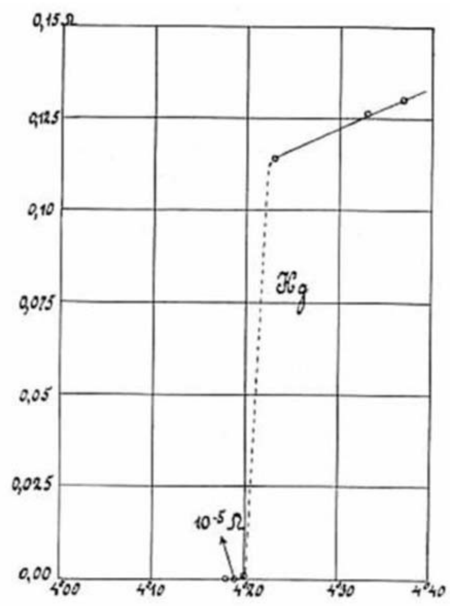
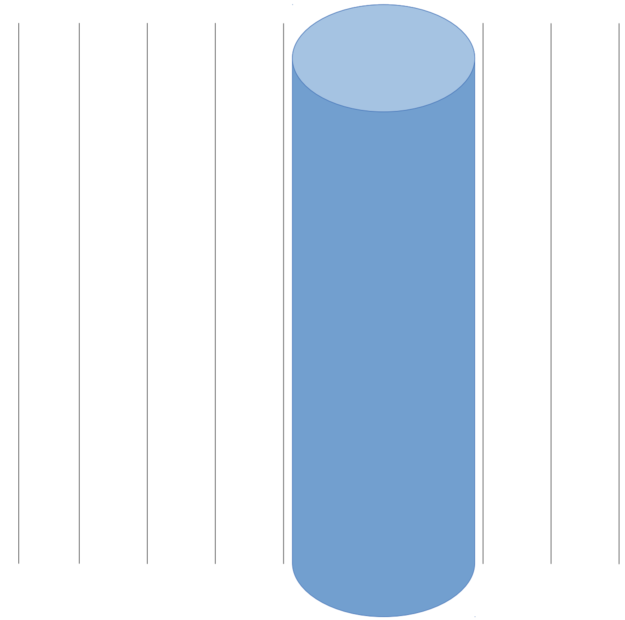
Application of µSR Superconductors



Kamerlingh Onnes 1911 Hg zero resistance

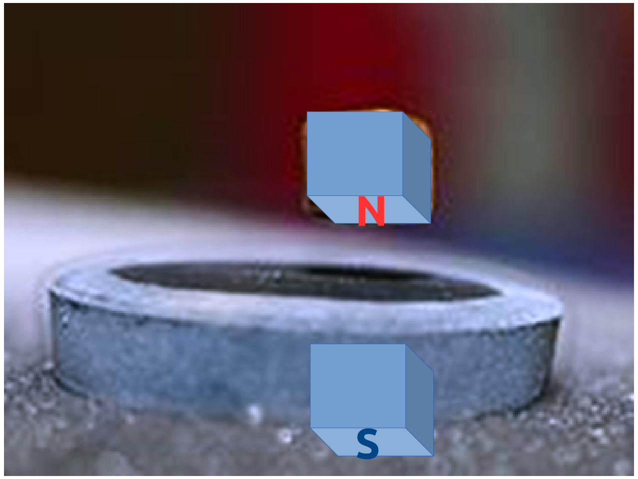
Persistent eddy currents: screening



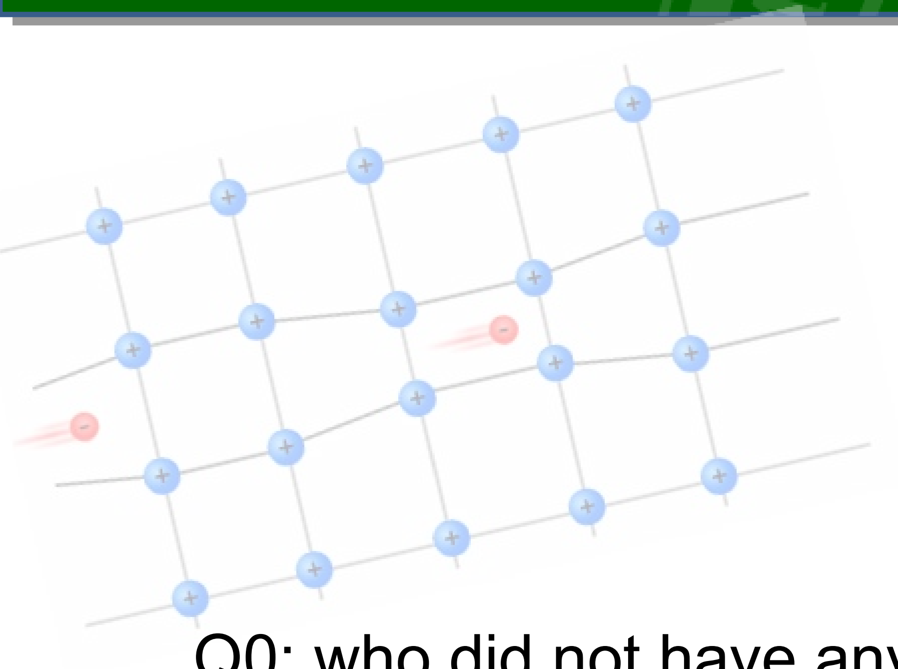
Roberto De Renzi

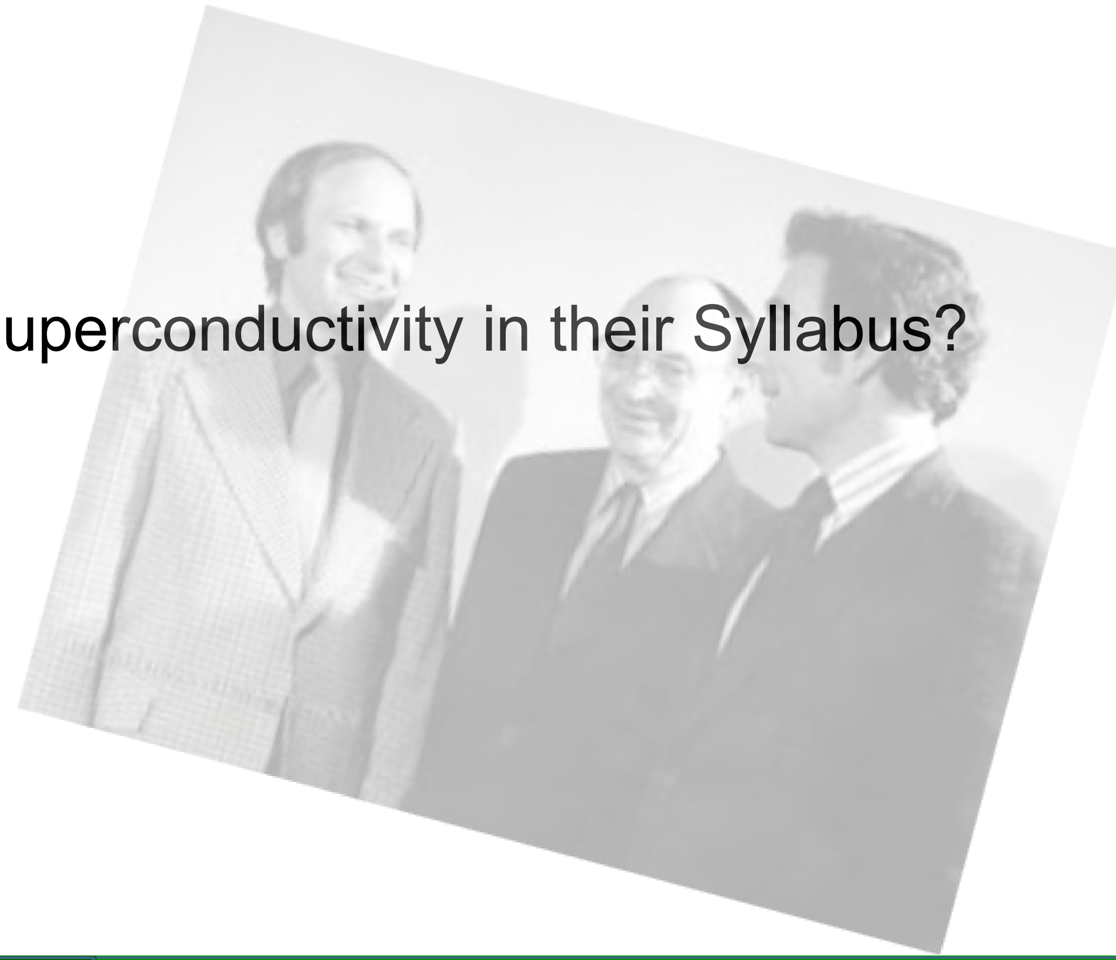
Dept. SMFI, University of Parma

Levitation



μSR in superconductors



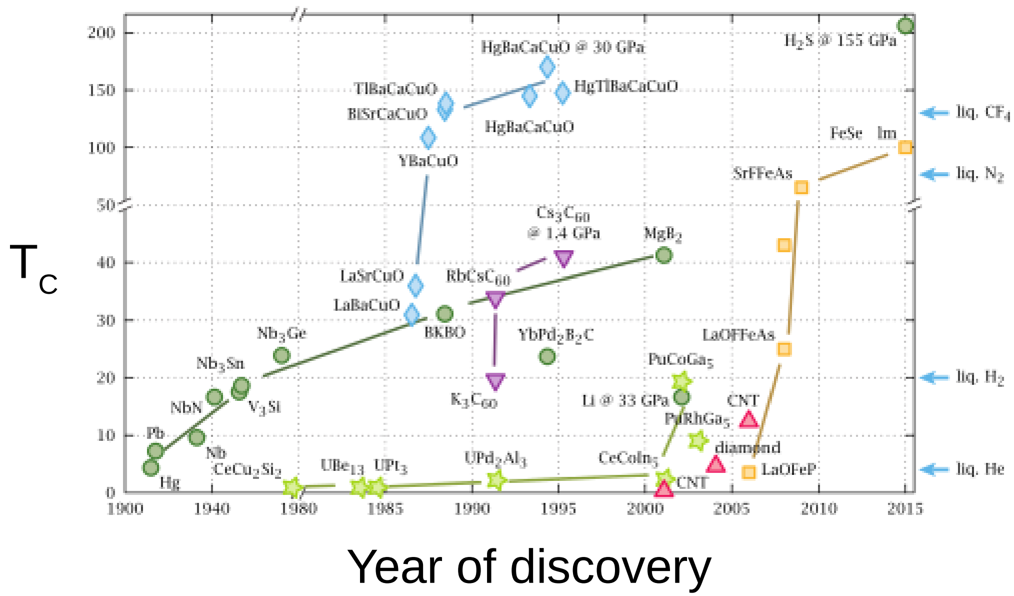


Q0: who did not have any superconductivity in their Syllabus?

DEPARTMENT OF MATHEMATICAL, PHYSICAL AND COMPUTER SCIENCES

Outline

- Superconductors
  - Meissner effect: magnetic field expulsion
  - London penetration of the field
  - Pairs and free energy
  - The gap and the coherence length
  - Type I and type II
  - Abrikosov flux lattice
- Experimental examples
  - bulk isotropic case
  - anisotropic superconductors
  - LE muons
  - gap fits
  - Uemura plot
  - phase diagrams



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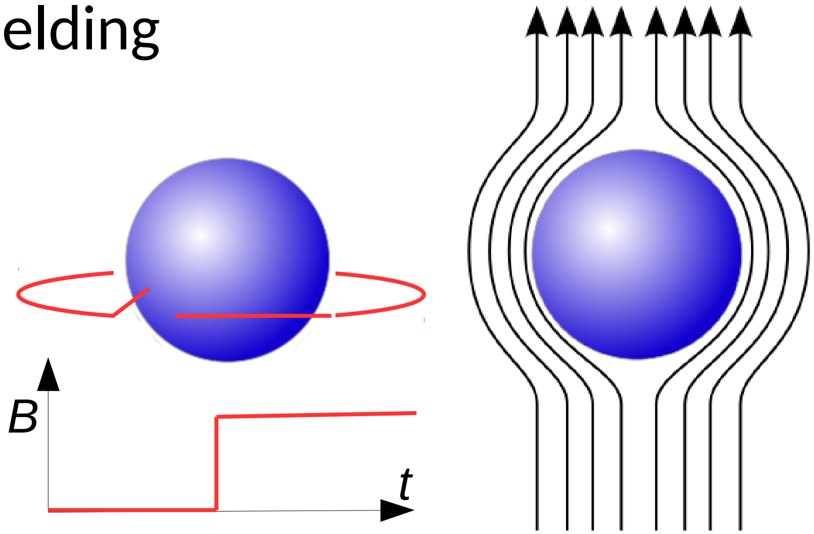
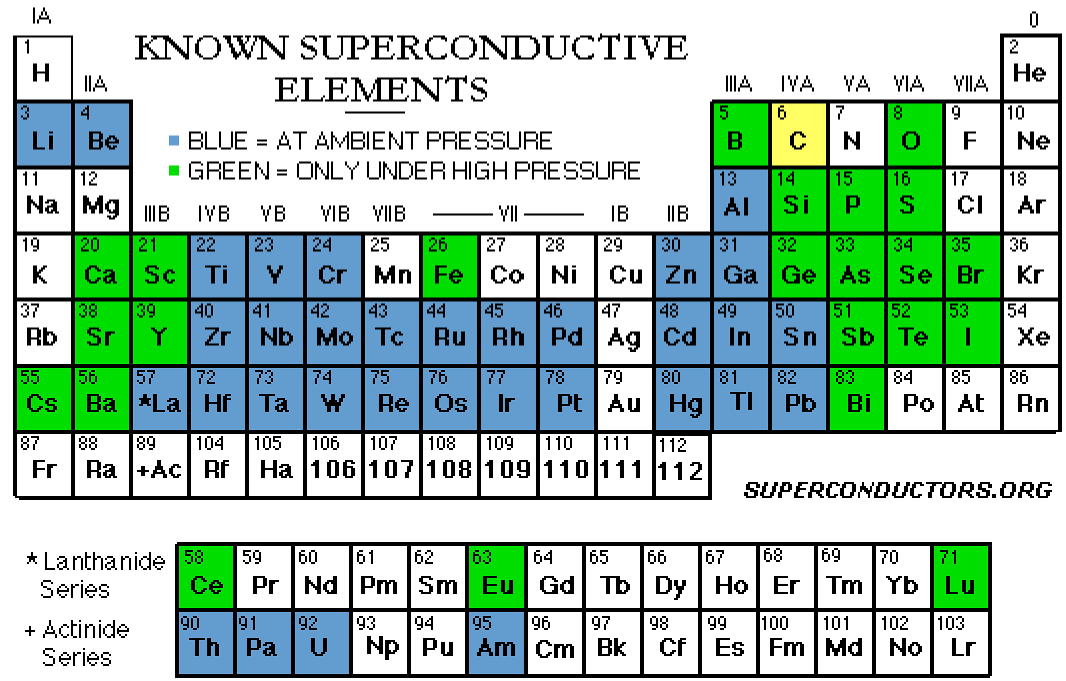
Meissner - Ochsenfeld effect

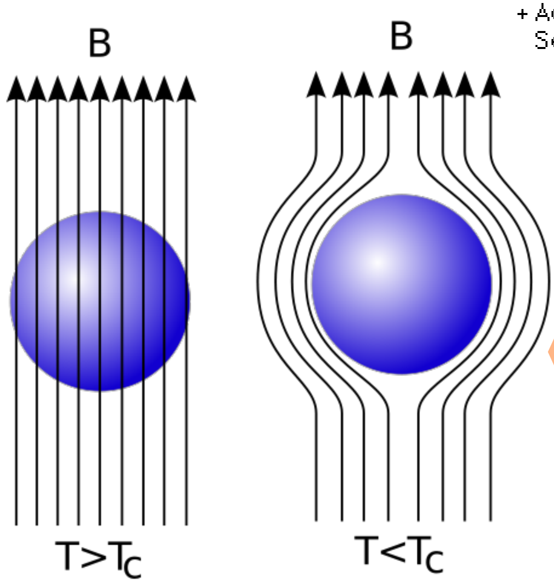
Shielding





Field expulsion:

cool a sample below T_c



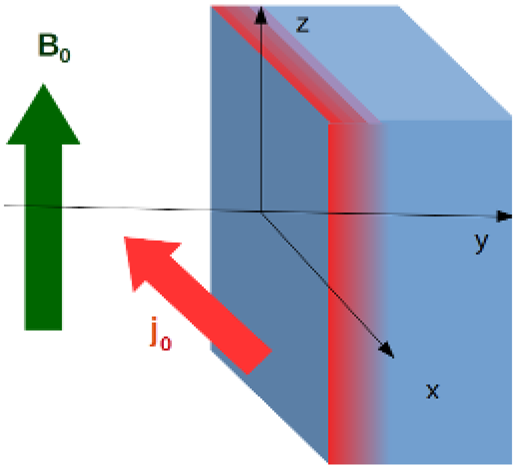
http://www.superconductors.org/Type1.htm

Meissner-Ochsenfeld effect

London model: the penetration depth

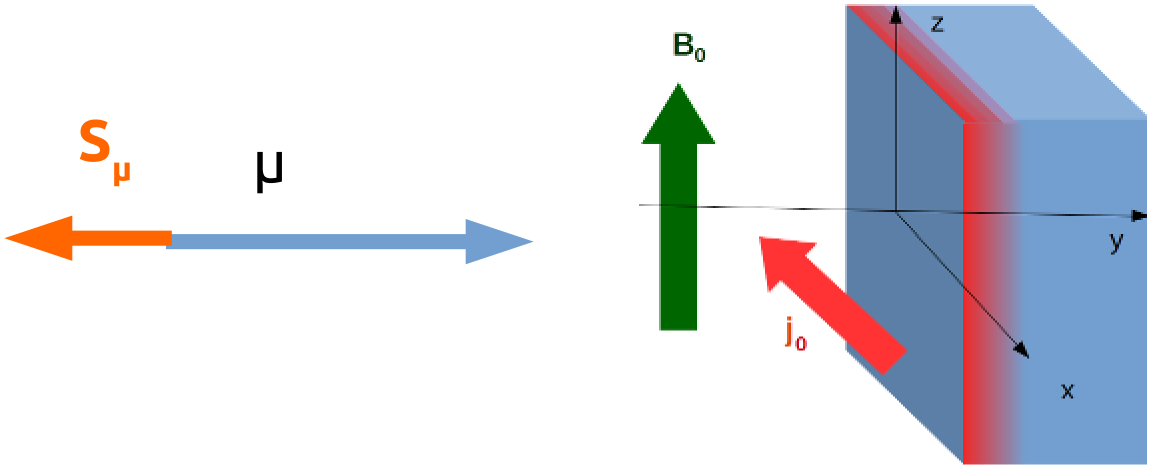
A first lengthscale $$\lambda = \sqrt{\frac{m}{\mu_0 n e^2}}$$

Ampere Maxwell law $$\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$



Guess the solution $$\mathbf{B} = B_0 e^{-y/\lambda} \hat{z}$$

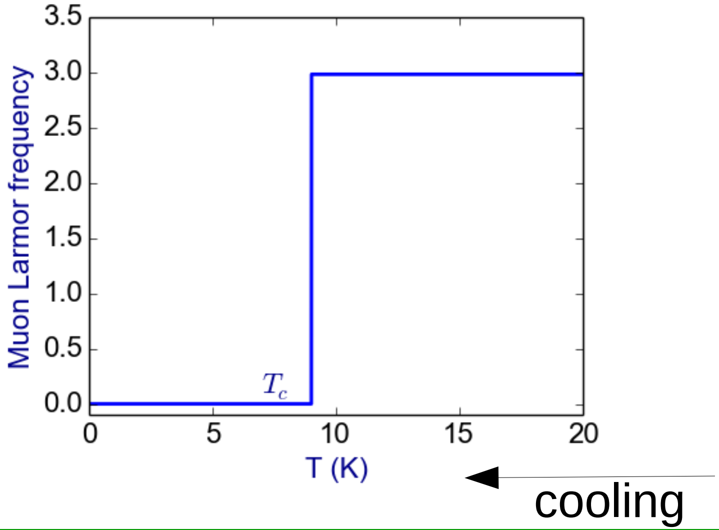
Right! $$\nabla \times \mathbf{B} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \partial_x & \partial_y & \partial_z \\ 0 & 0 & B_0 e^{-y/\lambda} \end{vmatrix} = \underbrace{-\frac{B_0}{\lambda} e^{-y/\lambda} \hat{x}}_{\mu_0 \mathbf{j}}$$



Q1: Implant muons in a Meissner state superconductor. What do you detect?

Above Tc a precession

When cooling below Tc the precession disappears



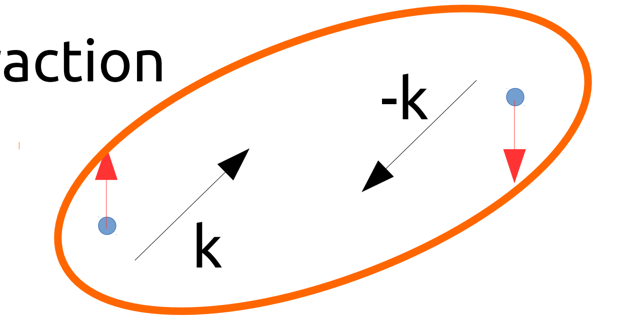
Summary of superconductor facts

- Only for $T < T_c$ (pretty low)
- Only below a critical field ($H < H_c$)
- Zero electrical resistance
- Magnetic field expulsion, requires a lenghtscale $\lambda = \sqrt{\frac{m^*}{\mu_0 n e^2}}$

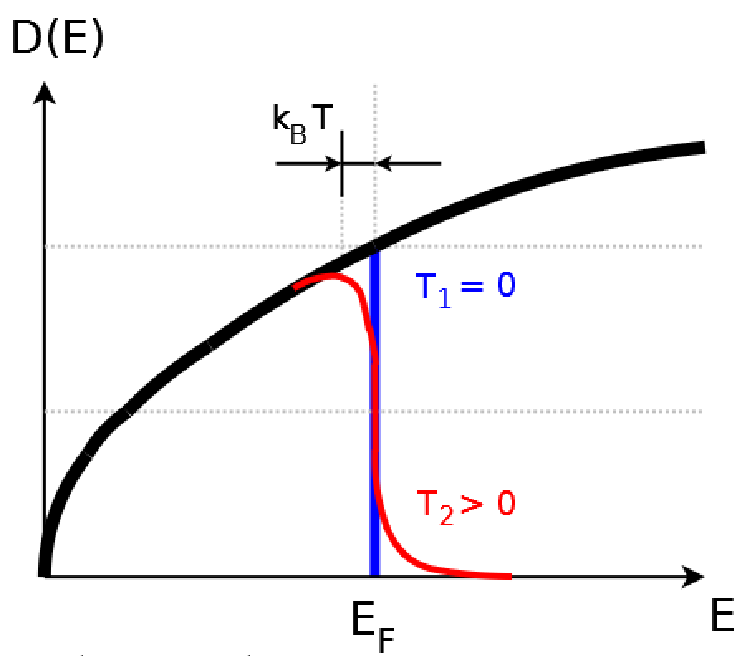
How can this be explained?

Microscopic model
Prototype: BCS

Attraction



Cooper pair, compound boson
condensation energy (binding) Δ



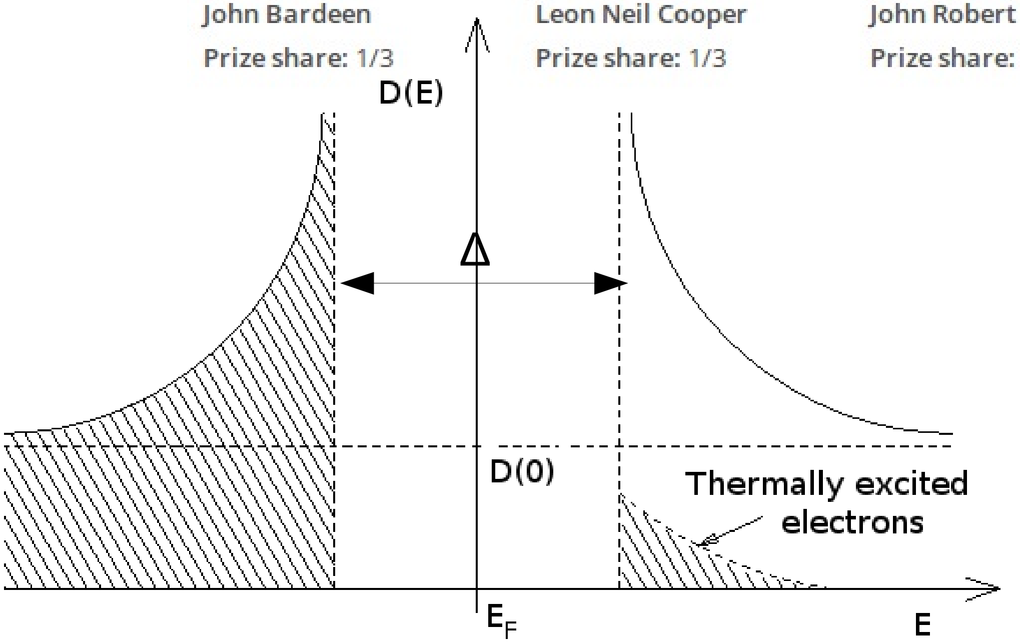
normal metal

The Nobel Prize in Physics 1972

John Bardeen
Prize share: 1/3

Leon Neil Cooper
Prize share: 1/3

John Robert Schrieffer
Prize share: 1/3



Mean free energy

Ginzburg-Landau

$$F - F_n = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4$$

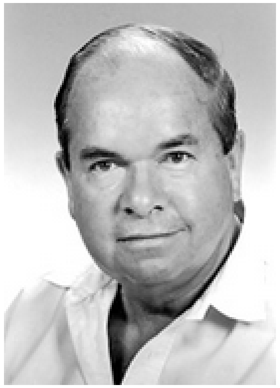
order parameter

magnetic free energy easy to add

$$F - F_n = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \frac{1}{2}m\left(\frac{j}{ne}\right)^2 + \frac{|\mathbf{B}|^2}{2\mu_0}$$

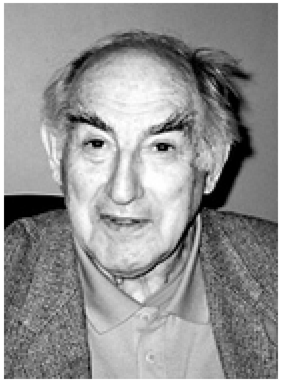
supercurrents $\hat{j} = \frac{e}{m}\hat{p} = \frac{e}{m}\left(-i\hbar\boldsymbol{\nabla} - e\mathbf{A}\right)$

The Nobel Prize in Physics 2003



Alexei A. Abrikosov

Prize share: 1/3

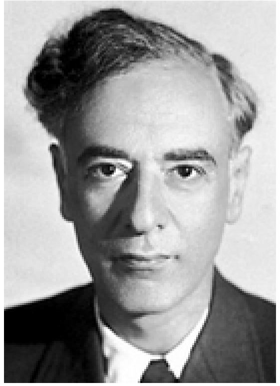


Vitaly L. Ginzburg

Prize share: 1/3

Anthony J. Leggett

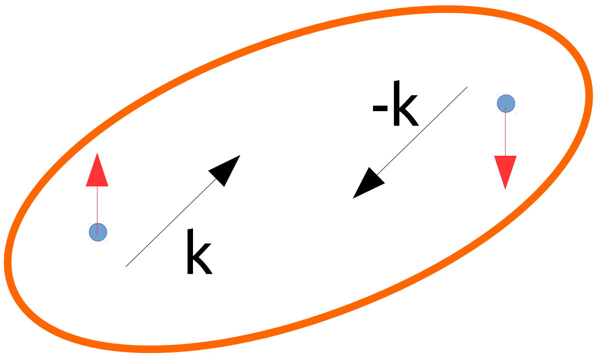
1962



Lev Davidovich Landau

Prize share: 1/1

The gap: a second lengthscale



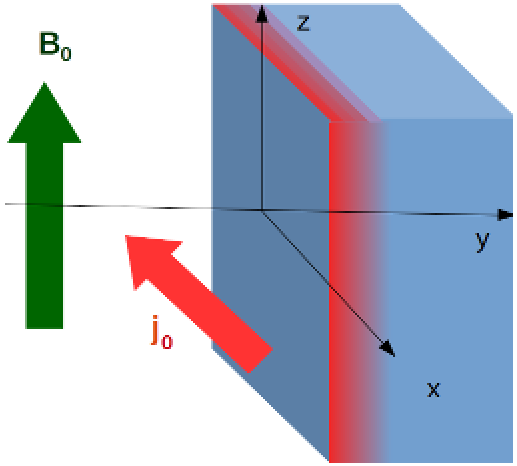
Cooper pair

Coherence length ξ

- how far can you pull a pair apart?

Inject an electron in a superconductor

- how far from the surface does it starts to pair (feel the attraction)?



$$\xi = \frac{\hbar}{\sqrt{2m|\alpha|}}$$

- Ginzburg Landau definition

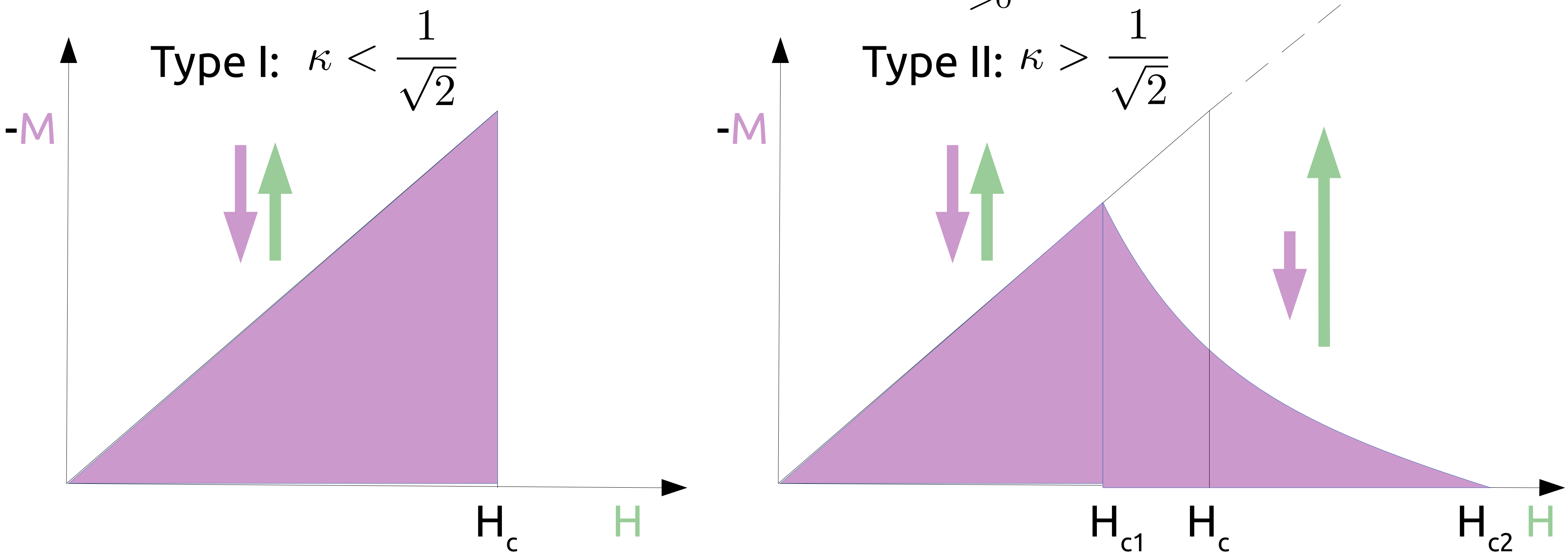
Type I and Type II superconductors

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

$$\Delta F = \underbrace{\alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4}_{<0} + \underbrace{\frac{1}{2}m\left(\frac{j}{ne}\right)^2 + \frac{|\mathbf{B}|^2}{2\mu_0}}_{>0}$$

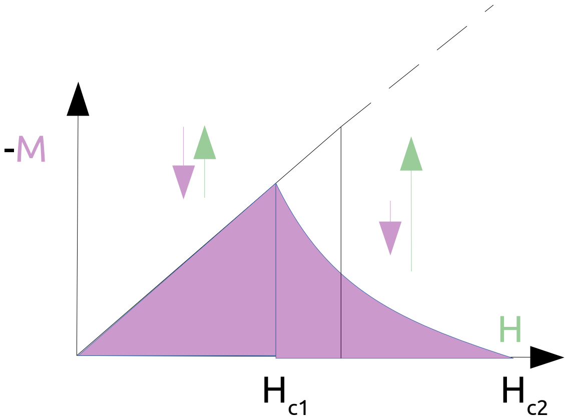
Type I: $\kappa < \frac{1}{\sqrt{2}}$

Type II: $\kappa > \frac{1}{\sqrt{2}}$



Abrikosov flux lattice

magnetic flux quantum $\Phi_0 = \frac{h}{2e} = 2.07 \cdot 10^{-15}\mathrm{Wb}$



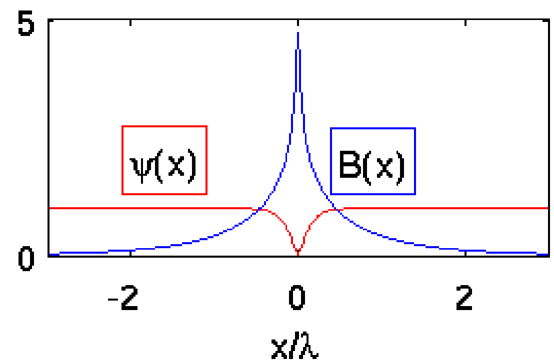
$H > H_{c1}$ partial field penetration

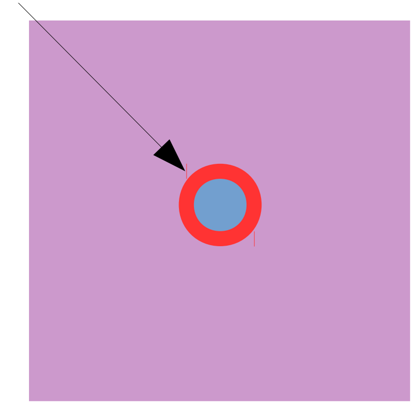
for $\kappa > \frac{1}{\sqrt{2}}$

periodic solution

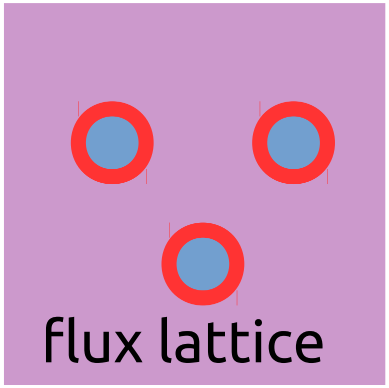
of GL equations

$H = H_{c1}$



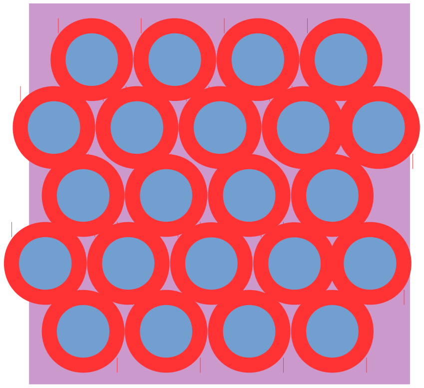


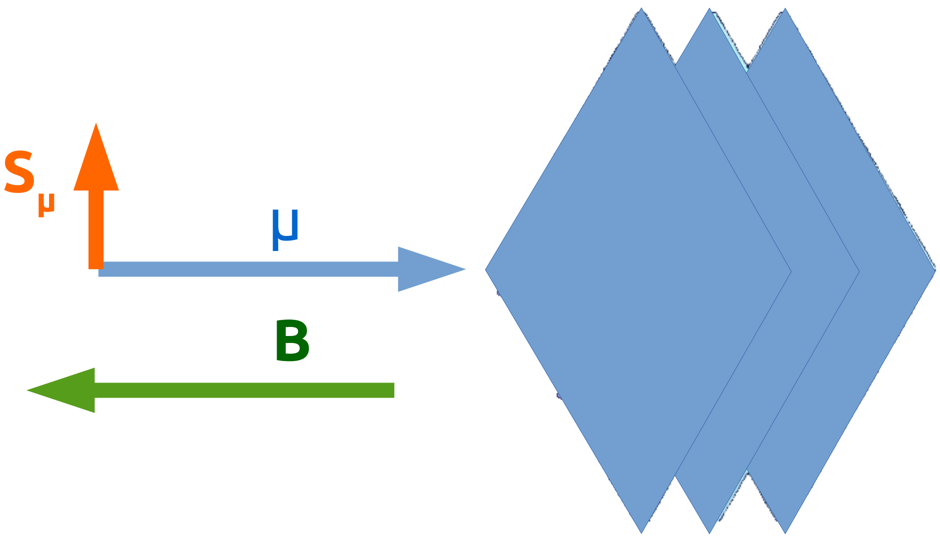
$H > H_{c1}$

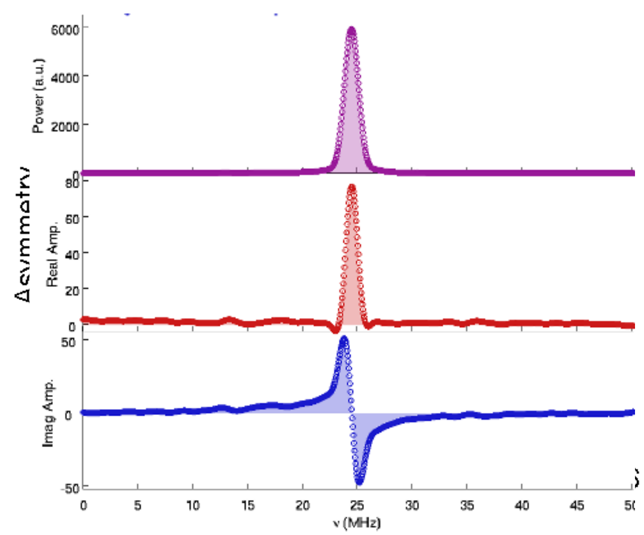


$H = H_{c2}$

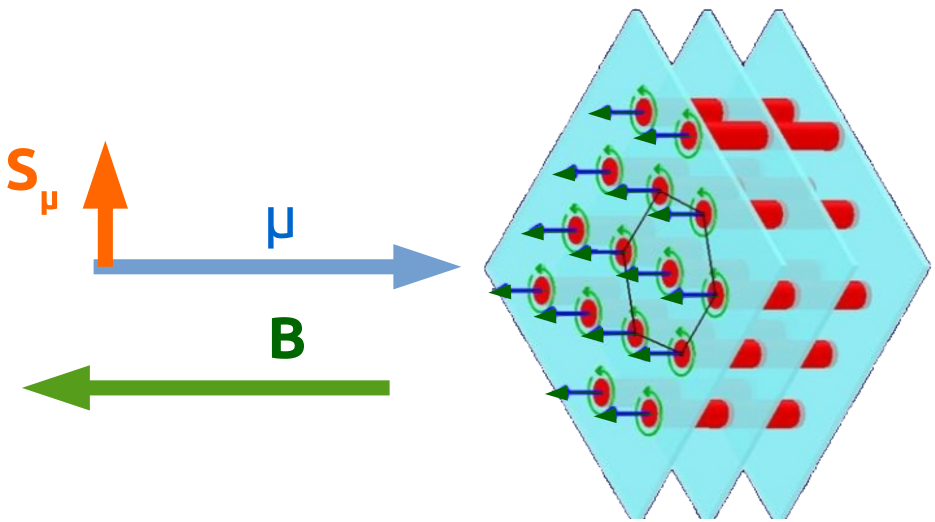
$\Delta F = 0$

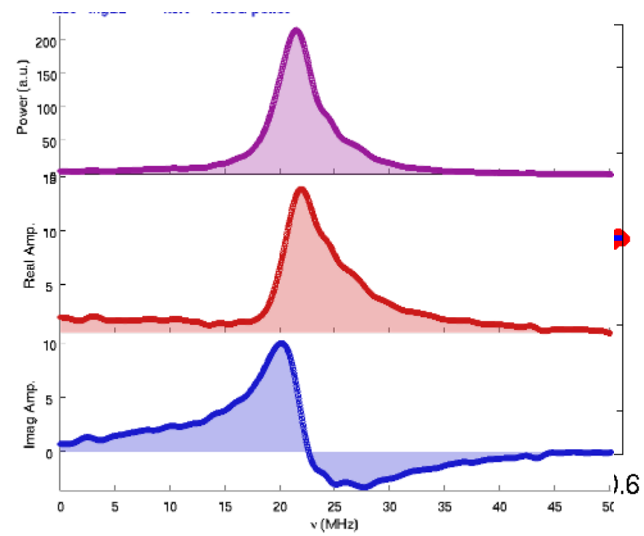






Q2: Homogeneously implant muons in a bulk FL. What do you expect to measure?





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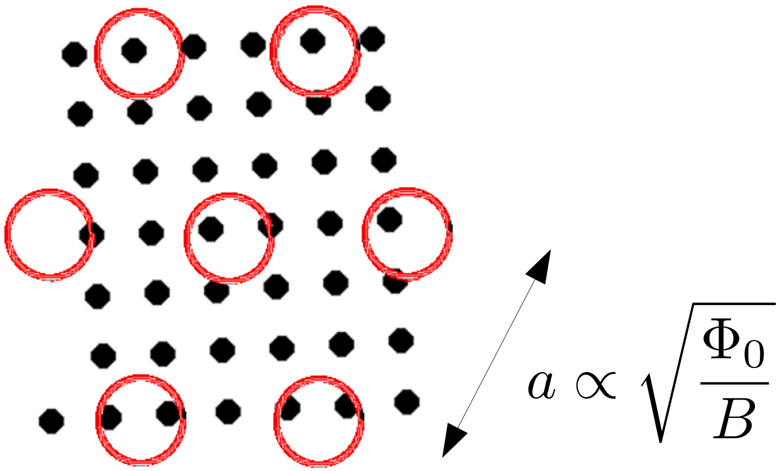
Field distribution in the FL

- the Flux Lattice is incommensurate to the crystal lattice

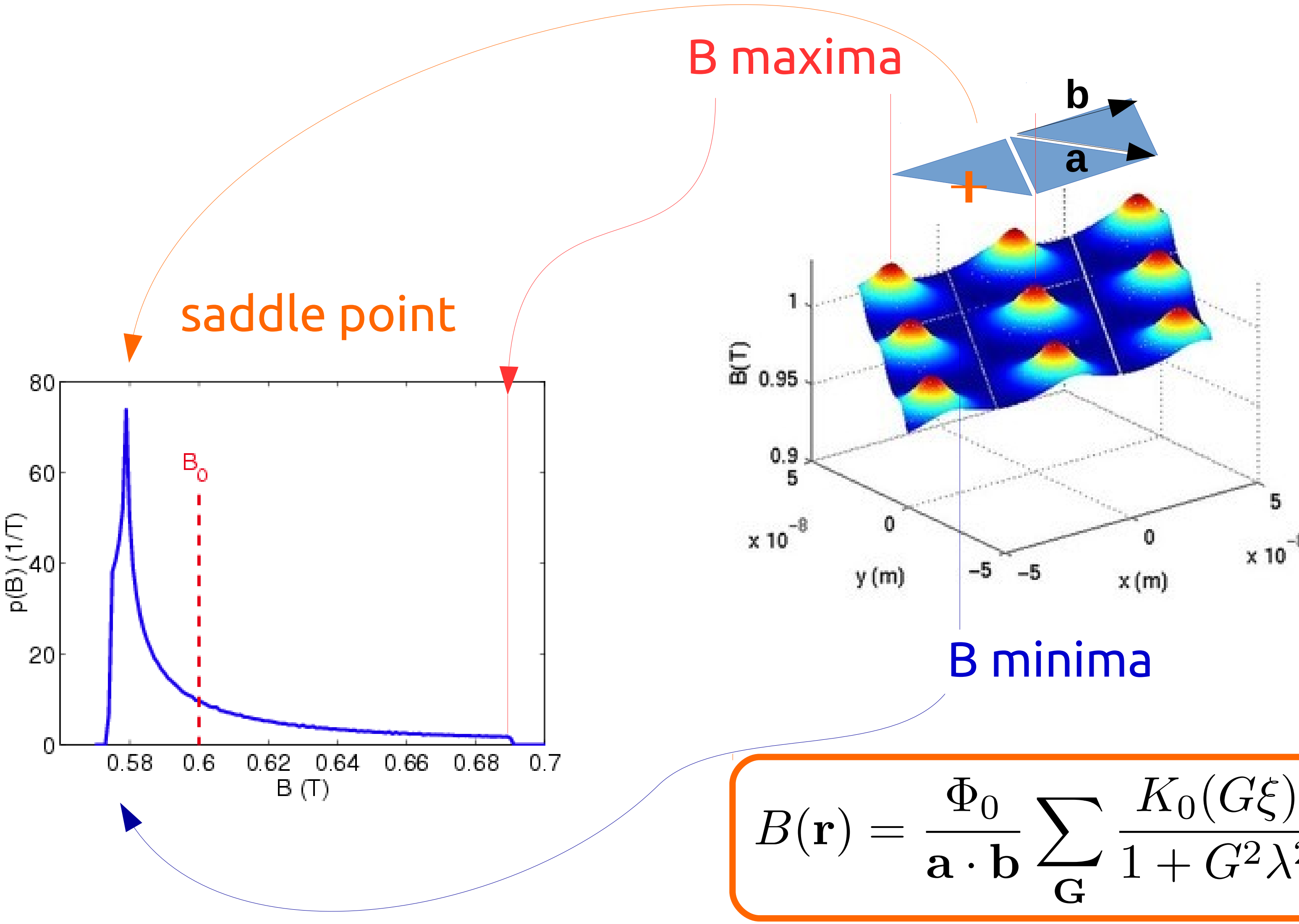


- whereas muons are interstitials in the crystal lattice

→ dense random sampling

Field distribution in the FL

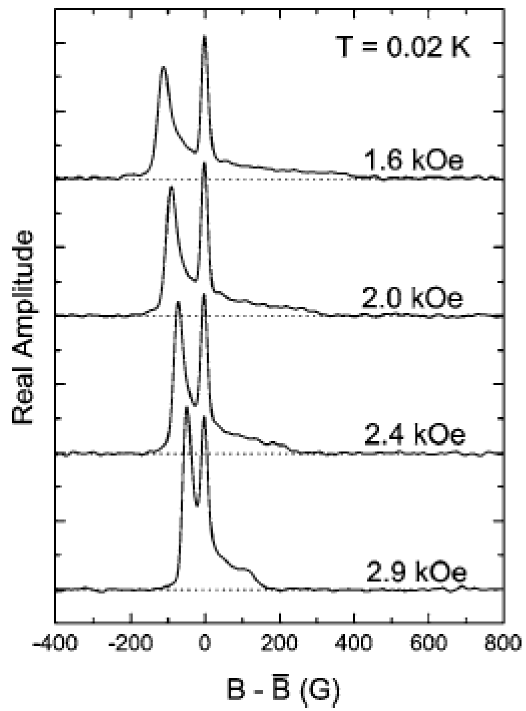
- GL equations predict



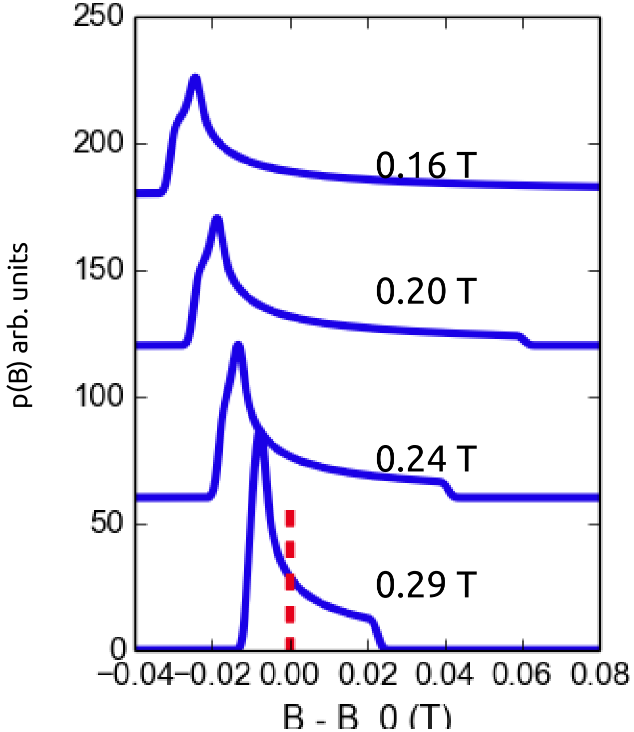
$$B(\mathbf{r}) = \frac{\Phi_0}{\mathbf{a}\cdot\mathbf{b}} \sum_{\mathbf{G}} \frac{K_0(G\xi)}{1+G^2\lambda^2} e^{i\mathbf{G}\cdot\mathbf{r}}$$

Experimental case
Vanadium

M. Laulajainen PHYSICAL REVIEW B 74, 054511 (2006)

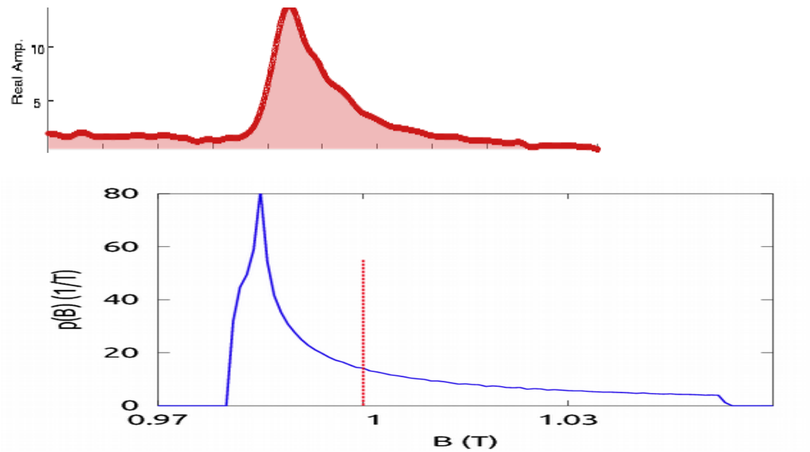


$$\lambda = 50\,\mathrm{nm} \quad \xi = 23\,\mathrm{nm}$$



Quck and dirty multigaussian fit

Comparison with polycrystal data

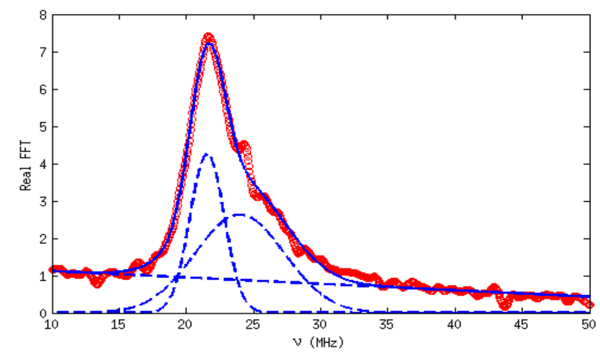


$$B(r) \otimes \exp\left(-\frac{r^2}{2\sigma^2}\right)$$

is it worth while?

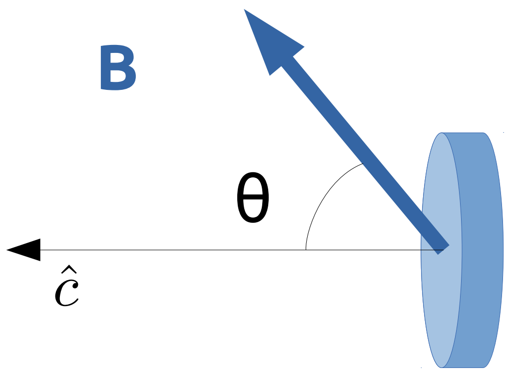
Second moment

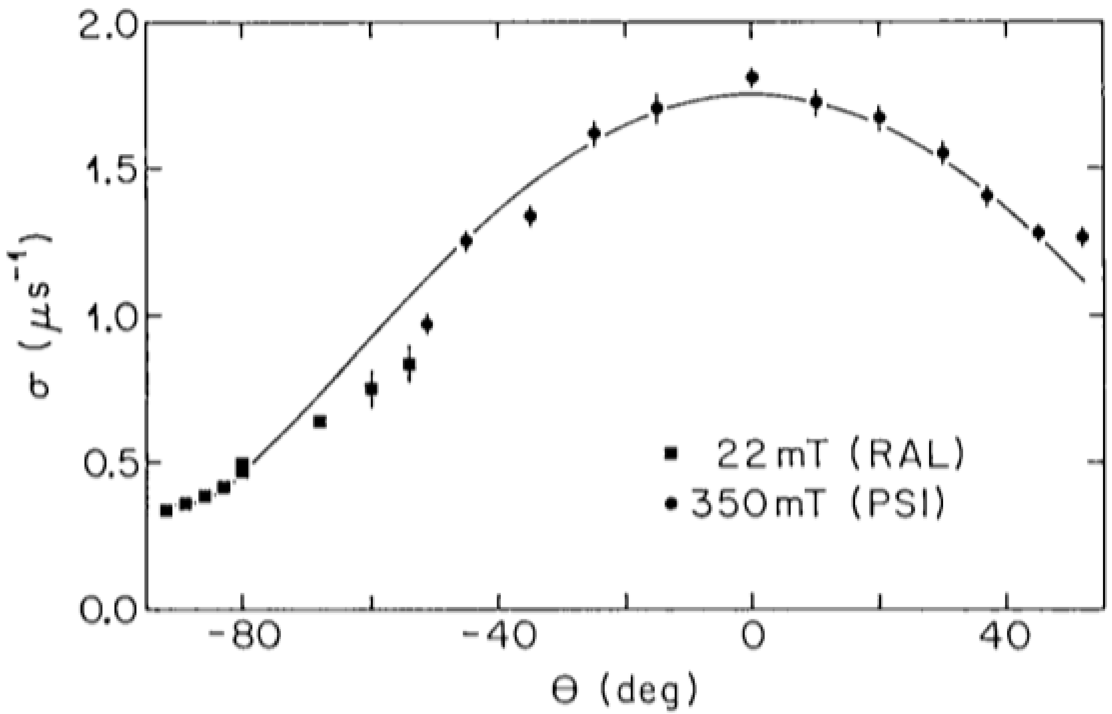
$$\langle \Delta B^2 \rangle = \left(\frac{\Phi_0}{\mathbf{a}\cdot\mathbf{b}}\right)^2 \sum_{\mathbf{k}\neq 0} \frac{K_0^2(k\xi)}{(1+\underbrace{k^2\lambda^2}_{k\lambda>1})^2} \propto \frac{1}{\lambda^4}$$



$$\sigma = \gamma_\mu \sqrt{\langle \Delta B^2 \rangle} \propto \frac{1}{\lambda^2}$$

$$\lambda = \sqrt{\frac{m}{\mu_0 n e^2}}$$





$$\begin{bmatrix} m_a & 0 & 0 \\ 0 & m_a & 0 \\ 0 & 0 & m a_c \end{bmatrix} \rightarrow \begin{bmatrix} \lambda_{ac} & 0 & 0 \\ 0 & \lambda_{ac} & 0 \\ 0 & 0 & \lambda_{aa} \end{bmatrix}$$

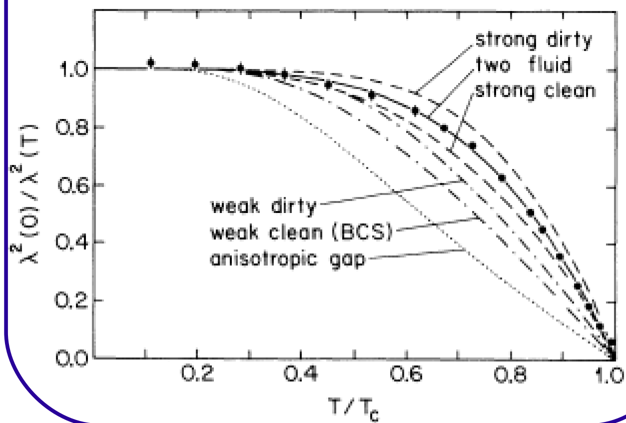
$$\sigma \propto \frac{1}{\lambda_{ac}\lambda_{aa}} \left[\sin^2\theta + \left(\frac{\lambda_{ac}}{\lambda_{aa}}\right) \cos^2\theta \right]$$

E.M. Forgan *et al.* Hyperfine Interactions 63, 71

σ(T): gap fits

$YBCO_{6.95}$ powders (!)

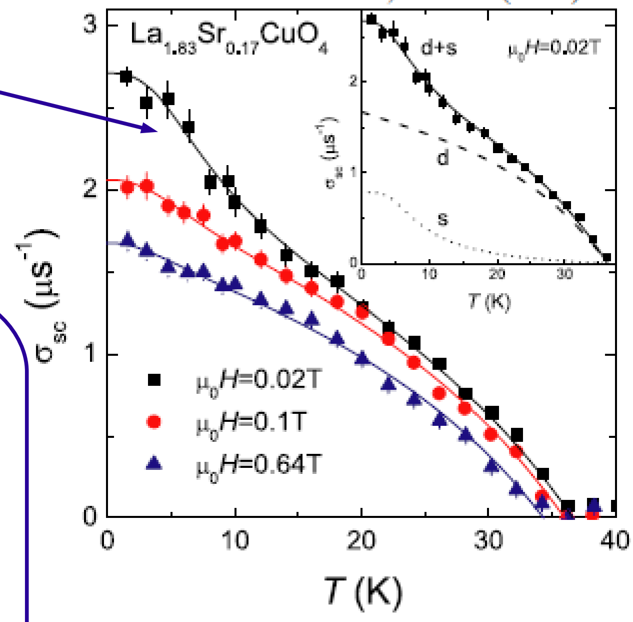
B. PÜMPIN *et al.* PRB42 8019 (1990)



$La_{1.83}Sr_{0.17}CuO_4$ crystal

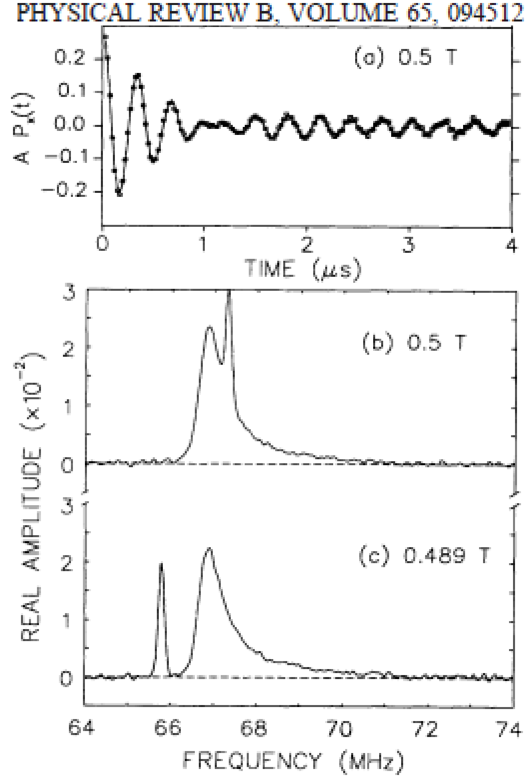
R. Khasanov, PRL **98**, 057007 (2007)

s-wave n_s

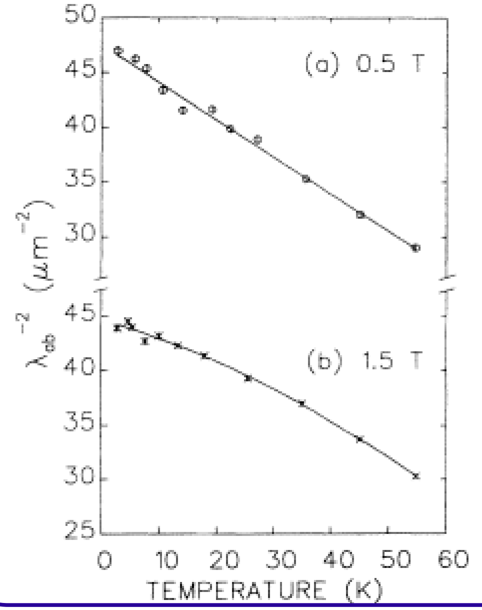


$YBCO_{6.95}$ crystal

PHYSICAL REVIEW B, VOLUME 65, 094512

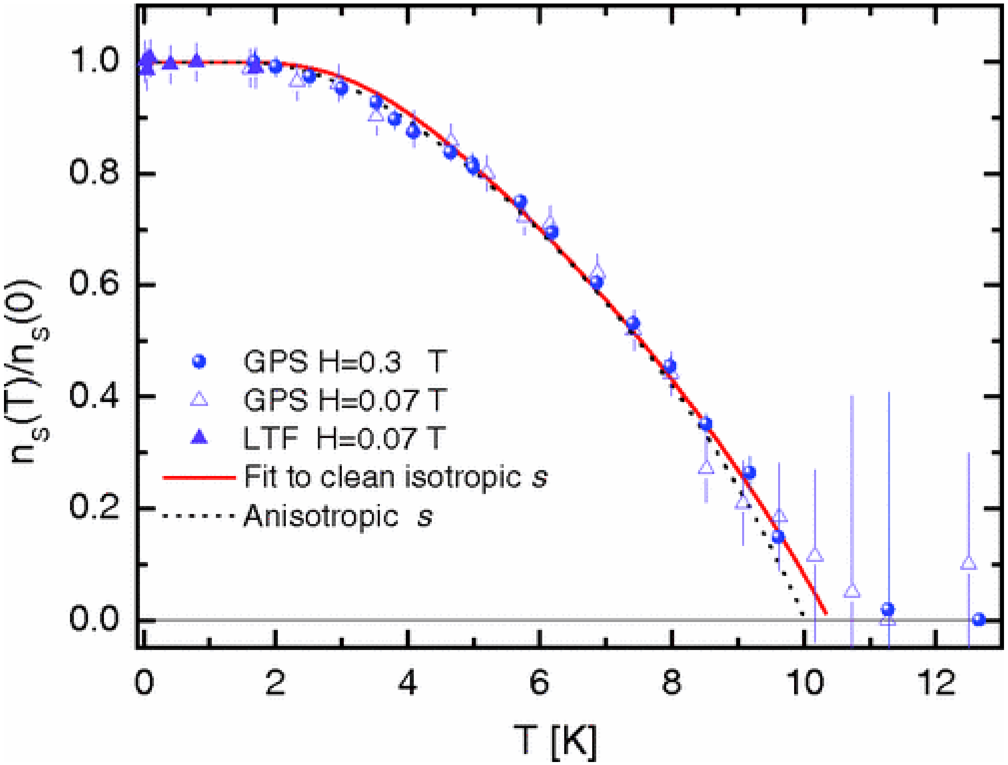


d-wave: lines of nodes

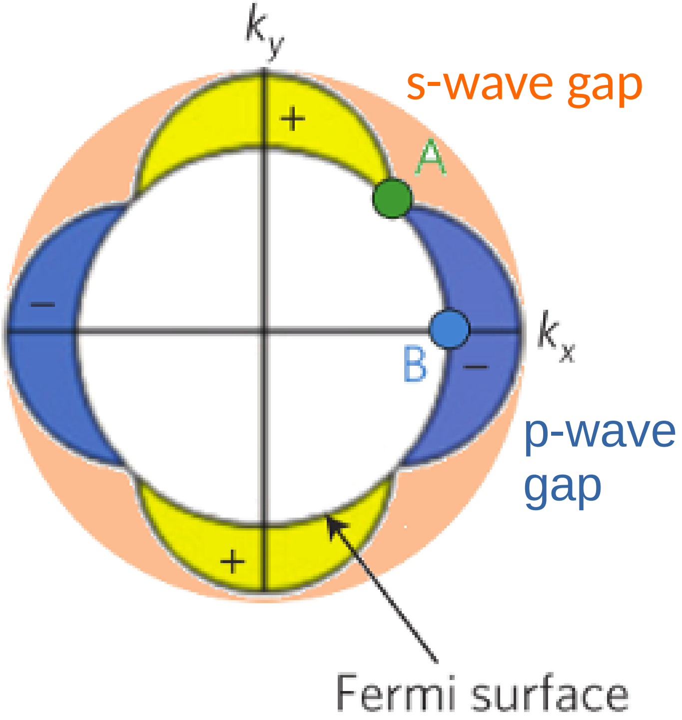


Field cool, then shift field down (pinned flux lattice)

BiS$_2$ ≈ CuO$_2$: conventional or unconventional superconductor?



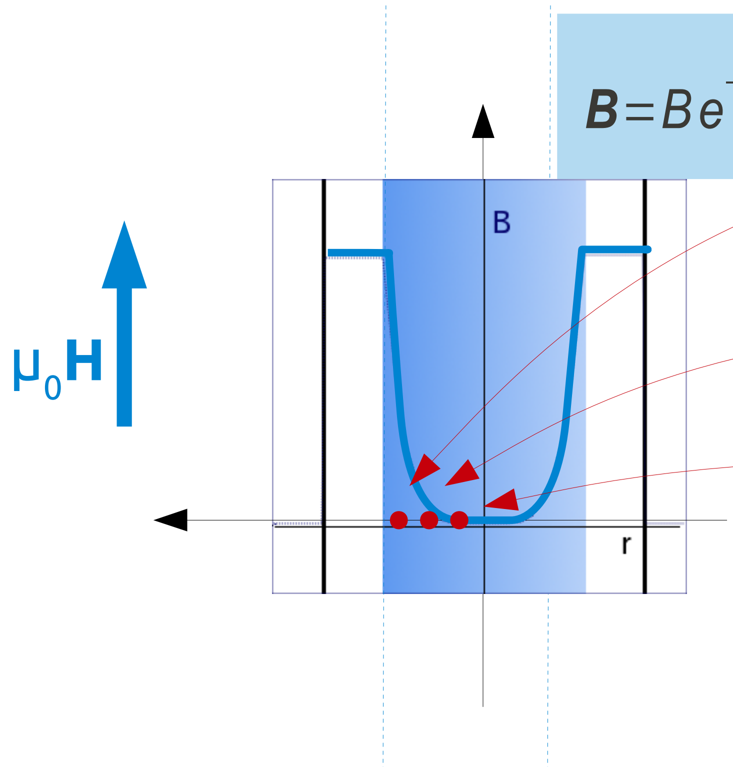
gap, i.e cost to break a Cooper pair



s-wave, not d-wave

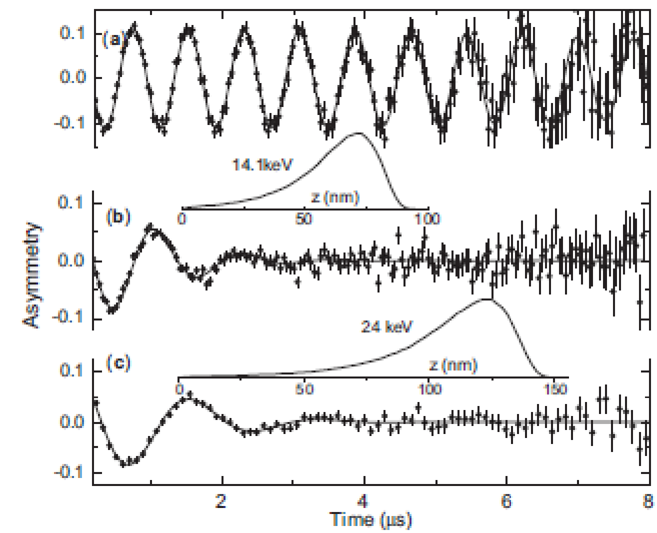
La Mura *et al.* Phys. Rev. B 88, 180509(R)

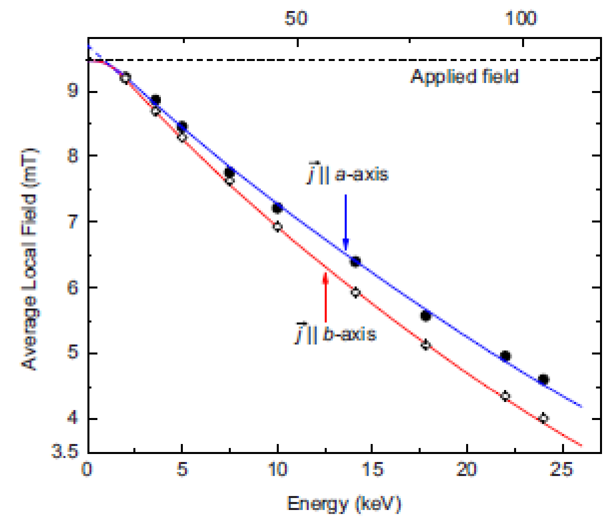
$$\mathbf{B} = B e^{-\frac{r}{\lambda}} \hat{z}$$



Field parallel to the surface decays exponentially with a penetration depth λ

Single crystal $YBa_2Cu_3O_{6.92}$





R. Kiefl et al. PRB 81 180502 (2010)

$$\sigma_\mu = \gamma_\mu \sqrt{\langle \Delta B^2 \rangle}$$
$$\propto \frac{1}{\lambda^2} = \frac{\mu_0 n_s e^2}{m}$$

B. PÜMPIN *et al.* PRB42 8019 (1990)

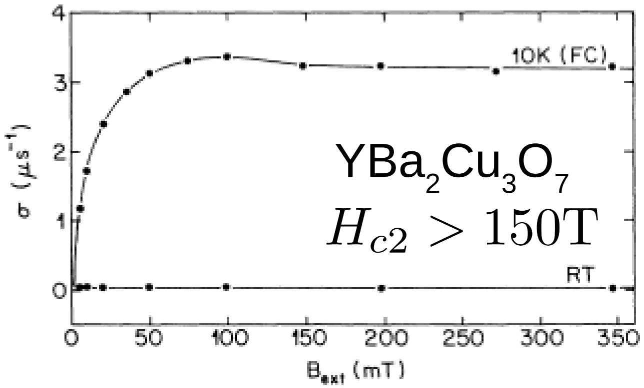
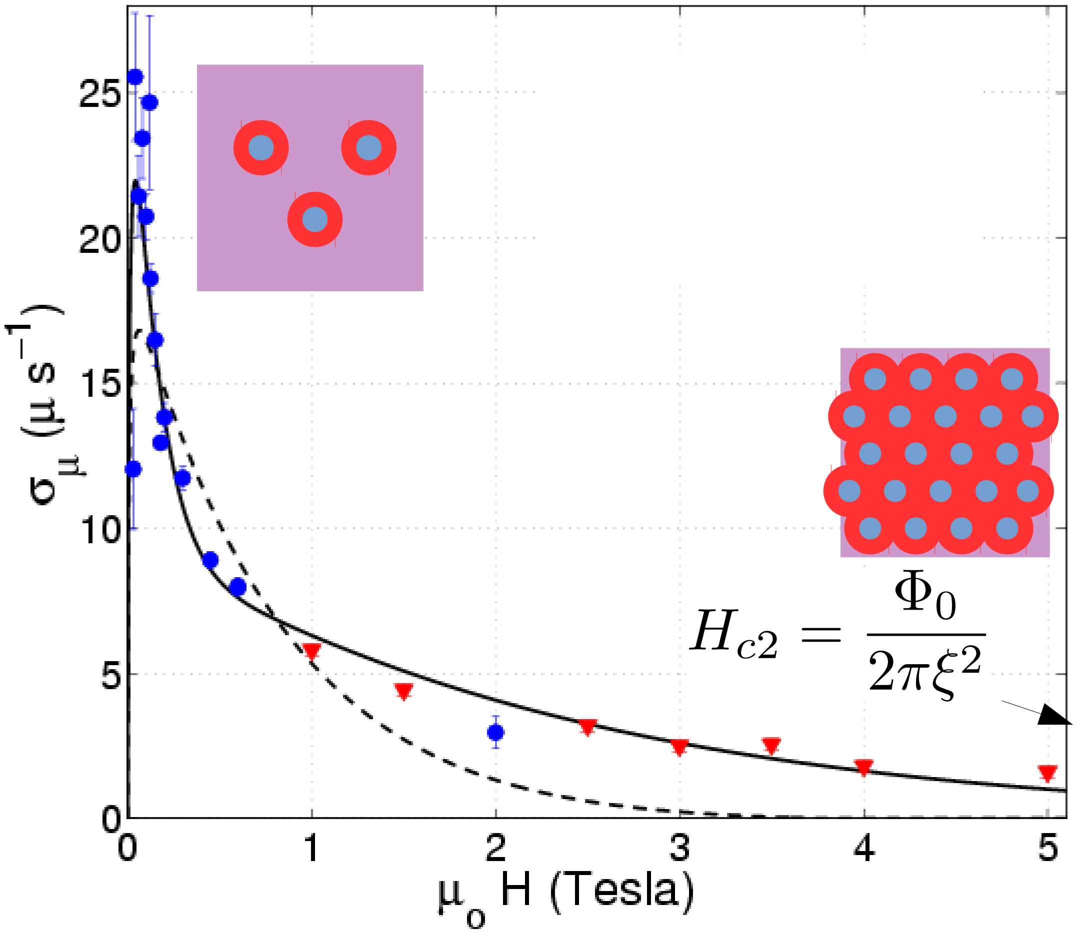


FIG. 2. Depolarization rate σ as a function of the external field B_{ext} (FC) for a sintered $YBa_2Cu_3O_x$ sample at 10 K and at room temperature (RT), respectively. The lines are guides to the eye.



S. Serventi Phys. Rev. Lett. 93 217003

Uemura plot

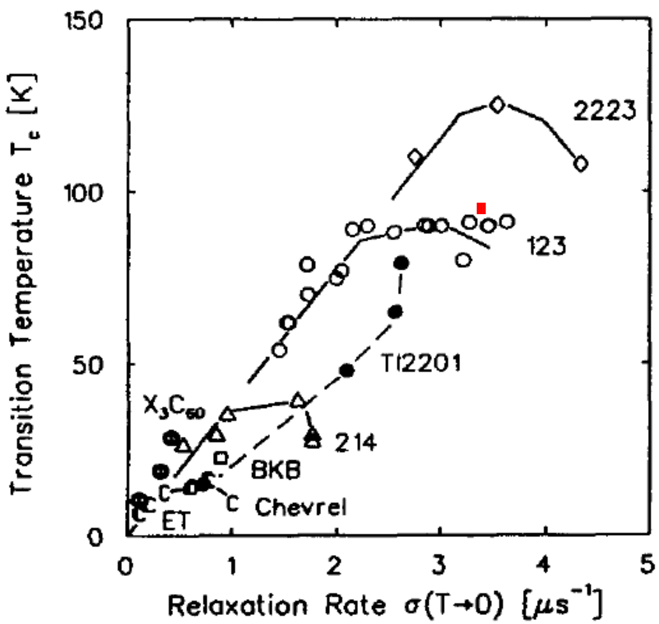
At T=0:

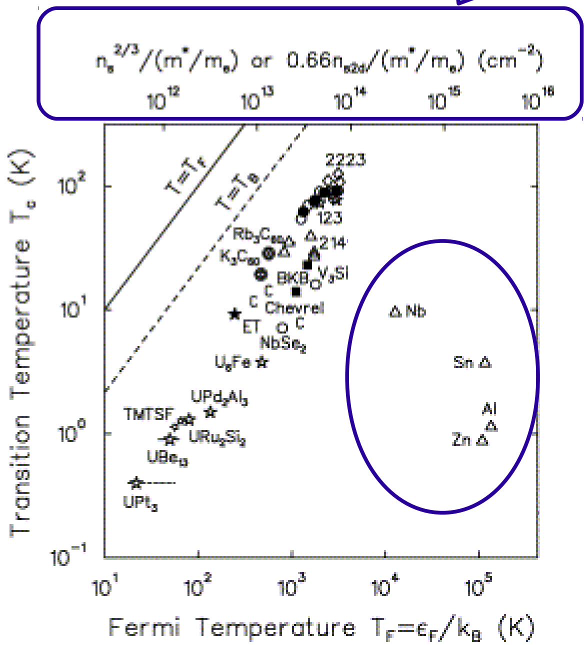
$$\sigma_\mu = \gamma_\mu \left(\langle B^2 \rangle - \langle B \rangle^2 \right)^{\frac{1}{2}} \propto \frac{1}{\lambda^2} \propto \frac{n_s}{m^*}$$

Y.J Uemura et al. Phys Rev Lett. 62, 2317 (1989) **500 cit**.

Y.J Uemura et al. Phys Rev Lett. 66, 2665 (1991) **300 cit.**

unconventional





conventional

σ → n_s → T_F

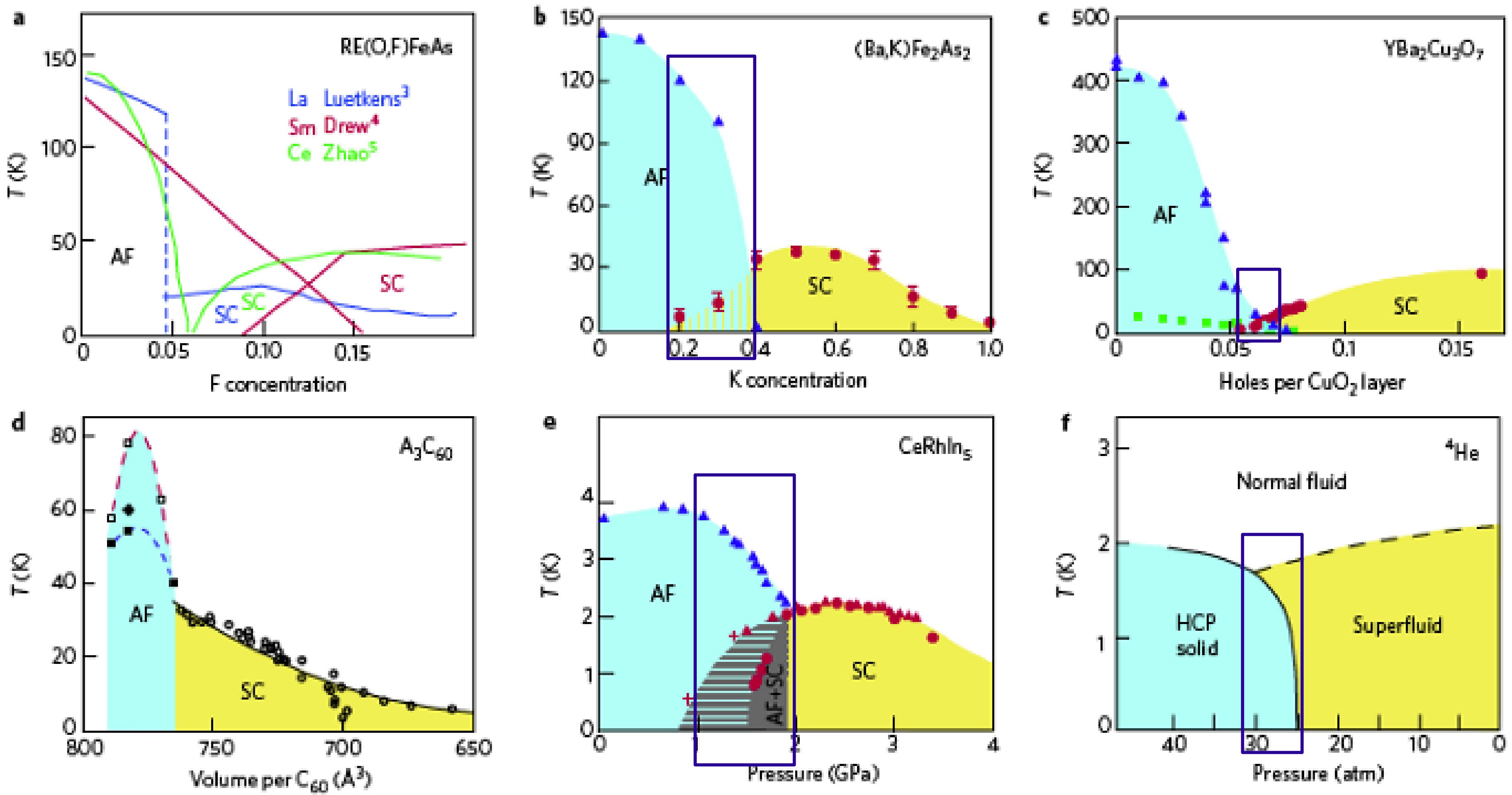
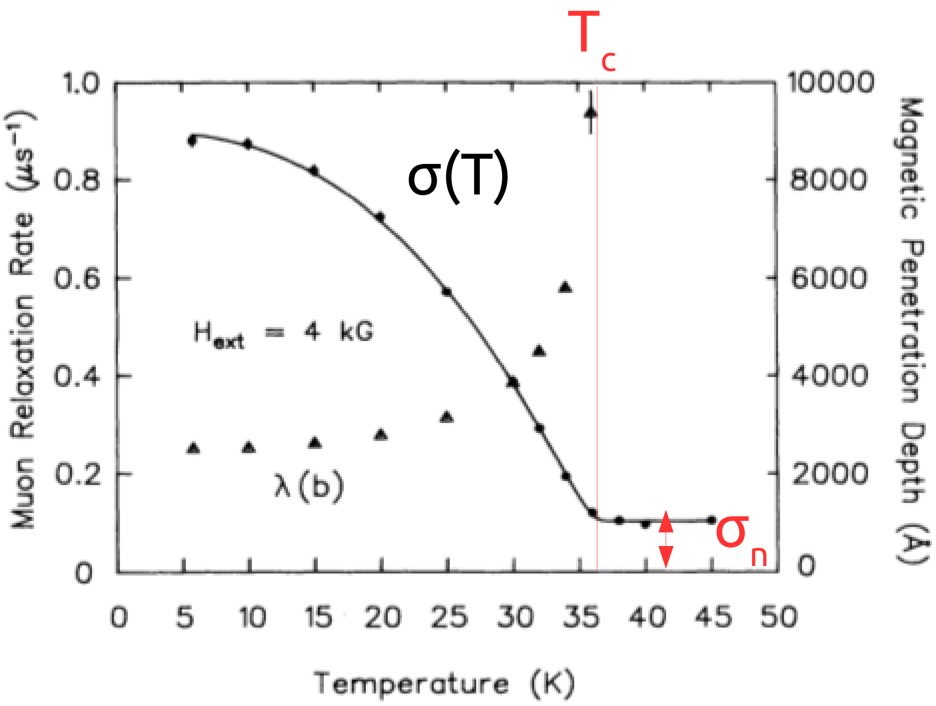


***Fig. 11.1** .Examples of phase diagrams showina commonalities of unconventional superconducting compound [Uem09] c, YBaCuO6+x, is from* S. Sanna Phys Rev Lett. 93 207001 (2004)

Y.J. Uemura Nature Materials 8 253 (2009)



Q3: How do we subtract the nuclear relaxation rate σ_n?

In quadrature: $$\gamma_\mu^2 \langle \Delta B^2 \rangle_\mu = \gamma_\mu^2 \langle \Delta B^2 \rangle_{FL} + \sigma_n^2$$

Recap

- Muons map the internal field distribution
- Two length scales, λ (currents, fields) and ξ (gap, wave function)
- Refined model (full distribution) for single crystal studies
- Rough model (second moment) for comparative studies
- $\sigma(T) \propto \lambda^{-2}(T)$: gap(s), symmetries
- coexistence with magnetism

That's it ...