MULTIGAP SUPERCONDUCTIVITY IN HEAVY FERMION SYSTEMS

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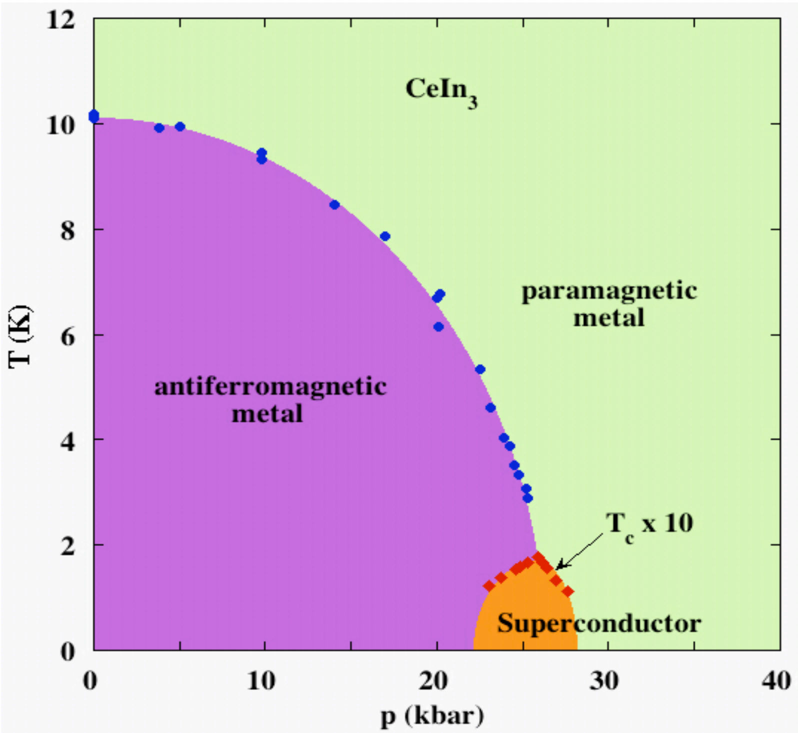
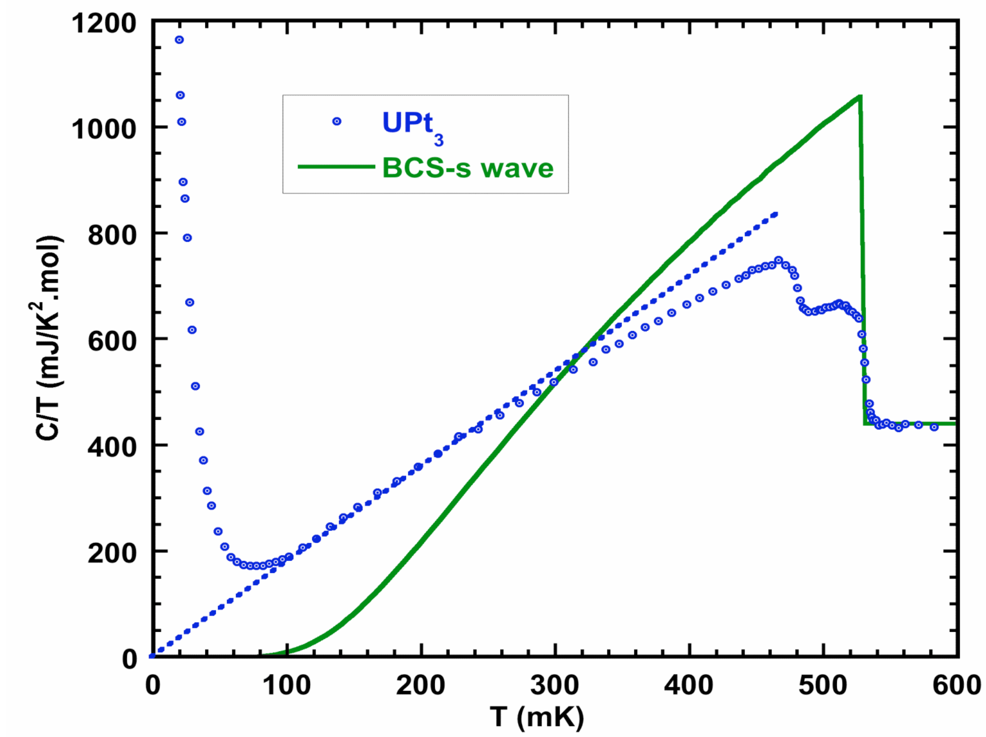
OUTLINE

- Introduction :
  - why multigap superconductivity in heavy fermion systems ?
  - Fermi Surface of $CeCoIn_5$ and $PrOs_4Sb_{12}$
- Results on $PrOs_4Sb_{12}$
  - low field scale from κ(H)
  - small gap estimate from κ(T)
  - consistent set of λ_{ij} to explain and $H_{c2}(T)$ and κ(H,T)
- Results on $CeCoIn_5$
  - low temperature behavior of κ(T):
    unpaired electrons/small gap ?
  - low field scale from κ(H)
- Summary

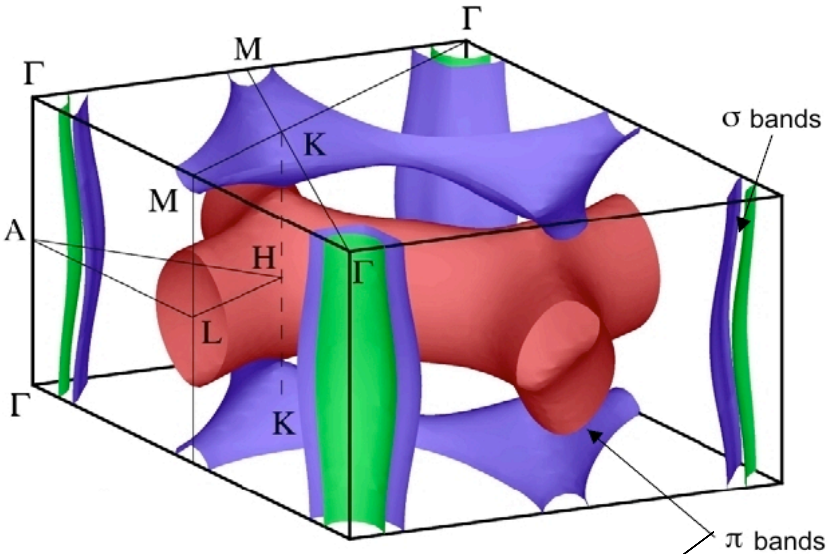
INTRODUCTION: heavy fermion superconductors

– $CeCu_2Si_2$ (1979), UBe_{13} (1983), UPt_3 (1984), $CeCoIn_5$ (2002), URhGe (2001)..
– 3D anisotropic (tetragonal, cubic, hexagonal)
– f electrons=> hard core + close to AF instability
– heavy quasiparticles (f electrons) build Cooper pairs
– "p,d,f wave"

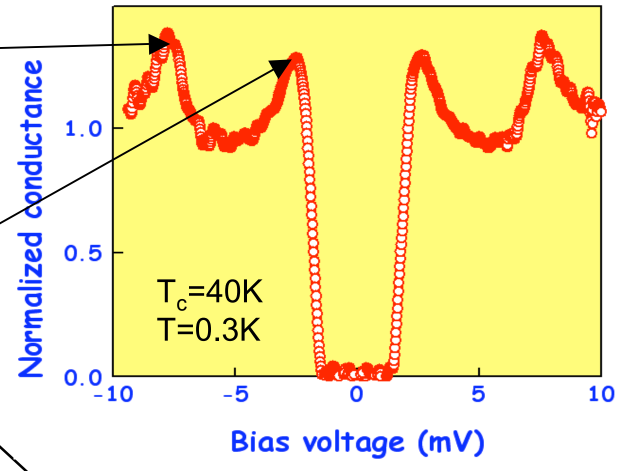


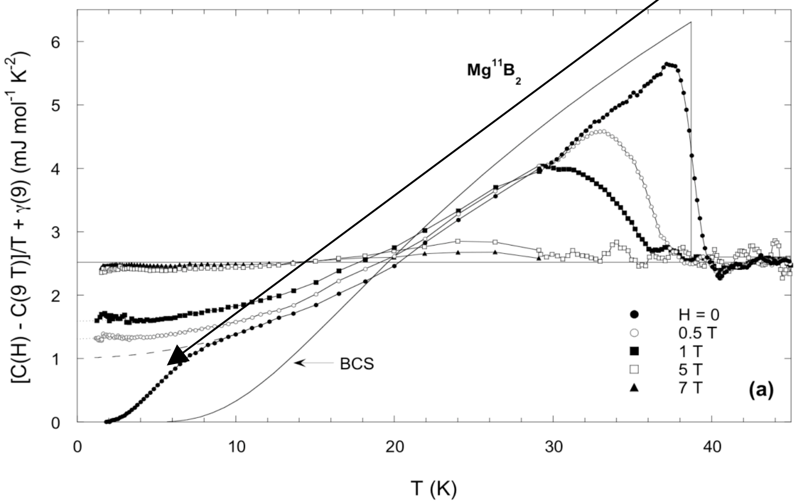


INTRODUCTION: MgB_2 paradigm of multigap superconductors

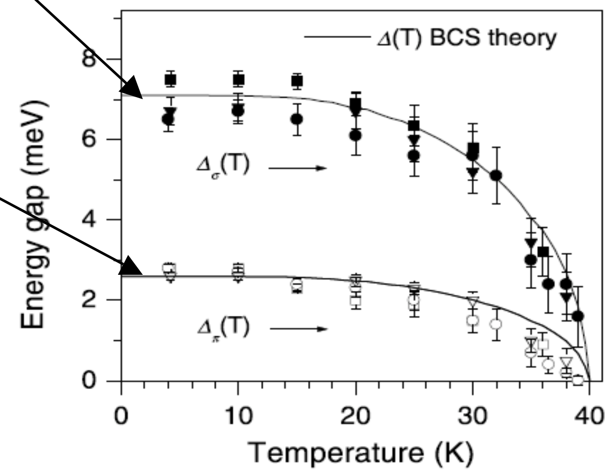


P. Martinez-Samper et al., Physica C **385** 233 (2003)



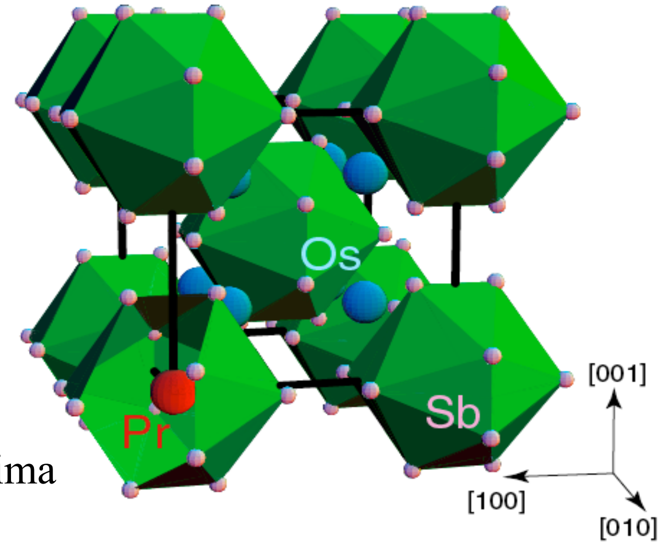


Bouquet et al. PRL 87 47001 (2001)



Samuely et al., Physica C 385 (2003) 244

$PrOs_4Sb_{12}$



H.Harima

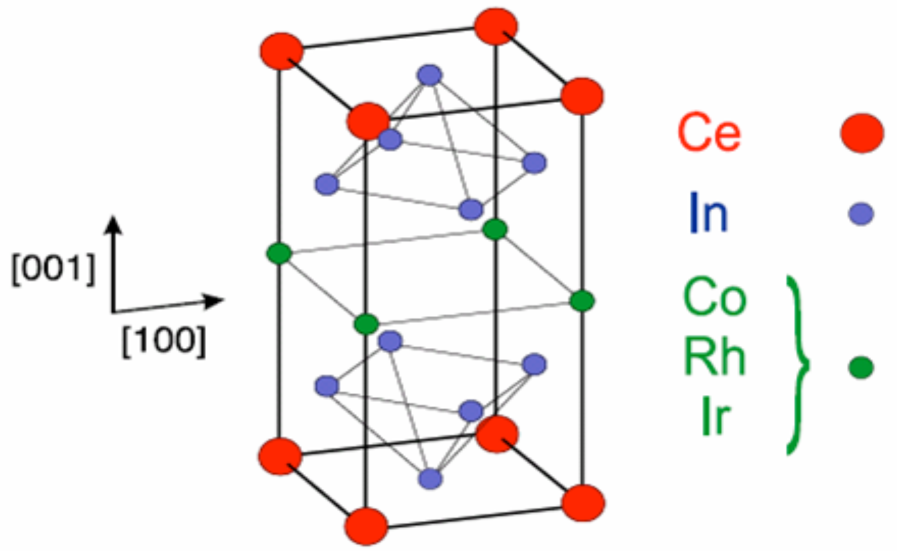
•filled skutterudite, RT_4X_{12}, cubic Im3, T_h symmetry

•Γ_1 non magnetic ground state, low lying Γ_4 triplet

•Heavy fermion Superconductor: T_c~1.7K

Bauer et al., PRB, **65**, 100506(R) (2002)

$CeCoIn_5$



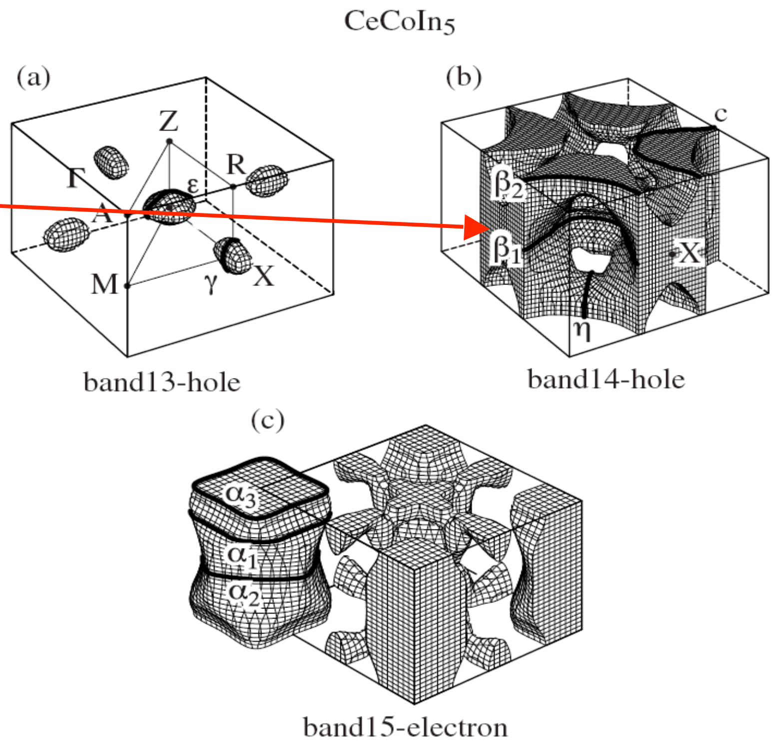
• Tetragonal crystal structure

• Space group P4/mmm

• Heavy fermion superconductor: T_c~2.3K

Petrovic *et al*, JP: Cond Matter **13** L337 (2001)

	Experimental	Theoretical
	m_c^* (m_0)	m_b (m_0)
$H \parallel [001] = 160$ kOe		
β_1	48	3.48
β_2	49	1.73
α_1	15	1.78
α_2	18	1.09
α_3	8.4	1.48
$H \parallel [110] = 150$ kOe		
ζ	33	
η	20	
ε	5.6	
$H \parallel [100] = 45$ kOe		
ε	12	
γ	4.3	
$H \parallel 42.5°$ from $[001] = 160$ kOe		
β_2	87	



R. Settai *et al*, J. Phys. Cond Matter **13** L627 (2001)

$$\frac{m^*}{m_0} \approx 4-87$$

INTRODUCTION: why MBSC in Heavy Fermion Superconductors ?

- BCS simple gap: $T_c \approx \theta_D \exp\left(-\frac{1}{\lambda - \mu^*}\right)$, with $\lambda = -N(0)V > 0$

- Multigap: set of coupling constants $\lambda_{ij} \approx V_{ij} N_j$
  - different density of states ?
  - different pairing strength ?

  both true for the "heavy fermions"

N_j: density of states of band j

V_{ij}: symmetric interaction matrix between bands i & j

Yields:

- different gap values / FS sheets (depends only on λ_{ij}): Δ_i
- different field scales

depends on λ_{ij} & v_{Fi}.

$$\mathbf{F}_L = e\mathbf{v}_F \times \mathbf{B}, \quad \text{or } H_{orb} = \frac{1}{2m^*}(\mathbf{p} - e\mathbf{A})^2$$

$$H_{c2}^i \approx \frac{\Phi_0}{2\pi \xi_0^{i\,2}}, \text{ with } \xi_0^i \approx \frac{\hbar v_{Fi}}{\Delta_i}$$

⇒ strong effect for heavy fermion systems

Role of quadrupolar fluctuations:

- mass enhancement ?(Goremychkin et al., PRL **93** 157003 (2004)) ?
- for pairing mechanism (but $LaOs_4Sb_{12}$…)?

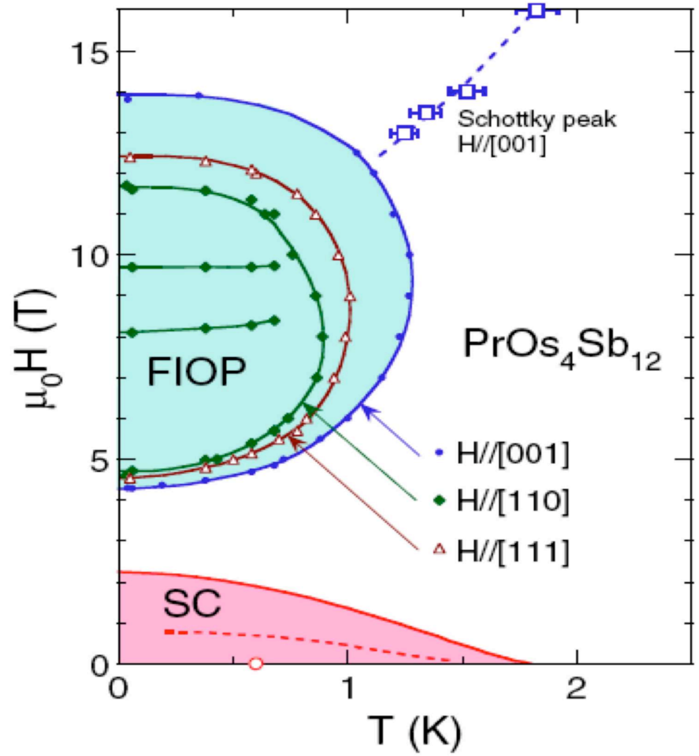
Unconventional Superconducting state ? (->T. Sakakibara & Y. Aoki et al., JPSJ **76** 051006-2007)

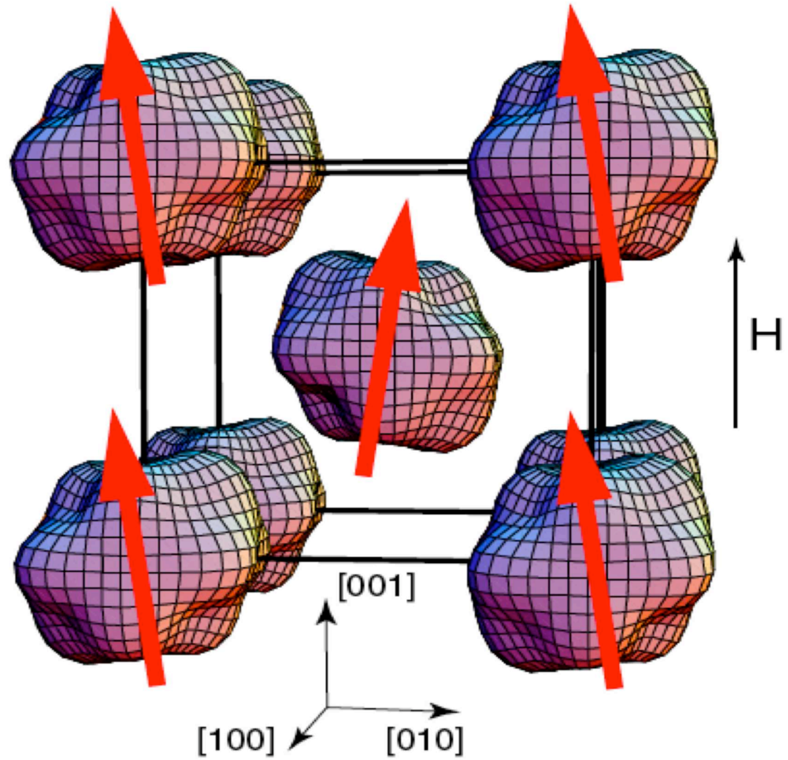
Aoki et al.,
JPSJ, **71**, 2098 (2002)

Koghi et al.,
JPSJ, **72**, 1002 (2003)

Tayama et al.,
JPSJ **72**, (2003) 1516

Figure: Y. Aoki et al.,
JPSJ **76** 051006-2007





$$j_e = \frac{1}{dV}\sum_i e v_i = e\rho\bar{v} = -\sigma\nabla V$$

$$j_q = \frac{1}{dV}\sum_i (\varepsilon_i - \mu) v_i = -\kappa\nabla T$$

$$\kappa = \frac{1}{3} c_v \bar{v} l$$

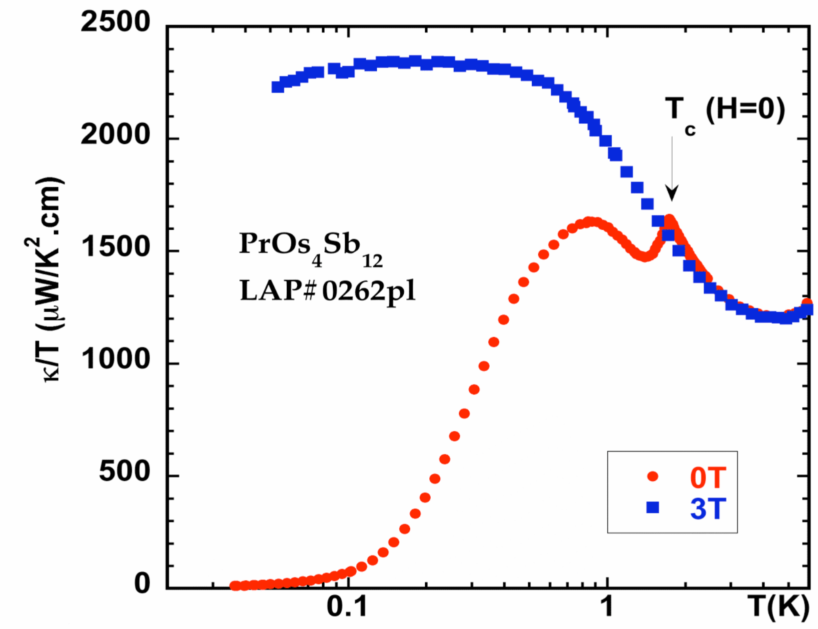
In metals, Wiedemann-Franz law: $\kappa_e/T = L_0\sigma$
(charge and thermal transport are equivalent)

Violated for superconductors:
- σ is infinite for T<Tc
- κ_e/T goes to zero as T goes to zero

Two fluid model.
- condensate of Cooper pairs with no entropy, short circuiting σ, no contribution to κ
- thermal conductivity: needs heat carriers : thermal excitations carrying entropy and heat

⇒κ(T) measures the number of thermal excitations

- Sensitive also to "the non f-bands"
- κ(T) probes the gaps
- κ(H) probes the field scale

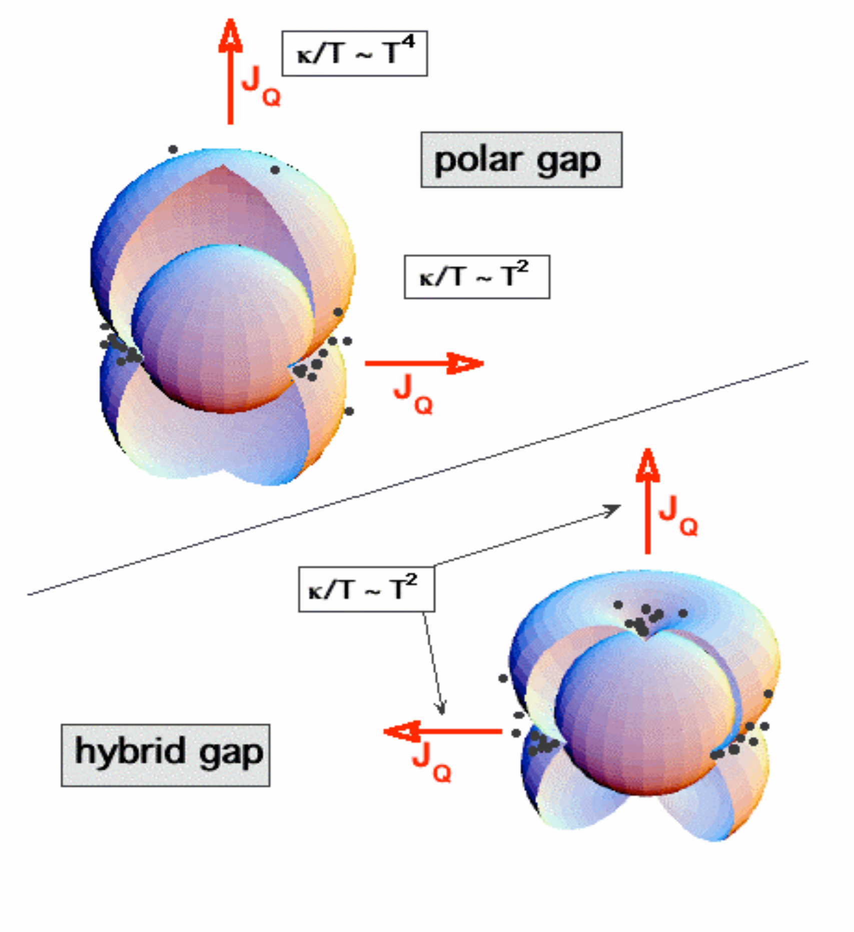


Heat carried by thermal excitations =>

- at low T/T_c , probes gap close to the nodes
- excitations with **k** // $\mathbf{J_Q}$
- no local (hyperfine...) contributions

Sensitive to scattering time (τ):

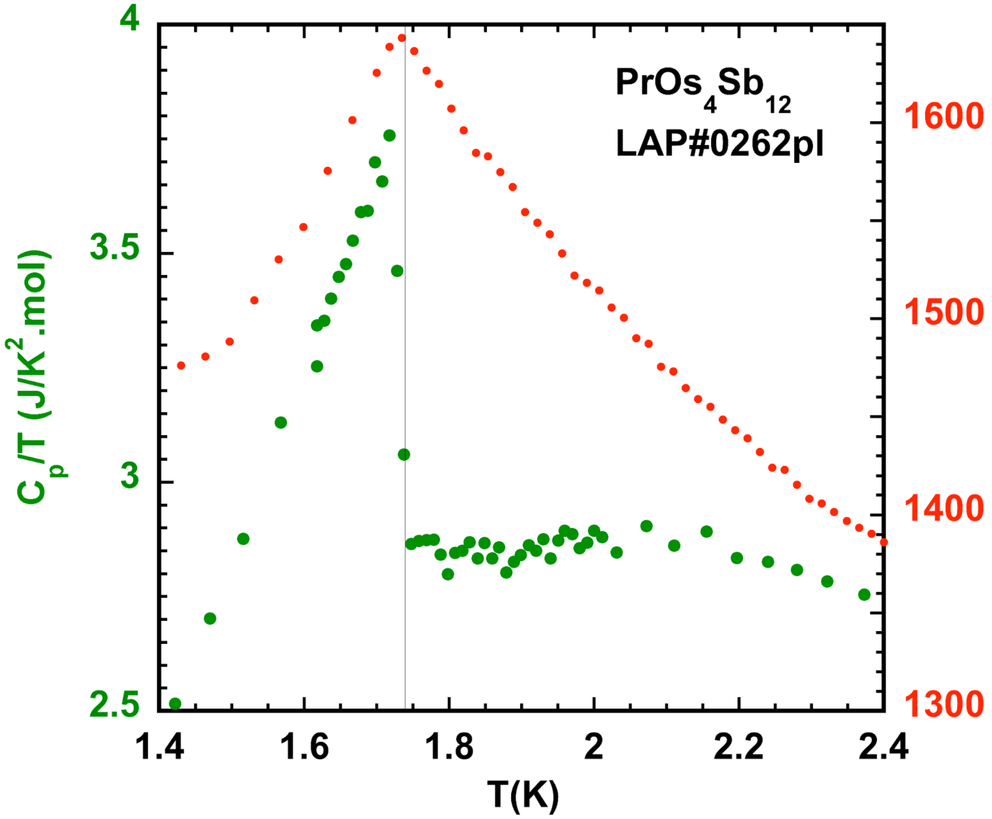
- resonant scattering close to the unitary limit ($\delta \sim \pi/2$) (Pethick and Pines 86)



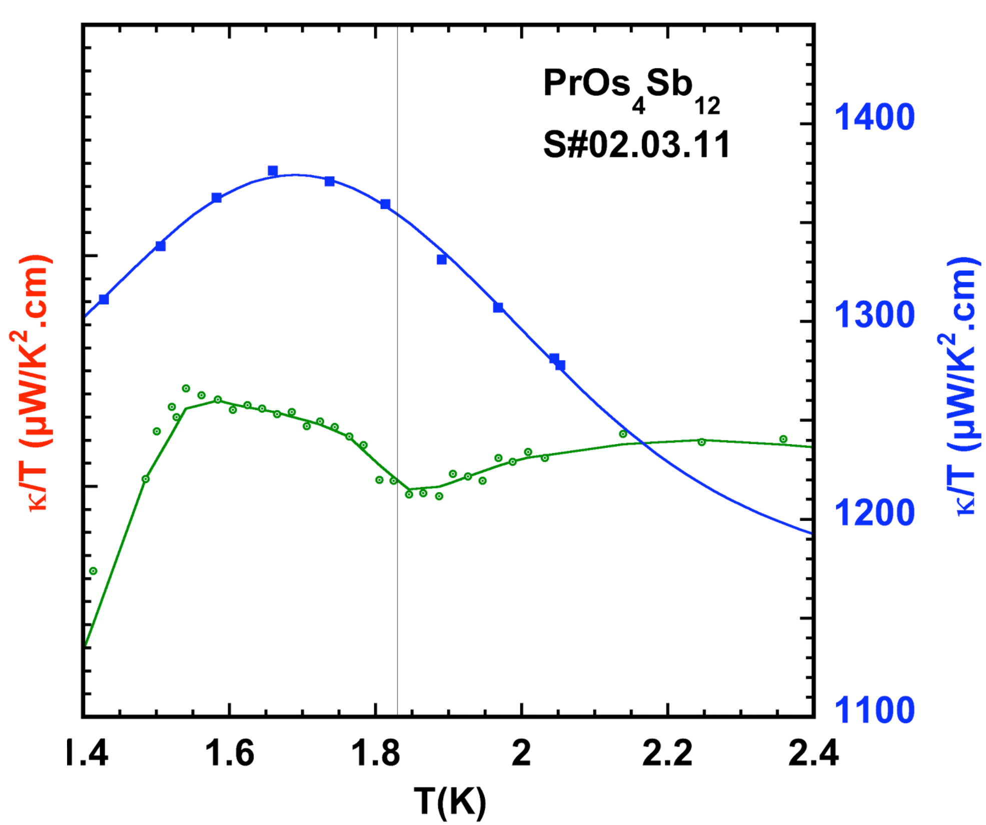
Thermal conductivity measurements on two different samples:

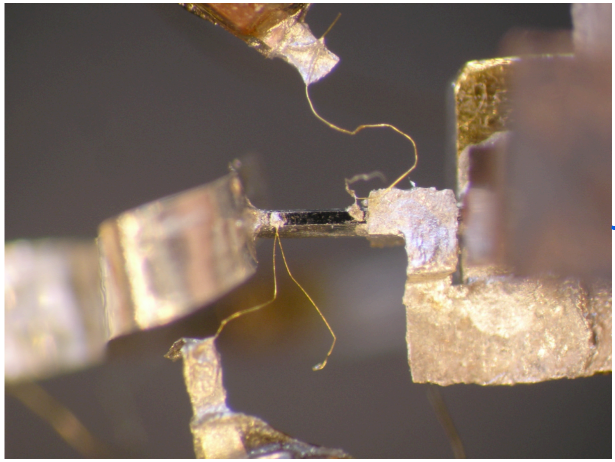
$$\frac{\rho(T_c)}{\rho(300K)} \approx 30 \qquad\qquad \frac{\rho(T_c)}{\rho(300K)} \approx 15$$

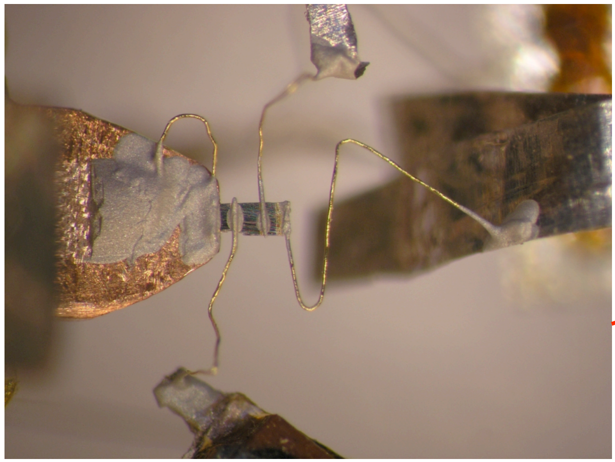
G. Seyfarth et al. PRL **97** 236403 (2006)

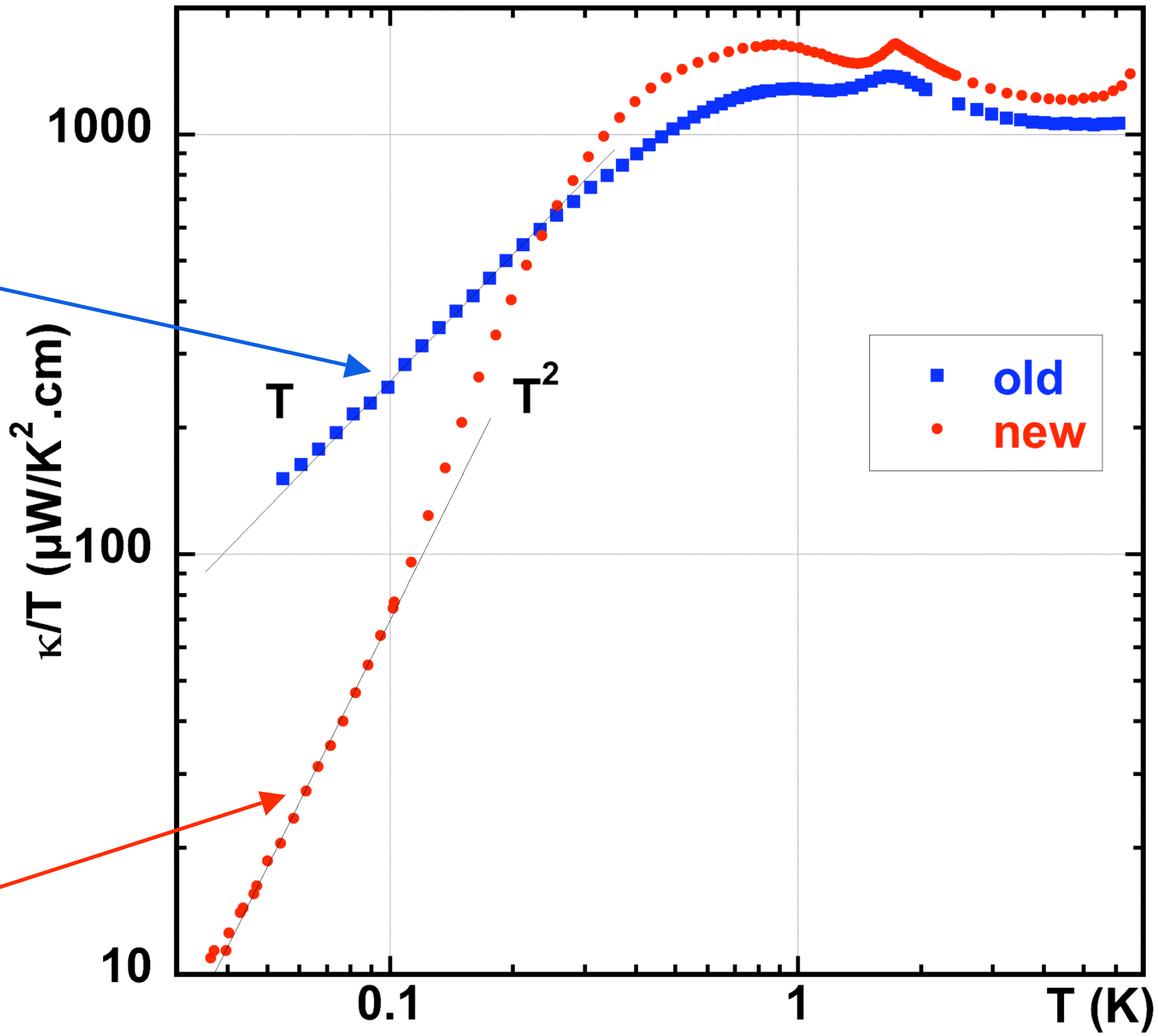


G. Seyfarth et al. PRL **95** 107004 (2005)





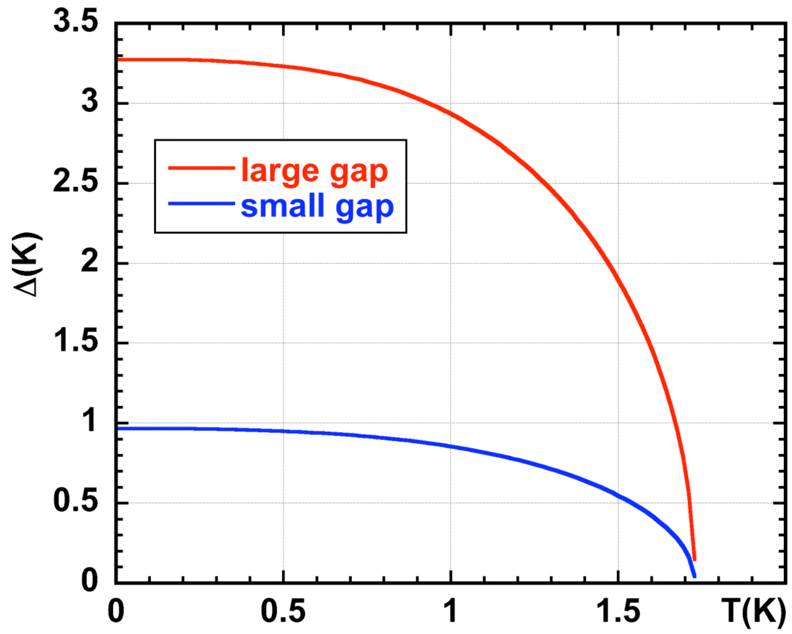


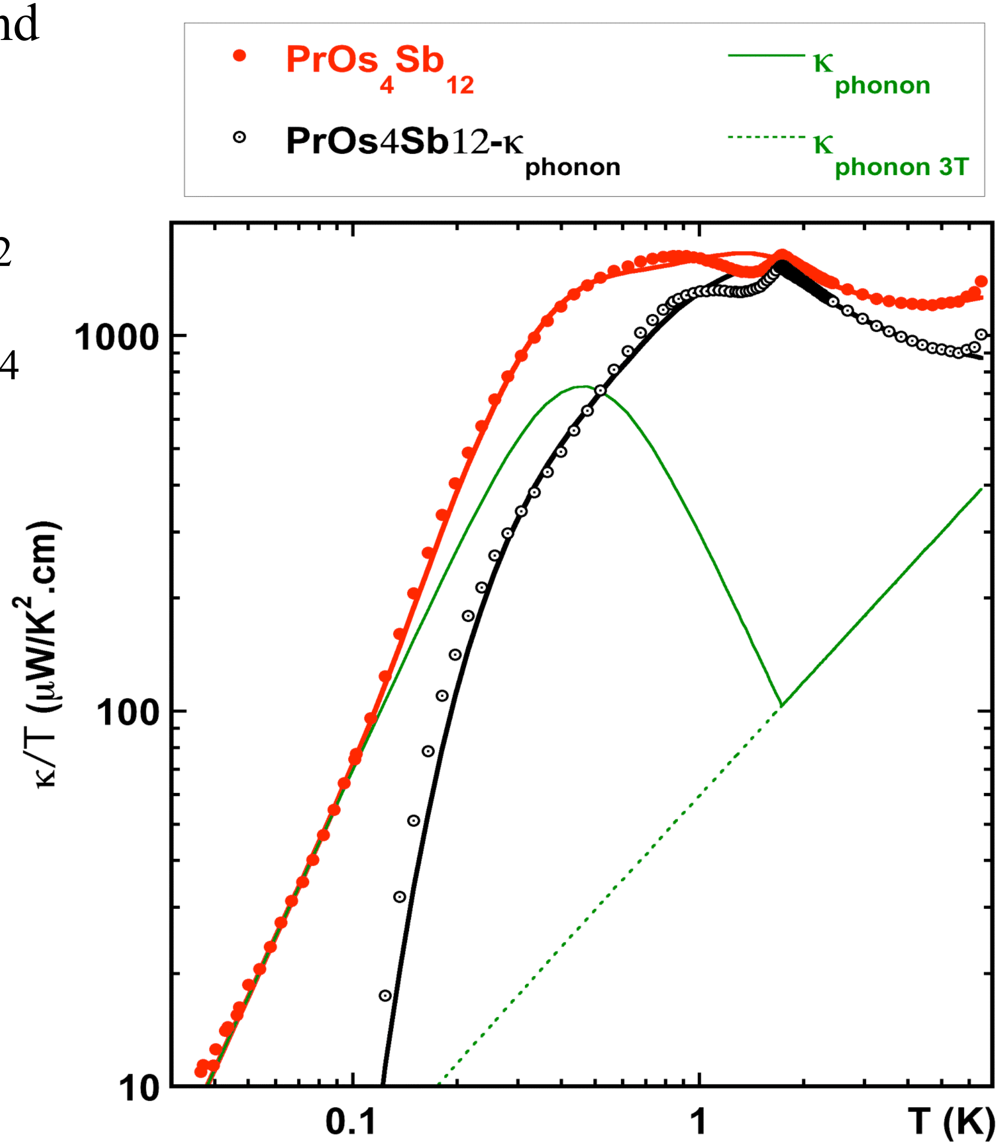

1000
100
10
κ/T (µW/K².cm)
0.1
1
T (K)
T
T²
old
new

Fit κ(T) with two parallel channels, and two fully open gaps.

See also:

- NQR ($1/T_1$) M. Yogi et al. JPSJ **75** 124702 (2006)
- $C_p(H,\theta)$ T. Sakakibara et al. JPSJ **76** 051004 (2007)

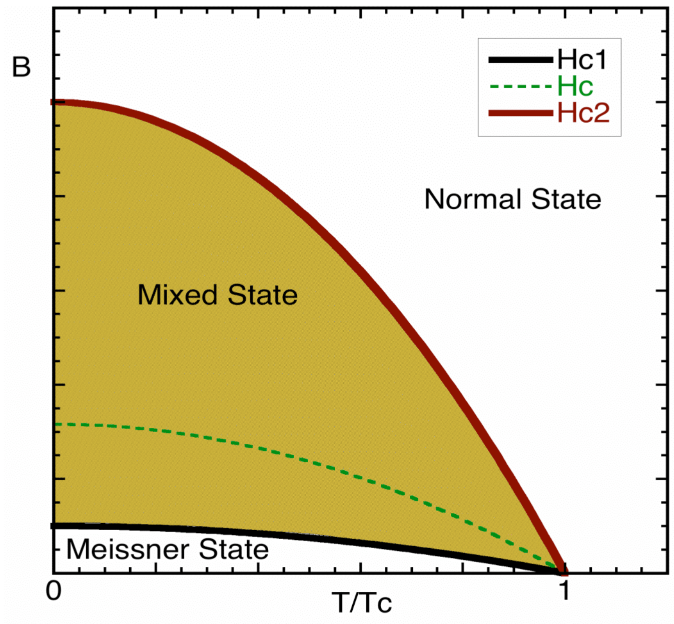


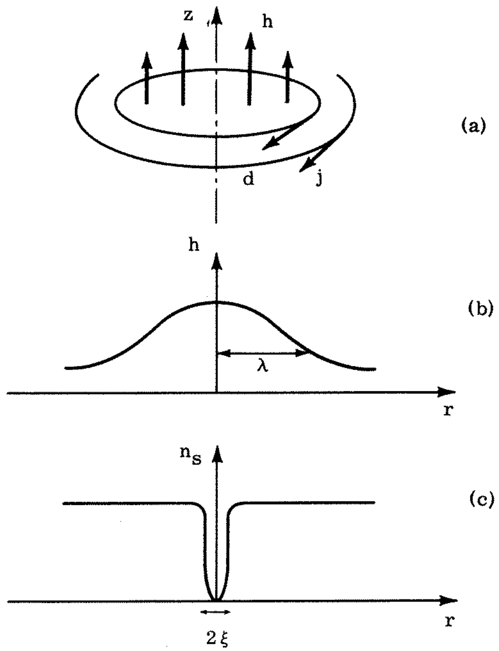


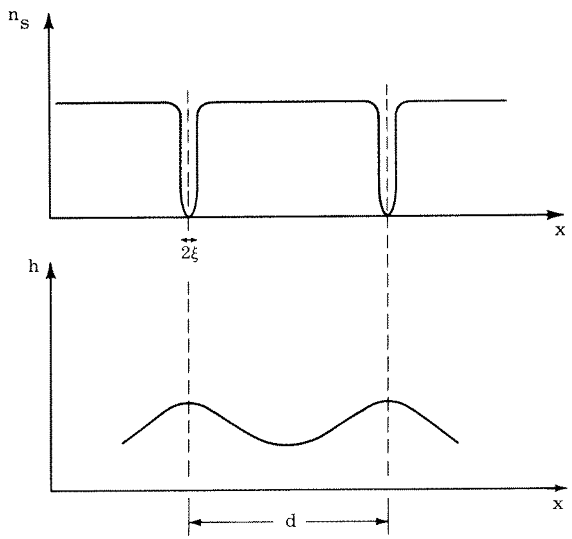
In the mixed state, for type II superconductors, B penetrates as flux lines…

Diameter of the flux “tubes” ~λ (created by supercurrents: vortices)

The superconducting state is destroyed in the vortex cores, of size ~ $\xi << \lambda$

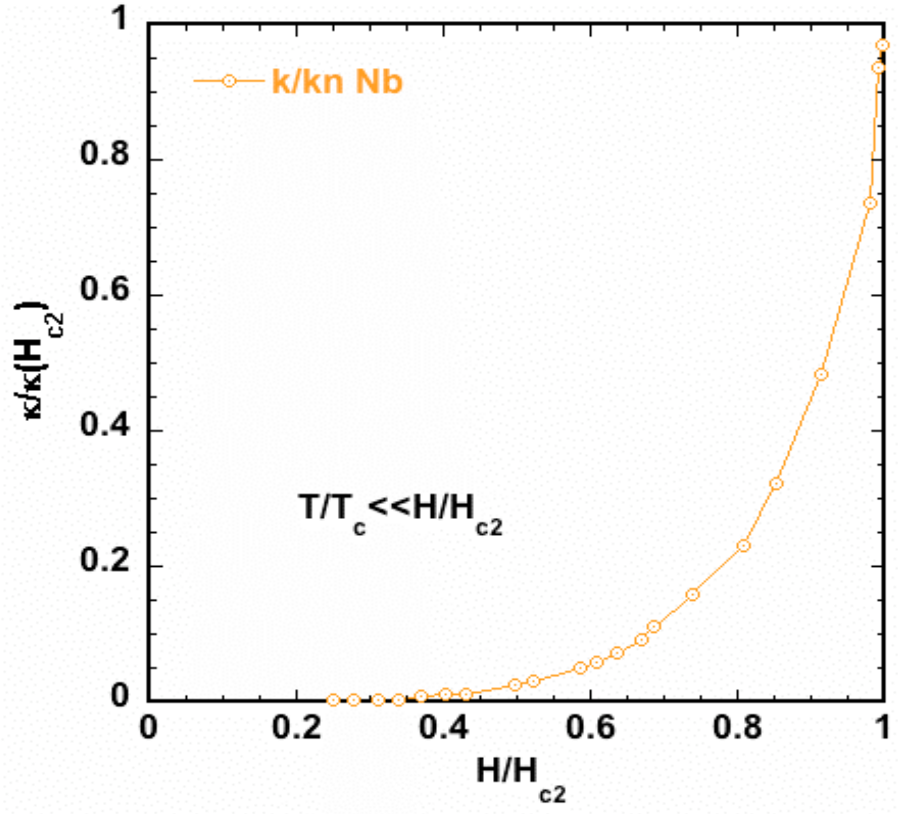




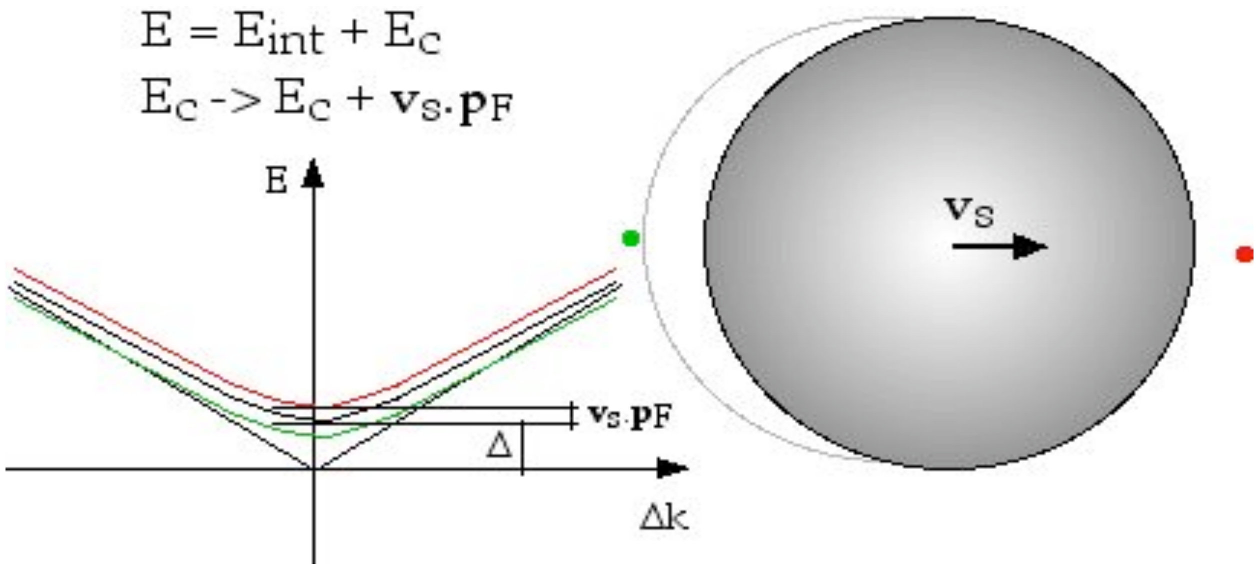


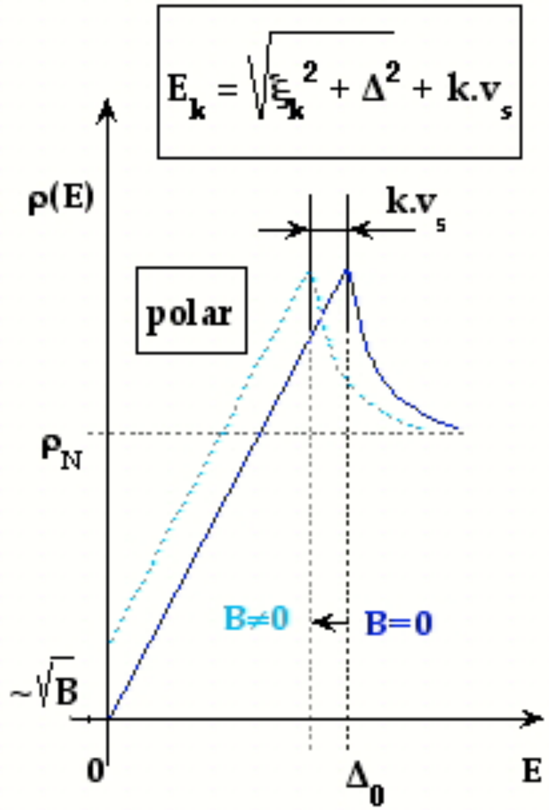
Magnetic field on type II superconductors:

- induce a mixed phase (vortices)
- new scattering mechanism
- recovery of normal state behaviour for B → B_{c2}
- at low T, low field : no effect



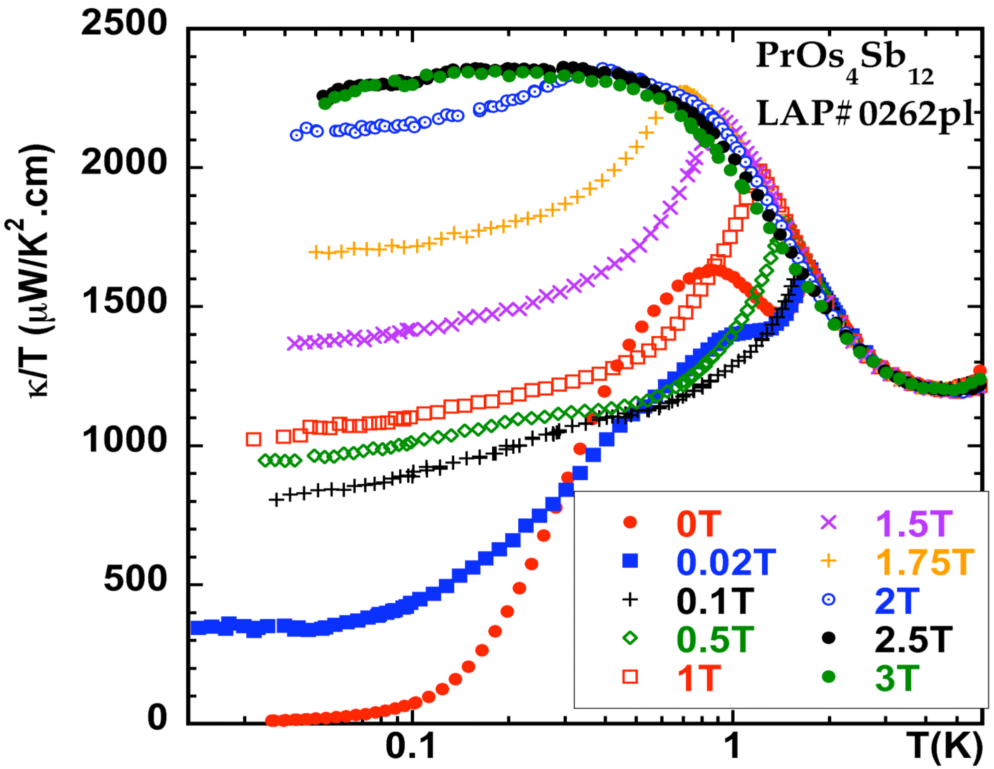
- to create vortices -> supercurrents in the bulk, for $B_{c1}<B<B_{c2}$.
  - Doppler shift of excitation spectrum (**k. v**$_S$)
  - if unconventional, with nodes of the gap => for T=0, √ B dependence of $\rho_d(0)$, C_p…
- At $T \neq 0$, for $\sqrt{(B/B_{c2})} \ll 1$ and $(T/T_c) \ll 1$:
  - scaling laws vs $x=(T/T_c)\sqrt{(B_{c2}/B)}$

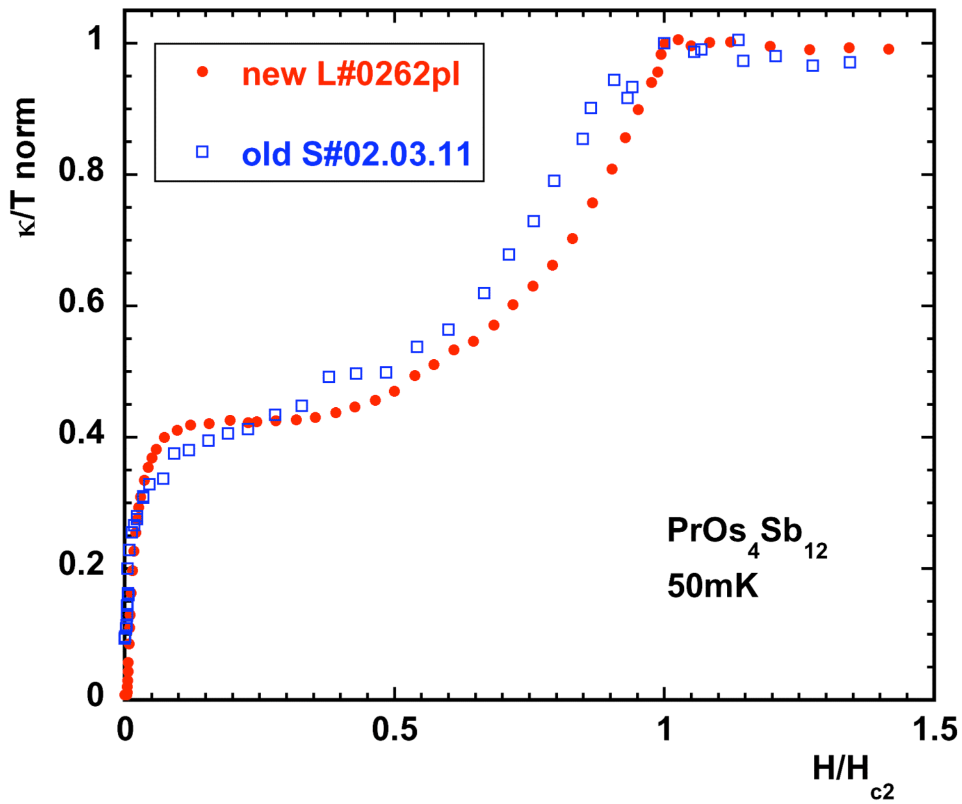




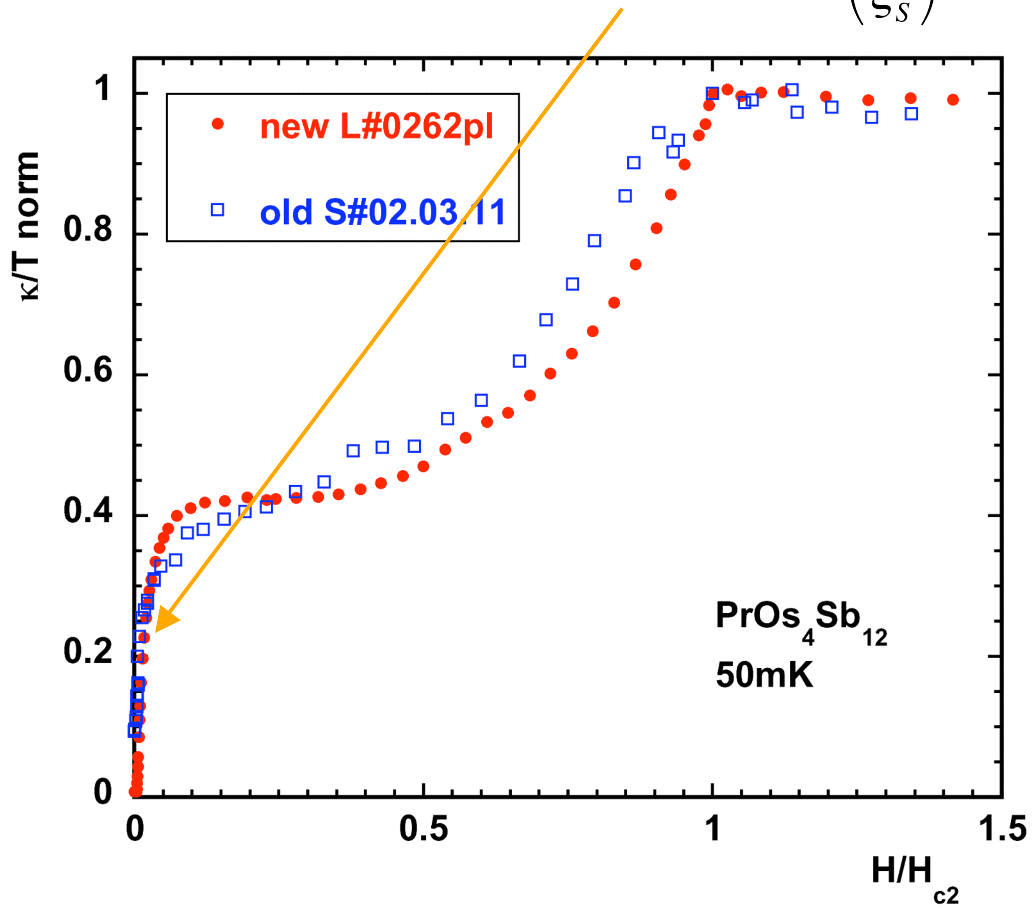
$PrOs_4Sb_{12}$: Field sweeps at T->0

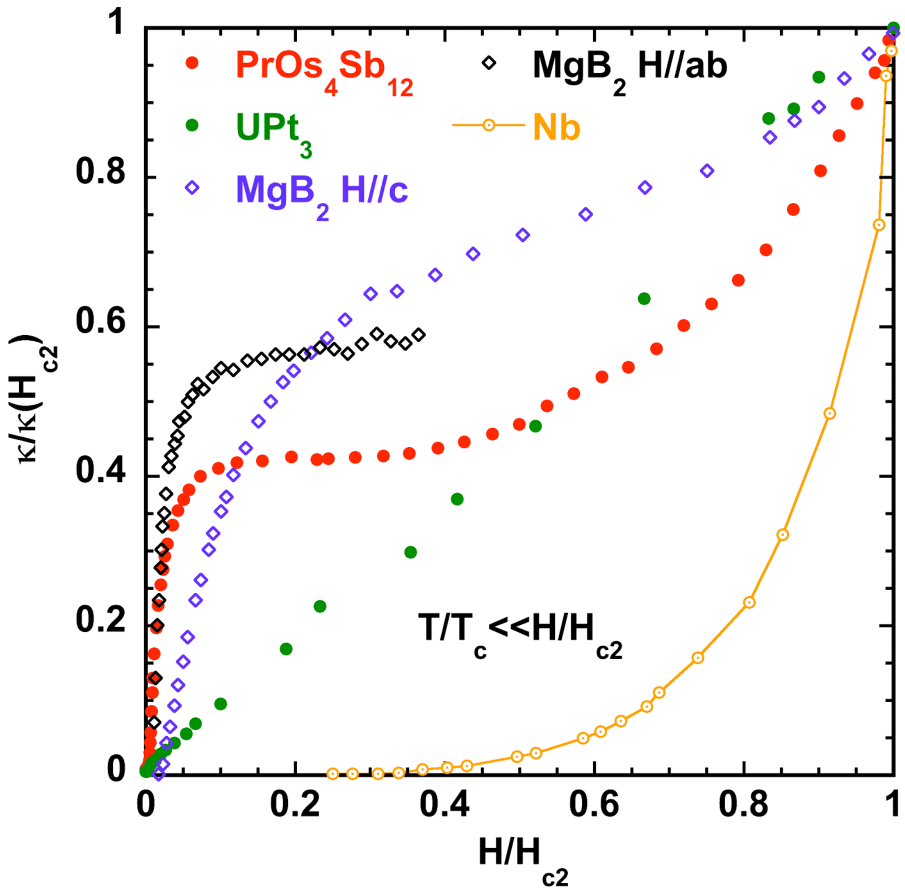
- "Normal metal" behavior below 0.07K at $H_{c2}/100$
- Very fast, robust increase of $\kappa(H,T\sim0)$





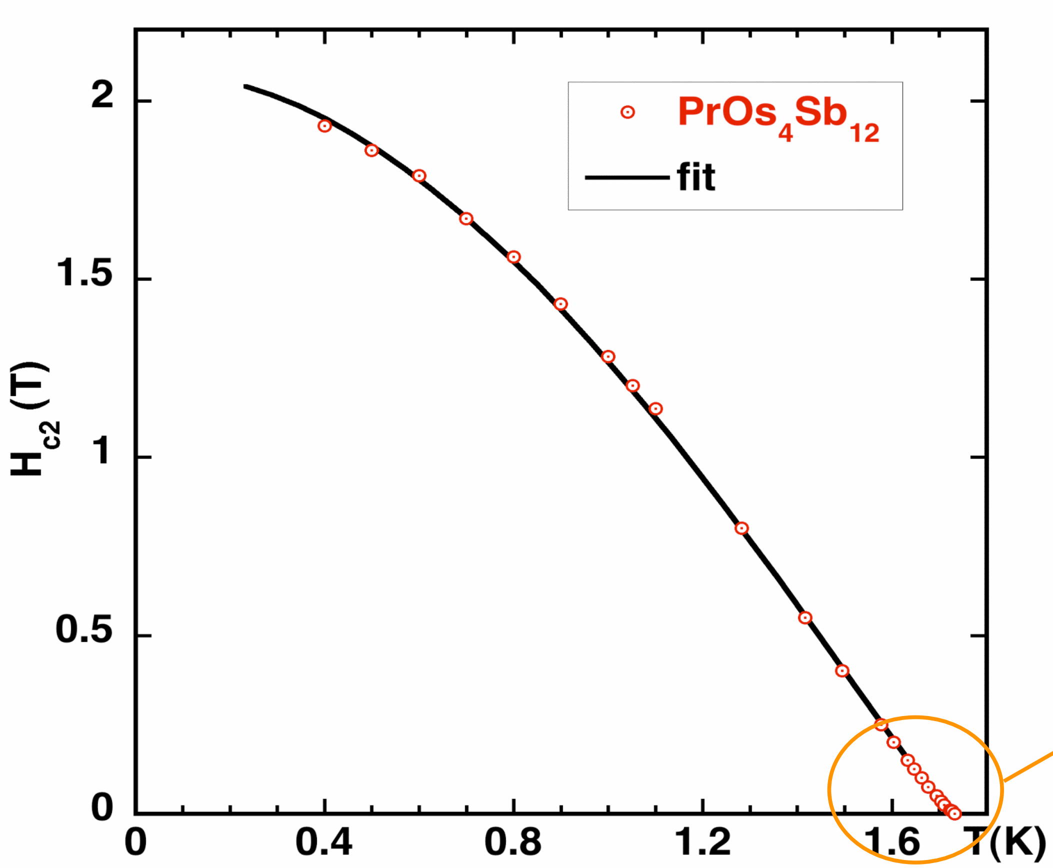
- Very fast increase of κ(H,T~0), reminiscent of MgB_2 (Data MgB_2: Sologubenko et al., PRB **66** 014504 (2002))
- low field scale: $H_{c2}^{s} \approx H_{c2}\left(\frac{\xi_L}{\xi_S}\right)^2 \approx H_{c2}\left(\frac{\Delta_S}{\Delta_L}\frac{v_{FL}}{v_{FS}}\right)^2$



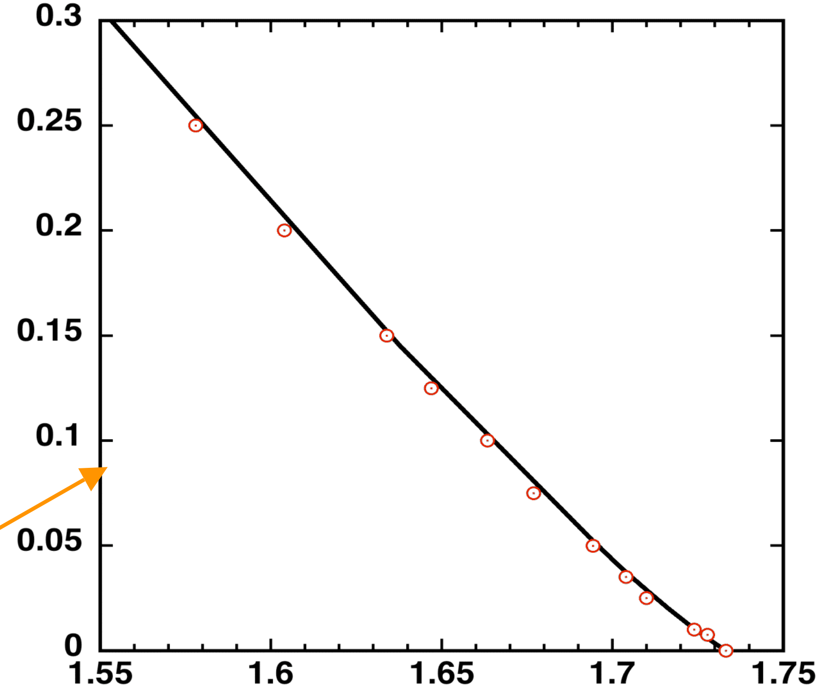


Fitting the two gaps (factor 3) and H_{c2} requires :

λ_{21}=0.2 λ_{11} & λ_{12}=λ_{22}=0.07 λ_{11} meaning at least $V_{21} \sim 0.2\, V_{11}$



$$H^s_{c2} \approx H_{c2}\left(\frac{\Delta_S}{\Delta_L}\frac{v_{FL}}{v_{FS}}\right)^2 \approx \frac{H_{c2}}{350} \approx H_{c1}$$



$PrOs_4Sb_{12}$: Summary

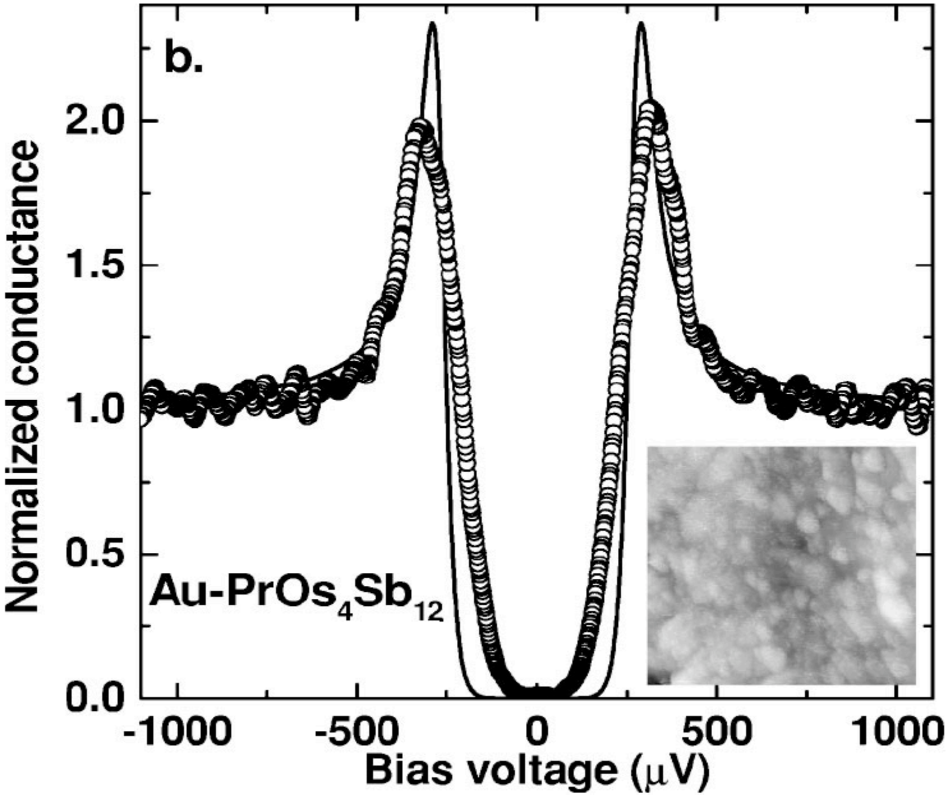
- Multigap superconductivity: confirmed on single transition samples, confirmed on H_{c2}, κ(H) and κ(T).
- From H_{c2}, κ(H), small gap associated with band of light mass
- From κ(T), difference in λ_{ij} from density of states and coupling strength !

$\lambda_{ij} \approx V_{ij} N_j$, $V_{21} << V_{11}$

N_j: density of states of band j

V_{ij}: symmetric interaction matrix

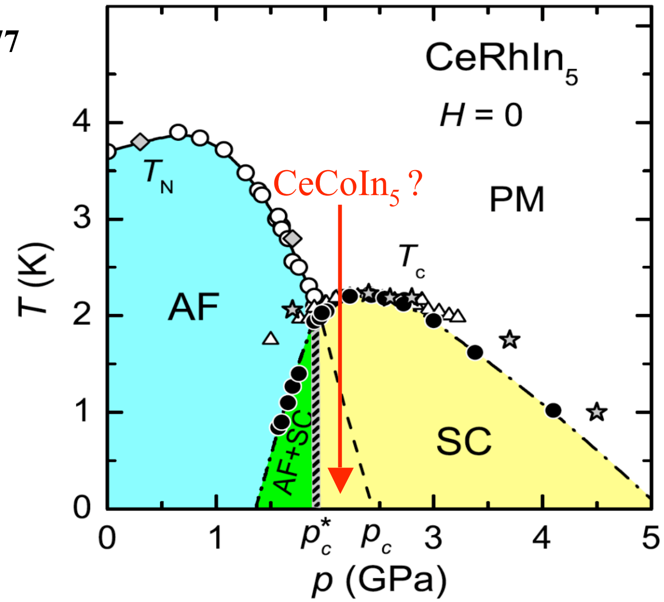
- Fully open gaps, small one of order 1K (compatible with NMR, $C_p(H,\theta)$, STM:

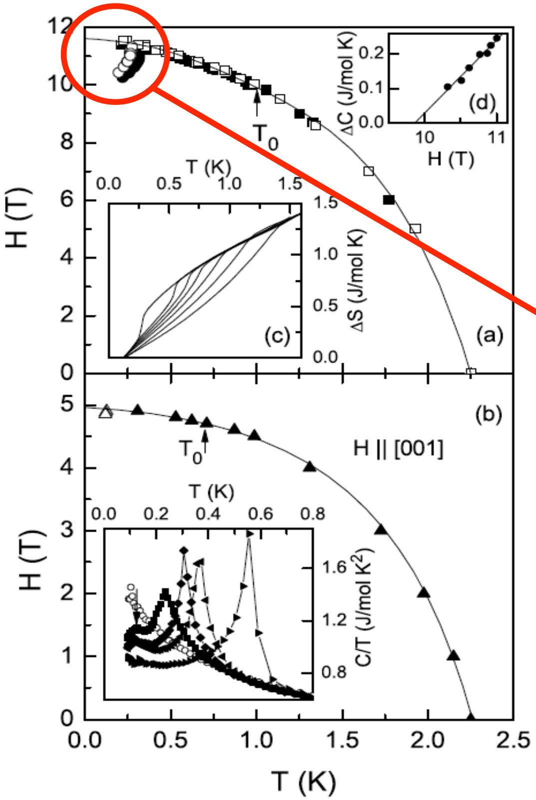


H. Suderow et al. PRB **69** 060504R (2004)

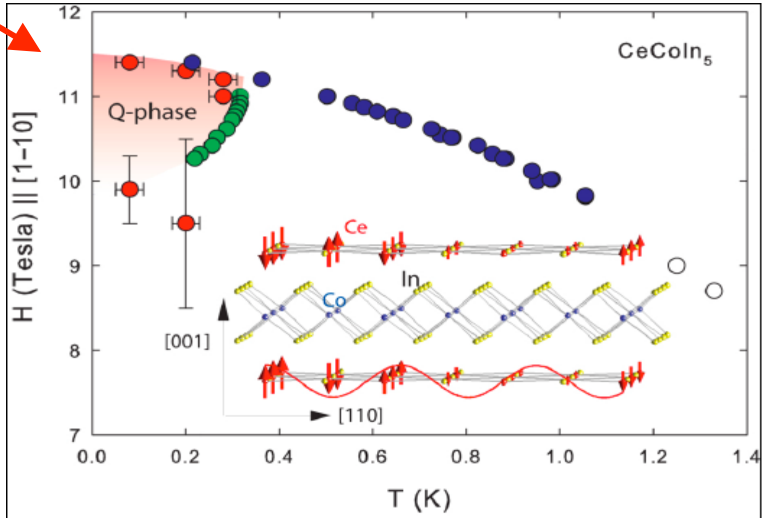
- Close to a QCP (Poster L. Howald)
- complex phase diagram in field
- (FFLO & AF order ?)
- d_{x2-y2} order parameter ?

G. Knebel et al., JPSJ **77** (2008) 114704





Bianchi et al. PRL **91** (2003) 187004



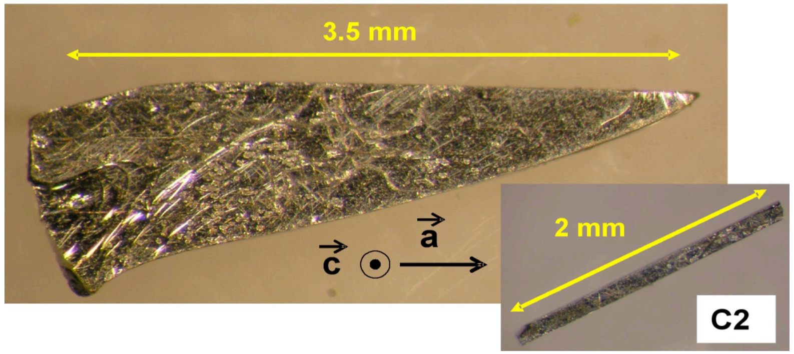
Neutrons : Kenzelmann et al., Science **321**(2008)1652

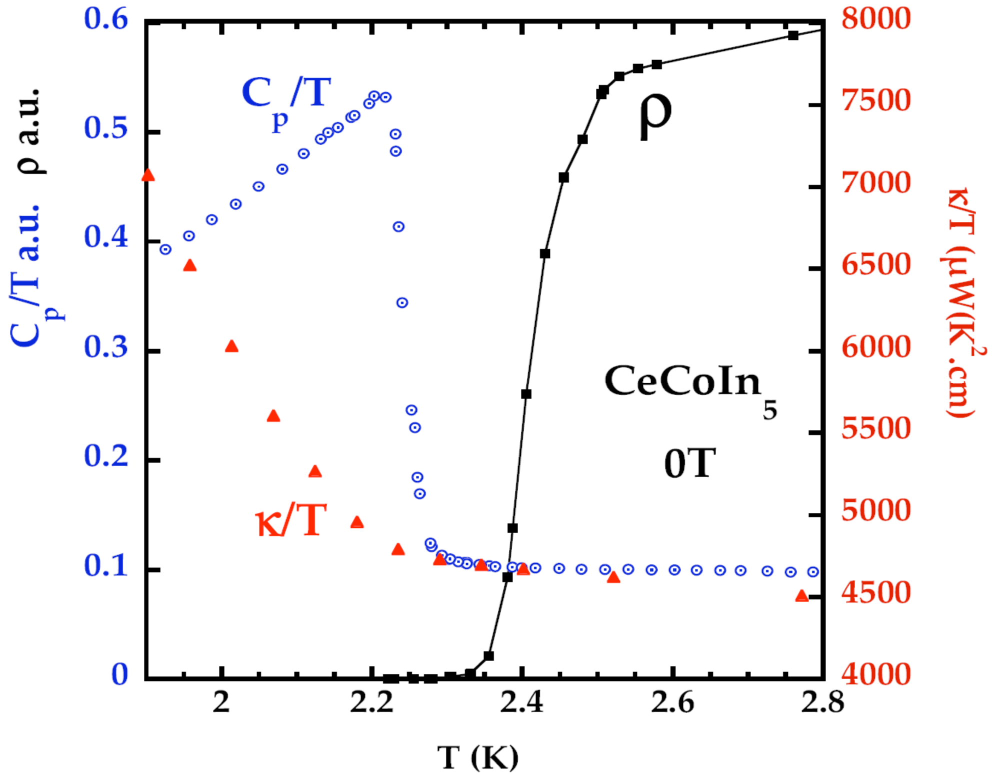
NMR : V. Mitrovic, C. Berthier, M. Horvatic et al., to be published

- Sharp superconducting transition in specific heat (ΔT_c ~ 70mK @ 2.3K)
- Correspondence between κ and C_p
- T_c from ρ ~10% higher: usual in 115 family.

$$\frac{\rho(T_c)}{\rho(300K)} \approx 6$$

(up to 9 in Los Alamos samples)
- bar shaped, along a axis

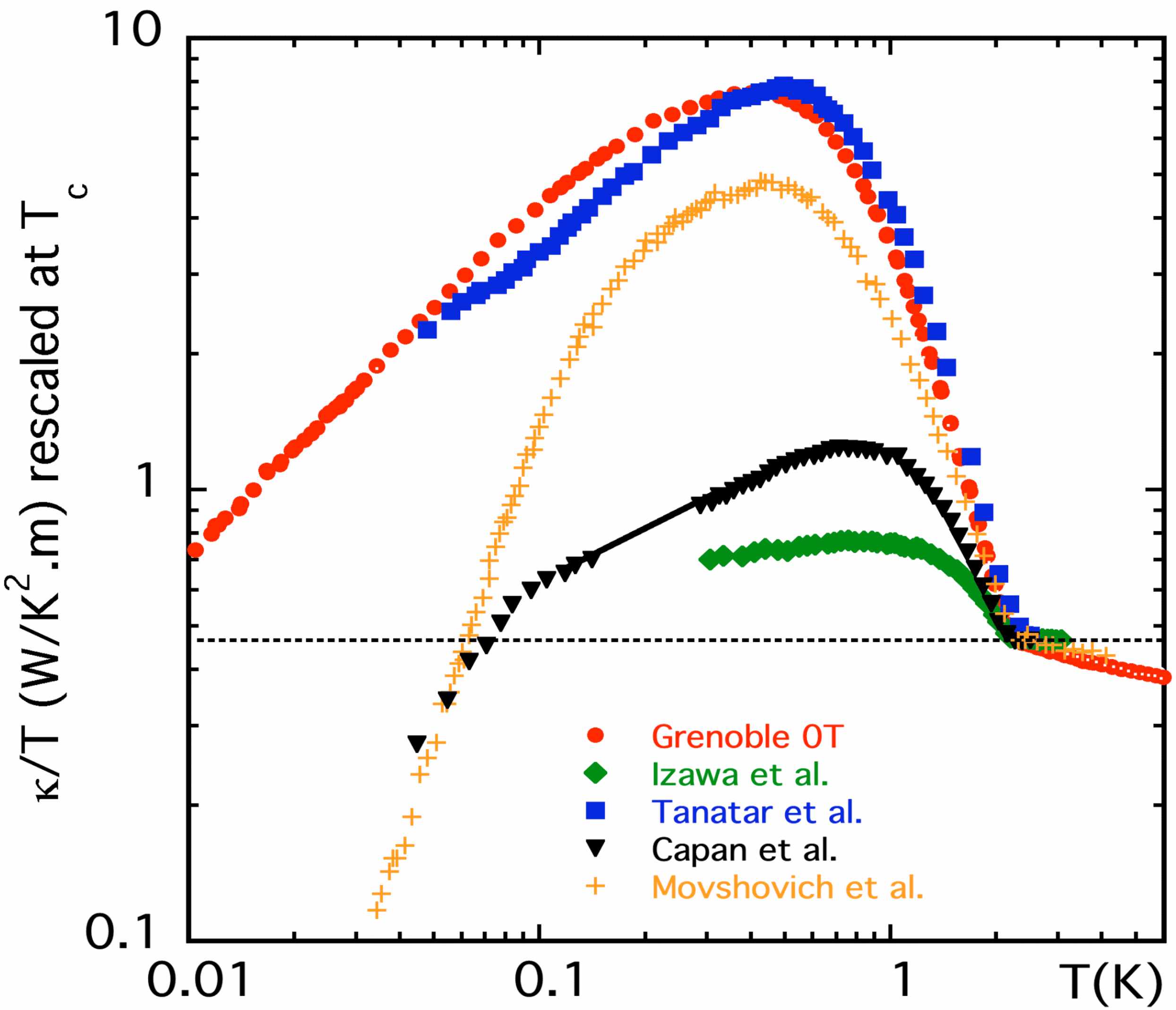




- a huge dispertion of the results in the litteratur

- a very large κ/T even very low T:

  κ/T (10mK) > κ/T (T_c)

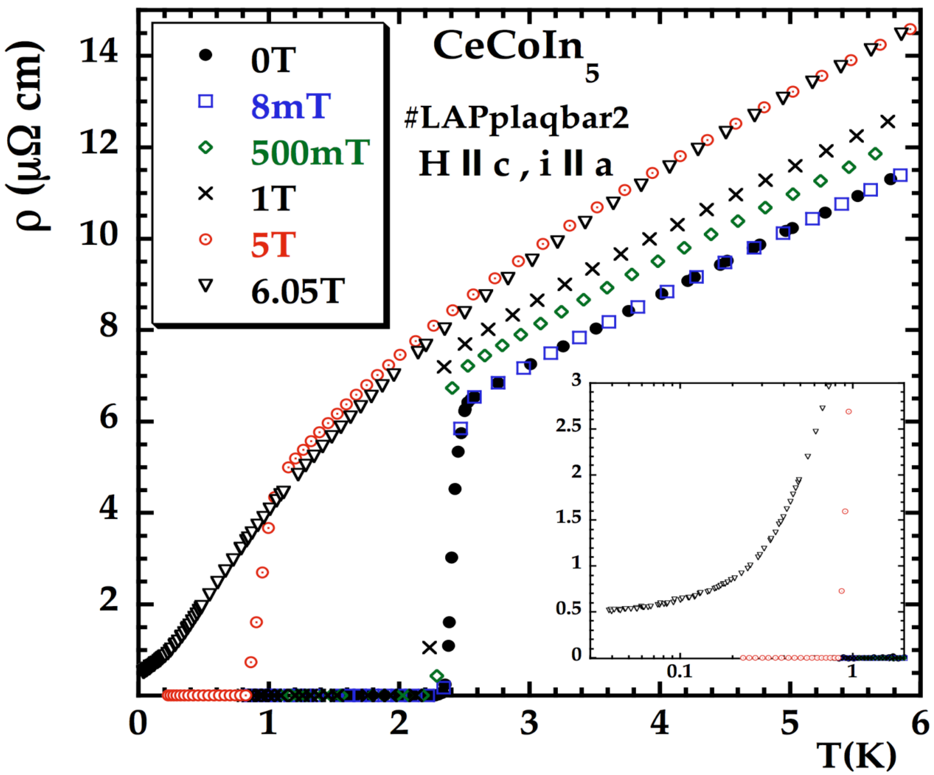


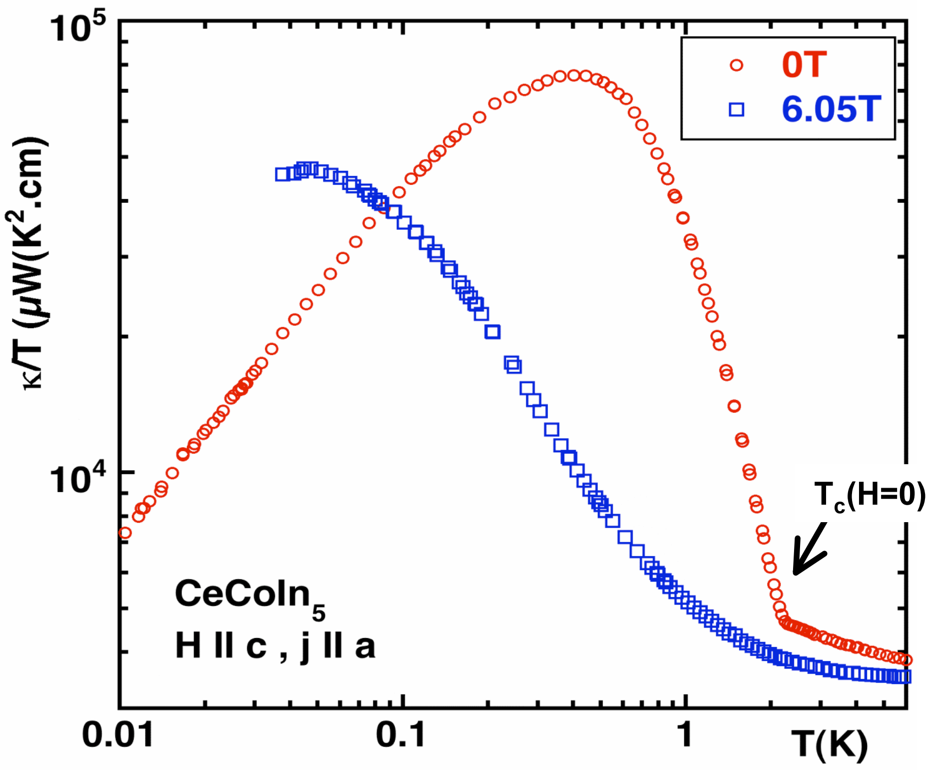
At T_c: very large contribution of inelastic scattering (QCP)

At 6T, $\rho(2.3K)/\rho_0 \sim 16$

Below T_c, fast suppression of inelastic scattering (Kasahara et al. PRB **72** 214515 (2005)): for H=0, $(\kappa/T)_{max} / (\kappa/T(T_c)) \sim 16$, with maximum at ~0.4K

Consequence (?) : At 10mK *($T/T_c = 4.10^{-3}$)*, $\kappa/T(10mK) > \kappa/T(T_c)$





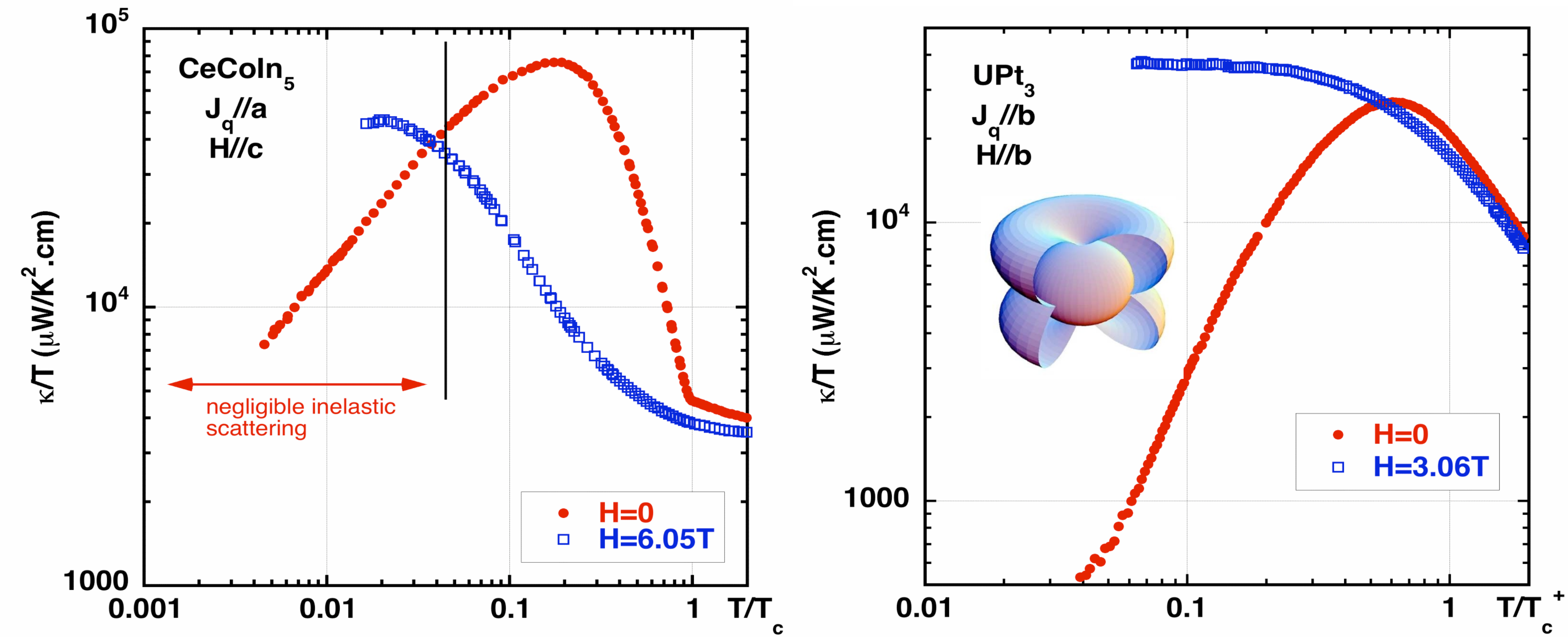
In $CeCoIn_5$, inelastic scattering negligible below 0.1K~$0.043T_c$

then $\kappa(T)/T \sim 0.5\ \kappa_n(T)/T$ (T->0)

at 10mK ($T/T_c \sim 4.10^{-3}$) $\kappa(T)/T \sim 7.10^{-2}\ \kappa_n(T)/T$ (T->0)

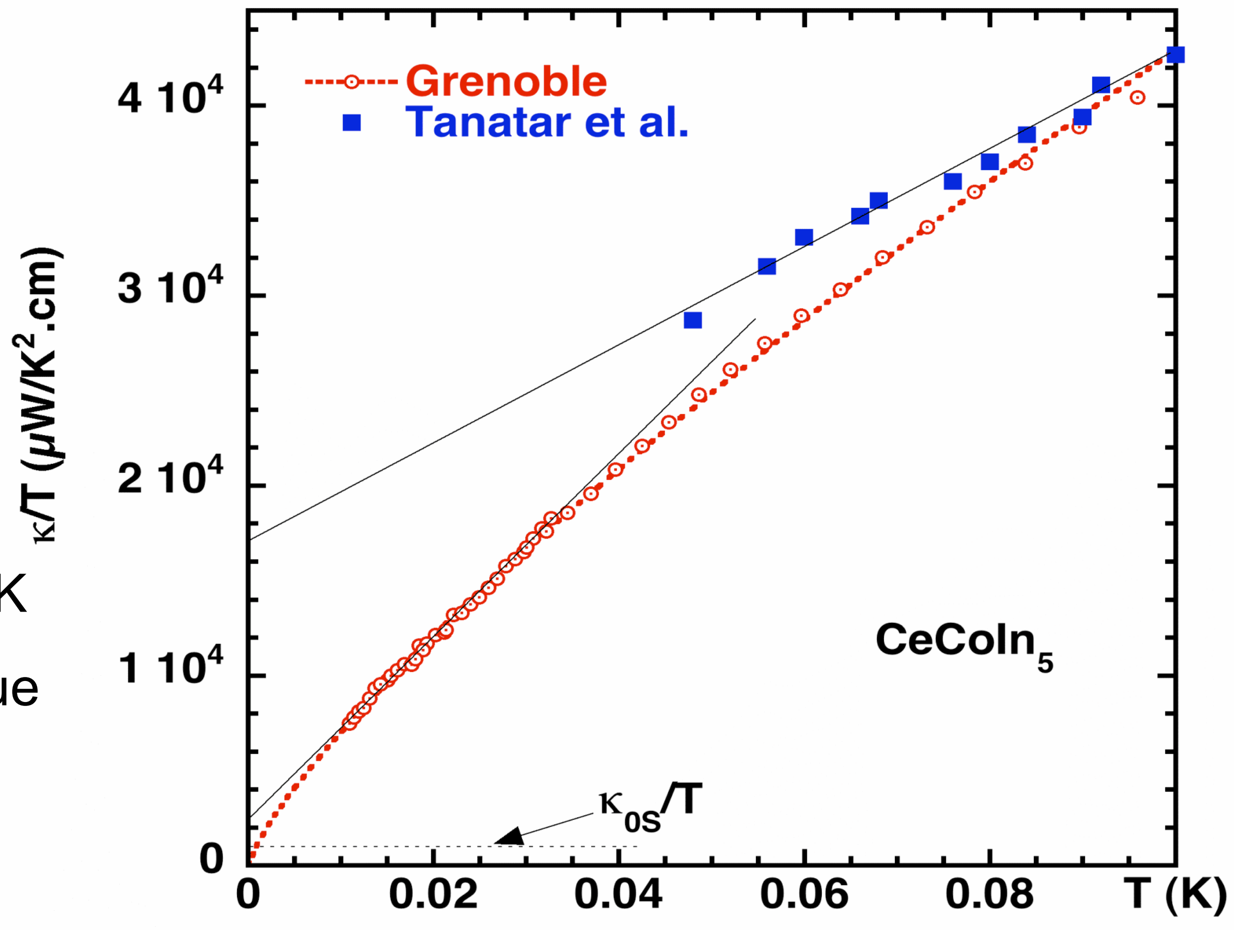
In UPt_3, at $T/T_c \sim 4.10^{-2}$, $\kappa(T)/T \sim 10^{-2}\ \kappa_n(T)/T$ (T->0)

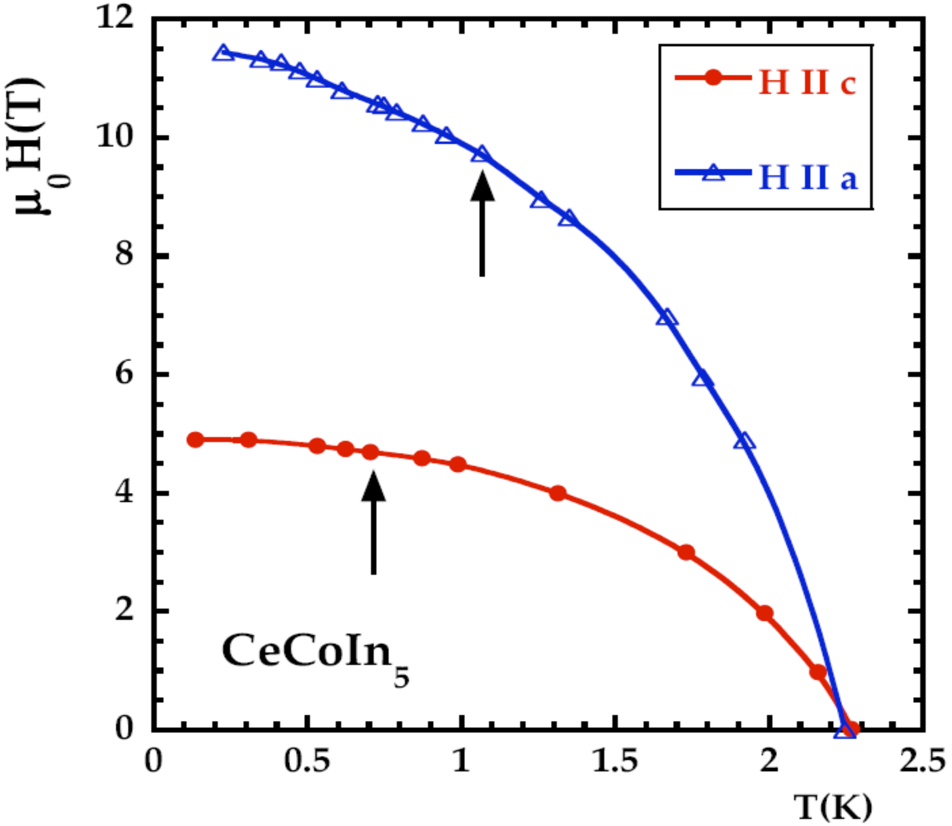
=> need *nodes* AND a *small gap* to explain the large κ(T) in $CeCoIn_5$



Proposal of Tanatar et al., PRL 95 067002 (2005)

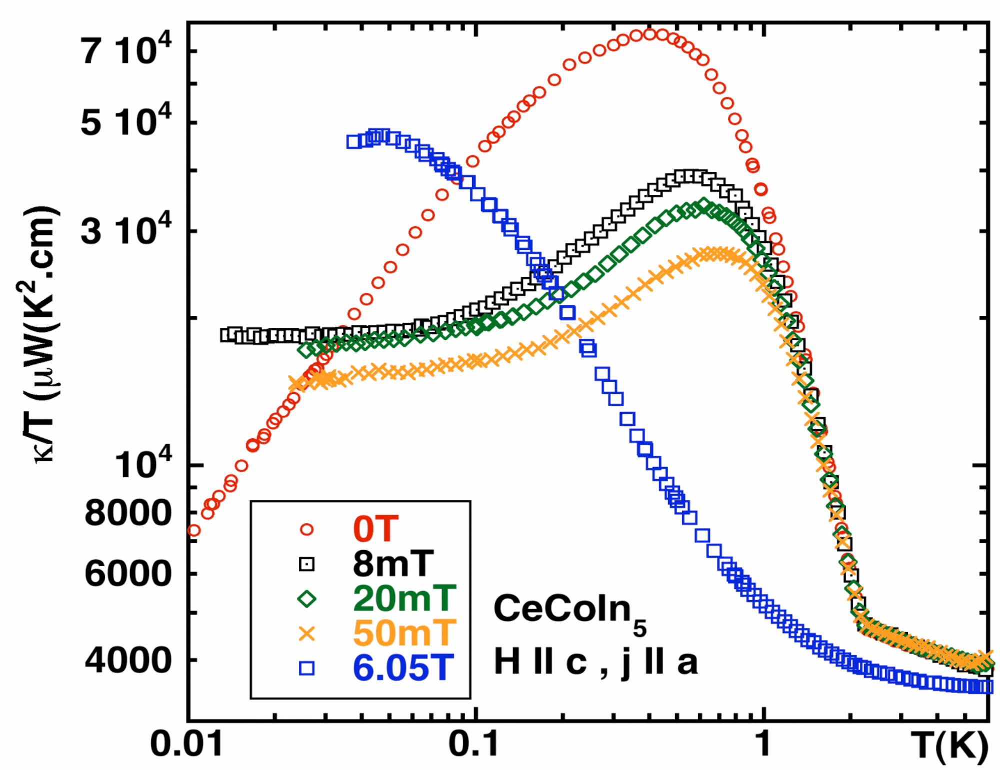
- Present data: no need for unpaired electrons down to 10mK
- κ/T may extrapolate to any value below 3 mW/K^2.cm
- Compatible with a « universal limit »

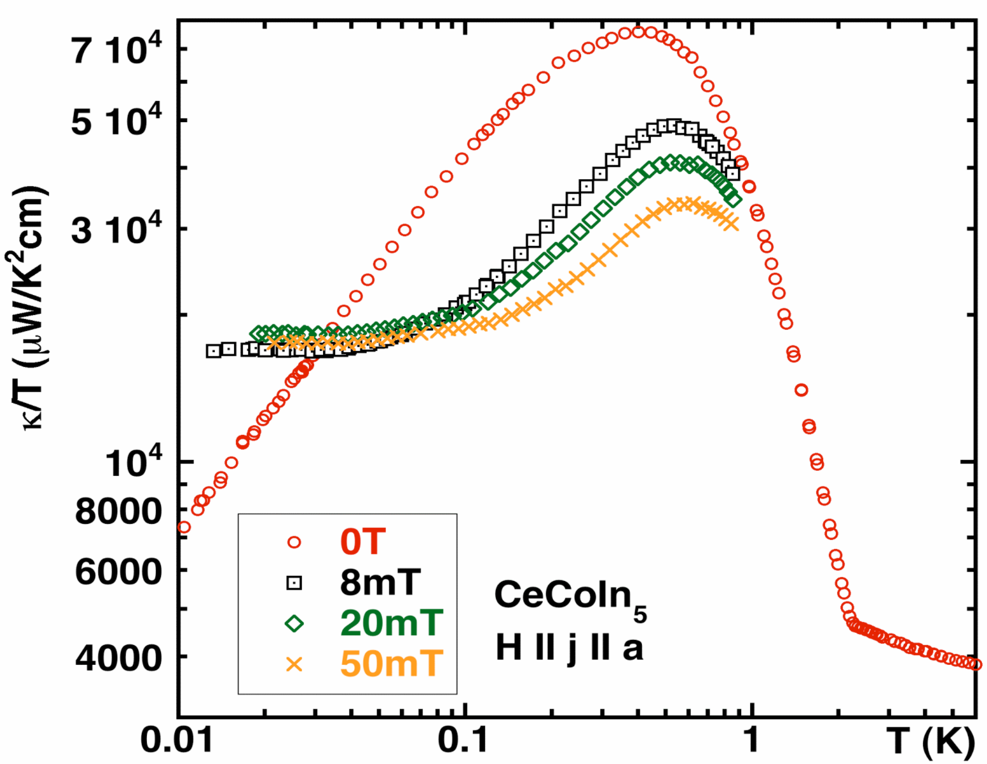




Bianchi et al., PRL **91**, 187004 (2003)

As in $PrOs_4Sb_{12}$, fast recovery of "normal state behavior":
T→0, $\kappa/T(B=8mT \sim 0.0015\ B_{c2}) \sim 0.4\ \kappa_n/T(B=6T)$





Both in $CeCoIn_5$ and $PrOs_4Sb_{12}$:

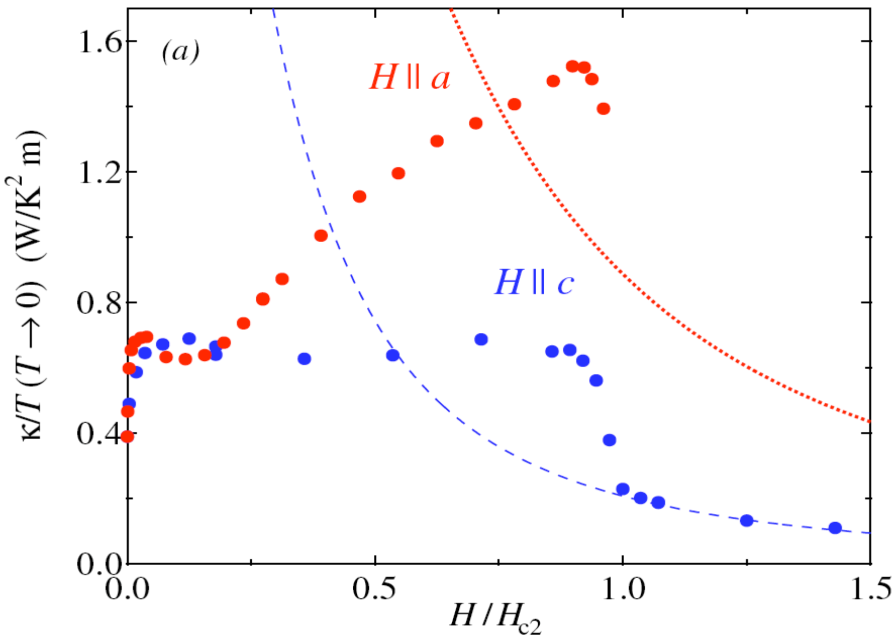
$\kappa(T)$ at low T: reveals a small gap ($\Delta_S \ll 1.76 k_B T_c$), but no unpaired electrons

$\kappa(H, T\to0)$: reveals very small additional characteristic field, of order or lower than H_{c1}

Confirms the idea: multigap connected with f-character
pairing mechanism related to f-electrons.

For $CeCoIn_5$, other MBSC supports:

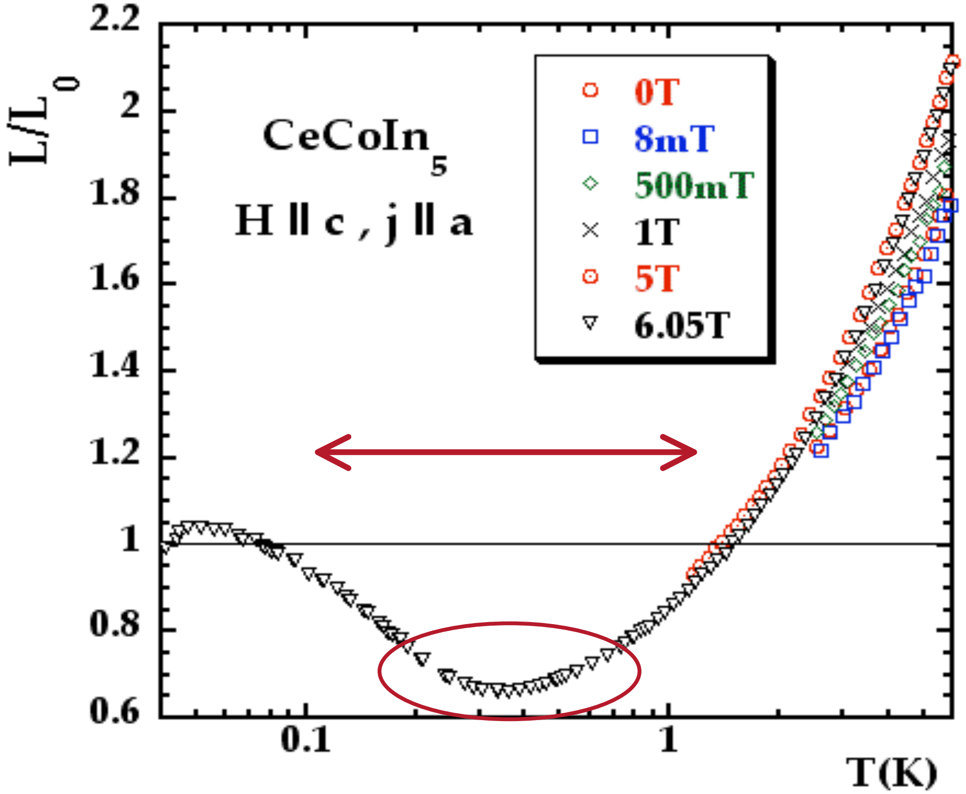
- T&H dependent magnetic anisotropy
Xiao et al. PRB **73** 184511 (2006)
- Point Contact Spectroscopy
Rourke et al. PRL **94** 107005 (2005)
- but not in
Park et al. PRB **72** 052509 (2005)

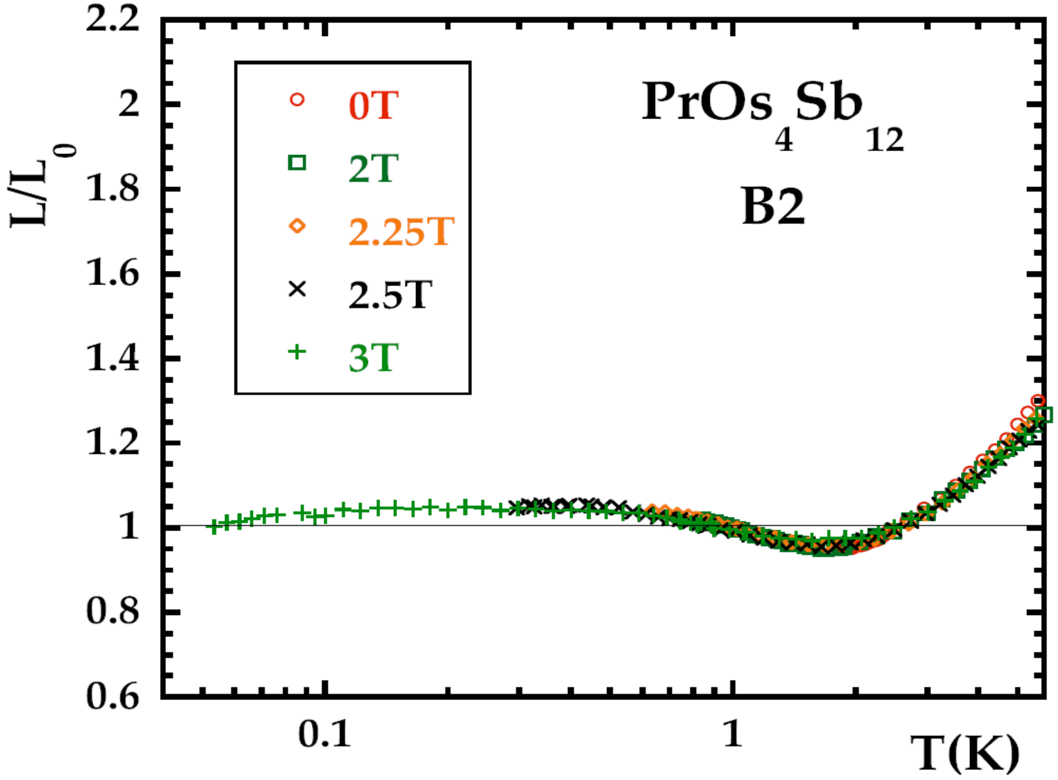


Also found in URu_2Si_2
Kasahara et al., PRL **99** 116402 (2007)

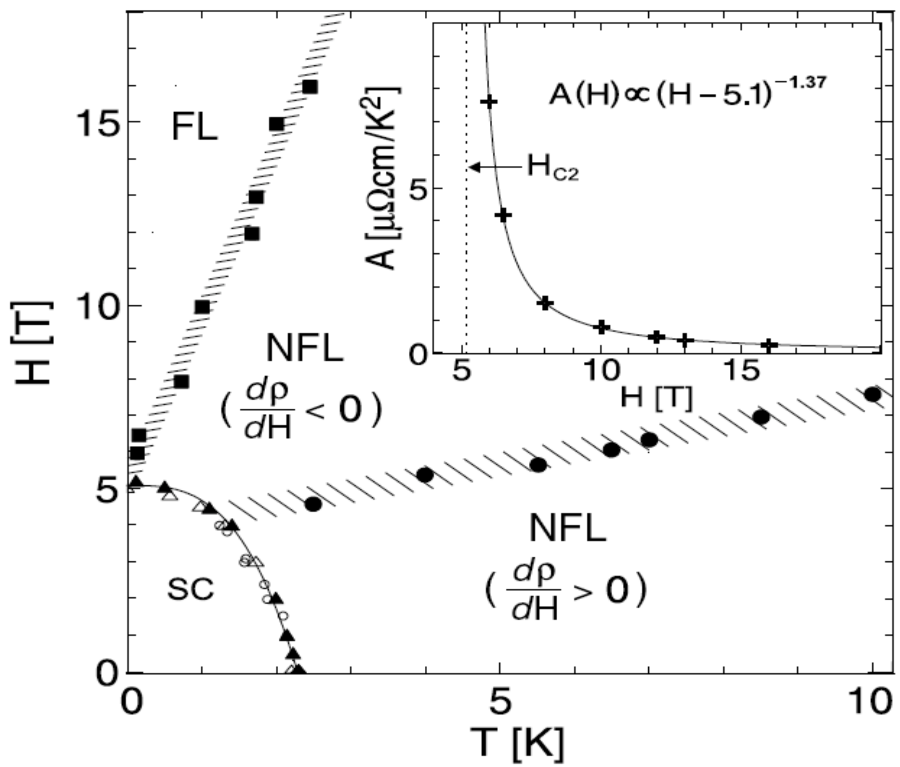
Indeed a very wide range of inelastic scattering : L/L_0 down to 0.65 !
Below 0.1K (T/Tc=0.043), inelastic scattering should be negligible

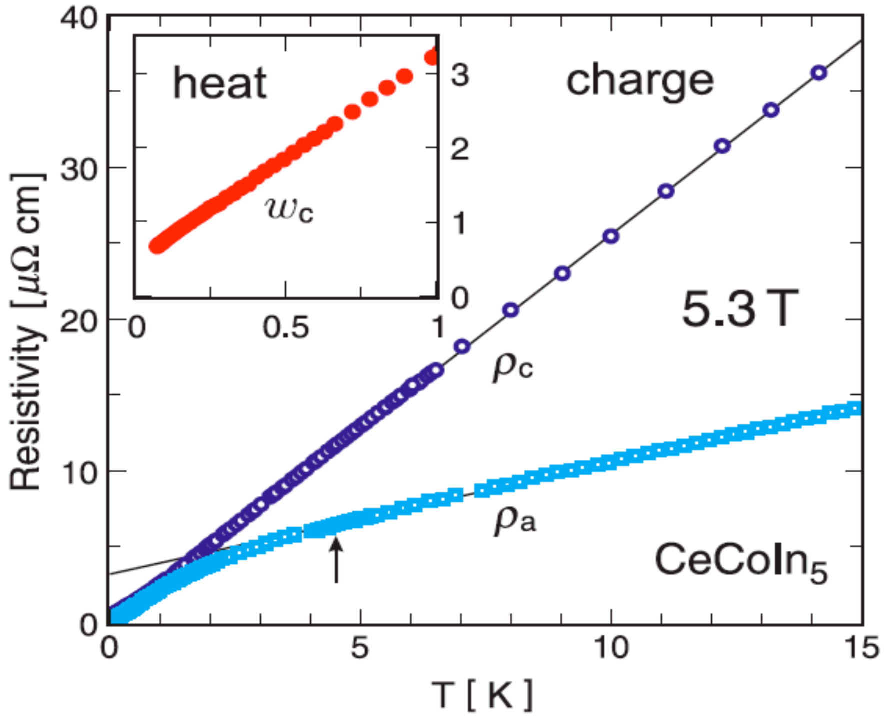
$$L = \frac{\kappa}{\sigma T}$$





Quantum Critical Point



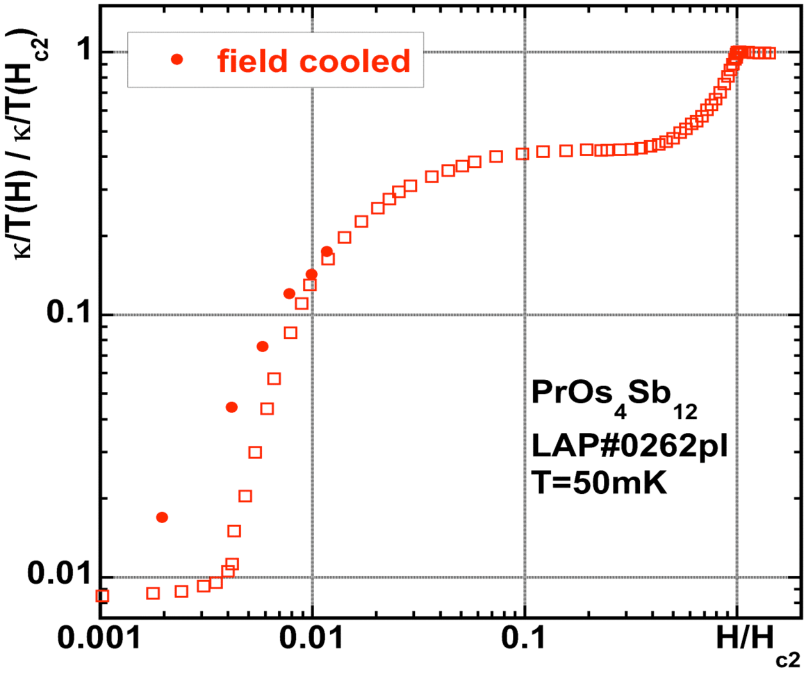


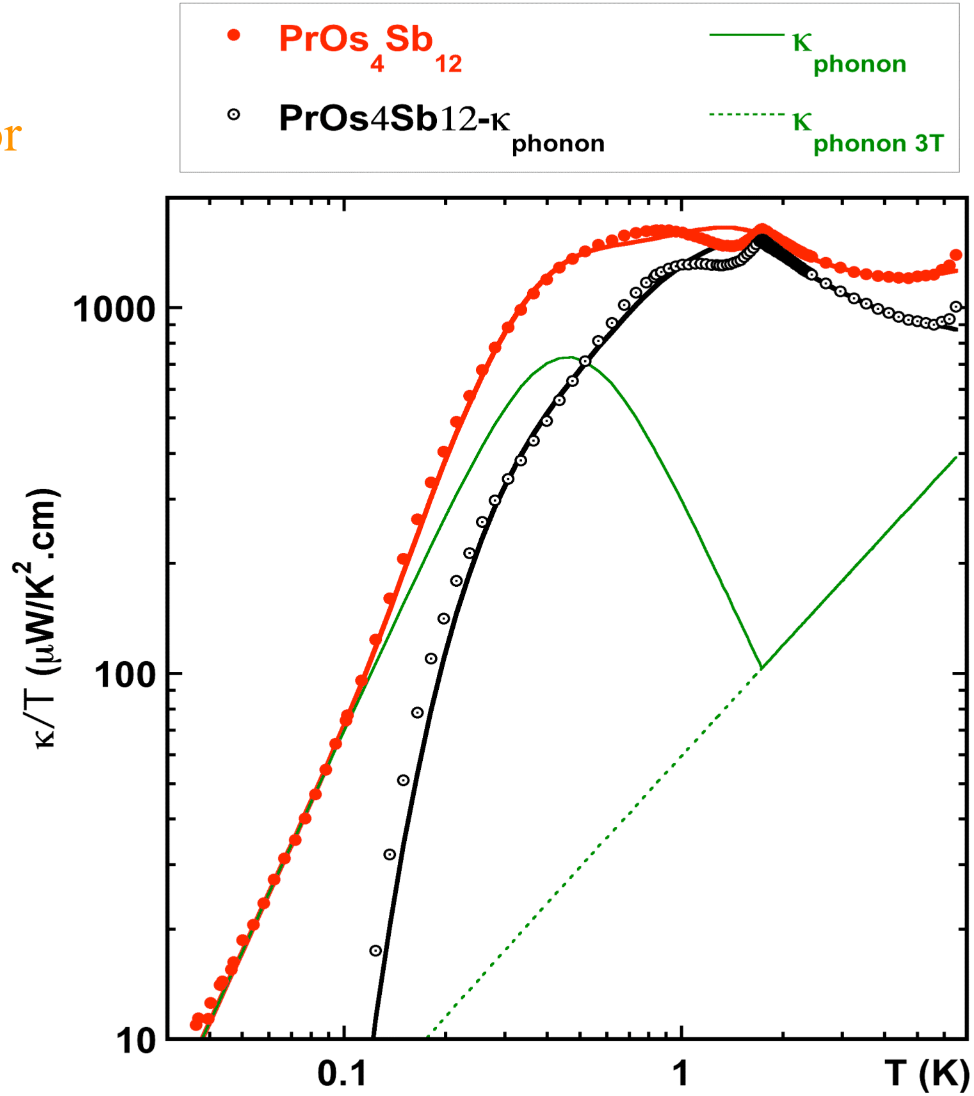
Johnpierre Paglione, M. A. Tanatar, D.G. Hawthorn, Etienne Boaknin, R.W. Hill, F. Ronning,M. Sutherland, Louis Taillefer, C. Petrovic and P. C. Canfield
PRL **91** 246405 (2003)

Violation of a universal law at a quantum critical point
M.A. Tanatar, Johnpierre Paglione, Louis Taillefer and C. Petrovic
Nature ?…

$PrOs_4Sb_{12}$: Temperature dependence of κ(T)

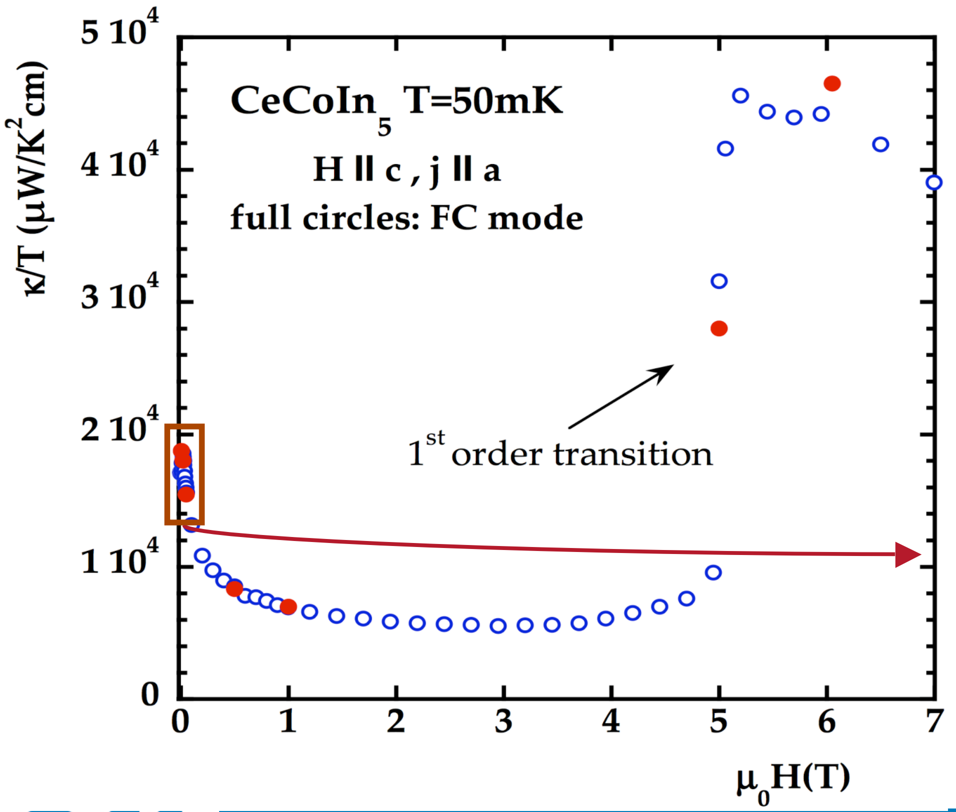
Relevant parameters: the small gap (~1K) and the weight/channel (0.35 for small gap)

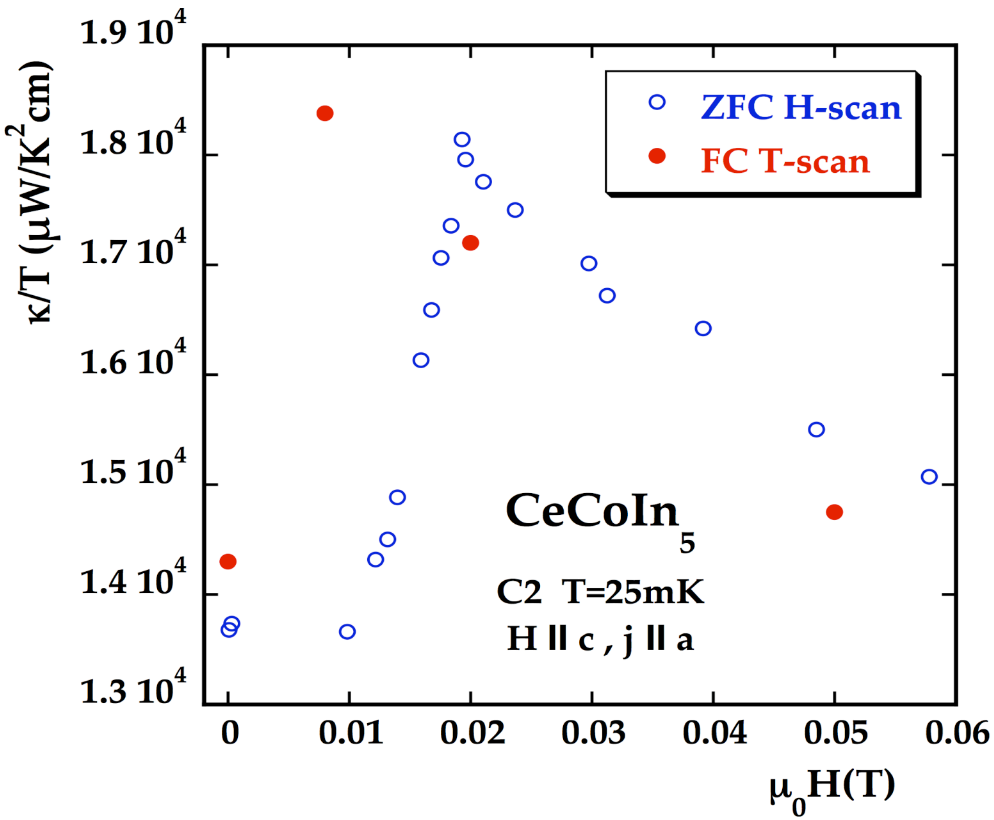




Field scans @ 50/25mK with H // c and j // a:

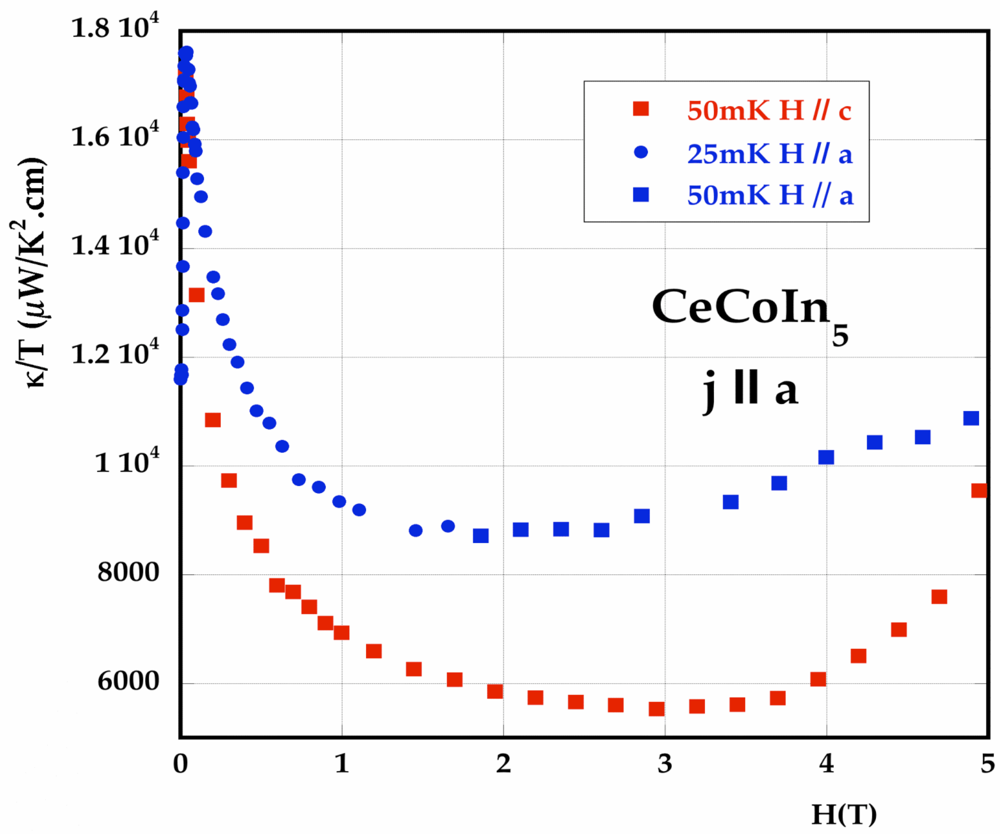
- Recover the known complex behavior (K. Izawa et al. PRL 87 057002 (2001))
- Small gap "suppressed" as soon as H>H$_{c1}$ $H^S_{c2} \leq H_{c1} \sim 0.0015 H_{c2}$

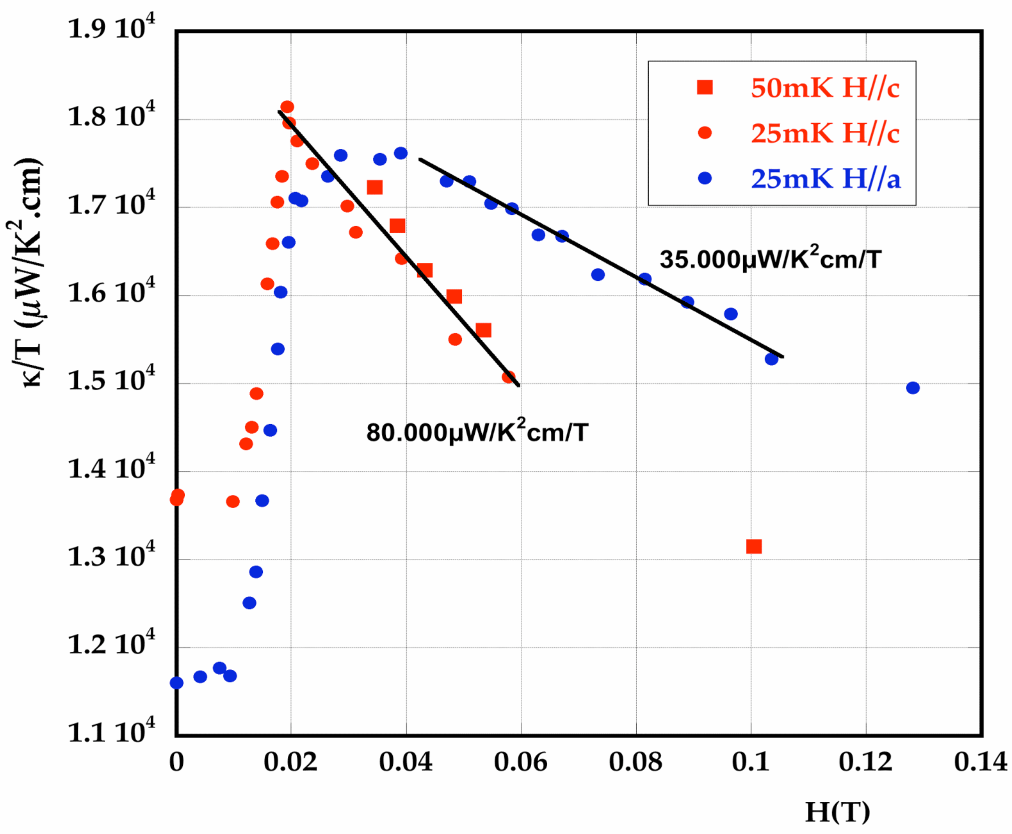


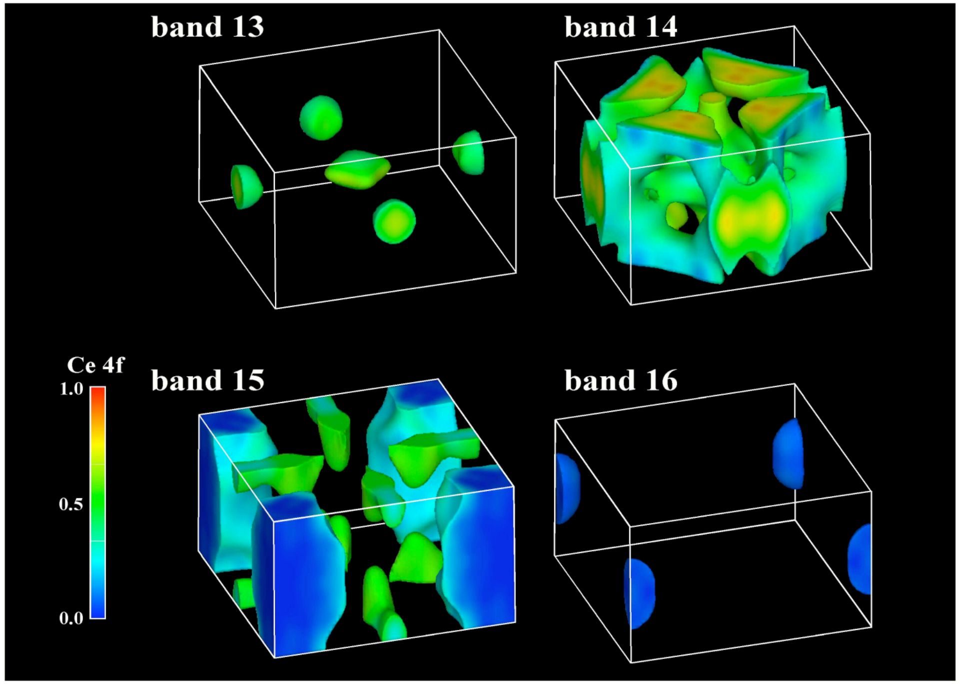


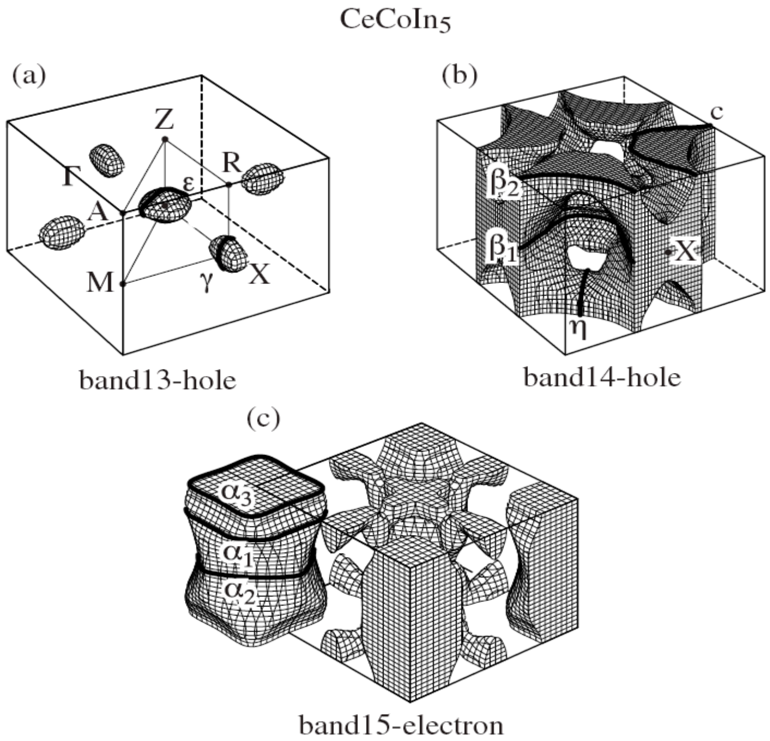
$CeCoIn_5$: anisotropy of the field sweep

- Confirm strong κ enhancement at extremely small magnetic fields, weather H // a or H // c $\quad H^S_{c2} \leq H_{c1} \sim 0.0015 H_{c2}$
- Initial "jump"of κ(T->0, H), with immediate saturation of DOS effect (meaning $H^S_{c2} << H_{c1}$), then a decrease due to τ(H).







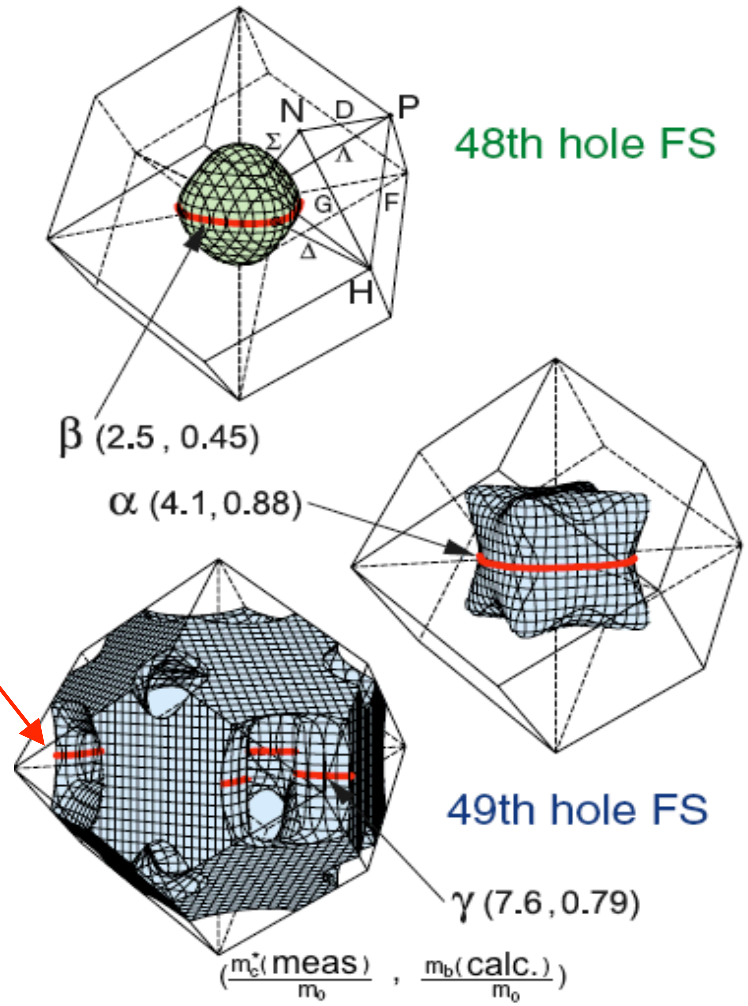


T. Maehira, T. Hotta, K. Ueda, and A. Hasegawa (JPSJ **72** 854 (2003)) & private communication

H. Harima in J. Phys. Cond Matter **13** L627 (2001)

		$PrOs_4Sb_{12}$ (Exper.)	(Theor.)	$LaOs_4Sb_{12}$
Field direction	Branch	m_c^* (m_0)	m_c^* (m_0)	m_c^* (m_0)
$H\|\langle 100\rangle$	α	4.1	0.88	2.5
	β	2.5	0.45	0.71
	γ	7.6	0.79	2.8
$H\|\langle 110\rangle$	α	4.9	1.82	4.1
	β	3.9	0.39	0.65
$H\|\langle 111\rangle$	α	5.8	1.27	2.8
	β	2.4	0.38	0.65

H. Sugawara et al., PRB 66 220504 (2002)



H. Harima in Y. Aoki et al. JPSJ **76** 051006-2007