The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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Miniworkshop on
New States of Stable and Unstable Quantum Matter
(14 - 25 August 2006)

Fermi surface sensitive experiments on quantum criticality

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These are preliminary lecture notes, intended only for distribution to participants

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Fermi surface sensitive experiments on quantum criticality

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- Fermi surface reconstructions across QCPs
- Experimental evidence: A brief review
- Some news on $YbRh_2Si_2$
- New field-induced QCP: $Ce_3Pd_{20}Si_6$

Acknowledgements

$YbRh_2Si_2$

S. Friedemann, T. Lühmann, N. Oeschler, S. Wirth: MPI CPfS — **Hall effect**

O. Trovarelli, C. Geibel: MPI CPfS — **Samples**

P. Gegenwart, K. Tenya, Y. Tokiwa, F. Steglich: MPI CPfS — **Discussions**

P. Coleman, Q. Si: Rutgers/Rice — **Theoretical support**

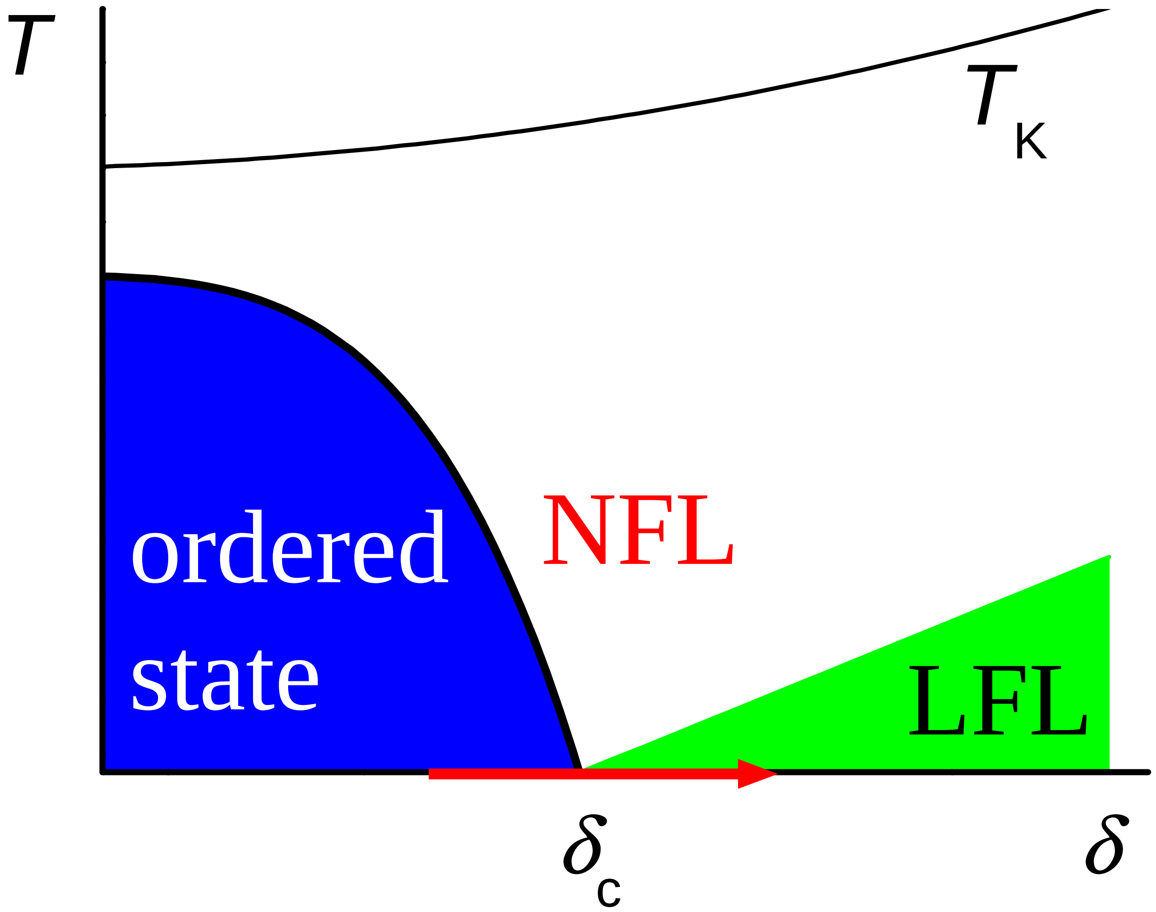
$Ce_3Pd_{20}Si_6$

J. Custers, M. Kriegisch, H. Müller, M. Müller: TU Vienna — **Susceptibility, resistivity**

A. Pikul: MPI CPfS — **Specific heat**

A. M. Strydom: Johannesburg — **Samples**

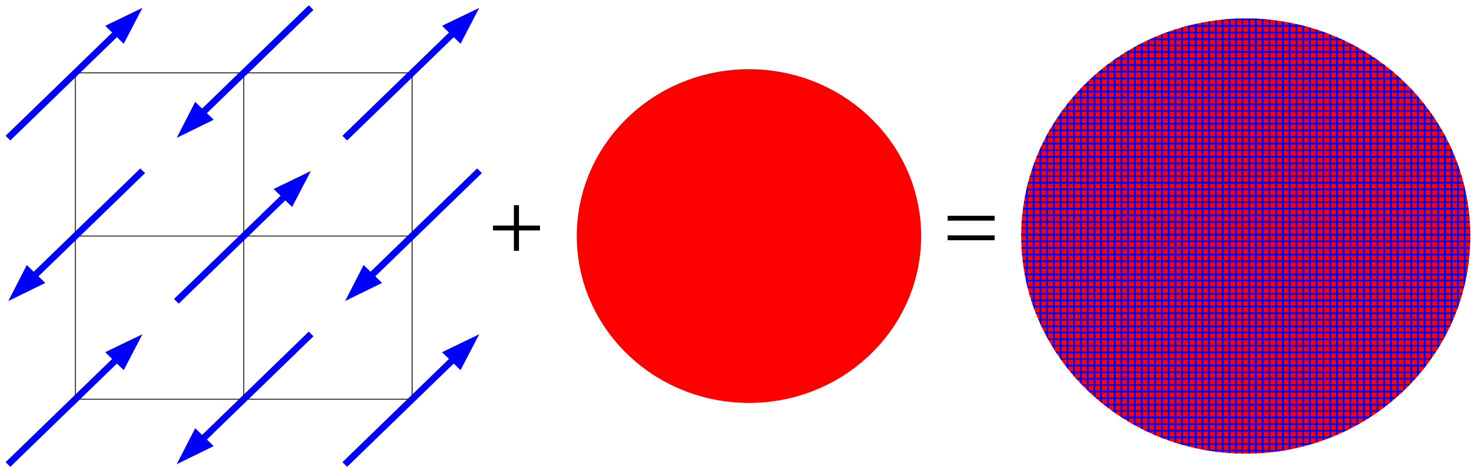
How does the Fermi surface evolve through a heavy-fermion QCP?



Continuously: SDW QCP

Discontinuously: Alternative scenarios for QCPs

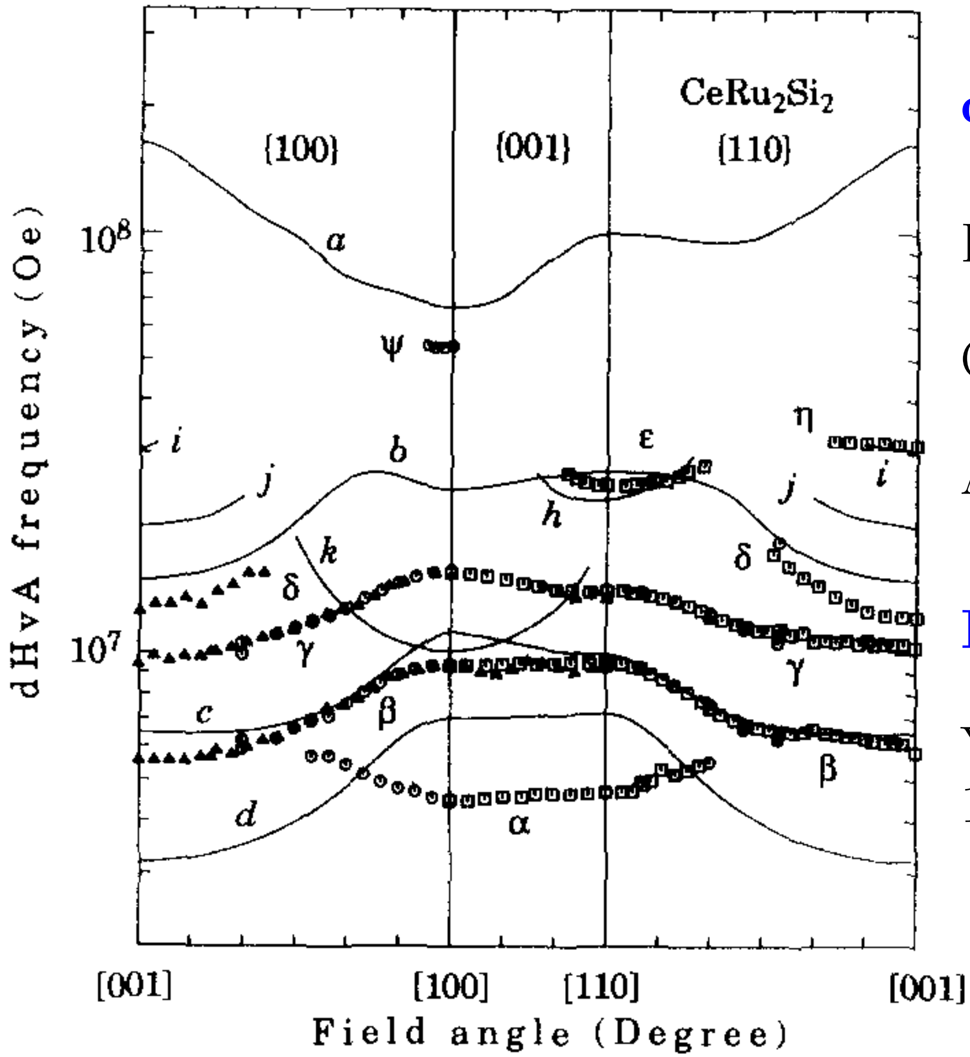
The “large Fermi surface” picture



If the Kondo lattice is a Fermi liquid, the localized spins contribute to the Fermi sea volume as electrons.

(e.g., Martin, PRL 48 (1982) 362
Oshikawa, PRL 84 (2000) 3370)

De Haas - Van Alphen vs LDA bandstructure: $CeRu_2Si_2$



dHvA experiment:

Lonzarich, JMMM 76&77 (1988) 1

Ōnuki et al., JPSJ 61 (1992) 960

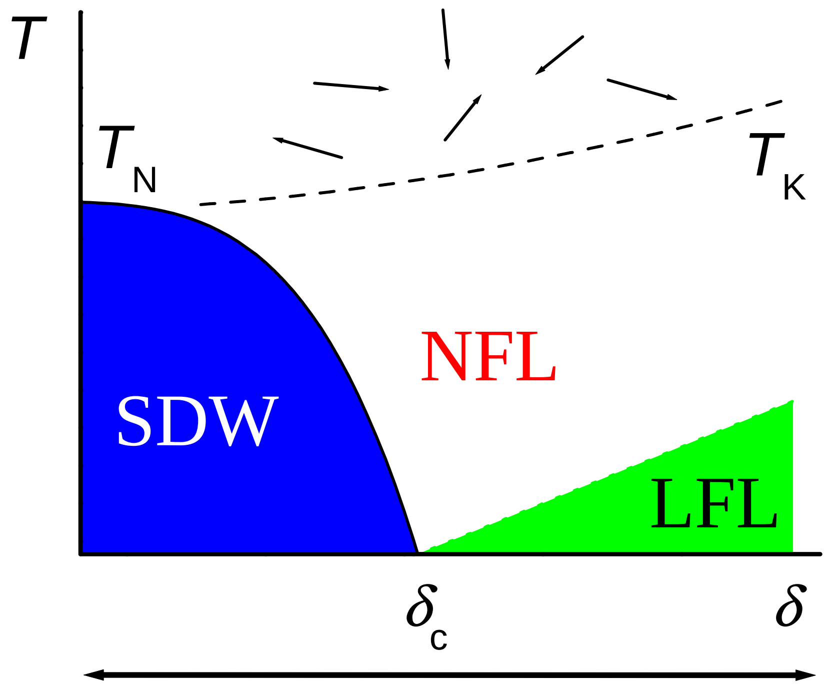
Aoki et al., JPSJ 61 (1992) 3457

LDA calculation, itinerant $4f$

Yamagami & Hasegawa, Physica B 186-188 (1993) 136

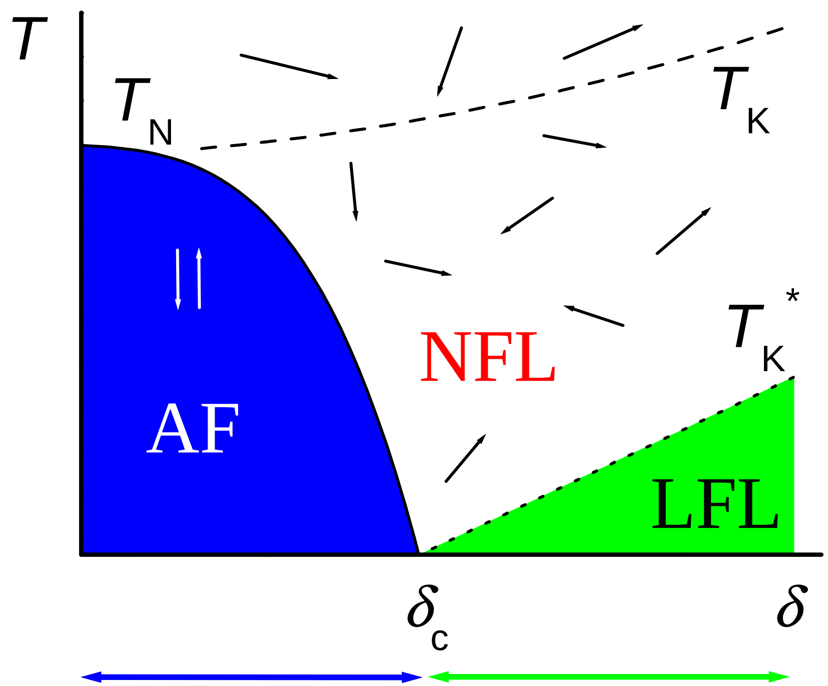
QCP scenarios

SDW



Hertz, Millis, Moriya, Continentino, Lonzarich, ...

Breakdown of Kondo screening at QCP



Schröder, Coleman, Pépin, Si, ...

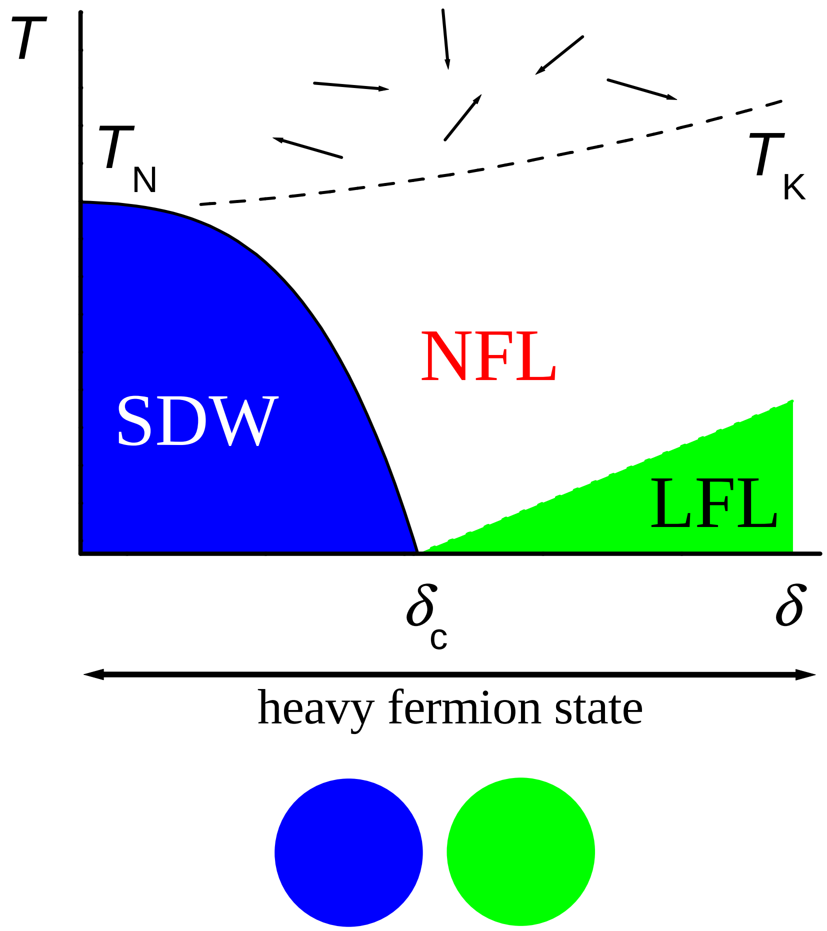
Local criticality: Si et al.

Spin-charge separation: Coleman, Pépin

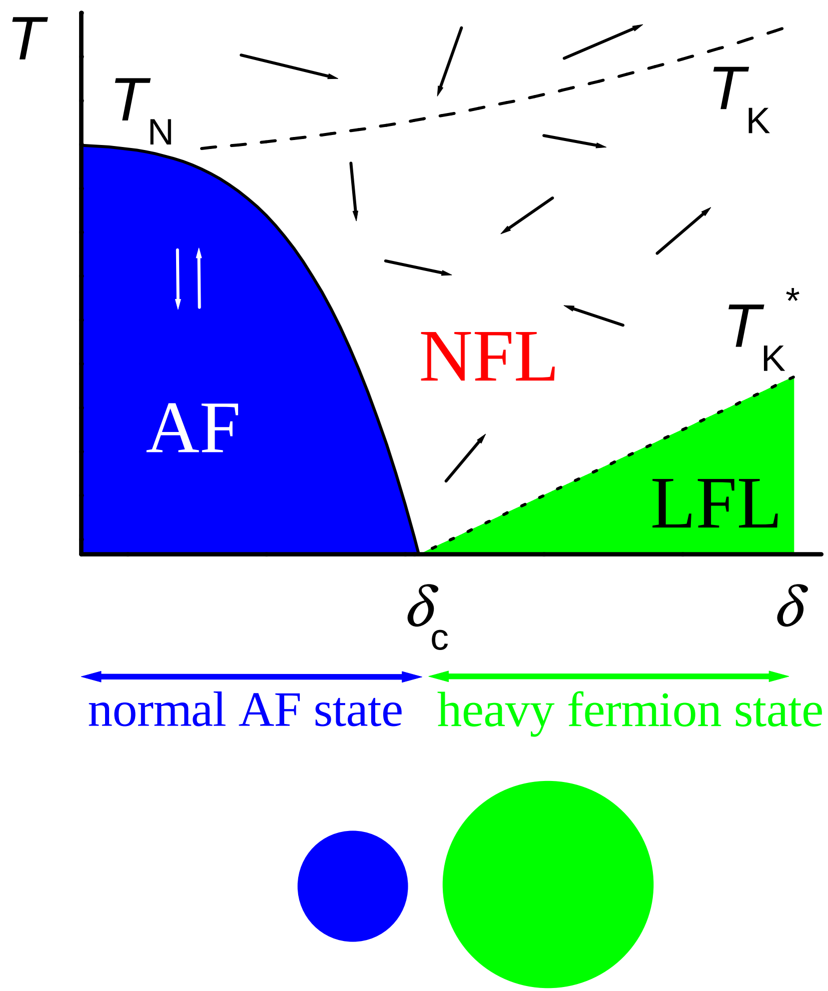
Fractionalized FL: Senthil et al., ...

QCP scenarios

SDW



Breakdown of Kondo screening at QCP

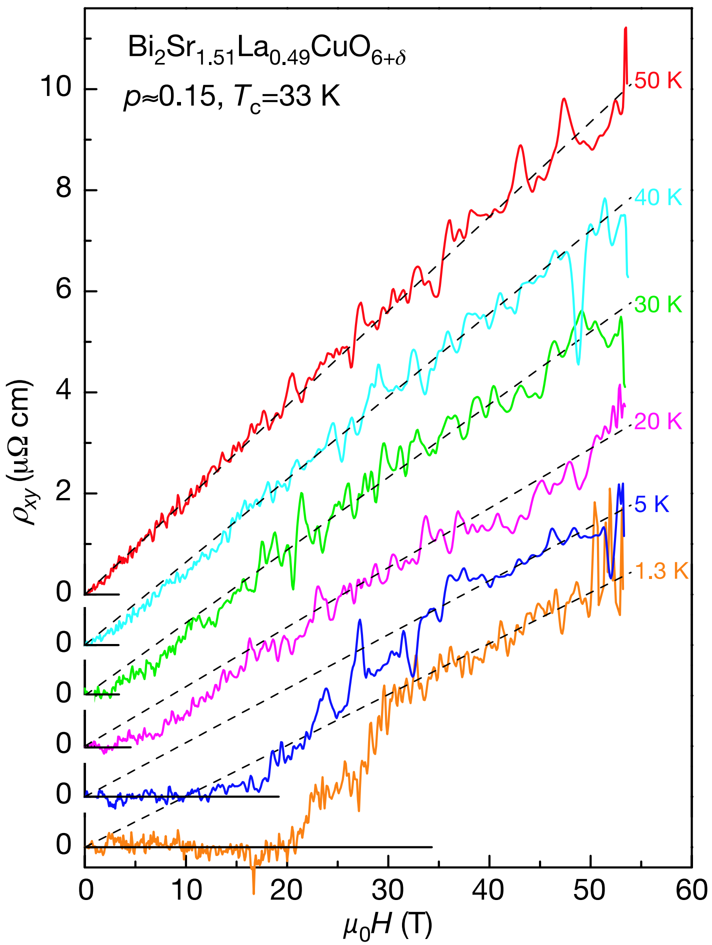


(Coleman et al., JPCM 13 (2001) R723)

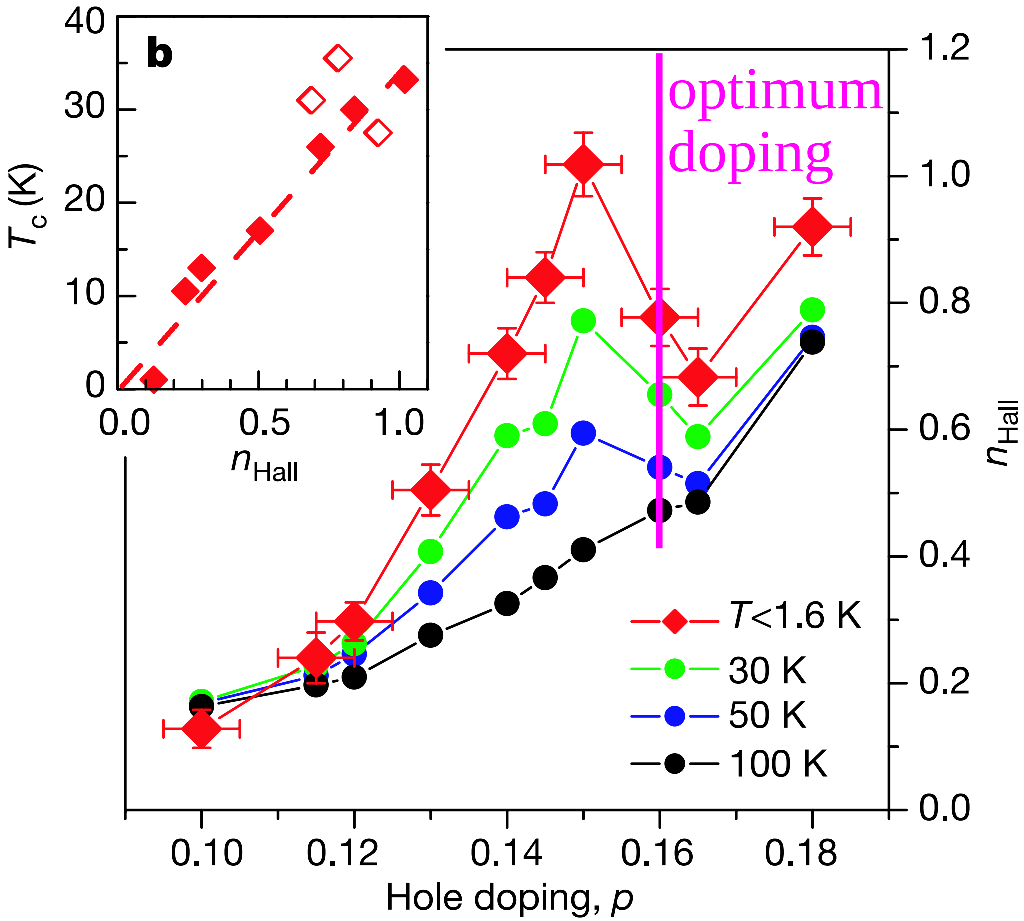
A brief review

Hall effect in $Bi_2Sr_{1.51}La_{0.49}CuO_{6+\delta}$:

Hall resistivity vs field



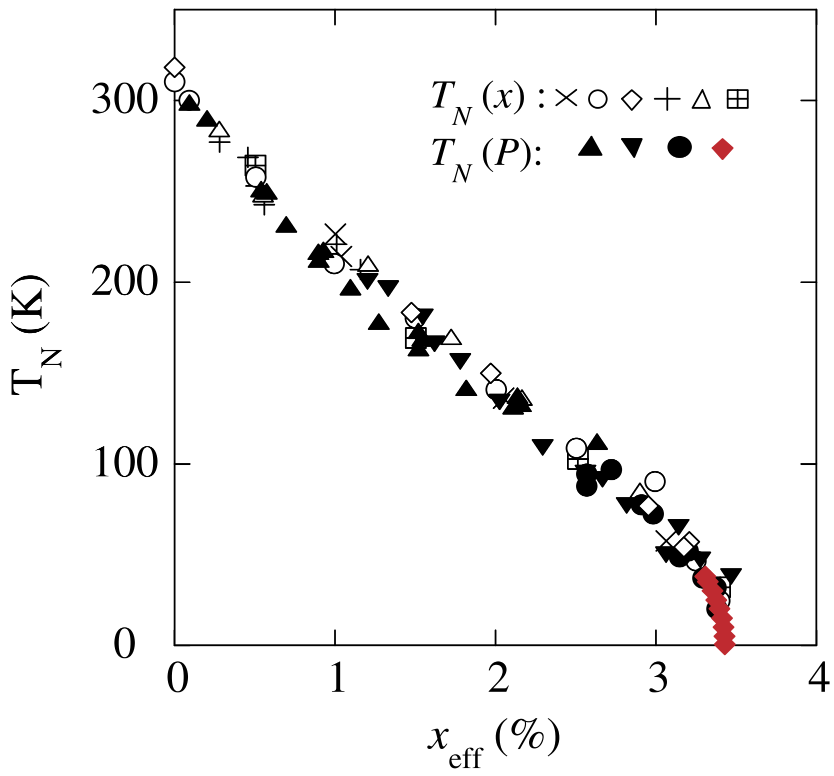
Hall number vs doping



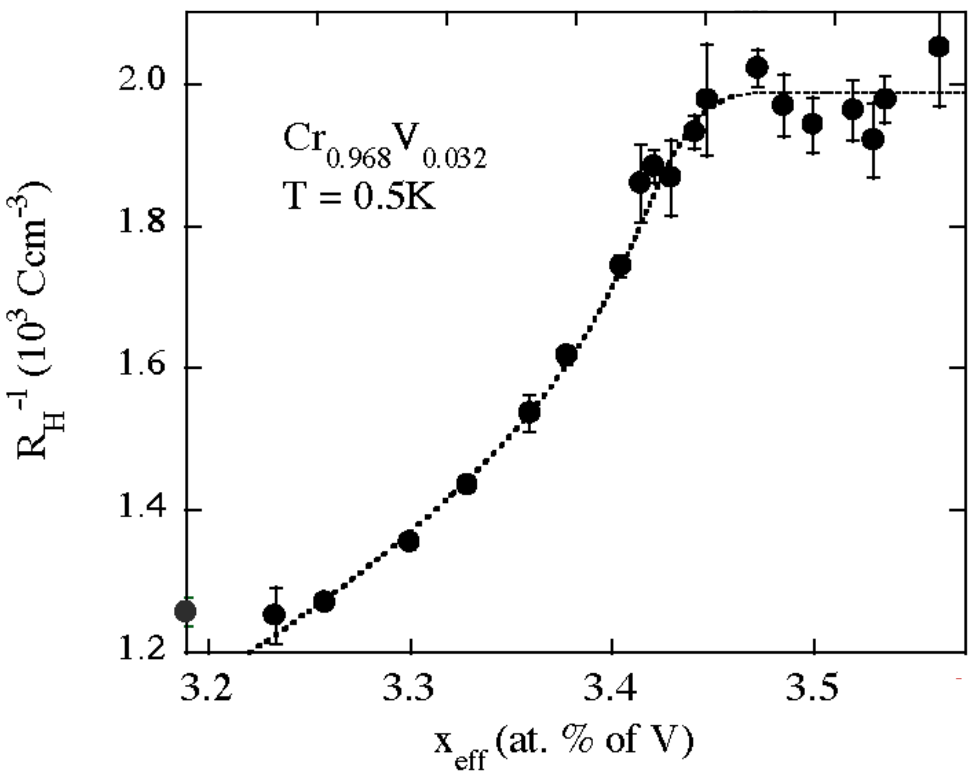
(Balakirev et al., Nature 424 (2003) 912)

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

Phase diagram



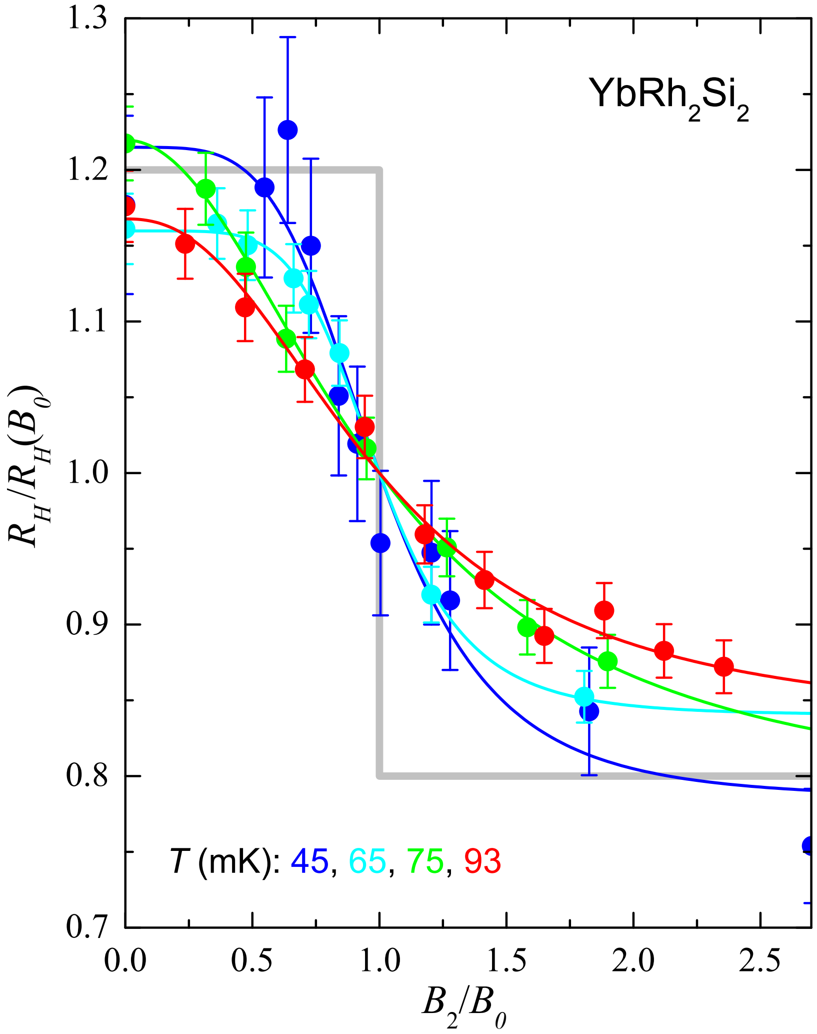
Inverse Hall coefficient



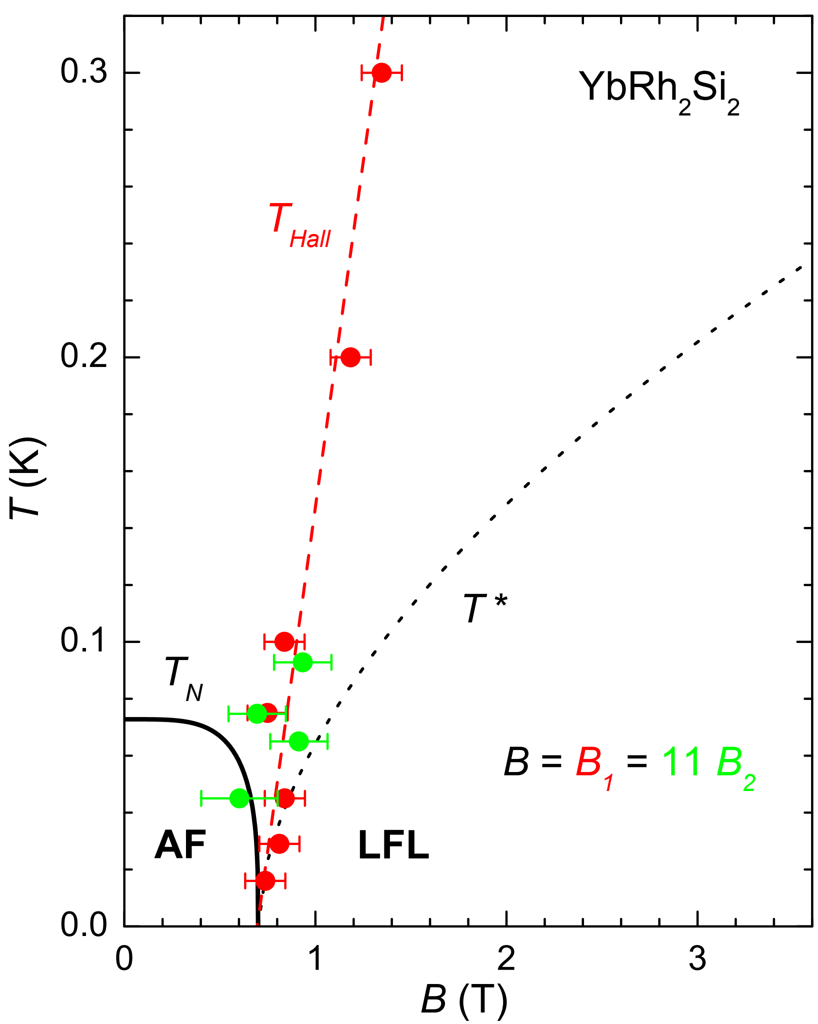
(Lee et al., PRL 92 (2004) 187201)

Hall effect at field-induced induced QCP of $YbRh_2Si_2$:

Hall coefficient vs field



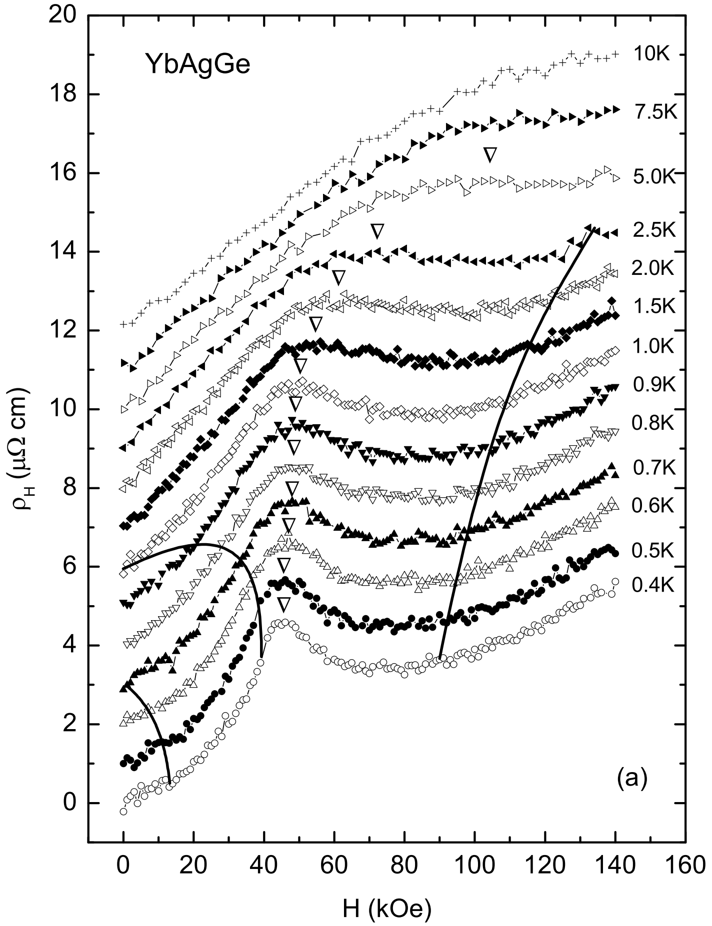
Phase diagram



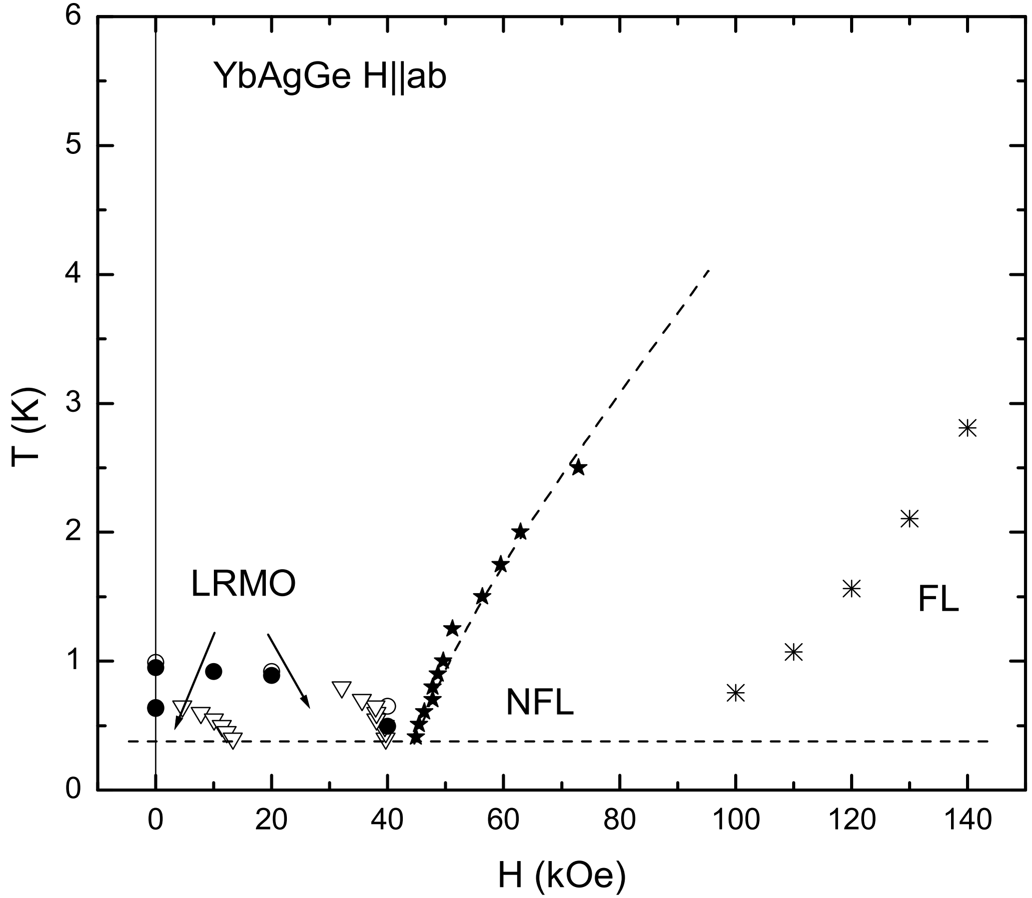
(Paschen et al., Nature 432 (2004) 881)

Hall effect in YbAgGe:

Hall resistivity vs field



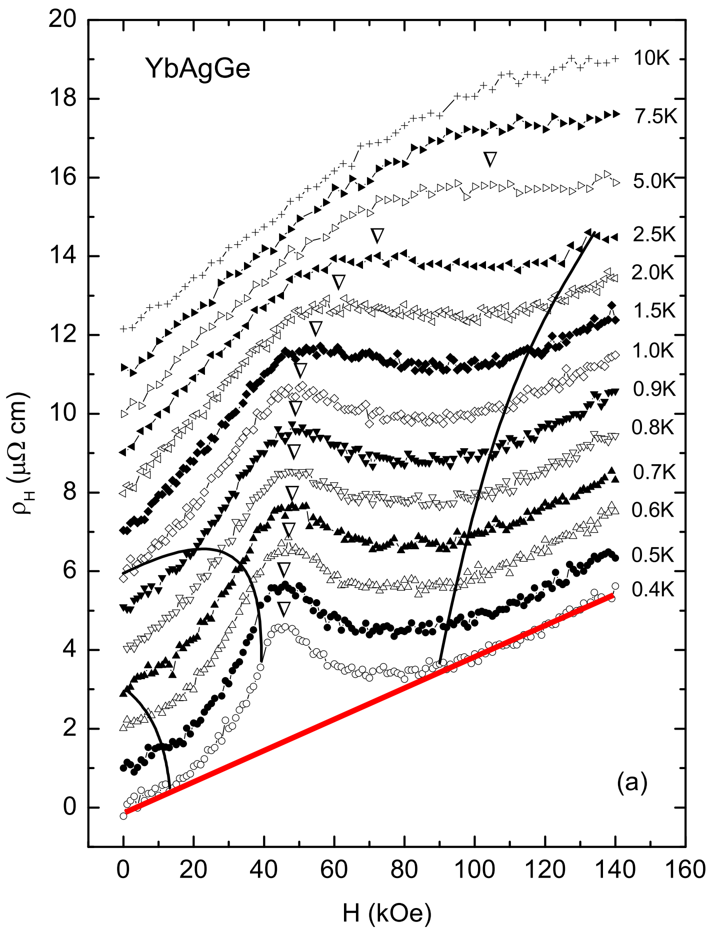
Phase diagram



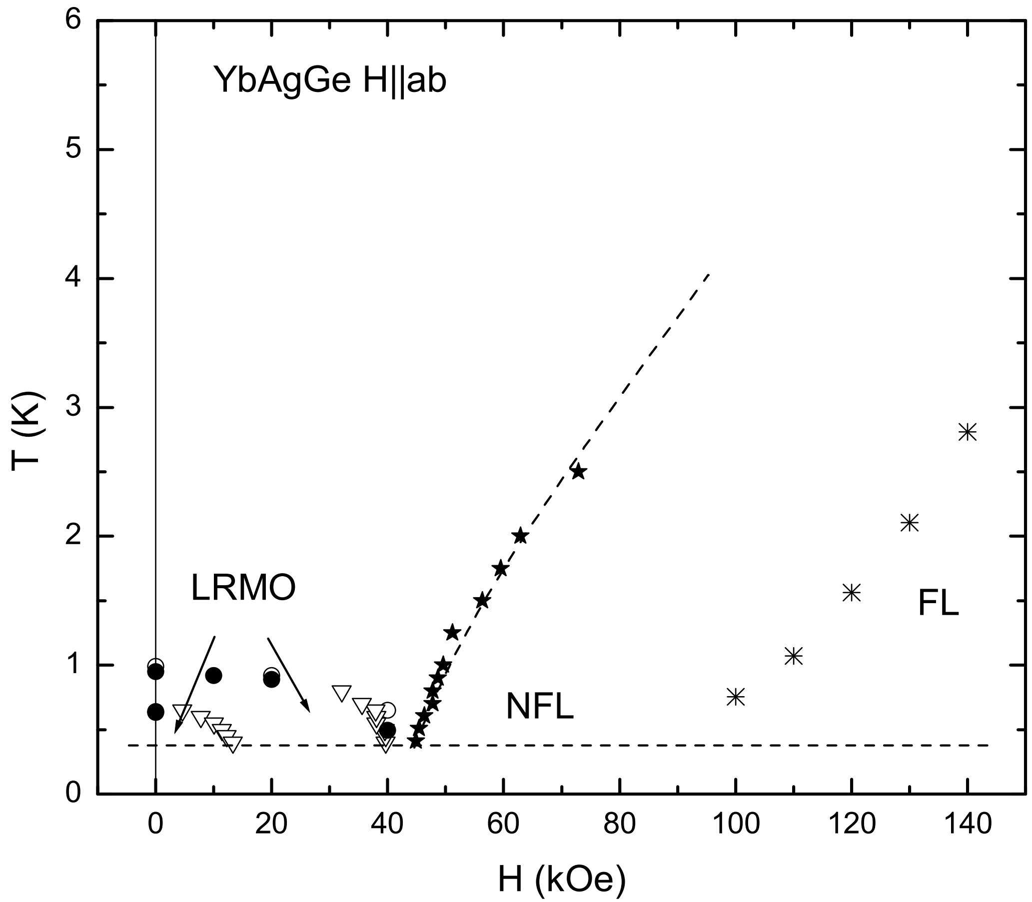
(Bud'ko et al., PRB 71 (2005) 054408)

Hall effect in YbAgGe:

Hall resistivity vs field



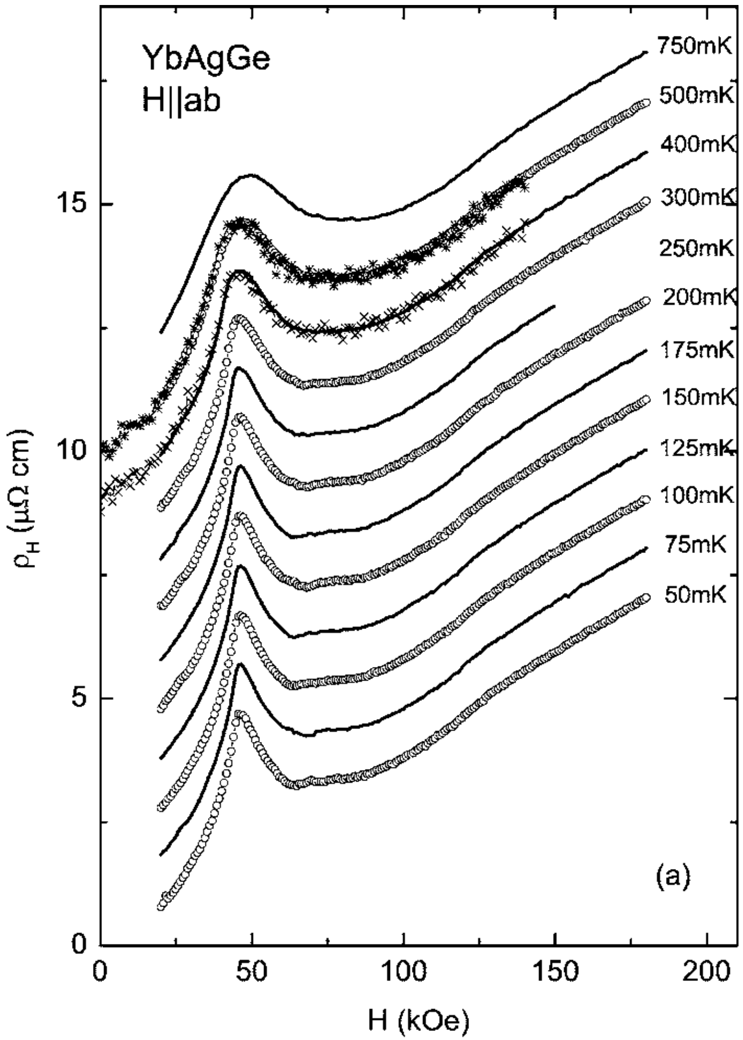
Phase diagram



(Bud'ko et al., PRB 71 (2005) 054408)

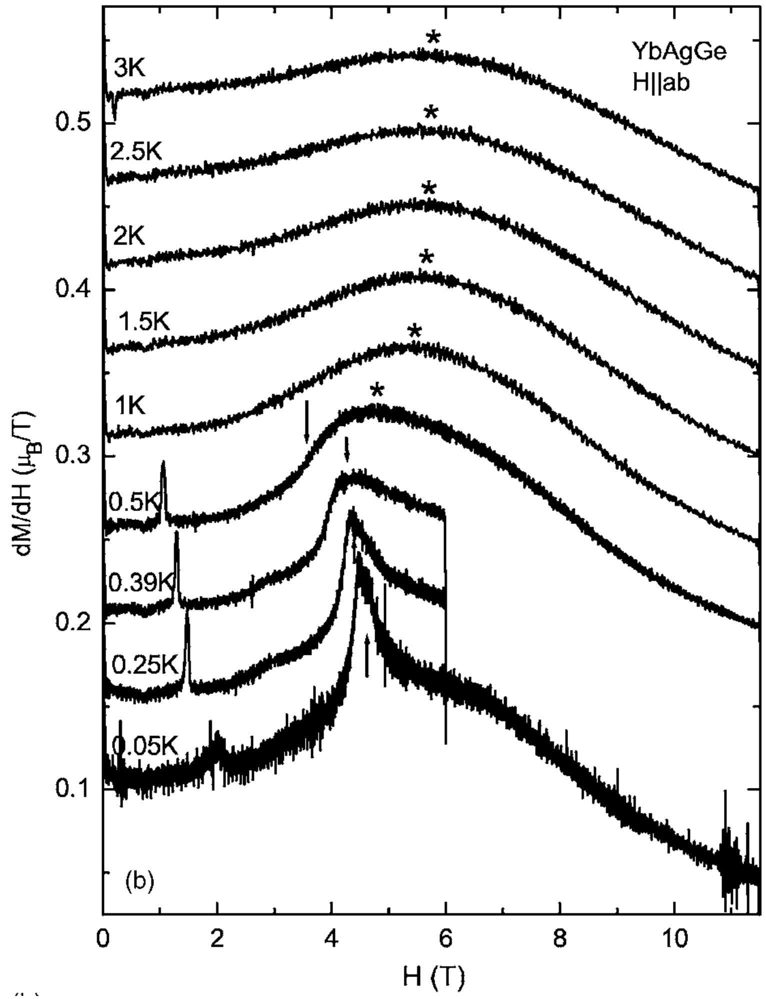
... Hall effect in YbAgGe:

Hall resistivity vs field



(Bud'ko et al., PRB 72 (2005) 172413)

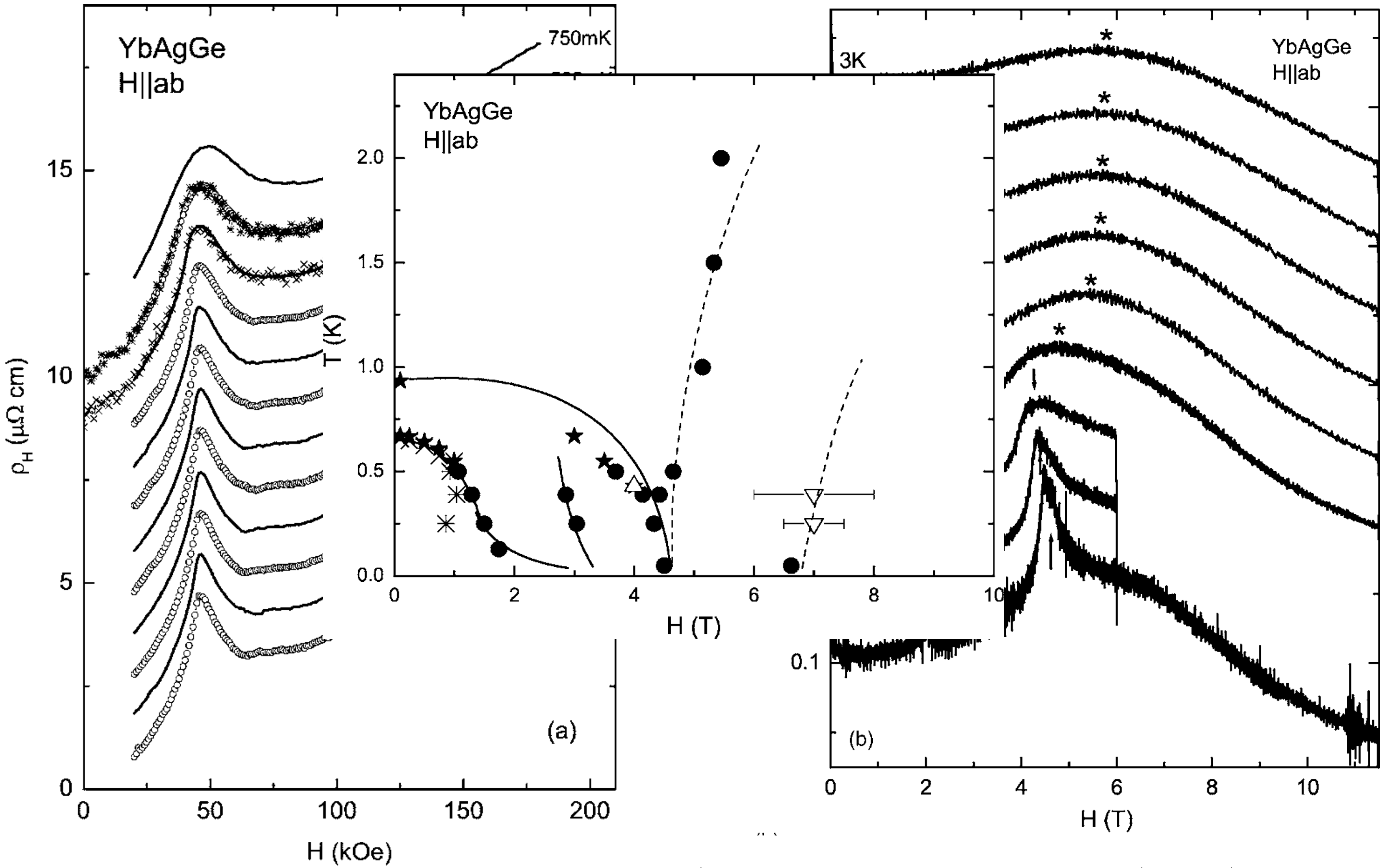
dM/dH vs field



(Tokiwa et al., PRB 73 (2006) 094435)

... Hall effect in YbAgGe:

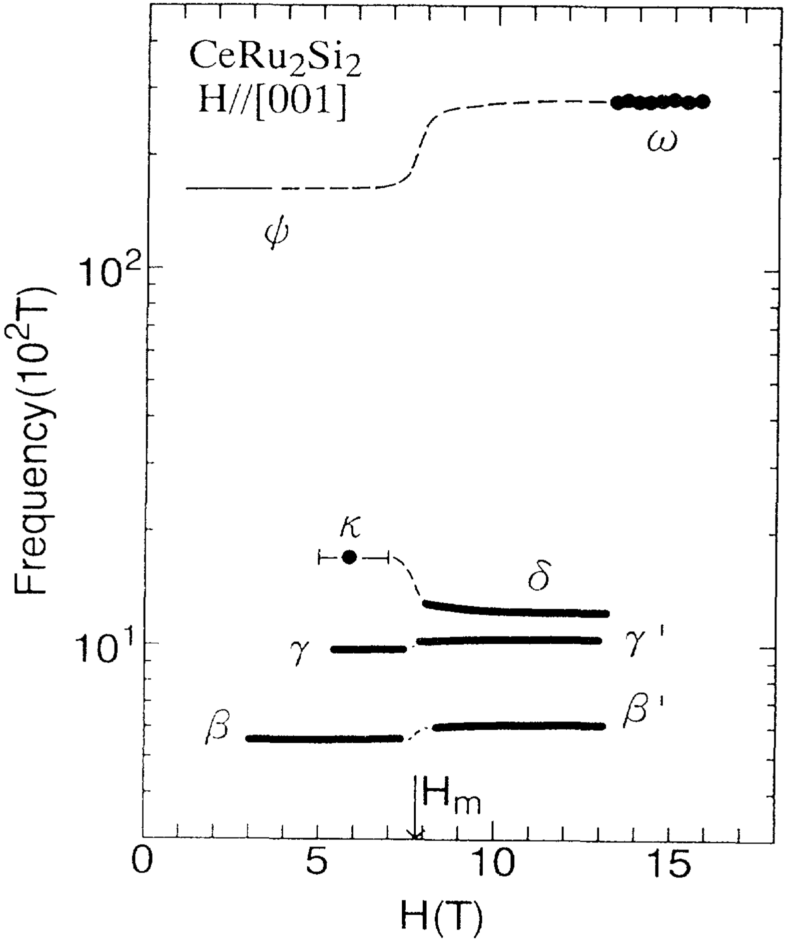
Hall resistivity vs field dM/dH **vs field**



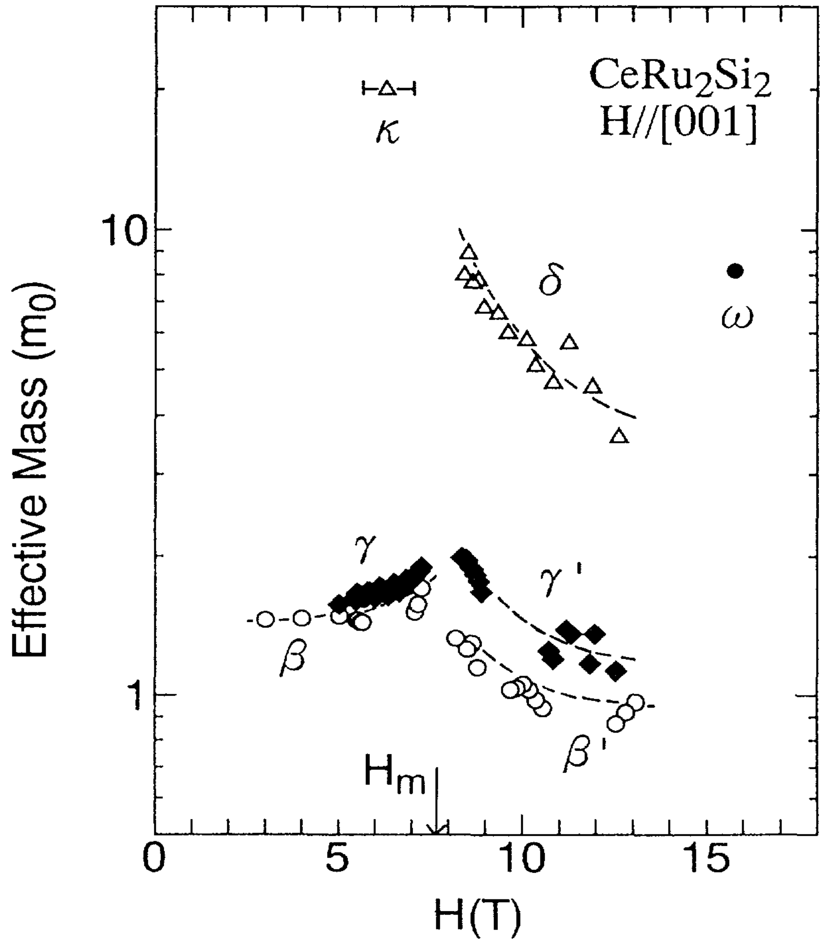
(Bud'ko et al., PRB 72 (2005) 172413) (Tokiwa et al., PRB 73 (2006) 094435)

De Haas - van Alphen studies: $CeRu_2Si_2$

dHvA frequency vs field



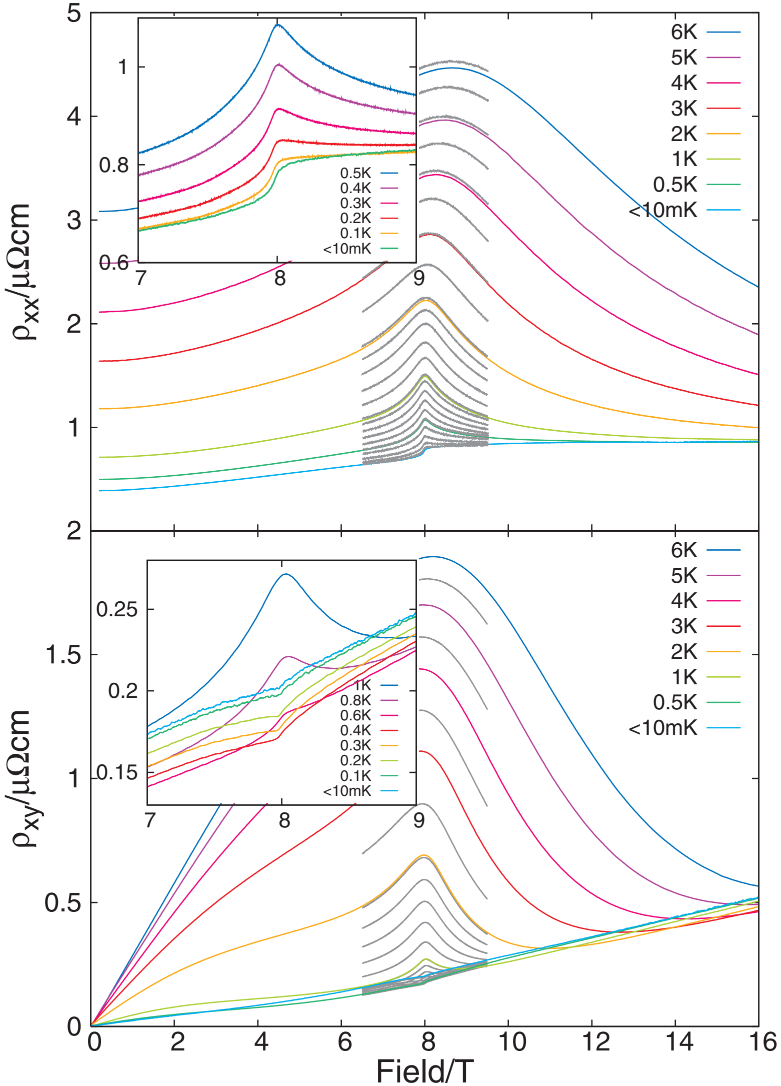
Effective mass vs field



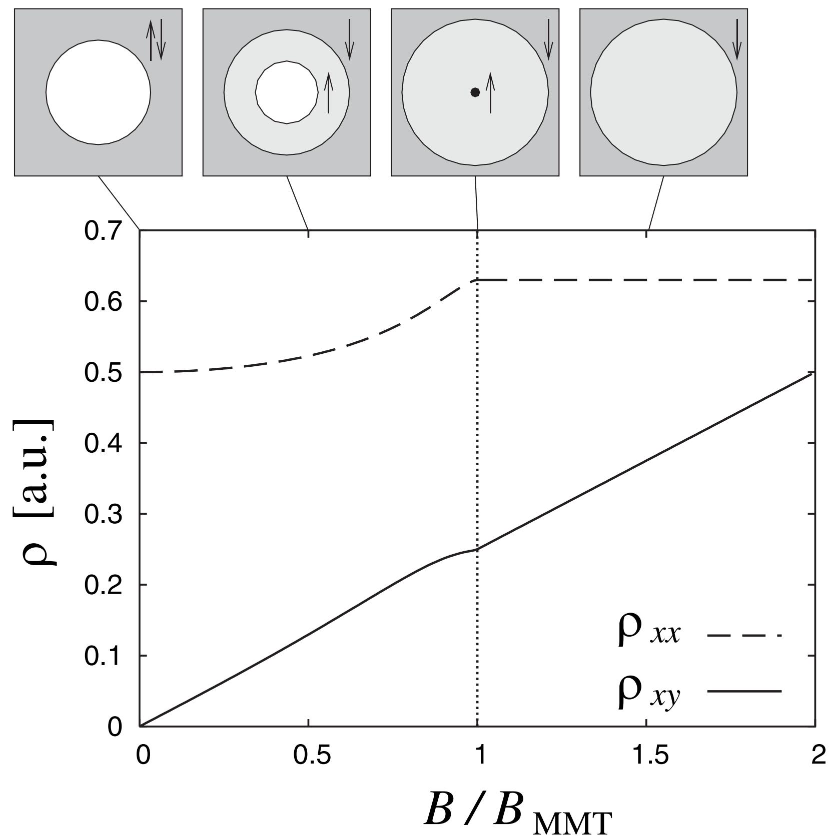
(Aoki et al., PRL 71 (1993) 2110)

Hall effect measurements on $CeRu_2Si_2$

ρ_{xx} and ρ_{xy} vs field



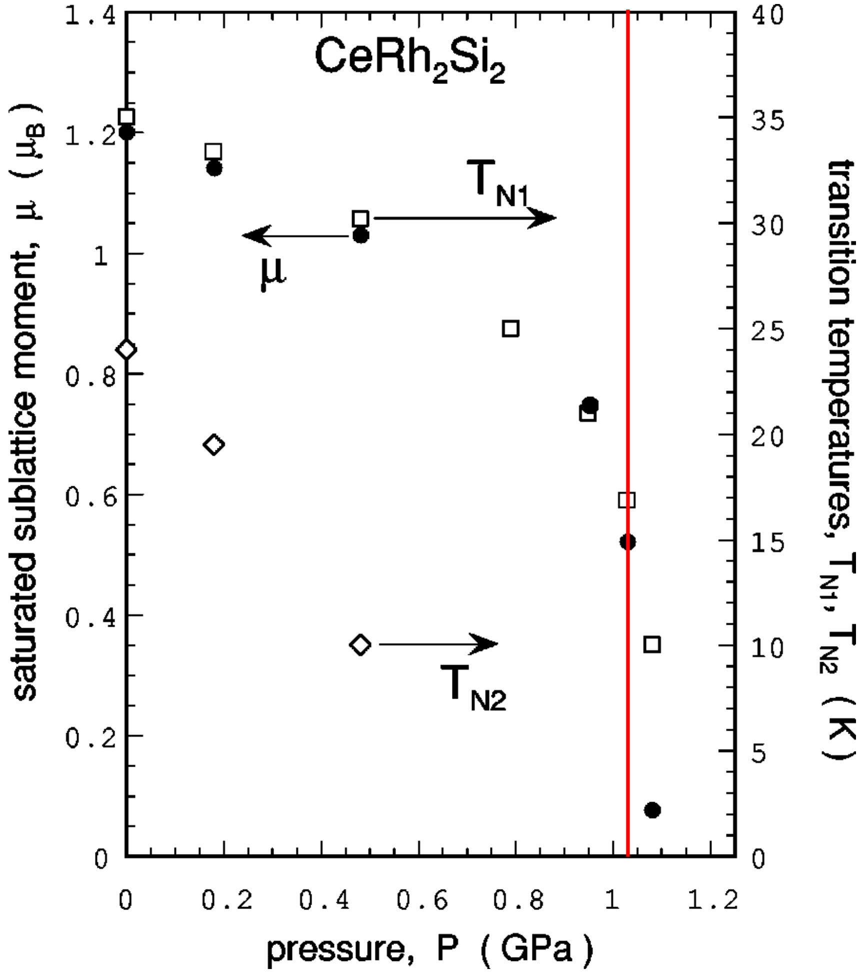
ρ_{xx} and ρ_{xy} for model system



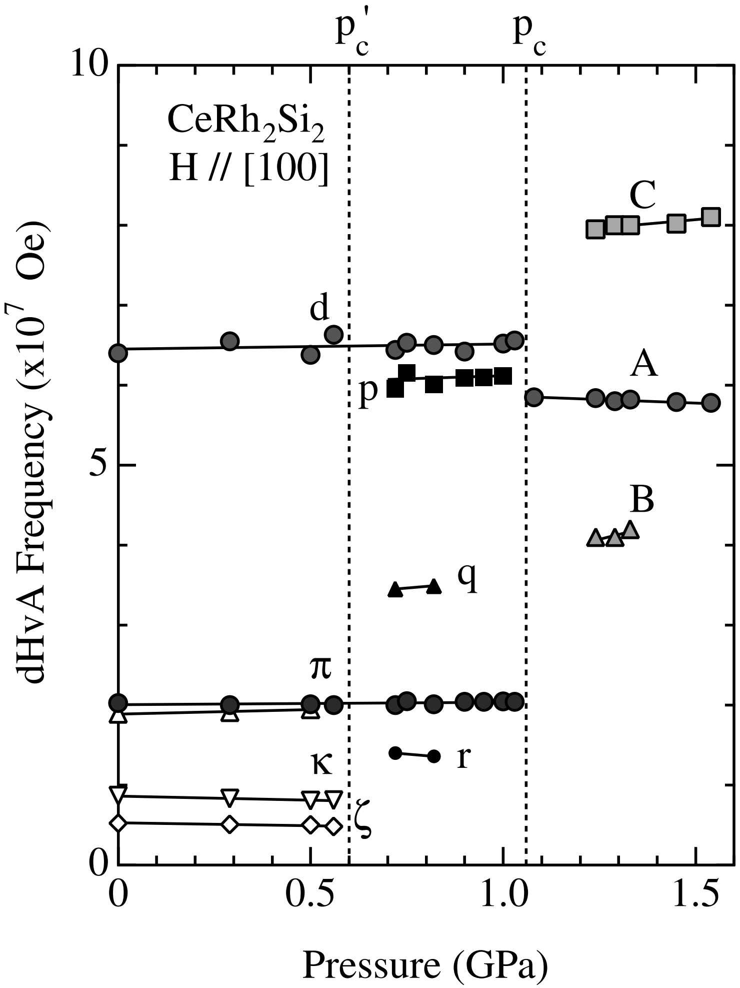
(Daou et al., PRL 96 (2006) 026401)

De Haas - van Alphen studies: $CeRh_2Si_2$

Neutron diffraction



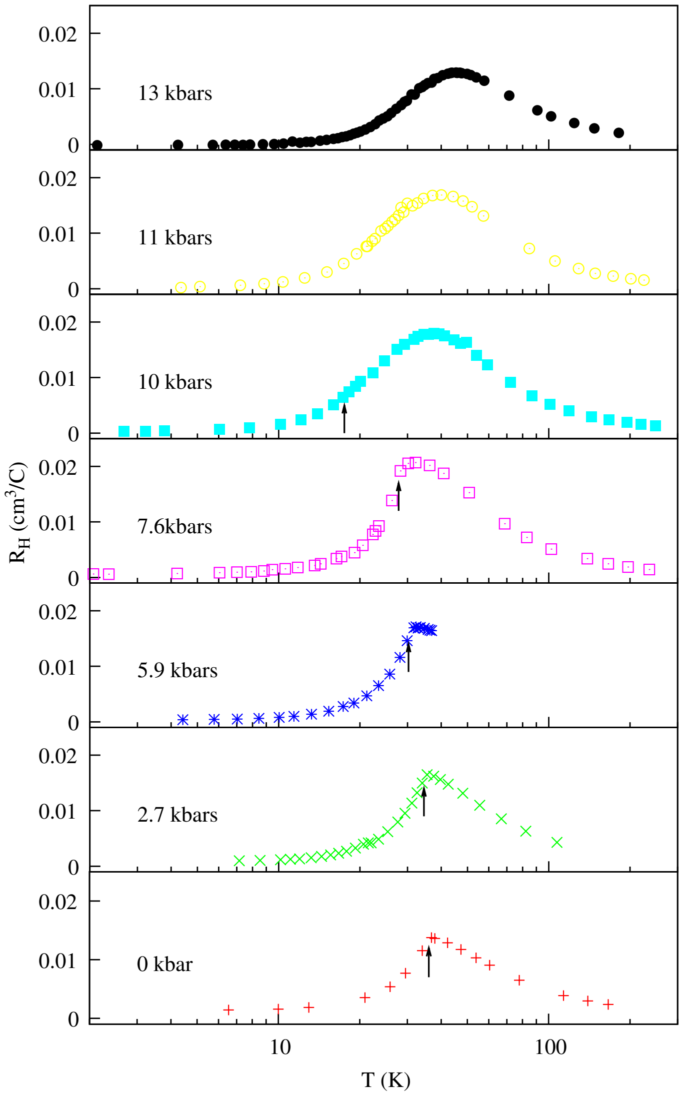
dHvA frequency



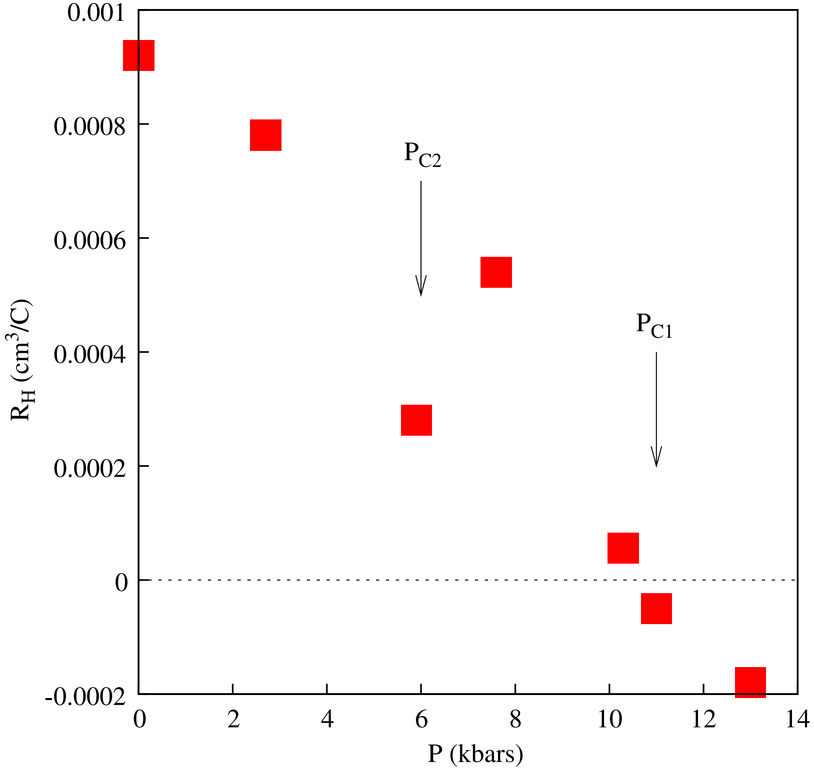
(Kawarazaki et al., PRB 61 (2000) 4167) (Araki et al., JPCS 63 (2002) 1133)

Hall effect measurements on $CeRh_2Si_2$

Hall coefficient vs temperature



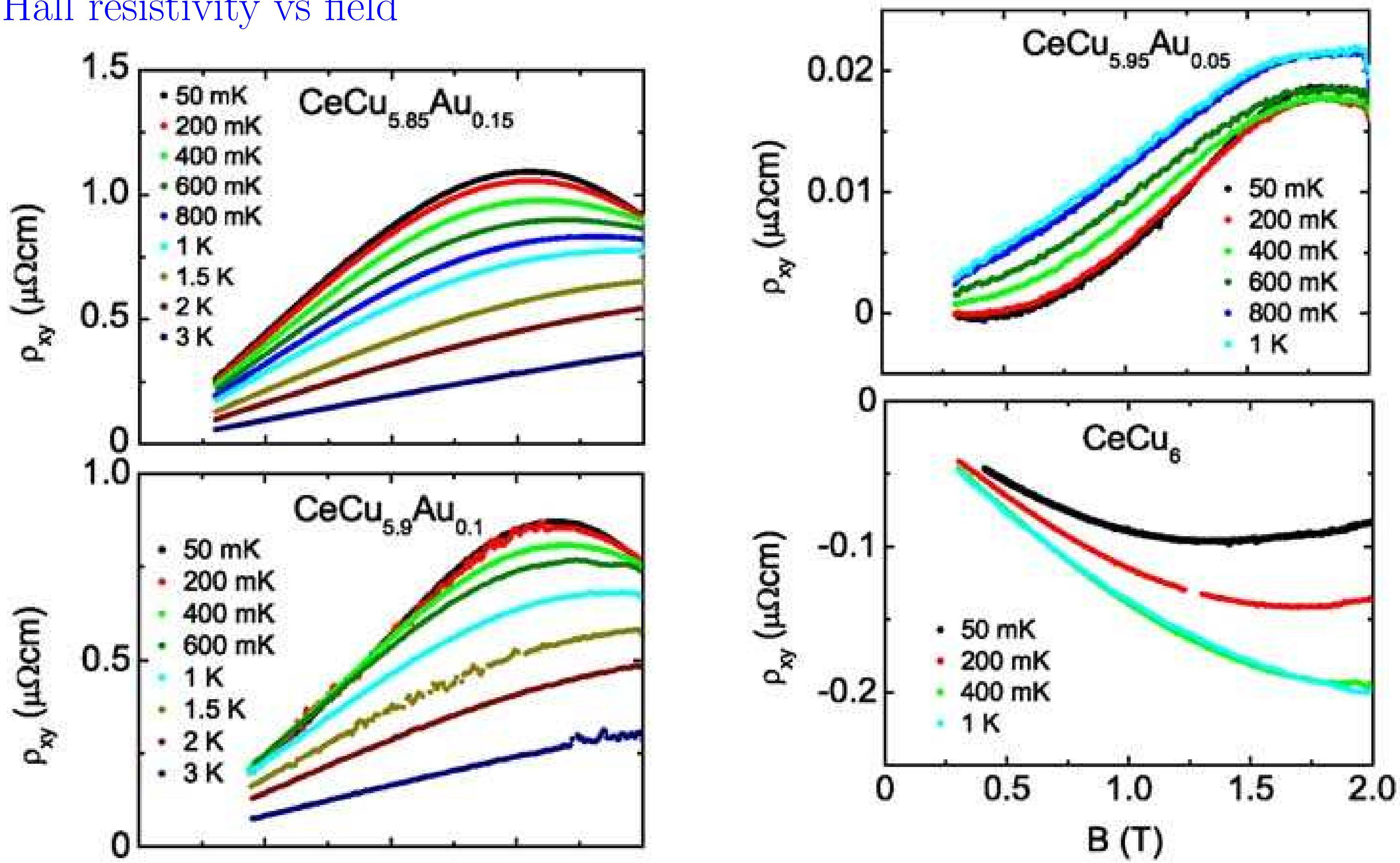
Residual Hall coefficient vs pressure



(Boursier et al., Physica B 378-380 (2006) 76)

Hall effect measurements on $CeCu_{6-x}Au_x$

Hall resistivity vs field

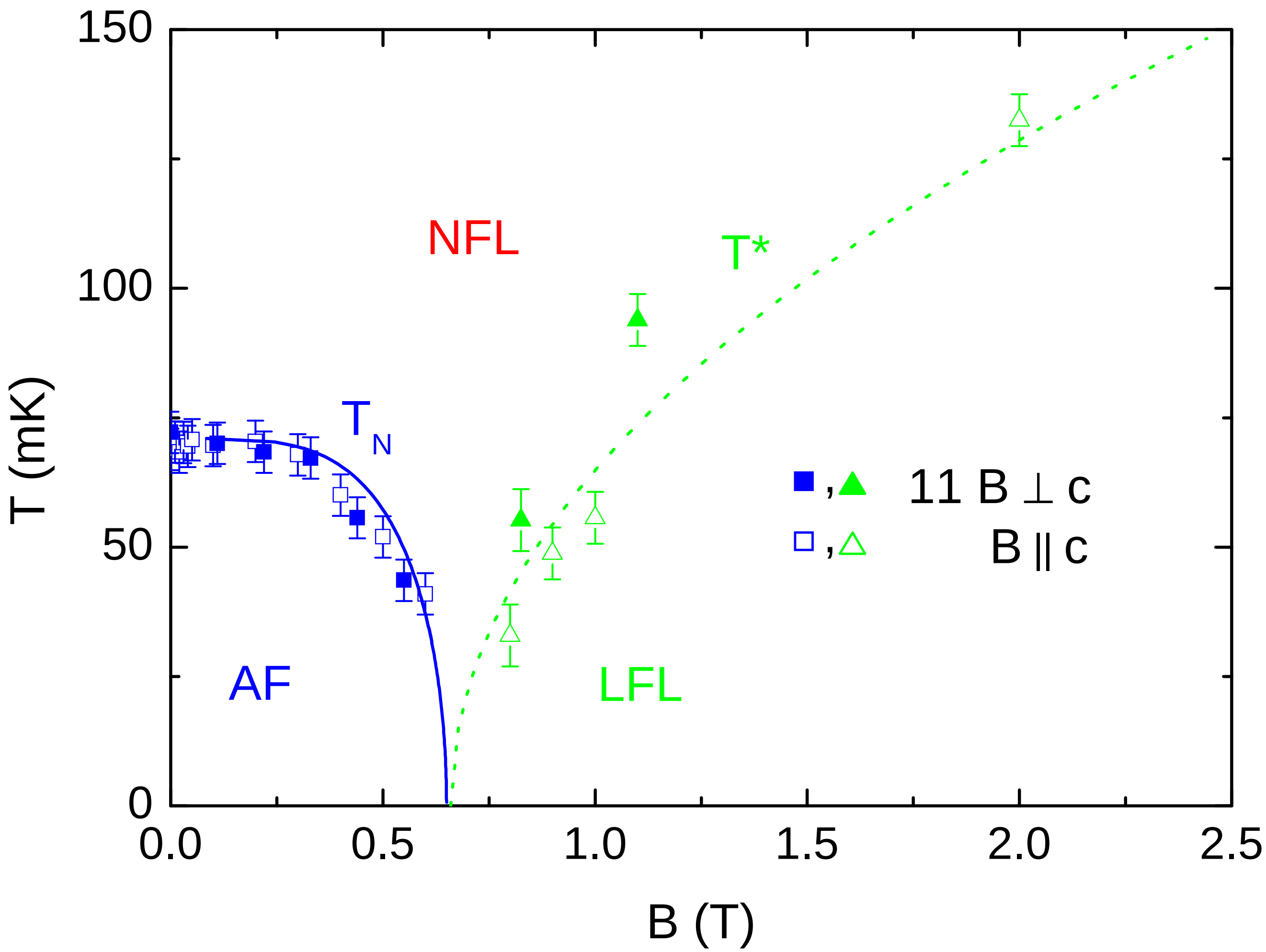


(v. Löhneysen et al., Physica B 378-380 (2006) 44)

Some news on $YbRh_2Si_2$

$YbRh_2Si_2$

Phase diagram



Single crystals:

$RRR \approx 60$

$\rho_0 \approx 1\ \mu\Omega\text{cm}$

$T_K \approx 25$ K

$T_N = 70$ mK

$\mu \approx 2 \times 10s^{-3} \mu_B/\text{Yb}$

$B_{1c}(\parallel c) \approx 0.7$ T

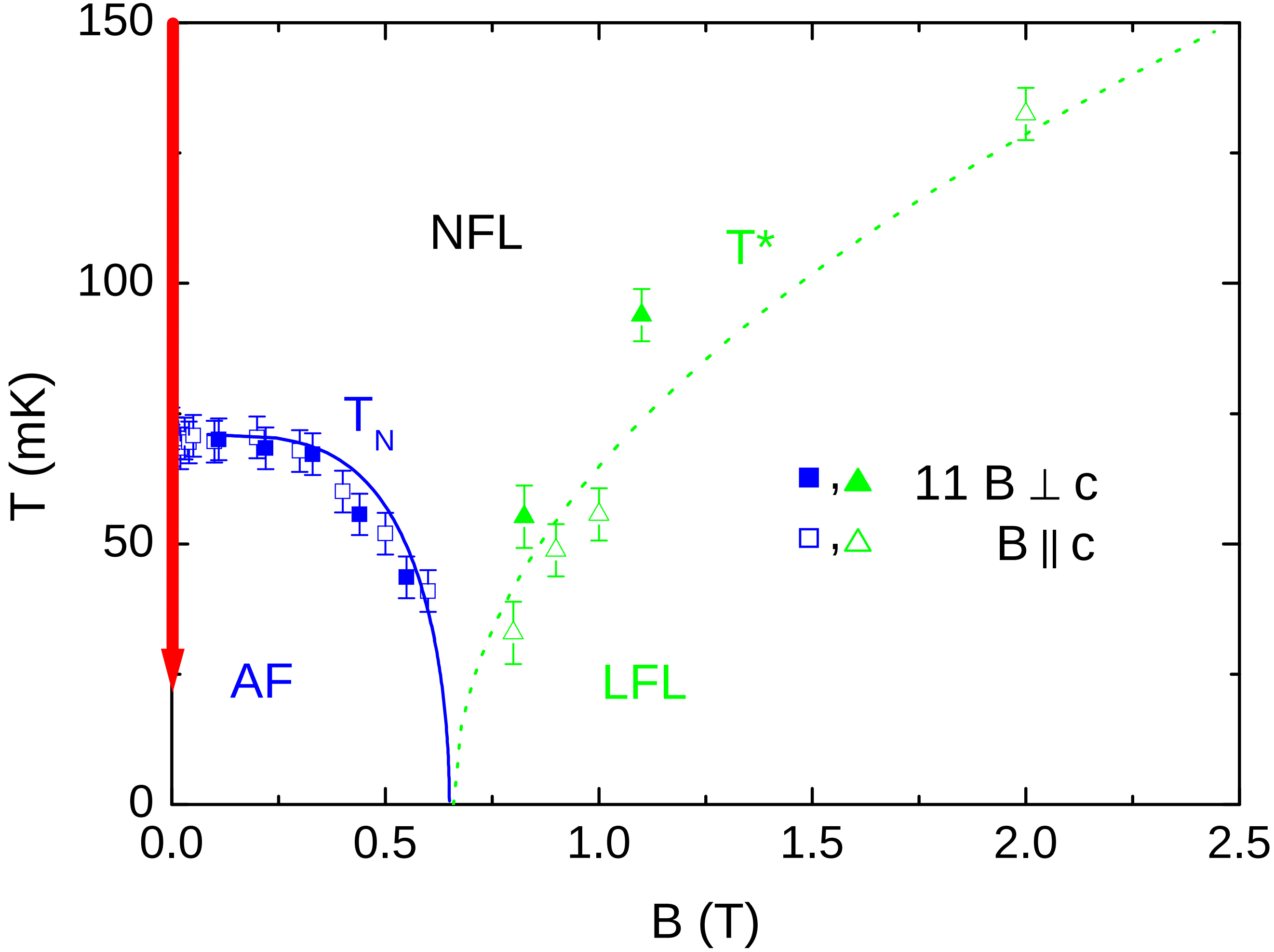
$B_{2c}(\perp c) \approx 0.06$ T

$B_{1c} \approx 11 B_{2c}$

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

Hall effect in $YbRh_2Si_2$

Initial Hall coefficient vs T



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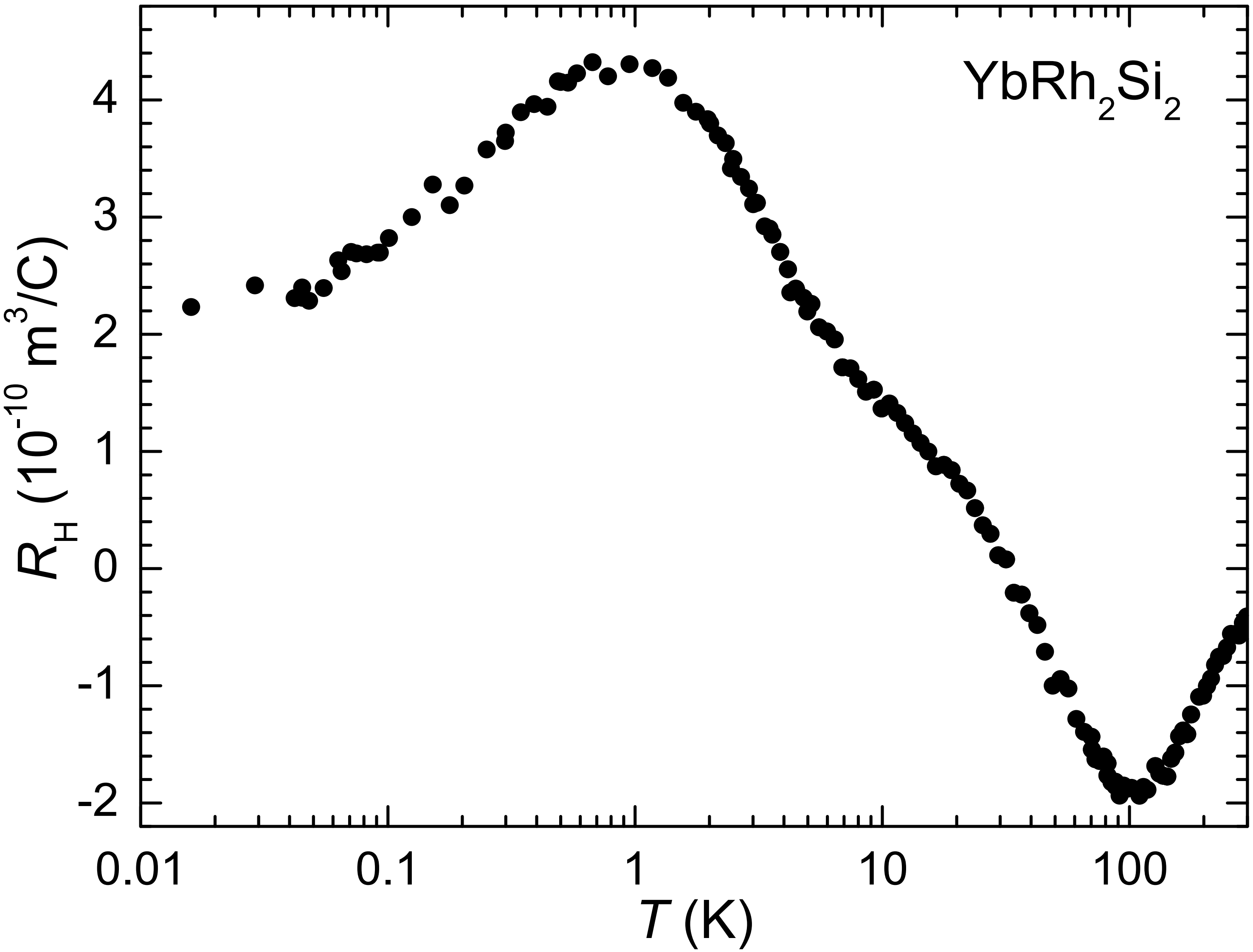
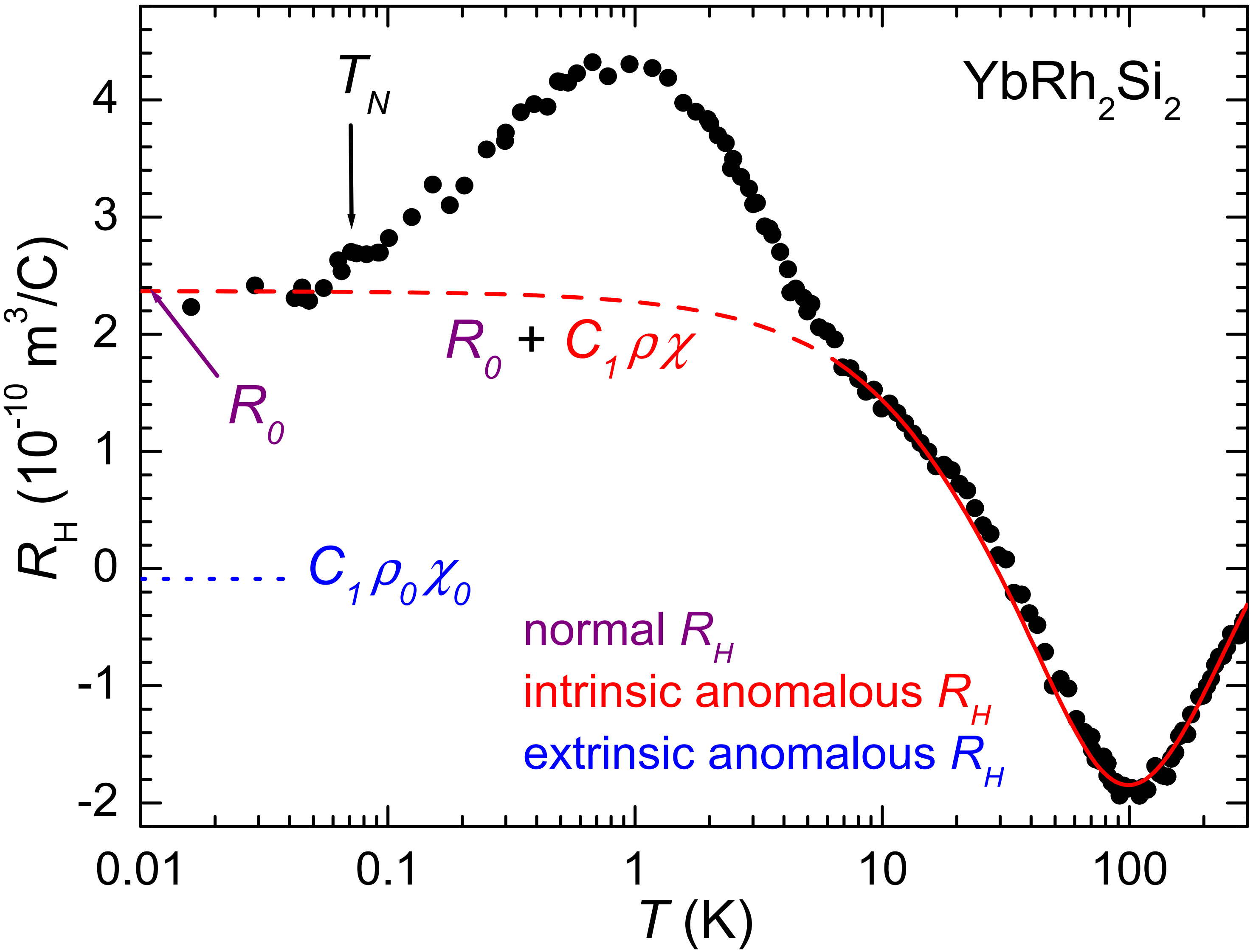
(Gegenwart et al., PRL 89 (2002) 056402)

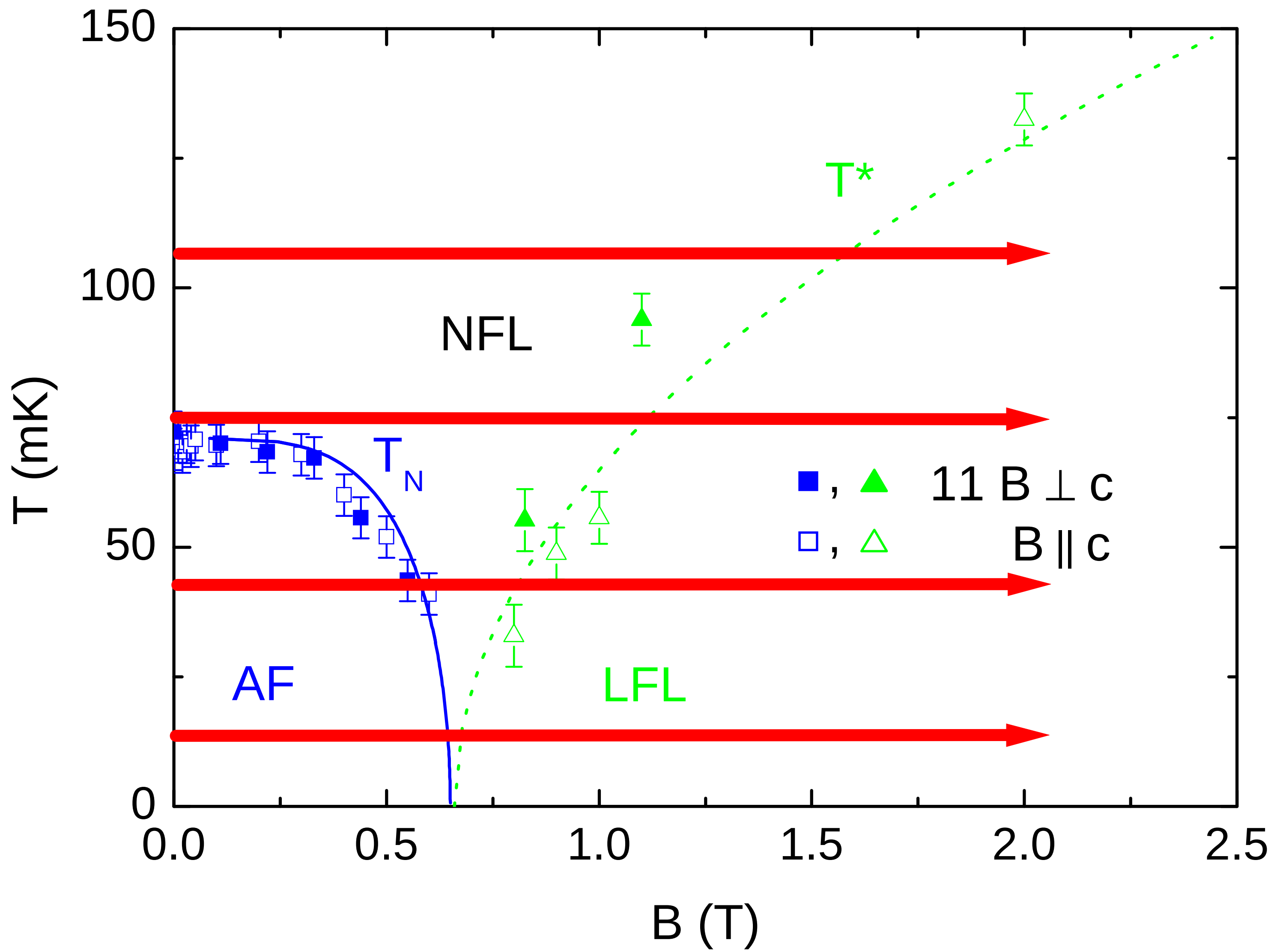
Initial Hall coefficient vs T ($R_H = d\rho_H/dB|_{B=0T}$)



Initial Hall coefficient vs T ($R_H = d\rho_H/dB|_{B=0T}$)

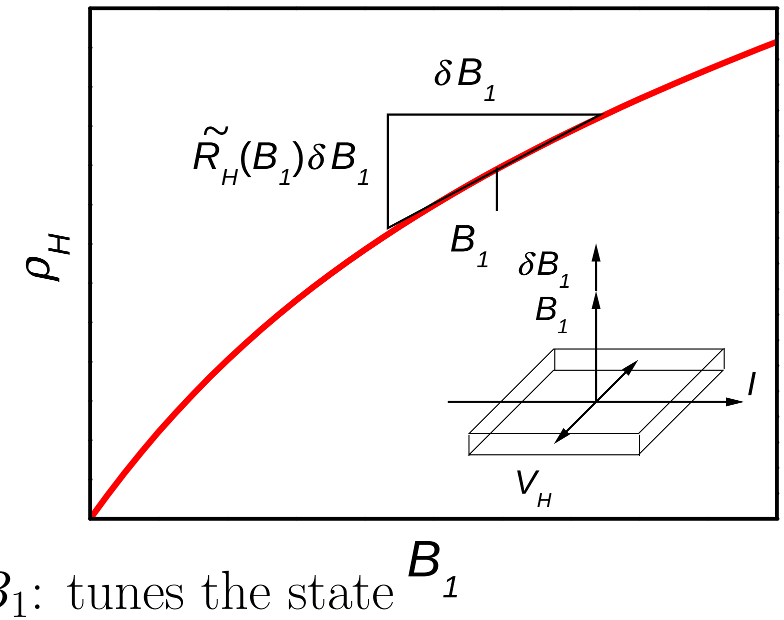


Hall measurements vs field



Single- and crossed-field experiments

Single-field: “transverse” tuning



B_1: tunes the state

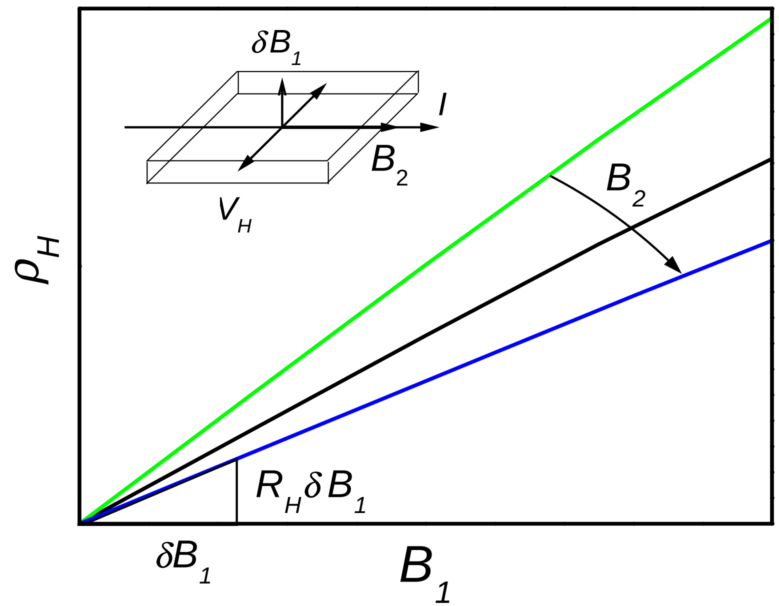
δB_1: probes the Hall response

Differential Hall coefficient:

$$\tilde{R}_H(B_1) = R_H(B_1) + \left[\frac{\partial \rho_H(B_1)}{\partial B_1}\right]_{\text{tuning}}$$

“orbital” “Zeeman”

Crossed-field: “longitudinal” tuning



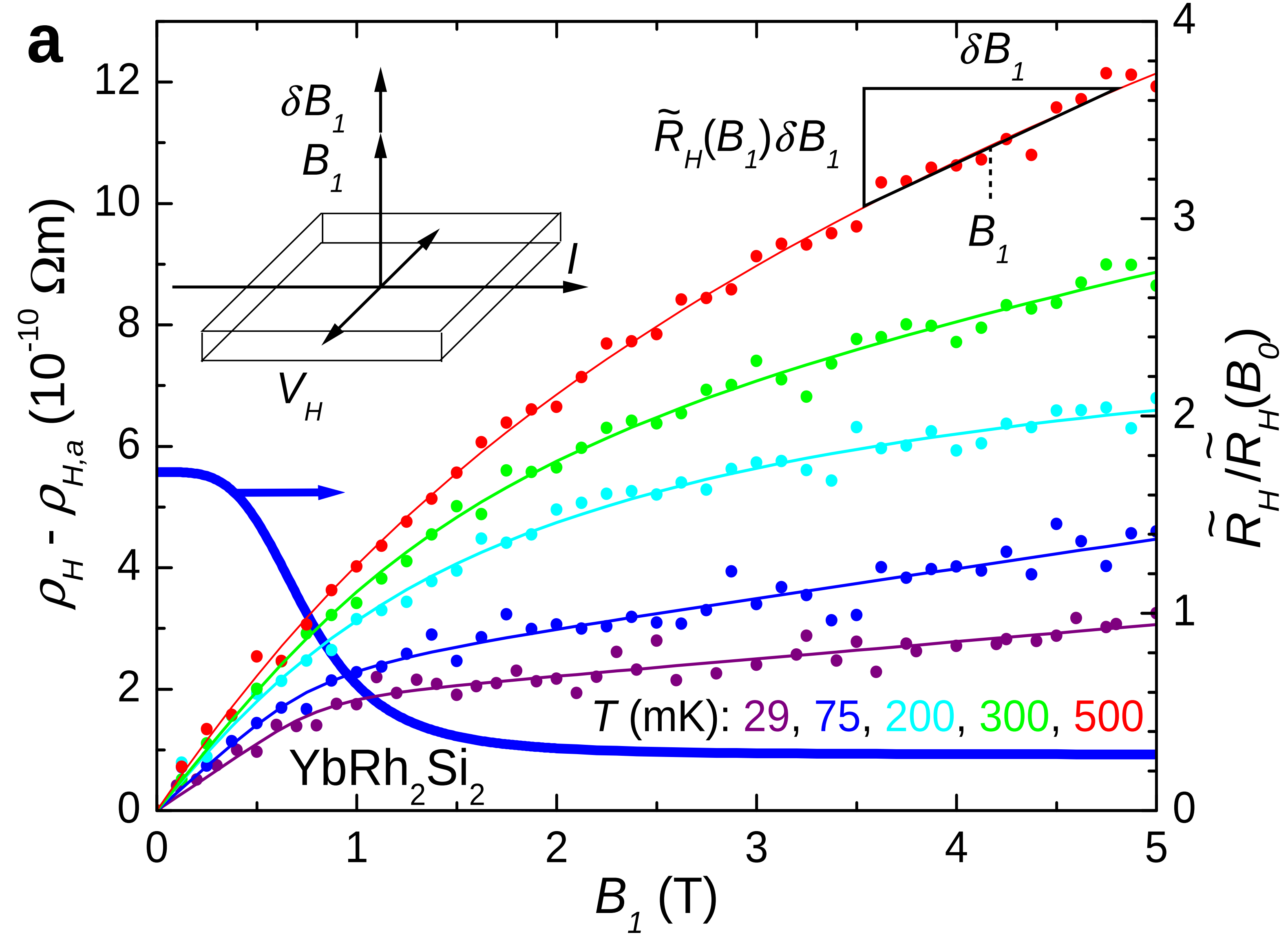
B_2: tunes the state

δB_1: probes the Hall response

Hall coefficient (linear response):

$$R_H(B_2) \equiv \lim_{B_1 \to 0} \frac{\rho_H(B_2, B_1)}{B_1}$$

Single-field experiment: Hall resistivity ρ_H vs field B_1



Fitting function

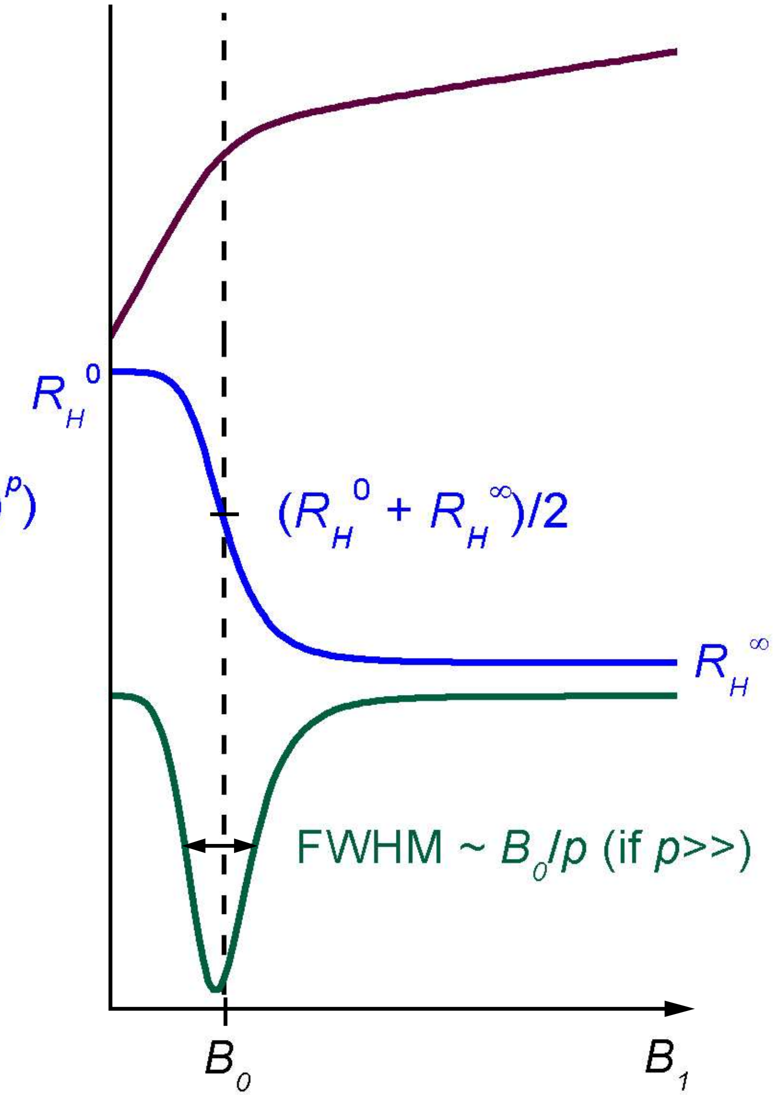
$$\int \tilde{R}_H(B)dB$$

↑

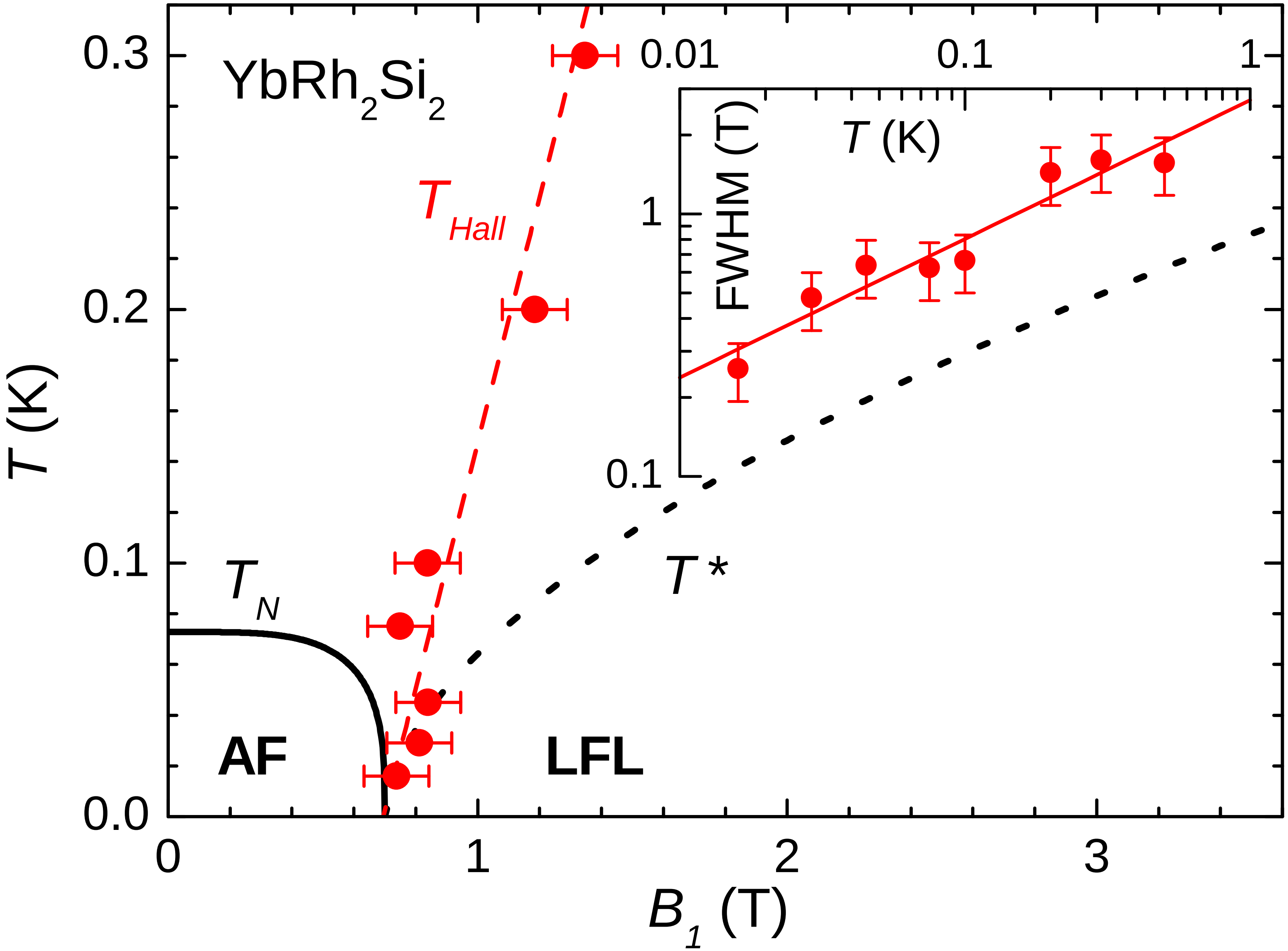
$$\tilde{R}_H(B_1) = R_H^{\infty} - (R_H^{\infty} - R_H^{0})/(1 + (B_1/B_0)^p)$$

↓

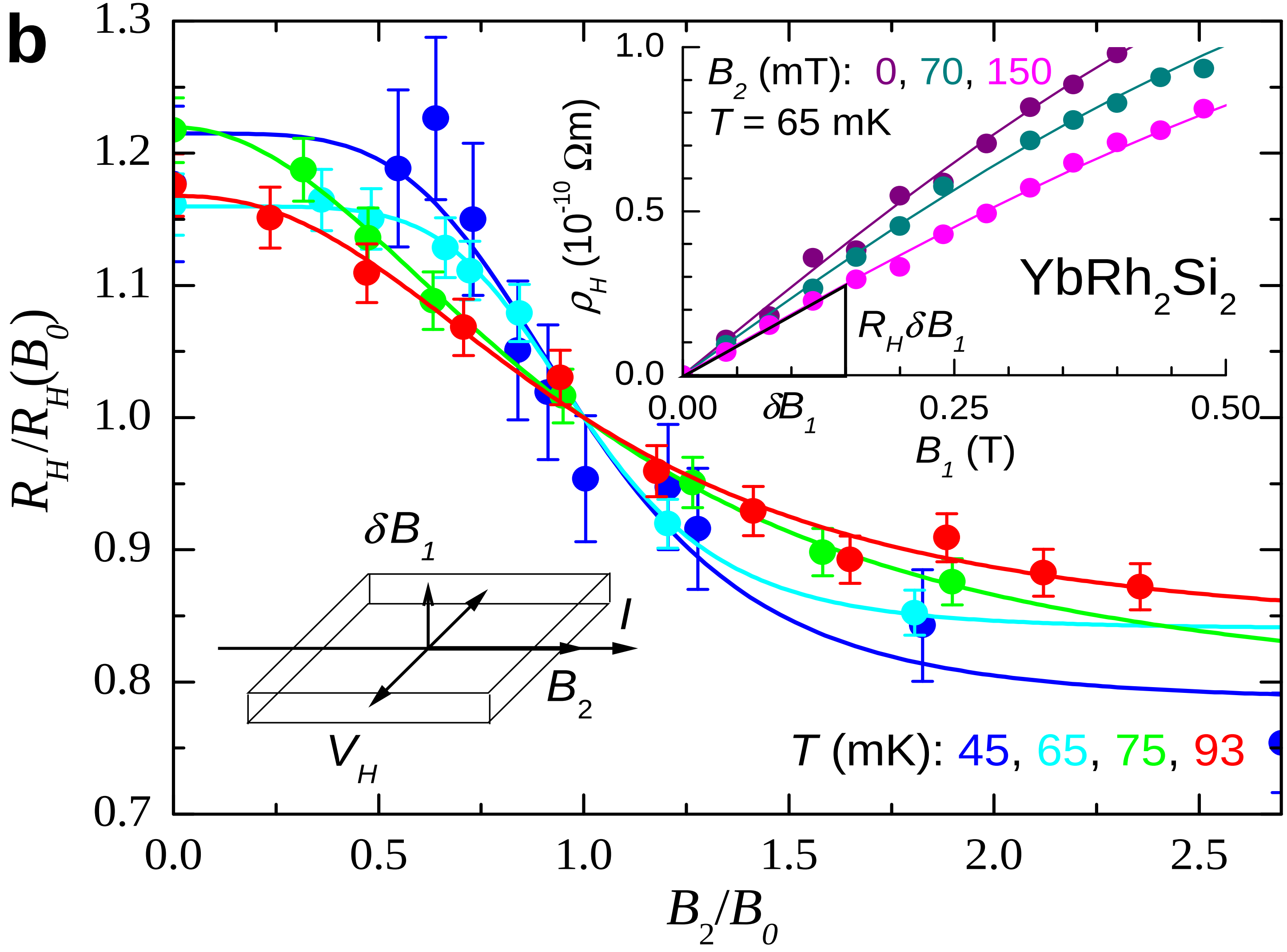
$$d\tilde{R}_H(B_1)/dB_1$$



Phase diagram

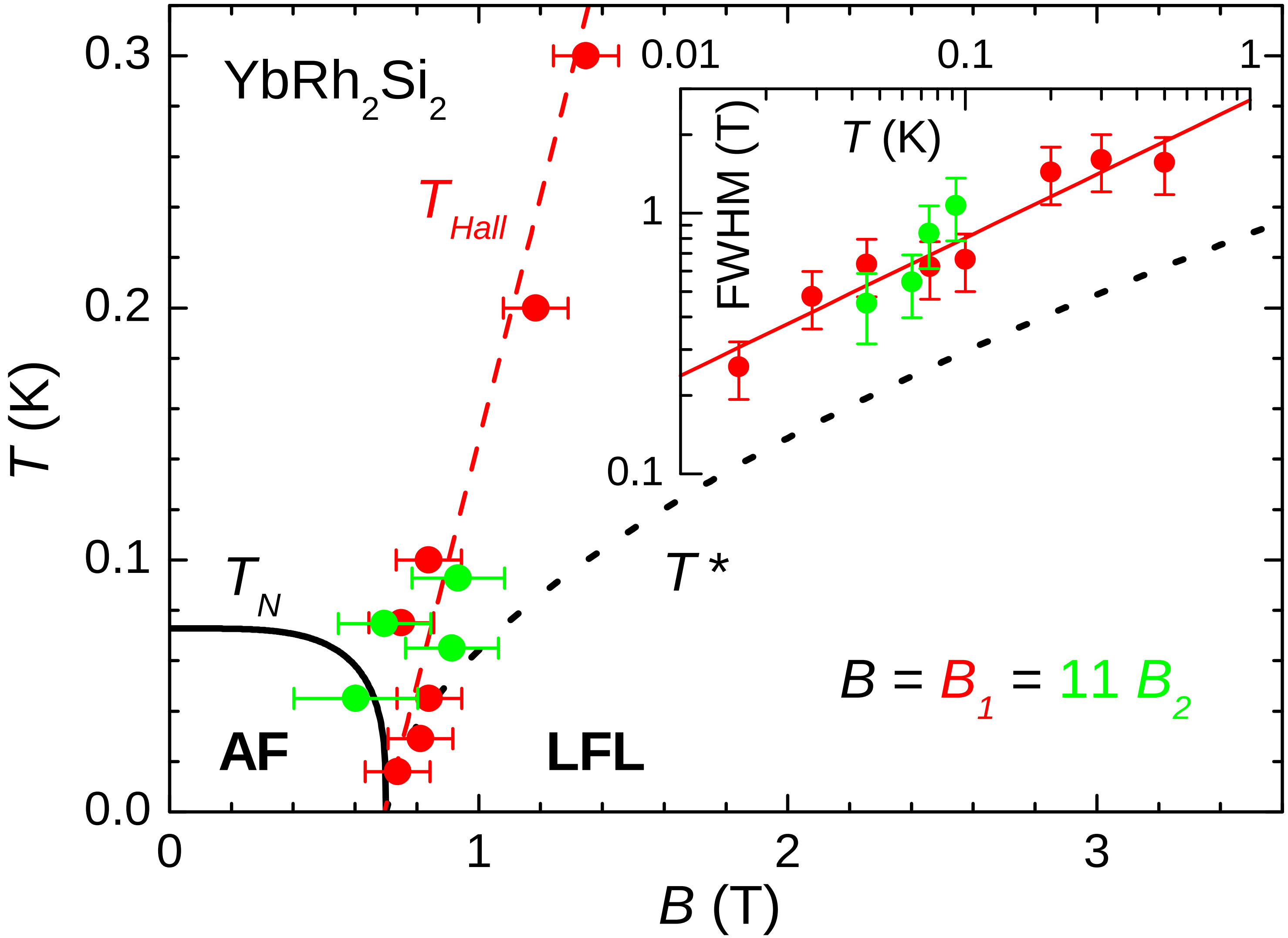


Crossed-field experiment: Hall resistivity vs B_1 at different B_2



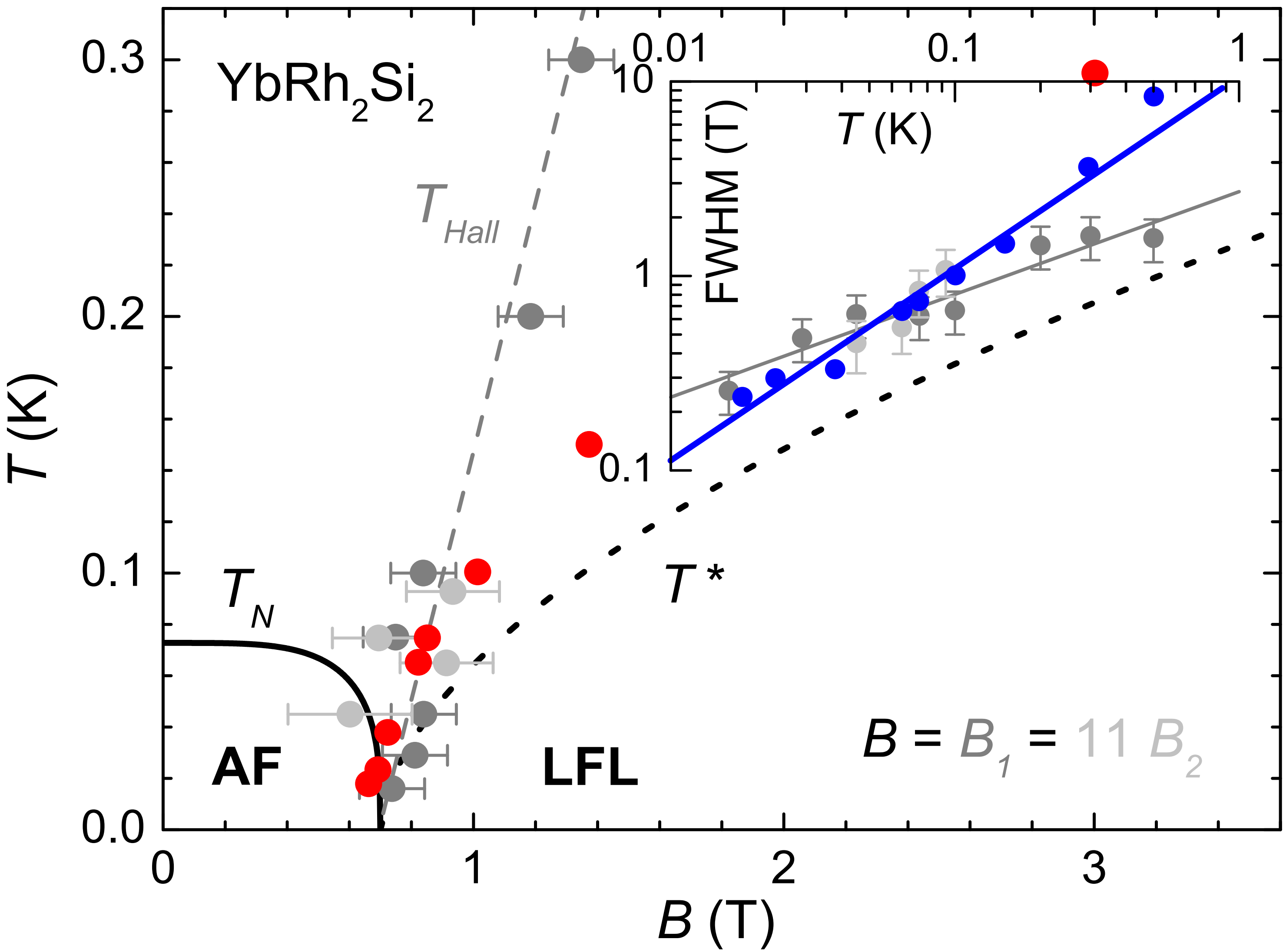
$\Delta R_H/R_H = 35\%$, $\Delta m << 0.002\mu_B$ (μSR): Huge effect!

Phase diagram



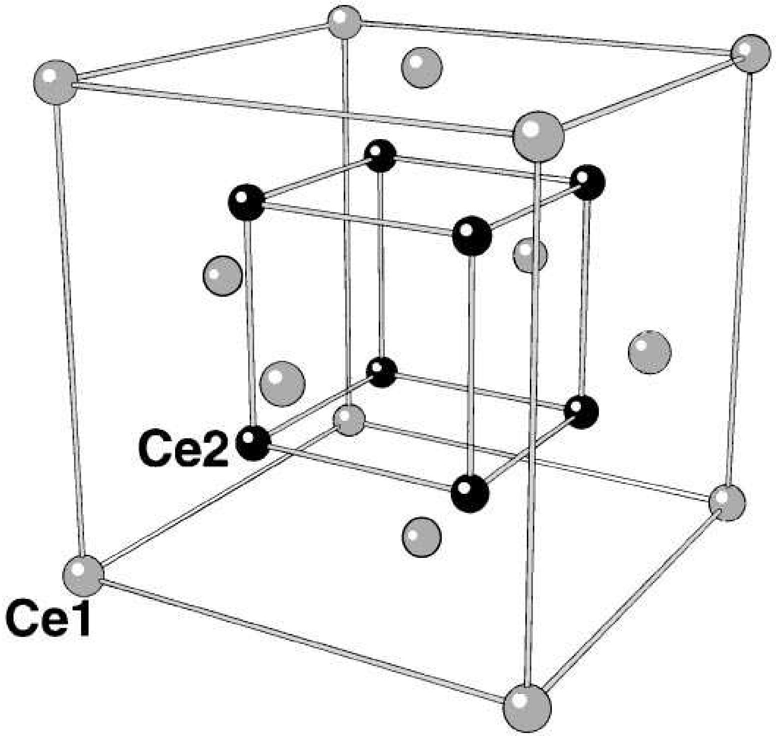
"Zeeman" term unimportant here

Phase diagram



"Zeeman" term unimportant at small T

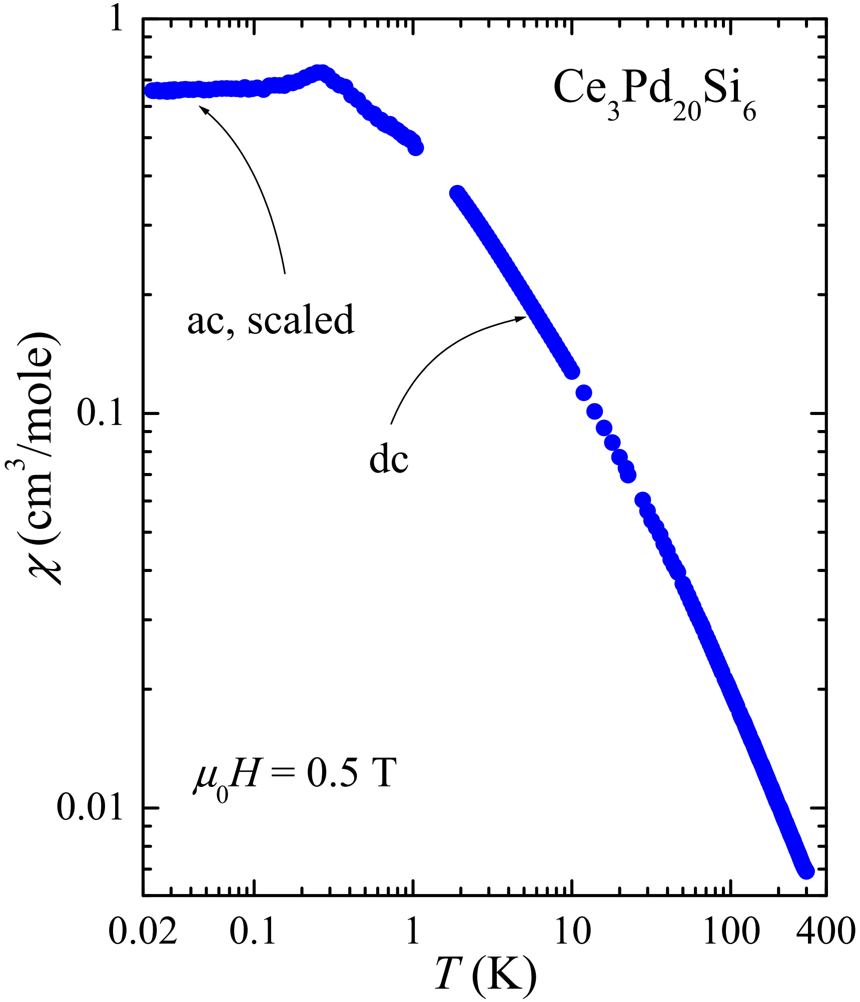
$Ce_3Pd_{20}Si_6$



cubic crystal structure
space group $Fm\bar{3}m$
Ce in 2 different polyhedra:
1: 6 Si, 12 Pd; 2: 16 Pd

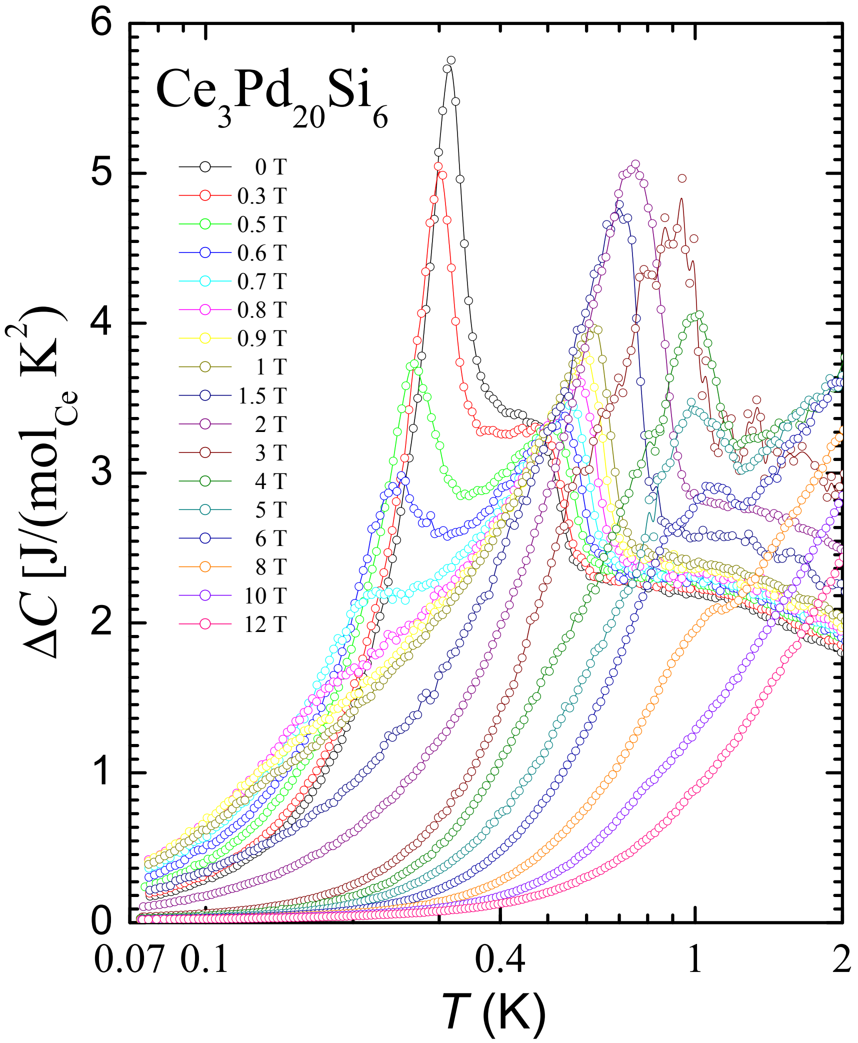
(Gribanov et al., JAC 204 (1994) L9)

Magnetic susceptibility

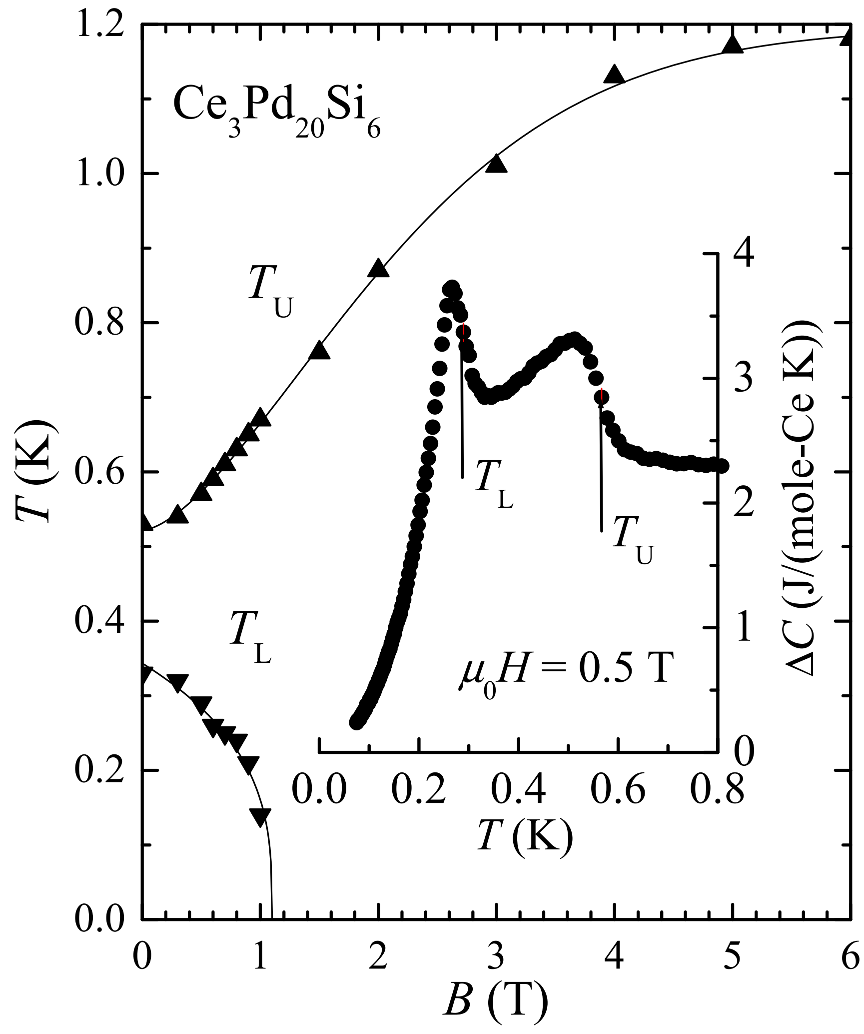


Similar to earlier findings of Kitagawa et al., PRB 53 (1996) 5101

Specific heat

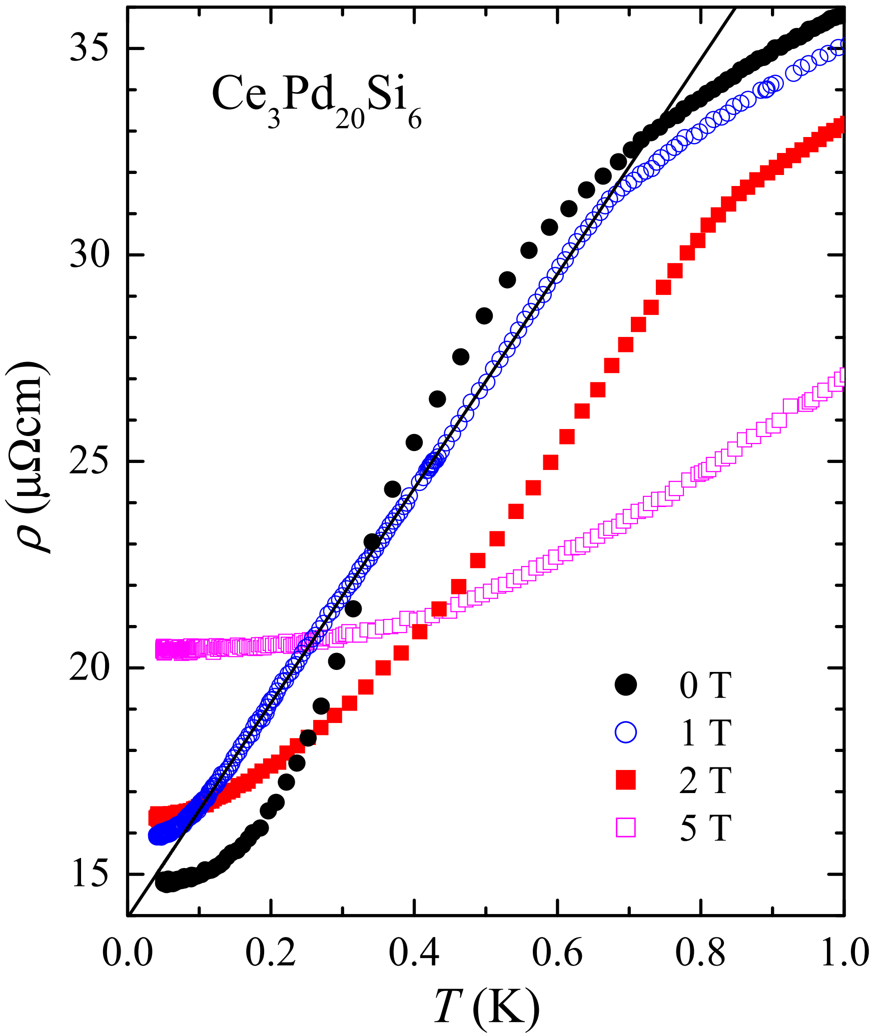


Phase diagram

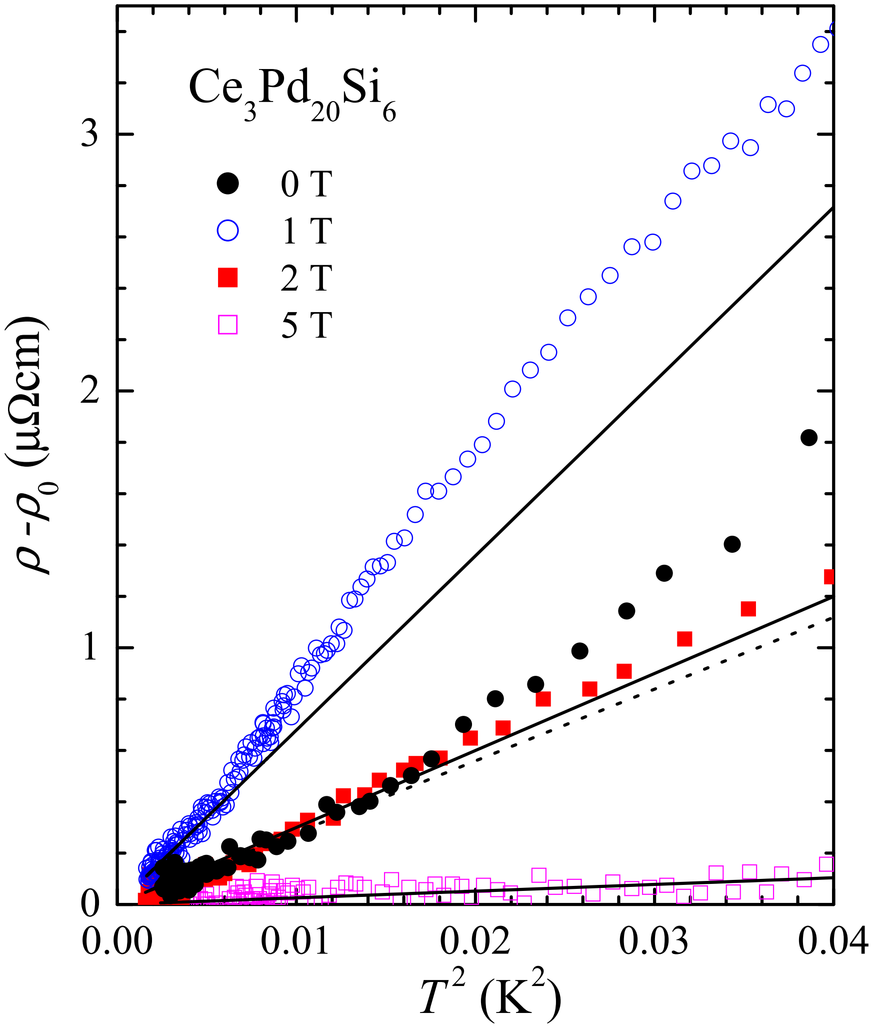


(Strydom et al., Proc. RHMF06)

Electrical resistivity vs T



Electrical resistivity vs T^2



(Paschen et al., submitted to JMMM, Proc. ICM06)

Conclusion

Review:

- Large number of Hall effect and dHvA experiments

$YbRh_2Si_2$:

- New crossed-field data confirm old ones
- Deviations of old single-field curves from new crossed-field curves above 150 mK do not change the main conclusions
- Crossover of $R_H(B_2)$ sharpens with lowering T and extrapolates to step at $T = 0$, in conflict with SDW QCP

$Ce_3Pd_{20}Si_6$:

- New field-induced quantum critical compound
- Large single crystals available!