UNIVERSITY OF CAMBRIDGE

Cold atoms in a spin

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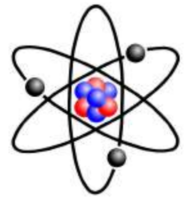
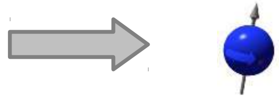
Ketterle's experiment



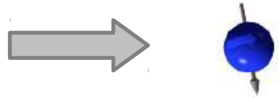
^{6}Li atom

$|F = 1/2, m_F = 1/2\rangle$



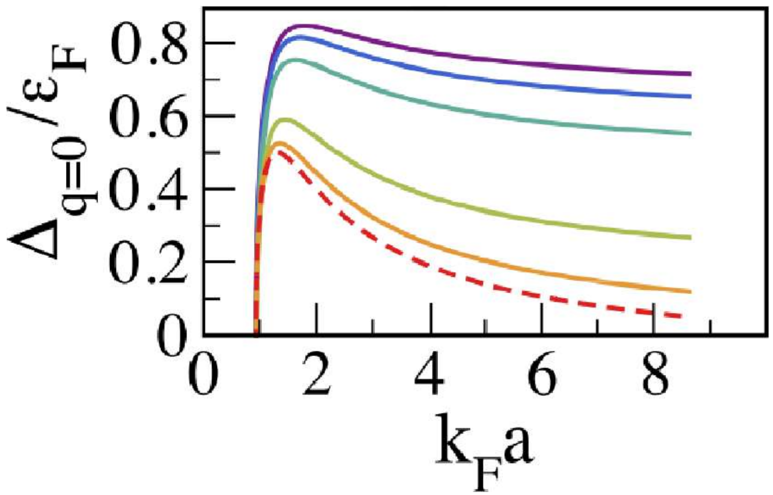
Up spin electron

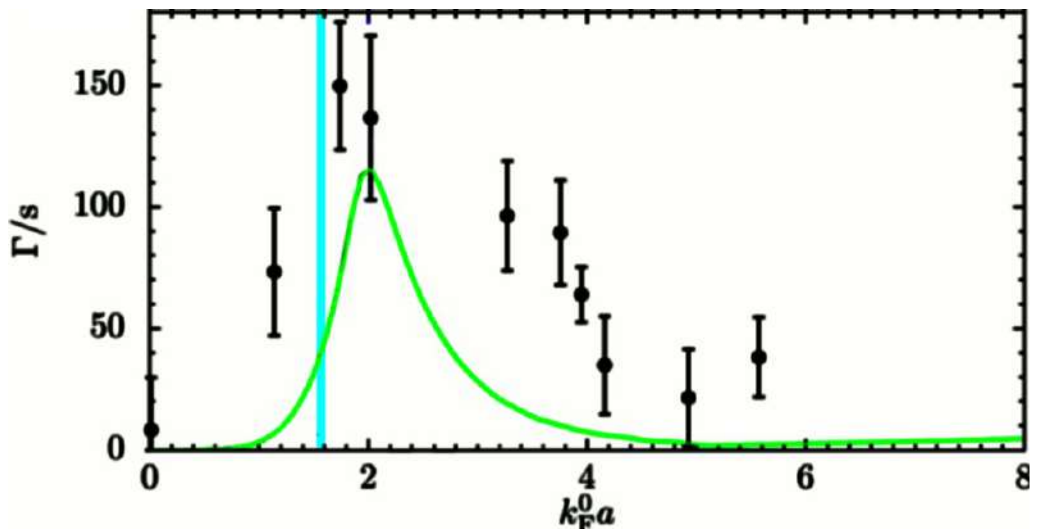
$|F = 1/2, m_F = -1/2\rangle$



Down spin electron

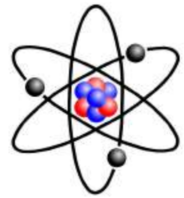
$$\Gamma = \Gamma_0 (k_F a)^6 n_\uparrow n_\downarrow (n_\uparrow + n_\downarrow)$$





Jo *et al*, Science **325**, 1521 (2009); GJC & Simons PRL **103**, 200403 (2009)
Pekker et al, PRL **106**, 050402 (2011); Petrov, PRA **67**, 010703(R) (2003)

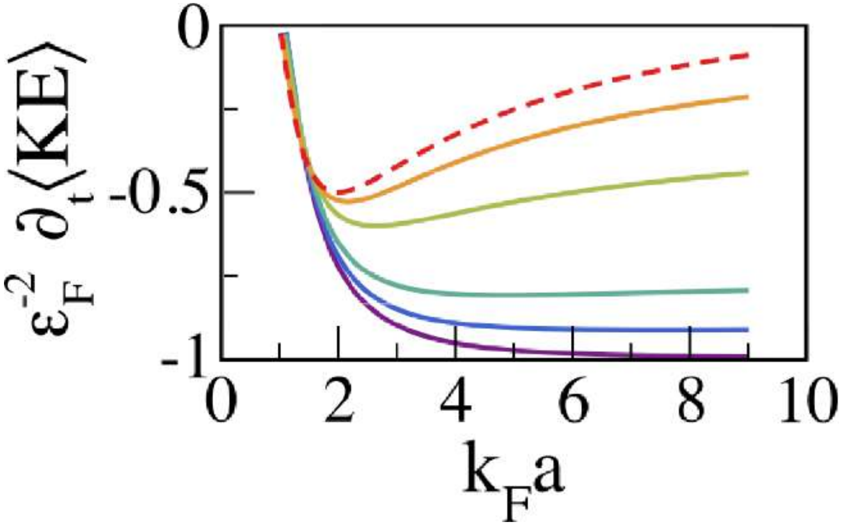
Ketterle's experiment

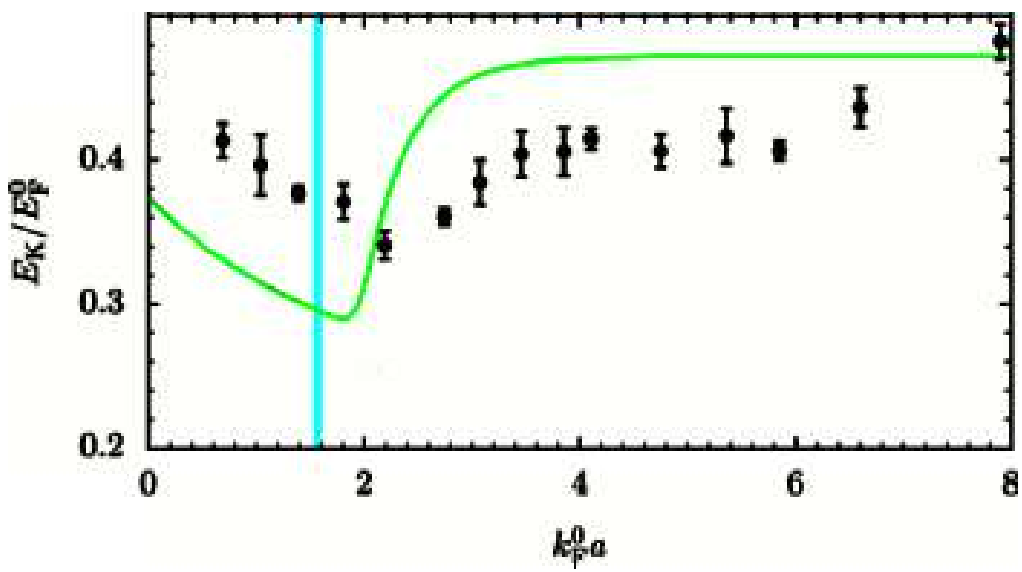


^{6}Li atom

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

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

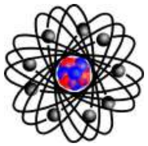




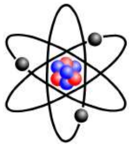
Mysteries about magnetism

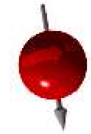
- Competing many-body instabilities
  Pekker *et al*, PRL **106**, 050402 (2011)
- Absence of domains
  Ho in "Magnetized Gas Points to New Physics", Science (2009)
- Tan relations
  Barth & Zwerger, Annals of Physics **326**, 2544 (2011)
- Instability of fully polarized state
  Zhai, PRA **80**, 051605 (2009)
- Textured phases
  Uhlarz, Pfleiderer & Hayden, PRL **93**, 256404 (2004)
  GJC, Green & Simons, PRL **103**, 207201 (2009)

Mass imbalance ferromagnetism



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

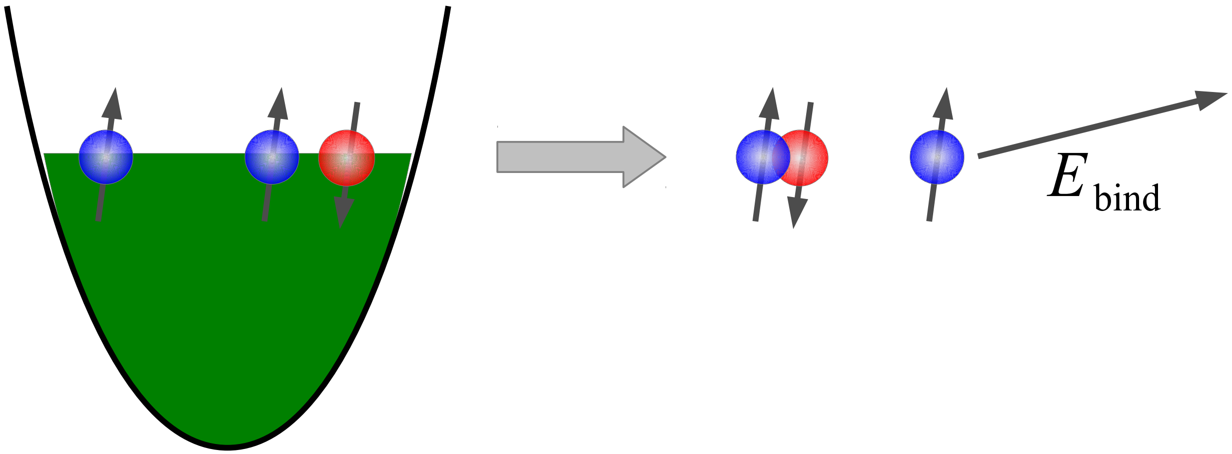


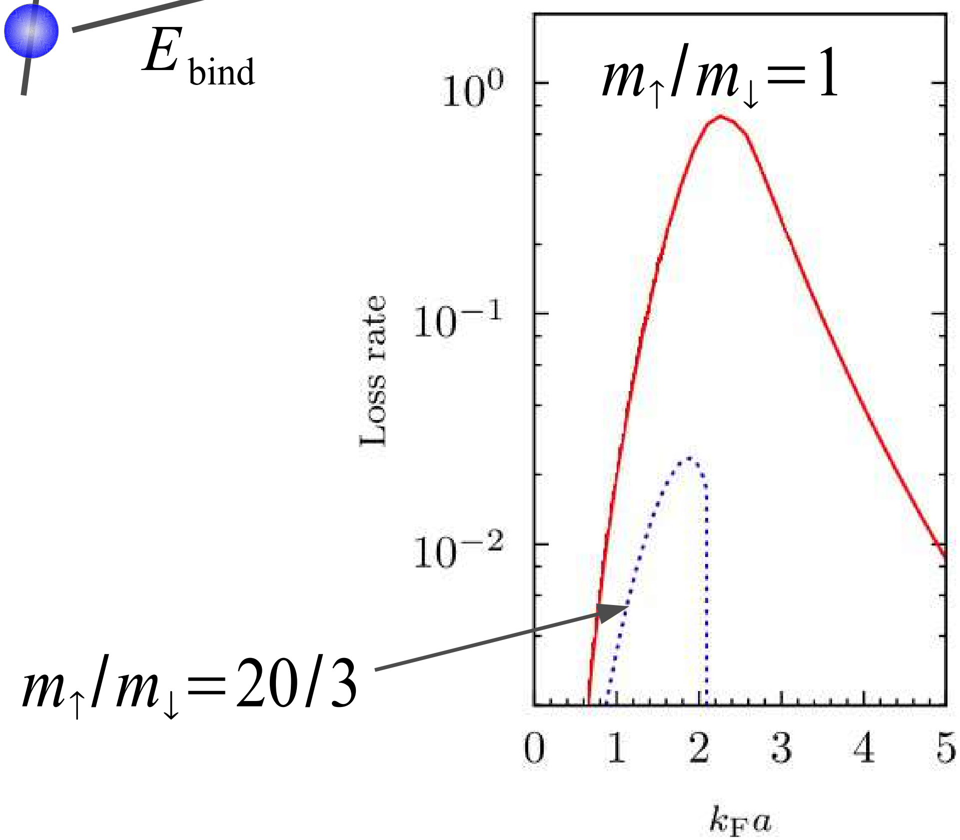
^{6}Li atom, m=6m_0 →  Down spin electron

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

- Two and three-body losses suppressed
  Keyserlingk & GJC, PRA **83**, 053625 (2011)
- Phase separates into just two domains
  Keyserlingk & GJC, PRA **83**, 053625 (2011)
- Experimental procedure used to study polarons
  Kohstall et al, arXiv:1112.0020; Massignan & Brunn, Eur. Phys. J D 65, 83 (2011); Massignan arXiv:1112.1029

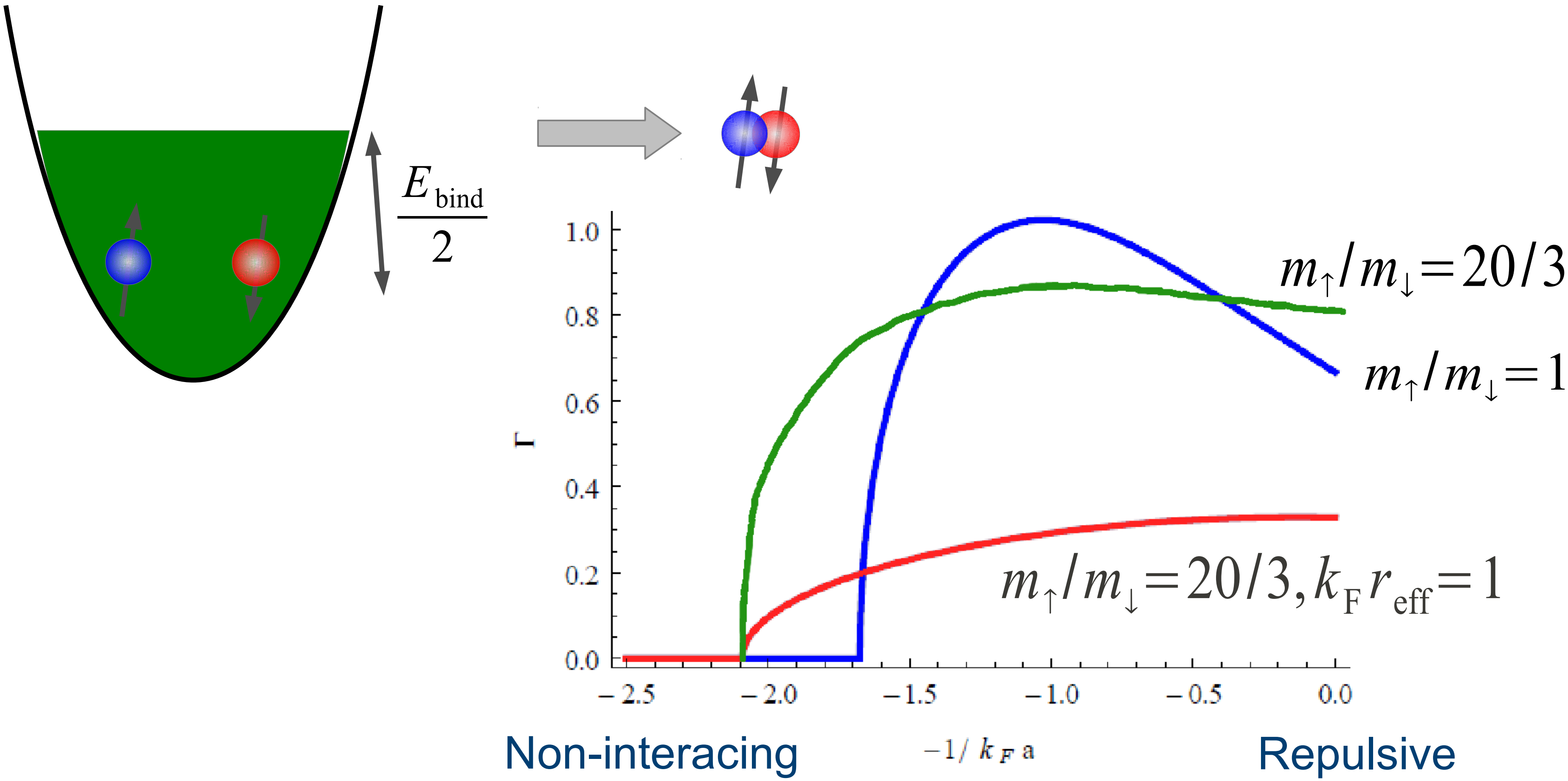
Three-body loss





Petrov, PRA **67**, 010703(R) (2003)
Keyserlingk & GJC, PRA **83**, 053625 (2011)

Two-body loss



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

Magnetization instabilities

- Energy change due to magnetization $\delta m_z^{\omega,\vec{q}}$ and $\delta m_\perp^{\omega,\vec{q}}$

$$\delta E = g \sum_{\omega,\vec{q}} \left|\delta m_z^{\omega,\vec{q}}\right|^2 \left[1 - \frac{g}{2}\left(\Pi_{\uparrow\downarrow}^{\omega,\vec{q}} + \Pi_{\downarrow\uparrow}^{\omega,\vec{q}}\right)\right] + g \sum_{\omega,\vec{q}} \left|\delta m_\perp^{\omega,\vec{q}}\right|^2 \left[\frac{1 - g^2 \Pi_{\uparrow\uparrow}^{\omega,\vec{q}} \Pi_{\downarrow\downarrow}^{\omega,\vec{q}}}{1 - g\left(\Pi_{\uparrow\uparrow}^{\omega,\vec{q}} + \Pi_{\downarrow\downarrow}^{\omega,\vec{q}}\right)/2}\right]$$

Stoner instability

- Energy change due to magnetization $\delta m_z^{\omega,\vec{q}}$ and $\delta m_\perp^{\omega,\vec{q}}$

$$\delta E = g \sum_{\omega,\vec{q}} \left|\delta m_z^{\omega,\vec{q}}\right|^2 \left[1 - \frac{g}{2}\left(\Pi_{\uparrow\downarrow}^{\omega,\vec{q}} + \Pi_{\downarrow\uparrow}^{\omega,\vec{q}}\right)\right] + g \sum_{\omega,\vec{q}} \left|\delta m_\perp^{\omega,\vec{q}}\right|^2 \left[\frac{1 - g^2 \Pi_{\uparrow\uparrow}^{\omega,\vec{q}} \Pi_{\downarrow\downarrow}^{\omega,\vec{q}}}{1 - g\left(\Pi_{\uparrow\uparrow}^{\omega,\vec{q}} + \Pi_{\downarrow\downarrow}^{\omega,\vec{q}}\right)/2}\right]$$

- Instability to phase separation

$$g\left(\nu_\uparrow \nu_\downarrow\right)^{1/2} = 1$$

Magnetization texture

- Energy change due to magnetization $\delta m_z^{\omega,\vec{q}}$ and $\delta m_\perp^{\omega,\vec{q}}$

$$\delta E = g \sum_{\omega,\vec{q}} \left|\delta m_z^{\omega,\vec{q}}\right|^2 \left[1 - \frac{g}{2}\left(\Pi_{\uparrow\downarrow}^{\omega,\vec{q}} + \Pi_{\downarrow\uparrow}^{\omega,\vec{q}}\right)\right] + g \sum_{\omega,\vec{q}} \left|\delta m_\perp^{\omega,\vec{q}}\right|^2 \left[\frac{1 - g^2 \Pi_{\uparrow\uparrow}^{\omega,\vec{q}} \Pi_{\downarrow\downarrow}^{\omega,\vec{q}}}{1 - g\left(\Pi_{\uparrow\uparrow}^{\omega,\vec{q}} + \Pi_{\downarrow\downarrow}^{\omega,\vec{q}}\right)/2}\right]$$

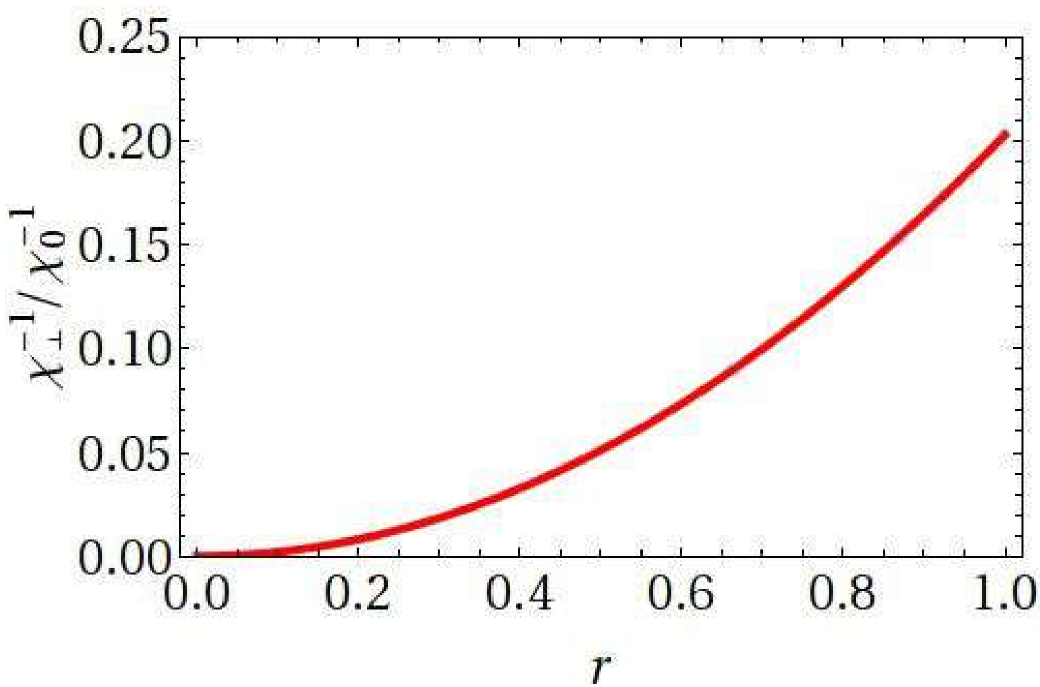
- Instability to textured phase

$$g(\nu_\uparrow \nu_\downarrow)^{1/2} = 1 + \frac{q^2}{24 p_{F\uparrow}^2} + \frac{q^2}{24 p_{F\downarrow}^2}$$

Orientation of magnetization

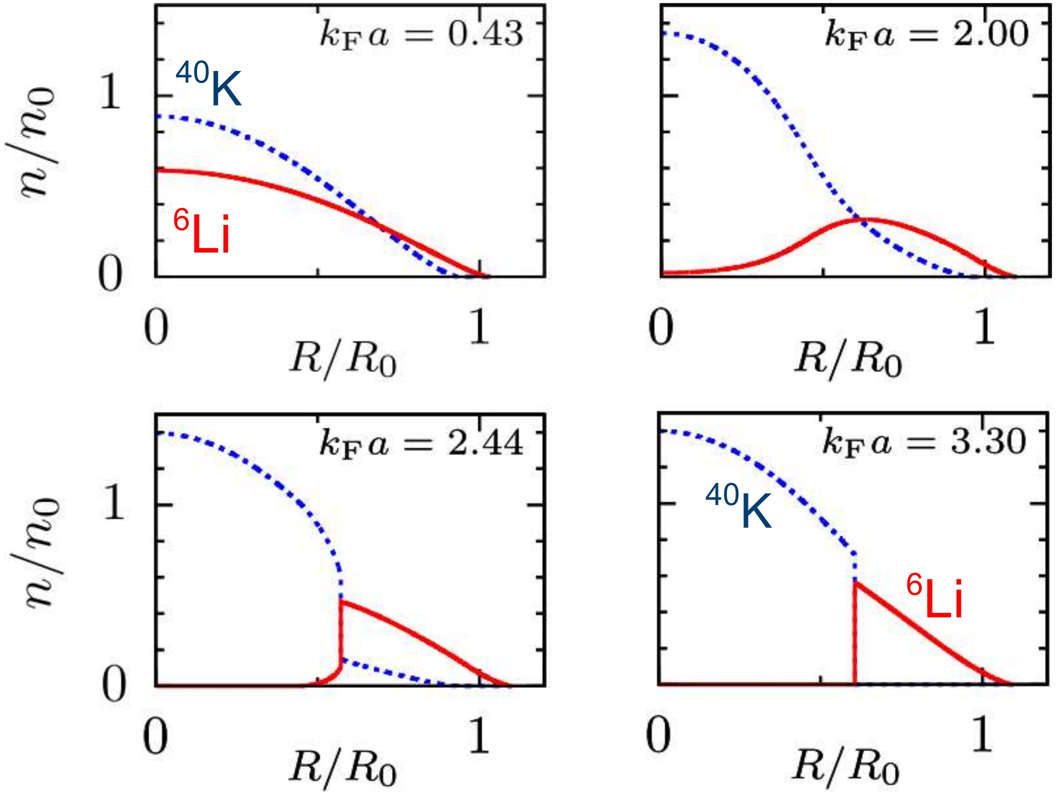
- Instability to magnetization in x-y plane

$$\chi_{\perp}^{-1} > \chi_0^{-1}\left(\frac{36\,r^2}{175} - \frac{8\,|r^3|}{2625}\right) > 0 \qquad r = \frac{m_1 - m_2}{m_1 + m_2} \qquad 0 \leqslant |r| \leqslant 1$$

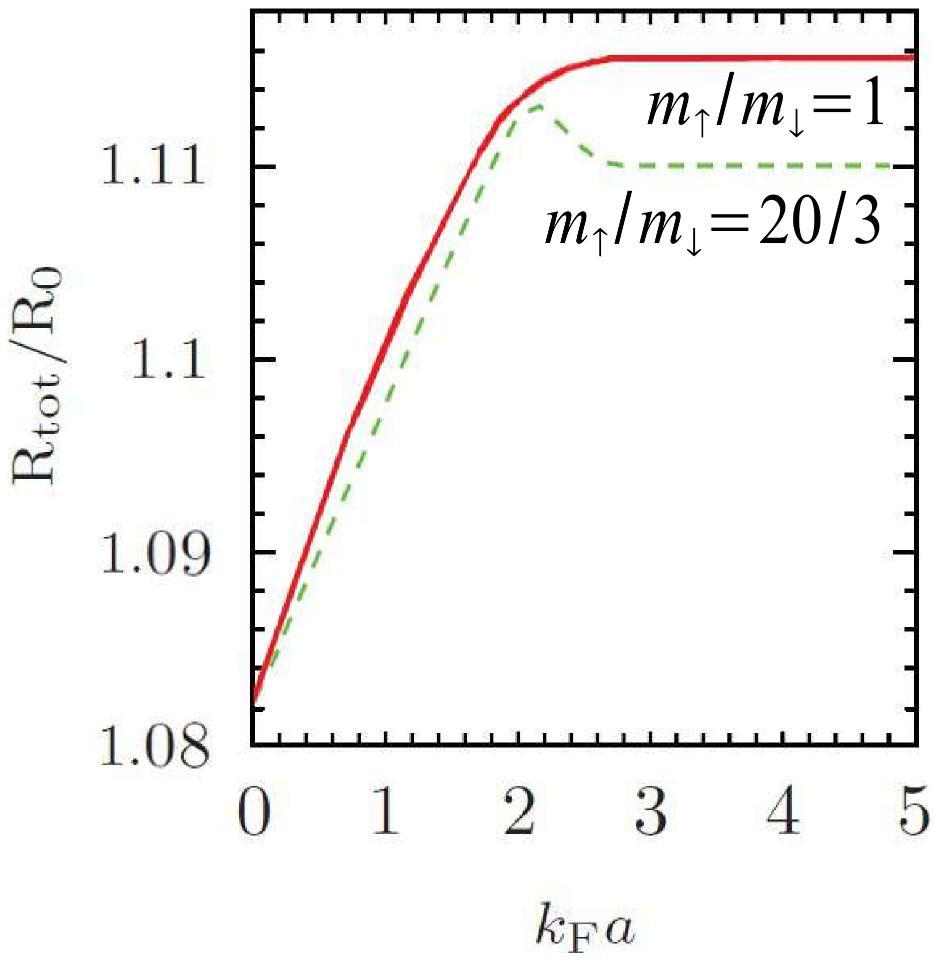


Trapped behavior

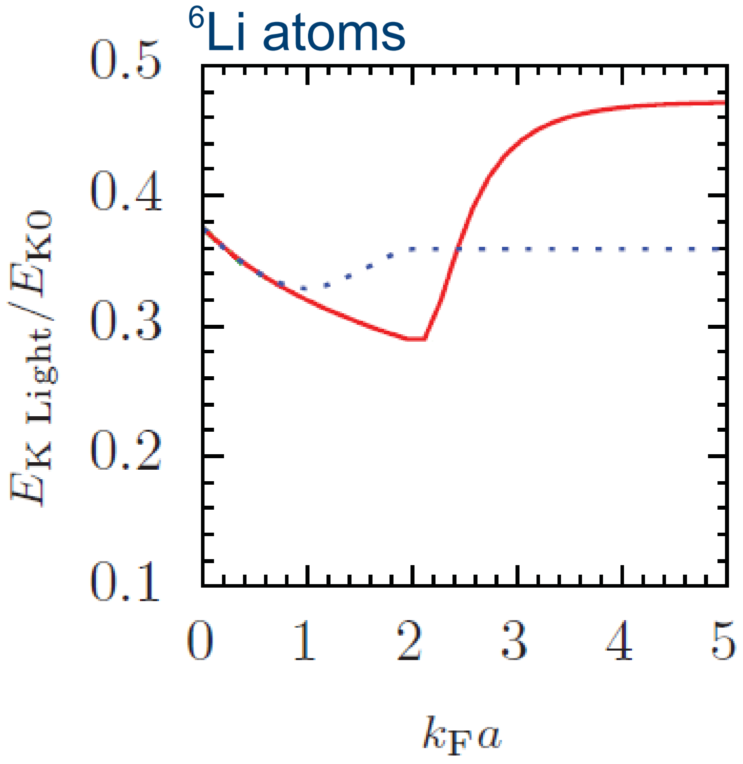
- At zero interaction strength atoms spread all over trap, at high interaction strength light atoms forced to outside

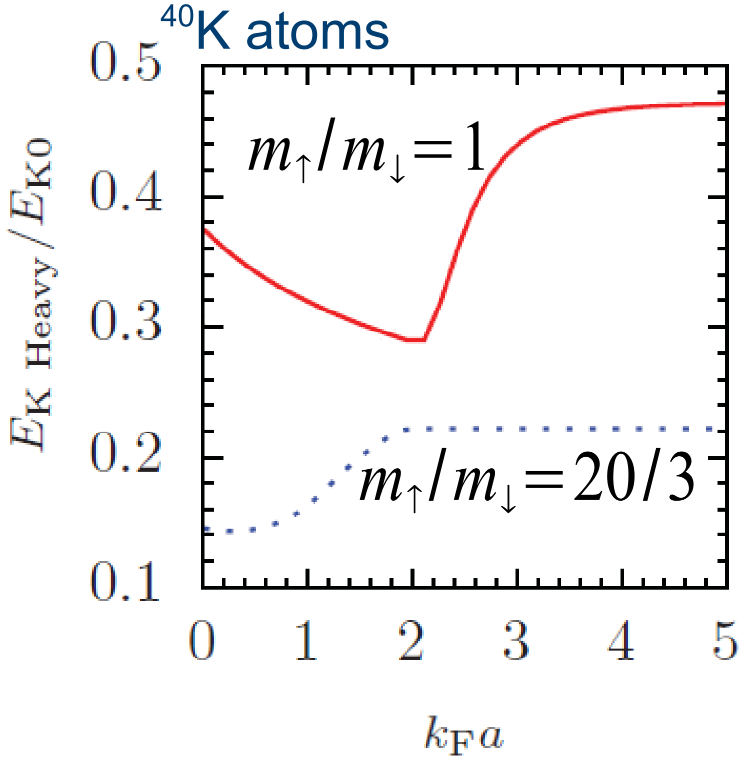


Cloud size maximum



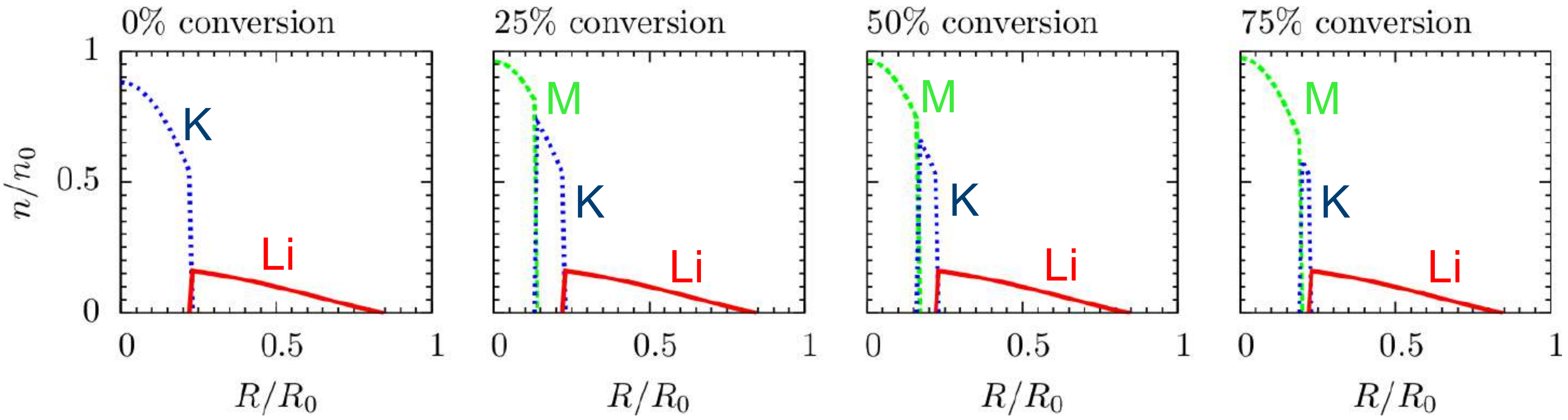
Kinetic energy plots



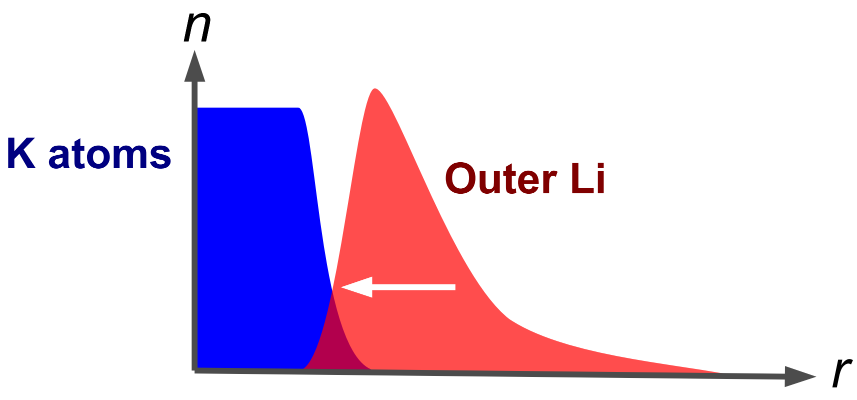


Trapped behavior

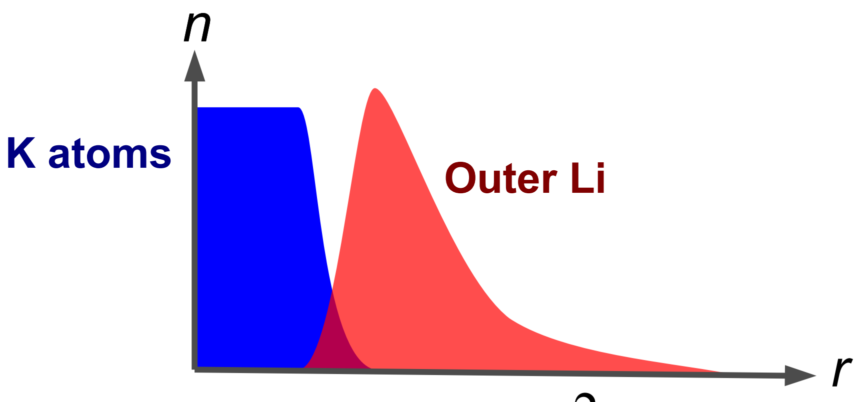
- Heavier molecules reside at trap center



Are losses responsible for phase separation?



Is Li-K repulsion responsible for phase separation?



$$P_{\mathrm{K}} = n_{\mathrm{K}} T_{\mathrm{K}} \qquad P_{\mathrm{Li}} = \frac{2}{5} n_{\mathrm{Li}} T_{\mathrm{F,Li}}$$

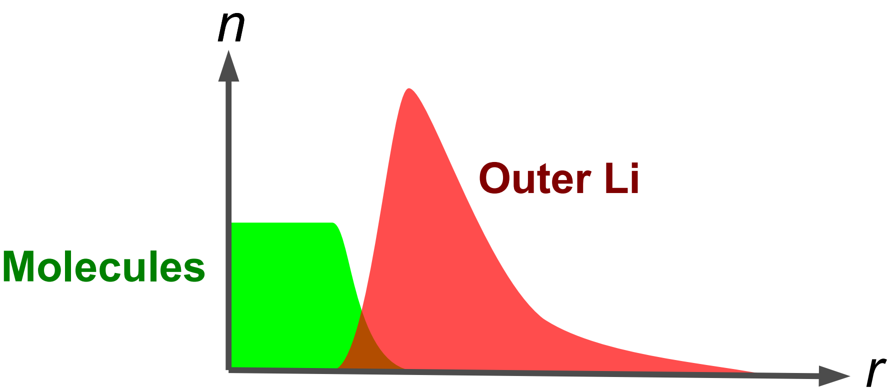
- Temperature is $T_{\mathrm{K}} \approx 0.3\, T_{\mathrm{F,Li}}$
- Density of atoms is $n_{\mathrm{K}} \approx 0.5 \mathrm{n}_{\mathrm{Li}}$.

$$\frac{P_{\mathrm{K}}}{P_{\mathrm{Li}}} = \frac{5}{2} \frac{n_{\mathrm{K}}}{n_{\mathrm{Li}}} \frac{T_{\mathrm{K}}}{T_{\mathrm{F,Li}}} \approx 0.4$$

Are the molecules responsible for phase separation?

- From the scattering lengths
  [Levinsen arXiv:1101.5979]

$$g_{\mathrm{Li-M}} \approx 0.98\, g_{\mathrm{Li-K}}$$
$$g_{\mathrm{K-M}} \approx 0.49\, g_{\mathrm{Li-K}}$$
$$g_{\mathrm{M-M}} \approx 0.057\, g_{\mathrm{Li-K}}$$

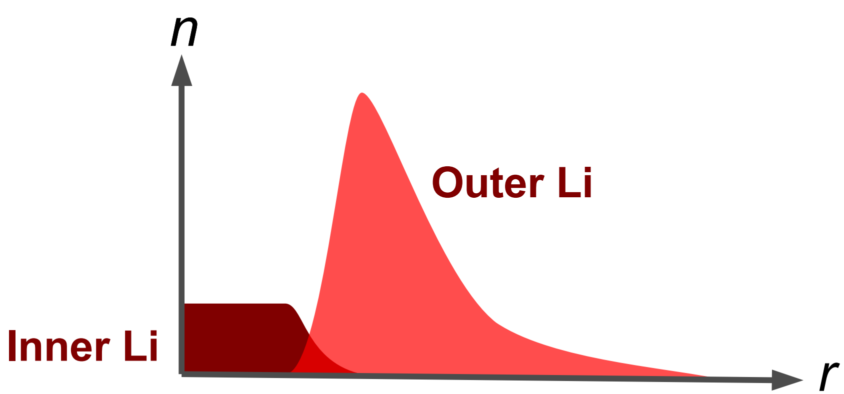


$$P_{\mathrm{M}} = n_{\mathrm{M}} T_{\mathrm{M}} \qquad P_{\mathrm{Li}} = \frac{2}{5} n_{\mathrm{Li}} T_{\mathrm{F,Li}}$$

- The Li-molecule *T*-matrix is similar to the Li-K *T*-matrix so the molecules also drive phase separation

$$\frac{P_{\mathrm{M}}}{P_{\mathrm{Li}}} \approx 0.4$$

Is heating responsible for phase separation?



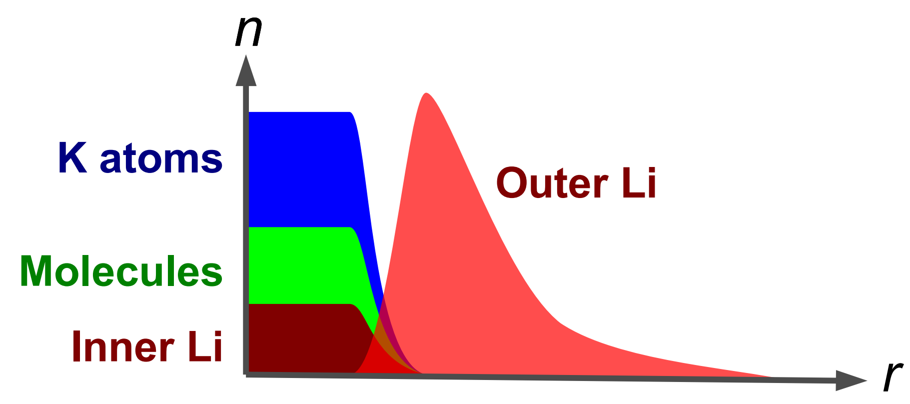
$P_{\mathrm{i}} = nT$ $\qquad$ $P_{\mathrm{Li}} = \frac{2}{5} n_{\mathrm{Li}} T_{\mathrm{F,Li}}$

- Inner classical gas, in thermal equilibrium with central K atoms with temperature $T_{\mathrm{K}} \approx 0.3\, T_{\mathrm{F,Li}}$ demands

  $n \approx 1.3\, n_{\mathrm{Li}}$

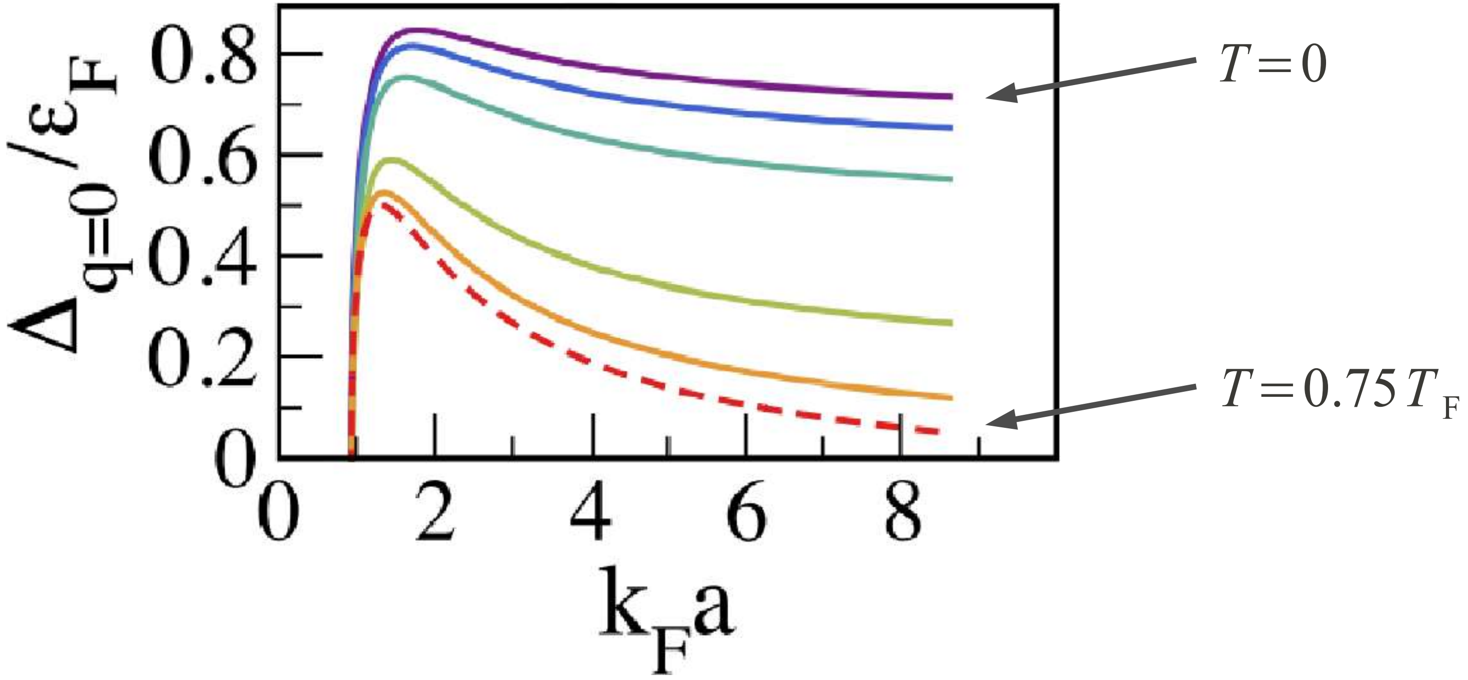
- Reactivation of losses also precludes heating mechanism

What drives phase separation?



- Repulsion from the inner K atom combined with molecules is sufficient to support phase separation
- Continual losses and heating appear negligible

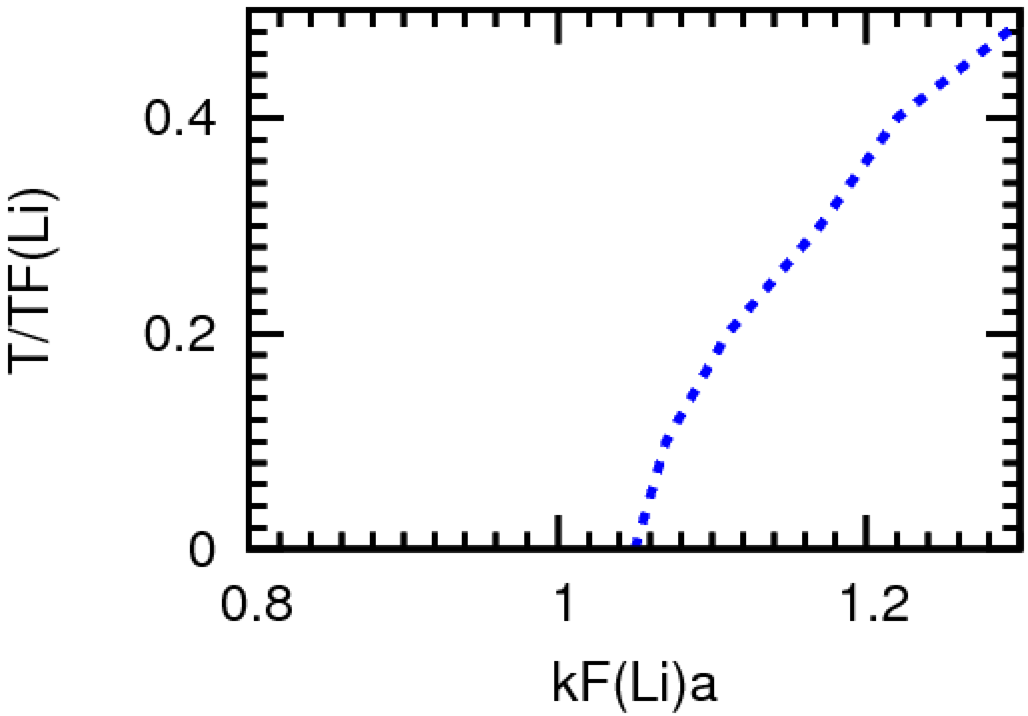
Pairing rate reduces with temperature



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

Magnetism at finite temperature

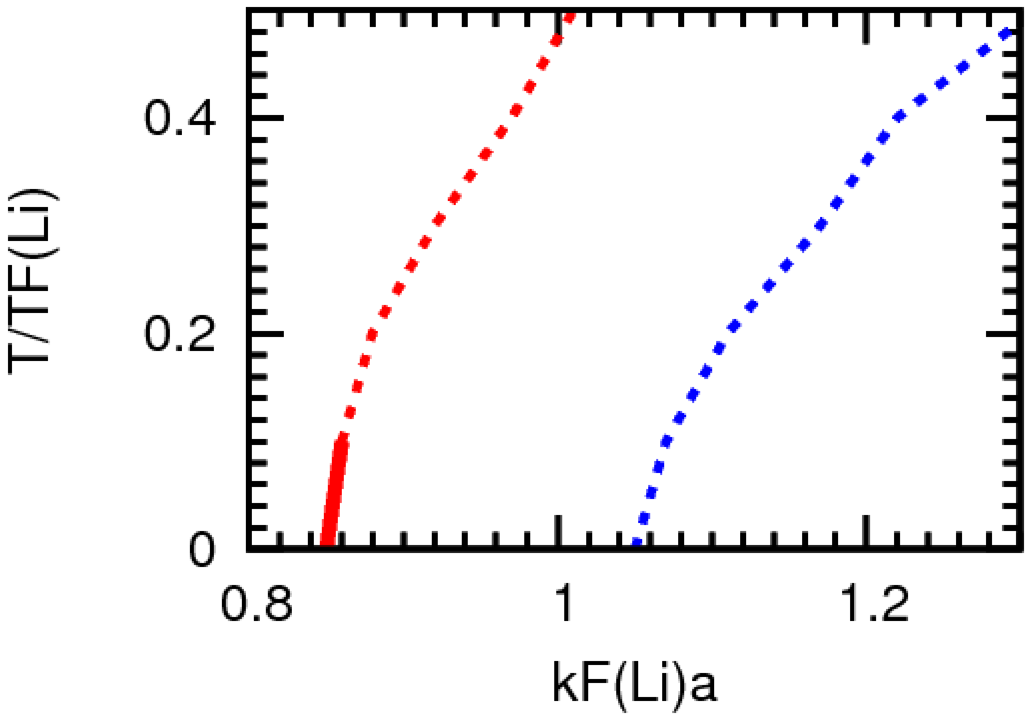
$$F = \frac{1}{V}\sum_{\vec{k},\sigma} \epsilon_{\vec{k},\sigma}\, n(\epsilon_{\vec{k},\sigma}) + \frac{2k_F a}{\pi \nu V^2} N_\uparrow N_\downarrow$$



GJC & Simons, PRA **79**, 053606 (2009)

Magnetism at finite temperature

$$F=\frac{1}{V}\sum_{\vec{k},\sigma}\epsilon_{\vec{k},\sigma}\,n(\epsilon_{\vec{k},\sigma})+\frac{2k_F a}{\pi\nu V^2}N_\uparrow N_\downarrow-\frac{2}{V^3}\left(\frac{2k_F a}{\pi\nu}\right)^2\frac{\sum_{\vec{k}_1,\vec{k}_2,\vec{k}_3,\vec{k}_4} n(\epsilon_{\vec{k}_1,\uparrow})\,n(\epsilon_{\vec{k}_2,\downarrow})[n(\epsilon_{\vec{k}_3,\uparrow})+n(\epsilon_{\vec{k}_4,\downarrow})]}{\epsilon_{\vec{k}_1,\uparrow}+\epsilon_{\vec{k}_2,\downarrow}-\epsilon_{\vec{k}_3,\uparrow}-\epsilon_{\vec{k}_4,\downarrow}}$$



GJC & Simons, PRA **79**, 053606 (2009)

Temperature reduced scattering cross-section

- Thermally averaged scattering cross-section
  Bruun & Smith, PRA **72**, 043605 (2005)

- $$\langle \sigma \rangle = \frac{\int d^3 p_1 d^3 p_2 f(p_1^2/2\mathrm{m}_1) f(p_2^2/2\mathrm{m}_2) \sigma(\vec{p}_\mathrm{r})}{\int d^3 p_1 d^3 p_2 f(p_1^2/2\mathrm{m}_1) f(p_2^2/2\mathrm{m}_2)}$$

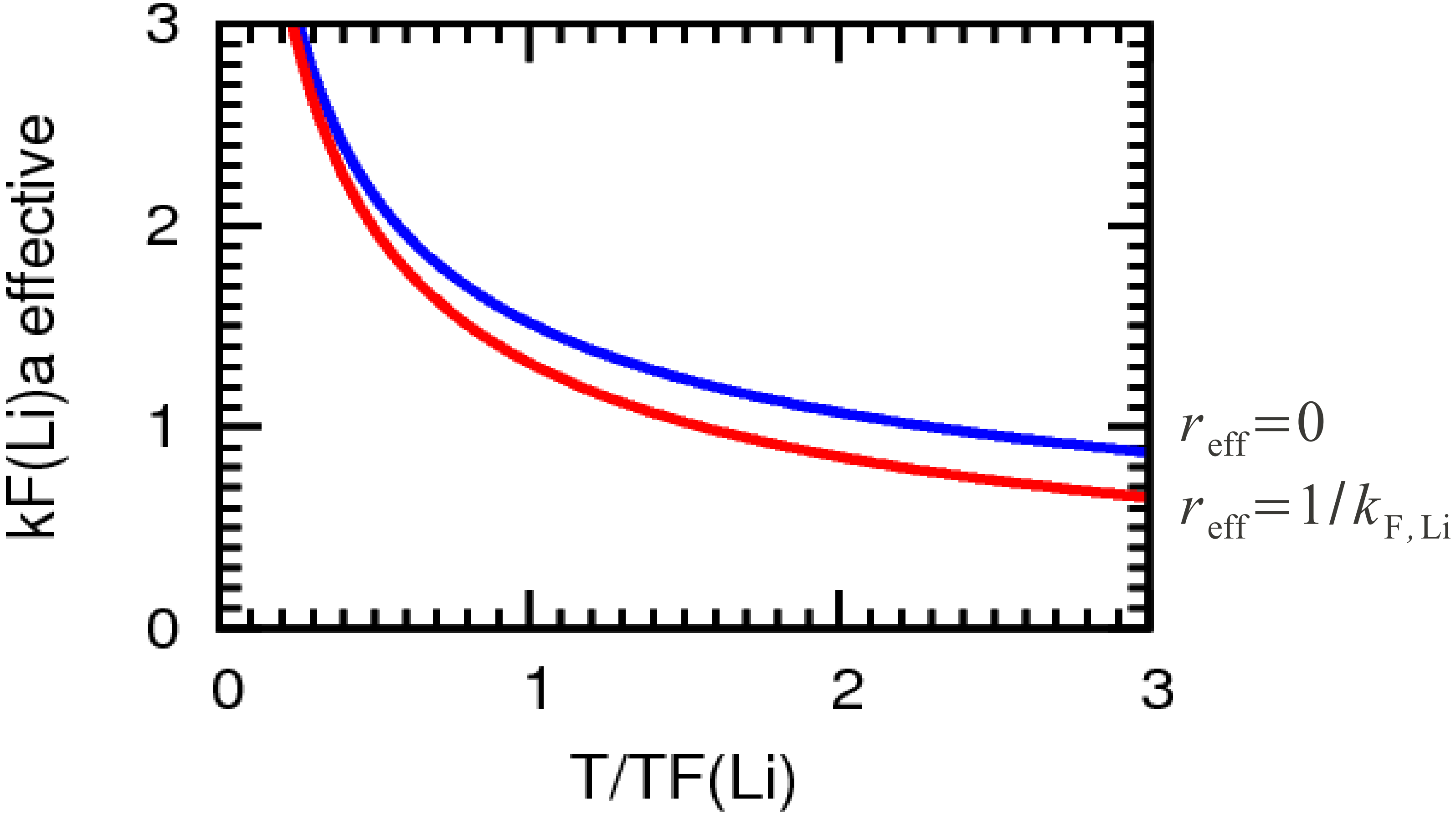
  with

  $$\sigma(\vec{p}_\mathrm{r}) = \frac{4\pi a^2}{(1 - r_\mathrm{eff} a p_\mathrm{r}^2/2)^2 + a^2 p_\mathrm{r}^2} \qquad \vec{p}_\mathrm{r} = \left(\frac{\vec{p}_1 m_2}{m_1 + m_2} - \frac{\vec{p}_2 m_1}{m_1 + m_2} \right)$$

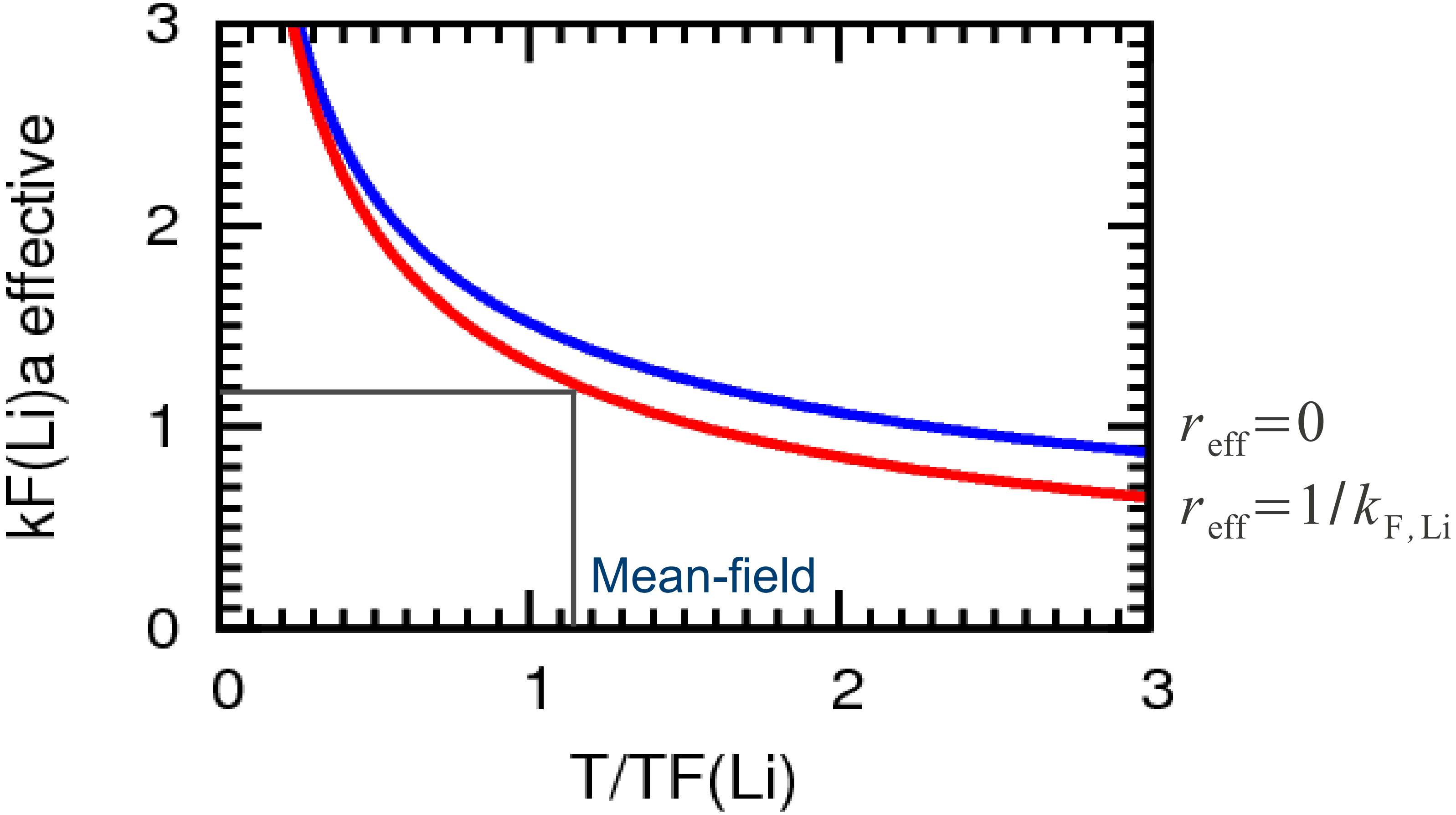
- In the high temperature unitarity limit

  $$\langle \sigma \rangle = \frac{4\pi}{T} \frac{m_1 + m_2}{m_1 m_2} \frac{1}{\sqrt{1 + \frac{T r_\mathrm{eff}^2}{2} \frac{m_1 m_2}{m_1 + m_2}}}$$

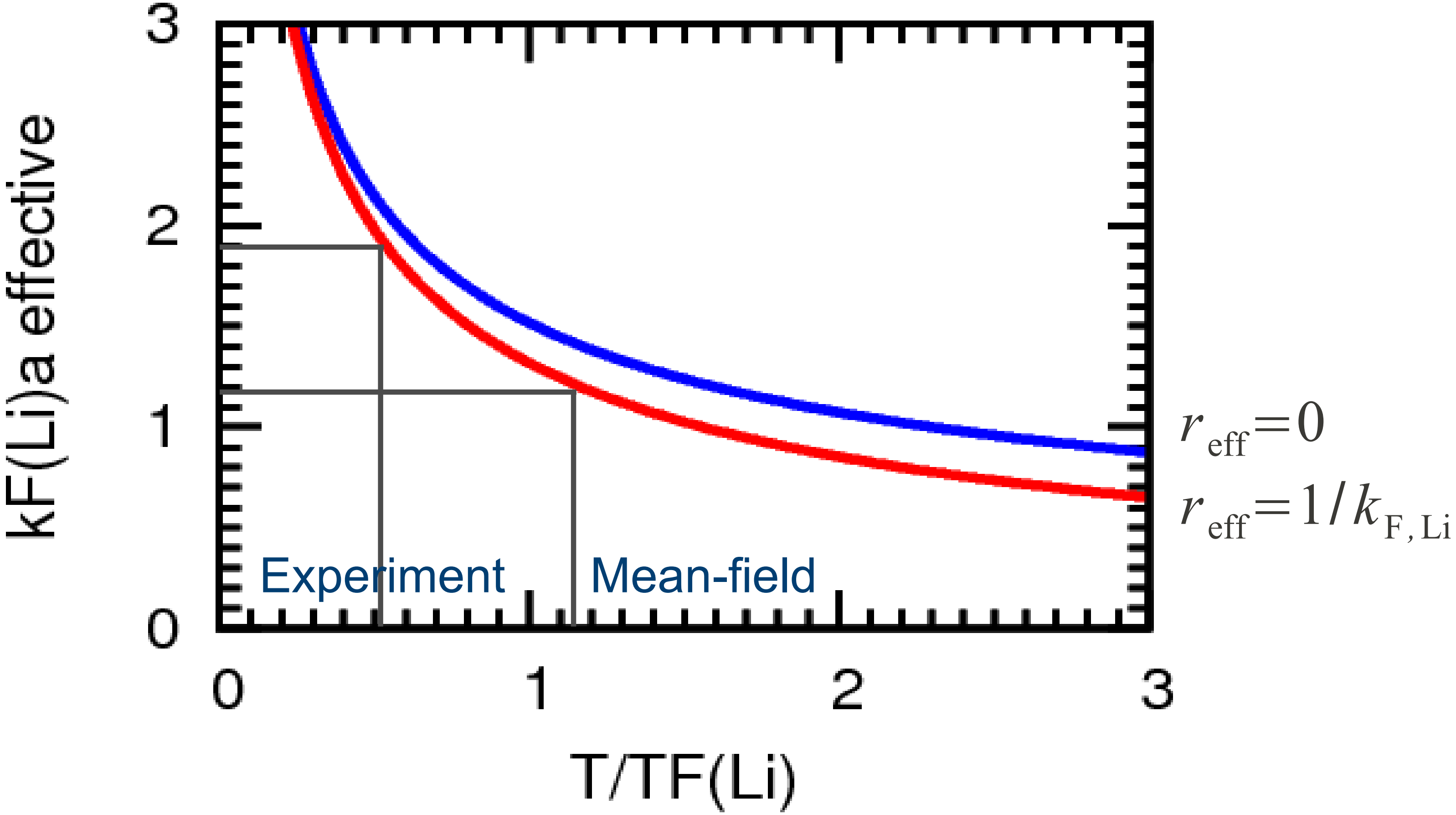
Temperature reduced scattering cross-section



Temperature reduced scattering cross-section



Temperature reduced scattering cross-section



Conclusions

- The behavior of repulsively interacting gases of Fermions remains an important unanswered question
- Mass imbalance suppresses competing many-body instabilities and gives explicit domain formation
- Feshbach molecules and K atoms together drive phase separation
- High temperature further reduces pairing losses