

Superconduttività : aspetti fondamentali e recenti sviluppi

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**Corso di aggiornamento A.I.F.
7 Novembre 2018**

Gli elettroni si respingono e si attraggono: magnetismo e superconduttività nella materia

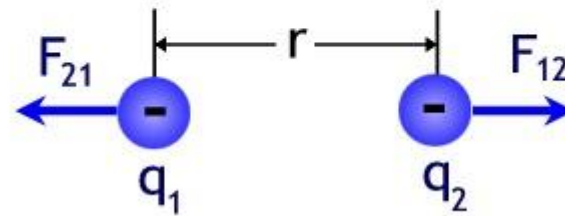
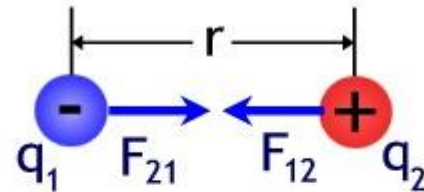


Forza di Coulomb e momenti magnetici



Charles-Augustin de Coulomb

$$\vec{F}_{12} = k_e \frac{q_1 q_2}{r^2} \hat{\mathbf{r}}$$

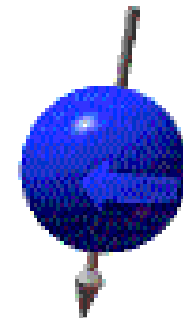


$$S=1/2$$

$$\vec{\mu}_s = -2\mu_B \vec{S}$$



$$m_s = +1/2$$



$$m_s = -1/2$$

Principio di esclusione di Pauli

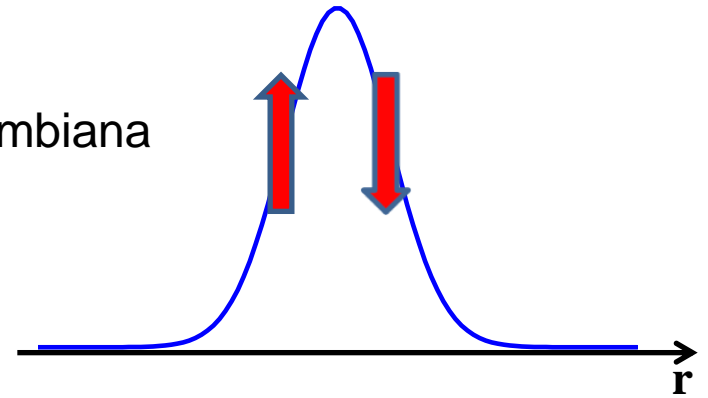
"Due elettroni non possono occupare simultaneamente lo stesso stato"



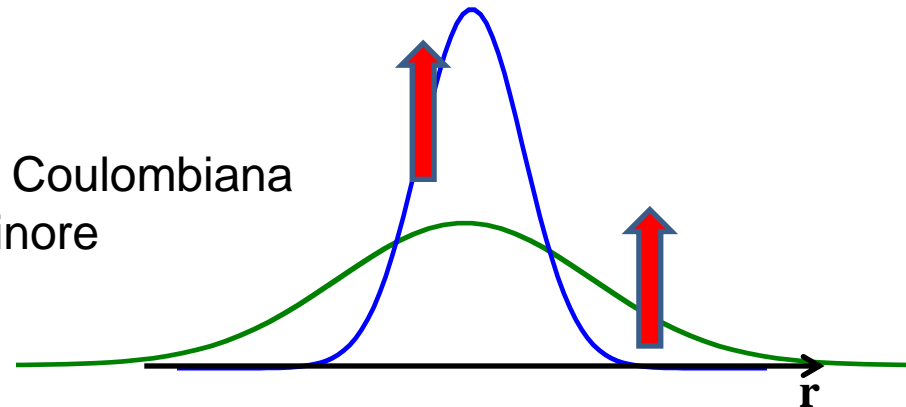
Wolfgang Pauli



Repulsione Coulombiana maggiore



Repulsione Coulombiana minore



Ferromagnetismo

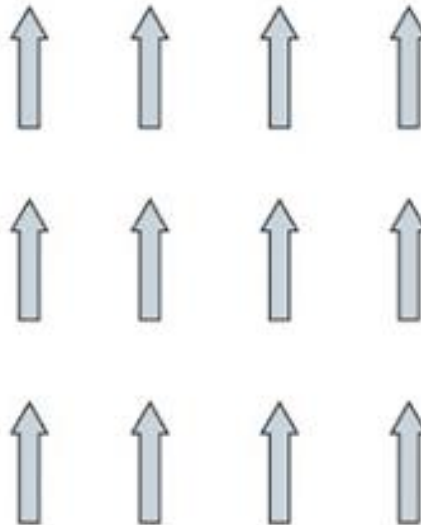
Repulsione Coulombiana + Principio di Pauli



Interazione di scambio

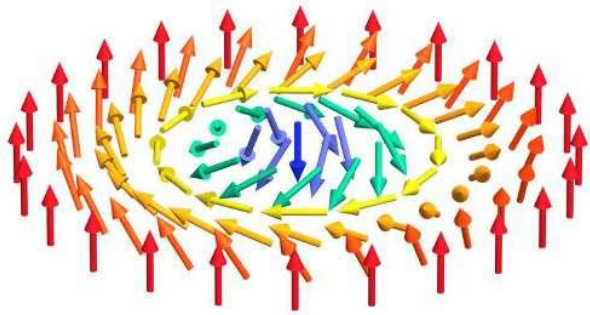


Magnetismo



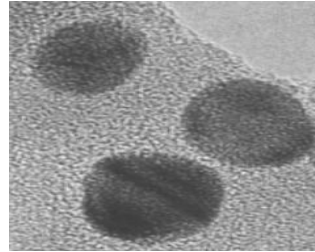
ferromagnete

Magnetismo

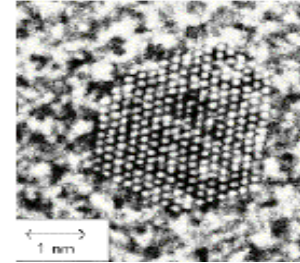


Eccitazioni di spin

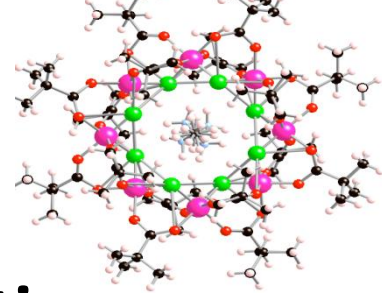
← 30 nm →



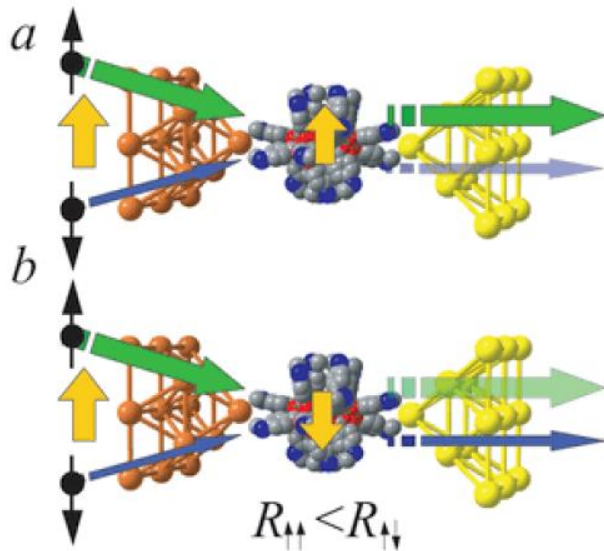
← 5 nm →



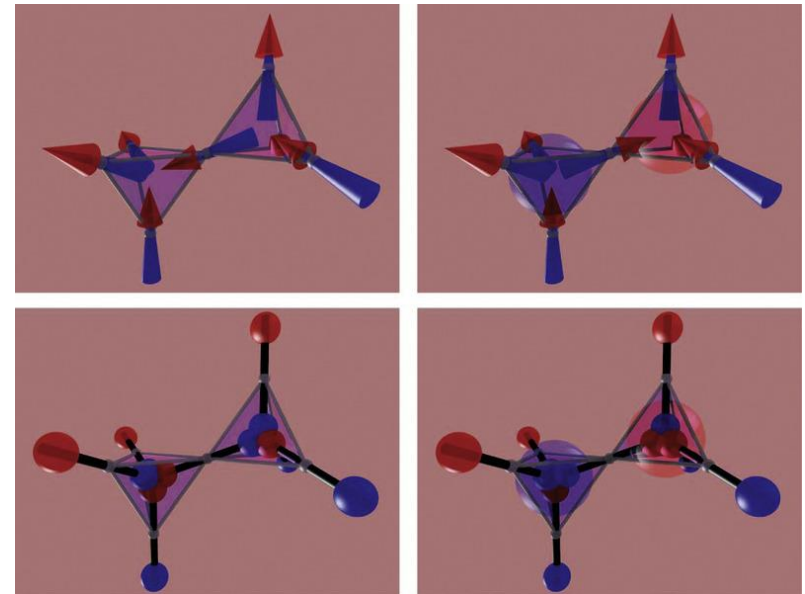
← ~1 nm →



Nanomagnetismo



Spintronica

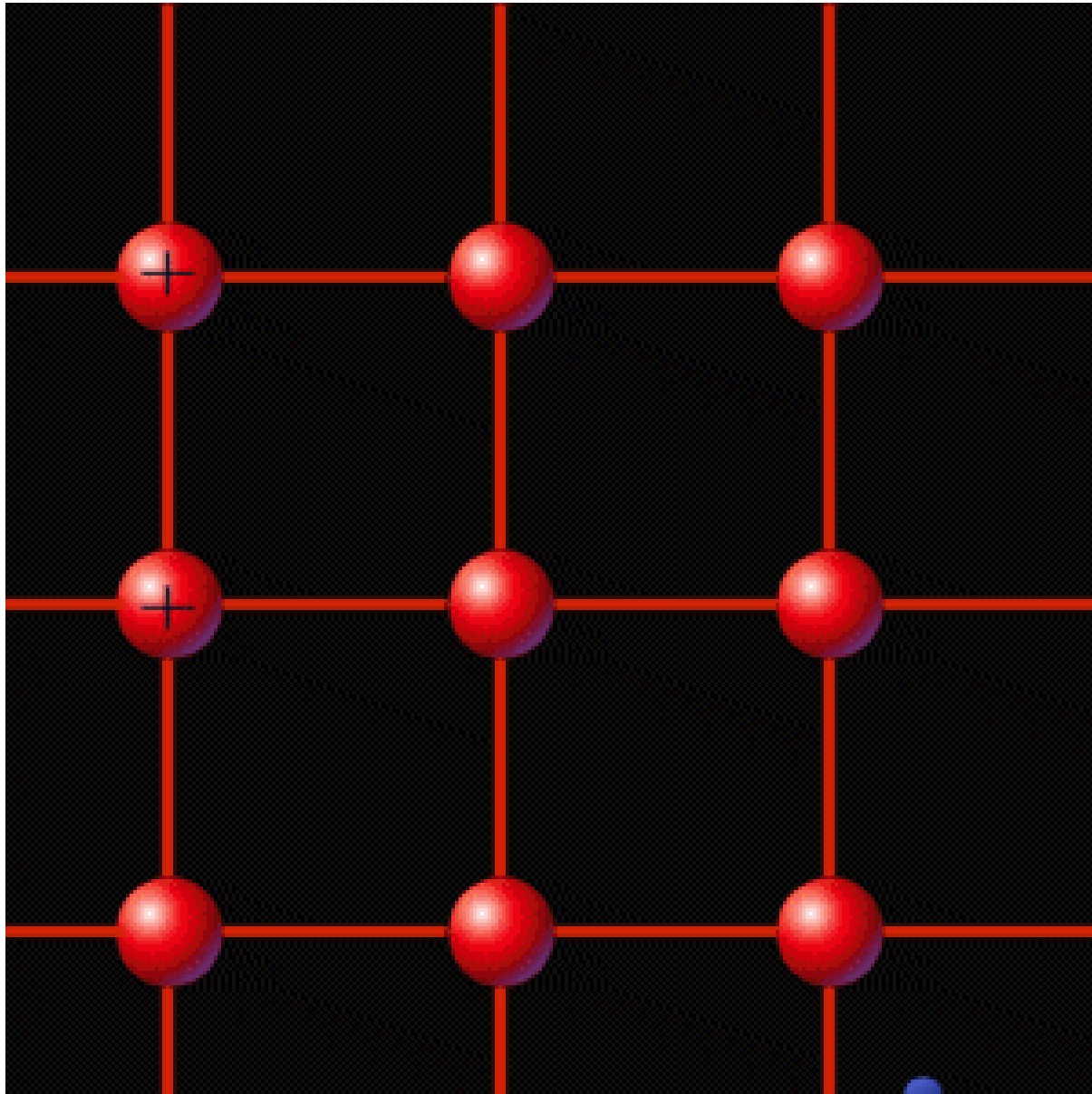


Nuove fasi magnetiche

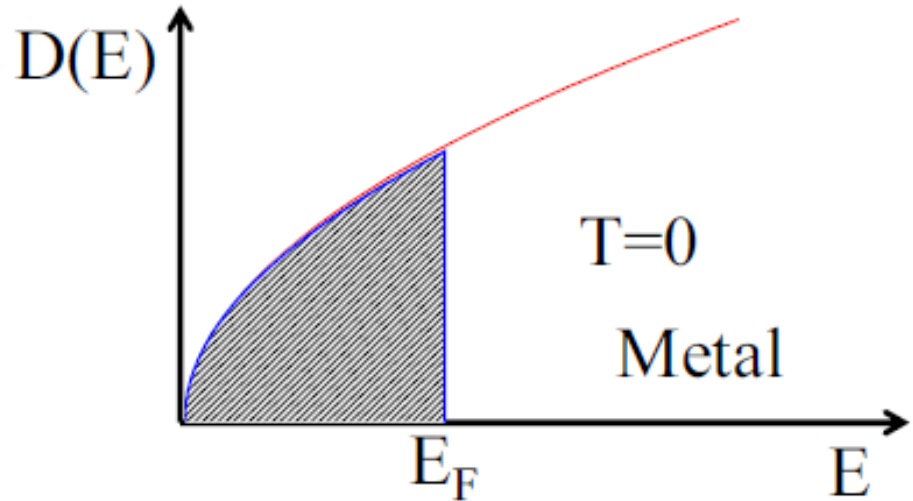
Gli elettroni si attraggono

Formazione dinamica di coppie di elettroni (Coppie di Cooper)

$$E_F / \hbar \gg \omega_D$$

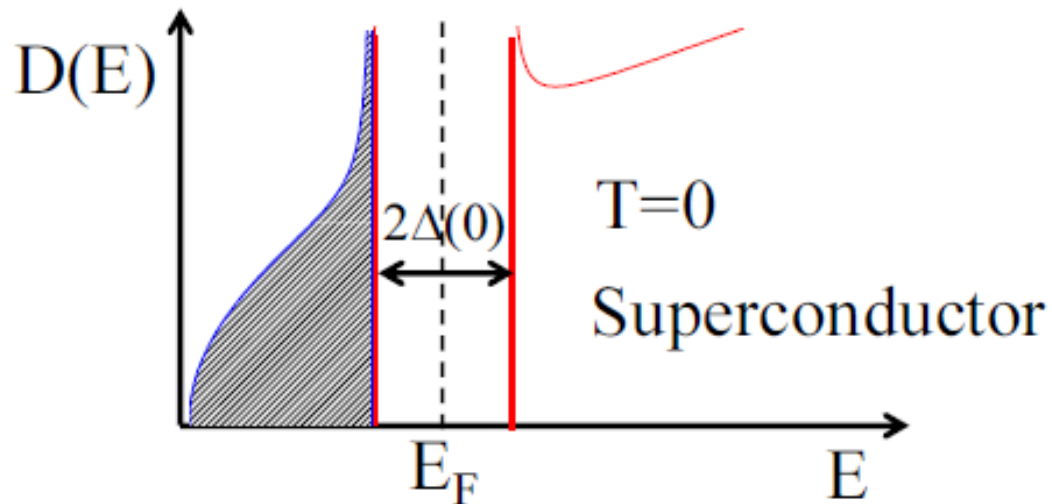


Superconduttività



$$\Delta(0) = 2\hbar\omega_D \exp[-1/\lambda]$$

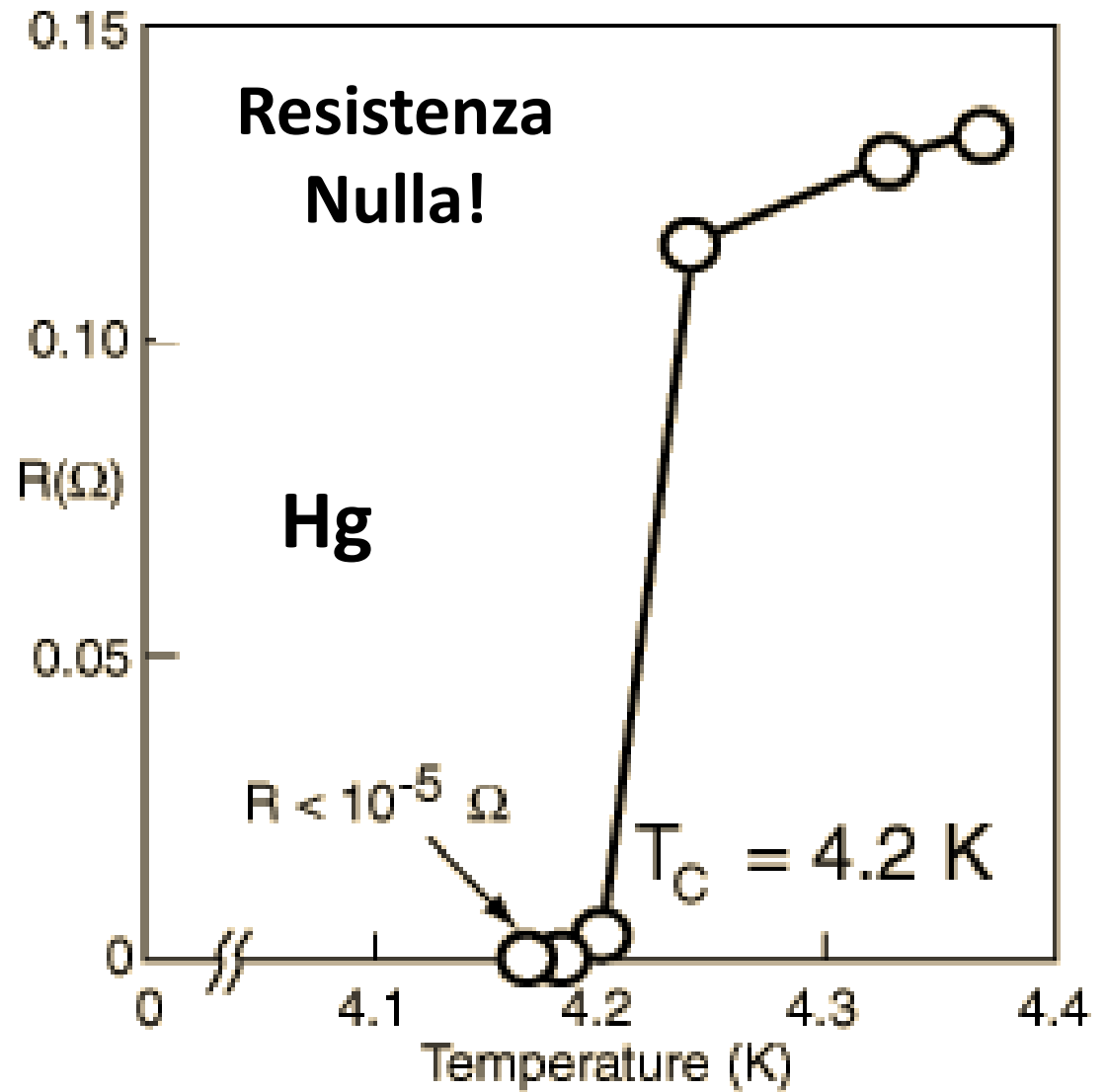
$$\lambda = D(E_F)V$$



Superconduttività



H.Kamerlingh Onnes

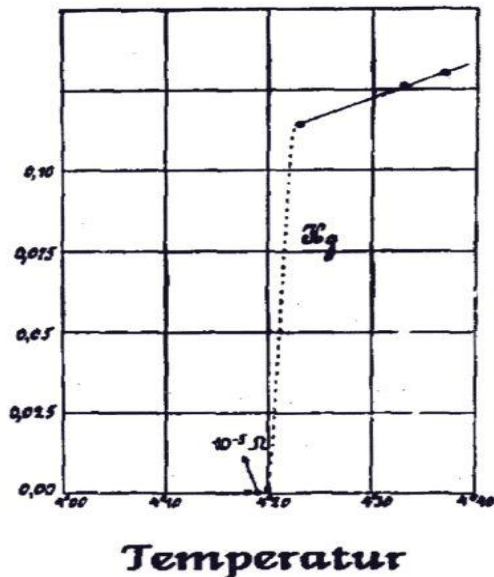


Sviluppo tecnologico



Kamerlingh Onnes

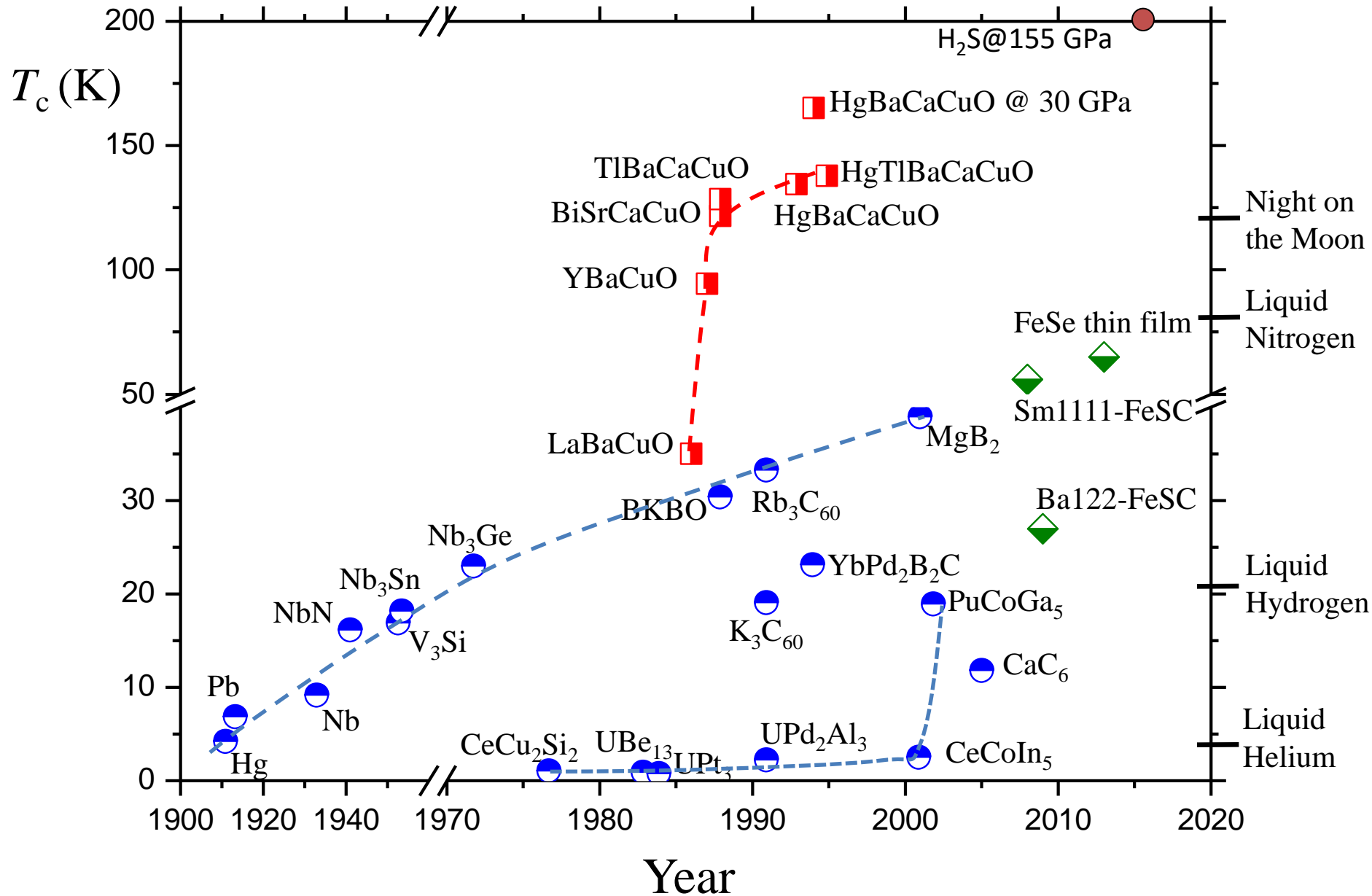
Zero resistance



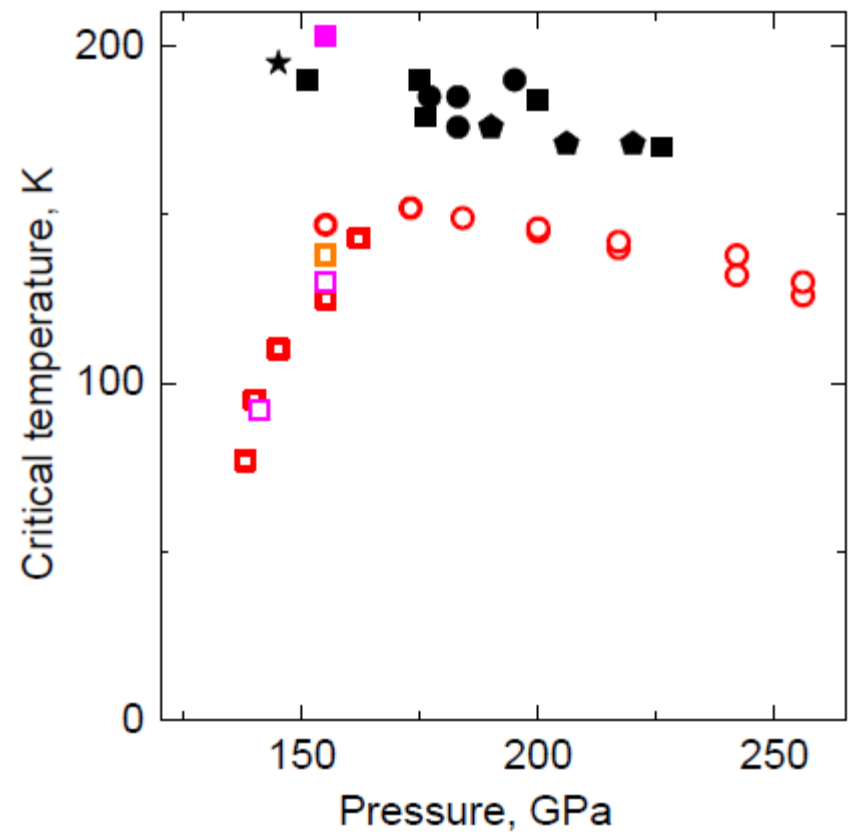
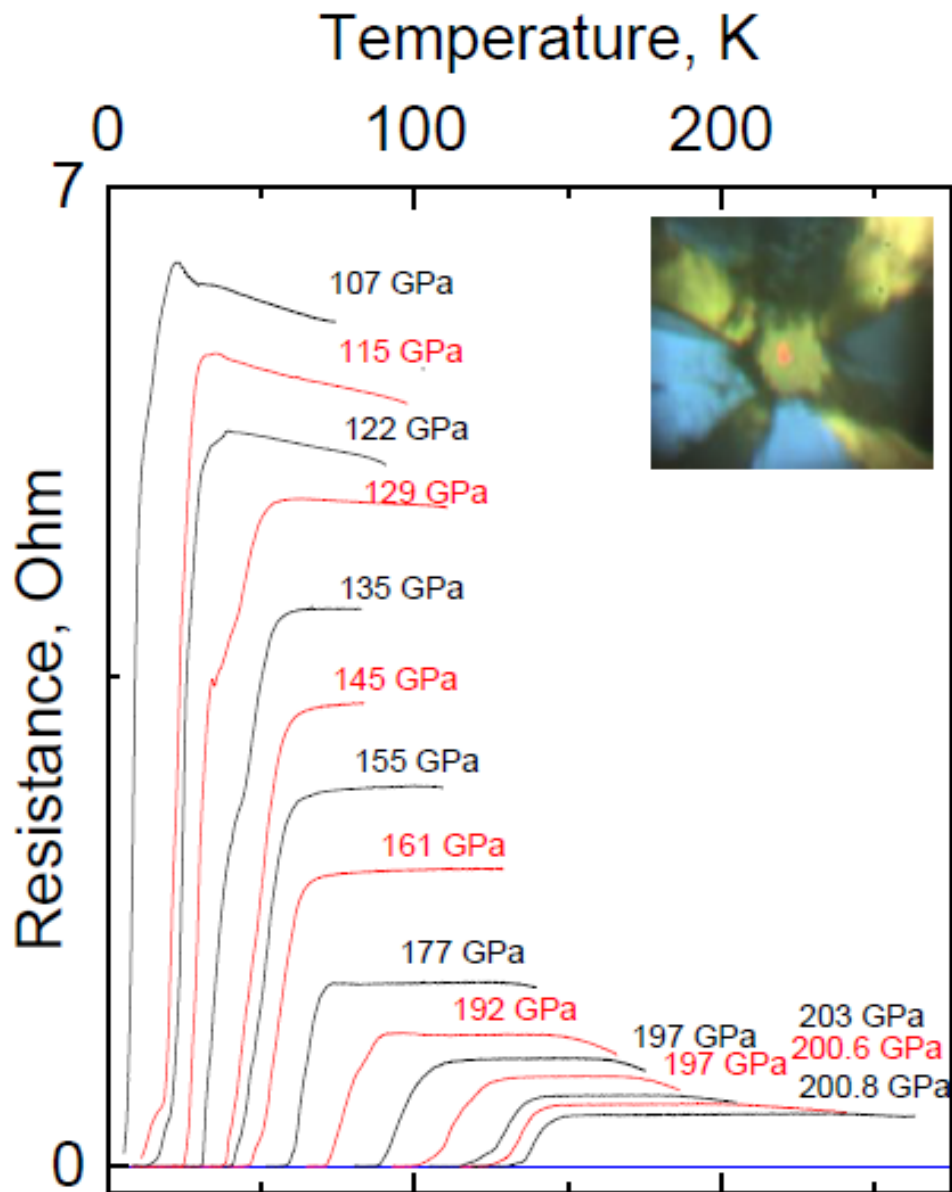
In 1911 a PhD student ,**Von Holst**, from very precise measurements realized that a novel state of matter was showing up.

The experimental setup was realized thanks to the talent of the glass blower **Oskar Kesserling**

Superconduttività dal 1911 ad oggi



H₂S superconductivity



A.P.Drozdov et al., Nature 525, 73 (2015)

Superconduttività

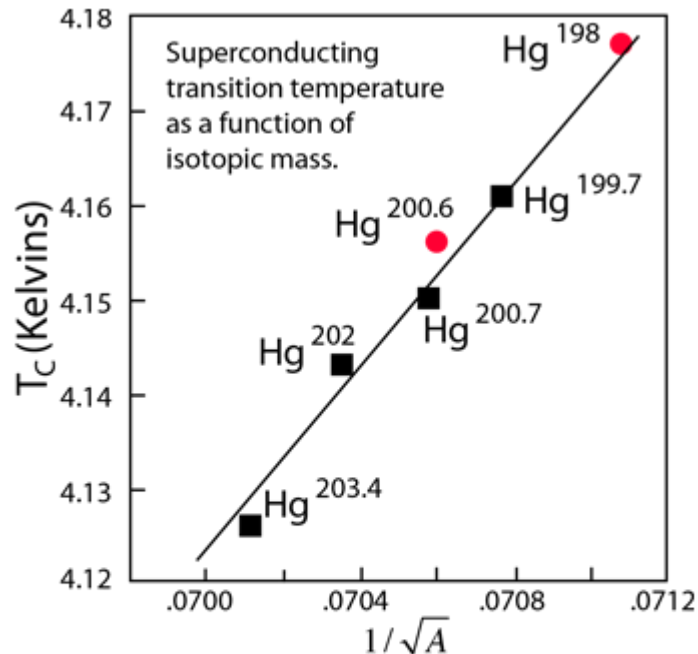
Superconduttori Convenzionali

$$E_F \gg \hbar\omega_D$$

$$T_c = \frac{1.14\hbar\omega_D}{k_B} \exp[-1/D(E_F)V] \quad , \quad 2\Delta(0) = 3.5 k_B T_c$$

Effetto isotopico

$$M^{1/2} \cdot T_c = \text{cost.}$$



E.Maxwell, Phys.Rev.78, 477 (1950);

A.A.Reynolds et al., Phys.Rev.78, 487 (1950)

Superconduttività

Superconduttori a base di Cu e Fe

$$U_C \sim E_F \gtrsim J \gtrsim \hbar\omega_D$$

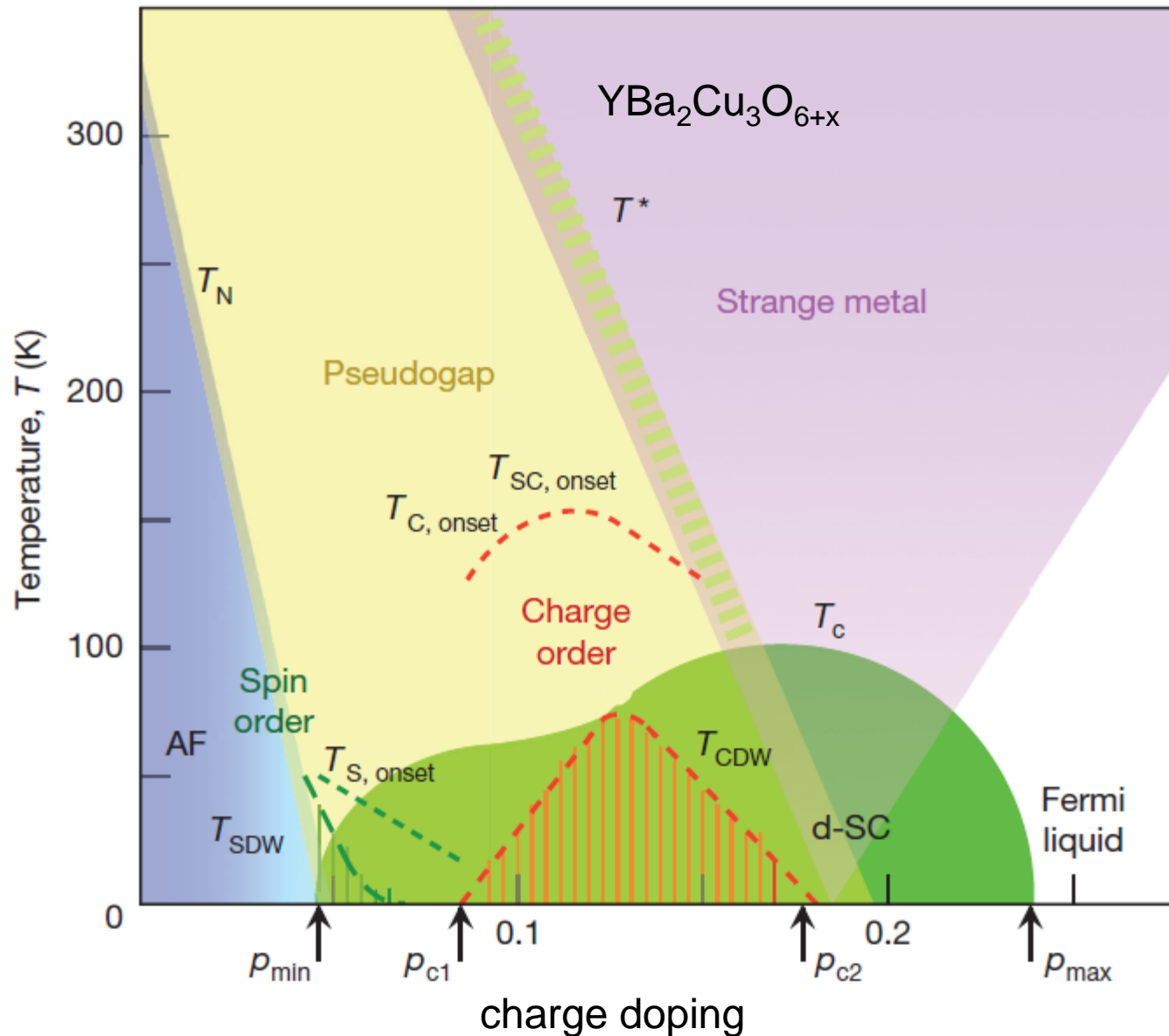
Banda di conduzione mezza piena

$$U_C < E_F \quad \text{conduttore}$$

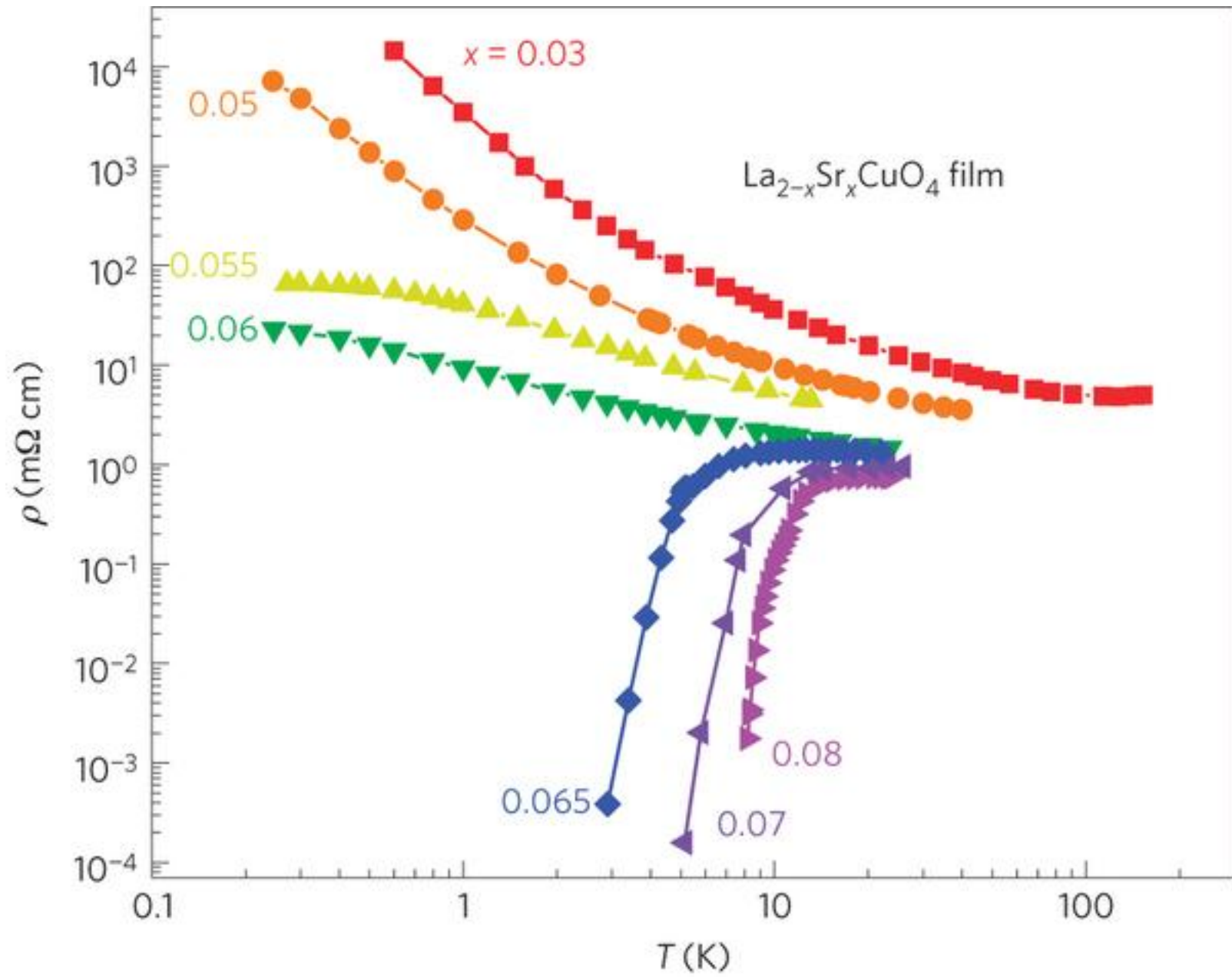
$$U_C > E_F \quad \text{isolante}$$

Superconduttori ad alta T_c a base di Cu

B. Keimer et al., Nature. **518**, 179 (2015)

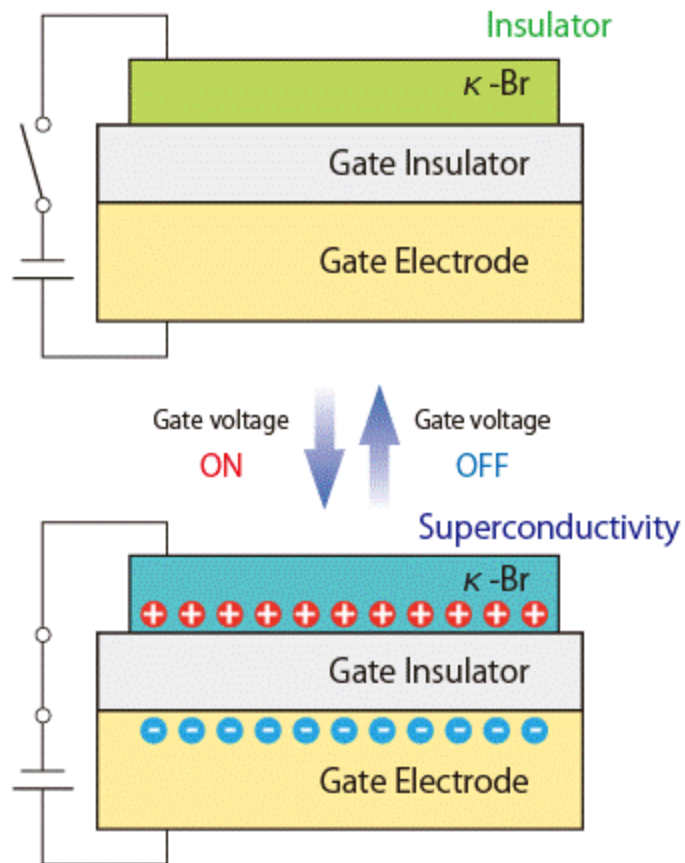


Superconduttività nei Cuprati

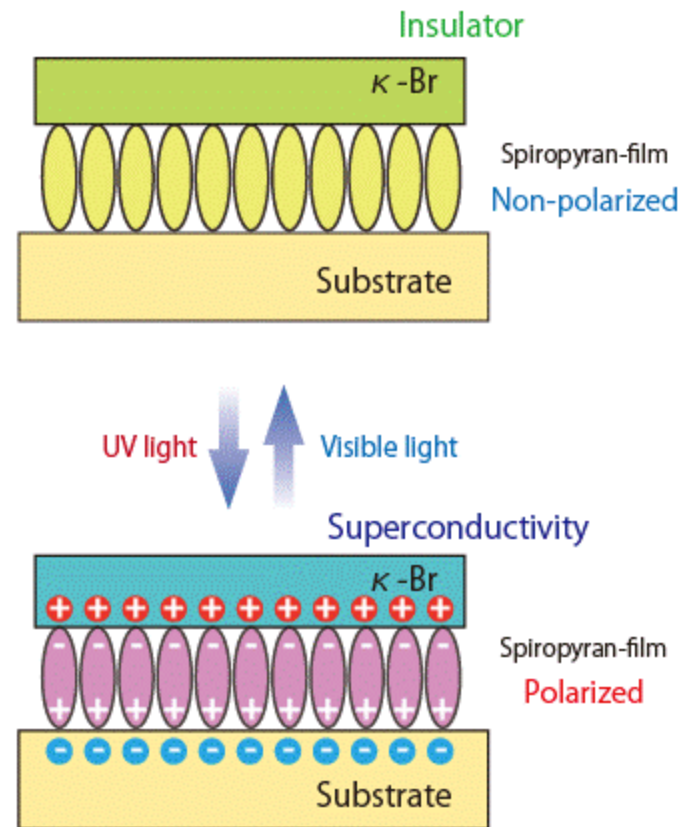


Superconduttività in FET

A. Conventional FET

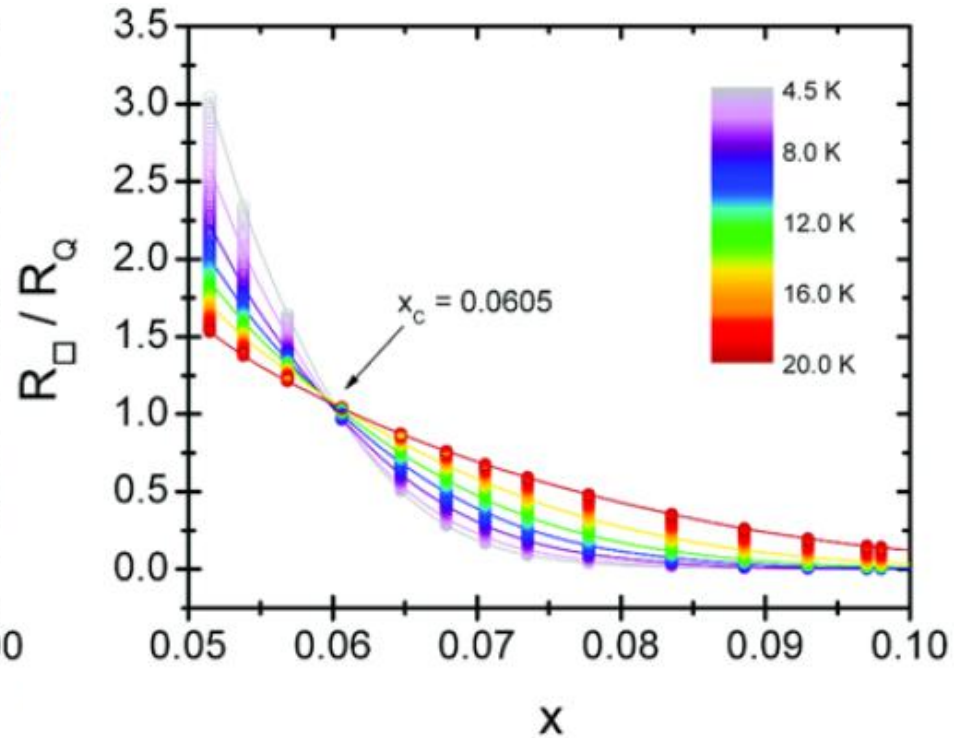
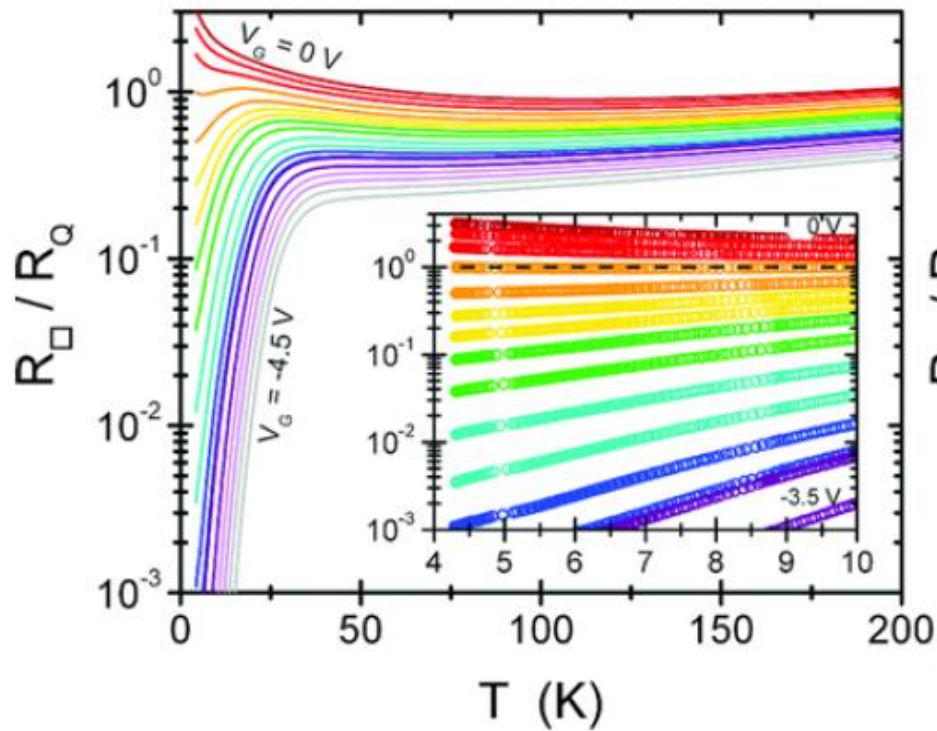


B. Novel Photo-active FET



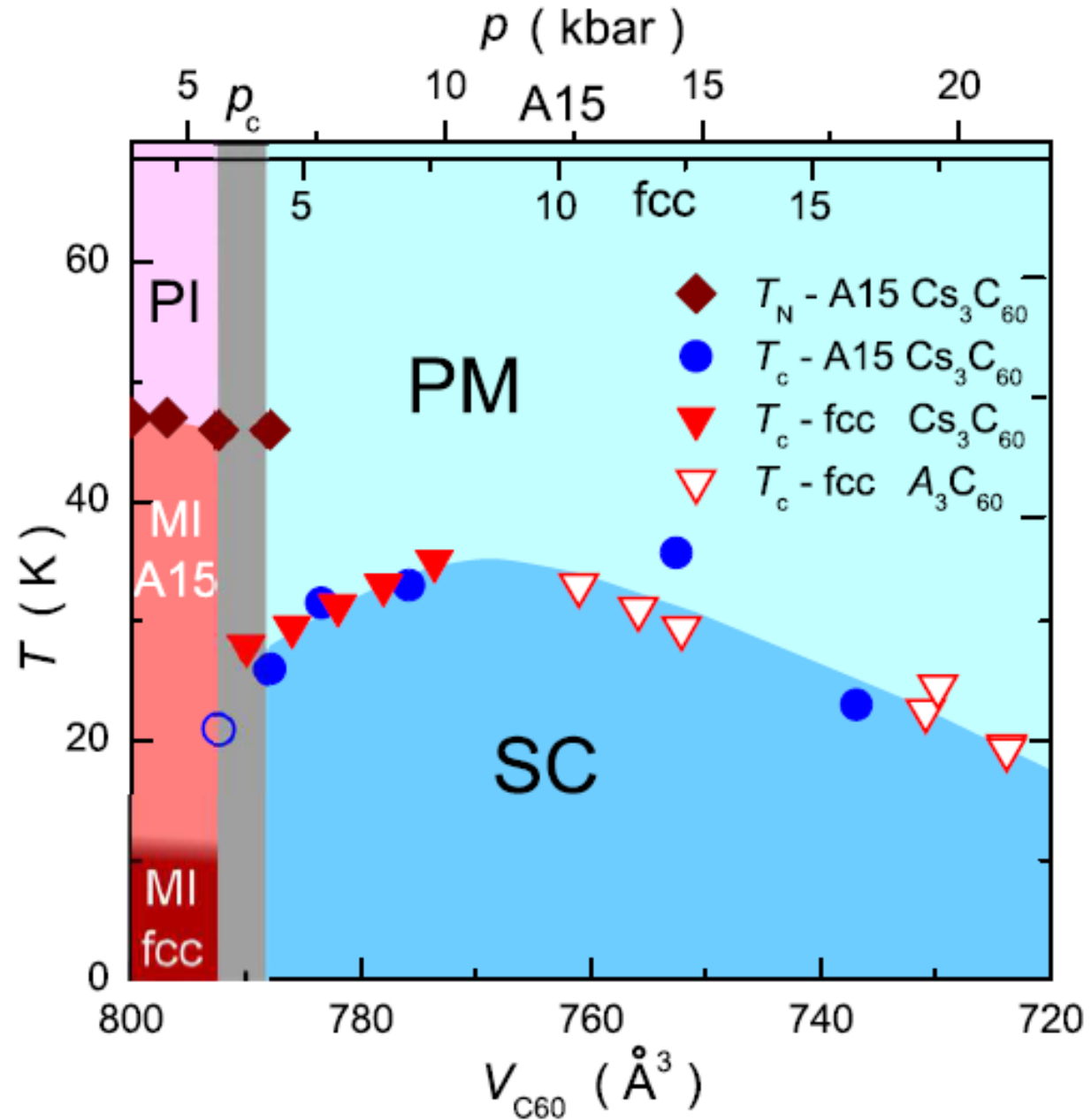
Superconduttività in FET

G.Dubuis et al., J.Supercond.Nov.Magn. **26**, 749 (2013)



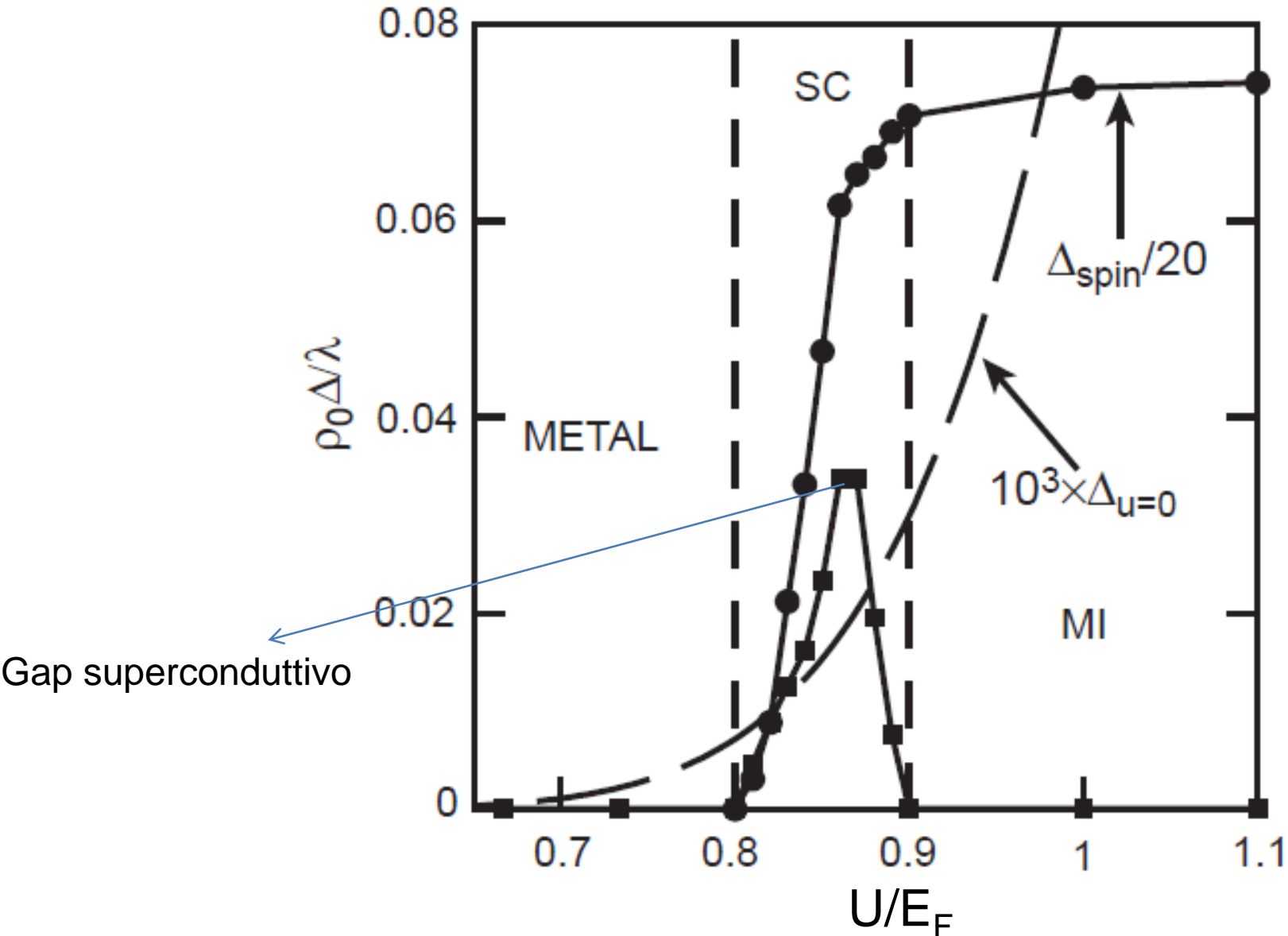
Superconduttività nelle fulleriti

Y.Ihara et al., EPL **94**, 37007 (2011)



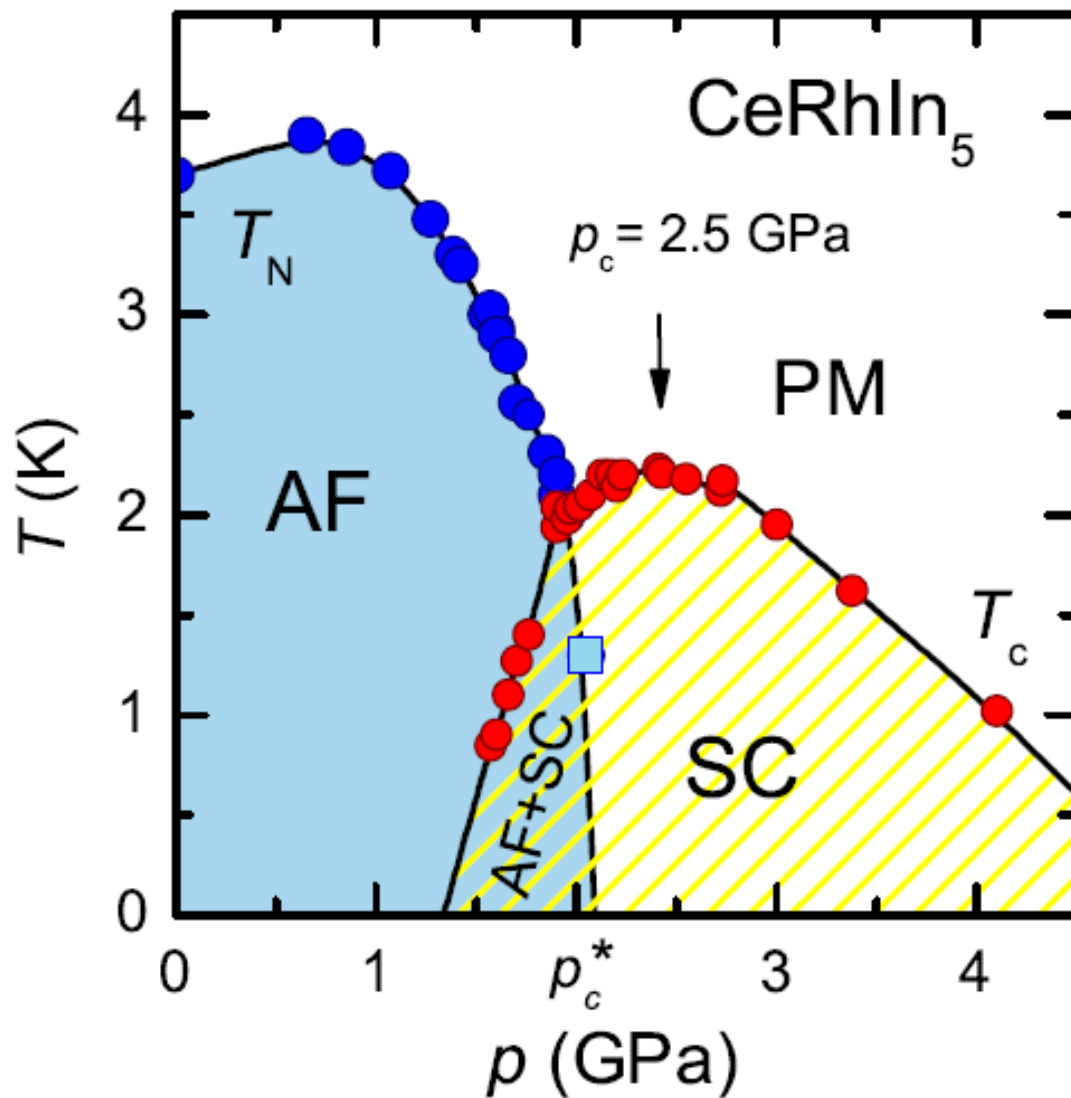
Superconduttività in prossimità di fasi isolanti

M.Capone et al., Science **296**, 2364 (2002)



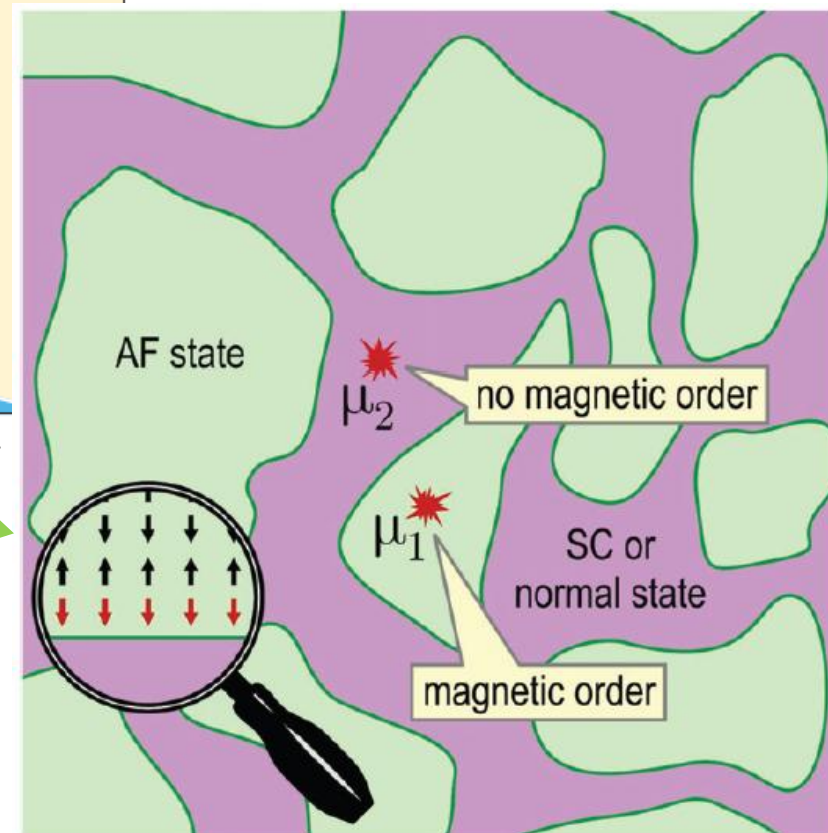
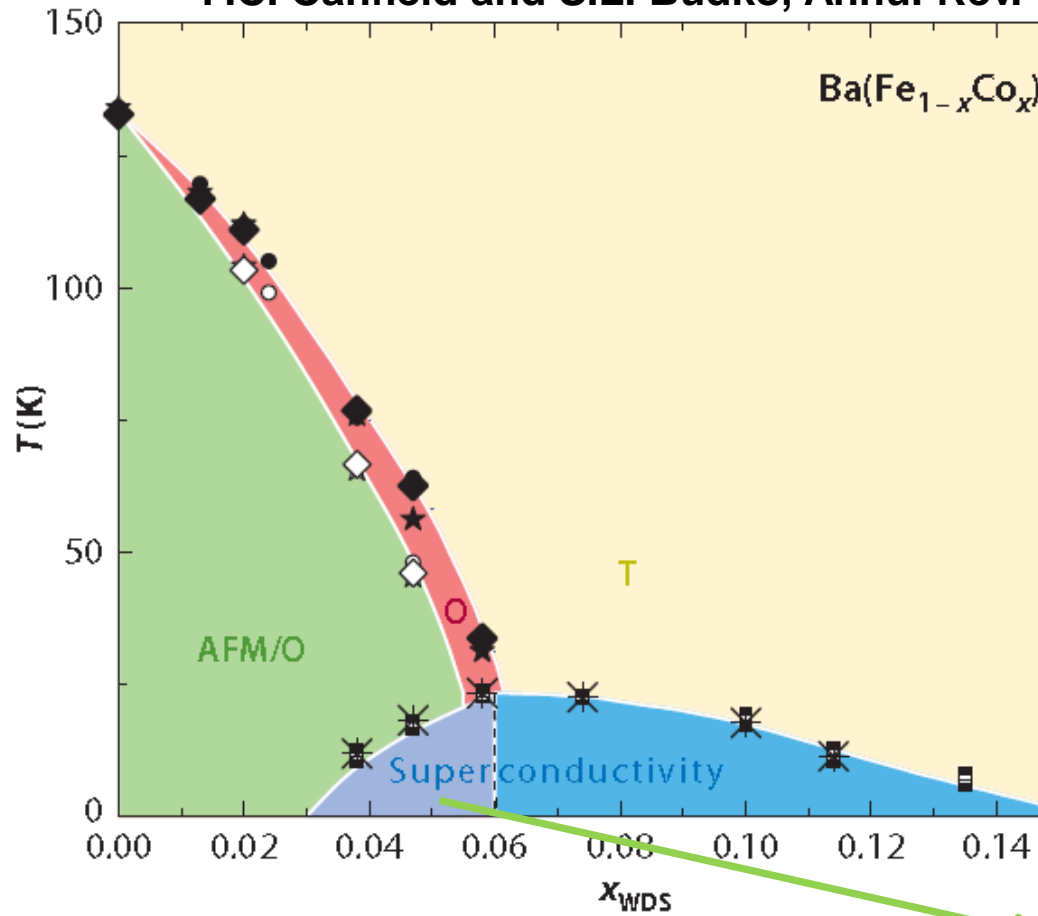
Superconduttività in sistemi a fermioni pesanti

G.Knebel et al., Compt.Ren.Phys.12, 542(2011)



Magnetismo e Superconduttività Coesistono

P.C. Canfield and S.L. Budko, Annu. Rev. Condens. Matter Phys. 1, 27(2010)

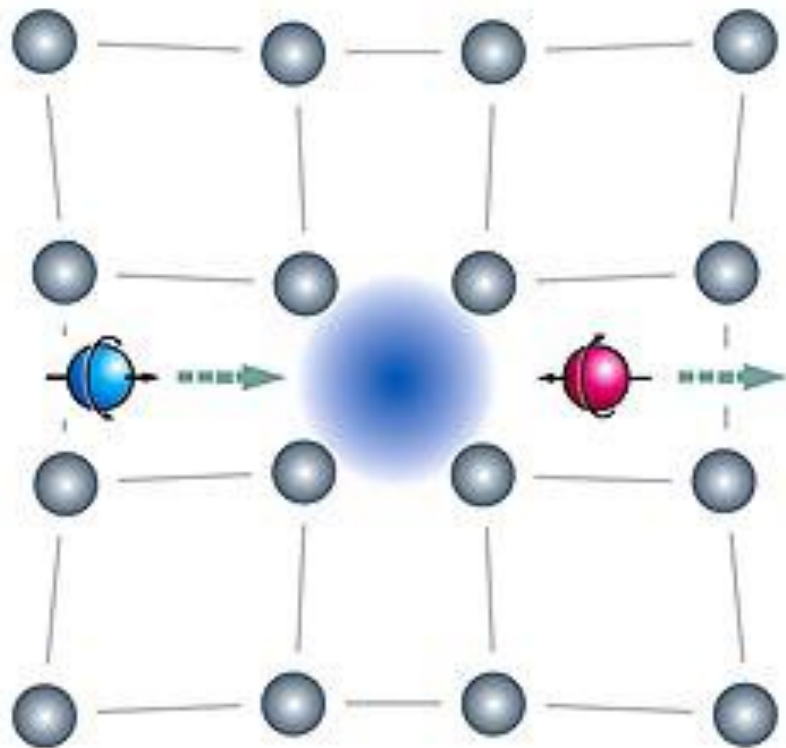


Magnetismo e Superconduttività competono



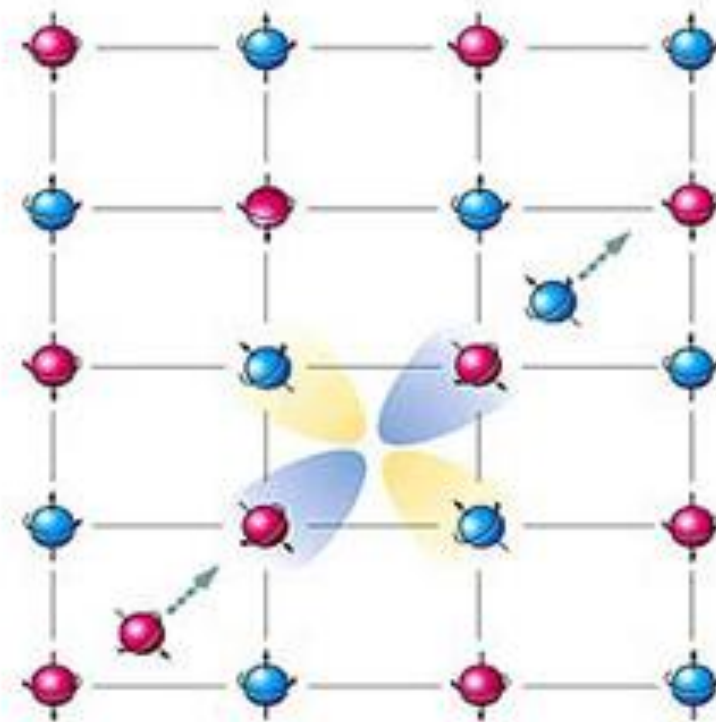
Superconduttività indotta dal magnetismo...

Accoppiamento
fononico
(vibrazioni reticolari)



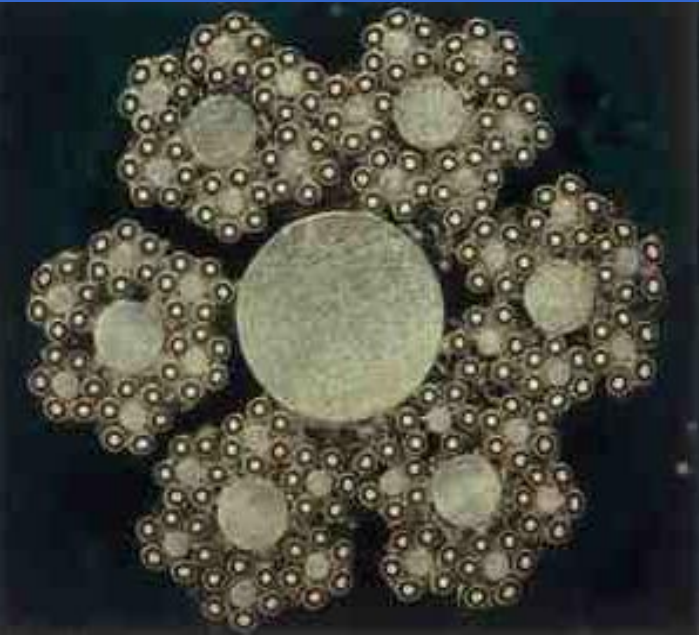
Superconduttori
convenzionali

Accoppiamento
magnetico
(eccitazioni di spin)



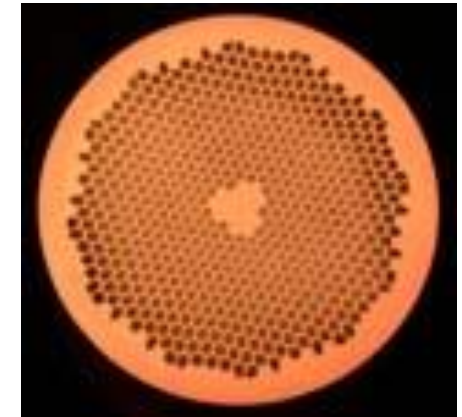
Superconduttori
a base di Cu e Fe

Trasmissione di corrente elettrica



Cavi di Nb_3Sn
Fatti da fili di
10 micron di diametro

Correnti sino a
 10^6 Amp/cm^2



**Cavi basati su superconduttori
ad alta temperatura per
distribuire GigaWatt di potenza
In una rete di diversi km**

**Pirelli:
cavo da 10^8 Watt a Detroit**



Applicazioni di Potenza



SMES (Superconducting Magnet Energy Storage) da **50 Megawattora** con solenoidi superconduttori costituiti da cavi con diversi Km di lunghezza e intensità del campo 2 Tesla.

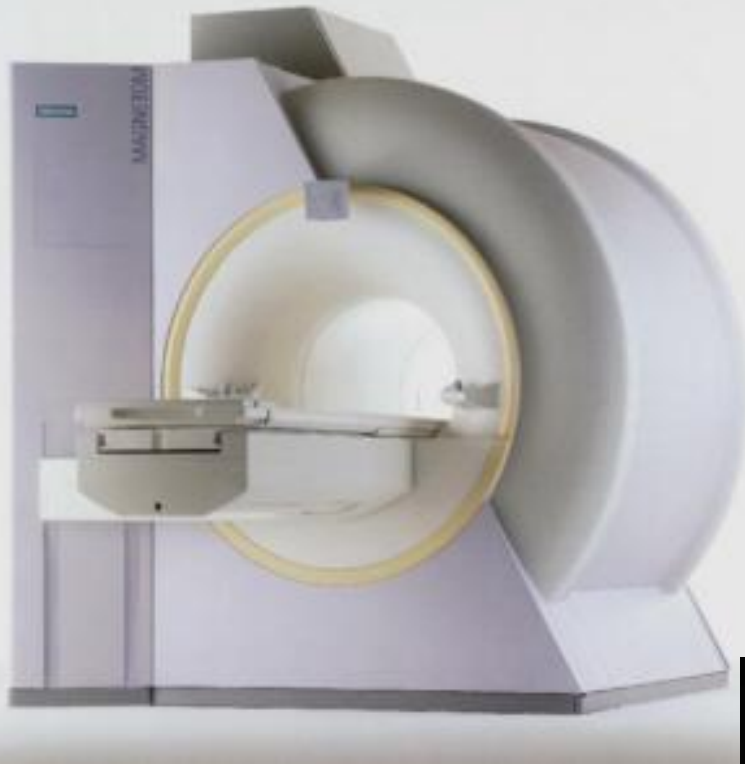
Progetto ECCOFLOW – Milano

a2a in collaborazione con **RSE** hanno costruito un dispositivo a superconduttore, limitatore di corrente di corto circuito (tra i primi in Europa) su Media Tensione, al fine di :

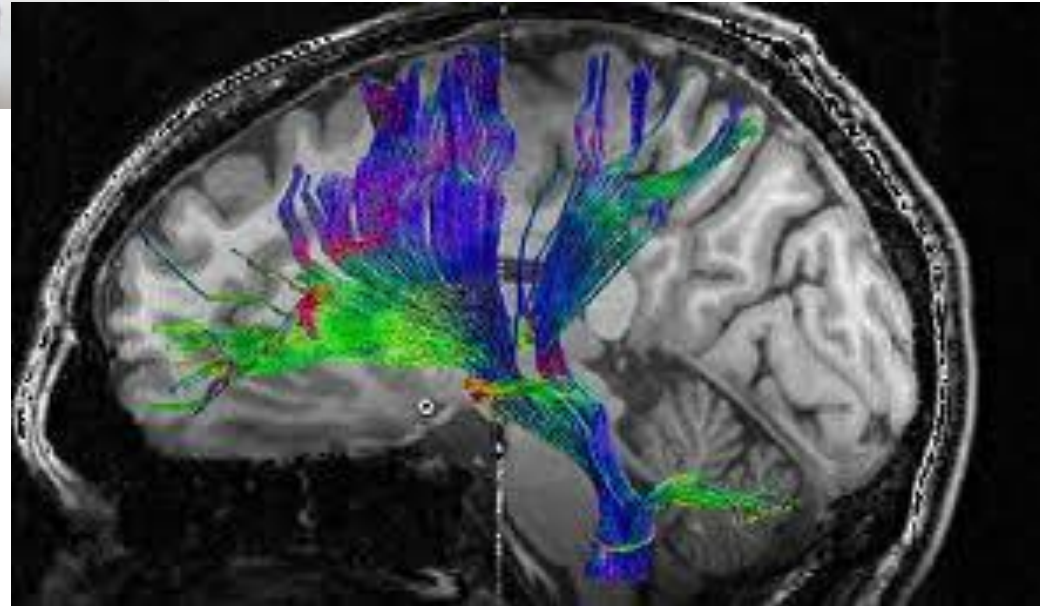
- ridurre i rischi di danneggiamento di importanti componenti della rete;
- ridurre gli effetti dei cali/buchi di tensione



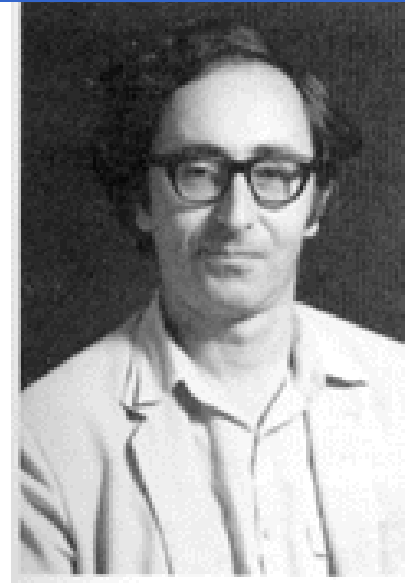
Superconduttori per la Diagnostica Medica



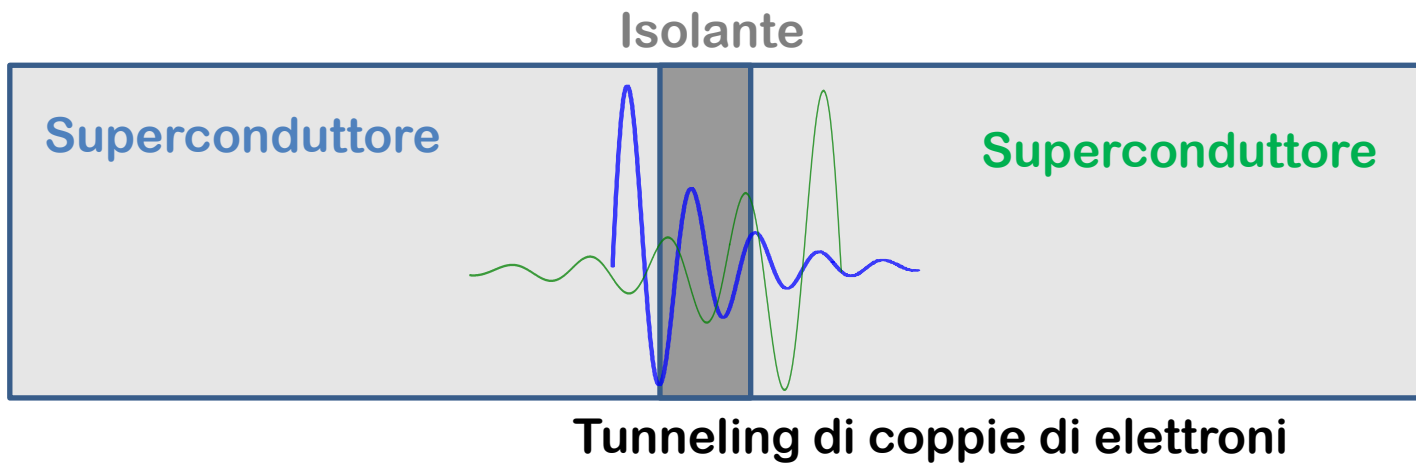
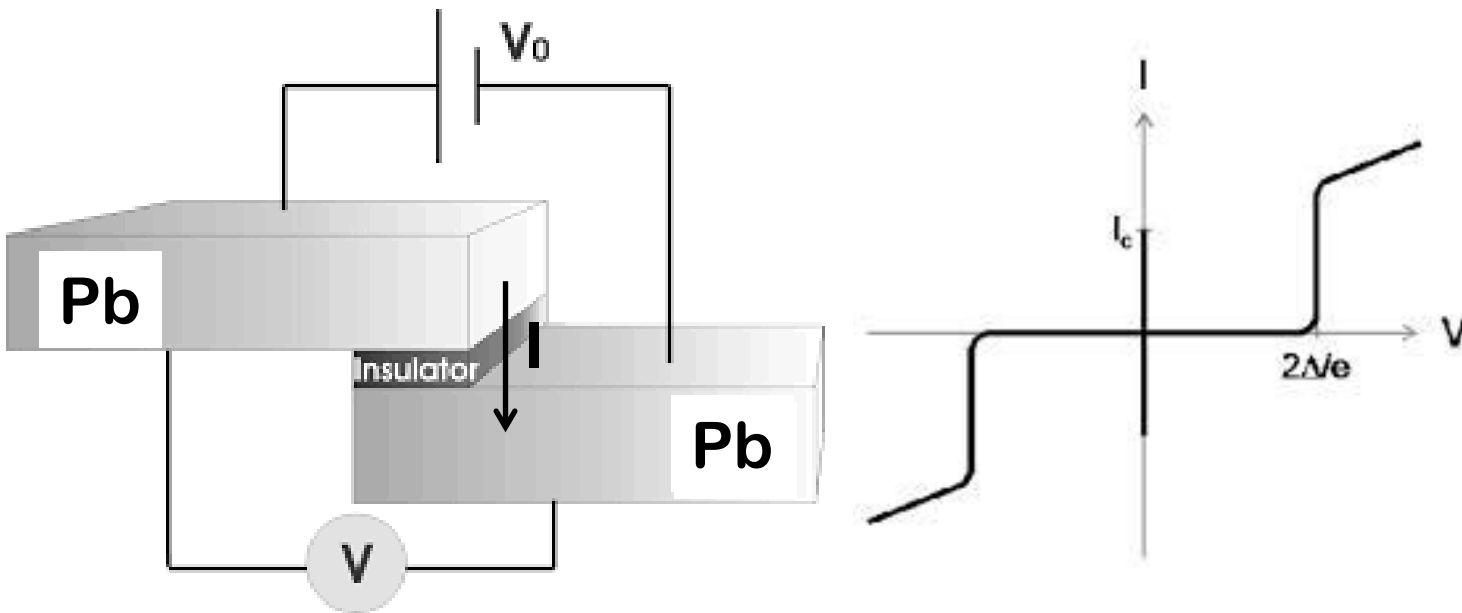
**Tomografia a
Risonanza Magnetica Nucleare**



Effetto Josephson

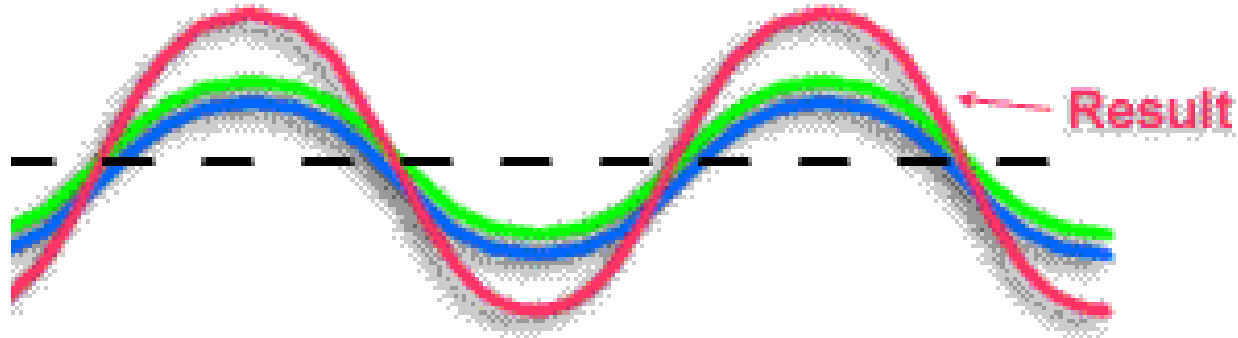


Brian Josephson

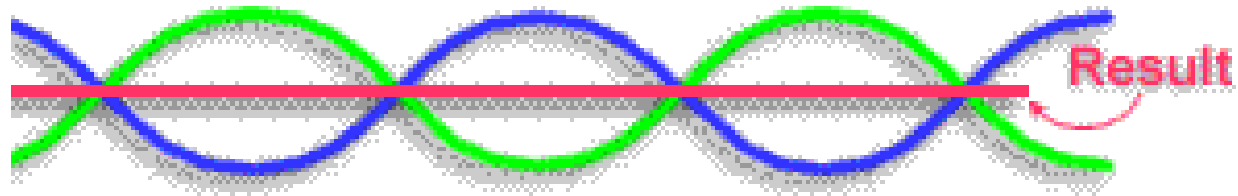


Interferenza fra coppie di elettroni → fra onde

Constructive Interference



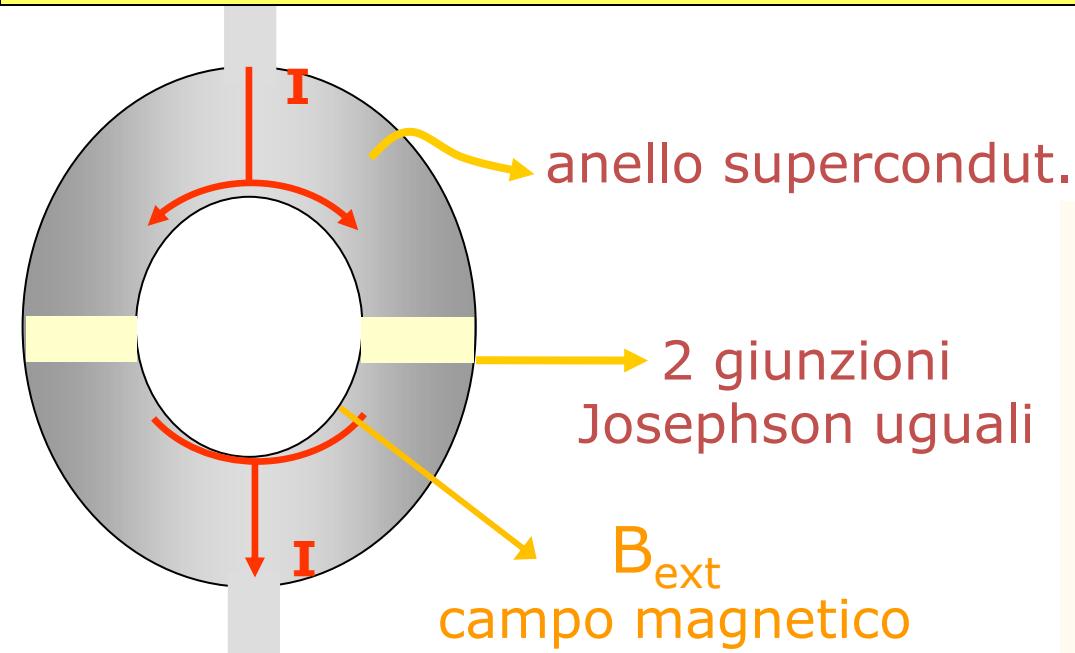
Destructive Interference



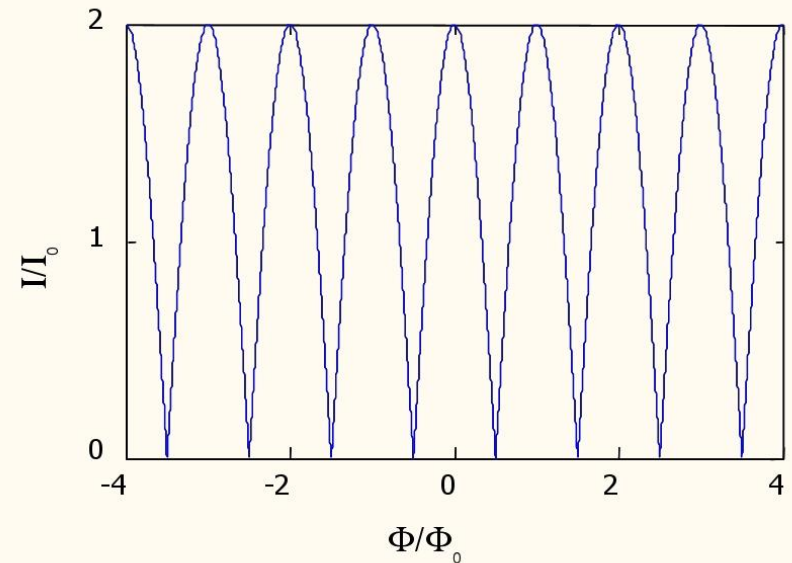
In una giunzione Josephson il processo d'interferenza è fortemente dipendente dall'intensità del campo magnetico applicato

SQUID-Superconducting Quantum Interference Device

Sensibile a circa 10 fT → meno di un milionesimo del campo terrestre

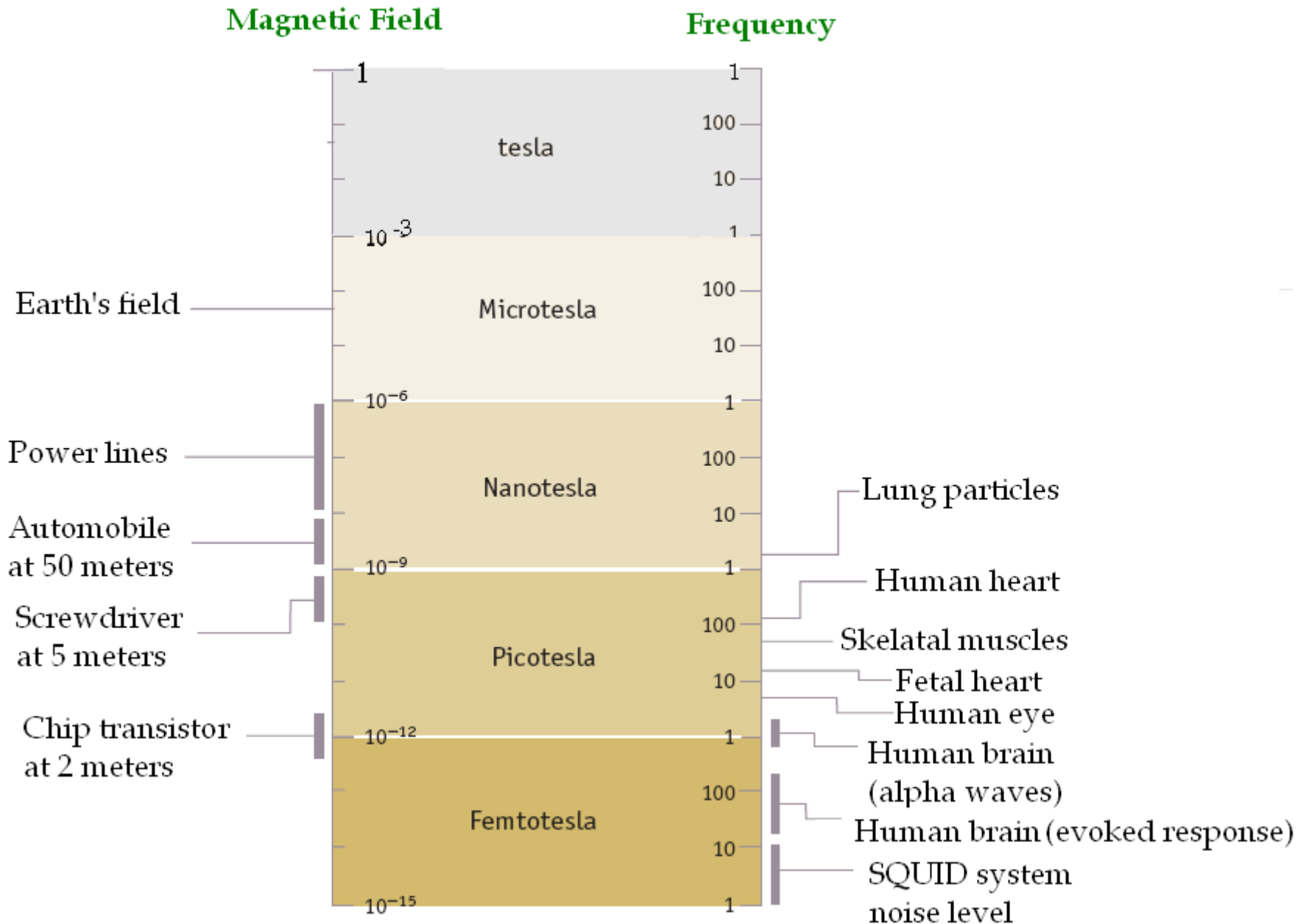


I_c è funzione periodica del flusso magnetico

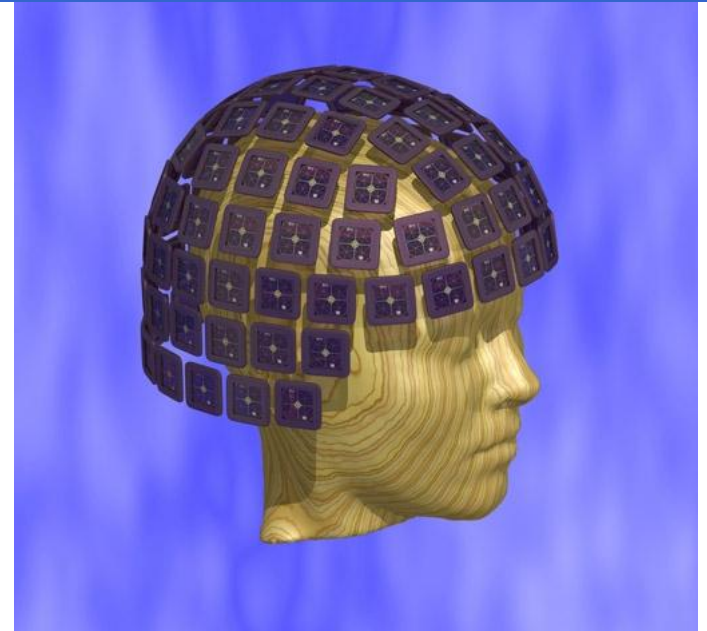
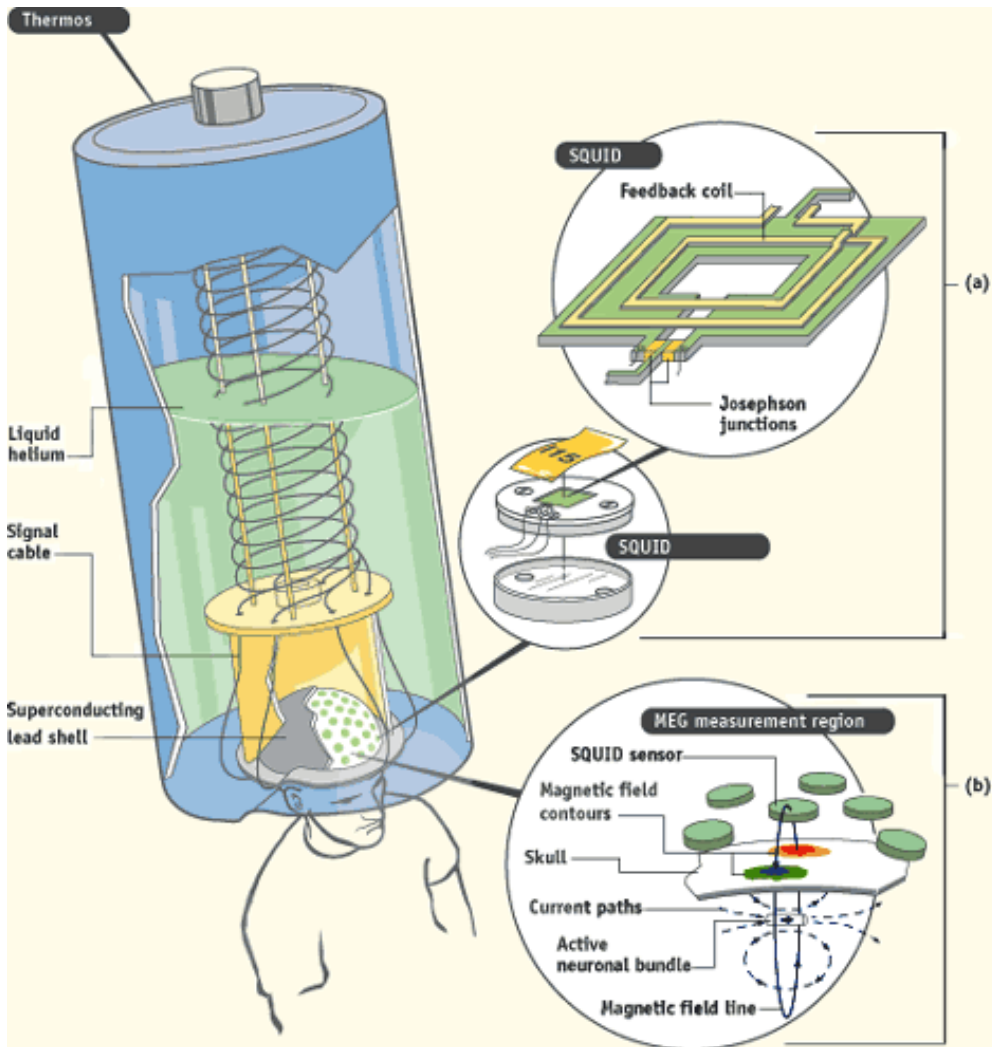


$$\Phi_0 \approx 2.07 \cdot 10^{-15} \text{ T} \cdot \text{m}^2$$

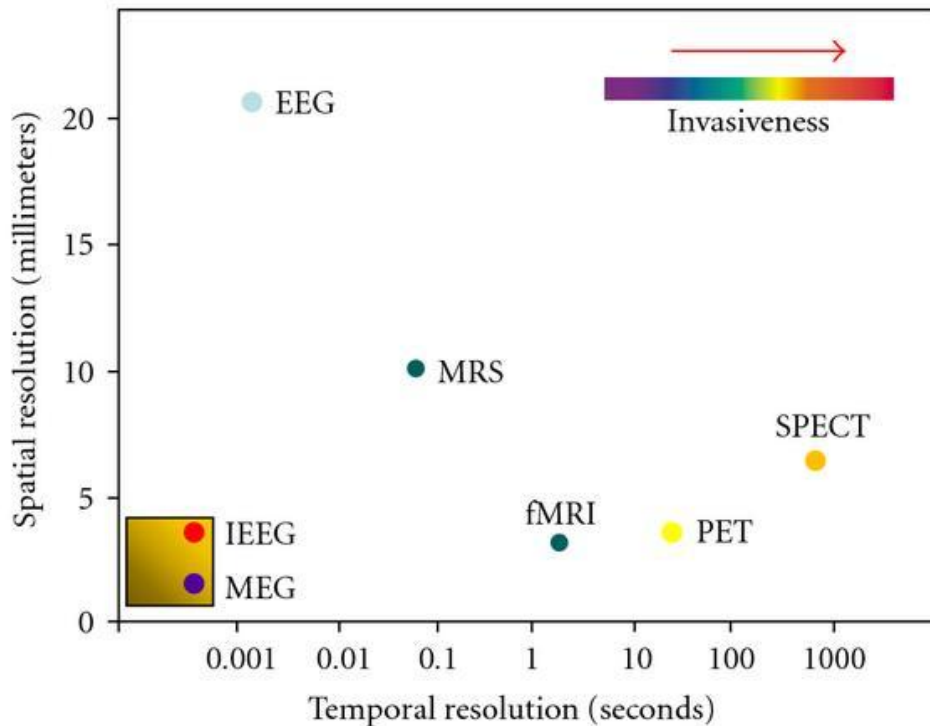
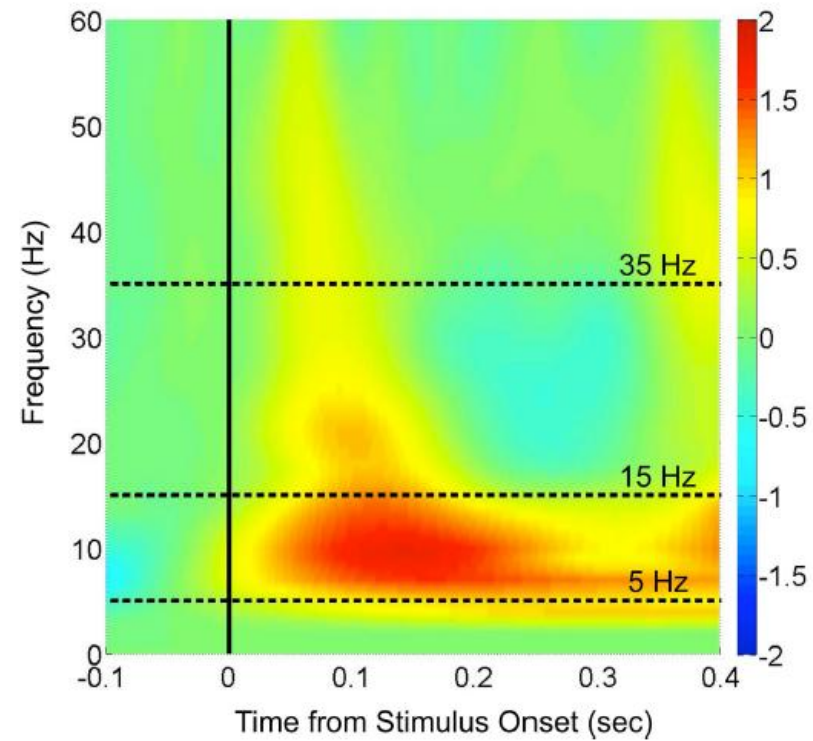
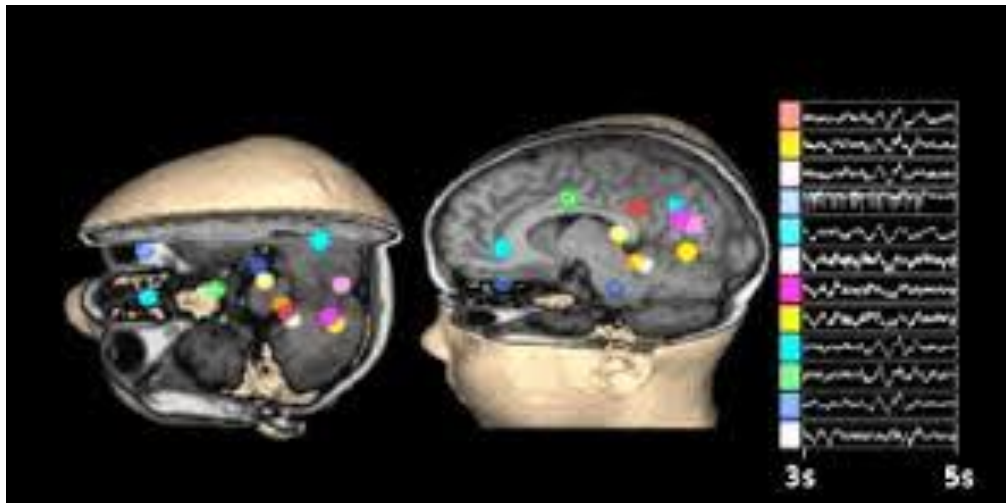
Campi magnetici in medicina



Magnetoencefalografia



MEG-Buona risoluzione spaziale e ottima risoluzione temporale



Quantum Computing

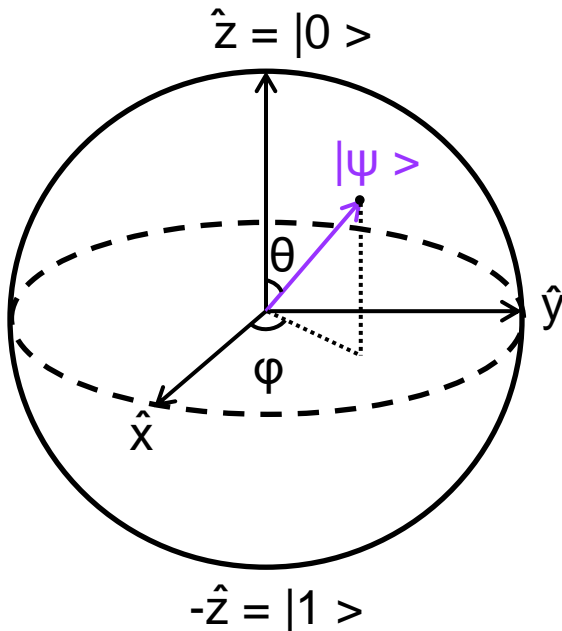
- **Bit classico**
- Vale solo 0 o 1



- **Quantum bit (Qubit)**
- Una qualsiasi sovrapposizione di 0 e 1



$$|\psi\rangle = a|0\rangle + b|1\rangle$$



Quantum Bit:

$$\begin{aligned} |\psi\rangle &= \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle \\ &= a|0\rangle + b|1\rangle \end{aligned}$$

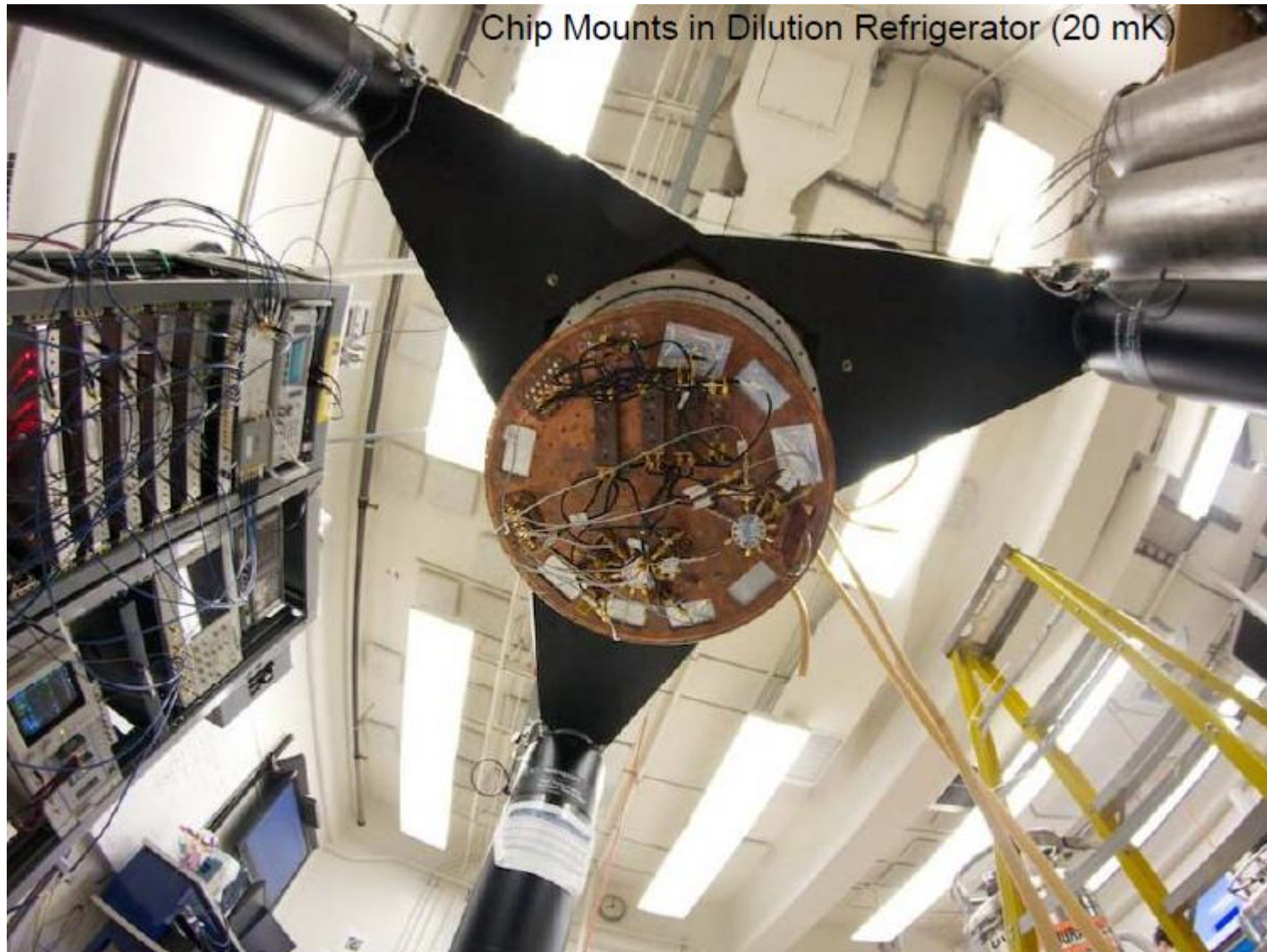
Un qualsiasi vettore che connette l'origine alla superficie della sfera rappresenta uno stato.

Classical computers



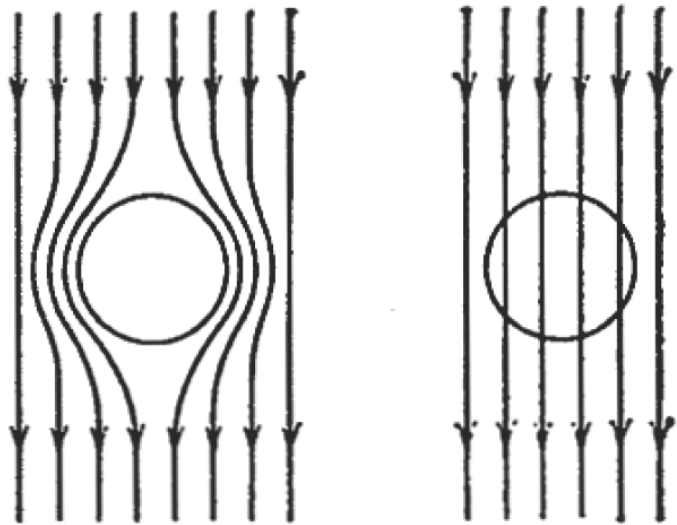
Computer Classico

Josephson junctions for quantum computers



Quantum Computer

Effetto Meissner



Campo Magnetico Espulso dal Superconduttore
Superconduttore "espulso dal campo magnetico"

$$B=0$$



Walther Meissner

Cos'è un superconduttore?

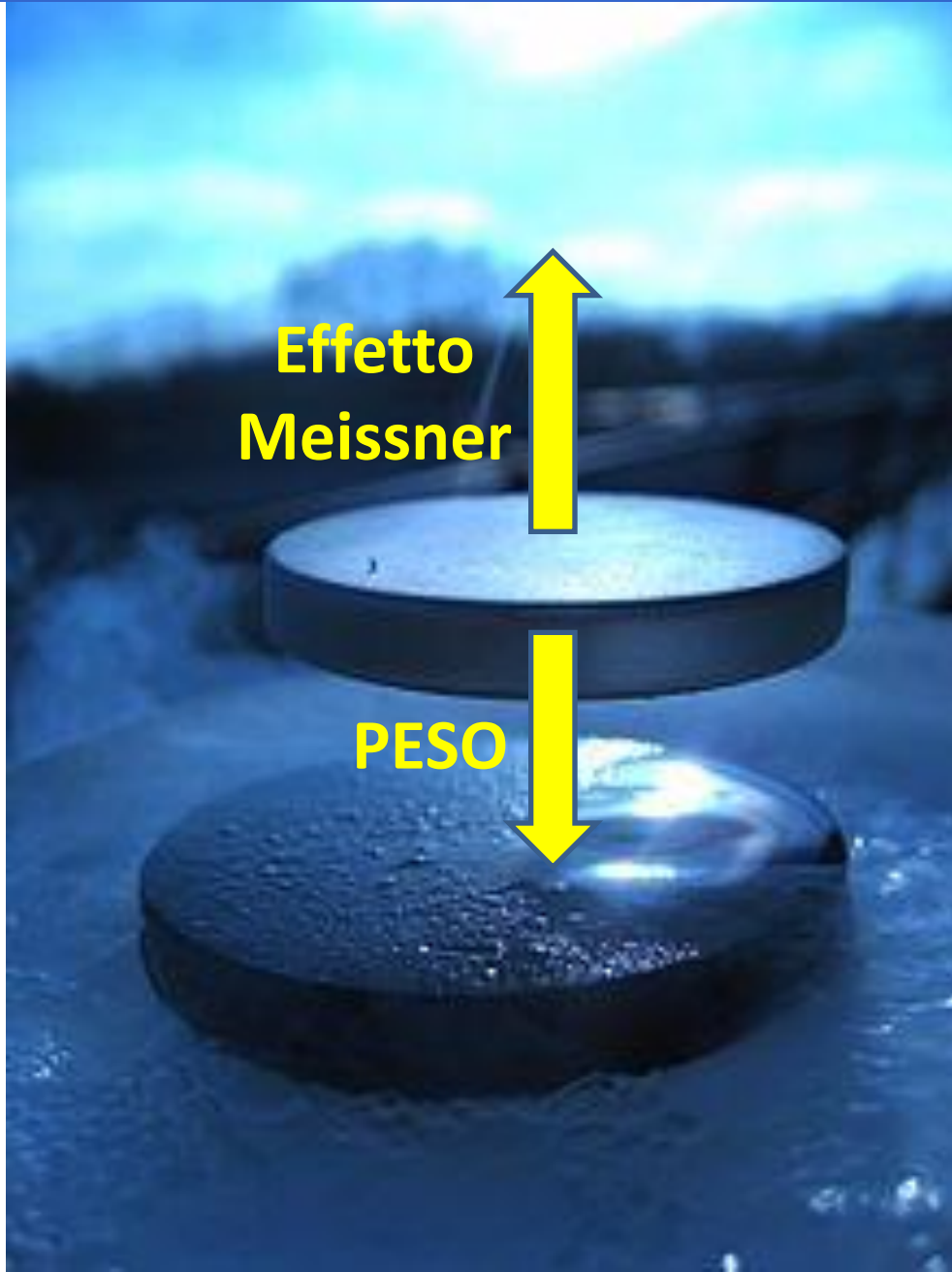
Da un punto di vista fenomenologico un superconduttore è caratterizzato da

$$\rho=0 \text{ in } H=0$$

E

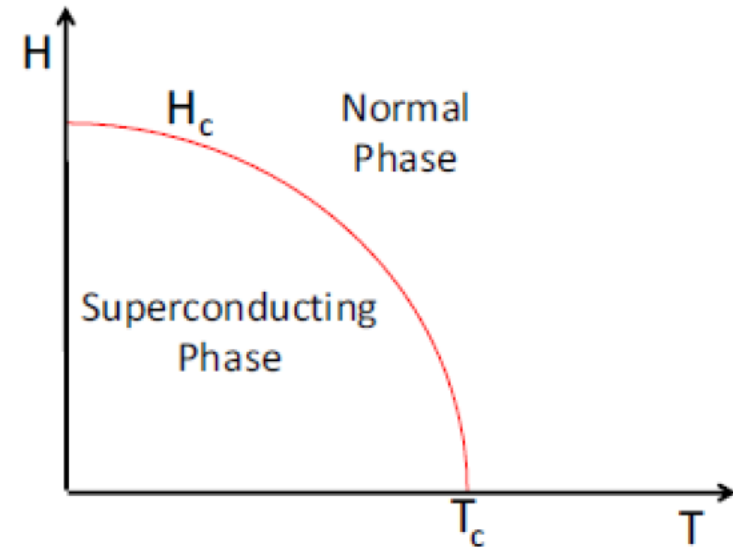
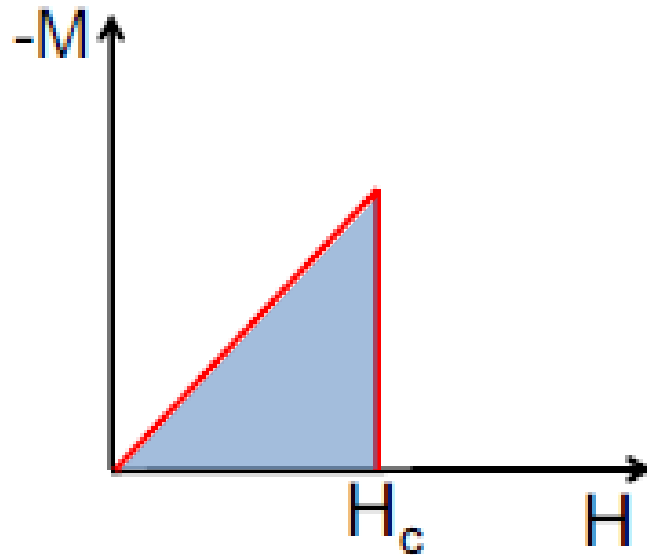
$$B=0 \text{ per } H < H_{c1}$$

Levitazione Magnetica

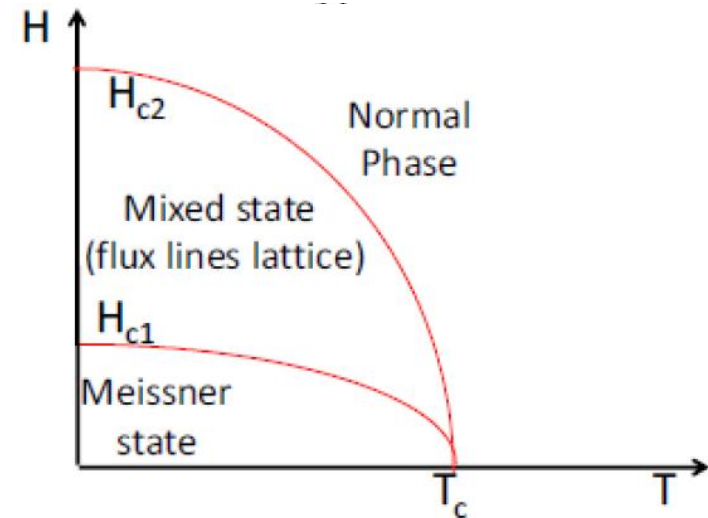
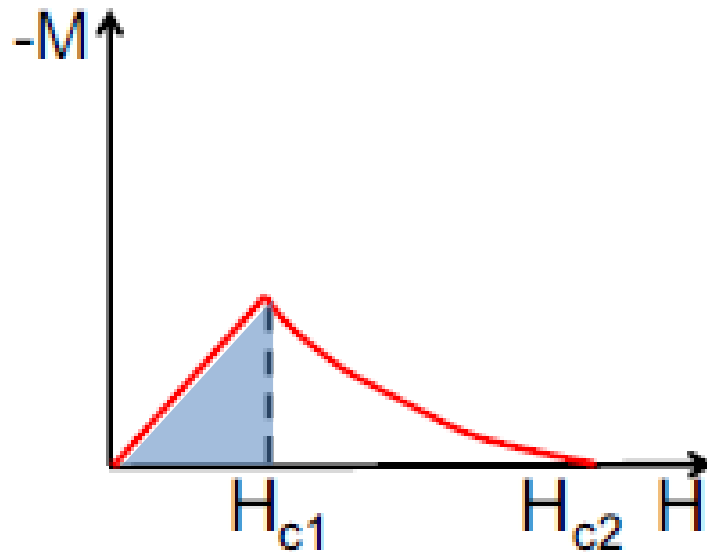


Levitazione Magnetica

SC I tipo



SC II tipo

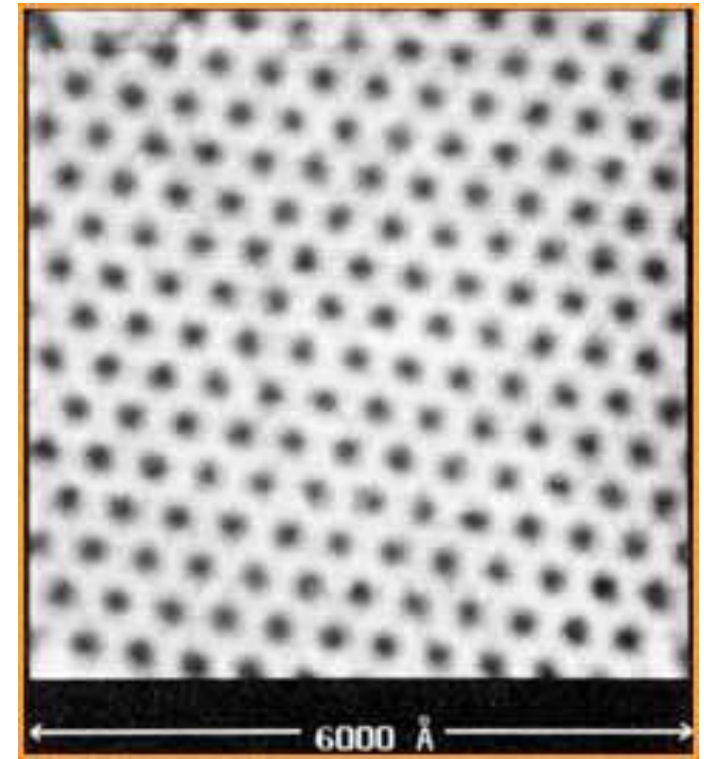
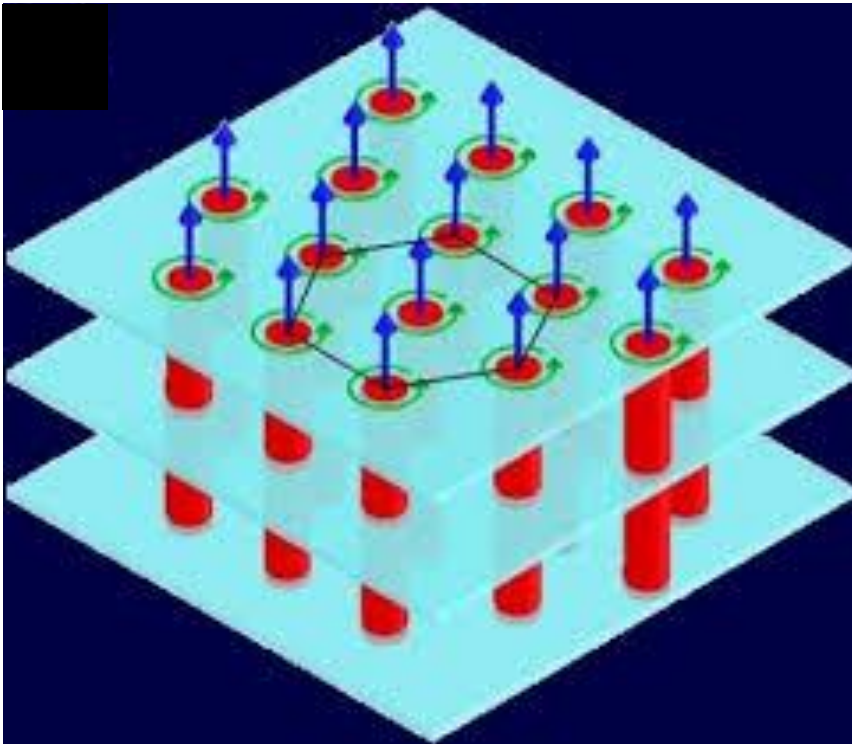


Reticolo di linee di flusso: $H > H_{c1}$

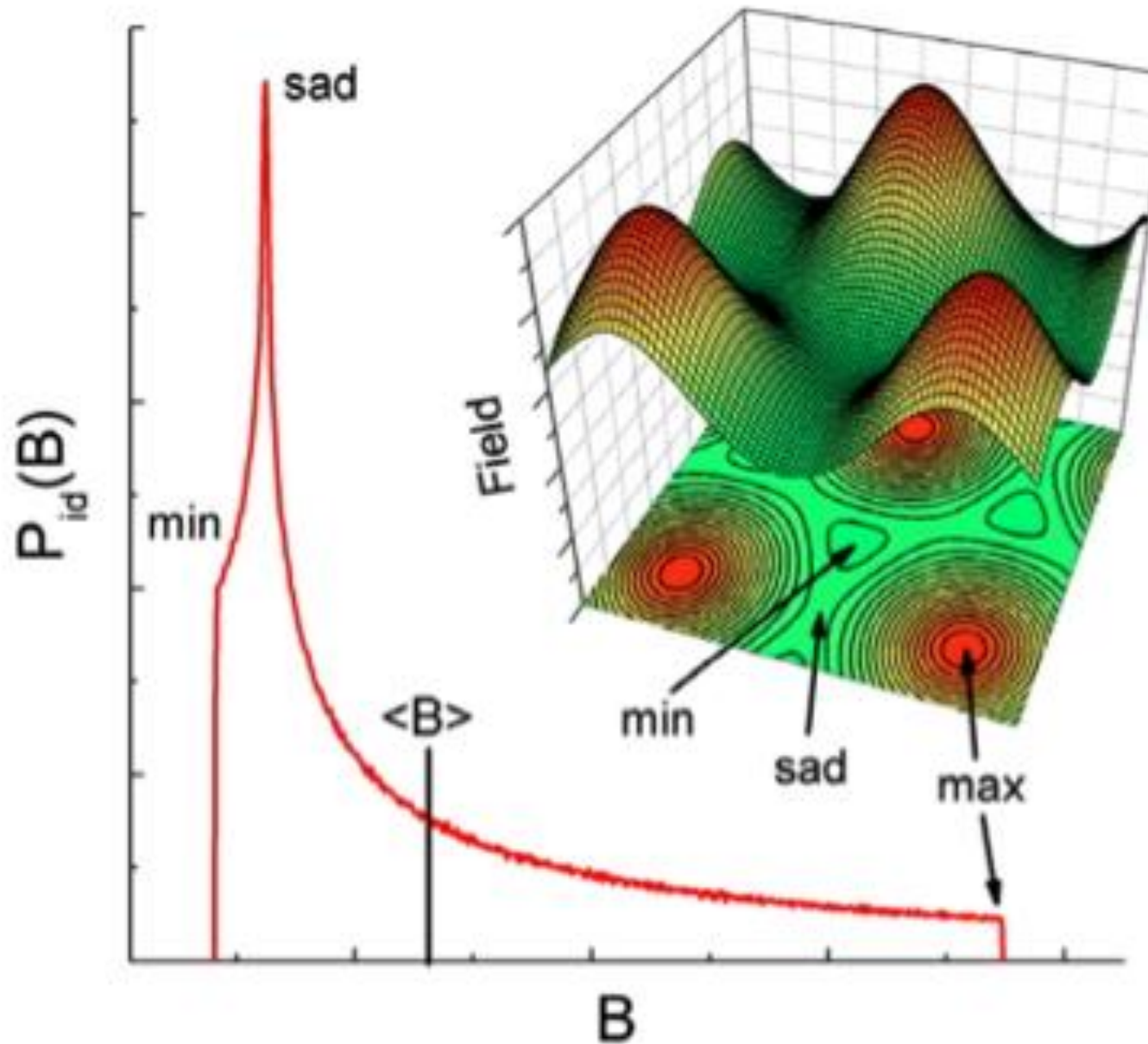
$$\Phi_0 = \frac{hc}{2e}$$

$$\Phi_0 = 2.07 \times 10^{-7} \text{ Gauss} \cdot \text{cm}^2$$

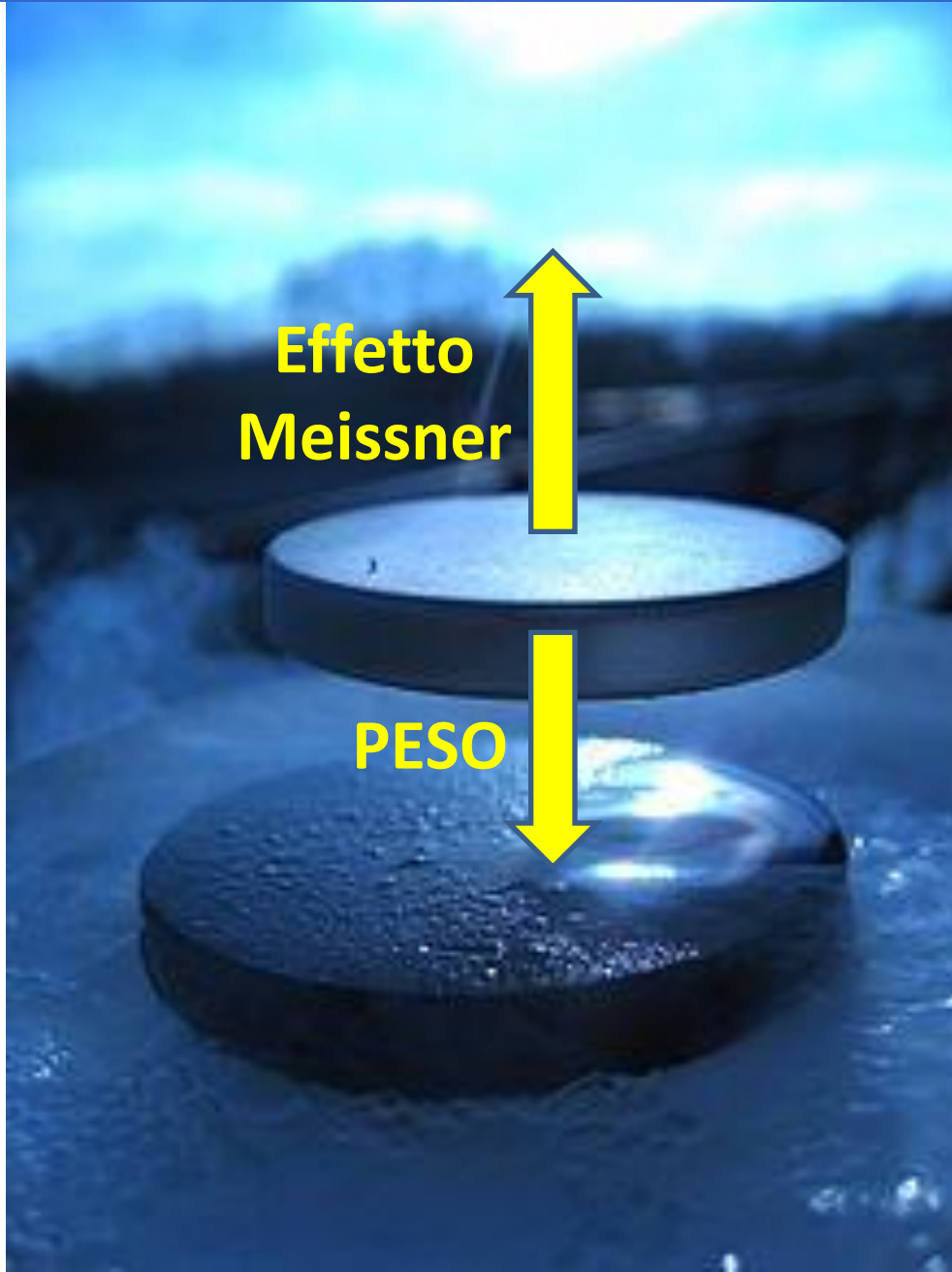
NbSe₂ (STM)



Reticolo di linee di flusso



Levitazione Magnetica



Ancoraggio delle linee di flusso

<https://www.youtube.com/watch?v=1kKMoQZ1JKo>

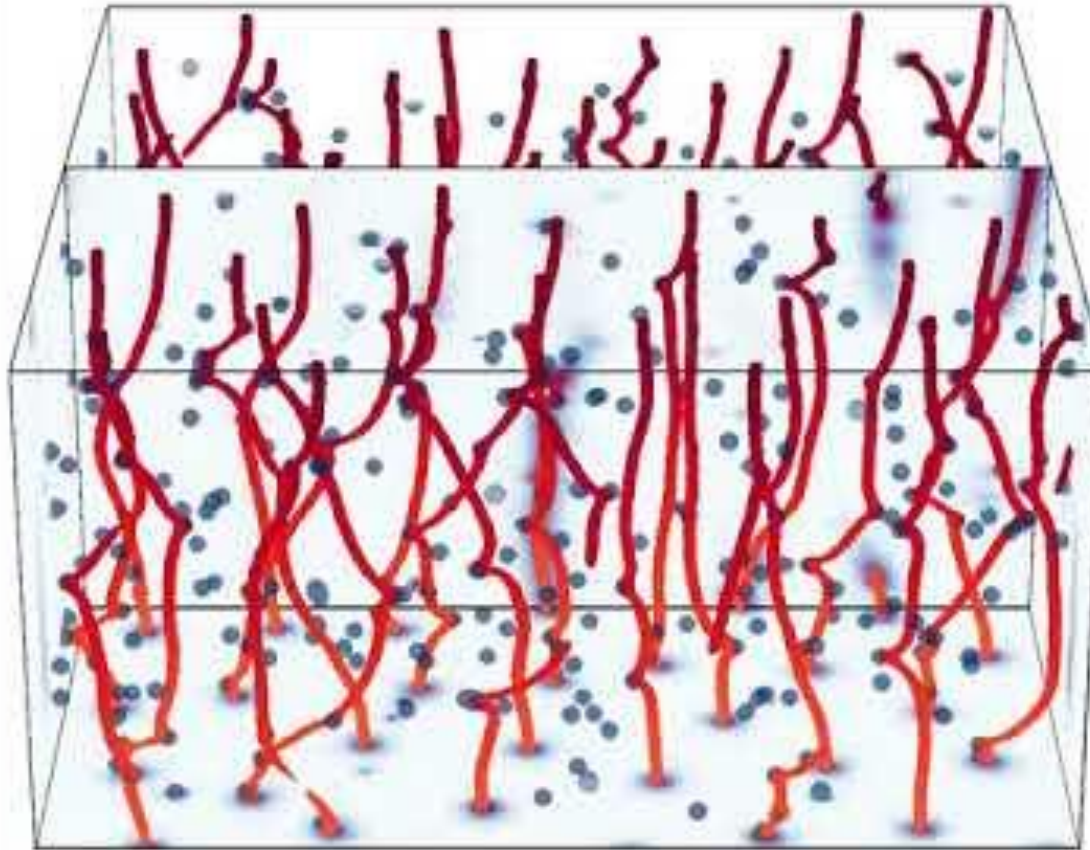


Diagramma di fase dell'Acqua

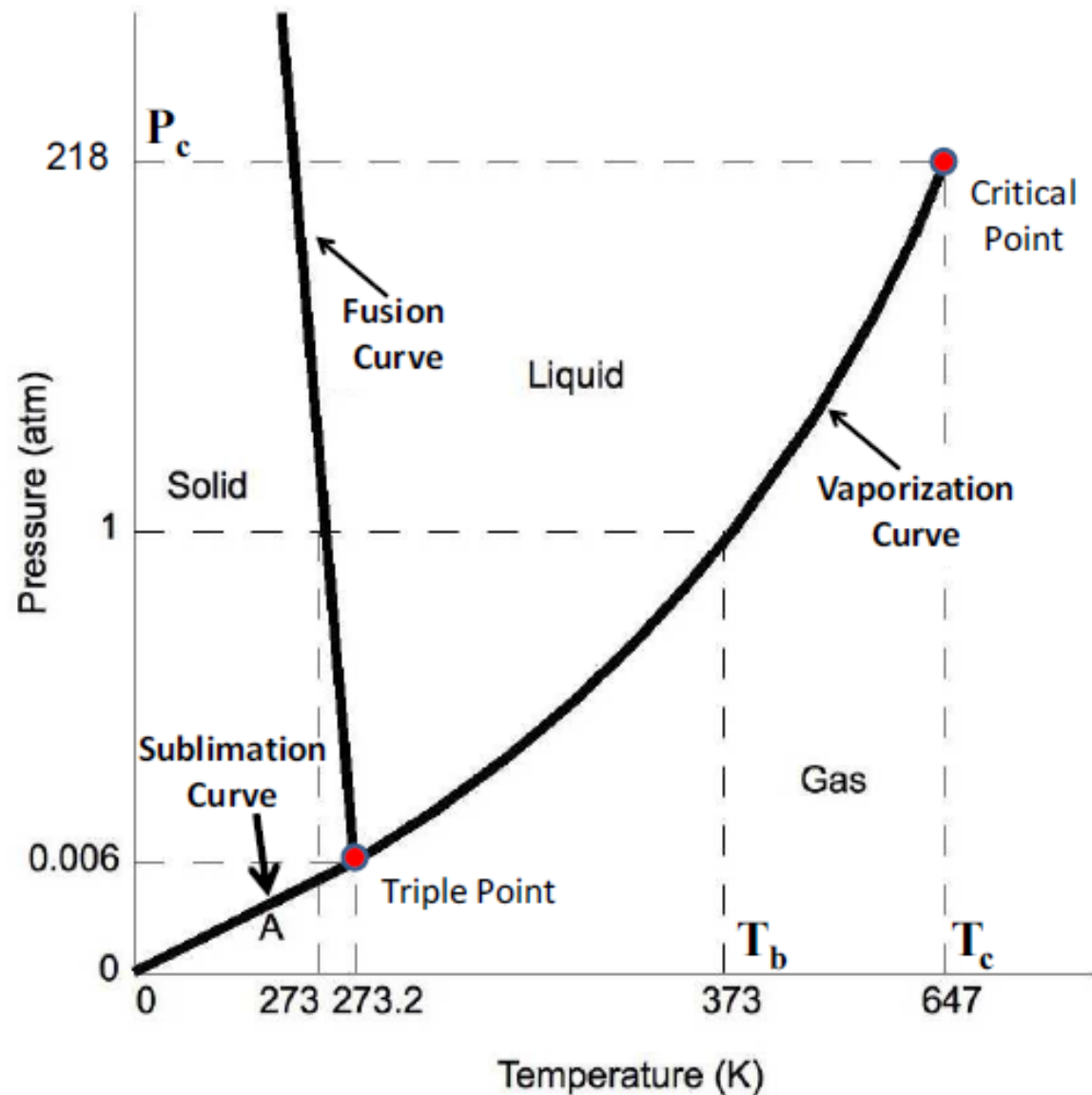
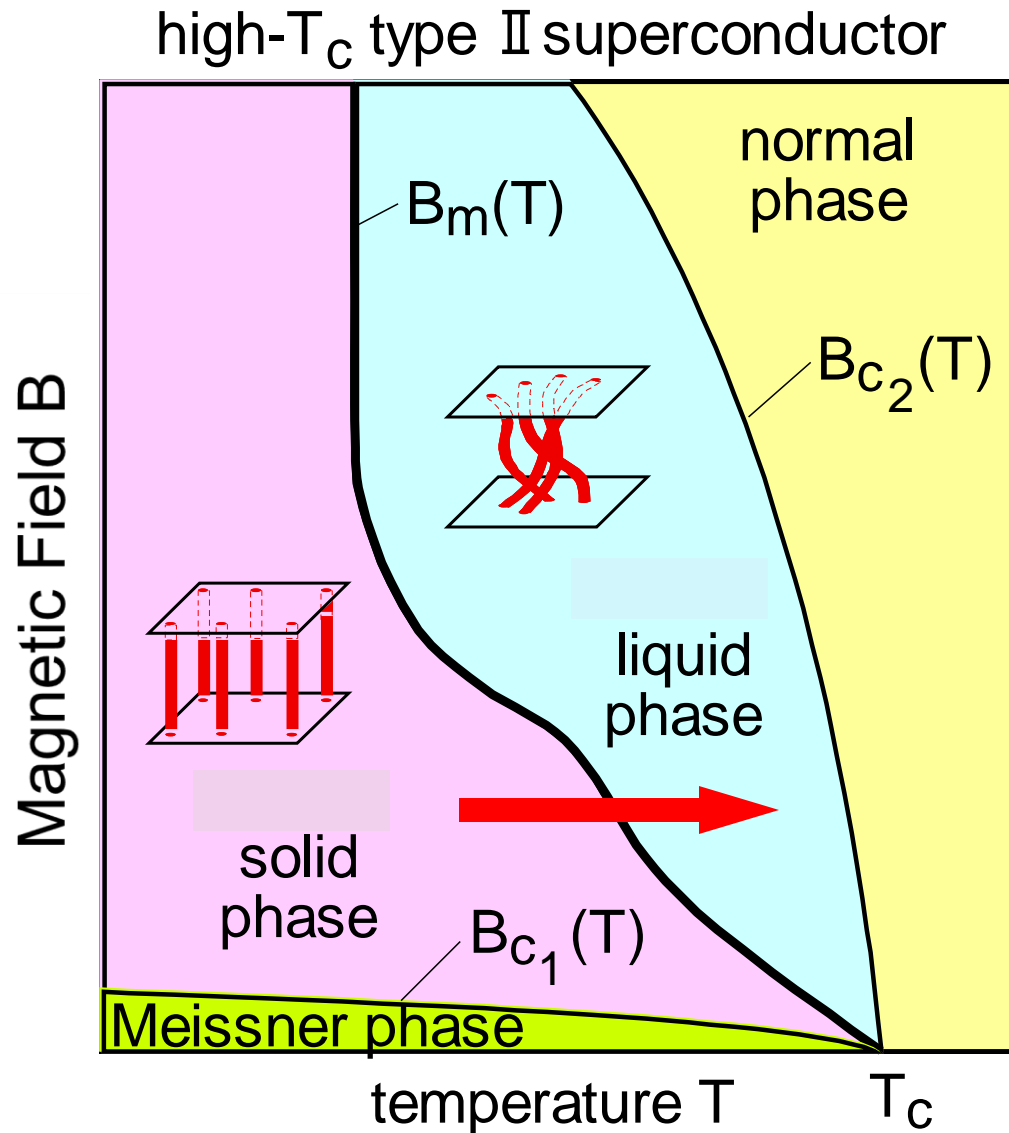
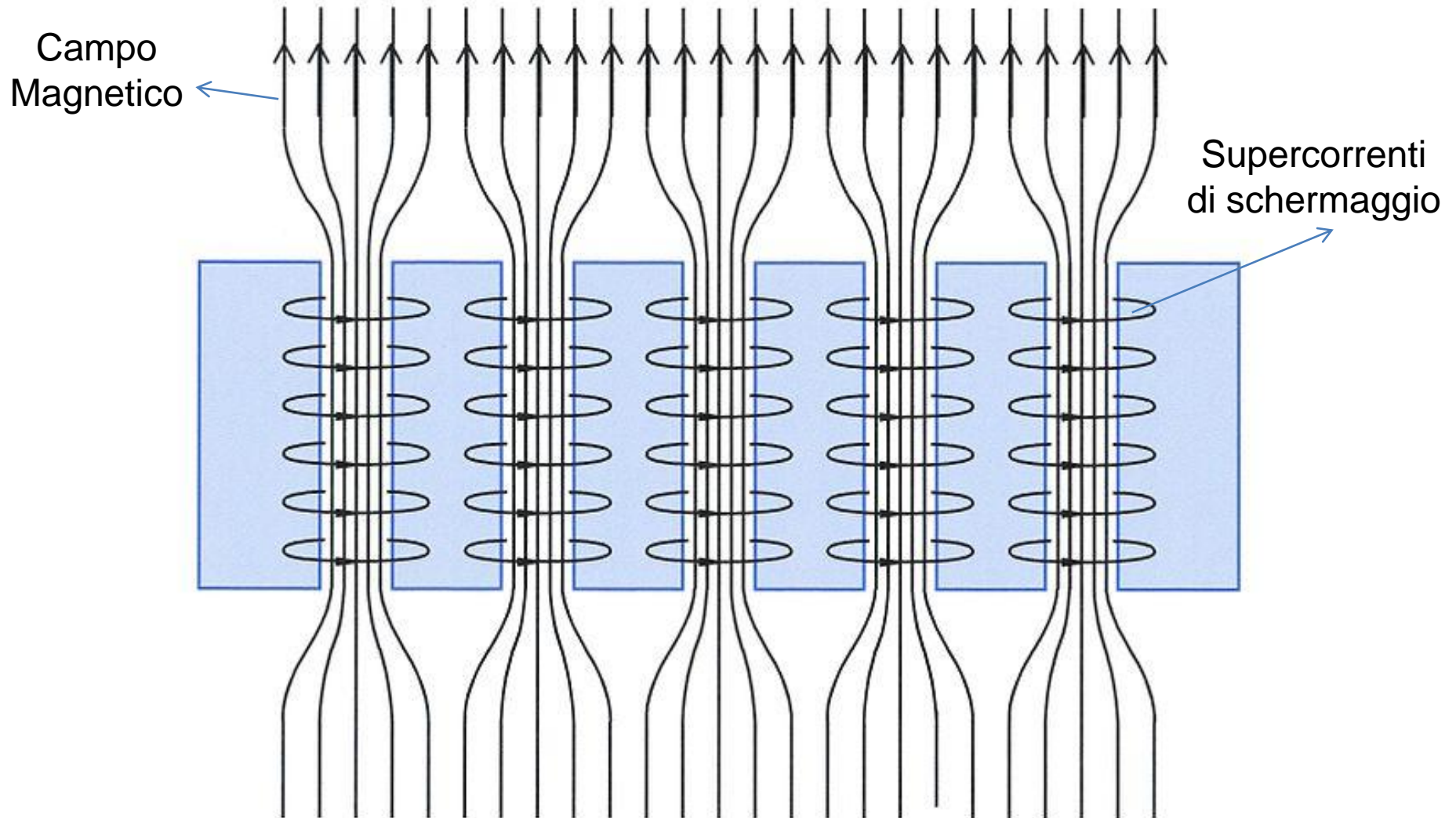


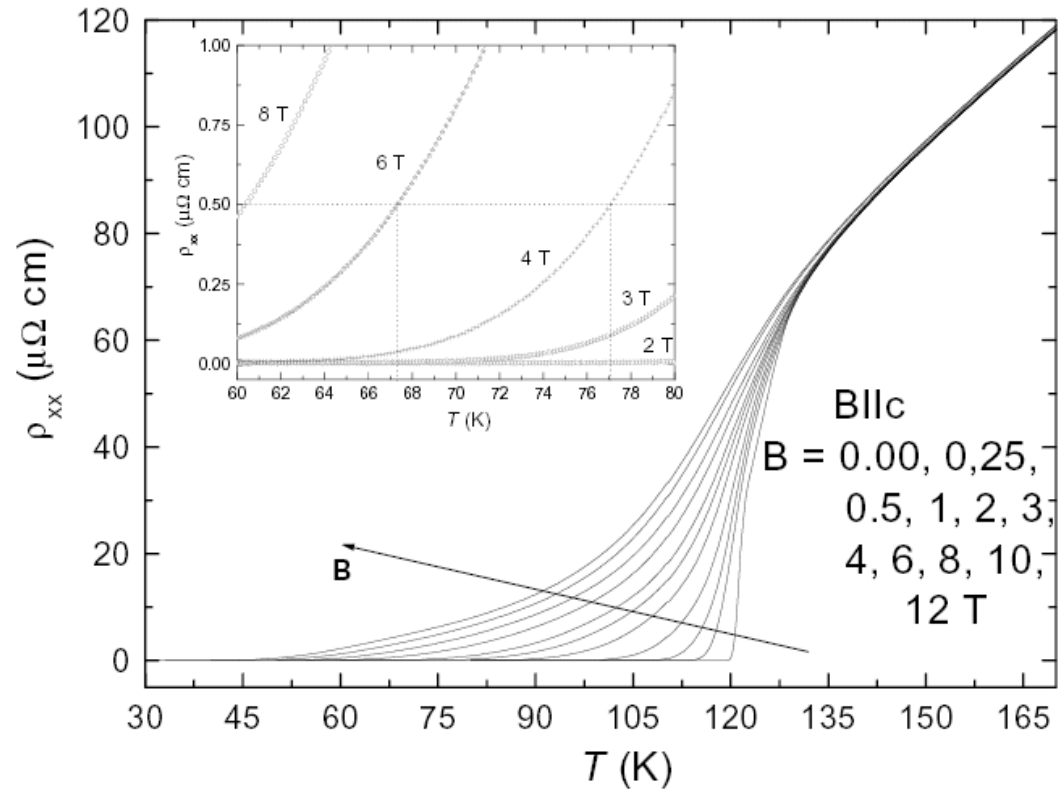
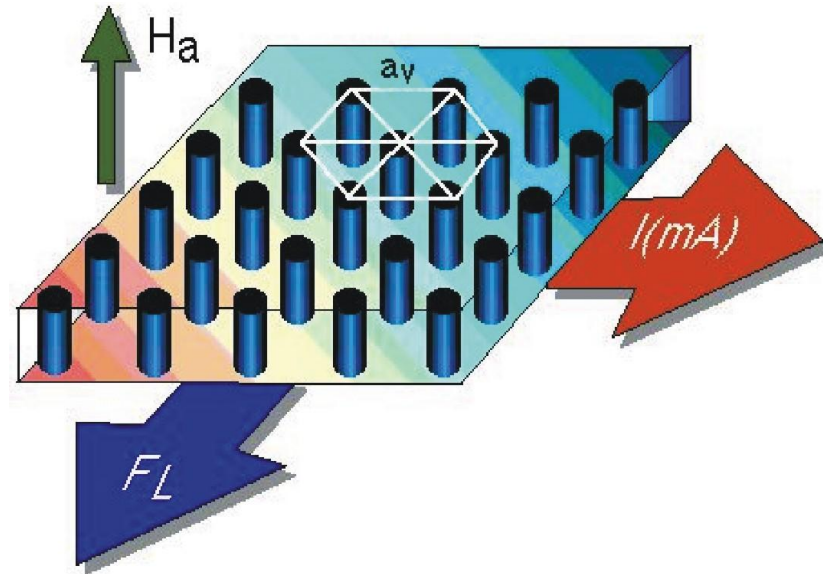
Diagramma di fase B-T di un Superconduttore



Moto dei flussoni: resistività non nulla



Moto dei flussoni: resistività non nulla



Cos'è un superconduttore?

Da un punto di vista fenomenologico un superconduttore è caratterizzato da

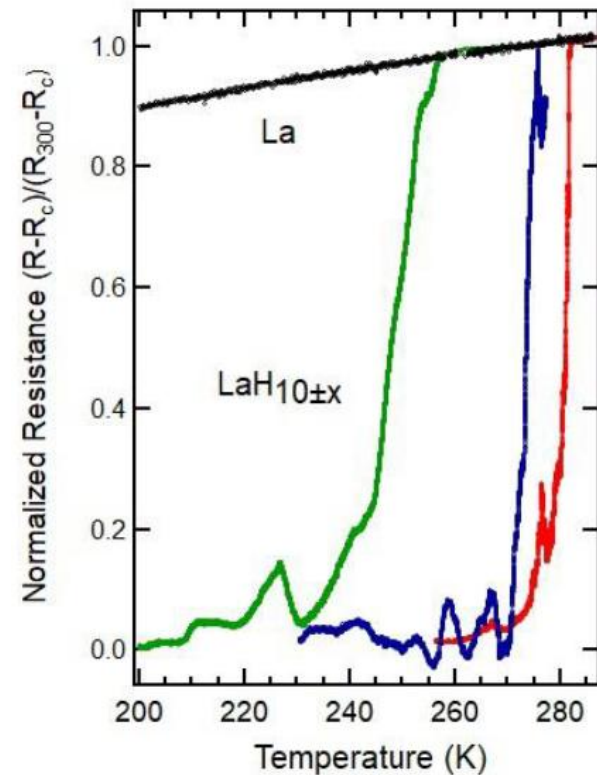
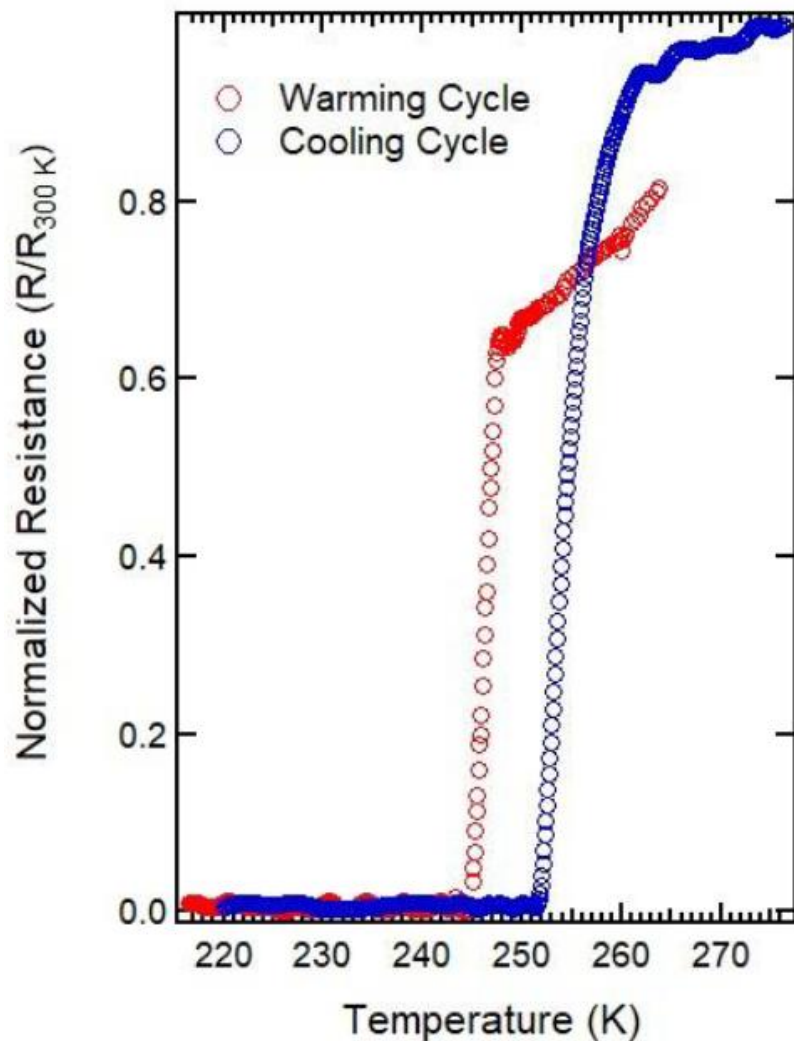
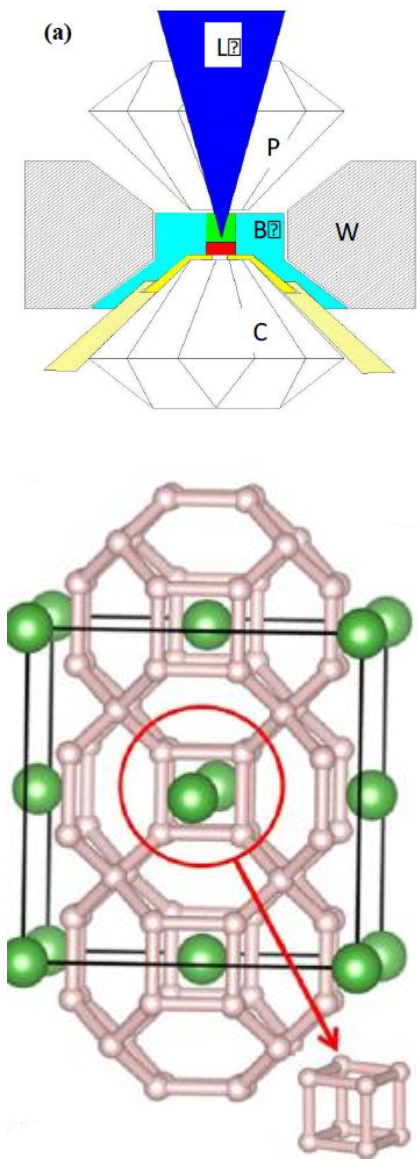
$$\rho=0 \text{ in } H=0$$

E

$$B=0 \text{ per } H < H_{c1}$$

Superconduttività a temperatura ambiente

M.Somayazulu et al., arXiv:1808.07695



100 anni di Superconduttività → 9 premi Nobel

Discovery of superconductivity H. Kamerlingh Onnes(1911) in Hg

1913 Nobel prize

Perfect diamagnetism: Meissner and Ochsenfeld(1933)

London equation: F. and H. London(1933)

Ginzburg-Landau theory: 1950s

2003 Nobel prize (with Abrikosov)

Isotope effect: H. Frohlich(1950)

BCS theory: J. Bardeen, L. Cooper and J.R. Schrieffer(1957) 1972 Nobel prize

Tunneling: Josephson (1957) 1973 Nobel prize

Hi-Tc superconductivity: J. G. Bednorz and K. A. Muller(1986) in Ba-La-Cu-O system. 1987 Nobel prize

