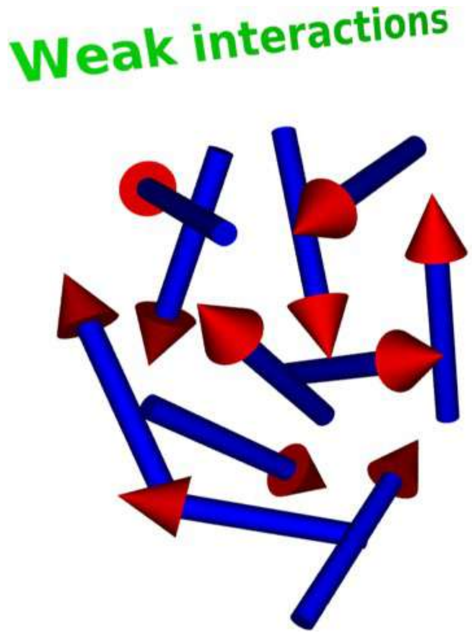
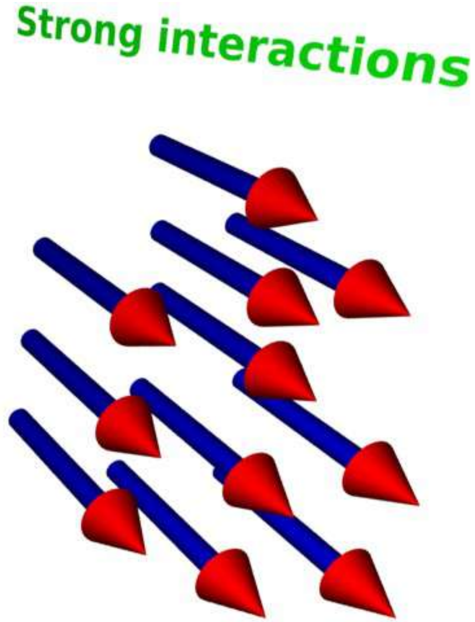
New experimental protocols to probe the Stoner transition in a Fermi gas





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

1. Weizmann Institute of Science, 2. University of Cambridge, 3. University of Oxford

Stoner instability with repulsive interactions

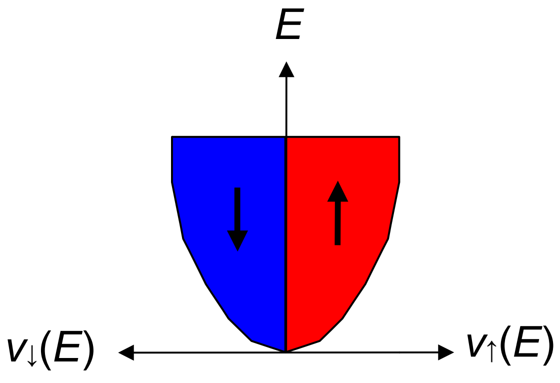
$$\hat{H} = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + g \sum_{kk'q} c^\dagger_{k\uparrow} c^\dagger_{k'+q\downarrow} c_{k'+q\downarrow} c_{k'\uparrow}$$

- Following a mean-field approximation

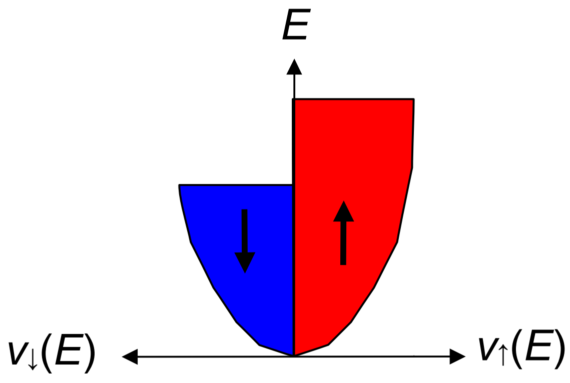
$$E = \sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}} n_\sigma(\epsilon_{\mathbf{k}}) + g N_\uparrow N_\downarrow$$

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

Not magnetised

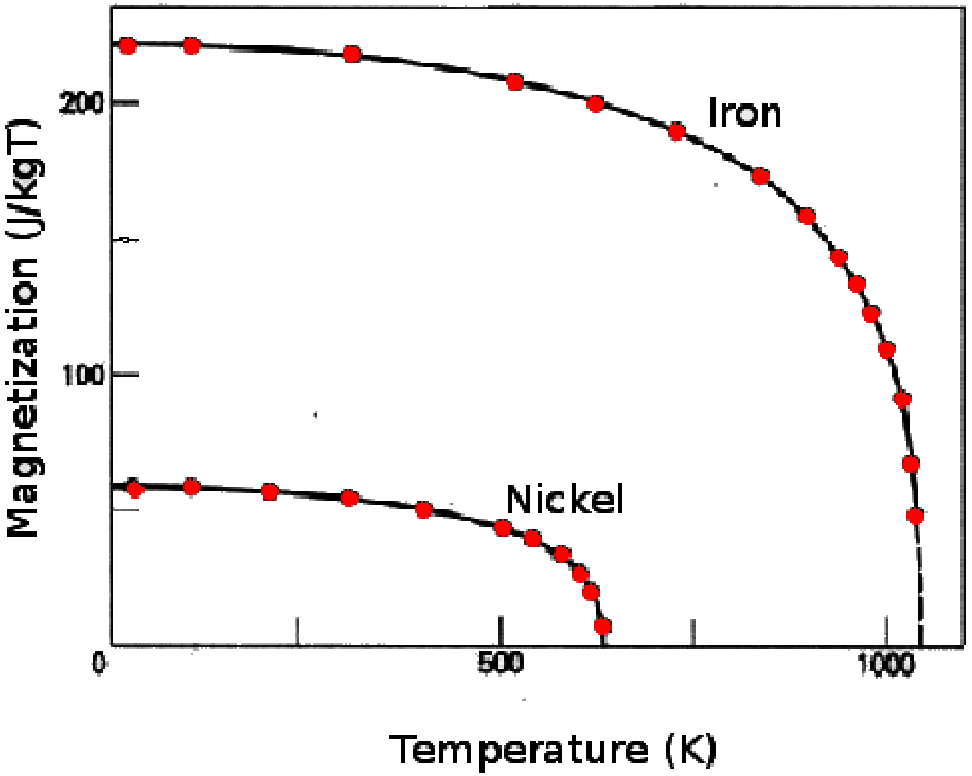


Partially magnetised

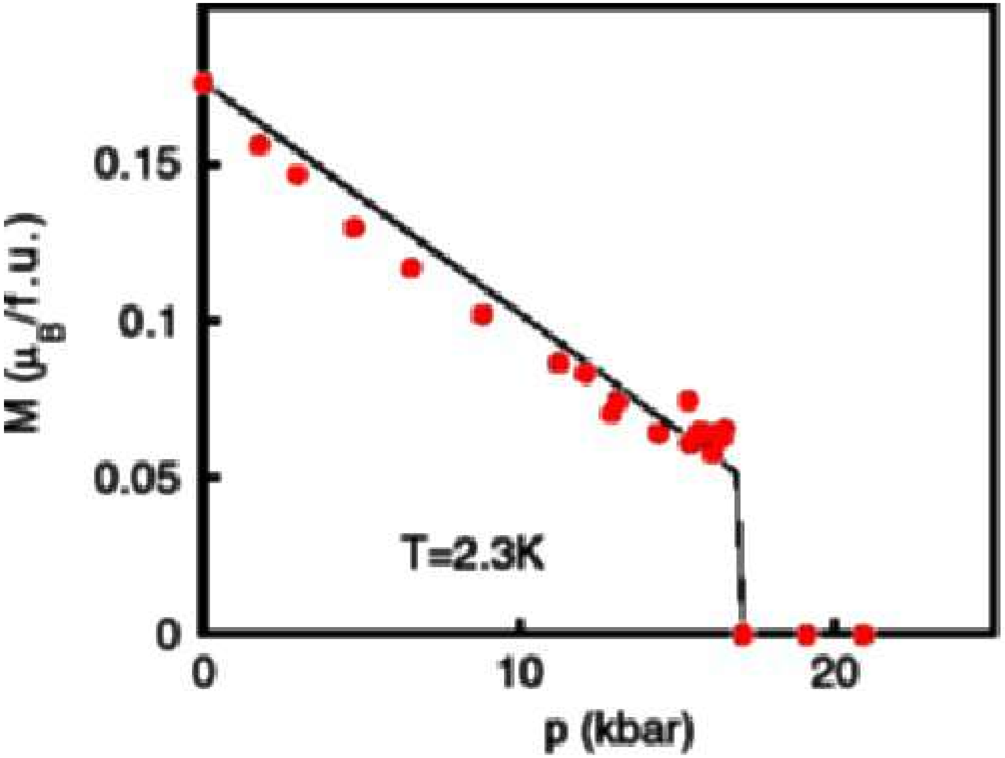


Ferromagnetism in solid state

Second order in iron & nickel

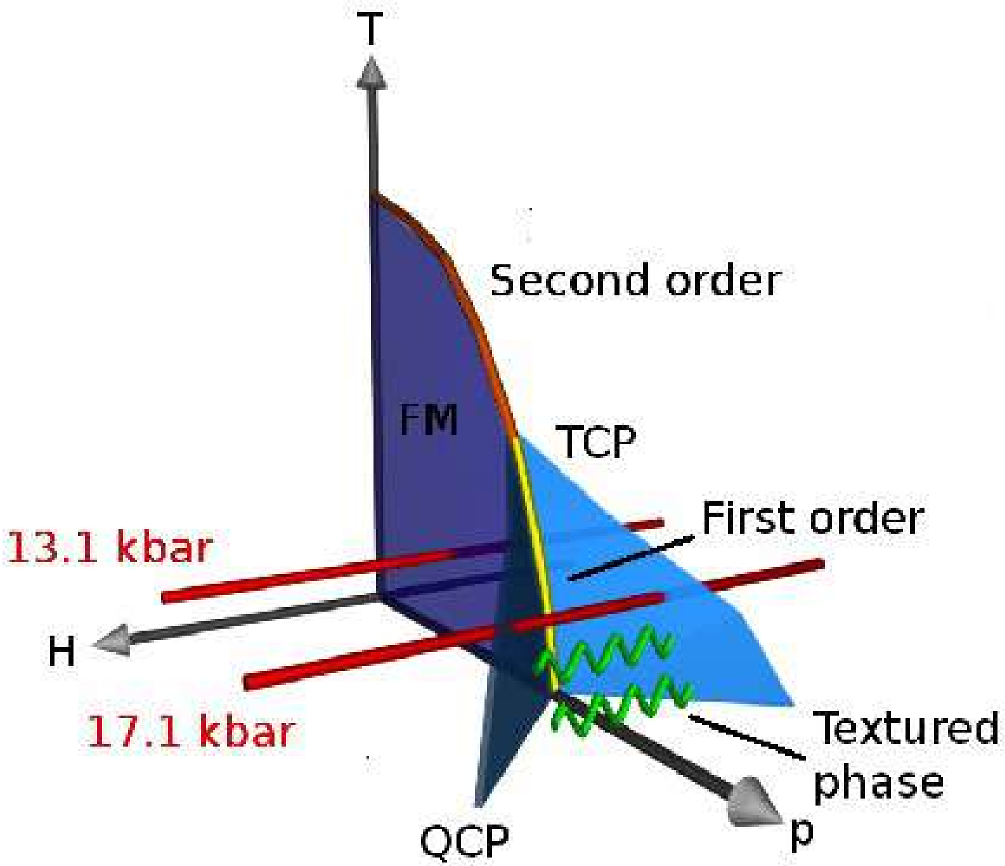


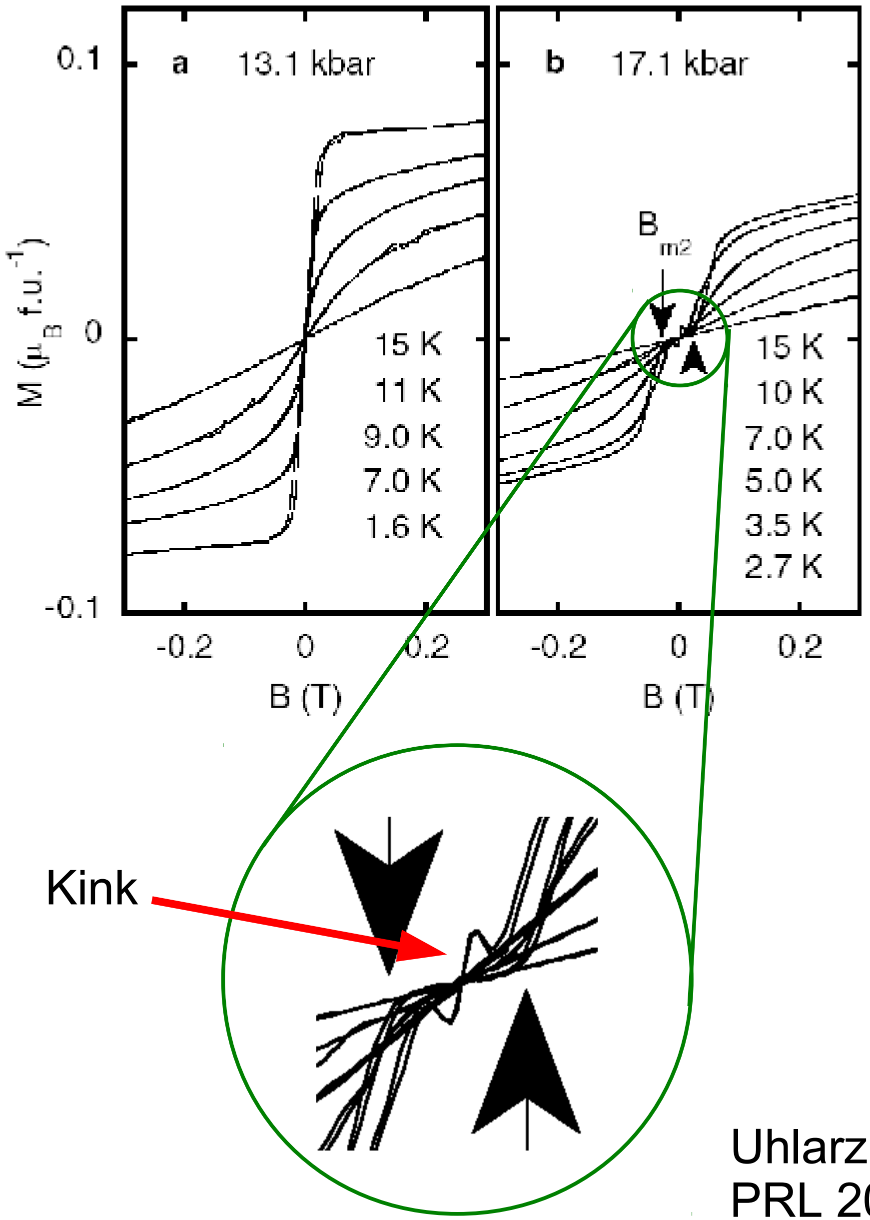
First order in $ZrZn_2$



Uhlarz *et al.*, PRL 2004

Further phase reconstruction in $ZrZn_2$

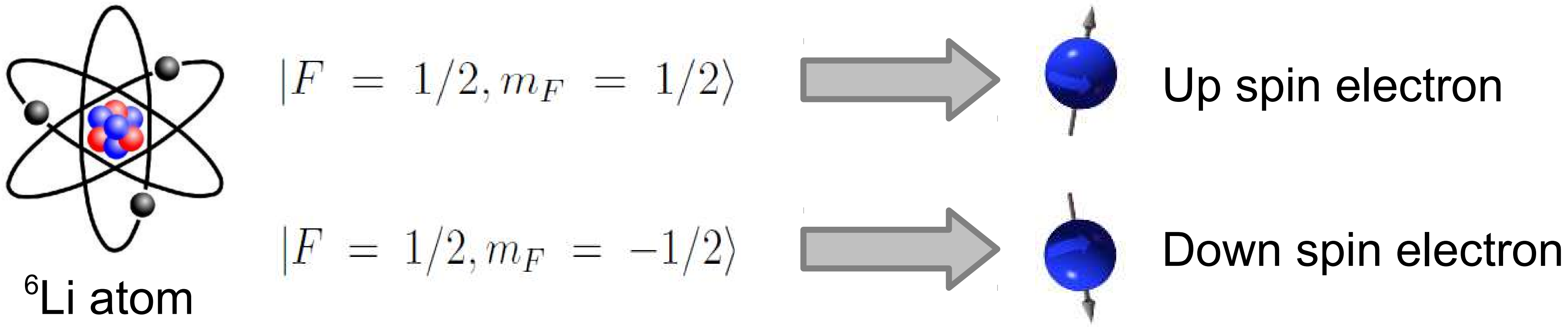




Uhlarz *et al.*, PRL 2004

Atomic gases: a new forum for ferromagnetism

- A gas of atoms simulates electrons in a solid



^{6}Li atom

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

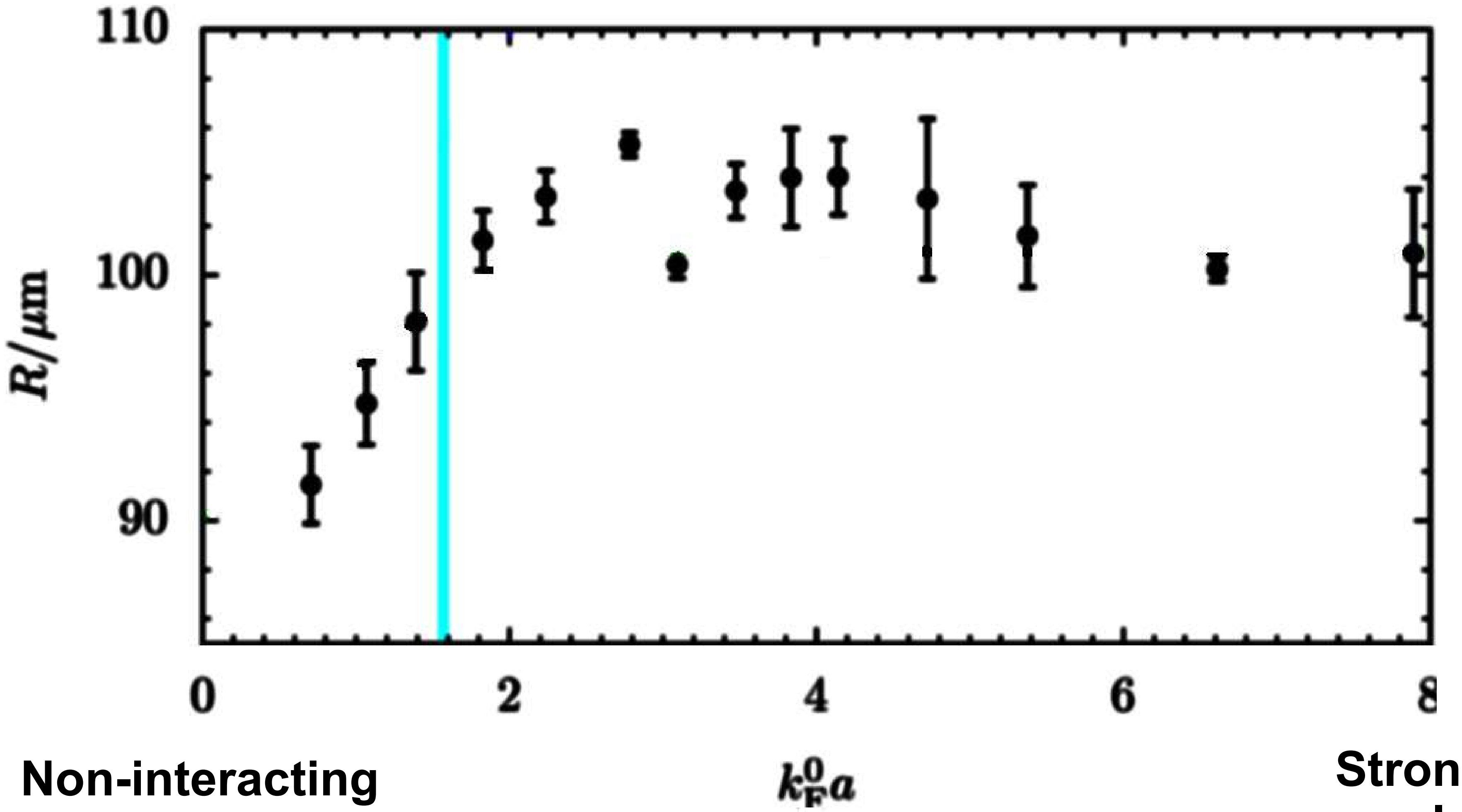
$|F = 1/2, m_F = -1/2\rangle$ → Down spin electron

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

Outline

- Experimental results and mean-field analysis
- Competing many-body instabilities
- Experimental protocols that circumvent atom loss
  - Collective modes within a spin spiral
  - Ferromagnetism with mass imbalance

Experimental evidence for ferromagnetism

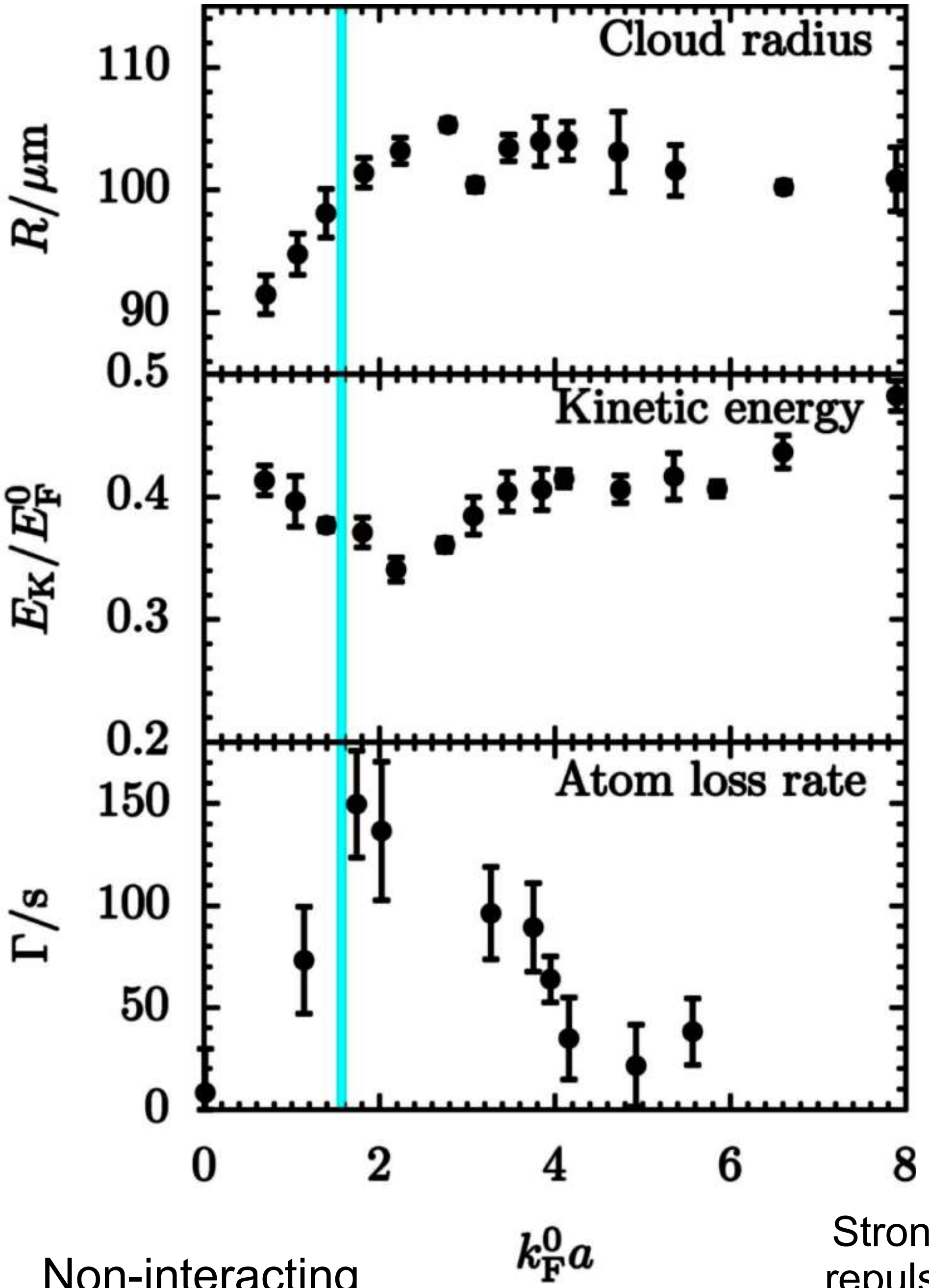


Non-interacting

Strongly repulsive

Jo *et al*, Science **325**, 1521 (2009)

Further key experimental signatures



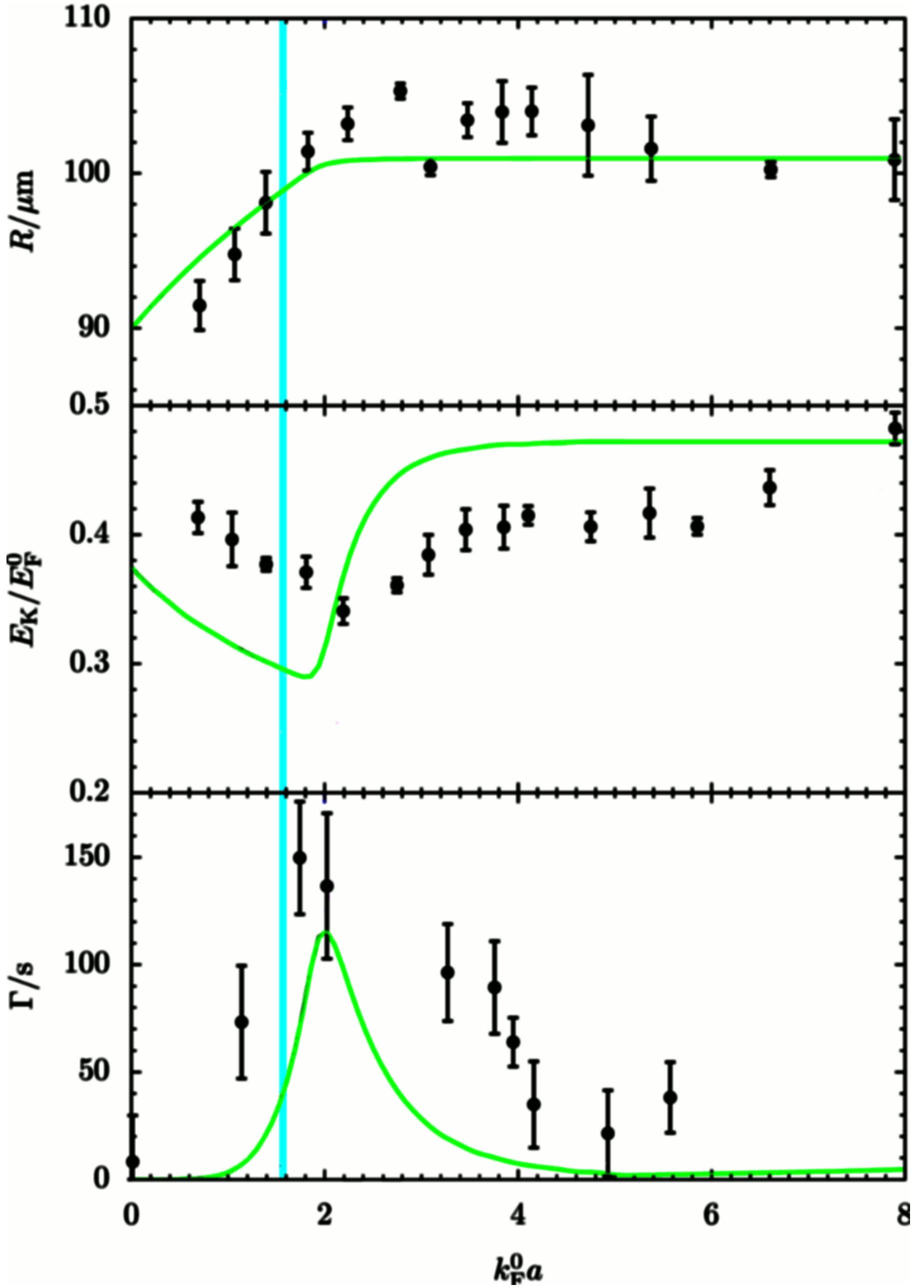
Non-interacting

Strongly repulsive

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

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

Mean-field analysis & consequences of trap



LeBlanc *et al*, PRA **80**, 013607 (2009); GJC & Simons, PRL **103**, 200403 (2009)

Outline: consequences of atom loss

- Experimental results and mean-field analysis
- Competing many-body instabilities
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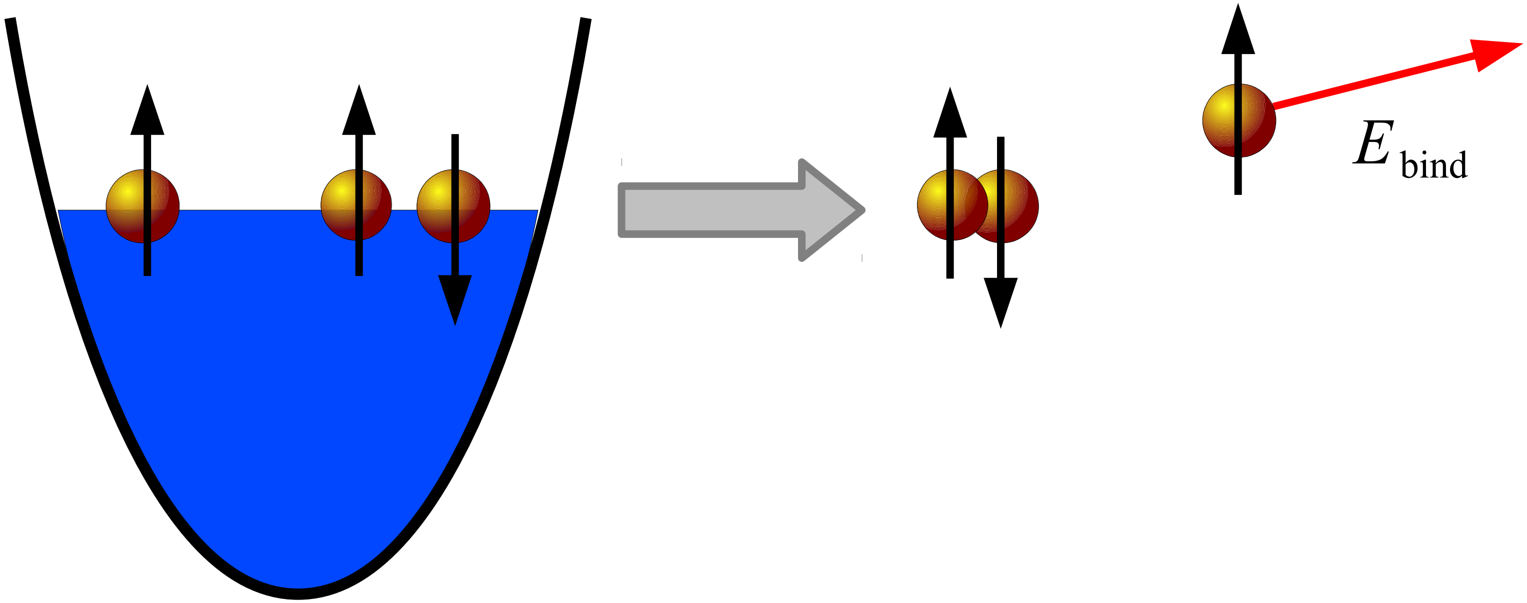
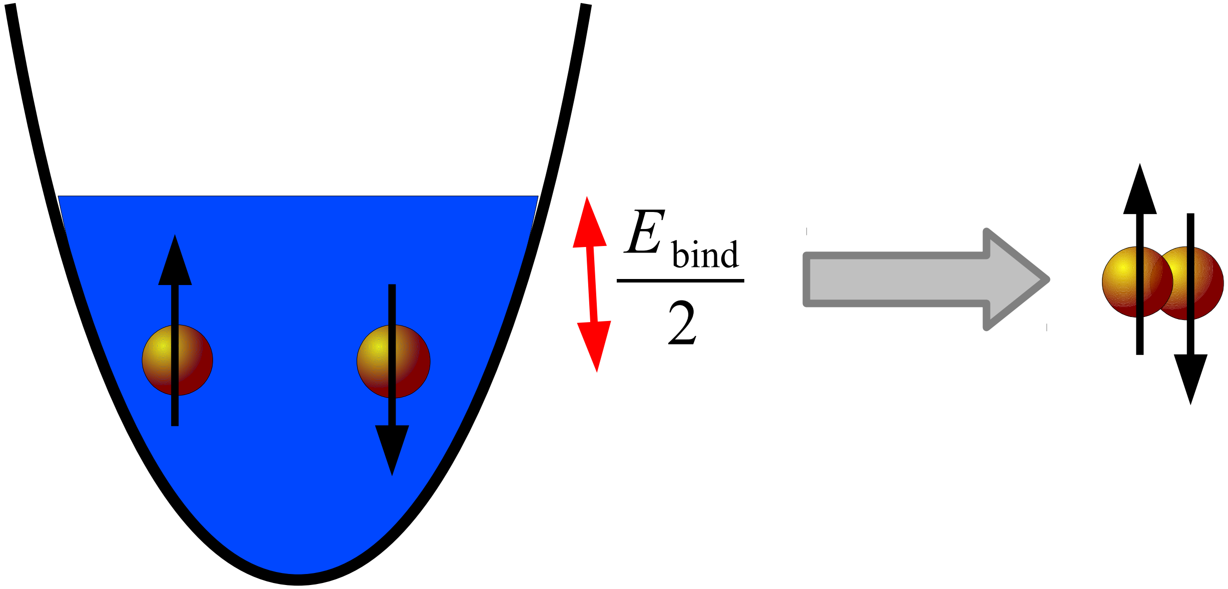
Two versus three-body loss

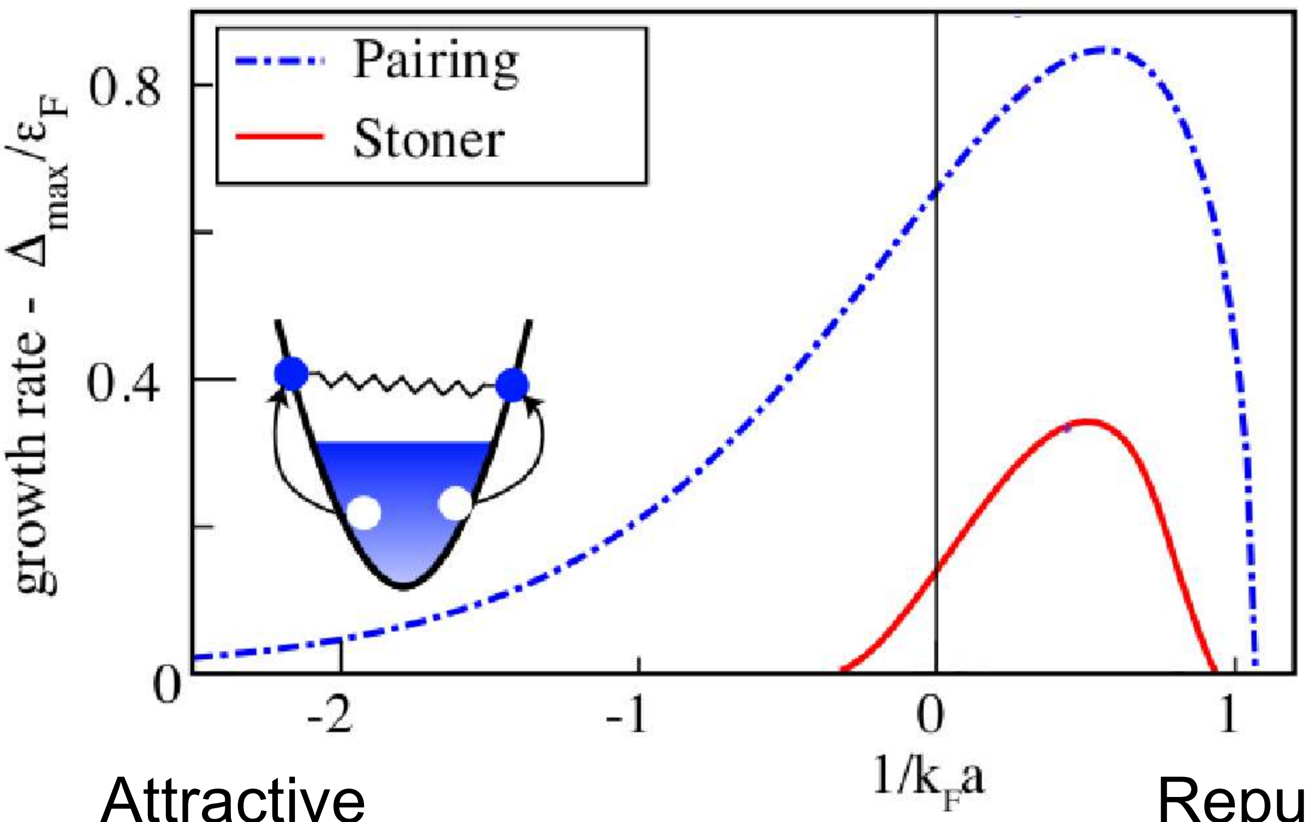
Three-body mechanism



Two-body mechanism



Two-body loss

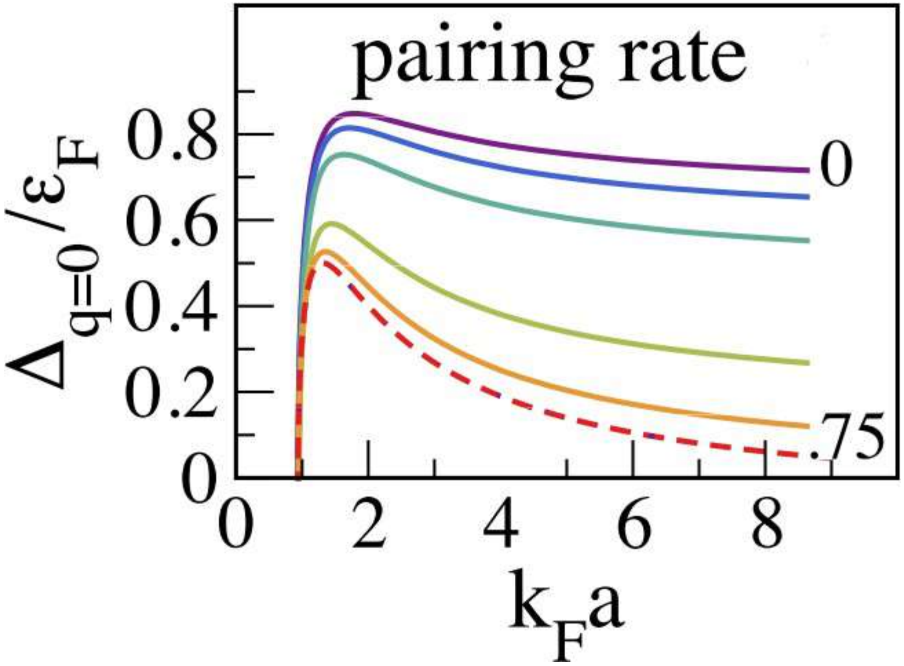


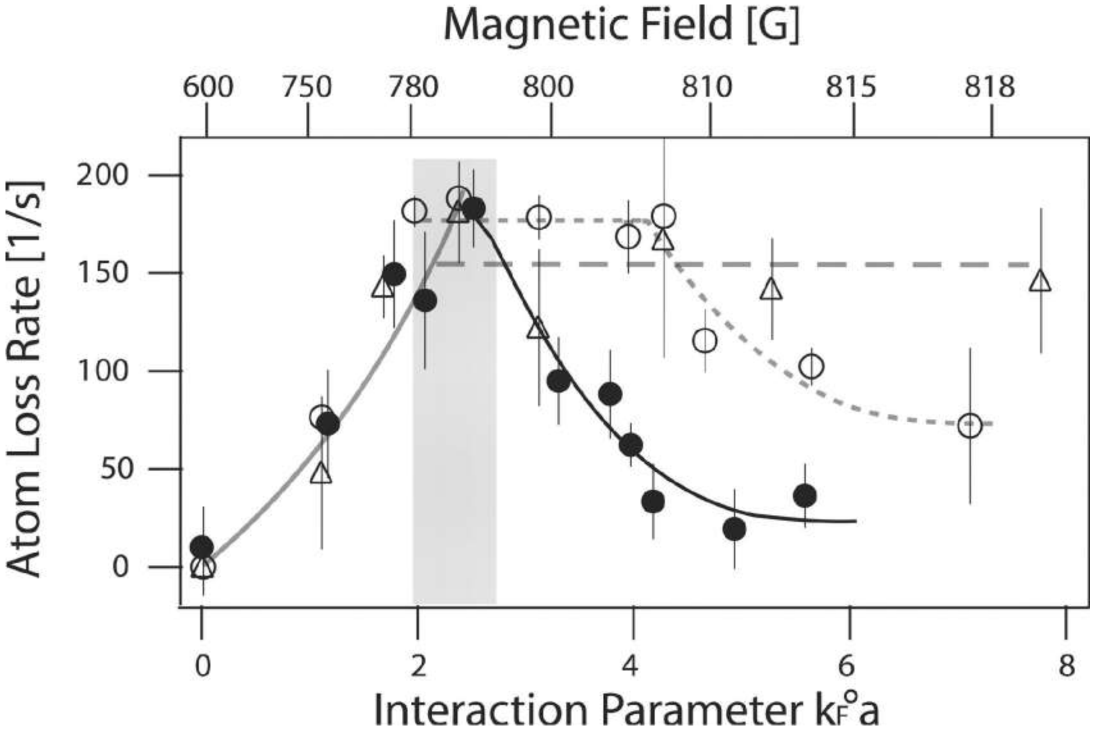
Attractive

Repulsive

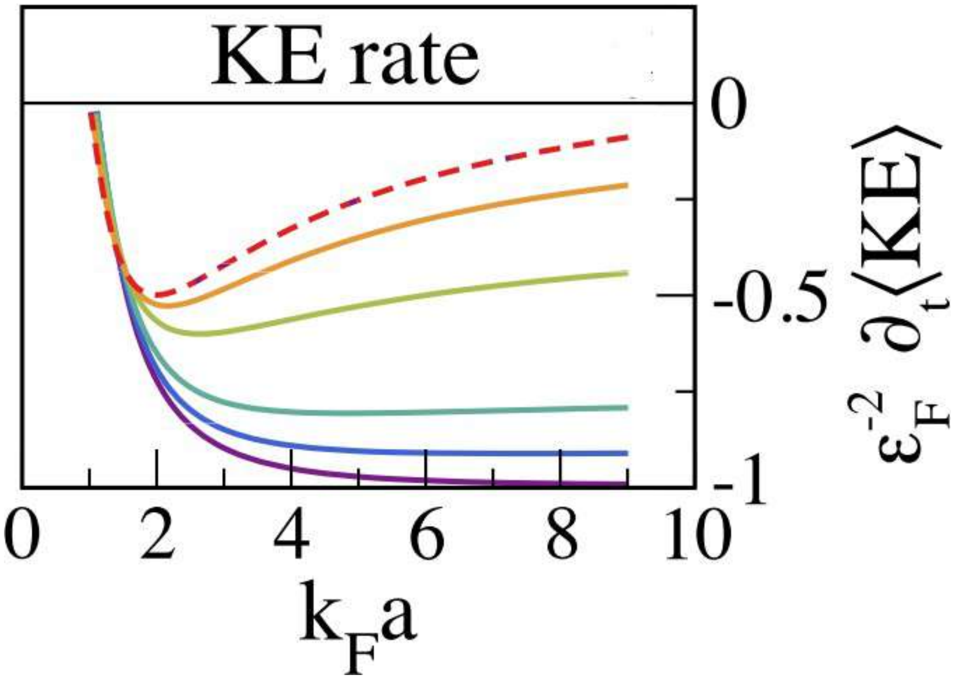
Pekker, PRL **106**, 050402 (2011)

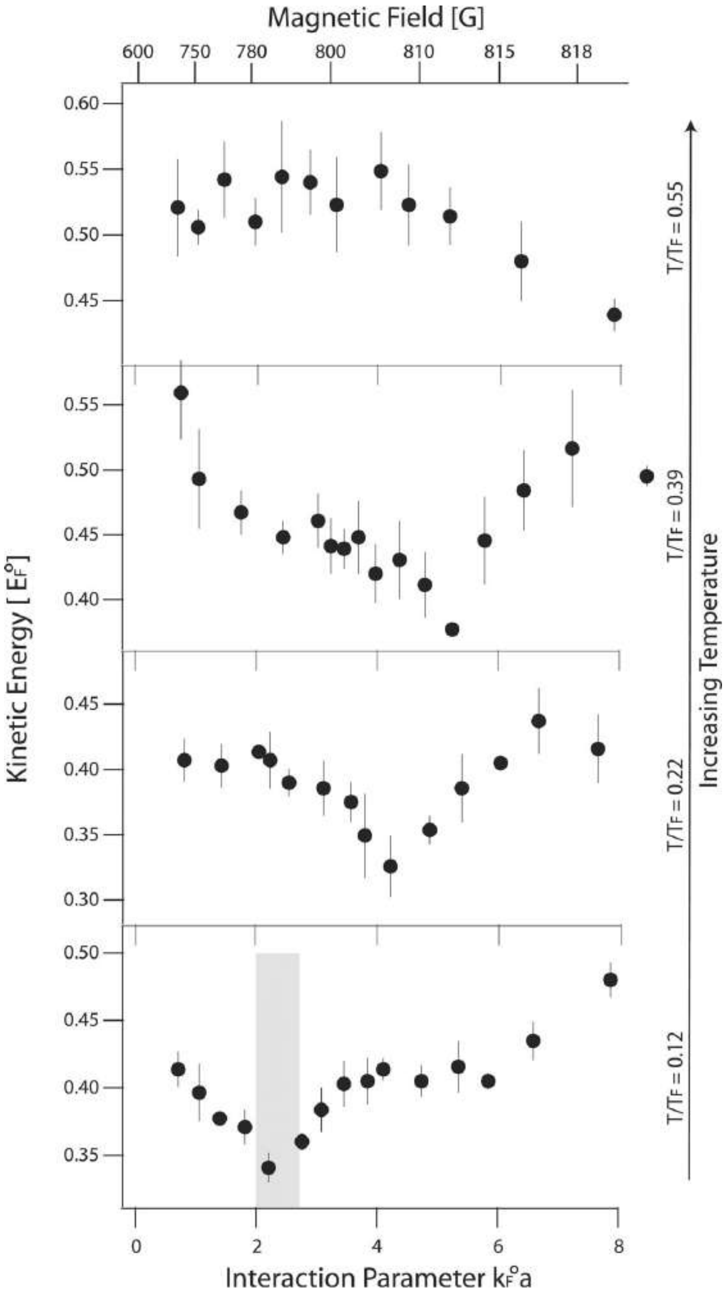
Two-body loss





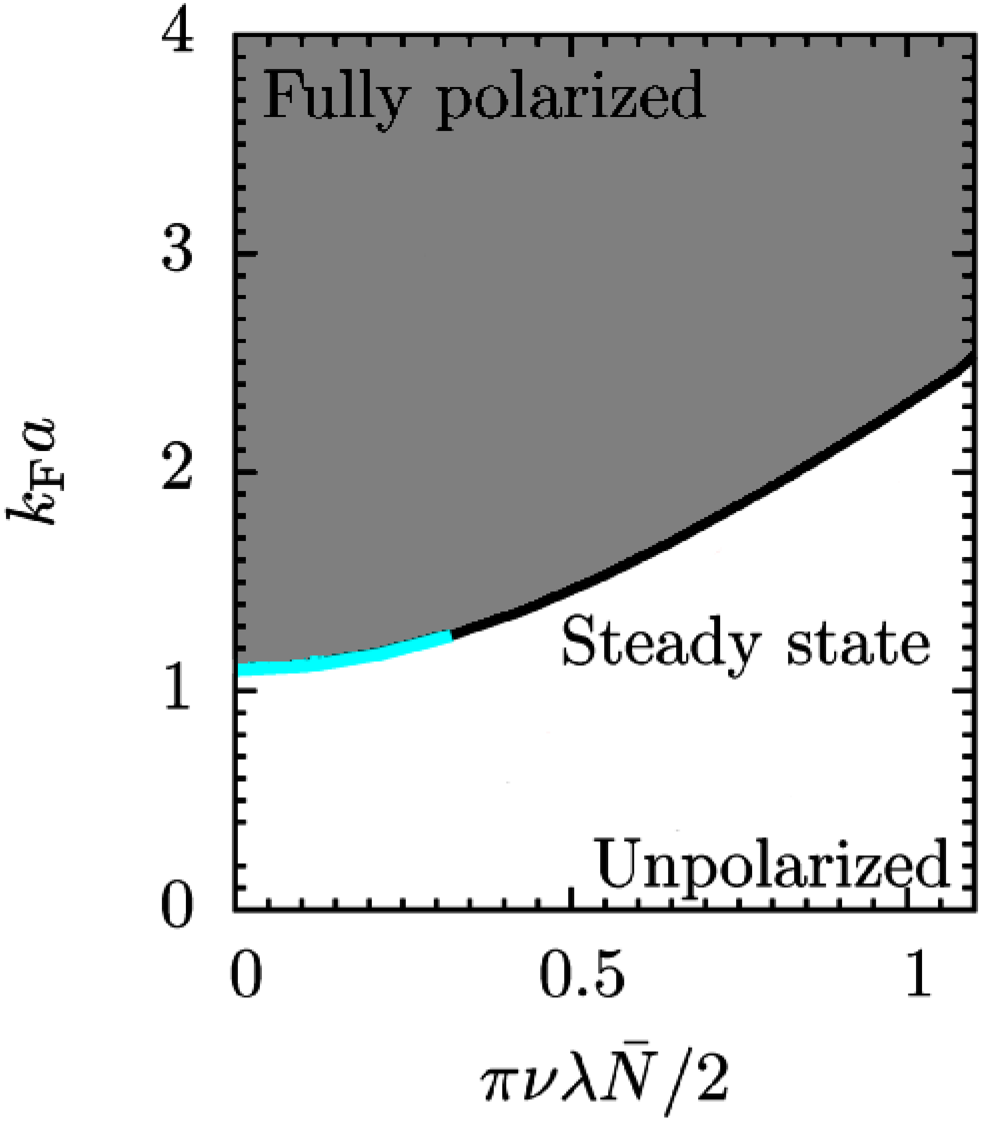
Two-body loss





Phase boundary with atom loss

- Atom loss raises the interaction strength required for ferromagnetism



Conduit & Altman, Phys. Rev. A **83**, 043618 (2011)

Outstanding questions

- Two-body competing instability
  [Pekker et al., Phys. Rev. Lett. **106**, 050402 (2011)]

- Three-body loss interaction renormalization
  [GJC & Altman, Phys. Rev. A **83**, 043618 (2011)]

- Instability of fully polarized gas with single spin impurity
  [Zhai, Phys. Rev. A **80**, 051605(R) (2009)]

- Instability of gas with contact interactions (Tan relations)
  [Barth & Zwerger, arXiv:1101.5594]

Outline: protocols to avoid loss

- Experimental results and mean-field analysis
- Competing many-body instabilities
- Experimental protocols that circumvent atom loss
  - Collective modes within a spin spiral
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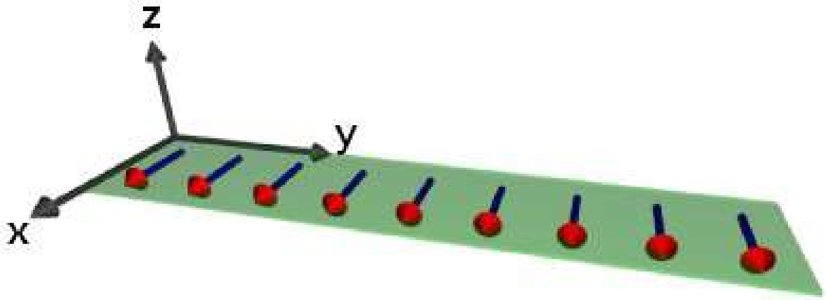
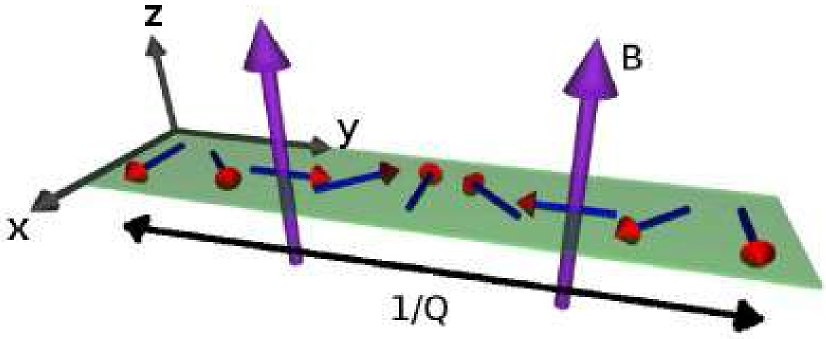
Alternative strategy: spin spiral

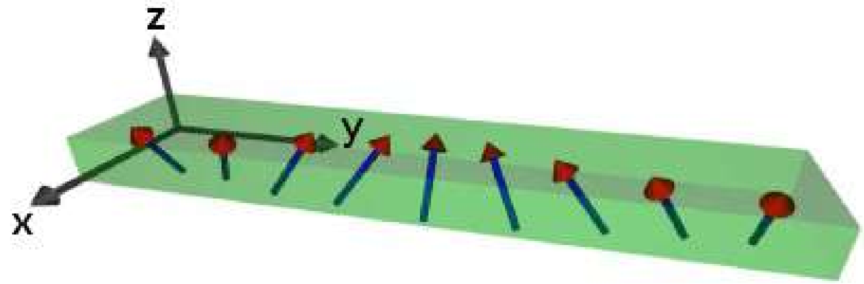
(a) Fully polarized state



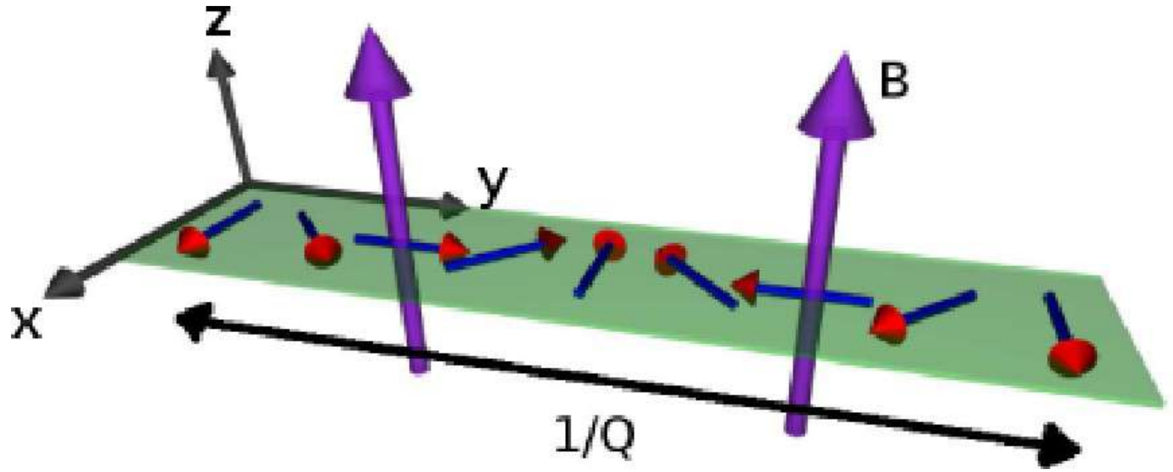
(b) Magnetic field gradient forms spin spiral



(c) Interactions cant the spiral



Heisenberg model



- Describe with Heisenberg Hamiltonian

$$\hat{H} = -J \sum_{i \neq j} \hat{S}_i \cdot \hat{S}_j$$

- Dispersion gives mode growth for $k < Q$ independent of sign of J

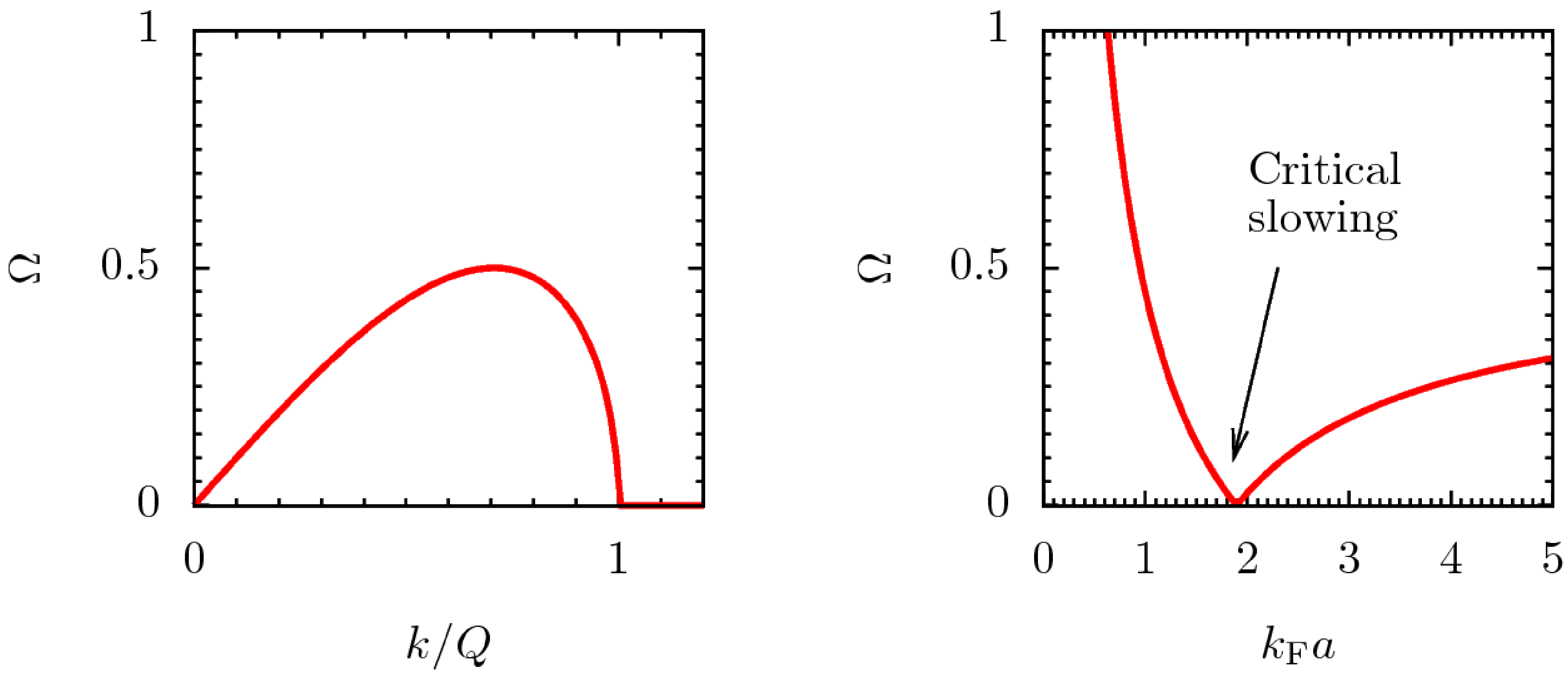
$$\Omega = \pm JSa^2 k \sqrt{Q^2 - k^2}$$

GJC & Altman, PRA **82**, 043603 (2010)

Spin spiral collective modes

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

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



Spin spiral collective modes

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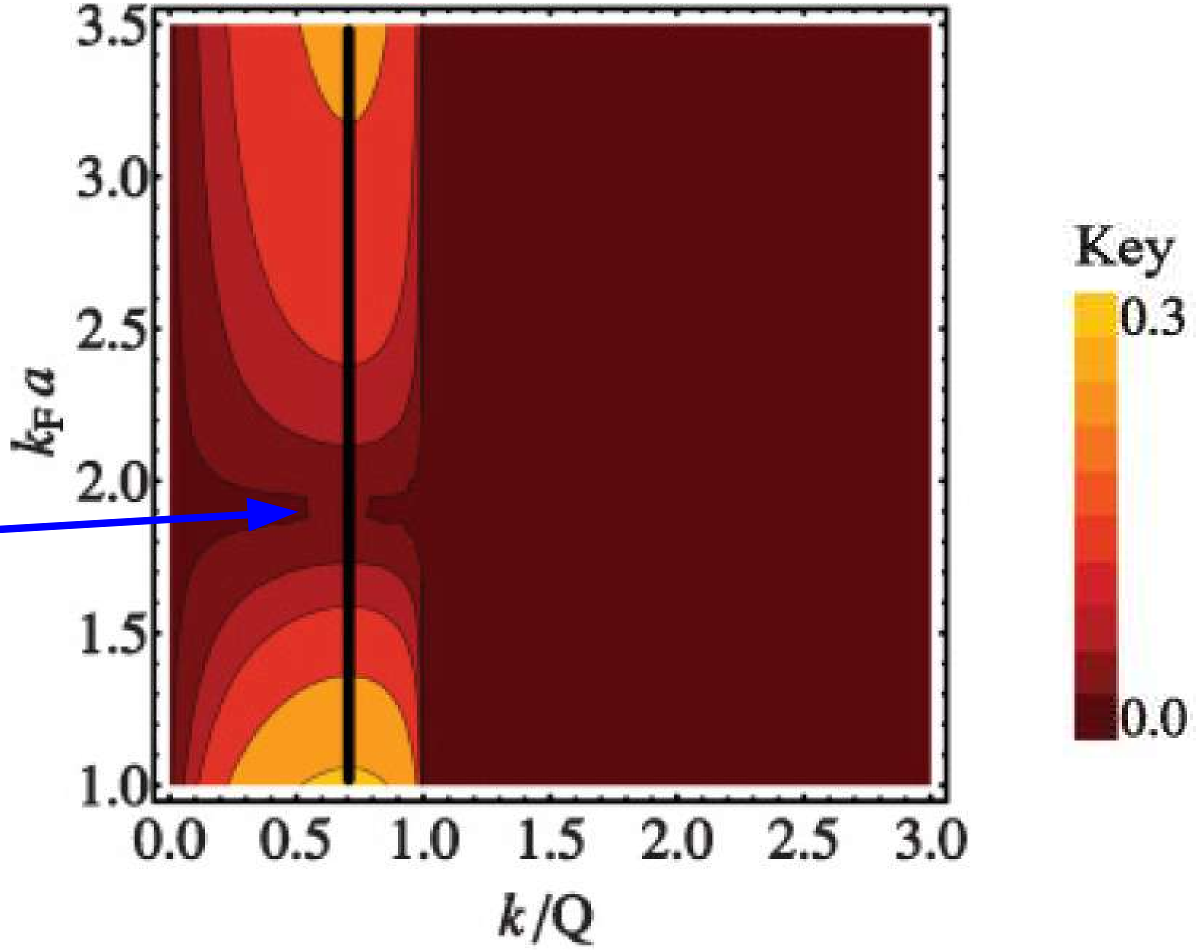
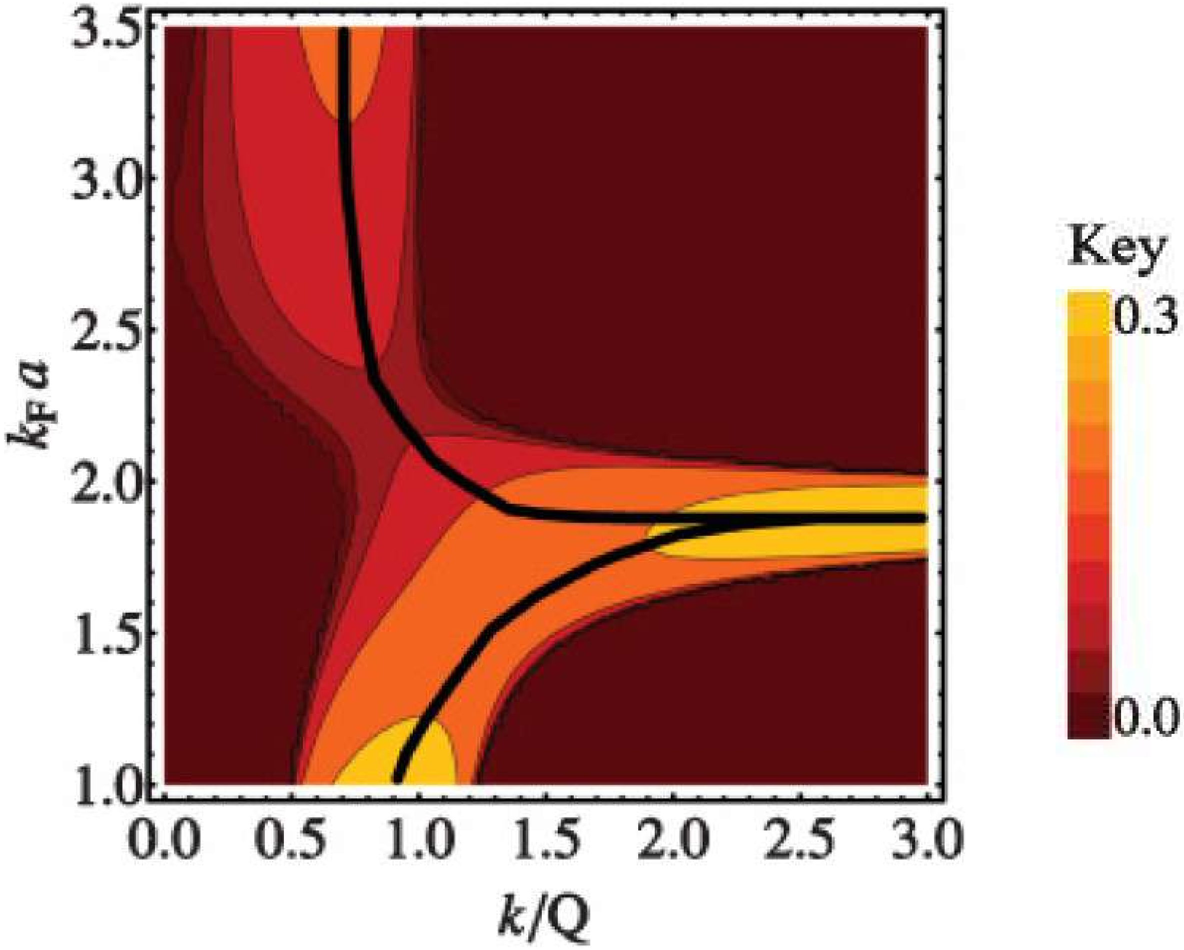
$$\Omega=\pm\left(\frac{1}{2}-\frac{2^{2/3}3}{5\mathrm{k}_F a}\right)k\sqrt{Q^2-k^2}$$



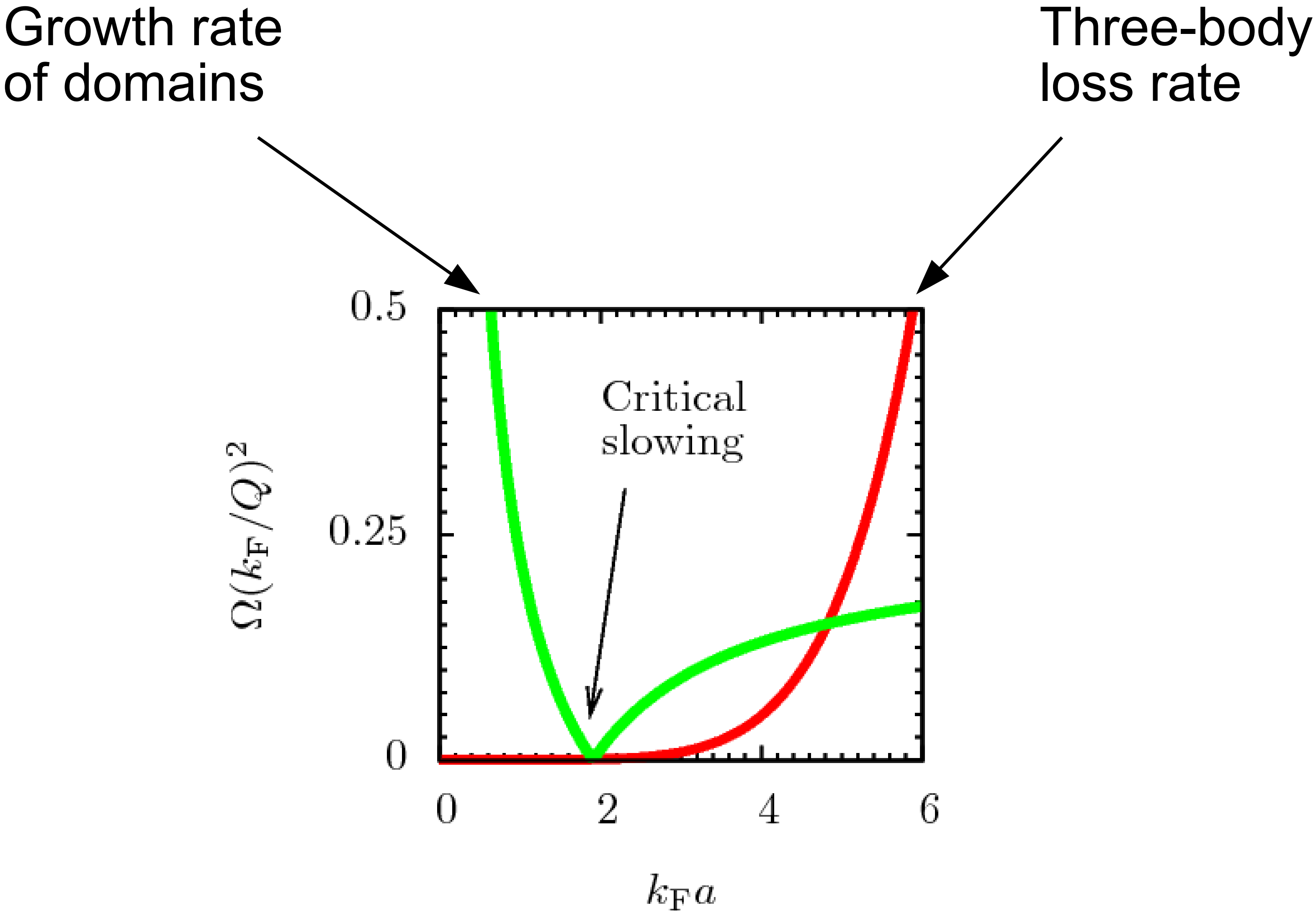
Critical slowing

Spin spiral collective modes

- Critical slowing down is eliminated and a new unstable branch develops
- Long-wavelength instabilities are quenched on the paramagnetic side of the transition



Overcoming loss

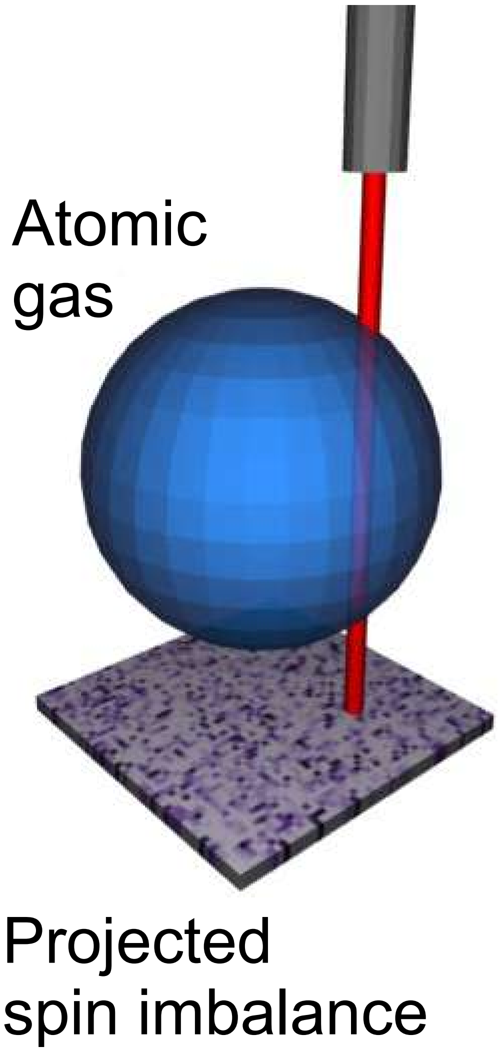


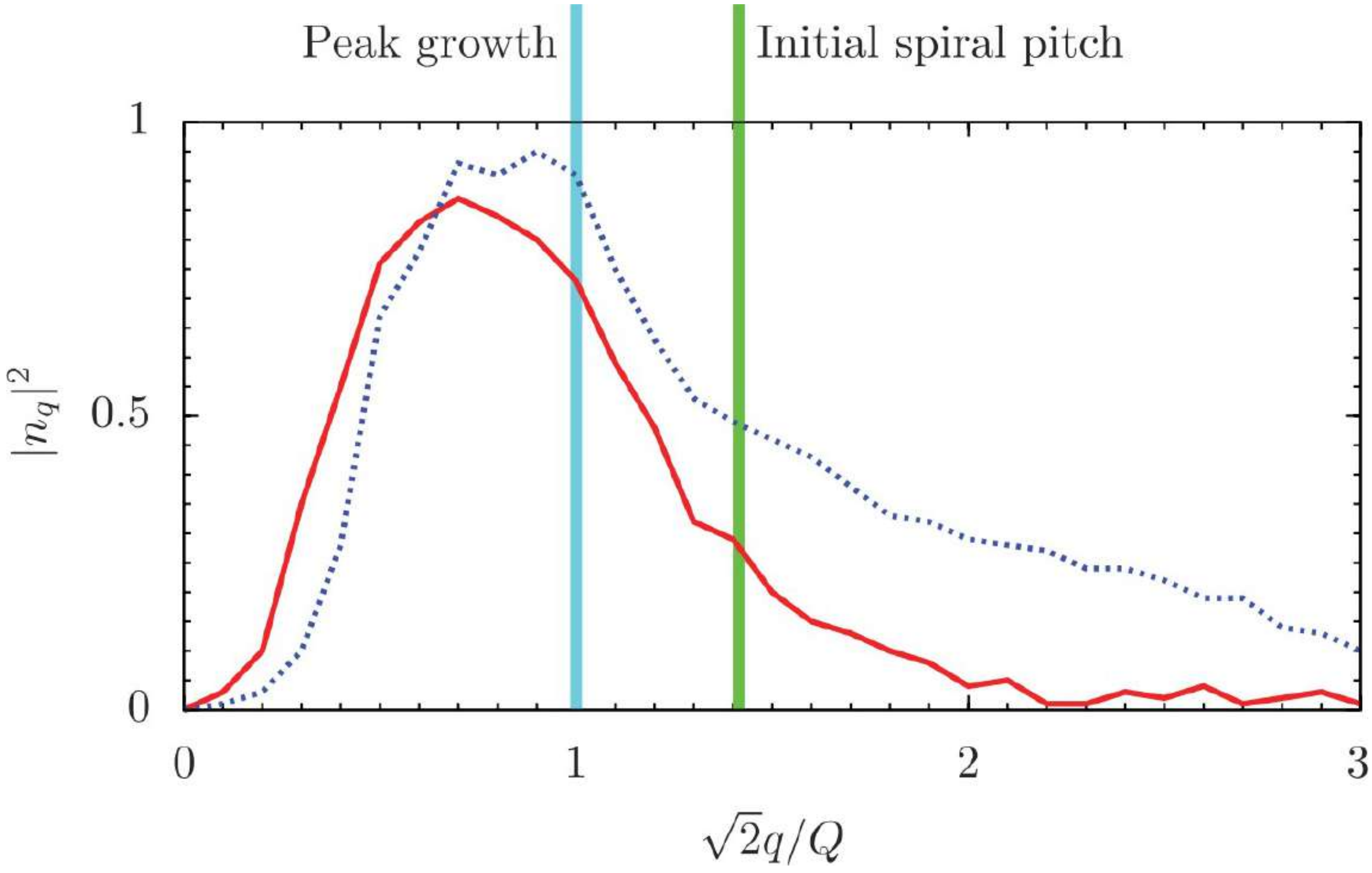
Growth rate
of domains

Three-body
loss rate

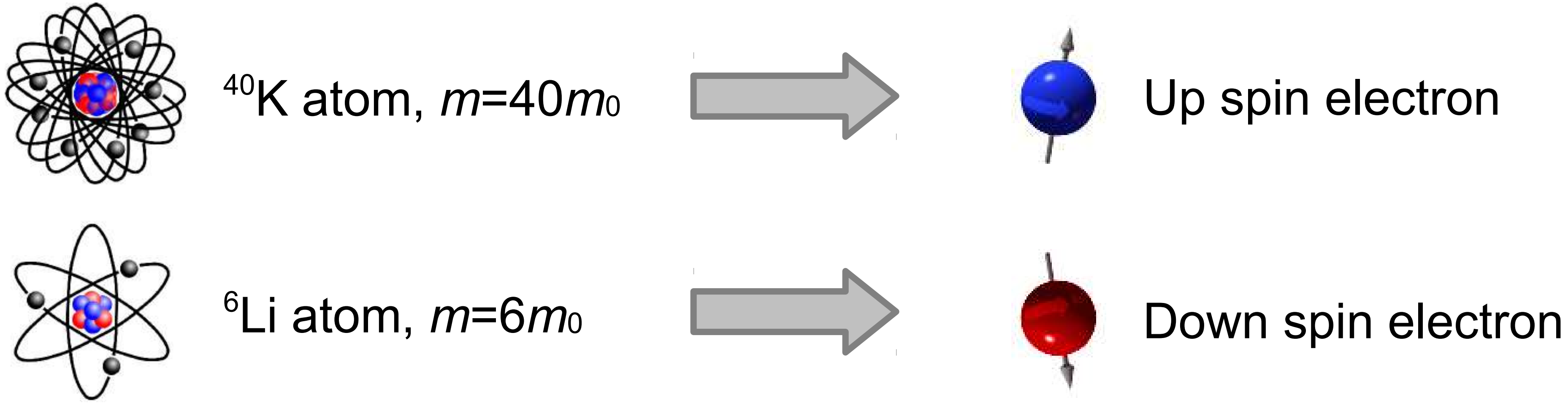
Phase-contrast imaging

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





Mass imbalance ferromagnetism



^{40}K atom, m=40m_0

Up spin electron

^{6}Li atom, m=6m_0

Down spin electron

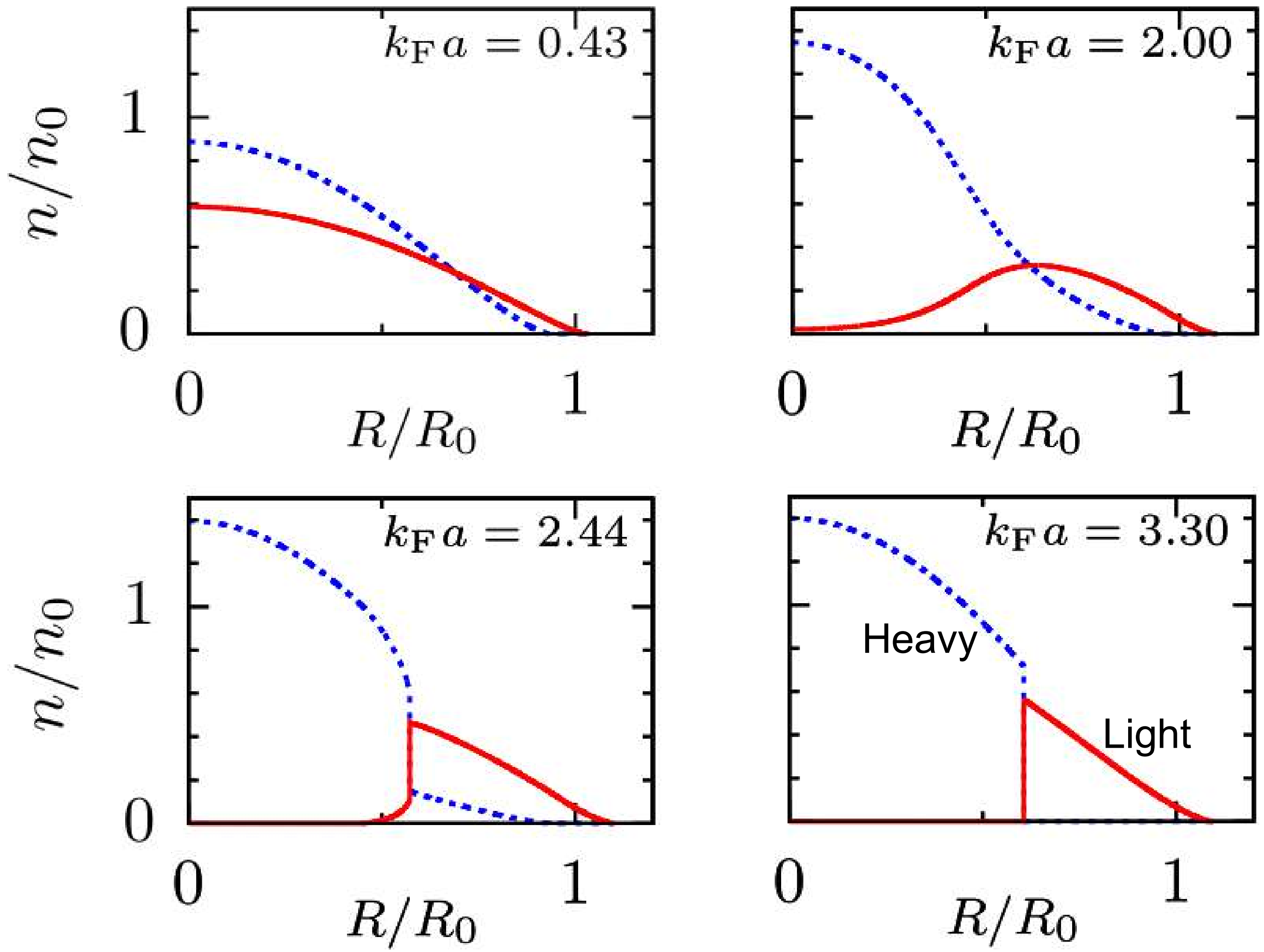
$$\hat{H}=\sum_{\boldsymbol{k}}\frac{k^2}{2\mathrm{m}_\uparrow}c^\dagger_{\boldsymbol{k}\uparrow}c_{\boldsymbol{k}\uparrow}+\sum_{\boldsymbol{k}}\frac{k^2}{2\mathrm{m}_\downarrow}c^\dagger_{\boldsymbol{k}\downarrow}c_{\boldsymbol{k}\downarrow}+g\sum_{\boldsymbol{k}\boldsymbol{k}'\boldsymbol{q}}c^\dagger_{\boldsymbol{k}\uparrow}c^\dagger_{\boldsymbol{k}'+\boldsymbol{q}\downarrow}c_{\boldsymbol{k}'+\boldsymbol{q}\downarrow}c_{\boldsymbol{k}'\uparrow}$$

- Magnetic moment formed along quantization axis

Keyserlingk & GJC, accepted for PRA

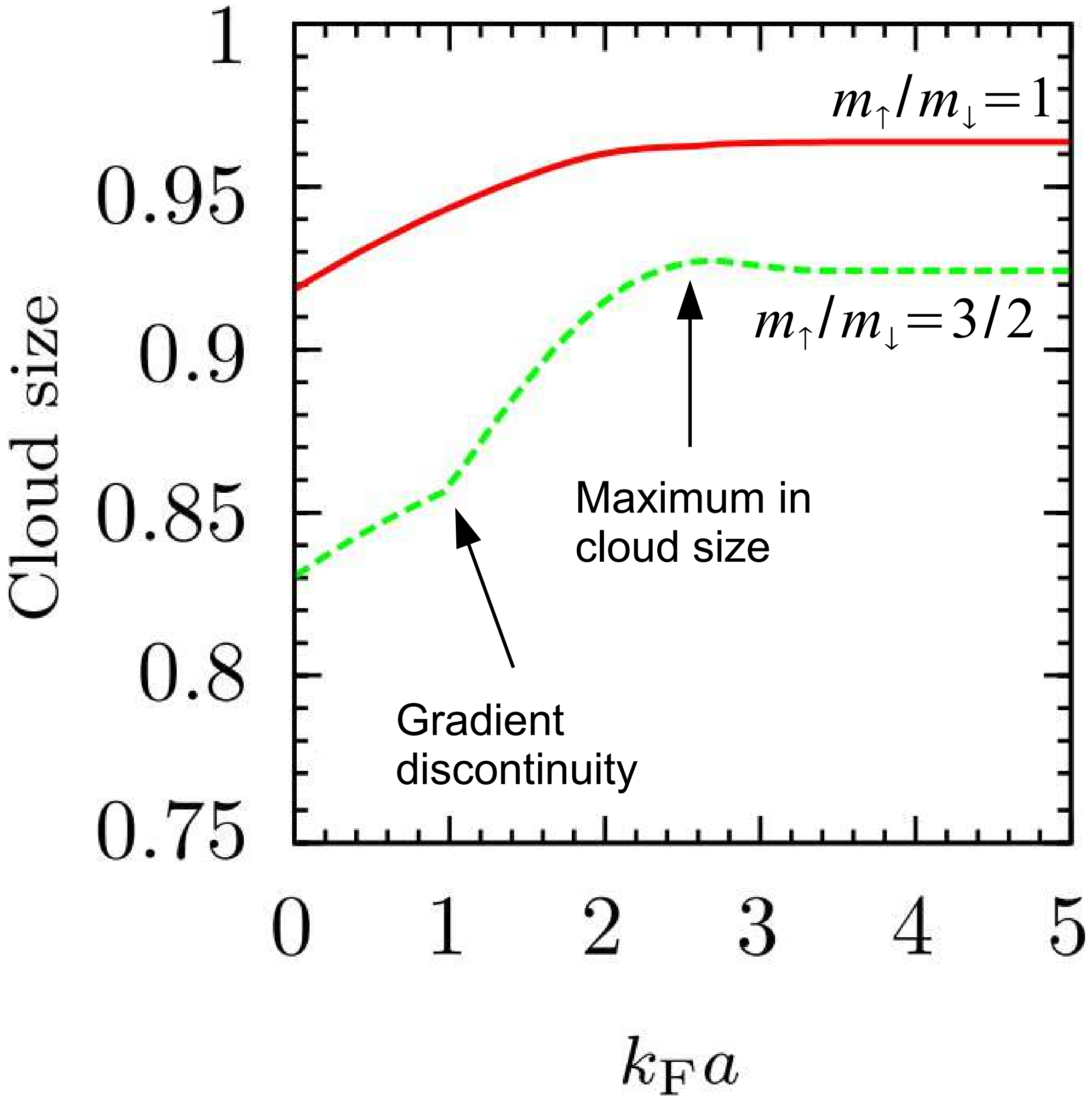
Behavior in a trap

- 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

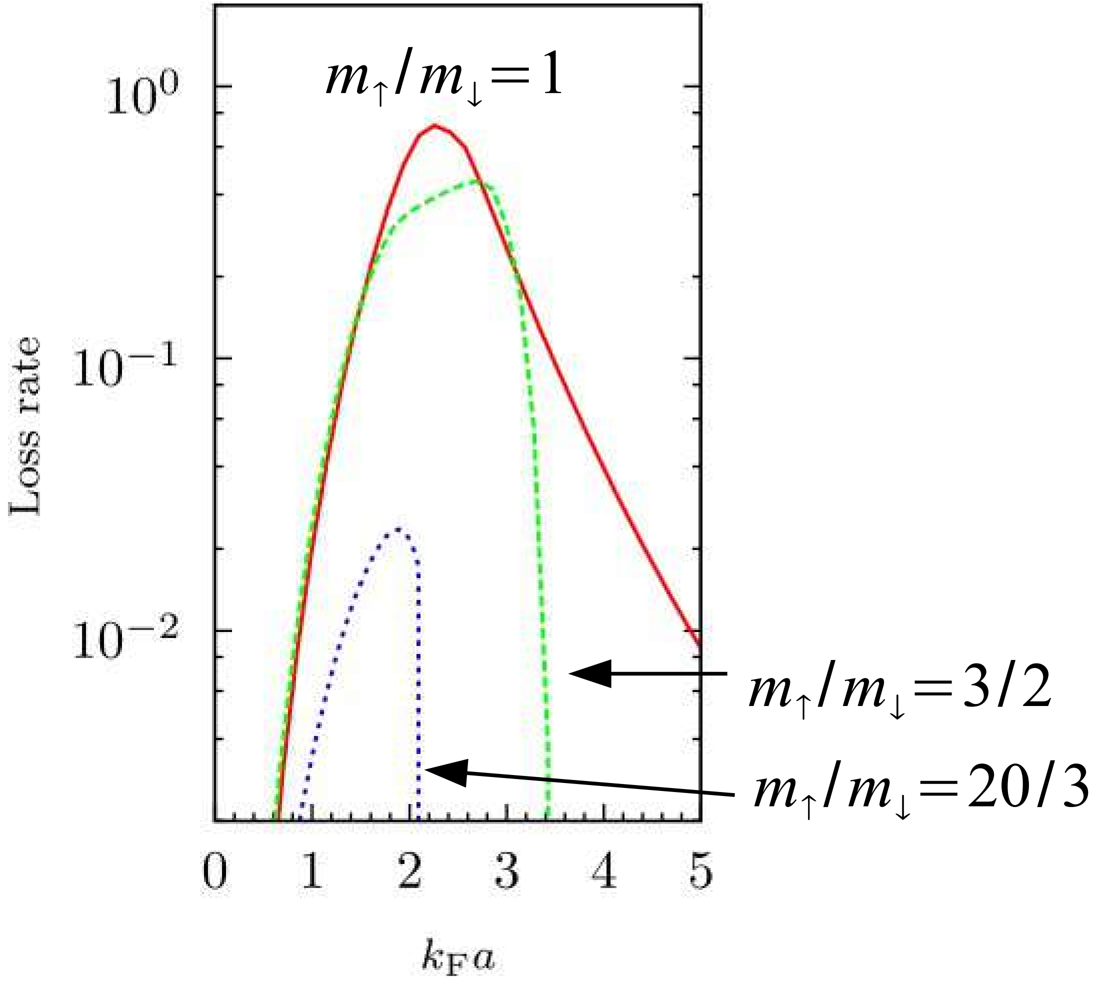


Maximum in cloud size

Gradient discontinuity

Reduced three-body losses

- Dramatically reduced three-body loss



Summary

- Equilibrium theory provides a reasonable qualitative description of the transition

- Competing many-body instabilities provide alternative explanation

- 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