Férmions ultra-frios em redes óticas

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Átomos ultrafrios armadilhados

Bósons e férmions

Redes óticas

Bósons e férmions

Férmions fortemente correlacionados em geral

Férmions fortemente correlacionados em armadilhas

Protocolo para observar antiferromagnetismo

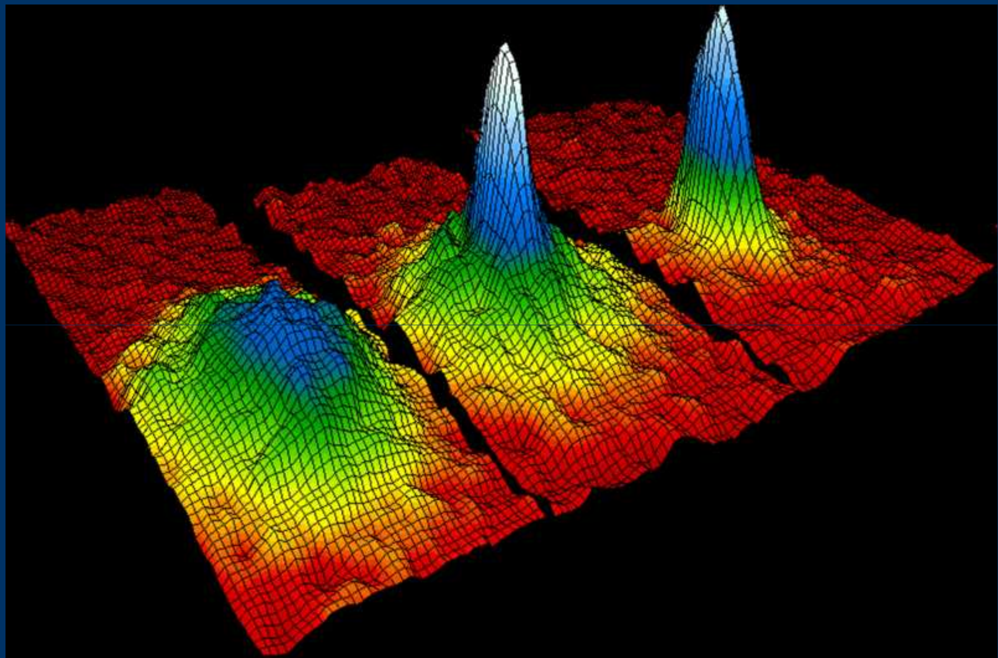
Conclusões

Átomos ultrafrios armadilhados

Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, E. A. Cornell

Science 95



Condensados de ^{87}RB

2,5 x10^{12} átomos/cm^3

170nK

15 s

Eric A. Cornell
Wolfgang Ketterle
Carl E. Wieman

2001

Bósons

Armadilha magneto ótica

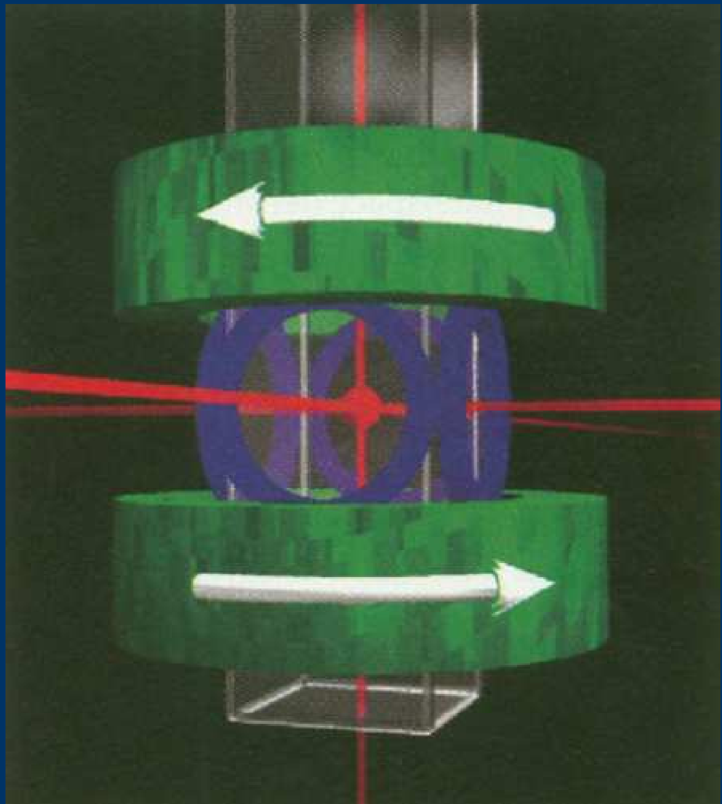
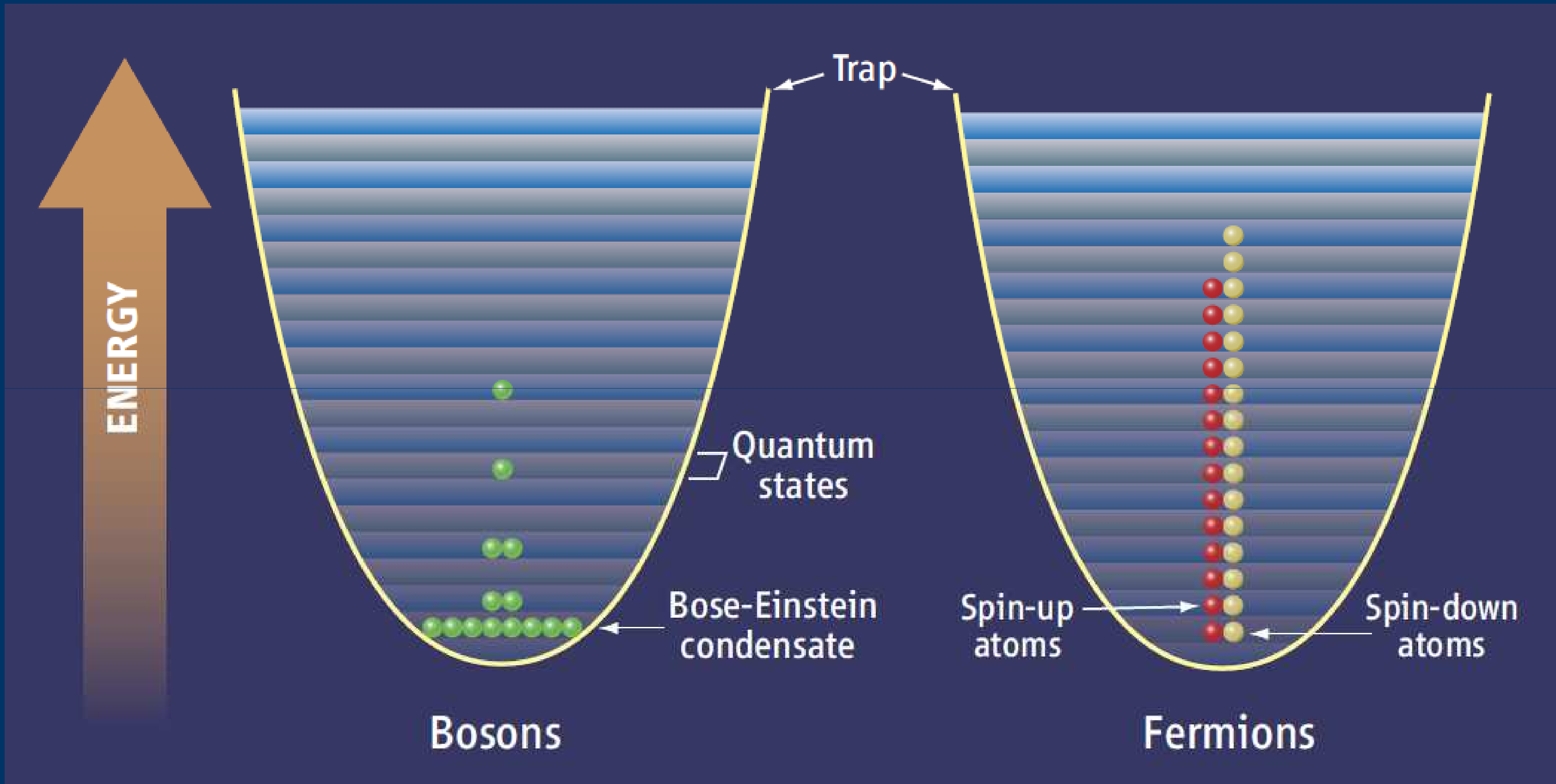


Fig. 1. Schematic of the apparatus. Six laser beams intersect in a glass cell, creating a magneto-optical trap (MOT). The cell is 2.5 cm square by 12 cm long, and the beams are 1.5 cm in diameter. The coils generating the fixed quadrupole and rotating transverse components of the TOP trap magnetic fields are shown in green and blue, respectively. The glass cell hangs down from a steel chamber (not shown) containing a vacuum pump and rubidium source. Also not shown are coils for injecting the rf magnetic field for evaporation and the additional laser beams for imaging and optically pumping the trapped atom sample.

Potencial confinante

Bósons x Férmions



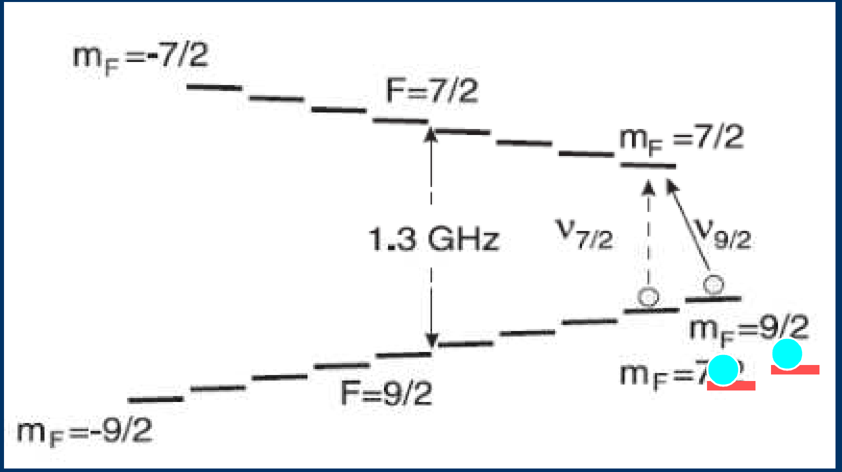
Férmions

Science
1999

Onset of Fermi Degeneracy in a Trapped Atomic Gas

B. DeMarco and D. S. Jin*†

^{40}K



Estados
hiperfinos

|F=9/2 MF=9/2>

|F=9/2 MF=7/2>

20% systematic uncertainty in T/T_F

Enorme atividade experimental

Creation of ultracold molecules from a Fermi gas of atoms

Cindy A. Regal*, Christopher Ticknor*, John L. Bohn* & Deborah S. Jin†

$^{40}K_2$

Nature 2003

Bose-Einstein Condensation of Molecules

S. Jochim,[1] M. Bartenstein,[1] A. Altmeyer,[1] G. Hendl,[1] S. Riedl,[1] C. Chin,[1] J. Hecker Denschlag,[1] R. Grimm[1,2]*

^{6}Li

Science 2003

Fermionic Superfluidity with Imbalanced Spin Populations

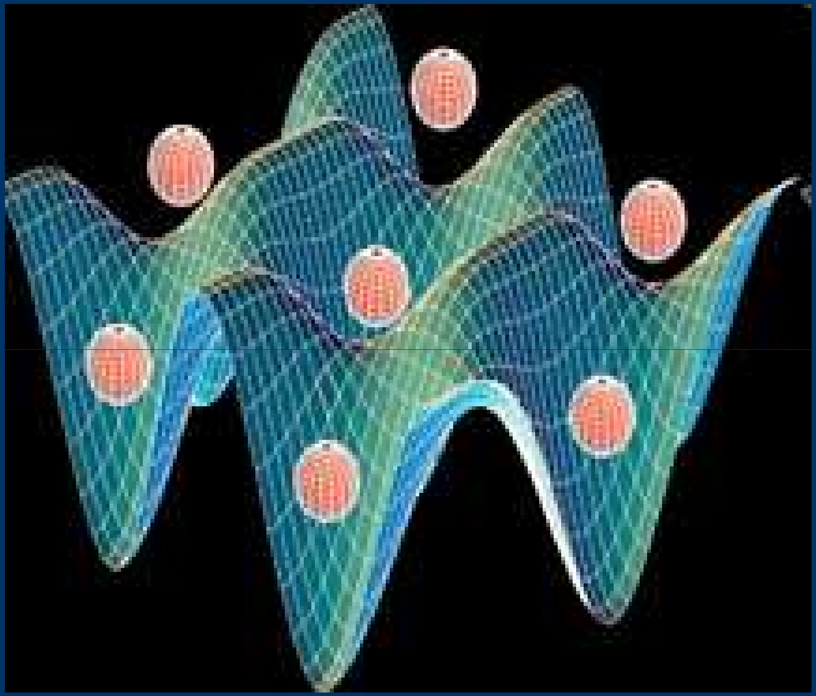
Martin W. Zwierlein,* André Schirotzek, Christian H. Schunck, Wolfgang Ketterle

^{6}Li

Science 2006

Redes óticas

Redes óticas



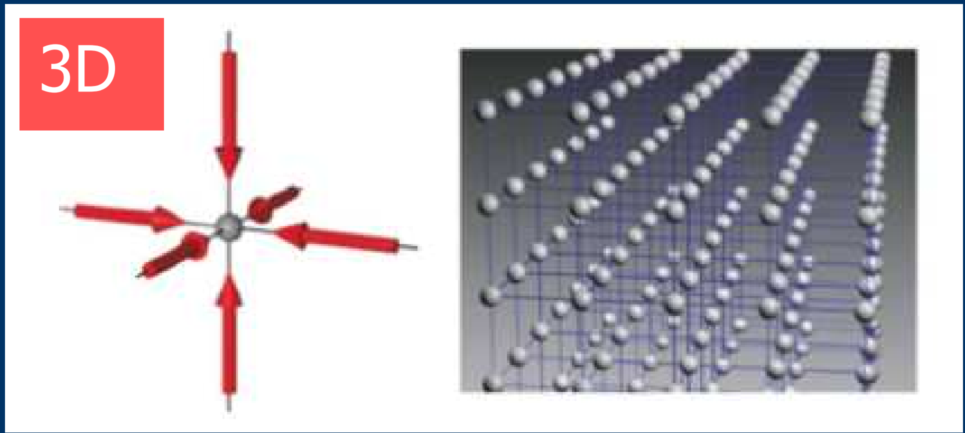
Potencial confinante

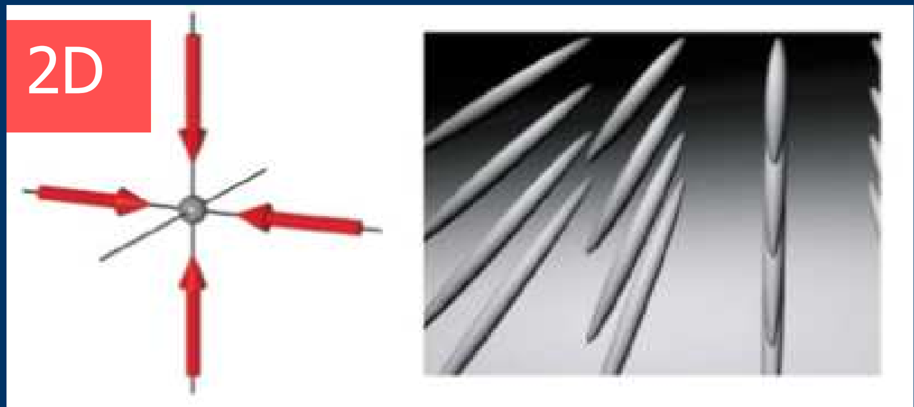
+

Potencial periódico

Redes óticas

Dimensão





1D

Redes óticas

Potencial periódico + Potencial confinante

V_0

$V_\perp$

$a = \lambda/2$

Laser

$\lambda \Rightarrow$ Comprimento de onda do laser

Confinamento magnético

Escala de energia

$$E_R = \frac{2\pi^2\hbar^2}{m\lambda^2}$$

Energia de recuo

Laser YAG λ=1.06μm e átomos de ^{6}Li

$E_R \approx 1.4\ \mu K \approx 29.1\ kHz$

nK - μK

Densidades ~ 10^{14} átomos/cm^3

Espalhamento elástico

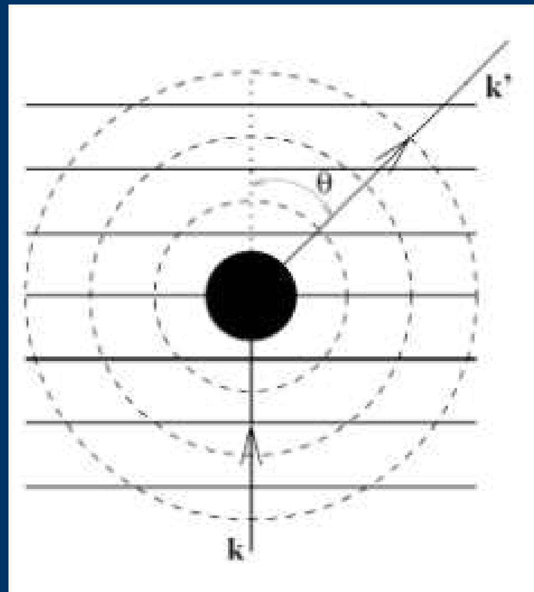
átomos iguais $\Rightarrow$ estados hiperfinos diferentes

$|S\ M_S>$ $\begin{cases} |\uparrow> \\ |\downarrow> \end{cases}$

r$\rightarrow\infty$

$$\psi(\vec{r}) \sim e^{i\vec{k}\bullet\vec{r}} + \underbrace{f(\vec{k},\vec{k}')}\frac{e^{i\vec{k}'\bullet\vec{r}}}{r}$$

Scattering amplitude



Decomposição em ondas parciais

$$f(\vec{k},\vec{k}') = \sum_{l=0}^{\infty} f_l(k) P_l(\cos\theta)$$

Sistema ultrafrio e diluído

Partículas lentas

$k \to 0$

s-wave: $l = 0$

$$f_0(k) \cong \frac{\delta_0(k)}{k} = -a_s$$

s-wave scattering length

$$\sigma_0 = 4\pi a_s^2$$

Ressonâncias de Feshbach

Átomos em auto-estados do operador de spin

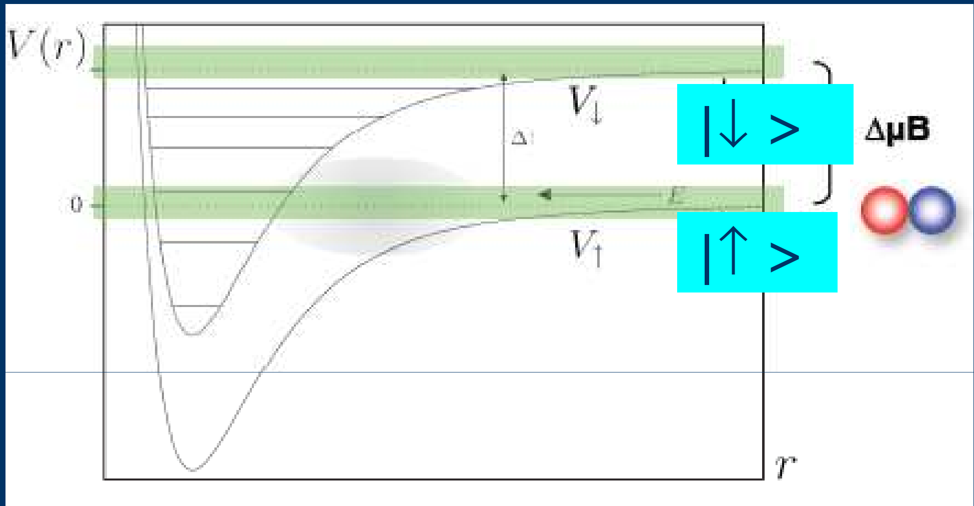
$$|S\ \ M_S> \begin{cases} |\uparrow> \\ |\downarrow> \end{cases}$$

Na presença de um campo magnético

Efeito Zeeman

$$\Delta E = E(\uparrow) - E(\downarrow) = \Delta\mu B$$

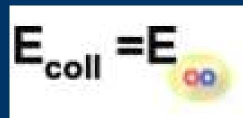
Ressonância de Feshbach



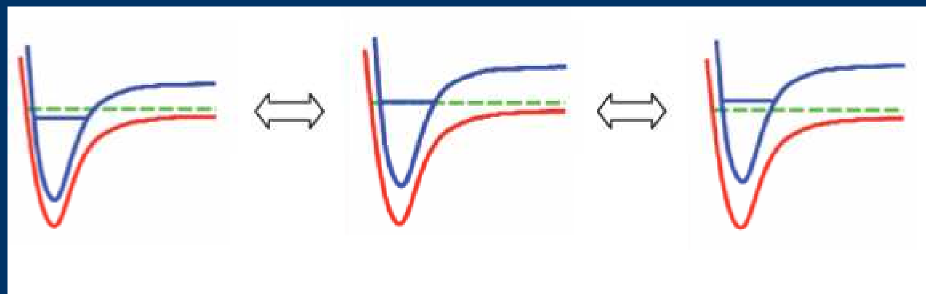
Zeeman spliting

$$\Delta E = E(\uparrow) - E(\downarrow) = \Delta\mu B$$

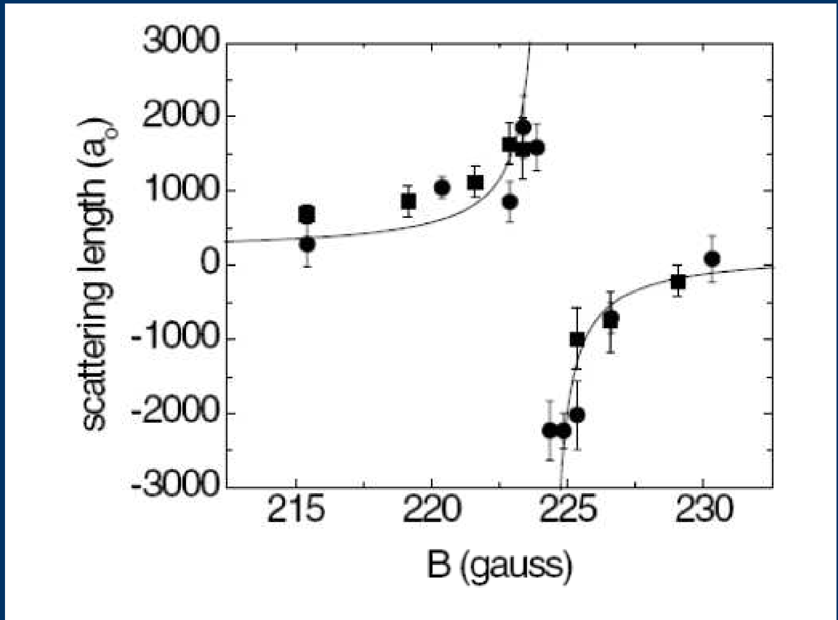
Ressonância de Feshbach



$\Delta\mu B$ → ajustável



s-wave scattering lenght



Regal e Jin 2003

$^{40}K \rightarrow$ férmion

Spin S=9/2

Positivo ou negativo

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

Creation of ultracold molecules from a Fermi gas of atoms

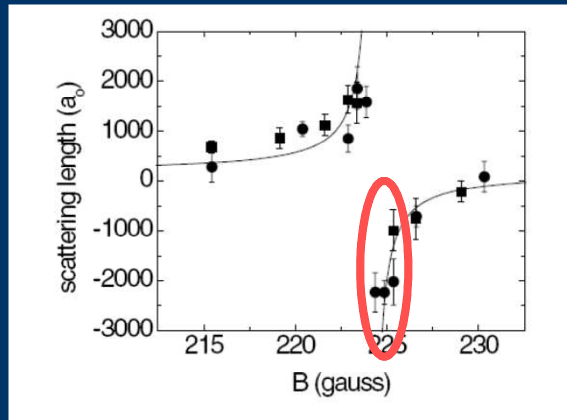
Cindy A. Regal*, Christopher Ticknor*, John L. Bohn* & Deborah S. Jin†

Nature 2003

|F=9/2 MF=-5/2>

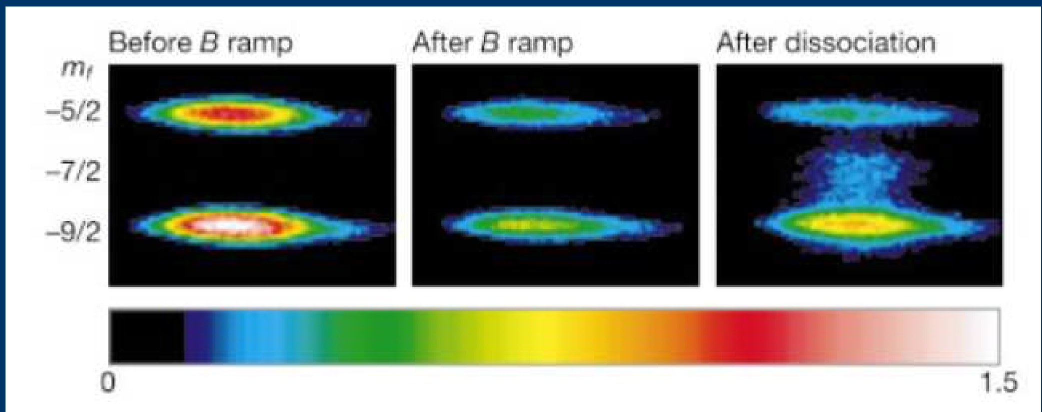
|F=9/2 MF=-9/2>

$^{40}K_2$



$a_s > 0$

Interação atrativa

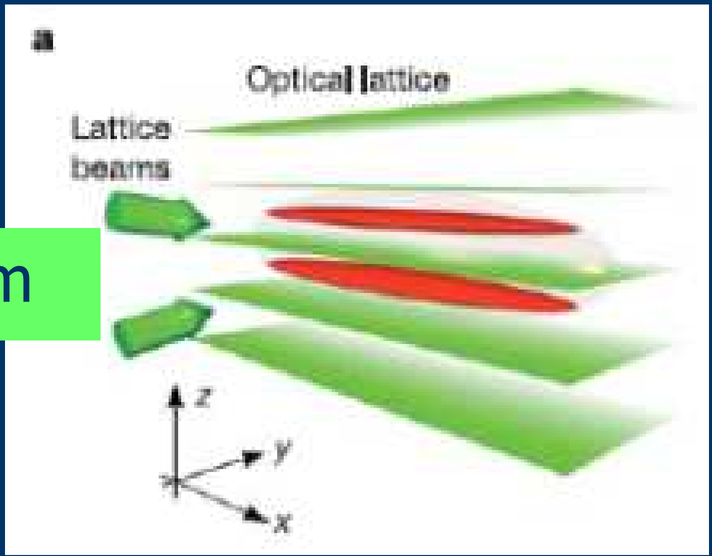


Berezinskii-Kosterlitz-Thouless crossover in a trapped atomic gas

Zoran Hadzibabic[1], Peter Krüger[1], Marc Cheneau[1], Baptiste Battelier[1] & Jean Dalibard[1]

^{87}RB

Nature 2006



d_z=3 μm

120 x 10 x 0.2 μm^3

d = 2

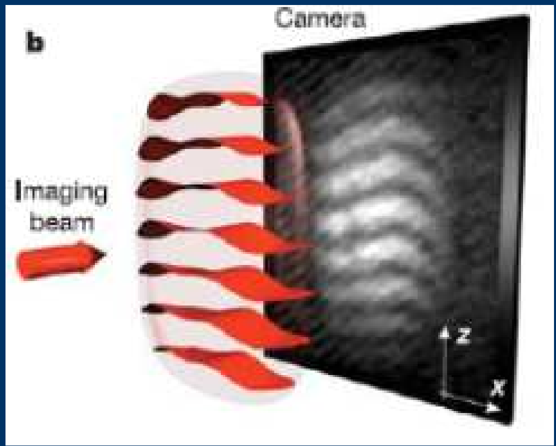
$T < T_{KT}$

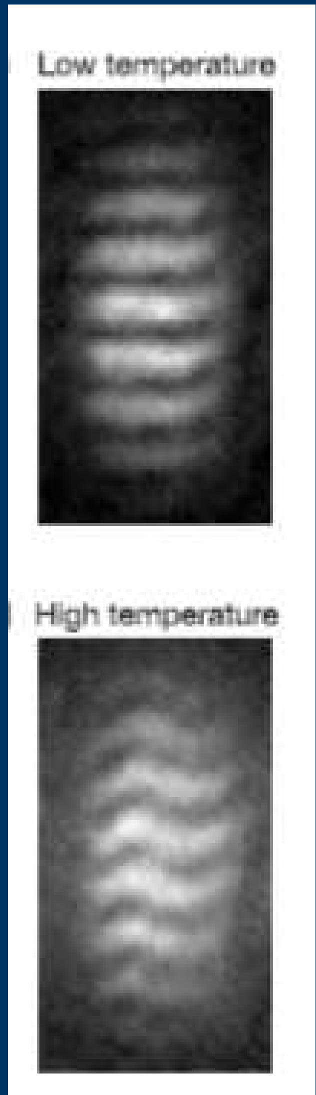
$$\Gamma(r) \sim r^{-\eta(T)}$$

$T > T_{KT}$

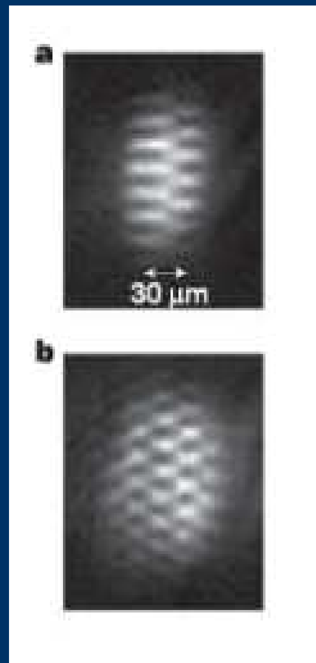
$$\Gamma(r) \sim e^{\frac{-r}{\xi(T)}}$$

Transição de fase topológica





Proliferação de vórtices livres a Temperaturas altas



$k_B T_{KT} = \pi \rho_s / 2$

Fases ordenadas

Bósons

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch*

Nature
2002

Condensados de ^{87}RB

A Mott insulator of fermionic atoms in an optical lattice

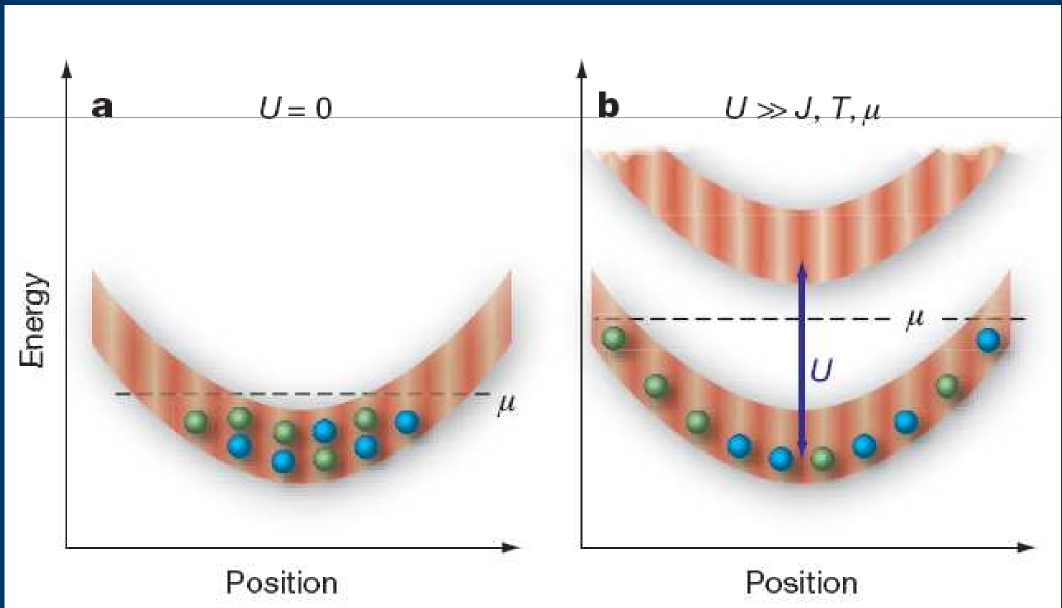
Robert Jördens[1]*, Niels Strohmaier[1]*, Kenneth Günter[1,2], Henning Moritz[1] & Tilman Esslinger[1]

Férmions

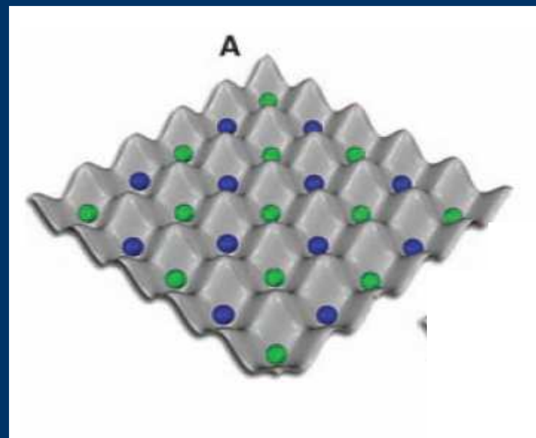
^{40}K

Nature 2008

1 átomo por "sítio"

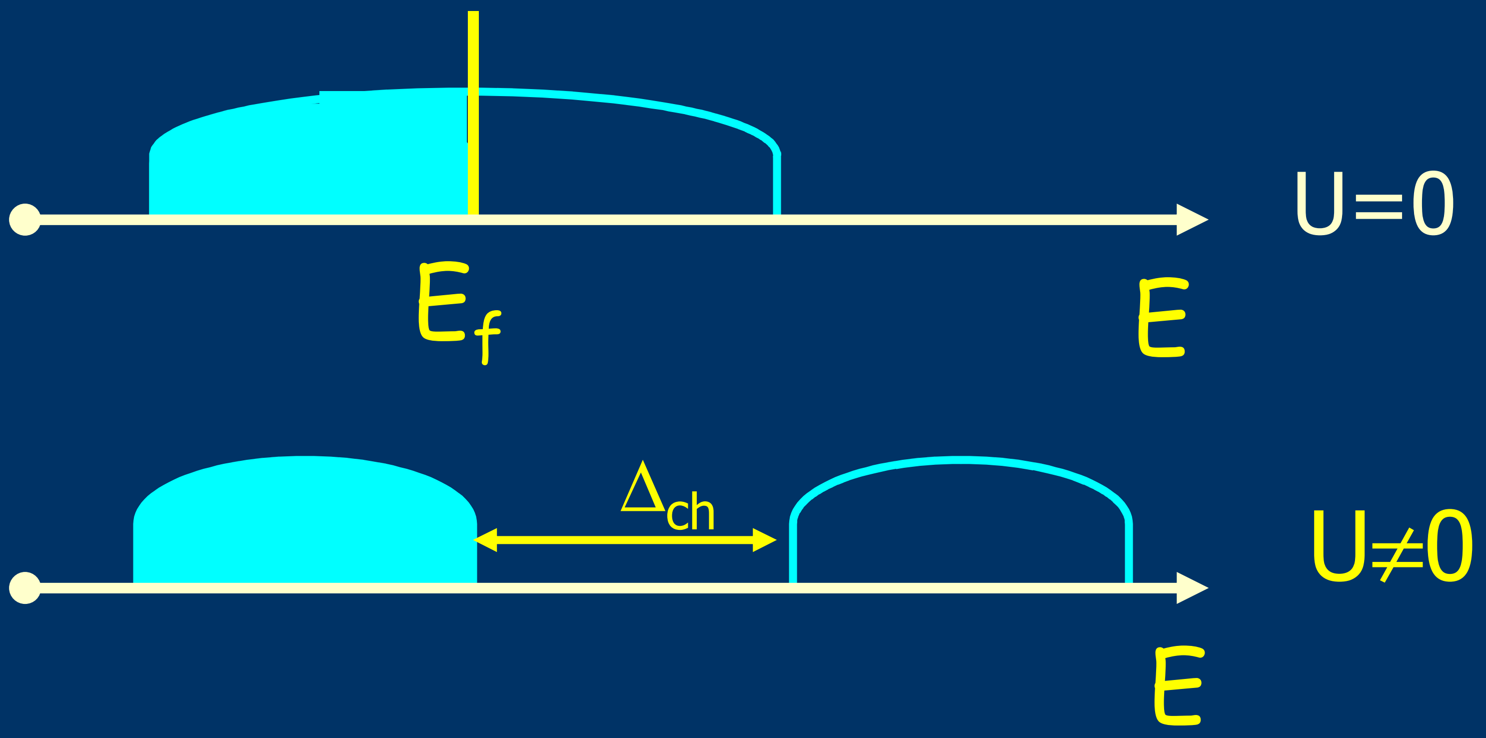


T ~ nK



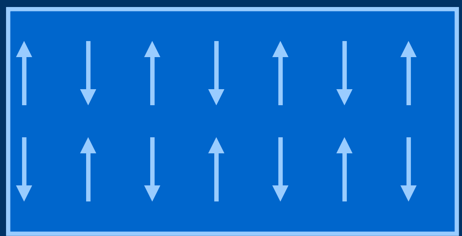
Transição de Mott

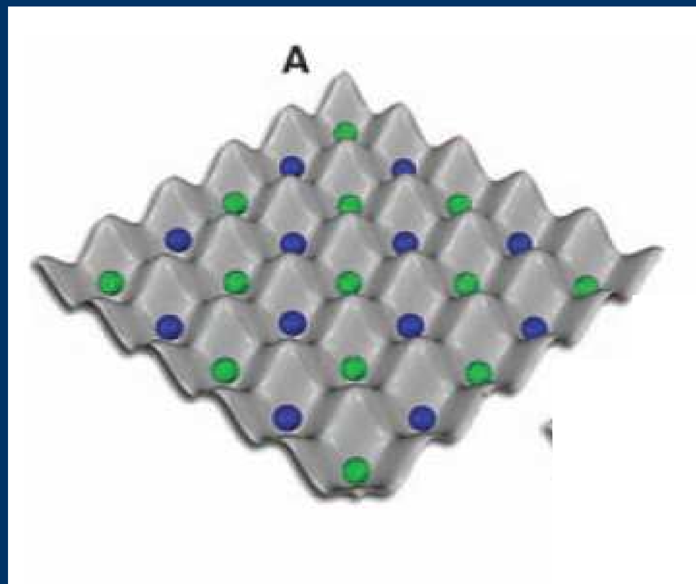
Metal - Isolante



Isolante de Mott

Corrida em busca do antiferromagnetismo





Experimentos

- Schneider et al. Science 322, 1520 (2008) *[Bloch]*
- Jordens et al Nature 455, 204 (2008) *[Esslinger]*

•Liao et al Nature 467, 567-569 (2010) *[Hulet]*

•Sanner et al PRL 106, 010402 (2011) *[Ketterle]*

^{40}K

$$\left|F,m_F\right\rangle = \left|\frac{9}{2},\frac{-9}{2}\right\rangle \equiv \left|\downarrow\right\rangle$$

$$\left|F,m_F\right\rangle = \left|\frac{9}{2},\frac{-7}{2}\right\rangle \equiv \left|\uparrow\right\rangle$$

$$\lambda \approx 1000nm$$

$$t \sim 10nK$$

$$U/t \sim 10$$

$$J = 4t^2/U \approx 4nK$$

^{6}Li

$$\left|F,m_F\right\rangle = \left|\frac{1}{2},\frac{-1}{2}\right\rangle \equiv \left|\downarrow\right\rangle$$

$$\left|F,m_F\right\rangle = \left|\frac{1}{2},\frac{1}{2}\right\rangle \equiv \left|\uparrow\right\rangle$$

Como observar?

A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice

Waseem S. Bakr[1], Jonathon I. Gillen[1], Amy Peng[1], Simon Fölling[1] & Markus Greiner[1]

Nature 2009

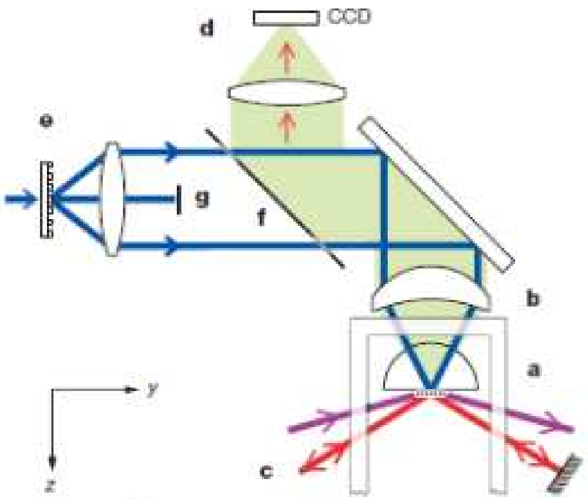


Figure 1 | Diagram of the quantum gas microscope. The two-dimensional atom sample (**a**) is located a few micrometres below the lower surface of a hemispherical lens inside the vacuum chamber. This lens serves to increase the numerical aperture (NA) of the objective lens outside the vacuum (**b**) by the index of refraction, from NA = 0.55 to NA = 0.8. The atoms are illuminated from the side by the molasses beams (**c**) and the scattered fluorescence light is collected by the objective lens and projected onto a CCD camera (**d**). A 2D optical lattice is generated by projecting a periodic mask (**e**) onto the atoms through the same objective lens via a beam splitter (**f**). The mask is a periodic phase hologram, and a beam stop (**g**) blocks the residual zeroth order, leaving only the first orders to form a sinusoidal potential.

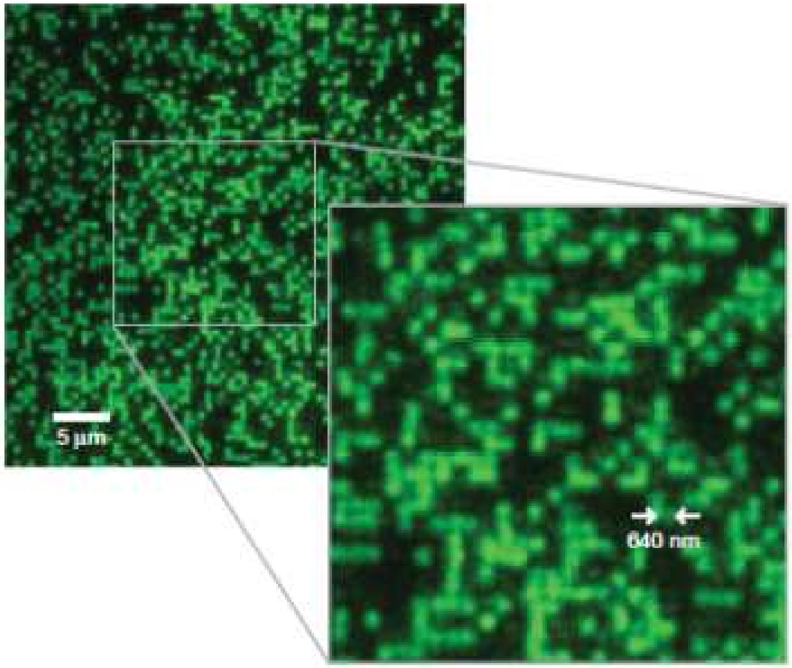


Figure 3 | Site-resolved imaging of single atoms on a 640-nm-period optical lattice, loaded with a high density Bose–Einstein condensate. Inset, magnified view of the central section of the picture. The lattice structure and the discrete atoms are clearly visible. Owing to light-assisted collisions and molecule formation on multiply occupied sites during imaging, only empty and singly occupied sites can be seen in the image.

Como observar?

PRL 106, 145302 (2011) PHYSICAL REVIEW LETTERS week ending 8 APRIL 2011

Probing Nearest-Neighbor Correlations of Ultracold Fermions in an Optical Lattice

Daniel Greif, Leticia Tarruell,* Thomas Uehlinger, Robert Jördens, and Tilman Esslinger
Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland
(Received 2 December 2010; revised manuscript received 1 February 2011; published 5 April 2011)

$$\mathcal{P}_{i,i+1} = \sum_{\sigma} \langle n_{i,\sigma} n_{i+1,\bar{\sigma}} (1 - n_{i,\bar{\sigma}})(1 - n_{i+1,\sigma}) \rangle,$$

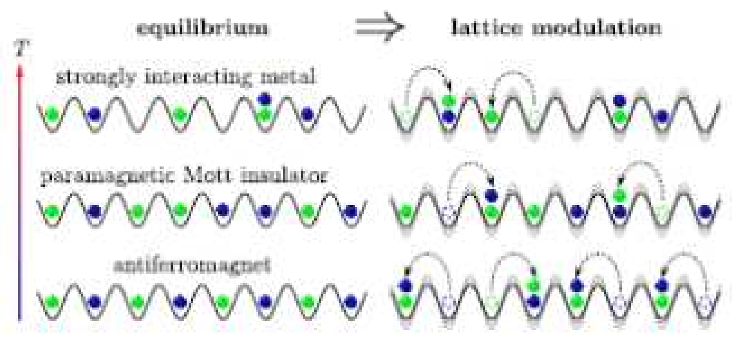
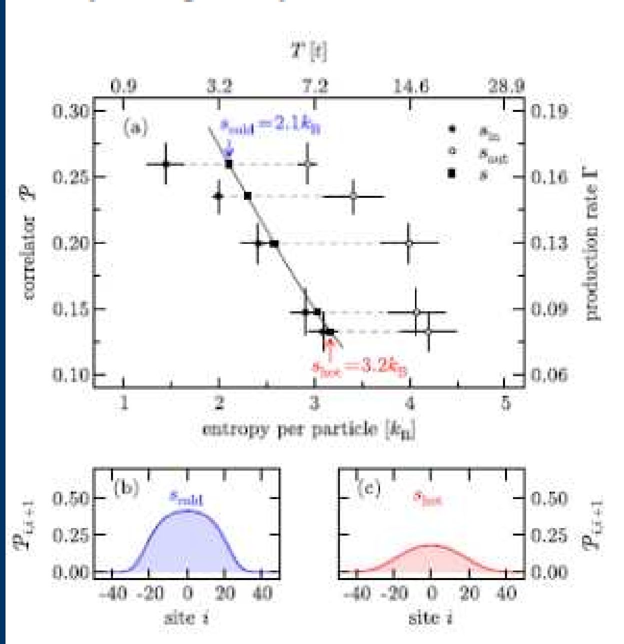
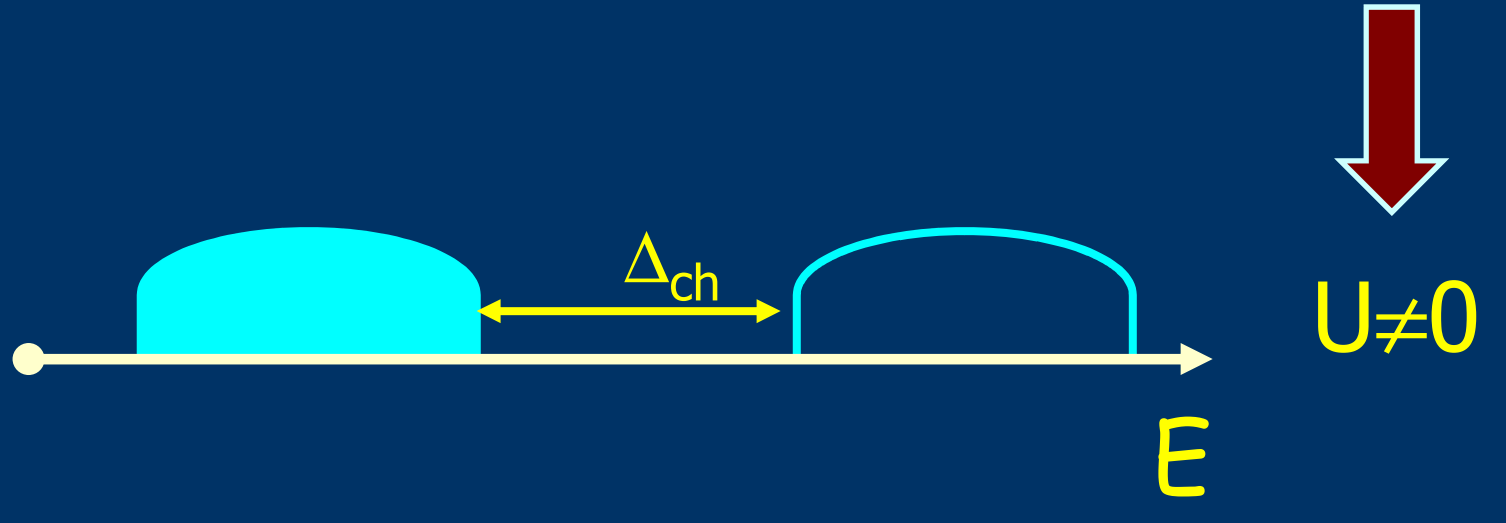


FIG. 1 (color online). Probing nearest-neighbor correlations for different phases. A periodic lattice modulation causes tunneling of particles to neighboring sites. The number of created doublons strongly depends on the state of the many-body system (strongly interacting metal, paramagnetic Mott insulator, or antiferromagnet) and can be used to determine the nearest-neighbor correlator $\mathcal{P}_{i,i+1}$ [10].

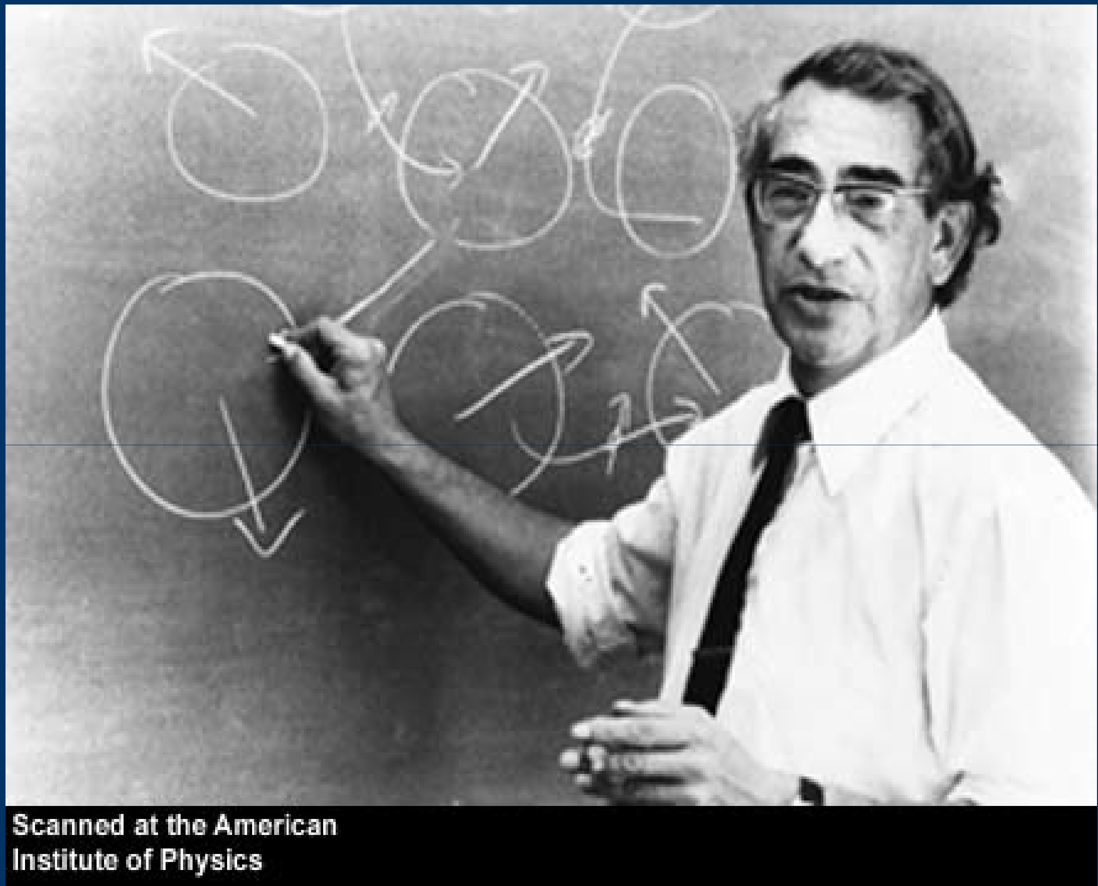


Férmions fortemente correlacionados em redes óticas



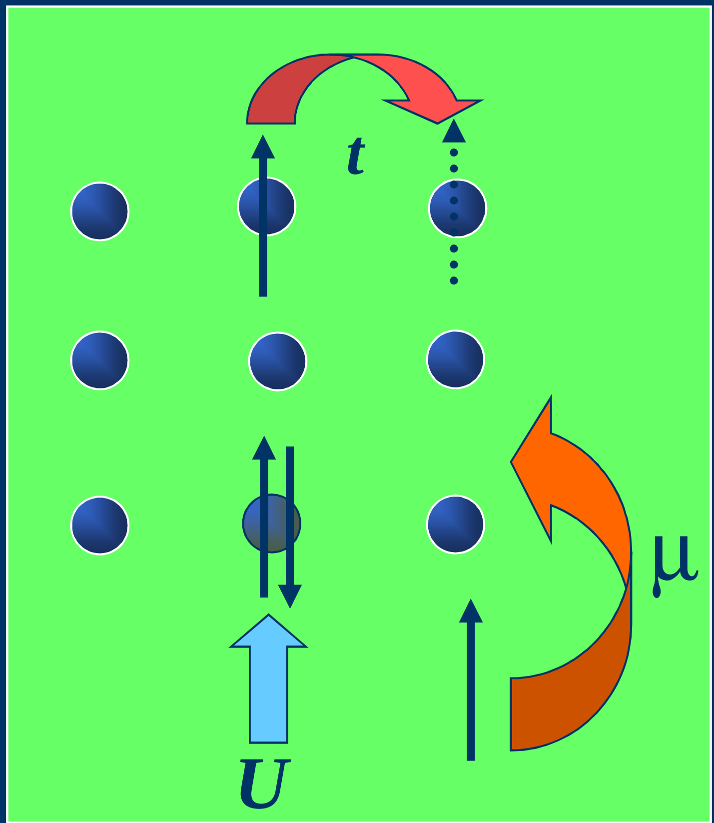
O modelo de Hubbard

Ou o “modelo de Ising” para sistemas com férmions fortemente correlacionados



John Hubbard (1931-1980)

O modelo de Hubbard



$$H = -t\sum_{<i,j>\sigma}\left(c^{+}_{i\sigma}c_{j\sigma} + c^{+}_{j\sigma}c_{i\sigma}\right)$$

$$+U\sum_{i} n_{i\uparrow}n_{i\downarrow}$$

$$-\mu\sum_{i,\sigma} c^{+}_{i\sigma}c_{i\sigma}$$

Competição

Localização X Itinerância

U

t

Transição metal-isolante

Ordenamento magnético

Modelo de Hubbard atrativo

$U<0$

Interação atrativa

fenomenológica

Formação de pares

superfluidez

Não mais!

Modelo mais simples a incorporar as correlações eletrônicas

Uma única banda

banda s

Correlação eletrônica intra-sítio

Hopping de primeiros vizinhos

Sem desordem

Modelo mais simples a incorporar as correlações eletrônicas

Simples demais?

Uma única banda

Correlação eletrônica intra-sítio

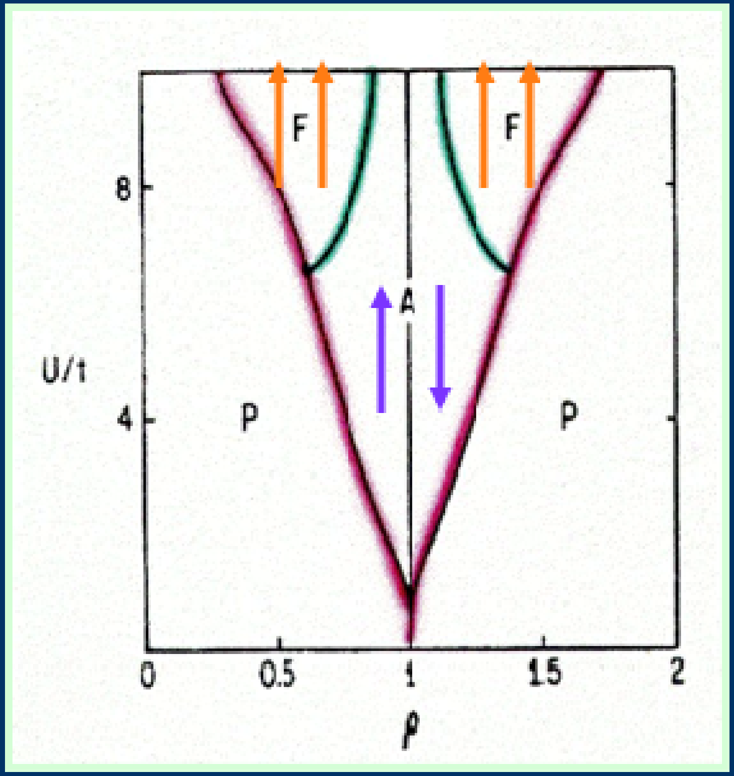
Hopping de primeiros vizinhos

Sem desordem

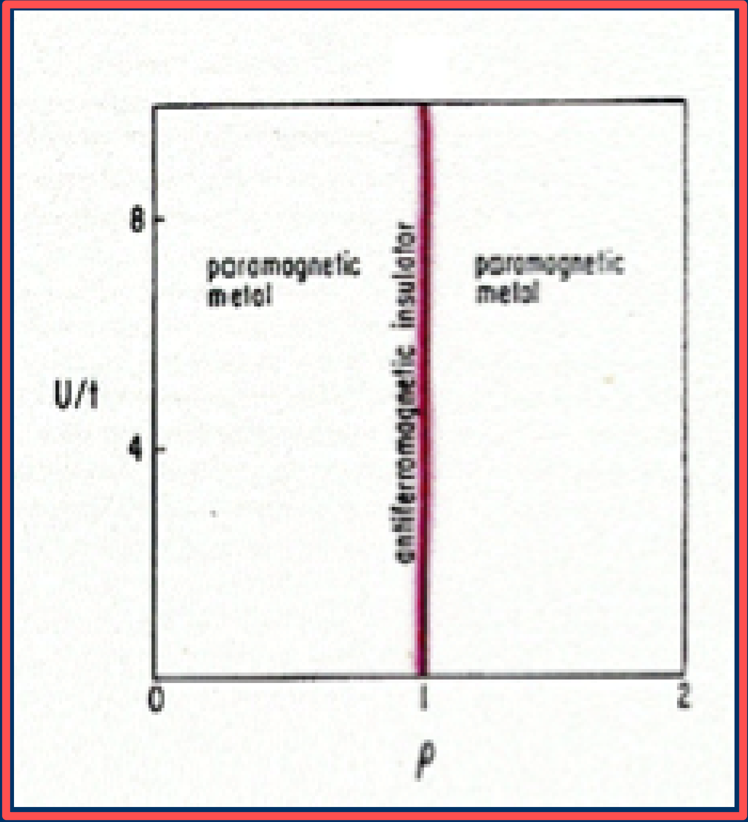
Apesar de muito simples não tem solução conhecida!

Diagrama de fase: rede quadrada a $T = 0$

Campo Médio (Hartree-Fock)



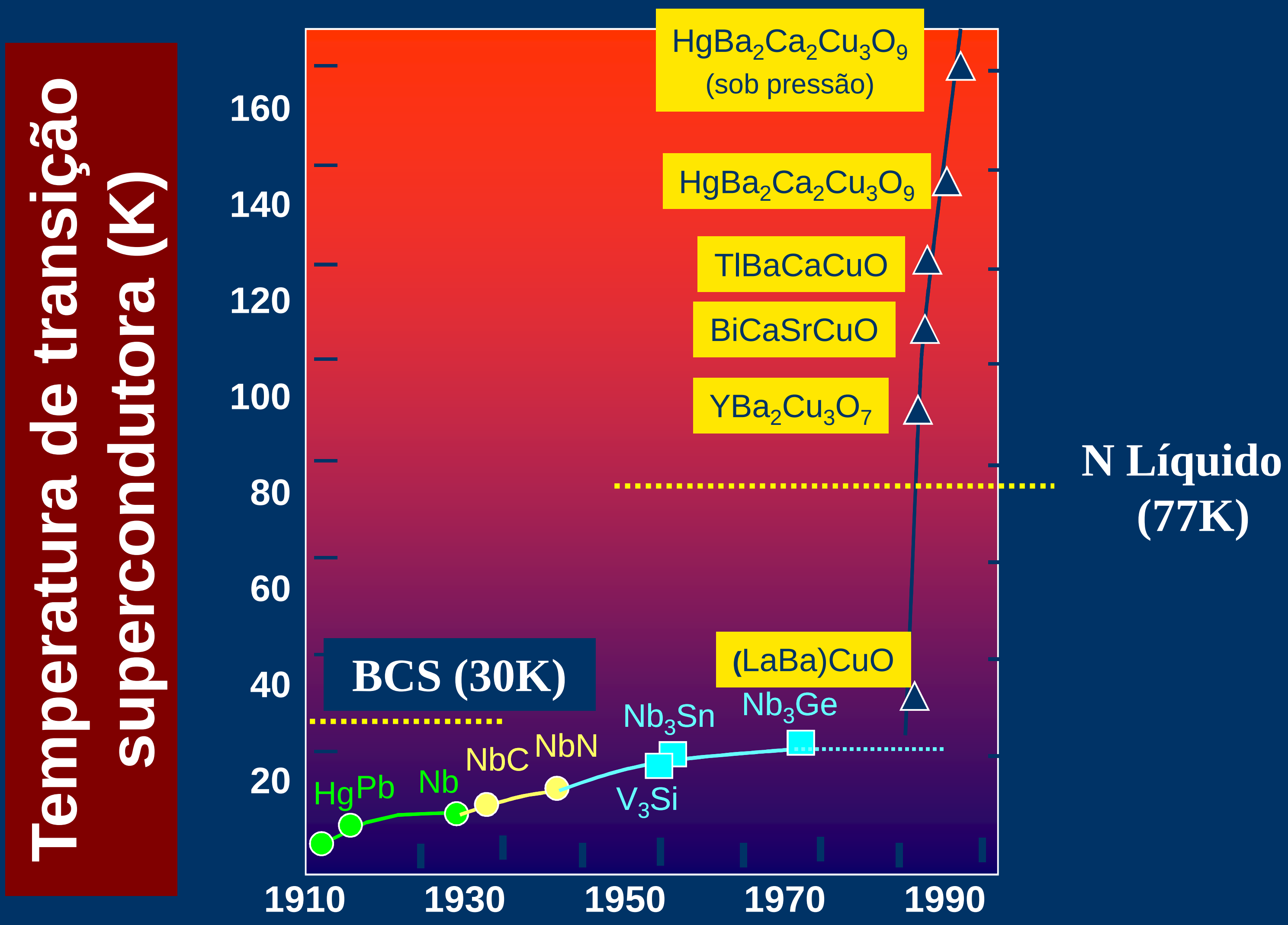
QMC



Hirsch, PRB (1985); Hirsch & Tang, PRL (1989)

Por que estamos interessados no modelo de Hubbard hoje?

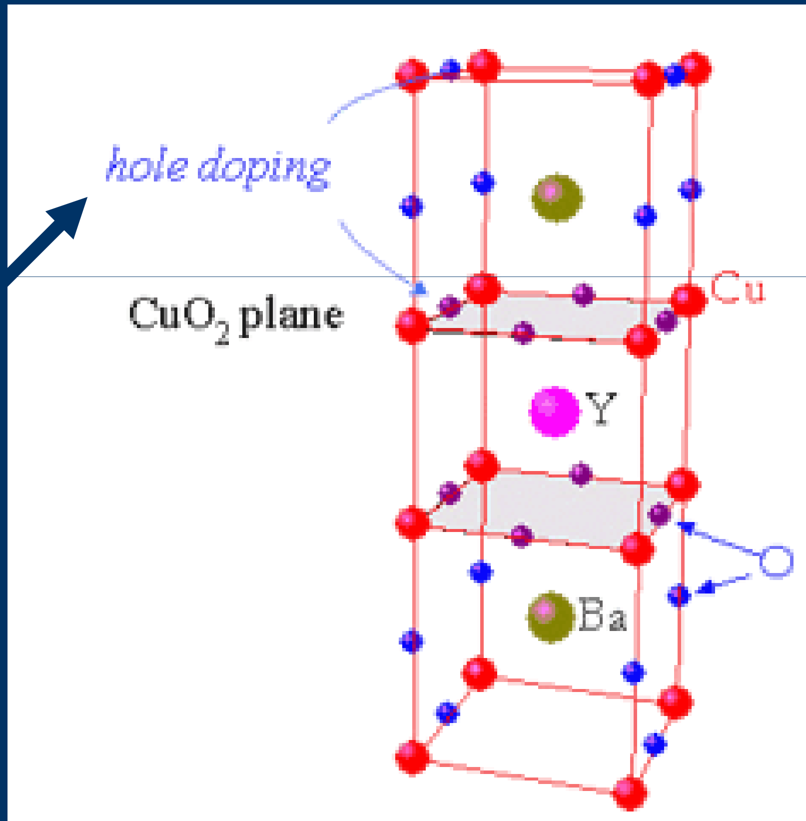
Materiais Supercondutores



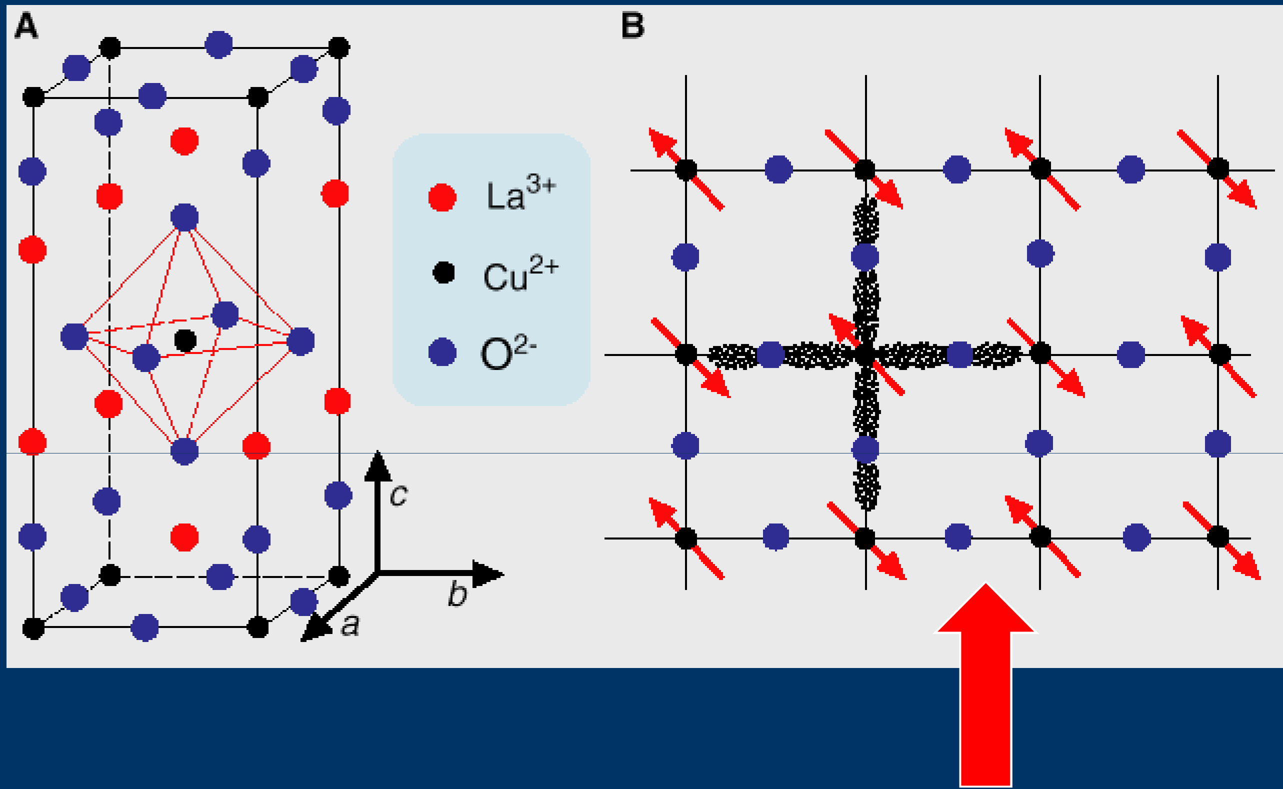
Supercondutores de alta temperatura crítica

$YBa_2Cu_3O_{7-\delta}$

Reservatório de elétrons ou buracos



Sem dopagem



Isolante de Mott
ANTIFERROMAGNÉTICO

Diagrama de fases

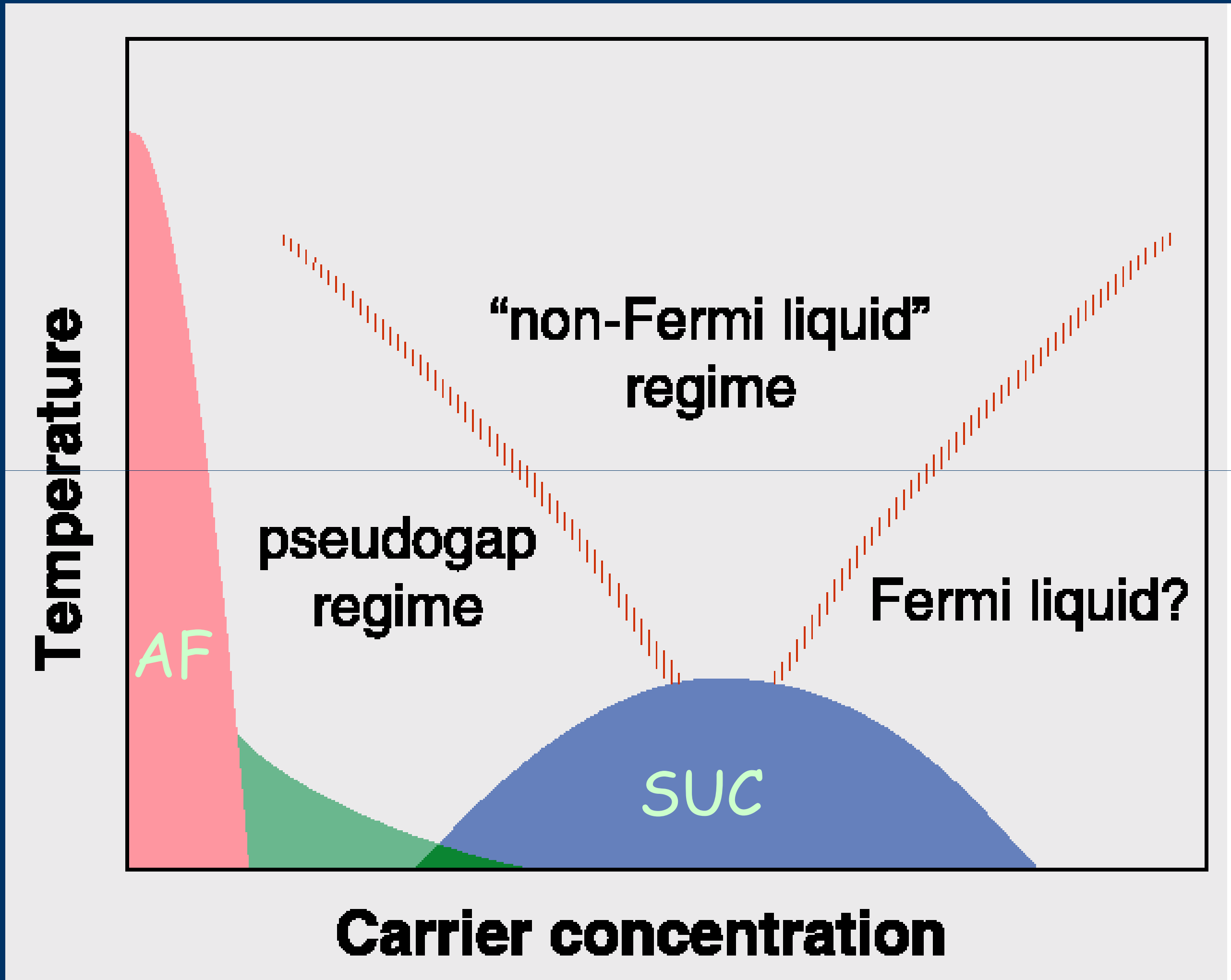
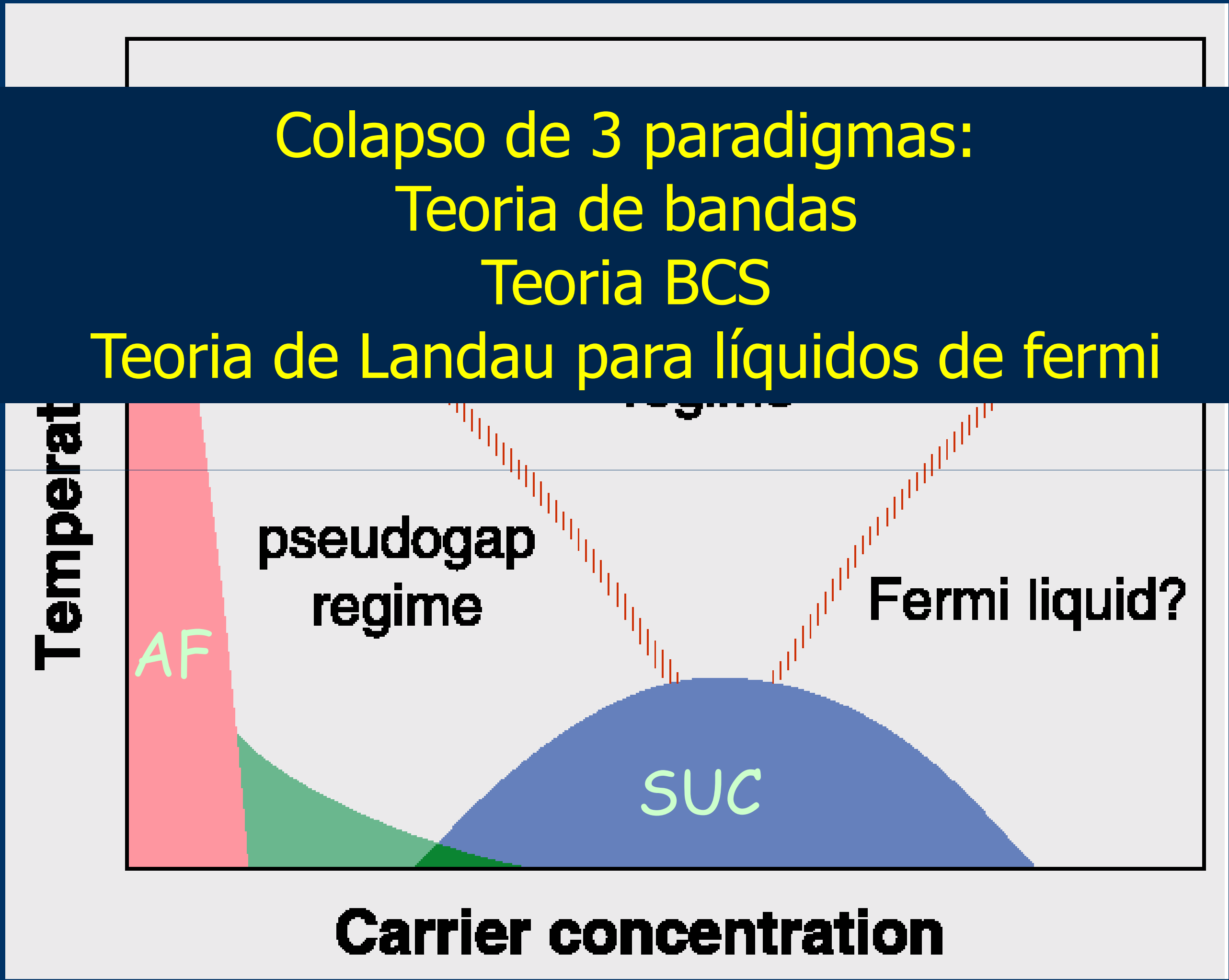


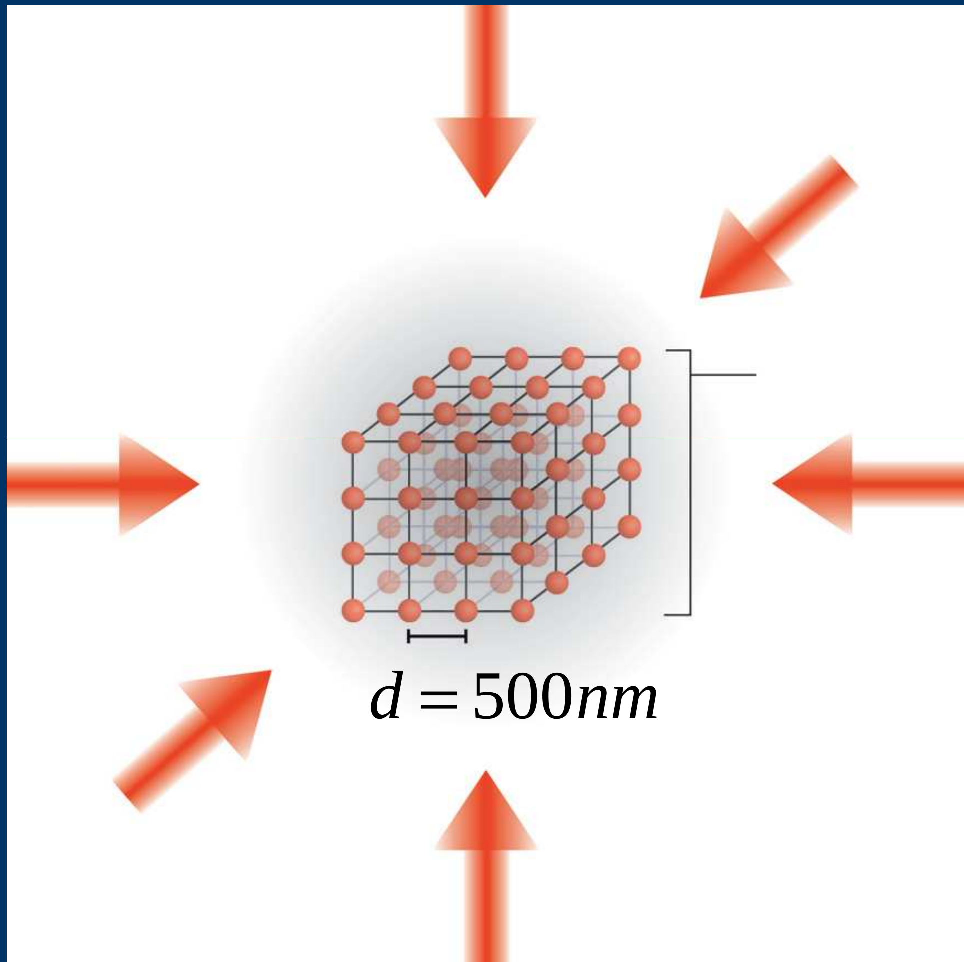
Diagrama de fases



Colapso de 3 paradigmas:
Teoria de bandas
Teoria BCS
Teoria de Landau para líquidos de fermi

Um modelo tão simples quanto o modelo de Hubbard pode descrever a Física dos supercondutores de alta temperatura?

Emulation of Hubbard model in Optical Lattices



Modelo mais simples a incorporar as correlações eletrônicas

Simples demais?

Uma única banda

Correlação eletrônica intra-sítio

Hopping de primeiros vizinhos

Sem desordem

Modelo mais simples a incorporar as correlações eletrônicas

Simples demais?

Não em redes óticas!

Uma única banda

Correlação eletrônica intra-sítio

Hopping de primeiros vizinhos

Sem desordem

Férmions fortemente correlacionados

Ótica	Matéria condensada
Redes óticas	Núcleo atômico + elétrons de caroço
Estados Hiperfinos	$n_\uparrow$ e $n_\downarrow$
Scattering lenght	Intensidade da interação

Modelo de Hubbard

U/t e T/t ⟷ V_0/E_R e T/E_R

$$t = E_R \frac{4}{\sqrt{\pi}} \left(\frac{V_0}{E_R}\right)^{\frac{3}{4}} \exp\left(-2\sqrt{\frac{V_0}{E_R}}\right)$$

$$U = E_R 4\sqrt{2\pi} \frac{a_s}{\lambda} \left(\frac{V_\perp}{E_R}\right)^{\frac{1}{4}} \left(\frac{V_0}{E_R}\right)^{\frac{1}{2}}$$

U positivo ou negativo!

Porém...

Quanto resfriar? Como resfriar?

Como lidar com uma densidade que varia ao longo da armadilha?

Fermions in 3D optical lattices: Cooling protocol to obtain Antiferromagnetism

tclp@if.ufrj.br

Richard Scalettar

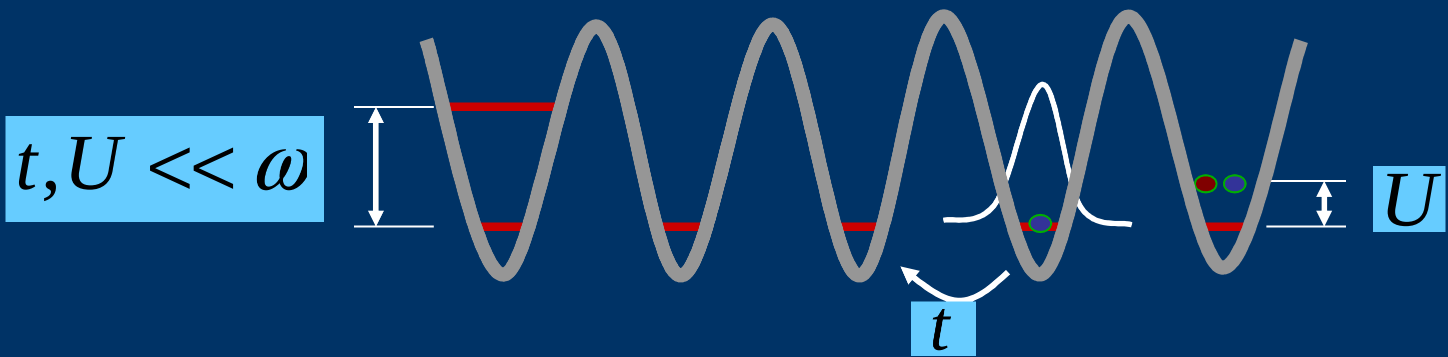
Yen Lee Loh
Nandini Trivedi
Mohit Randeria

QMC+LDA

Phys. Rev. Lett. 107, 086401 (11)

Simulações com a armadilha

$$H = -t \sum_{<r,r`>\sigma} (c^{+}_{r\sigma} c_{r`\sigma} + c^{+}_{r`\sigma} c_{r\sigma}) \quad + U \sum_{r} n_{r\uparrow} n_{r\downarrow} \quad + \sum_{r,\sigma} (\alpha_t r^2 - \mu_0)\, n_{r\sigma}$$



$$\alpha_t = \frac{1}{2} m \omega_0^2 d^2$$

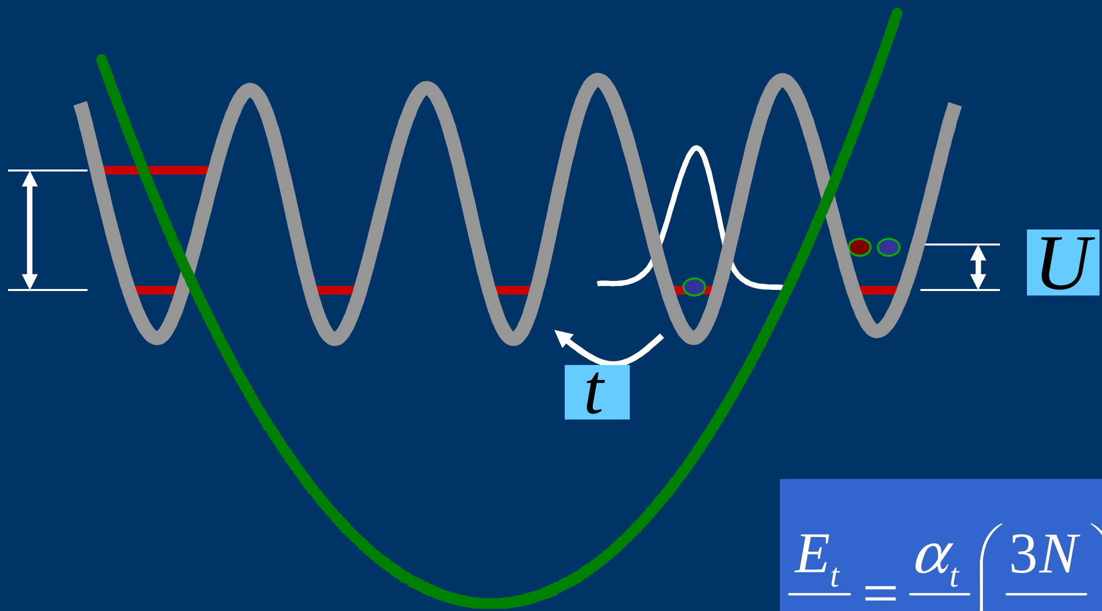
$$\frac{E_t}{t} = \frac{\alpha_t}{t} \left(\frac{3N}{8\pi} \right)^{\frac{2}{3}}$$

Dimensionless compression

Simulações com a armadilha

$$H= -t \sum_{\langle r,r`\rangle\sigma} \left(c^{+}_{r\sigma} c_{r`\sigma} + c^{+}_{r`\sigma} c_{r\sigma}\right) + U \sum_{r} n_{r\uparrow} n_{r\downarrow} + \sum_{r,\sigma} \left(\alpha_t r^2 - \mu_0\right) n_{r\sigma}$$

$$t, U << \omega$$



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Dimensionless compression

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$$\frac{E_t}{t} = \frac{\alpha_t}{t} \left(\frac{3N}{8\pi}\right)^{\frac{2}{3}}$$

Dimensionless compression

Potencial químico dependente da posição

$$\mu(r) = \mu_0 - \alpha_t \frac{r^2}{d^2}$$

μ_0

Controla o número de átomos na armadilha

$N \sim 10^4 - 10^6$

$$\alpha_t = \frac{1}{2} m \omega_0^2 d^2$$

Controla a compressão da armadilha

ν= [20 - 120] Hz ⇨ α_t=[0.0006-0.21] t

^{40}K

LDA

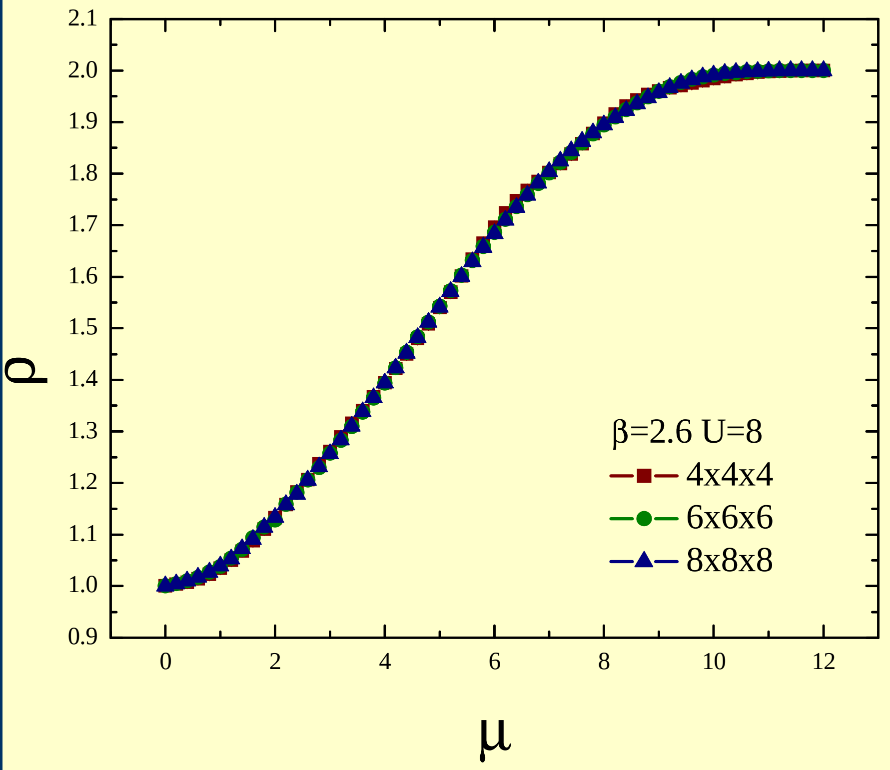
Armadilha esférica

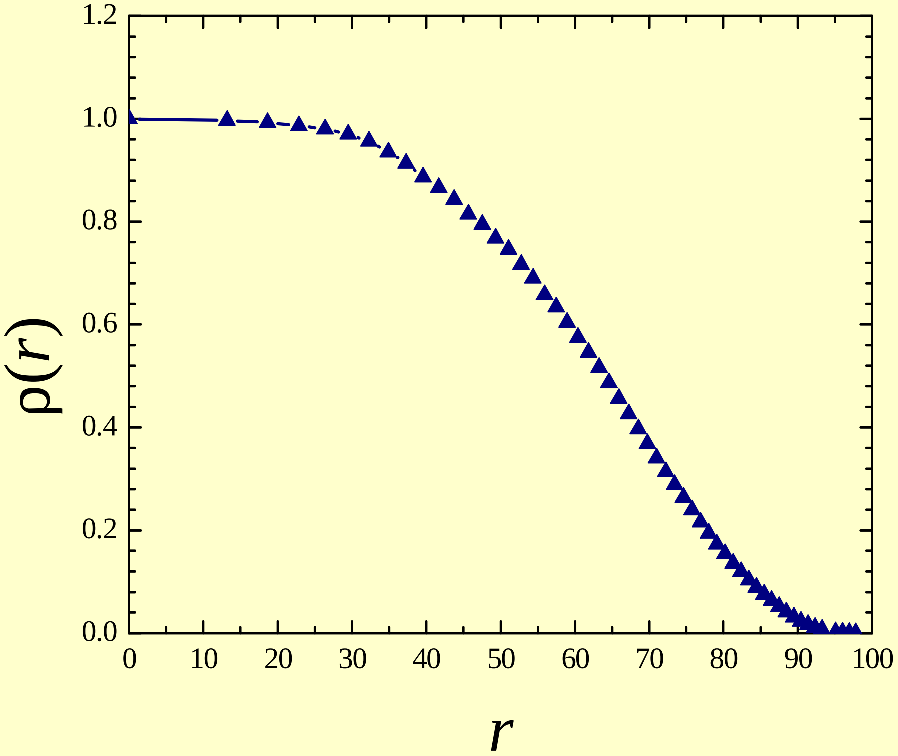
$\mu(r)$ ⇨ $\rho(r)$ ⇨

$$N = \int dr^3 \rho(r) = \frac{4\sqrt{2}\pi}{(m\omega^2)^{3/2}} \int_{-\infty}^{\mu_0} d\mu \sqrt{\mu_0 - \mu}\,\rho(\mu)$$

Potencial químico dependente da posição

$\rho(\mu)$ → $\mu(r) = \mu_0 - \alpha_t \frac{r^2}{d^2}$ → $\rho(r)$



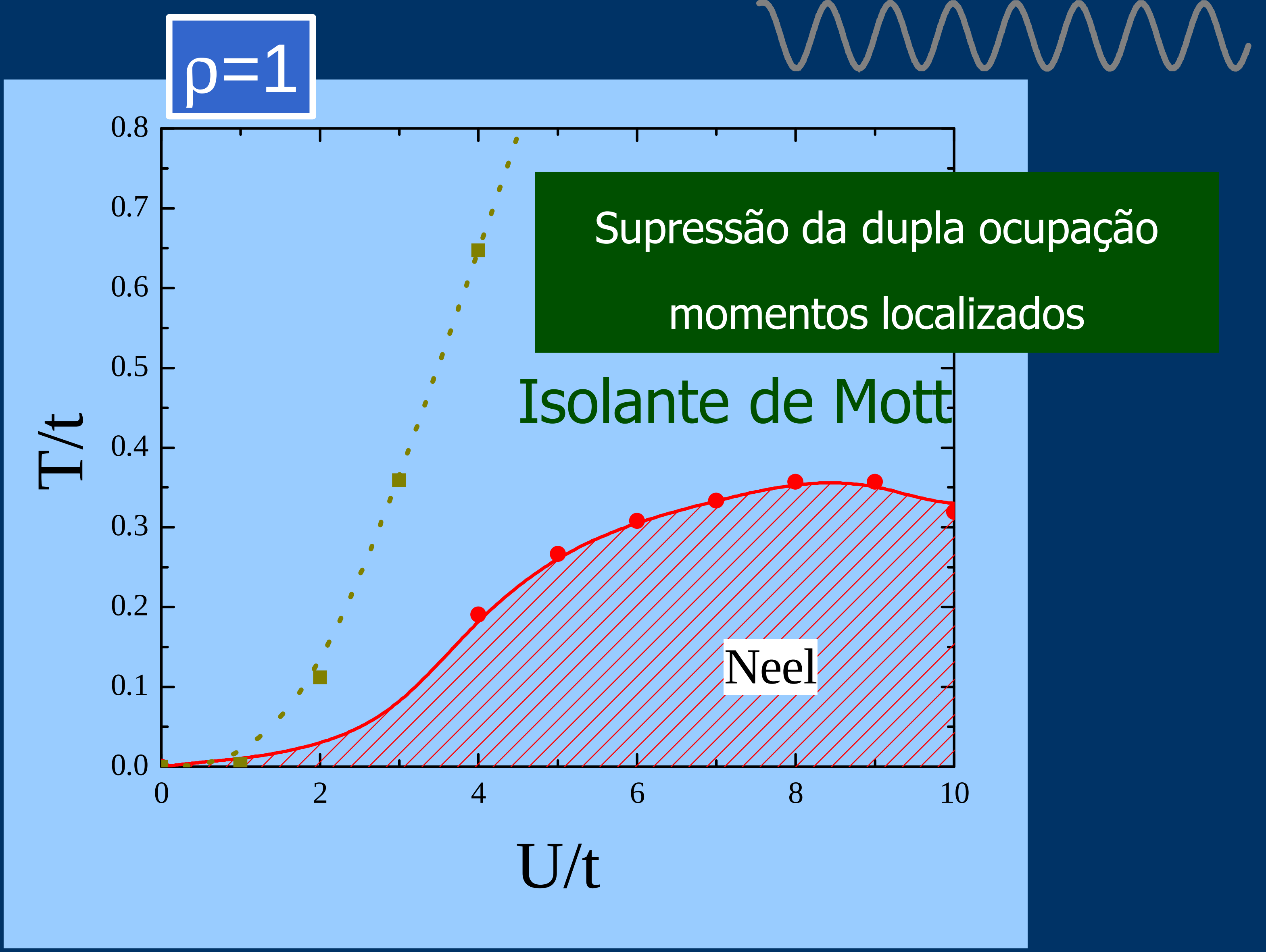


1º passo

Mais simples!

O que acontece no sistema homogêneo, sem armadilha?

Sistema 3D sem armadilha



Como determinar T?

Onset of Fermi Degeneracy in a Trapped Atomic Gas

B. DeMarco and D. S. Jin*†

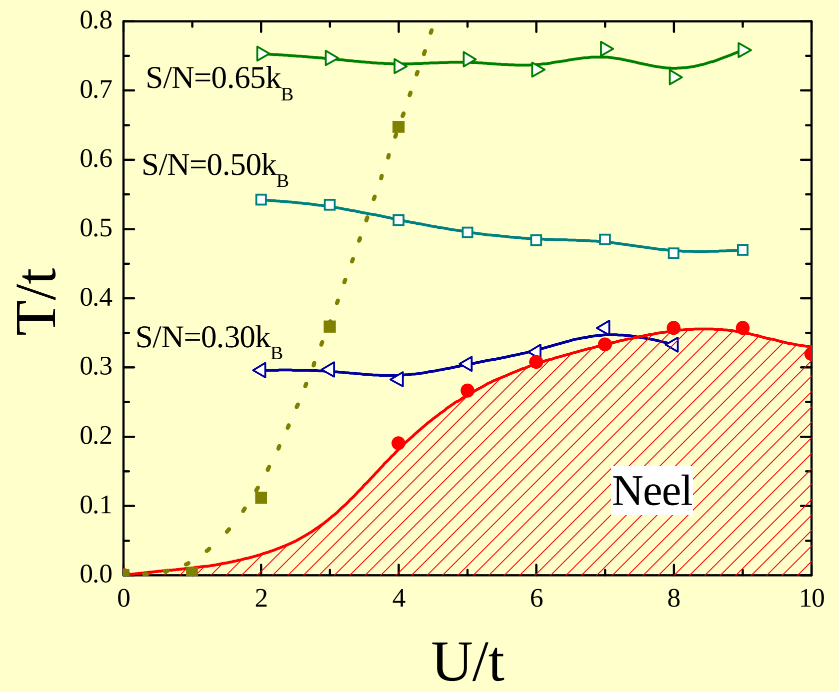
20% systematic uncertainty in T/T_F

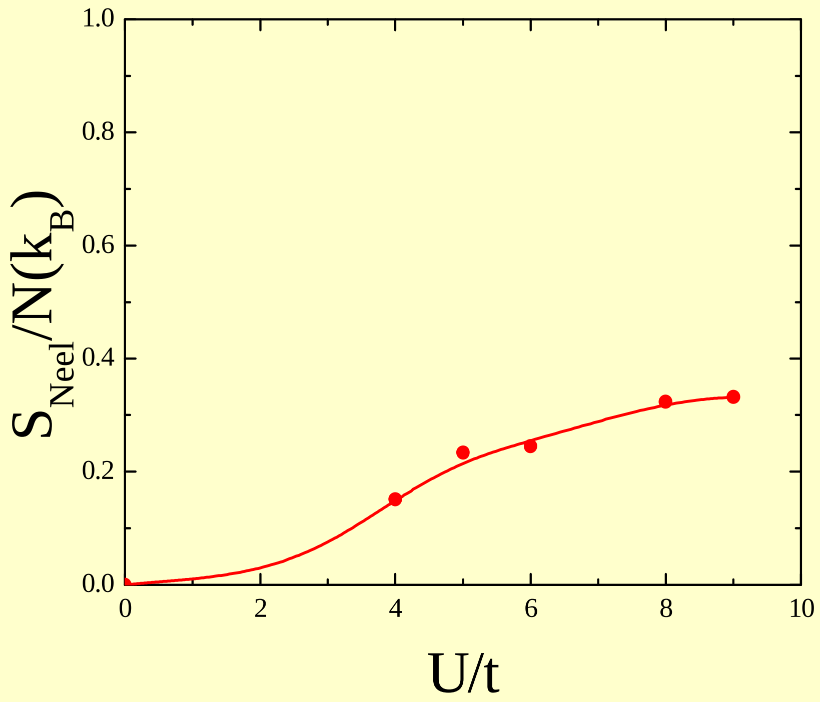
Nestes sistemas T não é bem conhecida.

Suposição: o experimento é realizado adiabaticamente

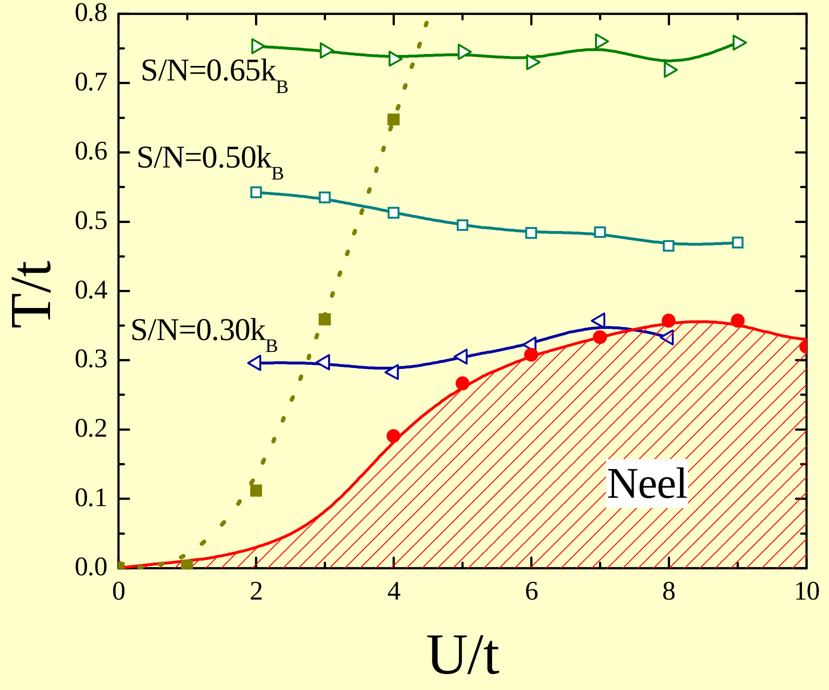
A entropia é a grandeza relevante

Restrições para a entropia sem o confinamento $\rho=1$

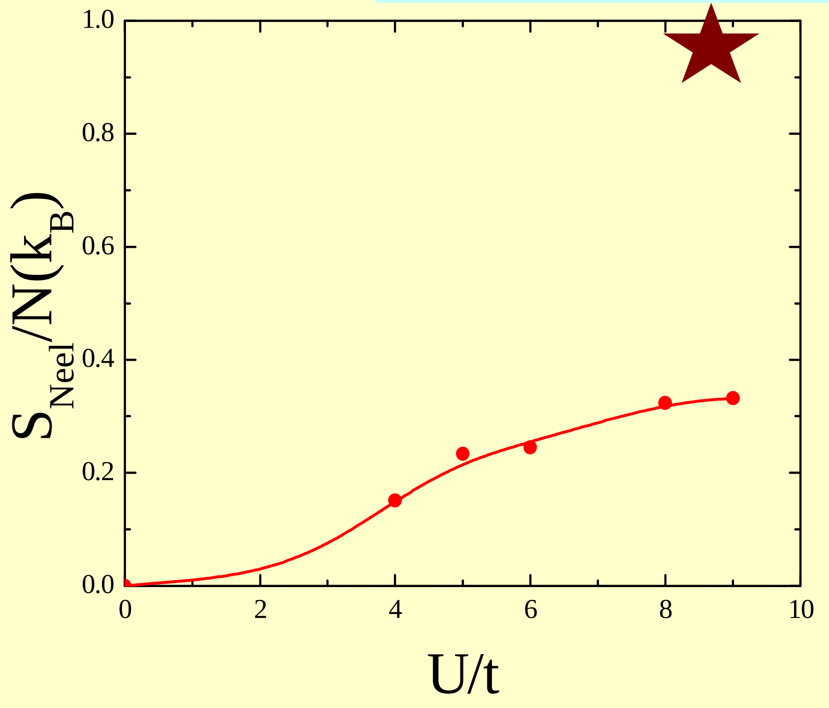




Restrições para a entropia sem o confinamento



Experimentos



Simulações com a armadilha

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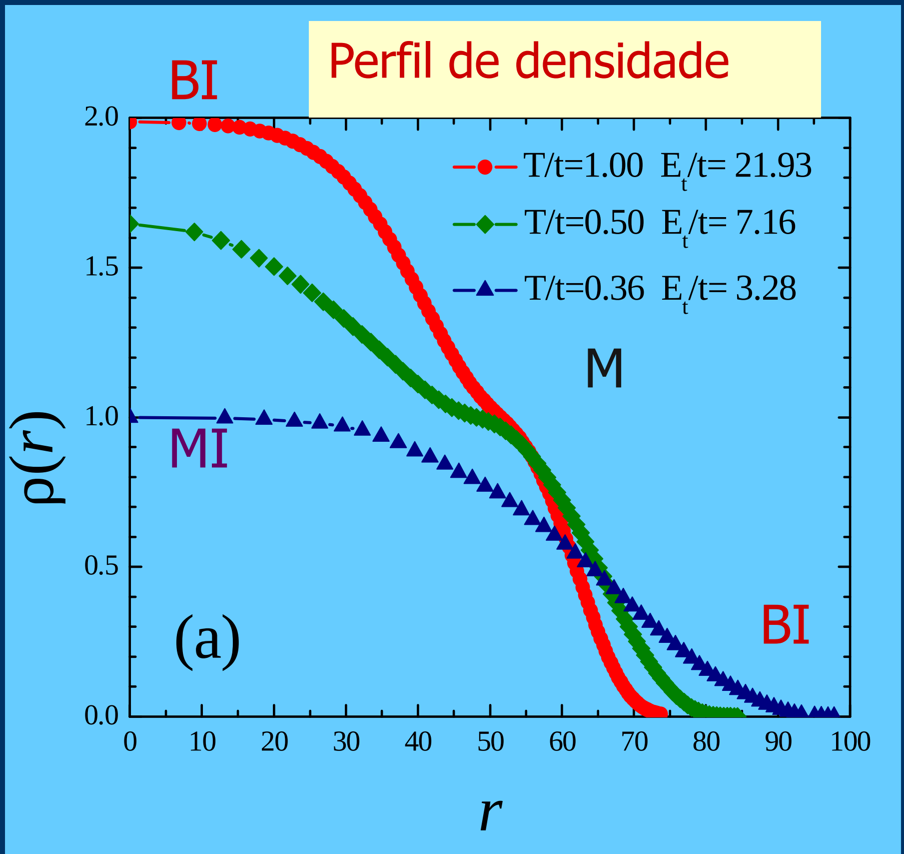
$$\alpha_t = \frac{1}{2} m \omega_0^2 d^2$$

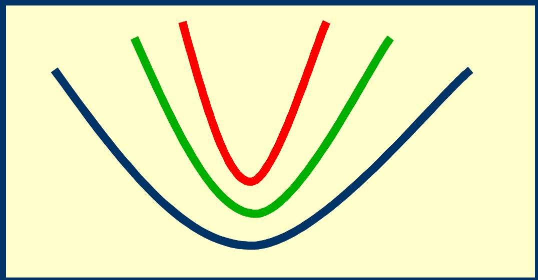
$$\frac{E_t}{t} = \frac{\alpha_t}{t} \left(\frac{3N}{8\pi} \right)^{\frac{2}{3}}$$

Dimensionless compression

Perfil de densidade

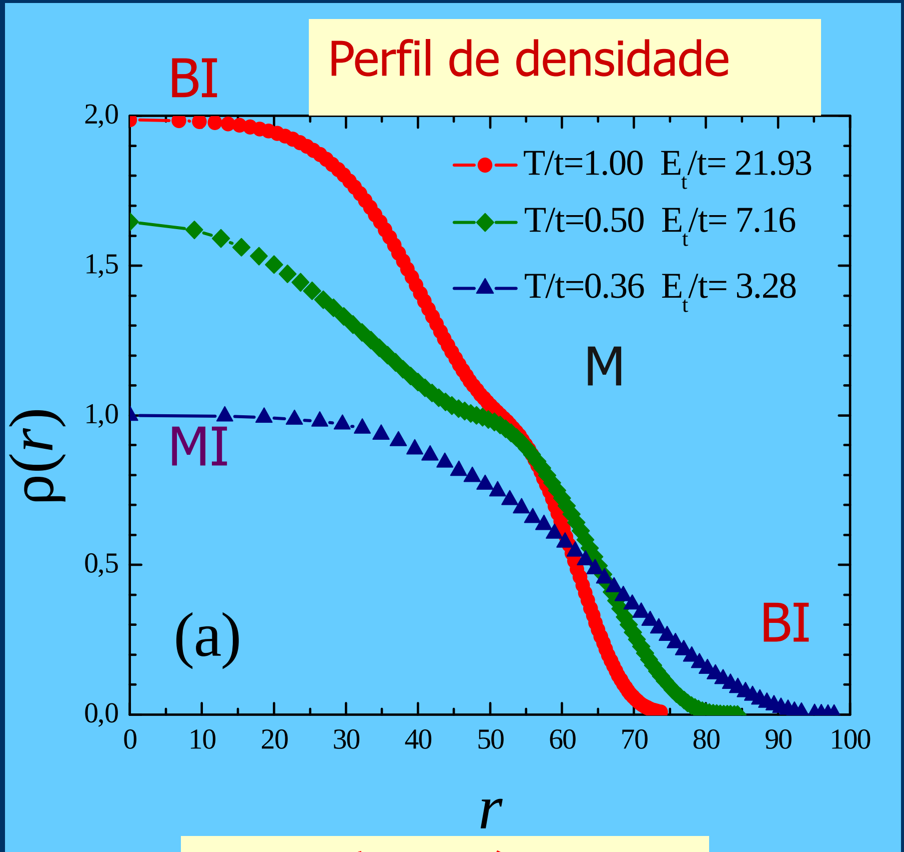
S/N=0.65 k_B N=1.3x10^6 U/t=8

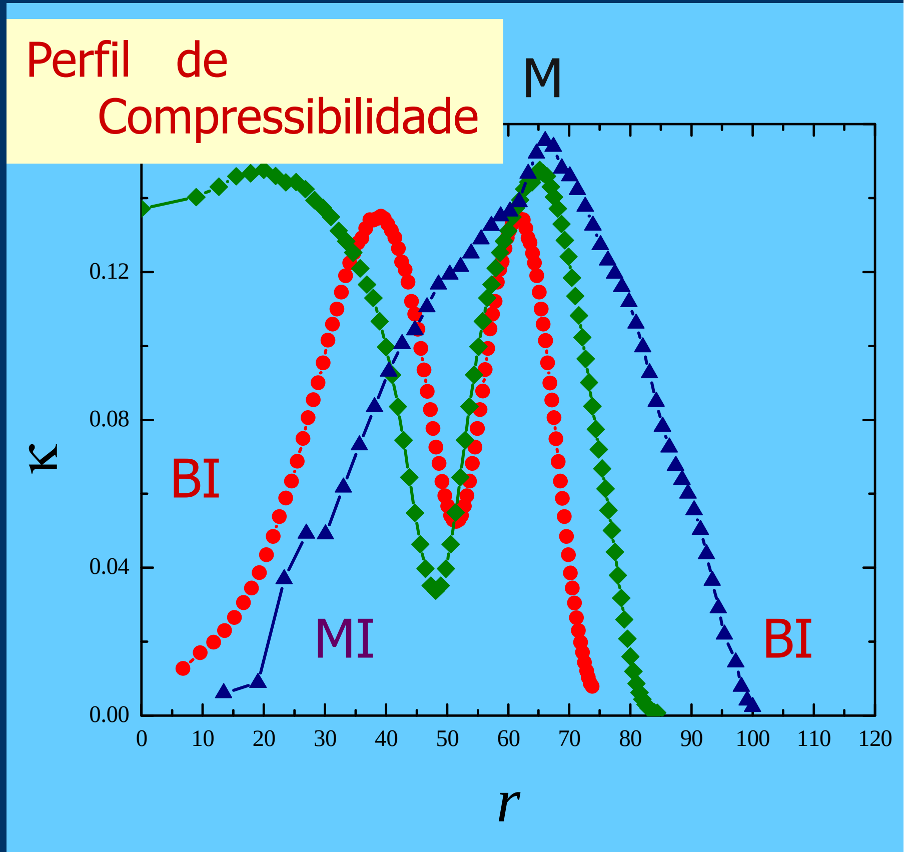


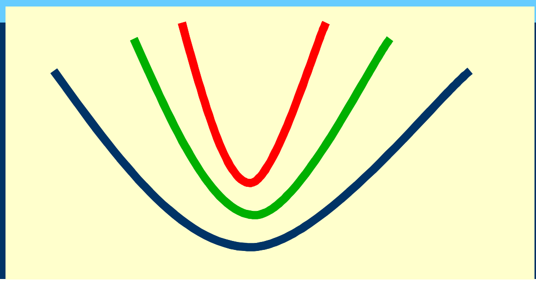


Descomprimindo com S/N fixo

$S/N=0.65\ k_B$ $N=1.3\times10^6$ $U/t=8$







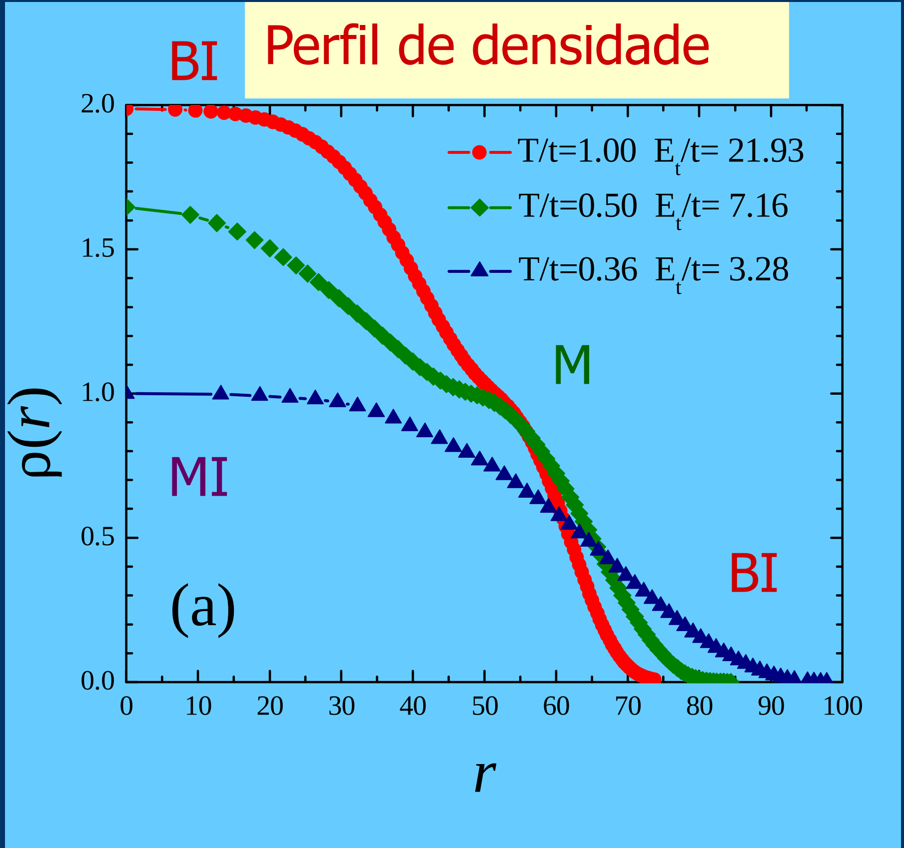
$$\kappa = -\frac{1}{m\omega^2 r}\frac{d\rho}{dr} = -\frac{1}{2\alpha r}\frac{d\rho}{dr}$$

Resfriando por descompressão com S/N fixo

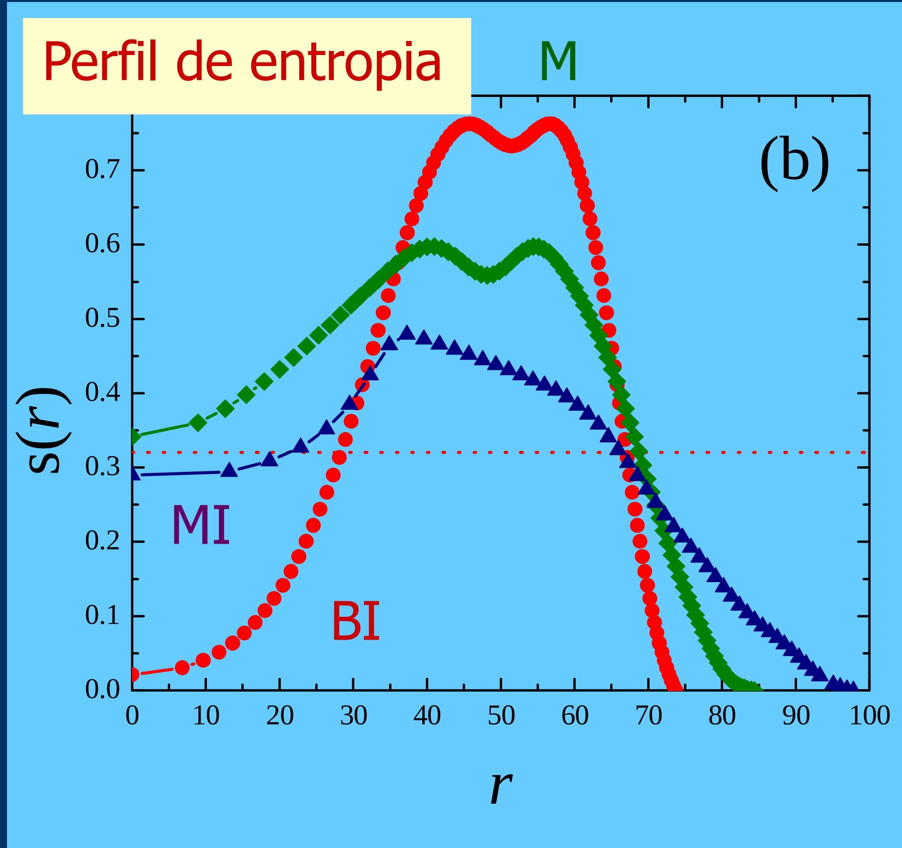
$S/N=0.65\ k_B \quad N=1.3\times10^6 \quad U/t=8$

Redistribuição da entropia

Perfil de densidade



Perfil de entropia



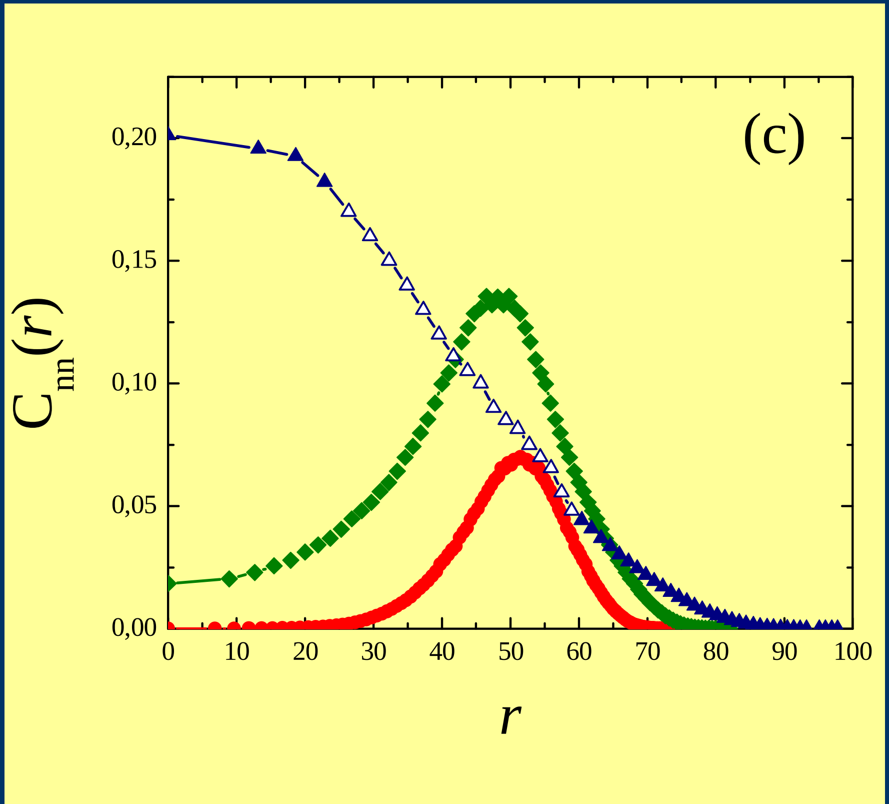
BI⇨ entropia → 0

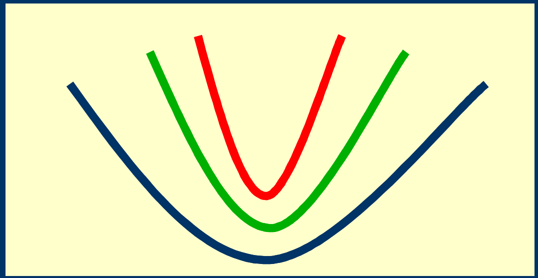
M⇨ sorvedouros de entropia

MI⇨ baixa entropia, mas finita devido a ondas de spin

Correlações AF

$$C_{nn}(r) = \left| \left\langle \vec{S}_r \cdot \vec{S}_{r+\delta} \right\rangle \right|$$



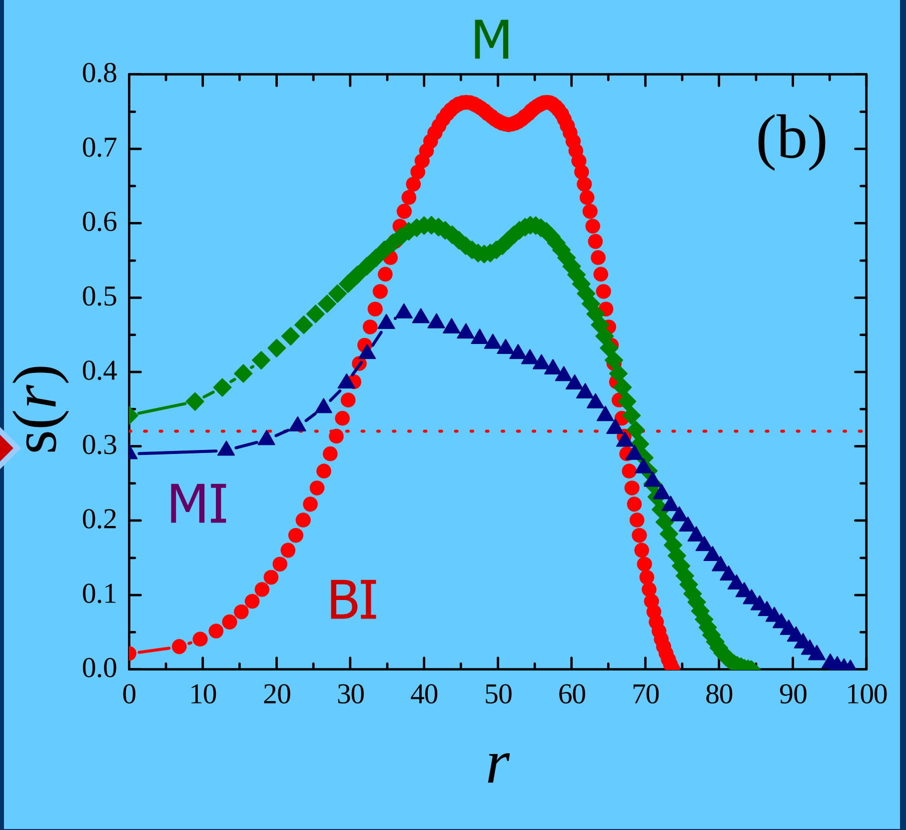


Observando AF

S/N=0.65 k_B N=1.3x10^6 U/t=8

Mesmo quando a entropia total por sítio está acima da entropia crítica para observar AF no sistema homogêneo, a entropia no centro da armadilha pode estar abaixo de

s_{Neel}~0.3k_B



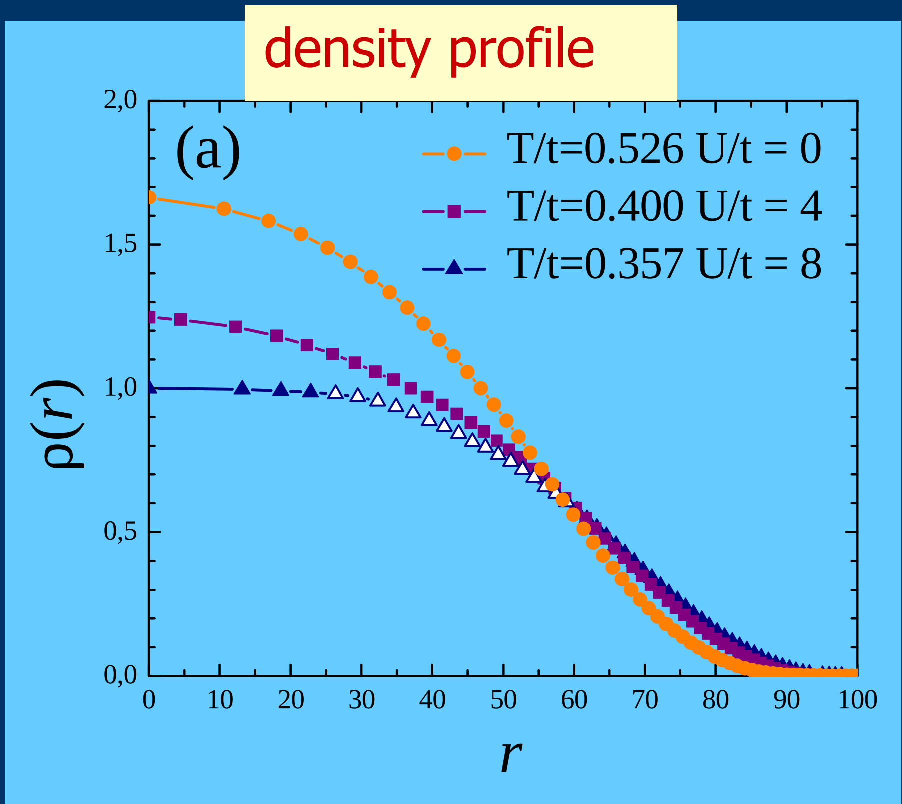
$$\kappa = -\frac{1}{m\omega^2 r}\frac{d\rho}{dr} = -\frac{1}{2\alpha r}\frac{d\rho}{dr}$$

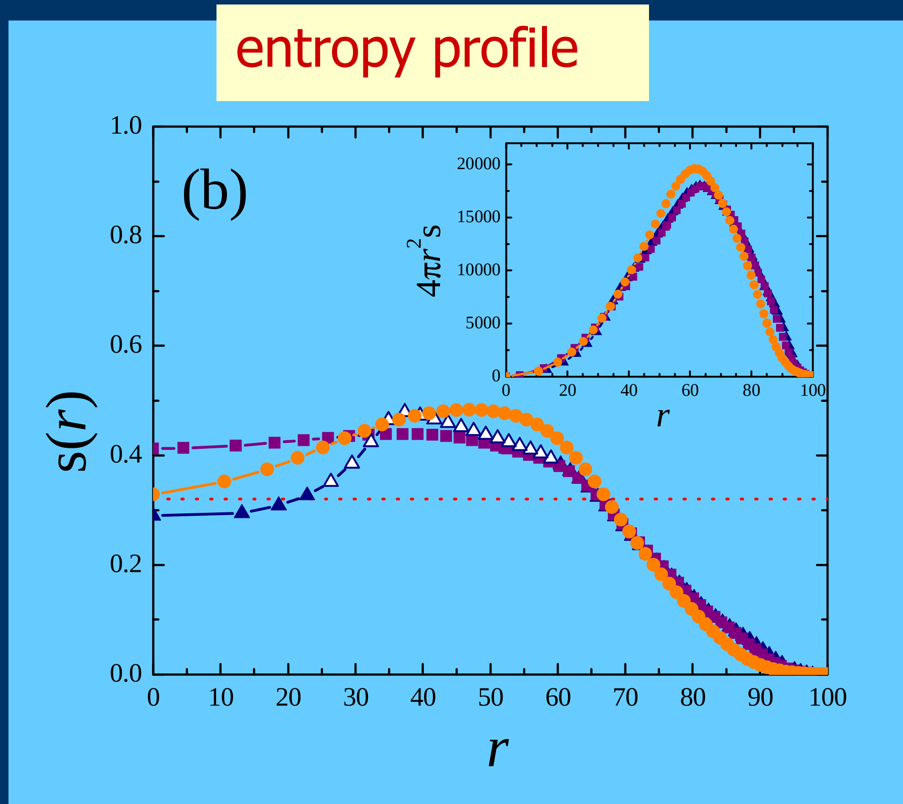
Resfriar aumentando U com S/N fixo na armadilha

$S/N = 0.65\ k_B$ $N = 1.3\times10^6$

$\alpha_t = 0.00115t$ $E_t/t = 3.28$

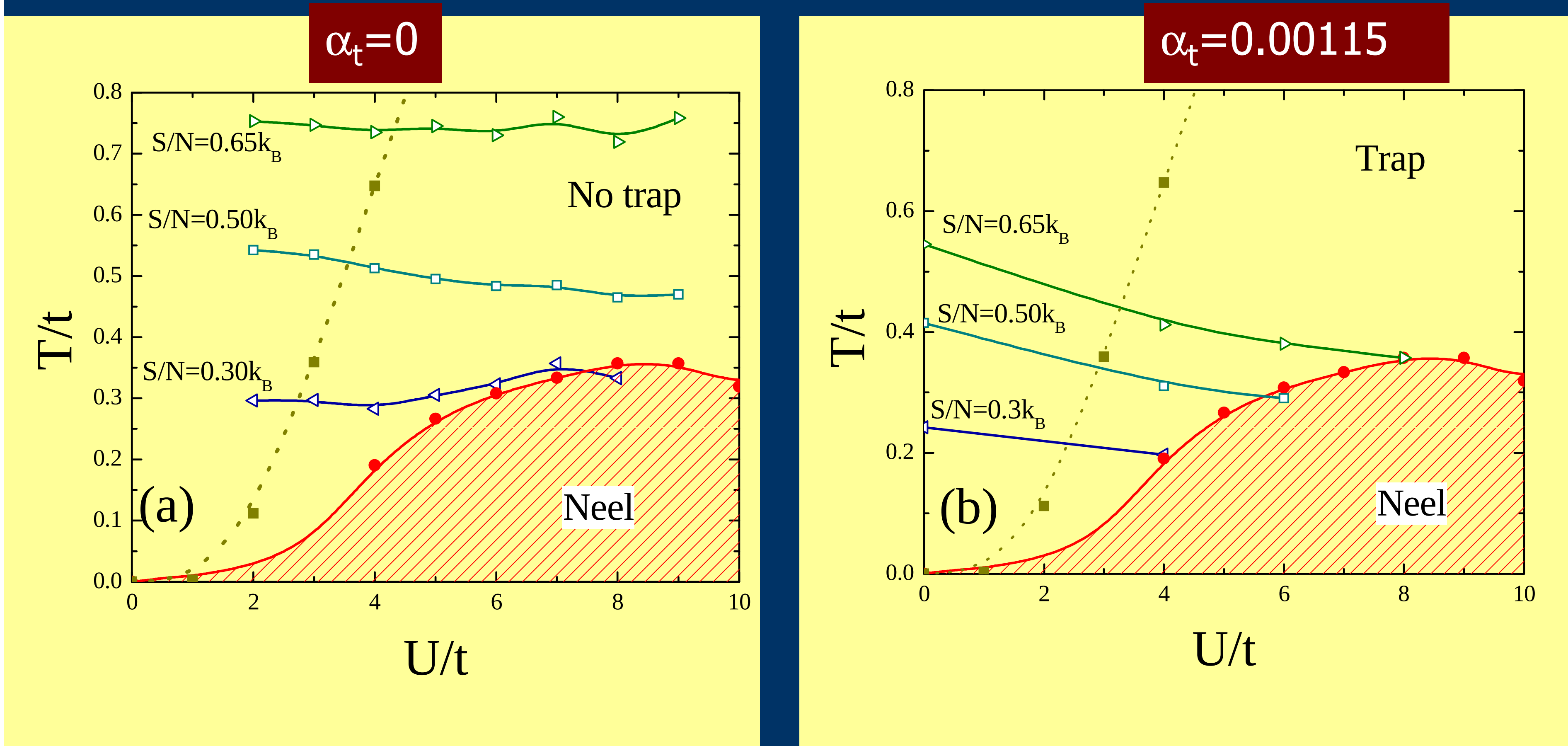
$$S = 4\pi \int r^2 dr s(r)$$





Quando U aumenta a nuvem expande e a tempereatura cai

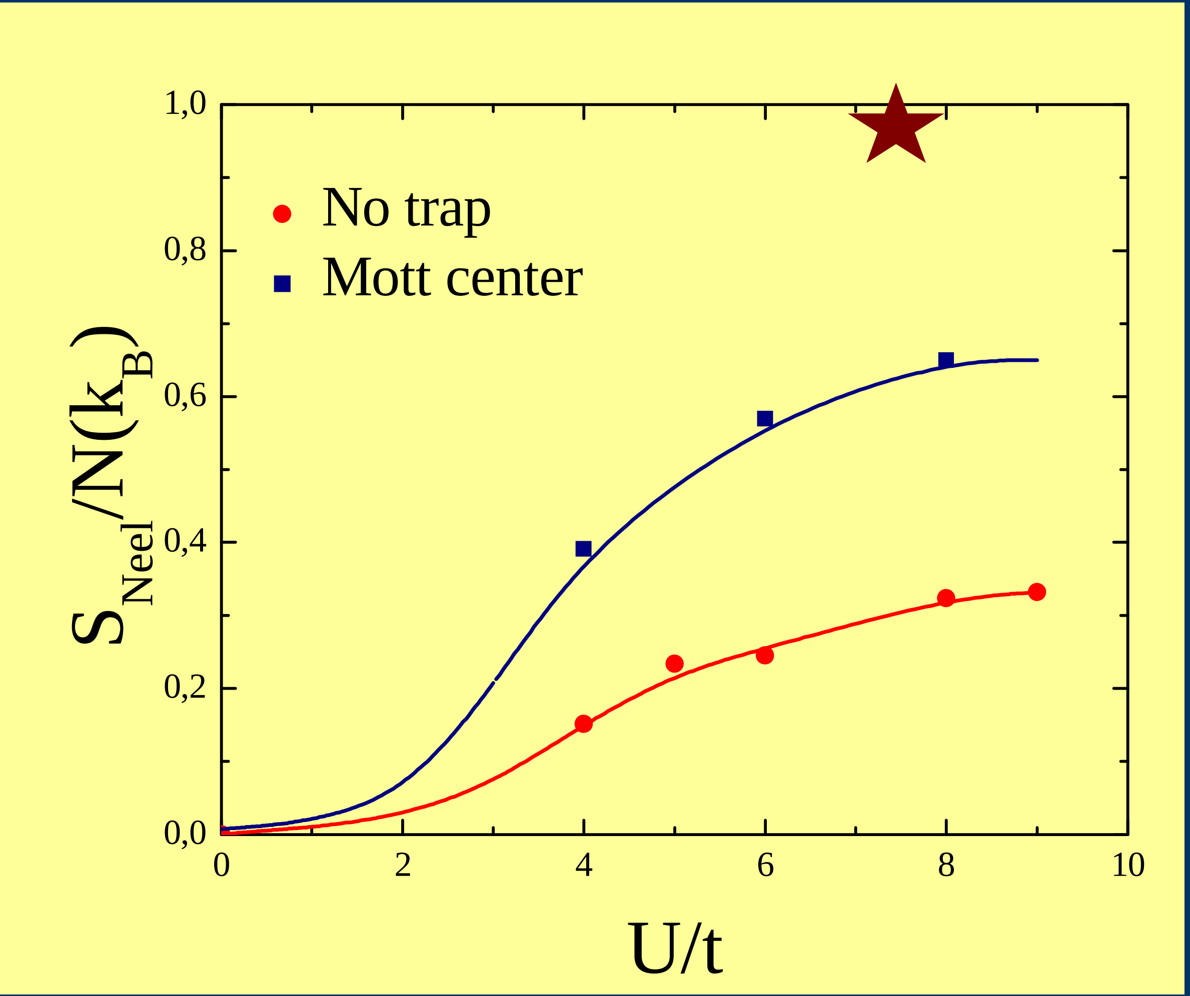
Restrições para a entropia



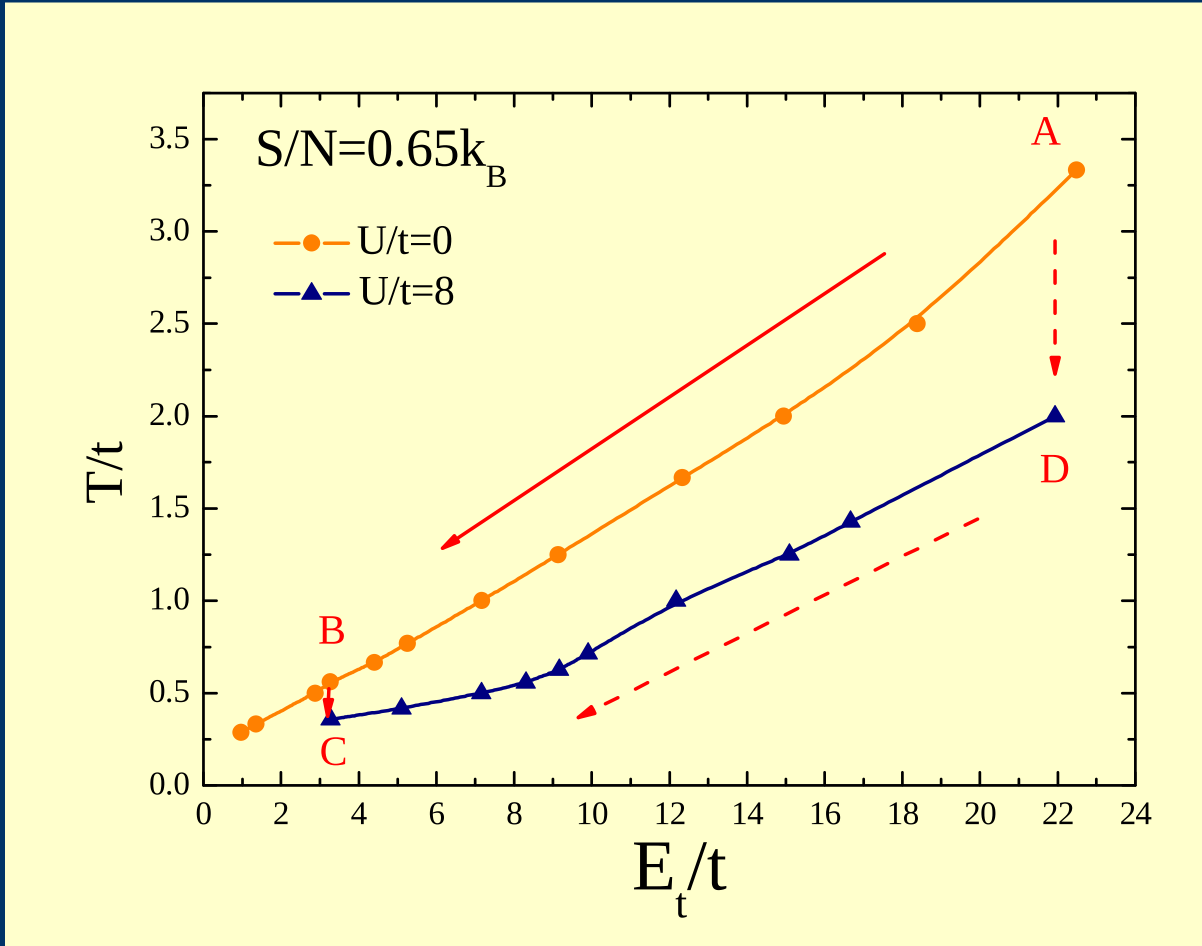
Isentropica ~ isoterma

Isentropica → resfriamento Pomeranchuck

Restrições para a entropia



Protocolo



Parâmetros ótimos

U/t =8

S/Nk_B=0.65

Resfriar descomprimindo a armadilha

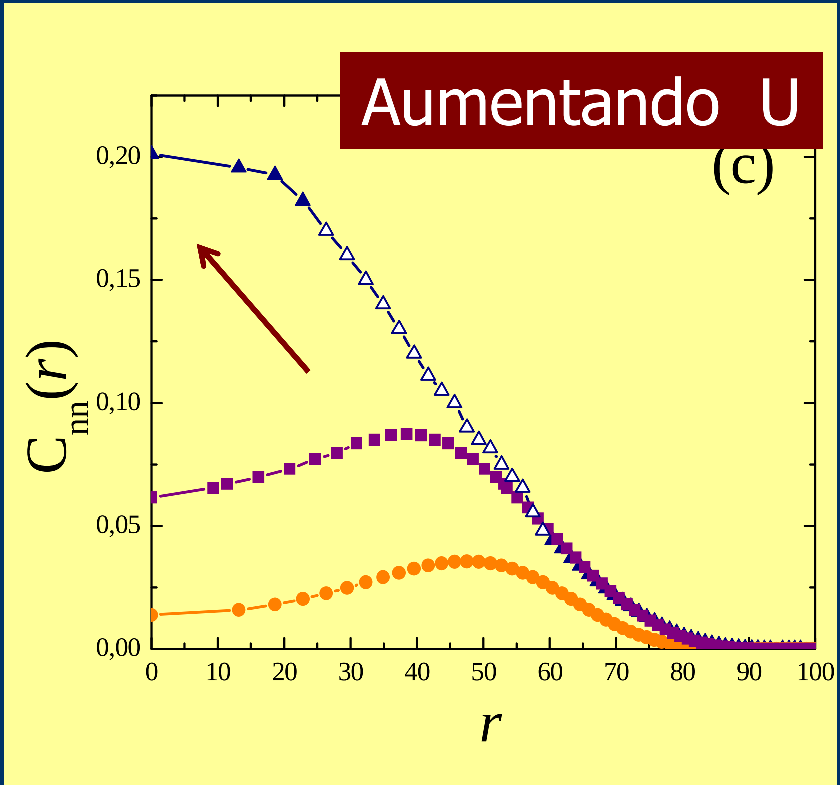
Resfriar aumentando U

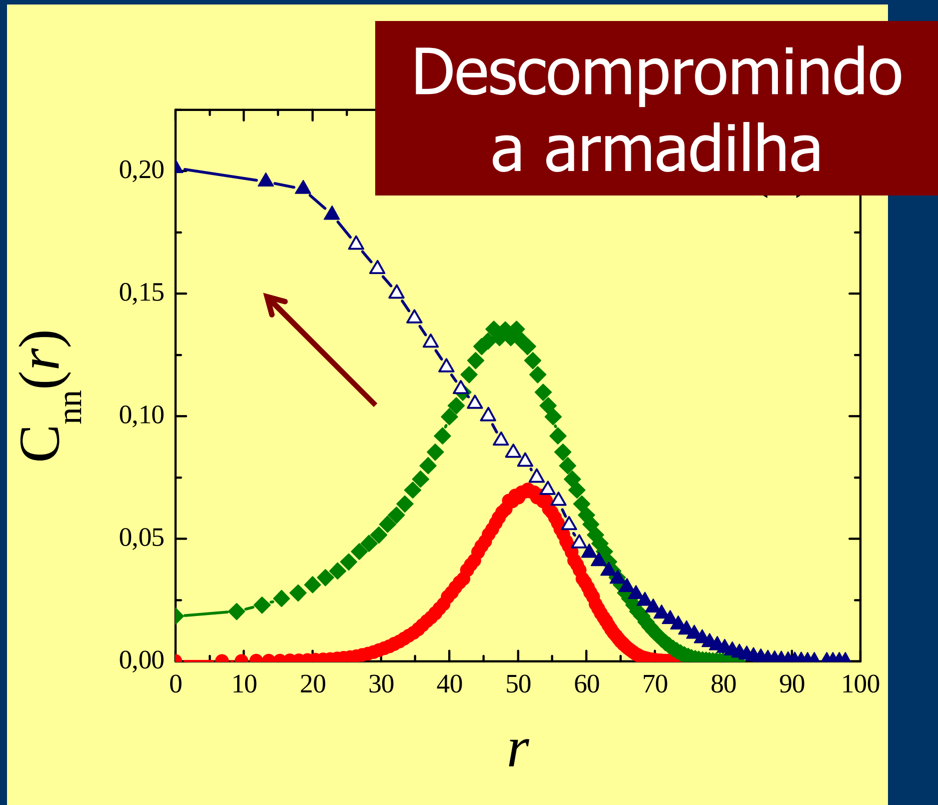
$$\frac{E_t}{t} = \frac{\alpha_t}{t}\left(\frac{3N}{8\pi}\right)^{\frac{2}{3}}$$

Dimensionless compression

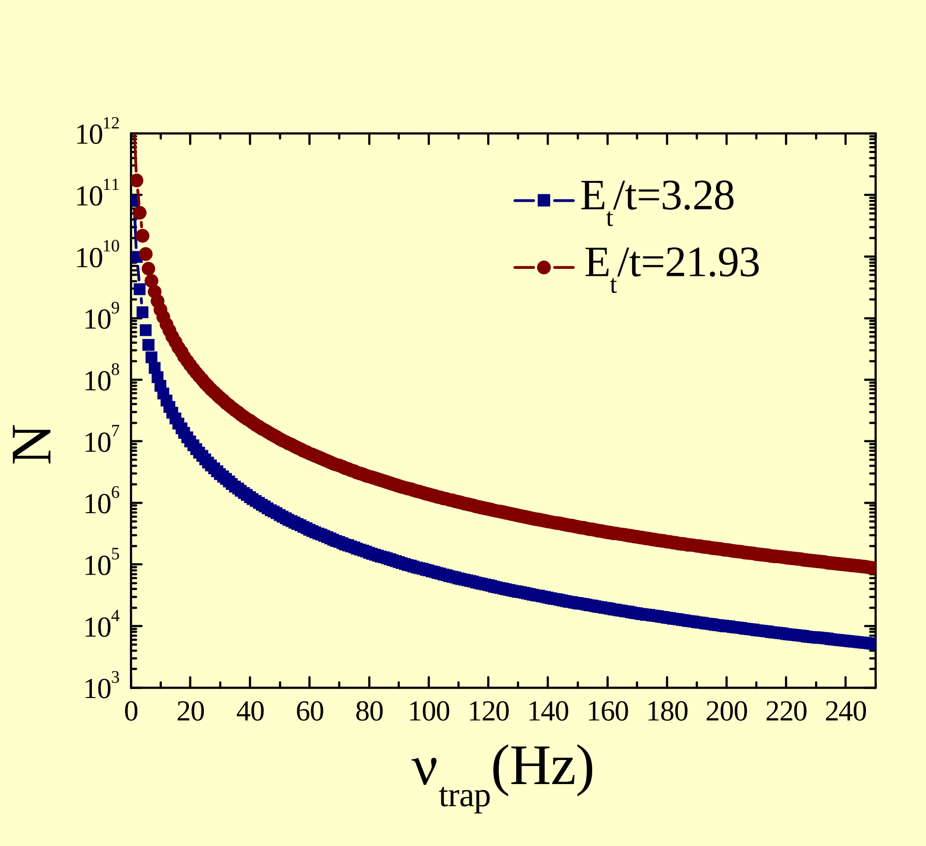
Aumento das correlações antiferromagnéticas

$$C_{nn}(r) = \left|\left\langle \vec{S}_r \cdot \vec{S}_{r+\delta} \right\rangle\right|$$





O que dizer aos experimentais?



Experimentos I Bloch

Para observar AF

$S/N=1k_B \Leftrightarrow T_i=0.1\ T_F$

$S/N=0.65k_B \Leftrightarrow T_i=0.06\ T_F$

ν_{trap}=10-120 Hz

ν_{trap}=10-120 Hz

N= 1.5-2.5 x10^5 átomos

N= 10^6 átomos

U/t>8

U/t=8

$$\frac{E_t}{t} = \frac{\alpha_t}{t}\left(\frac{3N}{8\pi}\right)^{\frac{2}{3}}$$

Dimensionless compression

^{40}K

Conclusões

Sistemas armadilhados são bastante diferentes do sistema homogêneo

Resfriamento Pomeranchuk

$S/N^{Neel}_{trap} > S/N^{Neel}_{homogeneous}$

Para observar antiferromagnetismo

$S/N \sim 1k_B \Leftrightarrow T_i = 0.1\ T_F$

$N = 10^5$ átomos

$U/t > 8$

$S/N = 0.65k_B \Leftrightarrow T_i = 0.06\ T_F$

$N = 10^6$ átomos

$U/t = 8$

Agradecimentos

CNPq

FAPERJ
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Ohio Supercomputer Center

Em busca de estudantes e pós-docs!

tclp@if.ufrj.br