Beyond Landau Fermi liquid and BCS superconductivity near quantum criticality

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Lecture 2
Fermi liquids, Kondo effect and heavy fermions

Contents of Lecture 2

Landau Fermi liquids

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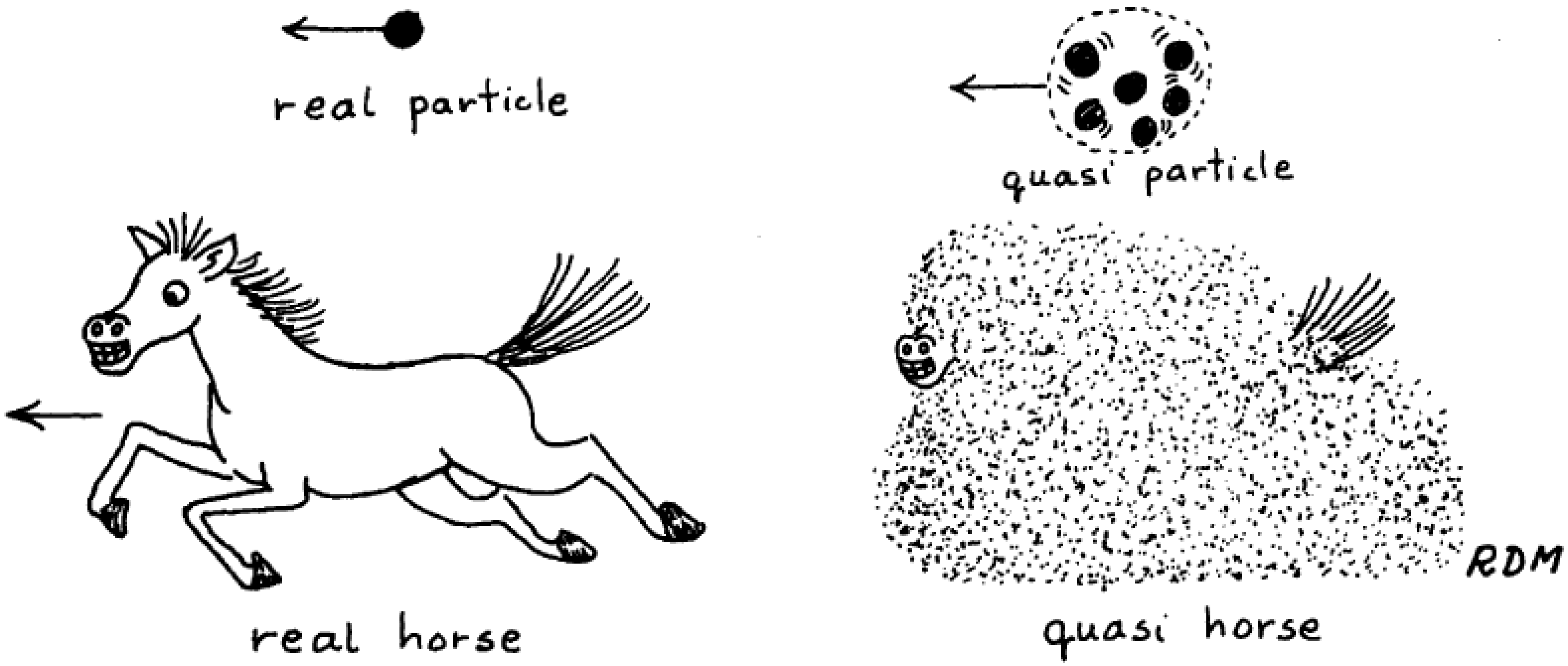
See standard textbooks on interacting electron systems, e. g.,

G.Baym, C, Pethick, *Landau Fermi-liquid Theory: Concepts andapplications*, Wiley 1991 (also available online)

See also: H. v. Löhneysen, A. Rosch, M. Vojta, and P. Wölfle, *Fermi liquid instabilities at magnetic quantum phase transitions*, Rev. Mod. Phys. **79**, 1015 (2007) , In particular p.1018-1027

See also N. W. Ashcroft, N. D. Mermin, *Solid State Physics*, Saunders College Publishing1976, in particular ch. 17

Noninteracting independent free particles and quasiparticles



R. D. Mattuck, in: A guide to Feynman diagrams in the many-body problem ,
McGraw-Hill 1967;2nd edition , Dover 1992

Kondo effect:
concept of a local Fermi liquid

THE ELECTRICAL RESISTANCE OF GOLD BELOW 1°K

by W. J. DE HAAS, H. B. G. CASIMIR and G. J. VAN DEN BERG

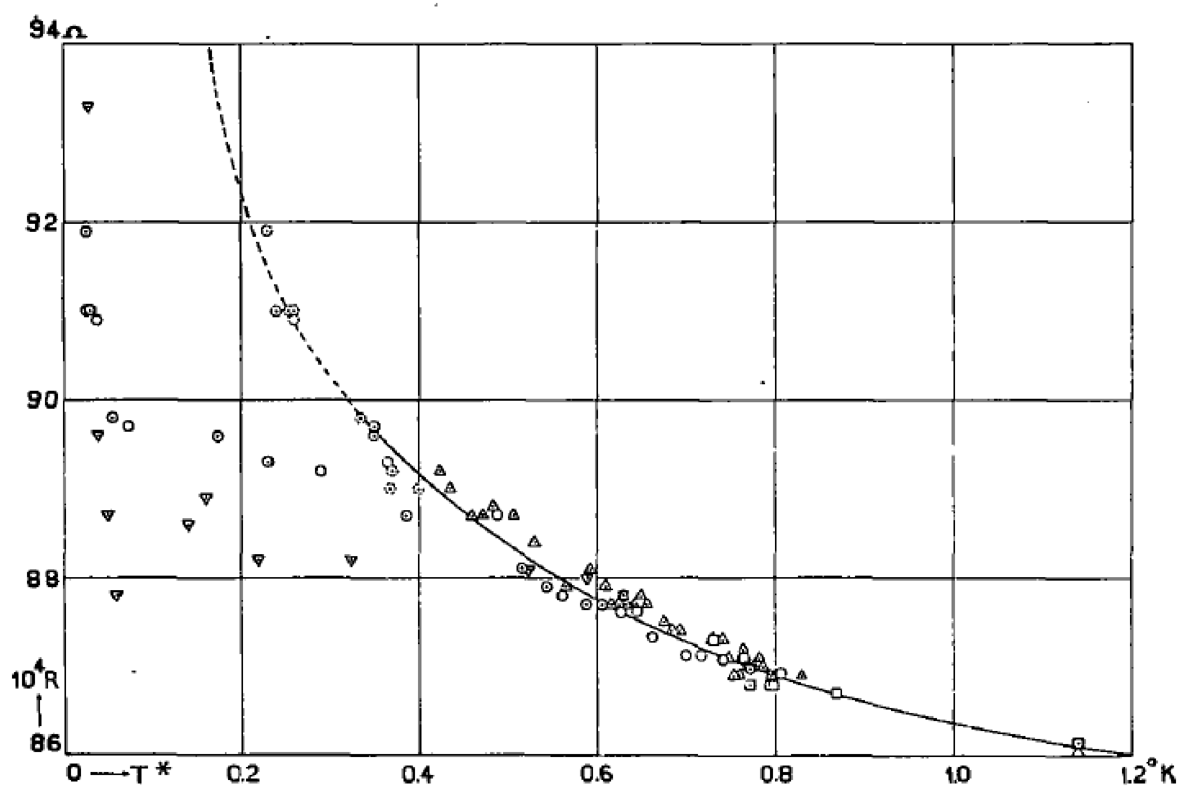
Communication No. 251*c* from the Kamerlingh Onnes Laboratory at Leiden

Dedicated to Professor Max Planck on the occasion of his eightieth birthday

Summary

The resistance of gold was determined at temperatures below 1°K, obtained by adiabatic demagnetization of iron-ammonium-alum. The increase observed at ordinary liquid helium temperatures is much more pronounced below 1°K and our results suggest, that the resistance may become infinite at the absolute zero-point.

Physica **5**, 225 (1938)



J. Kondo 1964: explanation of the resistance minimum in metals

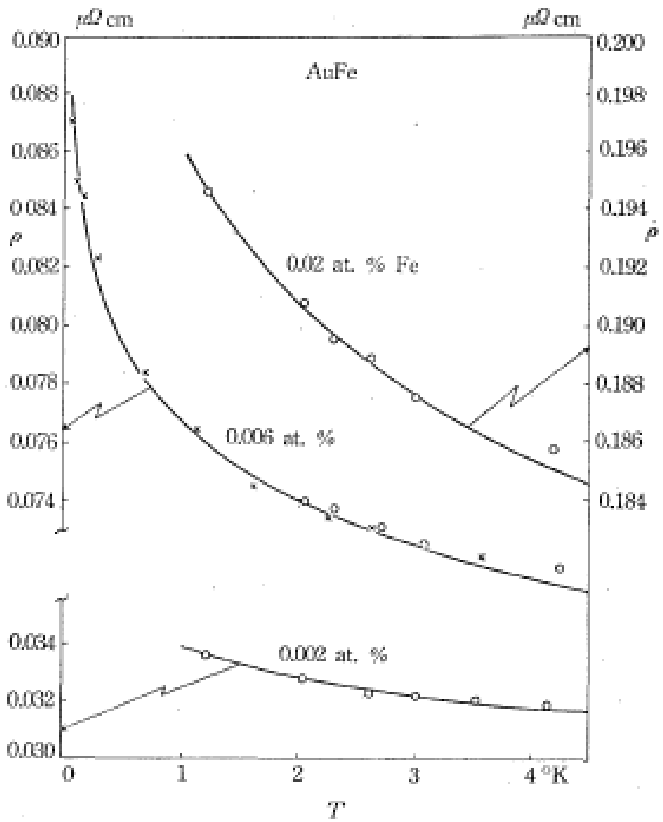


Fig. 1. Comparison of experimental and theoretical ρ–T curves for dilute AuFe alloys.

Progress of Theoretical Physics, Vol. 32, No. 1, July 1964

Resistance Minimum in Dilute Magnetic Alloys

Jun Kondo

Electro-technical Laboratory
Nagatacho, Chiyodaku, Tokyo

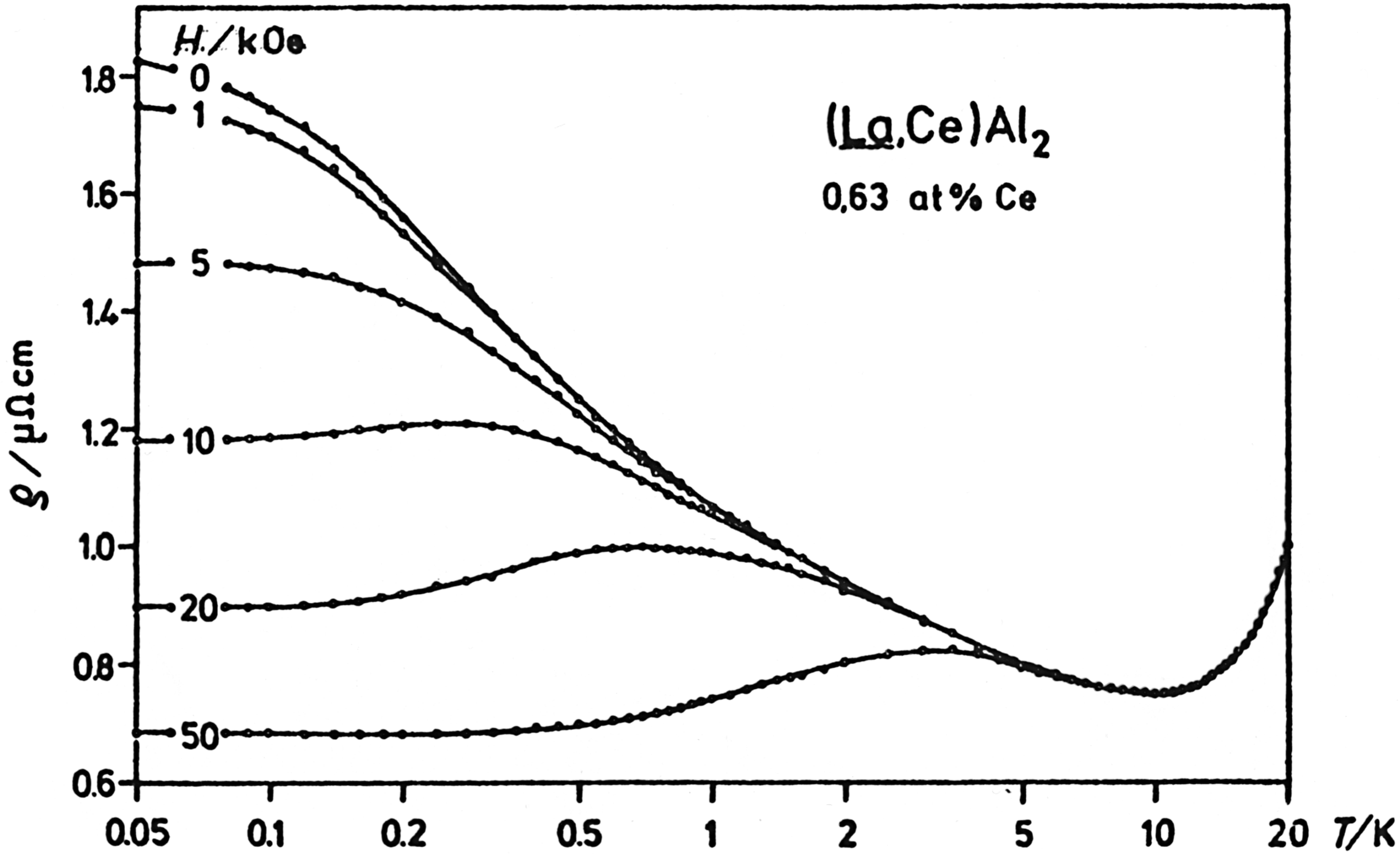
(Received March 19, 1964)

Based on the *s-d* interaction model for dilute magnetic alloys we have calculated the scattering probability of the conduction electrons to the second Born approximation. Because of the dynamical character of the localized spin system, the Pauli principle should be taken into account in the intermediate states of the second order terms. Thus the effect of the Fermi sphere is involved in the scattering probability and gives rise to a singular term in the resistivity which involves $c \log T$ as a factor, where c is the concentration of impurity atoms. When combined

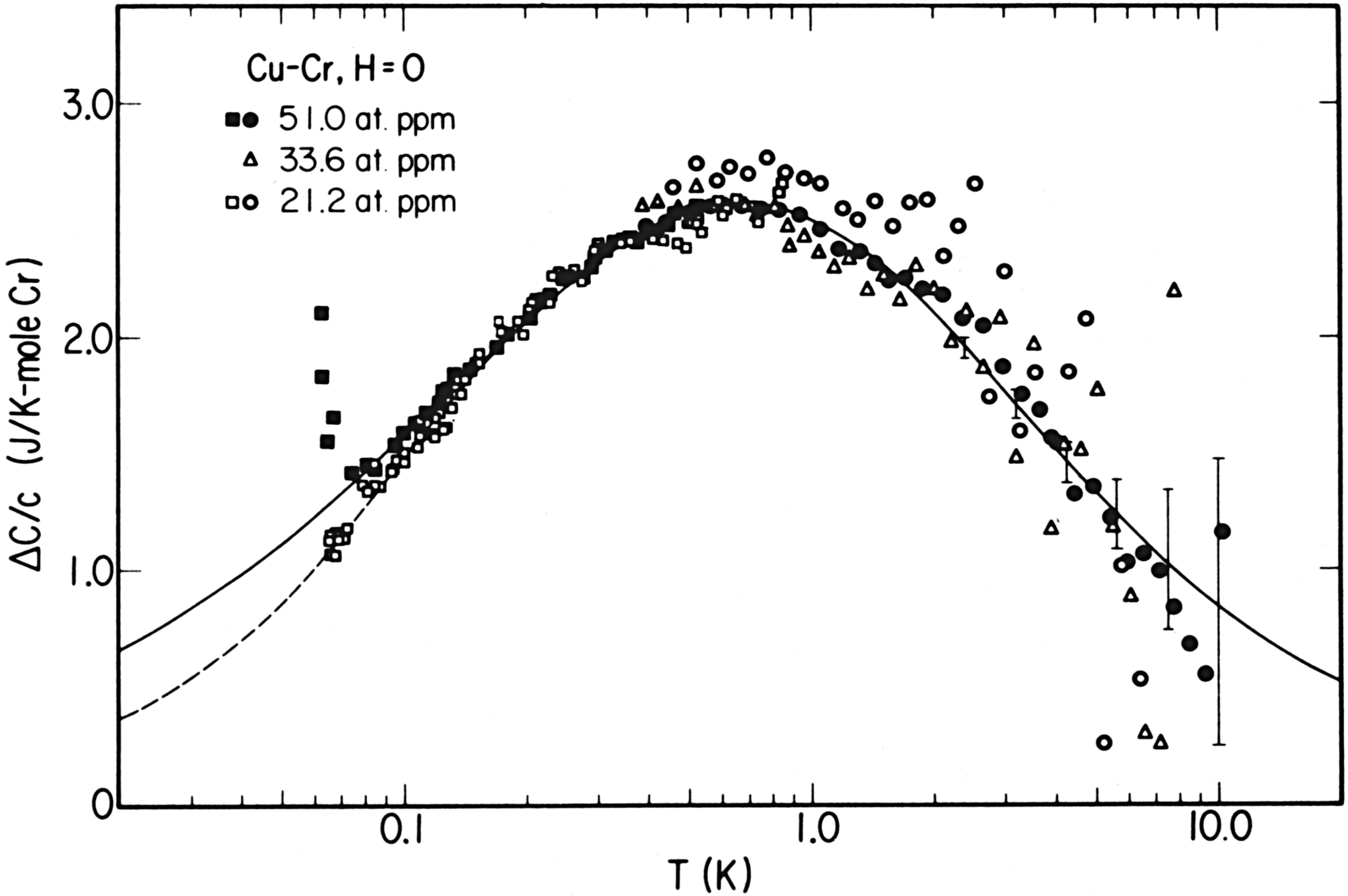
Kondo Hamiltonian

$$\mathcal{H} = -2J\,\mathbf{S}\,\mathbf{s}$$

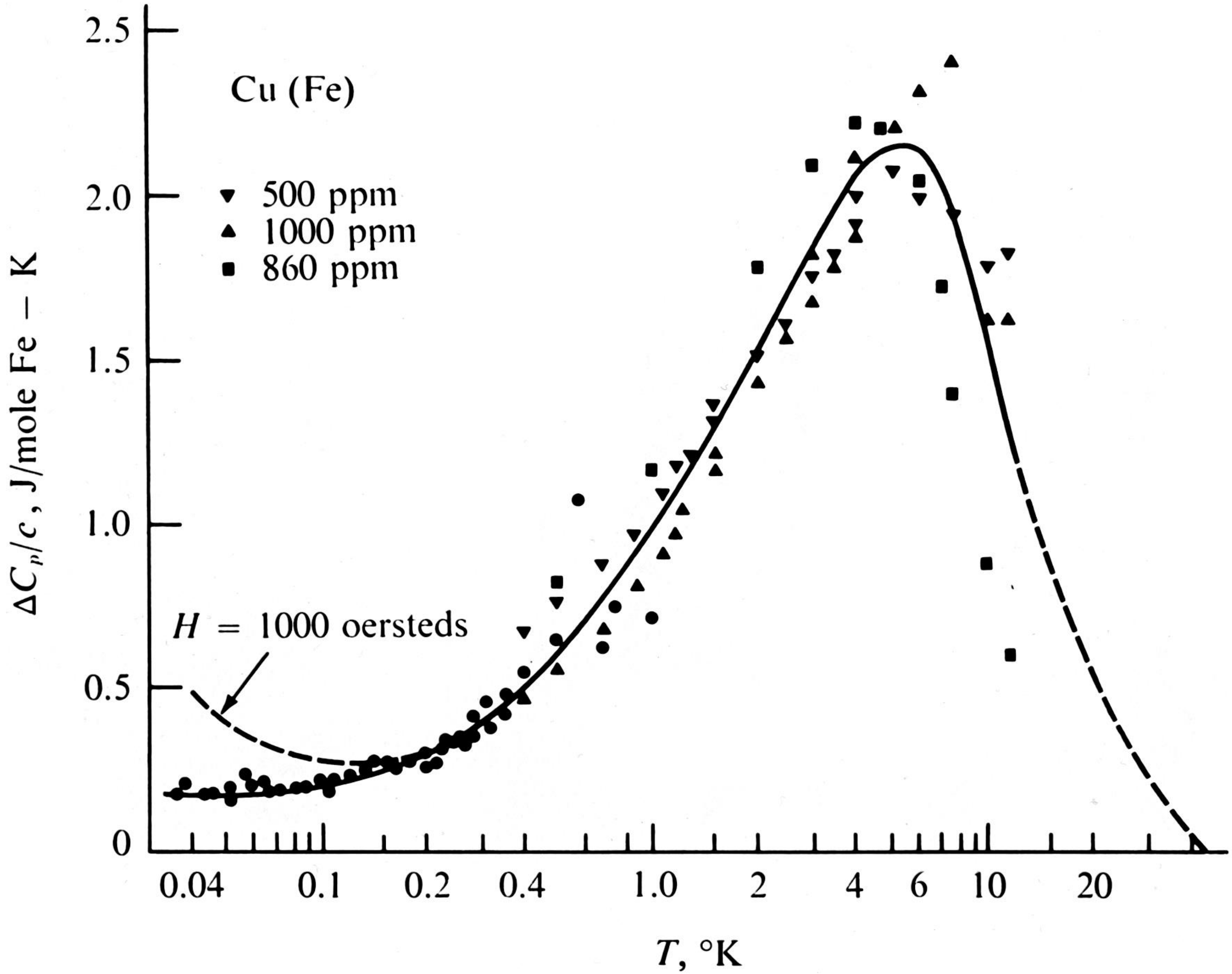
Electrical resistivity of $(La,Ce)Al)_2$



Kondo anomaly of the specific heat of Cu-Cr



Kondo anomaly of the specific heat of Cu-Fe



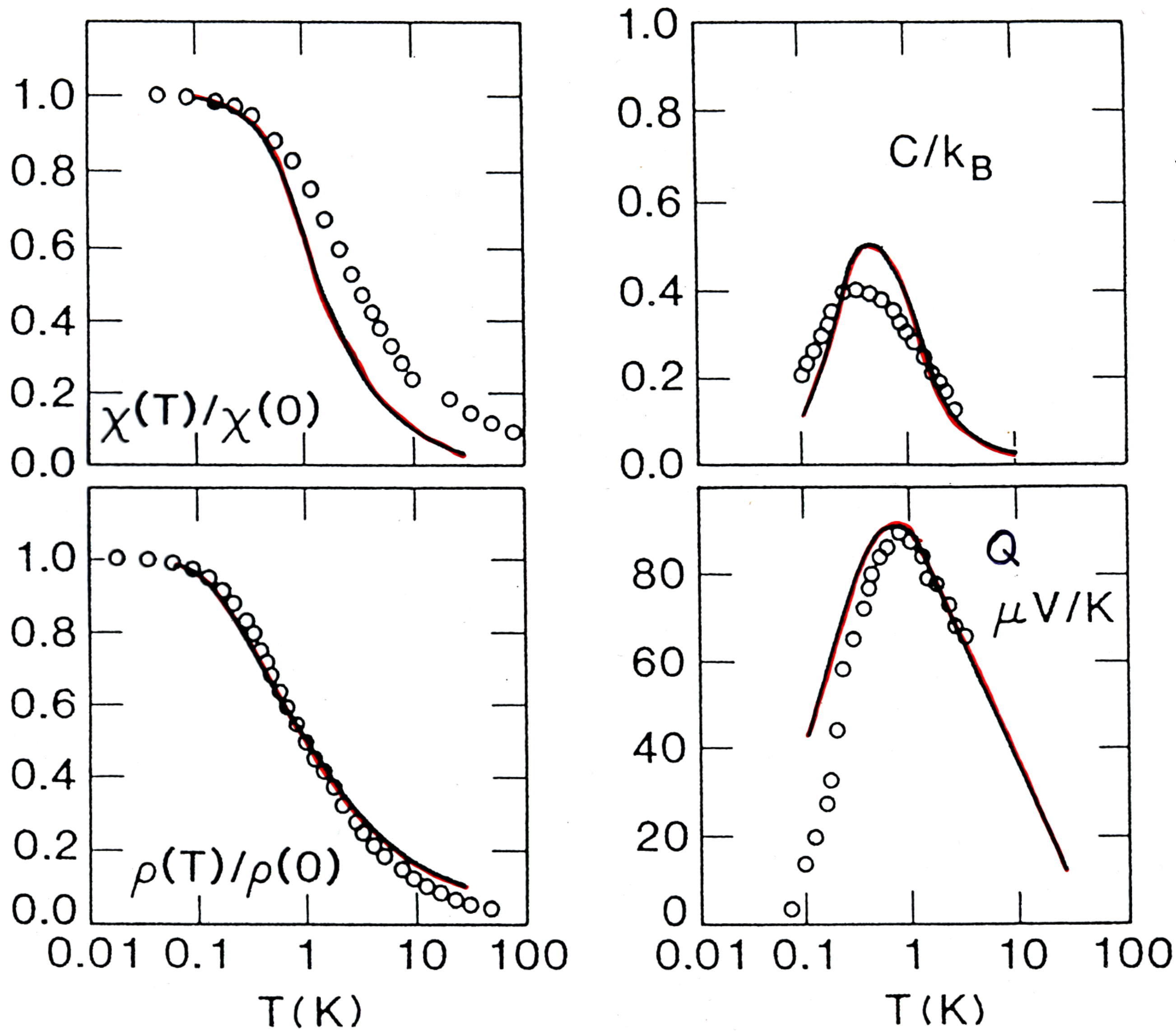
Kondo anomalies of (La,Ce)B_6

Magneitc susceptibiliy

Specific heat

Electrical resistivity

Thermo-electric power

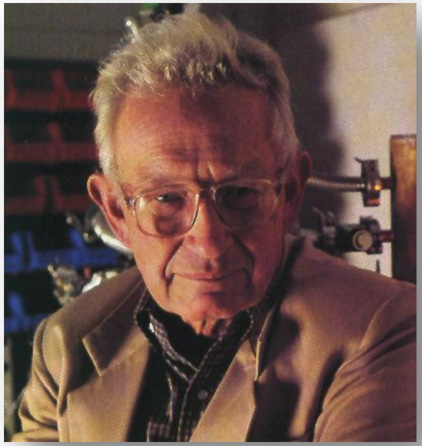


○○○ Exp'nt

Theory

T_K = 1 K

Anderson model for a magnetic impurity in a metal



P.W. Anderson, Phys. Rev. ***124*** *(1961)*

Two important parameters:

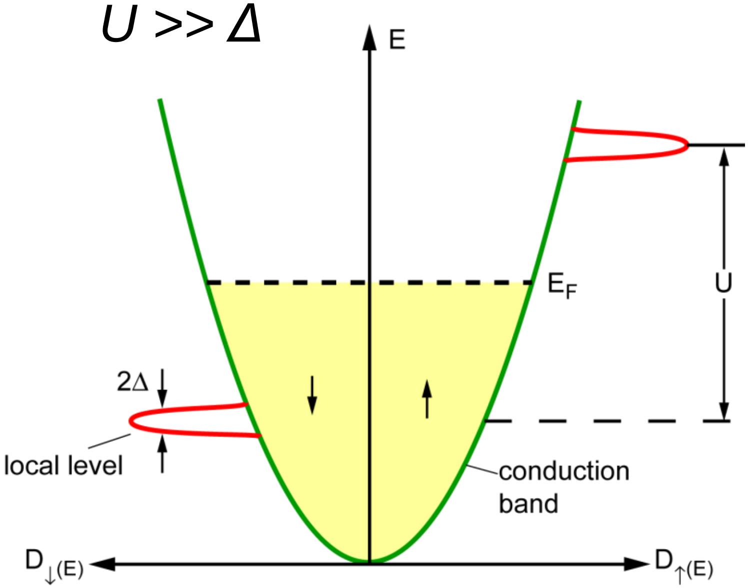
hybridization with conduction electrons:

$\Rightarrow$ broadening Δ of local level

on-site Coulomb repulsion *U* on local level

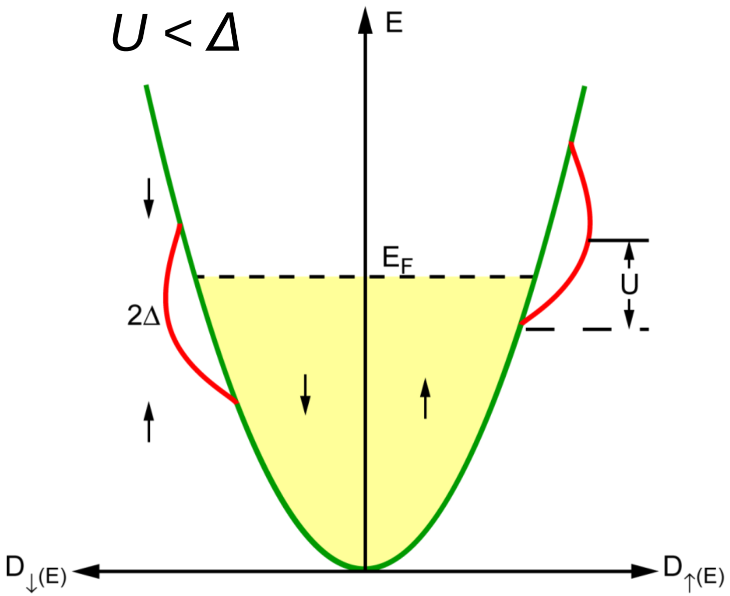
$\Rightarrow$ tendency to single occupancy, i. e., local moment

$U >> \Delta$



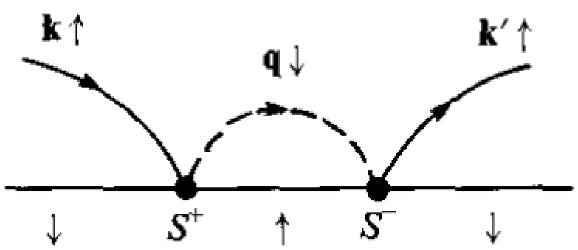
stable magnetic moment

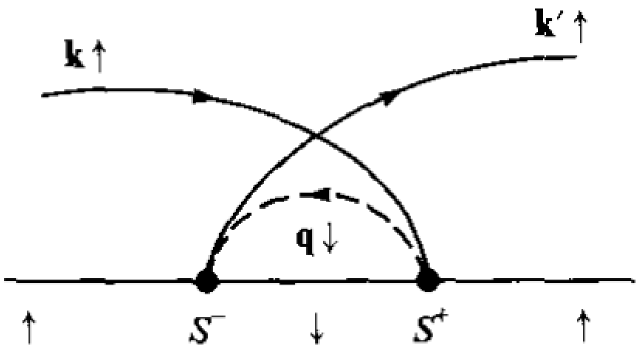
$U < \Delta$



local magnetic moment „lost“

Second-order scattering processes of conduction electrons by magnetic impurities (Kondo scattering)



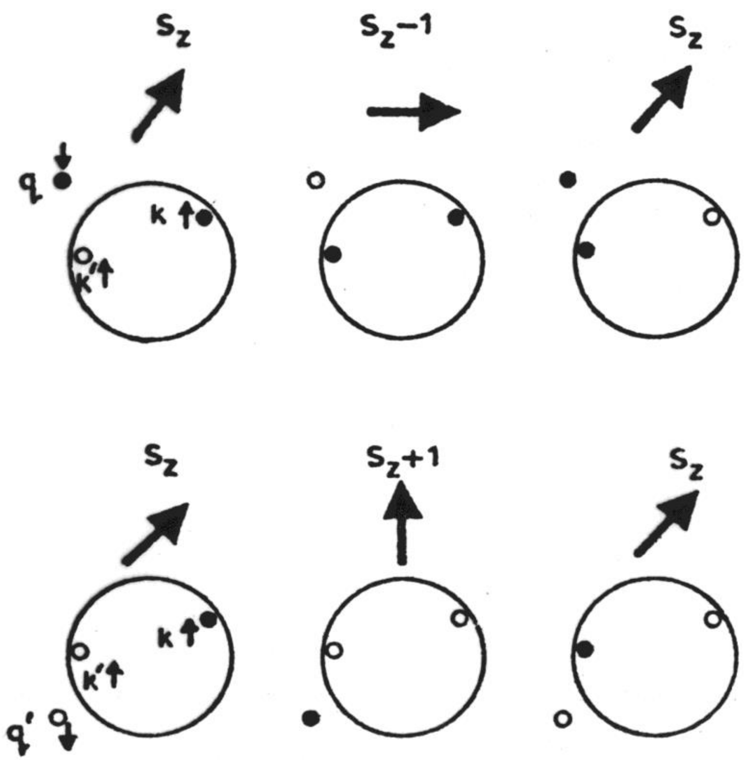


Intermediate state involvinga conduction-band particle (*i*) or hole (*ii*)

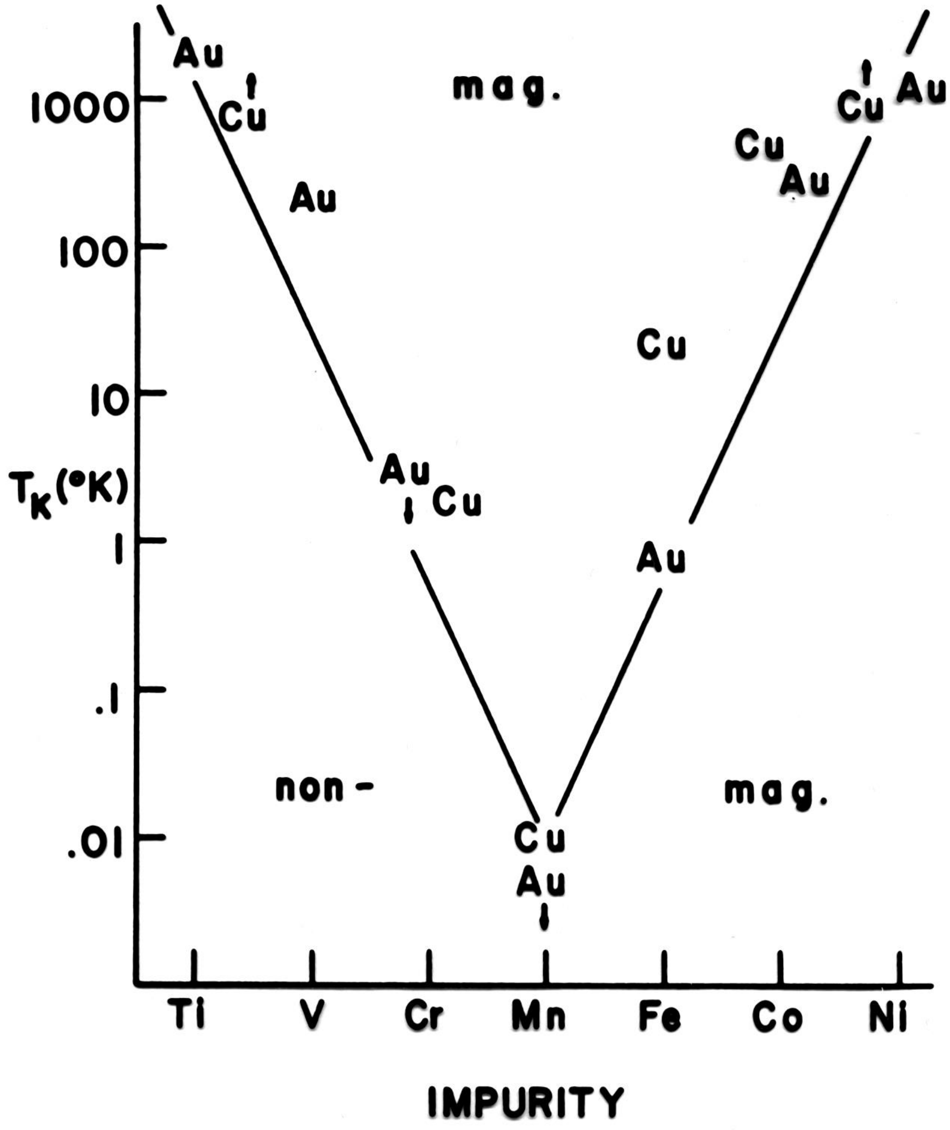
(*i*)

Illustration

(*ii*)



Kondo temperature T_K of *3d* transition-metal impurities in noble-metal hosts



Relation between Anderson and Kondo models

Schrieffer-Wolff transformation (1966) maps Anderson impurity Hamiltonian onto an effective spin Hamiltonian

$$\mathcal{H} = -2J\,\mathbf{S}\,\mathbf{s} \quad \text{with } J = J_0 + J_1$$

J_0 : Heisenberg exchange integral between localized and conduction electrons > 0

$$J_1 = \langle V_{lc}\rangle^2\, U \,/\, (E_l - E_F)\,(E_l - E_F + U) < 0$$

if hybridization sufficiently strong, then $|J_0| < |J_1|$

$\Rightarrow$ antiferromagnetic exchange J < 0 (spin-singlet formation)

Note: in rare-earth metals angular momentum not quenched,

e.g., Ce^{3+} $4f^1$ configuration: $^2F_{5/2}$ Hund's rule ground state,

six-fold degeneracy lifted by crystal field

Modified Kondo Hamiltonian

B. Coqblin, J. R. Schrieffer, Phys. Rev. ***185****, 847 (1969)*

Origin of heavy masses $m \approx 100\ m_0$ in rare-earth alloys: Kondo effect

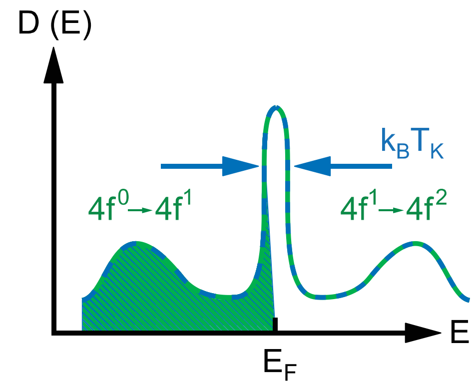
Two “ingredients“ for Kondo effect of isolated 4f impurities in metals

- hybridization of 4*f* and conduction electrons
- strong on-site electron repulsion in 4f state

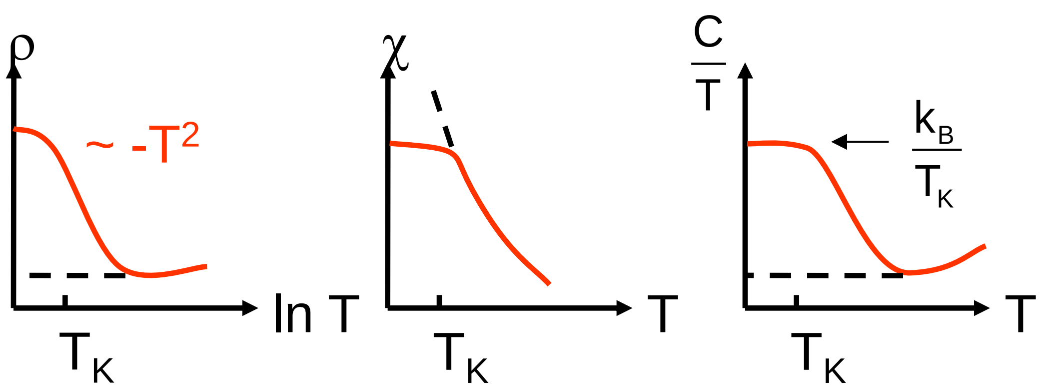
singly occupied lowest 4*f* state will be screened by conduction electrons: singlet formation

Resonance at E_F due to virtual excitions from 4*f* state to E_F

Kondo resonance



“Kondo anomalies“ at low *T*



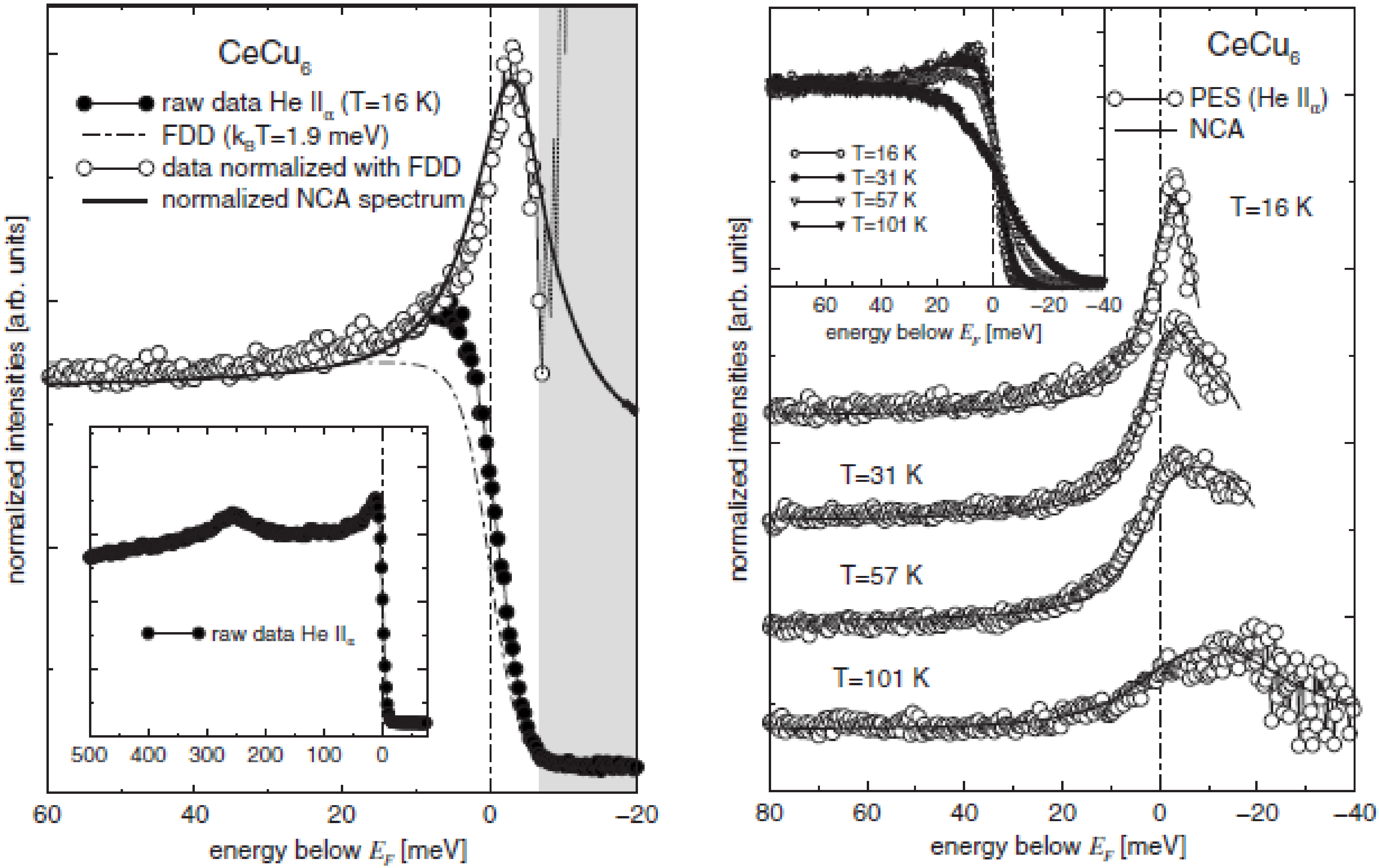
“local Fermi liquid“

Heavy-fermion system: lattice-coherent superposition of Kondo anomalies

Heavy-fermion systems

Kondo resonance in the heavy-fermion system $CeCu_6$

D. Ehm et al., Phys. Rev. B ***76****, 04511 (2007)*

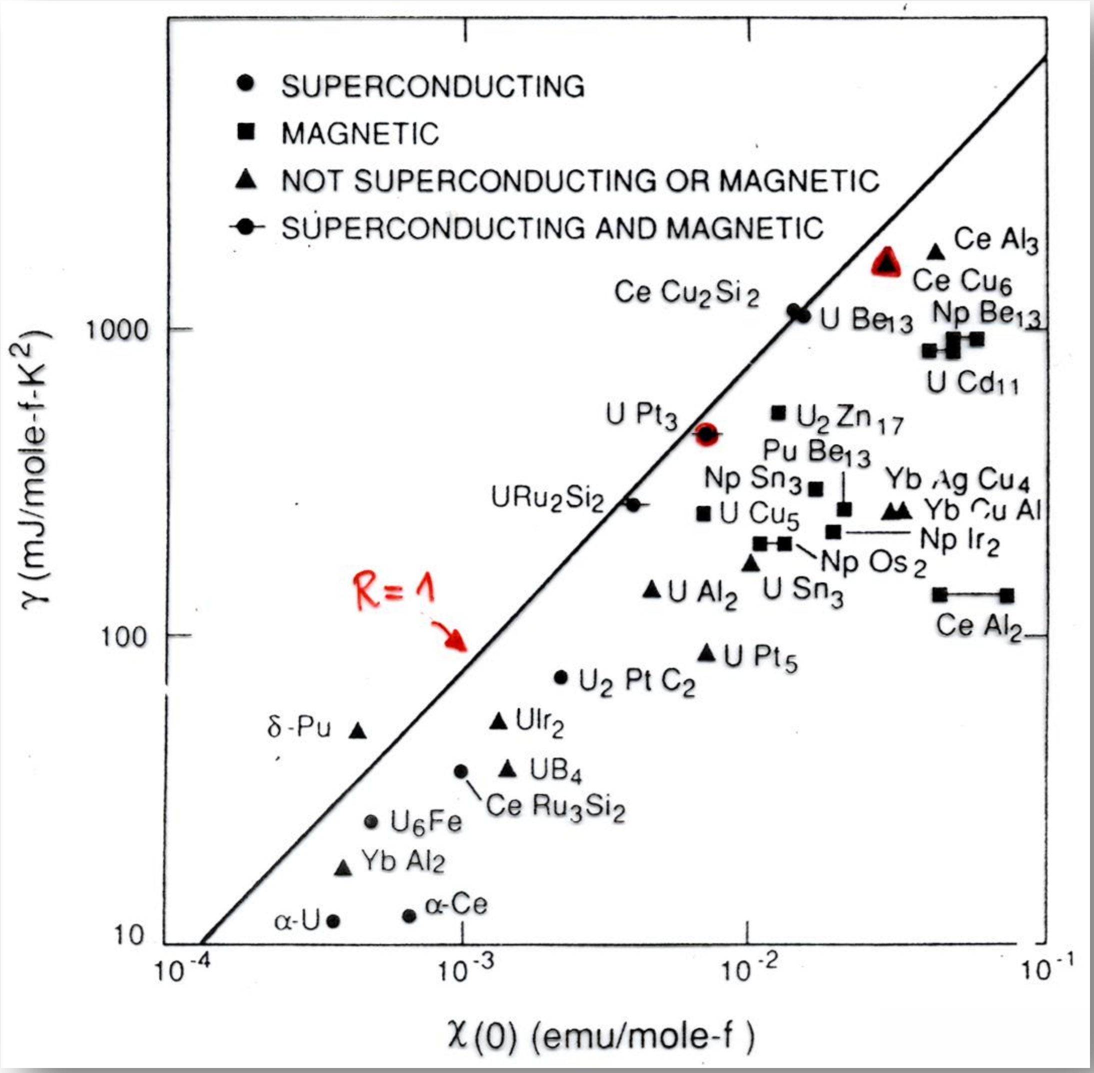


Wilson relation between the specific-heat coefficient γ and the Pauli susceptibility

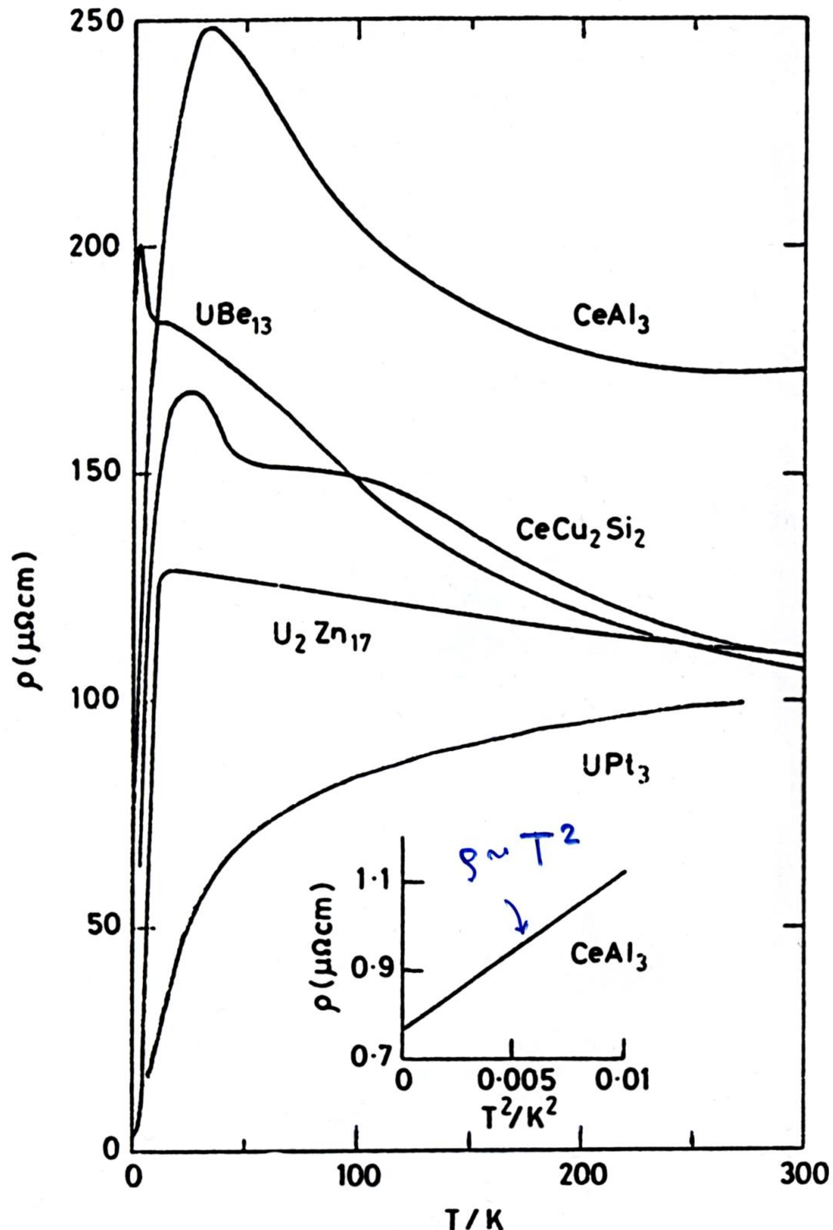
Z. Fisk et al.

Heavy-fermion systems:

$F_0^a \sim -0.5$



Electrical resistivity of heavy-fermion systems



Kondo-like increase of $\rho(T)$ toward low T

Coherence maximum below T_K, cf. Bloch theorem

At lowest T, $\rho(T) = \rho + AT^2$, cf. Fermi liquid

Kadowaki-Woods ratio of the specific-heat coefficient γ and the coefficient *A* of the T^2 resistivity

Specific heat

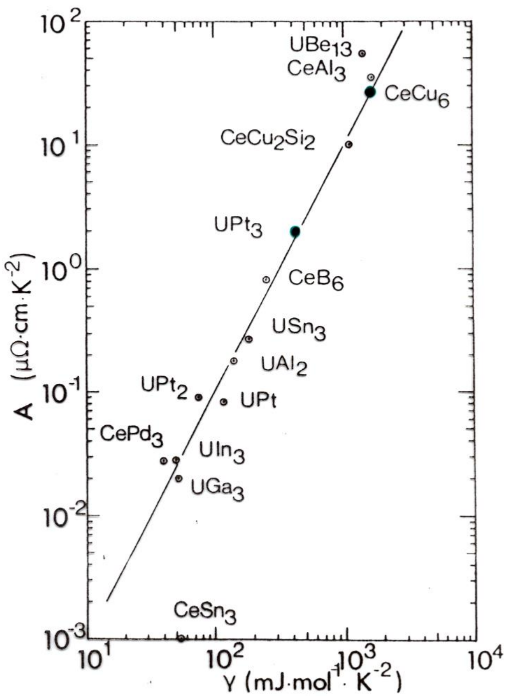
$$C = \gamma T, \quad \gamma \sim m^*/m_0 = E_F^0/E_F$$

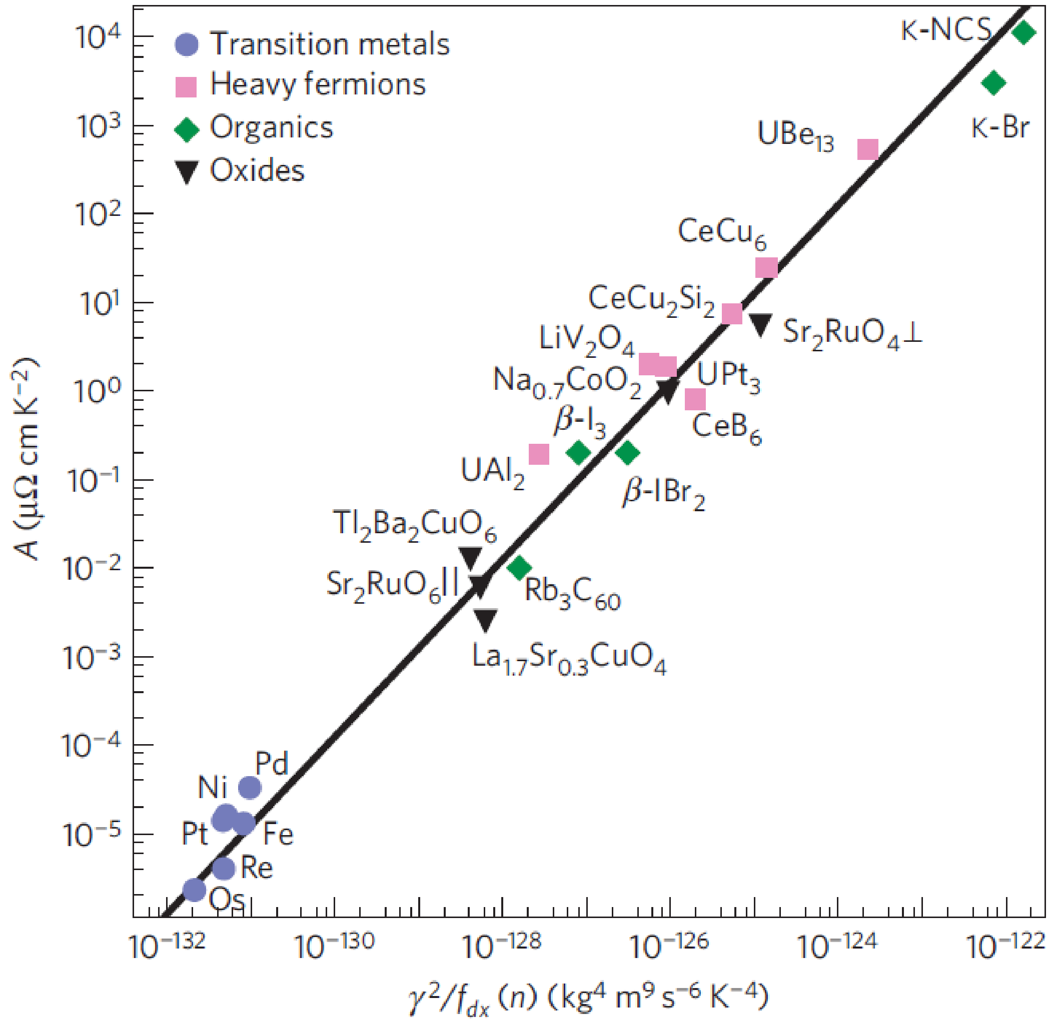
Electrical resistivity

$$\rho = \rho_0 + A(k_B T/E_F)^2$$

$$\Rightarrow A \sim \gamma^2$$

K. Kadowaki, S.B. Woods, Solid State Commun. ***58,*** *507 (1986)*





A. C. Jacko et al., Nature Phys. ***5****, 422 (2009)*

Quantum phase transitions in heavy-fermion systems

Competition between Kondo effect and RKKY interaction Leading to quantum criticality in heavy-fermion systems

Kondo effect

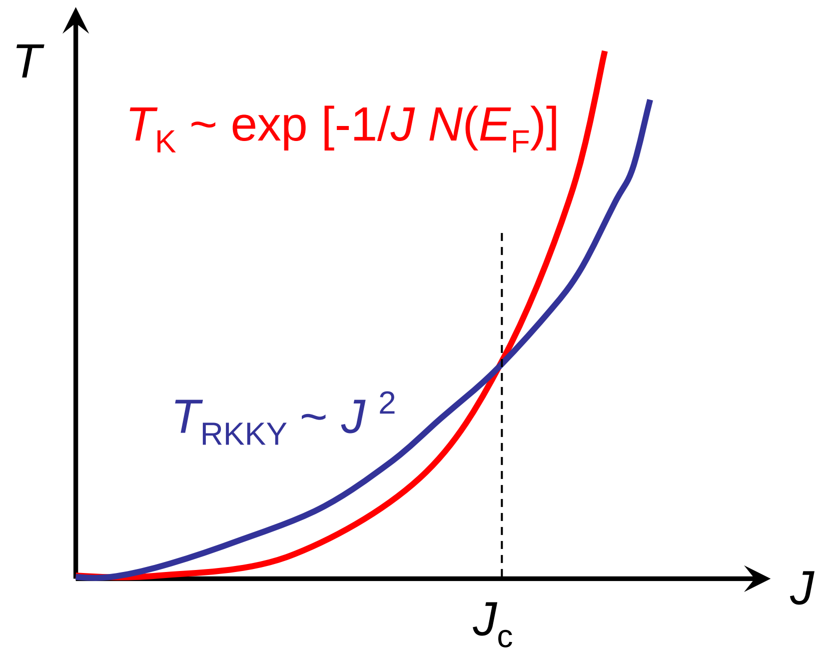
Formation of local singlets with conduction electrons

⇒ nonmagnetic groundstate

RKKY interaction

Polarization of conduction electrons via J is sensed by another magnetic ion

⇒ tendency towards
magnetic order



S. Doniach, Physica ***91B,*** *231 (1977)*

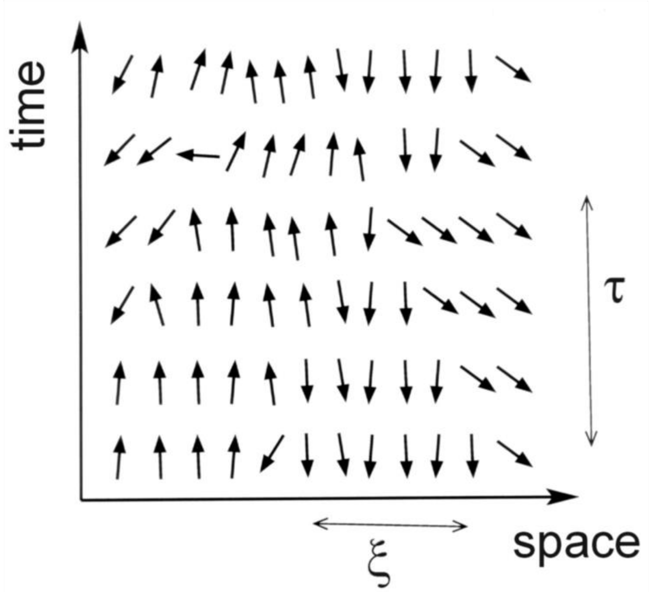
Quantum phase transitions (2^{nd} order)

Energy scale of quantum effects: $\frac{\hbar}{\tau}$

classical case: $\frac{\hbar}{\tau} \ll k_B T \approx k_B T_c$, quantum fluctuations negligible

quantum case: $\frac{\hbar}{\tau} \geq k_B T$, possible if $T_c \rightarrow 0$

spatial *and* temporal fluctuations determine dynamics, $\tau \sim \xi^z$



effective dimension $d_{eff} = d + z$

new universality classes

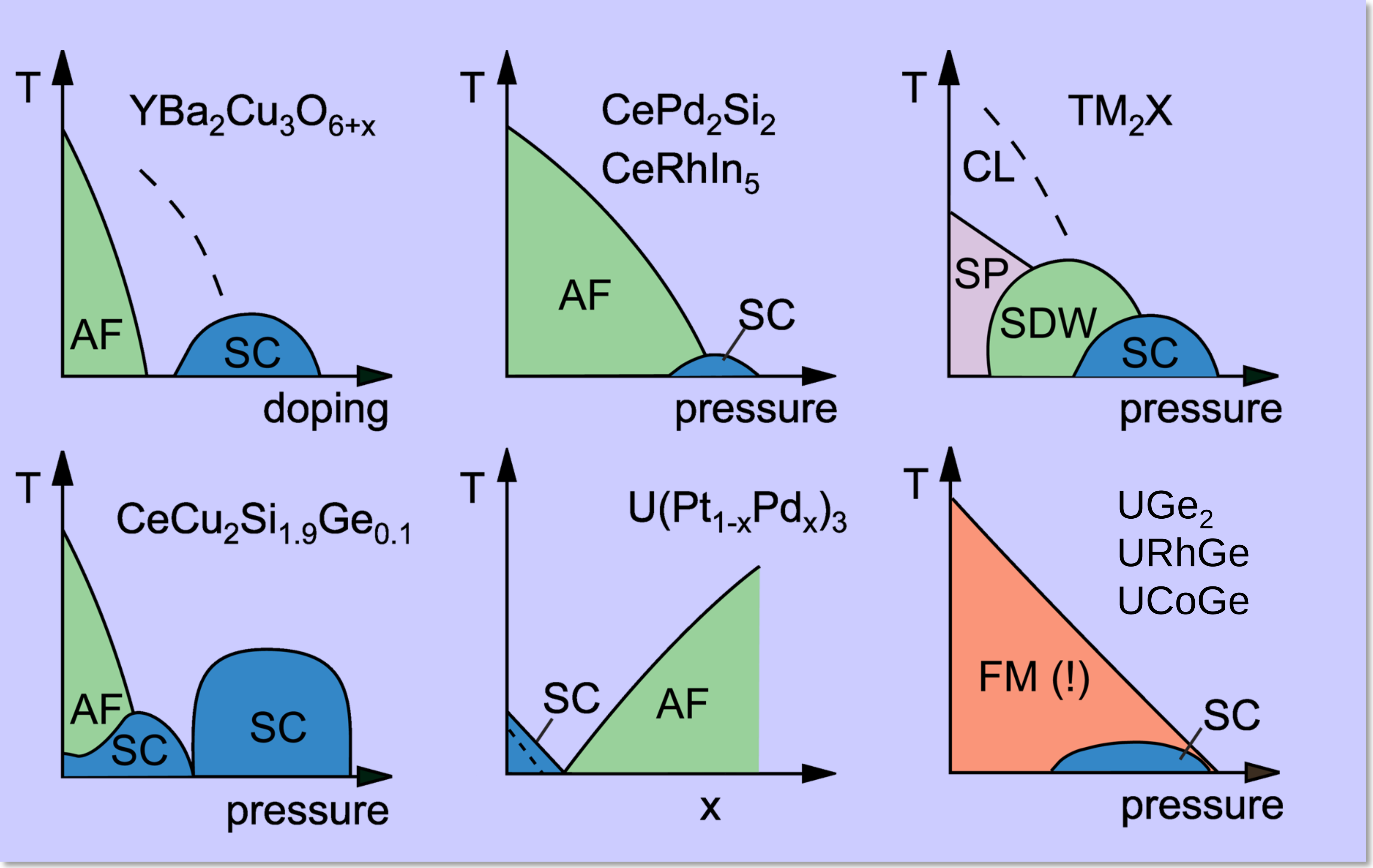
role of temperature

control paramter

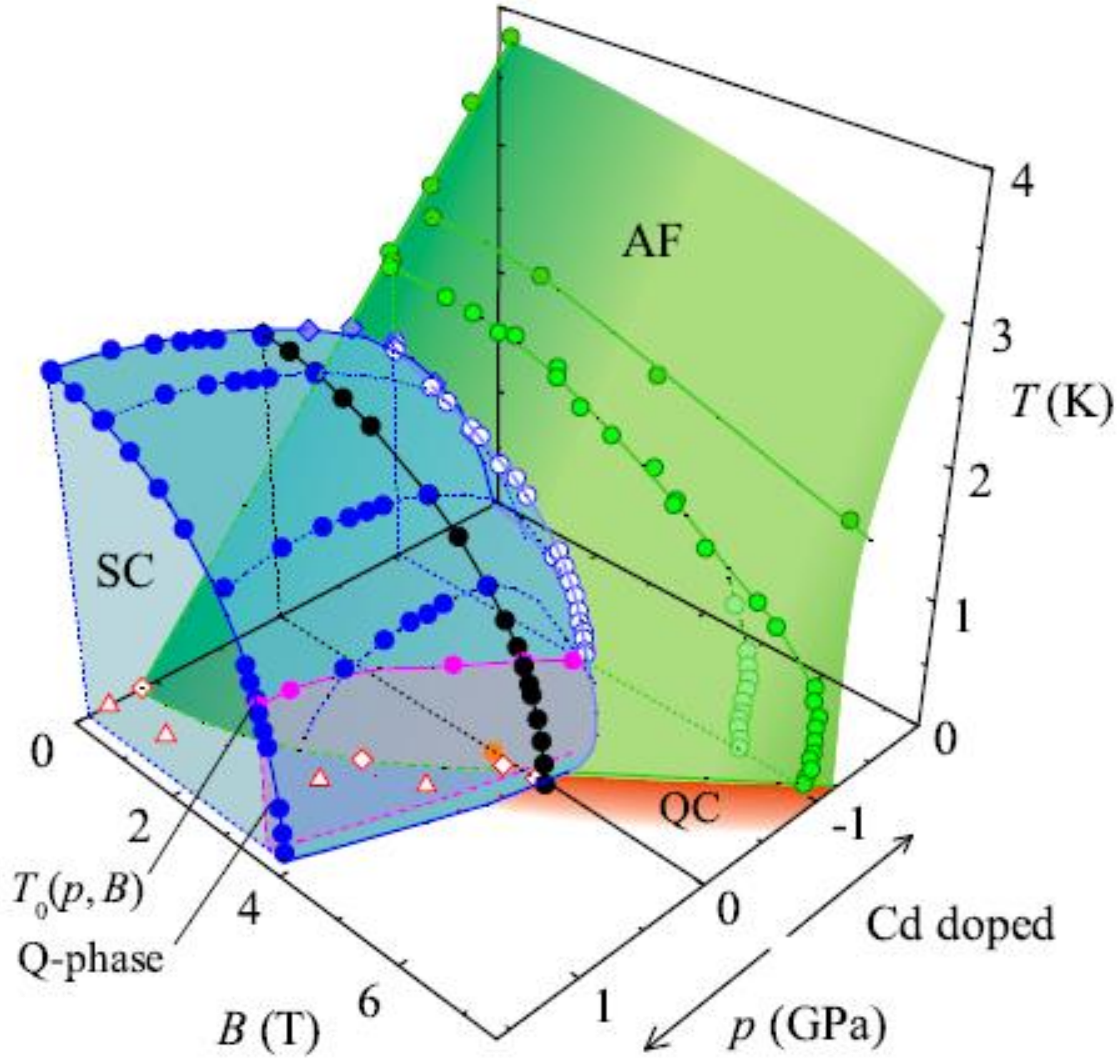
thermal excitations via $k_B T$

finite system size $\tau \leq \hbar / k_B T$

Interplay of superconductivity and magnetism near quantum critical points



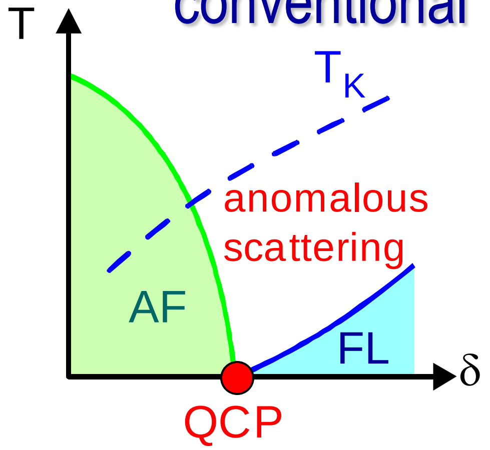
Interplay of superconductivity and antiferromagnetism at quantum criticality in $CeCoIn_5$



S. Zaum et al., PRL 2012

Scenarios for quantum criticality in heavy-fermion systems

conventional



Scattering of heavy quasiparticles by spin fluctuations: diverging *m** for 3D FM and 2D AF

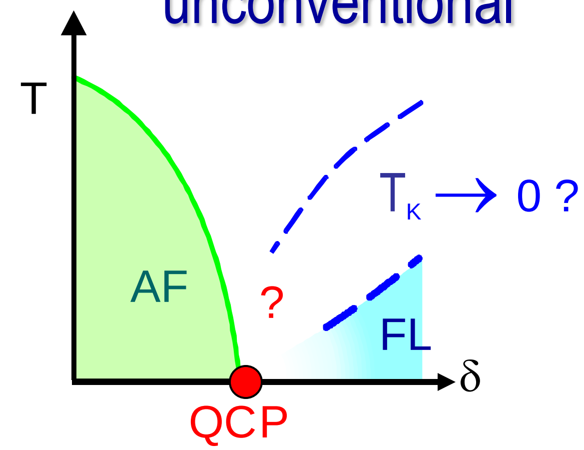
$CeCu_2Si_2$

$CeNi_2Ge_2$

$Ce_{1-x}La_xRu_2Si_2$

Hertz, Millis, Moriya, Rosch et al.

unconventional



Unbinding of composite heavy quasiparticles: change of Fermi volume

$CePd_2Si_2$

$CeCu_{6-x}Au_x$

$YbRh_2Si_2$

$UCu_{5-x}Pd_x$

Multiple energy scales?
Dimensionality ?
Disorder effects ?

Coleman, Si, Pepin et al.