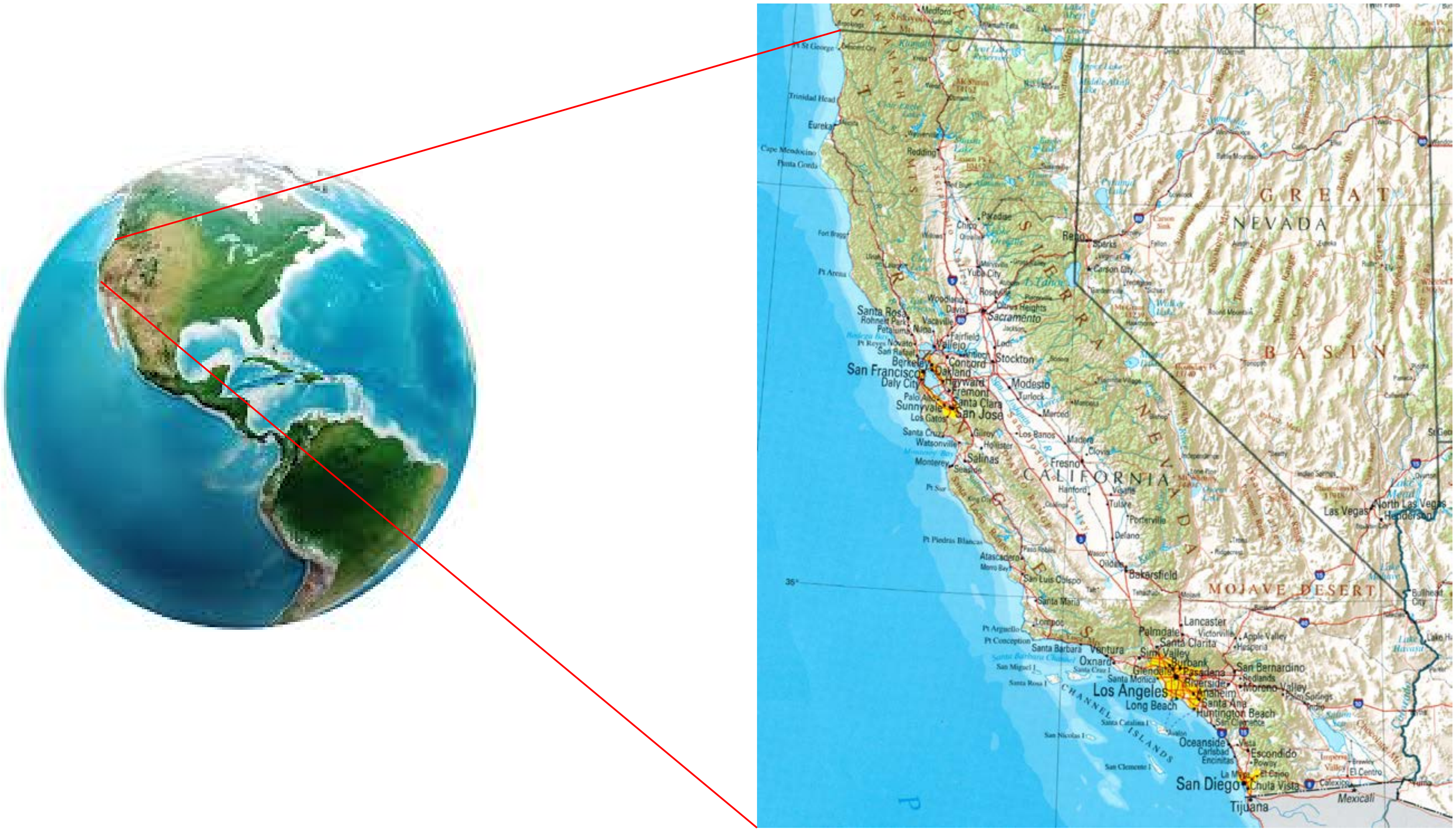
Minicurso de Supercondutividade Experimental

IFGW Escola de Inverso 2015: Fenômenos emergentes em Magnetismo e Supercondutividade

Universidade de Campinas
Instituto de Física "Gleb Wataghin"
20-31 Julho 2015

Nicholas Curro , UC Davis Dept of Physics

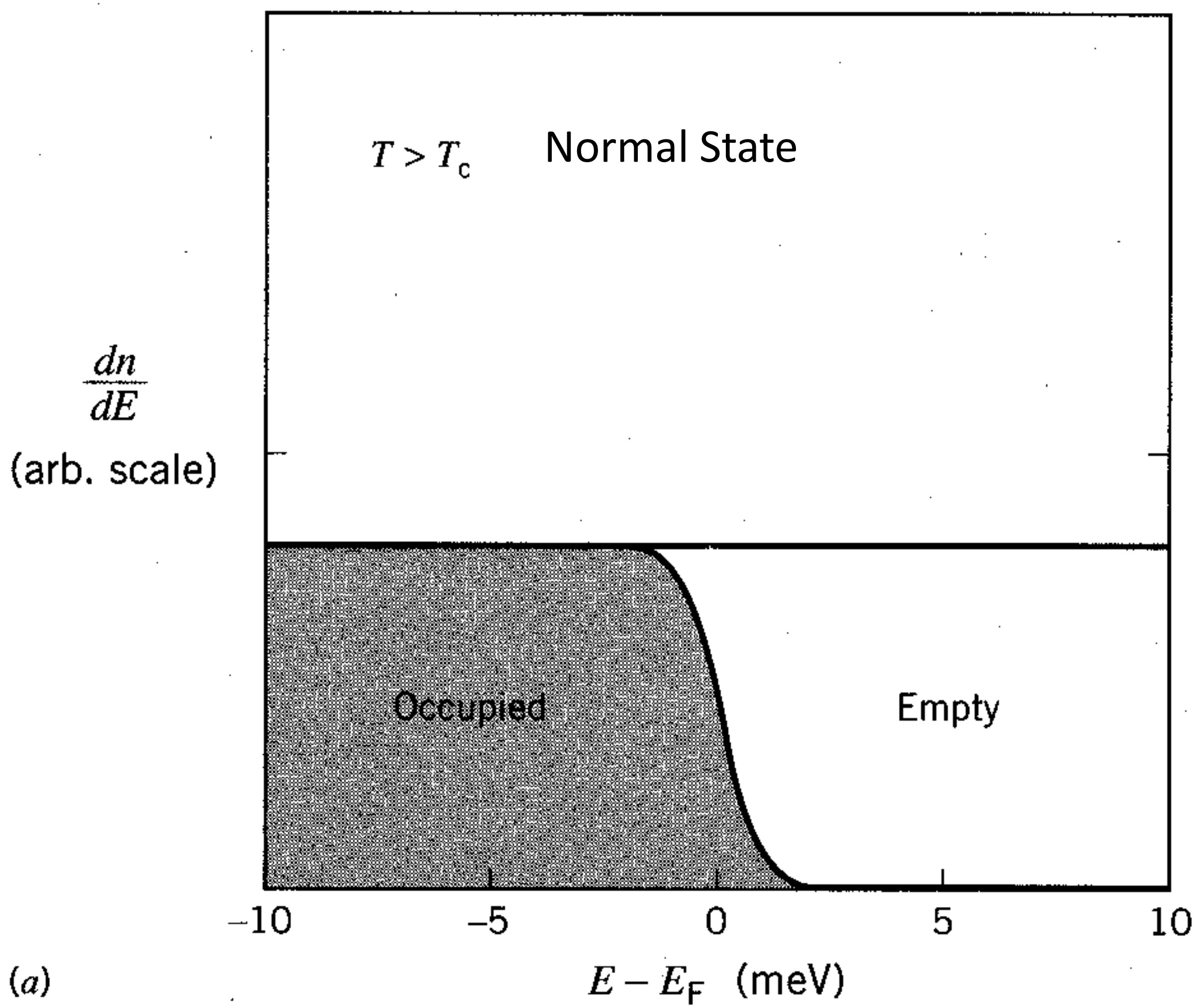
Cade o UC Davis?



Universidade da California

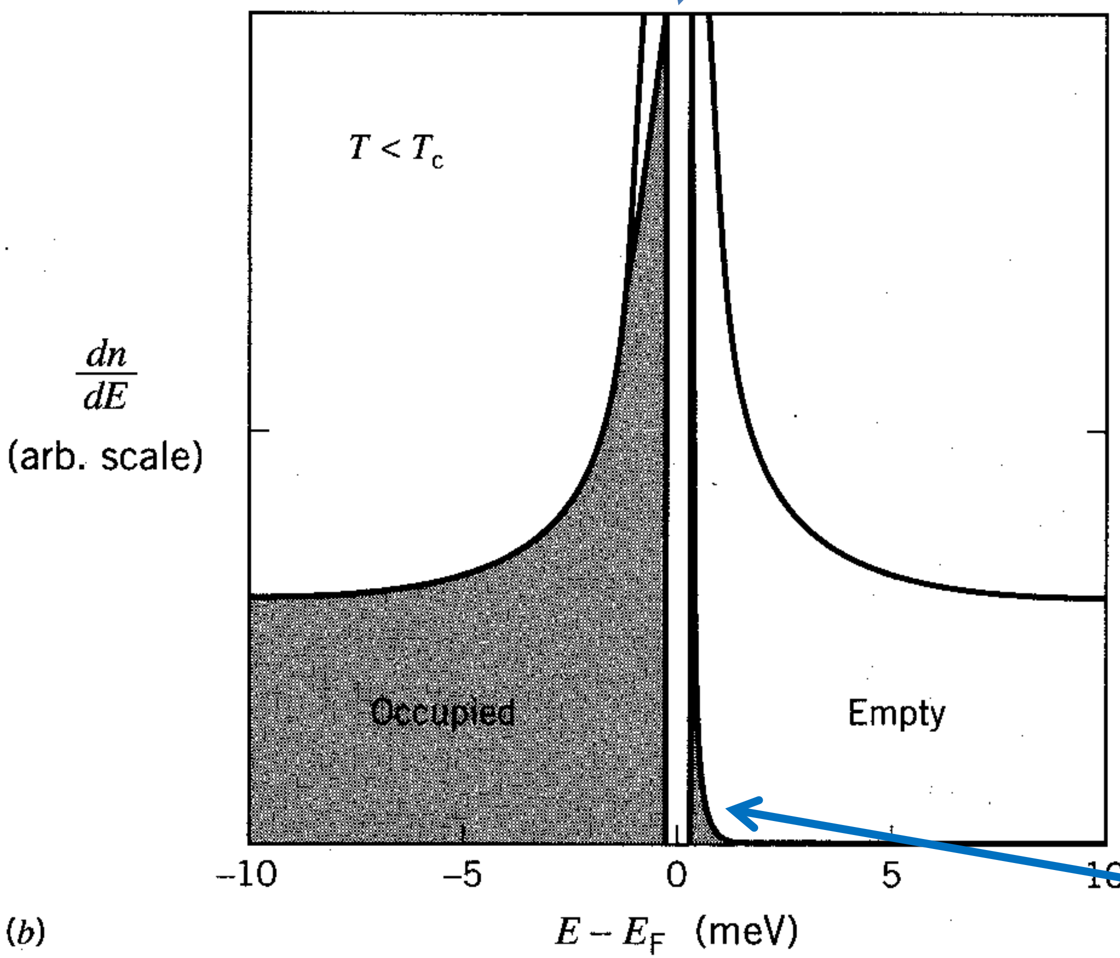
10 campuses
238700 Undergraduates
50400 Postgraduate
19700 Academic Staff

Energy Gap



The density of states in a normal metal is constant, and the states are occupied up to the Fermi level at E_F

Energy Gap



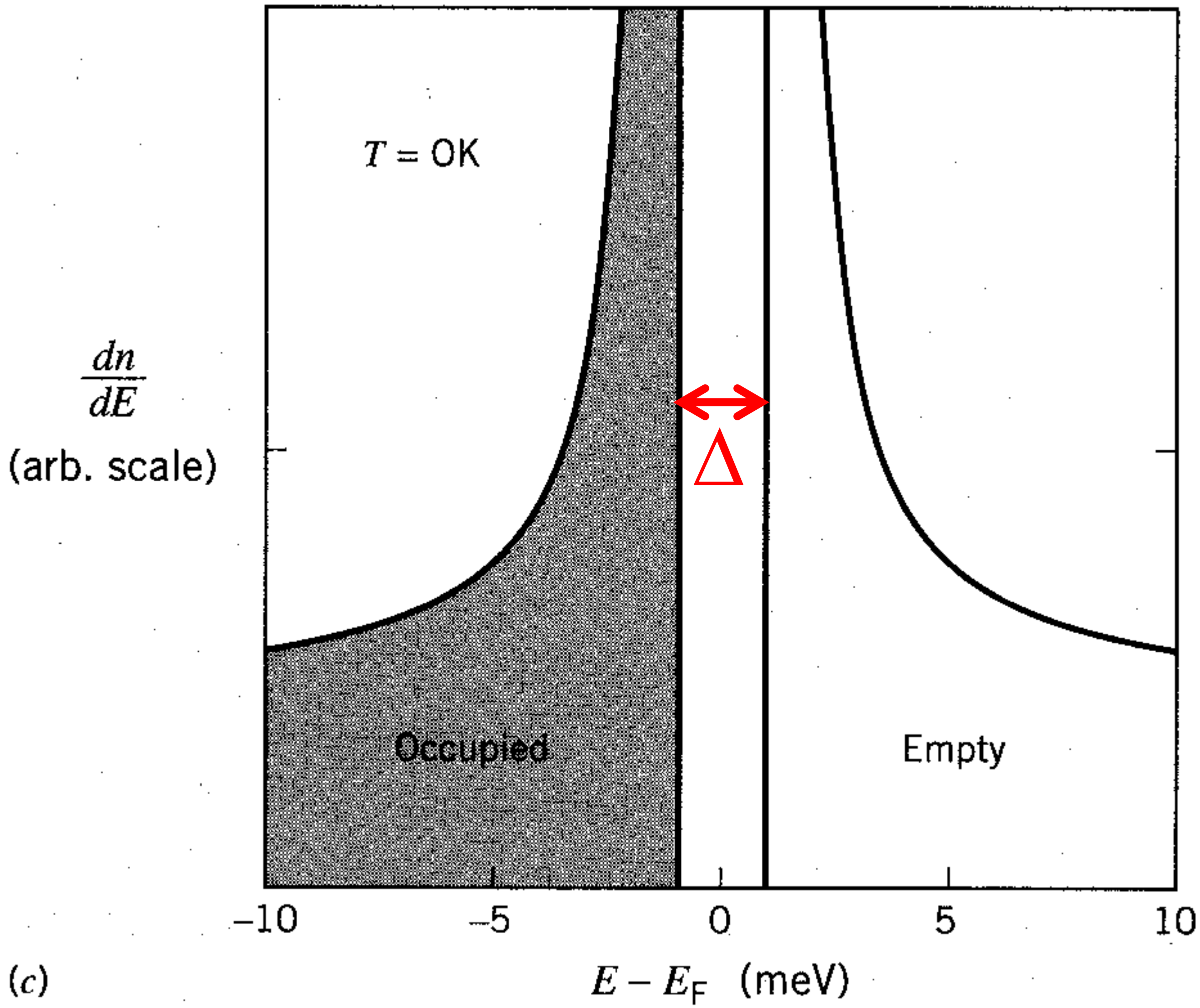
Superconducting Energy gap

In a superconductor, a **superconducting gap** develops at the Fermi surface

$$N_{\rm BCS}(E) = \frac{E}{\sqrt{E^2 - \Delta^2}} N_{\rm N}(E)$$

Thermally excited quasiparticles

Energy Gap



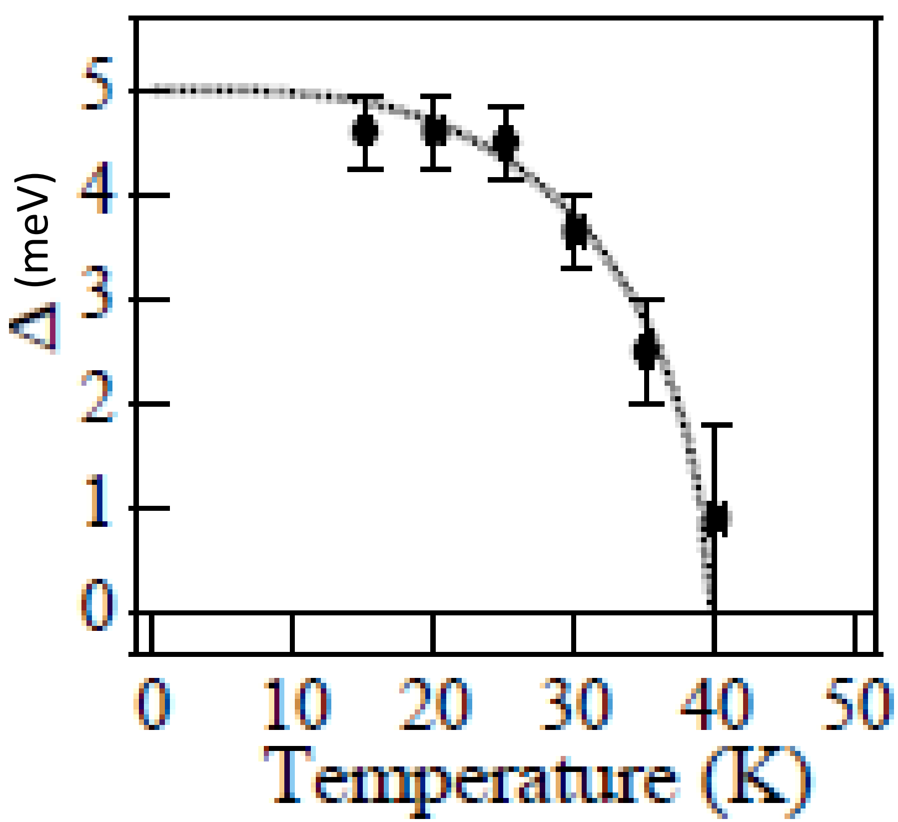
No quasiparticles at T=0 means Specific heat, thermal conductivity vanish!

Any property that probes the Fermi surface will exhibit dramatic changes

BCS: $\Delta = 3.2k_BT_c$ ~ a few meV

Supercurrent is carried by the **superconducting condensate**, not the quasiparticles

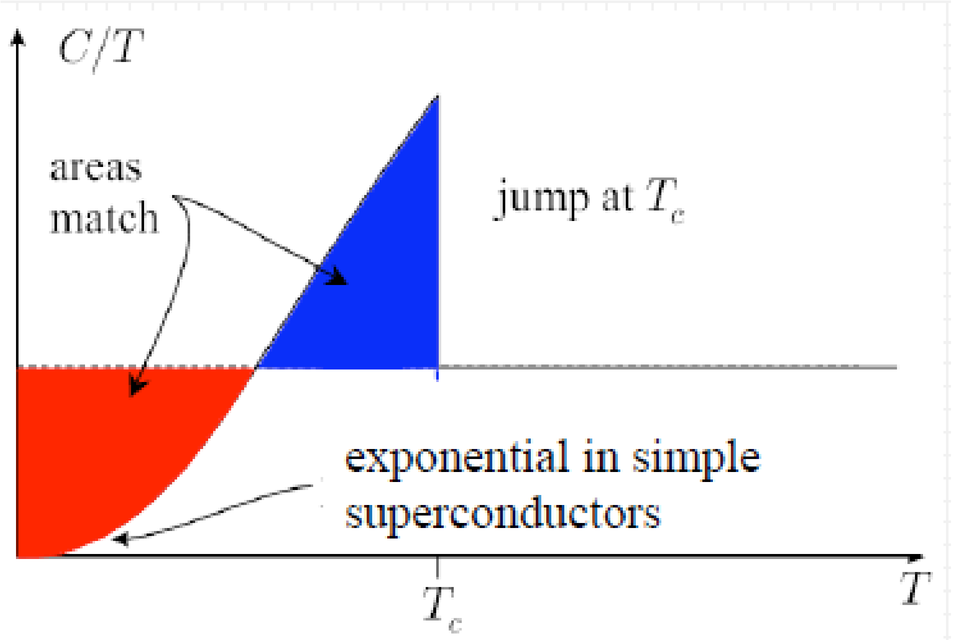
Temperature Dependence of Gap



MgB_2
T_c = 39.5K
Takahashi et al, 2001

Measured directly from Angle Resolved Photoemission Spectroscopy (ARPES)

Specific Heat

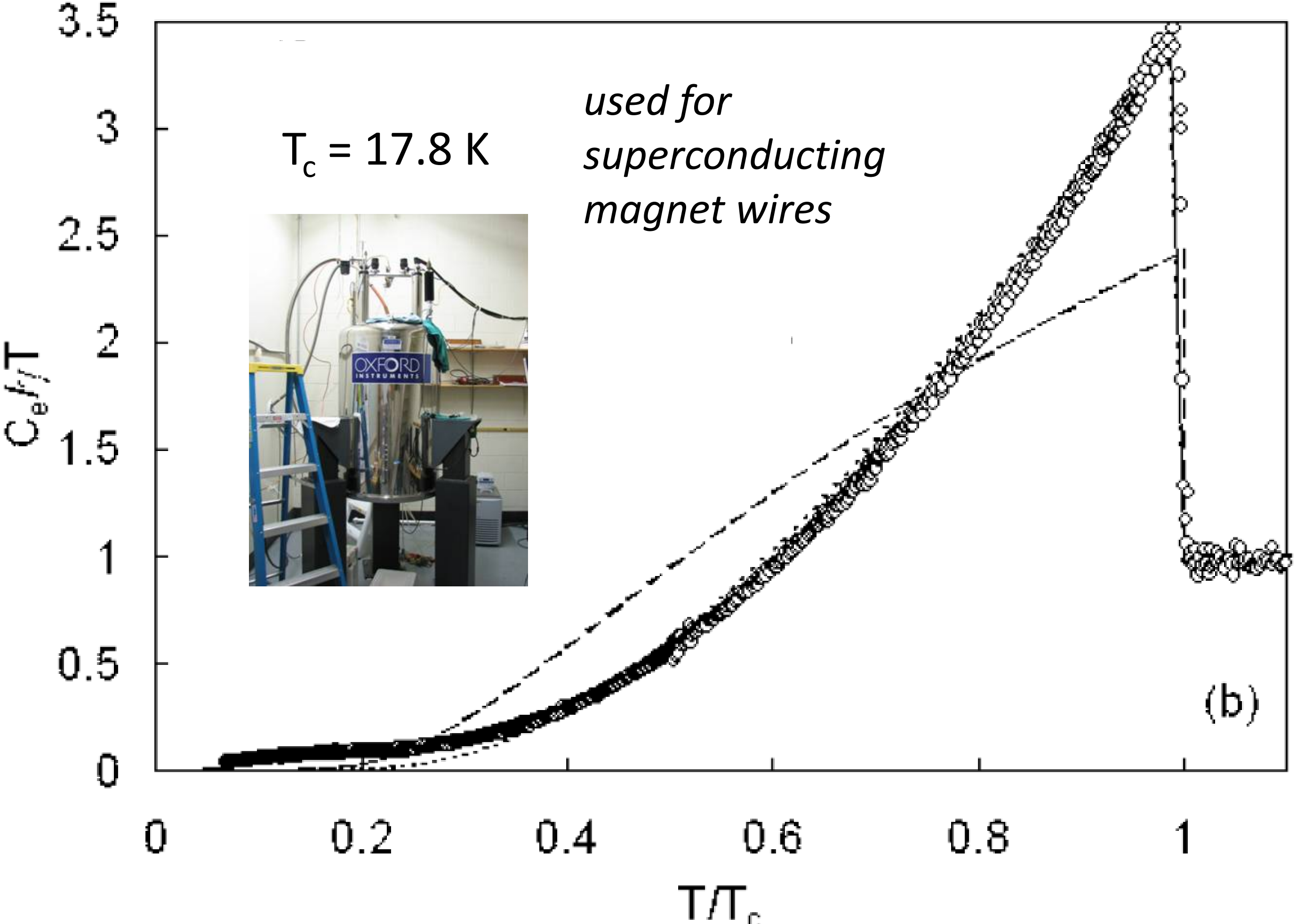


Experiments that probe the Fermi surface can probe the superconducting gap

Electronic specific heat of metal: $C/T \sim N(E_F)$

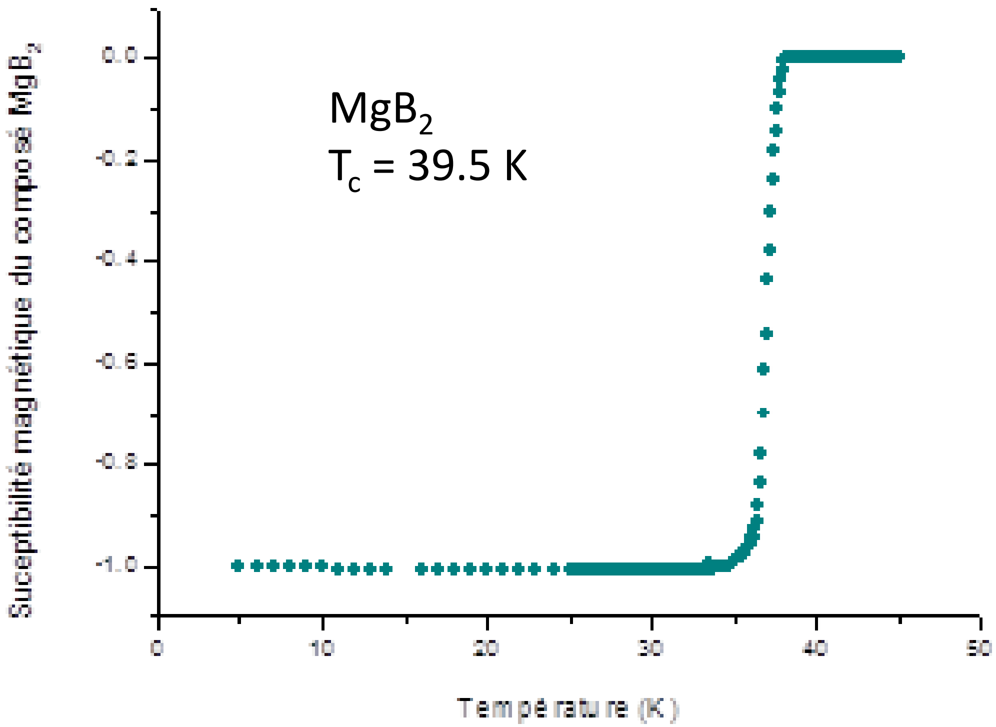
In SC state: $C/T \sim e^{-\Delta/k_B T}$

Example: Nb_3Sn



Guritano et al. PRB 2004

Magnetic Susceptibility



$$B = H + 4\pi M$$

$$M = \chi H$$

$$\Rightarrow \chi = -\frac{1}{4\pi}$$

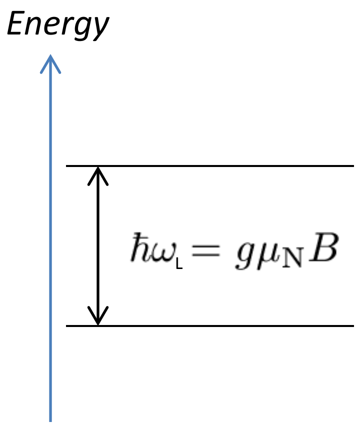
(cgs units, SI: χ = -1)

$$\chi = \chi_{orb} + \chi_{spin}$$

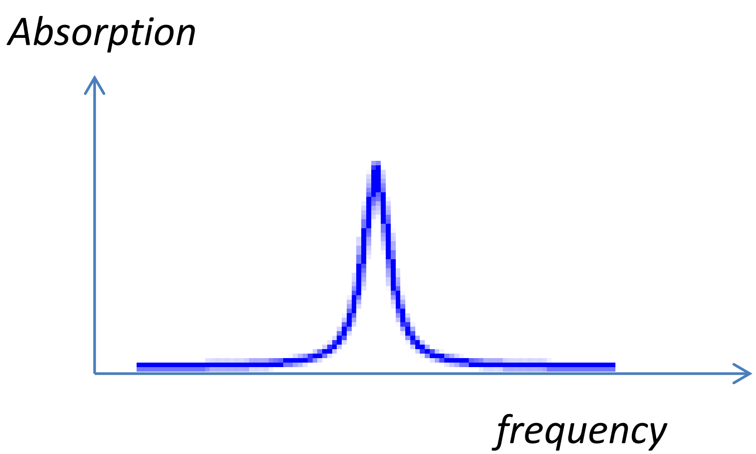
Susceptibility dominated by orbital screening currents. Spin susceptibility can be probed by NMR (see later)

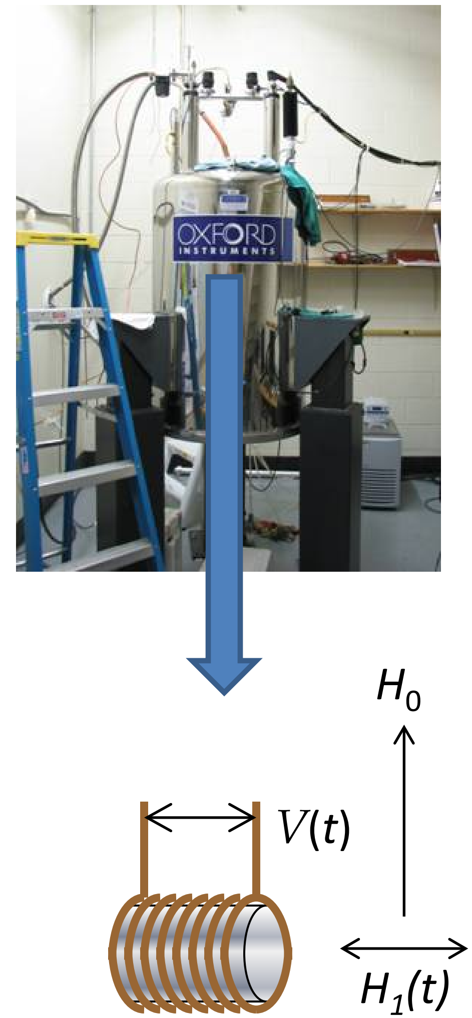
$$\chi_s = \mu_B^2 N(E_F)$$

Nuclear Magnetic Resonance



~ 100 MHz





Spin Susceptibility

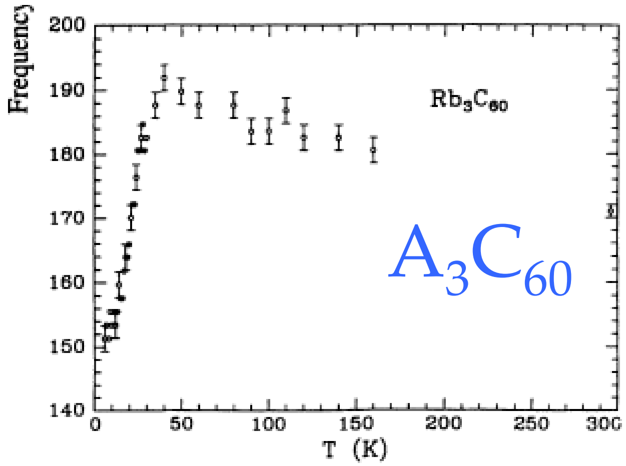
- NMR resonance frequency decreases:

$$f = \gamma H_{internal}(1 + K)$$

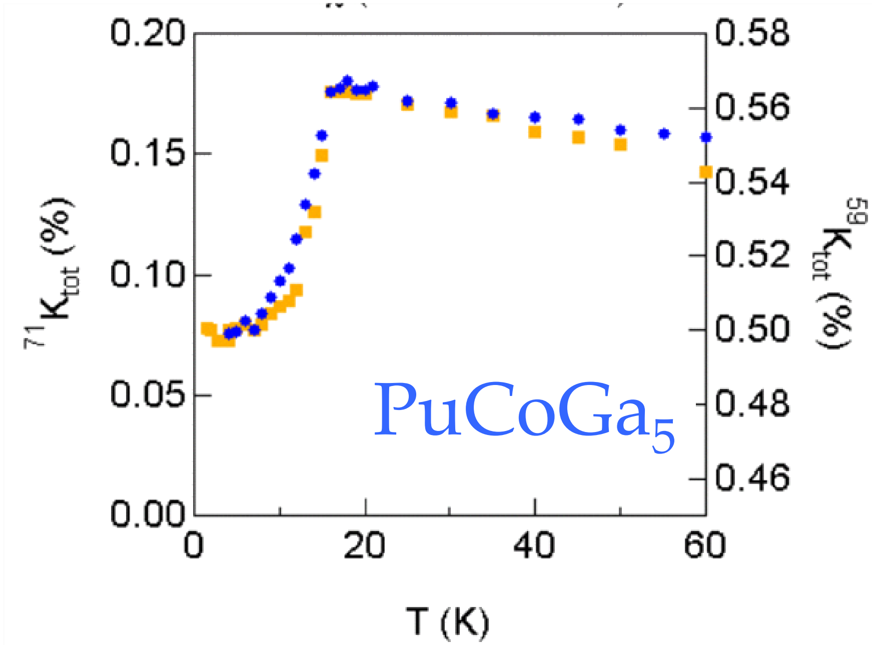
K = Knight shift

$K = A\chi_s$

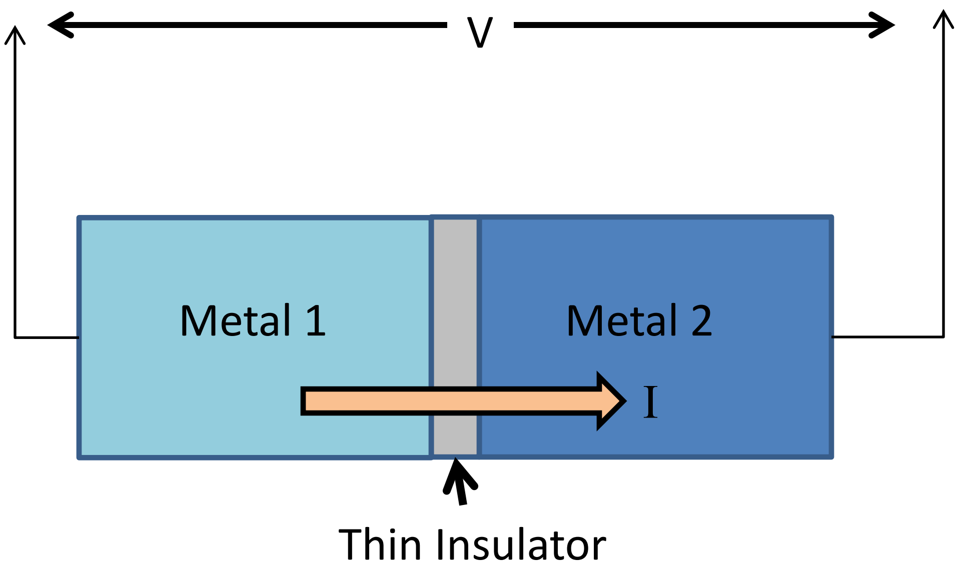
A = Hyperfine coupling



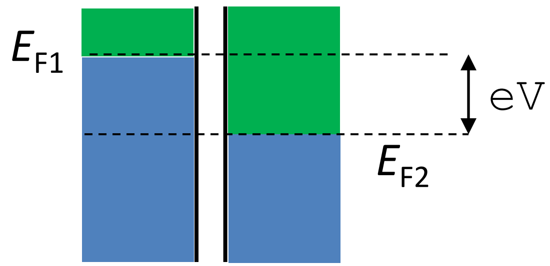
In many superconductors, the Knight shift is suppressed below T_c. This reflects the fact that the Cooper pairs in in a **singlet state**!



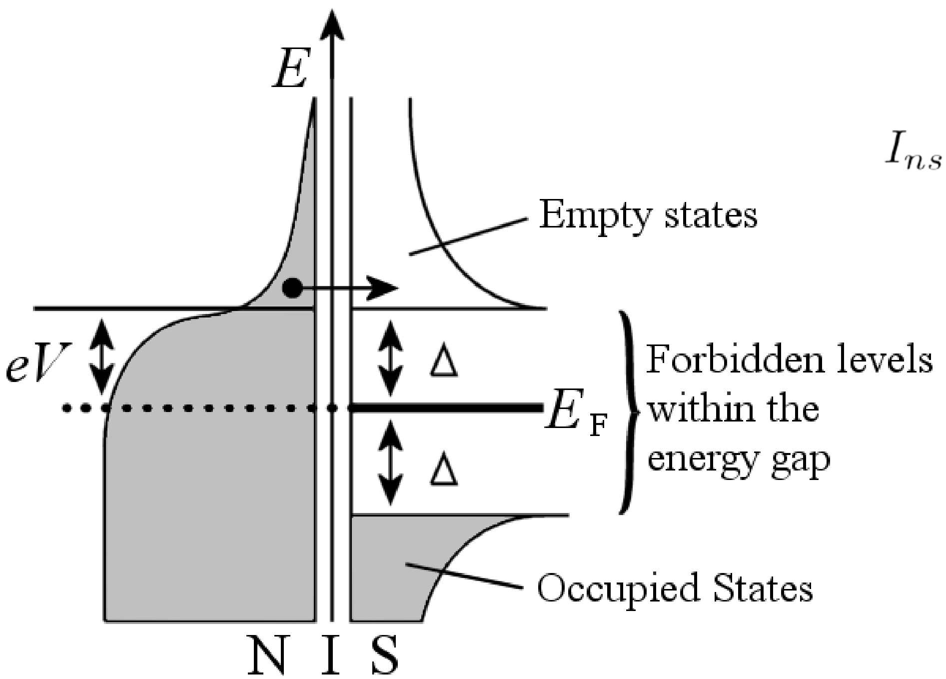
Tunneling: NIN junction



$$I \sim \int N_1(E+eV)N_2(E)[f(E)-f(E+eV)]dE \sim N_1(E_F)N_2(E_F)eV$$



Tunneling: NIS Junction

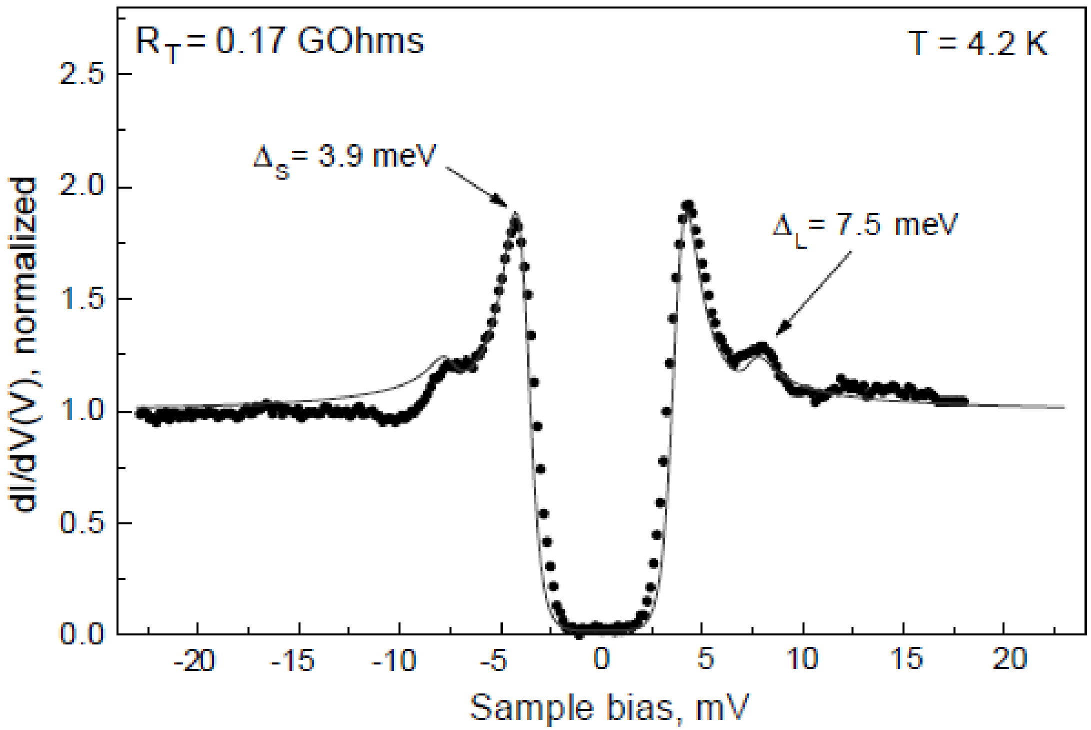


$$I_{ns} \sim N_n(E_F) \int N_s(E)[f(E) - f(E_eV)]dE$$

$$\boxed{\Rightarrow \frac{dI_{ns}}{dV} \sim N_s(eV)}$$

Can probe density of states directly by measuring the differential conductance

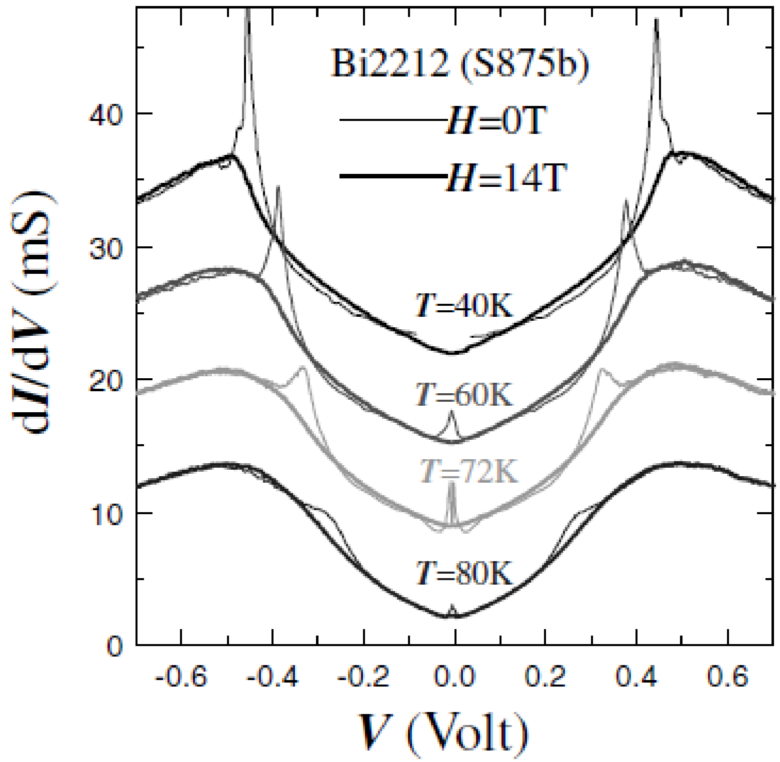
Example: MgB_2



Note the presence of two gaps!

Giubelio et al, EPL (2002)

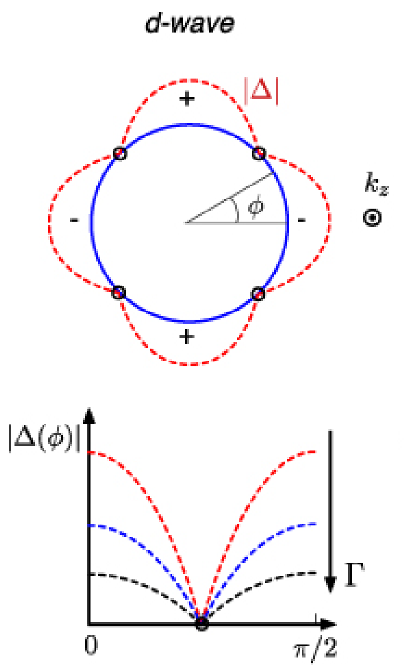
Example: High T_c



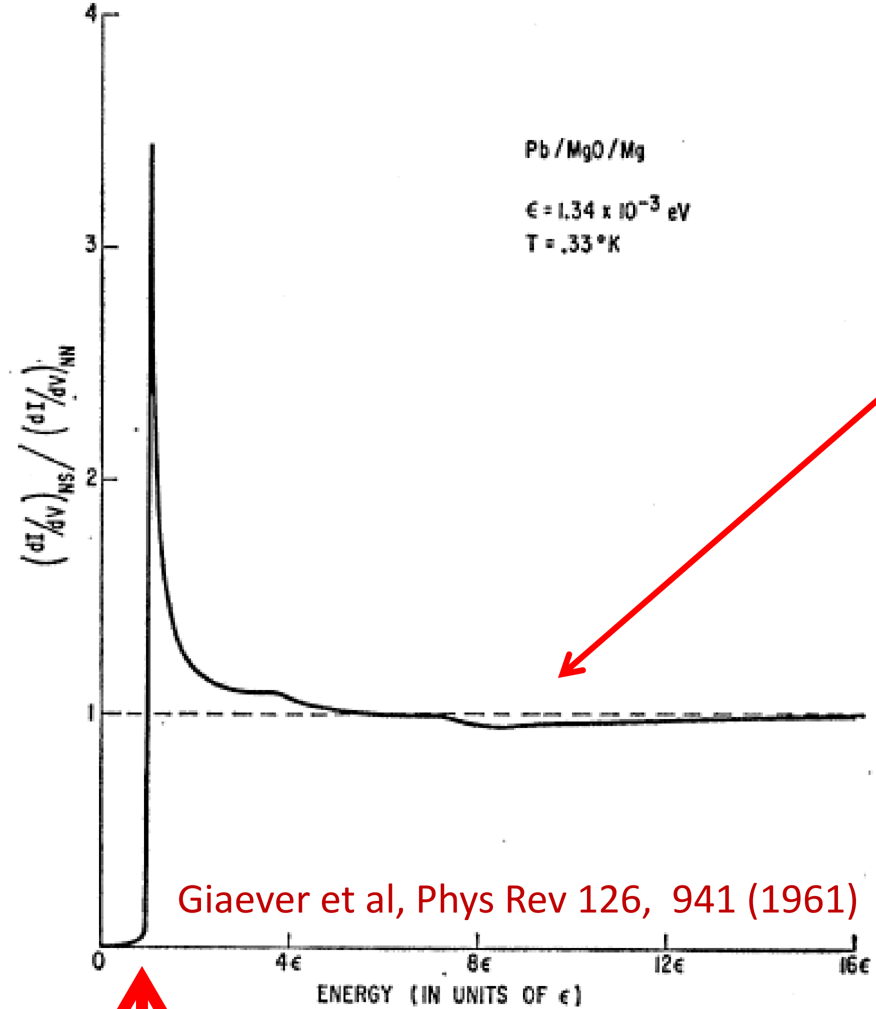
Krasnov et al., PRL (2001)

Does not show flat DOS , but something more like a V shape

This is due to the d-wave nature of the superconducting gap



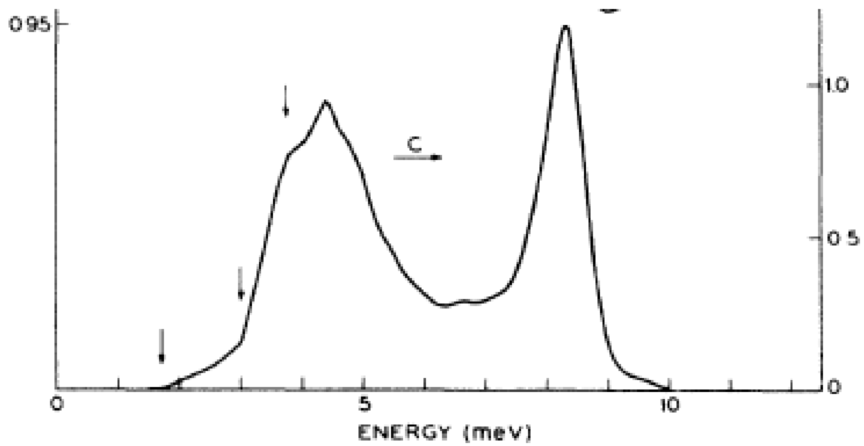
Example: Pb



Structure above energy gap reflects phonon density of states

Energy gap

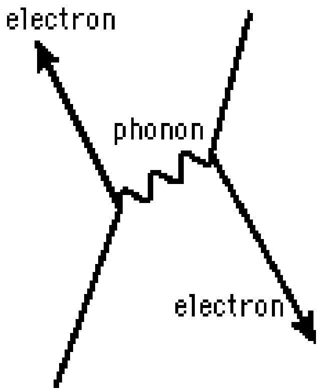
Phonon Mechanism



$$\alpha^2(\omega)F(\omega)$$

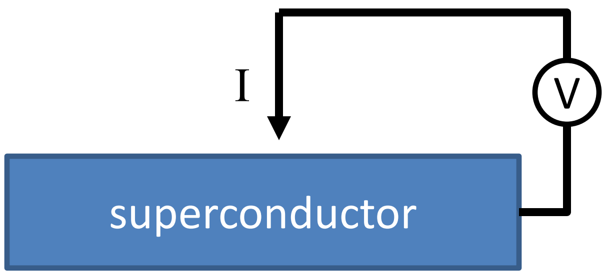
Calculated from Eliashburg Equations

McMillan and Rowe, Phys Rev Lett (1965)

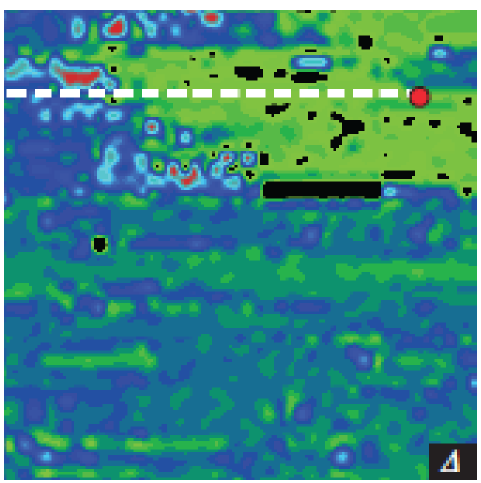


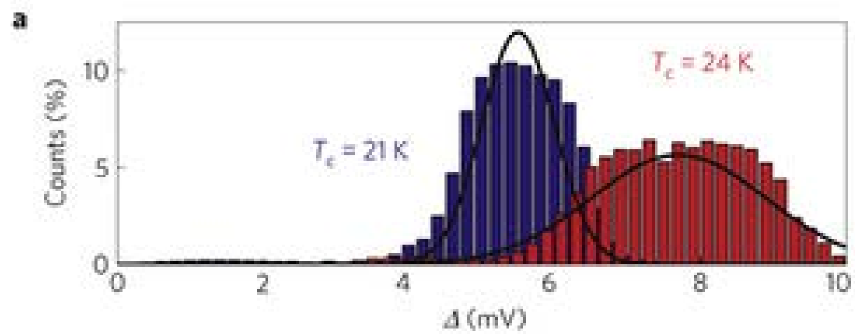
The fact that the phonon density of states is reflected in the electronic density of states below Tc provides strong support for the idea that **electron-phonon coupling** plays a role in the superconducting mechanism

Scanning Tunneling Microscopy



STM: Scan tip over surface using piezomechanical devices, measuring I vs V as a function of position

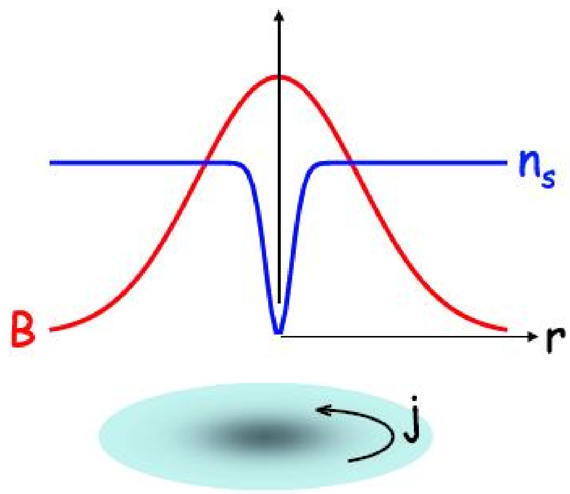




"**Gap Map**" – positional variation of SC gap in La(Pr,Ce)CuO4 cuprate (Zhao et al, Nature Phys. 2011)

Vortex Line

GL Equation shows that for sufficiently high fields, the free energy is lower if flux can penetrate rather than simply screening the field



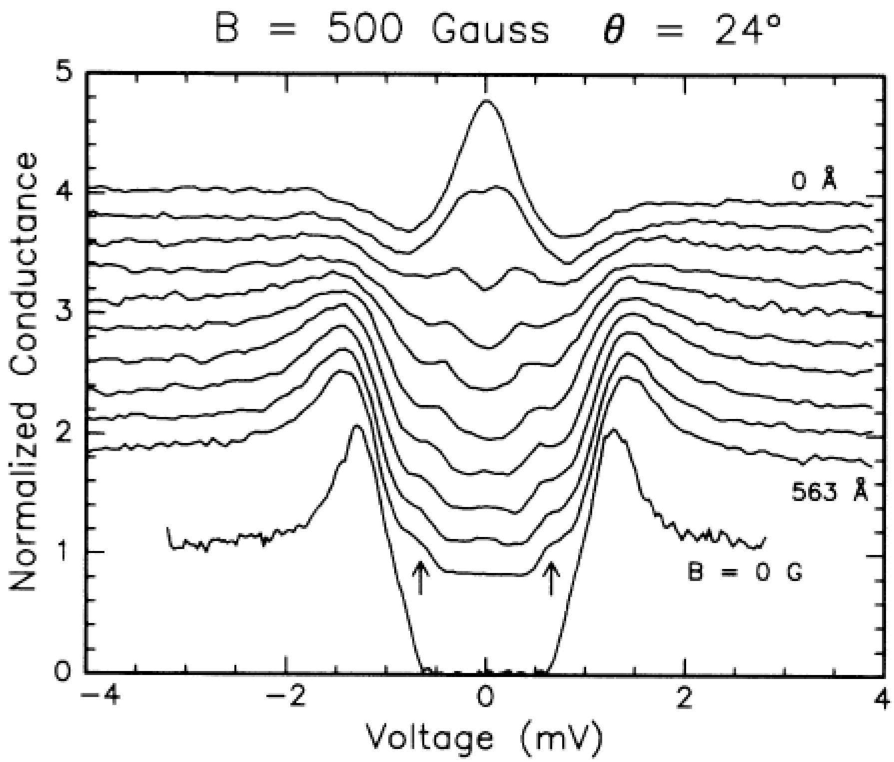
Core is normal (radius ξ)
Field is screened over length scale λ

Flux is quantized in superconductors because the phase of Ψ must be an integral of 2π

Total flux enclosed: $\int \vec{B} \cdot d\vec{a} = \frac{hc}{2e} \equiv \Phi_0$

Flux Quantum $\Phi_0 = 2.07 \times 10^{-7}$ G cm^2

Vortex Imaging

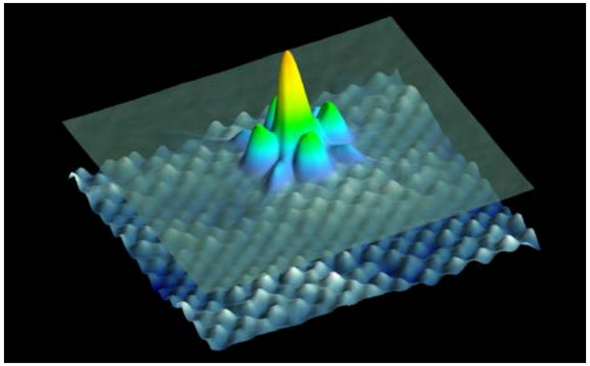


Hess et al, PRL (1990)

2H-NbSe$_2$
T$_c$ = 7.2K
Scanning Tunneling Microscocy

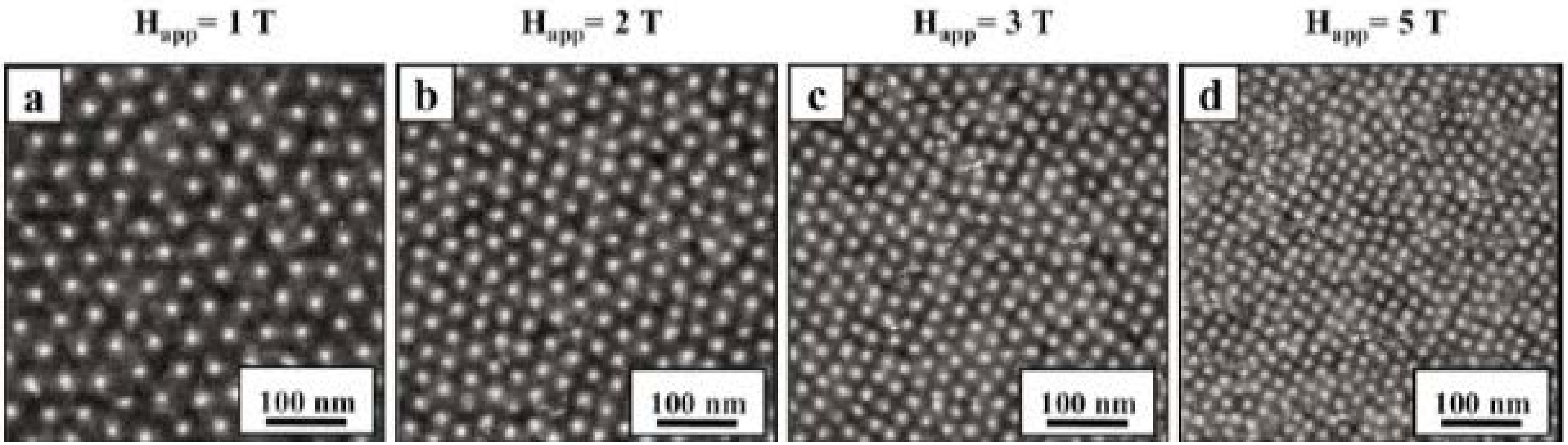
Far from vortex, observe the usual s-wave gap.

In vortex core, see localized states!



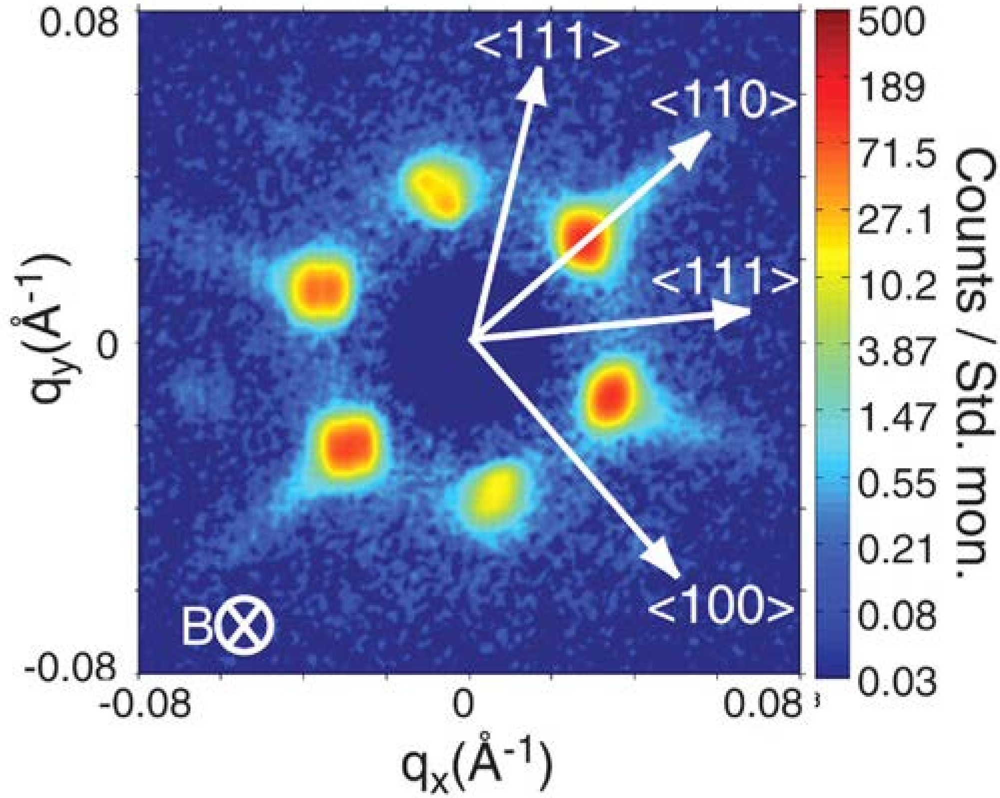
Vortices lines can be “seen” by various scanning techniques (scanning SQUIDs, scanning tunneling microscopy, etc.)

Vortex Lattice

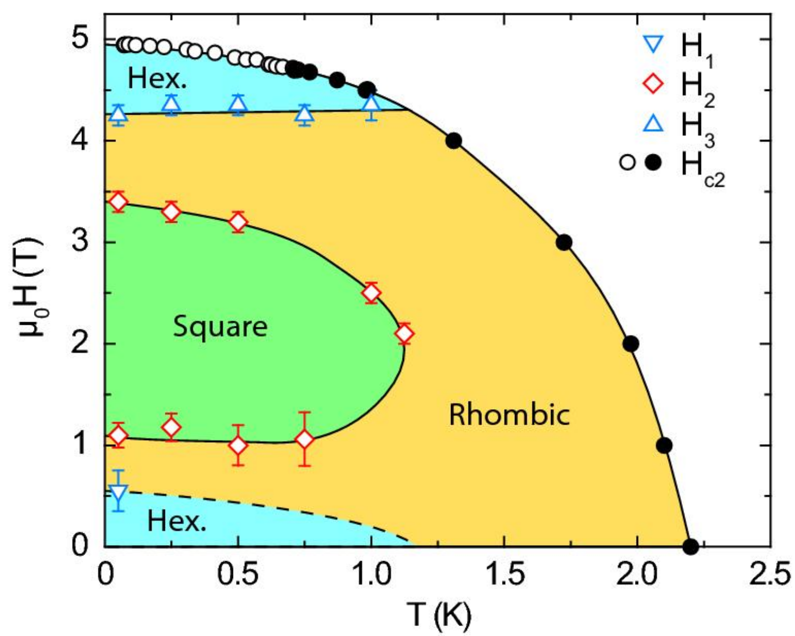


- Spacing between vortices depends on the field
- Typically several hundred Å
- Vortex – Vortex Interaction is repulsive
- Lowest energy state is hexagonal lattice

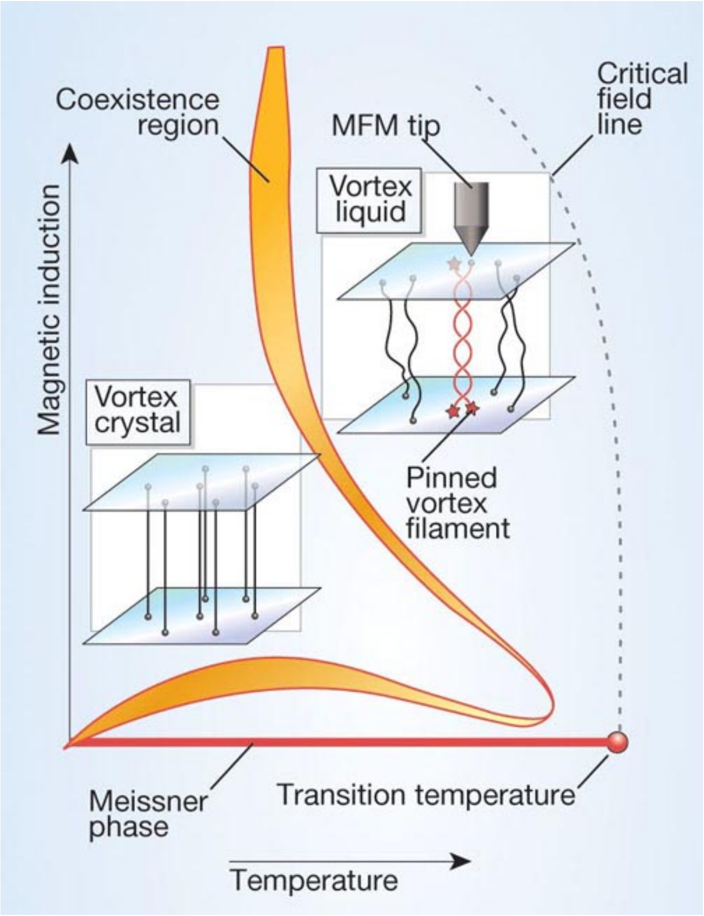
Vortex lattice - Scattering



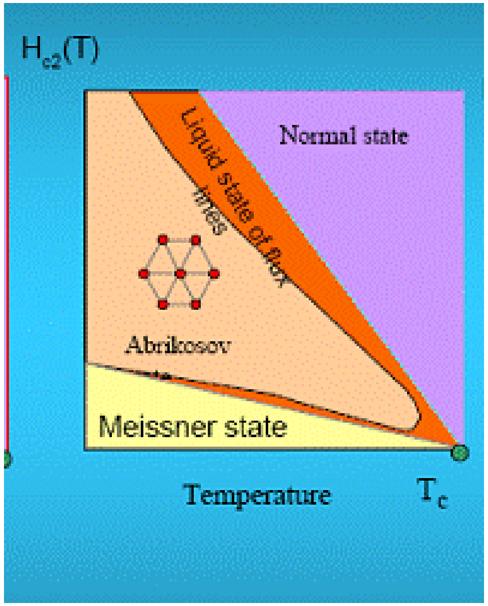
Small angle neutron scattering – (SANS). Neutrons experience Bragg scattering from lattice. Use small angles because the vortices are far apart (compared to unit cell lengths)



Vortex Matter

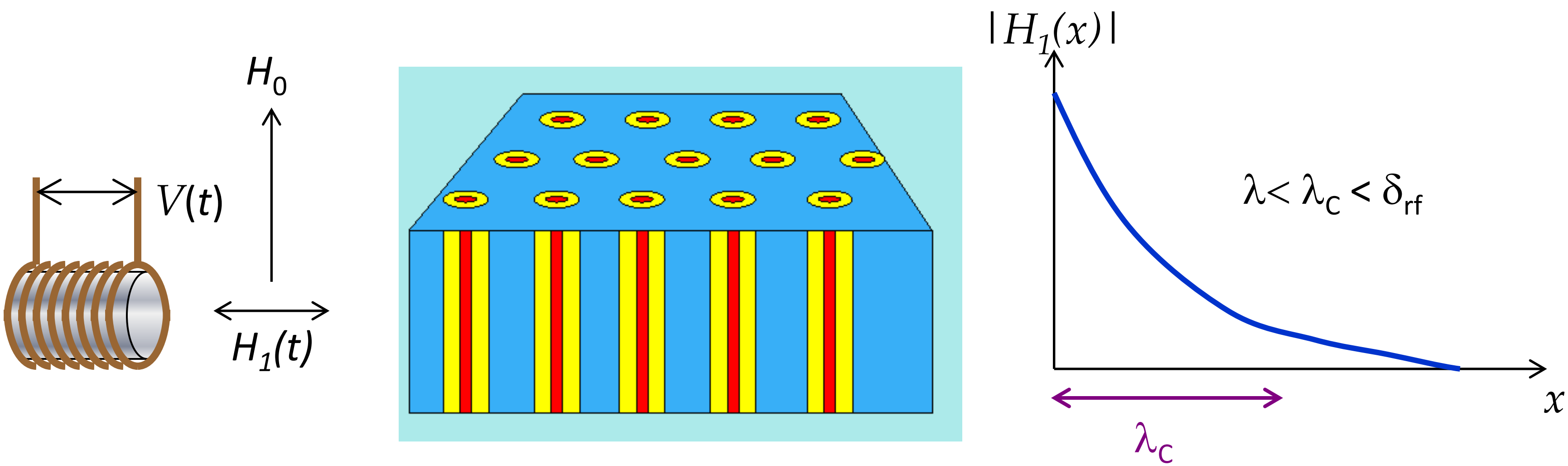


- Vortices can vibrate, move, become glassy, and melt!
- Principle of emergence
- Defects can pin vortices



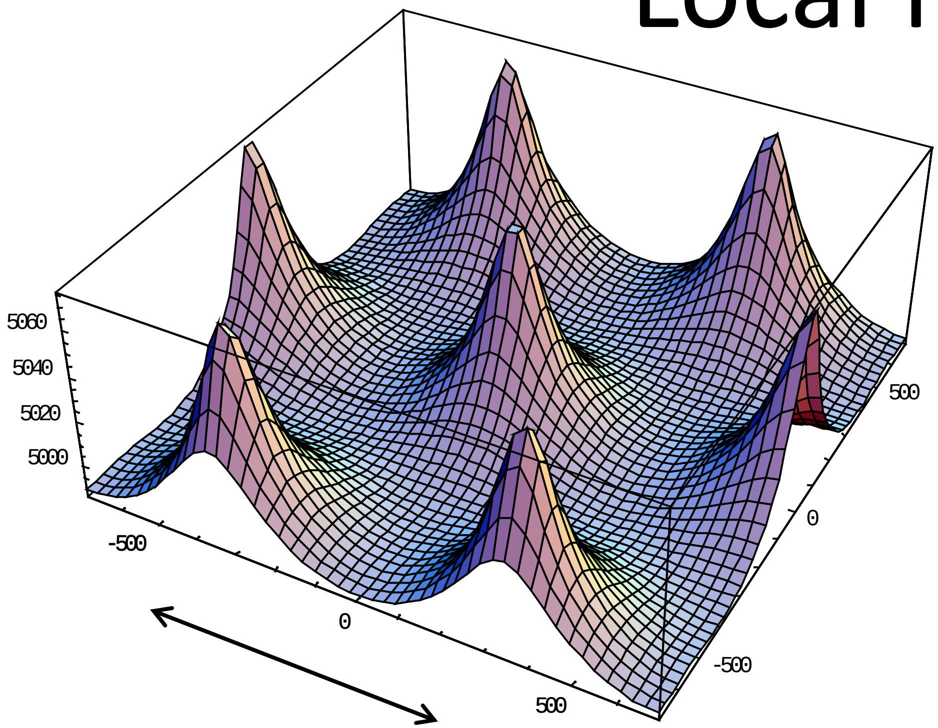
Measurements of the Vortex Lattice

Nuclear magnetic resonance (NMR) and **muon spin rotation (μSR)** are local probes and can measure the properties of the local field distribution

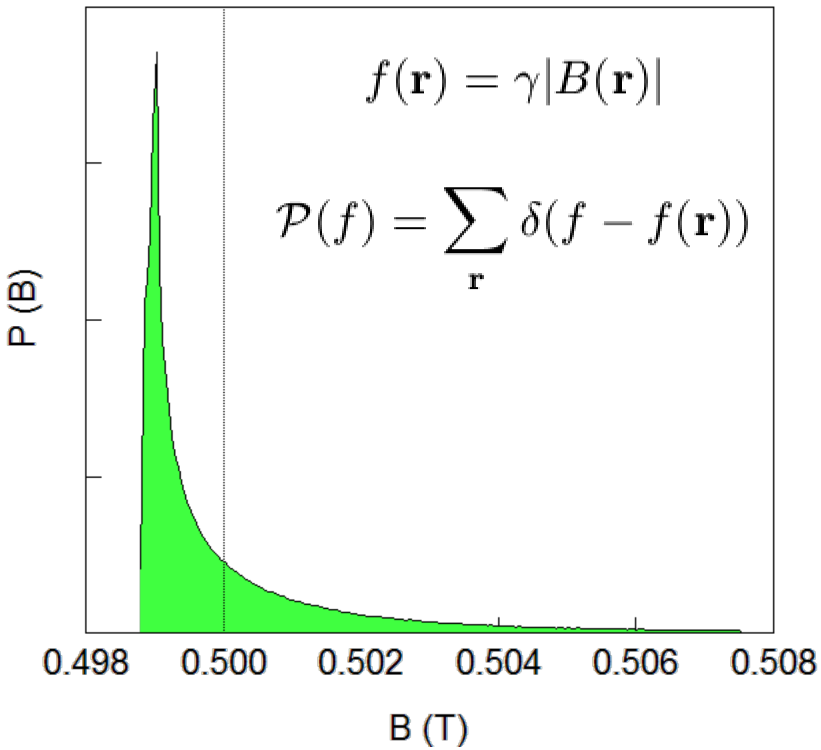


Signal intensity drops in superconducting state

Local field

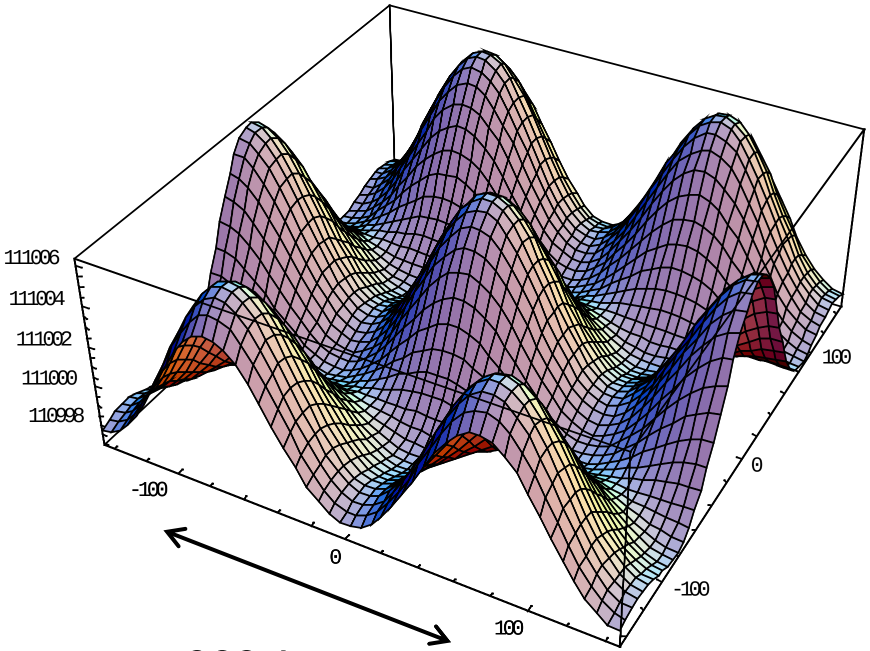


~ 1000 A
H/H_{c2} ~ 0.17



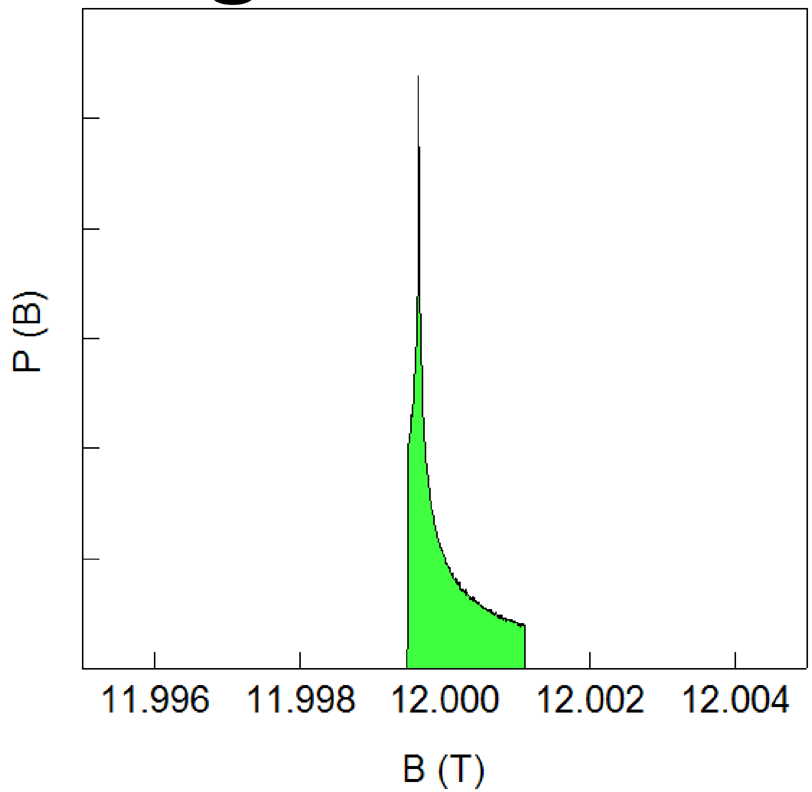
Nuclei resonate at local field
Spectrum is a histogram of local field distribution

Local field at large H



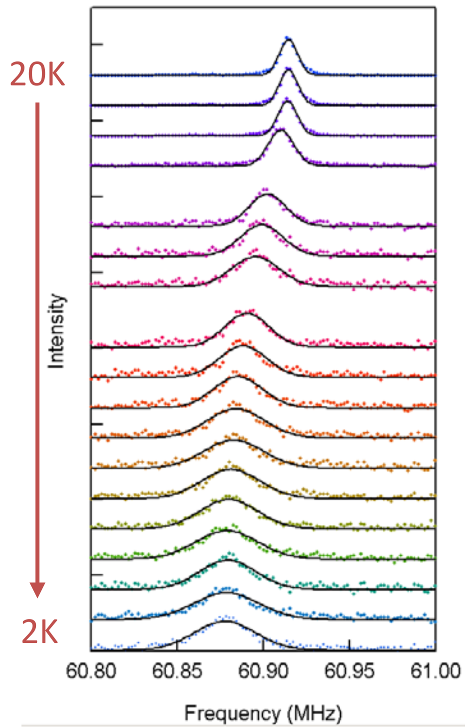
~ 200 A

H/H_{c2} ~ 0.8

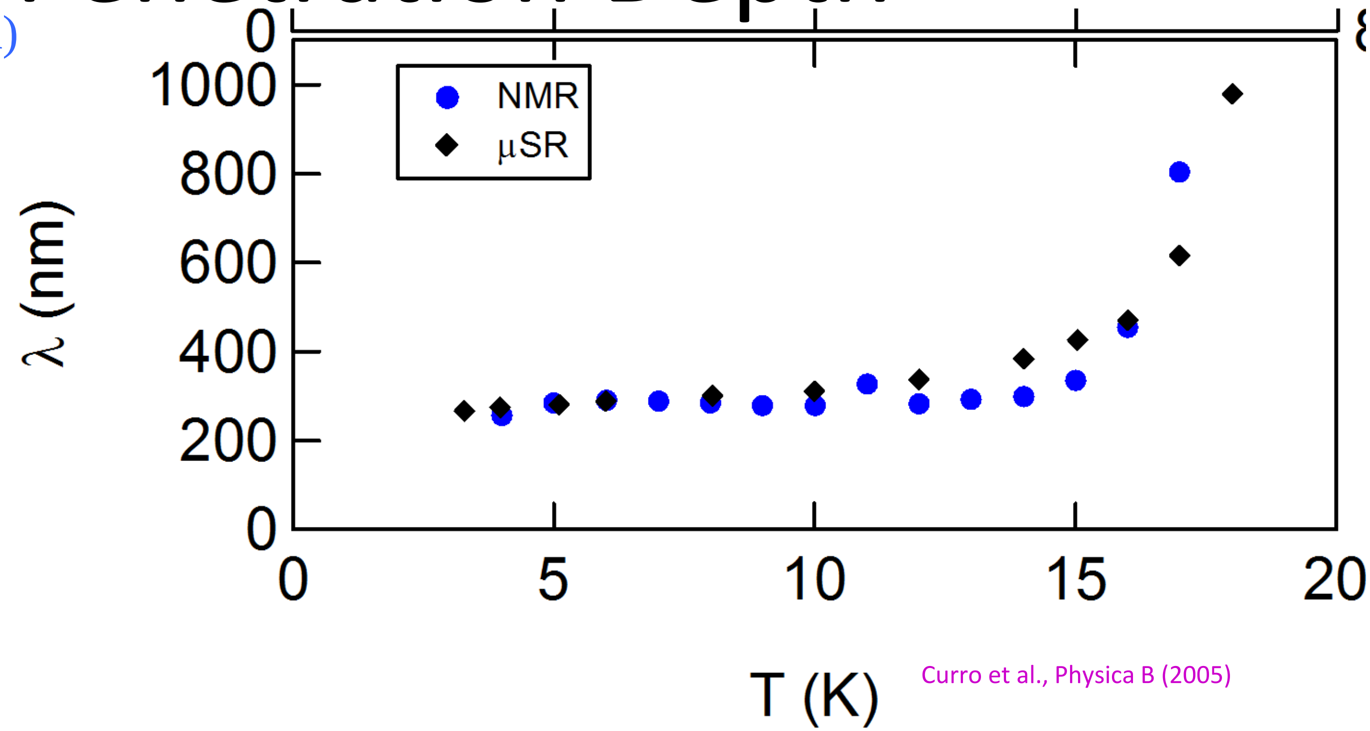


Penetration Depth

PuCoGa$_5$ (T_c = 18.5 K)



^{59}Co NMR



Curro et al., Physica B (2005)

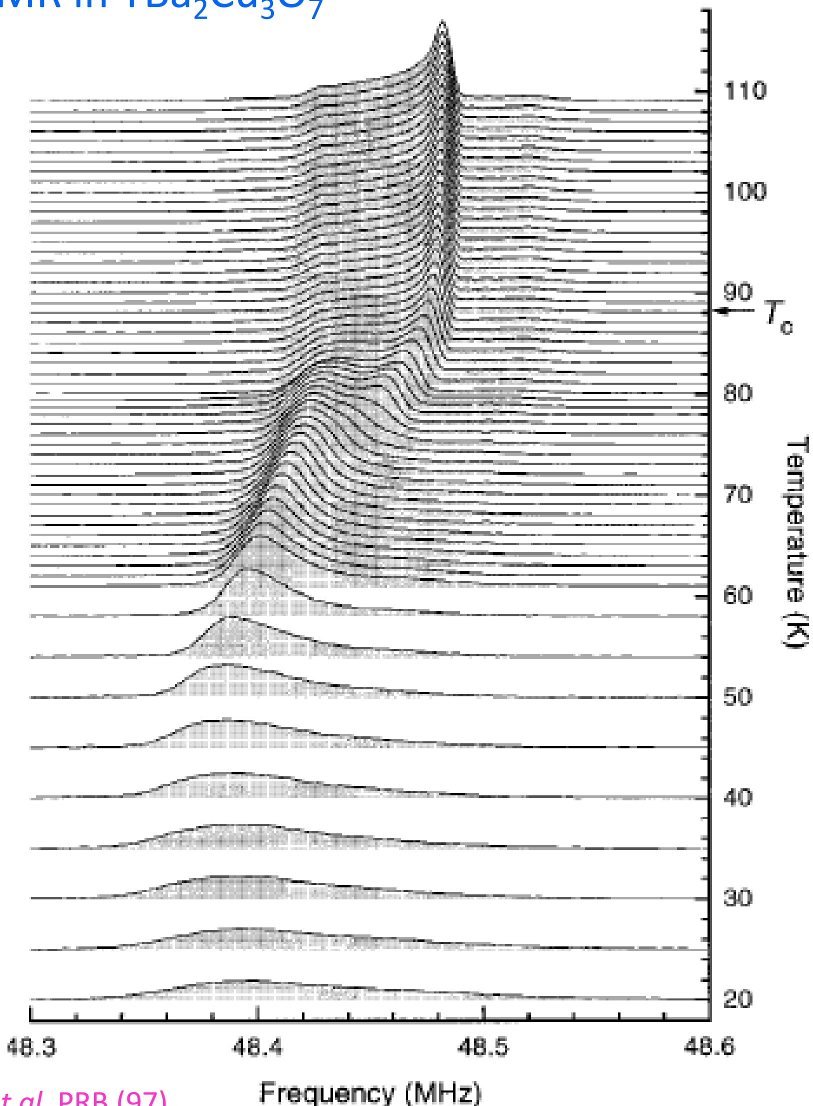
$$\langle \Delta B^2 \rangle \approx 0.0037(\phi_0 / \lambda^2)^2$$

Line broadening is a direct measure of the penetration depth (and hence superfluid density)

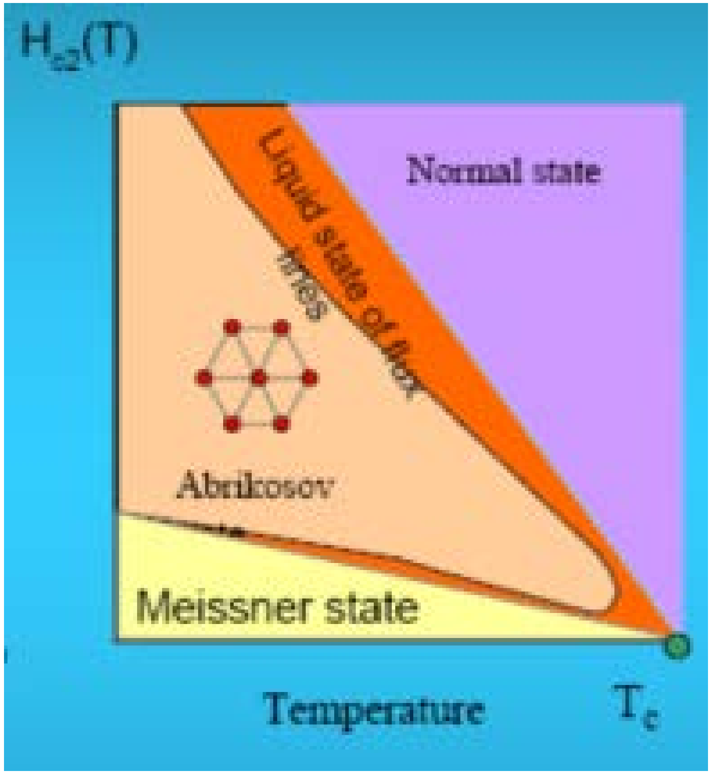
Can also do these measurements with **muon spin rotation (μSR)** with great precision

Vortex lattice melting

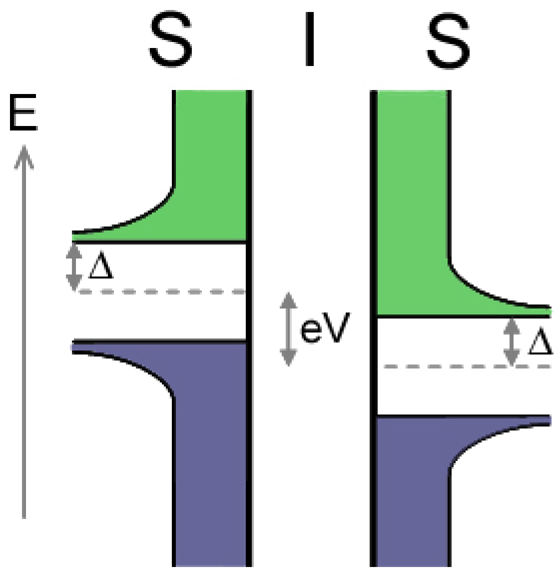
^{17}O NMR in $YBa_2Cu_3O_7$

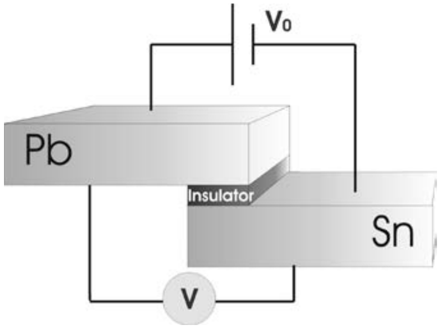


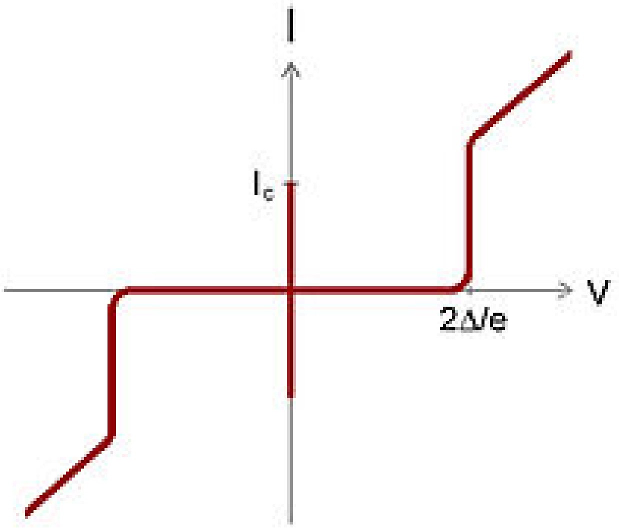
A. P. Reyes *et al*, PRB (97)



Tunneling: SIS

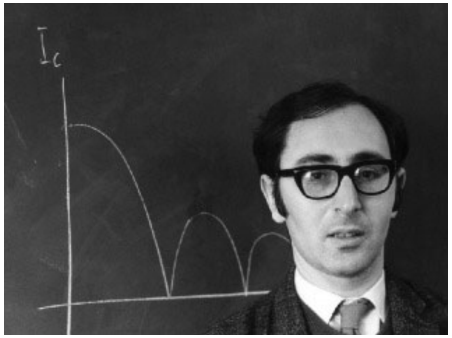




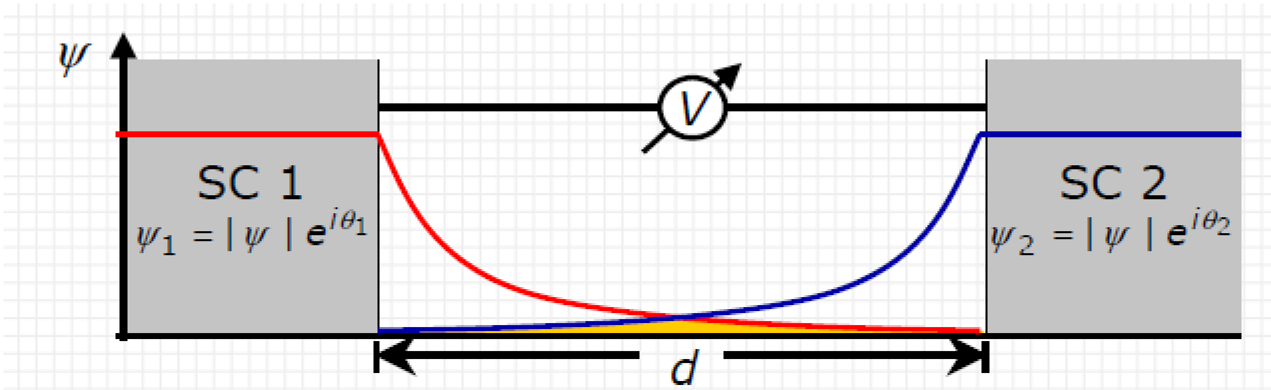


Zero-voltage supercurrent predicted by Brian Josephson

I_0 is the Josephson pair current



Phase Behavior



Phase difference θ_1-θ_2 = ϕ behaves as: $$\frac{\partial \phi}{\partial t} = \frac{2eV}{\hbar}$$

0

GL supercurrent : $$J_s = \frac{-2e\hbar n}{m}\left(\nabla\theta + \frac{2eA}{\hbar}\right)$$

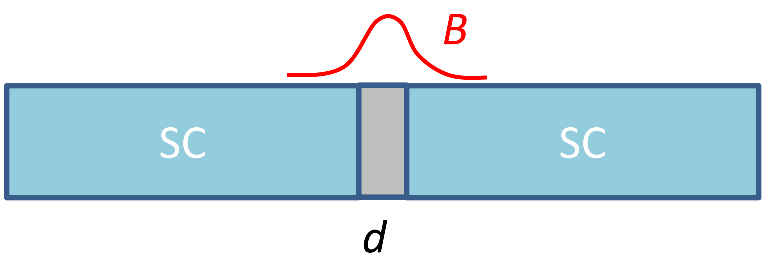
ϕ/d

$$\boxed{\Rightarrow I = I_0 \sin\left[\phi_0 + \frac{2e}{\hbar}\int_0^t V(t)dt\right]}$$

Very unusual relationship between I and V. Get current flow even when V=0. **DC Josephson Effect**

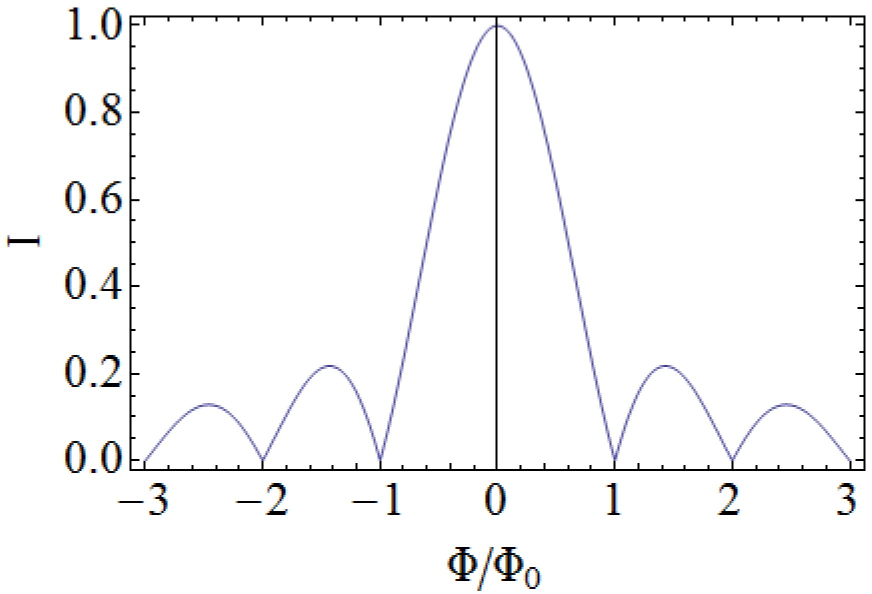
Supercurrent versus Field

In the presence of a field, the maximum supercurrent through the device develops an interference pattern:

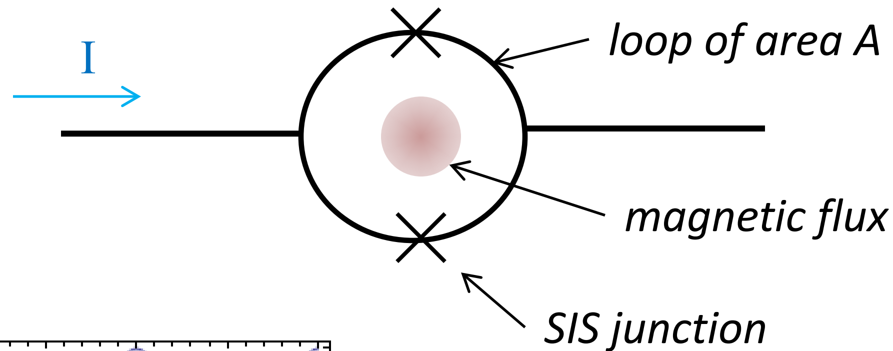


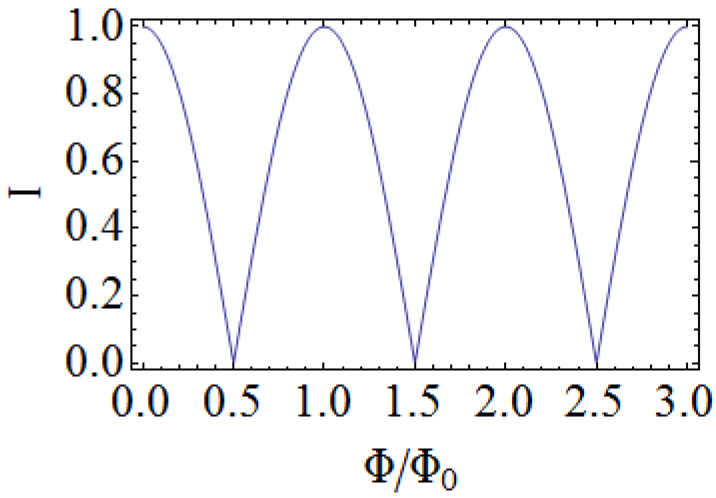
This means the SIS junction can be used to measure flux very precisely!

$$I = I_0 \left| \frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0} \right|$$



SQUIDs





$$I = I_0 \cos(\pi \Phi / \Phi_0)$$

Superconducting Quantum Interference Device – can measure fields as small as 10^{-10} G

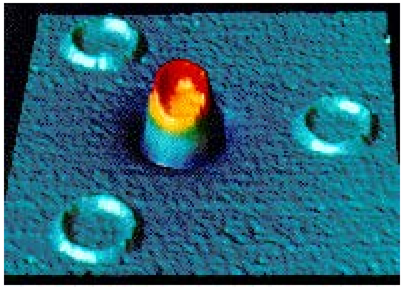
Typical devices are made from thin films and are micron-sized

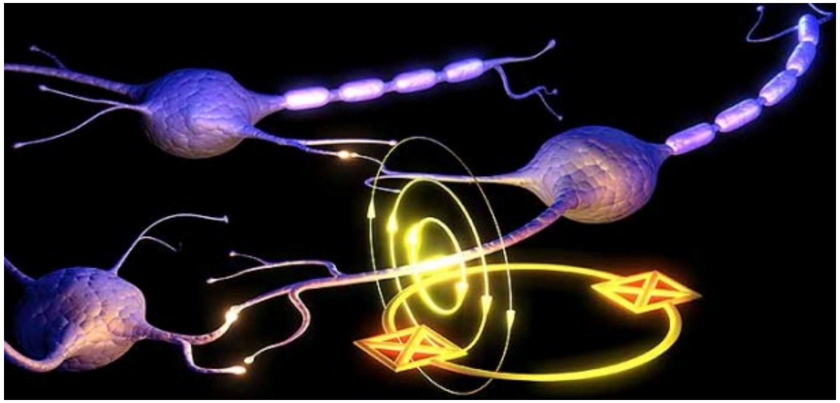
Show Picture

SQUID Applications

Magnetometers for measuring properties of materials

Scanning SQUID Microscopy
(imaging of vortices)





Magnetoencephalography - imaging magntic fields in brain as small as femto-Tesla) caused by currents from firing neurons

Coherence Effects

BCS Theory tells us that the Cooper pairs are formed from the pairing of a spin-up and spin-down electron. When a Cooper pair breaks apart to form quasiparticles, these are superpositions of spin-up and spin down electrons are called **Bogoliubons:**

$$\begin{aligned}
\alpha^{\dagger}{}_{\mathbf{k}\uparrow} &= \psi^{\dagger}{}_{\mathbf{k}} \begin{pmatrix} u_{\mathbf{k}} \\ v_{\mathbf{k}} \end{pmatrix} = c^{\dagger}{}_{\mathbf{k}\uparrow} u_{\mathbf{k}} + c_{-\mathbf{k}\downarrow} v_{\mathbf{k}} \\
\alpha_{-\mathbf{k}\downarrow} &= \psi^{\dagger}{}_{\mathbf{k}} \begin{pmatrix} -v_{\mathbf{k}} \\ u_{\mathbf{k}} \end{pmatrix} = c_{-\mathbf{k}\downarrow} u_{\mathbf{k}} - c^{\dagger}{}_{\mathbf{k}\uparrow} v_{\mathbf{k}}
\end{aligned}$$

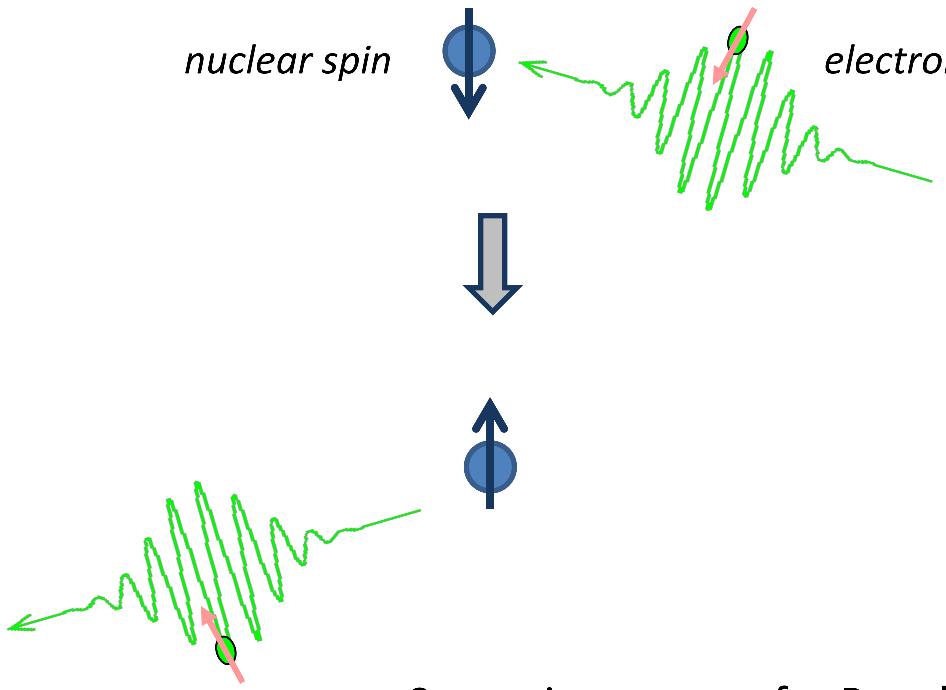
Superposition amplitudes (from BCS)

Electron creation operators

This means that some processes such as spin-scattering will be modified in a superconductor

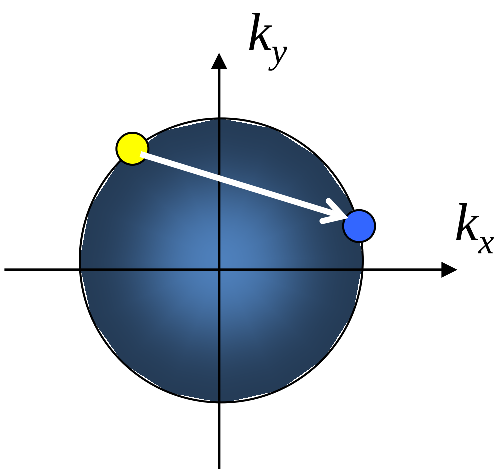
Hyperfine Interactions in Metals

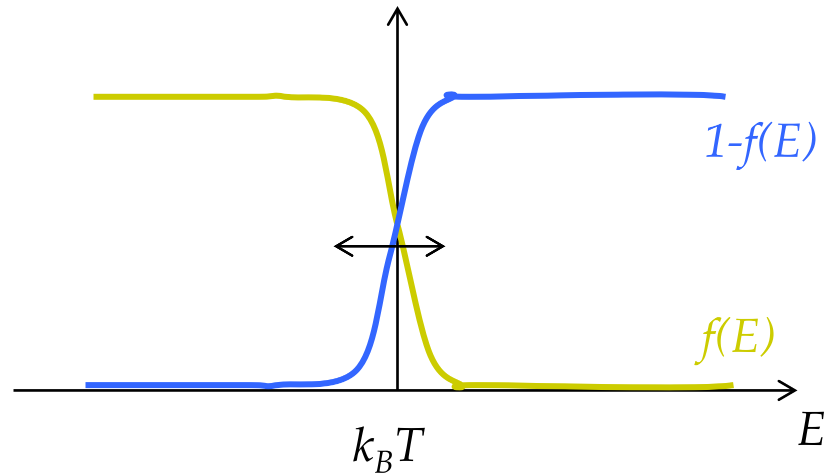
Nuclear spins relax by spin-flip scattering from electrons:



Scattering process for Bogoliubons requires taking into account the **coherent superposition** of spin-up and spin-down electrons!

Spin Lattice Relaxation





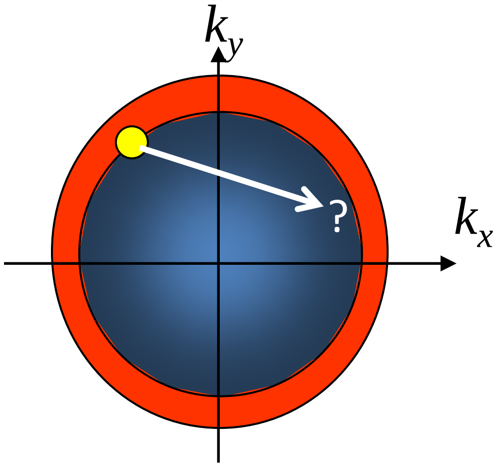
$$\begin{aligned}
\frac{1}{T_1} &\propto A^2 \int \overbrace{N(E_F + g\mu_N H) f(E_F + g\mu_N H)}^{\text{Initial state}} \overbrace{N(E_F - g\mu_N H)(1 - f(E_F - g\mu_N H))}^{\text{Final state}} dE \\
&\propto A^2 N^2(E_F) \int f(E_F)(1 - f(E_F)) dE \\
&\propto A^2 N^2(E_F) k_B T
\end{aligned}$$

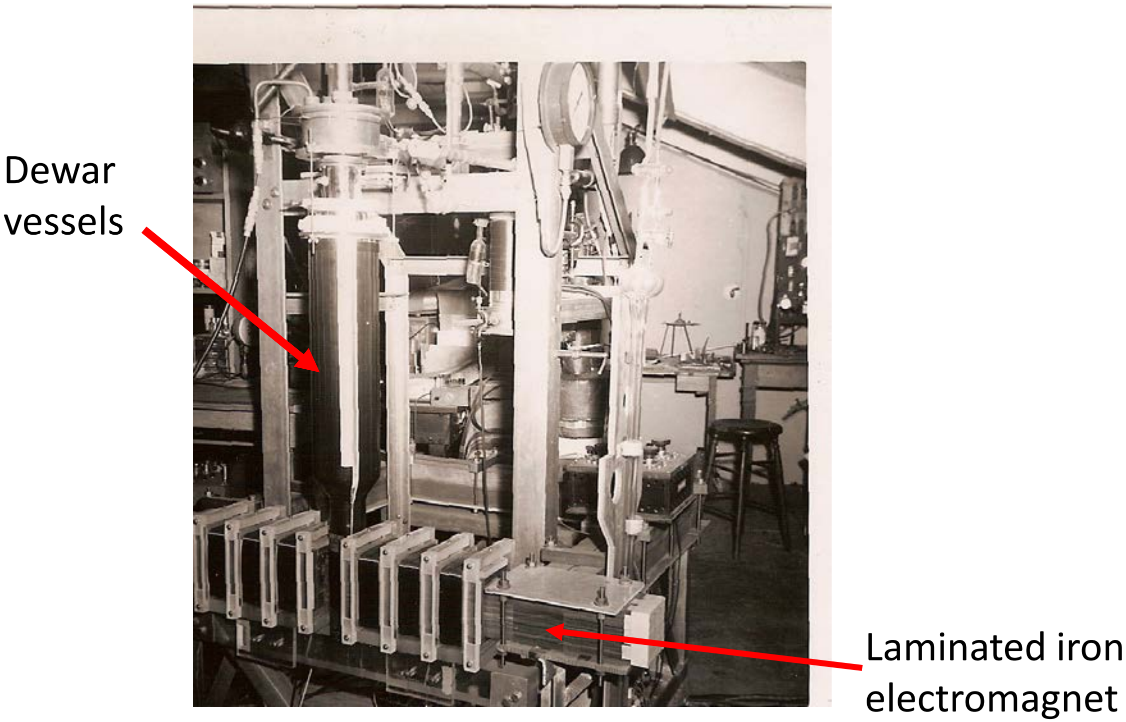
In metals, $T_1T \sim N^2(E_F)$; a sensitive probe of the spin-flip scattering by electrons at the Fermi surface. (Korringa relaxation)

Bardeen's Colloquium

Circa 1955 John Bardeen gives colloquium at Urbana in which he describes the possibility of an energy gap at the Fermi level

Charlie Slichter in audience realizes implications for T_1





John Bardeen in his office in Urbana

Spin Flip Scattering from Buguilubons

$$
\begin{aligned}
T_1^{-1} &\propto A^2 \int c^\dagger_{\mathbf{k}'\downarrow} c_{\mathbf{k}\uparrow} d\mathbf{k} d\mathbf{k}' \\
&\propto A^2 \int (u_{\mathbf{k}'} \alpha^\dagger_{\mathbf{k}'\downarrow} - v_{-\mathbf{k}'} \alpha_{-\mathbf{k}'\uparrow})(u_{\mathbf{k}} \alpha_{\mathbf{k}\uparrow} + v_{-\mathbf{k}} \alpha^\dagger_{-\mathbf{k}\downarrow}) d\mathbf{k} d\mathbf{k}' \\
&\propto A^2 \int (u_{\mathbf{k}'} u_{\mathbf{k}} \alpha^\dagger_{\mathbf{k}'\downarrow} \alpha_{\mathbf{k}\uparrow} + v_{-\mathbf{k}'} v_{-\mathbf{k}} \alpha_{-\mathbf{k}'\uparrow} \alpha^\dagger_{-\mathbf{k}\downarrow}) d\mathbf{k} d\mathbf{k}' \\
&\quad + A^2 \int (u_{\mathbf{k}'} v_{-\mathbf{k}} \alpha^\dagger_{\mathbf{k}'\downarrow} \alpha^\dagger_{-\mathbf{k}\downarrow} - v_{-\mathbf{k}'} u_{\mathbf{k}} \alpha_{-\mathbf{k}'\uparrow} \alpha_{\mathbf{k}\uparrow}) d\mathbf{k} d\mathbf{k}' \\
&\propto A^2 \int \underbrace{(u_{\mathbf{k}'} u_{\mathbf{k}} - v_{\mathbf{k}'} v_{\mathbf{k}})}_{\text{Coherence factor}} \underbrace{\alpha^\dagger_{\mathbf{k}'\downarrow} \alpha_{\mathbf{k}\uparrow}}_{\text{Bogoilubons}} d\mathbf{k} d\mathbf{k}'
\end{aligned}
$$

vanishes

Note that there is no relaxation from Cooper pairs (singlets have no spin!). Relaxation by spin-flip scattering from Bogoliubons, which must be thermally excited over the superconducting energy gap.

Hebel-Slichter Coherence Factor

BCS Theory Predictions

$$u_{\mathbf{k}'}u_{\mathbf{k}} - v_{\mathbf{k}'}v_{\mathbf{k}} = \frac{1}{2}\left[1 \pm \frac{\Delta^2}{E_{\mathbf{k}}E_{\mathbf{k}'}}\right]$$

Coherence factor; - is for ultrasonic attenuation, + is for spin-flip scattering

$$E_{\mathbf{k}} = \sqrt{\epsilon_{\mathbf{k}}^2 + \Delta^2}$$

Bogoliubon energy

$$N_{\mathrm{BCS}}(E) = \frac{E}{\sqrt{E^2 - \Delta^2}} N_{\mathrm{N}}(E)$$

Density of states

$$\frac{1}{T_1} \propto A^2 \int C_+(E, E') N_{\mathrm{BCS}}(E) f(E) N_{\mathrm{BCS}}(E')(1 - f(E'))dE$$

$$\frac{R_s}{R_n} = \frac{2}{k_B T}\int_{\Delta}^{\infty} \frac{(EE' + \Delta^2) f(E)[1 - f(E')]}{[(E^2 - \Delta^2)(E'^2 - \Delta^2)]^{1/2}} dE; \quad E' = E \pm \hbar\omega_{\mathrm{nuc}}.$$

Full expression

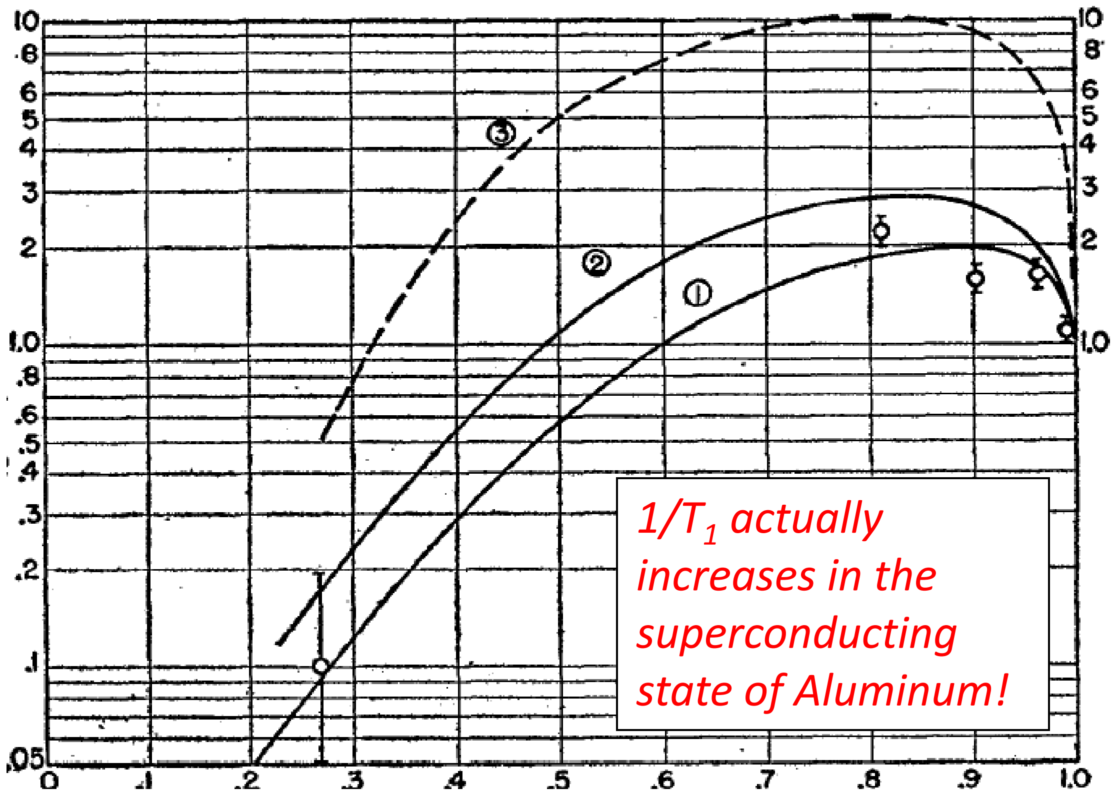
There is a singular increase at E = Δ

Spin Flip Scattering

Hebel-Slichter Coherence Peak

R_S/R_N

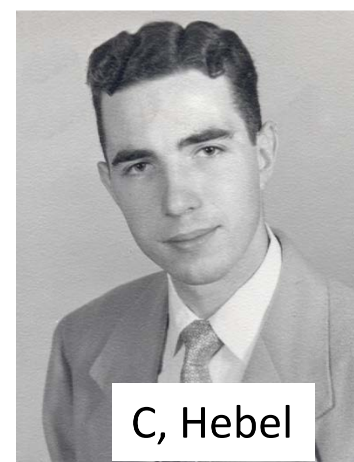
R = $1/T_1$



T/T_C

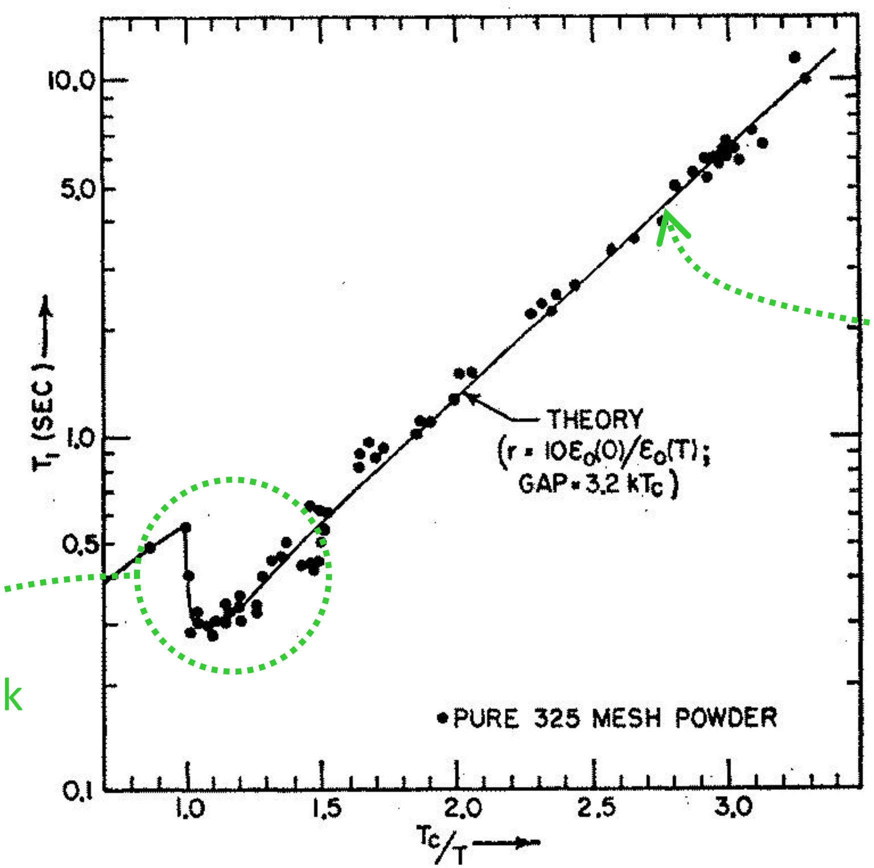
Hebel and Slichter, Phys Rev **102**,901 (1957) and **113**,1504 (1959)

This experiment provided strong evidence for the validity of the BCS theory; no other theory could explain an *increase*



Low Temperatures

For T << T_c, the Buguilobons are gapped out, hence the spin lattice relaxation is gapped out exponentially



$$\log(T_1) \sim \Delta/k_B T$$

Activated behavior

Coherence peak

Al Redfield

Y. Masuda and A. G. Redfield, Phys. Rev. **125,** 159 (1962)