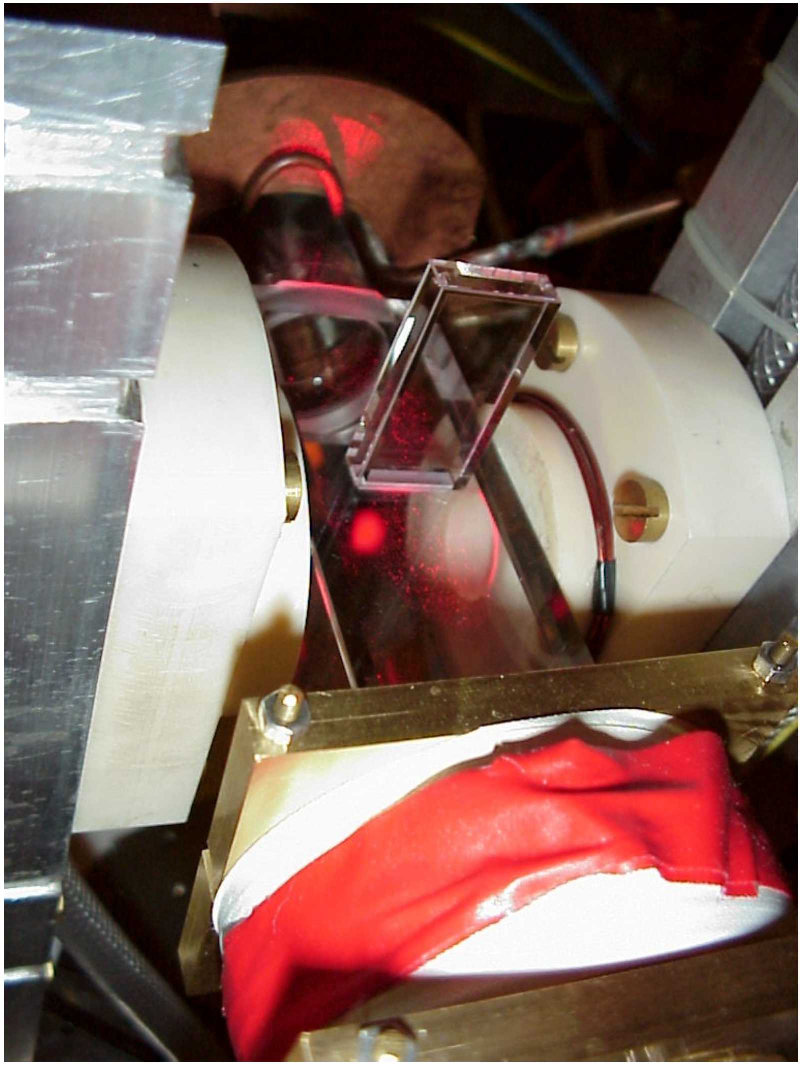
$$\mathbf{F} = -\,\alpha\,\mathbf{v} - k\,\mathbf{r}$$

3D Molasses
Doppler effect

Trapping
Zeeman effect
Produces imbalance
in rad pressure forces

b' = 10 Gauss / cm
I = a few mW per beam

Lithium magneto-optical trap



Trapping:

$$\vec{F} = -\vec{k}.\vec{r}$$

In addition, cooling:

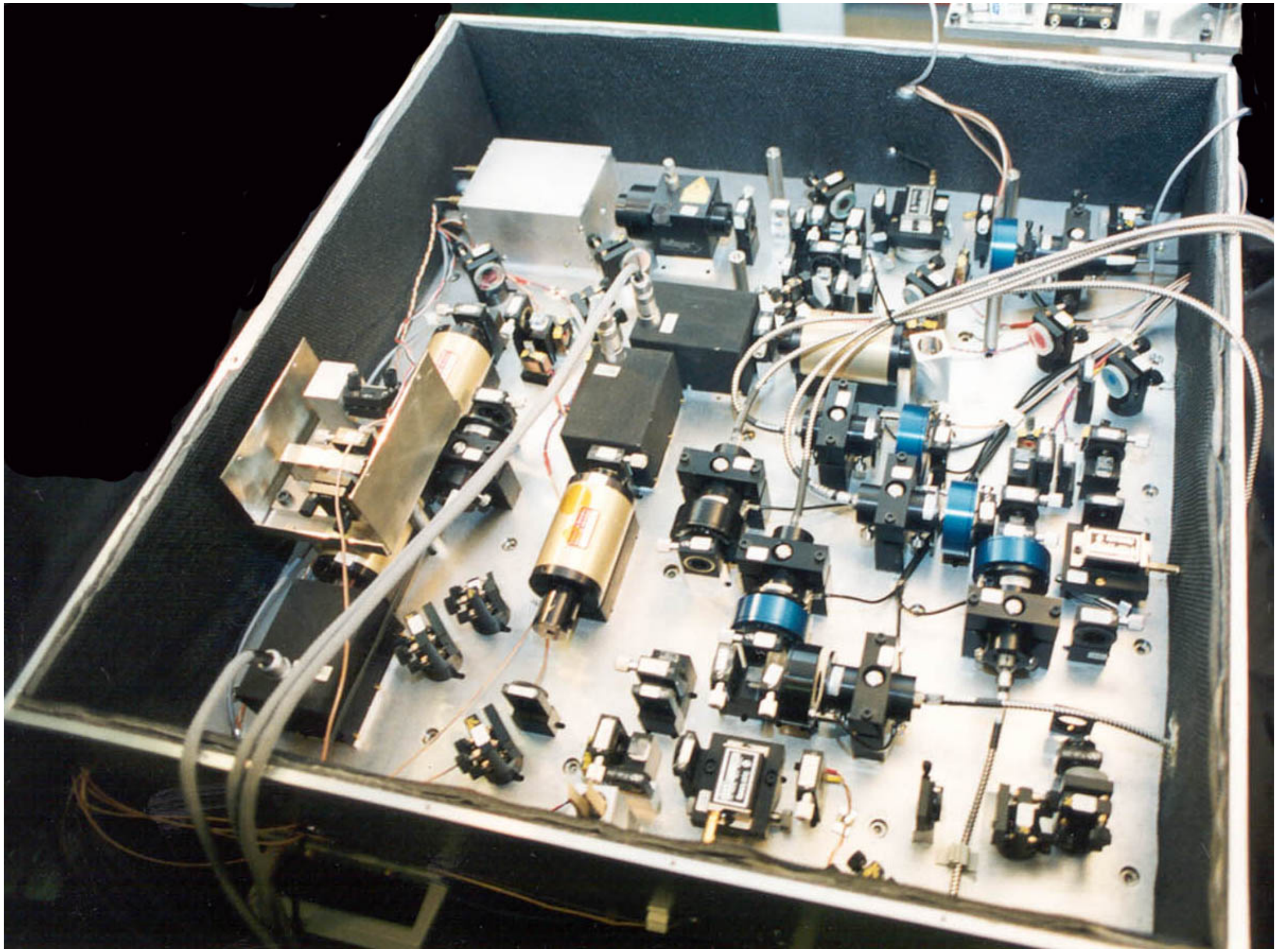
$$\vec{F} = -\vec{k}.\vec{r} - \alpha\vec{v}$$

Doppler cooling
+ sub-doppler cooling
Considerable increase
in phase-space density:

$$n\lambda_{DB}^{3} \sim 10^{-6}$$

Up to a few 10^{10} atoms
Density 10^{11}at/cm^3

Optical bench for laser cooling



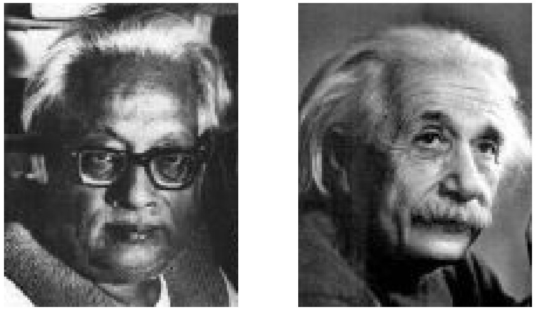
l'Observatoire de Paris SYRTE

PHARAO

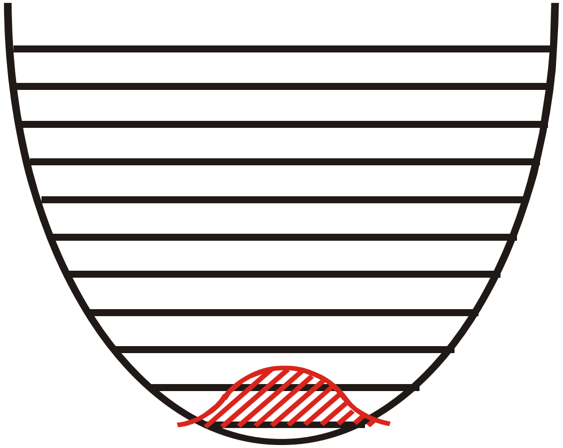
Bose-Einstein condensation and Fermi degeneracy

Quantum statistics in harmonic traps

- Bose-Einstein statistics (1924)



Bose-Einstein condensate

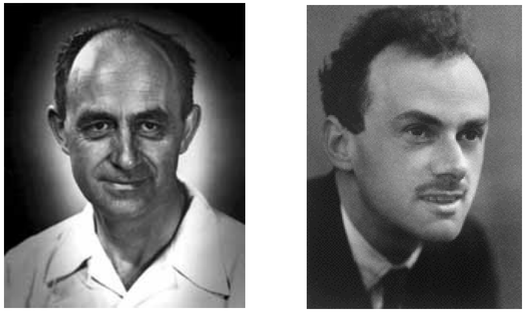


Bose enhancement

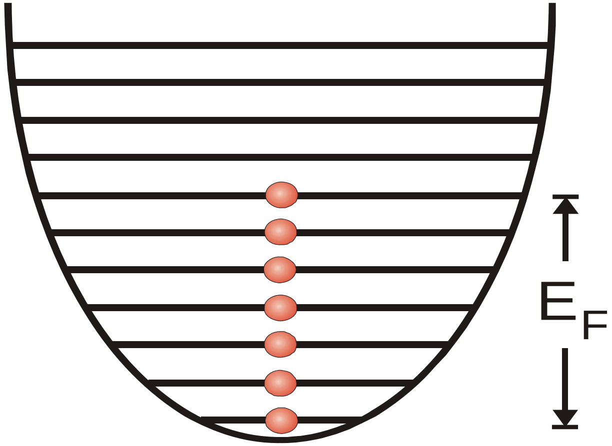
$$T_C = \frac{\hbar\omega}{k_B}(0.83\ N)^{1/3}$$

Dilute gases: 1995, JILA, MIT

- Fermi-Dirac statistics (1926)



Fermi sea

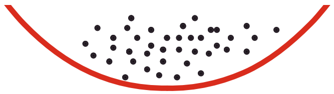


Pauli Exclusion

$$T \ll T_F = \frac{\hbar\omega}{k_B}(6\ N)^{1/3}$$

Dilute gases: 1999, JILA

Bose-Einstein Condensates: orders of magnitude



Dilute gas of atoms at temperature T confined in harmonic potential :

$$V(\vec{r}) = \frac{1}{2} m\omega^2 r^2$$

Condensation threshold:

$$N = 1.202 \left(\frac{k_B T}{\hbar\omega} \right)^3 \quad \xLeftrightarrow[k_B T \gg \hbar\omega]{} \quad n_0 \lambda^3 = 2.612 \quad \left\{ \begin{array}{l} n_0 : \text{central density} \\ \lambda = \dfrac{h}{\sqrt{2\pi m k_B T}} \end{array} \right.$$

Liquid helium :

10^{27} atoms/m^3

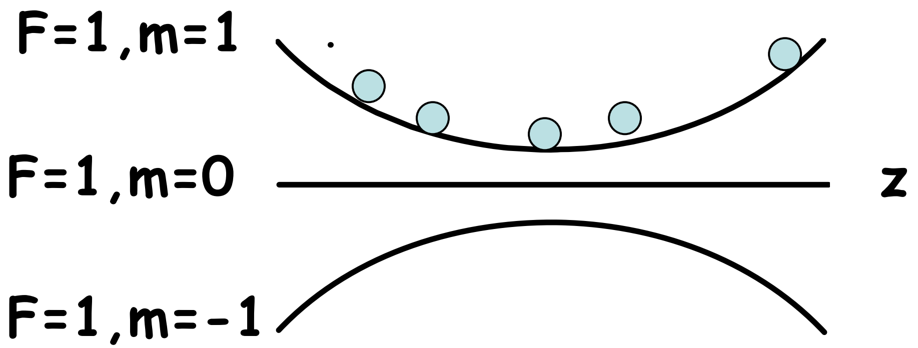
$n_0^{-1/3} = 10$ Å $T \sim 1$ K

Gaseous condensate

10^{19} at/m^3

$n_0^{-1/3} = 0.5$ µm $T \sim 1$ µK

Magnetic trap



$$E = -\vec{\mu}.\vec{B} = +|\vec{\mu}||\vec{B}|$$

Maxwell's equations:
No max of |B| in vacuum.

Local minimum of */B/*

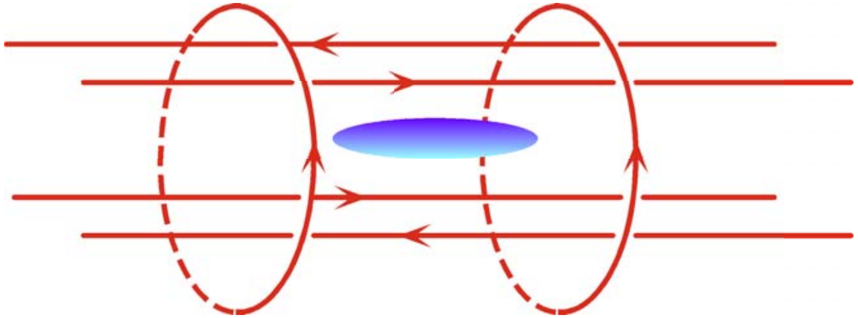
+ spin polarisation

$$\boxed{V=|\mu||B|}$$

Atoms cannot be magnetically trapped in the lowest energy state.

- Two-body inelastic collisions

Example: Ioffe-Pritchard trap
Trap depth 1 mK
Loaded with laser cooled atoms
Or cryo-cooled atoms (Harvard)

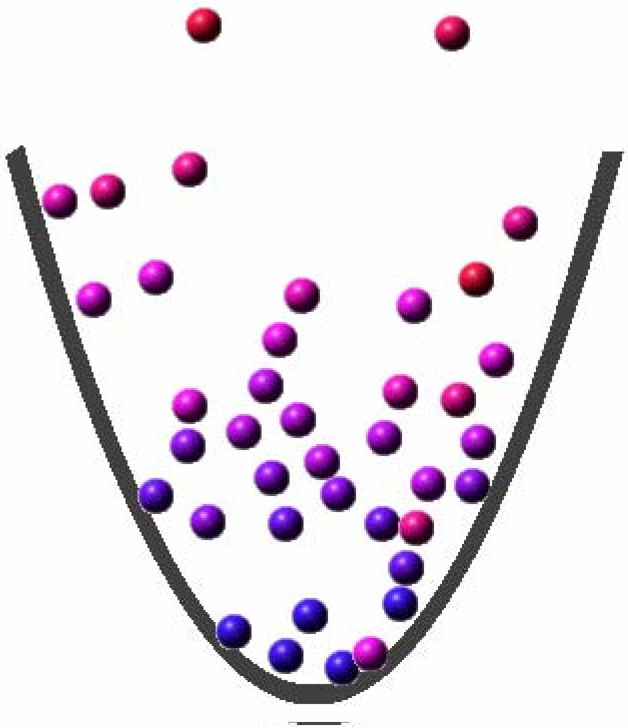


Evaporative cooling

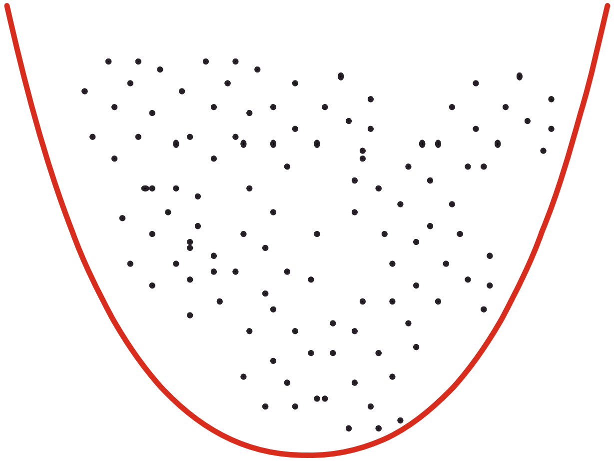
- The only known method to reach quantum degeneracy

- Remove hot atoms
- Elastic collisions ensure re-thermalisation

$$\gamma_{elastic} / \gamma_{inelastic} \geq 150$$



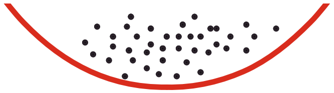
Evaporative cooling (2)



$N \longrightarrow N / 100$

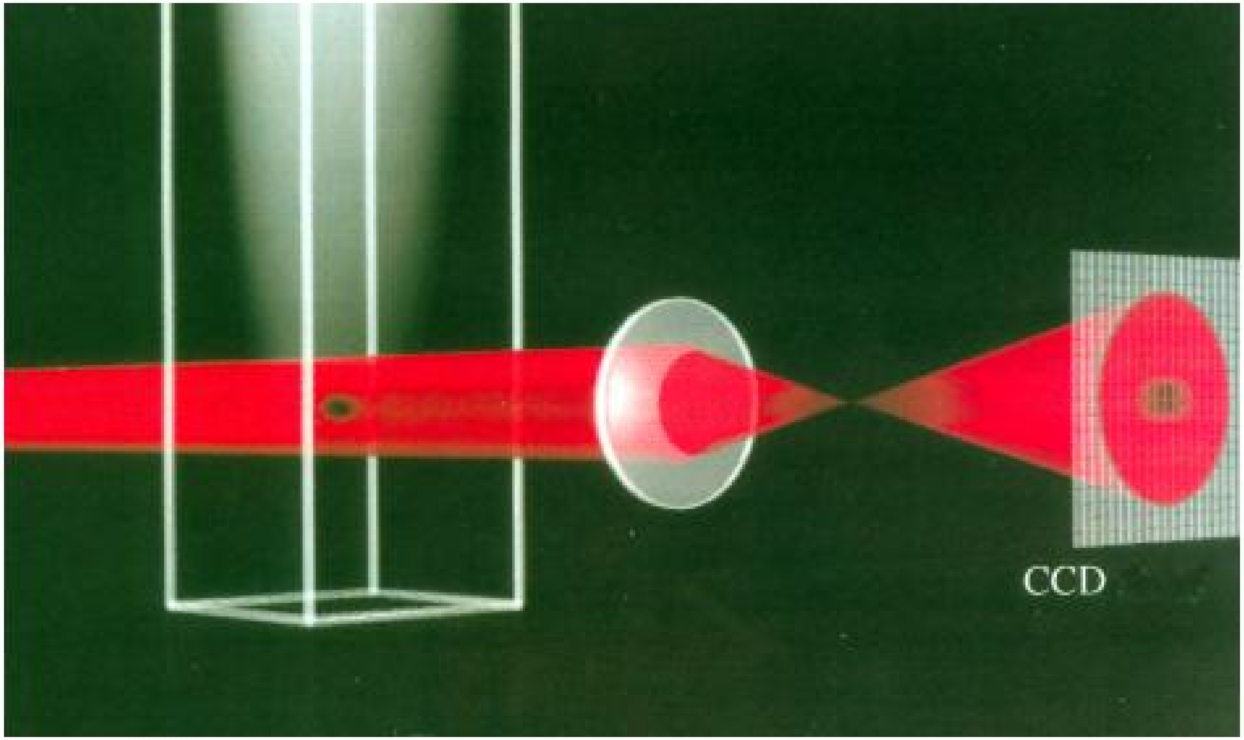
$T \longrightarrow T / 1000$

Phase-space density $n\lambda^3$
multiplied by 10^7



Duration : 5 to 30 seconds, $N_f = 10^5$ to 10^7 atoms, $T_f = 0.2$ to 2 μK

Imaging cold atomic clouds and condensates



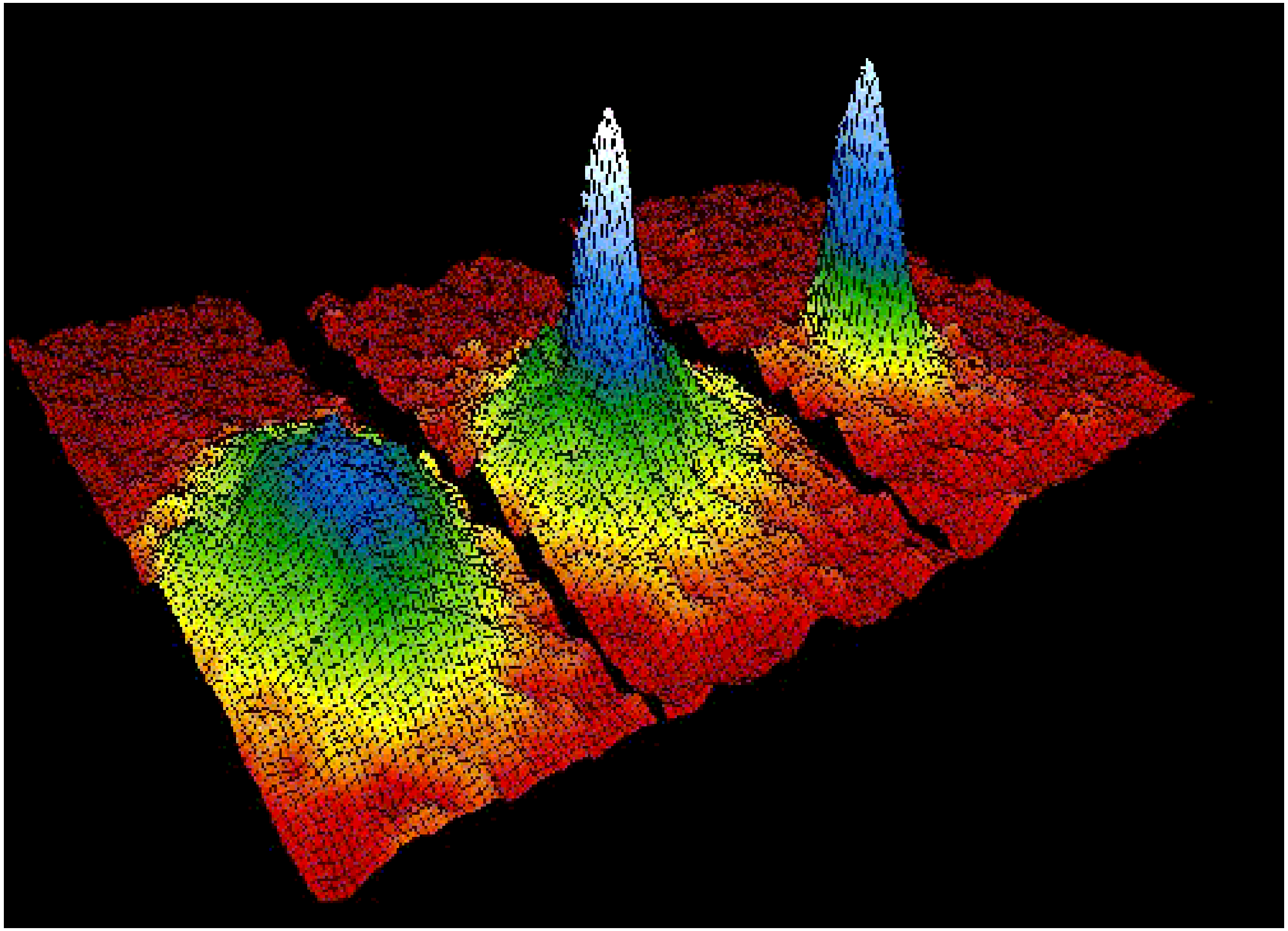
Absorption imaging

1) In situ measurement: spatial distribution in the trap

2) After time of flight expansion: velocity distribution

Bose-Einstein Condensation in Rubidium 87

JILA - Boulder



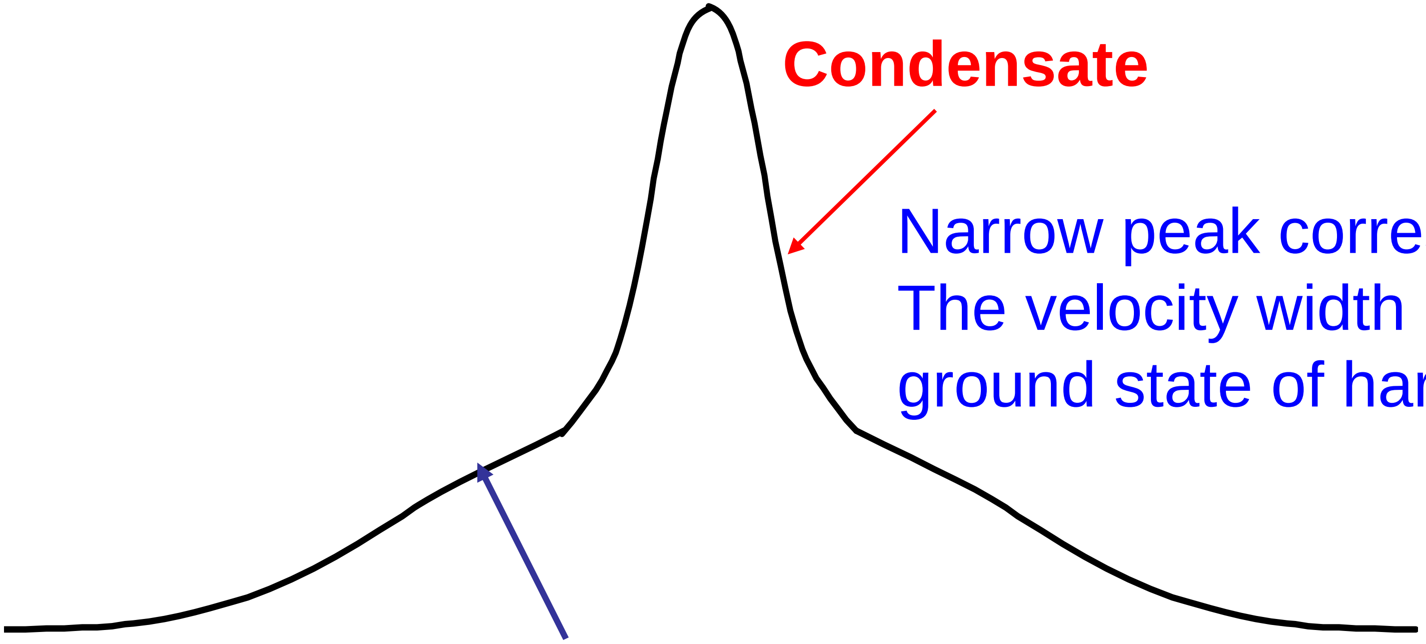
1000 atoms in ground state of magnetic trap.

Remark:
Metastable systems
The true ground state of Rb at 1 μK is a piece of solid

Science, 269, 198 (1995)
M. Anderson, E. Cornell and C. Wieman

+ Sodium, Lithium, Hydrogen, Potassium
Helium (2s state), Cesium, Ytterbium

Bimodal distributions



Condensate

Narrow peak corresponding to
The velocity width of
ground state of harmonic trap

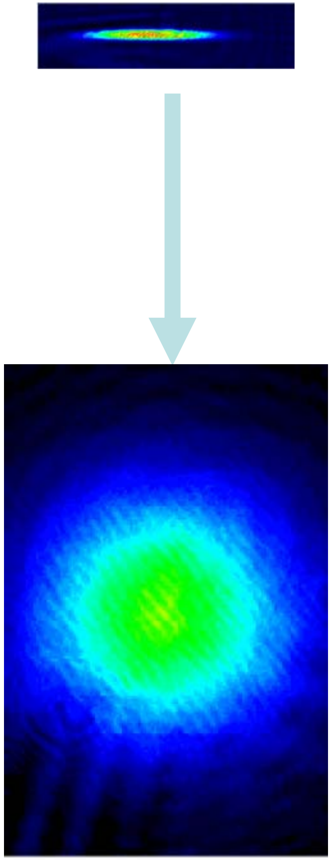
non condensed atoms

Thermal atoms in excited states: broader distribution

Condensate signature

A few millions atoms in anisotropic magnetic trap

$T > T_c$



Boltzmann Gas

$$\frac{1}{2}mv_i^2 = \frac{1}{2}kT$$

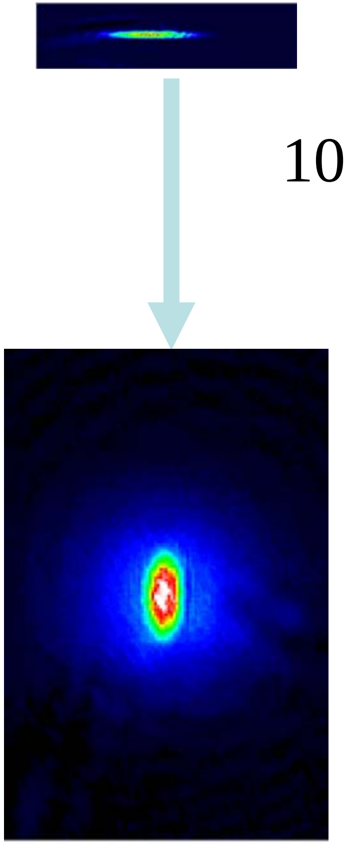
isotropic

Time of flight

$T < T_c$

0,5 to 1 μK

100 μm * 5 μm



condensate

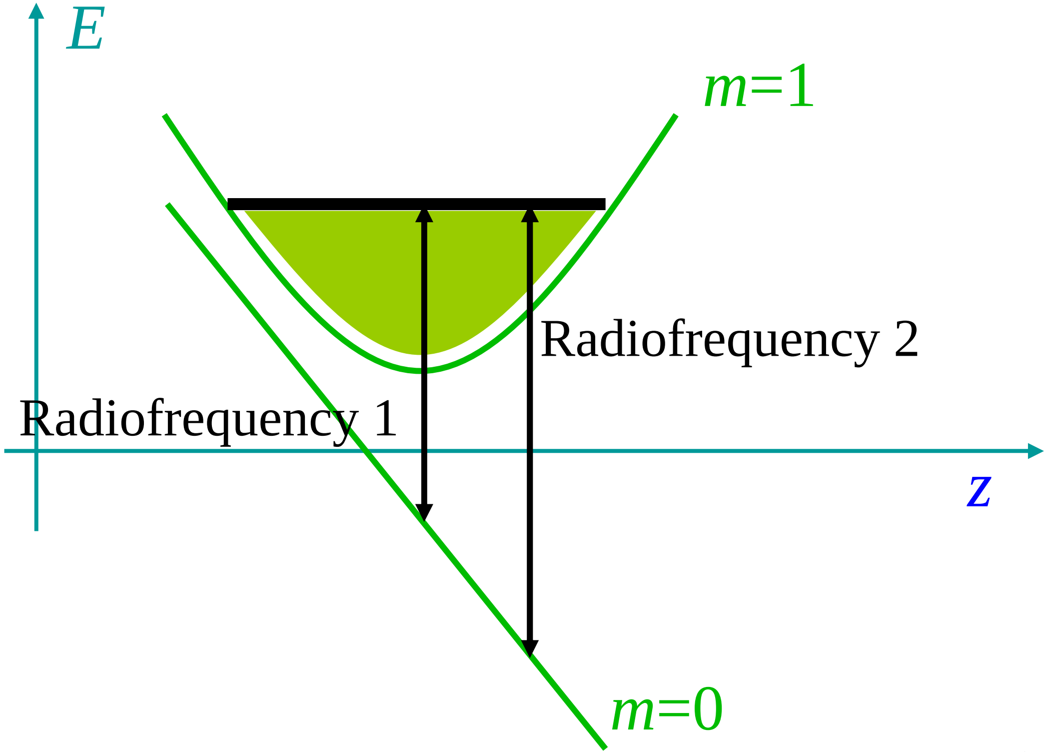
$$\frac{1}{2}mv_i^2 = \frac{1}{4}\hbar\omega_i$$

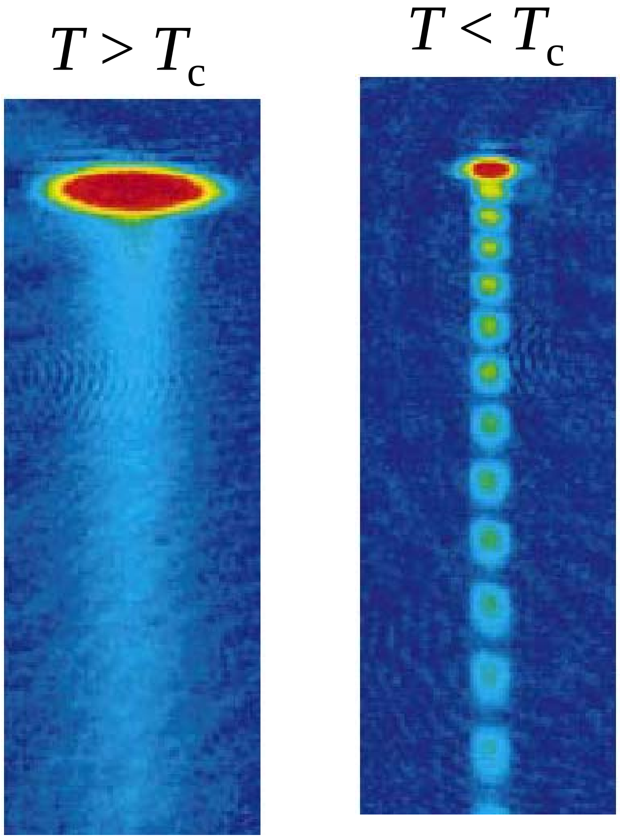
without interactions

anisotropic

Coherence of Bose-Einstein condensates

Young slit experiment, Munich





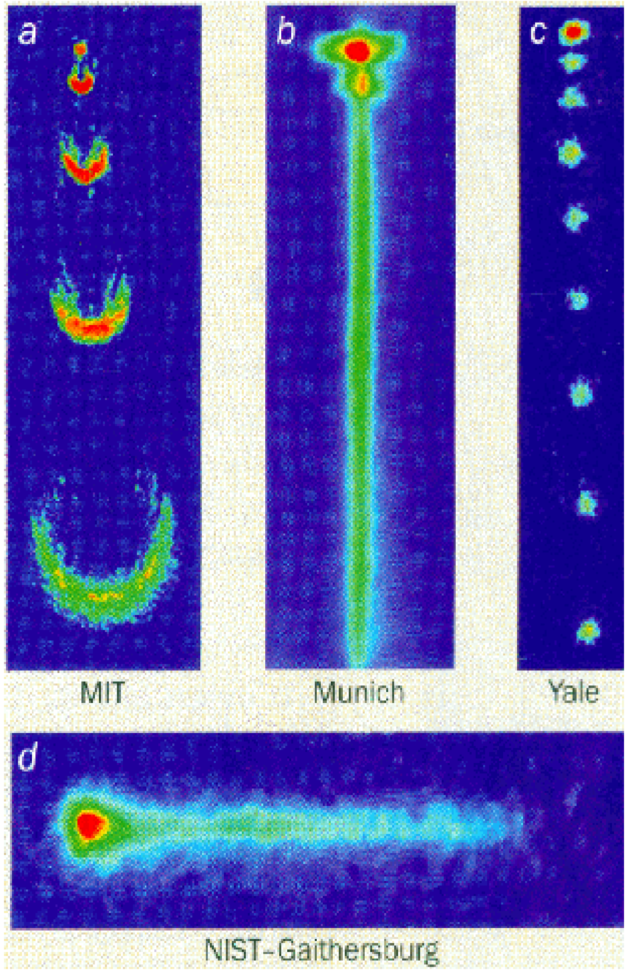
$$n_{out}(z) = \left|\psi_{\mathrm{out}}(z-z_1) + \psi_{\mathrm{out}}(z-z_2)\right|^2$$

$$\sim \frac{1}{\sqrt{z}}\left\{2 + 2\cos\left(q\sqrt{z} + (\omega_1-\omega_2)t\right)\right\}$$

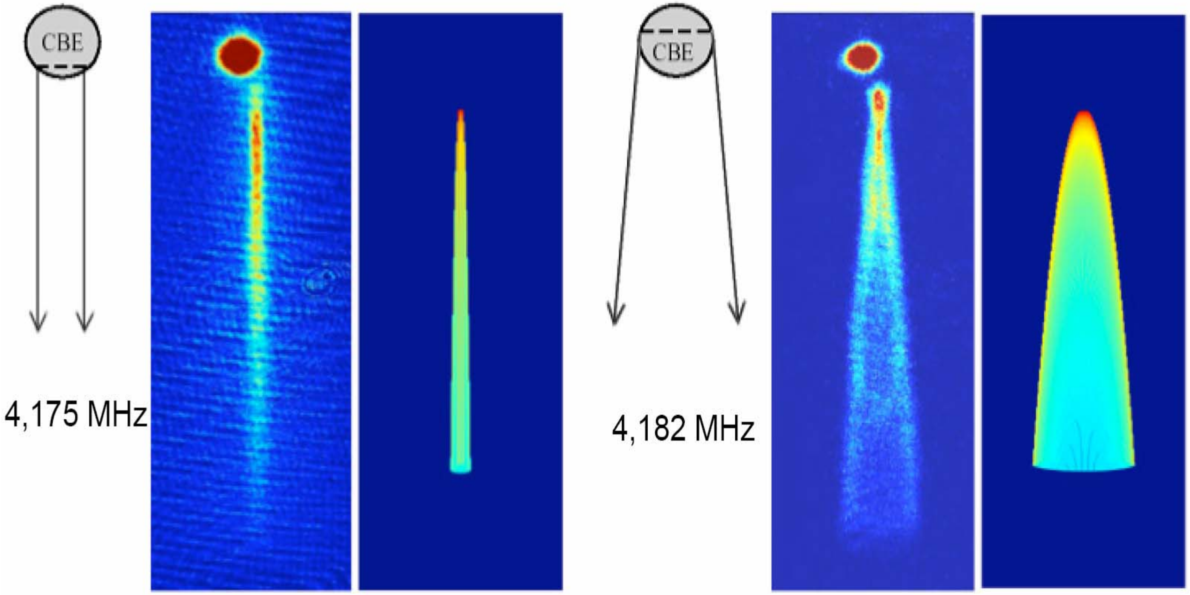
$$q = m(z_2 - z_1)\sqrt{2g}\,/\,\hbar$$

High contrast reveals macroscopic occupation of single quantum state

Atom lasers



Orsay



Influence of atom-atom interactions

So far limited flux:
less than 10^6 /second

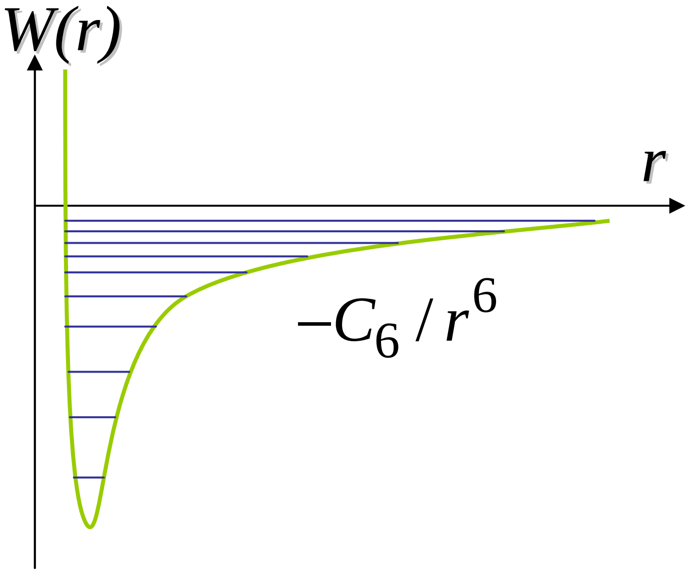
Control of interactions within a condensate

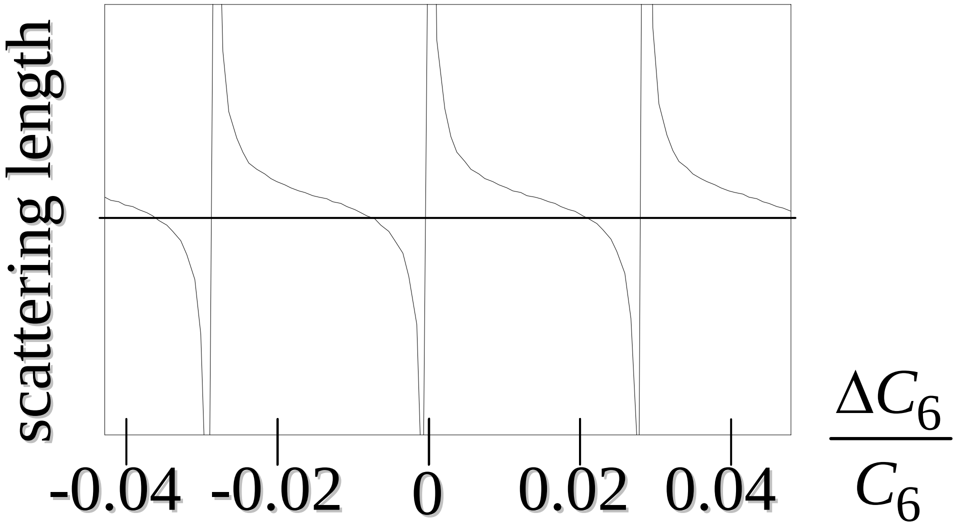
Gross-Pitaevski equation :

$$\left(-\frac{\hbar^2}{2m}\Delta + V(\vec{r}) + Ng\,\left|\psi(\vec{r})\right|^2\right)\psi(\vec{r}) = \mu\,\psi(\vec{r})$$

$$g = \frac{4\pi\hbar^2 a}{m}$$

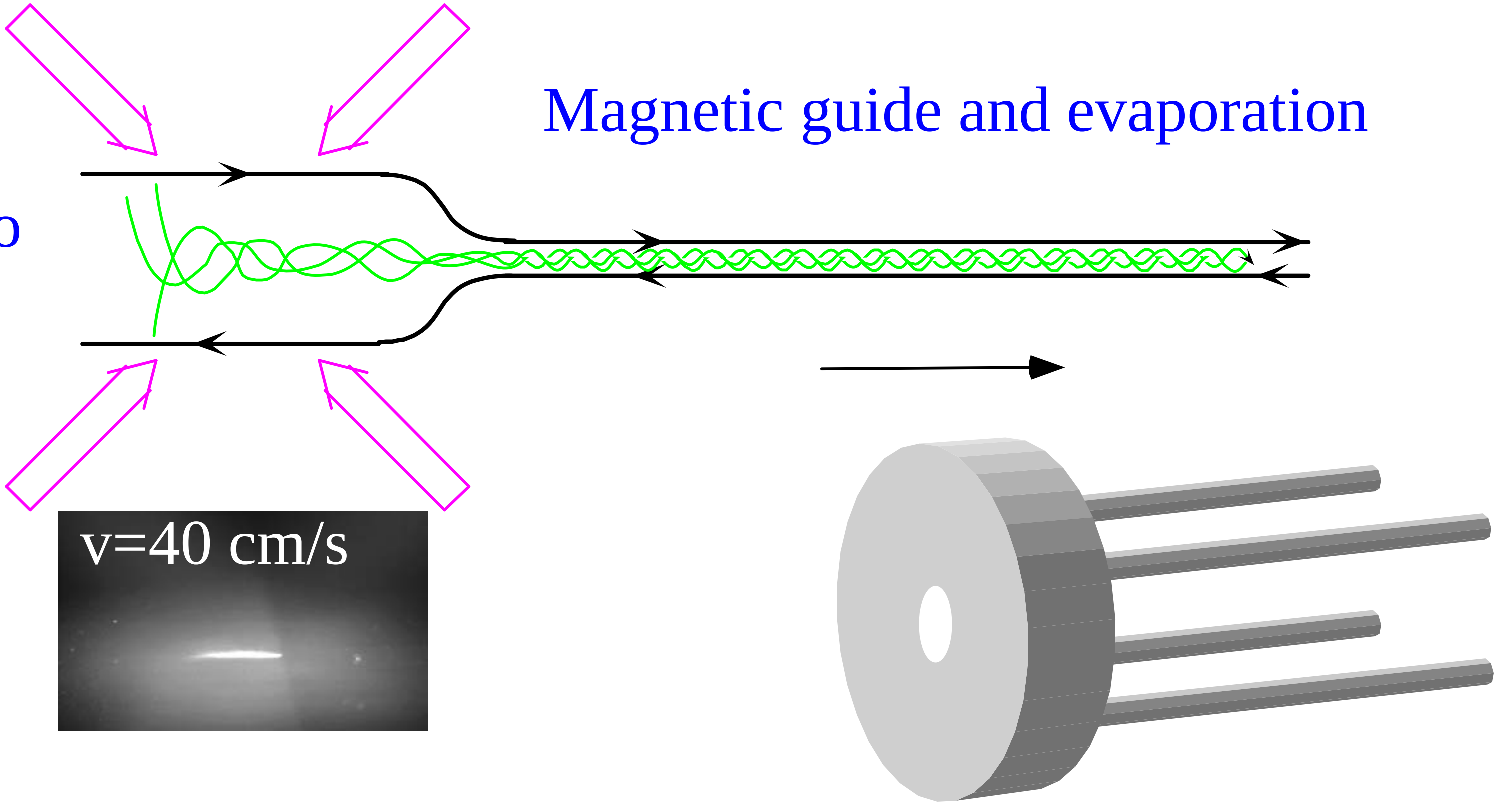
a : scattering length





$|a|$ varies typically between 1 and 100 nanometers (Bohr radius : 0,05 nm)

Towards a continuous atom laser



2D magneto -optic trap

Magnetic guide and evaporation

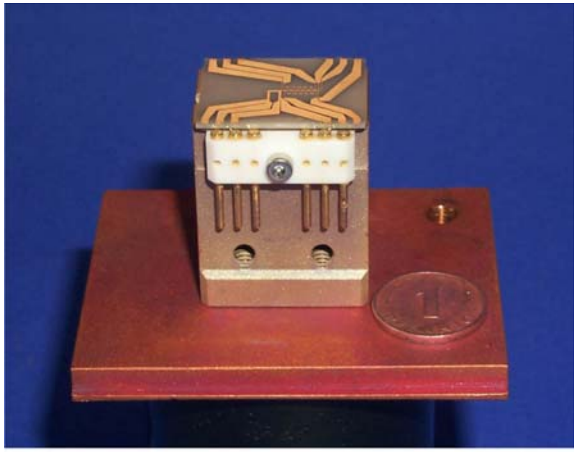
Expected flux: 10^7 condensed atoms /second
Factor 20 gain in phase-space density over 4 meters

In progress at ENS

Condensates on a chip

All wires for magnetic trapping and manipulation are integrated on a chip with a few cm^2 area

Munich
Reichel et al.



Gold wires (10μm) on silicon substrate

Greatly simplifies vacuum requirements, power requirements,
Condensates with a few 10^5 atoms
Application to atom interferometry on a chip
Quantum sensors in space

More than 10 groups with condensates and Fermi gas on chips

FURTHER READING

- BOSE-EINSTEIN CONDENSATION IN ATOMIC GASES, Proceedings of the International School of Physics « Enrico Fermi », Course CXL, **ed. M. Inguscio, S. Stringari, C.E. Wieman,** IOS Press, 1999.
- LASER MANPULATION OF ATOMS AND IONS, Proceedings of the International School of Physics « Enrico Fermi », Course CXVIII, ed. **E. Arimondo, W.D. Phillips, F. Strumia,** Elsevier Science, 1992.