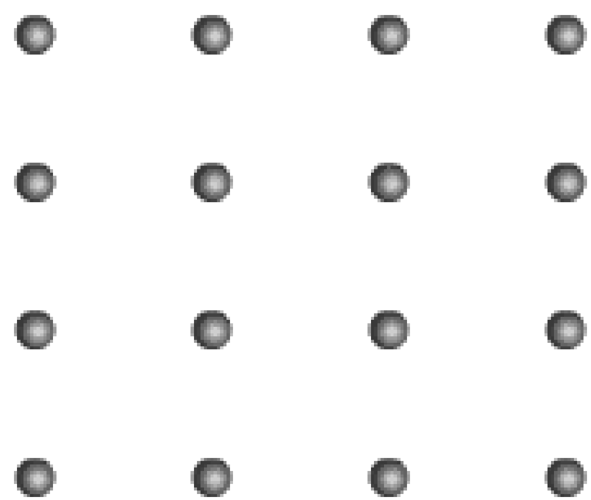
Superconductivity & the search for a stronger "glue"

Jeff Sonier

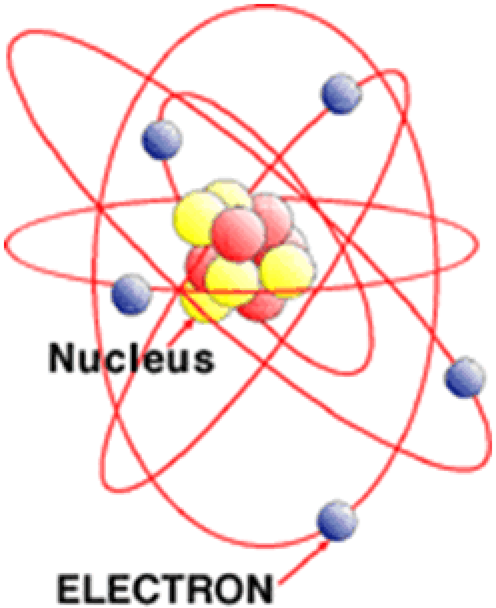
SFU SIMON FRASER UNIVERSITY
ENGAGING THE WORLD

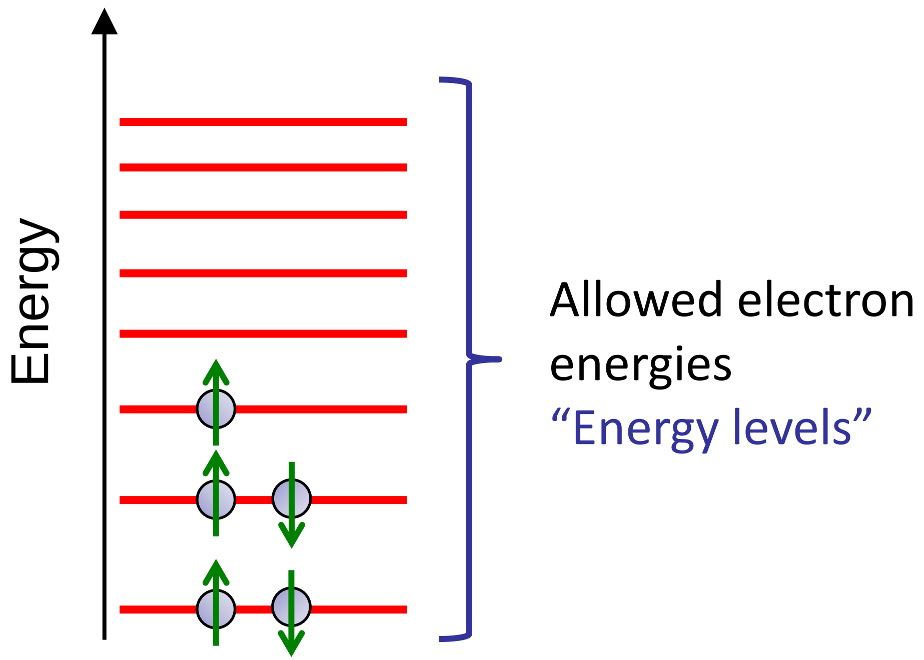


Modern Electronics

Exploit the electronic structure of materials.

Electrons – Electronic Structure

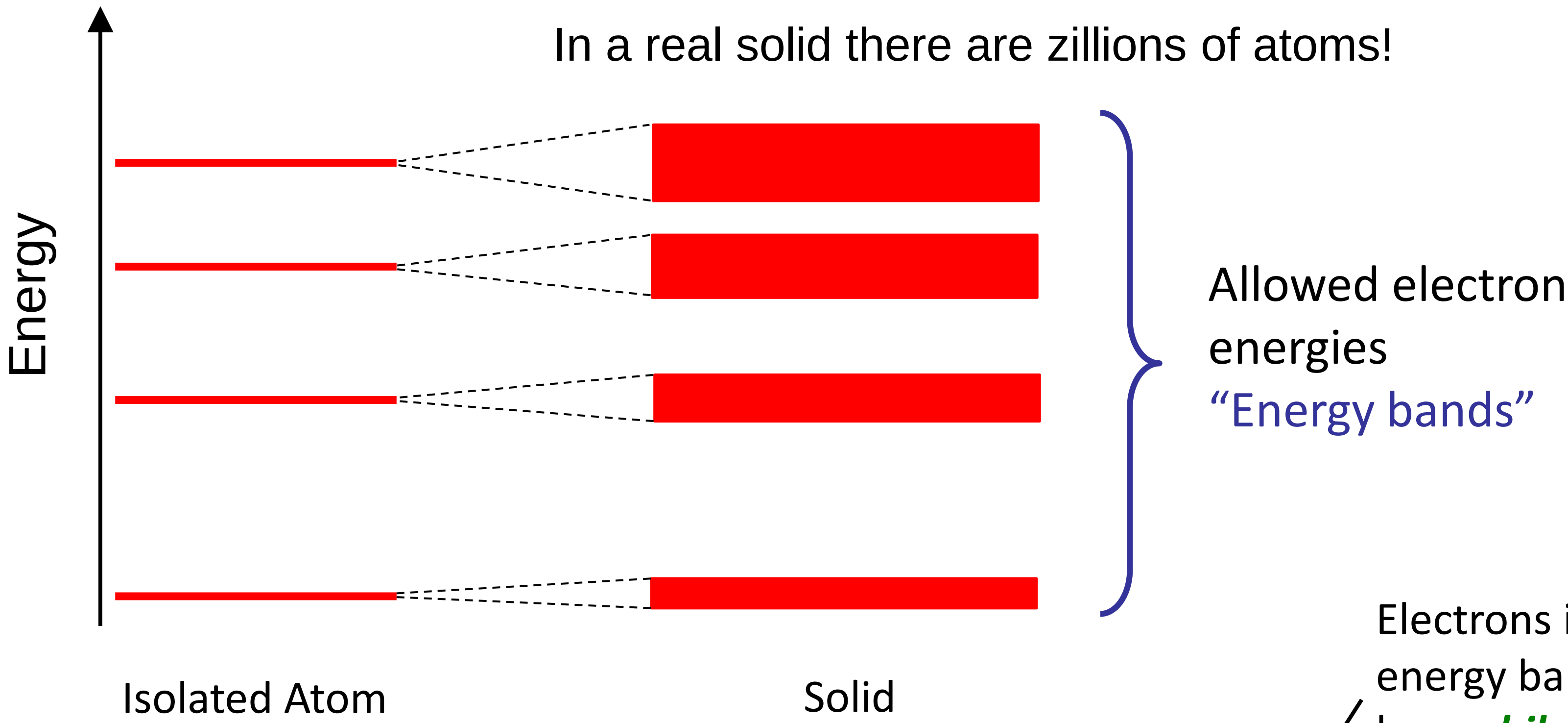




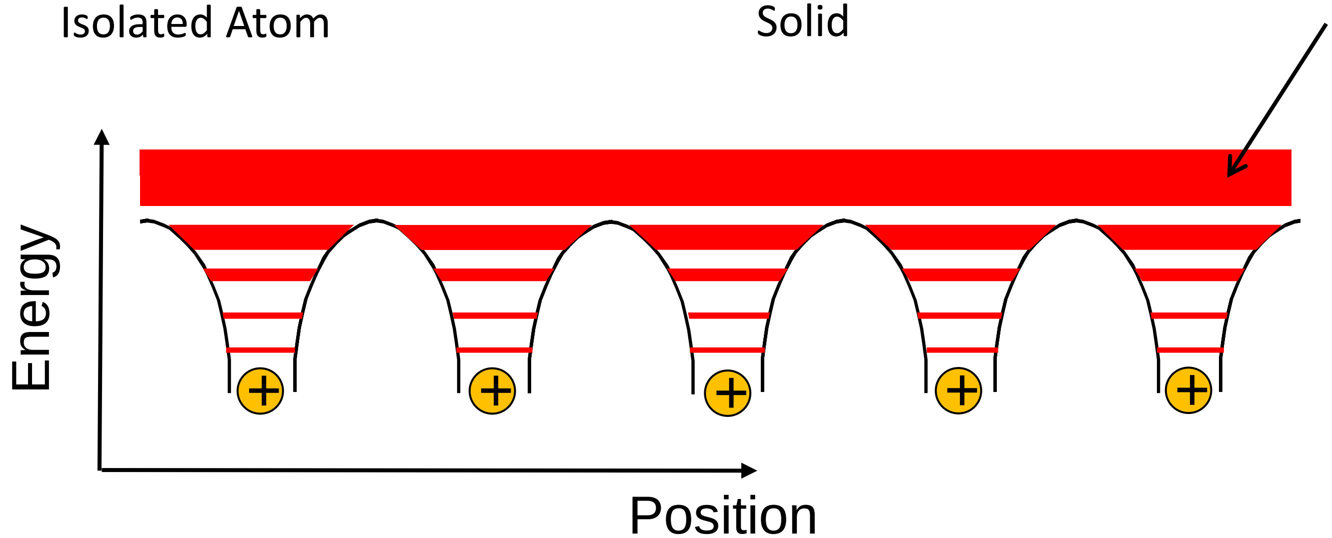
Electrons not only have ***negative charge***, they have ***spin*** (*Up* or *Down*)

Electrons in a Solid

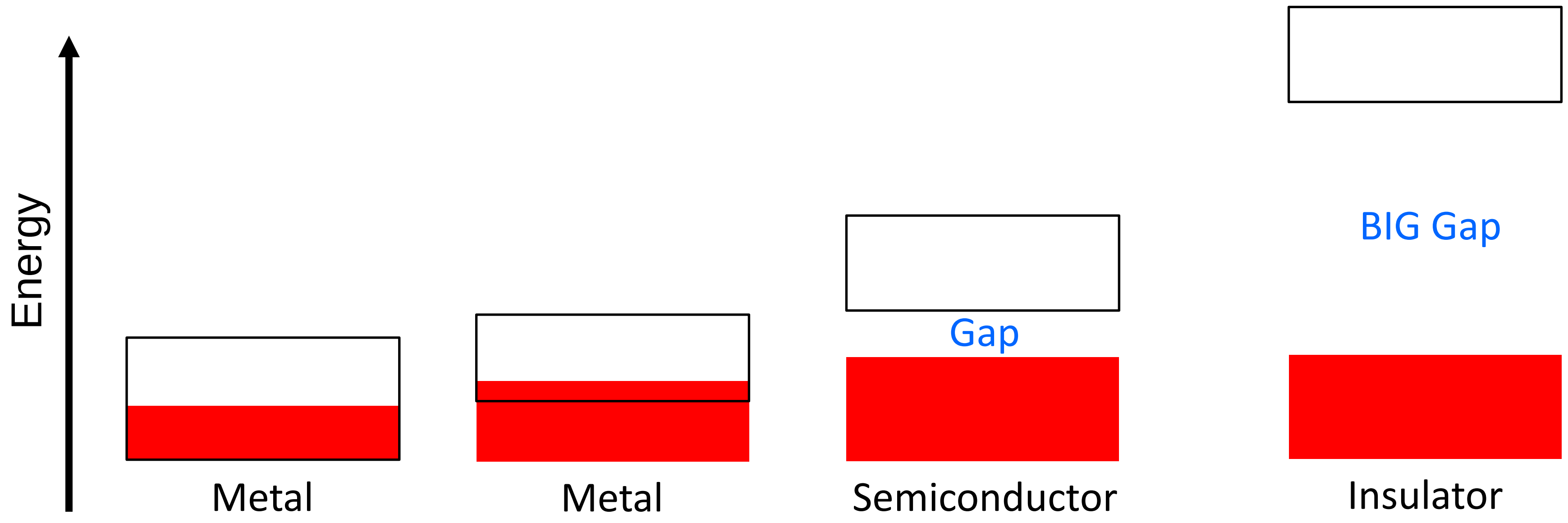
In a real solid there are zillions of atoms!



Electrons in this energy band can be ***mobile***!



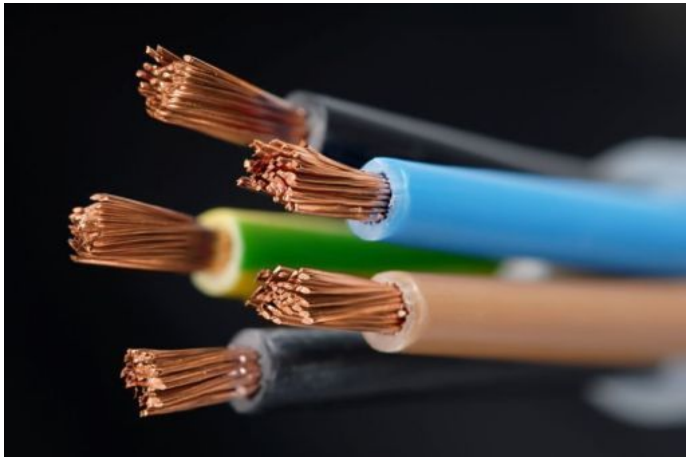
The band structure of a solid determines how well it conducts electricity.

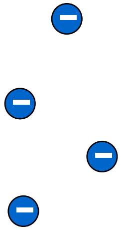


Mobile Electrons in a Metal – Charge Carriers

Resistance to the flow of electrical current is caused by electrons ***scattering*** from:

- lattice vibrations (phonons)
- defects and impurities
- electrons





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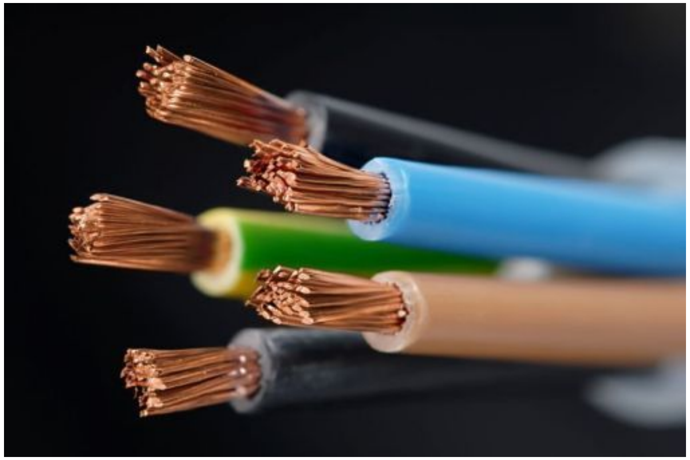
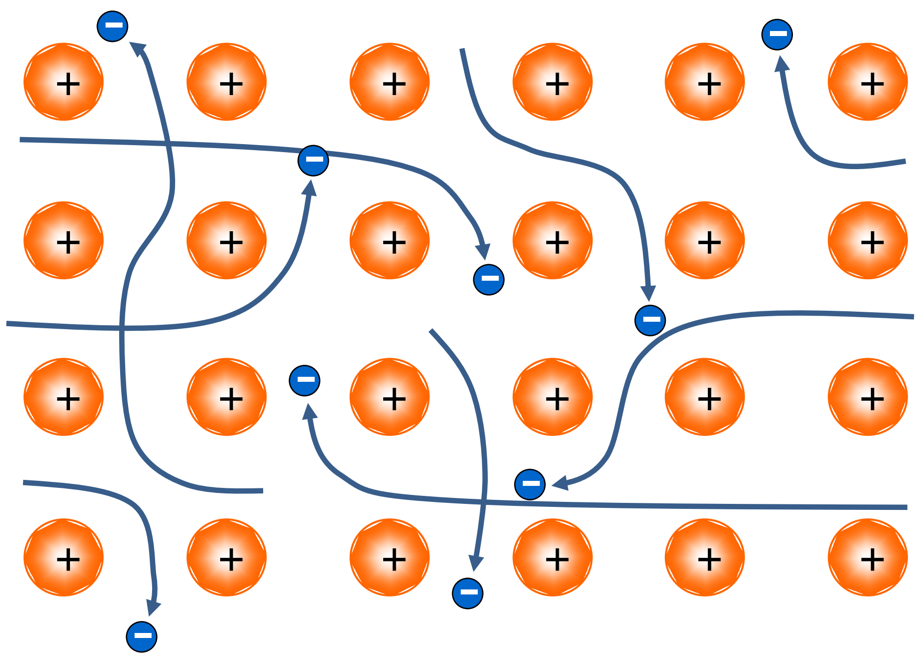


Resistance causes ***losses*** in the transmission of electric power and ***heating*** that limits the amount of electric power that can be transmitted.

Mobile Electrons in a Metal

In a 1 cm^3 metal there are ~ 10^{23} mobile electrons.



These electrons interact mutually via Coulomb ***repulsion***.

Puzzle:
Thermodynamic and transport properties (e.g. electrical conductivity) of metals are well described in terms of ***non-interacting*** electrons!

Fermi Liquid Theory (1950s)

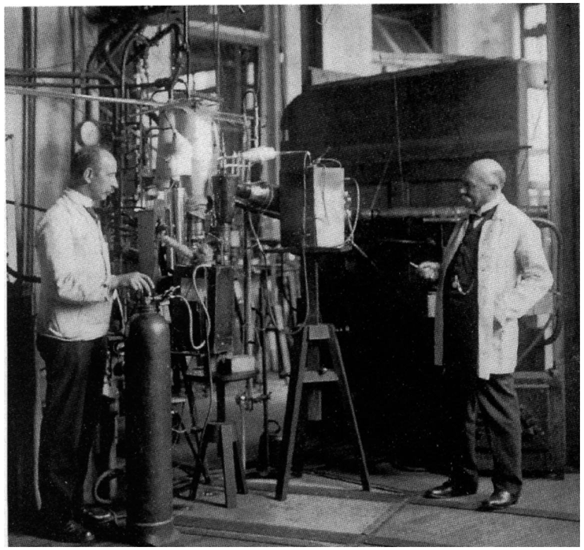
One of the major challenges of theoretical solid state physics is to understand the effects of interactions in solids. A cornerstone of the understanding of such interactions is ***Landau's theory of Fermi liquids***, which states that despite the interactions an electron gas in a metal has a behavior close to the one of a non-interacting system.

Modern Solid State Physics - *Beyond Fermi Liquid Theory*

In many materials, interactions are strong and can lead to drastic effects such as ***superconductivity***!

What is superconductivity?

The first superconductor was **discovered in 1911** by H. Kamerlingh Onnes at the University of Leiden, 3 years after he first liquefied helium.



Heike Kamerlingh Onnes
(1853-1926)

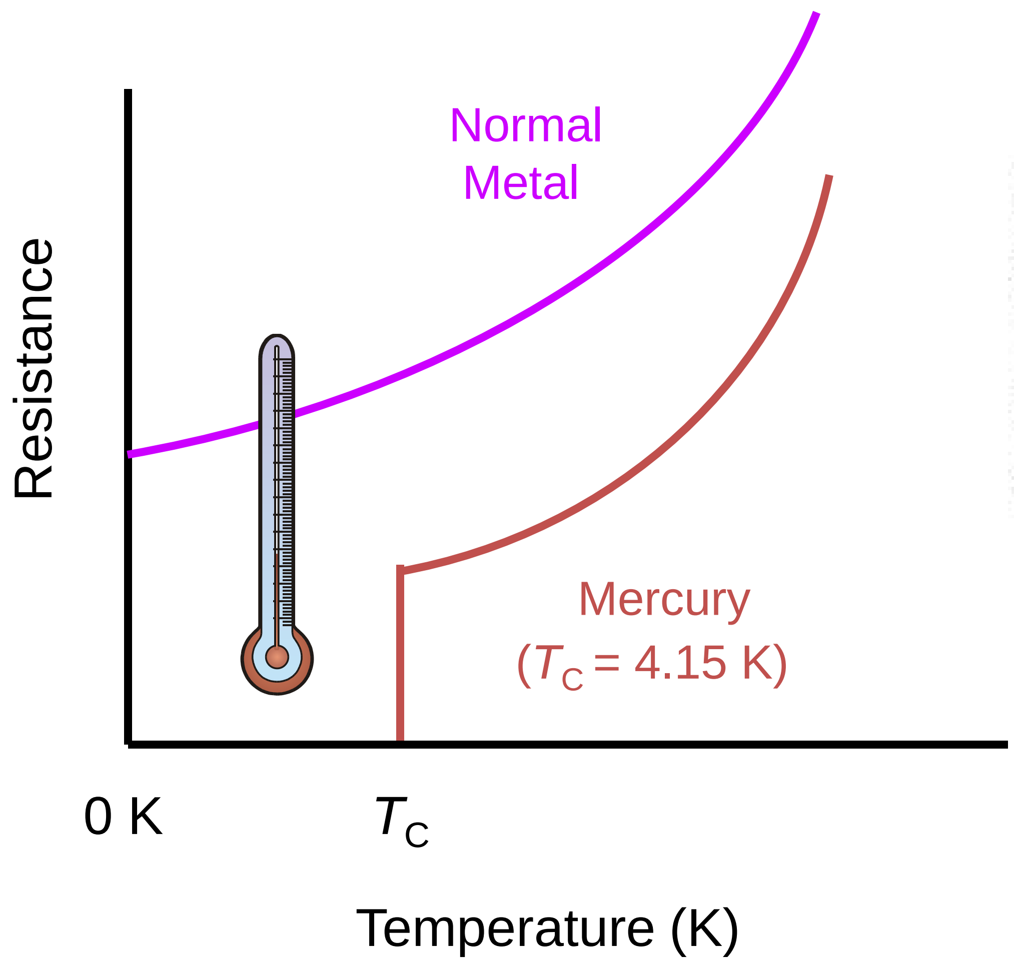
The Nobel Prize in Physics 1913

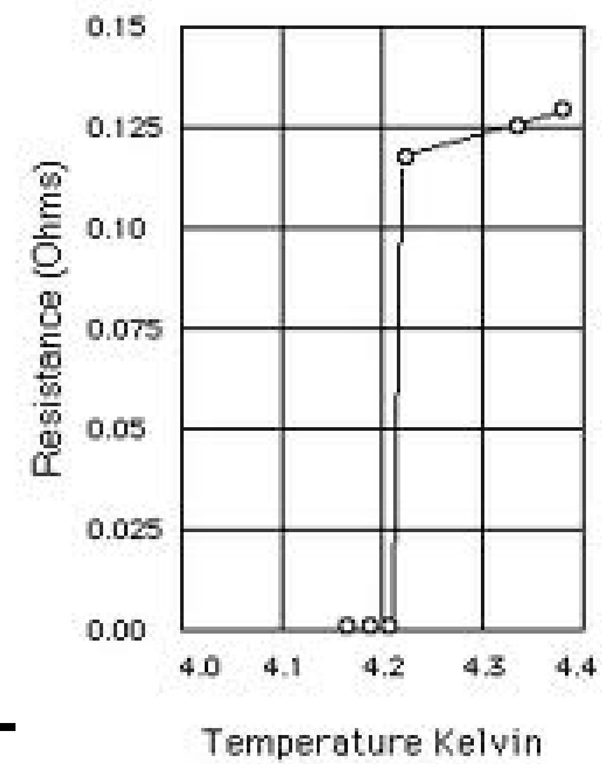
Properties of a Superconductor

A superconductor is a material that exhibits both **perfect conductivity** and **perfect diamagnetism**.

Zero Electrical Resistance

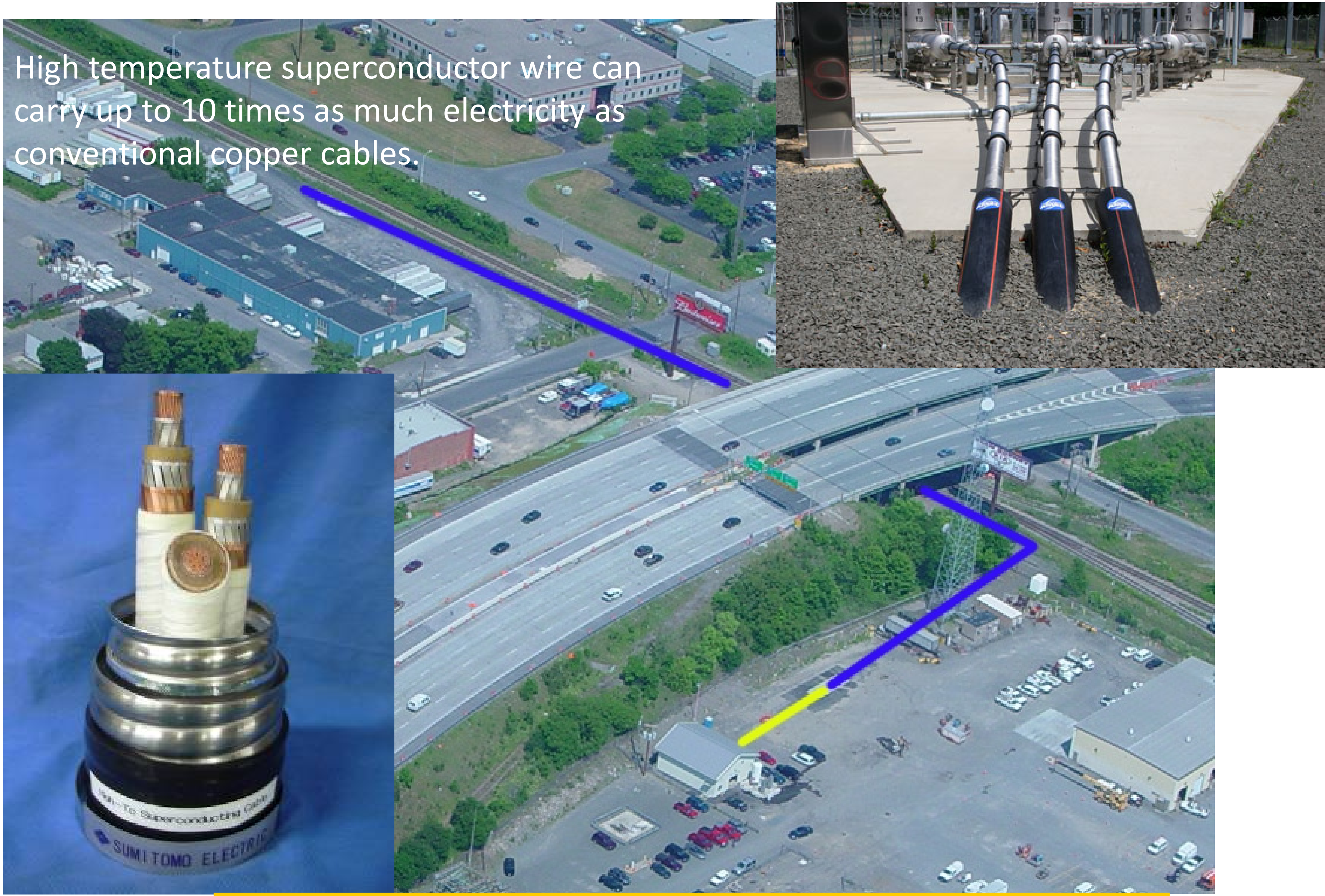
Onnes found that the electrical resistance of various metals (e.g. Hg, Pb, Sn) vanished below a **critical temperature** T_c.





Superconducting Power Cables

High temperature superconductor wire can carry up to 10 times as much electricity as conventional copper cables.

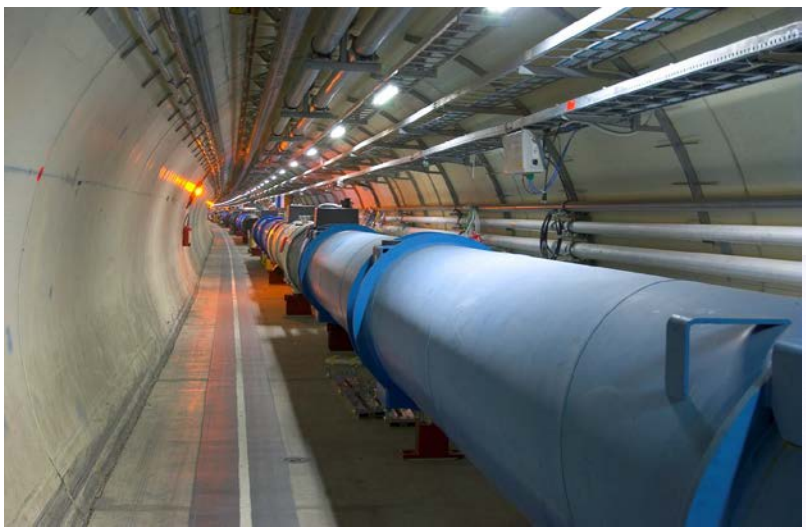


Bi-2223 cable -Albany New York - commissioned fall 2006
February 2008 updated with YBCO section

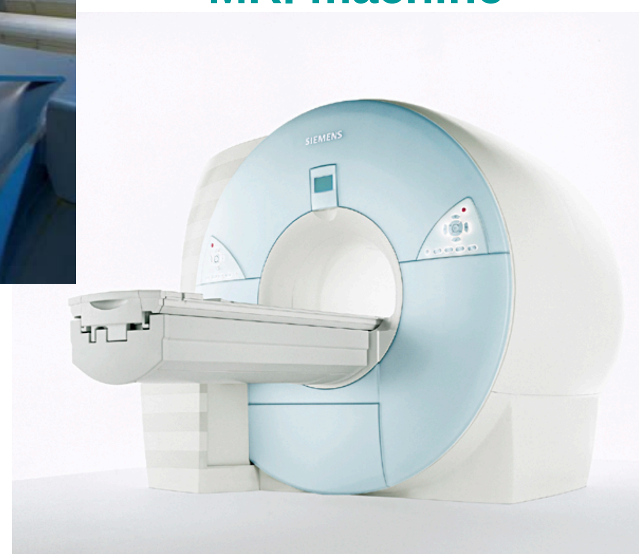
Superconducting Magnets

The absence of zero electrical resistance means that **persistent currents** flow in a superconducting ring. A major application of this property is **superconducting magnets**. With no energy dissipated as heat in the coil windings, these magnets are cheaper to operate and can sustain larger electric currents (and hence produce **greater magnet fields)** than electromagnets.

27 km Large Hadron Collider (LHC)



MRI machine



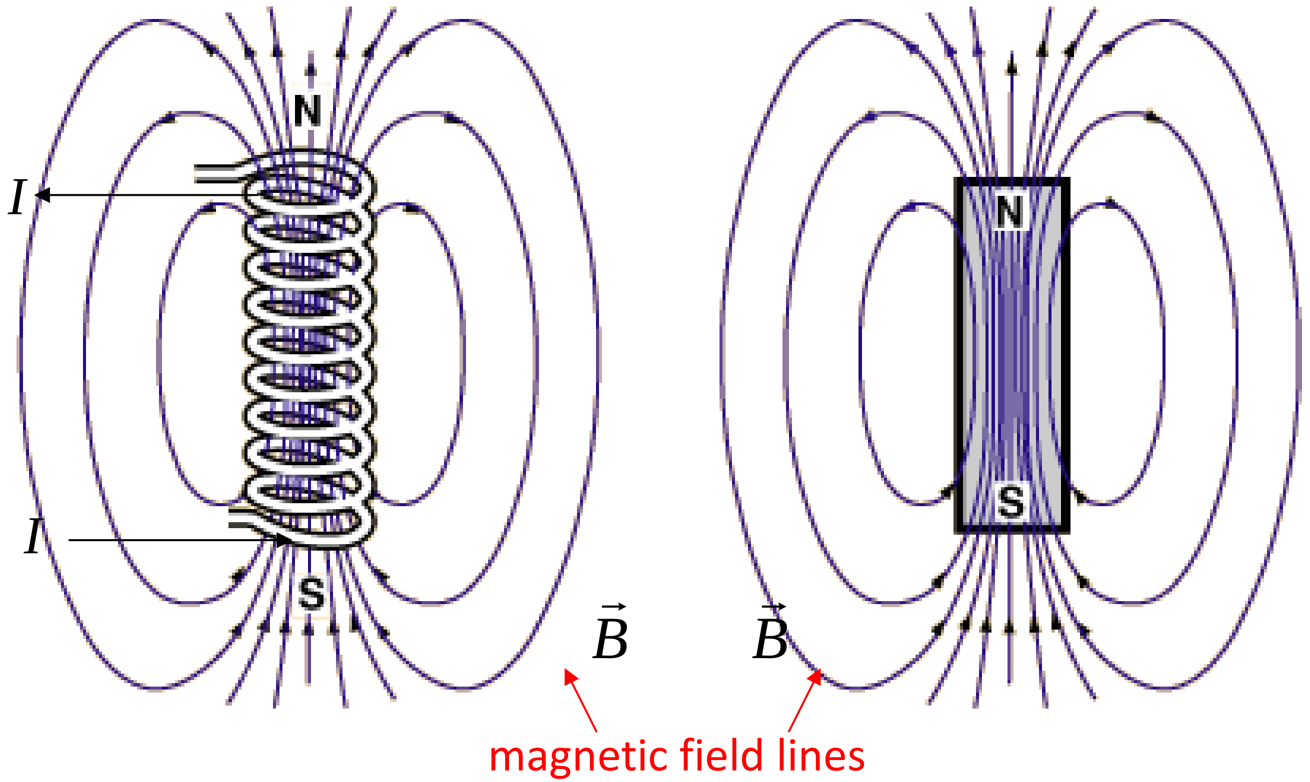
HELIOS

Magnetic Field

Magnetic field is produced by electric current (*i.e.* **moving** electric charge)

Electromagnet
Macroscopic currents in wires
e.g. solenoid

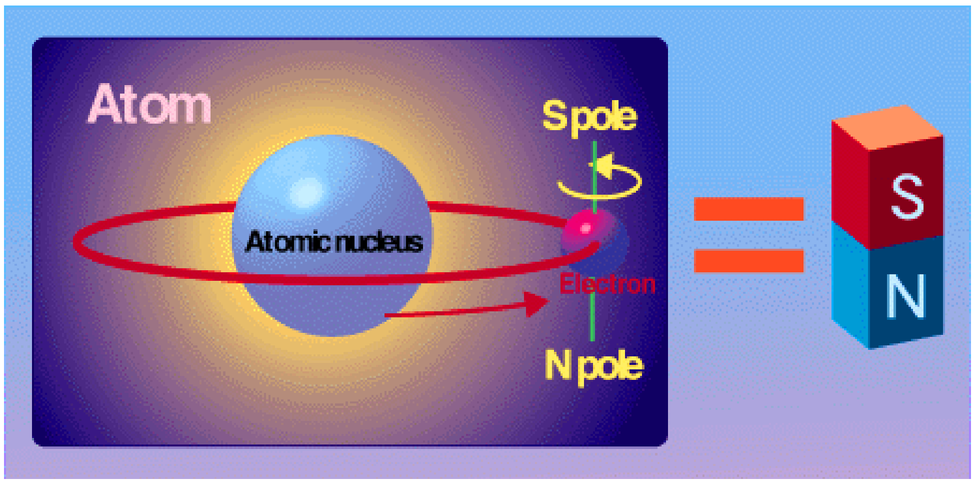
Permanent Magnet
Microscopic currents in materials
e.g. bar magnet



Bar Magnet

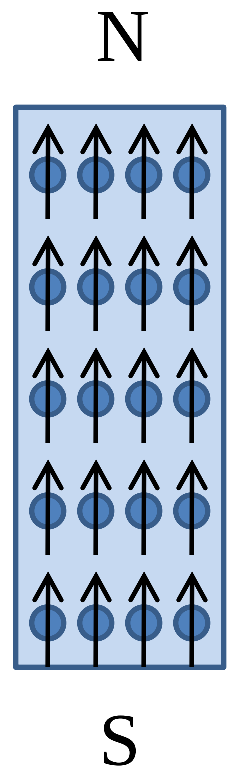
Electrons in atomic orbits are **moving charge** and hence give rise to **magnetic field**. In addition the electrons have an **intrinsic magnetic moment** that also contributes.

Simplified view of an atom



Each atom is like a tiny bar magnet.

Atom:

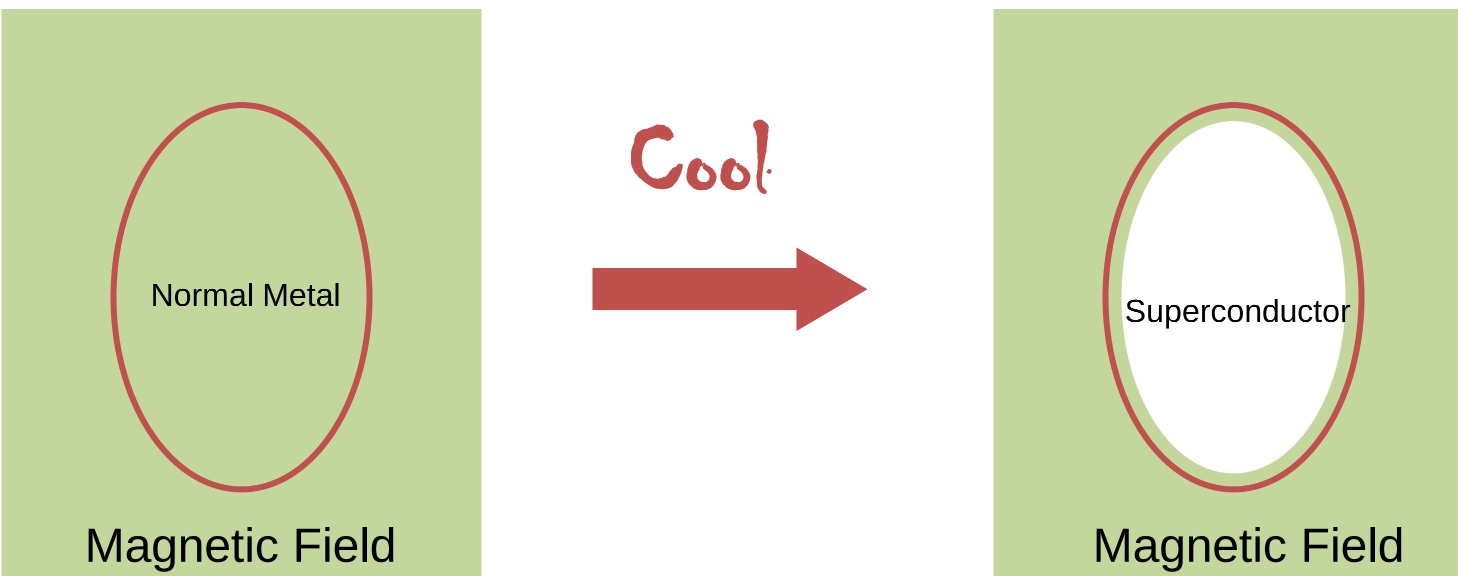


In a **bar magnet**, the microscopic magnets are preferentially aligned

Perfect Diamagnetism

In 1933, Meissner and Ochsenfeld discovered that magnetic field in a superconductor is **expelled** as it is cooled below T_c.

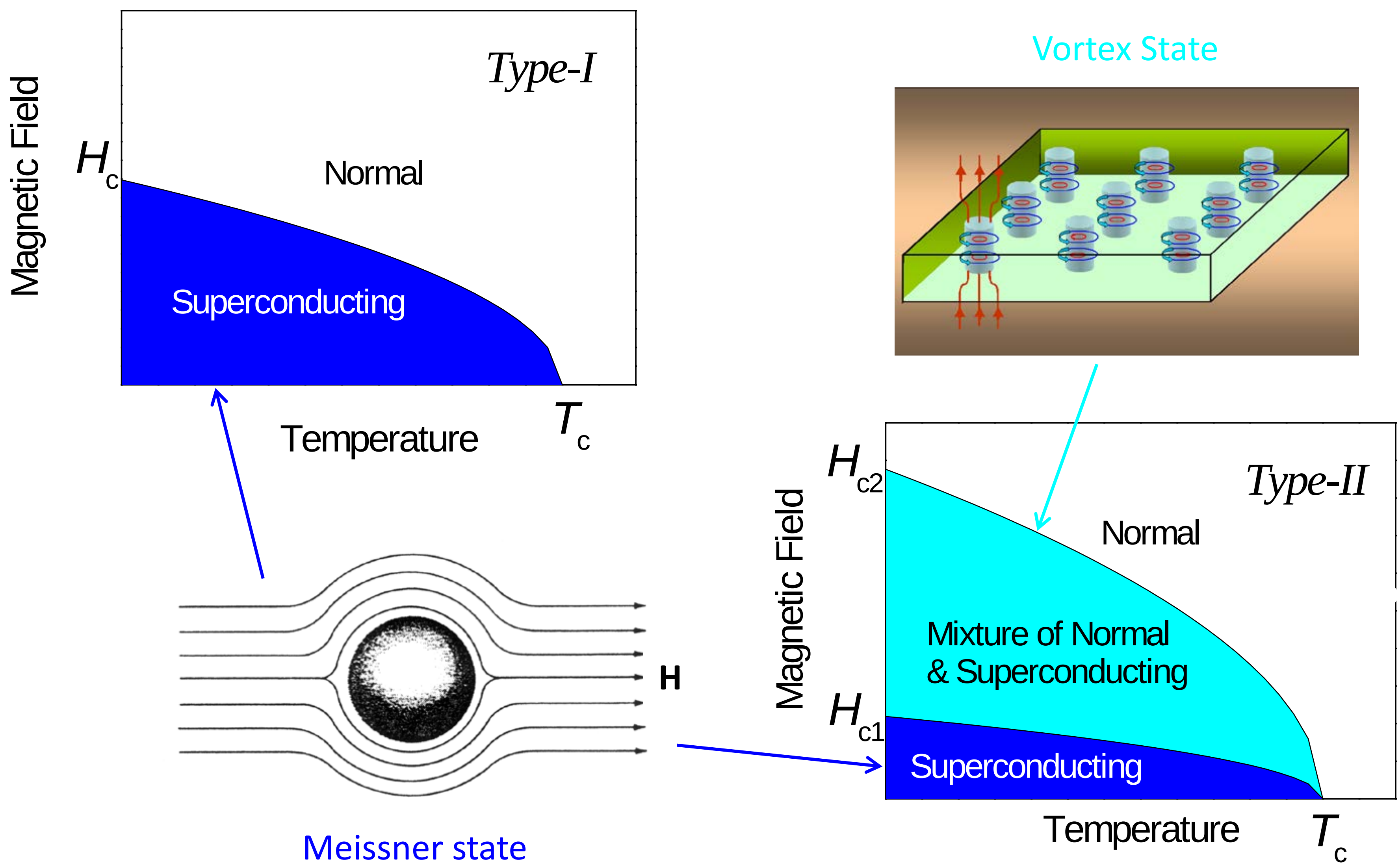
"Meissner Effect"



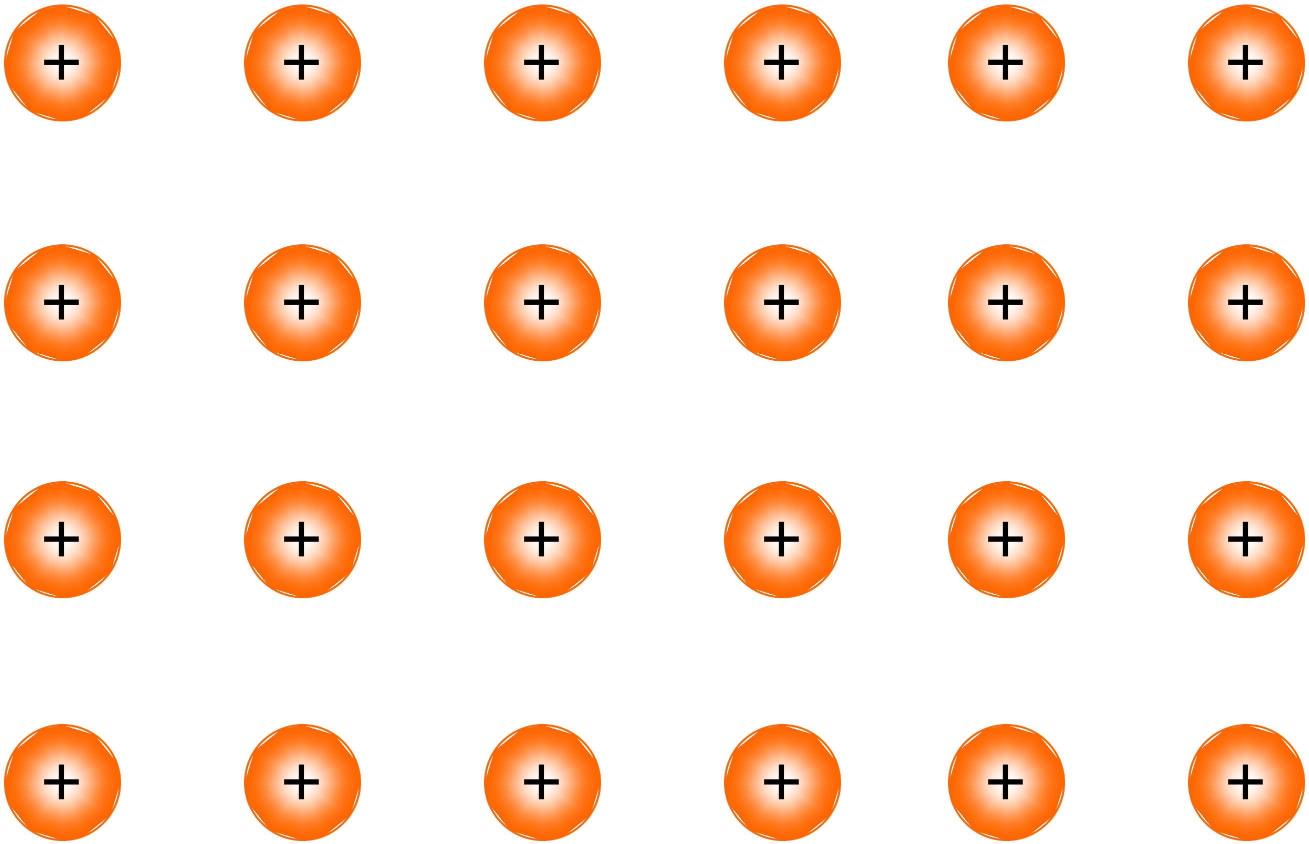
However, there is a limit as to how much field a superconductor can take! Superconductivity is destroyed above a **critical magnetic field** $H_c(T)$, separating the "normal" and superconducting states.

A magnetic field is expelled from a superconductor (Meissner effect)

Magnetic Response of Type-I and Type-II Superconductors



The way to superconductivity…



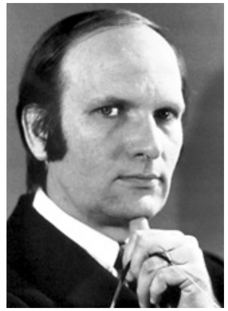
“Cooper pairs”: *pairs of electrons* caused by electron-phonon interaction

BCS Theory of Superconductivity

1972

J. Bardeen

L.N. Cooper



J.R. Schrieffer

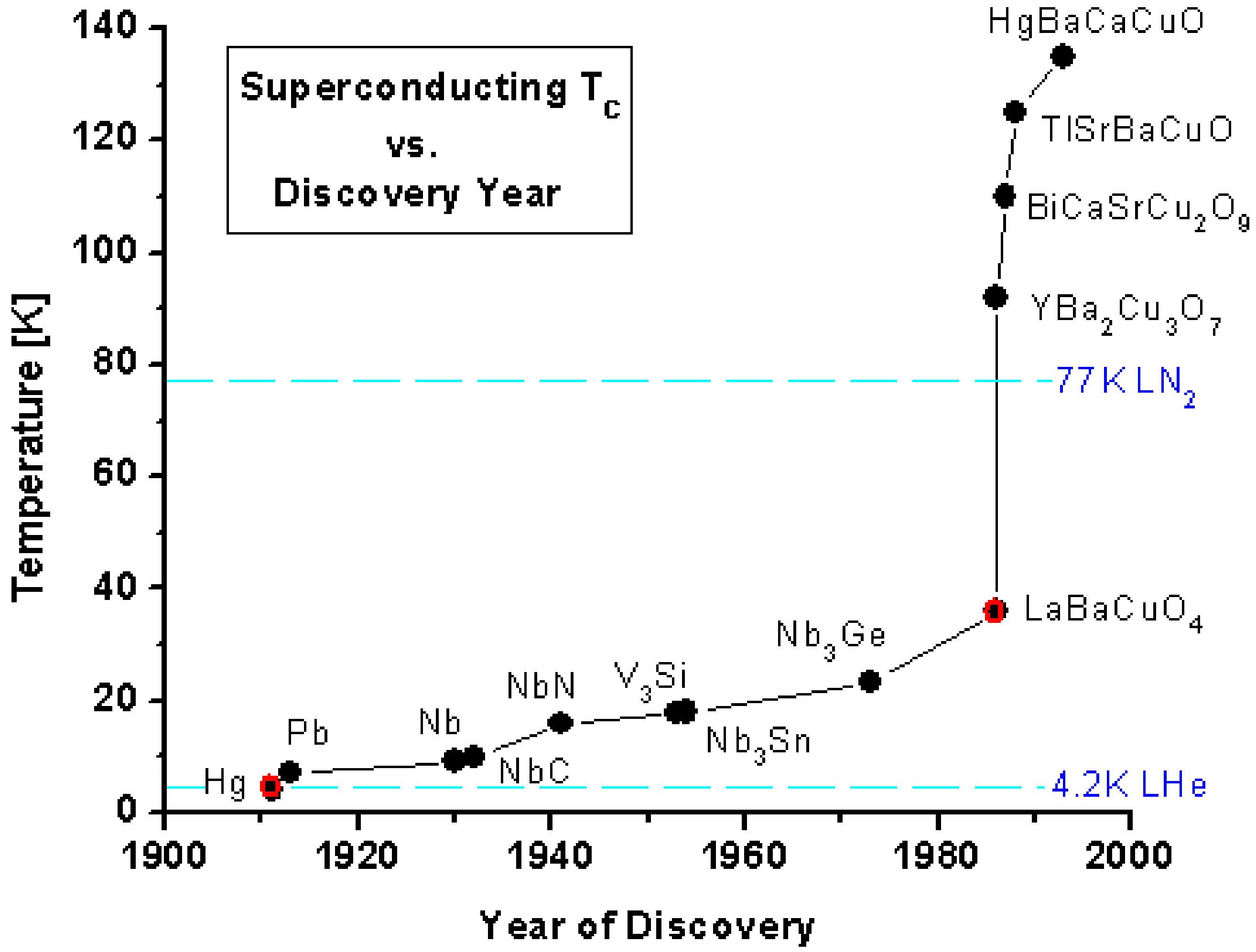
General idea - Electrons pair up ("Cooper pairs") and form a ***coherent quantum state***, making it impossible to deflect the motion of one pair without involving all the others.

Zero resistance and the Meissner effect require that the Cooper pairs share the same phase $\Rightarrow$ "**quantum phase coherence**"

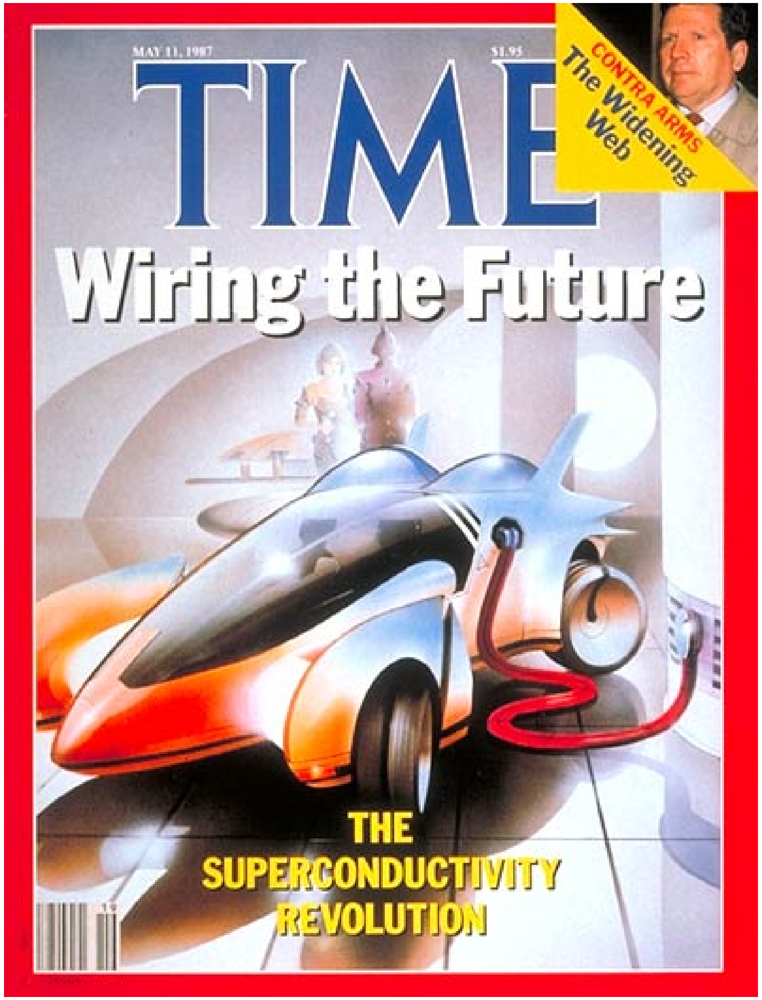
The BCS state is characterized by a complex ***macroscopic wave function***:

$$\Psi(\vec{r}) = \underbrace{|\Psi_0|}_{\text{Amplitude}} e^{i\underbrace{\theta(\vec{r})}_{\text{Phase}}}$$

History of Superconductivity



Discovery of High-T_c Superconductivity

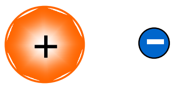


Time Magazine May 11, 1987

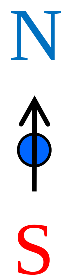
GM advertisement April, 2009

Mobile vs. Bound Electrons

Bound electrons can give rise to localized magnetic moments:

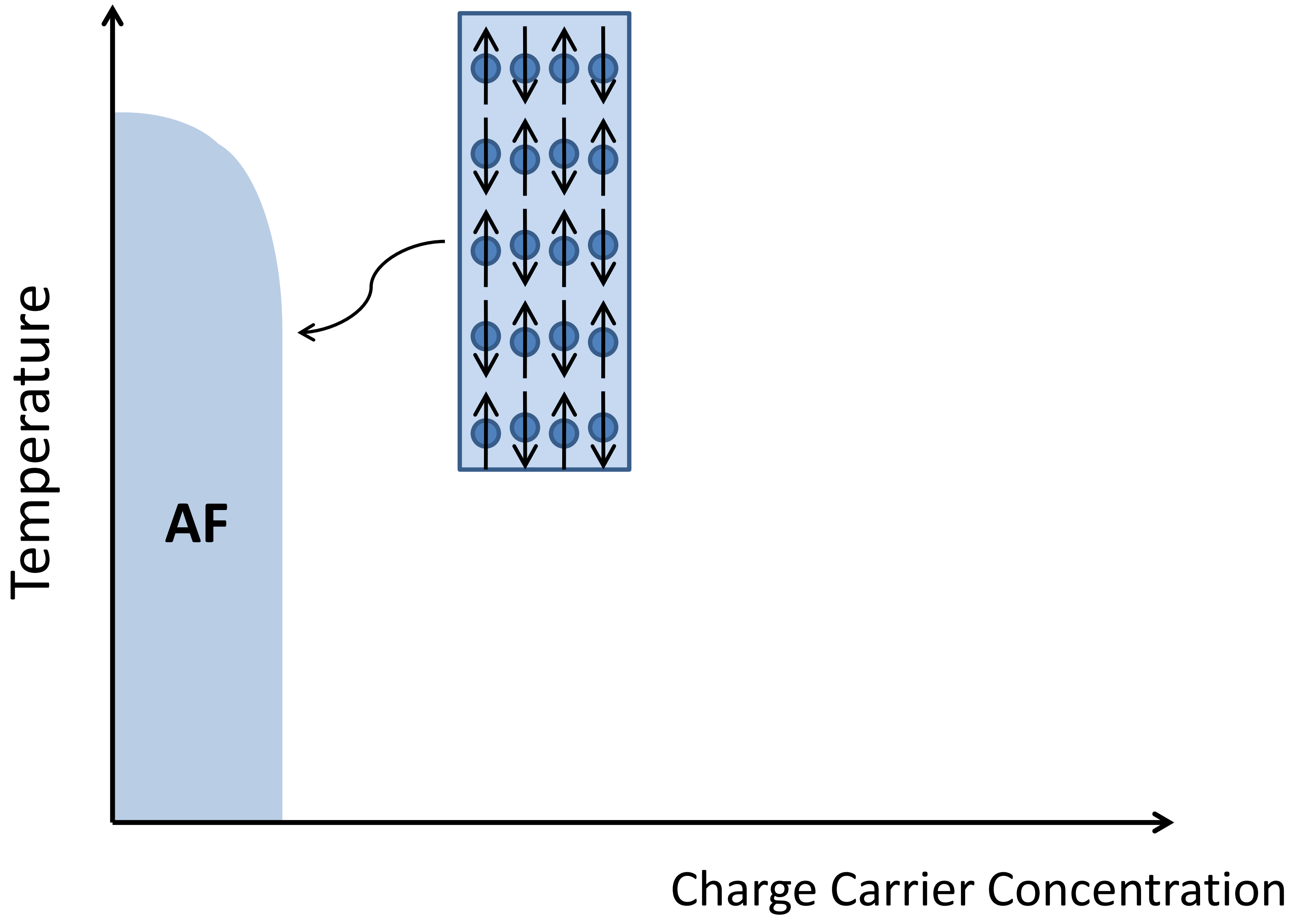


Acts like a tiny bar magnet.

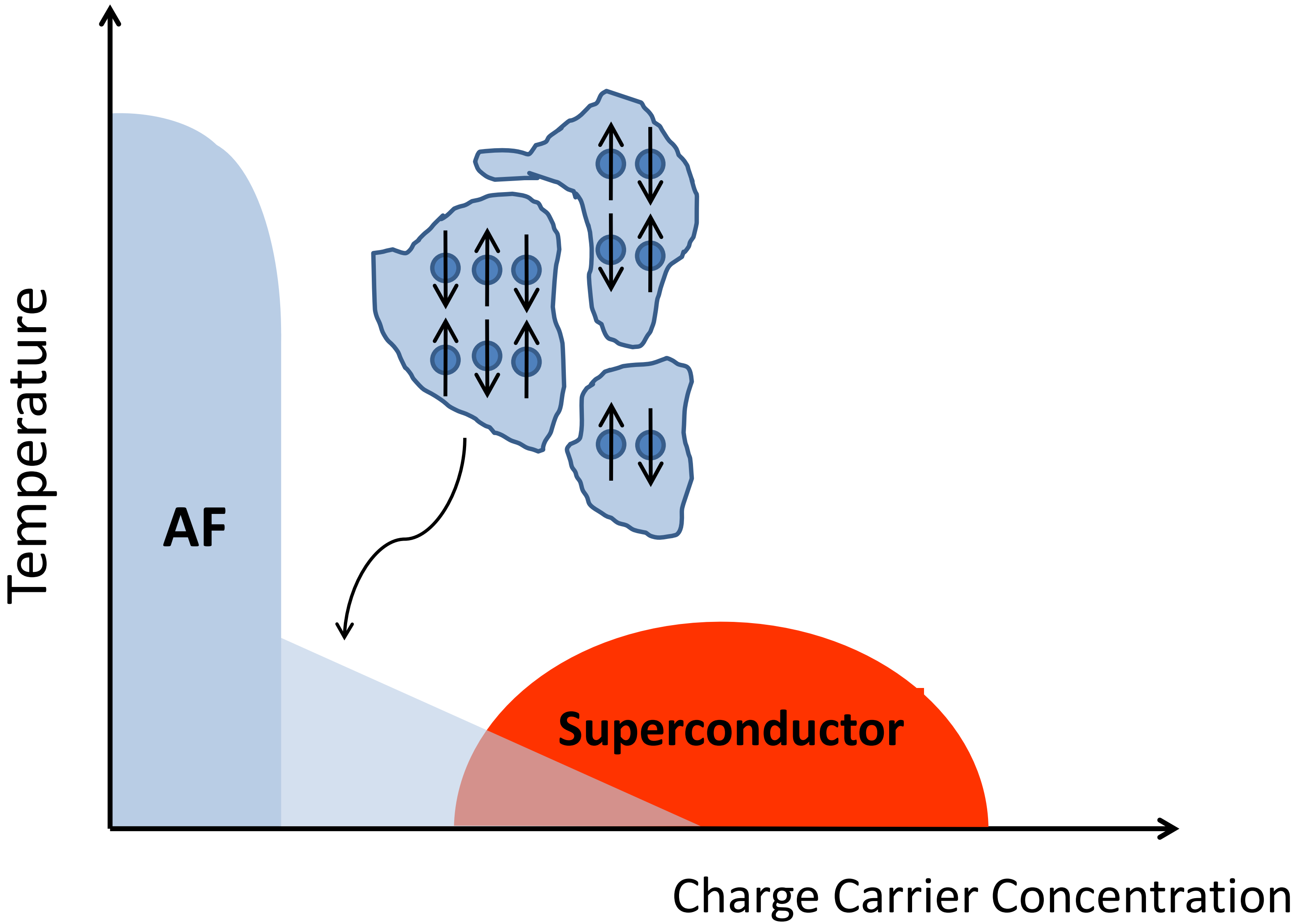


Mobile electrons carry electrical current:

Generic Phase Diagram

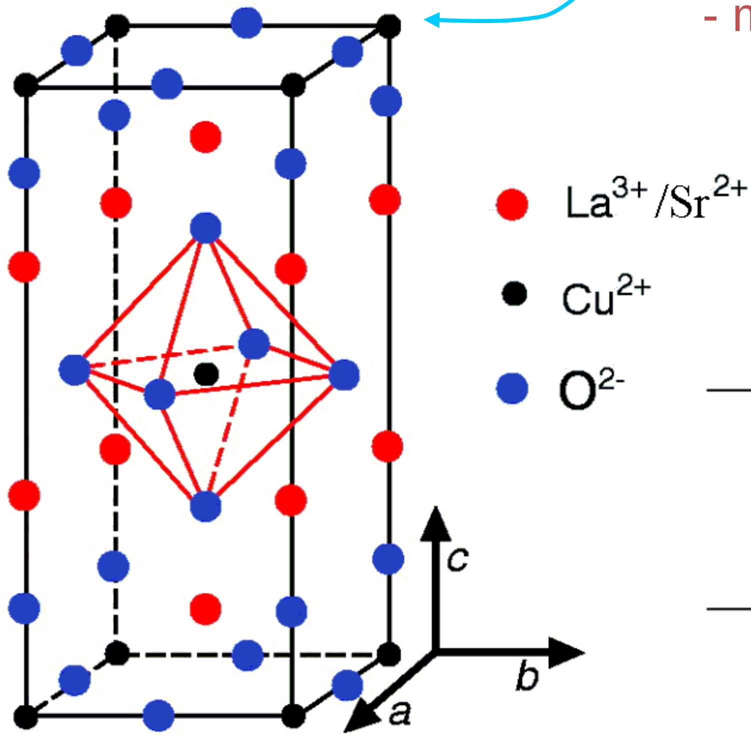


Generic Phase Diagram

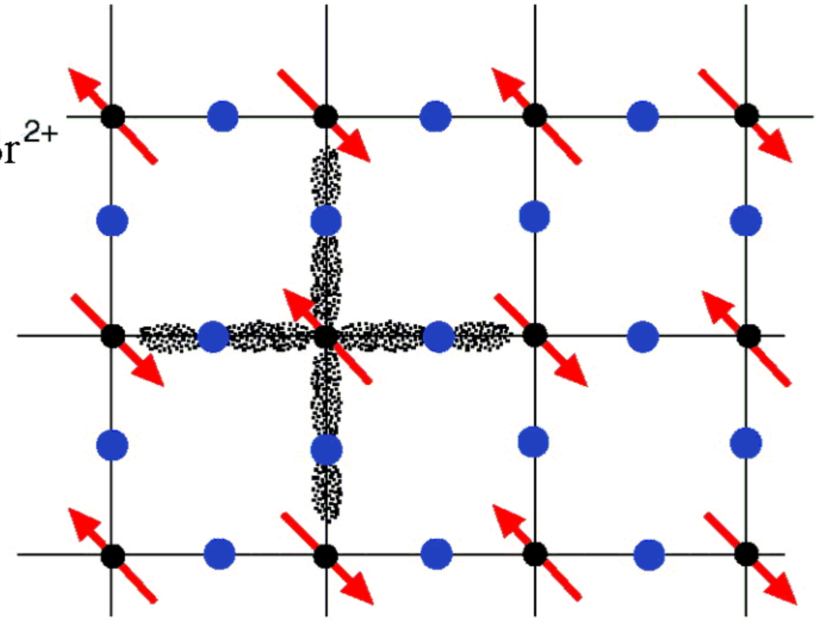


High-T_c Cuprates

$La_{2-x}Sr_xCuO_4$



CuO_2 planes are generic ingredient
- superconductivity is quasi-2D
- magnetism associated with Cu spins



Antiferromagnet → **Superconductor**

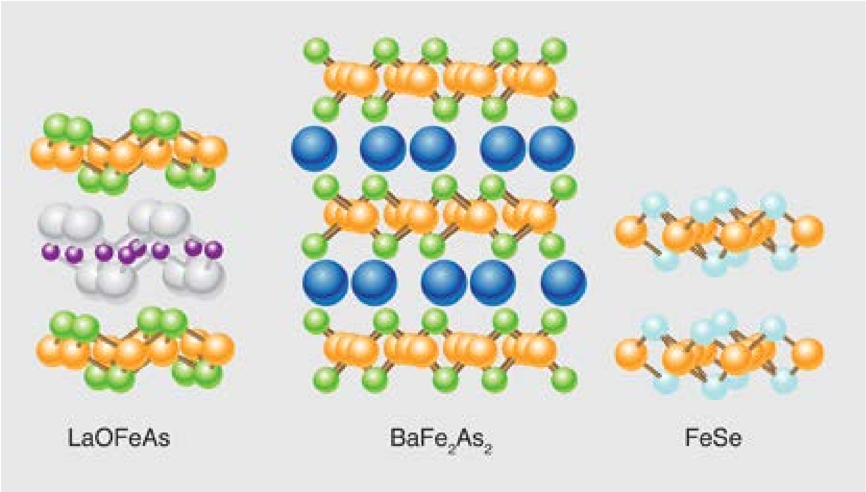
Hole doping by cation substitution or oxygen doping

2008: Beginning of the Iron Age

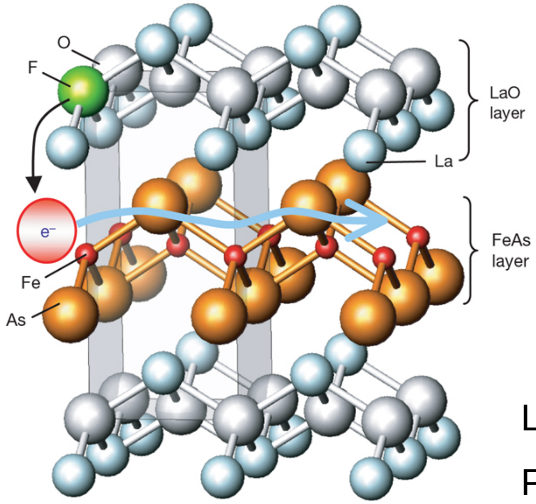
Science **Top 10 Breakthroughs of the Year**

Discovery of iron–based high-T_c superconductors

Y. Kamihara *et al.*, J. Am. Chem. Soc. **130**, 3296 (2008)



Many chemical substitutions are possible.

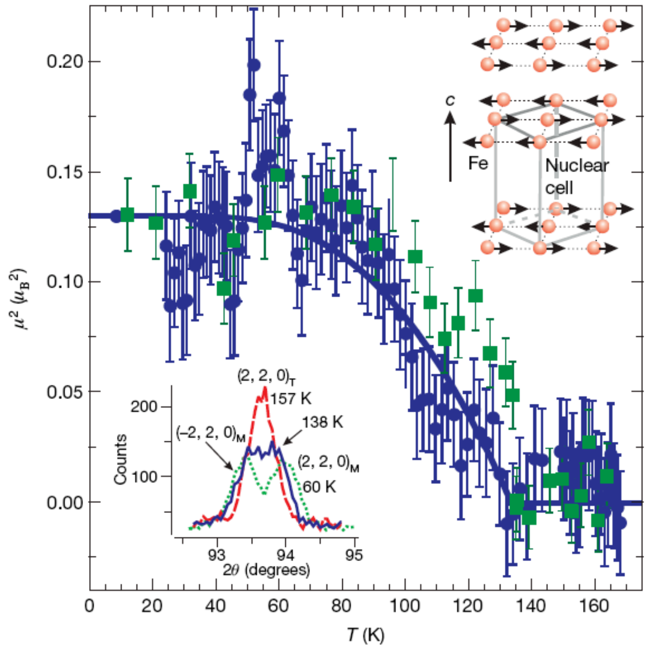


$LaO_{1-x}F_xFeAs$ T_c = 26 K

$PrO_{1-x}F_xFeAs$ T_c = 55 K

They have **layered** structures & exhibit **antiferromagnetic order** like high-T_c cuprates.

Long-range SDW order in LaOFeAs



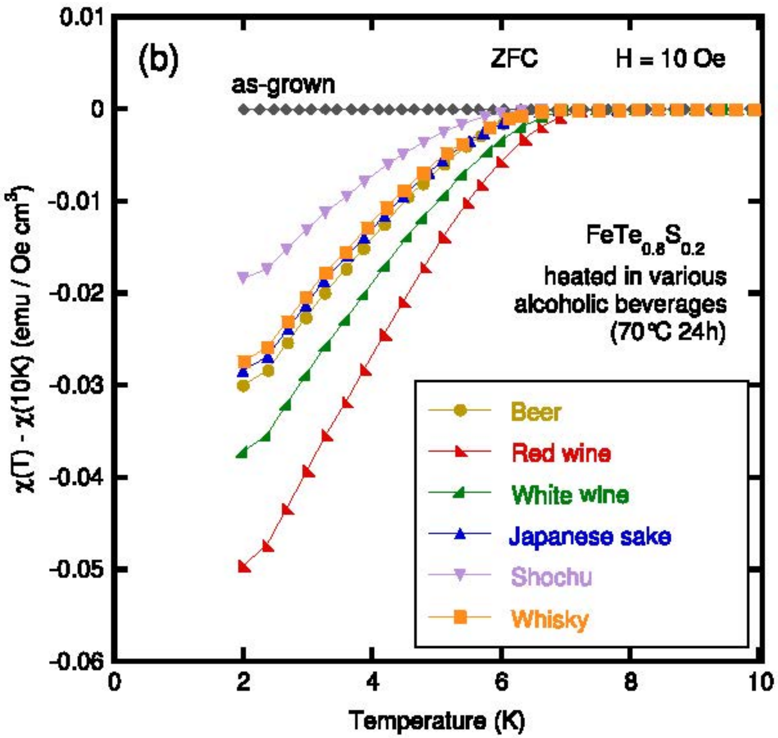
de la Cruz *et al.* Nature **453**, 899 (2008)

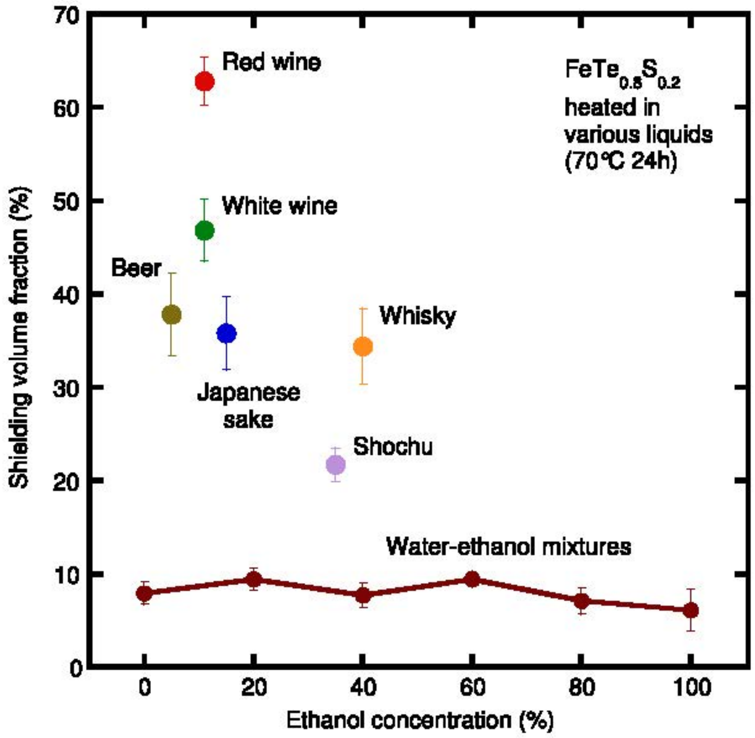
Structural transition (from tetragonal to orthorhombic or monoclinic) at T_c~150K and a magnetic transition at T_c~134K

Fe moment = 0.36 μ_B : VERY SMALL!

Alcoholic beverages induce superconductivity in $FeTe_{1-x}S_x$

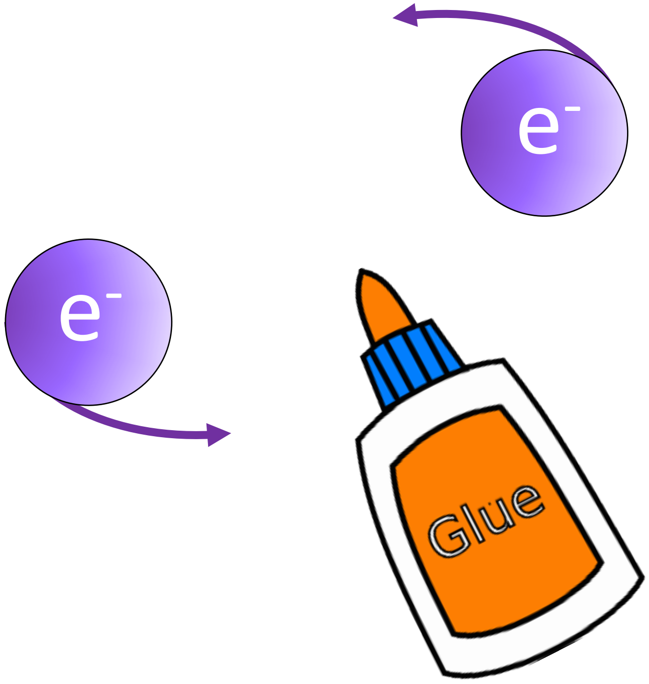
K. Deguchi *et al.*, Supercond. Sci. Technol. **24**, 05008 (2011)





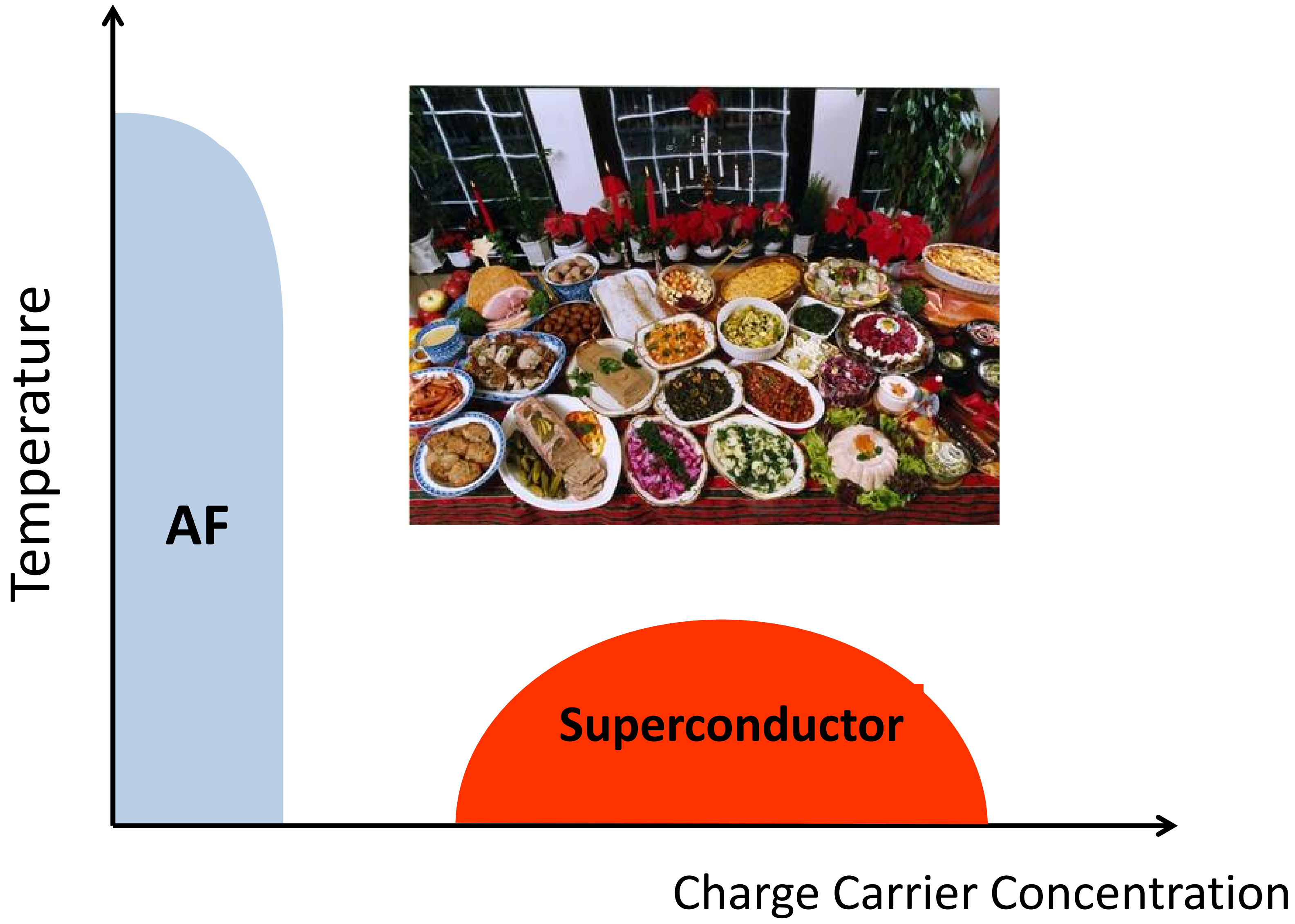
High-Temperature Superconductors

What is the microscopic "glue" that binds the electrons into pairs?

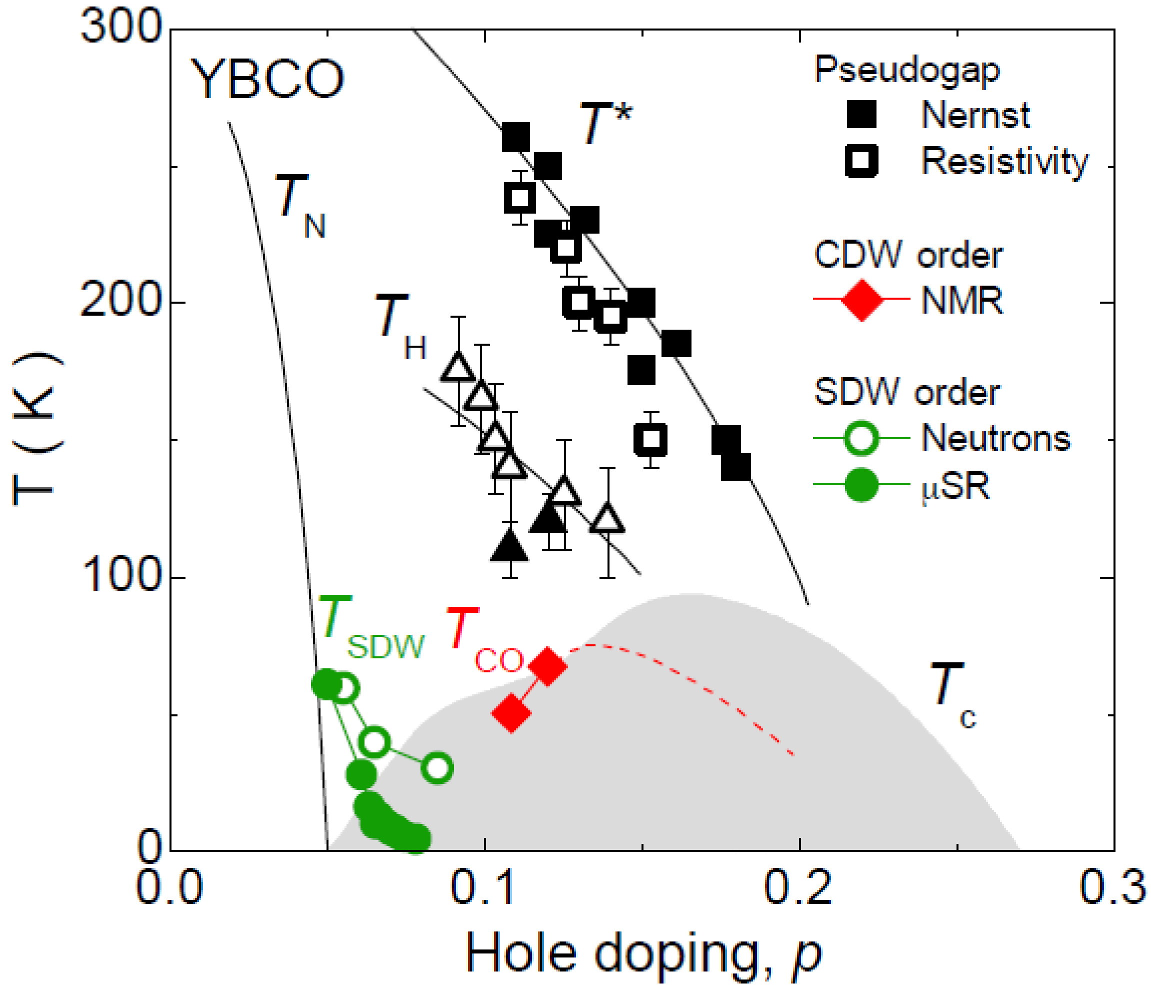


- Phonons (lattice vibrations)?
- Magnetism?
- Something else?

Generic Phase Diagram



Normal State “Smorgasborg”



N. Doiron-Leyraud & L. Taillefer, *Physica C* **481**, 161 (2012)

$$\Psi(\vec{r}) = \left|\Psi_0\right| e^{i\theta(\vec{r})}$$

BCS wave function describing the superconducting state

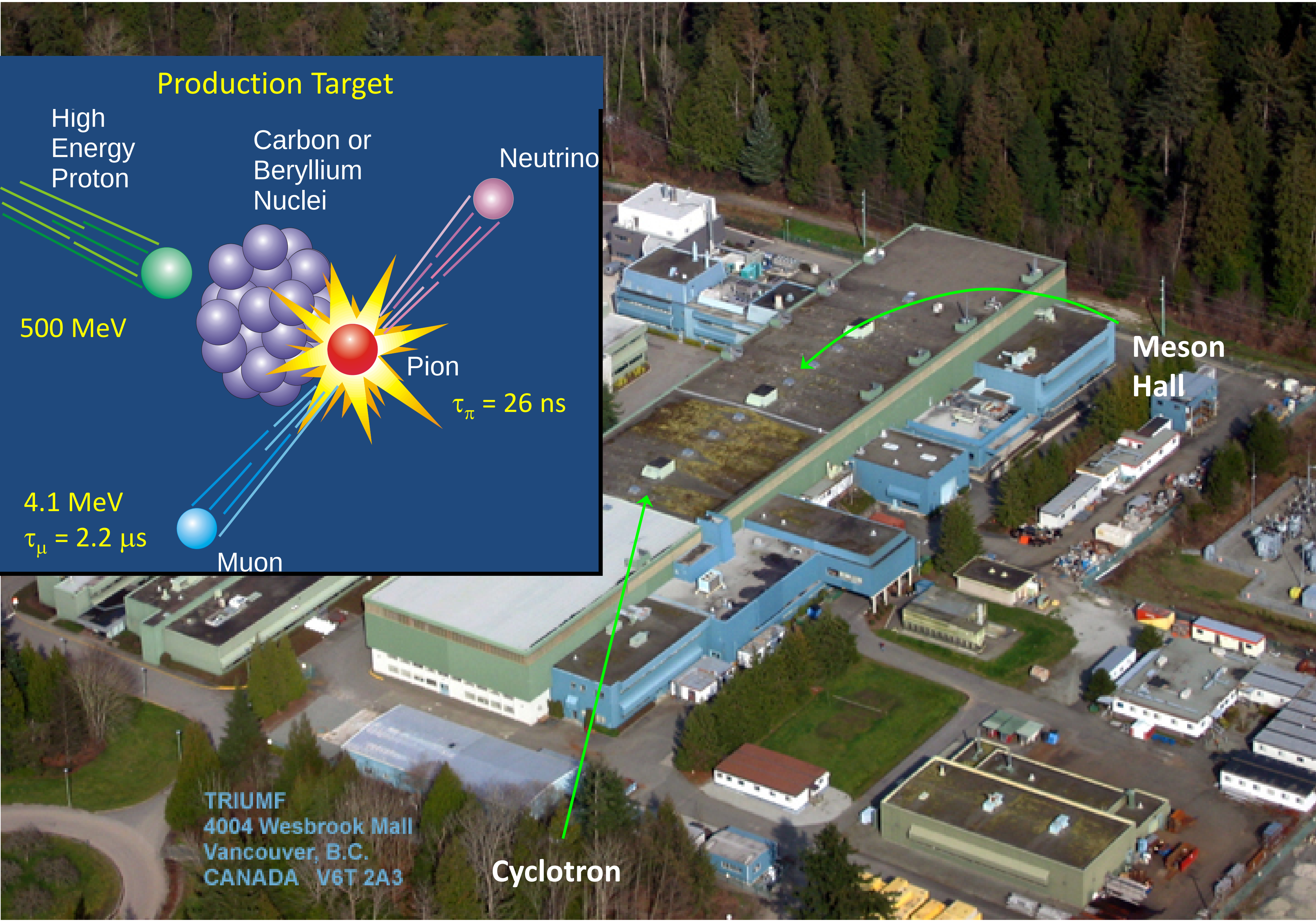
In the superconducting state, both the pairing amplitude $\left|\Psi_0\right|$ and the phase $\theta(\vec{r})$ are ***rigid***.

The superconducting state can be destroyed by ***fluctuations*** of the amplitude, phase, or both.

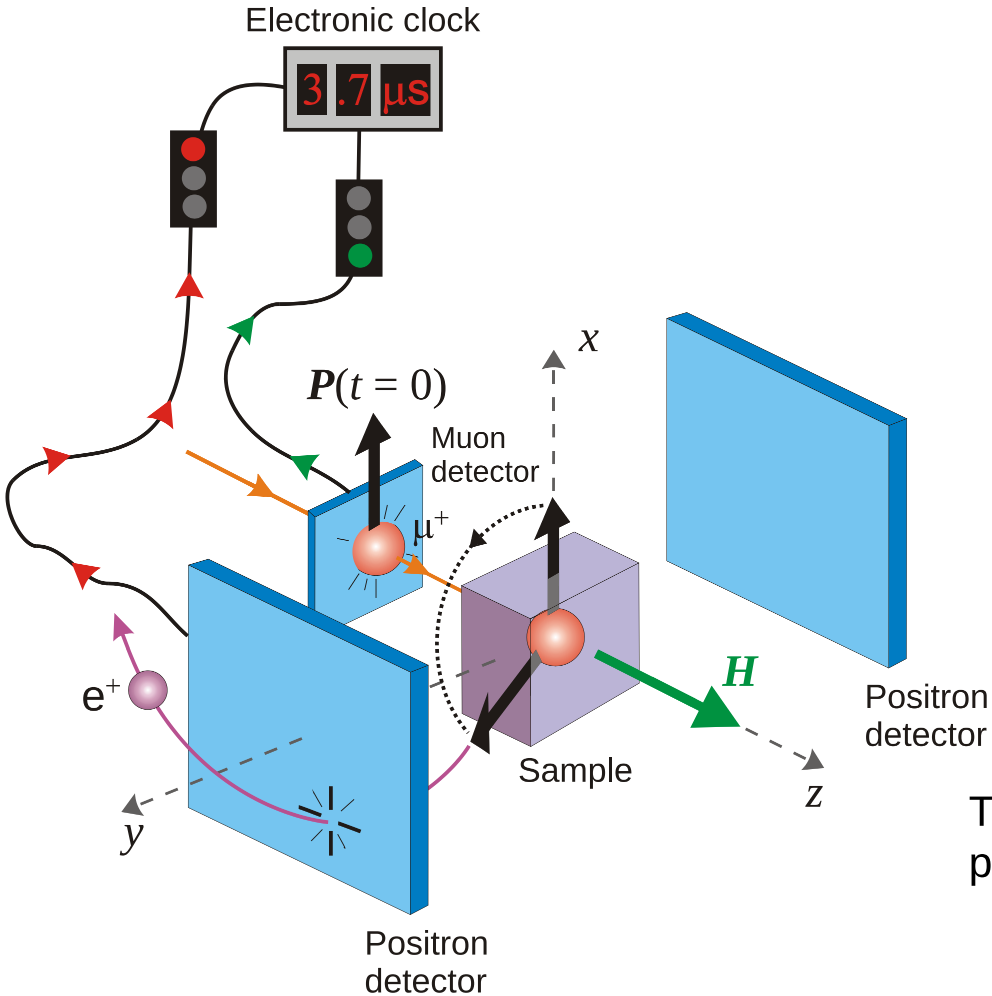
- **Low-Temperature Superconductor**
  Superconductivity destroyed by ***amplitude*** fluctuations
  i.e. destruction of Cooper pairs

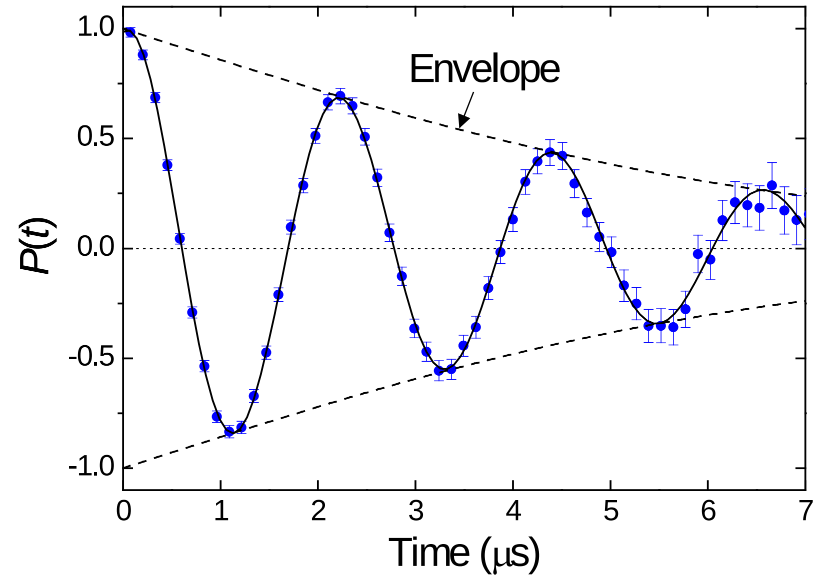
- **High-Temperature Superconductor**
  Superconductivity destroyed by ***phase*** fluctuations
  i.e. destruction of long-range phase coherence of Cooper pairs

Consequently the simple binding of electrons into Cooper pairs and short-range phase coherence may occur at temperatures well *above* T_c!


Production Target
High
Energy
Proton
Carbon or
Beryllium
Nuclei
Neutrino
500 MeV
Pion
τ_π = 26 ns
4.1 MeV
τ_μ = 2.2 μs
Muon
Meson
Hall
TRIUMF
4004 Wesbrook Mall
Vancouver, B.C.
CANADA V6T 2A3
Cyclotron

Transverse-Field μSR



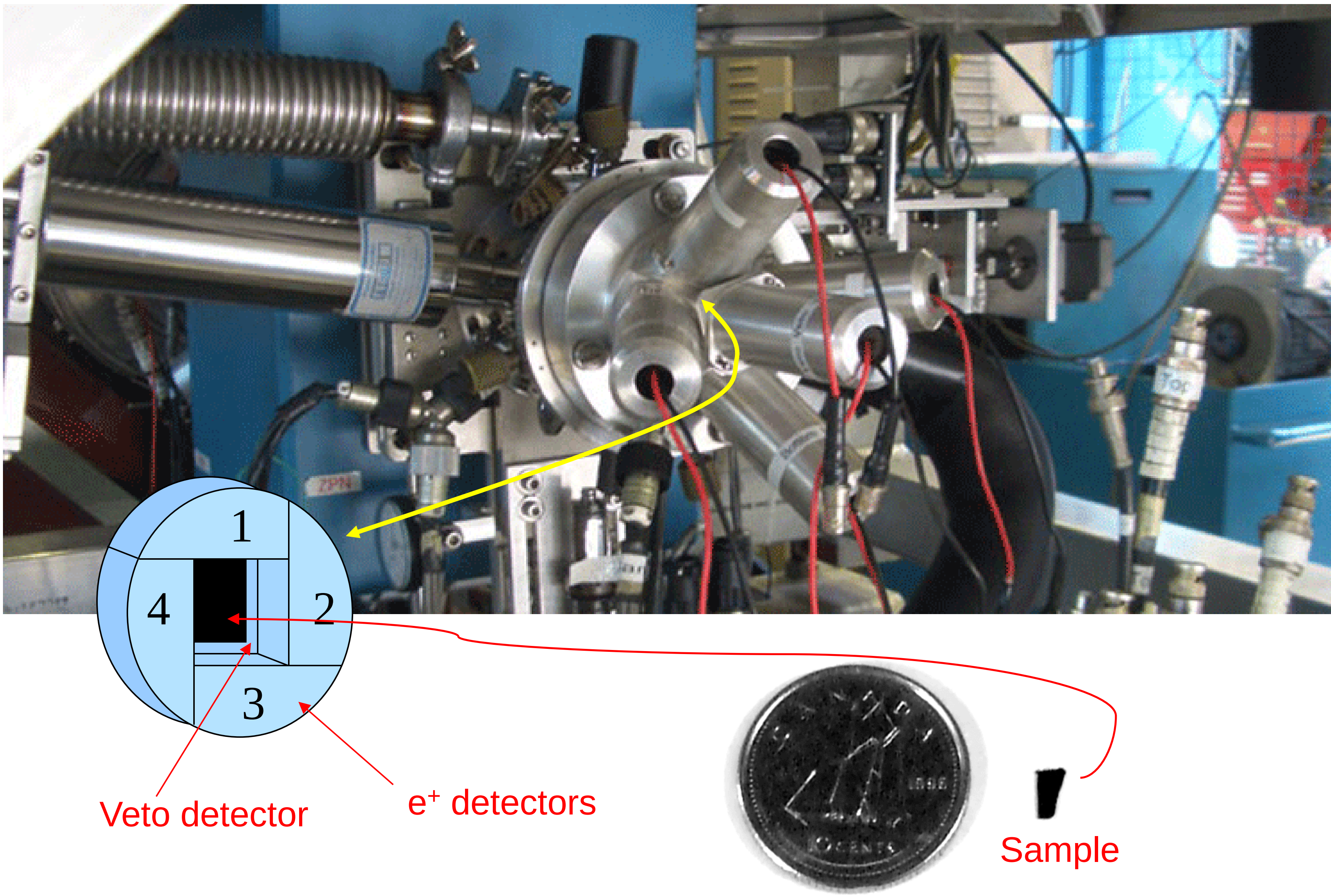


The time evolution of the muon spin polarization is described by:

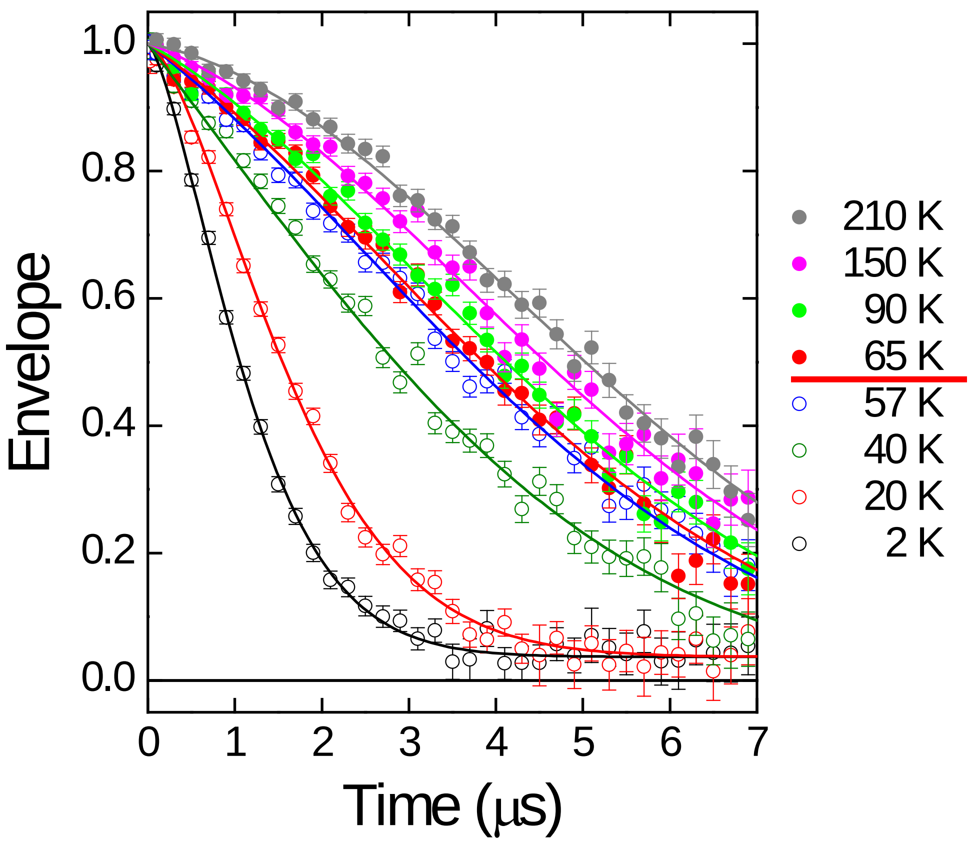
$$P(t) = G(t)\cos(\gamma_\mu B_\mu t + \phi)$$

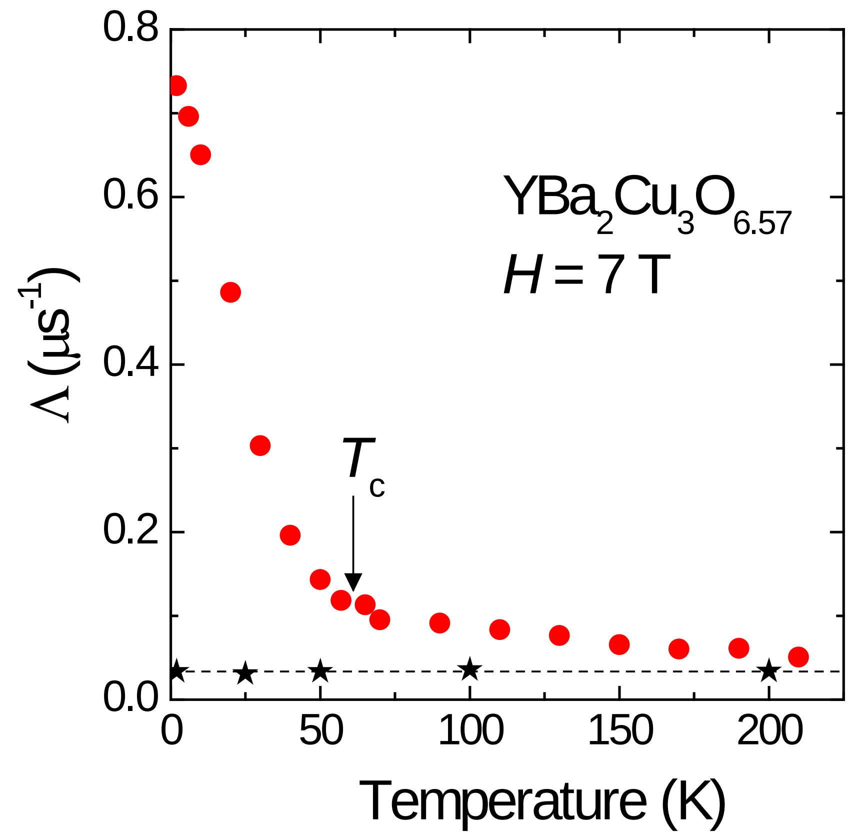
where $G(t)$ is a relaxation function describing the ***envelope*** of the TF-μSR signal.

HiTime: High transverse-field (7 T) μSR spectrometer



Relaxation of TF-μSR Signal in $YBa_2Cu_3O_{6.57}$ (T_c = 62.5 K) at H = 7T





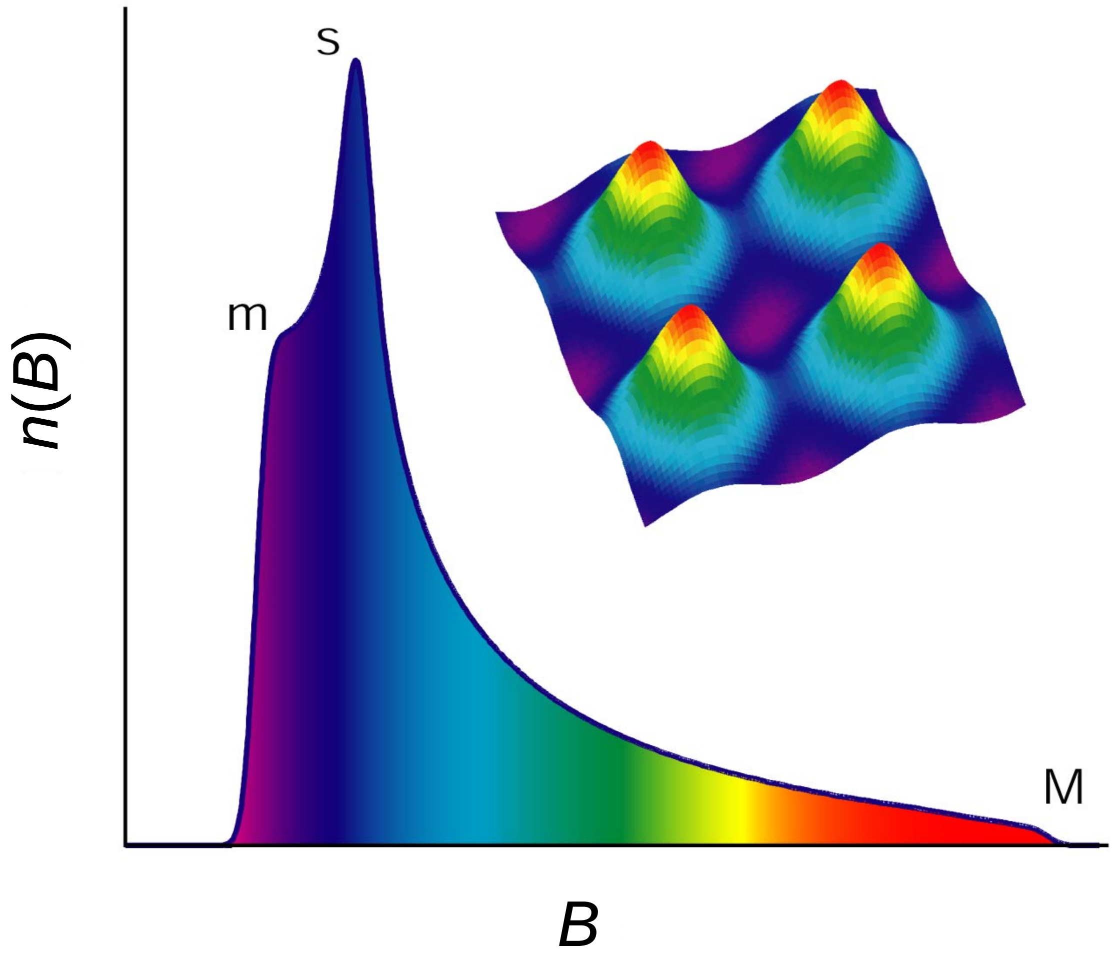
$$G(t) = \underbrace{\exp[(-\Lambda t)^{\beta}]}_{\text{spatial field inhomogeneity}} \overbrace{\exp(-\Delta^2 t^2)}^{\text{nuclear dipoles}}$$

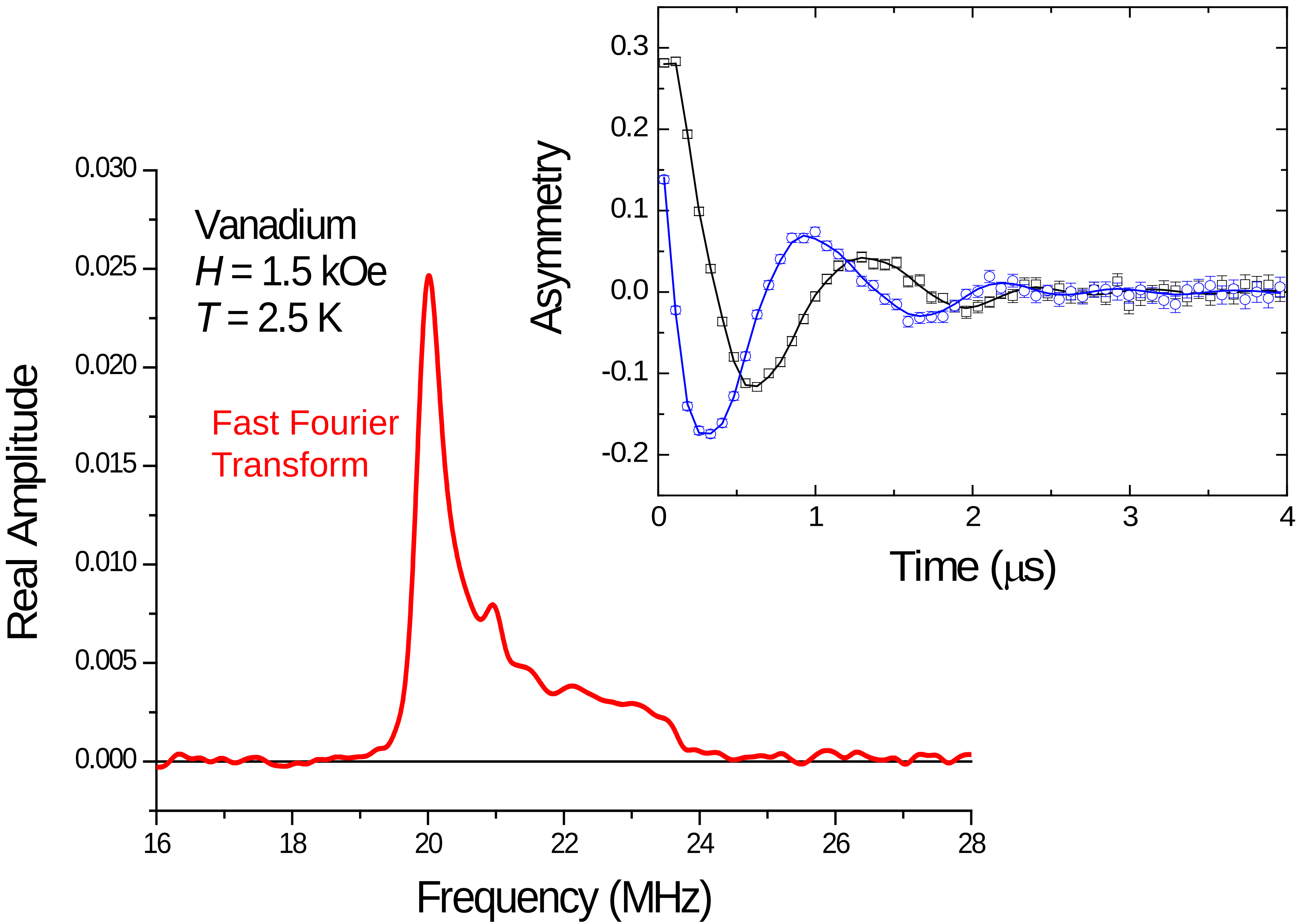
spatial field inhomogeneity (**β = 1 at $T \geq$ 40 K**)

Vortex Lattice of a Type-II Superconductor

TF-μSR is ideally suited to measure the **internal magnetic field distribution**

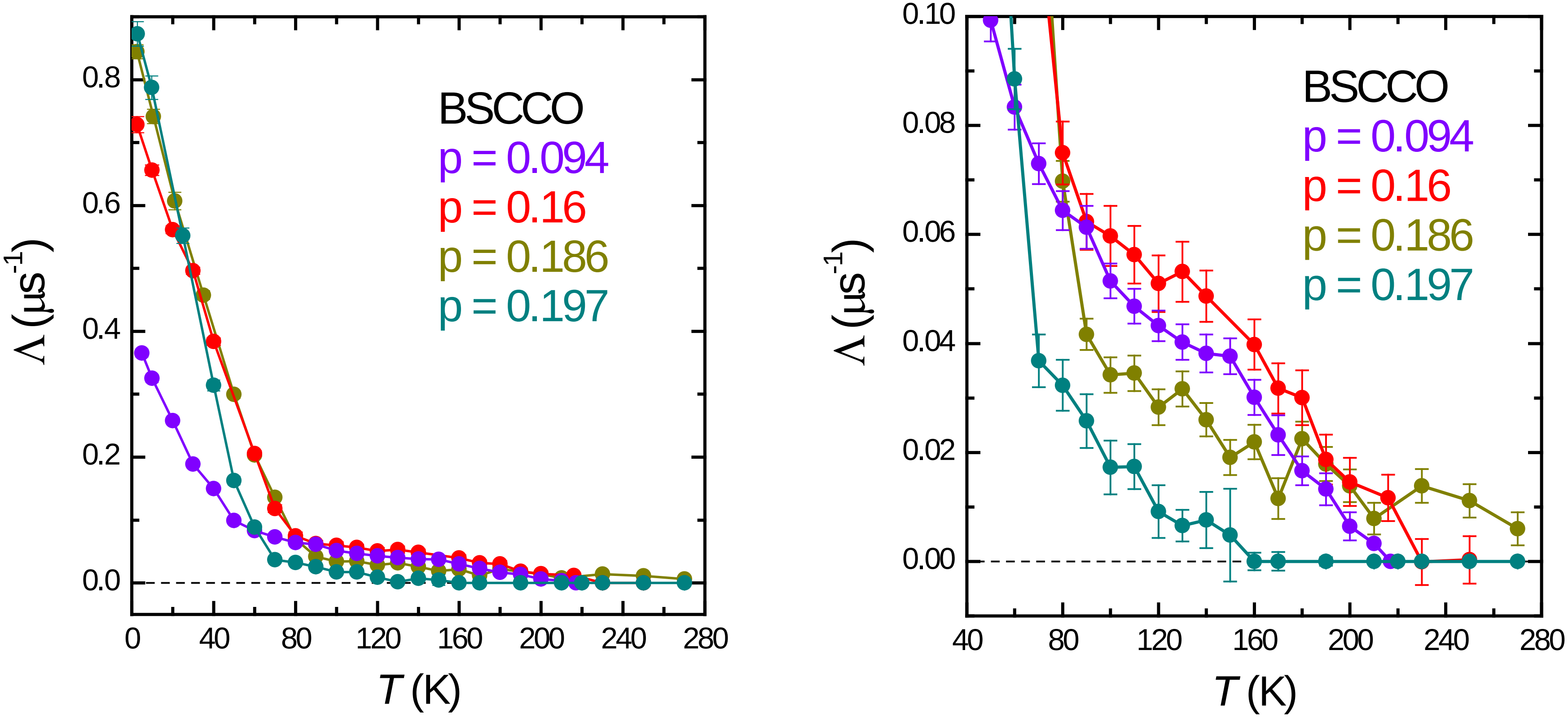
e.g. field distribution of a square vortex lattice (from Mitrovic *et al.*)





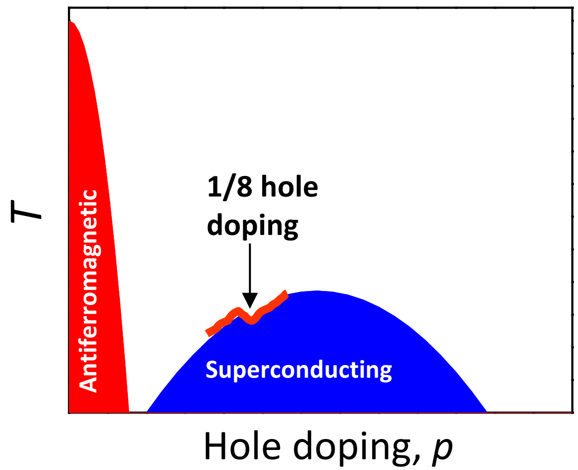
Vanadium
H = 1.5 kOe
T = 2.5 K
Fast Fourier
Transform
Real Amplitude
Frequency (MHz)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
16
18
20
22
24
26
28
Asymmetry
Time (μs)
0.3
0.2
0.1
0.0
-0.1
-0.2
0
1
2
3
4

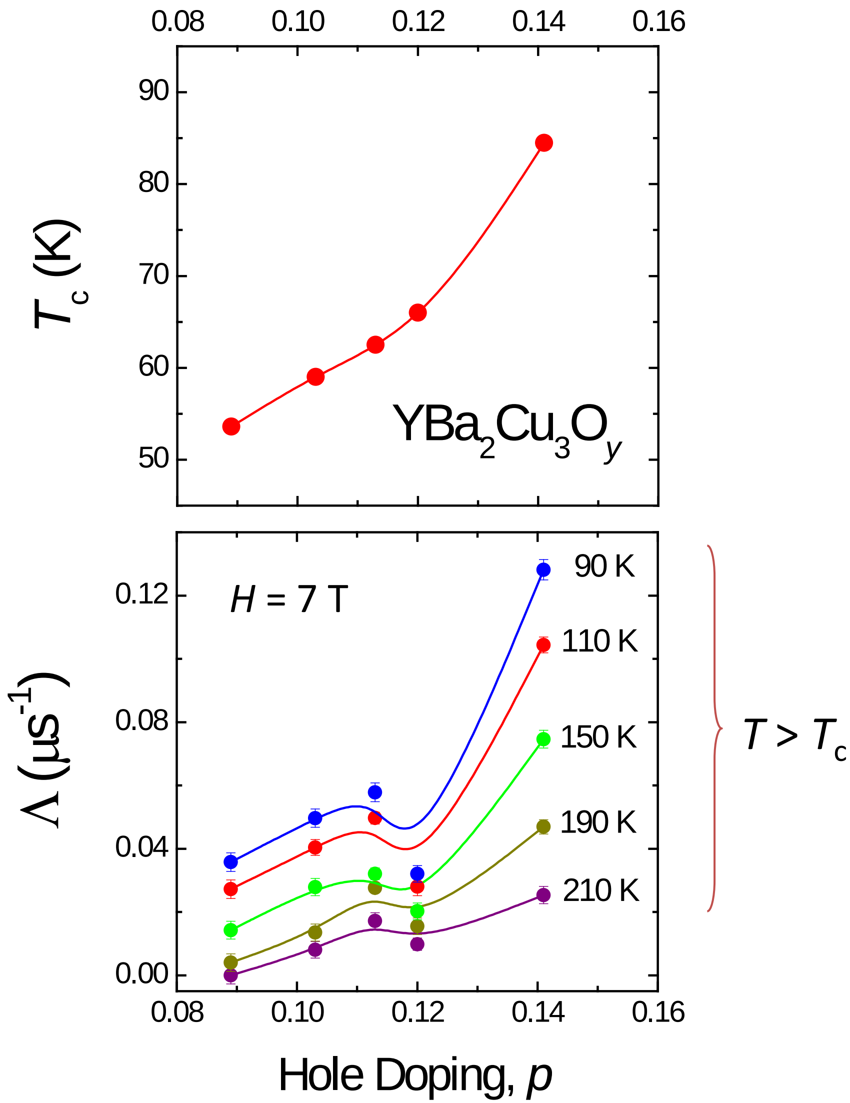
$Bi_{2+x}Sr_{2-x}Ca_2Cu_2O_{8+\delta}$ (BSCCO)



Magnetic Response Above T_c

Observation #1

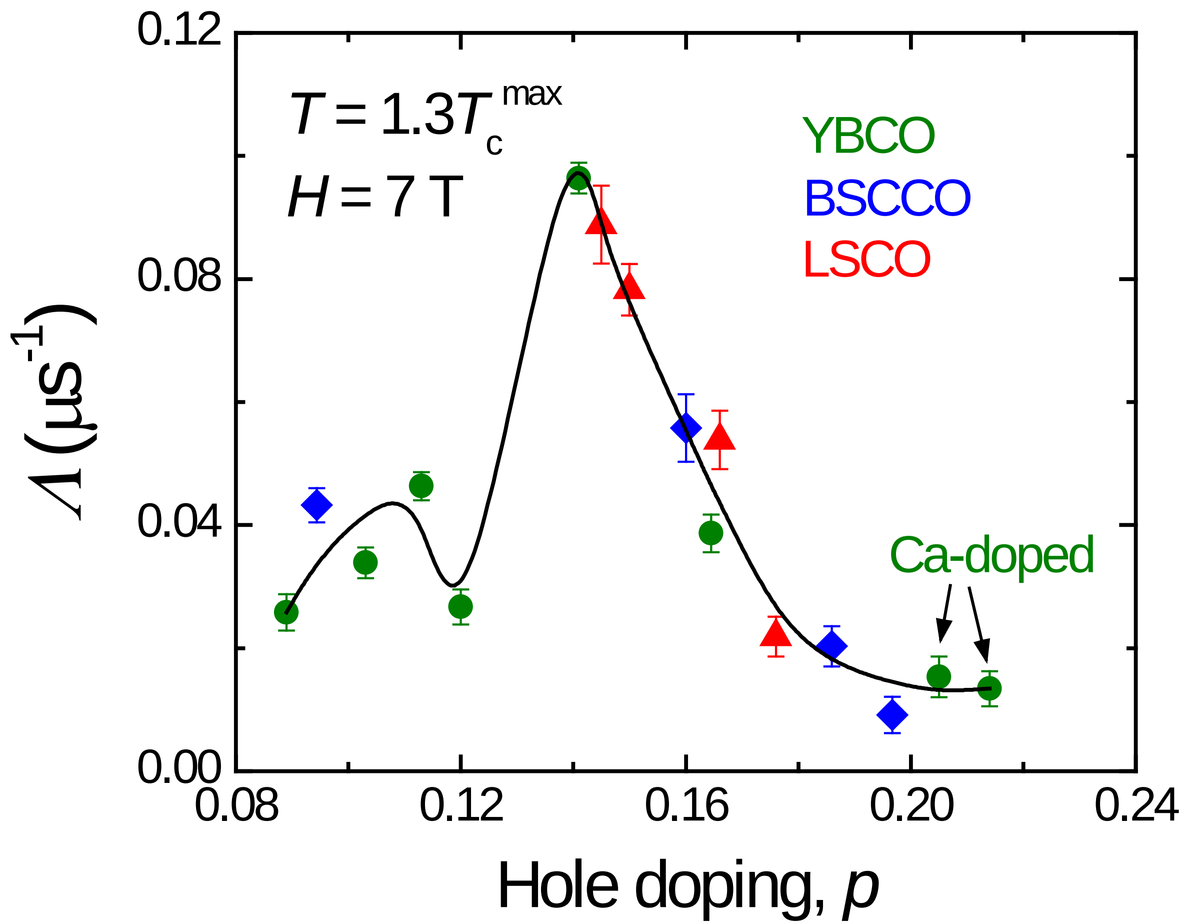




Spatial field inhomogeneity above T_c **tracks** bulk superconductivity!

Magnetic Response Above T_c

Observation #2



Universal scaling!

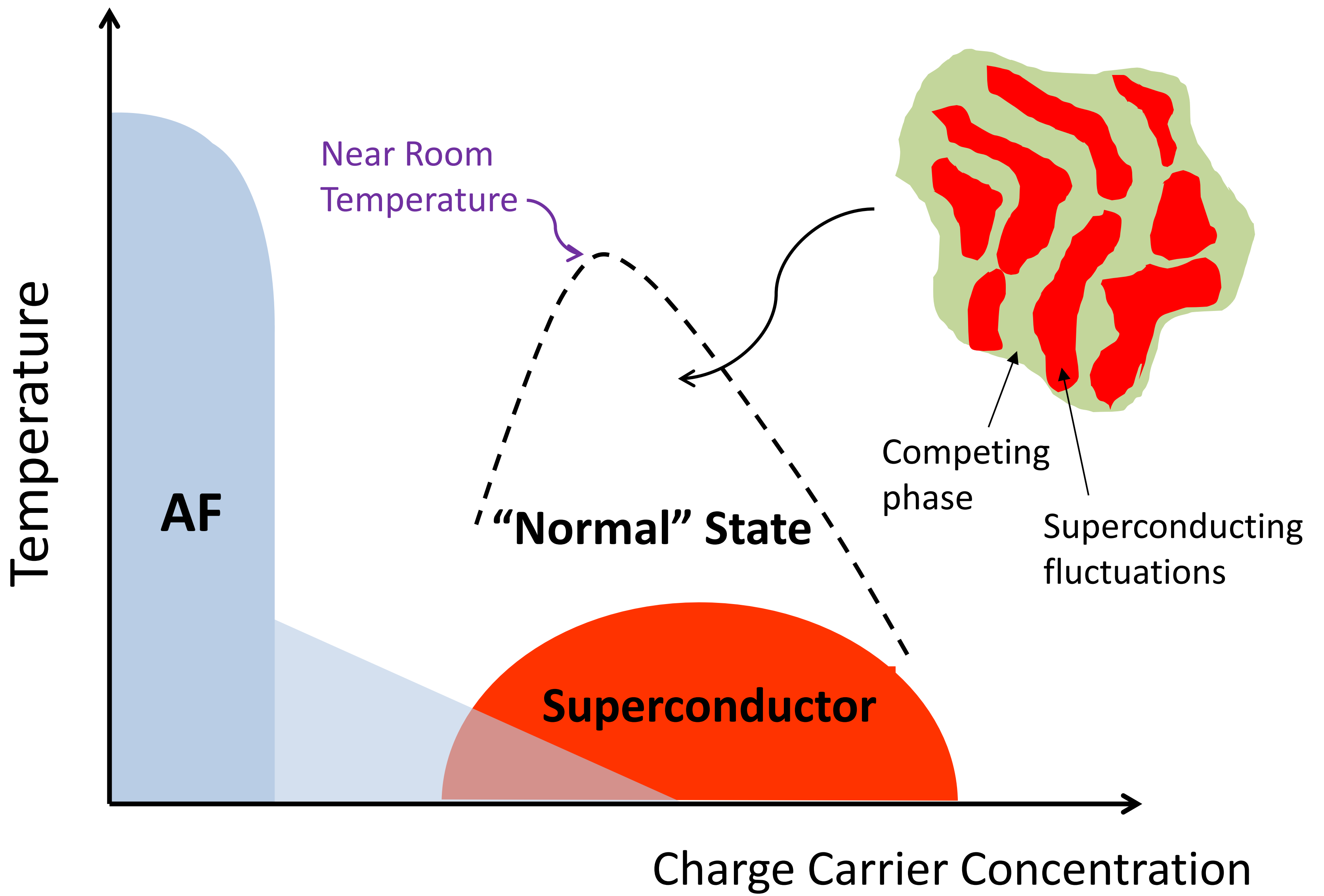
T_c^{max} is maximum value of T_c for each compound

What does this tell us?

- The spatially inhomogeneous magnetic response above T_c is **related** to superconductivity.

- There is a universal **competing phase** that causes the spatial inhomogeneity in the normal state (i.e. the electron fluid has a tendency toward inhomogeneity).

Generic Phase Diagram



Back to the Glue

The pairing glue may be **magnetic** in origin, but what competes with superconductivity may also be.

Its complicated!