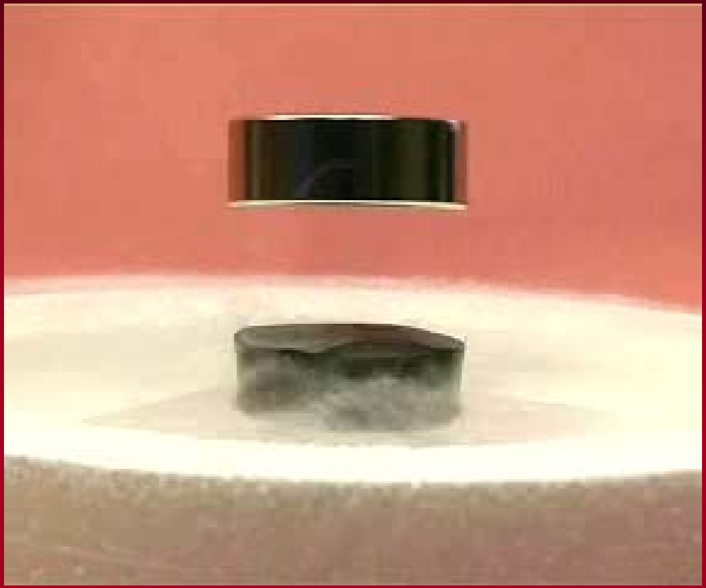
μSR and Superconductivity



Bob Cywinski

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Muon Training Course, April 2008

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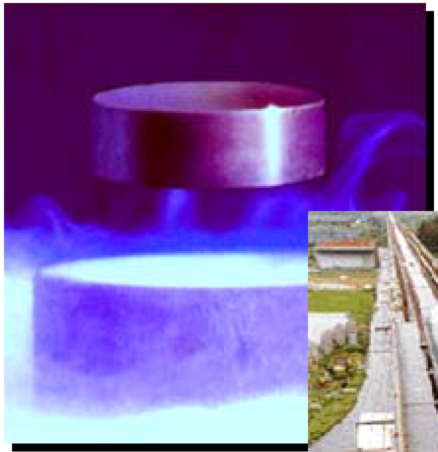
Superconductivity

“Superconductivity is perhaps the most remarkable physical property in the Universe”

David Pines



The superconducting elements

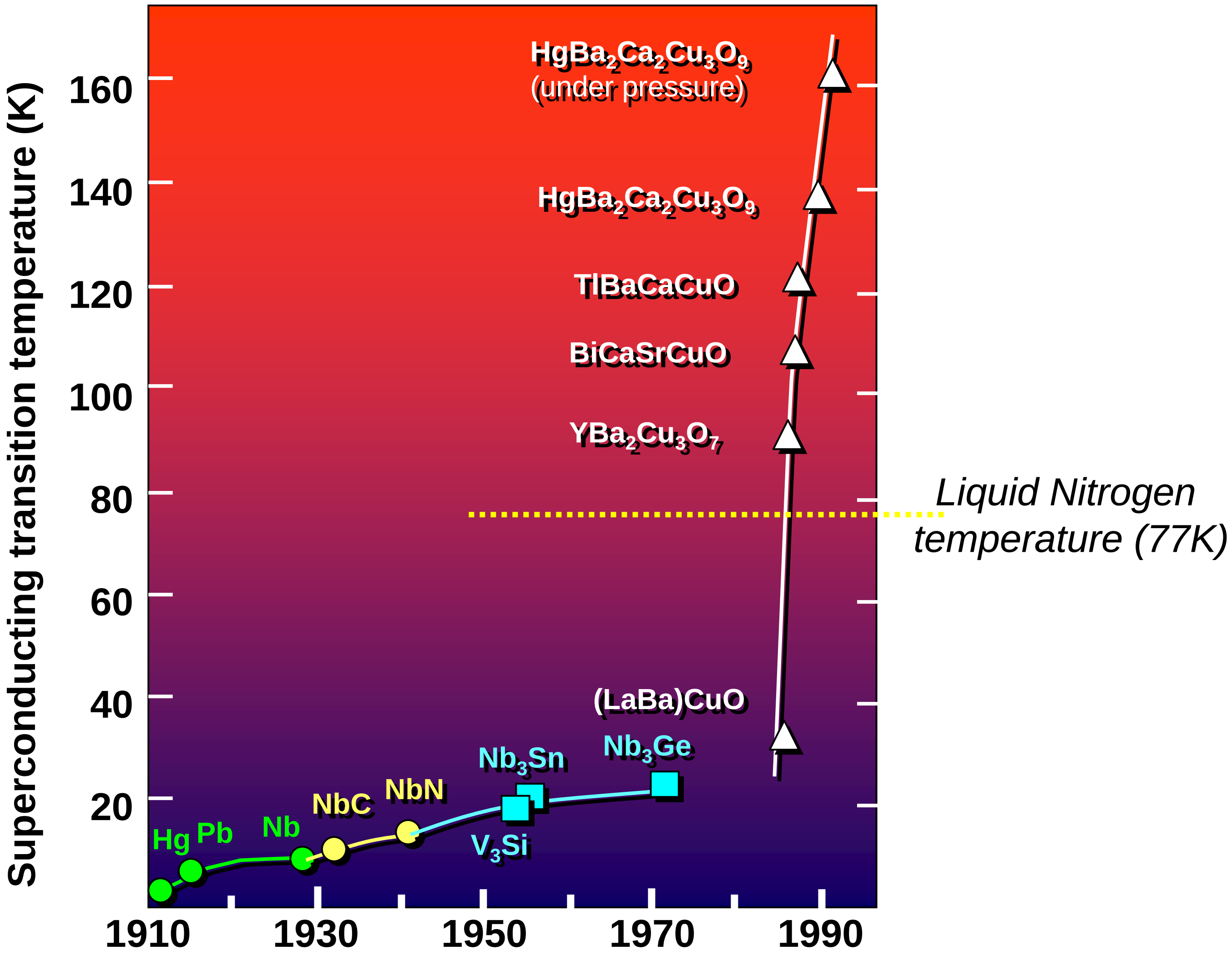
Transition temperatures (K)
Critical magnetic fields at absolute zero (mT)

Li	**Be** 0.026											**B**	**C**	**N**	**O**	**F**	**Ne**
Na	**Mg**											**Al** 1.14 10	**Si**	**P**	**S**	**Cl**	**Ar**
K	**Ca**	**Sc**	**Ti** 0.39 10	**V** 5.38 142	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn** 0.875 5.3	**Ga** 1.091 5.1	**Ge**	**As**	**Se**	**Br**	**Kr**
Rb	**Sr**	**Y**	**Zr** 0.546 4.7	**Nb** 9.5 198	**Mo** 0.92 9.5	**Tc** 7.77 141	**Ru** 0.51 7	**Rh** 0.03 5	**Pd**	**Ag**	**Cd** 0.56 3	**In** 3.4 29.3	**Sn** 3.72 30	**Sb**	**Te**	**I**	**Xe**
Cs	**Ba**	**La** 6.0 110	**Hf** 0.12	**Ta** 4.483 83	**W** 0.012 0.1	**Re** 1.4 20	**Os** 0.655 16.5	**Ir** 0.14 1.9	**Pt**	**Au**	**Hg** 4.153 41	**Tl** 2.39 17	**Pb** 7.19 80	**Bi**	**Po**	**At**	**Rn**

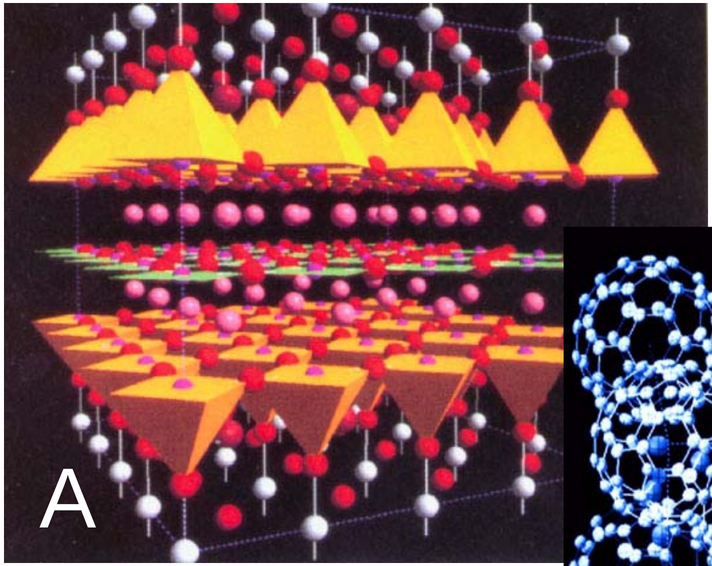
Nb
(Niobium)
T_c=9K
H_c=0.2T

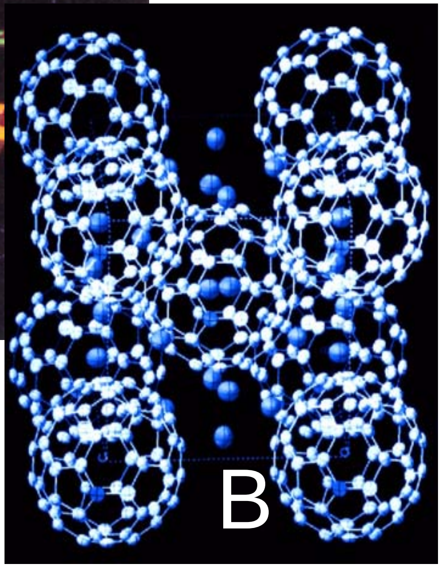
Fe
(iron)
T_c=1K
(at 20GPa)

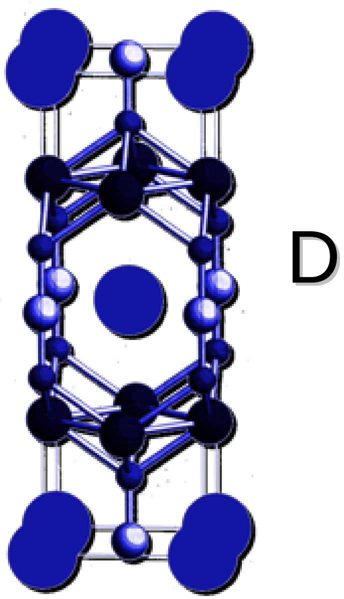
Superconductivity in alloys and oxides

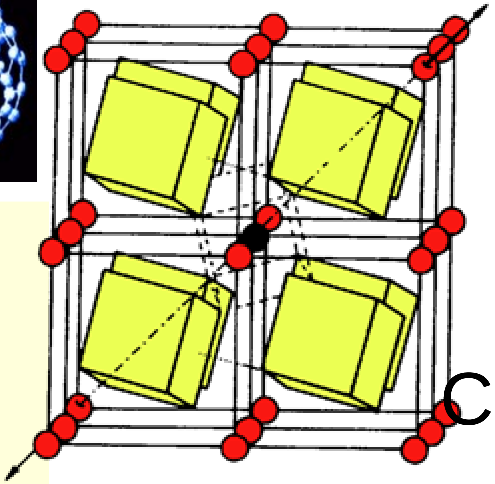


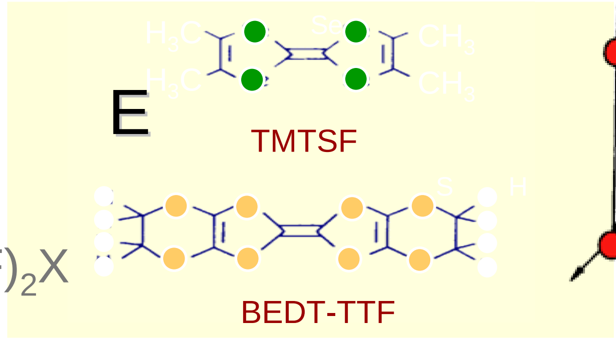
Families of Superconductors





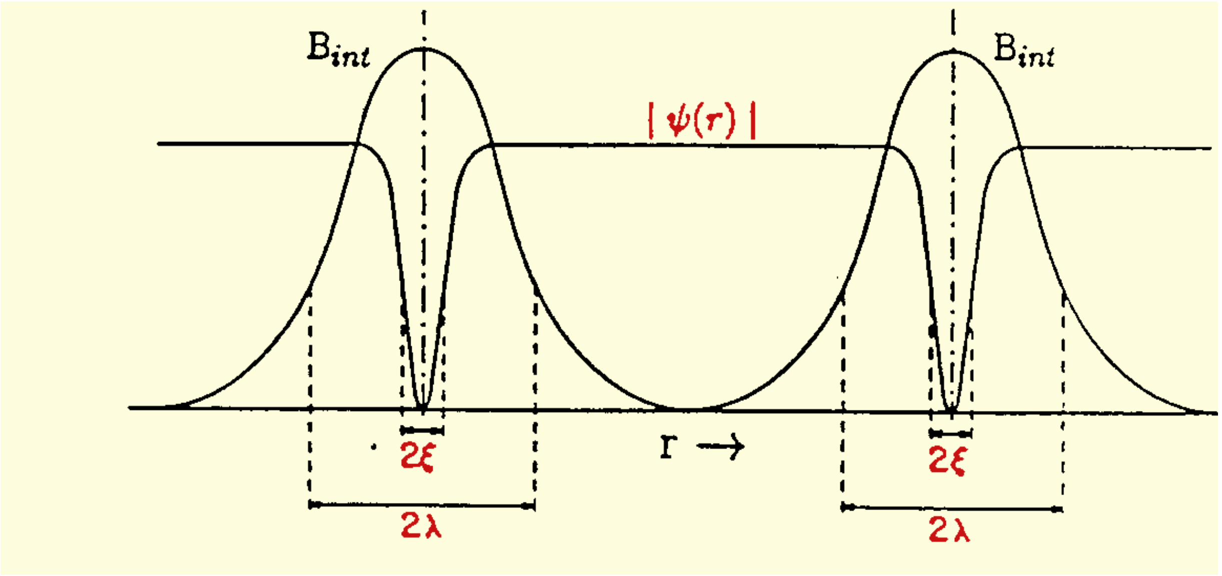






A. High temperature cuprates
B. Buckminsterfullerenes
C. Chevrel phases ($M_xMo_6X_8$)
D. RNi_2B_2C
E. Organics (eg $(BEDT\text{-}TTF)_2X$)

The two characteristic length scales



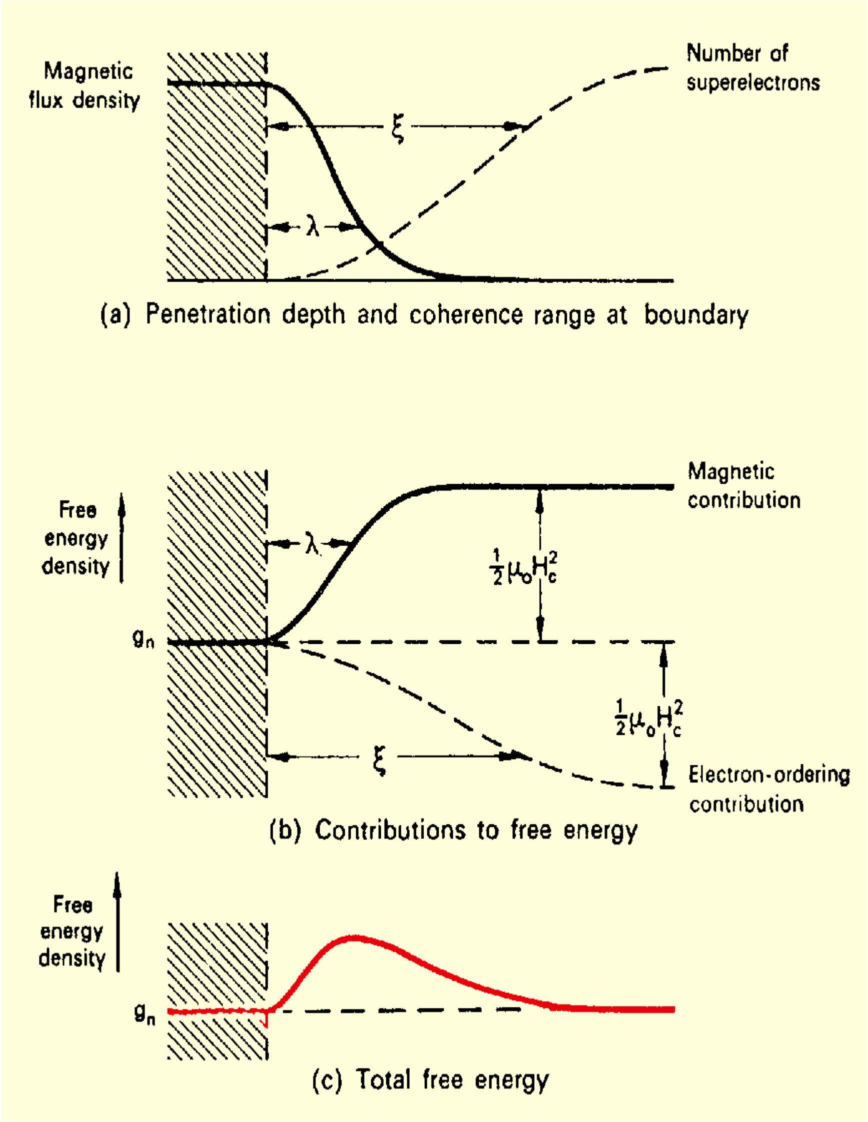
ξ - *the coherence length*

The length scale over which the superconducting wave function Ψ varies

λ - *the penetration depth*

The length scale over which the flux density varies

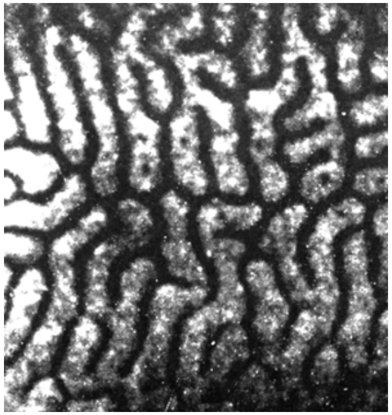
Type I superconductivity; ξ>λ



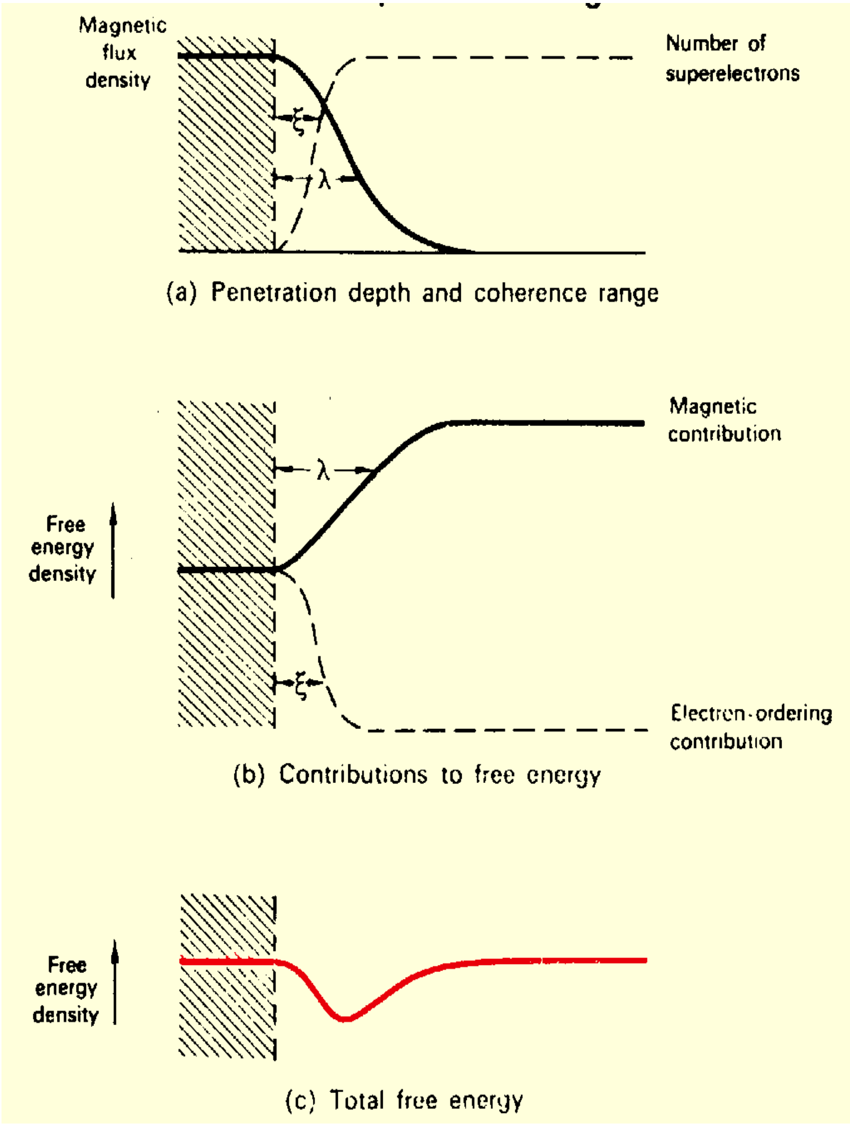
Creating a surface between normal and superconducting regions costs energy…..

…. hence relatively few thick normal "domains" form (under conditions of large demagnetising factors)

This is the *intermediate state*



Type II superconductivity; λ>ξ

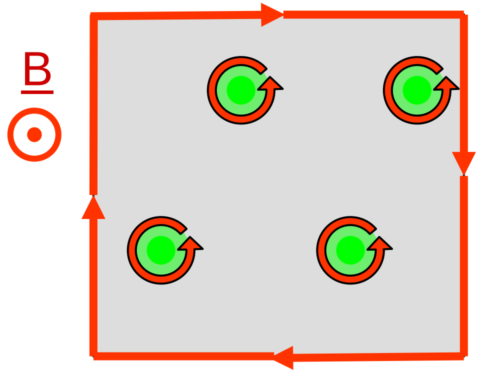


Here the surface energy is negative, ie flux penetration occurs spontaneously to reduce energy

Therefore as many small regions of normal domains (*flux lines*) form as possible

This is the *mixed state*

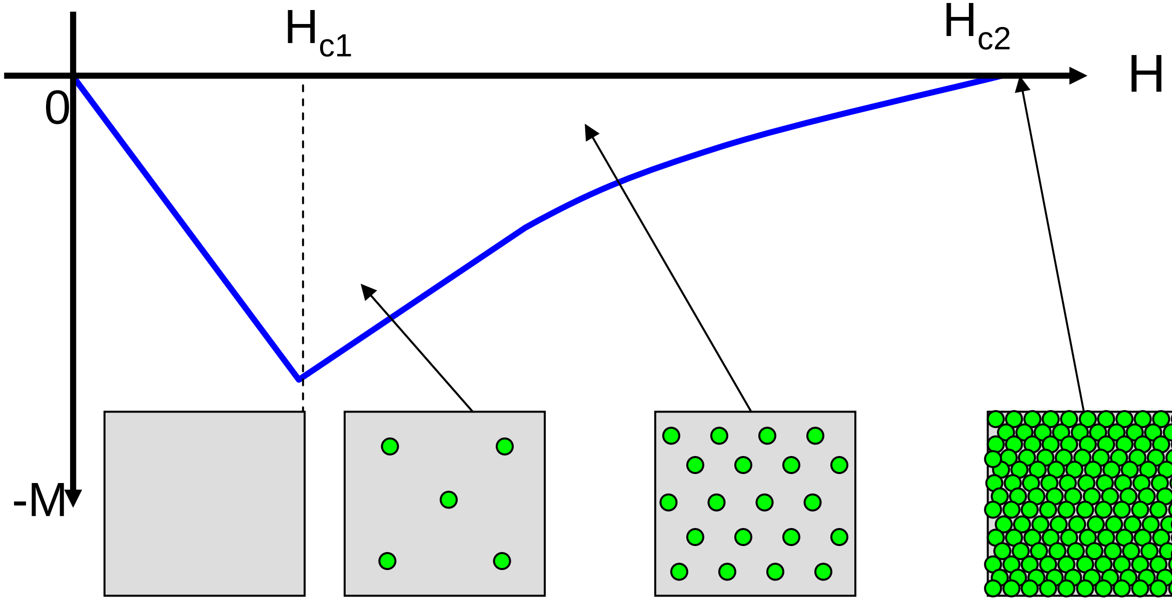
The mixed state in Type II superconductors



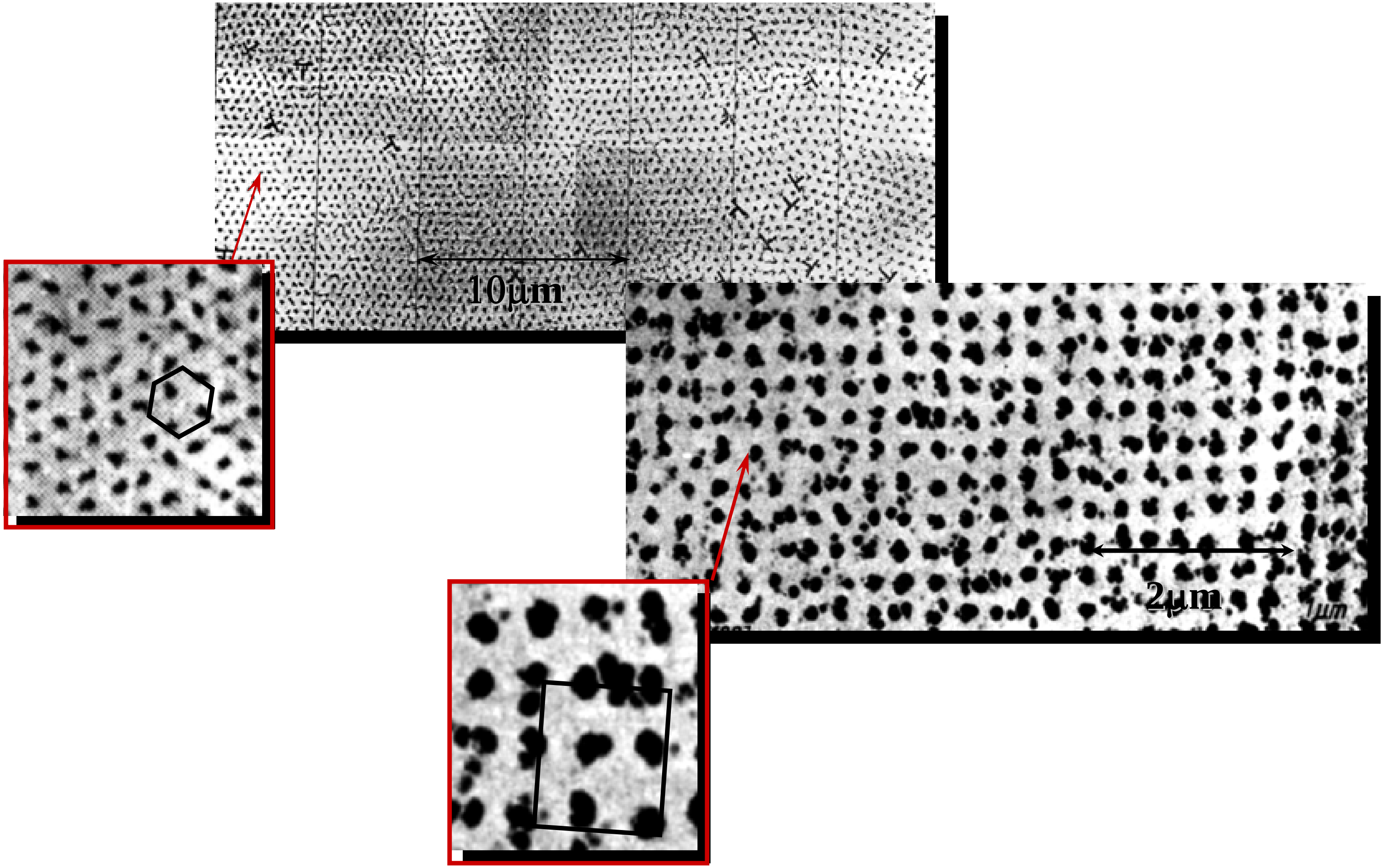
$H_{c1} < H < H_{c2}$

The bulk is diamagnetic but it is threaded with normal cores

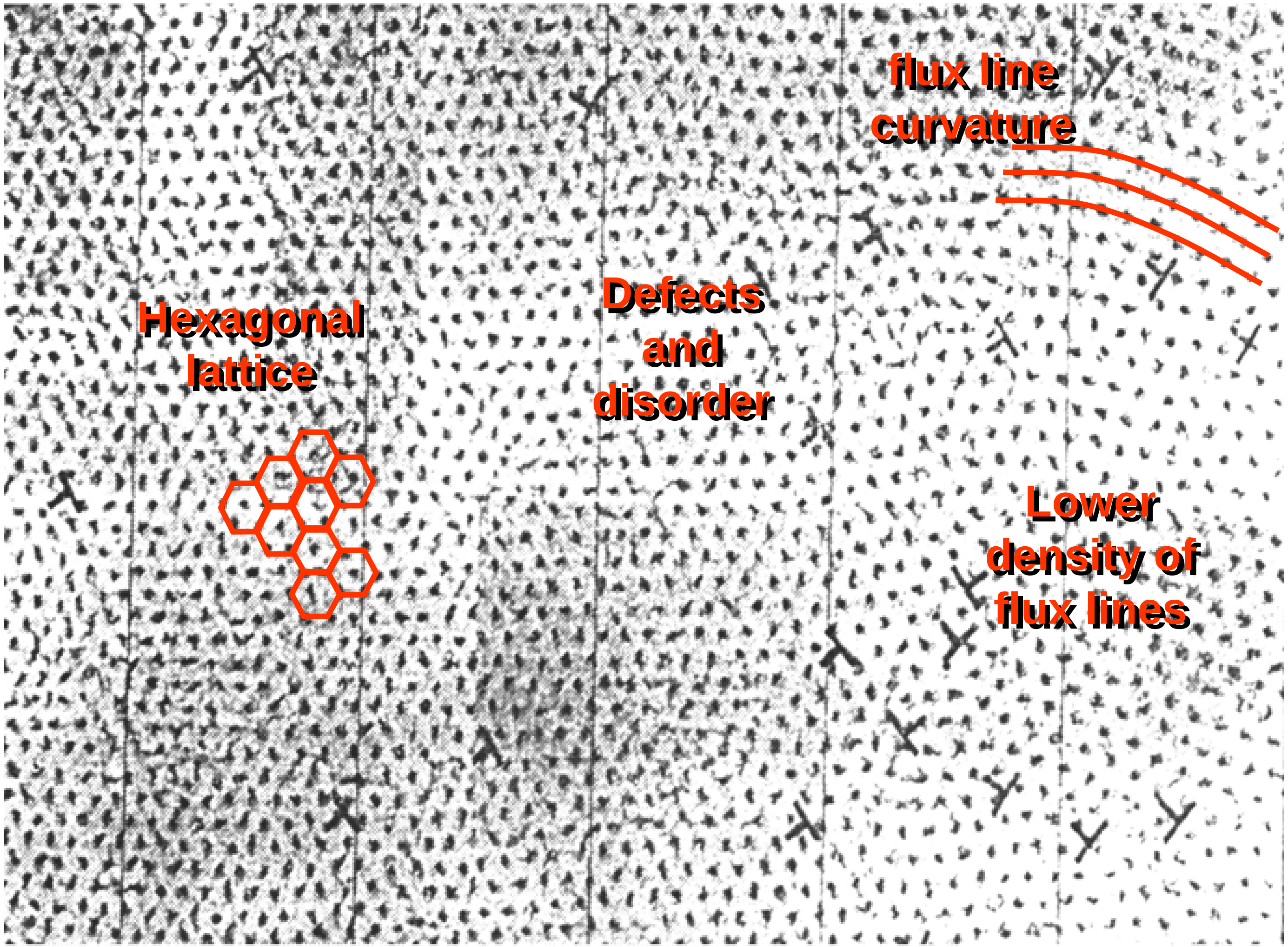
The flux within each core is generated by a *vortex* of supercurrent



The flux lattice



The flux line lattice



Field distributions

In the London limit (ξ is very small) the variation of field around a vortex is

$$B(r) = \frac{\Phi_o}{2\pi\lambda^2} K_o\left(\frac{r}{\lambda}\right)$$

where K_o is a Hankel function of zero order, and

$$B(r) \Rightarrow \frac{\Phi_o}{2\pi\lambda^2} \ln\left(\frac{r}{\lambda}\right) \quad \text{for } \xi << r << \lambda$$

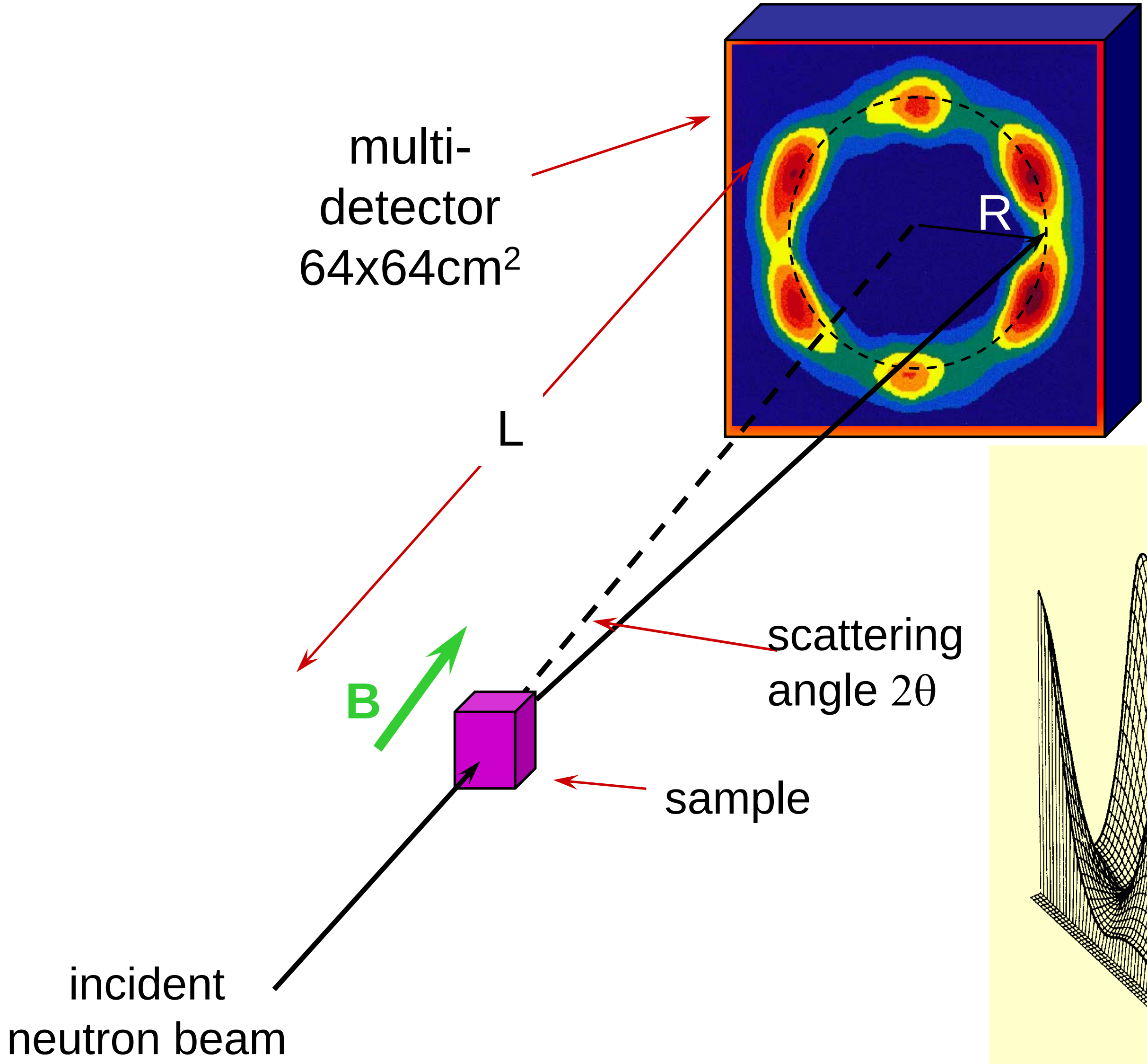
$$B(r) \Rightarrow \frac{\Phi_o}{2\pi\lambda^2} \sqrt{\frac{r}{\lambda}} \exp(-r/\lambda) \quad \text{for } r >> \lambda$$

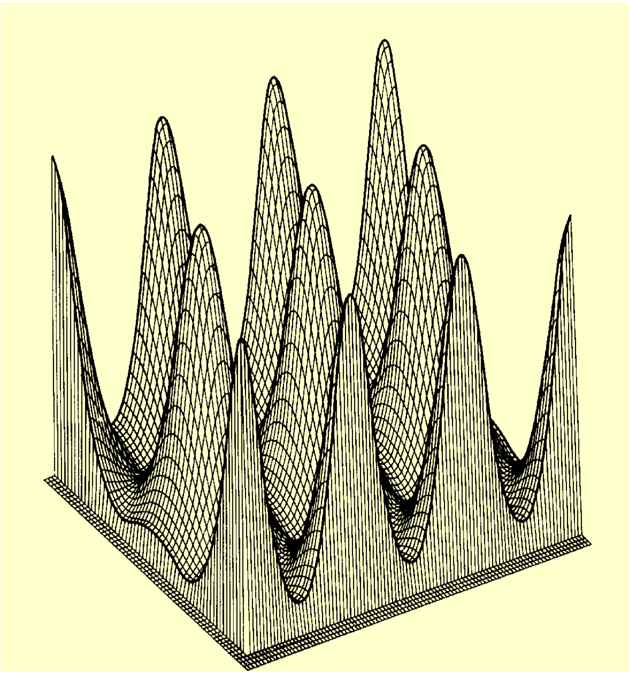
For fields somewhat above H_{c1} typical flux line separation is $a<\lambda$ and flux lines overlap

Since each flux line carries one flux quantum Φ_o (=h/2e) the average internal flux density for triangular and square flux lattices are respectively

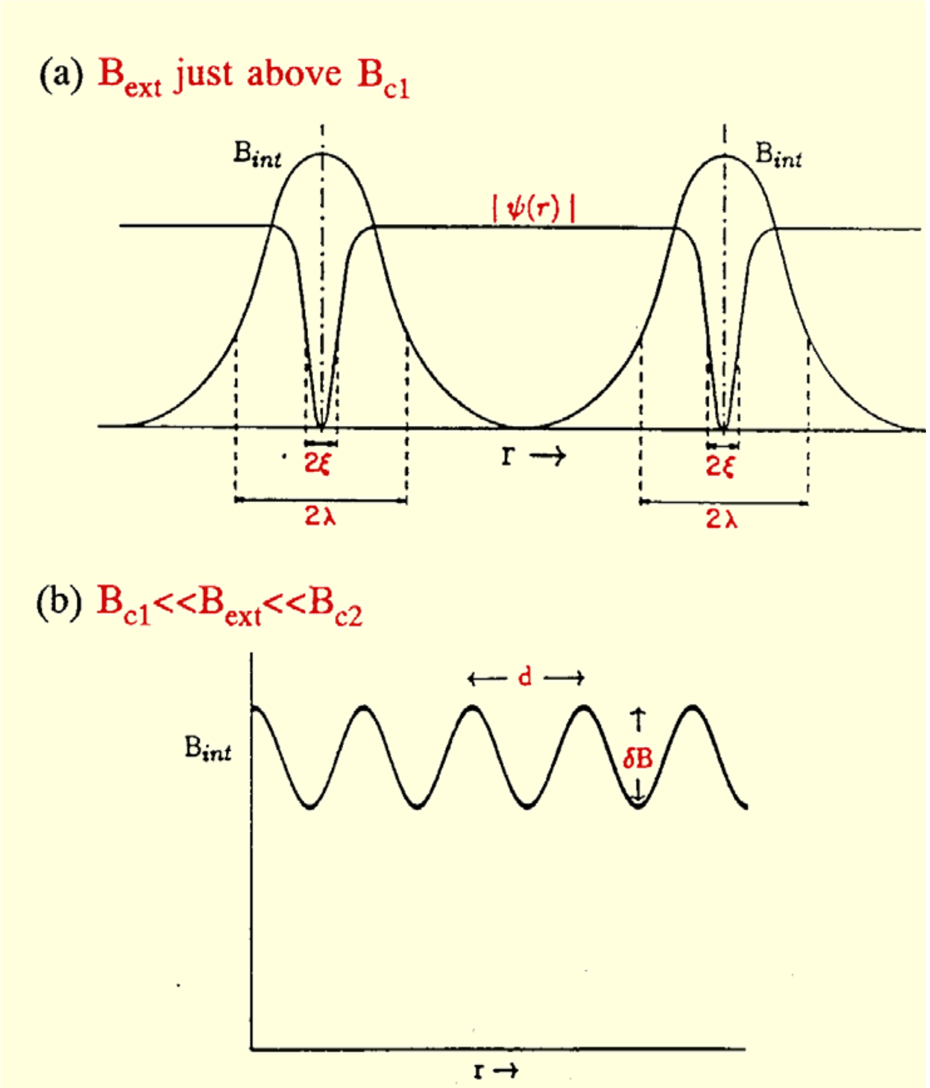
$$B_T = \frac{\sqrt{3}\Phi_o}{2a^2} \qquad B_S = \frac{\Phi_o}{a^2}$$

Small angle neutron scattering

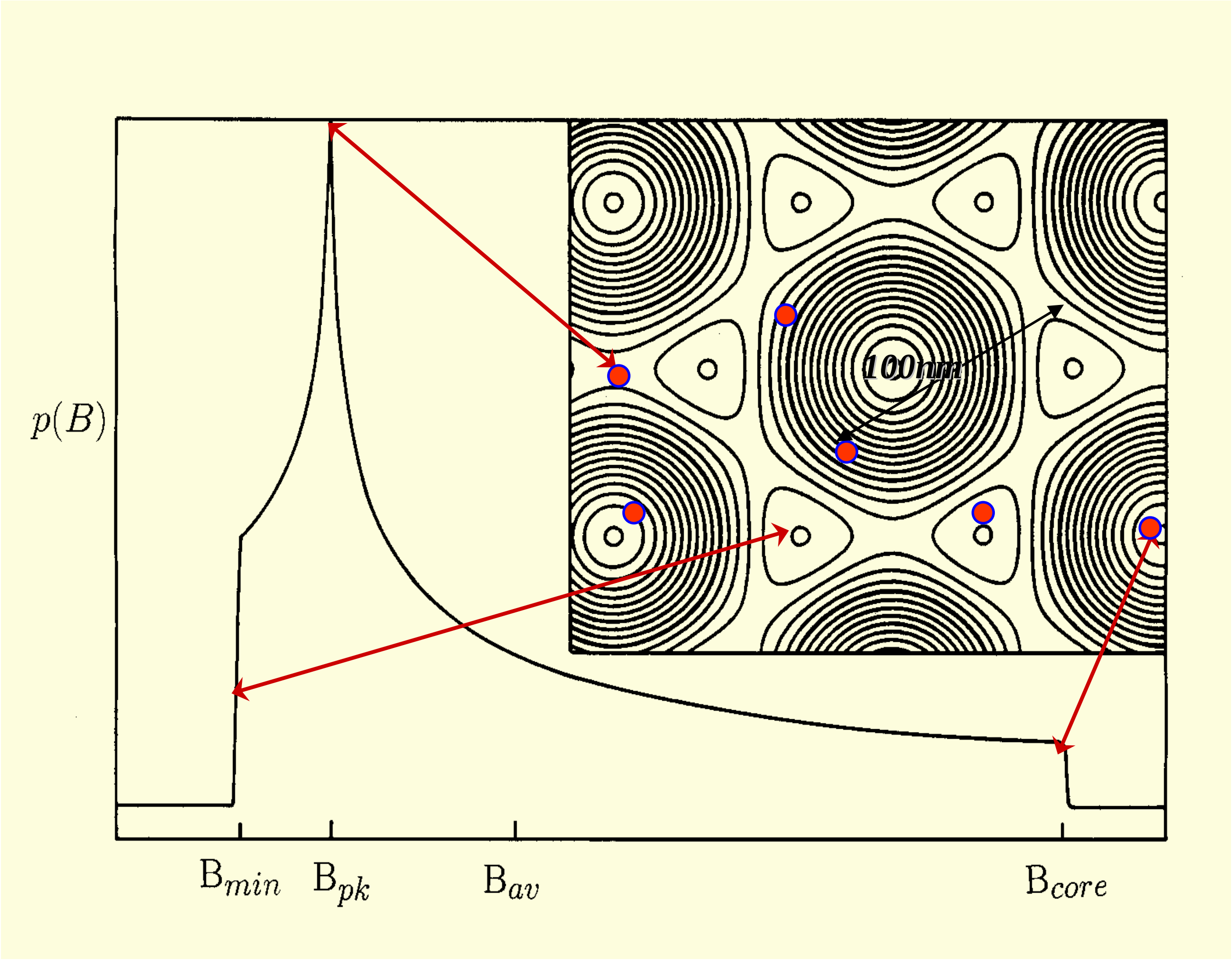




Flux distrbutions



Probing the flux lattice with muons



Calculating the field distribution

For an ideal flux lattice the internal flux density is periodic and

$$B(\underline{r}) = \langle B \rangle \sum_{G} b_G \exp(i\underline{G}\cdot\underline{r})$$

where $\underline{G}$ is a reciprocal lattice vector of the flux lattice

In the London limit the fourier components $b_G = \dfrac{1}{1+\lambda^2|G|^2}$

The second moment of the field distribution is given by

$$\langle \Delta B^2 \rangle^{\frac{1}{2}} = \left[\int_{\substack{\text{unit}\\ \text{cell}}} \left(B^2(r) - \langle B \rangle^2 \right) dr \right]^{1/2}$$

Therefore $\langle \Delta B^2 \rangle^{\frac{1}{2}} = \langle B \rangle \left[\sum_{G\neq 0} b_G^2 \right]^{1/2} = \langle B \rangle \left(\sum_{G\neq 0} \dfrac{1}{(1+\lambda^2|\underline{G}|^2)^2} \right)^{1/2}$

For $H >> H_{c1} = \dfrac{\Phi_o}{4\pi\lambda^2} \ln\left(\dfrac{\lambda}{\xi}\right)$ (so that $\lambda .G >> 1$) we find

$$\boxed{\langle \Delta B^2 \rangle^{\frac{1}{2}} = \left[\frac{0.00371\Phi_o^2}{\lambda^4} \right]^{1/2}}$$

Relating σ to the penetration depth

The effects of distortions and defects in the flux lattice often smear the flux distribution, p(B), and lead to a Gaussian form for p(B)

In this case the transverse field relaxation, $G_x(t)$ is also Gaussian:

$$G_x(t) = e^{-\sigma^2 t^2}$$

and

$$\overline{\Delta B^2} = \frac{2\sigma^2}{\gamma_\mu^2}$$

$$\boxed{\sigma = \frac{75780}{\lambda^2}}$$

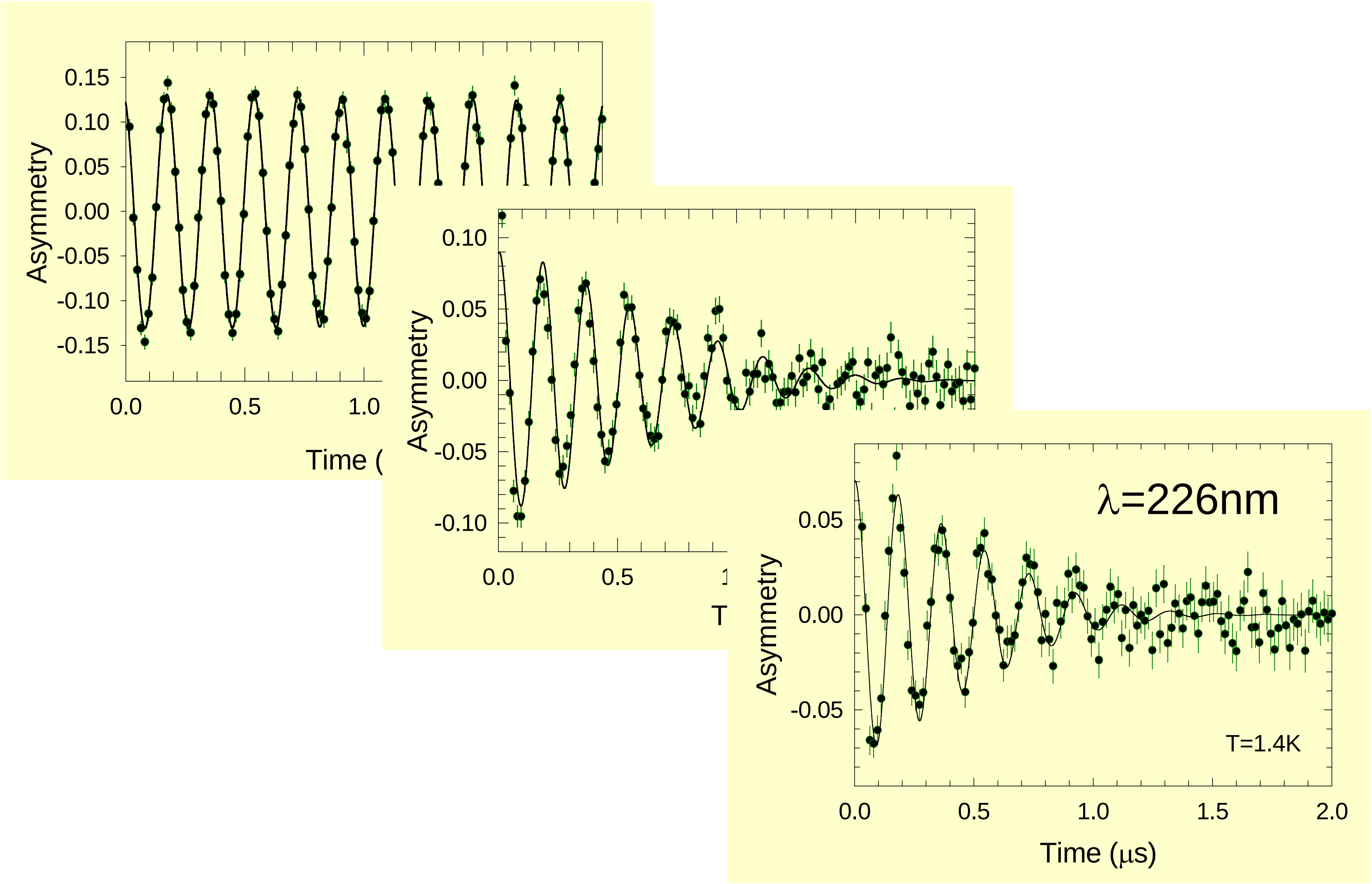
with σ in μs^{-1} and λ in nm.

The Gaussian approximation thus provides a simple relationship between σ and λ,

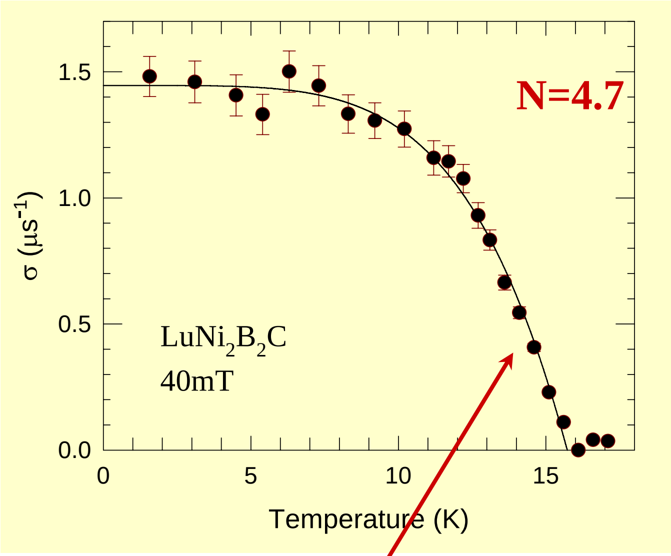
-and is often a reasonable approximation

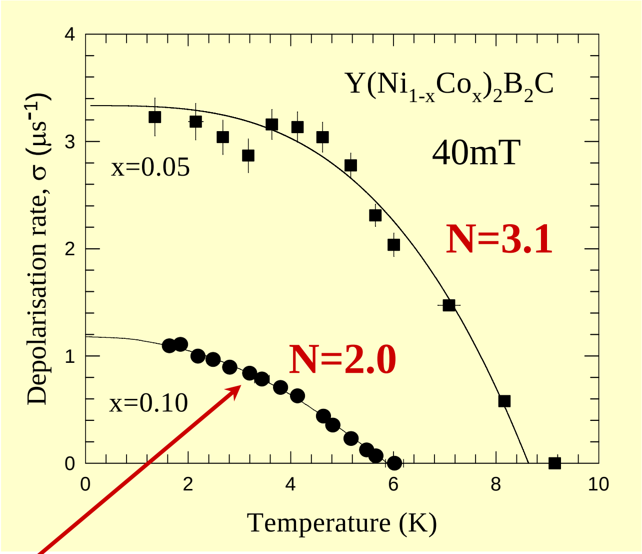
But ideally Max Ent should be used to extract the field profile

$LuNi_2B_2C$ T_c=16K

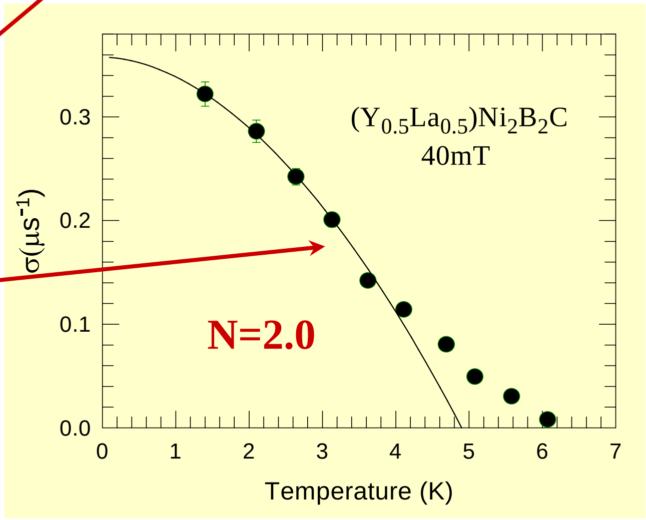


Temperature dependence of λ



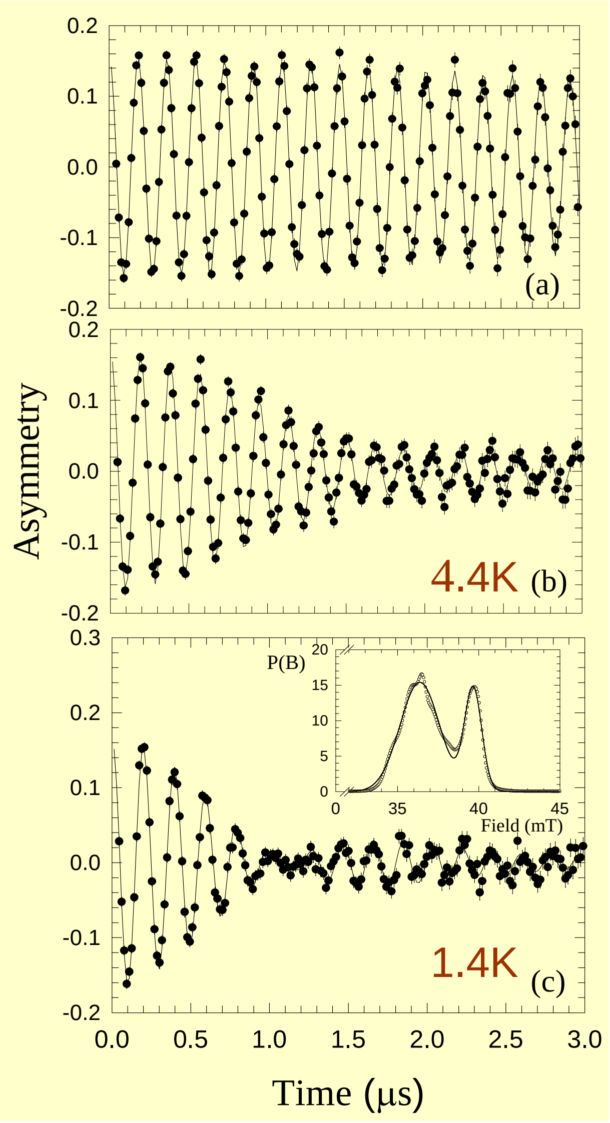


$$\sigma(T)=\sigma(0)\left[1-\left(\frac{T}{T_C}\right)^N\right]$$



Hillier and Cywinski

YB_6, T_c=6K

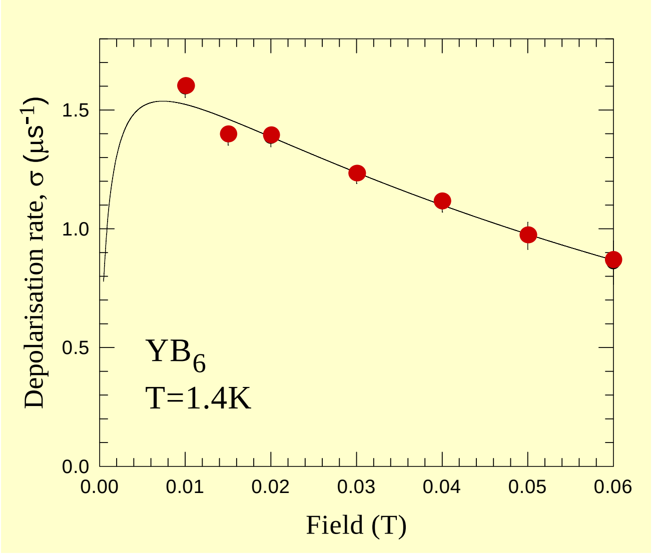


A D Hillier and R Cywinski Applied Mag Res 13 (1997)

As the applied field increases the effects of the core size, ξ, must be taken into account

$$b_G = \frac{\exp(-\xi^2 G^2/4)}{1+\lambda^2 |G|^2}$$

is a reasonable approximation, yielding both λ and ξ from σ



λ=192nm, ξ = 33nm

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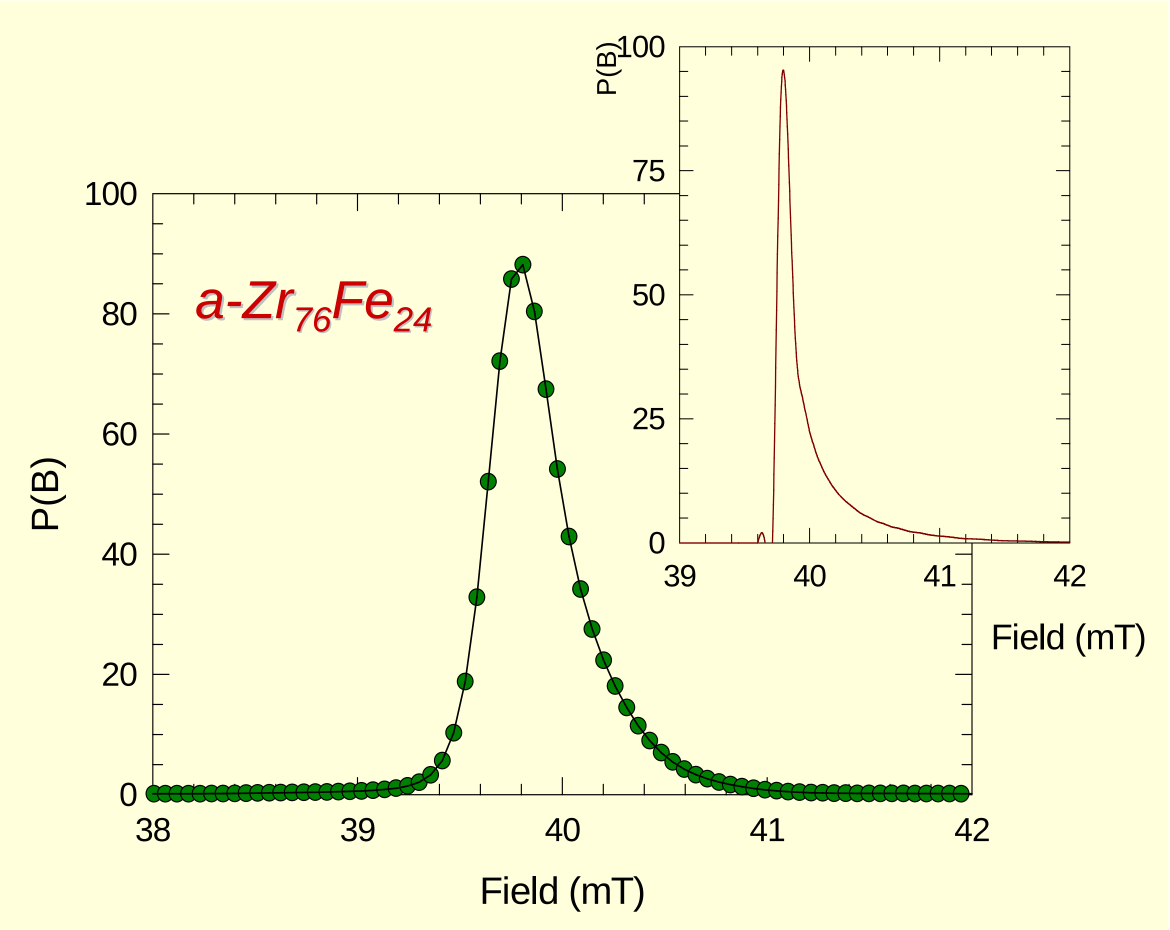
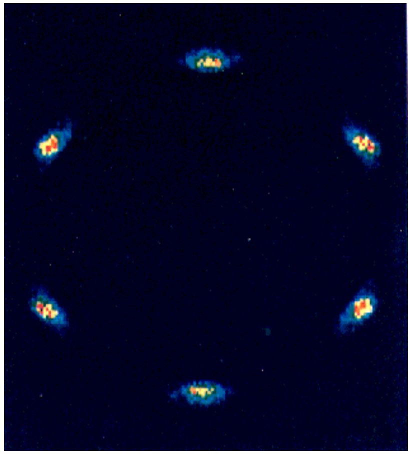
Amorphous Zr-Fe - using max ent

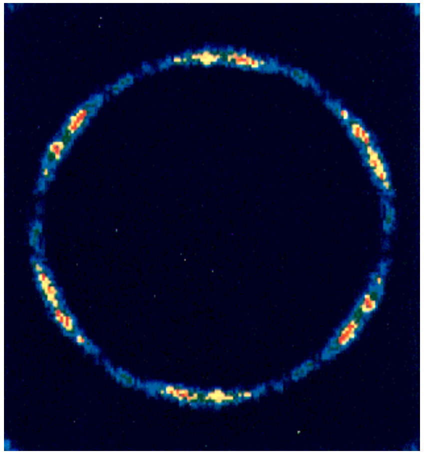


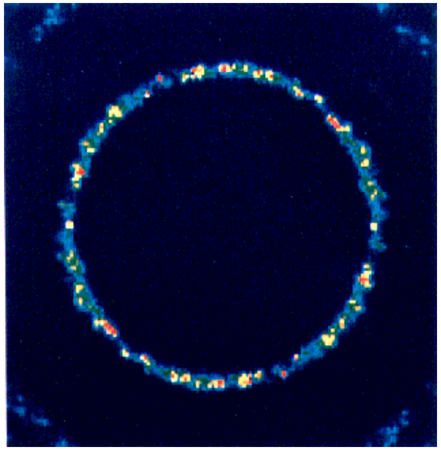
T_c = 1.7K , λ = 500nm, ξ = 29nm

Manuel and Kilcoyne

Flux lattice melting





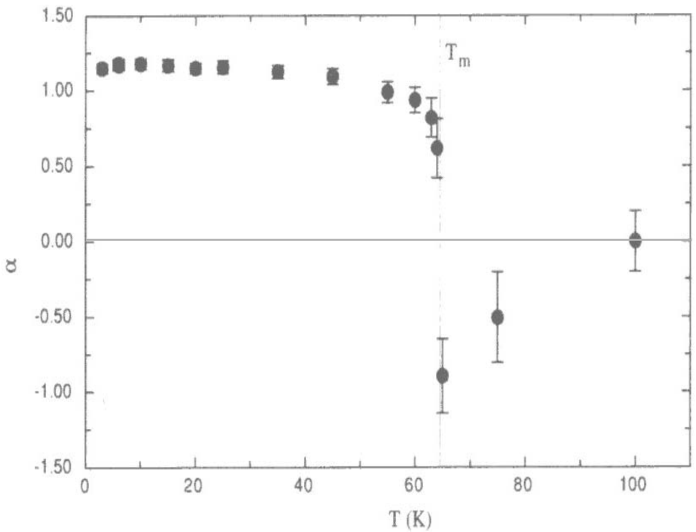


$T<T_m<T_c$

$T_m<T<T_c$

The effects of vortex lattice melting in the high temperature can be measured via the asymmetry of P(B), as defined by

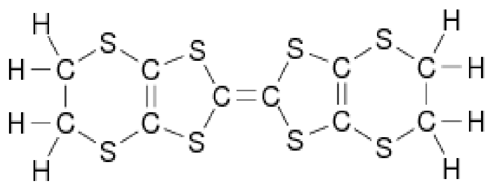
$$\alpha = \langle \Delta B^3 \rangle^{1/3} / \langle \Delta B^2 \rangle^{1/2}$$

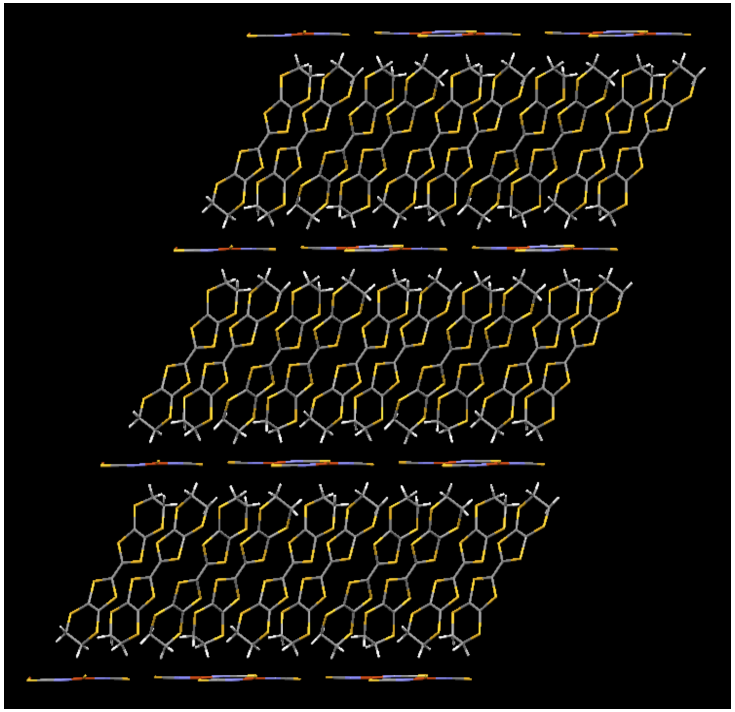


Lee et al PRB 55 (1997) 5666

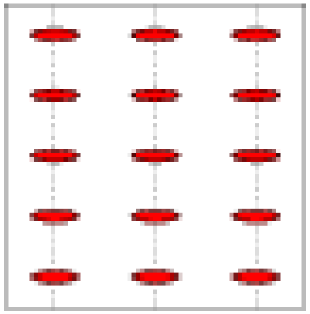
Melting/Decoupling of vortices in $ET_2Cu(SCN)_2$

BEDT-TTF (ET)

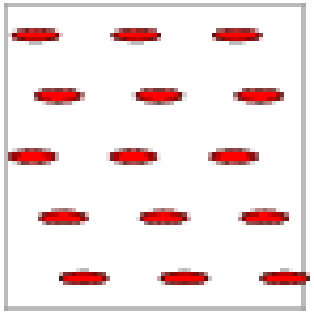




3D Flux Lattice

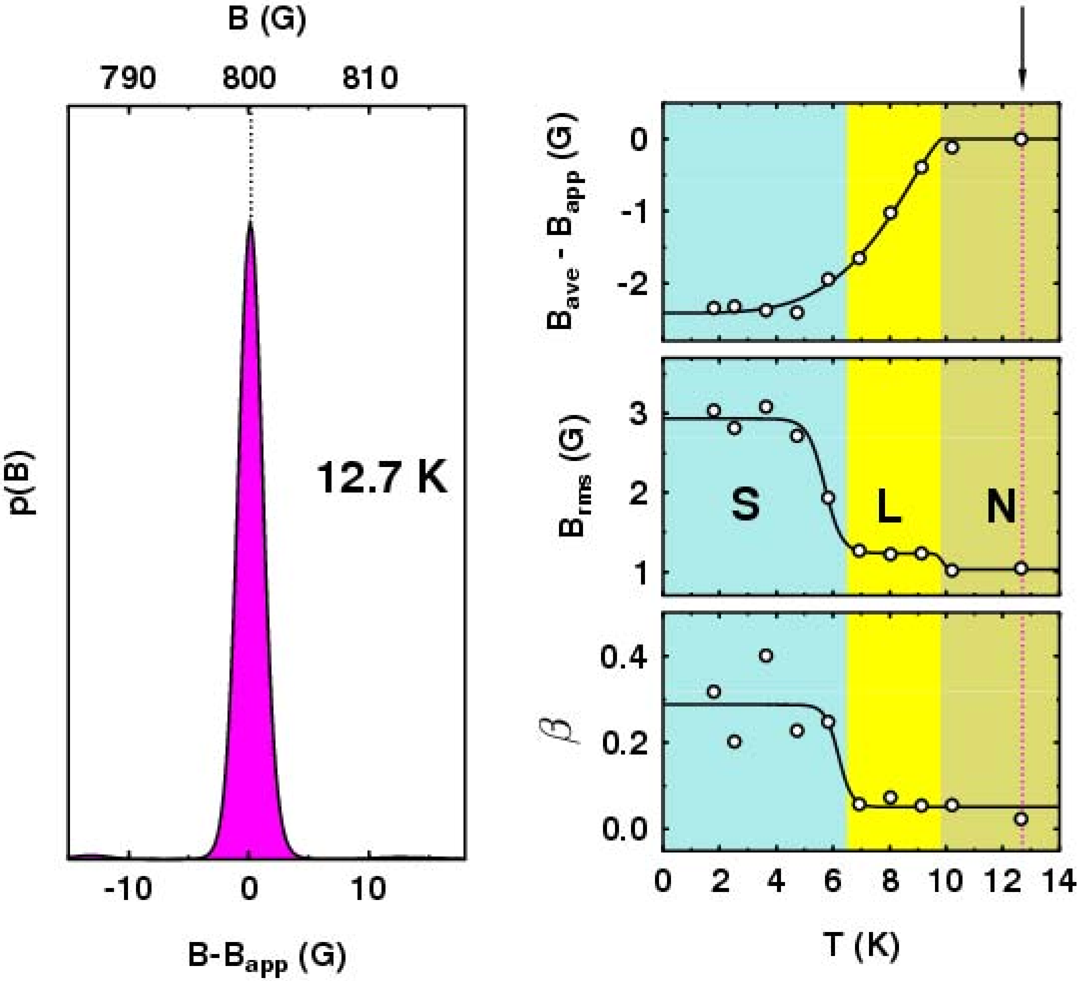


Decoupled 2D Layers

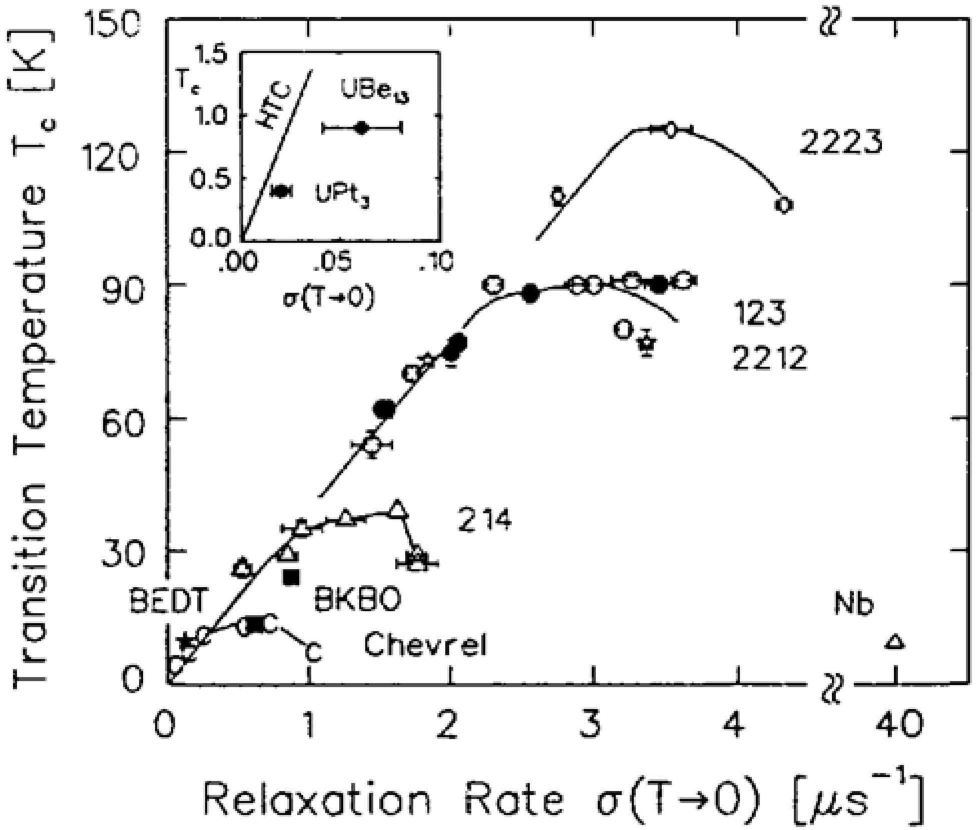


Pratt et al

Melting/Decoupling of vortices in $ET_2Cu(SCN)_2$



Uemura's universal correlations



(Uemura, PRL 66 (1991) 2665)

The Uemura plot

The general London formula gives

$$\lambda(0) = \left[\frac{m^*/m_e}{4\pi n_s r_e} \left(1 + \frac{\xi}{l_e} \right) \right]^{1/2}$$

so in the clean limit ($\xi/l_e \ll 1$), we have

$$\sigma(0) \propto \frac{n_s(0)}{m^*}$$

Note that for a quasi-2d non-interacting electron gas the Fermi temperature is given by

$$k_B T_F = (\hbar^2 \pi) \frac{n_{s2d}}{m^*}$$

Uemura's result therefore implies a *direct correlation* between T_C and T_F

The Uemura plot

For a 3d system, the Fermi temperature is given by

$$k_B T_F = (\hbar^2/2)(3\pi^2)^{2/3} n_s^{\,2/3} / m^*$$

As the Sommerfeld constant, γ, is given by

$$\gamma = \left(\frac{\pi}{3}\right)^{2/3} \frac{k_B^2 m^* n_e^{1/3}}{\hbar^2}$$

$\lambda(0)$, and hence $\sigma(0)$, can then be combined with γ to provide

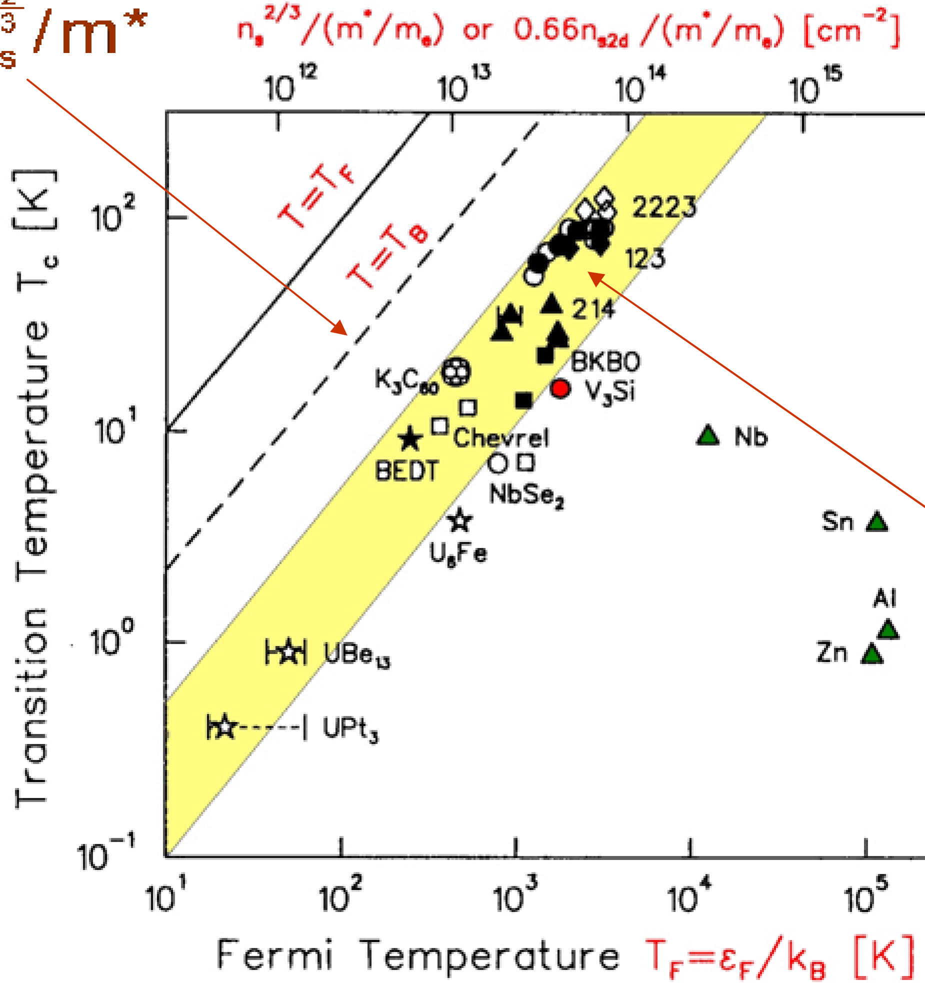
$$k_B T_F \propto \sigma(0)^{3/4} \gamma^{-1/4}$$

This is the basis of the generalised Uemura plot of T_c v T_F

Uemura and Cywinski
Muon Science p165-172 (Editors: S L Lee, S H Kilcoyne and R Cywinski, IOP Publishing 1999)

Evidence for unconventional superconductivity?

$k_B T_B \approx \hbar^2 n_s^{\frac{2}{3}} / m^*$



$$\frac{1}{100} < \frac{T_C}{T_F} < \frac{1}{10}$$

$$\frac{T_C}{T_B} \leq \frac{1}{30}$$

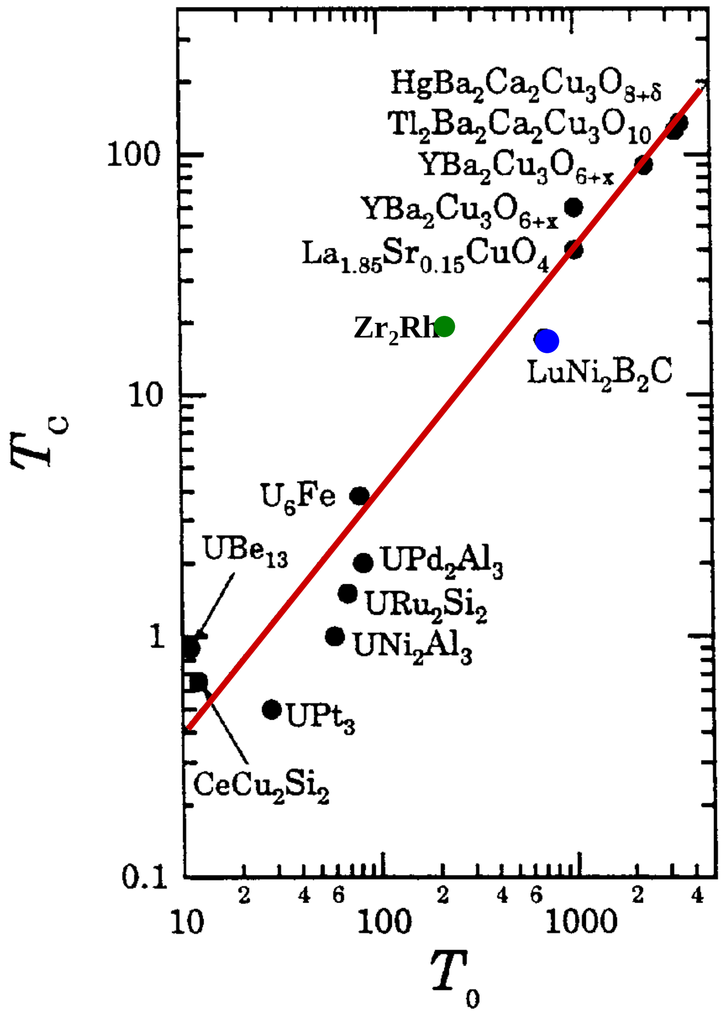
Uemura et al PRL 66 (1991) 2665

Spin fluctuations as the pairing mechanism ?

Experiment shows that T_c also correlates with the effective "spin fluctuation" temperature, as measured with neutrons, in many "exotic" superconductors:

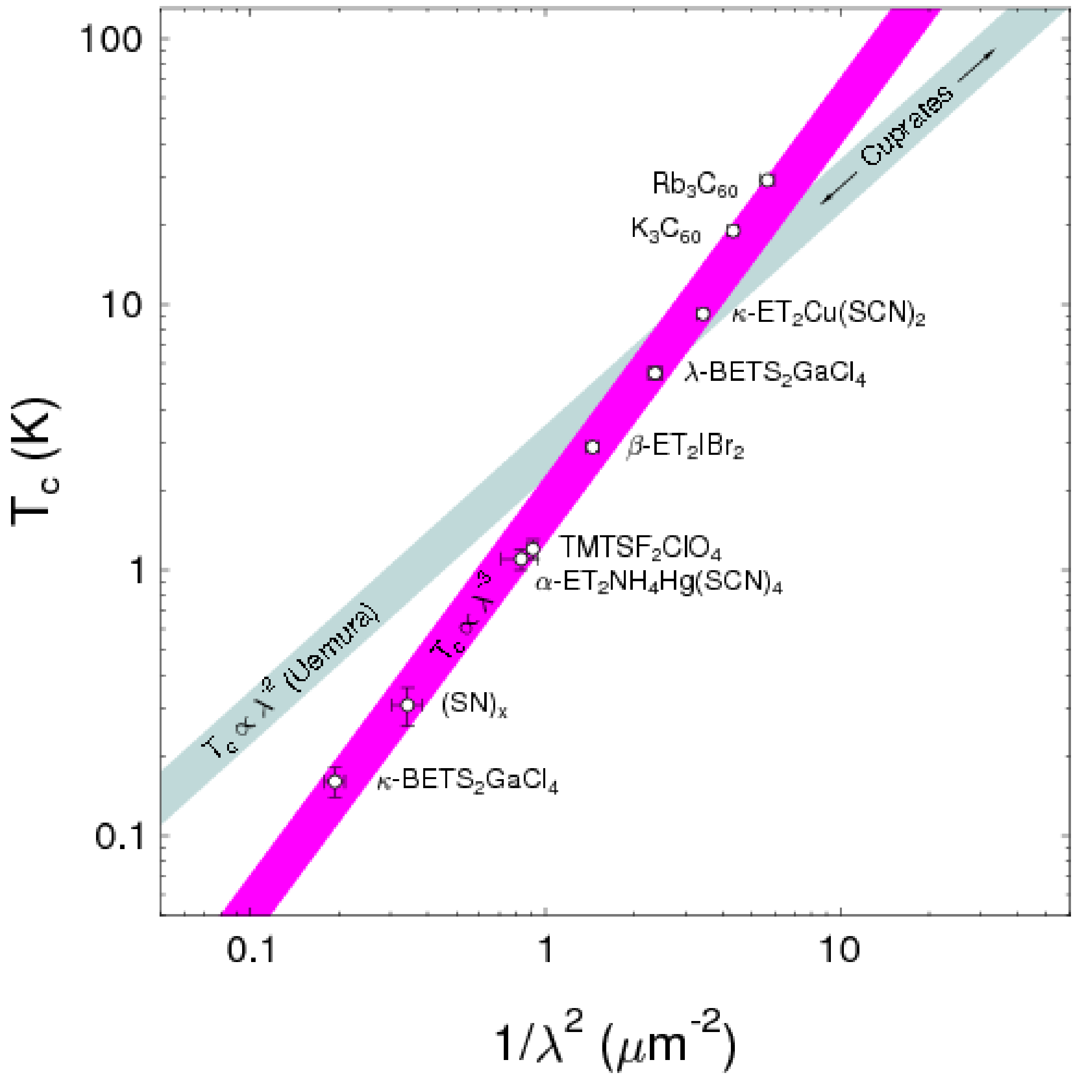
$T_c/T_o \sim 1/30$

Within the framework of Self Consistent Renormalsation (SCR) theory this suggests that similar antiferromagnetic spin fluctuations may be responsible in all systems



Nakamura, Moriya and Ueda
J Phys Soc Japn 65 (1996) 4026

Molecular superconductors



Molecular systems appear to have their own empirical scaling law:

T_c follows $1/\lambda^3$ rather than $1/\lambda^2$

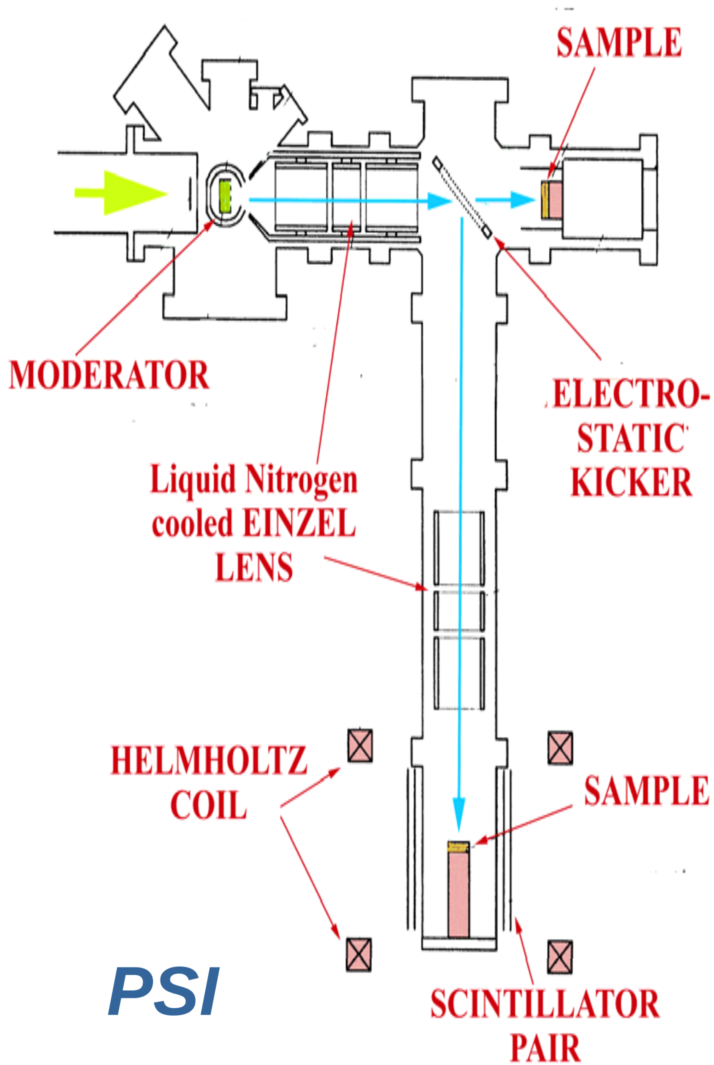
$\Rightarrow T_c \propto (n_s/m_b)^{3/2}$

Pratt and Blundell

Cold muons and superconductivity

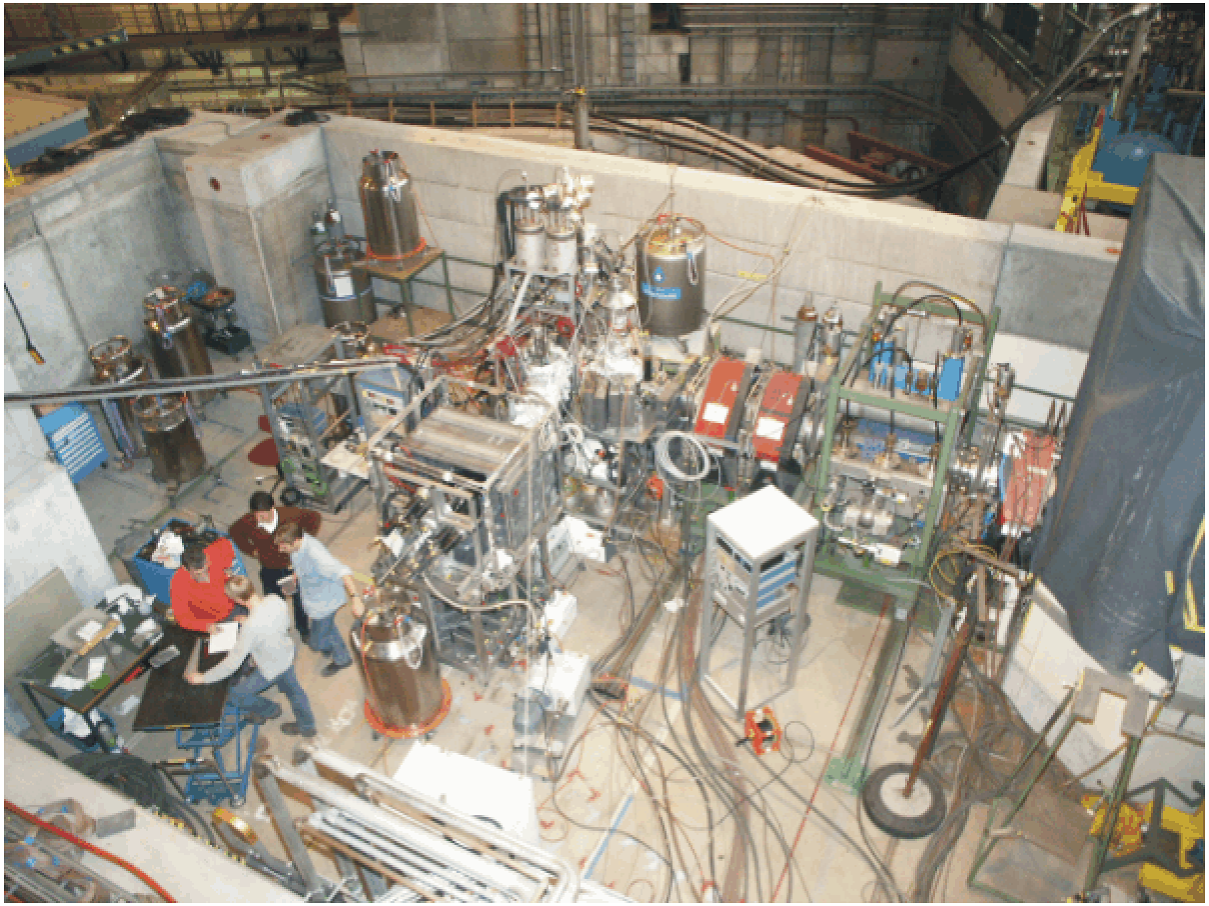
Muons are cryogenically moderated and energy selected to tune localisation depth within the sample:

E(keV)	*R(nm)*	*ΔR(nm)*
0.010	0.5	0.3
0.100	2.1	1.3
1.0	13.1	5.4
10.0	75.0	18.0
30.0	244.0	36.0



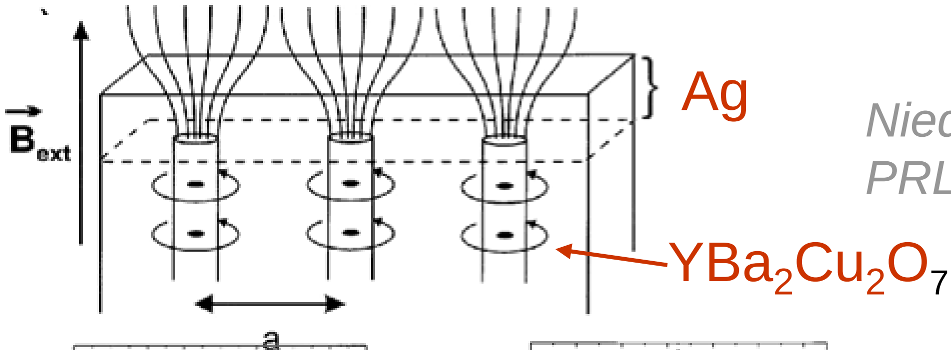
See Morenzoni in "Muon Science" eds Lee, Kilcoyne and Cywinski, 1998

Cold muons at PSI

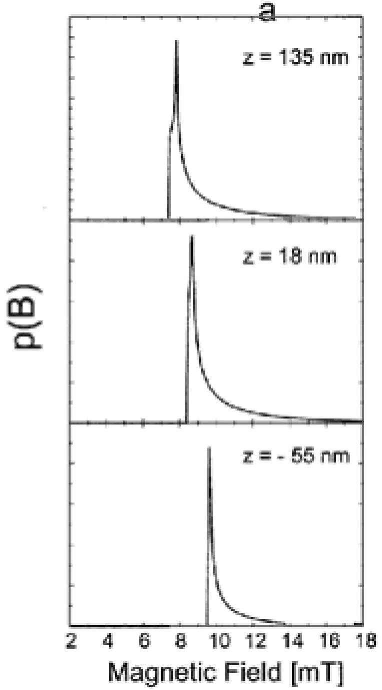


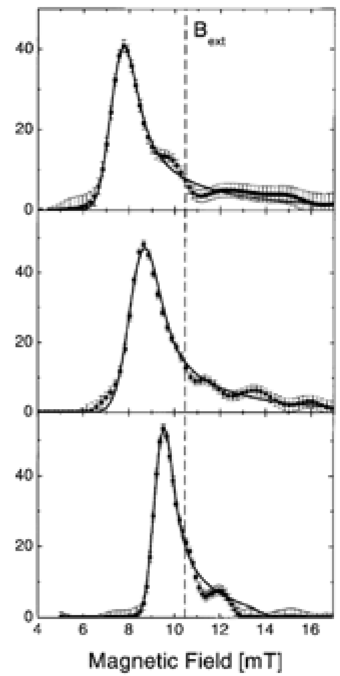
….but the efficiency is very low (~10^{-5})

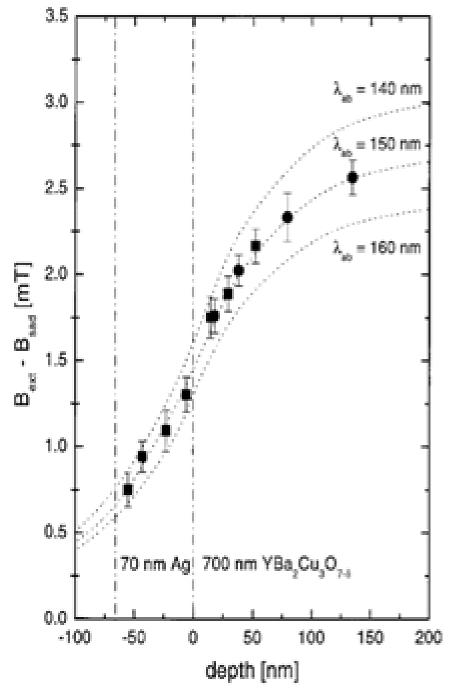
Flux penetration with cold muons



Niedermayer, Forgan et al
PRL83, 3935, 1999







simulated

measured

Conclusions

Transverse field muon spin rotation is a sensitive probe of the superconducting state offering some of the most precise measurements of the penetration depth in bulk samples

MuSR complements small angle neutron scattering measurements which provide information on *long range order* of the flux line lattice

MuSR provides access to estimates of the fundamental parameters of the superconducting state, and allows their temperature dependence to be measured – this can provide new insights into the underlying physics of superconductivity