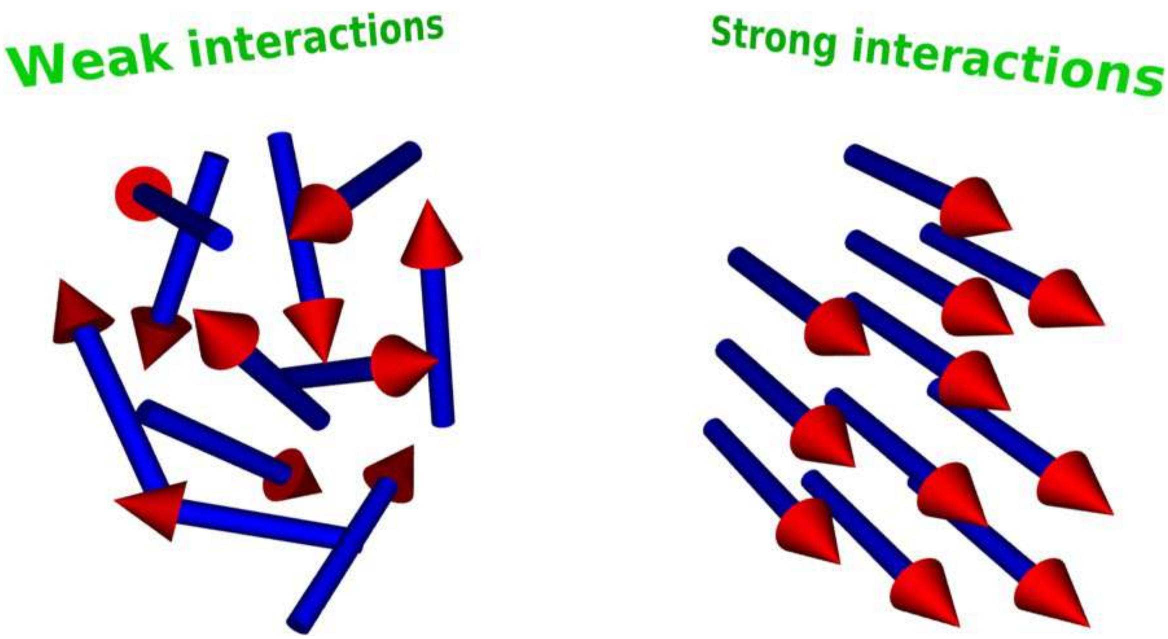
The realization of itinerant ferromagnetism in an atomic Fermi gas



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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)

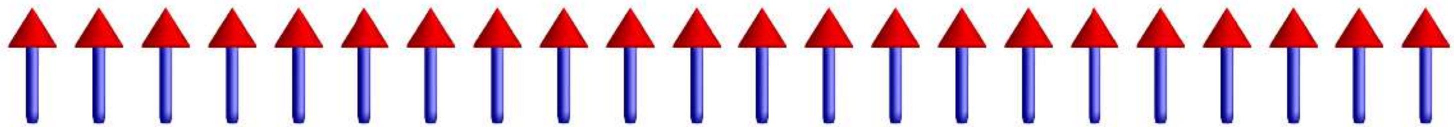
G.J. Conduit & B.D. Simons, Phys. Rev. Lett. **103**, 200403 (2009)

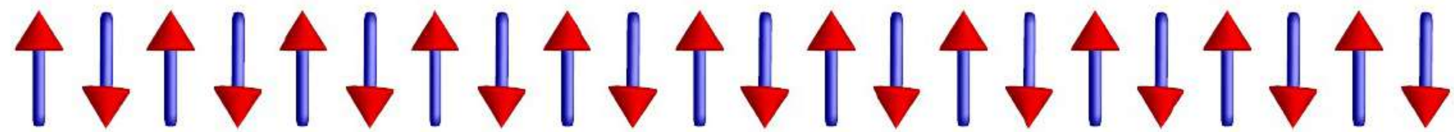
G.J Conduit & E. Altman, Phys. Rev. A **82**, 043603 (2010)

G.J. Conduit, Phys. Rev. A **82**, 043604 (2010)

What is itinerant ferromagnetism?

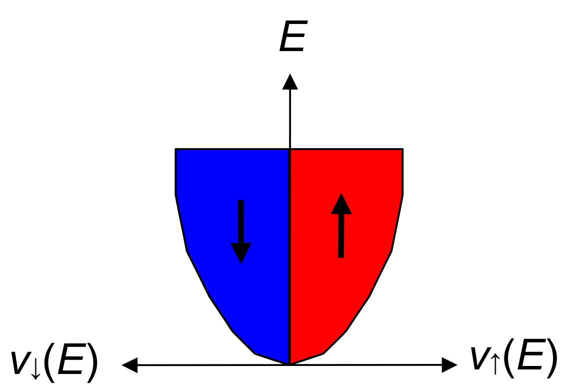
- **Localized ferromagnetism**: moments confined in real space

Ferromagnet: 

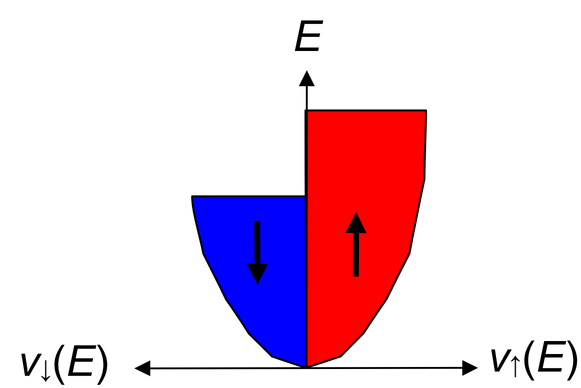
Antiferromagnet: 

- **Itinerant ferromagnetism**: electrons in Bloch wave states

Not magnetised



Partially magnetised



Stoner instability with repulsive interactions

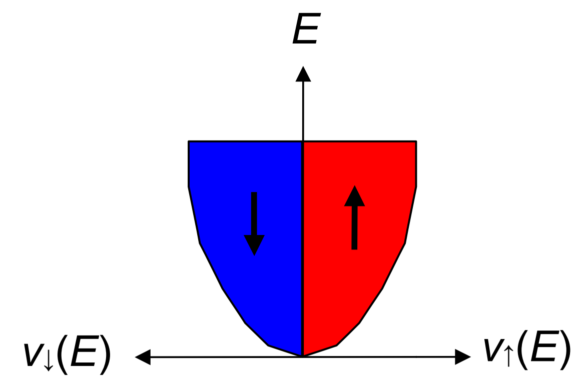
$$\hat{H} = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + g \sum_{kk'q} c^\dagger_{k\uparrow} c^\dagger_{k'+q\downarrow} c_{k'+q\downarrow} c_{k'\uparrow}$$

- Following a mean-field approximation

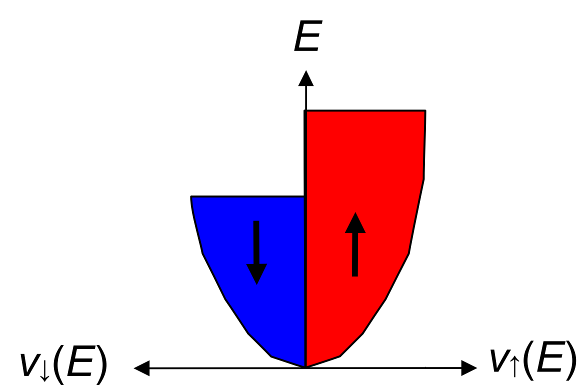
$$E = \sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}} n_\sigma(\epsilon_{\mathbf{k}}) + g N_\uparrow N_\downarrow$$

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

Not magnetised



Partially magnetised

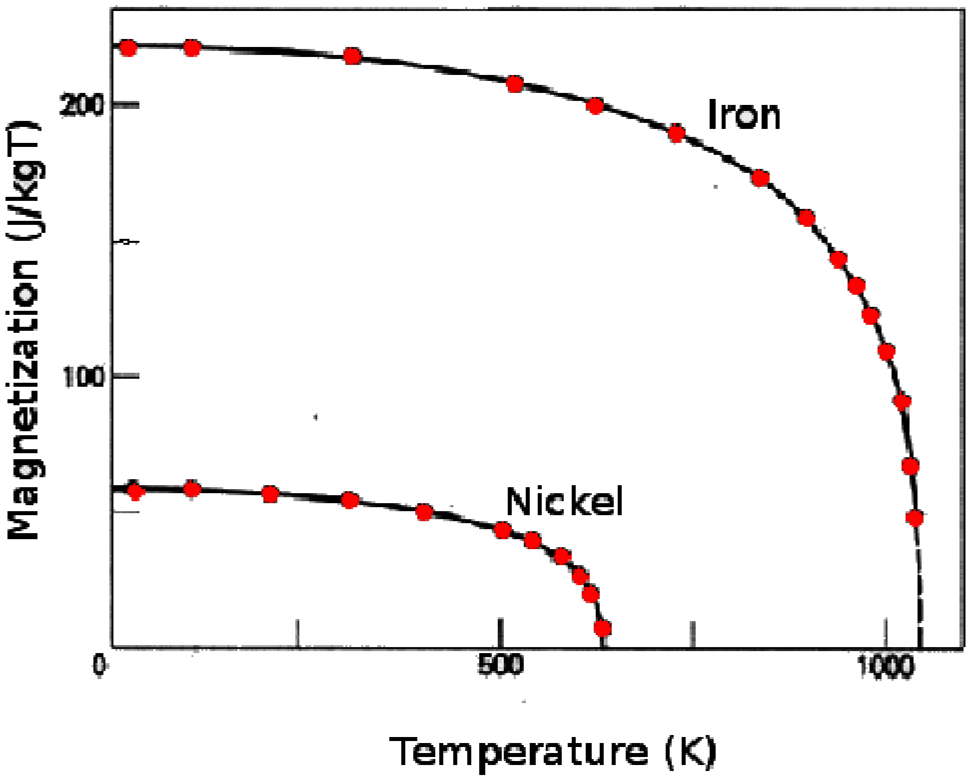


Conduit & Simons, Phys. Rev. A **79**, 053606 (2009)

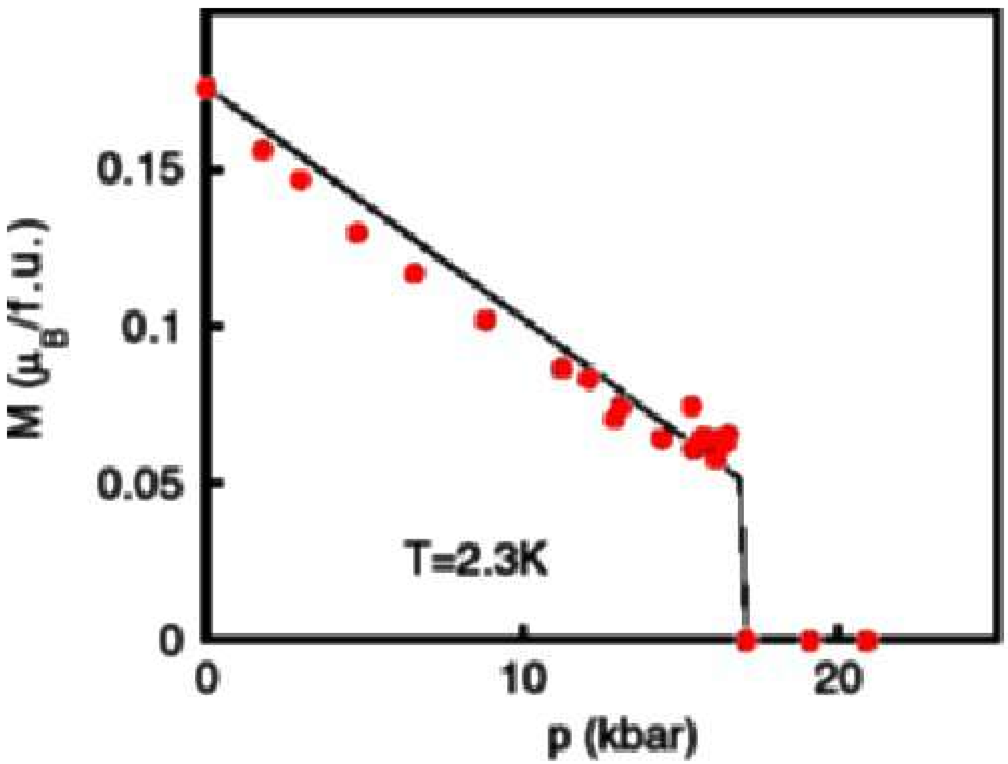
Jo, Lee, Choi, Christensen, Kim, Thywissen, Pritchard & Ketterle, Science **325**, 1521 (2009)

Ferromagnetism in solid state

Second order in iron & nickel

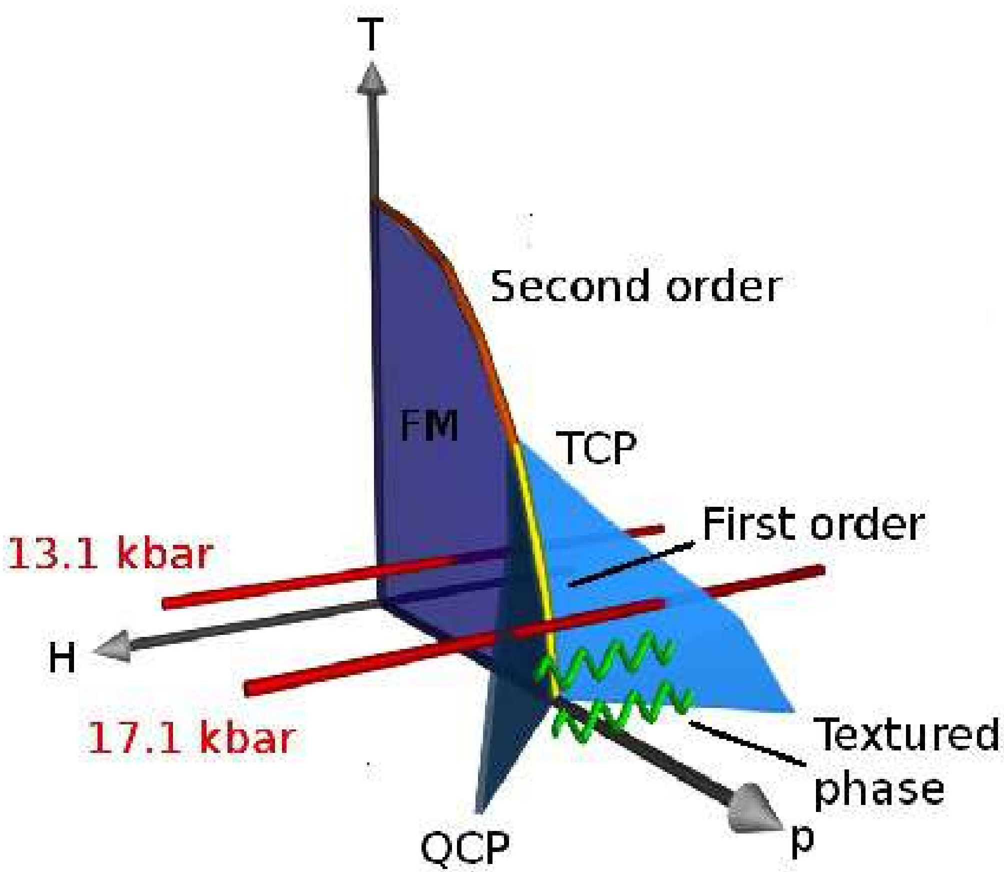


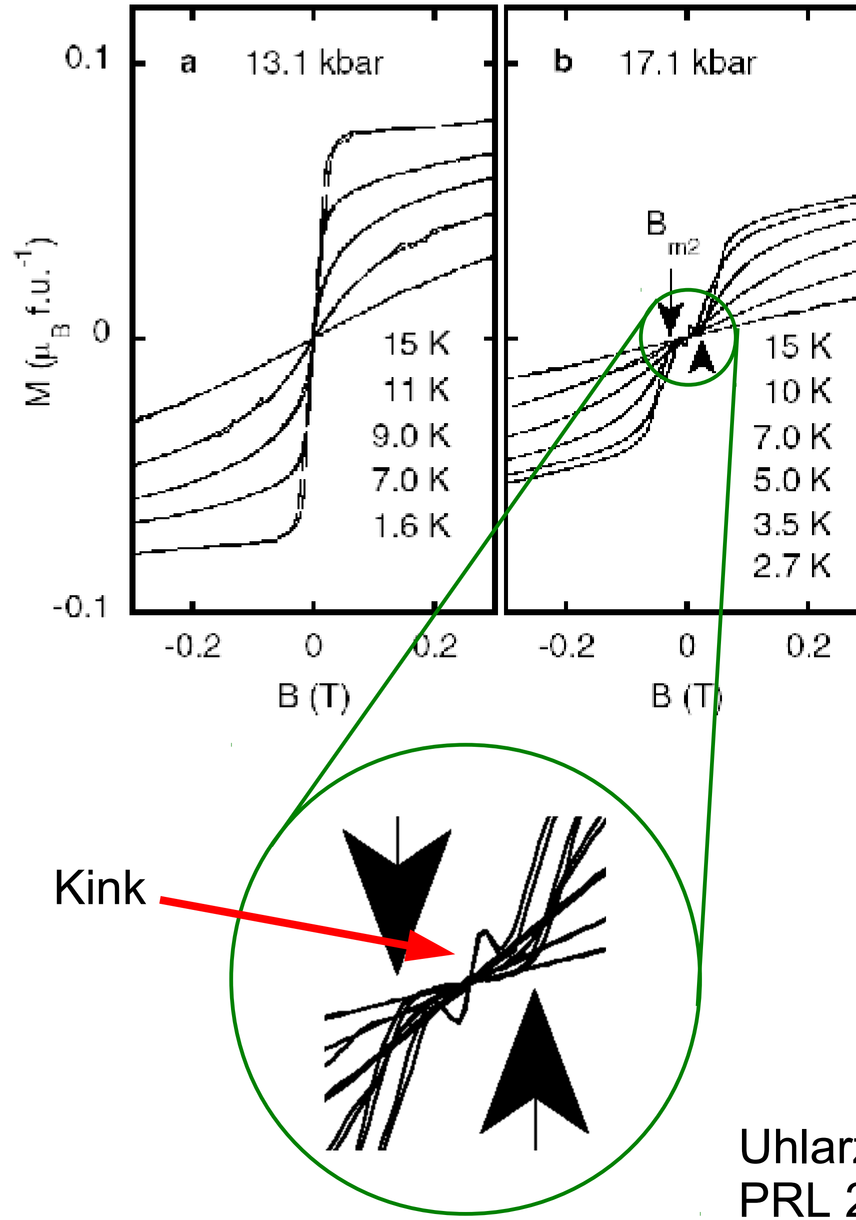
First order in $ZrZn_2$



Uhlarz *et al.*, PRL 2004

Further phase reconstruction in $ZrZn_2$

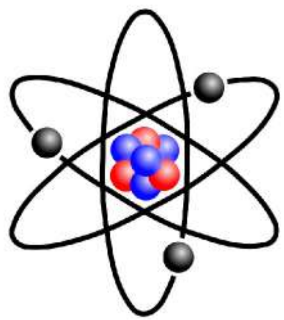




Uhlarz *et al.*, PRL 2004

Atomic gases: a new forum for many-body physics

- A gas of atoms simulates electrons in a solid

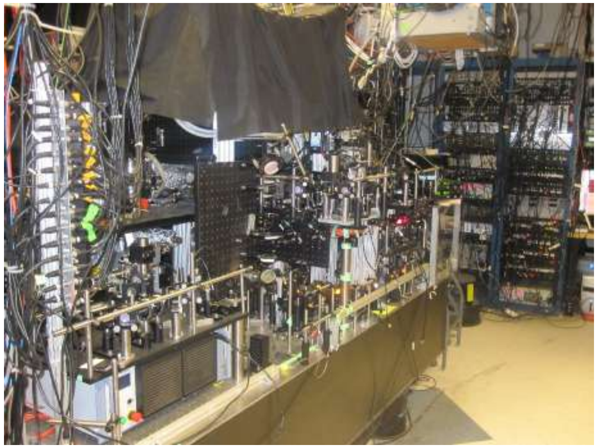


^{6}Li atom

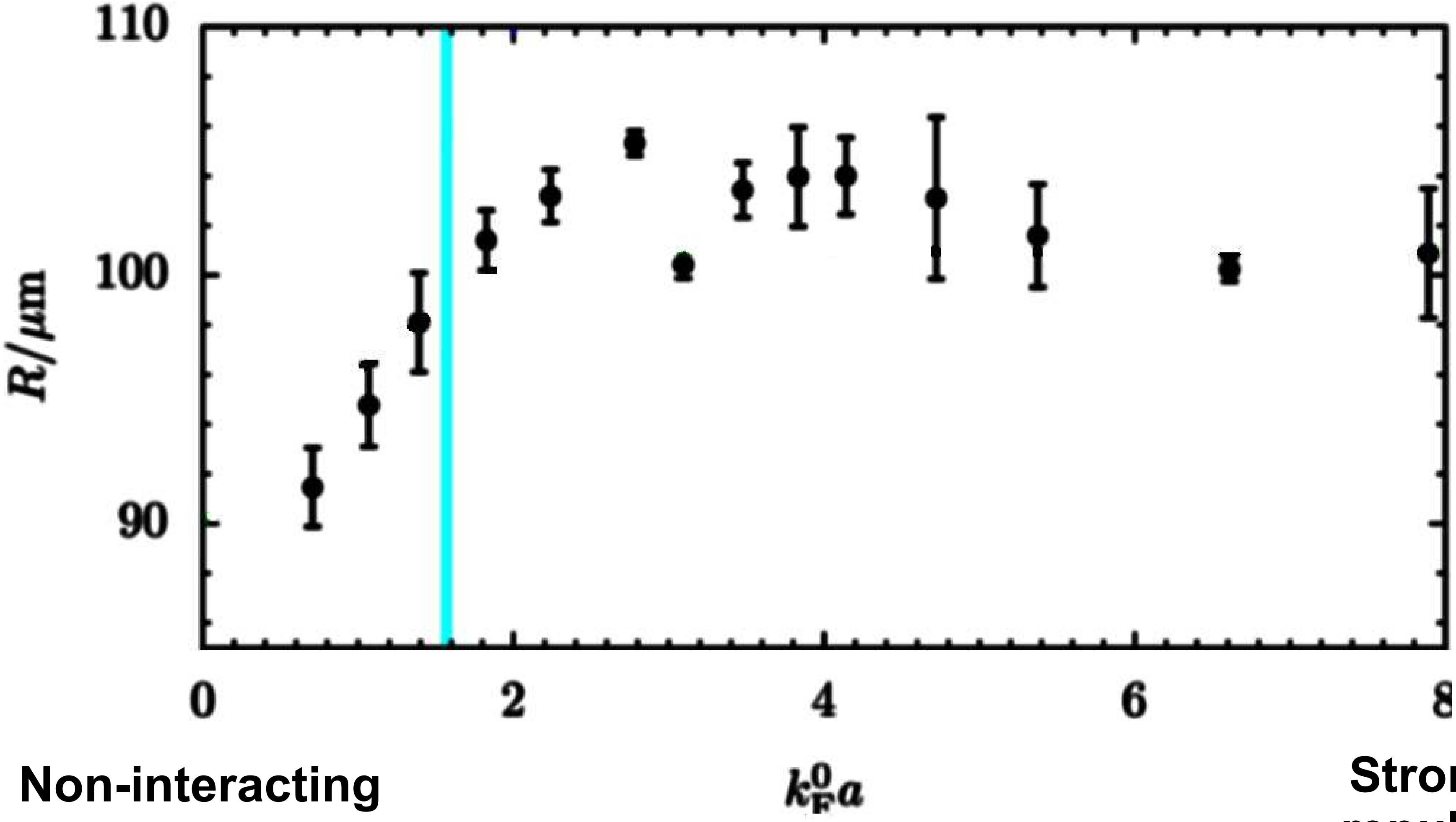
$|F = 1/2, m_F = 1/2\rangle$ →  Up spin electron

$|F = 1/2, m_F = -1/2\rangle$ → Down spin electron

- Key experimental advantages:
  - Magnetic field controls interaction strength
  - Contact interaction
  - Clean system

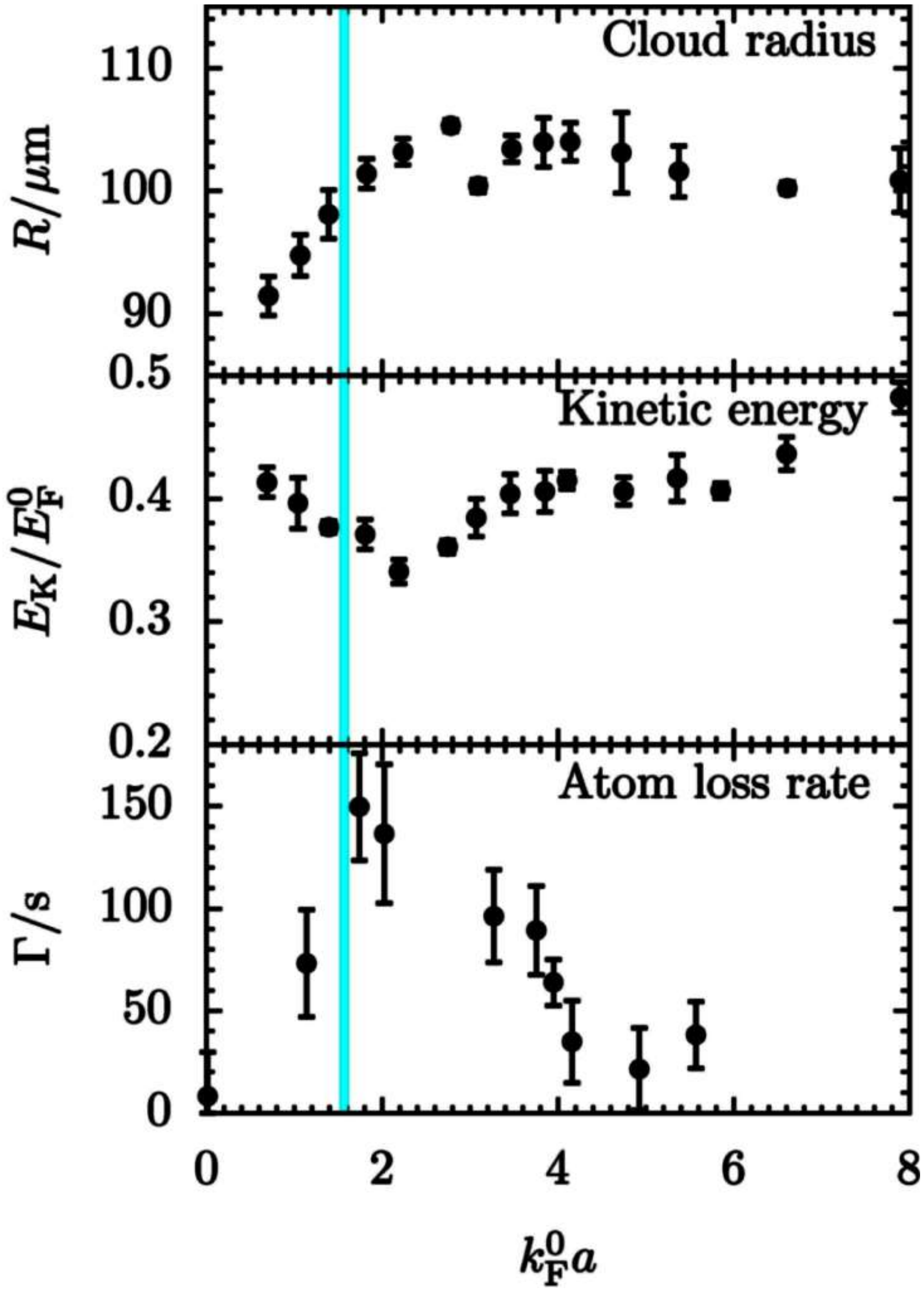


Experimental evidence for ferromagnetism



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

Further key experimental signatures



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

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

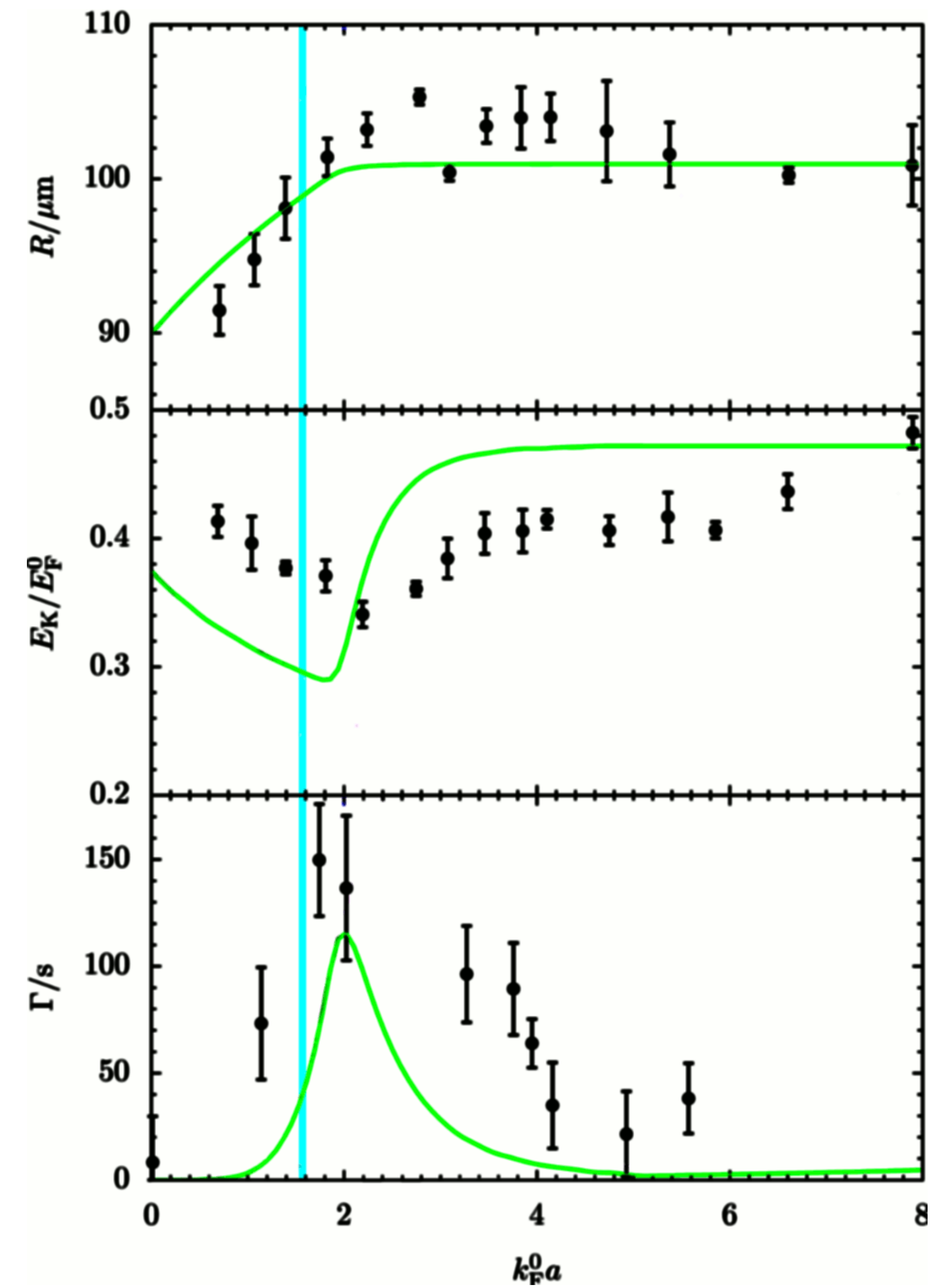
Jo, Lee, Choi, Christensen, Kim, Thywissen, Pritchard & Ketterle, Science **325**, 1521 (2009)

Outline

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

Mean-field analysis & consequences of trap

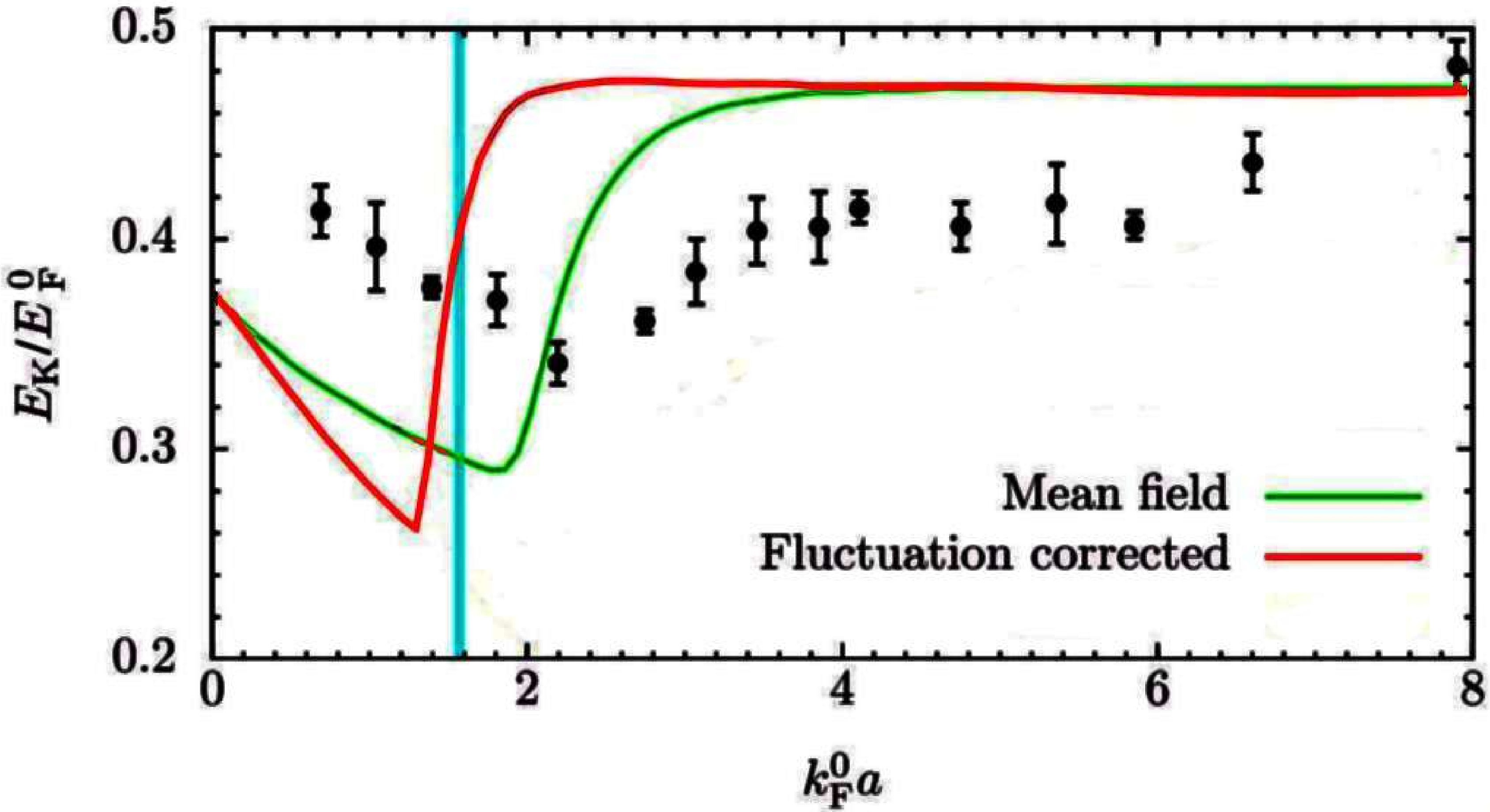
- Recovers qualitative behavior[1] but transition at $k_F a$=1.8 instead of $k_F a$=2.2



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

Fluctuation corrections

- Fluctuation corrections give $k_F a$=1.1 and QMC $k_F a$=0.8



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

Outline: consequences of atom loss

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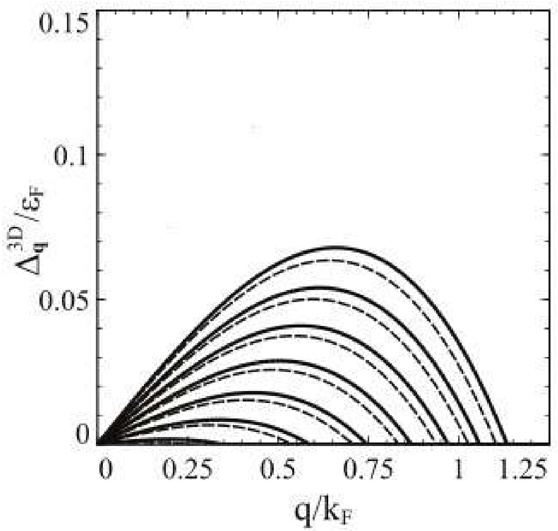
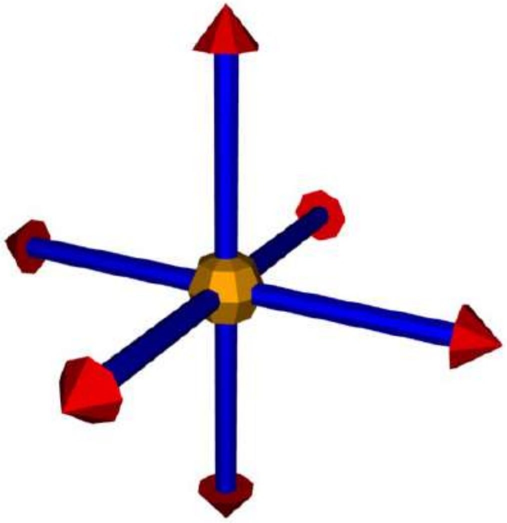
Initial growth of domains

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



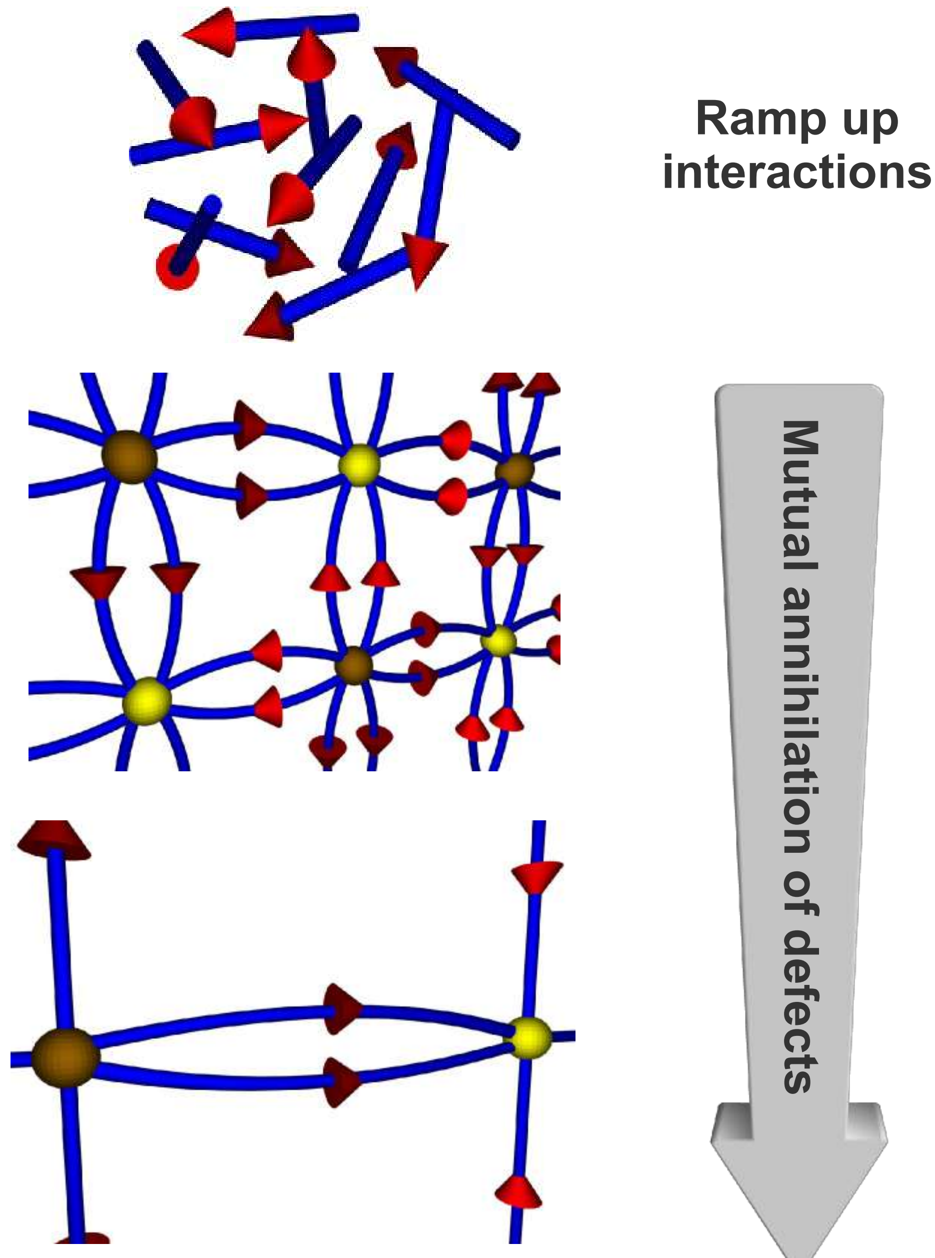
- Ferromagnetic quench *deep* beyond the spinoidal line leads to the condensation of topological defects



Condensation of topological defects

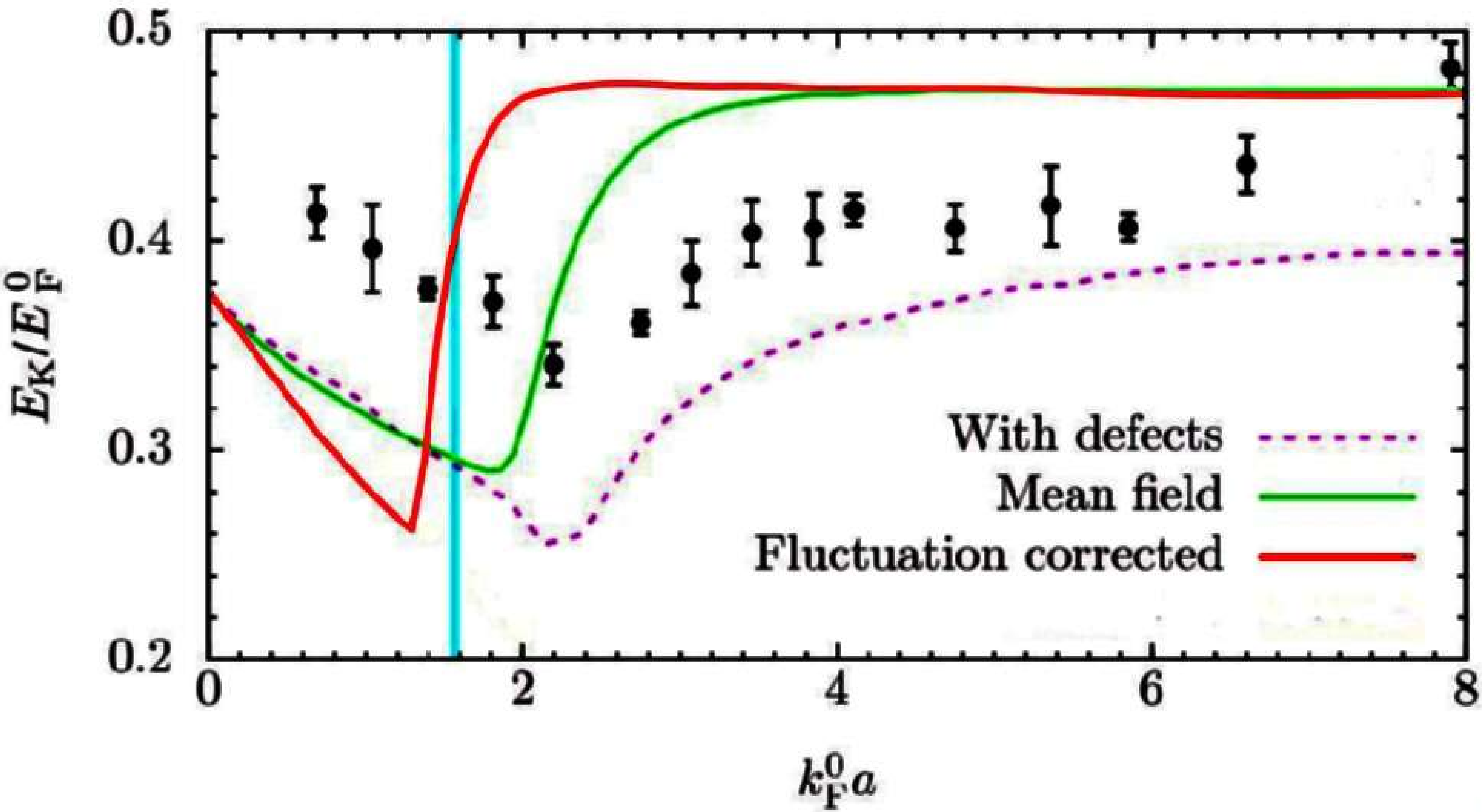
- Defects freeze out from paramagnetic state

- Defects grow as $L \sim t^{1/2}$
  [Bray, Adv. Phys. **43**, 357 (1994)]



Consequences of defect annihilation

- Defect annihilation raises required interaction strength

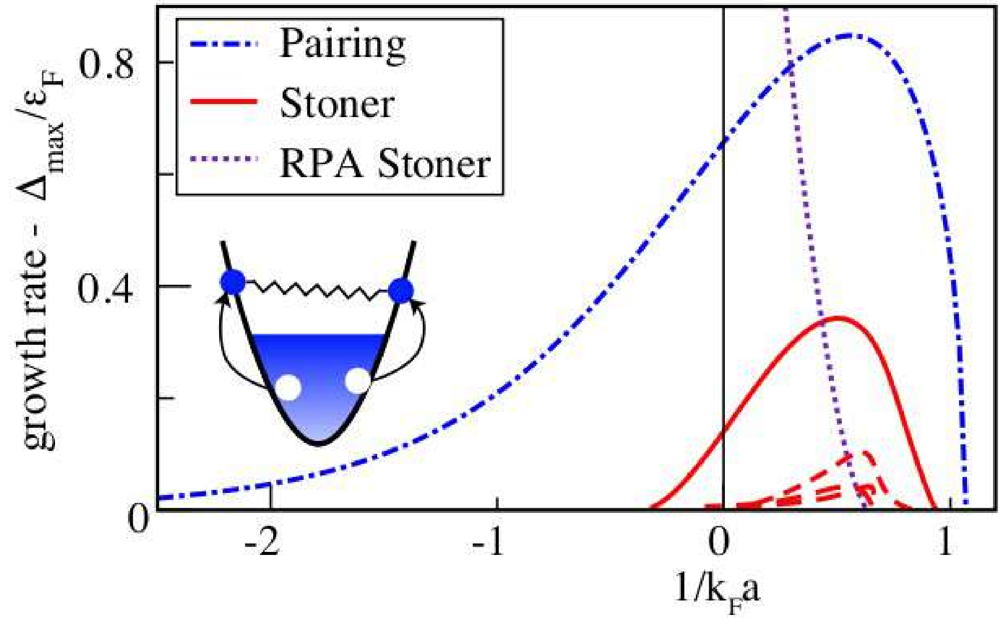


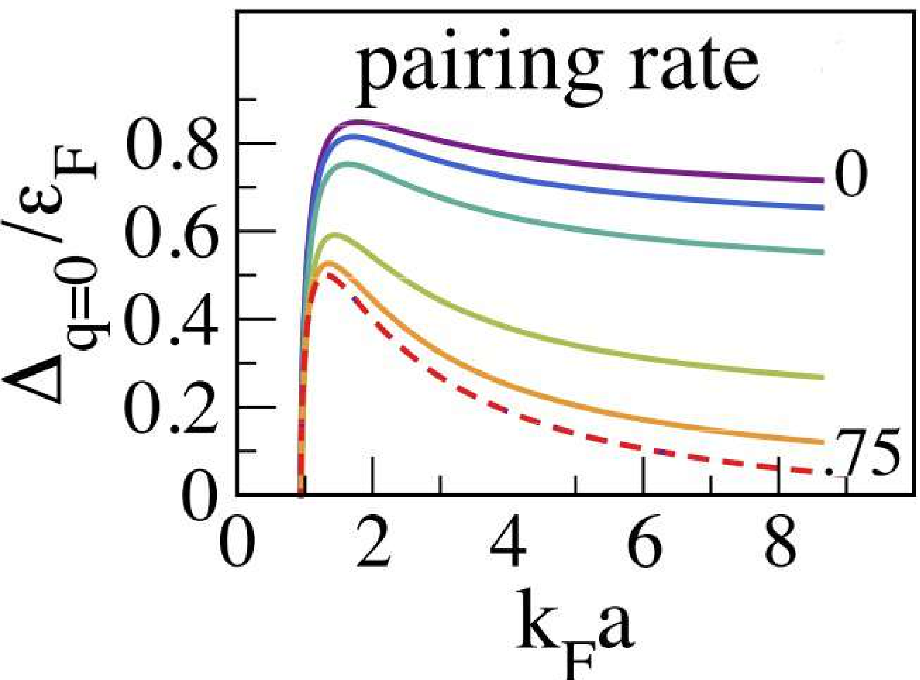
Conduit & Simons, Phys. Rev. Lett. **103**, 200403 (2009), Babadi *et al*. arXiv 0908.3482 (2009)

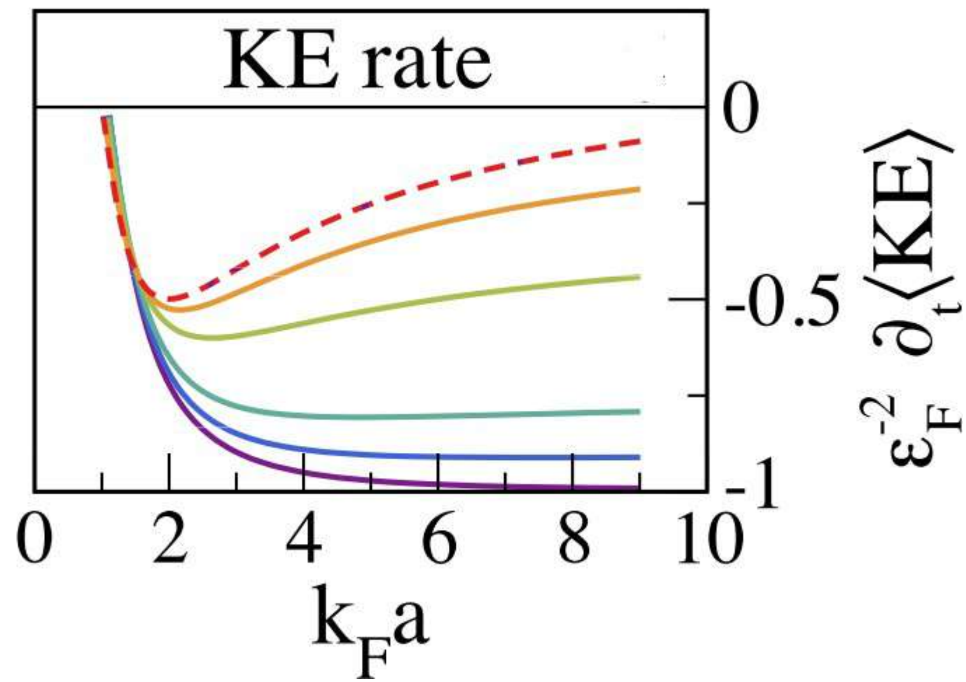
Two-body loss

Two-body mechanism

- Feshbach molecules can be formed by a two body process [Pekker, PRL 2010]
- Requires $k_F^2/m<1/2ma^2$, $k_Fa<1/\sqrt{2}$



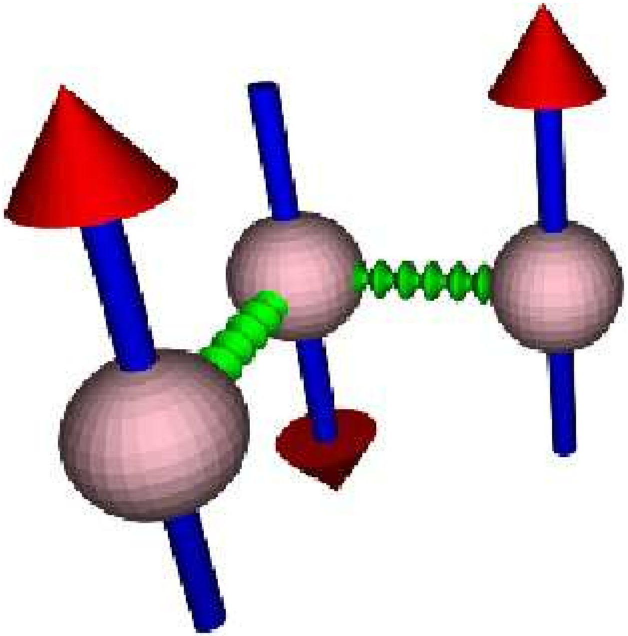




Three-body loss

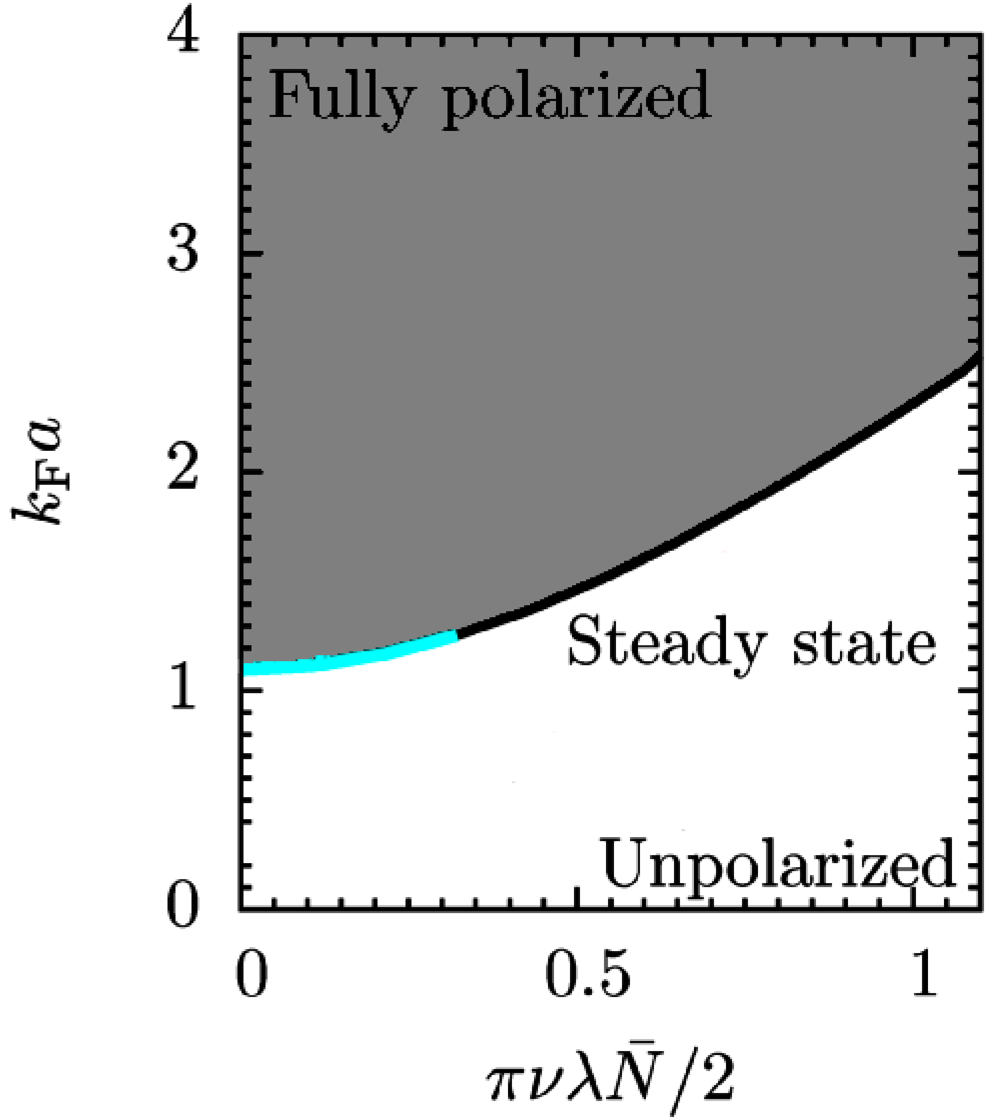
Three-body mechanism

- 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)]



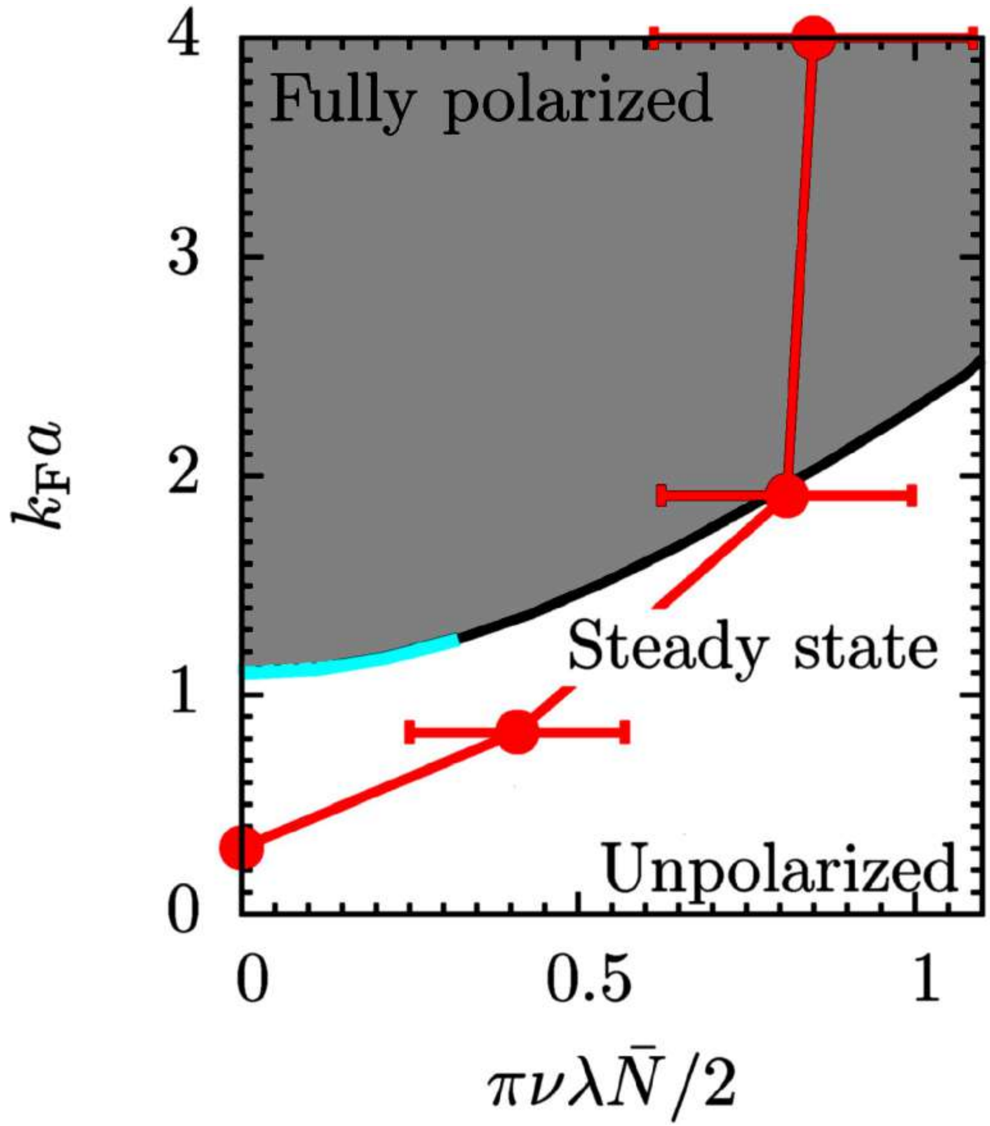
Phase boundary with atom loss

- 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: consequences of atom loss

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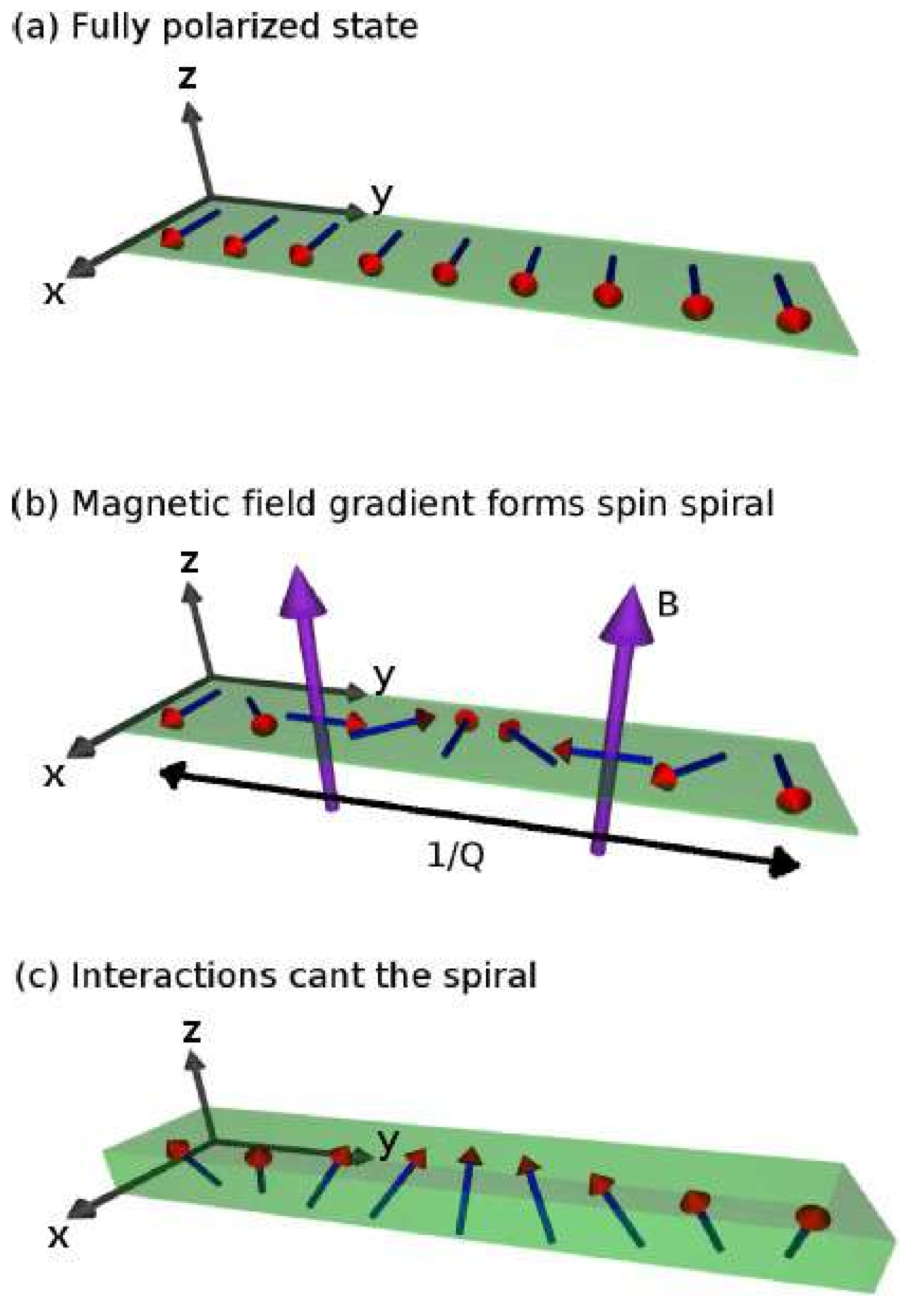
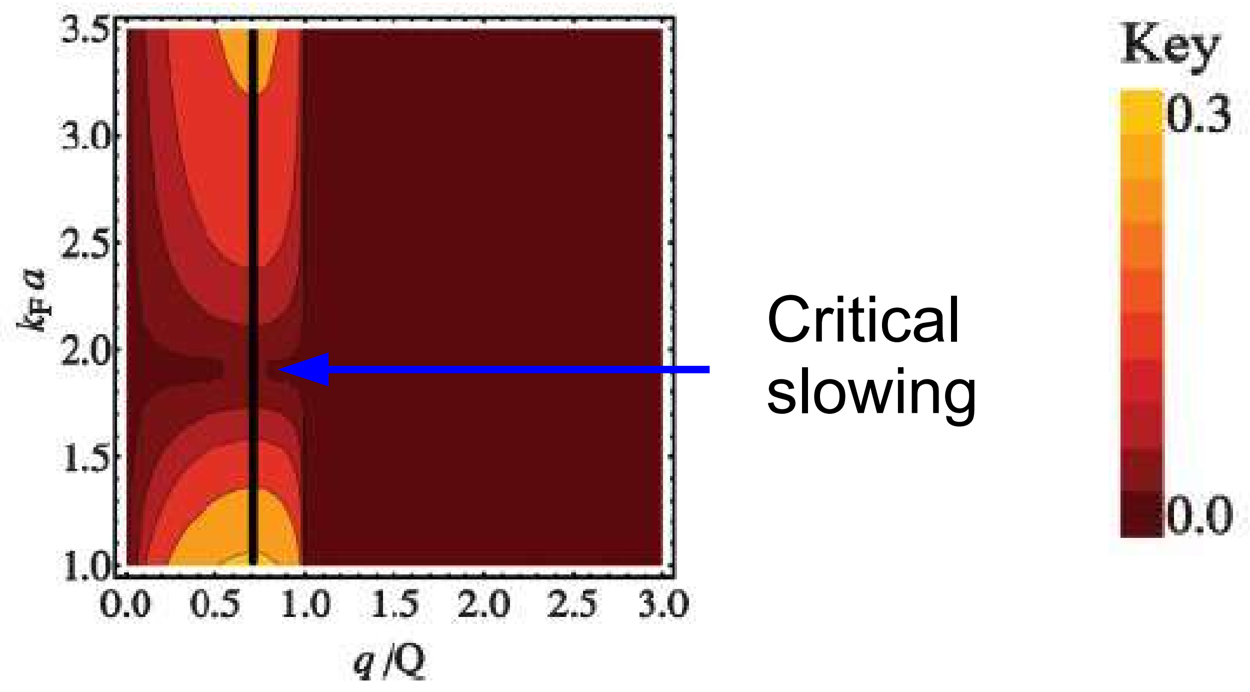
Alternative strategy: spin spiral



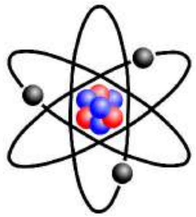
Spin spiral collective modes

- Exponentially growing collective modes if $q<Q$ [GJC & Altman, PRA **82**, 043603 (2010)]

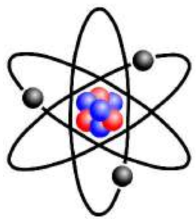
$$\Omega(q) = \pm\left(\frac{1}{2} - \frac{2^{2/3}3}{5k_F a}\right) q\sqrt{q^2 - Q^2}$$



Mass imbalance ferromagnetism



^{6}Li atom, $m=6m_0$ → Up spin electron

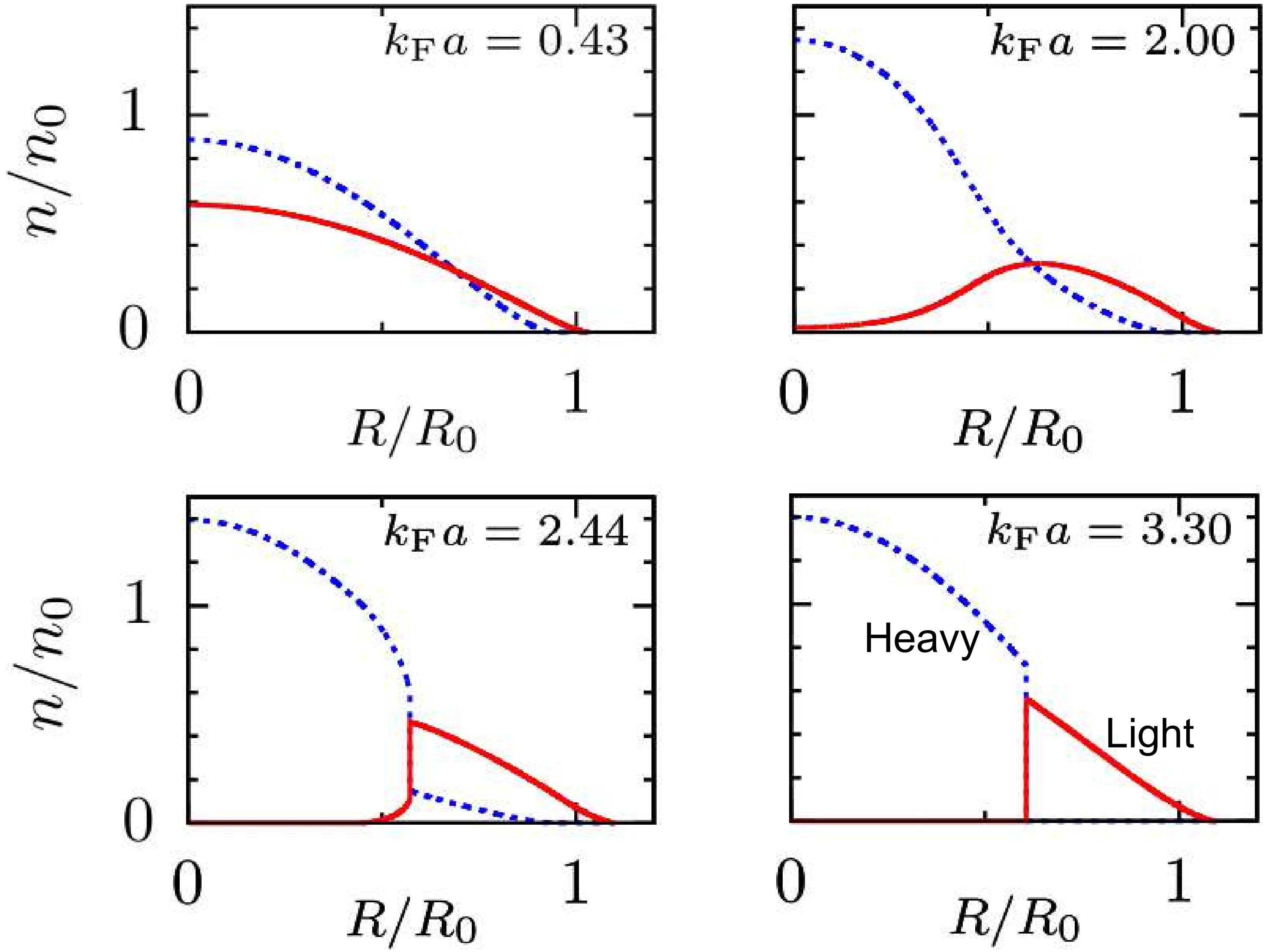


^{40}K atom, $m=40m_0$ → Down spin electron

- Magnetic moment formed along quantization axis
- Modified Stoner criterion $g\sqrt{\nu_\uparrow \nu_\downarrow}=1$
- At zero interactions heavy particles have lower pressure $P \sim n^{5/3}/m$ so more concentrated at center
- At strong interactions heavy particles at center and light particles at outside

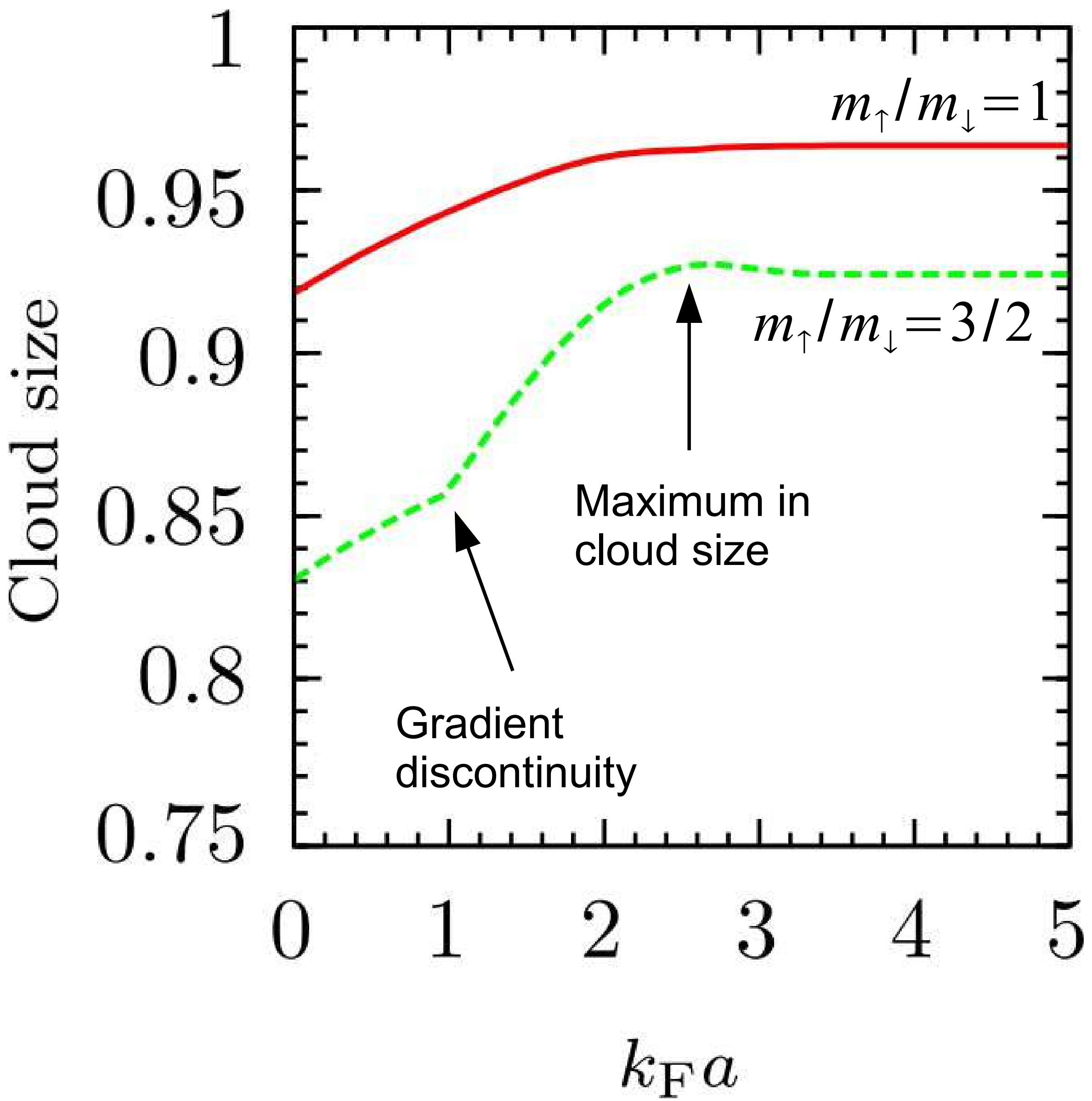
Behavior in a trap

- At zero interaction strength atoms spread all over trap, at high interaction strength light atoms forced to outside



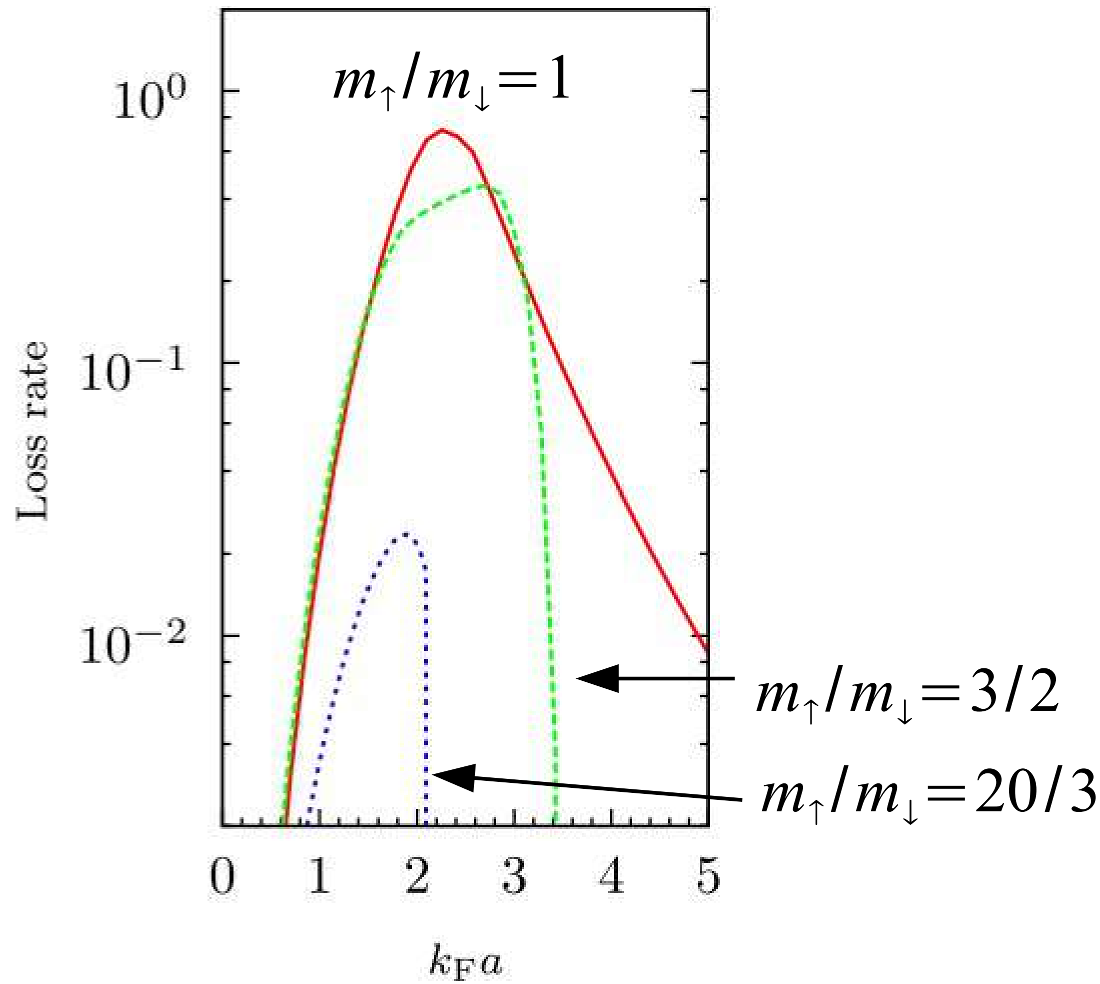
Unique signatures of ferromagnetism

- Expulsion creates unique signatures of ferromagnetism



Unique signatures of ferromagnetism

- Dramatically reduced loss



Summary

- Equilibrium theory provides a reasonable qualitative description of the transition
- Dynamical effects can provide a better description of ferromagnetism but also disrupt the ferromagnetic phase
- Circumvent three-body loss by studying the evolution of a spin spiral
- Suppress losses and give stronger signatures of ferromagnetism by studying mass imbalance
- Answer long-standing questions about solid state ferromagnetism and motivate new research arenas

Damping of fluctuations by atom loss

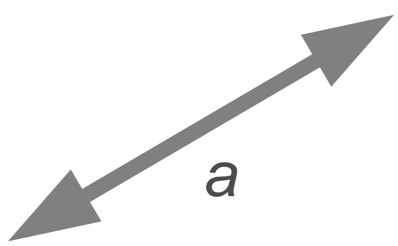
- Atom loss rate, $\lambda'[n_\uparrow(\mathbf{r}) + n_\downarrow(\mathbf{r})]n_\uparrow(\mathbf{r})n_\downarrow(\mathbf{r})$, is

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

- 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

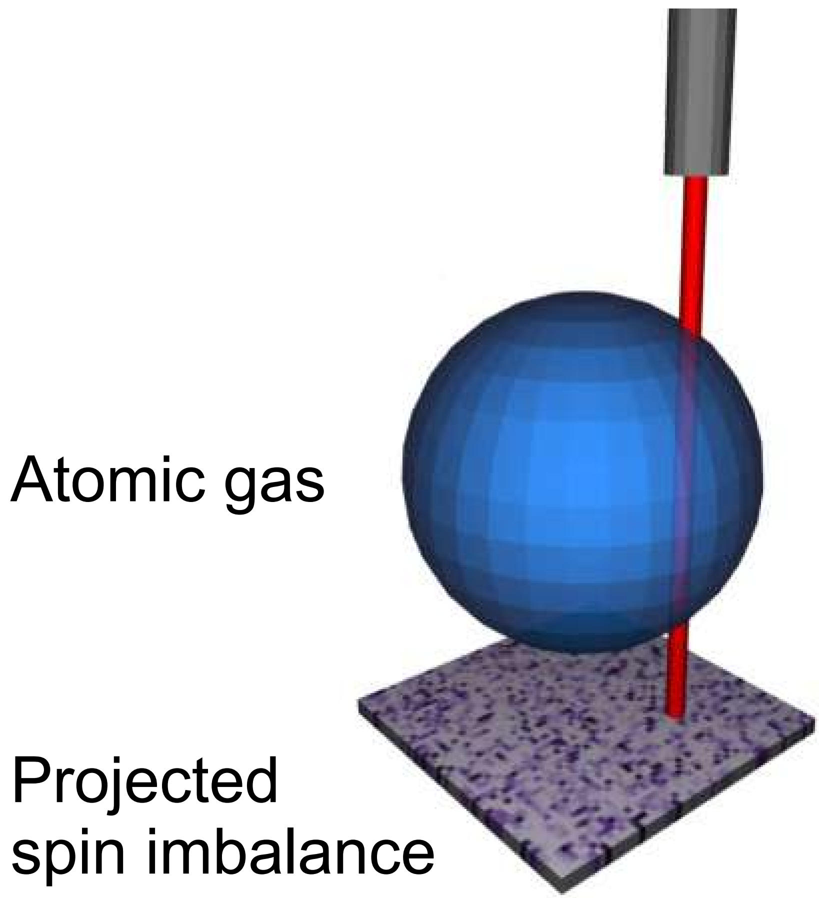


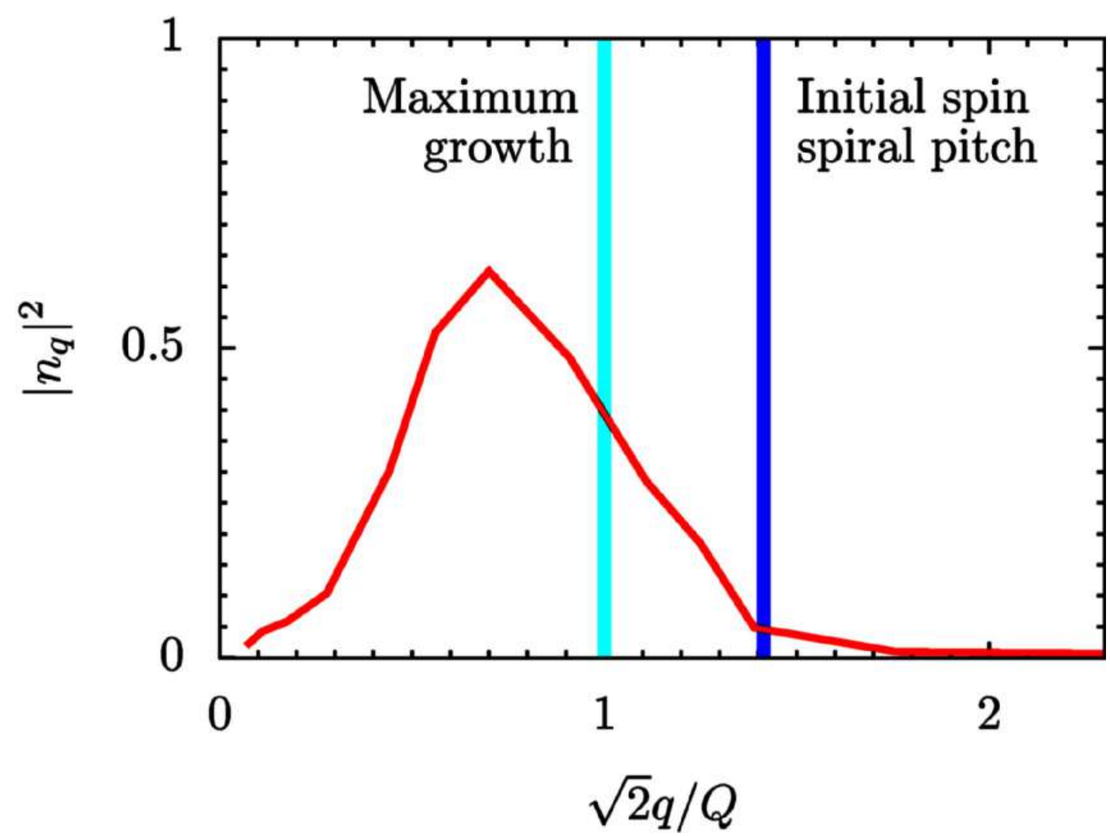
- Loss damps fluctuations so inhibits the transition

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

Phase-contrast imaging

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





Outlook

- First order transition
- Textured phase
- Mass imbalance
- SU(N) spins
- Two-dimensional itinerant ferromagnetism