

# *Fenômenos magnéticos em altos campos e baixas temperaturas*

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**Universidade de São Paulo**

# Baixas Temperaturas - Geladeira ?

Congelador → - 20 °C

Geladeira → 4 °C



# Baixas Temperaturas - Antártica ?

Temperatura mais baixa já registrada na Terra!

**Estação Vostok**

**-89.2°C** em 21 de Julho de 1983



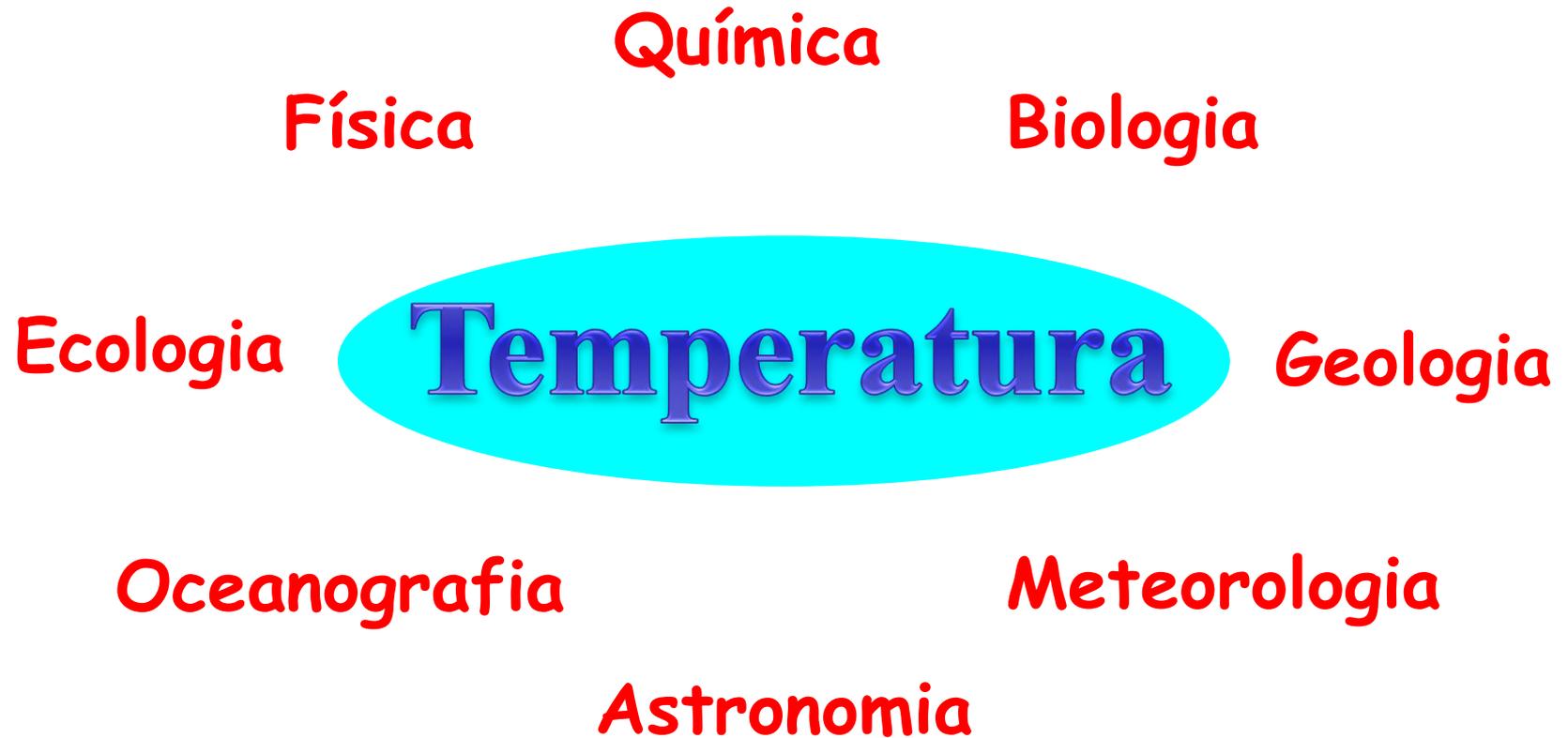
View of the main drag



Plaque commemorating the coldest temperature recorded on Earth

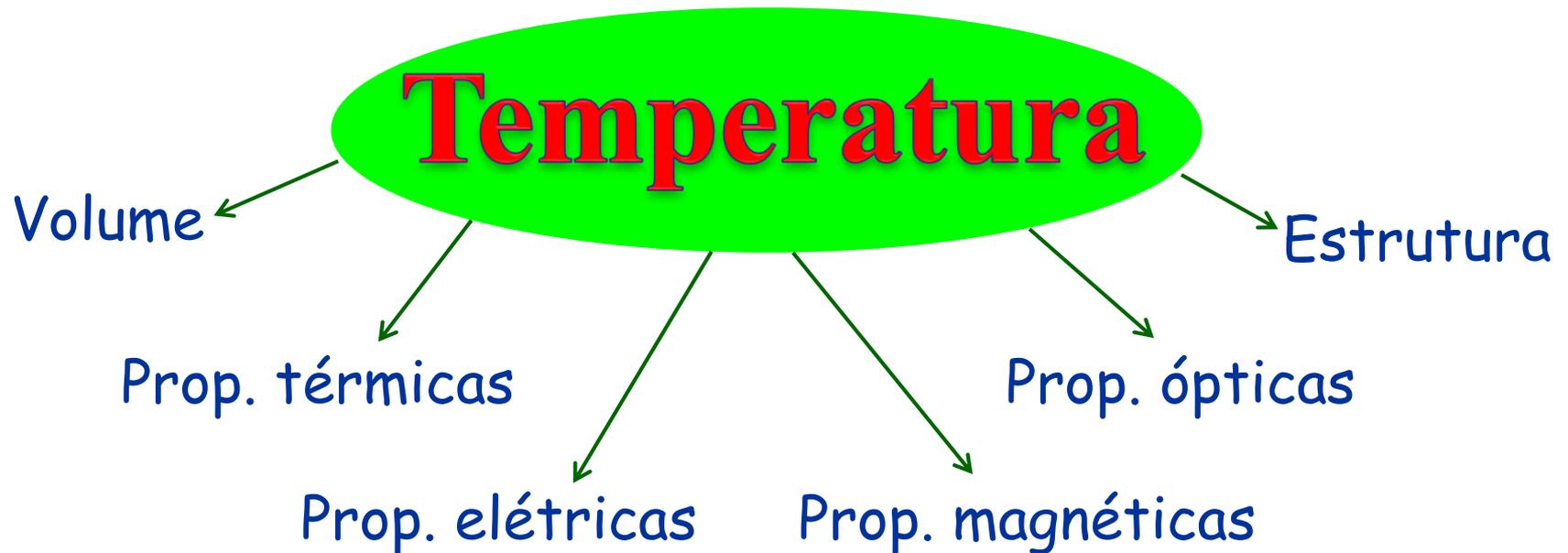
# Importância da temperatura

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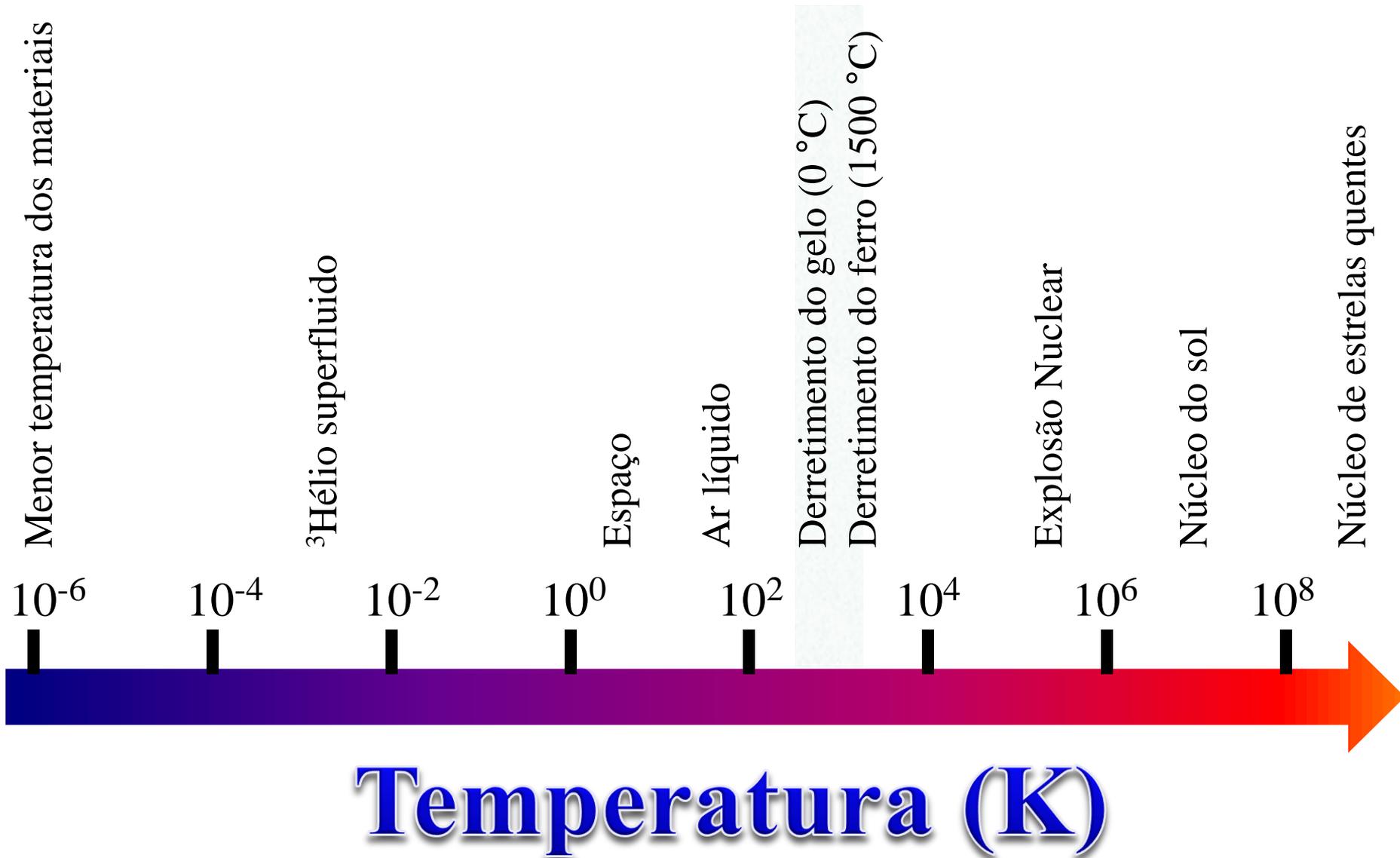


# Física da Matéria condensada

## Propriedades dos Materiais:

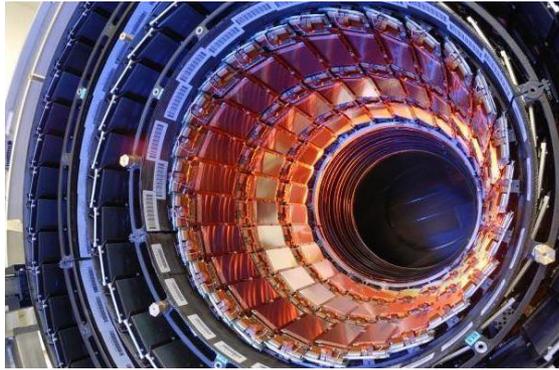


# Ampla espectro de temperatura



# Baixas Temperaturas - Por que estudar ?

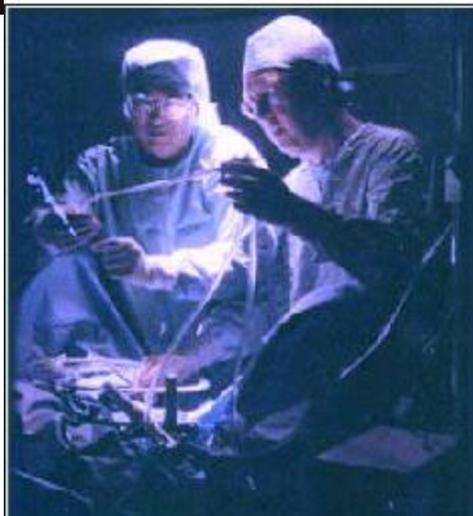
Pesquisa em Física - LHC



Veterinária



Medicina:  
Cirurgia  
criogênica



Transporte criogênico de gás natural



Medicina - RMN



# Baixas Temperaturas - Por que estudar ?

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## Combustível



100 t  $\text{LH}_2$  + 600 t  $\text{LO}_2$

## Cryonics (?)



Corpo inteiro (\$\$\$\$\$)

Neuropaciente (\$\$\$)

Animal de estimação (\$\$)...

# Como obter baixas temperaturas ?

## Criogenia

$T < 123 \text{ K} (-150 \text{ °C})$

Ramo da Física que envolve a produção e estudo das baixas temperaturas e do comportamento dos materiais nessas temperaturas.

## 1) Nitrogênio Líquido 77 K (-196 °C)



Ar ~ 80% N<sub>2</sub>

Antigo  
Liquefator  
de N<sub>2</sub> do  
IF-USP

Como obter baixas temperaturas ?

## 2) Hélio Líquido 4,2 K (-269 °C)

Fonte do gás: Reservas de gás natural subterrâneo

EUA, Rússia, Norte da África → 10% He

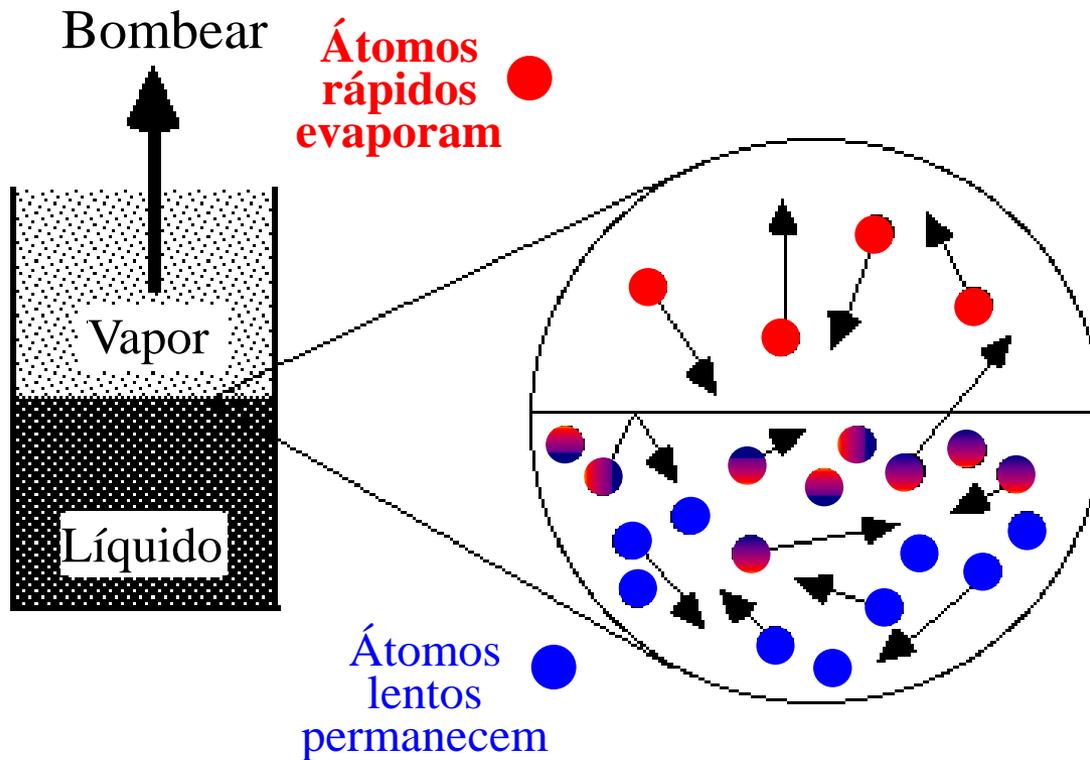


Liquefação do Gás:

Liquefator  
de He do  
IF-USP

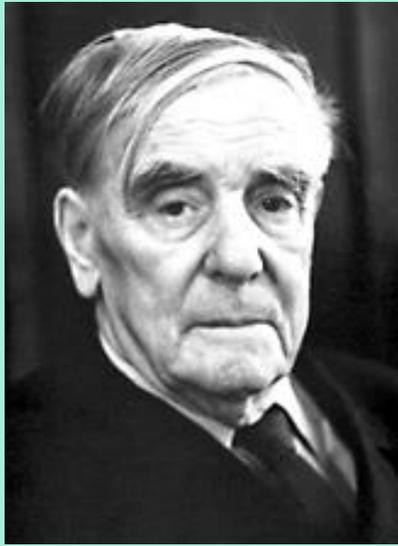
# Como obter baixas temperaturas ?

## 2) Hélio Líquido Bombeado 1,3 K (-272 °C)



Importância das bombas de vácuo em Física de Baixas temperaturas !

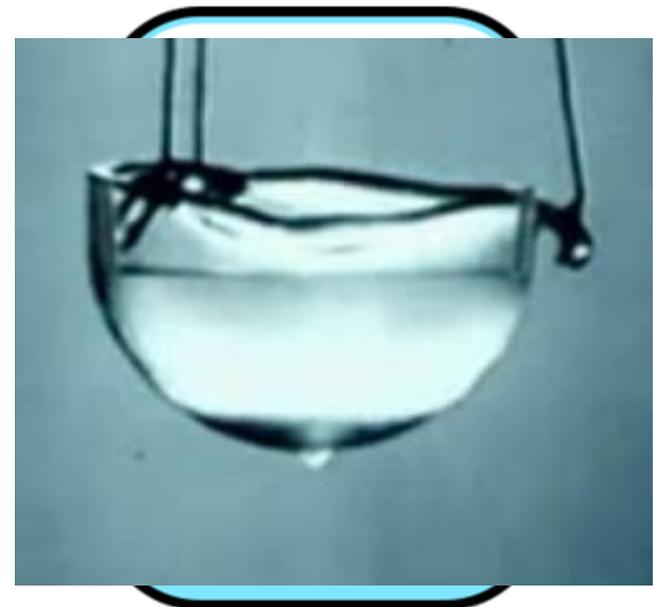
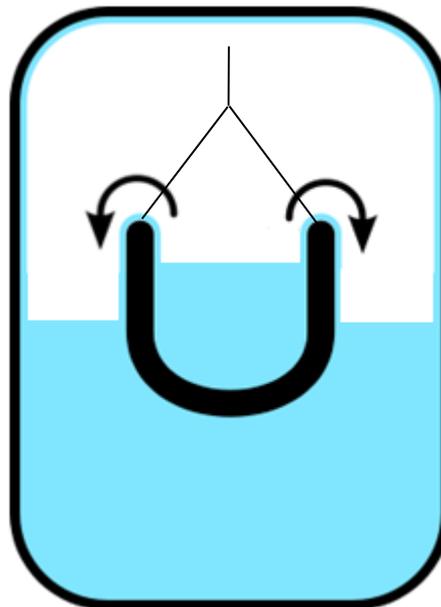
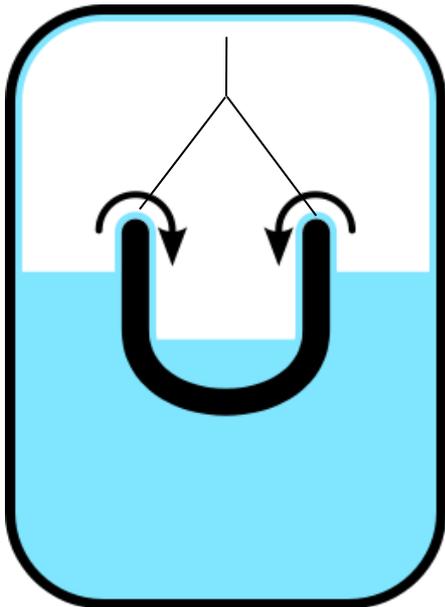
# Superfluidez do Hélio líquido



Pyotr Kapitsa (1894-1984)

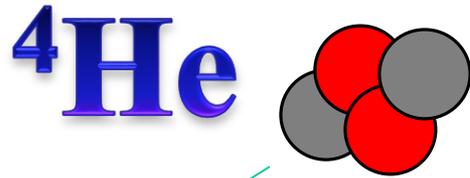
Transição Lambda  $T = 2,2 \text{ K}$

Viscosidade Nula !

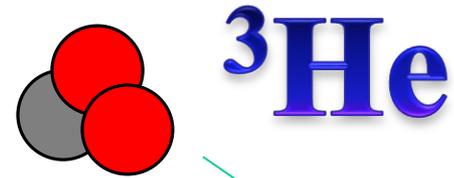


# Como obter baixas temperaturas ?

## 3) Hélio-3 Líquido Bombeado 0,3 K



2 prótons + 2 nêutrons



2 prótons + 1 nêutron

Abundância Natural de  ${}^3\text{He}$ : 0.000137%

Subproduto de usinas nucleares ou do  
desmantelamento de armas nucleares

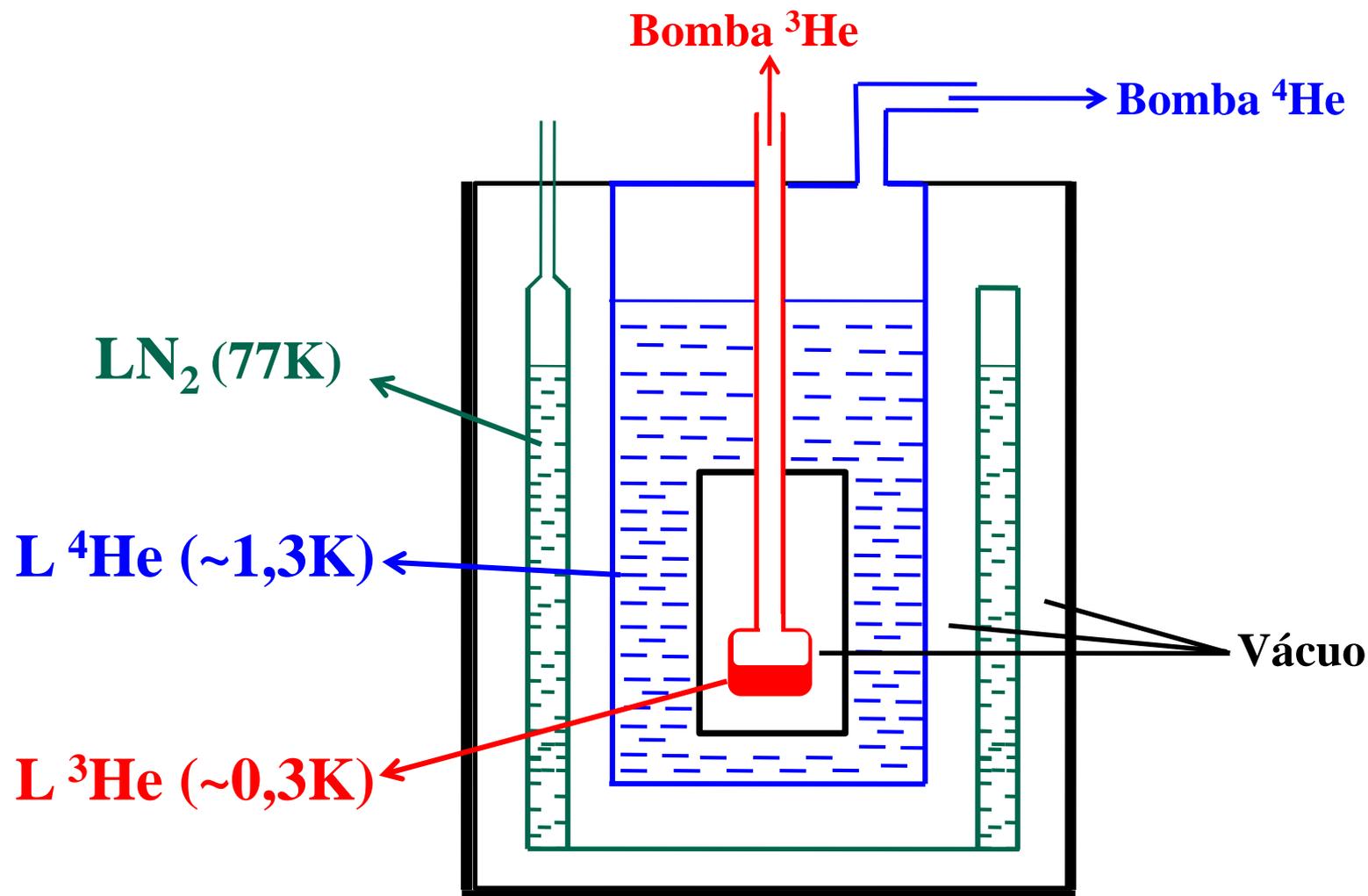
Trítio

Alto custo ~ US\$ 300 por litro de gás

300mL ~ US\$ 20.000

# Como obter baixas temperaturas ?

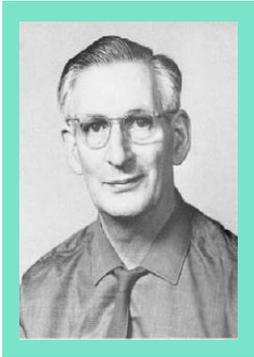
## Refrigerador de $^3\text{He}$



Como obter baixas temperaturas ?

## 4) Refrigerador de Diluição ( $\text{He}^3/\text{He}^4$ )

$T = 0,01 \text{ K}$  (10 mK)



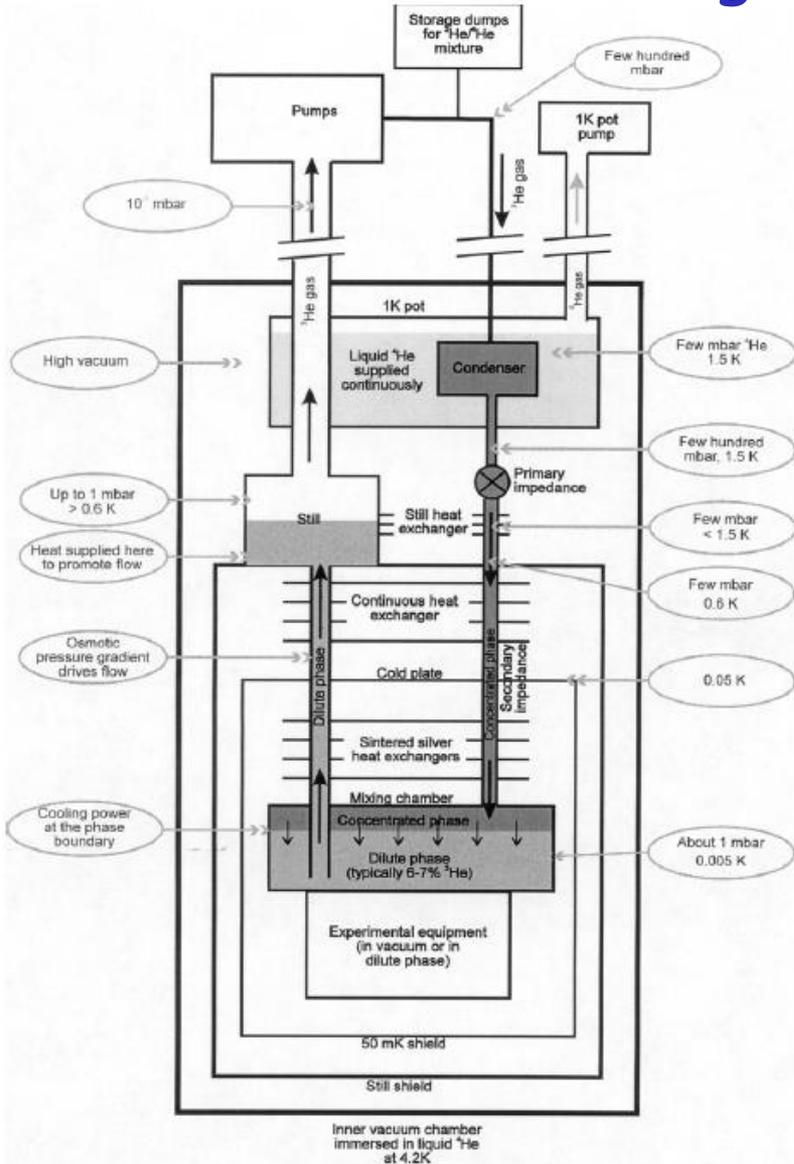
Heinz London (1907-1970)



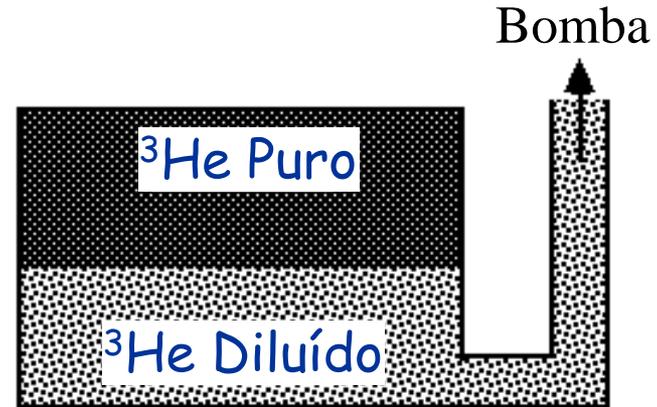
Refrigeradores de diluição do  
IF - USP

# Como obter baixas temperaturas ?

## Refrigerador de Diluição T = 10 mK



- Separação de Fases  $^3\text{He}$ - $^4\text{He}$
- Solubilidade Finita



$^3\text{He}$  líquido  $\rightarrow$   $^3\text{He}$  "gás"

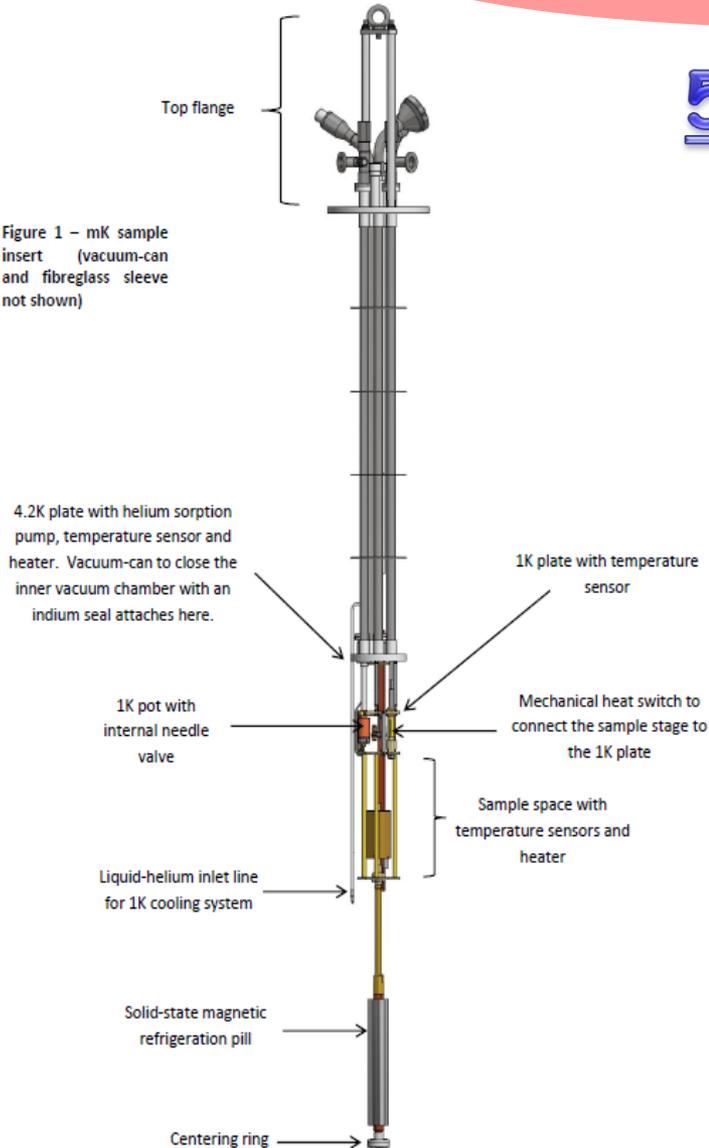
# Como obter baixas temperaturas ?

Mais frio ainda ???

## 5) Refrigeração magnética

### 2. mK sample insert

Figure 1 – mK sample insert (vacuum-can and fibreglass sleeve not shown)

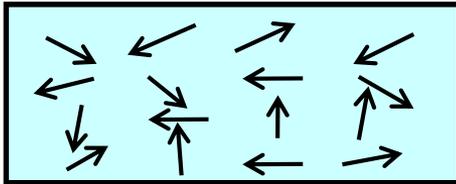


**Eletrônica**  
**T= 0,003 K (3 mK)**

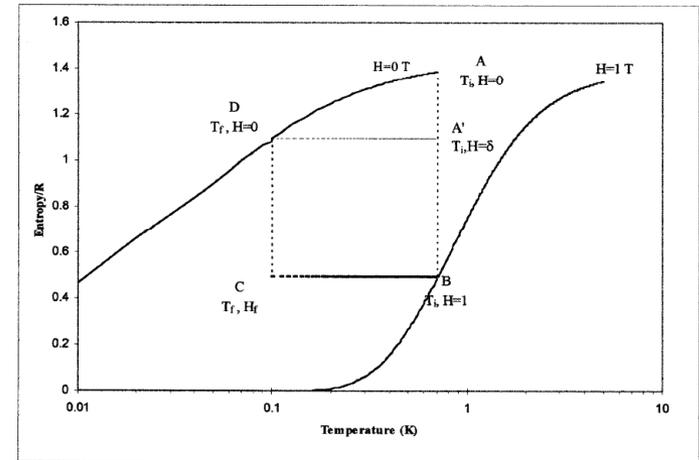
**Nuclear**  
**T= 0,000001 K (1 $\mu$ K)**

# Desmagnetização Adiabática

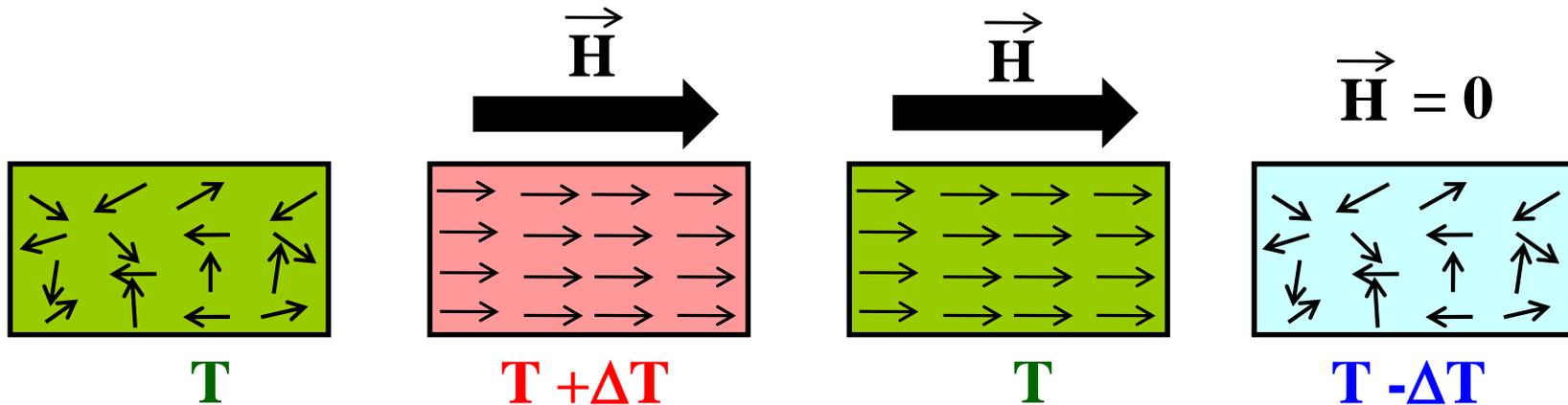
## Paramagnetismo



Baixa interação  
entre spins



## Efeito magnetocalórico



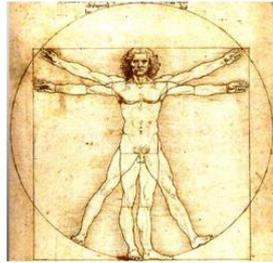
T - ΔT → Elétrons 3mK  
T - ΔT → Núcleos 1μK

Figure 2 Typical Magnetic Cycle of an ADR.

# Magnetismo

## Campos Magnéticos

0,0000000003 T  
( $3 \times 10^{-10}$  T)



Corpo humano

0,00003 T  
( $3 \times 10^{-5}$  T)



Superfície da terra

0,0001 T  
( $10^{-4}$  T)



Fios de eletrodomésticos

0,01 T  
( $10^{-2}$  T)



Superfície do sol

0,3 T  
( $3 \times 10^{-1}$  T)



Ímã de geladeira

0,4 T  
( $4 \times 10^{-1}$  T)



Alto-falante

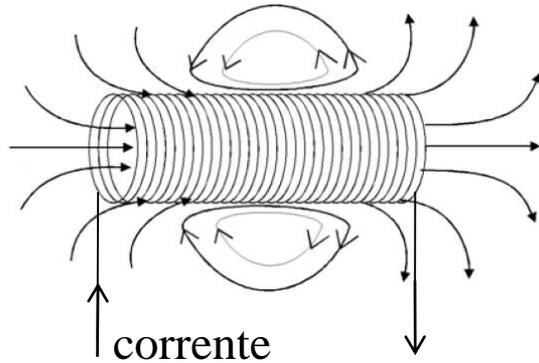


Nota de 100 dinares da Sérvia

Nikola Tesla  
(1856-1943)

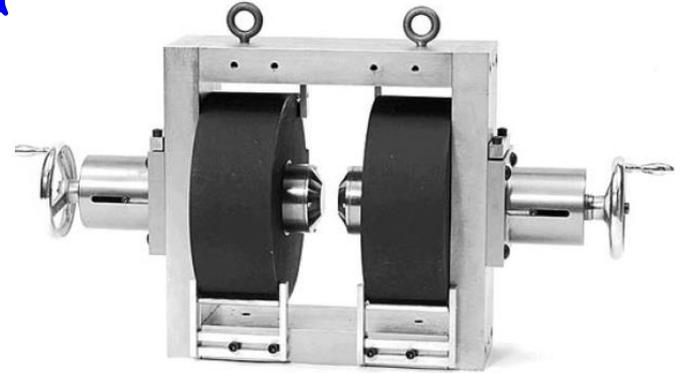
# Magnetismo

## Campos magnéticos



## Eletroímã

$H < 2 \text{ T}$



## Solenóide supercondutor



Nb-Ti

$T_c \sim 10 \text{ K}$

$H \sim 9 \text{ T}$

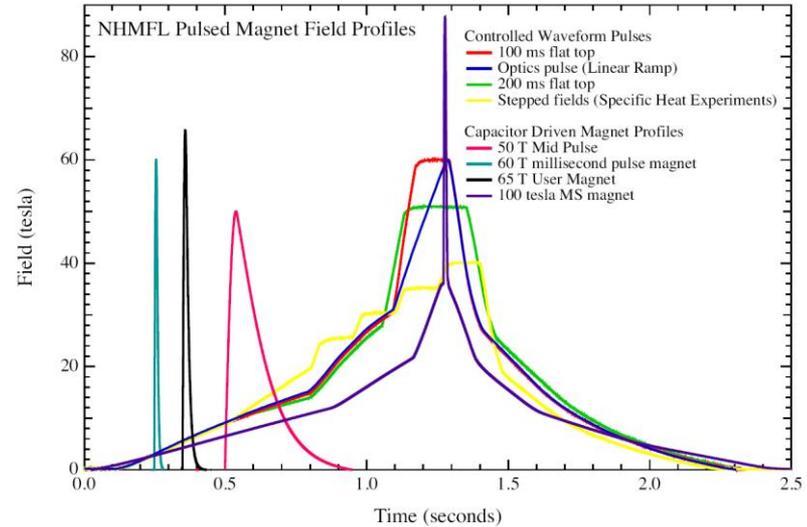
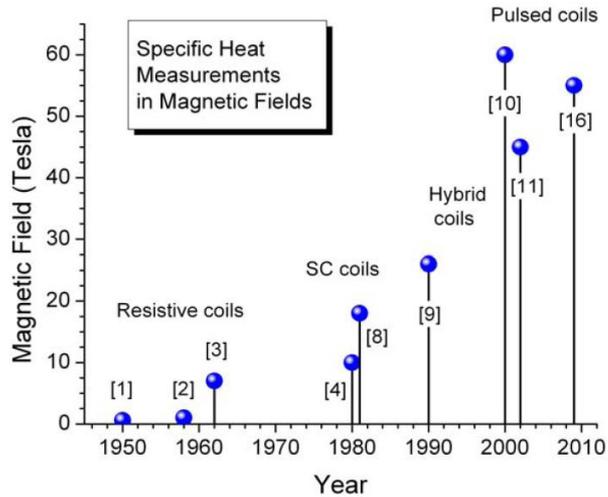
Nb<sub>3</sub>Sn

$T_c \sim 18 \text{ K}$

$H \sim 20 \text{ T}$



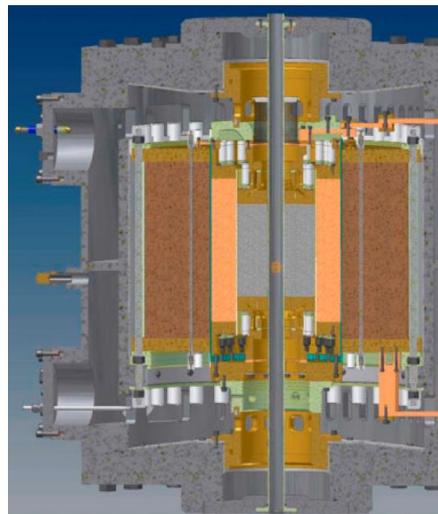
# Produção de altos campos magnéticos



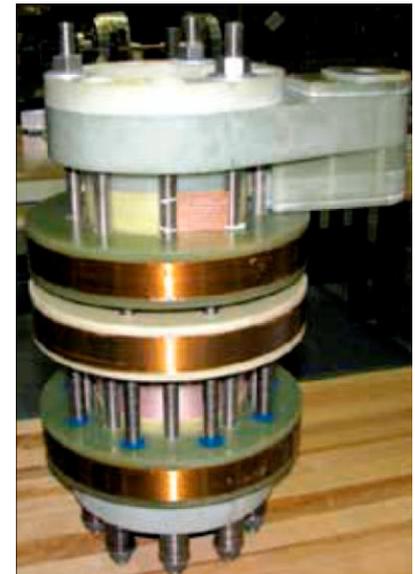
**SC (H=20 T)**



**Bitter**

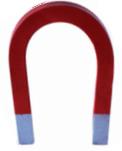


**Campo pulsado**

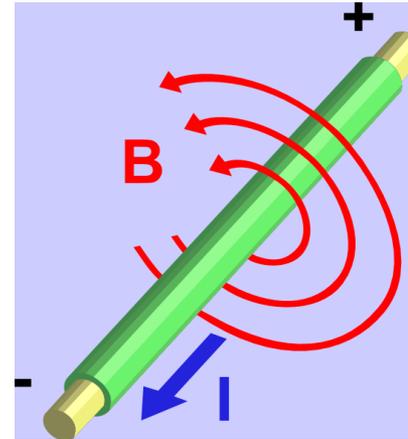


# Magnetismo

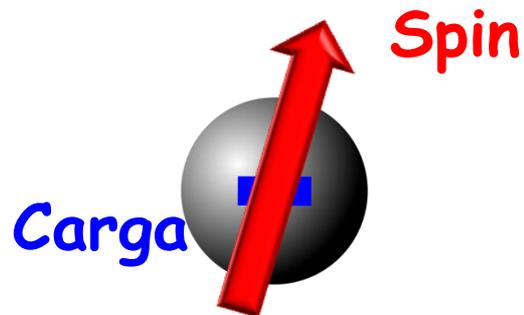
## Propriedades Magnéticas da Matéria



- Cargas em movimento

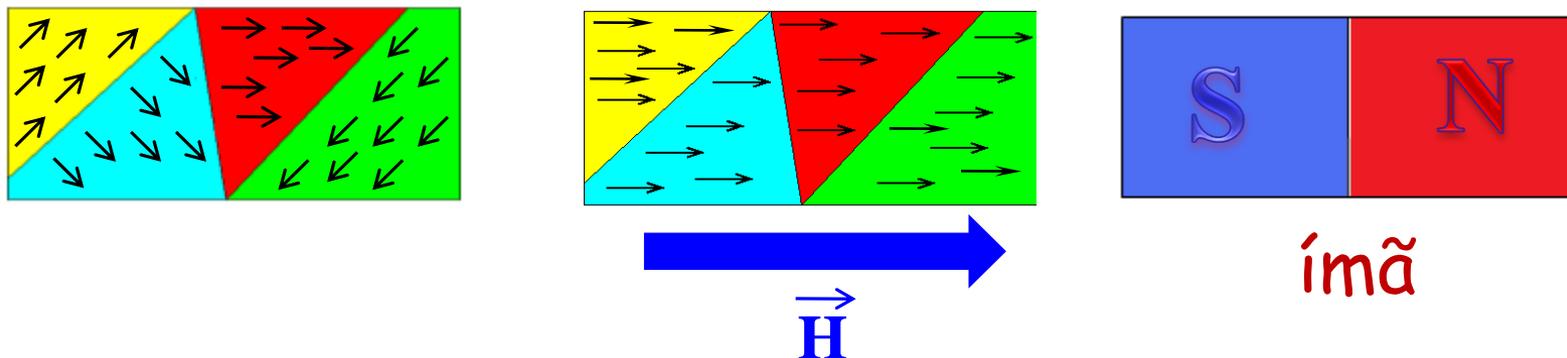


- Campo magnético intrínseco do elétron: Spin

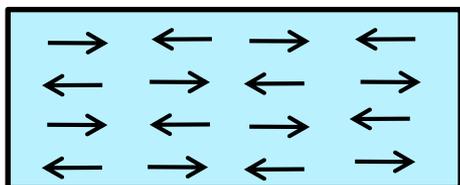


# Magnetismo dos sólidos

## Ferromagnetismo: Alinhamento paralelo de spins



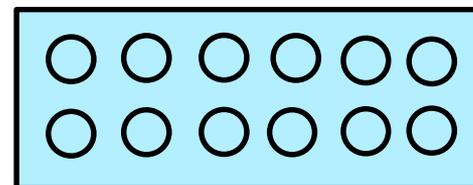
## Antiferromagnetismo



Alinhamento  
antiparalelo de spins



## Diamagnetismo

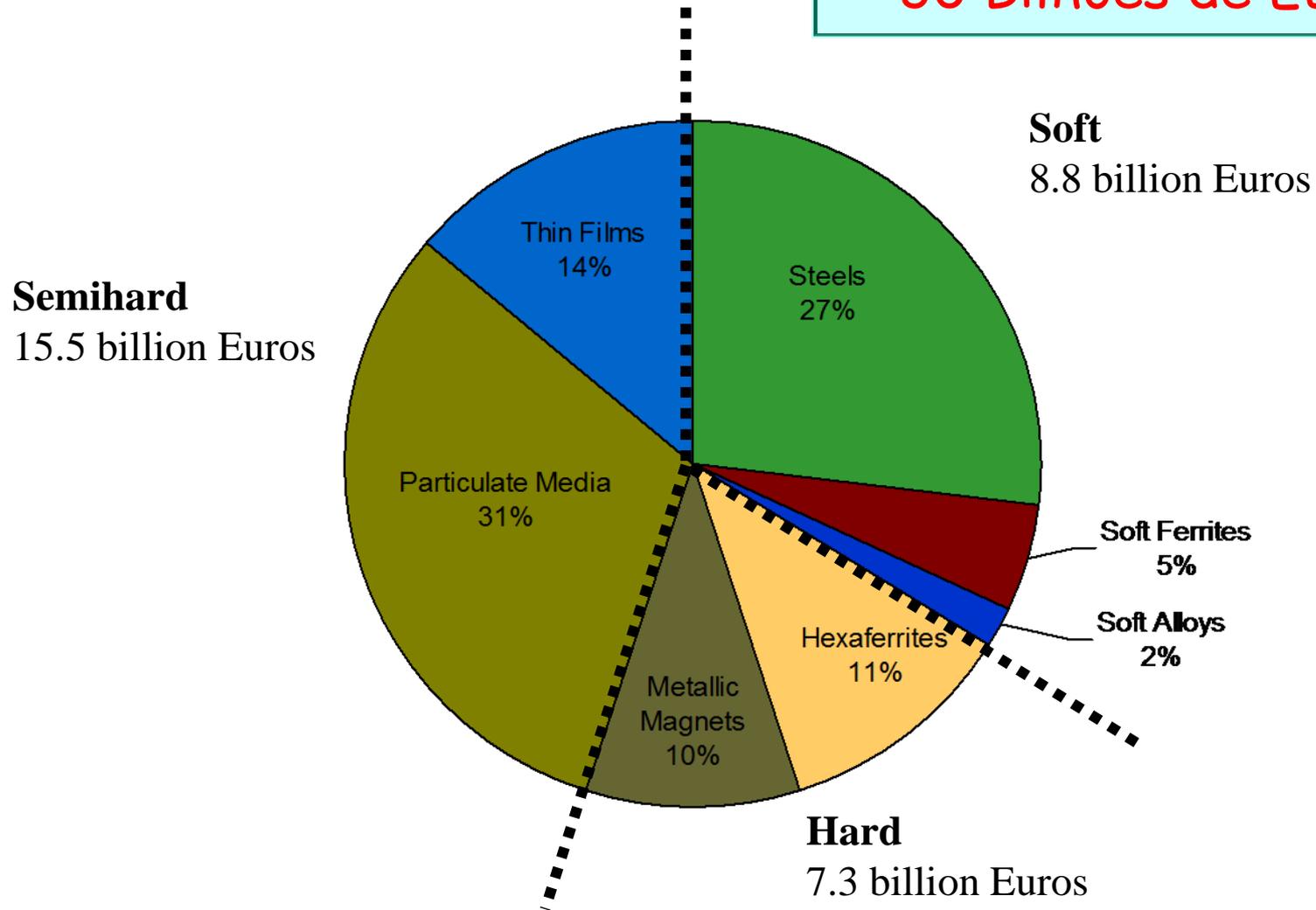


Supercondutores:  
Diamagnetos perfeitos

# Magnetismo - Por que estudar ?

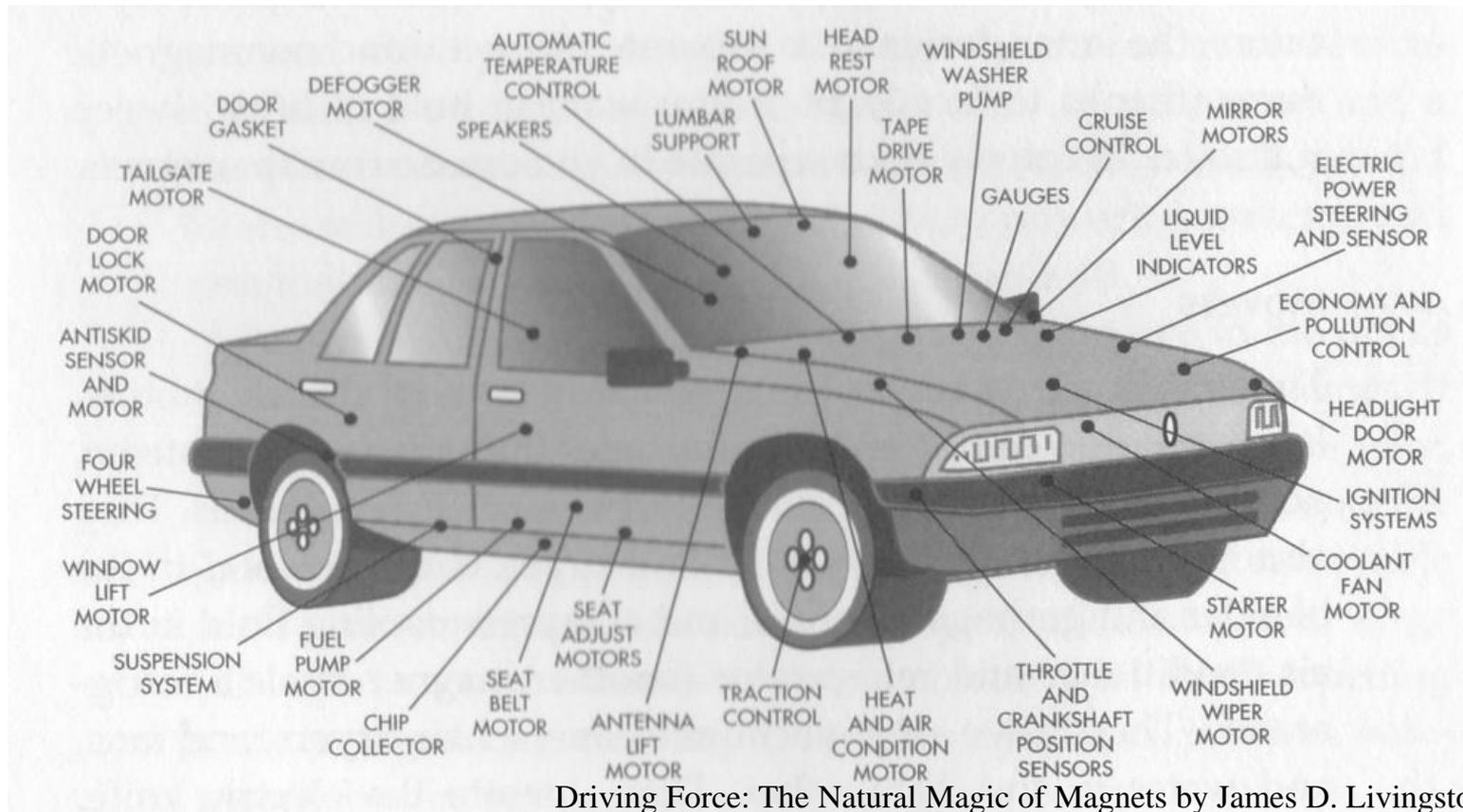
## Materiais magnéticos no mercado mundial

~ 30 Bilhões de Euros



# Magnetismo - Por que estudar ?

## Algumas aplicações de materiais magnéticos em um carro



Motores elétricos, alto-falantes...

# Magnetismo- Por que estudar ?

Indústria de Gravação Magnética

Mercado estimado em US\$100 bilhões ano

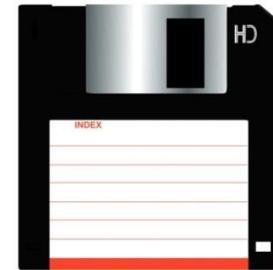
Som



Imagem



Tudo !!



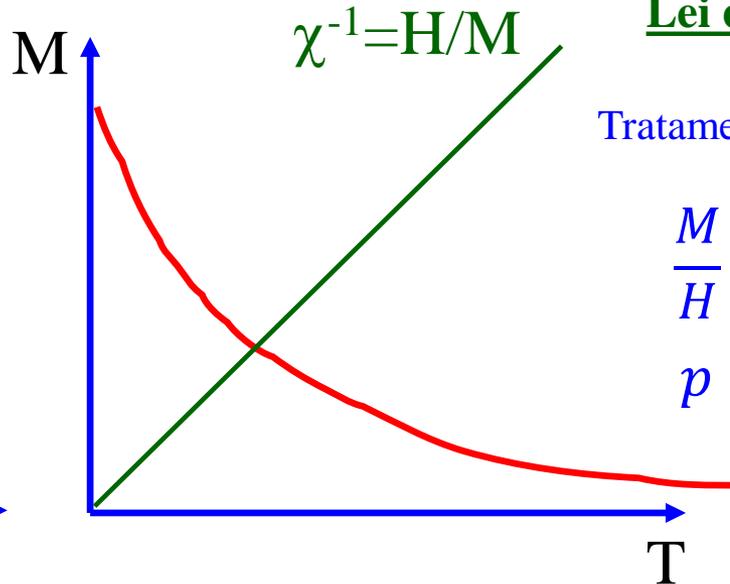
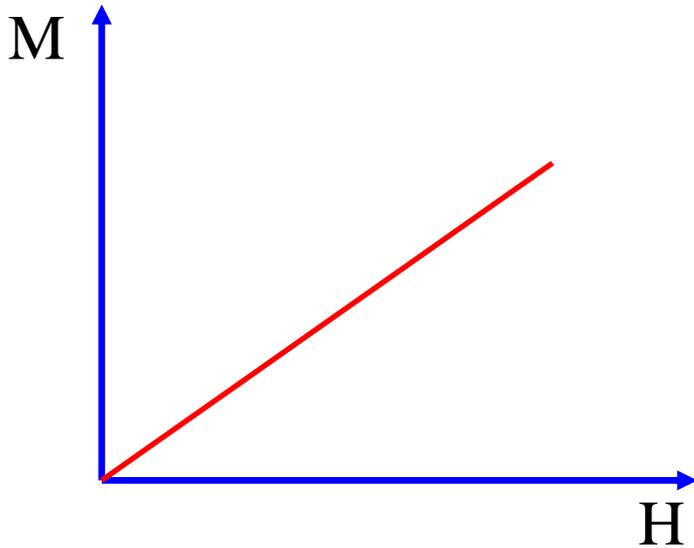
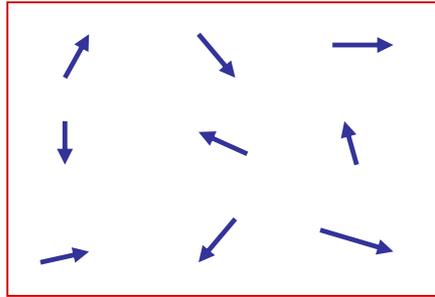
# Magnetismo

Estudando materiais magnéticos:

Temperatura (T)

Campos Magnéticos (H)

Paramagnetismo



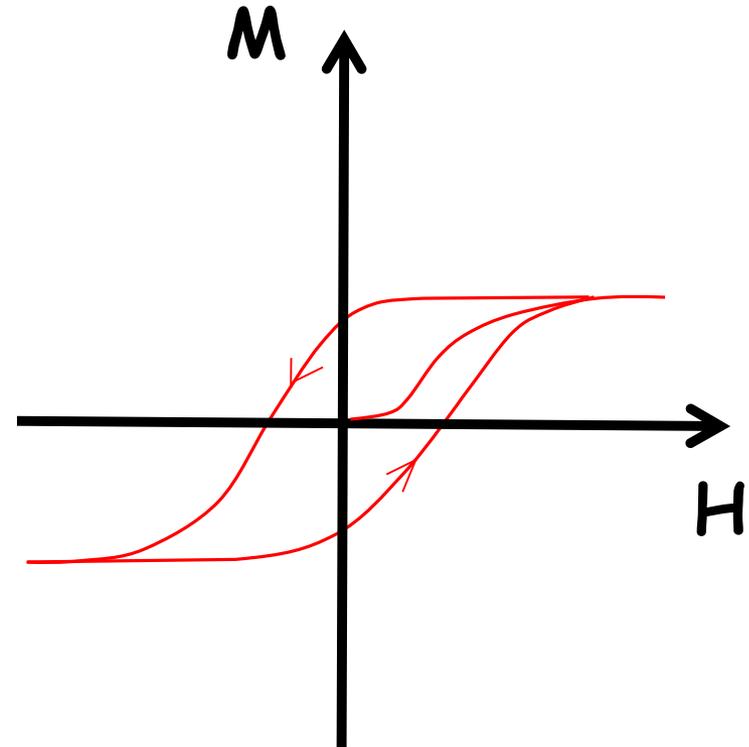
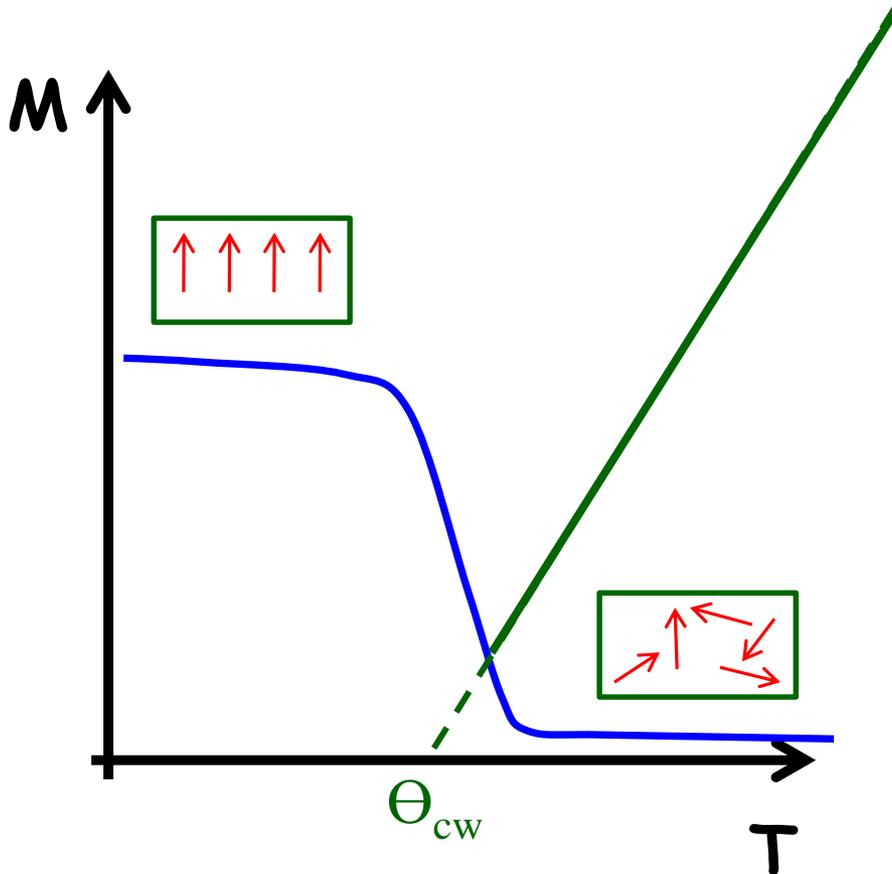
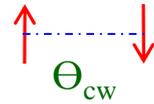
Lei de Curie: Derivar !

Tratamento Clássico/Quântico:

$$\frac{M}{H} = \frac{Np^2\mu_B^2}{3k_B T}$$
$$p = g[J(J+1)]^{\frac{1}{2}}$$

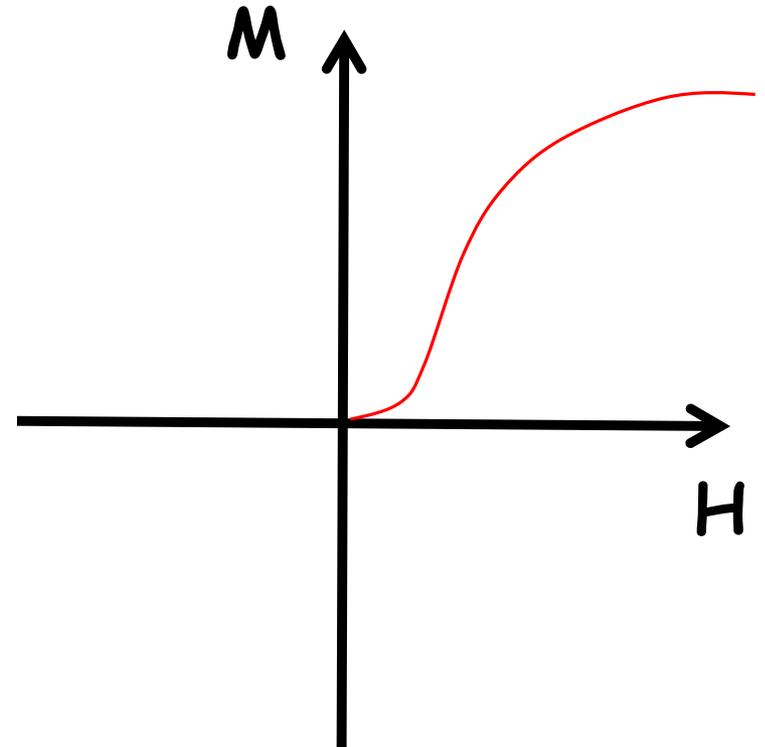
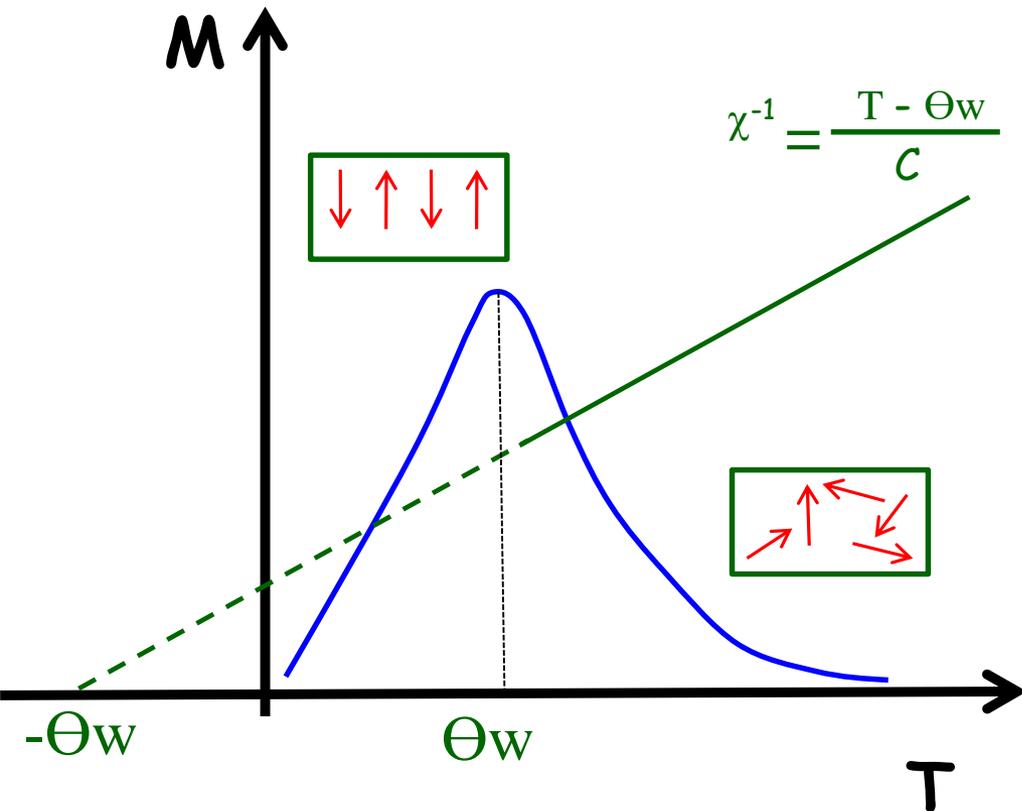
## Ferromagnetismo

Lei de Curie-Weiss:  $\chi^{-1} = \frac{T - \Theta_{cw}}{C}$ ,  $T \gg T_C$   
(Aproximação de campo médio)

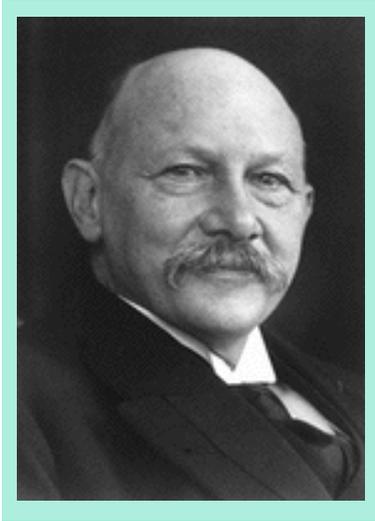


# Magnetismo

## Antiferromagnetismo



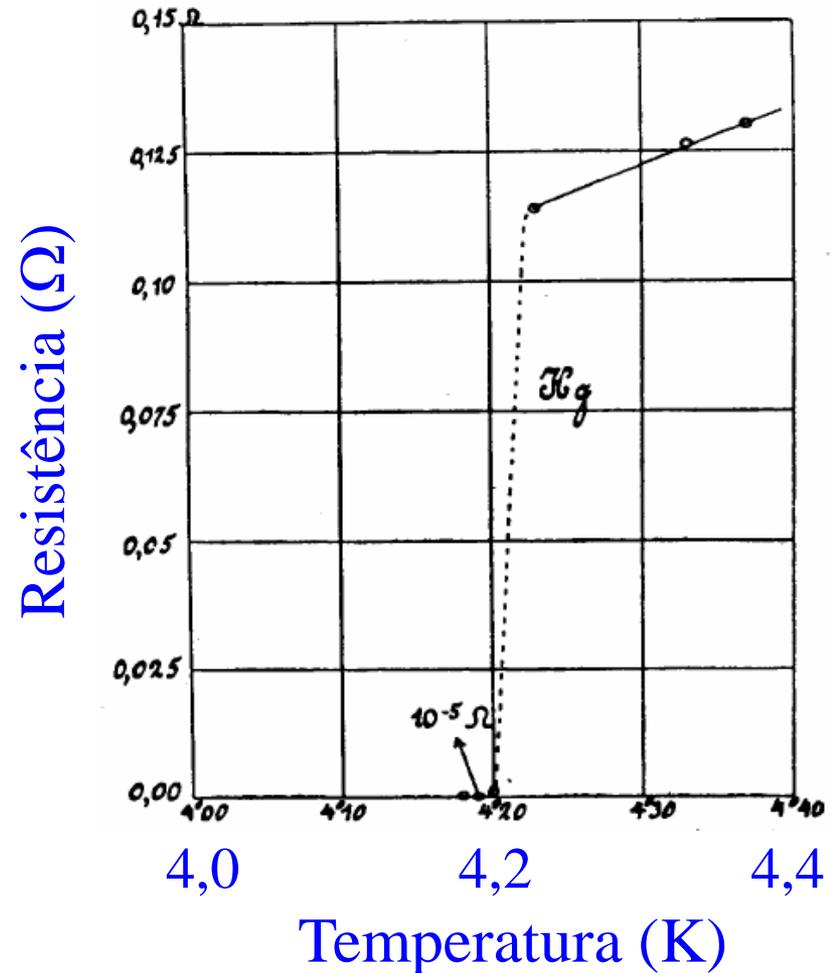
# Supercondutividade



Kamerlingh Onnes  
(1853 - 1926)

Primeiro a liquefazer  
o gás Hélio em 1908

Descobre supercondutividade  
no mercúrio em 1911



# Supercondutividade

## Os elementos supercondutores

Li	Be 0.026											B	C	N	O	F	Ne
Na	Mg											Al 1.14 10	Si	P	S	Cl	Ar
K	Ca	Sc	Ti 0.39 10	V 5.38 142	Cr	Mn	Fe	Co	Ni	Cu	Zn 0.875 5.3	Ga 1.091 5.1	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr 0.546 4.7	Nb 9.5 198	Mo 0.92 9.5	Tc 7.77 141	Ru 0.51 7	Rh 0.03 5	Pd	Ag	Cd 0.56 3	In 3.4 29.3	Sn 3.72 30	Sb	Te	I	Xe
Cs	Ba	La 6.0 110	Hf 0.12	Ta 4.483 83	W 0.012 0.1	Re 1.4 20	Os 0.655 16.5	Ir 0.14 1.9	Pt	Au	Hg 4.153 41	Tl 2.39 17	Pb 7.19 80	Bi	Po	At	Rn

Temperatura de transição  $T_C$  (K)

Campo magnético crítico (mT)

**Nb**  
(Nióbio)  
 $T_c = 9K$

**$T_c$  mais alto**

Bons condutores  
não são supercondutores

**Fe**  
 $T_c = 1K$   
( $p = 20GPa$ )

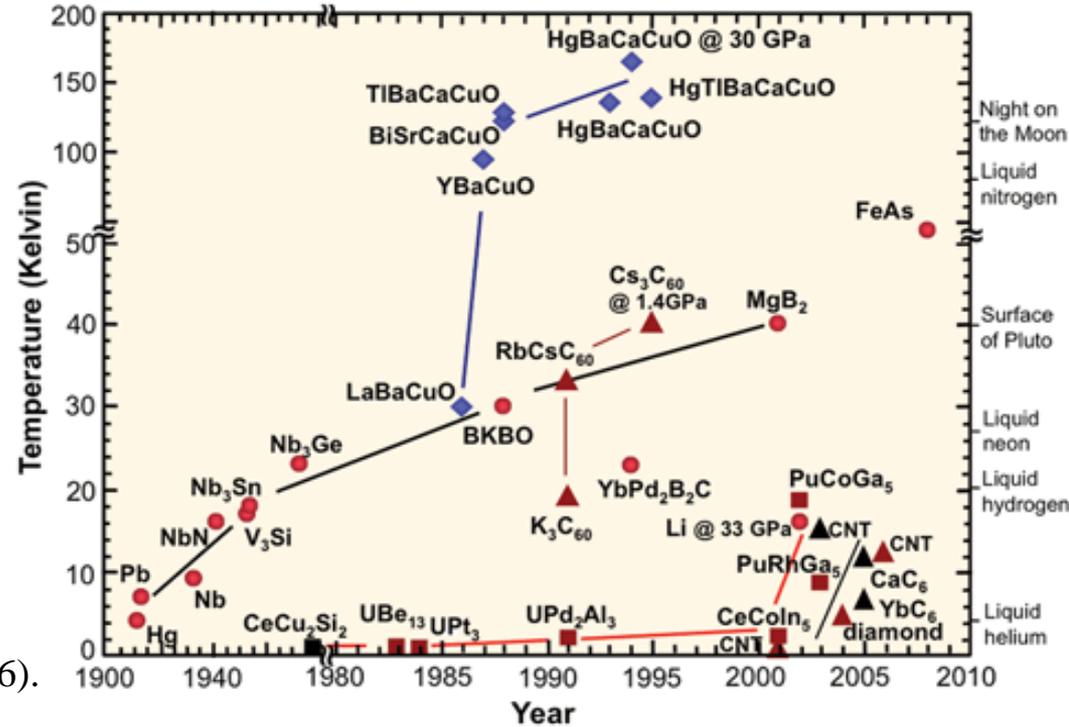
**Supercondutor sob pressão**

# Supercondutividade

## Prêmios Nobel

1. H. Kamerlingh Onnes (1913).
2. L. Davidovich Landau (1962).
3. J. Bardeen, L. N. Cooper, and J. R. Schrieffer (1972).
4. L. Esaki, I. Giaever, and B. D. Josephson (1973).
5. G. Bednorz and K. A. Müller (1987).
6. A. A. Abrikosov, V. L. Ginzburg, and A. J. Leggett (2003).
7. M. Kosterlitz, D. Haldane, D. J. Thouless (2016).

## Evolução da $T_c$ dos supercondutores de 1900-2010



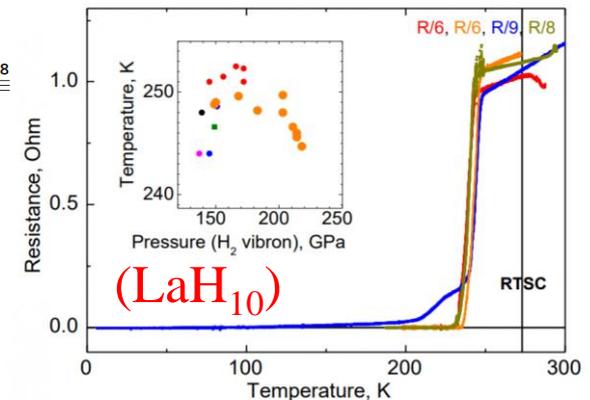
## LETTER

<https://doi.org/10.1038/s41586-019-1201-8>

### Superconductivity at 250 K in lanthanum hydride under high pressures

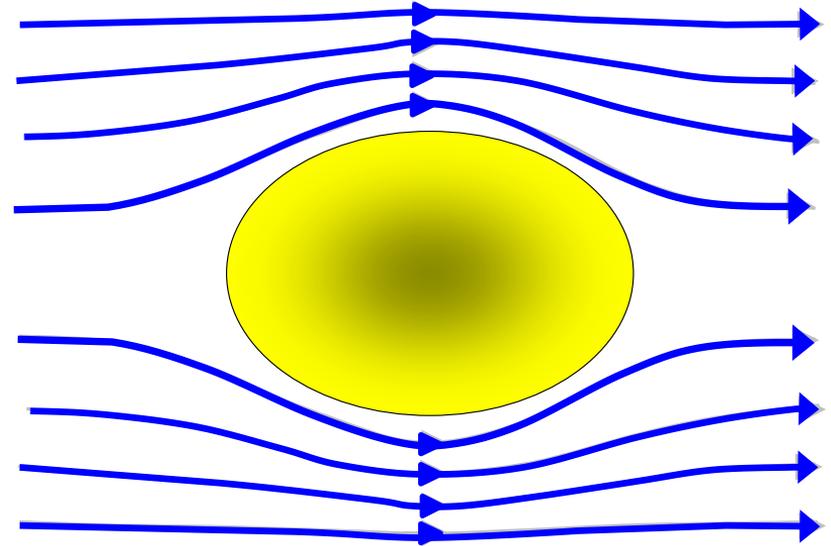
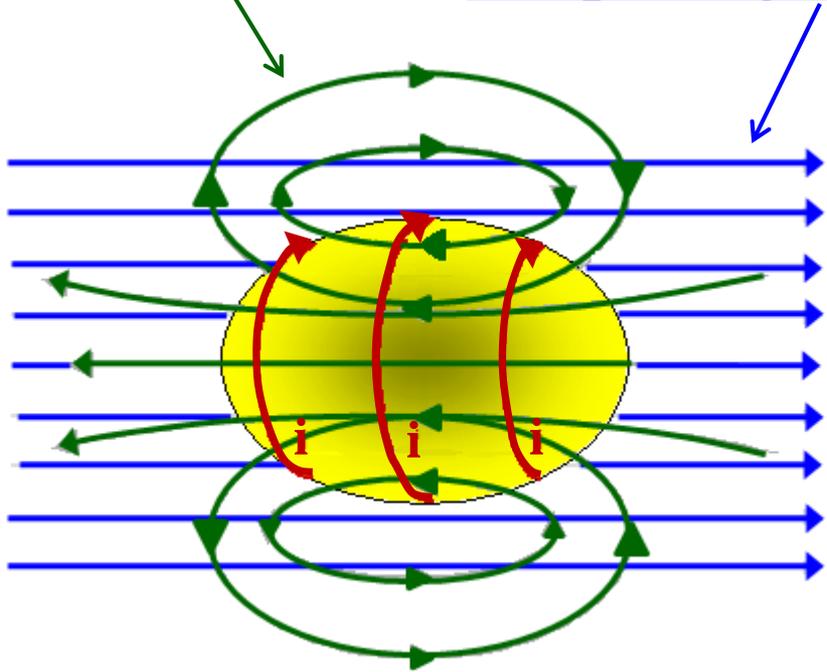
A. P. Drozdov<sup>1,7</sup>, P. P. Kong<sup>1,7</sup>, V. S. Minkov<sup>1,7</sup>, S. P. Besedin<sup>1,7</sup>, M. A. Kuzovnikov<sup>1,6,7</sup>, S. Mozaffari<sup>2</sup>, L. Balicas<sup>2</sup>, F. F. Balakirev<sup>3</sup>, D. E. Graf<sup>2</sup>, V. B. Prakapenka<sup>4</sup>, E. Greenberg<sup>4</sup>, D. A. Knyazev<sup>1</sup>, M. Tkacz<sup>5</sup> & M. I. Erements<sup>1\*</sup>

528 | NATURE | VOL 569 | 23 MAY 2019



# Supercondutividade

Campo magnético gerado pelas correntes superficiais blindam o campo magnético externo



**Efeito Meissner (1933)**

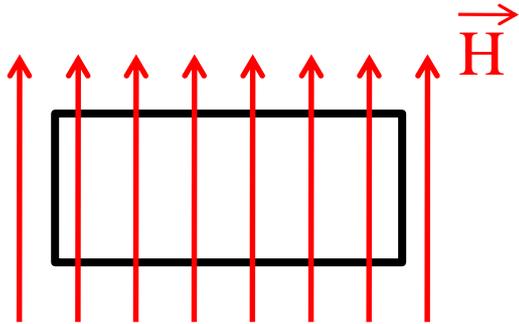


Fritz Meissner  
(1882-1974)

O campo magnético é nulo dentro de um supercondutor

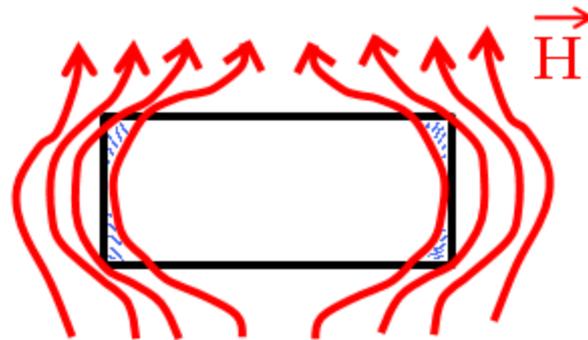
# Supercondutividade

## Supercondutores tipo I e tipo II



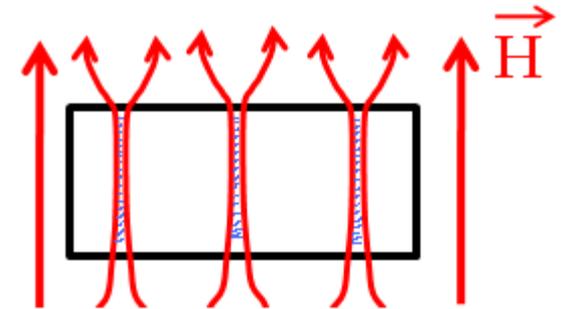
Normal

$$T > T_c$$



Tipo I

Campo magnético penetra  
somente numa pequena  
profundidade



Tipo II

Campo magnético  
penetra  
em "tubos" formando  
regiões normais  
dentro do material

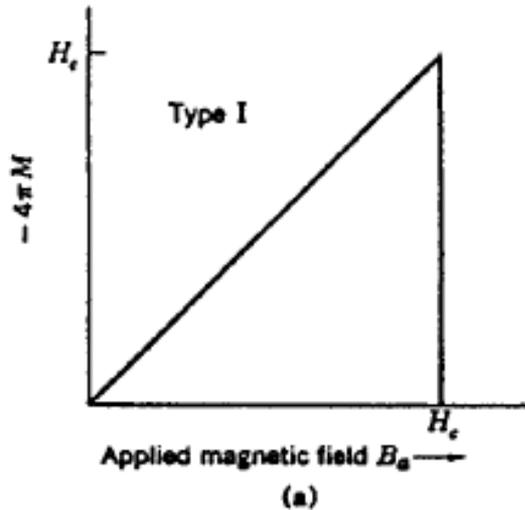
Tipo I : Hg, In, Al, Zn, ...

Tipo II : Nb, Nb<sub>3</sub>Sn, V<sub>3</sub>Si, ...

# Supercondutividade

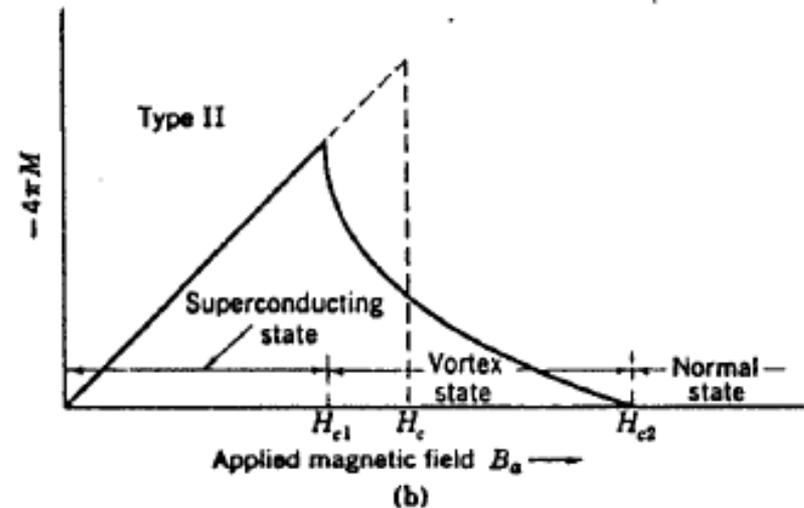
**Campo Crítico:** Se um campo magnético externo é aumentado acima de um valor crítico ( $H_c$ ), o supercondutor será revertido para um estado normal com resistividade.

## Supercondutor Tipo 1



**Transição ocorre abruptamente em  $H_c$**

## Supercondutor Tipo 2



**Transição ocorre de maneira gradual**

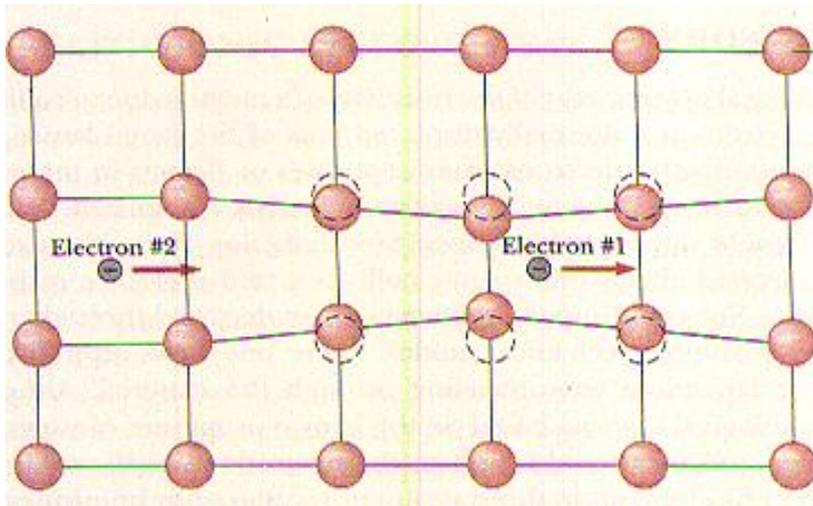
# Supercondutividade

Explicação (Tipo I):

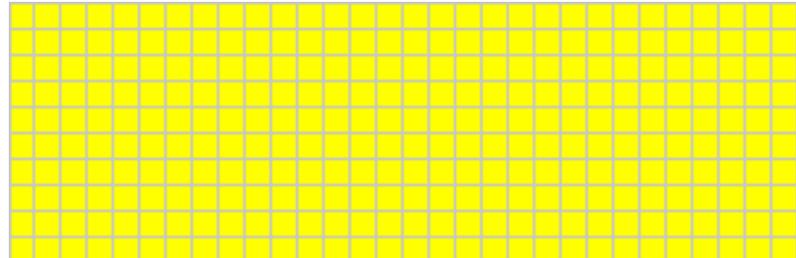
Teoria BSC



Bardeen, Cooper e Schrieffer  
(1957) - 46 anos !



Um elétron pode atrair outro elétron  
devido as vibrações da rede cristalina



## Supercondutividade em Alta Temperatura

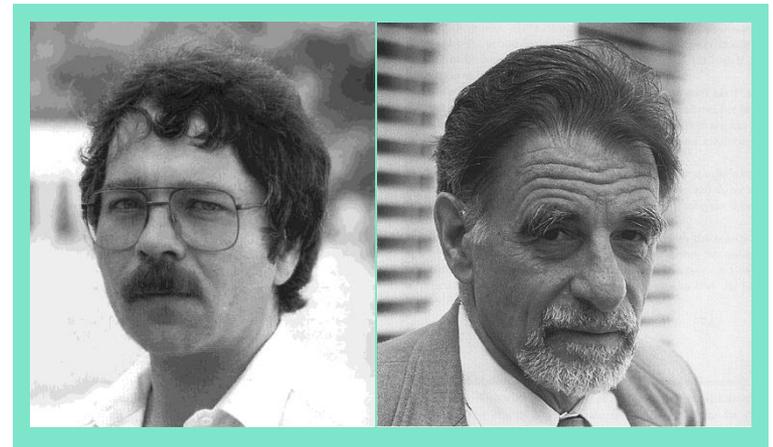
**$T > 30 \text{ K}$**

Óxidos de Cobre com metais de transição e terras raras

$\text{LaBaCuO} \rightarrow 40 \text{ K} / -233 \text{ }^\circ\text{C}$

$\text{YBaCuO} \rightarrow \underline{92 \text{ K}} / -181 \text{ }^\circ\text{C}$

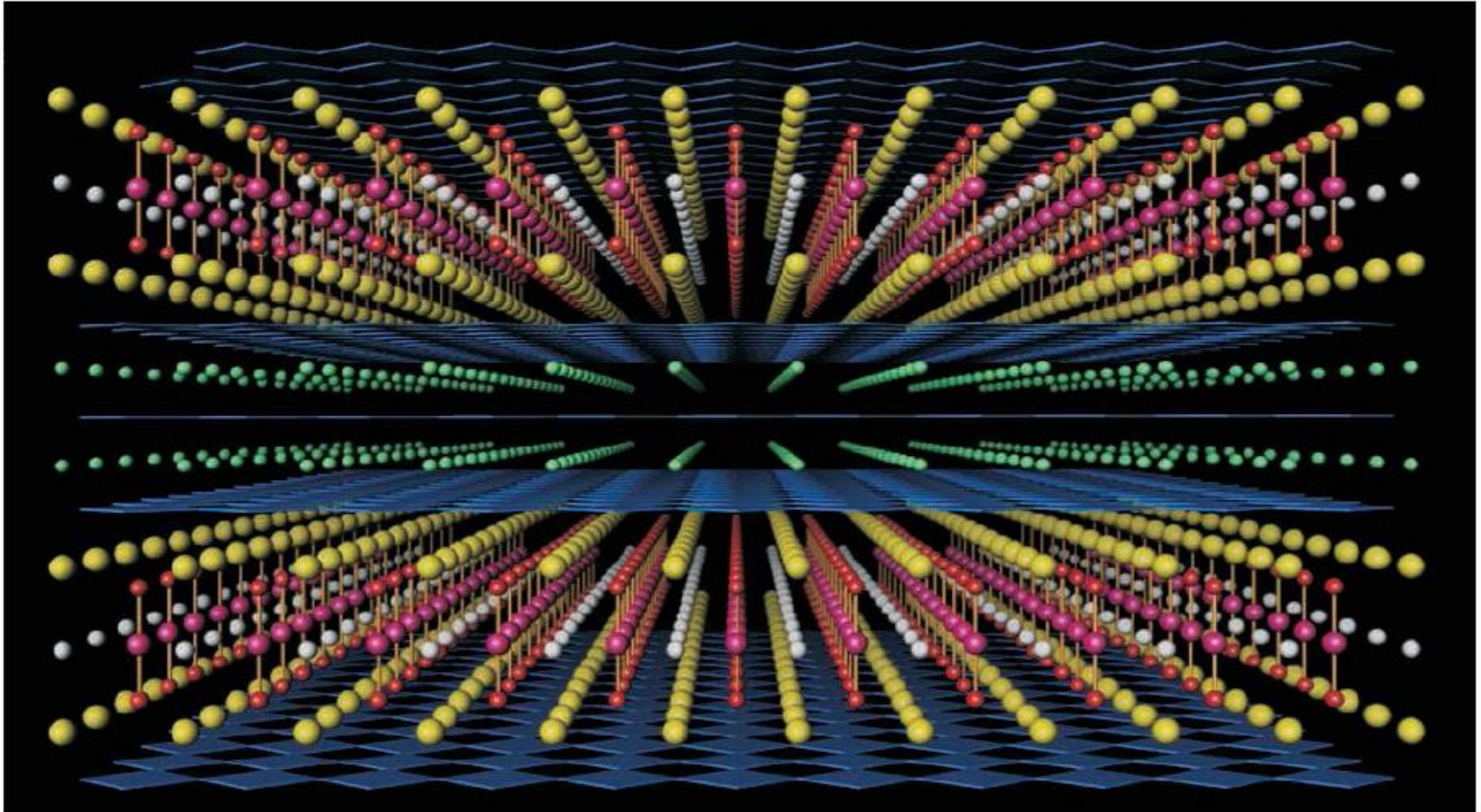
$\text{HgTlBaCaCuO} \rightarrow 138 \text{ K} / -135 \text{ }^\circ\text{C}$



Bednorz e Müller  
(1986)

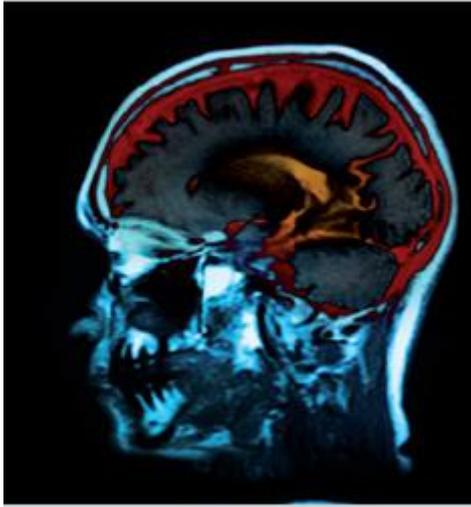
# Explicação ?

# Estrutura Planar



# Supercondutividade

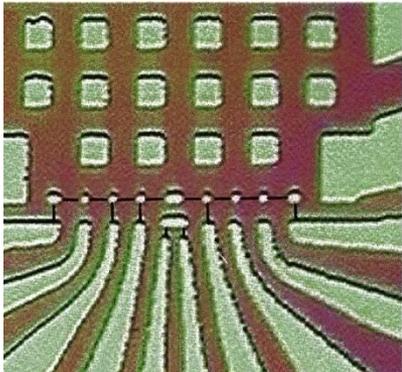
## Aplicações Tecnológicas



MRI



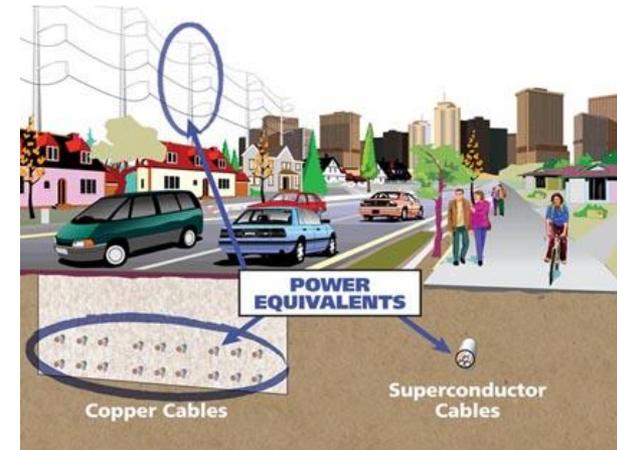
JR-Maglev MLX01 - 581 Km/h



Circuitos digitais



Motores



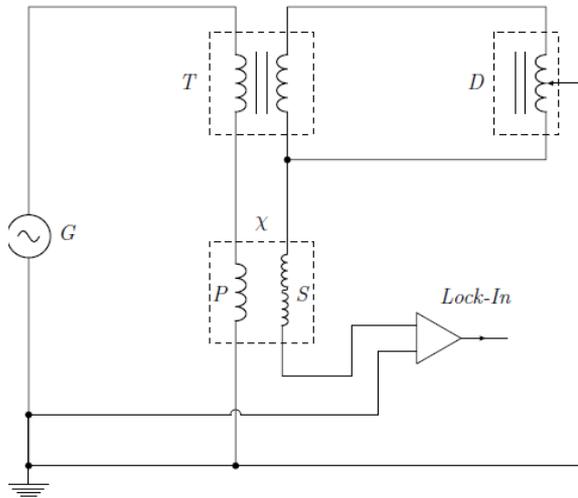
Cabos

# Técnicas Experimentais

## Susceptibilidade magnética ac

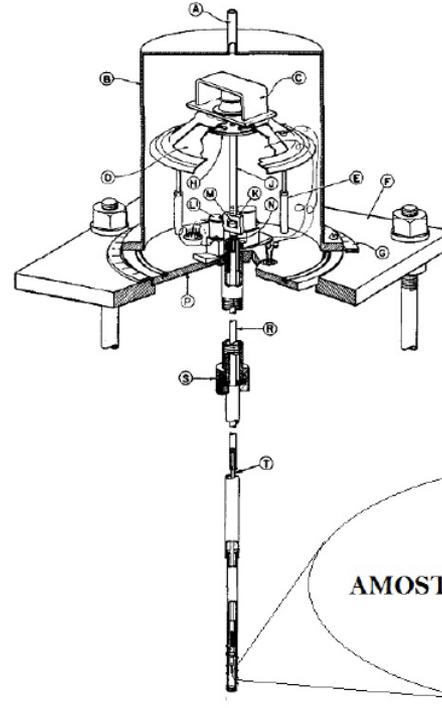
$$H_T = H + h_{ac} \quad h_{ac} = h_0 \cos(\omega t)$$

### Ponte de indutância mútua



$$\chi = \frac{dM}{dh_{ac}}$$

## Magnetômetro de Amostra Vibrante

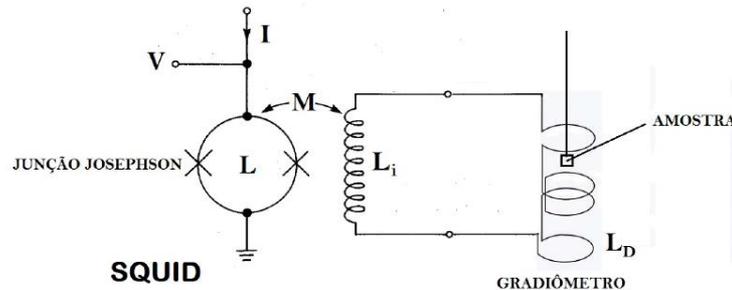


$$V(t) = \sum_n \int_S \frac{\partial \mathbf{B}(t)}{\partial t} \cdot d\mathbf{S}$$

AMOSTRA

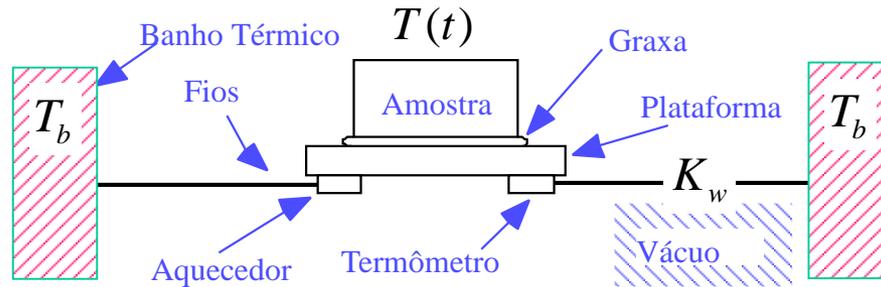
LOCK-IN

## Magnetômetro SQUID



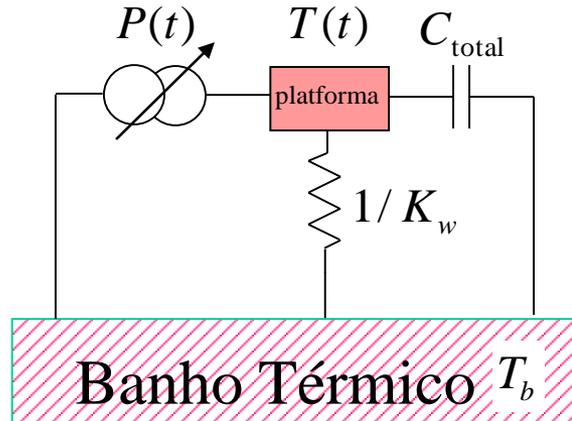
# Técnicas Experimentais

## Calor Específico: Método semi-adiabático



Alto vácuo:  $<10^{-4}$  torr p/ minimizar condução térmica para o banho

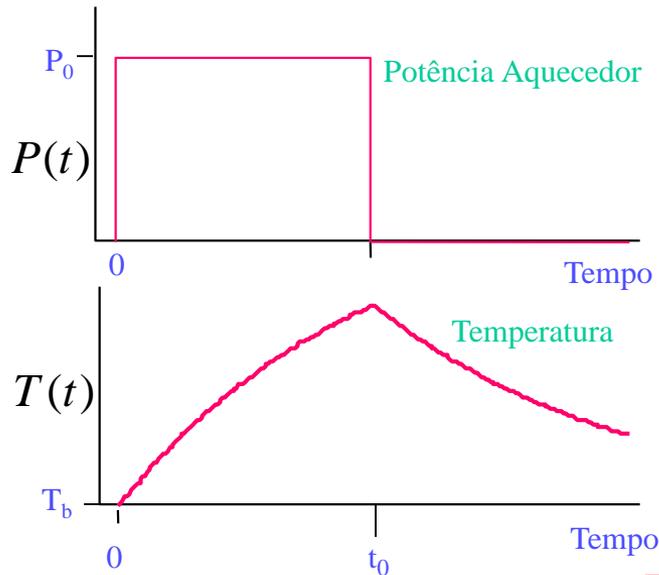
Para pequenas mudanças de temperatura:



$$C_{total} \frac{dT(t)}{dt} = P(t) - K_w (T(t) - T_b)$$

# Técnicas Experimentais

Pulso de calor / Monitoração da temperature:



$$C_{\text{total}} \frac{dT(t)}{dt} = P(t) - K_w (T(t) - T_b), \quad P(t) = \begin{cases} P_0 & (0 \leq t \leq t_0) \\ 0 & (t > t_0) \end{cases}$$

Com :  $T_{\text{on}}(0) = T_b, \quad T_{\text{on}}(t_0) = T_{\text{off}}(t_0),$

$$T(t) = \begin{cases} T_{\text{on}}(t) = P_0 \tau (1 - e^{-t/\tau}) / C_{\text{total}} + T_b & (0 \leq t \leq t_0) \\ T_{\text{off}}(t) = P_0 \tau (1 - e^{-t_0/\tau}) e^{-(t-t_0)/\tau} / C_{\text{total}} + T_b & (t > t_0) \end{cases}$$

Onde:

$$\tau = C_{\text{total}} / K_w$$

conhecido:  $P_0, t_0$

desconhecido  $C_{\text{total}}, K_w, T_b$

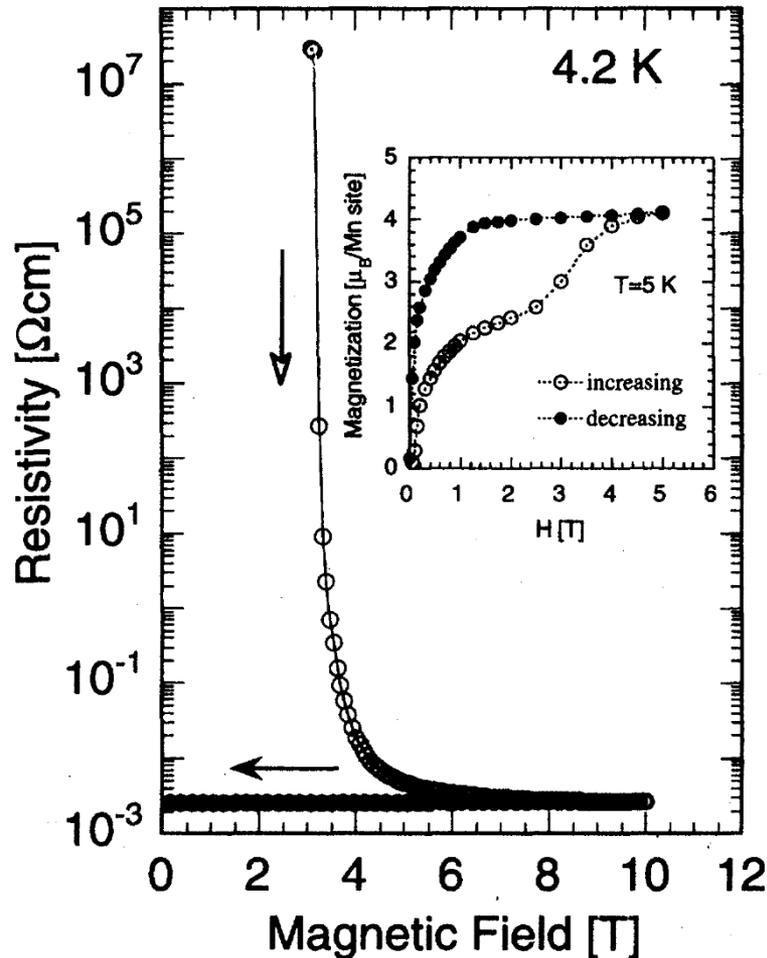
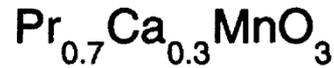
Encontra  
incógnitas  
minimizando S

Tempos e  
temperaturas  
medidos

$$S(C_{\text{total}}, K_w, T_b) = \sum_i (T(t_i) - T_i)^2$$

# Manganitas

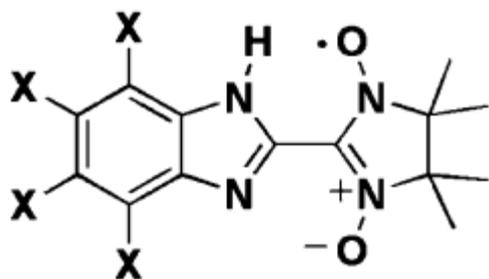
## Magnetoresistência Colossal (CMR)



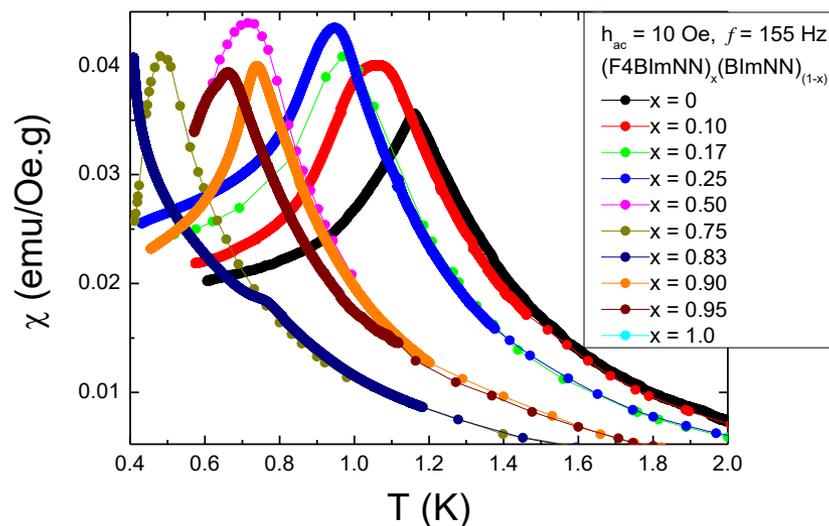
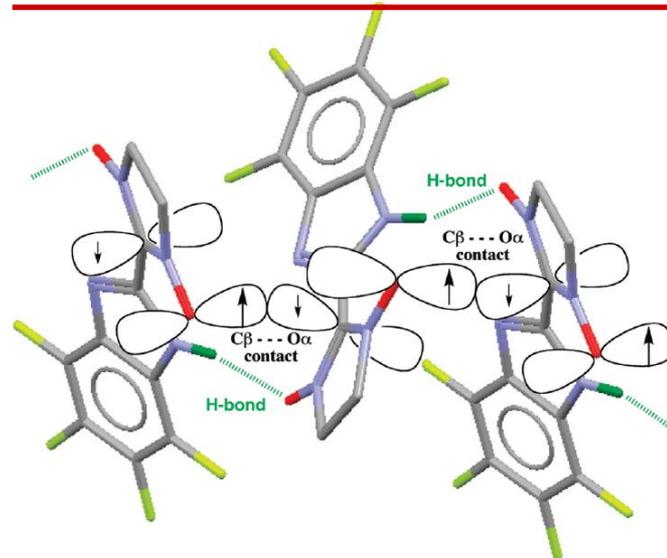
$$\text{MR} (\%) = 100 \frac{|\rho(H) - \rho(0)|}{\rho(0)}$$

# Magnetismo Molecular

## Ordem magnética em compostos PURAMENTE ORGÂNICOS

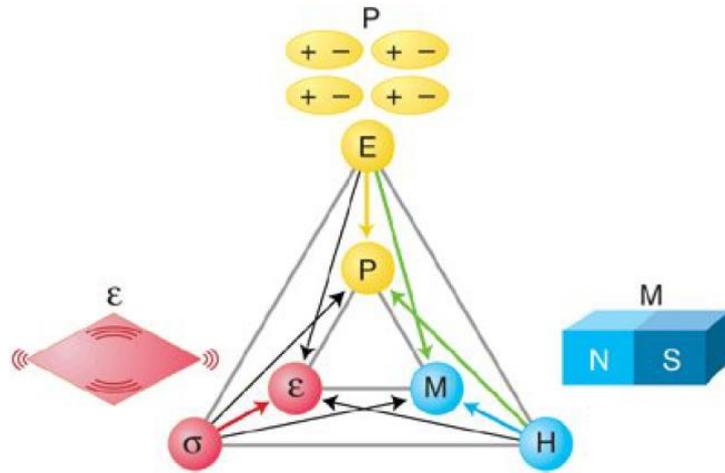


**BImNN**    **X = H**  
**F4BImNN** **X = F**

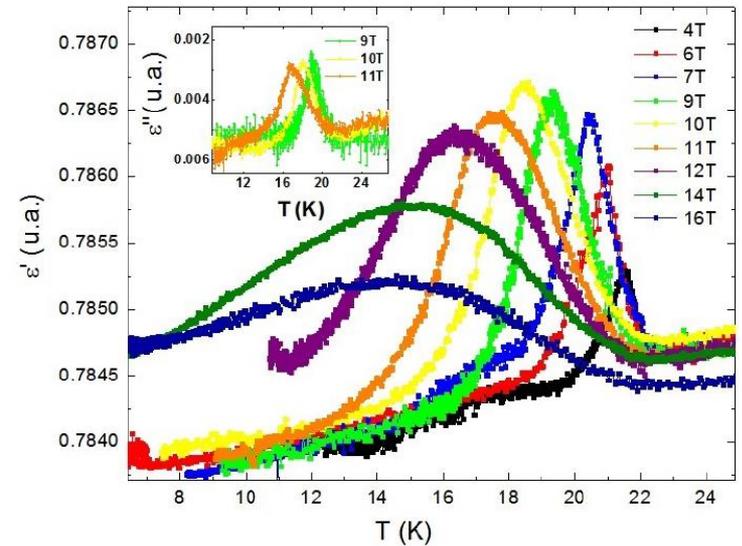
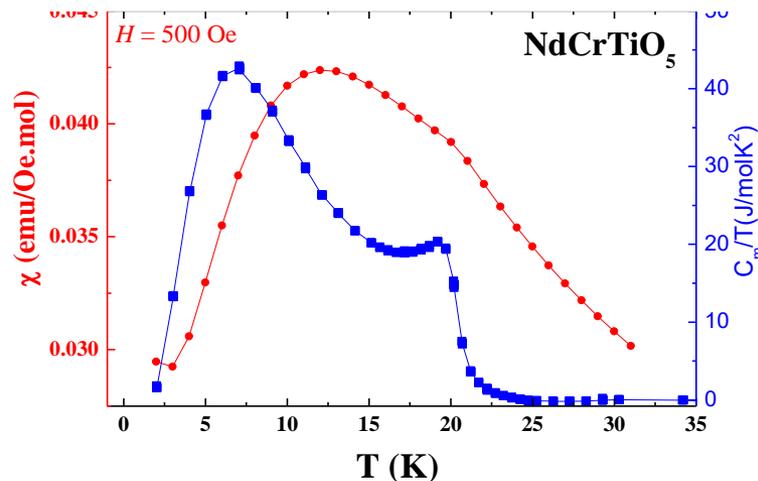
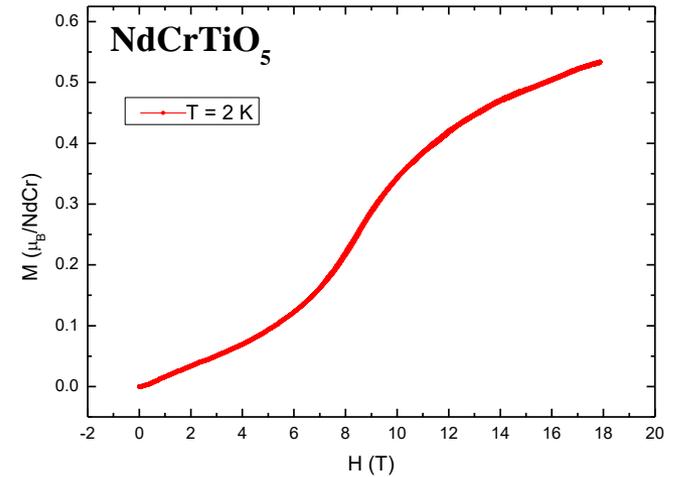


G. Seber et al., J. Am. Chem. Soc. **134**, 3825(2012)

# Multiferróicos - Magnetoelétricos



**Figura 4.1.:** Controle de fase em ferróicos e multiferróicos. Campo elétrico  $E$ , magnético  $H$ , e a tensão  $\sigma$  controlam a polarização elétrica  $P$ , a magnetização  $M$  e a deformação  $\epsilon$ , respectivamente. Em um material ferróico,  $P$ ,  $M$  ou  $\epsilon$  são gerados de forma espontânea para produzir ferroeletricidade, ferromagnetismo ou ferroelasticidade, respectivamente. Em um multiferróico a coexistência de ao menos duas formas ferróicas de ordenamento conduz a interações adicionais. Em um multiferróico magnetoelétrico, um campo magnético pode controlar  $P$  ou um campo elétrico pode controlar  $M$  (setas verdes). (retirado de [23])

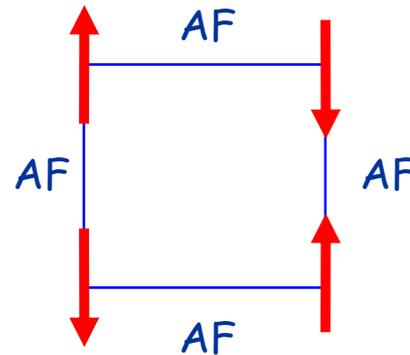
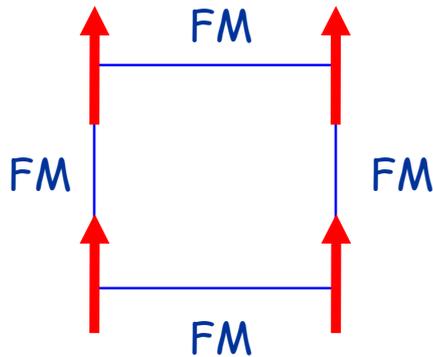


**Figura 6.11.:** Permissividade elétrica efetiva em função da temperatura para o  $\text{NdCrTiO}_5$  em diferentes campos magnéticos. *Insert:* perda dielétrica ( $\epsilon''$ ) para alguns campos.

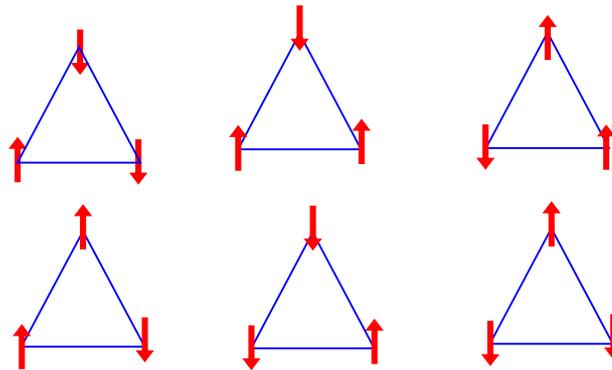
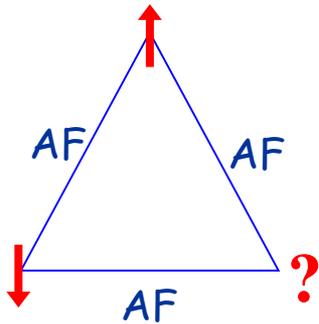
# Magnetos Geometricamente Frustrados

"I Can't get no satisfaction..."

Spins Não Frustrados:



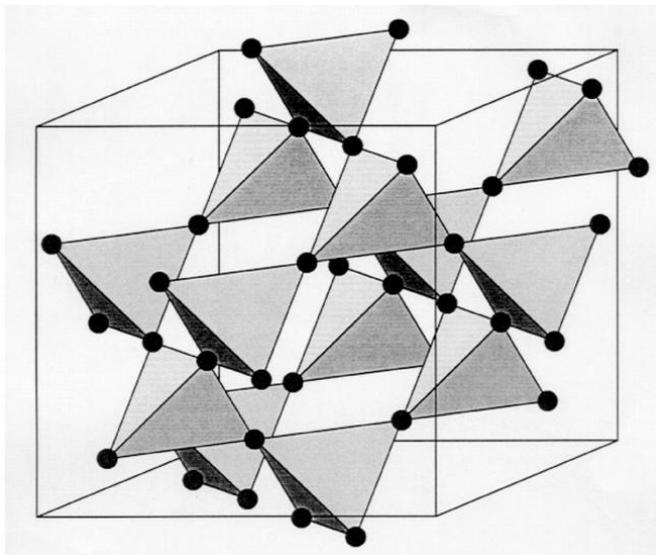
Spins Frustrados:



6 configurações equivalentes em energia

# Rede pirocloro $R_2 M_2 O_7$

Rede dos átomos R



$Gd_2Ti_2O_7$  Ordem de  
 $Gd_2Sn_2O_7$  longo alcance

$Tb_2Ti_2O_7$  Líquido de Spin

$Tb_2Mo_2O_7$   
 $Y_2Mo_2O_7$  Vidro de Spin

$Ho_2Ti_2O_7$

$Dy_2Ti_2O_7$

$Ho_2Sn_2O_7$

$Dy_2Sn_2O_7$

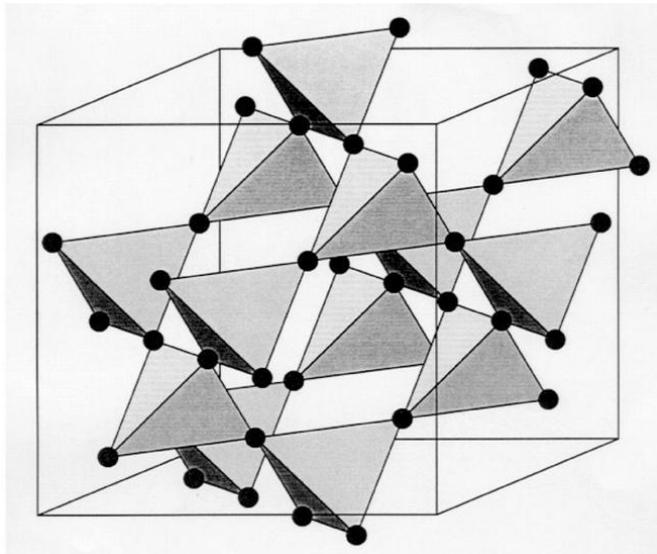
Gelo de Spin

Dinâmica de spins persistente (Até  $T \sim 10$  mK !)

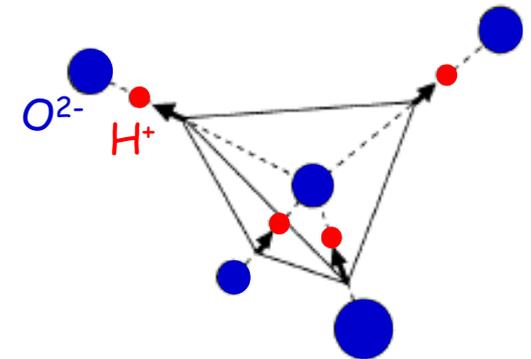
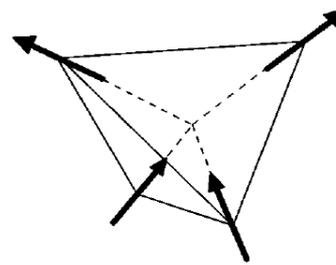
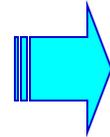
# Gelos de spins

Rede magnética pirocloro  $R_2M_2O_7$  ( $Dy_2Ti_2O_7$ ,  $Ho_2Ti_2O_7...$ )

Rede dos átomos R (Dy, Ho)



- Forte Anisotropia
- $J_{FM} \sim 2$  K

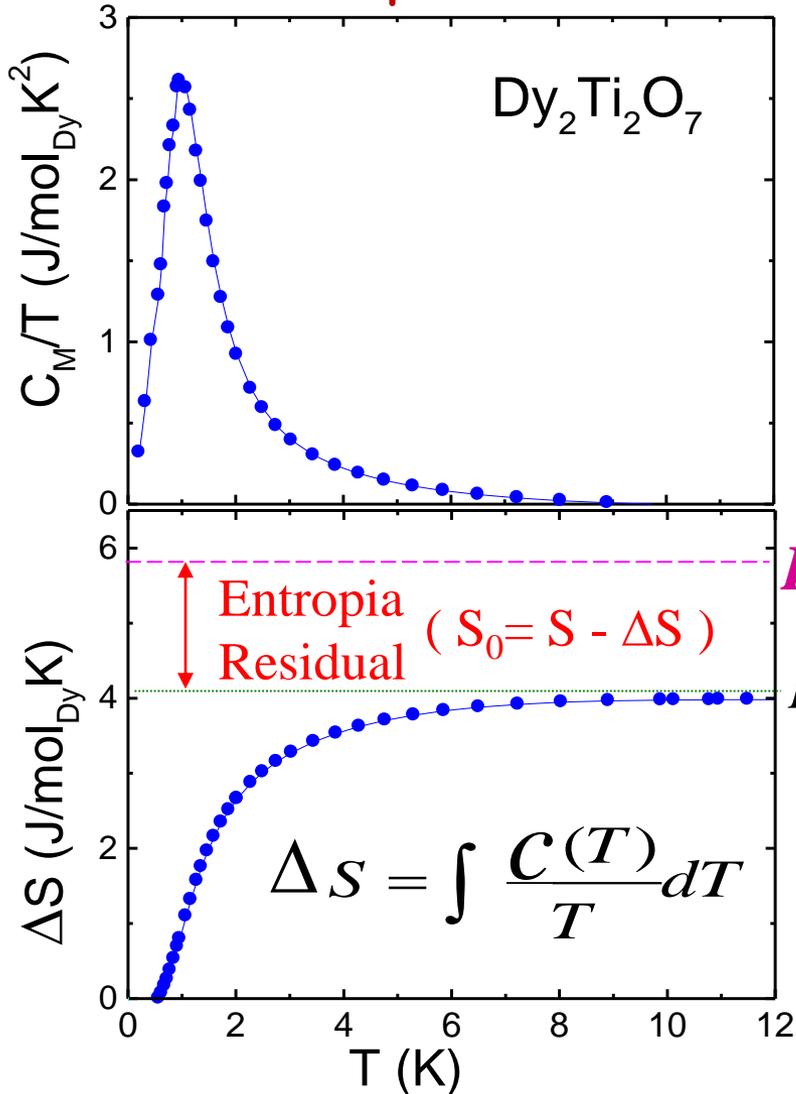


Alta degenerescência - Frustração !

M. J. Harris *et al.* Phys. Rev. Lett. **79**, 2554 (1997).

# Entropia Residual

Calor específico



Cálculo para o gelo:

$$S_0 = K_B \ln \left\{ 2^N \left( \frac{6}{16} \right)^{N/2} \right\}$$

$$S_0 = 0.5 R \ln 1.5$$

L. Pauling, *J. Am. Chem. Soc.* **57**, 2680 (1935).

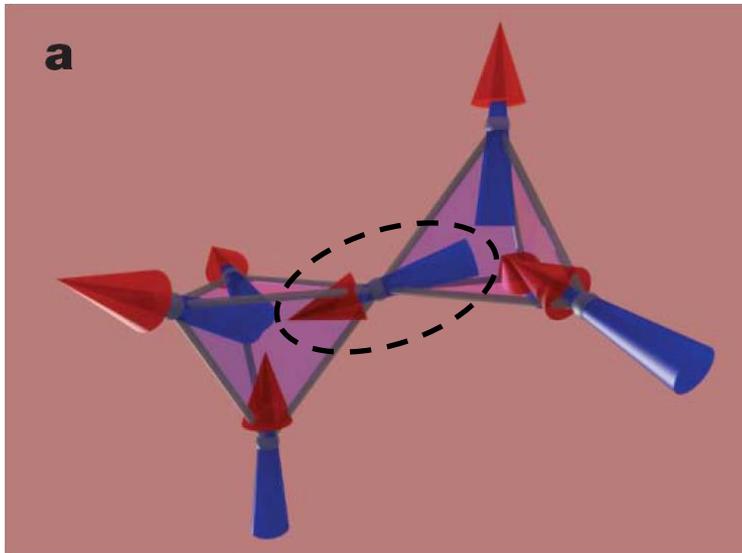
A.P. Ramirez *et al.*, *Nature* **399**, 333 (1999).

# Monopolos em Gelos de spins

---

## Estado Fundamental

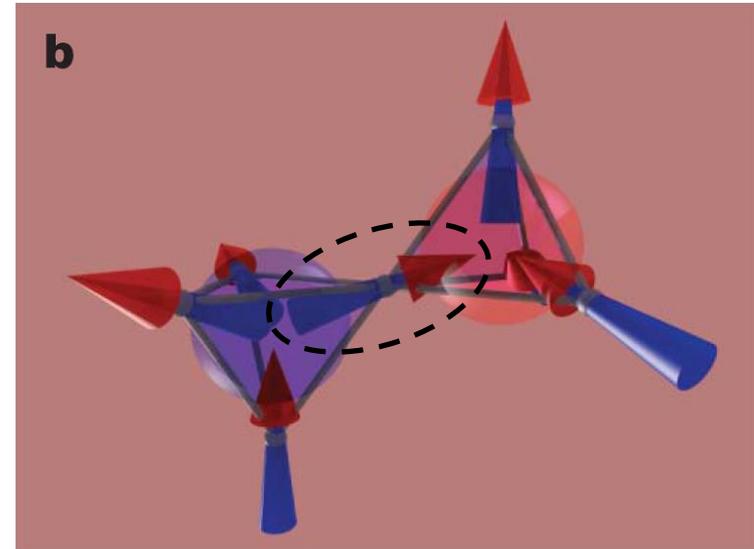
Regras do Gelo: **Two in-Two out**



Carga magnética **nula**  
por tetraedro

## Estado Excitado

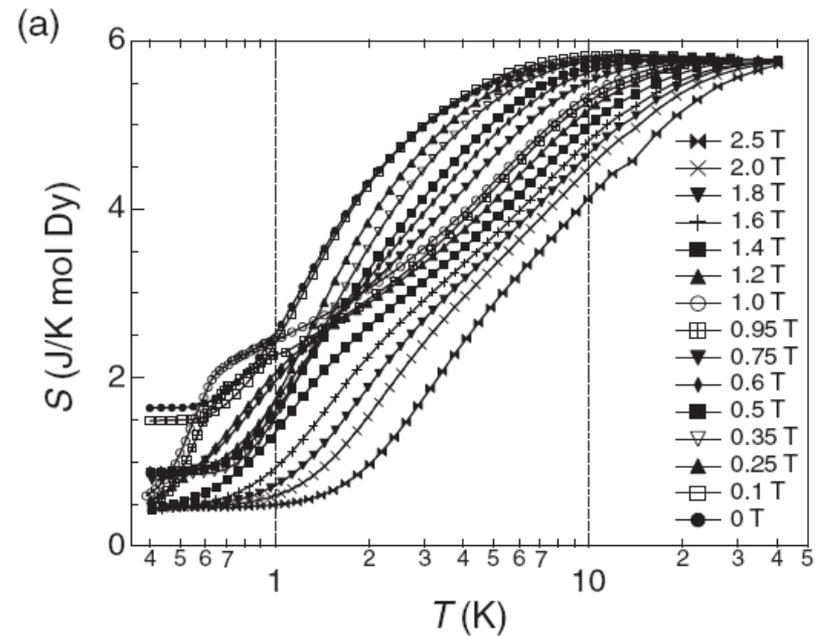
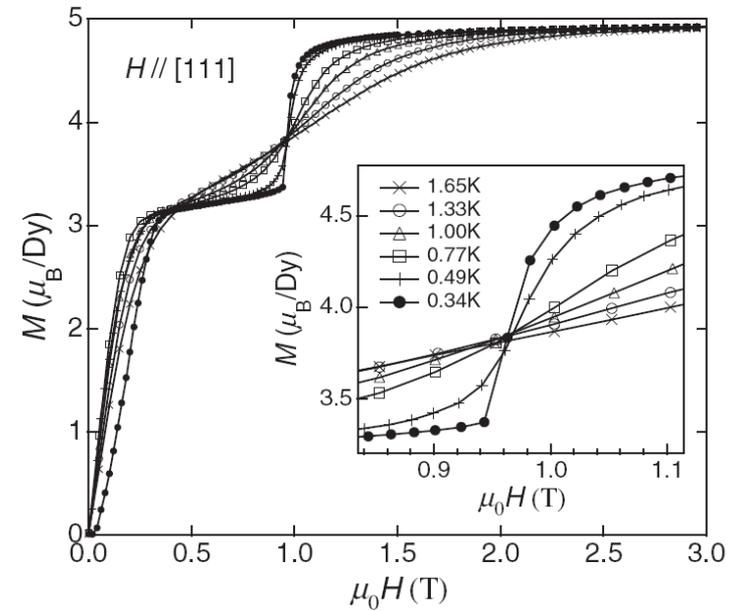
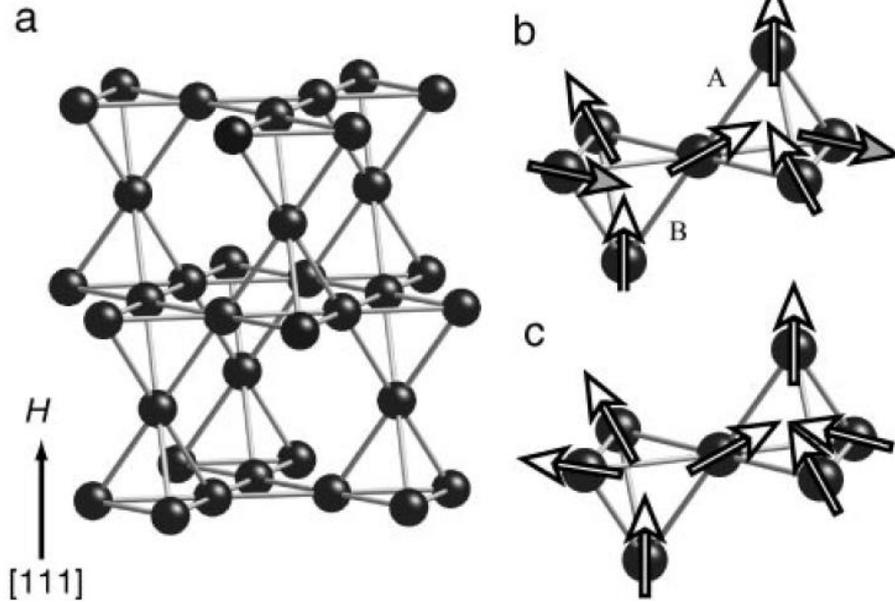
**Invertendo um spin**



Carga magnética **não nula**  
por tetraedro

**"Criação de par de monopolos"**

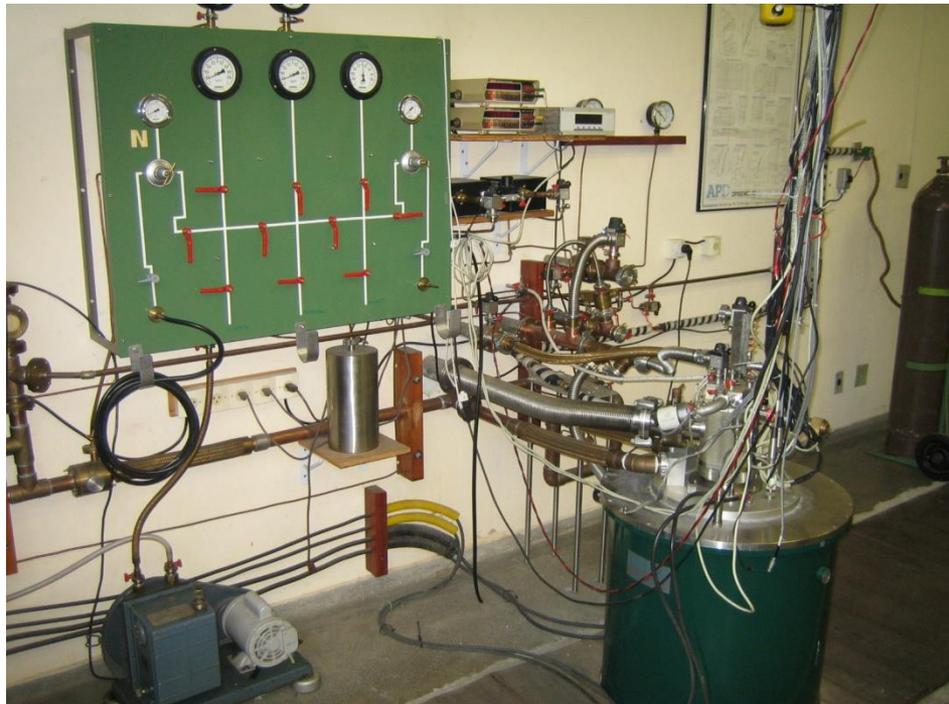
# Gelos de spins $\text{Dy}_2\text{Ti}_2\text{O}_7$



Z. Hiroi *et al.*, J. Phys. Soc.  
Jpn **72**, 411(2003).

# Laboratório de Estado Sólido e Baixas Temperaturas

Medidas de propriedades magnéticas



Bobina supercondutora ~ 17 Tesla  
Refrigerador de diluição  $T > 0,02$  K

Medidas de resistividade e susceptibilidade



Bobinas supercondutoras ~ 20 Tesla  
Criostato de  $\text{He}^3$   $T > 0,4$  K

# Laboratório de Estado Sólido e Baixas Temperaturas



Medidas de propriedades magnéticas  
(SQUID)



Bobinas supercondutoras ~ 7 Tesla

Temperatura  $2\text{K} < T < 300\text{K}$

# Laboratório de Estado Sólido e Baixas Temperaturas



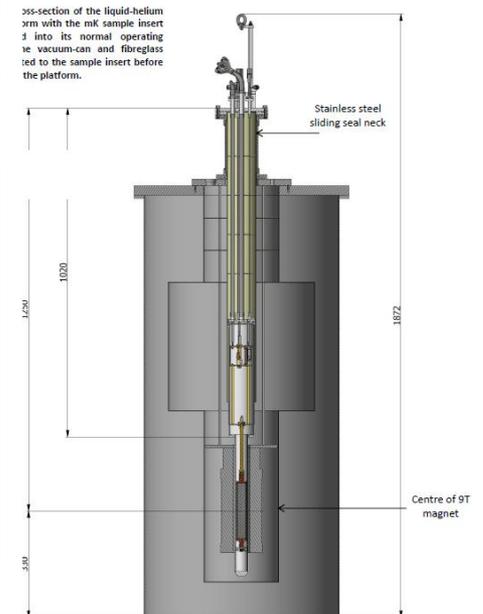
Magnetização, Resistividade, Calor Específico.....

$H < 9$  Tesla e  $T: 0,05$  K - 1000K

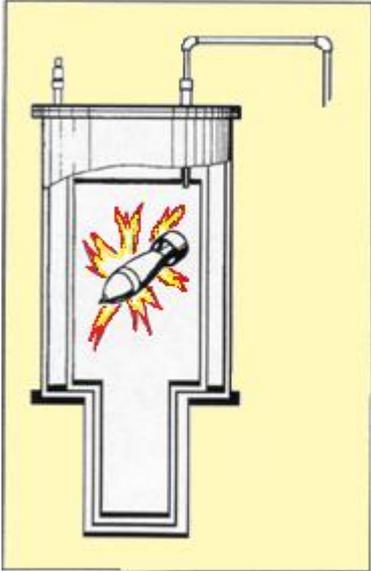
Tudo isso sem He líquido!!!!



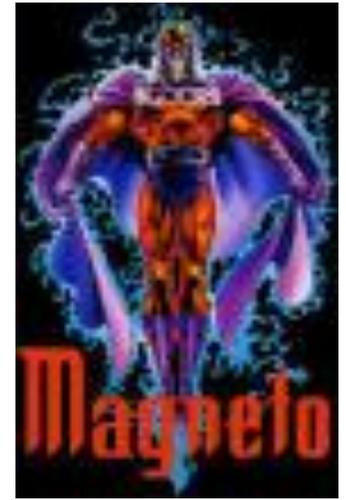
ADR



Don't panic



Muito obrigado  
pela atenção !

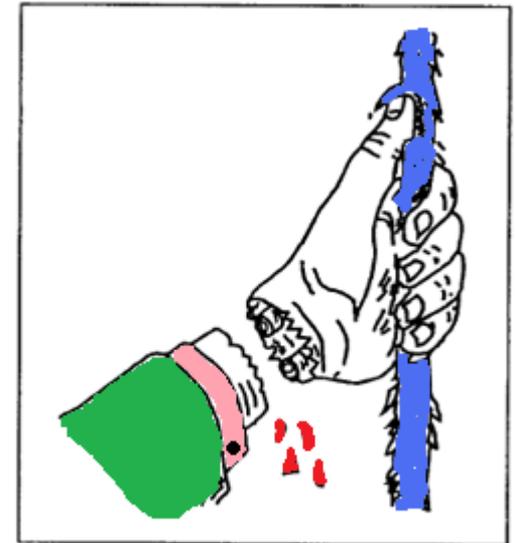


X-Men

Extreme cold

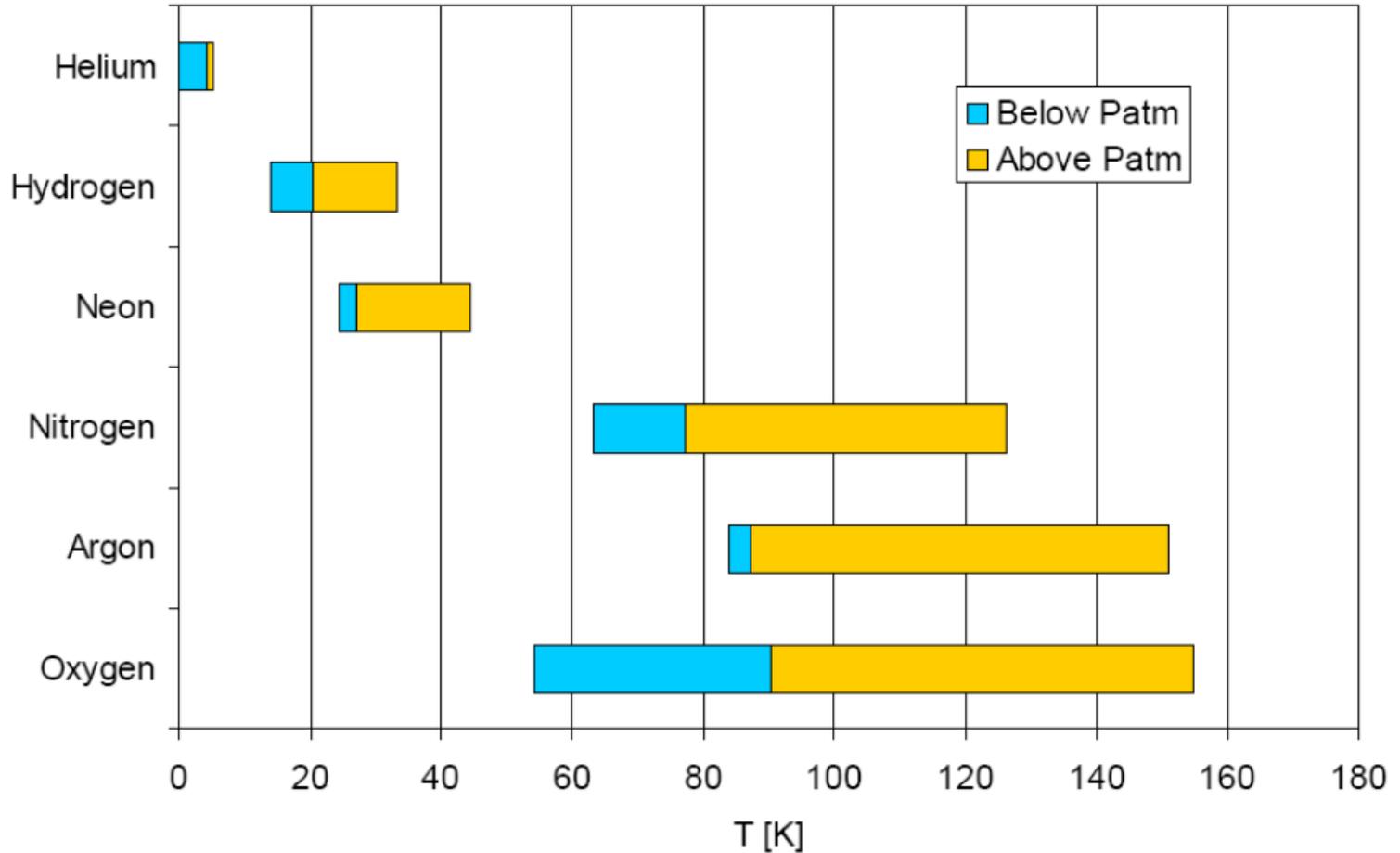


Pinky and The Brain

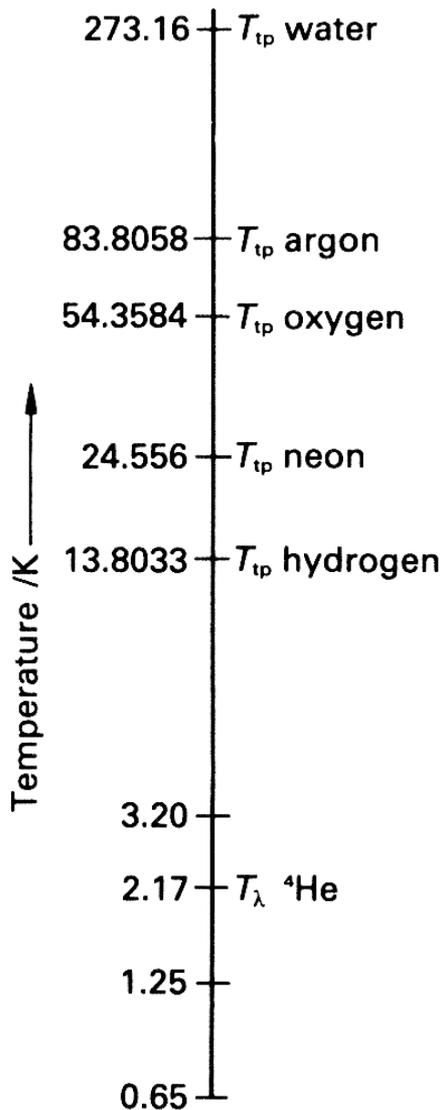


# Cooling with cryogenic liquids

## Useful range of cryogenes



# Termometria

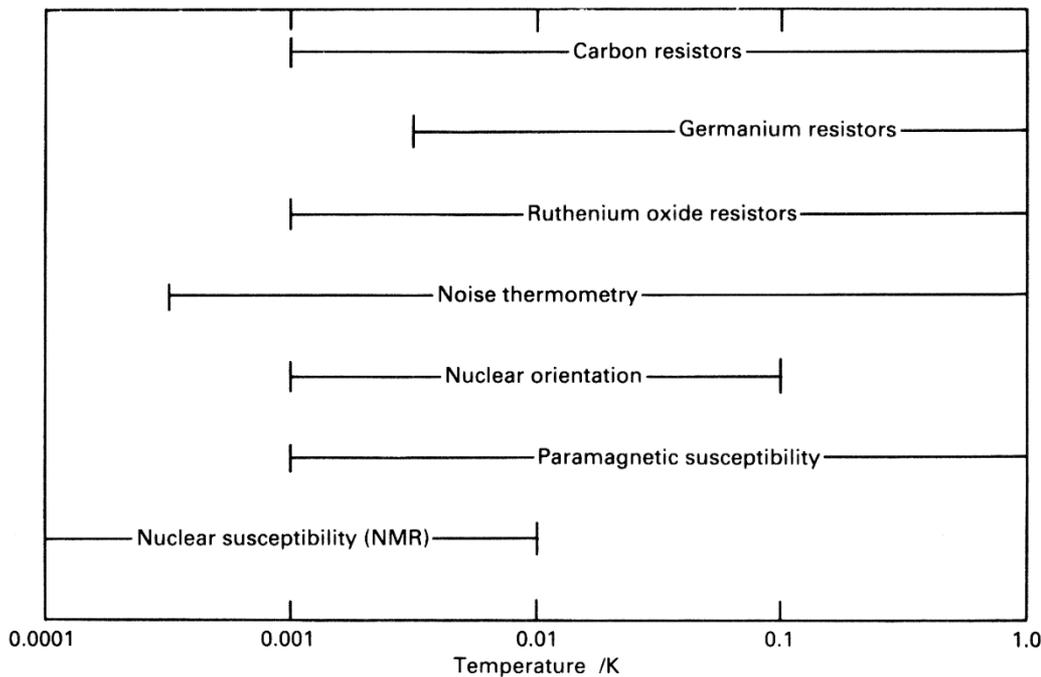
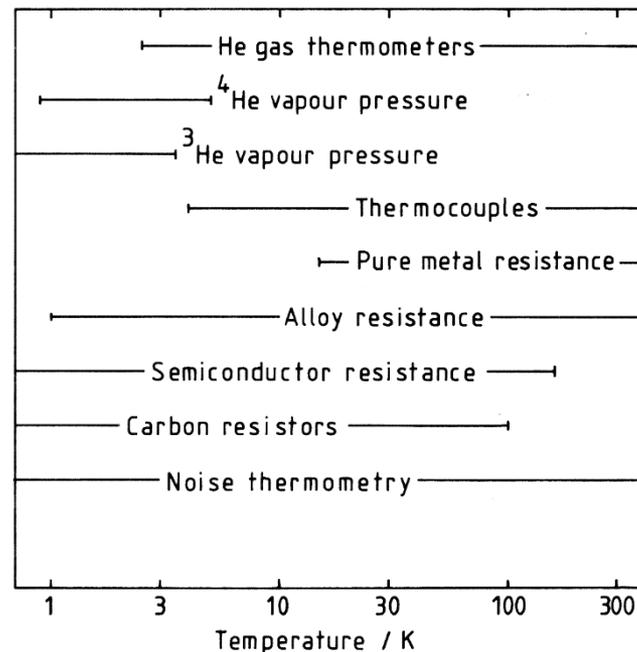


Platinum resistance thermometry

Constant volume gas thermometry

$^4\text{He}$  vapour pressure

$^3\text{He}$  vapour pressure



# Primary Thermometers

A reasonable question at this point is: “What is a primary thermometer?” The answer: it is a thermometer that is based on a well understood physical principle and is reliable. In other words, it gives us the absolute temperature and gives repeatable results.

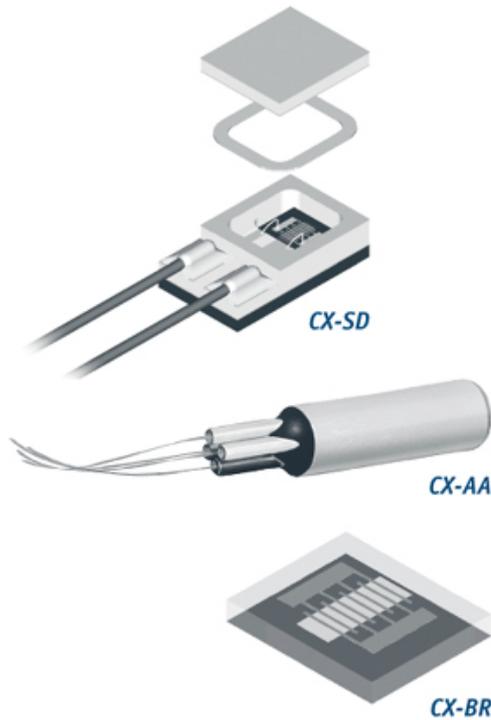
Several temperature scales for the superfluid  $^3\text{He}$  regime have been proposed; four of major interest are:

- The Helsinki scale: based on nuclear orientation thermometry.
- The La Jolla scale: based on noise thermometry.
- The Cornell scale: based on  $^3\text{He}$  melting curve thermometry.
- The Greywall scale: based on the properties of liquid  $^3\text{He}$ .

The four principal methods of primary thermometry are:

1. Gas thermometry in which the pressure is measured, based on the equation of state for an ideal gas,  $PV = nRT$  (where  $n$  is the number of moles of gas) with small corrections for non-ideality in a real gas such as helium.
2. Acoustic gas thermometry dependent on measuring the sound velocity in a gas, e.g. helium, and subject to the same virial corrections as gas thermometry (dielectric constant gas thermometry is similar).
3. Electrical noise in a resistor of  $R$  ohms using the mean square voltage  $\overline{V^2} = 4kTR\Delta f$  where  $\Delta f$  is the frequency bandwidth.
4. Total black body radiation measurement.

# negative T coefficient: Cernox



## Description

Cernox™ thin film resistance cryogenic temperature sensors offer significant advantages over comparable bulk or thick film resistance sensors. The smaller package size of these thin film sensors makes them useful in a broader range of experimental mounting schemes, and they are also available in a chip form. They are easily mounted in packages designed for excellent heat transfer, yielding a characteristic thermal response time much faster than possible with bulk devices requiring strain-free mounting. Additionally, they have been proven very stable over repeated thermal cycling and under extended exposure to ionizing radiation.

## PACKAGING OPTIONS AA, BC, BG, BO, BR, CD, CO, CU, ET, LR, MR, SD

▶ [Click here for Adding Length to Sensor Leads](#)

## Features

- Low magnetic field- induced errors
- Temperature range of 100 mK to 420 K (model dependent)
- High sensitivity at low temperatures and good sensitivity over a broad range
- Excellent resistance to ionizing radiation
- Bare die cryogenic temperature sensor with fast characteristic thermal response times: 1.5 ms at 4.2 K, 50 ms at 77 K
- Broad selection of models to meet your thermometry needs
- Excellent stability
- Variety of packaging options

## CX-1010 – the Ideal Replacement for Germanium RTDs

*The CX-1010 is the first Cernox™ designed to operate down to 100 mK, making it an ideal replacement for Germanium RTDs. Unlike Germanium, all Cernox models have the added advantage of being able to be used to room temperature. In addition, Cernox is offered in the incredibly robust Lake Shore SD package, giving researchers more flexibility in sensor mounting.*

## The Lake Shore SD Package – The Most Rugged, Versatile Package in the Industry

*The SD package, with direct sensor-to-sapphire base mounting, hermetic seal, and soldered copper leads, provides the industry's most rugged, versatile cryogenic temperature sensors with the best sample to chip connection. Designed so heat coming down the leads bypasses the chip, it can survive several thousand hours at 420 K (depending on model) and is compatible with most ultra high vacuum applications. It can be indium soldered to samples without sensor calibration shift.*