Geometrical Frustration and Quantum Criticality

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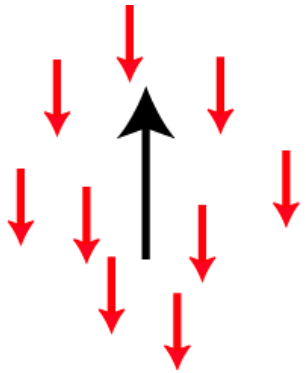
Heavy Fermions: Kondo Lattices

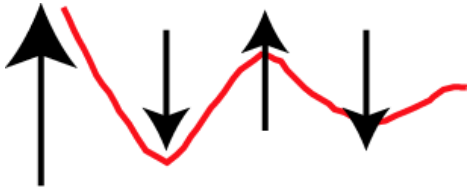
- Exchange Interaction J generates two competing energy scales

Kondo Effect

$T_K \sim \exp(-1/nJ)$

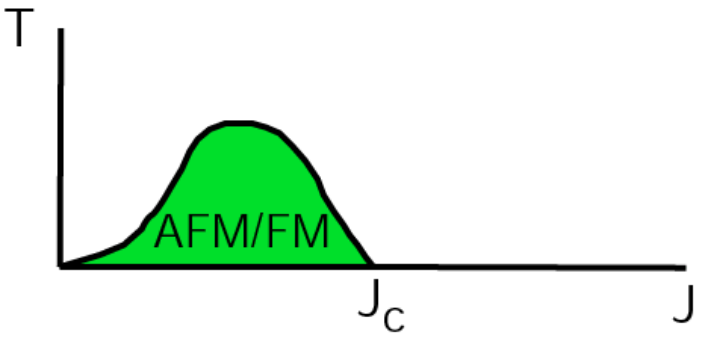


RKKY Interaction

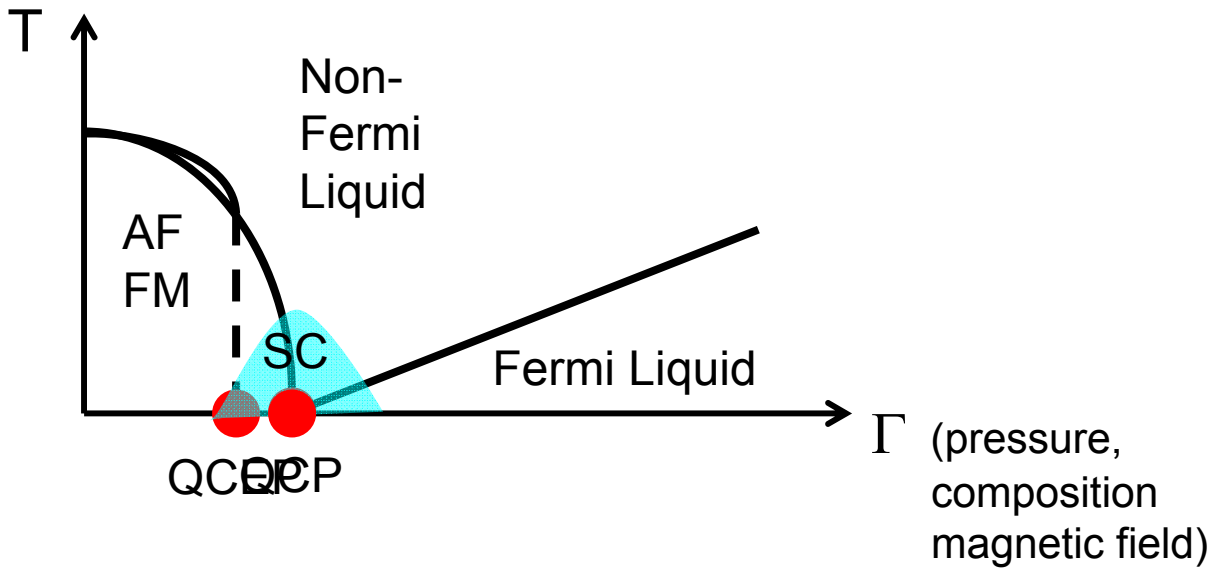


$T_N \sim J^2$

- Generic `Doniach ' Phase Diagram:



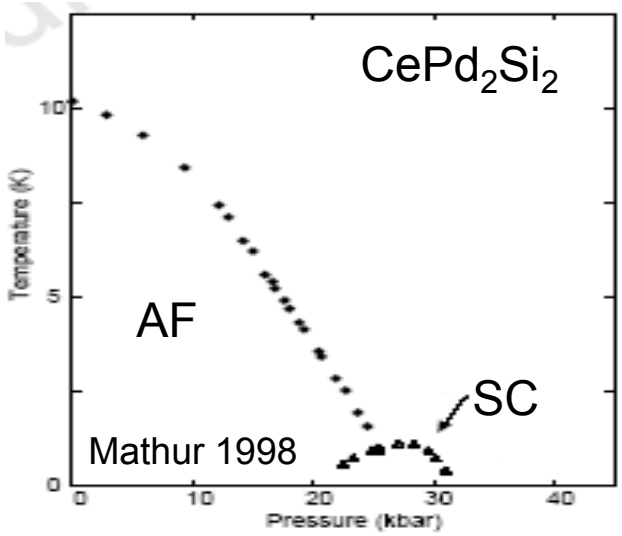
The Heavy Fermion Phase Diagram



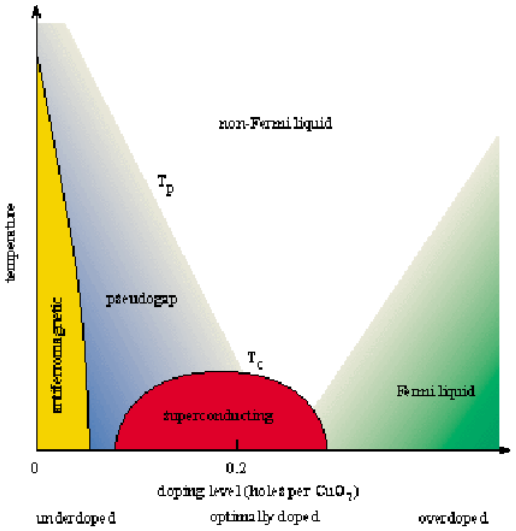
- Disappearance of magnetic order $T_{N,C} \rightarrow 0$: unconventional critical phenomena (Quantum Critical Point, Quantum Critical Endpoint).
- Destruction of normal metal $T_{FL} \rightarrow 0$: replaced by unconventional metal.
- Collective instabilities of unconventional metals:
  - unconventional superconductivity
  - partial `nematic' order

QCPs: Universal Organizing Scheme?

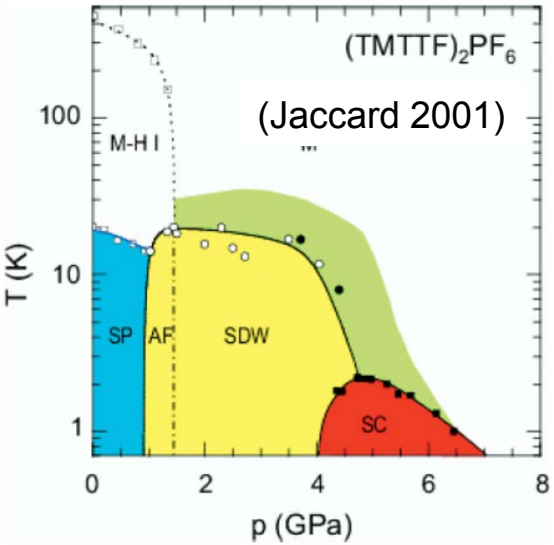
Heavy Electron Intermetallics

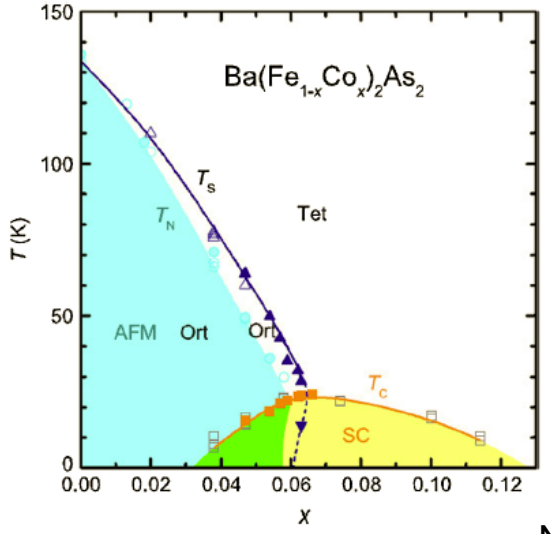


Cuprates



Organic Conductors



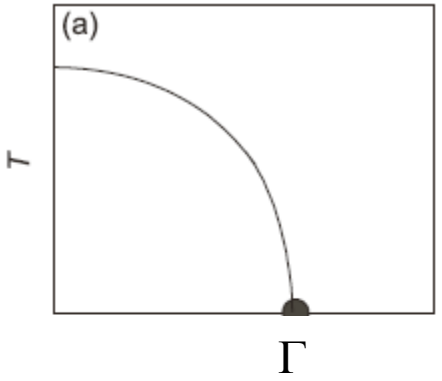


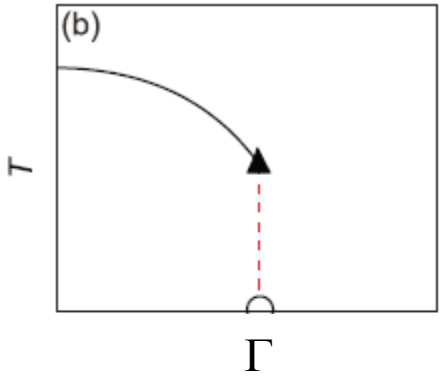
Nandi 2010

Suppression of Magnetic Order

Conventional QCP
$T_{N,C} \rightarrow 0$

$YbRh_2Si_2$, CeXIn5
$CeCu_{6-x}Au_x$, $Cr_{1-x}V_x$
$Ni_{1-x}Pd_x$



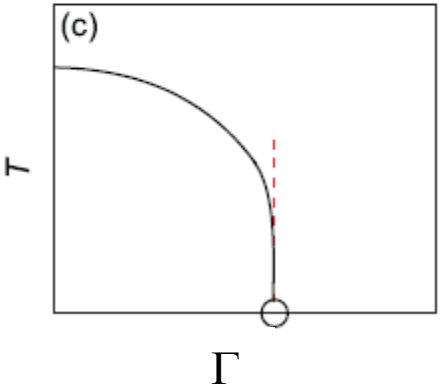


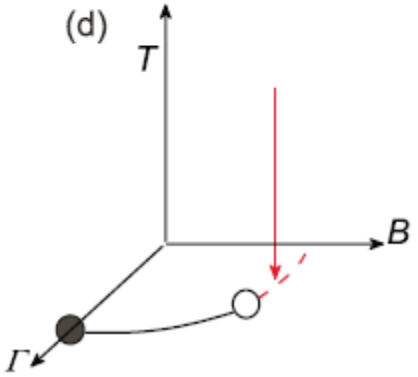
Tricritical point
$T_C \rightarrow 0$ QCEP

$FeCl_2$, MnSi, $ZrZn_2$,
UGe_2

QCEP $T_{N,C}=0$

$CeRh_2Si_2$, Yb_3Pt_4
$CeNiGe_3$, Yb_5Pt_9



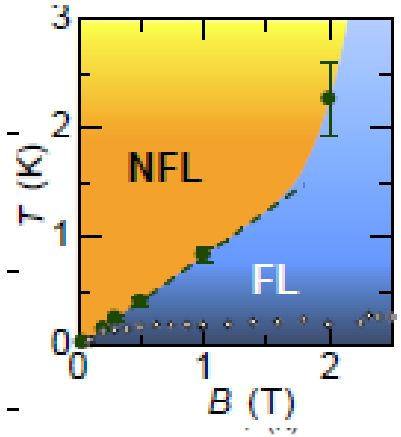


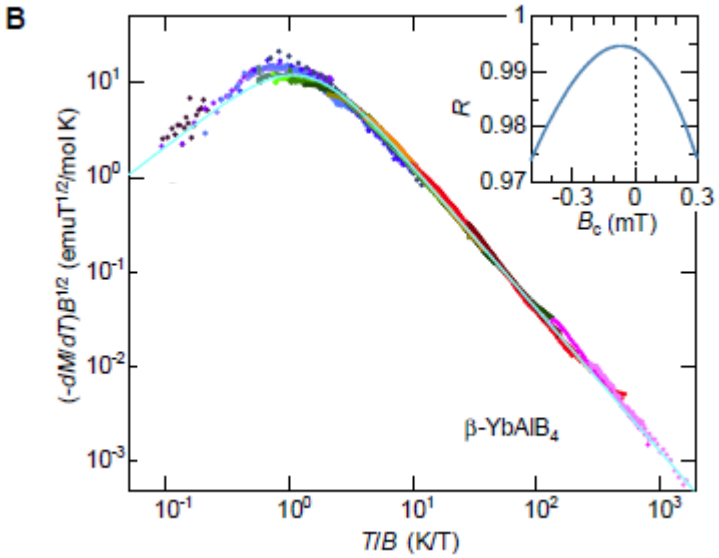
Metamagnetic
(no phase transition)

$CeRu_2Si_2$, $Sr_3Ru_2O_7$

Field-Tuned Quantum Criticality T_C=0, H=0

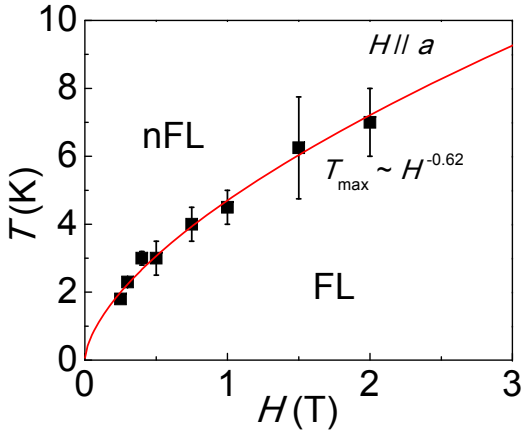
β-$YbAlB_4$

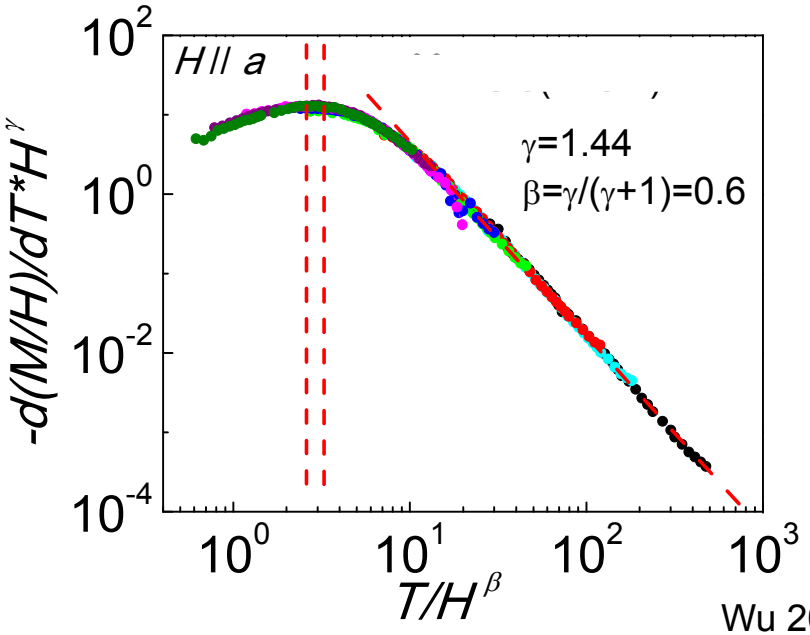




Matsumoto 2011

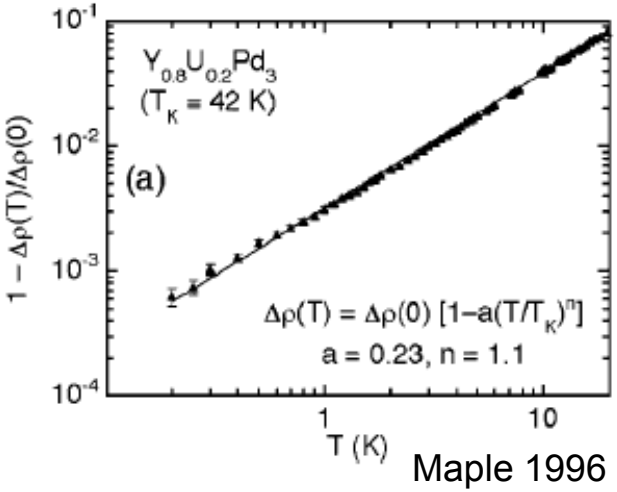
YFe_2Al_{10}



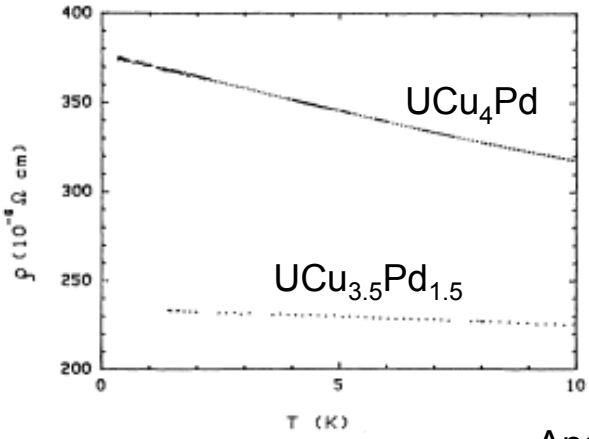


Wu 2012

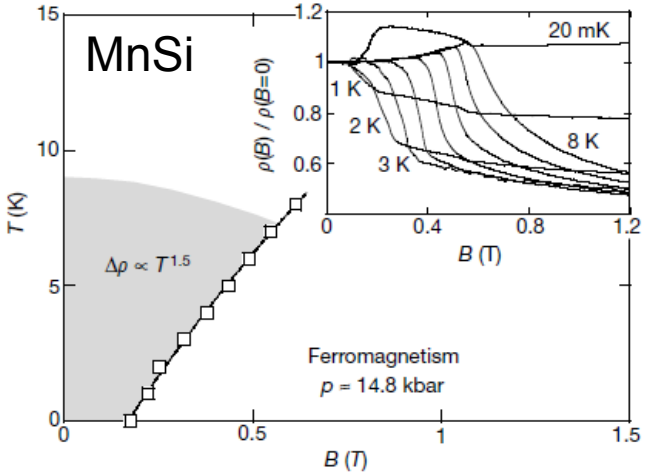
Non-Fermi Liquid Metals



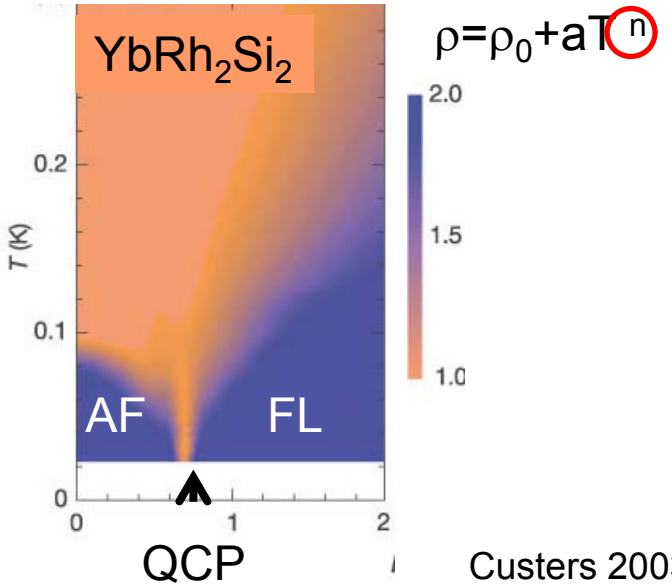
Maple 1996



Andraka 1993



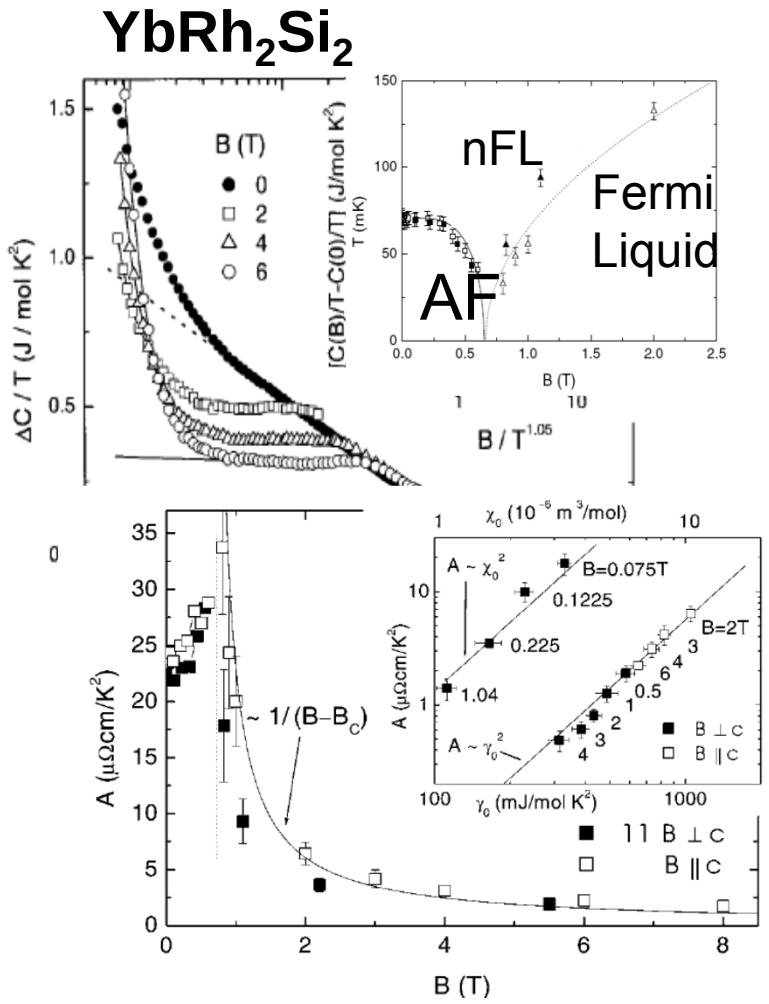
Pfleiderer 2001

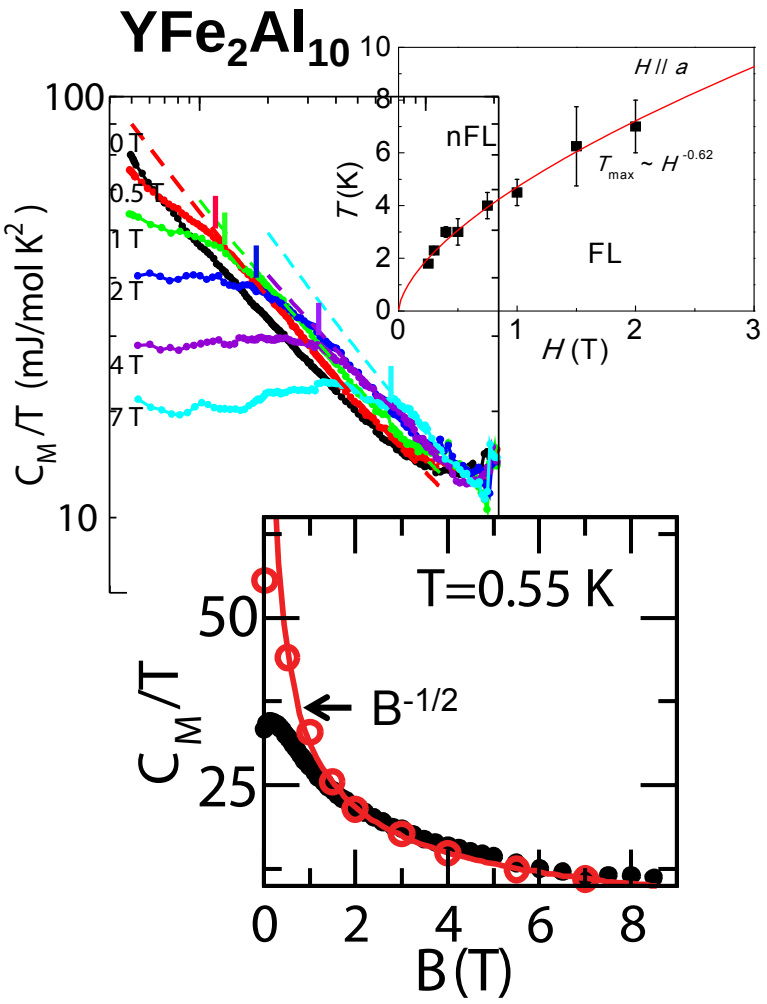


QCP

Custers 2003

Breakdown of Fermi Liquid Phase at QCP





- $T_{FL} \rightarrow 0$: divergence of quasiparticle mass enhancement m*/m at QCP

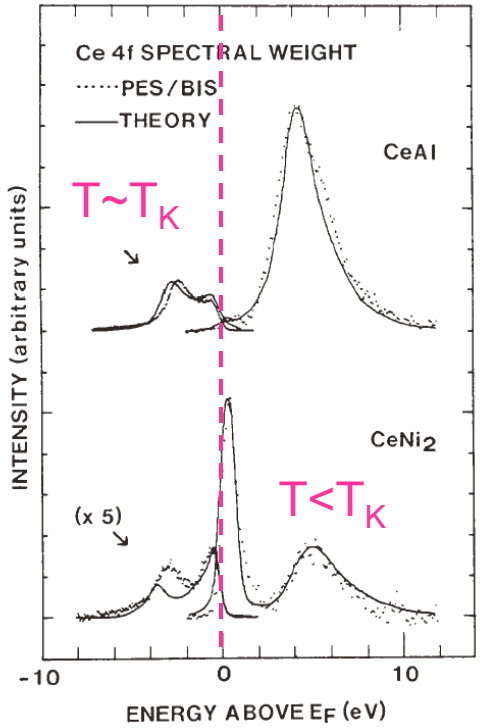
$YbRh_2Si_2$ ($B=B_{QCP}$): γ = 0.65 J/mol-Yb-K^2

YFe_2Al_{10} (B=0.5 T): γ~42 mJ/mol-Fe-K^2

$YbRh_2Si_2$: $\gamma(B) \sim (B-B_{QCP})^{-1/2}$

YFe_2Al_{10}: $\gamma(B) \sim B^{-1/2}$

f-electrons and the Fermi Surface: the Kondo resonance



Allen 1990

- $T>>T_K$: Localized moments decoupled from conduction electrons

  f-electrons excluded from (small) Fermi surface

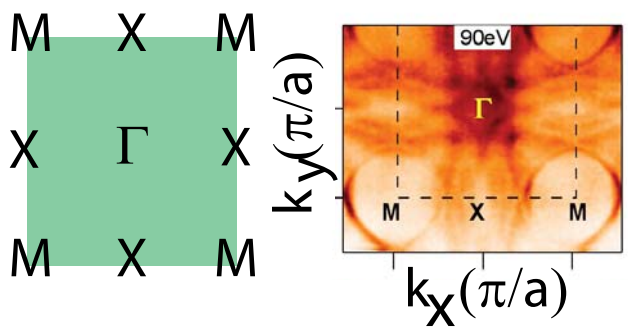
- $T<<T_K$: Formation of Kondo singlet

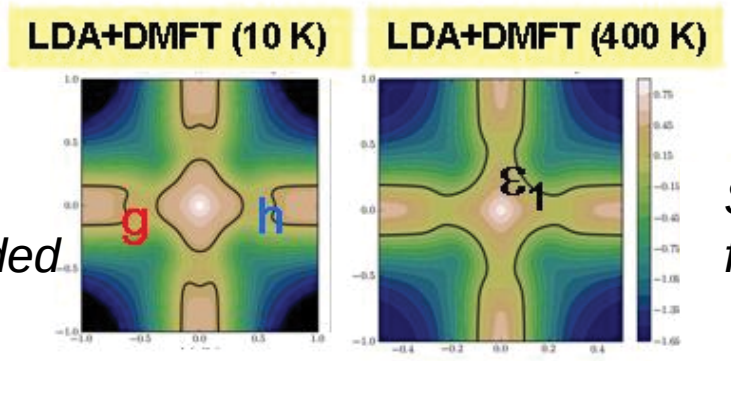
  f-electrons included in (large) Fermi surface

Kondo Coherence and the Fermi Surface Volume

$CeIrIn_5$

Haule and Allen
(unpublished)



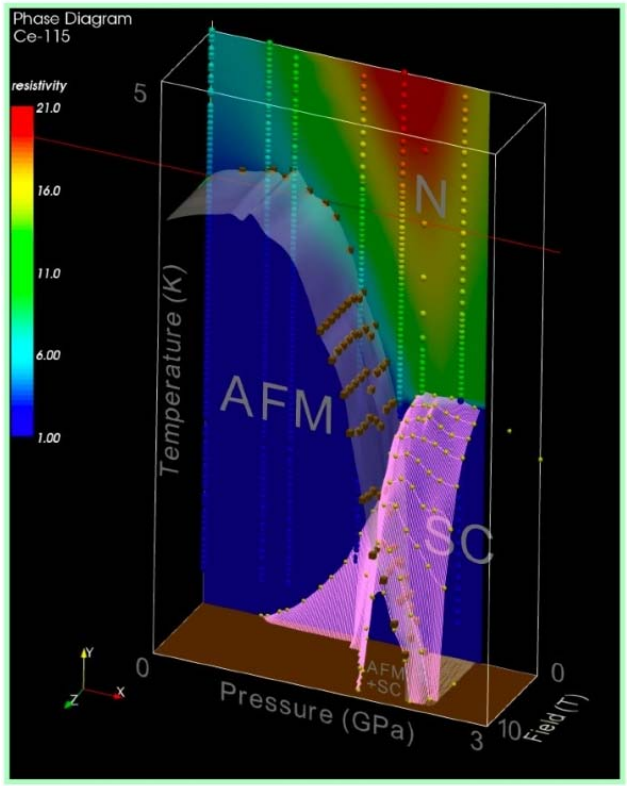


Large FS
f-electron included

Small FS
f-electron excluded

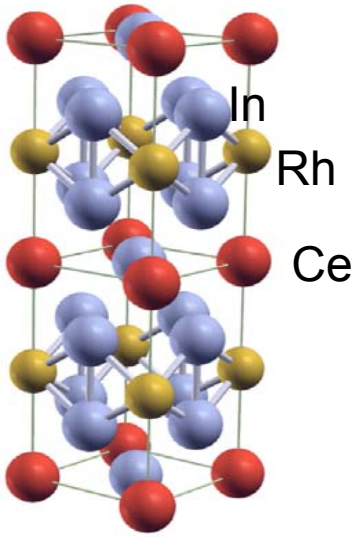
- Does the Fermi surface expand in Kondo lattice systems when the renormalized bands form on cooling?
- T=26 K: Fermi surface of $CeIrIn_5$ resembles 400 K LDA+DMFT calculation
  f-electron is localized, excluded from (small) Fermi surface.
- Comparison of ARPES and LDA+DMFT well suited to detecting electron delocalization transitions.

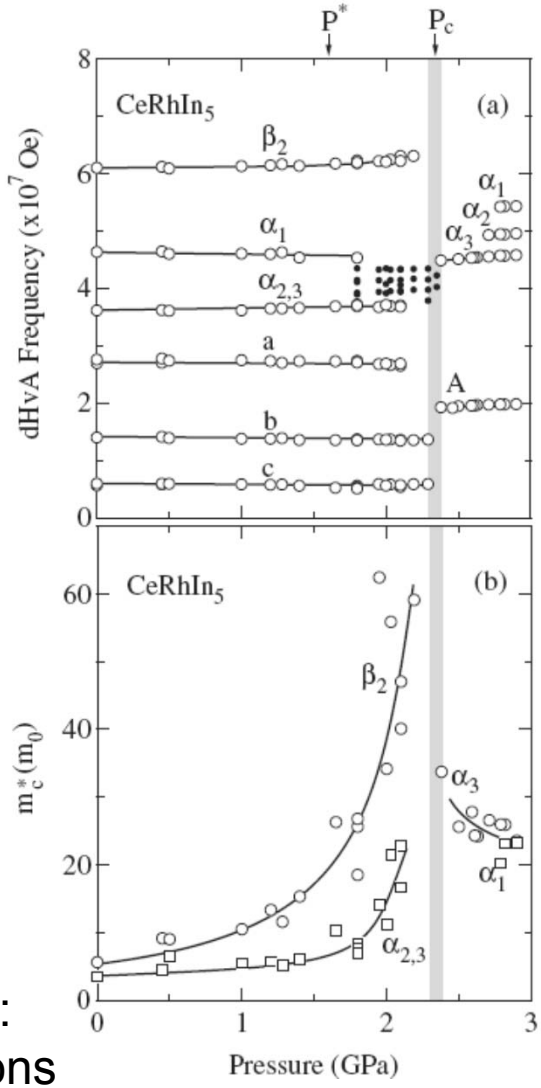
T=0 Electronic Delocalization and the QCP



Data: Tuson Park
Figure rendition: Mathias Graf

$CeRhIn_5$

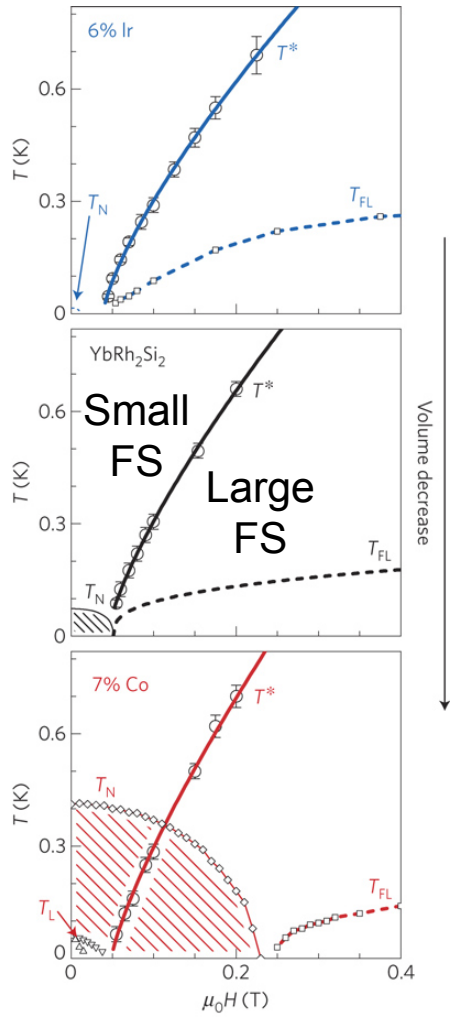




- de Haas- van Alphen measurements at P_C=2.3 GPa QCP:
  - Discontinuous change in Fermi surface dimensions
  - Divergence of quasiparticle mass
- Superconductivity near P_C.

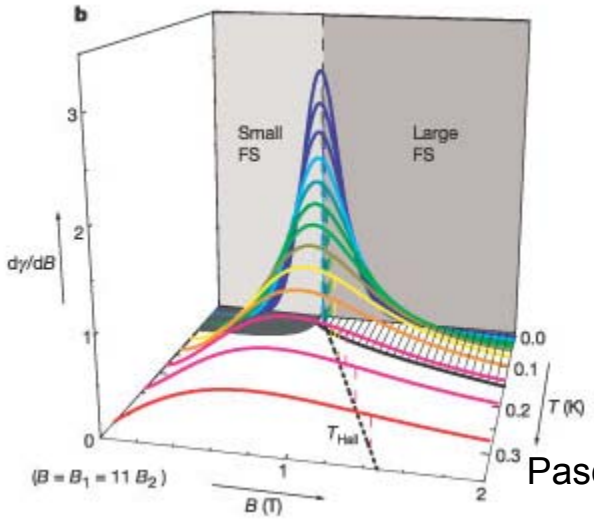
(Shishido 2005)

Electronic Delocalization detached from the QCP



Friedemann 2009

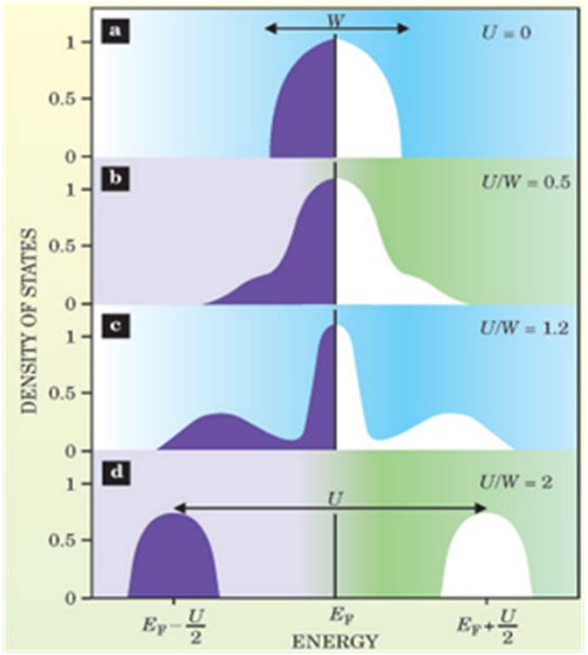
$YbRh_2Si_2$



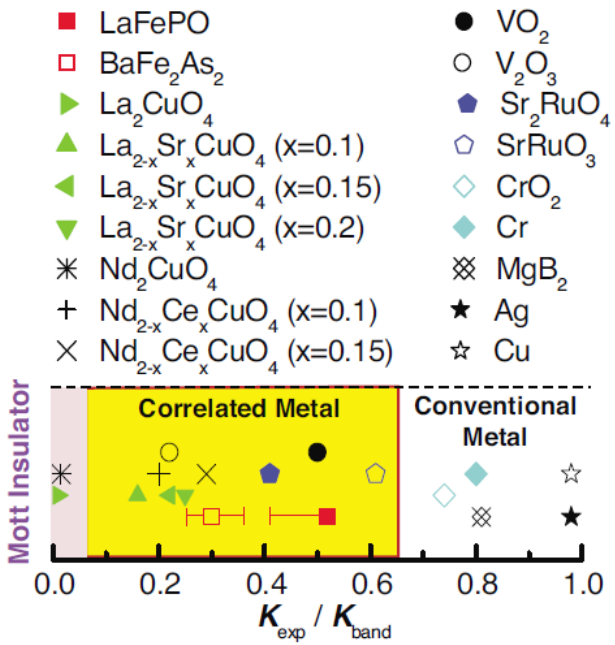
Paschen 2004

- T=0: Jump in Fermi surface volume (small FS to large FS) for H=H*
- Since $T \ll T_K \approx 25$ K, analogous to T=0 Mott transition?

A General Description of Electronic Delocalization?



Kotliar and Vollhardt 2004



Qazilbash 2009

- Heavy fermion delocalization:
  - metal-metal transition: weaker correlations than oxides
  - larger mass enhancement (small K_{exp}/K_{band})

- Still needed: a non-Kondo metal with localized moments (small FS)

Two-Step Electronic Delocalization in Pressurized LaMnPO