Exploring the Physics of Quantum Phase Transitions

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Outline

Introduction

- Doniach Diagram
- Heavy Fermion
- Quantum Phase Transition

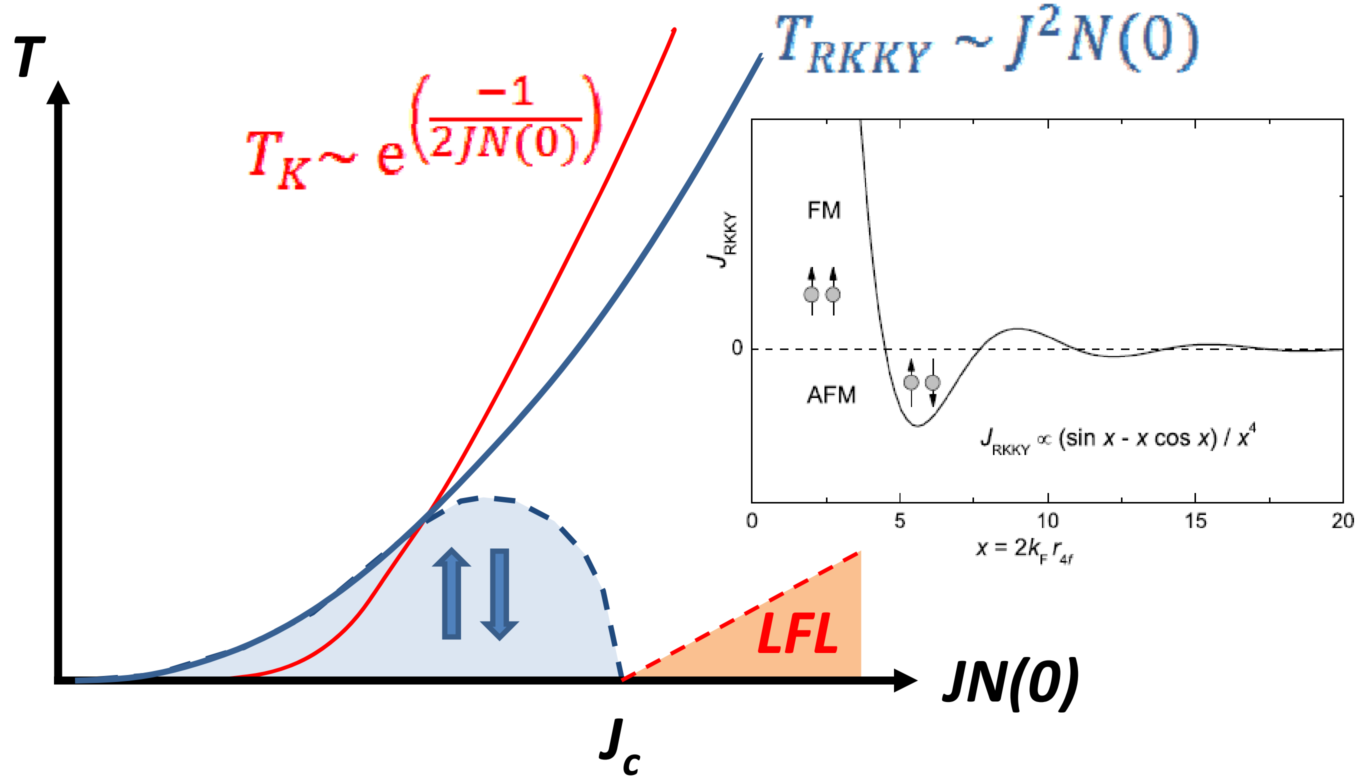
Experimental

- $YbRh_2Si_2$
- $Ce_3Pd_{20}Si_6$

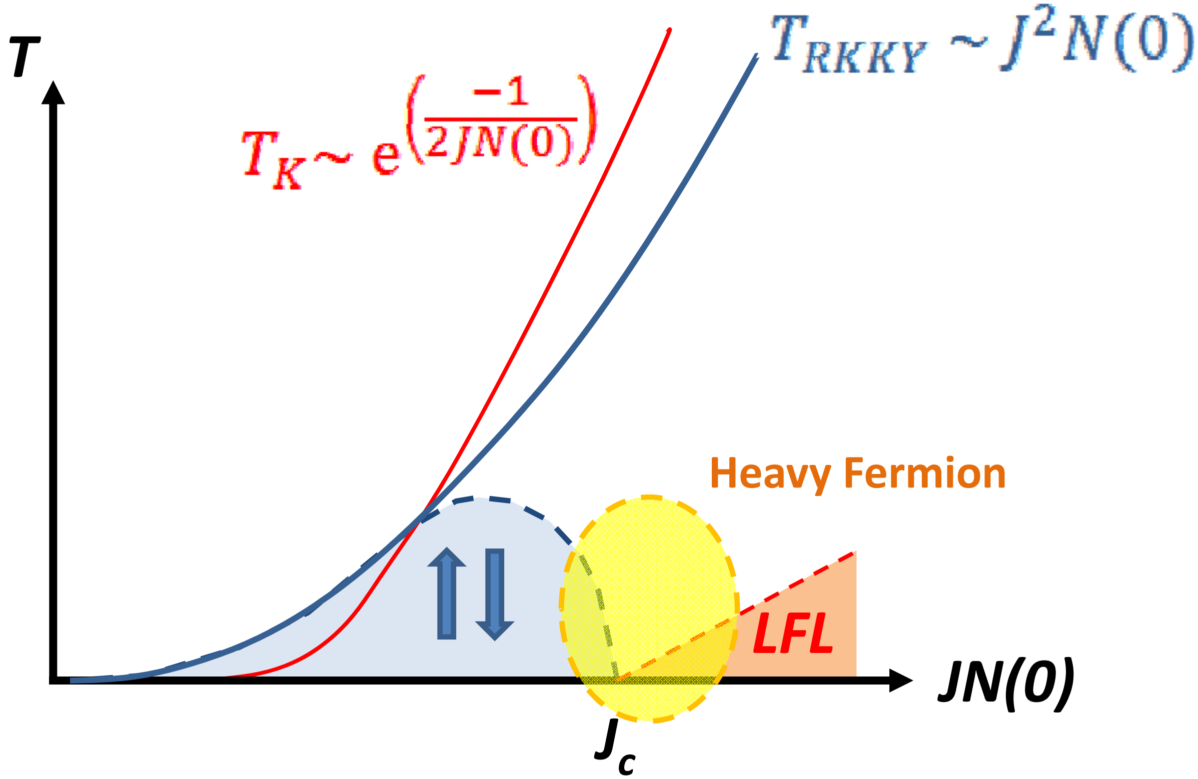
Conclusion

- Global Phase Diagram
- Outlook

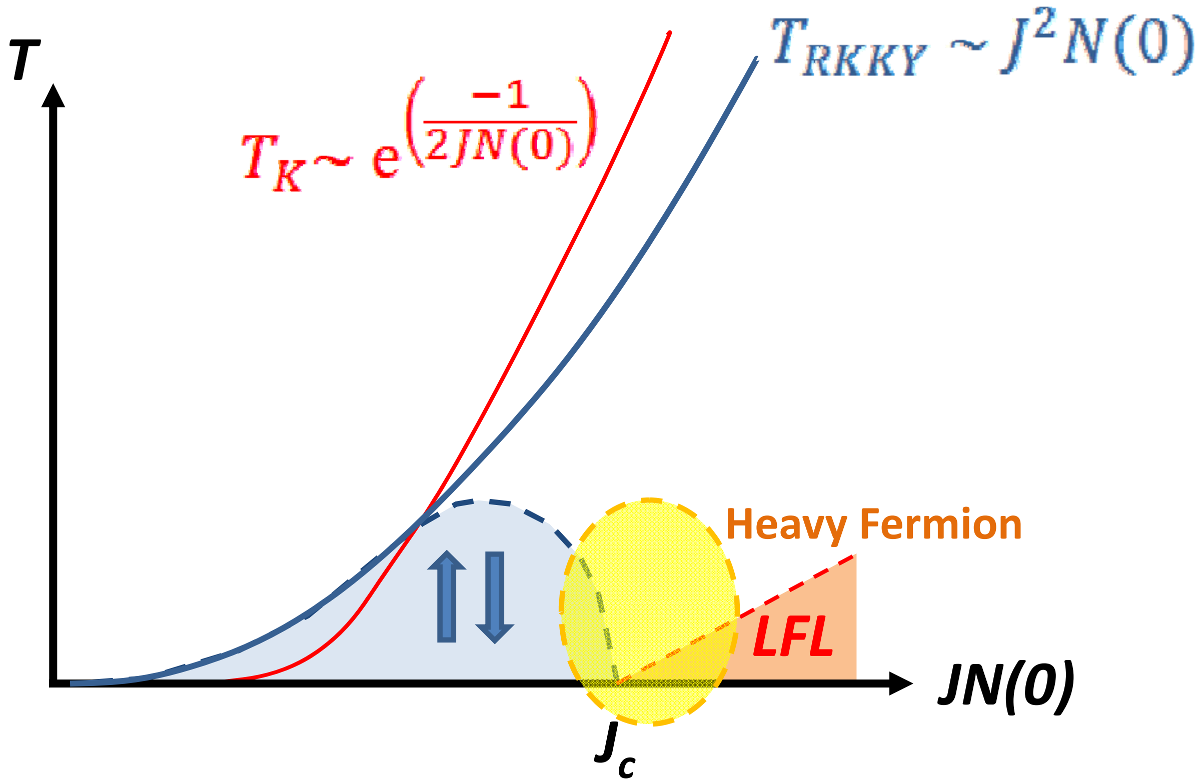
Doniach Diagram



Doniach Diagram

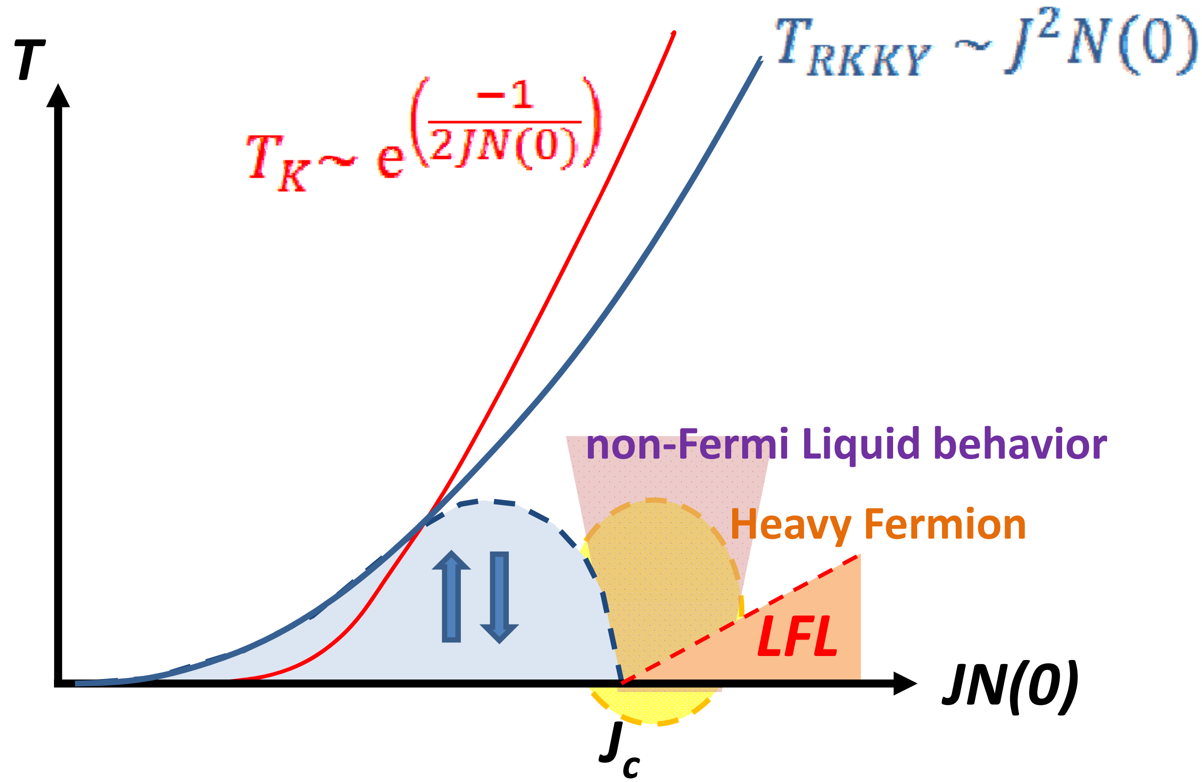


Doniach Diagram



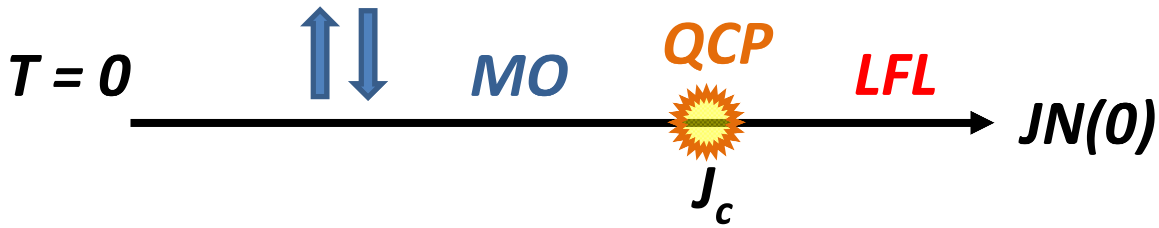
Tuning *J* by doping, pressure, magnetic field changes ground state from magnetic and paramagnetic

Doniach Diagram



Tuning *J* by doping, pressure, magnetic field changes ground state from magnetic and paramagnetic

Quantum Phase Transition

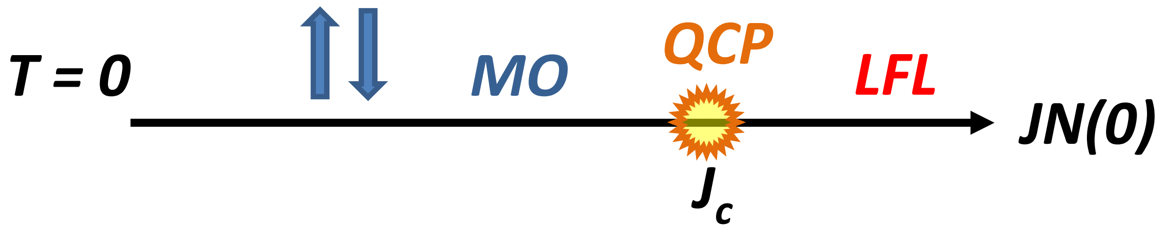


At $T = 0$ phase transition solely induced by zero point quantum fluctuations

↓

Quantum Critical Point

Quantum Phase Transition



At *T = 0* phase transition solely induced by zero point quantum fluctuations

↓

Quantum Critical Point

Spin Density Wave (SDW) ⟷ Localized Moment (Kondo breakdown)

quantum mechanical extension of classical theory of critical phenomena. At the QCP magnetic fluctuations have infinite range in both space and time. Magnetic order is accomplished by a SDW instability.

J. Hertz, Phys. Rev. B **14,** 1165 (1976).
A.J. Millis, Phys. Rev. B **48,** 7183 (1993).
T. Moriya and K. Ueda, Adv. Phys. **49,** 555 (2000).

critical magnetic fluctuations (2D) have infinite range in time, but are localized in space. As a consequence the Kondo screening breaks down upon approaching the QCP from the paramagnetic side, and the bare moments order

P. Coleman *et al.,* J. Phys. Condens. Matter **13,** R723 (2001).
Q. Si *et al.,* Nature **413,** 804 (2001).
T. Senthil *et al.,* Phys. Rev. B **69,** 035111 (2004).
T. Senthil *et al.,* Science **303,** 1490 (2004).
C. Pepin, Phys. Rev. Lett. **98,** 206401 (2007).

QCP finite temperature

Fermi Liquid

Property	
C/T	$const.$
χ	$const.$
$\Delta\rho$	aT^2
α/T	$const.$

Spin Density Wave (AFM)

Property	Dimension	
	$d = 3$	$d = 2$
C/T	$\gamma - \sqrt{T}$	$c \log T_0/T$
χ	$T^{\frac{3}{2}}$	$\chi_0 - dT$
$\Delta\rho$	$T^{\frac{3}{2}}$	T
α/T	${}^{1}/_{T} \log\log(1/T)$	$T^{-\frac{1}{2}}$

Localized Moment

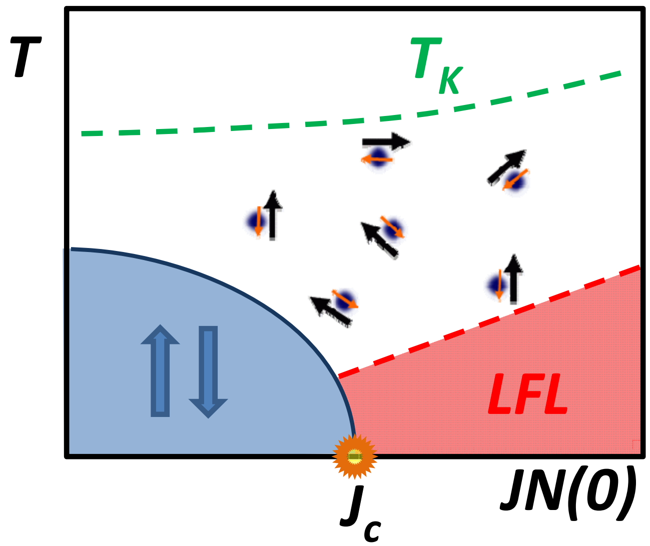
(Kondo breakdown)

Property	Dimension $d = 2$
C/T	$c \log T_0/T$
χ	
$\Delta\rho$	T Ᵽ
α/T	

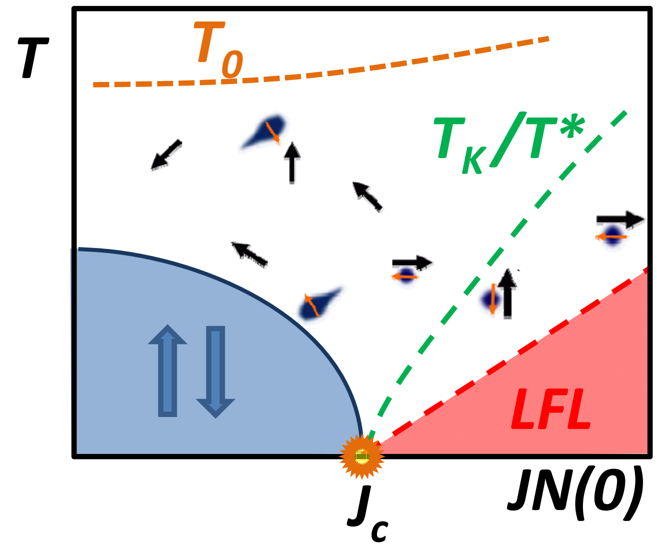
Ᵽ *often observed*

QCP phase diagram

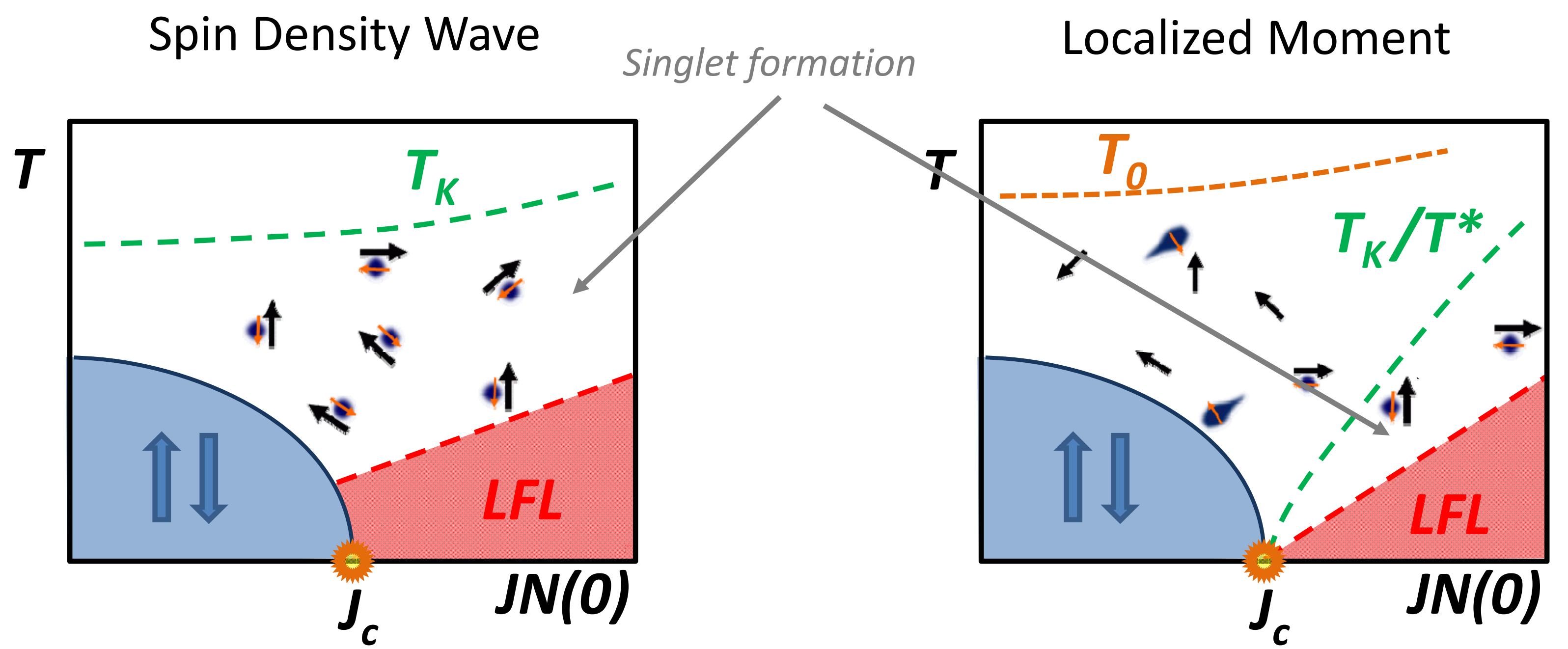
Spin Density Wave



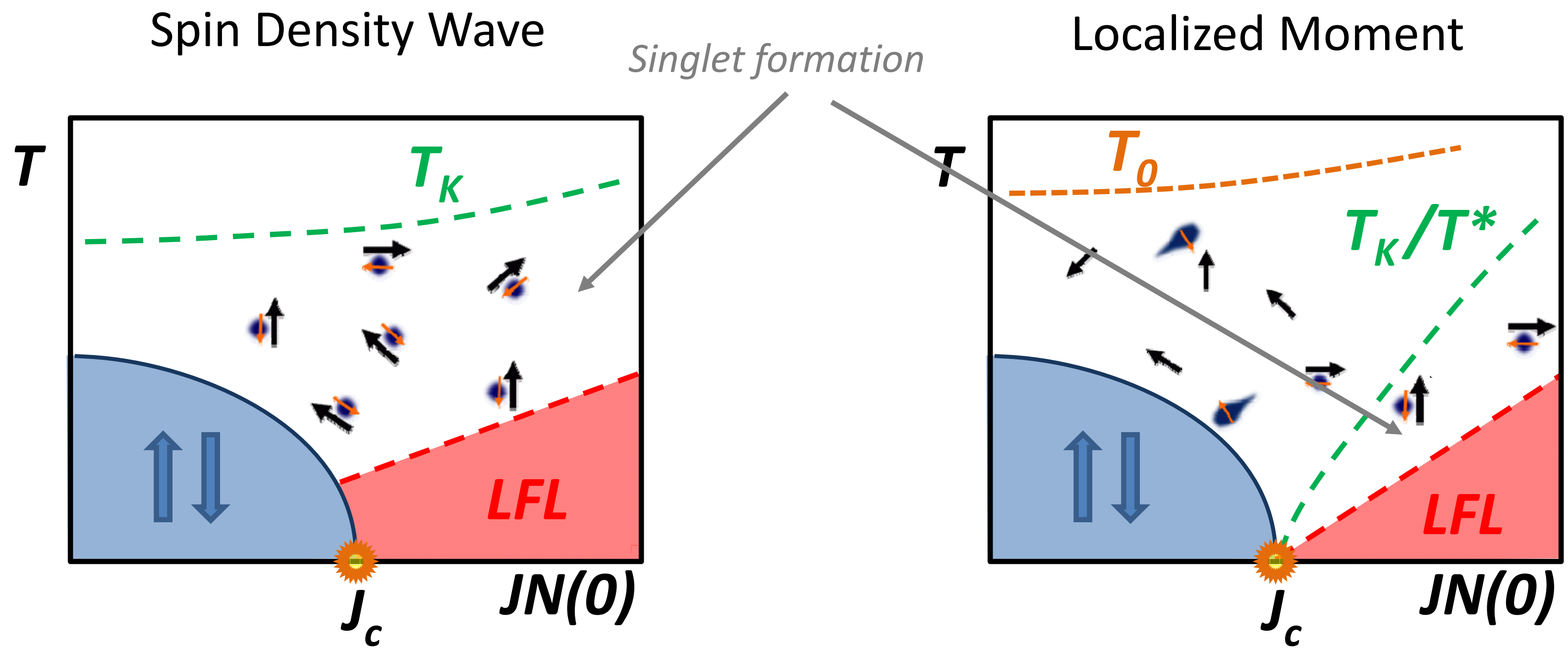
Localized Moment



QCP phase diagram



QCP phase diagram



On both sites of the QCP the heavy quasiparticle (Kondo screening) exists

↓

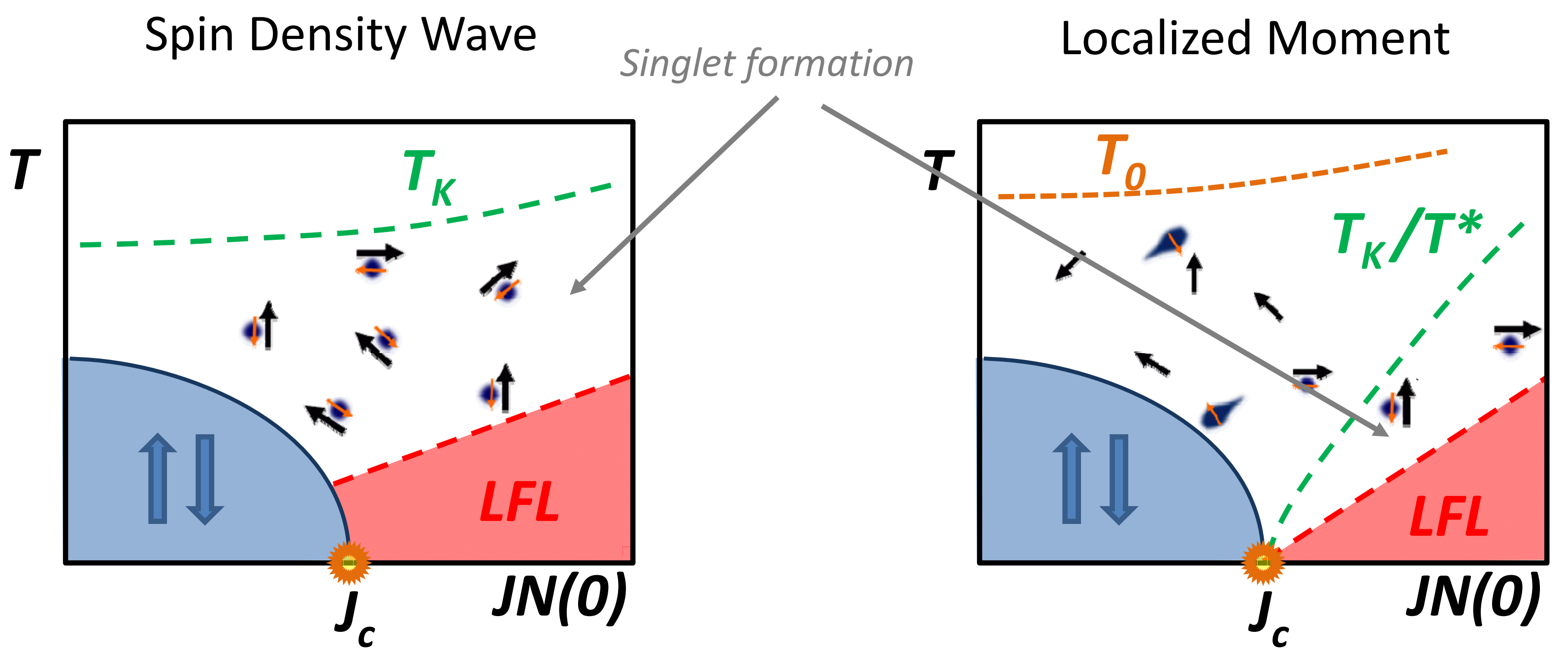
Fermi Volume remains *constant*

Break-up of the composite conduction electron + spin *f*-atom at QCP

↓

Fermi Volume is *large* in LFL
Fermi Volume is *small* in mag. order

QCP phase diagram



On both sites of the QCP the heavy quasiparticle (Kondo screening) exists

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Fermi Volume remains *constant*

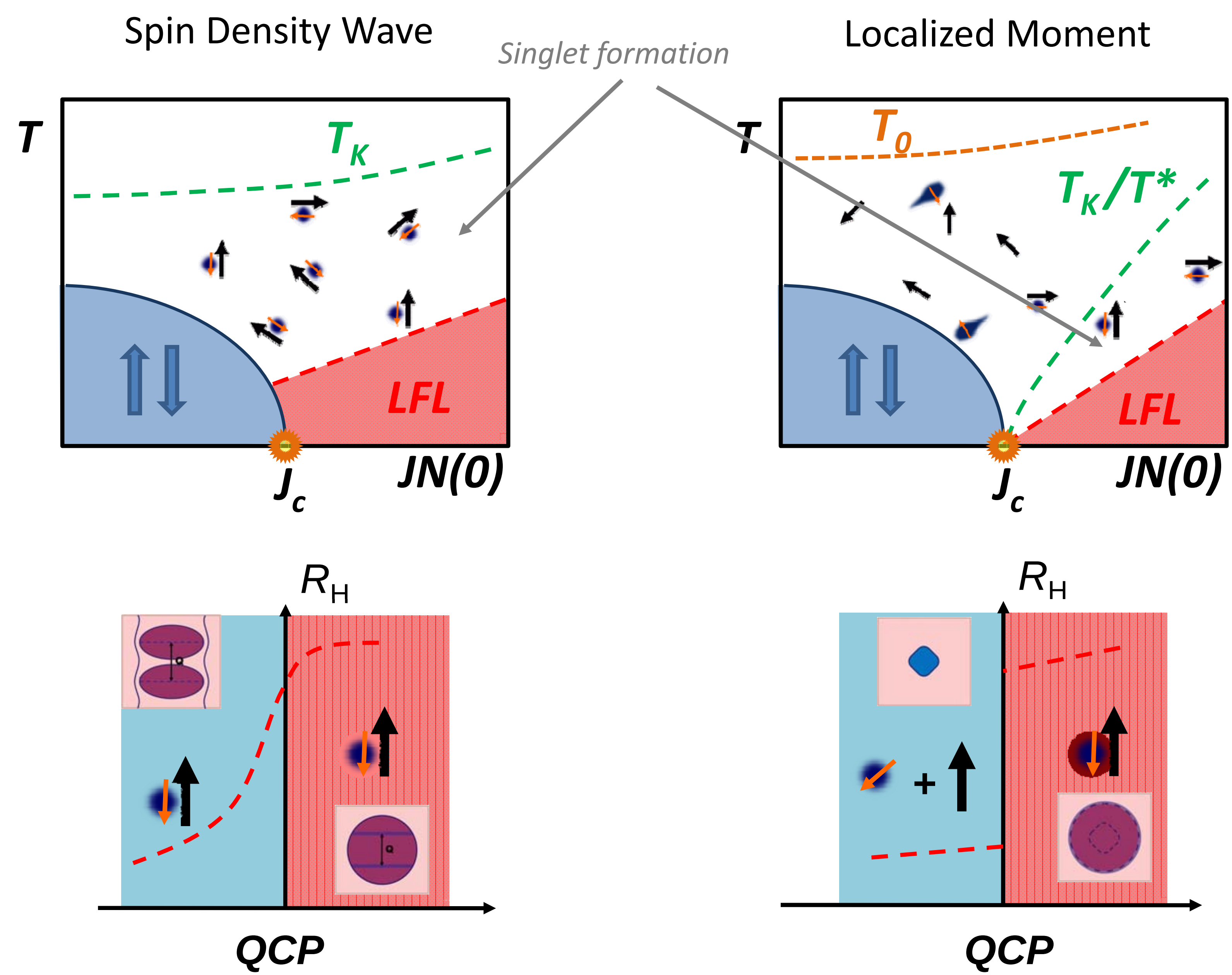
Break-up of the composite conduction electron + spin *f*-atom at QCP

↓

Fermi Volume is *large* in LFL
Fermi Volume is *small* in mag. order

Hall experiment measures Fermi Volume

QCP Hall-Resistivity

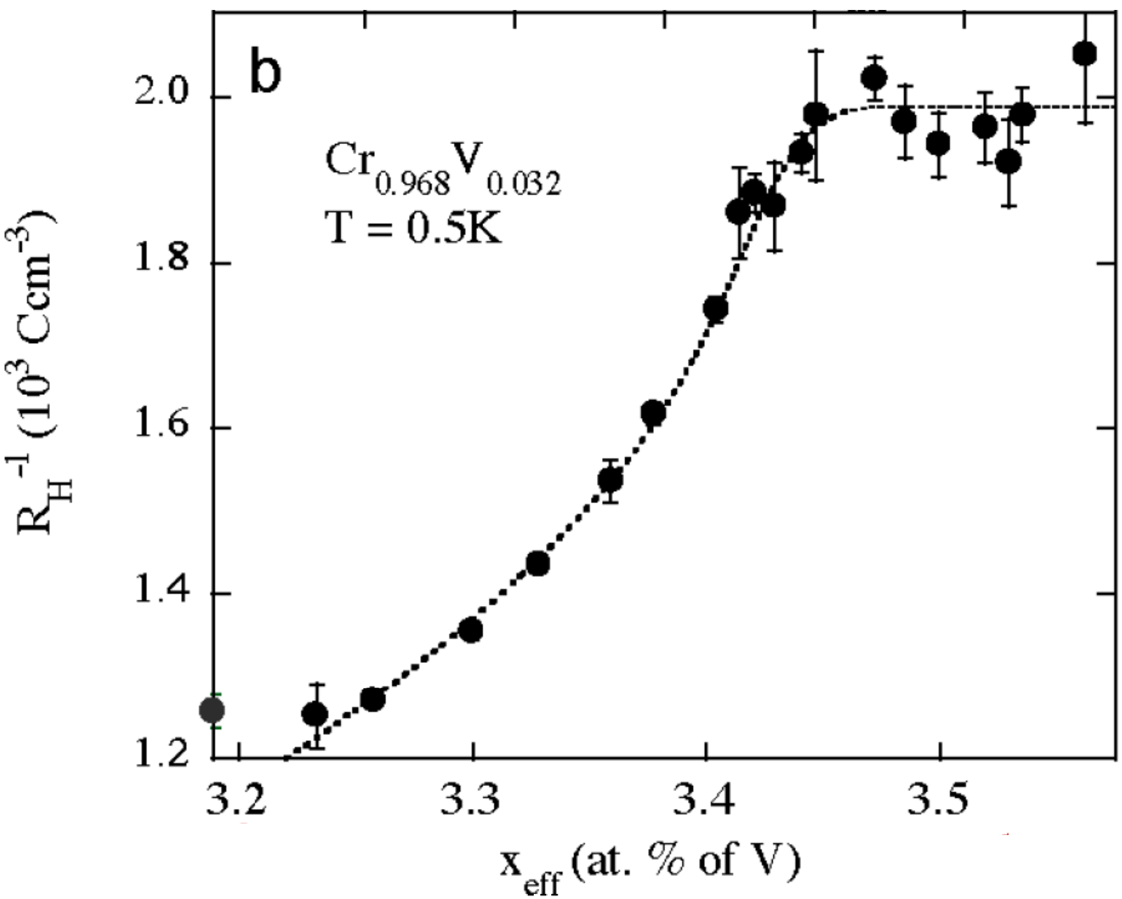


Smooth transition of Hallcoefficient

Jump in Hallcoefficient

P. Coleman *et al.,* J. Phys. Condens. Matter **13,** R723 (2001).

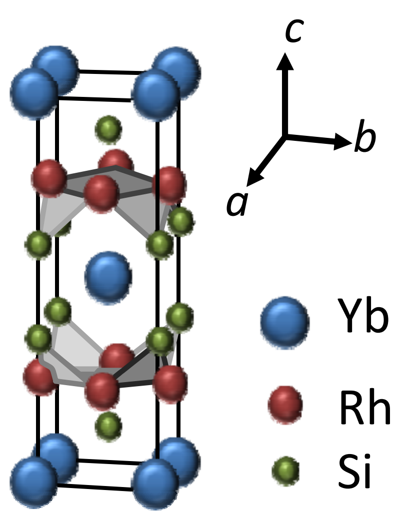
QCP Hall-Resistivity



Lee *et al.* PRL **92**, 187201 (2004)

Example SDW

$YbRh_2Si_2$

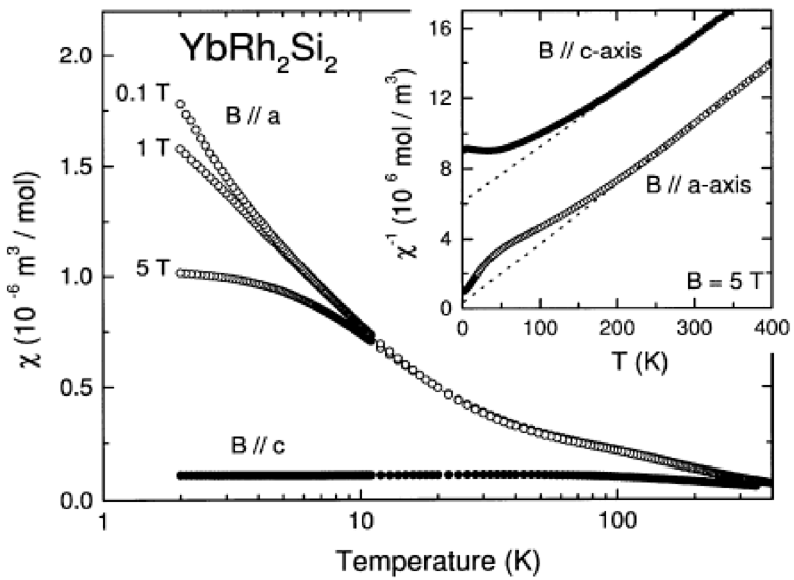


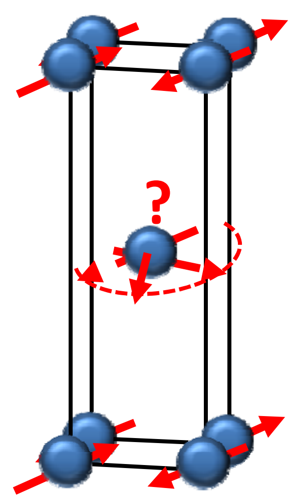
$ThCr_2Si_2$ structure ($I4/mmm$)
$a = 4.007 \pm 0.005$Å
$c = 9.858 \pm 0.005$Å

Yb^{3+} ($J = 7/2$)
T_{300K}: $\mu_{eff} = 4.5\ \mu_B$

CEF excitations:
0 – 17 – 25 – 43meV
(0 – 200 – 290 – 500K)

O.Stockert *et al.* Physica B **378-380**, 157 (2006)

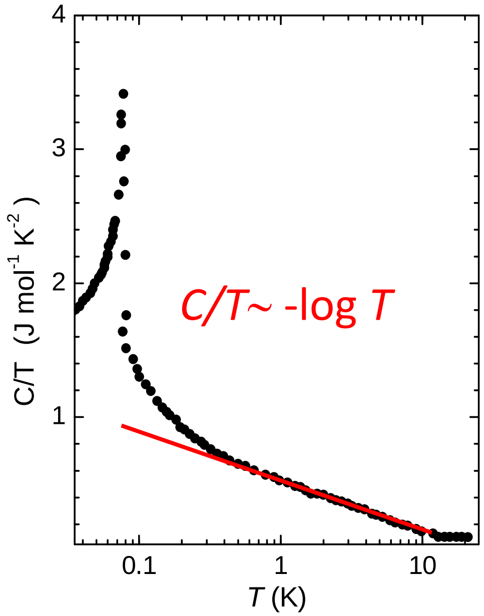


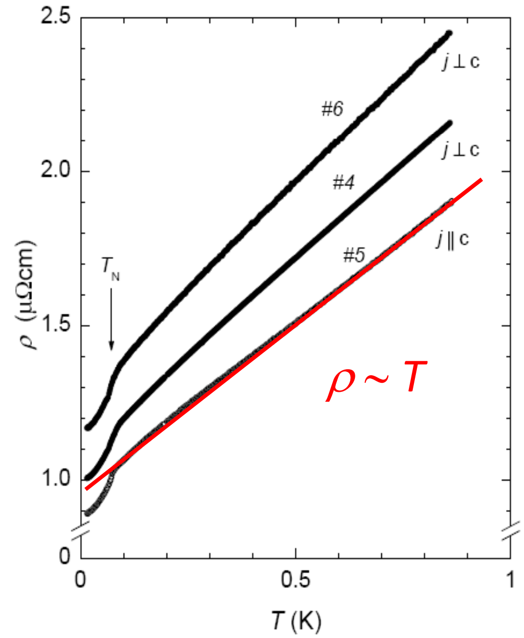


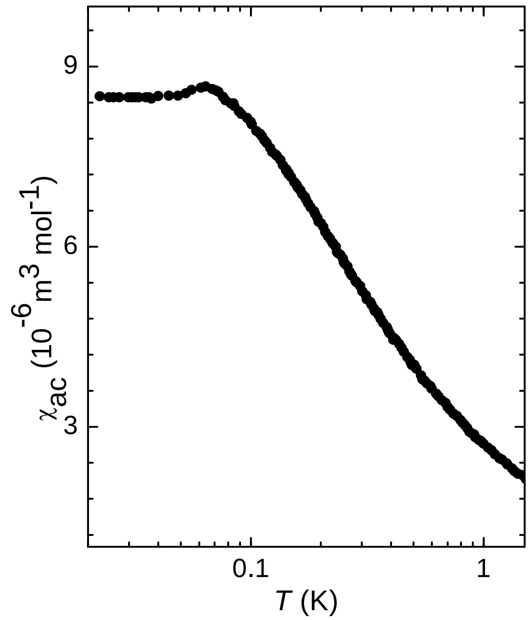
Θ_w^a = -9K
Θ_w^c = -180K
M^a / M^c = 20 (@2K)

O.Trovarelli *et al.* Physica B **284-288**, 1507 (1999)

$YbRh_2Si_2$ low Temperature







$YbRh_2Si_2$ is a heavy Fermion

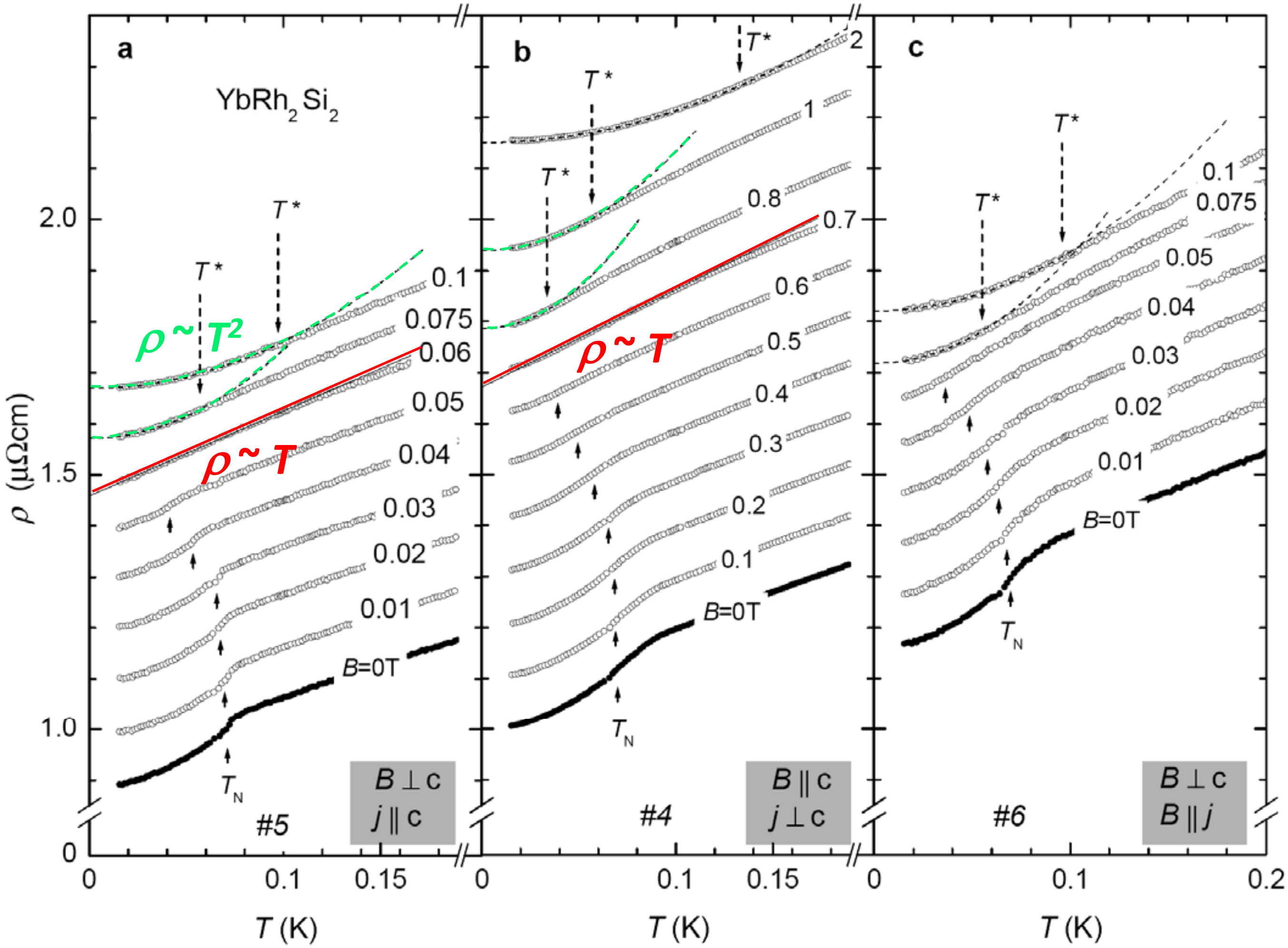
Antiferromagnetic order at ≈ 70mK

Above T_N pronounced non-Fermi liquid behavior

↓

Close to a QCP

$YbRh_2Si_2$ tuning to QCP



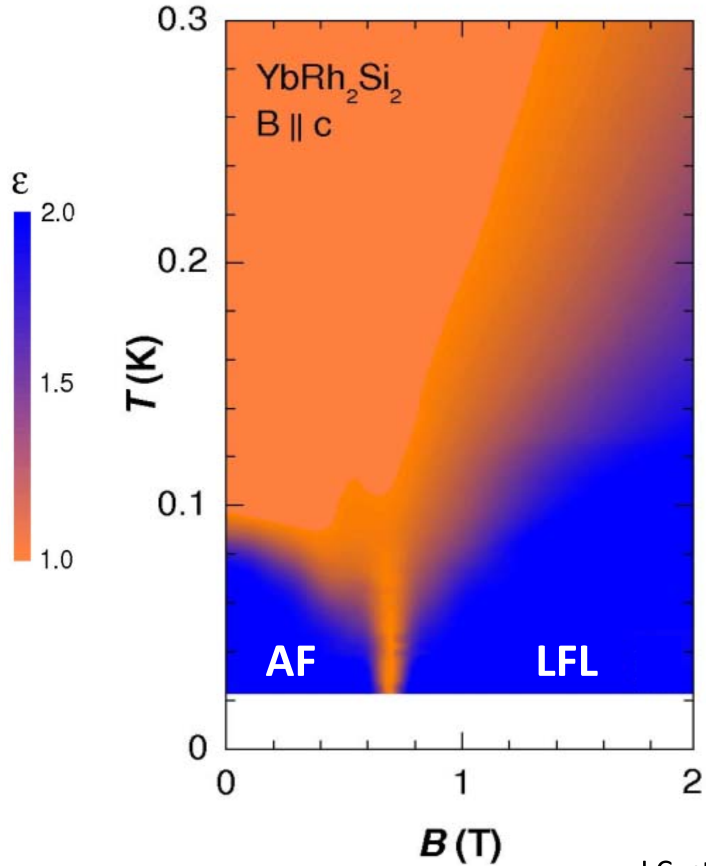
P. Gegenwart *et al.* PRL **89**, 056402 (2002)

Tuning $YbRh_2Si_2$ to QCP by applying small magnetic field

critical field: $B_c \perp c = 11\, B_c \parallel c$

$YbRh_2Si_2$ tuning to QCP

$$\rho \sim T^{\varepsilon}$$

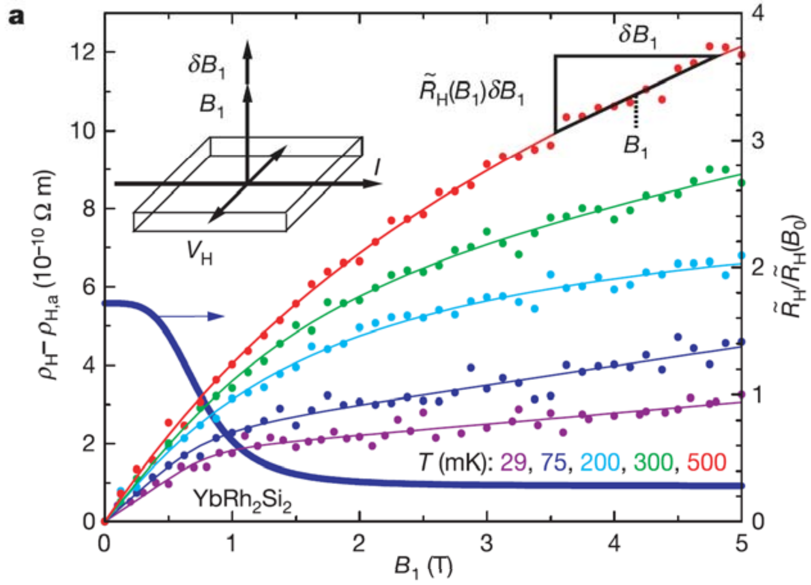


J.Custers *et al.* Nature **424**, 524 (2003)

Tuning $YbRh_2Si_2$ to QCP by applying small magnetic field

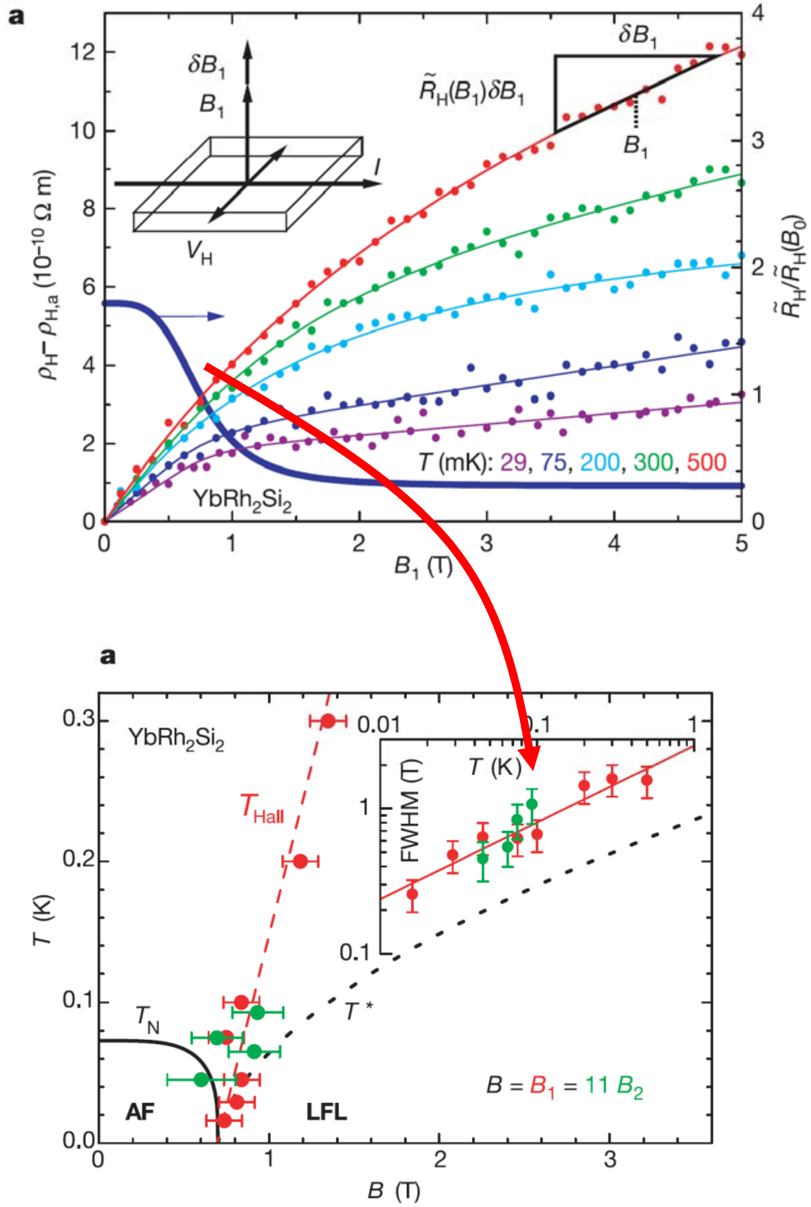
critical field: $B_c \perp c = 11\, B_c \parallel c$

$YbRh_2Si_2$ Hall experiment

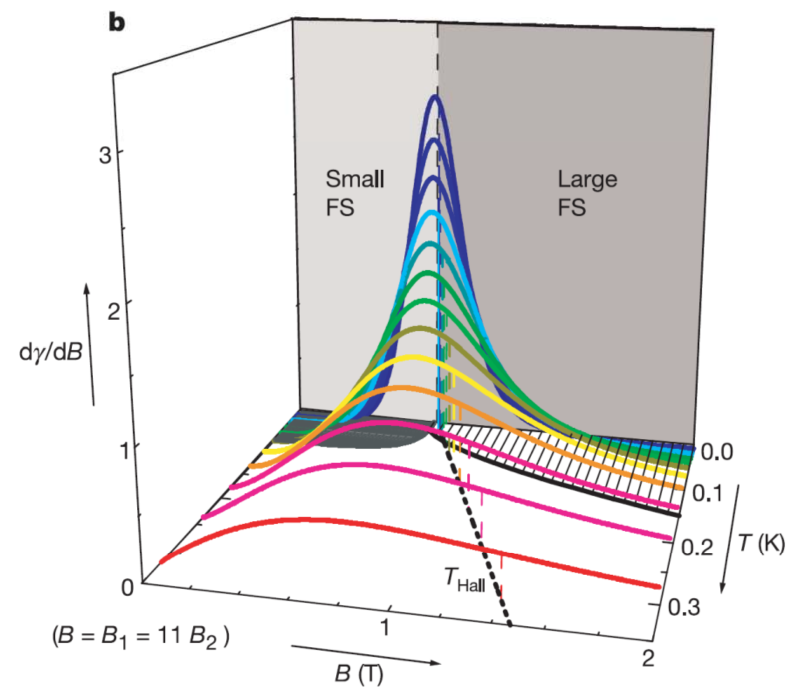


S. Paschen *et al.* Nature **432**, 881 (2004)

$YbRh_2Si_2$ Hall experiment

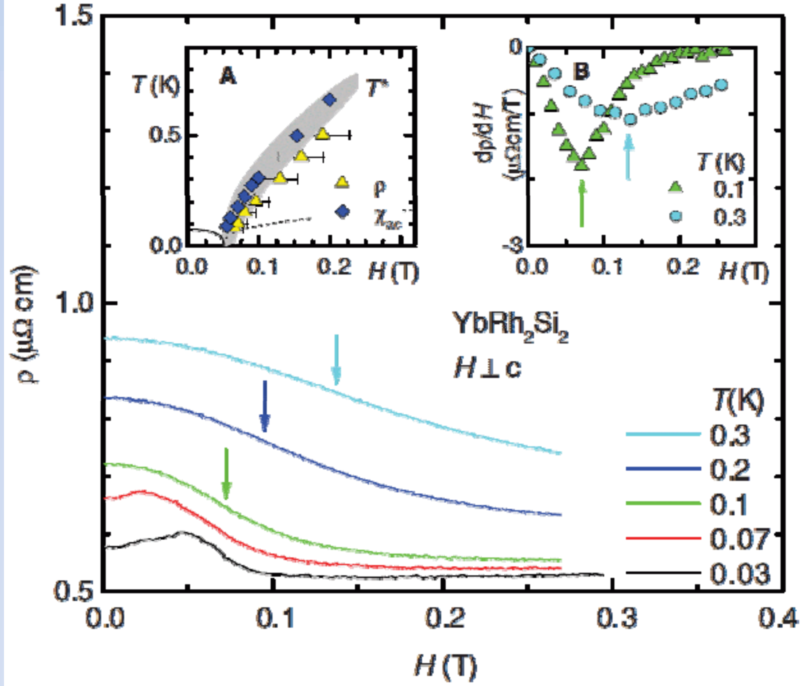


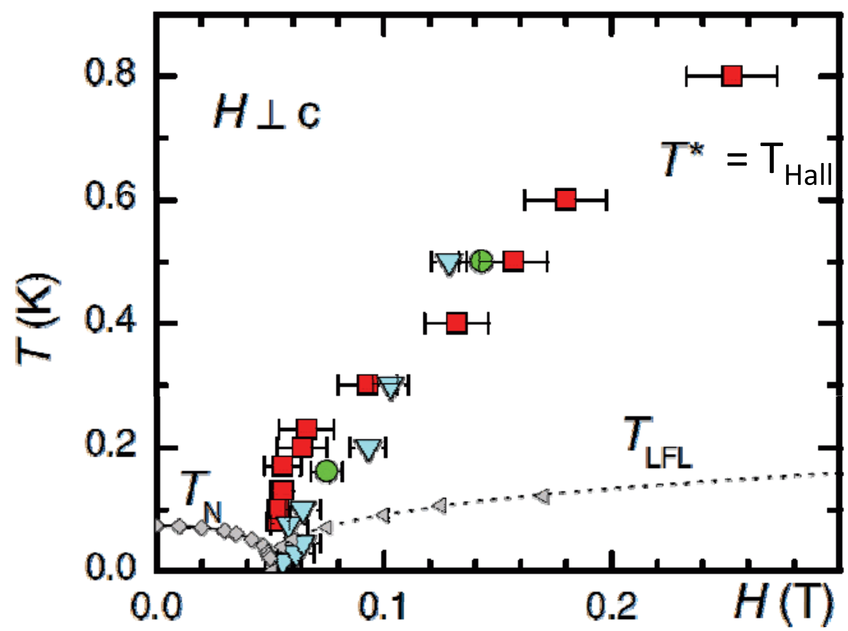
For $T \rightarrow 0$ Fermi Surface will "jump"



S. Paschen *et al.* Nature **432**, 881 (2004)

$YbRh_2Si_2$ alternative exp.



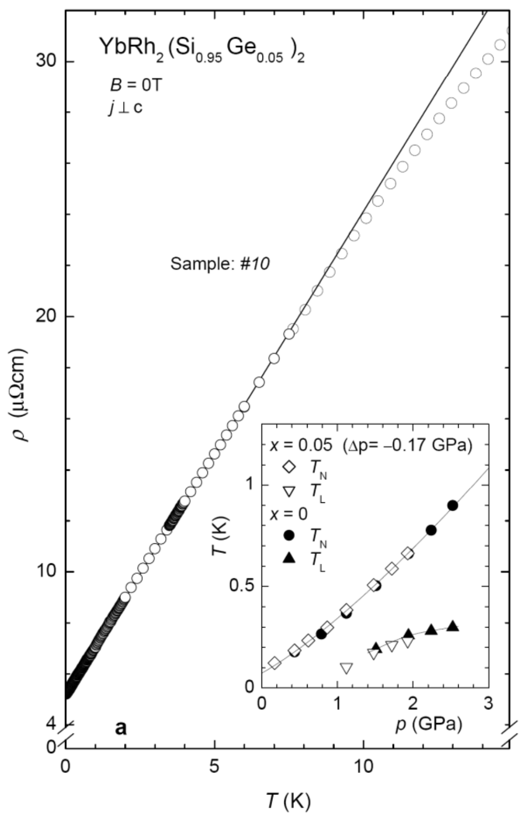


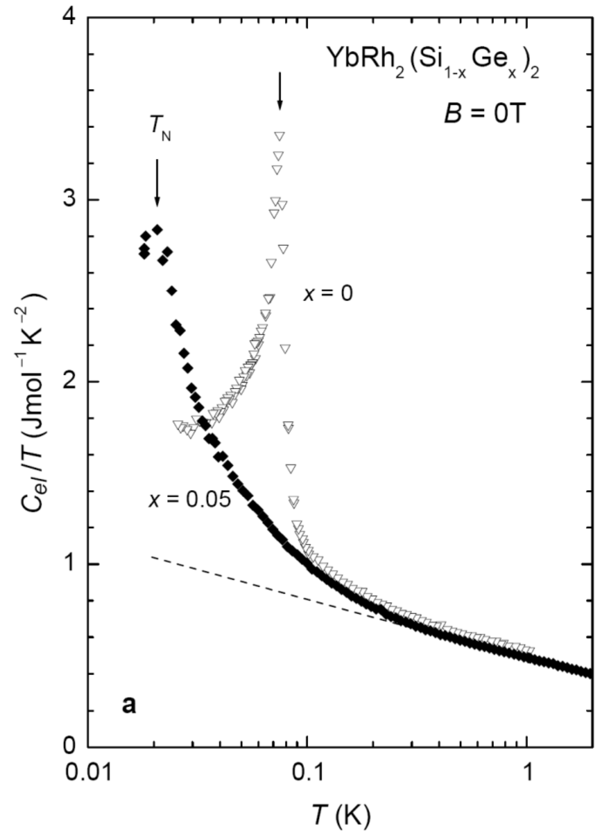
P. Gegenwart *et al.* Science **315**, 969 (2007)

Rescale to critical field: $B_c \perp c = 11\, B_c \parallel c$

T^* -line (T_{Hall}) visible in magnetoresistance, magnetostriction and ac susceptibility

$YbRh_2Si_2$ doping





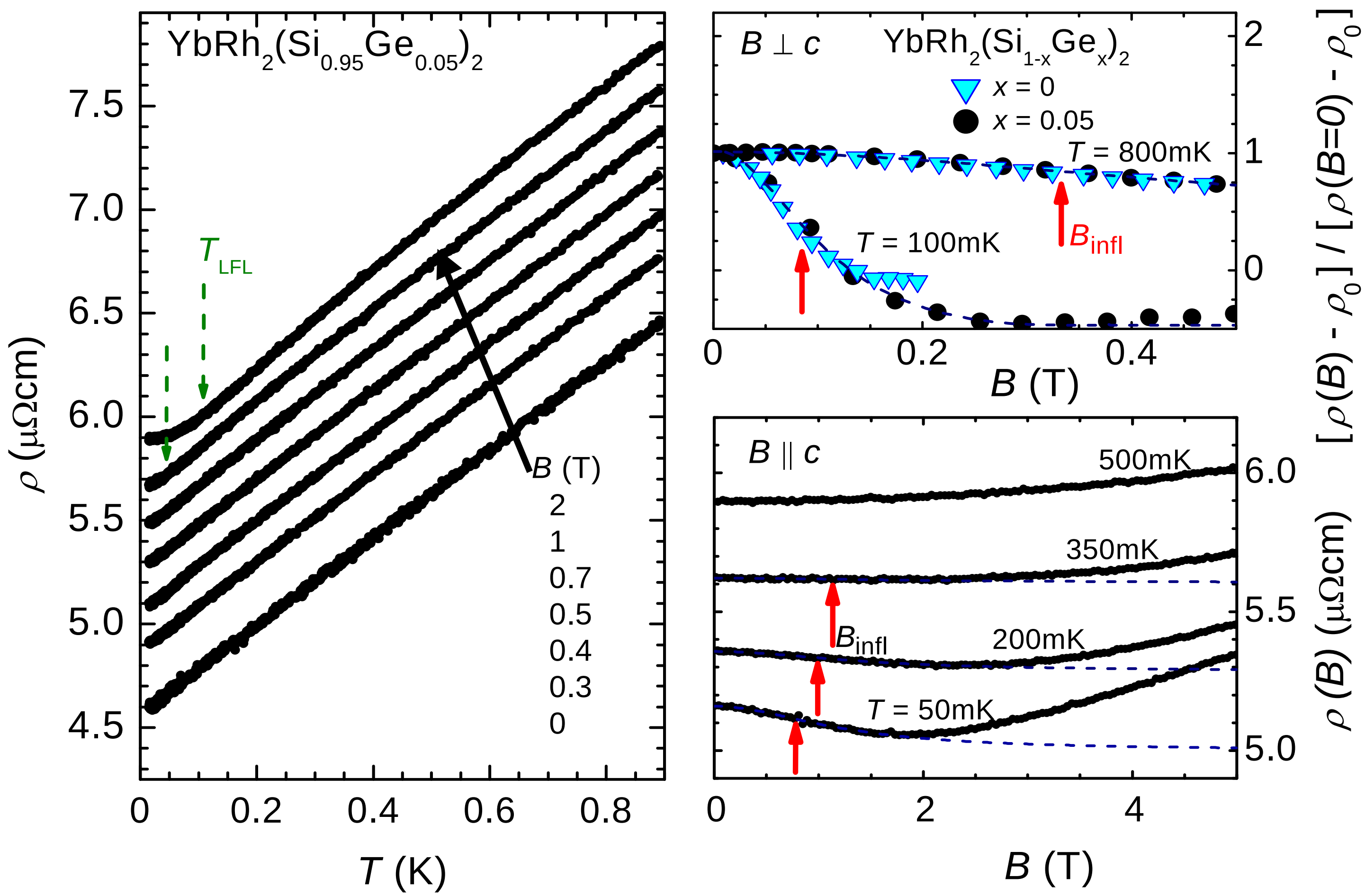
Ge is isoelectronic to Si, but has slightly larger atomic radius

↓

apply negative pressure

Pressure shift corresponds to volume increase: $\Delta V = 0.14 \pm 0.03 Å^3$

$YbRh_2Si_2$ doping

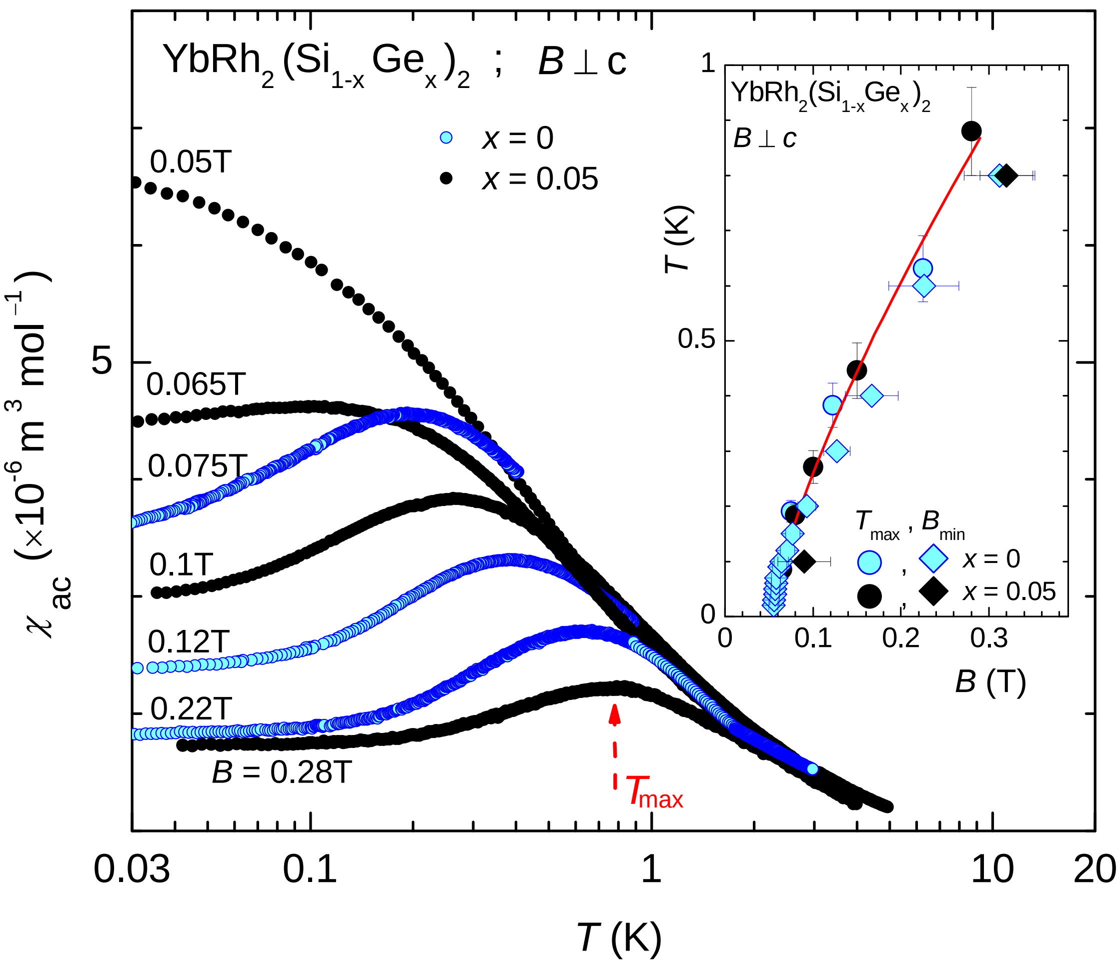


ρ ∼***T*** (NFL behavior)
over wide *B*-range

same signatures as in $YbRh_2Si_2$ of
Hall jump in magnetoresistance of
Ge doped $YbRh_2Si_2$

Custers *et al.* PRL **104**, 186402 (2010)

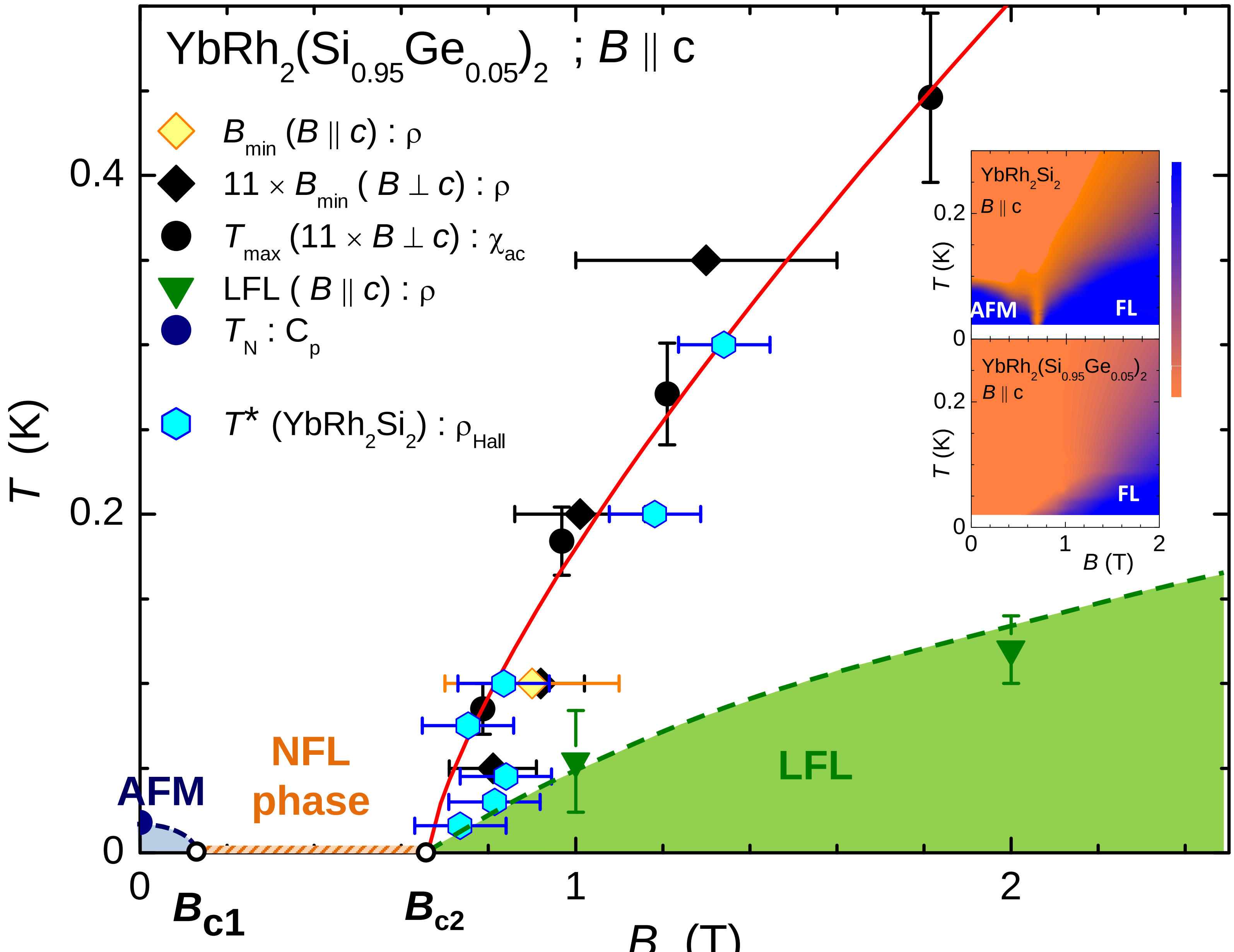
$YbRh_2Si_2$ doping



Signatures of Hall jump (T^*) at same position in $B - T$ diagram

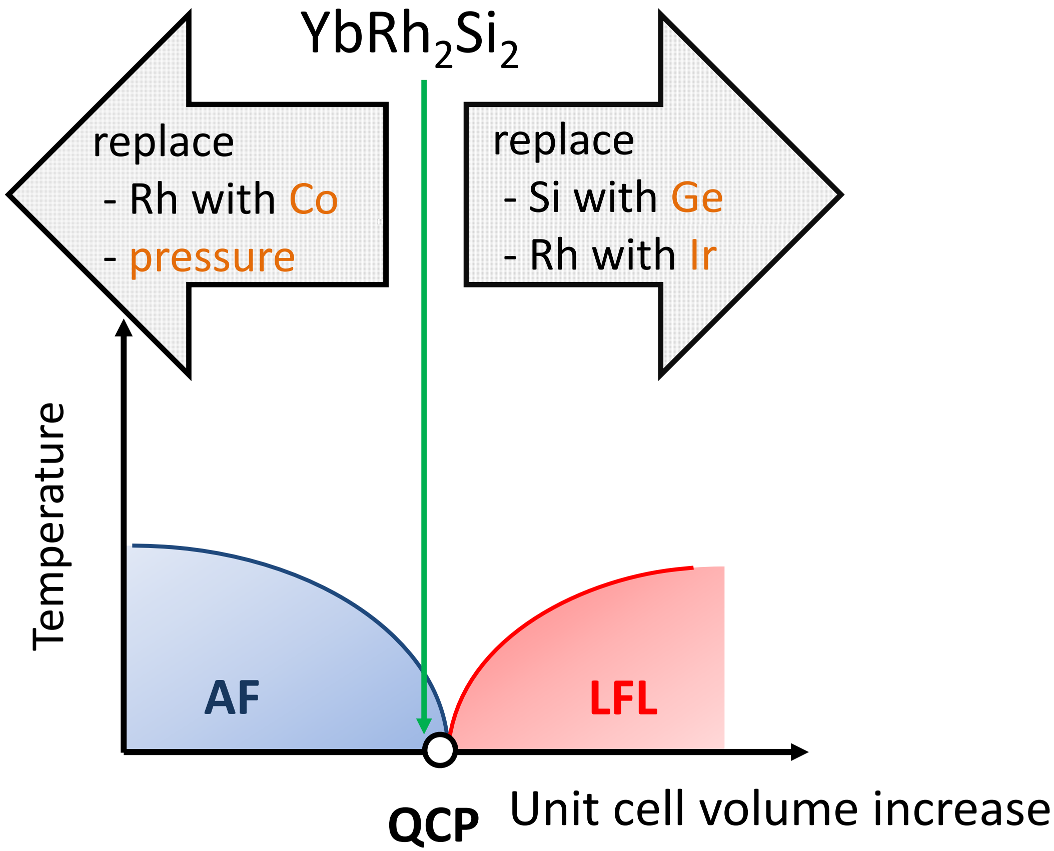
J. Custers *et al.* PRL **104**, 186402 (2010)

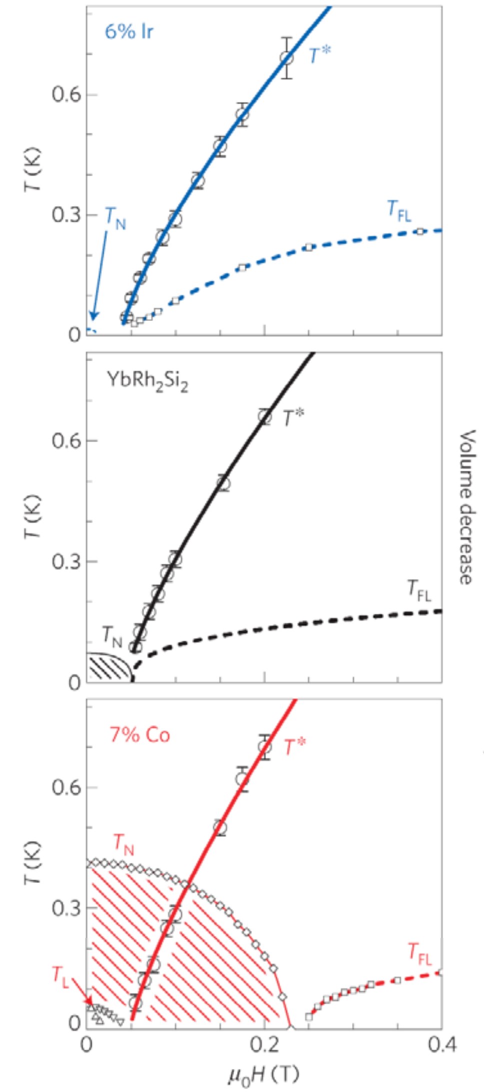
$YbRh_2Si_2$ doping



Custers *et al.* PRL **104**, 186402 (2010)

$YbRh_2Si_2$ doping



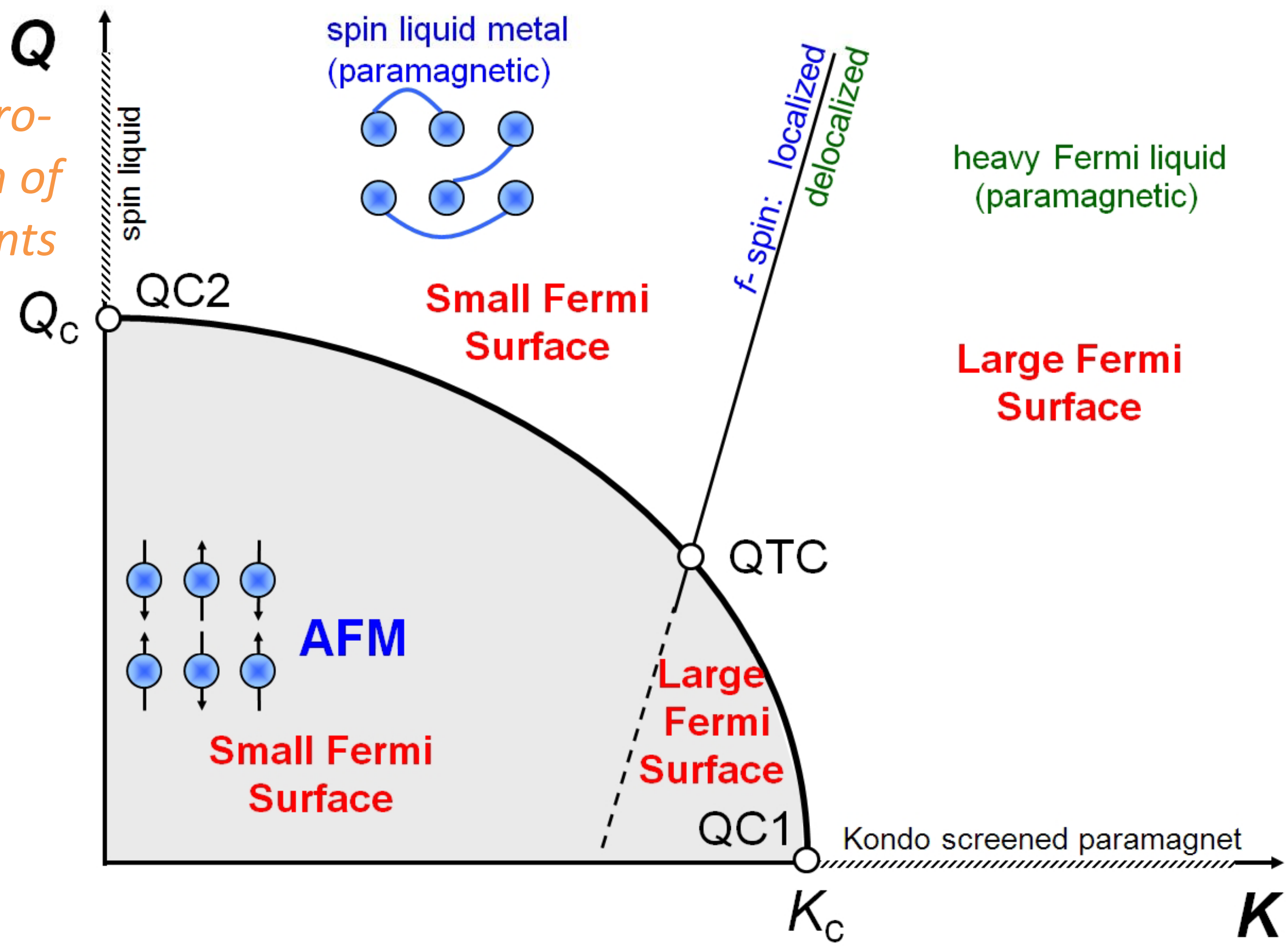


S.Friedemann *et al.* Nat.Phys **5**, 465 (2009)

T^*-line (T_{Hall}) does not change in position!
Disentanglement from AFM order with QCP (Fermi surface change)

Extended Doniach Diagram

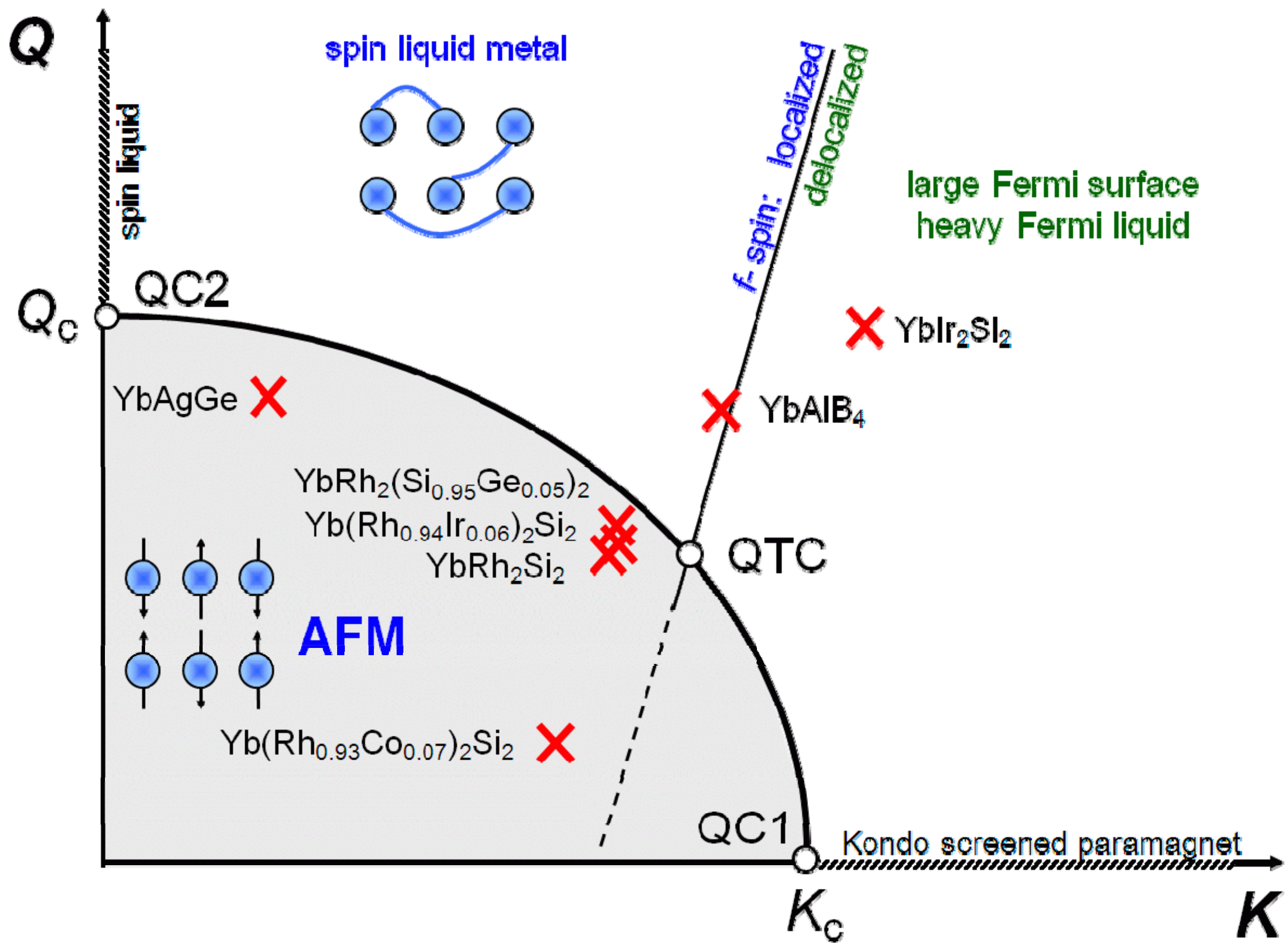
Quantum zero-point motion of Local Moments



Effective Kondo coupling

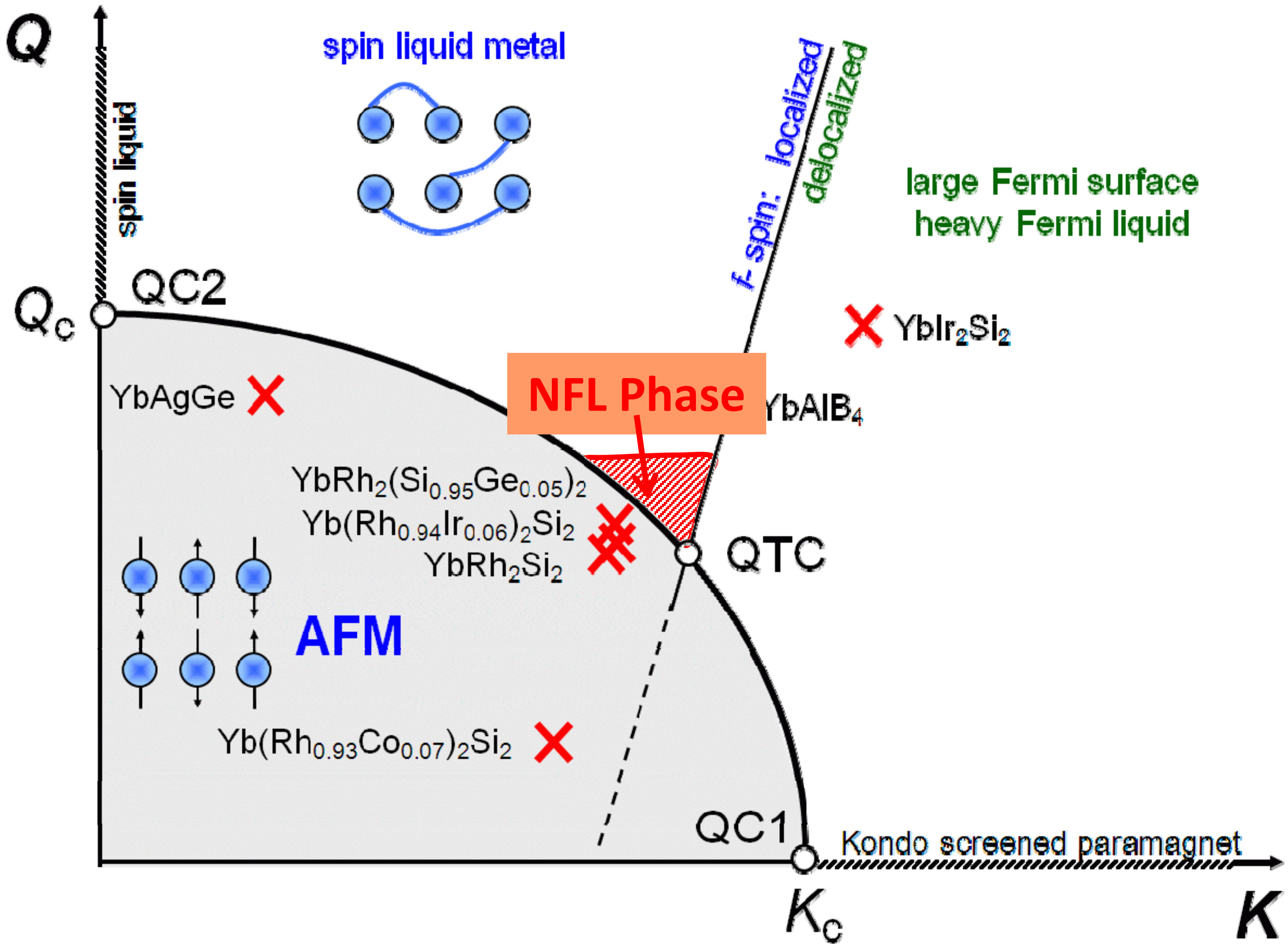
J. Custers *et al.* PRL **104**, 186402 (2010)

Extended Doniach Diagram



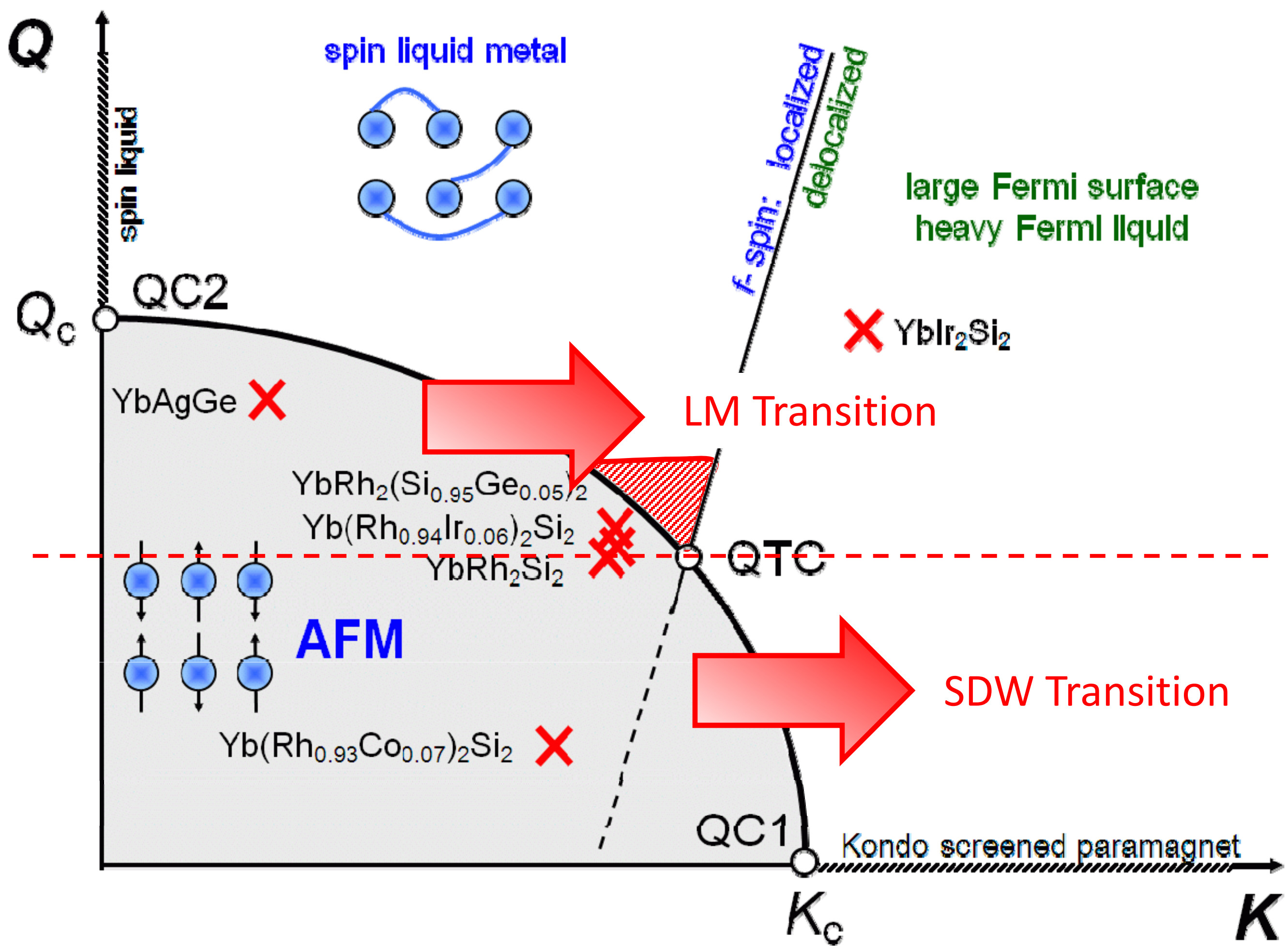
J. Custers *et al.* PRL **104**, 186402 (2010)

Extended Doniach Diagram



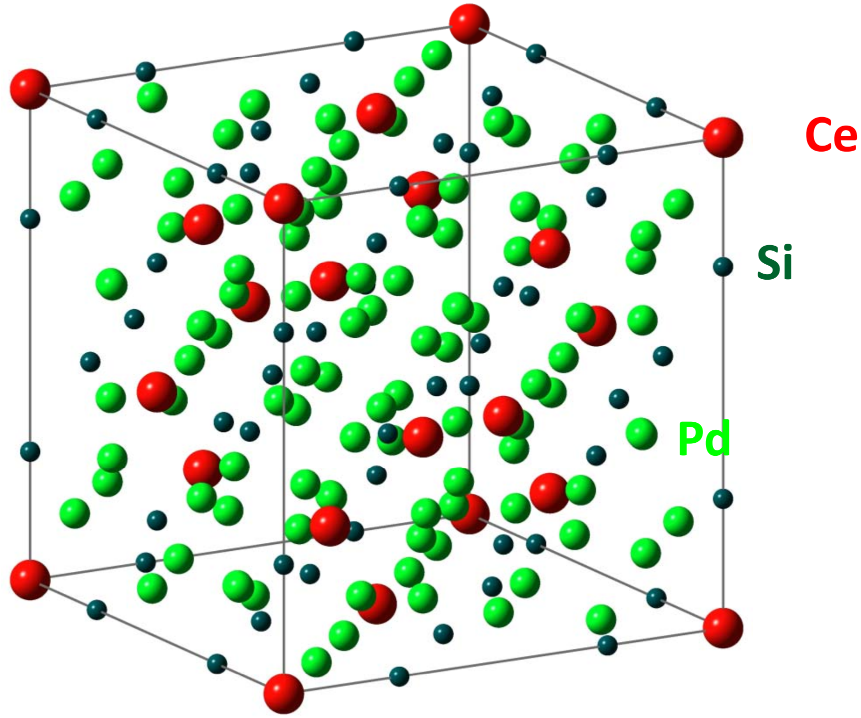
J. Custers *et al.* PRL **104**, 186402 (2010)

Extended Doniach Diagram



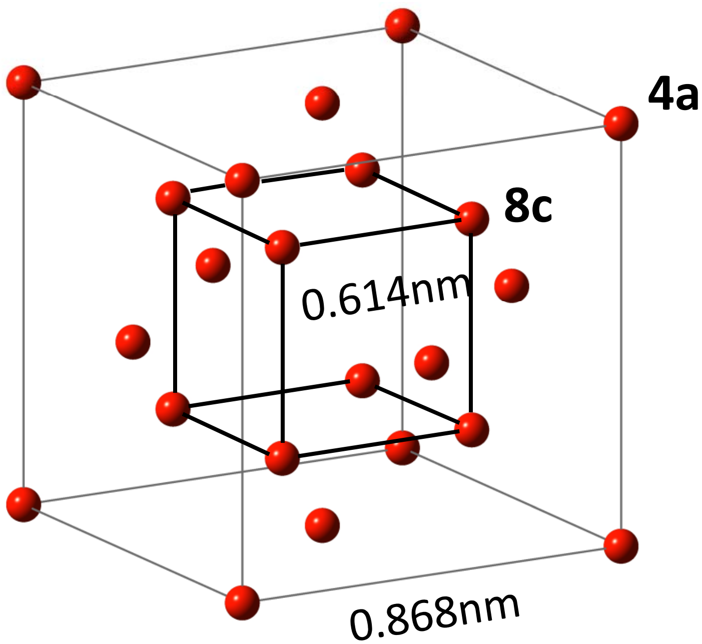
J. Custers *et al.* PRL **104**, 186402 (2010)

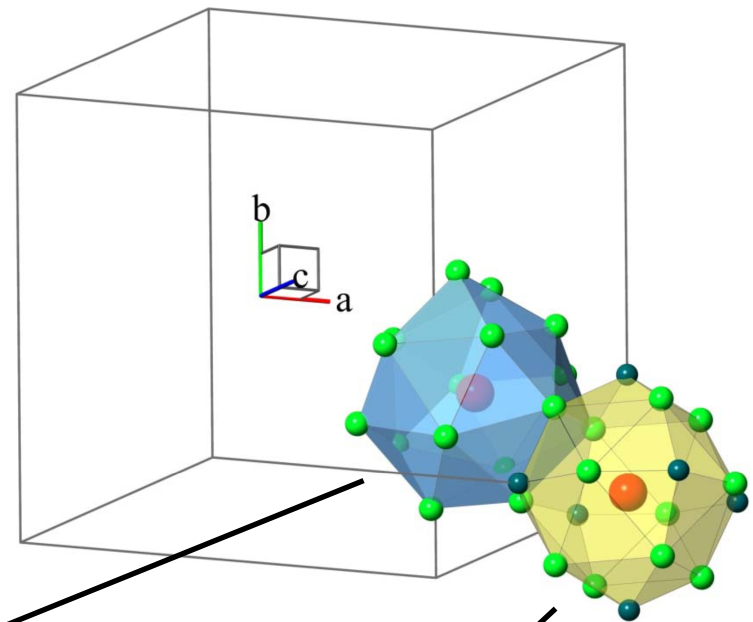
$Ce_3Pd_{20}Si_6$



Structure:	Cubic
Space group:	$Fm\bar{3}m$
Lattice parameter:	12.161Å
Atoms in unit cell:	116

$Ce_3Pd_{20}Si_6$

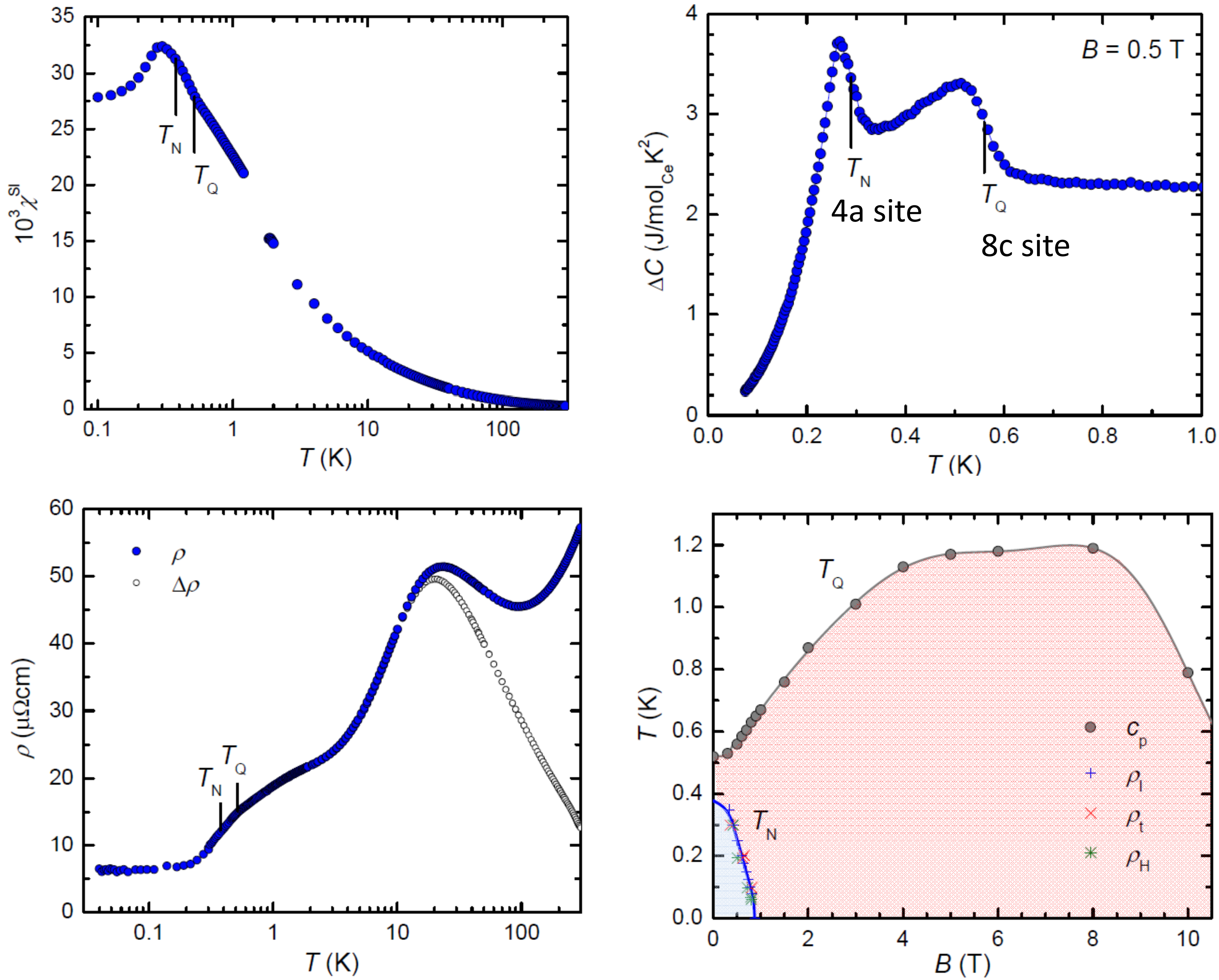




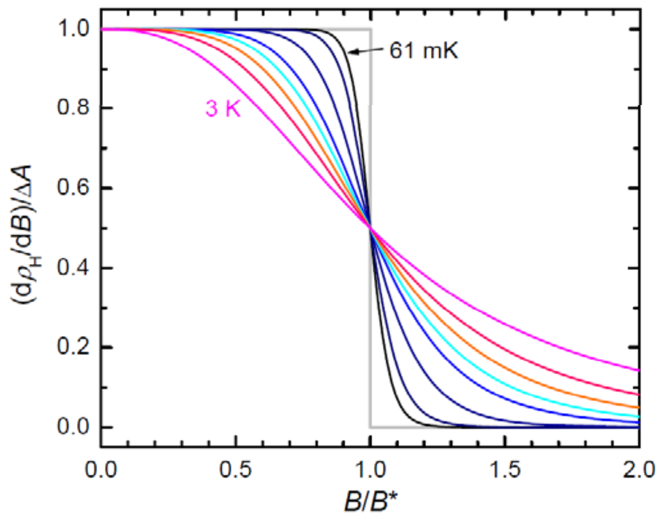
Ce2-site: 8c position
surrounded by 16 Pd atoms
T_d site symmetry

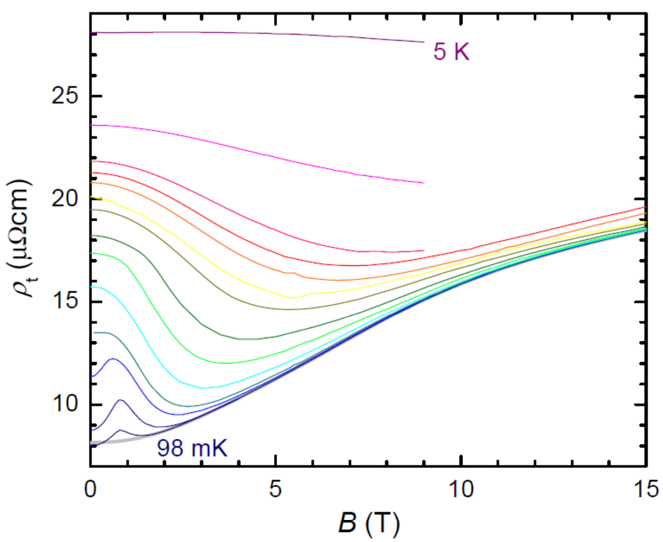
Ce1-site: 4a position
surrounded by 12 Pd atoms and 6 Si atoms
O_h site symmetry

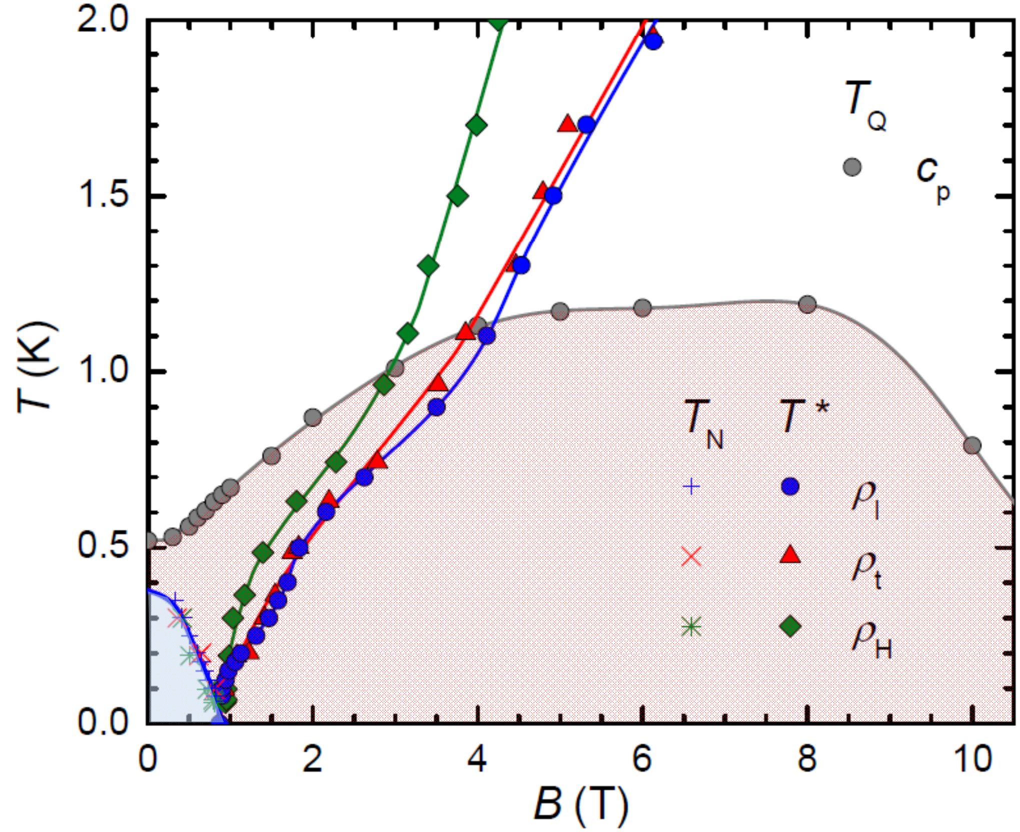
$Ce_3Pd_{20}Si_6$ properties



$CePd_{20}Si_6$ QCP





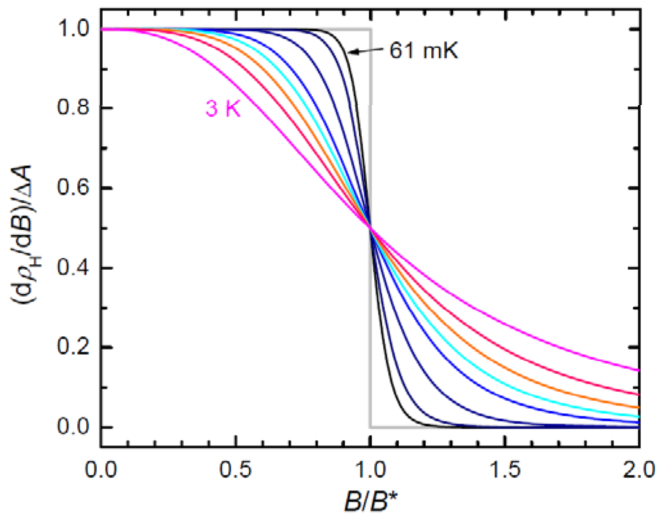


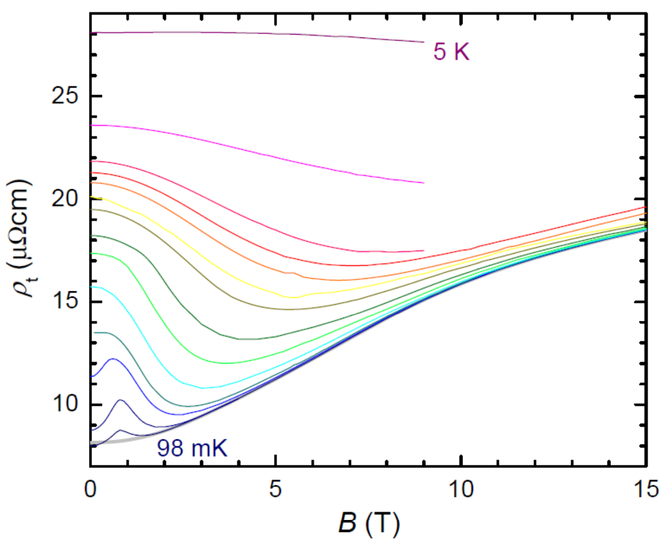
Similar behavior of Hall resistivity and magnetoresistance as reported for $YbRh_2Si_2$.

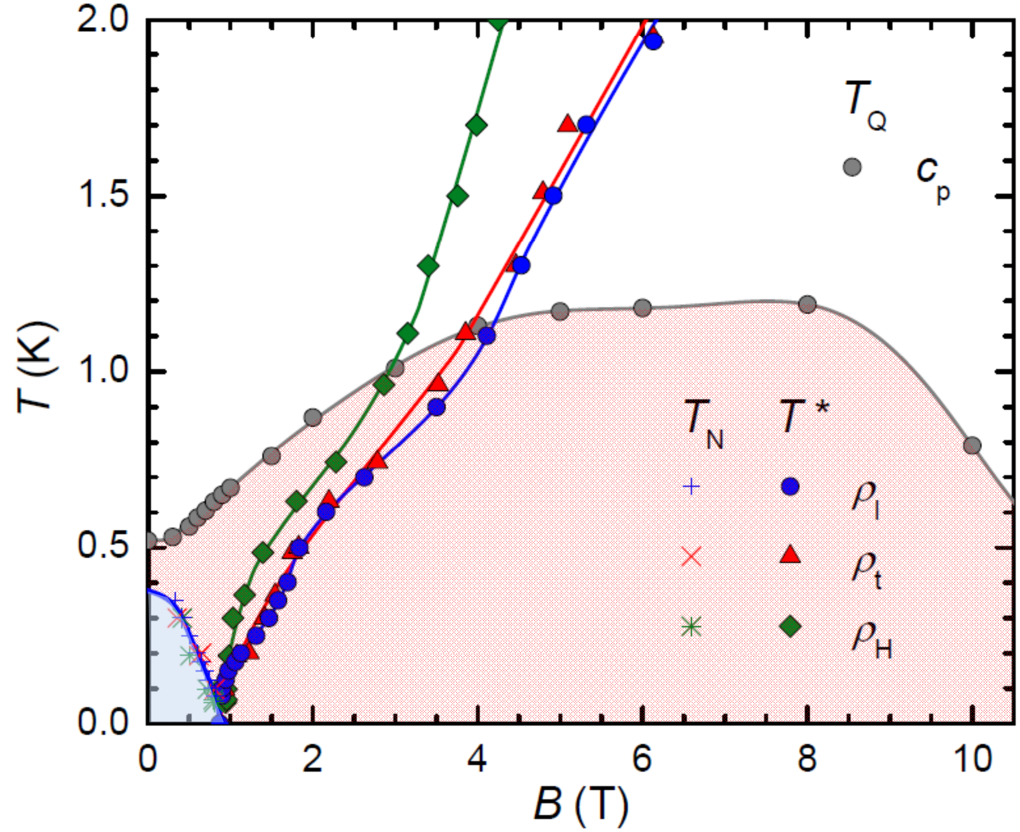
Kondo breakdown in cubic (structure) system

J. Custers *et al.* Nature Mat. **11**, 189 (2012)

$Ce_3Pd_{20}Si_6$ QCP



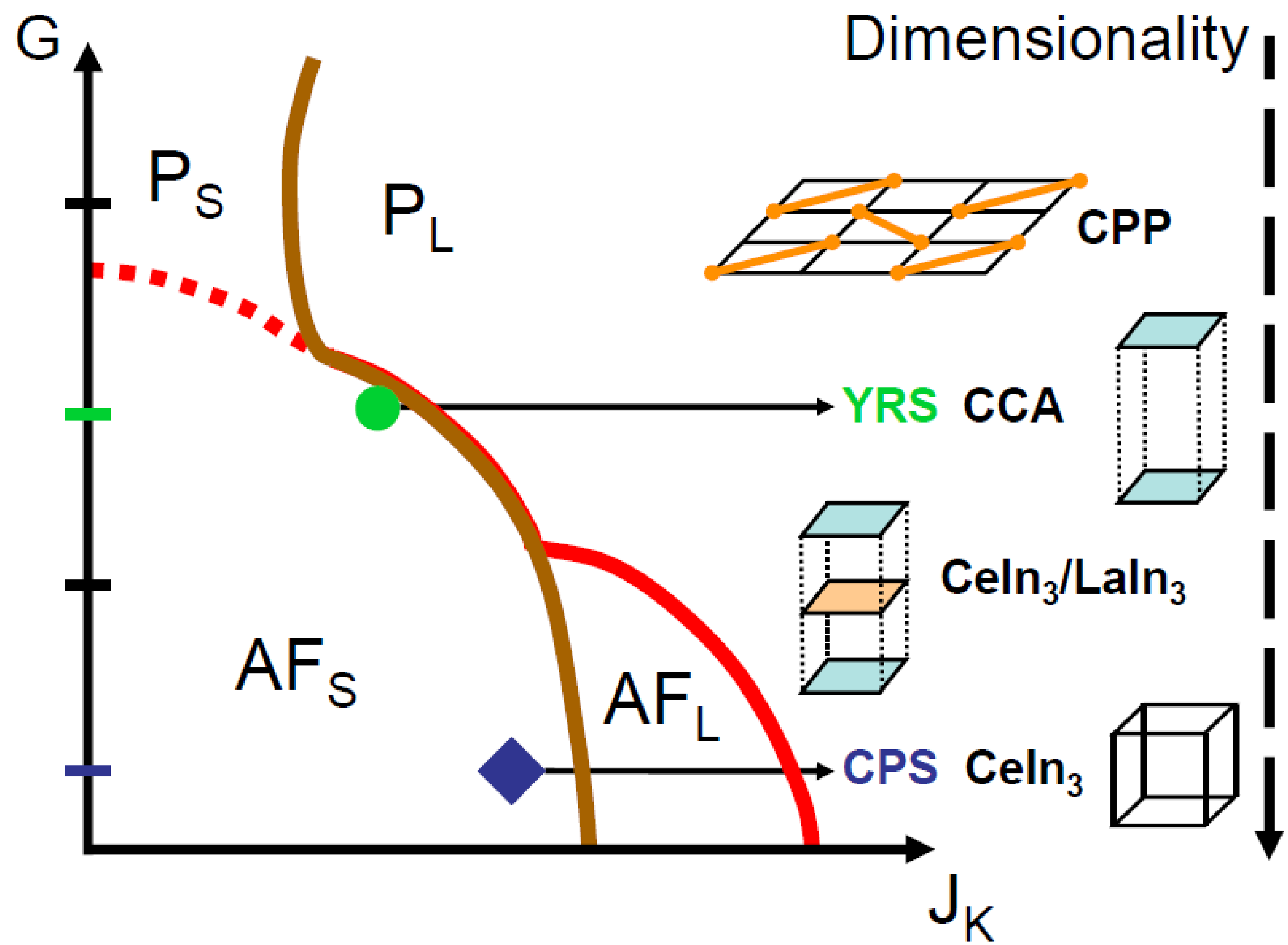




Similar behavior of Hall resistivity and magnetoresistance as reported for YbRh$_2$Si

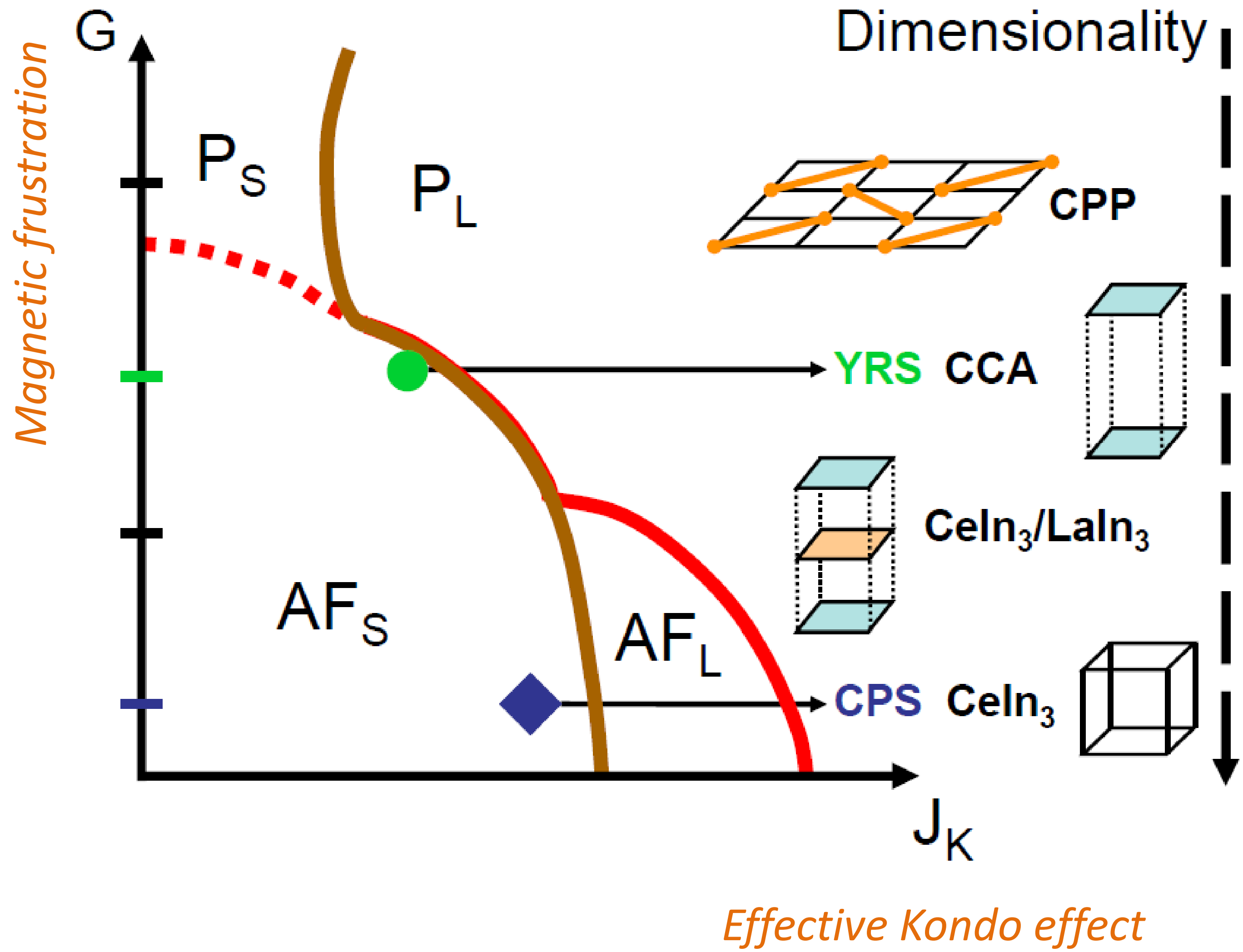
Kondo breakd UNEXPECTED bic (structure) system

Global Phase Diagram



Q. Si, Physica B, **378–380,** 23 (2006)
J. Custers *et al.* Nature Mat. **11**, 189 (2012)

Global Phase Diagram



Q. Si, Physica B, **378–380,** 23 (2006)
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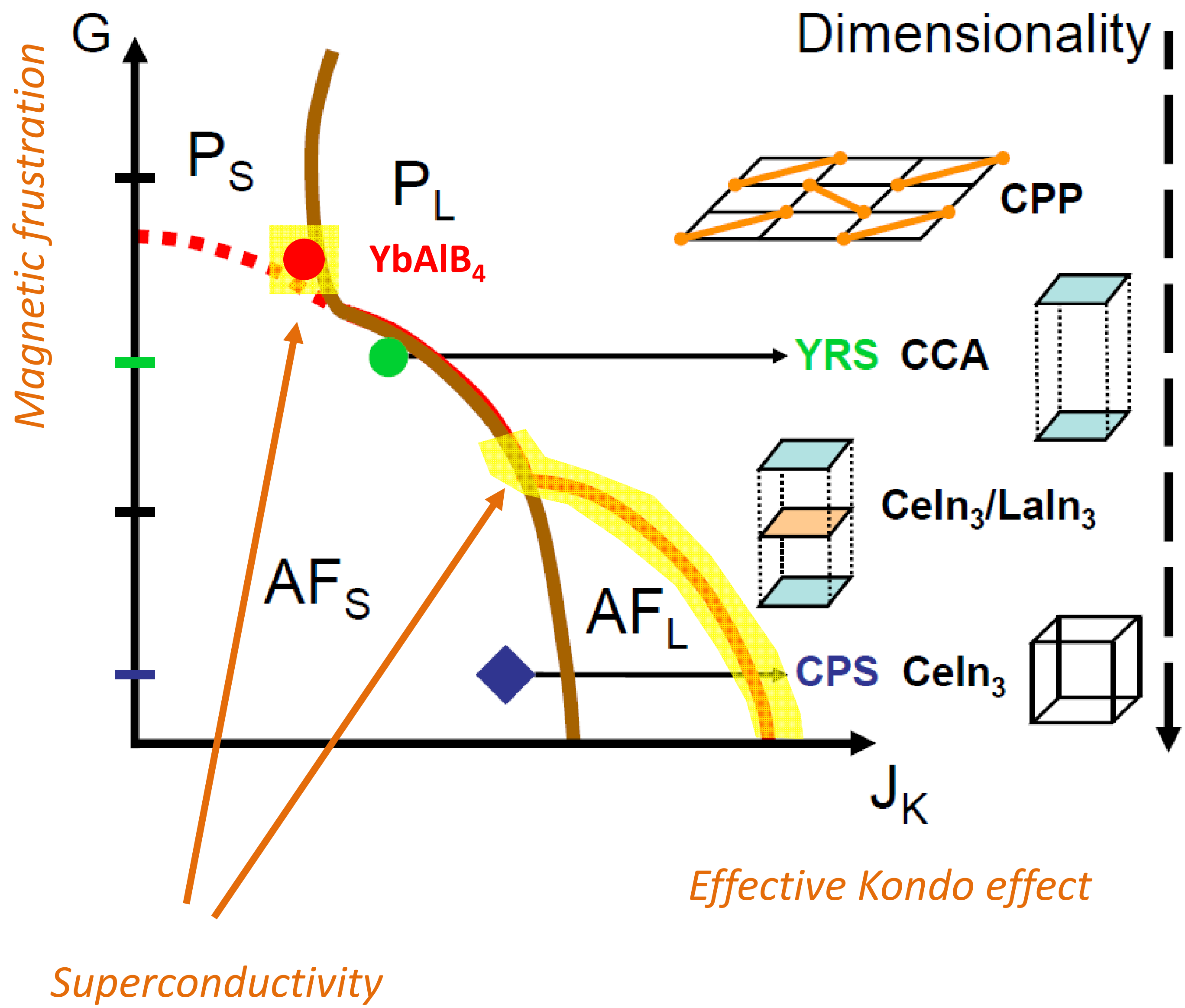
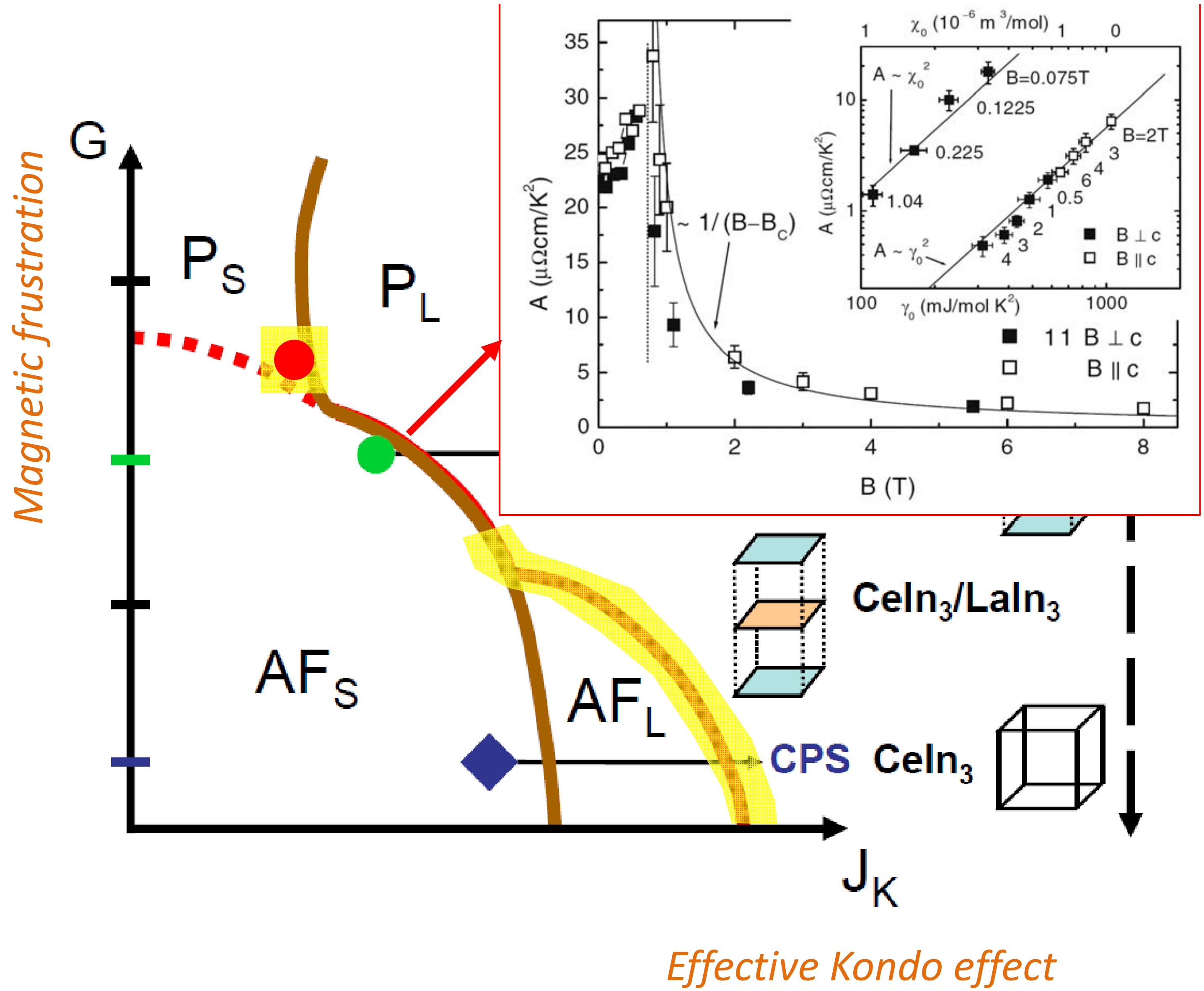
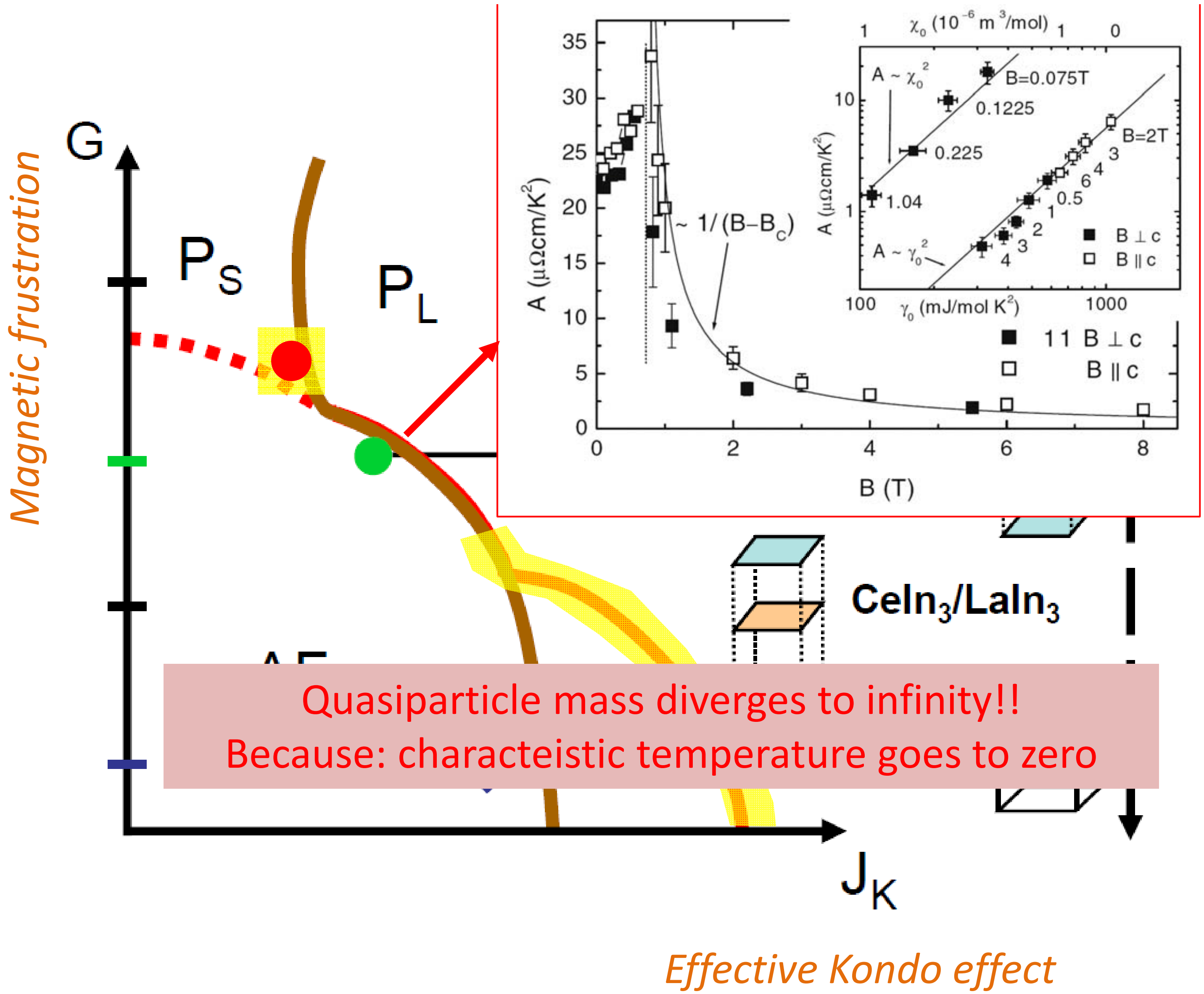
Global Phase Diagram



Global Phase Diagram



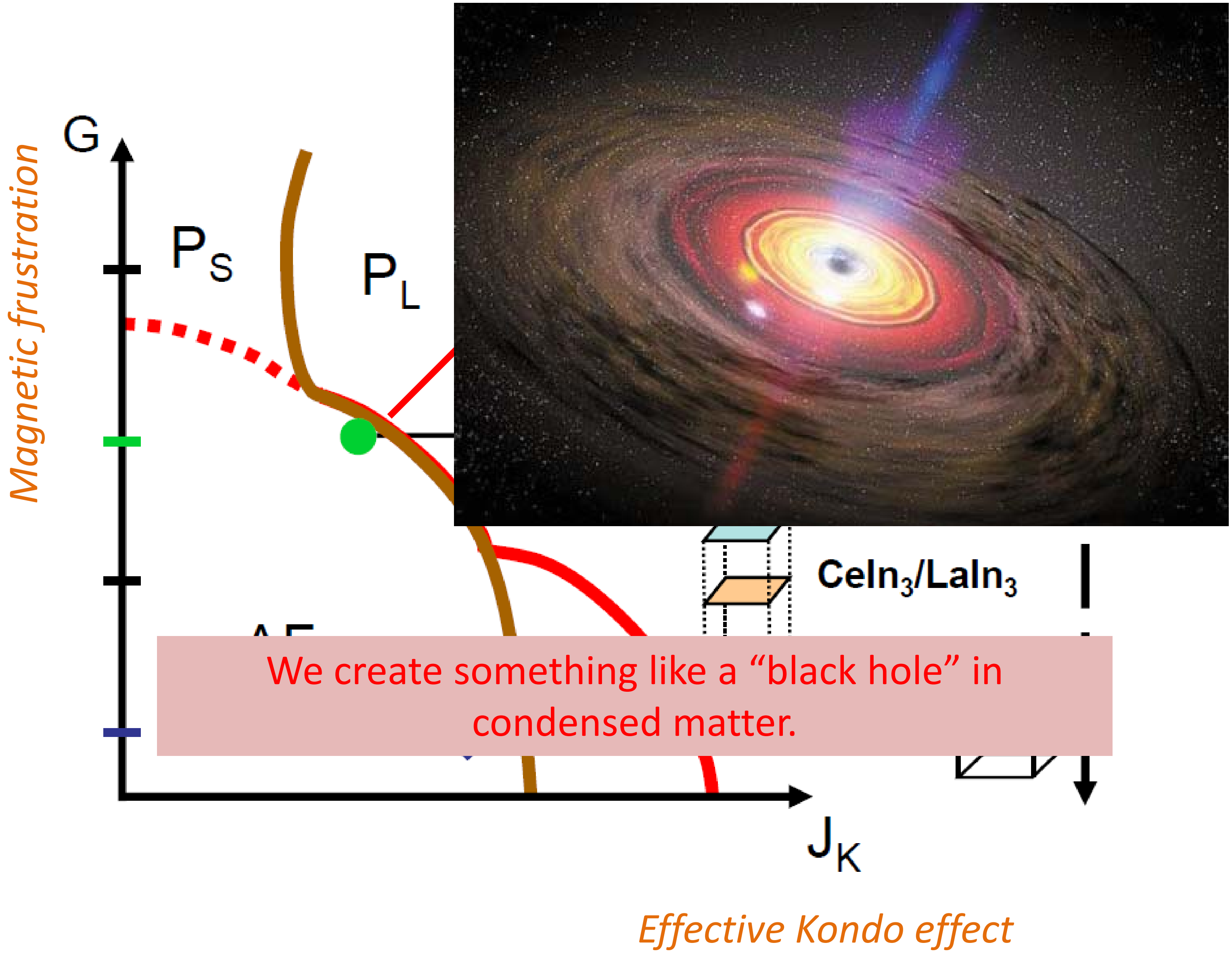
Global Phase Diagram



Quasiparticle mass diverges to infinity!!

Because: characteistic temperature goes to zero

Global Phase Diagram



We create something like a "black hole" in condensed matter.

Outlook

New approaches necessary.

Theory: *Incorporate String theory (The quantum theory of a black hole in a 3+1-dimensional negatively curved AdS universe is holographically represented by a CFT (quantum critical field theory) in 2+1 dimensions;*
Čubrović *et al.* Science **325**, 439 (2009)*)*

Material Science: *tailoring new materials ($CeIn_3$-$LaIn_3$ layered films;*
Shishido *et al.* Science **327**, 980 (2010)*,*
Graphene;
Herbut Physics ***2****, 57 (2009))*

Experimental Physics: *lower temperatures*
cold atoms
systematic study; same type of experiments on all compounds

Thank you

for your attention