Fermi surface reconstructions at heavy fermion quantum critical points

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- Fermi surface evolution with temperature
- Fermi surface evolution with tuning parameter, across QCP
- A new *cubic* quantum critical material: $Ce_3Pd_{20}Si_6$
- An old *cubic* material: CeB_6 (time permitting)
- Open questions

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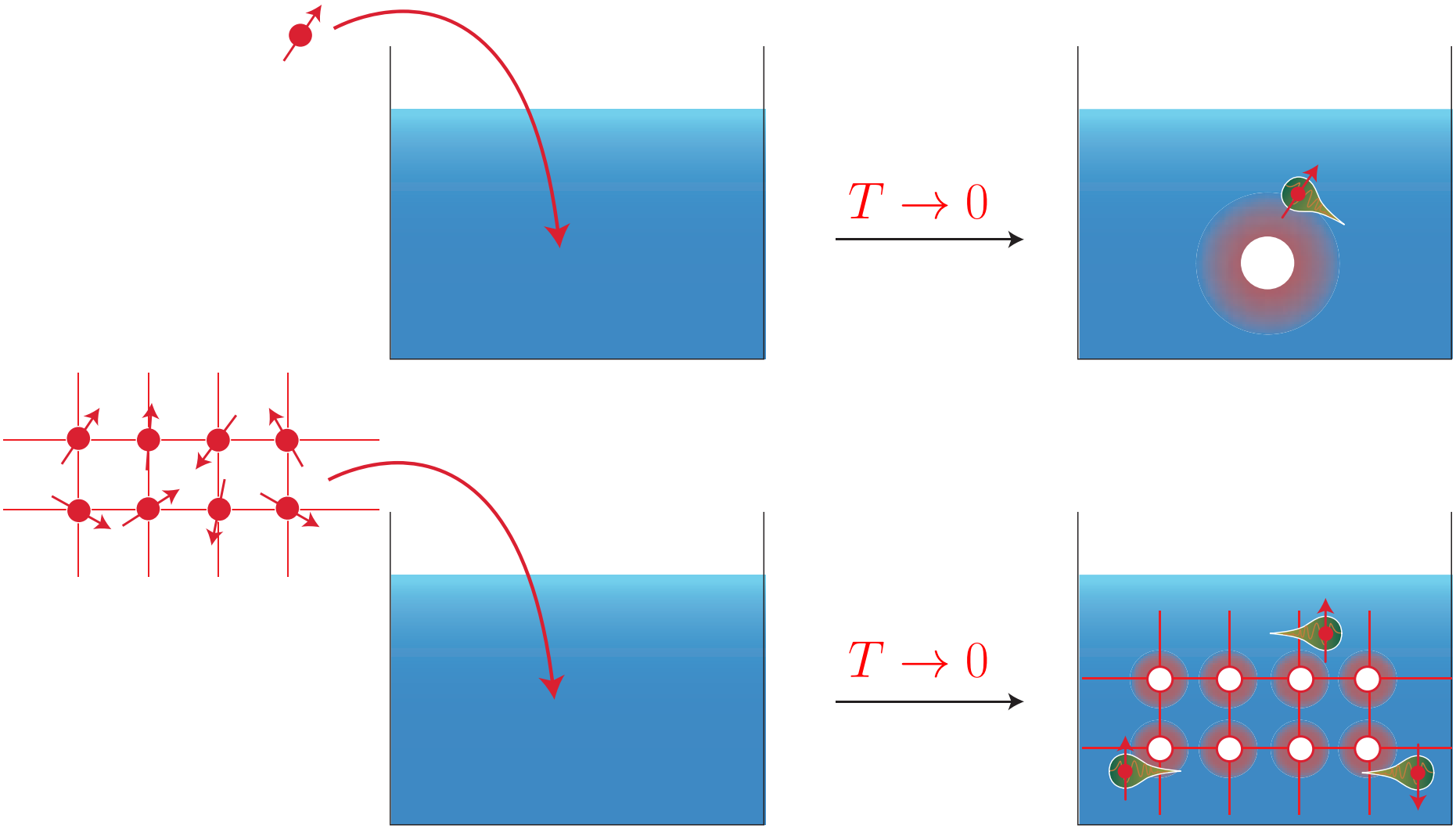
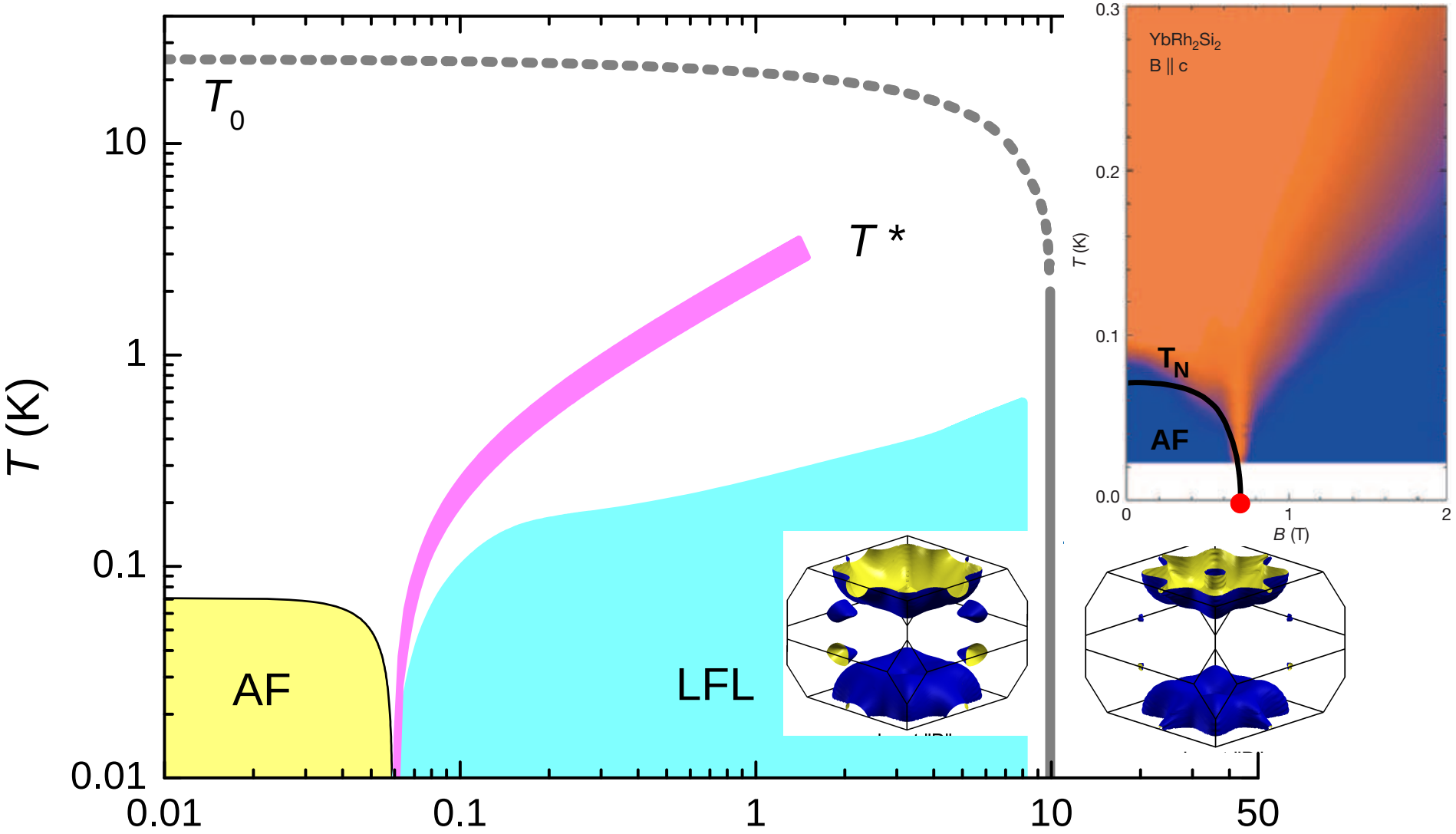
Fermi surface evolution with temperature

Kondo effect and heavy fermion compounds



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

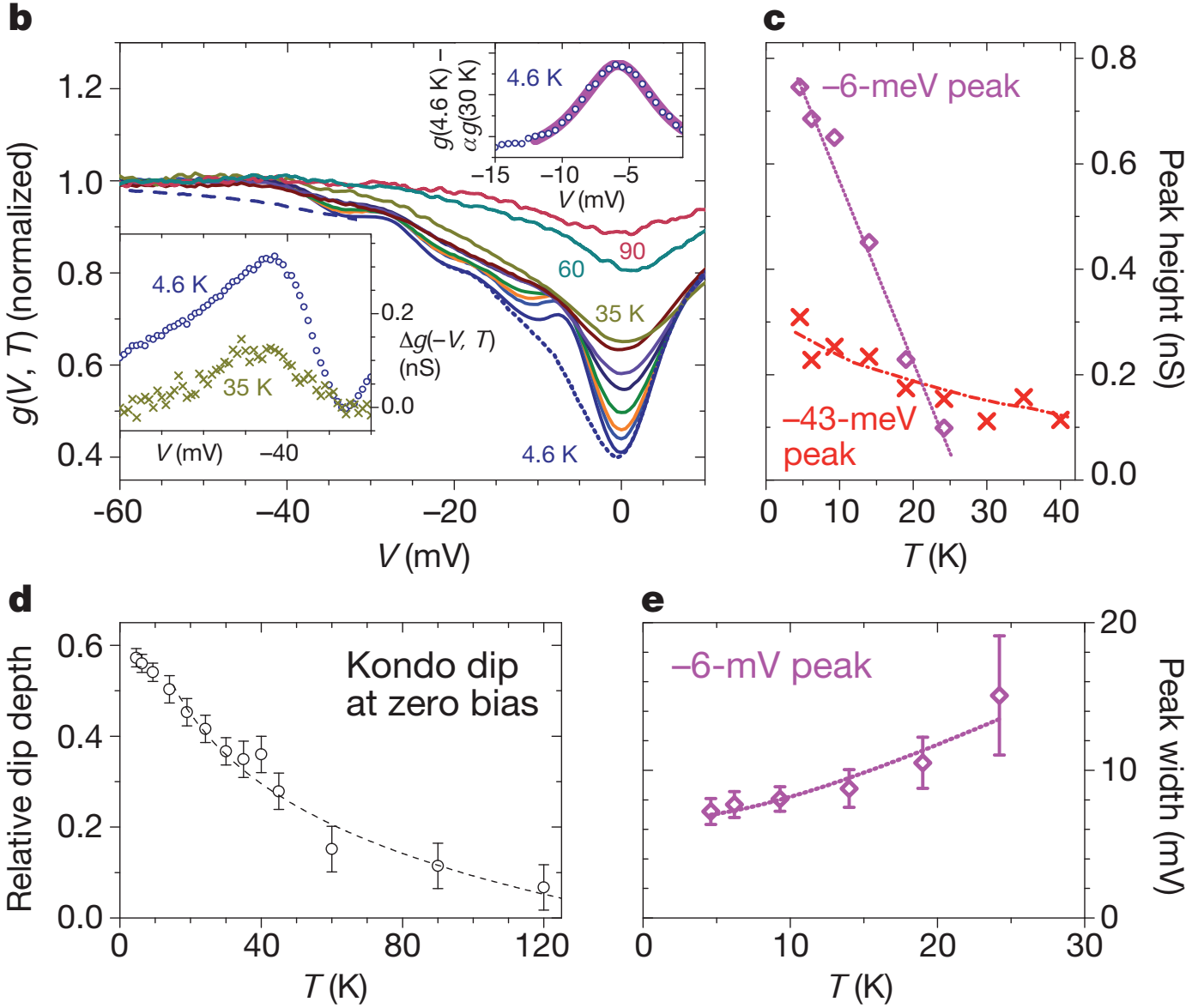
$YbRh_2Si_2$: Prototypal quantum critical heavy fermion system



(Custers et al., Nature 424 (2003) 524)

(Gegenwart et al., Nature Phys. 4 (2008) 186; Rouke et al., PRL 101 (2008) 237205)

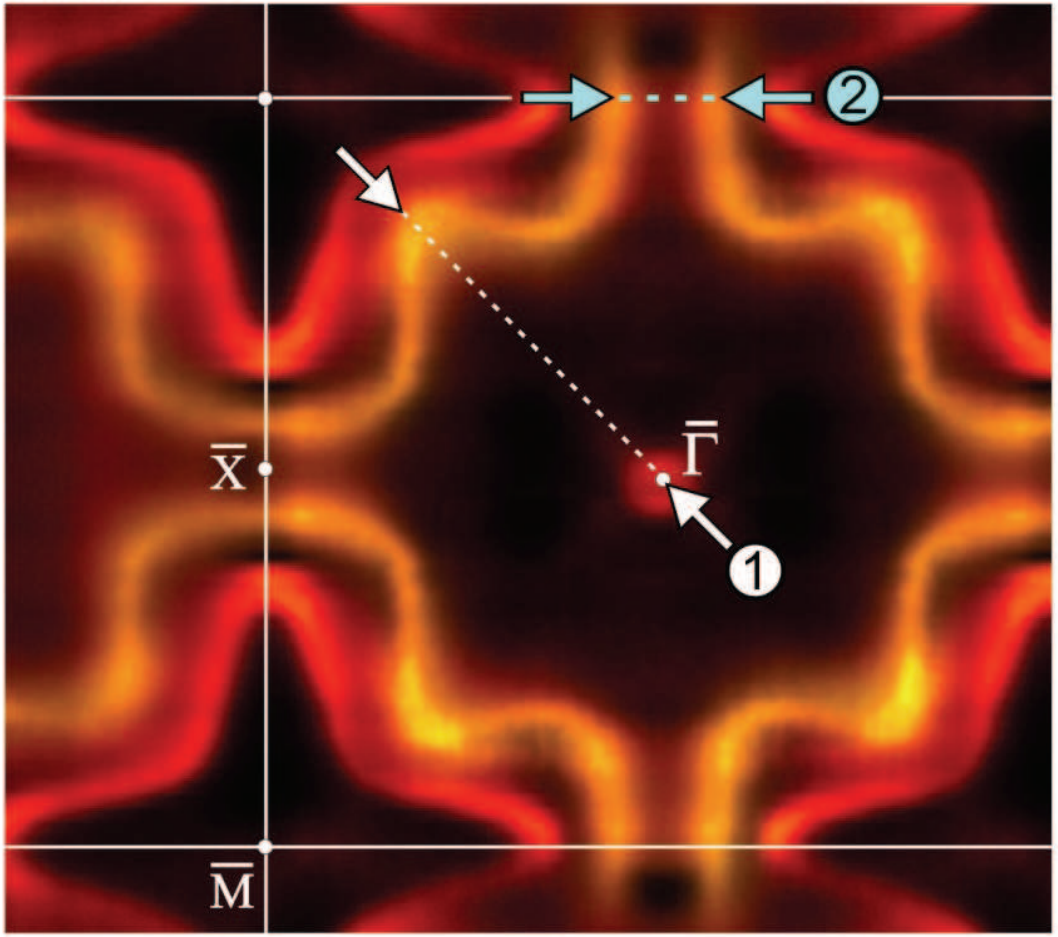
STM study of $YbRh_2Si_2$



(Ernst et al., Nature 474 (2011) 362) Kondo lattice, CEF, single ion Kondo features

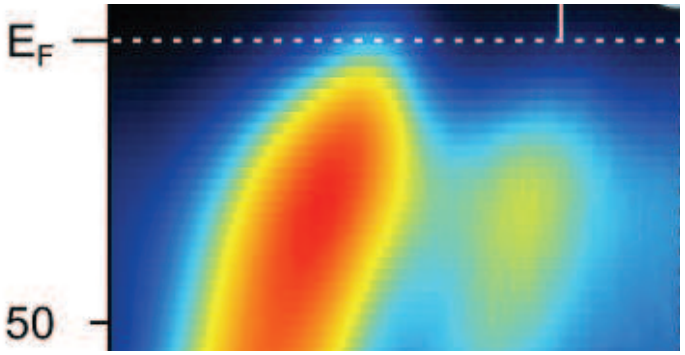
ARPES study of $YbRh_2Si_2$

$T \approx 10\,\mathrm{K}$

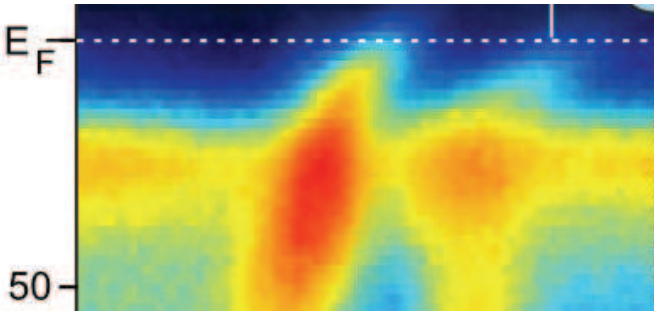


(Danzenbächer et al., PRL 107 (2011) 267601)

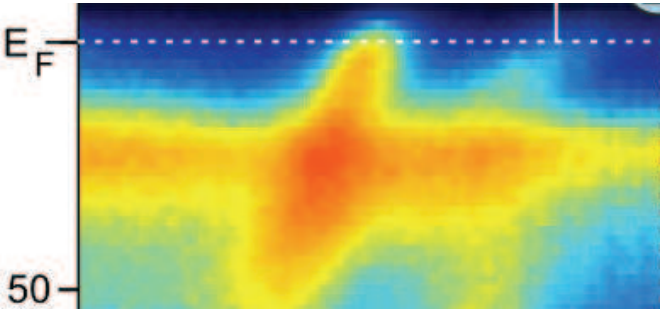
$T \approx 95\,\mathrm{K}$



$T \approx 35\,\mathrm{K}$



$T \approx 1\,\mathrm{K}$

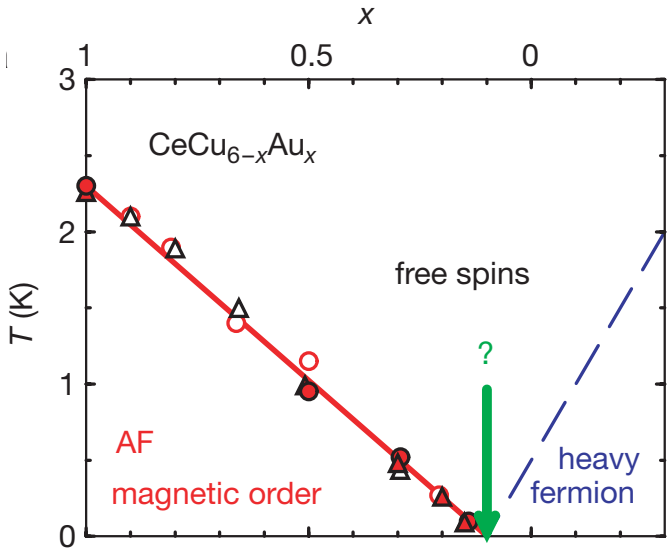


(Kummer et al., unpublished; see Zwicknagl talk at IRONIC)

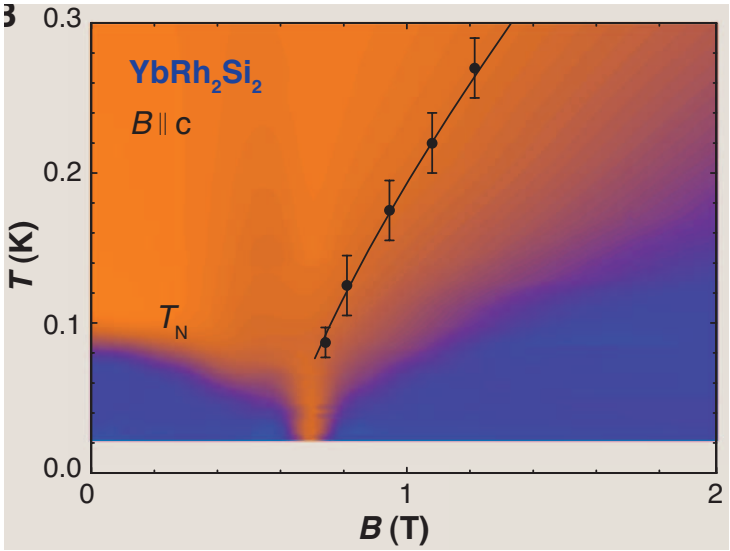
Fermi surface evolution with tuning parameter, across QCP

Heavy fermion quantum criticality: NFL and novel phases at $T_N \to 0$

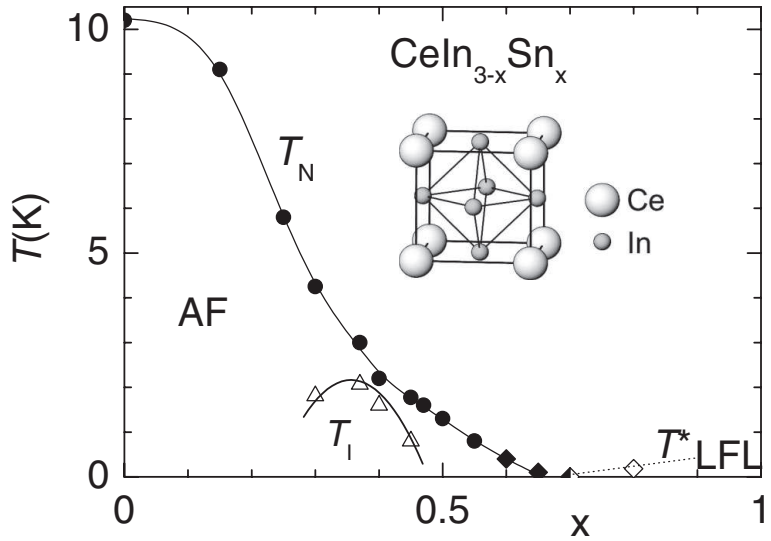
$CeCu_{6-x}Au_x$ (Schröder et al., Nature 2000)



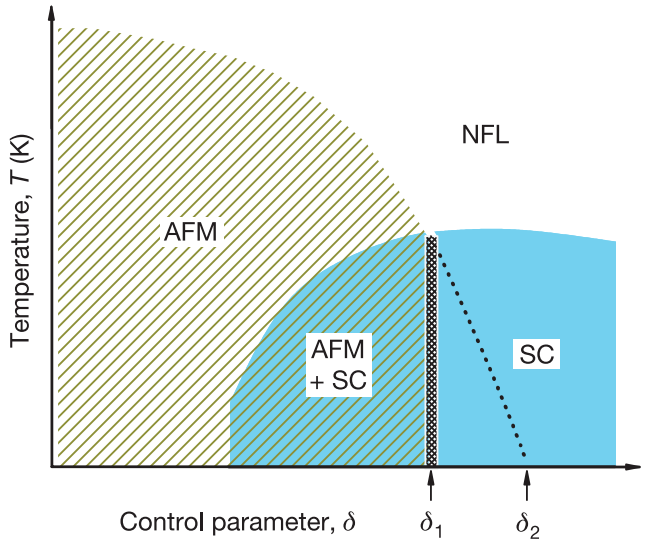
$YbRh_2Si_2$ (Custers et al., Nature 2001)



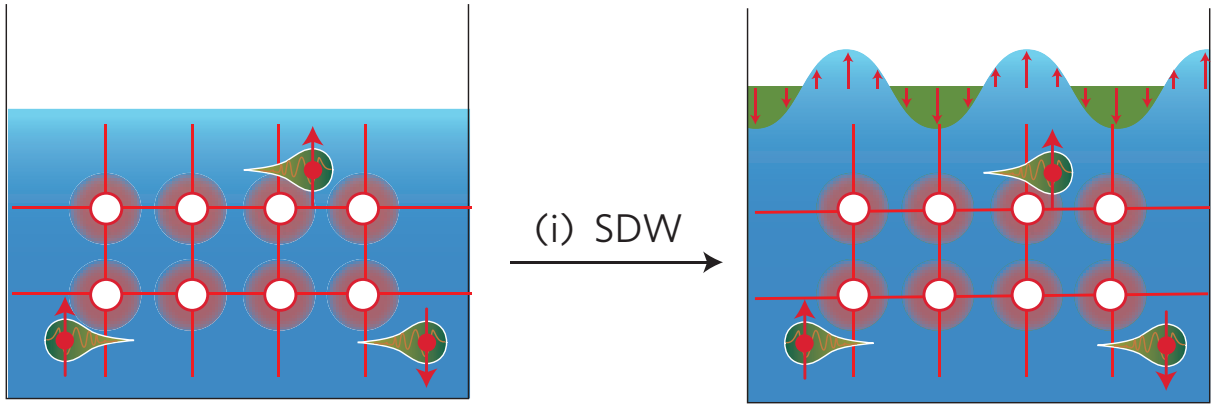
$CeIn_{3-x}Sn_x$ (Küchler et al., PRL 2006)



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

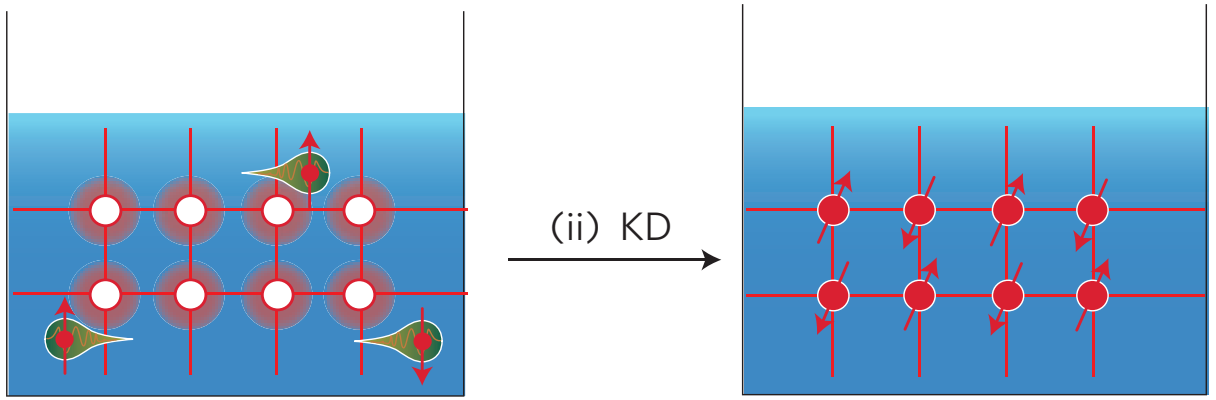


Standard scenario: Spin density wave (SDW) formation (Hertz, Millis, ...)



Paramagnet Itinerant antiferromagnet

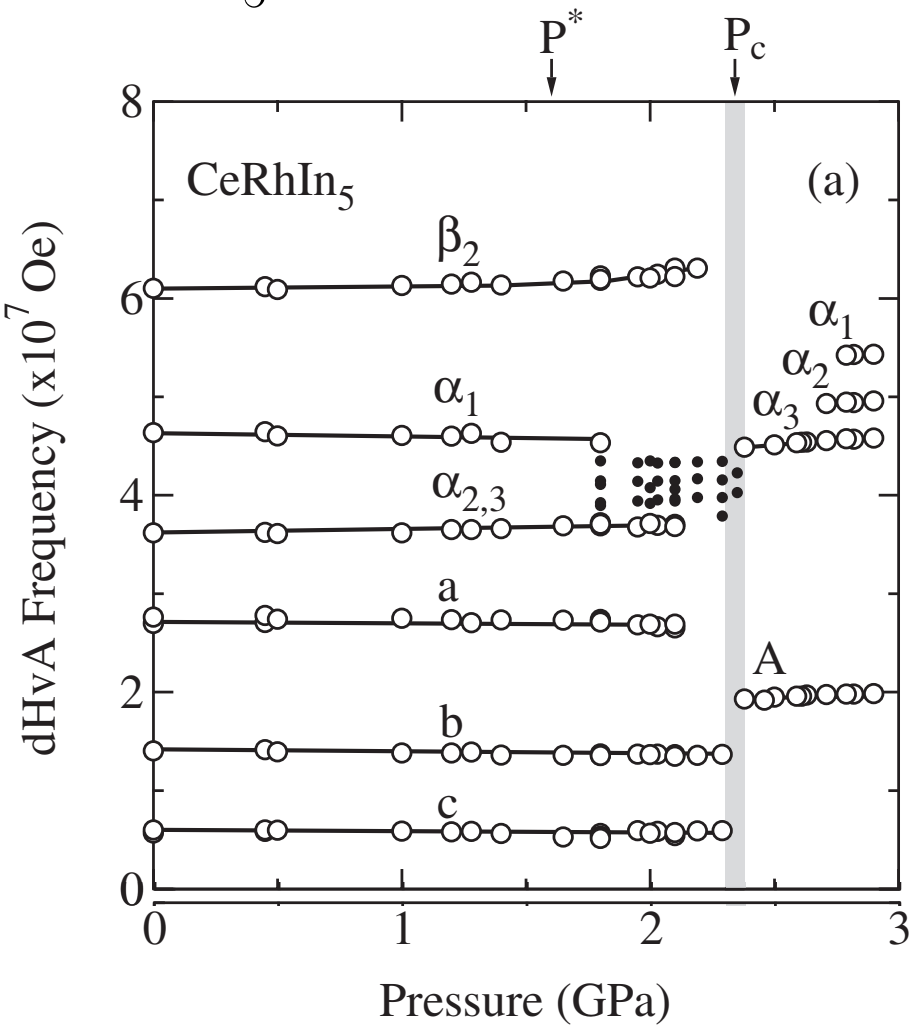
Alternative scenario: Kondo breakdown (Coleman, Si, Schröder, ...)



Paramagnet Local moment antiferromagnet

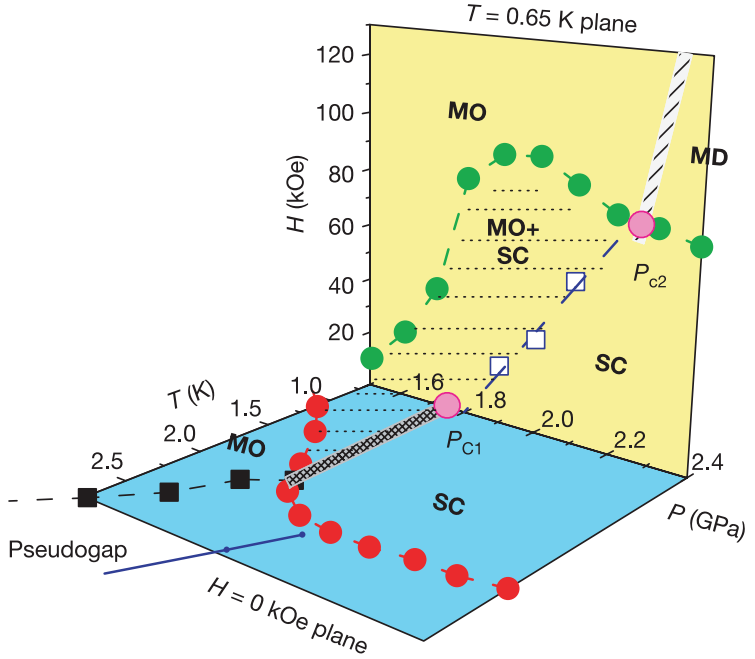
(Coleman, Nature Mater. 11 (2012) 185, news & views)

De Haas-van Alphen studies in $CeRhIn_5$

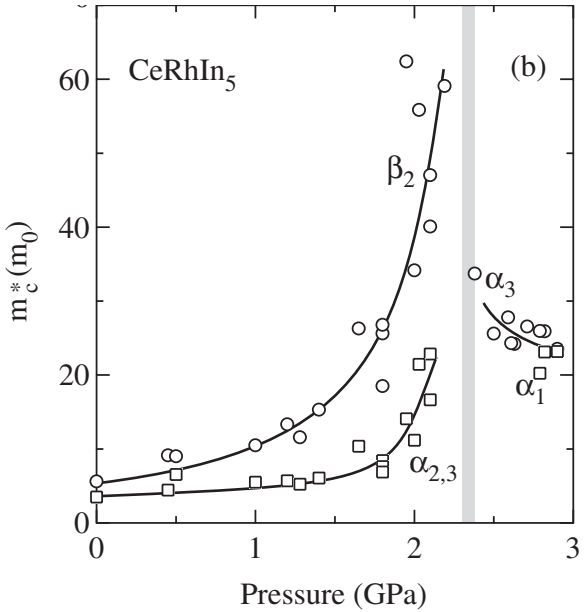


$10\,\mathrm{kOe} < H < 16.9\,\mathrm{kOe}$

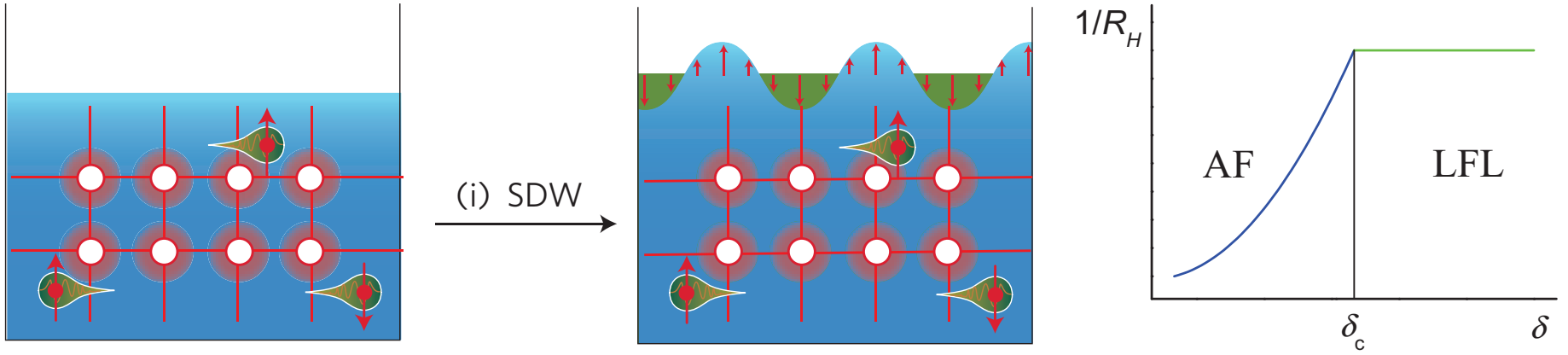
(Shishido et al., JPSJ 74 (2005) 1103) ↑ →



(Park et al., Nature 440 (2006) 65)

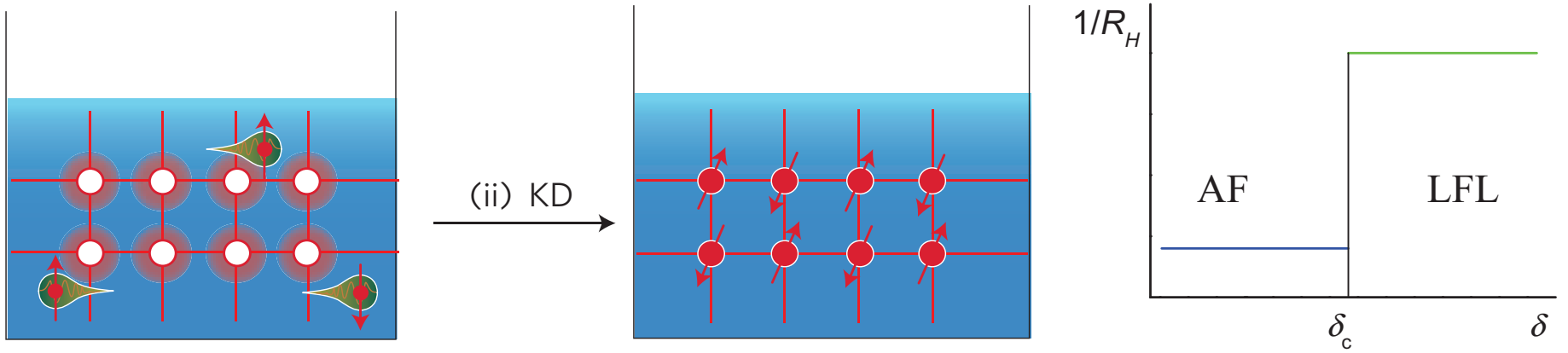


Standard scenario: Spin density wave (SDW) formation (Hertz, Millis, ...)



Paramagnet Itinerant antiferromagnet continuous R_H

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

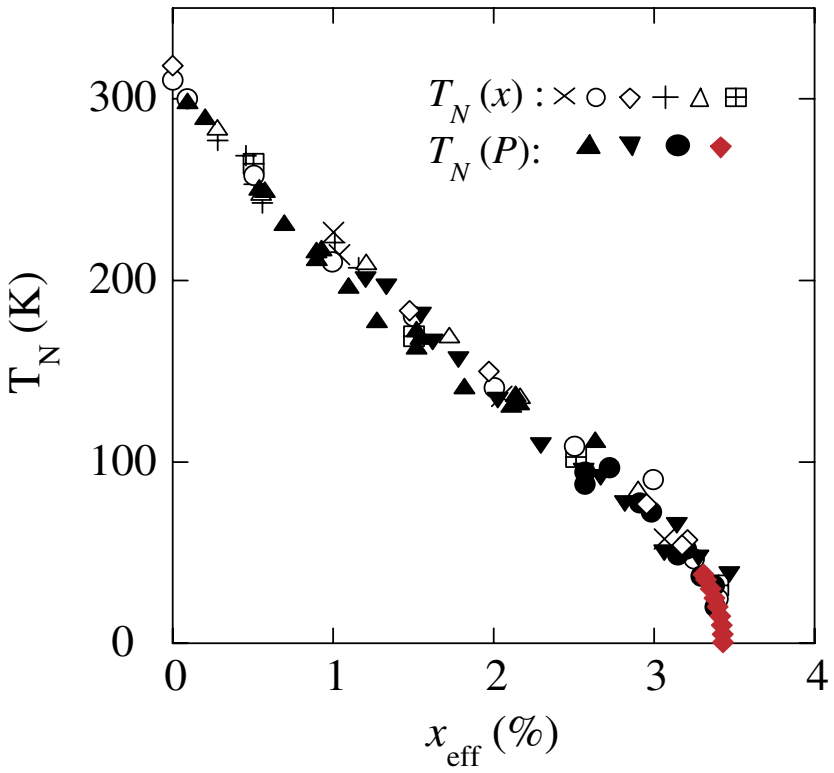


Paramagnet Local moment antiferromagnet jump in R_H

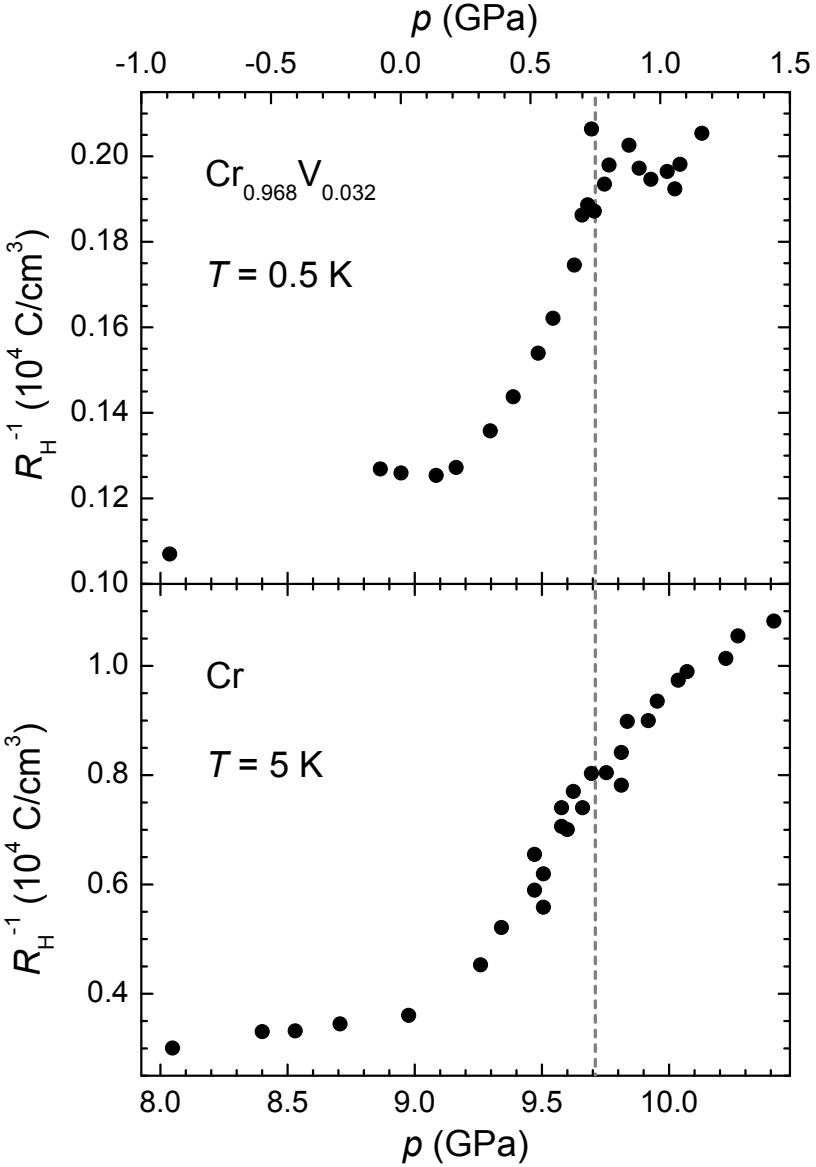
use Hall effect (Coleman et al., J. Phys. Condens. Matter 13 (2001) R723) ↑

Hall effect at doping/pressure induced QCP of prototypical SDW system $Cr_{1-x}V_x$

Phase diagram

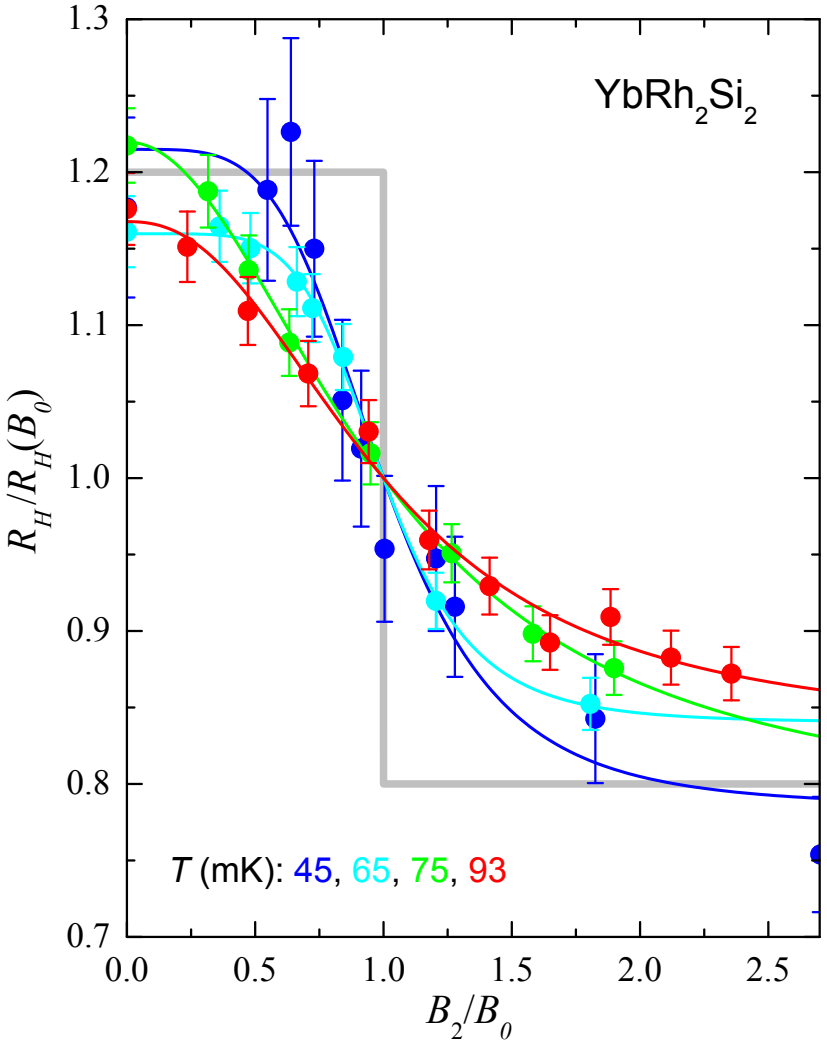


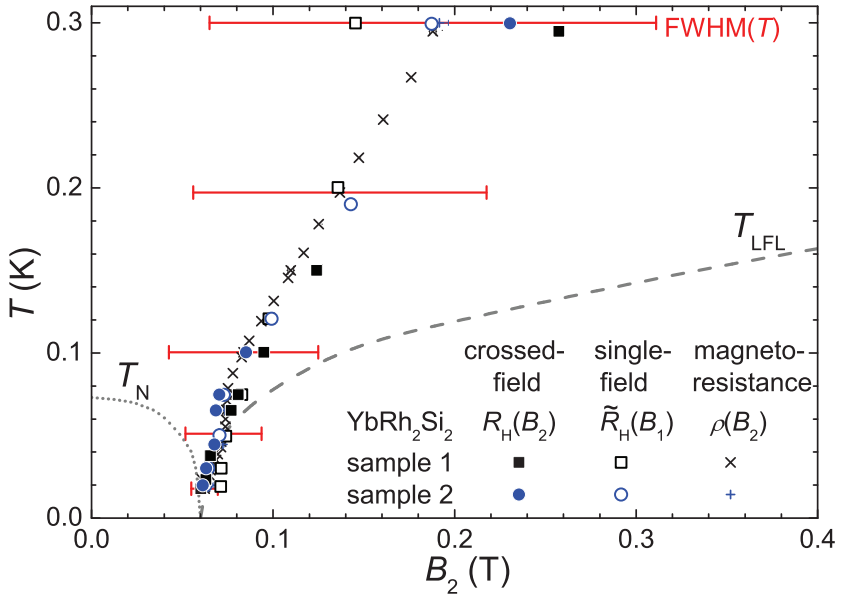
Inverse Hall coefficient

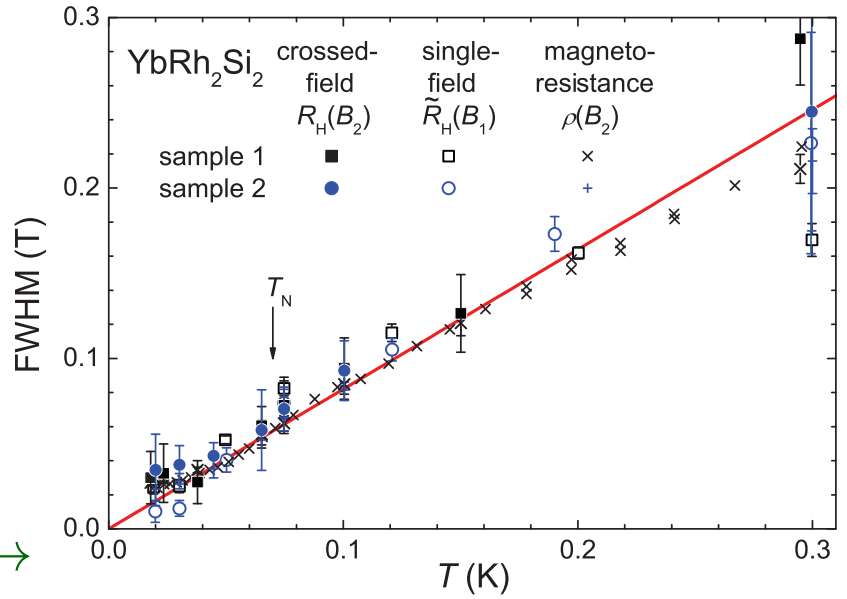


(Lee et al., PRL 92 (2004) 187201,
Jaramillo et al.,PNAS 107 (2010) 13631)

Hall effect in $YbRh_2Si_2$: Discovery of T^*





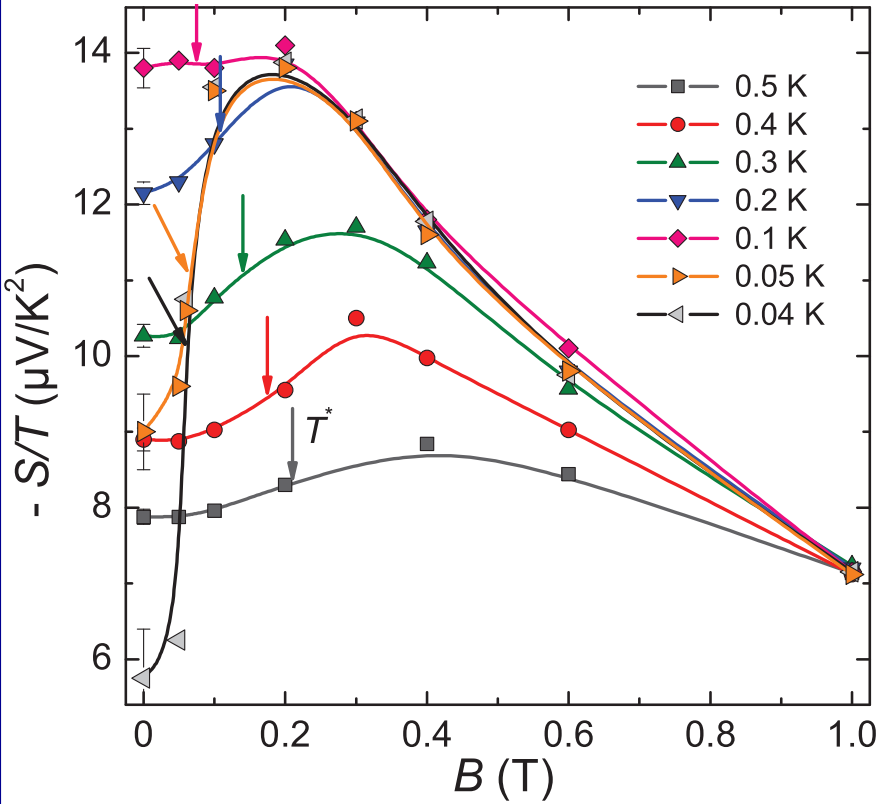


(SP et al., Nature 432 (2004) 881) ↑

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

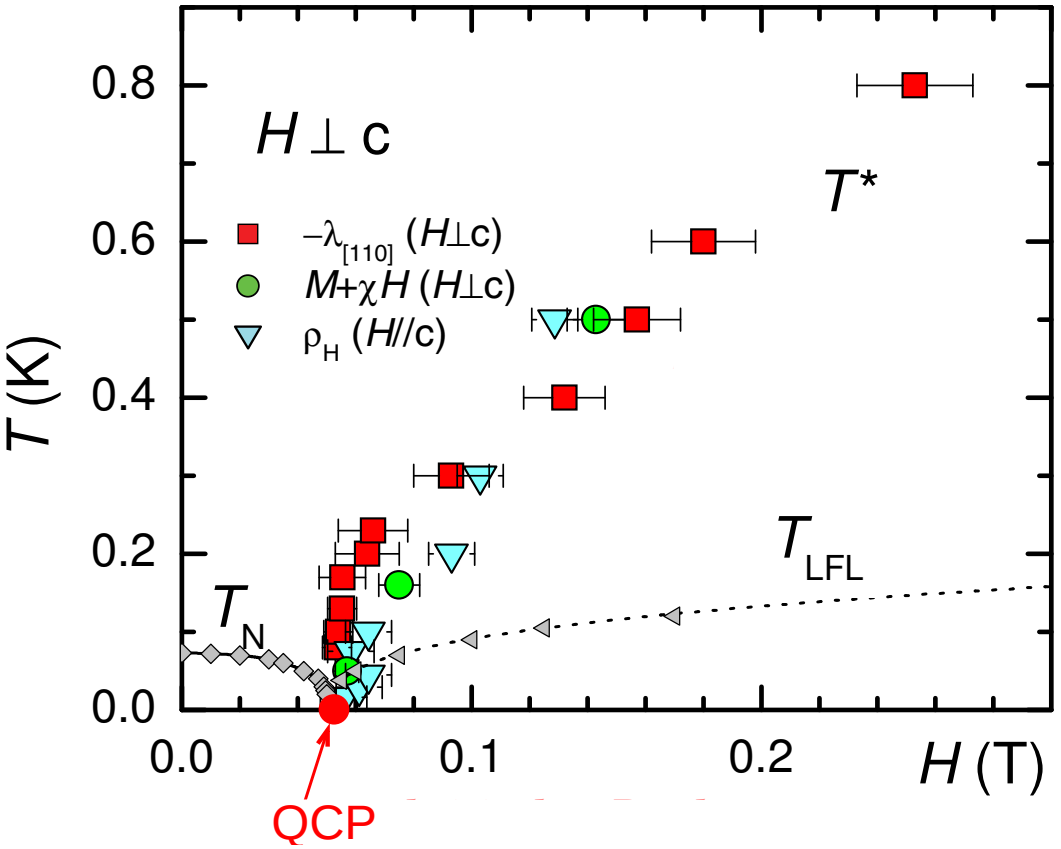
Thermodynamic evidence of $T^* \rightarrow$ New energy scale

Thermopower



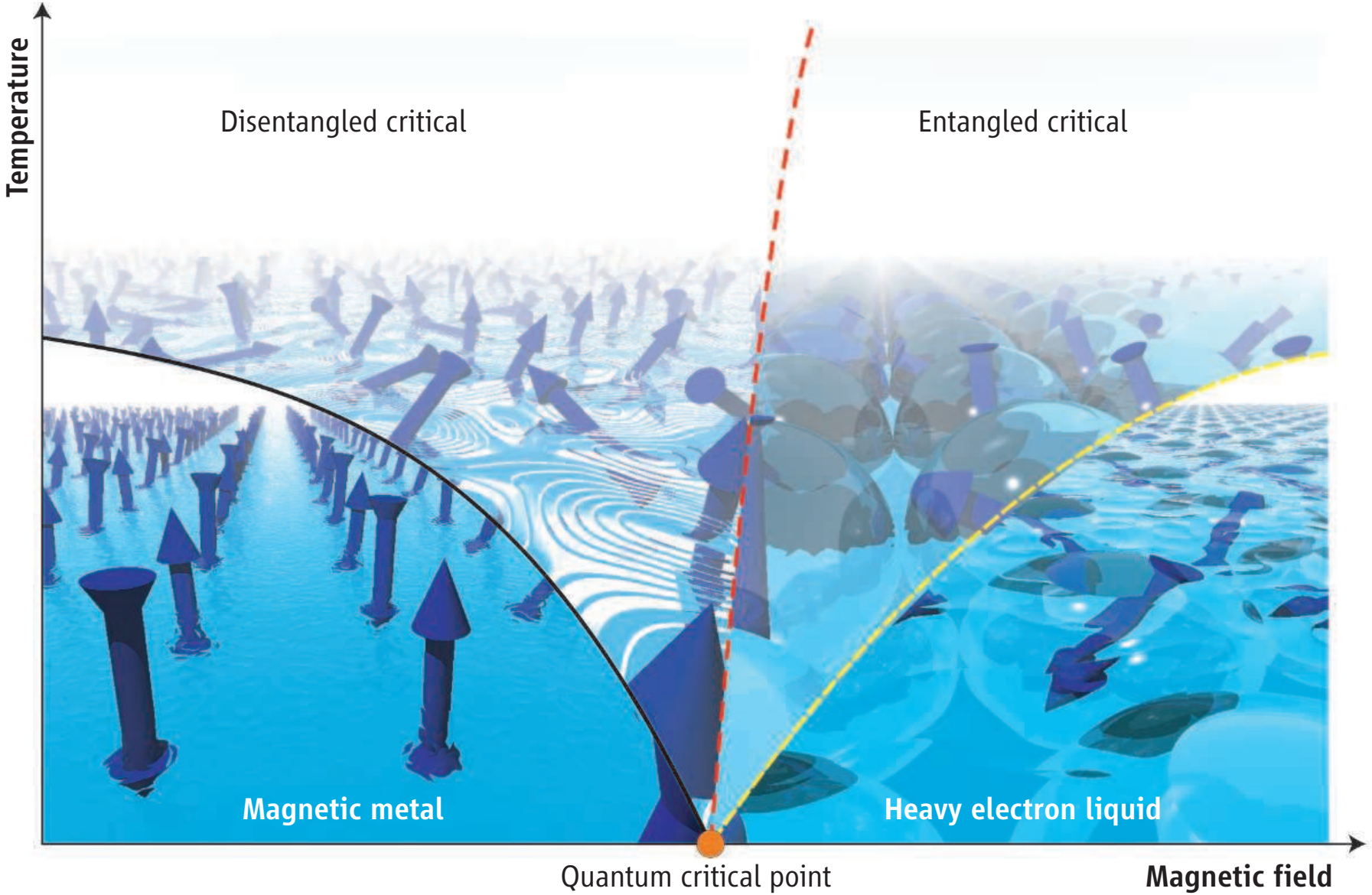
(Hartmann et al., Phys. Rev. Lett. 104 (2010) 096402)

Magnetostriction, magnetization



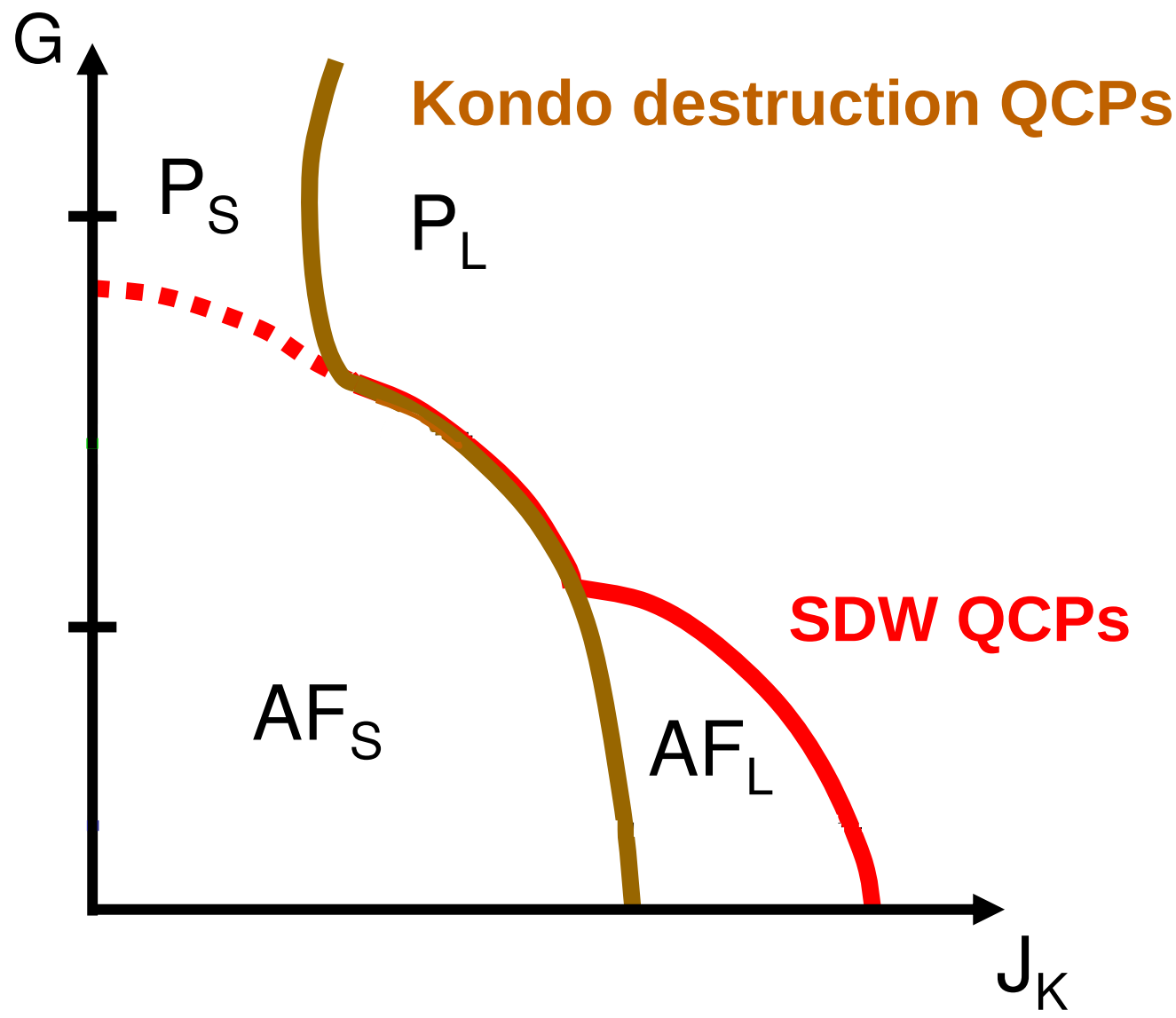
(Gegenwart et al., Science 315 (2007) 969)

The Kondo breakdown QCP - cartoon



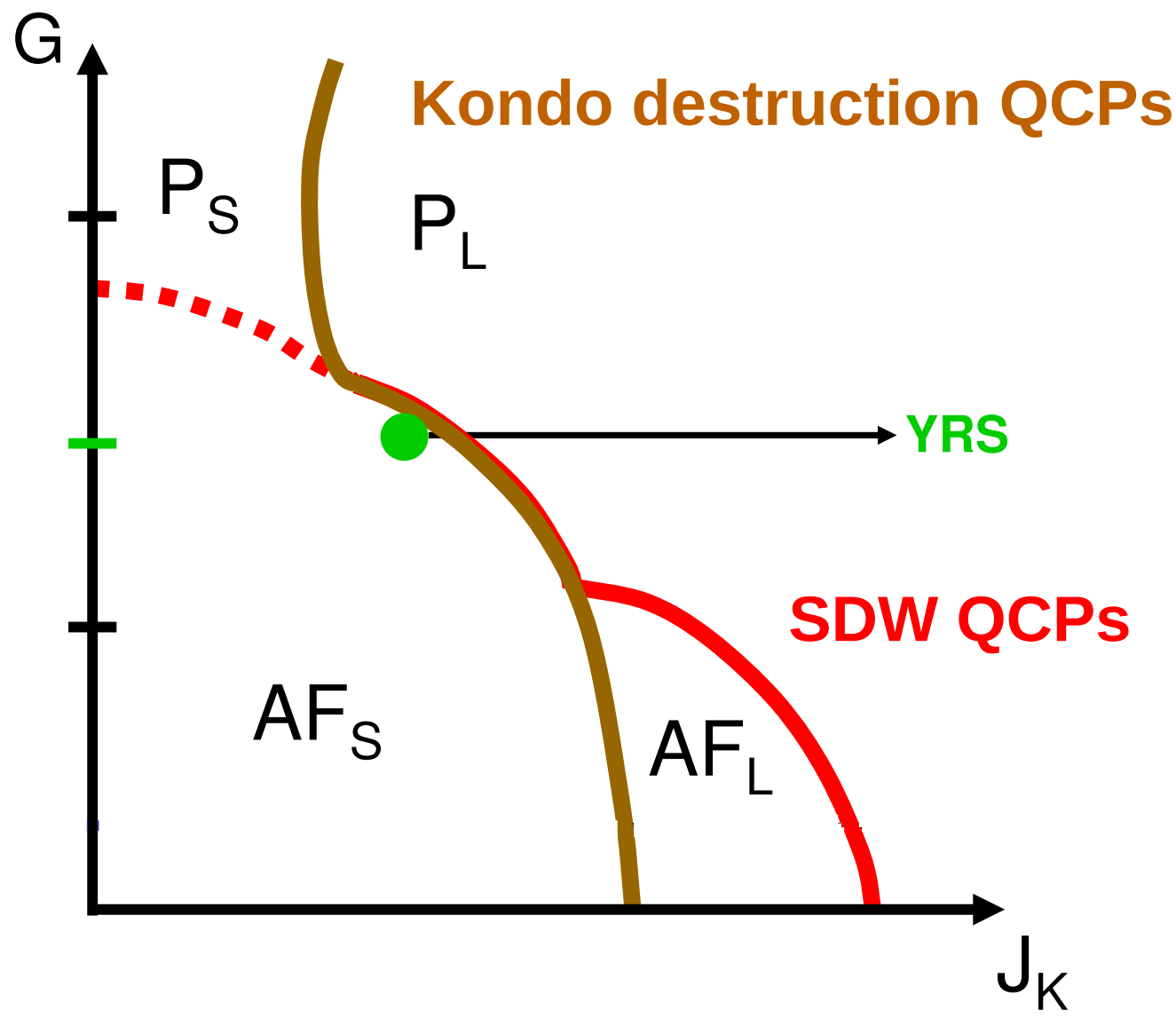
(Schofield, Science 315 (2007) 945)

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 $T = 0$

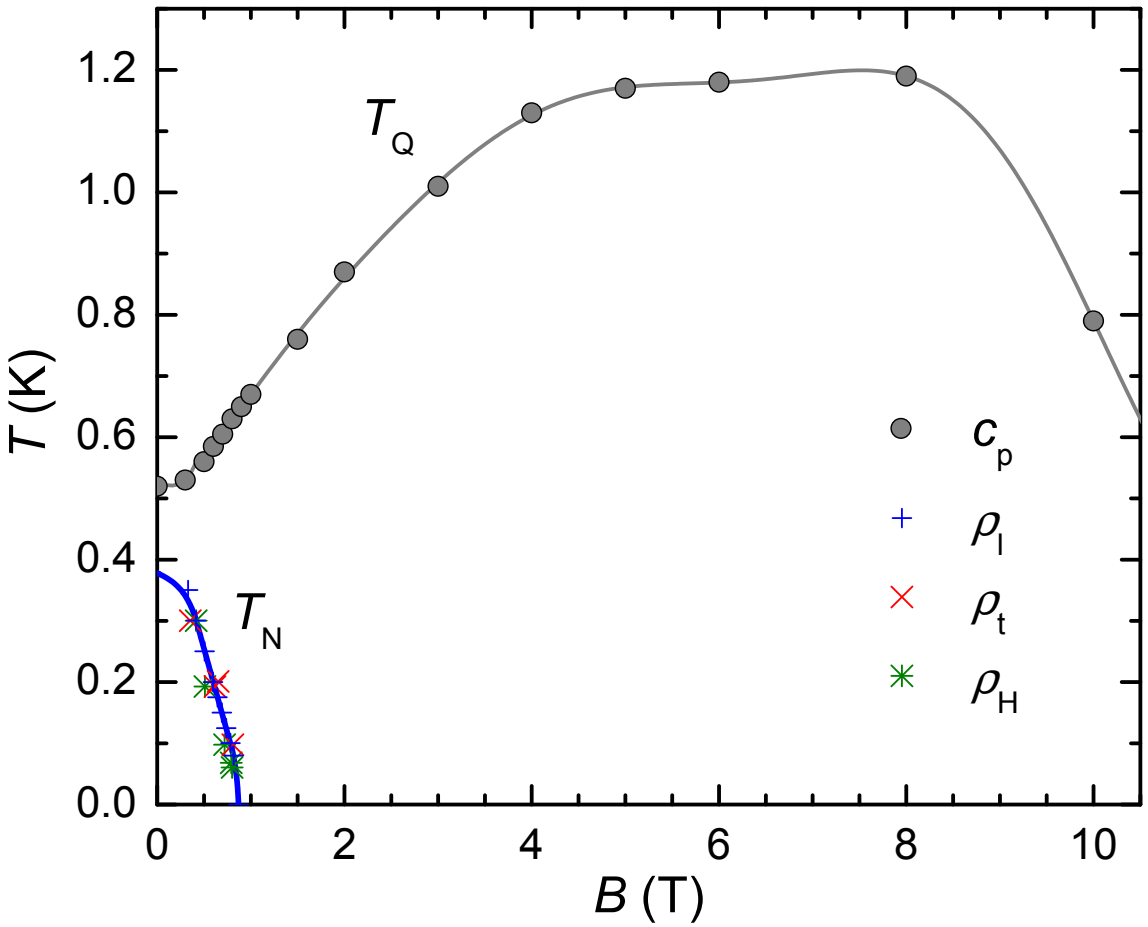


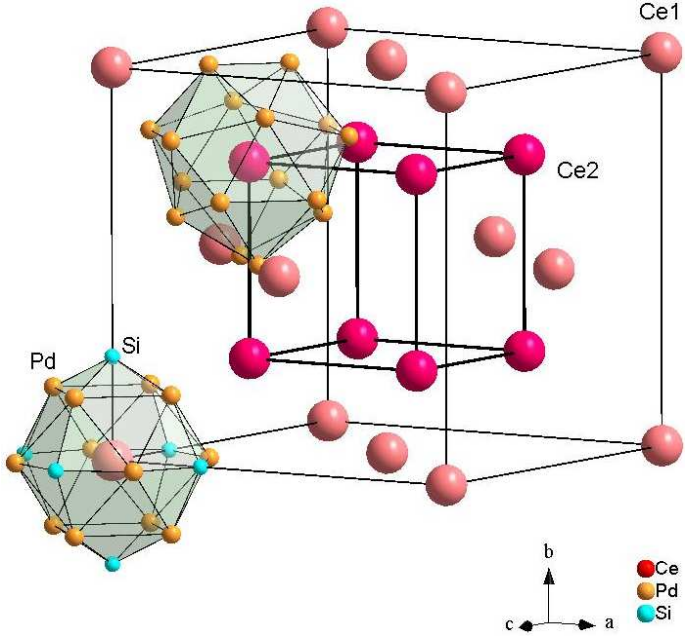
(Si, Physica B 378-380 (2006) 23; Phys. Stat. Sol. 247 (2010) 476)

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

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

Temperature-field phase diagram (pc)





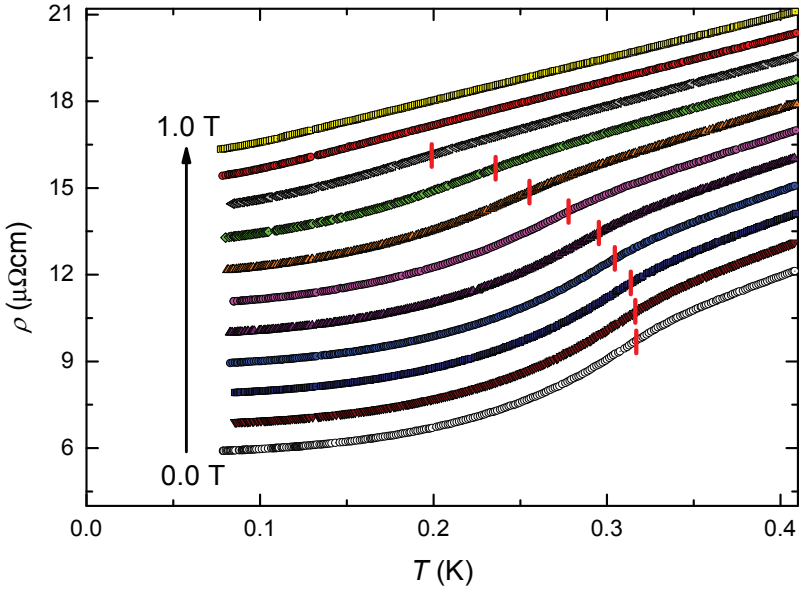
Cubic, $Fm\bar{3}m$

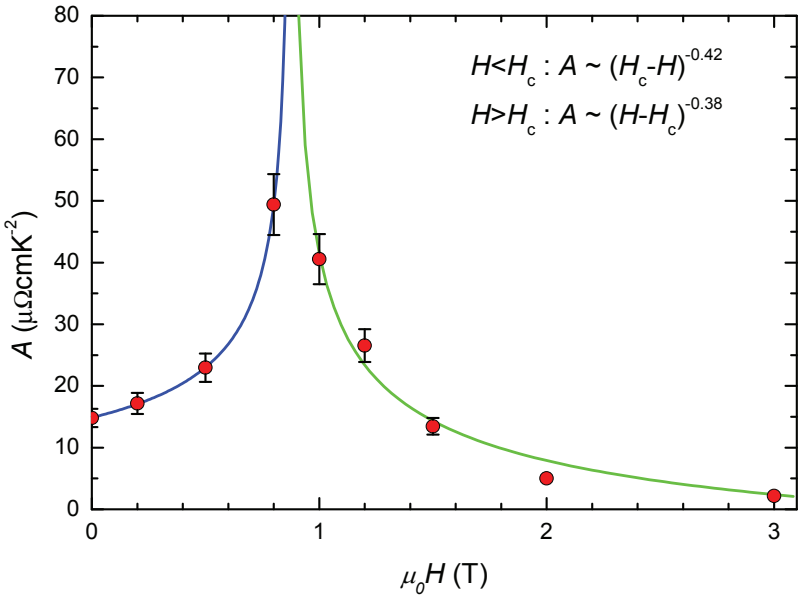
Ce1: fcc, $4a$

Ce2: sc, $8c$

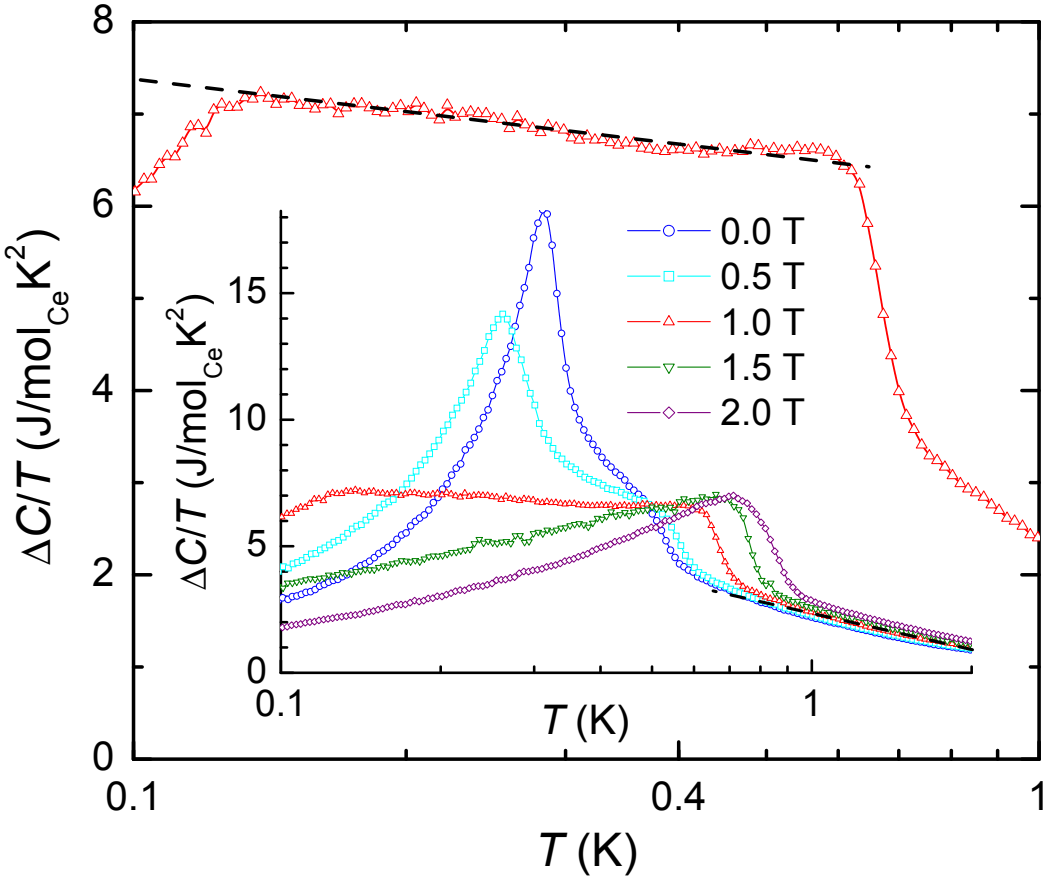
Non-Fermi liquid properties of $Ce_3Pd_{20}Si_6$ at critical field $B_c \approx 0.9\,\mathrm{T}$

Electrical resistivity





Specific heat



$\Delta\rho \sim T$

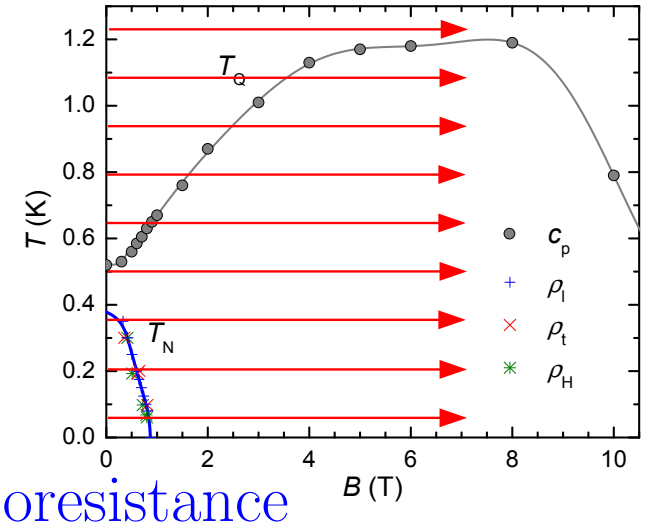
SDW (AFM, $d = 3$): $\Delta\rho \sim T^{3/2}$

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

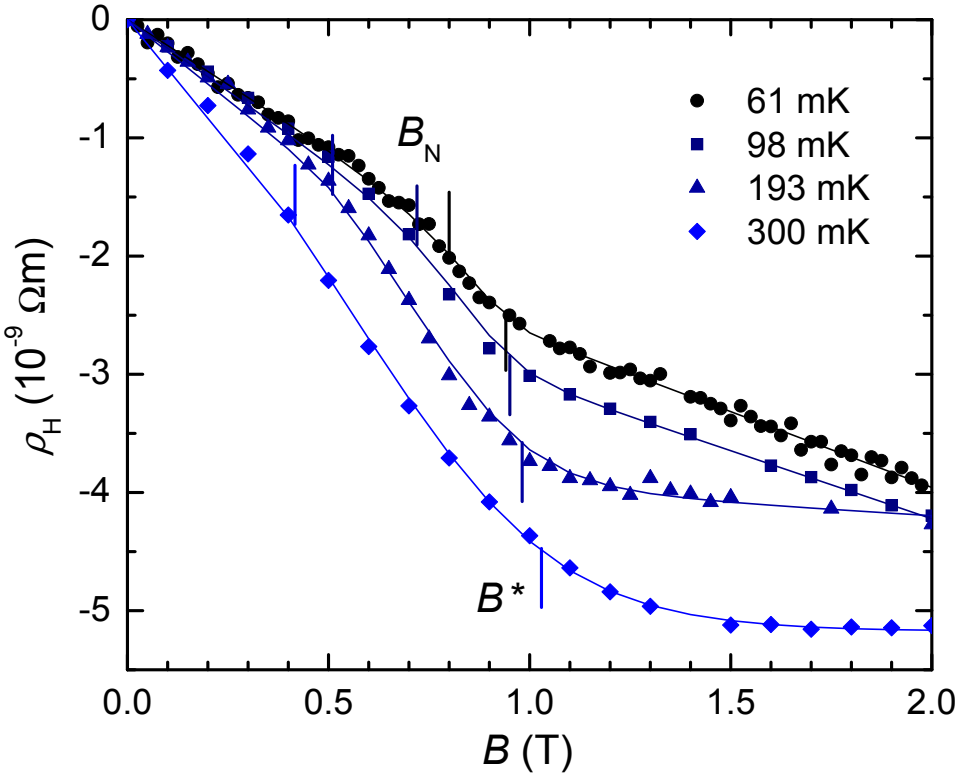
SDW (AFM, $d = 3$): $\Delta C/T = \gamma - b\sqrt{T}$

Isotherms crossing phase diagram

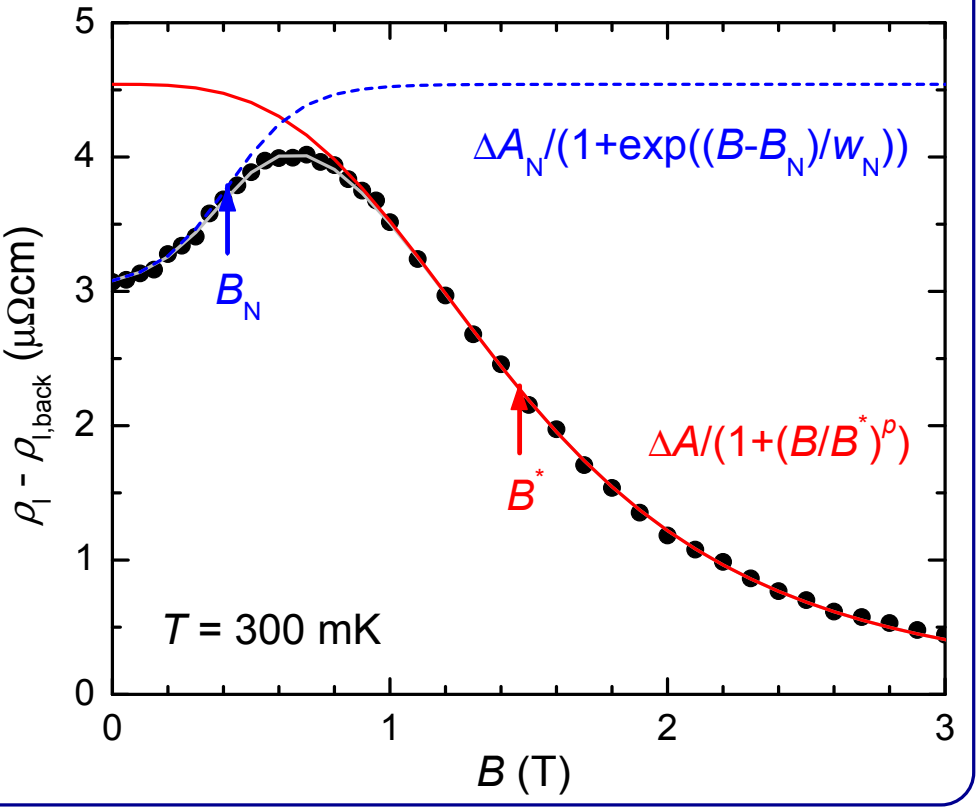
(Custers et al., Nature Mater. 11 (2012) 189)



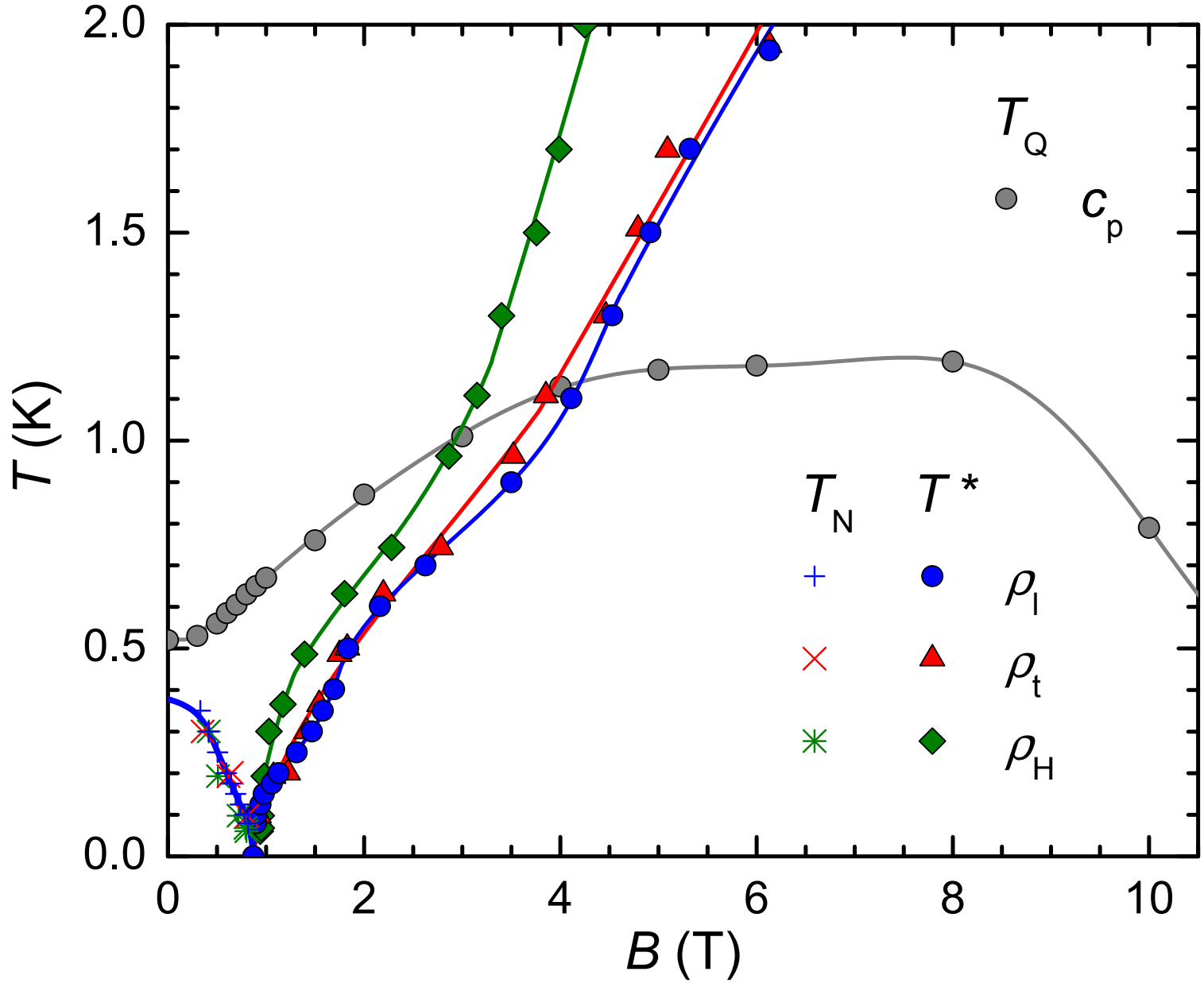
Hall effect



Magnetoresistance

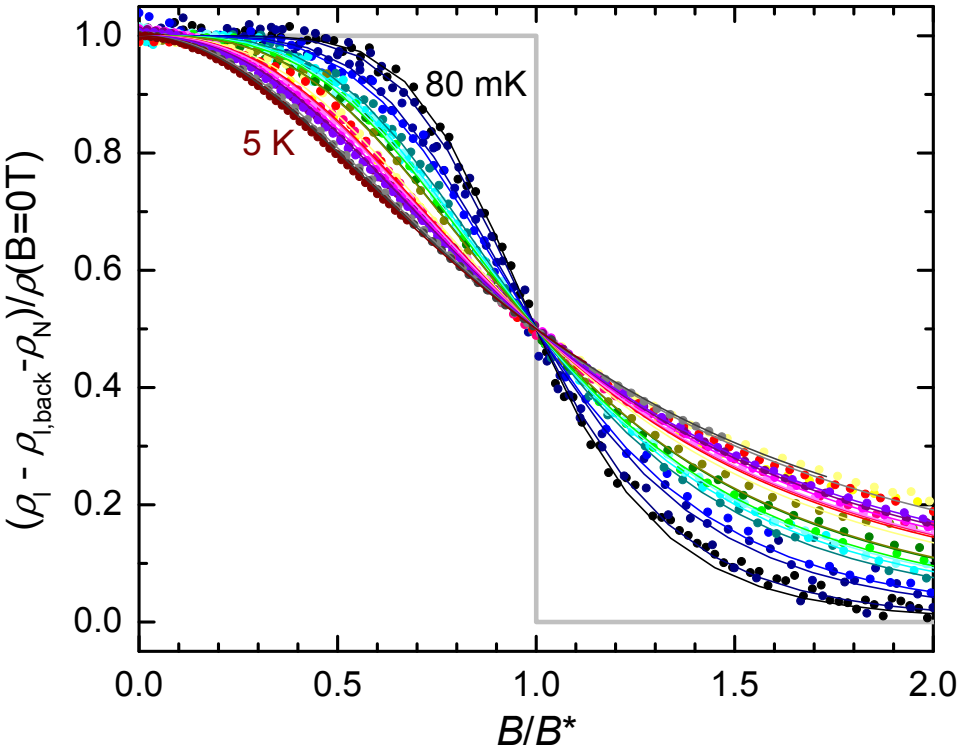


Phase diagram of $Ce_3Pd_{20}Si_6$ with T^* scale

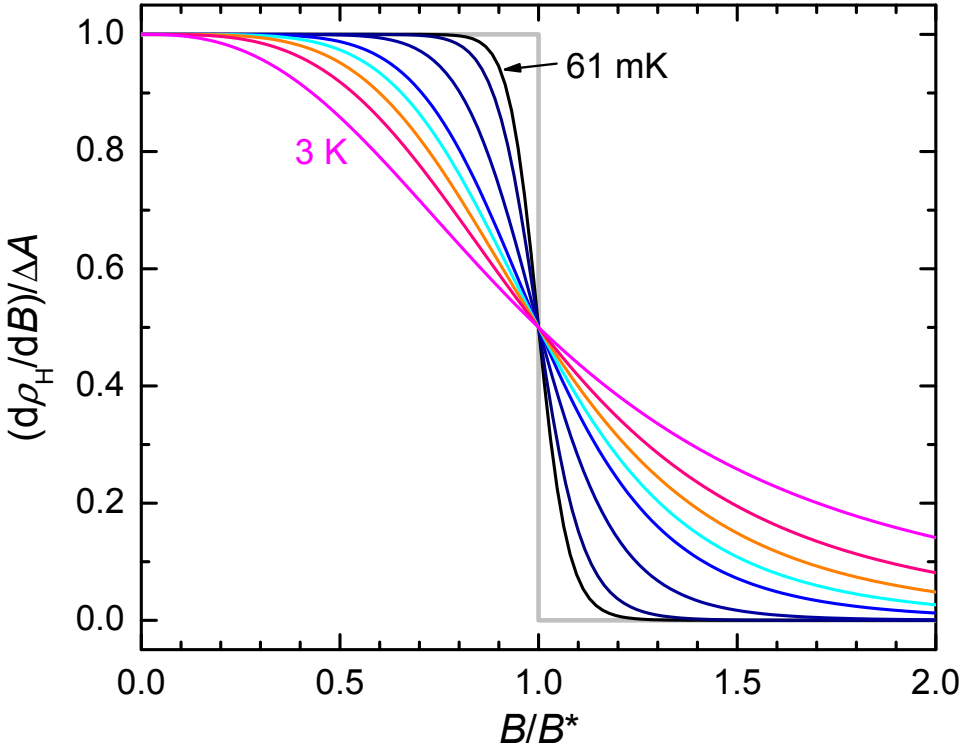


Crossovers in magnetotransport of $Ce_3Pd_{20}Si_6$ at B^*

Longitudinal magnetoresistance

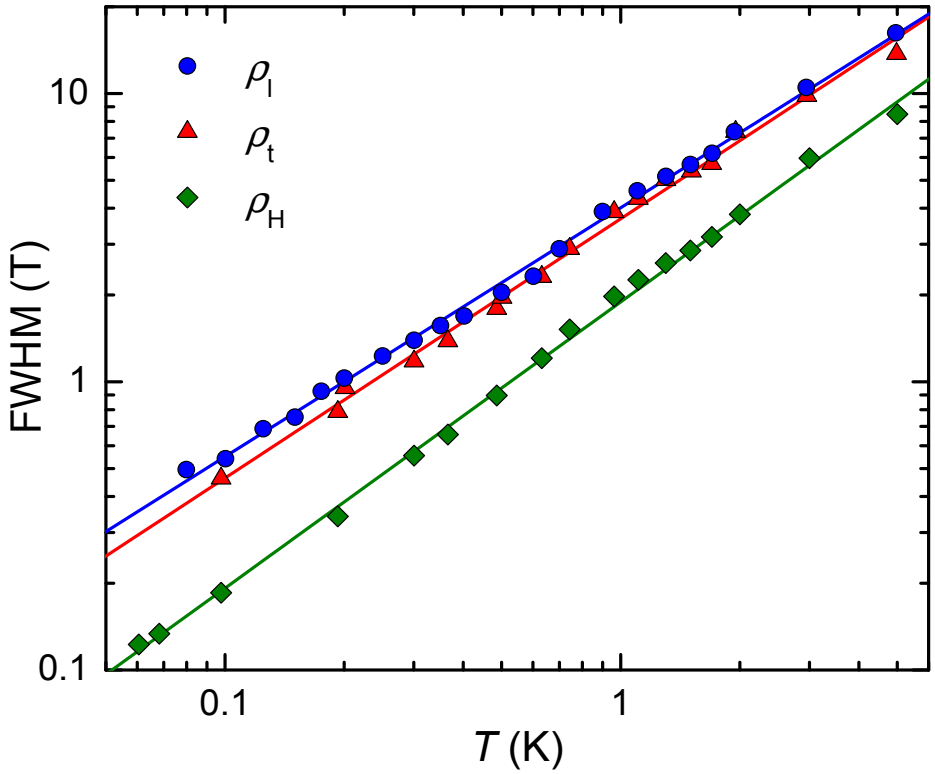


Differential Hall coefficient

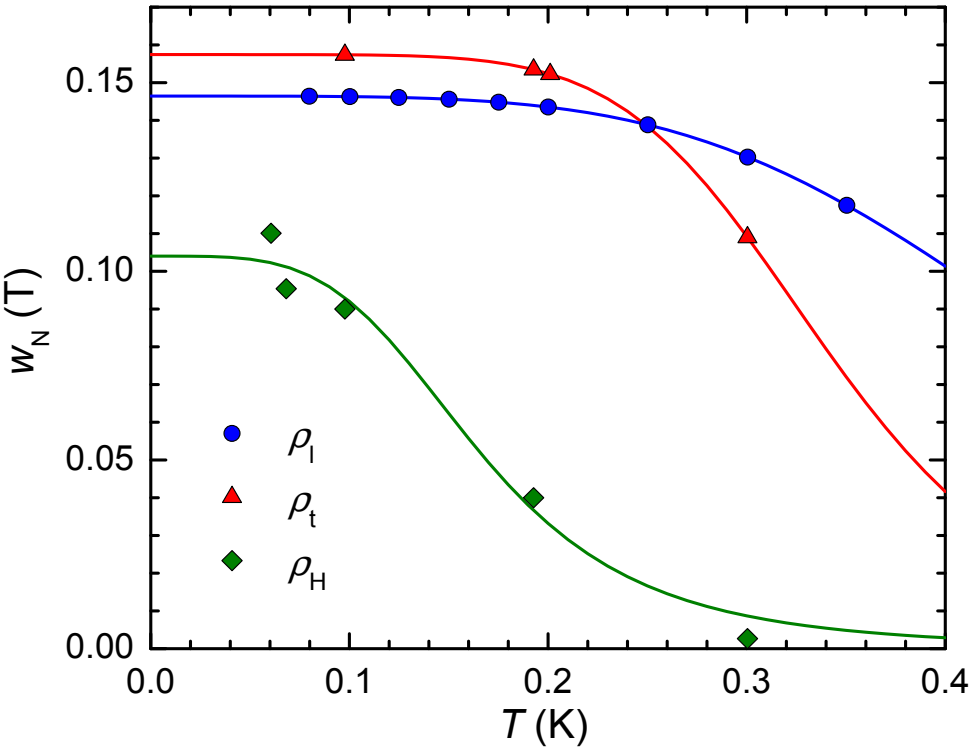


Crossovers at B^* vs transition at B_N

Width of crossover at B^*

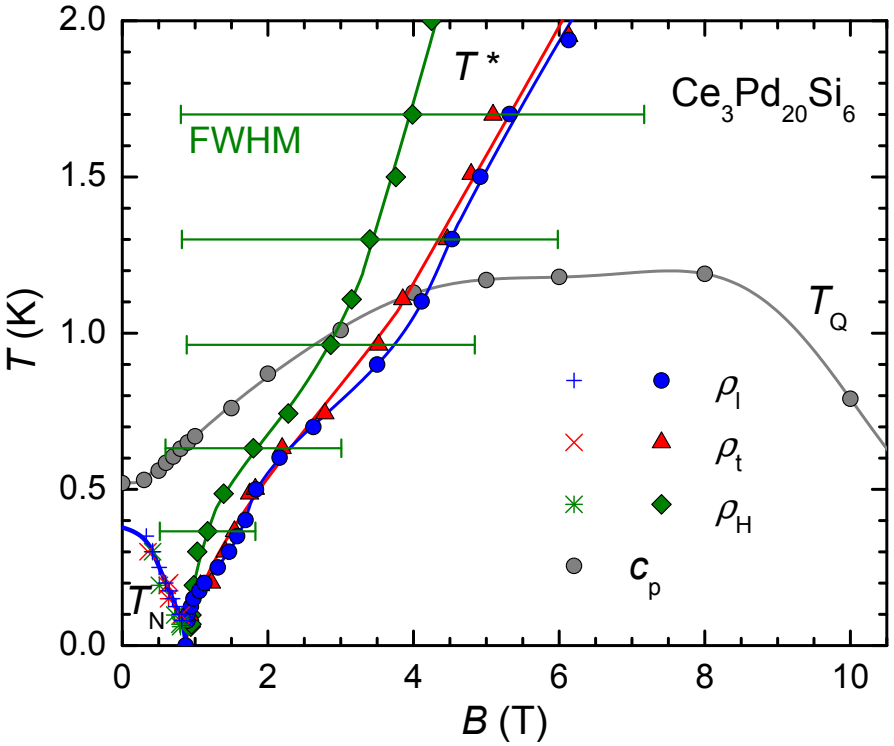


Width of transition at B_N

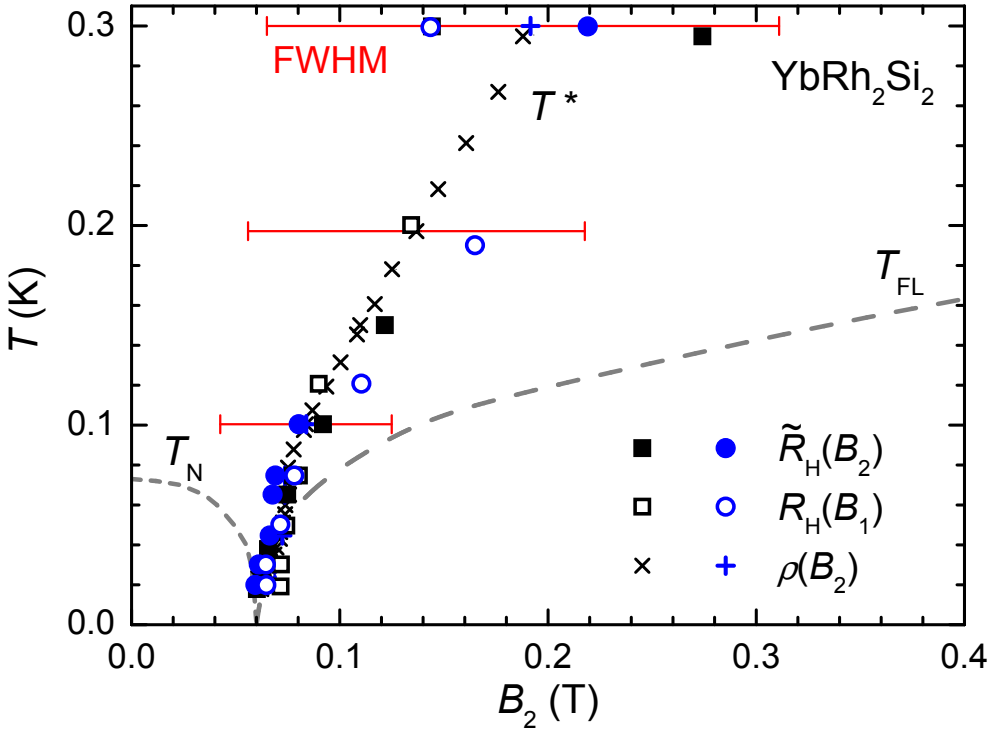


A new cubic material: $Ce_3Pd_{20}Si_6$

cubic $Ce_3Pd_{20}Si_6$

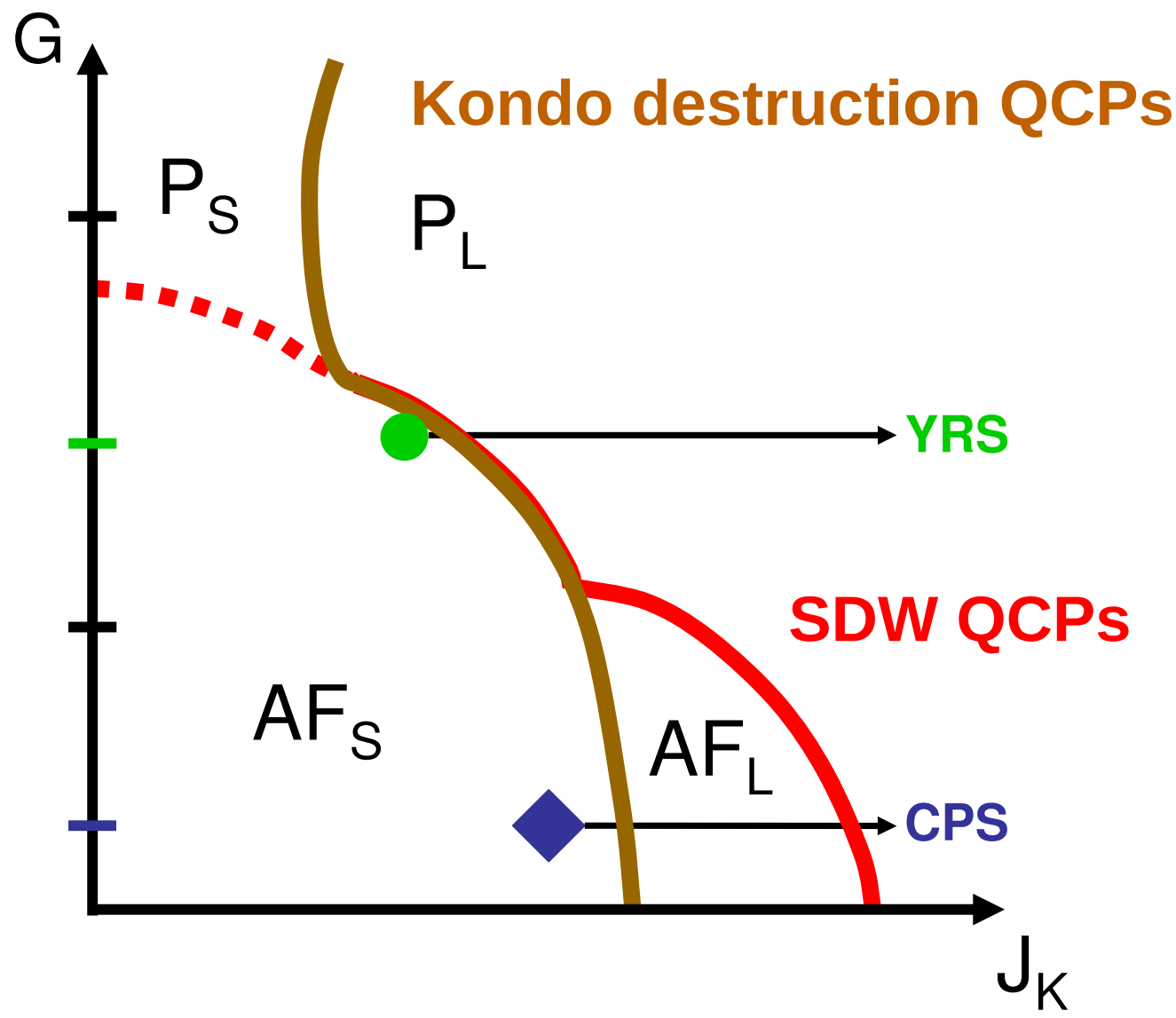


tetragonal $YbRh_2Si_2$



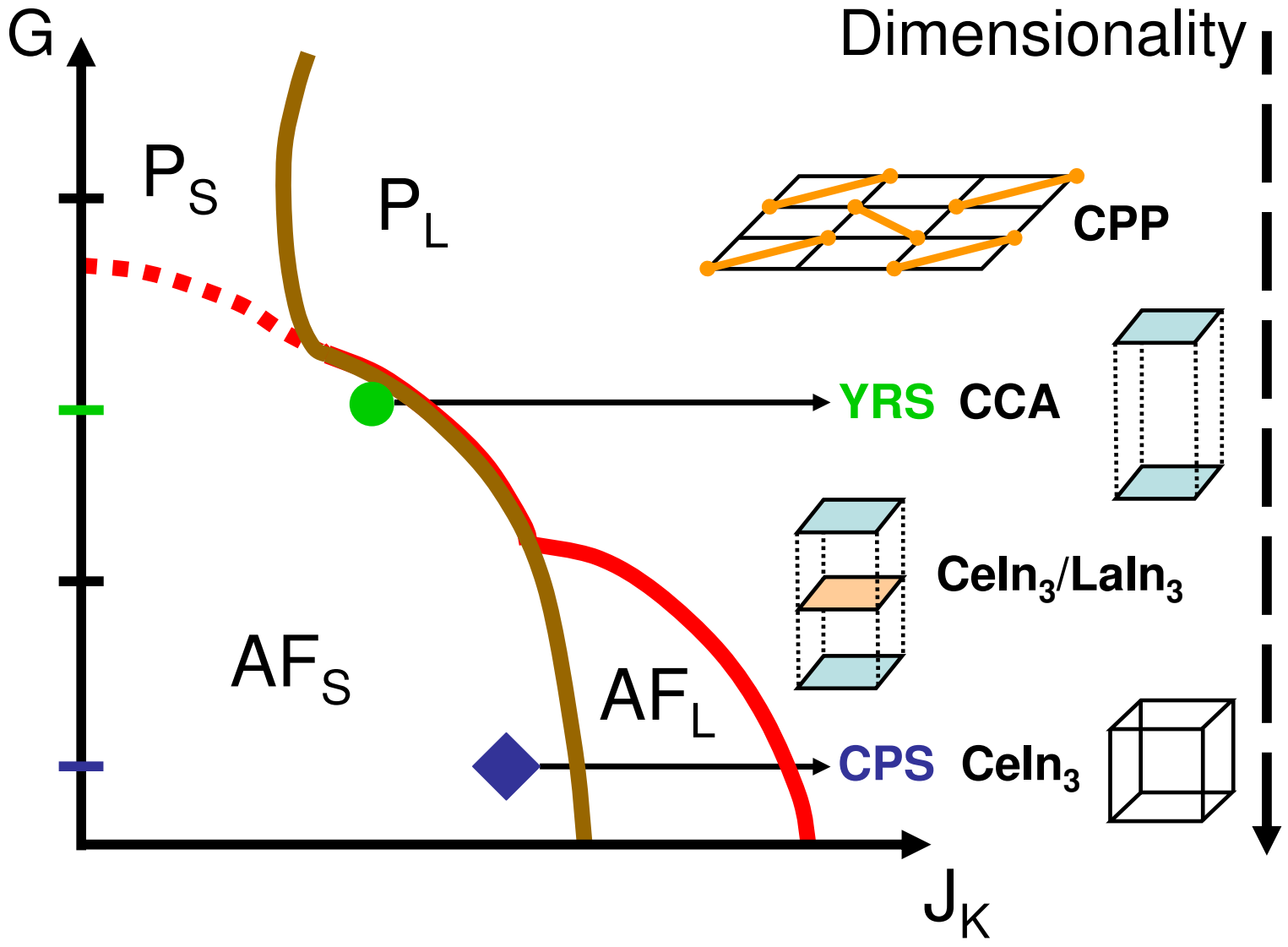
(Si and SP, Phys. Stat. Solidi 250 (2013) 425)

Placement of $Ce_3Pd_{20}Si_6$ in global phase diagram



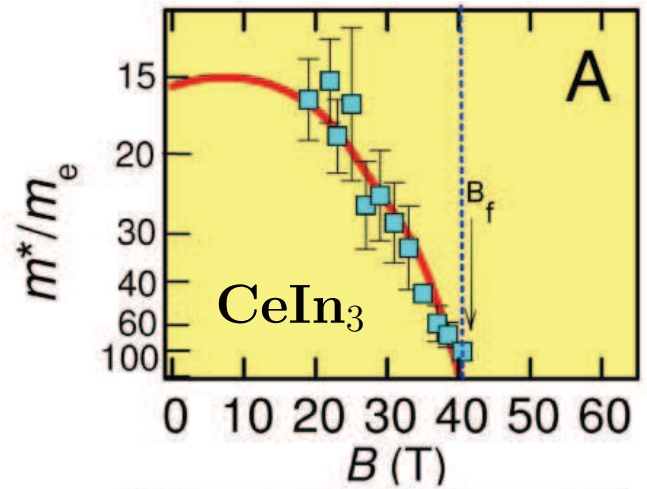
(Custers et al., Nature Mater. 11 (2012) 189)

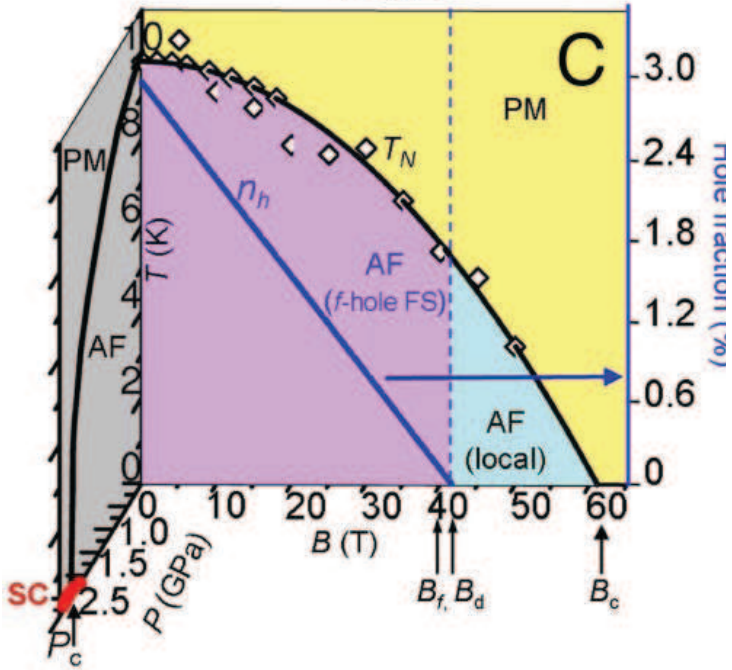
Materials-based global phase diagram



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

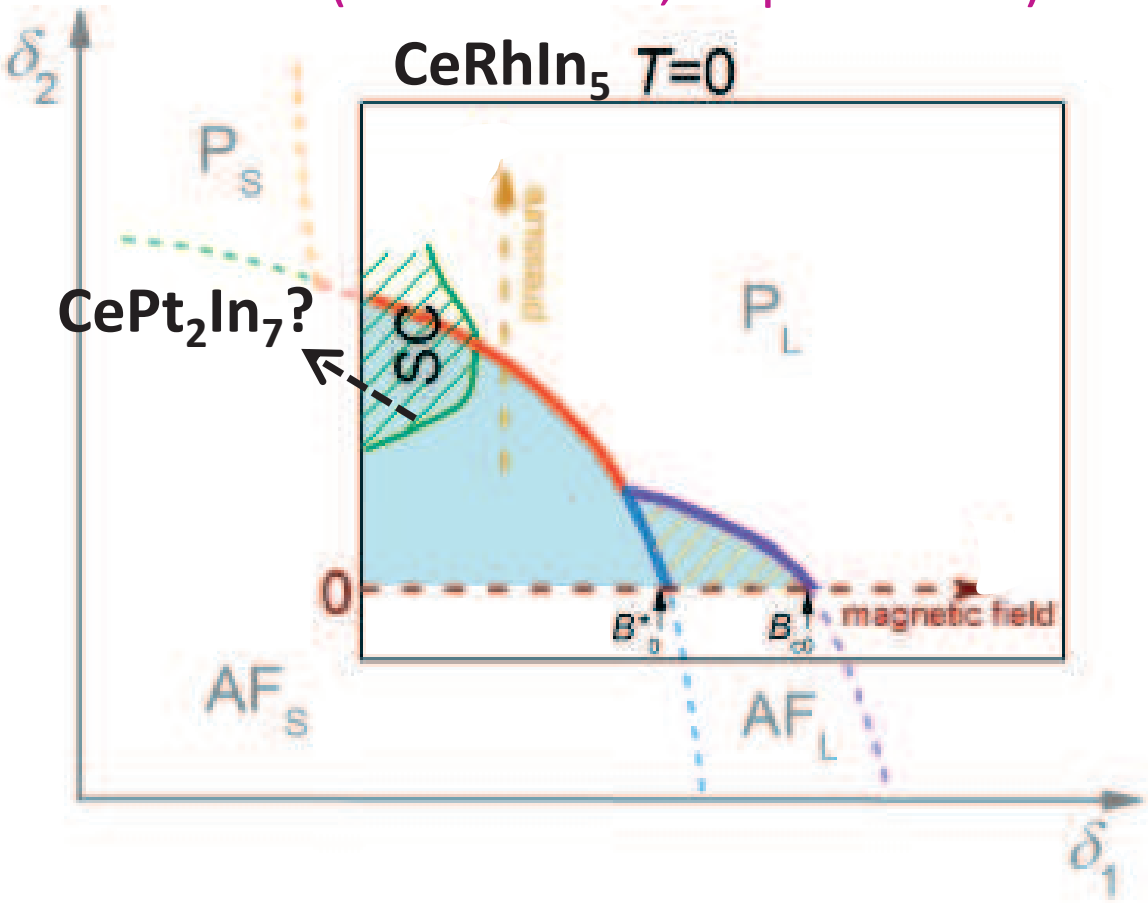
Kondo destruction within ordered phase in other materials





(Sebastian et al., PNAS 106 (2009) 7741)

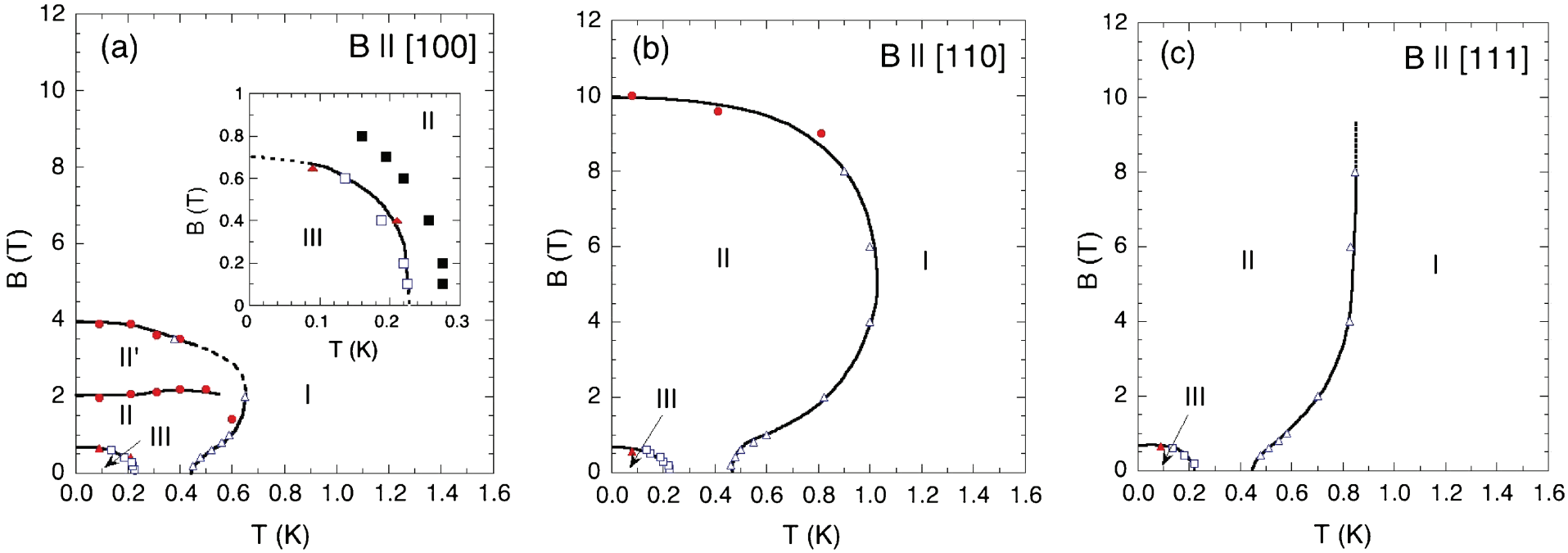
(L. Jiao et al., unpublished)



(talk Thompson on Monday)

Phase diagram of $Ce_3Pd_{20}Si_6$ single crystals

From magnetization:



(Mitamura et al., J. Phys. Soc. Jpn. 79 (2010) 074712)

Can there be multiple Kondo destruction transitions as function of a single tuning parameter?

Can there be Kondo destruction from orbital moments?

Tools beyond Hall effect to probe Fermi surface reconstructions at heavy fermion quantum critical points?

Superconducting domes at Kondo destruction QCP?