Magnetic quantum phase transitions

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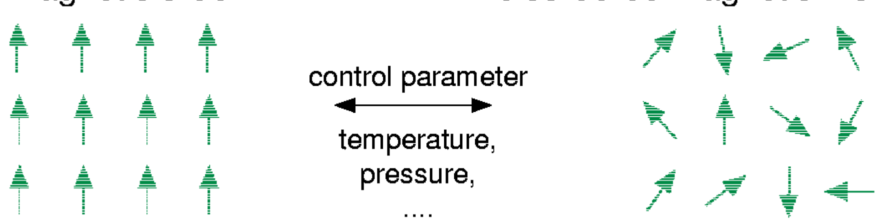
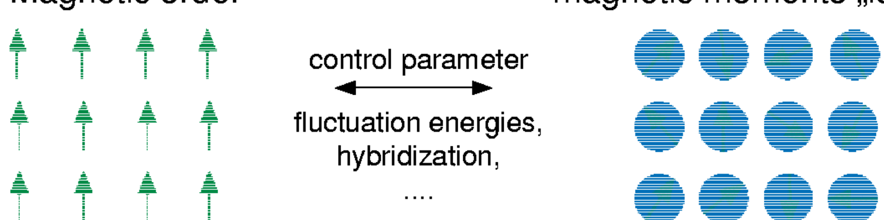
Magnetic instabilities in metals

Magnetic order disordered magnetic moments



Magnetic order magnetic moments „lost“



scenarios:
charge fluctuations, Kondo effect, itinerant magnetism

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Outline

Quantum phase transition in $CeCu_{6-x}Au_x$

- magnetic fluctuations at QCP probed by INS
- “bandstructure“ of heavy quasiparticles from Hall effect
- anisotropic pressure dependence of magnetic order
- pressure vs. field tuning: change of dimensionality ?

Magnetic instability in the case of strong disorder: $UCu_{5-x}Pd_x$

- Quantum phase transition “intercepted“ by spin-glass order ?

Quantum critical point at pressure-driven ferromagnetic instability (?)

- how a “spin solid“ melts: partial order in MnSi
- hard matter getting soft ?

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O. Stockert*** R. Vollmer

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**now at TU München, **now at Kent State, ***now at MPI Dresden*

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L. Pintschovius, D. Reznik — *neutron scattering*

P. Estrela, A. de Visser — *thermal expansion*

R. Chau, M. B. Maple — *$UCu_{5-x}Pd_x$*

M. Garst, A. Rosch, P. Wölfle,
P.Coleman, R. Ramazashvili — *theory*

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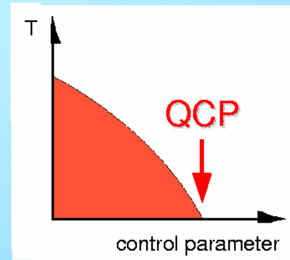
Magnetic quantum phase transitions in metals: important issues

Non-Fermi-liquid behavior:
What happens to the Fermi surface?

Low energy scales, otherwise masked by magnetic interaction, may become important as $T_c \to 0$:
Possibility of novel phases



Examples

- Superconductivity in the vicinity of quantum critical points
- Low-dimensional fluctuations over an extended *x*-range in $CeCu_{6-x}Au_x$
- Partial order in MnSi

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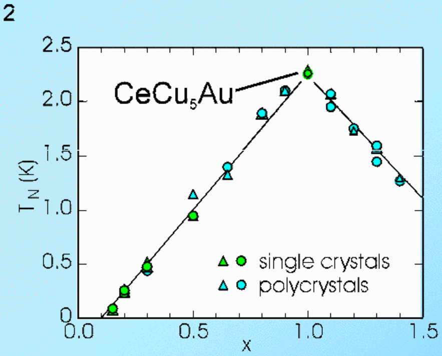
Quantum phase transition in $CeCu_{6-x}Au_x$

$CeCu_6$: heavy fermions with $\gamma = 1.6$ J/molK^2

non-magnetic groundstate
Onuki, Amato

short lived AF correlations
Aeppli, Rossat-Mignod



Alloying with Au: long-range AF order
"negative lattice pressure" explains $T_N(x)$ for x < 1

Onset of AF order at x_C = 0.1: quantum phase transition

Non-Fermi liquid behavior:

$$\frac{C}{T} = a \ln\left(\frac{T_0}{T}\right), \quad \rho = \rho + AT, \quad T_N \sim x - x_C$$

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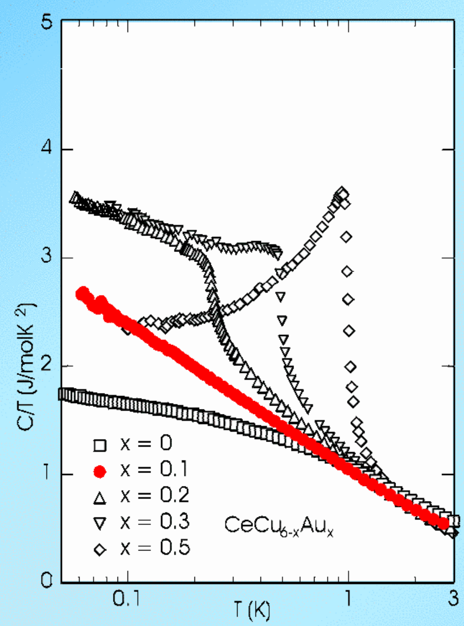
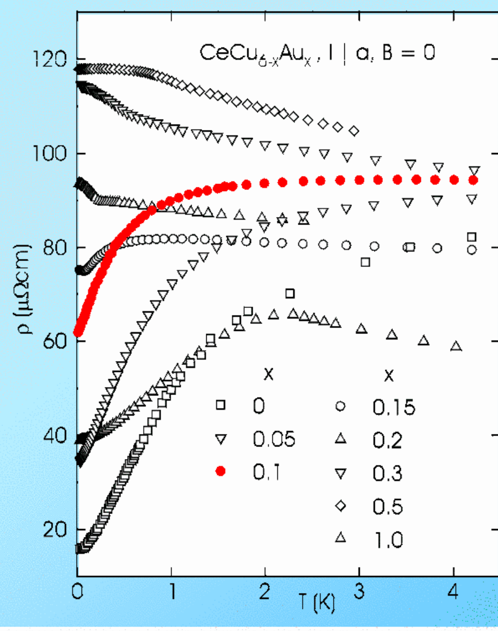
Non-Fermi liquid effects at quantum critical point in $CeCu_{6-x}Au_x$

Specific heat



Electrical resistivity



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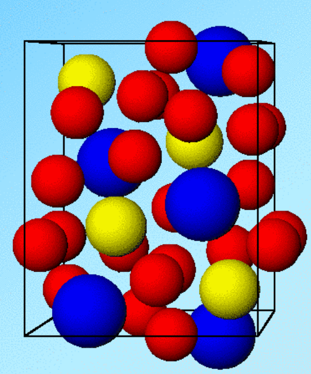
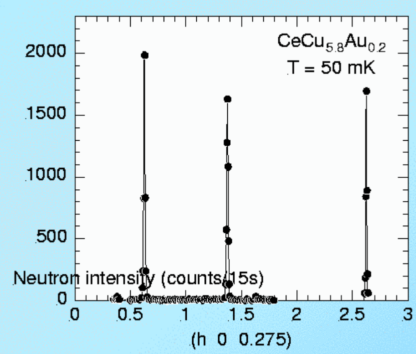
Crystal structure and magnetic order of $CeCu_{6-x}Au_x$

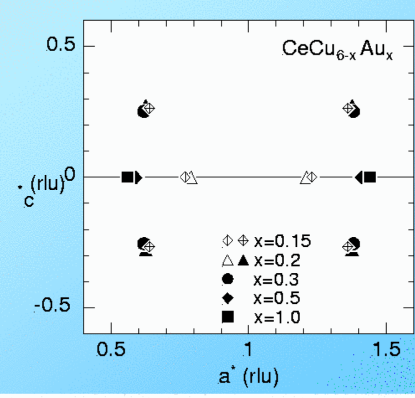
Orthorhombic structure
Pnma



Incommensurate three-dimensional magnetic ordering
...

... confined to the *a*c** plane





$CeCu_6$:
small monoclinic distortion suppressed for $x > 0.15$

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Spin-fluctuation scenario of the quantum critical point

Hertz, Millis, Moriya, Lonzarich, Rosch

		specific heat coefficient C/T	electrical resistivity $\Delta\rho$
$d = 3$	FM ($z = 3$)	$\sim \ln(T_0/T)$	$\sim T^{5/3}$
	AF ($z = 2$)	$\sim 1 - \beta\sqrt{T}$	$\sim T^{3/2}$ (dirty limit)
$d = 2$	FM ($z = 3$)	$\sim T^{-1/3}$	$\sim T^{4/3}$
	AF ($z = 2$)	$\sim \ln(T_0/T)$	$\sim T$

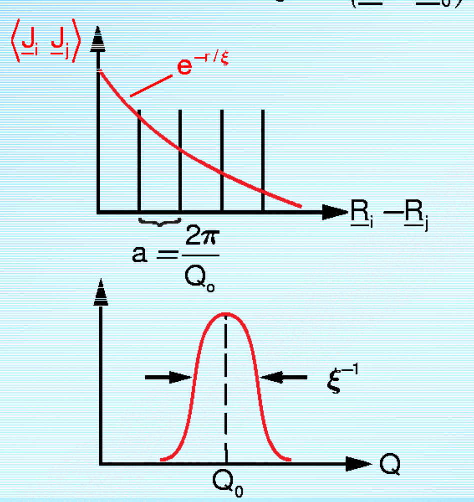
$CeCu_{6-x}Au_x$: quasi-twodimensional fluctuations?

$\Rightarrow$ inelastic neutron scattering

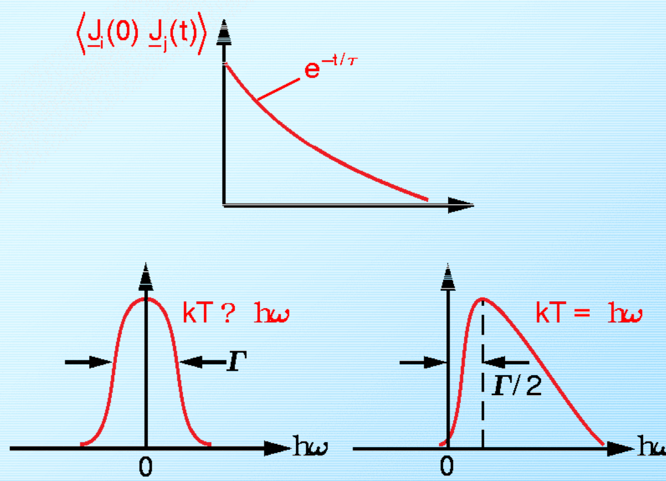
Inelastic neutron scattering

$$S(\underline{Q},\omega):\ \sum_{i,j}\int e^{i\underline{Q}(\underline{R}_i-\underline{R}_j)}\underbrace{\left\langle \underline{J}_i(0)\,\underline{J}_j(t)\right\rangle}_{\text{spin-spin correlation function}} e^{-i\omega t}dt$$

$$S(\underline{Q},\omega=\mathrm{const}):\ \frac{1}{\xi^{-2}+(\underline{Q}-\underline{Q}_0)^2}$$

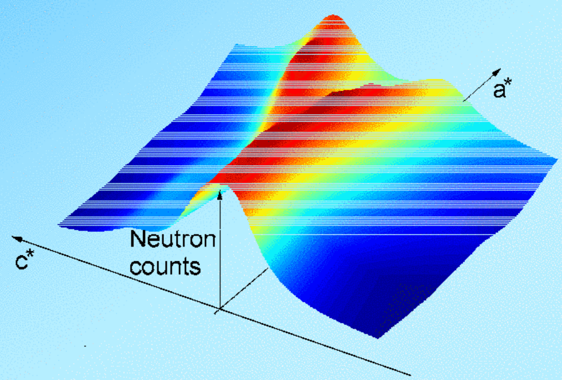


$$S(Q=\mathrm{const},\omega):\ \frac{1}{1-e^{-\hbar\omega/kT}}\ \frac{\omega\,\Gamma/2}{(\Gamma/2)^2+\omega^2}$$



Inelastic neutron scattering intensity of $CeCu_{5.9}Au_{0.1}$

From scans along c* in the *a*c** plane



energy transfer $\hbar\omega = 0.1$ meV

1D features in k-space

A 2D features in real space

⇒ quasi-2D fluctuations

Coupling to 3D quasiparticles

$d = 2$, $z = 2$

⇒ $d_{eff} = d + z = 4$

Spin-density wave scenario:

$$\frac{C}{T} = a \ln\left(\frac{T_0}{T}\right), \quad \Delta\rho \sim T$$

$$T_N \sim |\delta - \delta_C|, \quad \delta = p,x$$

Hertz, Millis, Moriya, Lonzarich, Rosch

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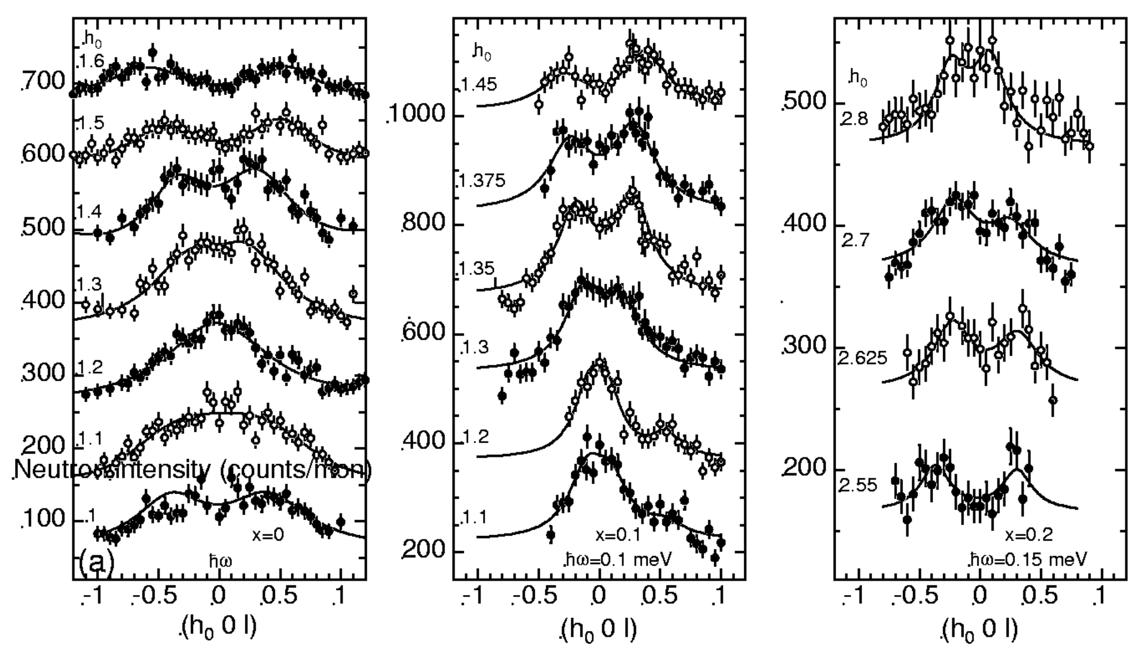
Inelastic neutron scattering intensity in the *a*c** plane



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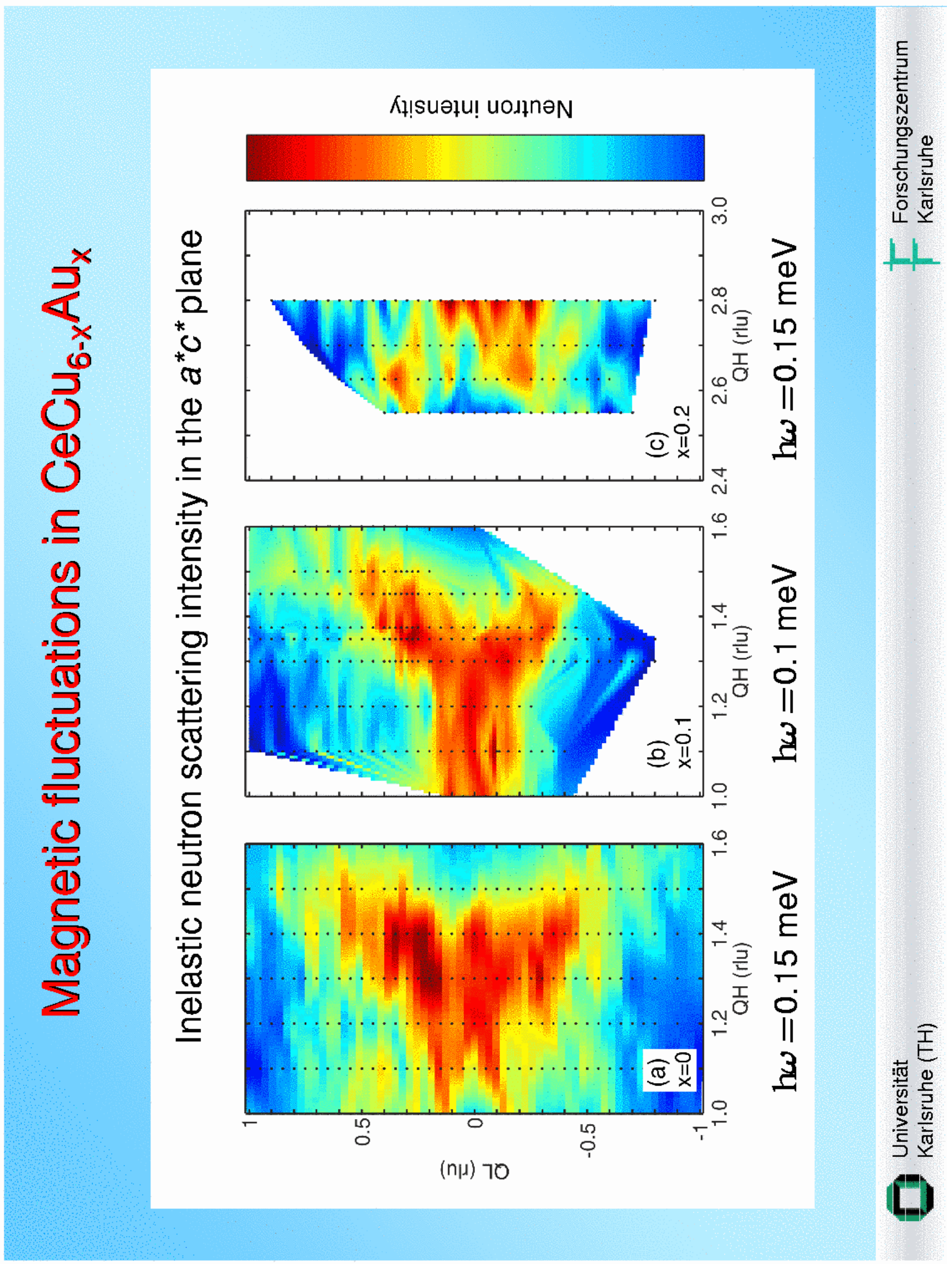
Magnetic fluctuations in $CeCu_{6-x}Au_x$
Inelastic neutron scattering intensity in the a*c* plane
(a) x=0
(b) x=0.1
(c) x=0.2
QL (rlu)
QH (rlu)
Neutron intensity
ħω = 0.15 meV
ħω = 0.1 meV
ħω = 0.15 meV
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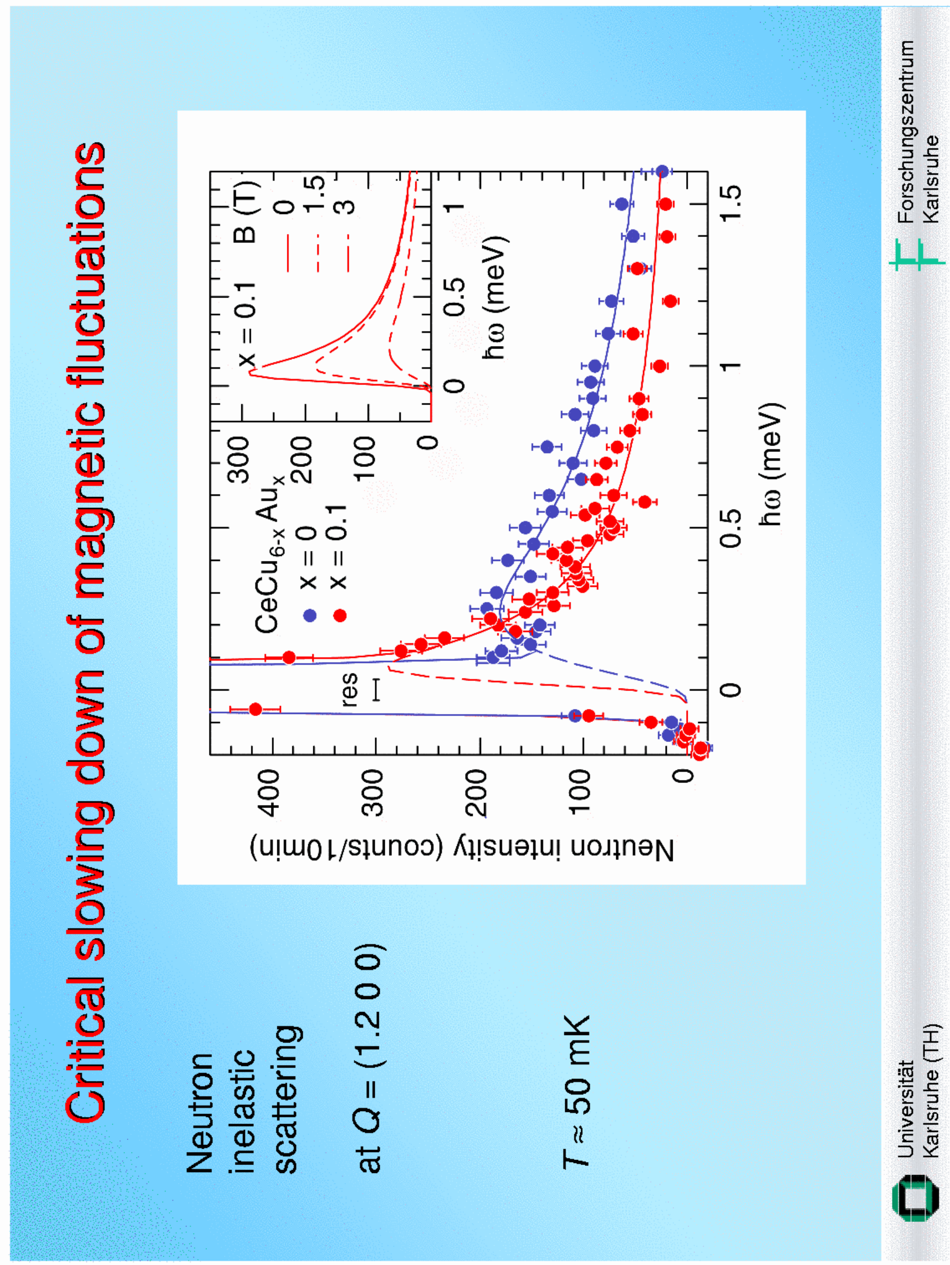
Critical slowing down of magnetic fluctuations
Neutron inelastic scattering
at Q = (1.2 0 0)
T ≈ 50 mK
$CeCu_{6-x}Au_x$
x = 0
x = 0.1
res
Neutron intensity (counts/10min)
ħω (meV)
x = 0.1 B (T)
0
1.5
3
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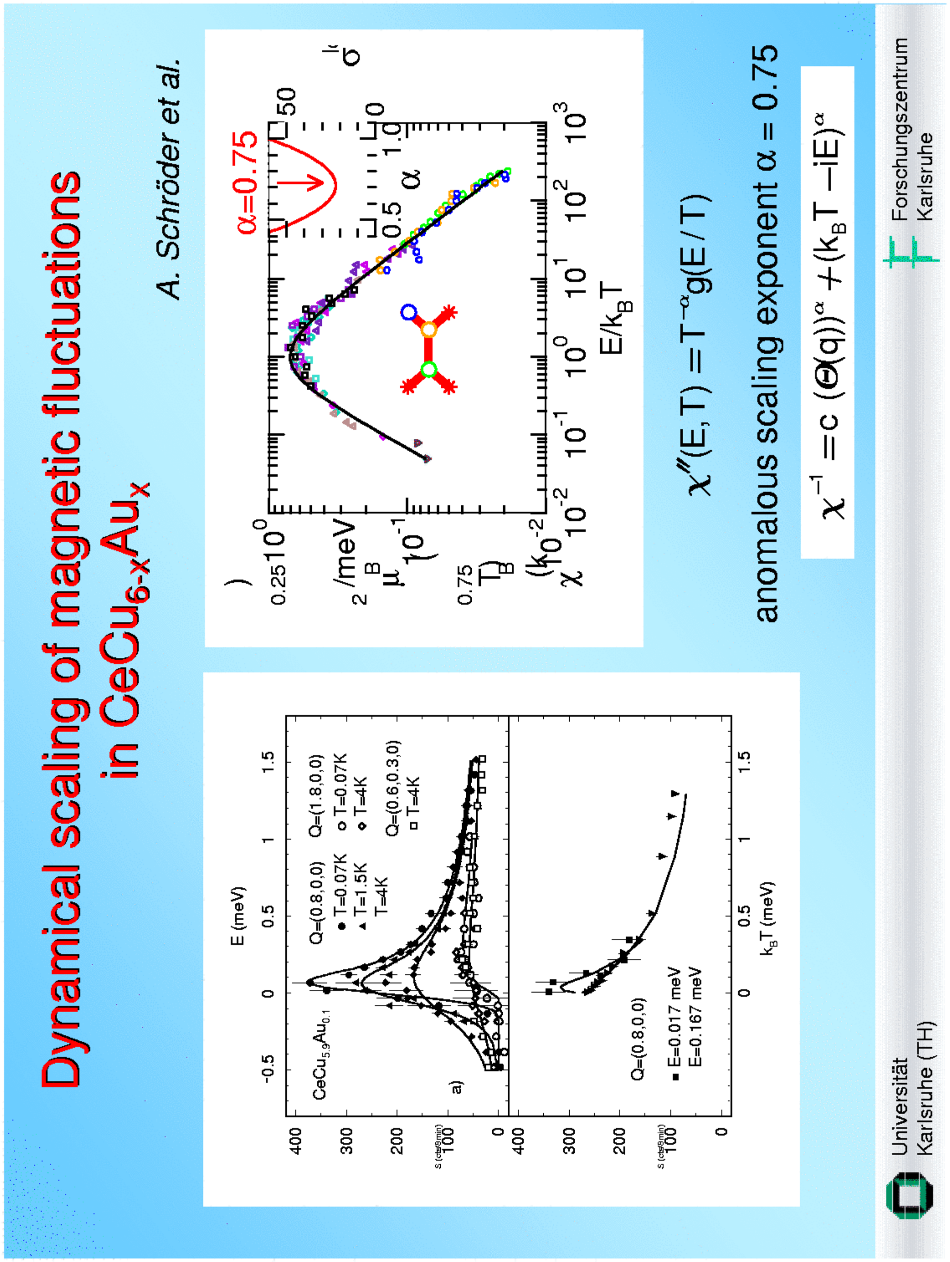
Dynamical scaling of magnetic fluctuations in CeCu6-xAux
A. Schröder et al.
α=0.75
χ″(E,T) = T^-α g(E/T)
anomalous scaling exponent α = 0.75
χ^-1 = c (Θ(q))^α + (kBT − iE)^α
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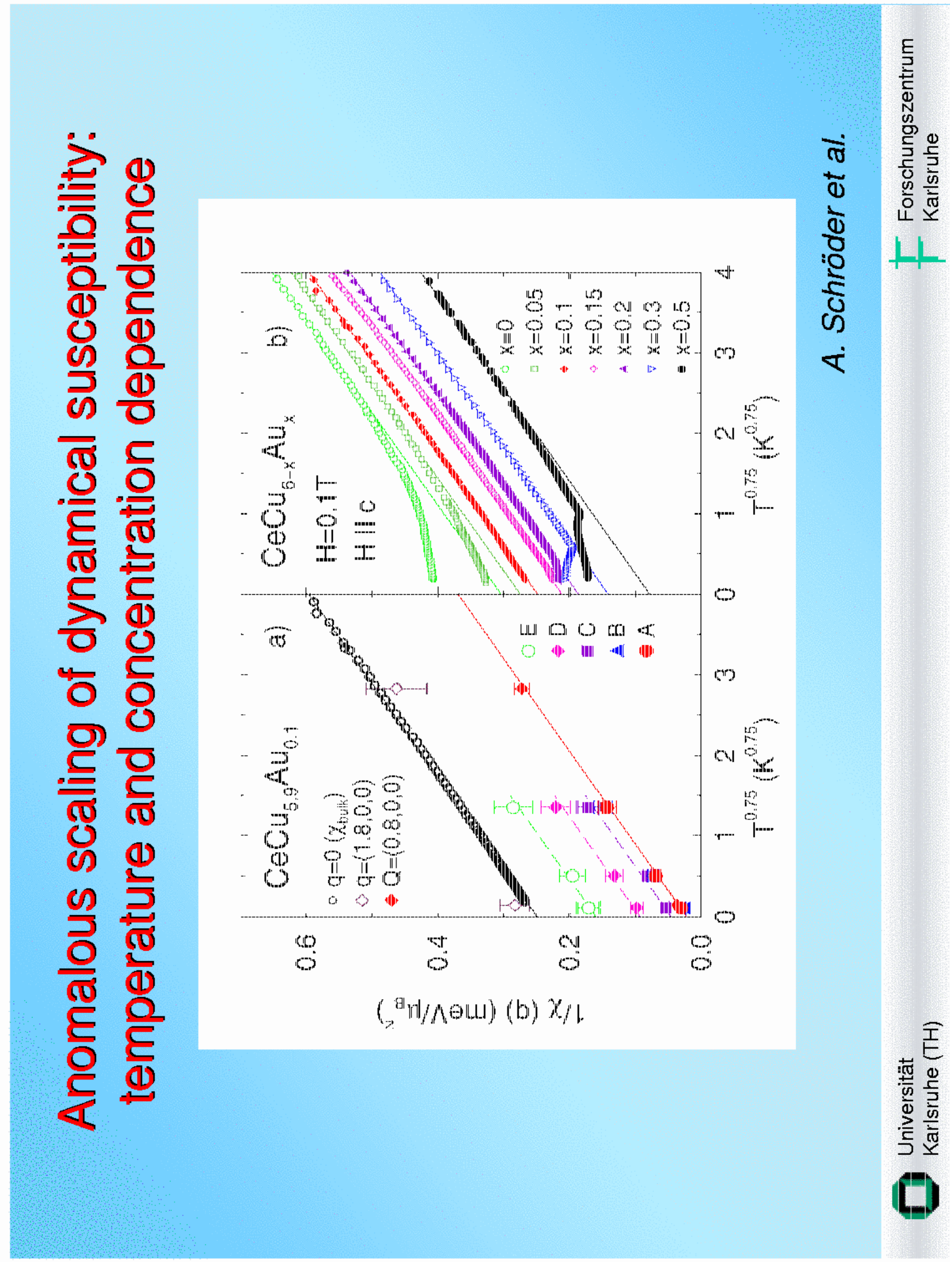
Anomalous scaling of dynamical susceptibility: temperature and concentration dependence
A. Schröder et al.
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Breakdown of Fermi liquid in $CeCu_{6-x}Au_x$?

Scaling: $\chi^{-1}(q,E,T) \sim \chi_0^{-1}(E,T) + (\Theta(q))^{\alpha}$

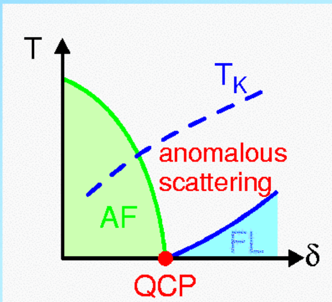
$\chi_0^{-1}(E,T)$: E/T scaling with $\alpha \approx 0.75$

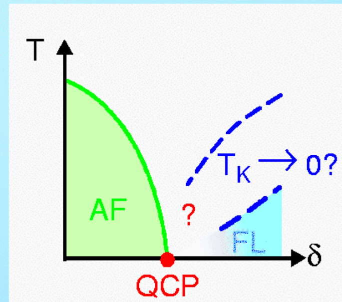
independent of q: local effect

Schröder et al.

What happens to the Fermi surface?

Two scenarios





magnetic instability

quasiparticles and spin fluctuations

Hertz,Millis,Moriya, Rosch et al.

breakdown of Fermi liquid

local instability

Coleman,Si, Pepin et al.

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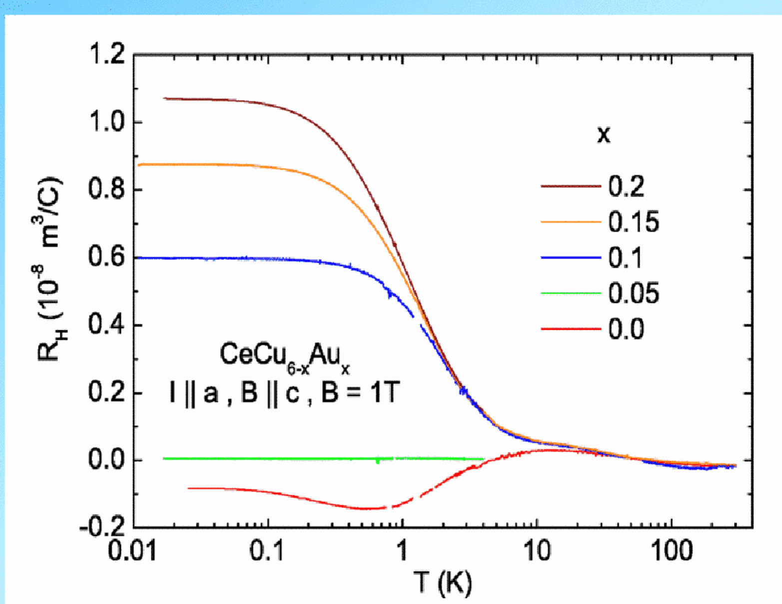
Hall constant of $CeCu_{6-x}Au_x$



$T > 20$ K ($T >> T_K$):
R_H independent of x

$T < 10$ K:
strong x dependence

sign change from $R_H < 0$ for $x = 0$ to $R_H > 0$ for $x > 0.05$

$T \lesssim 0.1$ K:
development of a coherent ground state: R_H independent of T down to ~ 20 mK

Possibility:
hole-like to electron-like Fermi surface of heavy quasiparticles

Problems:
anomalous Hall effect
different scattering rates

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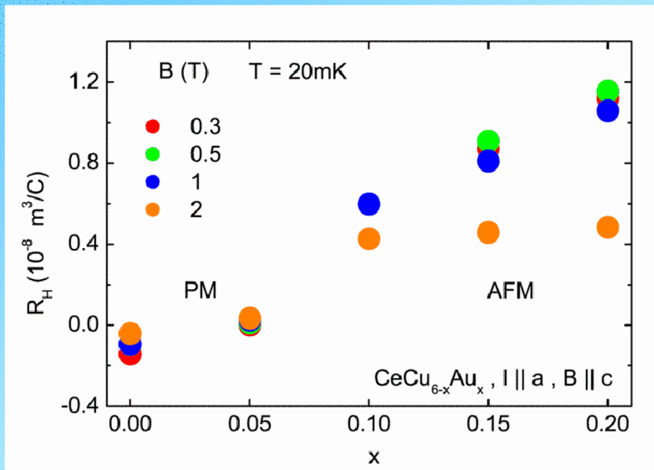
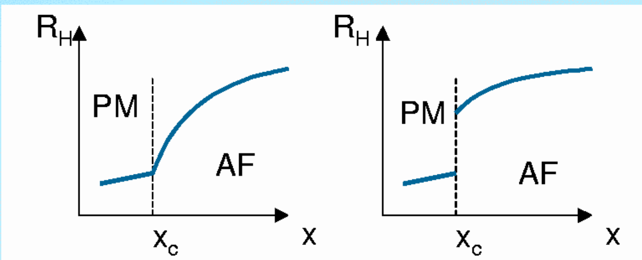
Evolution of $R_H\ (T \to 0)$ with x





Different scenarios

SDW: $R_H(x)$ continuous

local quantum criticality:
$R_H(x)$ discontinuous or
$dR_H(x)/dx$ singular

$R_H(p)$ needed to distinguish between different scenarios

Here: strong B dependence of $R_H\ (T \to 0)$ for $x > 0.1$
related to anomalous Hall effect?

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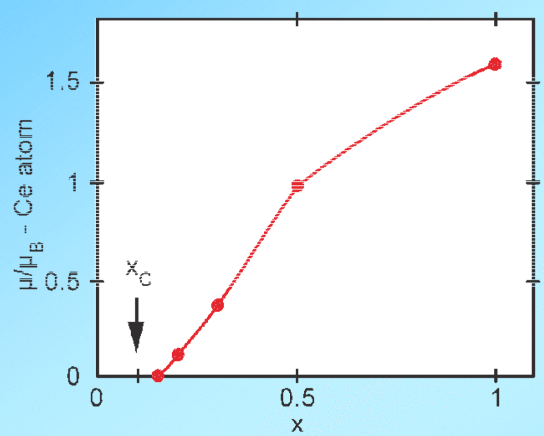
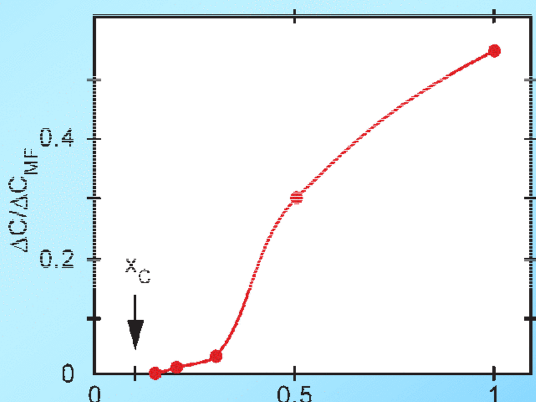
Evolution of ordered magnetic moment in $CeCu_{6-x}Au_x$

from neutron scattering



Initially very small moments in the ordered state

specific heat anomaly



ΔC_{MF} = 1.5 J/moleK^2

compatible with $R_H(x)$??

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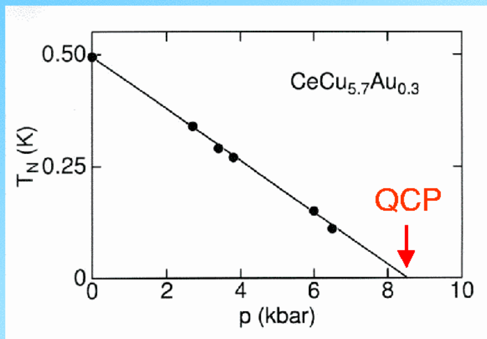
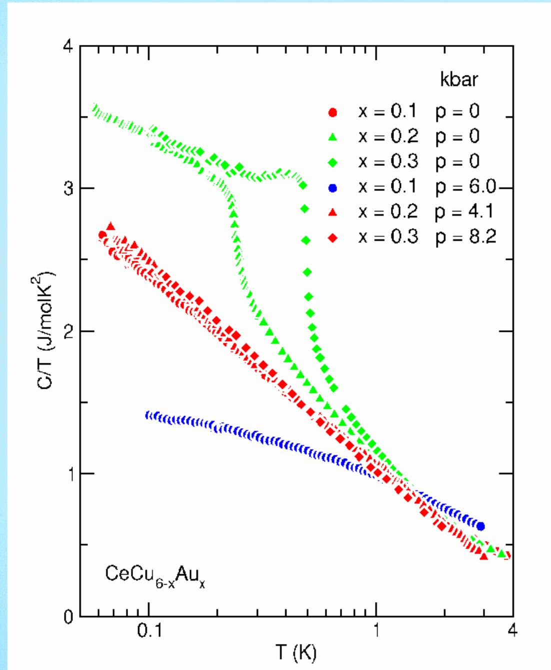
Interplay of concentration and pressure tuning

Pressure dependence of T_N



Specific heat

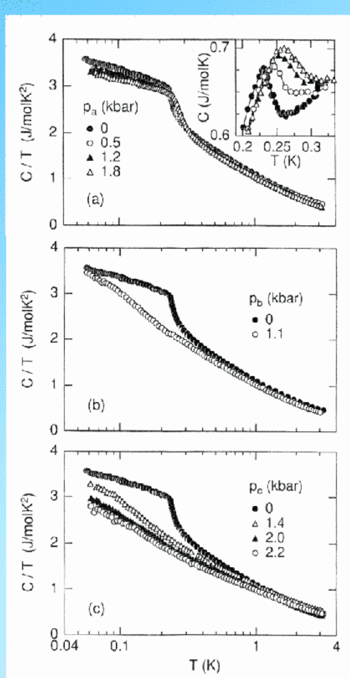


Surprising universality of C/T at quantum critical points

x = 0.1	p = 0
x = 0.2	p = 4.1 kbar
x = 0.3	p = 8.2 kbar

Suggestive of 2D fluctuations under pressure

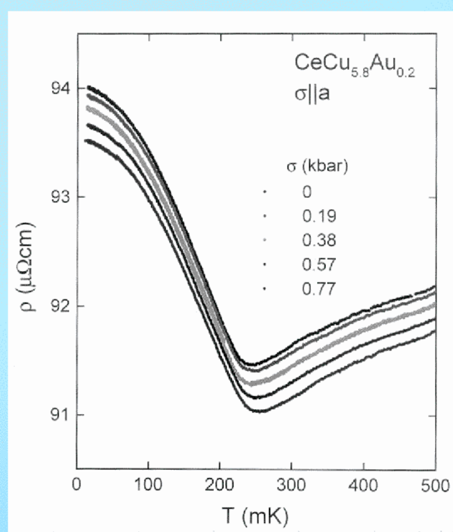
Specific heat of $CeCu_{5.7}Au_{0.3}$ under uniaxial pressure



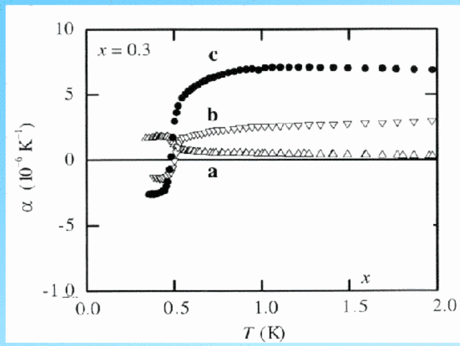
increase of T_N for stress σ along the *a* axis!

decrease of T_N for stress σ along *b* and *c* axes

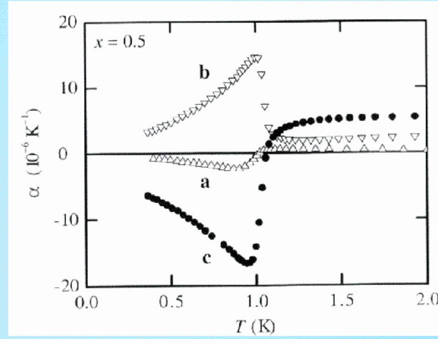
Electrical resistivity under stress along *a*



Thermal expansion of $CeCu_{6-x}Au_x$



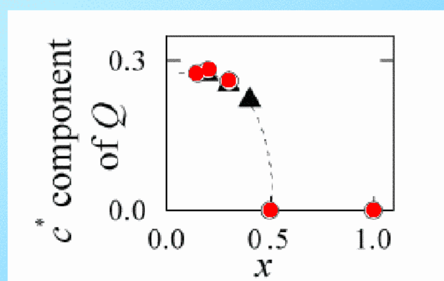
$\Delta\alpha_a < 0$; $\Delta\alpha_b$, $\Delta\alpha_c > 0$



$\Delta\alpha_a > 0$; $\Delta\alpha_b < 0$; $\Delta\alpha_c > 0$

P. Estrela, A. de Visser

Ehrenfest relation $$\frac{\delta T_N}{\delta \sigma_i} = T_N V_m \frac{\Delta\alpha_i}{\Delta C_P}$$

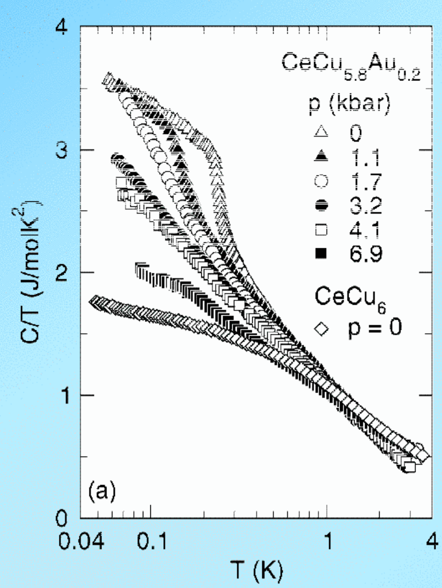


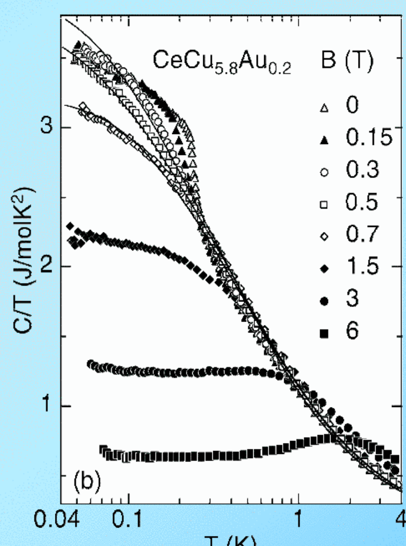
Difference between x = 0.3 and 0.5 related to change in magnetic ordering wave vector **Q** ?

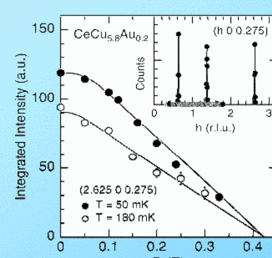
Tuning the magnetic instability of $CeCu_{1-x}Au_x$ (x = 0.2) by pressure or magnetic field: Specific heat

at p_c: $C/T \sim \ln(T_o/T)$
2D fluctuations (?)

at B_c: $C/T \sim \gamma_0 - a'\sqrt{T}$
standard 3D fluctuations - SRC (?)



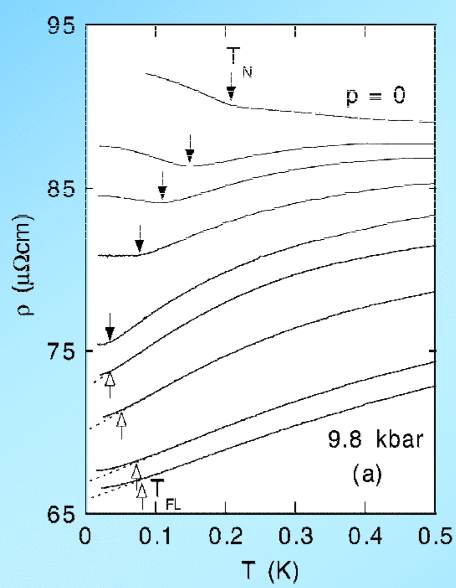




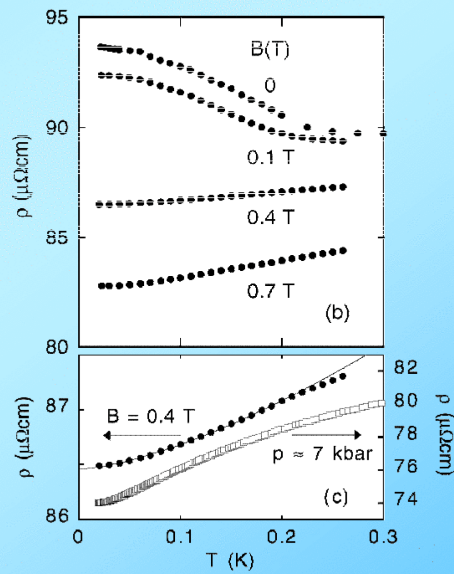
Field dependence of elastic scattering intensity

Tuning the magnetic instability of $CeCu_{1-x}Au_x$ (x = 0.2) by pressure or magnetic field: Electrical resistivity

at p_c: $\rho(T) = \rho_0 + A'T$
2D fluctuations (?)



at B_c: $\rho(T) = \rho_0 + A''T^{1.5}$
standard 3D fluctuations - SRC (?)



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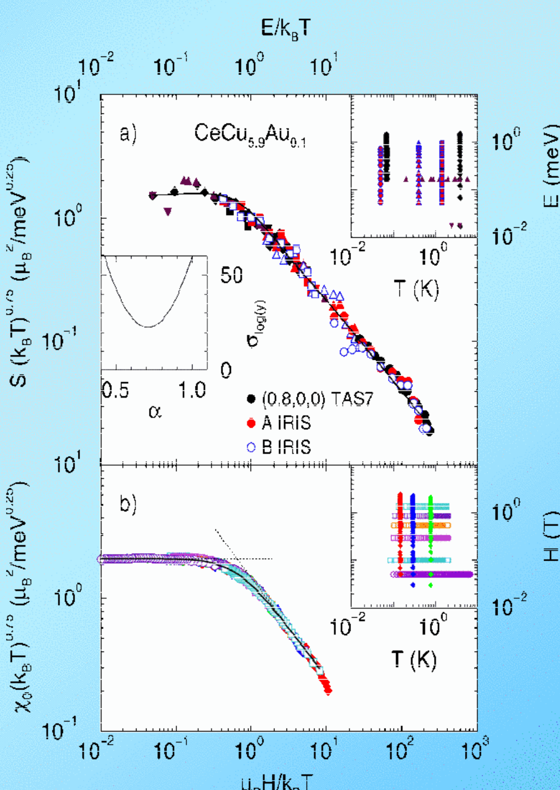
Magnetic-field / temperature scaling of the magnetization in $CeCu_{5.9}Au_{0.1}$

$$\chi^{-1}(q,E,T) = \left[\left(\left[T^2 + \left(\frac{g\mu_B}{k_B}\right)^2 H^2\right]^{1/2} - iE/a\right)^{\alpha} + \theta(q)^{\alpha}\right] C^{-1}$$



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Magnetic fluctuations in $CeCu_{6-x}Au_x$

Strongly anisotropic fluctuations in $CeCu_{6-x}Au_x$ observed over a large concentration range around the quantum critical point. Observation in $CeCu_6$ rules out a disorder-induced scenario.

Origin of low dimensionality and of change of $\boldsymbol{Q}$ vector and $dT/d\sigma_i$ unclear – strong anisotropy of RKKY coupling? Effect of magnetic field?

Low dimensionality also suggested for $YbRh_2Si_2$, but $C/T \sim T^{-1/3}$.
2D fluctuations are essential for local quantum-criticality scenario (Q. Si).

Other systems, e. g. $Ce_{1-x}La_xRu_2Si_2$ and $CeNi_2Ge_2$, indicate more conventional 3D behavior compatible with Hertz-Millis scenario.

Pronounced change of Hall constant at low T from negative to positive values with x.

More experiments needed, in particular neutron scattering.
Challenge: inelastic neutron scattering under pressure below 1 K.

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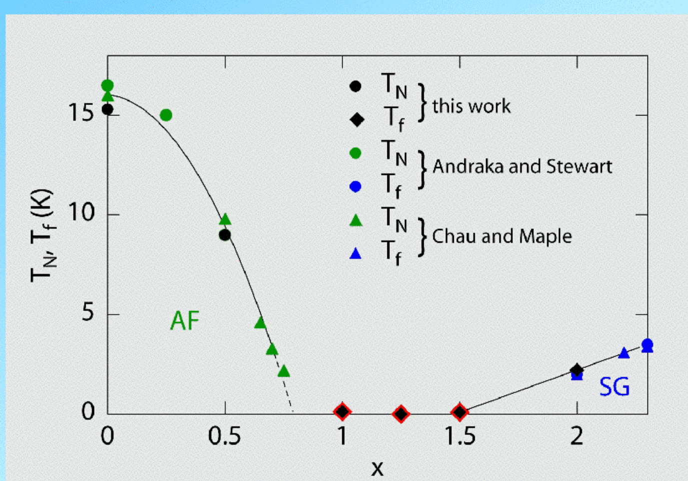
$UCu_{5-x}Pd_x$: magnetic instability in the presence of strong disorder

Andraka, Stewart
Bernal et al.



UCu_4Pd:
$\rho \approx 290\ \mu\Omega cm$ for $T \to 0$

NFL behavior in thermodynamic properties:
- distribution of Kondo temperatures due to disorder ?
- anomalous single-ion scaling of $\chi(\omega, q)$

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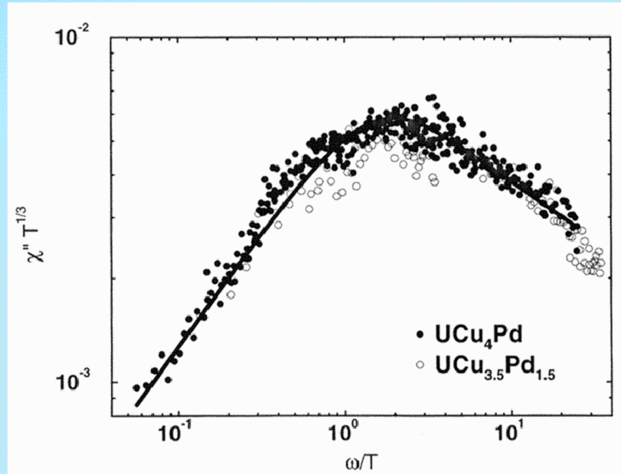
Dynamic scaling of magnetic fluctuations in $UCu_{5-x}Pd_x$

$\chi'' \cdot T^{\alpha} : (T/\omega)^{\alpha} Z(\omega/T)$

$\alpha = 0.33$

independent of *q*: single-ion effect

$CeCu_{5.9}Au_{0.1}$: $\alpha = 0.75$



What determines α ?

α = 0.33 is in line with static susceptibility

M. C. Aronson et al.

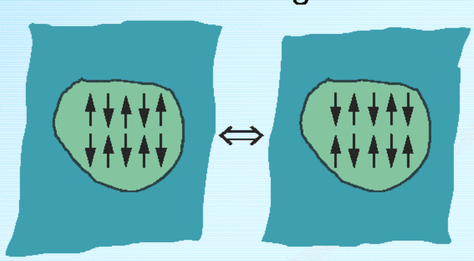
$\chi \sim T^{-0.34}$

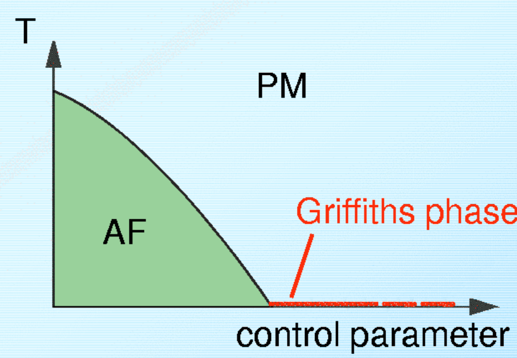
deviations at lower $T \Rightarrow$ magnetic correlations: spin glass

Griffiths phase near a magnetic instability induced by disorder

large magnetically ordered regions in paramagnetic background

tunneling





distribution of tunneling rates:

$C/T \sim \chi \sim T^{-1+\lambda}$

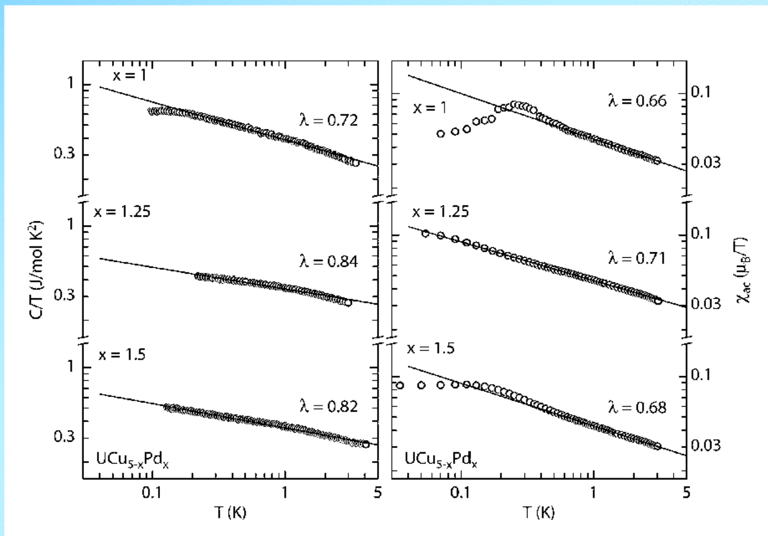
prediction of λ?

tunneling in the presence of dissipation?

$UCu_{5-x}Pd_x$: Griffiths phase scenario?

Proximity to a magnetic instability in the case of strong disorder:

NFL behavior with $C/T \sim \chi \sim T^{-1+\lambda}$ for $T \rightarrow 0$



NFL behavior gives way to spin-glass phase for x = 1 and 1.5

x = 1.25 away from instability: λ slightly larger (λ = 1 for FL)

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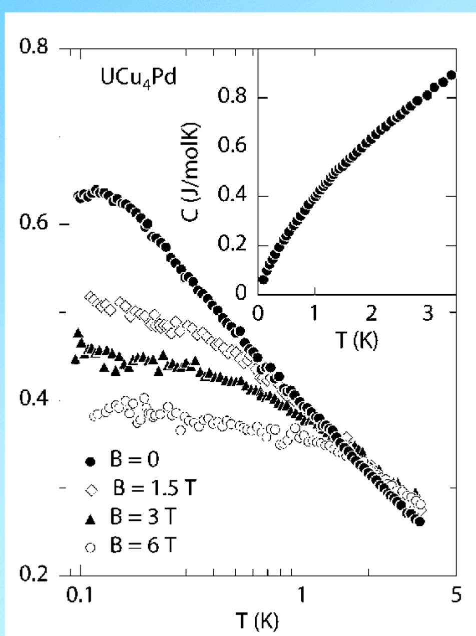
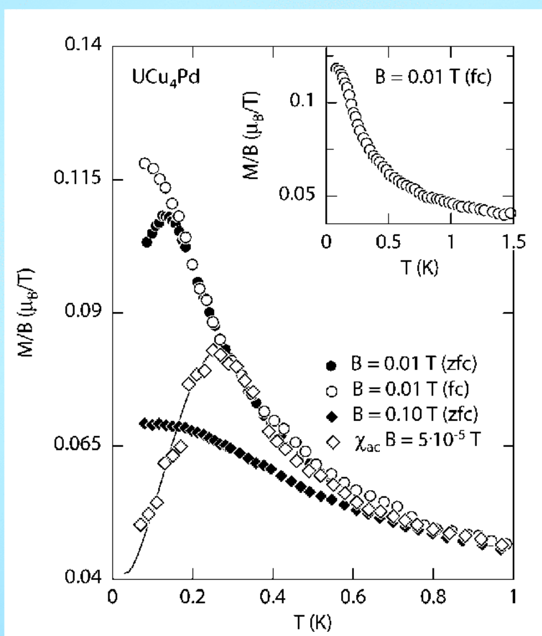
Spin-glass behavior of UCu_4Pd

specific heat



magnetic susceptibility



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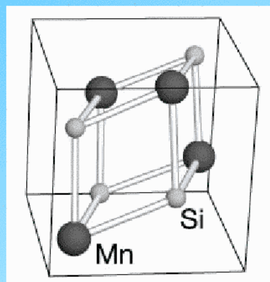
The weak itinerant ferromagnet MnSi



Representative of weak itinerant magnets:

$ZrZn_2$, Sc_3In, Ni_3Al, YNi_3, CoS_2, ...

cubic, B20 structure, no inversion symmetry

ferromagnetic: $T_c = 29.5$ K, $\mu = 0.4\ \mu_B$

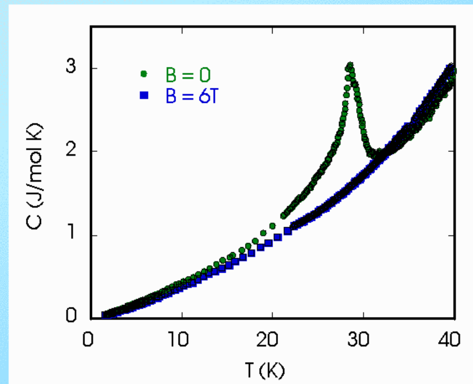
Specific heat: small entropie change at T_c

at low T: $\gamma \approx 38$ mJ/mol K^2

Spin-orbit coupling leads to a helical twist of the magnetization

$\lambda = 175$ Å

Magnetic superlattice reflections along <111> close to Bragg peaks



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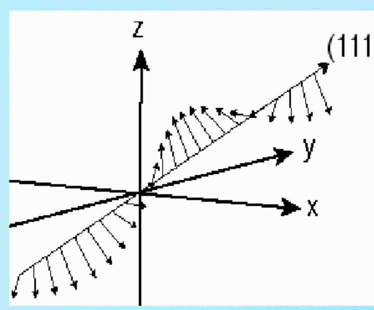
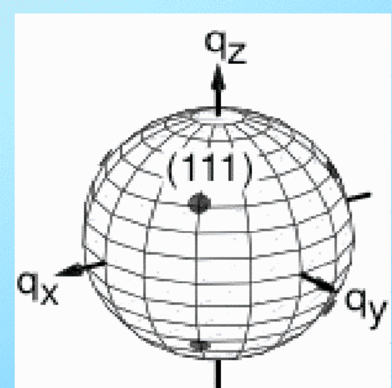
Characteristic energy scales in MnSi

- ferromagnetic exchange
- spin-orbit coupling:
  Dzyaloshinsky-Moriya interaction
  $\mathbf{s} \cdot (\nabla \times \mathbf{s})$
  leads to long-wavelength spiral structure
  $\lambda \approx 175$ Å (cf. $a = 4.558$ Å)
- crystal field potential ($P2_13$):
  helix locked at <111> or <100>, not <110>

  sharp satellite reflections at <111> positions around nuclear Bragg peaks





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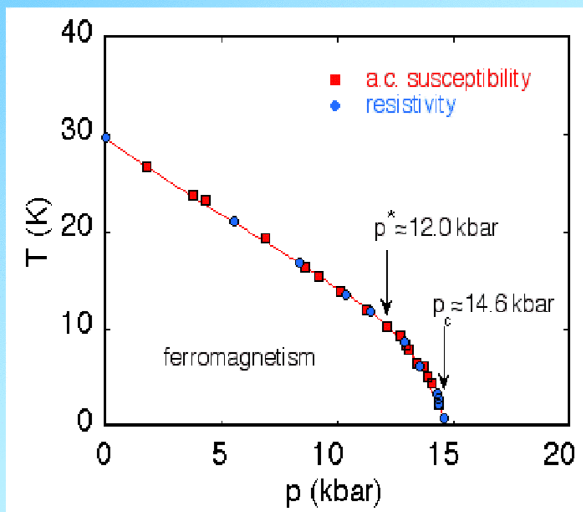
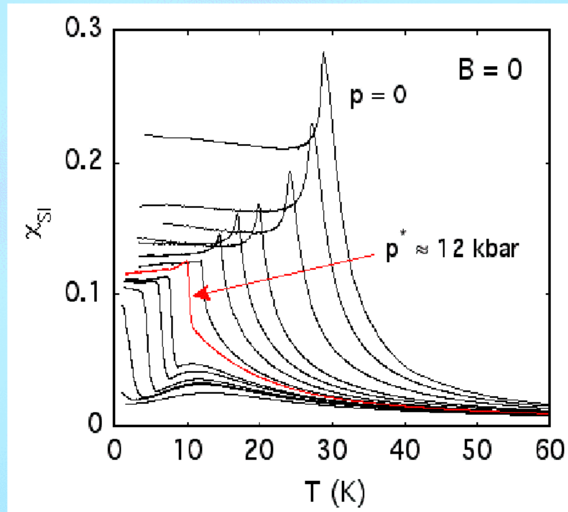
Phase diagram of MnSi under pressure

C. Pfleiderer et al. 1997, 2003

Pressure dependence of the Curie temperature



Magnetic susceptibility under pressure



Transition becomes first-order above p*

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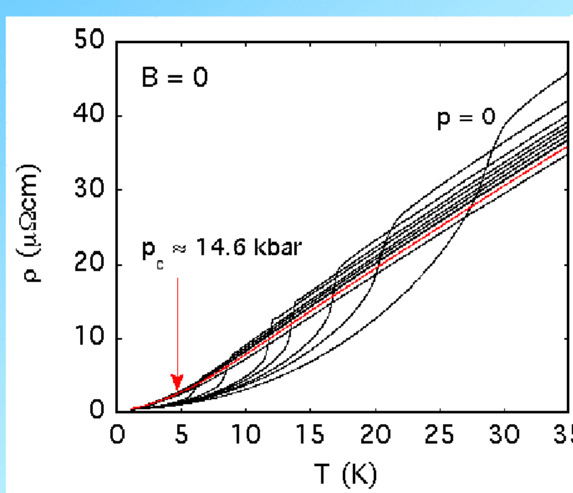
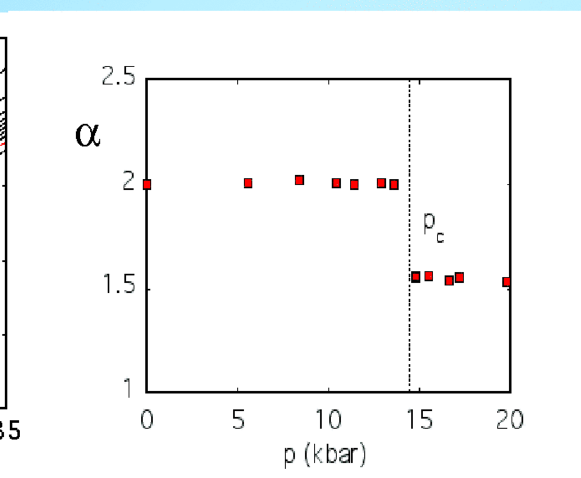
Electrical resistivity of MnSi under hydrostatic pressure

C. Pfleiderer et al. 1997, 2001; N. Doiron-Leyaud et al. 2003





Fermi-liquid T dependence

$\rho(T) = \rho_0 + AT^{\alpha}$, $\alpha = 2$

observed for $p < p_c$, $T < T_c$ only

Non-Fermi-liquid behavior

$\alpha = 3/2$

for $p > p_c$ over large p, T range

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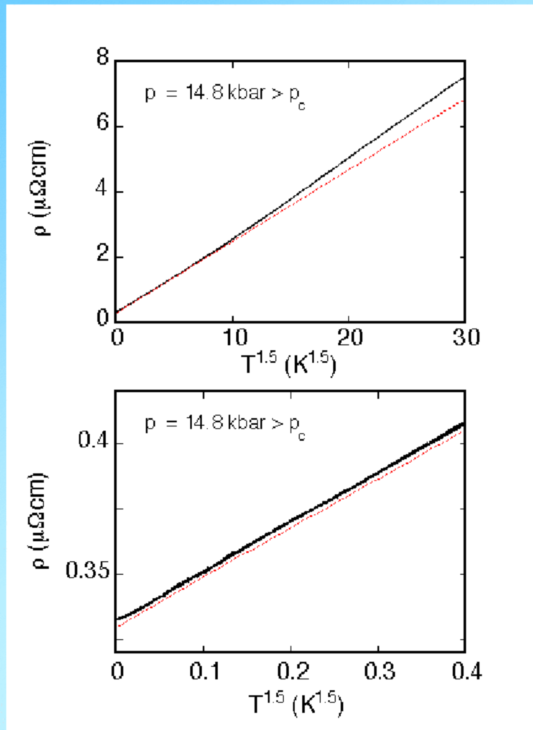
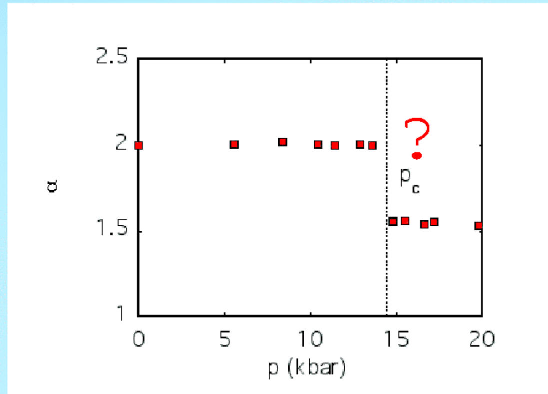
Non-Fermi-liquid phase of MnSi for $p > p_c$



C. Pfleiderer et al., N. Doiron-Leyaud et al.



$\rho(T) = \rho_0 + AT^{\alpha}$, $\alpha = 3/2$

between ~ 10 mK and 6 K

α insensitive to ρ_0

α insensitive to pressure

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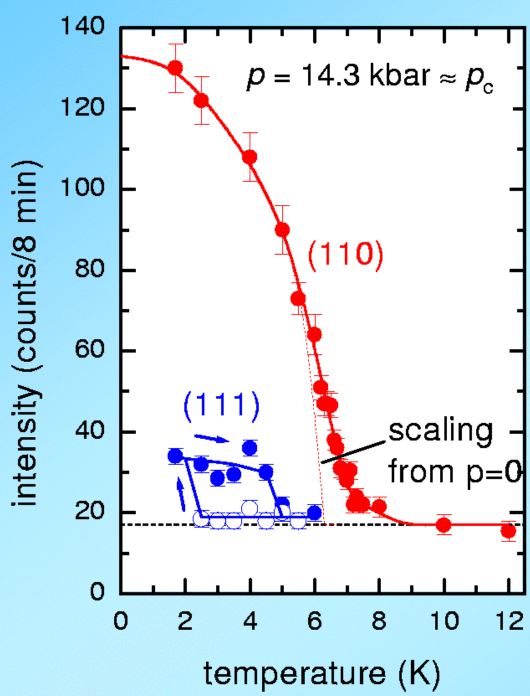
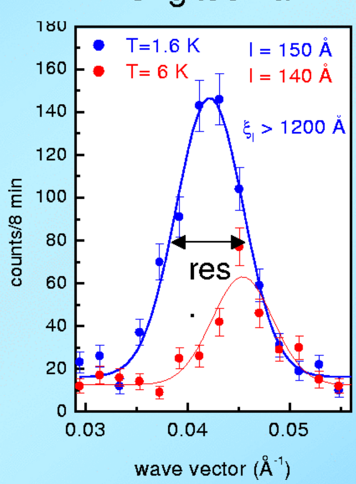
Temperature dependence of elastic scattering at $p \approx p_c$

LLB, CEA Saclay: triple-axis spectrometry with cold neutrons

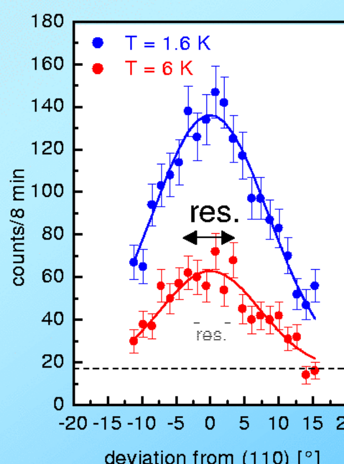


longitudinal



long range order along the helical direction (resolution limited)

transverse



wide angular distribution of helical direction

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Strange magnetic state of partial order

Observed around and even above p_c, with sluggish onset

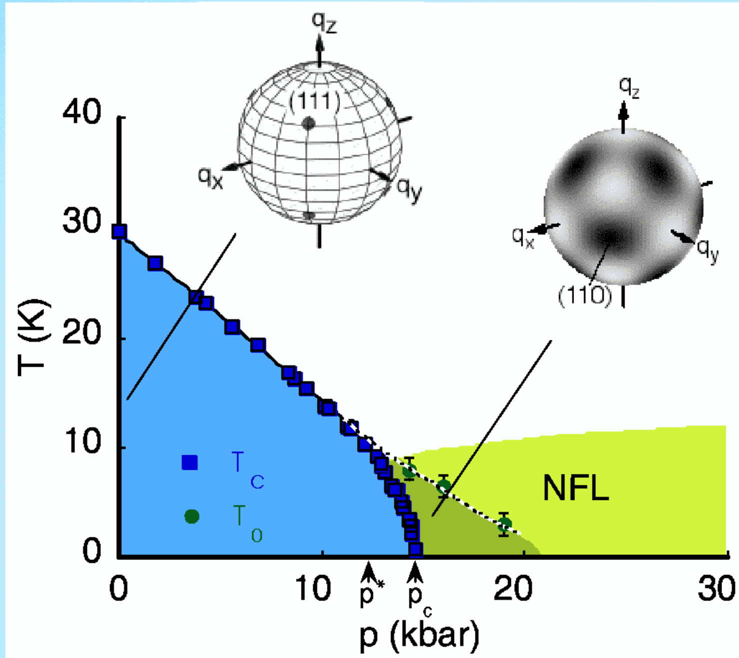
Order remains helical with little change of periodicity and total intensity compared to $p = 0$

Long-range (> 2000 Å) order along propagation direction of the helix

Propagation directions are distributed over a very wide angular range: "partial order"

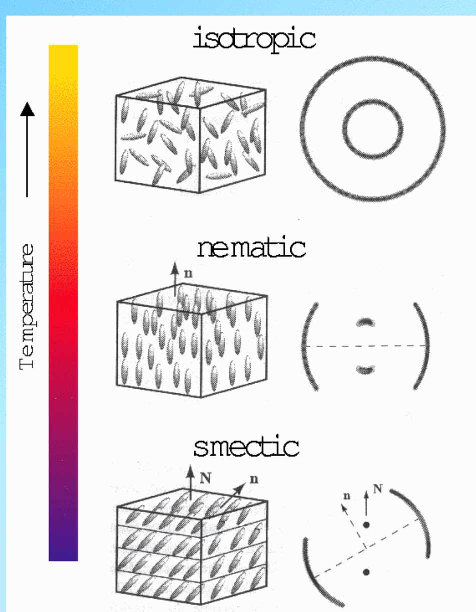
Static or dynamic? Energy resolution $\Delta E = 0.05$ meV

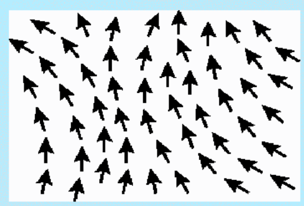
Partial order also seen in NMR experiments: W. Yu et al., 2004



Strange magnetic state: analogy with partial order in liquid crystals

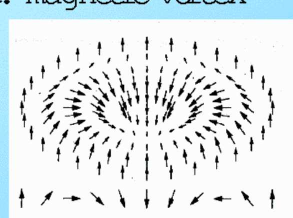
How does long-range order melt?





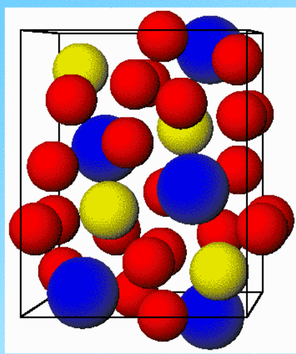
Pinning of helix lost (weakest scale)
- domain walls?
- proliferation of topological defects?
- static or slow dynamics?

Example: magnetic vortex

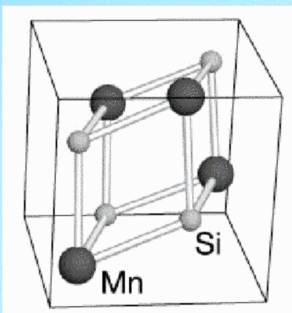


A. Bogdanov, 1989

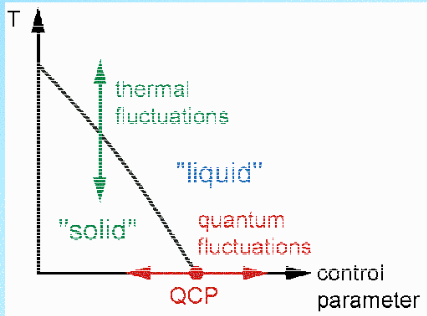
Hard matter getting soft near a QCP ?



$CeCu_{6-x}Au_x$

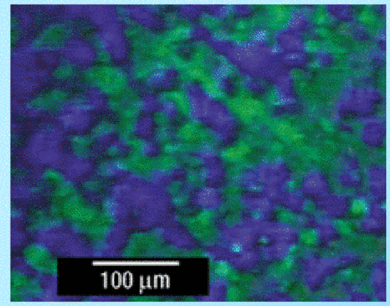


MnSi



Temperature is the only or at least dominant energy scale

Liquid crystal blue phase



Myoglobin

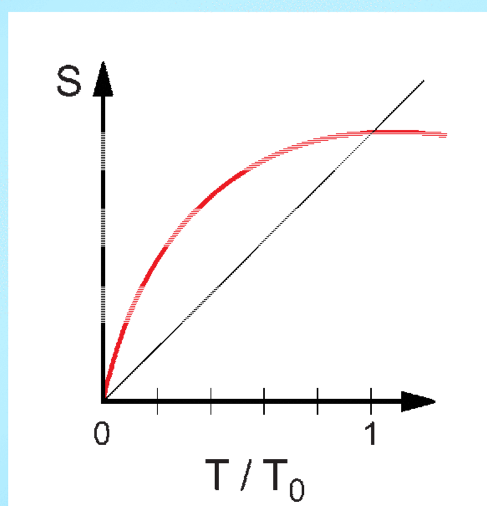
Entropy emerging from the quantum critical point

$CeCu_{6-x}Au_x$: $C/T = a \ln(T_o/T)$

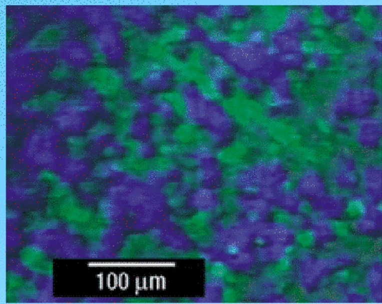
$\rightarrow$ $S = aT(1 + \ln(T_o/T))$

$YbRh_2Si_2$: $C/T = a' T^{-1/3}$

$\rightarrow$ $S = (^2/_3)\, a' T^{2/3}$



increasing relative importance of entropy as $T \rightarrow 0$!



Crystalline liquids: the blue phases

D. C. Wright and N. D. Mermin, Rev. Mod. Phys. 61, 385 (1989)

Blue phases: frustrated defect phases, observed in a narrow temperature interval, $\Delta T \approx 1$K, for highly chiral liquid crystals between the isotropic liquid and the cholesteric phase.

Blue phases I and II: crystals with "lattice constants" comparable to λ of visible light; diffraction pattern corresponds to "crystallites" with helical order along different, albeit well-defined directions.

Blue phase III (or "blue fog"): amorphous-like diffraction pattern.

Optimization of blue-phase stability in $d = 4$ (cf. tiling of pentagons).

Ginzburg-Landau analysis: Blue phases not stable in chiral ferromagnets
Speculation: does extra time dimension near QPT provide stability?

"The puzzle they (the blue phases) present is not widely known, and the apparent solution to that puzzle has been found in a more thoughtful application of existing theories, rather than through the introduction of radically new ideas."

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Conclusions and open questions

- How does a metallic "spin solid" melt at a quantum critical point ?
  - Break up of three-dimensionality ?
  - What happens to the Fermi-surface ?
  - Disparity between transport and thermodynamics, cf. $YbRh_2Si_2$?
- New phases at a quantum critical point
  - Partial magnetic order – a new magnetic state: static or dynamic ?
  - Relation to anomalous non-Fermi-liquid behavior $\Delta\rho(T) = AT^{3/2}$?
- $UCu_{5-x}Pd_x$: What is a robust feature of disorder at a QPT (T.Vojta) ?
- Can one draw formal analogies between hard matter near a quantum phase transition and soft matter ? How about $\hbar$?

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