united nations educational, scientific and cultural organization
international atomic energy agency
the abdus salam international centre for theoretical physics
ICTP 40th Anniversary

SMR.1572 - 30

Workshop on
Novel States and Phase Transitions in Highly Correlated Matter

12 - 23 July 2004

MnSi

Christian PFLEIDERER
Physikalisches Institut
Universität Karlsruhe
Wolfgang-Gaede-Str. 1
76131 Karlsruhe
GERMANY

MnSi

Christian Pfleiderer

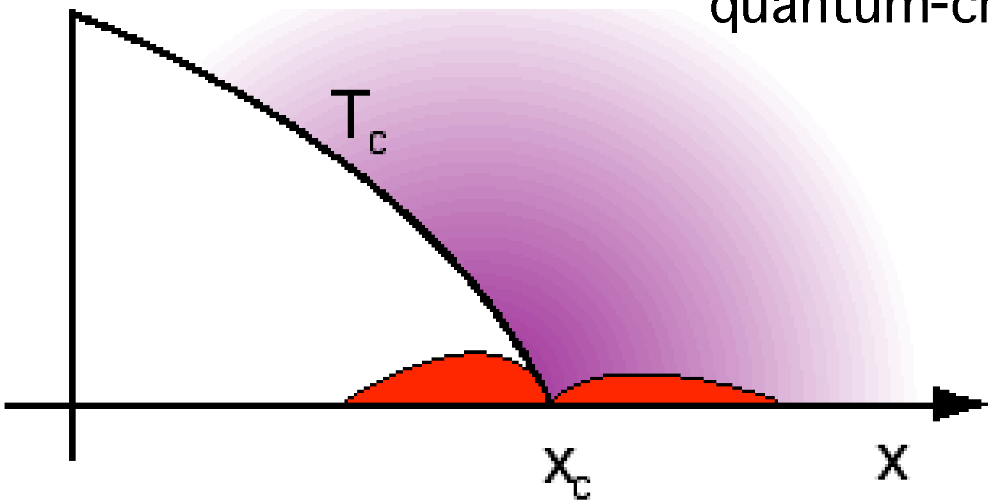
Universität Karlsruhe

Collaborations

Karlsruhe	M. Uhlarz A. Bogdanov M. Garst	L. Pintschovius (IFP) D. Reznik (LLB, IFP) H. v. Löhneysen
Köln	A. Rosch	
Cambridge	G. G. Lonzarich S. R. Julian	
Grenoble	C. Thessieu A. N. Stepanov M. Couach J. Flouquet	

Acknowledgements: M. Turlakov, J. Schmalian, I. Mazin, U. Rößler

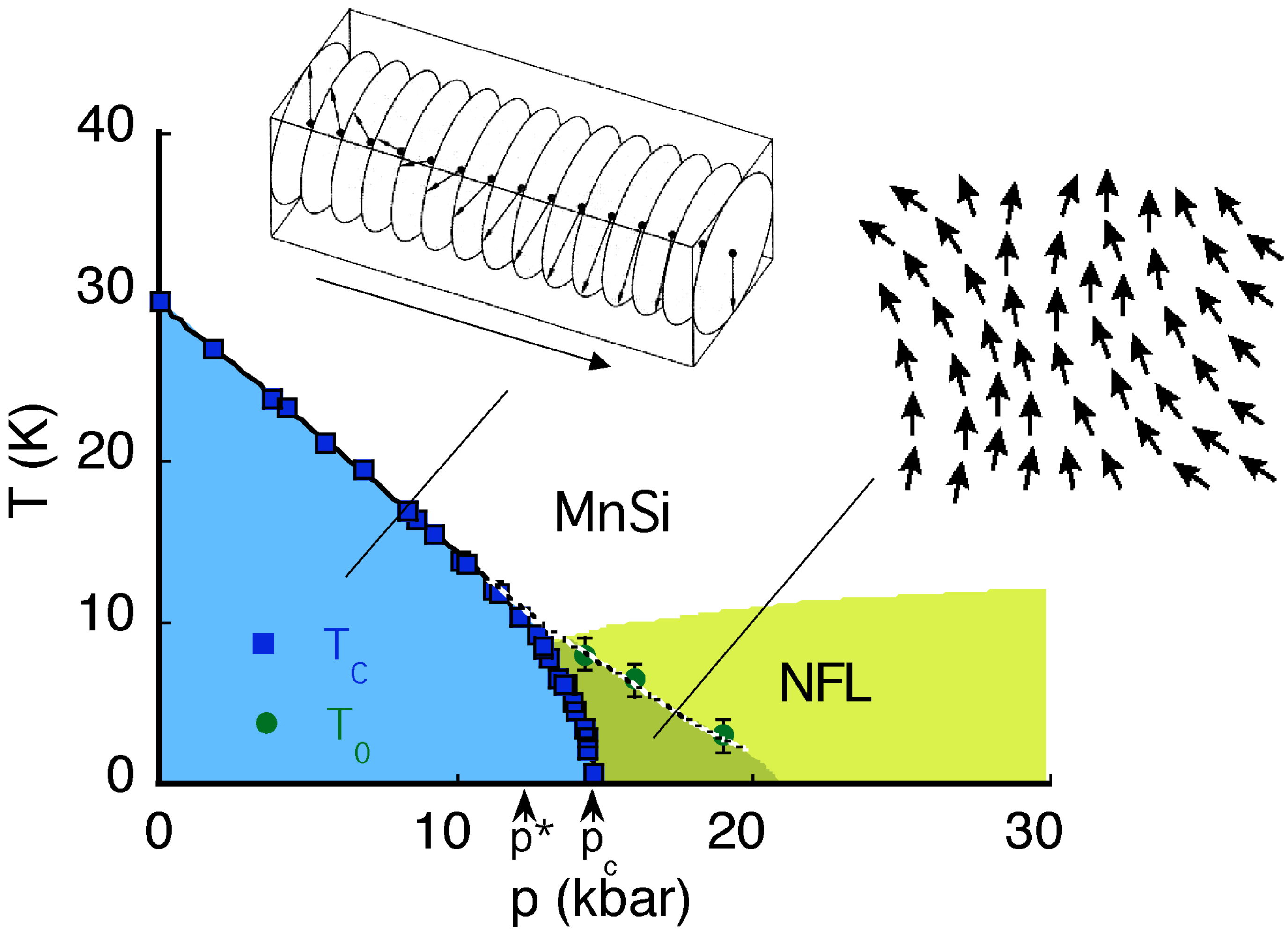
Why study quantum phase transitions?



for $T_c \rightarrow 0$:
quantum-critical continuum

at T=0 exact QM wave function:
quantum coherence ⇒ novel states

Instead of an Overview ...



Weak "Itinerant-Electron" Ferromagnets

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

⇒ Dzyaloshinsky-Moriya interaction

1958 B. Matthias: ferromagnetism in $ZrZn_2$ (C15 Laves phase)

„FM without magnetic elements“

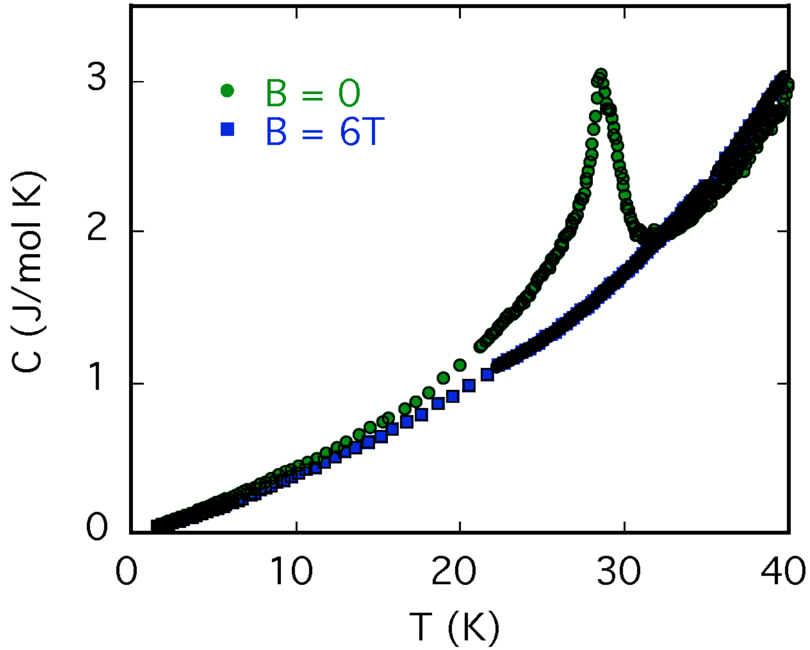
„new“ material class: MnSi, Sc_3In, Ni_3Al, YNi_3, CoS_2, ...

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

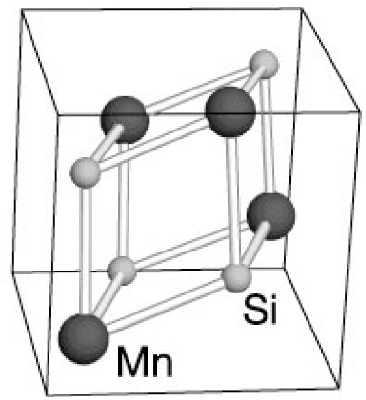
⇒ weakly exchange split band magnets

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

Some Basic Properties of MnSi



very nice metallurgy!!
“perfect” single crystals!



Ferromag.: $T_C \approx 30$ K
$\mu_s \approx 0.4$ mB/f.u.
$\gamma \approx 38$ mJ/mol K^2

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

B20 structure:
no inversion symmetry

Search for quantum criticality

„break-through“ for paramagnons:

$$\langle m_\nu^2 \rangle = 4\hbar \int \frac{d^3\mathbf{q}}{(2\pi)^3} \int_0^\infty \frac{d\omega}{2\pi} n(\omega) \mathrm{Im}\chi_\nu(\mathbf{q},\omega)$$

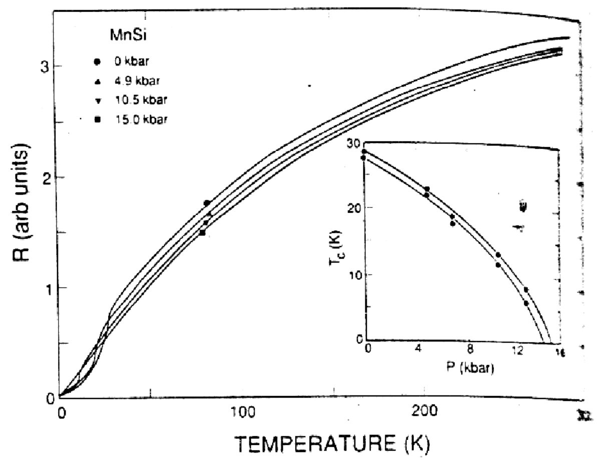
origin of Curie-Weiss susceptibility:
itinerant spin fluctuations

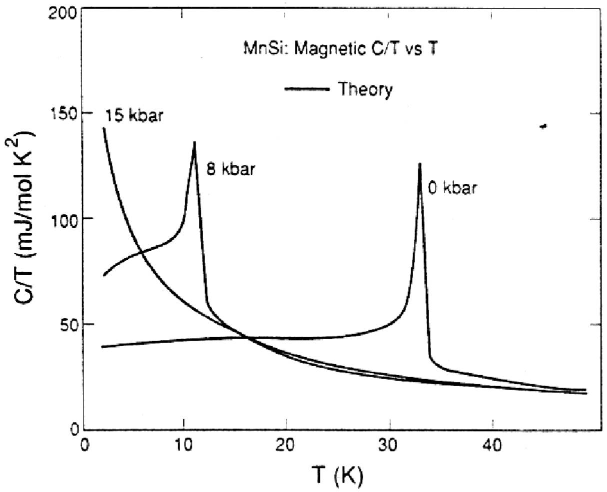
quantitative estimate of T_c

$$T_c = 2.387 c M_0^{3/2} \frac{(\hbar\gamma)^{1/4}}{k_\mathrm{B}}$$

(MnSi expt.: 29.5K, calc.: 31K)

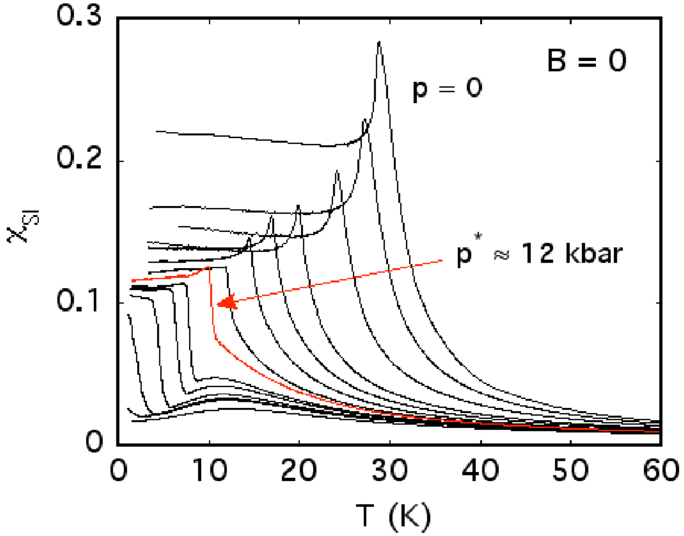
Lonzarich, Moriya,... (1984/85)



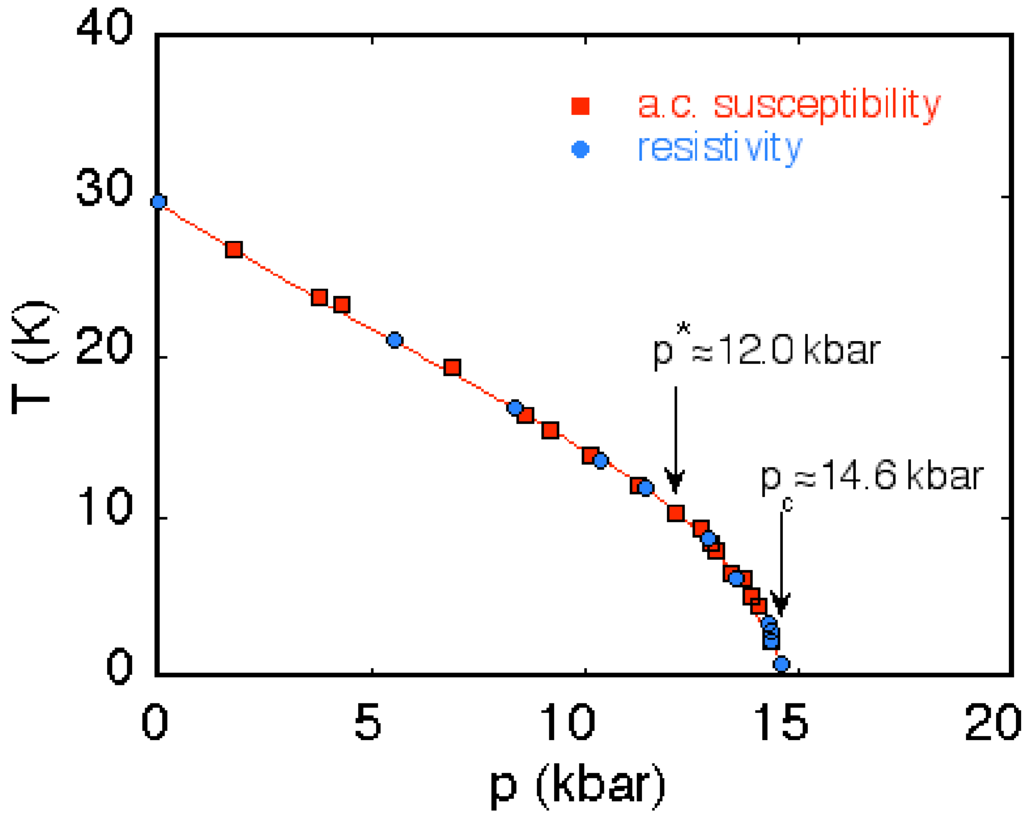


Thompson,Fisk, Lonzarich Physica B 161 (1989) 317

Pressure-Temperature Phase Diagram of MnSi

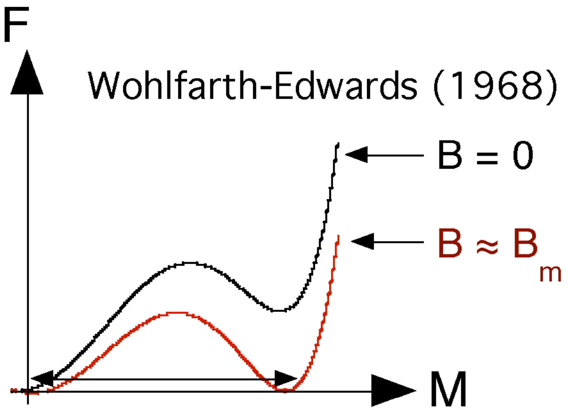


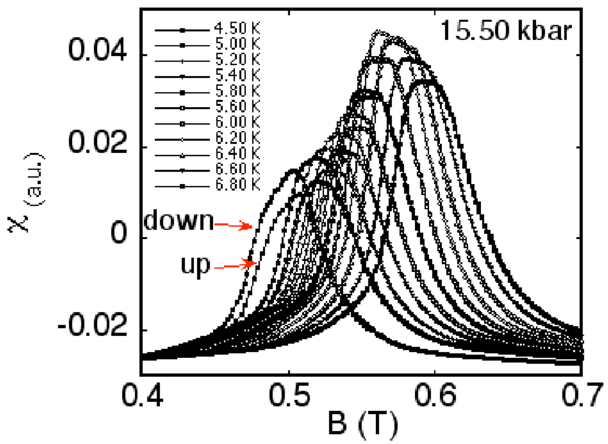
1st order transition
for 12kbar<p<p_c

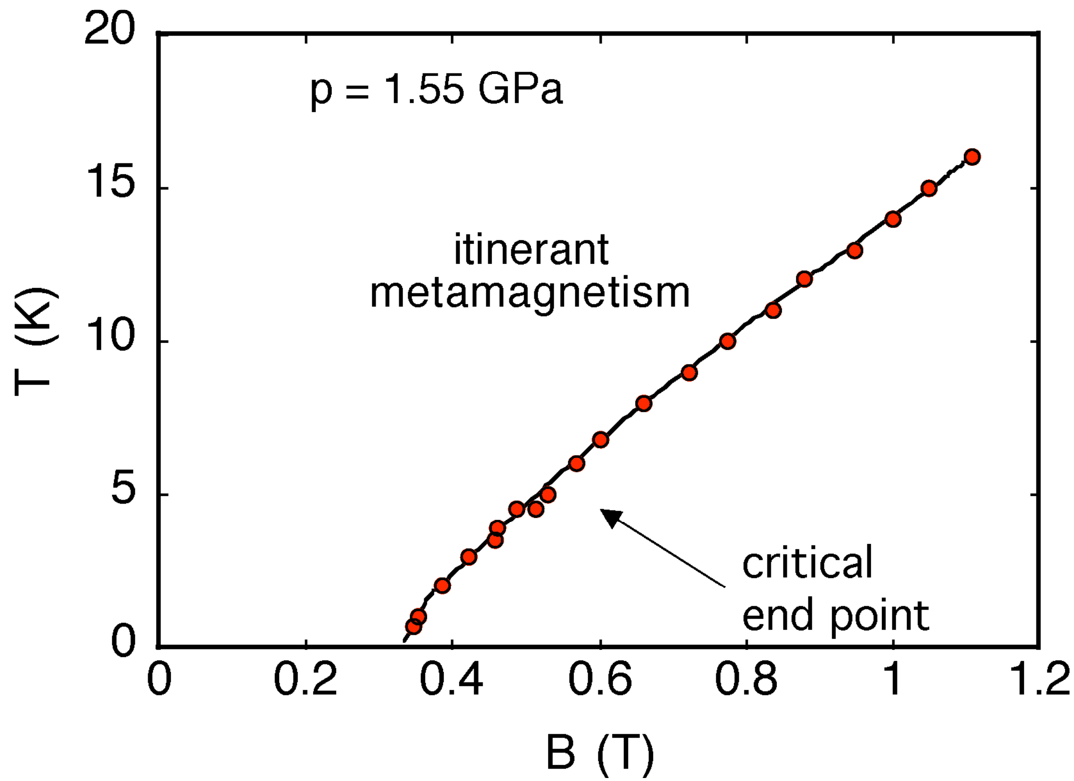


CP et al., Phys. Rev. B 55 (1997) 8330.

Itinerant Metamagnetism in MnSi for $p>p_c$

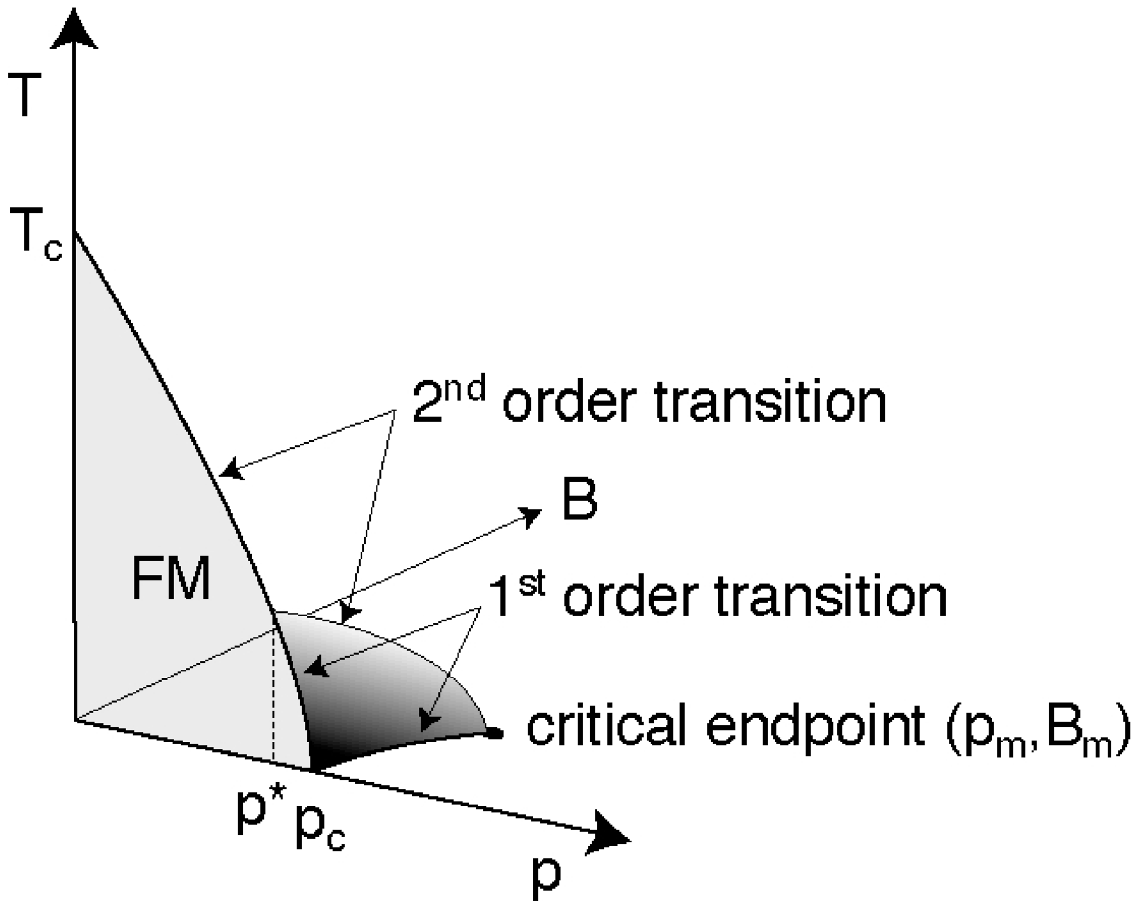






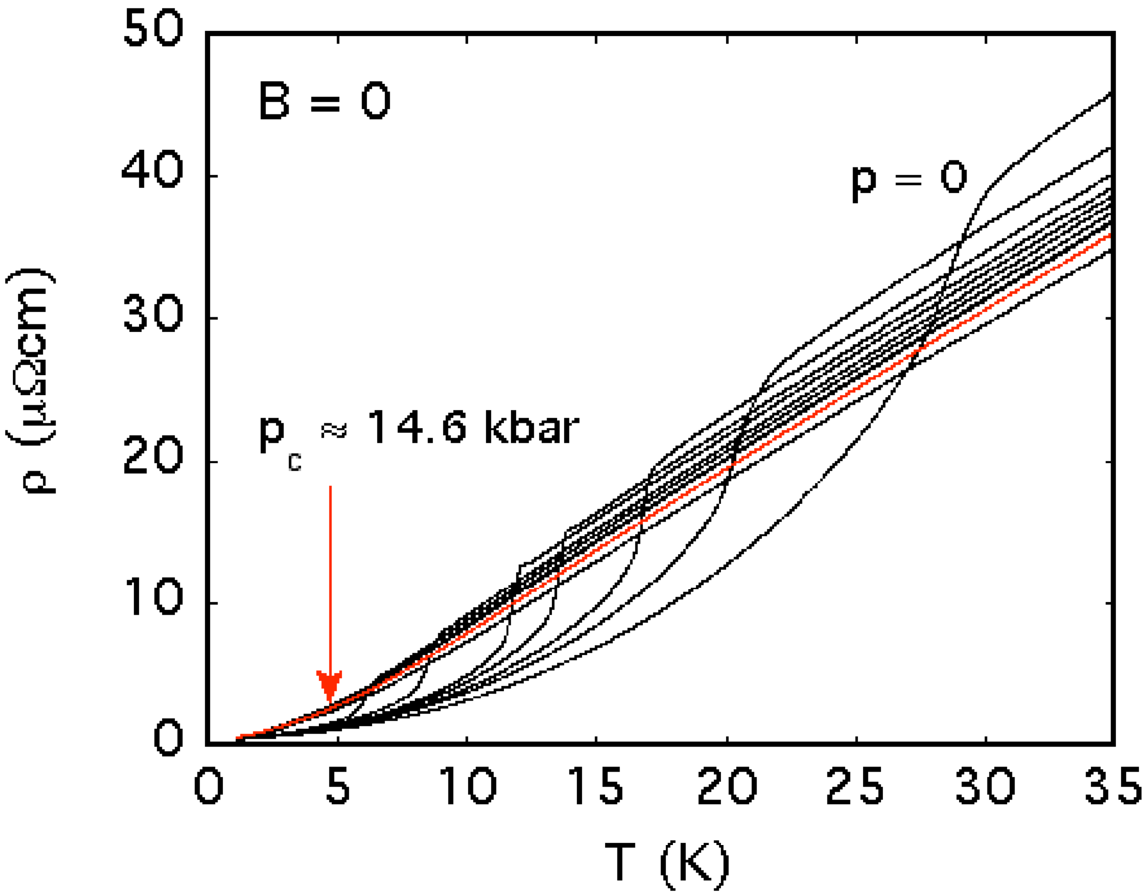
Thessieu, CP, Stepanov, Flouquet, J. Phys.: Cond. Matter **9** (1997) 6677.

Proposed Generic Phase Diagram of Itinerant Ferromagnets



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

Pressure Dependence of the Electrical Resistivity

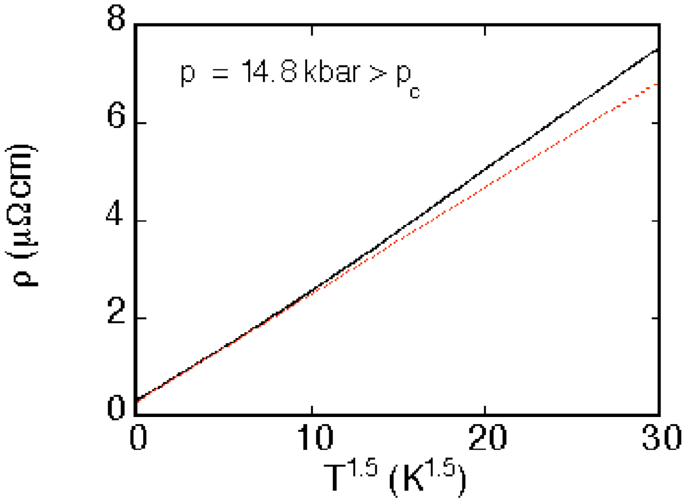


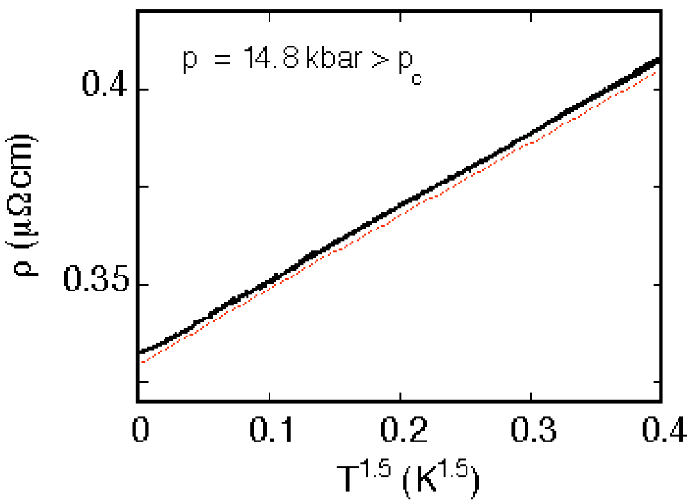
Fermi liquid:

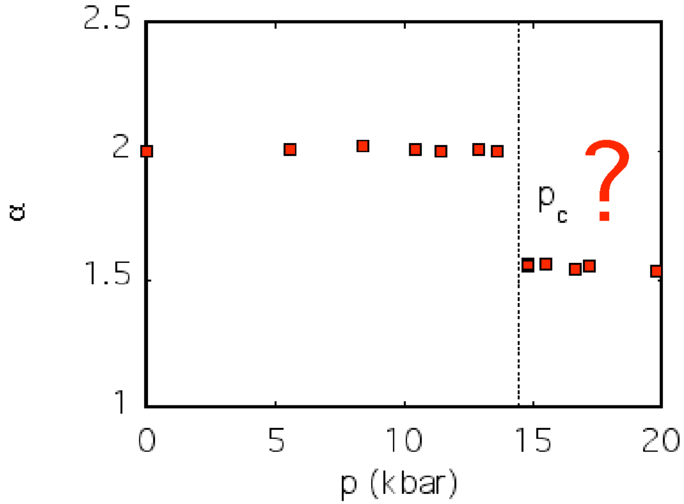
$$\rho(T)=\rho_0+AT^2$$

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

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







$\rho(T) = \rho_0 + \Delta\rho(T)$

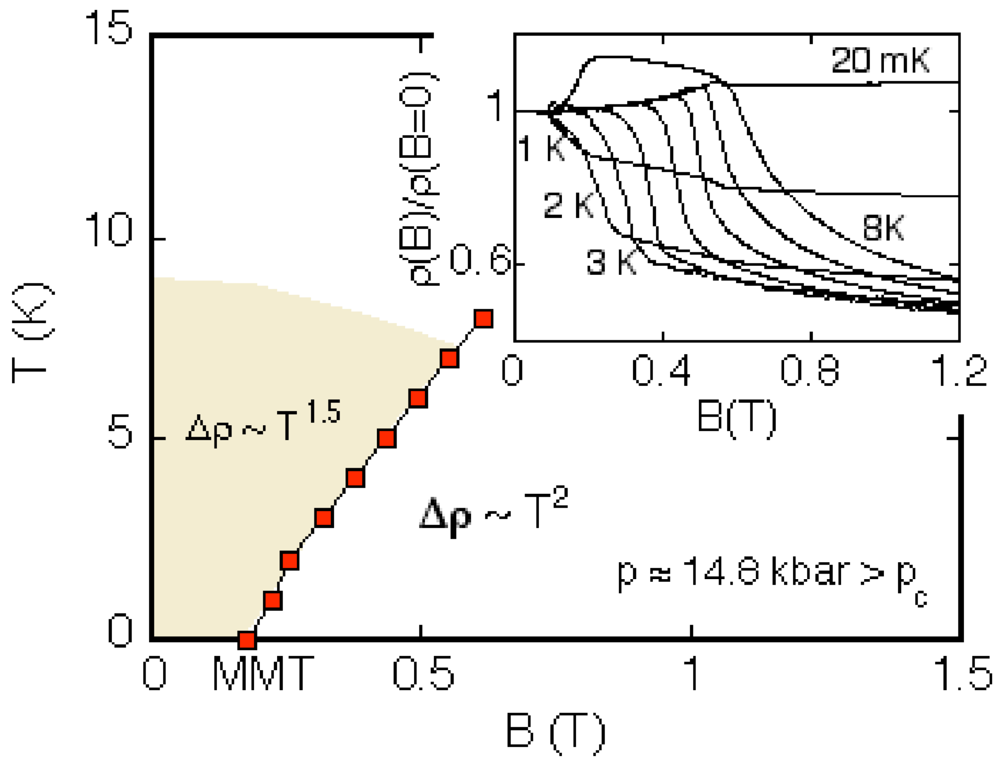
$\rho_0 << \Delta\rho(T) \propto T^{3/2} << \rho_0$

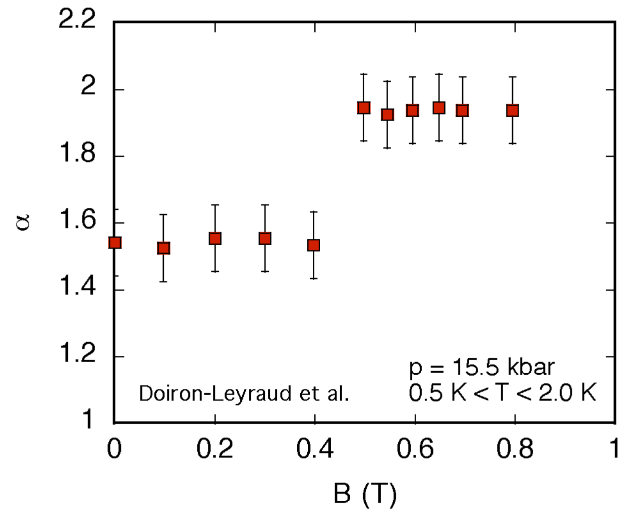
⇨ mK < T < several K

⇨ α insensitive to p

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

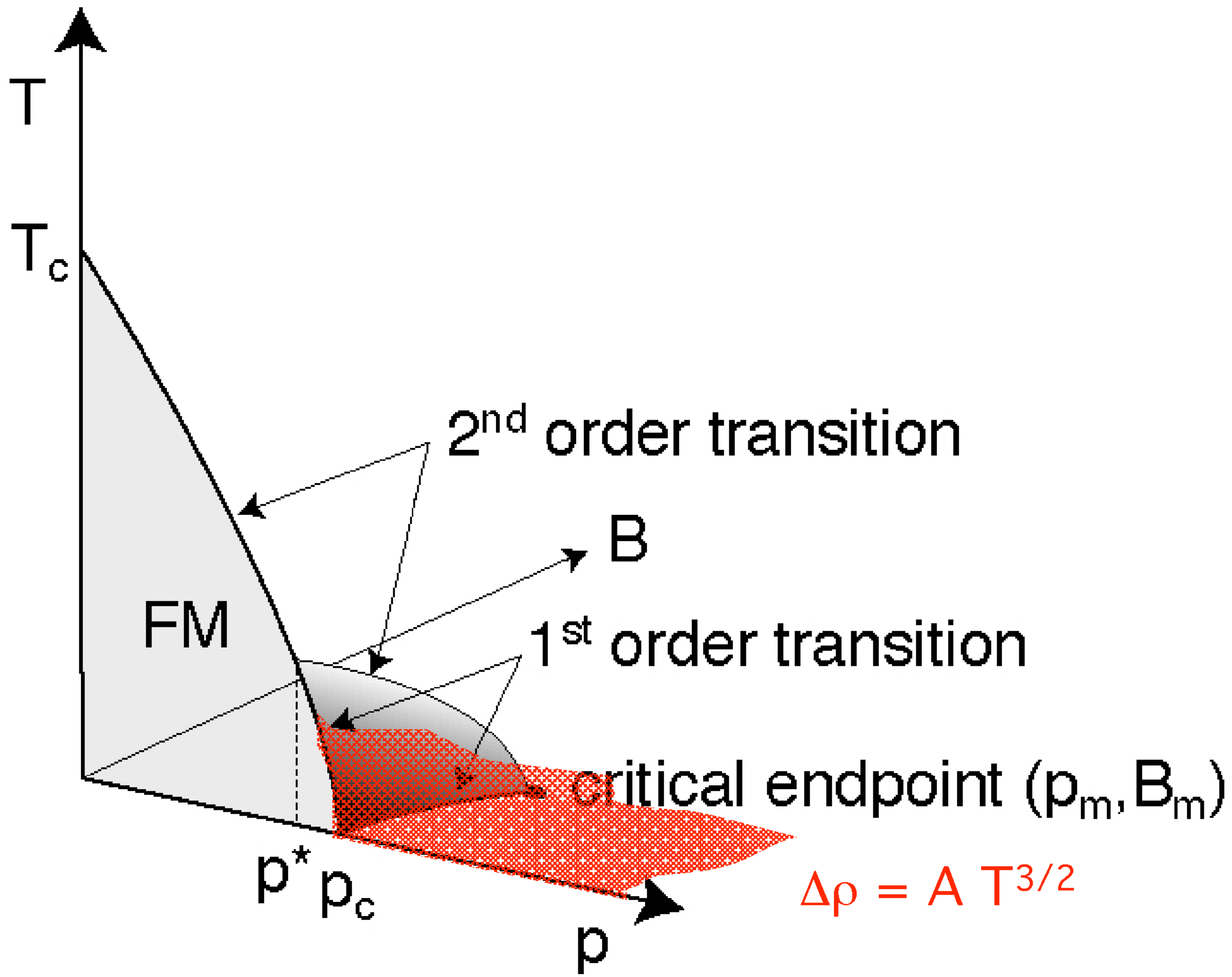
Variation of $T^{3/2}$ with Magnetic Field near p_c





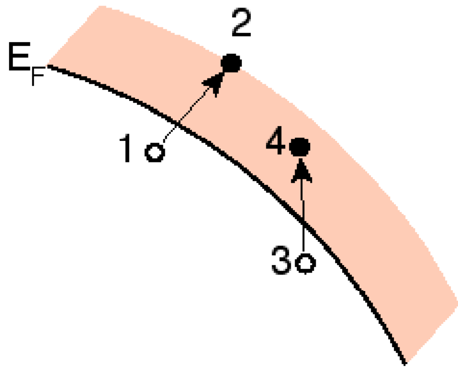
- NFL phase stable up to MMT
- drop of ρ at B_c

Phase diagram of MnSi revisited



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

Landau (1957)

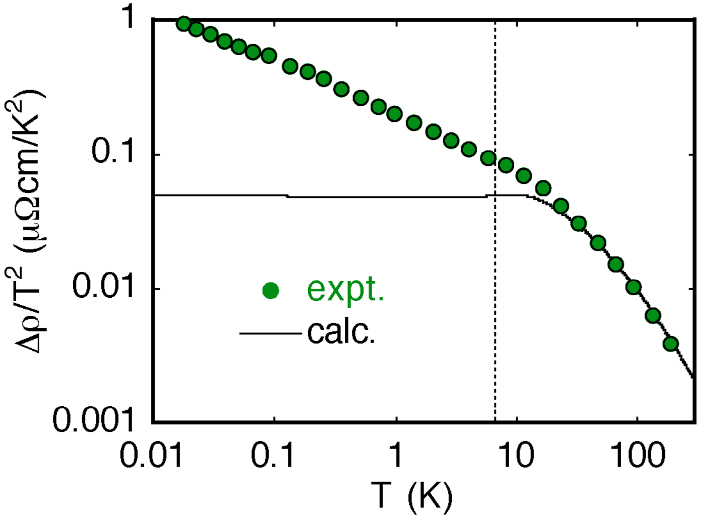


$$1/\tau = a\,(\varepsilon_1 - E_F)^2 + b\,(k_B\,T)^2$$

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

electrical resistivity (Pauli)

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

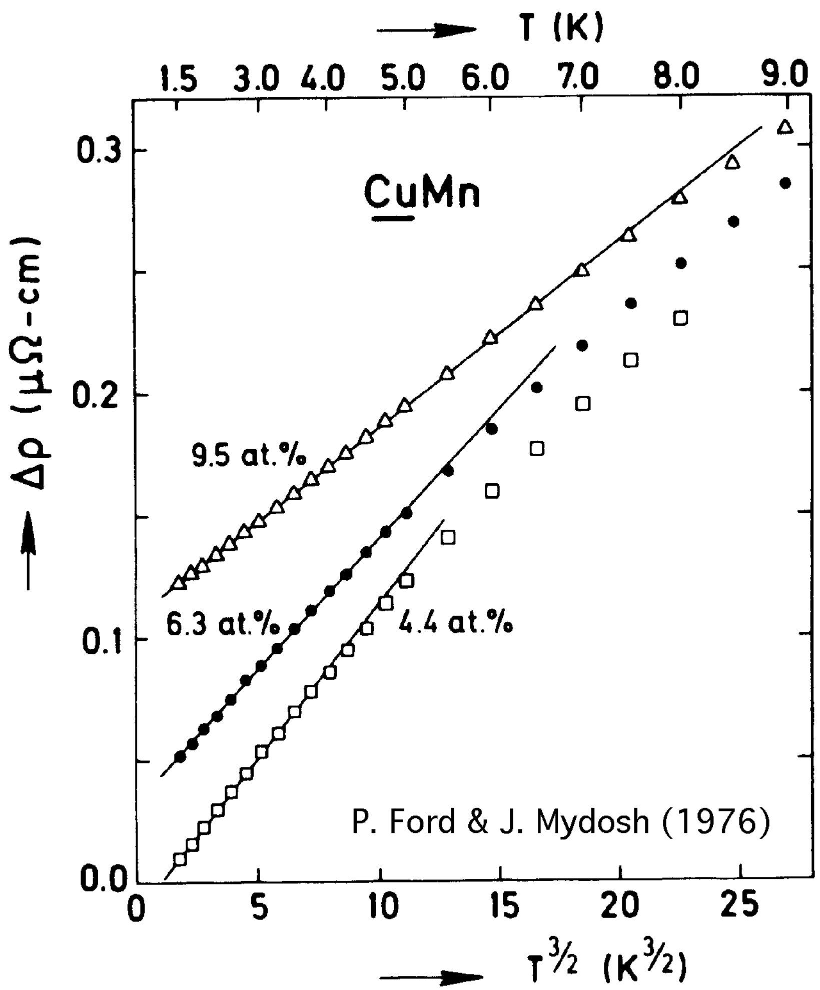


$\Delta\rho/T^2=A$ singular für $T \to 0$

phenomenology inconsistent with Pauli principle

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

Origin of the $T^{3/2}$ Resistivity?



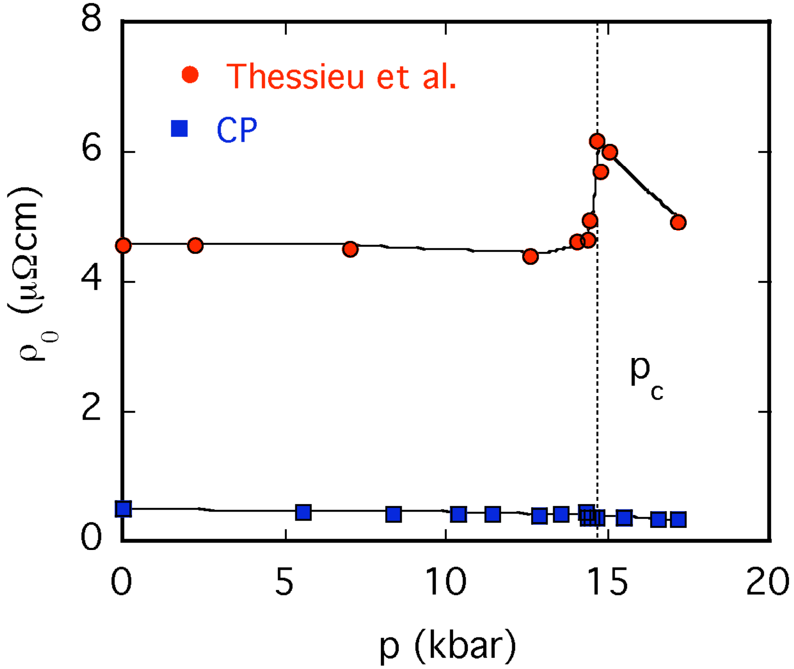
Metallic spin-glasses

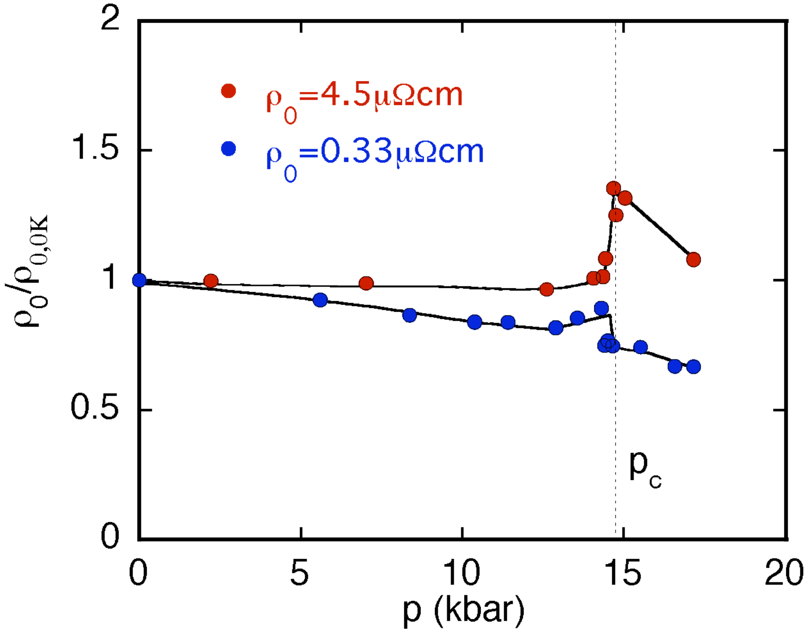
Is the NFL phase of MnSi
an intrinsic “glassy” state?

BUT: high purity single crystals

mean free path $\approx$ 3000Å!
structural perfect (cf. Silicon)

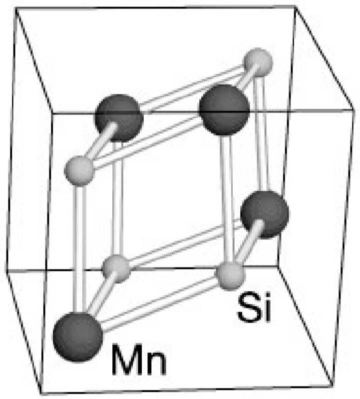
Pressure dependence of the residual resistivity





maximum near p_c vanishes for better samples

Characteristic Energy Scales in MnSi



cubic (B20)
no inversion

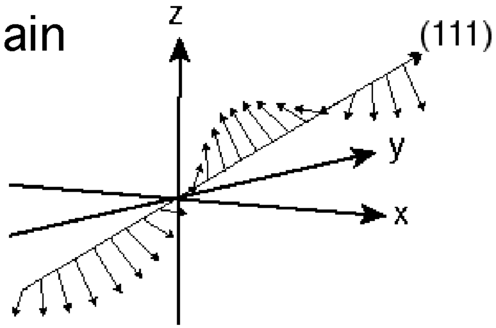
(1) ferromagnetism

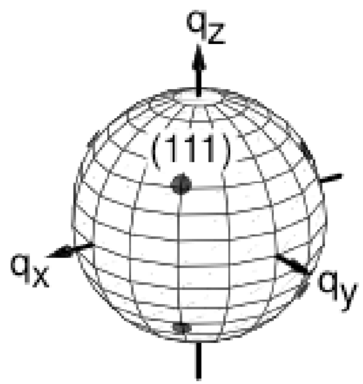
(2) spin-orbit coupling:
Dzyaloshinsky-Moriya interaction
$\mathbf{s} * (\nabla \times \mathbf{s})$, rotation-invariant
$\lambda \approx 170$ Å (a = 4.558 Å)

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

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

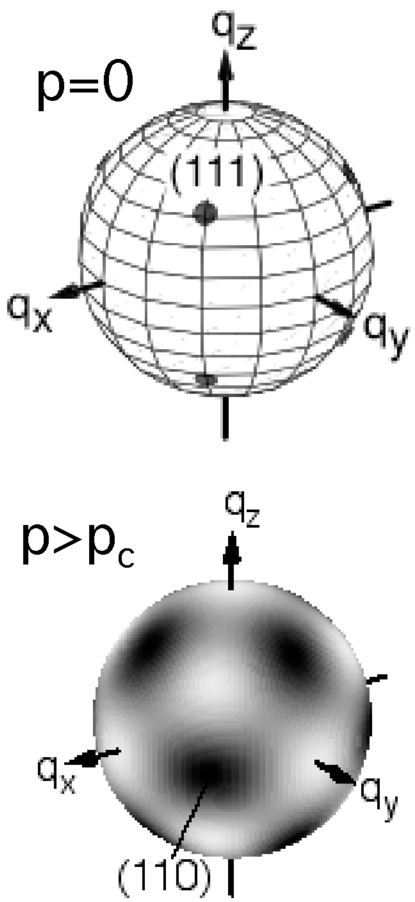
single domain

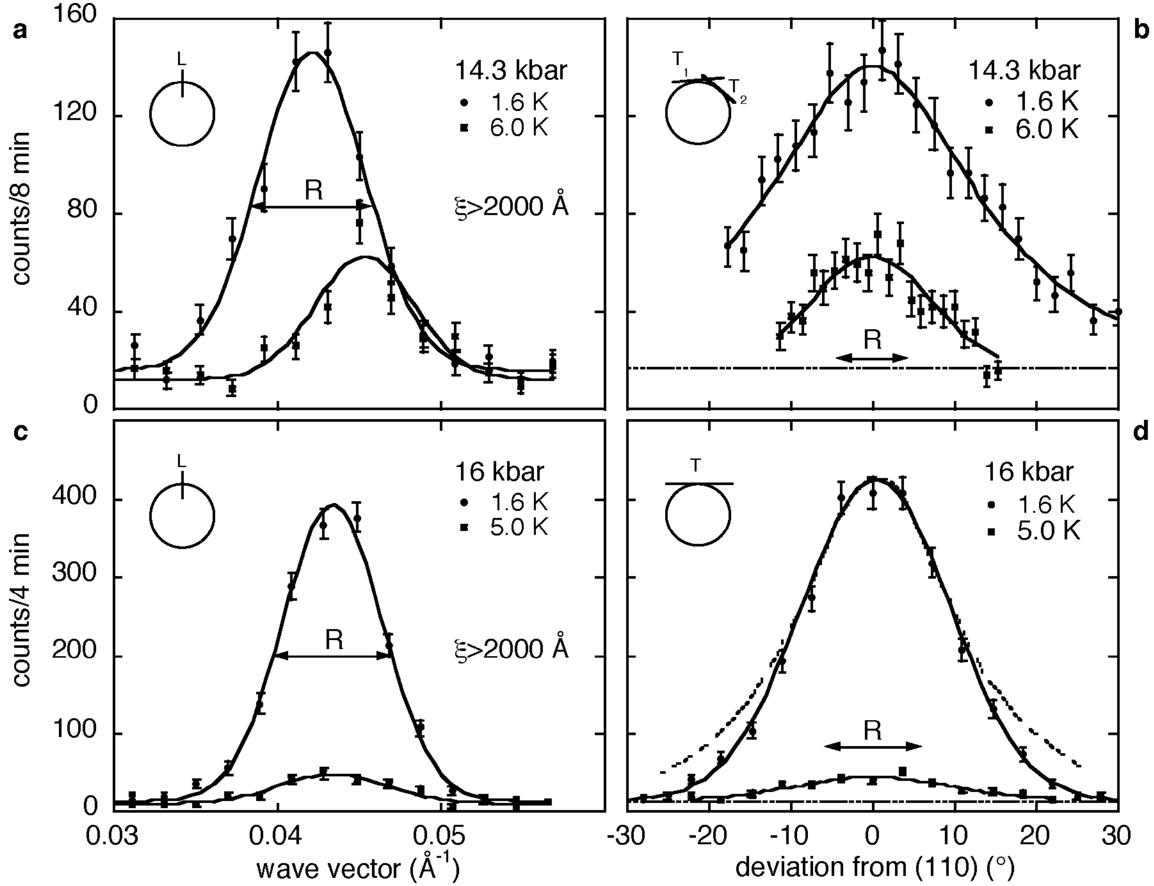




magn. domains
in recip. space:
sharp satellites

Partial Magnetic Order in the NFL-Phase of MnSi

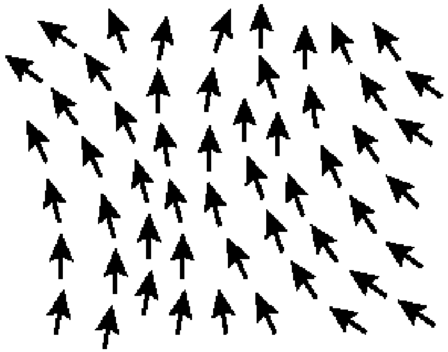




experiments at 4F1 (LLB Saclay)

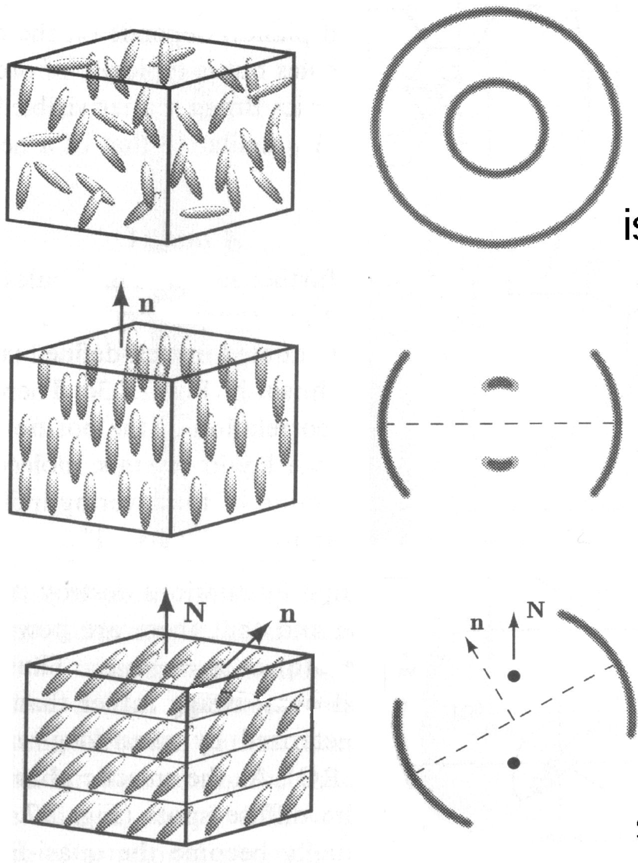
CP et al., Nature, **427** (2004) 227

Analogy with Partial Order in Liquid Crystals



loss of pinning
(weakest scale)
flat crystal field potential

⇨ disordered chunks of helix



isotropic

nematic

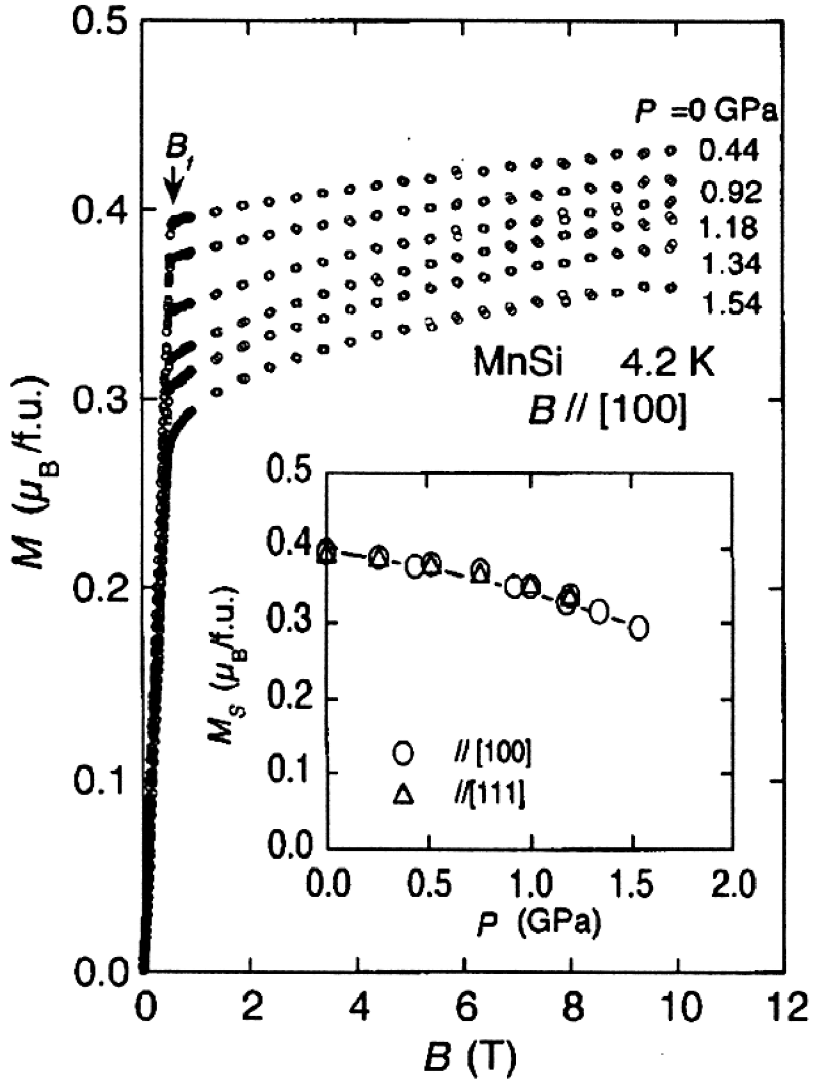
smectic

Analogy with cholesterics?

Size of partially ordered moment

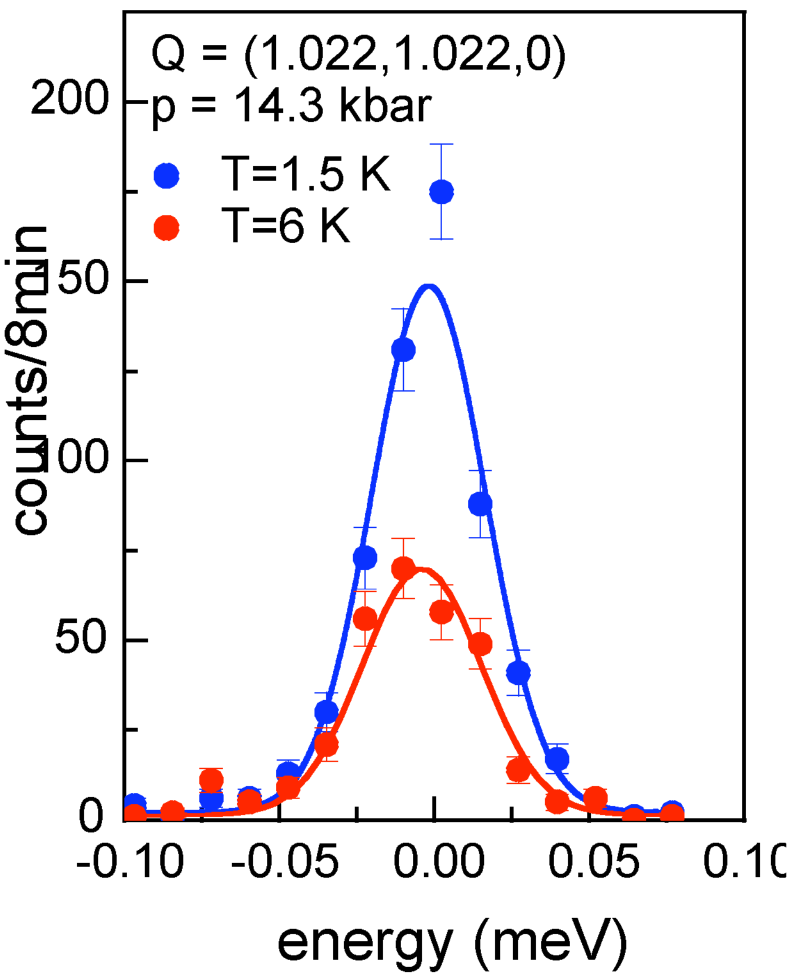
integrated scattering intensity of partial order unchanged: large moment survives p_c
(„no“ amplitude reduction at p_c)

consistent with magnetisation: ordered moment in 0.6T weakly pressure dependent



Koyama, et al., PRB **62** (2000) 986

Energy dependence near p ≈ p_c



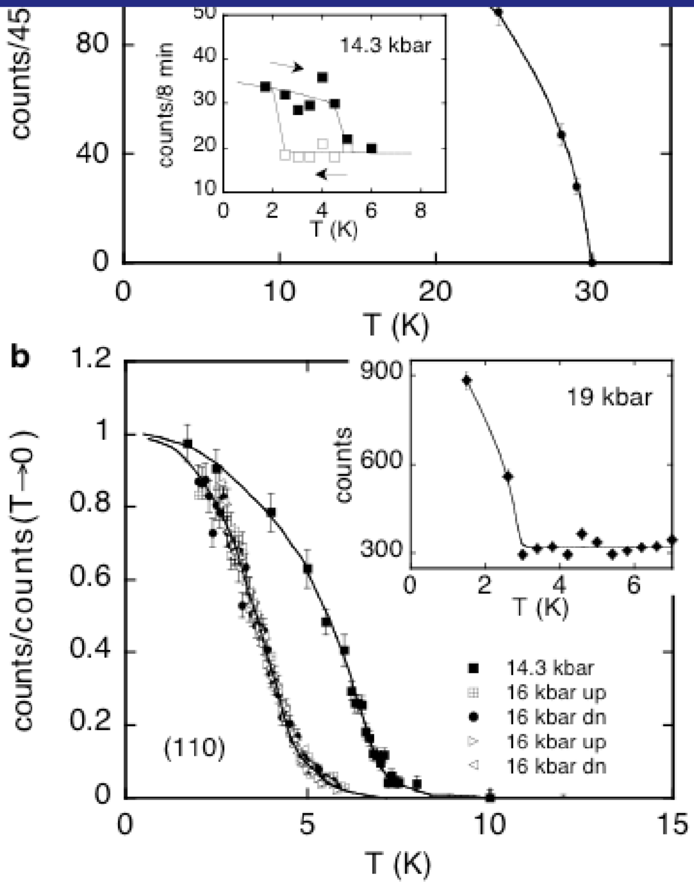
resolution limited:

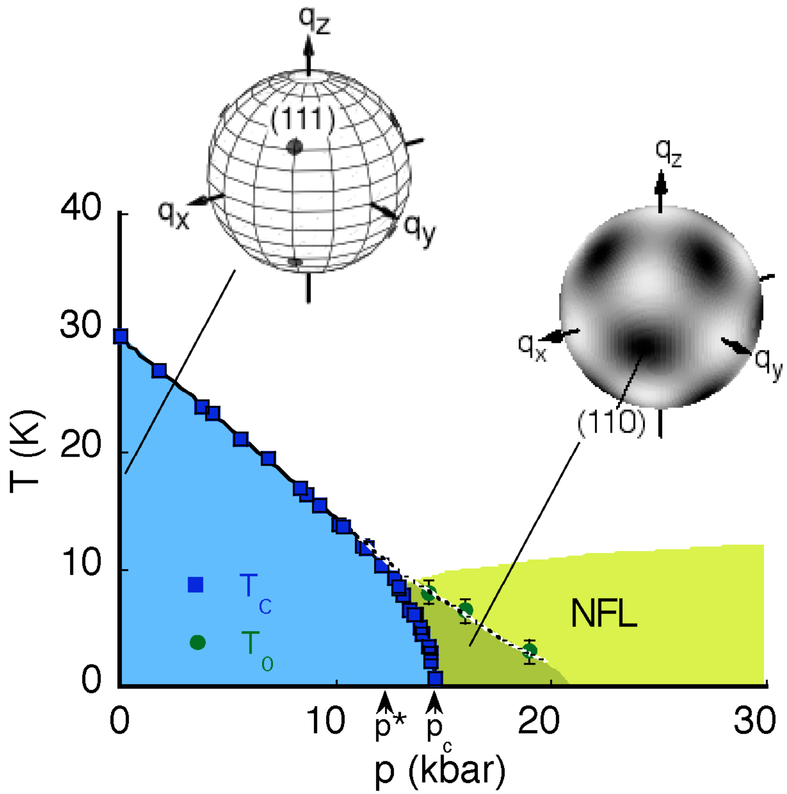
$\Delta\omega \approx 50\mu eV$ (0.5K)

no broadening with T

quasi-static (very slow)

Temperature Dependence of the Partial Order

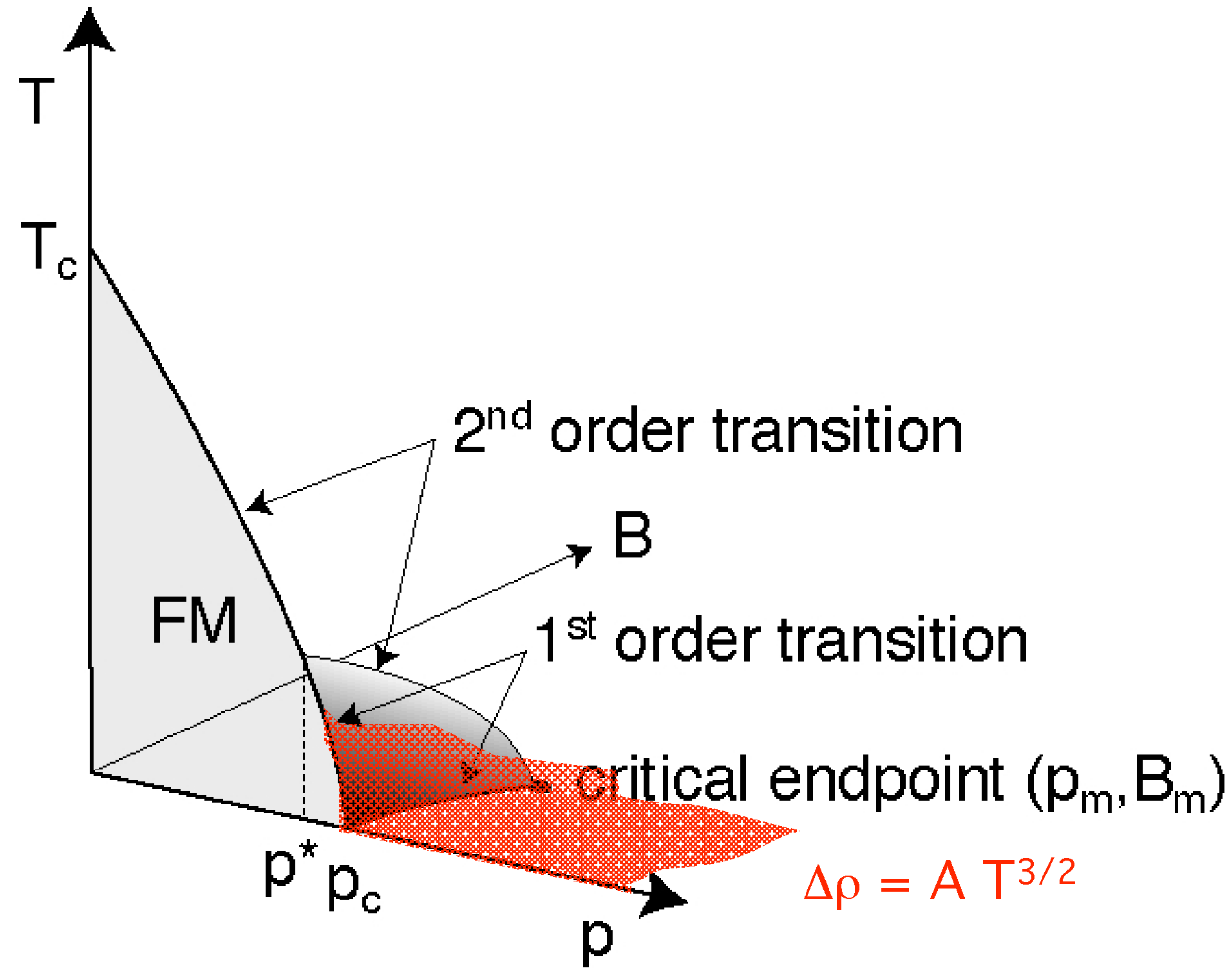




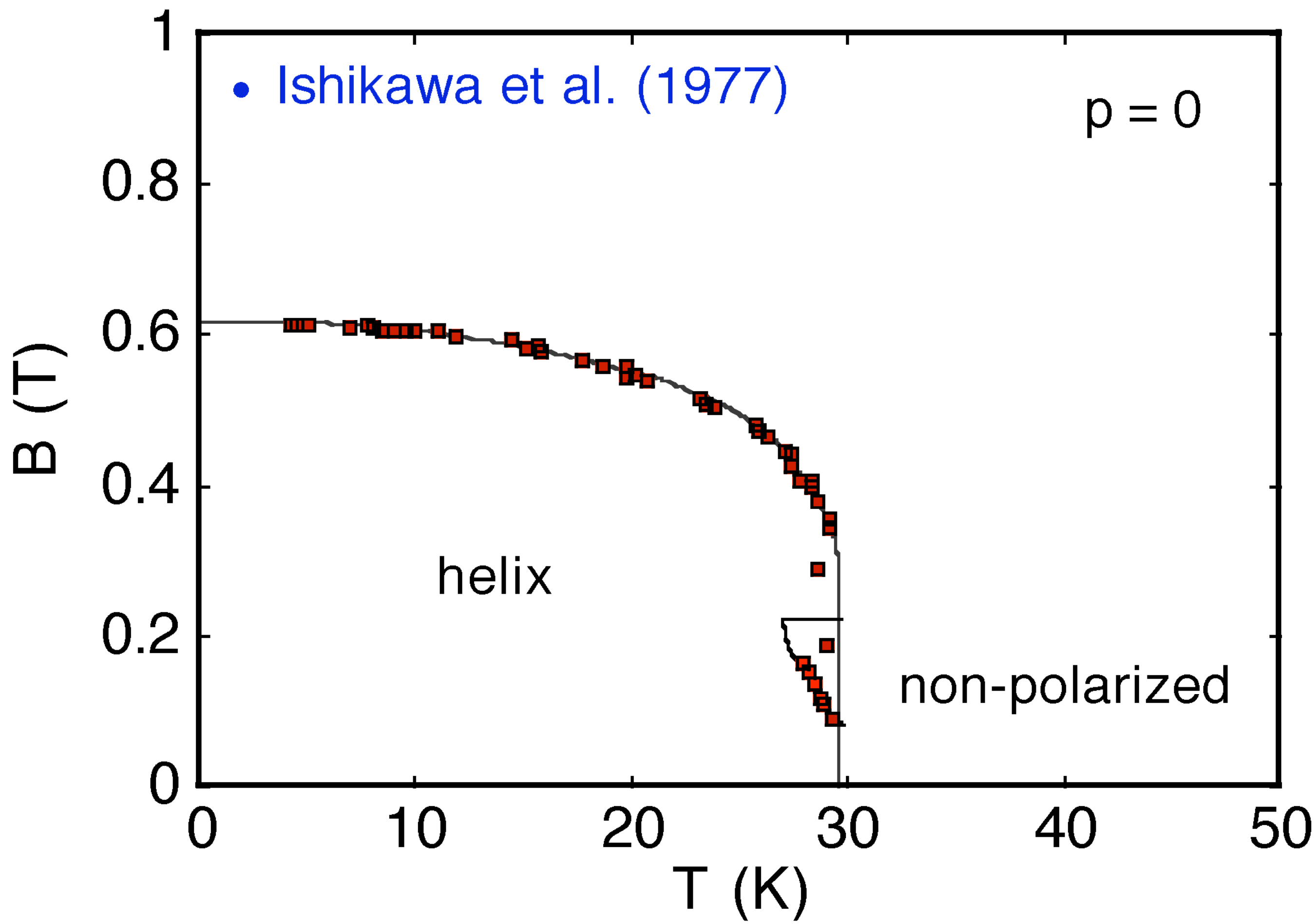
crossover

(not sharp phase transition)

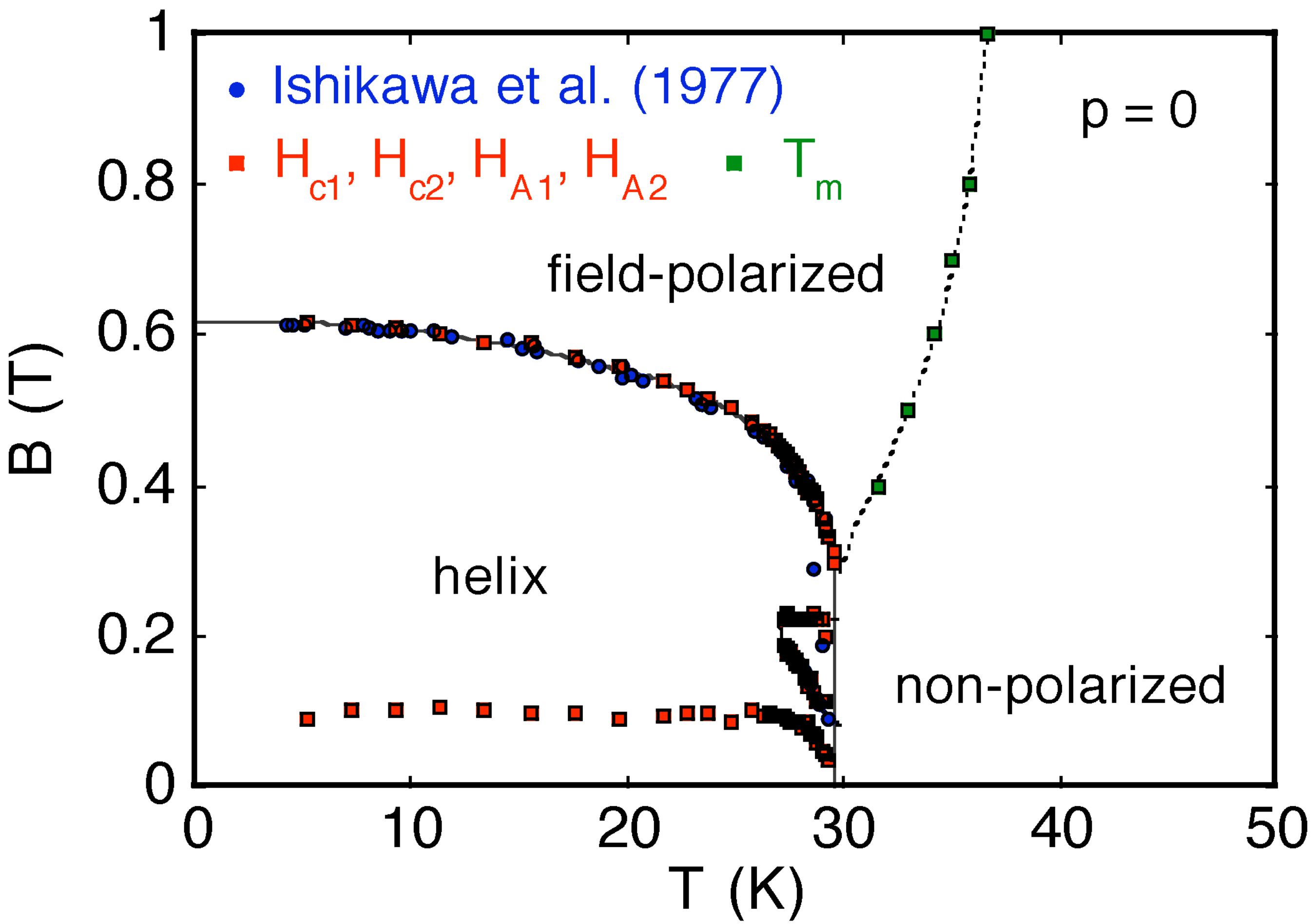
What about the magnetic field dependence?



Magnetic phase diagram at p=0



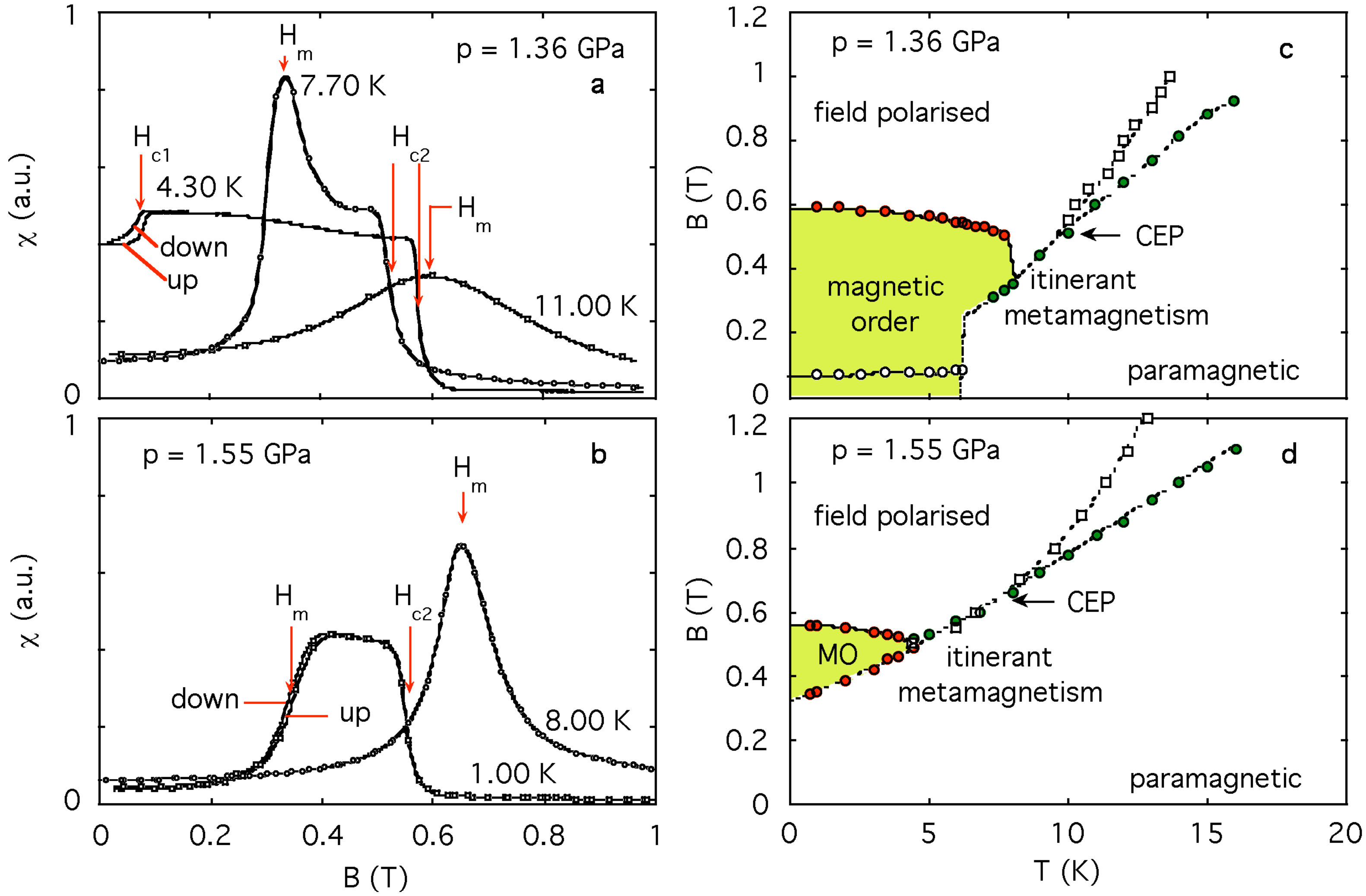
Magnetic phase diagram at p=0



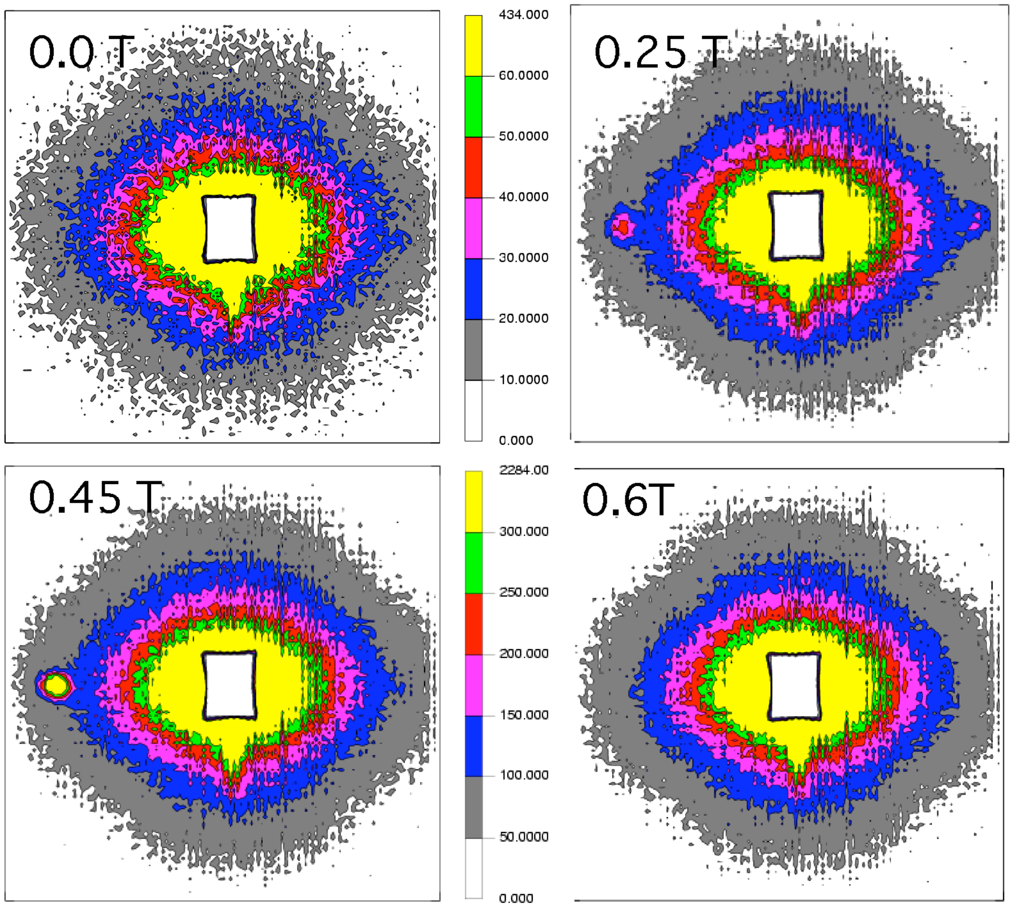
$B_c \approx 0.6T$

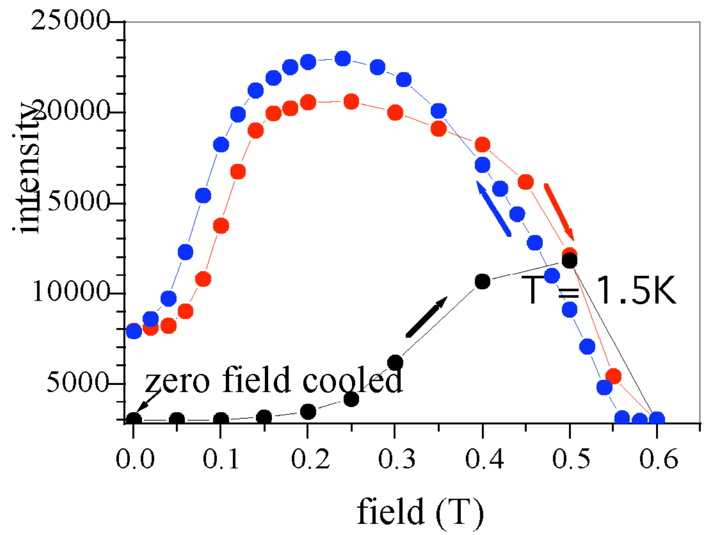
Thessieu, CP, Stepanov, Flouquet, JPCM **9**, 6677 (1997)

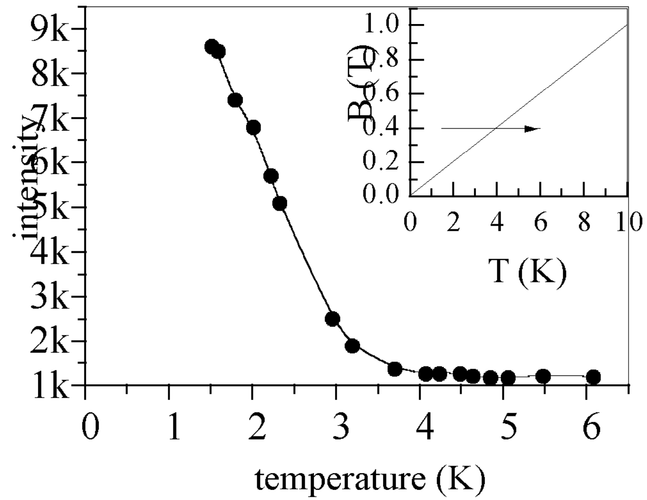
Magnetic phase diagram near p_c



Magnetic Field Dependence above p_c



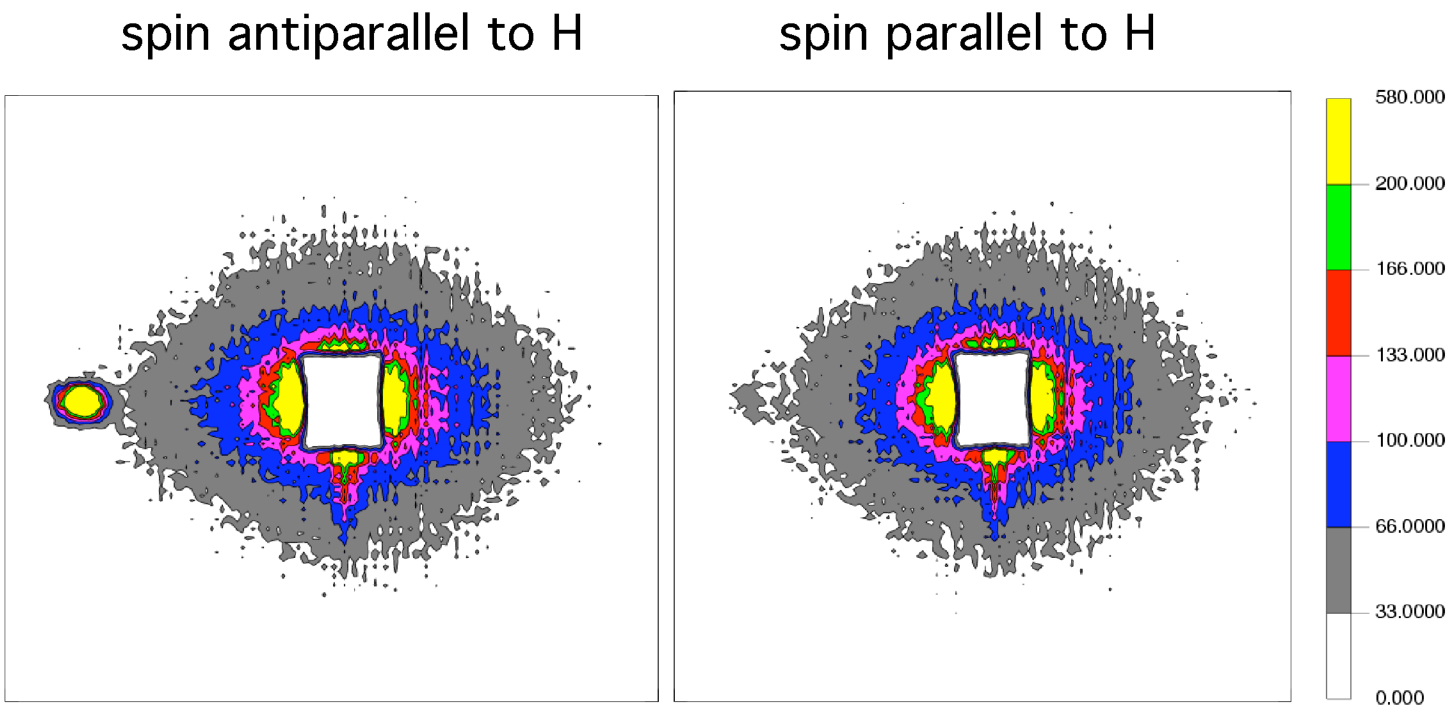




$p \approx 18$ kbar > p_c SANS at V4 HMI Berlin

Magnetic field induced long-range order.

Chirality above p_c



$p \approx 18$ kbar

H = 0.3 T   T = 1.5 K

Chirality of longitudinal order unchanged.

Towards a theory of the phase diagram of MnSi

Rosch, et al.:

- anomalous Goldstone modes
- role of spin-orbit coupling

Turlakov, Schmalian:

- magnetic rotons

Vojta, Belitz, Kirkpatrick, et al.:

- breakdown of Ginzburg-Landau-Wilson

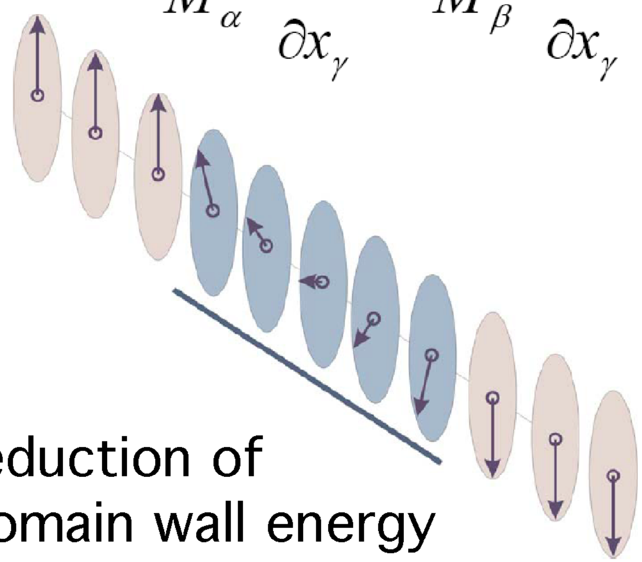
“Change” role of spin-orbit coupling?

spin-orbit coupling:
(Dzyaloshinsky-Moriya)

$$W_{DM} = D_{ij}\boldsymbol{S}_i \times \boldsymbol{S}_j$$

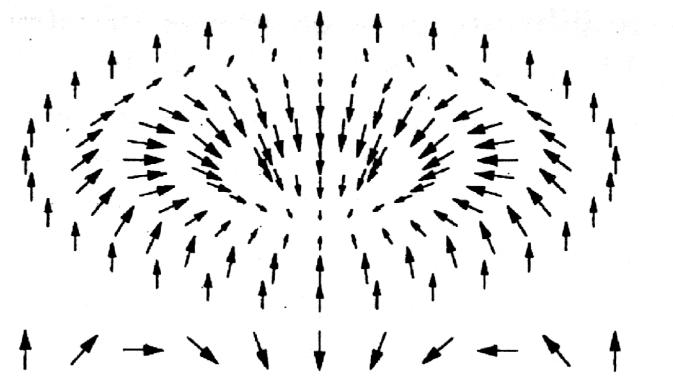
Lifshitz invariants

$$M_\alpha \frac{\partial M_\beta}{\partial x_\gamma} - M_\beta \frac{\partial M_\alpha}{\partial x_\gamma}$$



reduction of
domain wall energy

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



Instead of a Summary ...