$YbRh_2Si_2$: an unconventional metal

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Outline:

- Antiferromagnetic quantum critical point (QCP) in heavy-fermion metals
- Non-Fermi-liquid (NFL) phenomena in $YbRh_2Si_2$
- Magnetic field-induced QCP
- (Negative) pressure effects
- Disparity between $\Delta\rho(T)$ and $\gamma(T)$

Collaboration:

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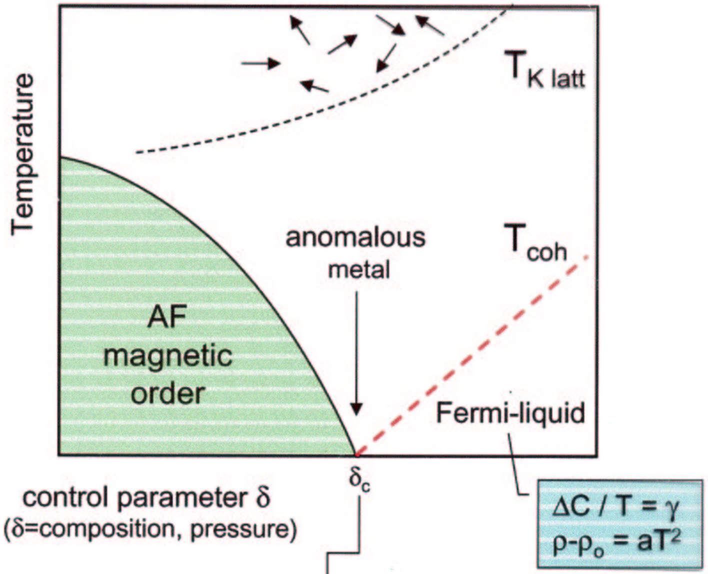
Antiferromagnetic quantum critical point in heavy-fermion metals

Magnetic QCP - Generic Phase Diagram - HF Metals

Itinerant Scenario (Hertz/Millis)



$\Delta C / T = \gamma$
$\rho - \rho_o = aT^2$

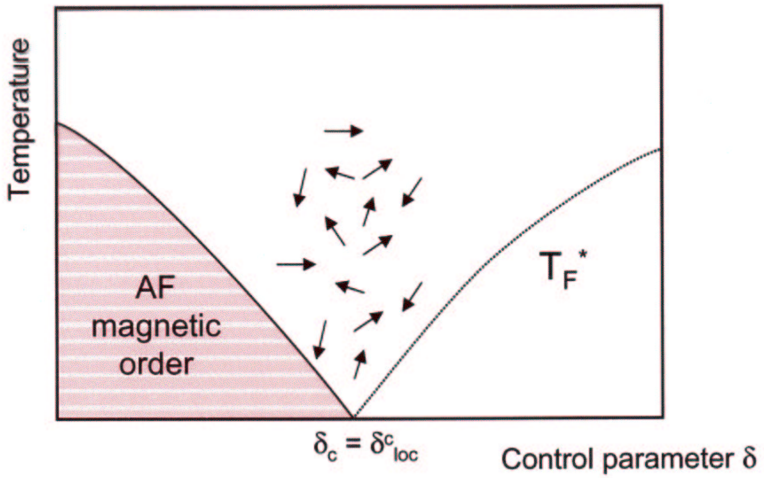
low-lying, long-range fluctuations → anomalous T-dependence of

quasiparticle mass: $m^* \sim \Delta C / T$

scattering cross-section ~ $a = \Delta\rho / T^2$

Magnetic order through a SDW instability

Locally-Critical Scenario



- $CeCu_{6-x}Au_x$ A. Schröder et al. Nature 407, 351 (2000)

Anomalous E/T dependence of $\chi(\mathbf{q},E,T)$

⇒ E/T scaling at x_c

⇒ Non-Curie-Weiss susceptibility: $\chi^{-1} \propto \Theta + aT^{\alpha}$, $\alpha < 1$

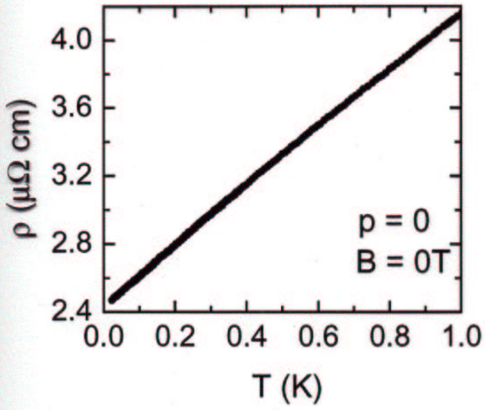
Dynamics at atomic length scale are critical

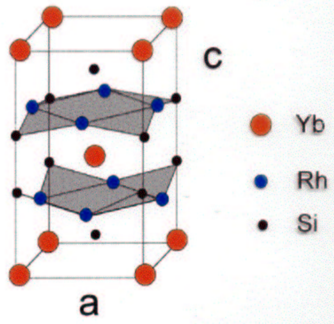
- Theoretical approach:

R. Ramazashvili, P. Coleman et al. Nature 407, 351 (2000)
Q. Si et al. Nature 413, 804 (2001)

Non-Fermi-Liquid (NFL) Effects in $YbRh_2Si_2$

(O. Trovarelli *et al.*, Phys. Rev. Lett. **85**, 626 (2000))





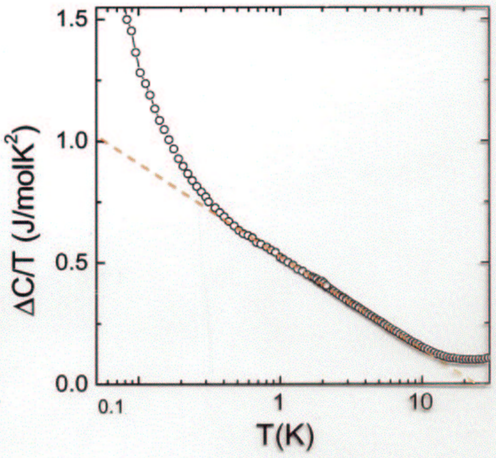
"SDW scenario"

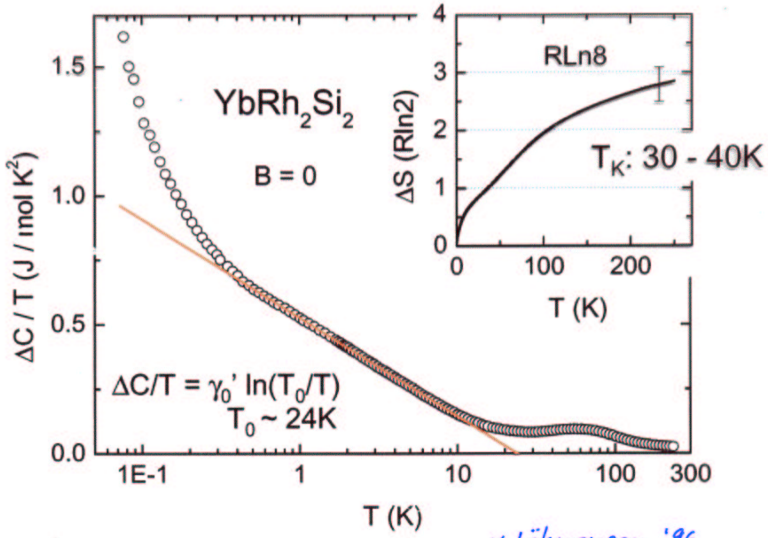
$\Delta\rho \sim T^{d/z}$

AF-SF : z=2

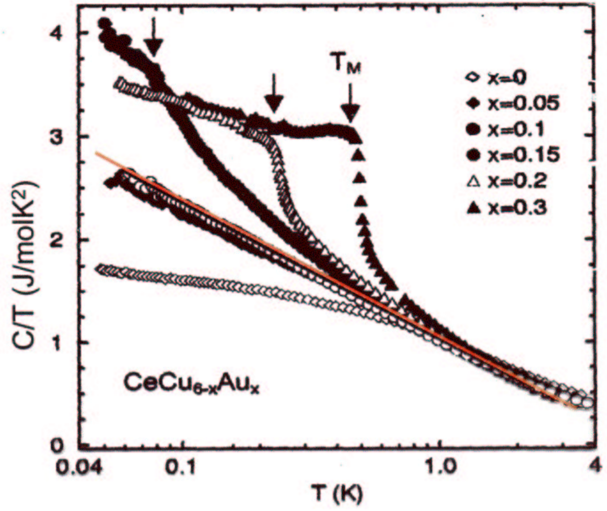
$\Delta\rho \sim T$: d=2

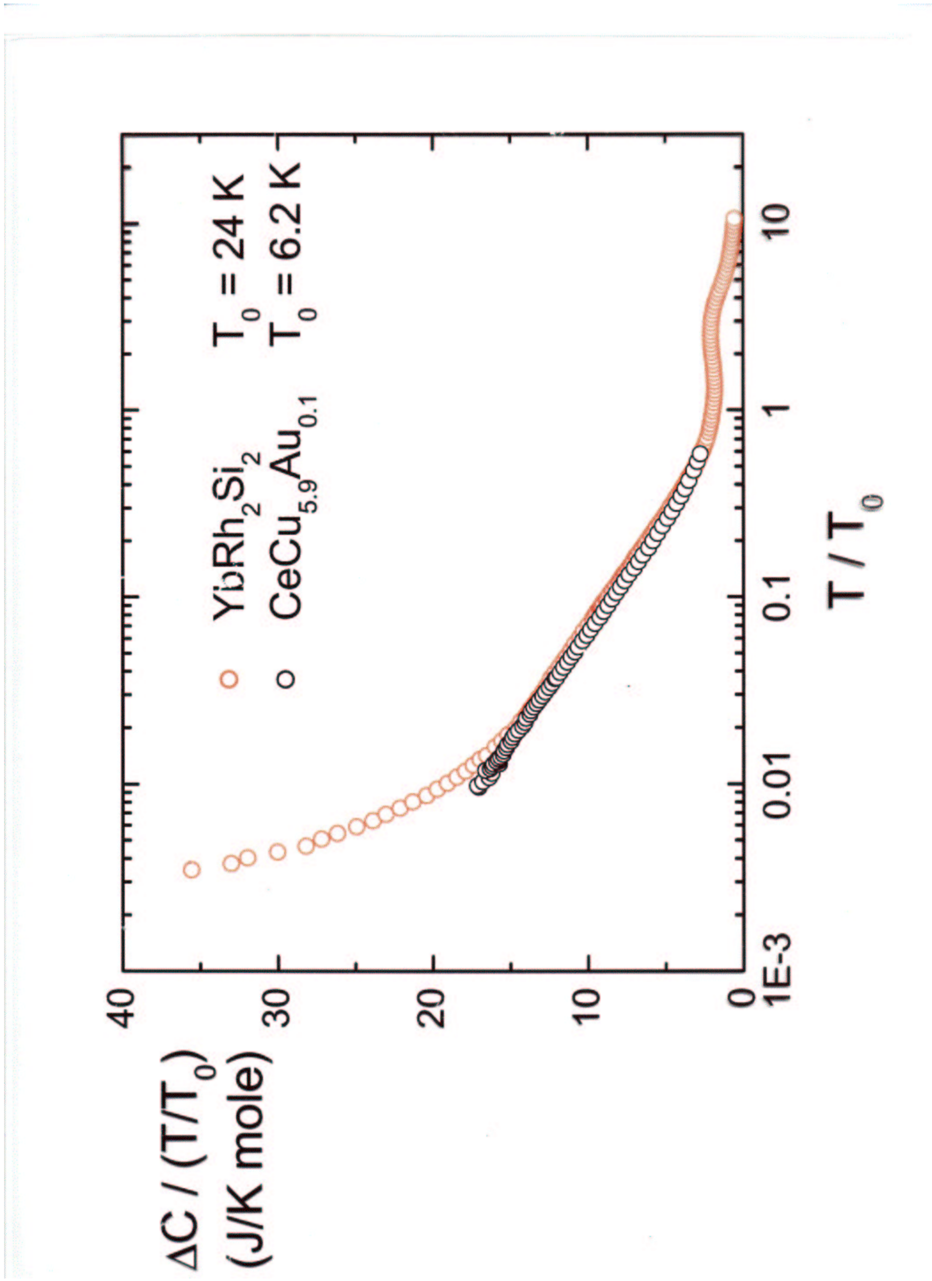
2D AF-SF in 3D Fermi sea

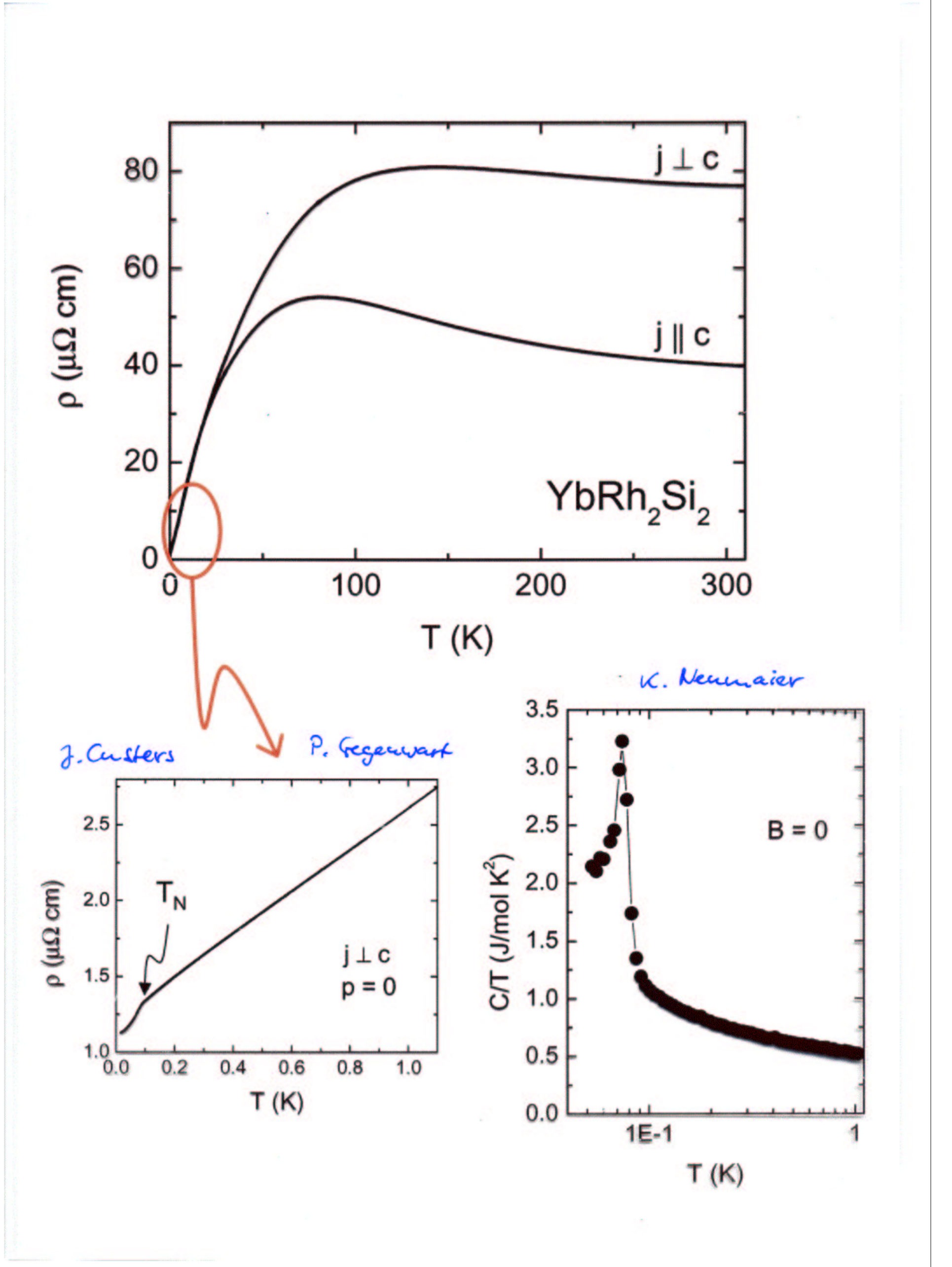




v. Löhneysen '96



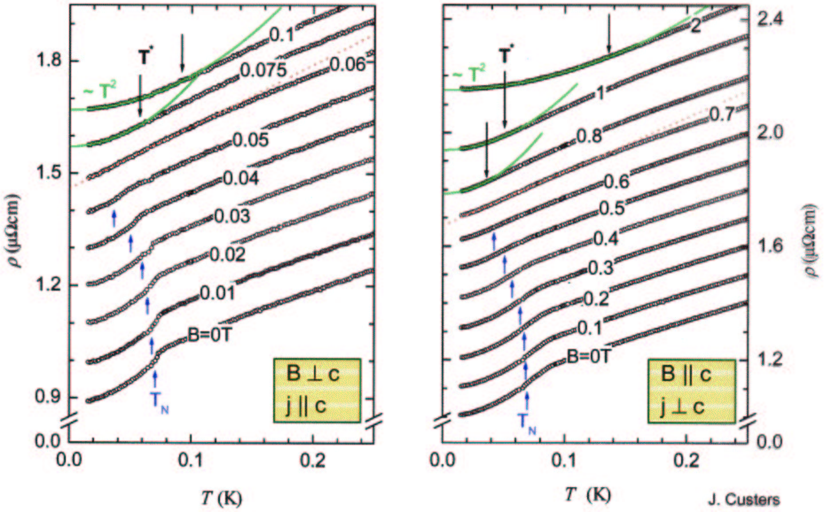

ΔC / (T/T₀) (J/K mole)
T / T₀
YbRh₂Si₂ T₀ = 24 K
CeCu₅.₉Au₀.₁ T₀ = 6.2 K
40
30
20
10
0
1E-3
0.01
0.1
1
10


ρ (μΩ cm)
T (K)
j ⊥ c
j ∥ c
YbRh₂Si₂
0
20
40
60
80
100
200
300
J. Custers
P. Gegenwart
ρ (μΩ cm)
T_N
j ⊥ c
p = 0
1.0
1.5
2.0
2.5
0.0
0.2
0.4
0.6
0.8
1.0
T (K)
K. Neumaier
C/T (J/mol K²)
B = 0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
1E-1
1
T (K)

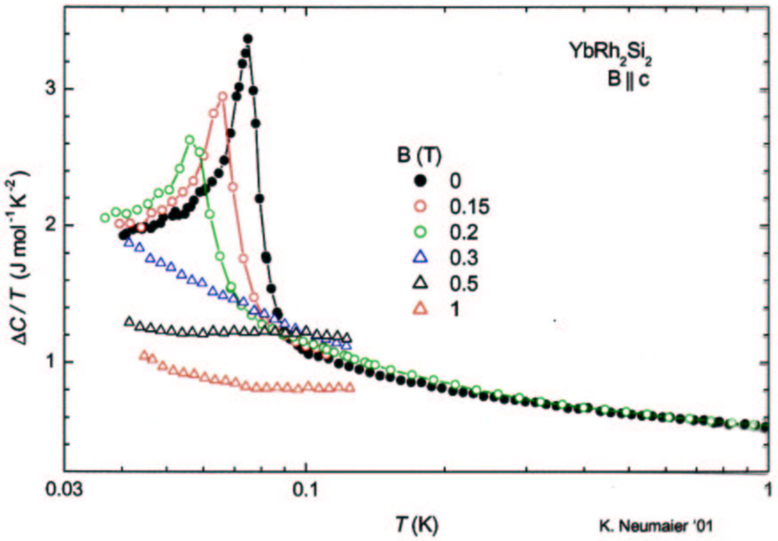
Magnetic field-induced quantum critical point

Field Induced NFL Behavior

(P. Gegenwart *et al.*, Phys. Rev. Lett. **89**, 056402 (2002))

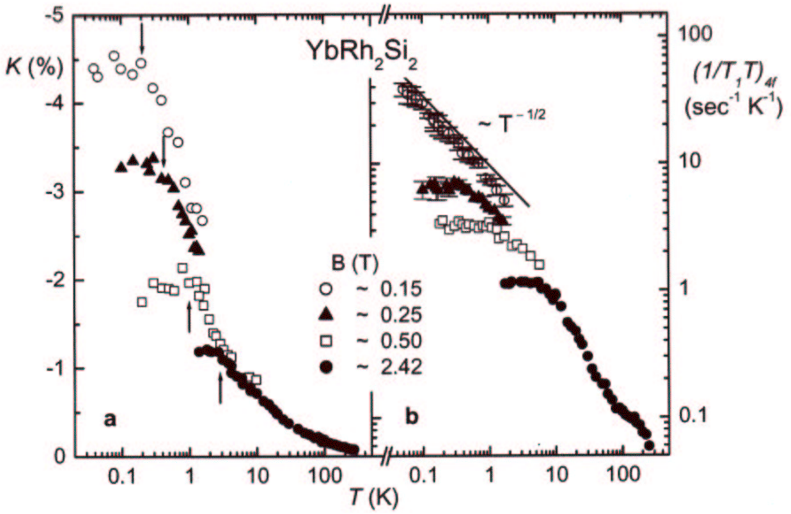


J. Custers
P. Gegenwart



^{29}Si NMR

(K. Ishida *et al.*, PRL **89**, 107202 (2002))



non-interacting electron system

$$S = (1/T_1T)\big/K_s^2 = \pi\gamma^2\hbar k_B\big/\mu_B^2 \equiv S_0$$

dominating FM / AF fluctuations: S < S$_0$ / S > S$_0$

YbRh$_2$Si$_2$ S ≈ 0.1 S$_0$
⇒ FM fluctuations dominating

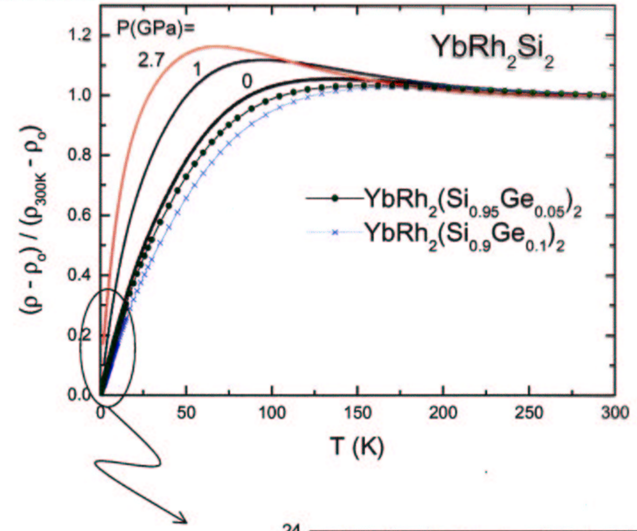
BUT: When $B \to B_c^+$ and $T \to 0$
$K = const$ and $(1/T_1T)_{4f} \propto T^{-1/2}$

critical AF fluctuations near B = B$_c$

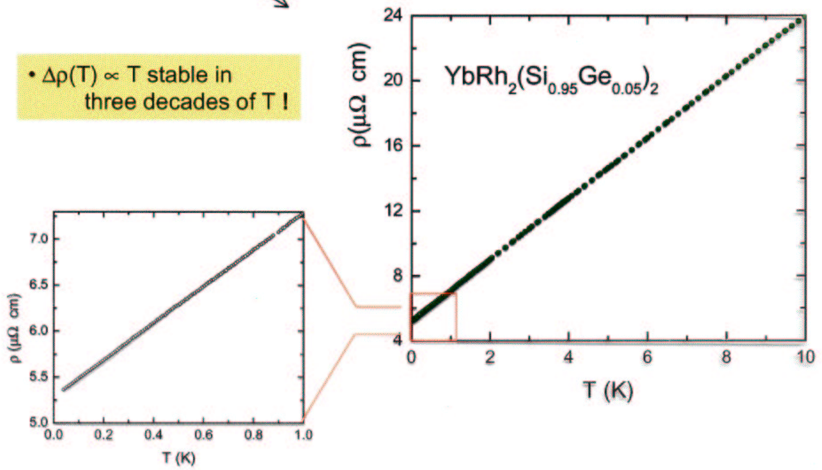
(Negative) pressure effects

Hydrostatic pressure vs Ge-doping in YbRh$_2$Si$_2$

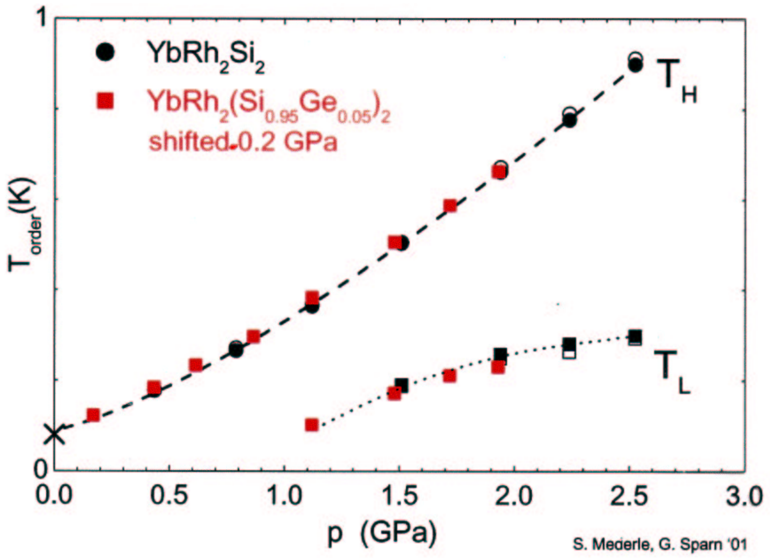
Electrical resistivity



- Δρ(T) ∝ T stable in three decades of T !

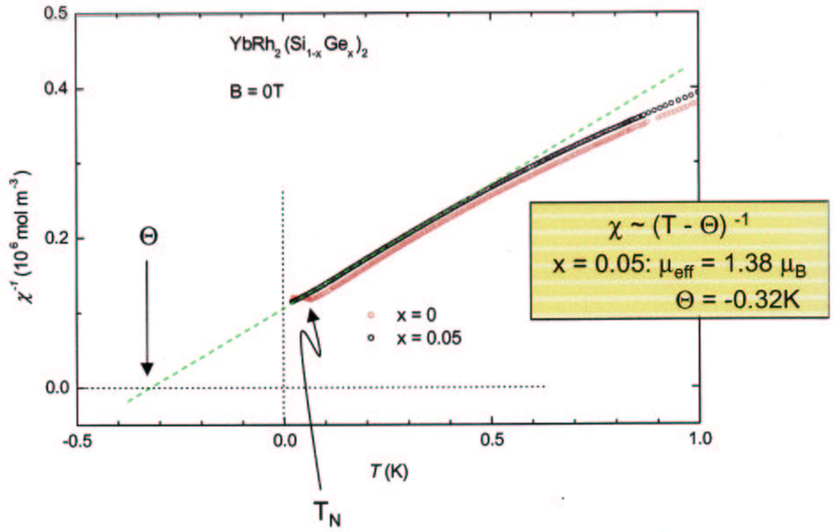


Effect of Pressure



S. Mederle, G. Sparn '01

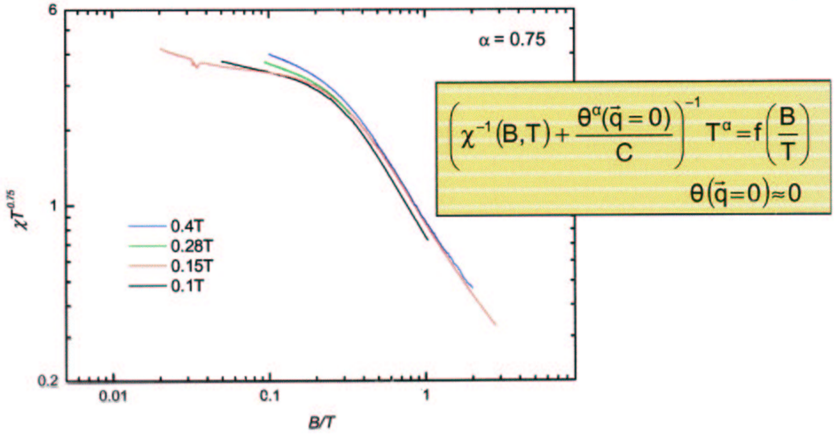
Nature of QCP



$\chi \sim (T - \Theta)^{-1}$

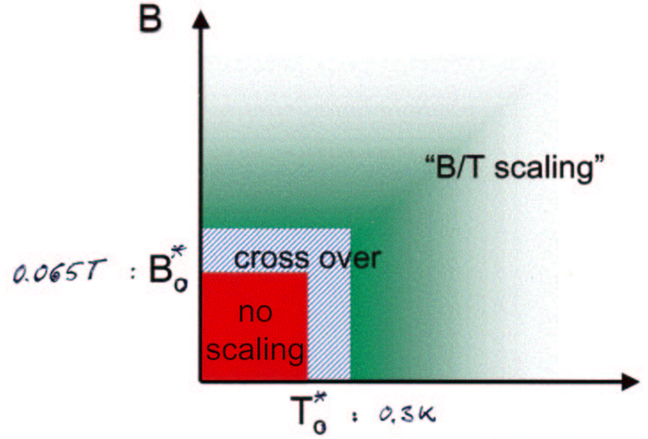
x = 0.05: $\mu_{eff} = 1.38\ \mu_B$

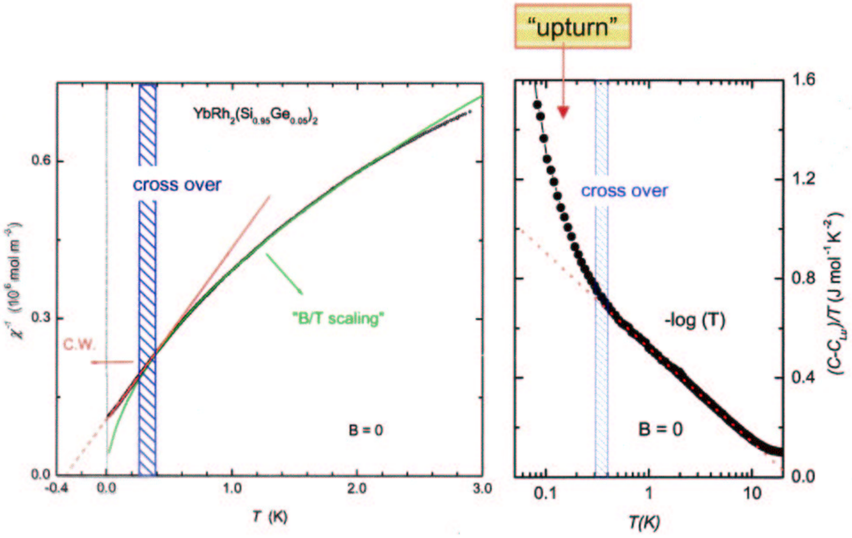
$\Theta = -0.32$K



$$\left(\chi^{-1}(B,T) + \frac{\theta^{\alpha}(\vec{q}=0)}{C}\right)^{-1} T^{\alpha} = f\left(\frac{B}{T}\right)$$

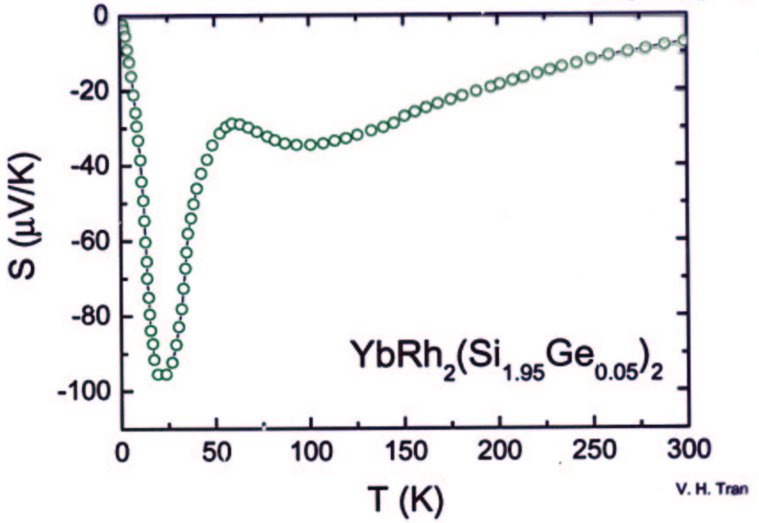
$$\theta(\vec{q}=0) \approx 0$$



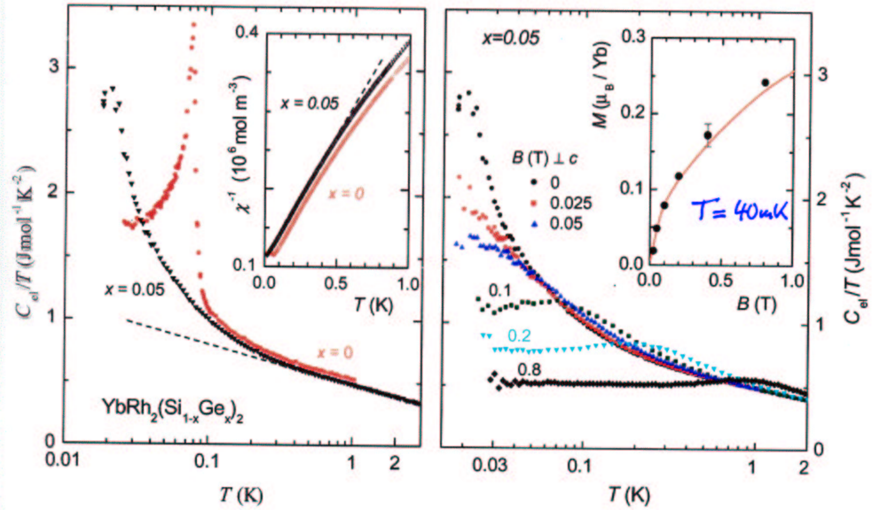


Thermoelectric Power

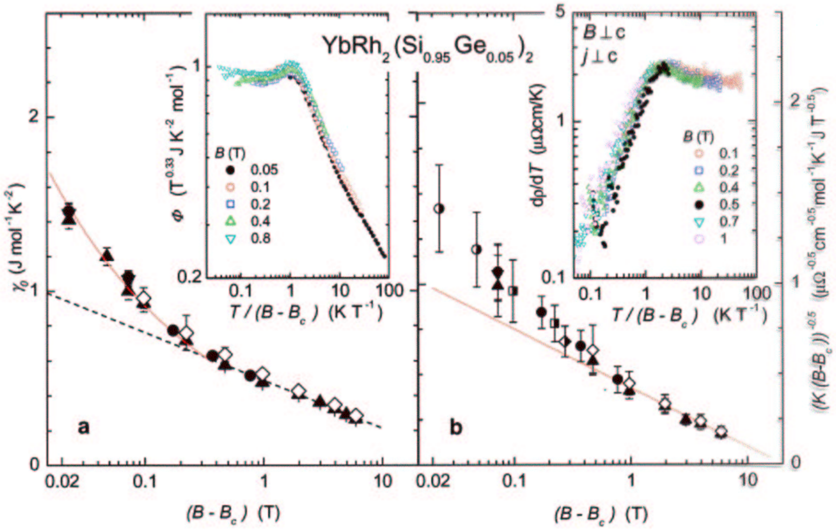
V. H. Tran '00



Low-*T* $\gamma(T)$ and $\chi(T)$ for $YbRh_2(Si_{1-x}Ge_x)_2$



Field induced LFL state for $YbRh_2(Si_{0.95}Ge_{0.05})_2$



$B \perp c$: $B_c = 0.027T$

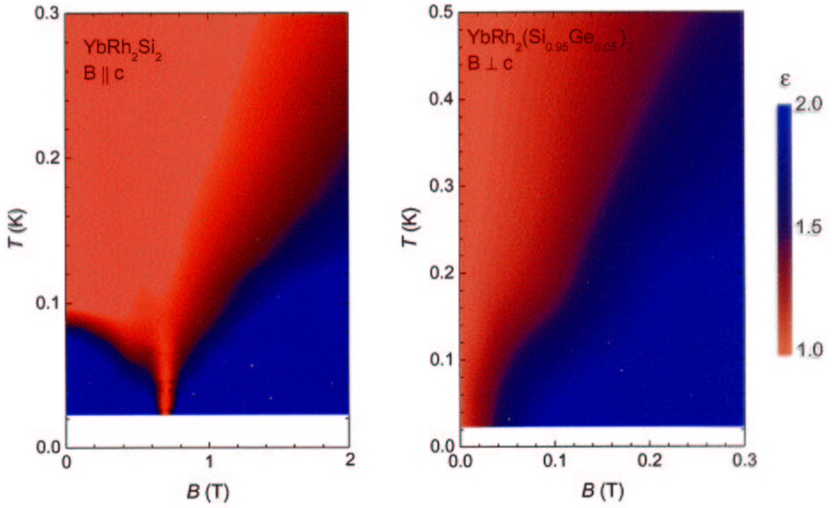
2D SDW	expt.
$\gamma_0 \propto -\ln(B-B_c)$	$\propto (B-B_c)^{-0.33}$
$K = A/\gamma_0^2 \propto ((B-B_c)\ln^2(B-B_c))^{-1}$	deviates towards lower values

Two temperature scales

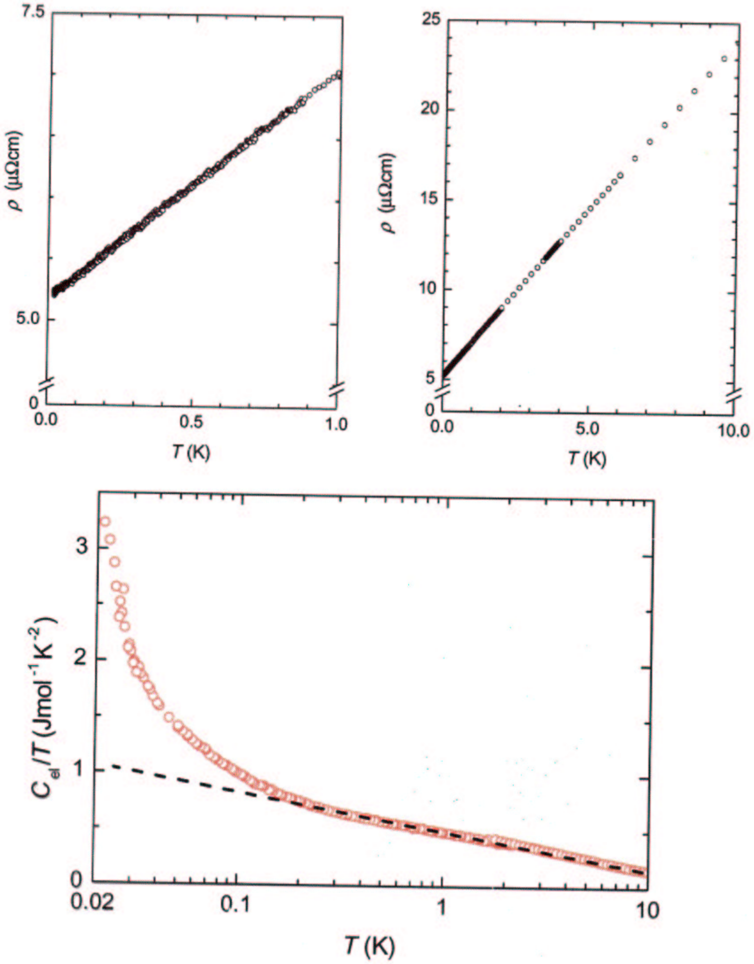
$T_F^* \propto \gamma_0^{-1} \propto (B-B_c)^{0.33}$

$T_0 \propto (B-B_c)$

$YbRh_2(Si_{1-x}Ge_x)_2$: $\Delta\rho \sim T^{\varepsilon}$



Disparity between low-T $\Delta\rho(T)$ and $\gamma(T)$ in $YbRh_2(Si_{0.95}Ge_{0.05})_2$ (B=0)



Conclusion

- First stoichiometric Yb-based compound showing NFL effects already at p=0, B=0

$\Delta\rho \propto T$ $\Delta C/T \propto -\ln T$ in a large T-range

- At elevated temperatures (T > 0.3 K) and fields (B > 0.065T)

Non-Curie-Weiss Susceptibility

B/T scaling

Similar to $CeCu_{6-x}Au_x$ [Schröder et al., Nature 407, 351 (2000)]

On approaching the QCP:

- Curie-Weiss (q=0) susceptibility, $\mu_{eff} \approx 1.4\mu_B$
  $\Theta \approx -0.3$ K

- Disparities between $\Delta\rho$ (T) and γ (T):

$\Delta\rho$ (T) ("light" ~~compound~~ component of qu.p.) agrees with SF theory

γ (T) ("heavy" ~~compound~~ component of qu.p.) disagrees with SF theory

⇒ break-up of the heavy ("composite") fermion at the QCP