INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

SMR. 767 - 20

MINIWORKSHOP ON STRONG CORRELATIONS
AND QUANTUM CRITICAL PHENOMENA
(4 - 22 July 1994)

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EXPERIMENTS ON NFL BEHAVIOUR AND QUANTUM PHASE TRANSITIONS

Please also refer to previous lecture notes for the ICTP Spring College in Condensed Matter on Quantum Phases :

NR. 16 : Magnetic phase transitions at low temperatures - Part I
MPTI Magnetic fluctuation spectra & the Quasiparticle scattering rate

NR. 17 : Magnetic phase transitions at low temperatures - Part II

NR. 21 : Magnetic phase transitions at low temperatures - Part III

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These are preliminary lecture notes, intended only for distribution to participants.

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ICTP July 1994

Lectures 1 and 2
(combined)

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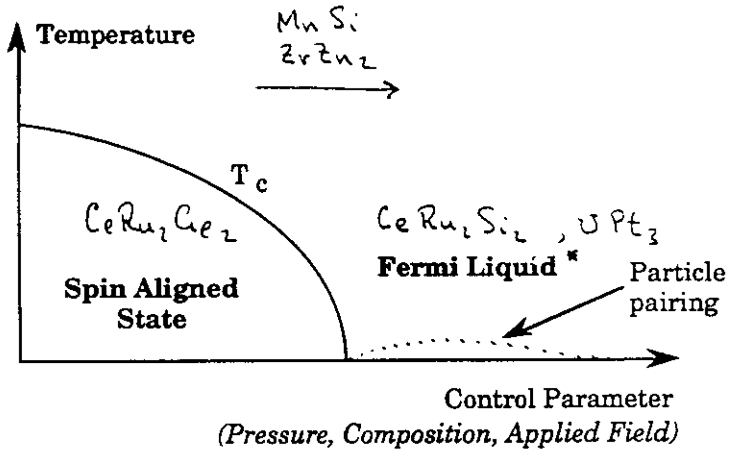
Magnetic to Fermi Liquid Transitions at Low Temperatures



(* with unusual quasiparticles)

- 3d ferromagnetic metals near critical lattice spacing or composition #

  heavy fermion compounds and low dimensional conductors

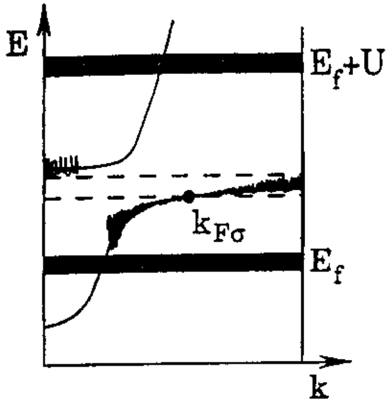
- Quantum Critical Phenomena (breakdown of conventional view of elementary excitations).

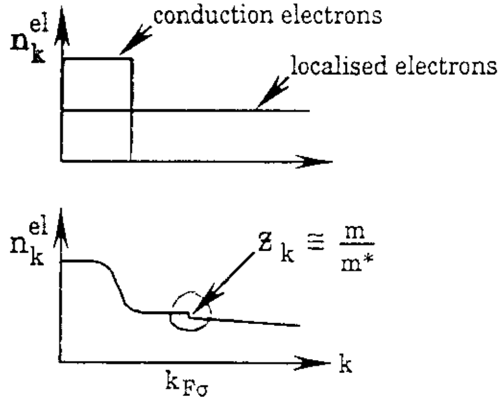
  Fluctuation frequency $\Gamma_q \geq kT_c/\hbar$ near the critical pressure or composition.

- Quantum Order (fermion condensations, novel magnetism and superconductivity).

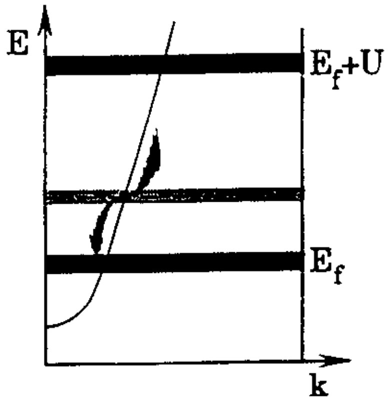
See also ICTP notes April 94 "Magnetic Phase Transitions at Low Temperatures"

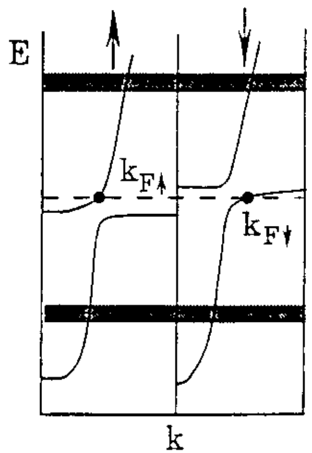
Quasiparticle Description of Coupled System of Conduction Electrons and Localised f-electrons





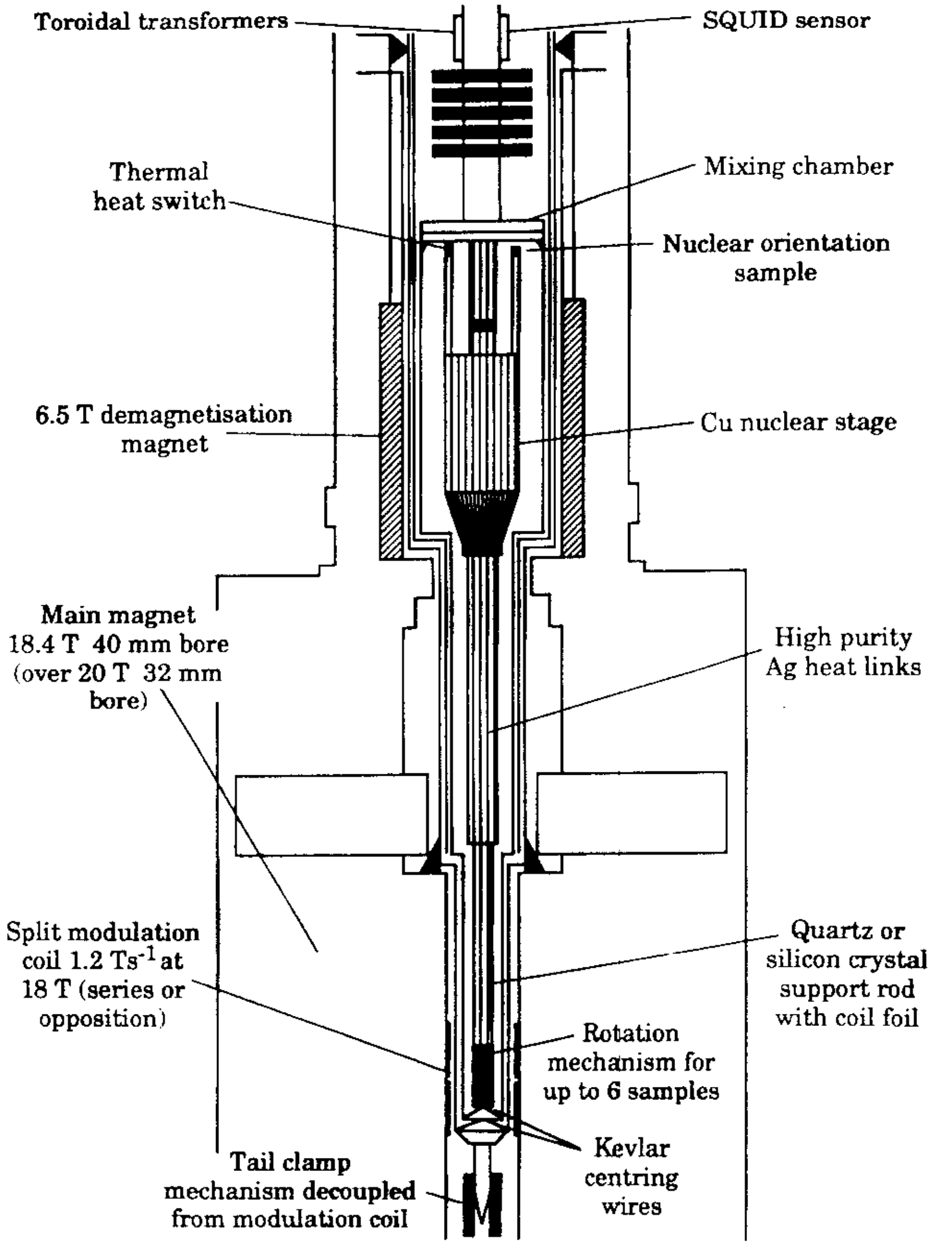
Fermi surface includes nearly localised f - electrons (Luttinger's Theorem) and quasiparticle mass is enhanced



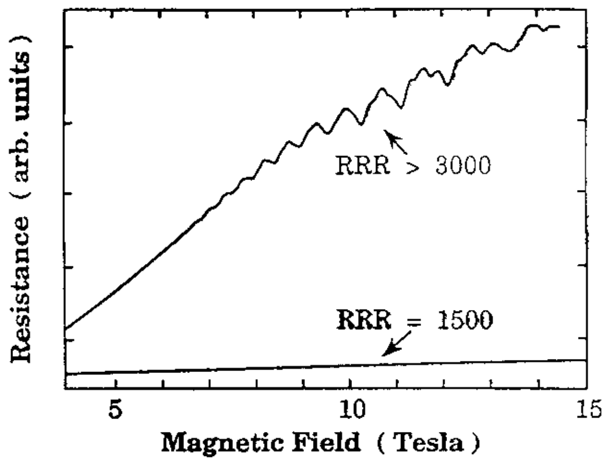


Fermi surface is unchanged but quasiparticle mass is enhanced

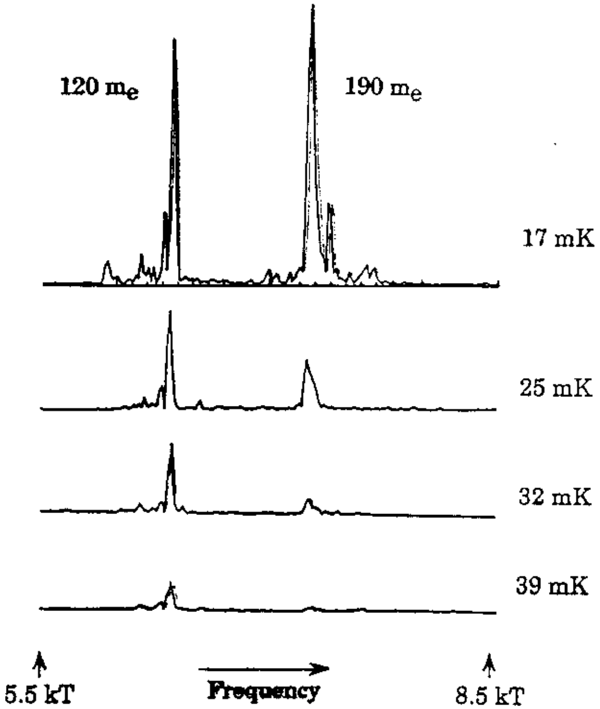
Dilution Refrigerator-Magnet System with Cu Nuclear Demagnetisation Stage



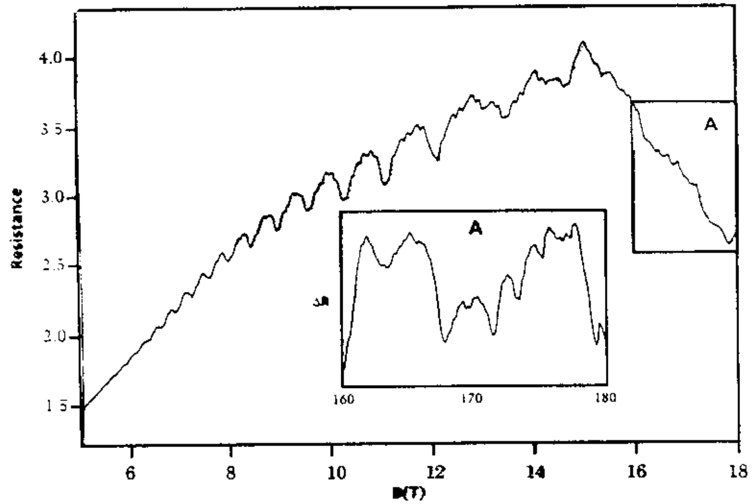
UPt_3: Magnetoresistance in Ultra-Pure Whiskers ($B \perp c$)

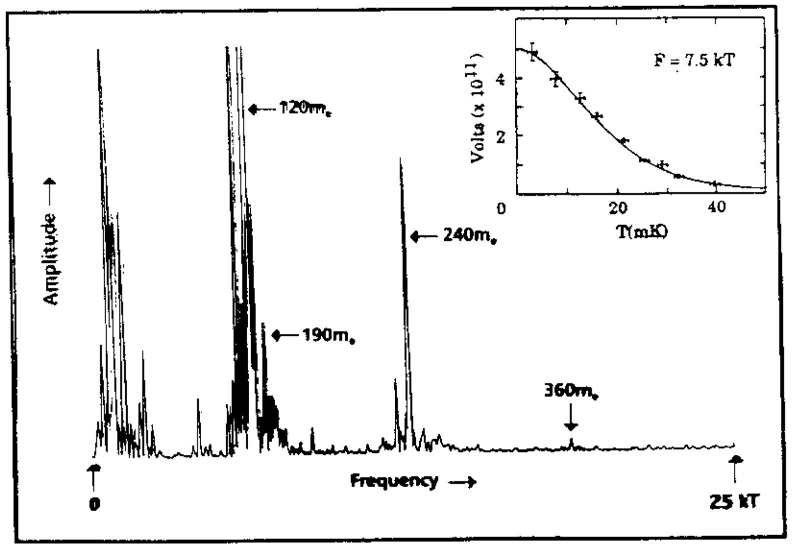


Julian & GL



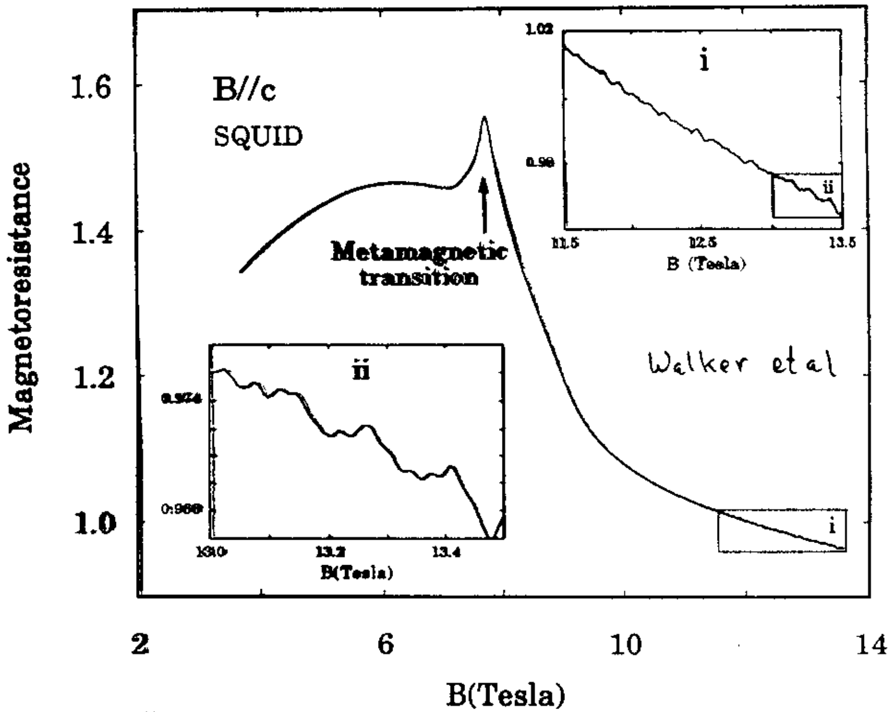
UPt_3: Study of Heavy Quasiparticles via the Oscillatory Magnetoresistance

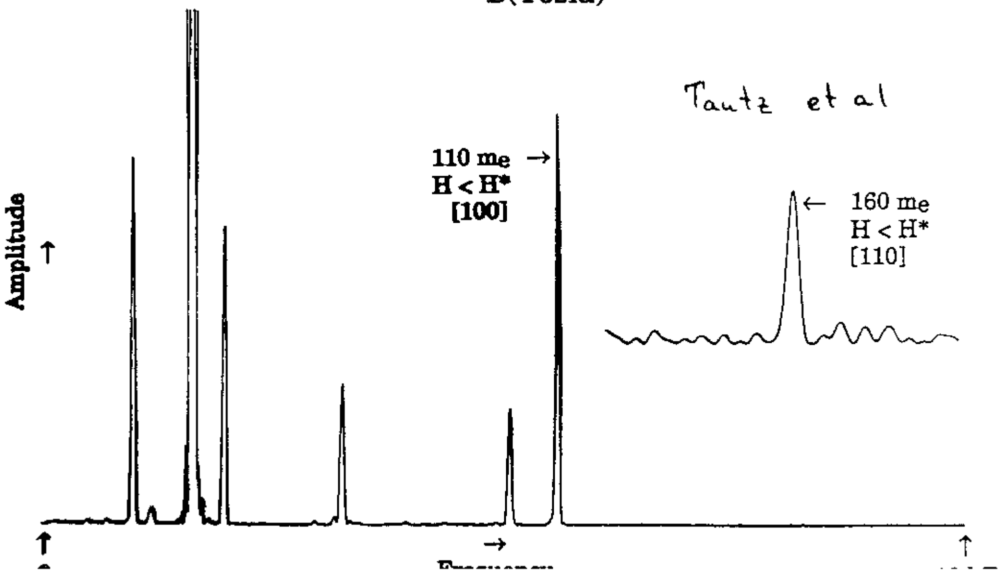




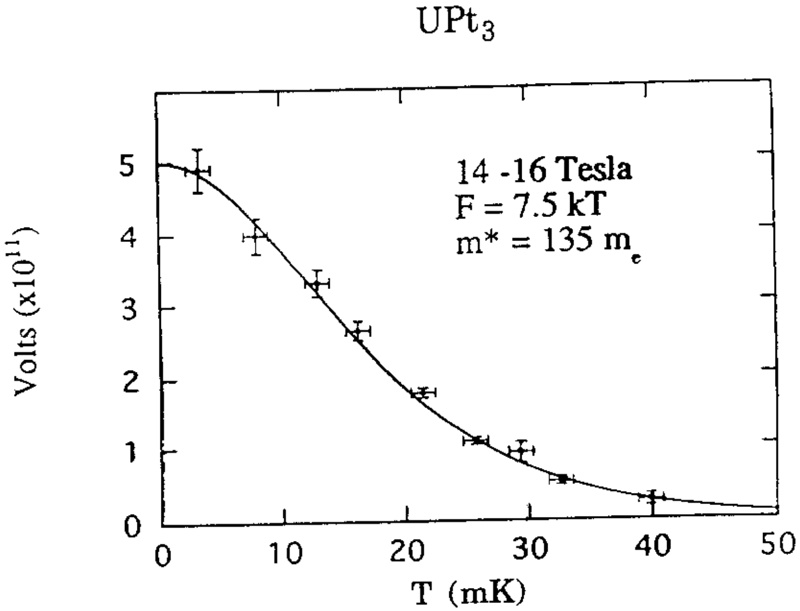
Julian & GL

$CeRu_2Si_2$





Temperature Dependence of the Oscillatory Magnetoresistance

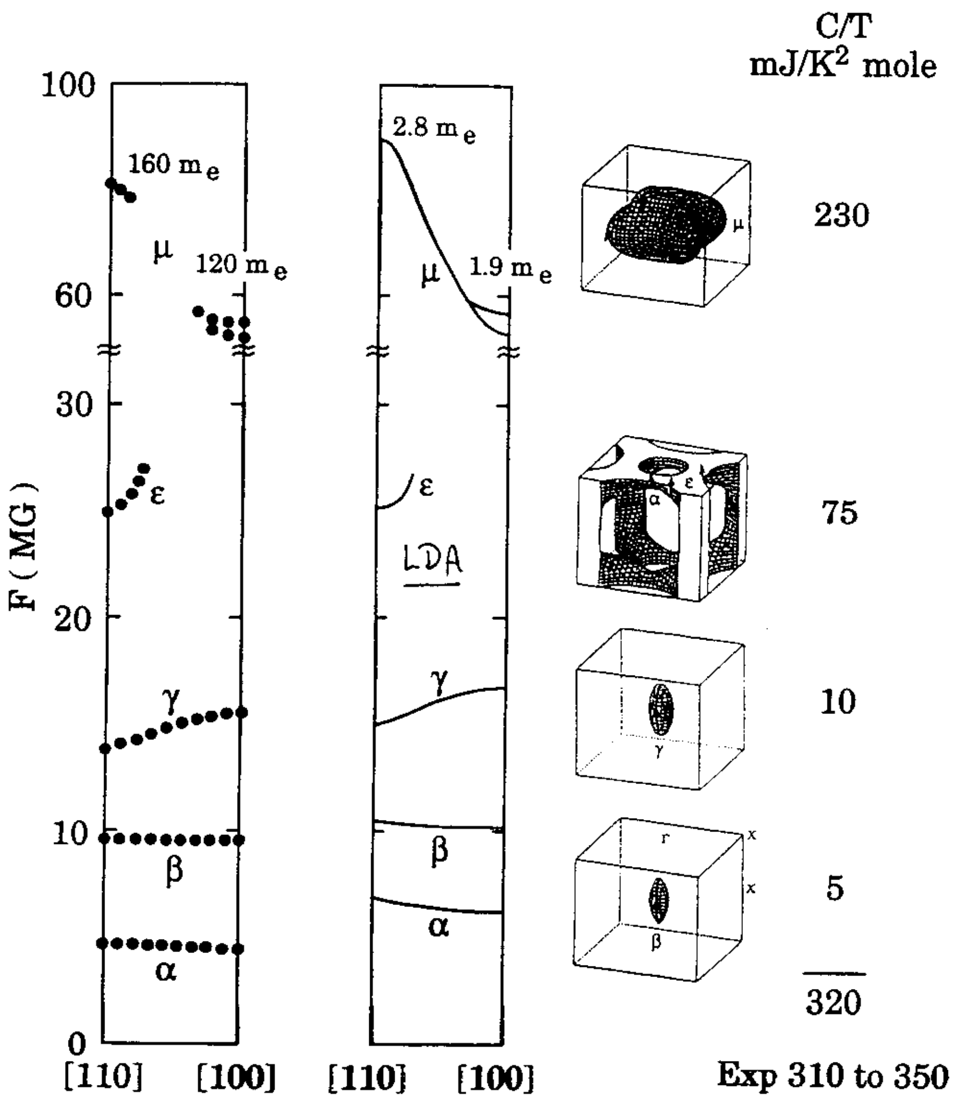


Amplitude = Average of $e^{i2\pi\varepsilon/\hbar\omega_c}$ over thermal broadening function $P(\varepsilon)$ of width $\sim kT$

— for $P(\varepsilon) = -\frac{\partial}{\partial\varepsilon}$ (Fermi Function)

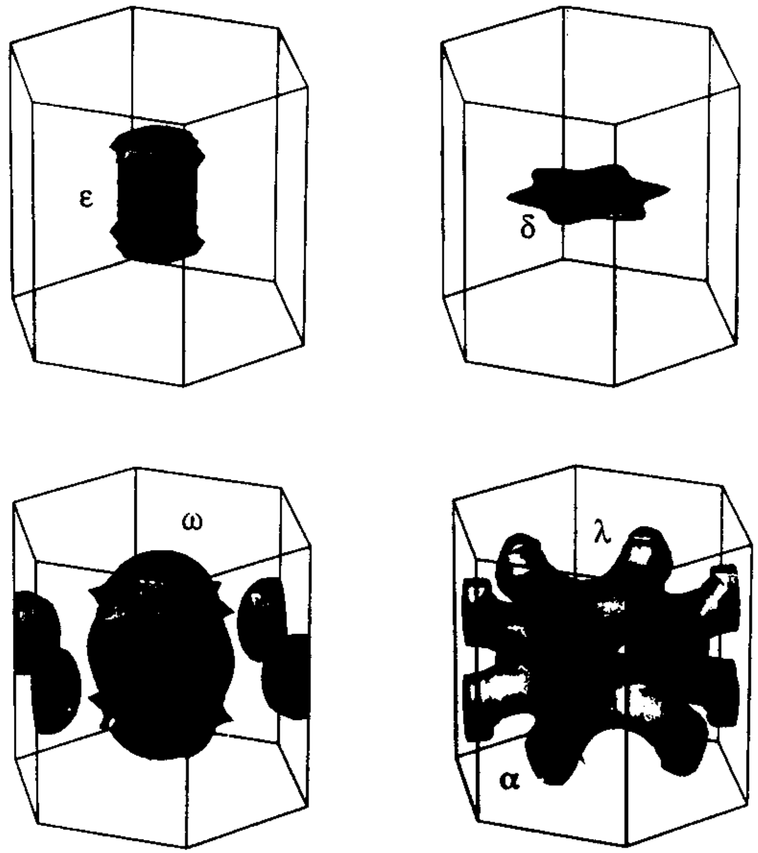
Julian & GL

$CeRu_2Si_2$

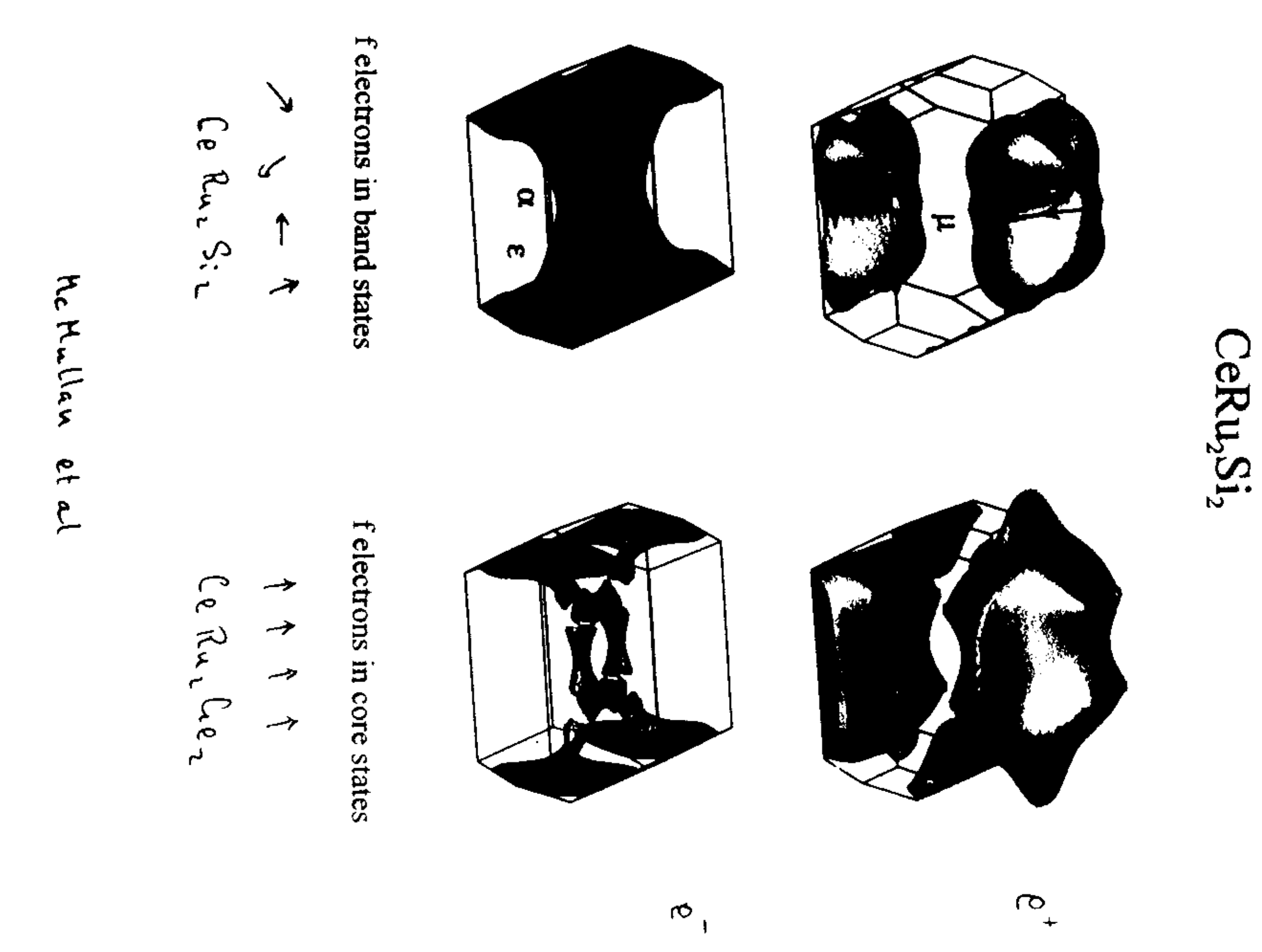


Tautz et al

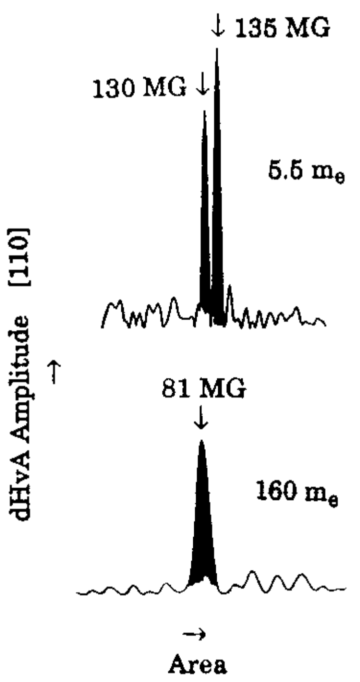
UPt_3

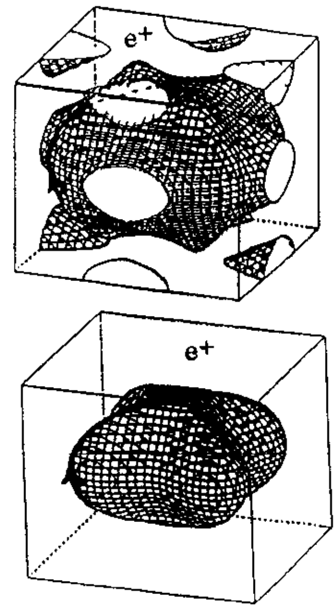


McMullan, Julian & GL



Fermi Surfaces of $CeRu_2Ge_2$ and $CeRu_2Si_2$





$CeRu_2Ge_2$
Spin
aligned ↑ ↑ ↑ ↑

$CeRu_2Si_2$
Spin
non-aligned ↗ ↓ ←

Conclusions (All Sheets): $CeRu_2Ge_2$: $n_e = n_h - 1$, $CeRu_2Si_2$: $n_e = n_h$

"Local" f electrons with fluctuating moments determine Fermi volume of $CeRu_2Si_2$

Limits of the Landau Fermi Liquid Model

- Long range current-current interaction
- At very low temperatures and in ultra pure samples

  - $S/T \to ln(T/T^*)$ "mass" (for $T \ll T^*$)

  $\rho/T^2 \to 1/T^{1/3}$ "cross-section" (before Pauli constraint)

- Long range quasiparticle-quasiparticle molecular field coupling near magnetic phase transitions ($T_c \to 0$).

Magnetic Fluctuation Relaxation Spectrum Γ_q

- For a Fermi Liquid# at low T and q

$$\Gamma_q \cong \frac{2}{\pi}\, \upsilon_F\, q\, \frac{\chi_p}{\chi_q} \to \gamma q\,(\chi^{-1} + cq^2)\,.$$

Recall $\chi_{q\omega}^{-1} = \chi_p^{-1}\left(1 - \frac{i\pi\omega}{2\upsilon_F q}\right) - \lambda + \vartheta\left(\frac{i\omega)^2}{q^2}\right) + \vartheta(q^2)$

- The dynamical susceptibility and power spectrum at low q and ω

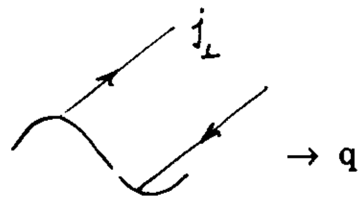
$$\chi_{q\omega}^{-1} \cong \chi_q^{-1}\left(1 - i\,\frac{\omega}{\Gamma_q}\right), \quad \left\langle m_{q\omega} m_{-q-\omega}\right\rangle = 2\hbar(1+n_\omega)\chi''_{q\omega}$$

- Dynamical exponent $\Gamma_q \propto q^z$

  $z = 1$ normal state

  $z = 3$ critical $\chi^{-1} \to 0$ ($d_{eff} = d + z > 4$).
  $T \to 0$ if $d > 1$

- cf. transverse current fluctuations in normal state of an ideal conductor at low T and q

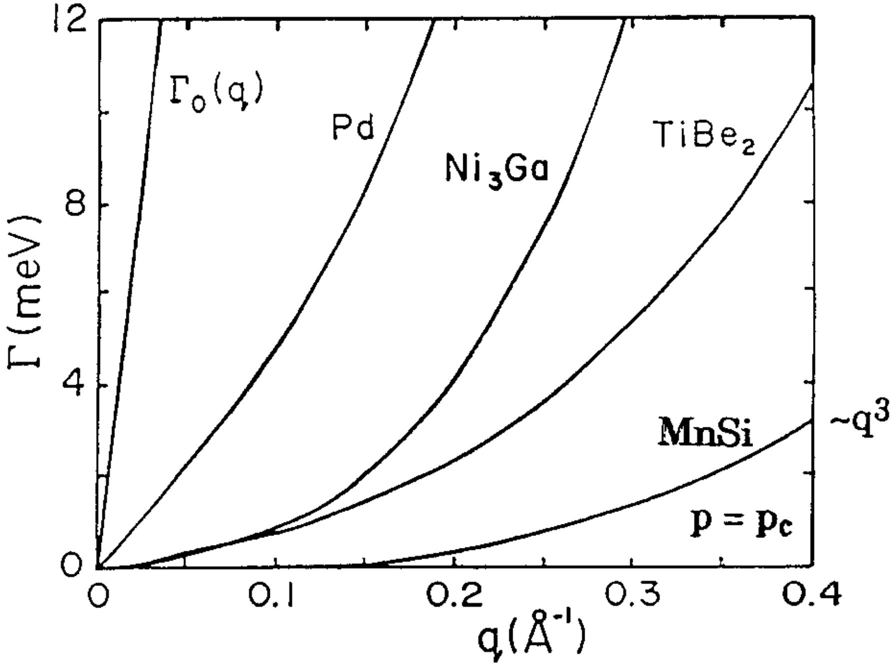


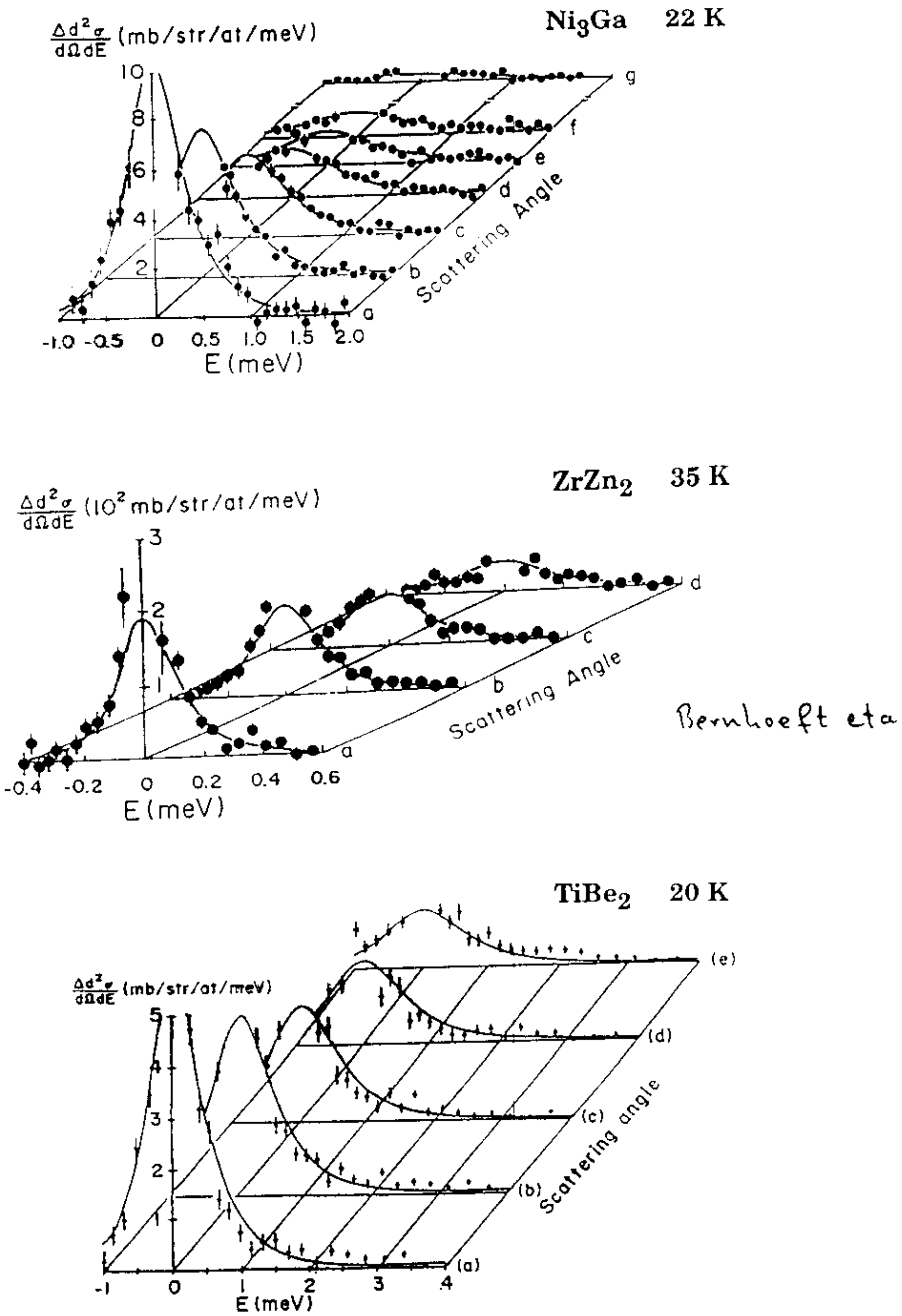
$$\Gamma_q \cong \frac{2}{\pi}\, \upsilon_F q\, (\lambda_L q)^2\,,$$

$z = 3$, but $\lambda_L^2 \gg c\,\chi_p$.

Refs: eg: Doniach, Moriya, Hertz, Holstein ... in 7
Millis, Sachdev, Reizer, ... in 90's

Spin Fluctuation Rate in Nearly Ferromagnetic Transition Metals



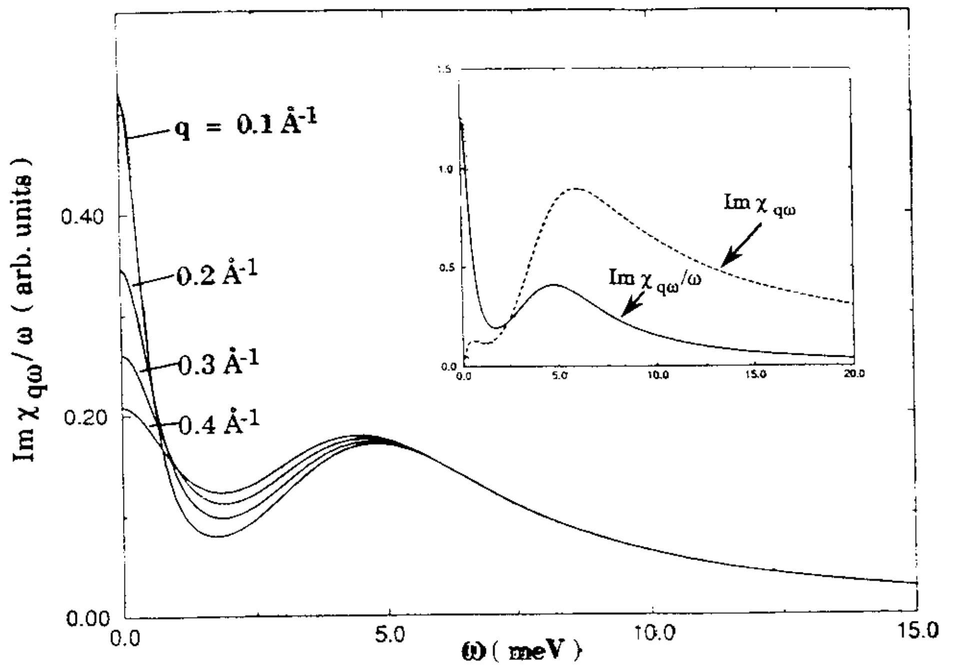


Exp: Bernhoeft and Lonzarich; Ishikawa et al. (MnSi)
Calc: McMullan and Lonzarich; Winter et al.

$$\Gamma_q = \gamma q(\chi^{-1} + cq^2) \to q^{z=3} \quad \text{for} \quad T \to T_c.$$

z = Dynamical Exponent; deff = d + z → 6.

Model for the Dynamical Susceptibility for UPt$_3$ at Low q and ω



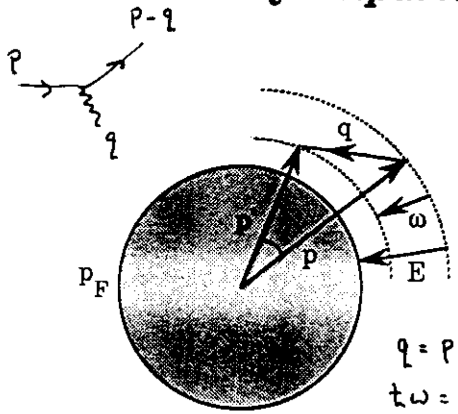
Bernhoeft & GL

$$\chi_{q\omega} = \frac{\beta_\omega}{1-\lambda^2\alpha_{q\omega}\beta_\omega}$$

$$\alpha_{q\omega} = \alpha(1-i\omega/\eta q)^{-1}, \qquad \beta_\omega = \beta(2-\delta)\left(1-\frac{i\omega}{v}+\frac{1}{1-\frac{i\omega}{v}}-\delta\right)^{-1}$$

$\Gamma_q = \frac{2}{\pi} v_F^*\left(1+F_0^a\right)q$, Estimate $\left(1+F_0^a\right)^{-1} \sim 5$

Quasiparticle Scattering Rate



$q = p - p'$
$\hbar\omega = \varepsilon_p - \varepsilon_{p'}$

- At T → 0 near the Fermi level

$$\tau_p^{-1} = \frac{\lambda^2}{\hbar^2}\sum_{p'}{}^{*}\left\langle m_{q\omega}m_{-q-\omega}\right\rangle$$

$$\sim \int q\,dq\,d\omega\,\frac{\omega q}{\omega^2+q^{2z}}$$

-

d = 3	z = 1 (FL)	z = 3 (MFL)
τ_E^{-1}	E^2	E
m_E^*	E^0	*ln* (E*/E)

-

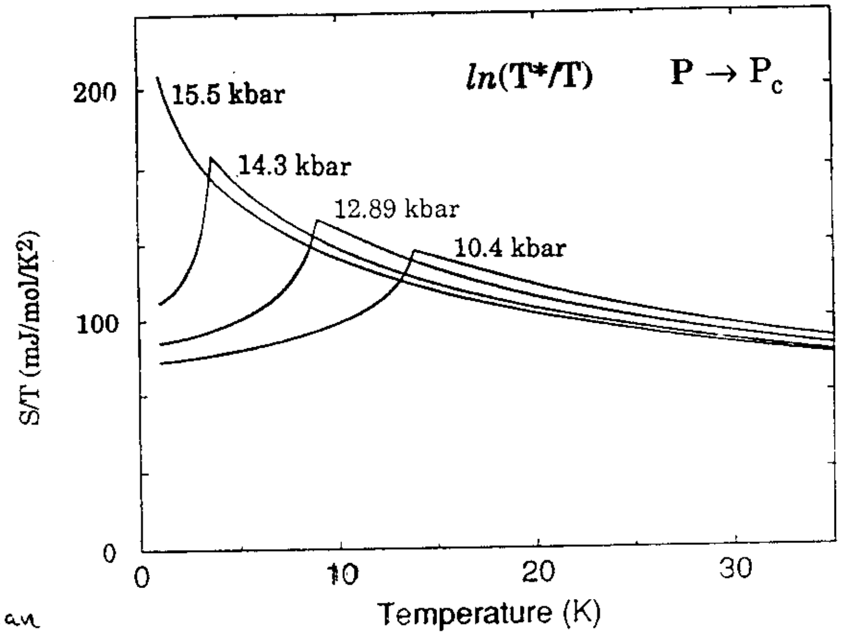
d = 3	z = 1 (FL)	z = 3 (MFL)
τ^{-1}	T^2	T
C/T	T^0	*ln* (T*/T)
ρ	T^2	T^ζ
$\Delta\chi^{-1}$	T^2	T^γ

ζ = 5/3 in the absence of drag corrections.

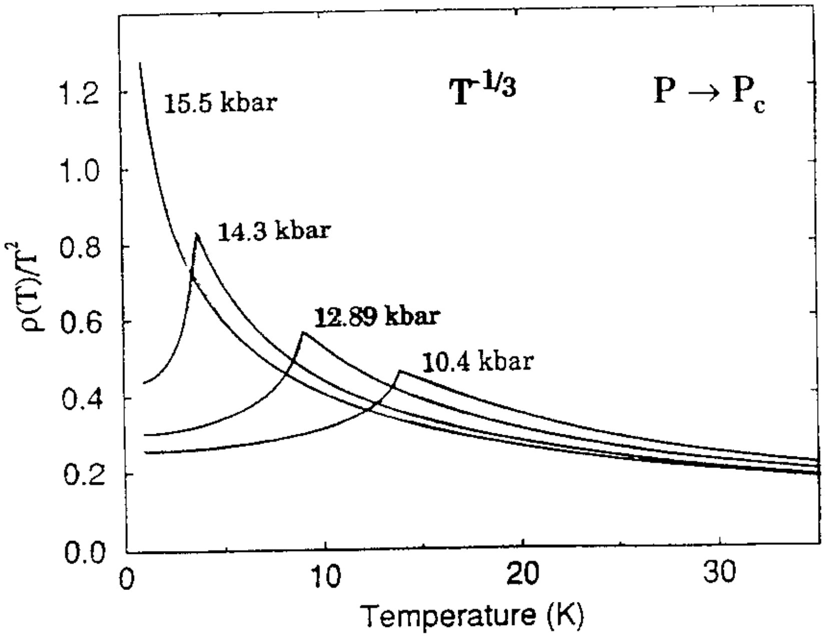
γ = 4/3 in self-consistent Hartree approximation for coupling of magnetic fluctuations.

Higher oder corrections of same qualitative form!
see eg Altshuler, Ioffe & Millis 1994

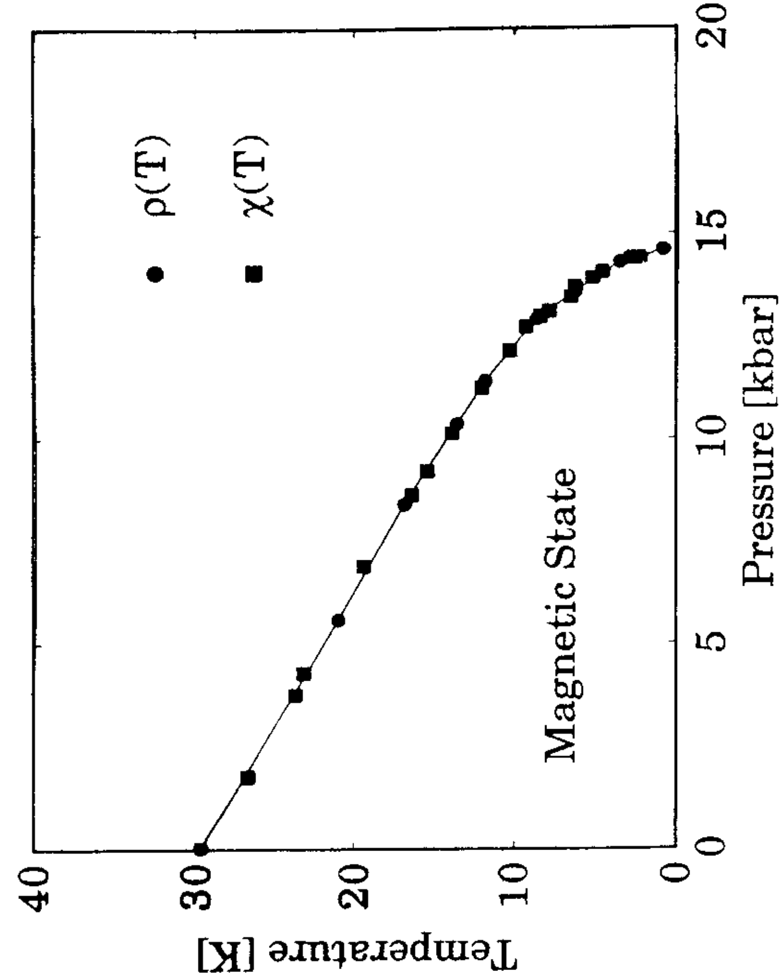
Calculated Temperature and Pressure Variations of the Entropy and Resistivity



McMillan & GL

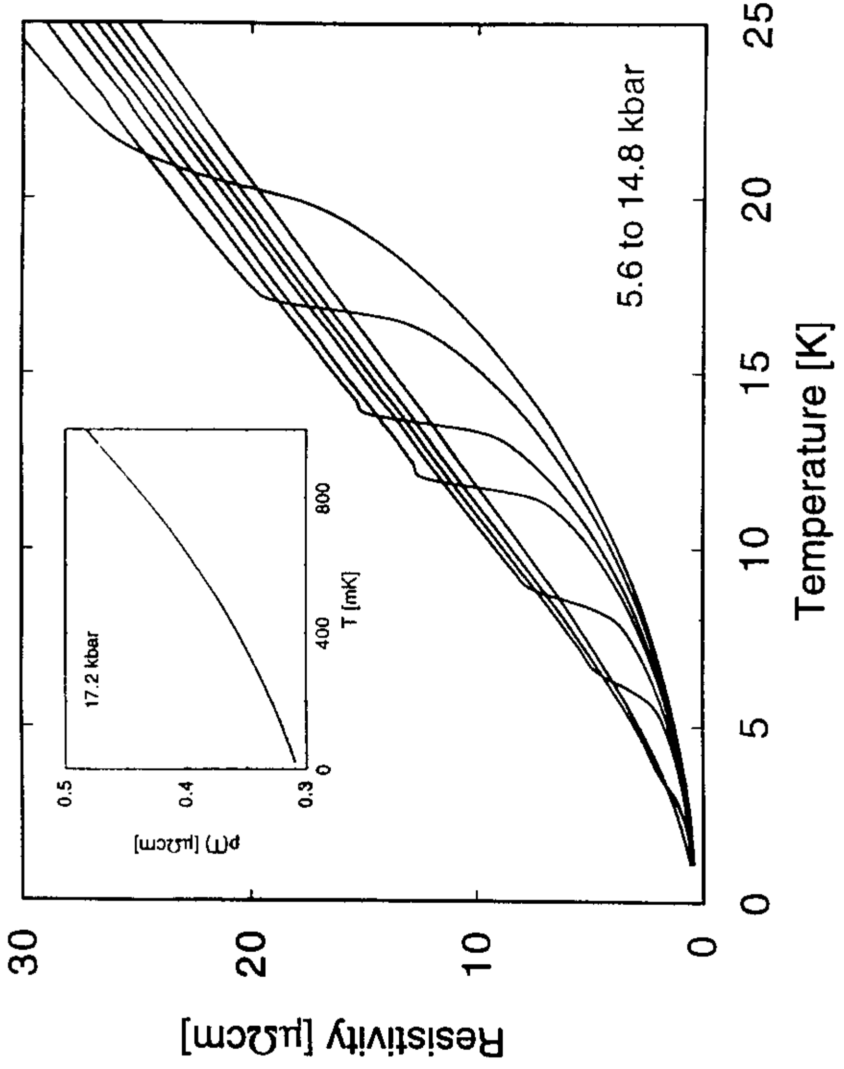


Phase Diagram of MnSi

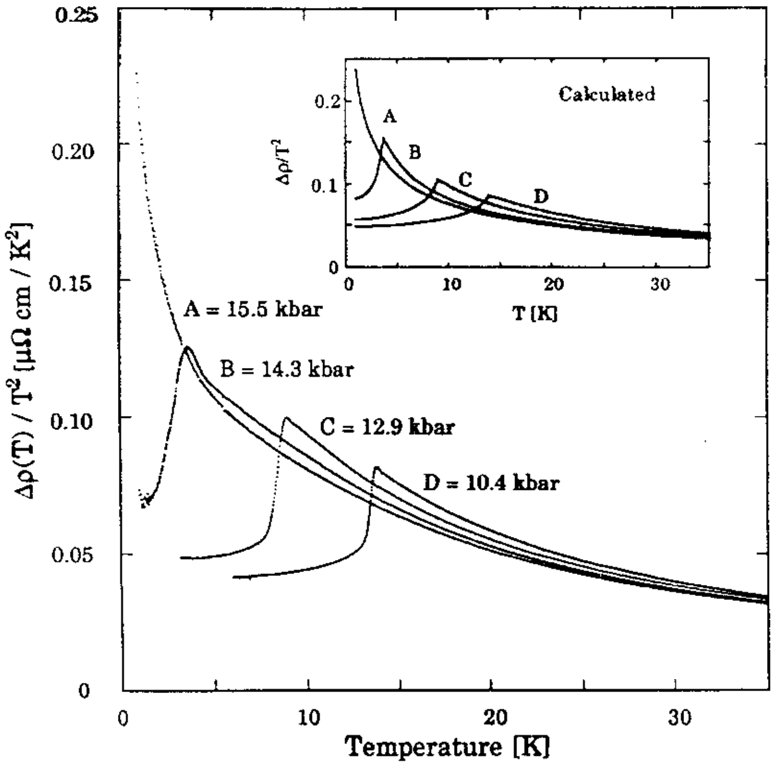


Pfleiderer & GL

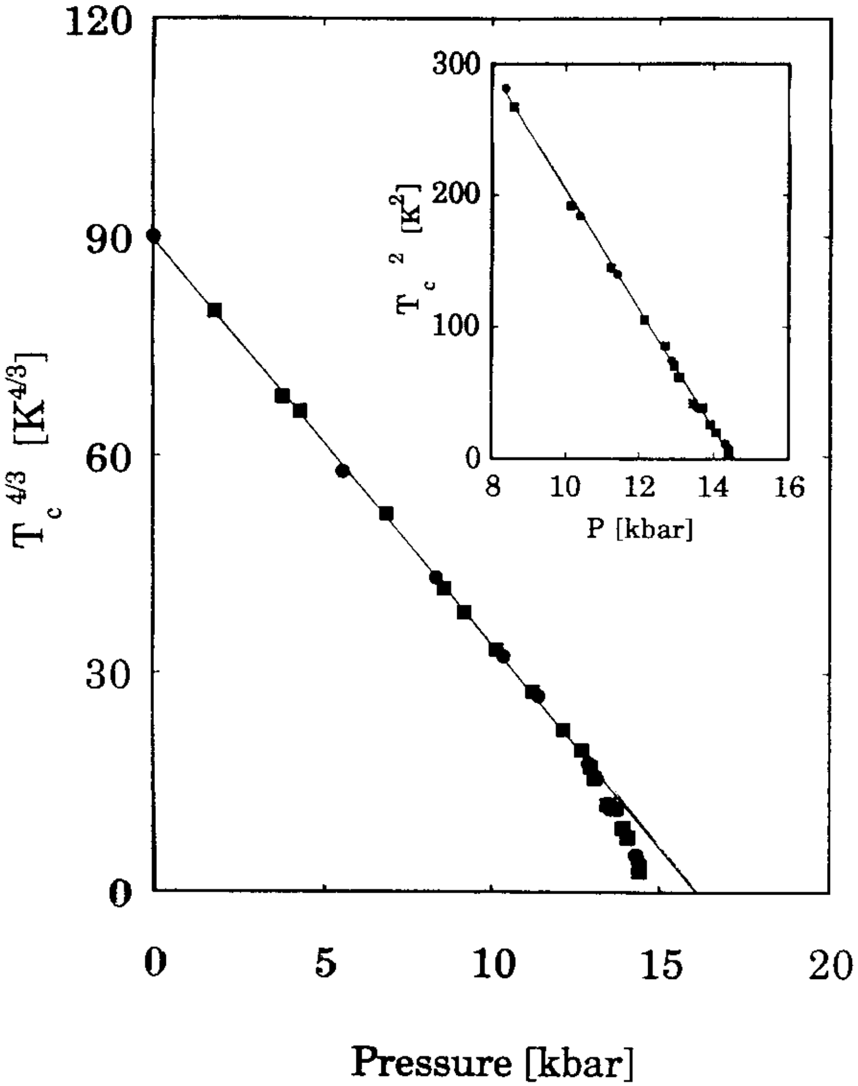
Pressure and Temperature Dependence of the Resistivity



Temperature Dependence of $\Delta\rho(T)/T^2$



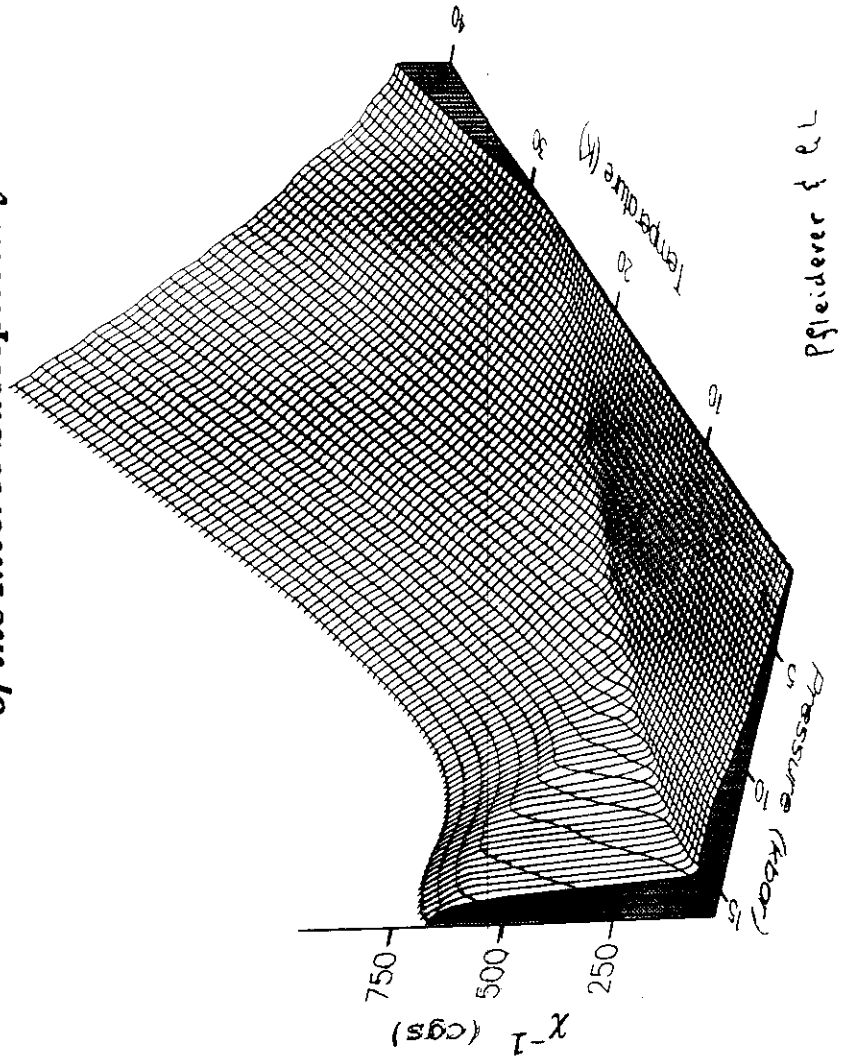
Pressure Dependence of the Transition Temperature



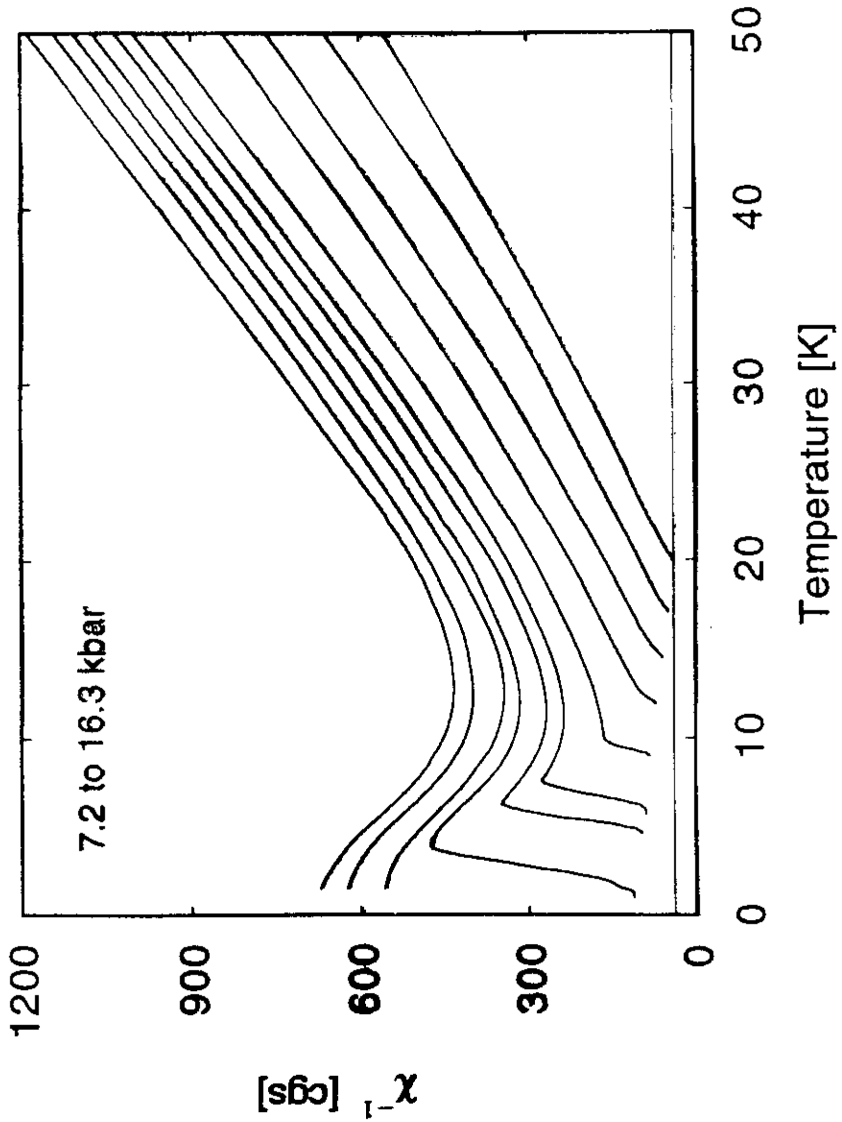
Expected form of Landau functional

$$F[M] \sim \Big[\underbrace{(P-P_c) + T^{4/3}}\Big] M^2 + \cdots \quad (d_{eff} > 4)$$

Temperature and Pressure Dependence of the Inverse Susceptibility



Temperature and Pressure Dependence of the Inverse Susceptibility



Langevin Model for $m(rt)$

- $\dot{m} = \alpha\, m \times B_{eff} - \gamma * [am + bm^3 + dm^5 - B_{eff}$

  $B_{eff} = B + c\nabla^2 m$

  $\gamma_q = \gamma q$

- Take $m \to M + m$ $\quad B \to B + h$
  and average in limit of strong damping

  $$\Delta\chi^{-1} = 5\left(b + \frac{\Delta b}{2}\right)\overline{m^2} - \alpha\gamma^{-2} * \frac{\partial}{\partial M}\overline{(m \times \dot{m})}$$

  $\Delta b = 14 d\overline{m^2}$, $\quad \chi^{-1} = a + \Delta\chi^{-1}$

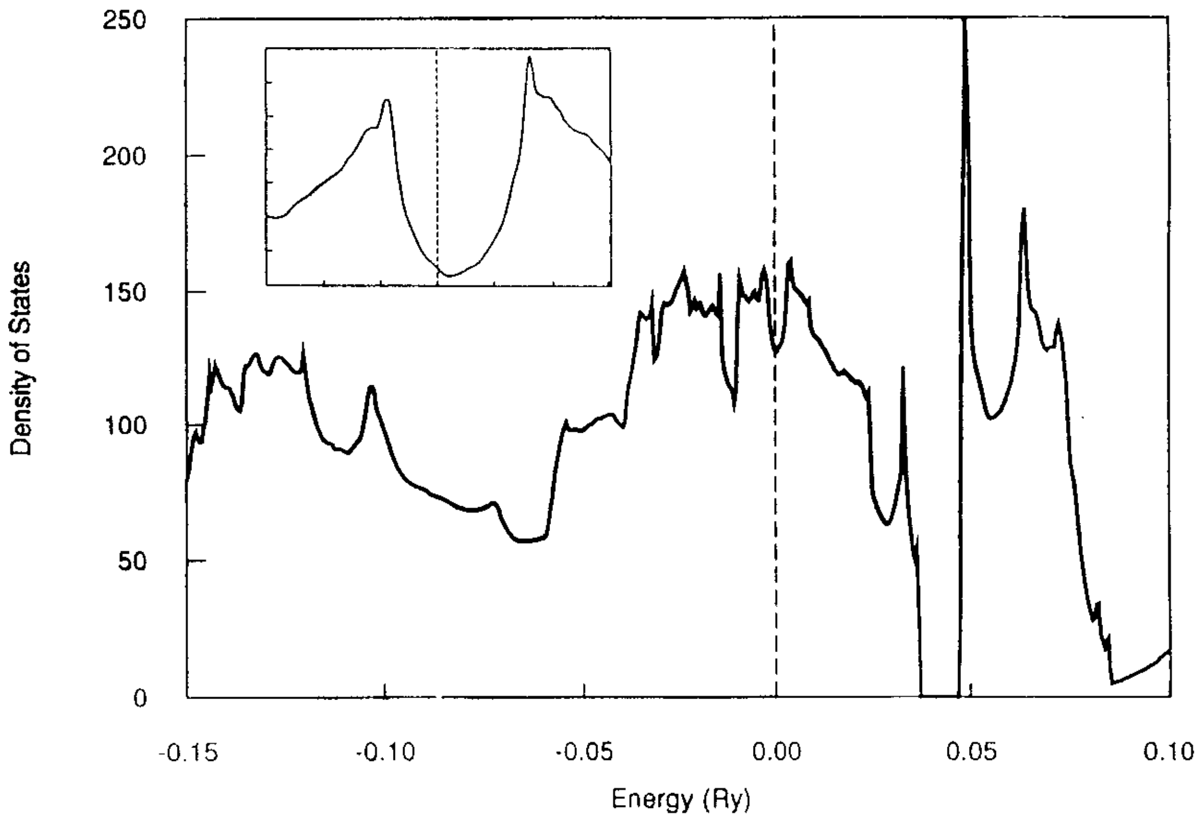
  $\overline{m^2} = \frac{1}{\beta V}\sum_k' \chi_k$, $\quad \chi_k^{-1} = \chi^{-1} + cq^2 + \frac{|\nu|}{\gamma q}$

  $k = (q, i\nu)$

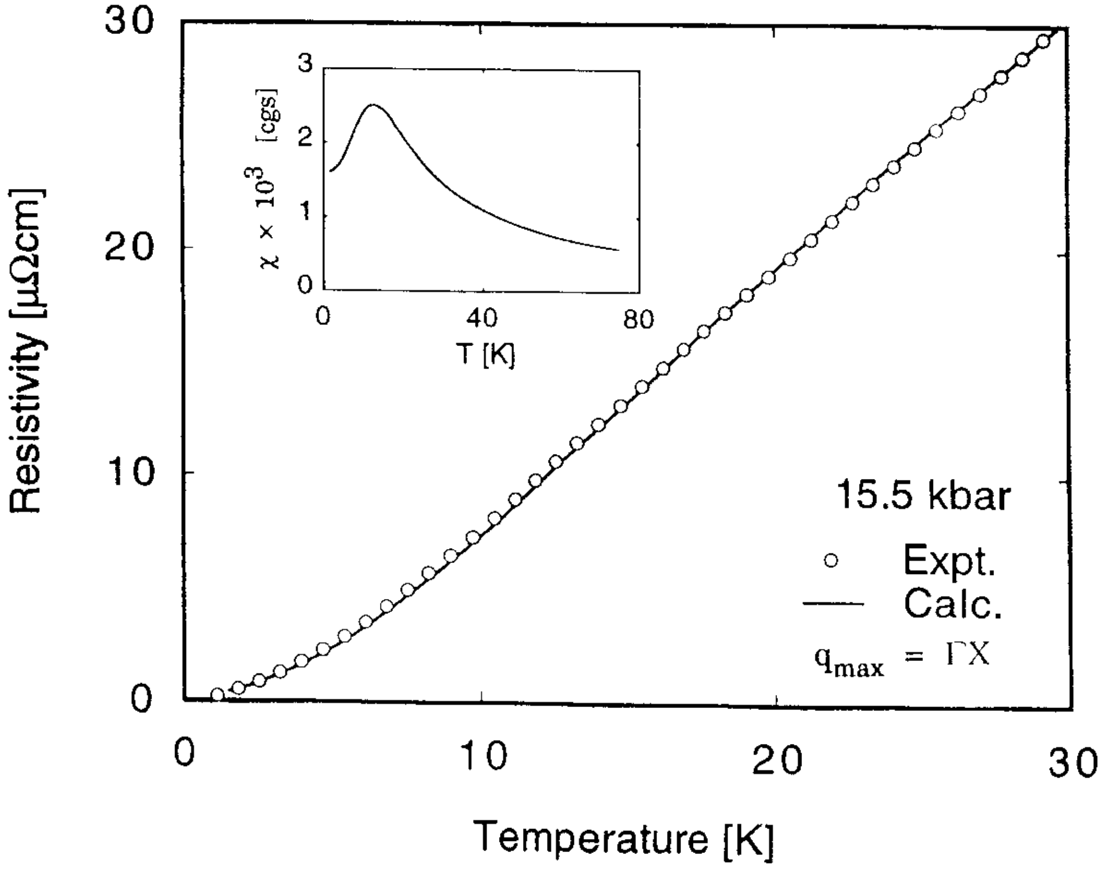
- Euclidean Action $\quad (\beta F[m] \to A[m]/\hbar)$

  $$A[m] = \frac{1}{2}\sum_k' \left(a + cq^2 + \frac{|\nu|}{\gamma q}\right)|m_k|^2 + (m^3) + (m^4) + (m^6)$$

D.O.S (States/Cell /Ry)

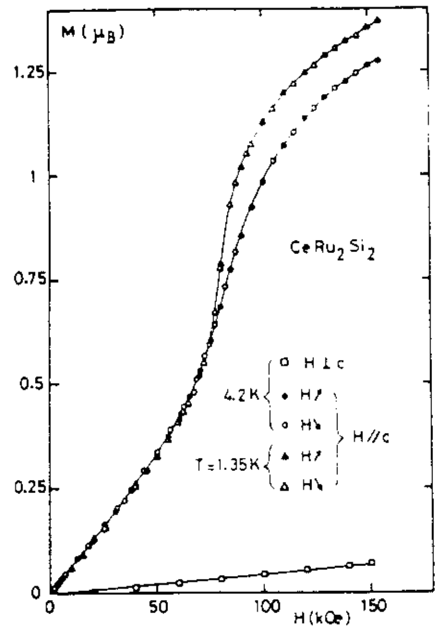


Temperature Variation of the Resistivity near p_c



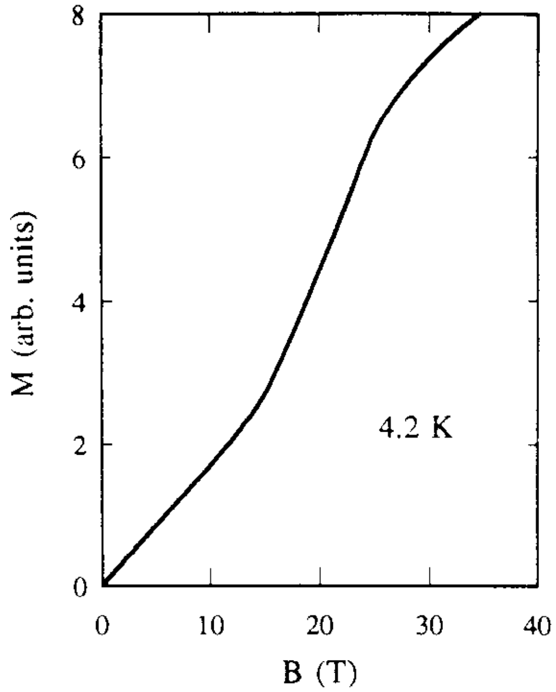
The Heavy Fermion Metamagnetic Transition

$CeRu_2Si_2$

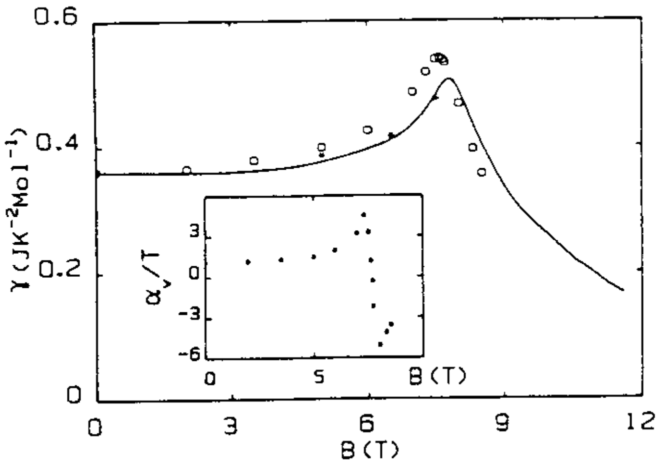


Haen et al
J. Low Temp. Phys **67** (1987) 391

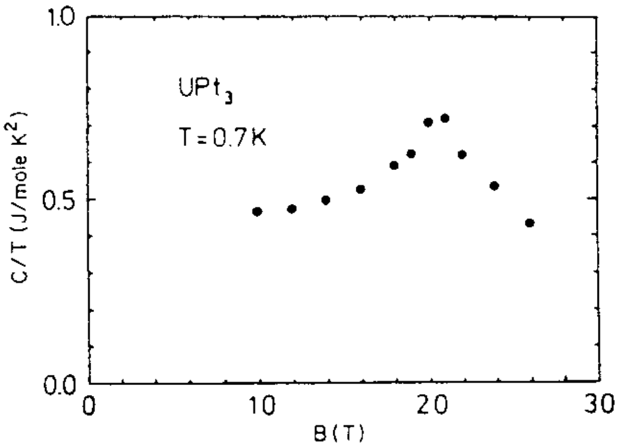
UPt_3



de Visser et al.
Physics Letters **113A** (1986) 489



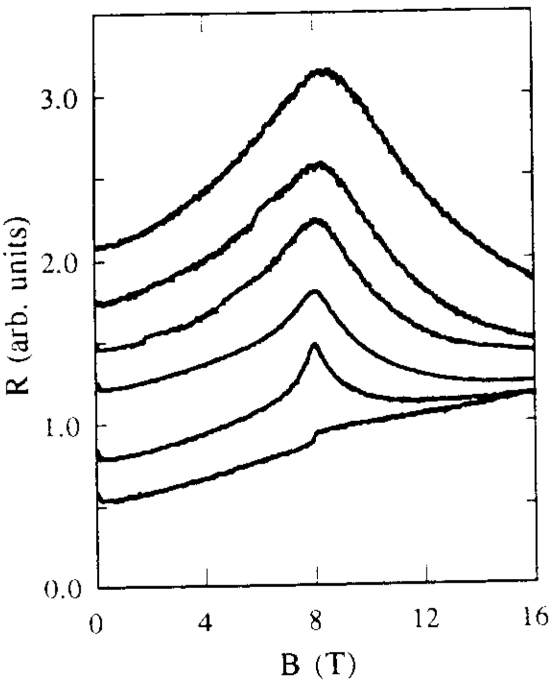
van der Meulen et al.
Phys. Rev. B **44** (1991) 814

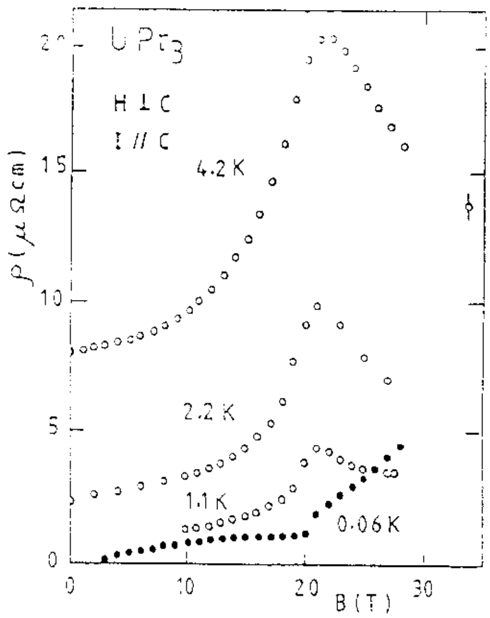


Muller et al.
Phys. Rev. B **40** (1989) 2614

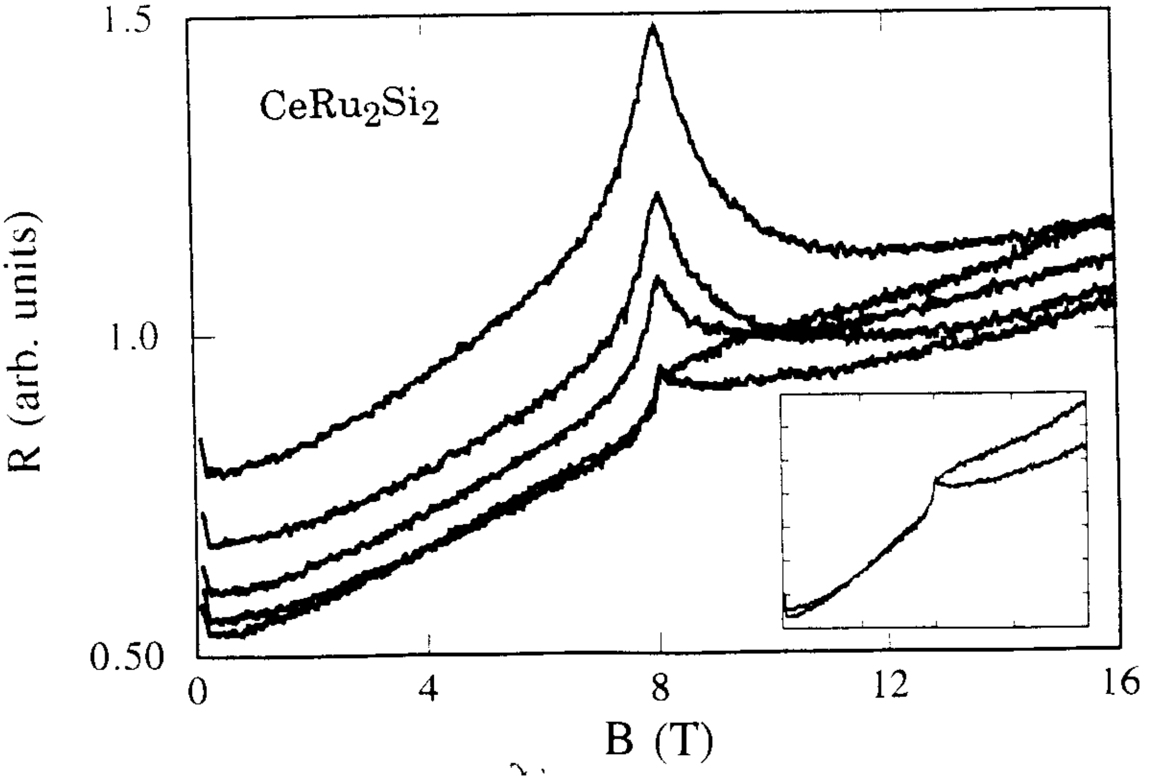
Magnetoresistance and the Metamagnetic Transition

$CeRu_2Si_2$

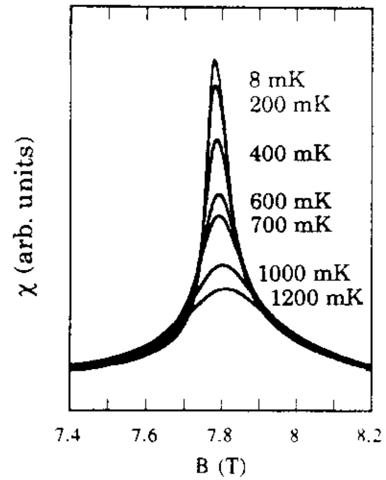


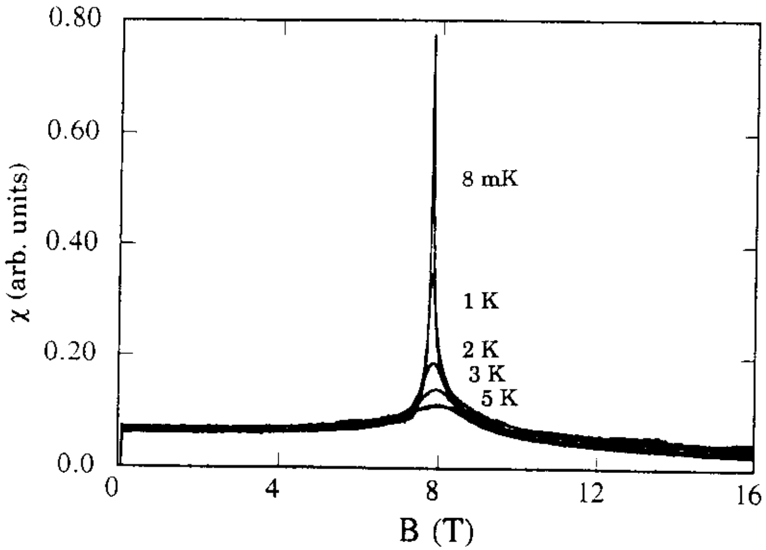


Taillefer et al.
J. Magn. Magn. Mater.
76-77 (1988) 218

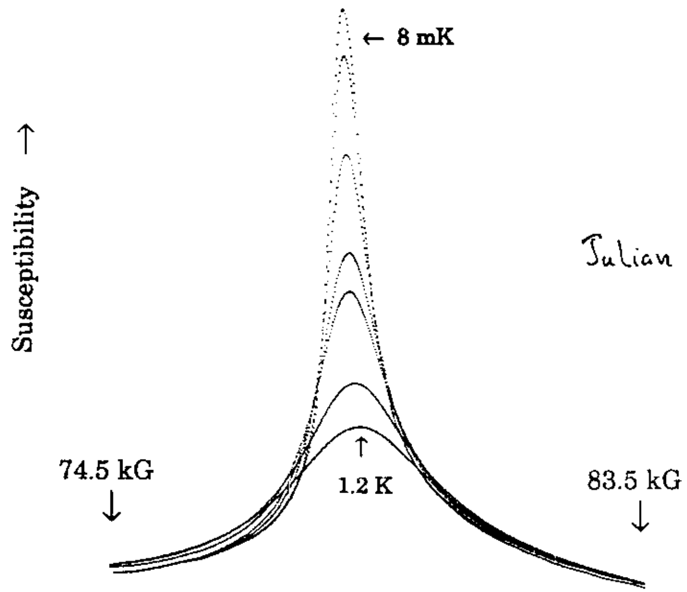


$CeRu_2Si_2$: Susceptibility vs Temperature

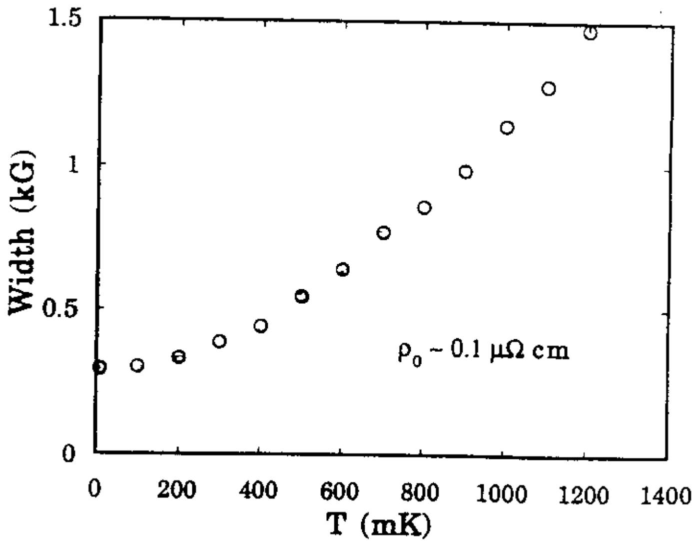




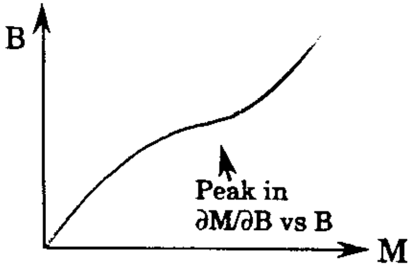
$CeRu_2Si_2$: Metamagnetic Transition for B along the c-axis

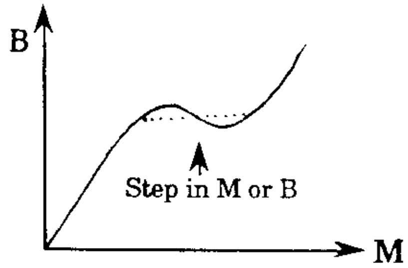


Julian et al



Metamagnetic Transition





Mean Field Model ($b < 0$)

$$B = aM + bM^3 + dM^5$$

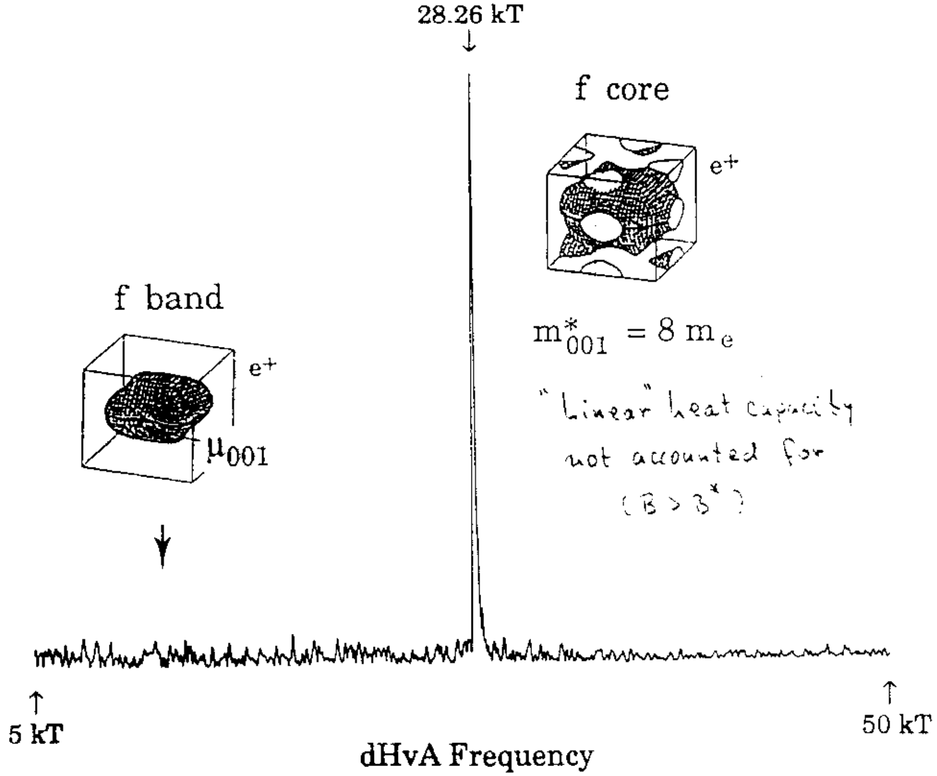
Fluctuation Corrections

$$a \rightarrow a + 3\left(b + \frac{\Delta b}{2}\right) \overline{m^2}$$

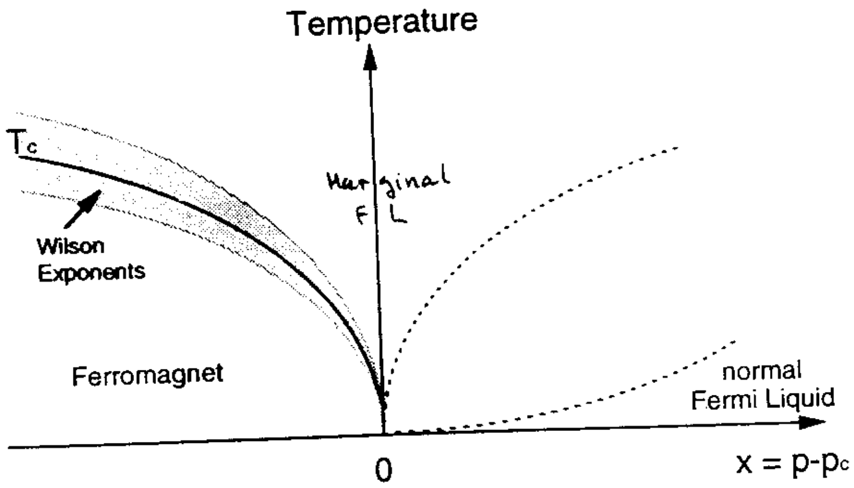
$$b \rightarrow b + 10\, d\, \overline{m^2}$$

$$\overline{m^2} = \frac{1}{\beta V} \Sigma \chi_{q,i\nu}$$

$CeRu_2Si_2$: High Frequency dHvA Spectrum above the Metamagnetic Transition (B along [001], 7 mK)



Conclusions



$CeRu_2Si_2$ and UPt_3 may be described within a Fermi Liquid Model in which the f moments and conduction electrons form charged fermion quasiparticles that account for the linear coefficient of the heat capacity.

MnSi and $ZrZn_2$ near their critical pressures exhibit properties consistent with the predictions of a Marginal Fermi Liquid arising from the exchange of highly dispersive critical fluctuations in the spin density.