# Low-Temperature Physics of Strongly Correlated Electrons

The study of electronic correlations in condensed matter has led to the discovery of various fascinating phenomena which also have strong technological impact. Functional materials often display different states like magnetic – nonmagnetic or metallic – insulating, which compete with each other. This competition is strongest near quantum critical points, where condensed matter undergoes smooth transformations from one quantum phase to another. The driving fluctuations are both collective and quantum mechanical, leading to emergent low-temperature phases with fascinating properties such as diverging charge carrier masses or high-temperature superconductivity. In order to study quantum criticality, clean, high-quality samples are required. The group synthesises single- and polycrystals as well as thin films of rare-earths based heavy-fermion metals, ruthenates, and iron-pnictides using various techniques. Thermodynamic, magnetic and transport experiments are performed down to temperatures as low as 10 mK and in magnetic fields up to 18 Tesla.

## Quantum criticality

Recently, a strategy for the discovery of novel quantum phases in condensed matter has been found, which is based on the continuous suppression of magnetic order by suitable variation of a non-thermal parameter, as indicated in Figure 1. Heavy-fermion metals are prototype systems to investigate quantum critical points. They contain a dense lattice of instable f-moments embedded in the sea of conduction electrons. Dependent on the strength of their mutual interaction they are either magnetically ordered or paramagnetic at low temperatures. A tiny change in composition, pressure or applied magnetic field could then tip the balance from one to the other side and the strong quantum fluctuations associated with this competition leads to drastic deviations from the standard model of metals, Landau's Fermi liquid theory. This is demonstrated in Figure 2 for quantum critical $YbRh_2Si_2$, which displays a linear, as opposed to quadratic, behavior in the electrical resistivity, accompanied by a divergence of the effective charge carrier masses.

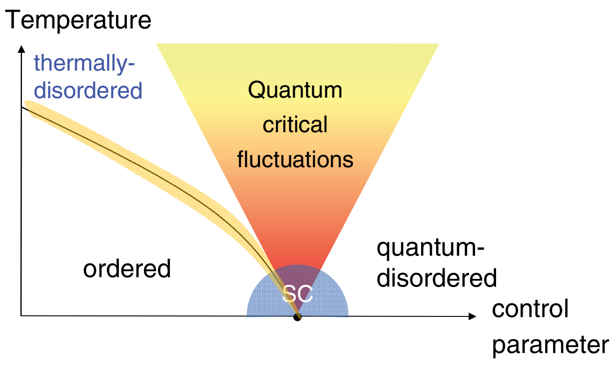



**Fig. 1:** Quantum criticality, arising from the continuous suppression of an ordered state by tuning a non-thermal control parameter such as pressure, doping or magnetic field. The quantum critical state is distinct from the phases at both sides because it contains highly collective low-energy excitations. This type of quantum criticality is often accompanied by a window of superconductivity (SC).

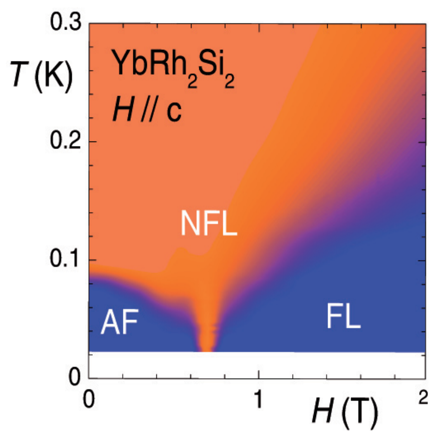



**Fig. 2:** Violation of the Fermi liquid (FL) theory near a quantum critical point. The heavy-fermion system $YbRh_2Si_2$ orders antiferromagnetically (AF) at very low temperatures. The suppression of this order by a magnetic field drives the system through a quantum critical point, above which non-Fermi liquid behavior (NFL) is observed. In this regime, the resistivity varies linearly with temperature as indicated by the orange colour (blue: quadratic behavior), indicating a divergence of the scattering rate of mutual collisions between the charge carriers.

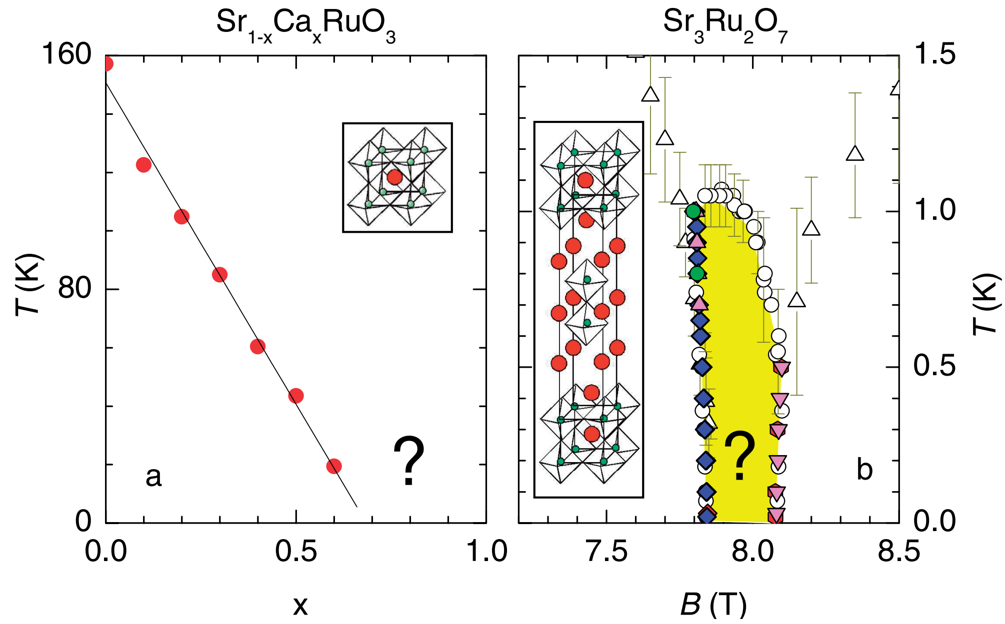



**Fig. 3:** Novel metallic states in cubic (a) and layered ruthenates (b). The red dots in the left panel indicate the ferromagnetic Curie temperature, which is suppressed by Ca-doping x. The low-temperature regime for 0.7 ≤ x ≤ 1 displays signatures of a "non-Fermi liquid" phase. The yellow region in (b) highlights the "electronic nematic phase" of $Sr_3Ru_2O_7$, which occurs in close vicinity to a putative metamagnetic quantum critical end point.

To study the electronic properties near the quantum critical point, high-quality samples are required. The group prepares single crystals of heavy-fermion systems by flux, Bridgeman, and crucible-free floating-zone techniques. For the latter, a four-mirror optical furnace is utilized (see Figure 5) in which large high-quality single crystals can be obtained. After structural, chemical and physical characterization, selected crystals are studied in detail by low-temperature thermodynamic, transport and magnetic techniques using $^3He/^4He$ dilution refrigerators down to 10 mK.

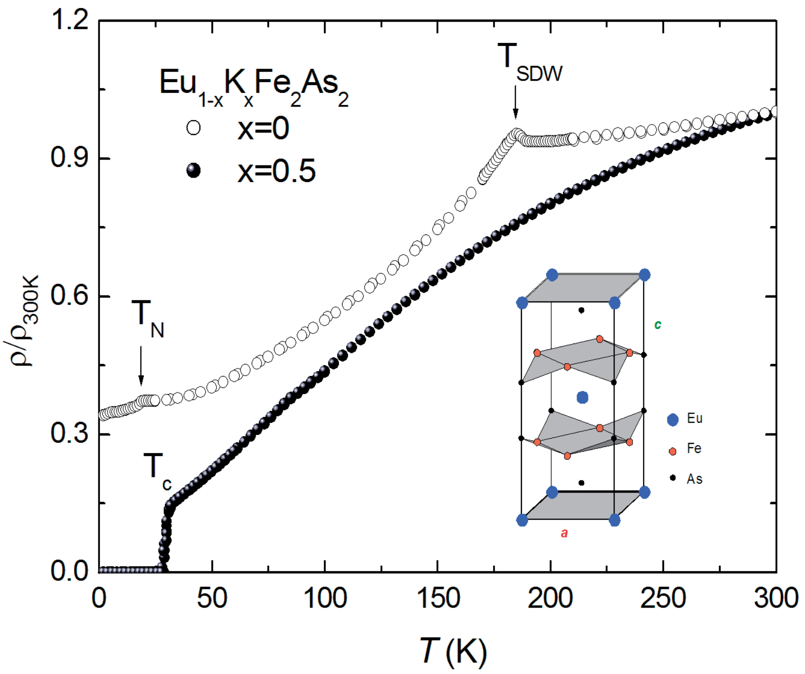
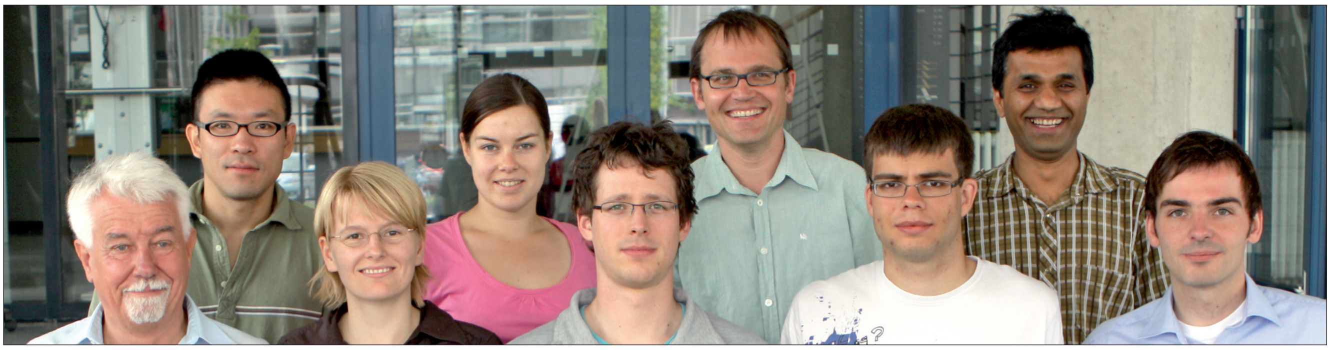



**Fig. 4:** Superconductivity the iron-pnictide $Eu_{1-x}K_xFe_2As_2$. The undoped system (x=0) displays a spin-density-wave (SDW) due to iron 3d-states, as well as a local-moment antiferromagnetic ordering ($T_N$) due to europium 4f-moments. Once the SDW is suppressed by K-doping, superconductivity at 32 K emerges out of a highly unusual normal state with linear resistivity.



## Unconventional superconductivity

Superconductivity (SC), discovered by Heike Kamerlingh Onnes in 1911, is characterized by exactly zero electrical resistance and the exclusion of the interior magnetic field. Until 1979 when heavy-fermion SC was discovered, all superconductors where conventional, i.e. SC is mediated by lattice vibrations and restricted to very low temperatures. By contrast, SC in heavy-fermion systems could be related to the strong magnetic fluctuations near the quantum critical point, as sketched in Figure 1. Further classes of "unconventional" superconductors have been found close to the disappearance of long-range magnetic order, among which the high-Tc cuprate superconductors with transition temperatures up to 160 K are most prominent. SC can even appear in weak itinerant ferromagnets close to the ferromagnetic quantum critical point. Very recently, the observation of transition temperatures up to 56 K in iron-based compounds has attracted much interest. In these systems, layers of iron-pnictides form an antiferromagnetic (spin-density-wave) state. When this magnetic ordering is suppressed by the application of pressure or by suitable doping, unconventional superconductivity emerges as shown in Fig. 4 for the system $Eu_{1-x}K_xFe_2As_2$.

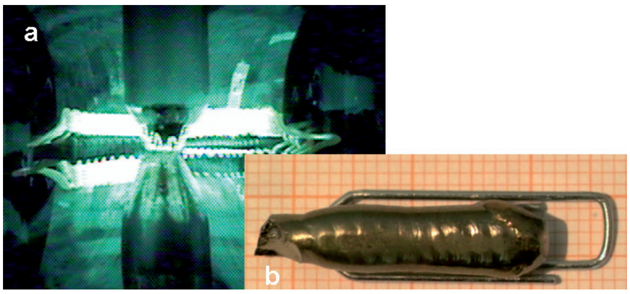



**Fig. 5**: Photographs of the stretched melt at the beginning of the single crystal growth in the image furnace (a) and resulting single crystal of the quantum critical heavy-fermion system $CeNi_2Ge_2$ (b).

## Discontinuous ferromagnetic quantum phase transitions

In contrast to their antiferromagnetic counterparts, ferromagnetic quantum phase transitions are often discontinuous at low temperatures, leading to first-order transitions and electronic phase separation. In some cases, evidence for extended regions in the phase diagram has been found, where Landau's Fermi liquid theory breaks down and novel metallic behavior emerges. The group investigates such states in the ruthenates $Sr_{1-x}Ca_xRuO_3$ and $Sr_3Ru_2O_7$, which crystallize in the cubic and layered perovskite structure, respectively, cf. Figure 3.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### Philipp Gegenwart

Philipp Gegenwart, born in 1967 in Frankfurt/Main, studied Physics at the Darmstadt University of Technology. From 1994 until 1998 he worked on his PhD in the group of Frank Steglich on superconductivity and magnetism in heavy-fermion systems. In 1998, he moved to the Max-Planck Institute for Chemical Physics of Solids (MPI CPFS) in Dresden, where, in 2000, he was appointed head of the competence group "Low Temperatures". The research in his group focused on the rapidly developing field of quantum phase transitions. From 2004-2005 he worked as a visiting scientist at the School of Physics and Astronomy in St. Andrews (Scotland) in the group of Andy Mackenzie on metamagnetic quantum criticality in the bilayer ruthenate $Sr_3Ru_2O_7$. After return to the MPI CPFS in Dresden, he moved to his current position at the Georg-August University in October 2006.