Partial order in the non-Fermi liquid phase of a pure metal

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Collaborations

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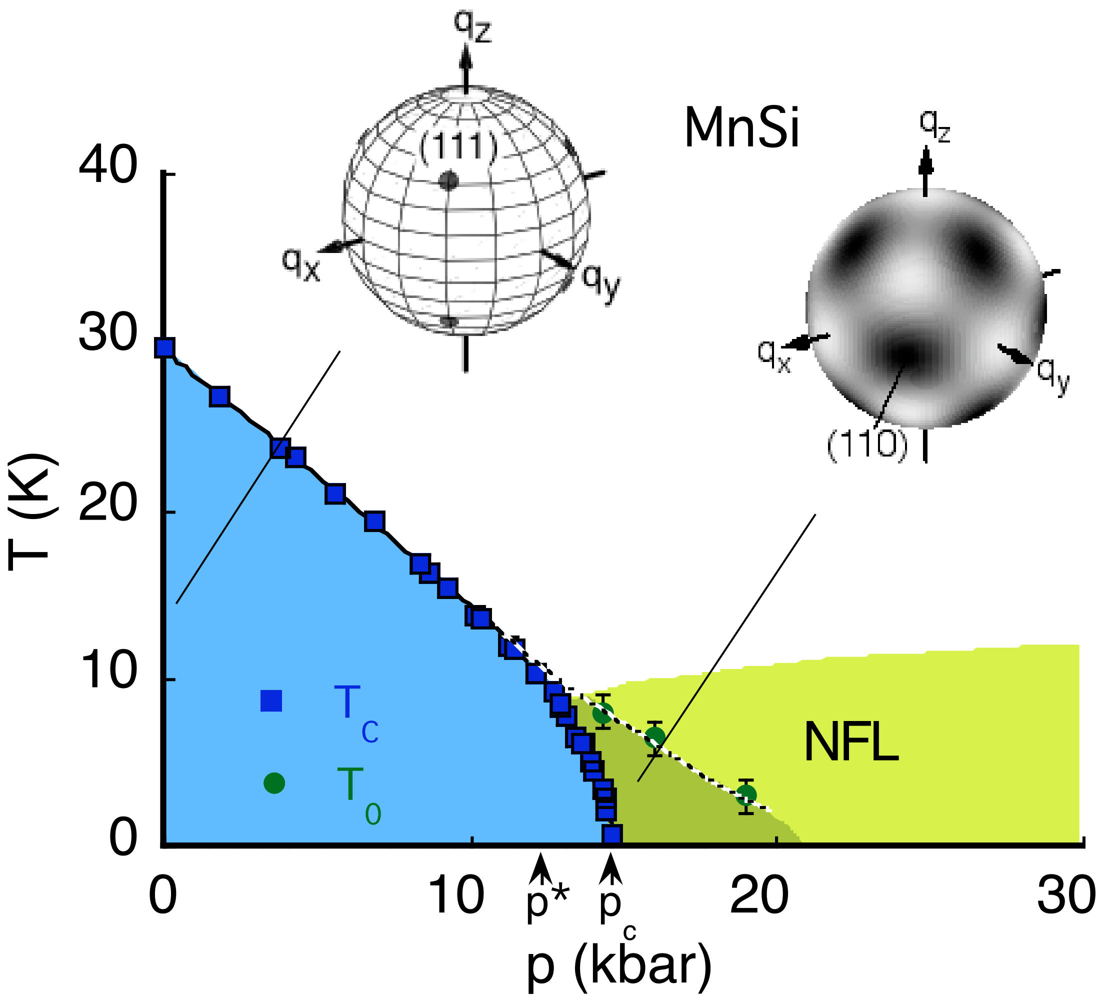
Instead of an Overview ...



historic starting point

metals: (good) conductors, metallic gloss, maleable, ...

E. Wiechert

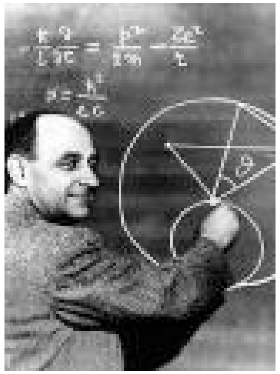
J.J. Thompson

Drude

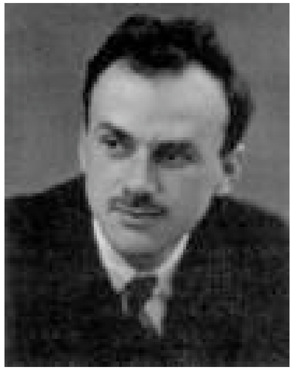
discovery of electron (1897)

“ideale” gas of electrons
Wiedemann-Franz law

Origin of Fermi Liquid Theory: The Sommerfeld Model



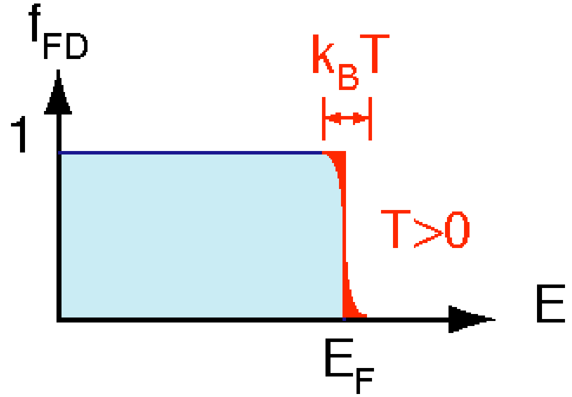
E. Fermi



P. Dirac

W. Pauli

metal = big molecule
Fermi-Dirac statistics
Pauli paramagnetism
(1927)



$f_{FD} = 1/(\exp[(\square-\square)/k_BT]+1)$

purely combinatorially

A. Sommerfeld

heat capacity
conductivity
(1928)

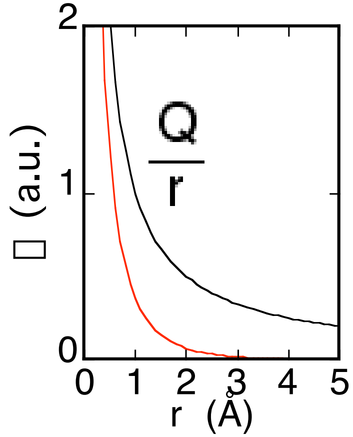
charge transport through
„free“ electrons

From the Sommerfeld to the Standard Model

not considered:

(1) Coulomb interactions

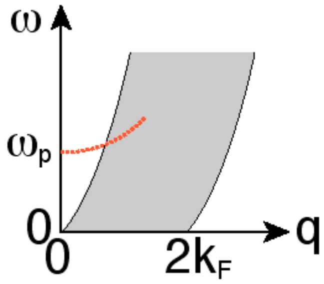
$E_F \approx$ eV; $V_C \approx$ eV



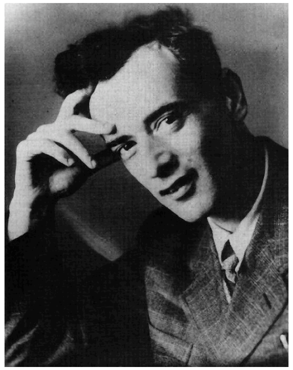
Thomas-Fermi screening

$$\frac{Q}{r}\exp(-\kappa r)$$

(2) collective excitations

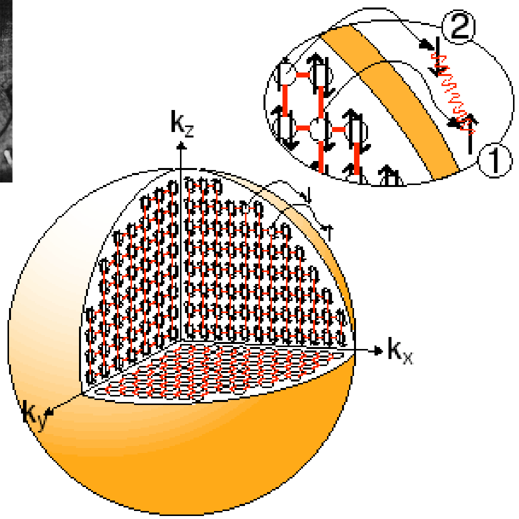


e.g. plasmons
D. Pines (1953)



L. Landau
(1957)

„approximately“
fermions ?



$1/\tau = a\,(\varepsilon_1 - E_F)^2 + b\,(k_B\,T)^2$

for $T \to 0$ always long-lived!

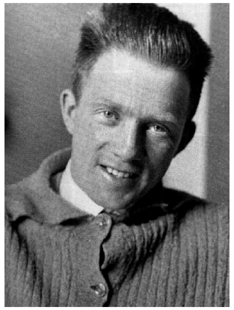
$\rho(T) = A T^2 + \rho_0$

$C(T)/T = \gamma \approx$ const

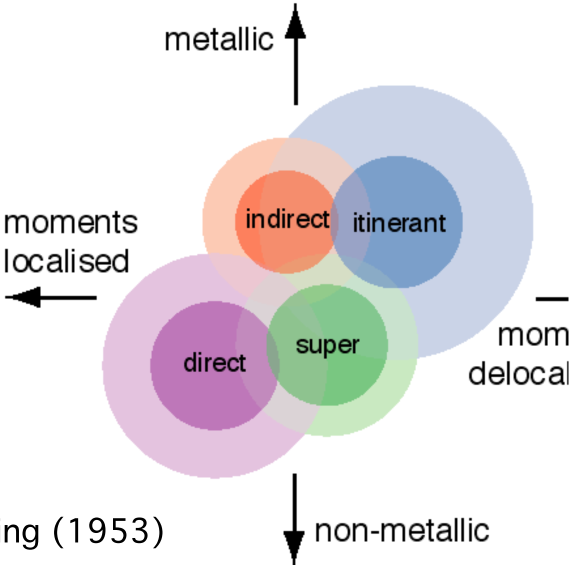
$\chi(T) \approx$ const'

Magnetism of the Conduction Electrons

Origin of the
Weiss molecular field?

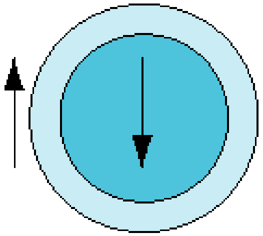

W. Heisenberg

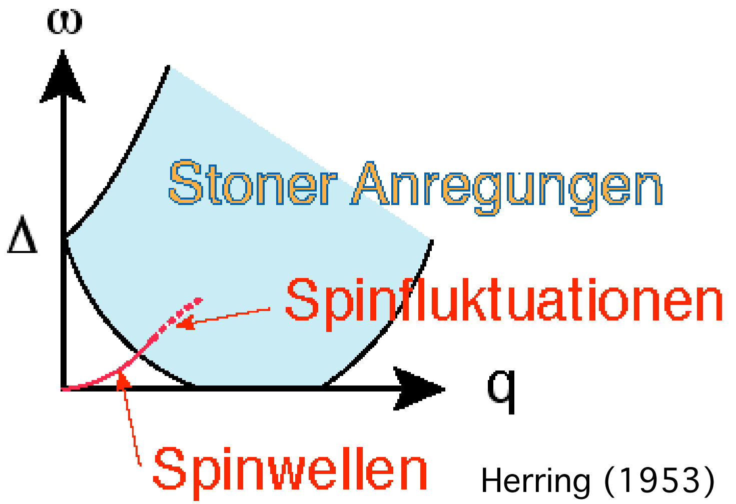

F. Bloch



Herring (1953)

modern definition:
magnetism of conduction electrons
≈ exchange splitting of Fermi surface

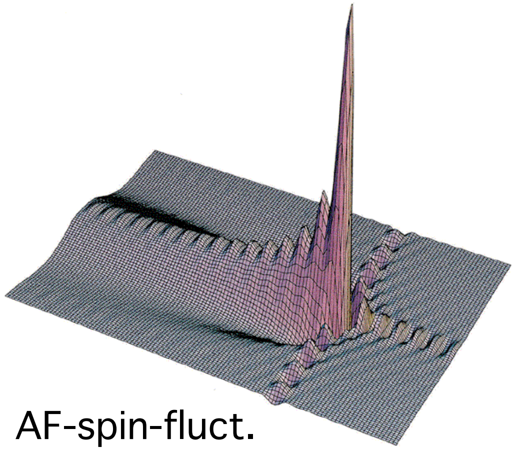

ferromagnetism



Herring (1953)
Izuyama & Kubo (1964)
Moriya & Lonzarich (1985)

Pathological Cases of the Standardmodel

charge transport through
single-particle quasi-particles:
electron + „dressing“ cloud

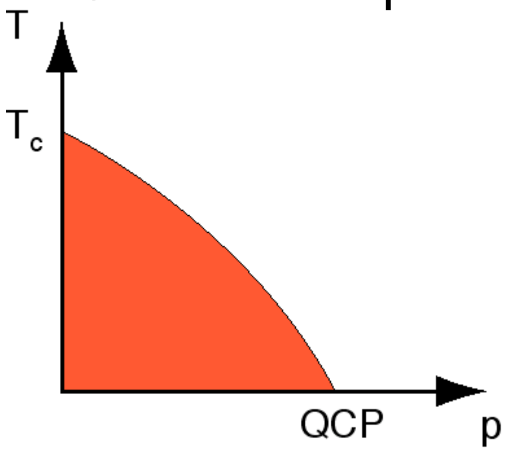


nature of dressing cloud?

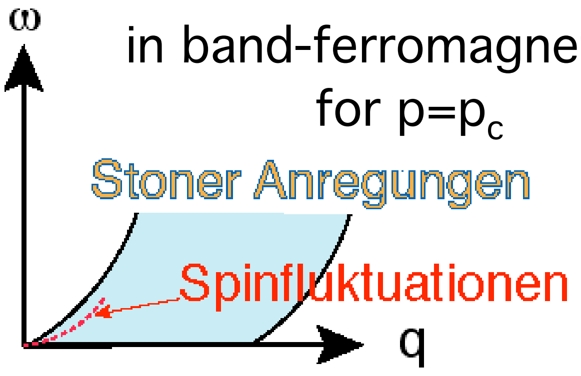
- phonons
- magnons
- plasmons
- excitons

....

Gedankenexperiment:



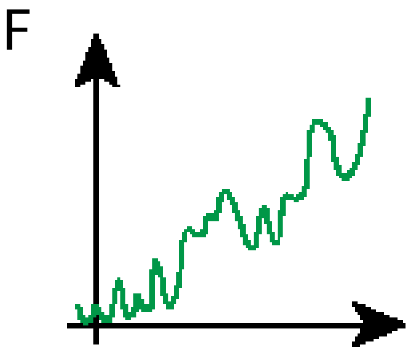
in band-ferromagnets
for $p=p_c$



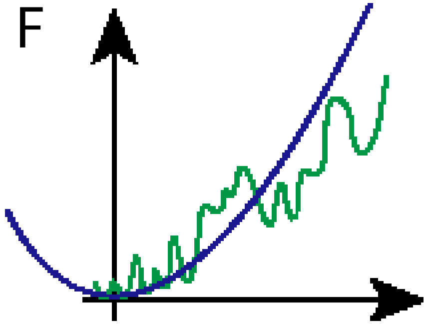
- single-particle or collective?
- condensation (supercond.)?

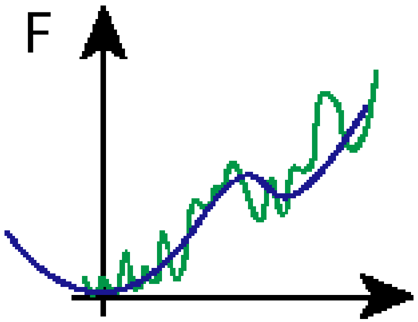
How well does linear response theory work?

free energy landscape



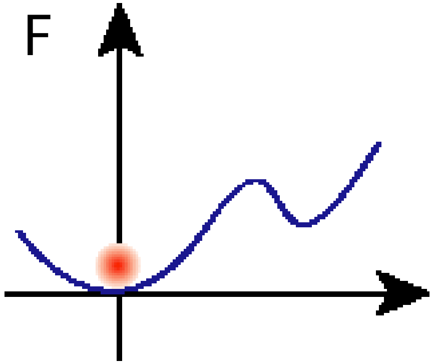
level of approximation

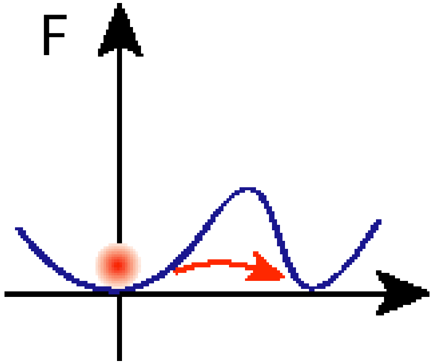




first order QPT &
metamagnetism

extreme non-linearities





Weak “Itinerant-Electron” Ferromagnets

pre-60ies: local moment **ferri**magnets

□ Dzyaloshinsky-Moriya interaction

1958 B. Matthias: ferromagnetism in $\mathrm{ZrZn_2}$ (C15 Laves phase)

„FM without magnetic elements“

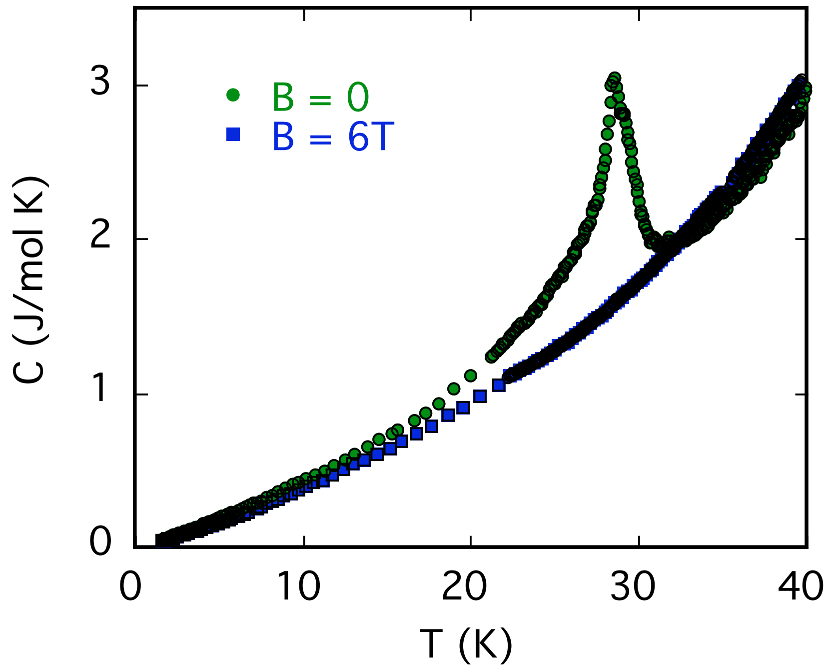
„new“ material class: MnSi, $\mathrm{Sc_3In}$, $\mathrm{Ni_3Al}$, $\mathrm{YNi_3}$, $\mathrm{CoS_2}$, ...

- low ordering temperature
- small ordered moments
- large Curie-Weiss moment
- unsaturated magnetisation M(B)
- small entropy of order

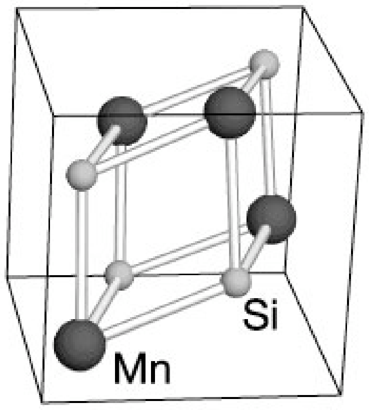
□ weakly exchange split band magnets

□ self-consistent linear response theory (Moriya, Lonzarich, ...)

Some Basic Properties of MnSi



very nice metallurgy!!
“perfect” single crystals!

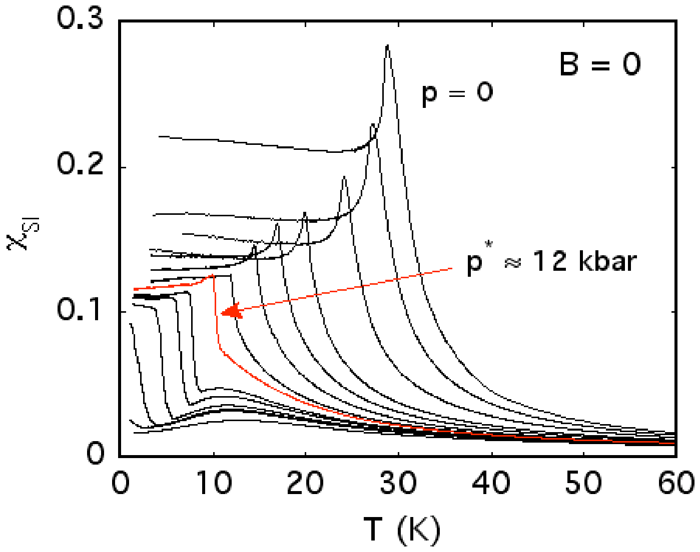


Ferromag.: T_C ≈ 30 K
□$_s$ ≈ 0.4 mB/f.u.
□≈ 38 mJ/mol K^2

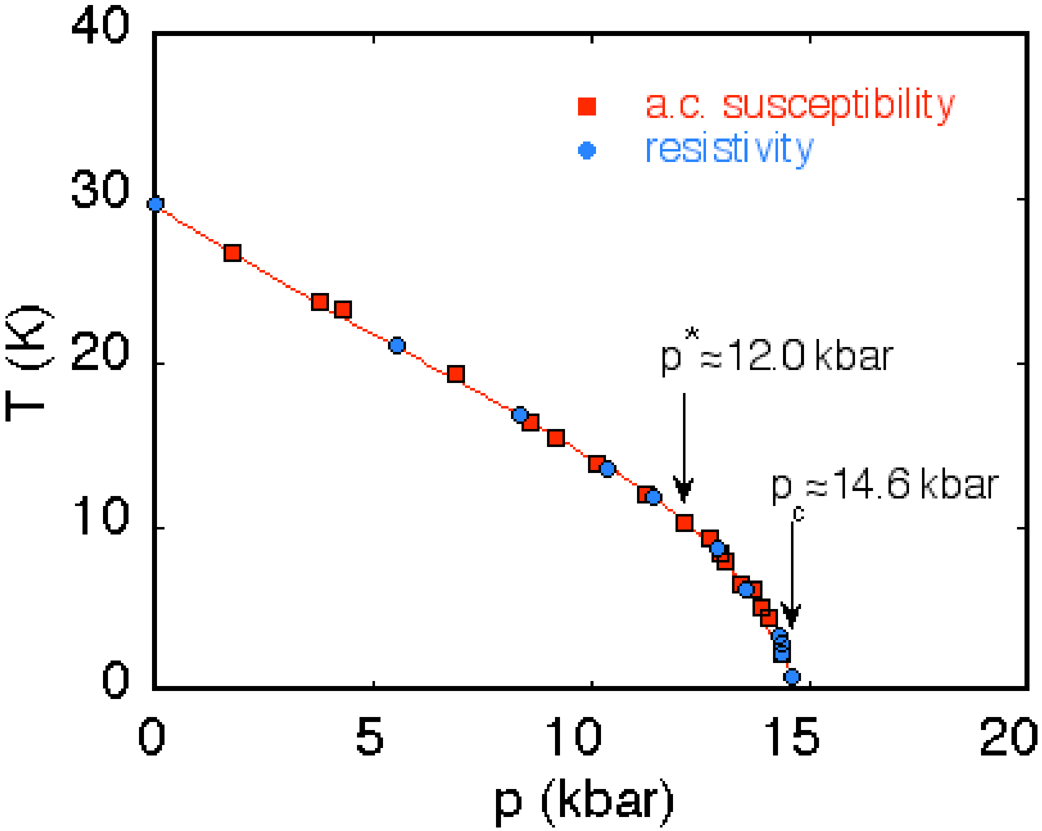
n-scattering & dHvA : spin-split FL
QP dressing cloud: paramagnons

B20 structure:
no inversion symmetry

Pressure-Temperature Phase Diagram of MnSi

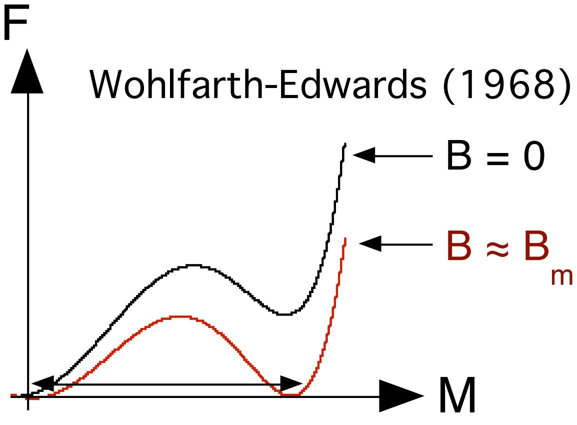


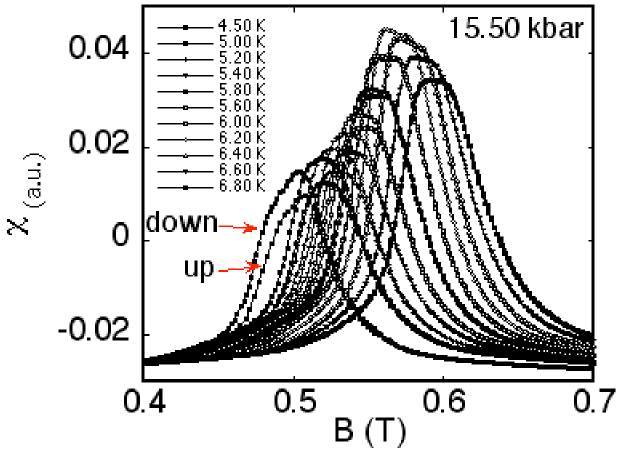
1^{st} order transition
for $12\text{kbar}<p<p_c$

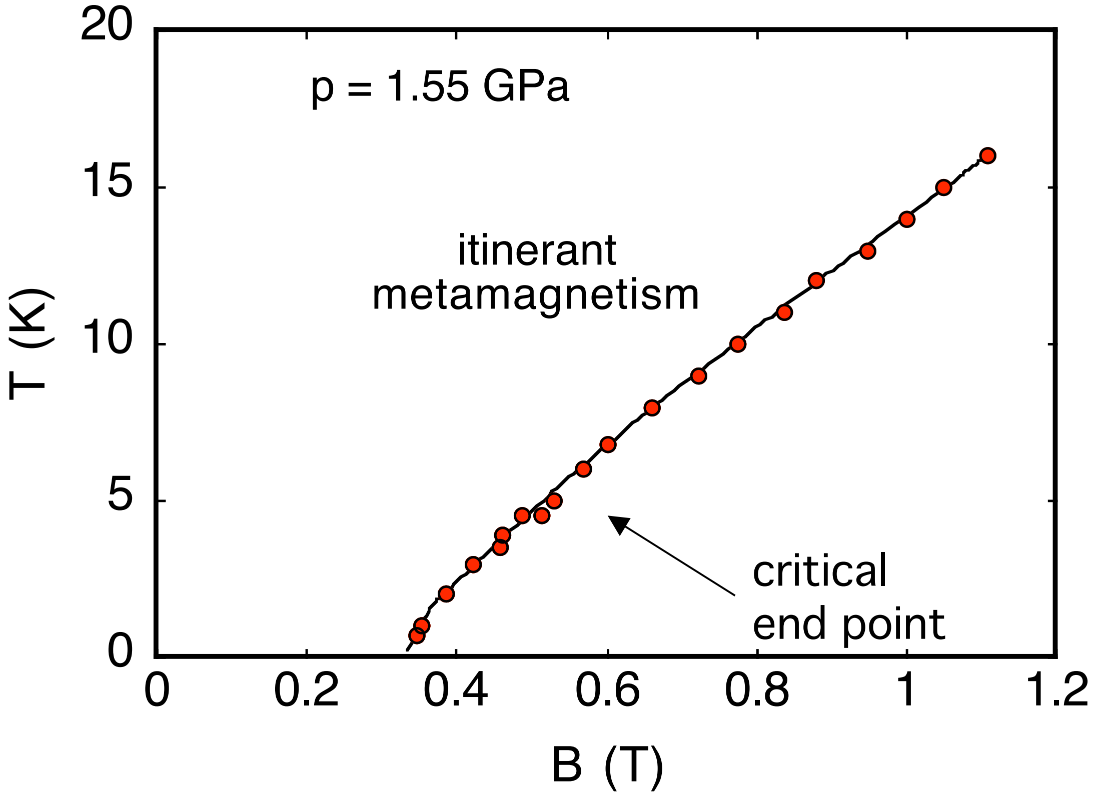


CP et al., Phys. Rev. B **55** (1997) 8330.

Itinerant Metamagnetism in MnSi for $p>p_c$

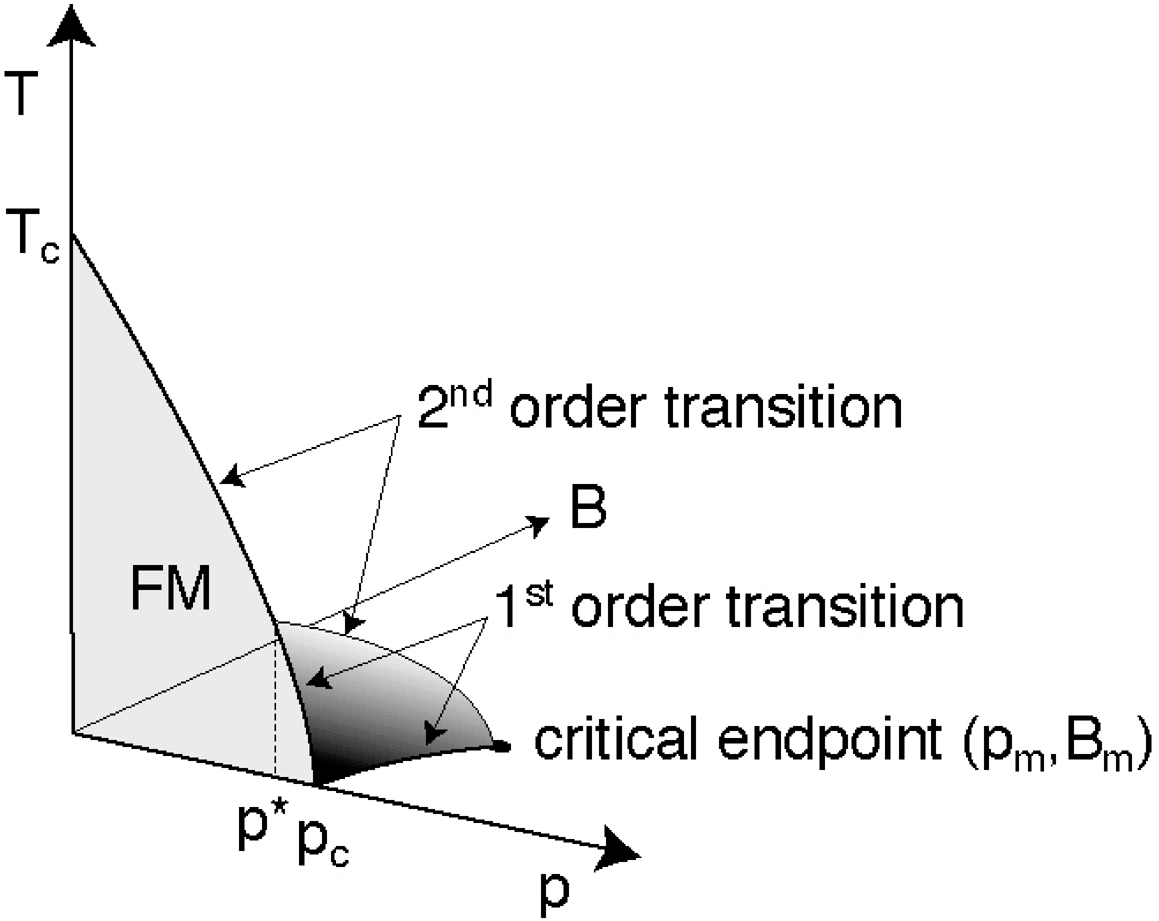






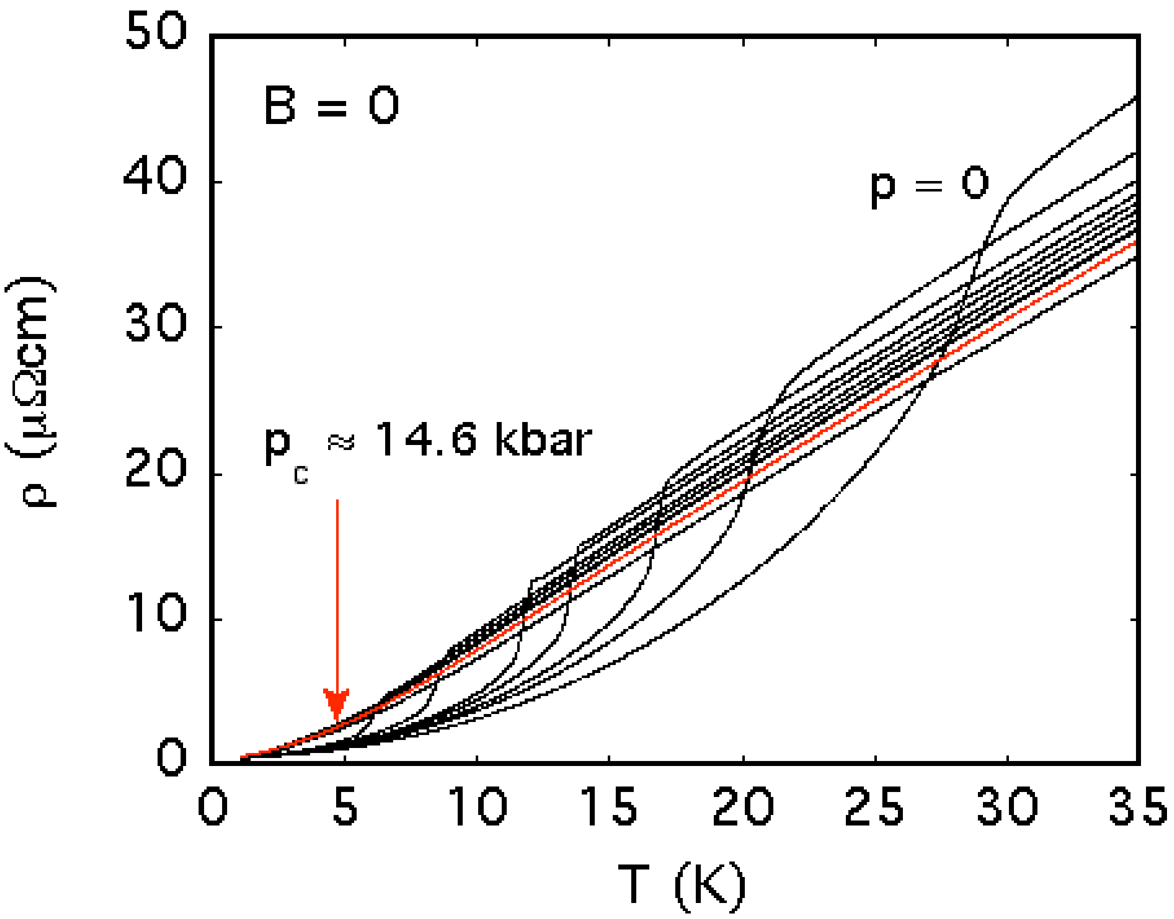
Thessieu, CP, Stepanov, Flouquet, J. Phys.: Cond. Matter **9** (1997) 6677.

Proposed Generic Phase Diagram of Itinerant Ferromagnets



also seen in:
$ZrZn_2$
UGe_2 (PRL **89** 147504)

Pressure Dependence of the Electrical Resistivity

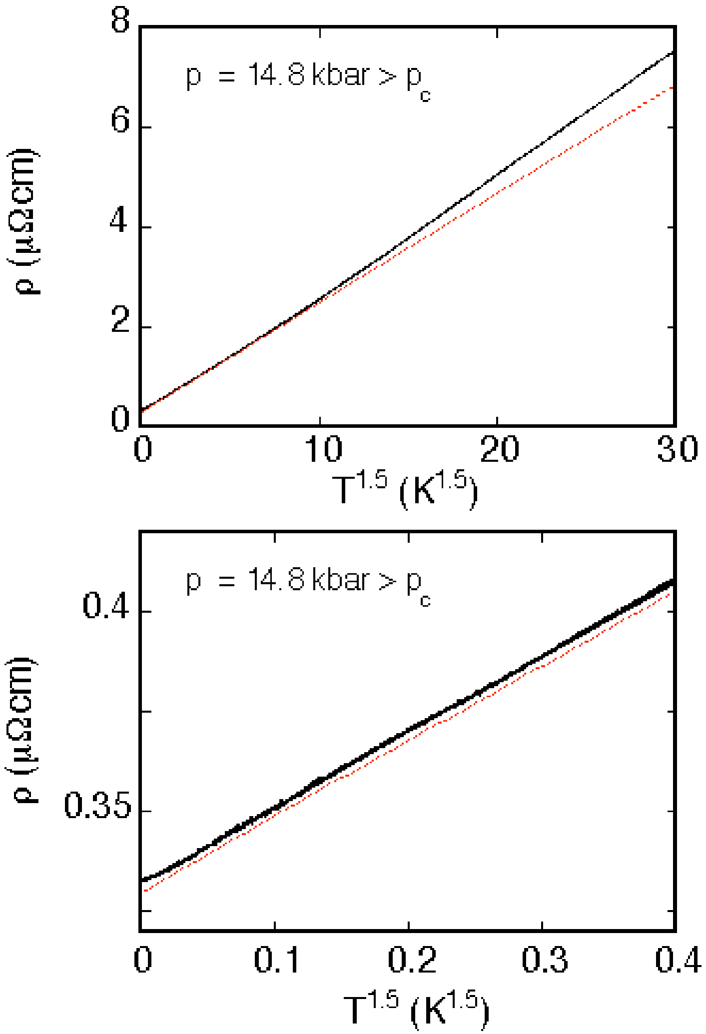


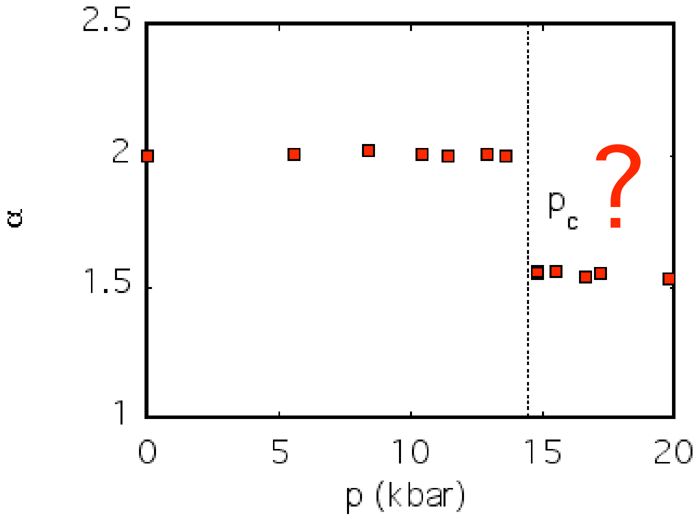
Fermi liquid:

$$\rho(T)=\rho_0+AT^2$$

consequence of phase space constraint for QP-QP scattering by Pauli principle

Non-Fermi Liquid Phase of MnSi for $p>p_c$





$\square(T)= \square_0 + \square\square(T)$

$\square_0 << \square\square(T) \mu T^{3/2} << \square_0$

⇨ mK < T < several K

⇨ □ insensitive to p

⇨ □ insensitive to $\square_0$

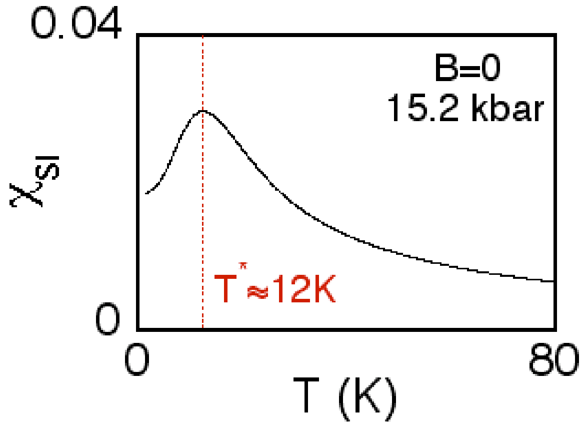
CP et al., Nature **414** (2001) 427.
CP Physica B **328** (2003) 100.
Doiron-Leyraud et al., Nature **425** (2003) 595.

Comparison of Experiment and Theory for MnSi

Fermi liquid: □≈constant

⇨ Pauli principle

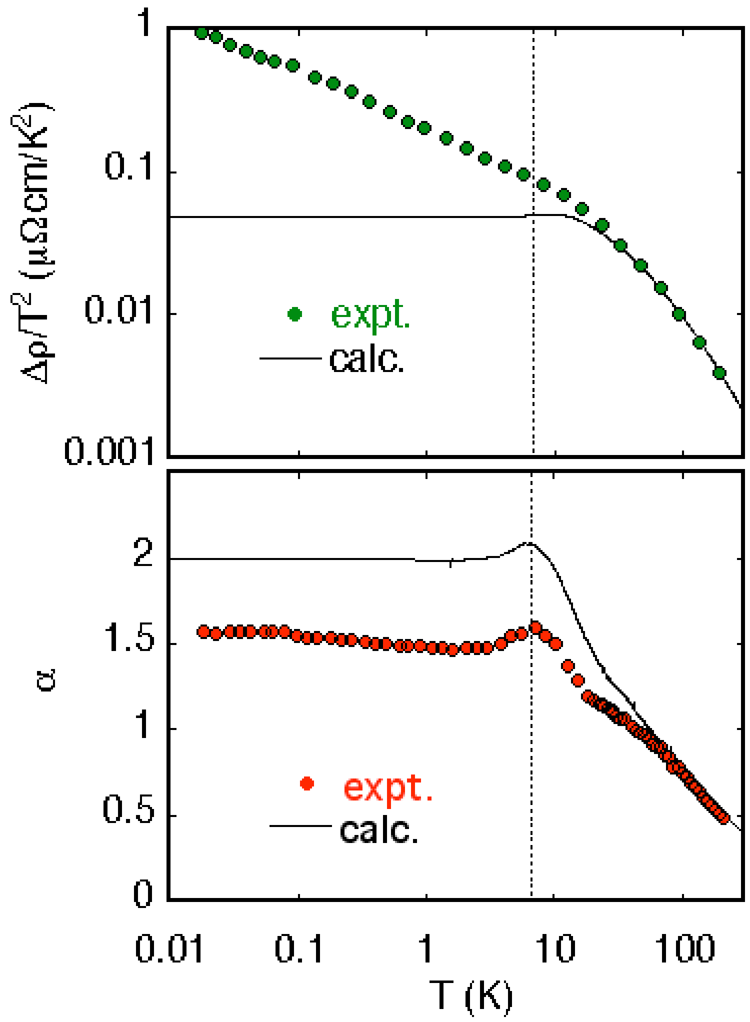
⇨ □□(T)/T^2 ≈ constant



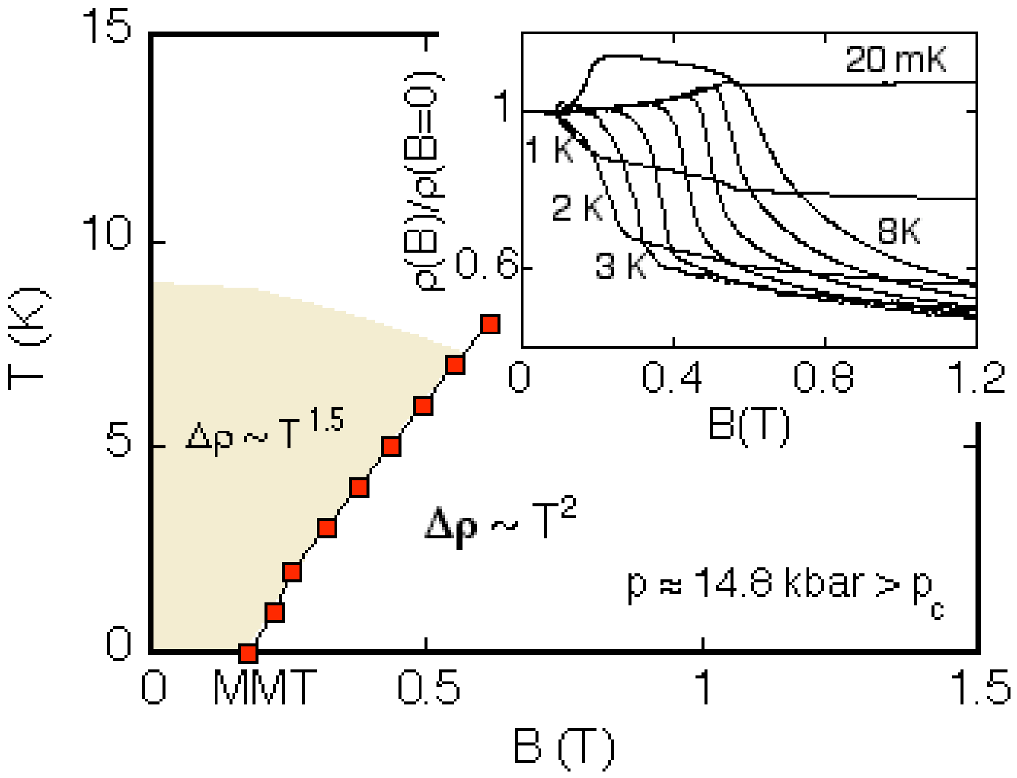
Boltzmann equation &

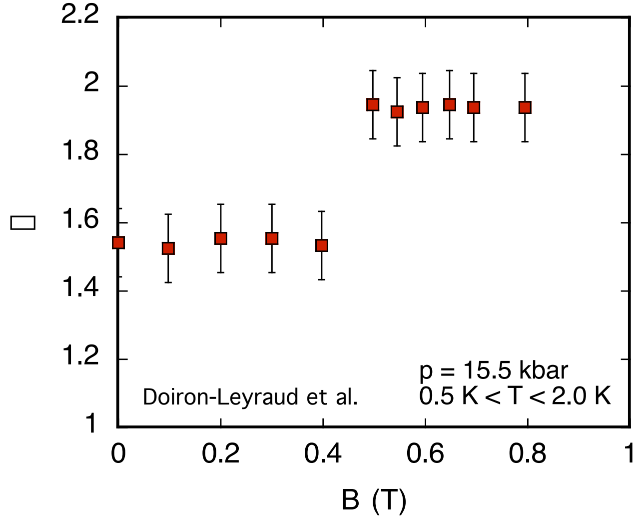
$\square_{q\square}^{\square 1} = \square^{-1} + cq^2 - i\square/q$

⇨ expect T^2 for $T<T^*$



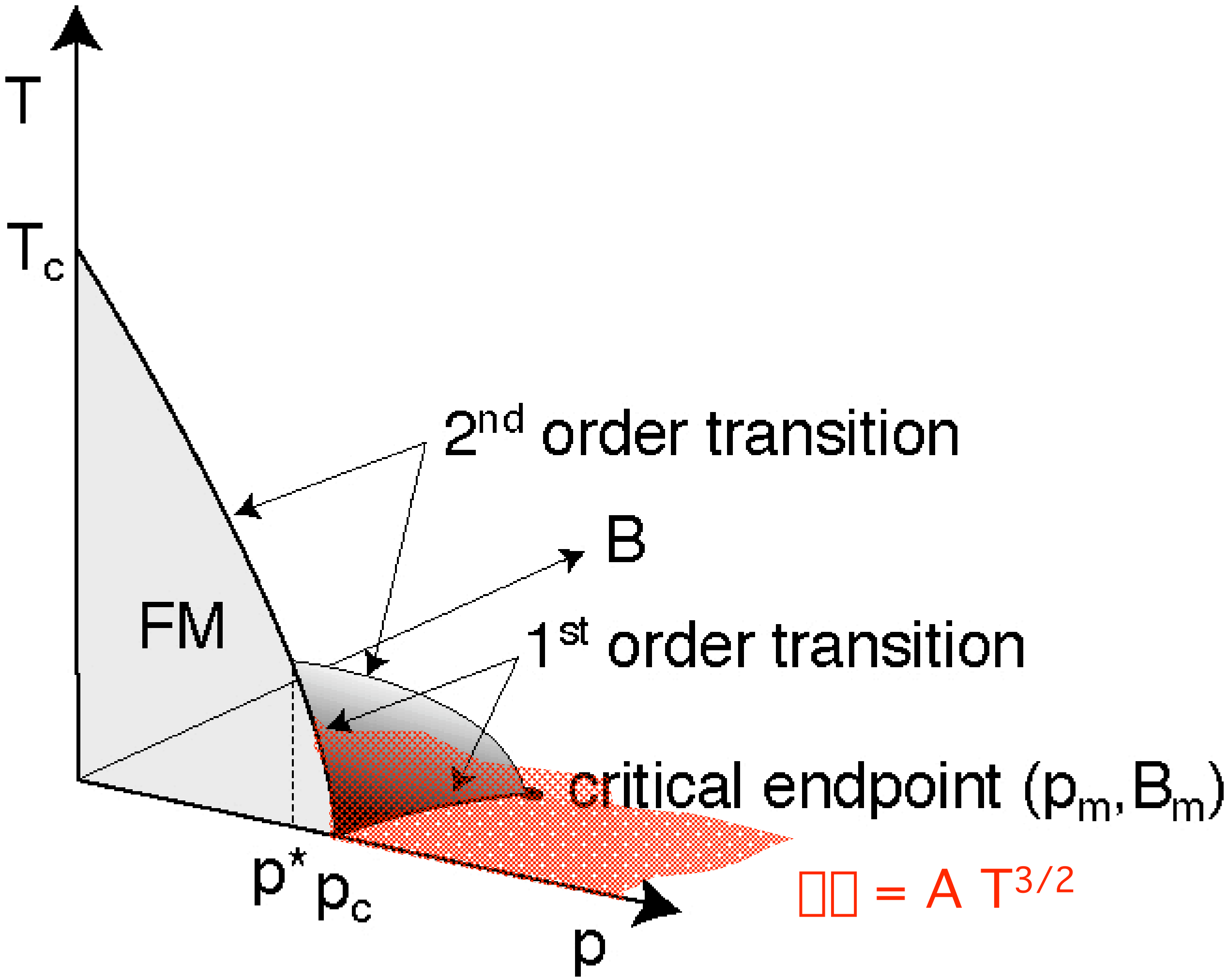
Variation of $T^{3/2}$ with Magnetic Field near p_c





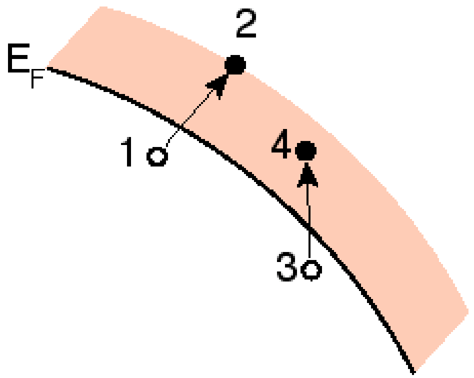
- NFL phase stable up to MMT
- drop of ▯ at B_c

Regime of the Non-Fermi Liquid Phase



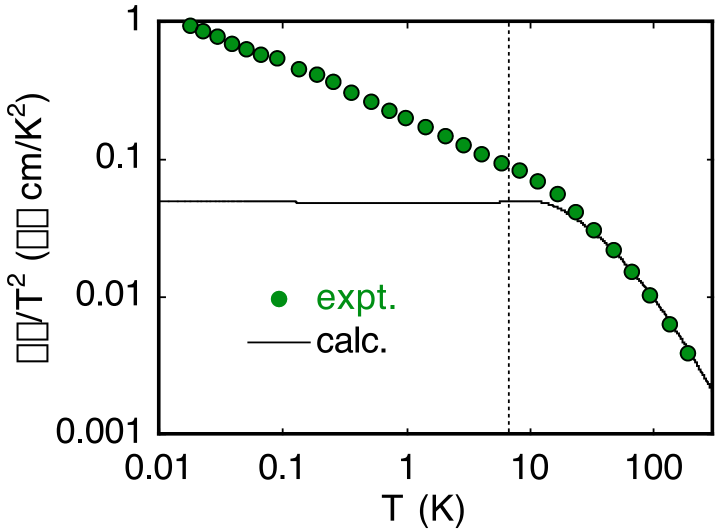
What is special about the $T^{3/2}$ resistivity?

Landau (1957)



$1/\square = a\,(\square_1 - E_F)^2 + b\,(k_B\,T)^2$
for $T\square\ 0$ always long-lived!

electrical resistivity (Pauli)
$\square(T) = AT^2 + \square_0$

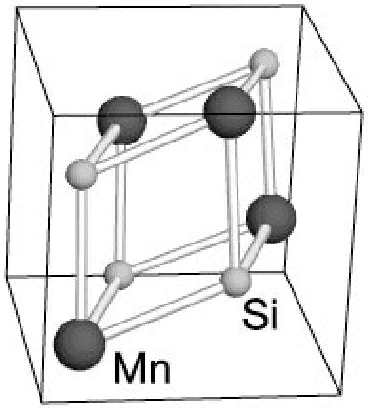


$\square\square/T^2 = A$ singular für $T\square\ 0$

phenomenology inconsistent
with Pauli principle

collective charge transport?
fractional charge carriers?
....

Characteristic Energy Scales in MnSi



cubic (B20)
no inversion

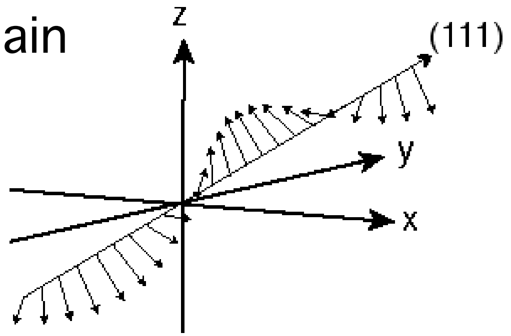
(1) ferromagnetism

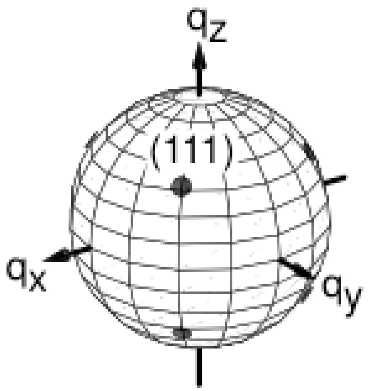
(2) spin-orbit coupling:
Dzyaloshinsky-Moriya interaction
s * (□ □**s**), rotation-invariant
□ ≈ 170 Å (a = 4.558 Å)

(3) crystal field potential ($P2_13$):
helix locked at <111> or <100>
(not <110>)

cool from high T:
- ferromagnetic fluctuations
- chiral fluctuations (Q)
- 2nd order phase transition

single domain





magn. domains
in recip. space:
sharp satellites

Magnetisation & Neutron Diffraction at High Pressure

- miniature clamp cell
- ideal for M, □, C, □
- $p < 22$ kbar

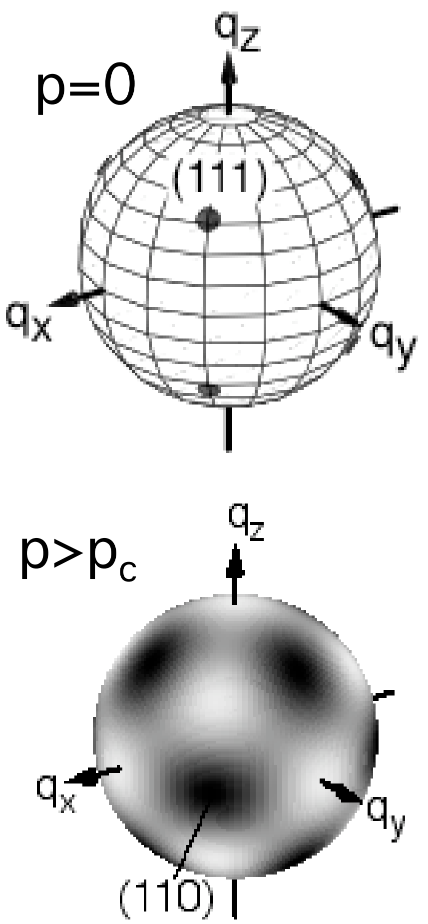
Laboratoire Léon Brillouin (Saclay)
- 4F1: triple-axis, cold neutrons

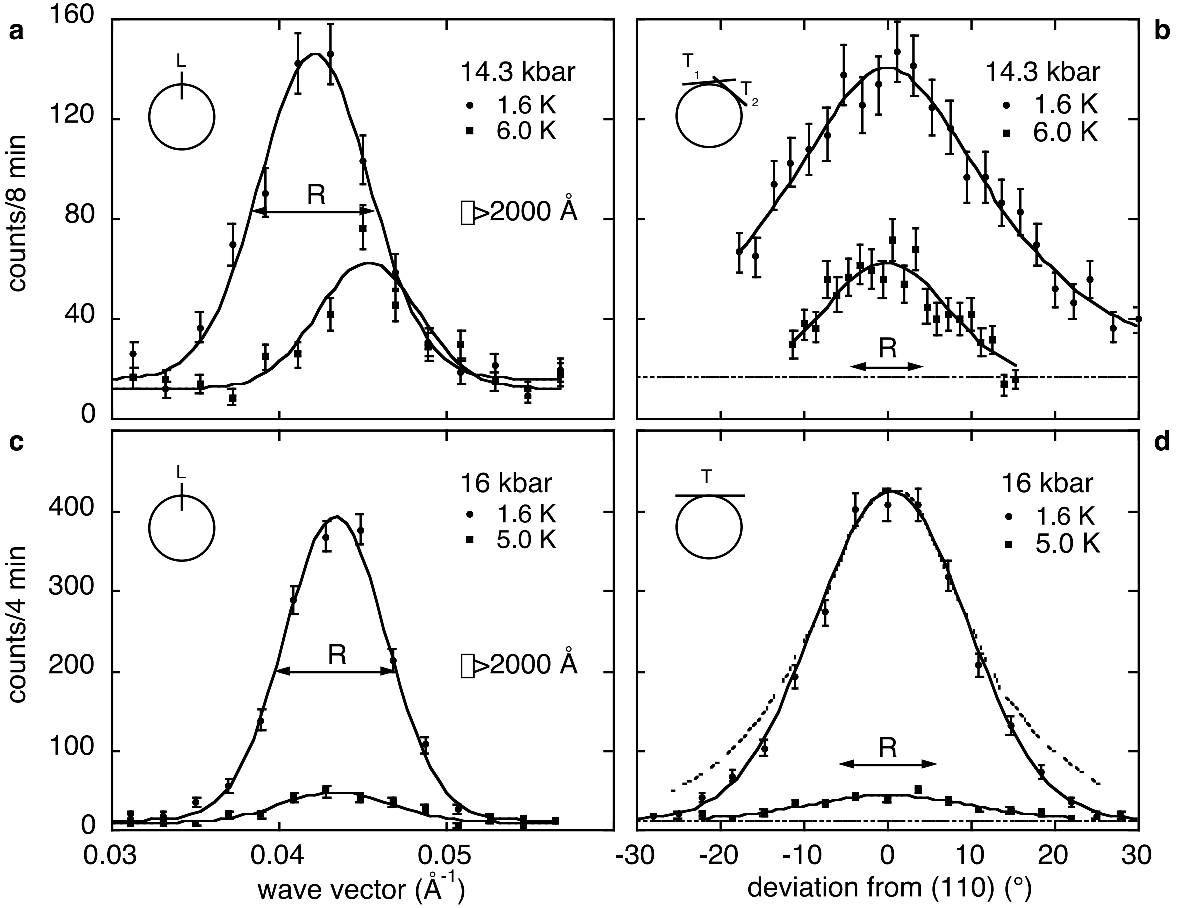
Hahn-Meitner-Institut (Berlin)
- V4: small angle scattering (SANS)

Institut Laue Langevin (Grenoble)
- D23: Diffraction

(first used in UGe_2)

Strange Magnetic Order in the NFL-Phase of MnSi



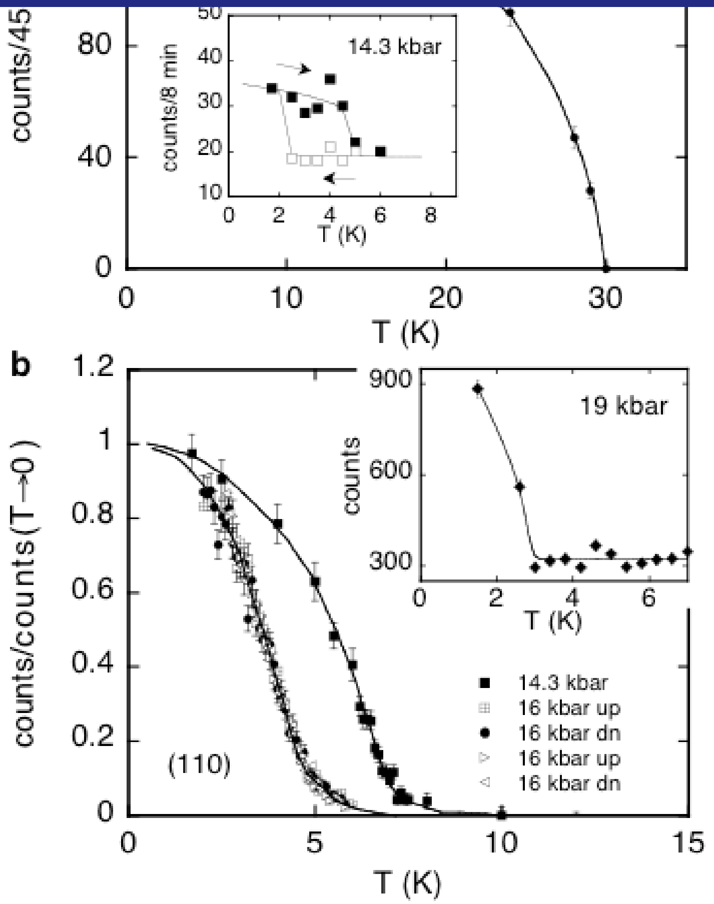


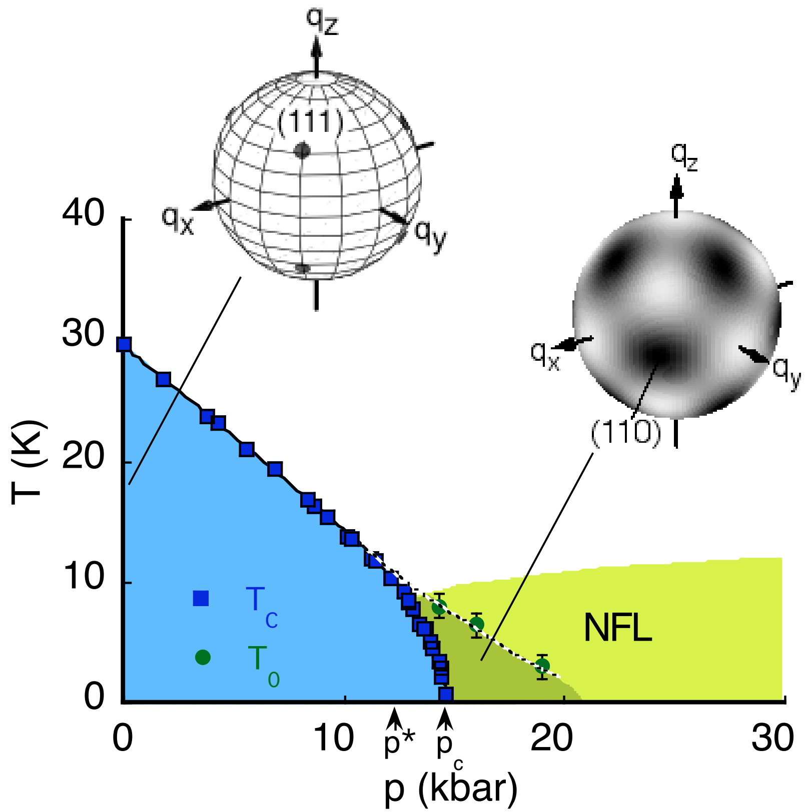
experiments at 4F1 (LLB Saclay)

large „static“ moment survives p_c
(energy resolution 0.05meV)

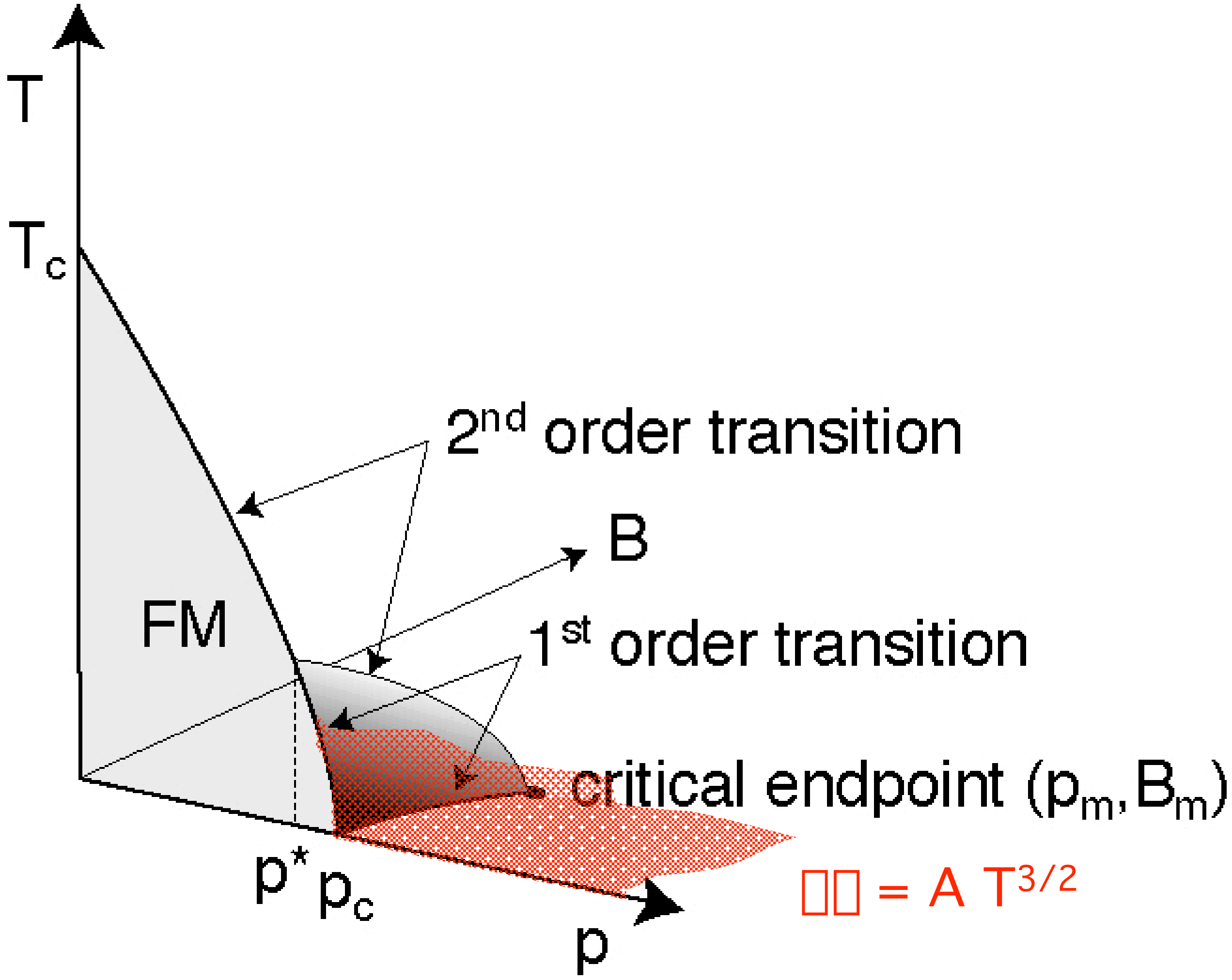
CP et al., Nature, **427** (2004) 227

Pressure vs Temperature Regime of the Strange Behaviour



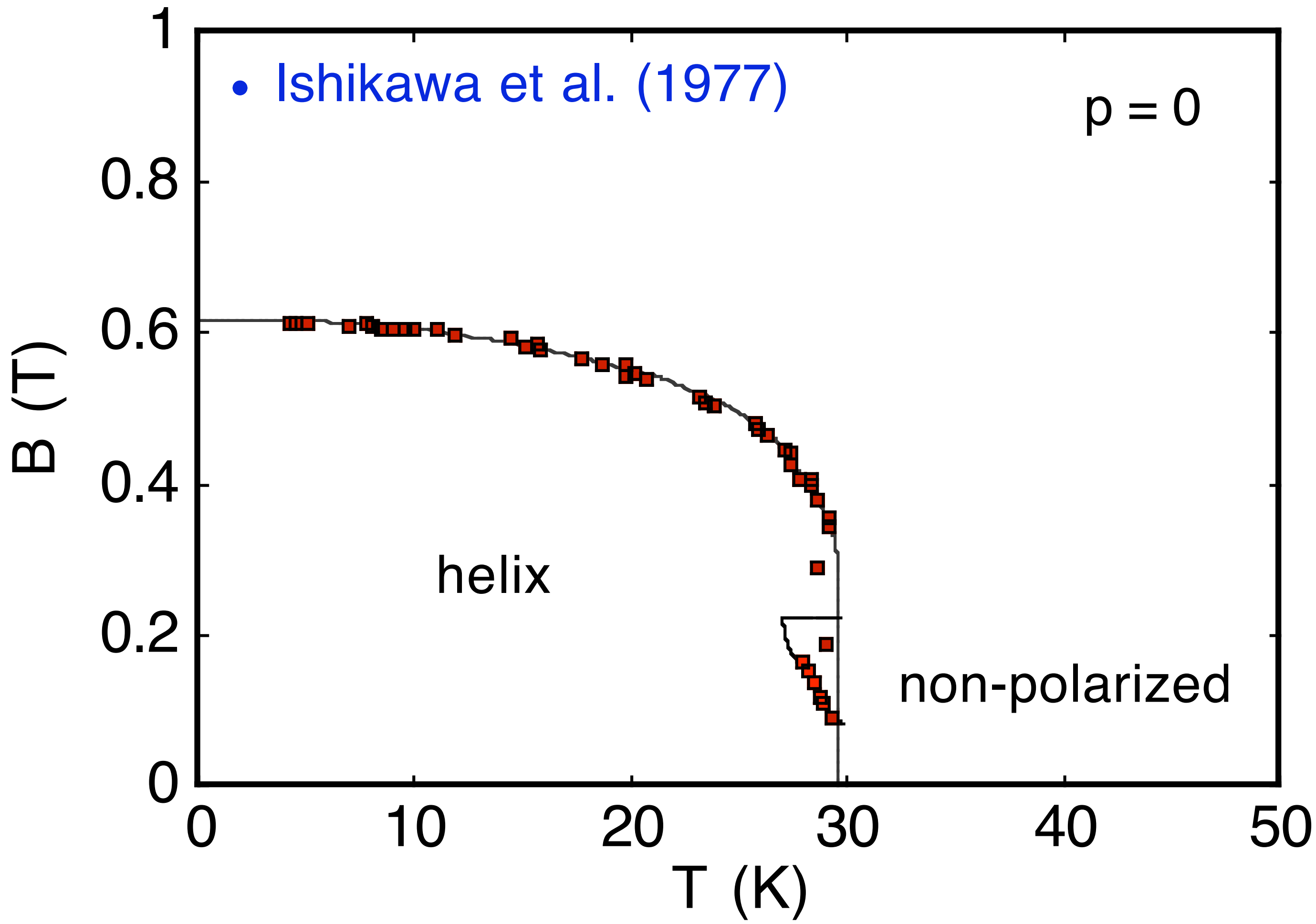


What about the magnetic field dependence?

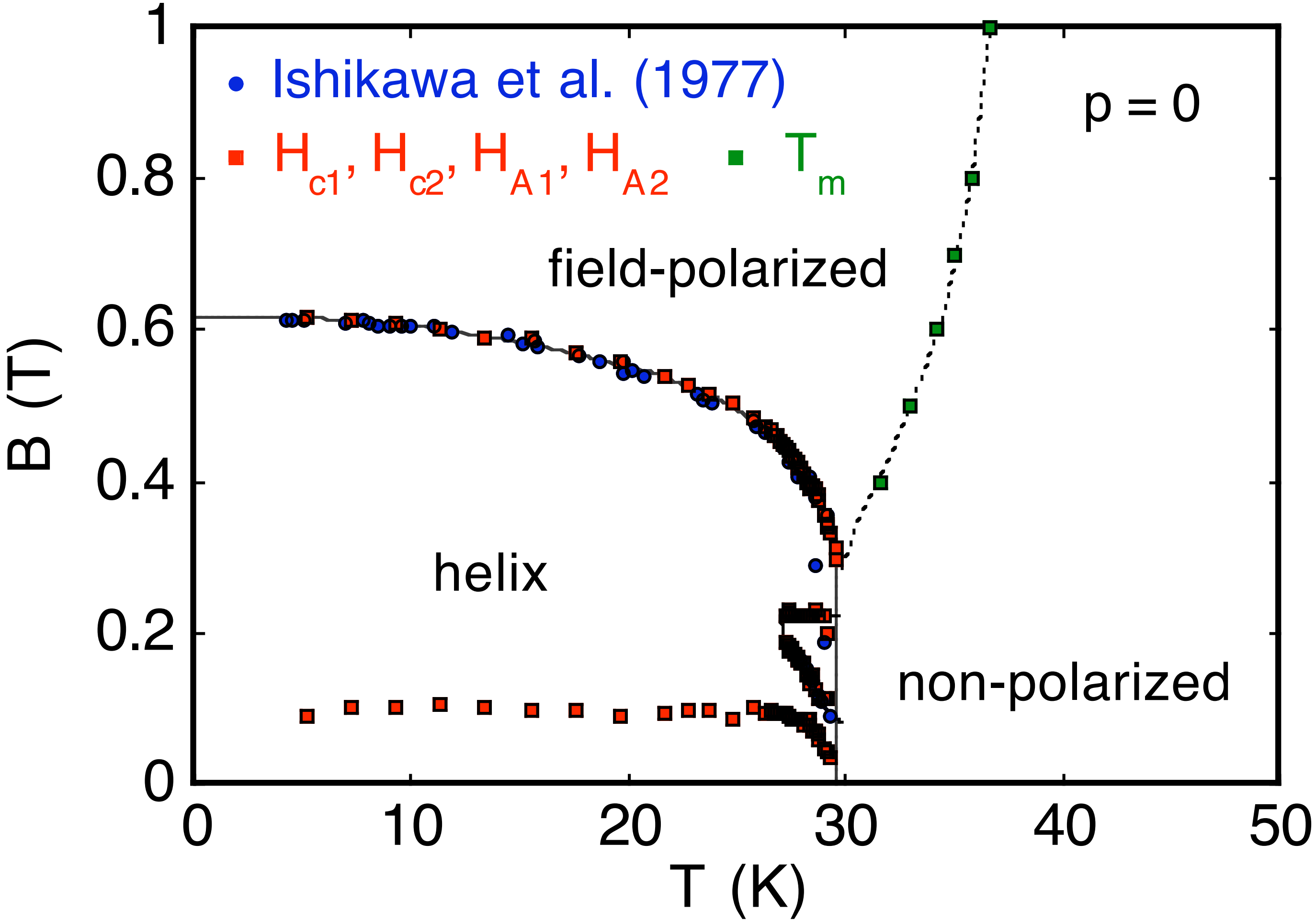


□□ = A $T^{3/2}$

Magnetic phase diagram at p=0



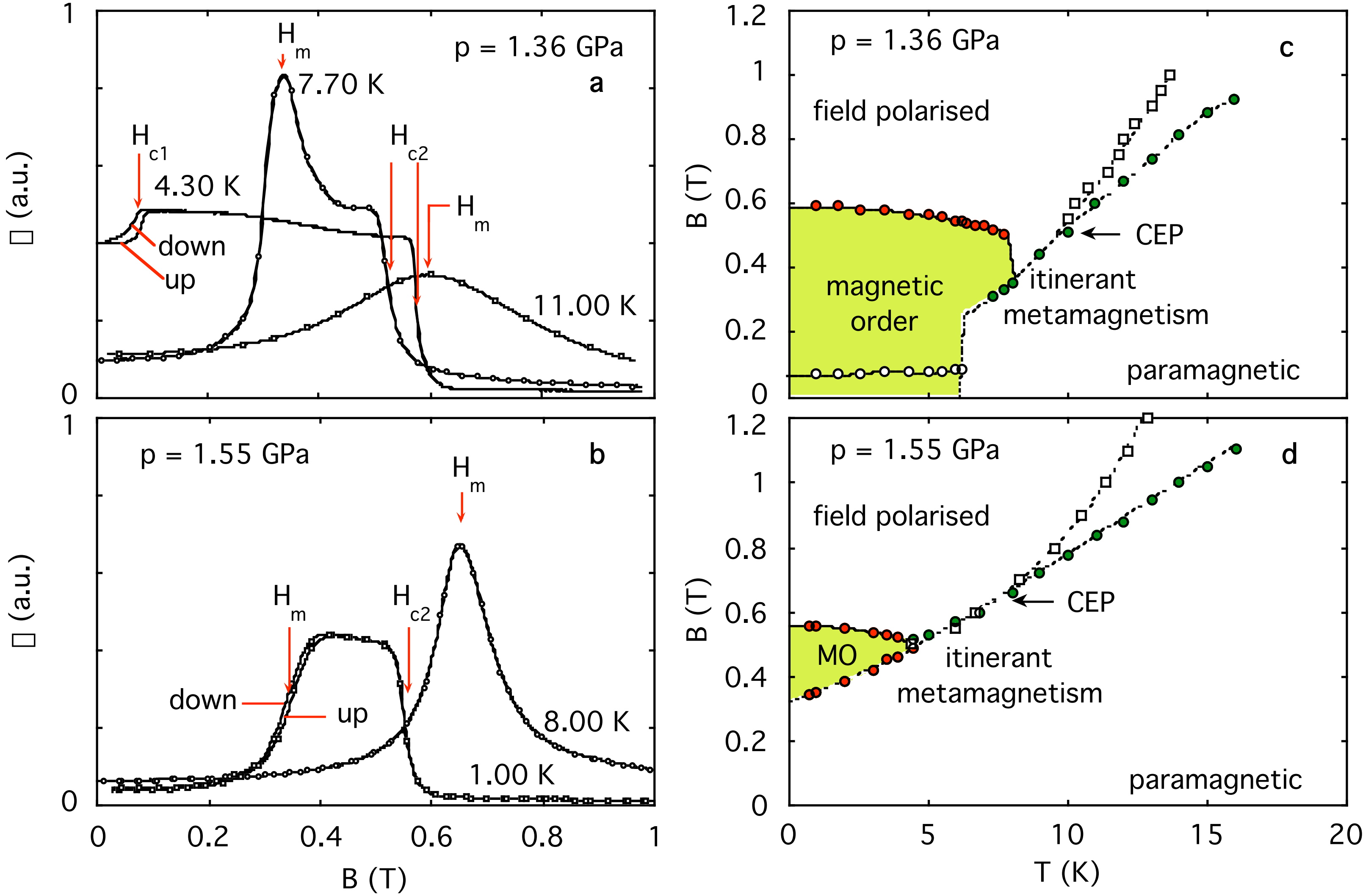
Magnetic phase diagram at p=0



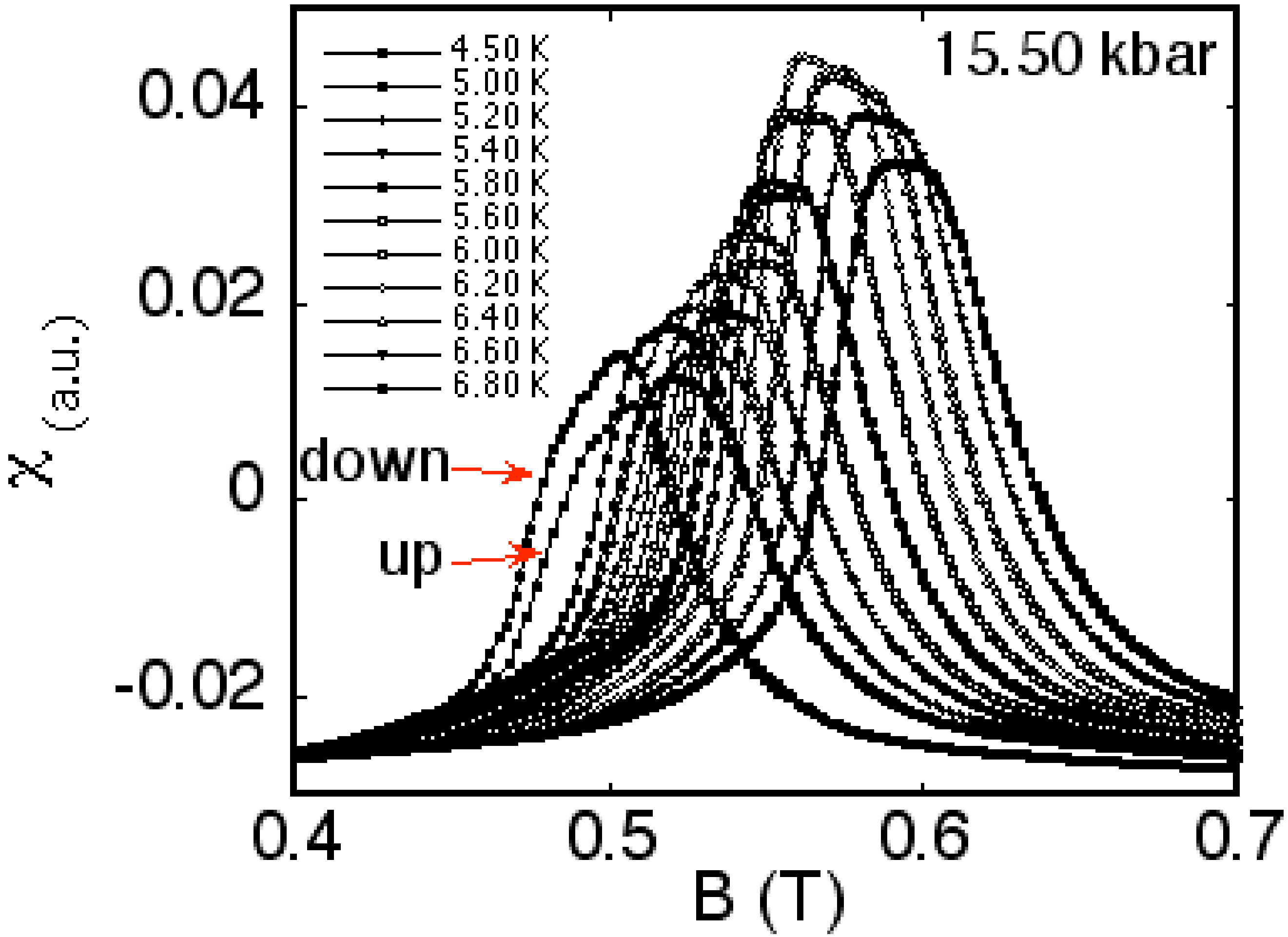
$B_c \approx 0.6$T

Thessieu, CP, Stepanov, Flouquet, JPCM **9**, 6677 (1997)

Magnetic phase diagram near p_c

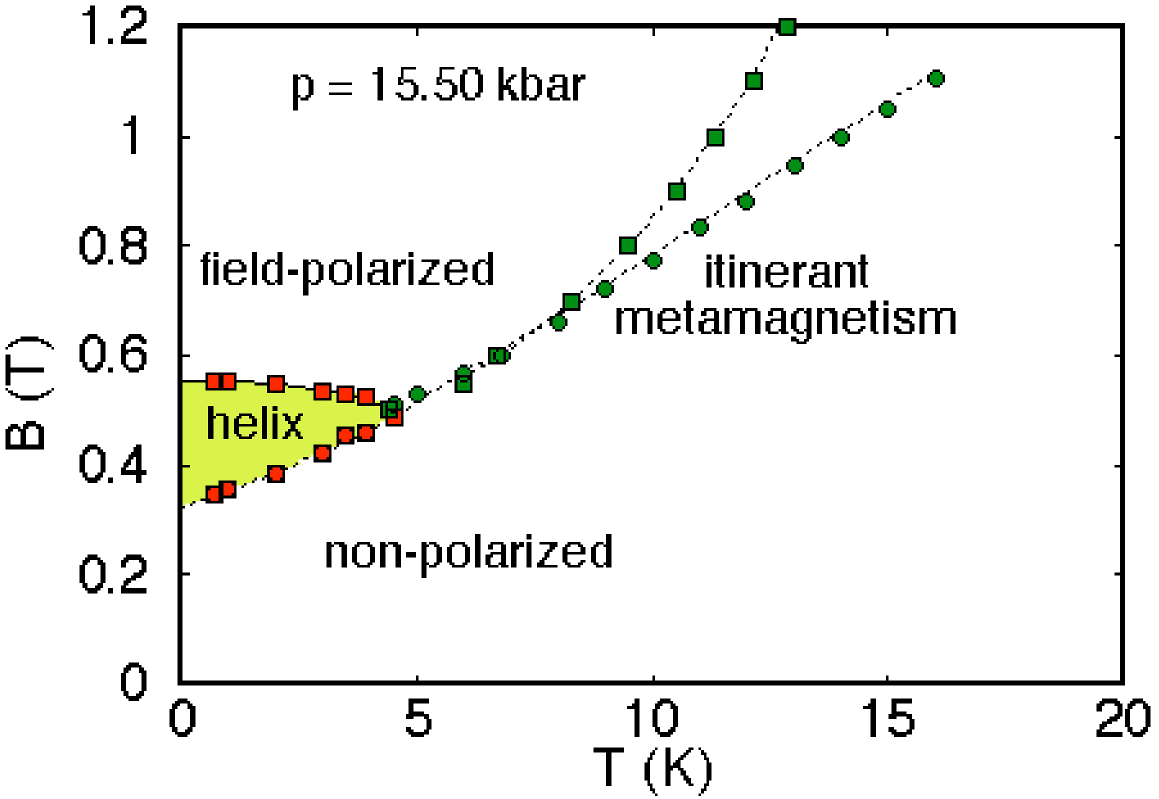


Hysteresis of a.c. susceptibillity above p_c



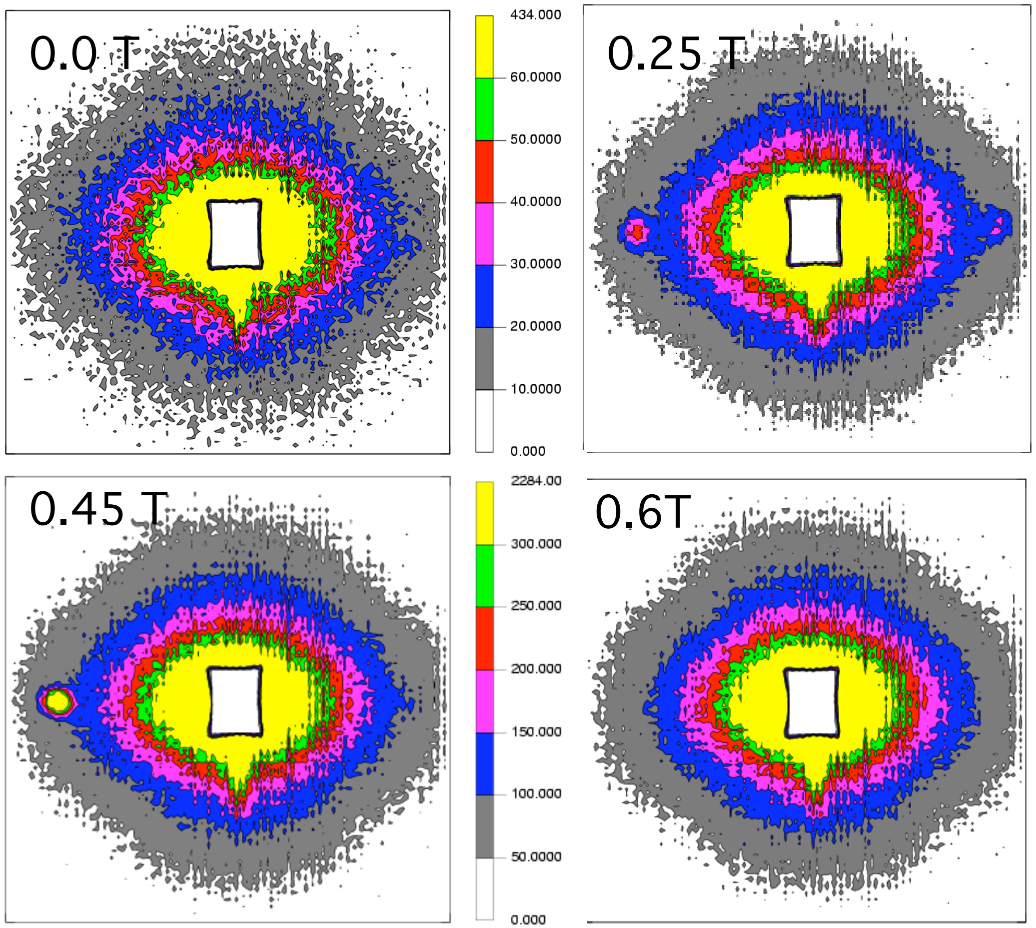
CP RSI **68**, 1532 (1997)

Magnetic phase diagram above p_c



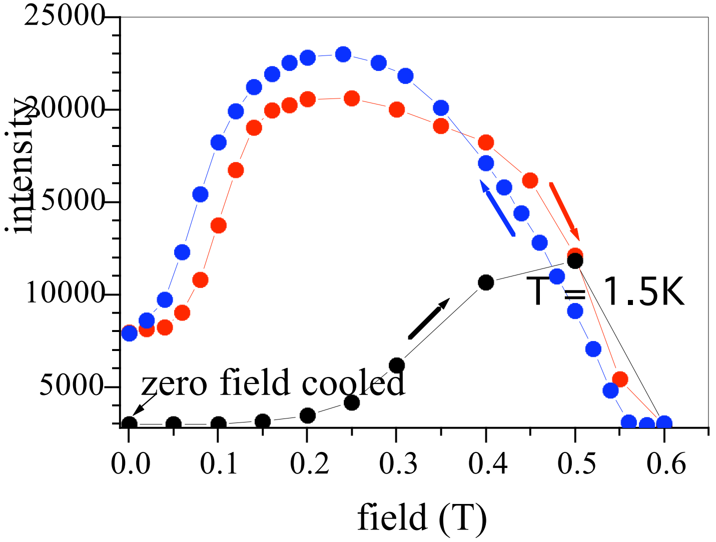
Magnetic Field Dependence above p_c

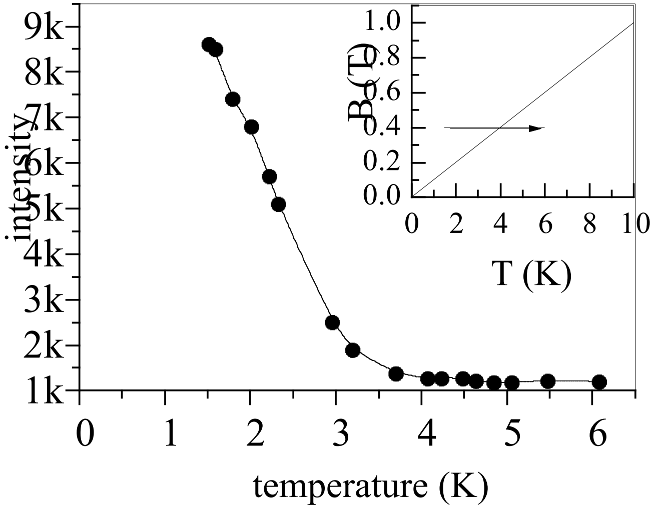
(first results)



$p \approx 18$ kbar $> p_c$

SANS at V4 HMI Berlin

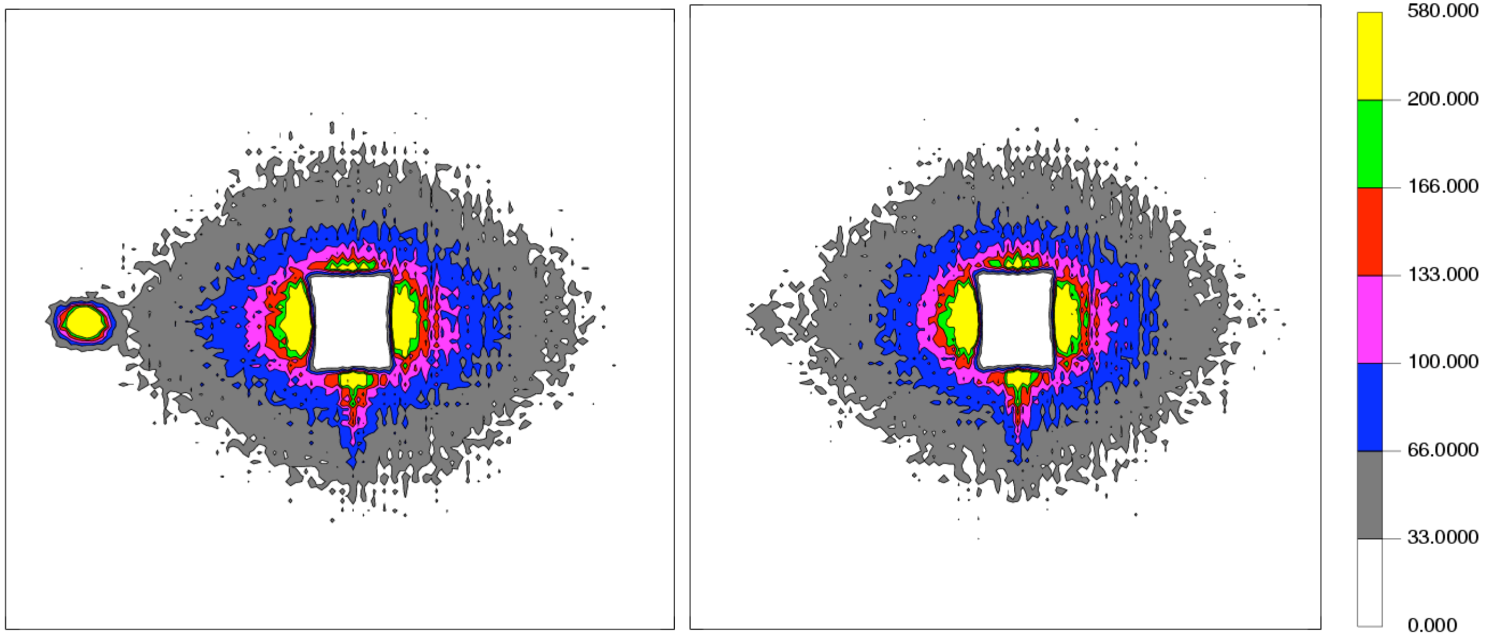




Magnetic field induced long-range order.

Chirality above p_c

(first results)



spin antiparallel to H

spin parallel to H

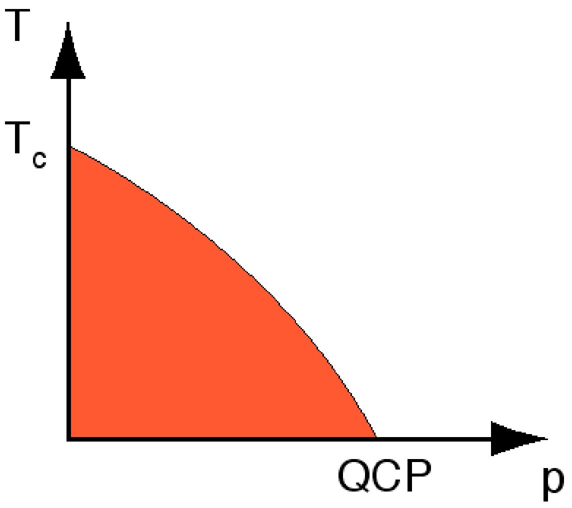
p≈18 kbar

H = 0.3 T T = 1.5 K

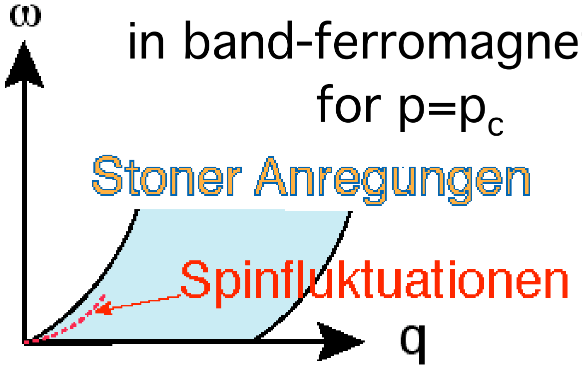
Chirality of longitudinal order unchanged.

Back to the original Gedankenexperiment

Quantum melting of
itinerant magnetism



in band-ferromagnets
for $p=p_c$

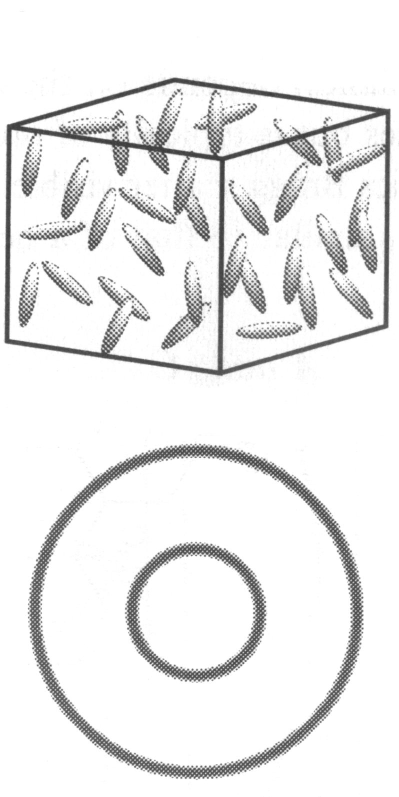


- single-particle or collective?
- condensation (supercond.)?

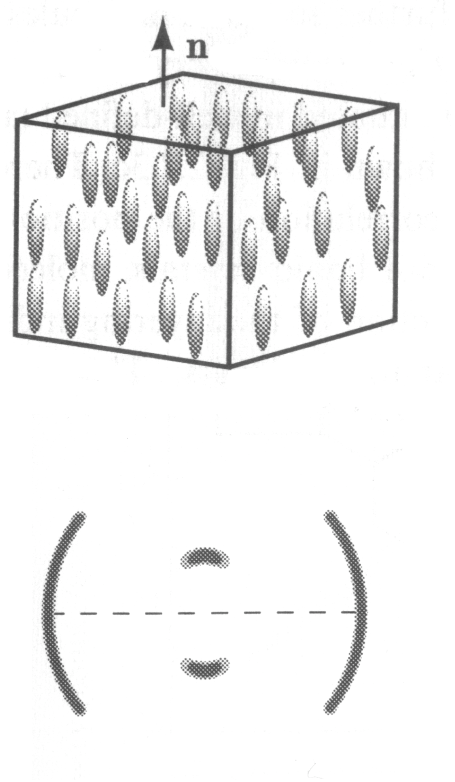
previous assumption: soft modes (amplitude)

Analogy with Partial Order in Liquid Crystals

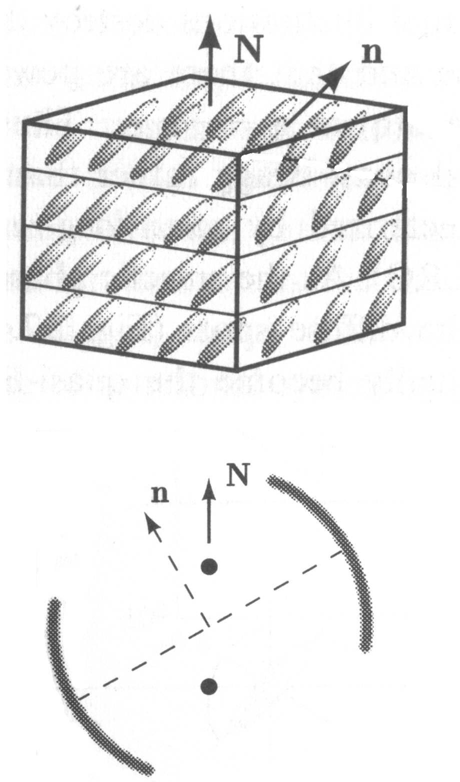
isotropic



nematic

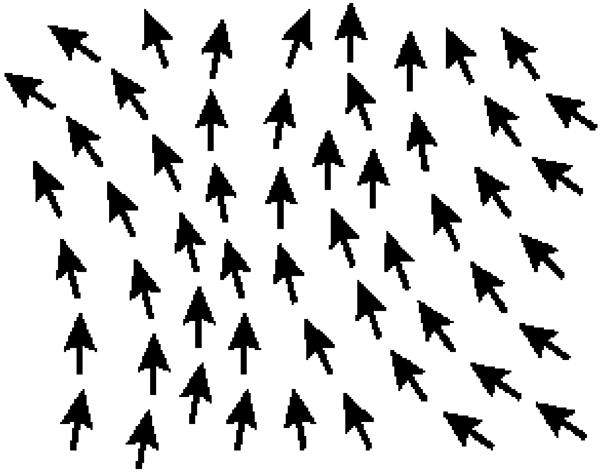


smectic



Analogy with cholesterics?

Brreak-up of long range order



simplest view:
loss of pinning (weakest scale)
pressure flattens the crystal field potential

⇨ distribution of chunks of helix

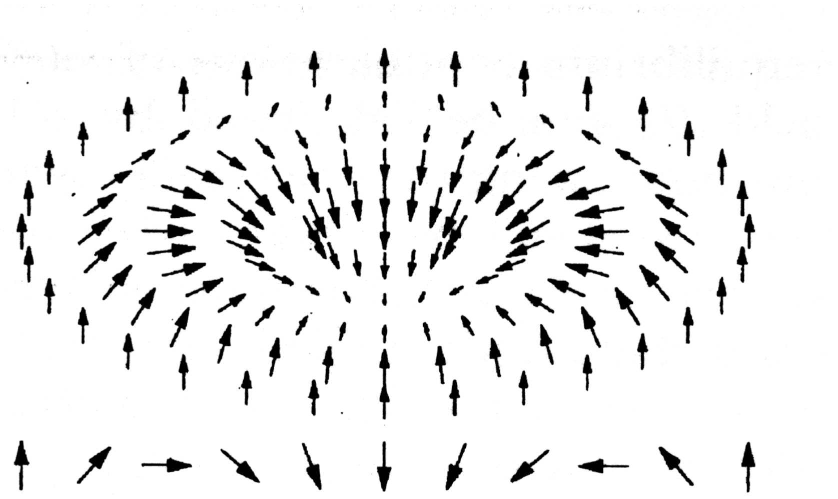
“Change” of role of spin-orbit coupling?

spin-orbit coupling:
Dzyaloshinsky-Moriya
$\mathbf{s} * (\square\ \square\, \mathbf{s})$
rotation-invariant

more generally:
Lifshitz invariants
$m_j \partial_i m_k - m_k \partial_i m_j$

causes reduction of
domain wall energy

Prediction of magnetic vortex
like superconducting vortex
(doubly modulated state)
A. Bogdanov, JETP (1989)



Some Questions

for experimentalists:

- What is known about the specific heat?
- What is known about other transport properties?
- What do the excitation spectra look like?
- ...

for theoreticians:

- What is the origin of the NFL-phase?
- Why is it so stable?
- What is the nature of the „partial order“?
- Why is the intensity located around <110>?
- Can you predict topological order we can look for?
- ...

Instead of a Summary ...