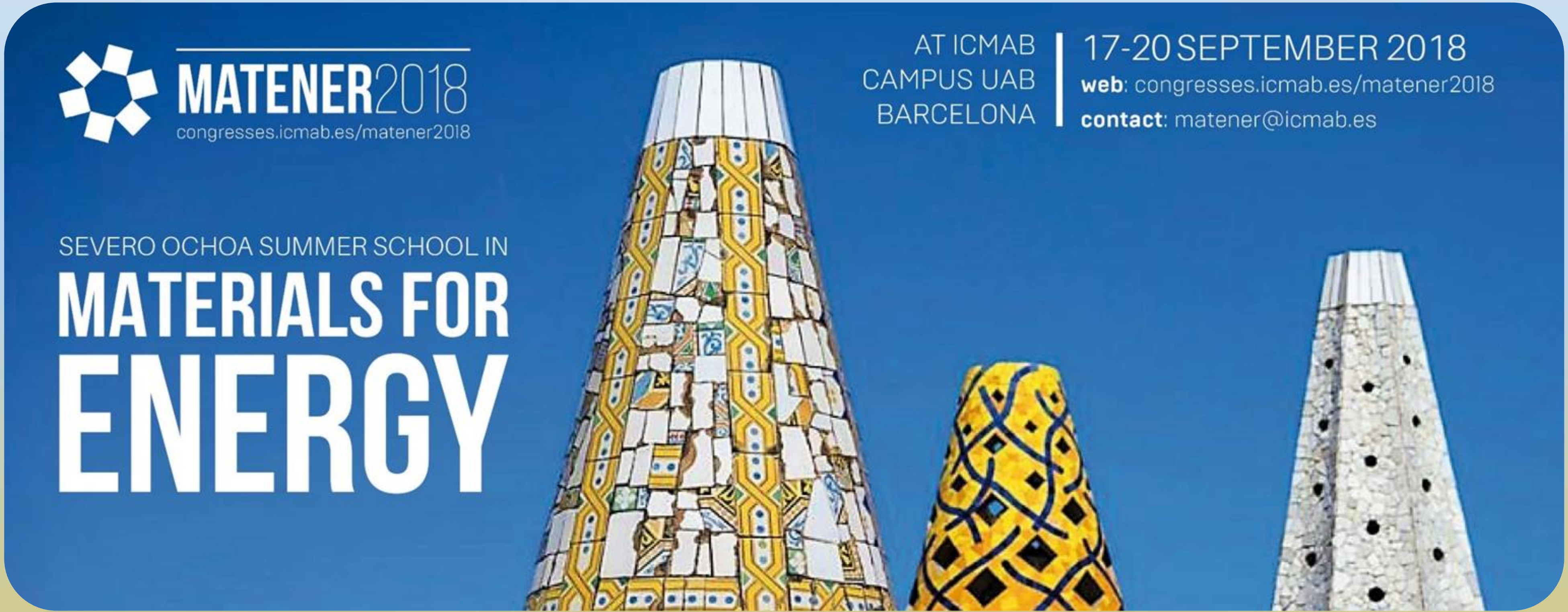

SUPERCONDUCTIVITY

(Tutorial)

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UNIVERSITÀ DEGLI STUDI DI GENOVA

SPIN

Outline

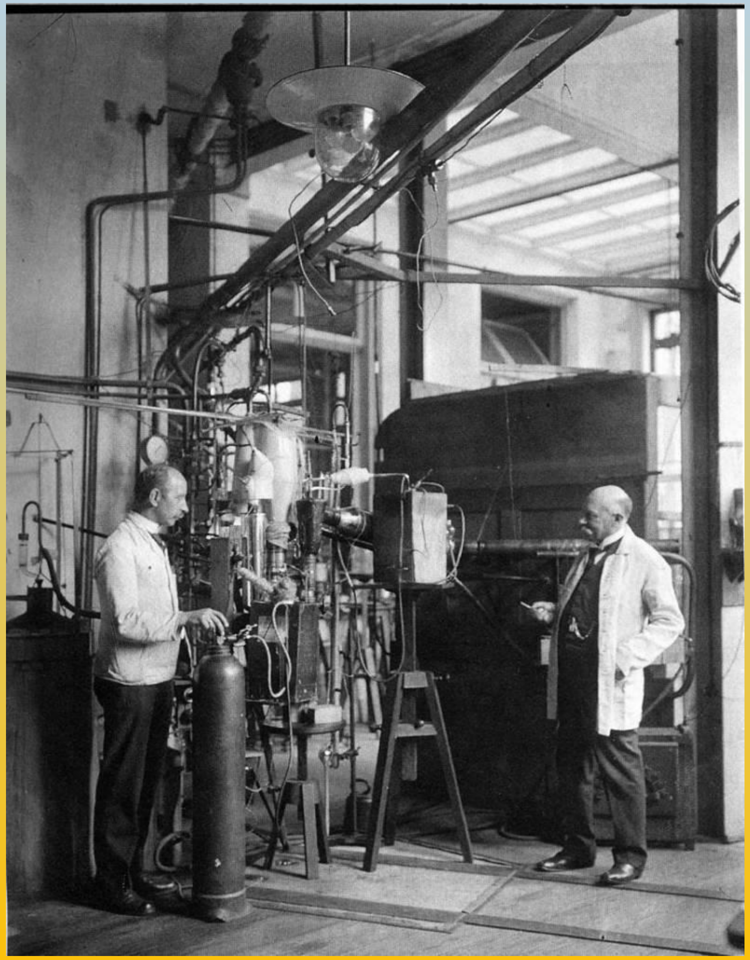
- ⤇ **Story of superconductivity phenomenon** going through the discovery of its main properties.
- ⤇ **Microscopic theory of superconductivity** and main parameters which characterize the superconducting state.
- ⤇ **Magnetic properties** and main mechanisms which allow a superconductors to carry superconducting current.
- ⤇ Main **superconducting materials.**
- ⤇ Peculiarities and issues of **novel superconducting materials.**

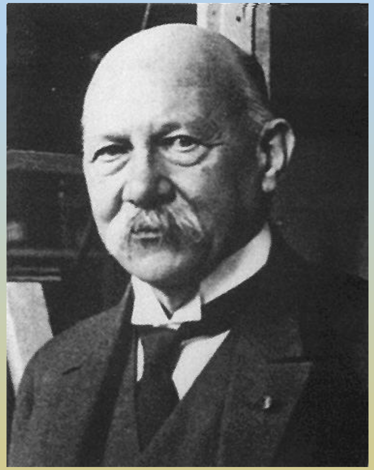
Kammerlingh Onnes, Leiden

1911: discovery of superconductivity

1908: Liquefaction of Helium

1913: Nobel price

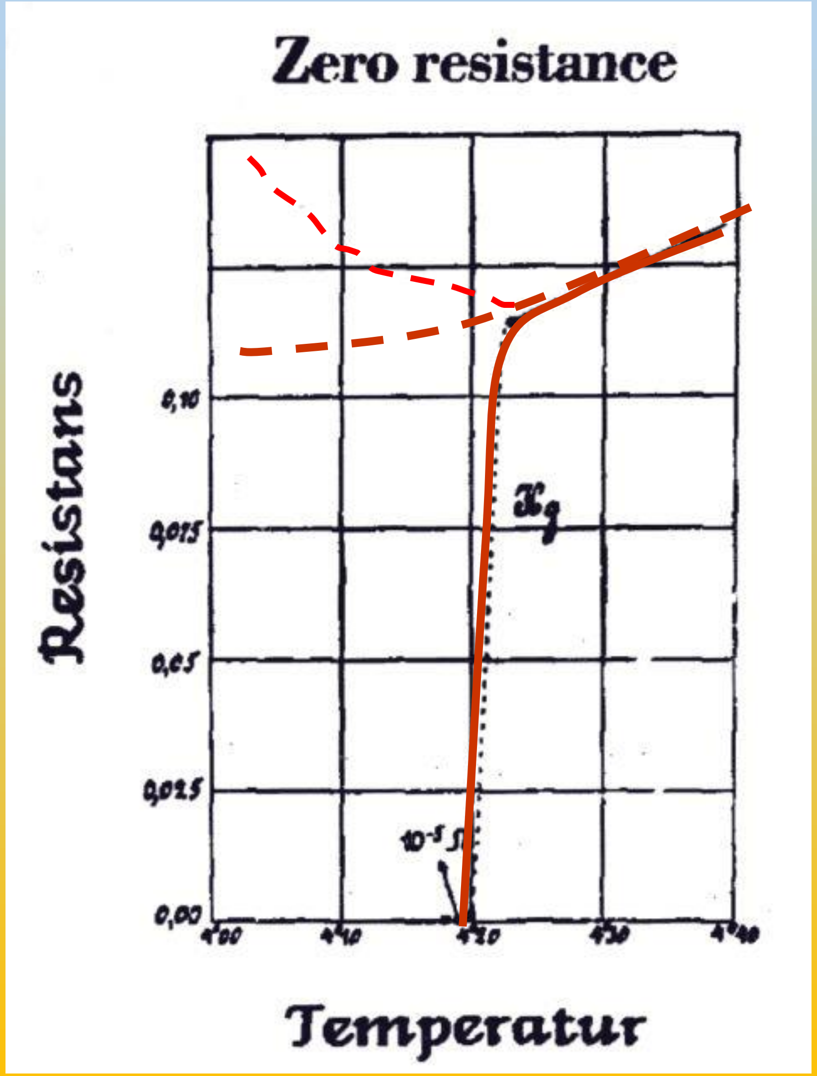




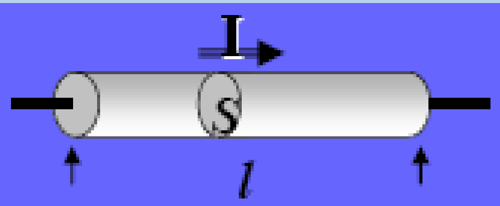
1913

⇨ He was measuring the resistivity of Hg to investigate the behavior of resistivity at low temperature

⇨ He noticed that the electrical resistance dropped to zero at 4.2K



The consequences of the Zero Resistance State (R =0)



$$V = RI$$

$$R = \rho \frac{l}{S}$$

R= 0 implies no Joule dissipation in cable conducting current

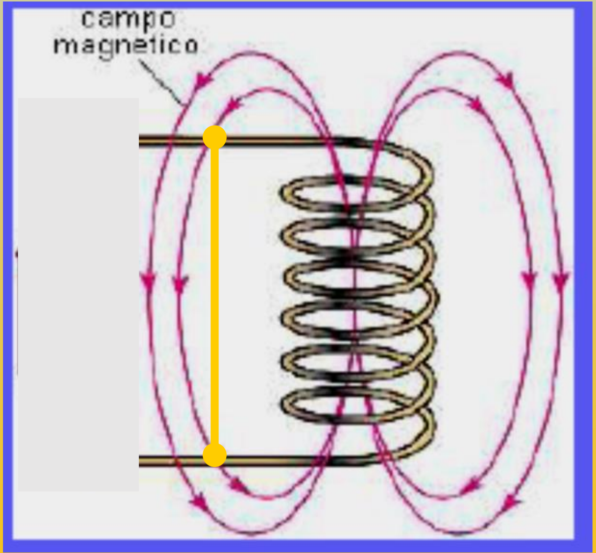
R= 0 implies that current can flow in a loop without decay

R= 0 implies that large magnetic field can be realized through solenois with large current flowing in persistent mode

$$I = I_0 e^{-\frac{t}{\tau}}$$

$$\tau = \frac{L}{R}$$

$$P = RI^2$$



Kammerlingh Onnes's Visions
Construction of a 10 T Magnet with Hg und Pb Wires

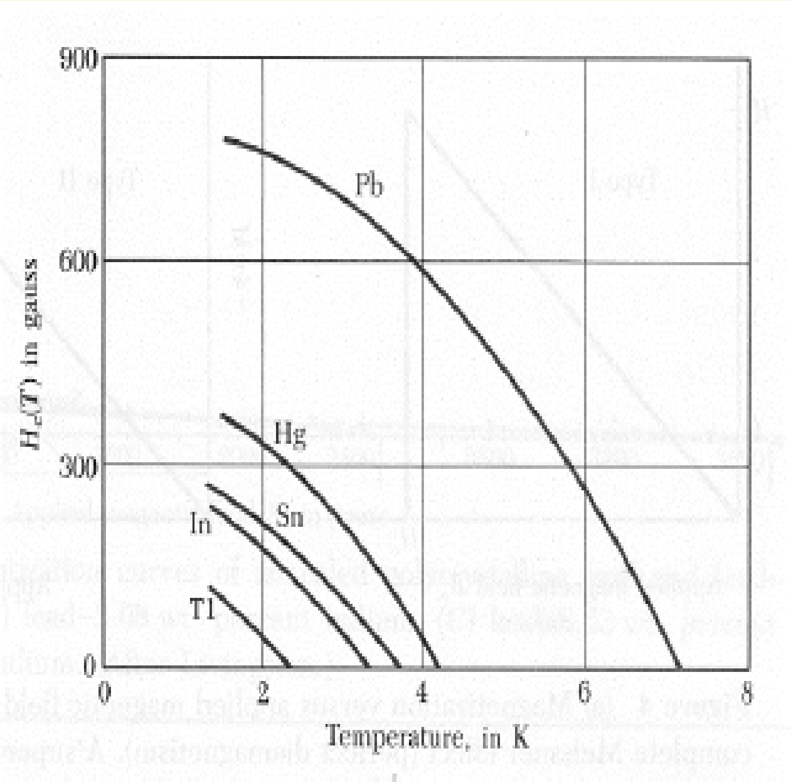
Presented at 3° International Congress on Refrigeration , Chikago 1913

Superconducting Magnet Coil
Experiments with Hg-and Pb wires failed
The coil lost superconducting properties already at small Current densities and at Magnetic Fields of several 100 Gauss.

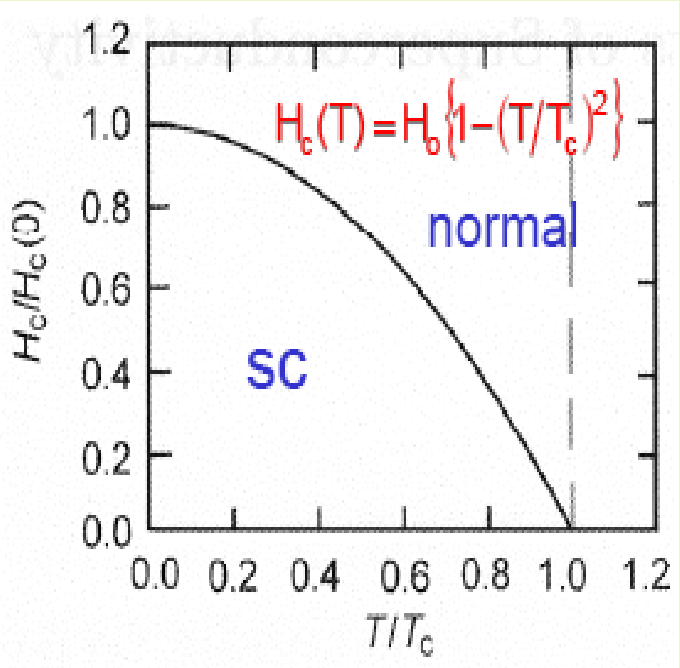
Superconductivity can be destroyed also by an external magnetic field , which is called **critical field, H_c**
(Kamerlingh Onnes 1914)

Critical Field

Temperature dependence of Hc(T)



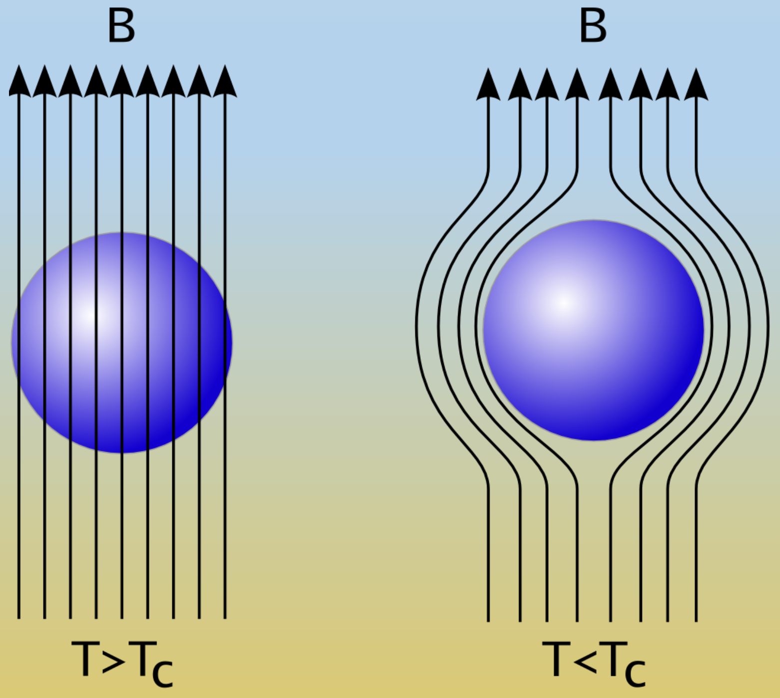
All curves can be collapsed onto a similar curve after re-scaling



Empirically :

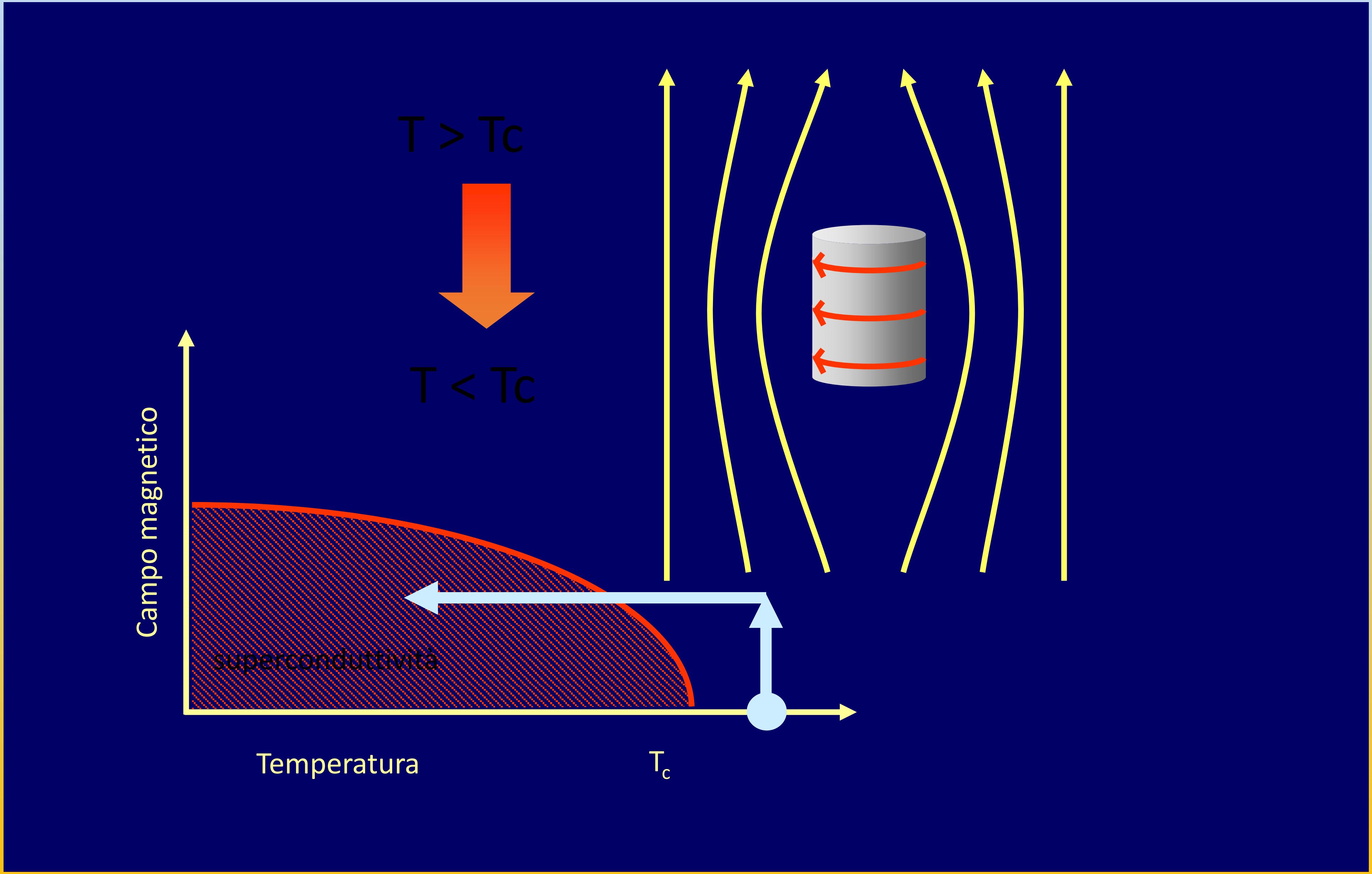
$$H_c(T) = H_c(0)\left[1-(T/T_c)^2\right].$$

1933: Meissner-Ochsenfeld effect



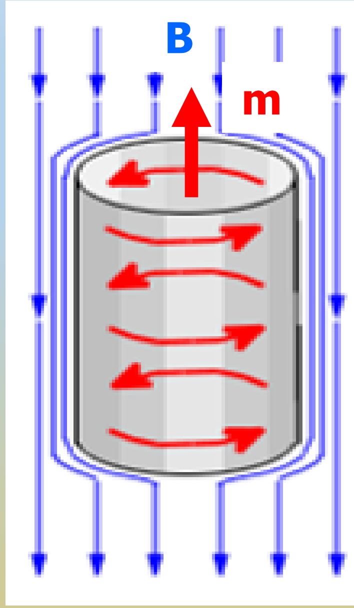
Magnetic field does not penetrated the superconductor

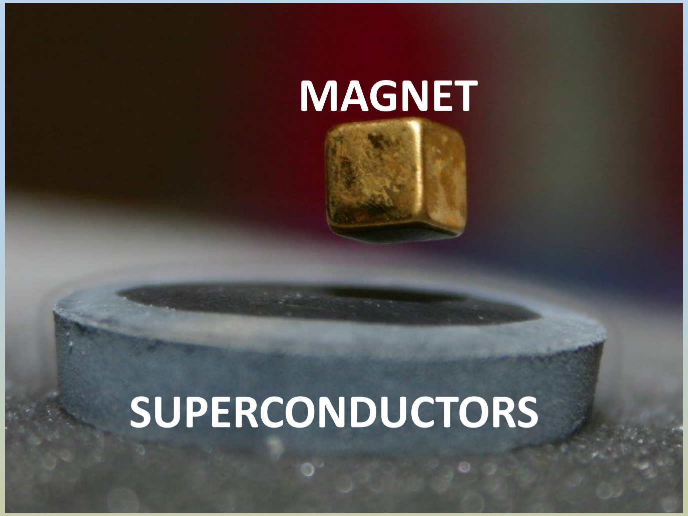
Ideal conductor!   Ideal diamagnetic!

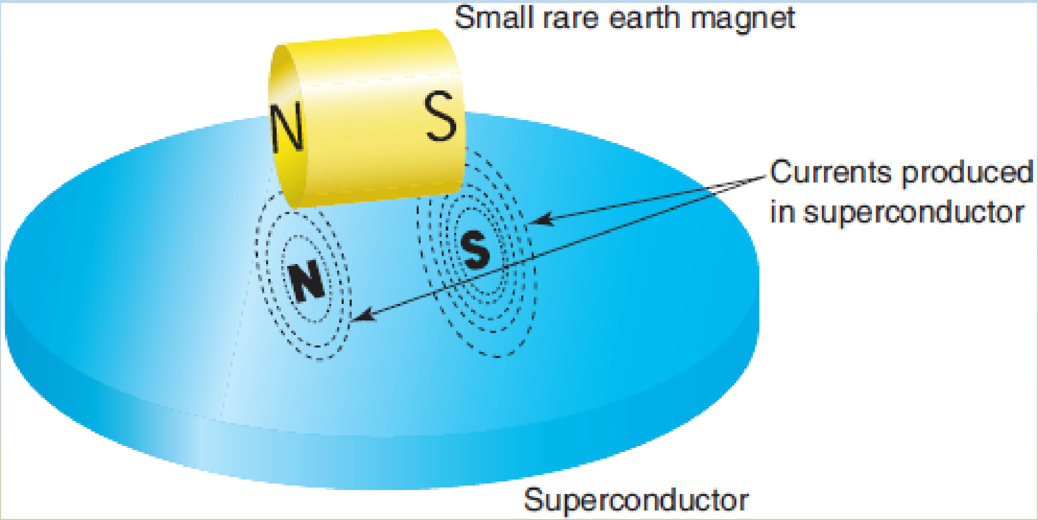


T > Tc
T < Tc
Campo magnetico
superconduttività
Temperatura
T_c

The consequences of the perfect diamagnetisms χ=-1







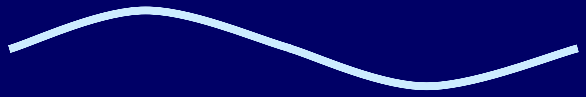
The expulsion of the magnetic field, generates **great magnetic moments**, able to levitate extremely large masses like the coaches of a train

ELECTRODINAMIC LEVITATION
The future (2025) maglev train between **Tokyo and Osaka** will be the **fastest train** in the world with a speed approximately **1000 km/h.**

The quantum coherence

1950: Ginzburg-Landau Phenomenology Ψ-Theory of Superconductivity

$T > T_c$



$T < T_c$

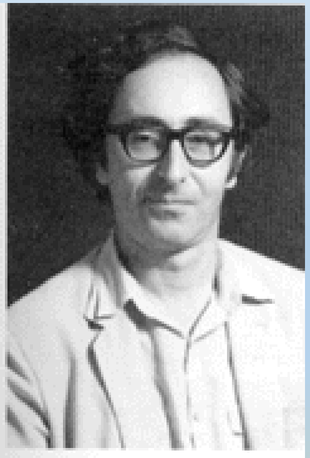
A macroscopic wave function describes the system as a whole

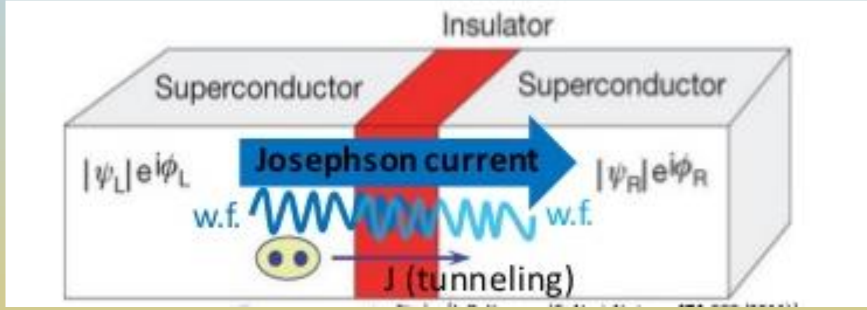
Macrscopic quantum effects

1962: Josephson effect

Super electrons cross the insulanting junction between the two superconductors as a consequence of the phase difference between the two superconductors

1973

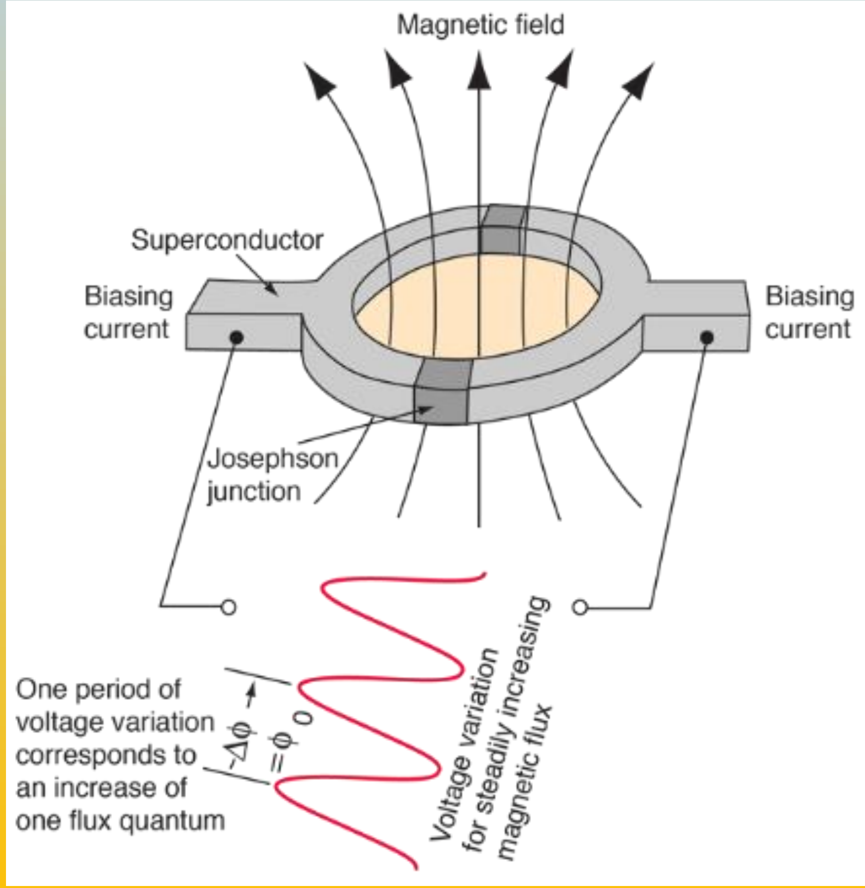




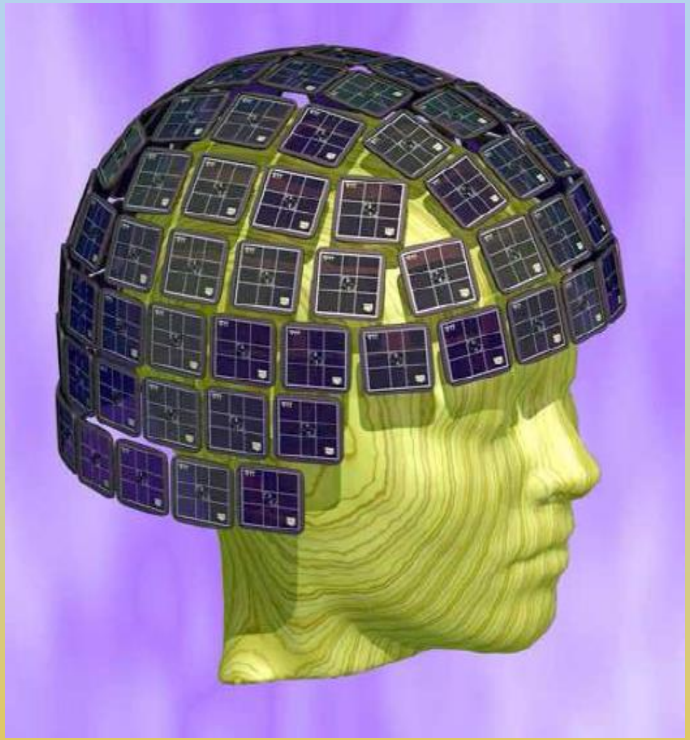
SQUID

superconducting quantum interference device

it is based on the presence of two superconductive junctions and on the interference due to the phase difference across the two junctions



SQUID for biomagnetisms

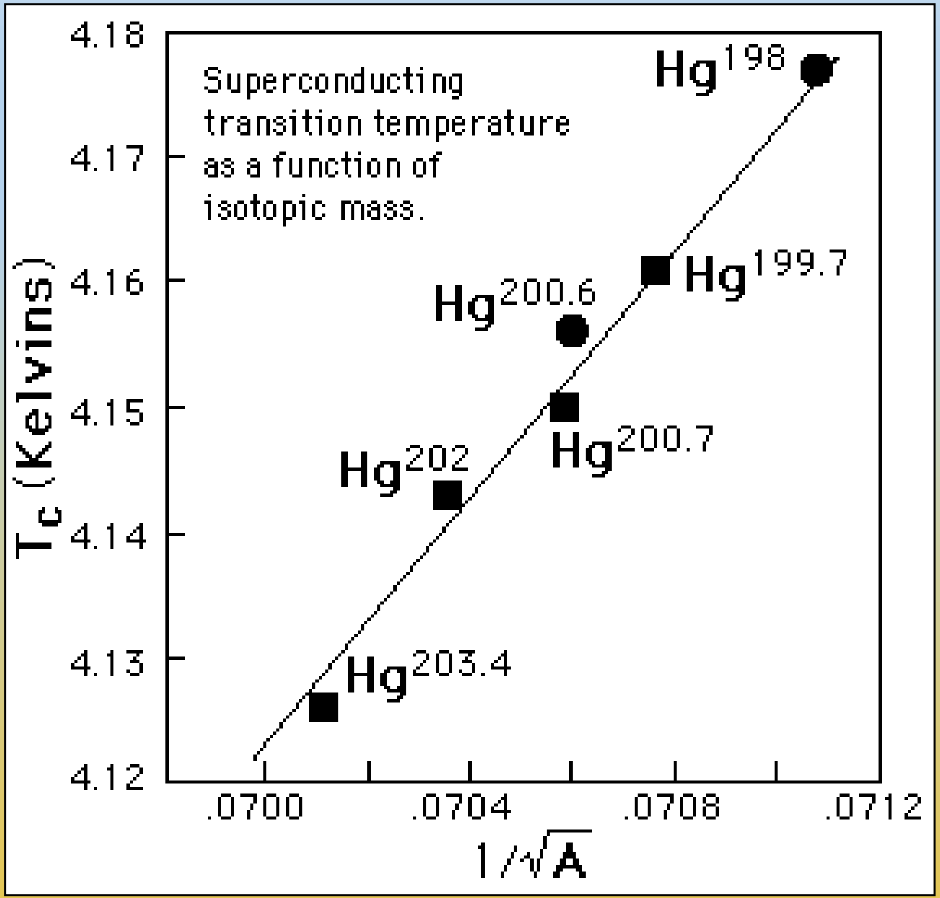


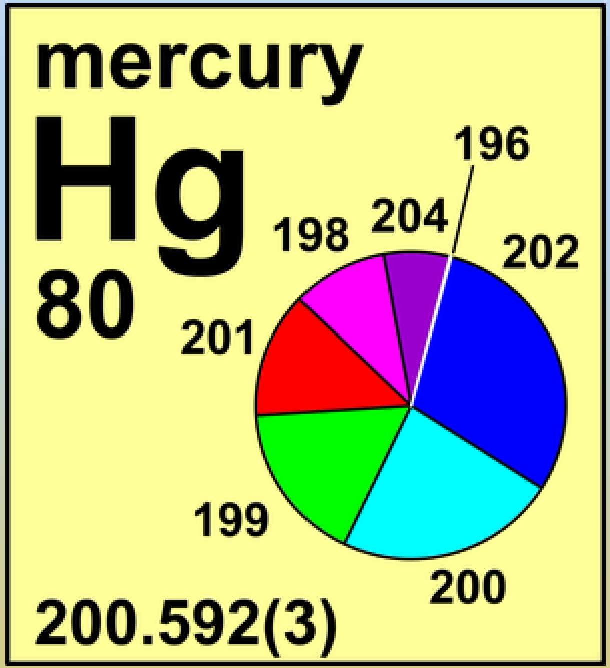
SQUID sensitivity	10^{-14} T
Heart magn. field	10^{-10} T
Brain magn. field	10^{-13} T
Earth magn. field	10^{-5} T
Fridge magnet	10^{-2} T

1957: Microscopic theory of superconductivity (Bardeen, Cooper, Schrieffer)

1972

1950: Isotopic effect



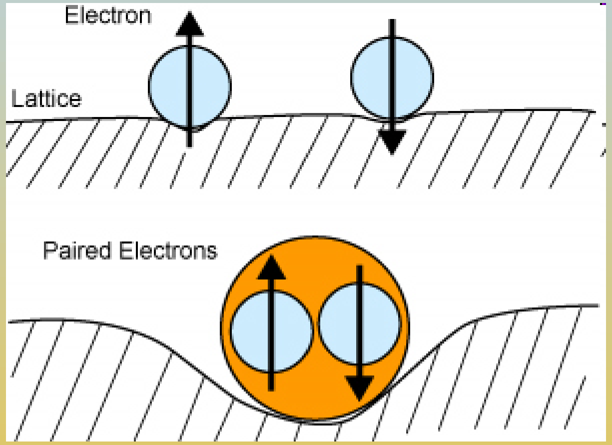


Isotopic effect suggests that the ion lattice plays a crucial role

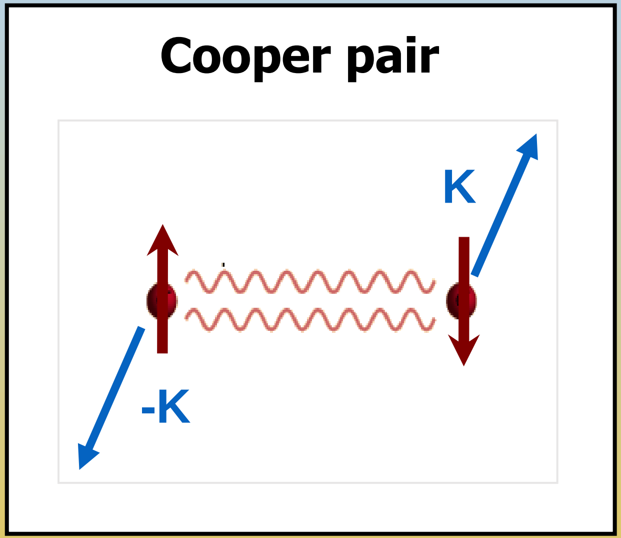
$$T_c \sim M^{-1/2}, \qquad H_c \sim M^{-1/2}.$$

BCS- Theory of superconductivity

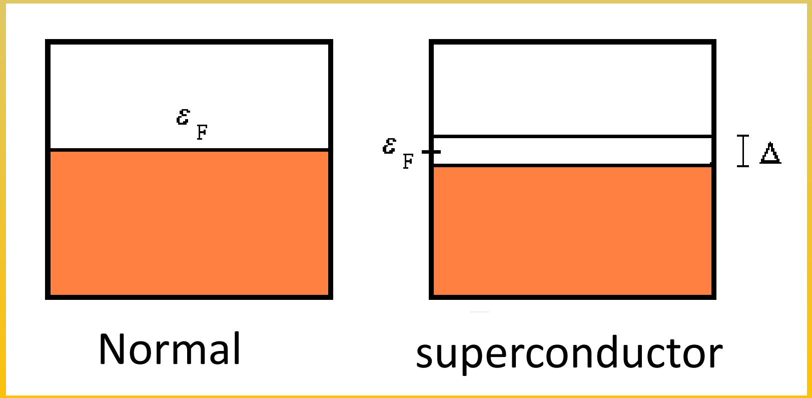
- in the presence of **an attractive interaction** provided by the lattice



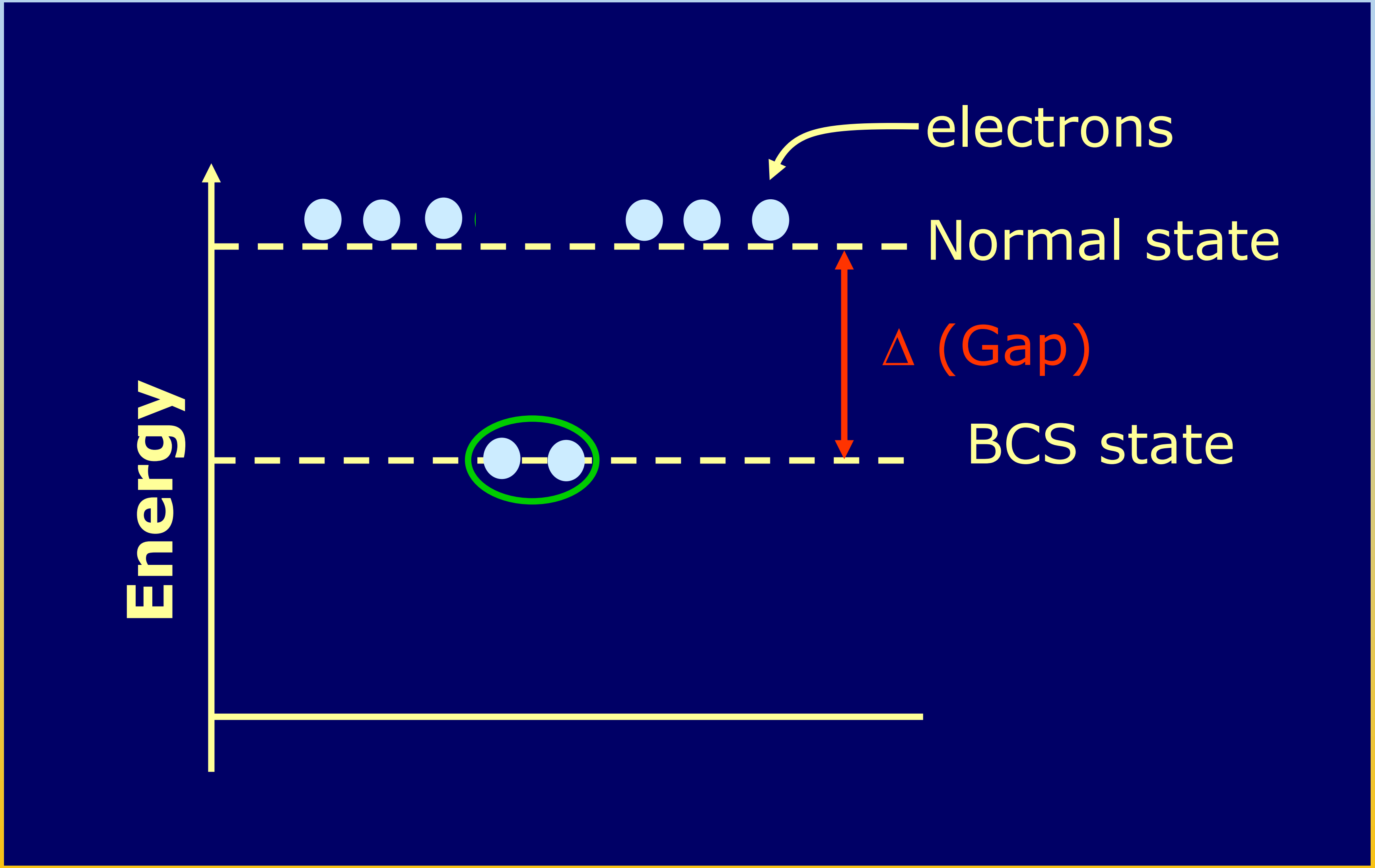
- electrons form pairs of opposite impulse and spin: the **Cooper pairs**

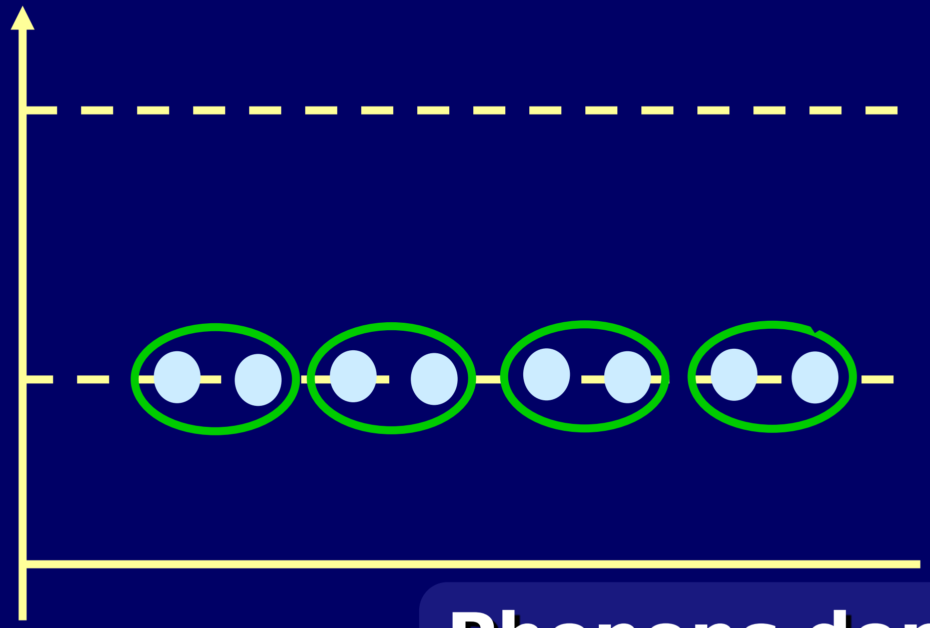


- An **energy gap opens** in the energy spectrum which stabilizes the supercoducting state



Energy gap



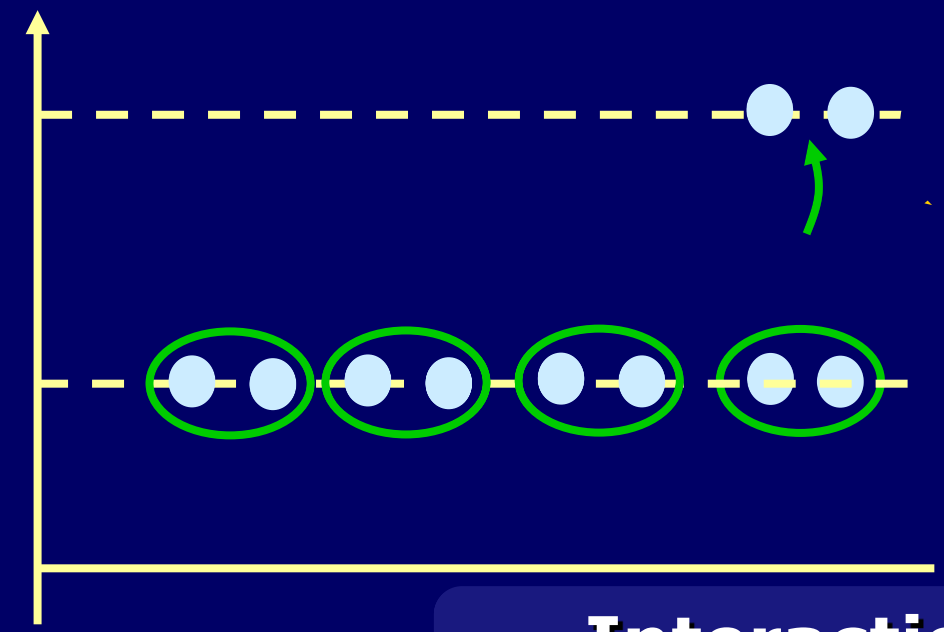


$\hbar\omega < \Delta$

A T< Tc

Phonons don’t have energy enough to breack the Cooper pairs

$\rho = 0$



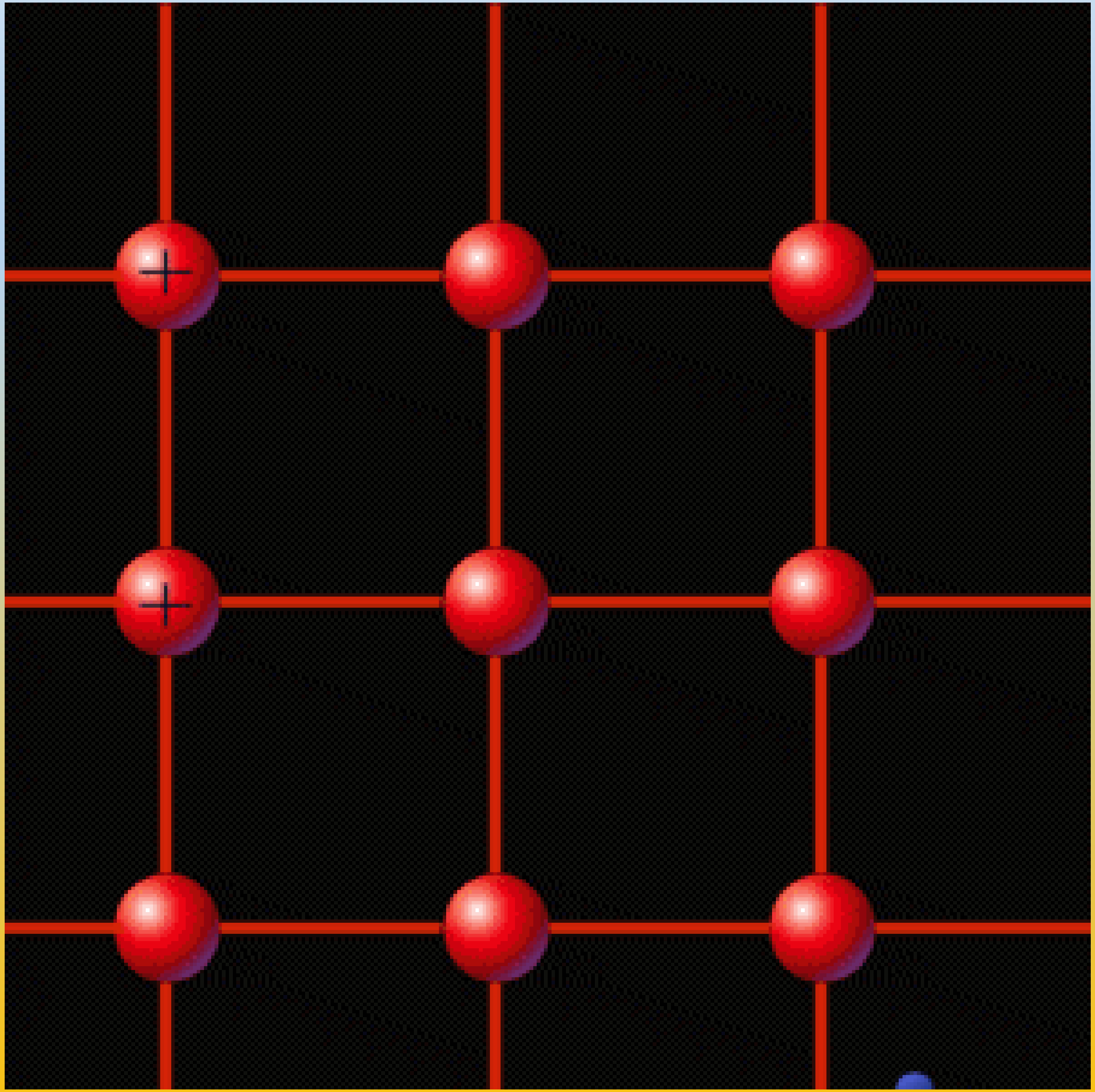
$\Delta \rightarrow 0$

A $T \rightarrow T_c$

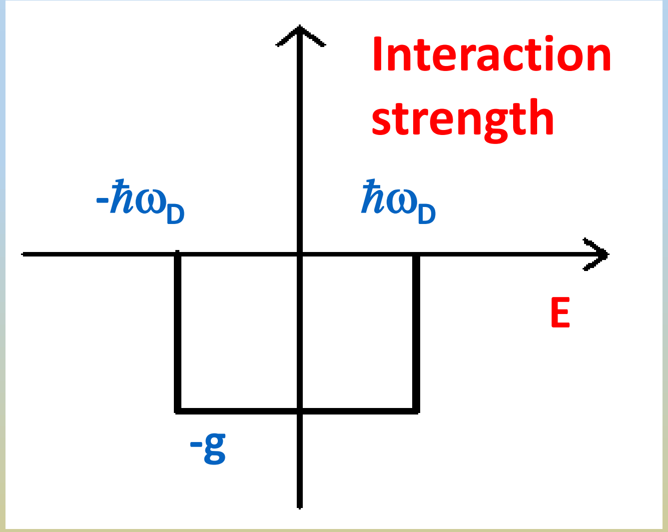
Interaction with phonons break the Cooper pairs

$\rho \neq 0$

Electron pairing mechanisms

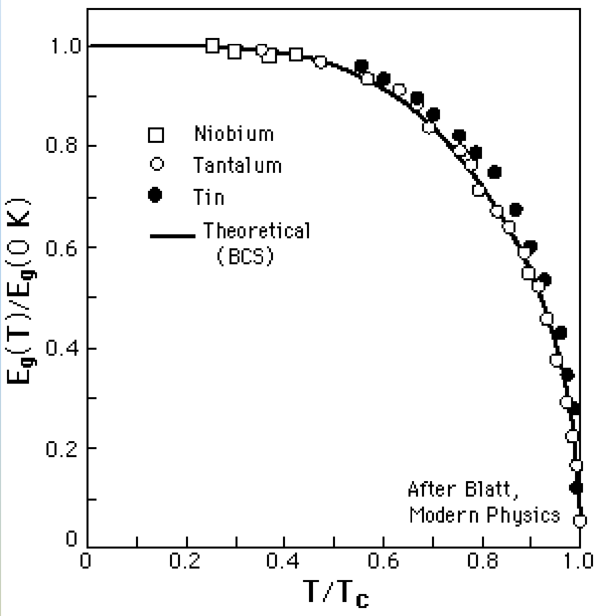


BCS theory predictions



Energy Gap

$$\Delta = \hbar\omega_D \exp\left(-\frac{1}{g}\right)$$



Critical temperature

T_c~1-20 K

$$T_c = \Theta_D \exp\left(-\frac{1}{g}\right)$$

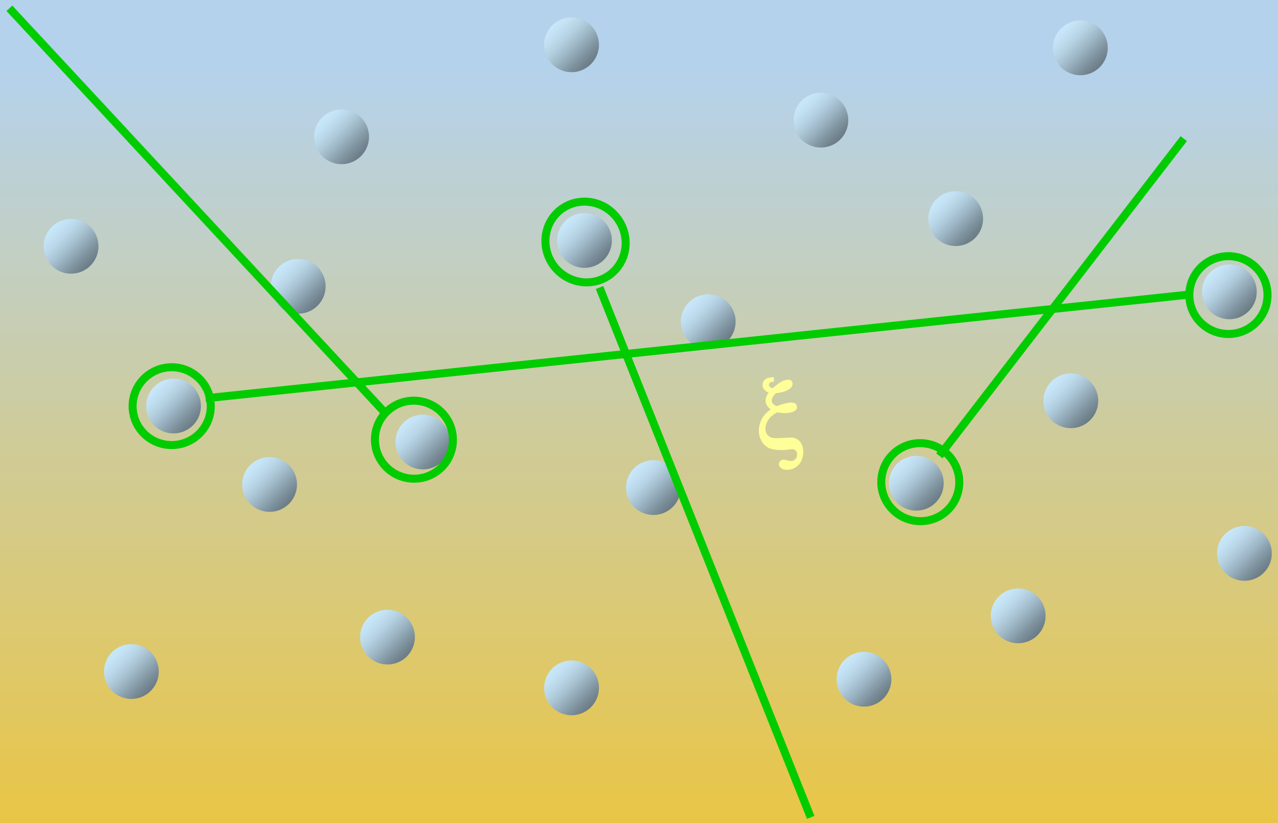
10^{-2} - 10^{-1}

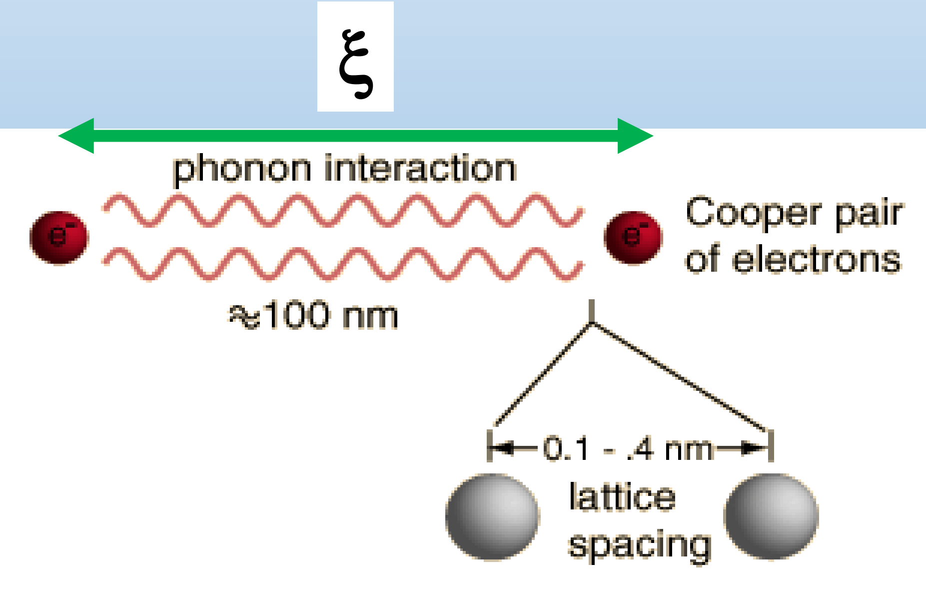
Θ_D Debye Temperature

Θ_D~100-400 K

T_{cmax}~ 30-40 K

Coherence length





For the superconducting elements the coherence length can be as large as hundreds nm, much larger than the lattice spacing.

⇒ between the two electrons of a pair, there may be thousands of electrons belonging to other pairs.

➲ ξ ~ size of the Cooper pair

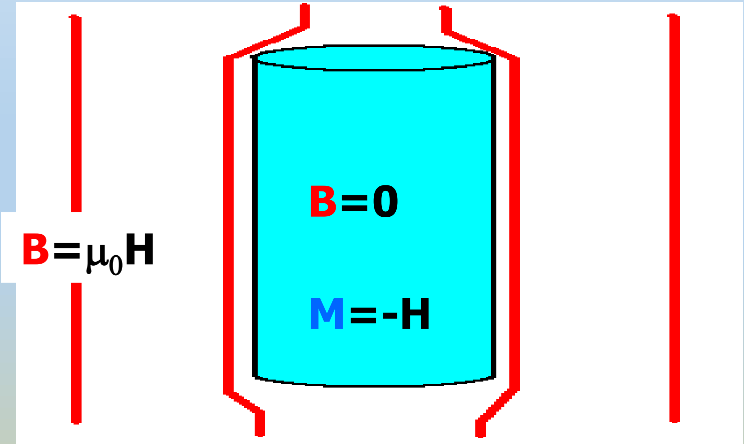
MAGNETIC PROPERTIES

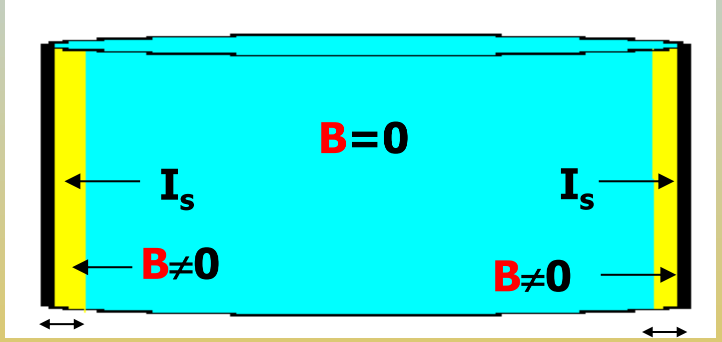
2 classes of superconductors with different properties

TYPE I
(elements)

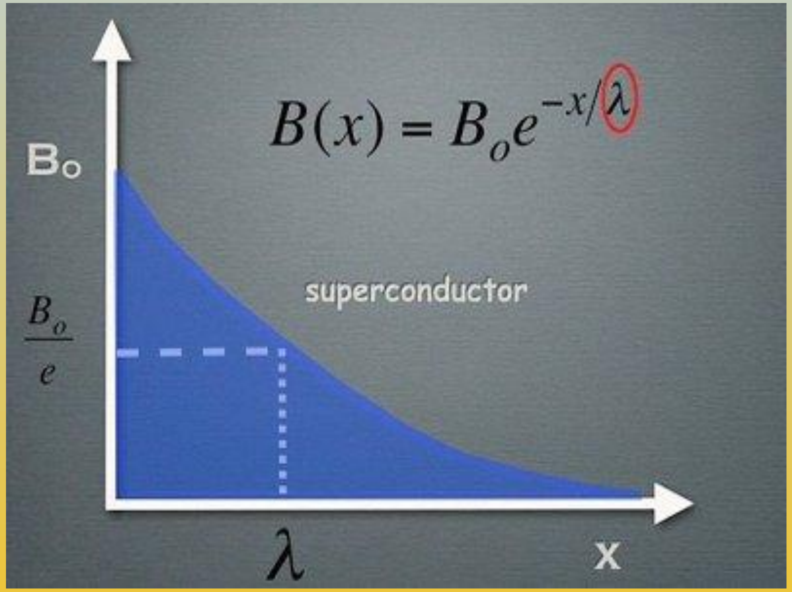
TYPE II
(alloys, composites, ...)

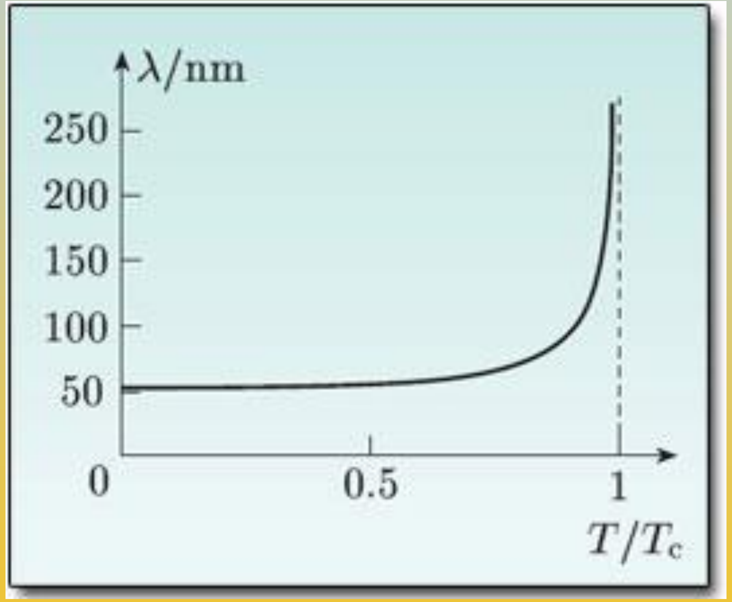
London penetration depth
1935: Brothers London theory



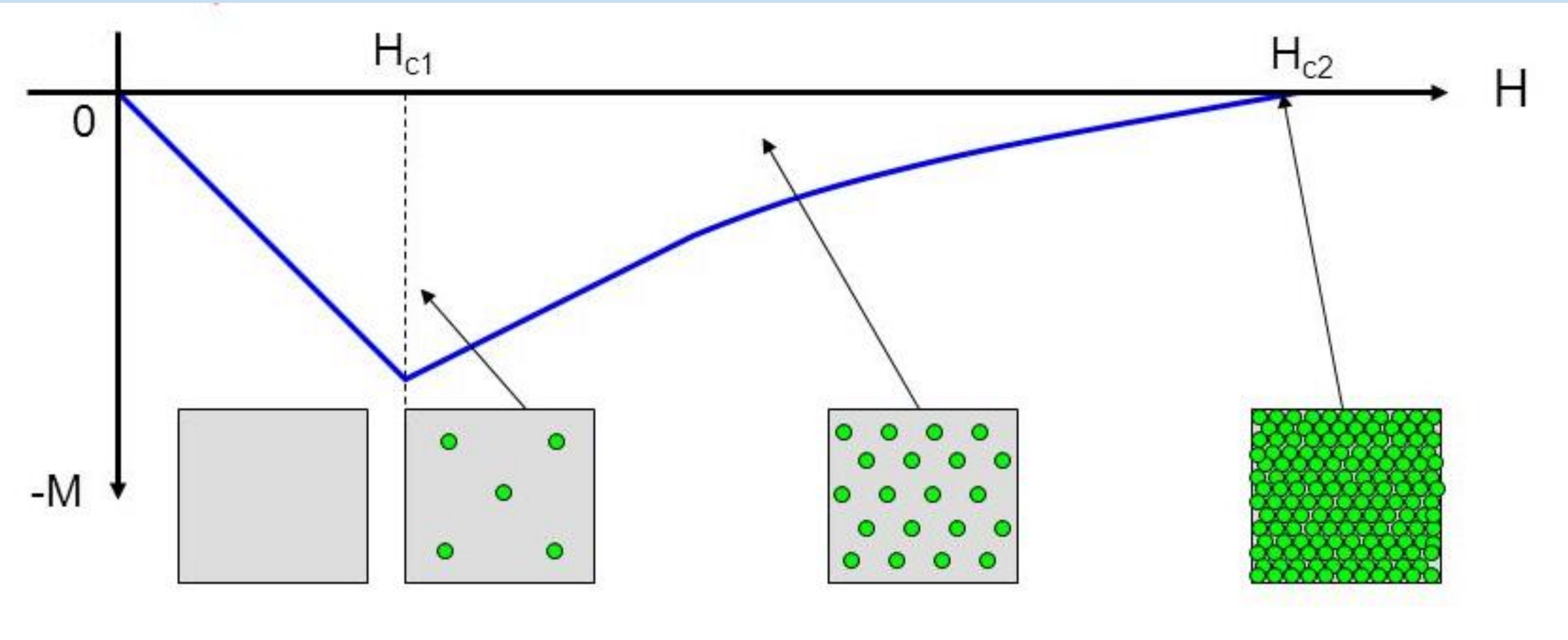


The magnetic field does not change abruptly to zero within the superconducting material.
In the superficial thickness where the superconducting currents flow, the magnetic field goes progressively to zero



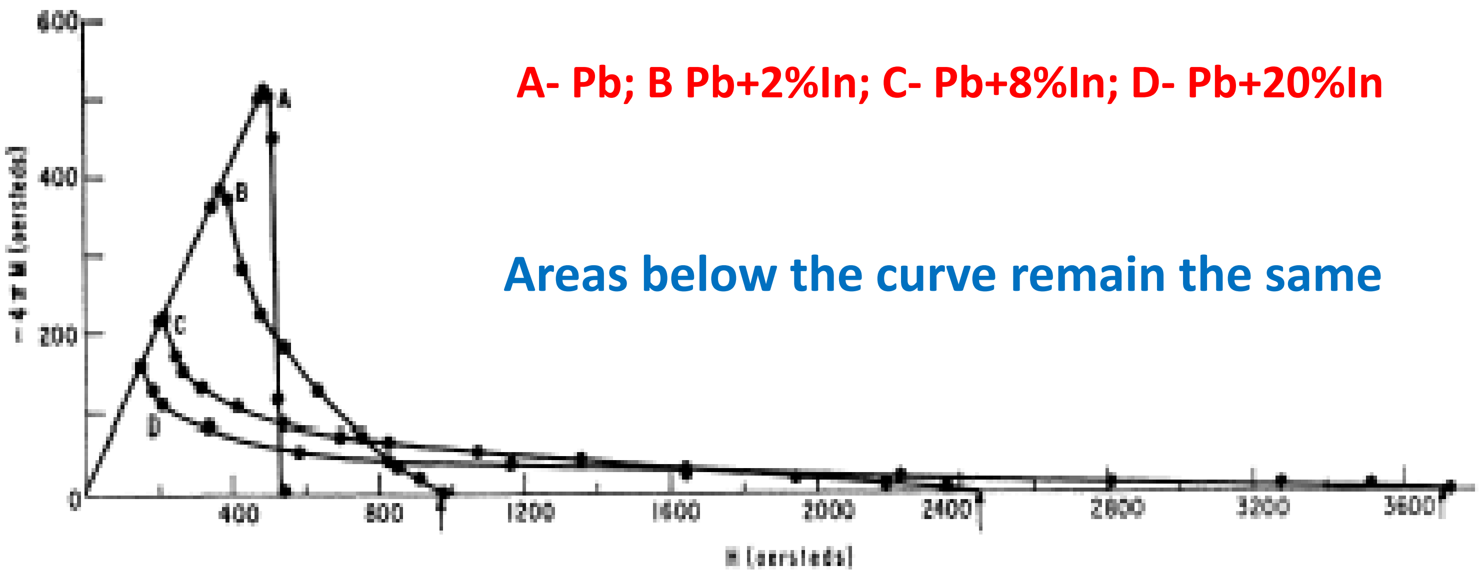


Magnetization curves



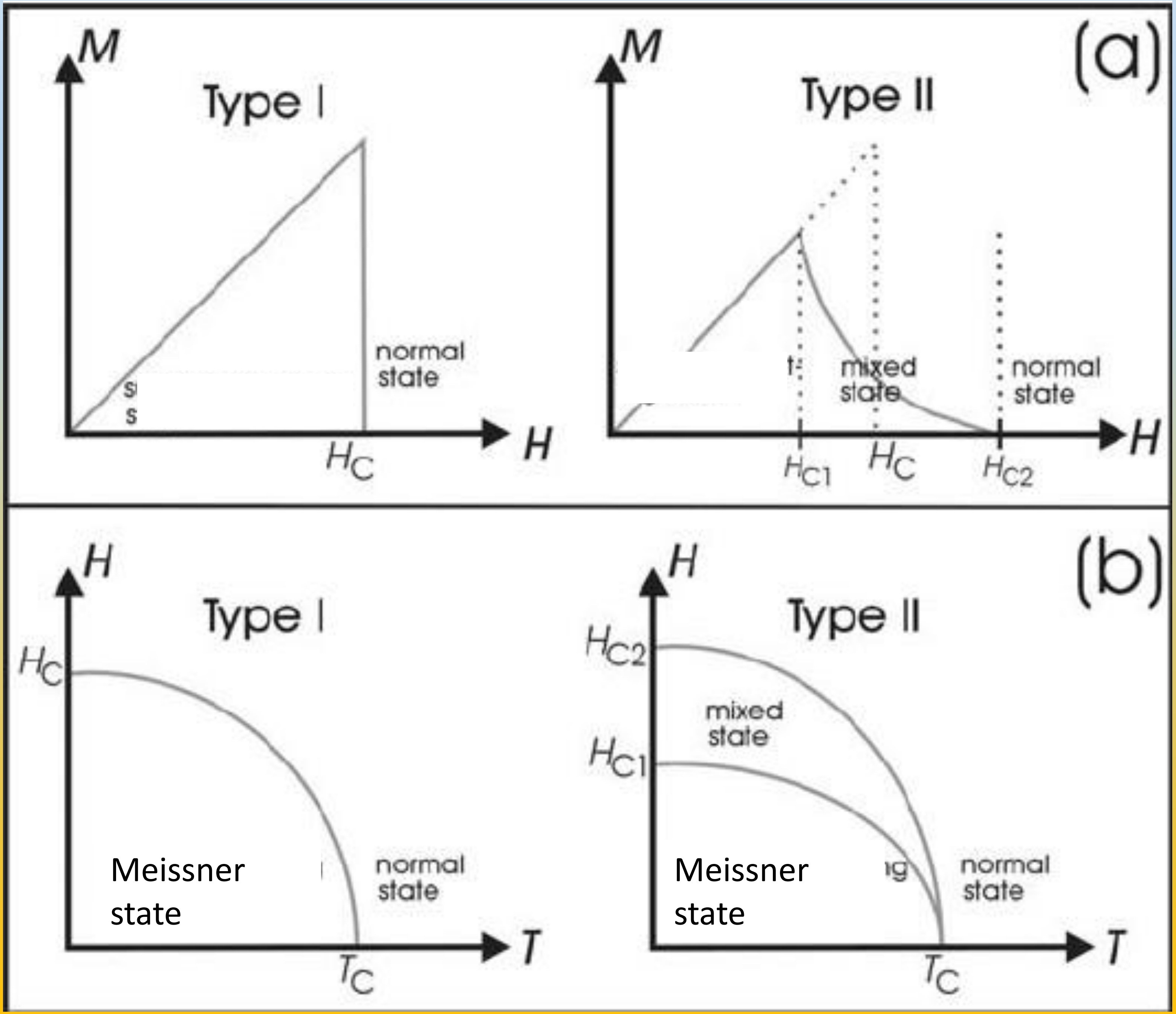
$H_{c2} > H_c$

Type II superconductors can be high field superconductors



A- Pb; B Pb+2%In; C- Pb+8%In; D- Pb+20%In

Areas below the curve remain the same


M
Type I
normal
state
H
H_C
M
Type II
(a)
mixed
state
normal
state
H
H_{C1}
H_C
H_{C2}
H
Type I
H_C
Meissner
state
normal
state
T
T_C
H
Type II
(b)
H_{C2}
mixed
state
H_{C1}
Meissner
state
normal
state
T
T_C

Who is of I or II type?

$$\kappa = \frac{\lambda}{\xi} \qquad \text{Ginzburg-Landau parameter}$$

$$\kappa < \frac{1}{\sqrt{2}} \quad \text{Type I} \quad ; \quad \kappa > \frac{1}{\sqrt{2}} \quad \text{Type II}$$

Material	T_c (K)	ξ (nm)	λ (nm)	κ (λ/ξ)
Type I				
Cd	0.56	760	110	0.14
Al[a]	1.18	550	40	0.03
In[a]	3.41	360	40	0.11
Sn[a]	3.72	180	42	0.23
Ta	4.4	93	35	0.38
Pb[a]	7.20	82	39	0.48
Type II				
Nb[a]	9.25	39	50	1.28
Pb–In	7.0	30	150	5.0
Pb–Bi	8.3	20	200	10
Nb–Ti	9.5	4	300	75
Nb–N	16	5	200	40
$PbMo_6S_8$ (Chevrel)	15	2	200	100
V_3Ga (*A15*)	15	≈ 2.5	90	≈ 35
V_3Si (*A15*)	16	3	60	20
Nb_3Sn (*A15*)	18	3	65	22
Nb_3Ge (*A15*)	23.2	3	90	30
K_3C_{60}	19	2.6	240	92
Rb_3C_{60}	29.6	2.0	247	124
$(La_{0.925}Sr_{0.075})_2CuO_4$[b]	37	2.0	200	100
$YBa_2Cu_3O_7$[b]	89	1.8	170	95
HgBaCaCuO	126	2.3		
$HgBa_2Ca_2Cu_3O_{8+\delta}$	131			100
MgB_2	39	10	80	10
$SmFeAsO_{0.7}F_{0.3}$	58	2.5	200	80
KBaFe2As2	38	3	200	67
Fe(Se,Te)	18	1.5	400	300

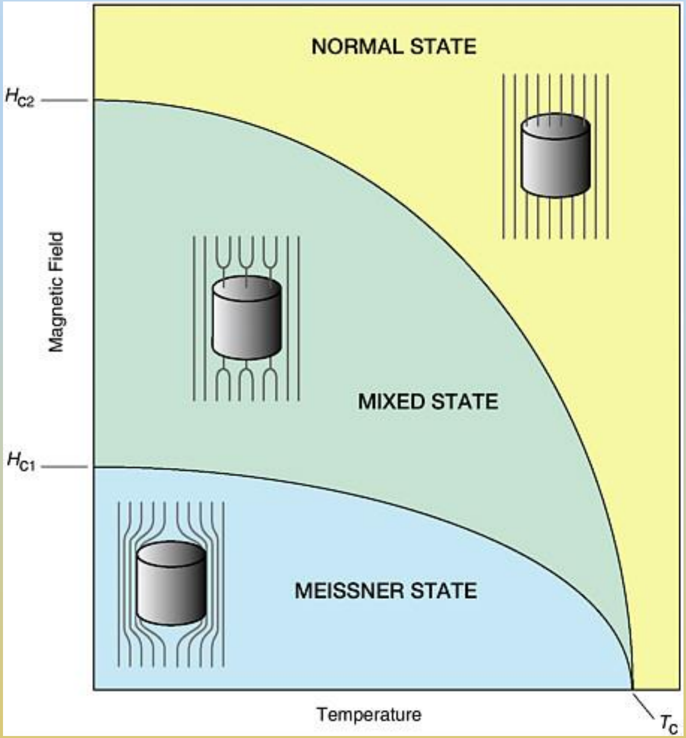
With disorder → **Type II**

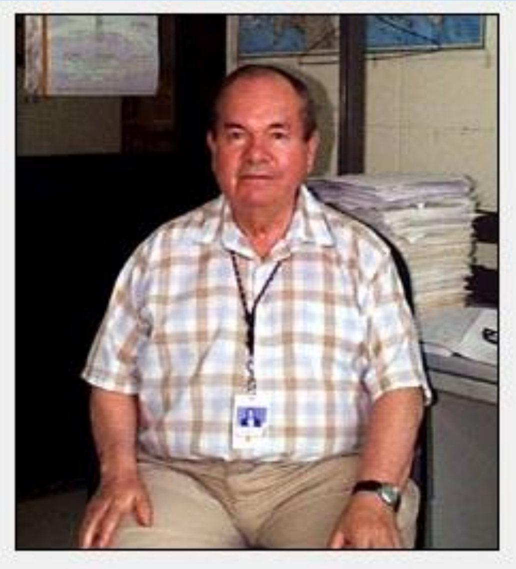
$$\lambda = \left(\frac{m}{2e^2\mu_0 n_s}\right)^{1/2} \quad \uparrow$$

$$\xi \propto \frac{n_s^{1/3}}{T_c} \quad \downarrow$$

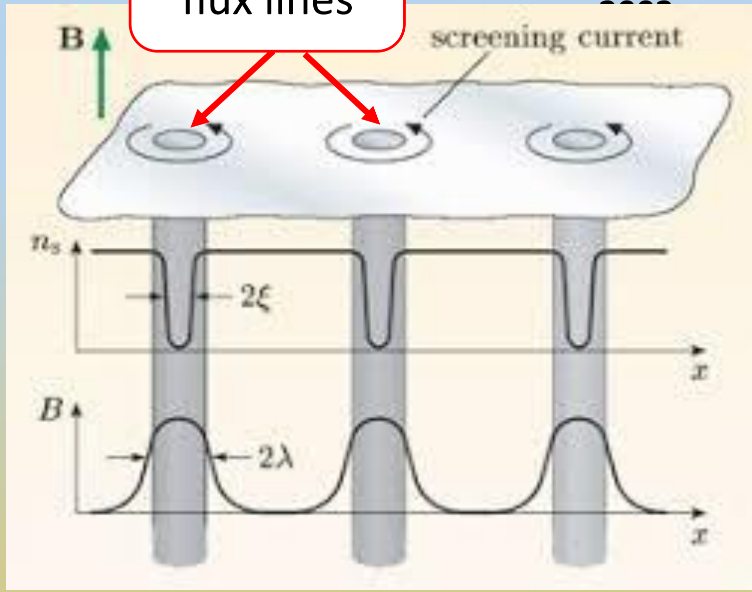
$$\kappa = \frac{\lambda}{\xi} \quad \uparrow$$

1957: What the mixed state is (Abrikosov)

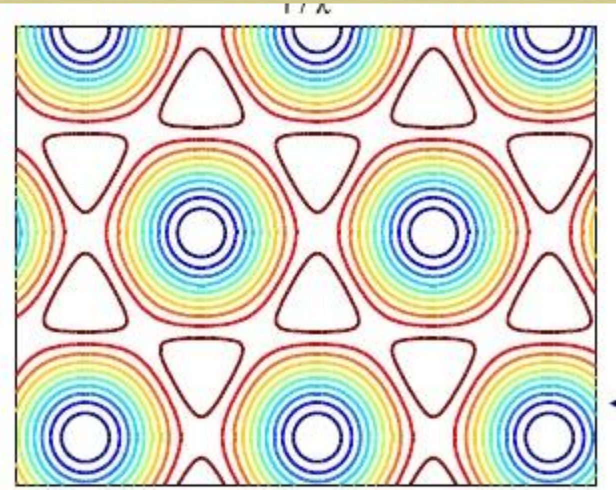




Quantized flux lines



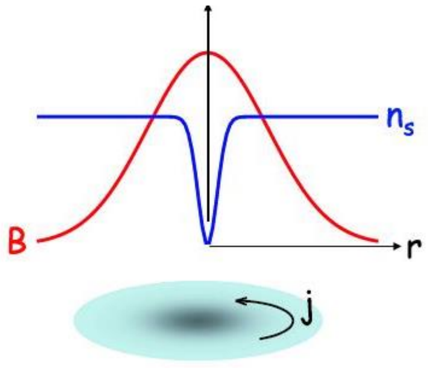
- ⤇ Quantized flux lines (fluxons/vortices) enter the superconductor
- ⤇ **Fluxons** form an exagonal lattice

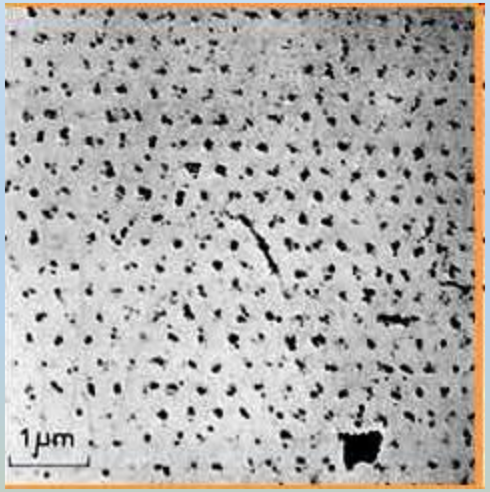


Abrikosov solution near Hc2 – Contours of B

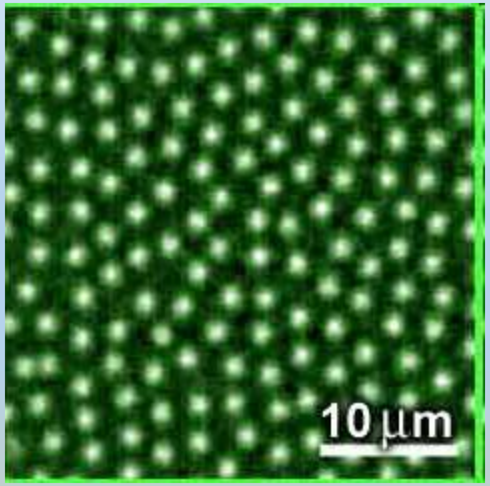
$$\Phi_0 = \frac{h}{2e}$$

$$2.067 \times 10^{-15} Wb$$

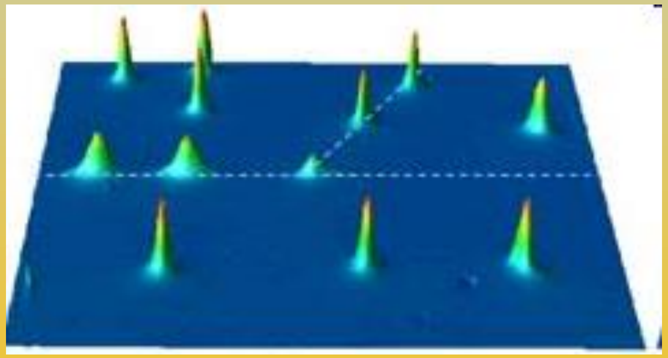




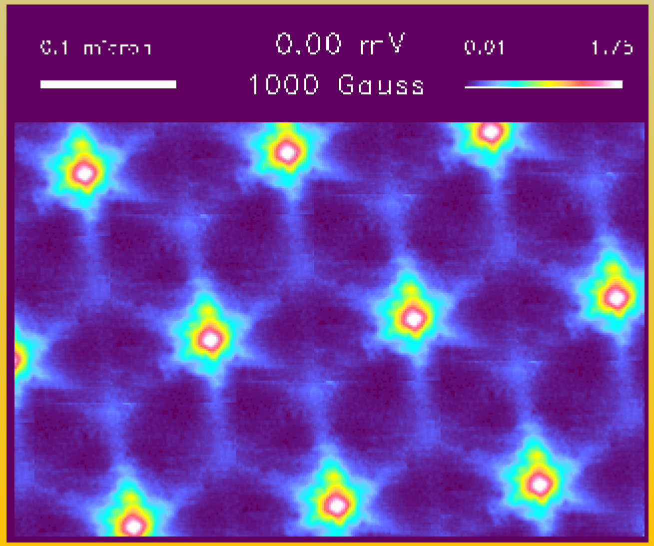
U. Essmann and H. Trauble
Max-Planck Institute, Stuttgart
Physics Letters 24A, 526 (1967)



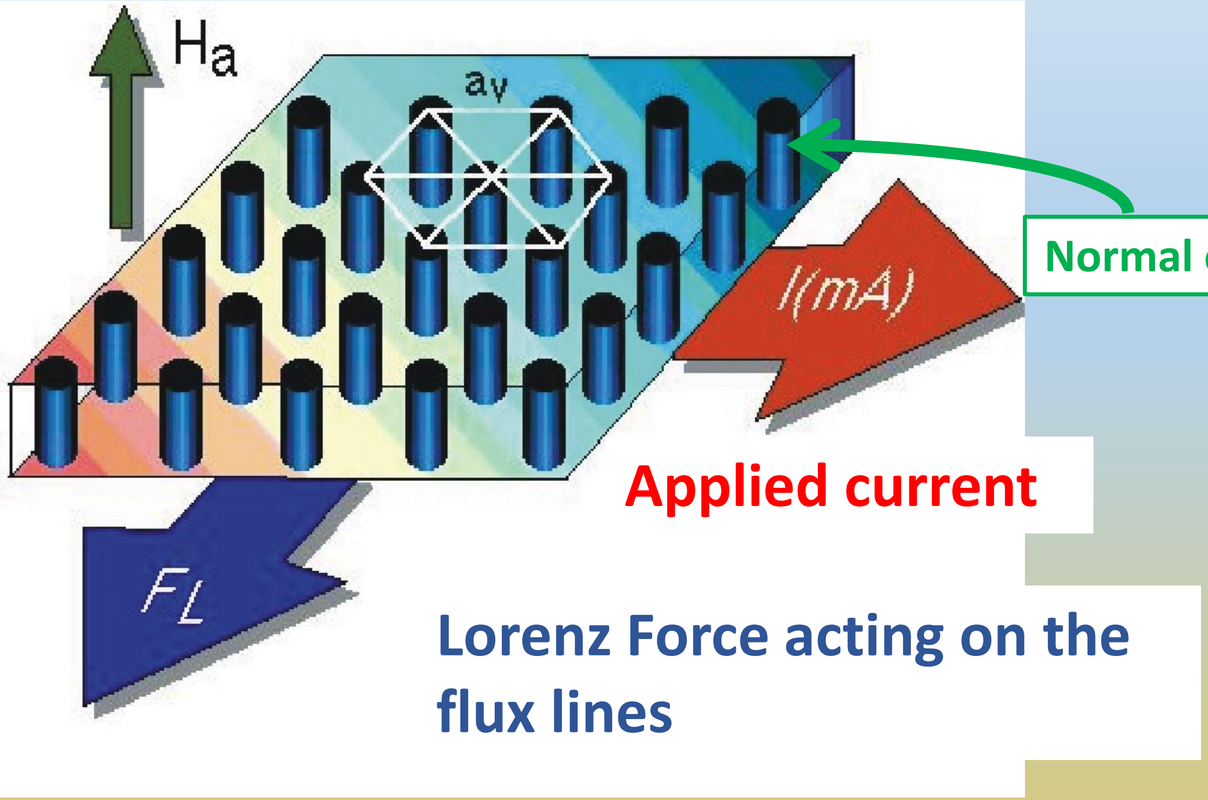
Magneto-optical image of Vortex lattice, 2001
P.E. Goa et al.
University of Oslo
Supercond. Sci. Technol. 14, 729 (2001)

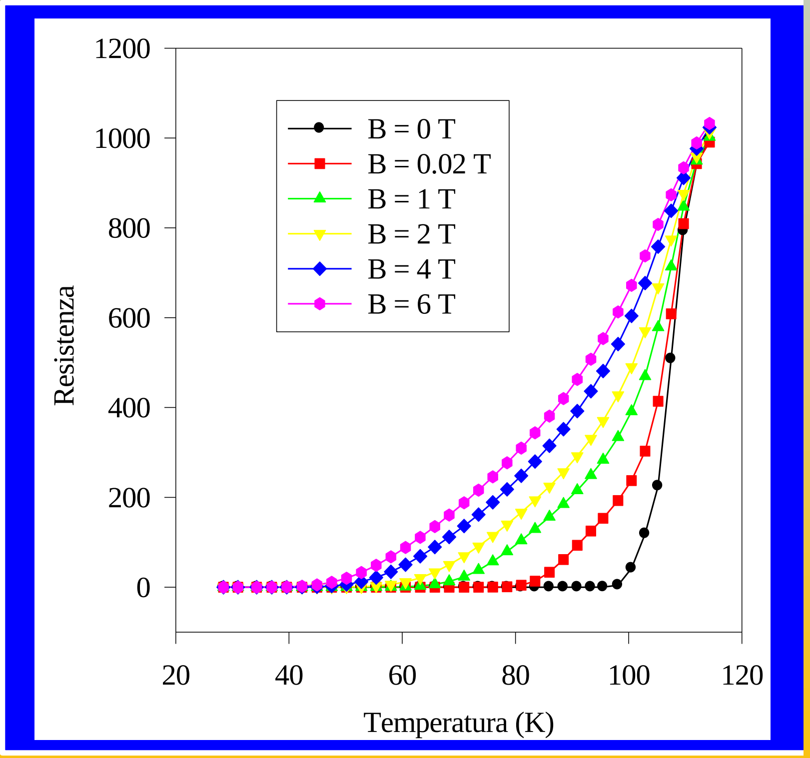


Scanning SQUID Microscopy of half-integer vortex, 1996
J. R. Kirtley et al. IBM Thomas J. Watson Research Center
Phys. Rev. Lett. 76, 1336 (1996)



Dissipation in the mixed state



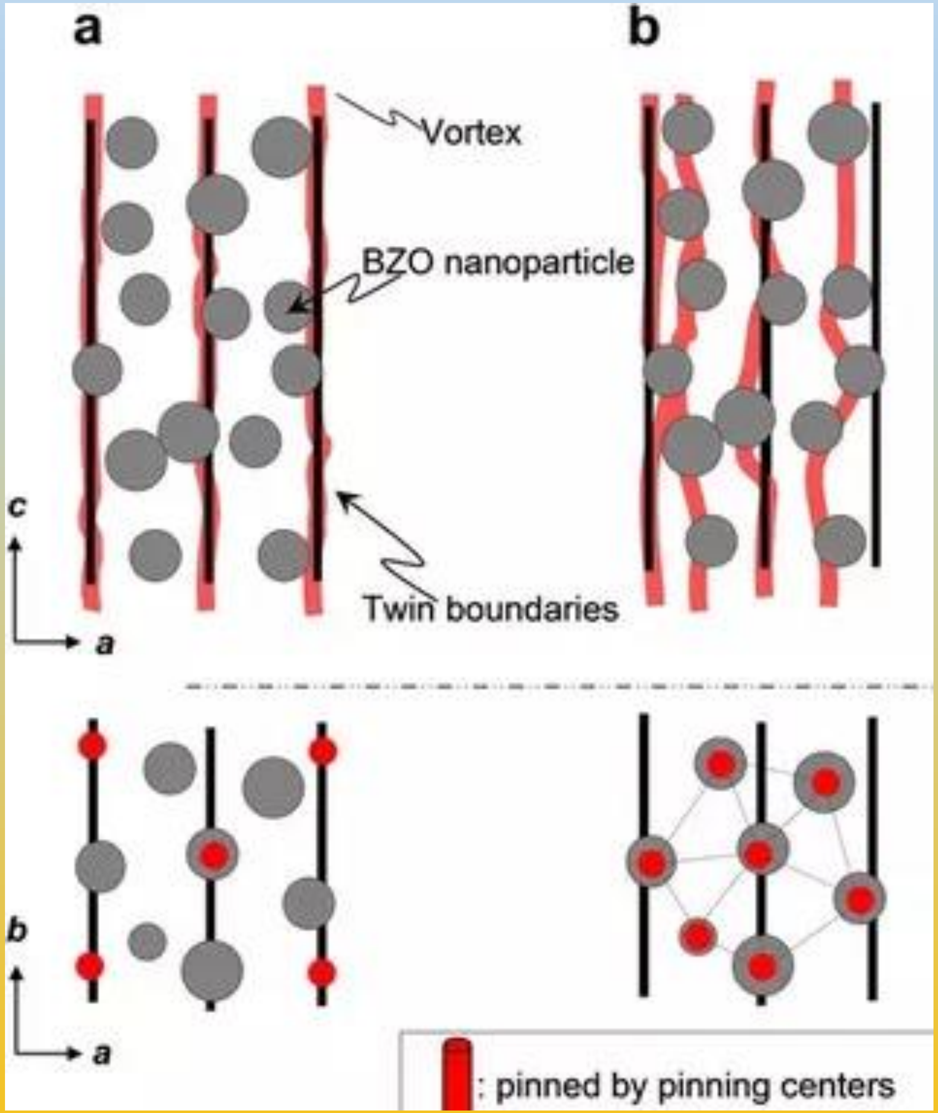


⤇an **applied current** exerts a force on the vortices

⤇the motion of the fluxons whose core is made up of **normal electrons** causes dissipation

⤇The system is superconducting but it **is resistive and dissipates**

Vortex pinning



The flux motion reduces the current that the superconductor can curry without dissipation.

SOLUTION: to introduce defects which pinn the vortices

Critical current I_c:
the maximum current that the superconductors can curry without dissipation

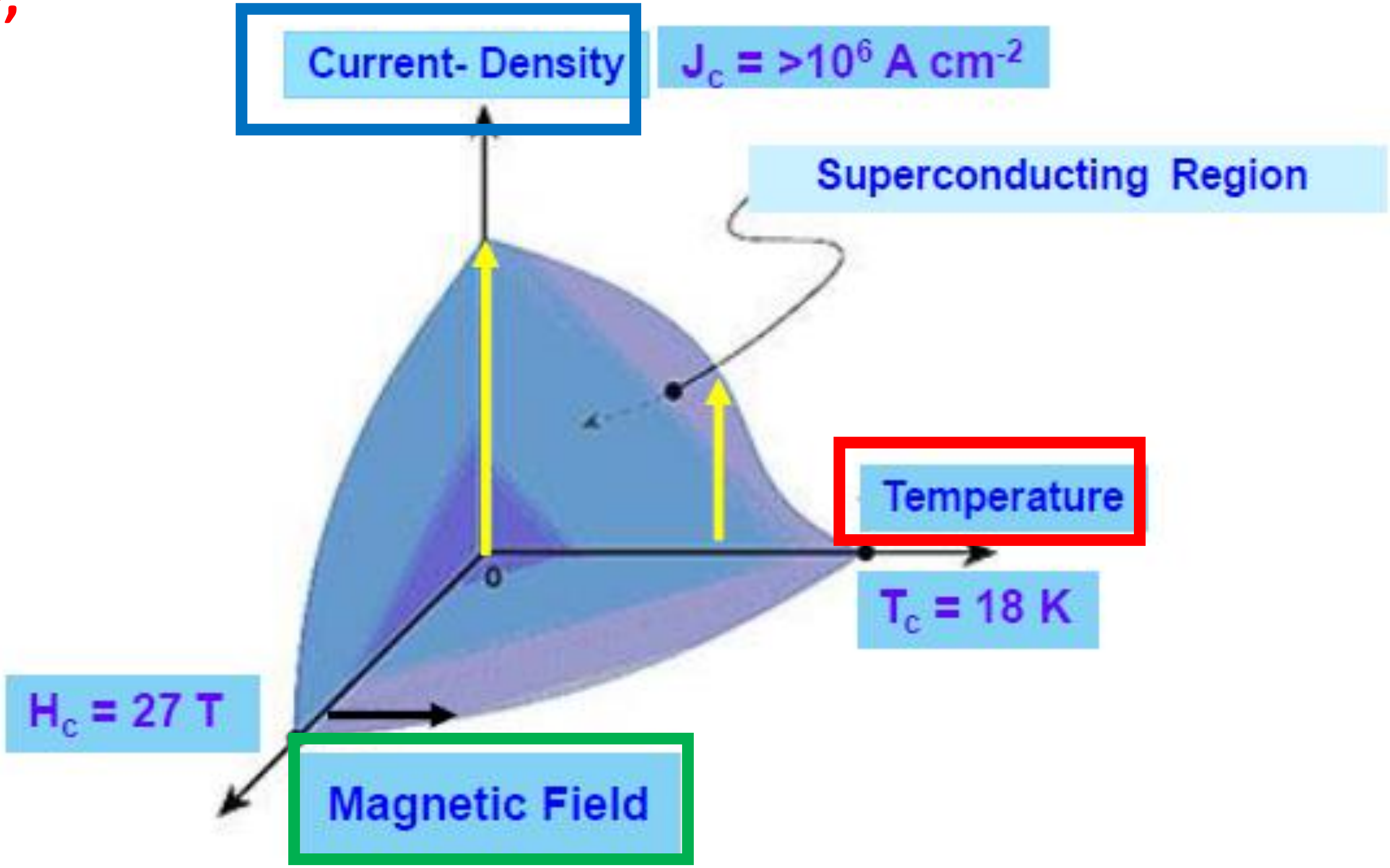
The region in which a superconductors can work without dissipation is limited by the three parameters:

Nb$_3$Sn (NbTi)

The criticat temperature;

The critical field;

The critical current.



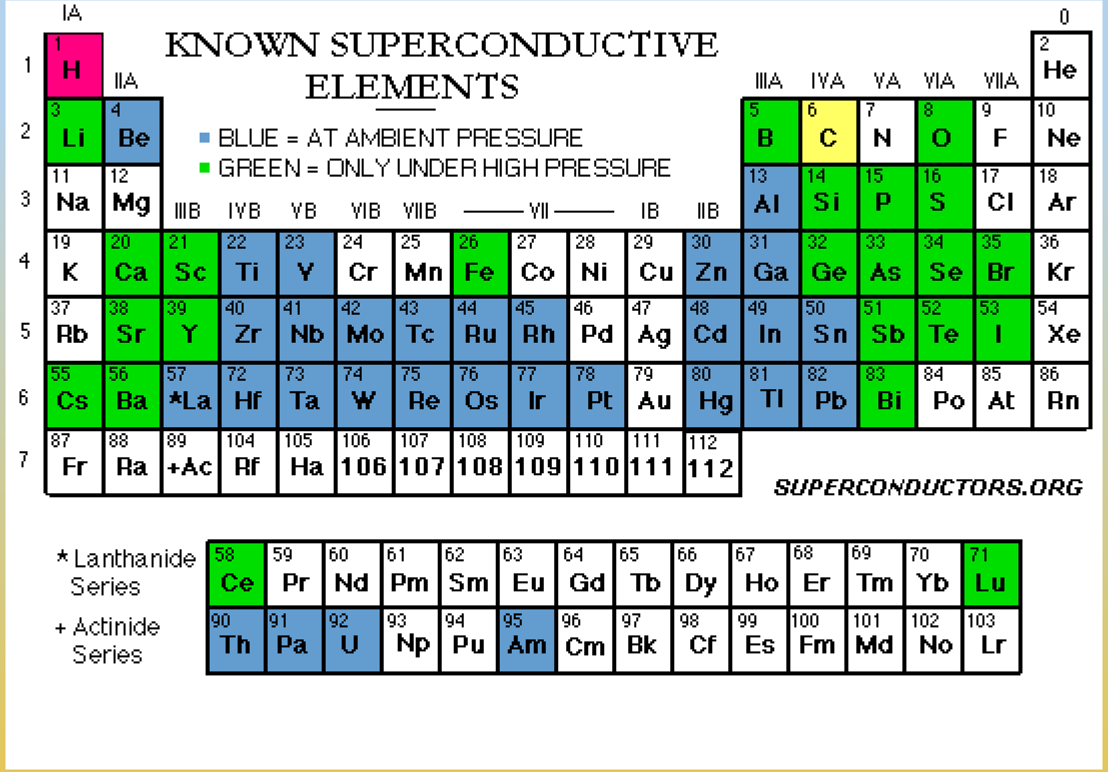
High Current and high Field Applications since 1961

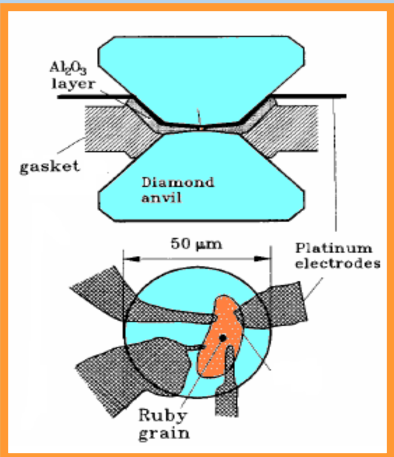
J.E.Kunzler *et al.*,Phys.Rev.Lett. 6:3 (1961) 89

The superconducting materials

Superconductive elements

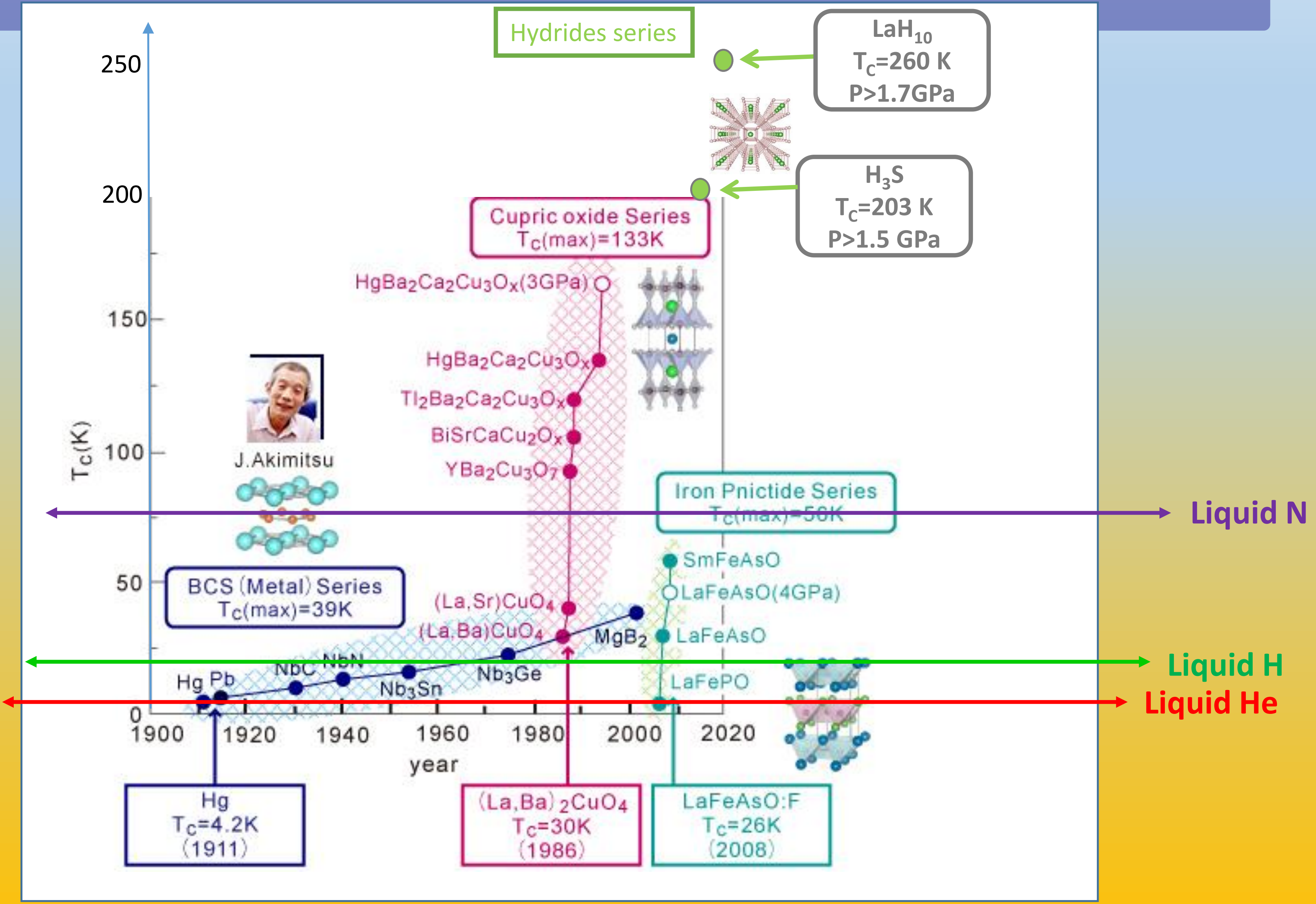
Future ?





Record Pressure:
250 GPa
2,500,000 atmospheres

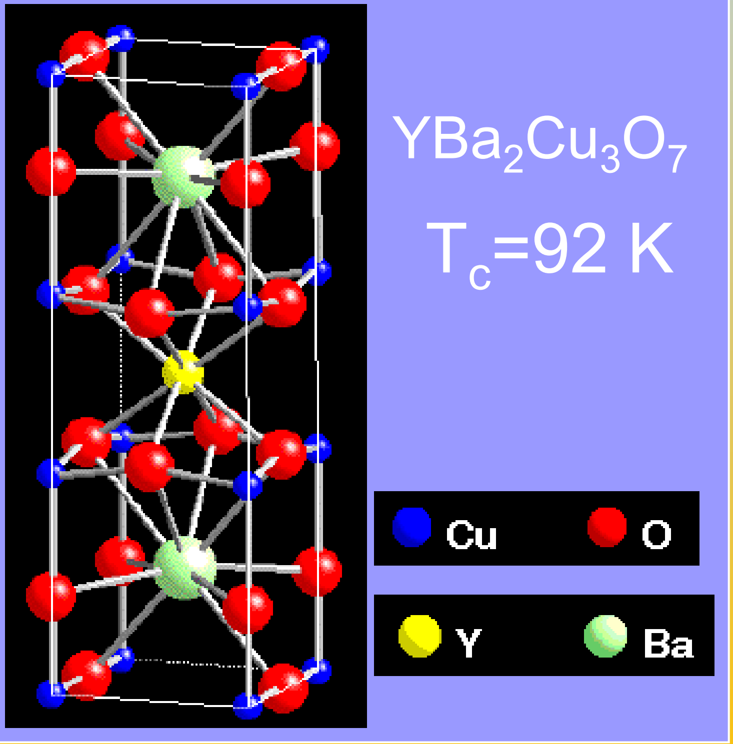
Story of the superconducting materials



High Temperature superconductors (HTS)

1986 Bednorz and Müller 1986

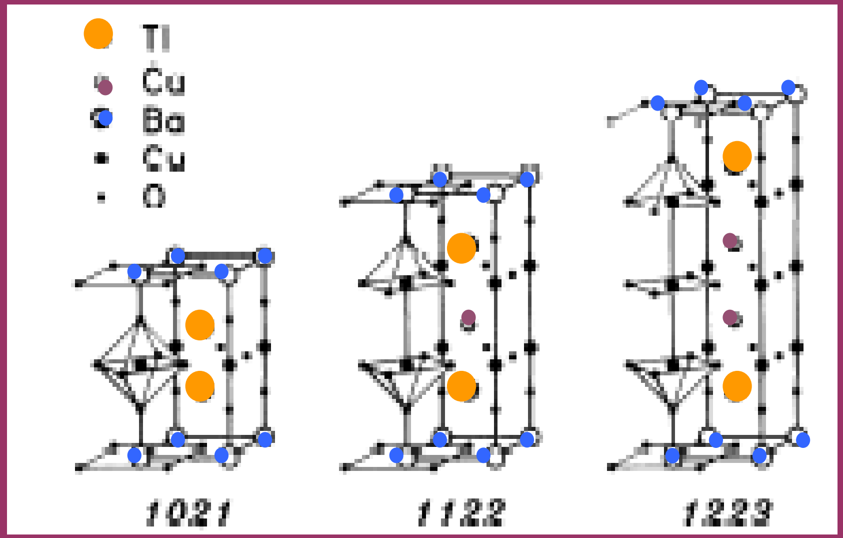
1987



$YBa_2Cu_3O_7$

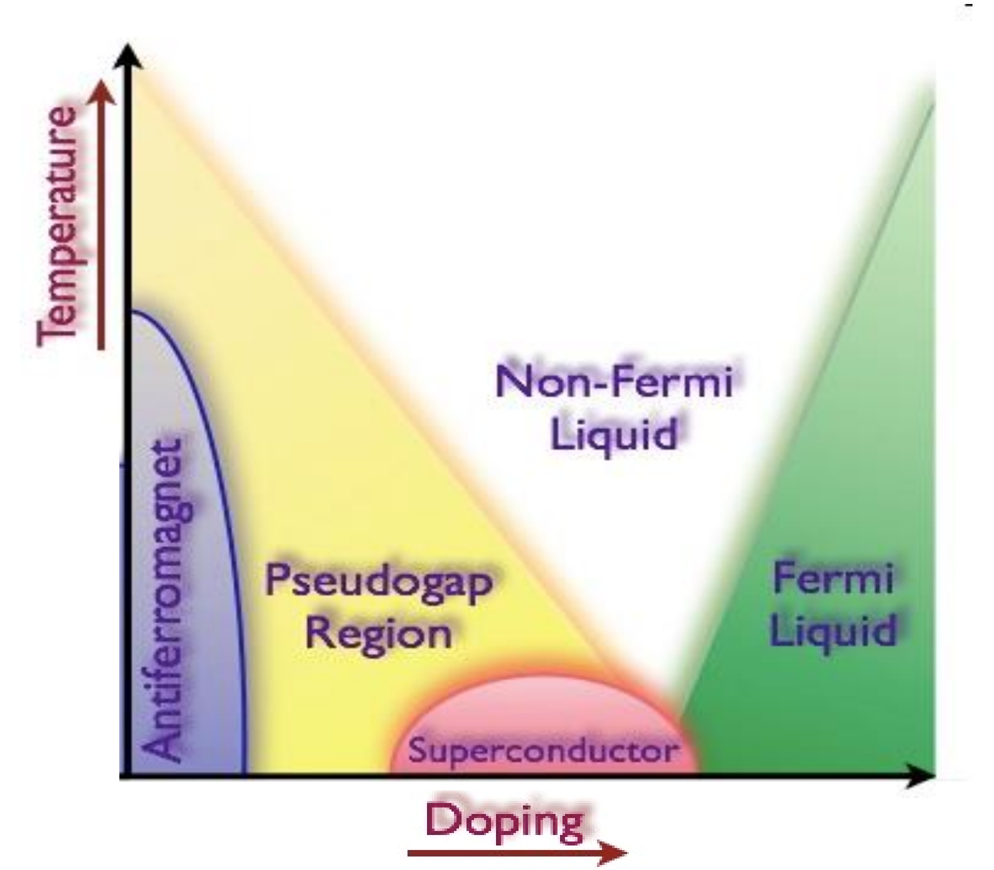
T_c=92 K

- Ceramic materials charactized by CuO_2 layers spaced by a reservoir block
- Conduction (and superconductivity) occurring in the CuO_2 layers
- Maximum T_c = 165 K in $HgBa_2Ca_2Cu_3O_{8+d}$ under pressure



T_c(K) 10-40 65-85 100-110

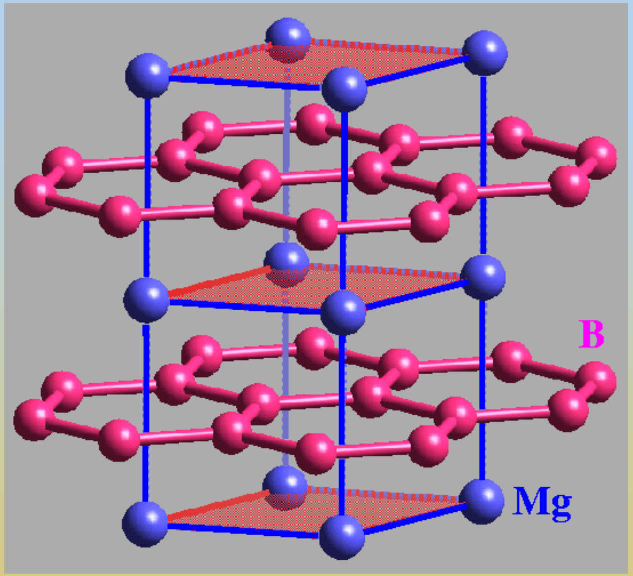
The increasing of CuO_2 layer increases T_c



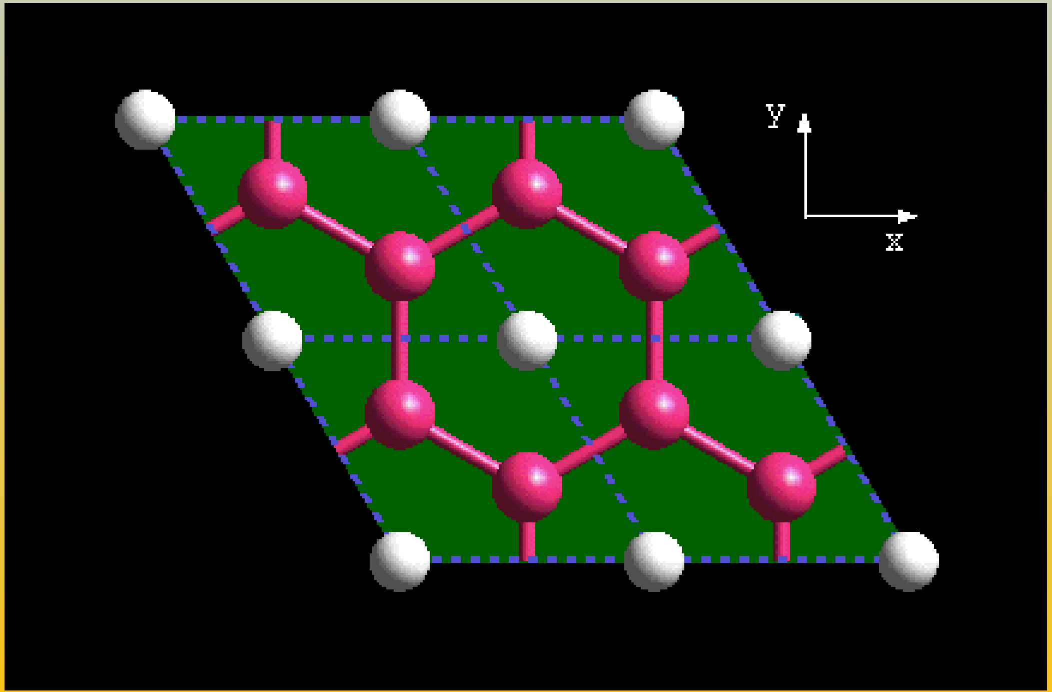
- Complex phase diagram as a function of the doping in the CuO_2 planes
- The coupling between electron is determined by unconventional mechanism (not mediated by the phonons) not yet completely clarified

MgB2

Akimitzu (2001)



- T_c = 39 K
- Layered structure
- Metallic system
- Electron pairing mediated by the optical mode of B ions
- Conventional superconductivity

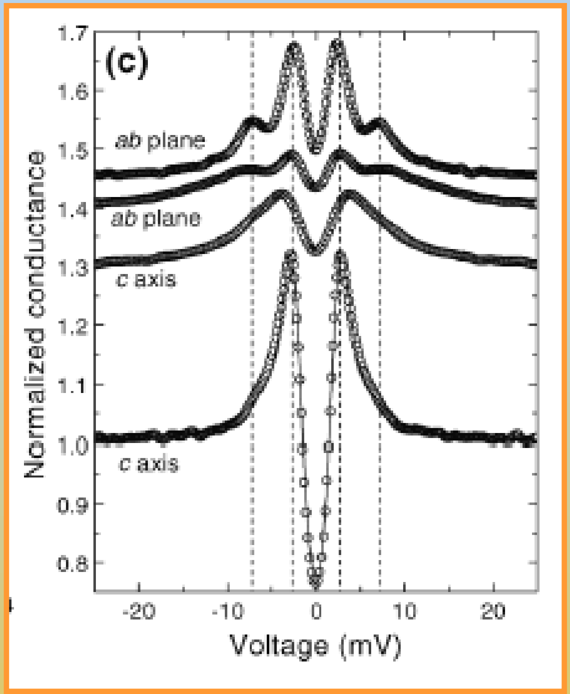


T_c = 39 K is too near the maximum T_c predicted by the BCS theory!!

MgB_2 first example of a two-gap superconductor

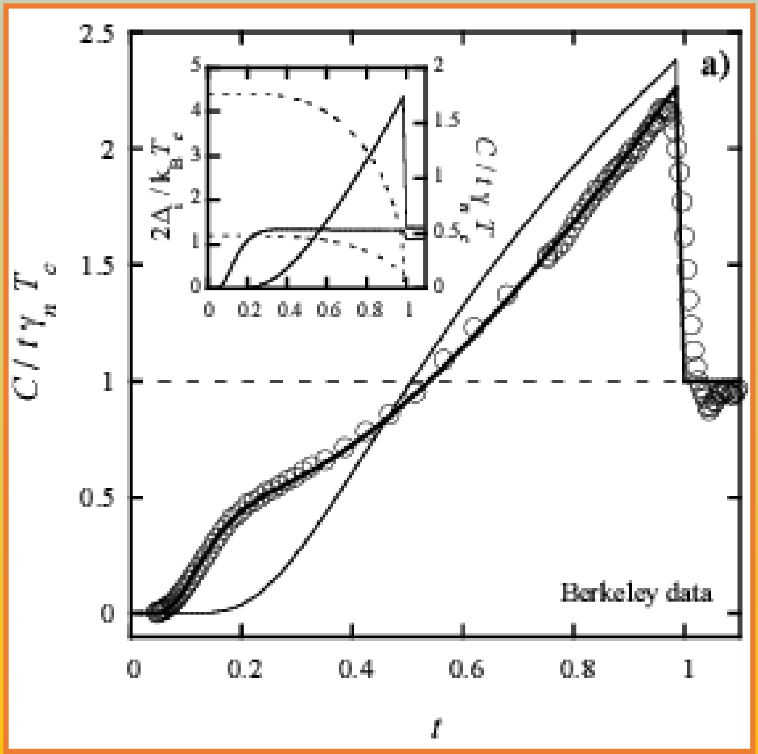
VOLUME 89, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 2002

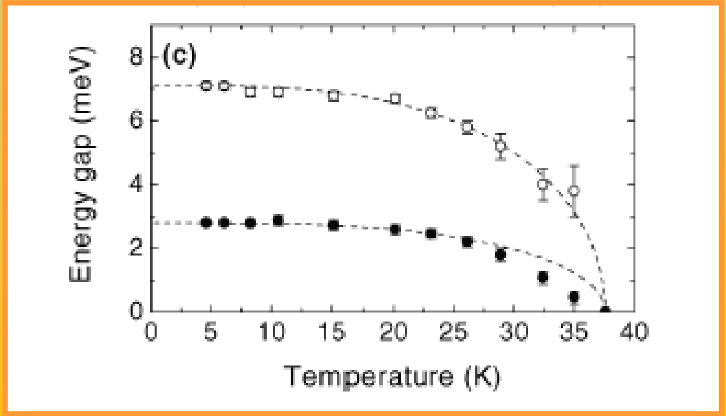
Direct Evidence for Two-Band Superconductivity in MgB_2 Single Crystals from Directional Point-Contact Spectroscopy in Magnetic Fields



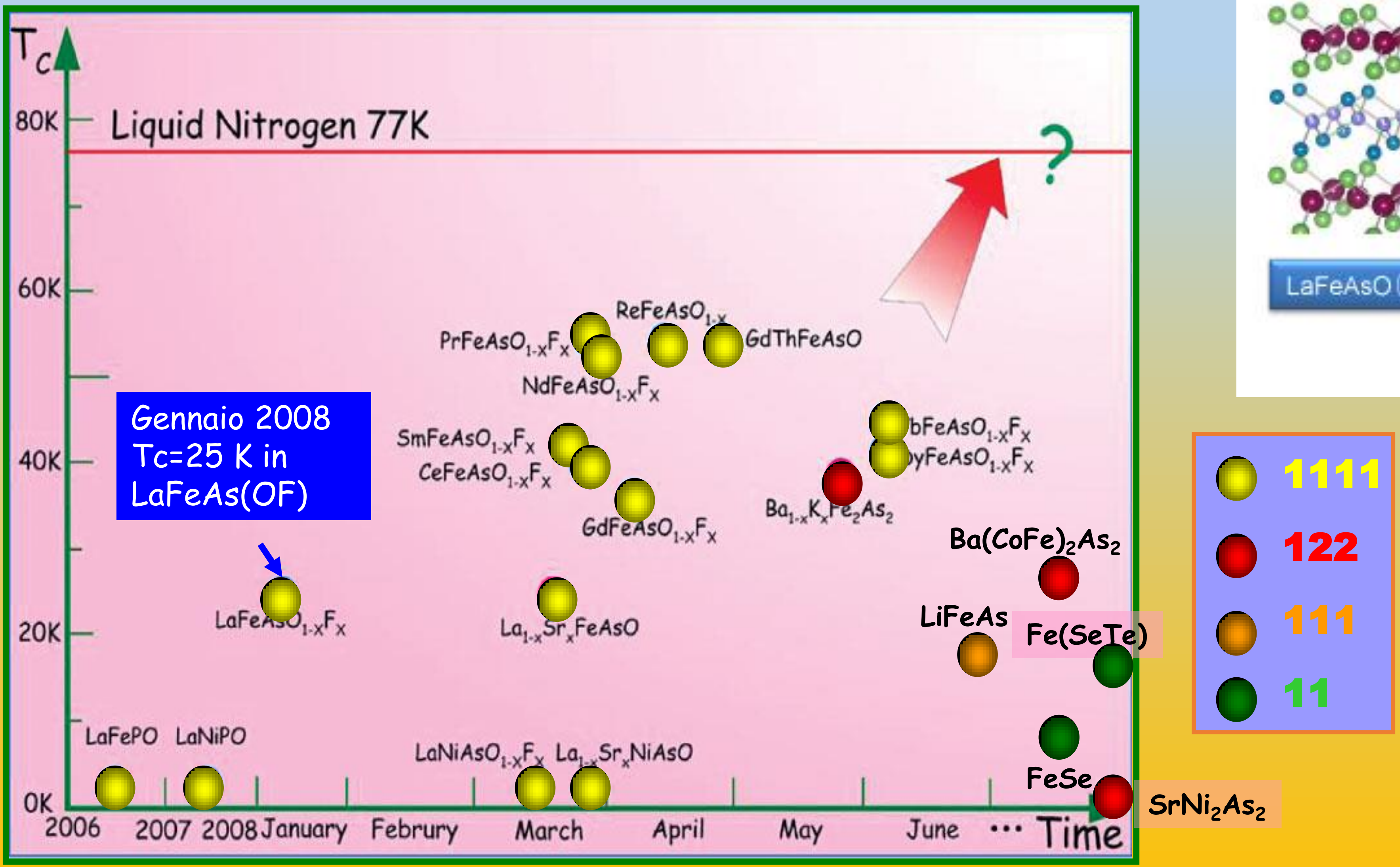
VOLUME 87, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 2001

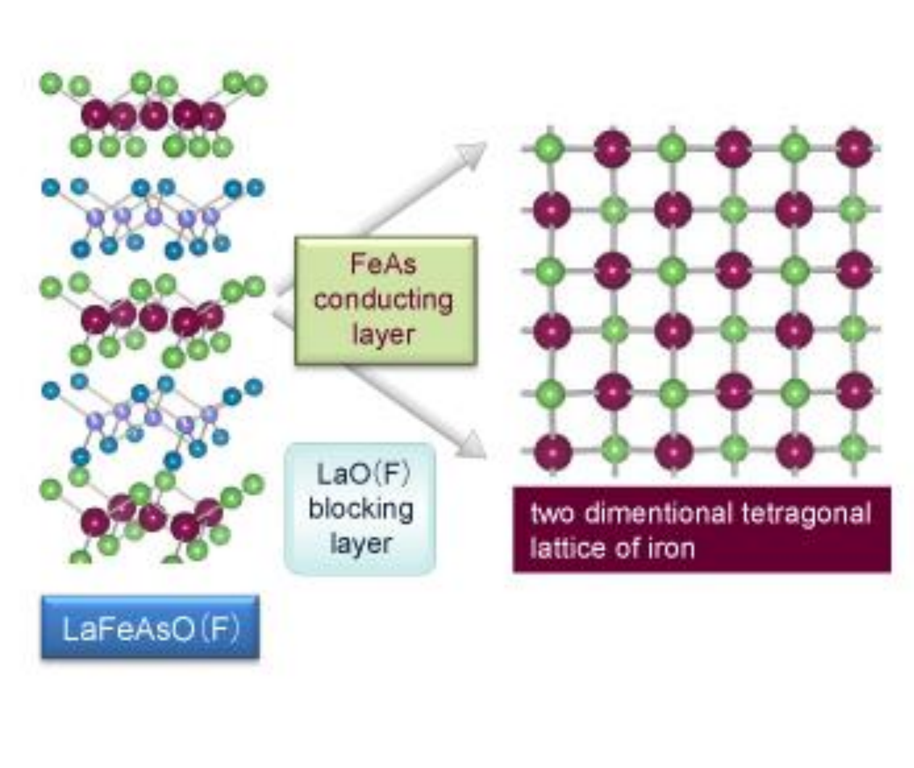
Specific Heat of $Mg^{11}B_2$: Evidence for a Second Energy Gap



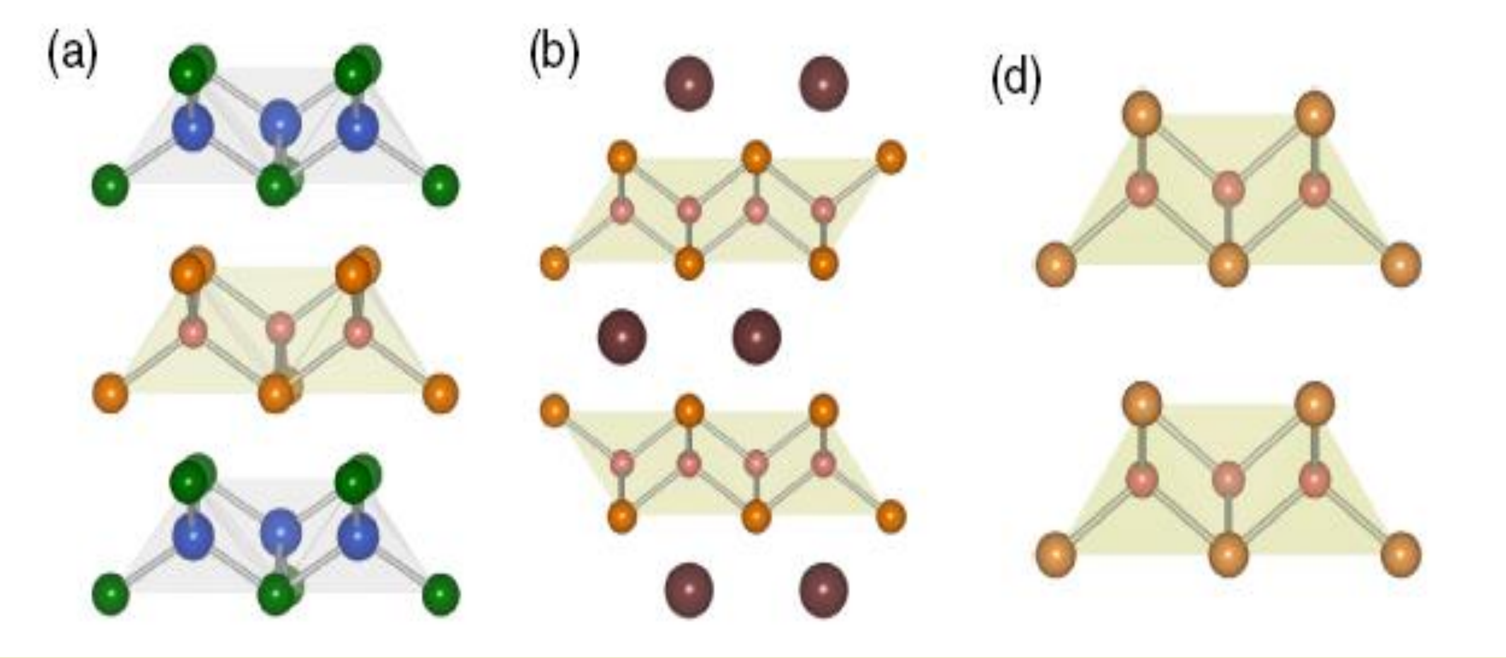


Iron based superconductors

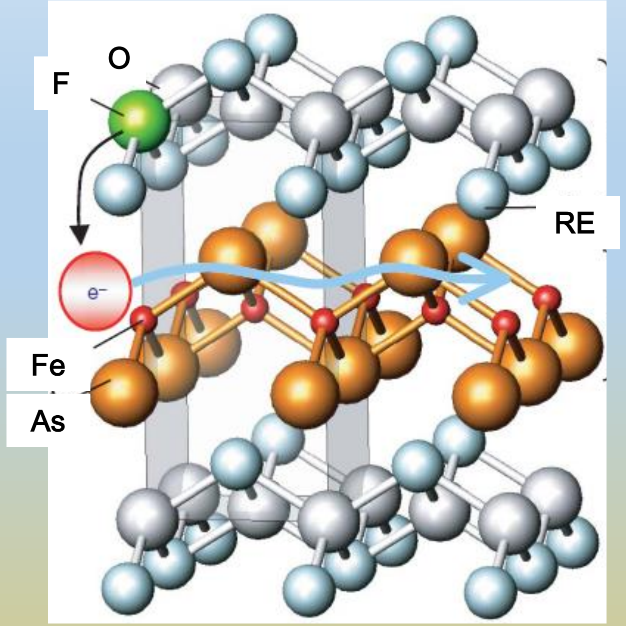


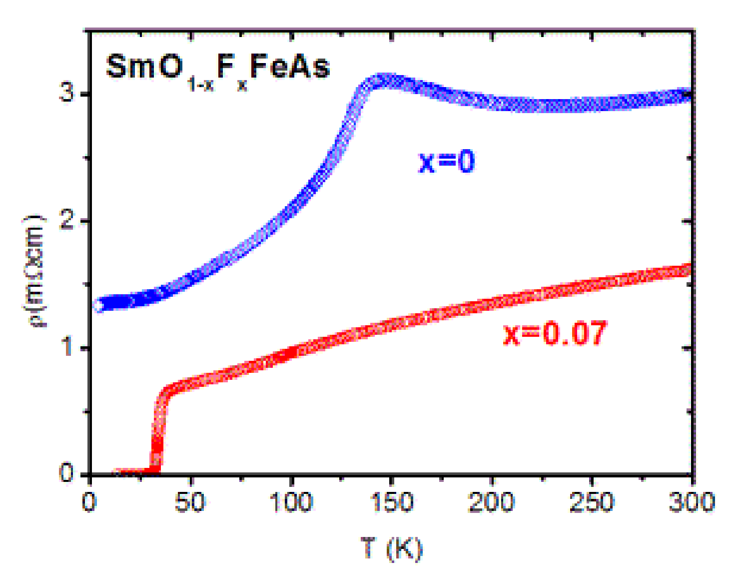


The most famous families

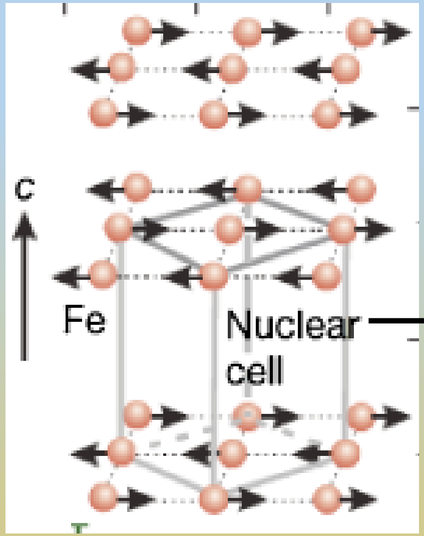


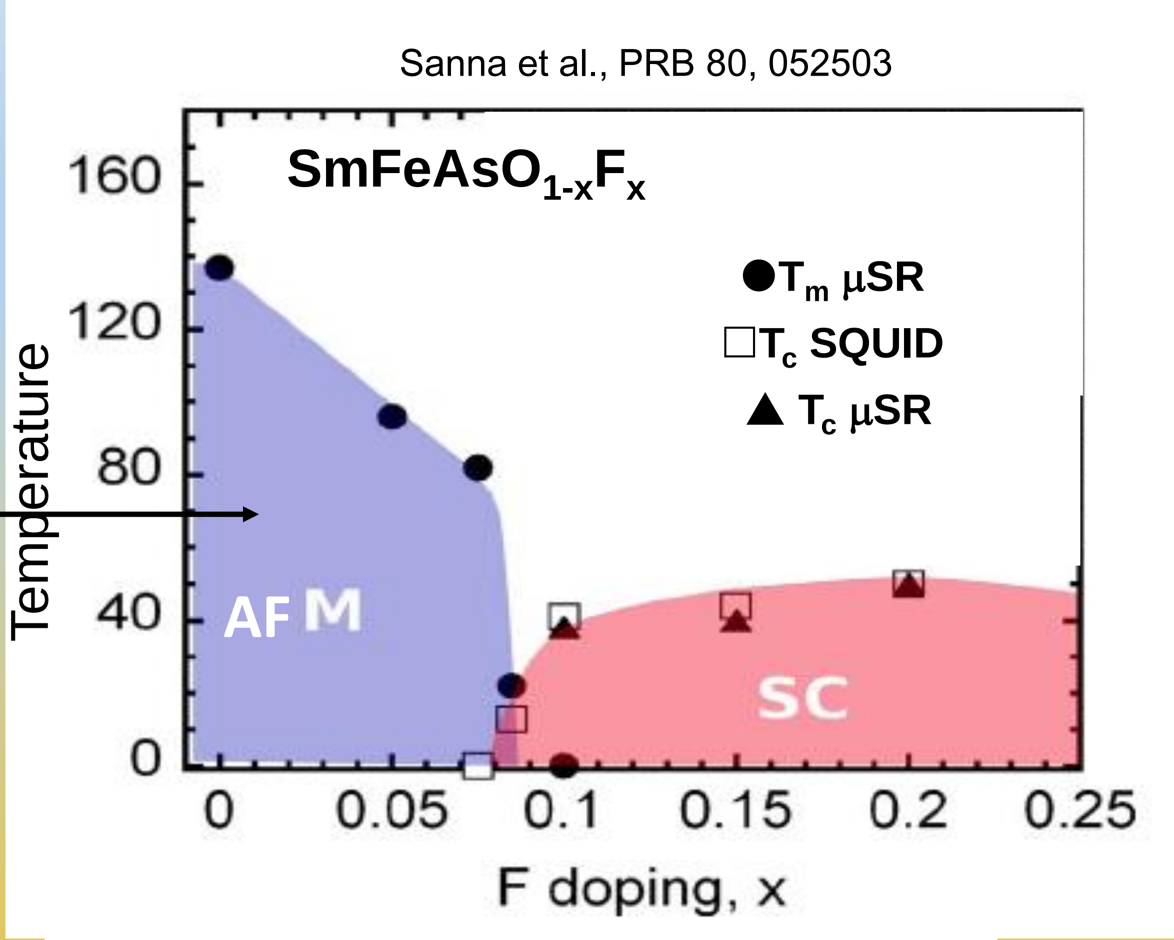
*RE*FeAsO	*AE*Fe_2As_2	Fe(Se,Te)
1111	**122**	**11**
$T_{c,max}$ = 58 K	$T_{c,max}$ = 40 K	$T_{c,max}$ = 21 K





Phase diagram as a function of doping





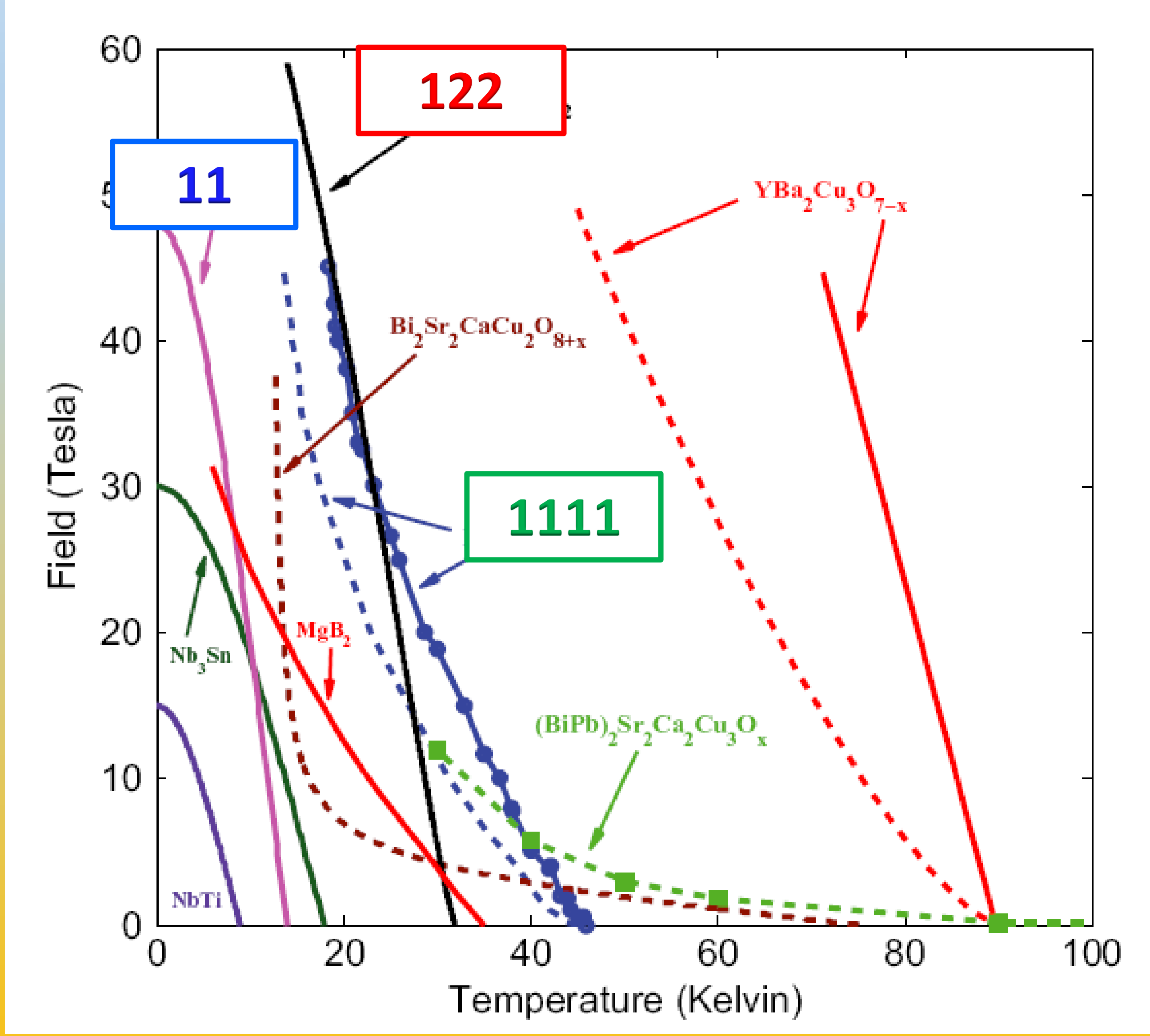
- superconductivity occurs upon doping
- proximity with magnetic ordering
- Anisotropic structure

Analogies with HTS

and with MgB_2

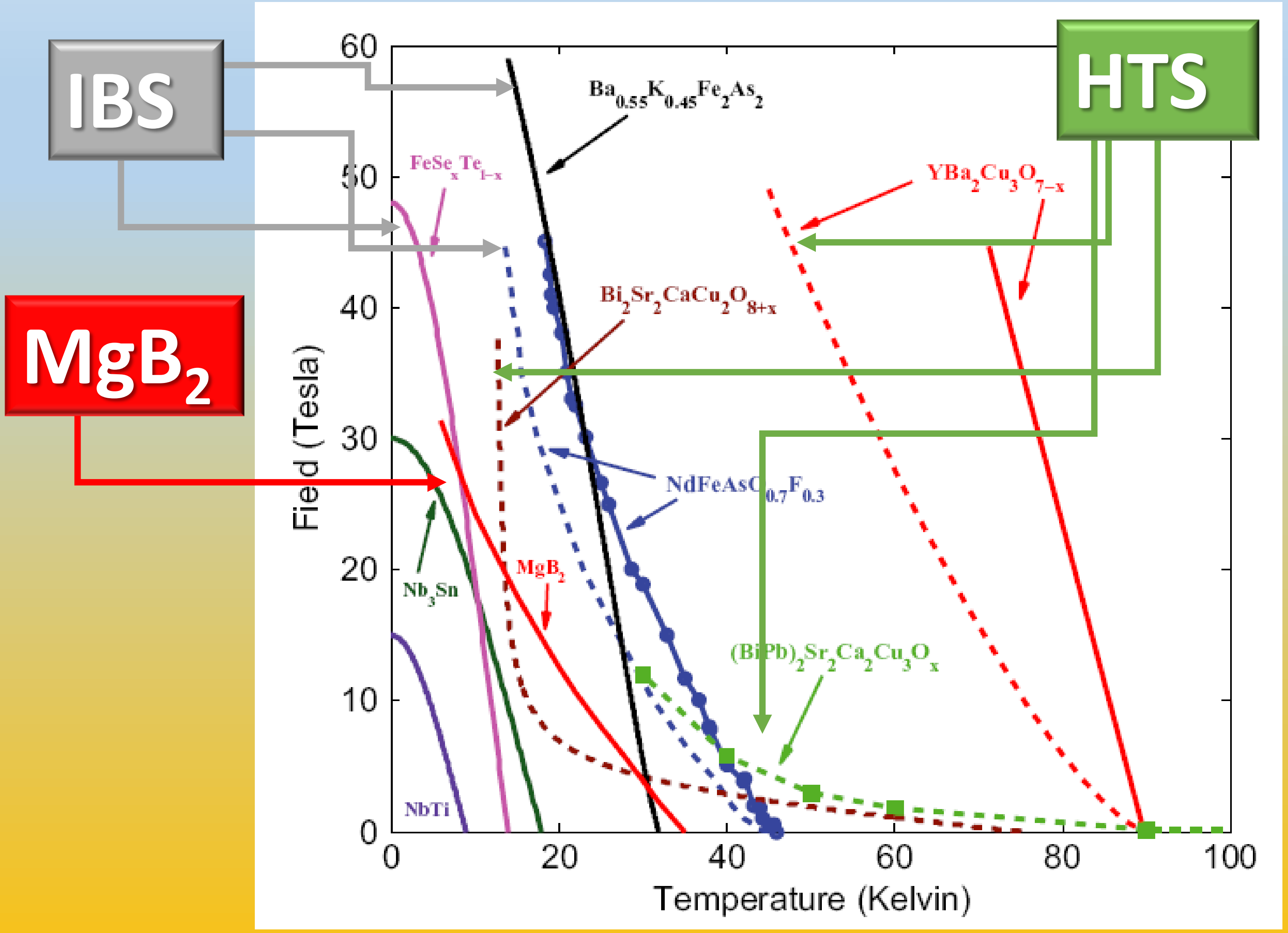
- two-gap superconductivity

Upper critical Fields



C. Tarantini et al., PRB 84, 184522 (2011)

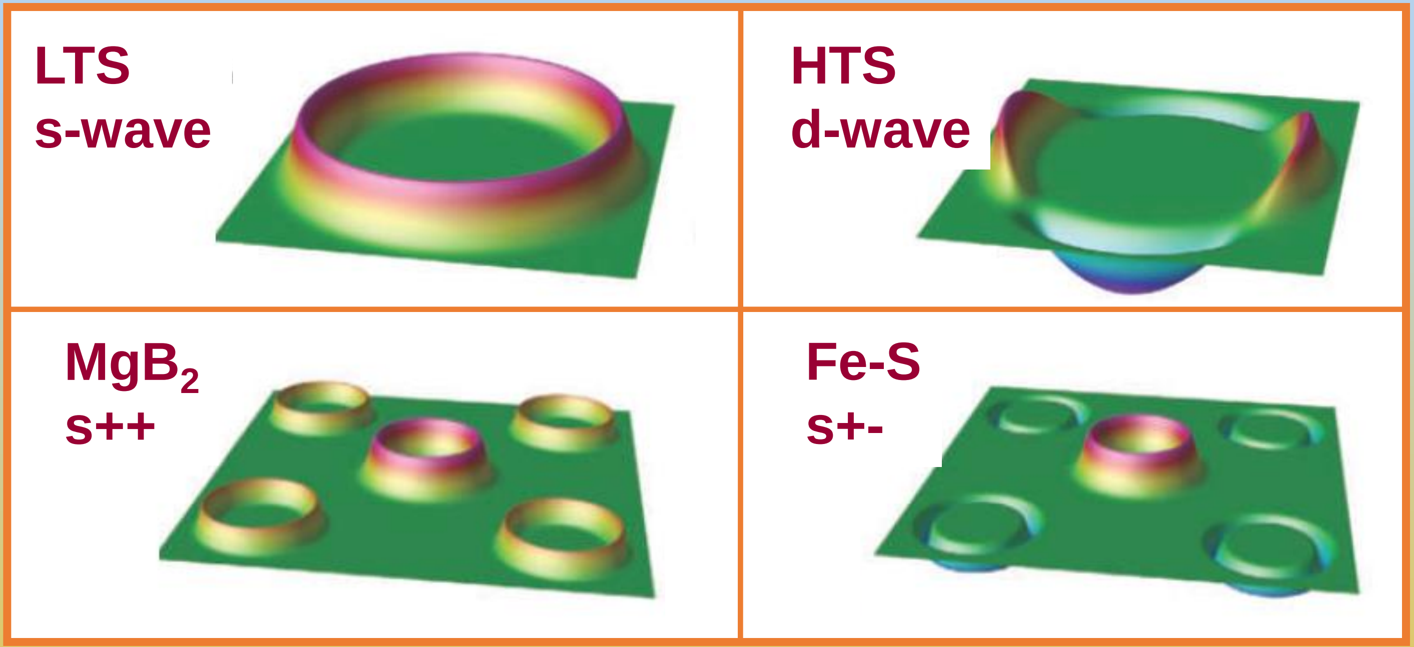
Upper critical Fields



C. Tarantini et al., PRB 84, 184522 (2011)

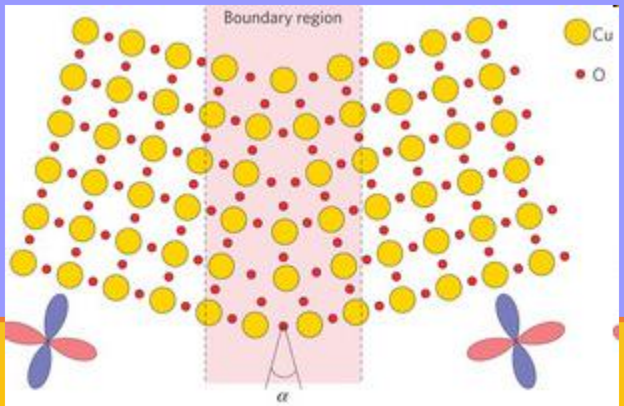
Peculiarities and issues of novel superconducting materials

1: Not conventional order parameter (Cooper pair wave function)



What does it imply
a not conventional oder parameter ?

Wheak coupling between grains



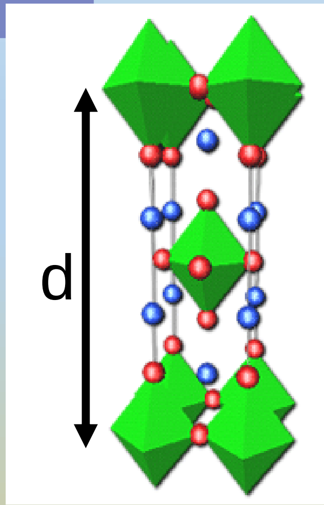
Peculiarities and issues of novel superconducting materials

2: Small coherence length

$$\xi \propto \frac{n_s^{1/2}}{T_c}$$

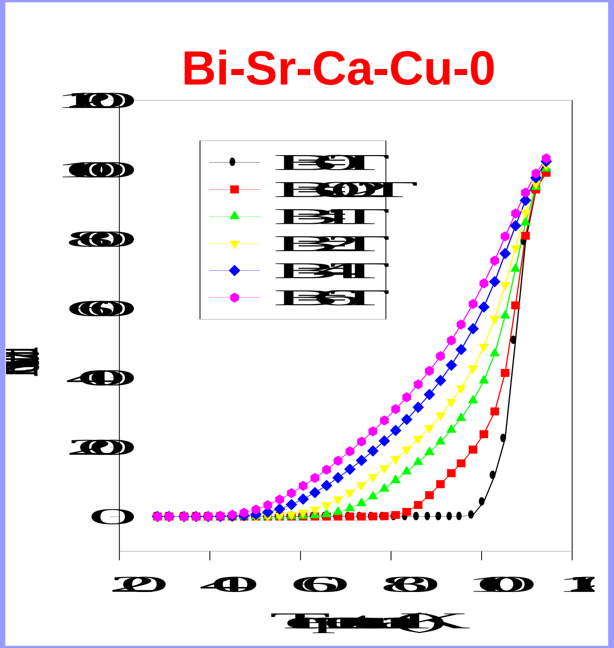
3: Large structural anisotropy

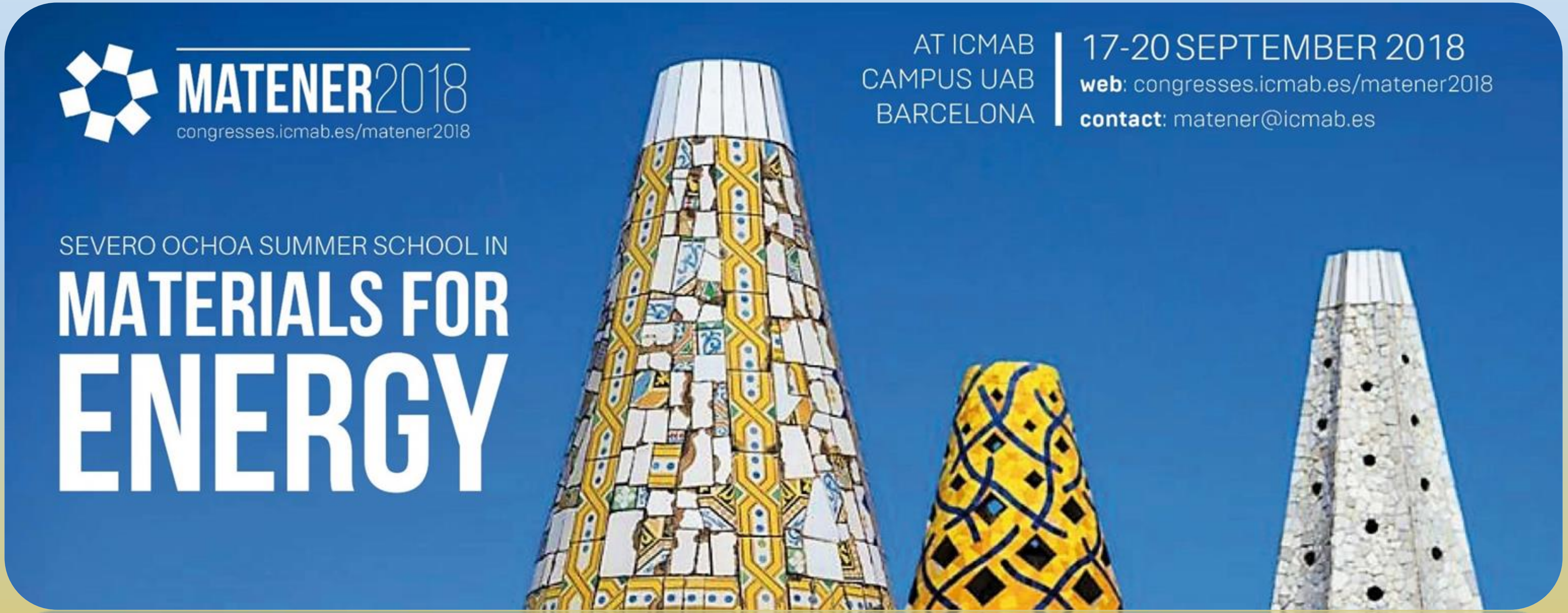
$$\xi_c < \frac{\xi_{ab}}{\gamma} < d$$



Small ξ
and large anisotropy:
What does it imply ?

Giant dissipation in presence of an applied magnetic field





THANK YOU FOR YOUR ATTENTION