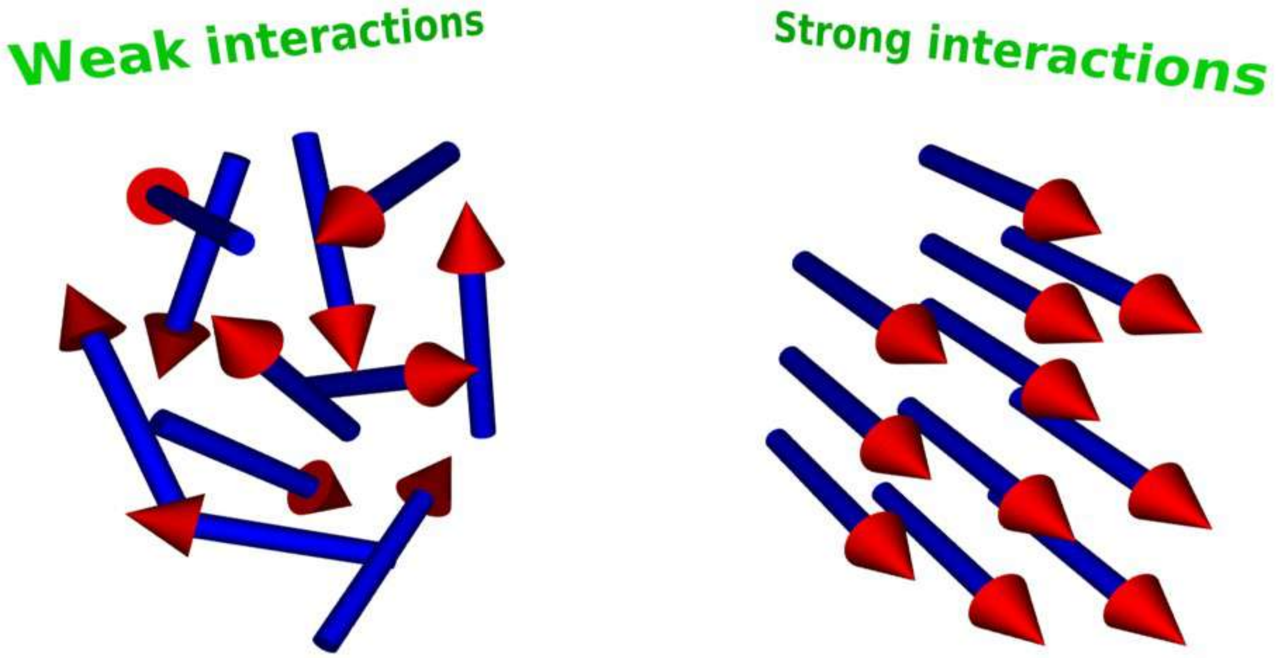
Perspectives on itinerant ferromagnetism in an atomic Fermi gas



Gareth Conduit[1, 2], Ben Simons[3] & Ehud Altman[1]

1. Weizmann Institute, 2. Ben Gurion University, 3. University of Cambridge

G.J. Conduit & B.D. Simons, Phys. Rev. A **79**, 053606 (2009)

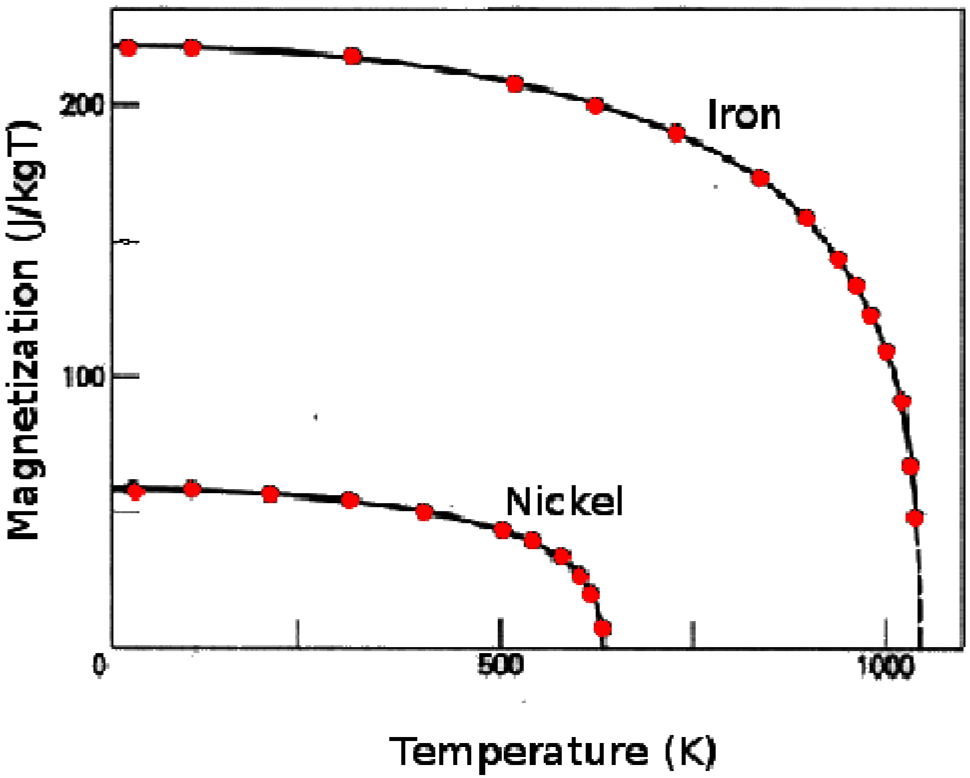
G.J. Conduit, A.G. Green & B.D. Simons, Phys. Rev. Lett. **103**, 207201 (2009)

G.J. Conduit & B.D. Simons, Phys. Rev. Lett. **103**, 200403 (2009)

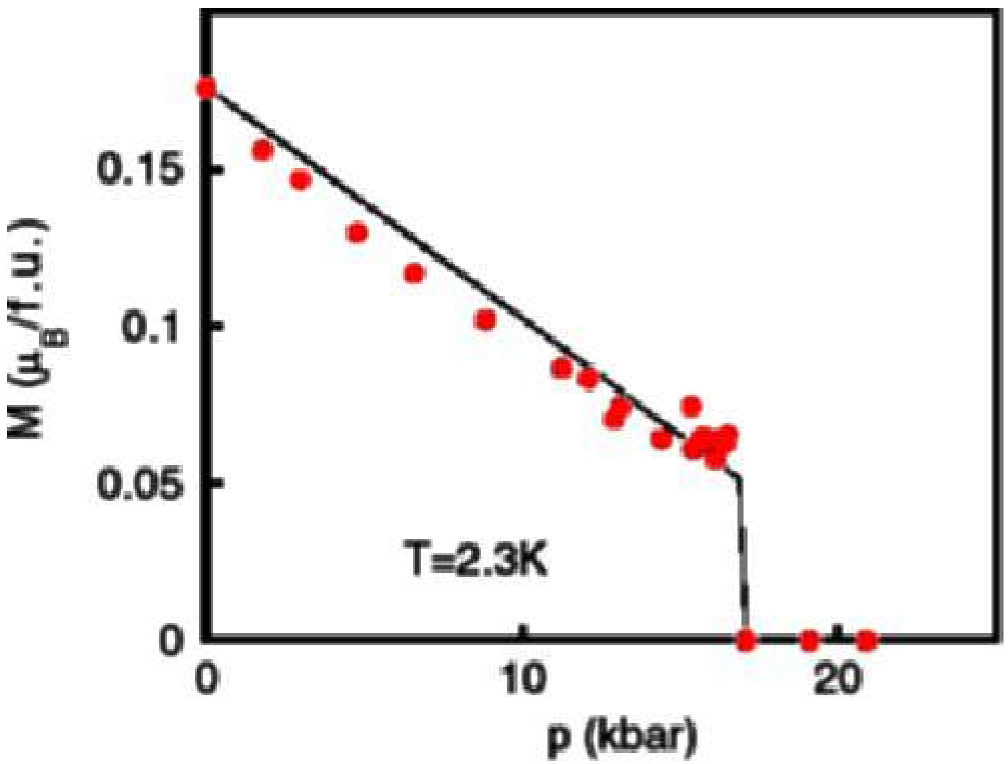
G.J Conduit & E. Altman, arXiv: 0911.2839

Ferromagnetism in solid state

Second order in iron & nickel

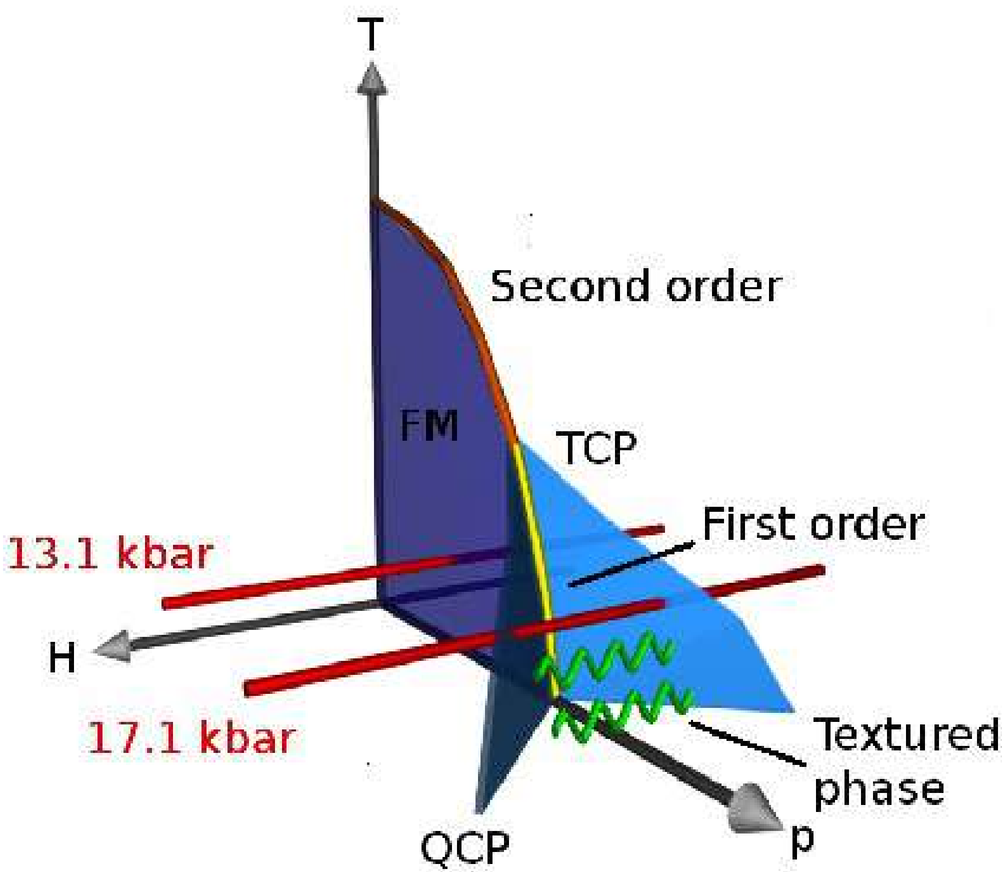


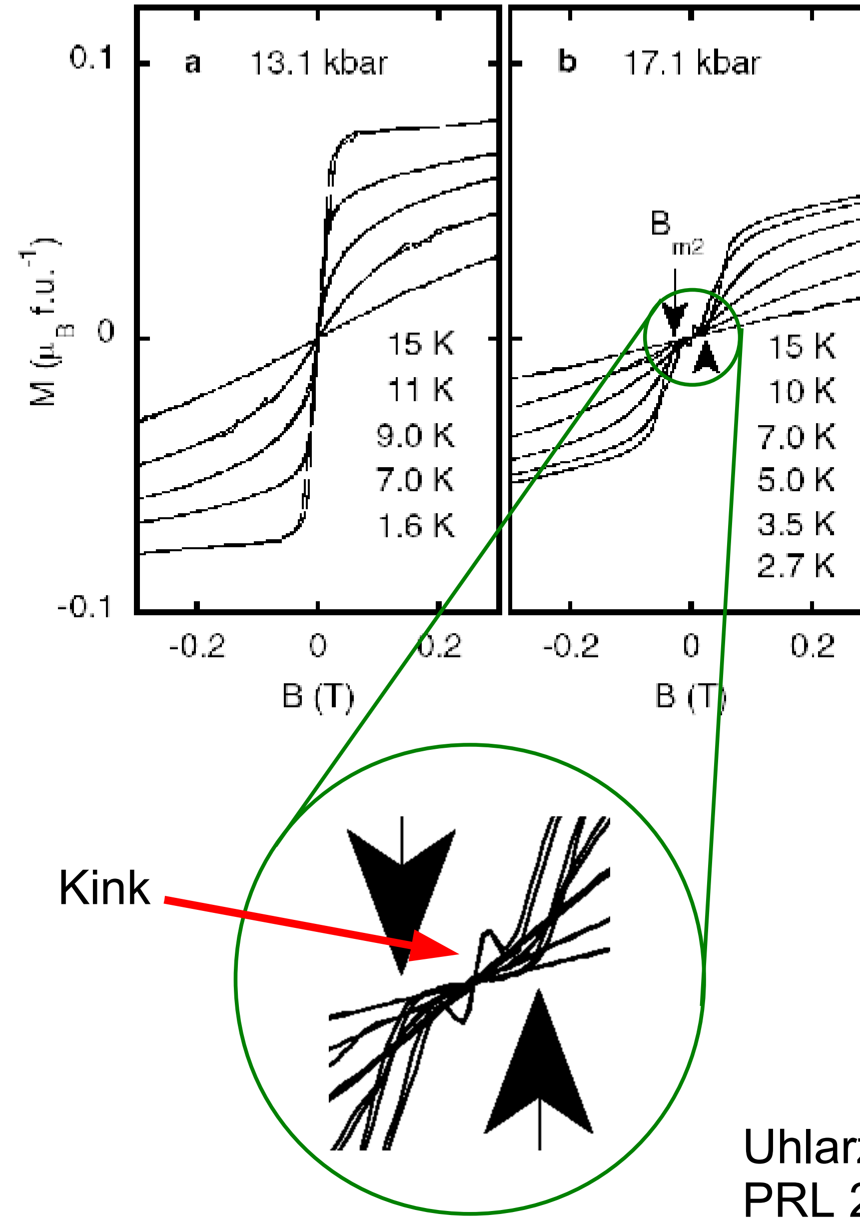
First order in $ZrZn_2$



Uhlarz *et al.*, PRL 2004

Further phase reconstruction in $ZrZn_2$





Uhlarz *et al.*, PRL 2004

Stoner instability with repulsive interactions

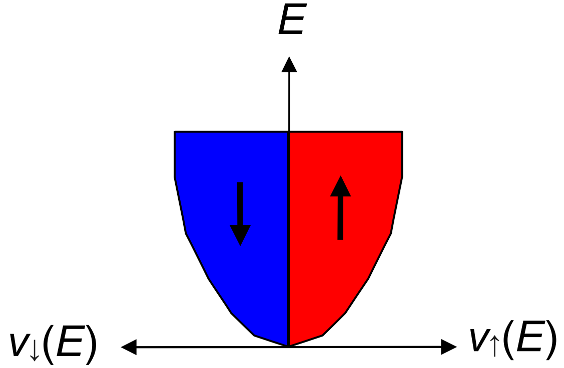
- Use two ^{6}Li states to represent pseudo up and down-spin electrons

$$\hat{H}=\sum_{\mathbf{k}\sigma}\epsilon_{\mathbf{k}}c^{\dagger}_{\mathbf{k}\sigma}c_{\mathbf{k}\sigma}+g\sum_{\mathbf{k}\mathbf{k}'\mathbf{q}}c^{\dagger}_{\mathbf{k}\uparrow}c^{\dagger}_{\mathbf{k}'+\mathbf{q}\downarrow}c_{\mathbf{k}'+\mathbf{q}\downarrow}c_{\mathbf{k}'\uparrow}$$

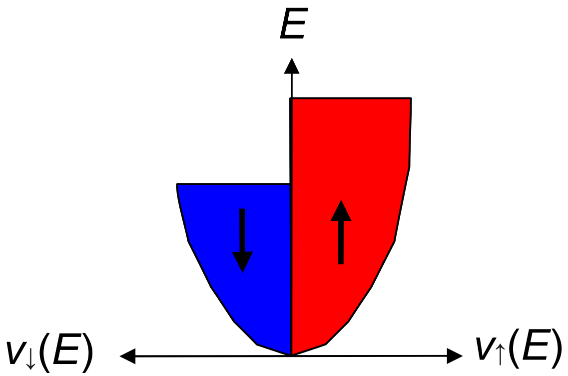
$$F=F_0+\frac{1-g\nu}{2\nu}m^2+um^4$$

- A Fermi surface shift increases the kinetic energy and potential energy falls
- Ferromagnetic transition occurs if $g\nu>1$

Not magnetised



Partially magnetised



Conduit & Simons, Phys. Rev. A **79**, 053606 (2009)

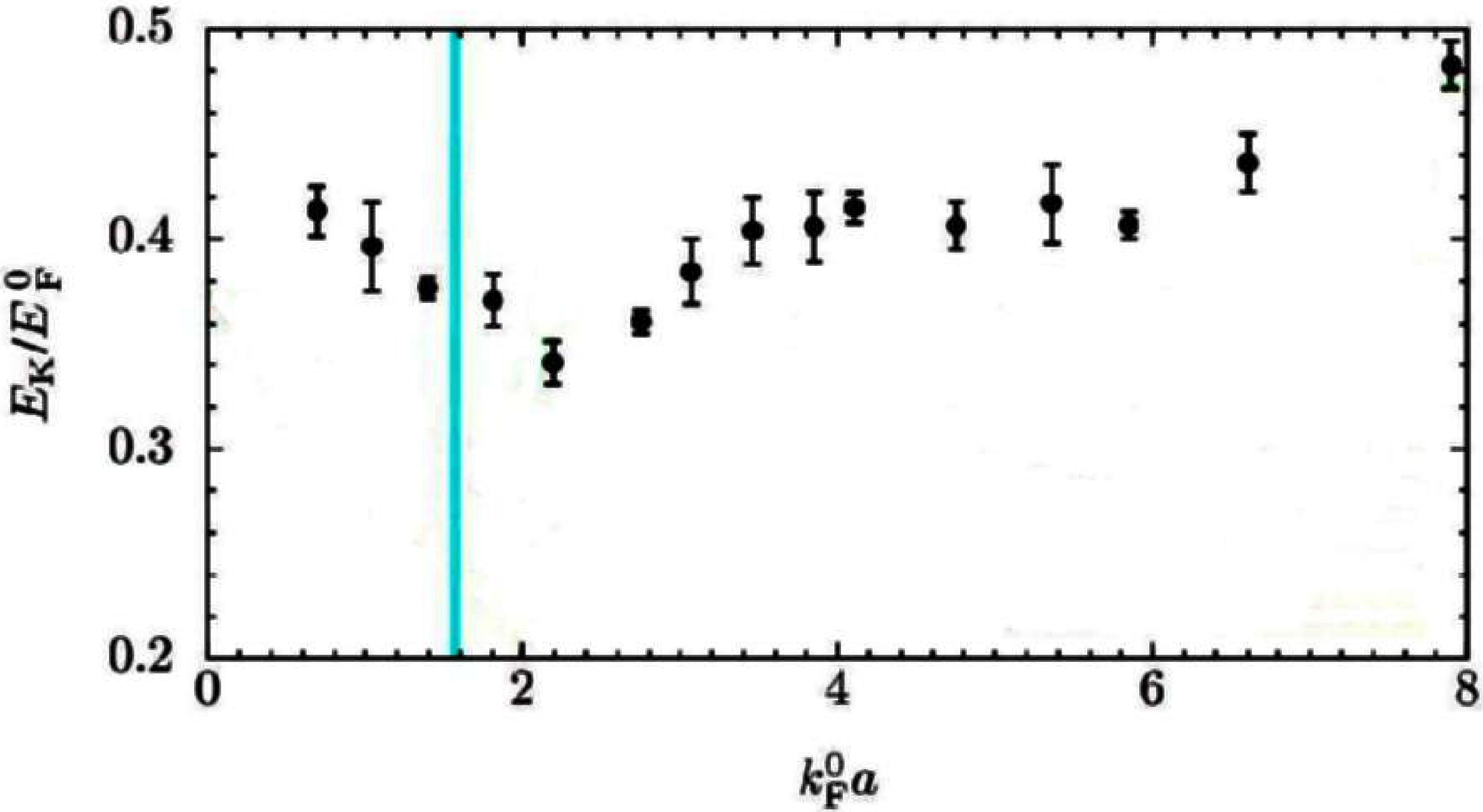
Jo, Lee, Choi, Christensen, Kim, Thywissen, Pritchard & Ketterle, Science **325**, 1521 (2009)

Why study ferromagnetism with cold atoms?

- Key experimental advantages
  - Feshbach resonance
  - Clean system
  - True contact interaction
- Answer long-standing questions from the solid state
  - Is the ferromagnetic phase stable?
  - Is the transition first or second order?
  - Are there exotic phases near to the tricritical point?
- New physics
  - Two and one-dimensional ferromagnetism
  - Effects of population and mass imbalance
  - Non-equilibrium magnetism

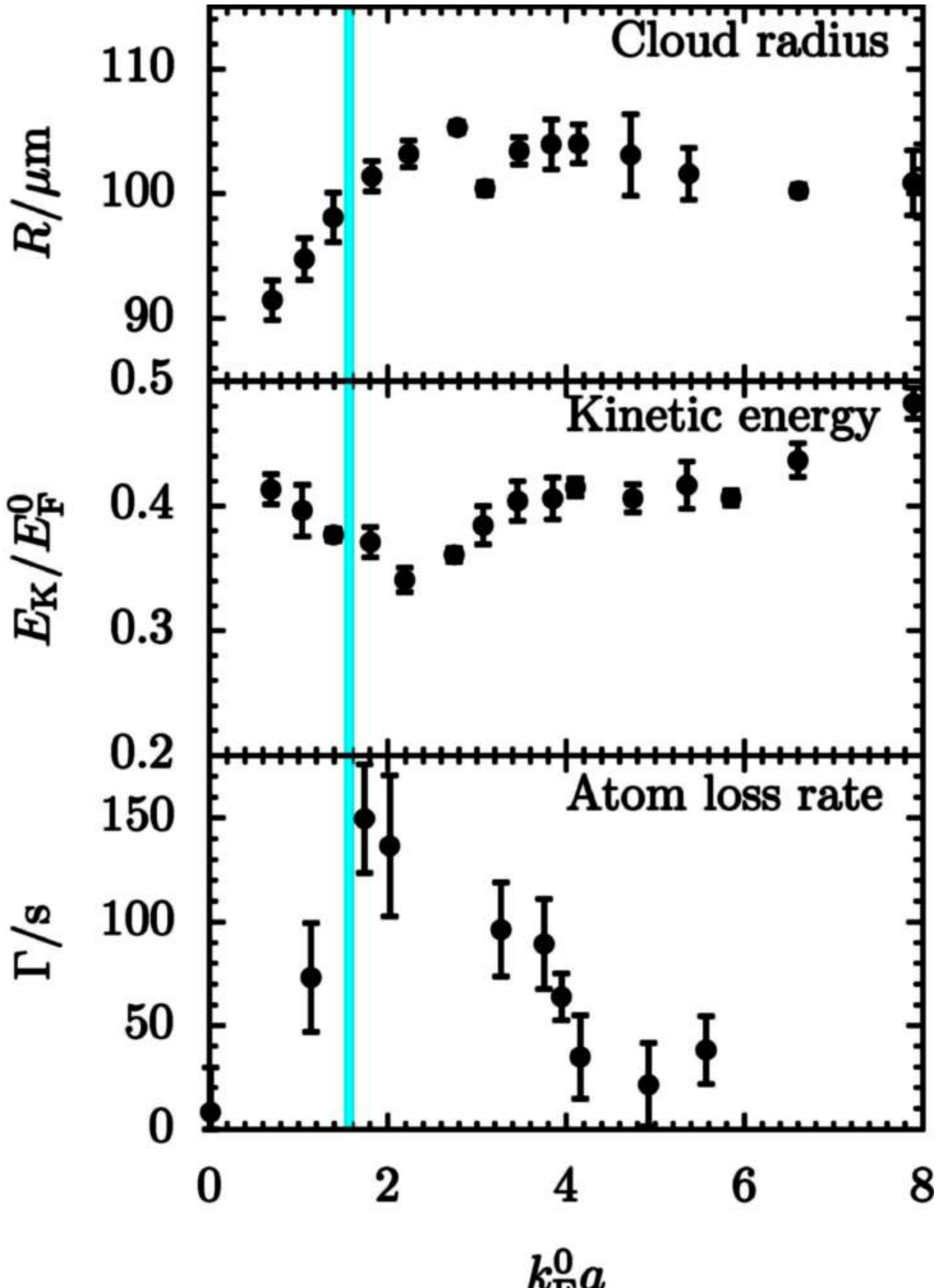
Experimental evidence for ferromagnetism

- Minimum in kinetic energy at $k_F a \approx 2.2$



Jo, Lee, Choi, Christensen, Kim, Thywissen, Pritchard & Ketterle, Science **325**, 1521 (2009)

Further key experimental signatures



$$E_K \propto n^{5/3}$$

$$\Gamma \propto (k_F a)^6 n_\uparrow n_\downarrow (n_\uparrow + n_\downarrow)$$

Jo, Lee, Choi, Christensen, Kim, Thywissen, Pritchard & Ketterle, Science **325**, 1521 (2009)

Outline

- Equilibrium analysis with mean field & fluctuation corrections
  - Fluctuation corrections lead to emergence of first order transition
- Stoner transition in the presence of atom loss
  - Condensation of topological defects
  - Renormalization of interaction strength
- Experimental protocols that circumvent three-body loss
  - Collective modes within a spin spiral

Equilibrium study of ferromagnetism

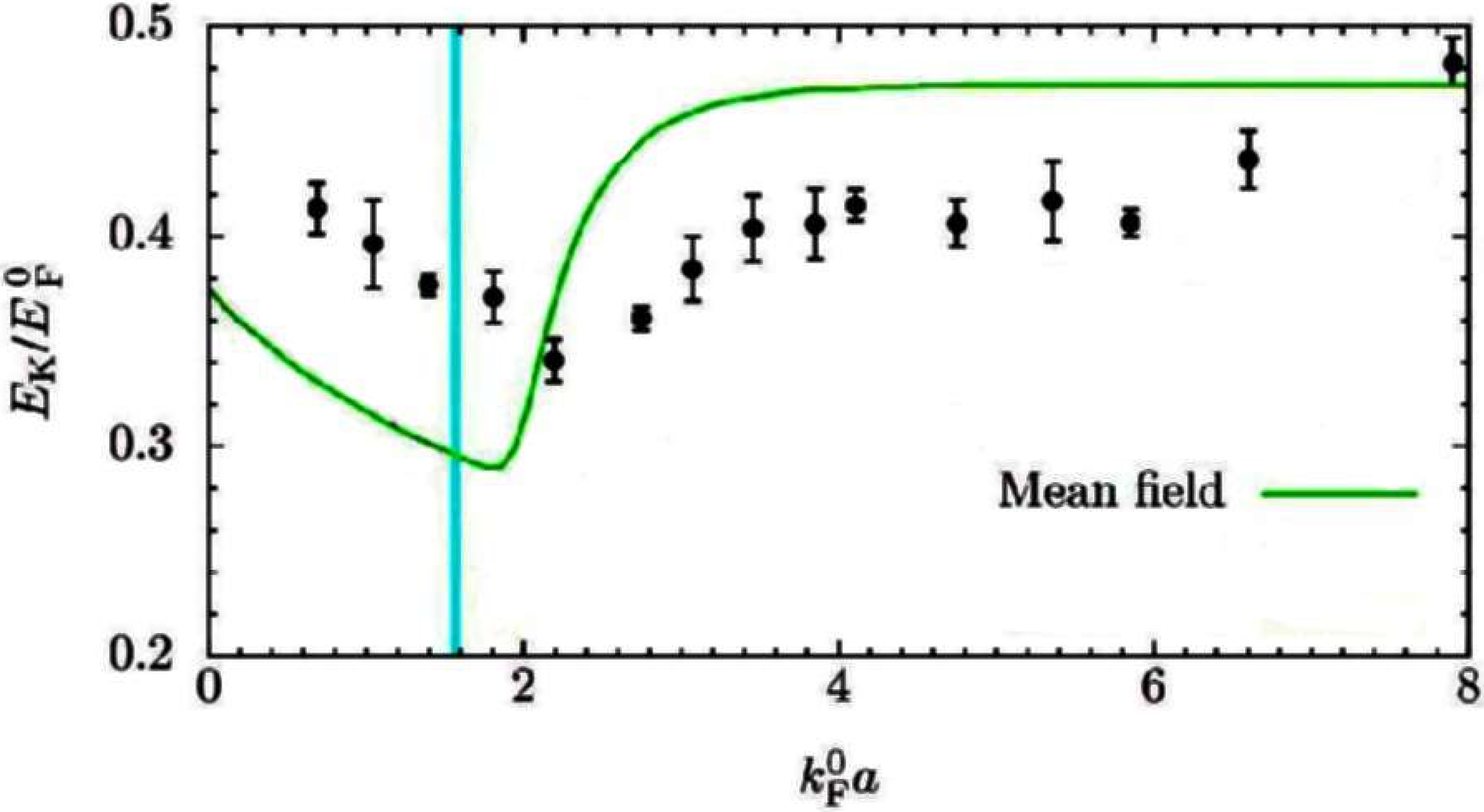
$$Z=\int D\psi \exp\left(-\iint d\tau\, d\boldsymbol{r} \sum_{\sigma} \bar{\psi}_{\sigma}(-i\hat{\omega}+\hat{\epsilon}-\mu)\psi_{\sigma}-g\bar{\psi}_{\uparrow}\bar{\psi}_{\downarrow}\psi_{\downarrow}\psi_{\uparrow}\right)$$

- Decouple with the average magnetisation *m* gives the Stoner criterion

$$F=F_0+\frac{1-g\nu}{2\nu}m^2+um^4+vm^6$$

Mean-field analysis & consequences of trap

- Recovers qualitative behavior[1] but transition at $k_F a$=1.8 instead of $k_F a$=2.2



[1]LeBlanc, Thywissen, Burkov & Paramekanti, Phys. Rev. A **80**, 013607 (2009) & Conduit & Simons, Phys. Rev. Lett. **103**, 200403 (2009)

Fluctuation corrections

$$Z=\int D\psi \exp\left(-\iint d\tau\, d\mathbf{r} \sum_{\sigma} \bar{\psi}_{\sigma}(-i\hat{\omega}+\hat{\epsilon}-\mu)\psi_{\sigma} - g\,\bar{\psi}_{\uparrow}\bar{\psi}_{\downarrow}\psi_{\downarrow}\psi_{\uparrow}\right)$$

- Integrate over fluctuations in magnetization and density and develop a perturbation theory in interaction strength

$$F=F_0+\frac{1-g\nu}{2\nu}m^2+um^4+vm^6+g^2\left(r\,m^2+w\,m^4\ln|m|\right) \qquad k_{\mathrm{F}}a_{\mathrm{crit}}=1.05$$

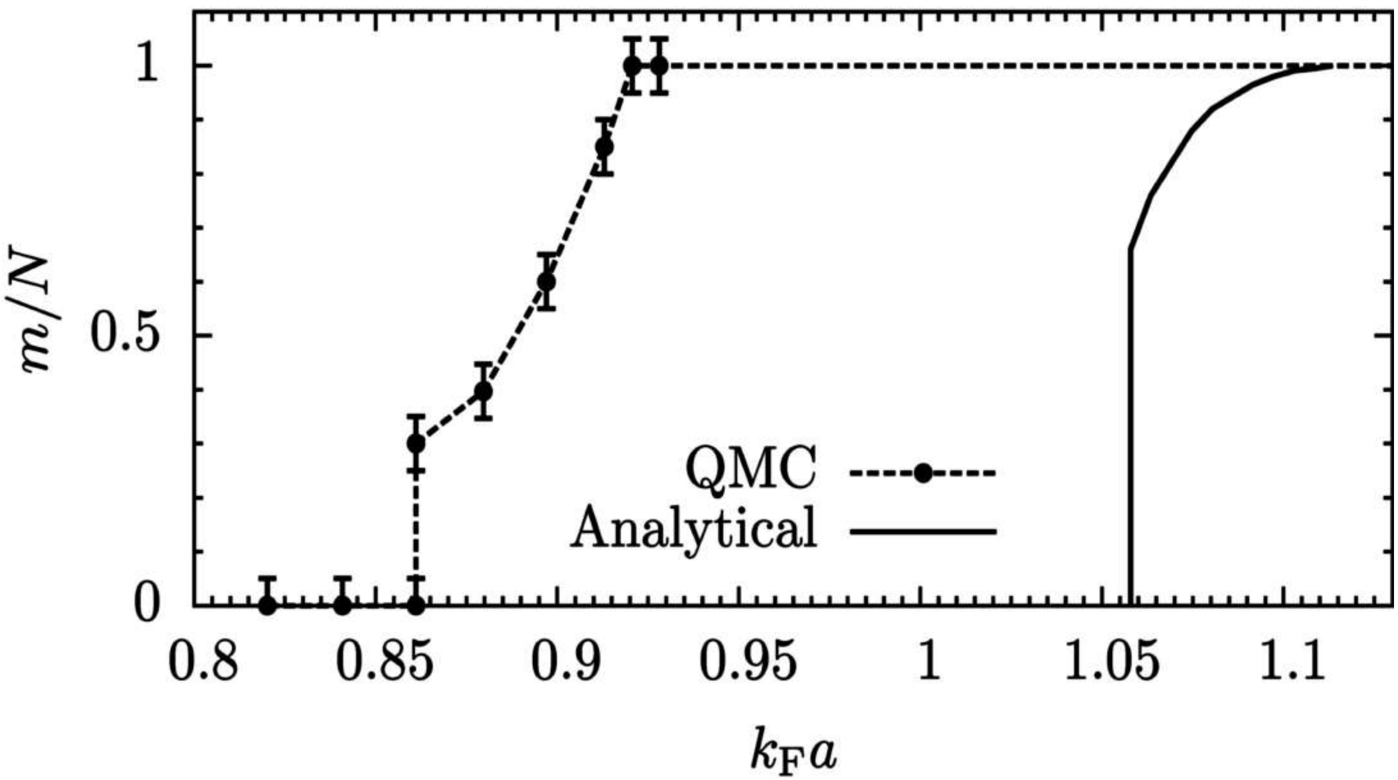
- First order transition[1]

[1]Abrikosov (1958), Duine & MacDonald (2005), Belitz *et al*. Z. Phys. B (1997) & Conduit & Simons (2009)

Quantum Monte Carlo verification

$$F = F_0 + \frac{1-gv}{2v} m^2 + um^4 + vm^6 + g^2\left(r\,m^2 + w\,m^4 \ln|m|\right) \qquad k_F a_{crit} = 1.05$$

- Verified by *ab initio* Quantum Monte Carlo calculations[1]

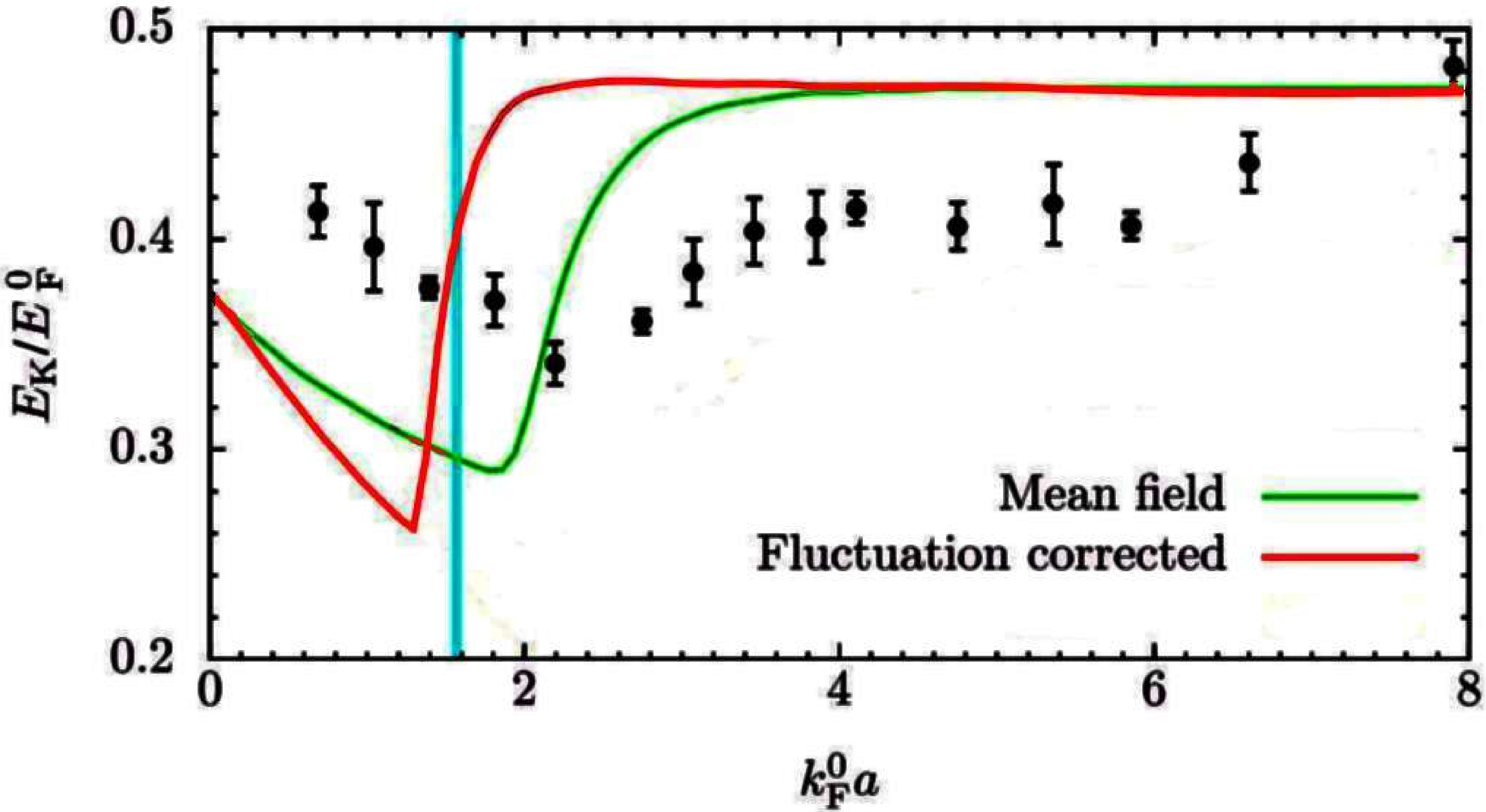


[1]Conduit & Simons, Phys. Rev. Lett. **103**, 200403 (2009)

Chang, Randeria & Trivedi, arXiv:1004.2680, Pilati, Bertaina, Giorgini & Troyer arXiv:1004.1169

Fluctuation corrections

- Fluctuation corrections encourage ferromagnetism



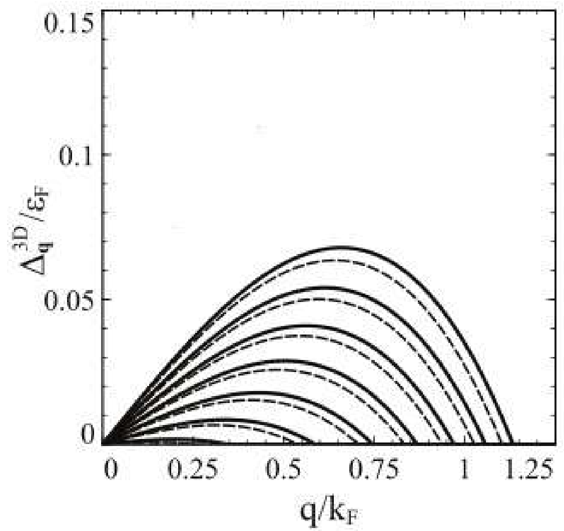
Conduit & Simons, Phys. Rev. A **79**, 053606 (2009) &
Conduit & Simons, Phys. Rev. Lett. **103**, 200403 (2009)

Outline: three-body loss

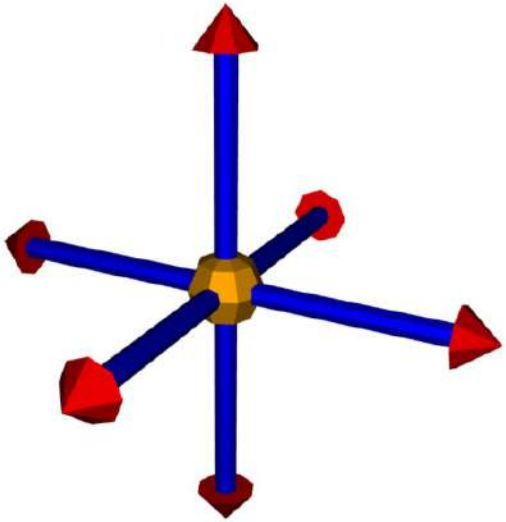
- Equilibrium analysis with mean field & fluctuation corrections
  - Fluctuation corrections lead to emergence of first order transition
- The Stoner transition in the presence of atom loss
  - Condensation of topological defects
  - Renormalization of interaction strength
- Experimental protocols that circumvent three-body loss
  - Collective modes within a spin spiral

Initial growth of domains

- Quench leads to domain growth [Babadi *et al*. arXiv:0908.3483], applies for $k_F a < 1.06 k_F a_c$



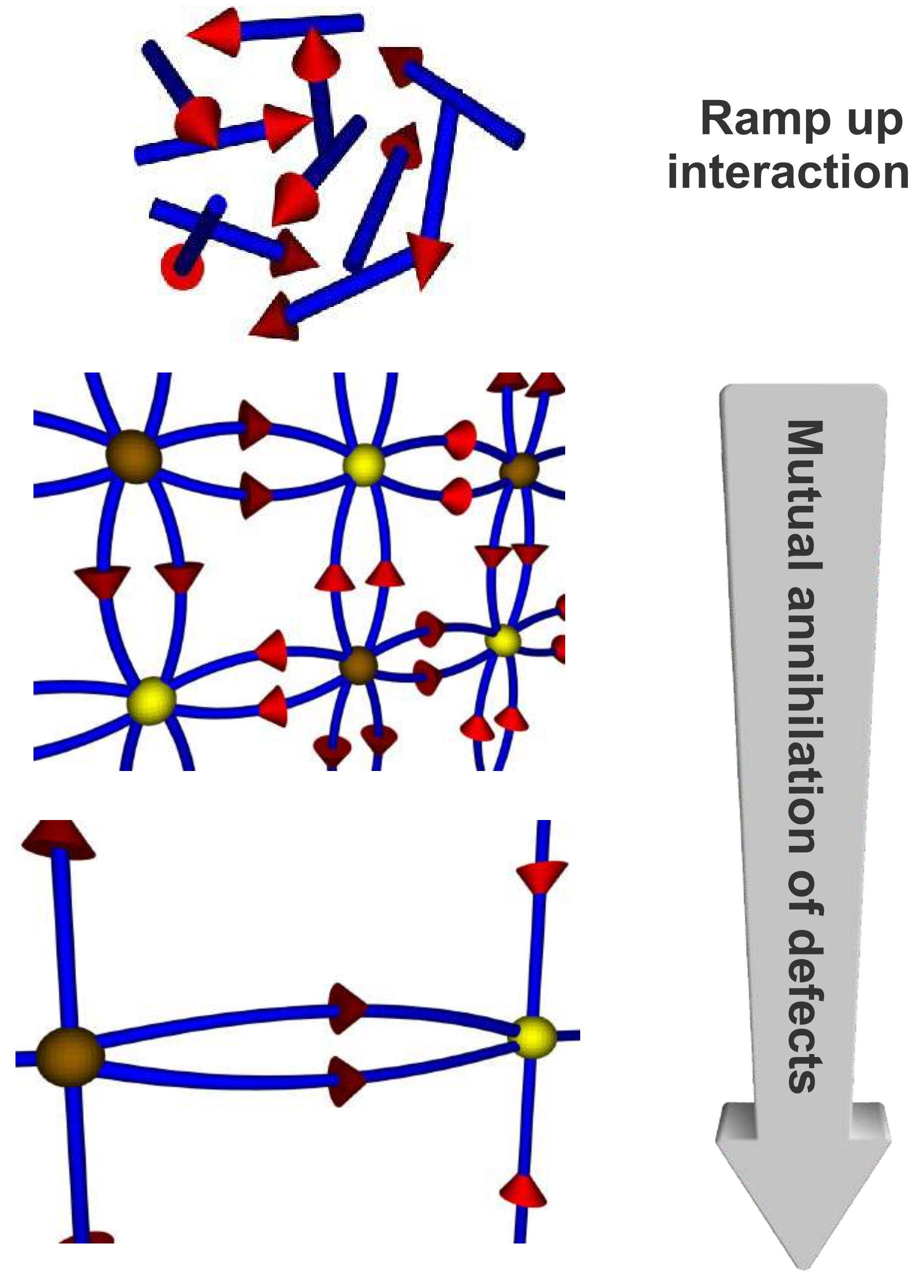
- Ferromagnetic quench *deep* beyond the spinoidal line leads to the condensation of topological defects



Condensation of topological defects

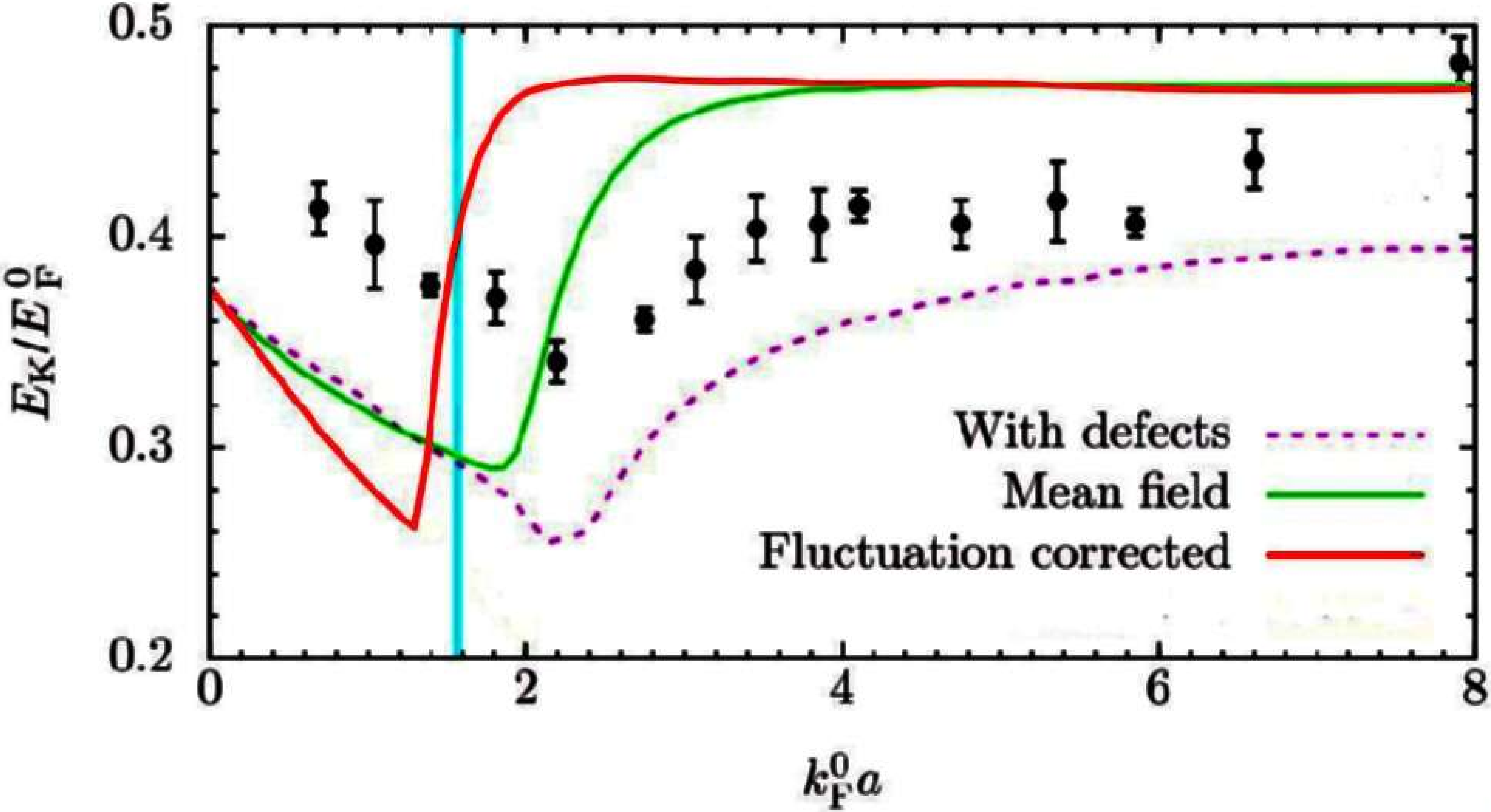
- Defects freeze out from paramagnetic state

- Defects grow as $L \sim t^{½}$
  [Bray, Adv. Phys. **43**, 357 (1994)]



Consequences of defect annihilation

- Defect annihilation raises required interaction strength

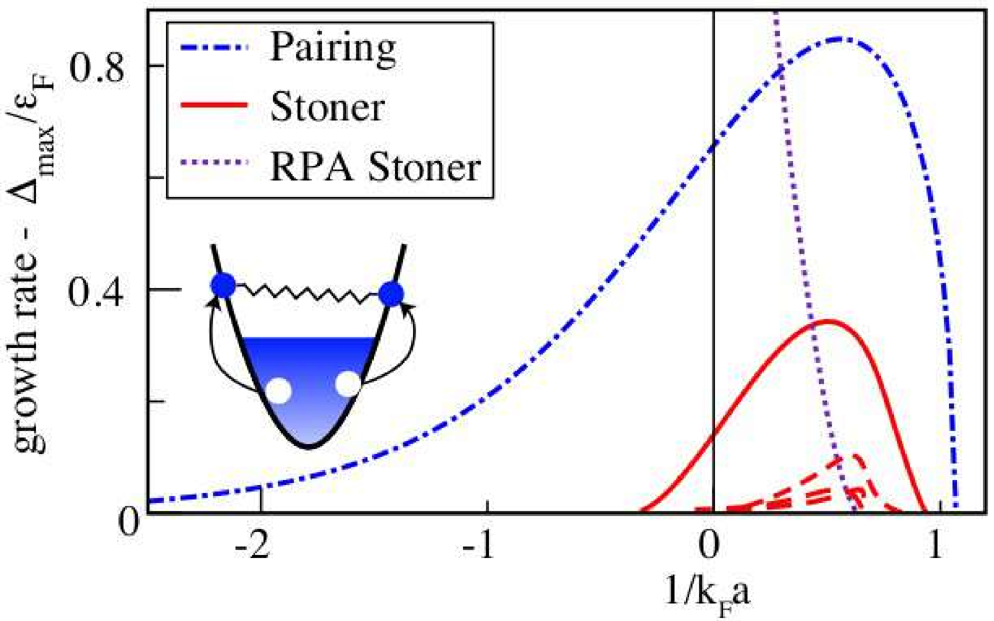


Conduit & Simons, Phys. Rev. Lett. **103**, 200403 (2009), Babadi *et al*. arXiv 0908.3482 (2009)

Two versus three-body loss

Two-body mechanism

- Feshbach molecules can be formed by a two body process [Pekker, unpublished]
- Requires $k_F^2/m<1/2ma^2$, $k_F a<1/\sqrt{2}$



Three-body mechanism

- A third-body can remove the excess energy
- Rate $\lambda'[n_\uparrow(\mathbf{r}) + n_\downarrow(\mathbf{r})]n_\uparrow(\mathbf{r})n_\downarrow(\mathbf{r})$ [Petrov 2003]
- In boson systems, three-body scattering drives the formation of a Tonks-Girardeau gas [Syassen *et al*., Science **320**, 1329 (2009)]

Damping of fluctuations by atom loss

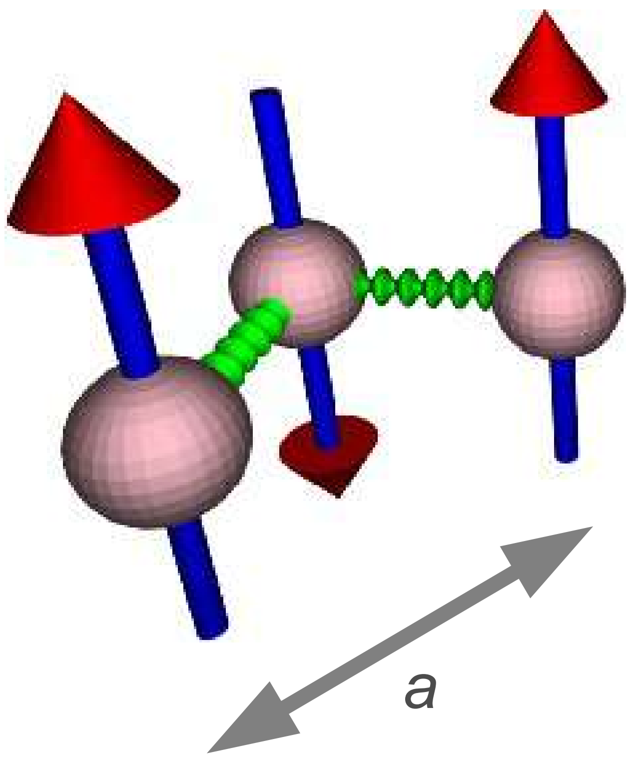
- Atom loss rate, $\lambda'[n_\uparrow(\mathbf{r}) + n_\downarrow(\mathbf{r})]n_\uparrow(\mathbf{r})n_\downarrow(\mathbf{r})$, is

  $\lambda'\chi(\mathbf{r}-\mathbf{r}')[c_\uparrow^\dagger(\mathbf{r}')c_\uparrow(\mathbf{r}') + c_\downarrow^\dagger(\mathbf{r}')c_\downarrow(\mathbf{r}')]c_\uparrow^\dagger(\mathbf{r})c_\downarrow^\dagger(\mathbf{r})c_\downarrow(\mathbf{r})c_\uparrow(\mathbf{r})$

- A mean-field approximation, $\overline{N} = n_\uparrow(\mathbf{r}') + n_\downarrow(\mathbf{r}')$ places interactions on same footing as interactions

  $S_{\text{int}} = (g + i\lambda\overline{N})c_\uparrow^\dagger(\mathbf{r})c_\downarrow^\dagger(\mathbf{r})c_\downarrow(\mathbf{r})c_\uparrow(\mathbf{r})$

- Also include atom source $-i\gamma c_\sigma^\dagger c_\sigma$ to ensure gas remains at equilibrium

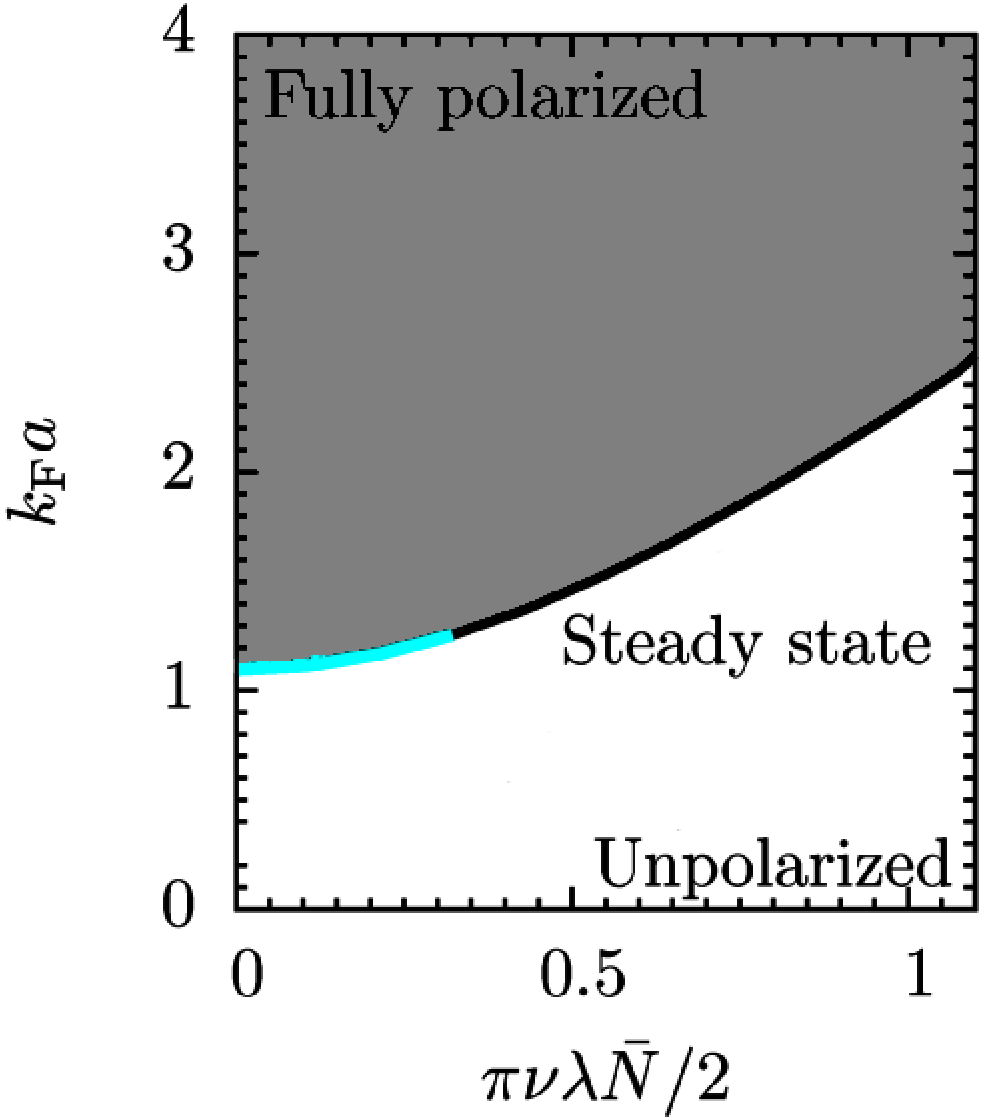


- Loss damps fluctuations so inhibits the transition

$$F = F_0 + \frac{1-g\nu}{2\nu} m^2 + u m^4 + v m^6 + \left(g^2 - \lambda^2 \overline{N}^2\right)\left(r m^2 + w m^4 \ln|m|\right)$$

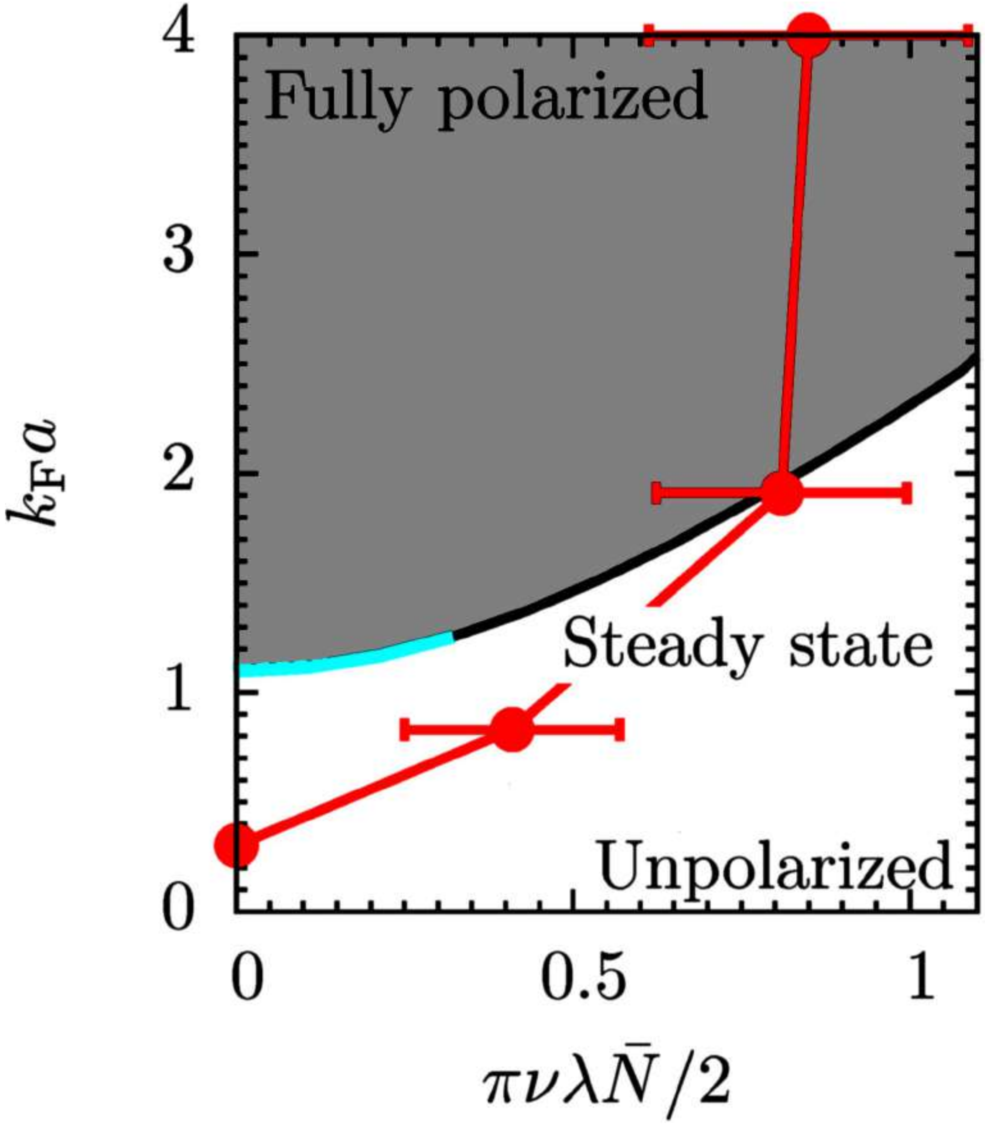
Phase boundary with atom loss

- Atom loss raises the interaction strength required for ferromagnetism



Conduit & Altman, arXiv: 0911.2839

Interaction renormalization with atom loss



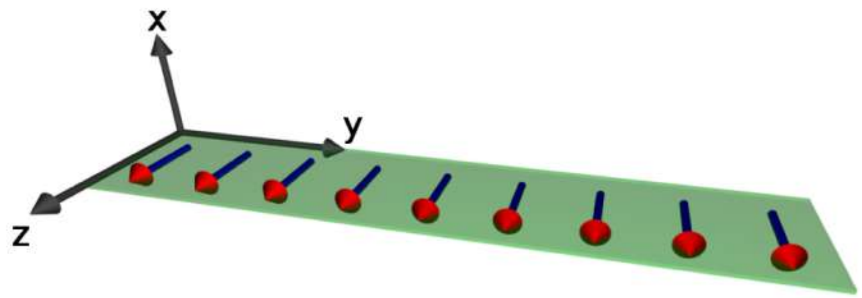
Conduit & Altman, arXiv: 0911.2839; Huckans *et al*. PRL **102**, 165302 (2009)

Outline: evolution of a spin spiral

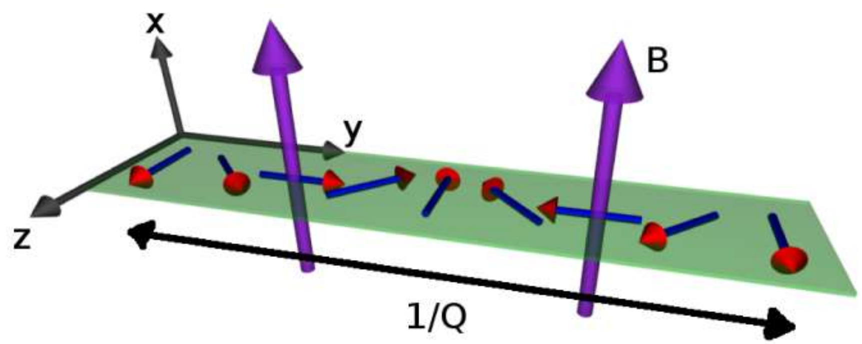
- Equilibrium analysis with mean field & fluctuation corrections
  - Fluctuation corrections lead to emergence of first order transition
- The Stoner transition in the presence of atom loss
  - Condensation of topological defects
  - Renormalization of interaction strength
- New experimental protocol to circumvent three-body loss
  - Collective modes within a spin spiral

Alternative strategy: spin spiral

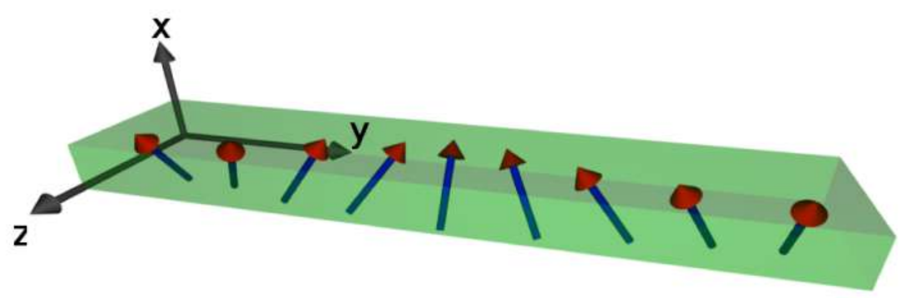
(a) Fully polarized state



(b) Applied magnetic field forms spin spiral



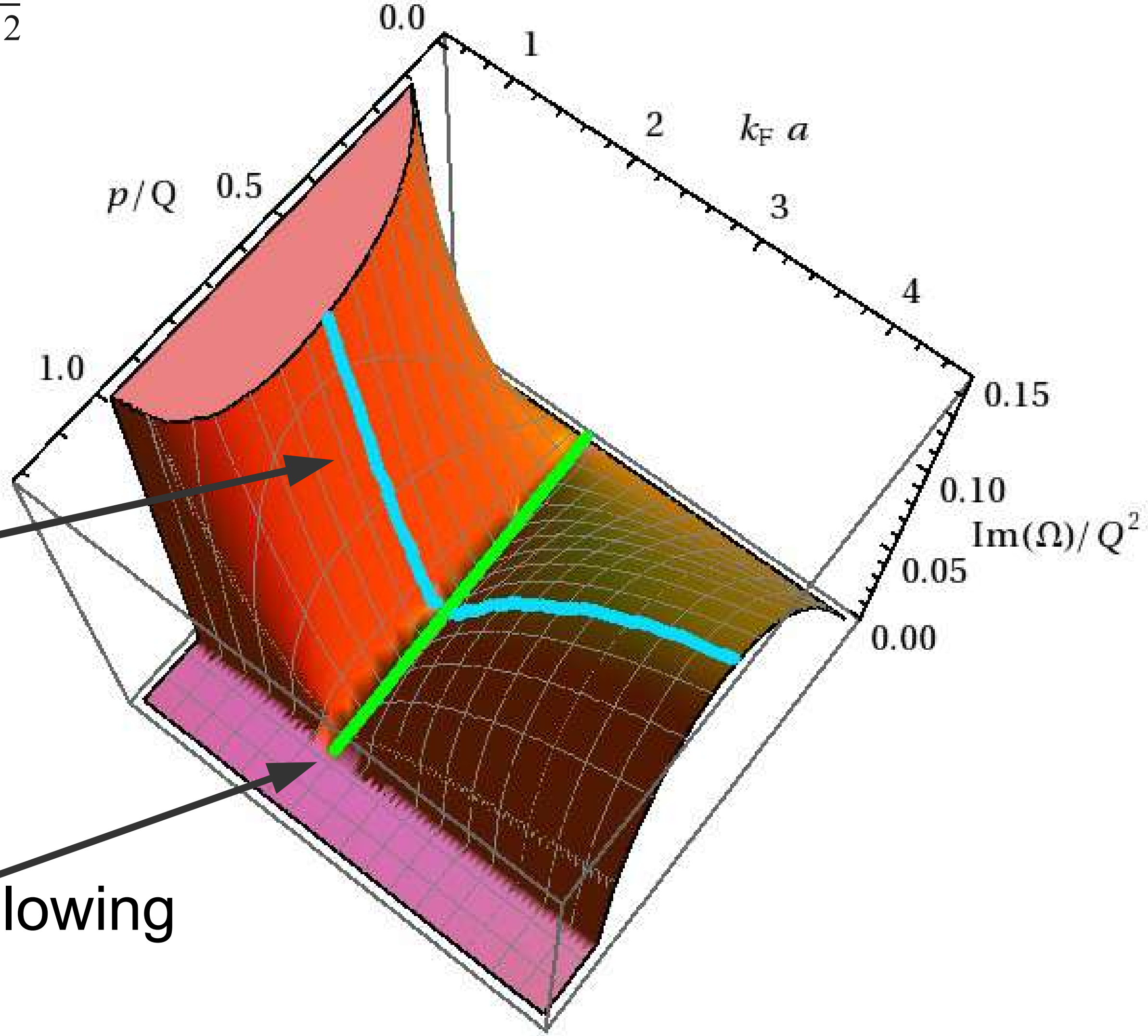
(c) Interactions cant the spiral



Spin spiral collective modes

- Exponentially growing collective modes if $p<Q$

$$\Omega(p)=\pm\left(\frac{1}{2}-\frac{2^{2/3}3}{5k_F a}\right)p\sqrt{p^2-Q^2}$$

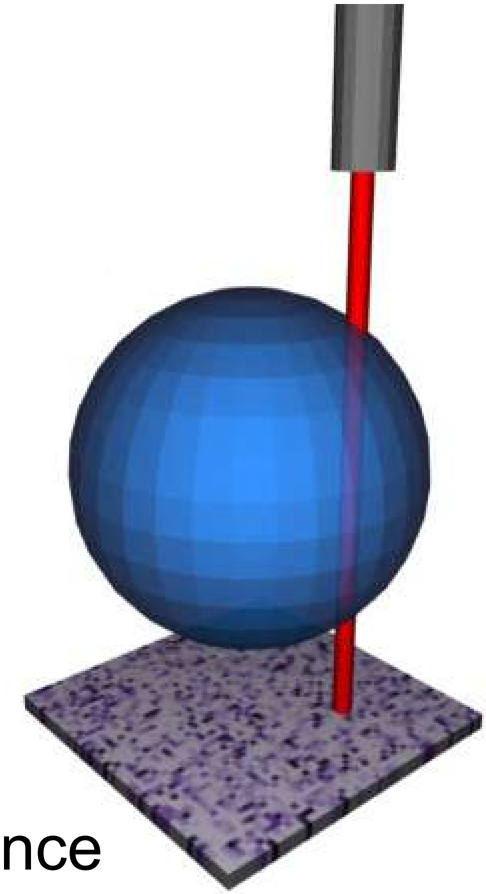


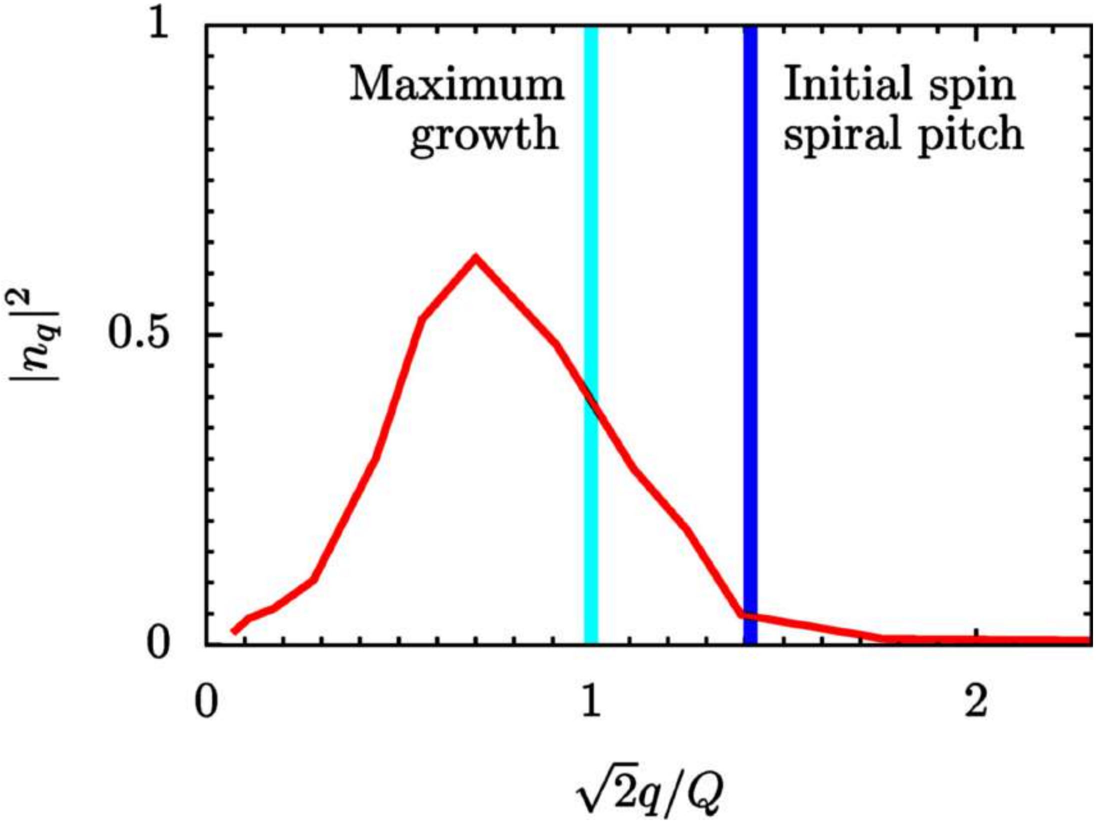
Maximum growth at p=Q/√2

Critical slowing

Phase-contrast imaging

- Phase-contrast imaging displays signatures of domain growth
- Domain size fixed across the sample





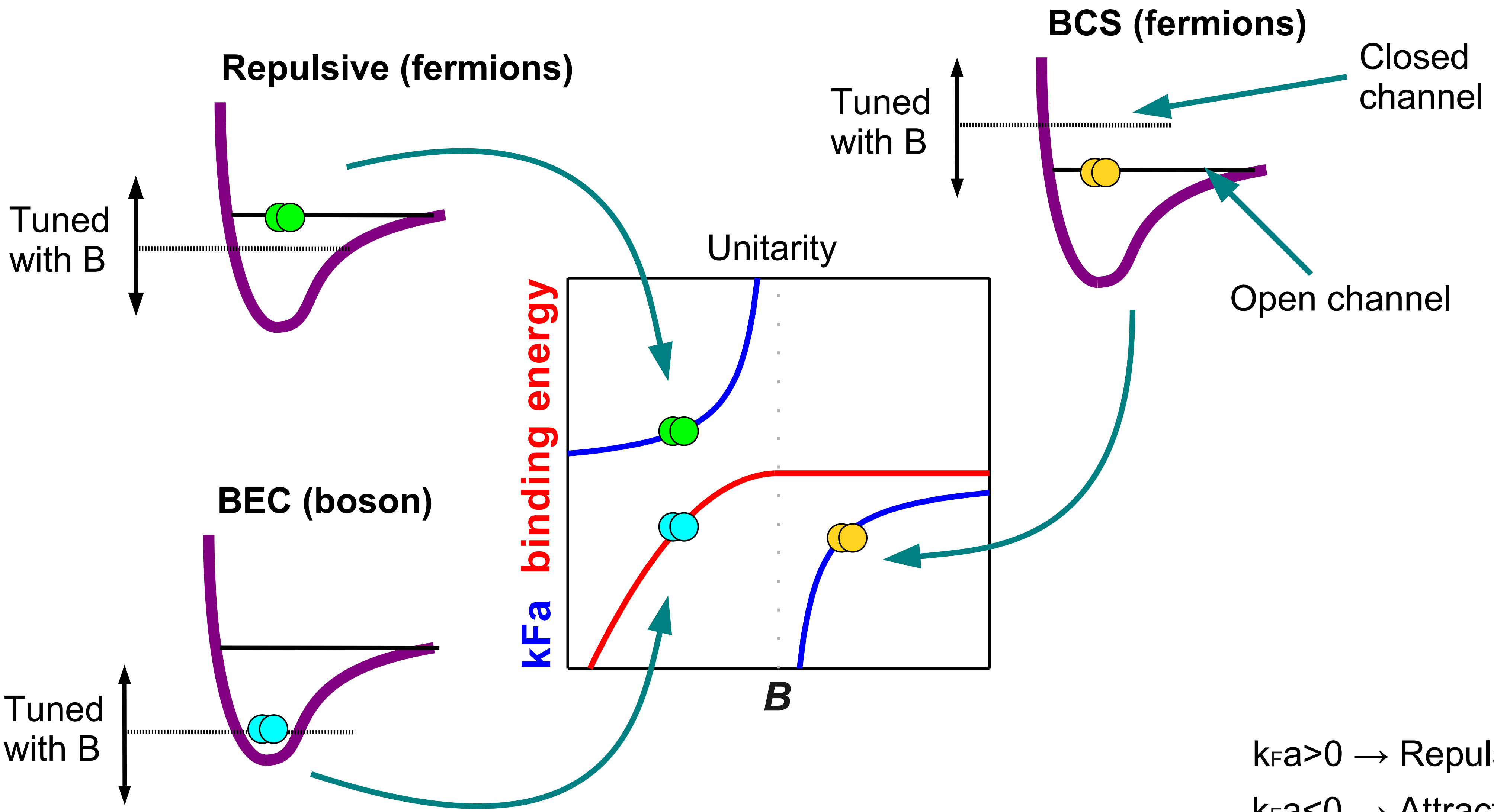
Summary

- Equilibrium theory provides a reasonable qualitative description of the transition
- Discrepancy in the interaction strength could be accounted for by:

1) Non-equilibrium formation of the ferromagnetic phase
2) Renormalization of interaction strength due to atom loss

- Circumvent three-body loss by studying the evolution of a spin spiral

Feshbach resonance

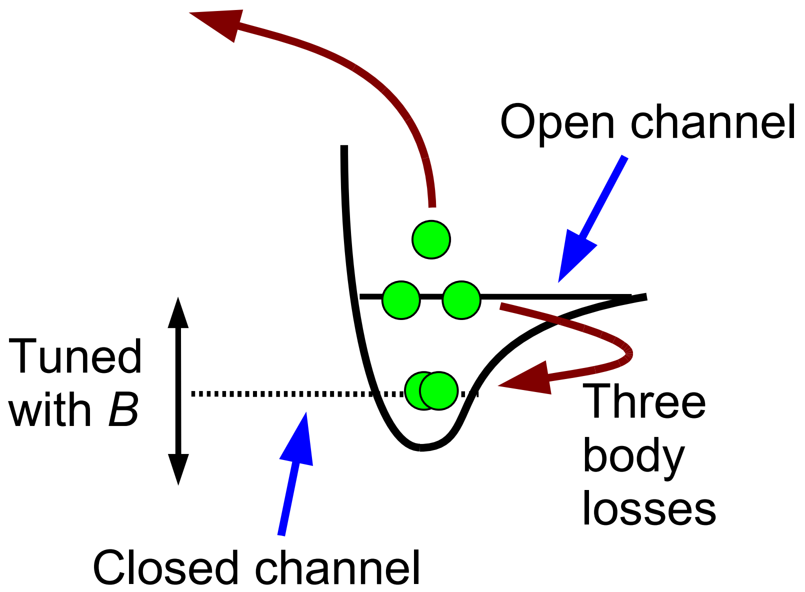


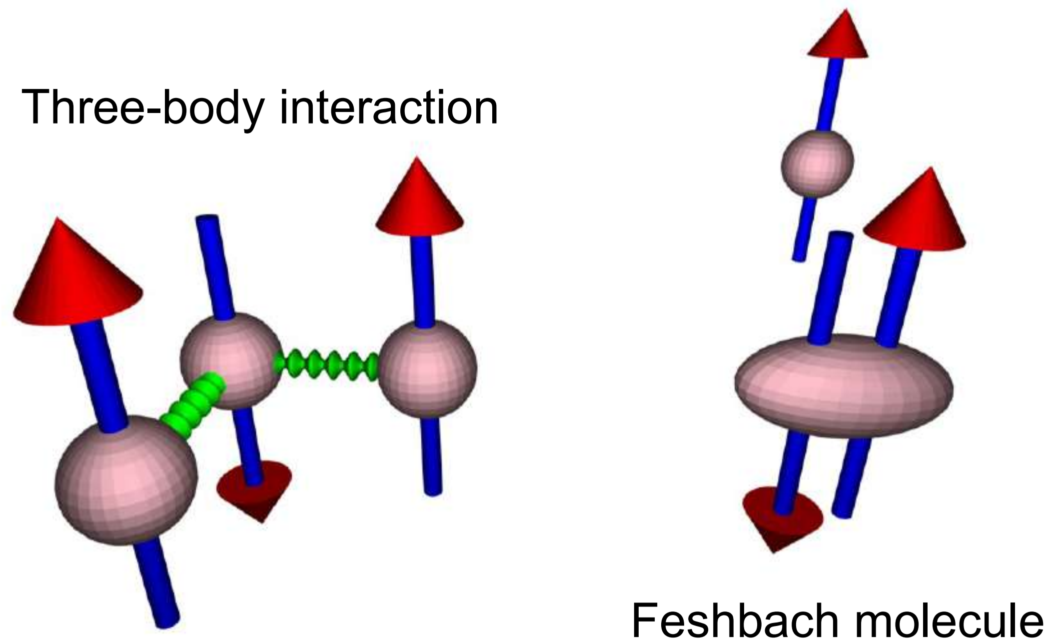
$k_F a > 0 \rightarrow$ Repulsive

$k_F a < 0 \rightarrow$ Attractive

- Note instability to BEC molecular state on repulsive side of resonance

Three-body losses

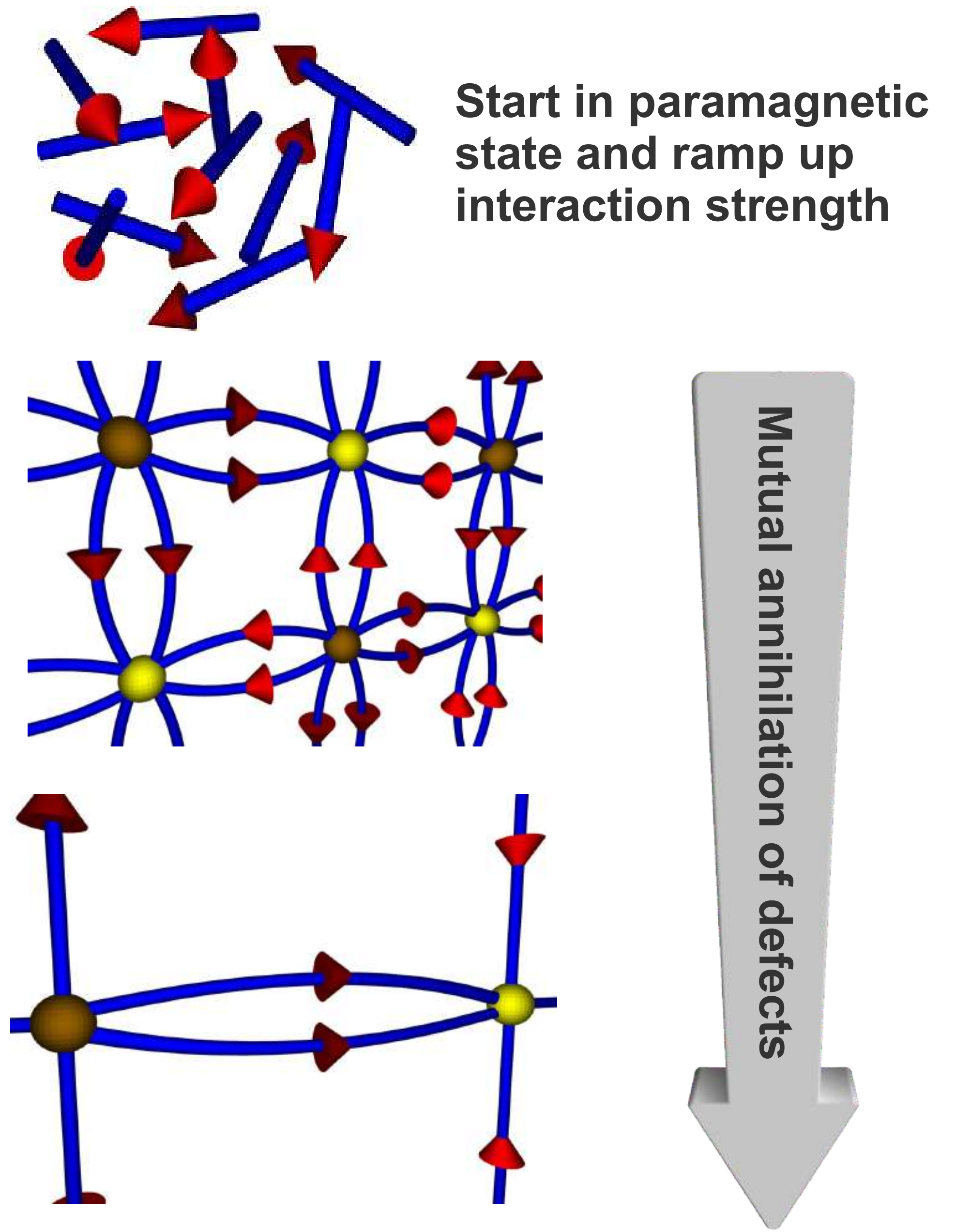




- In boson systems, three-body scattering drives the formation of a Tonks-Girardeau gas [Syassen *et al*., Science **320**, 1329 (2009)]
- The experiment is an opportunity to study not only ferromagnetism but also three-body loss and dynamics

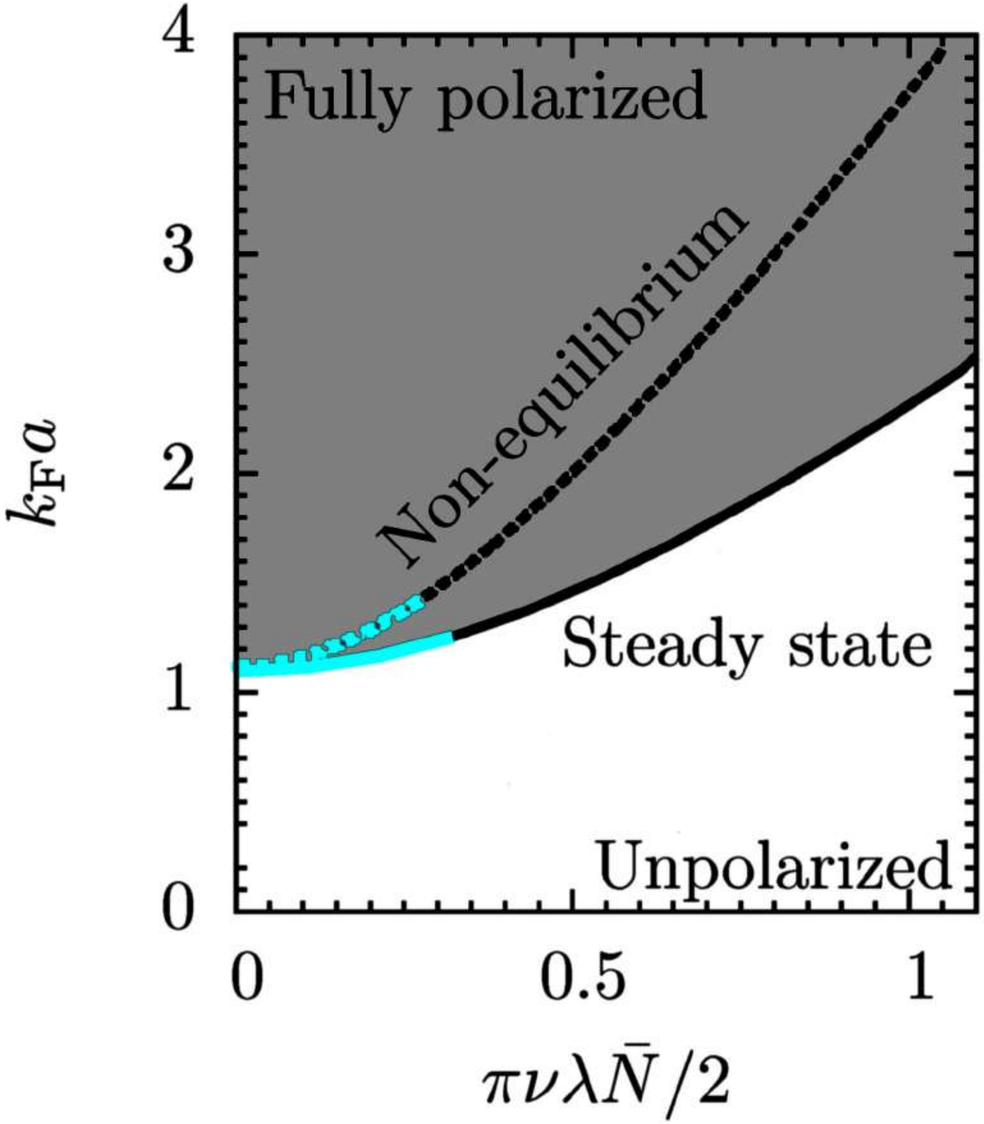
Condensation of topological defects

- Defects freeze out from disordered state
- Defect annihilation hinders the formation of the ferromagnetic phase thus raising the required interaction strength
- Defect radius $L \sim t^{1/2}$ [Bray, Adv. Phys. **43**, 357 (1994)]



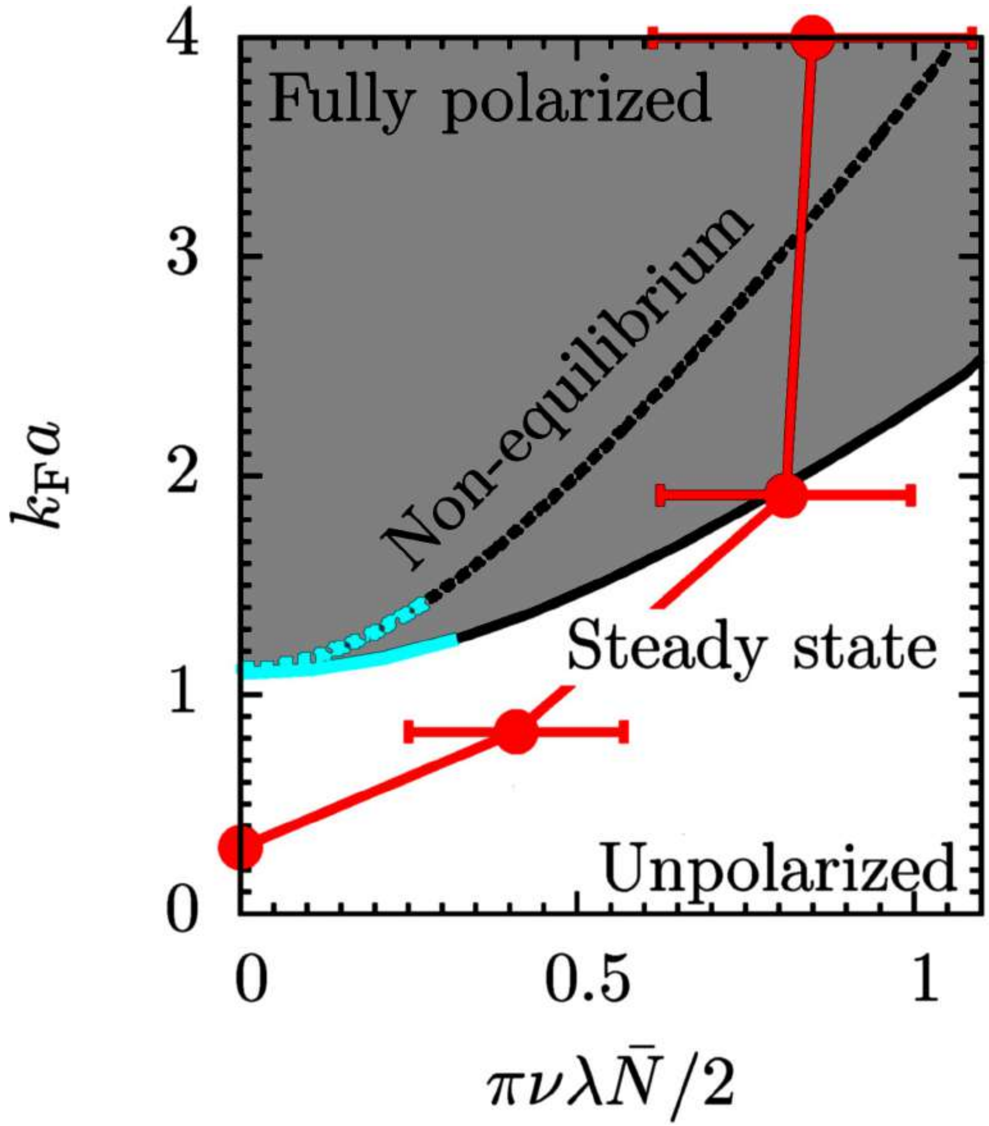
Phase boundary with atom loss

- Atom loss raises the interaction strength required for ferromagnetism



Conduit & Altman, arXiv: 0911.2839

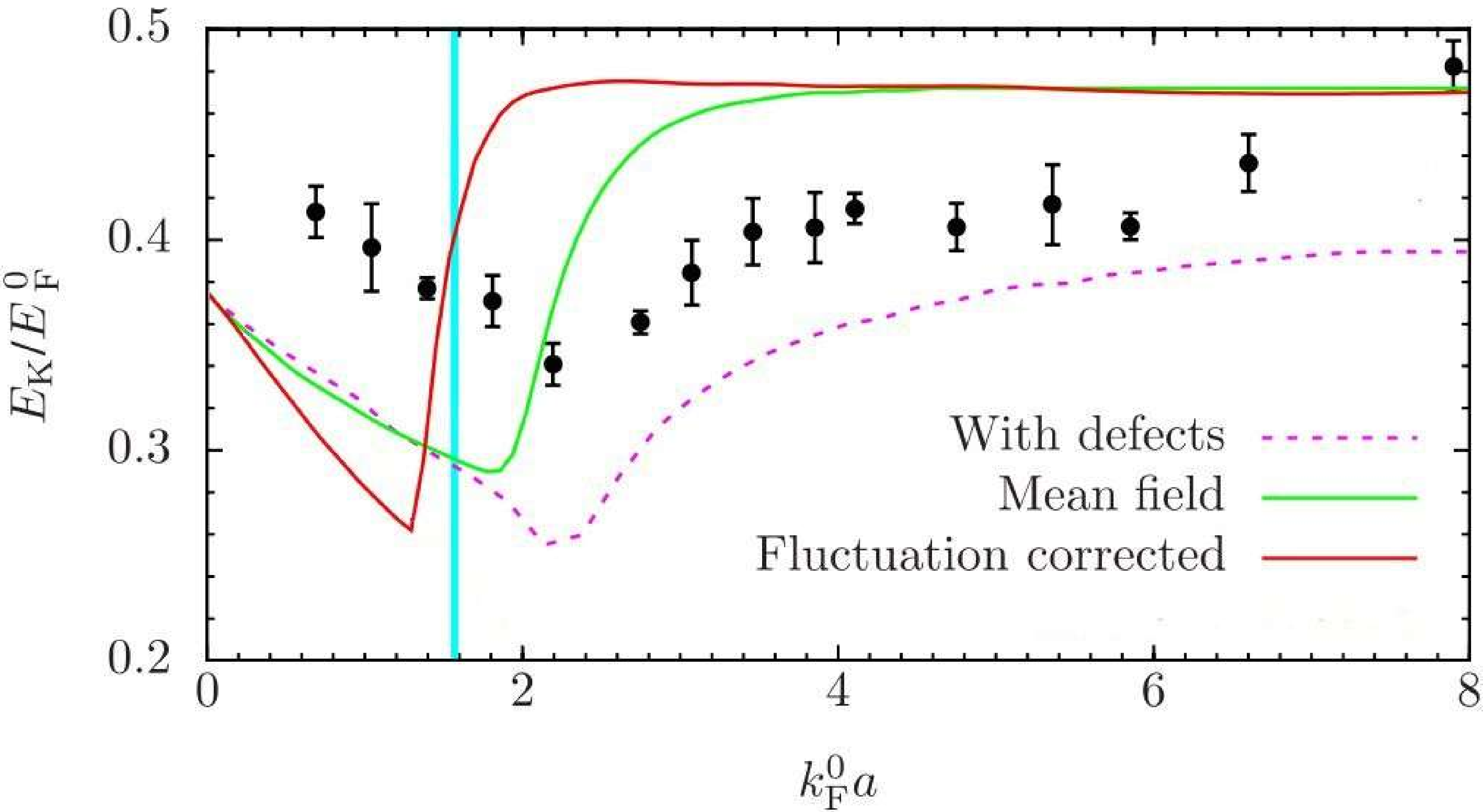
Interaction renormalization with atom loss



Conduit & Altman, arXiv: 0911.2839; Huckans *et al*. PRL **102**, 165302 (2009)

Condensation of topological defects

- Condensation of defects inhibits the transition



Conduit & Simons, Phys. Rev. Lett. **103**, 200403 (2009)

First order phase transition and Quantum Monte Carlo verification

- First order transition into uniform phase with TCP

- QMC also sees first order transition

Summary of equilibrium results

Momentum distribution

New approach to fluctuation corrections

$$Z=\int D\psi \exp\left(-\int \sum_{\sigma} \bar{\psi}_{\sigma}(-i\omega+\epsilon-\mu)\psi_{\sigma}-g\int \bar{\psi}_{\uparrow}\bar{\psi}_{\downarrow}\psi_{\downarrow}\psi_{\uparrow}\right)$$

- Analytic strategy:

  1) Decouple in both the density and spin channels (previous approaches employ only spin)

  2) Integrate out electrons

  3) Expand about uniform magnetisation

  4) Expand density and magnetisation fluctuations to second order

  5) Integrate out density and magnetisation fluctuations

- Aim to uncover connection to second order perturbation theory
- Unravel origin of logarithmic divergence in energy and relation to tricritical point structure

Analytical method

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

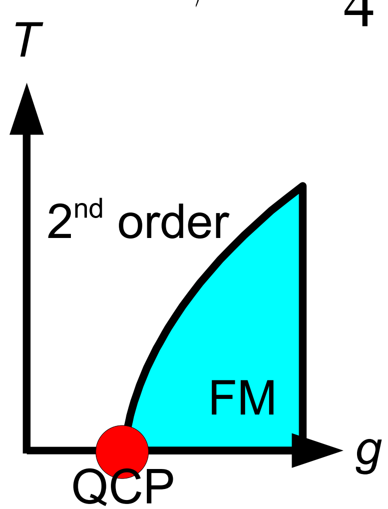
$$Z=\int D\psi \exp\left(-\int \sum_\sigma \bar{\psi}_\sigma(-i\omega+\epsilon-\mu)\psi_\sigma - g\int \bar{\psi}_\uparrow \bar{\psi}_\downarrow \psi_\downarrow \psi_\uparrow\right)$$

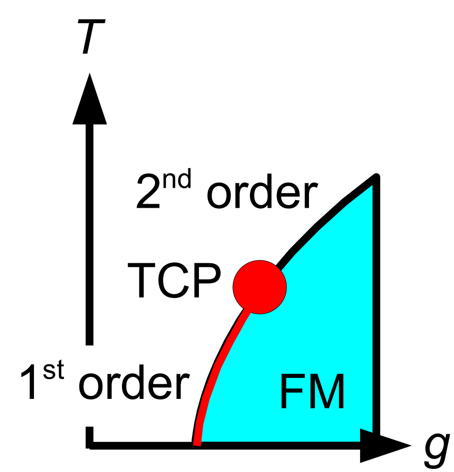
- Decouple using only the average magnetisation $m=\bar{\psi}_\downarrow \psi_\uparrow - \bar{\psi}_\uparrow \psi_\downarrow$

  gives $F \propto (1-g\nu)m^2$ i.e. the Stoner criterion

- Belitz-Kirkpatrick-Vojta (soft particle-hole & magnetisation) [Belitz *et al.* Z. Phys. B 1997]

$$F=\frac{1}{2}\left(|\omega|/\Gamma_q+r+q^2\right)m^2+\frac{u}{4}m^4\ln(m^2+T^2)+\cdots-hm$$





Quantum Monte Carlo verification

- First order transition into uniform phase with TCP

- QMC also sees first order transition

Cold atomic gases — spin

- Two fermionic atom species have a *pseudo-spin*:

^{6}Li	$m_F=1/2$	maps to	spin 1/2
^{6}Li	$m_F=-1/2$	maps to	spin -1/2

- The up-and down spin particles *cannot* interchange — population imbalance is fixed. Possible spin states are:

$\left\|\uparrow\uparrow\right\rangle$	$S=1$, $S_z=1$	State not possible as S_z has changed
$\left\|\downarrow\downarrow\right\rangle$	$S=1$, $S_z=-1$	State not possible as S_z has changed
$\left(\left\|\uparrow\downarrow\right\rangle+\left\|\downarrow\uparrow\right\rangle\right)/\sqrt{2}$	$S=1$, $S_z=0$	Magnetic moment in plane
$\left(\left\|\uparrow\downarrow\right\rangle-\left\|\downarrow\uparrow\right\rangle\right)/\sqrt{2}$	$S=0$, $S_z=0$	Non-magnetic state

- Ferromagnetism, if favourable, must form in-plane

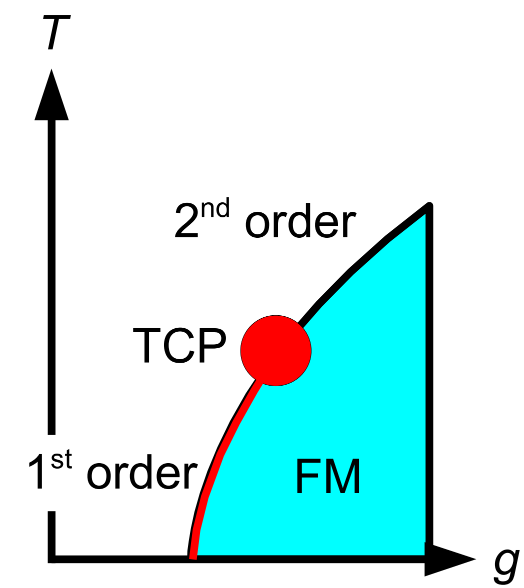
Particle-hole perspective

- To second order in *g* the free energy is

$$F=\sum_{\sigma,\boldsymbol{k}}\epsilon_{\boldsymbol{k}}^{\sigma}n(\epsilon_{\boldsymbol{k}}^{\sigma})+gN^{\uparrow}N^{\downarrow}$$

$$-\frac{2g^2}{V^3}\sum_{\boldsymbol{p}}\int\int\frac{\rho^{\uparrow}(\boldsymbol{p},\epsilon_{\uparrow})\rho^{\downarrow}(-\boldsymbol{p},\epsilon_{\downarrow})}{\epsilon_{\uparrow}+\epsilon_{\downarrow}}d\epsilon_{\uparrow}d\epsilon_{\downarrow}$$

$$+\frac{2g^2}{V^3}\sum_{\boldsymbol{k}_{1,2,3,4}}\frac{n(\epsilon_{\boldsymbol{k}_1}^{\uparrow})n(\epsilon_{\boldsymbol{k}_2}^{\downarrow})}{\epsilon_{\boldsymbol{k}_1}^{\uparrow}+\epsilon_{\boldsymbol{k}_2}^{\downarrow}-\epsilon_{\boldsymbol{k}_3}^{\uparrow}-\epsilon_{\boldsymbol{k}_4}^{\downarrow}}\delta(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{k}_3-\boldsymbol{k}_3)$$



with $\epsilon_{\boldsymbol{k}}^{\sigma}=\epsilon_{\boldsymbol{k}}+\sigma gm$ and a particle-hole density of states

$$\rho^{\sigma}(\boldsymbol{p},\epsilon)=\sum_{\boldsymbol{k}}n(\epsilon_{\boldsymbol{k}+\boldsymbol{p}/2}^{\sigma})\left[1-n(\epsilon_{\boldsymbol{k}-\boldsymbol{p}/2}^{\sigma})\right]\delta\left(\epsilon-\epsilon_{\boldsymbol{k}+\boldsymbol{p}/2}^{\sigma}+\epsilon_{\boldsymbol{k}-\boldsymbol{p}/2}^{\sigma}\right)$$

- Enhanced particle-hole phase space at zero magnetisation drives transition first order
- Recover $m^4\ln m^2$ at *T*=0
- Links quantum fluctuation to second order perturbation approach[1]

[1]Abrikosov 1958 & Duine & MacDonald 2005

Quantum Monte Carlo: Textured phase

- Textured phase preempted transition with $q=0.2k_F$

***T*=0**

Modified collective modes

- Collective mode dispersion

- Collective mode damping