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SMR.1766 - 5

Miniworkshop on
New States of Stable and Unstable Quantum Matter
(14 - 25 August 2006)

Logarithmic fermi liquid breakdown in $NbFe_2$

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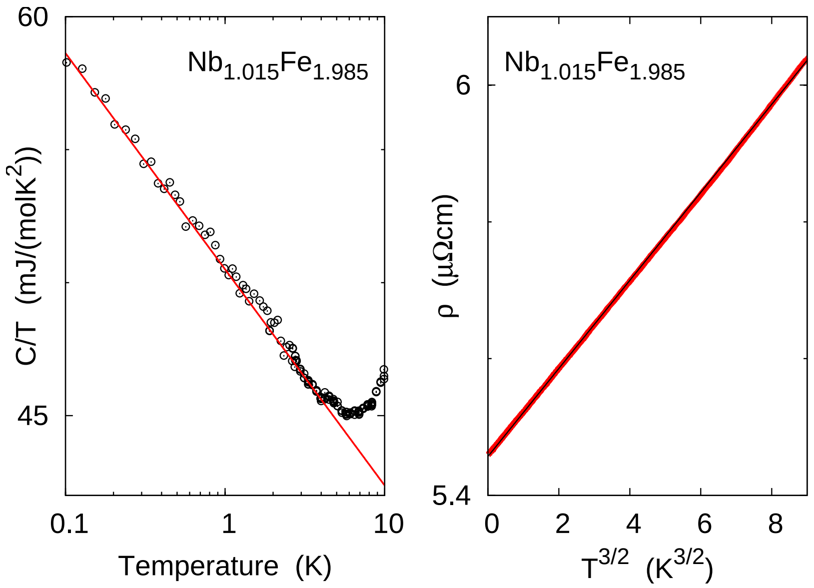


$NbFe_2$

Trieste 14/8/06

Prospecting
Colleagues and Co-workers

The border of ferromagnetism
Band magnetism
Quantum criticality
First-order transitions
Anomalous power laws

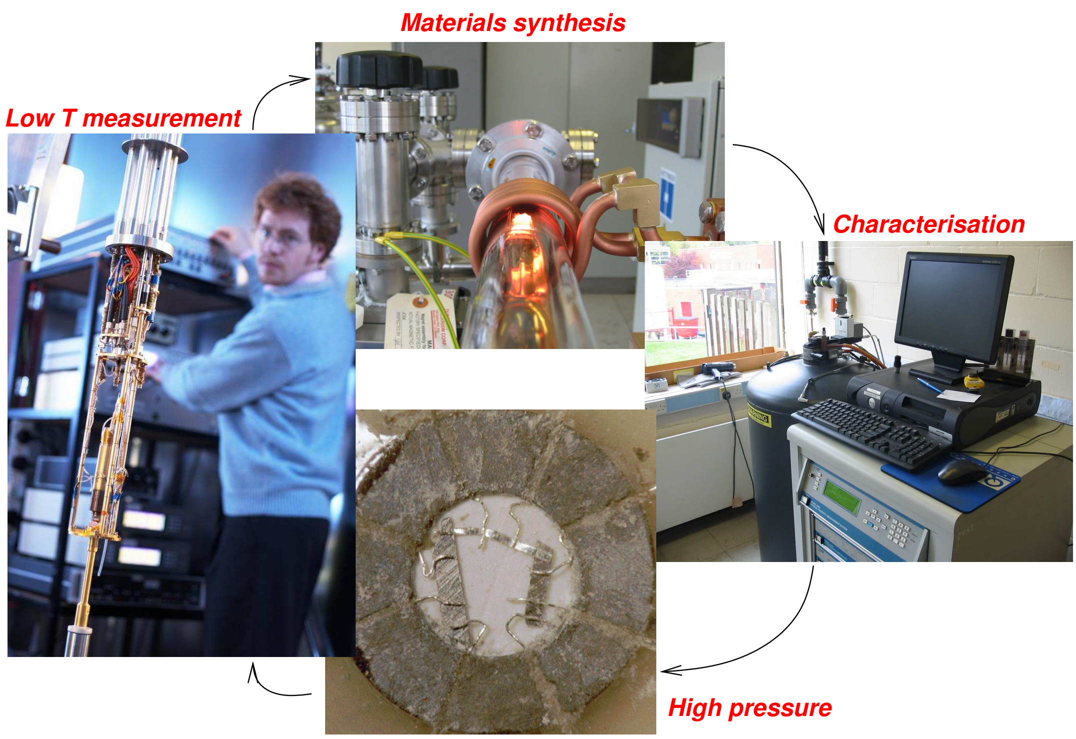
Ordered states in $NbFe_2$
Incipient ferromagnet
Unidentified order
Susceptibility
Magnetisation
Transition anomalies

Tuning $NbFe_2$
Composition
Approaching the qcp
QCP Resistivity
QCP Heat capacity
Pressure

Scenarios for $NbFe_2$
Metamagnetism?
Magnetism?
Examples of helical order

Conclusions
Scenarios on border of FM

Prospecting for new states



Colleagues and Co-workers

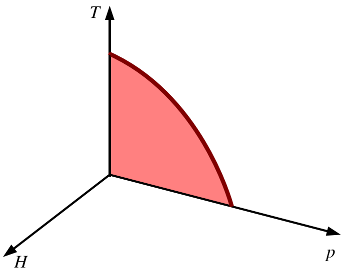
- **Manuel Brando,** Dennis Moroni, Carsten Albrecht
- **Ben Simons:** Cambridge, Santiago Grigera: St. Andrews
- **Rafik Ballou,** Bjorn Fåk: Grenoble
- **Daniel Grüner,** Guido Kreiner: Dresden

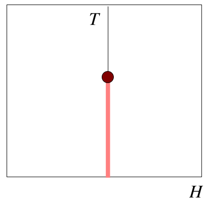
The border of band ferromagnetism – in broad strokes

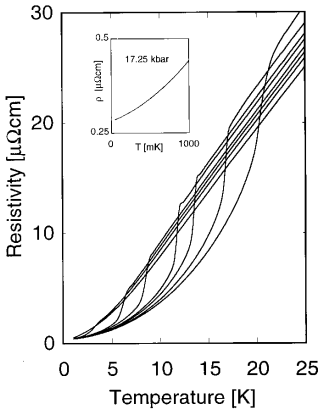
- **Band magnet** ($ZrZn_2$, Ni_3Al, MnSi), Pauli susceptibility: $\chi_0 \propto g(E_F)$
- Exchange-enhanced: $\chi = \frac{\chi_0}{1-I\chi_0}$
- Landau **free energy:** $F = \mu_0 \left(\frac{a}{2}M^2 + \frac{b}{4}M^4 - HM\right)$
- **Equation of state** at $T = 0$: $H = aM + bM^3$
- Add T-dependent **fluctuations:** $H = \overline{H} + h,\ M = \overline{M} + m$
- **Average:** $\overline{H} = a\overline{M} + b\overline{M}^3 + 3b\overline{M}\left\langle m^2\right\rangle$
- **Modified equation of state** at finite T: $\overline{H} = (a + \Delta a(T))\,\overline{M} + b\overline{M}^3$

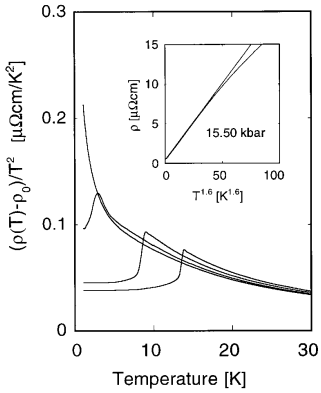
$$\chi^{-1}(T) = \chi^{-1}(0) + \Delta a(T) \simeq \chi^{-1}(0) + 3b\left\langle m^2\right\rangle(T)$$

Quantum criticality on the border of ferromagnetism: MnSi(?)





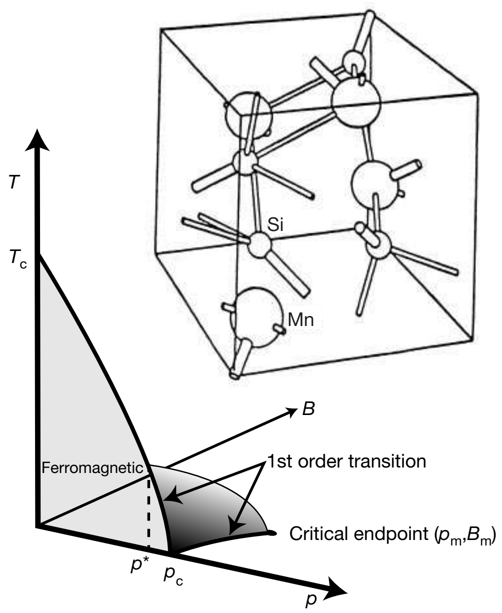




[MnSi: Pfleiderer *et al.* PRB **55** 8330 (1997)]

- Pressure **tunes transition** temperature.
- Ferromagnetism **disappears.**
- Scattering cross-section **diverges.**

What really happens: first-order transition into helical state, metamagnetism



[Pfleiderer *et al.* Nature **414**, 424 (2001)]

- Long-wavelength **helical order** in MnSi.
- **First order** transition as $p \to p_c$.
- Susceptibility **does not diverge.**
- **Metamagnetism** beyond p_c.

What really happens: anomalous power-laws

Theory: critical fluctuations cause resistivity power-law.

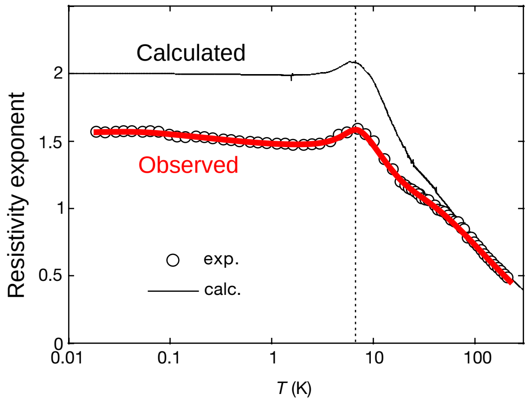
- $\langle m^2 \rangle \sim T^{d/z} = T^{3/3}$ (**dynamic exponent** z**:** relaxation rate $\Gamma_q \propto q^z$)
- **Small-angle scattering** correction $\sim T^{2/3} \rightarrow$

$$\Delta\rho \sim T^{5/3}$$

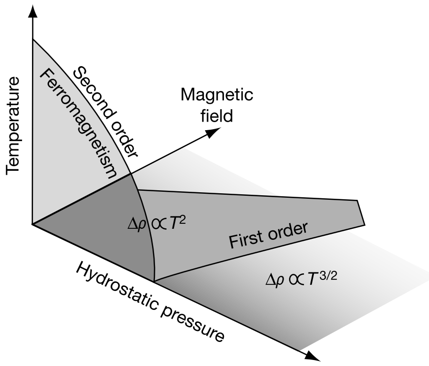
- **But:** MnSi **not critical,** expect T^2 at low T.

Observation:
Robust $\Delta\rho \sim T^{3/2}$

- **Similar** in $ZrZn_2$, but Fe shows $T^{5/3}$ [Holmes and Jaccard (2002)]

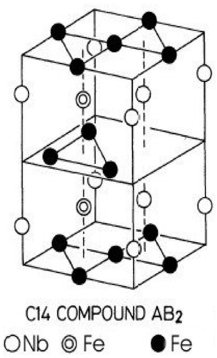


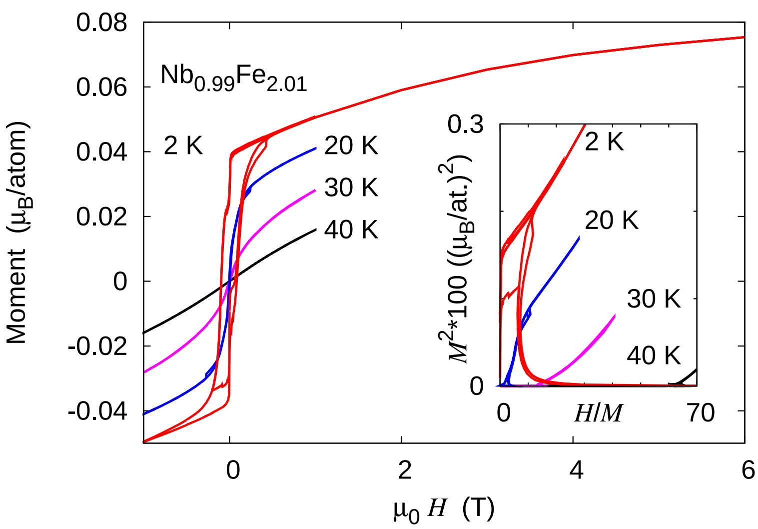
[Pfleiderer *et al.* Nature **414**, 424 (2001)]



[Doiron-Leyraud *et al.* Nature **425**, 595 (2003)]

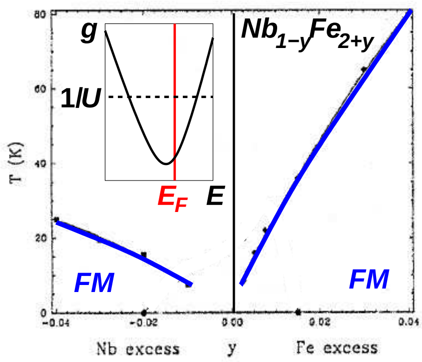
Incipient ferromagnet at zero pressure: $NbFe_2$



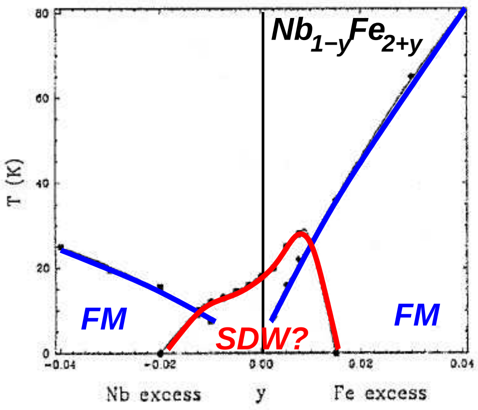


- Hexagonal, Fe-atoms form **frustrated** Kagomé layers.
- On the threshold to **FM**
- Fermi level in **DOS valley?**

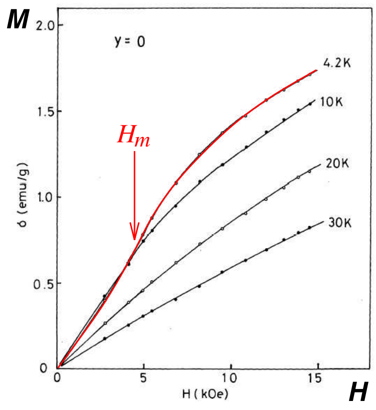
[Crook and Cywinski, JMMM **140-144**, 71 (1995)]



Unidentified order in stoichiometric $NbFe_2$

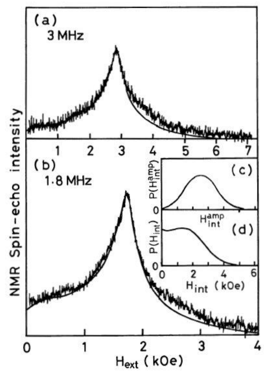


[Crook and Cywinski, JMMM **140-144**, 71 (1995)]



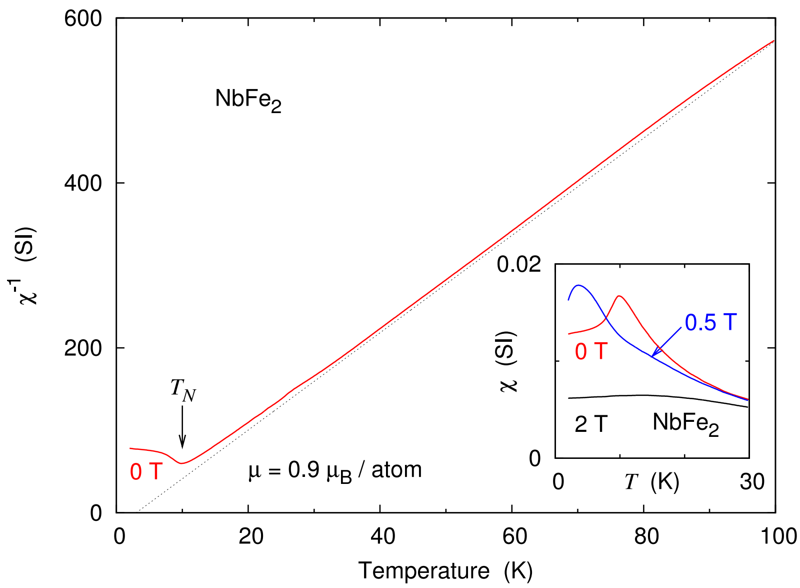
[Shiga JPSJ **56** (1987) 4040]

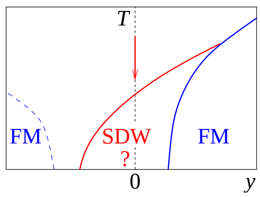
- On the border of **FM:** unidentified order.
- **Metamagnetic** magnetisation curves.
- NMR line-broadening proves **magnetic order.** Suggests **spin density wave** (SDW).



[Yamada JPSJ **59** (1990) 2976]

Low temperature metallic magnetism in $NbFe_2$





- **Curie-Weiss** $\theta_W \sim 5$ K, $\mu_{eff} \sim 1\mu_B$
- Stoner factor $\simeq$ **120.**
- Transition $T_N = 10$ K, **AFM?**

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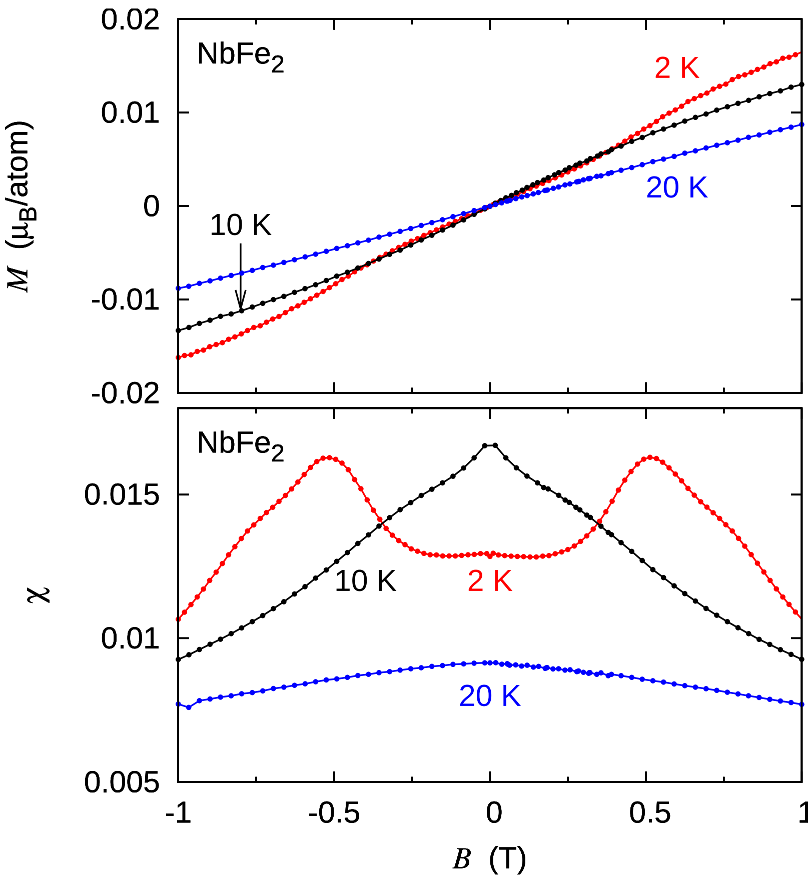
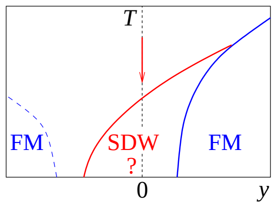
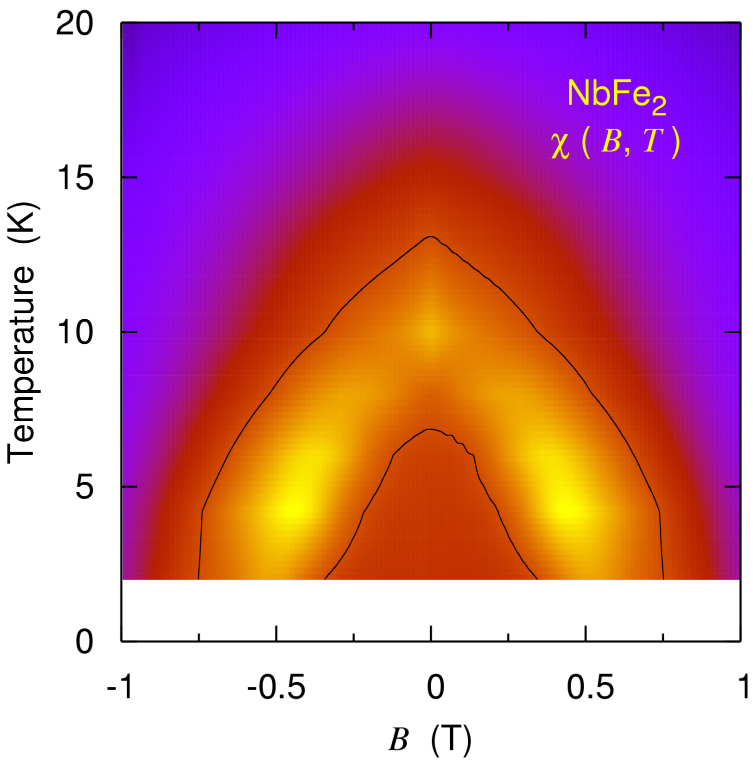
$NbFe_2$, magnetisation

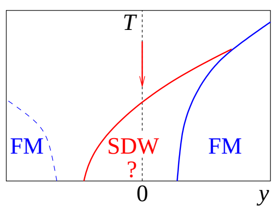




- **Step** in $M(H)$ at 0.5 T, 2 K.
- Therefore **maximum in χ**.
- Maximum $\rightarrow H = 0$ for $T \rightarrow 10$ K.

$NbFe_2$, $B - T$ phase diagram





- χ maxima form **ridge**.
- Ridge separates **low-T phase.**
- Small **critical field.**

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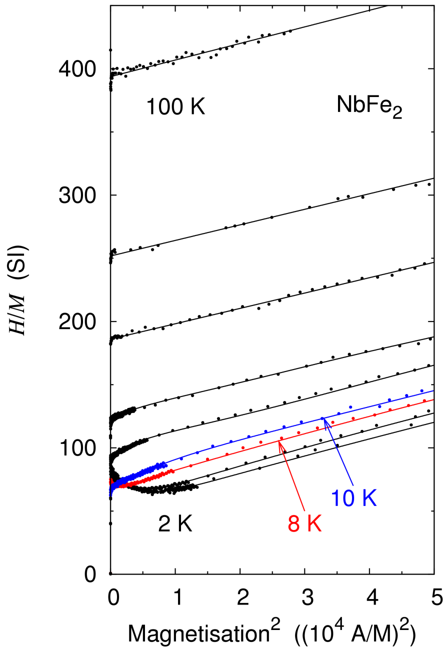
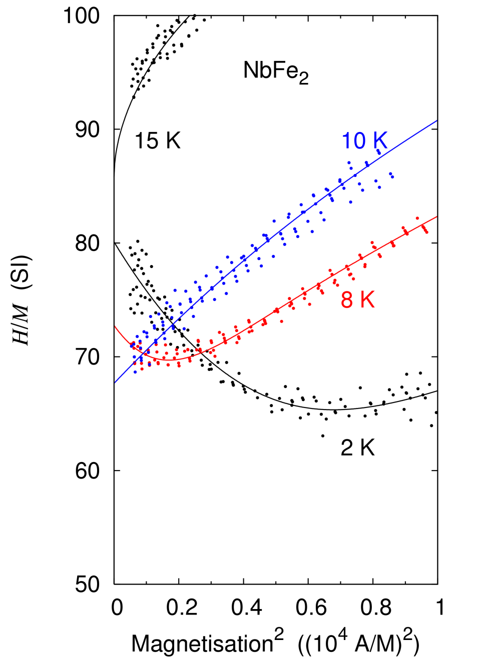
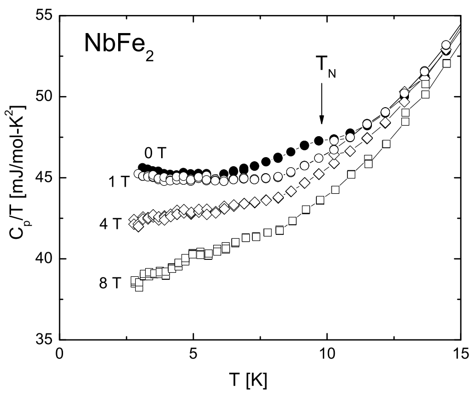
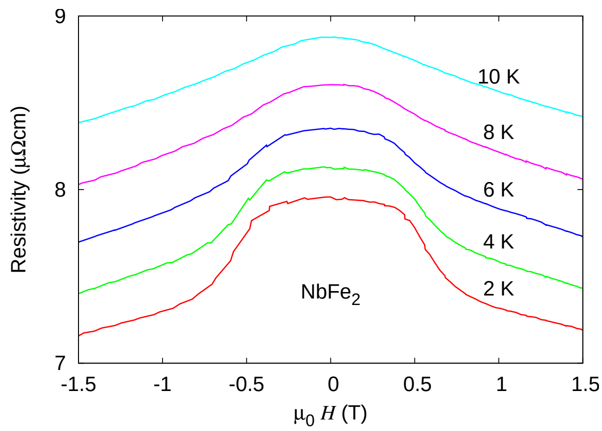
$NbFe_2$, Arrott plots





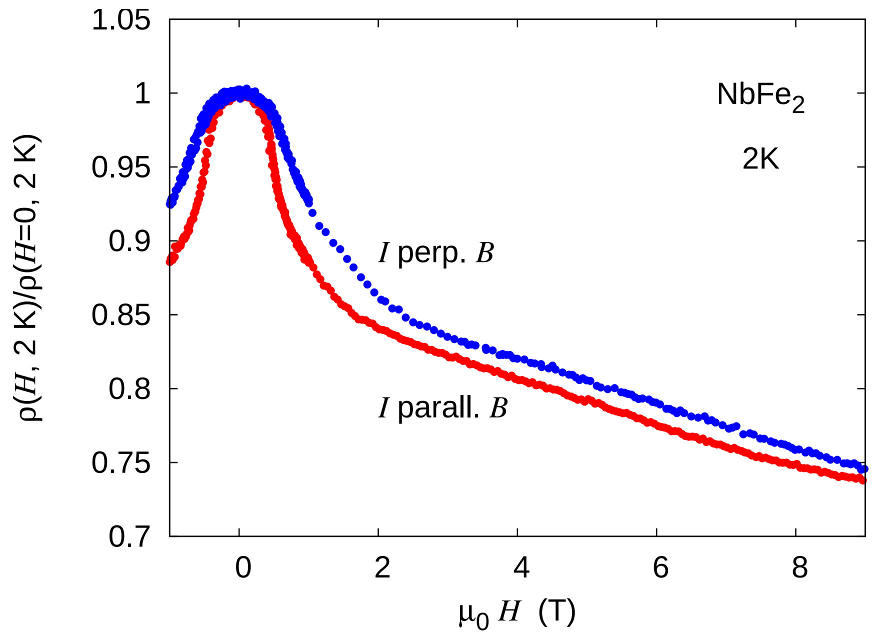
Phase transition anomalies





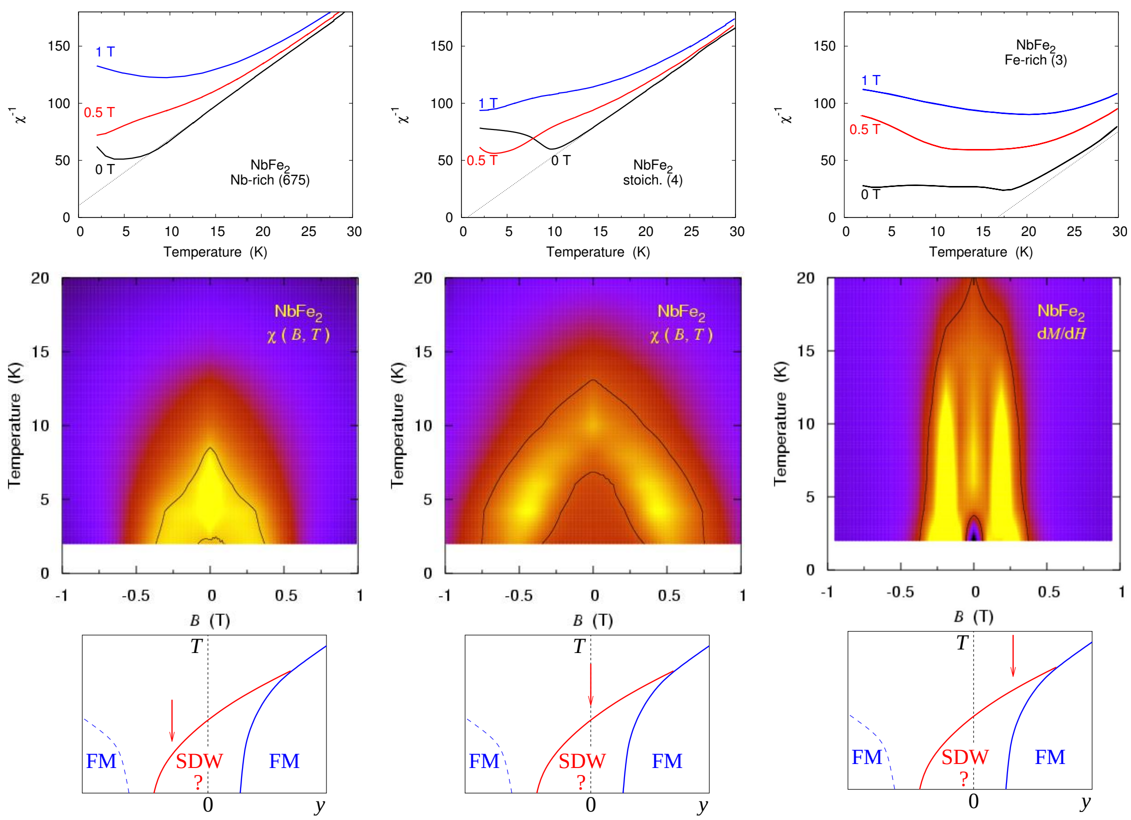
- Weak **hump** in C/T near T_N.
- Pronounced **magnetoresistance** for $T < T_N$. Anomaly disappears at T_N.

Magnetoresistance orientation dependence



- Magnetoresistance jump **sharper for $I||B$**.

$Nb_{1-y}Fe_{2+y}$ – composition as control parameter



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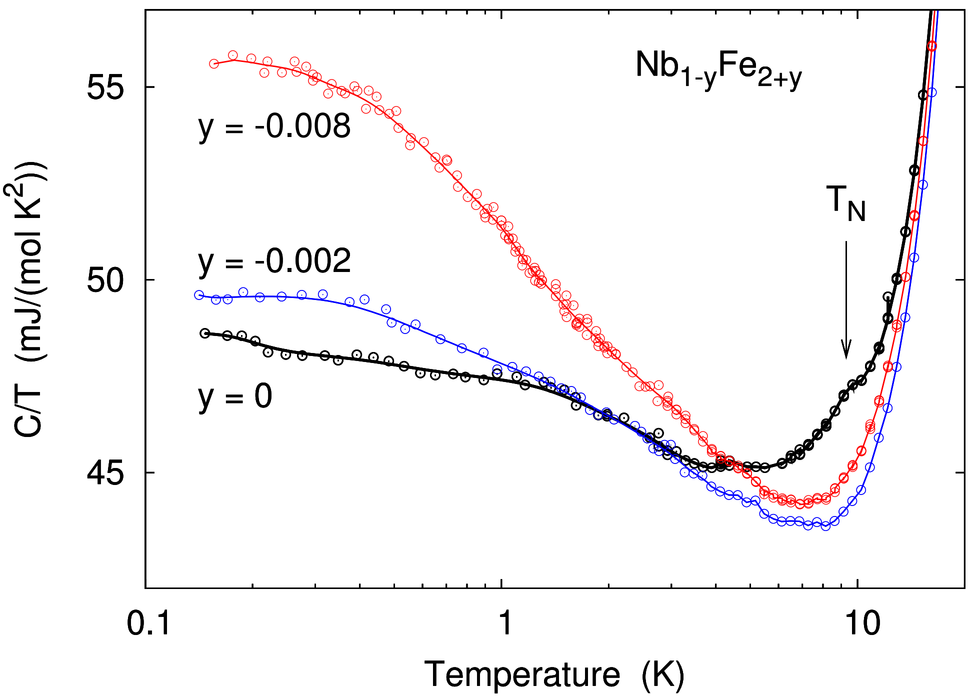
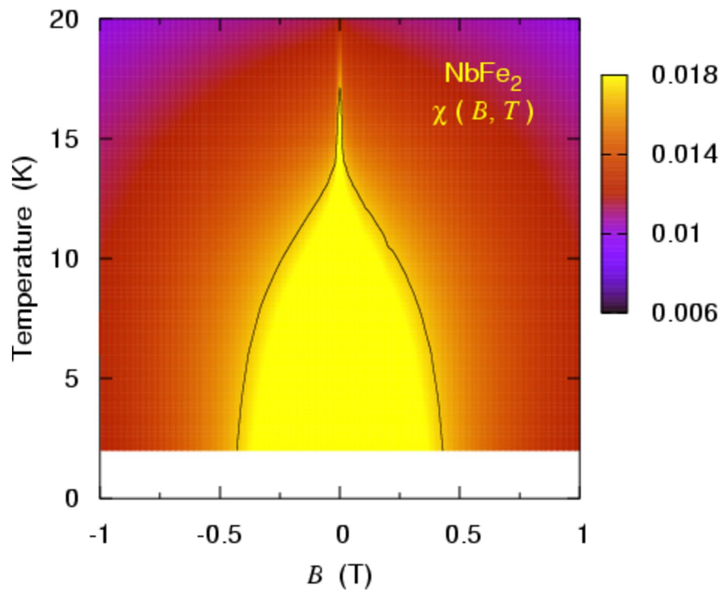
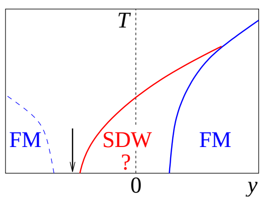
Approaching the quantum critical point in $NbFe_2$



$NbFe_2$ – quantum critical composition





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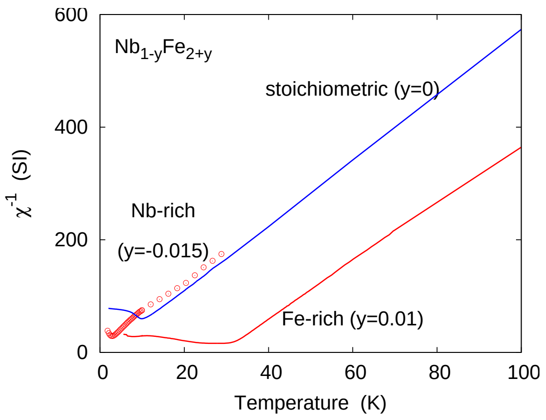
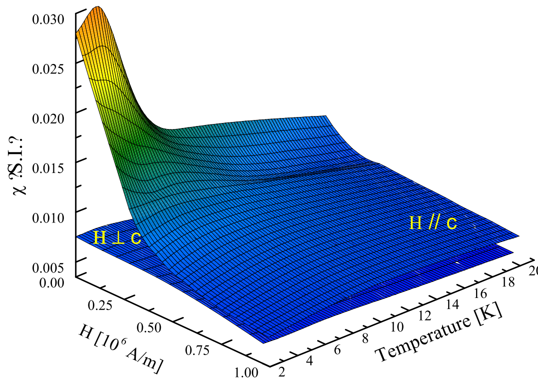
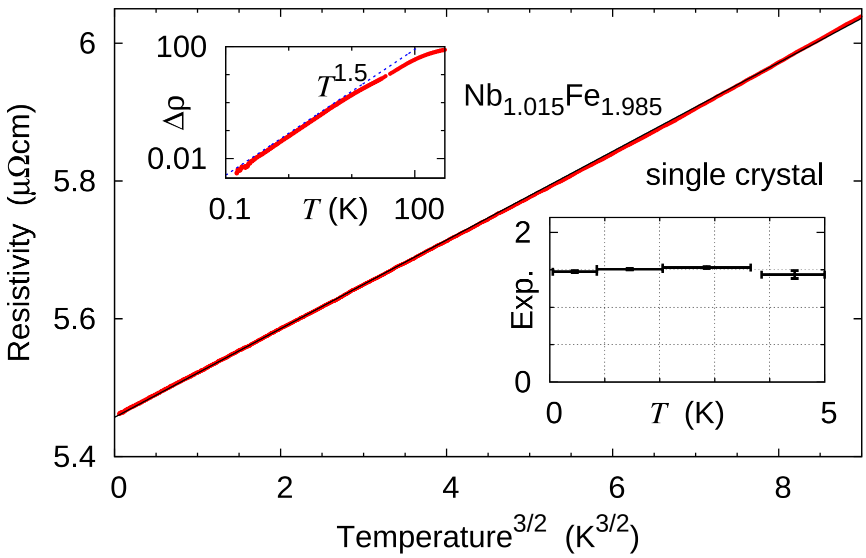
$NbFe_2$, susceptibility close to quantum critical point

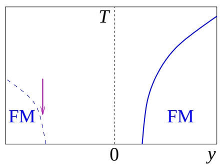




- **Tune to quantum critical point** by changing composition.
- **Single crystal** $Nb_{1.015}Fe_{1.985}$ almost critical.
- Study **quantum criticality** in single crystal at ambient pressure.

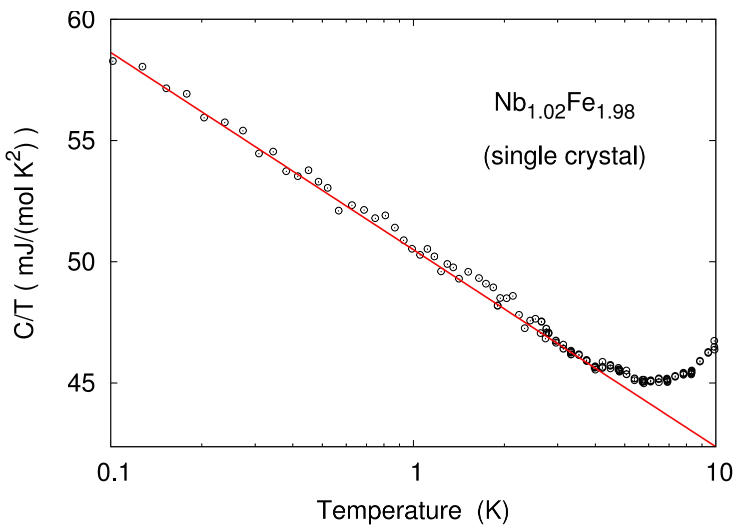
$NbFe_2$, resistivity close to quantum critical point

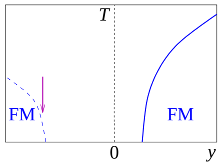




- **Power-law temperature dependence** $\Delta\rho \sim T^{3/2}$ below 4 K. Similar to high-pressure MnSi.
- Anomalous resistivity from high T **down to base** T.

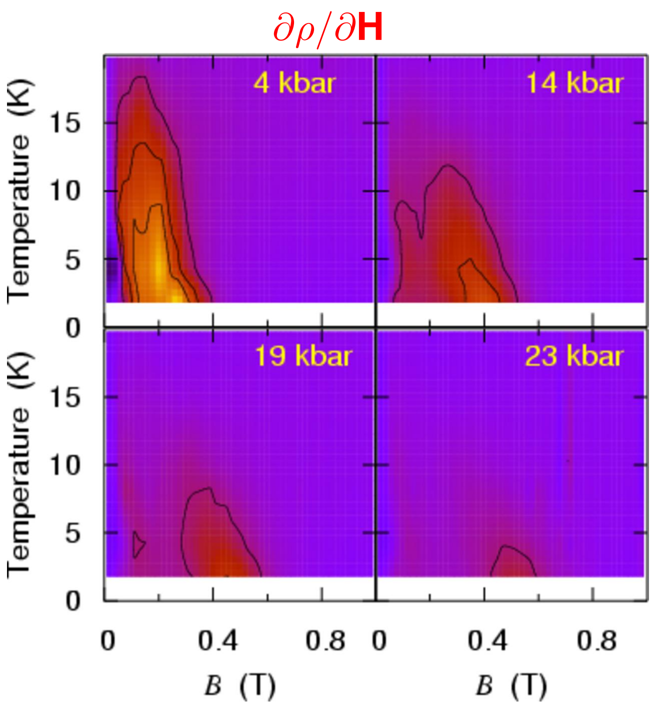
$NbFe_2$, heat capacity close to critical point

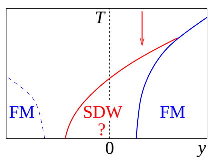




- **Enhanced** $\gamma \sim 50\ \mathrm{mJ/molK^2}$ ($\sim$ 3$\times$ band structure DOS).
- $C/T \sim \log T$ over wide temperature range, logarithmic breakdown of Fermi liquid.

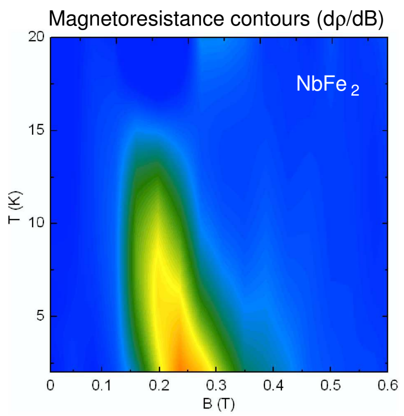
$NbFe_2$ – high pressure

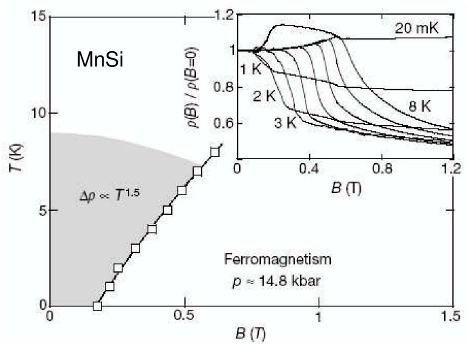




- Critical field H_c **increases.**
- T_N **decreases.**
- Extrapolated critical pressure $\sim$ 40 kbar

Paramagnetic metamagnetism in $NbFe_2$?



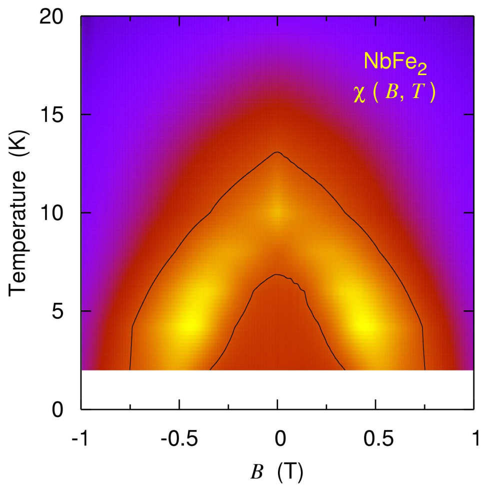


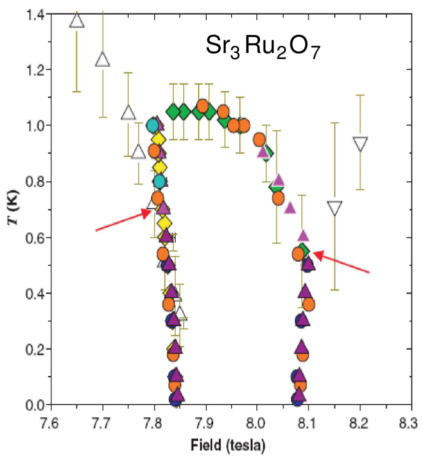
[Pfleiderer et al., Nature 414, 427 (2001)]

Is there really long-range order in $NbFe_2$, or are the anomalies due to metamagnetic transitions, like in MnSi?

- **High suscept.** χ. On threshold of FM (Stoner-factor $\simeq$ 120).
- **Low critical fields** $H_c \sim 0.3\ \mathrm{T}$ compared to T_N.
- **No order seen by neutrons** (yet).

The case in favour of order in $NbFe_2$

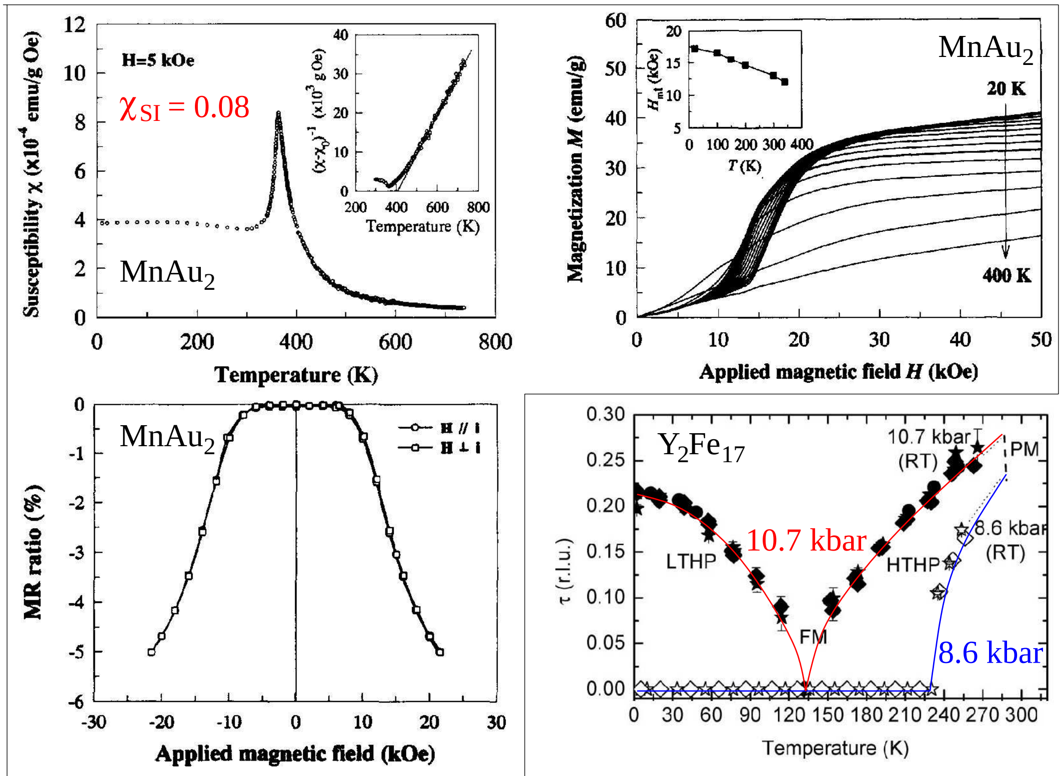




[Grigera et al. Science 306, 1154 (2004)]

- **Separate low-T, low-H region** on χ contours.
- **NMR lines broaden** on cooling through T_N.
- **Arrott plots** show distinct low T vs. high T behaviour.

Examples of helical order



[Samata et al., J. Phys. Ch. Sol. 59, 377 (1998)]

[Prokhnenko et al., PRL 94, 107201 (2005)]

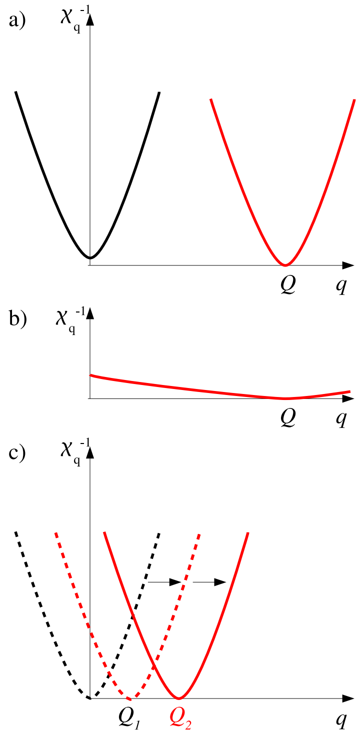
What's going on in $NbFe_2$ (and maybe others)?

Key results:

- **High suscept.** χ. On threshold of FM (Stoner-factor $\simeq 120$).
- **Low critical fields** $H_c \sim 0.3$ T compared to $T_N \sim 10$ K.
- On approaching FM, H_c **decreases:** Non-FM order **grows out of FM state.**
- **NMR** shows magn. order, but **neutrons do not** (yet).

Low-Q - order (e.g. long-wavelength helical ordering?)

Scenarios:



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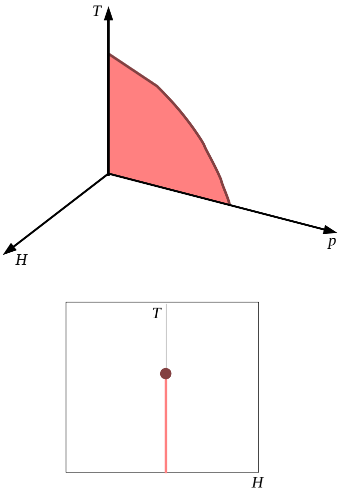
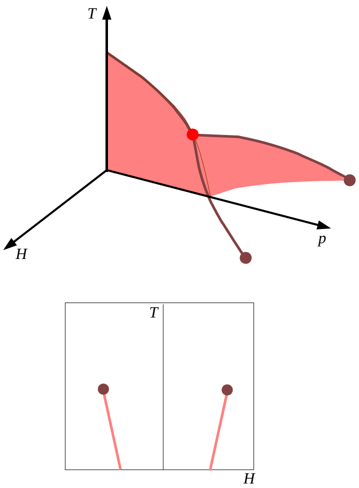
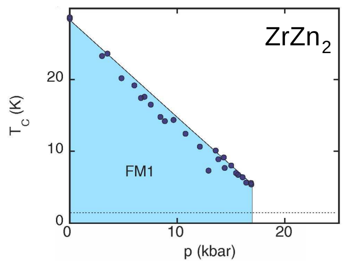
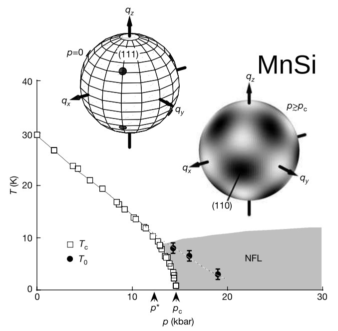
What lies on the border of ferromagnetism?





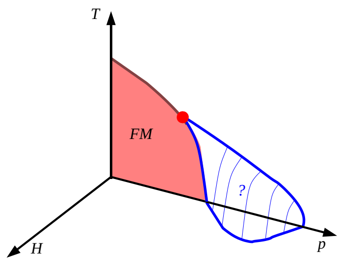


[Uhlarz et al, PRL 93, 256404 (2004)]

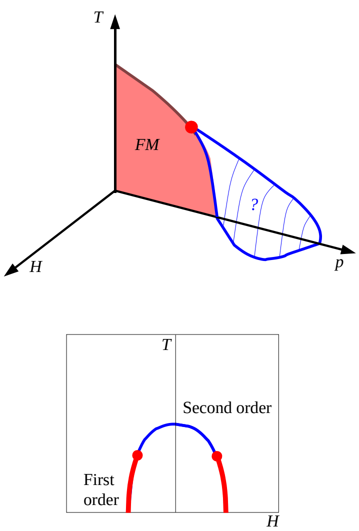


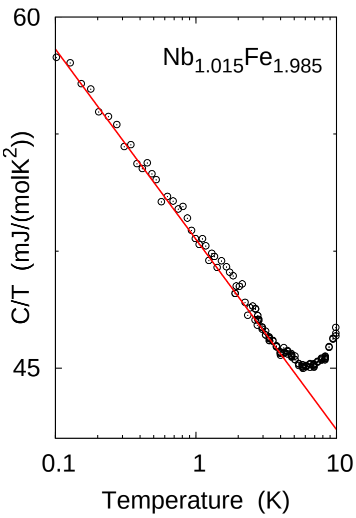
[Pfleiderer et al., Nature 427, 227 (2004)]

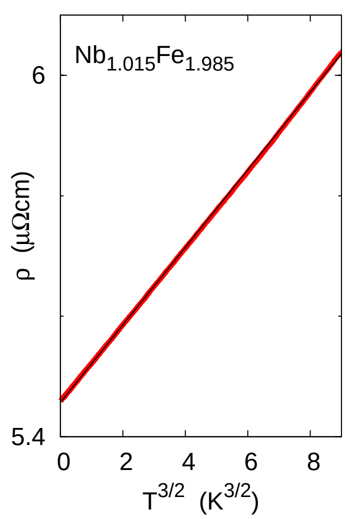
- Ferromagnetism disappears **continuously.** Examples: ???
- Or: Tricritical point; first order, **metamagnetism**. MnSi, $ZrZn_2$.



Do band magnets like to twist?







- **Susceptibility surprisingly low at T_c** ($<<$ 1) in many band ferromagnets.
- Other **candidates:** $ZrZn_2$, CoS_2, Ca_2RuO_4, ...
- A tendency towards twisting order parameter (cf. FFLO)? Inherent in Fermi liquid?

NbFe$_2$
Trieste 14/8/06
Prospecting
Colleagues and Co-workers
The border of ferromagnetism
Band magnetism
Quantum criticality
First-order transitions
Anomalous power laws
Ordered states in NbFe$_2$
Incipient ferromagnet
Unidentified order
Susceptibility
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Transition anomalies
Tuning NbFe$_2$
Composition
Approaching the qcp
QCP Resistivity
QCP Heat capacity
Pressure
Scenarios for NbFe$_2$
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Examples of helical order
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