Interplay of incipient magnetism and superconductivity in heavy-fermion metals

F. Steglich
MPI for Chemical Physics of Solids, 01187 Dresden, Germany

experiments

neutron scattering	J. Arndt, O. Stockert, M. Loewenhaupt (TUD)
Hall effect, MR	S. Friedemann, S. Wirth
ac-susc., dc-magn.	S. Lausberg, T. Westerkamp, M. Brando
single crystals	H.S. Jeevan, C. Krellner, C. Geibel

theory: S. Kirchner, Q. Si (Rice), P. Coleman (Rutgers), G. Zwicknagl (Braunschweig)

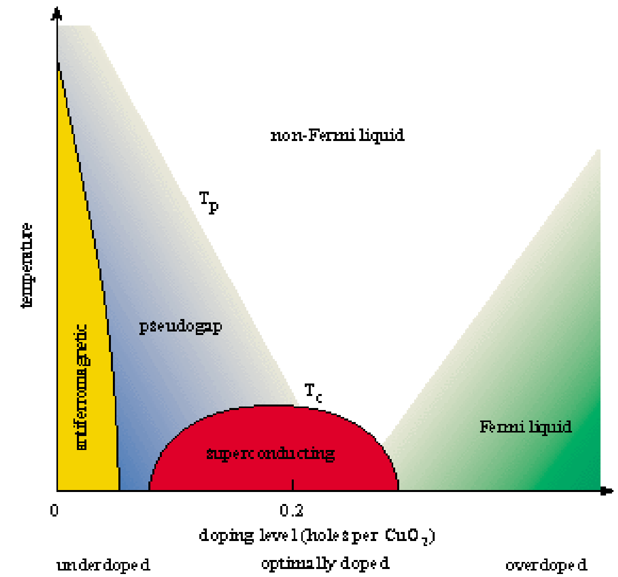
funding: DFG FOR 960 „Quantum Phase Transitions“

Heavy-Fermion Superconductors

	T_c(K)	
$CeCu_2Si_2$	0.6	('79 DA/K)
[p = 2.9 GPa:	2.3	('84 GE/GR)]
$CeNi_2Ge_2$	0.2	('97 DA, '98 CA/GR)
$CeIrIn_5$	0.4	('00 LANL)
$CeCoIn_5$	2.3	('00 LANL)
Ce_2CoIn_8	0.4	('02 NA)
Ce_2PdIn_8	0.7	('09 WR)
$CePt_3Si$	0.7	('03 VI)
p > 0		
$CeCu_2Ge_2$	0.6	('92 GE)
$CePd_2Si_2$	0.4	('94 CA)
$CeRh_2Si_2$	0.4	('95 LANL)
$CeCu_2$	0.15	('97 GE/KA)
$CeIn_3$	0.2	('98 CA)
$CeRhIn_5$	2.1	('00 LANL)
Ce_2RhIn_8	1.1	('03 LANL)
$CeRhSi_3$	0.8	('05 SE)
$CeIrSi_3$	1.6	('06 OS)
$CeCoGe_3$	0.7	('06 OS)
$Ce_2Ni_3Ge_5$	0.26	('06 OS)
$CeNiGe_3$	0.4	('06 OS)
$CePd_5Al_2$	0,57	('08 OS)
$CeRhGe_2$	0.45	('09 OS)
$CePt_2In_7$	2.1	('10 LANL)
$CeIrGe_3$	1.5	('10 OS)

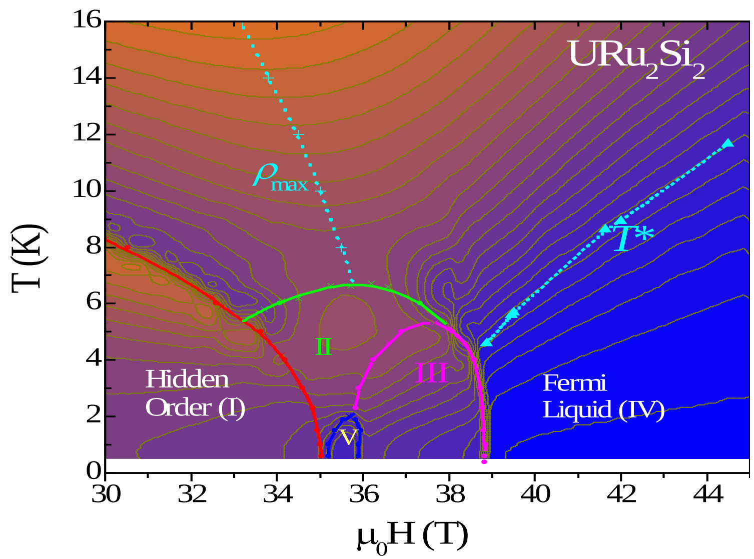
	T_c(K)	
$PrOs_4Sb_{12}$	1.85	('01 UCSD)
β-$YbAlB_4$	0.08	('08 TO/IR)
p > 0		
Eu metal	1.8-2.8	('09 SL, OS)
UBe_{13}	0.9	('83 Z/LANL)
UPt_3	0.5	('84 LANL)
URu_2Si_2	1.4	('84 K/DA)
UNi_2Al_3	1.2	('91 DA)
UPd_2Al_3	2.0	('91 DA)
URhGe	0.3	('01 GR)
UCoGe	3.0	('07 AM/KA)
p > 0		
UGe_2	0.7	('00 CA/GR)
UIr	0.14	('04 OS)
$NpPd_5Al_2$	5.0	('07 OS)
$PuCoGa_5$	18.5	('02 LANL)
PuRhGa5	8.7	('03 KA)
p > 0		
Am metal	2.2	('05 KA)

Novel phases near QCPs



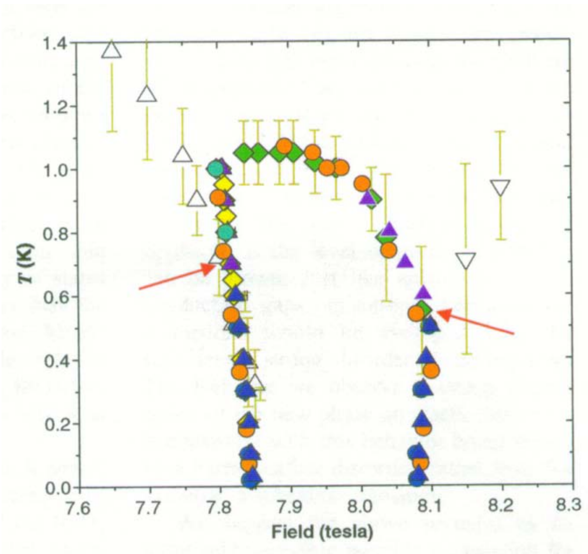
• **High-T_c superconductivity in cuprates**

(G. Bednorz, K.A. Müller '86)



• **Hidden order and more in URu_2Si_2**

(K.H. Kim et al. '04)

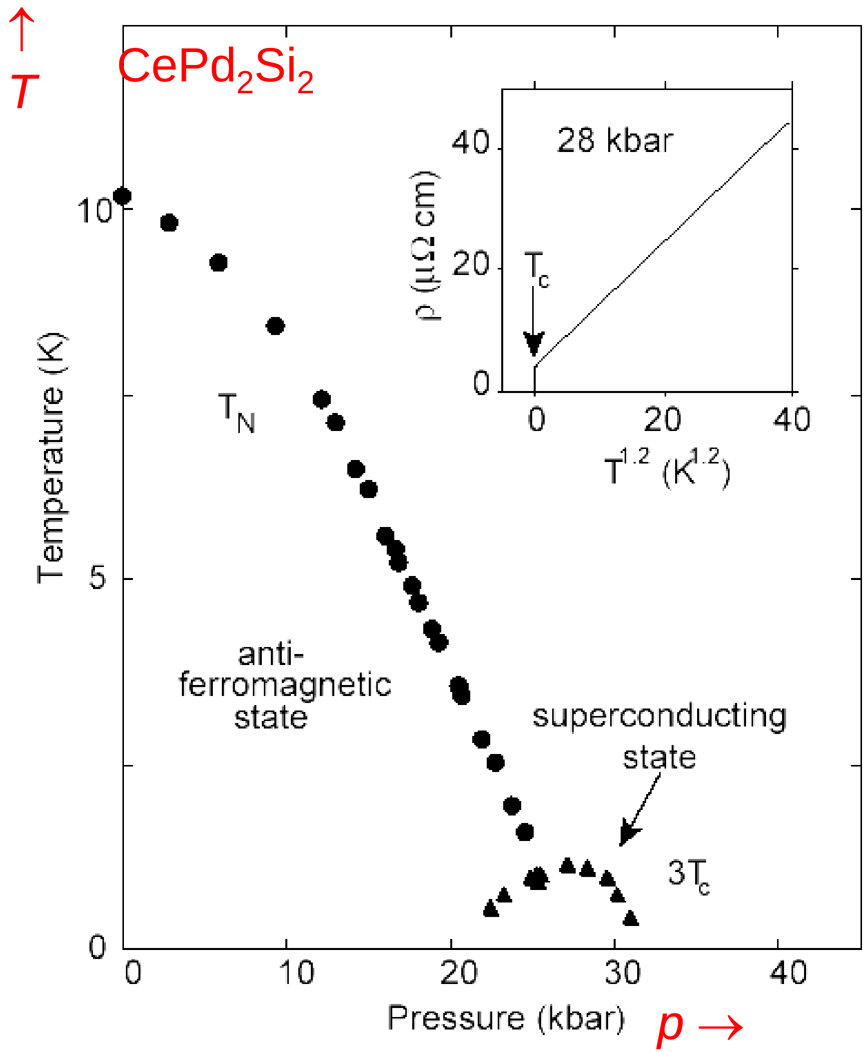


• **Disorder sensitive phase in $Sr_3Ru_2O_7$**

(S. A. Grigera et al. '04)

Non-Fermi-liquid superconductor: $CePd_2Si_2$

[N.D. Mathur et al., Nature **394**, 39 (1998)]

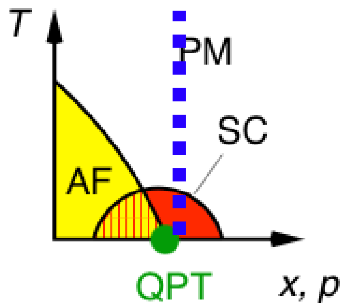


- AF QCP at p_c = 28 kbar
- T_c = 0.4 K at p=p_c
- NFL normal state
- SC mediated by strong spinfluctuations ?

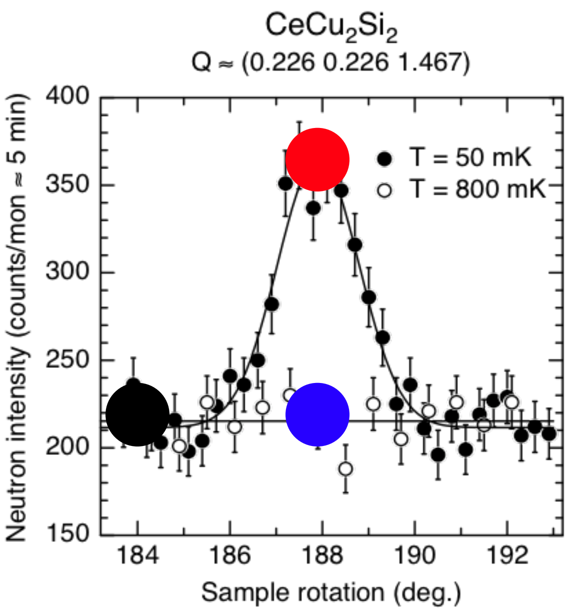
cf. K. Miyake et al.,
Phys. Rev. B **34**, 6554 (1986).
D.J. Scalapino et al.,
Phys. Rev. B **34**, 8190 (1986).

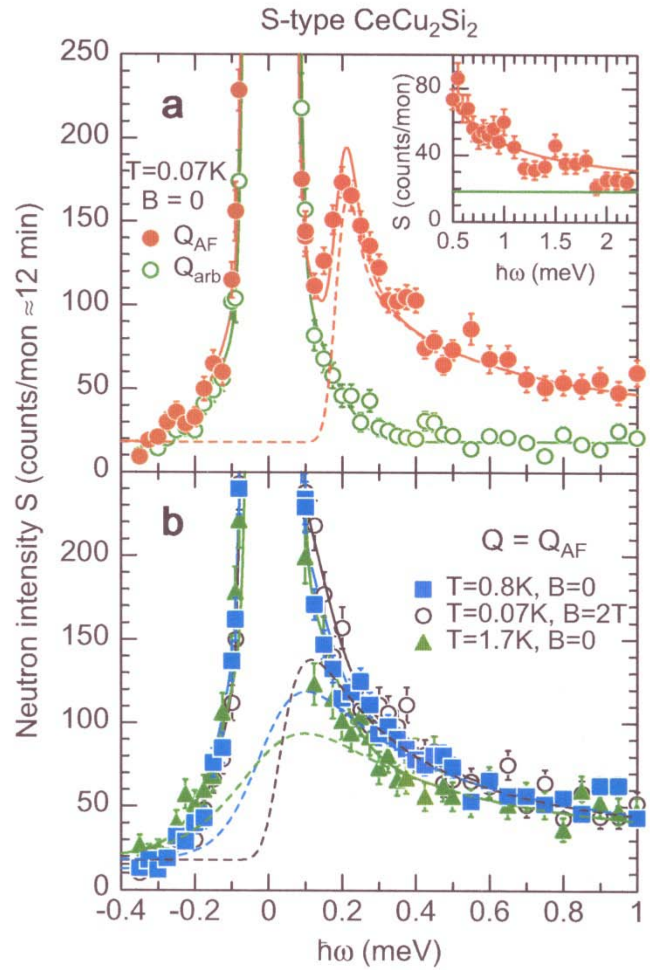
Spin gap in superconducting $CeCu_2Si_2$

[O. Stockert et al., Nature Phys. **7**, 119 (2011)]



IN12/ILL
$k_f = 1.15$ Å^{-1}
ΔE = 57 μeV
(FWHM)





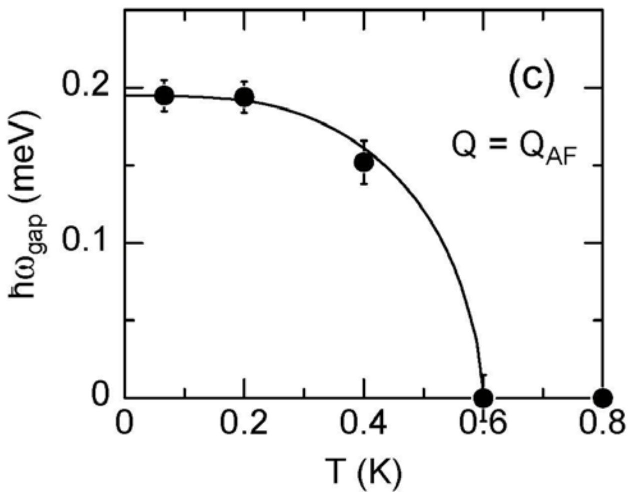
Q = $Q_{AF/nesting}$:
T_c = 600 mK

Spin excitation gap below T_c
at $\hbar\omega_0 \approx 0.2$ meV

$\hbar\omega_0 / k_B T_c \approx 3.9$

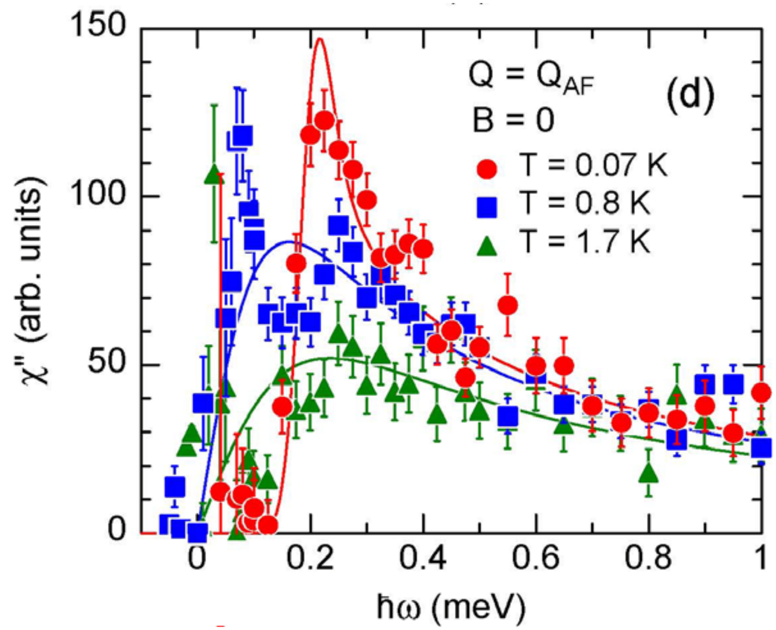
T-dependence of spin excitations

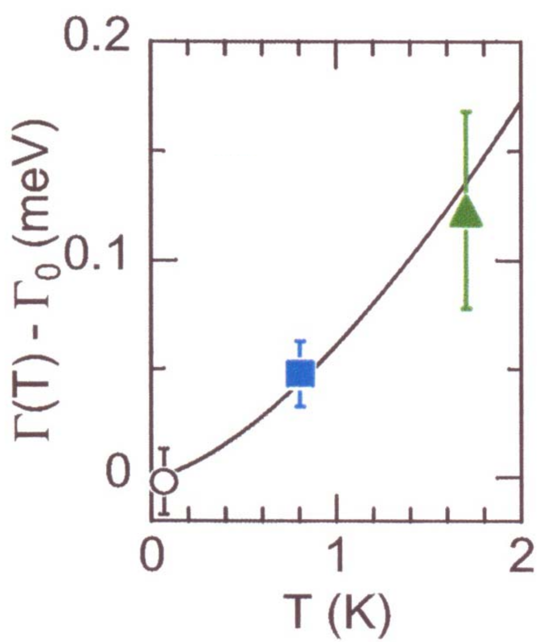
[O. Stockert et al., Nature Phys. **7**, 119 (2011)]



BCS: $2\Delta_0/k_BT_c$ = 4.3, Ohkawa '87

Cu-NQR: = 5.0, Ishida et al. '99, Fujiwara et al. '08





Quantum critical spin fluctuations in $CeCu_2Si_2$

[J. Arndt et al. (to be published)]

3D-SDW QCP (HMM) scenario:

$\Delta\rho \sim T^{1.5}$, $\gamma = \gamma_0 - bT^{0.5}$ (P. Gegenwart et al. '98)

$\Gamma(Q_{AF}) \sim \chi(Q_{AF})^{-1} \sim T^{3/2}$ [$\chi(Q_{AF})\,\Gamma(Q_{AF})$ = const. for param. HF metals (Y. Kuramoto '87)]

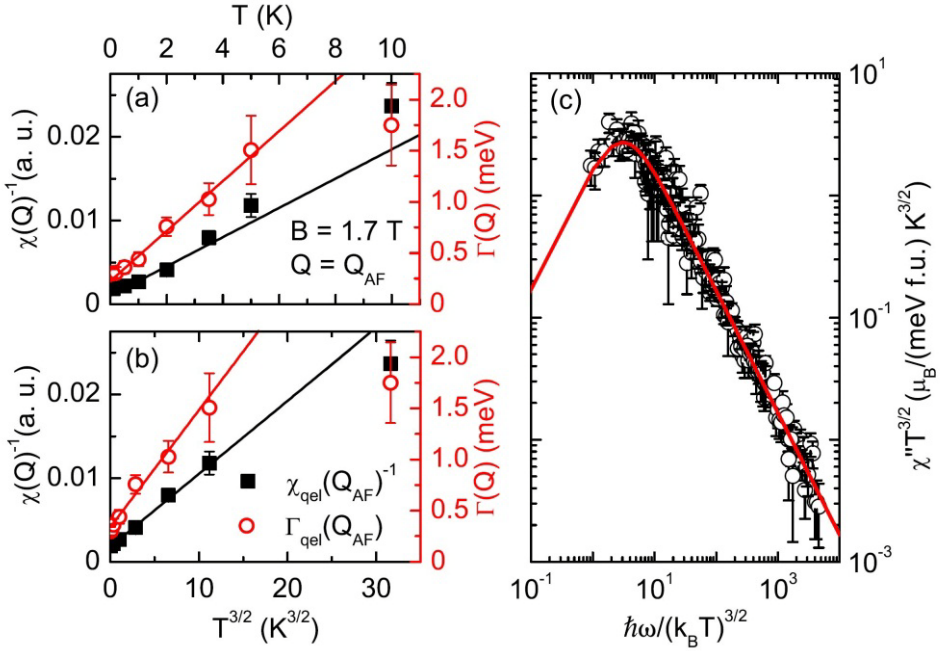
$\chi'' T^{3/2} = f(\hbar\omega/(k_B T)^{3/2})$

$\chi(Q_{AF})^{-1} = c_1 + c_2 T^{\alpha}$

$\Gamma(Q_{AF})$: dto

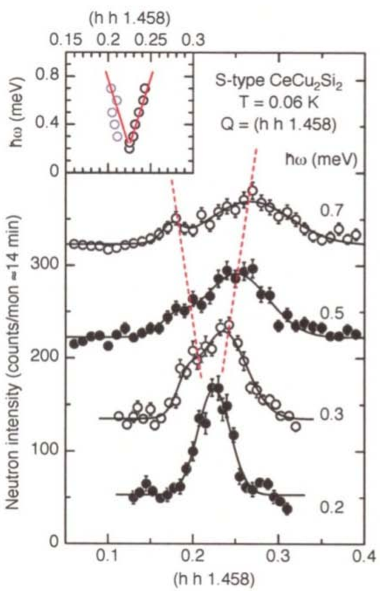
$\alpha = 1.57 \pm 0.08$

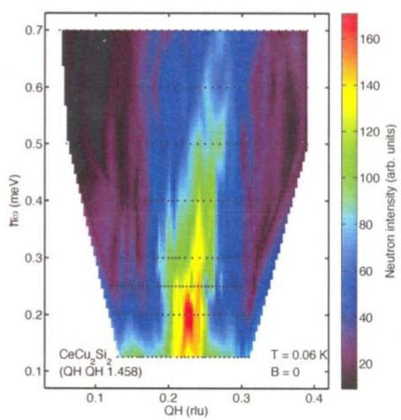
$\alpha = 1.38 \pm 0.16$



q-dependence of spin excitations

[O. Stockert et al., Nature Phys. **7**, 119 (2011)]





paramagnon velocity, v_P

$\omega_P = v_P q$; $Q = Q_{AF} \pm q$

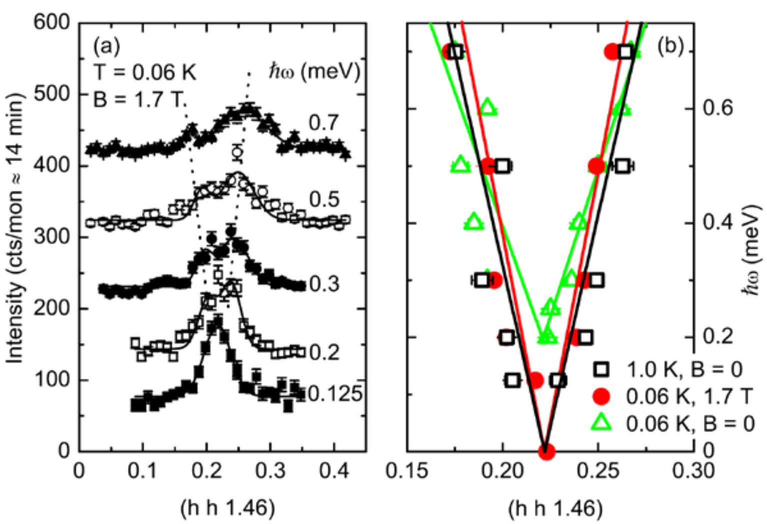
$v_P = (4.44 \pm 0.86)$ meVÅ [(670 ± 130) m/s]

averaged Fermi velocity, v_F^*

$v_F^* \approx 57$ meVÅ [8600 m/s]

[Rauchschwalbe et al. '82]

$v_P / v_F^* \approx 8$ % (retarded interaction)



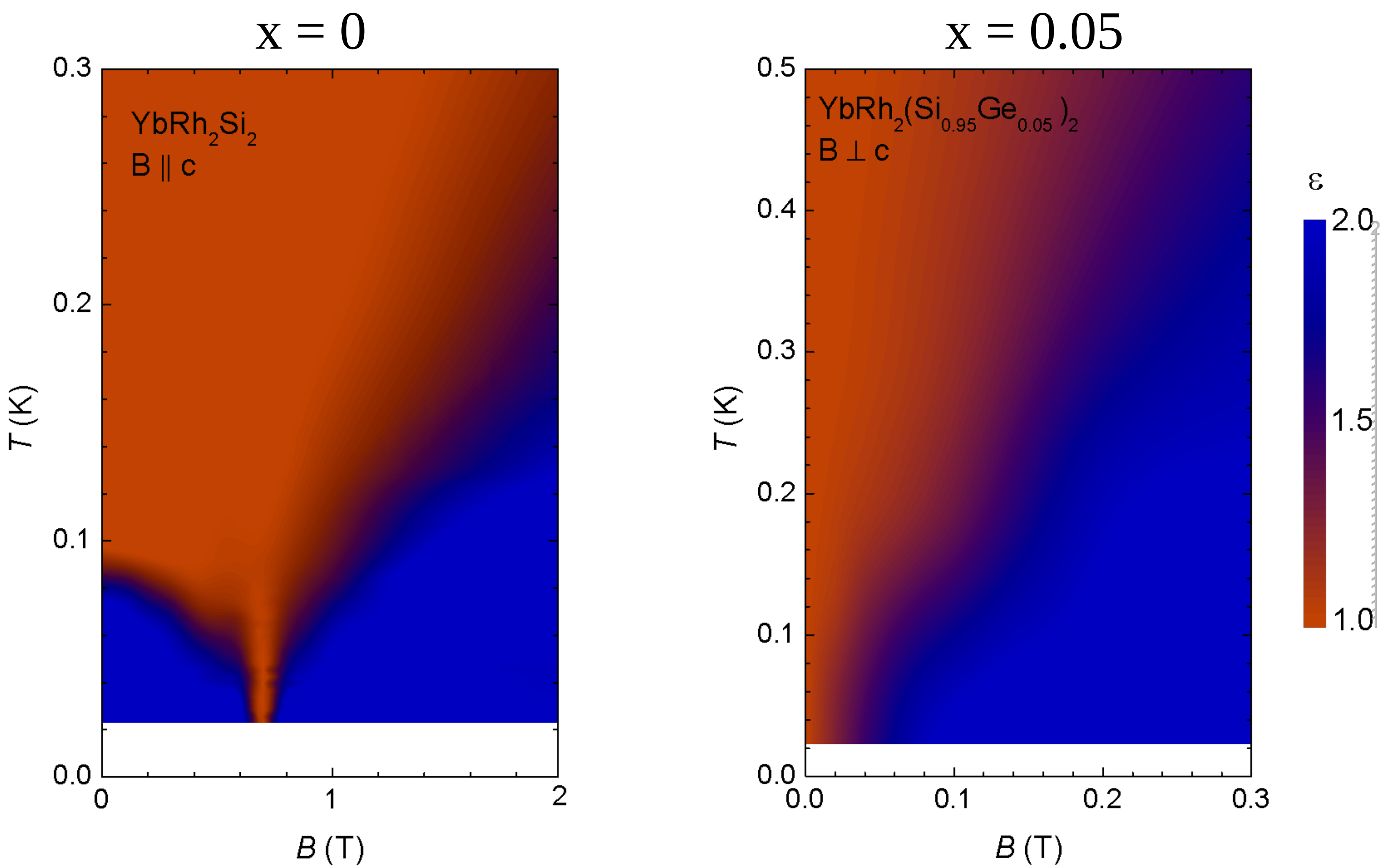
$v_{pn} = (6.9 \pm 0.2)$ meVÅ

(J. Arndt et al., to be published)

T - B phase diagram of $YbRh_2(Si_{1-x}Ge_x)_2$

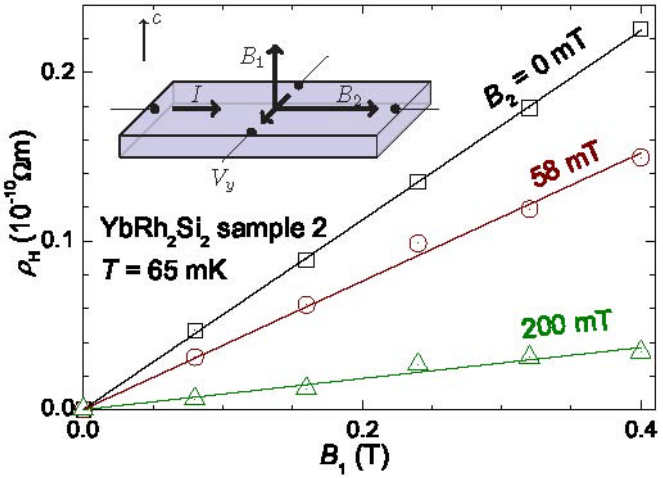
[J. Custers et al., Nature **424**, 524 (2003)]

$\Delta\rho \sim T^{\varepsilon}$, $\varepsilon = 2$ (blue), $\varepsilon = 1$ (red)



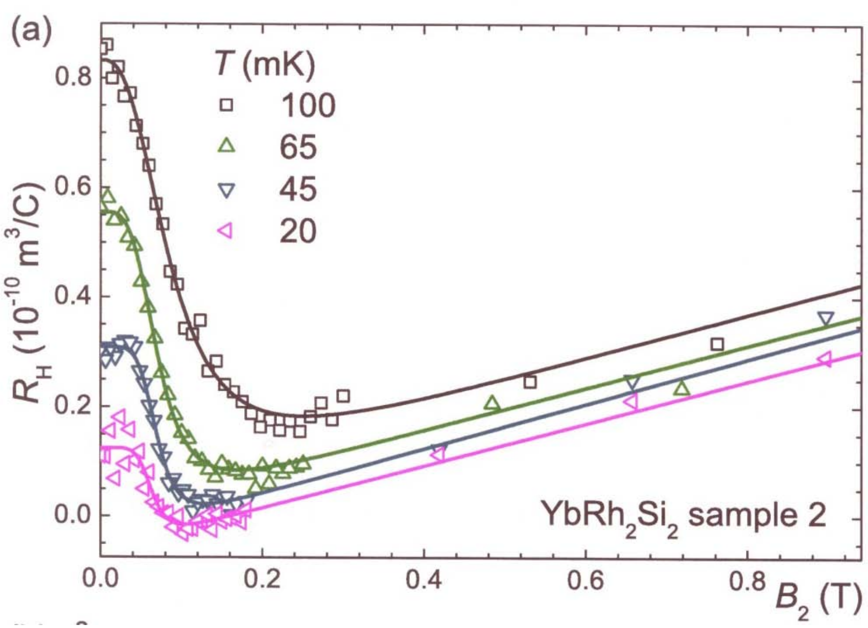
Crossed-field Hall-effect results

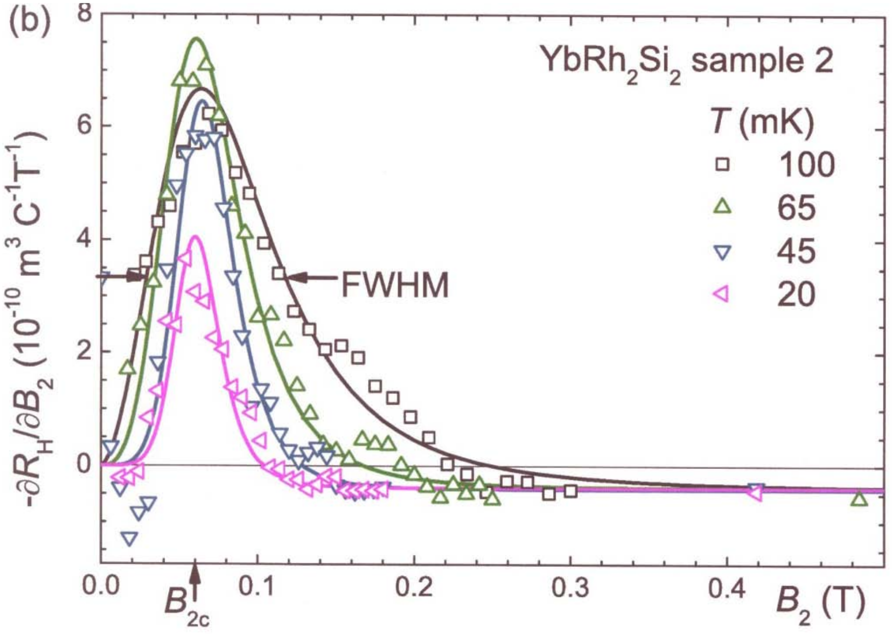
[S. Friedemann et al., PNAS **107**, 14547 (2010)]



$$R_H(B_2) = \lim_{B_1 \to 0} \rho_H(B_1, B_2)/B_1$$

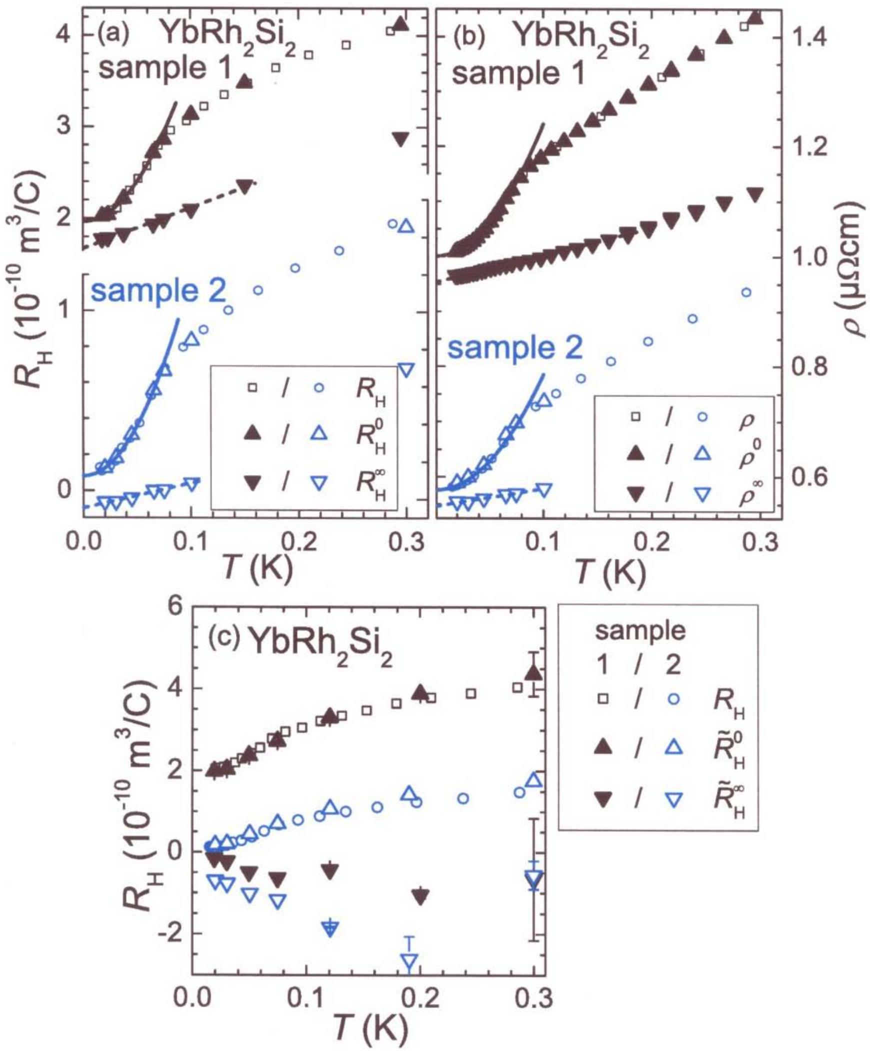
solid lines: $$R_H(B_2) = R_H^{\infty} - \frac{R_H^{\infty} + mB_2 - R_H^0}{1 + (B_2/B_0)^p} + mB_2$$





Limiting values of the Hall and MR crossover

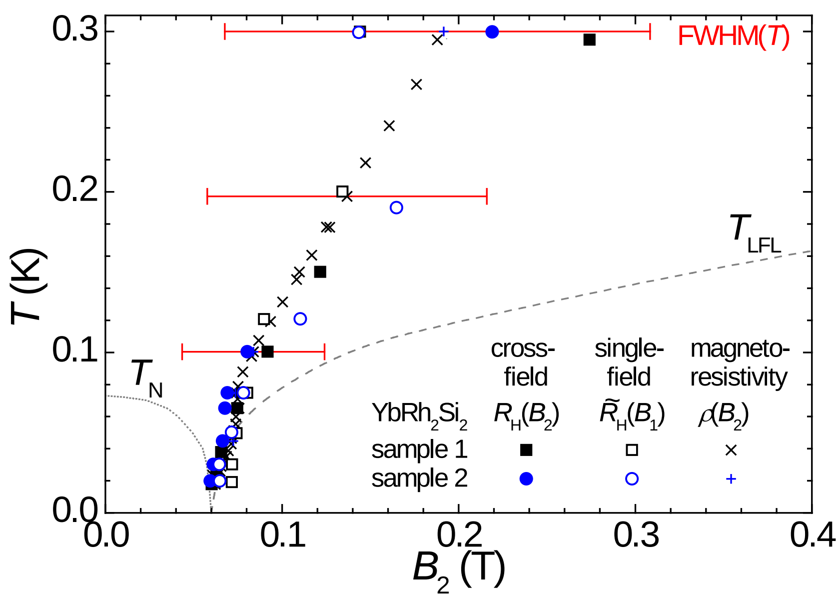
[S. Friedemann et al., PNAS **107**, 14547 (2010)]



Fermi surface collapse

[S. Friedemann et al., PNAS **107**, 14547 (2010)]

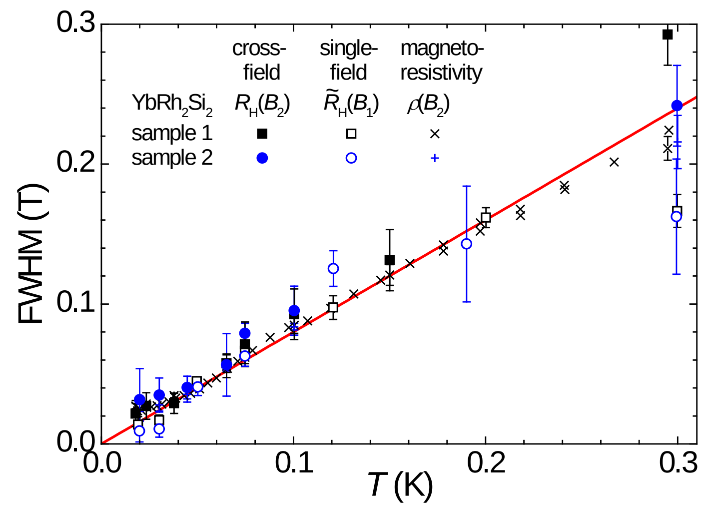
Crossover position T*(B)



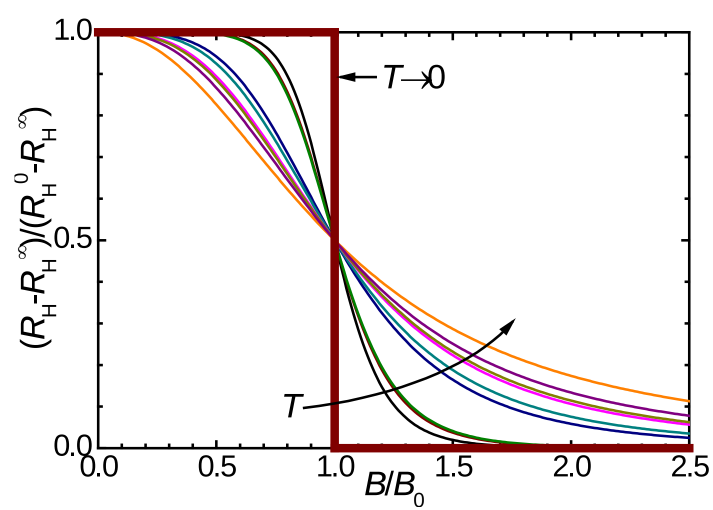
T*(B) agrees with data from ρ, λ, M

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

Crossover width

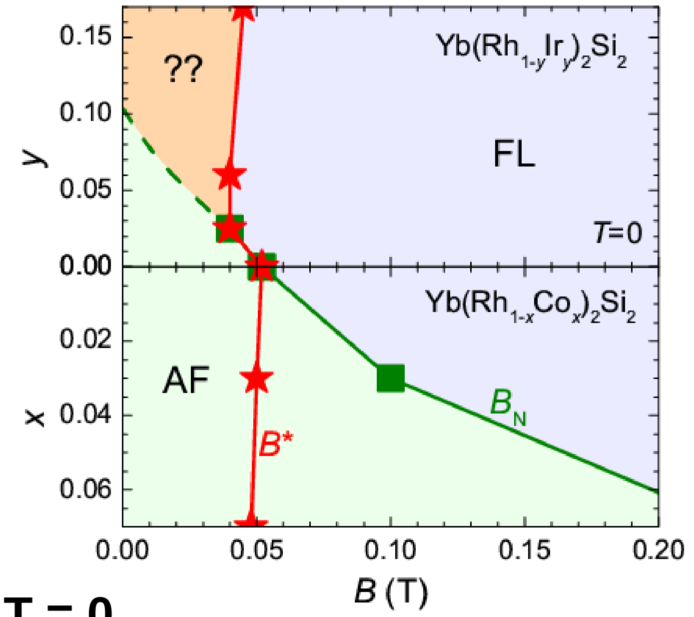


FWHM ~ T ↷ ω/T scaling (Q. Si, S. Kirchner)



Global phase diagram

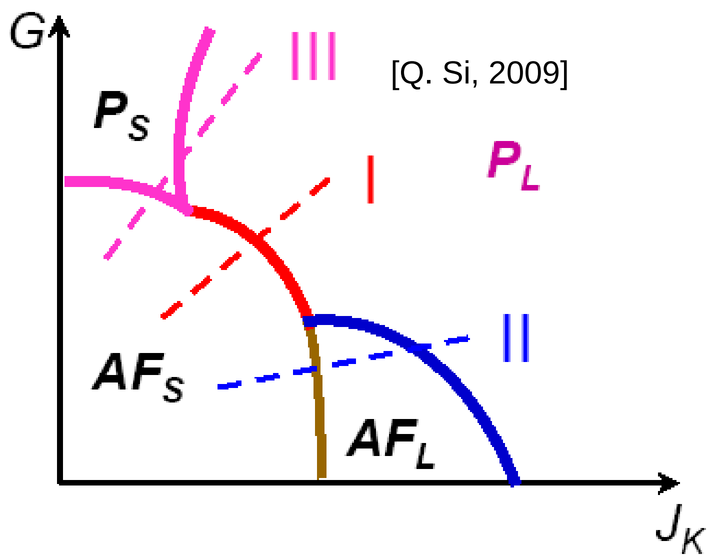
[S. Friedemann et al., Nature Phys. **5**, 465 (2009)]



6 % Ir : intermediate (spin-liquid, SL ?!) phase: $B_N = 0.15 < B < B^* = 45$ mT

7 % Co: Kondo breakdown within AF phase (like in pure $YbRh_2Si_2$ under pressure)

T = 0



III : 6 % Ir

I : pure $YbRh_2Si_2$

II : 7 % Co

y(Ir) > 10 % : Kondo breakdown without magnetism

Interplay between superconductivity and quantum criticality

CeCu_2Si_2 (p ≈ 0)

• 3D SDW QCP („conventional QCP")

• d-wave SC due to SDW fluctuations

SDW order in other NFL superconductors, e.g., CePd_2Si_2 ?

YbRh_2Si_2

• coinciding AF & Kondo-breakdown QCPs
(„unconventional QCP")

• no SC (T ≥ 10 mK)

Why?

• fm correlations?

• unconventional QCP?
cf. $CeRhIn_5$ under pressure [Shishido et al. (2005); Park et al. (2006)]

• T_c < 10 mK ?

Cooperation with E. Schuberth (WMI, TUM)

(ac-susc., dc-magn., spec. heat, T > 1 mK)