Excitation spectrum of a fermionic condensate

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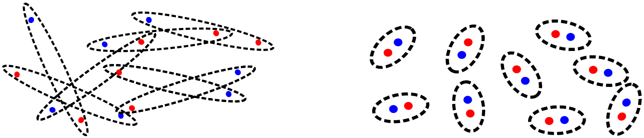
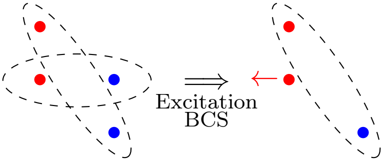
Pair-condensed Fermi gases

Condensate of pairs of fermionic atoms, BCS-BEC crossover

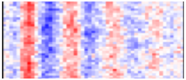
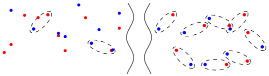


Experiments in Yale (N. Navon), MIT (M.Zwierlein), Lens (G. Roati), Swinburne (Vale)...

Single-particle excitations



Collective modes

- Phonons 
- Higgs modes 
- Pairing mode ($T \approx T_c$) 

Method: Linear Response (in RPA)

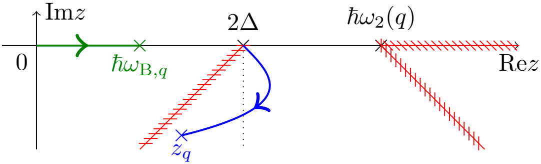
$$\hat{H}_0 = \sum_{\mathbf{k}} \left(\frac{\hbar^2 k^2}{2m} - \mu \right) \hat{a}^\dagger_{\mathbf{k}} \hat{a}_{\mathbf{k}} + g_0 \int \mathrm{d}^3 r \hat{\psi}^\dagger_\uparrow(\mathbf{r}) \hat{\psi}^\dagger_\downarrow(\mathbf{r}) \hat{\psi}_\downarrow(\mathbf{r}) \hat{\psi}_\uparrow(\mathbf{r}),$$

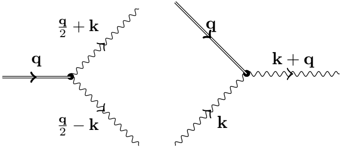
response to drive forces:

$$\hat{H}_{\mathrm{drive}} = \int \mathrm{d}^3 r \left[\phi(\mathbf{r},t) \hat{\psi}^\dagger_\uparrow \hat{\psi}^\dagger_\downarrow + \mathrm{h.c} + u(\mathbf{r},t) \sum_\sigma \hat{\psi}^\dagger_\sigma \hat{\psi}_\sigma \right]$$

Density and pair-field response to the drive

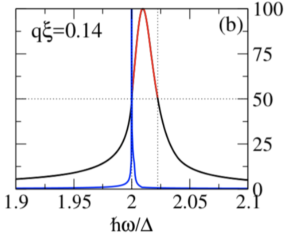
$$\begin{pmatrix} \mathrm{i}\Delta\delta\theta \\ \delta|\Delta| \\ \delta\rho \end{pmatrix} = \chi(\omega, \mathbf{q}) \begin{pmatrix} 2\mathrm{Re}(\phi) \\ 2\mathrm{iIm}(\phi) \\ u \end{pmatrix}, \qquad \det \chi^{-1}(z_{\mathbf{q}}, \mathbf{q}) = 0$$

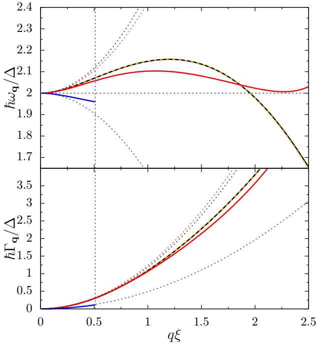




Higgs modes

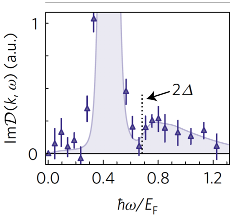
$$z_{\mathbf{q}} = 2\Delta + \zeta \frac{\mu}{\Delta} \frac{\hbar^2 q^2}{2m} + O(q^3)$$

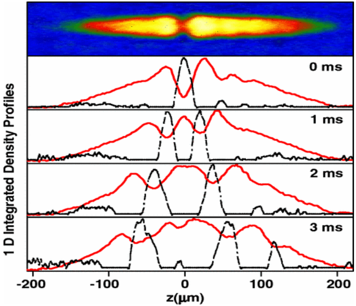




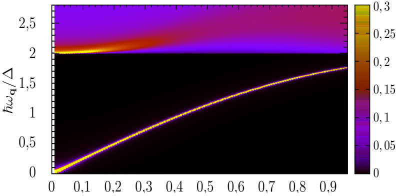
So far measurements only in $q = 0$ (quench of interactions). Analogy with superconductors.

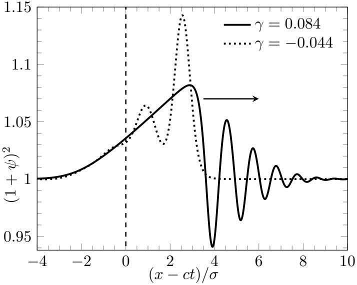
Also visible in the density response





The sign of the dispersion can change $\hbar\omega_q = \hbar c q + \gamma q^3$





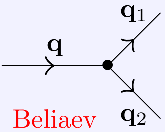
Phonons: damping mechanisms

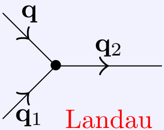
For dissipative properties (viscosity, thermal conductivity...) you need phonon-phonon interactions. $\hbar\omega_q \to \hbar\omega_q - i\hbar\Gamma_q/2$

$$\hat{H}_{\text{hydro}} = E_0 + \sum_{\mathbf{q}} \hbar\omega_{\mathbf{q}} \hat{b}^\dagger_{\mathbf{q}} \hat{b}_{\mathbf{q}} + \hat{H}_3 + \hat{H}_4 + \dots$$

Convex branch

3-phonons processes





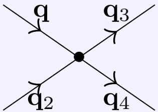
$$\hat{H}_3 \to \hat{b}^\dagger_{\mathbf{q}_1} \hat{b}^\dagger_{\mathbf{q}_2} \hat{b}_{\mathbf{q}_3} + \text{h.c.}$$

$$\Gamma_q^{\text{BL}} \propto q^5 \quad \text{at } T = 0$$

$$\Gamma_q^{\text{BL}} \underset{\hbar\omega_q \approx k_{\text{B}} T}{\propto} T^5$$

Concave branch

4-phonons processes



Landau-Khalatnikov

$$\hat{H}_4 \to \hat{b}^\dagger_{\mathbf{q}_3} \hat{b}^\dagger_{\mathbf{q}_4} \hat{b}_{\mathbf{q}_1} \hat{b}_{\mathbf{q}_2}$$

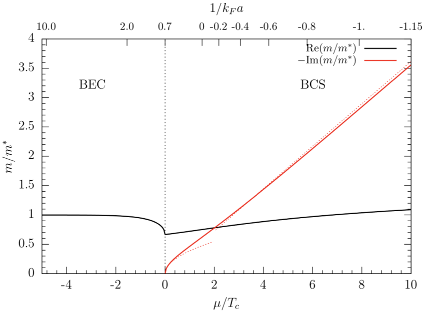
$$\Gamma_q^{\text{LK}} = 0 \quad \text{at } T = 0$$

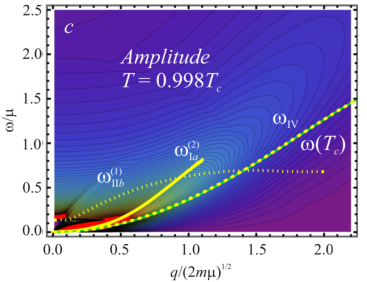
$$\Gamma_q^{\text{LK}} \underset{\hbar\omega_q \approx k_{\text{B}} T}{\propto} T^7$$

Pairing mode at and above T_c

At T_c, the window of visibility of phonons/Higgs modes shrinks to $\omega \lesssim 2\Delta$ and $q \lesssim 1/\xi_{\text{pair}}$. Elsewhere: quadratic pairing mode

$$z_{\mathbf{q}}^{(T_c)} = \frac{\hbar^2 q^2}{4m^*} + O(q^3/k_F^3)$$





Exists above T_c as a precursor of the phase transition.

$$z_{\mathbf{q}}^{(T_c)} = \frac{\hbar^2 q^2}{4m^*} - \alpha(T - T_c)$$

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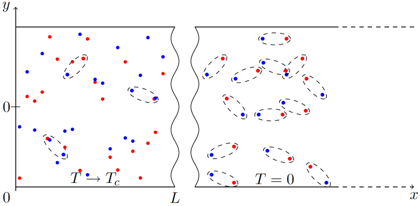

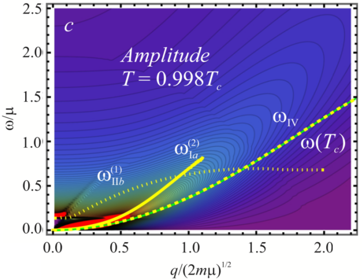

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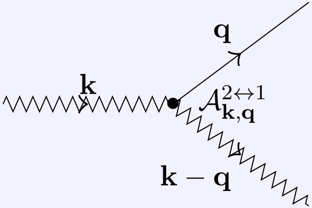
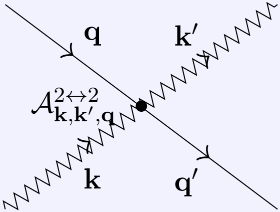
Fermionic quasiparticles beyond mean-field

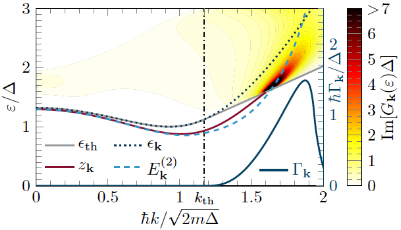
The fermionic quasiparticles are perturbed by the presence of collective modes

At $T = 0$



At $T \neq 0$





$$\Gamma_{k_0} \propto \frac{T^7}{c^6 \rho^2}$$

Nice analogy with rotons in Helium or dipolar Bose gases.