

# Unconventional Superconductivity in Heavy Fermion Systems

Changkai Zhang

Fakultät für Physik  
Ludwig-Maximilians-Universität München

High- $T_c$  Superconductivity  
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F. Steglich, S. Wirth, Rep. Prog. Phys. 79 084502 (2016)  
P. Coleman, Heavy Fermions, arXiv:cond-mat/0612006

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- 1 Heavy Fermion Material with Kondo Lattice
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  - Kondo Lattice and Localized Fermions
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# Magnetic Impurities and Kondo Effect

The resistance unexpectedly increases as temperature decreases in Cu and Au-specimens.

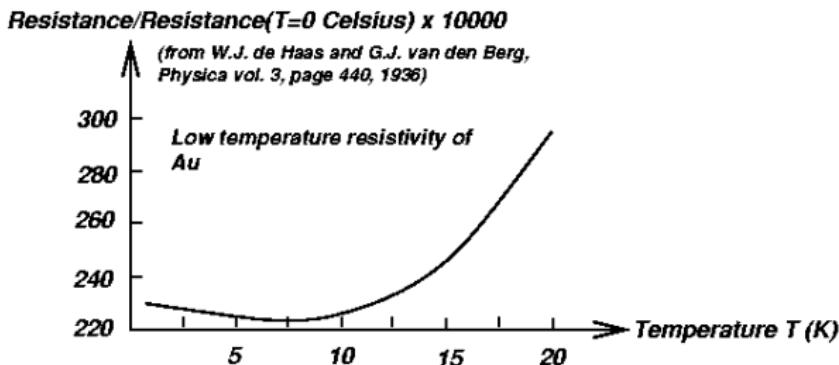


Figure: W. J. de Haas, G. J. van den Berg, *Physica* vol.3 (1936)

The resistance versus temperature of *pure* Au.

Observe an increase of resistance below 8 K.

# Magnetic Impurities and Kondo Effect

Magnetic impurities (e.g. Fe, Ce) can scatter conduction electrons and lead to extra resistance.

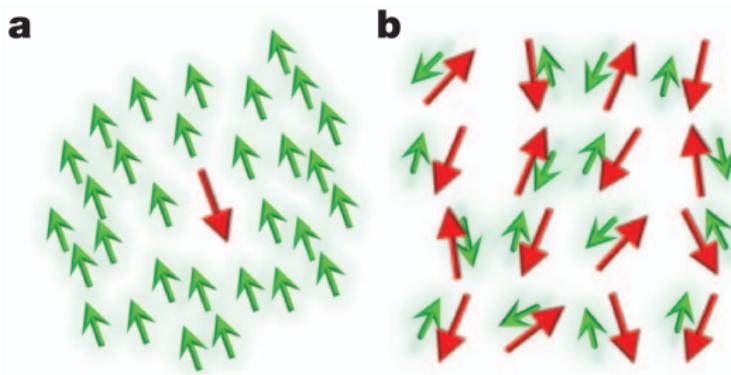


Figure: P. Aynajian, A. Gyenis et al. *Nature* **486**, 201–206 (2012)

Left: Single magnetic impurity screened antiferromagnetically by conduction electrons.

Right: Kondo lattice created by 100% magnetic impurity doping.

# Magnetic Impurities and Kondo Effect

Jun Kondo explained this by the AF coupling between the spin of localized  $3d$  or  $4f$  electrons & that of conduction electrons.

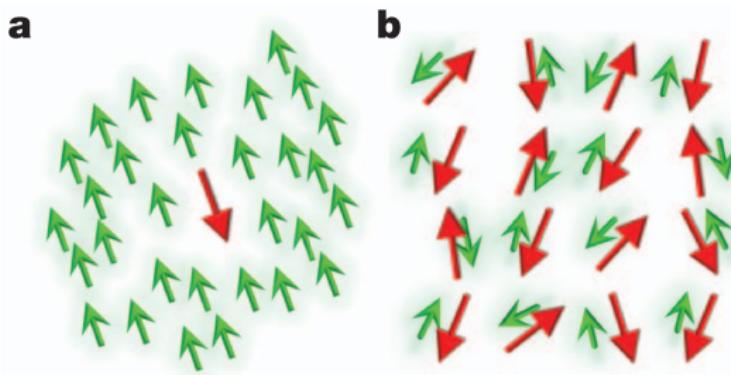


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Left: Single magnetic impurity screened antiferromagnetically by conduction electrons.

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# Anderson Impurity Model

In 1961, Anderson gave the first microscopic model for the formation of magnetic moments in metals:

$$H = \sum_{k,\sigma} \epsilon_k n_{k\sigma} + E_f n_f + U n_{f\uparrow} n_{f\downarrow} \\ + \sum_{k,\sigma} V(k) [c_{k\sigma}^\dagger f_\sigma + f_\sigma^\dagger c_{k\sigma}]$$

where the first line is the kinetic terms of conduction and 4f electrons and the interaction between 4f electrons; the second line describes the interaction between conduction electrons and impurity spins.

# Experimental Platform Using Lathanide Elements

## PERIODIC TABLE OF ELEMENTS

Atomic Number	Symbol	Name	Chemical Group Block
1	H	Hydrogen	Nonmetal
3	Li	Lithium	Alkali metal
11	Na	Sodium	Alkali metal
19	K	Potassium	Alkali metal
37	Rb	Rubidium	Alkali metal
55	Cs	Cesium	Alkali metal
87	Fr	Francium	Alkali metal
4	Be	Beryllium	Alkaline earth metal
12	Mg	Magnesium	Alkaline earth metal
20	Ca	Calcium	Alkaline earth metal
38	Sr	Samarium	Alkaline earth metal
56	Ba	Boron	Alkaline earth metal
88	Ra	Rutherfordium	Alkaline earth metal
21	Sc	Samarium	Transition metal
39	Y	Yttrium	Transition metal
40	Zr	Zirconium	Transition metal
41	Nb	Niobium	Transition metal
42	Mo	Molybdenum	Transition metal
72	Hf	Hafnium	Transition metal
73	Ta	Tantalum	Transition metal
74	W	Tungsten	Transition metal
104	Rf	Rutherfordium	Transition metal
105	Db	Dubnium	Transition metal
106	Sg	Singeenium	Transition metal
57	La	Lanthanum	Lanthanide
58	Ce	Cerium	Lanthanide
59	Pr	Praseodymium	Lanthanide
60	Nd	Neodymium	Lanthanide
61	Pm	Promethium	Lanthanide
62	Sm	Samarium	Lanthanide
63	Eu	Europium	Lanthanide
64	Gd	Gadolinium	Lanthanide
65	Tb	Terbium	Lanthanide
66	Dy	Dysprosium	Lanthanide
67	Ho	Holmium	Lanthanide
68	Er	Erbium	Lanthanide
69	Tm	Thulium	Lanthanide
70	Yb	Ytterbium	Lanthanide
71	Lu	Lucentium	Lanthanide
89	Ac	Actinium	Actinide
90	Th	Thorium	Actinide
91	Pa	Protactinium	Actinide
92	U	Uranium	Actinide
93	Np	Neptunium	Actinide
94	Pu	Futherfordium	Actinide
95	Am	Americium	Actinide
96	Cm	Gutium	Actinide
97	Bk	Berillium	Actinide
98	Cf	Cerium	Actinide
99	Es	Eschenium	Actinide
100	Fm	Fermium	Actinide
101	Md	Mendelevium	Actinide
102	No	Noberium	Actinide
103	Lr	Lanthanum	Actinide

# Kondo Lattice and Localized Fermions

Kondo effect can be studied by La-based material doped by Ce as magnetic impurities. 100% doping creates Kondo lattice.

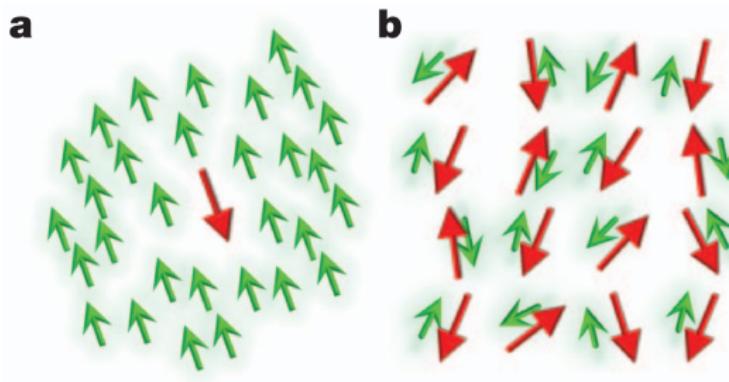


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Left: Single magnetic impurity screened antiferromagnetically by conduction electrons.

Right: Kondo lattice created by 100% magnetic impurity doping.

# Kondo Lattice Model

In 1961, Anderson gave the first microscopic model for the formation of magnetic moments in metals:

$$H = \cdots + \sum_{k,\sigma} V(k) [c_{k\sigma}^\dagger f_\sigma + f_\sigma^\dagger c_{k\sigma}]$$

Kondo lattice model of heavy fermion systems is simply a periodic version of the Anderson impurity model:

$$\begin{aligned} H = & \sum_{k,\sigma} \epsilon_k n_{k\sigma} + \sum_{j,\sigma} E_f n_{j,\sigma}^f + U \sum_j n_{j\uparrow}^f n_{j\downarrow}^f \\ & + \frac{V}{\sqrt{N}} \sum_{k,j,\sigma} [c_{k\sigma}^\dagger f_{j,\sigma} e^{-ik \cdot j} + f_{j,\sigma}^\dagger c_{k\sigma} e^{ik \cdot j}] \end{aligned}$$

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# Band Structure in Heavy Fermion Materials

Hybridization between  $4d$  electrons and conduction electrons gives rise to a peak in the quasi-particle density of states.

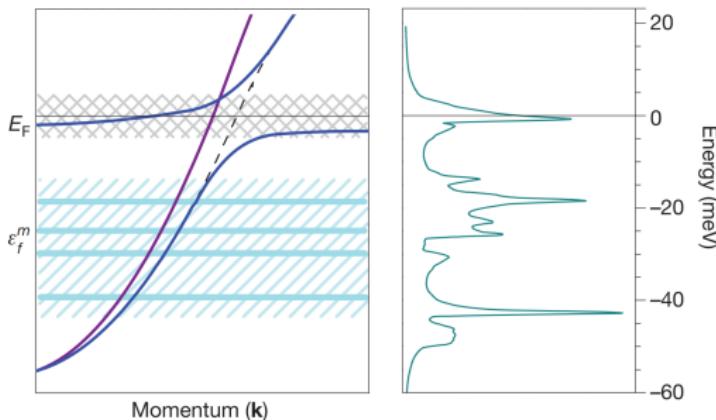


Figure: S. Ernst, S. Kirchner et al. *Nature* **474**, 362–366 (2011)

Left: Renormalized energy band structure of quasi-particles. Flat band occurs near Fermi energy.

Right: Renormalized quasi-particle density of states. A peak emerges near Fermi energy.

# Consequences of Heavy Fermions

Flat energy band implies:

- Large electron effective mass
- Large density of states
- Highly localized wave function

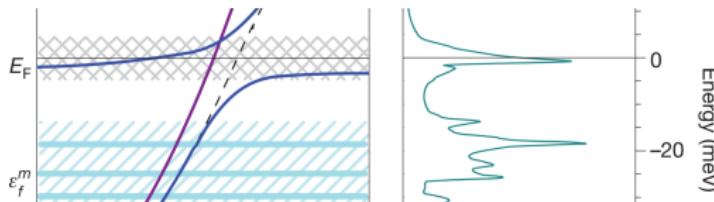


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# Magnetic Impurities & BCS Superconductivity

Magnetic impurities introduces spin-exchange scattering of conduction electrons off the local  $4f$ -shell.

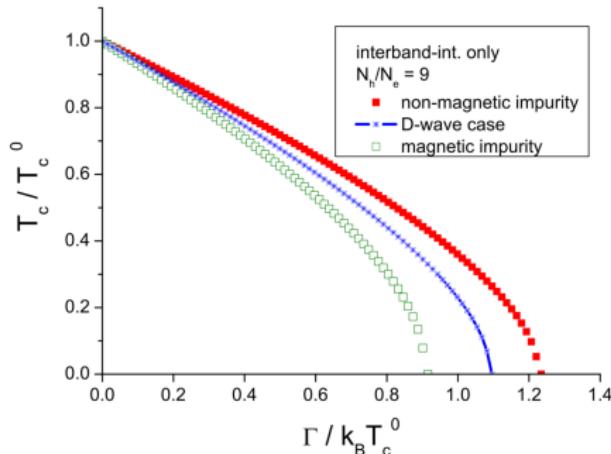


Figure: Y. Bang, H. Choi, H. Won, Phys. Rev. B **79**, 054529 (2009)

Normalized critical temperature versus normalized impurity scattering strength.  
Critical temperature drops to zero as the amount of magnetic impurities increase.

# Unconventional Superconductivity in CeCu<sub>2</sub>Si<sub>2</sub>

CeCu<sub>2</sub>Si<sub>2</sub> was discovered to have unconventional bulk superconductivity below  $T_c \approx 0.6$  K.

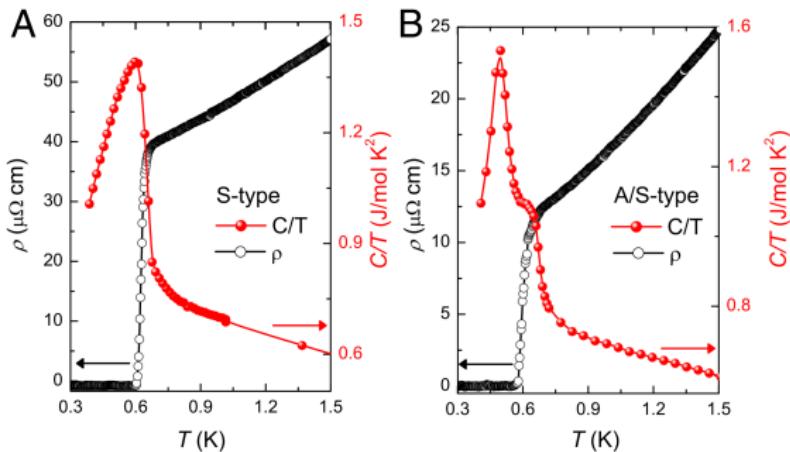


Figure: G. Pang, M. Smidman, J. Zhang et al. PNAS, 115(21) (2018)

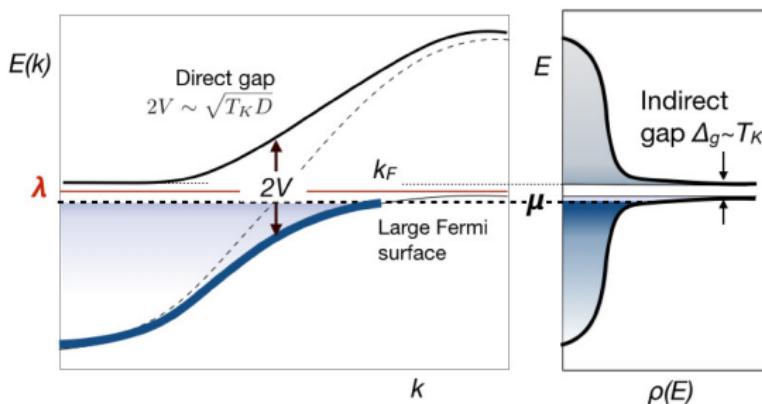
Specific heat and resistivity of S-type (superconducting) CeCu<sub>2</sub>Si<sub>2</sub> and S/A-type (superconducting/antiferromagnetic) CeCu<sub>2</sub>Si<sub>2</sub>.

# Unconventional Superconductivity in $\text{CeCu}_2\text{Si}_2$

- Non-magnetic reference system  $\text{LaCu}_2\text{Si}_2$  (replacing Ce with La) is not superconducting.
- Doping with non-magnetic impurities in  $\text{CeCu}_2\text{Si}_2$  destroys superconductivity.
- High-quality single crystals of  $\text{CeCu}_2\text{Si}_2$  grown in 1983 confirms the finding.
- Same year, heavy fermion superconductivity was reported for U-based materials, e.g.  $\text{UPt}_3$ ,  $\text{U}_2\text{PtC}_3$ ,  $\text{URu}_2\text{Si}_2$ .
- Electron-phonon interaction can not account for the superconductivity. New pairing mechanism must be operational.

# Small Band Gap Created by Hybridization

Hybridization between conduction and  $4f$  electrons opens a small band gap which can lead to insulating states.



**Figure:** Piers Coleman, arXiv:1509.05769

Left: Dispersion for the Kondo lattice mean-field theory.

Right: Renormalized density of states, showing a *hybridization gap*.

# Kondo Insulating States in SmB<sub>6</sub>

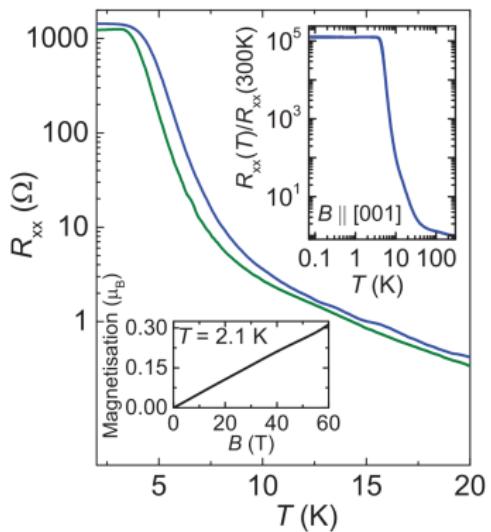


Figure: B. S. Tan et al, Science 349 6245 (2015)

Main: Resistance as a function of temperature on a  $\text{SmB}_6$  sample.

Top inset: Logarithmic plot of measured resistance from 80 mK up to high temperatures.

# Kondo Screening vs RKKY Interaction

Kondo screening and fundamental magnetic RKKY interaction are two competing interactions depending on the exchange integral  $J$ .

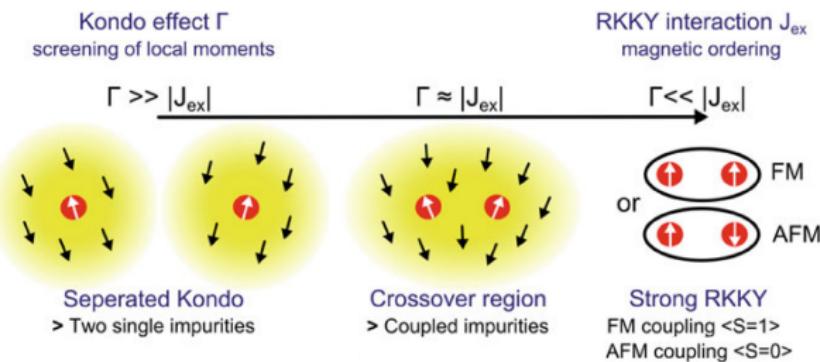


Figure: H. Prüser, *Springer Thesis*, Springer (2014)

Kondo effect and RKKY interaction between two magnetic impurities.  
 Two competing interactions create two phases and a quantum critical point.

# Emerging Quantum Critical Point

A quantum critical point (QCP) emerges at zero-temperature between the AF phase and heavy Fermi liquid phase.

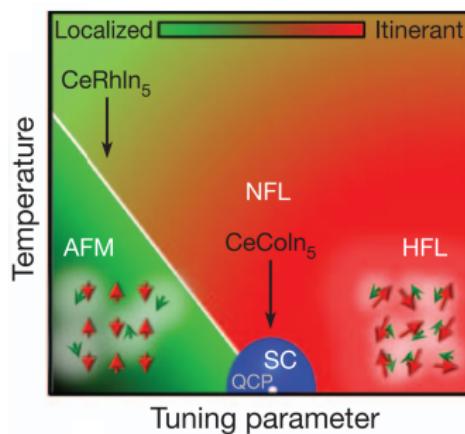


Figure: P. Aynajian, A. Gynis et al. *Nature* **486**, 201–206 (2012)

Schematic phase diagram of heavy fermion systems, where the electronic ground state can be tuned from antiferromagnetism to a heavy Fermi liquid.

# Mechanism of Heavy Fermion Materials

One of the most interesting questions is the microscopic origin of heavy fermion superconductivity:

- U-based: antiferromagnetic fluctuations
- CeCu<sub>2</sub>Si<sub>2</sub>: *valence* charge fluctuations
- PrOs<sub>4</sub>Sb<sub>12</sub>: plus quadrupole fluctuations
- UCoGe: Ferromagnetic spin fluctuations

# How Strong is Heavy Fermion Superconductivity?

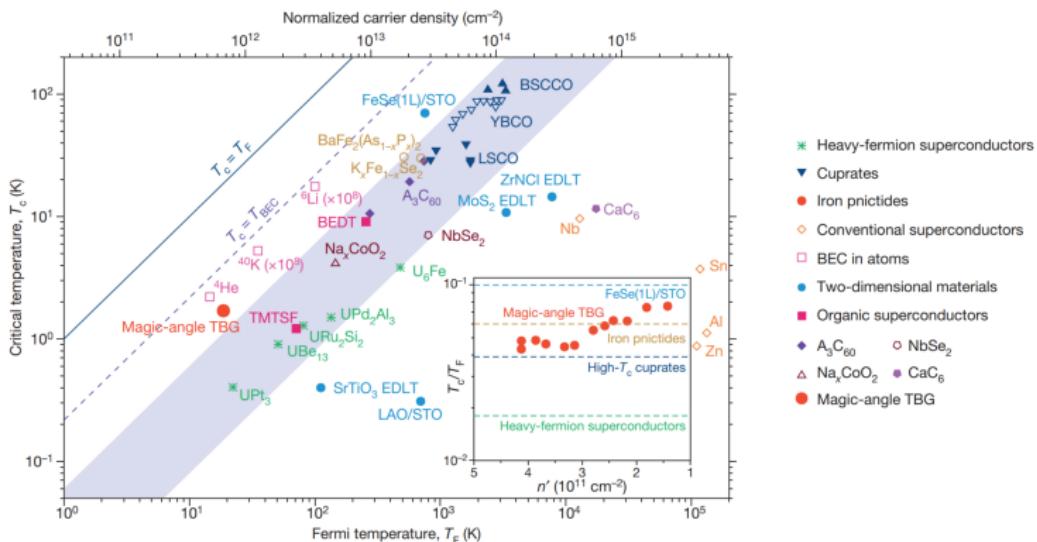


Figure: Cao Y et al. Nature, 2018, 556(7699): 43.

Logarithmic plot of critical temperature  $T_c$  vs Fermi temperature  $T_F$  for various superconductors  
 Heavy fermion superconductivity is much stronger than conventional BCS superconductivity.

# Summary

- Localized electrons have an enormous effective mass, leading to a flat energy band and thus a large density of states, which allows unconventional strong correlated physics to emerge.
- Hybridization between  $4f$  electrons of magnetic impurities and conduction electrons creates localized profile and thus heavy fermions.
- Unconventional superconductivity much stronger than BCS has been observed in heavy fermion systems near the quantum critical point between the antiferromagnetism and the heavy Fermi liquid.