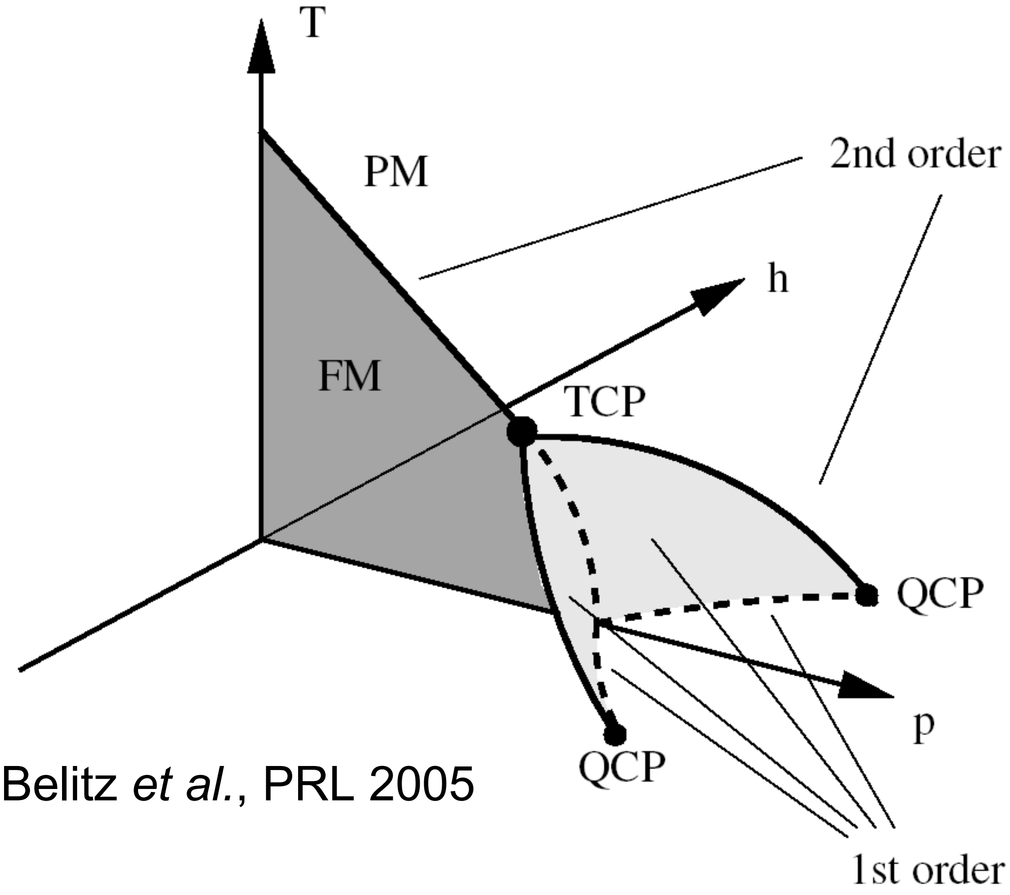
Quantum critical itinerant ferromagnetism

Gareth Conduit



Belitz *et al.*, PRL 2005

Gareth Conduit

Cavendish Laboratory

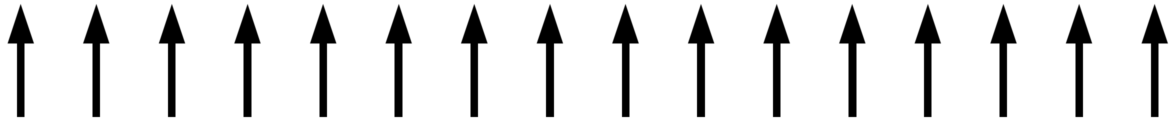
University of Cambridge

Two types of ferromagnetism

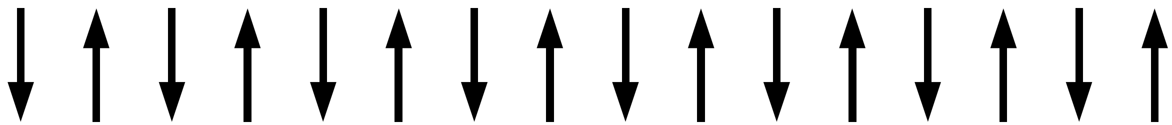
Gareth Conduit

- *Localised ferromagnetism*: moments localised in real space

Ferromagnet

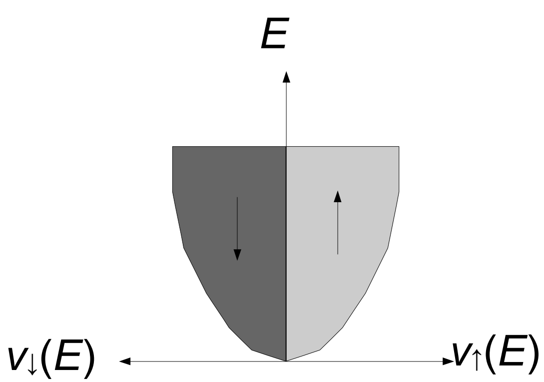


Antiferromagnet

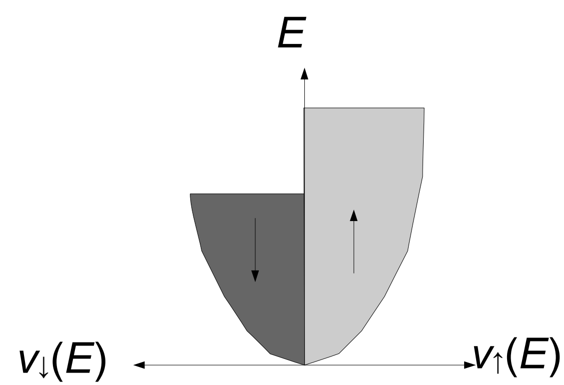


- *Itinerant ferromagnetism:* moments localised in reciprocal space

Not magnetised



Partially magnetised



Stoner model for itinerant ferromagnetism

Gareth Conduit

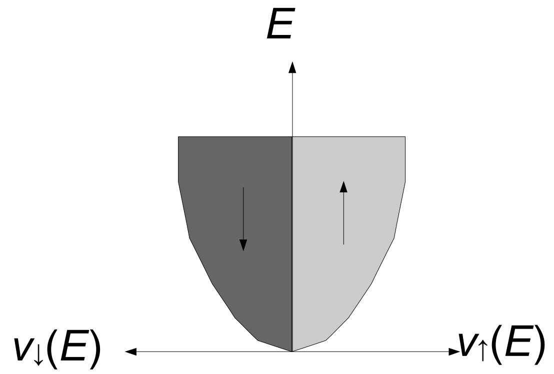
- Repulsive interaction energy $U=gn_{\uparrow}n_{\downarrow}$
- A ΔE shift in the Fermi surface causes:

  (i) Kinetic energy increase of $\frac{1}{2}\nu\Delta E^2$

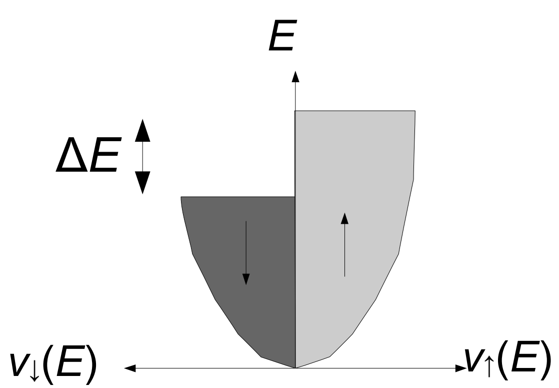
  (ii) Reduction of repulsion of $-\frac{1}{2}g\nu^2\Delta E^2$

- Total energy shift is $\frac{1}{2}\nu\Delta E^2(1-g\nu)$ so a ferromagnetic transition occurs if $g\nu>1$

Not magnetised



Partially magnetised



Ferromagnetism in iron

Gareth Conduit

- The Stoner model has a *second order* transition of e.g. iron and nickel

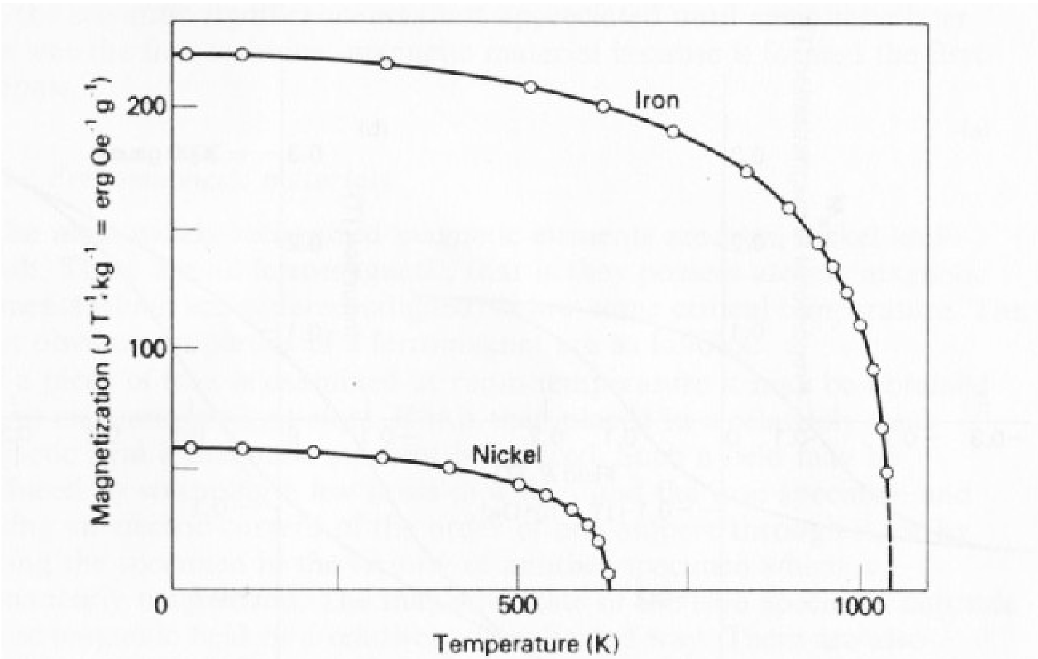


Figure 1.2 Spontaneous magnetization plotted against temperature for iron and nickel.

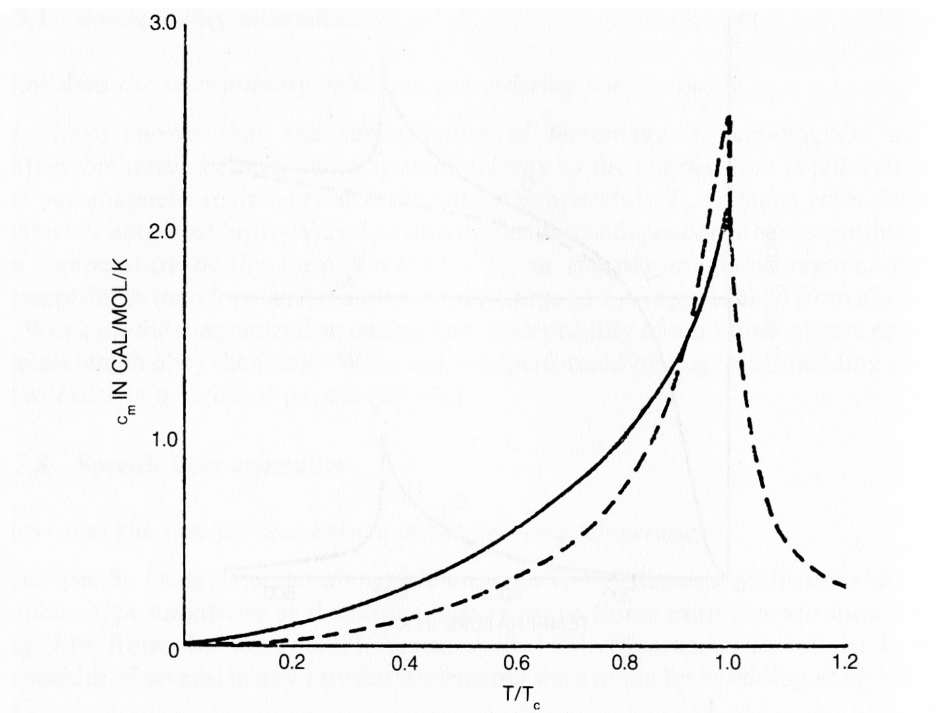


Fig. 9.20 Specific heat anomaly for nickel at its Curie point compared with the theoretical prediction.

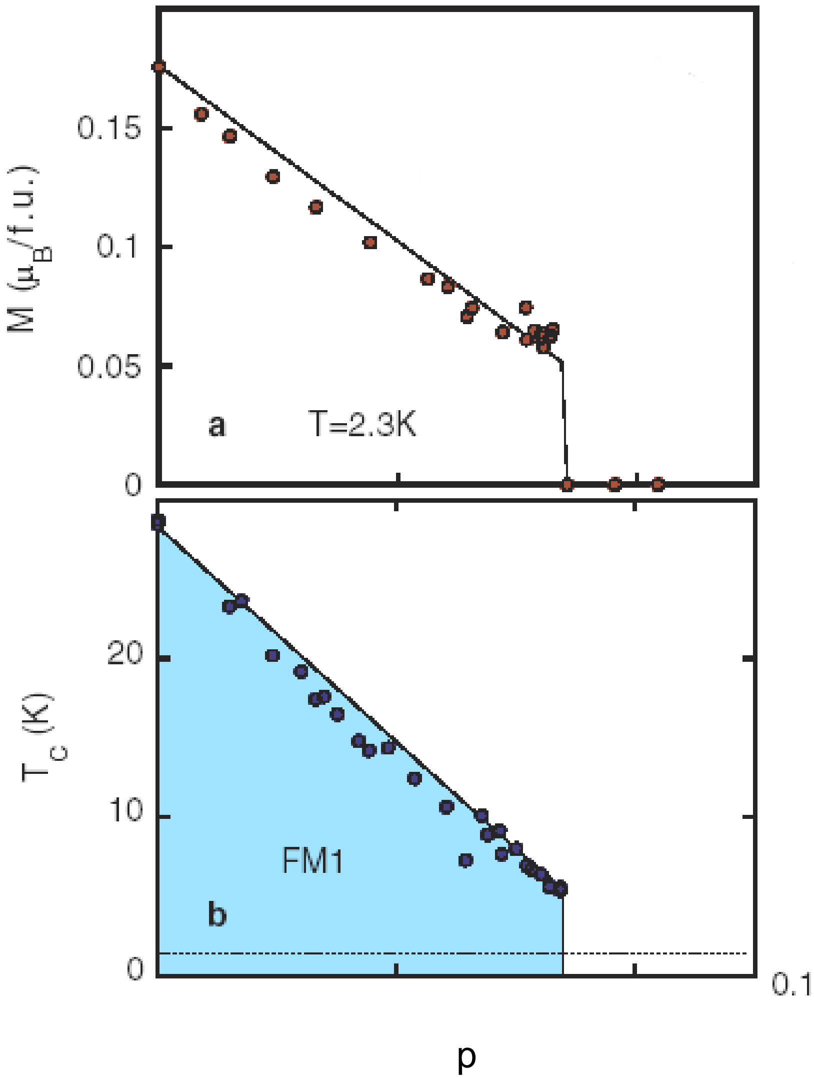
which is characterised by:

- Smoothly varying magnetisation
- A divergence of length-scales (peaked heat capacity and susceptibility)

Breakdown of Stoner criterion -- $ZrZn_2$

Gareth Conduit

- At low temperature and high pressure $ZrZn_2$ has a first order transition

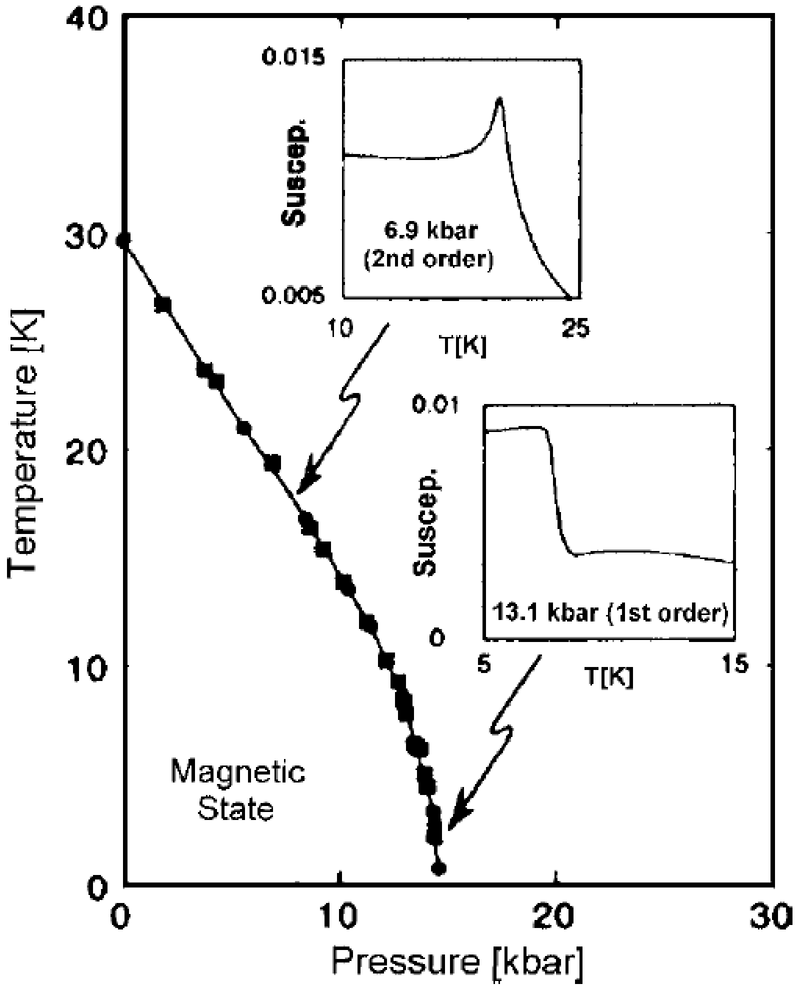


Uhlarz *et al.*, PRL 2004

Breakdown of Stoner criterion -- MnSi

Gareth Conduit

- MnSi also displays a first order phase transition

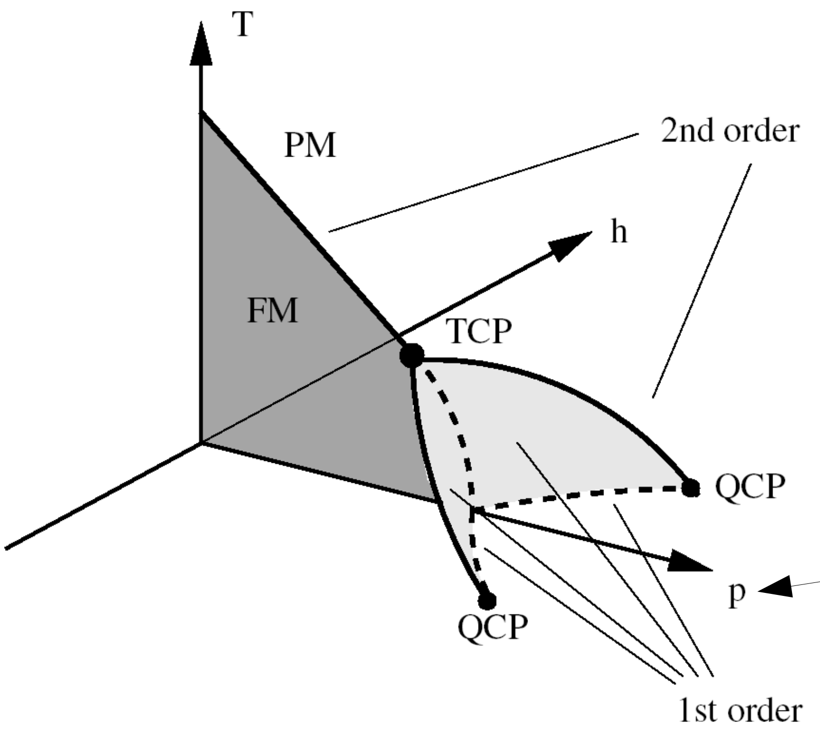


Pfleiderer *et al.*, PRB 1997
Vojta *et al.*, 1999 Ann. Phys. 1999

Breakdown of Stoner criterion

Gareth Conduit

- At low temperature UGe_2, $ZrZn_2$, MnSi, and others are first order



PM: Partially magnetised
FM: Fully magnetised
TCP: Tricritical point
QCP: Quantum critical point

(interaction strength)

- Here I describe two projects that investigate the first order behaviour:

(i) Probe the first order transition without the lattice

(ii) Motivated by the FFLO phase, apply the formalism to search for a putative textured phase

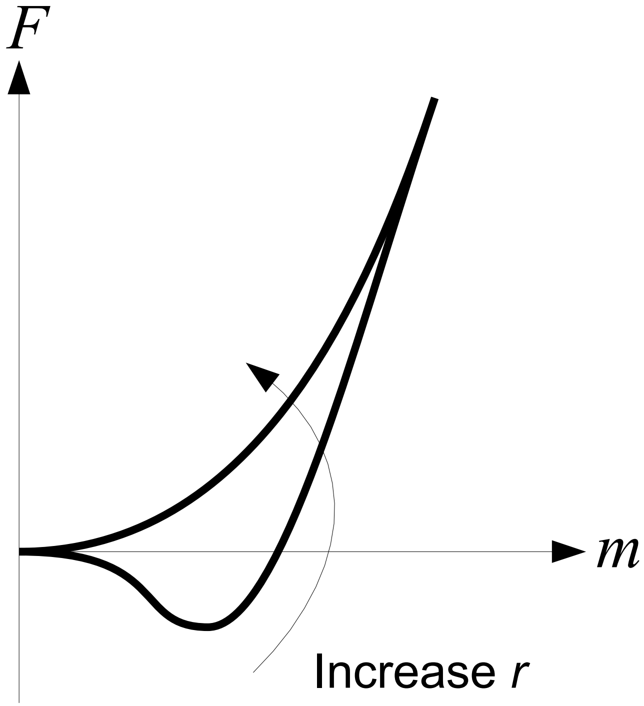
Landau expansion

Gareth Conduit

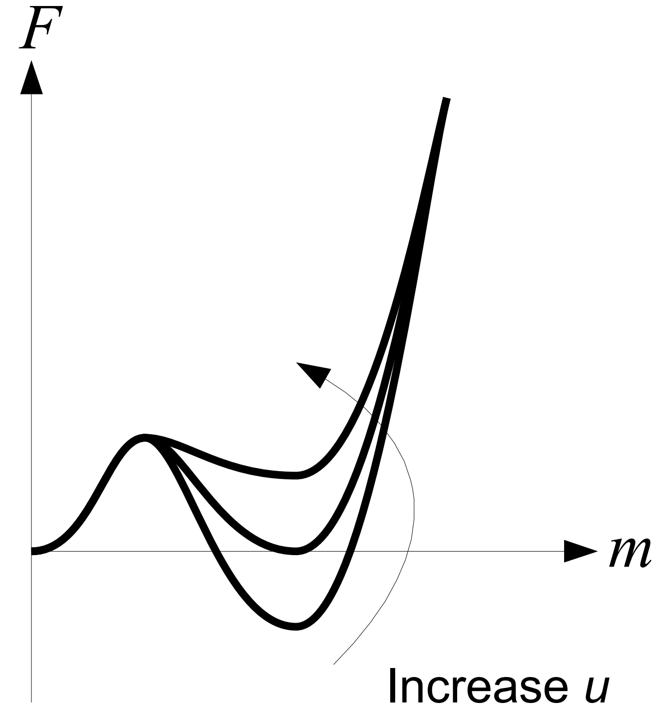
- To describe the transition we expand the total energy in the magnetisation

$$F = r\,m^2 + u\,m^4 + v\,m^6$$

Change sign of *r*,
second order transition



Change sign of *u*,
first order transition



Analytical method

Gareth Conduit

- System free energy $F=-k_B T \ln Z$ is found via the partition function

$$Z=\sum_{\{m(x,t)\}} \exp(-E[m(x,t)]/k_B T)$$

the summation includes spatial and temporal fluctuations of the magnetisation

- Using only the average magnetisation:

$$m(x,t)=\bar{m}$$

gives

$$F \propto (1-g\nu)\bar{m}^2$$

i.e. the Stoner criterion

Consequences of fluctuations

Gareth Conduit

$$Z=\sum_{\{m(x,t)\}}\exp(-E[m]/k_B T)$$

- We expand the energy to second order in fluctuations: $m \to \bar{m}+\phi$

$$Z=\sum_{\{\phi(x,t)\}}\exp\left(\frac{-1}{k_B T}\left(E[\bar{m}]+\phi^2(x,t)E''[\bar{m}]\right)\right)$$

- Larkin & Pikin [Zh. Eksp. Teor. Fiz. 1969] included auxiliary fluctuations of the lattice which introduced a negative magnetisation term, driving the transition first order

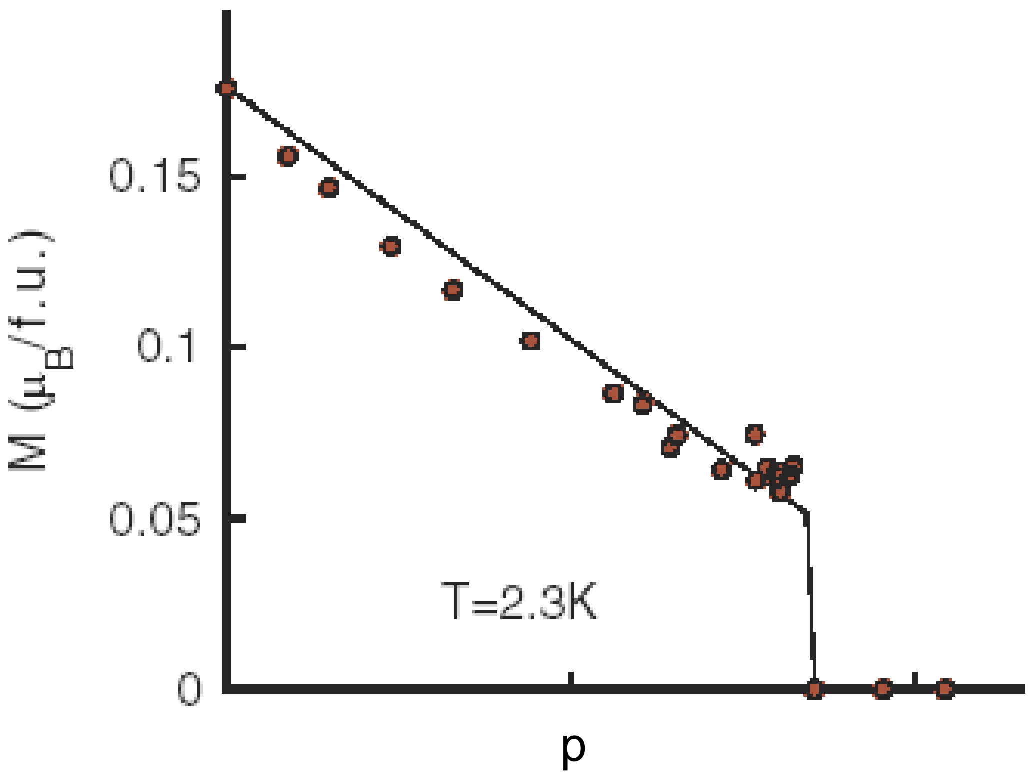
$$\begin{aligned}&=\int\exp(-[r m^2+u m^4+a\phi^2\pm 2\mathrm{a}\, m^2\phi]/k_B T)\,d\phi\\&=\int\exp(-[r m^2+(u-a)m^4+a(\phi\pm m^2)^2]/k_B T)\,d\phi\\&\sim\exp(-[r m^2+(u-a)m^4]/k_B T)\end{aligned}$$

- Similarly here considering the soft transverse magnetic fluctuations drives the transition of the longitudinal first order

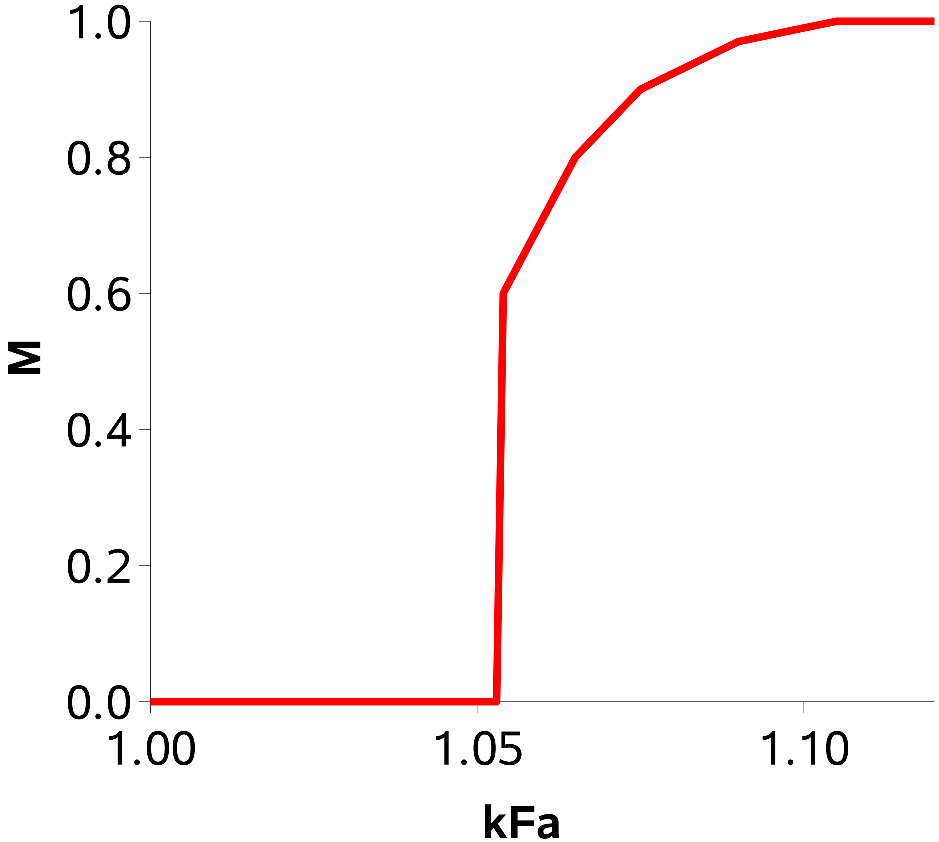
Fluctuation corrections

Gareth Conduit

- The results give the following phase diagram



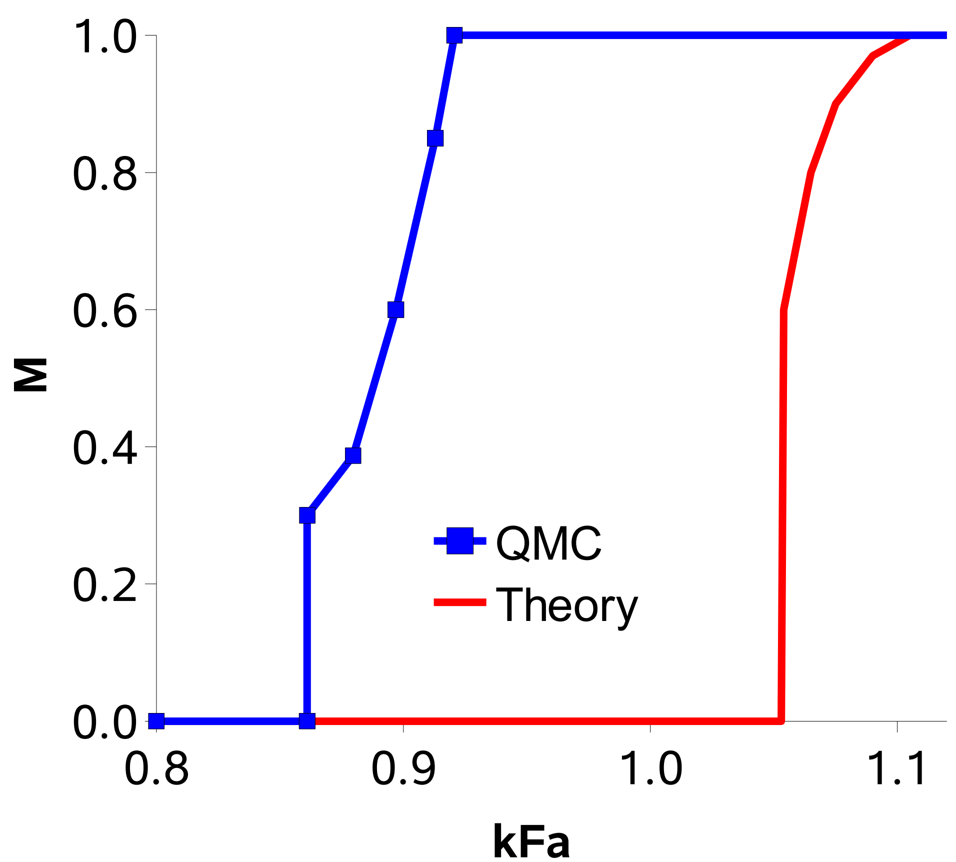
Uhlarz *et al.*, PRL 2004



QMC calculations

Gareth Conduit

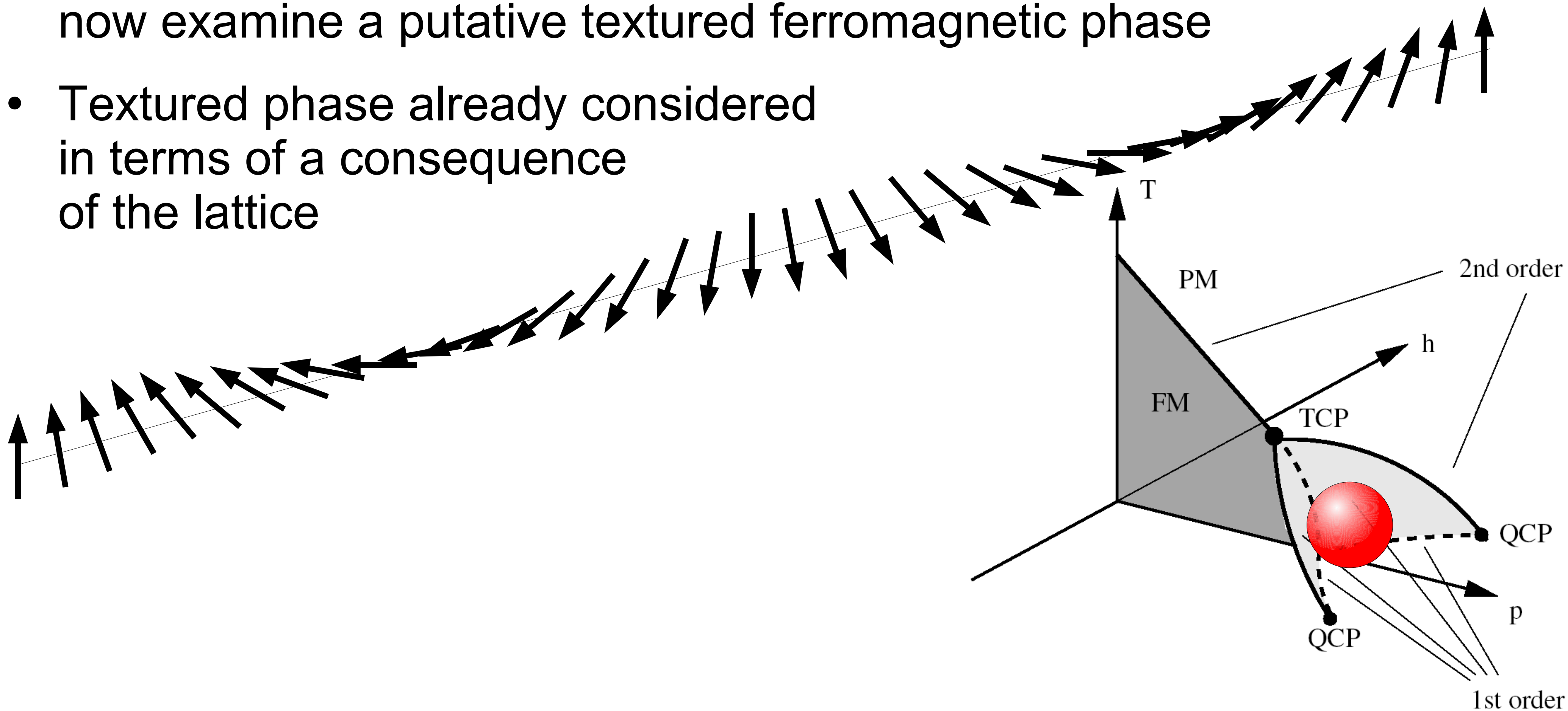
- Fluctuation corrections are not exact and higher order terms might destroy the first order phase transition
- Exact (except for the fixed node approximation) Quantum Monte Carlo calculations confirmed a first order phase transition



Summary of uniform work

Gareth Conduit

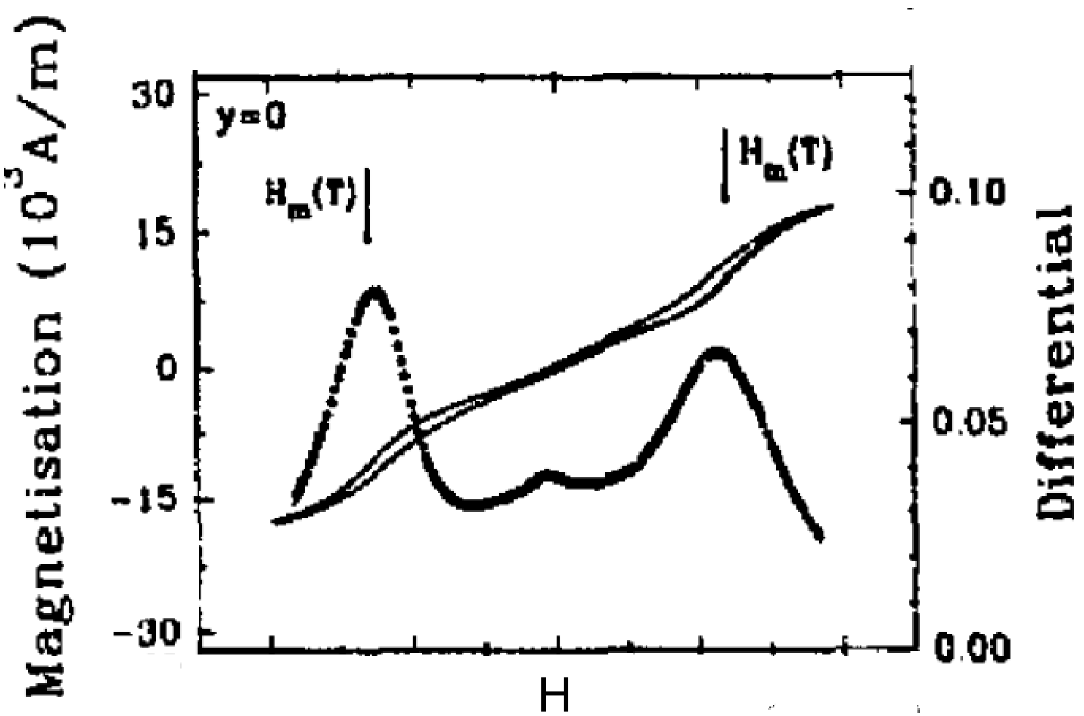
- Consideration of corrections due to fluctuations in magnetisation and density revealed a first order phase transition
- Nature of transition confirmed by Quantum Monte Carlo calculations
- Motivated by Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) and experiment now examine a putative textured ferromagnetic phase
- Textured phase already considered in terms of a consequence of the lattice

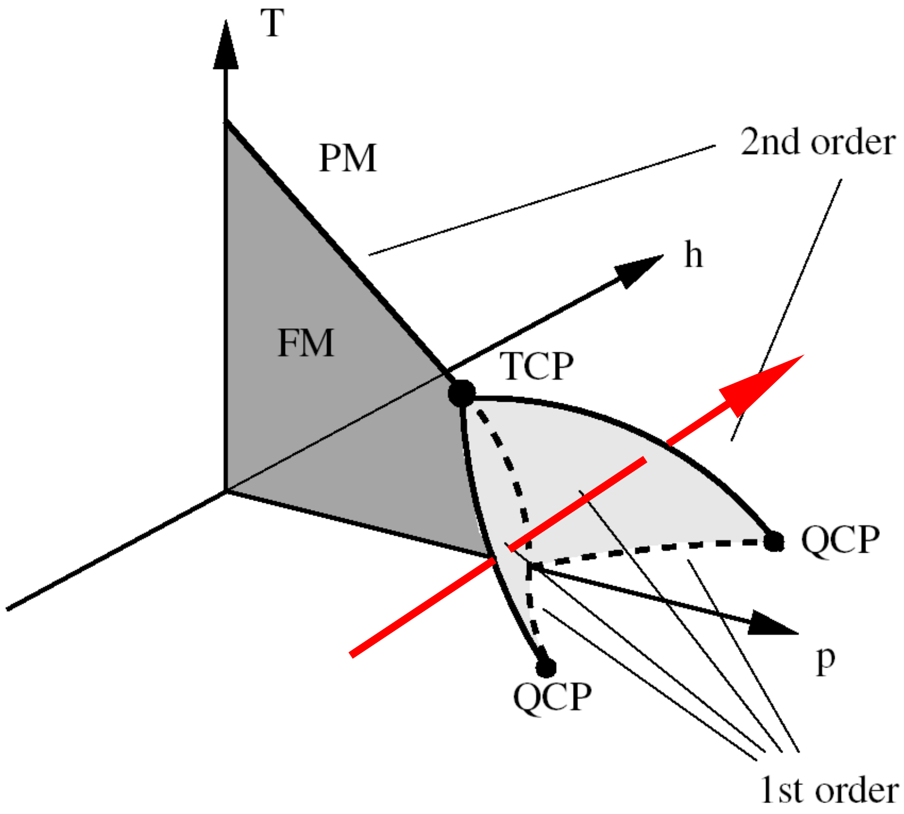


$NbFe_2$

Gareth Conduit

- $NbFe_2$ displays antiferromagnetic order where it is expected to be ferromagnetic -- could this be a textured ferromagnetic phase?



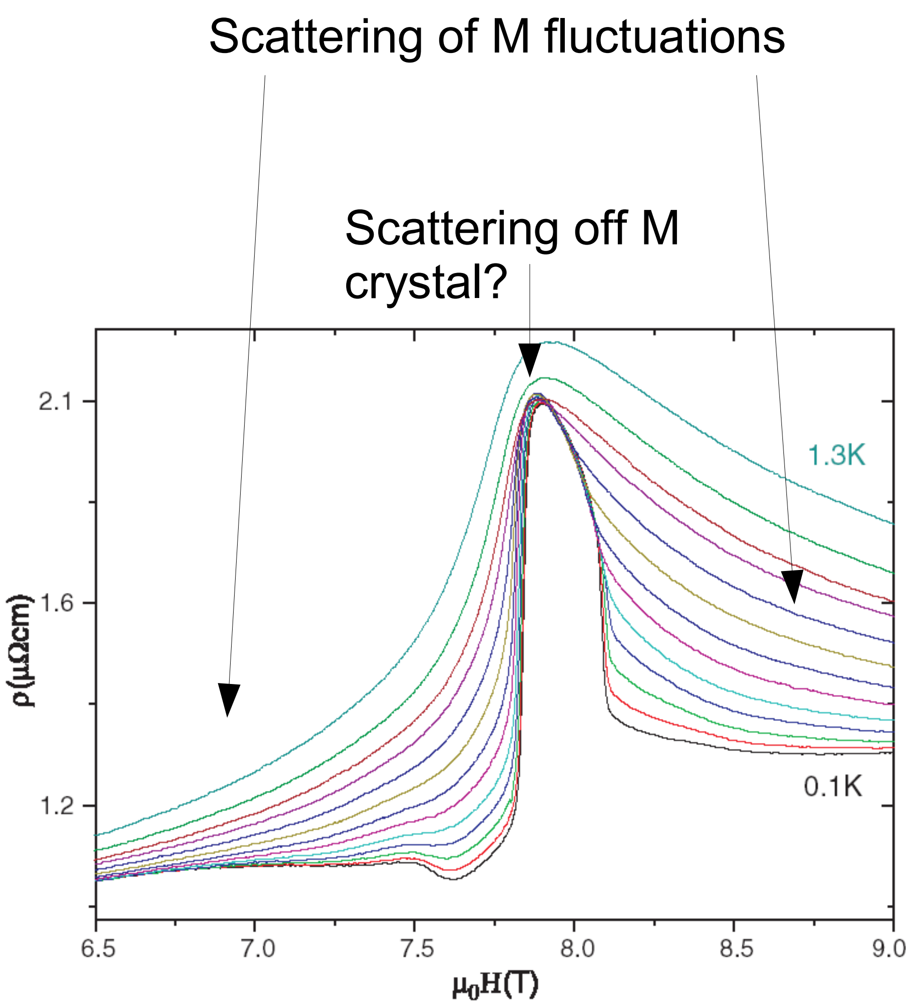


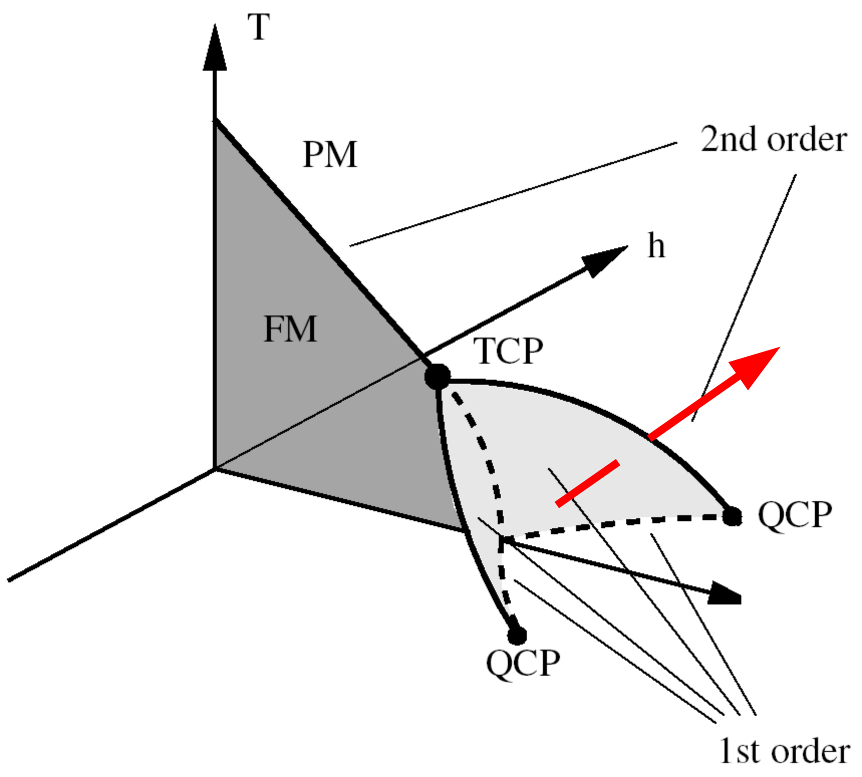
Crook & Cywinski, JMMM 1995

$Sr_3Ru_2O_7$

Gareth Conduit

- Resistance anomaly





- Consistent with a new crystalline phase

Grigera *et al.*, Science 2004

Ginzburg-Landau analysis

Gareth Conduit

- In analogy to FFLO[1] we can look at a Ginzburg-Landau analysis

$$F = r m^2 + \boldsymbol{u} m^4 + v m^6 + \frac{2}{3}\boldsymbol{u}(\nabla m)^2 + \frac{3}{5} v (\nabla^2 m)^2 - hm$$

- The first order transition is accompanied by a textured phase
- Consider the lowest order term in a Ginzburg-Landau expansion, which is a function of the wave vector *q* of the textured phase

$$F = \sum_q \alpha_q m_q^2$$

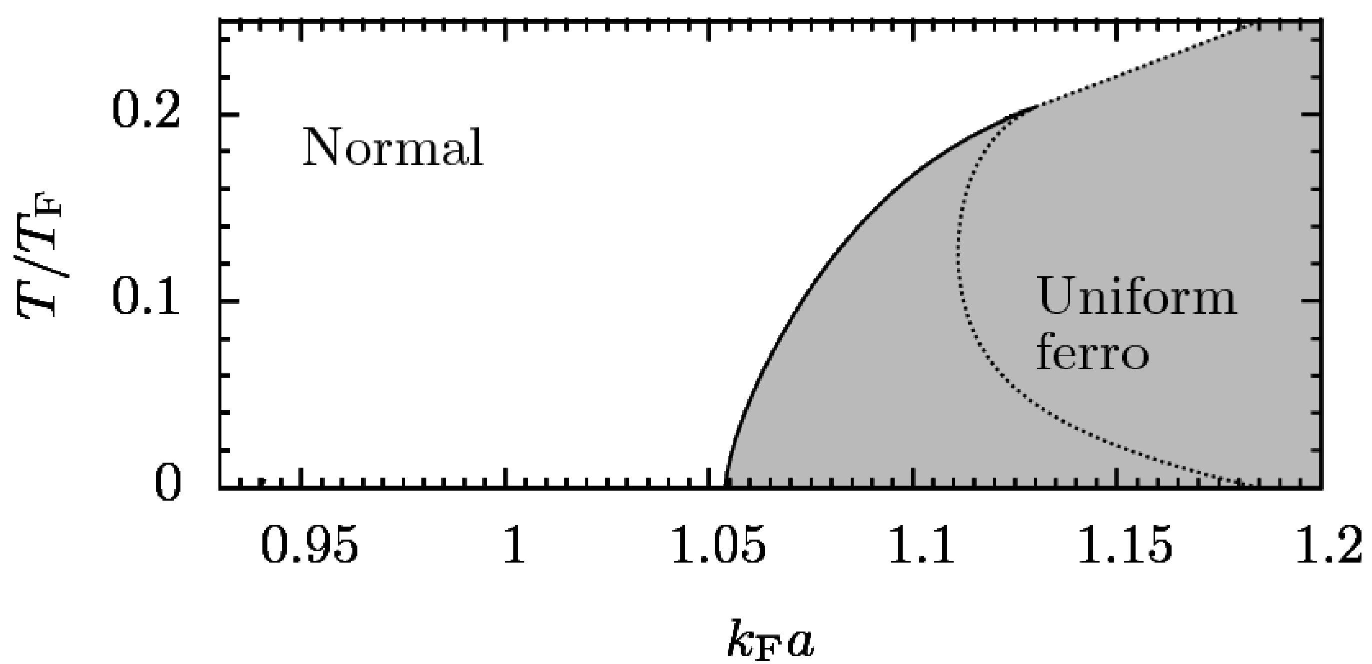
- When $\alpha_q > 0$ zero magnetisation is favourable, if $\alpha_q < 0$ a textured phase preempts the first order ferromagnetic transition

[1]Saint-James *et al*. 1969, [2]Buzdin & Kachkachi 1996

Analytical results

Gareth Conduit

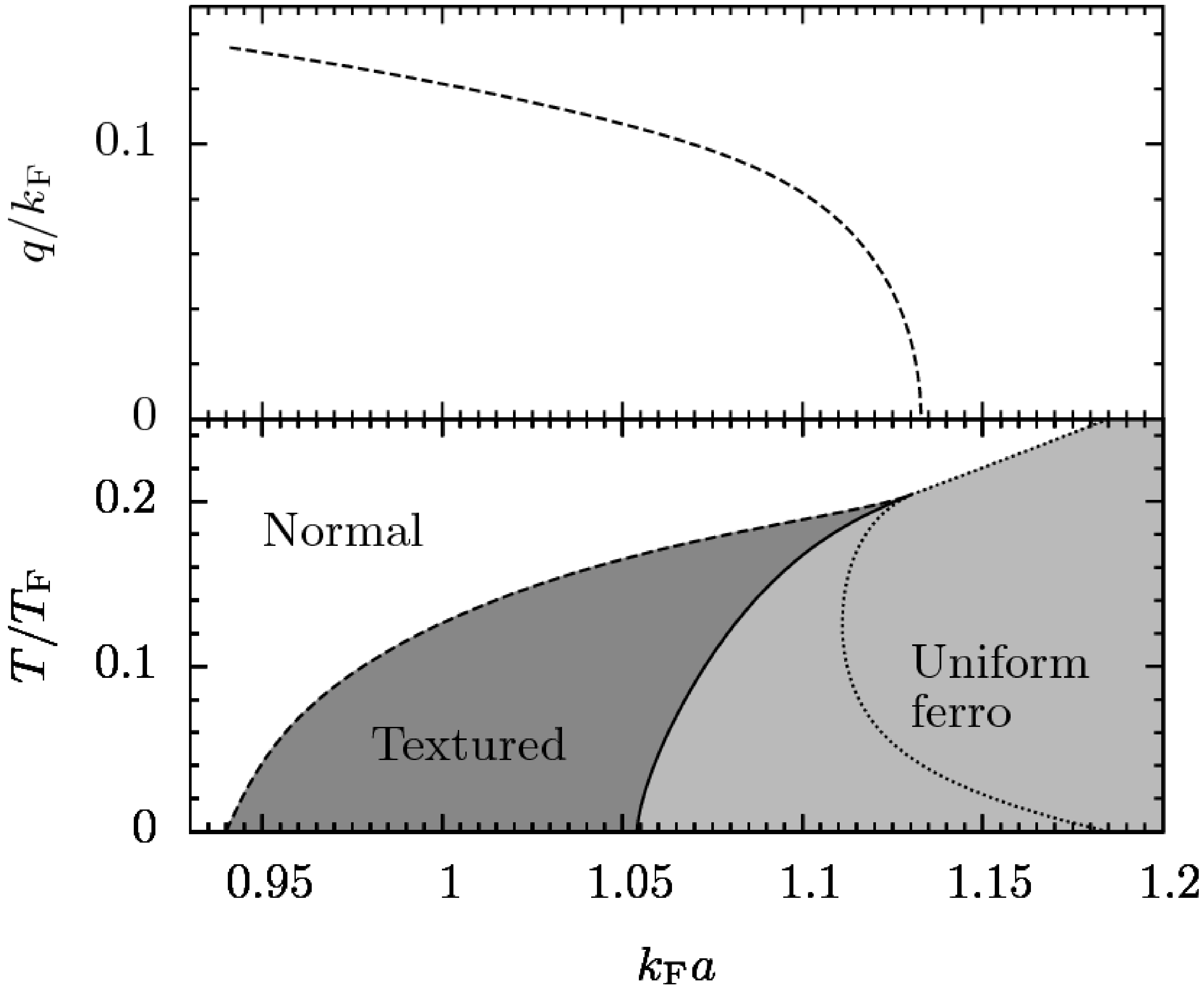
- The phase diagram of the uniform system is



Analytical results

Gareth Conduit

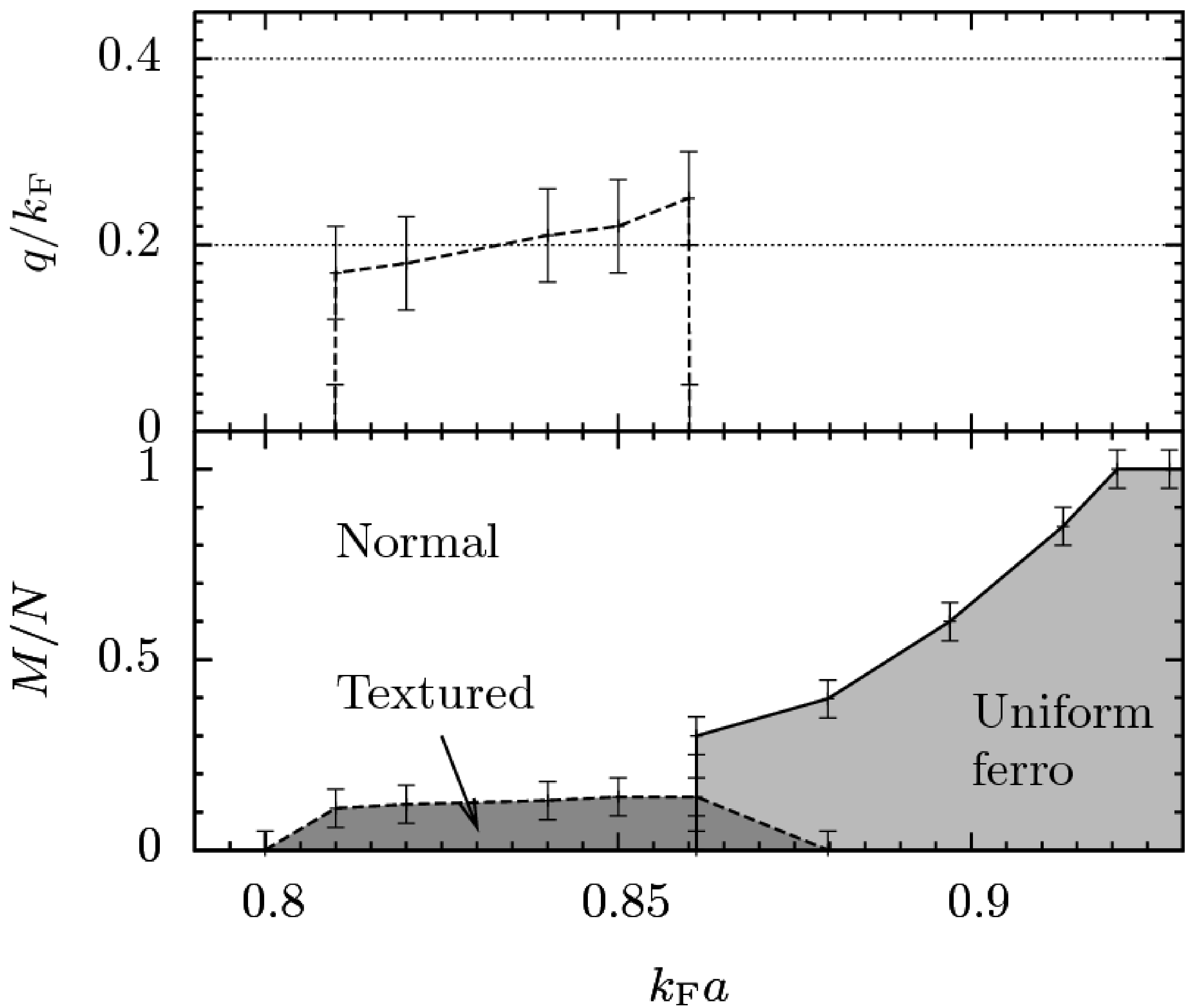
- Textured phase preempted transition with q=0.1k_F



QMC results

Gareth Conduit

- Textured phase preempted transition and penetrated uniform phase



Summary

Gareth Conduit

- Developed a field theoretic construction to understand the first order transition
- Ginzburg-Landau analysis of spin spiral textured ferromagnetic phase
- Confirmed the phases with QMC calculations
- Acknowledgements: Ben Simons & Andrew Green, EPSRC