The Abdus Salam International Centre for Theoretical Physics

2357-15

Innovations in Strongly Correlated Electronic Systems: School and Workshop

6 - 17 August 2012

Exploring heavy-fermion quantum criticality in the extreme 3D limit

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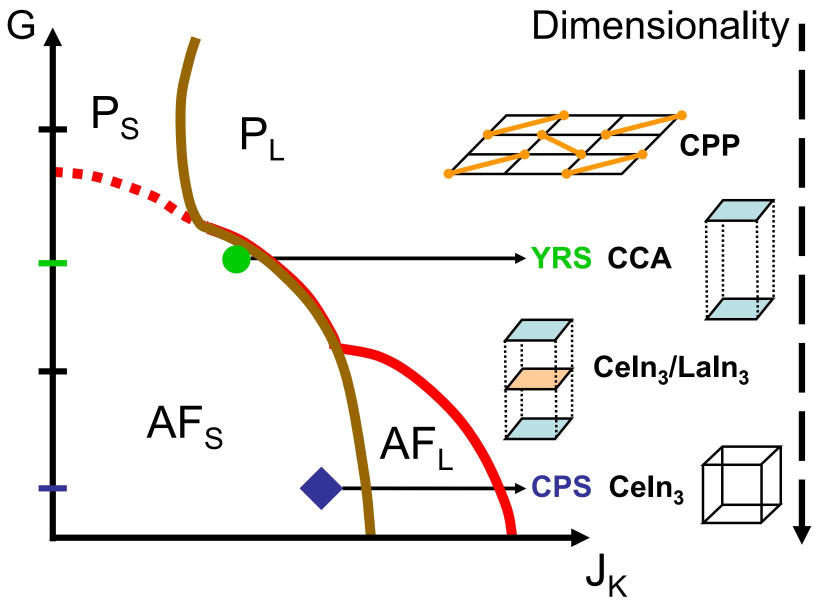

Exploring heavy-fermion quantum criticality in the extreme 3D limit

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- Heavy fermion quantum criticality: Historical perspective
- The case of $YbRh_2Si_2$
- The new *cubic* material $Ce_3Pd_{20}Si_6$
- Materials in the global phase diagram

$Ce_3Pd_{20}Si_6$: J. Custers, J. Hänel, K.-A. Lorenzer, M. Müller, A. Prokofiev, A. Sidorenko, H. Winkler

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Rice University, USA

$YbRh_2Si_2$: S. Friedemann*, P. Gegenwart*, C. Geibel, S. Hartmann*, C. Krellner*, N. Oeschler*, S. Wirth, A. Pikul*, S. Kirchner (& PKS), F. Steglich

Max-Planck-Institut für Chemische Physics fester Stoffe, Dresden

P. Coleman

Rutgers University, USA

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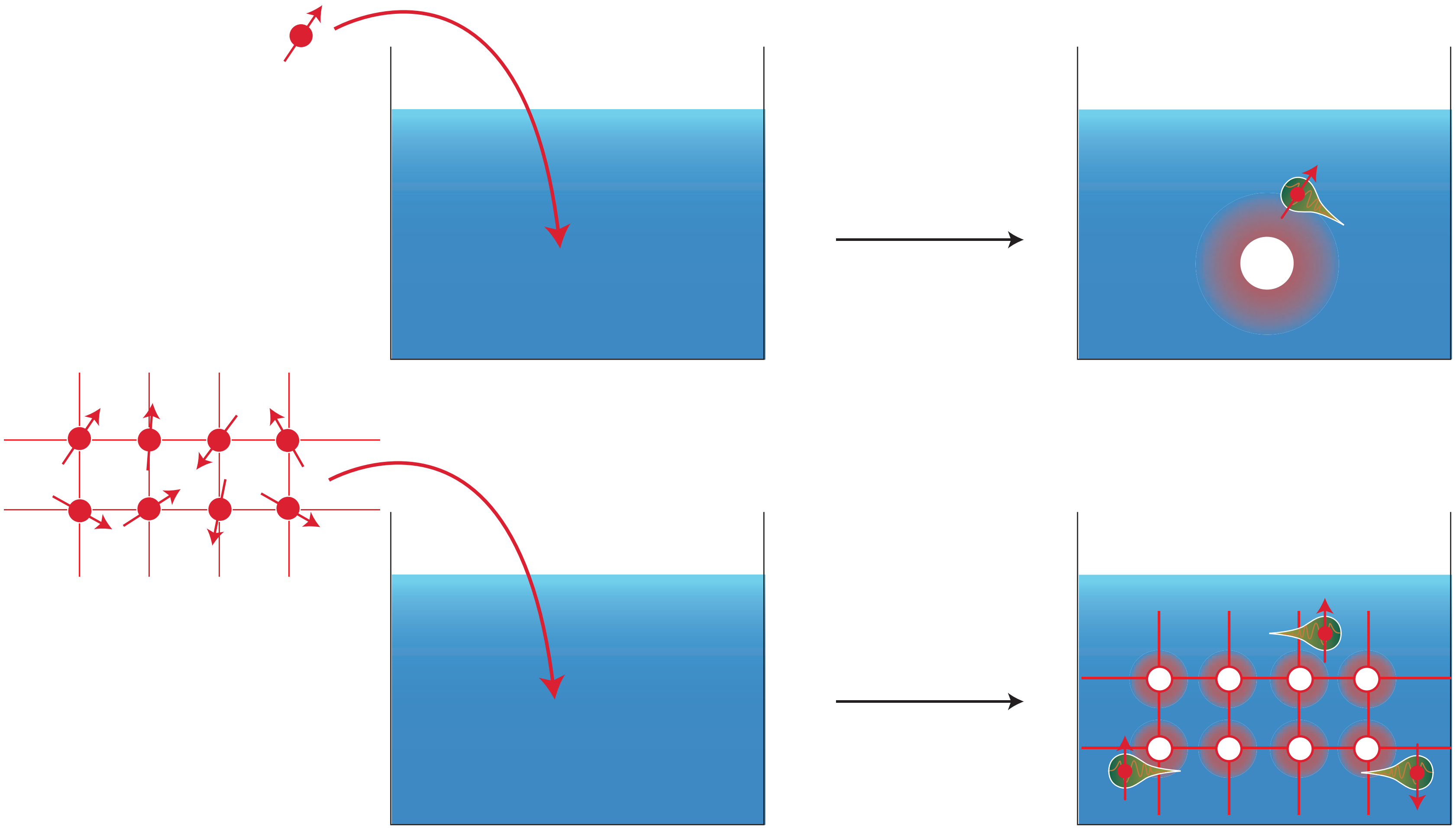
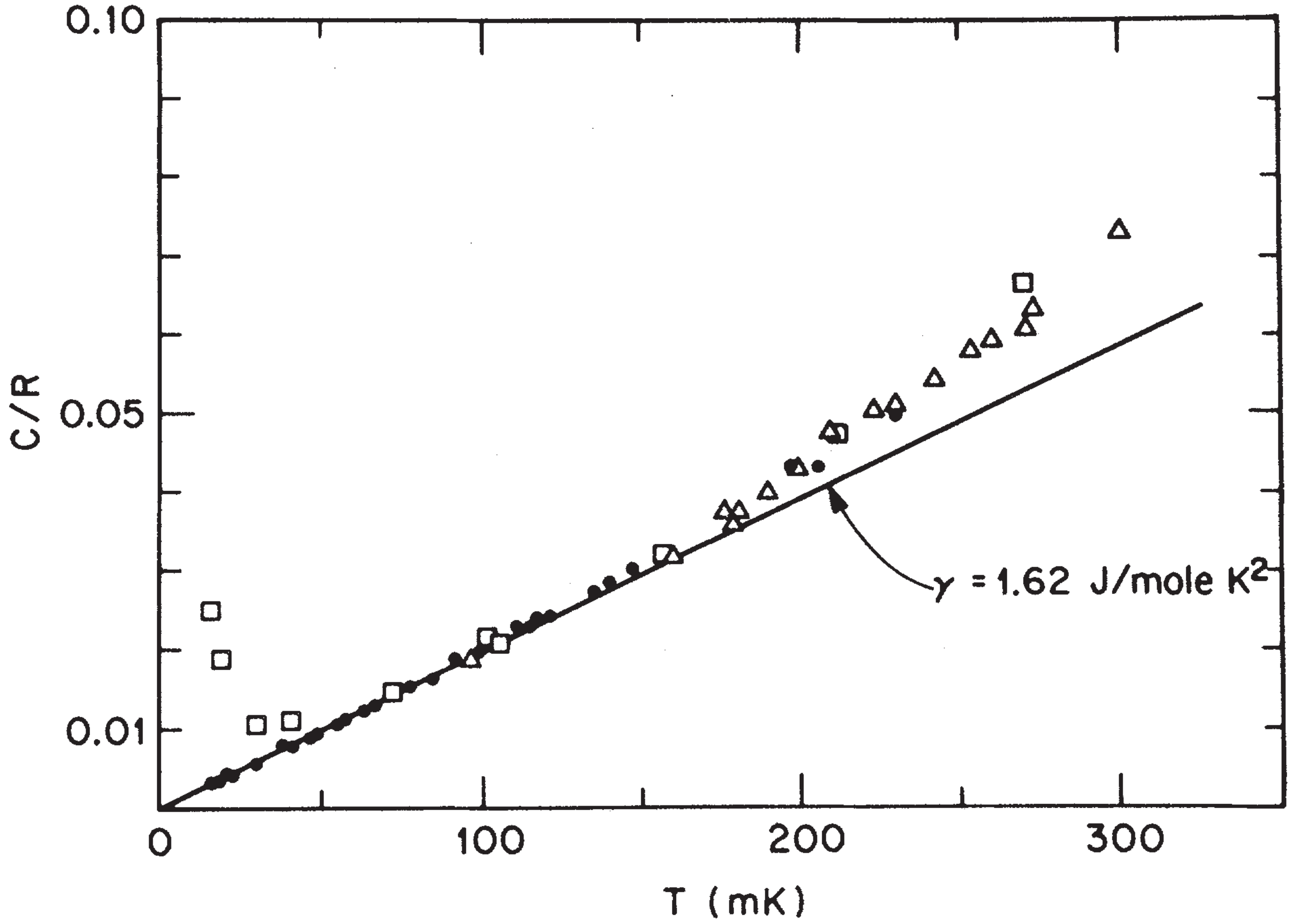
Kondo effect and heavy fermion compounds



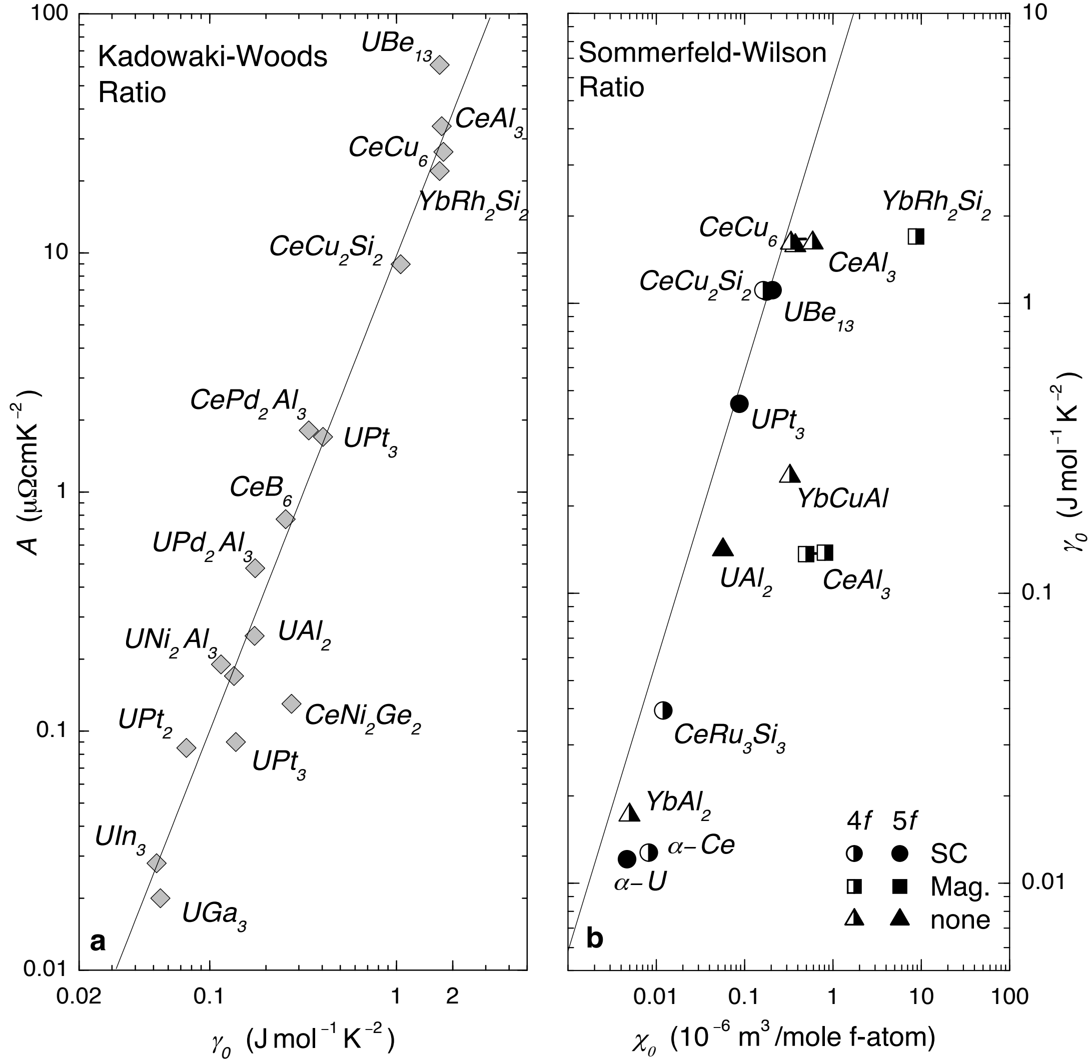
(Coleman, Nature Mater. 11 (2012) 185, news & views)

First heavy fermion/electron compound: $CeAl_3$



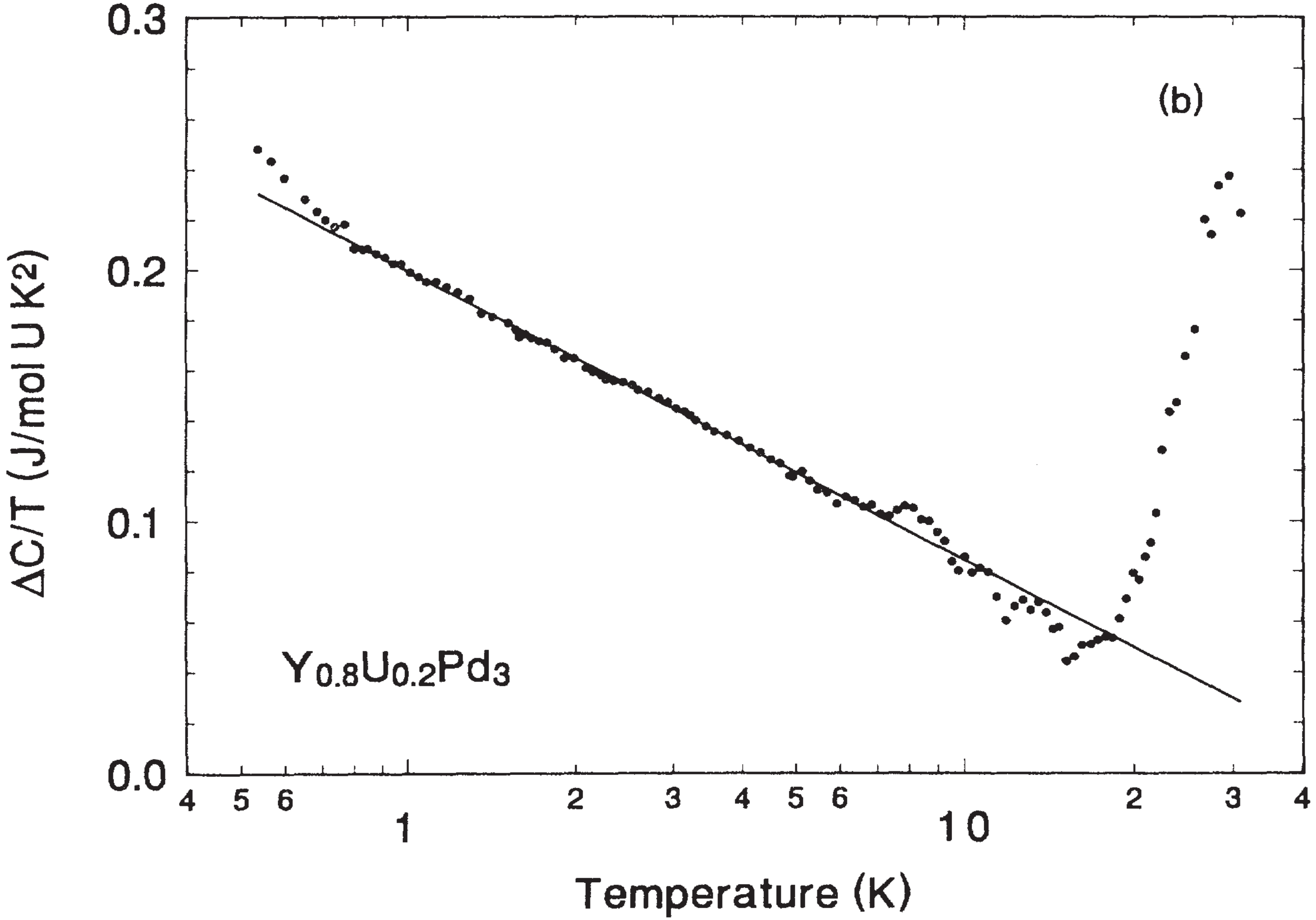
(Andres et al., Phys. Rev. Lett. 35 (1975) 1779.)

Kadowaki – Woods plot



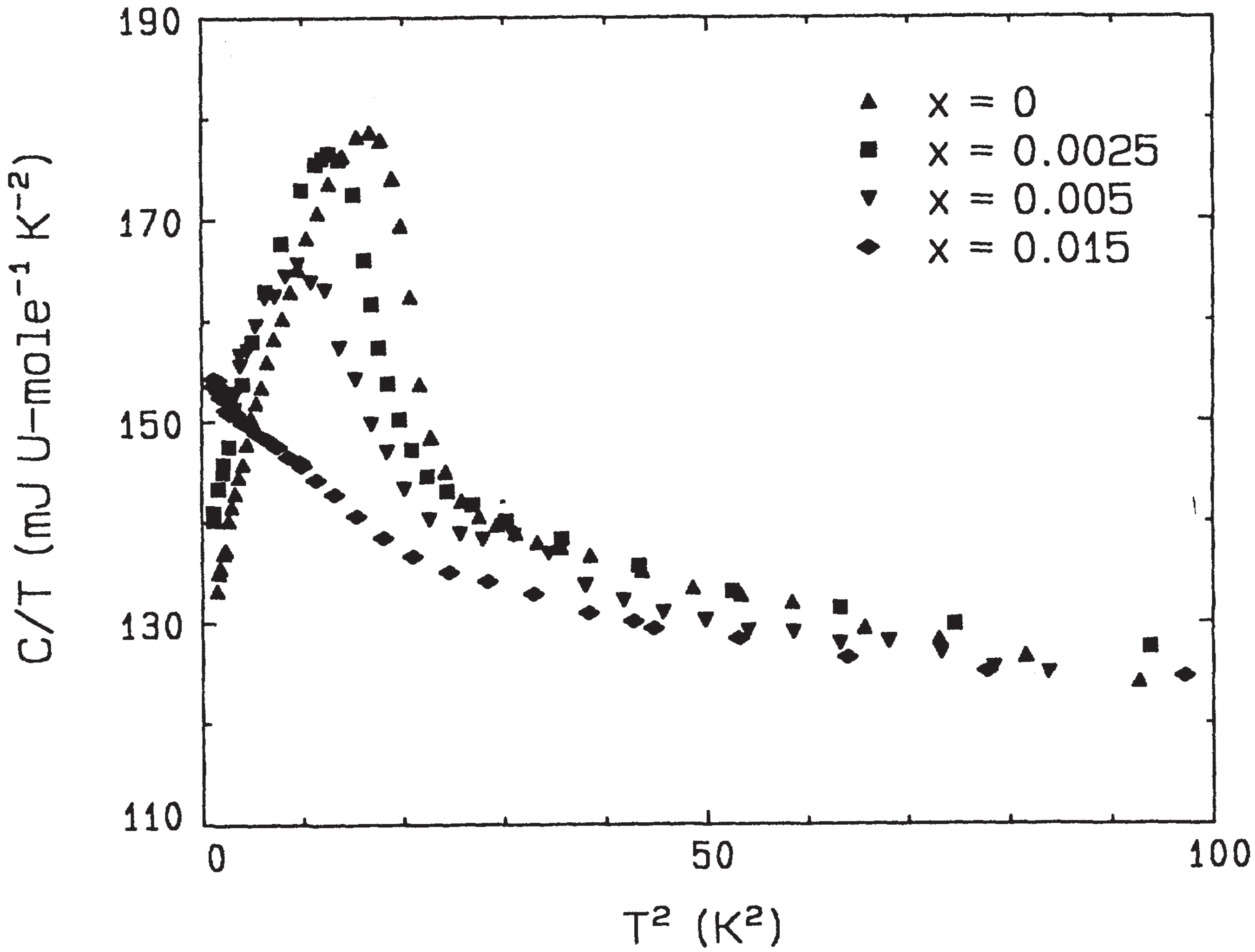
(Custers, PhD thesis, and Kadowaki & Woods, Solid State Commun. 58 (1986) 507)

Non-Fermi liquid behaviour: $Y_{0.8}U_{0.2}Pd_3$



(Seaman et al., Phys. Rev. Lett. 67 (1991) 2881)

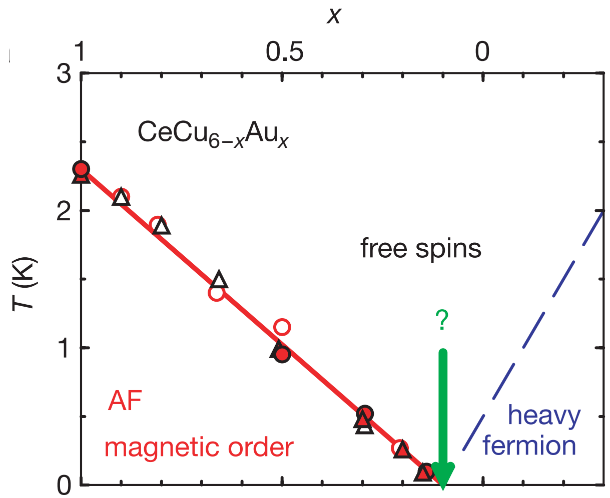
Non-Fermi liquid near magnetic order: $U_{1-x}Th_xNi_2Al_3$



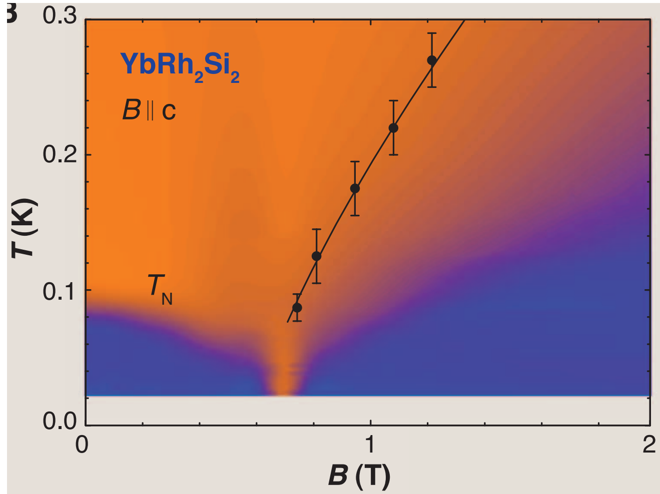
(Kim et al., Phys. Rev. B 47 (1993) 12403)

NFL behaviour at quantum critical points

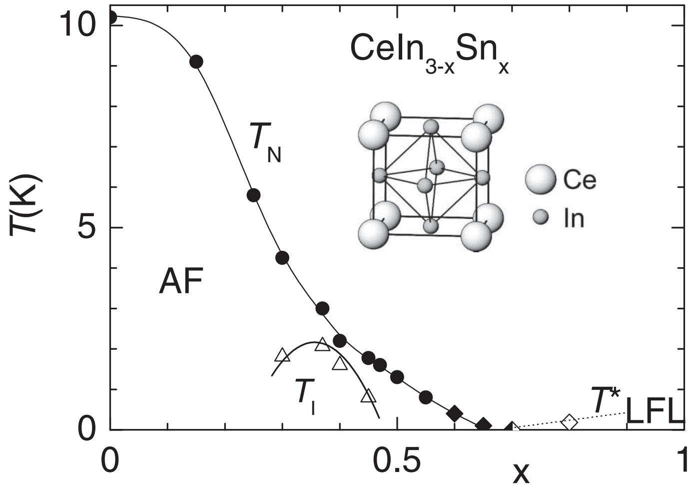
$CeCu_{6-x}Au_x$ (Schröder et al, Nature 2000)



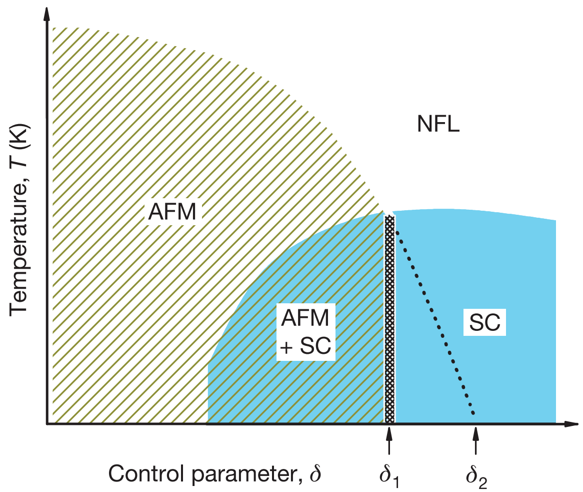
$YbRh_2Si_2$ (Custers et at., Nature 2001)



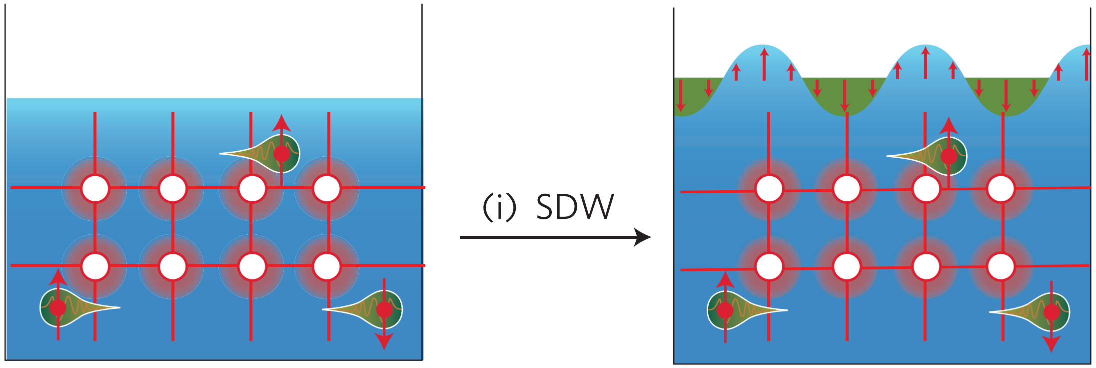
$CeIn_{3-x}Sn_x$ (Küchler et al, PRL 2006)



$CeRhIn_5$ (Park et at., Nature 2006)



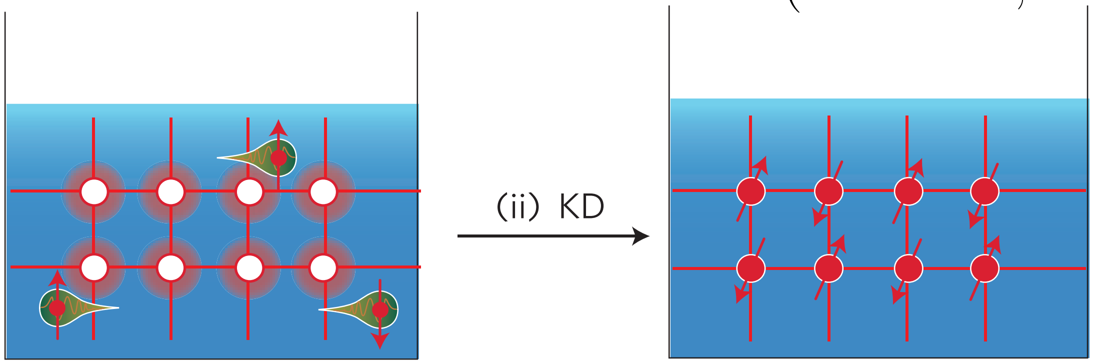
Standard scenario: Spin density wave (SDW) formation



Paramagnet

Itinerant antiferromagnet

Alternative scenario in 2D: Kondo breakdown (Coleman, Si, Schröder, ...)



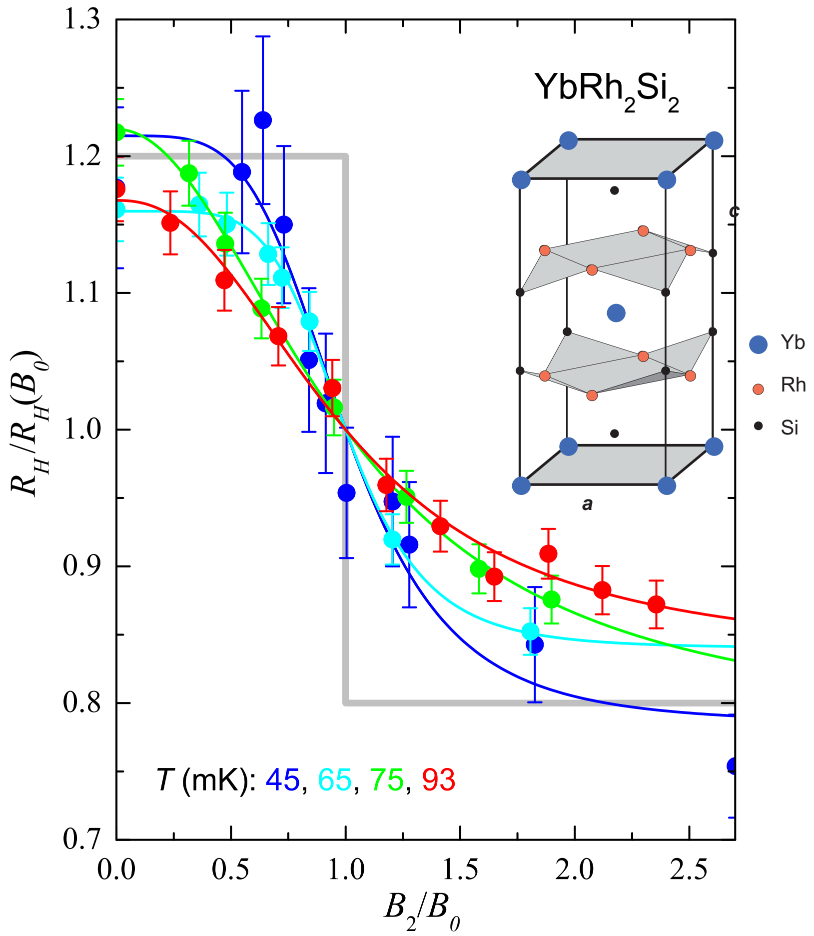
Paramagnet

Local moment antiferromagnet

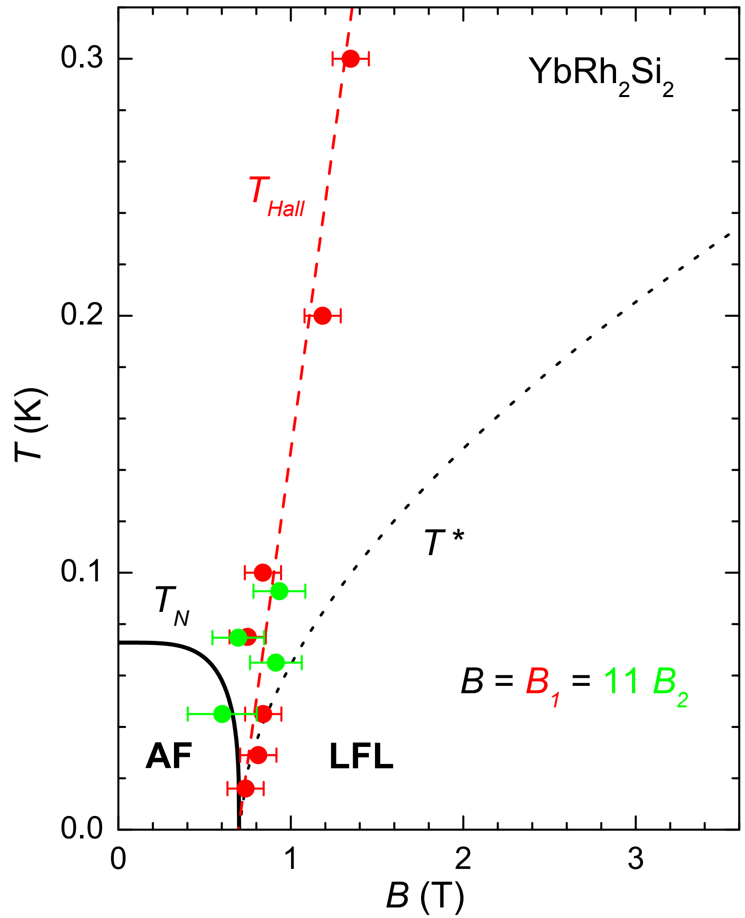
(Coleman, Nature Mater. 11 (2012) 185, news & views)

Hall effect in tetragonal $YbRh_2Si_2$ with 2D spin fluctuations

Hall coefficient vs field



Phase diagram

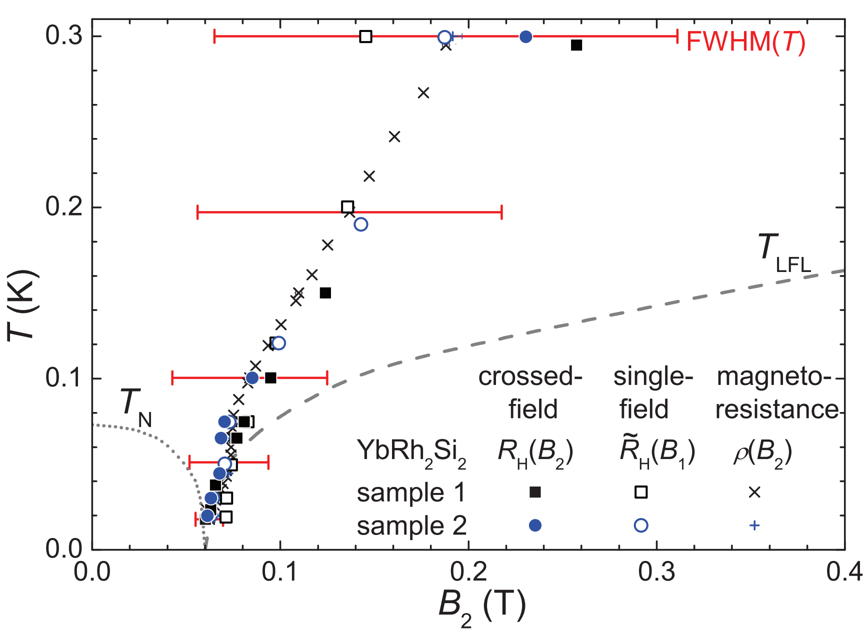


(SP et al., Nature 432 (2004) 881)

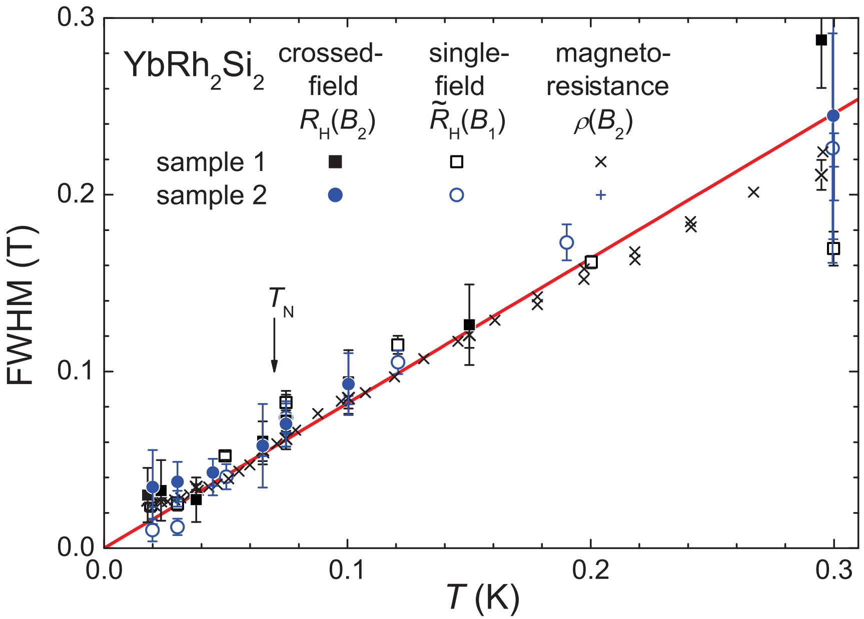
Hall effect in tetragonal $YbRh_2Si_2$ with 2D spin fluctuations:

Experiments on purest samples with enhanced resolution

Phase diagram



Crossover width



(Friedemann et al., PNAS 107 (2010) 14547)

FWHM $\sim T$ (valid up to 1 K)

Suggested scenarios (list incomplete ...):

Kondo breakdown/Orbital selective Mott transition:

Kondo lattice, Kondo-Heisenberg, PAM, Bose-Fermi Kondo models, ...

Coleman, Fabrizio, Kim, Kotliar, Pépin, Senthil, Si, Zaanen, ...

Lifshitz transition/Topological transition:

2D Kondo lattice model, band picture ...

Assaad, Vojta, Watanabe, ...

Valence transition/Valence criticality:

PAM with U_{fc}, band picture ...

Miyake, Norman, Watanabe, ...

Quantum tricritical point:

Self-consistent renormalization theory for spin fluctuations

Imada, Misawa, Yamaji

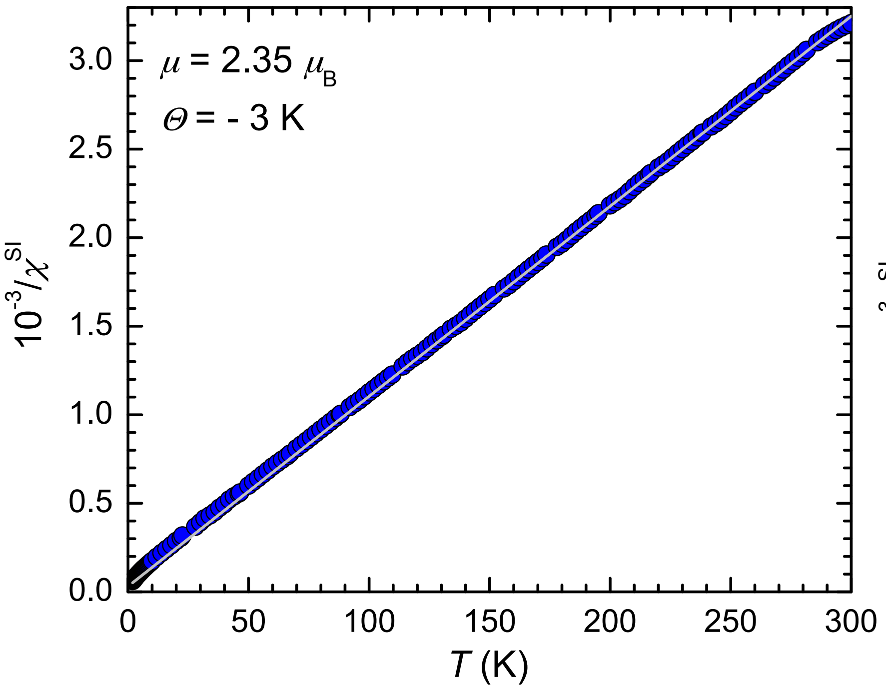
Weak-field breakdown:

Boltzmann transport theory

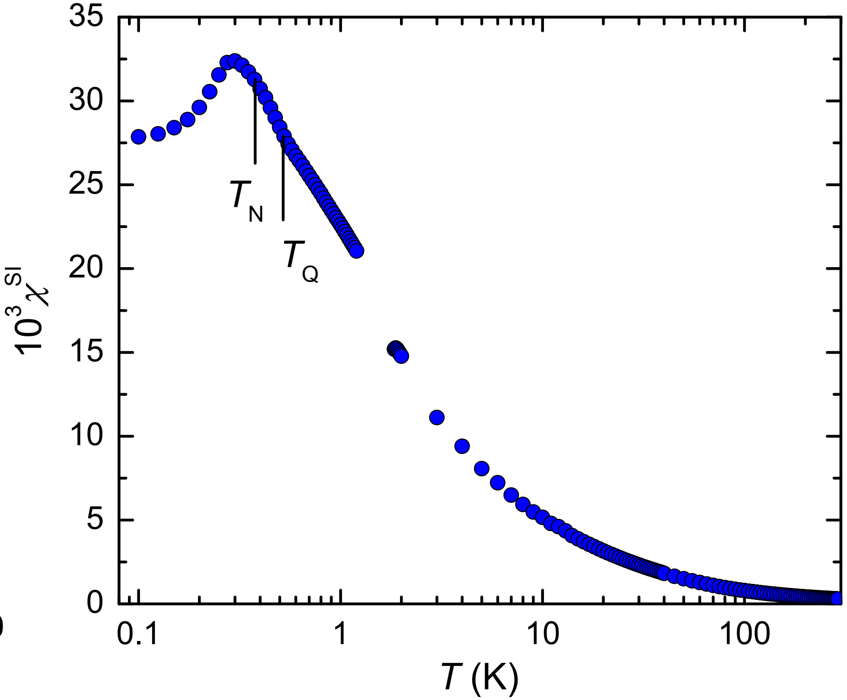
Schofield

A new *cubic* material: $Ce_3Pd_{20}Si_6$

Inverse susceptibility



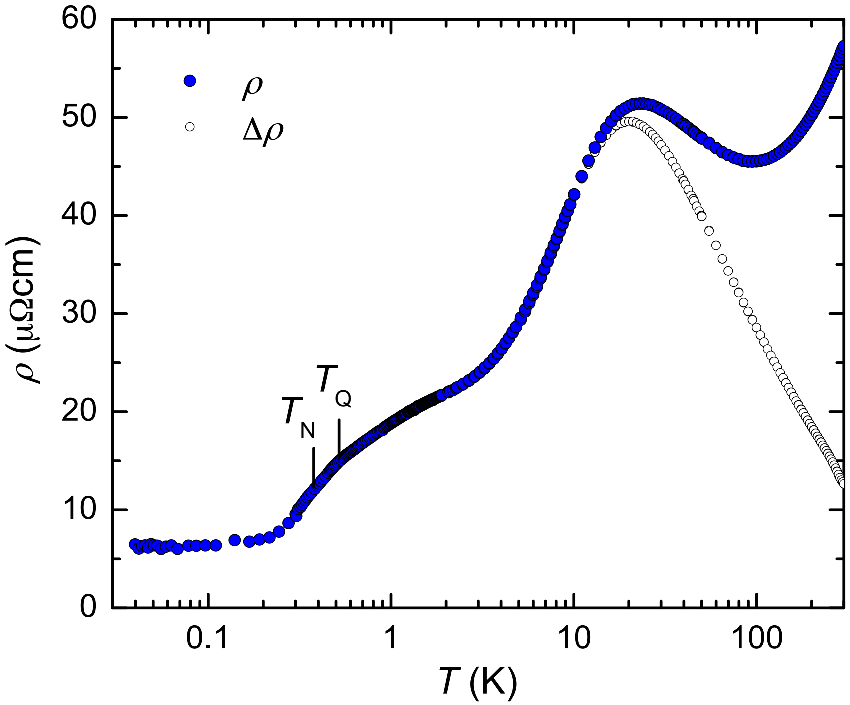
Susceptibility



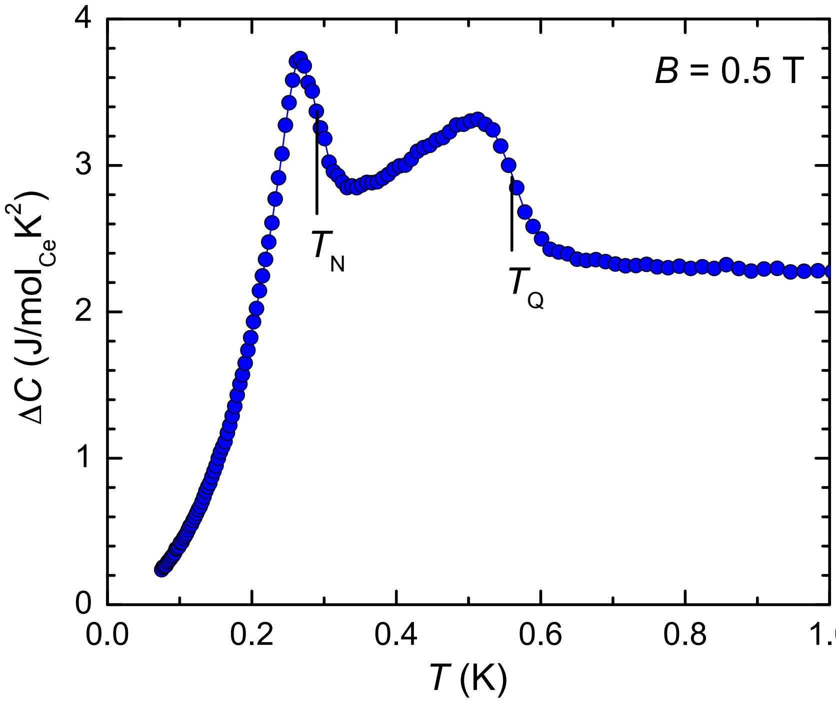
$$\chi_0 = 10 \cdot 10^{-6}\ \mathrm{m^3/mol\ Ce}$$

A new *cubic* material: $Ce_3Pd_{20}Si_6$

Electrical resistivity



Electronic specific heat



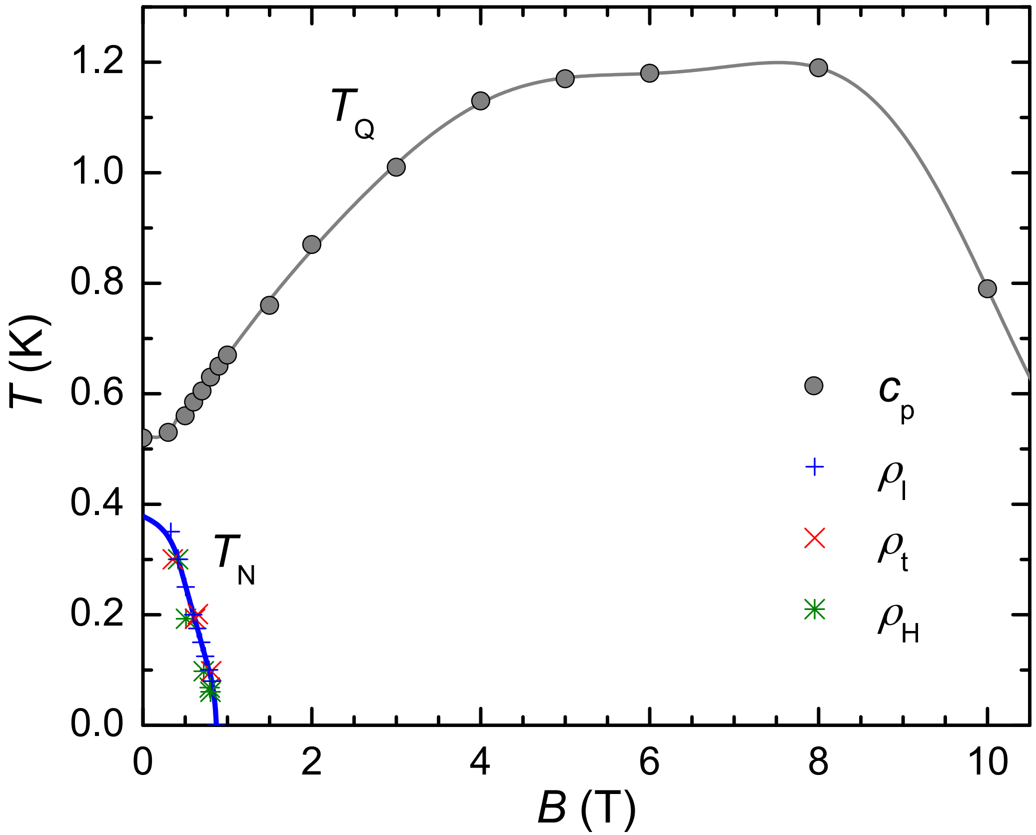
$\rho = \rho_0 + AT^2$, $A = 31\ \mu\Omega\text{cm}$

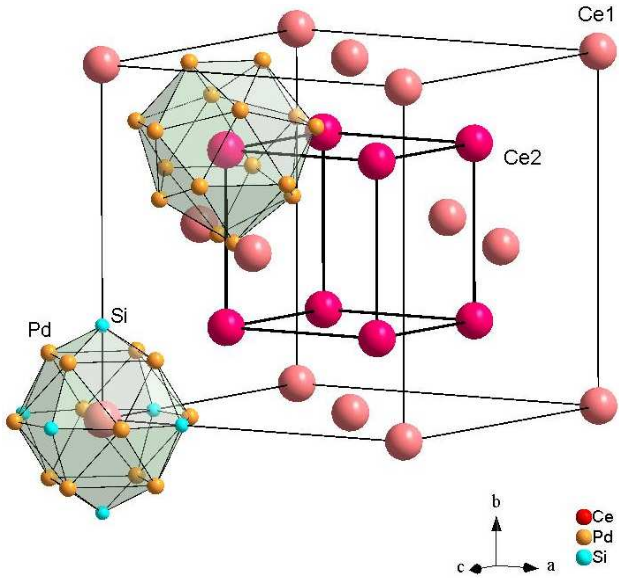
$\Delta C/T = \gamma + \beta T^2$, $\gamma = 1.45\ \text{J/molK}^2$

KW: $A/\gamma^2 = 1.47 \cdot 10^{-5}\ (\Omega\text{m/K}^2)/(\text{J/molK}^2)$

A new *cubic* material: $Ce_3Pd_{20}Si_6$

Temperature-field phase diagram





Cubic, $Fm\bar{3}m$

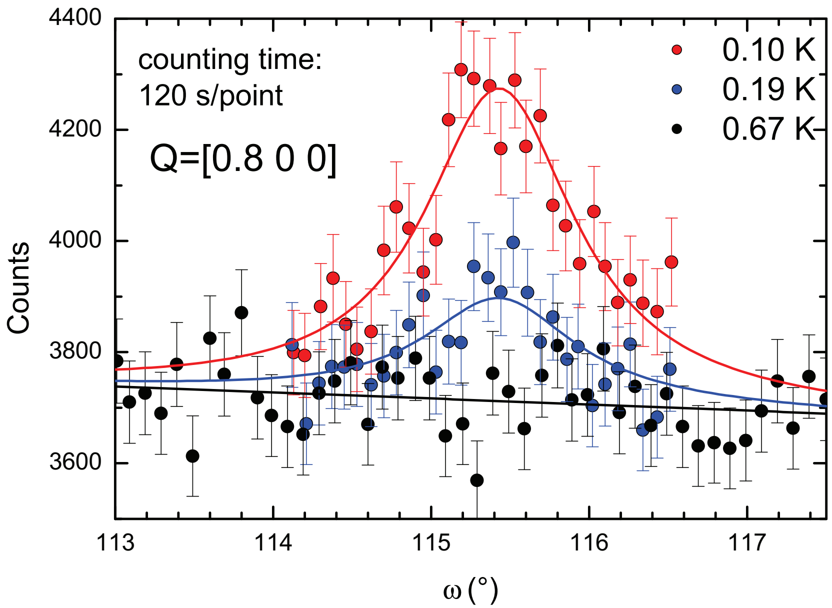
Ce1: fcc, $4a$, Γ_7, T_N

Ce2: sc, $8c$, Γ_8, T_Q

(Deen et al., Phys. Rev. B 81 (2010) 064427)

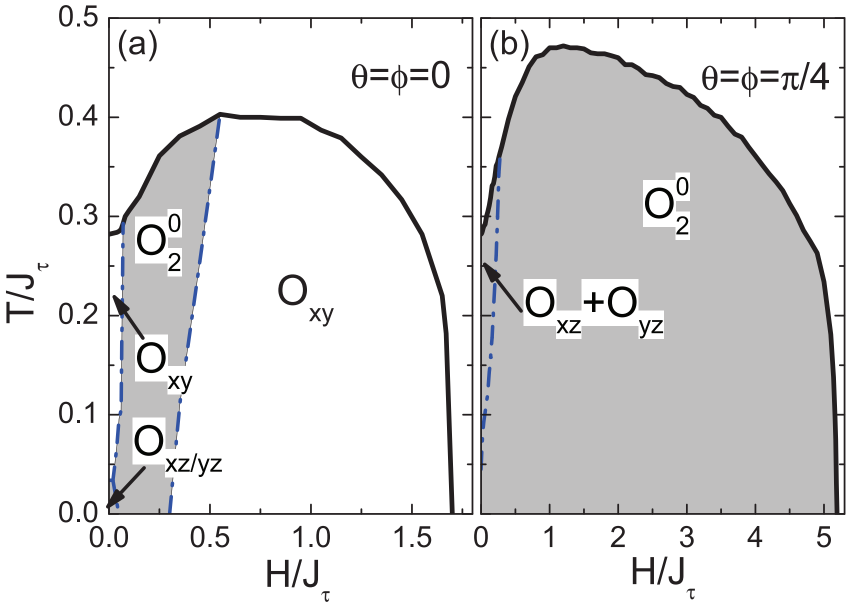
Ordered phases in $Ce_3Pd_{20}Si_6$

Below T_N



(Lorenzer, Deen et al., ILL, unpublished)

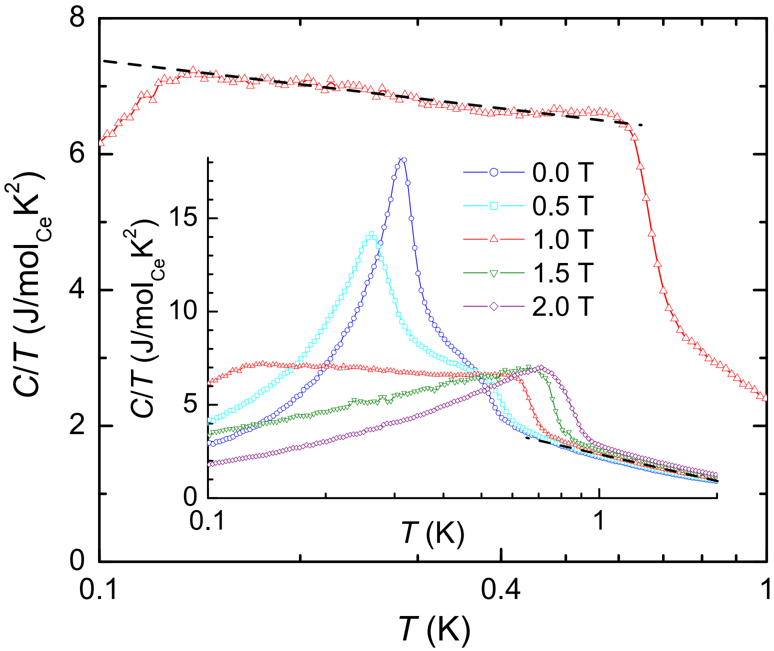
Below T_Q



(Custers et al., Nature Mater. 11 (2012) 189; SI)

Non-Fermi liquid properties of $Ce_3Pd_{20}Si_6$

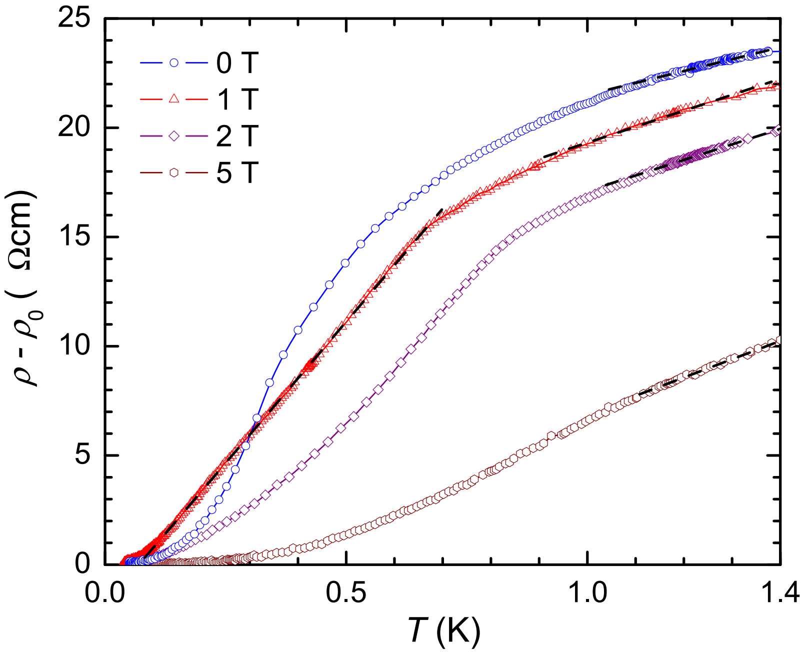
Specific heat



$\Delta C/T \propto -\ln T$

SDW (AFM, $d = 3$):
$\Delta C/T = \gamma - b\sqrt{T}$

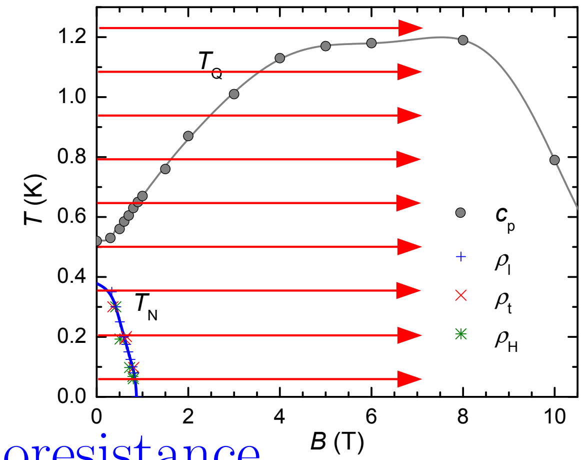
Electrical resistivity



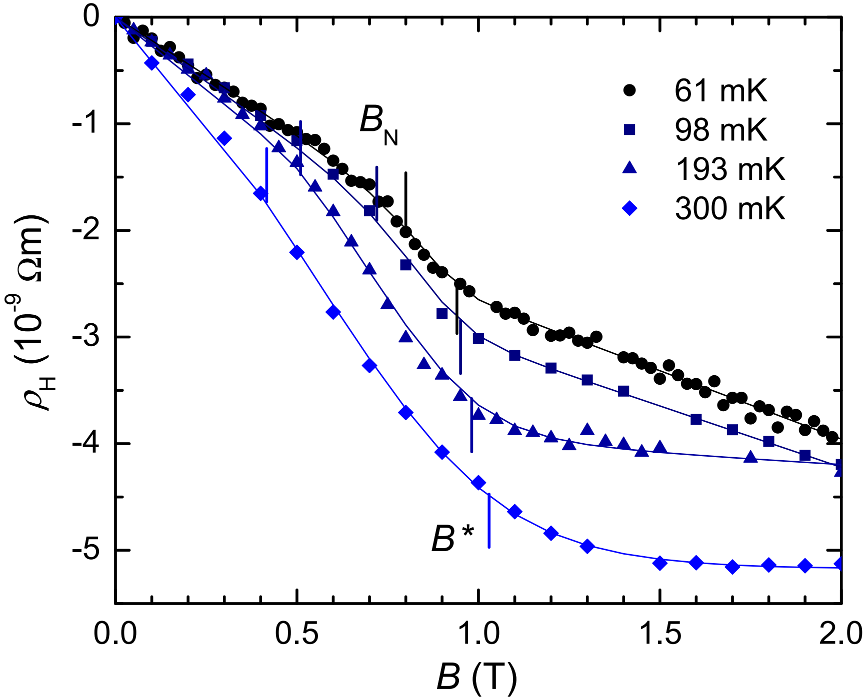
$\Delta\rho \sim T$

SDW (AFM, $d = 3$): $\Delta\rho \sim T^{3/2}$

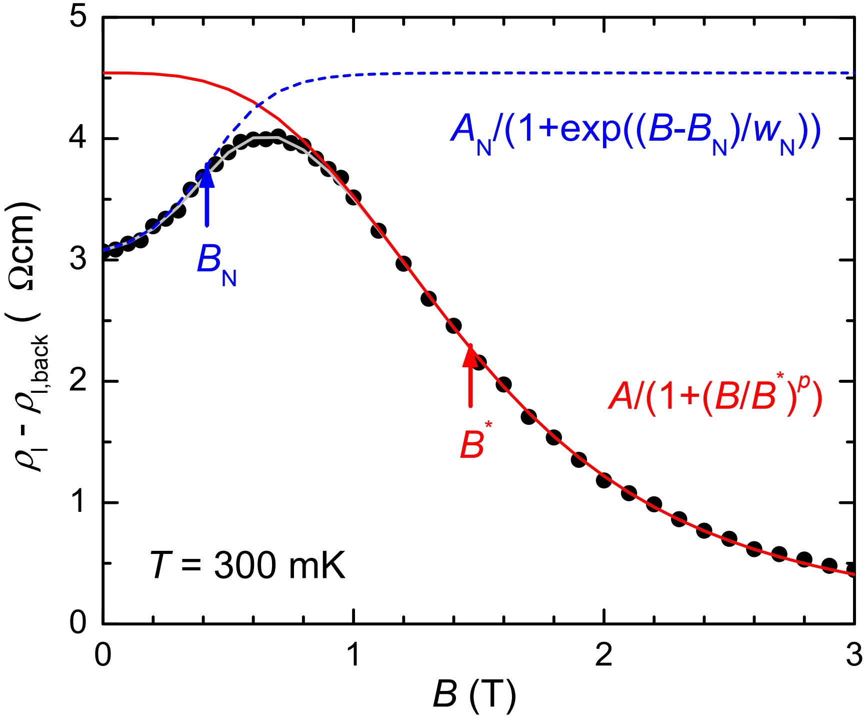
Isotherms crossing phase diagram



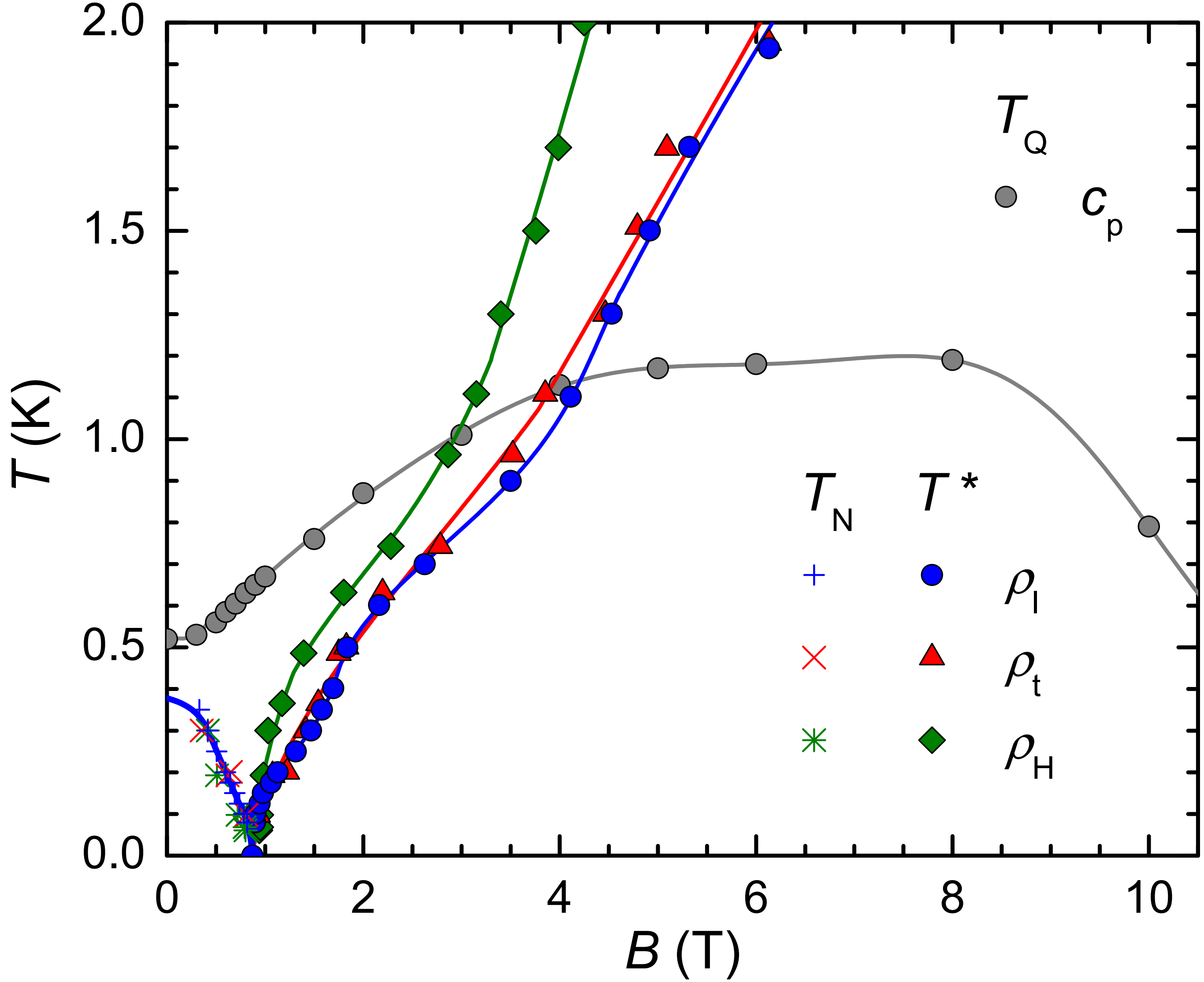
Hall effect



Magnetoresistance

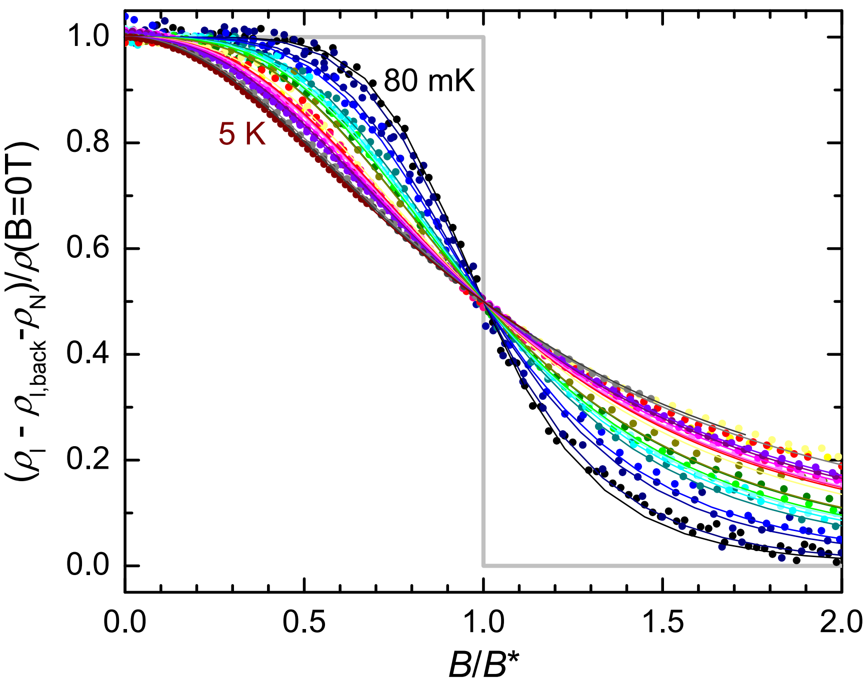


Phase diagram of $Ce_3Pd_{20}Si_6$ with T^* scale

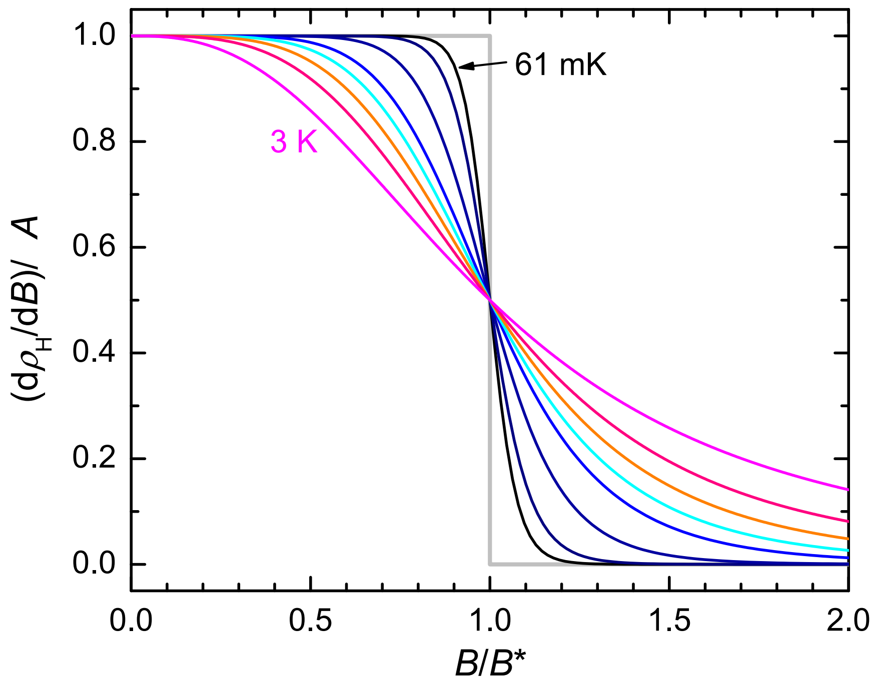


Crossovers in magnetotransport of $Ce_3Pd_{20}Si_6$ at B^*

Longitudinal magnetoresistance

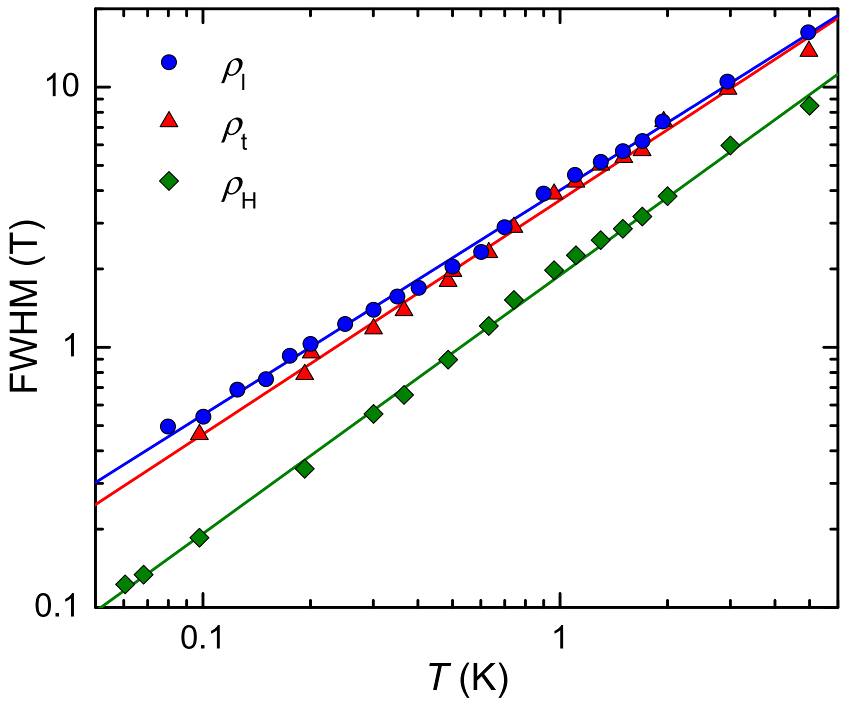


Differential Hall coefficient

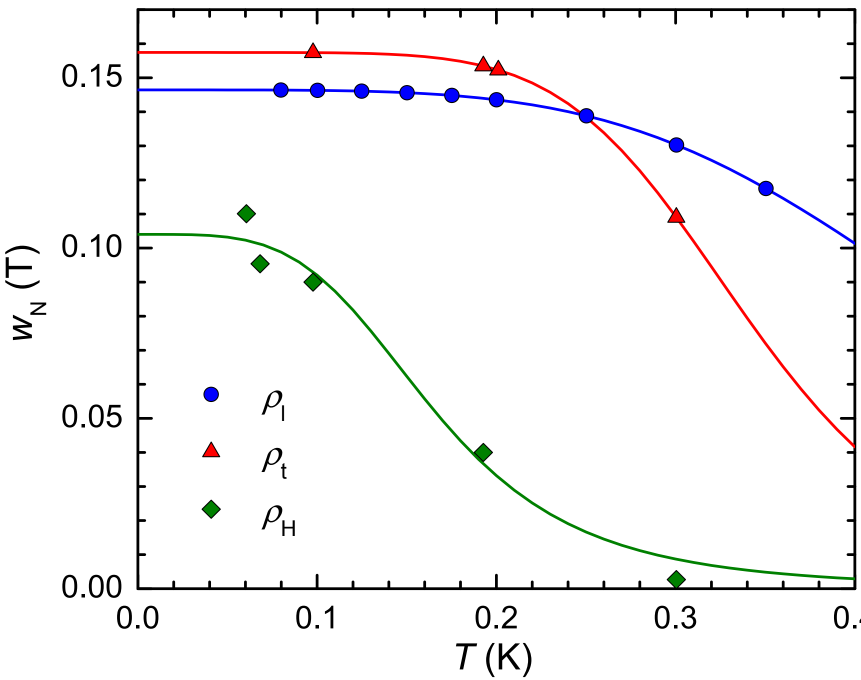


Crossovers at B^* vs transition at B_N

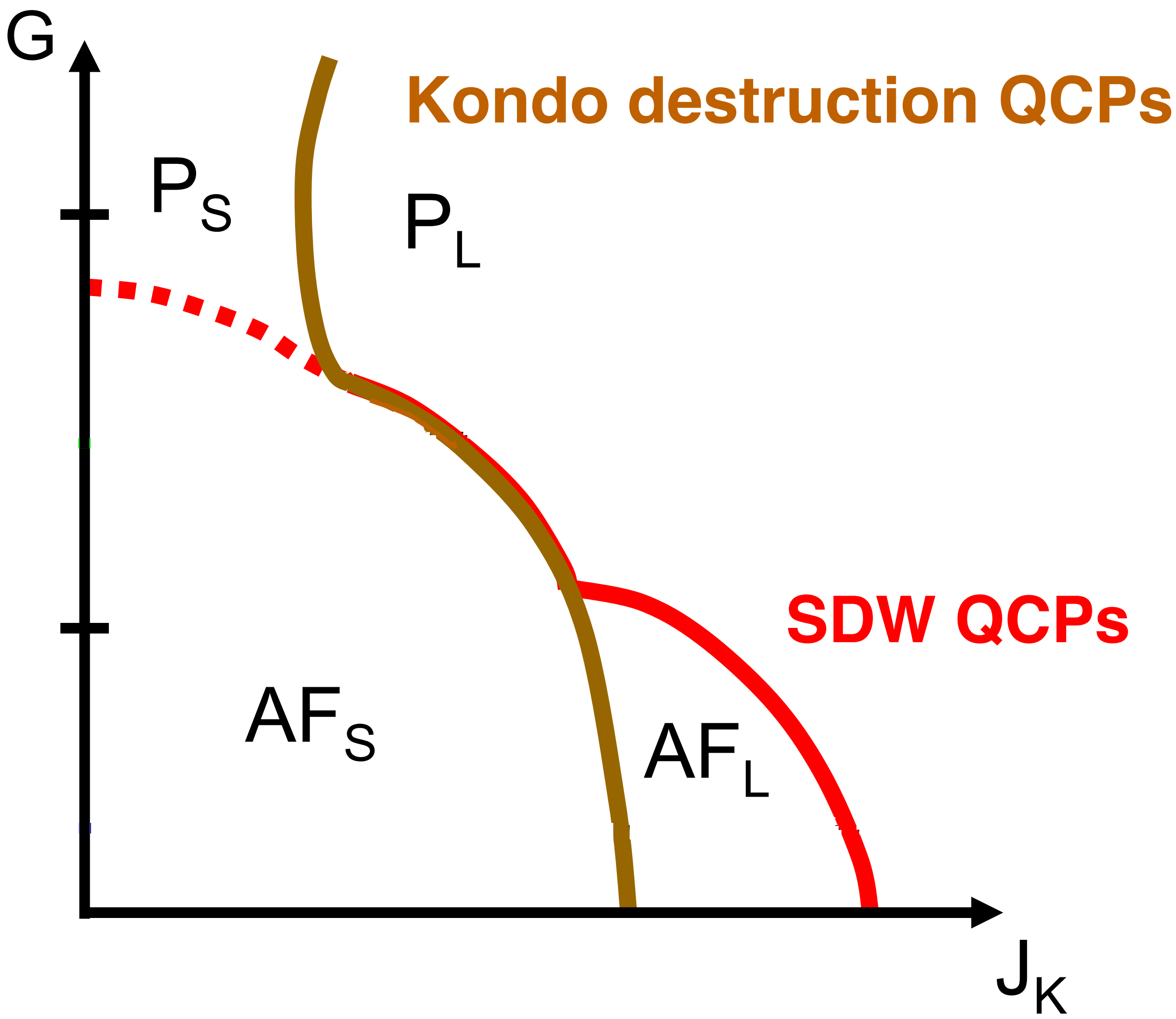
Width of crossover at B^*



Width of transition at B_N

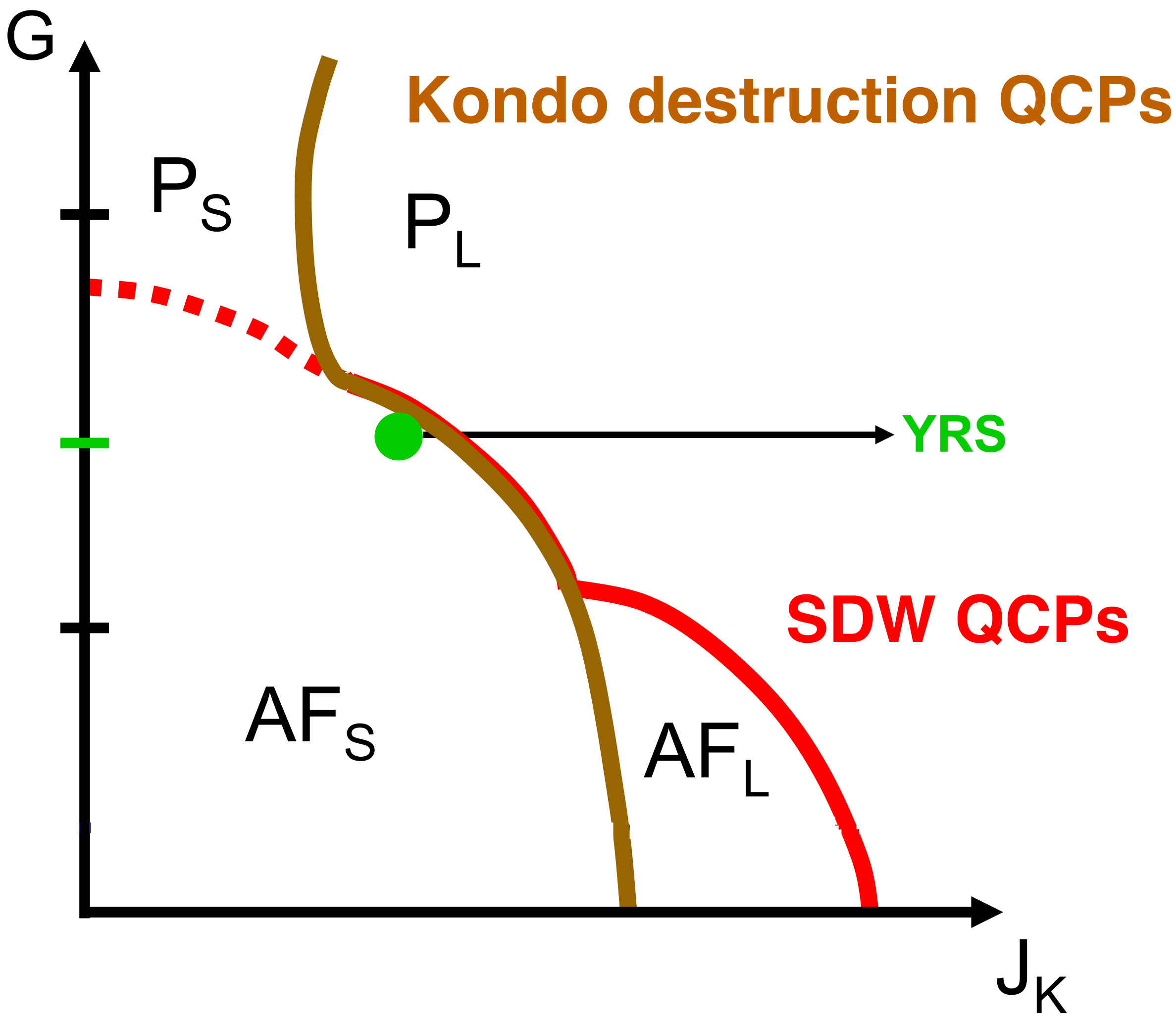


Suggested theoretical phase diagram at $T = 0$



(Si, Physica B 378-380 (2006) 23; Phys. Stat. Sol. 247 (2010) 476; also: Coleman et al.)

Suggested theoretical phase diagram at $T = 0$



(Si, Physica B 378-380 (2006) 23; Phys. Stat. Sol. 247 (2010) 476)

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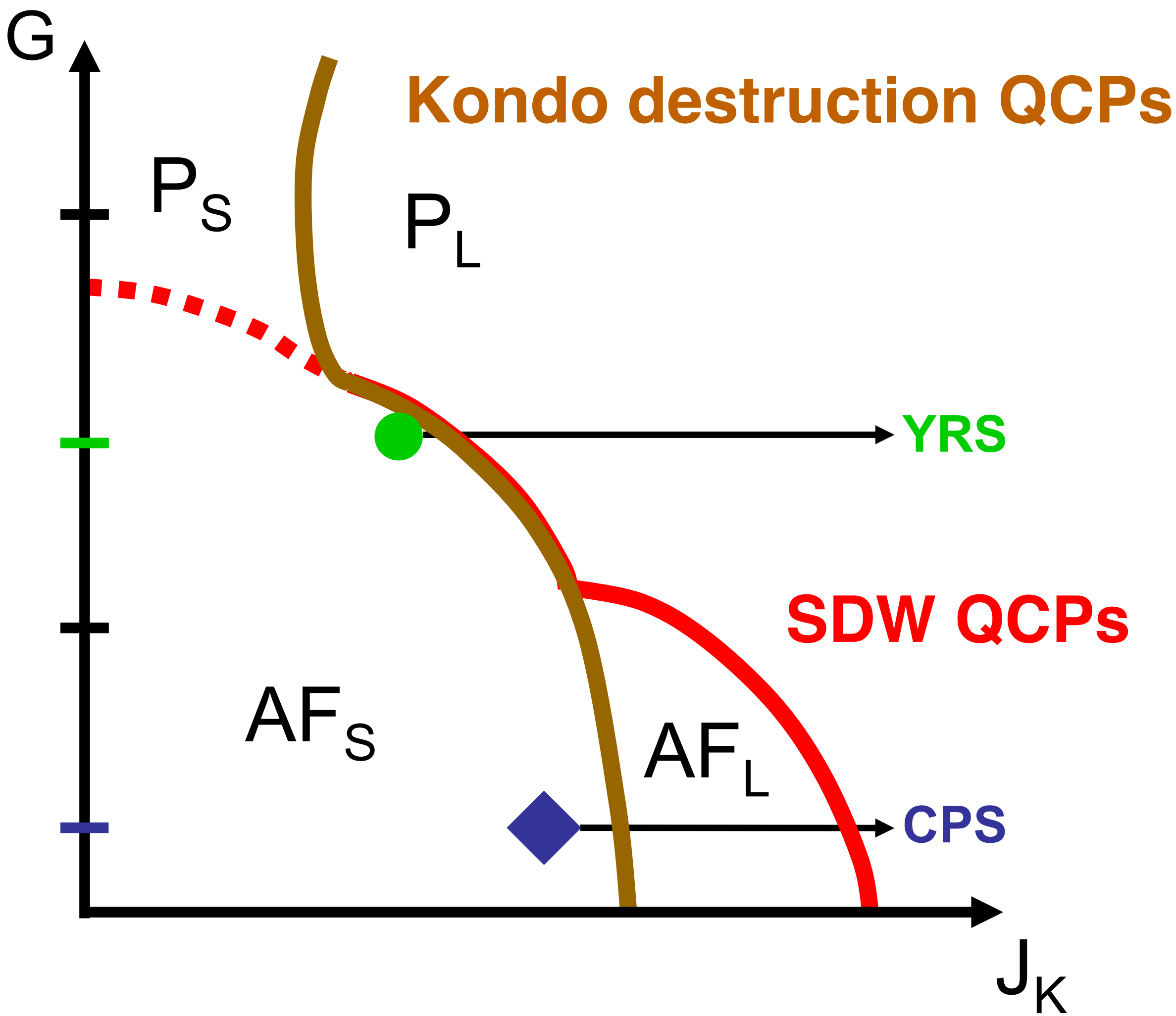
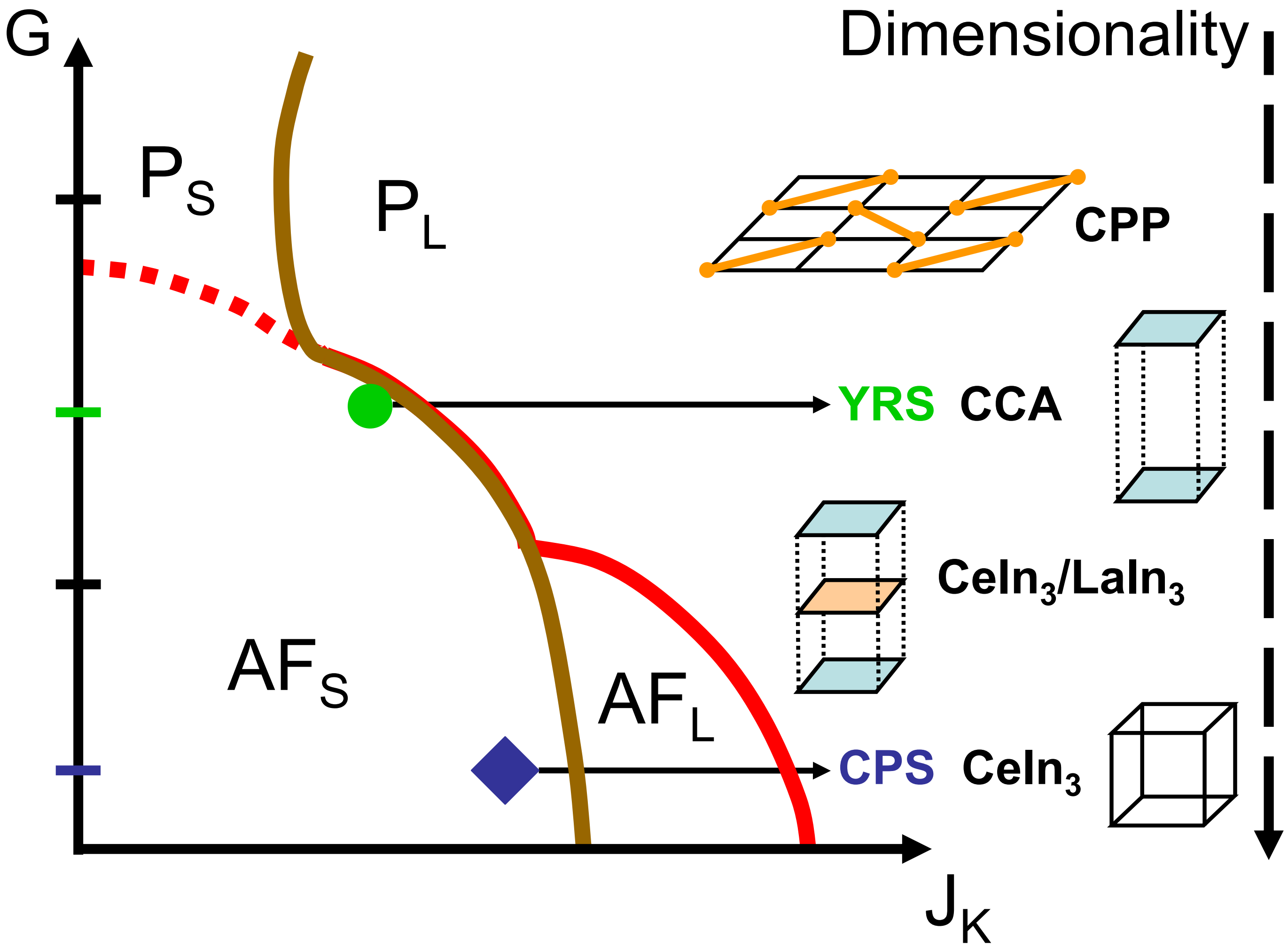


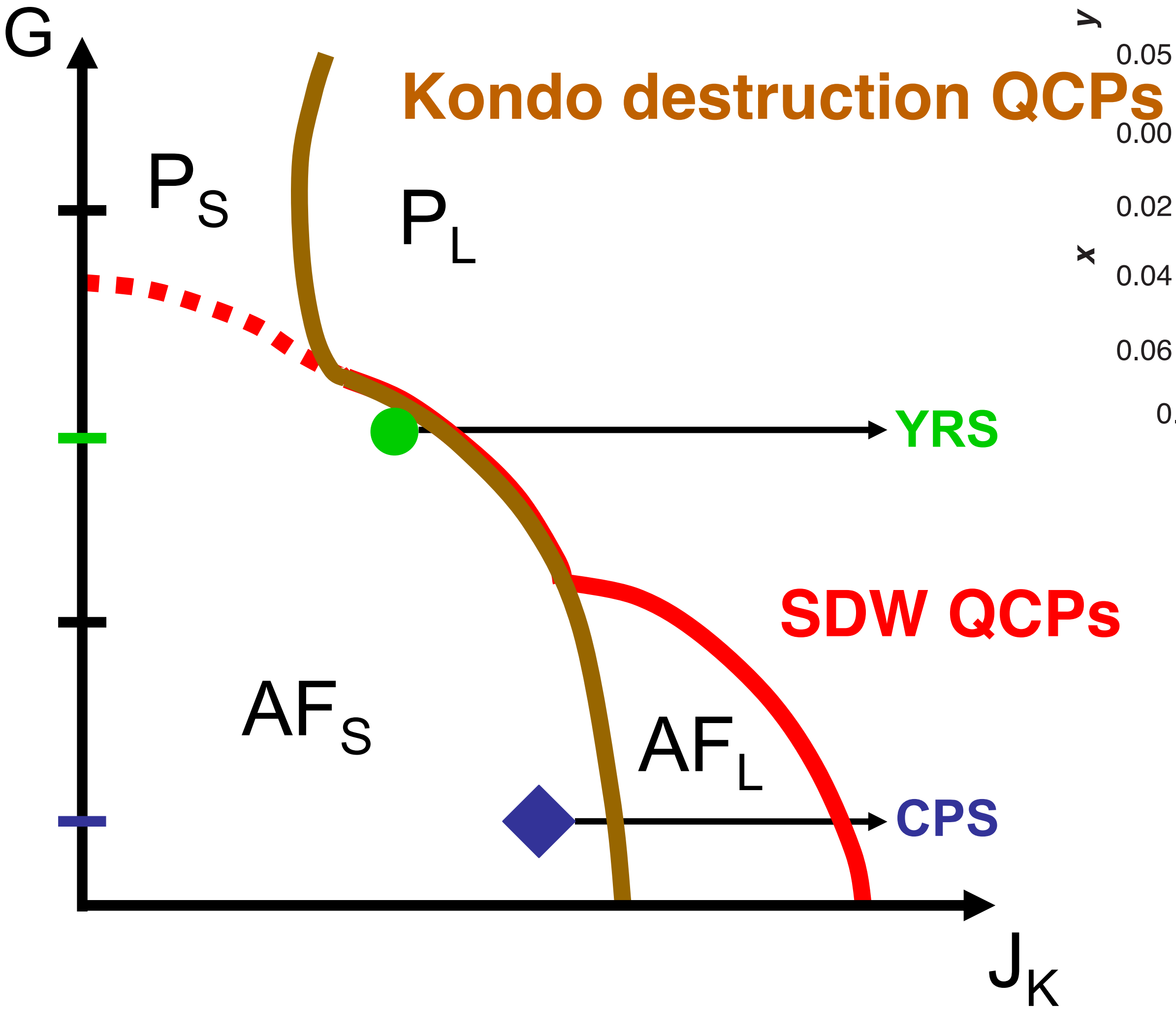
(Si, Physica B 378-380 (2006) 23; Phys. Status Solidi 247 (2010) 476)

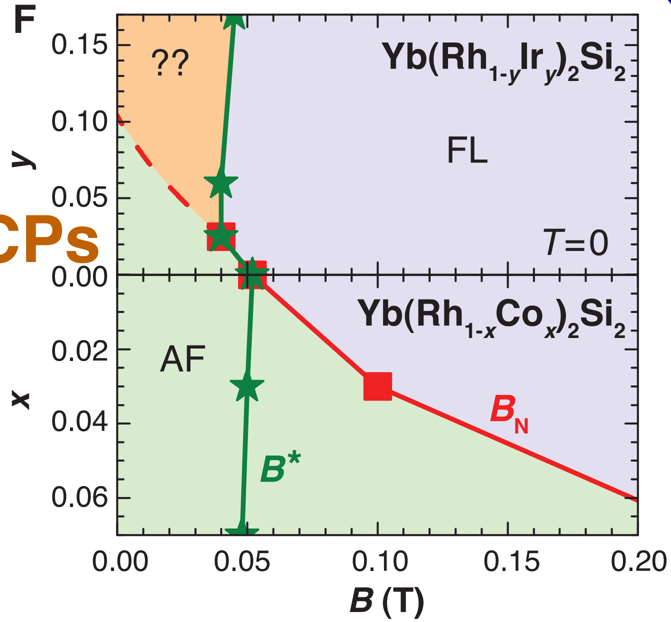
Materials-based global phase diagram



(Custers et al., Nature Mater. 11 (2012) 189)

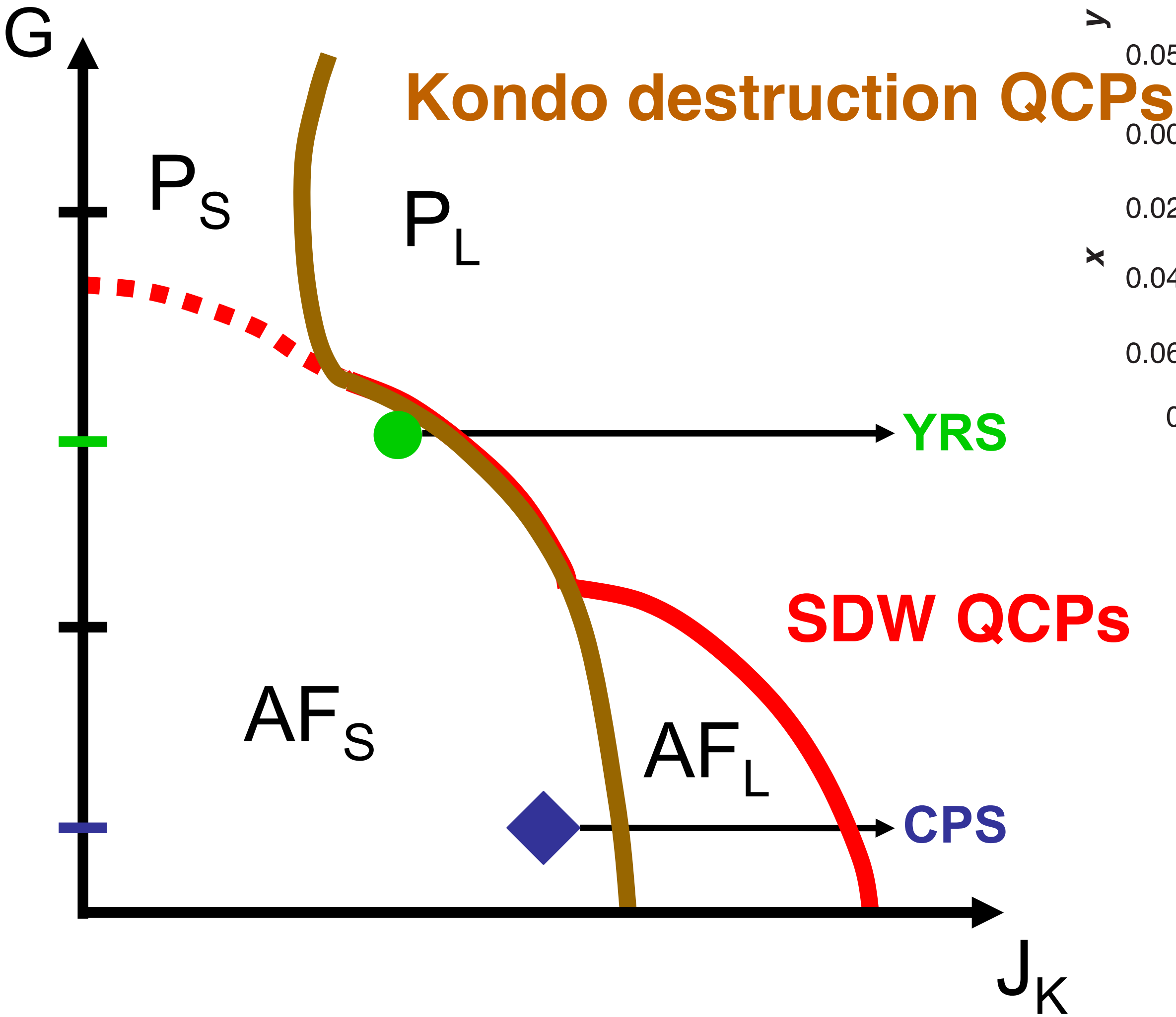
Materials-based global phase diagram

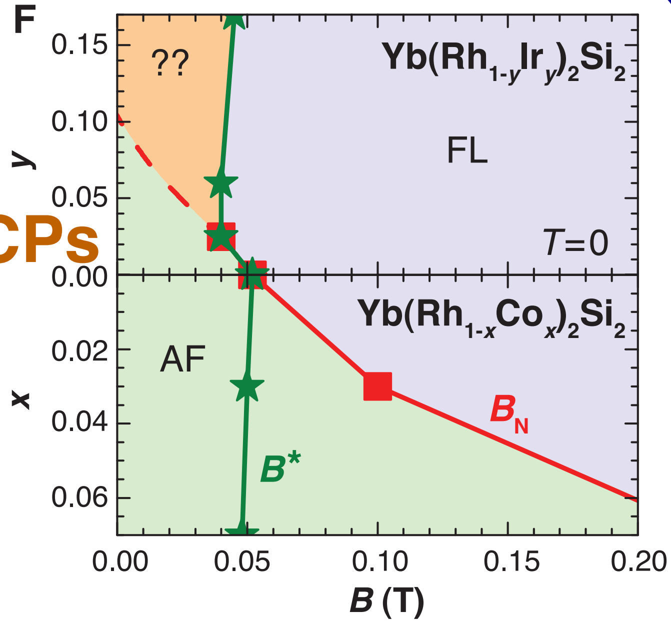


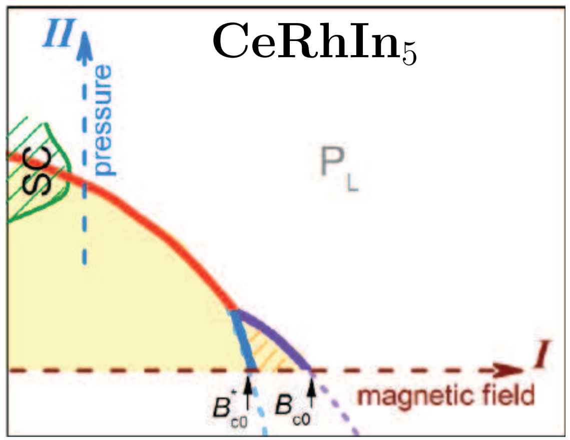


(Friedemann et al., Nat. Phys. 5 (2009) 465

Materials-based global phase diagram







(Friedemann et al., Nat. Phys. 5 (2009) 465; Yuan et al., to appear 2012)

Summary & Outlook

- $Ce_3Pd_{20}Si_6$: New *cubic* quantum critical heavy fermion compound
- Crossover in magnetotransport with similar characteristics as in $YbRh_2Si_2$, at $T \to 0$:
  - Crossover position coincides with B_c
  - Crossover width extrapolates to zero
- Important difference: QCP within other ordered phase!
  - Nature of this phase?
  - Nature of transition leaving this phase?
  - Can in Kondo breakdown scenario be related to higher dimensionality (lower G)
  - Other theoretical scenarios?
  - Extensions of theories to 3D?