Heavy Fermions and Quantum Phase Transitions: A Theorist's Perspective

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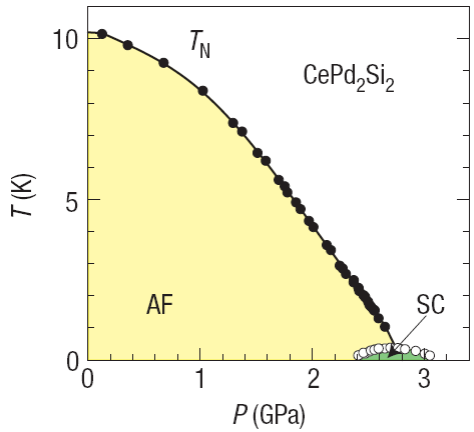
Rice University

Institute of Physics, CAS,
Beijing, Nov 10-12, 2012

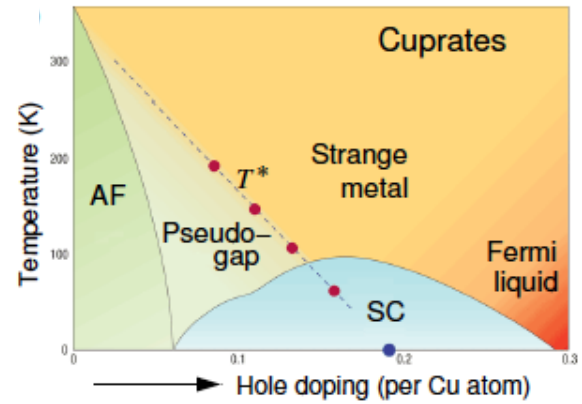
Superconductivity at the border of magnetism

Heavy fermions



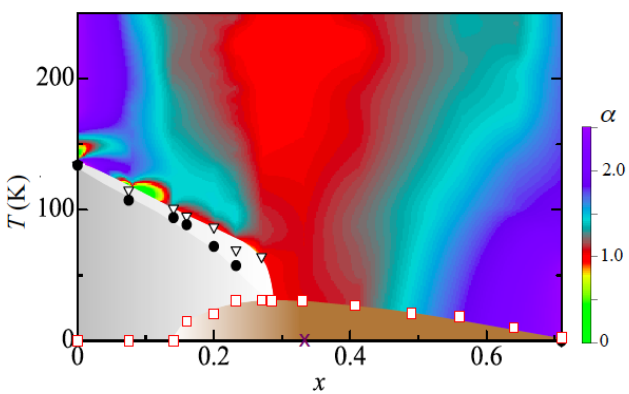
Mathur et al

Cuprates



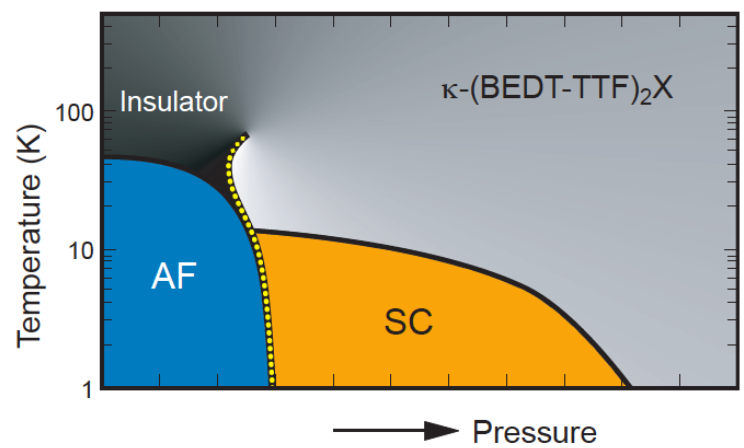
Broun

Pnictides



Kasahara et al

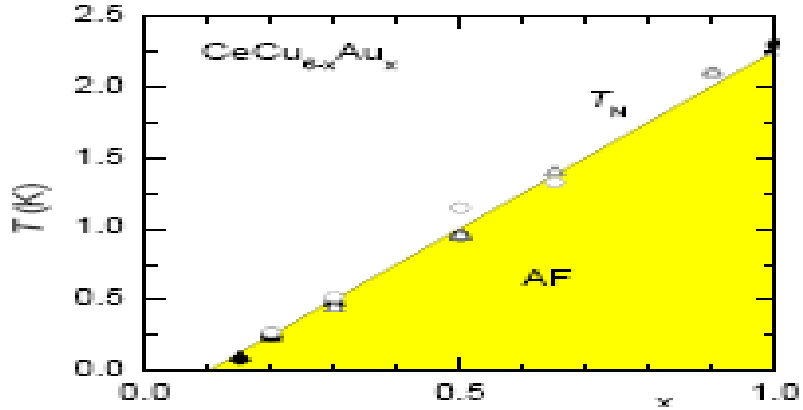
Organics



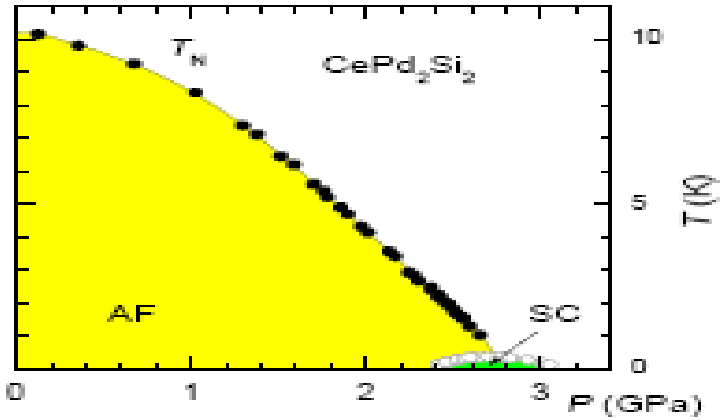
Faltermeier et al

Heavy fermion metals as prototype quantum critical points

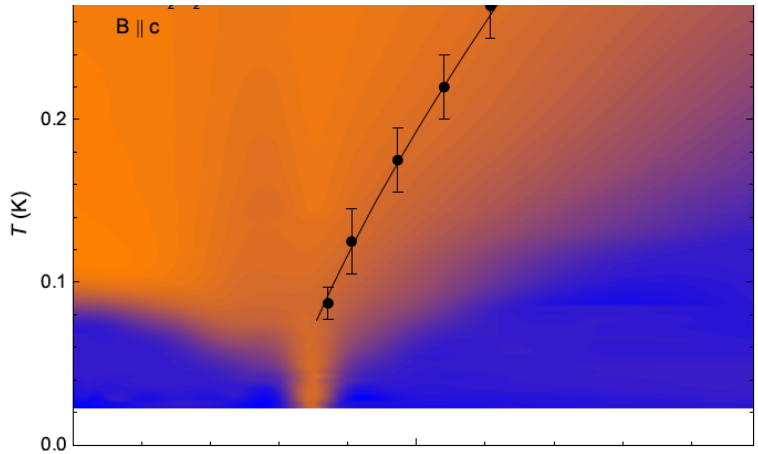
$CeCu_{6-x}Au_x$ H. v. Löhneysen et al



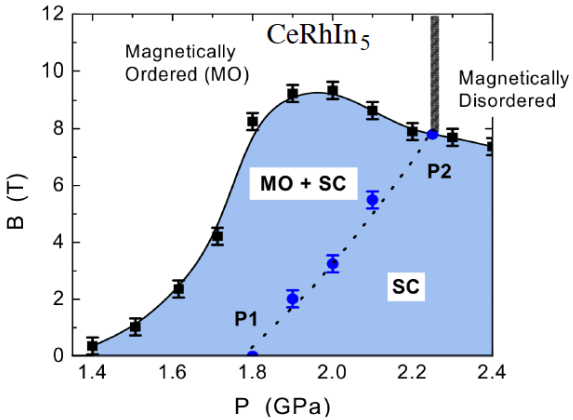
$CePd_2Si_2$ N. Mathur et al



$YbRh_2Si_2$ J. Custers et al

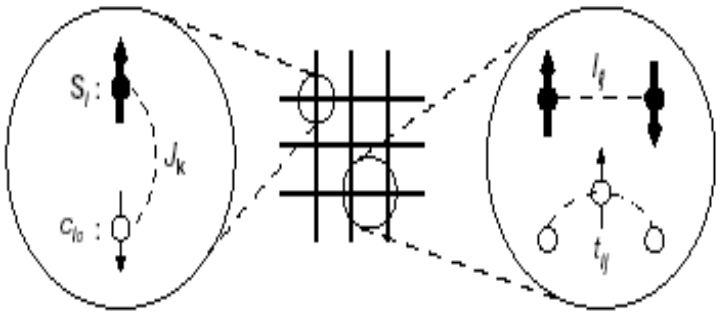


$CeRhIn_5$ T. Park et al



1. What is the Hamiltonian?

Kondo lattices:



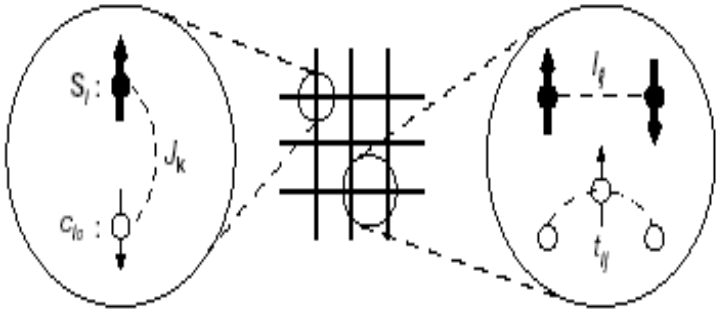
$$H = \sum_{ij} I_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{ij,\sigma} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} + \sum_i J_K \mathbf{S}_i \cdot \mathbf{s}_{c,i}$$

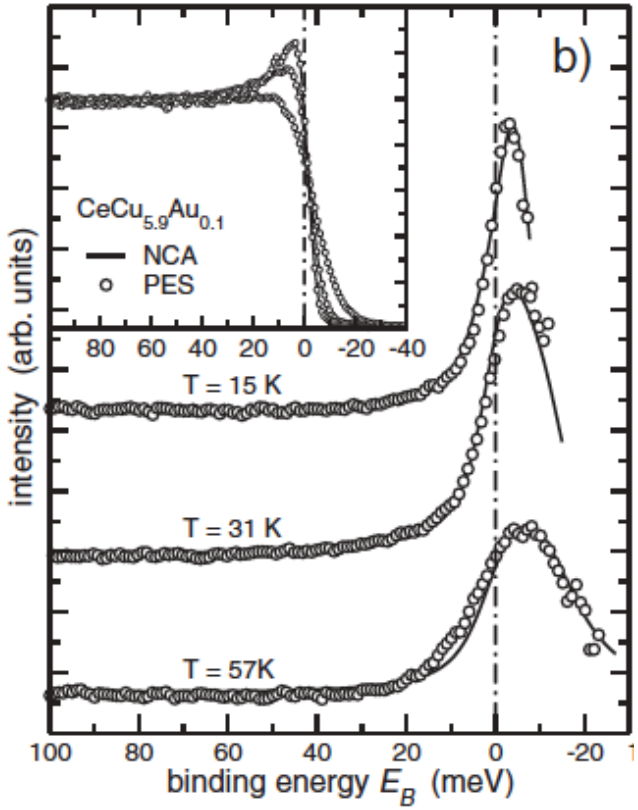
J. W. Allen

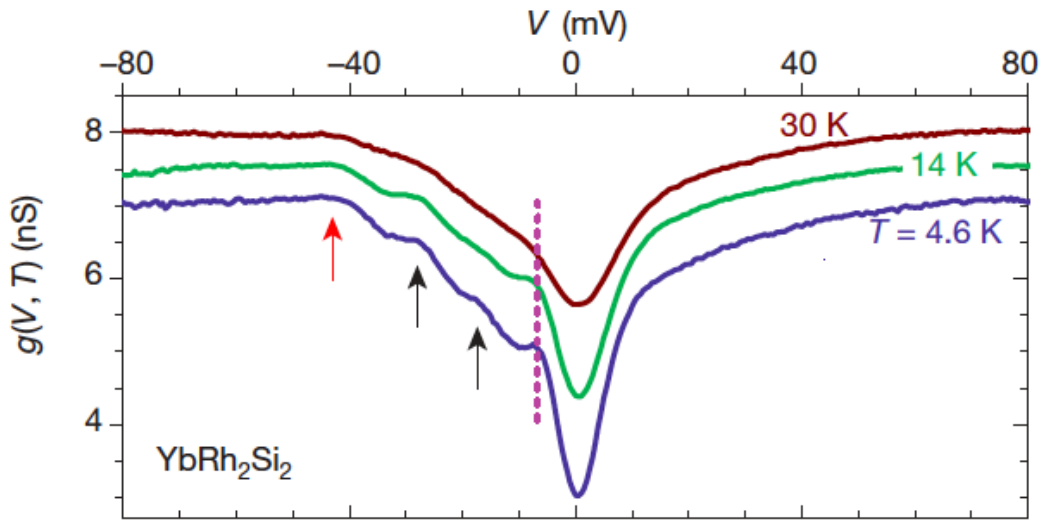
Y. F. Yang

P. Aynajian

Kondo lattices:



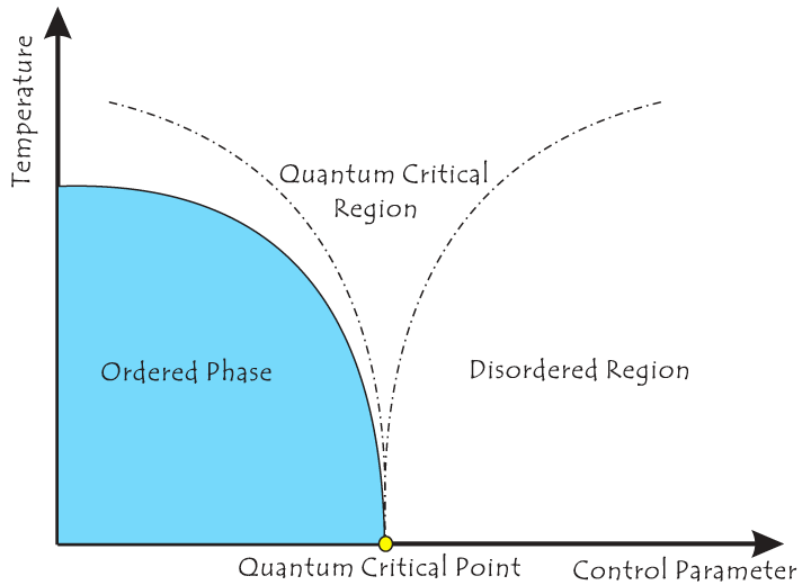




M. Klein et al, PRL 101, 266404 ('08)

S. Ernst et al, Nature 474, 362 ('11)

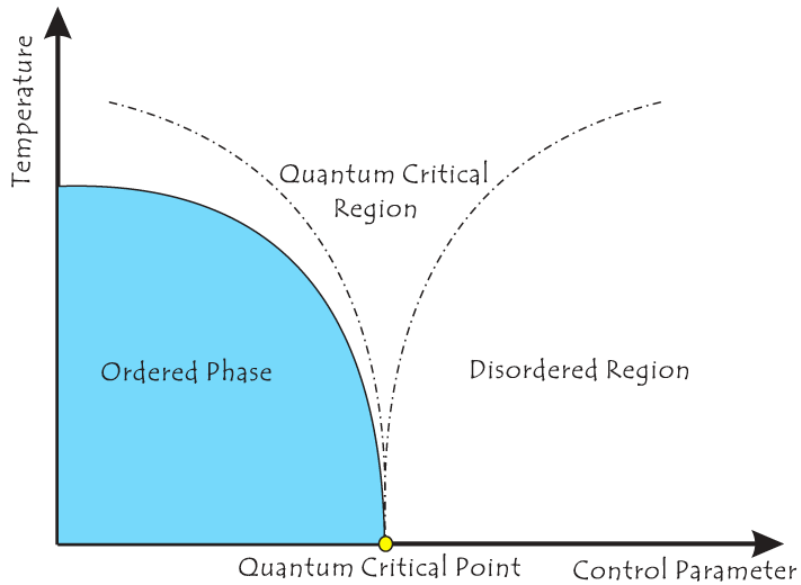
2. Quantum Criticality & Novel Phases



S. Paschen
C. Pépin
Shiyan Li
V. A. Sidorov

S. Friedemann
G-Q Zheng
K. Ueda
H. Xiao

C. Broholm
A. Strydom
F. M. Grosche
Z. A. Xu



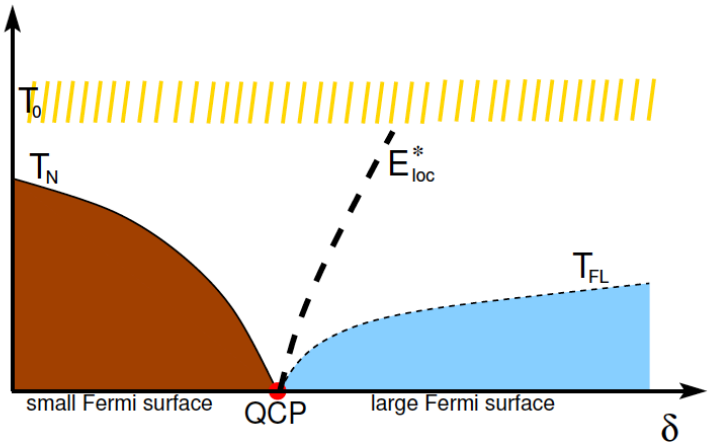
- **Competing states due to competing interactions**
- **Finite T: Quantum critical regime**
- **Beyond Landau?**

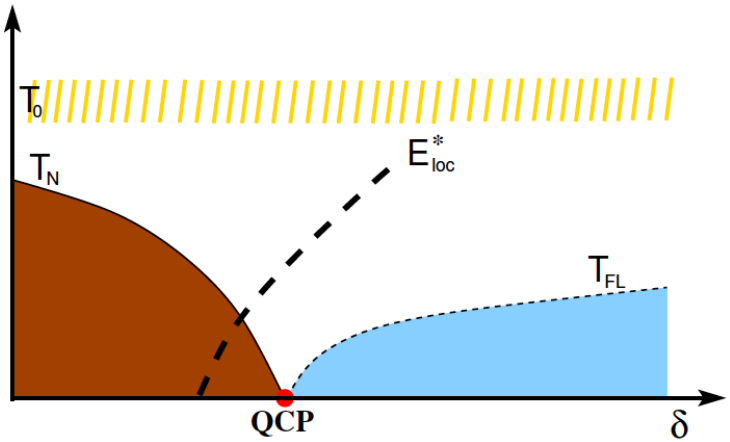
Special issue: J. Low Temp. Phys. (Oct 2010)

Focus issue: Nature Phys. (March 2008)

QS & F. Steglich, Science 329, 1161 (2010)

Collapse of Kondo scale



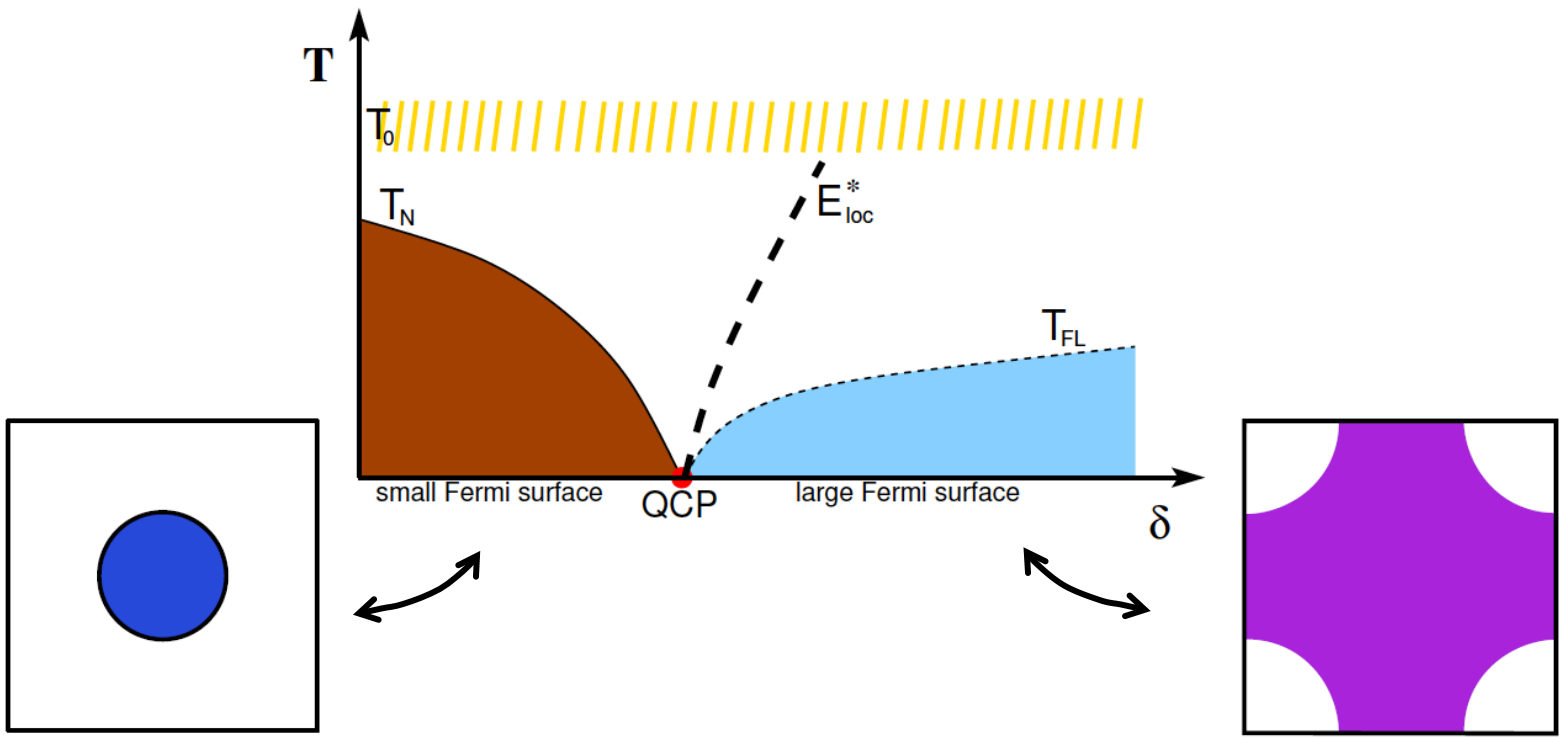


QS, S. Rabello, K. Ingersent, & J. L. Smith, Nature 413, 804 (2001);

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

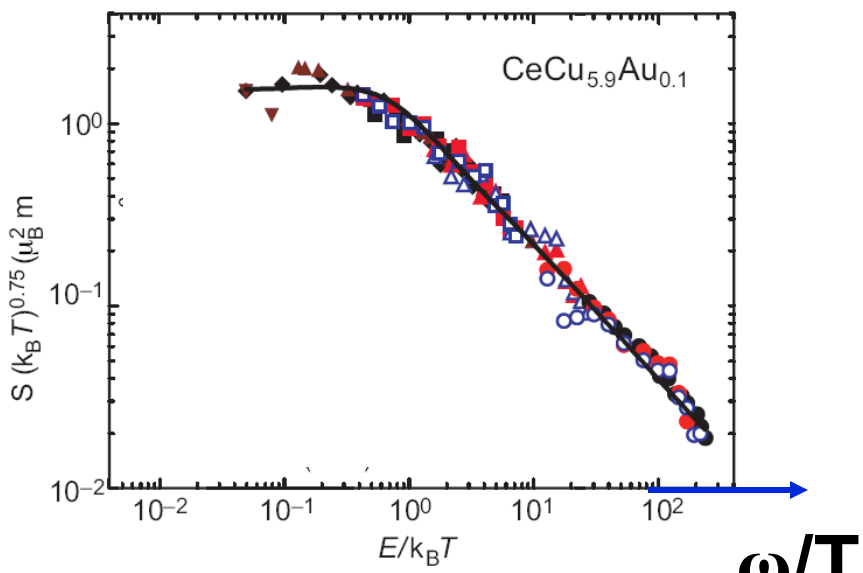
C. Pépin

- ω/T scaling in $\chi(\omega,T)$ and $G(\omega,T)$
- Collapse of a large Fermi surface
- Multiple energy scales



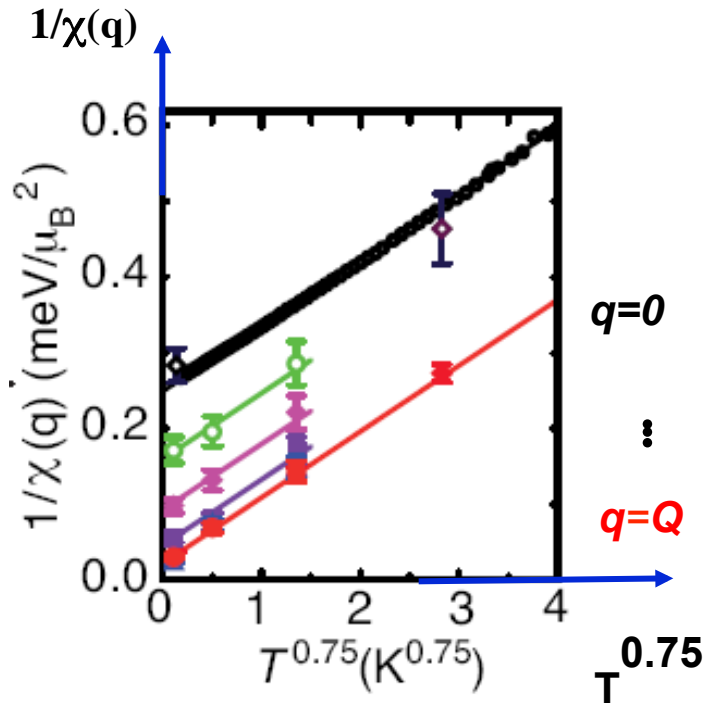
Dynamical Scaling

Fractional exponent α=0.75



INS @ AF Q

ω/T

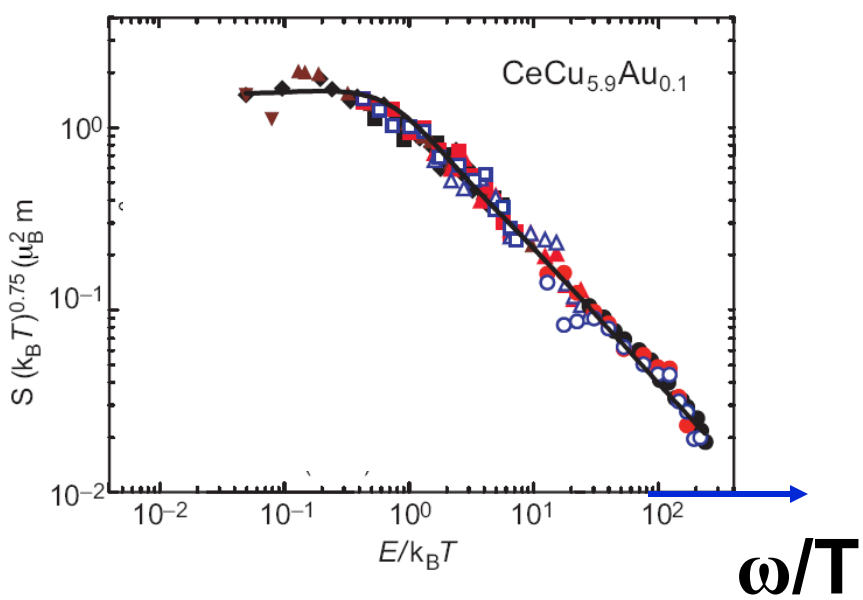


INS and M/H

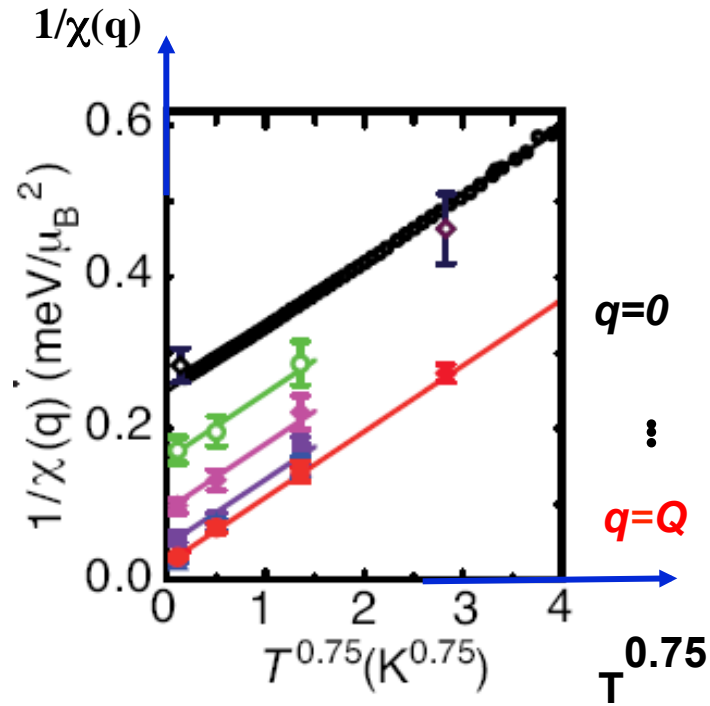
A. Schröder et al., Nature ('00);
O. Stockert et al; M. Aronson et al.

Dynamical Scaling

Fractional exponent α=0.75



ω/T

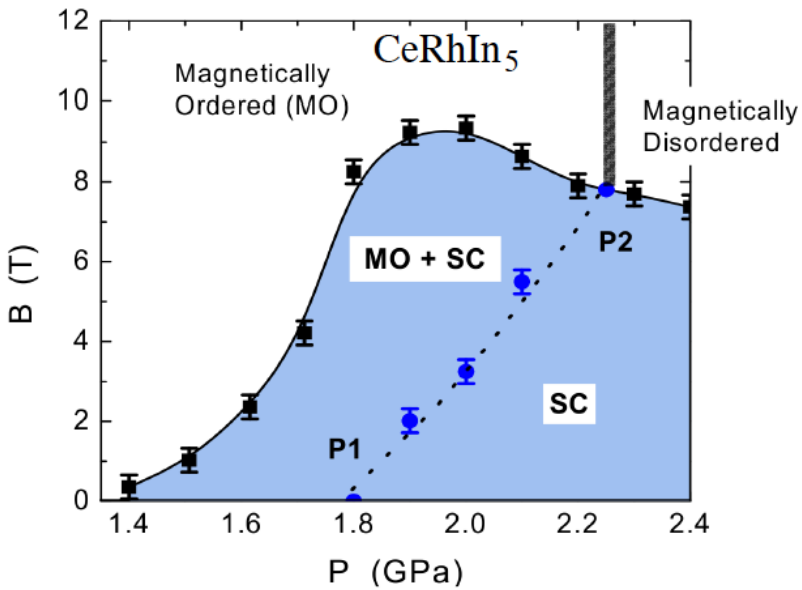


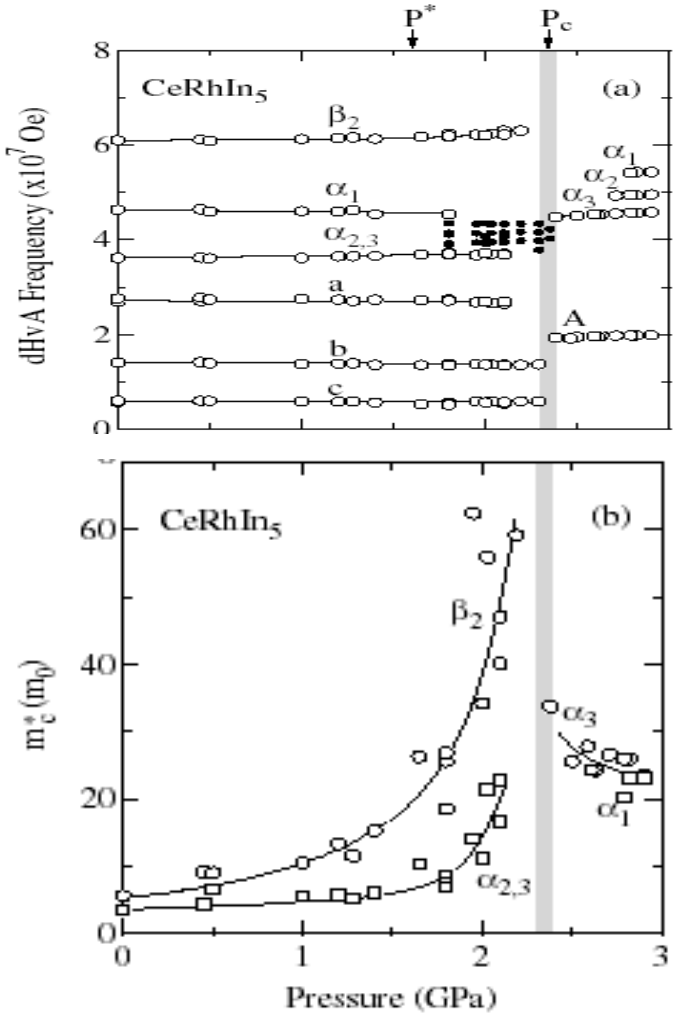
Marching towards the QC regime:

C. Broholm ($YbRh_2Si_2$)

P. Aynajian ($CeCoIn_5$)

Kondo-destruction QCP in $CeRhIn_5$



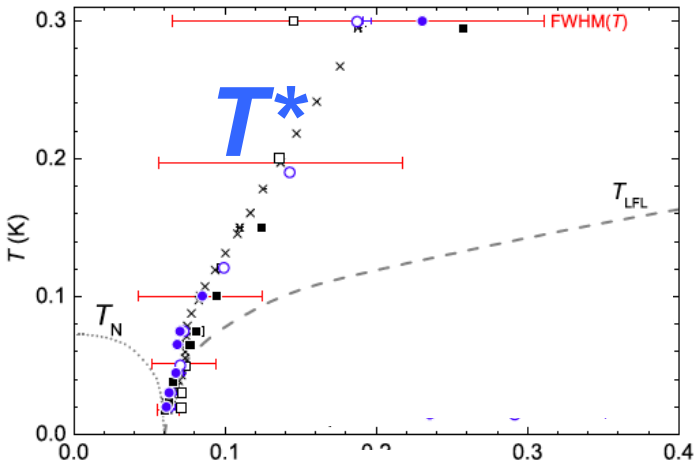


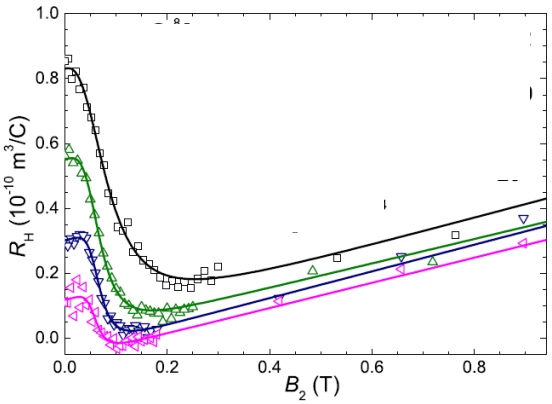
T. Park

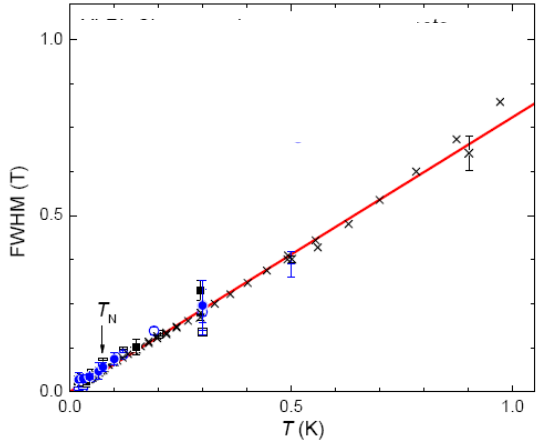
T. Park et al., Nature 440, 65 (’06);
G. Knebel et al., PRB74, 020501 (’06)

H. Shishido, R. Settai, H. Harima, & Y. Ōnuki, JPSJ 74, 1103 (’05)

Fermi Surface and Energy Scales in $YbRh_2Si_2$







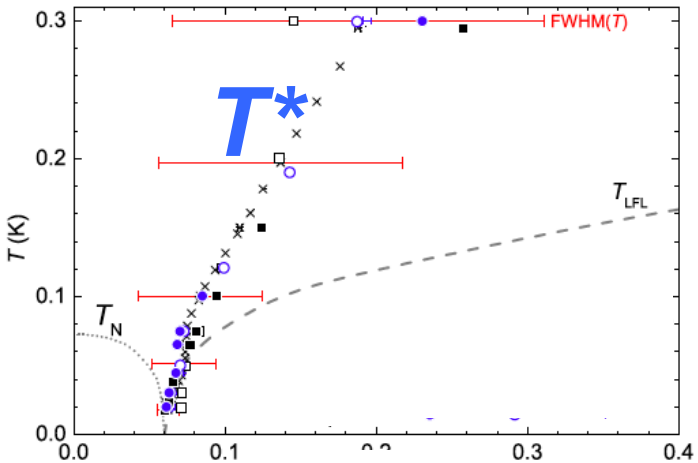
S. Paschen

S. Friedemann

S. Friedemann, N. Oeschler, S. Wirth, C. Krellner, C. Geibel, F. Steglich, S. Paschen, S. Kirchner, and QS, PNAS 107, 14547 (2010)

S. Paschen et al, Nature (2004); P. Gegenwart et al, Science (2007)

Spin dynamics in $YbRh_2Si_2$



C. Broholm

- Neutron scattering at last!
  - AF wavevector!
  - Spin resonance at H>H*

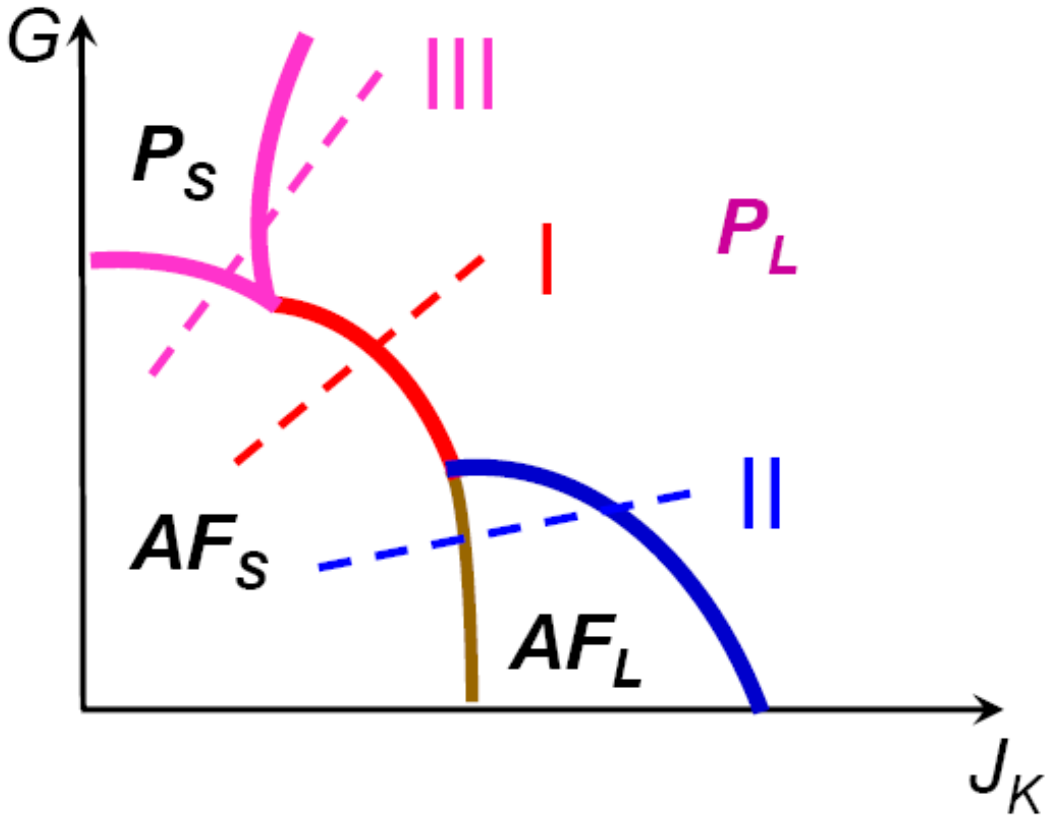
Heavy fermion metals:

quantum critical points

global phase diagram

Global Phase Diagram

G: frustration, reduced dimensionaltiy, …

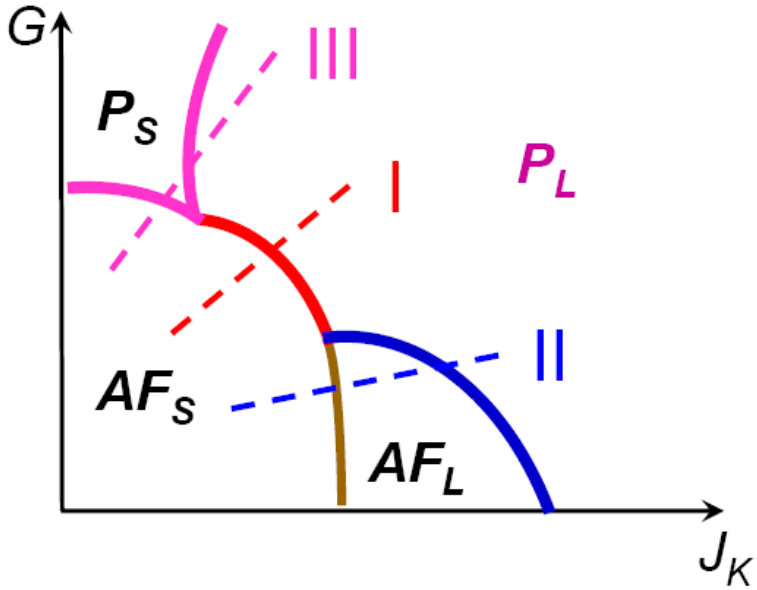


In contrast to:
single boundary
within Landau

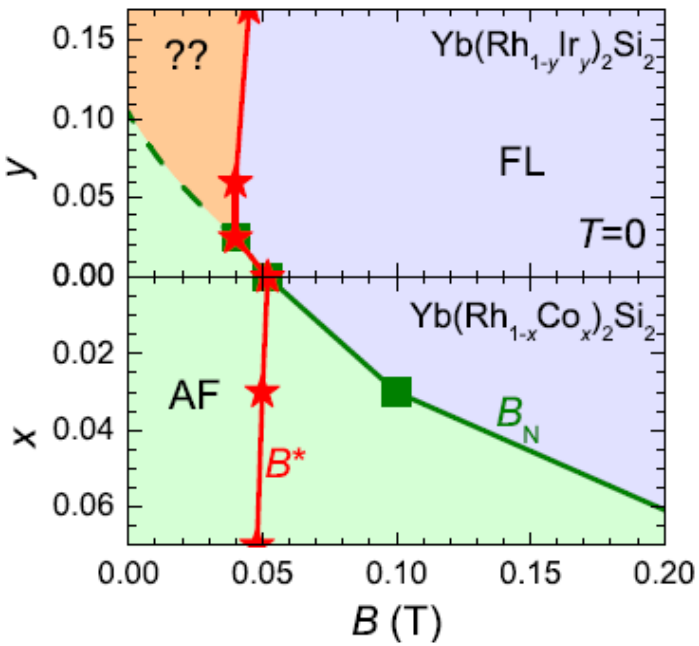
Q. Si, Physica B 378, 23 (2006); Phys. Status Solidi B247, 476 (2010)

also, P. Coleman & A. Nevidomskyy, JLTP 161, 182 (2010)

Global Phase Diagram



Pure and doped $YbRh_2Si_2$

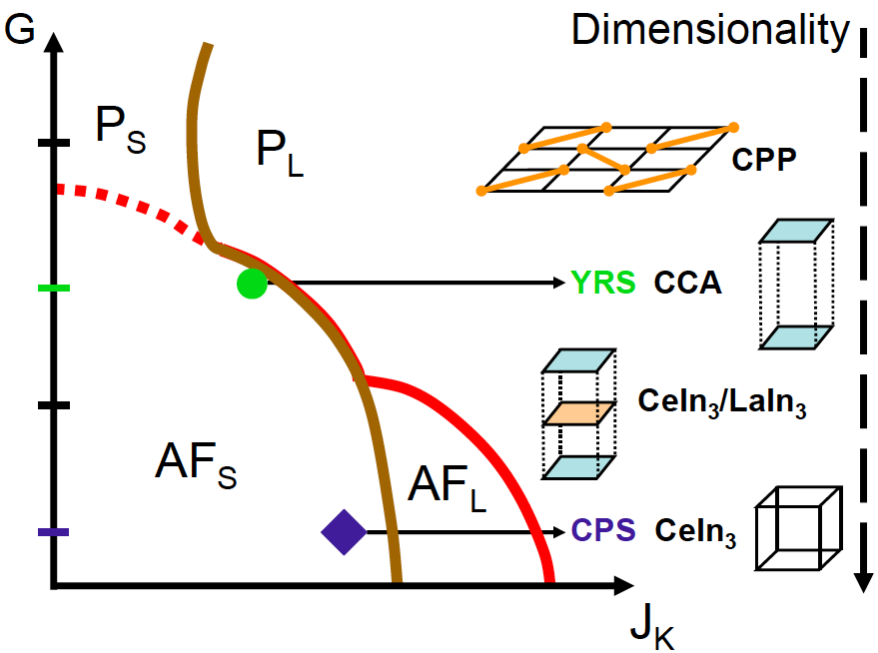


S. Friedemann et al, Nat. Phys. 5, 465 ('09)

S. Friedemann

Global Phase Diagram

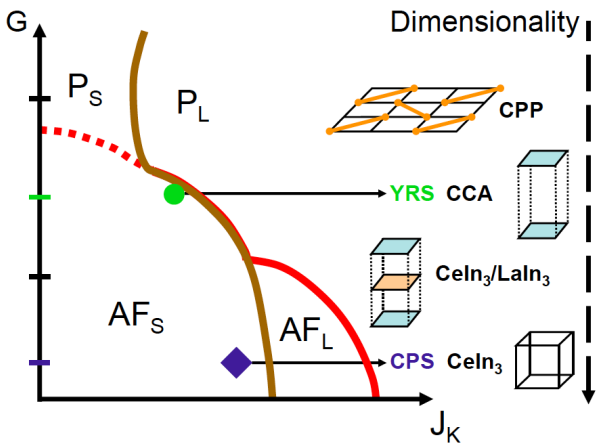
Effect of dimensionality – the case of cubic $Ce_3Pd_{20}Si_6$

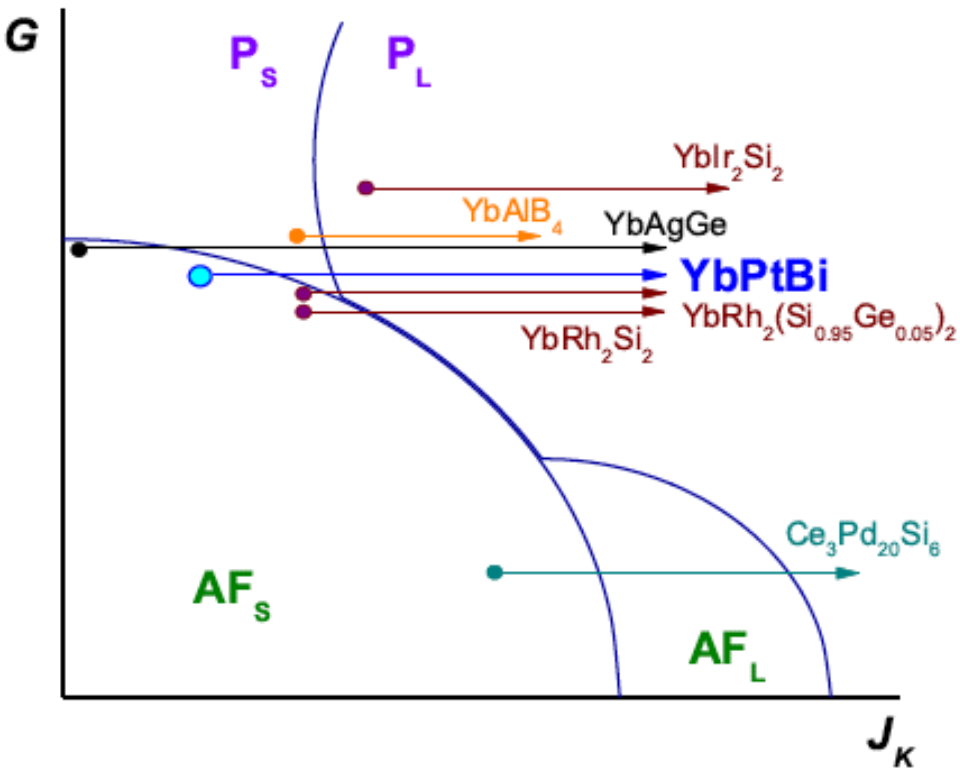


J. Custers, R. Yu, et al., Nature Materials 11, 189 (2012)

S. Paschen

Global Phase Diagram





Shastry-Sutherland Lattice Ce_2Pt_2Pb (M. C. Aronson)

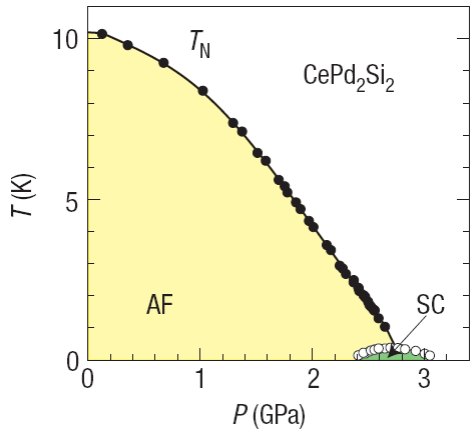
Kagome lattice CePdAl (H. v. Löhneysen)

…

E. D. Mun et al., arXiv:1211.0636

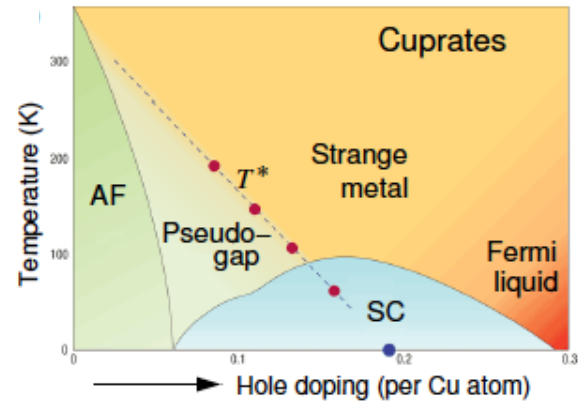
Superconductivity at the border of magnetism

Heavy fermions



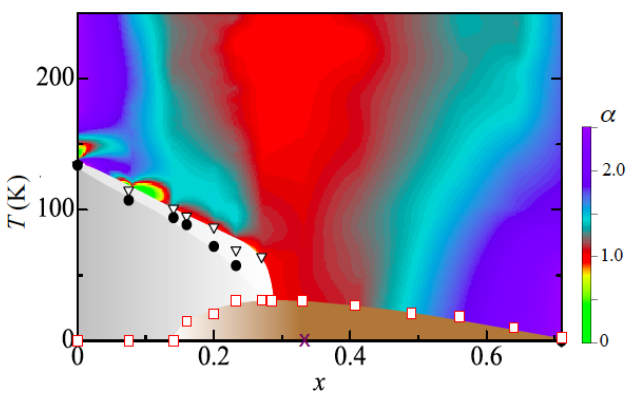
Mathur et al

Cuprates



Broun

Pnictides



Kasahara et al

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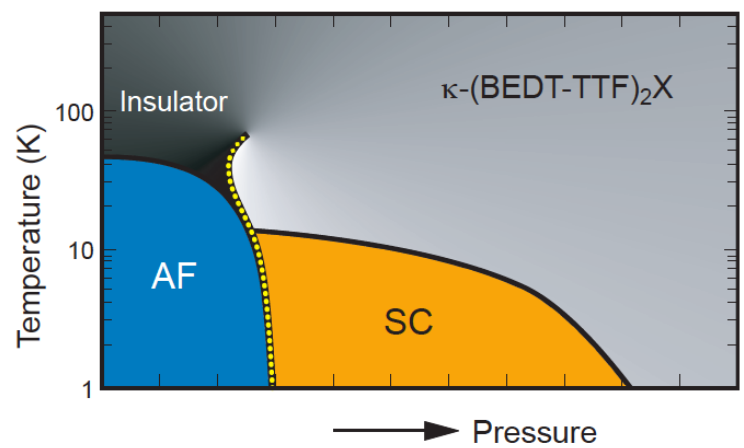
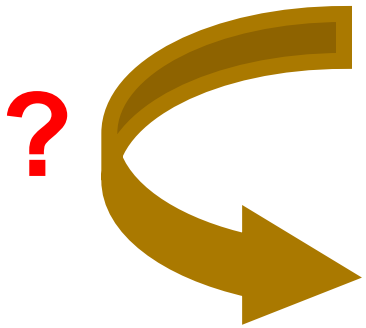


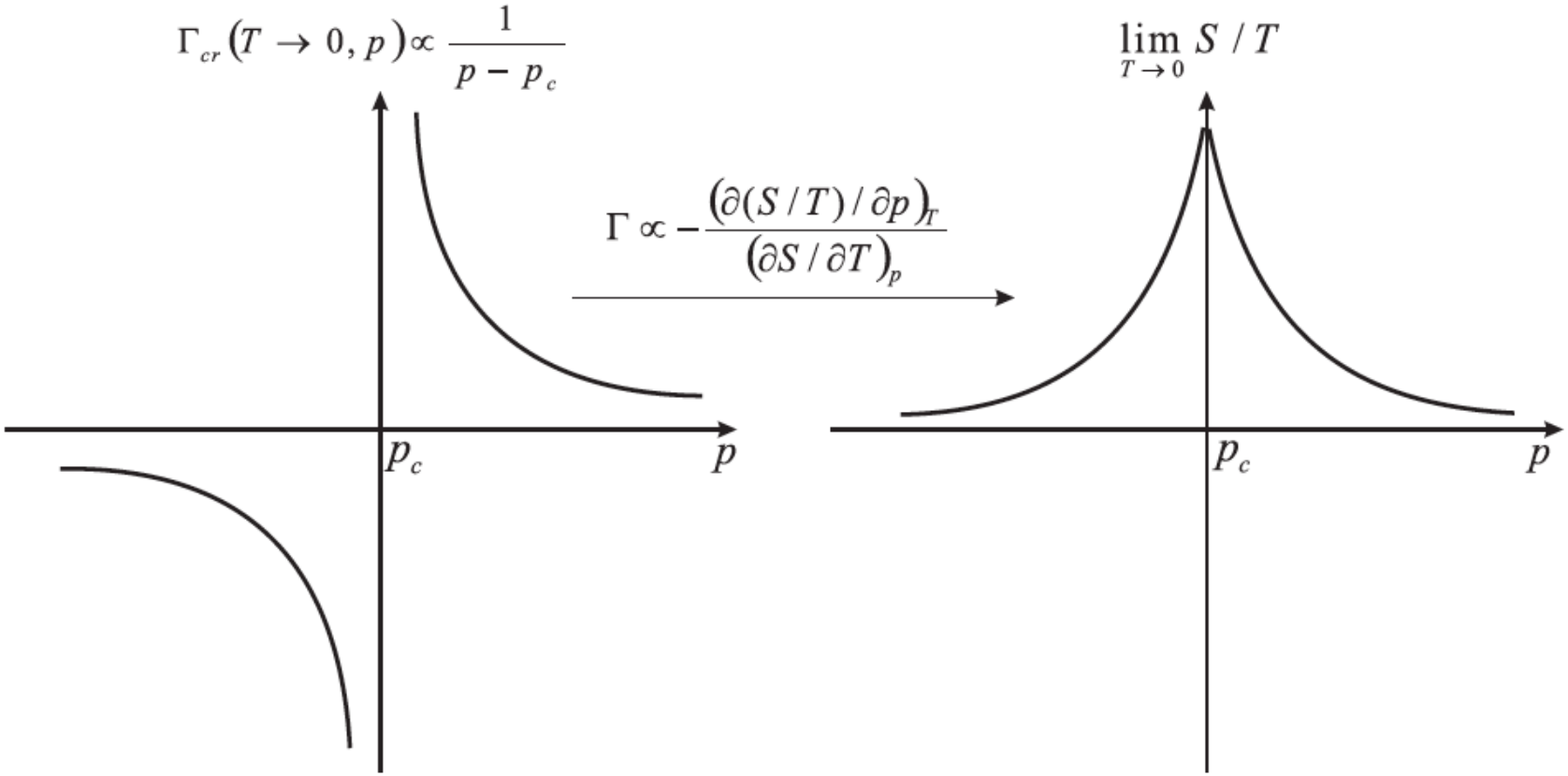
Faltermeier et al

Quantum critical points



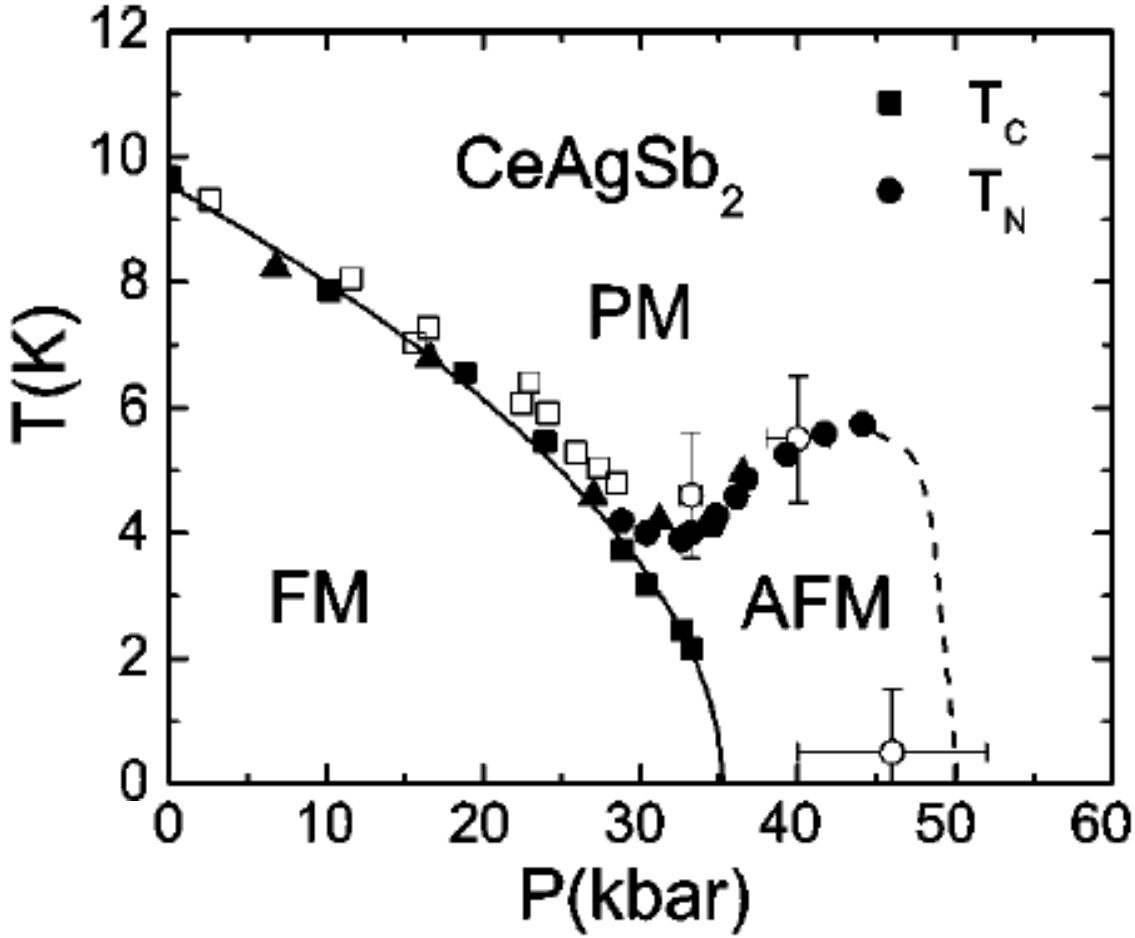
emergent phases

Entropy accumulation near QCP



L. Zhu, M. Garst, A. Rosch, QS,
PRL (2003)

Emergent phases near QCP



V. A. Sidorov et al, PRB 67, 224419 ('03)

Superconductivity at the border of magnetism

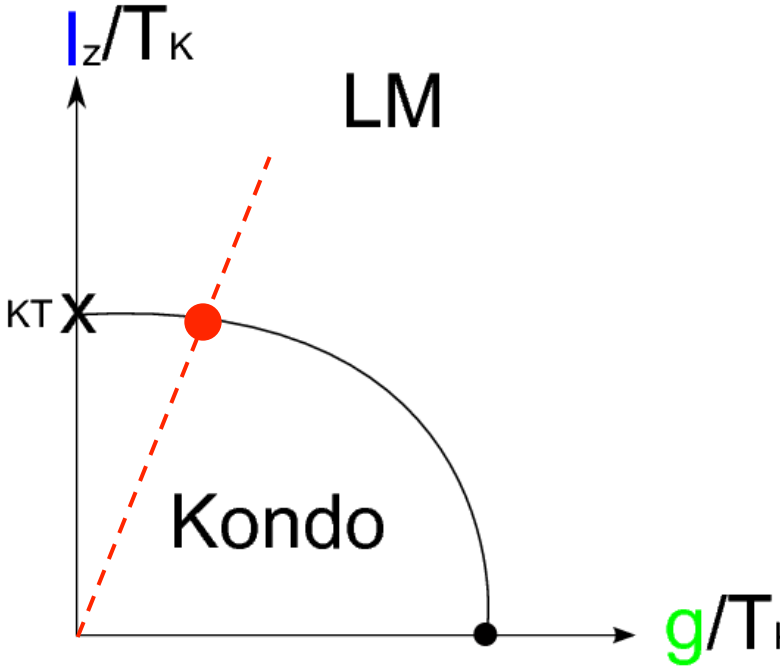
- Magnetic fluctuations a la Landau
  - glues for superconductivity

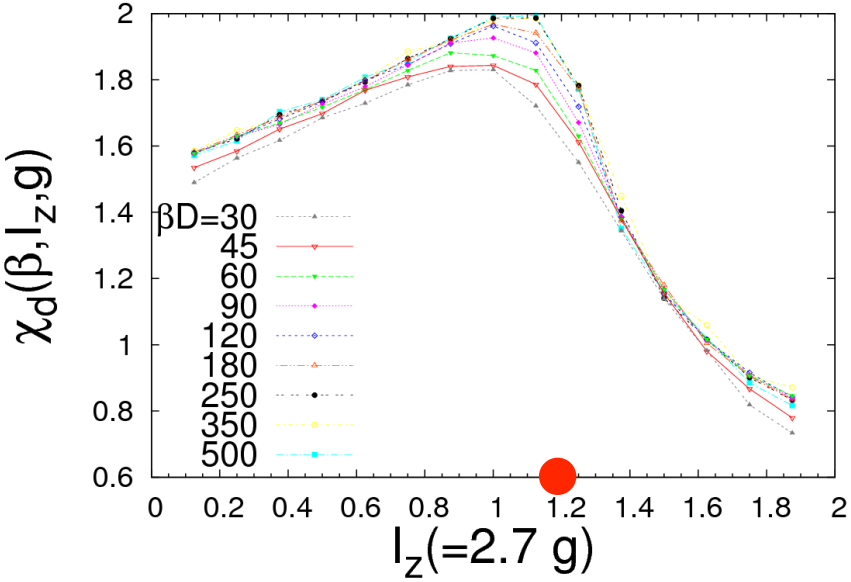
or

- Magnetism as proxy
  - new excitations in normal state

- Pairing suscep. Enhancement at Kondo destruction QCP

J. Pixley, MP44





3. Magnetism and Superconductivity

F. Ronning **T. Park**
L. Shu **G.-Q. Zheng**
K. Ishida **K. Ueda**
G.-M. Zhang **P. Dai**

- Microscopic coexistence vs phase separation
- Excitations in the coexistence region
- Odd-frequency pairing due to quantum criticality
- Exchange energy gain vs condensation energy

4. Kondo insulators/Heavy Fermion semiconductors

C. Petrovic

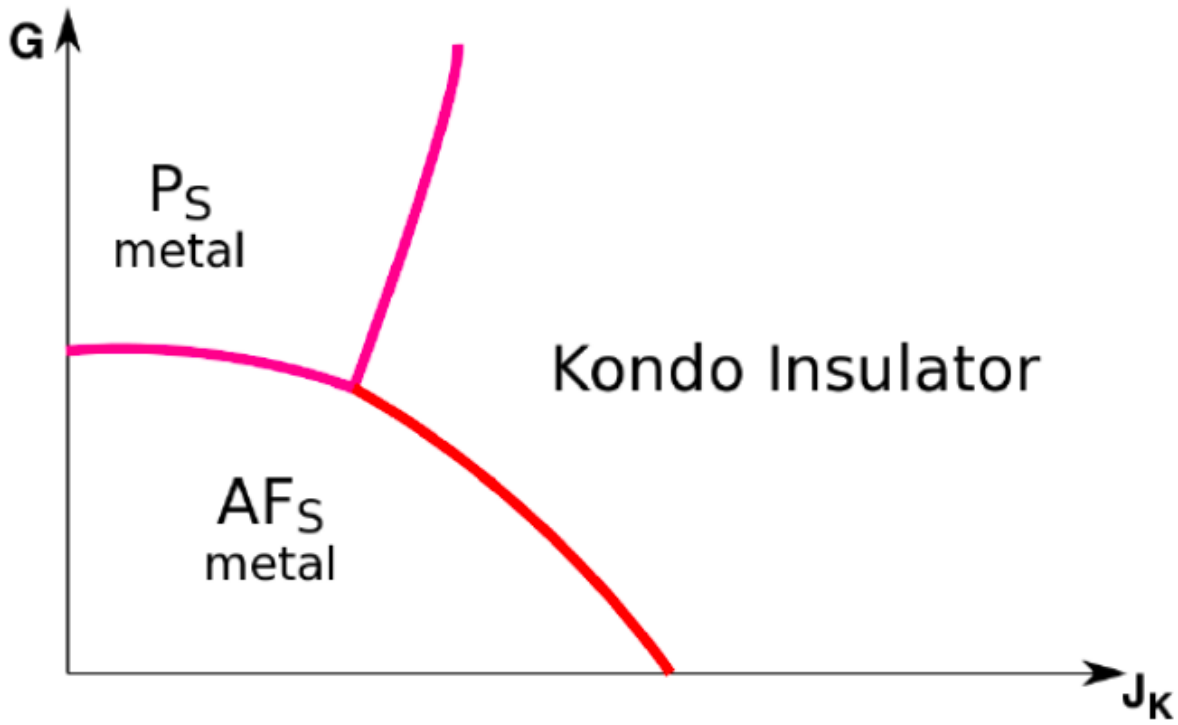
A. Strodym

$FeSb_2$ – towards tomorrow's thermoelectric materials (electron correlations save the world)?

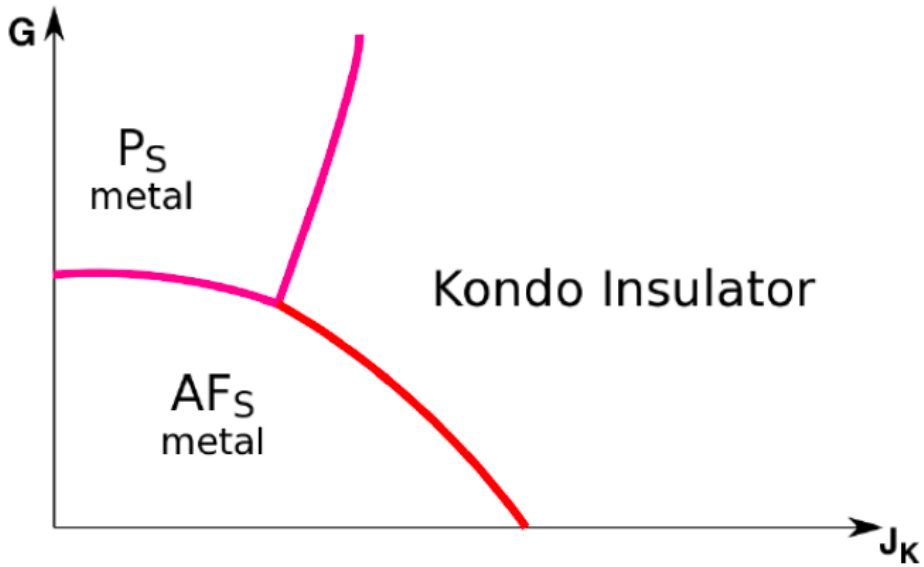
Petrovic

Peijie Sun (IOP/CAS)

Global phase diagram of Kondo insulators



Global phase diagram of Kondo insulators



$CeRu_2Al_{10}$:

Kondo insulator AF (**A. Strydom**)

Alternatively: “bad metal” AF?

Is YFe_2Al_{10} a failed “Kondo insulator”?

5. Ferromagnetism and the case for ferromagnetic QCP

S. Friedemann **G.-M. Zhang**

K. Ueda

Growing list of ferromagnetic heavy fermions:

--$URu_{2-x}Re_xSi_2$	N. P. Butch & M. B. Maple, PRL ('09)
--$YbNi_4P_2$	A. Steppke et al ('12)
--$CeRu_2Al_2B$	E. Baumbach et al, PRB ('12)

- Is there a metallic FM QCP?
  - Hertz-Moriya-Millis: NO!

- QCP of $YbNi_4P_2$ (**Friedemann**)
  - Because of 1D bandstructure?
  - Alternatively: because of Kondo effect?

6. The marching band of materials …

The # of materials discussed reached the large-N limit!!!

Extending the materials basis for QCP, Kondo insulators (eg spin-orbit physics), …