BASES PARA A FISICA PROXIMA DO ZERO DE TEMERATURA

(cooling and trapping atoms)

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AMO
Atomic, Molecular and Optical Physics

bio photonics

Nano plasmonics



Diffusion



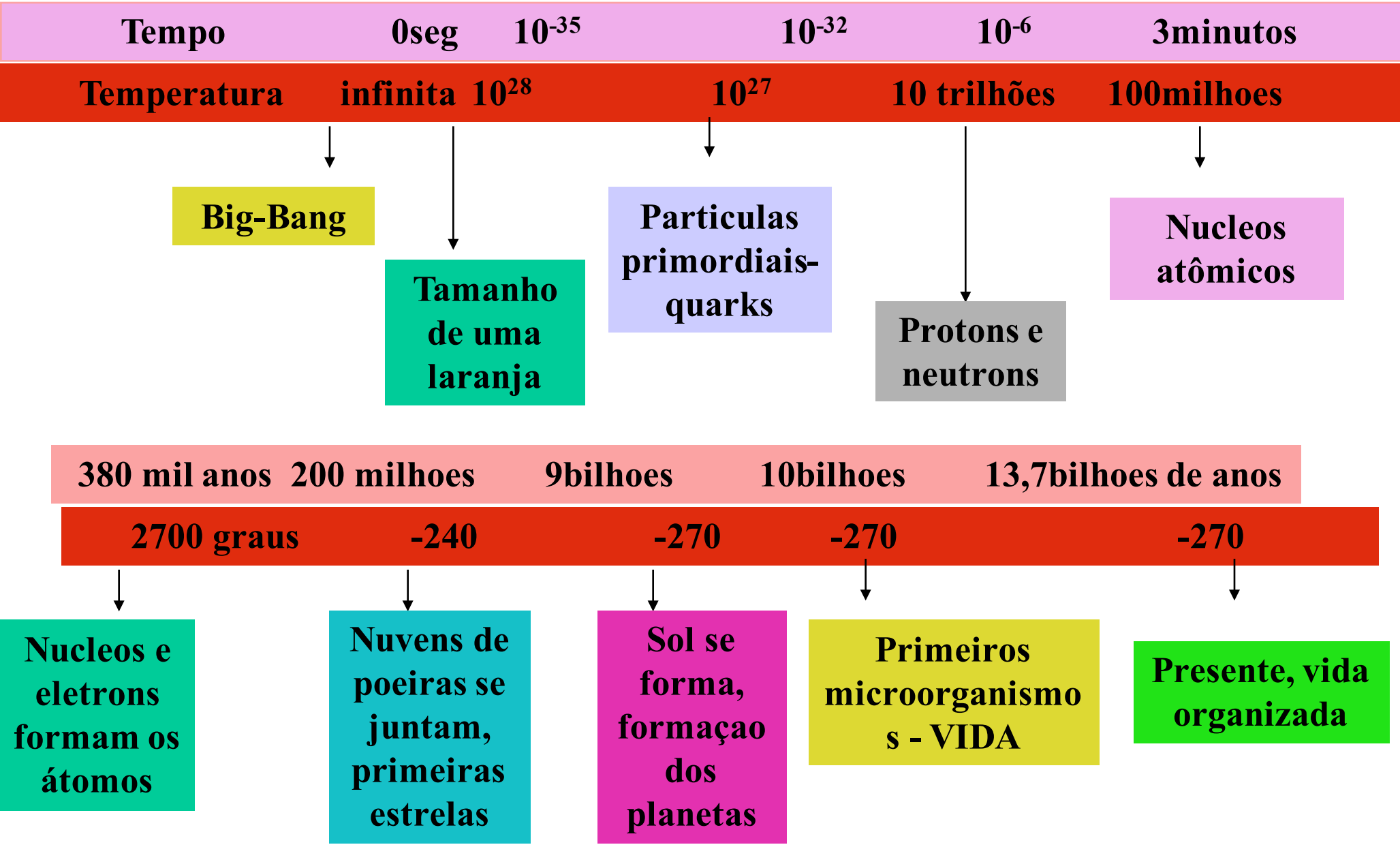
Innovation



Innovation with Social responsibility

http://cepof.ifsc.usp.br




Tempo 0seg 10^{-35} 10^{-32} 10^{-6} 3minutos
Temperatura infinita 10^{28} 10^{27} 10 trilhões 100milhoes
Big-Bang
Tamanho de uma laranja
Particulas primordiais-quarks
Protons e neutrons
Nucleos atômicos
380 mil anos 200 milhoes 9bilhoes 10bilhoes 13,7bilhoes de anos
2700 graus -240 -270 -270 -270
Nucleos e eletrons formam os átomos
Nuvens de poeiras se juntam, primeiras estrelas
Sol se forma, formaçao dos planetas
Primeiros microorganismos - VIDA
Presente, vida organizada

VAMOS RESFRIAR A MATÉRIA AO NOSSO REDOR

0,000001K

0 | **10^{-6} k** | **1k** | **100 k** | **200k** | **300k**

Condensado de Bose-Einstein

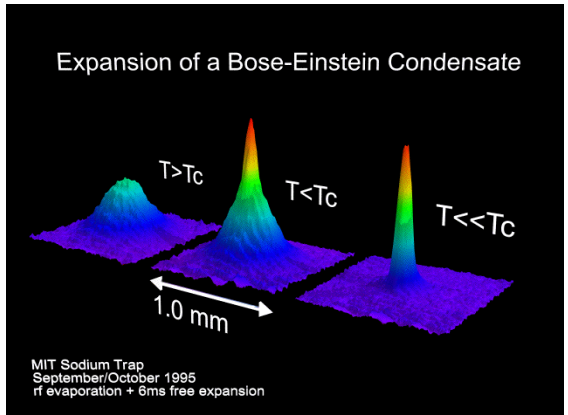
HÉLIO LIQUIDO

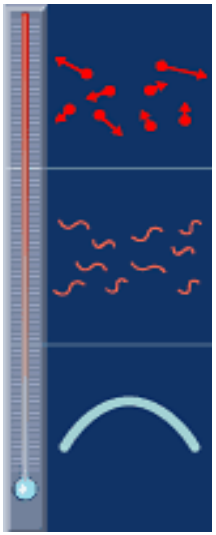
Super-fluído

NITROGÊNIO LIQUIDO

GÊLO

AGUA LÍQUIDA

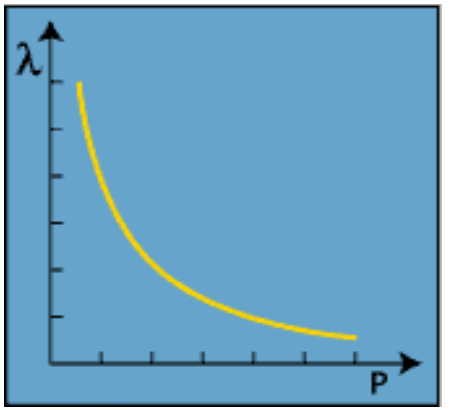




Comprimento de Onda De Broglie

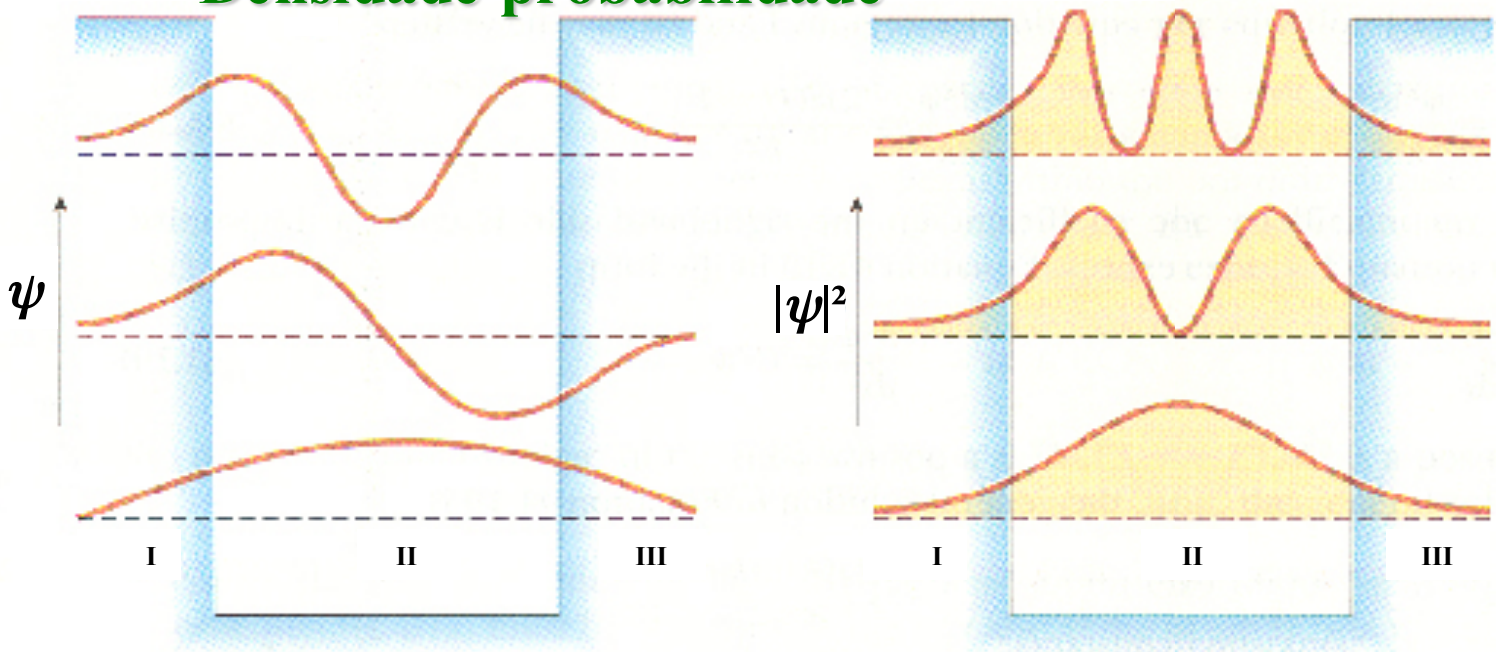
$$\lambda_D = \frac{h}{\sqrt{2\pi.M.K.T}}$$





$\lambda_D \sim$ **dimensão quântica**

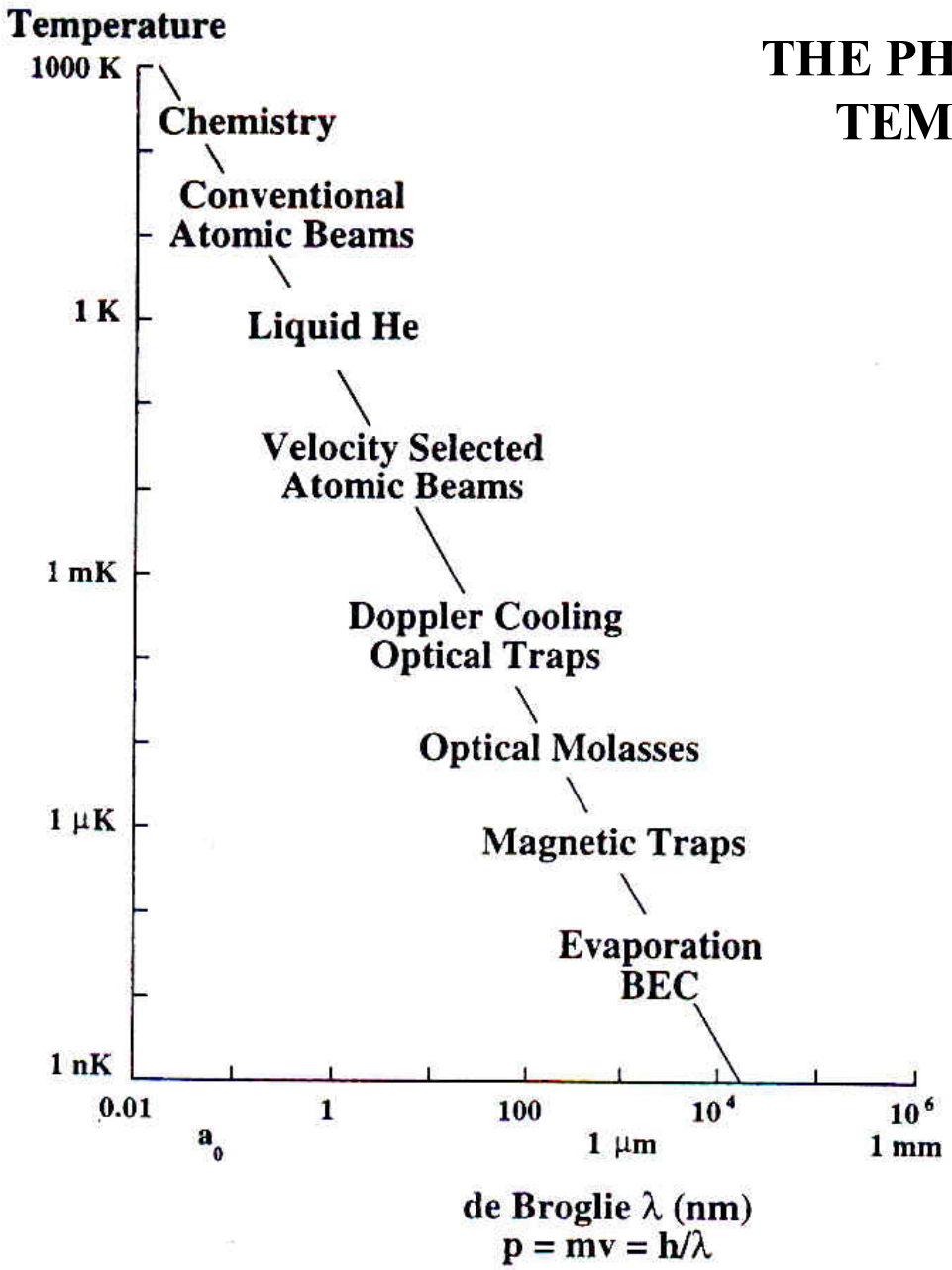
Densidade probabilidade



Provoca propriedades macroscópicas totalmente diferentes

Ex: pressão, etc.

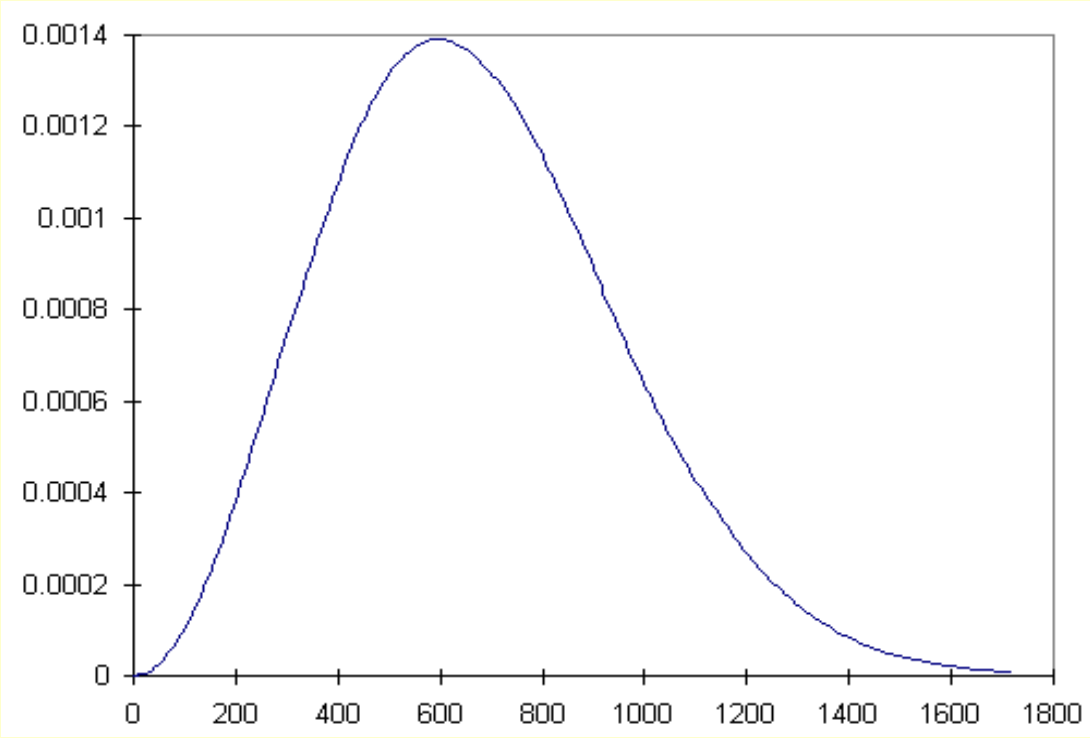
THE PHYSICS AT LOW TEMPERATURES

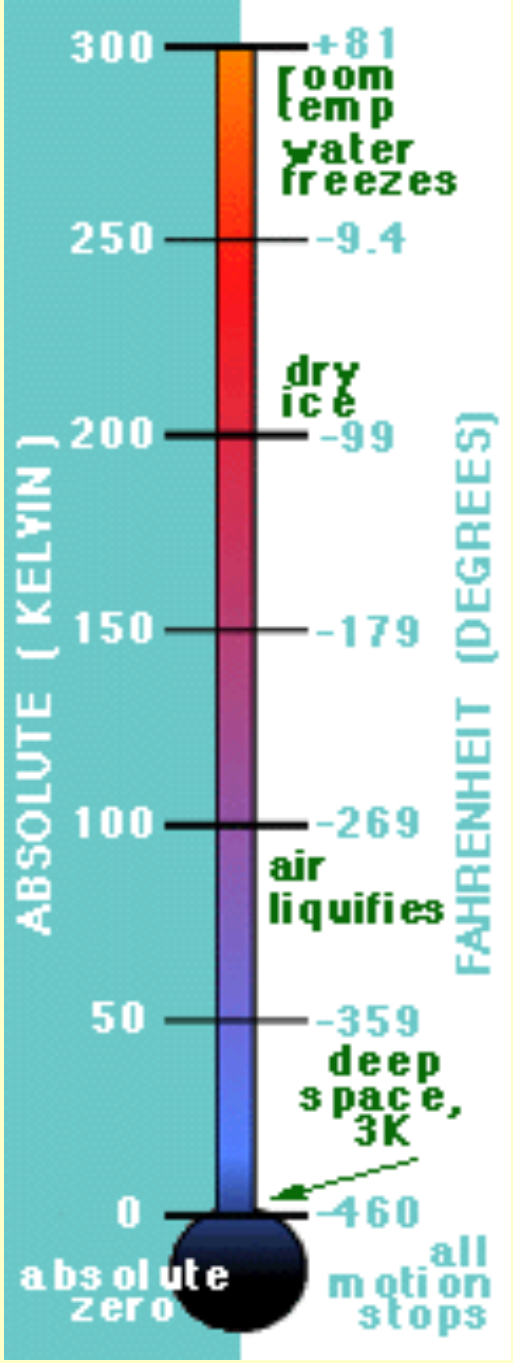


TEMPERATURE

$$\frac{1}{2} m.v^2 = \frac{3}{2} K.T$$

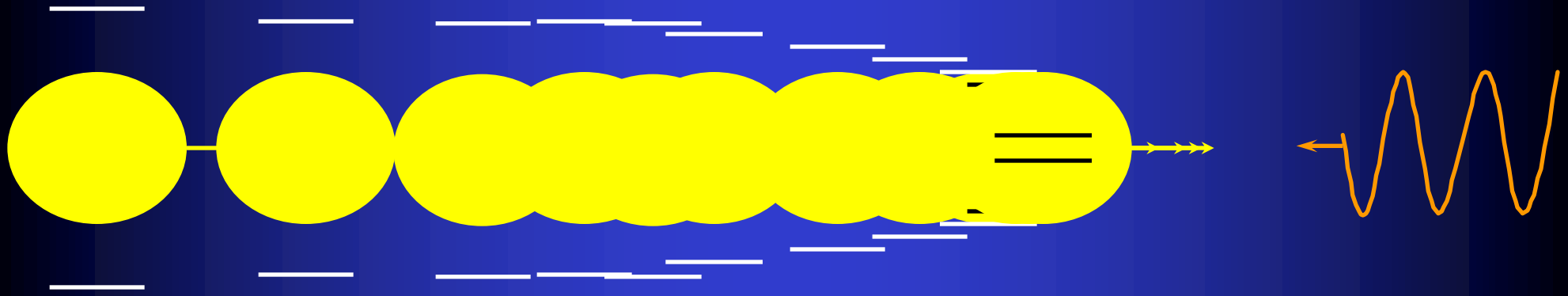
ATOMIC FRACTION.





RADIATION FORCE

INTERNAL STRUCTURE → MOMENTUM ABSORPTION



$$\overline{P} = \frac{h}{\lambda}$$



Laser Cooling

RADIATION FORCE

SPONTANEOUS

$$\overrightarrow{F1} = \frac{2\pi h \Gamma \Omega^2 \vec{k}}{4(\Delta \pm \vec{k}.\vec{V} \pm \gamma by)^2 + \Gamma^2 + 2\Omega^2}$$

$$where \quad \Omega^2 = \Omega_0^2 e^{-(x \pm s)^2 / w^2}$$

Dipolar

$$\overrightarrow{F2} = \frac{(2\pi h \Delta).GRAD\Omega^2}{4(\Delta \pm \vec{k}.\vec{V} \pm \gamma by)^2 + \Gamma^2 + 2\Omega^2}$$

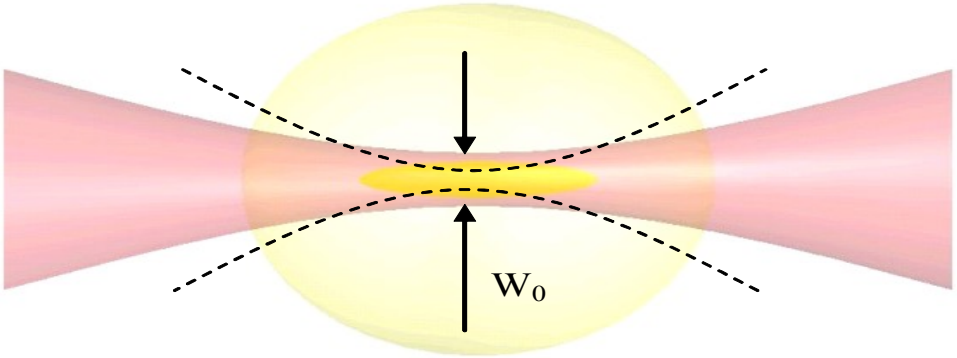
Dipolar

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$$U(r,z) = -\frac{U_0}{1+(z/z_R)^2}\exp(-2\frac{r^2}{w^2{}_o})$$

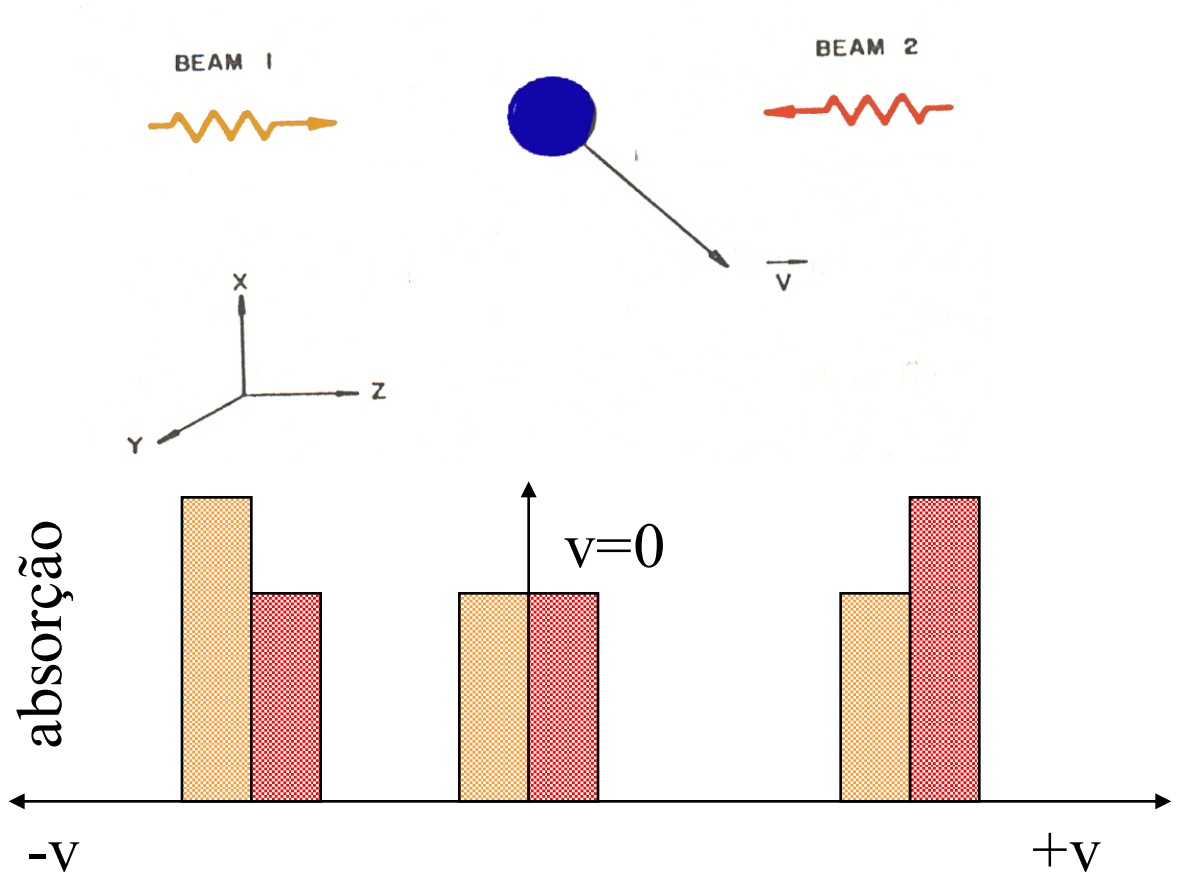
E – radiação fora da ressonancia

λ =0,8 - 10 μm



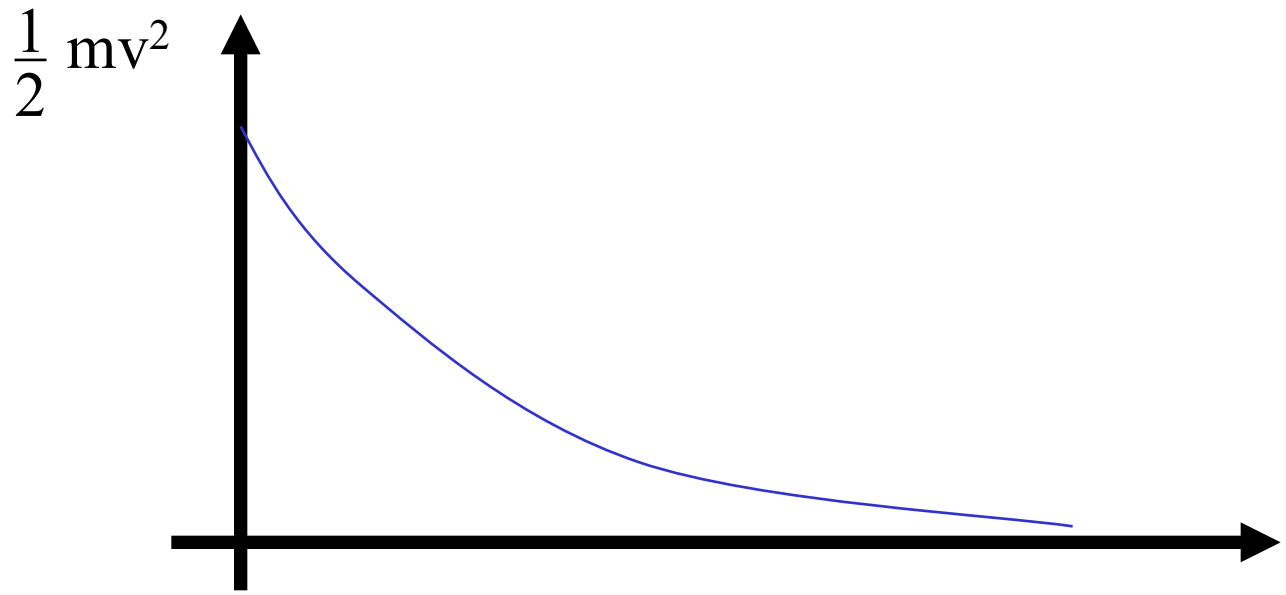
$$U_0 = \frac{\alpha_{stat} P_0}{\varepsilon_0 c \pi w^2{}_0}$$

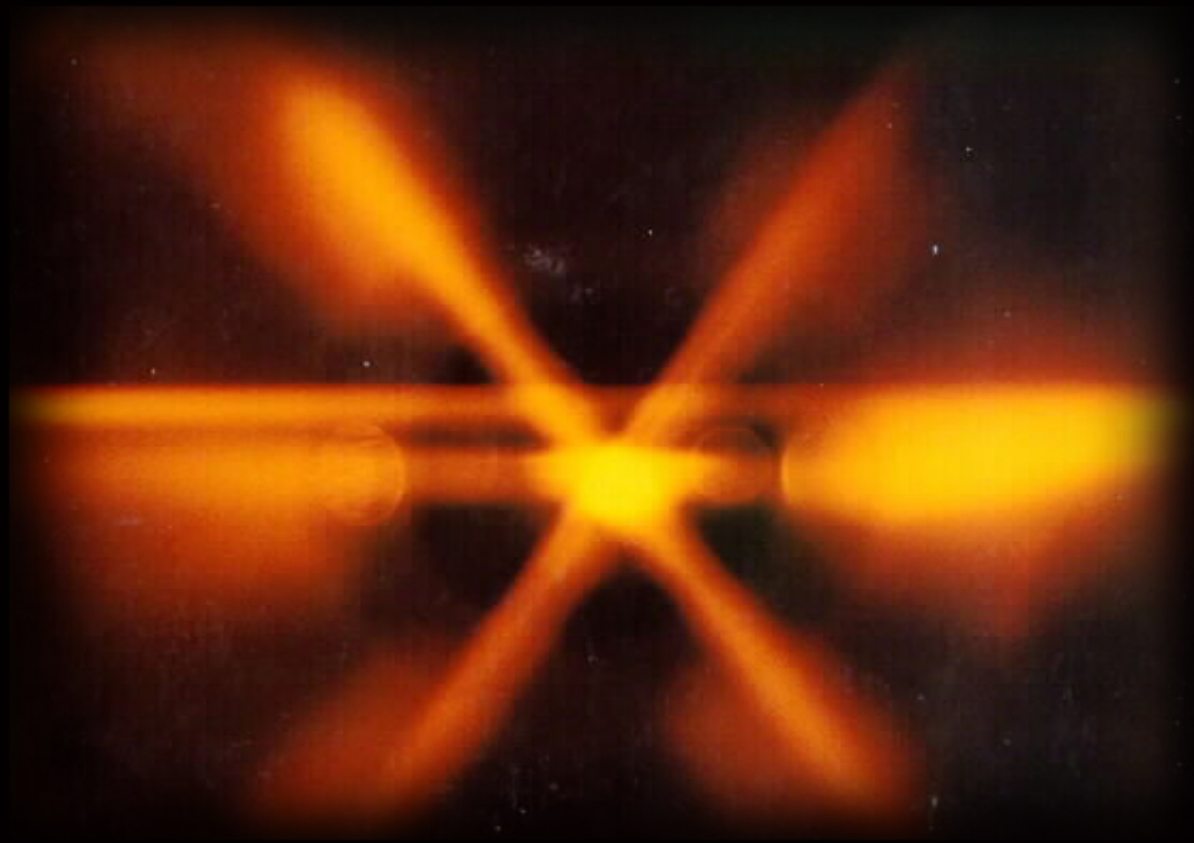
Optical molasses (SPONTANEOUS)



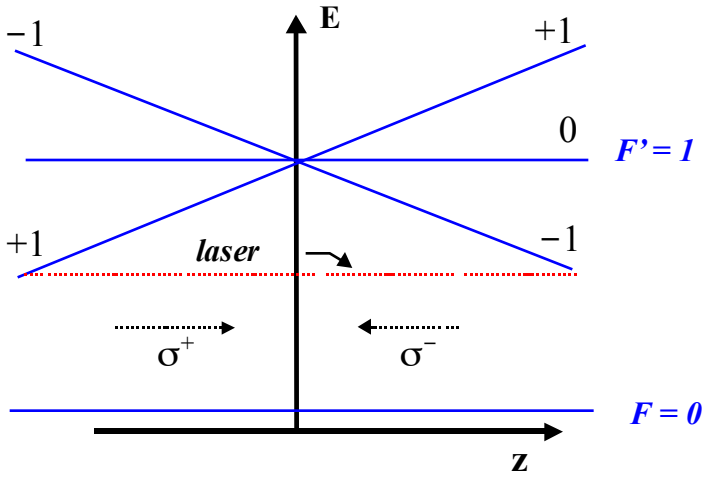
$$\vec{F} = -\alpha \vec{v}$$

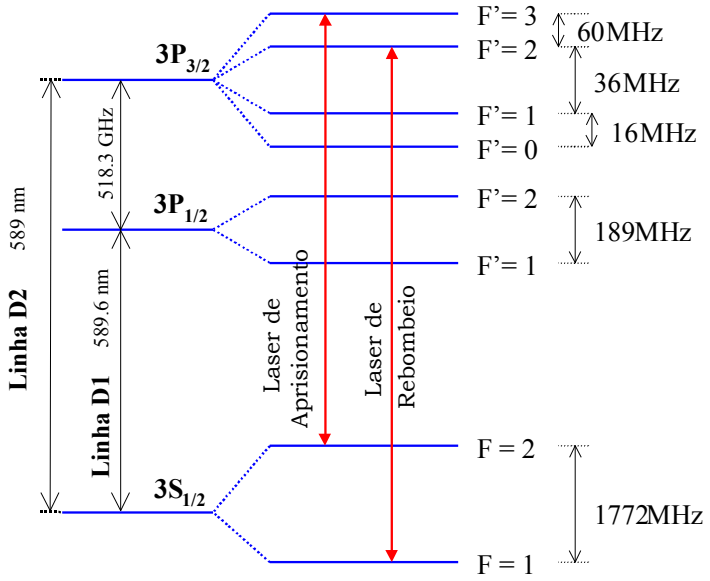
Damping force able to Remove energy

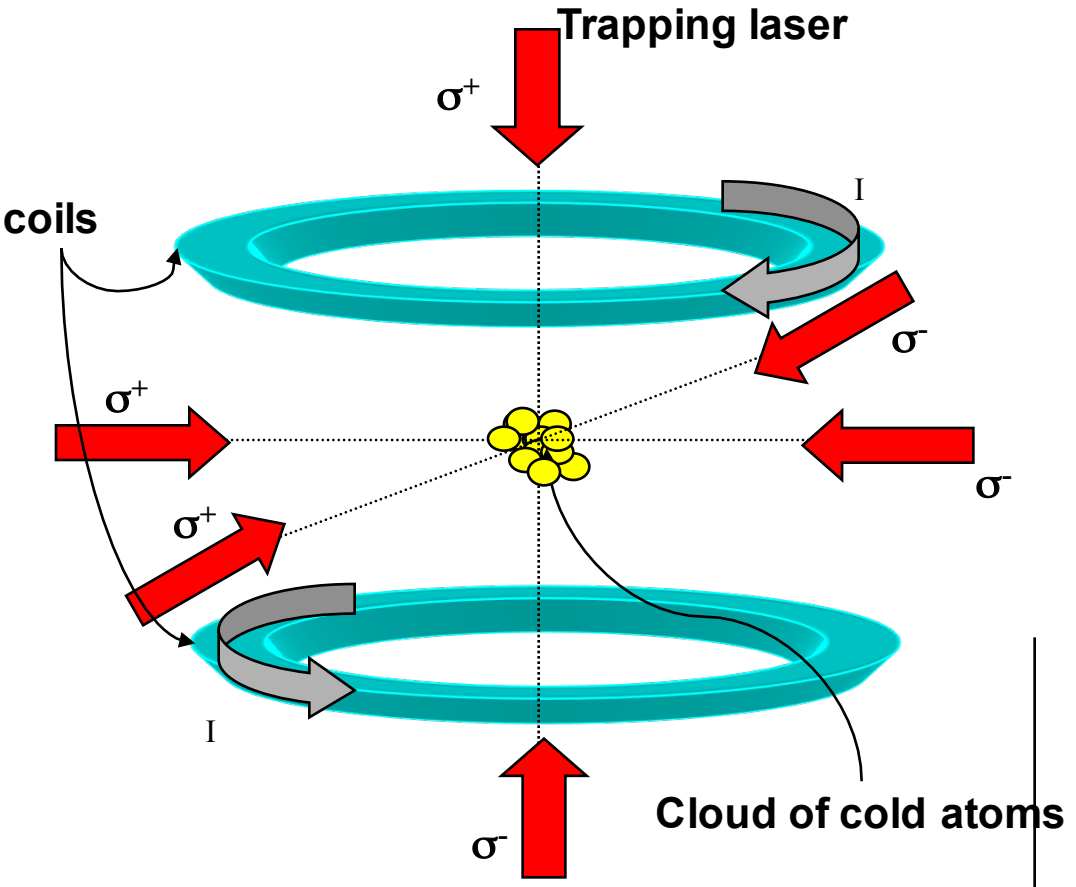


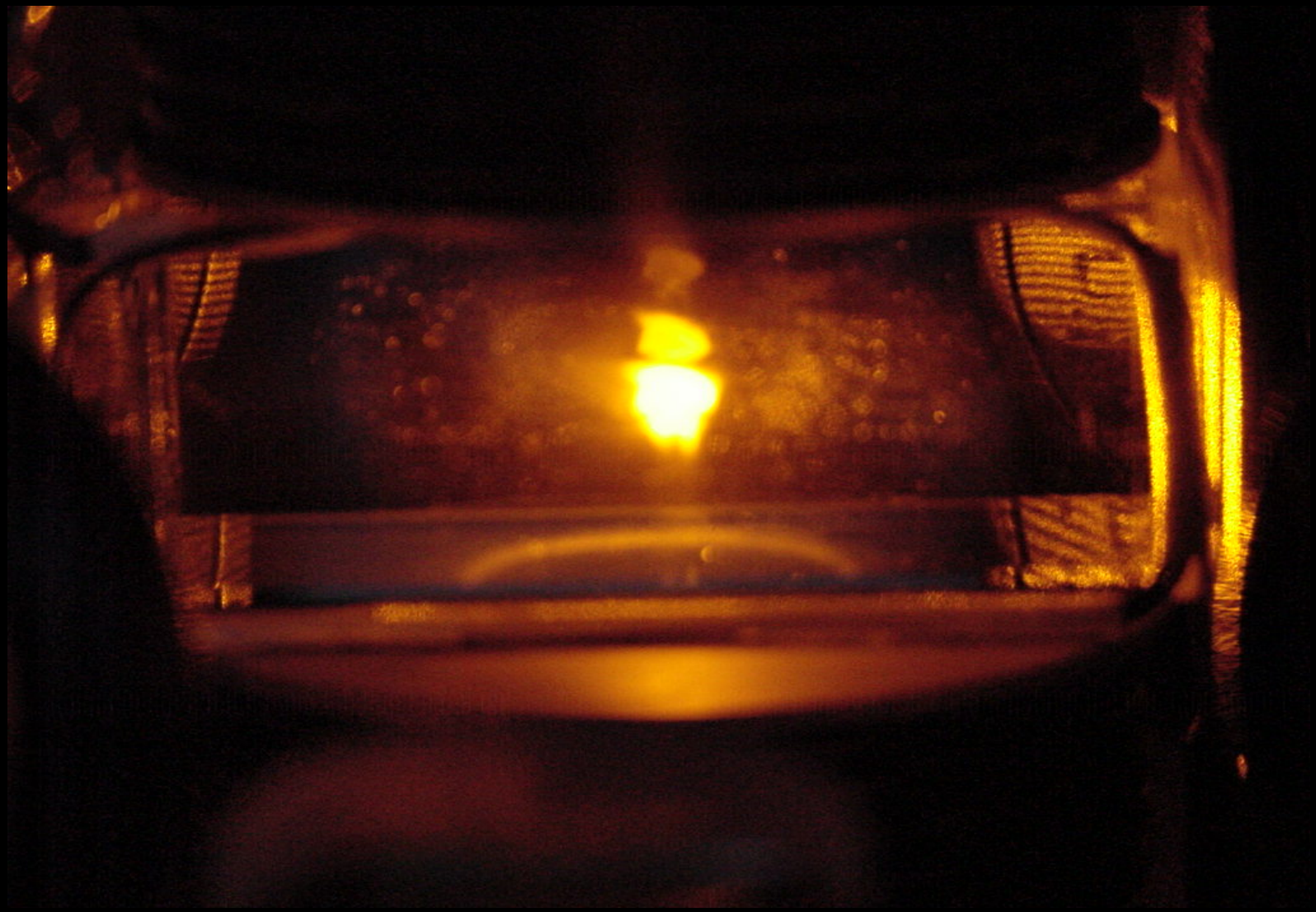


Magneto Optical Trap (MOT)









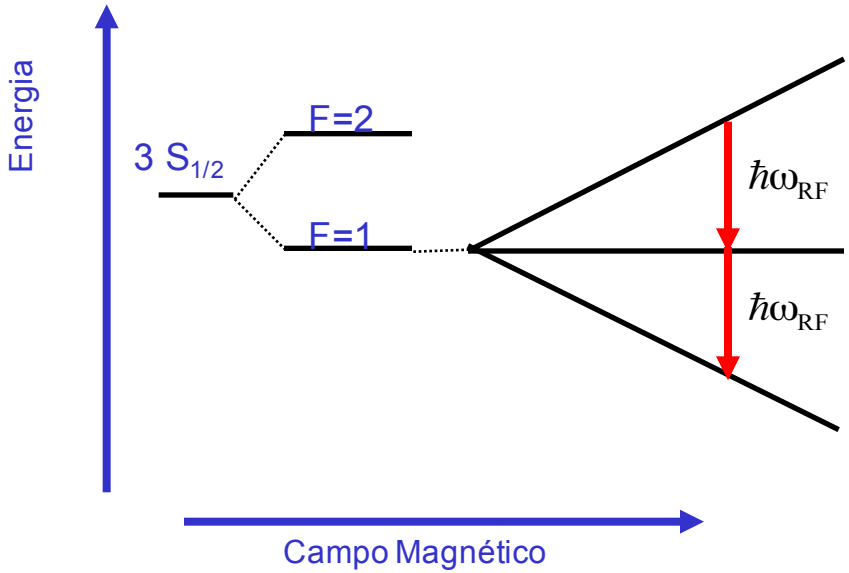
LiMITS

$$KT = \frac{h\Gamma}{4}$$

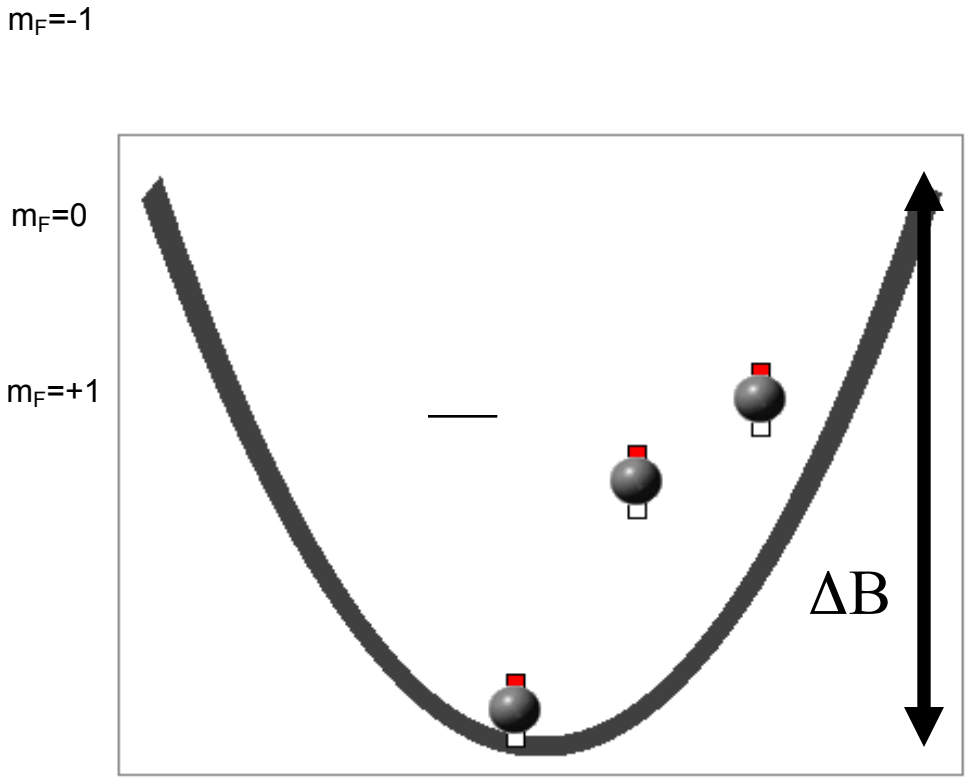
NEW FEATURES OVERCOME THIS LIMIT

CONFINAMENTO: Magnetic Trapping

Atom is like a permanent magnet → Restoring force towards the minimum of B



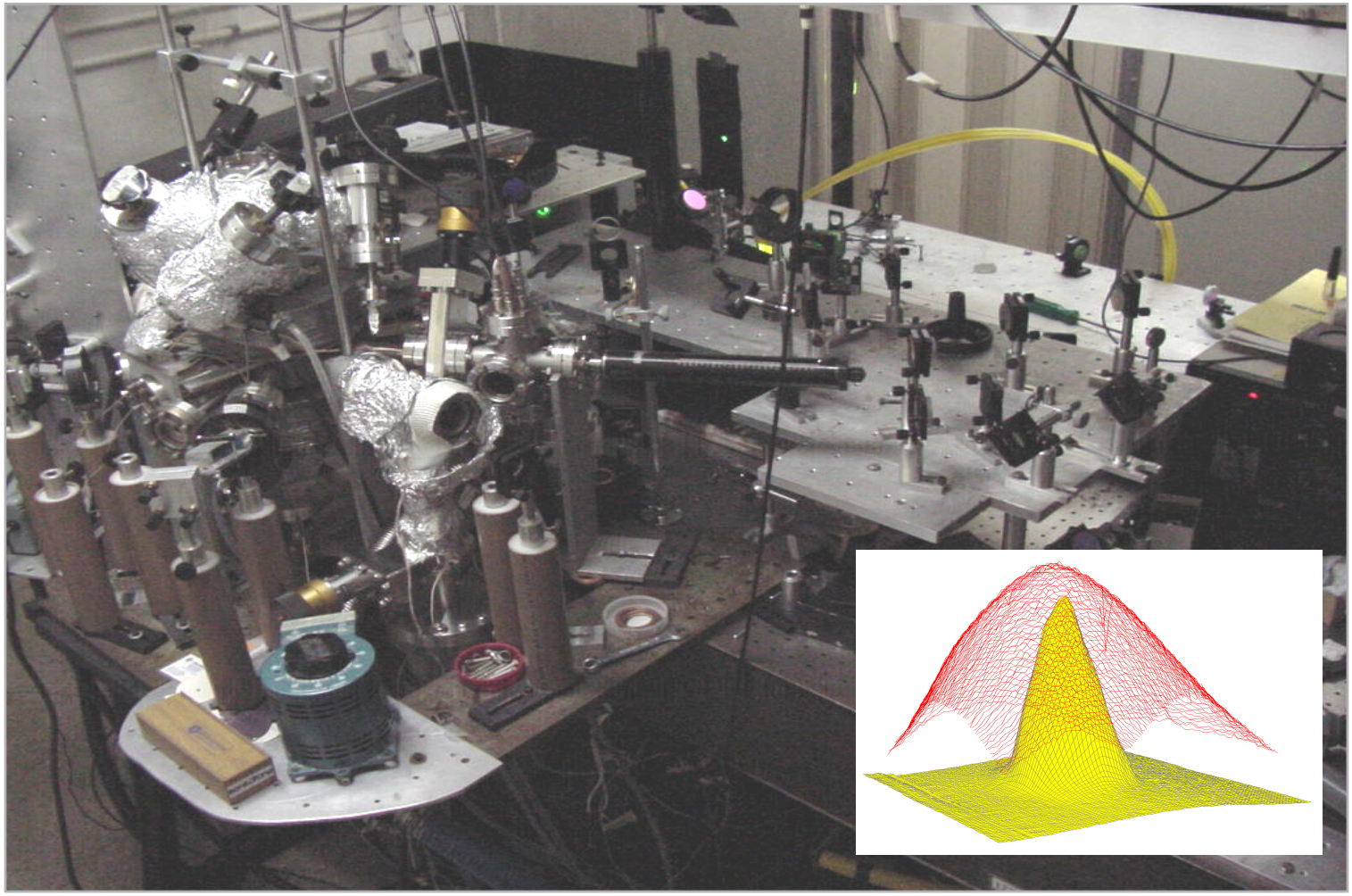
$$U = -\mu B$$

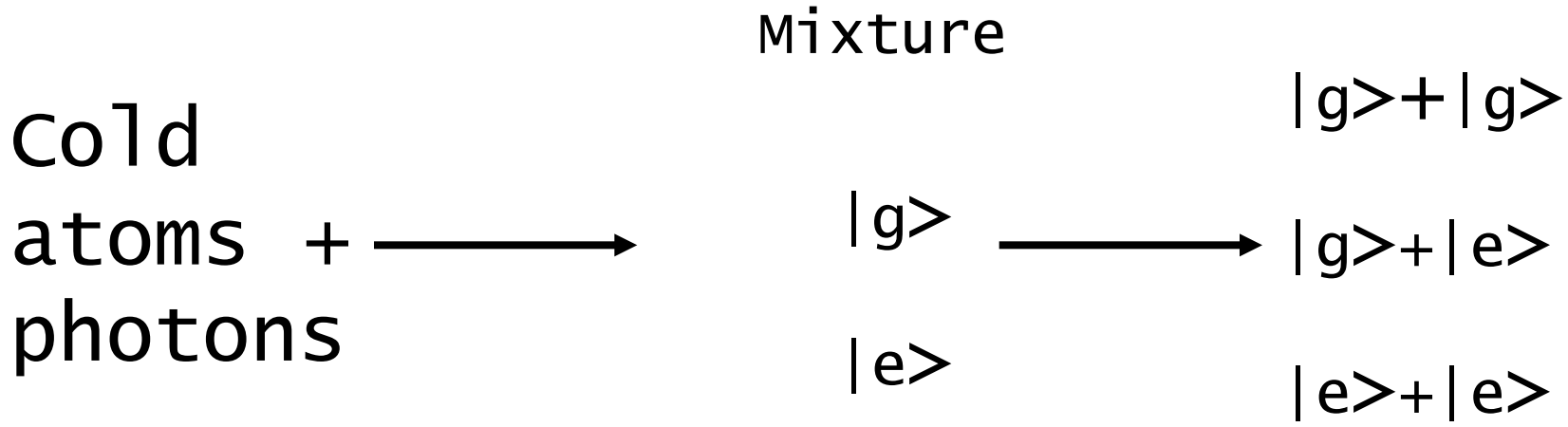


v (m/s)	ΔB
0,01(10^{-9}K)	0,002G
1	20G
10 (10^{-3}K)	0,2T
100	20T
1000 (10^{3} K)	2000 T

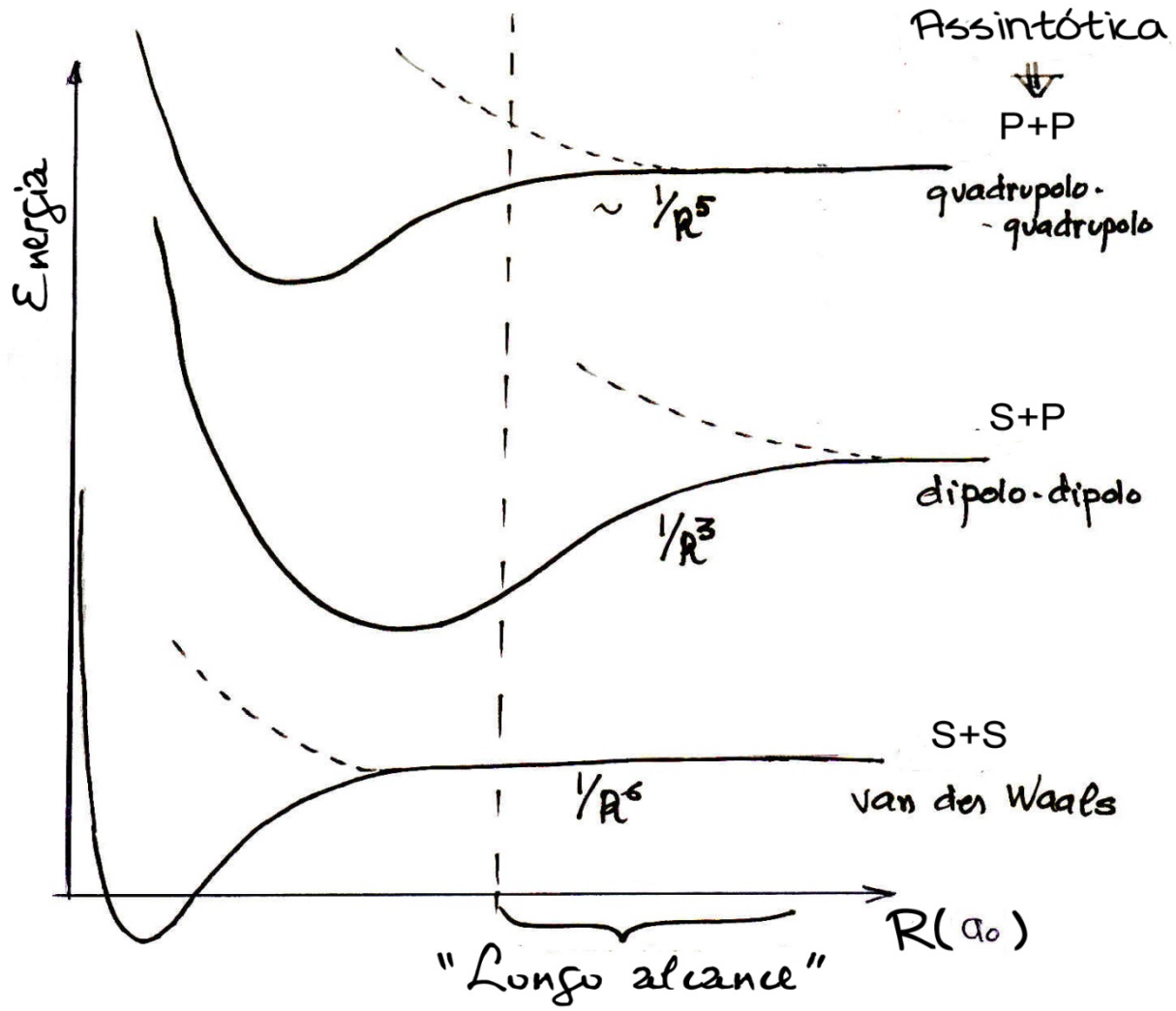
IS NECESSARY O BE COLD

Cold Collisions:MOT STAGE

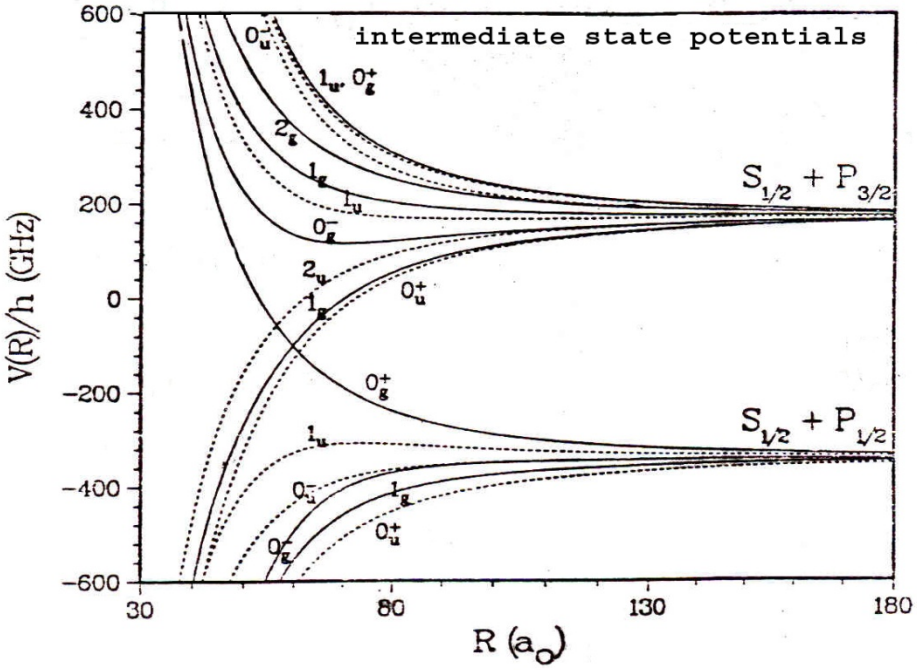



Mixture
Cold
atoms +
photons
|g>
|e>
|g>+|g>
|g>+|e>
|e>+|e>

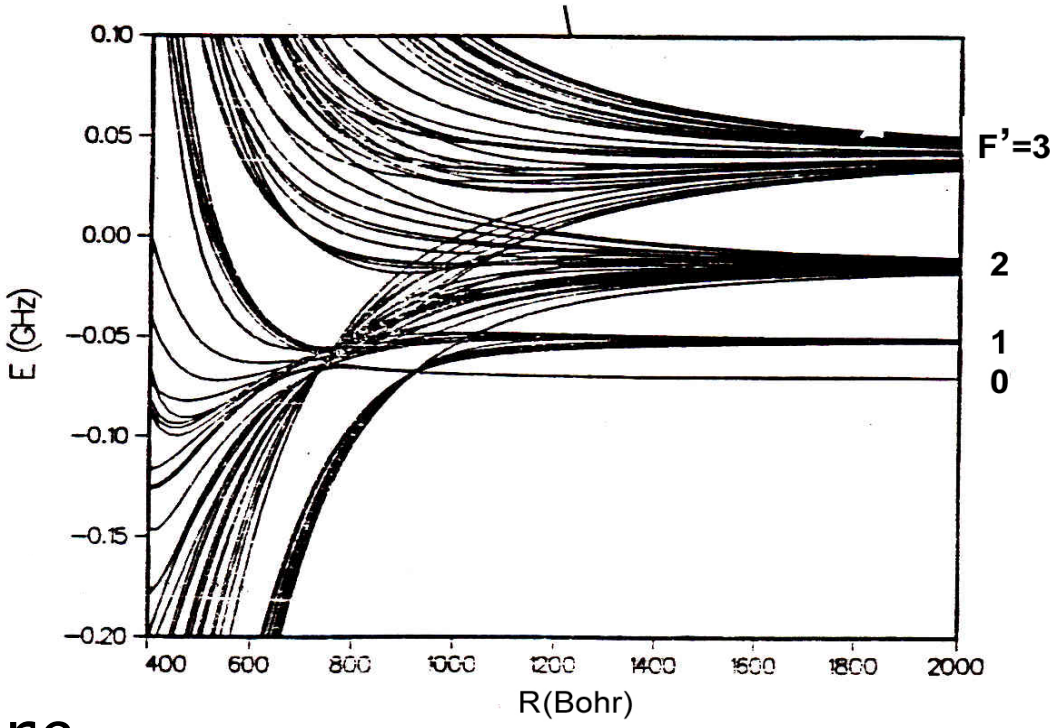
Potentials


Assintótica
P+P
quadrupolo-quadrupolo
~ 1/R^5
S+P
dipolo-dipolo
1/R^3
S+S
van der Waals
1/R^6
Energia
R(a0)
"Longo alcance"

In reality more complex than this



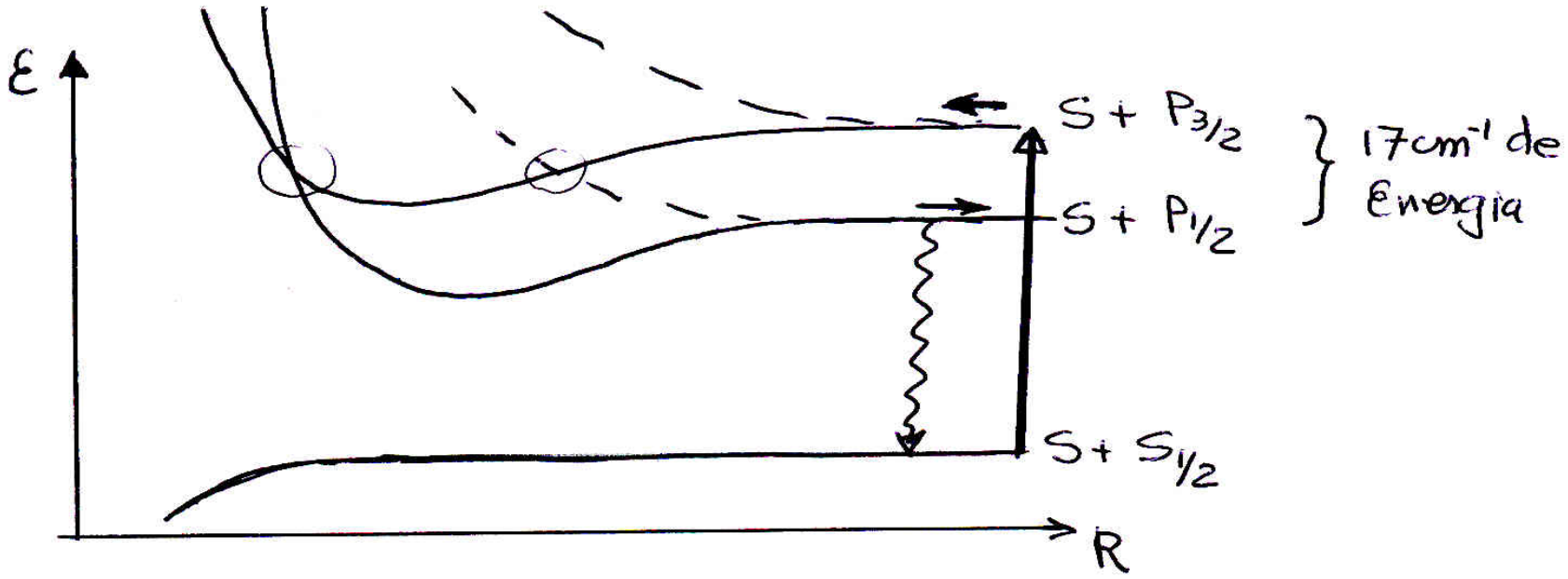
Fine Structure



Hyperfine Structure

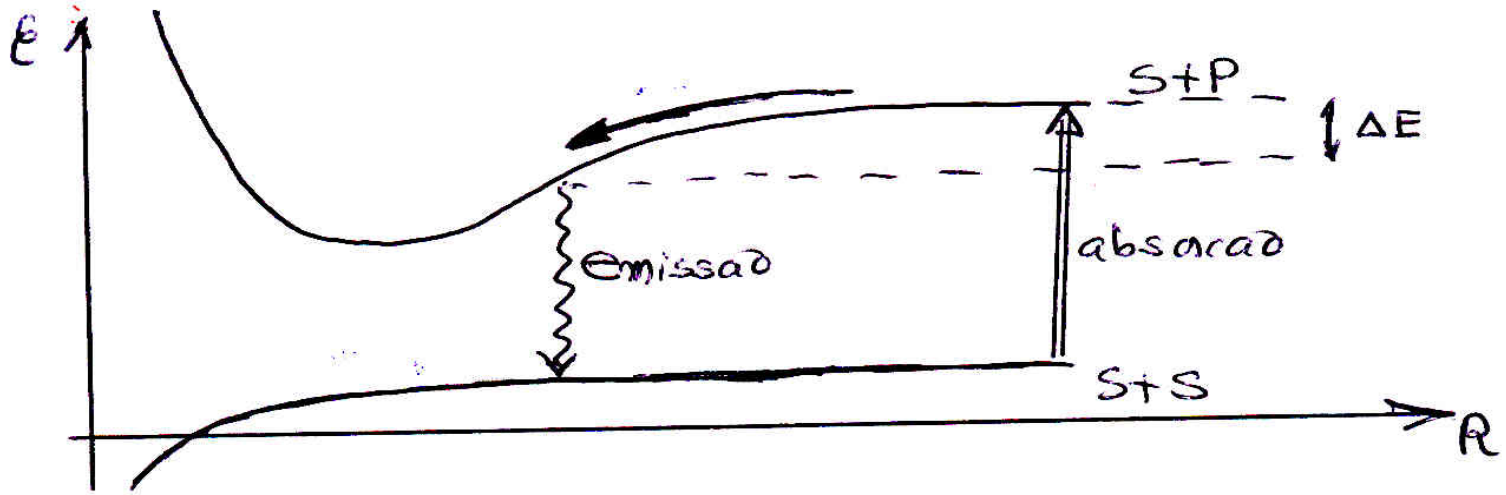
(|g>+|e>)

Fine Structure Change(FSC)

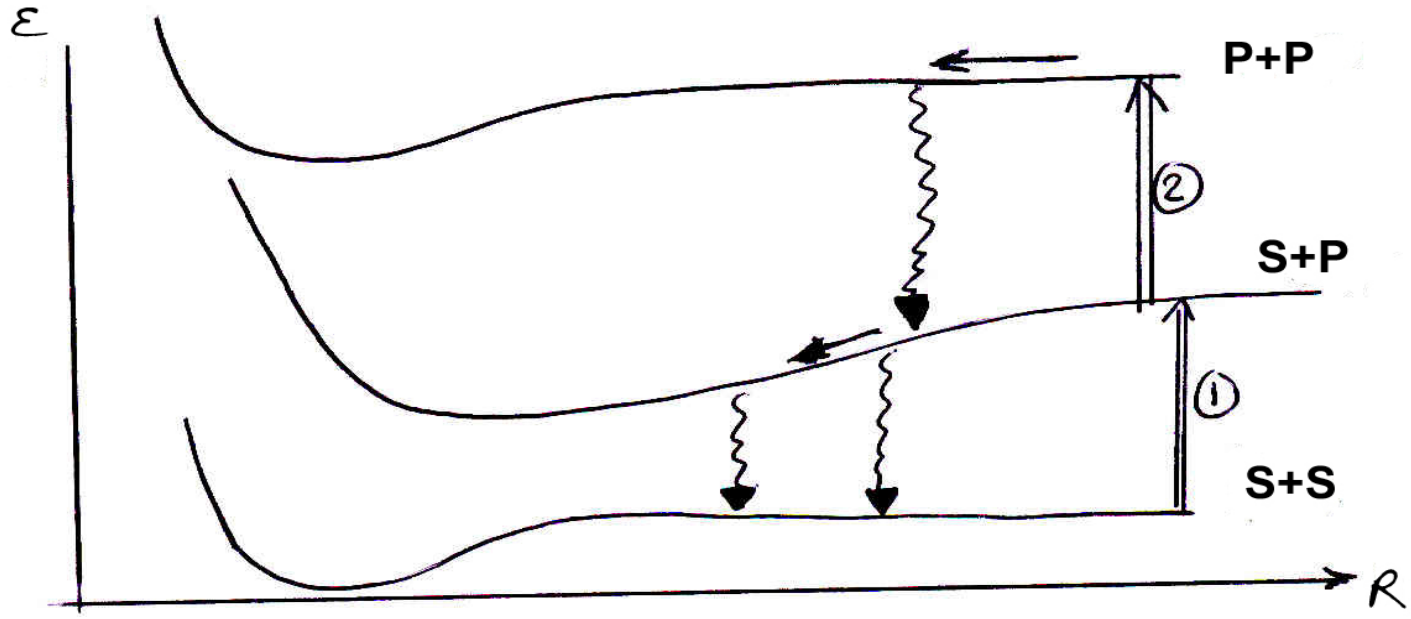


produce atoms at Na 60 m/s

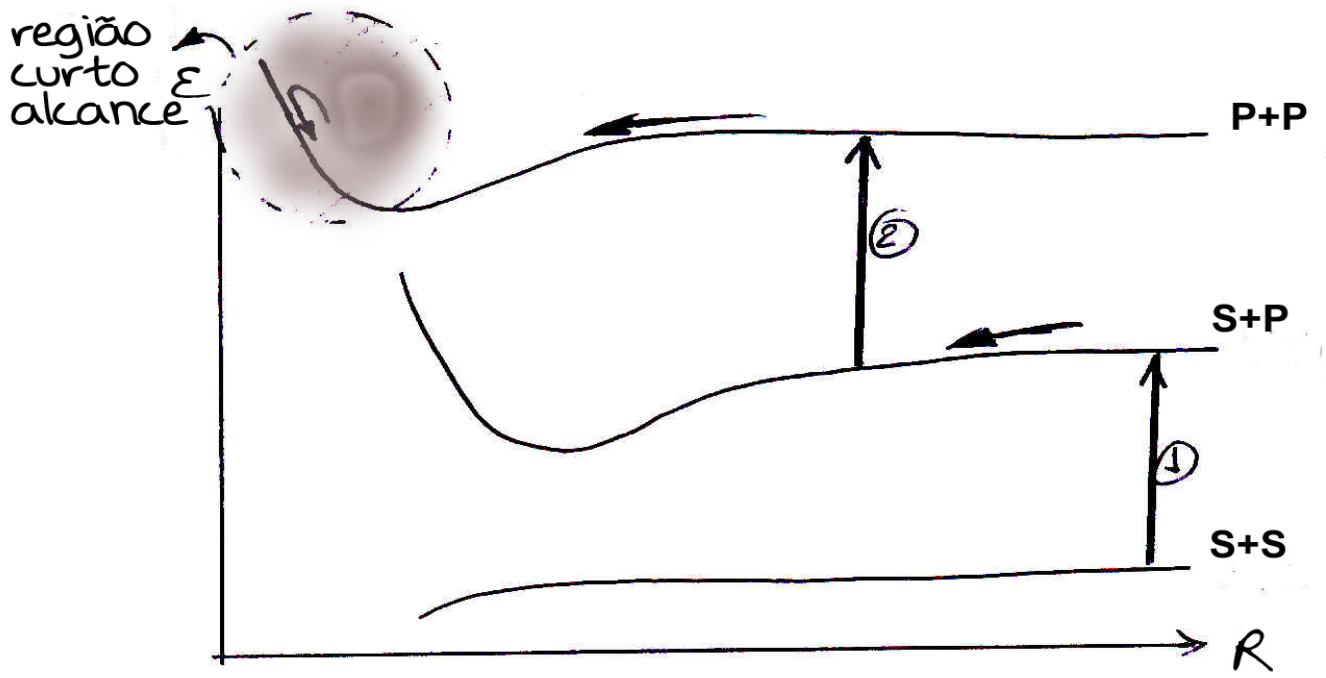
Radiative Escape (RE)



Excited+ excited



Chemical reaction starting at long range and
Taken place at short range

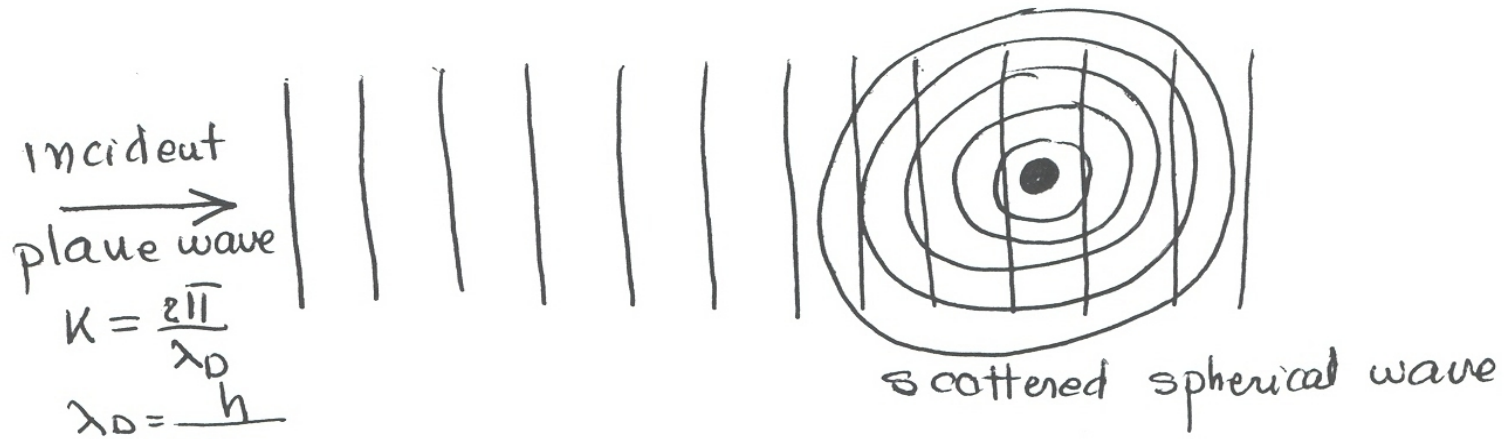


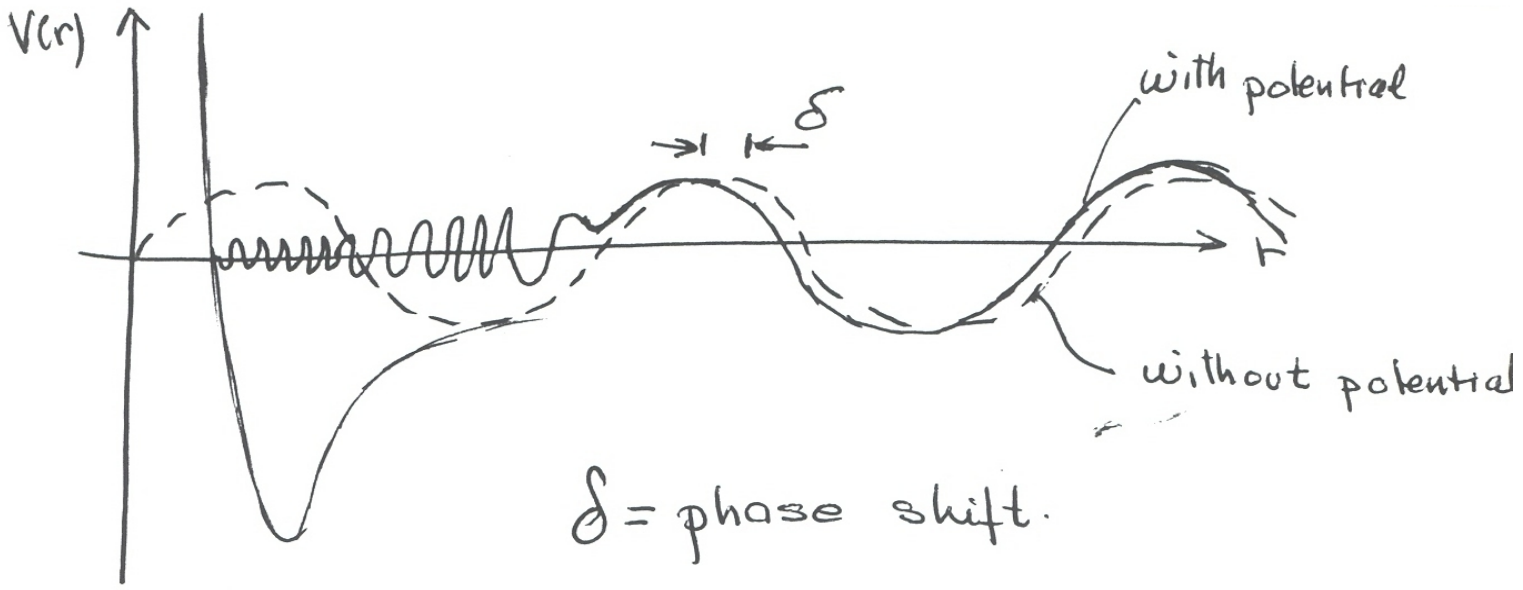
Scattering Length

Consider the atomic encocnter at low energy. (

$E =$







δ = phase shift.

Wave function for the center of mass motion

$$\psi = \underbrace{e^{ikz}}_{\text{incoming}} + \underbrace{\psi_{sc}(\vec{r})}_{\text{scattered.}}$$

→ At large interatomic separations → scattering is an outgoing spherical wave

$$E = \frac{\hbar^2 k^2}{2m_r} \qquad \psi = e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

At very low energy $k \to 0$; $f(\theta)$ approaches a constant.

$f(\theta) \to -a$

$$\psi = 1 - \frac{a}{r}$$

The constant a is called scattering Length

In this regime a is the only quantity that characterize the interaction

$\underline{a}$ is connected with phase shift $\underline{\delta}$

From scattering theory

$\frac{d\sigma}{d\Omega} = |f(\theta)|^2$ differential cross section

if $f(\theta) \to -a$ $\longrightarrow$ $\boxed{\sigma = 4\pi a^2}$

For a Central Potential

$$f(\theta) = \frac{1}{2ik} \sum_{l=0}^{\infty} (2l+1)\left(e^{i2\delta_l} - 1\right) P_l(\cos\theta)$$

$$\Downarrow$$

Total cross section

$$\sigma = \frac{4\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) \operatorname{sen}^2 \delta_l$$

partial waves

Very small $k \rightarrow l = 0$

$$\sigma = \frac{4\pi}{k^2} \operatorname{sen}^2 \delta_0$$

$$\Downarrow$$

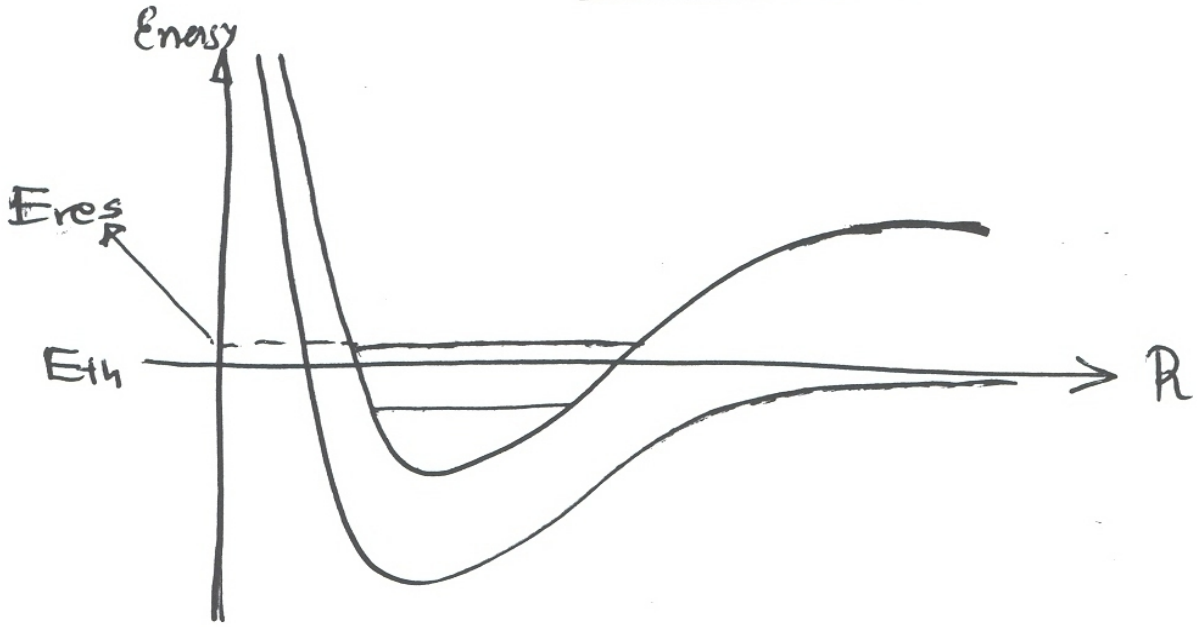
$$\delta_0 = -ka$$

If we have a single collision channel

→ a does not change

If there are other open channel

→ a can change



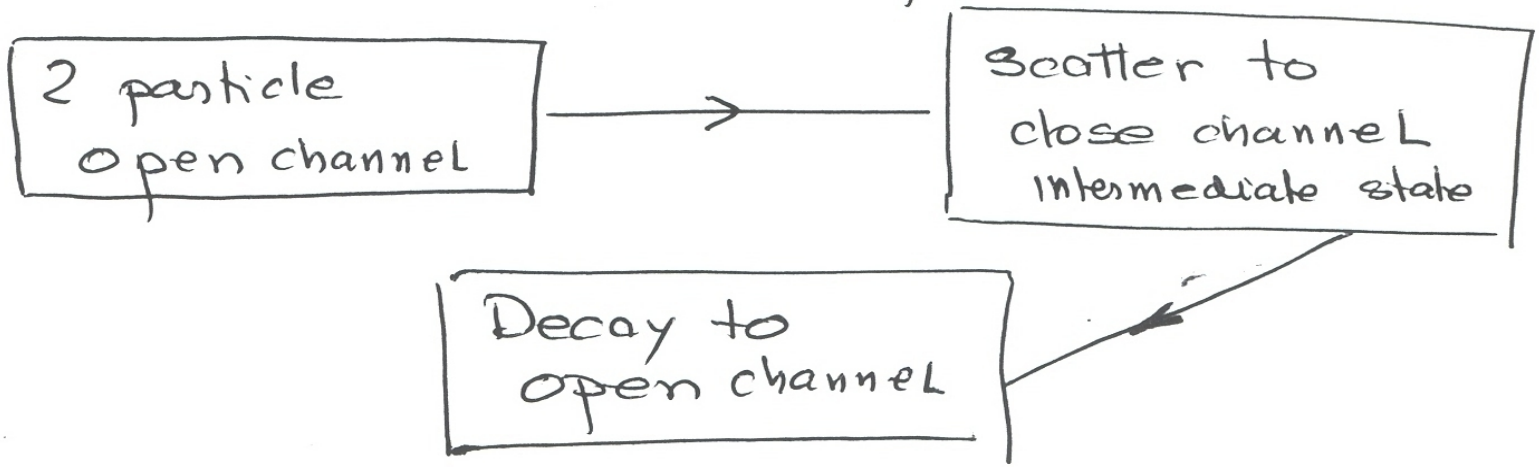
Elastic scattering in one channel can be altered if there is a low-energy bound state in a second channel which is closed. $\Rightarrow$ Feshbach resonance

$\Downarrow$

Make it possible to tune scattering length

Feshbach resonances happens $\longrightarrow$ total energy in an open channel matches the energy of a bound state

It is a second order process



$$a \sim \frac{C}{E - E_{res}}$$

E → energy in the open channel

E_{res}

$E > E_{res} \Rightarrow$ repulsion

$E < E_{res} \Rightarrow$ attraction

State may depend upon to external fields like B-field

$$a = a_0 \left(1 + \frac{\Delta B}{B - B_0} \right)$$

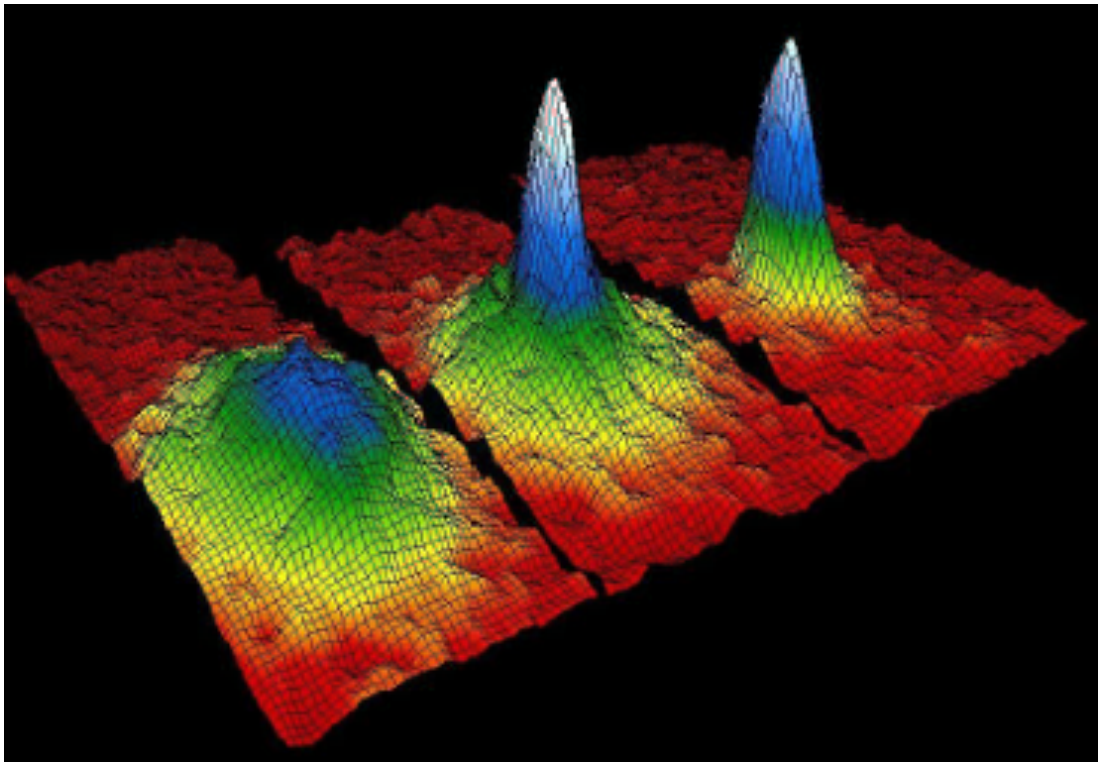
* Depends on the magnetic moments of the states and coupling between channels

Bose-Einstein CONDENSATION

A previsão em 1925



A. Einstein S. N. Bose



Rb, Na e Li and many others

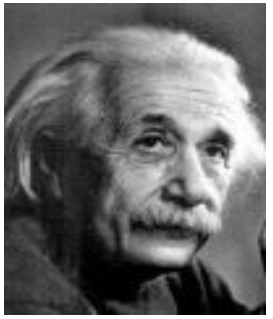
CHANGE IN THE MACROSCOPIC BEHAVIOR

Classical → Quantum

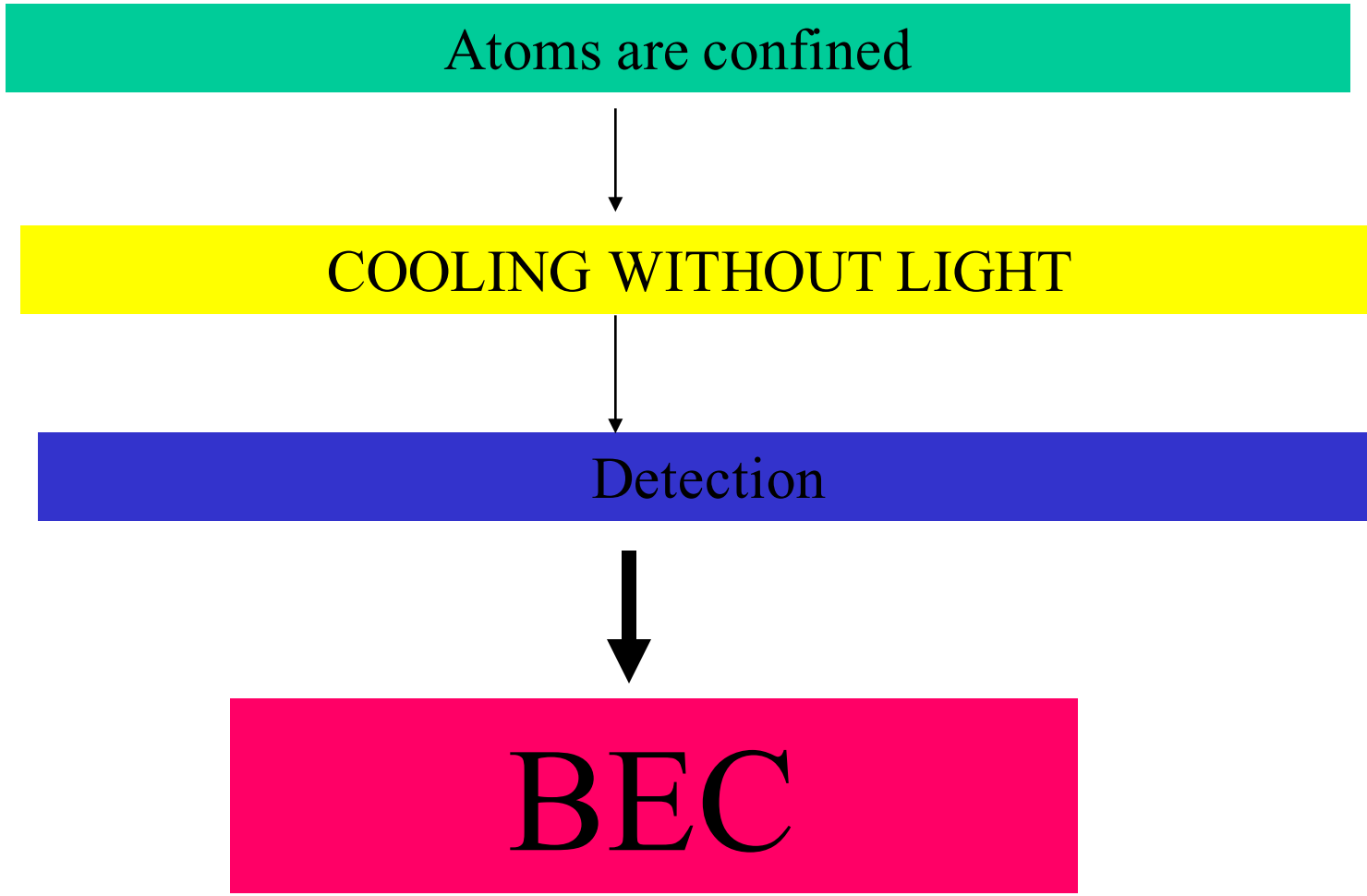
"normal" light → "Laser"



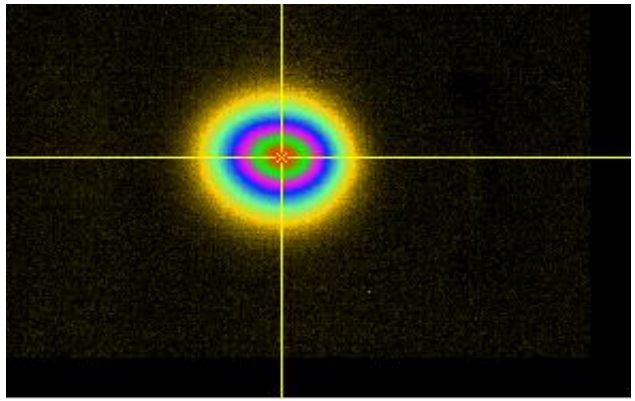
BEC



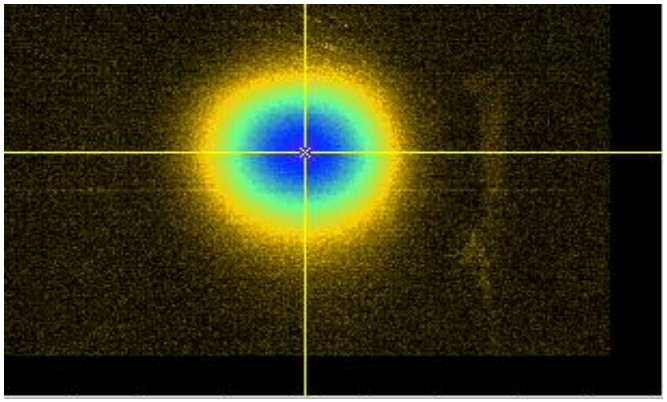
How to produce?



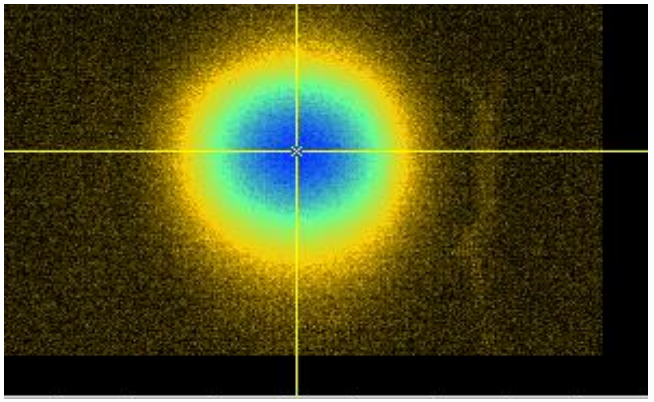
HOW TO MEASURE TEMPERATURE?



3 ms

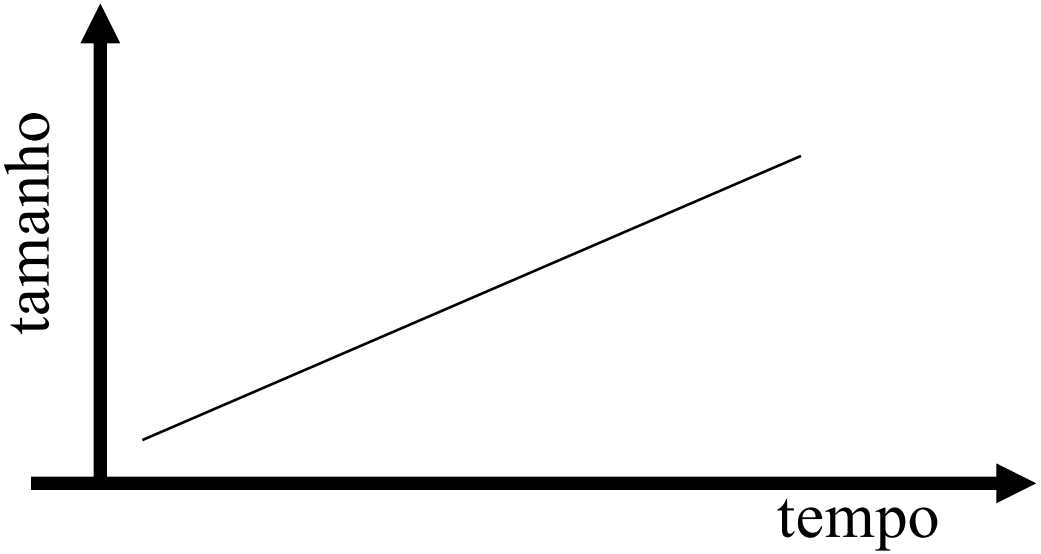


8 ms



12 ms

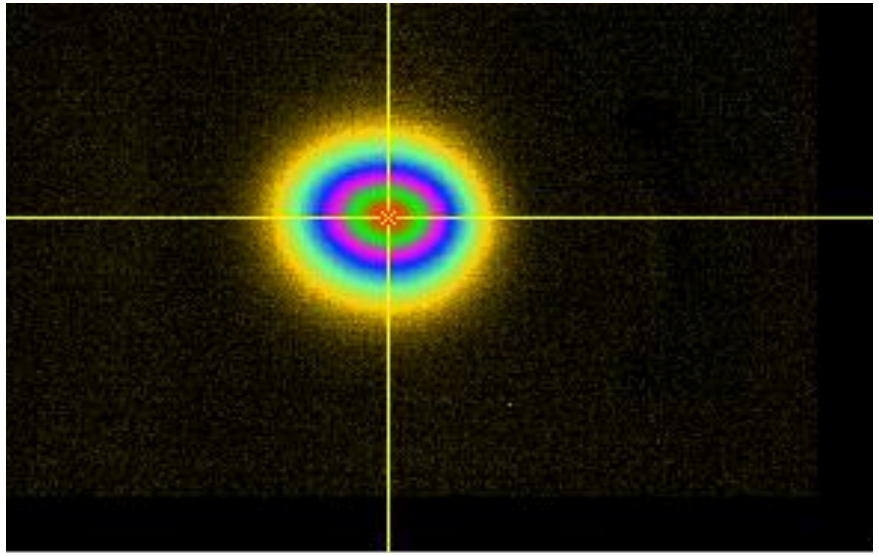
FROM THE PLOT WE OBTAIN T



V = 30 cm/s

T = 60 μK

MOT and Magnetic trapping is not cold enough to produce BEC

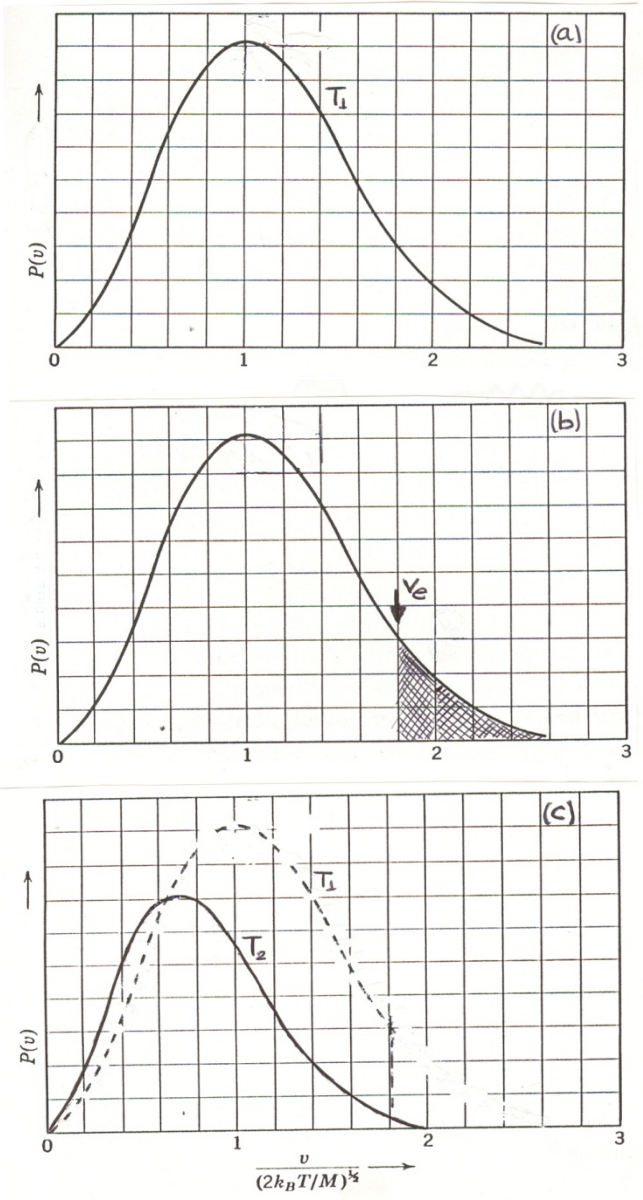


- It is necessary to cool even further down

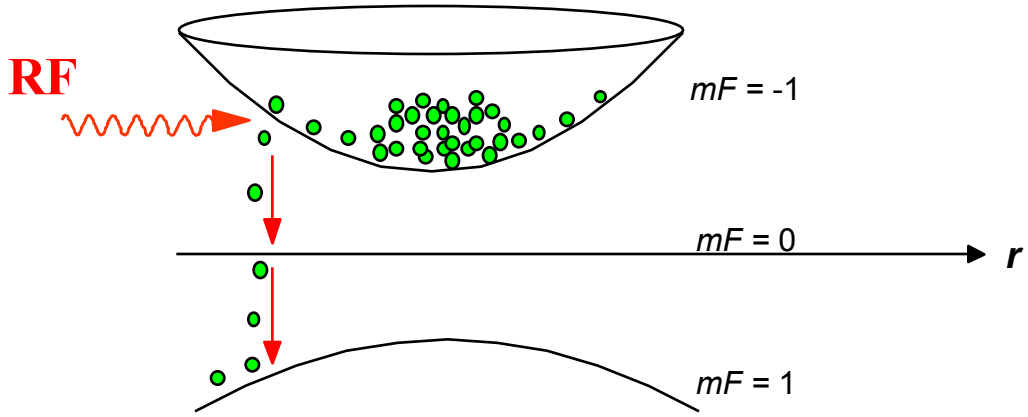
EVAPORATION



HOW DOES EVAPORATION WORKS?



EQUILIBRIUM VELOCITY DISTRIBUTION

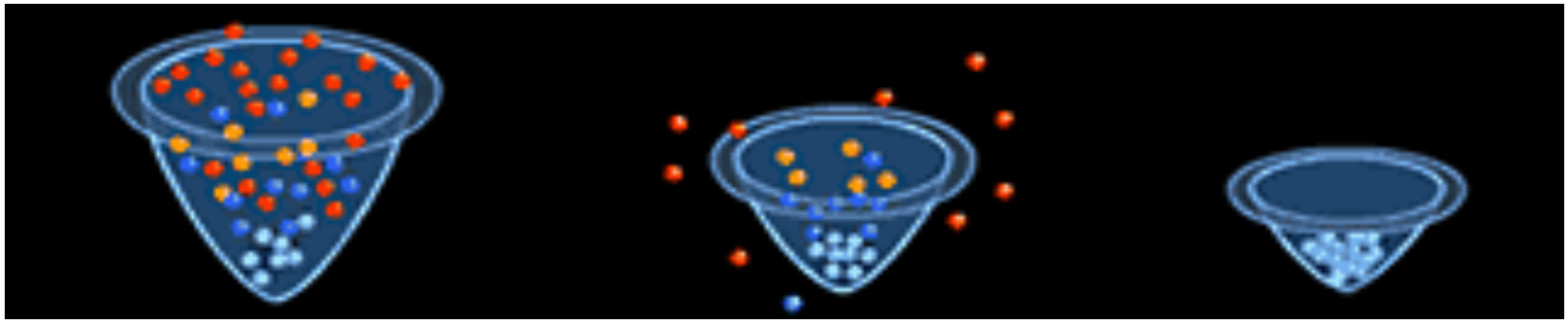


REMOVE FAST PART OF IT

THERMALIZATION

LET'S START WITH A CONFINED GAS AND EVAPORATE

beginning
10^9 átoms
100 μ K



λ_D GREW TO BECOME AS LARGE AS THE POTENTIAL

Final
10^4 átoms
100 nK

MANY ATOMS OCCUPY THE LOWEST QUANTUM STATE

UM POUCO DOS ASPECTOS FUNDAMENTAIS DO BEC

$$H(\mathbf{p},\mathbf{r}) = \frac{p^2}{2M} + U(\mathbf{r})$$

NUMBER OF PARTICLES $$N = N_0 + \int_0^\infty n_E \rho(E)\, dE$$

ENERGY $$E(T) = \int_0^\infty \varepsilon n_\varepsilon \rho(\varepsilon)\, d\varepsilon$$

$$n_\varepsilon = g_\varepsilon \left[\exp\left(\frac{\varepsilon - \mu}{kT} \right) - 1 \right]^{-1}$$

Occupation number

$$\rho(E) = \frac{2\pi (2M)^{3/2}}{h^3} \int_{V^*(t)} \sqrt{E - U(r)}\, d^3 r$$

Density of states

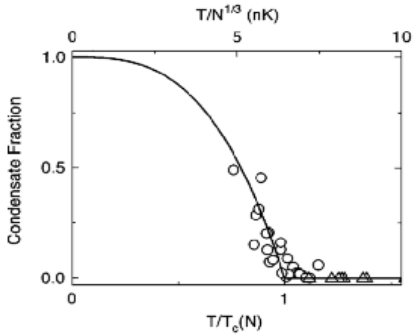
The critical temperature T_c by taking $N_0 = 0$ and $\mu = 0$.

Heat capacity

$$C(T) = \partial E(T)/\partial T$$

Ground state population

$$\frac{N_0}{N}$$



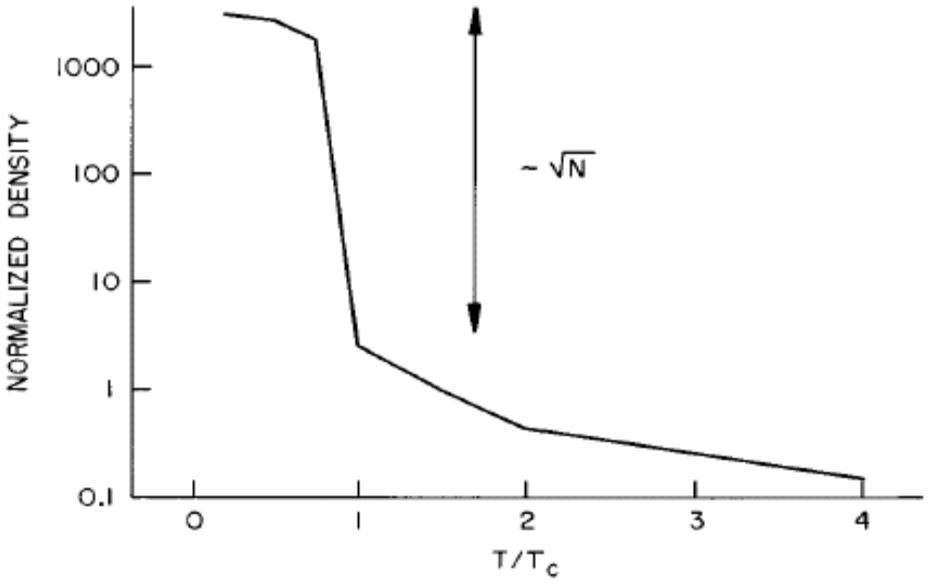
HARMONIC OSCILLATOR

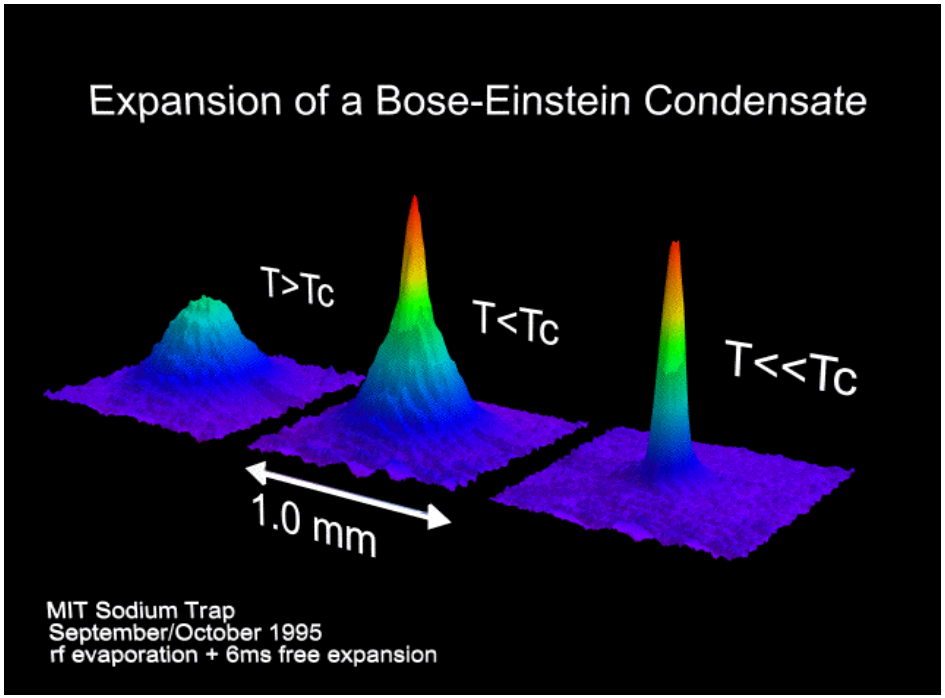
$$U(\mathbf{r}) = \tfrac{1}{2} M \omega^2 r^2$$

$$kT_c = 0.941 \hbar \omega N^{1/3}$$

HOW DOES THE SPATIAL DISTRIBUTION EVOLVES?

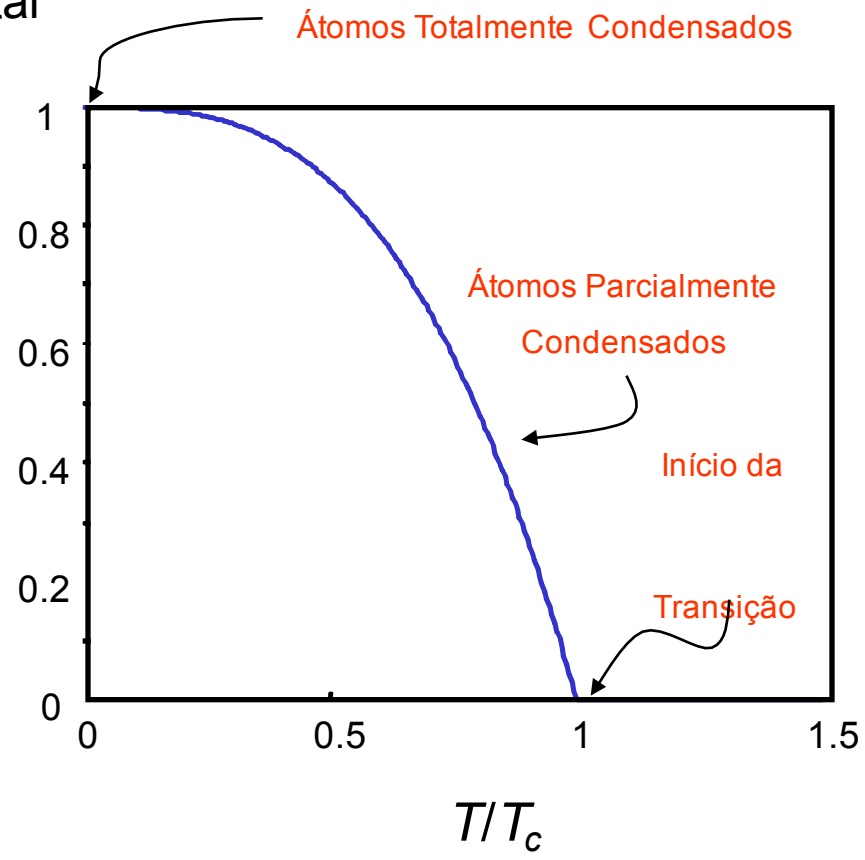
$$n(\mathbf{r},t) = \frac{1}{\Lambda_1^3}\sum_{j=1}^{\infty} \frac{\exp\left[j\left(\mu - \frac{1}{2} m\omega^2 r^2 \right)/kT \right]}{j^{3/2}} + N_0 |\psi_0|^2$$

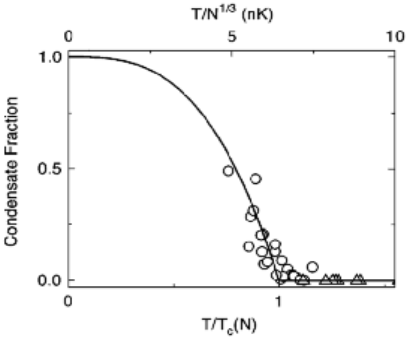




Fração de Ocupação do Estado Fundamental

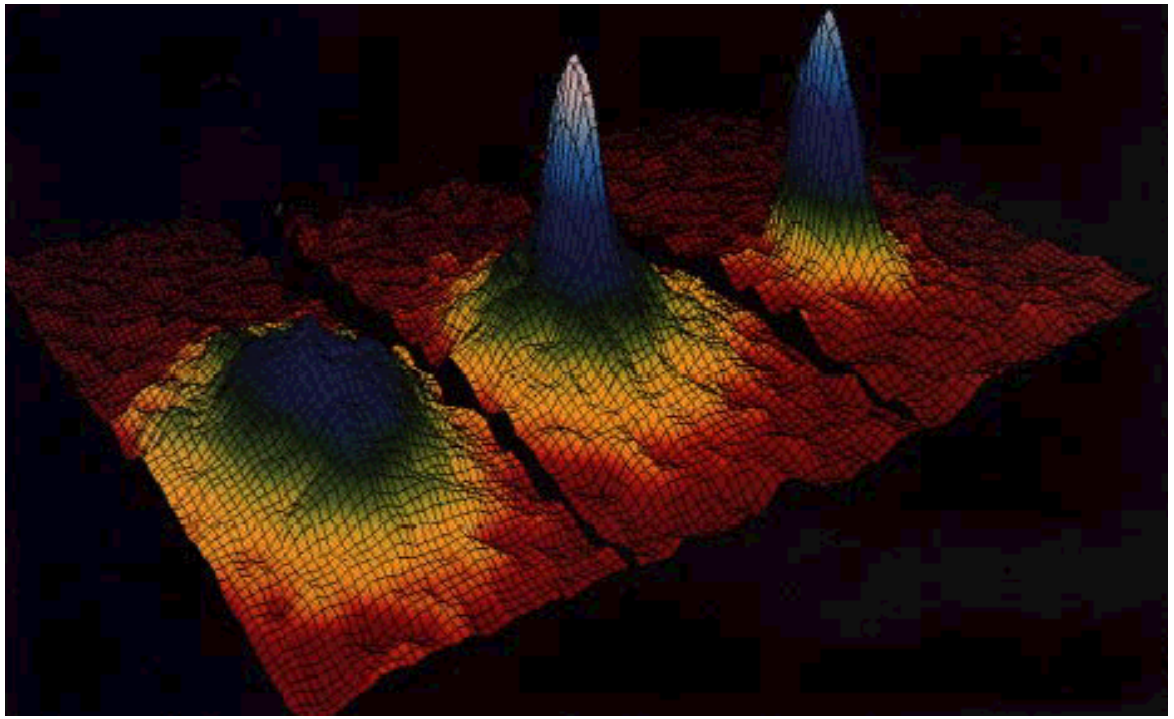
$$\frac{N_c}{N} = 1 - \left(\frac{T}{T_c}\right)^{3/2}$$

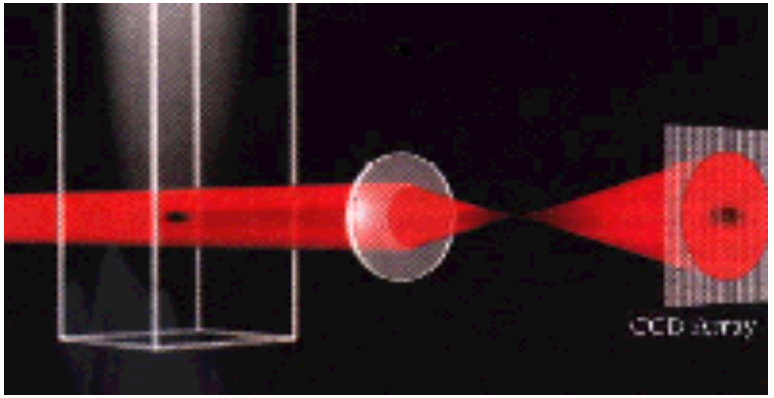




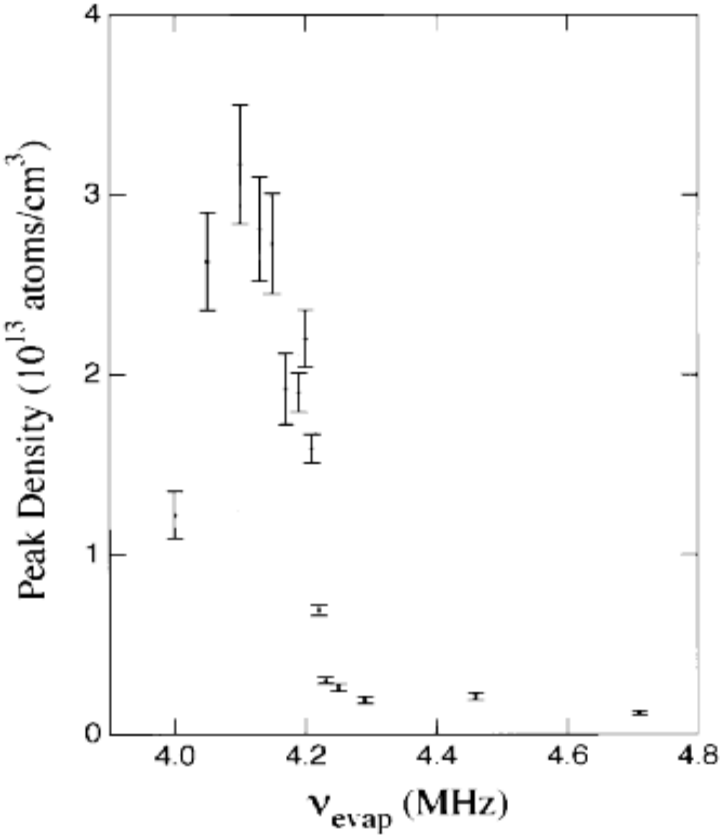
Como observar BEC?

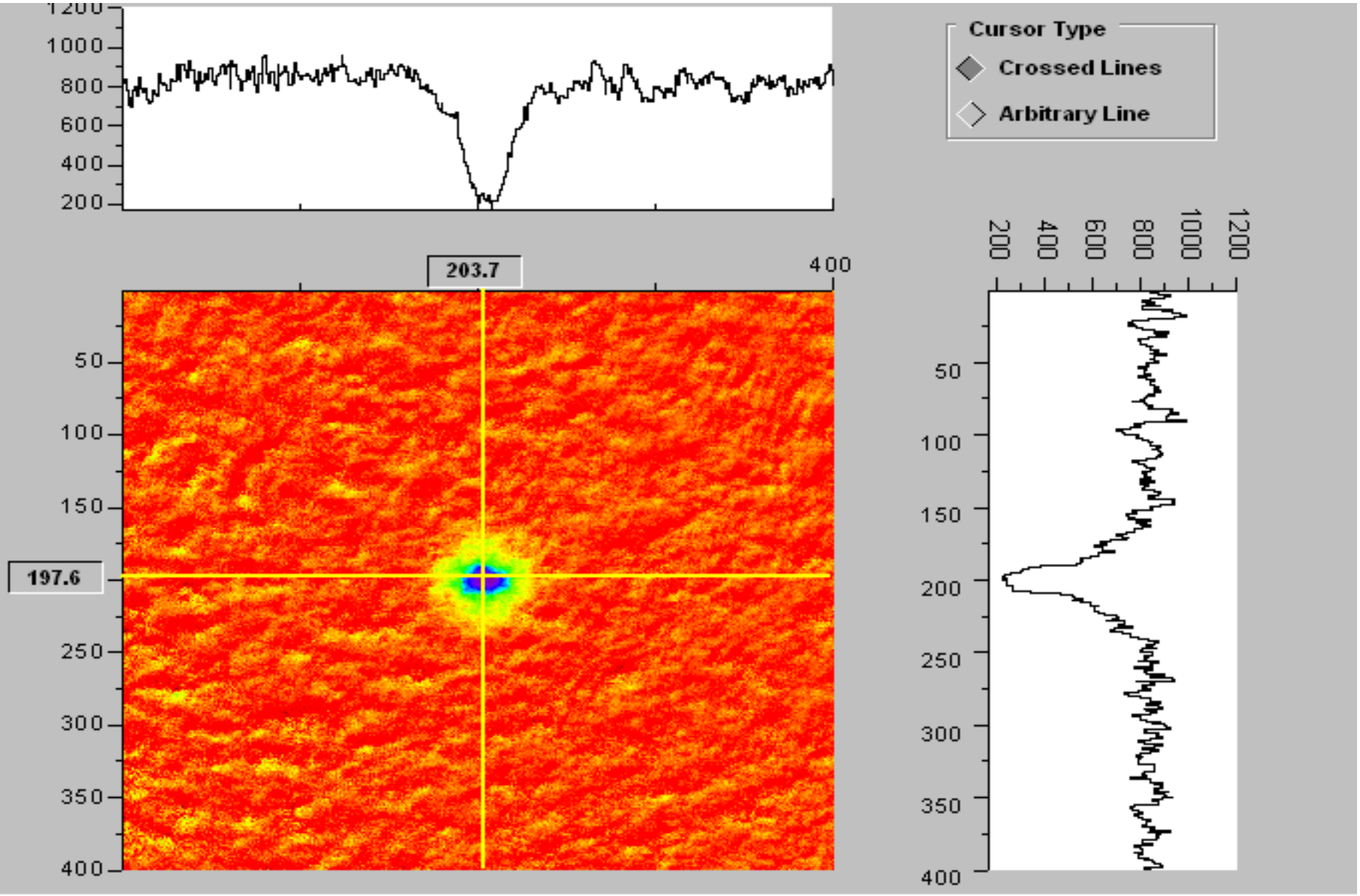
- 10^3 átomos
- $5 \cdot 10^{12}$ átomos/cm^3
- < 100 nK





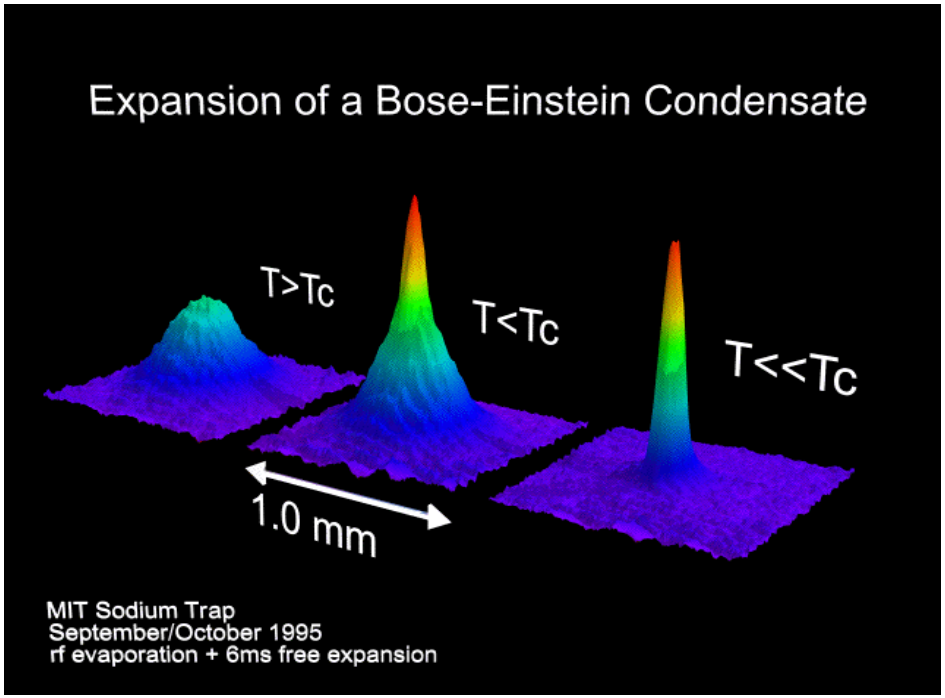
Sistema de Imagem baseada na absorção de um feixe ressonante

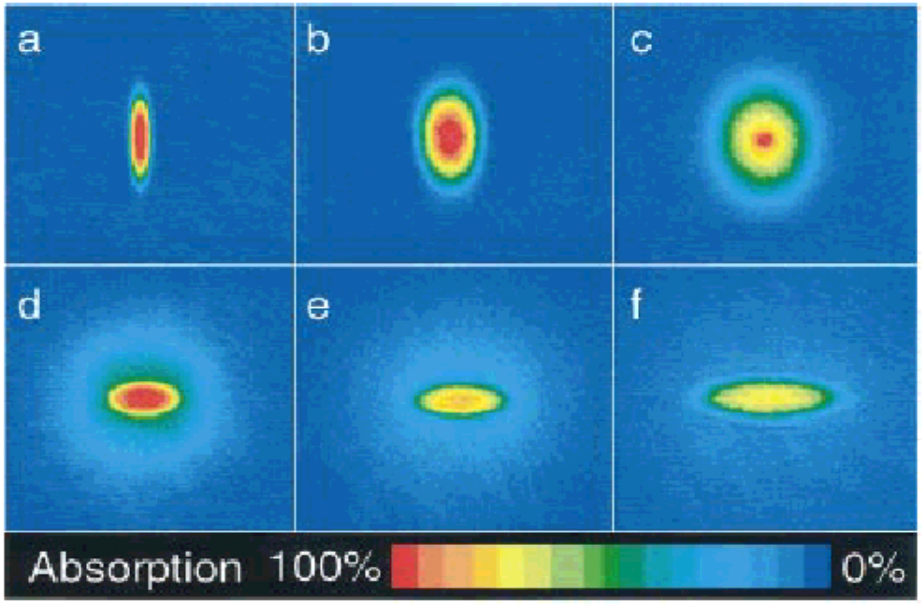



Cursor Type
Crossed Lines
Arbitrary Line
203.7
197.6
200
400
600
800
1000
1200
50
100
150
200
250
300
350
400

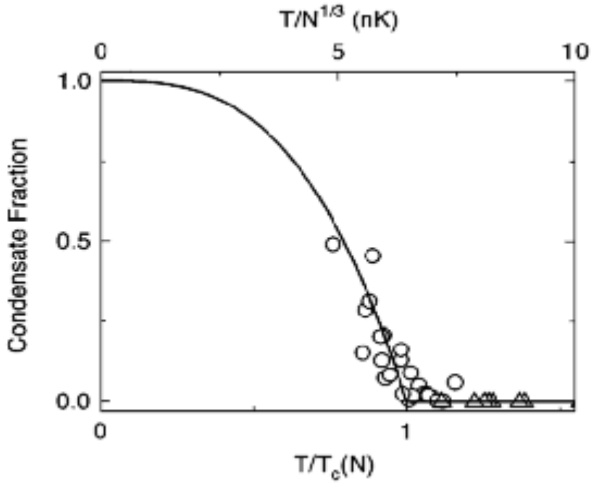
Condensação de Na (MIT)

- 10^7 átomos
- 10^{14} átomos/cm^3
- < 2 μK

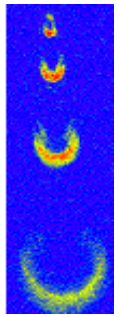




Fração de ocupação do estado fundamental como função da temperatura



Laser de Átomos



GP - Equation

$$i\hbar\frac{\partial}{\partial t}\Phi_0\left(\mathbf{r},t\right)=\left(-\frac{\hbar^2}{2m}\nabla^2+U\left(\mathbf{r},t\right)+U_0\left|\Phi_0\left(\mathbf{r},t\right)\right|^2\right)\Phi_0\left(\mathbf{r},t\right)$$

$$U_e(\mathbf{r},\,\mathbf{r}')=U_0\delta(\mathbf{r}-\mathbf{r}')\quad\text{with}\quad U_0=\frac{4\pi\hbar^2}{m}a_s$$

Thomas - Fermi →

* Neglecting the kinetic energy term
* Strong repulsive interaction

$$[U(r) + A|\varphi|^2]\varphi = \mu\varphi$$

→ $$|\varphi|^2 = n(r) = \frac{\mu - U(r)}{A}$$

For $U(r) = \mu$ → boudary of the cloud

$\varphi = 0$ outside

For a Harmonic Trap: $U(r) = \frac{1}{2} m\omega^2 r^2$

and $\int |\varphi|^2 d^3r = 1$

$$\longrightarrow \frac{1}{2} m\omega^2 R^2 = \mu \longrightarrow R^2 = \frac{2\mu}{m\omega^2}$$

Using $\int_0^R |\varphi|^2 d^3r = 1 \rightarrow \int_0^{\left(\frac{2\mu}{m\omega^2}\right)^{1/2}} \left(\mu - \frac{1}{2} m\omega^2 r\right) \frac{4\pi r^2 dr}{A} = 1$

$\longrightarrow$ extract

$$\mu = \frac{(15)^{2/5}}{2} \left(\frac{Na}{l_0}\right)^{2/5} \hbar\omega$$

$$l_0 = \sqrt{\frac{\hbar}{m\omega}}$$

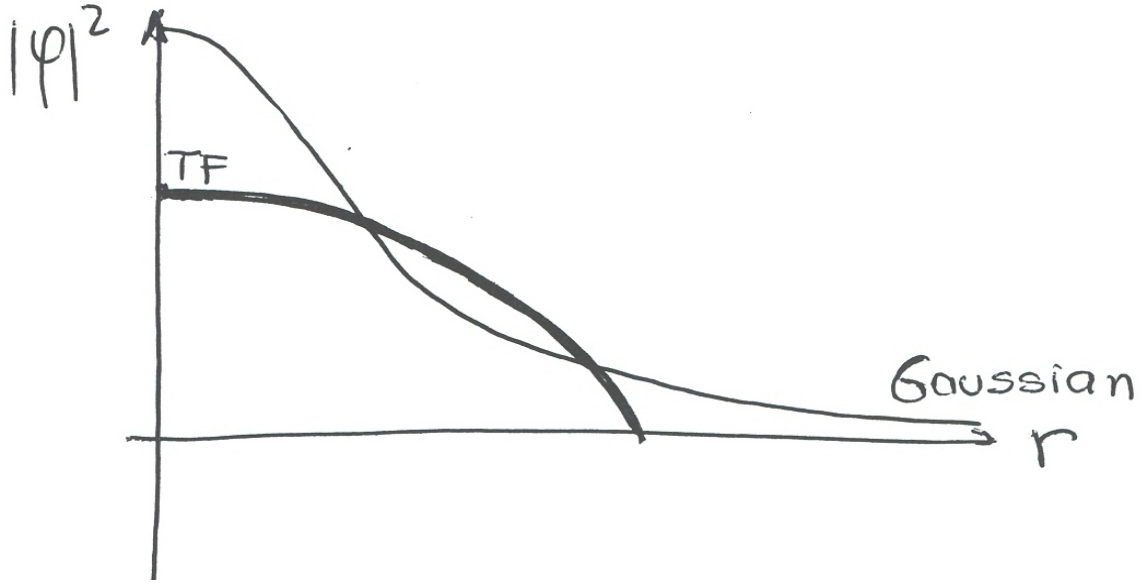
Since $\mu = \frac{\partial E}{\partial N} \longrightarrow E \cong \frac{5}{7} C' N^{7/5}$

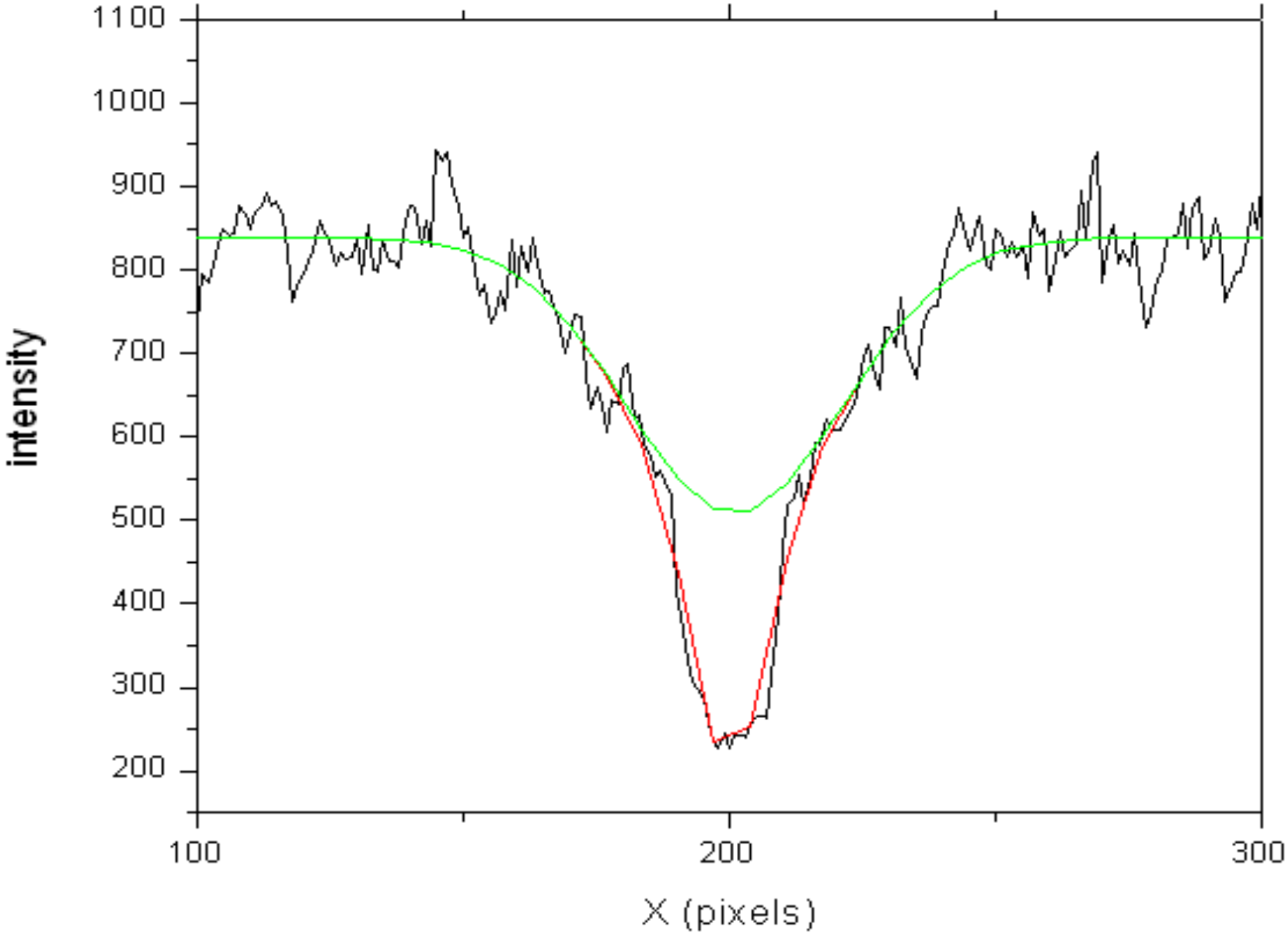
same cte appears in μ

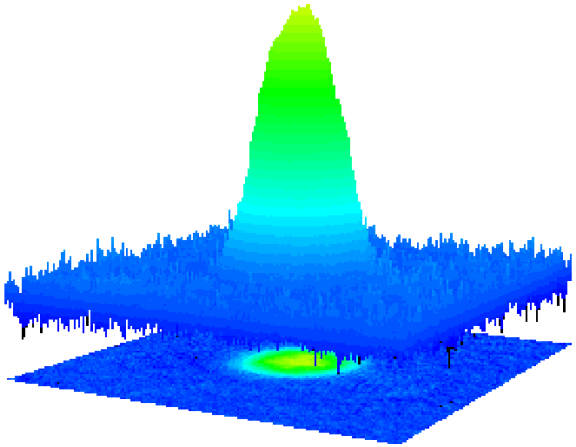
$$\frac{E}{N} \cong \frac{5}{7} C' N^{2/5}$$

$$\Longrightarrow \boxed{\frac{E}{N} = \frac{5}{7}\mu}$$

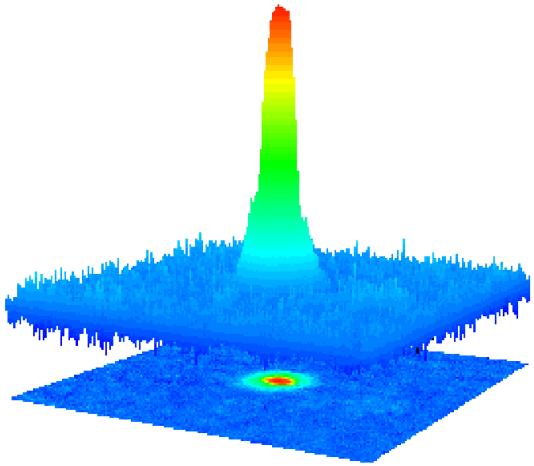
Energy of each particle in the system



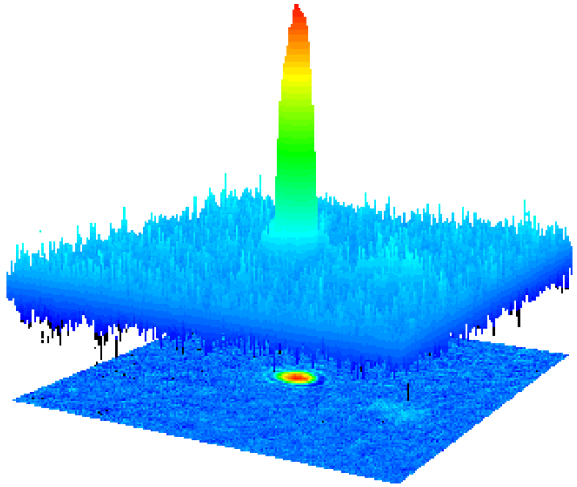

1100
1000
900
800
700
600
500
400
300
200
intensity
100
200
300
X (pixels)



$T > T_c$

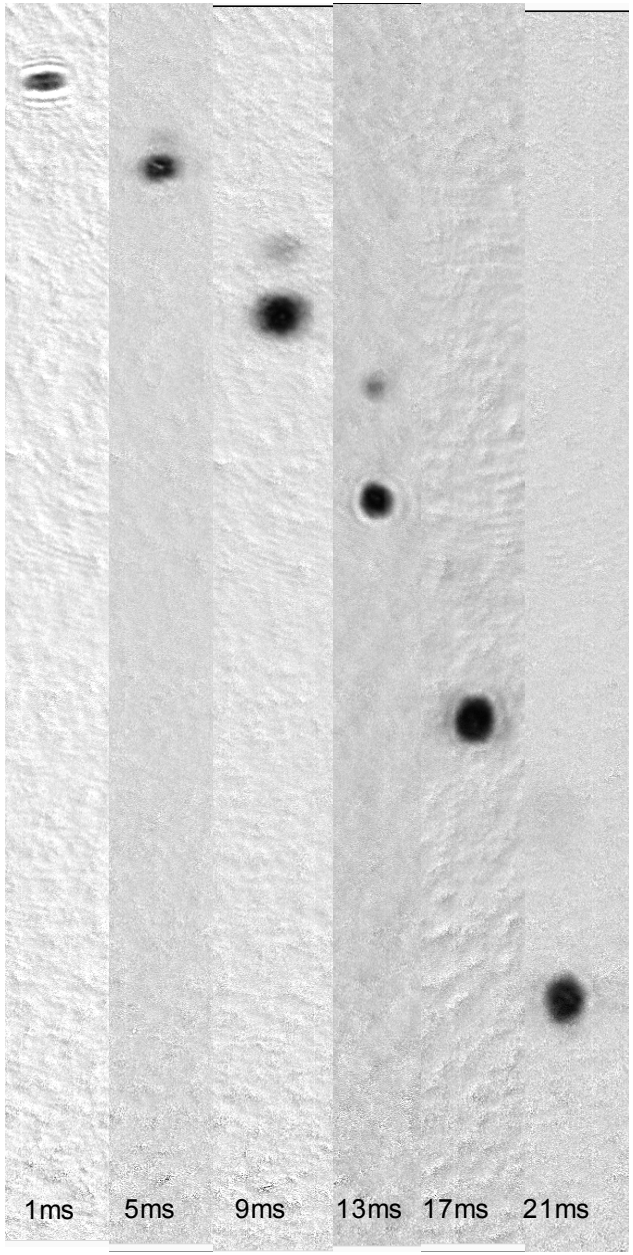


$T < T_c$

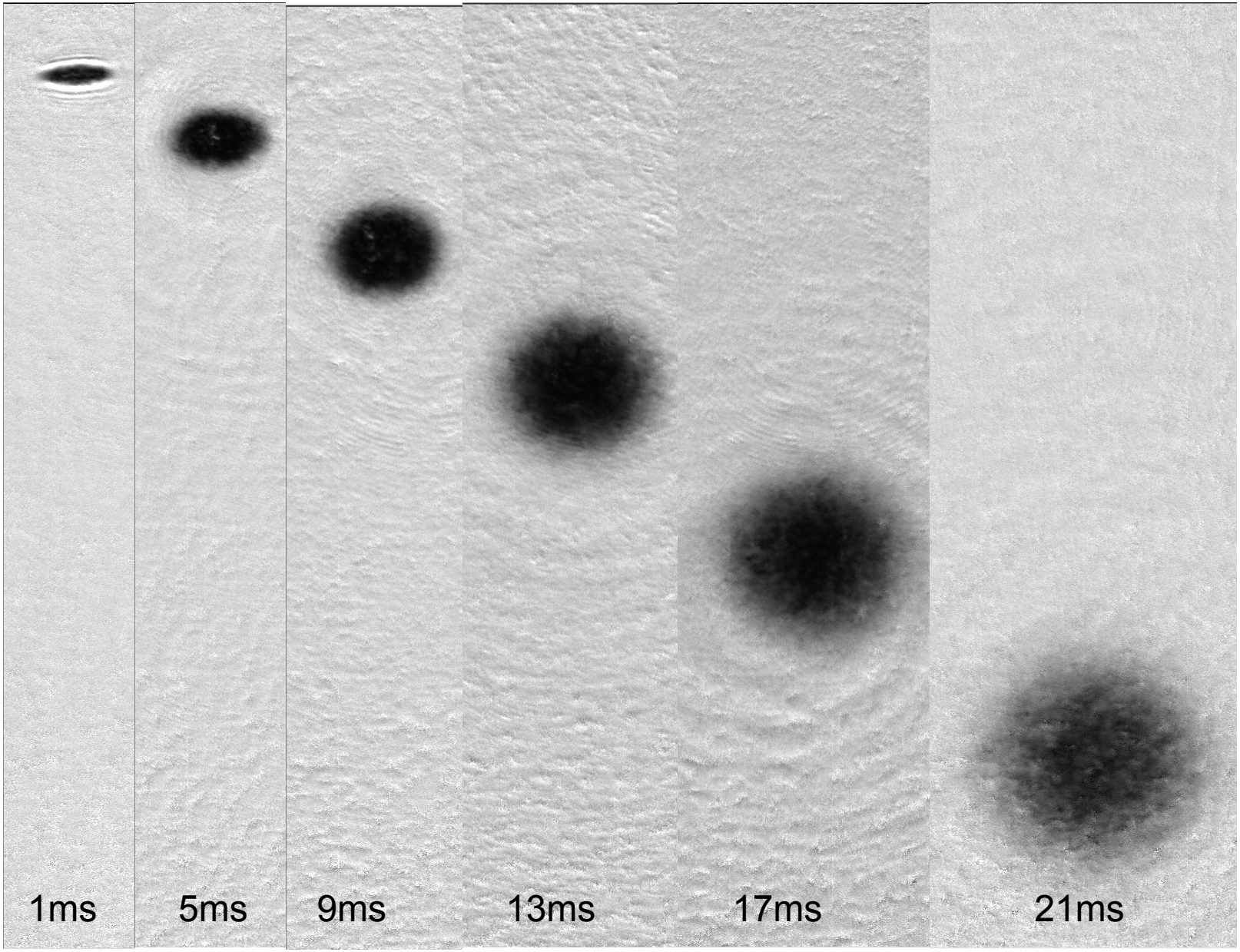


$T << T_c$

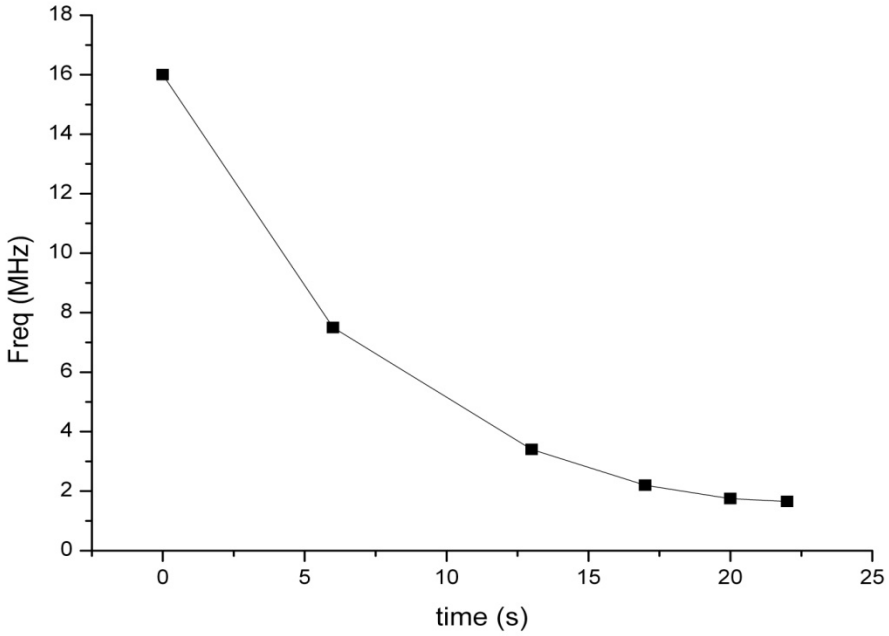
Free expansion of a quantum cloud (BEC) under gravity



Free expansion of a thermal cloud under gravity



Evaporative Cooling Results I



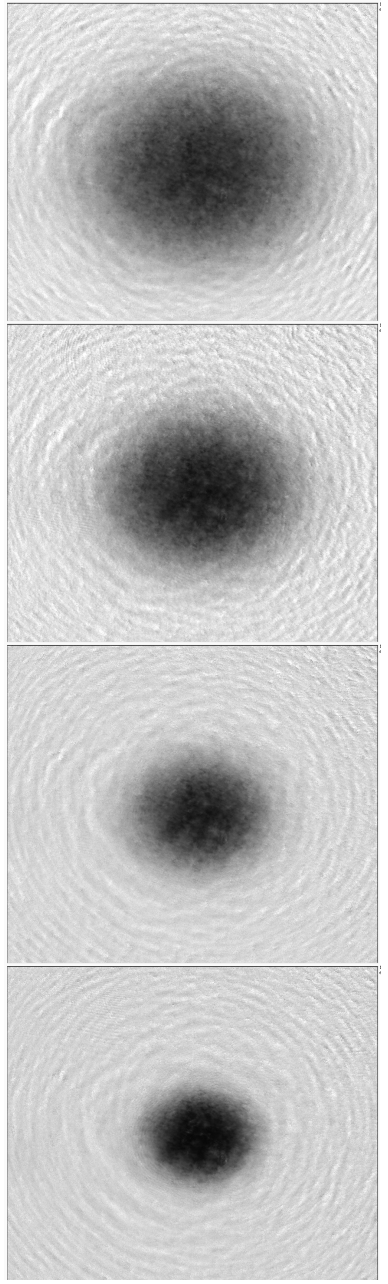
Final Frequency

3,4Mhz

2,8MHz

2,2MHz

1,98MHz



1,75Mhz

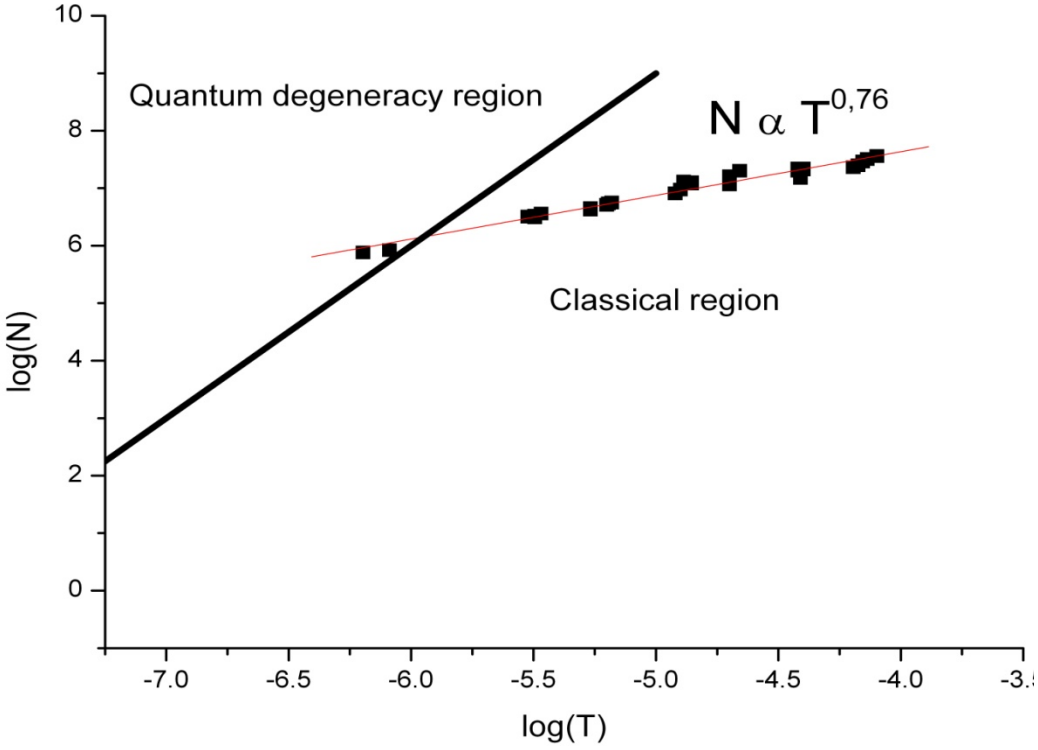
1,70MHz

1,65MHz

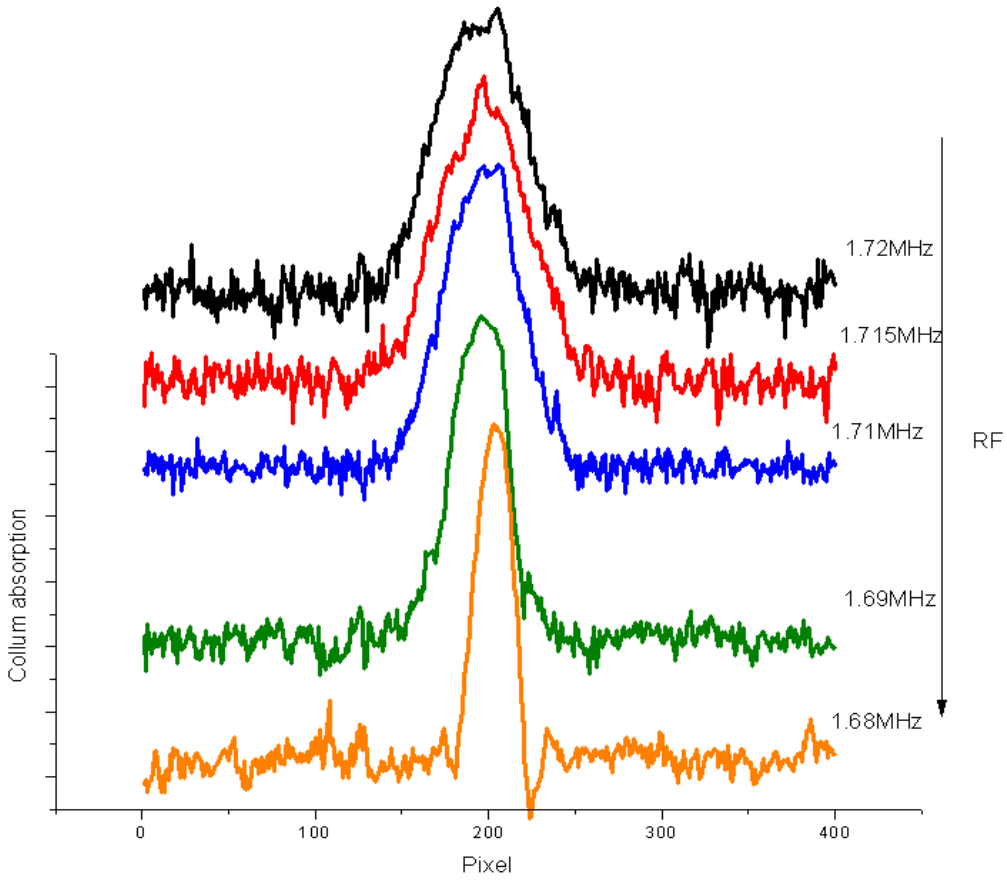
~1.9mm

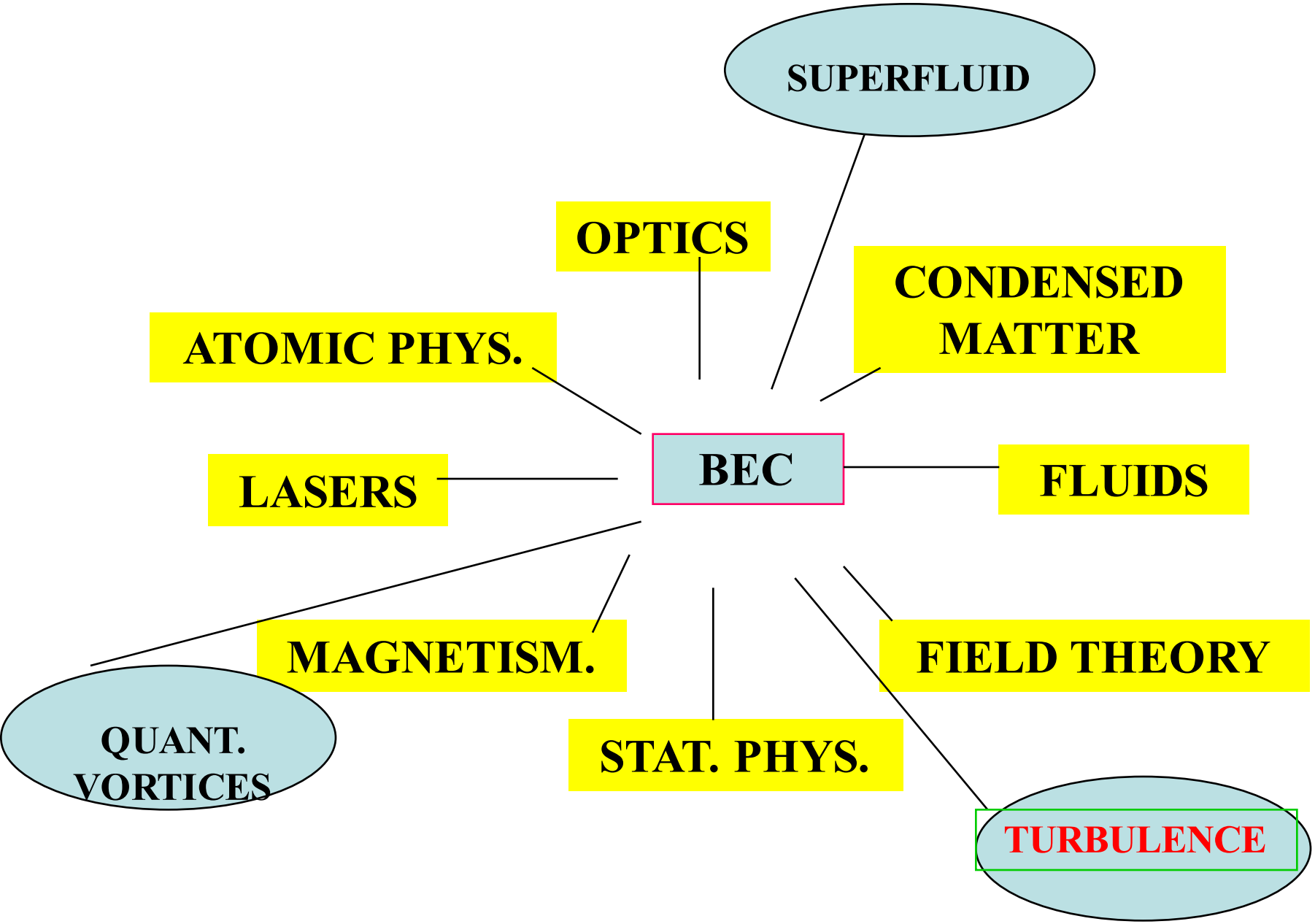
10 ms free expansion

Evaporative Cooling Results II



15 ms free expansion




SUPERFLUID
OPTICS
CONDENSED MATTER
ATOMIC PHYS.
BEC
LASERS
FLUIDS
MAGNETISM.
FIELD THEORY
QUANT. VORTICES
STAT. PHYS.
TURBULENCE