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Workshop on
Novel States and Phase Transitions in Highly Correlated Matter

12 - 23 July 2004

Towards a theory of the non-Fermi liquid phase in MnSi

Achim ROSCH
University of Cologne
Institute of Theoretical Physics
Zulpicher Strasse 77
D-50937 Cologne
GERMANY

These are preliminary lecture notes, intended only for distribution to participants

Towards a theory of the non-Fermi liquid phase in MnSi

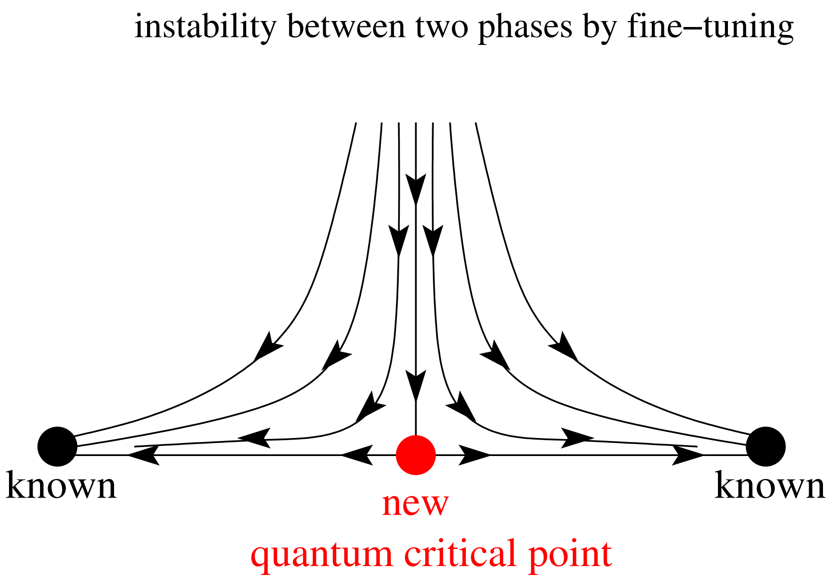
Achim Rosch, Markus Garst, Inga Fischer
Institut für Theoretische Physik, University of Cologne
Experiments: Christian Pfleiderer, University of Karlsruhe

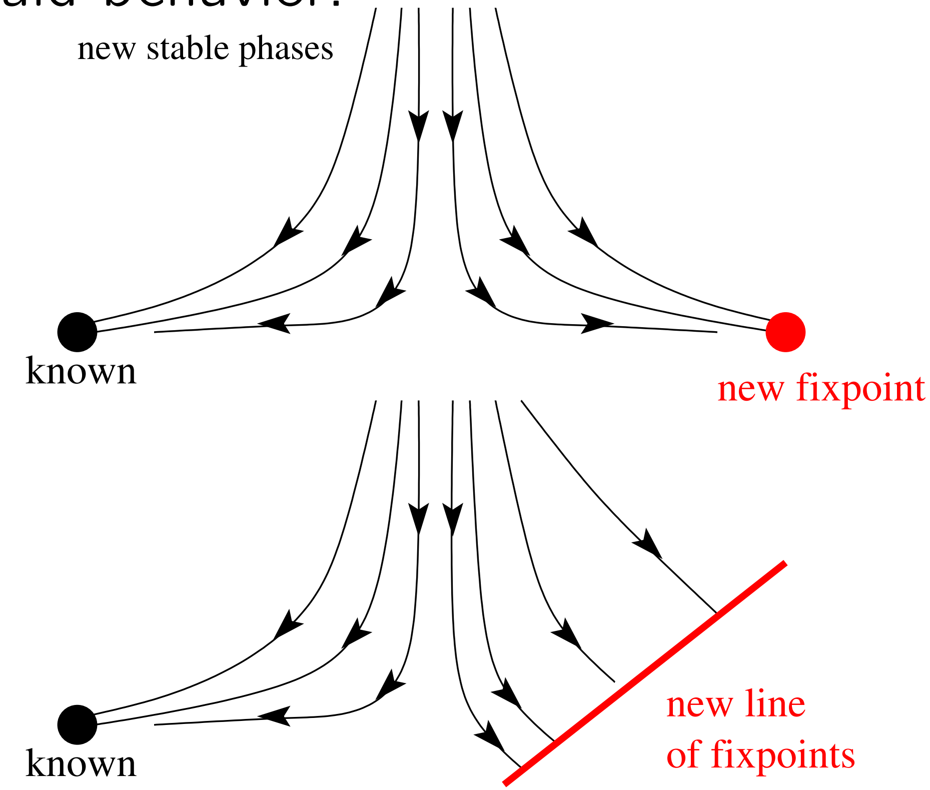
- A non-Fermi liquid **phase** in MnSi?
  Review of experiments
- Topological defects?
- Anomalous overdamped (pseudo-) Goldstone modes?
- Band structure in a spiral

Disclaimer:
Work in progress: many questions – few answers

Towards "novel phases" in metals

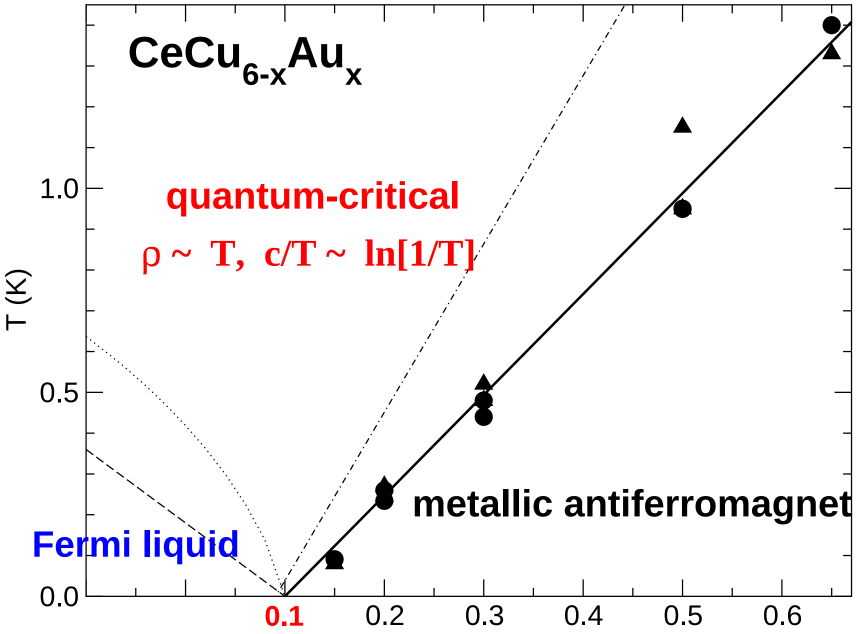
from Fermi liquids to non-Fermi liquid behavior:



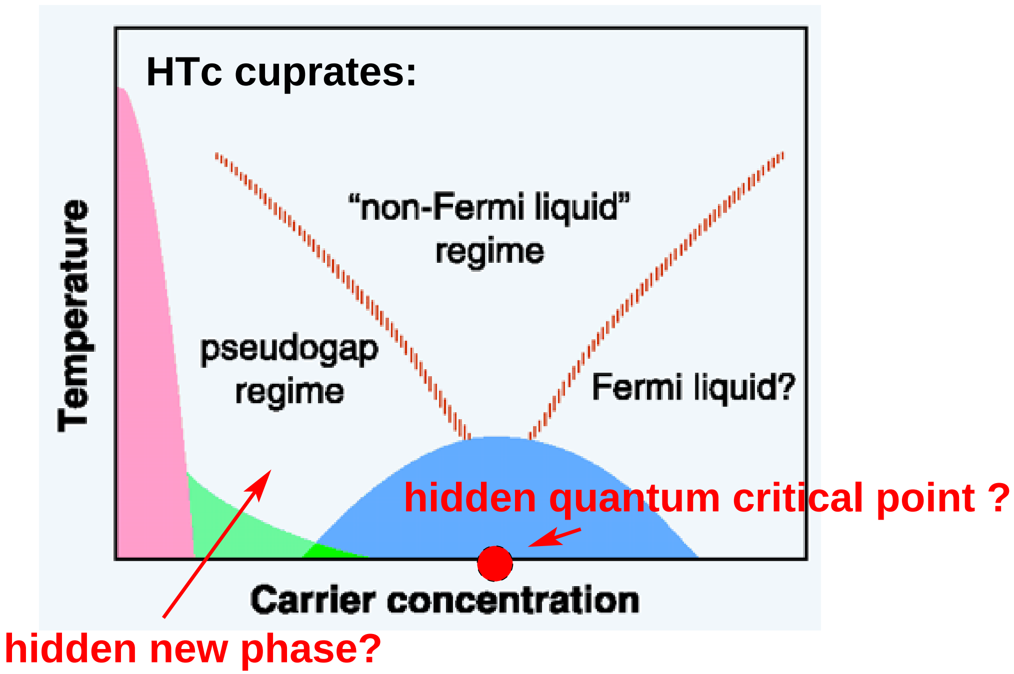


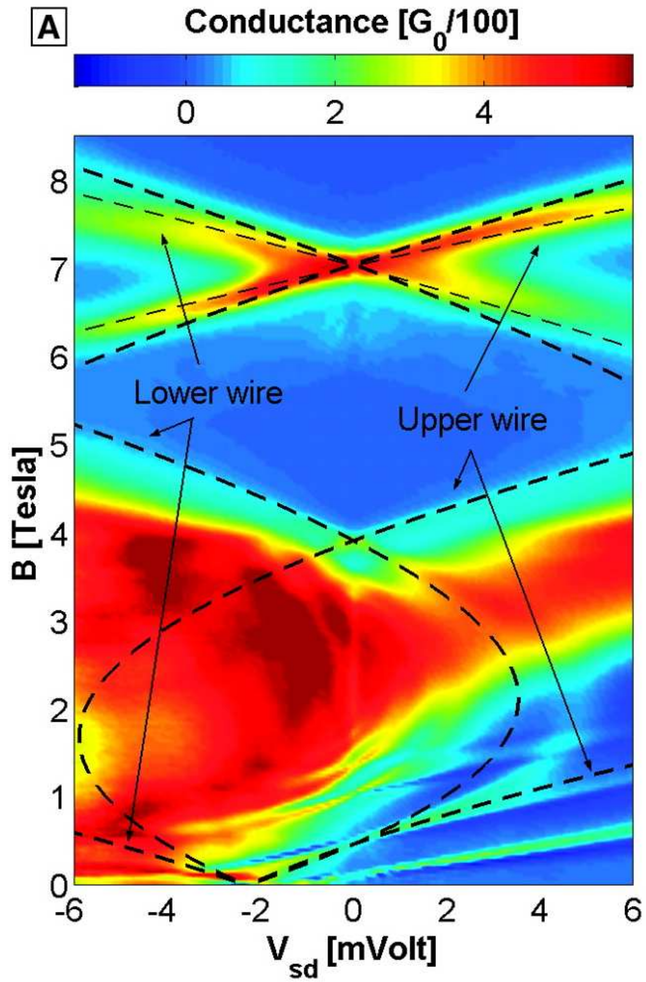
critical fluctuations, power-laws, scaling,...
dozends of systems, e.g. $CeCu_{6-x}Au_x$, $YbRh_2Si_2$, $CePd_2Si_2$, $NiS_{2-x}Se_x$...
diverging Grüneisen parameter

new quasiparticles, quantum number fractionalization
Luttinger liquids, fractional QHE, nematic metal, Griffiths singularities...
low dimensions!



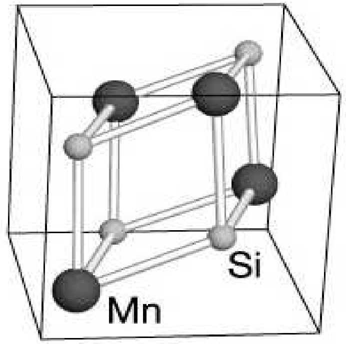
Löhneysen *et al* (96)





spectroscopy of Luttinger liquids
by parallel tunneling
Auslaender, Yacoby *et al.*

MnSi – a standard itinerant magnet



- text-book band-magnet below 30K (see Landau-Lifschitz, Vol.8, 3rd edition)

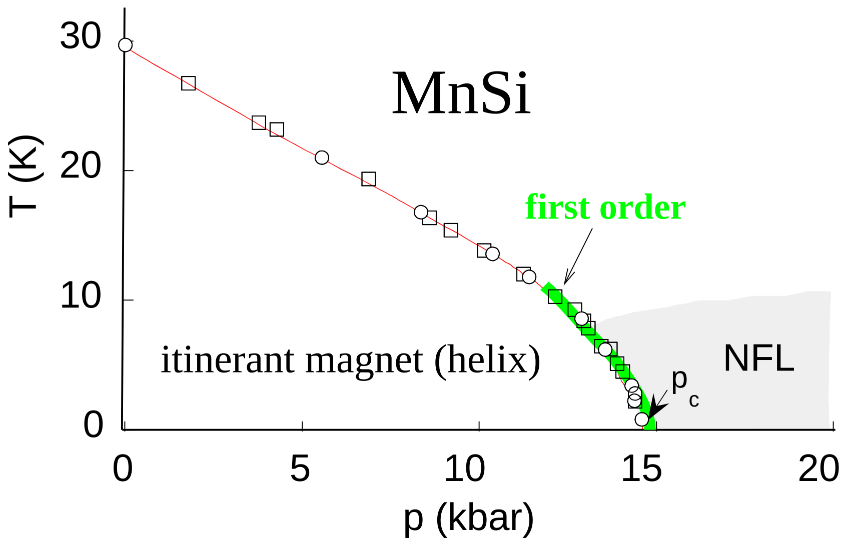
- Ginzburg-Landau theory for helical spin-density wave: Bak, Jensen (1980), Nakanishi *et al.* (1980)

- extremely clean (mean free path 3000-10000 Å)

- cubic but no inversion symmetry ($P2_13$)

- standard example for spin-fluctuation theory (Lonzarich, Moriya)

New physics under pressure!



C. Pfleiderer, Julian, Lonzarich, Nature (2001):

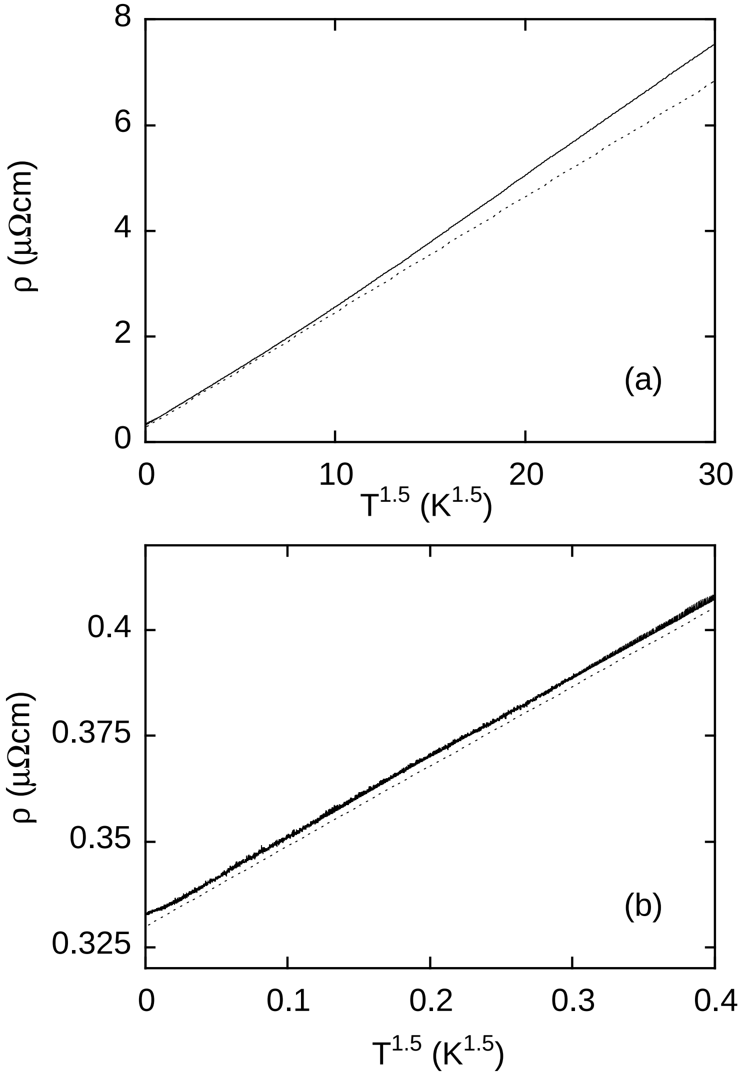
in MnSi for wide pressure range, $p > p_c$

$$\rho(T) - \rho_0 \sim T^{3/2}$$

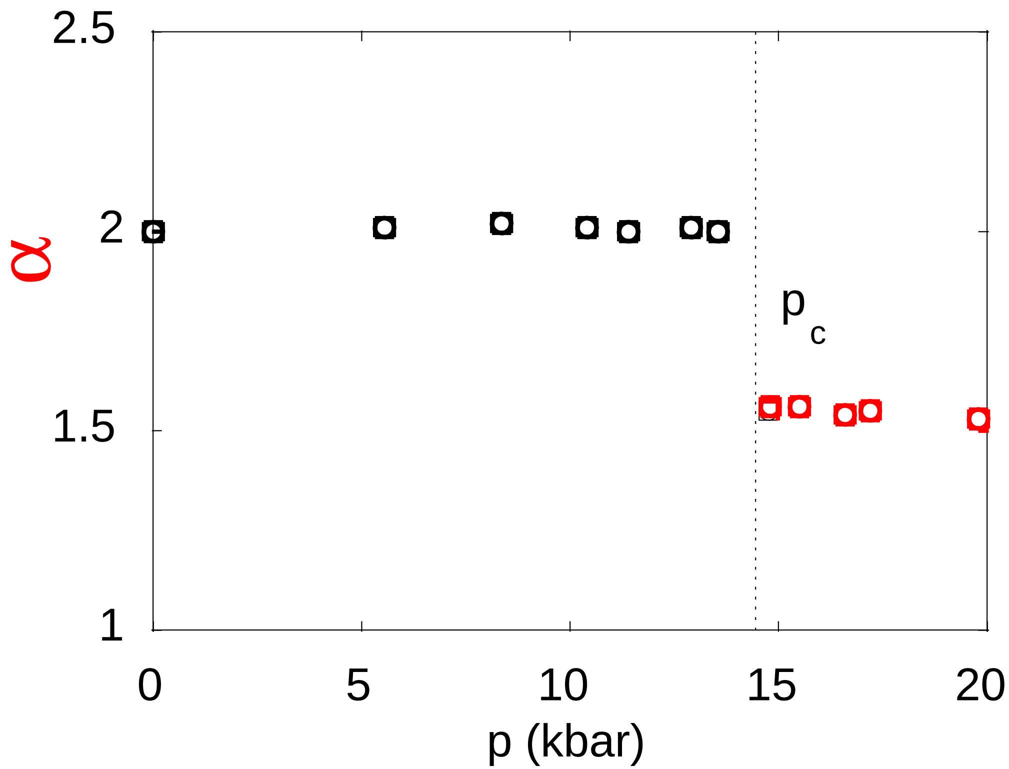
almost **3 decades** in T, very clean system

A genuine non-Fermi liquid phase**?**

resistivity $\rho(T) \sim T^{3/2}$ for almost 3 decades (10mK to 5K):

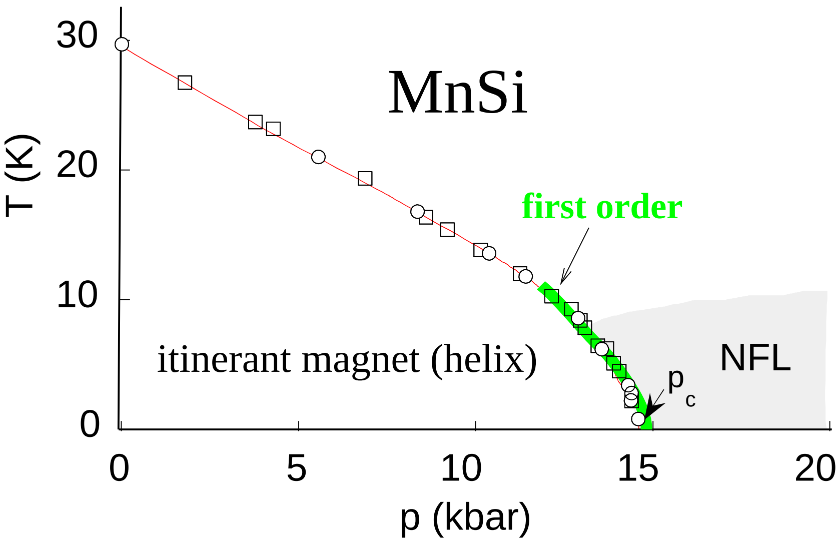


exponent α for $\Delta\rho(T) \sim T^{\alpha}$ for $T \to 0$



$\rho(T) \sim T^{3/2}$ for $p > p_c$ up to 28 kbar

(Lonzarich)



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$$\rho(T) - \rho_0 \sim \boldsymbol{T^{3/2}}$$

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A genuine non-Fermi liquid phase**?**

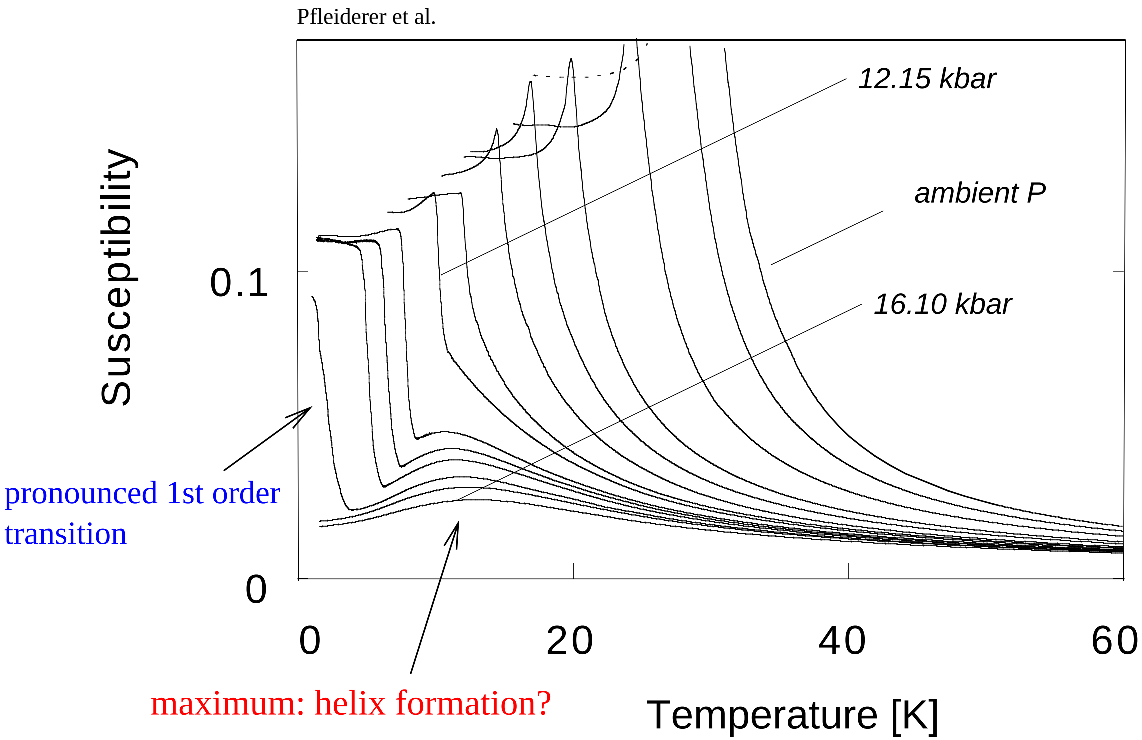
Alternative: **Quantum critical** behavior?

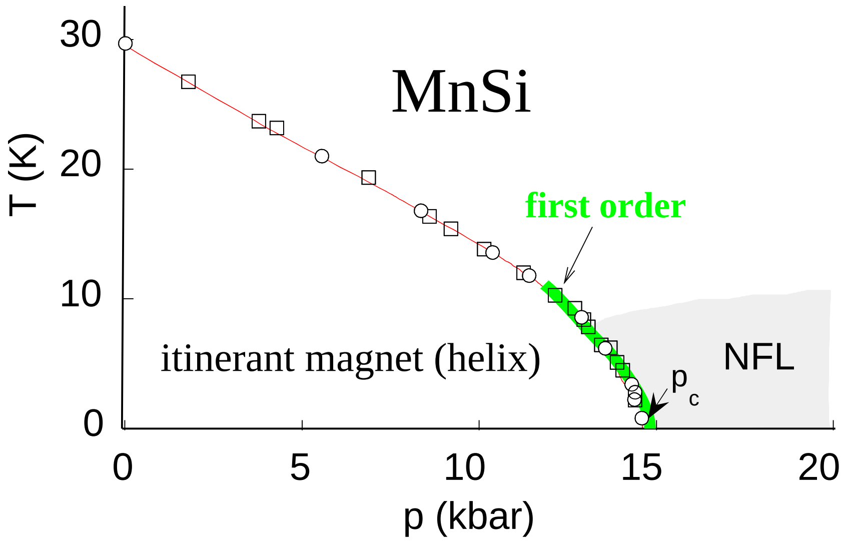
contra: NFL observed even for $\boldsymbol{p} \gg \boldsymbol{p_c}$ and low $\boldsymbol{T}$

first order transition close to $\boldsymbol{p_c}$

jump of χ and of local moment in NMR,μSR (Thessieu *et al.* 98)

Susceptibility, helix formation and first order transition





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in MnSi for wide pressure range, $p > p_c$

$$\rho(T) - \rho_0 \sim T^{3/2}$$

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Alternative: **Quantum critical** behavior?

contra: NFL observed even for $p \gg p_c$ and low T

first order transition close to p_c

jump of χ and of local moment in NMR,μSR (Thessieu *et al.* 98)

pro: maybe 2nd order endpoint at $p = p_c$?

A-coefficient, $\Delta\rho(T) \approx AT^2$, diverges for $p \to p_c$ in ord. phase

Neutrons: $T = 0$ ordered moment vanishes continuously for $p \to p_c$;

$\Rightarrow$ chimera of first and second order? (cf. $d = \infty$ Mott)

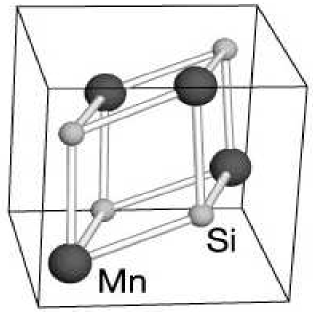
Quantum critical theory

Joerg Schmalian and Misha Turlakov (03):

NEXT TALK

Three distinct scales in MnSi:

- dominant: itinerant ferromagnet with large ordered moment ($0.4\mu_B$)
  $\Rightarrow$ fixes amplitude of local magnetization



- but: instable to formation of chiral helix due to weak **spin-orbit** coupling in non-centrosymmetric crystal:

  Dzyaloshinskii-Moriya interaction $\boxed{q_0 \int \vec{S} \cdot (\vec{\nabla} \times \vec{S})}$ **linear** in $\vec{k}$

  $\Rightarrow$ fixes pitch $1/q_0 \approx 150$Å of helix

- small correction: **spin-orbit** coupling breaks rotational symmetry in cubic crystal
  $\Rightarrow$ fixes direction of helix

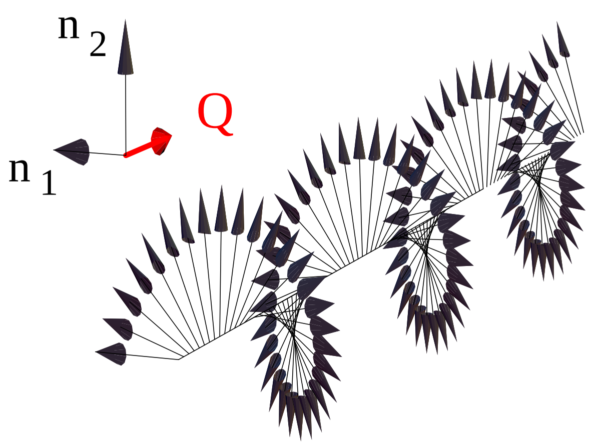
$$F = F(\vec{\Phi}^2) + \vec{k}^2 |\vec{\Phi}_{\vec{k}}|^2 + q_0 \vec{k} \cdot (\vec{\Phi}_{\vec{k}} \times \vec{\Phi}^*_{\vec{k}}) + k_x^4 |\vec{\Phi}_{\vec{k}}|^2 + k_x^2 \Phi_y^2 + \Phi_x^4 + cycl. + ...$$

$$F = F(\vec{\Phi}^2) + \vec{k}^2|\vec{\Phi}_{\vec{k}}|^2 + q_0\vec{k}\cdot(\vec{\Phi}_{\vec{k}} \times \vec{\Phi}^*_{\vec{k}}) + k_x^4|\vec{\Phi}_{\vec{k}}|^2 + k_x^2\Phi_y^2 + \Phi_x^4 + cycl. + ...$$

- first 3 terms minimized by **chiral** helix:

$$\vec{\Phi}(\vec{x}) = \Phi_0\left[\hat{n}_1\cos(\vec{Q}\vec{x}) + \hat{n}_2\sin(\vec{Q}\vec{x})\right]$$

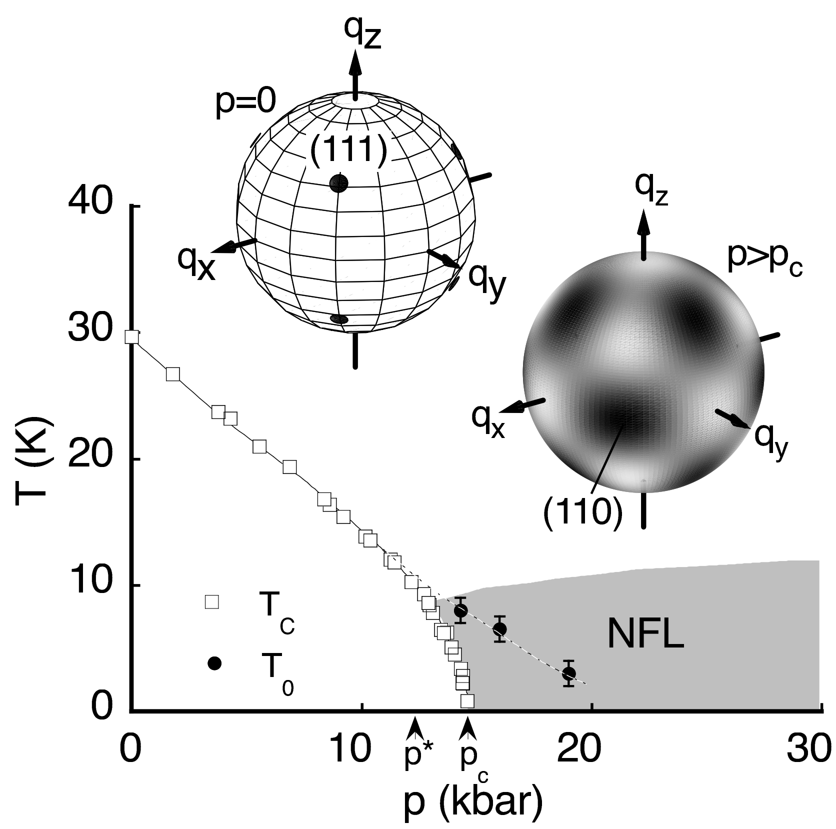
- $\hat{n}_1 \perp \hat{n}_2 \perp \vec{Q}$ form chiral "Dreibein"
  $\hat{n}_1(\hat{n}_2 \times \hat{Q}) = \pm 1$ dep. on sign of q_0
- pitch $1/|\vec{Q}| = 1/q_0$ large (150Å) as spin-orbit coupling weak
- direction of $\vec{Q}$ determined by **cubic terms**;
  $\Rightarrow \vec{Q}\|(1,0,0)$ or $\vec{Q}\|(1,1,1)$
  ($\vec{Q}\|(1,1,0)$ only possible if Φ^6, k^6 important)



What is origin of NFL behavior ?

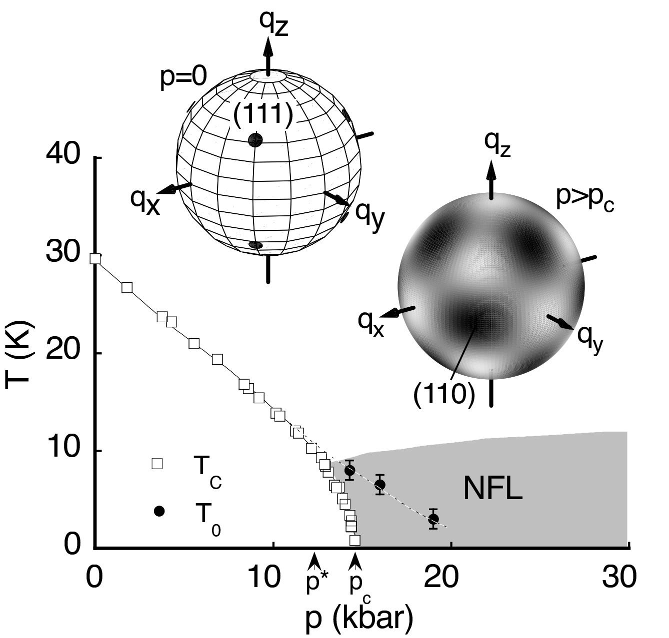
neutron scattering in disordered phase:

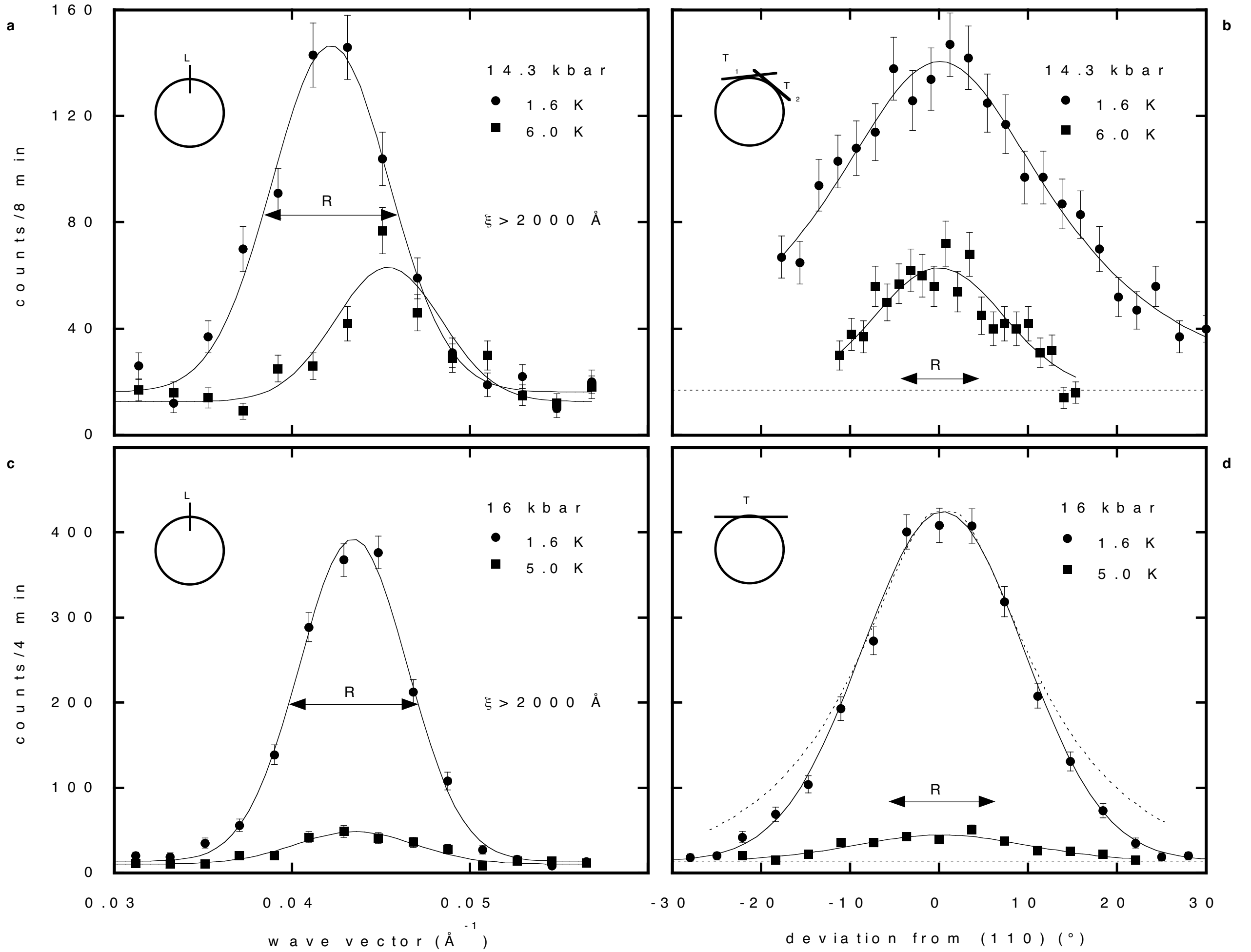
- spiral survives into disordered phase with **full** moment
- signal on **surface** of tiny sphere in reciprocal space
- **static** on neutron timescale close to p_c, (but note: **static** signal vanishes deep in NFL phase, fluctuations faster?)
- pitch $1/|\vec{Q}|$ unchanged (resolution limited) $\Rightarrow$ spiral intact
- direction $\vec{Q}/|\vec{Q}|$ fluctuating [predominantly in (1,1,0) directions]
  no signal left in (1,1,1) direction



C. Pfleiderer, D. Reznik, L. Pintschovius, v. Löhneysen, M. Garst, A. Rosch, Nature **427**, 227 (2004)

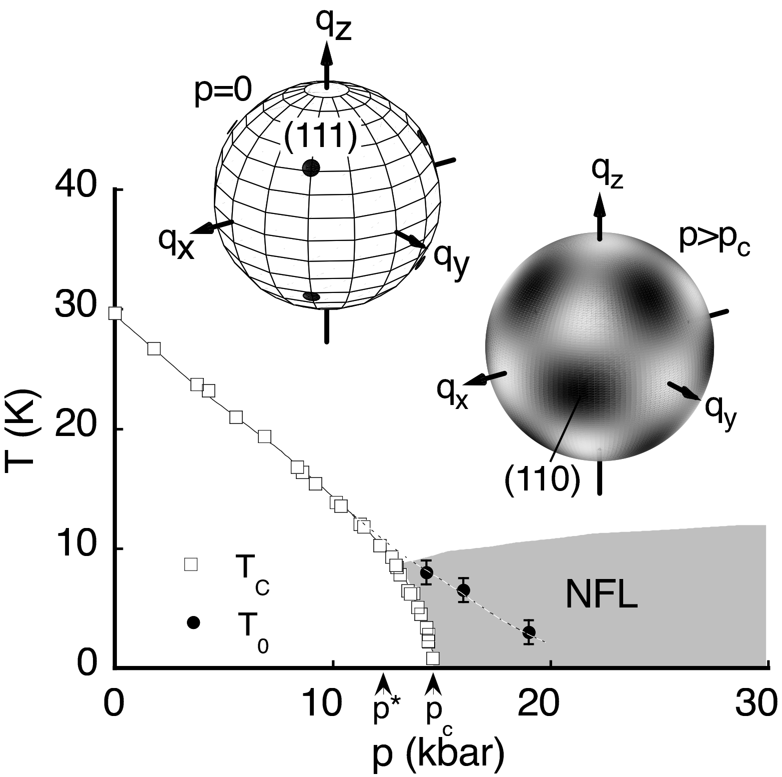
Momentum dependence:





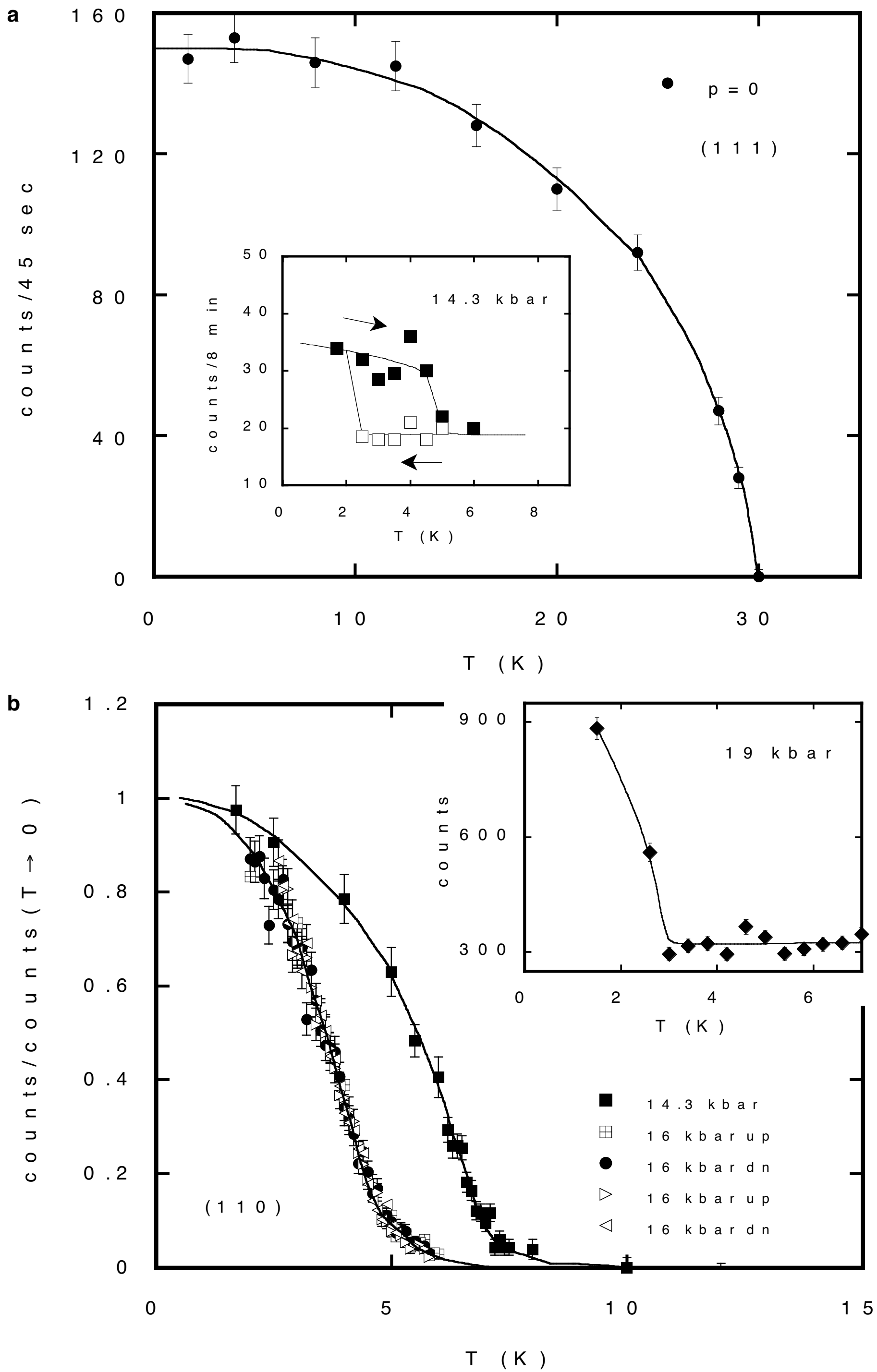
- resolution limited in radial direction
- broad in tangential direction, width increases towards lower T

Temperature dependence:



crossover or phase transition?

QCP?

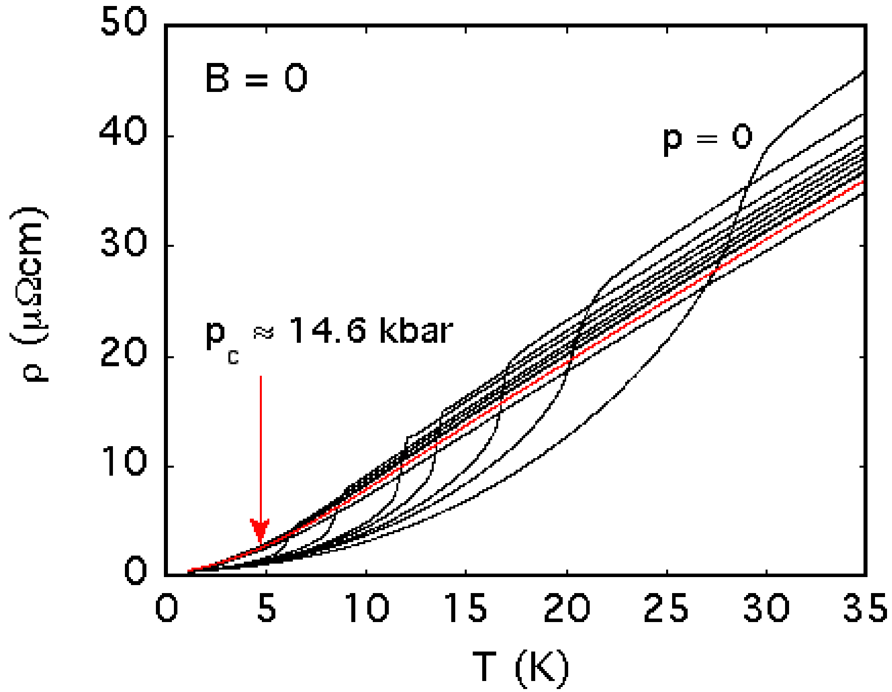


Magnetic order and transport

Major mystery:

No signature in ρ at onset of **partial** order despite the large moment involved!

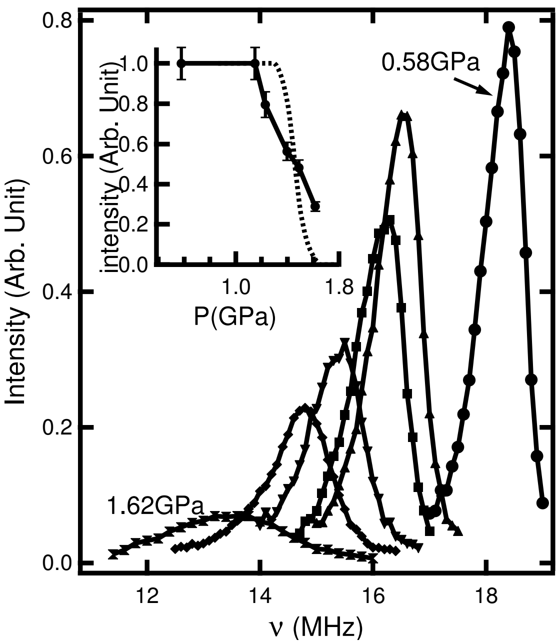
- in contrast: huge and sharp drop in ρ at onset of **long-range** order for $p < p_c$, main scattering mechanism frozen out
- Does fluctuating partial order exist in full NFL phase? maximum in χ at 10K: helix formation?

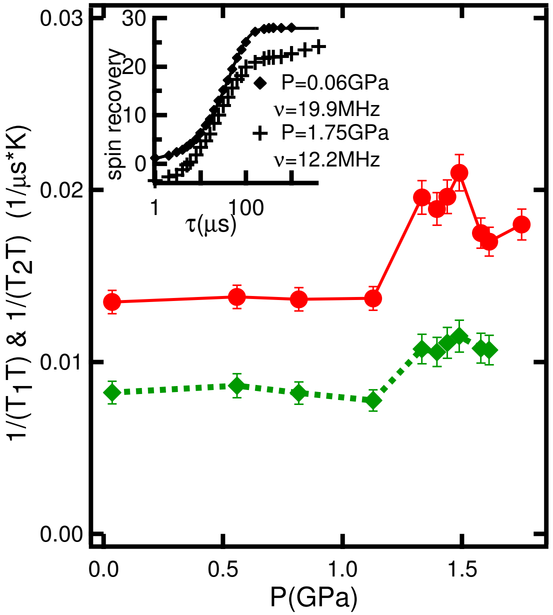


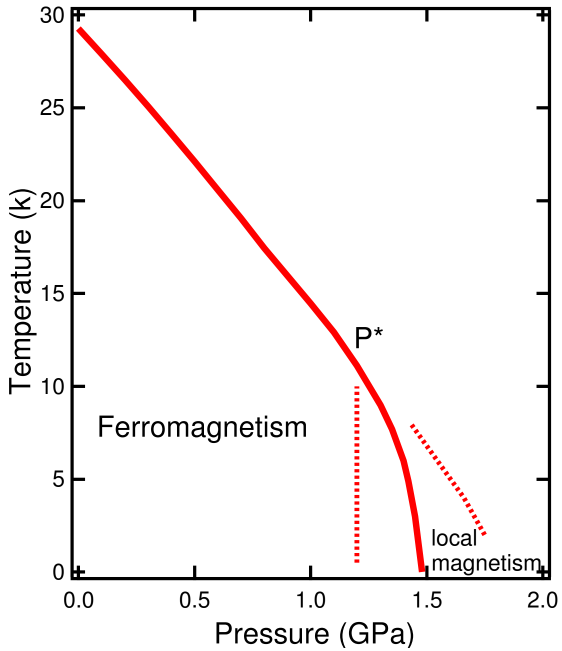
NMR (^{29}Si)

Thessieu, Kamishima, Goto, Lapertot (1998)

Yu, Zamborszky, Thompson, Sarrao, Torelli, Fisk, Brown (2003)







powdered samples ⇒ precise comparision to neutrons difficult

suggests partial order static on NMR scales?

Origin of NFL phase? Partial order

- Order parameter survives on intermediate (> 2000Å) length and time (neutron ω-resolution) scales
  exp. confirmed close to $\boldsymbol{p_c} \Rightarrow$ our assumption: valid also for $p \gg \boldsymbol{p_c}$

- NFL behavior seems to occur only when spiral is formed
  (indications: behavior in large magn. fields, maximum in $\chi(T)$)

Two scenarios:

1. scattering from soup of fluctuating topological defects

2. scattering from anomalous (pseudo-) Goldstone modes in "almost" ordered state

First scenario: scattering from topological defects

topological structure similar to cholesteric liquid crystals (replace director by vector)

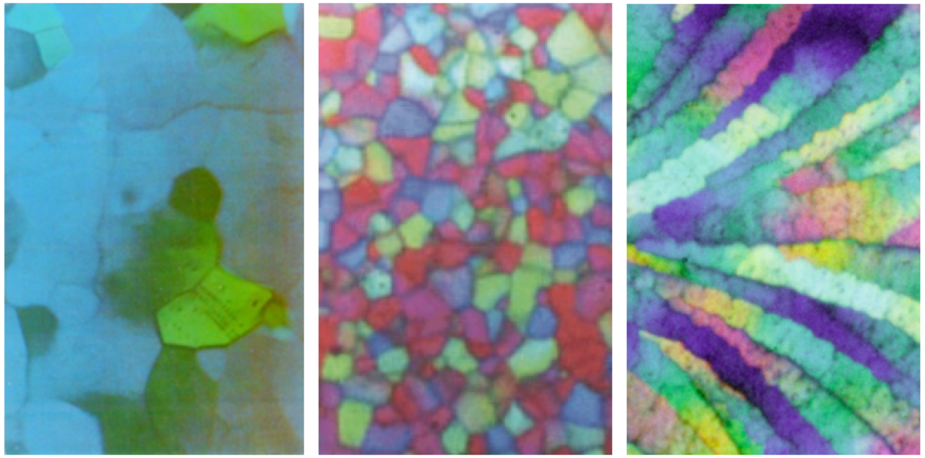
(review on topological defects: Mermin RMP 1979; blue phases: Wright,Mermin RMP 1989)

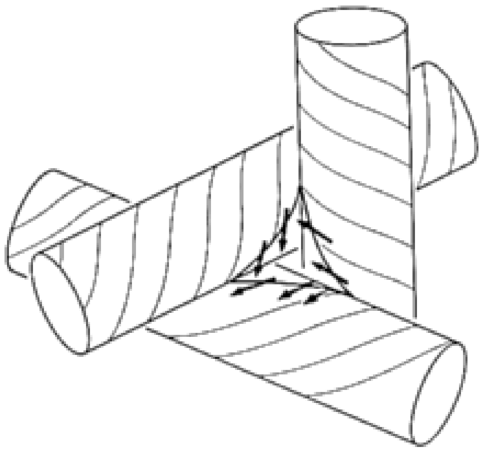
- order paramter exists locally but not globally
  $\Rightarrow$ finite density of topological defects

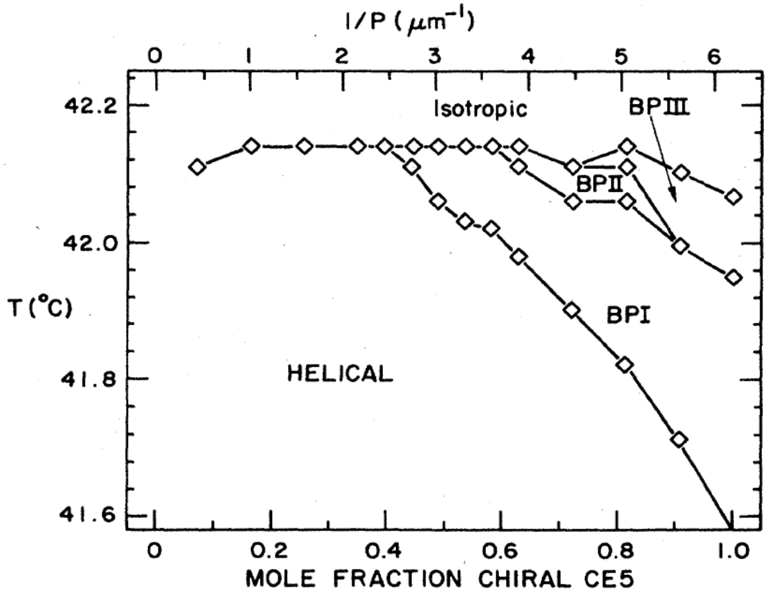
- domain walls, line defects, point defects?

Blue phases: networks of topological defects

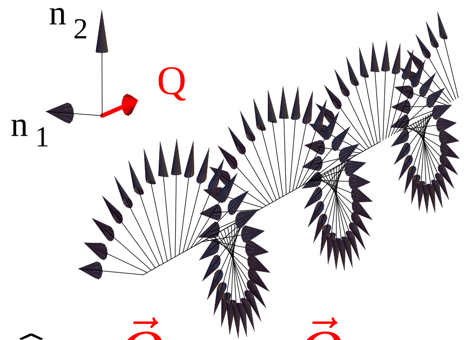
cholesteric liquid crystals: complex phase diagram
blue phase III: no long-range order







Classification of topological defects: homotopy groups

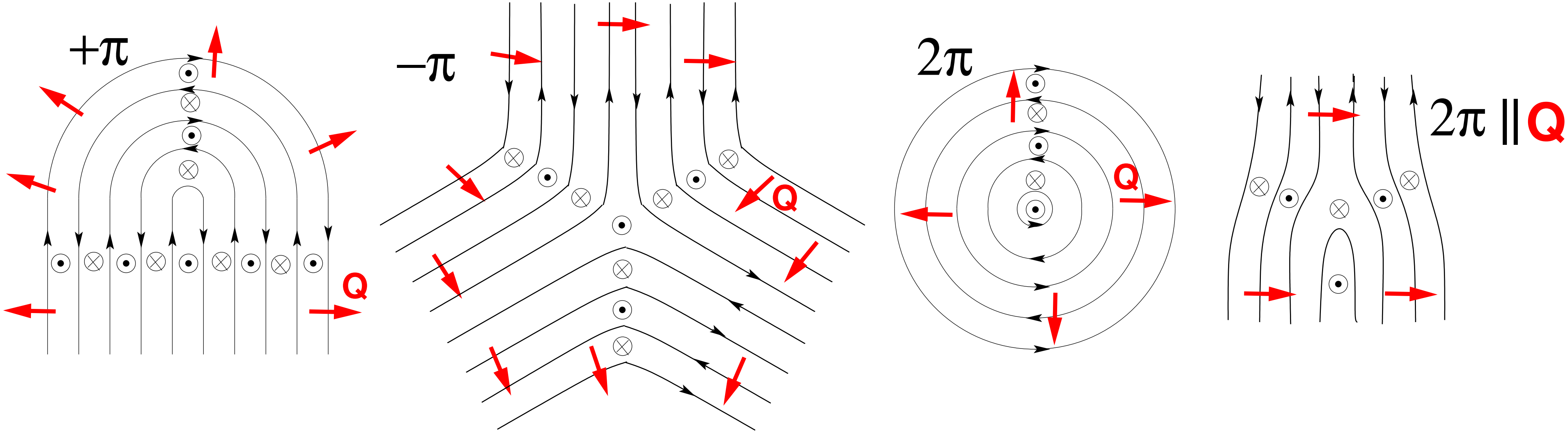


- neglect pinning of $\vec{Q}$ to cubic lattice ($1/|\vec{Q}| \gg a$)
- order parameter: 3 orthogonal vectors
  $\hat{\Phi}(\vec{x}) = \hat{n}_1 \cos[\vec{Q}\vec{x}] + \hat{n}_2 \sin[\vec{Q}\vec{x}]$
- **invariant** under rotation by π around $\hat{n}_1$: $\hat{n}_2 \to -\hat{n}_2$, $\vec{Q} \to -\vec{Q}$
- groundstate manifold: **SO(3)/Z$_2$**

  $\Pi_1(\mathbf{SO(3)/Z_2}) = \Pi_1(SU(2)/Z_4) = \mathbf{Z_4}$
- 3 types of line defects
  (in SU(2) pathes from 1 to $i\sigma_x$, to $-i\sigma_x$, to -1, i.e. rotations by π, $-\pi$ and 2π)
- domainwalls, **no** point defects
- **warning**: top. classification here not reliable
  small change of $\vec{Q}$ may lead to **large** change of $\vec{\Phi}(\vec{x})$
  $\Rightarrow$ **large** energy cost ?? $\Rightarrow$ some defects not realized, novel defects?

Line defects:

shown: directions of magnetization (black arrows) and $\vec{Q}$ vector (red)

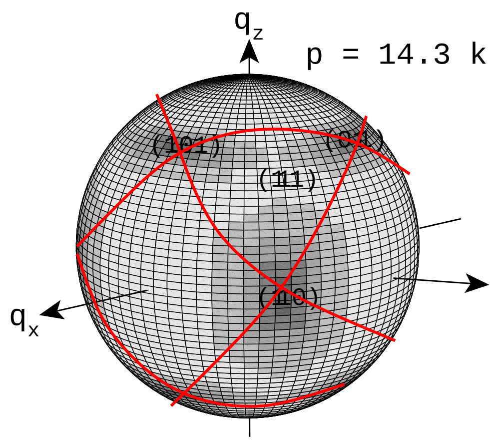


energy/length:

ln L L   ln L ln L

experiments: evidence for rotation of $\vec{Q}$? GL: $\vec{Q} \perp$ to (1,1,1):

closer look: probably not



Effective theory in presence of large local order parameter $\hat{\mathbf{\Phi}}(\vec{x},t)$:

- electrons follow adiabatically large OP $\hat{\mathbf{\Phi}}(\vec{x},t)$
  natural "quasi-particle": spin quantization axis $\parallel$ to $\hat{\mathbf{\Phi}}(\vec{x},t)$

- new "holons":

$$\tilde{c}_\sigma(\vec{x},t) = U(\vec{x},t) c_\sigma(\vec{x},t) U^\dagger(\vec{x},t)$$

  with $U(\vec{x},t)\left(\vec{\vec{S}}(\vec{x},t)\hat{\mathbf{\Phi}}(\vec{x},t)\right)U^\dagger(\vec{x},t) \equiv S_z(\vec{x})$

- by construction $[\vec{S},\tilde{c}_\sigma] = 0 \Rightarrow$ holons do **not** transform under global spin-rotation $\Rightarrow$ spin-charge separation (spin eaten up by OP)

- eff. field theory: gauge theory of topological defects
  interacting with $\tilde{c}$ (not worked out, possibly $U(1)$??)
  Physics: "holons" aquire Berry phases when encircling OP textures

- deconfining phase of this gauge theory: non Fermi liquid
  similar to other gauge theories, Z_2 or U(1)
  (Balents,Nayak,Senthil,Fisher,Sachdev,Muramatsu,Zaanen,Franz,Tešanović,...)

Is scattering from topological defects relevant?

Problem: distance of defects > 2000Å
but: inelastic mean free path can be smaller in $T^{3/2}$ regime

What are electrons scattering from?

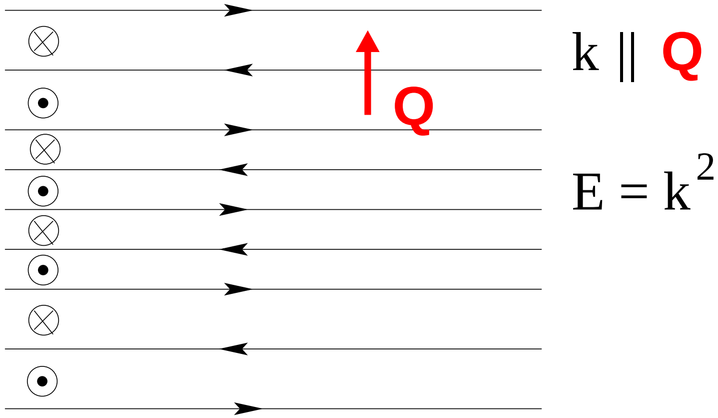
Scenario 2: Scatter from small fluctuations of OP on lengthscales **smaller** than distance of topological defects

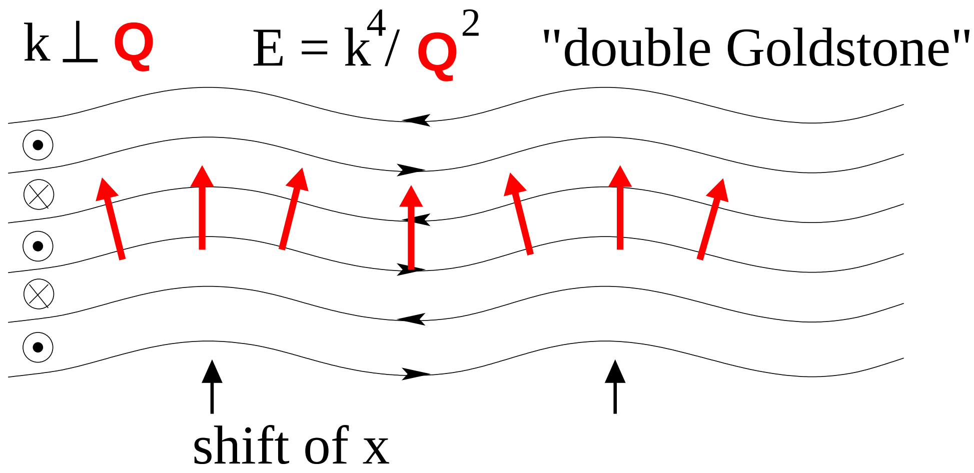
(pseudo-) Goldstone modes?

- in “disordered” phase, chiral spirals not pinned effectively by cubic lattice, stronger local fluctuations possible?

- calculate Goldstone modes in ordered phase neglecting (for a beginning) pinning to cubic lattice (pitch 150Å$\gg$ lattice spacing)

Anomalous Goldstone modes in a metallic chiral helix: $\vec{k}$ dependence





$$F = F(\vec{\Phi}^2) + \vec{k}^2|\vec{\Phi}_{\vec{k}}|^2 + q_0\vec{k}\cdot(\vec{\Phi}_{\vec{k}} \times \vec{\Phi}^*_{\vec{k}}) + k_x^4|\vec{\Phi}_{\vec{k}}|^2 + k_x^2\Phi_y^2 + \Phi_x^4 + cycl. + \ldots$$

- energy of Goldstone mode: $k_{\|}^2 + k_{\perp}^4/\mathbf{q_0^2}$ (like in smectics)

- correction from pinning to cubic background (cubic terms): $q_0^2 k_\perp^2$ relevant only for $k_\perp \ll q_0^2$

Anomalous Goldstone modes: damping

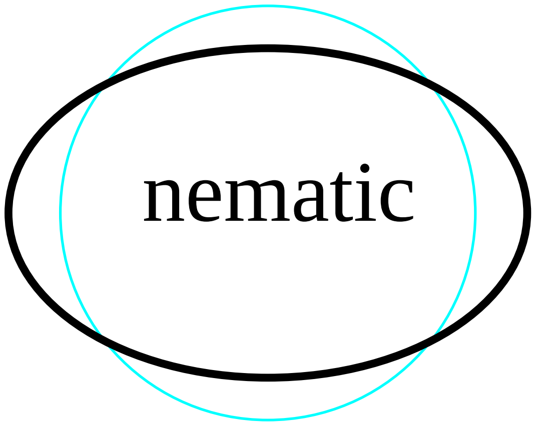
- "phonon-like" Goldstone mode: inconsistent with $\rho \sim T^{3/2}$

- overdamped Goldstone modes?

smectic-A liquid crystal	$\omega \sim q\lvert \sin 2\phi \rvert - \mathbf{i}\eta \mathbf{q}^2$	
^{3}He-A	$\omega \sim \mathbf{i}\mathbf{q}^3 \frac{\ln T}{T^2}$	(Wölfle 75)
nematic Fermi liquid	$G^{-1} = q^2 - \omega^2 - \mathrm{i}\omega \sin^2 2\phi$	**talk by Hae-Young Kee** (Oganesyan, Kivelson, Fradkin 01)

physics? ^{3}He-A: point node moves
nematic metal: gapless Fermi surface moves $\Rightarrow$ many p-h pairs

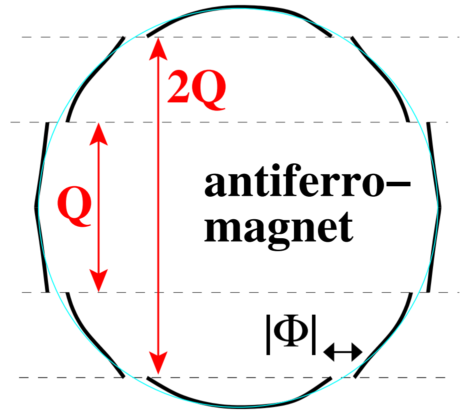
Fermi surface of nematic metal:

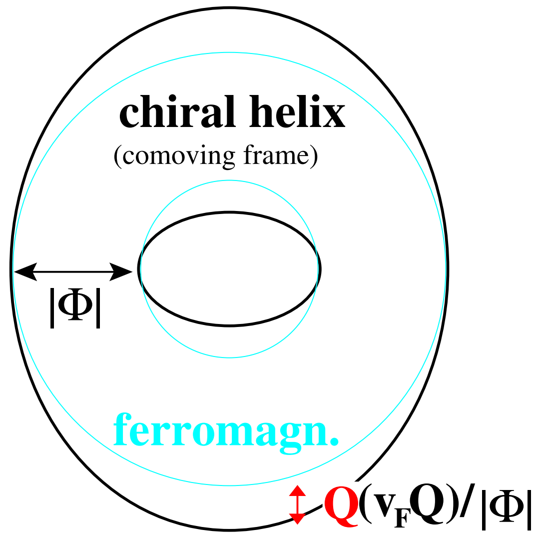


Anomalous Goldstone modes in a metallic chiral helix: damping

Electrons in chiral helix:

- in antiferromagn. metal: multiple gaps open (translational invariance broken)
- chiral helix: translation+simultaneous rotation unbroken U(1) symmetry $T_z U_z$ remains, $U_z = e^{iz\mathbf{Q}S_z}$
- simple description in comoving frame distortion of FM Fermi surface
- similar to nematic metal?
- **warning**: spin-orbit in band-structure neglected (see later)





Anomalous Goldstone modes in a metallic chiral helix: damping

within RPA: lowest eigenvalue of matrix of susceptibilities
in ordered phase
exact cancelations due to Goldstone theorem

$$G^{-1} \approx q_{\|}^2 + q_{\perp}^4/\mathbf{q_0^2} - \omega^2/\mathbf{q_0^2} - \mathbf{i}\omega|q|\mathbf{q_0^2}$$

corresponding resistivity (including vertex corrections ect.):

$$\Delta\rho \sim T^{\mathbf{2.5}}$$

incompatible with experimental $\rho \sim T^{\mathbf{1.5}}$

open questions: more realistic band structure
contributions from massive modes (Vekhter, Chubukov 04)
finite size of domains?

Electrons, helical order and spin-orbit coupling

up to now: only DM-interaction, other spin-orbit effects neglected

dominant contribution for $P2_13$ (T^4): $$H_{\text{SOC}} = \delta \sum_{i=1}^{3} k_i \sigma^i_{\alpha\beta} c^\dagger_{\vec{k}\alpha} c_{\vec{k}\beta}$$

(with $\delta \sim \vec{Q}$.)

in comoving coordinate system for $\vec{Q} \| z$:

$$\begin{pmatrix} \vdots \\ d^\dagger_{+,\mathbf{k}} \\ d^\dagger_{-,\mathbf{k}} \\ d^\dagger_{+,\mathbf{k}+\vec{Q}} \\ d^\dagger_{-,\mathbf{k}+\vec{Q}} \\ \vdots \end{pmatrix} \begin{pmatrix} \ddots & & & & & \\ & E_1(\mathbf{k}) & -k_z\delta & -k_x\delta & -k_x\delta & \\ & -k_z\delta & E_2(\mathbf{k}) & k_x\delta & k_x\delta & \\ & -k_x\delta & k_x\delta & E_1(\mathbf{k}+\vec{Q}) & -(k_z+\vec{Q})\delta & \\ & -k_x\delta & k_x\delta & -(k_z+\vec{Q})\delta & E_2(\mathbf{k}+\vec{Q}) & \\ & & & & & \ddots \end{pmatrix} \begin{pmatrix} \vdots \\ d_{+,\mathbf{k}} \\ d_{-,\mathbf{k}} \\ d_{+,\mathbf{k}+\vec{Q}} \\ d_{-,\mathbf{k}+\vec{Q}} \\ \vdots \end{pmatrix}$$

where $E_{1,2}(\mathbf{k}) = \frac{|\mathbf{k}|^2}{2m} + \frac{k_F^2}{2m} \pm \sqrt{\left(\frac{k_z\vec{Q}}{2m}\right)^2 + |\Phi|^2} - \delta k_z$

H_{SOC} induces mini-bands (breaks residual U(1) symmetry)

Electrons, helical order and spin-orbit coupling

bandstructure non-perturbative in small SO-interaction
map to tight-binding model in band-index space:

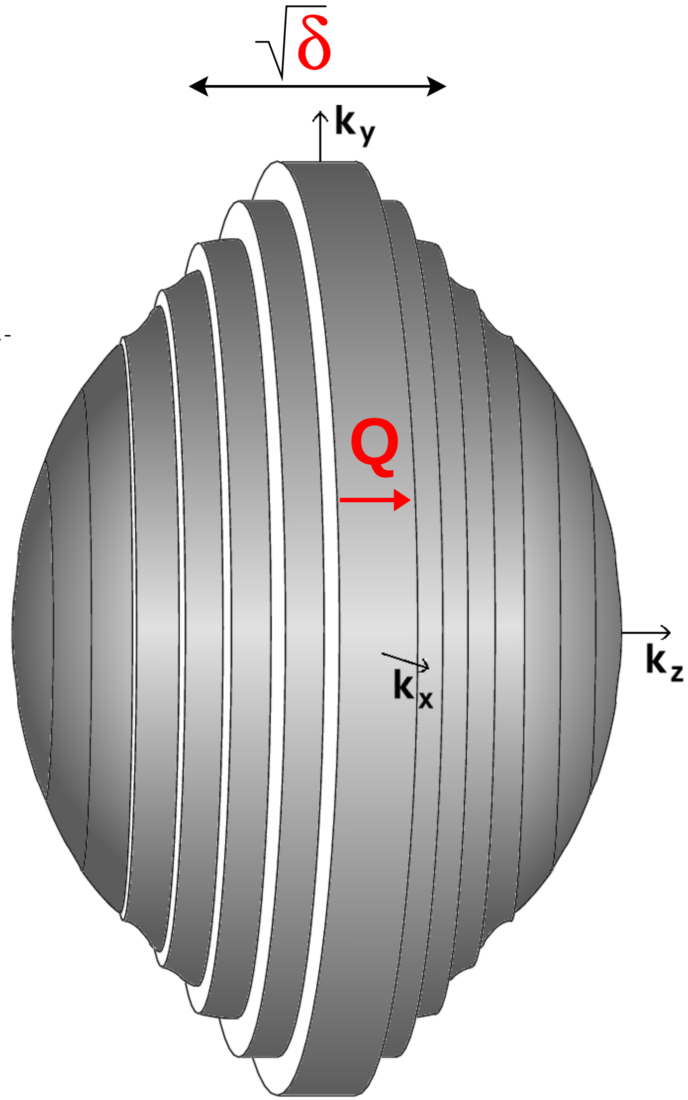
$$H_{TB} = \sum_n -\frac{1}{2m}\left(n\vec{Q} + k_z - m\delta\right)^2 d_n^\dagger d_n + k_x\delta\, d_{n-1}^\dagger d_n + k_x\delta\, d_n^\dagger d_{n-}$$

- for $\vec{k}_F \perp \vec{Q}$ superflat mini-bands

$$\text{bandwidth} \propto e^{-c\frac{\sqrt{\delta}}{Q}} \sim e^{-\frac{c'}{\sqrt{\delta}}}$$

bandgaps $\sim Q\sqrt{\delta}$

- electron motion $\|\vec{Q}$ stopped for large fraction of Fermi-surface: $\frac{k_z}{k_F} \lesssim \sqrt{\delta}$



Electrons, helical order and spin-orbit coupling

experimental consequences:

- de-Haas van-Alphen: unrealistically clean samples required
- resistivity: $\frac{\rho_{\parallel}-\rho_{\perp}}{\rho} \sim \delta^{3/2}$ small effect
- **huge** change in anomalous skin effect

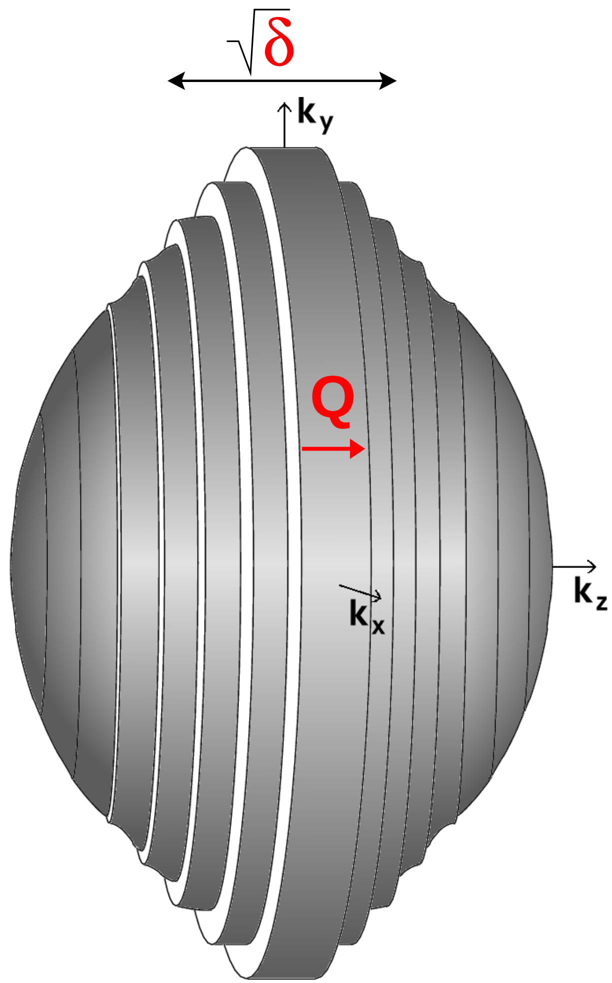
  determined by electrons moving

  parallel to surface with $v_{\perp}/v_{\parallel} < \Delta/l$,

  rotate spirals by B field $\parallel$ / $\perp$ to surface

  compare skin depth $\Delta^{\parallel}$, $\Delta^{\perp}$

  large for $k_F l_0 \gtrsim \frac{(\lambda k_F/\alpha)^{1/3}}{\sqrt{\delta}}$
- Hall effect?
- damping of Goldstone modes?
- inelastic scattering?



Conclusions? – No conclusions yet

- genuine NFL **phase** in MnSi?

  unique: clear exp. evidence for NFL phase AND hint towards origin

- scenario 1: local order remains, spin-charge separation,
  scattering from topological defects, Gauge theory

- scenario 2: scattering from (pseudo-) Goldstone modes
  anomalous $k_\perp$ dependence, **overdamped**

  but: wrong power-law for $\rho(T)$

- other options: scattering from domain-walls, texture-glass, ...

- large effects of spin-orbit coupling