Quasiparticle Concept

A short philosophical excurse

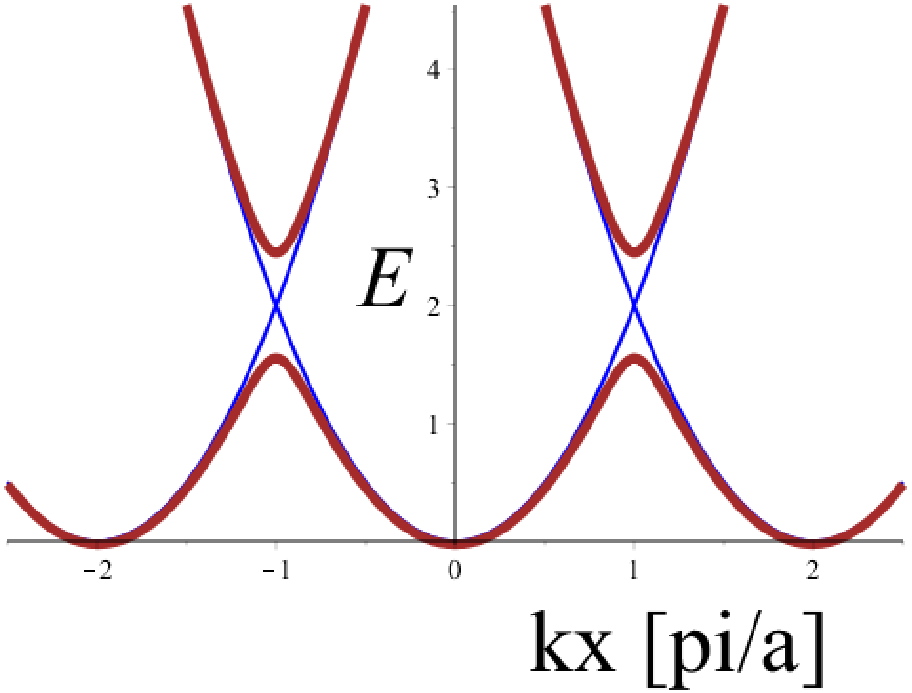
(Incomplete) List of Quasiparticles

Electron	Electronic quasiparticle in metals
Hole	Electronic quasiparticle in metals
Exciton	Bound state of electron and hole
Phonon	Lattice vibration in solids
Roton	Excitation in superfluid Helium 4
Holon	spin separated charge
Spinon	charge separated spin
Soliton	Domain wall
Skyrmion	Topological vortex
Anyon	neither bosons nor fermions
Dirac Fermion	massless fermion

Quasiparticles

! Caution !

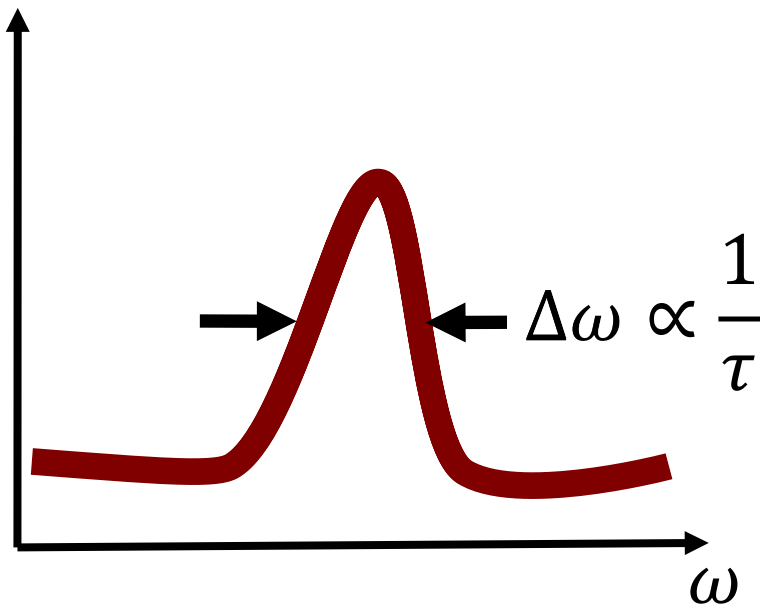
Electron refers to bare electron and electronic quasiparticle



Quasiparticle

Collective Excitation

- Well defined
- Long lived $\frac{1}{\tau} < \omega$



- Model for excitations
- Acts like weakly interacting particle
- Quantum numbers
- Dispersion relation
- Confined to host

$$? \, |0\rangle \, ?$$

Quasiparticle - Relevance

Applications	
• Electrons and Holes	metals & semiconductors industry
• Fluxon	SQUID
• Soliton	computing
• Spinon	spintronics
• Skyrmion	data storage

Fundamental Understanding

- Reductionism
- Emergence

Correlated Electron Systems

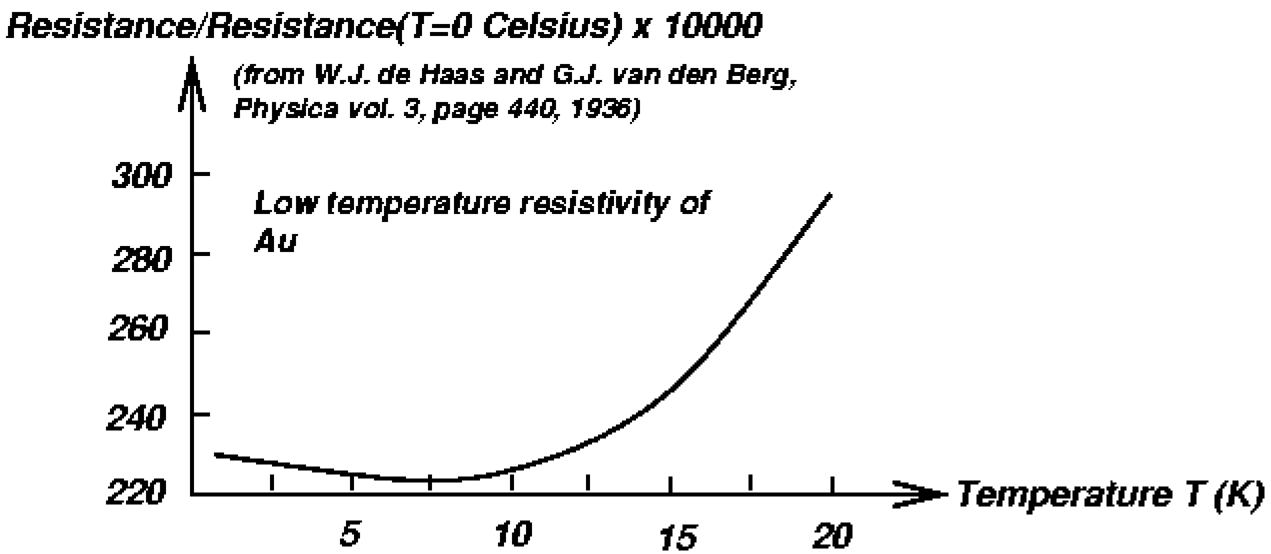
2) The Kondo Effect and Heavy Fermions

Literature

1. AC Hewson: *The Kondo Problem to Heavy Fermions*
2. Coleman, P. *Introduction to Many-Body Physics*.
3. Coleman, P. Heavy Fermions and the Kondo Lattice: a 21st Century Perspective, http://arxiv.org/abs/1509.05769

The puzzle

- Resistance minimum in dilute magnetic alloys



- Cannot be phonon nor electron scattering

$$\rho = \rho_0 + A\,T^2 + B\,T^5$$

The solution

- Kondo effect

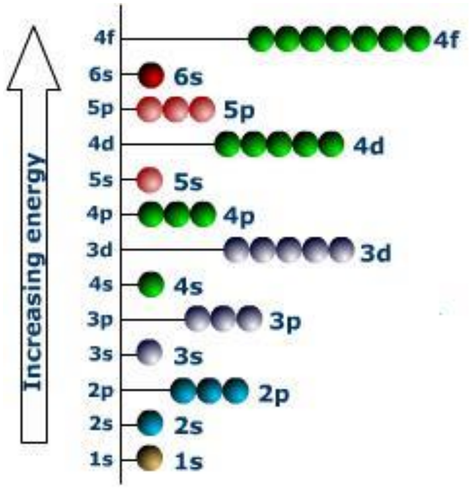
Scattering of conduction electrons on local moments

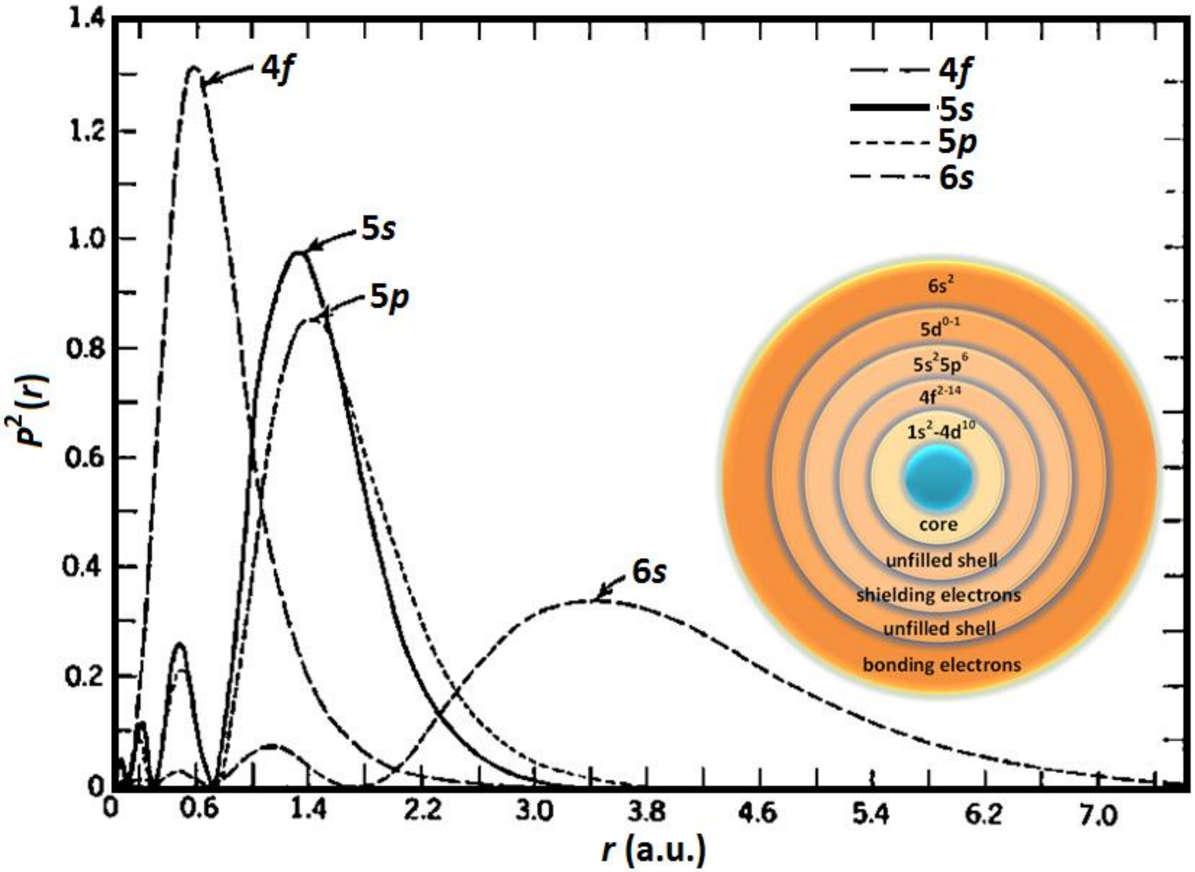
Conduction electrons vs local moments

- Radial extension of electron orbits
- 4f inside 6s shell

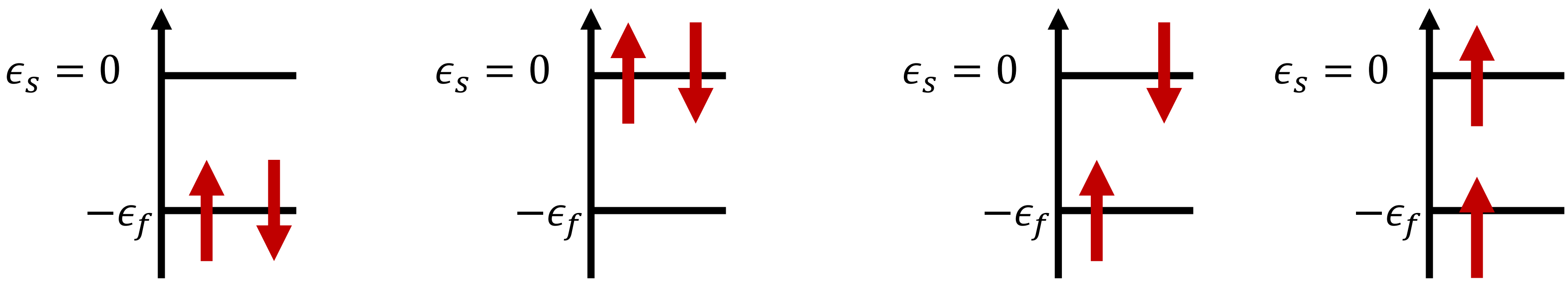
-> 4f localised

- Partial f-shell carries magnetic moment

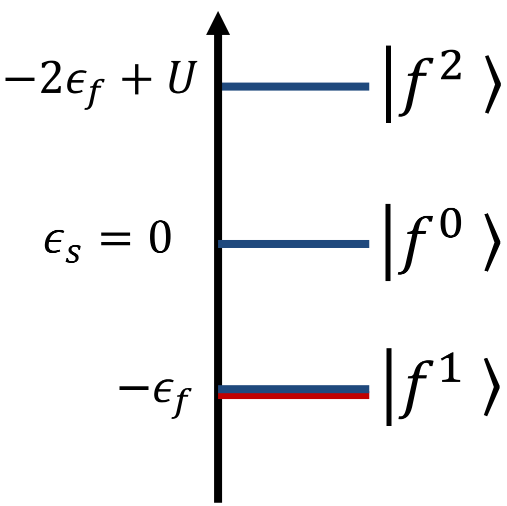




Local Moments in Metallic Host
single particle picture



$|f^2\rangle$ $|f^0\rangle$ $|f^1, s\rangle$ $|f^1, t\rangle$



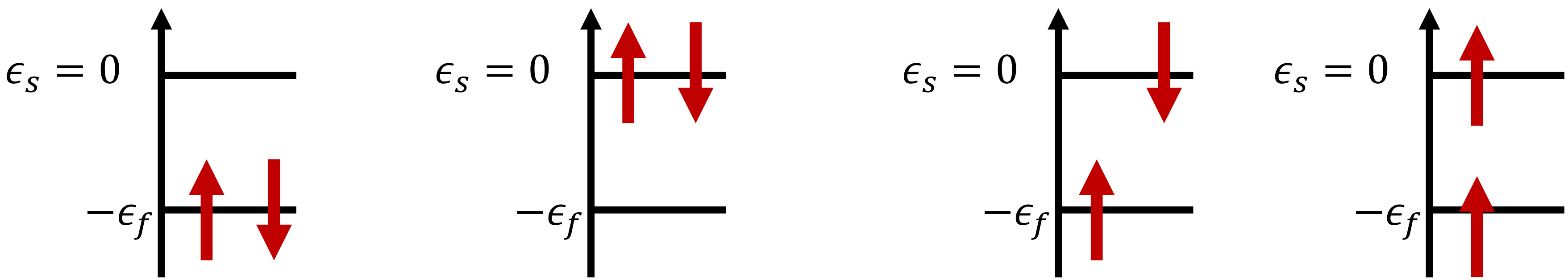
Singlets S=0

Triplet S=1

$$H_f = \epsilon_f n_{f\uparrow} n_{f\downarrow}$$

$$H_I = J\,\boldsymbol{S}\cdot\boldsymbol{s}$$

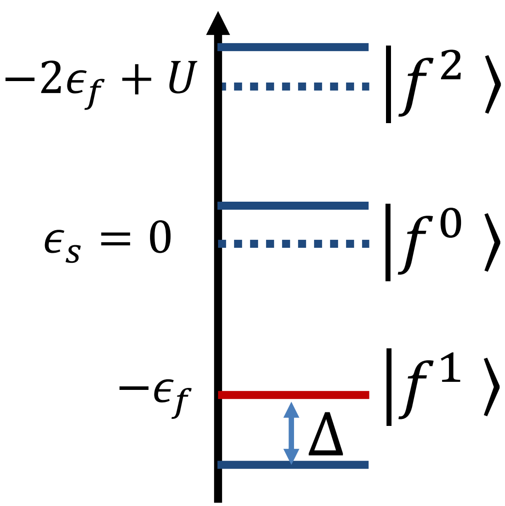
Local Moments in Metallic Host hybridisation V



$|f^2\rangle$ $\quad$ $|f^0\rangle \leftrightarrow |f^1, s\rangle$ $\quad$ $|f^1, t\rangle$

Singlets S=0

Triplet S=1



Hybridisation leads to Energy lowering of singlet state Δ

Kondo effect

- Interaction of Conduction electrons with local moments
- Antiferromagnetic

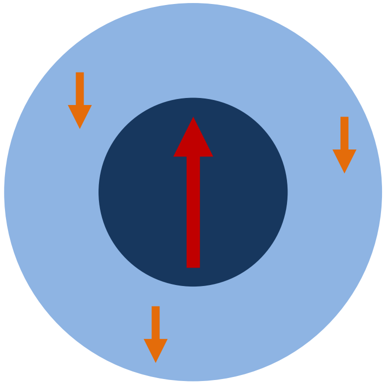
$$H_K = J\boldsymbol{S}\cdot\boldsymbol{s}$$

- Singlet energy lowered by

$$\Delta = -\epsilon_f \exp\left(-\frac{1}{2g(\epsilon_F)J}\right)$$

Kondo temperature

$$\mathrm{T}_K \approx \frac{\Delta}{k_B}$$



- Additional states at Fermi level

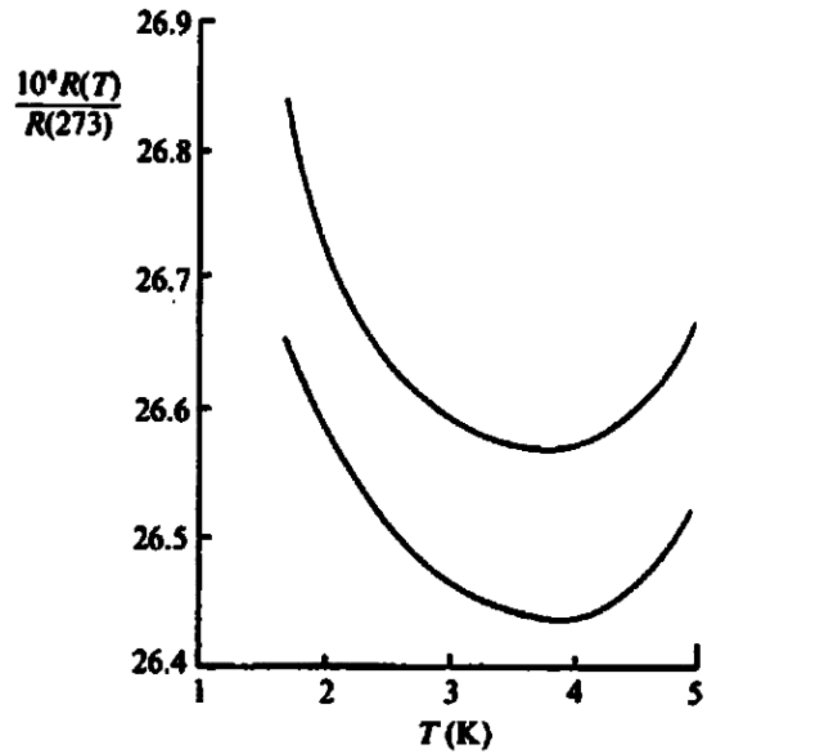
Resistance minimum

- Scattering rate

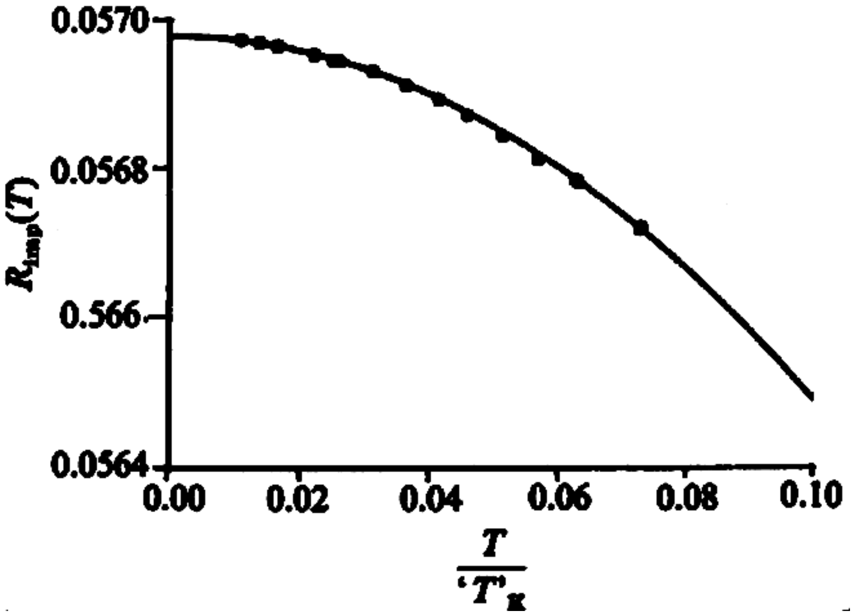
$$\frac{1}{\tau} \propto \left[Jg(\epsilon_F) + 2\big(Jg(\epsilon_F)\big)^2 \ln\left(\frac{T_\mathrm{K}}{T}\right) \right]$$

- Pertubation theory predicts log divergence for single impurities

$$\rho = \rho_0 + A\,T^2 + B\,T^5 + c_f \ln\left[\frac{T_K}{T}\right]$$



- Small problem:
- Logarithmic divergence
- Experiment shows saturation
- Can be explained by Kondo lattice model



Heavy Fermions

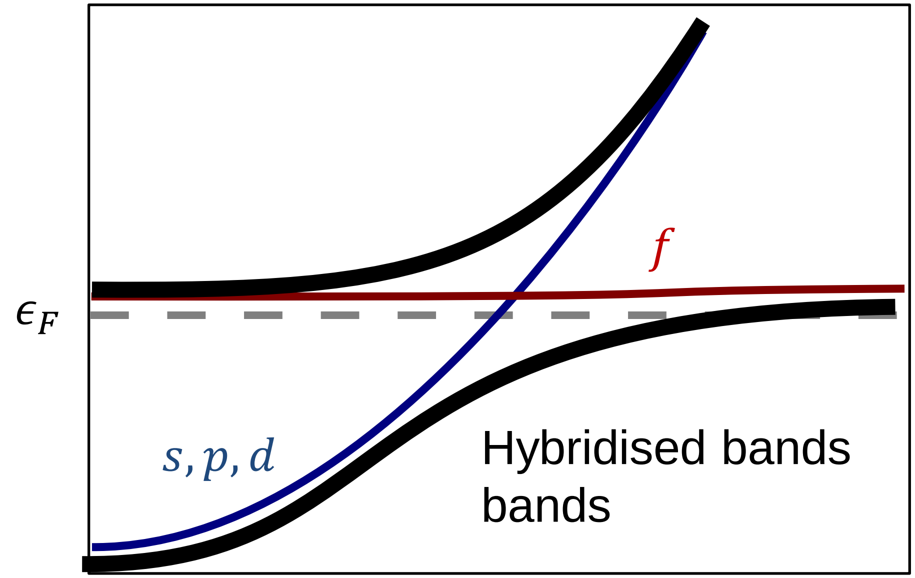
Lattice of magnetic moments

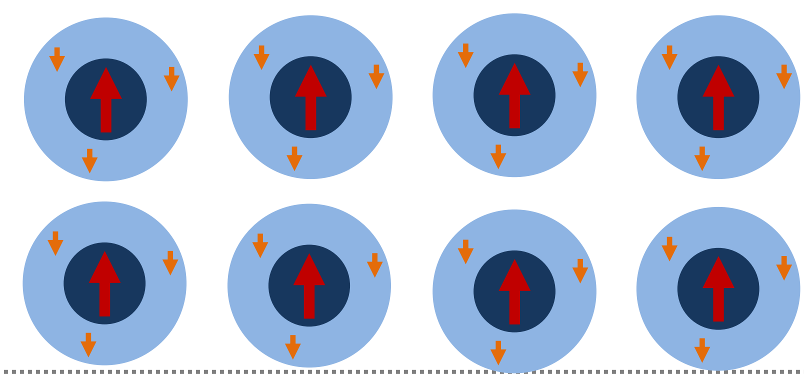
- Ce, Yb, U
- E.g. $CeCu_2Si_2$

hybridisation in Kondo Lattice

- Conduction band
- f-states at Fermi level
- Form new bands with large density of states
- Electronic quasiparticles

-> high effective mass

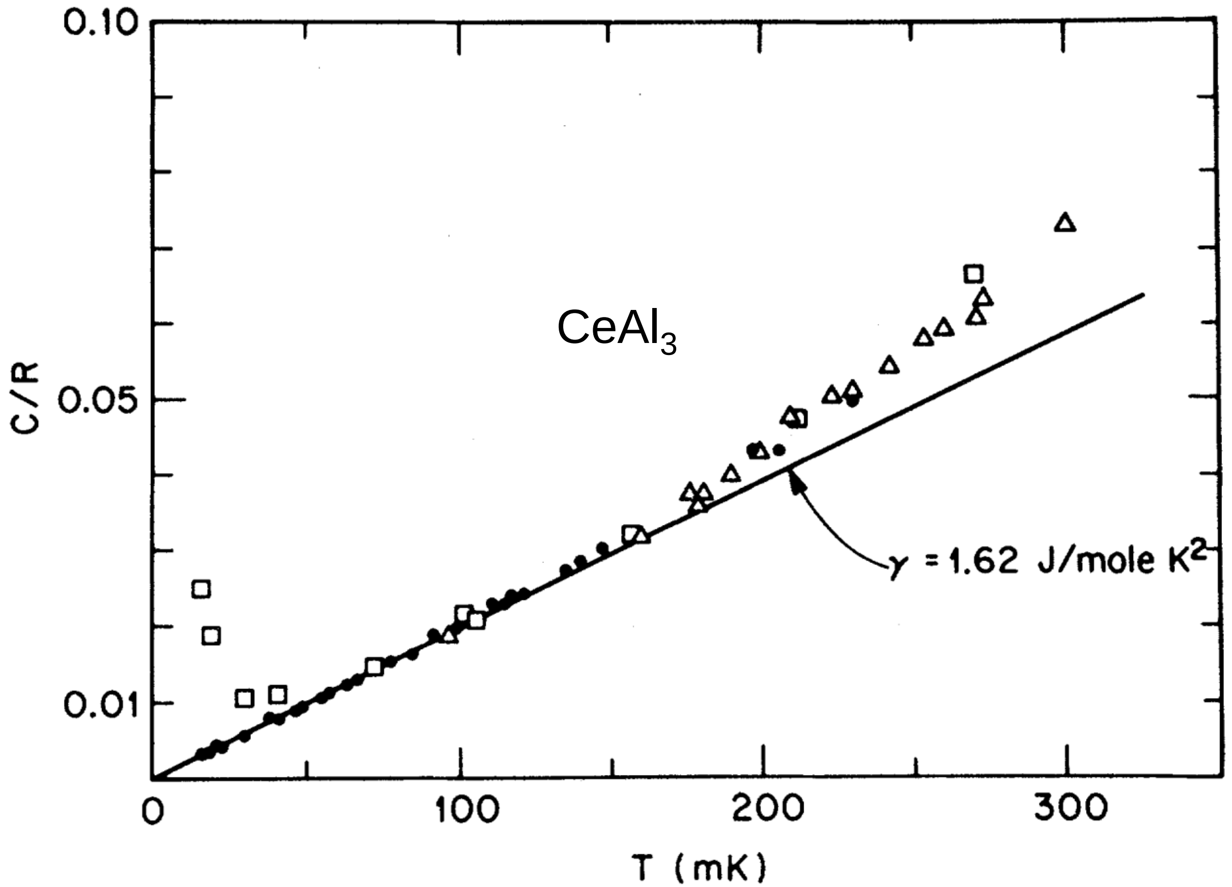




Heavy Fermions – Heat Capacity

$$\gamma = \frac{m^* k_F k_B^2}{3\hbar^3}$$

1000 times larger than Copper

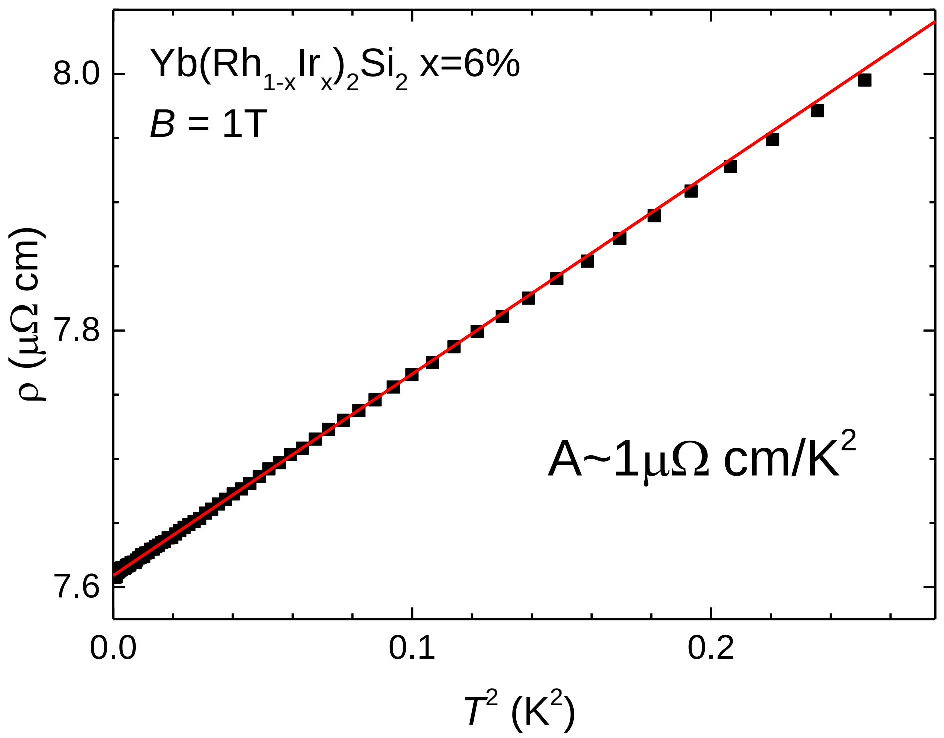


Andres, K, et al., PRL 35 1779 (1975)

Heavy Fermions – Electrical Resistivity

$$\rho = \rho_0 + AT^2$$

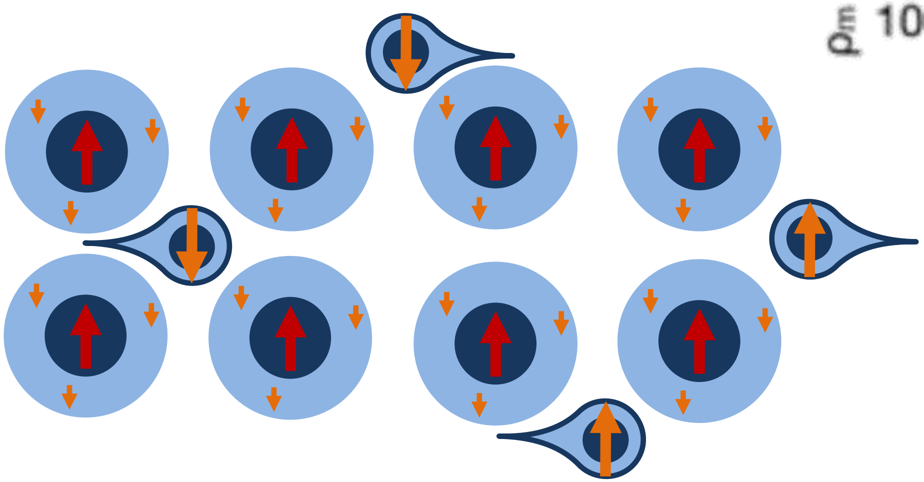
- Prefactor $A \propto g(E_F)^2$
- small for normal metals
  $A \sim 10^{-3} \mu\Omega\,\mathrm{cm/K^2}$
- Very much increased in Heavy Fermions

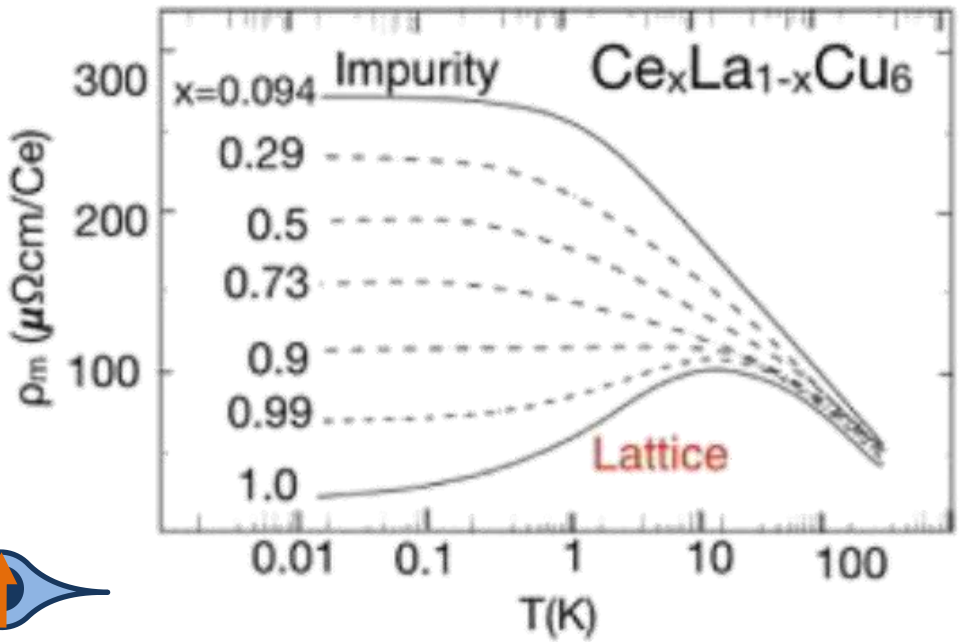


Heavy Fermions – Electrical Resistivity

- Coherent Transport at low temperature
- Single ion Kondo effect at high temperature

-> maximum around T_K





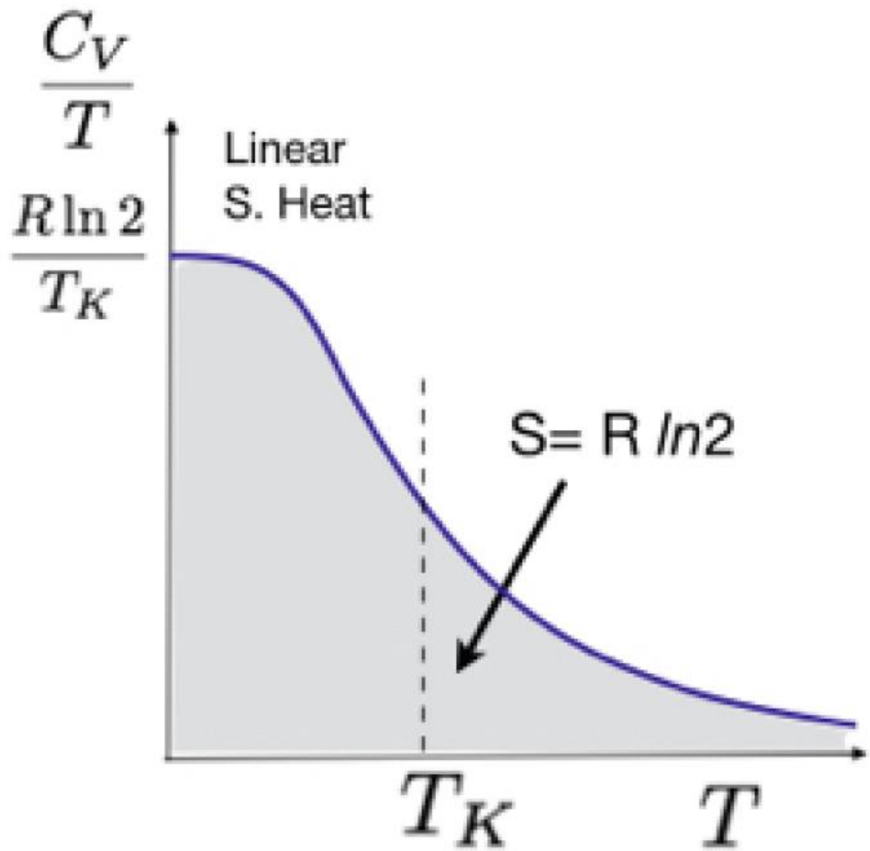
Heavy Fermions – Heat Capacity

- Fermi-liquid behaviour at low temperatures

$$\frac{C}{T} = \text{const.}$$

- Crossover around T_{K}
- Entropy corresponds to local moment

$$\frac{m^*}{m} = 1 + \frac{1}{3}F_1^s$$



Magnetic Susceptibility

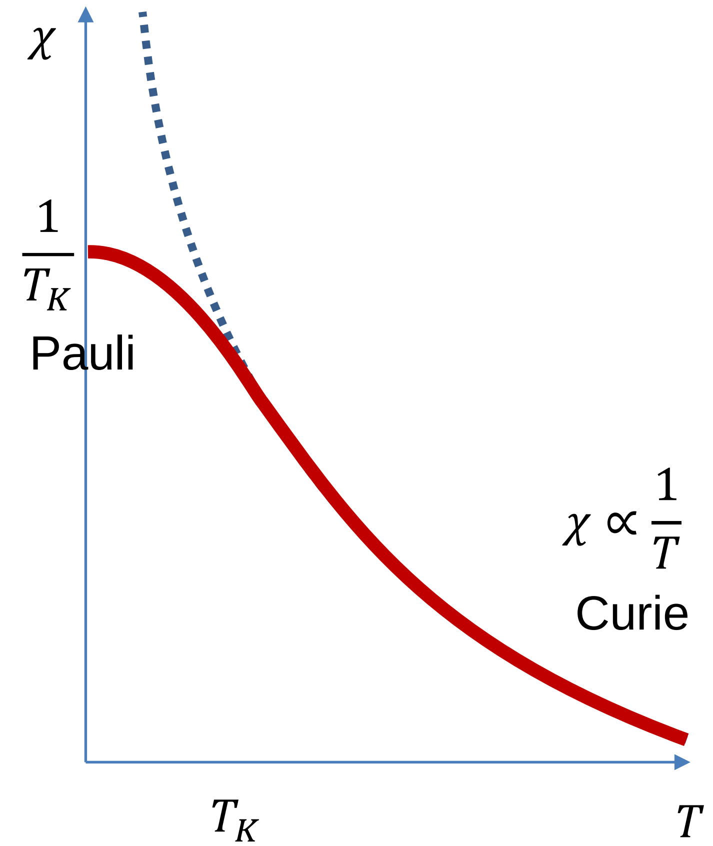
High T:

- free moments
- Curie

Low T:

- Screened moments
- Pauli
- Enhanced $(1/T_K)$

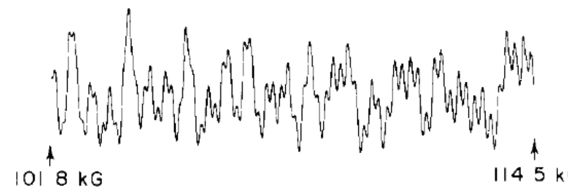
$$\chi_P = \frac{\mu_0 \mu_B^2 g(E_F)}{1 + F_0^a}$$

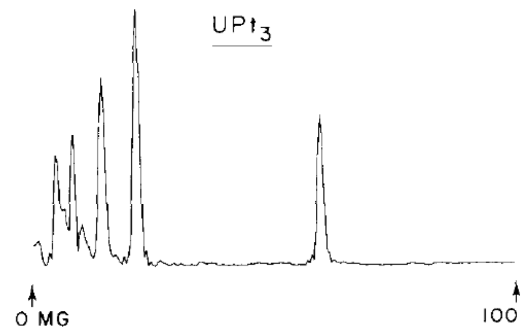


Heavy Fermions – Fermi Surface

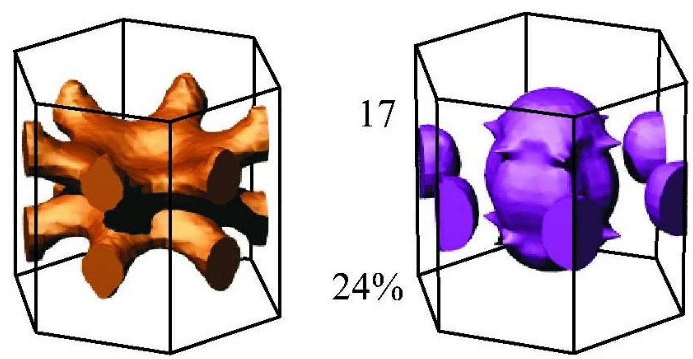
„Large" Fermi Surface detected with Quantum Oscillations

- Proof for Quasiparticle
- High mass





F (T)	m^*/m_0	$10^{-3}v_k^*$ (m·s^{-1})
200 ± 100	80 ± 10	. . .
1300 ± 20	24 ± 2	9.6
1034 ± 5	40 ± 2	5.1
740 ± 10	23 ± 1	7.5
638 ± 10	14 ± 1	11.5
210 ± 10	. . .	. . .
122 ± 2	6.0 ± 0.2	11.6
40 ± 4	11 ± 3	3.7

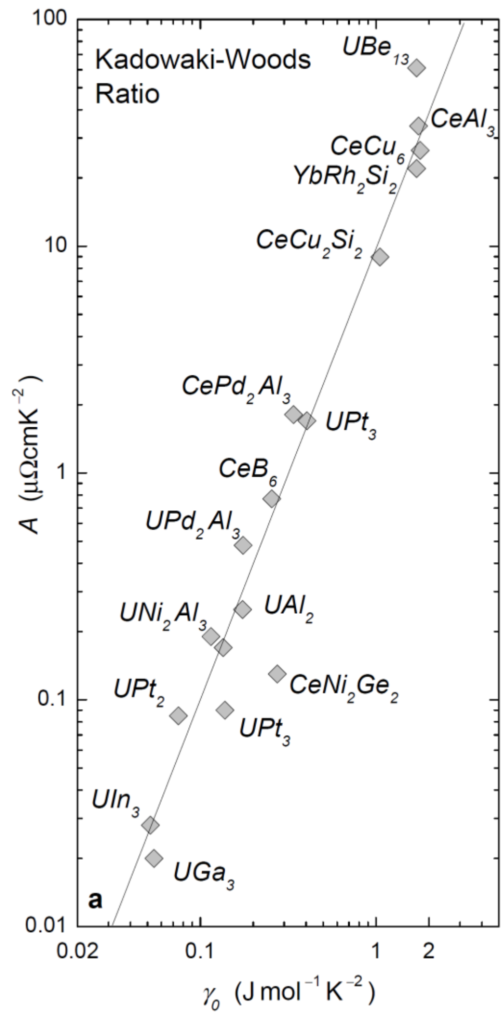


Kadowaki Woods ratio in HF

- Constant ratio of Sommerfeld and resistivity coefficients
- Observed in heavy fermion compounds
- Spanning many orders of magnitude

$$\frac{A}{\gamma^2} = const \approx 10\ \mu\Omega\,\mathrm{cm\,mol^2K^2J^{-2}}$$

Kadowaki, K. & Woods, S. B. *Solid State Commun.* **58,** 507–509 (1986).

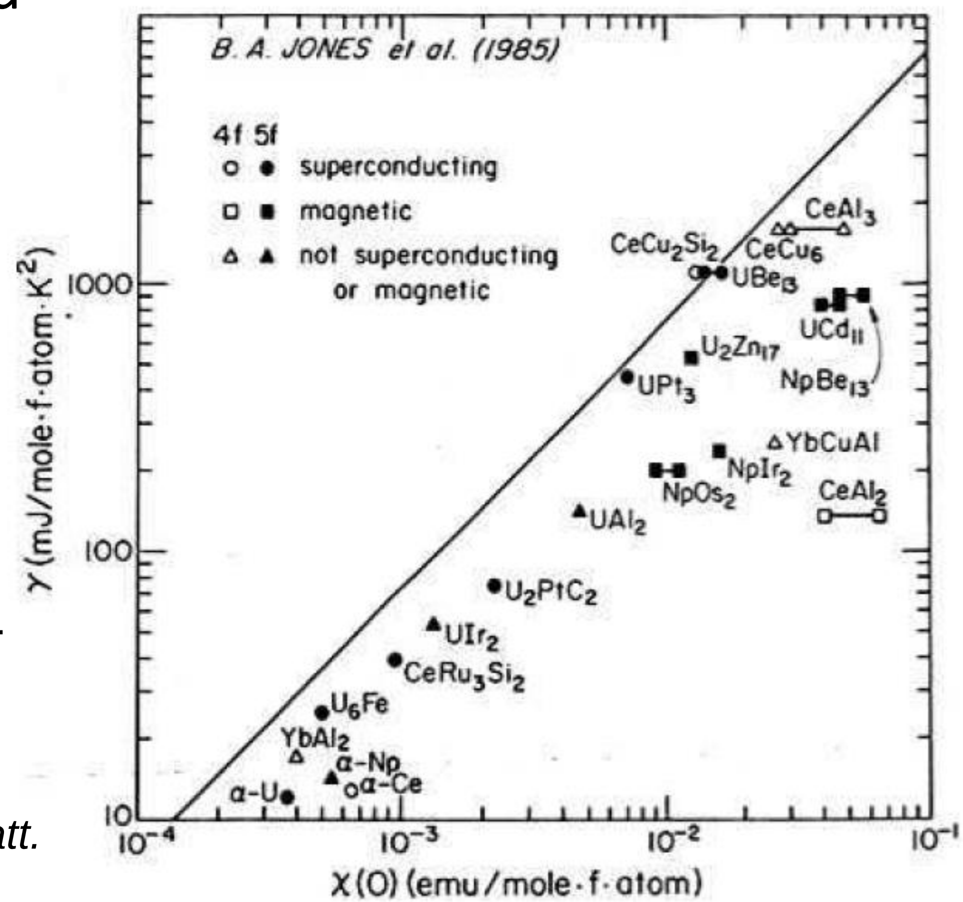


Sommerfeld-Wilson Ratio

- Constant ratio of Sommerfeld coefficient and susceptibility
- Direct measure for Landau parameter
- Spanning many orders of magnitude

$$SWR = \frac{\chi_0}{\gamma_0} = \frac{1}{1+F_0^a} \frac{3\mu_0\mu_{eff}^2}{\pi^2 k_B^2}$$

Lee, P. A., et al. *Comments Condens. Matt. Phys.* **12,** 99 (1986).



Evidence for heavy Quasiparticles

- ✓ Specific heat $C = \gamma T$
- ✓ Resistivity $\rho - \rho_0 = AT^2$
- ✓ $\frac{A}{\gamma^2} = const$
- ✓ $SWR = \frac{\chi_0}{\gamma_0} = \frac{1}{1+F_0^a}$
- ✓ Wiedemann-Franz
- ✓ Fermi surface
- ✓ …

- Should be able to do all the things a quasiparticle can do…

Heavy Fermion – Superconductivity

- Large jump in Specific heat
- Consistent with Rutgers formula

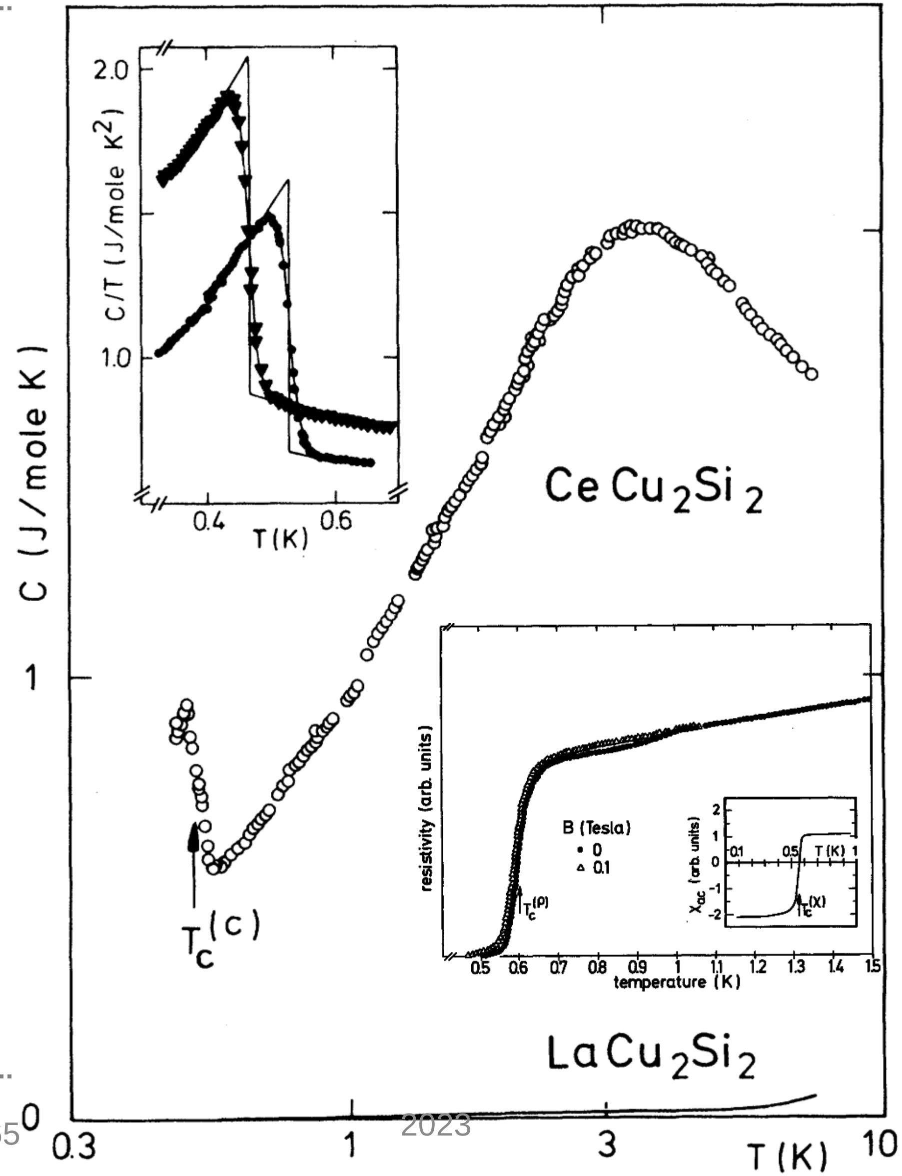
$$\Delta C = 1.43\, \gamma\, T_c$$

✓ Heavy electrons forming superconductor

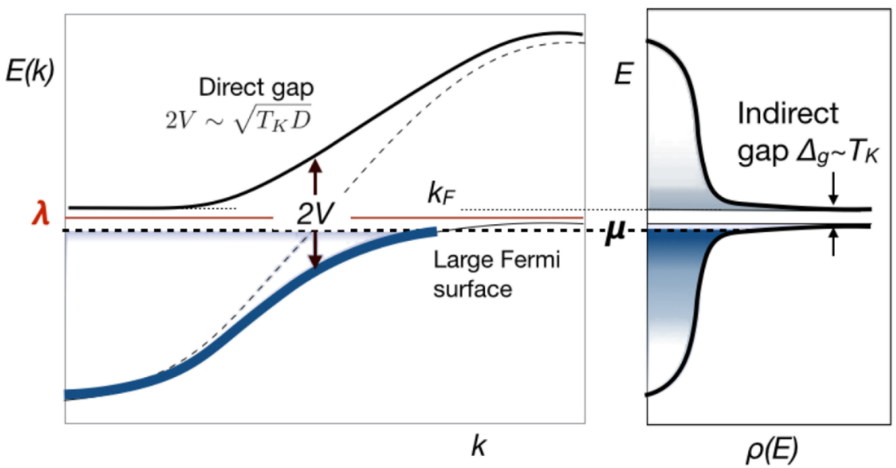
- Superconductivity in material with magnetic moments
- Retardation not possible with phonons

✓ Unconventional

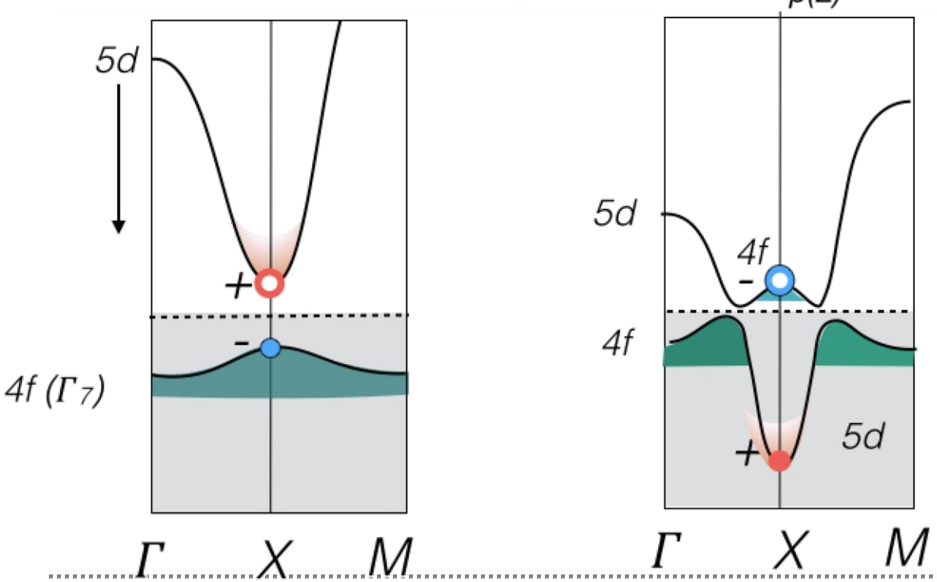
Steglich 1979



(Topological) Kondo Insulators



- Hybridisation band gap at ϵ_F
- Insulator at below T_K



- Topological as parity between f and s, d is opposite
- -> no adiabatic connection between bulk and vacuum
- -> metallic surface state