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XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

Non-Fermi-Liquid Behavior and Superconductivity in the Heavy-Fermion Compounds $CeCu_2Si_2$ and $CeNi_2Ge_2$

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„Strongly Correlated Electron Systems"

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Non-Fermi-Liquid behavior and superconductivity in the heavy-fermion compounds $CeCu_2Si_2$ and $CeNi_2Ge_2$

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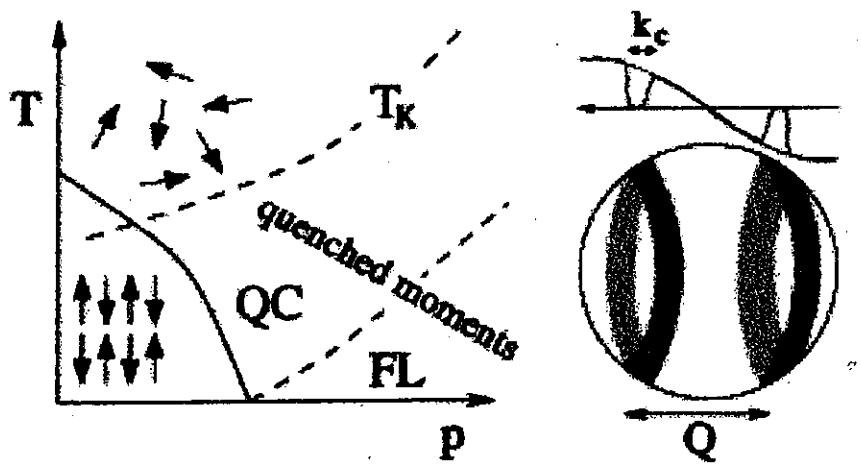
- motivation
- $CeCu_2Si_2$: interplay of SC and phase "A"
  NFL behavior at $T_A \rightarrow 0$
- $CeNi_2Ge_2$: NFL behavior and incipient SC
  in a very clean system
- conclusion

Introduction

Three different scenarios proposed for NFL behavior in HF systems (A. Rosch, Physica B 280, 341 (2000):

i) Scattering of Fermi liquid quasiparticles by strong spin fluctuations near the SDW instability

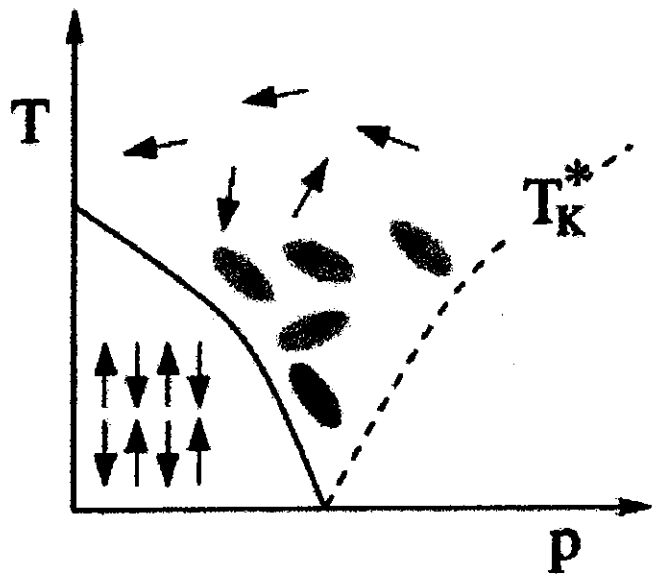


3-dim: (*Hertz,Millis*)

$C/T = \gamma_0 - \alpha T^{1/2}$

$\rho - \rho_0 \sim T^{3/2}$

ii) Breakdown of the Kondo effect due to the competition with the RKKY interaction

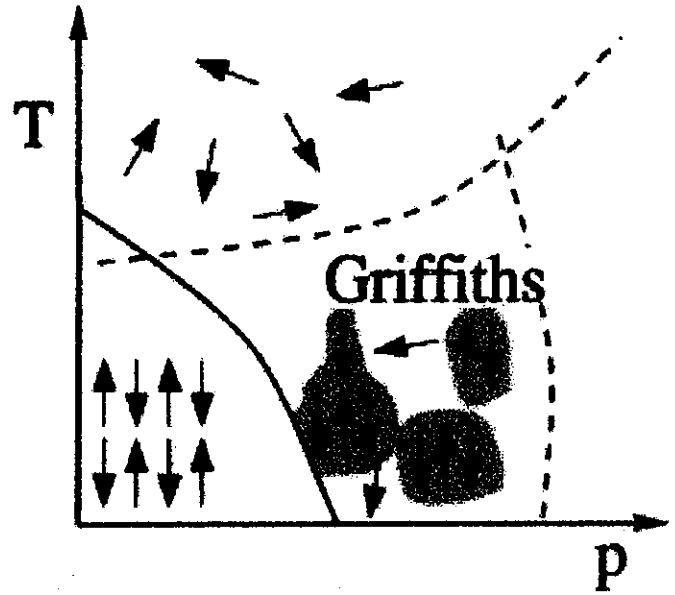


iii) Disorder

$Th_{1-x}U_xPd_2Al_3$,

$Y_{1-x}U_xPd_3$,

$UCu_{5-x}M_x$, ...



Also: distribution of T_K , spin-glass QCP

Two types of materials studied so far:

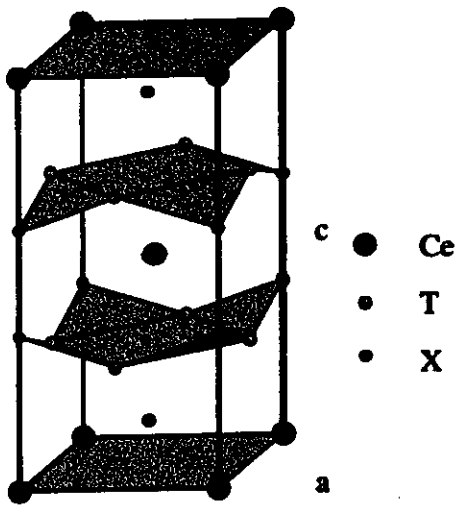
doped HF liquids like $CeCu_{6-x}Au_x$, $Ce_{1-x}La_xRu_2Si_2$,
difficulty: effect of disorder

– pressure experiments on HF antiferromagnets like
$CePd_2Si_2$, Ce_7Ni_3, ... difficulty: C(T) at low-*T*

NFL behavior in stoichiometric HF systems at p=0:
$CeCu_2Si_2$, $CeNi_2Ge_2$, $YbRh_2Si_2$,
UBe_{13}, U_2Pt_2In, $CeRu_4Sb_{12}$ (QCP ?)

Introduction

CeT_2X_2 structure:



HF SC: $CeCu_2Si_2$ (Steglich ´79)

PM HF:

$CeRu_2Si_2$ (Paulsen ´90)

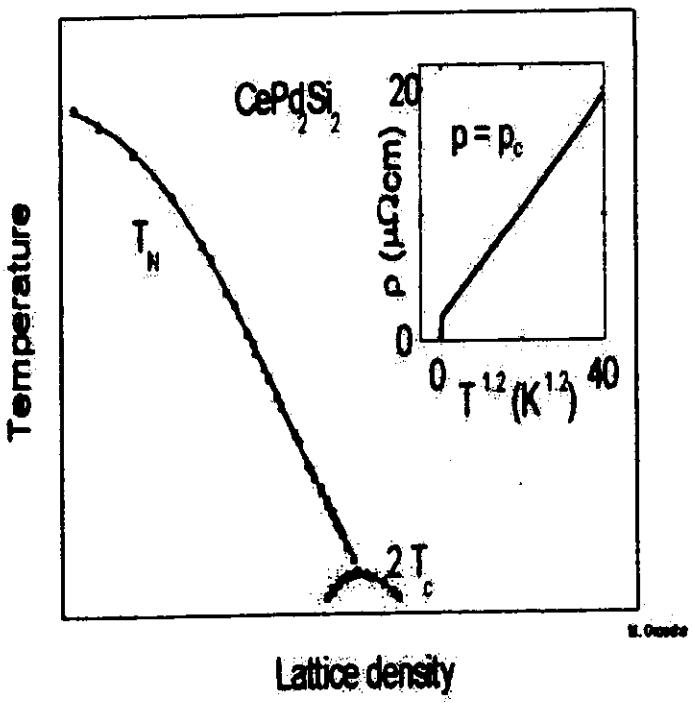
$CeNi_2Ge_2$ (Knopp ´88)

Afm ordered at p=0, HF SC for $p \geq p_c$:

$CeCu_2Ge_2$ (Jaccard ´92,´95)

$CePd_2Si_2$ (Grosche, Julian ´96, Raymond ´2000)

$CeRh_2Si_2$ (Movshovich ´96)

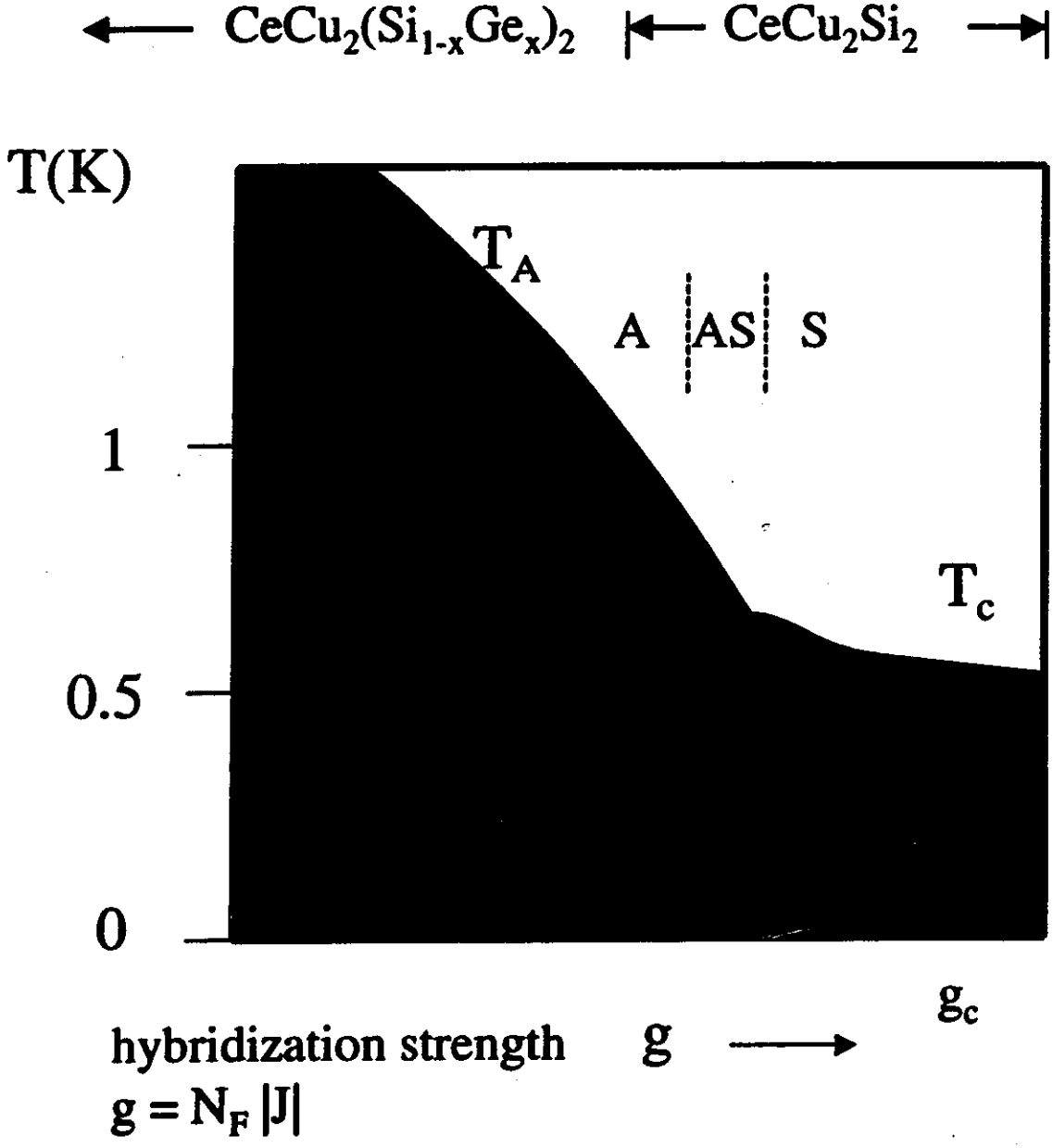


Coexistence of SC with afm around QCP ?

ρ(T) not sufficient !

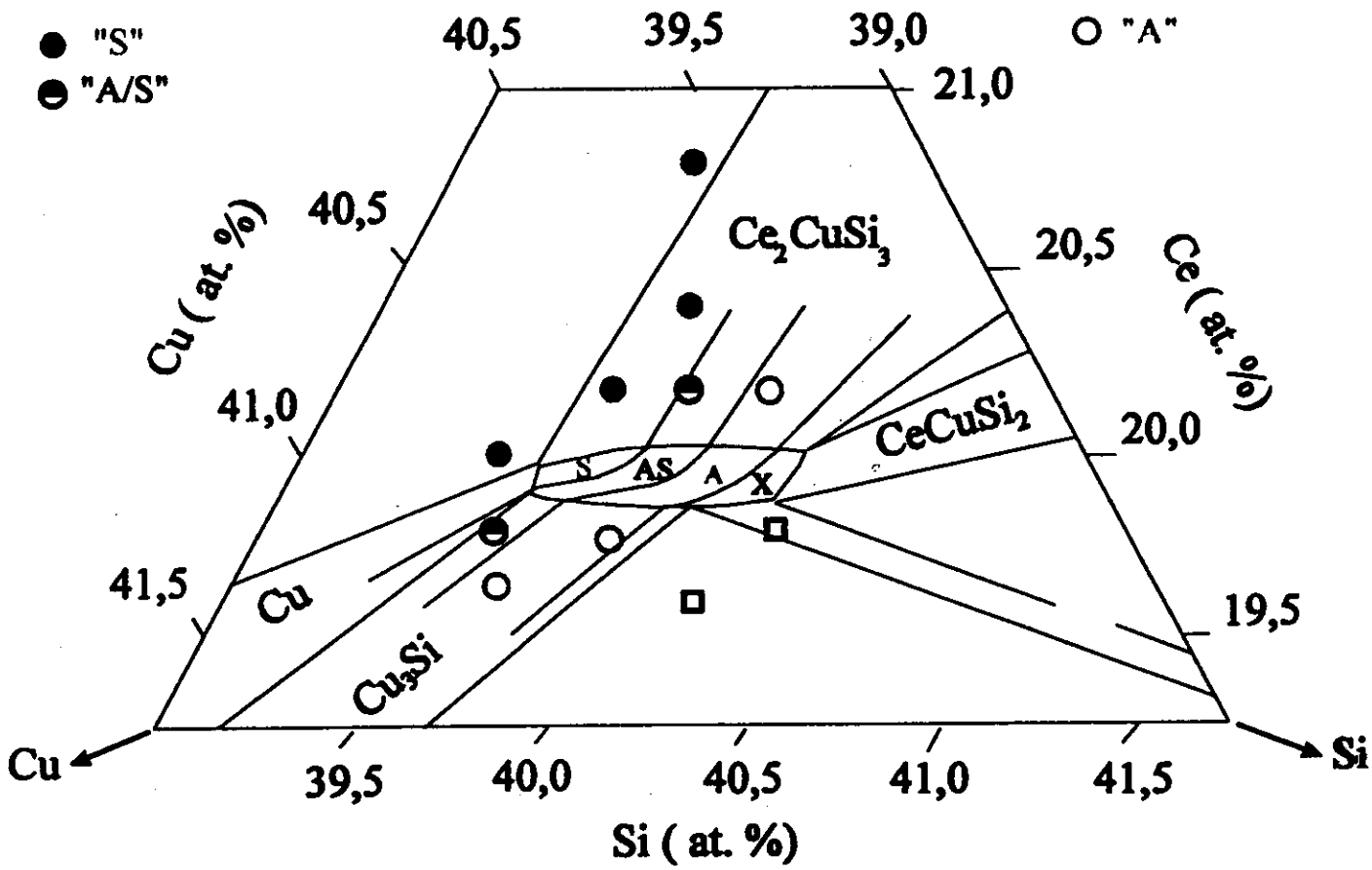
For $CeCu_2Si_2$: study of thermodynamic and microscopic measurements.

Interplay of SC with phase "A"



- High-pressure study (F. Thomas '96):
  SC stable up to p > 100 kbar !
- See also $CeCu_2Ge_2$ (D. Jaccard '97)

ground-state behavior ↔ composition

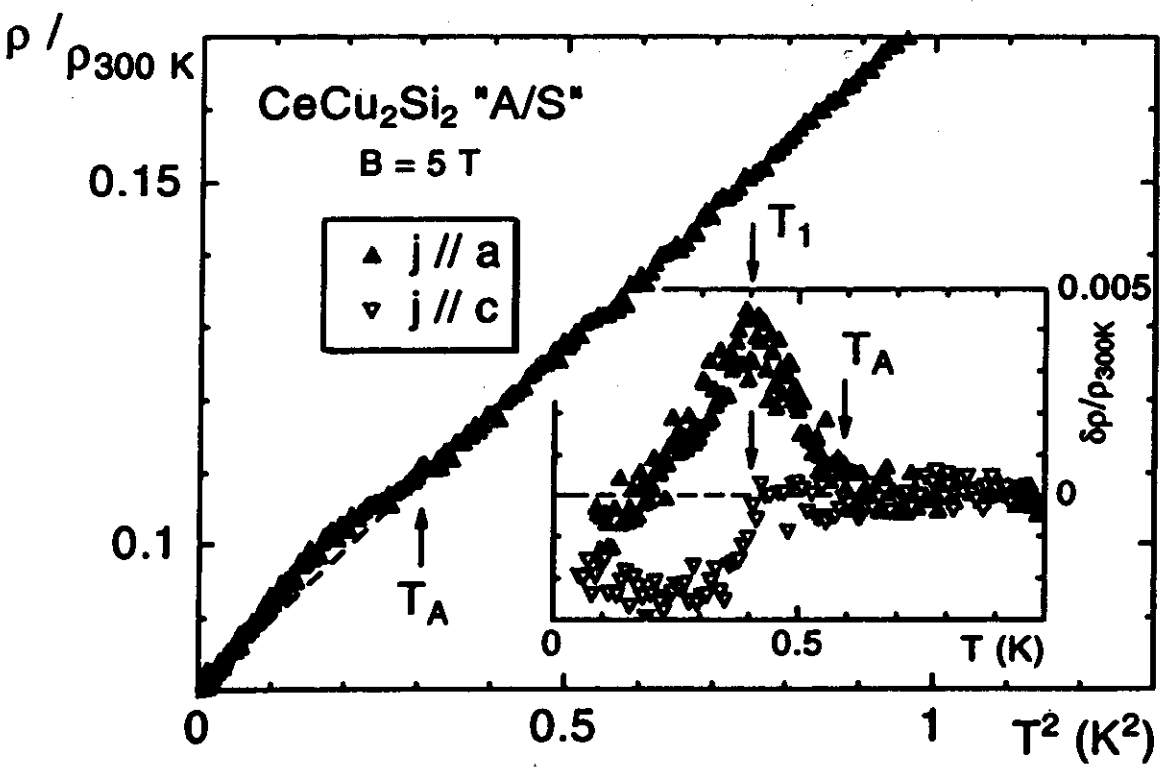


R. Müller-Reisener, C. Geibel '95

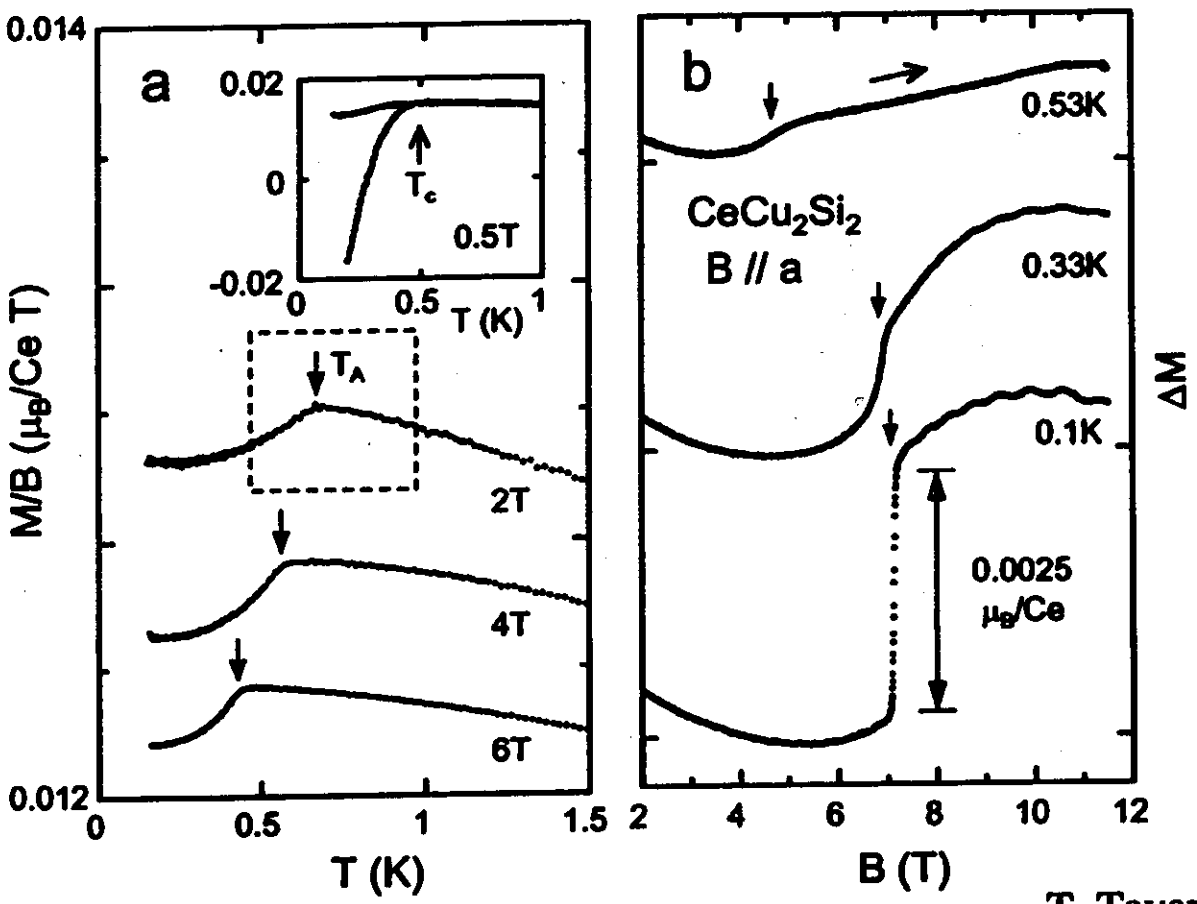
- ground-state behavior (SC and/or magnetic phase "A" depends sensitively on hybridization g between 4f- and conduction electrons
- g can be varied by: - external pressure
  - changes in composition

$CeCu_2Si_2$: phase "A"

- Thermodynamic measurements (C(T),α(T), ...):
  true phase-transition
- NMR: (K. Ishida et al. PRL 82, 5353 (1999)):
  SDW-state oscillating with ν ~ 1 MHz
- Resistivity: SDW (nesting in tetragonal plane)



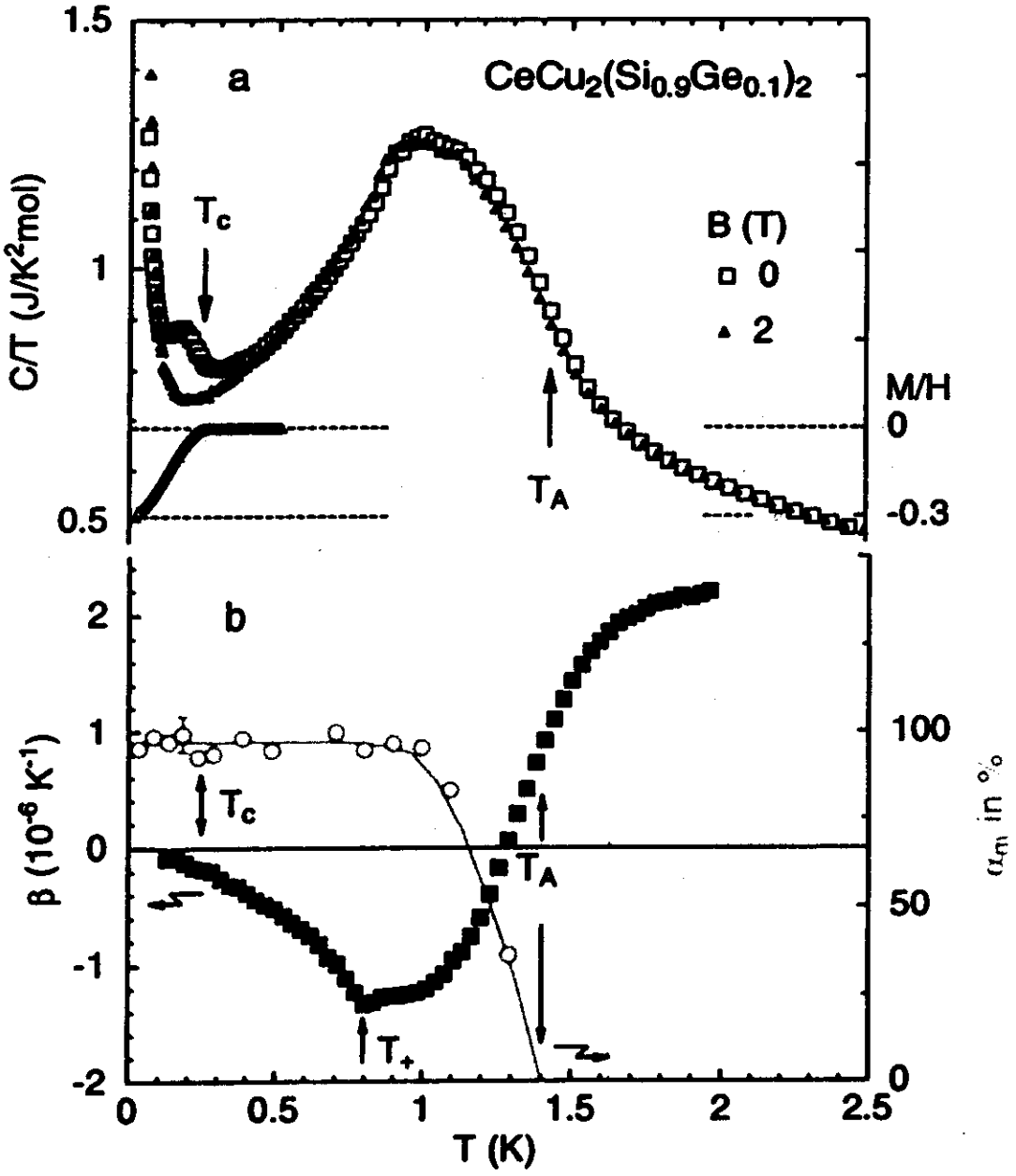
- **Low-T magnetization:**
  - drop at T_A ($\rightarrow$ AFM nature)
  - jump at 7 T: increase of saturation moment of only $2.5 \cdot 10^{-3}\ \mu_B$



T. Tayama '99

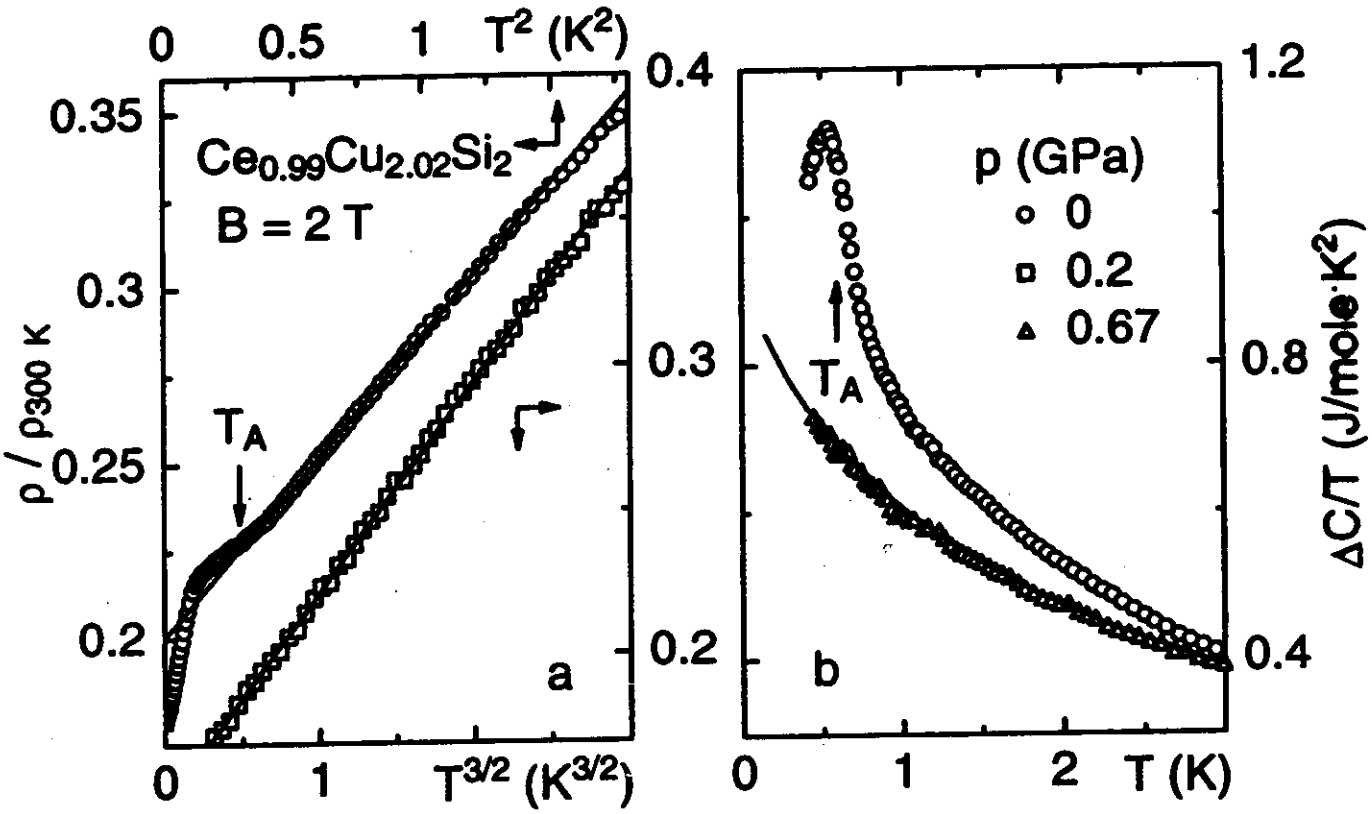
high quality single crystal: W. Assmus '93

Coexistence of weak SC and phase "A"



specific heat: L. Donnevert, C. Langhammer
thermal expansion: M. Deppe
μSR: A. Amato

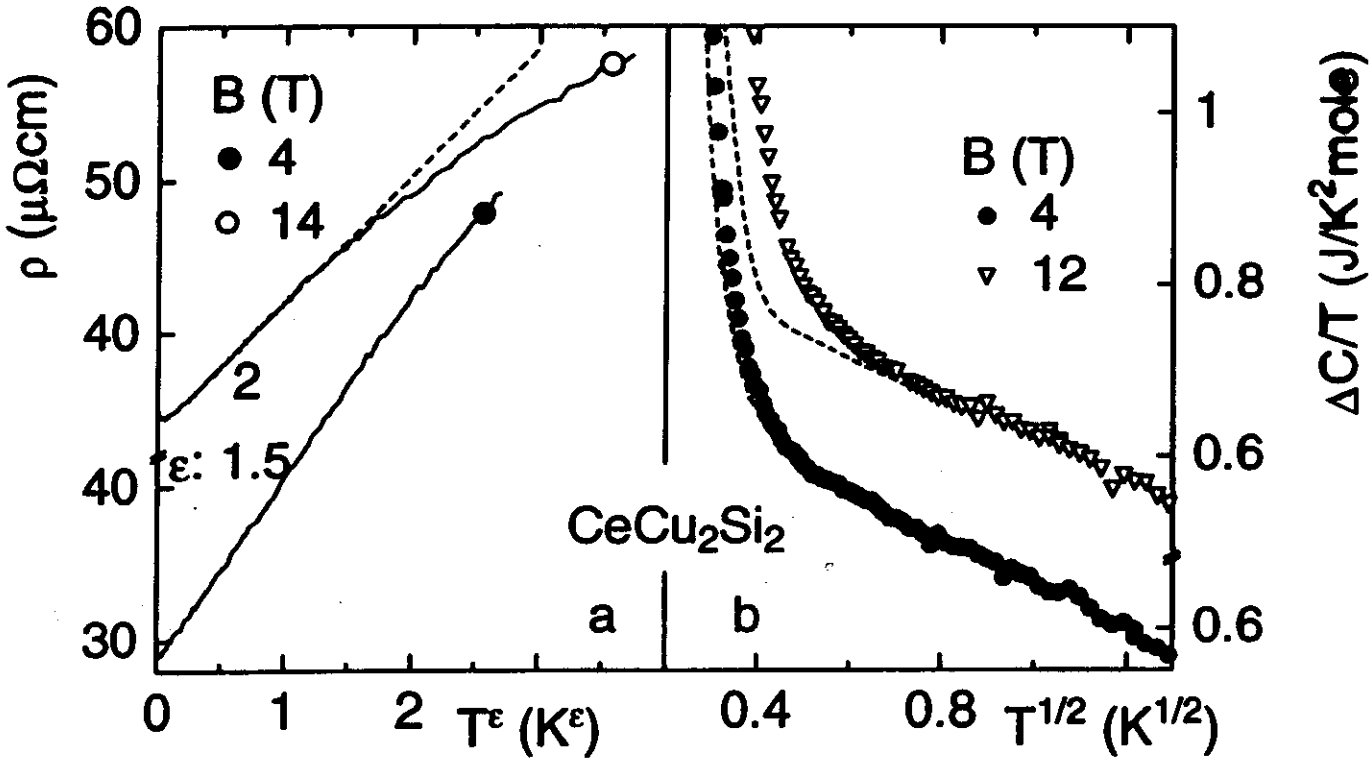
NFL behavior at $T_A \rightarrow 0$



A. Link, P. Gegenwart, P. Hellmann '96

- for $T \geq 0.35K$: behavior expected for 3d-afm QCP

low-T behavior at $T_A = 0$

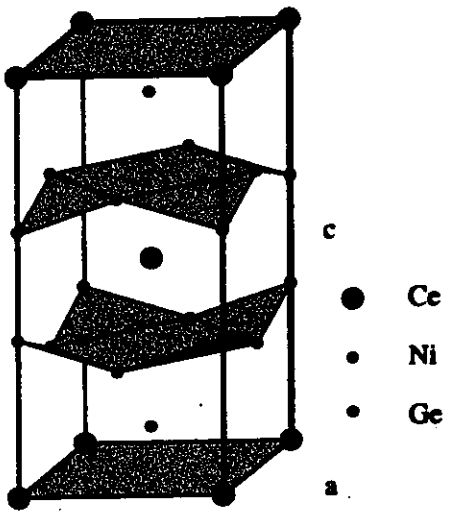


- B = 4T: $\Delta\rho \sim T^{3/2}$ down to 20 mK but strong upturn in C/T which is not due to a quadrupolar and/or Zeeman splitting of nuclear spins.
- B = 12 T: C/T unchanged but FL $\Delta\rho \sim T^2$ behavior in $\rho(T)$.

→ $\Delta\rho$ (charge degrees of freedom) and $\gamma(T)$ (spin degrees) behave very disparately.

→ decoupling of itinerant and local 4f parts out of which the Heavy Fermions are composed !

$CeNi_2Ge_2$: A HF metal near long-range afm order

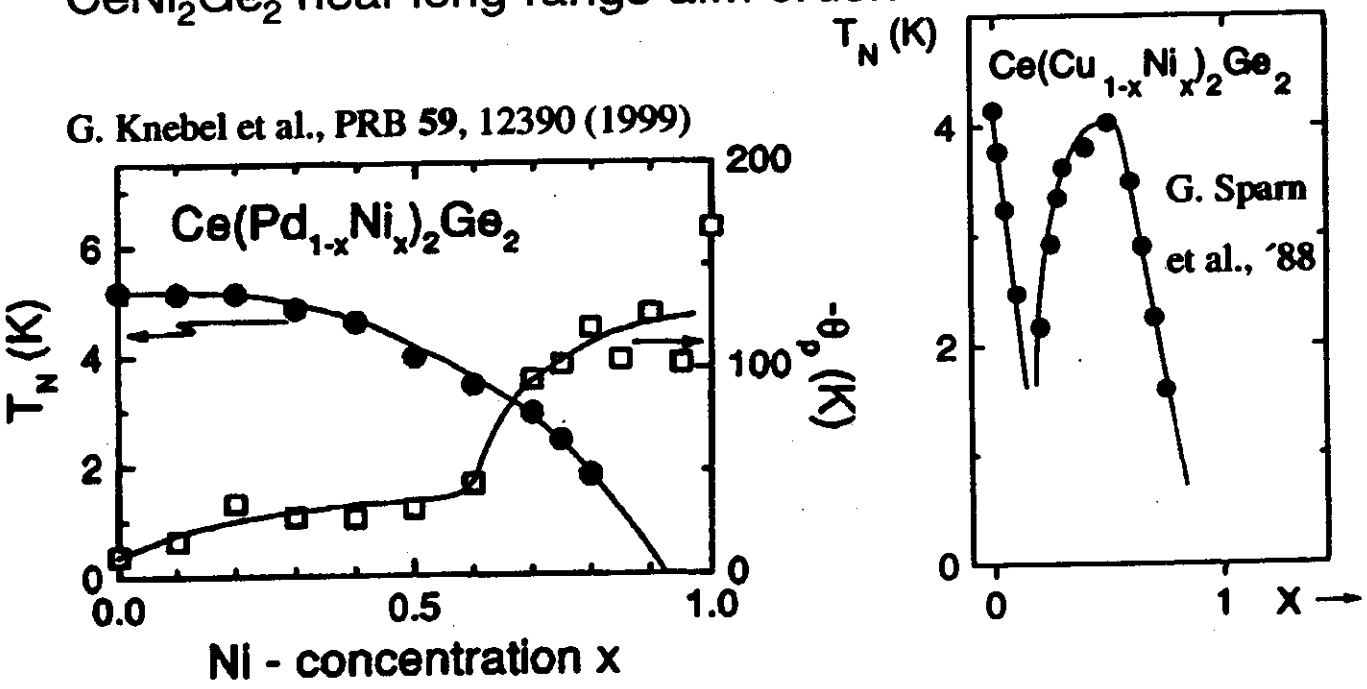


Knopp et al. Z. Phys. B 77, 95 (1989):

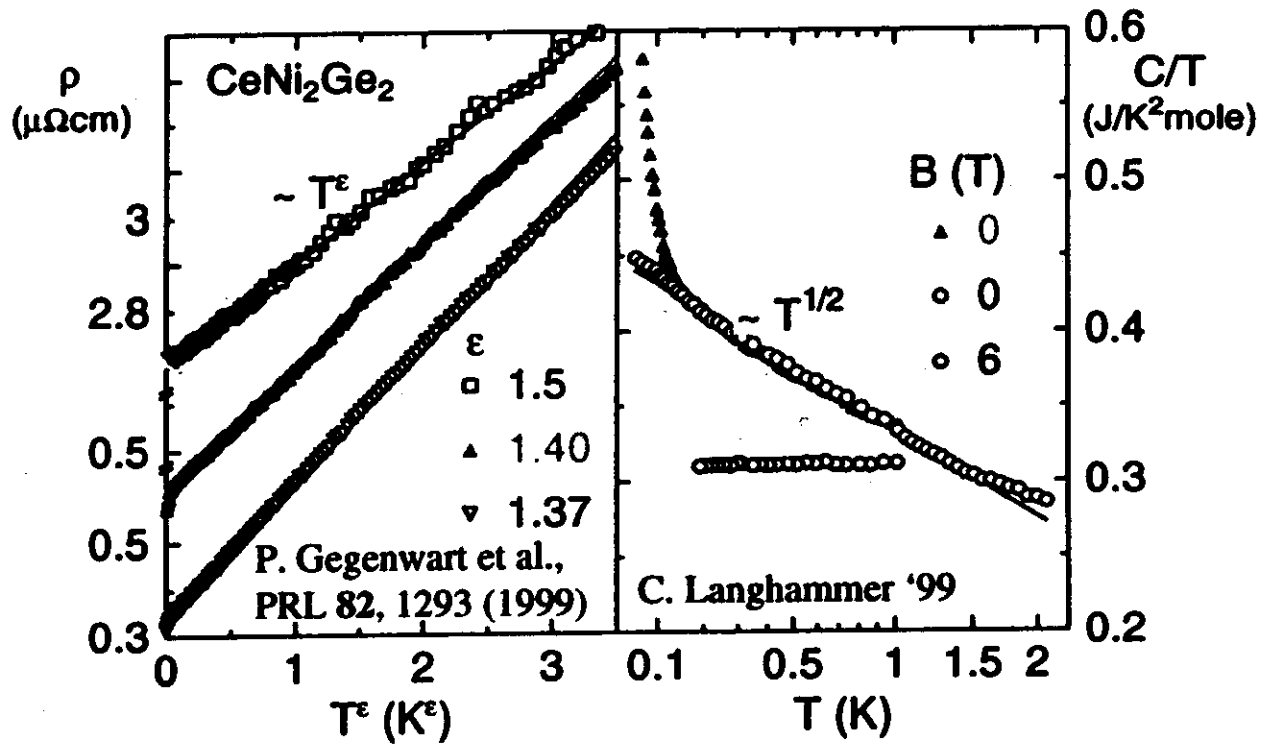
- $\gamma = 0.35$ J/K²mole
- $T_K = 30$ K from specific heat, magnetic relaxation rate (neutron-scattering) and maximum in χ(B//c) [1]
- $B_m = 42$ T for B // c [1]

[1]:Fukuhara et al. '96

$CeNi_2Ge_2$ near long-range afm order:



Non-Fermi-liquid behavior already at p=0



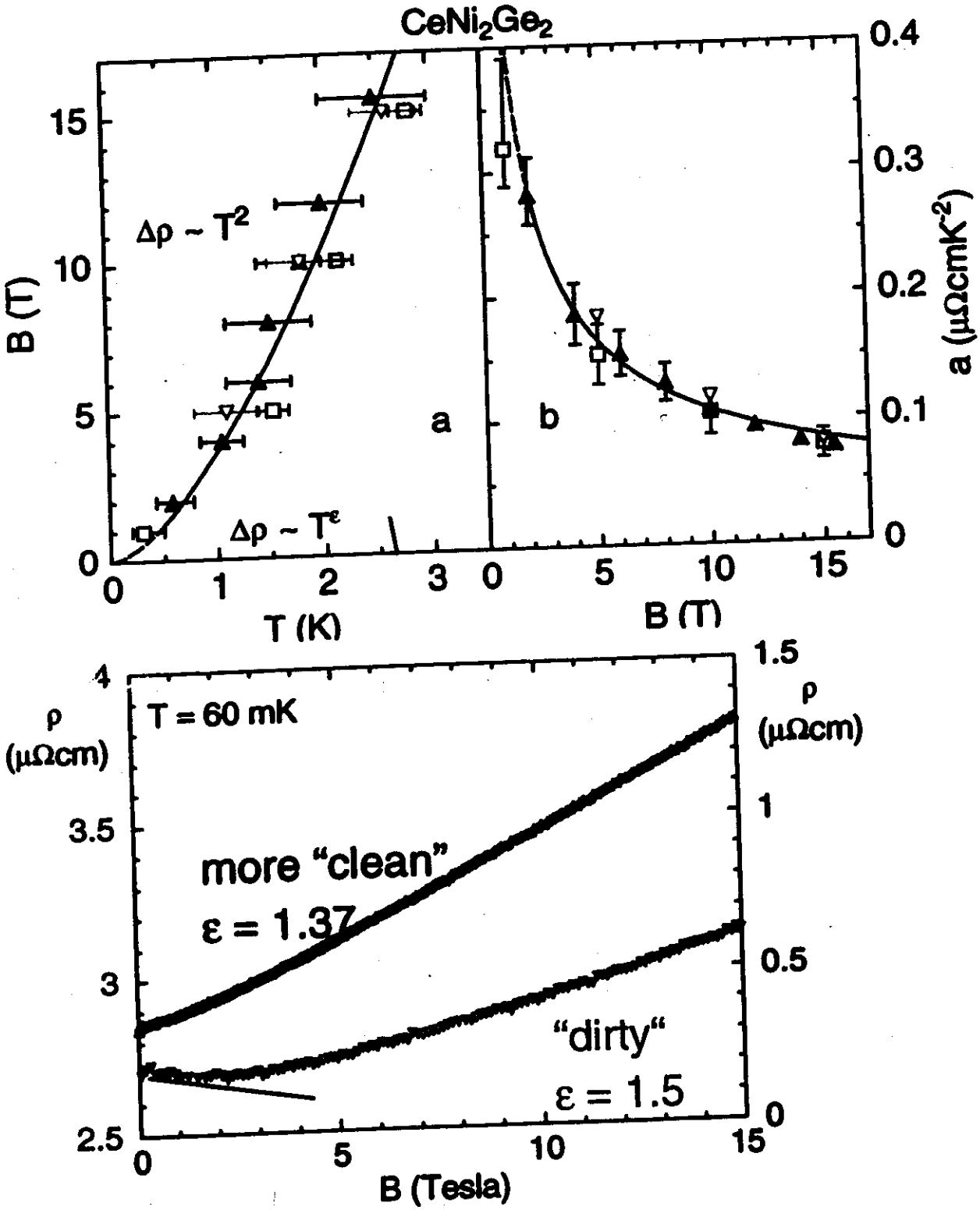
resistivity and specific heat → $CeNi_2Ge_2$ very close to 3D-afm quantum critical point

very clean samples → interplay of disorder and critical spin-fluctuations important (A. Rosch, PRL 82, 4280 (1999)):

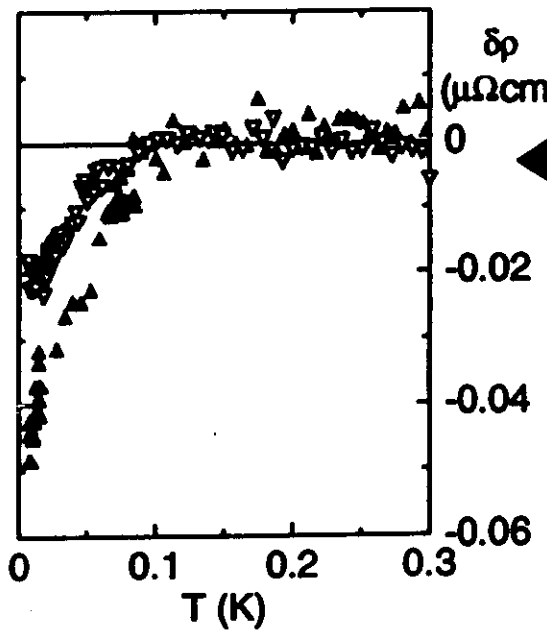
$\varepsilon = 1.5$ for $\rho_0 \geq 3\mu\Omega cm$

$1.3 \leq \varepsilon < 1.5$ for $0.17\ \mu\Omega cm \leq \rho_0 < 3\ \mu\Omega cm$

Suppression of Non-Fermi-liquid behavior in B > 0



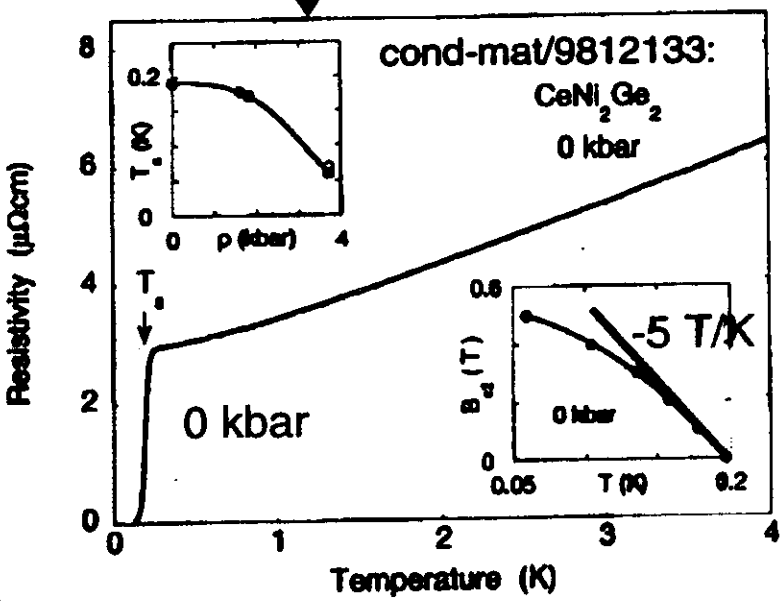
Observation of incipient superconductivity



30% drop in resistivity of different high-quality polycrystals

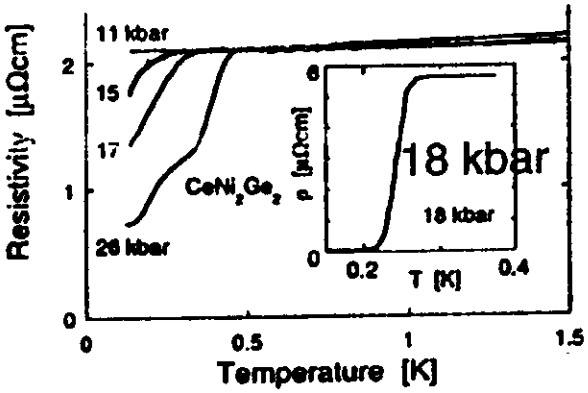
100% drop in resistivity in one particular piece of a single crystal:

F. M. Grosche et al., cond-mat/9812133:



pressure-induced SC:

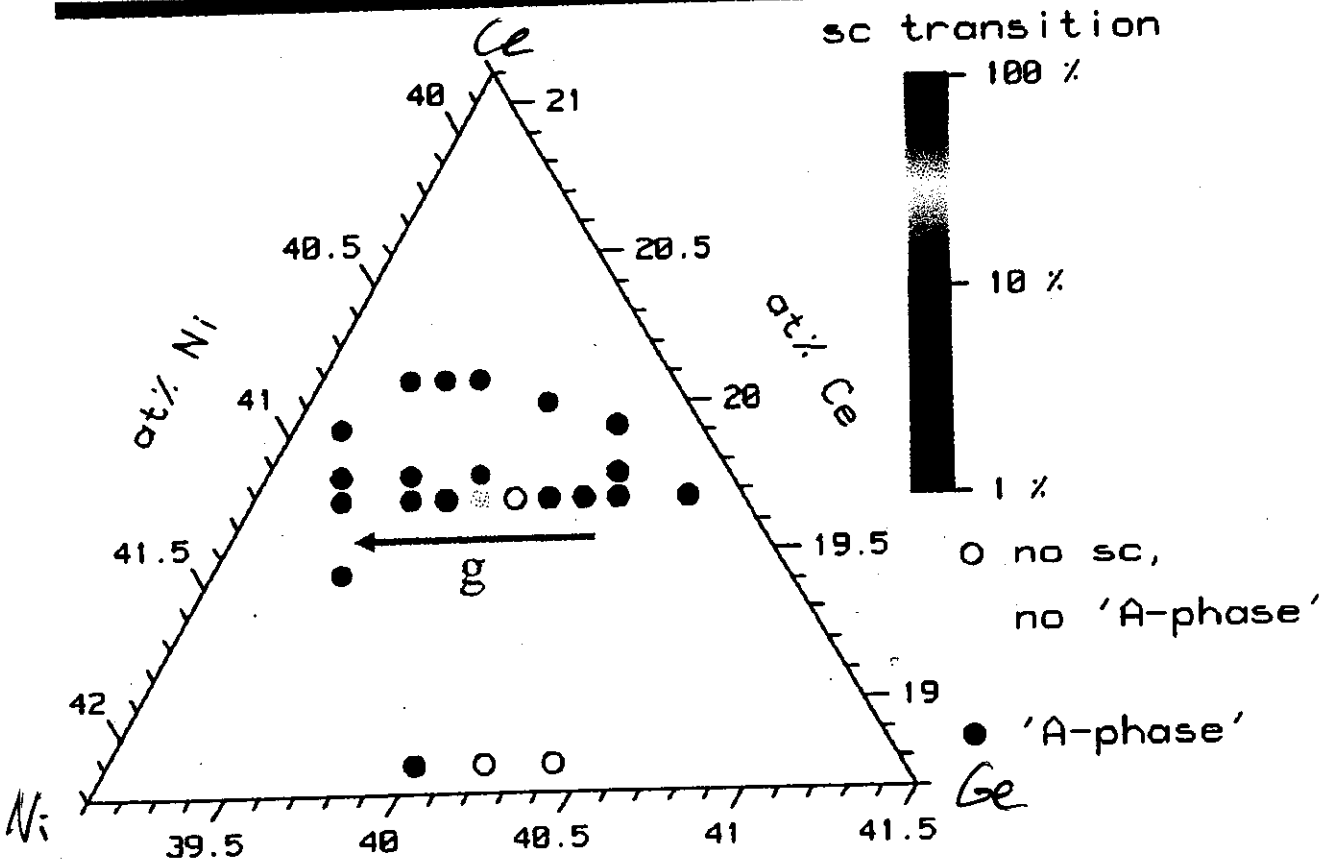
S.J.S. Lister et al., Z. Phys. B 103, 263 (97)

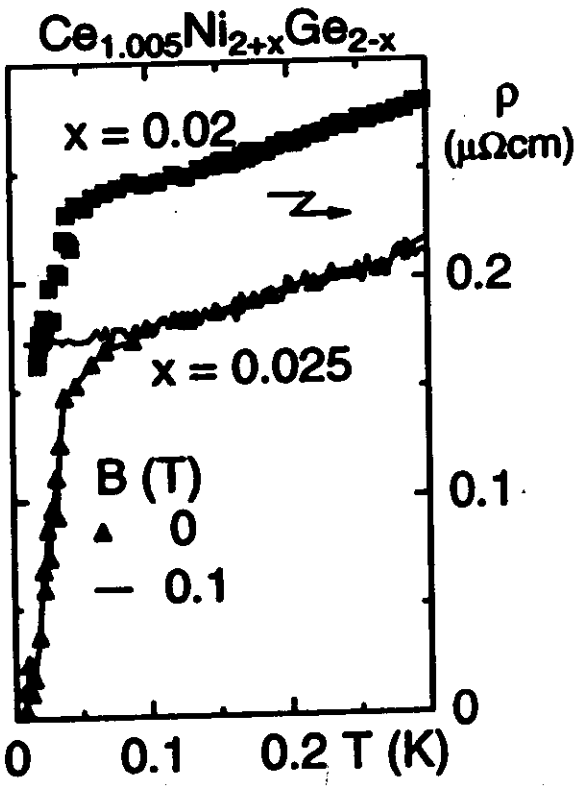


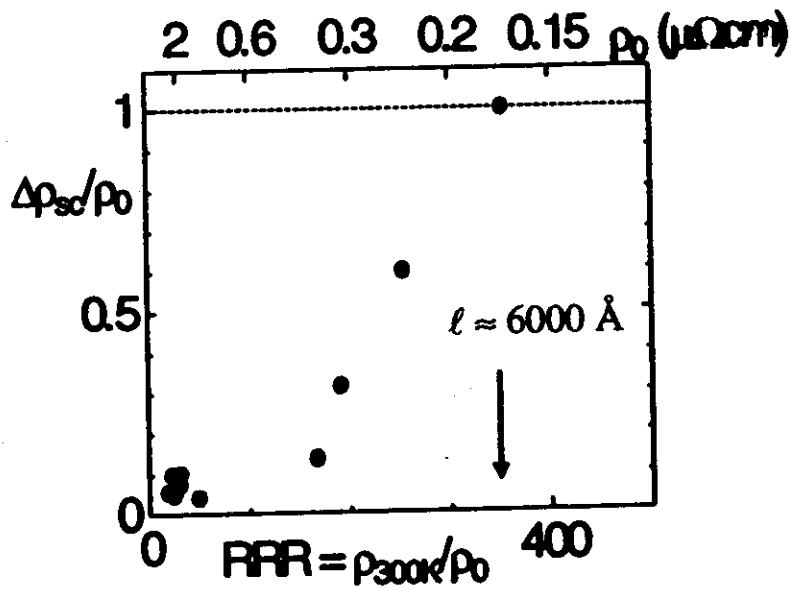
however: up to now not proven by thermodynamic measurement

ground-state behavior may depend very sensitively on exact stoichiometric composition (similar to $CeCu_2Si_2$) !

Systematic study on slightly off-stoichiometric $Ce_{1+x}Ni_{2+y}Ge_{2+z}$ polycrystals



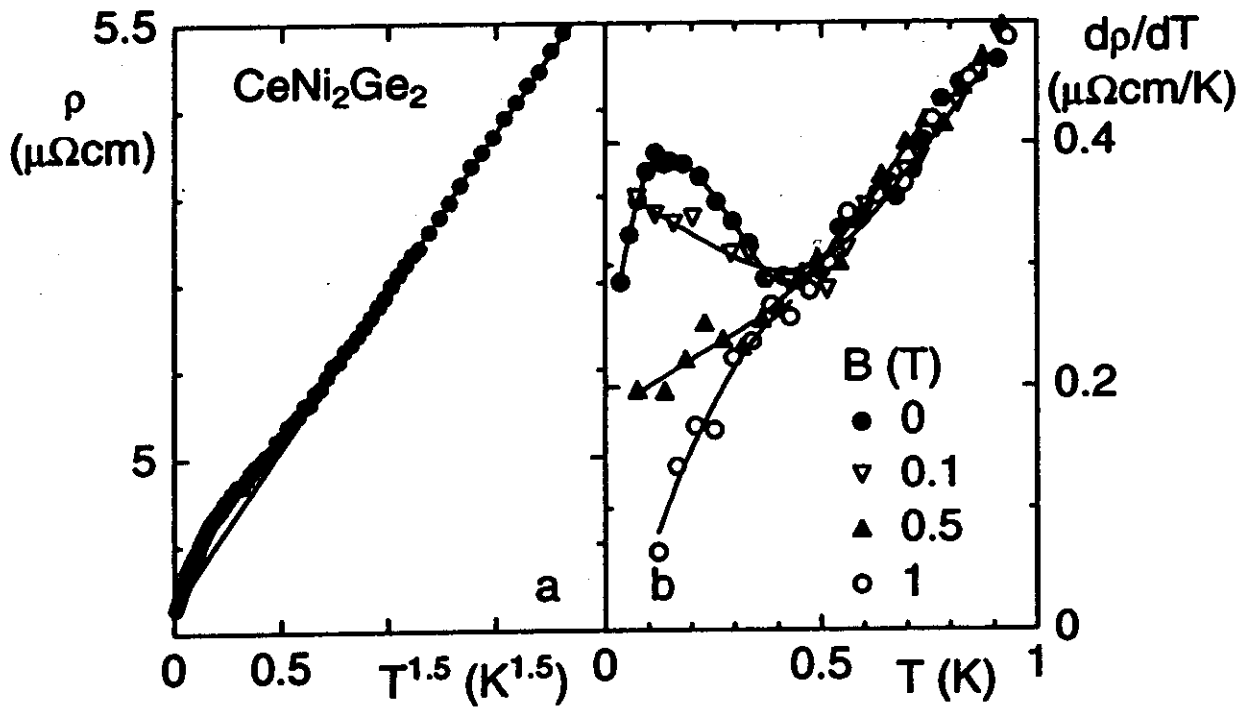




Clean limit SC → highly anisotropic order parameter !

Magnetic (?) anomaly in Ge-rich region

- less Ni-content (smaller g) → anomaly that resembles phase "A" in $CeCu_2Si_2$ (magnetic origin ?!)



Conclusions

- **The two stoichiometric HF compounds $CeCu_2Si_2$ and $CeNi_2Ge_2$ located** close to magnetic instability
- **Both systems show very strong composition and** pressure dependence of the ground-state behavior
- **$CeCu_2Si_2$:**

  both coexistence and competition of magnetic order with "dirty-limit" SC, SC not only around QCP (as found for $CePd_2Si_2$)
- **$CeNi_2Ge_2$:** "clean-limit" SC ?
- **NFL behavior:**

  for $T \geq 0.3$ K both C(T) and ρ(T) in accordance with predictions for "Nearly afm FL" (including interplay with disorder - see A. Rosch '99)
- **not yet understood** (for both systems):

- **resistivity and specific heat** behave very disparately
- **resistivity follows predictions while below 0.3 K large** upturn in C/T observed, **very likely of electronic origin !**

→ decoupling of itinerant and local 4f parts out of which the Heavy Fermions are composed !