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XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

YbRh2Si2: Pronounced Non-Fermi-Liquid Effects above a Low-Lying Magnetic Phase Transition

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$YbRh_2Si_2$: Pronounced Non-Fermi-Liquid Effects above a Low-Lying Magnetic Phase Transition

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Outline

+ Introduction - Motivation

+ Sample preparation

+ $YbRh_2Si_2$

+ Conclusions - Open questions

Non-Fermi-Liquid Effects in Stoichiometric HF compounds at p = 0

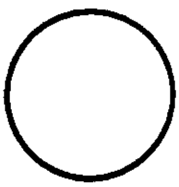
- Few known examples:

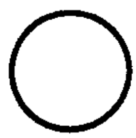
$CeNi_2Ge_2$, $CeCu_2Si_2$, $CeIrIn_5$, $CeRu_4Sb_{12}$,
UBe_{13}, U_2Pt_2In, U_2Co_2Sn

Alternative: Yb-based compounds ?

Comparison between Ce and Yb

magnetic	$Ce^{3+} \rightarrow 4f^1$ (J=5/2)	$Ce^{4+} \rightarrow 4f^0$ (J=0)	non-magnetic
	Pressure →		
non-magnetic	$Yb^{2+} \rightarrow 4f^{14}$ (J=0)	$Yb^{3+} \rightarrow 4f^{13}$ (J=7/2)	magnetic





Yb-based compounds: Problematic

+ Few examples of Yb-compounds with

$5\ K < T_K < 100\ K$

+ **Crucial point:** sample preparation

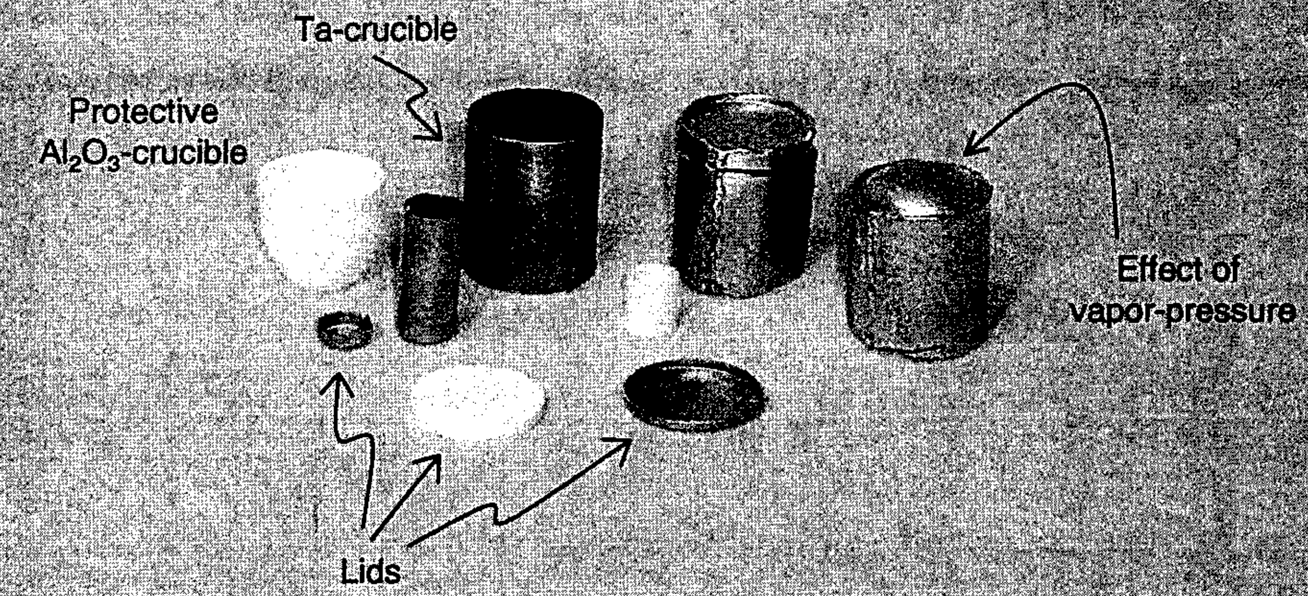
(Yb vapor-pressure:1 bar @ 1200°C)

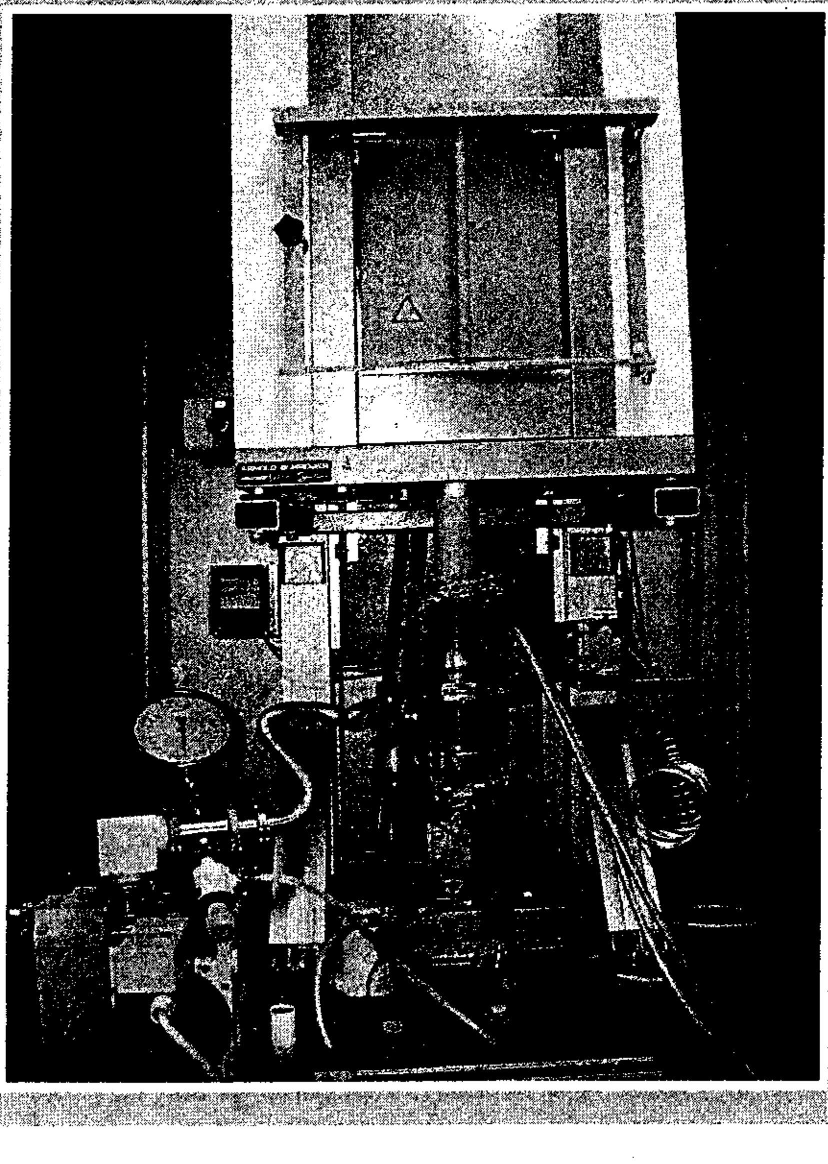
NFL behavior in Yb-based compounds

- **Alloying :** x-induced valence change in $YbCu_{5-x}Al_x$
- **Pressure :** Onset of magnetism in
  $YbCu_2Si_2$, Yb_2Ni_2Al, YbCuAl ($p > 8$ GPa)

But: ***No clear evidence of a QCP***

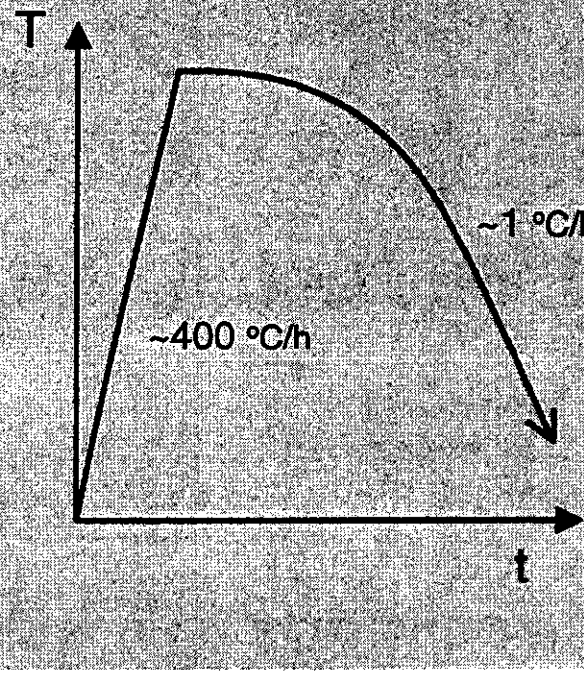
Sample preparation : Closed-crucible technique





Vertical furnace

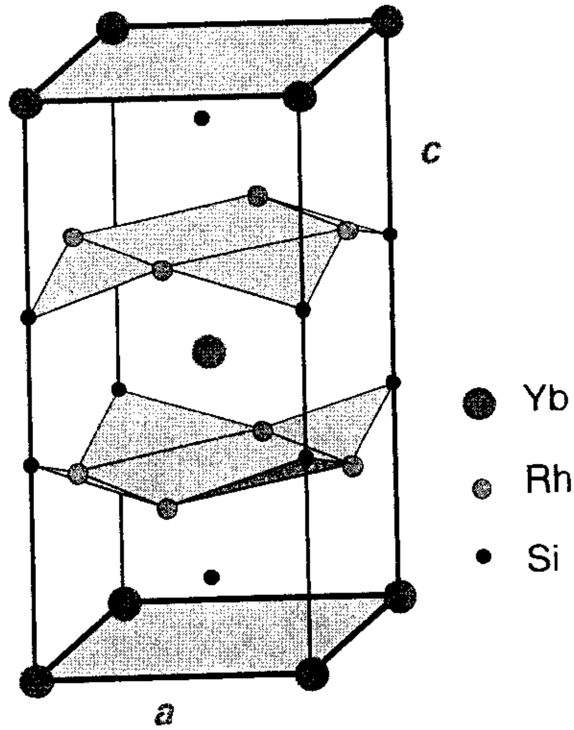
$T_{max} = 1750\ ^{o}C$



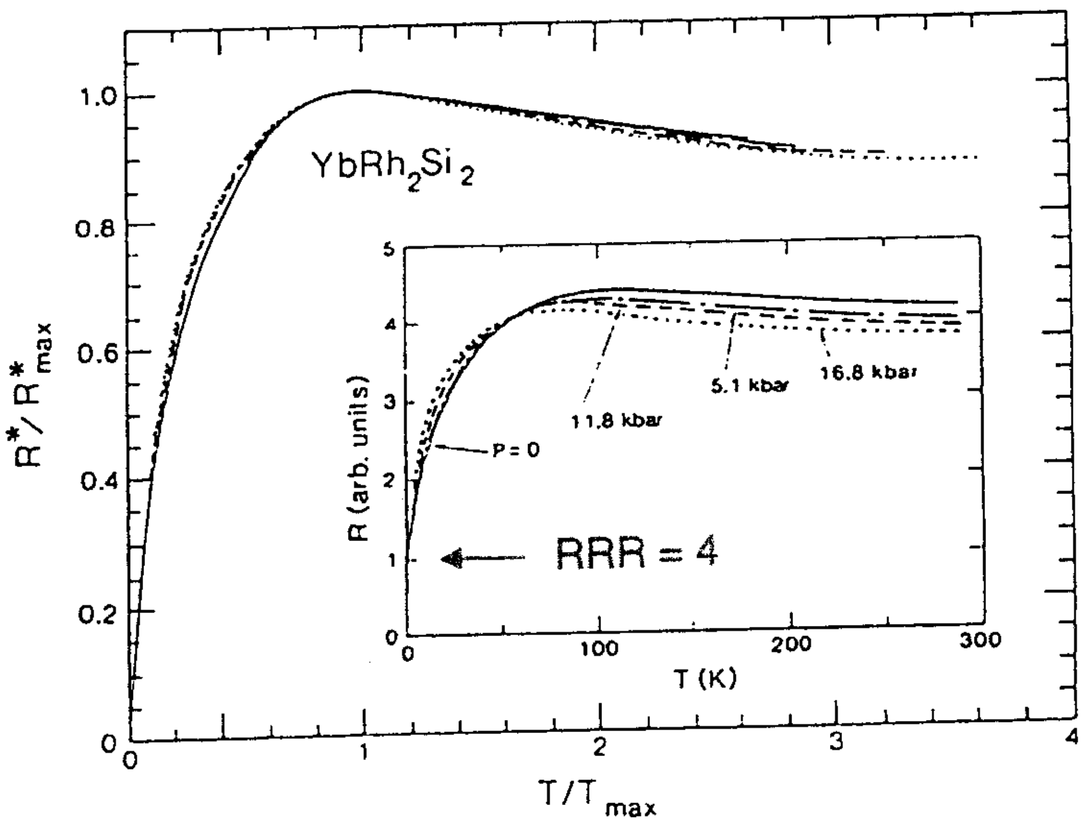
$YbRh_2Si_2$

Crystal Structure

- $ThCr_2Si_2$-type (*I4mmm*)
- a = 4.0073 Å, c = 9.8581 Å



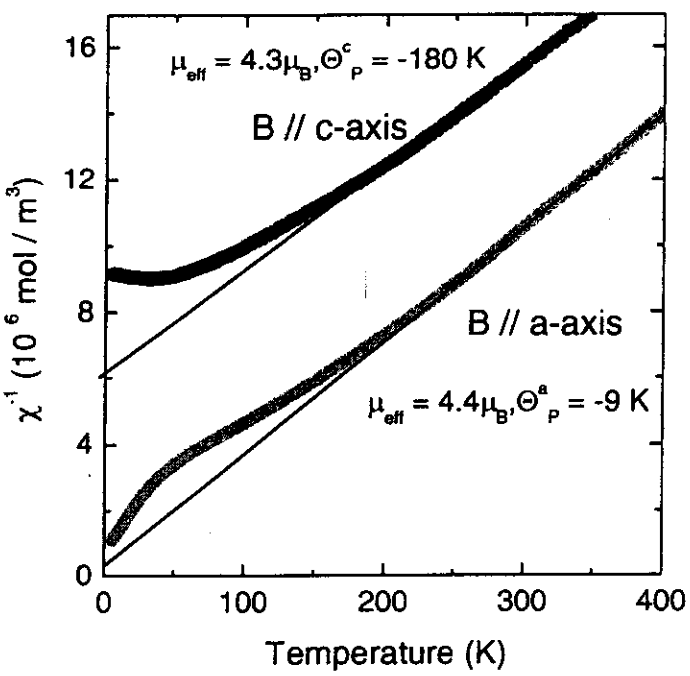
First Results:



J. D. Thompson et al. (1987) Bangalore Conference, India

$YbRh_2Si_2$ - Magnetic properties (p=0)

Magnetic Susceptibility - Magnetization

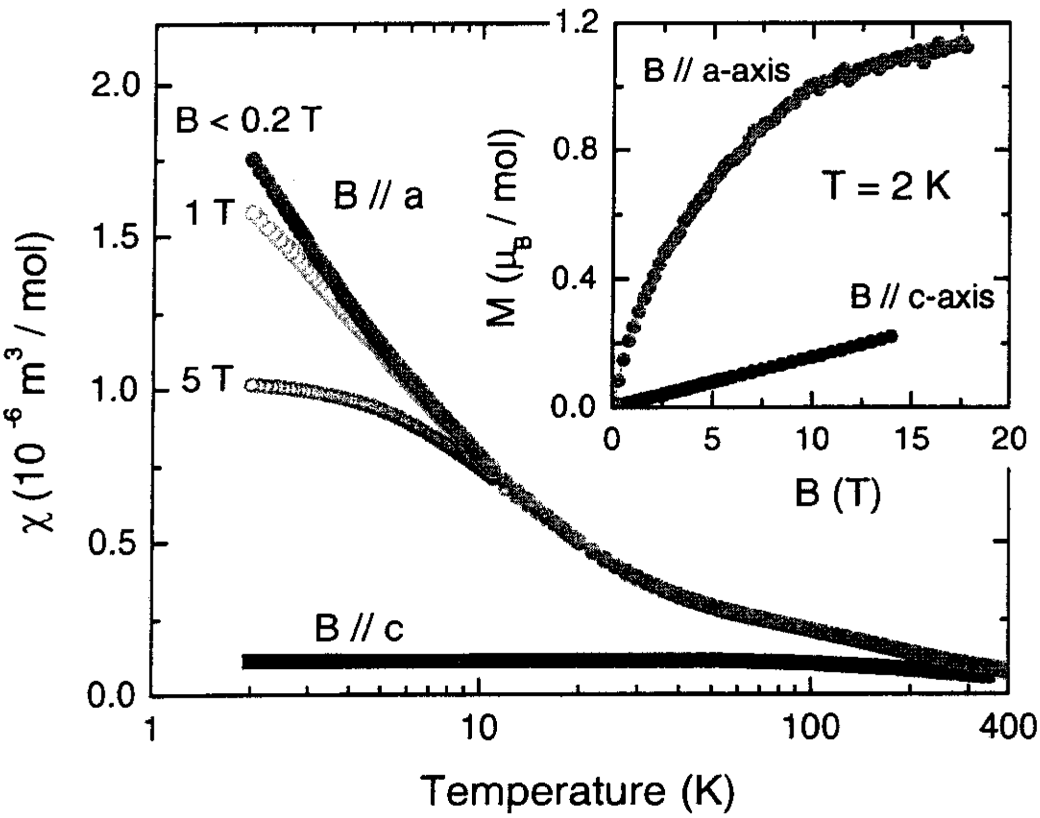


- Yb^{3+} moments at high temperature:

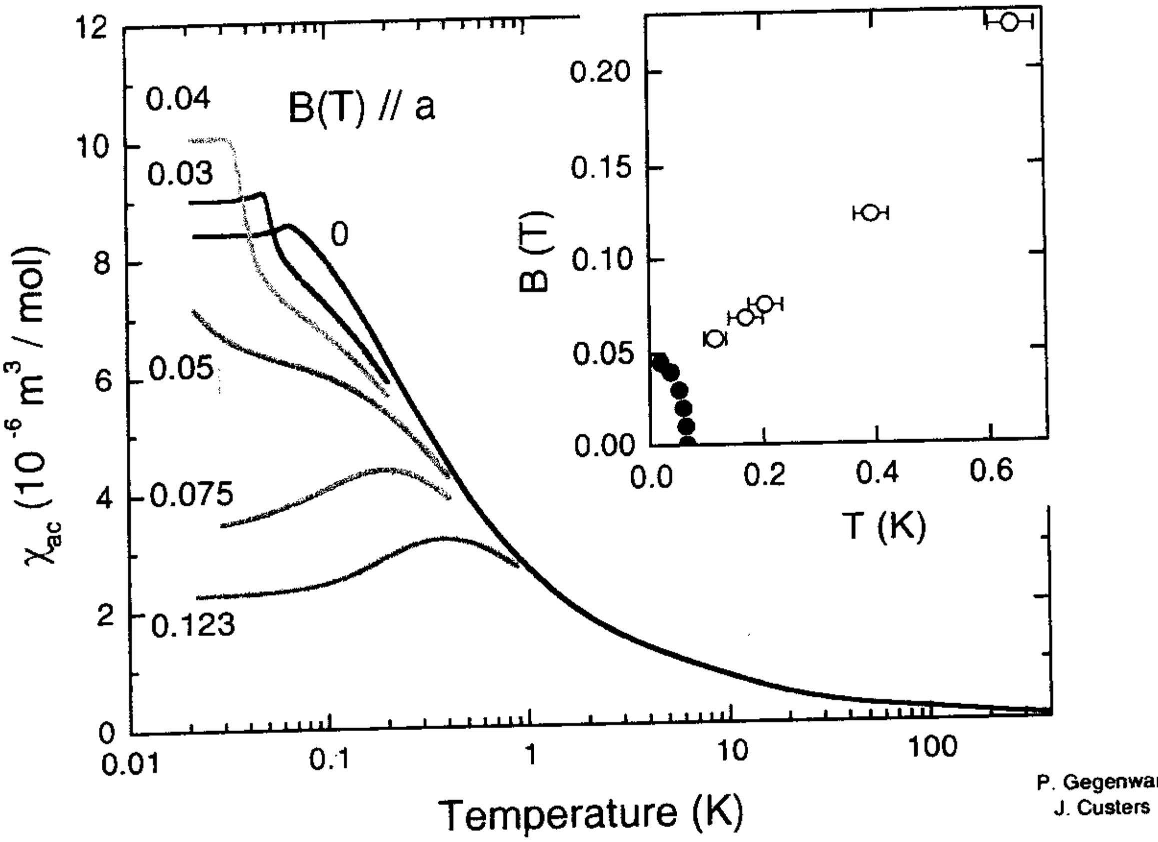
  (Yb^{3+}: $\mu_{eff} \approx 4.5\ \mu_B$)
- Strong single-ion anisotropy:

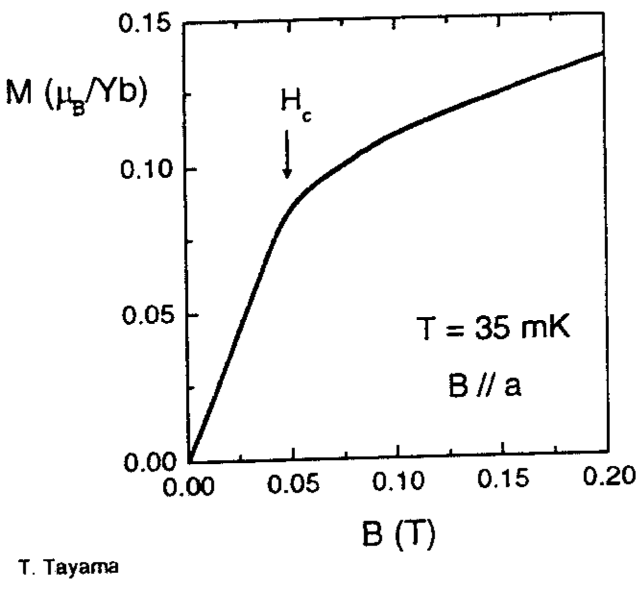
  $\chi_a/\chi_c \approx 20$ (T = 2 K)
- Moments form an "easy-plane" square lattice
- No metamagnetism up to

  B = 15 T (T = 2 K)



Low-Temperature Magnetic Susceptibility and Magnetization

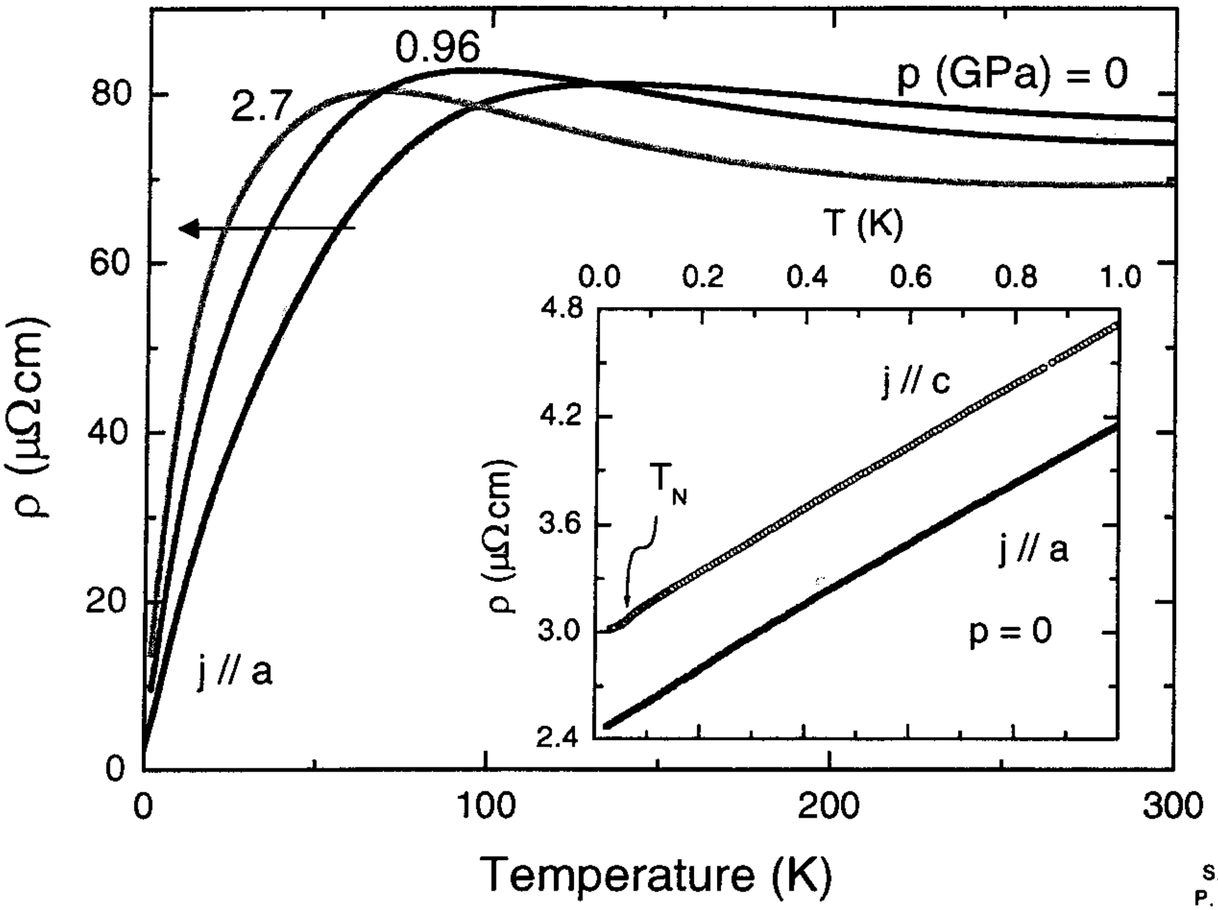




- Weak AF-like anomaly at $T_N \approx 65$ mK
- Critical field: $H_c \sim 450$ Oe
- Low moments involved: $m \approx 0.1\ \mu_B$

NFL effects at ambient pressure in $YbRh_2Si_2$

Electrical resistivity



S. Mederle,
P. Gegenwart
P. Hinze

- At p = 0:

Typical behavior of Heavy-Fermion compounds, but

$$\rho(T) = \rho_0 + bT^{\varepsilon},\ \varepsilon \sim 1 \qquad \text{for } T > T_N$$

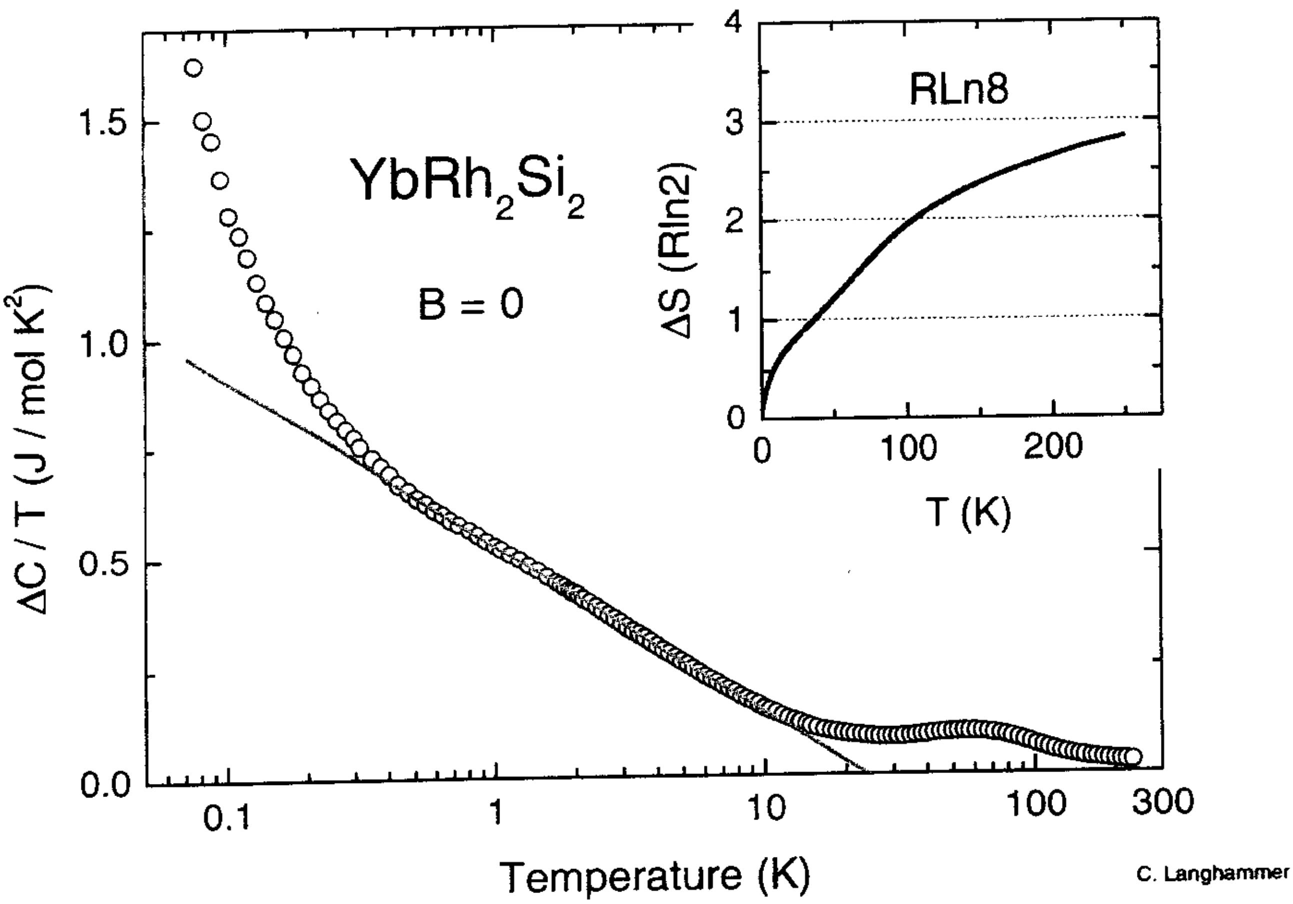
- For p > 0:

+ Drop in ρ(T) steeper and shifts to lower T
+ A maximum develops below 100 K

- Pressure dependence of ρ opposite as that of typical Ce-based heavy-fermions

NFL effects at ambient pressure in $YbRh_2Si_2$

Specific heat (B=0) $\Delta C = C_{YbRh_2Si_2} - C_{LuRh_2Si_2}$



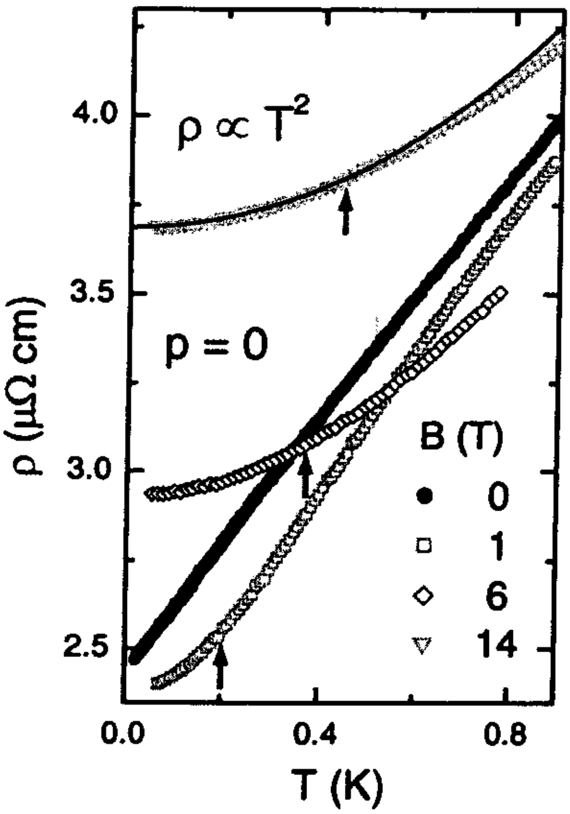
- $T < 10$ K: $\Delta C/T = \gamma_0' \ln(T_0/T)$, ($\gamma_0' = 0.17$ J/mol K^2, $T_0 \sim 25$ K)
- Entropy gain $\Delta S = \int \Delta C/T \, dT$:

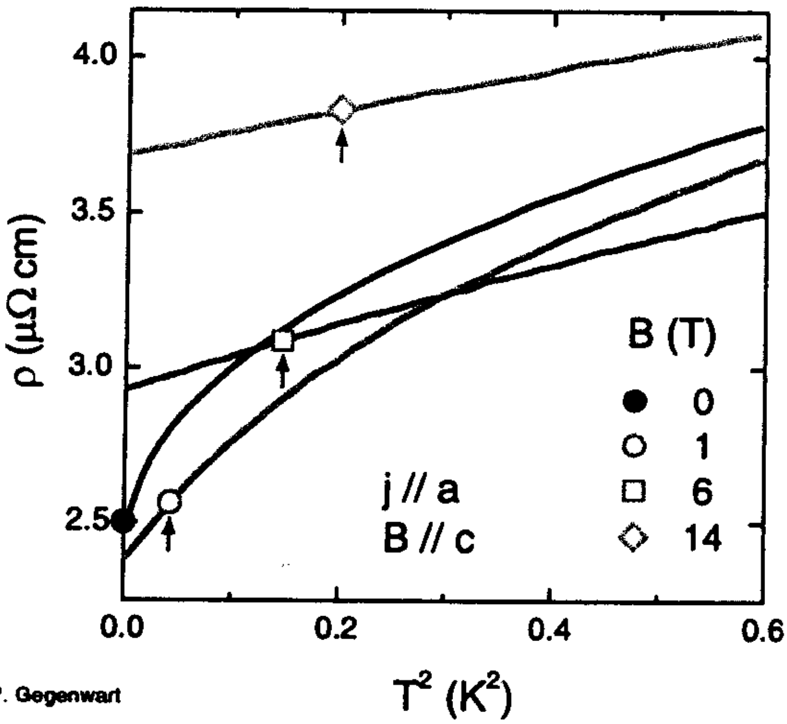
  $T = 10$ K: $\Delta S = 0.45$ Rln2 $\Rightarrow$ $T_K \approx 20\text{-}30$ K

  $T = 300$ K: $\Delta S \to$ Rln8 (4 doublets, $J = 7/2$)

Effect of applied magnetic field (p = 0)

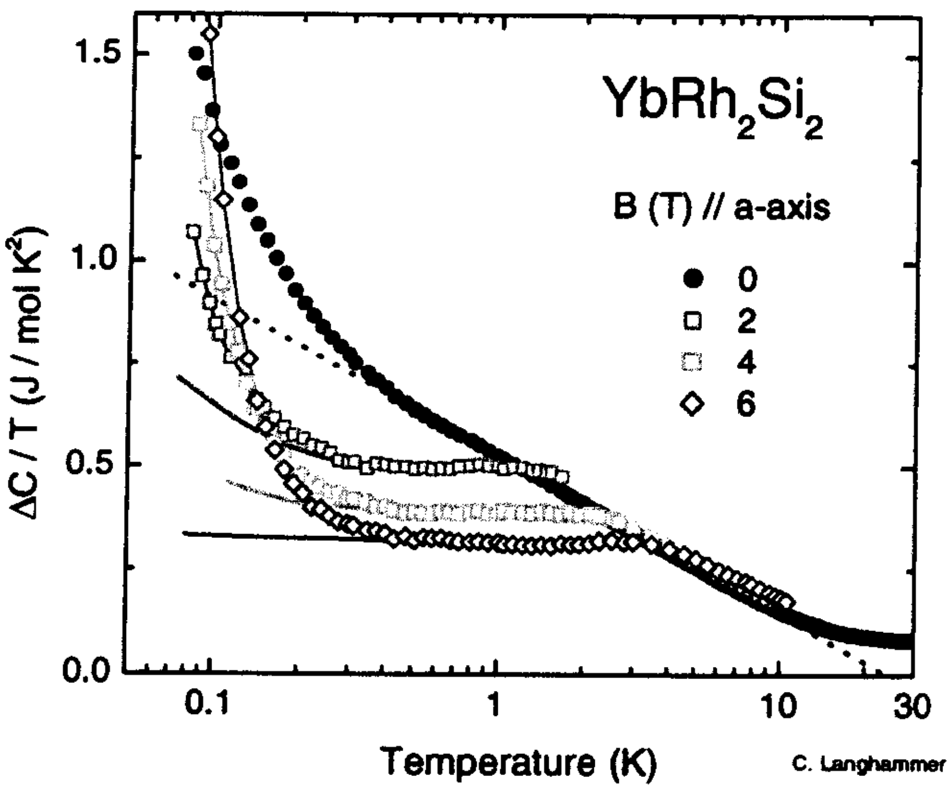
Electrical resistivity: $\rho \propto T^2$ law gradually recovered with $B > 0$





P. Gegenwart

Specific heat



C. Langhammer

- For $B = 0$:

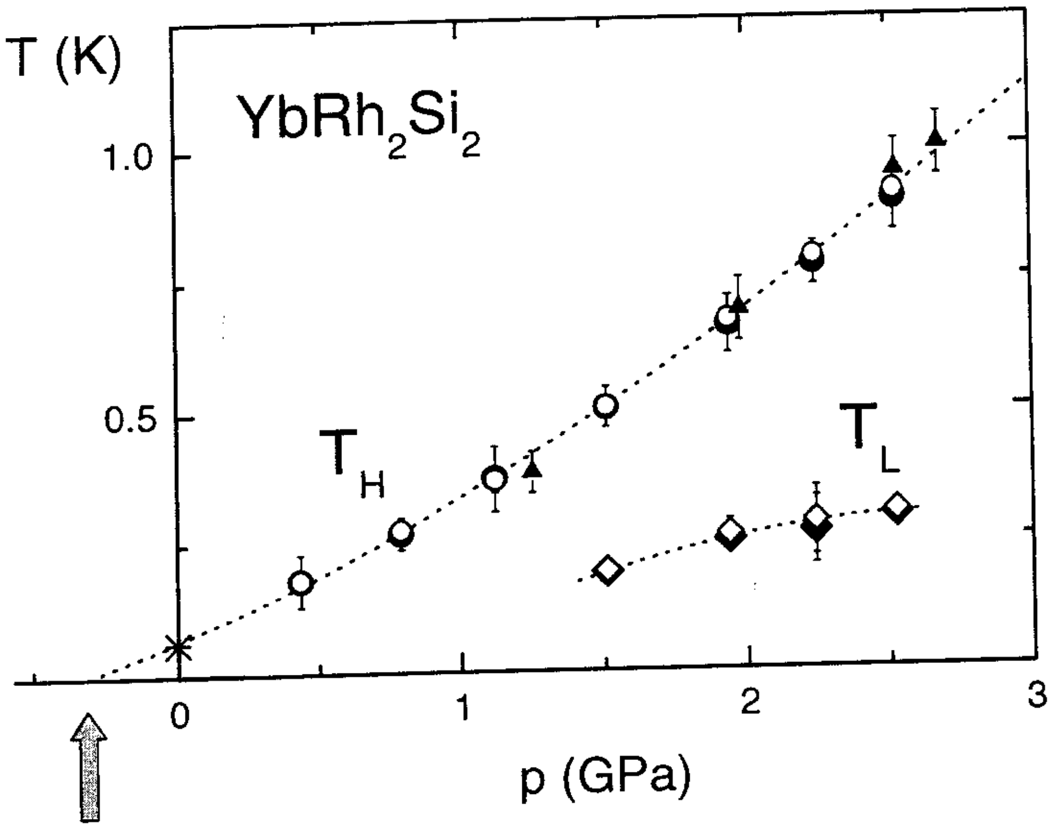
  $\Delta C/T = \gamma_0' \ln(T_0/T)$

- For $B > 0$:

  $\Delta C/T = \gamma_0 = \text{constant}$

- Response for $B > 0$ resembles, e.g., $CeCu_{6-x}Au_x$, $CeNi_2Ge_2$

Temperature-Pressure Phase Diagram of $YbRh_2Si_2$



S. Mederle
M. Grosche

$p_c \approx -0.3$ GPa

- Bulk Modulus: $B_o = (130 \pm 20)$ GPa ⇒

Tiny volume change
$\Delta V \approx +0.3\%$

$YbRh_2Si_2$ is situated at $p = 0$ very close to a magnetic QCP

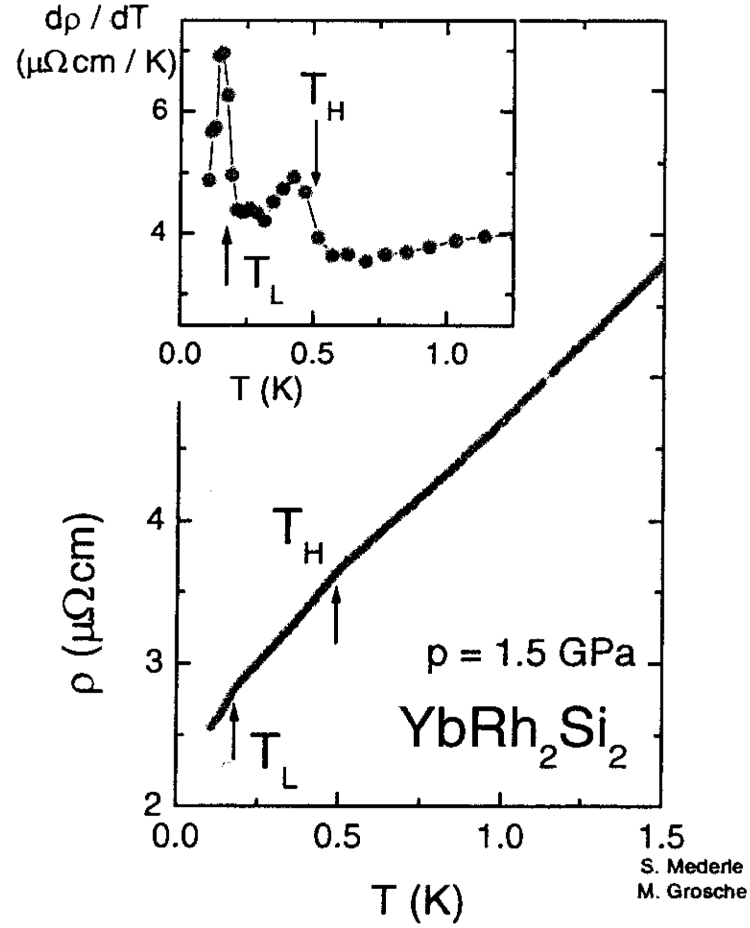
Effect of hydrostatic pressure (B = 0)

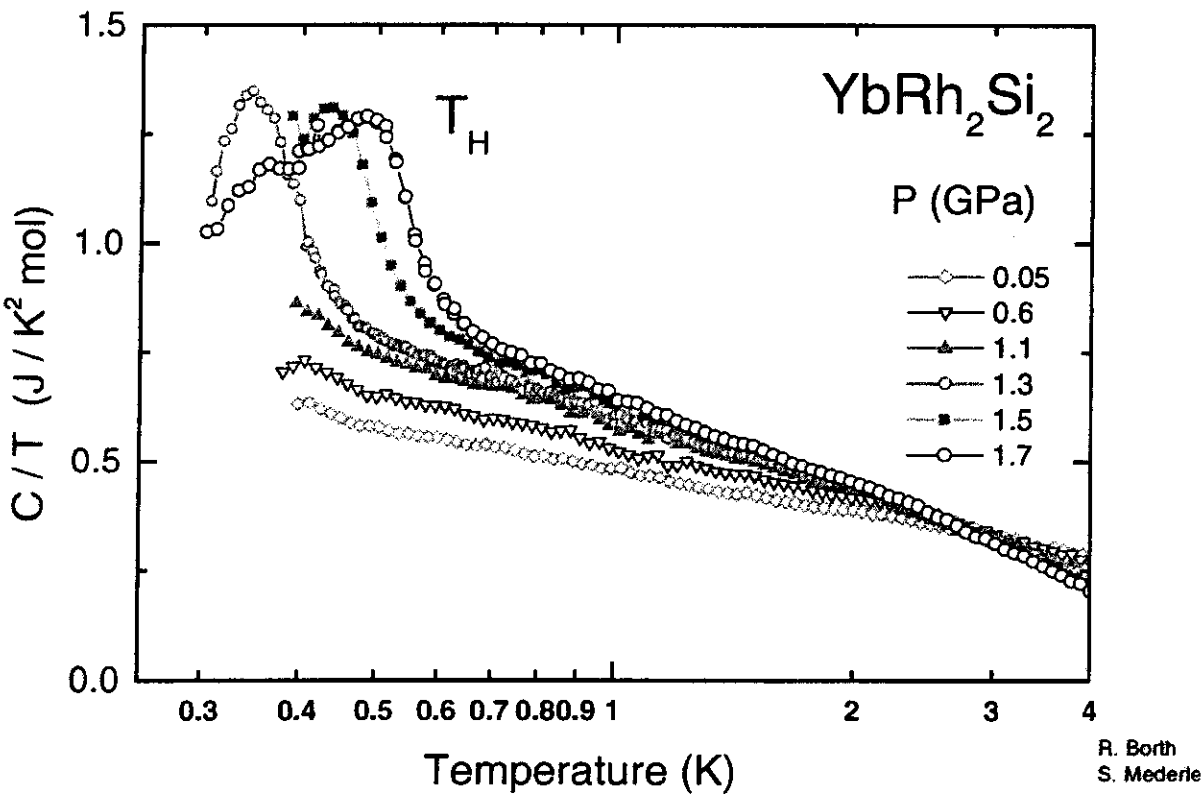
Electrical resistivity & Specific heat

- Anomalies in
  $\rho(T)$ at T_H and T_L

  C/T at T_H

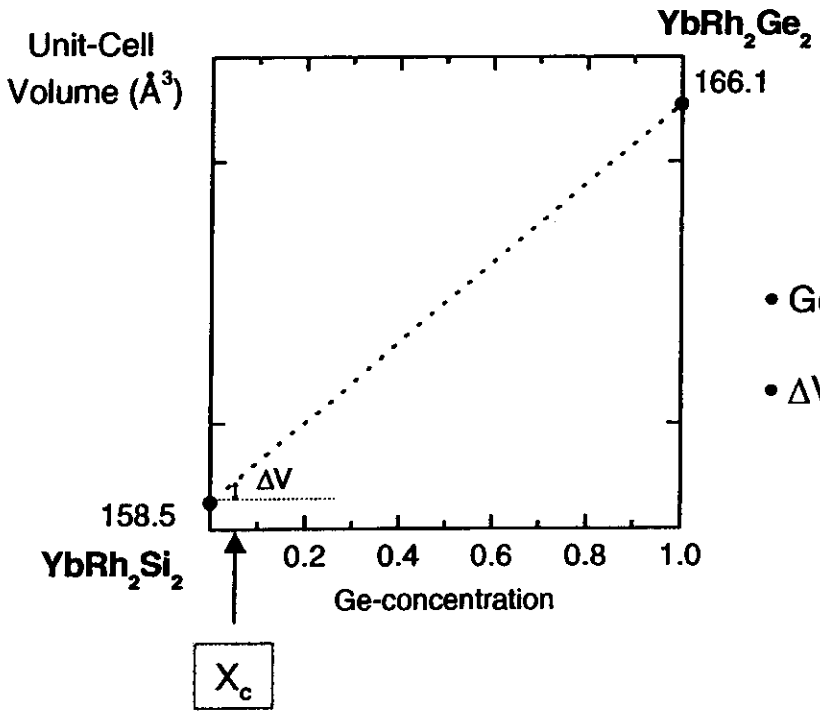
- $T > T_H$:
  $\rho(T) \propto T^{\varepsilon}$, $\varepsilon \sim 1$
  $C/T \propto -\ln(T)$





Fine-tuning of the QCP in $YbRh_2Si_2$

Doping with Ge: $YbRh_2(Si_{1-x}Ge_x)_2$



- Ge-doping expands the lattice
- $\Delta V \approx 0.3\%$ corresponds to:

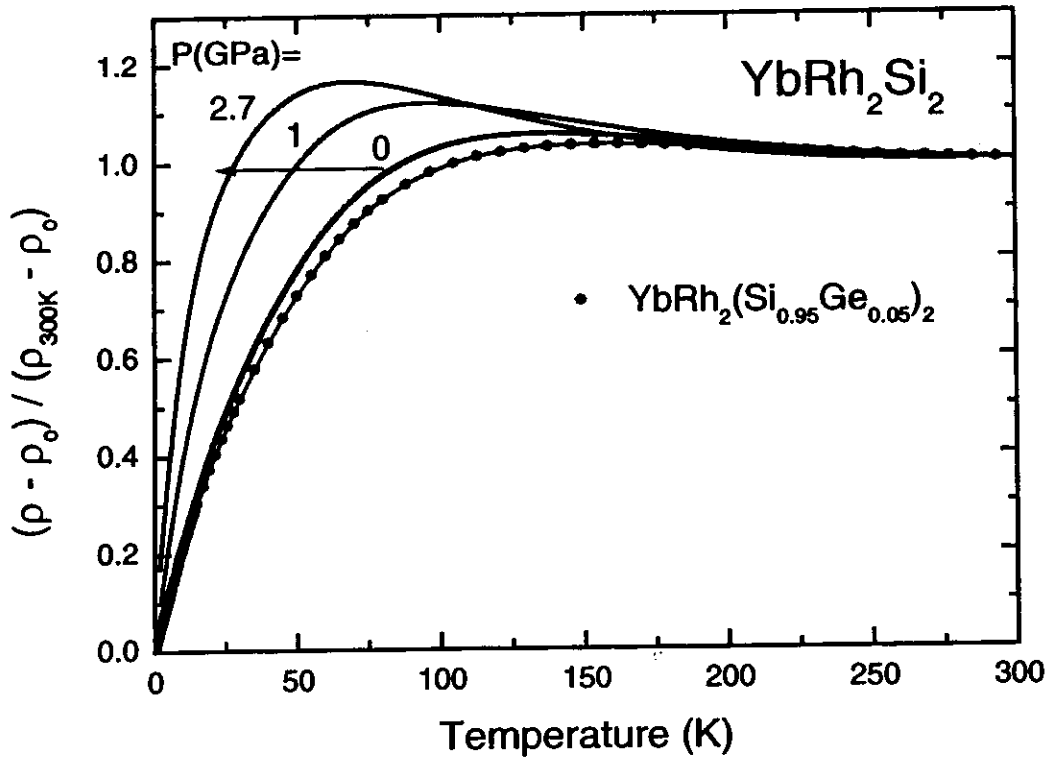
$X_c = (6 \pm 1)$ at.%-Ge

⇓

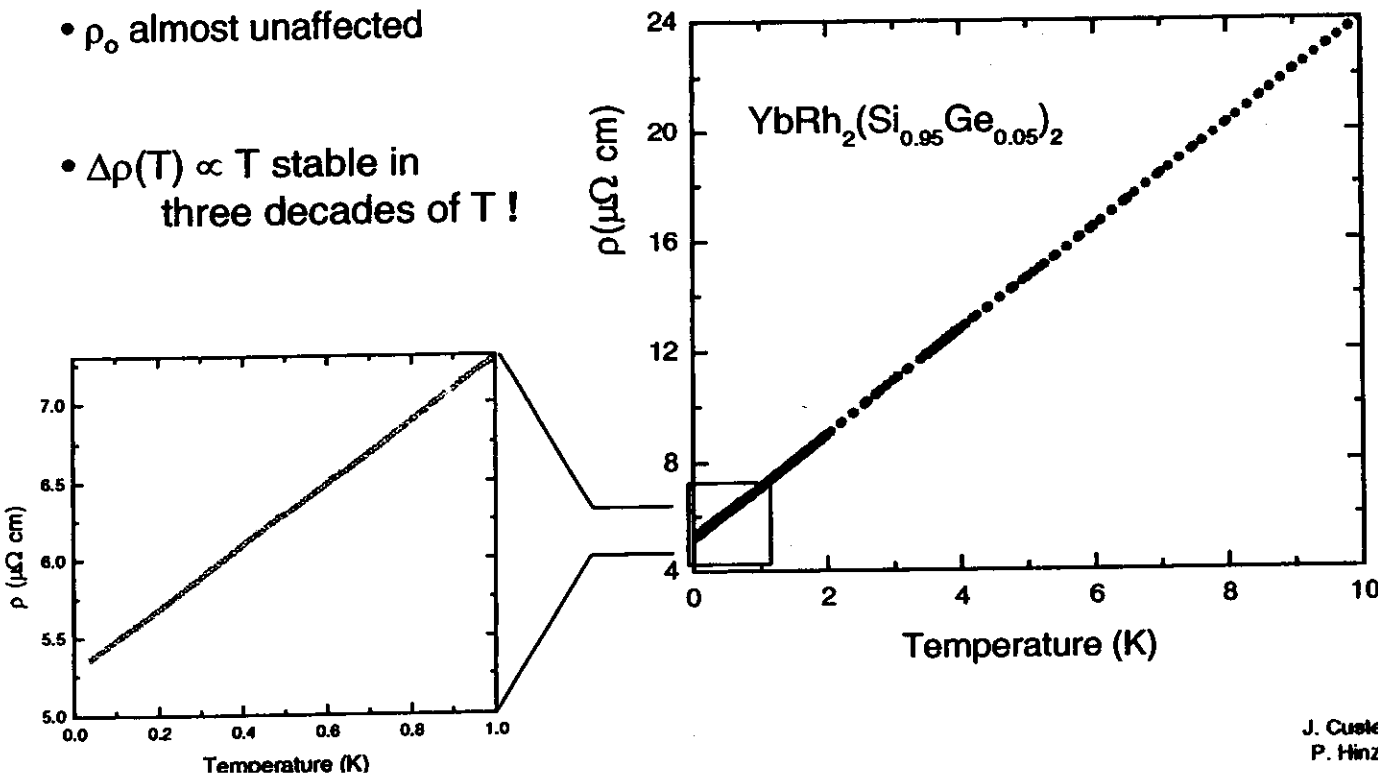
First attempt : $YbRh_2(Si_{0.95}Ge_{0.05})_2$

Hydrostatic pressure vs Ge-doping in $YbRh_2Si_2$

Electrical resistivity:



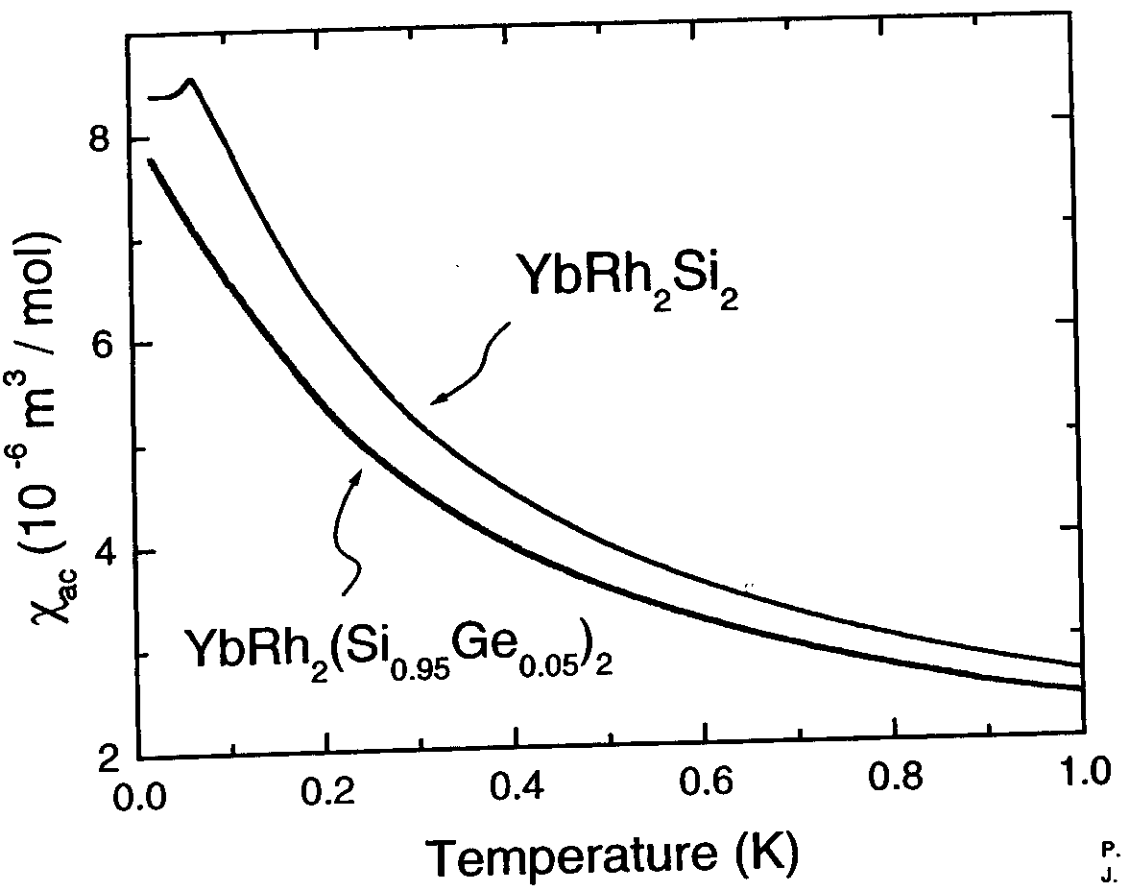
- Ge-doping : opposite effect as pressure
- Characteristic temperature slightly *increases*
- ρ_o almost unaffected
- $\Delta\rho(T) \propto T$ stable in three decades of T !



J. Custers
P. Hinze

Effect of Ge-doping in $YbRh_2Si_2$

Low-Temperature Magnetic Susceptibility



P. Gegenwart
J. Custers

- No indication of a phase transition down to 10 mK
- No Curie-Weiss type: $\chi(T) = C/(T-\Theta_P)$

$YbRh_2Si_2$: Summary

- First **stoichiometric** Yb-based compound showing NFL effects *already* at $p = 0$, $B = 0$

- $\Delta\rho \propto T$, $\Delta C/T \propto -\ln T$ in a large temperature-range

- Similarities to $CeCu_{6-x}Au_x$: quasi-2D magnetic fluctuations?

- Quantum critical behavior in an extended region of the phase diagram

Useful References

- First Reference about $YbRh_2Si_2$: J.D. Thompson et al., in Thoeretical and Experimental Aspects of Valence Fluctuations and Heavy Fermions, edited by L. C. Gupta and S.K. Malik (Plenum Press, NY, 1987), p. 151.

- About $YbRh_2Si_2$: O. Trovarelli et al., PRL 85 , 626 (2000), and references therein; Mederle et al. Proceedings SCES 2000, Recife.

- Magnetically mediated superconductivity in heavy fermion compounds. Mathur et al., Nature **394**, 39 (1998).

- $CeNi_2Ge_2$: P. Gegenwart et al., Phys. Rev. Lett. 82, 1293 (1999),
  F. M. Grosche et al., preprint, cond-mat/9812133,
  S. Koerner et al., J. Low Temp. Phys. 119, 147 (2000),
  D. Braithwaite et al. J. Phys. Condens. Matter 12, 1339 (2000).

- Recent paper about $CeCu_2Si_2$: P. Gegenwart et al., Phys. Rev. Lett. 81, 1501 (1998).

- $CePd_2Si_2$: S. Raymond and D. Jaccard, Phys. Rev. B. 61, 8679 (2000) and
  Nature paper of Mathur et al. (see above)

- $CeCu_{6-x}Au_x$: A. Schroeder et al. to be published
  H. v. Loehneysen, J. Phys.: Cond. Matter 8, 9689 (1996);
  O. Stockert et al., PRL 80, 5627 (1998).

- Bulk Modulus of related Yb-based compounds: Winkelmann et al., PRB 60, 3324 (1999).

- Problems with sample preparation: Z. Fisk and M.\,B. Maple, J. Alloys Comp. 183, 303 (1992); P.\,C. Canfield and Z. Fisk, Philos. Mag. B 70, 1117 (1992).

- $YbCu_{5-x}Al_x$, E. Bauer et al., Phys. Rev. B 60, 1238 (1999).

- Pressure experiments on $YbCu_2Si_2$, Yb_2Ni_2Al, YbCuAl: See PRL about $YbRh_2Si_2$.

- $CeRu_4Sb_{12}$, UBe_{13}: See PRL about $YbRh_2Si_2$.