Strongly interacting quantum gases

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Outline

- Prehistory and Introduction.
- Two-component Fermi gases. Strongly interacting regime
- Molecular BEC regime. Remarkable collisional stability
- Strongly interacting Bose gases
- Stability problem

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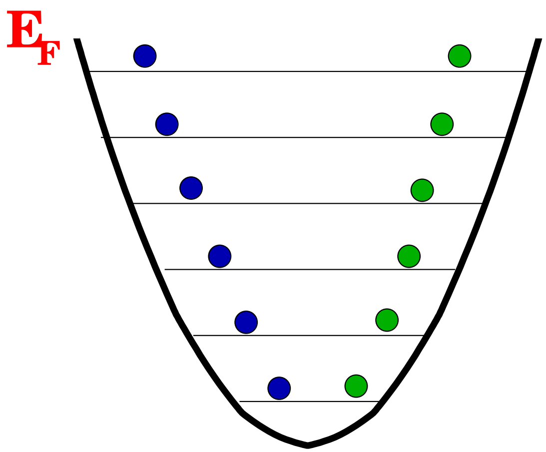
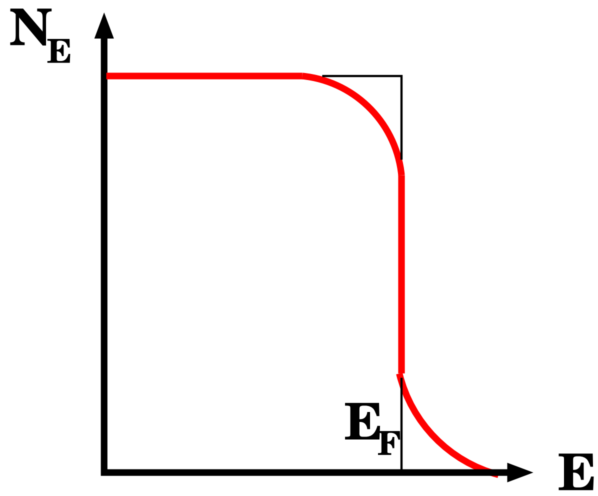
Two-component trapped Fermi gas





$$E_F = \frac{\hbar^2 k_F^2}{2m}; \quad k_F = (3\pi^2 n)^{1/3}; \quad E_F \sim N^{1/3}\hbar\omega$$

Weakly interacting gas $n|a|^3 \ll 1; \; k_F|a| \ll 1$

$a < 0 \rightarrow$ Interspecies attraction $\rightarrow$ Cooper pairing at low T

Superfluid BCS transition $\rightarrow T_c \sim E_F \exp\{-\pi/2k_F|a|\}$

$T_c \ll 0.1 E_F$ for ordinary a Very hard to reach

Two-component Fermi gases. Experiments ^{40}K ^{6}Li

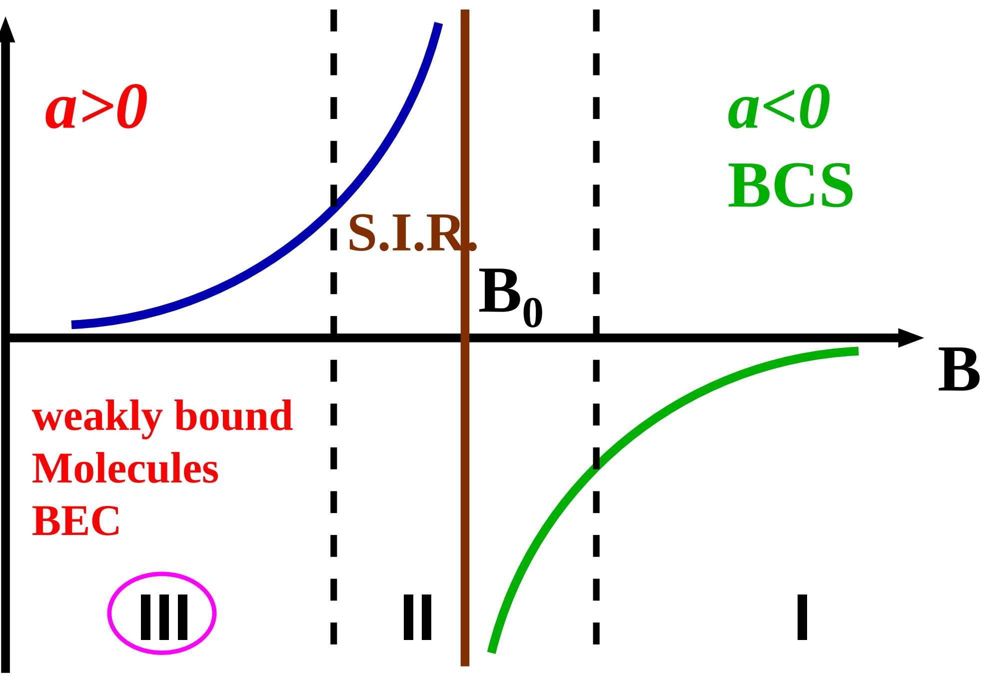
Dilute limit $nR_e^3 \ll 1$ Ultracold limit $\Lambda_T \gg R_e$

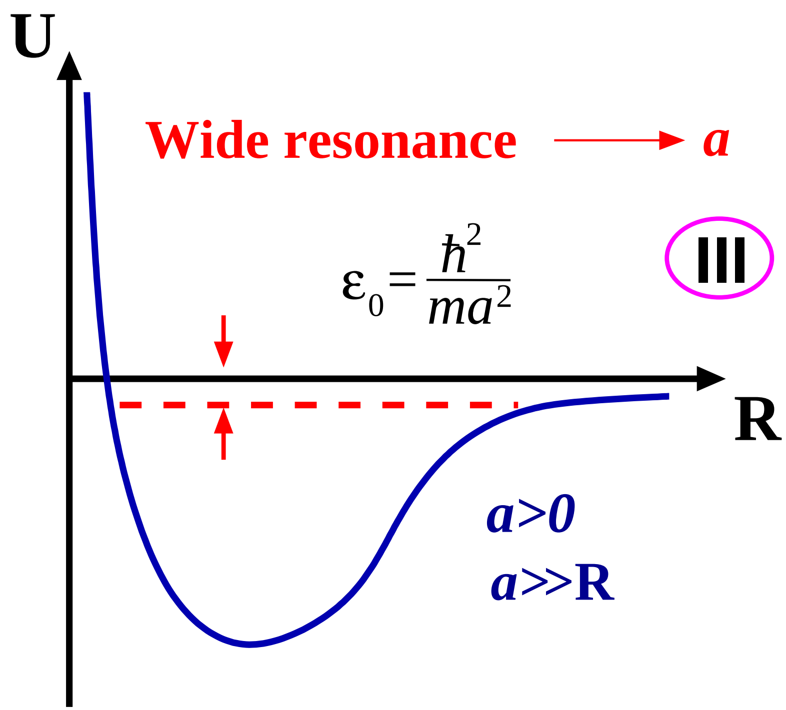
Quantum degeneracy $\rightarrow$ JILA 1998 ^{40}K

At present $n \sim 10^{13} - 10^{14}\mathrm{cm}^{-3}$; $T \sim 1\mu\mathrm{K}$

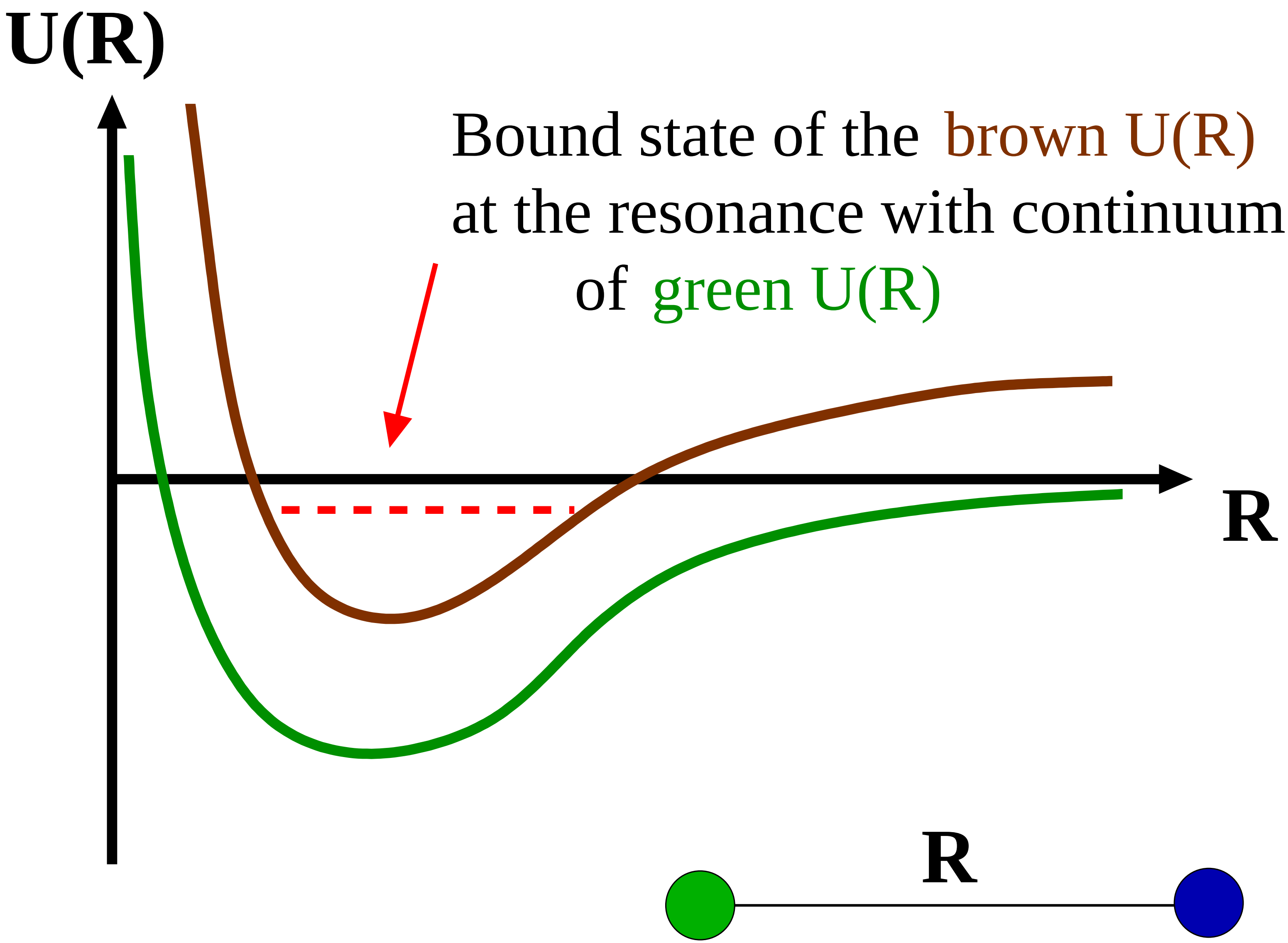
Superfluid behavior through vortex formation $\rightarrow$ MIT

BEC of bosonic molecules $\rightarrow$ presently in about 10 labs





Feshbach resonance



Strongly interacting regime

$T = 0 \quad k_F|a| \gg 1 \quad \rightarrow$ Only one distance scale $n^{-1/3}$

Only one energy scale $E_F \sim \hbar^2 n^{2/3}/m$

Universal thermodynamis (J. Ho)

Monte Carlo studies $\rightarrow \ \mu \approx 0.4 E_F$
(Carlson et al, Giorgini/Astracharchik, etc.)

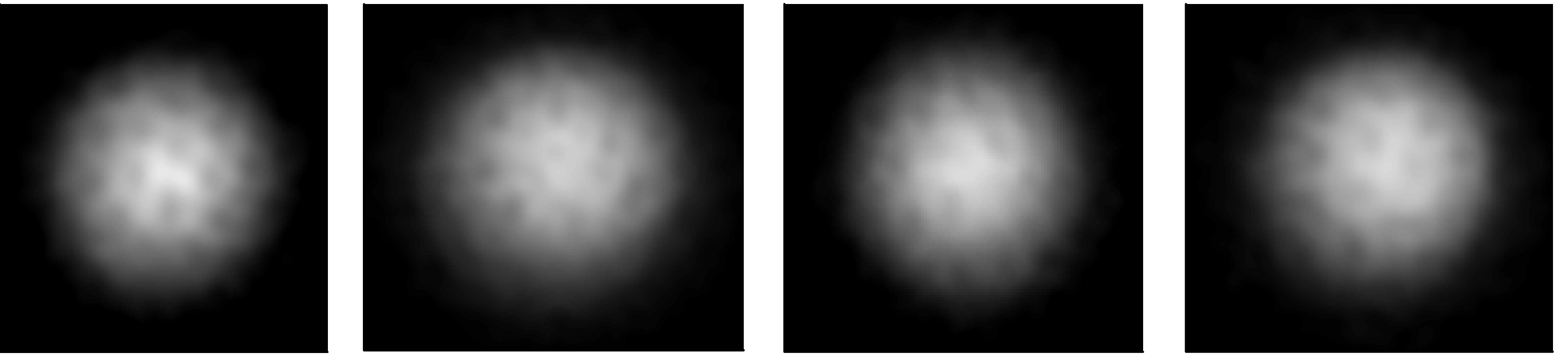
$T_c = 0.15 E_F$ UMASS-ETH

Theory $\rightarrow$ Nature of superfluid pairing, Transition temperature, Excitations

Experiments (JILA, MIT,Innsbruck, Duke,ENS, elsewhere)
Vortices (MIT)

Vortex lattices

MIT, Zwierlein et al., Science 05



B_f = 835 G
$1 / k_F a = 0$

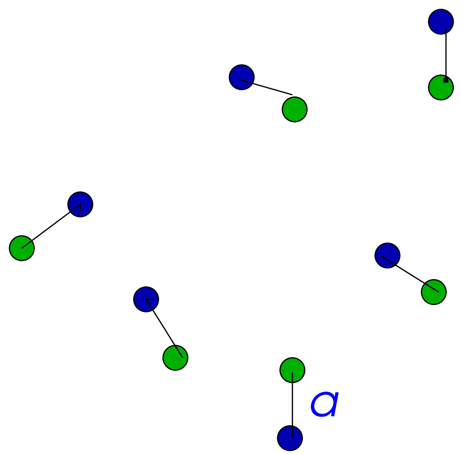
B_f = 843 G
$1 / k_F a = -0.13$

B_f = 854 G
$1 / k_F a = -0.27$

B_f = 864 G
$1 / k_F a = -0.39$

Direct proof of superfluidity !

Positive side of the resonance ($a > 0$). Gas of bosonic dimers

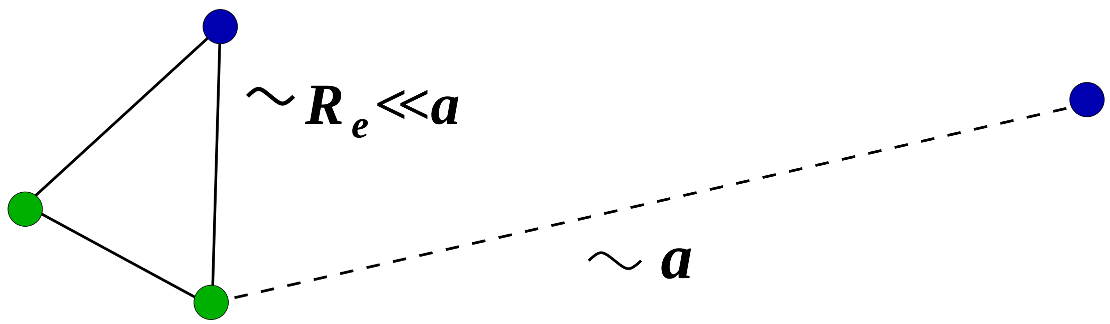


Size of a molecule

a

$na^3 \ll 1 \quad \Rightarrow$ weakly interacting Bose gas

mers $\rightarrow$ The highest rovibrational state $\Rightarrow$ Remarkable collisional satability



$$\alpha_{rel} \sim (k_{eff}R_e)^{2?} \sim (R_e/a)^{2?} \Rightarrow C(\hbar R_e/m)(R_e/a)^s; \quad s = 2.55$$

$\tau \sim (\alpha_{rel} n)^{-1} \sim$ seconds Petrov et al 2003)

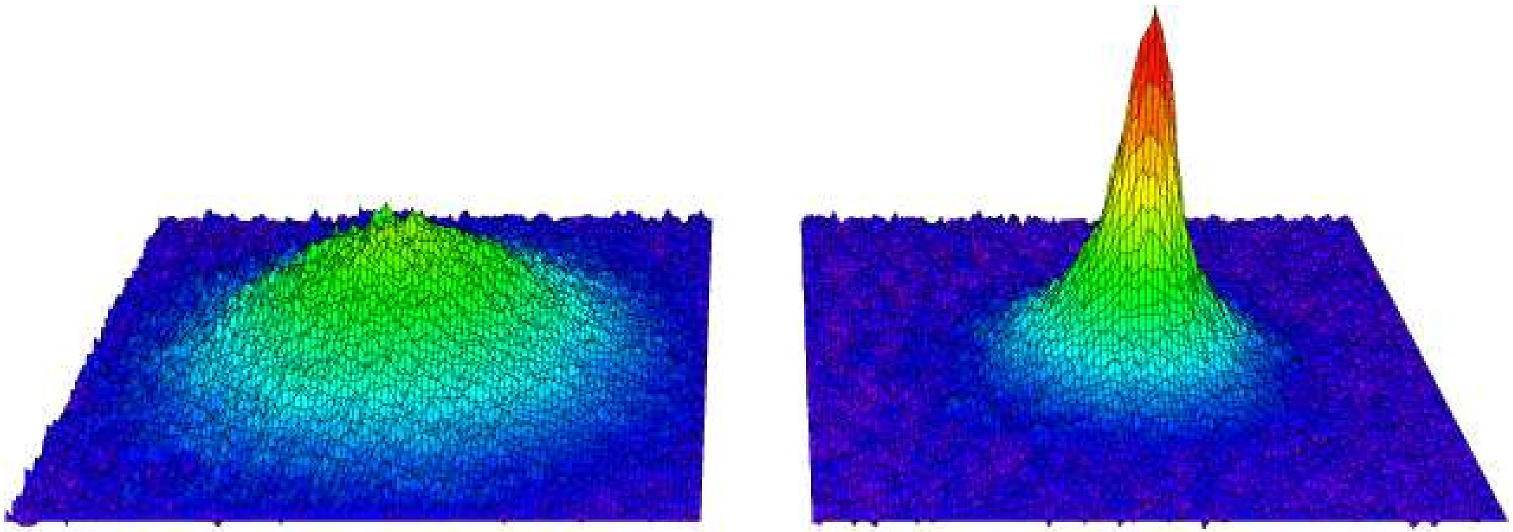
Bose-Einstein condensates of molecules

Suppressed relaxation **Fast elastic collisions** $a_{dd} = 0.6a$

Efficient evaporative cooling $\rightarrow$ BEC

The largest diatomic molecules in the world,
with the size up to ~ 3000Å

BEC $\Rightarrow$ JILA, Innsbruck, MIT, ENS, Rice, Duke



Strongly interacting Bose gas

Subtle question $\Rightarrow$ What about BEC at strong interactions?

Experiments (recent several years)

ENS (Salomon group). Stability at a finite $T \gtrsim 1\mu$K at different a (^{7}Li)

JILA (cornell group). Equilibration at low T with a short lifetime (^{85}Rb)

Stability problem

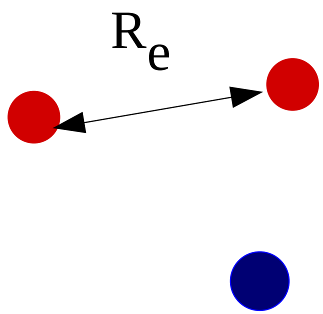
Initarity limit ($a \to \infty$). 3-body recombination

$$A + A + A \Rightarrow A_2 + A + \Delta E$$

Thompson model at $T = 0$ and $a \to \infty$

Two-component Fermi gas. Recombination to deeply bound states

$$\frac{1}{\tau_{rec}} \sim n\sigma v * (nR_e^3) \times (kR_e)^2$$



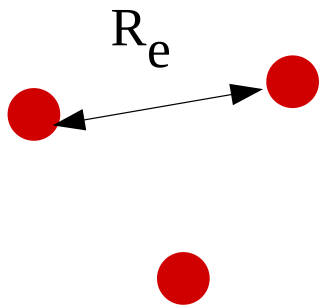
$$v \sim \frac{\hbar}{mR_e}; \ \ \sigma \sim \frac{1}{k^2}; \ \ k \sim n^{-1/3}$$

$$\frac{1}{\tau_{rec}} \sim \frac{\hbar R_e^4}{m} \times n^2 \sim (10 - 100) \text{ s at } n \sim 10^{13} \text{ cm}^{-3}$$

Stability problem

Bose gas. Recombination to deeply bound states at $T = 0$ and $a \to \infty$

$$\frac{1}{\tau_{rec}} \sim n\sigma v * (nR_e^3)$$



$$v \sim \frac{\hbar}{mR_e}; \;\; \sigma \sim \frac{1}{k^2}; \;\; k \sim n^{-1/3}$$

$$\frac{1}{\tau_{rec}} \sim \frac{\hbar R_e^2}{m} \times n^{8/3}$$

Faster by a factor of $\sim 1/(n^{2/3}R_e^2)$ ($\sim 10^5$ at $n \sim 10^{13}$ cm^{-3})

Stability problem

Large $a > 0$. Weakly bound dimers. Relaxation to deeply bound states

Two-component Fermi gas

$$\frac{1}{\tau_{rel}} \sim \frac{\hbar R_e}{m} \left(\frac{R_e}{a} \right)^{2.5} \times n$$

Bose gas

$$\frac{1}{\tau_{rel}} \sim \frac{\hbar a}{m} \times n$$

Faster by a factor of $(a/R_e)^{3.4}$ ($\sim 10^4$)

Equilibration problem

JILA experiment. Close to unitarity

3-body recombination to a weakly bound state. Very low T

$$\frac{1}{\tau_{rec}} \sim \frac{\hbar a^4}{m} \times n^2 \Rightarrow \frac{\hbar}{m} \times n^{2/3}$$

Equilibration rate

$$na^2 v \to \frac{\hbar}{m} \times n^{2/3}$$

Equilibration can be faster

Stability of a strongly interacting Bose gas at a finite T

ENS experiment. 3-body recombination at a finite $T > 1\mu$K

Recombination to a weakly bound state $a > 0 \Rightarrow \; \frac{1}{\tau_{rec}} \sim \frac{\hbar a^4}{m} \times n^2$

Finite T. When Λ_T becomes comparable with a one replaces a with Λ_T

$$\frac{1}{\tau_{rec}} \sim \frac{\hbar \Lambda_T^4}{\times} n^2 \sim \frac{n^2}{T^2}$$

Established in the ENS experiment

Stability of a strongly interacting Bose gas at a finite T