Itinerant Magnetism in Cold Atoms

TEXAS LONGHORNS

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Description:

Condensed Matter Physics

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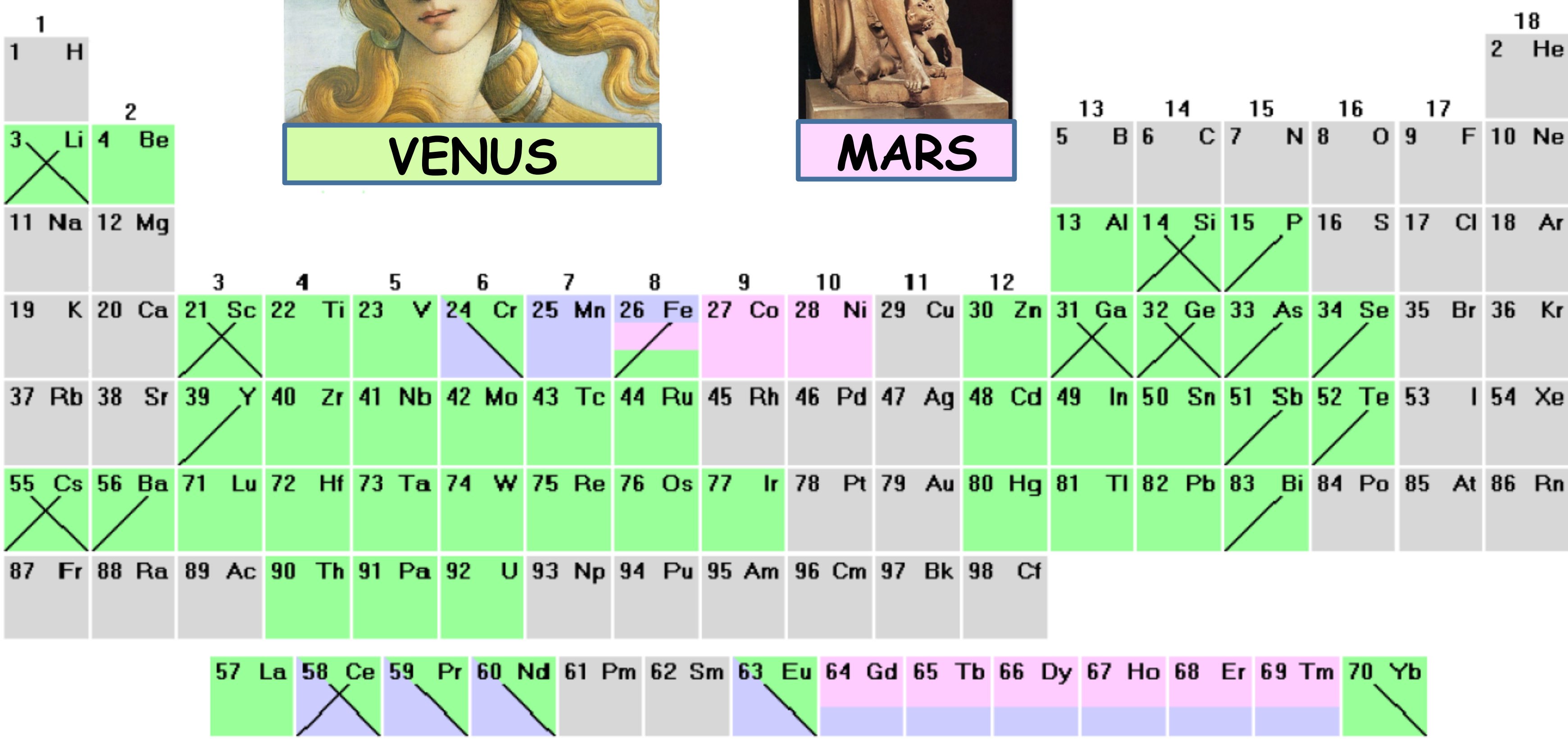
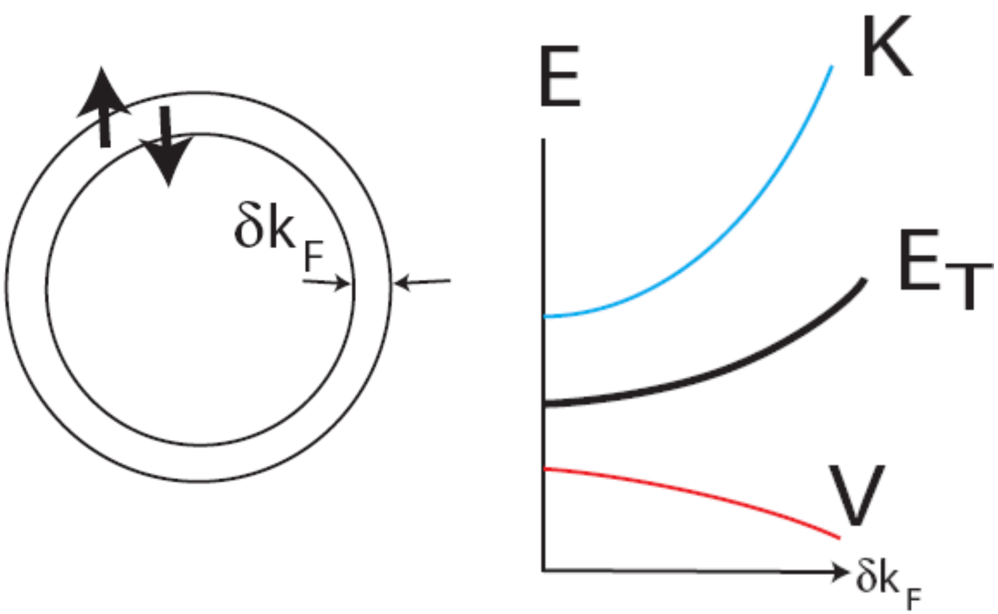


Itinerant ferromagnetism

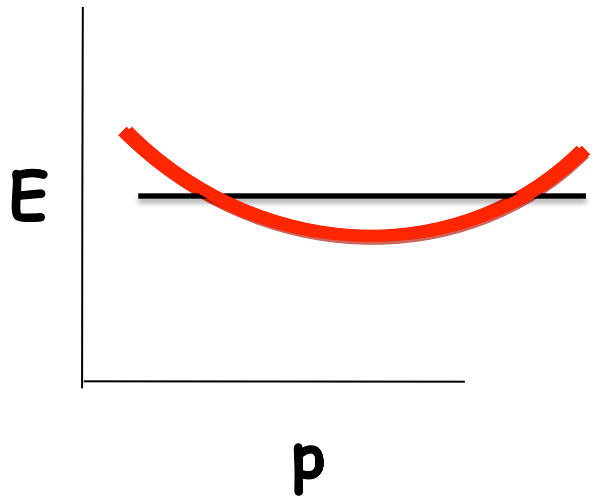
- Ferromagnetism results from cooperation between Pauli principle and Coulomb repulsion. The "Stoner" instability is a strong interaction instability determined by competition between kinetic and interaction energy:



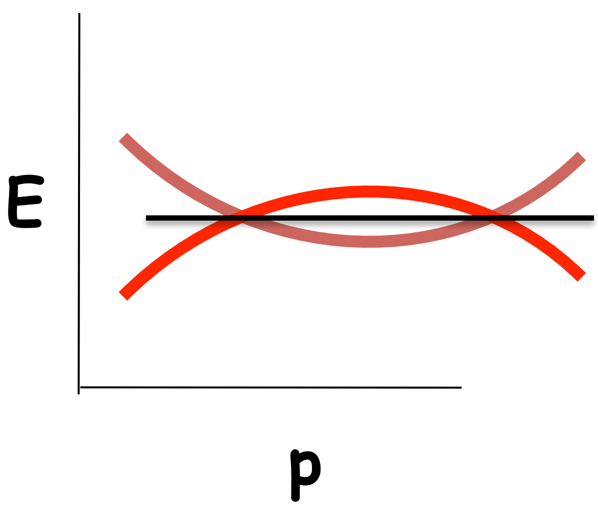
$$V(r) = g\delta(r)$$

$g > 0$

Two Stoner Criteria

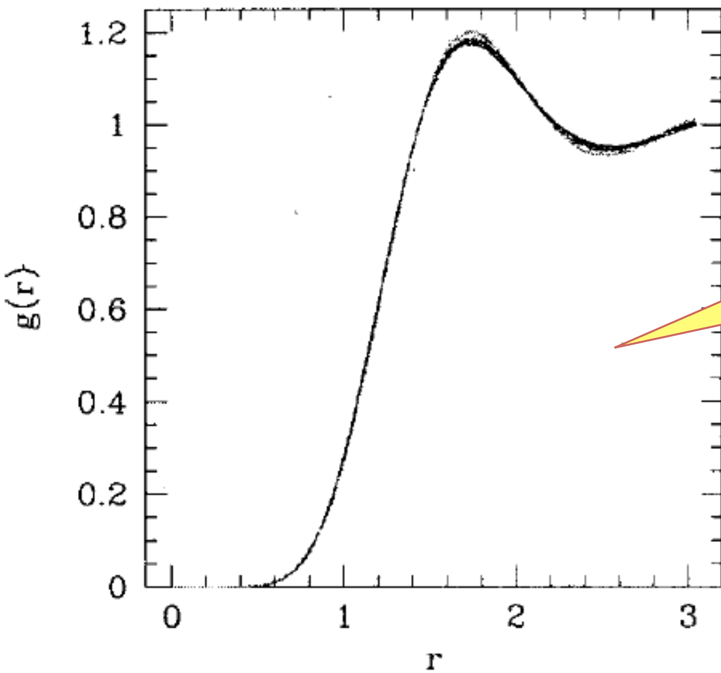


$$m_x = D(\epsilon_F)\, U\, m_x$$

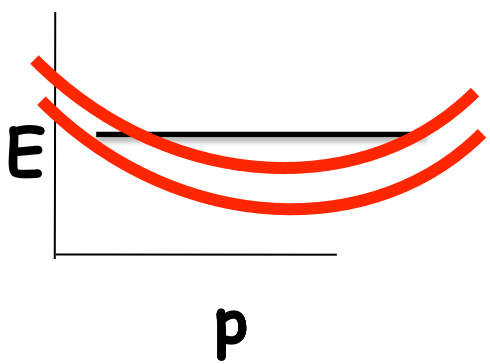


$$m_x = \frac{U D(\epsilon_F)}{2} \int dE\, \frac{m_x}{(E^2 + (U * m_x/2)^2)^{1/2}}$$

Magnetic Stoner Criteria

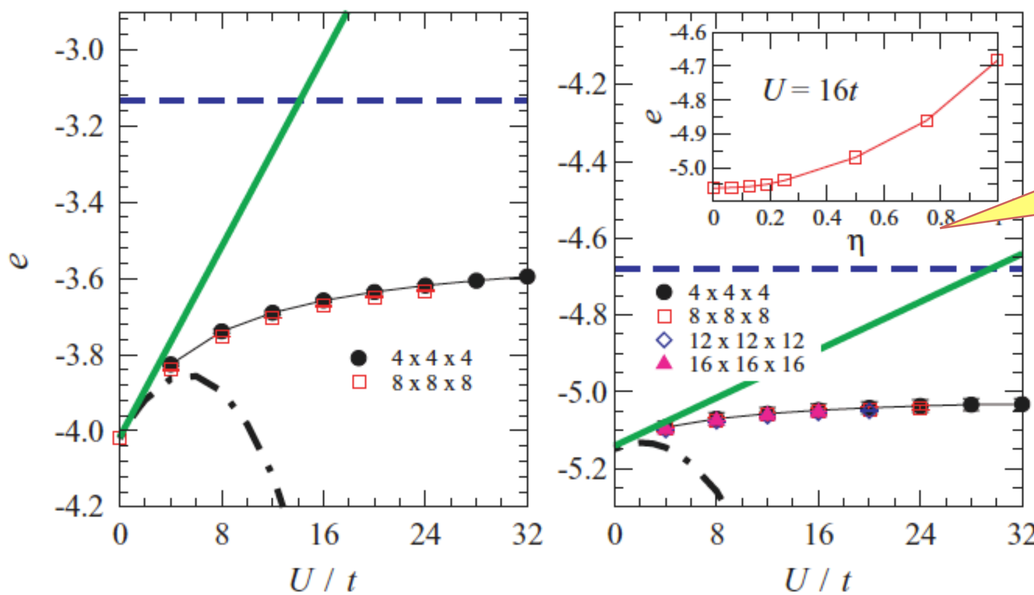


3D Electron Gas
Zong et al. PRL (2002)
$(DU)_c \approx 10$

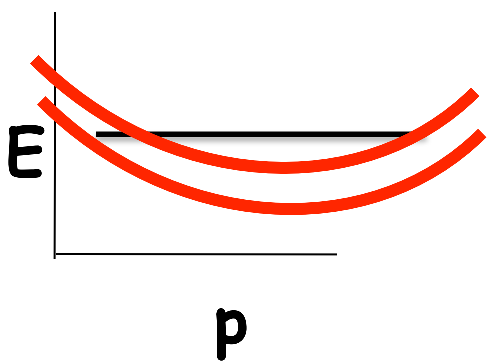


$$m_x = D(\epsilon_F)\, U\, m_x$$

Dilute Hubbard Model



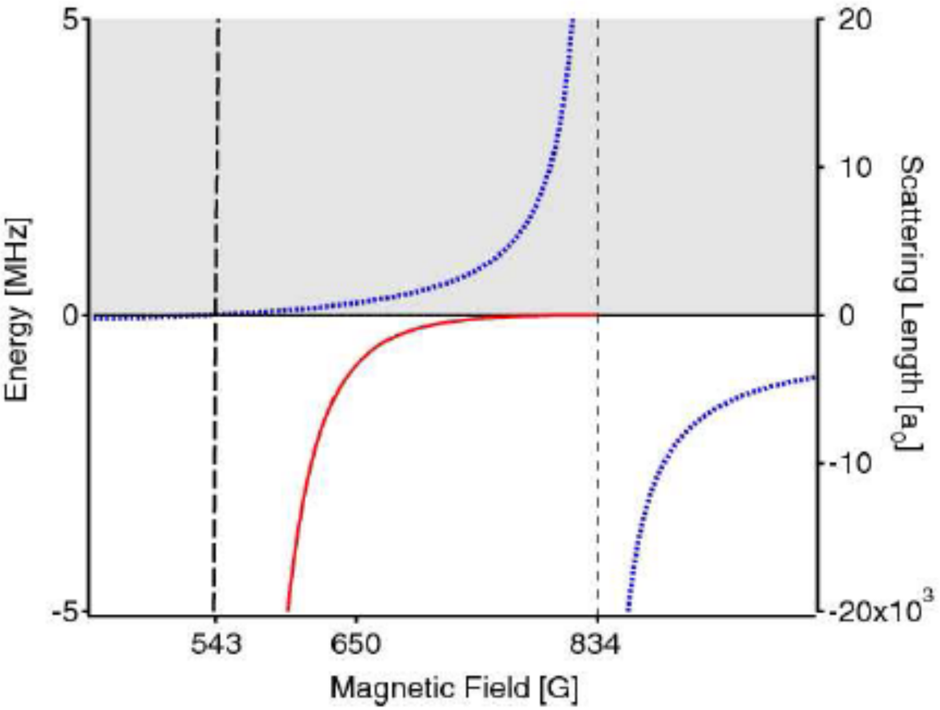
Chang *et al.*
PRA (2010)



$$m_x = D(\epsilon_F)\, U\, m_x$$

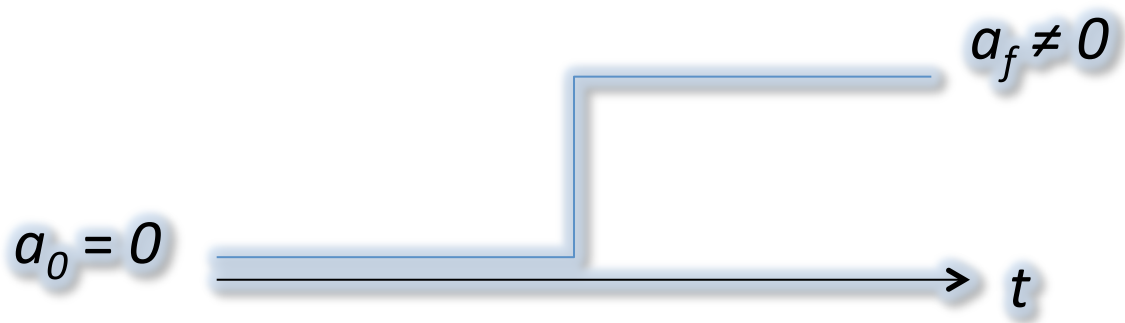
The Difference Between Boys and Girls

Even when the potential is attractive, the interaction appears to be repulsive when a bound state is just below the continuum.



Can we study ferromagnetism?

- How does a system behave after an interaction quench?



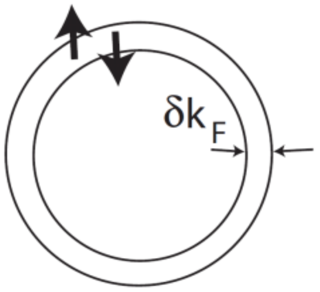
- Unpolarized gas:
  - D. Pekker et al., PRL 106, 050402 (2011).
  - M. Babadi et al., arXiv:0908.3483 (2009).

Can we study ferromagnetism?

Extra "knob" available in cold atoms:

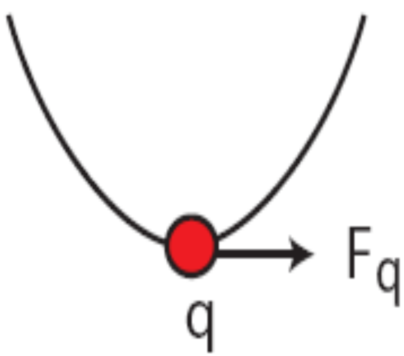
– Total spin is conserved on experimental time scales

$$\delta = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} = \frac{k_{F\uparrow}^3 - k_{F\downarrow}^3}{k_{F\uparrow}^3 + k_{F\downarrow}^3}$$



Linear instability analysis

- *System is in the ideal polarized Fermi gas initially.*
- *Response to small perturbations:*



$$q(\omega) = \chi_q(\omega) F_q(\omega)$$

$$q(t) \to q_0 \exp(i\omega_0 t), \;\; \chi_q(\omega_0) = \infty$$

Linear instability analysis

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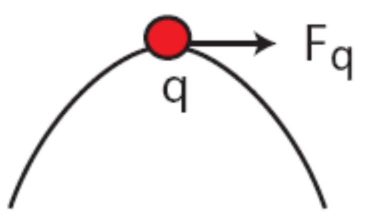
- Response to small perturbations:



$$q(\omega) = \chi_q(\omega) F_q(\omega)$$

$$q(t) \to q_0 \exp(i\omega_0 t), \;\; \chi_q(\omega_0) = \infty$$

- Instabilities appear as poles of the susceptibility with positive imaginary part: growth rate of the instability.

Observables

- Pairing at zero and finite momentum:

$$\Delta(r) = \langle \psi_\uparrow^\dagger(r)\psi_\downarrow^\dagger(r)\rangle \quad \longleftrightarrow \quad \Delta_P = \sum_k \langle c^\dagger_{\frac{1}{2}P+k\uparrow} c^\dagger_{\frac{1}{2}P-k\downarrow}\rangle$$

- Spin density and particle density:

$$n(r) = \langle n_\uparrow(r) + n_\downarrow(r)\rangle \qquad s_z(r) = \frac{\hbar}{2}\langle n_\uparrow(r) - n_\downarrow(r)\rangle$$

- Transverse spin density:

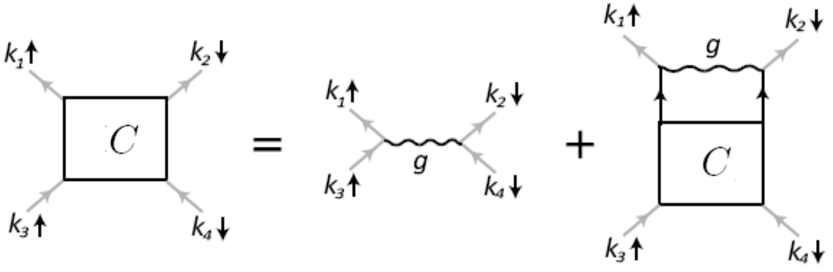
$$s_x = \frac{\hbar}{2}\langle \psi_\uparrow^\dagger(r)\psi_\downarrow(r)\rangle + \ h.c.$$

Model

- Interactions near Feshbach resonance are controlled by scattering length.

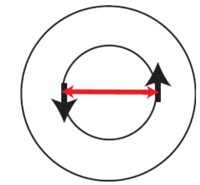
- Eliminate explicit appearance of interaction potential in favor of scattering Fermi sea amplitude: Cooperon.

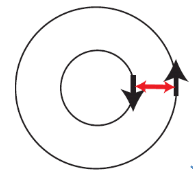
$$C^{-1}_{\uparrow\downarrow}(E,P) = \frac{m}{4\pi a} + i\frac{\pi}{2}\sqrt{E - \frac{P^2}{4m}} - \int_q \frac{n_{\uparrow \frac{1}{2}P-q} + n_{\downarrow \frac{1}{2}P+q}}{E - \xi_{\uparrow \frac{1}{2}P-q} - \xi_{\downarrow \frac{1}{2}P+q}}$$



Pairing instability

$$\delta = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$$





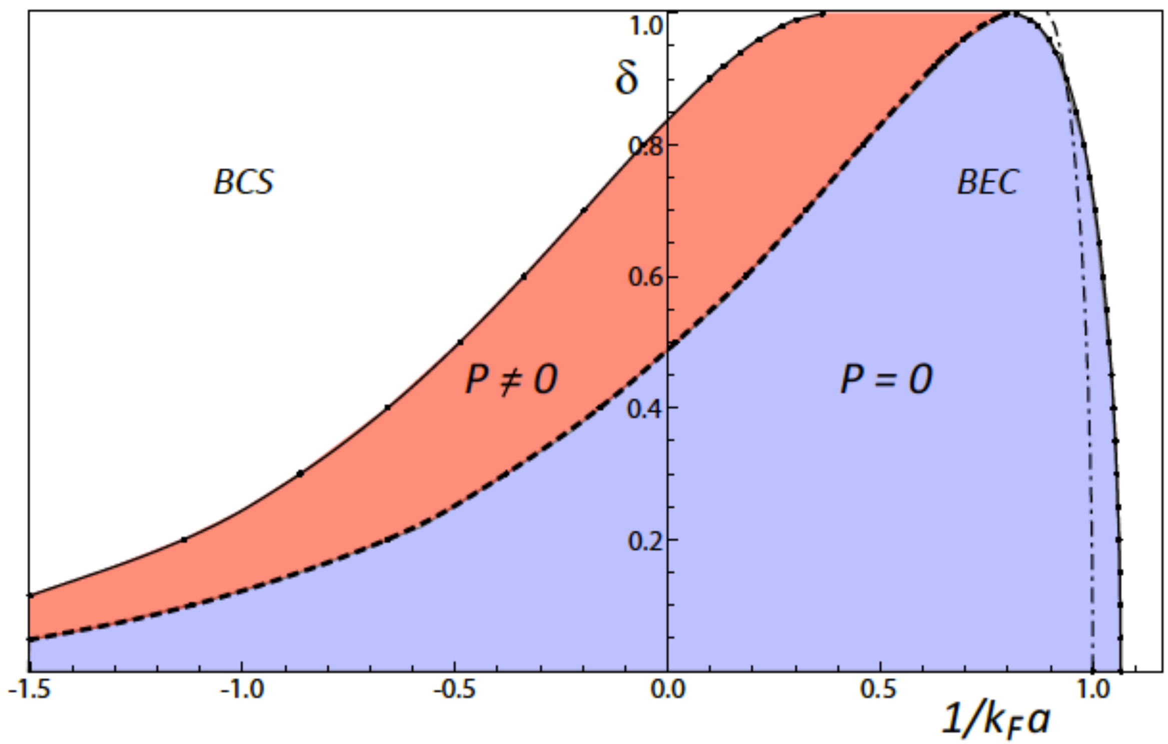
$$\frac{k_\uparrow^2}{2m} + \frac{k_\downarrow^2}{2m} = \frac{1}{ma^2}$$

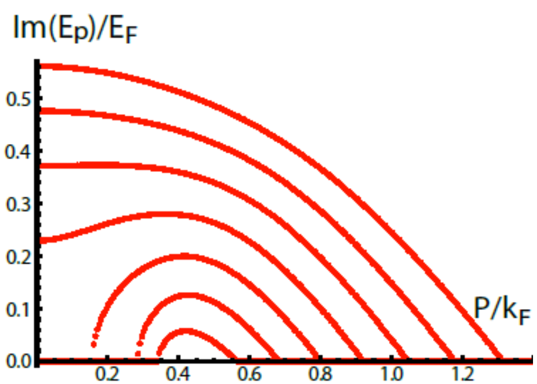
- Pairing instability diagram
  - Finite momentum pairing:

    P ≠ 0

  - Zero momentum pairing:

    P = 0



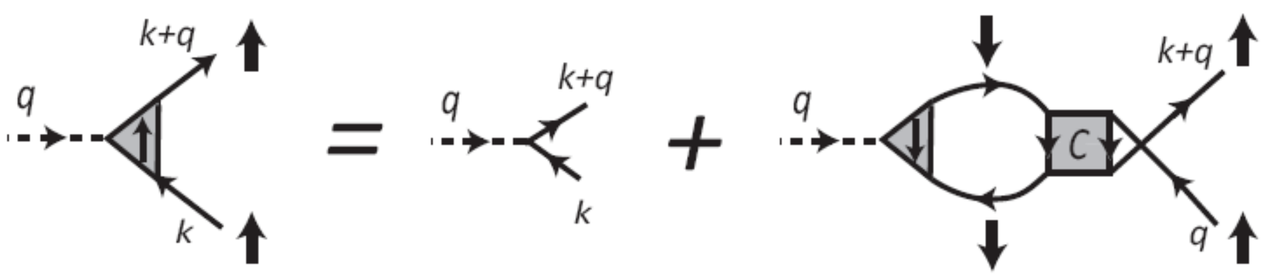


Density and longitudinal spin instability

- Density and spin responses are coupled in polarized gas,

$$\chi_{nn}(r,t),\ \chi_{zz}(r,t) \qquad \chi_{nz}(r,t)$$

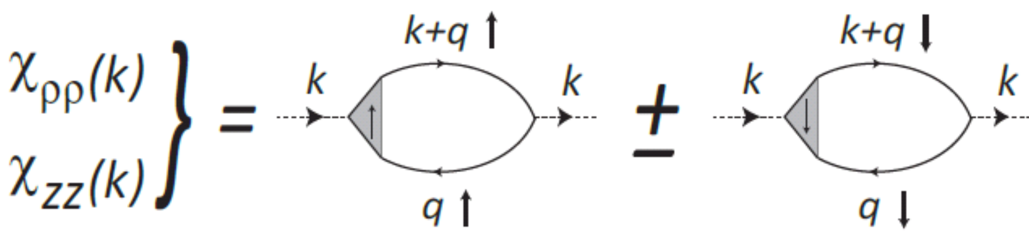
RPA with interaction potential replaced by cooperon,



$$\Gamma_q^{\uparrow}(k) = 1 + i\int \frac{d^4k'}{(2\pi)^4} G_{\downarrow}(q+k')G_{\downarrow}(k')C(k+k'+q)\Gamma_q^{\downarrow}(k')$$

Density and longitudinal spin instability

- Density and longitudinal spin susceptibilities:



- Fermi liquid form at low-frequency long-wavelength limit:

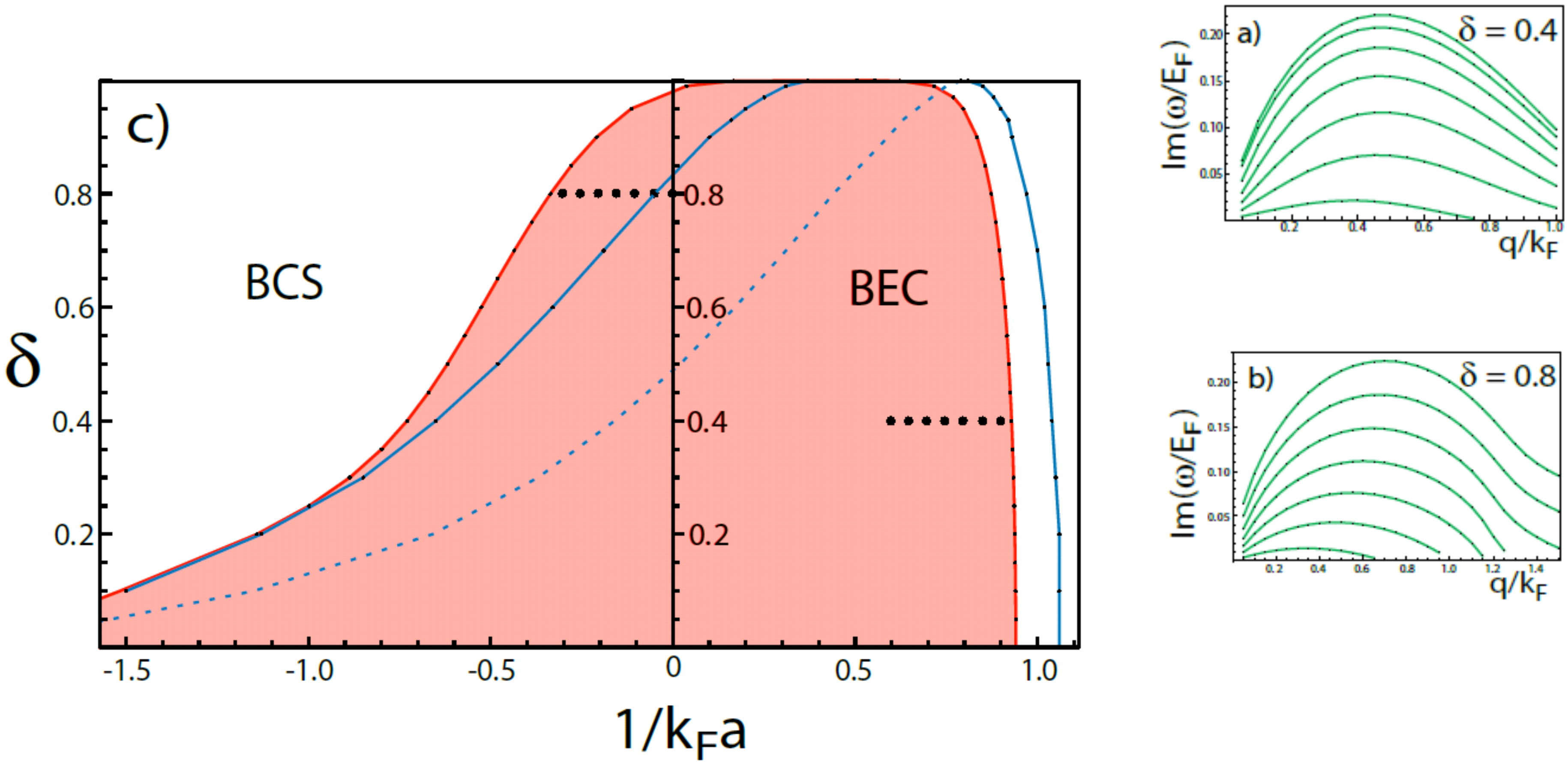
$$G_\sigma(k)G_\sigma(k+q) \to \frac{4\pi^3 i}{k_{F\sigma}^2}\zeta_\sigma(q,\hat{k})\delta(k_0-\epsilon_{F\sigma})\delta(k-k_{F\sigma})$$

$$\int \frac{d\Omega_{\hat{k}}}{4\pi}\,\zeta_\sigma(q,\hat{k}) = \chi^0_\sigma(q) = \int_k \frac{n_{k\sigma}-n_{k+q\sigma}}{\omega+\xi_k-\xi_{k+q}}$$

$$\Gamma^{\rho,s}_\sigma(k) = \frac{1\pm C_s(\omega)\chi^0_{\bar{\sigma}}(k)}{1-C_s^2(\omega)\chi^0_\uparrow(k)\chi^0_\downarrow(k)}$$

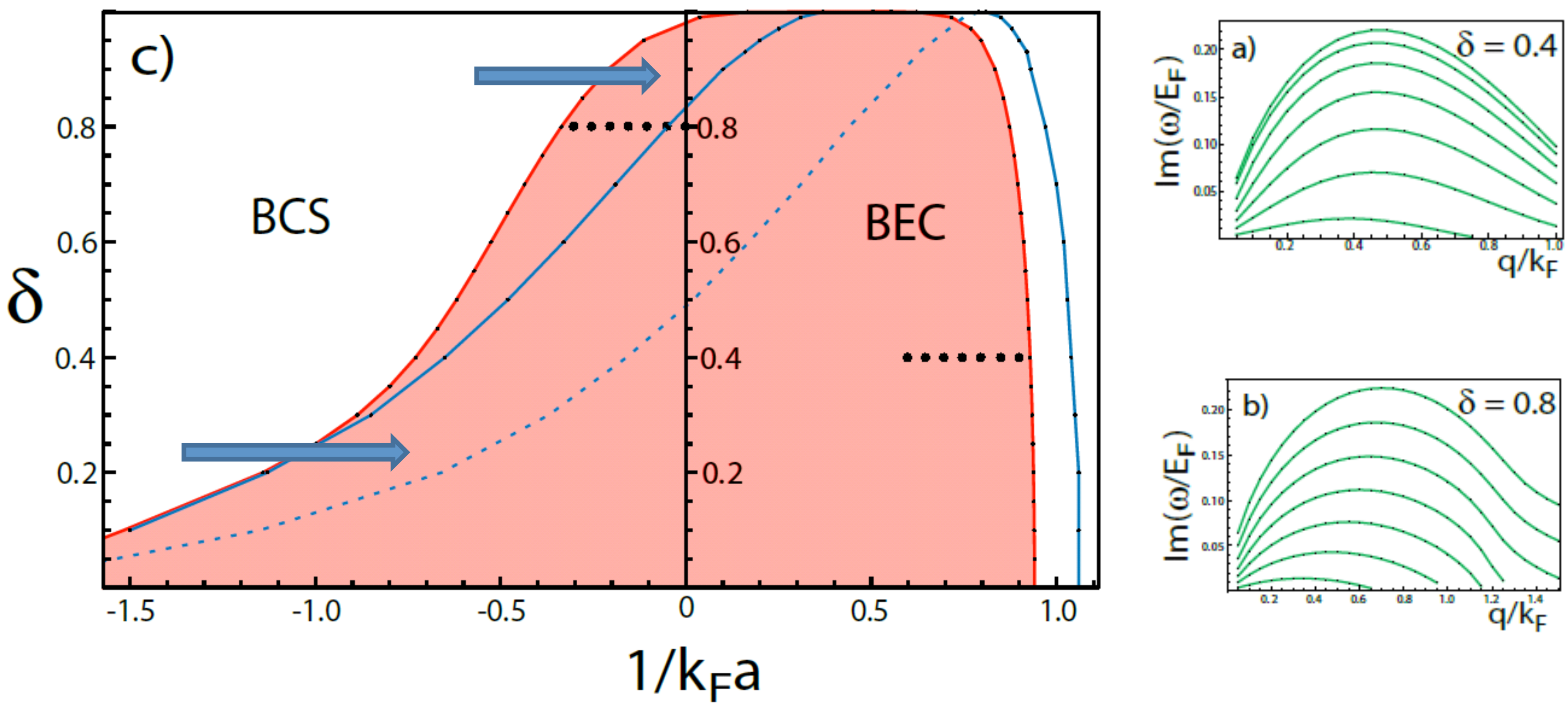
Density and longitudinal spin instabilities

- Instability diagram



Density and longitudinal spin instabilities

- Instability diagram



- Quenches in the polarized BCS side might bring new interesting unstable dynamics

Transverse spin instability

- We use simpler model with contact interaction pseudo-potential:

$$V_{\uparrow,\downarrow}(r) = g\delta(r)$$

- RPA takes a simpler form:

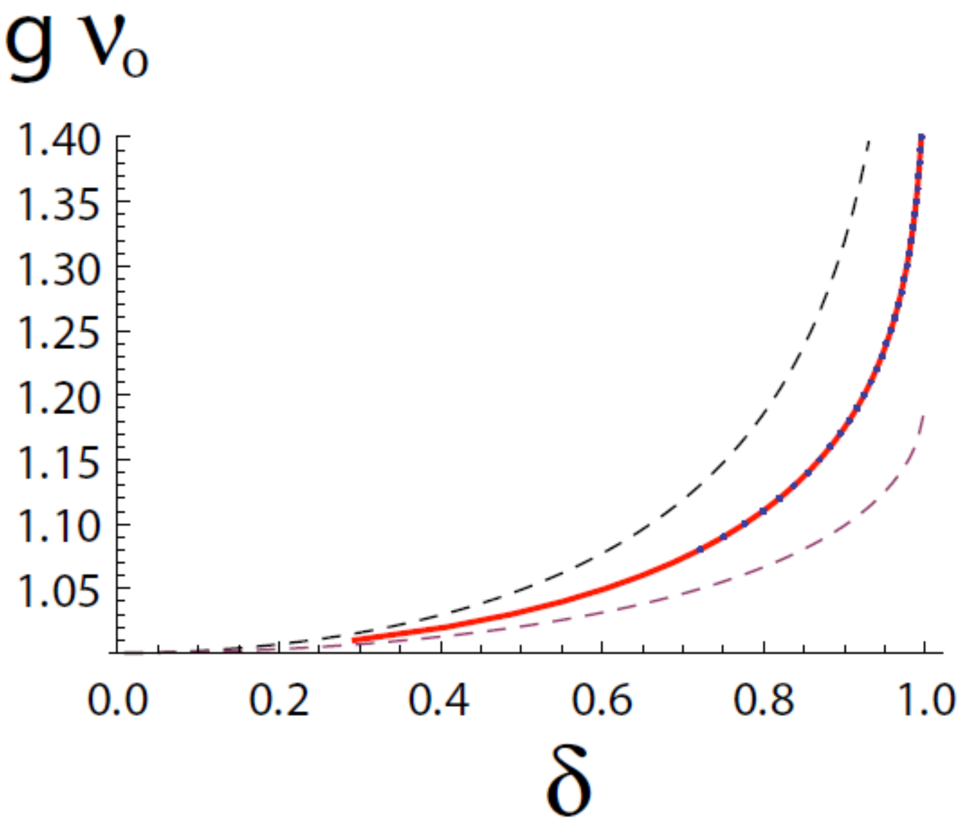
$$\chi^{RPA}_{\uparrow\downarrow}(q,\omega) = \frac{\chi^0_{\uparrow\downarrow}(q,\omega)}{1+g\chi^0_{\uparrow\downarrow}(q,\omega)}$$

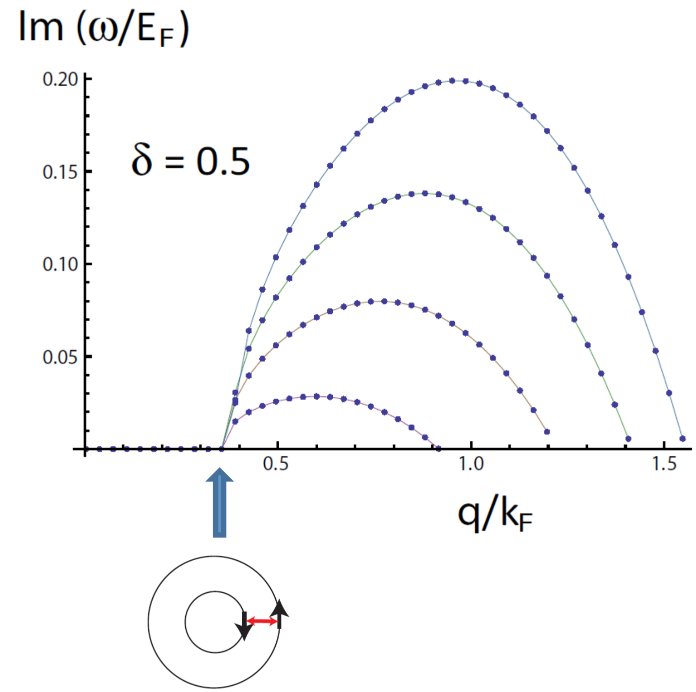
- Collective excitations stable (spin waves) and unstable (exponentially growing modes):

$$1+g\chi^0_{\uparrow\downarrow}(q,\omega) = 0$$

Transverse spin instability

- Critical interaction





Summary

- Pairing instabilities in polarized gas are dominated by finite momentum pairing in a large region of polarization – scattering length parameters.
- Density instabilities "cover" finite momentum pairing instability and can be precursors of phase separation.
- Repulsive longitudinal spin instability is covered by pairing on BEC side.
- Transverse instabilities are at finite momentum, and occur through spontaneous creation of spin waves and particle-hole excitations.