

Estatísticas Quânticas

(o jogo da cadeira)



A perda de identidade

partículas diferentes: **electrão / protão**

partículas idênticas: **todos os electrões são iguais!**



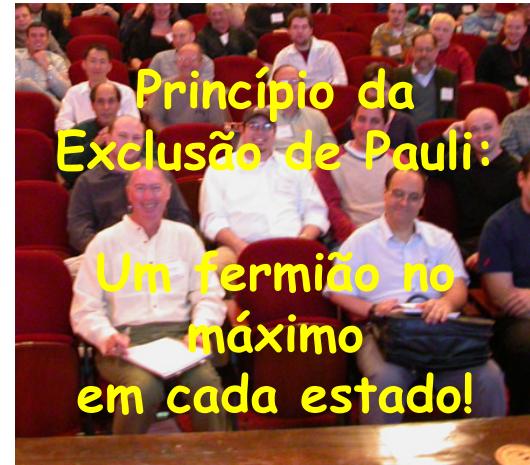
a mesma “configuração” !

~~partícula A no estado Ψ~~

estado Ψ com ou sem partículas

partículas indistinguíveis

2 famílias de partículas idênticas



Bosões

fotões,
 ^4He ,
etc

Conjunto par
de fermiões

spin inteiro!

Fermiões

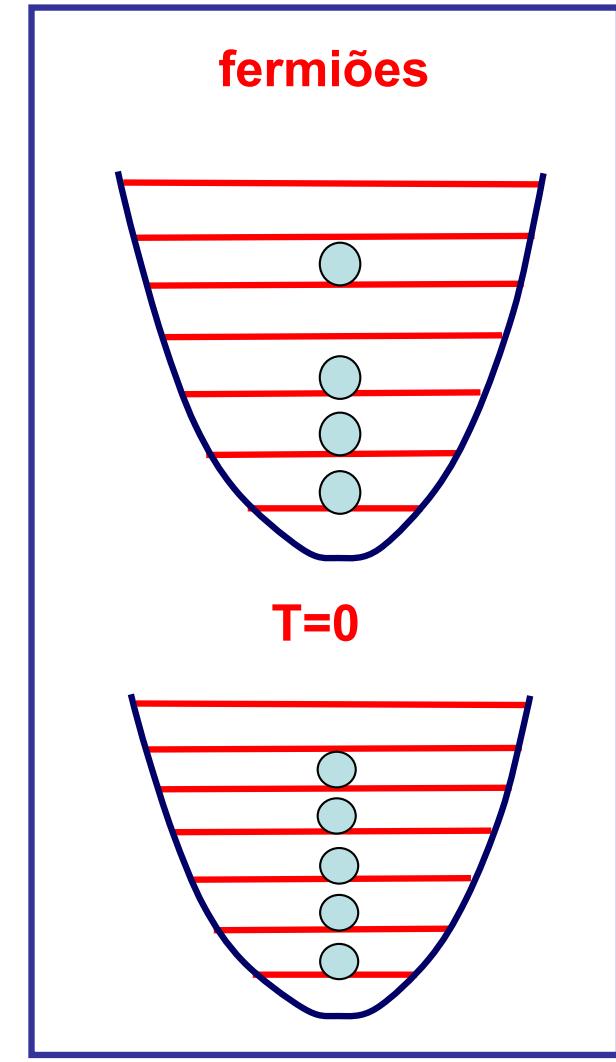
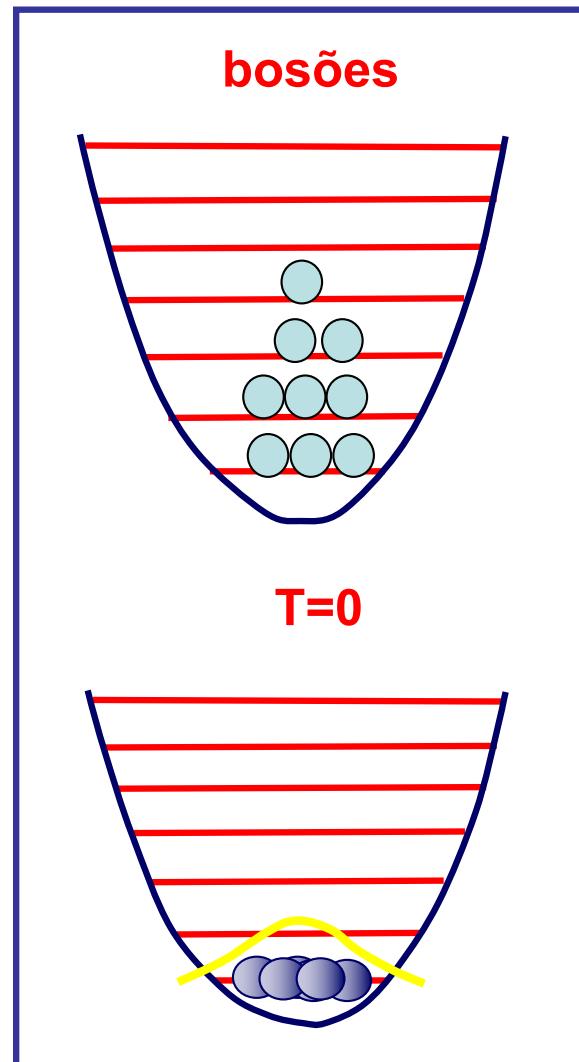
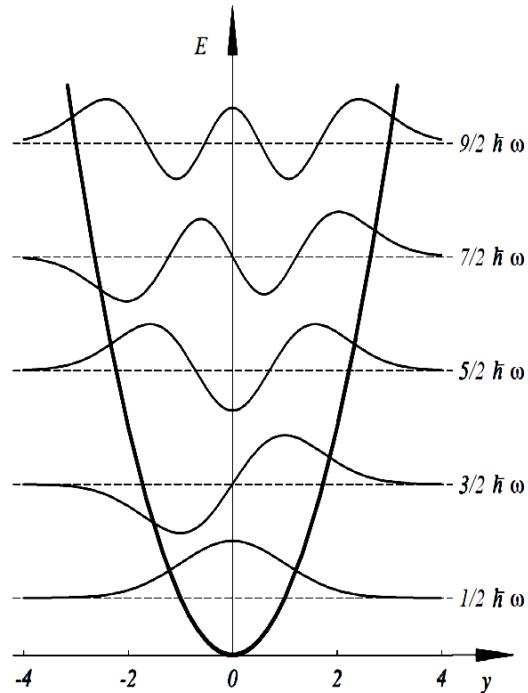
Electrão
Neutrão
protão

Conjunto ímpar
de fermiões

spin semi-inteiro!

partículas indistinguíveis

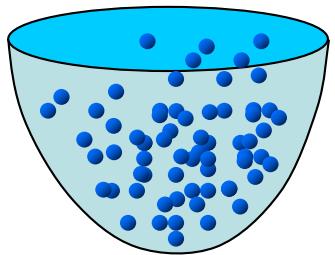
N partículas num
potencial harmônico



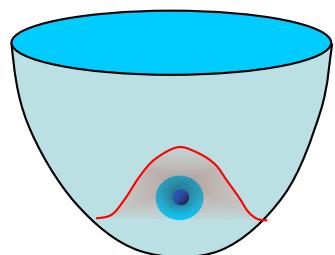
Condensação de Bose-Einstein (BEC)

CONDENSADO DE BOSE-EINSTEIN

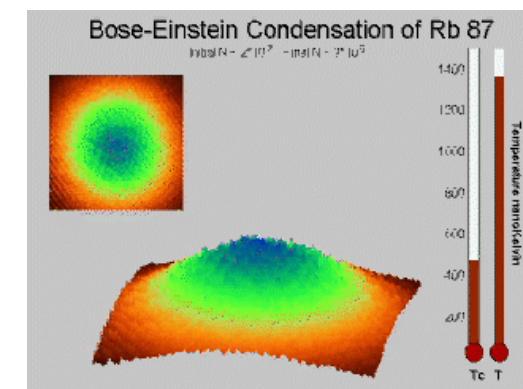
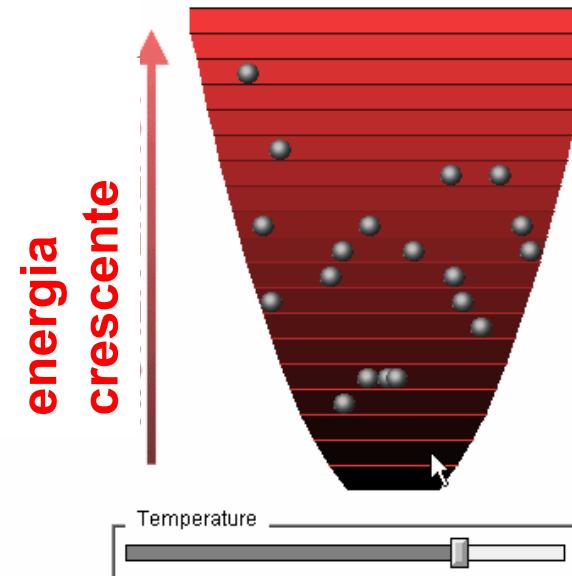
gás rarefeito confinado
(Rb, Na, Li)



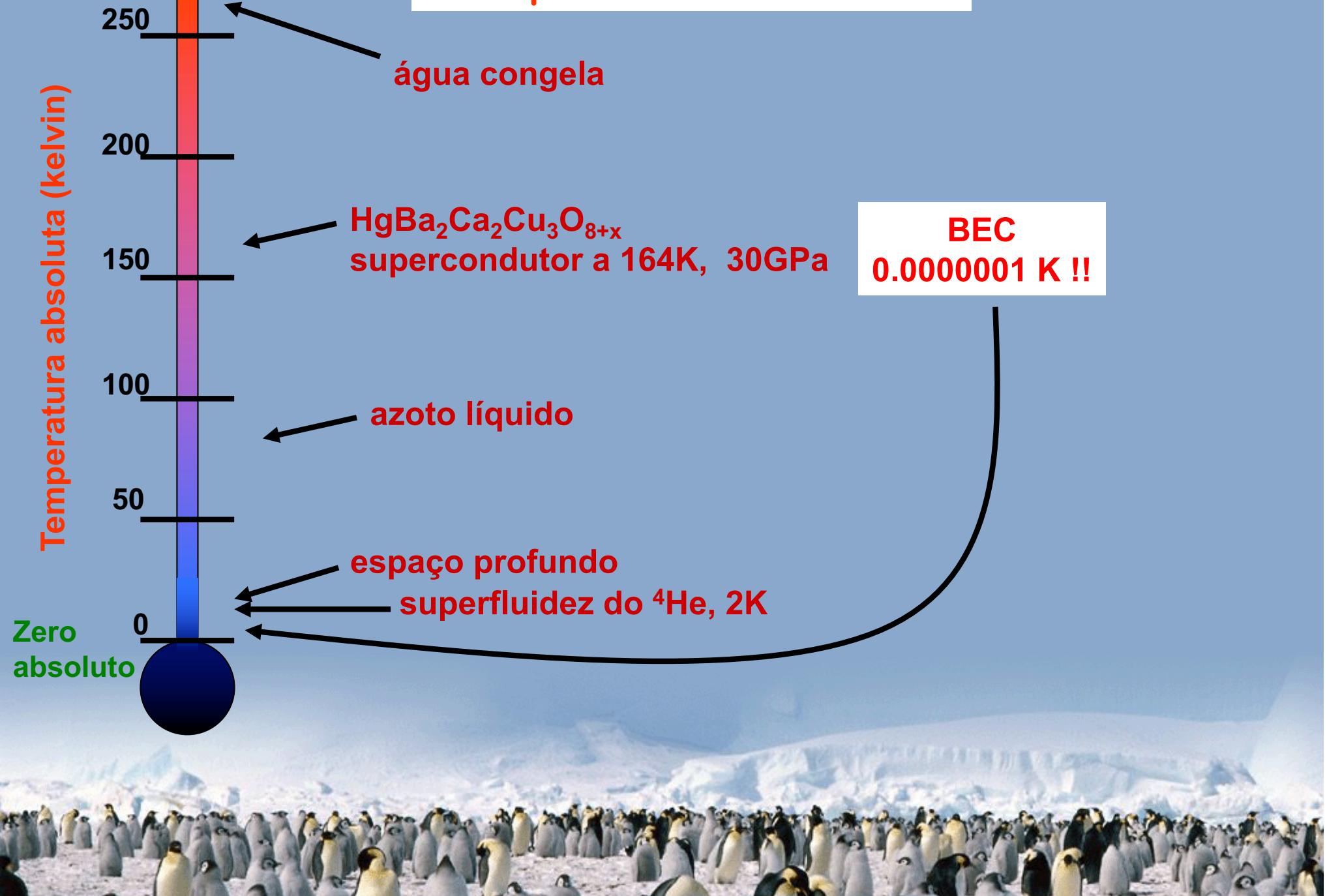
↓ Temperatura



“super-átomo”
no mesmo “volume”
que um átomo ocupa



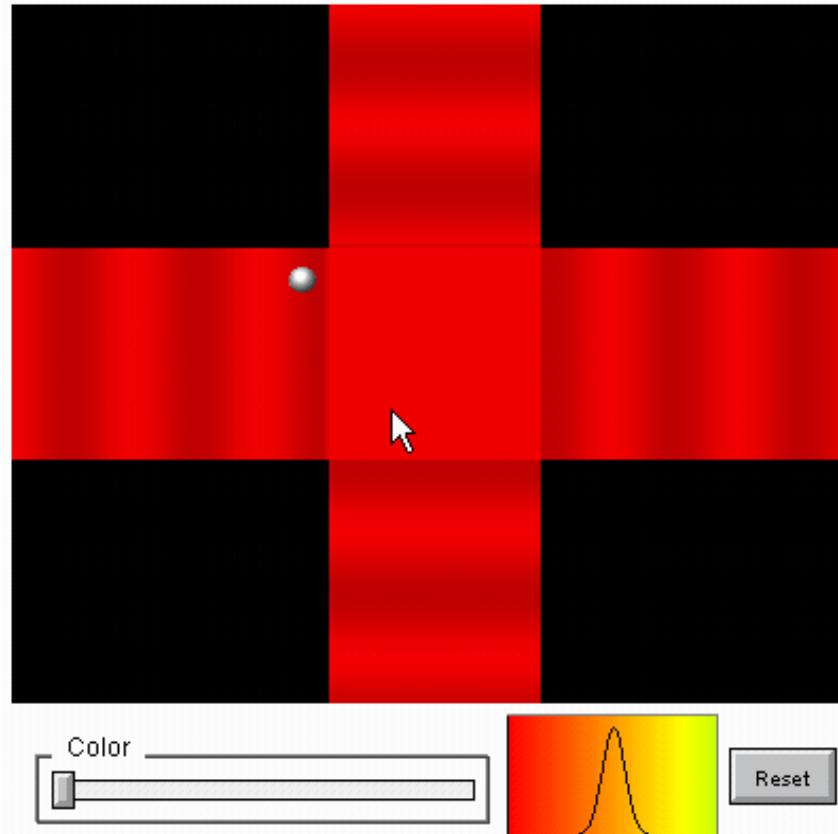
Temperaturas baixas?



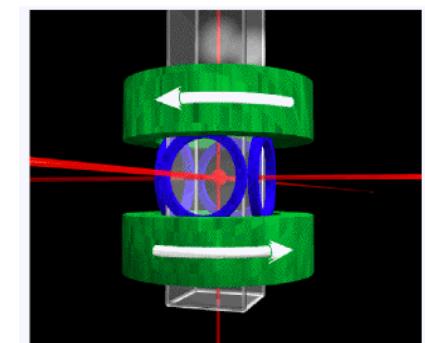
A wide-angle photograph of a massive colony of Emperor penguins. In the foreground, numerous penguins are standing on a light-colored, sandy or snow-covered ground. They are facing various directions, some looking towards the camera while others are in profile. Behind them, a range of snow-capped mountains rises against a clear blue sky. The scene is captured from a low angle, emphasizing the vastness of the colony and the surrounding environment.

como o fizeram?

arrefecimento por lasers



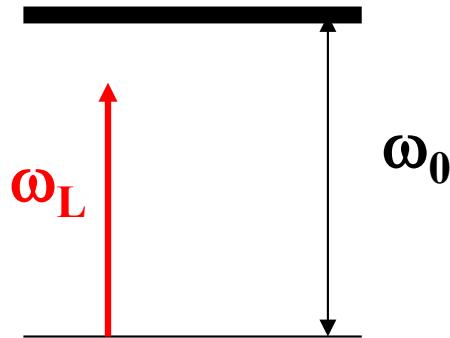
$T_f \sim .1 \text{ mK}$
 $N_f \sim 10^9 \text{ atomos}$



lasers e efeito Doppler

ω_L frequência do laser

ω_0 frequência de absorção



Efeito Doppler



$$\omega_L + kv$$



Ref LAB

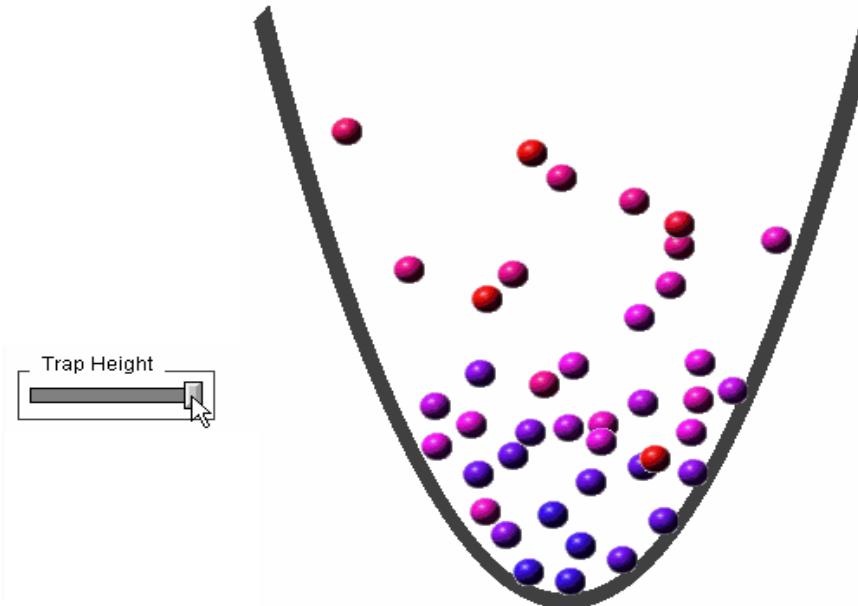
$$\omega_L - kv$$

Ref átomo

Absorção do fotão $\omega_L + kv$, e reemissão equiprovável em duas direcções opostas

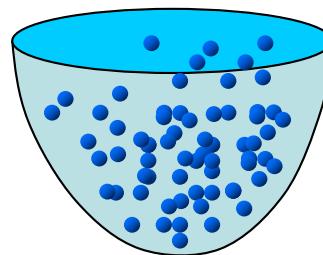
$$\longrightarrow F = -\alpha v \text{ (viscosidade)}$$

Como arrefecer a 0.0000001K? Por evaporação!

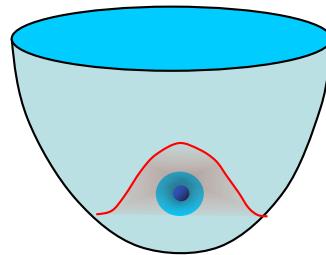


O QUE É UM CONDENSADO DE BOSE-EINSTEIN?

gás rarefeito confinado
(Rb, Na, Li)



condensado de
Bose-Einstein



↓
Temperatura

“super-átomo”
no mesmo “volume”
que um átomo ocupa

O papel de Einstein



4to40.com



1924—Bose descreve
o comportamento dos
fotões

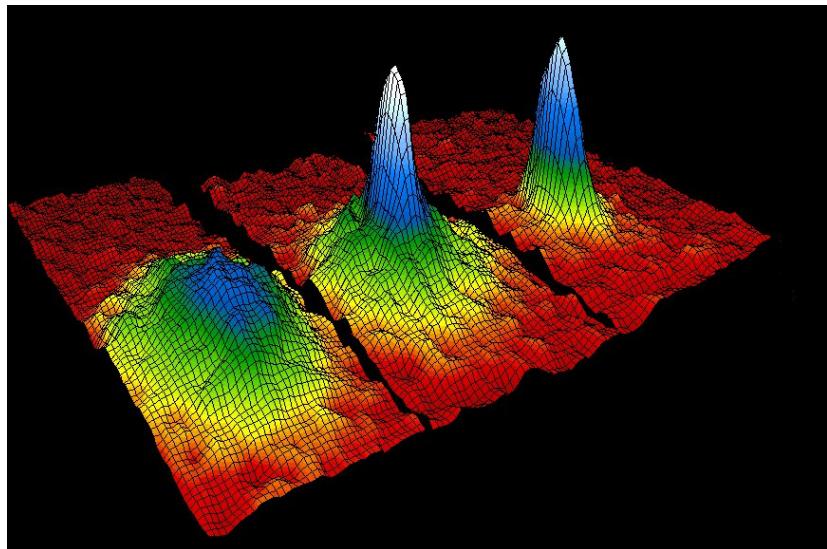
Einstein traduz para alemão e
acrescenta uma nota final



envia a Einstein,
após recusa da Philos. Mag.

Os primeiros condensados em 1995

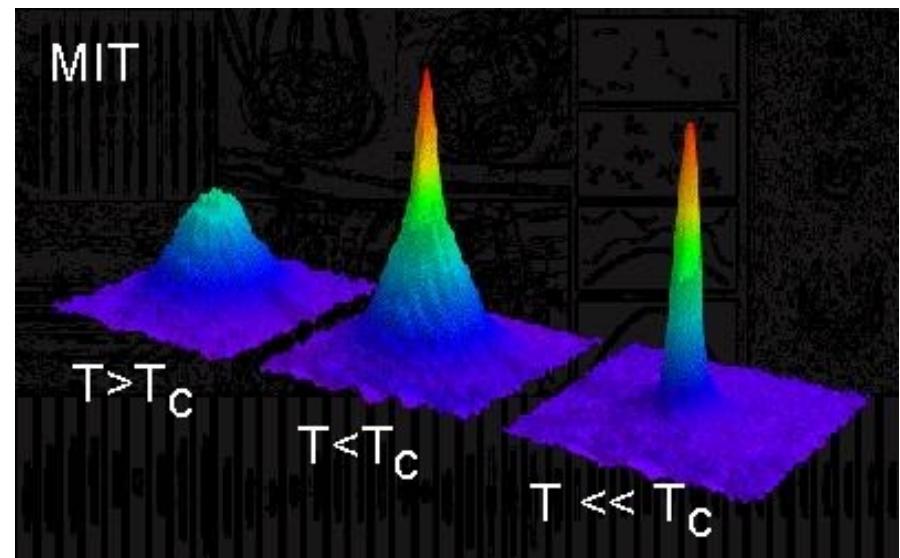
$T_c \sim 0,0000001 \text{ K}!$



Rubidio

C. Wieman e E. Cornell

Boulder, Colorado



Sódio

W. Ketterle

MIT

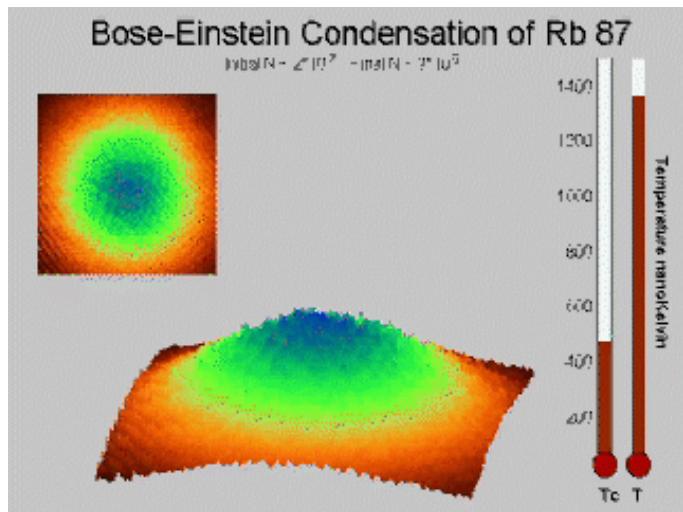
Prémio Nobel para a condensação de Bose-Einstein



Prémio Nobel da Física 2001 atribuído a
E. Cornell, W. Ketterle e C. Wieman



"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"



$T > T_c$

Distribuição gaussiana

$T < T_c$

pico no estado fundamental

BEC nos metais alcalinos ^{87}Rb , ^{23}Na , ^7Li :

- bosões (n° par de protões+neutrões+electrões).
- cada átomo tem um pequeno momento magnético (permite arrefecimento magnético).
- os átomos têm uma pequena interacção repulsiva e consequentemente não liquidificam nem solidificam até uma temperatura muito baixa.

Prémio Nobel para o arrefecimento de átomos

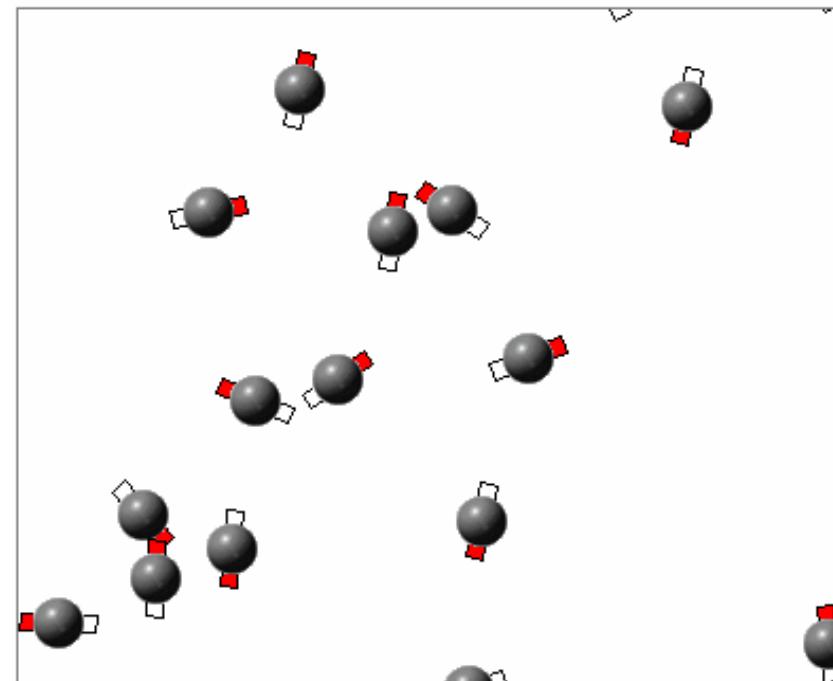
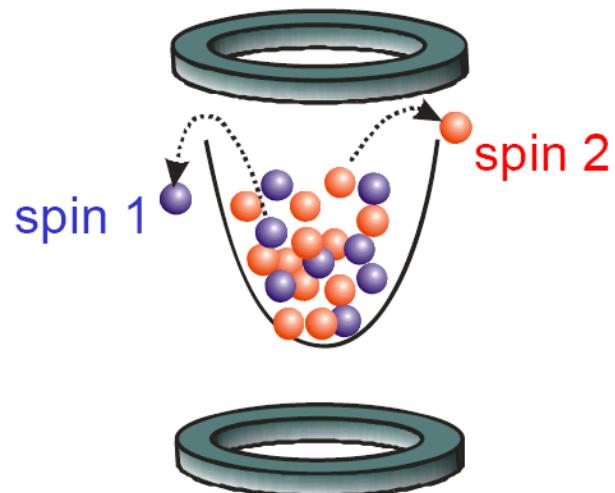
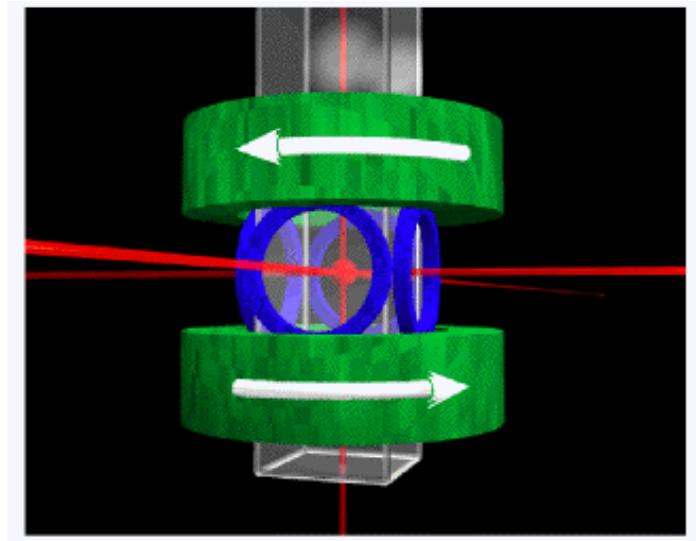


Prémio Nobel da Física 1997 atribuído a
W. Phillips, S. Chu e C. Cohen-Tannoudji

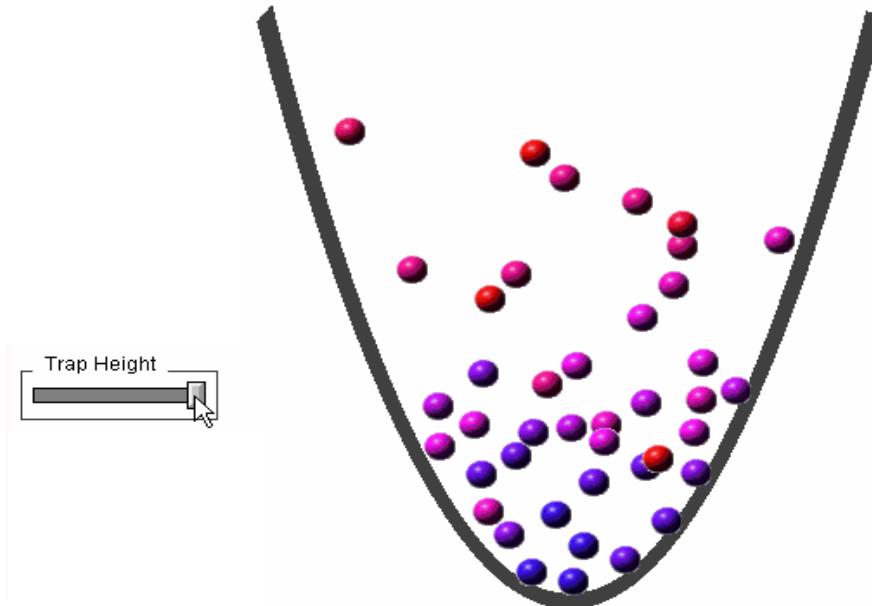
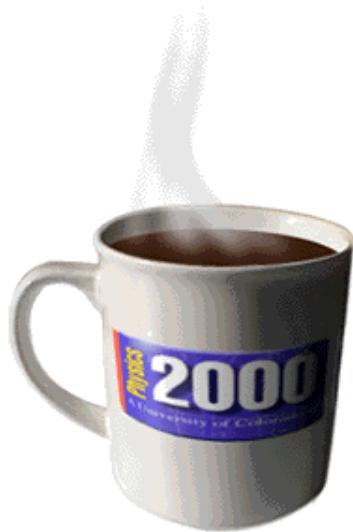


"for development of methods to cool and trap atoms with laser light"

Como arrefecer a 0.000001K? 1º) garrafa thermos magnética



Como arrefecer a 0.0000001K? 2º) por evaporação!



$$N \rightarrow N/20$$

$$T \rightarrow T/100$$

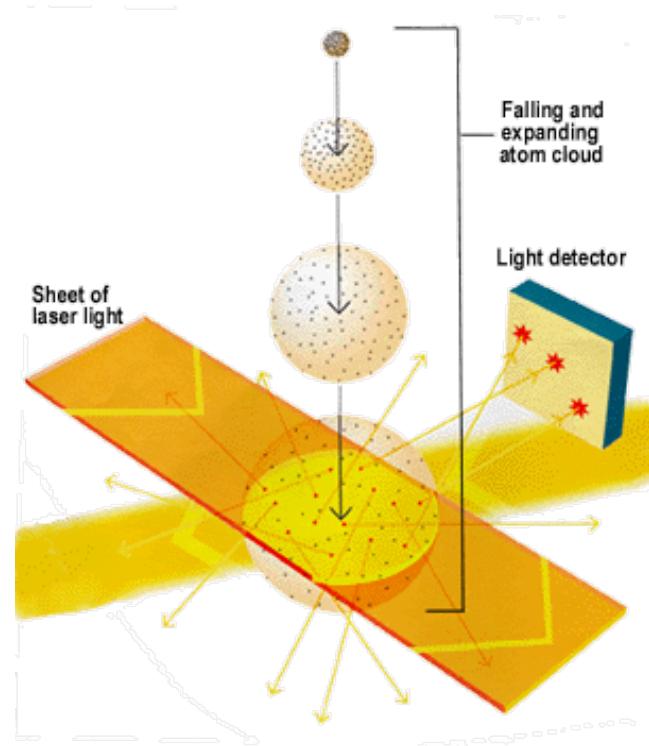
$$d \sim 100 \lambda \rightarrow d \sim \lambda$$

Duração : 1 a 100 segundos,

$N_f = 10^5$ a 10^7 átomos,

$T_f = 0.2$ a $2 \mu\text{K}$

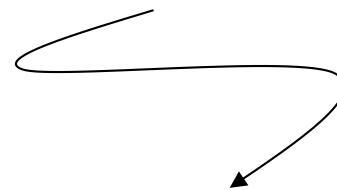
Observação do condensado e medição da temperatura



desliga-se o campo e a nuvem de átomos expande-se

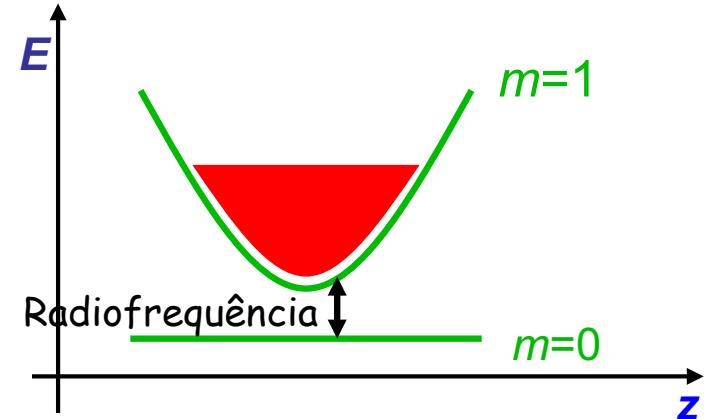
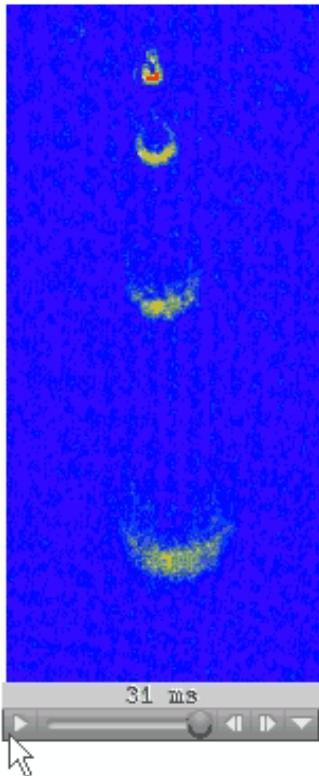


gases mais quentes têm uma distribuição de velocidades mais larga e expandem-se mais depressa



medindo-se o tamanho da nuvem após um certo tempo, determina-se a temperatura

Aplicações

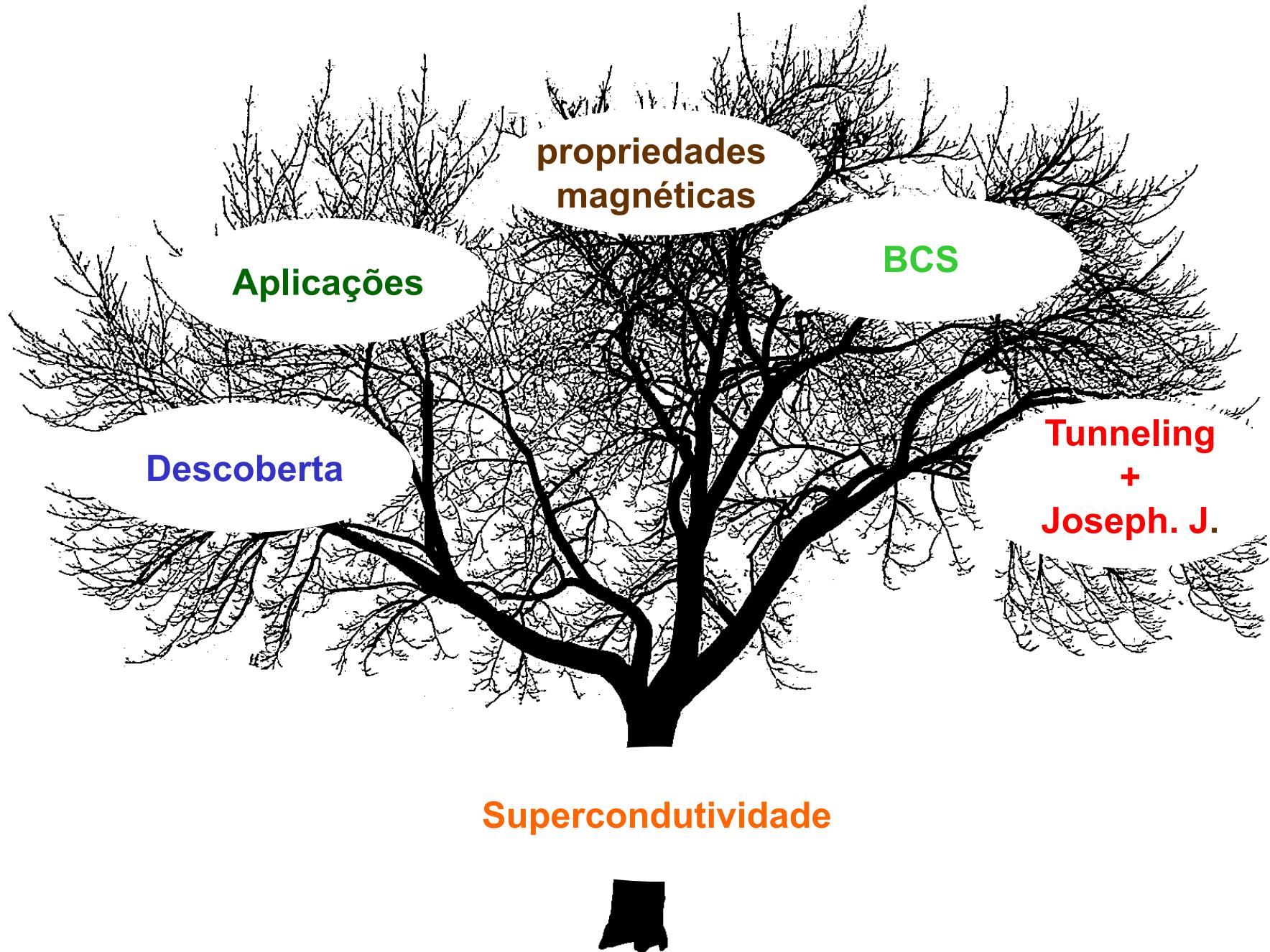


Laser atómico

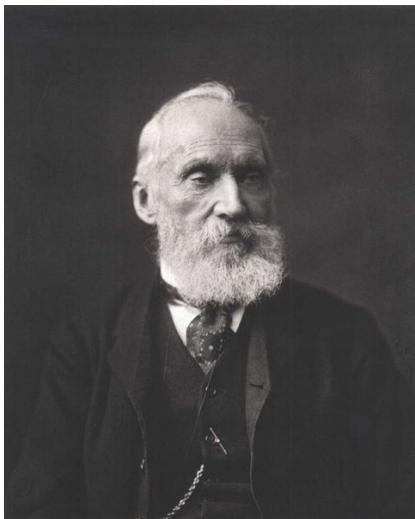
- Laser de luz: todos os fotões têm exactamente a mesma cor, direcção e fase .
- Laser de átomos: todos os átomos são exactamente o mesmo.

A photograph of a dark green, rectangular superconductor levitating above a blue surface with a white wave pattern. The background is a soft-focus green.

supercondutividade



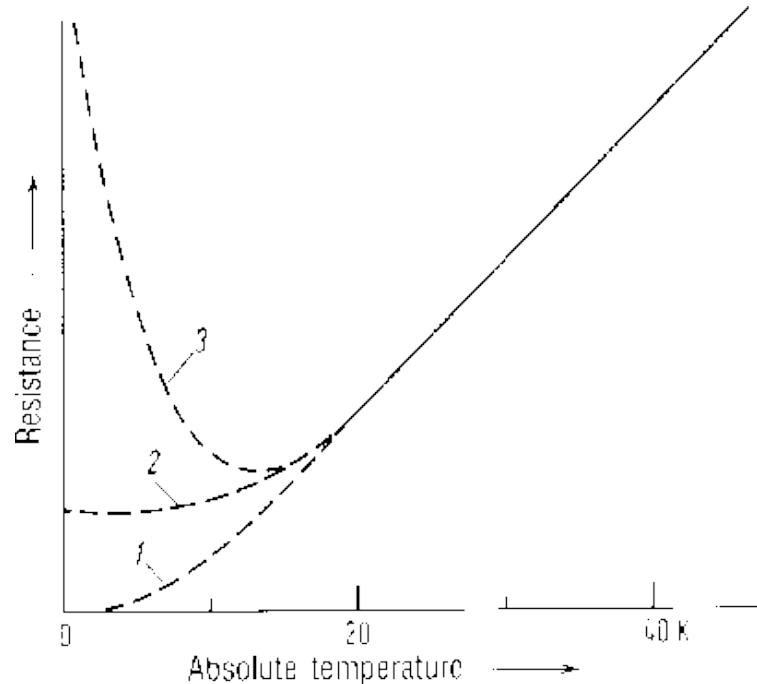
A descoberta da supercondutividade



Lord Kelvin

Electrões congelam a temperatura baixa

Isolador perfeito!



Paul Drude

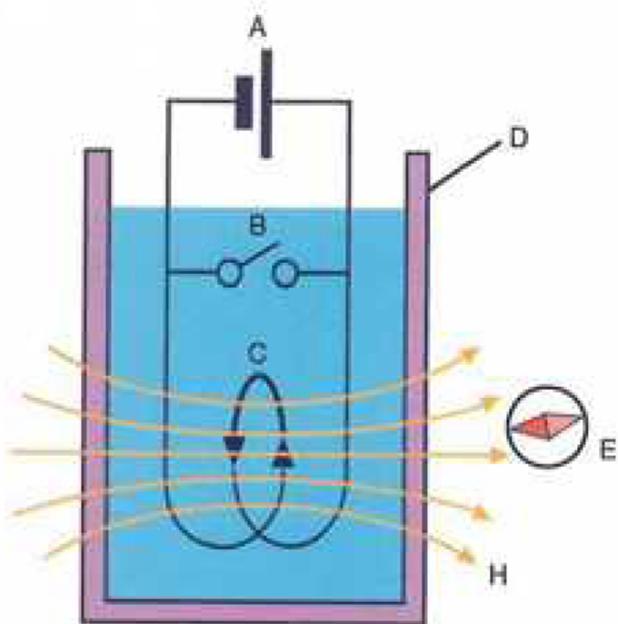
Agitação térmica desaparece

Condutor perfeito!

A descoberta da supercondutividade



Heike Kamerlingh Onnes



Mercúrio $T_c=4.19$ K

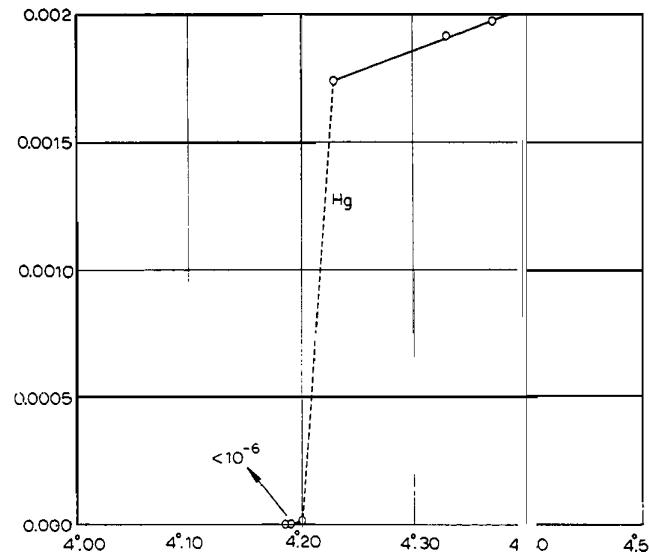
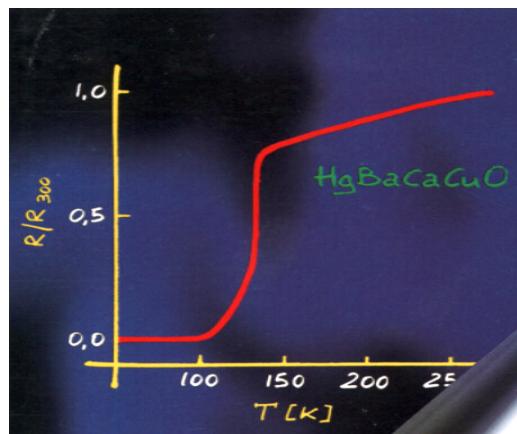


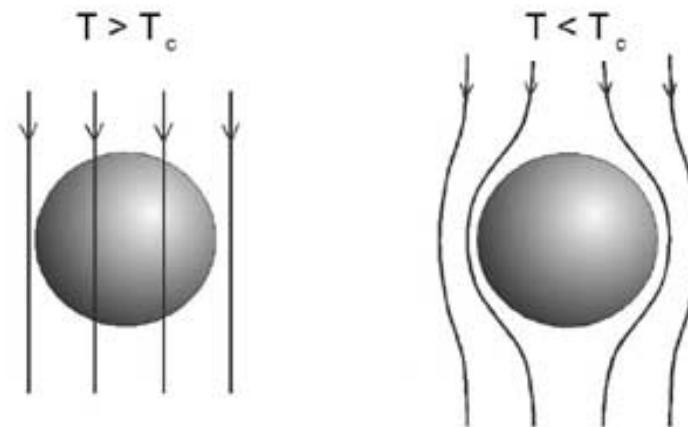
Fig. 17.

propriedades supercondutoras

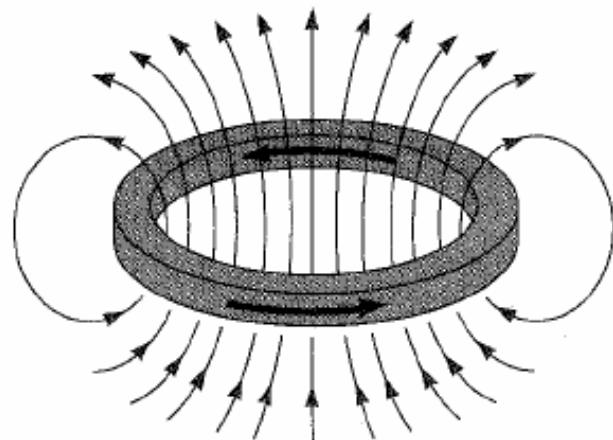
resistividade nula



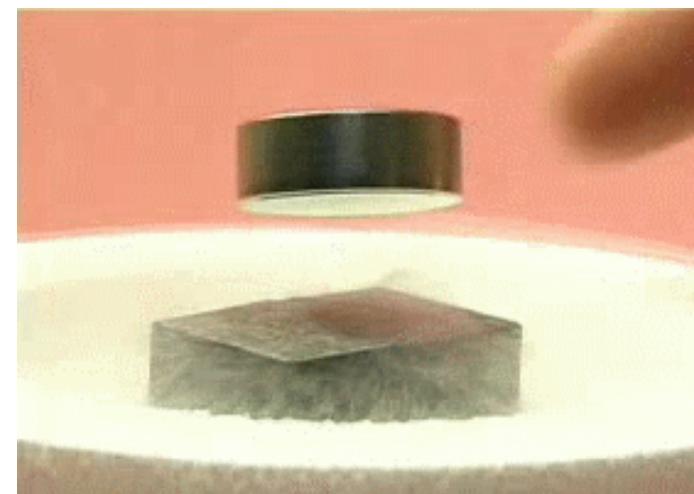
efeito meissner
(diamagnético perfeito)



correntes persistentes



Levitação



Superconductividade

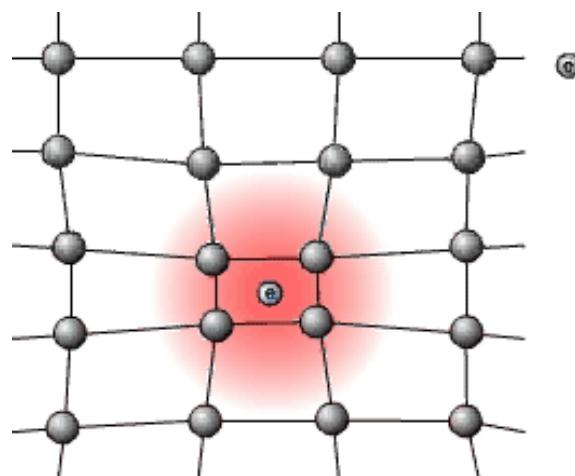
Electrões repelem-se!



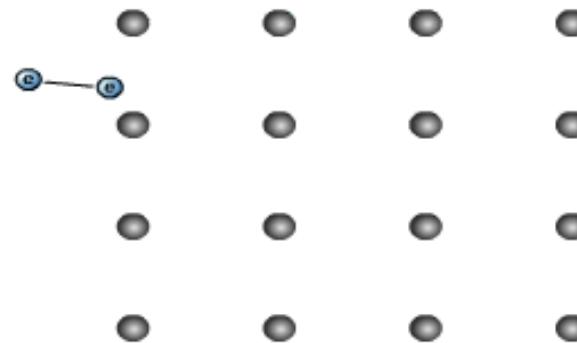
Mas...



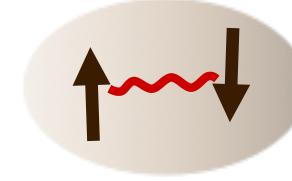
Interacção atractiva efectiva!



Resistividade nula!

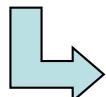


Pares de Cooper

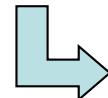


par de electrões $\stackrel{*}{=}$ bosão
(par de Cooper)

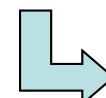
atração entre
fermiões



formação de bosões
(pares de Cooper)

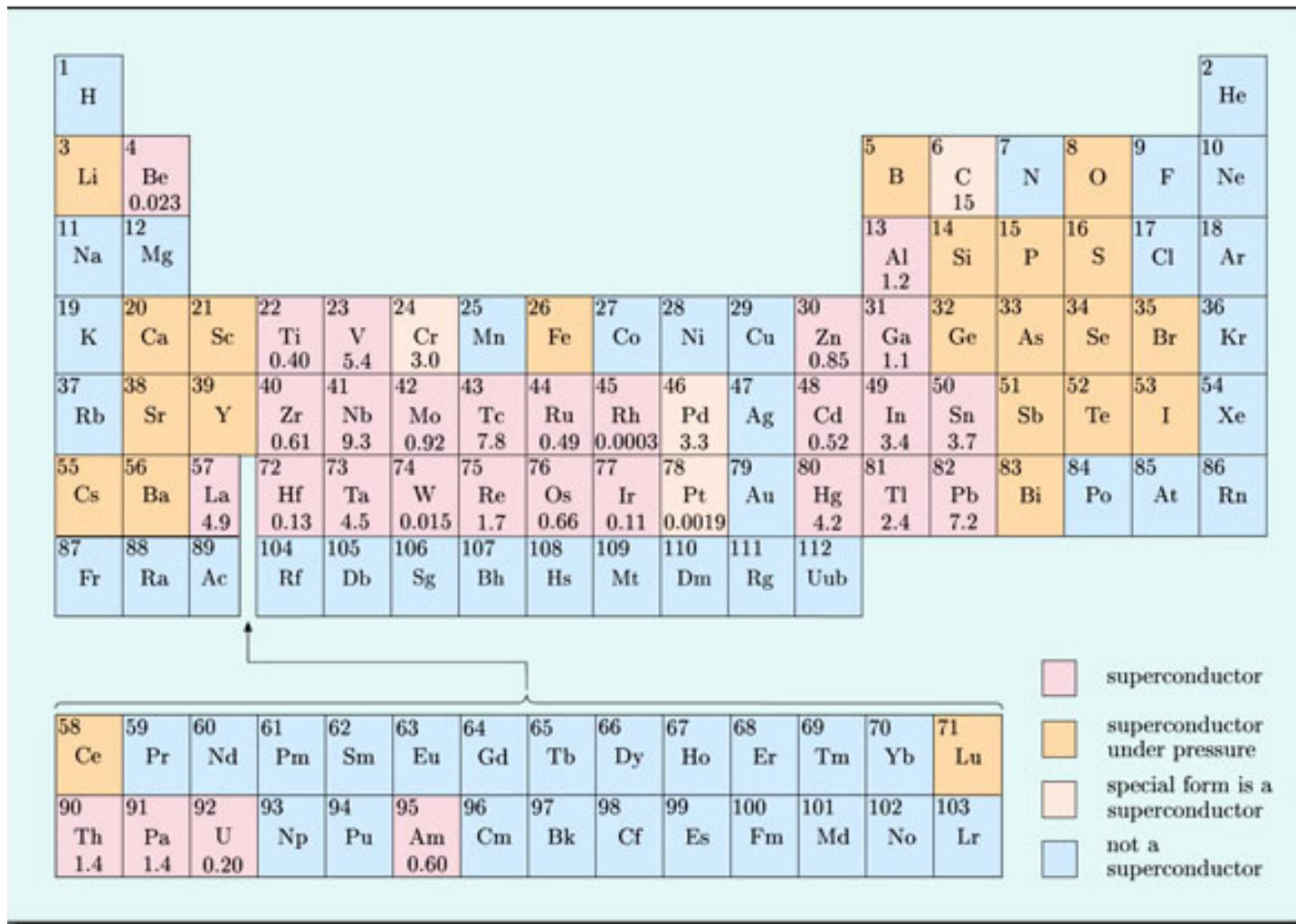


condensação de Bose
destes bosões

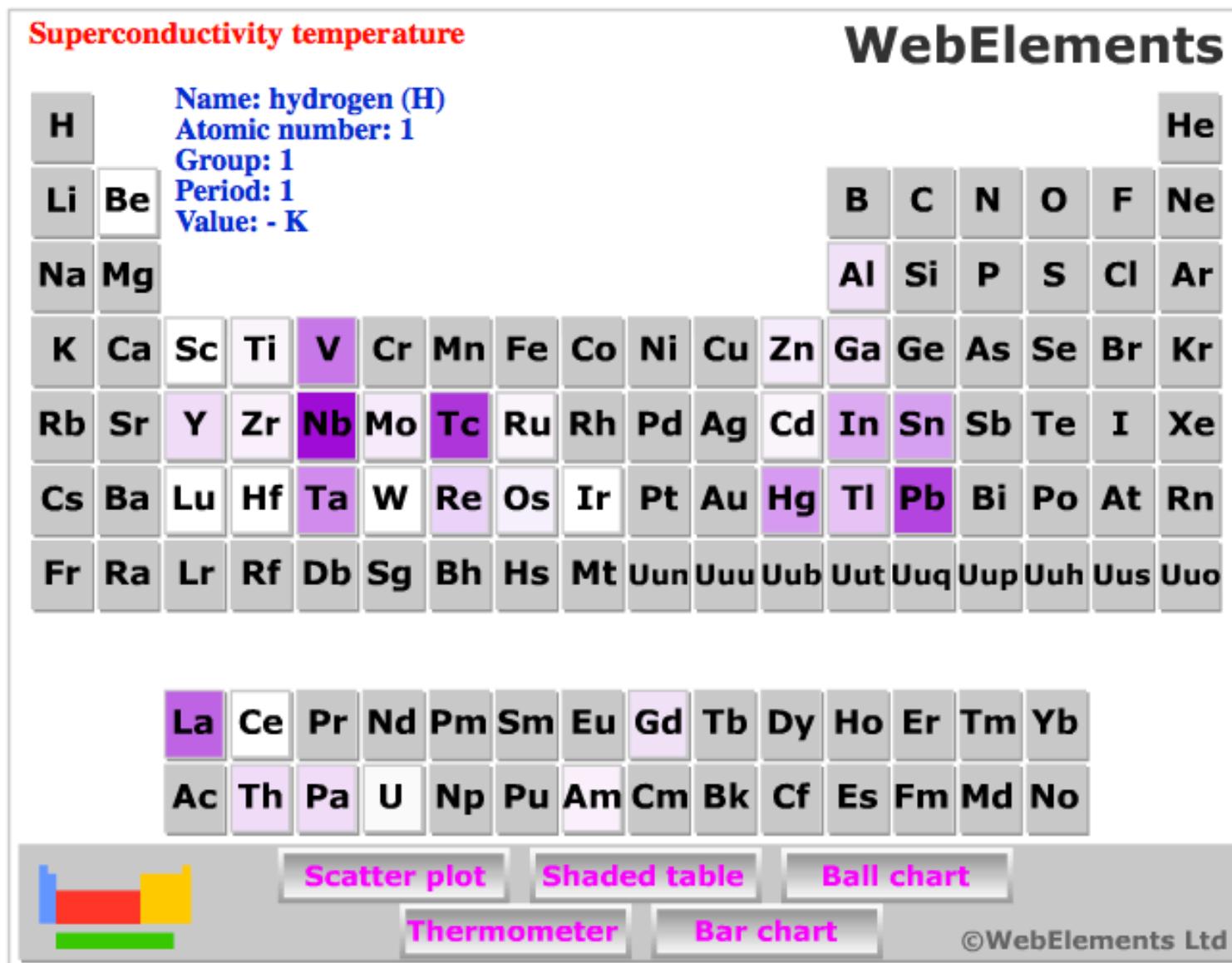


supercondutividade

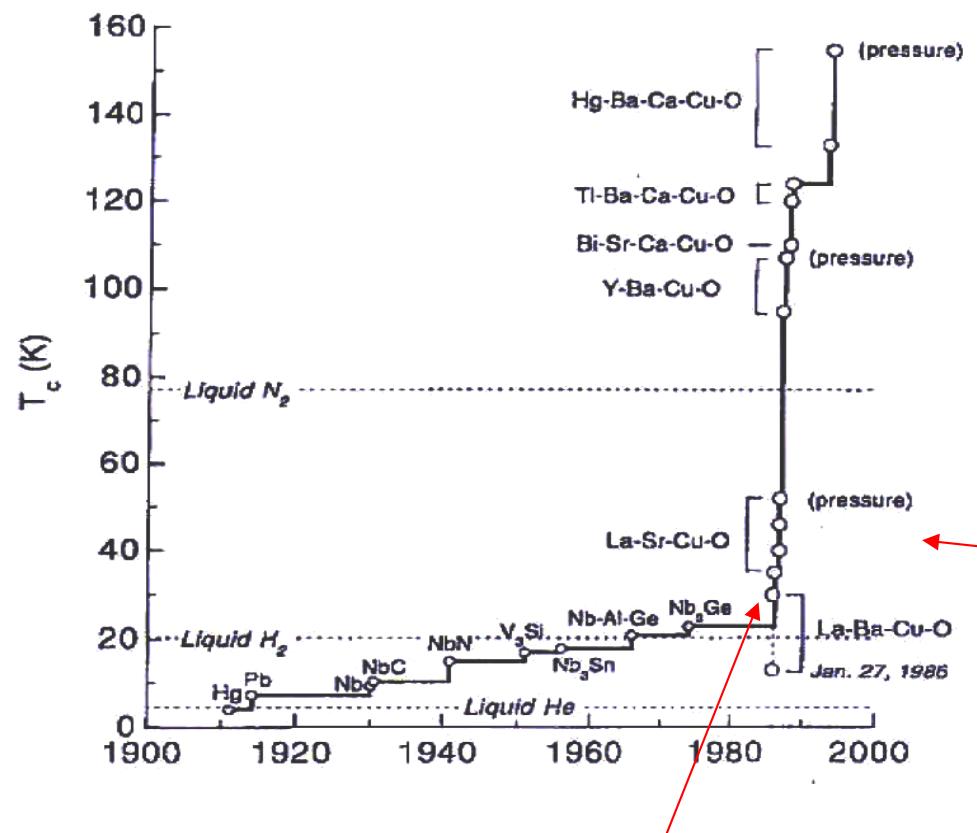
Elementos supercondutores



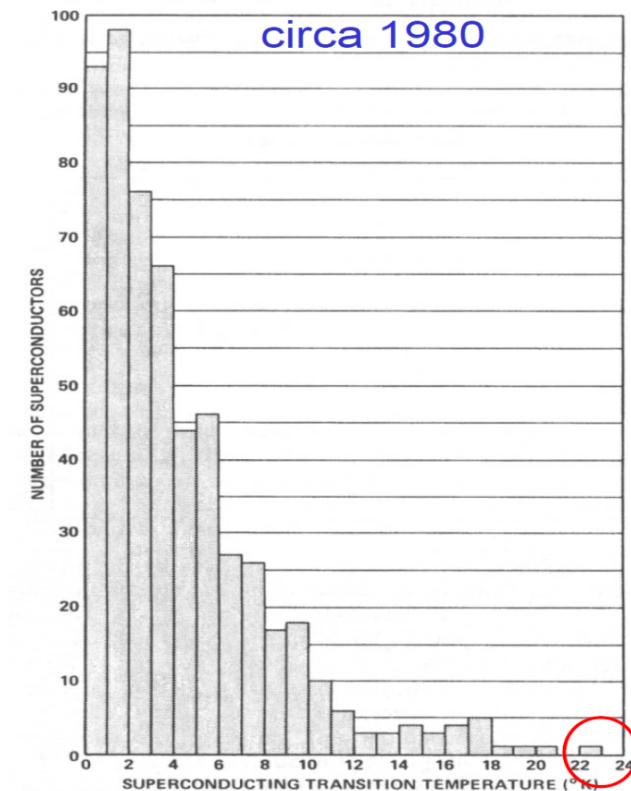
Elementos supercondutores



Temperaturas críticas

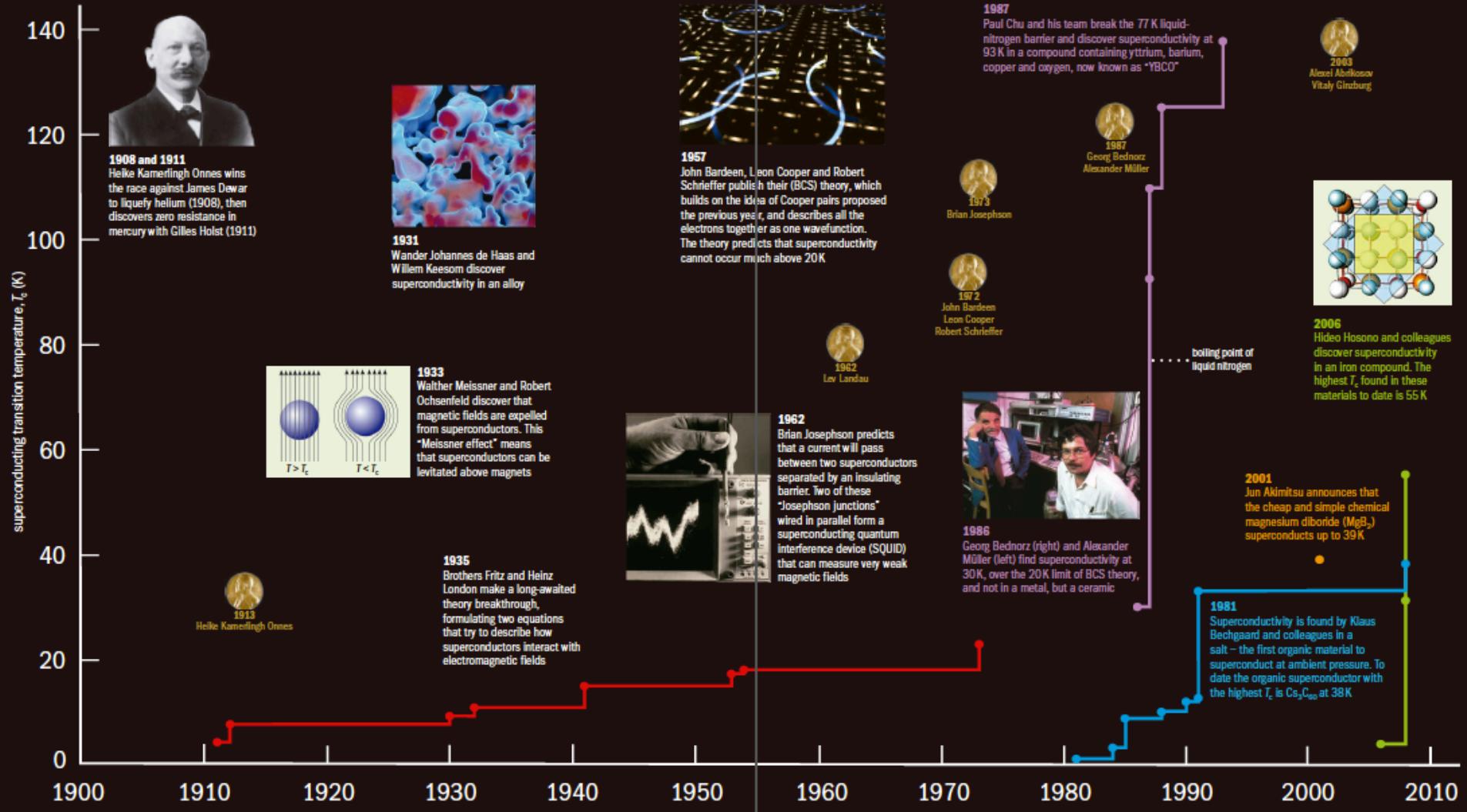


**2001,
revolução dos high Tc**
MgB₂
T_c = 40K



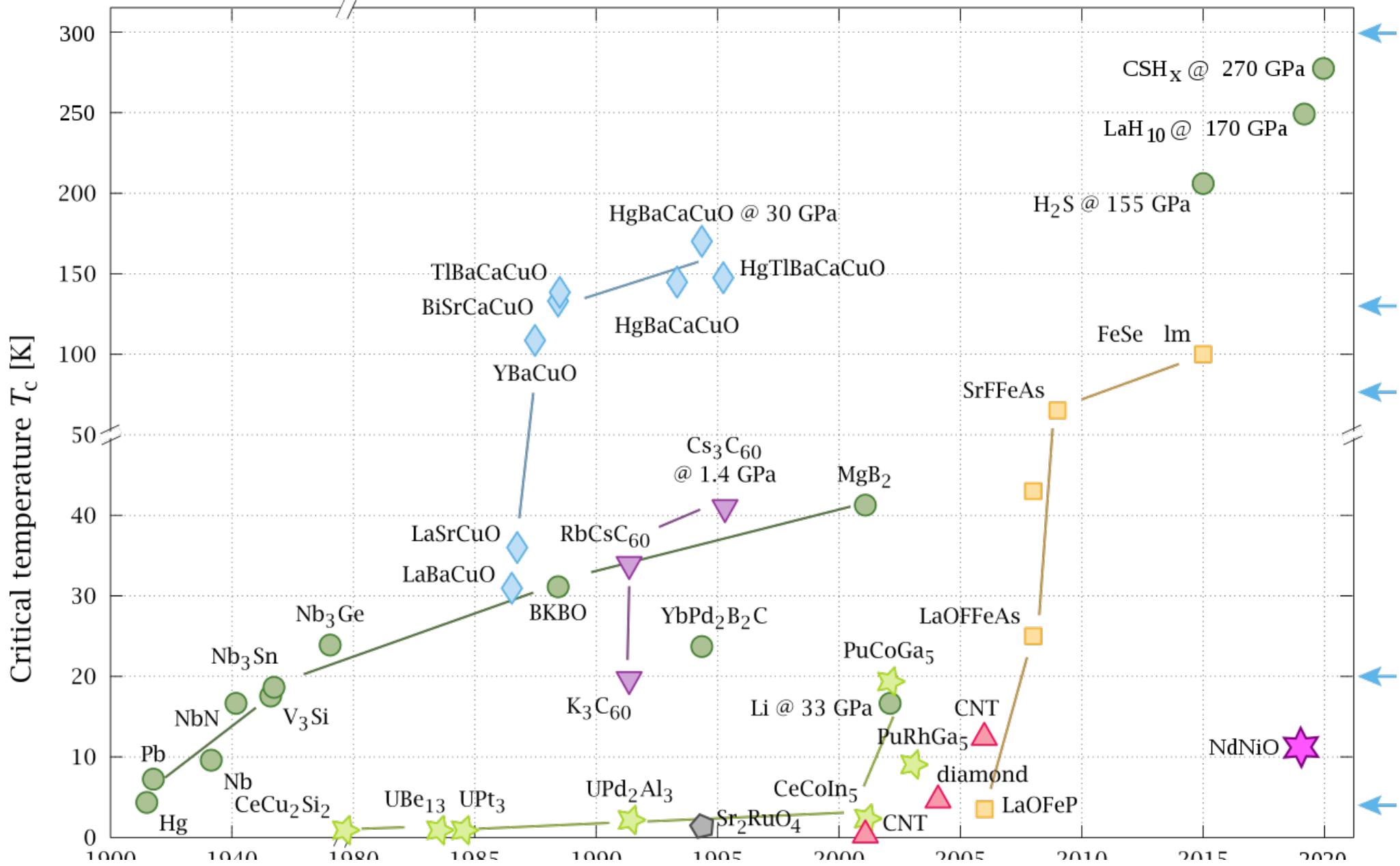
Temperaturas críticas

Superconductivity at 100



Temperaturas críticas

Timeline_of_Superconductivity_from_1900_to_2015



Prémios Nobel atribuidos por trabalho em supercondutividade

1913	Heike Kamerlingh Onnes	the Netherlands	liquid helium and superconductivity
1962	Lev Davidovich Landau	USSR	theories for liquid helium and ...
1972	John Bardeen Leon Neil Cooper John Robert Schrieffer	USA USA USA	BCS-theory
1973	Leo Esaki Ivar Giaever Brian David Josephson	Japan USA Great Britain	tunneling phenomena
			Josephson effect
1987	J. George Bednorz K. Alexander Müller	Germany Switzerland	discovery of superconductivity in ceramic materials
2003	Abrikosov, Ginzburg Leggett	USA Russia USA	theory of superconductors and superfluids

Aplicações

Conectus



**CONSORTIUM OF
EUROPEAN COMPANIES
DETERMINED TO USE
SUPERCONDUCTIVITY**



GRUPPO MALACALZA



ALSTOM

SIEMENS



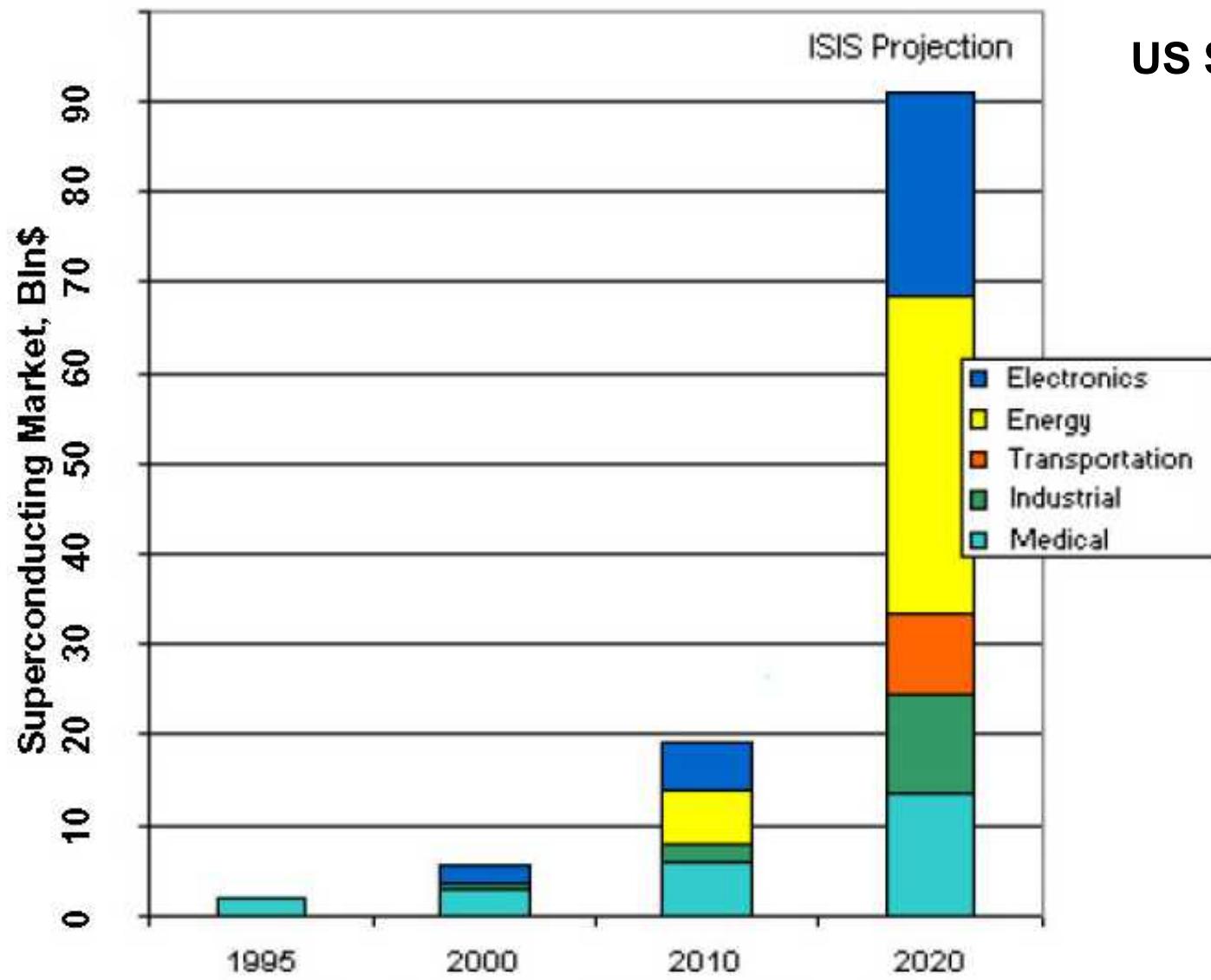
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft



Cryolectra



oerlikon
leybold vacuum



US \$38 billion by 2020.

Aplicações de grande escala

Large Scale Applications of Super-Conductivity	
Application	Major Technical Features
Power Cables	higher current densities, smaller conductor diameters, lower transmission losses, (side effect: oil-free)
Current Limiters	highly non-linear super-normal-conductor transition, self-controlled current limitation
Transformers	higher current densities, smaller size, lower weight, lower losses, (side effect: oil-free)
Motors / Generators	higher current densities, higher magnetic fields, smaller size, lower weight, lower losses
Magnets for RTD, Magnetic Energy Storage, Magnetic Separation, ...	higher current densities, higher & ultra-high magnetic fields, higher magnetic field gradients, smaller size, lower weight, lower losses
NMR Spectroscopy, MRI, ... Magnetic Levitation Systems	persistent currents, ultra-high temporal field stabilities stronger levitation forces, larger air gaps
Cavities for Accelerators (based on LTS sheets or coatings)	lower surface resistances, higher quality factors, higher microwave-power handling capability
Magnetic Bearings (based on HTS bulk material)	higher current densities, lower losses, stronger levitation forces, self-controlled autostable levitation

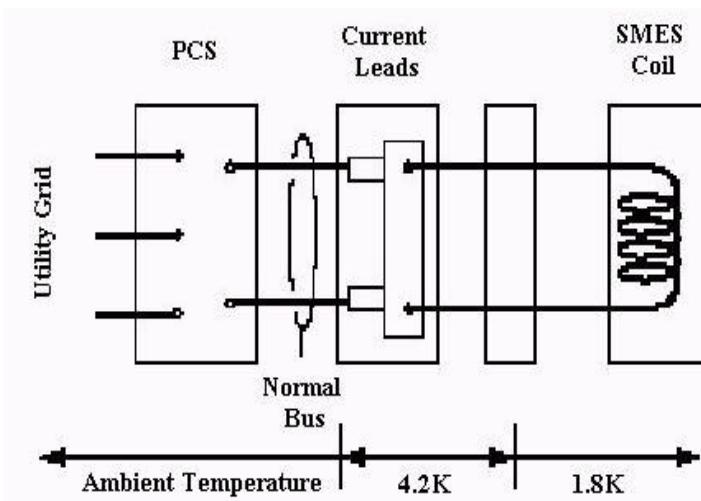
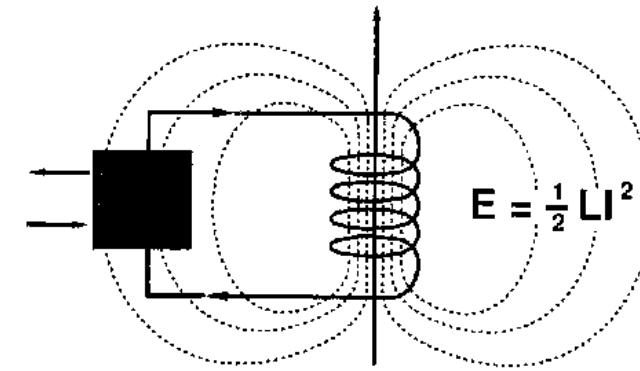
Aplicações

Medicina → Ressonância magnética

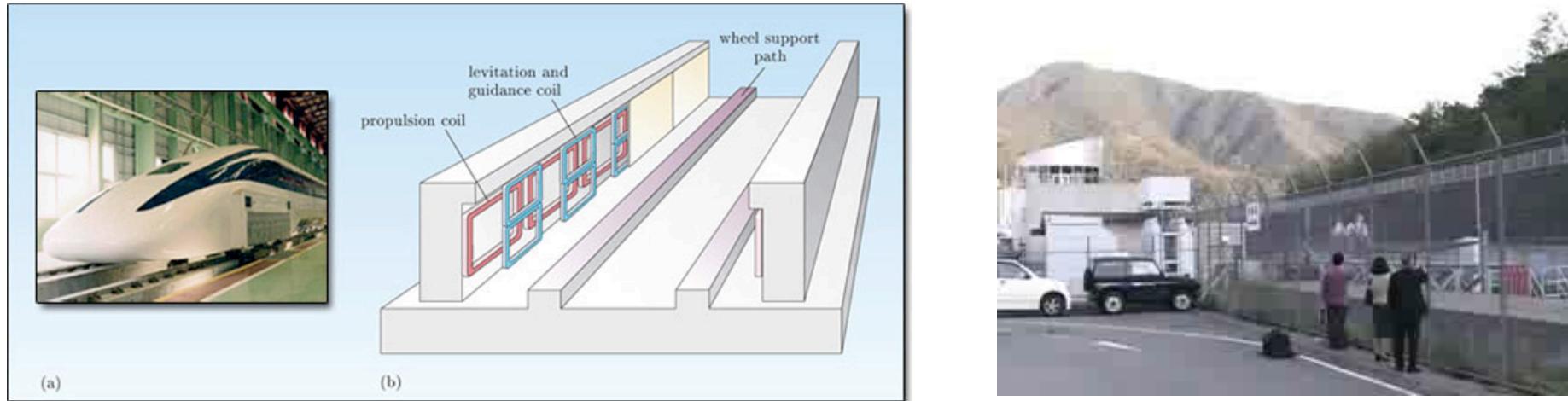


Aplicações

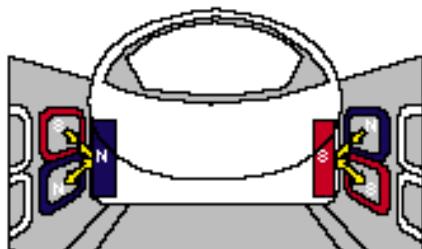
Armazenamento de Energia



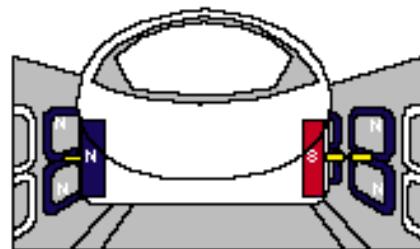
SUPERCONDUCTING MAGNETICALLY LEVITATED VEHICLE



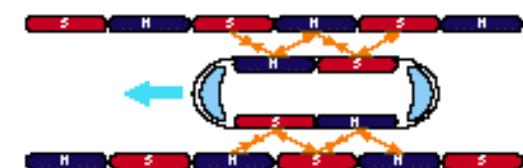
Levitação
magnética



Alinhamento
lateral

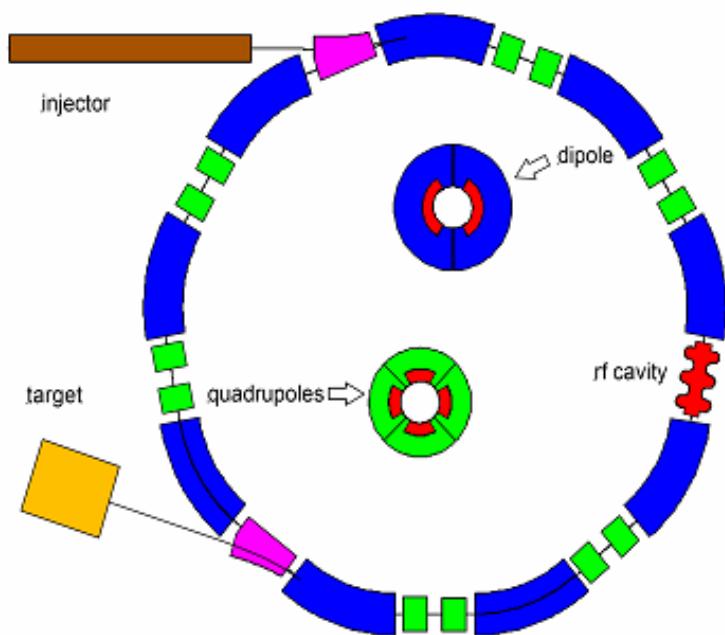


Propulsão



Aplicações

CERN- Centre Européen pour la Recherche Nucléaire

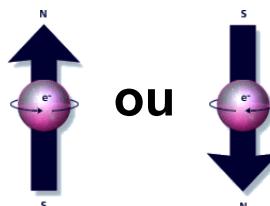


Aplicações de pequena escala

Electronics Applications of Super-Conductivity	
Application	Major Technical Features
High-Frequency Sensor Coils for NMR	lower resistive losses, higher quality factors, smaller size
Microwave Filters for Wireless Communication	lower surface resistances, smaller size, lower transmission losses, higher quality factors
Resonators for Oscillators & Other Passive Microwave Devices	lower surface resistances, higher quality factors, lower transmission losses, smaller size
Far-Infrared Bolometers	highly non-linear super-normal-conductor transition, higher irradiation-mediated temperature sensitivities
Microwave Detectors	highly non-linear junction characteristics, higher conversion efficiencies for frequency-mixing
X-Ray Detectors	lower particle excitation energies, higher photon energy resolutions
SQUID Sensors for RTD, Medical Diagnosis & Non-Destructive Testing SQUID-based Amplifiers	persistent currents, quantum interference effects, ultra-high magnetic field sensitivities low-noise low-signal amplification
Voltage Standards for Metrology & Industry	voltage steps in microwave-irradiated junction arrays, quantum-precision output voltages
Digital Circuits & Microprocessors	persistent currents, single flux quantum signal levels, ultra-fast ultra-low power data transfer & processing

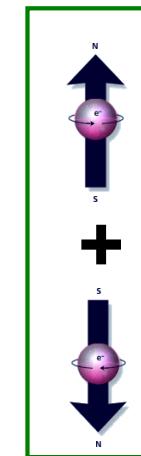
Computação quântica

Dois estados de spin do electrão:



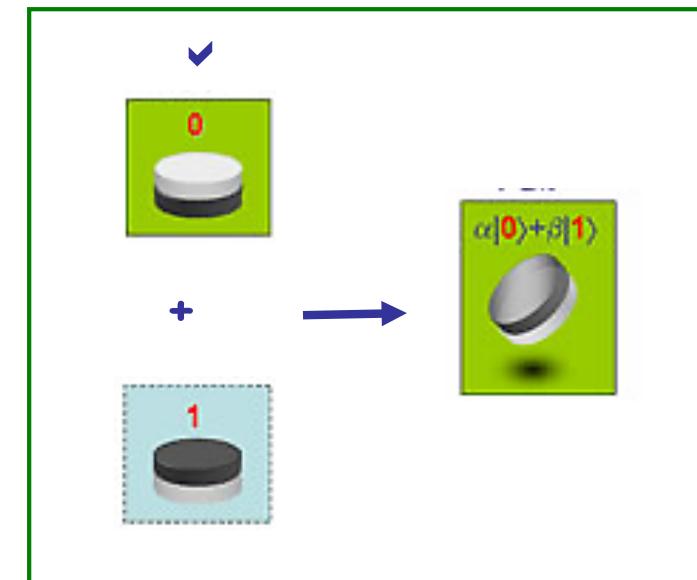
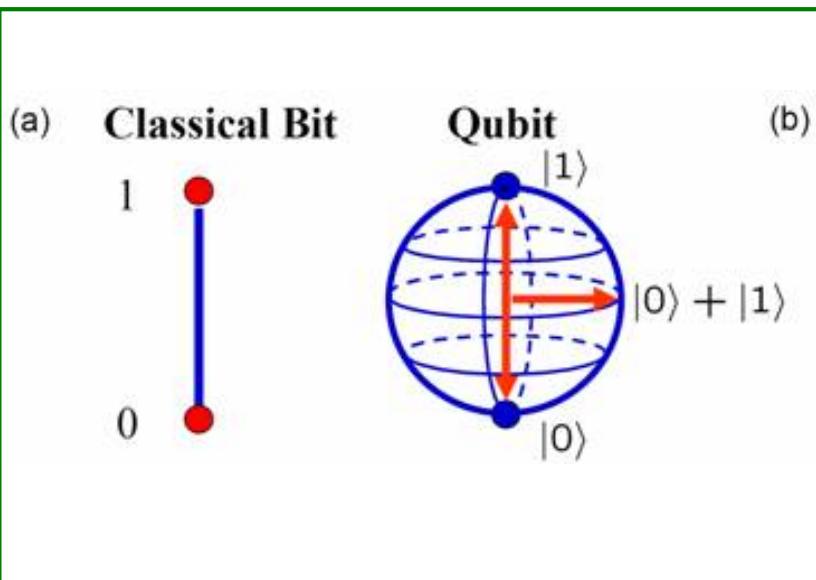
ou

Sobreposição:



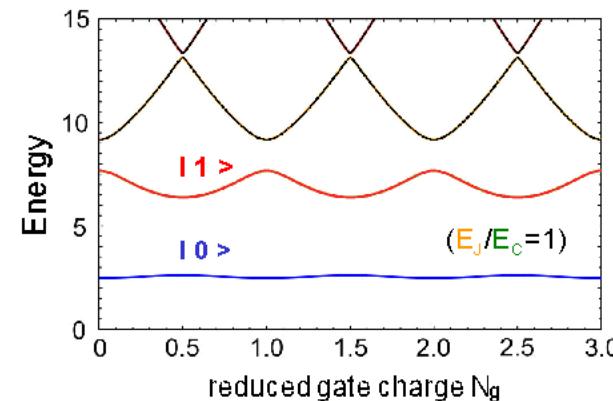
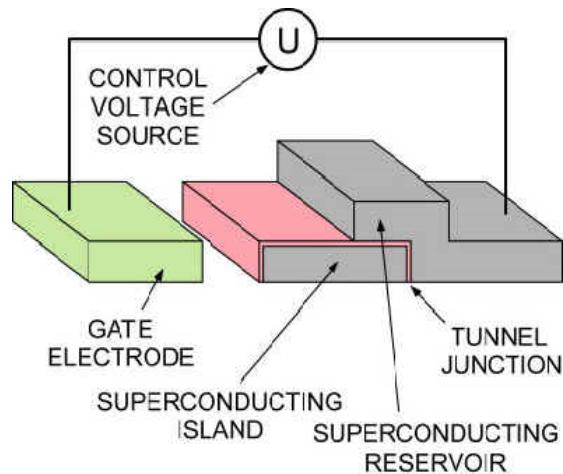
→ Qubit

Representações:



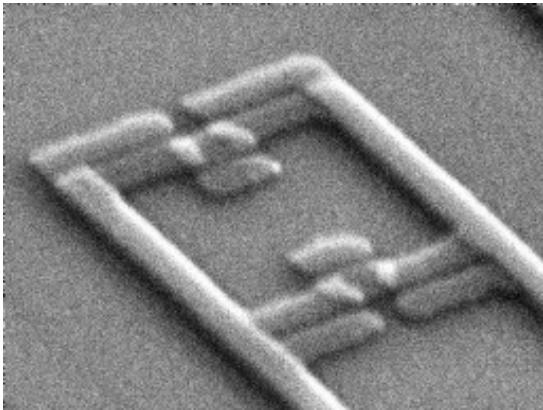
Qubit supercondutores

THE SINGLE COOPER PAIR BOX:



Qubit supercondutores

Flux qubit:

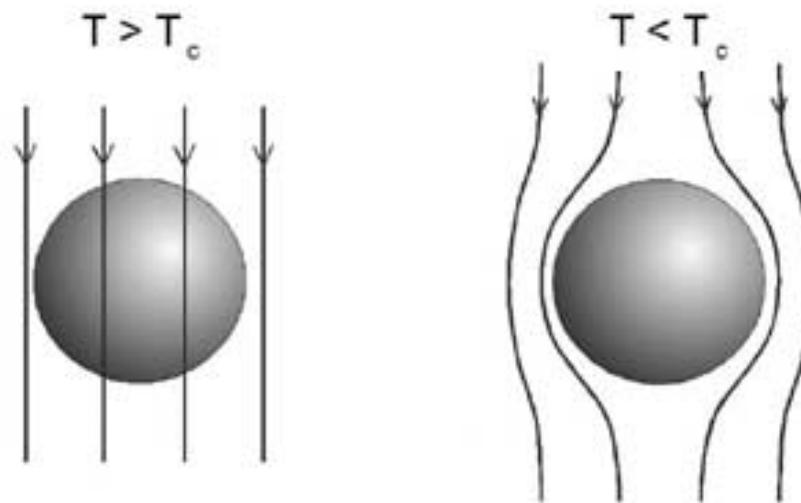


circulating currents
which can flow either
clockwise or counter-
clockwise

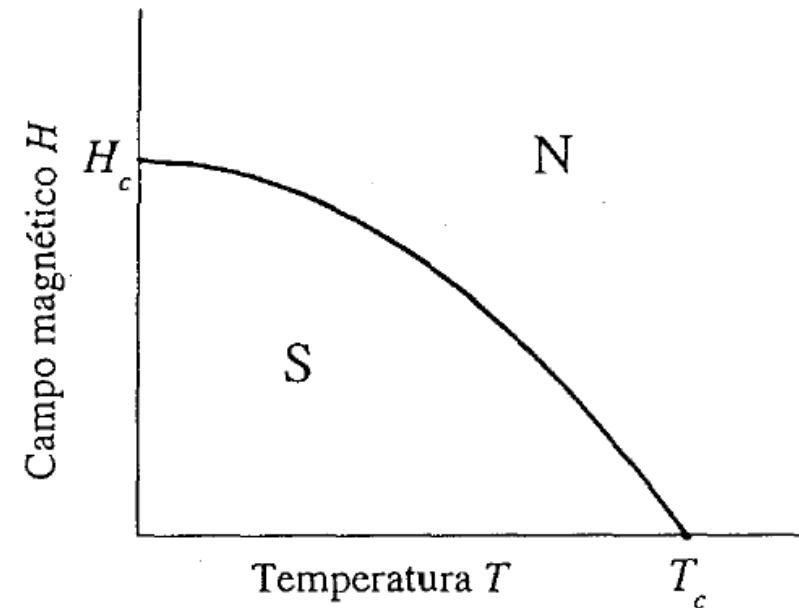
Propriedades magnéticas dos supercondutores

Efeito Meissner e campos críticos

efeito meissner
(diamagnético perfeito)

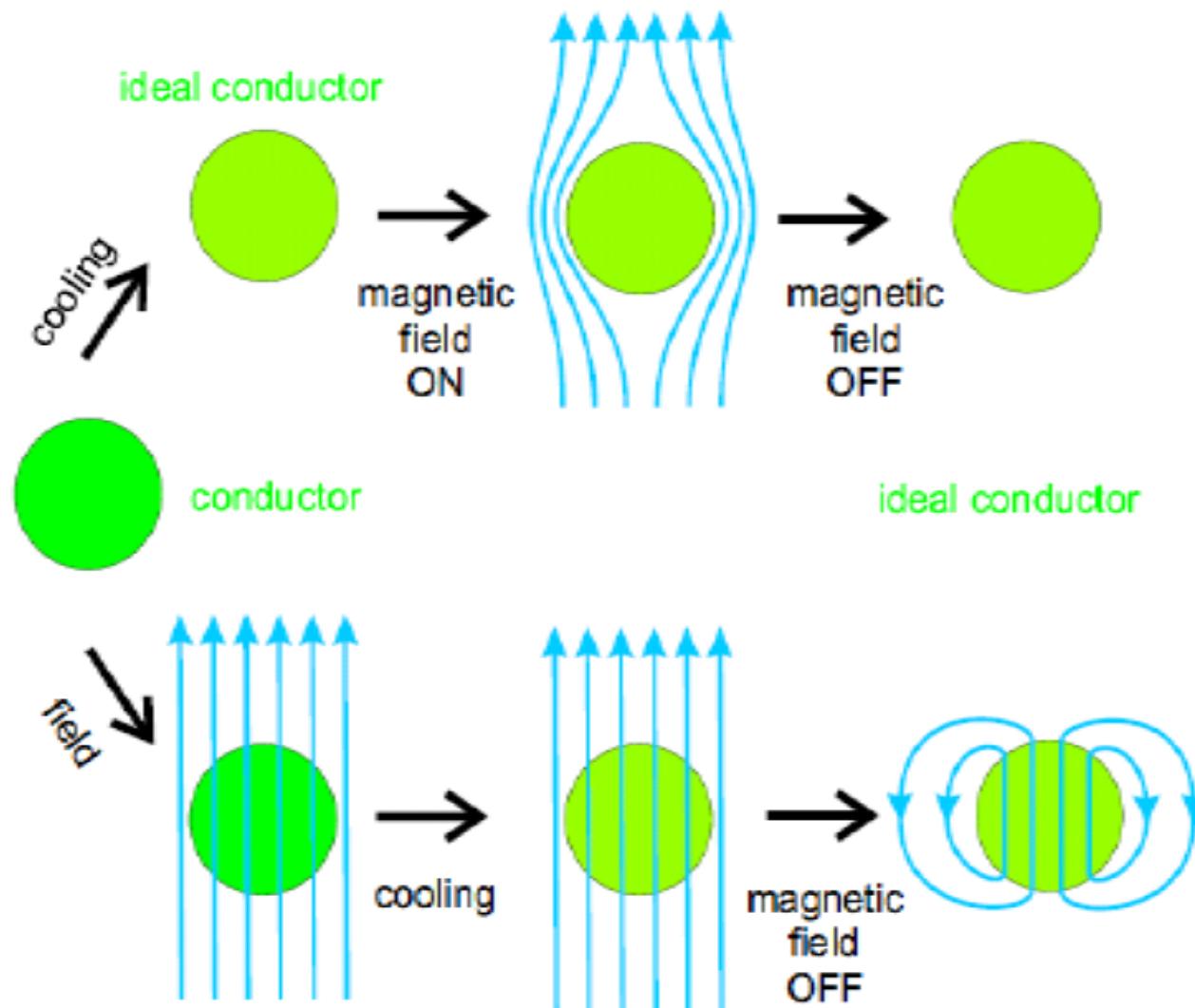


Campo magnético critico



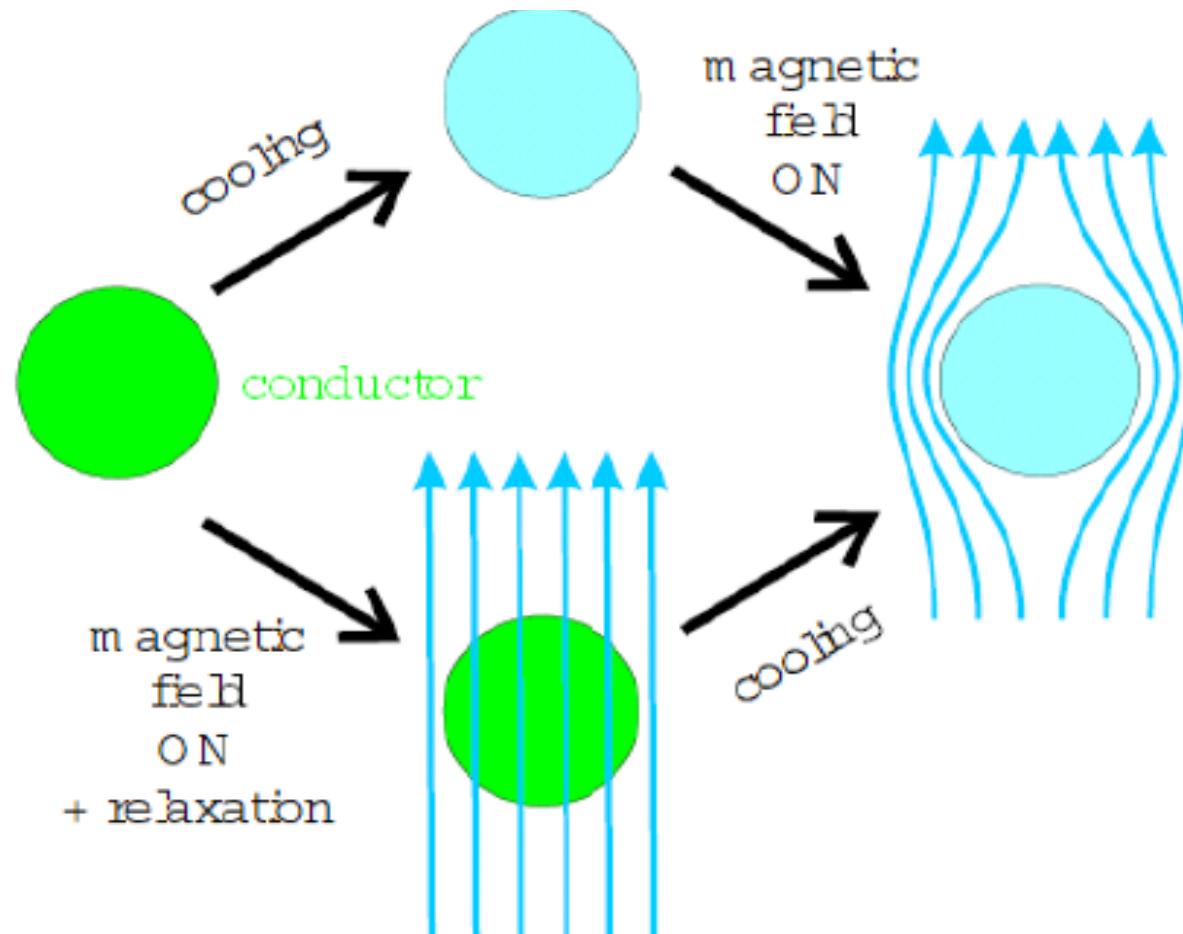
Diferença entre um supercondutor e um condutor perfeito

condutor perfeito



Diferença entre um supercondutor e um condutor perfeito

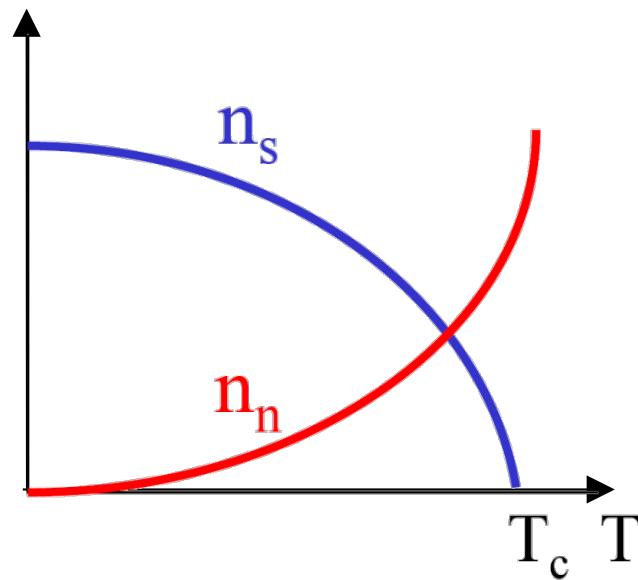
Supercondutor



2 fluids model

modelo dos dois fluidos:

densidades $n_s(T) + n_n(T) = n$

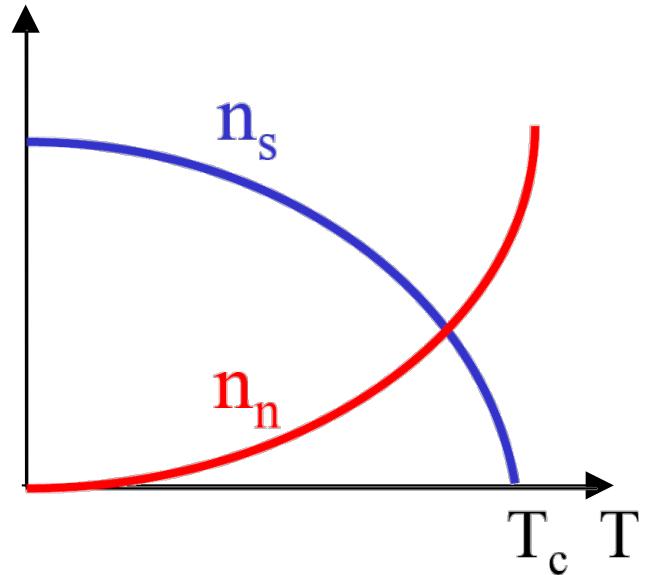


Termodinâmica: Gorter e Casimir

Equações de London

modelo dos dois fluidos:

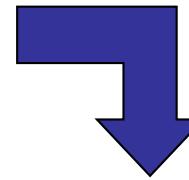
densidades $n_s(T) + n_n(T) = n$



campo eléctrico acelera “fluido”
supercondutor

$$mn_s dv_s / dt = en_s E.$$

$$J_s = en_s v_s$$



$$dJ_s / dt = (e^2 n_s / m) E$$

1ª Equação de London

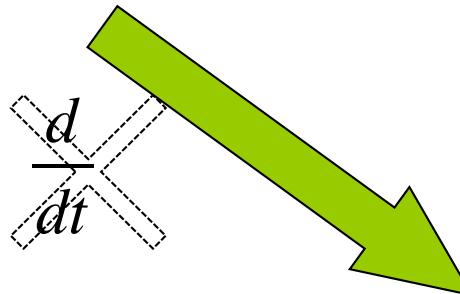
Equações de London

Equações
de
Maxwell

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0,$$

1ª Equação de London

$$d\mathbf{J}_s/dt = (e^2 n_s/m) \mathbf{E}$$



2ª Eq. de London

$$\nabla \times \mathbf{j}_s = -\frac{n_s e_s^2}{m} \mathbf{B}$$

The essential content of the second London is that screening of magnetic fields also applies to time-independent magnetic fields

London penetration depth

Equações de Maxwell

$$\nabla \times \mathbf{B}_{\text{in}} = \mu_0 \nabla \times \mathbf{M}$$
$$= \mu_0 \mathbf{J}_{\text{sh}}$$

$$\mathbf{J} = 0 \text{ (also } dD/dt = 0)$$

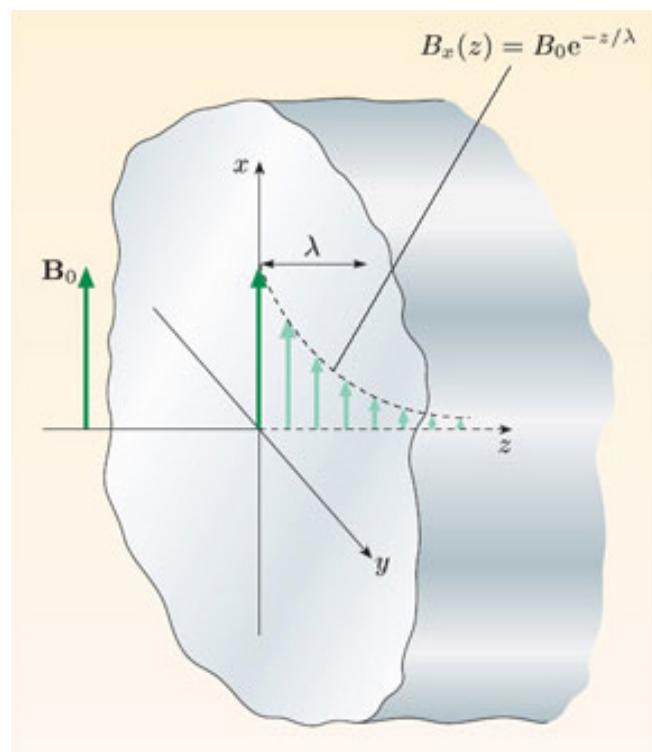
2ª Eq. de London

$$\nabla \times \mathbf{j}_s = -\frac{n_s e_s^2}{m} \mathbf{B}$$

shielding or demagnetization current density:

$$\mathbf{J}_{\text{sh}} = \nabla \times \mathbf{M}.$$

$$\nabla^2 \mathbf{B} = \frac{\mathbf{B}}{\lambda_L^2}$$



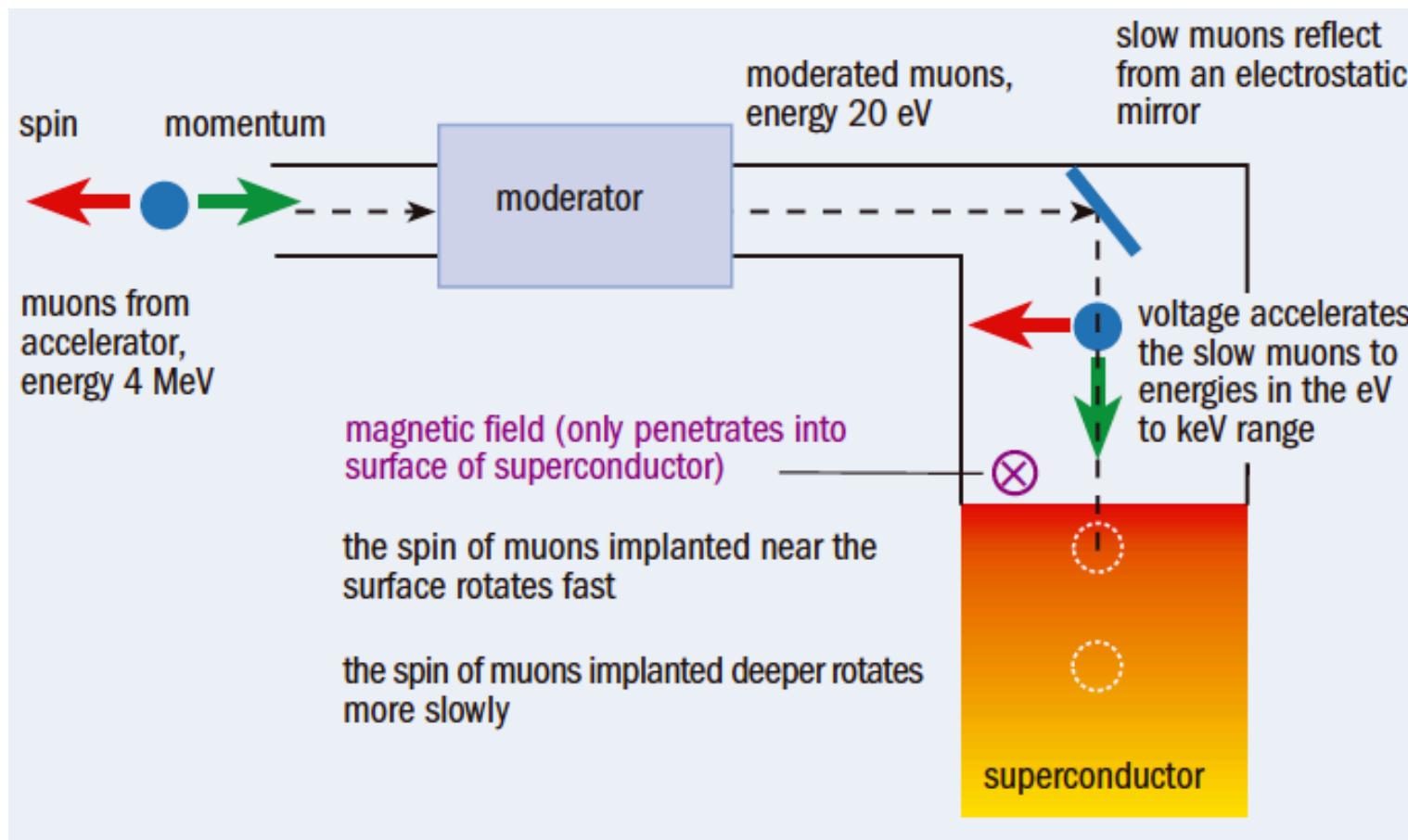
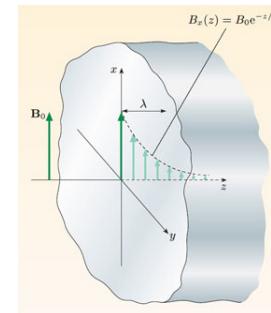
London penetration depth

$$\lambda = \left(\frac{m}{e^2 n_s(T) \mu_0} \right)^{1/2}$$

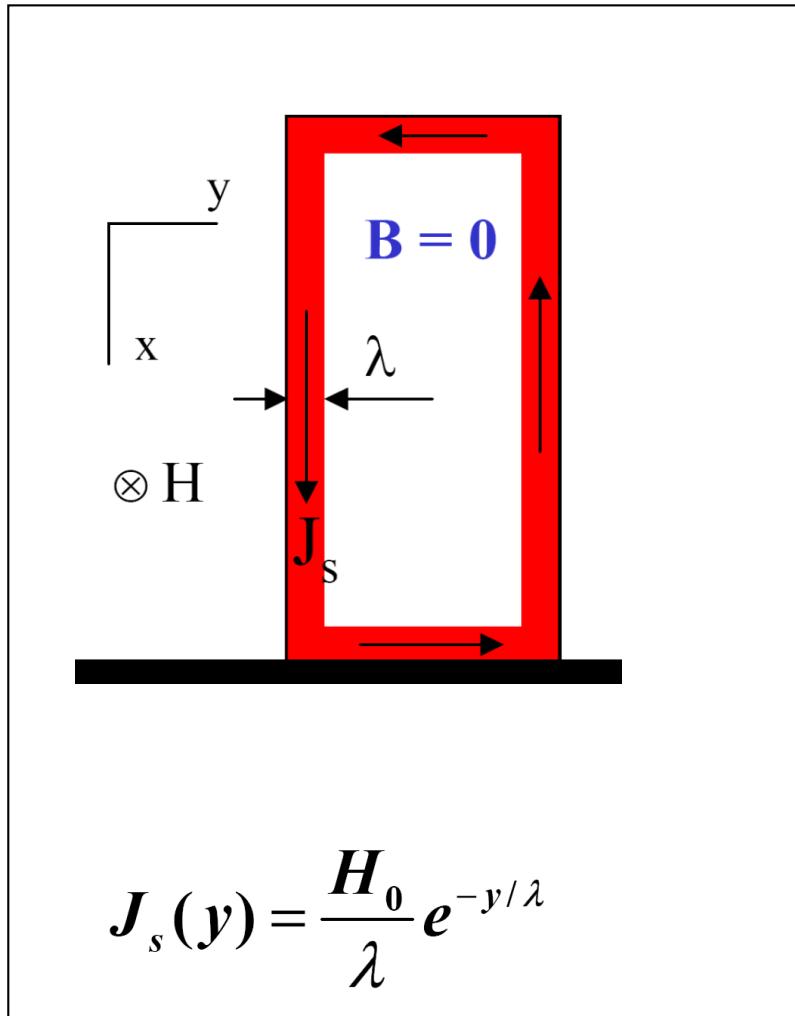
London penetration depth

London penetration depth

$$\lambda = \left(\frac{m}{e^2 n_s(T) \mu_0} \right)^{1/2}$$



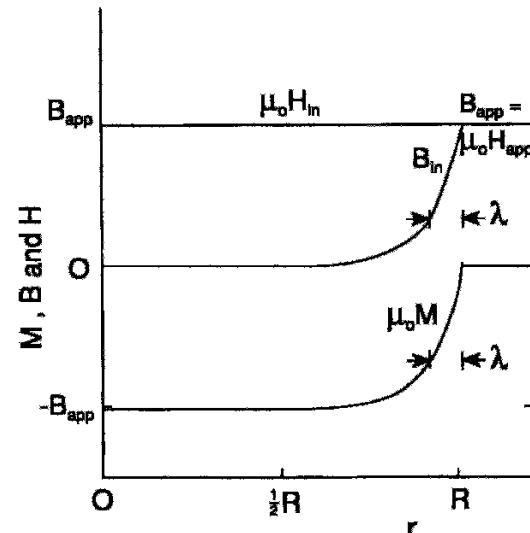
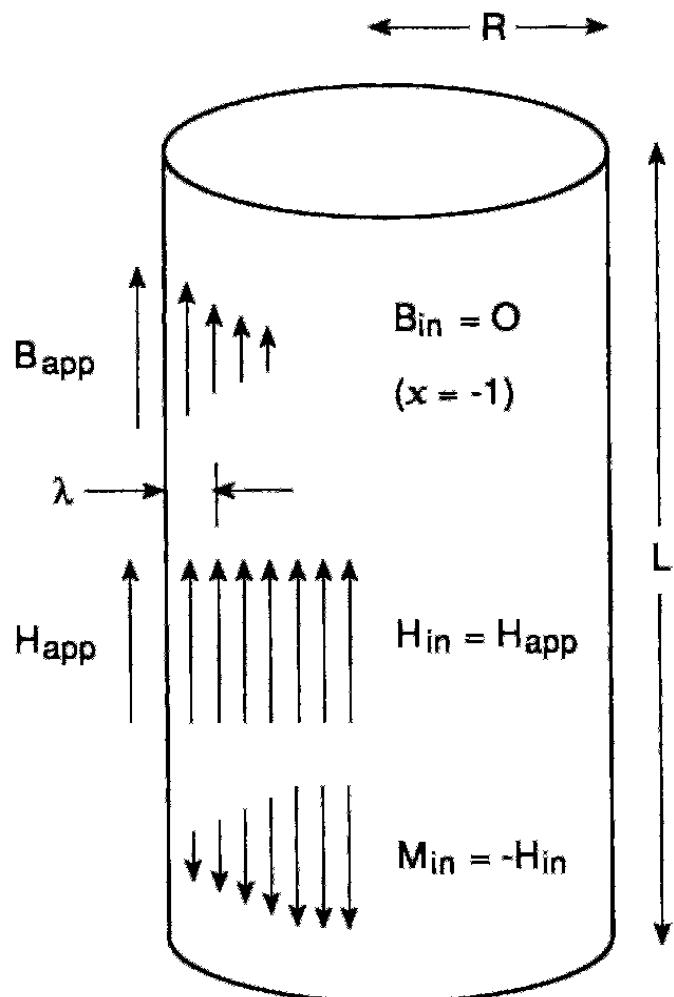
Correntes de superfície



$$n_s = 10^{29} \text{ m}^{-3}$$

$$\lambda = \left(\frac{m}{\mu_0 n_s e^2} \right)^{1/2} = 1.7 \times 10^{-8} \text{ m} \approx 20 \text{ nm.}$$

magnetic fields inside a superconducting cylinder

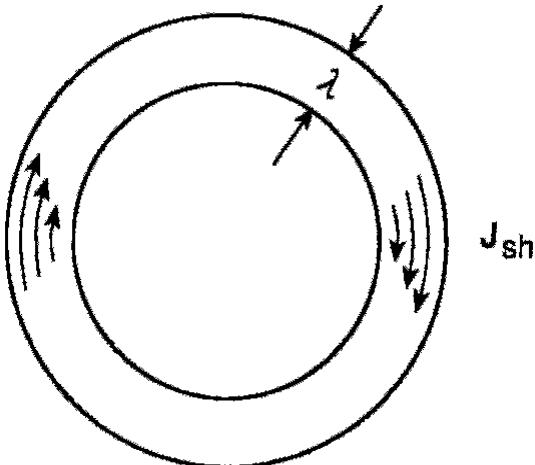
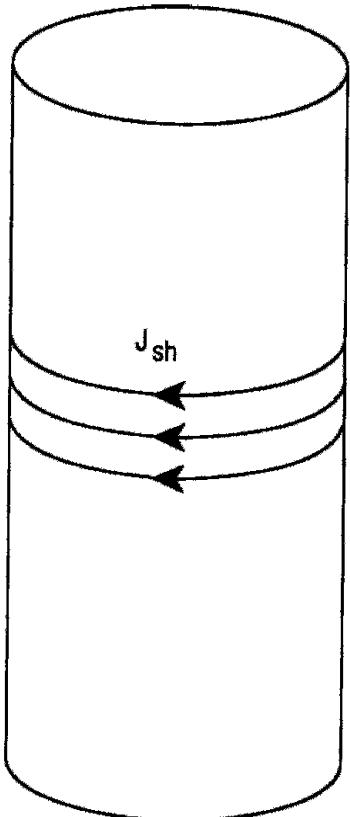


$$B_{in}(r) = \mu [H_{in} + M(r)]$$

$$B(r) \approx B_{app} \exp[-(R-r)/\lambda],$$

$$M(r) = -H_{app} \left\{ 1 - \exp \left[-\frac{(R-r)}{\lambda} \right] \right\},$$

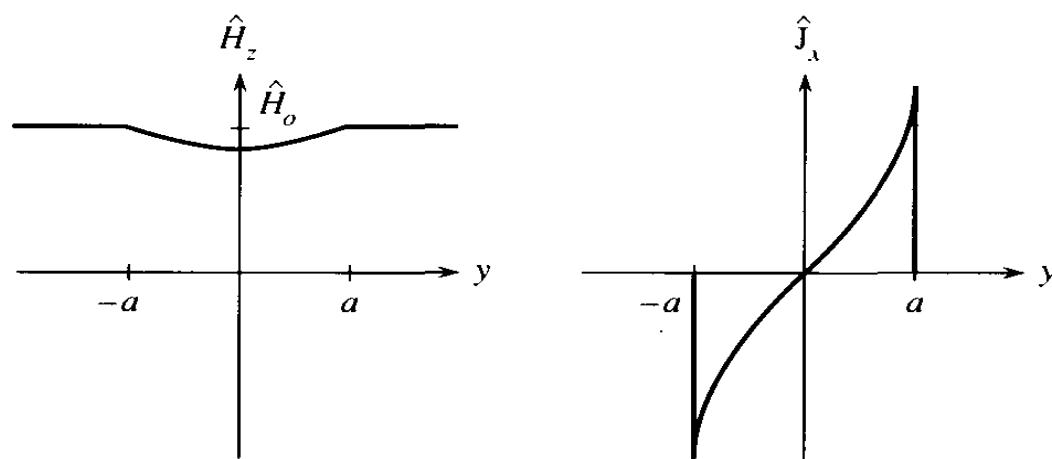
shielding current



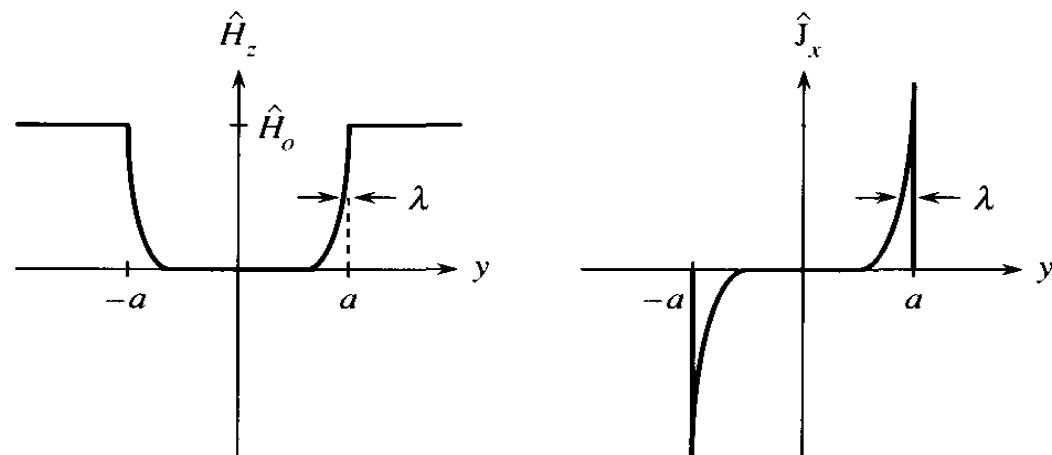
$$\nabla \times \mathbf{B}_{in} = \mu_0 \nabla \times \mathbf{M}$$
$$= \mu_0 \mathbf{J}_{sh}$$

$$\mathbf{J}_{sh}(r) = -\frac{1}{\mu_0} \cdot \frac{d\mathbf{B}}{dr}$$
$$\approx -\left(\frac{\mathbf{B}_{app}}{\mu_0 \lambda}\right) \exp\left[-\frac{(R-r)}{\lambda}\right]$$
$$\approx -\mathbf{J}_0 \exp\left[-\frac{(R-r)}{\lambda}\right],$$

Correntes de superfície



(a)



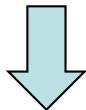
(b)

Figure 2.25 The distribution of field quantities in a perfect conductor;
(a) $(a/\lambda) \ll 1$ and (b) $(a/\lambda) \gg 1$.

Ginzburg-Landau theory

Landau model of 2nd order phase transitions

order parameter vanishes continuously at T_c



Free energy near a second order phase transition (Taylor series):

$$f(\psi) = \alpha\psi^2 + \frac{\beta}{2}\psi^4 \quad (\beta > 0)$$

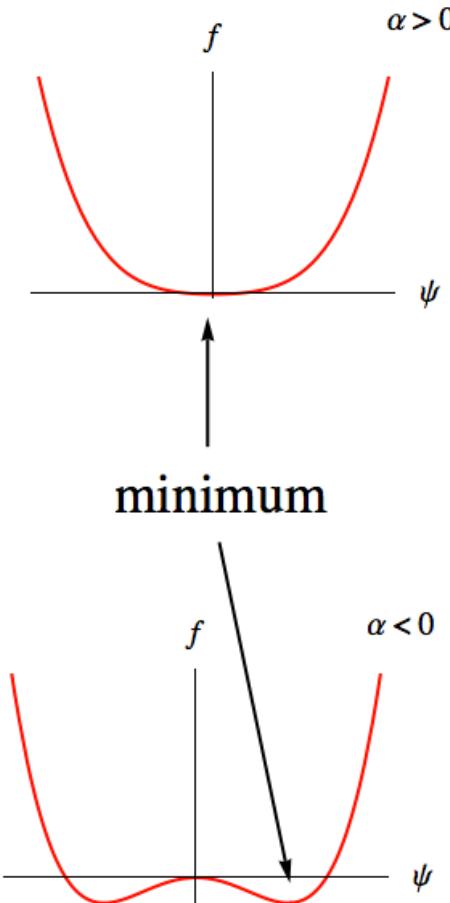
- order parameter real
- free energy density even function of the order parameter.



Phase transition occurs when $\alpha(T_c)=0$



$$\text{Expansion: } \alpha(T) = a(T - T_c) \quad (a > 0)$$



e.g: ferromagnetism

Ginzburg- Landau theory

ψ complex function:

$$\psi(\mathbf{r}) = |\psi| e^{i\phi(\mathbf{r})}$$

$$\psi^2 \rightarrow |\psi|^2$$

$$\psi^4 \rightarrow |\psi|^4$$

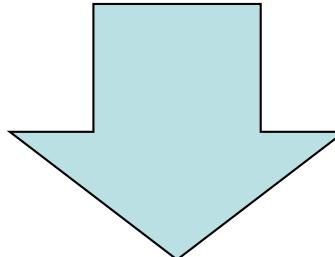
ψ can vary in space:

energy cost $|\nabla \psi|^2$

ψ couples to
electromagnetic field:

$$\nabla \rightarrow \nabla - iq\mathbf{A} / \hbar$$

\mathbf{A} vector potential; $q = -2e$



Ginzburg-Landau free energy density:

$$F = F_n + \alpha |\psi|^2 + \frac{\beta}{2} |\psi|^4 + \frac{1}{2m} |(-i\hbar\nabla + 2e\mathbf{A})\psi|^2 + \frac{|\mathbf{B} - \mathbf{B}_E|^2}{2\mu_0}$$

effective mass $m = 2m_e$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

F_n free energy in the normal phase,

Ginzburg- Landau theory

free energy: $F = \int f d\mathbf{r}$

minimization

$$\delta F = \int d\mathbf{r} \{ \delta\psi^* [\dots] + \delta\psi [\dots] \} + \int d\mathbf{r} \delta\mathbf{A} \cdot \{\dots\} = 0$$

Variation of the free energy with respect to the order parameter ψ^*

$$\alpha\psi + \beta |\psi|^2 \psi + \frac{1}{2m} (-i\hbar\nabla - 2e\mathbf{A})^2 \psi = 0$$

First Ginzburg–
Landau equation

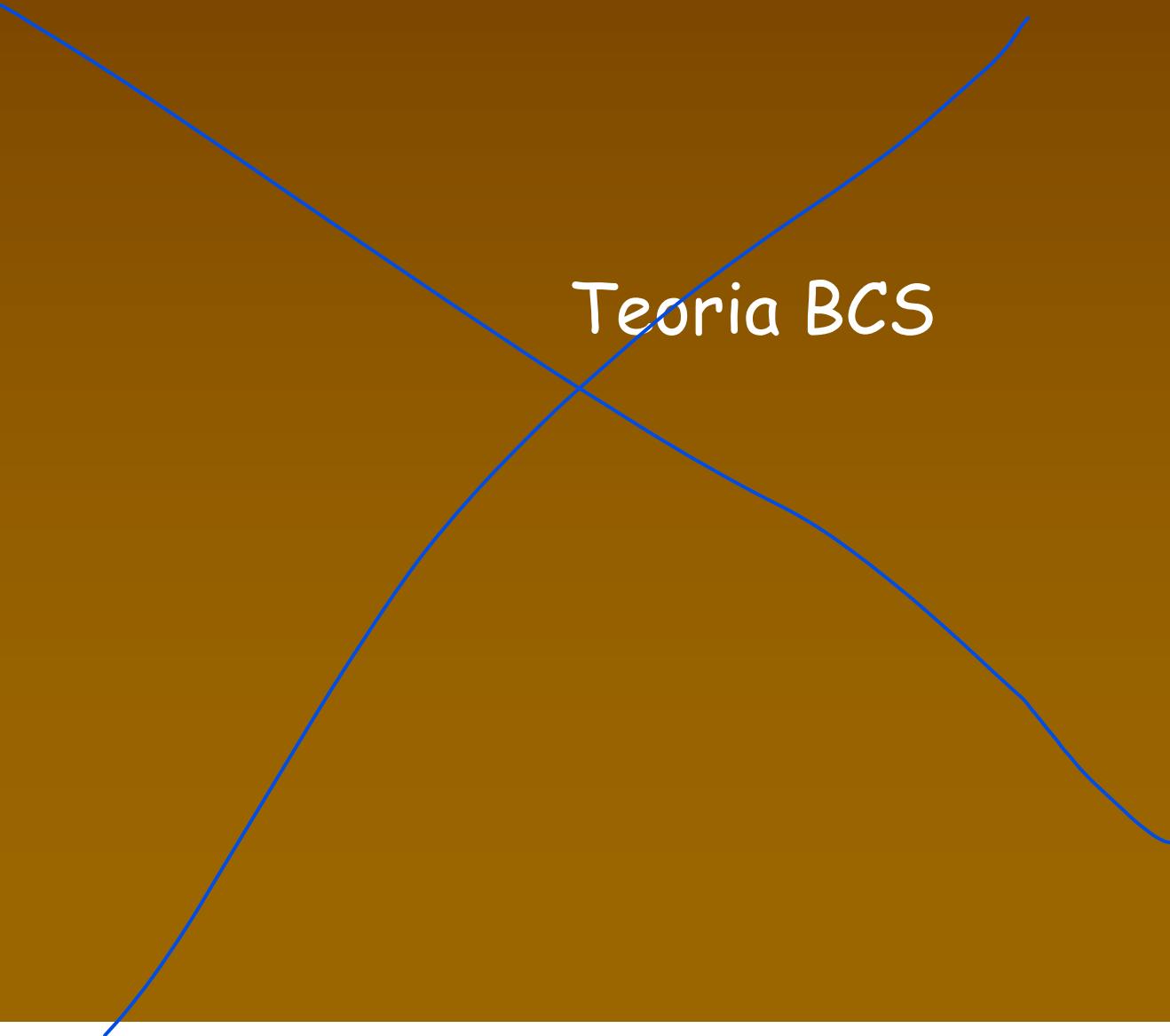
Variation of the free energy with respect to the vector potential A

$$\mathbf{j} = \frac{2e}{m} \operatorname{Re} \{ \psi^* (-i\hbar\nabla - 2e\mathbf{A}) \psi \}$$

Second Ginzburg–
Landau equation

Homogeneous superconductor, no fields, no currents

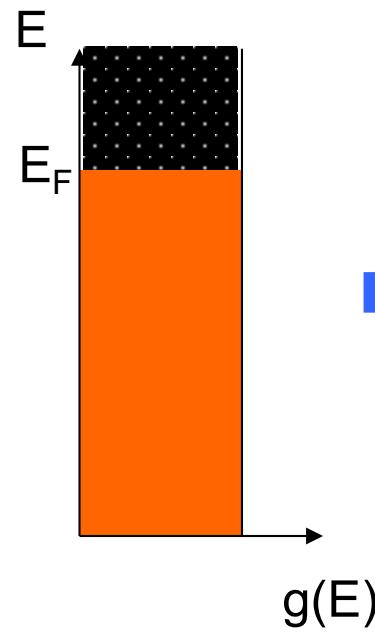
$$\alpha\psi + \beta |\psi|^2 \psi = 0 \longrightarrow |\psi|^2 = -\frac{\alpha}{\beta} \longrightarrow |\psi|^2 = -\frac{\alpha_0(T - T_c)}{\beta}$$



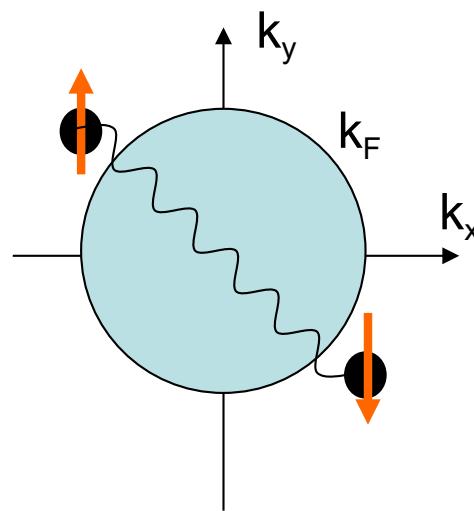
Teoria BCS

Teoria BCS

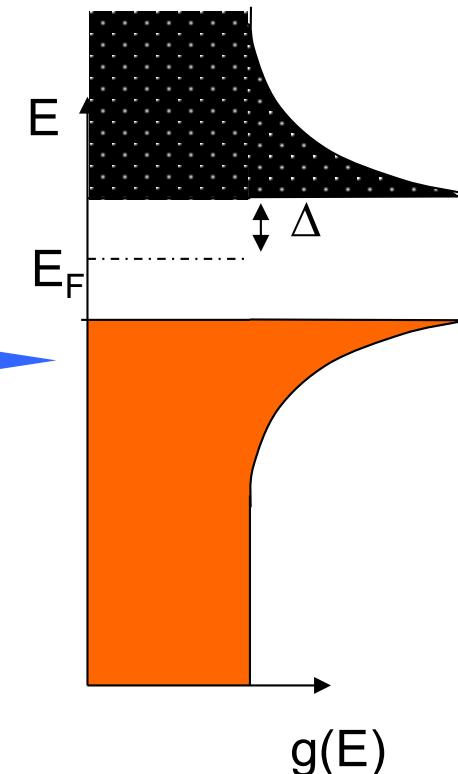
Banda de condução ($T=0$)



atração



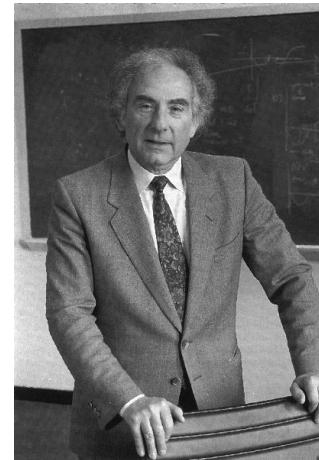
Instabilidade da superfície de Fermi!



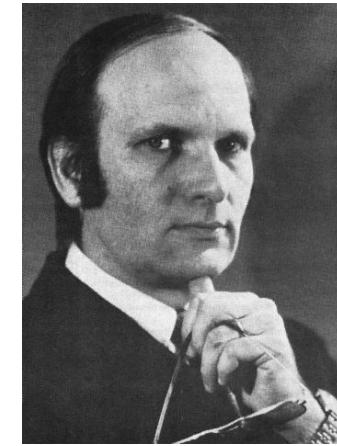
Teoria BCS



Bardeen



Cooper

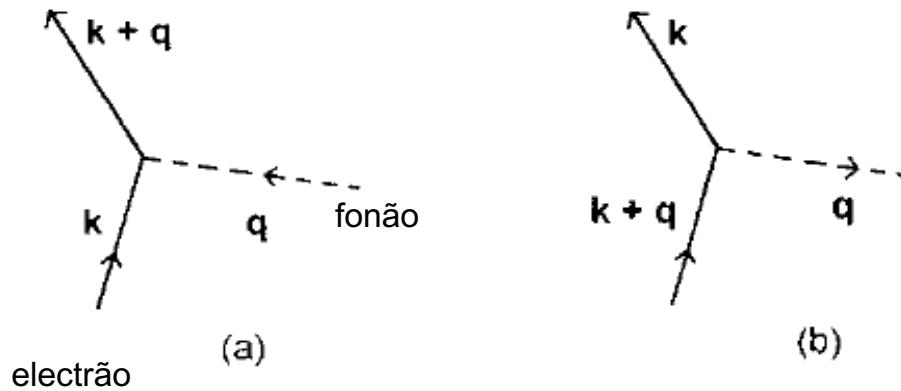


Schrieffer

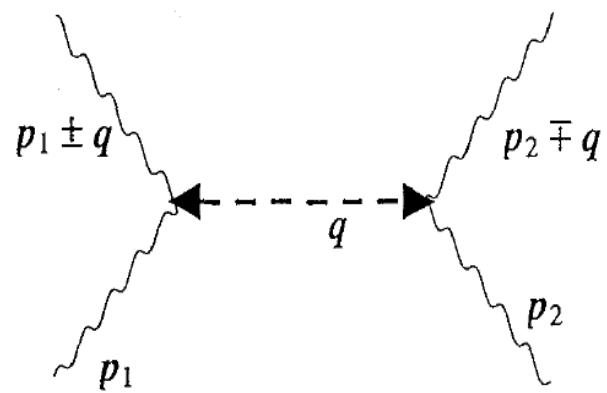
Prémio Nobel 1972

interacção electrão-fonão

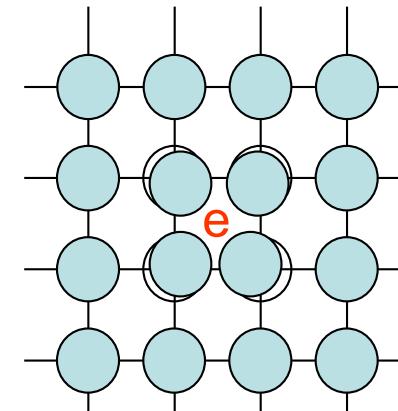
Diagrama de Feynman



troca de momento



Espaço Real

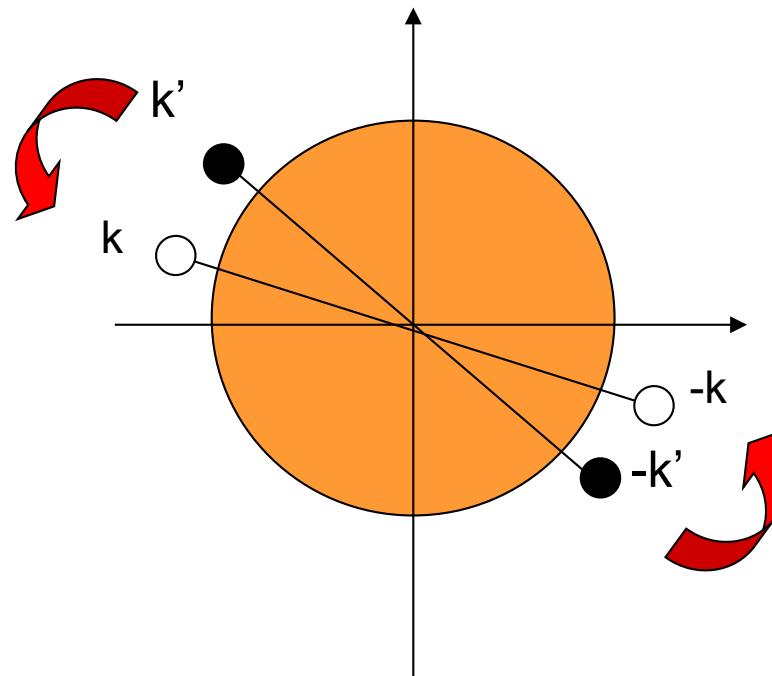


Teoria BCS

Hamiltoniano BCS:

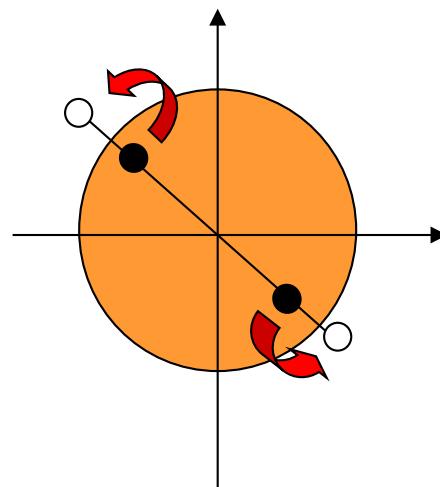
$$H = \sum_{\mathbf{k}, \sigma=\uparrow, \downarrow} \epsilon_{\mathbf{k}} c_{\mathbf{k}\sigma}^\dagger c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}, \mathbf{k}'} V_{\mathbf{k}, \mathbf{k}'} c_{\mathbf{k}, \uparrow}^\dagger c_{-\mathbf{k}, \downarrow}^\dagger c_{-\mathbf{k}', \downarrow} c_{\mathbf{k}', \uparrow}$$

< 0

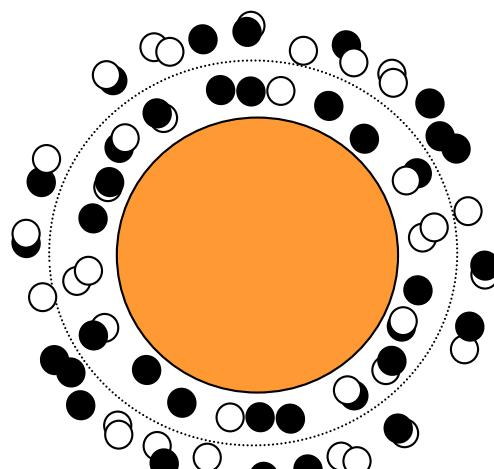


pares de Cooper
com momento nulo

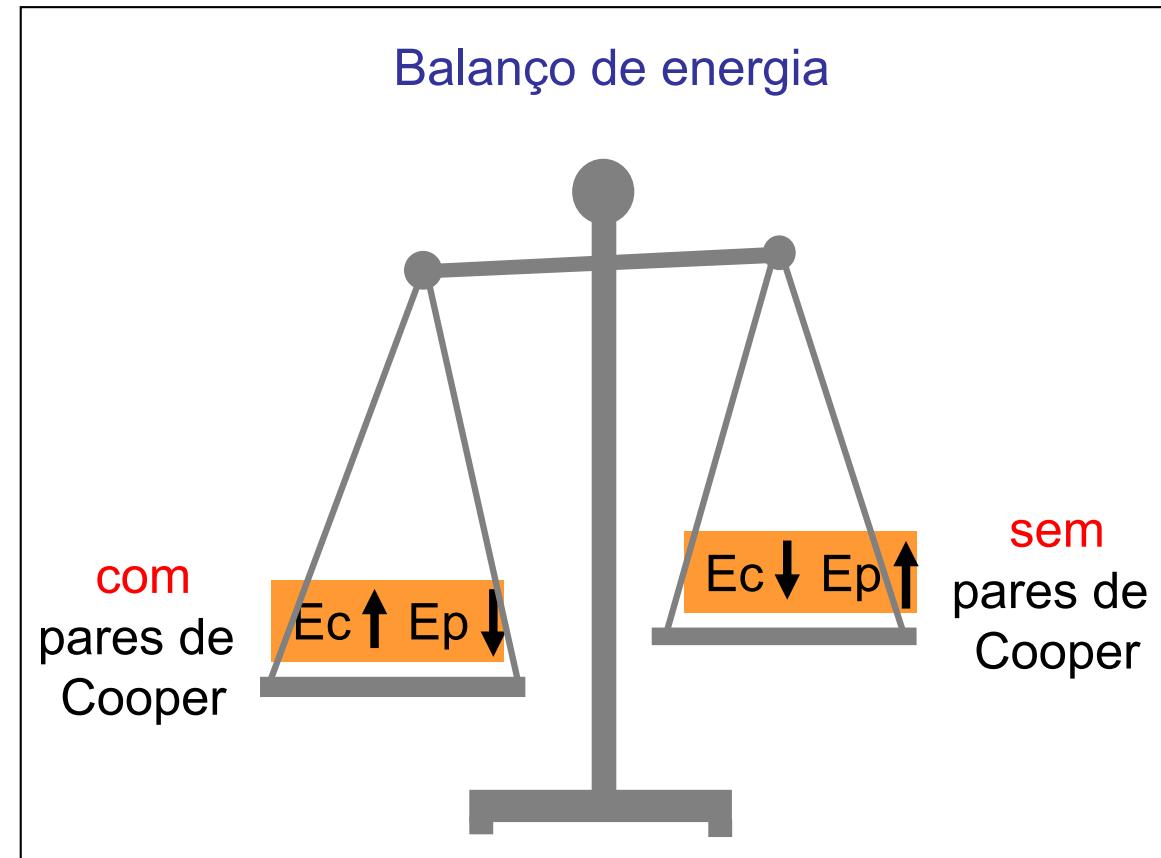
Teoria BCS



estado fundamental:



$$\Delta \cong 2\hbar\omega_D e^{-1/\lambda(0)V}.$$



energia de condensação:

$$E_s - E_n = -\frac{1}{2} \mathcal{N}(0) \Delta^2.$$

equação de gap ($H=0$)

Minimização da energia livre $F(\Delta)$



equação de gap (hiato)

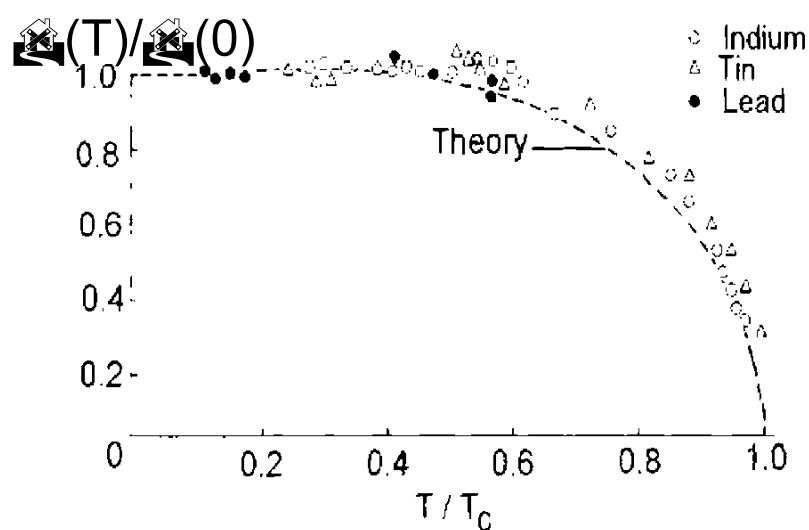
$$1 = \frac{V}{N} \sum_{\mathbf{k}} \frac{1 - f(E_{\mathbf{k}\uparrow}) - f(E_{\mathbf{k}\downarrow})}{2E_{\mathbf{k}}}$$

$$E = \sqrt{\xi^2 + \Delta^2},$$

$$\Delta = -VS^{-1} \sum_{\mathbf{k}} \langle a_{-\mathbf{k}\downarrow} a_{\mathbf{k}\uparrow} \rangle,$$

$f(E)$ Fermi – Dirac distribution

pares de Cooper com momento nulo



Supercondutores “anómalos”

Supercondutores "anômalos"

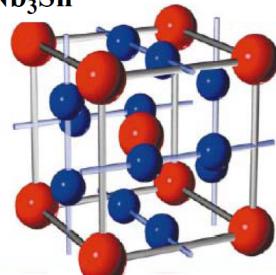
novidades!

convencionais

NbTi



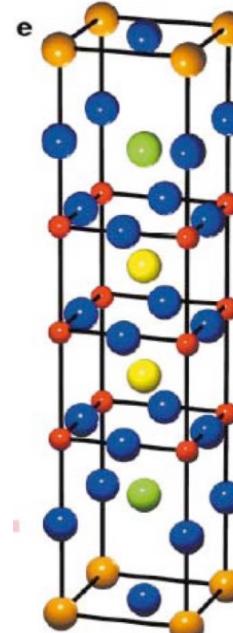
Nb₃Sn



Tc~20k

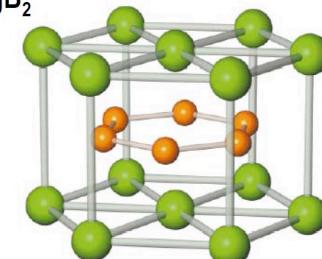
cuprates

Bi₂Sr₂Ca₂Cu₃O_x



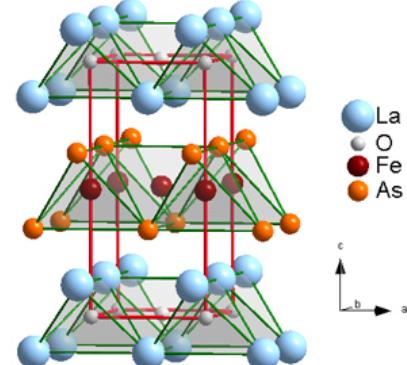
Tc~100k

MgB₂



Tc~40k

Iron based superc.



Supercondutores “anómalos”

Room temperature superconductivity!

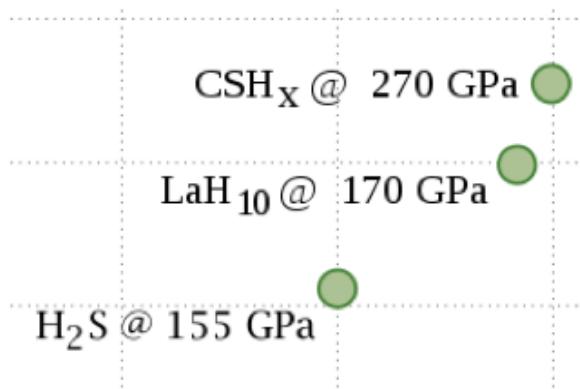
superhydrides can be considered to be doped versions of metallic hydrogen and therefore are naturally expected to have high T_c s.

hydride, any of a class of chemical compounds in which hydrogen is combined with another element.

Stinky hydrogen sulfide smashes superconductivity record
(2015)

203 kelvin in H_3S

<https://www.science.org/content/article/stinky-hydrogen-sulfide-smashes-superconductivity-record>

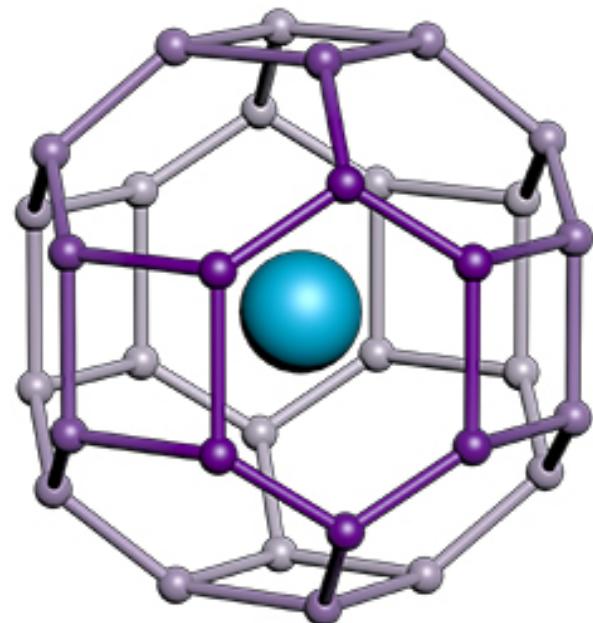


superhydride is a compound that contains an abnormally large amount of hydrogen

Supercondutores “anómalos”

Room temperature superconductivity! (wikipedia)

Lanthanum decahydride is a superhydride compound of [lanthanum](#) and hydrogen (LaH_{10}). It has a superconducting transition temperature $T_c \sim 250$ K (-23 °C; -10 °F) at a pressure of 150 [gigapascals](#) (GPa), and its synthesis required pressures above ~ 160 Gpa. A cubic form can be synthesised at 1,000 K (730 °C; $1,340$ °F), and a hexagonal crystal structure can be formed at room temperature.



The cubic form has each lanthanum atom surrounded by 32 hydrogen atoms, which form the vertices of an 18 faced shape called a [chamfered cube](#)

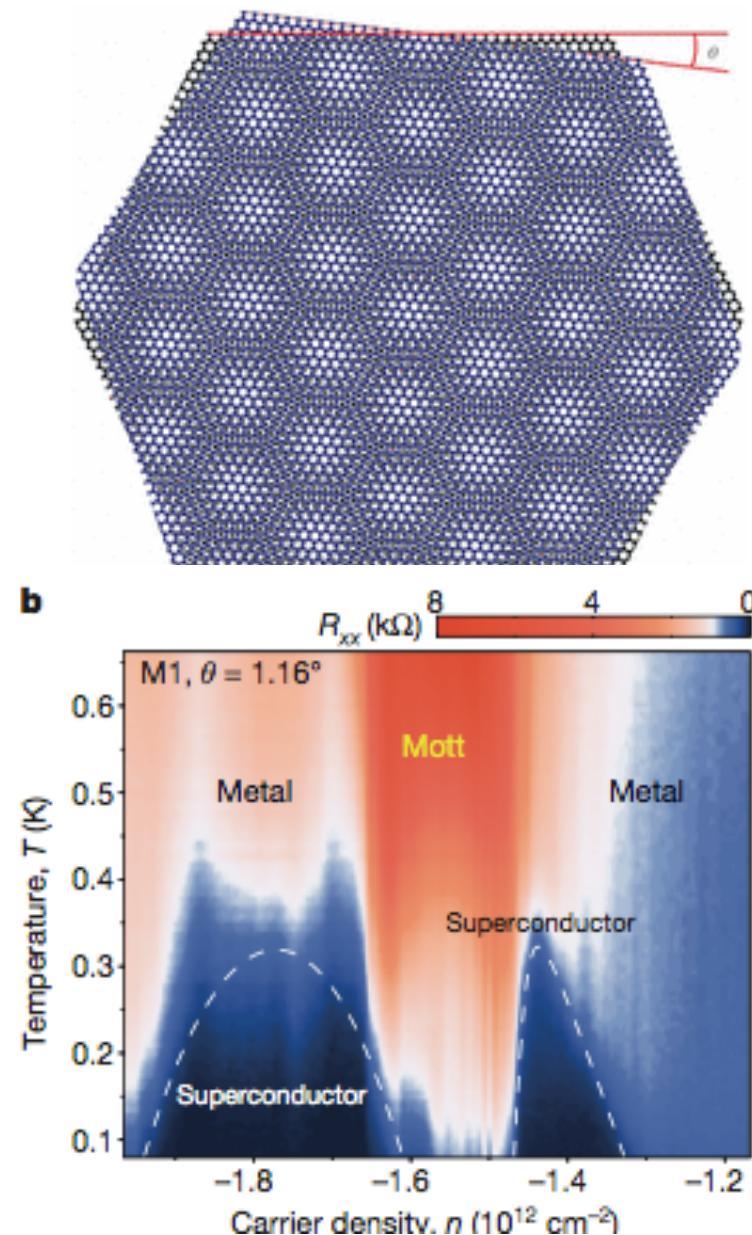
Supercondutores “anómalos”

Twisted bilayer graphene!

Two layers of graphene at different relative angles form a quasiperiodic structure, or moiré lattice, at a larger length scale than graphene’s lattice constant—see the larger hexagons in figure 1, in which the graphene sheets nearly align at their centers and increasingly misalign toward their edges.

At twist angles closer to the predicted magic angle 1.05° , the researchers observed critical temperatures of the order of 1.7 K

Cao, Y., Fatemi, V., Fang, S., Watanabe, K., Taniguchi, T., Kaxiras, E., & Jarillo-Herrero, P. (2018). *Unconventional superconductivity in magic-angle graphene superlattices*. *Nature*, 556(7699), 43–50. doi:10.1038/nature26160



Supercondutores de alta temperatura (cuprates)

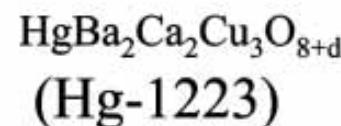
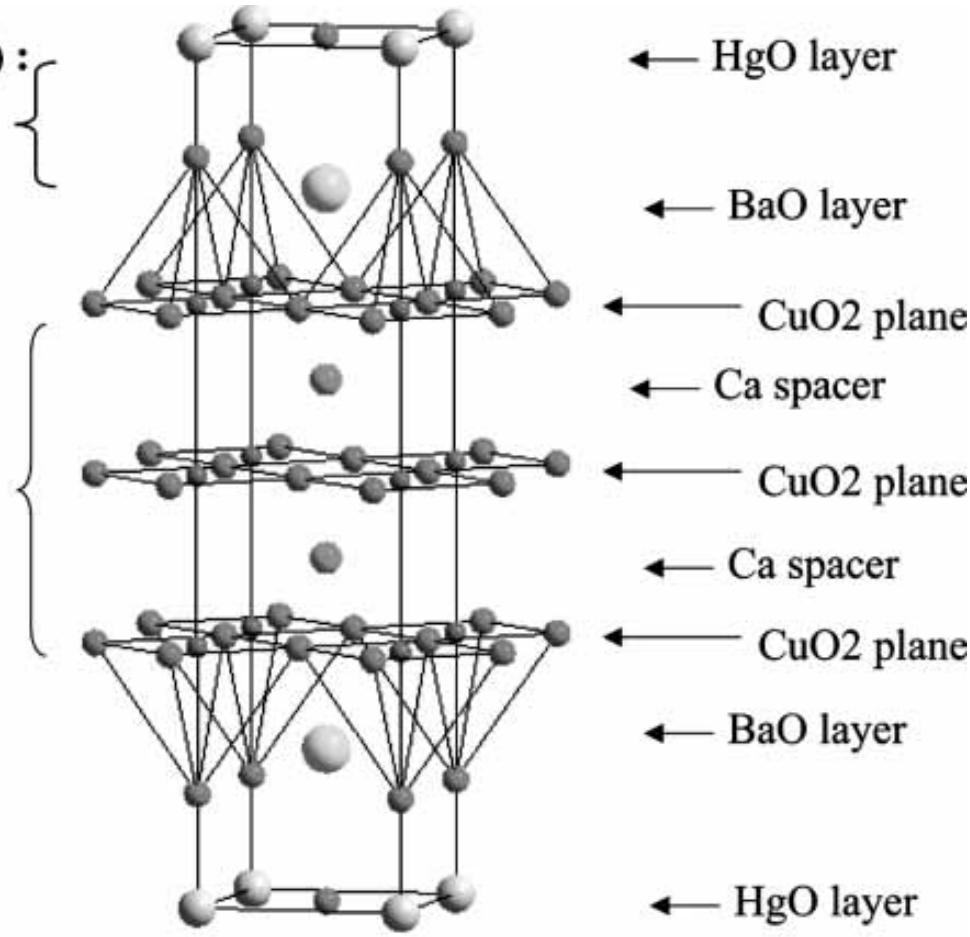
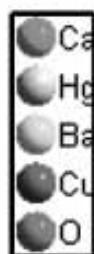
Structures

Charge reservoir (rock salt type) :

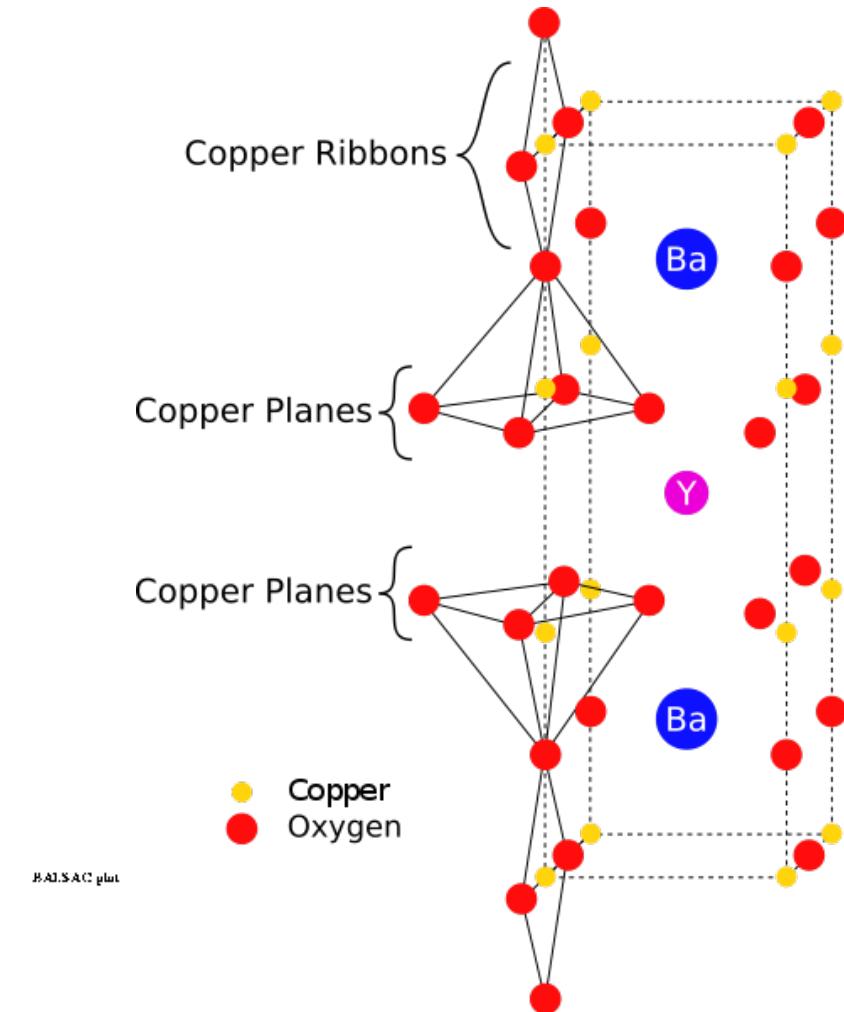
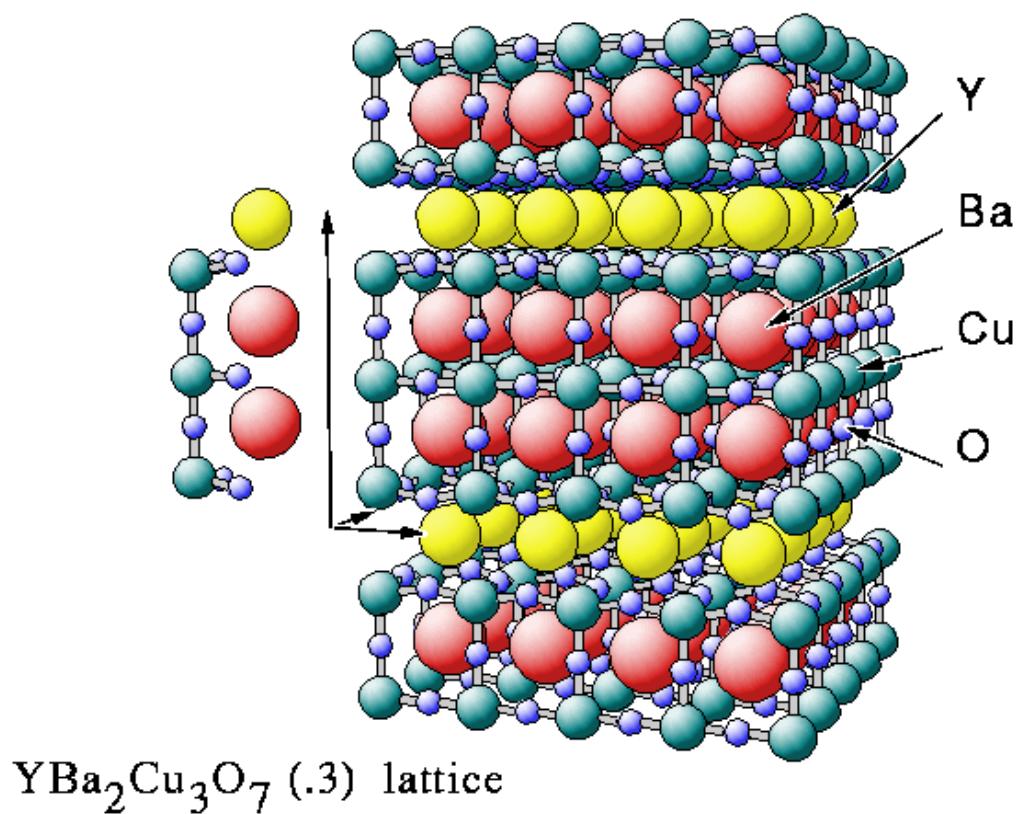
- 1 [HgO] heavy metal layer
- 2 [BaO] interfacial layers

Conducting block:

- 2 [Ca] spacer layers
- 3 [CuO₂] planes



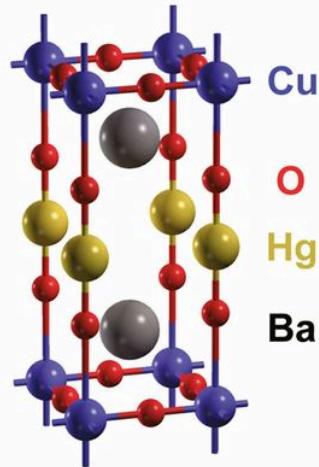
Structures



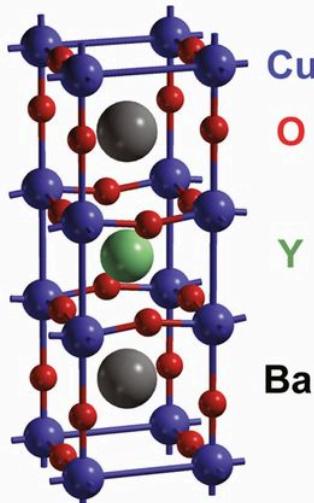
Structures

A

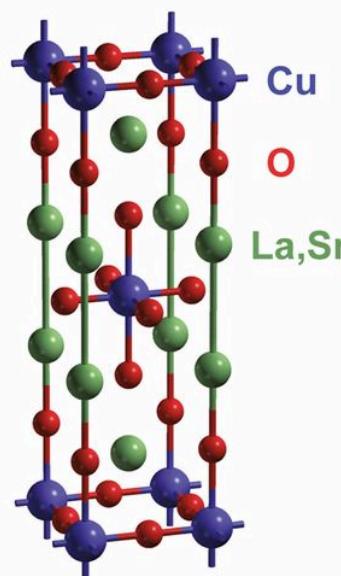
$\text{HgBa}_2\text{CuO}_{4+\delta}$
(Hg1201)



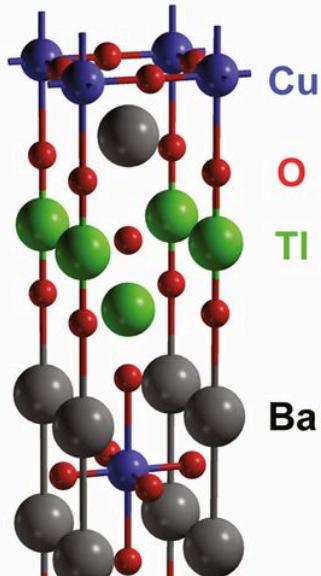
$\text{YBa}_2\text{Cu}_3\text{O}_{6+\delta}$
(YBCO)



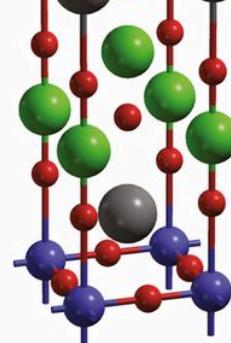
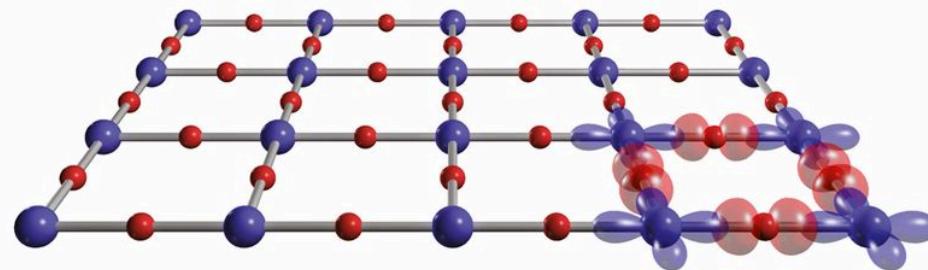
$\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$
(LSCO)



$\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$
(Tl2201)

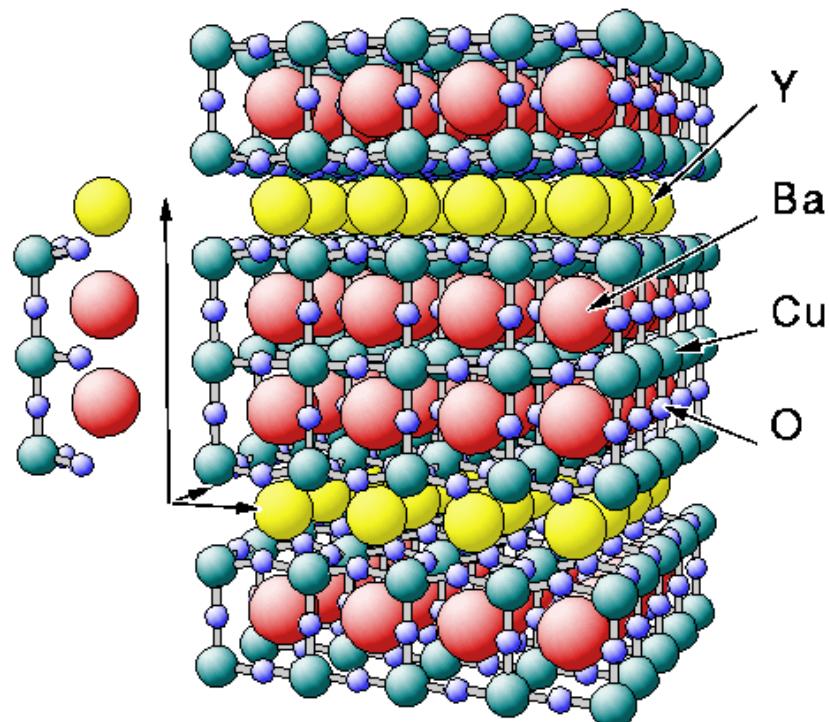


B

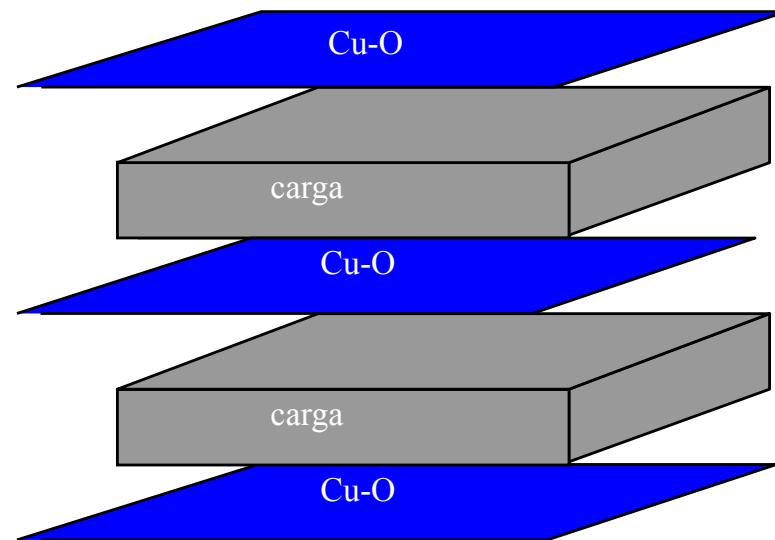


Structures

Sistemas quase-bidimensionais

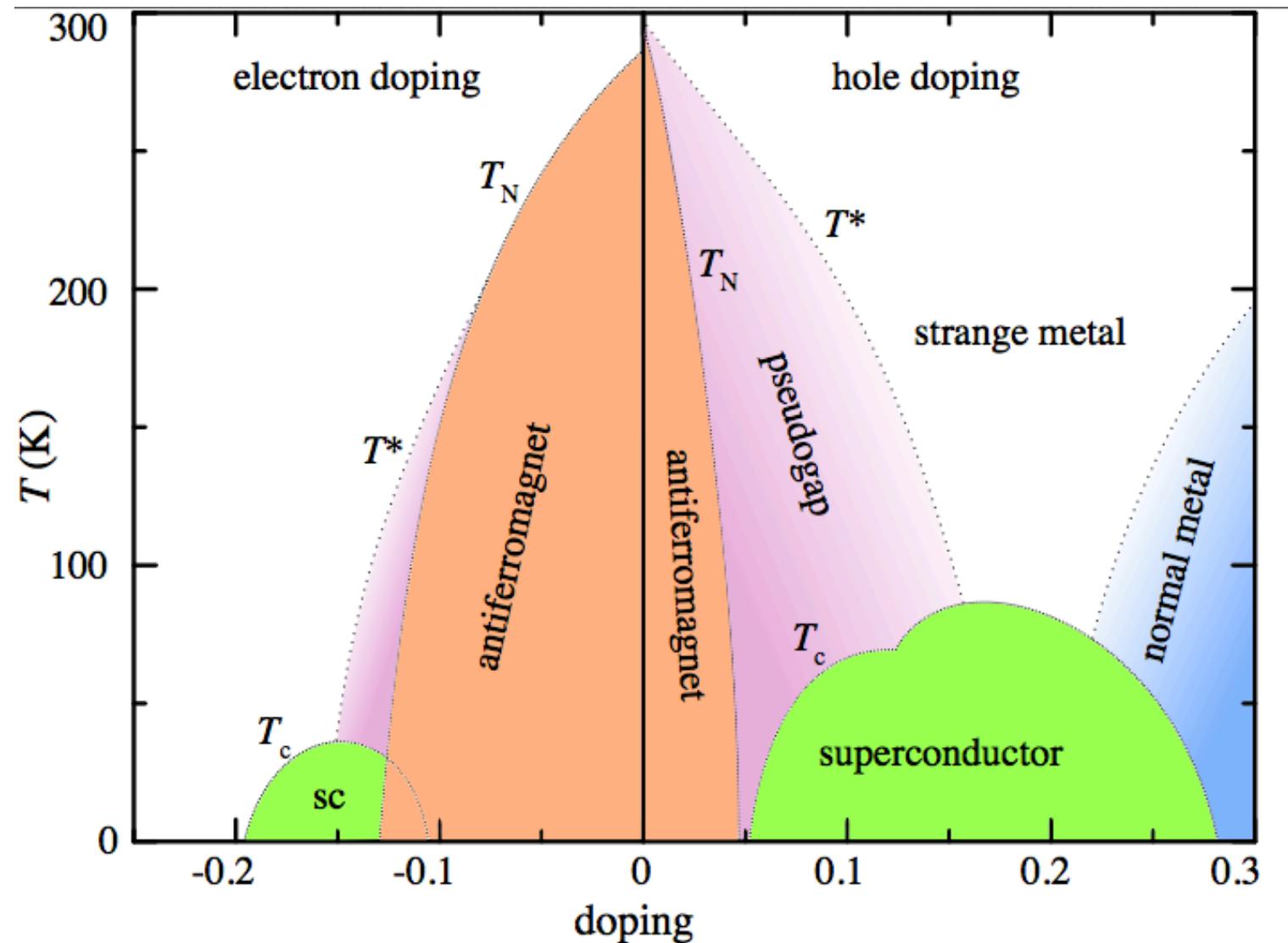


$\text{YBa}_2\text{Cu}_3\text{O}_7$ (.3) lattice



BALSA C plut

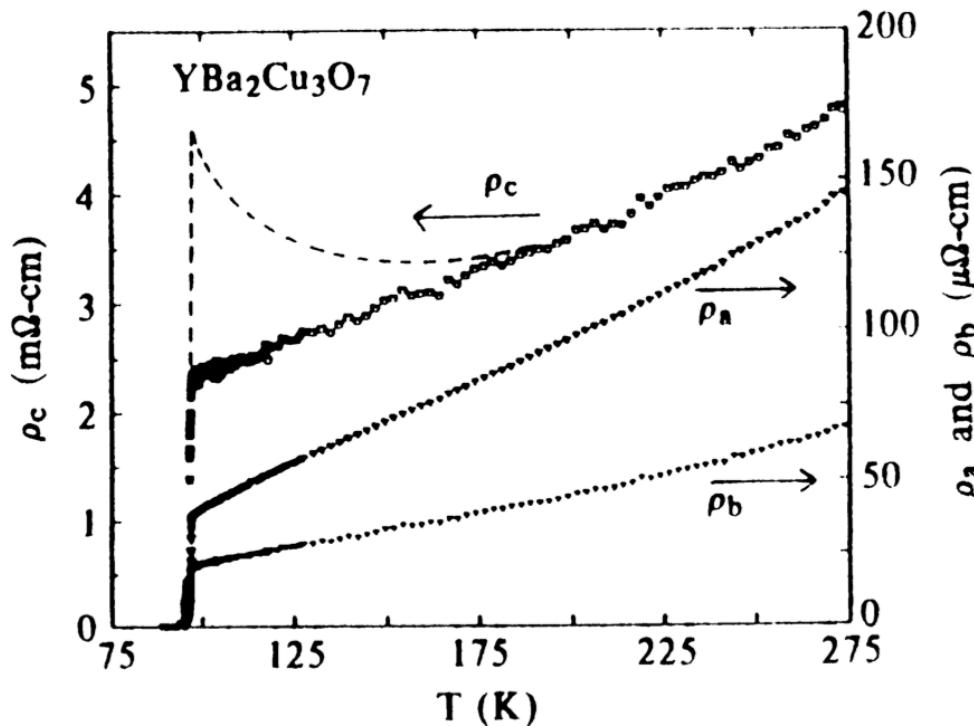
Phase diagram



Supercondutores de alta temperatura (cuprates)

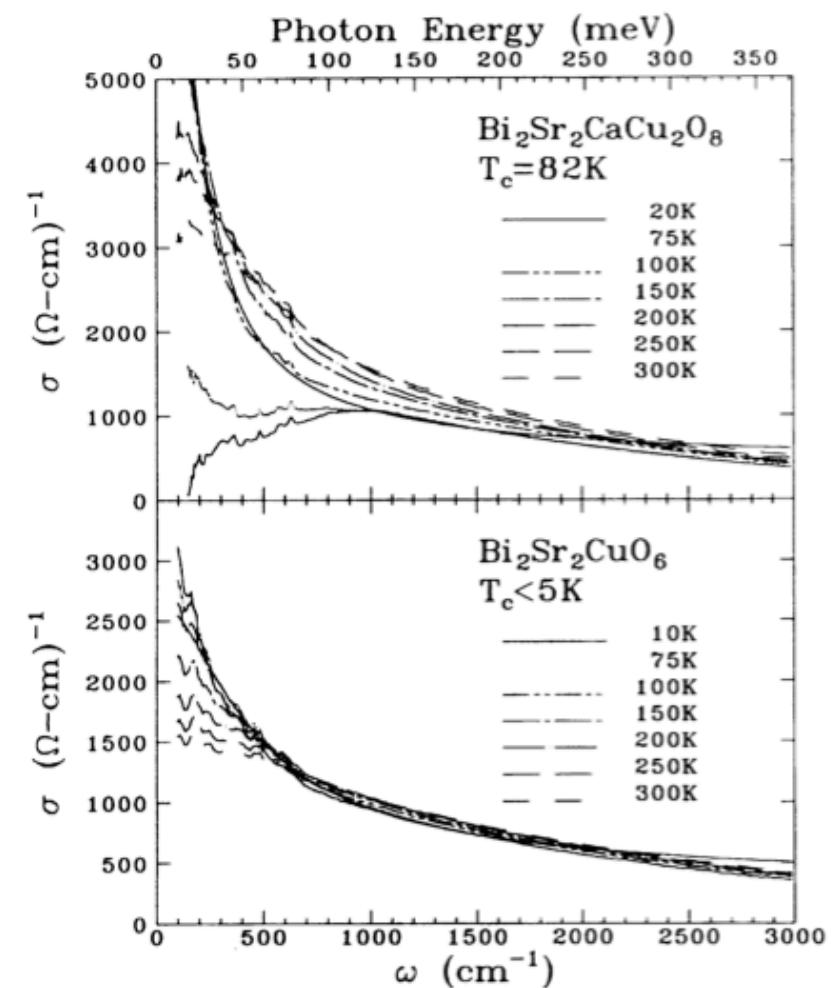
resistivity

optimally doped $\text{YBa}_2\text{Cu}_3\text{O}_7$



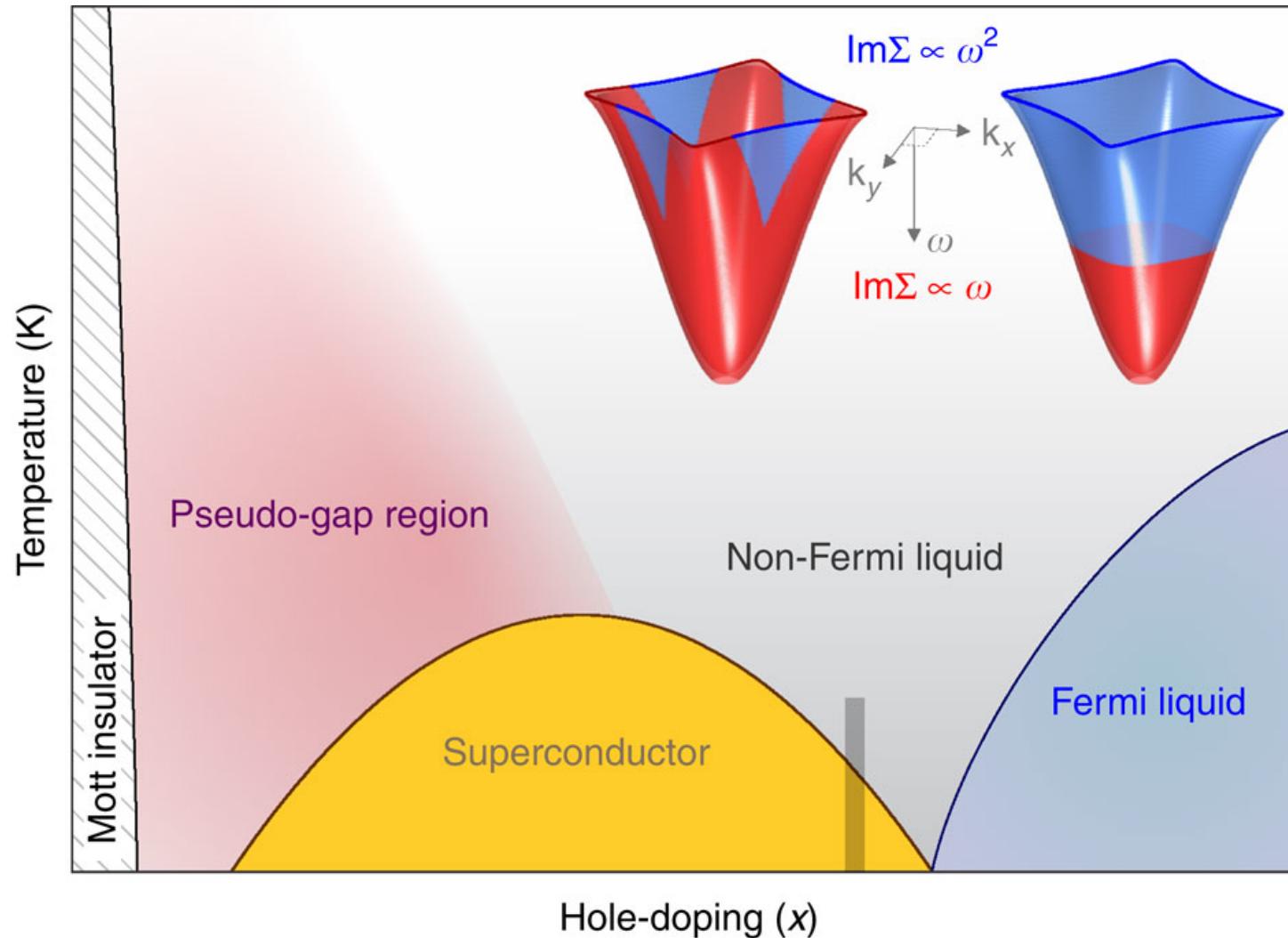
Linear resistivity $\frac{1}{\tau} \propto T$.

Optical conductivity

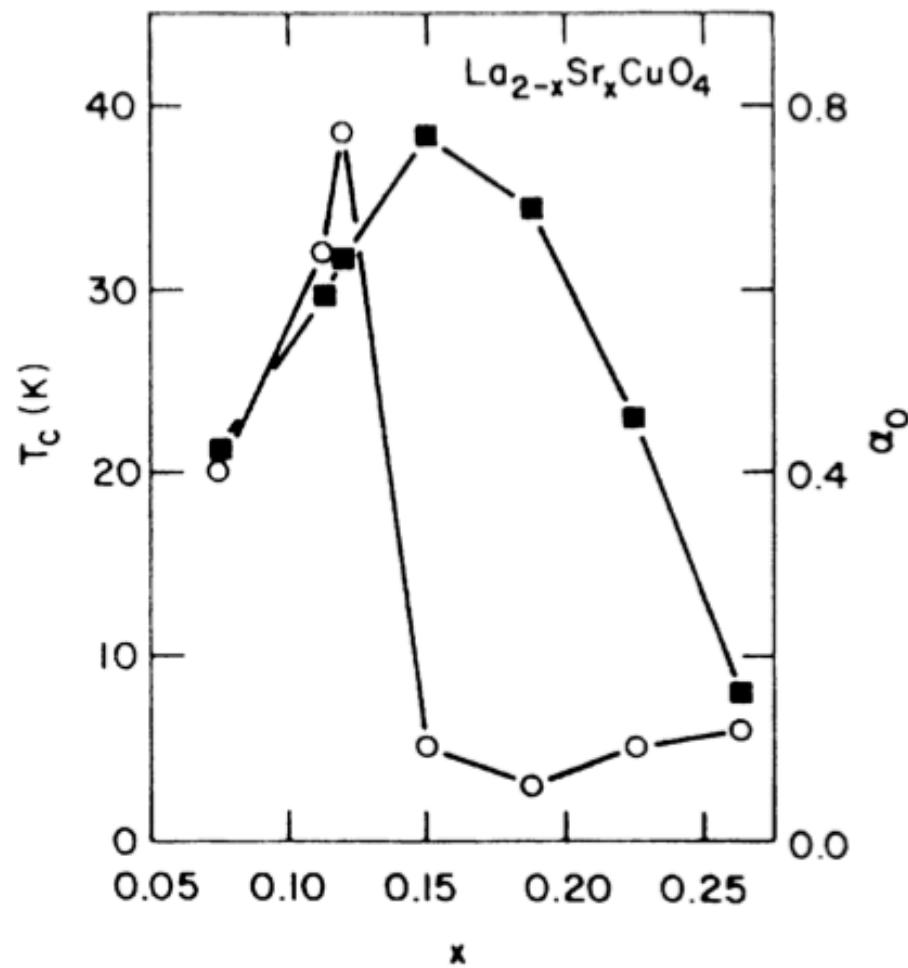


$$\sigma(\omega) \propto \omega^{-1}$$

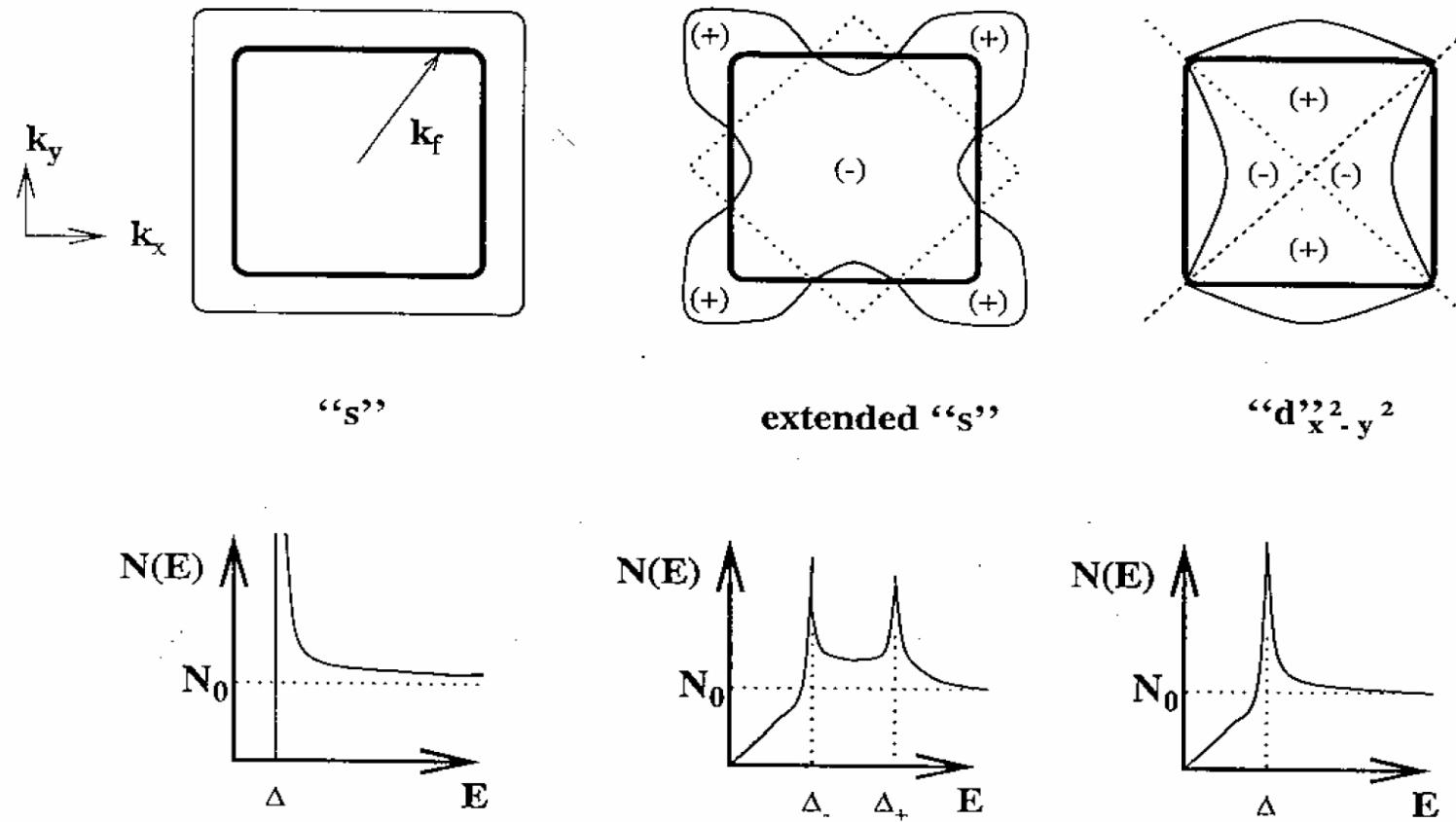
Phase diagram



Isotope effect

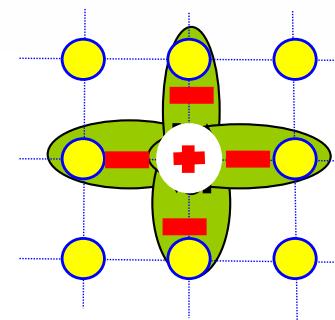


d-wave

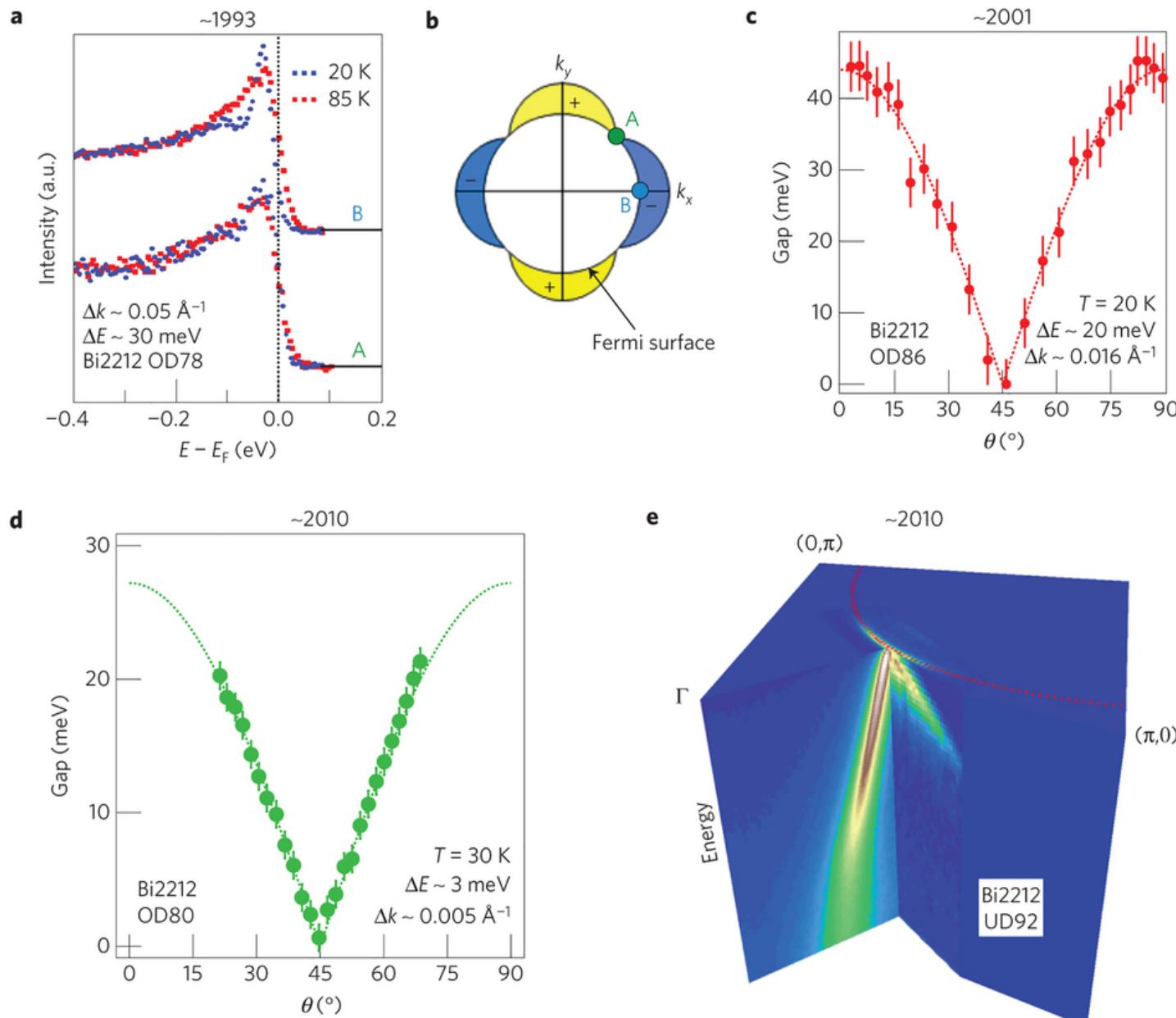


Pairing Potential

$$V_{\mathbf{k}, \mathbf{k}'} = -2V_0 \cos(2\theta_k) \cos(2\theta_{k'}) + \mu^*,$$



Supercondutores de alta temperatura (cuprates)



D wave symmetry

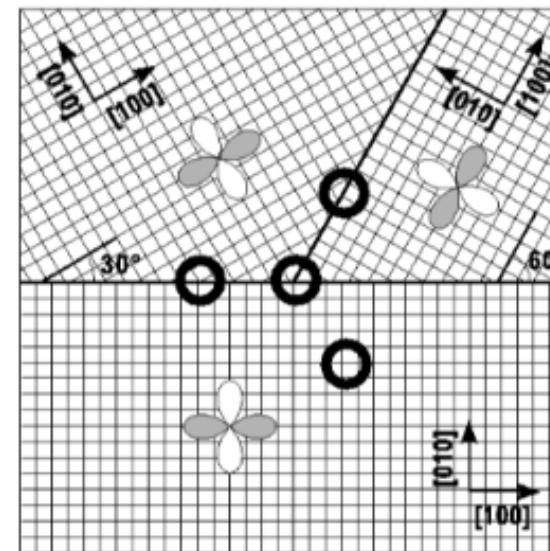
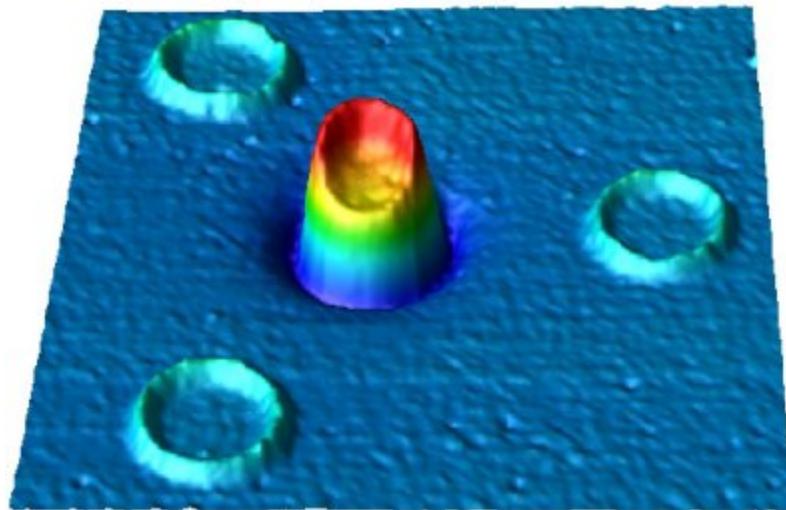


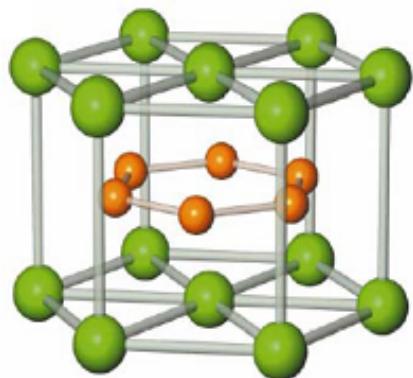
Fig. 16.12. Experimental configuration for the π -ring tricrystal experiment of Tsuei et al. [87]. The central, three-junction ring is a π -ring, which should show half-integer flux quantization for a $d_{x^2-y^2}$ superconductor, and the two-junction rings and 0-junction ring are 0-rings, which should show integer flux quantization, independent of the pairing symmetry

duas bandas- MgB_2

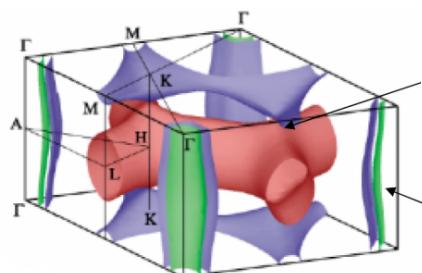
duas bandas- MgB_2

Duas bandas \rightarrow dois gaps

estrutura



superfície de Fermi



interacção electrão-fonão fraca

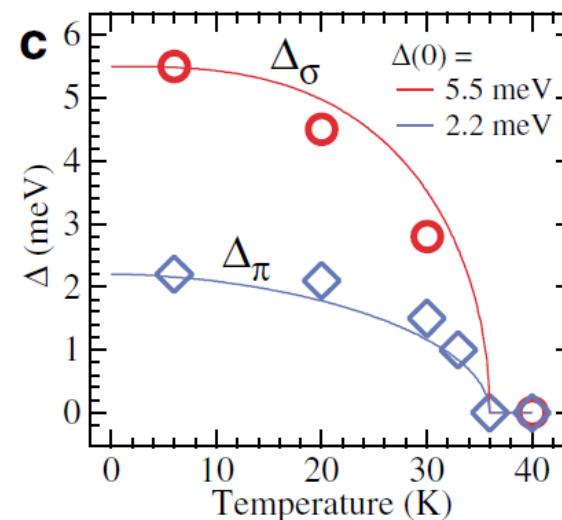
⌚ gap pequeno

interacção electrão-fonão forte

⌚ gap grande

ARPES

S. Tsuda et al, PRL 2003



duas bandas

Hamiltoniano

$$H = \sum_{ik\sigma} \xi_{k\sigma}^i c_{k\sigma}^{i\dagger} c_{k\sigma}^i - \sum_{ij, k_1 k_2} V_{ij} c_{i,k_1}^\dagger c_{i,-k_1}^\dagger c_{j,-k_2} c_{jk_2}^\dagger$$

gap

$$\Delta_i = - \sum_{j,k} V_{ij} \langle c_{i,-k} c_{j,k} \rangle,$$

interband interaction leads to a

$$-\Delta_i \Delta_j \cos(\phi_{ij})$$

coupling term in the free energy

Φ_{ij} diferença de fase entre Δ_i e Δ_j

Minimizando a energia livre

$$\phi_{ij} = 0$$

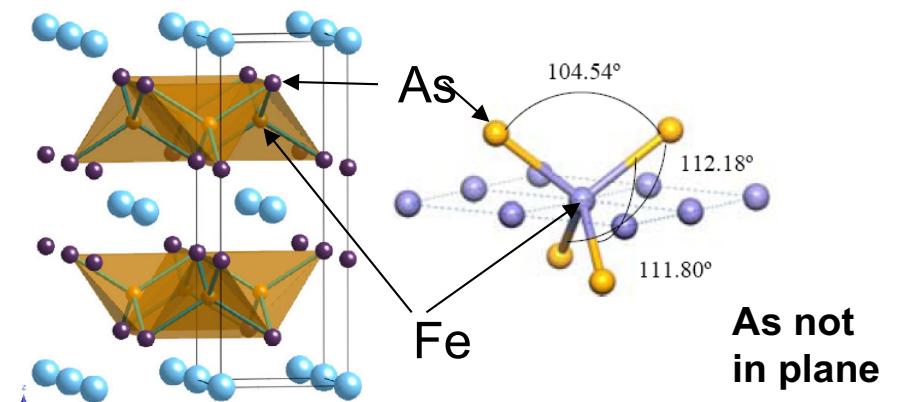
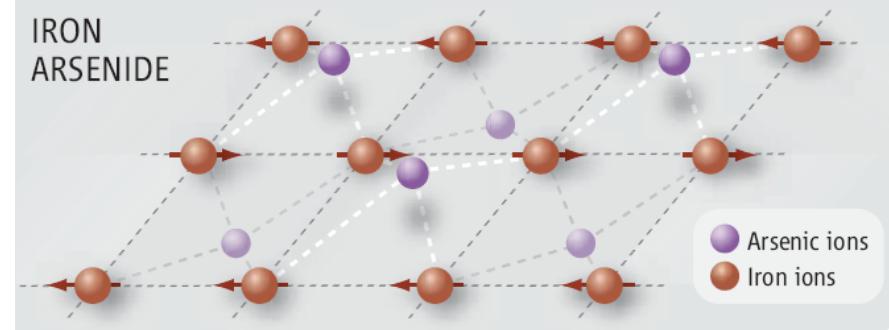
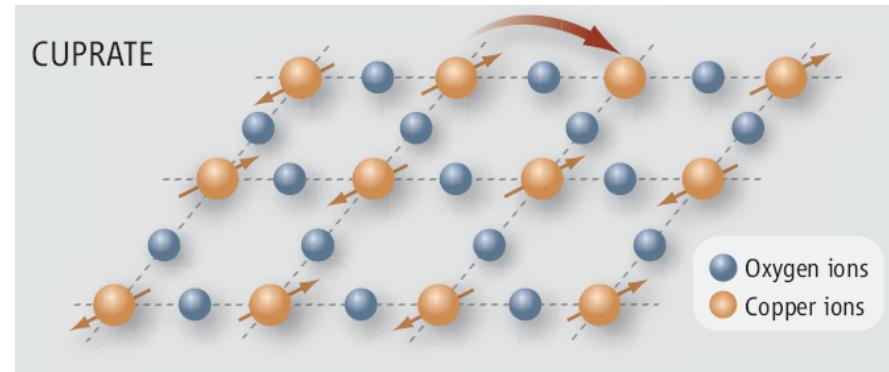
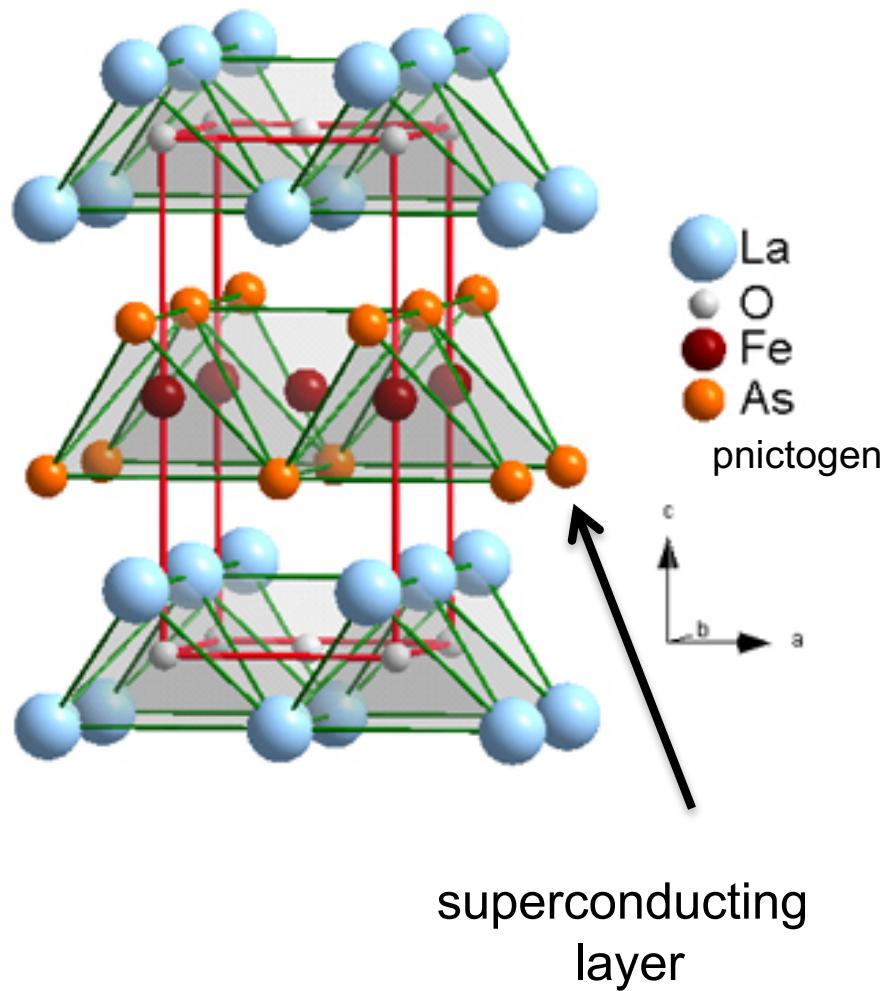
$$\Delta_i = \sum_j V_{ij} \int_0^{\omega_D} d\xi_j K_j(\xi_j, \Delta_j, T) \Delta_j$$

Suhl, Matthias, and Walker PRL
1959

Iron based superconductors

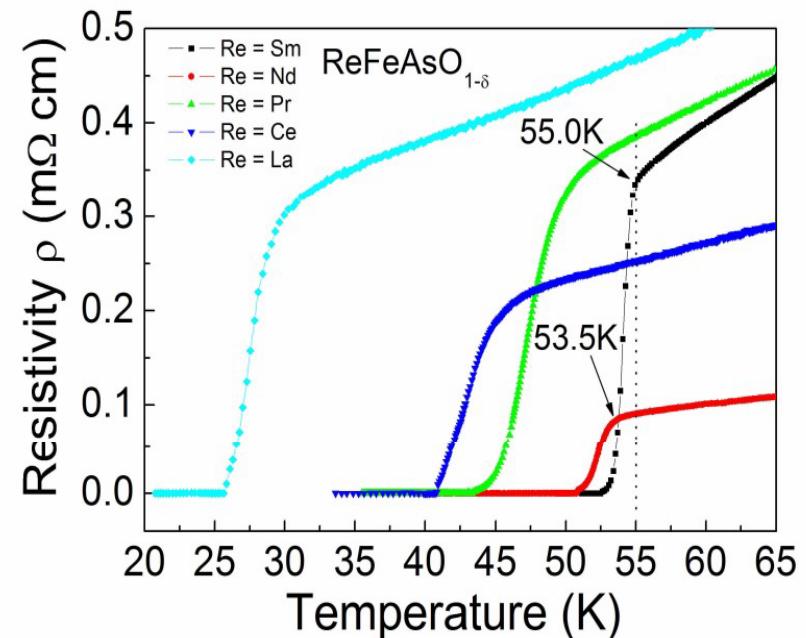
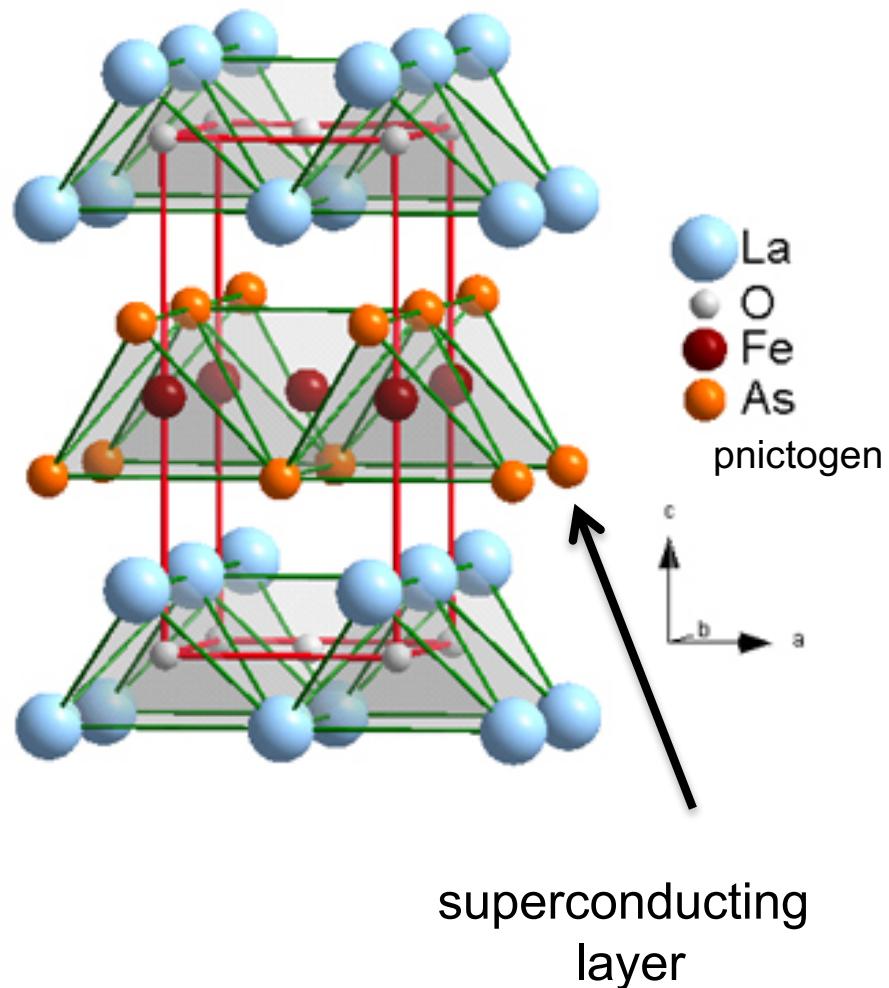
structure

LaFeAsO



Iron based superconductors

LaFeAsO



structure

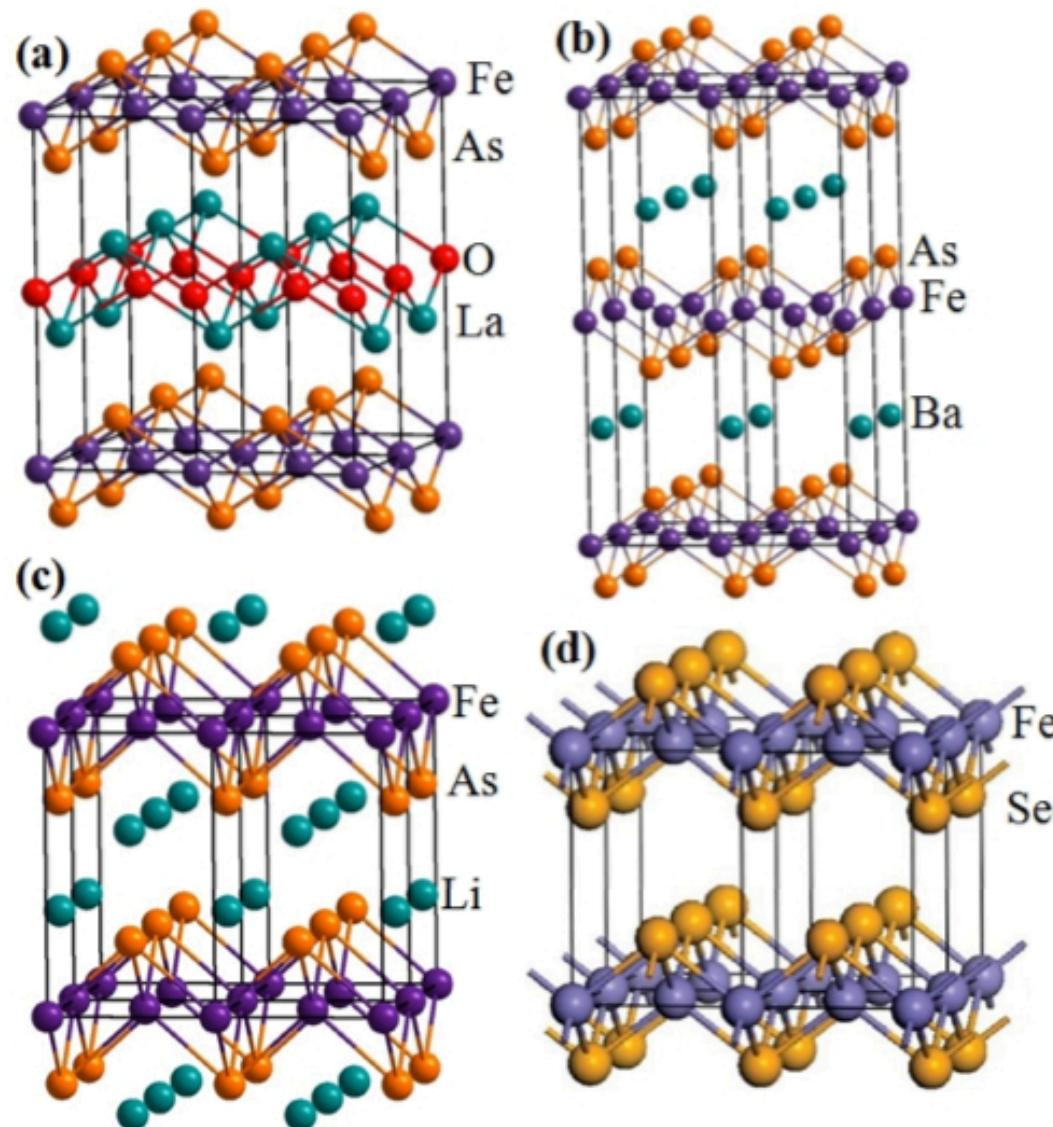
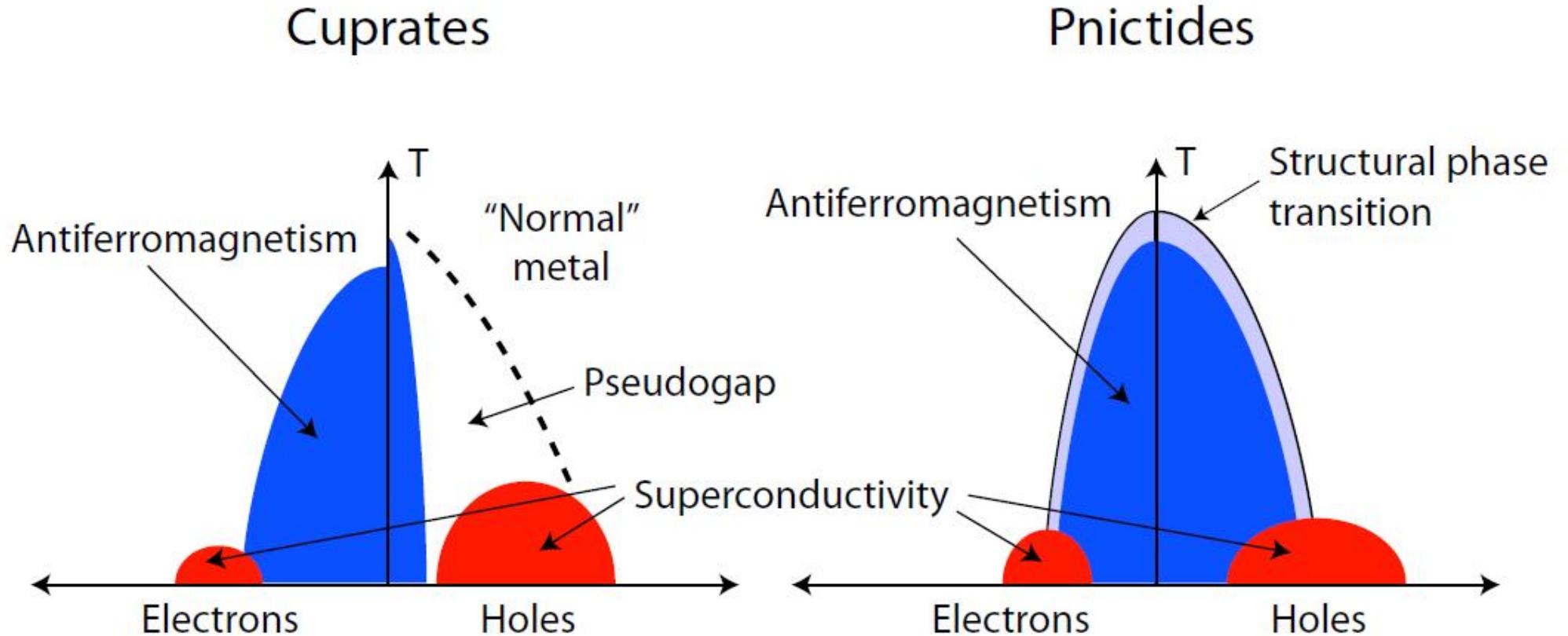


Fig. 1. Four families of iron-based superconductors,
(a) 1111, (b) 122, (c) 111, (d) 11 type. Fig. (d)

Phase diagram



Multiband superconductor

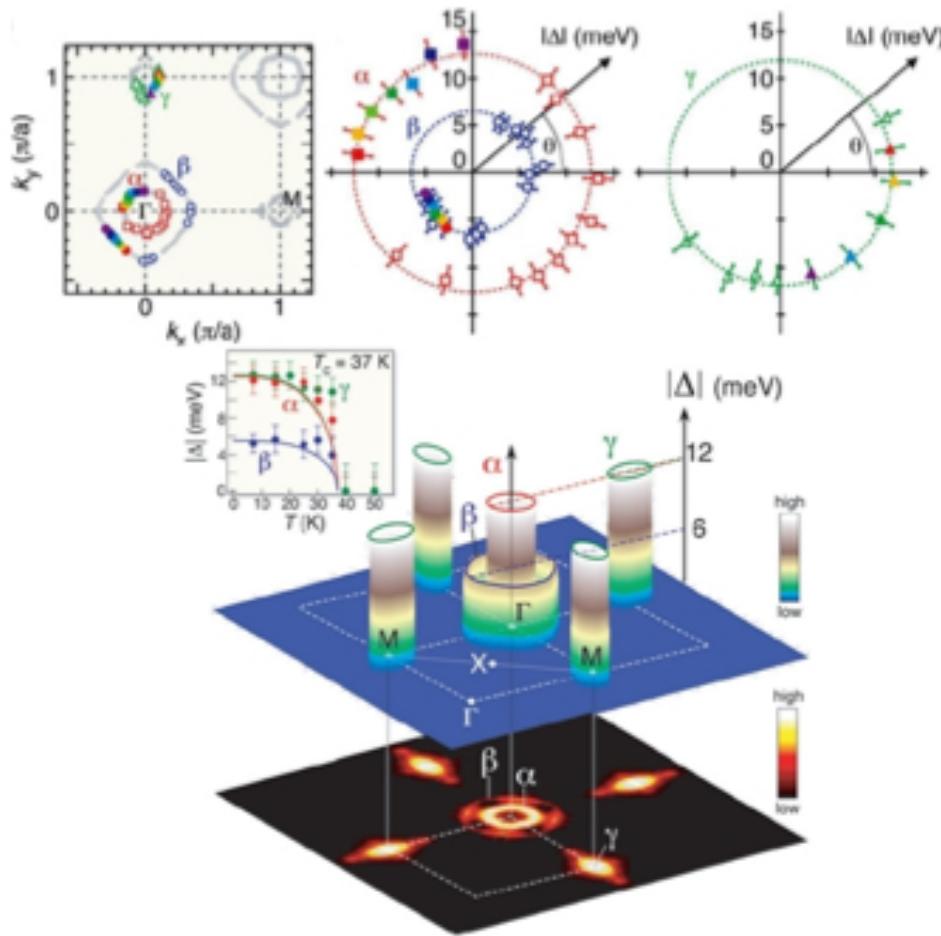


Fig. 18. (a) Fermi surface from ARPES and values of the superconducting energy gap (Δ) in $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ at 15 K. (b) Three-dimensional plot of Δ measured at 15 K on the three observed Fermi surface sheets (shown at the bottom as an intensity plot) and their temperature evolutions (inset). Fig. reprinted from Ref. 95: H. Ding *et al.*, *Europhys. Lett.* **83**, 47001 (2008). Copyright 2008 by EDP Sciences.

Gaps on the two FS around Γ are very different
Large gap in the inner Γ and M
Small gap in the outer Γ pocket

Multiband superconductor

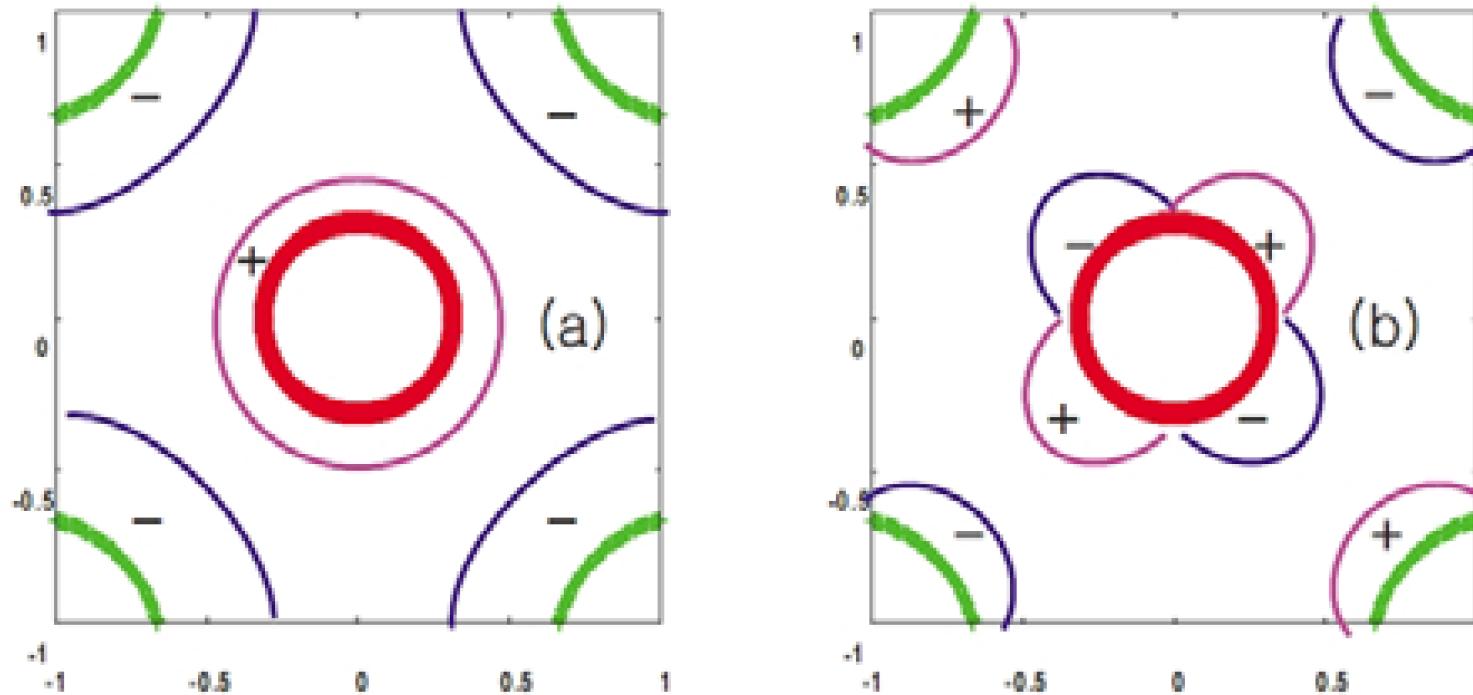
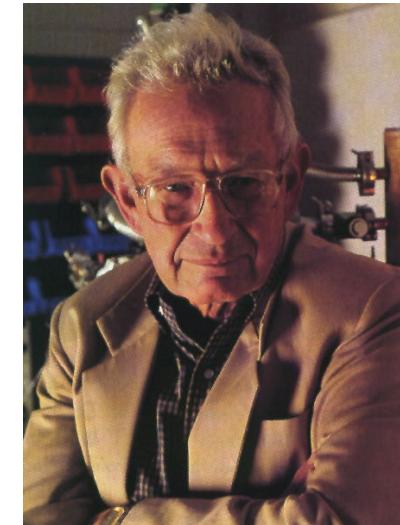
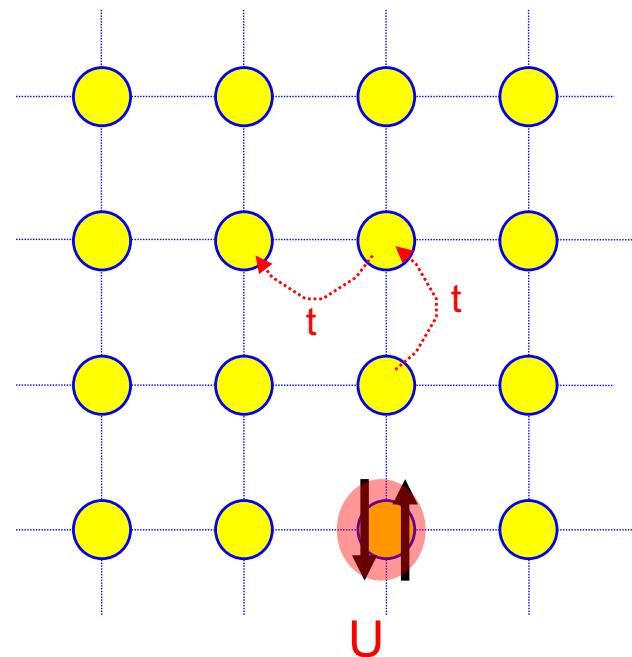


Fig. 20. $\pm s$ -wave gap and double d -wave gap. (a) $\pm s$ -wave gap and (b) double d -wave gap. Fig. reprinted from Ref. 113: Y. Bang and H.-Y. Choi, Phys. Rev. B **78**, 134523 (2008). Copyright 2008 by the American Physical Society.

Teorias de alta temp. crít.

Teorias de alta temp. crít.

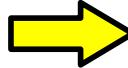
Física \approx 2D Hubbard

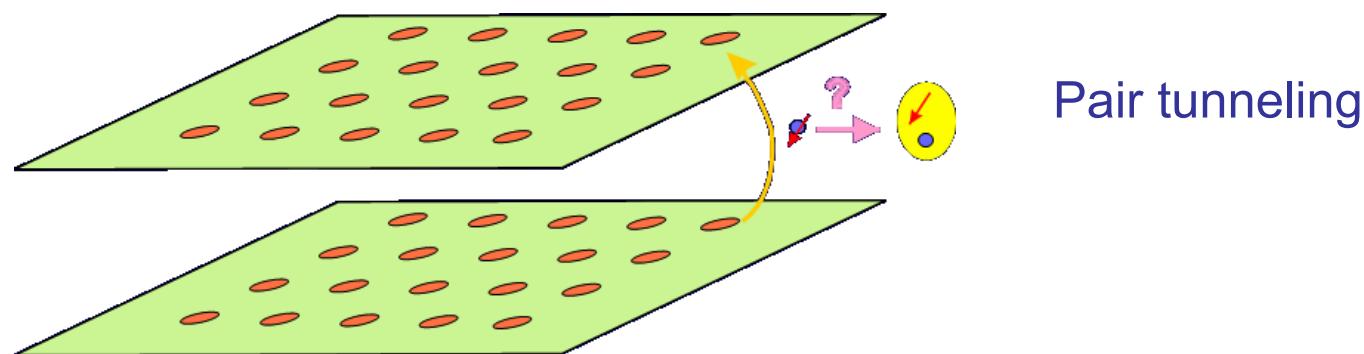


Anderson

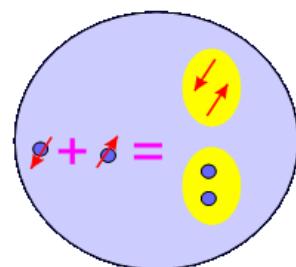
Prémio Nobel 1977

Separação de spin e carga?

Baixa Dimensionalidade + Correlações Fortes  **Líquido de Luttinger**
(a lá 1D)

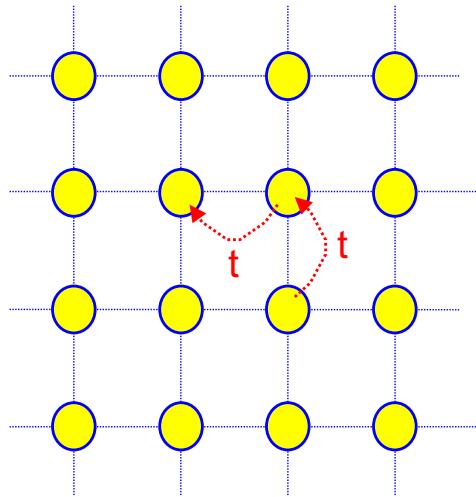


Pair tunneling

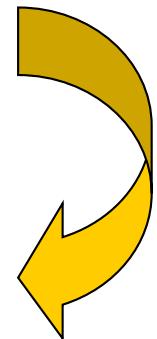
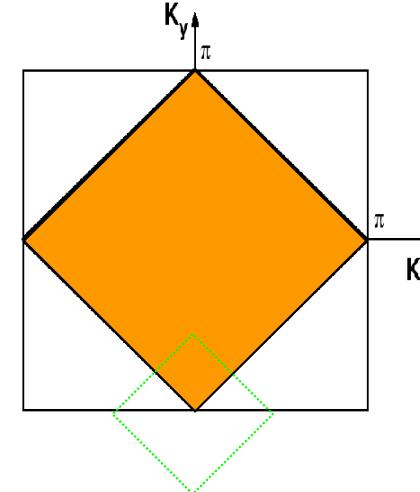


Electrões  spinões+holões

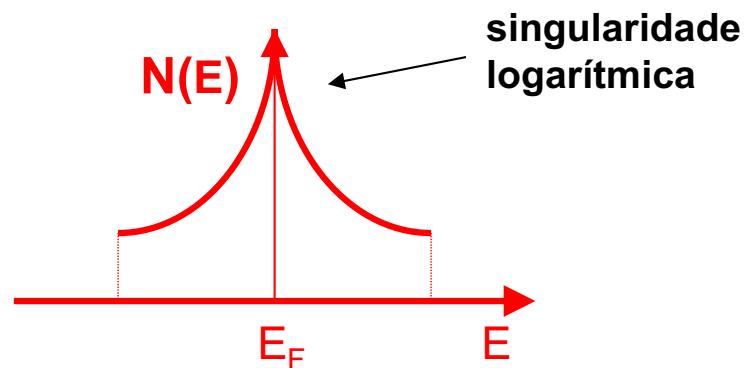
Cenário van Hove



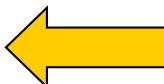
Superfície de Fermi:



Densidade de estados:

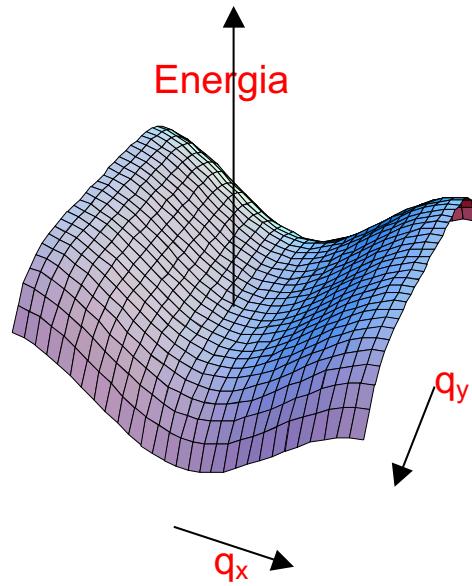


Cenário Van-Hove
(Newns, Labbe, Friedel, etc.)



Cenário van Hove

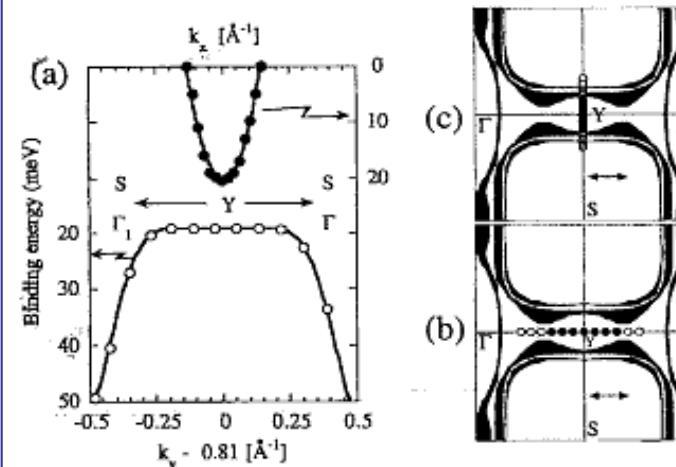
Ponto de sela extendido



$$\varepsilon(\mathbf{q}) = q_x^n - q_y^m$$

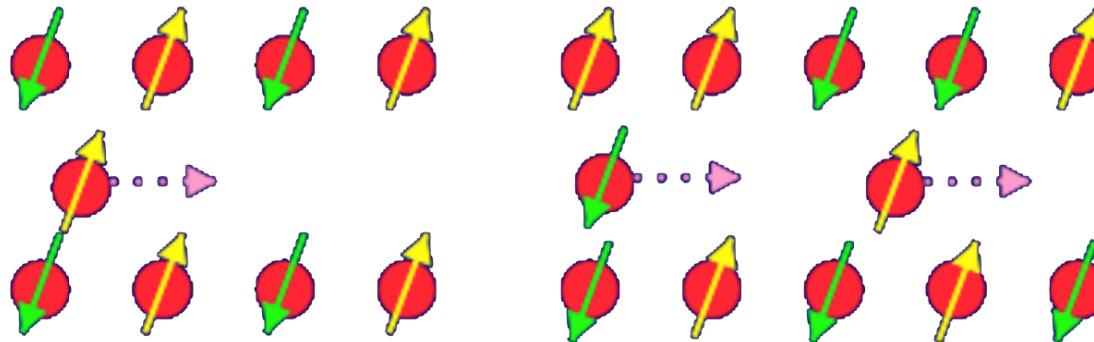
Fotoemissão

$\text{Yba}_2\text{Cu}_3\text{O}_8$: PRL 73, 3302 (1994)



Imada et al,
QMC on Hubbard model

Spin-fluctuations mediated attraction



antiferromagnetic wavevector $\mathbf{Q} = (\pi, \pi)$,

$$\chi(\mathbf{q}, \omega) \sim \frac{\chi_Q}{1 + \xi^2(\mathbf{q} - \mathbf{Q})^2 - i\omega/\omega_{SF}},$$

Effective interaction
between particles

$$V_{\mathbf{k}, \mathbf{k}'}^{\text{eff}} \sim g^2 \chi(\mathbf{k} - \mathbf{k}', \omega),$$

$$\Delta(\mathbf{k}) \sim -g^2 \chi(\mathbf{Q}) \Delta(\mathbf{k} + \mathbf{Q}),$$