Líquidos fermiônicos de baixa dimensionalidade

César Augusto Nieto Acuna

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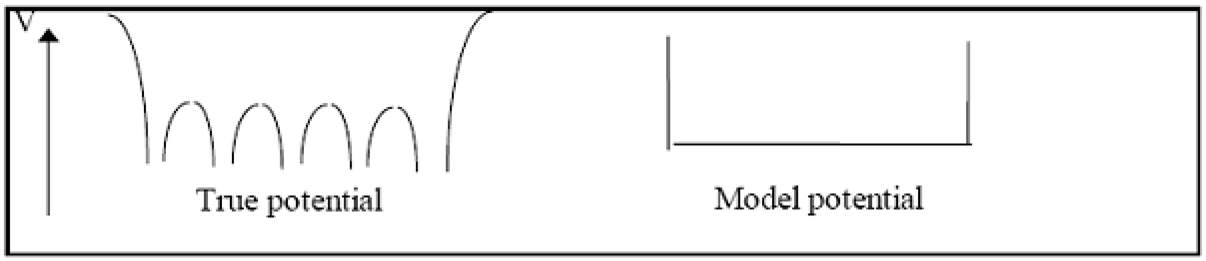
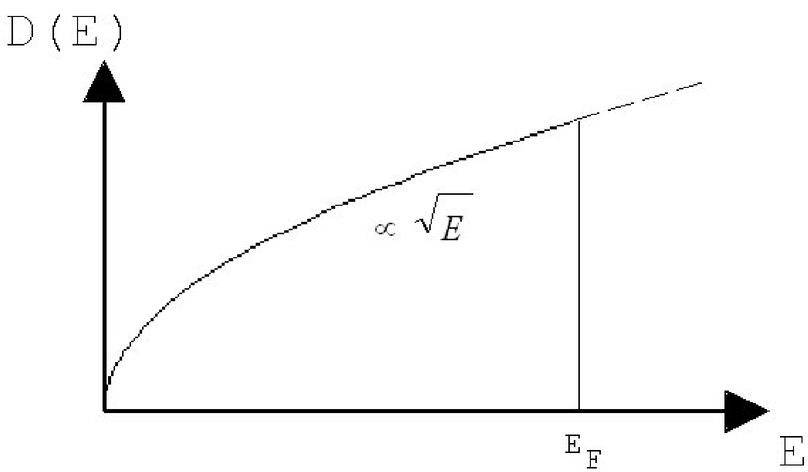
Em 3D modelo de elétron livre funciona muito bem

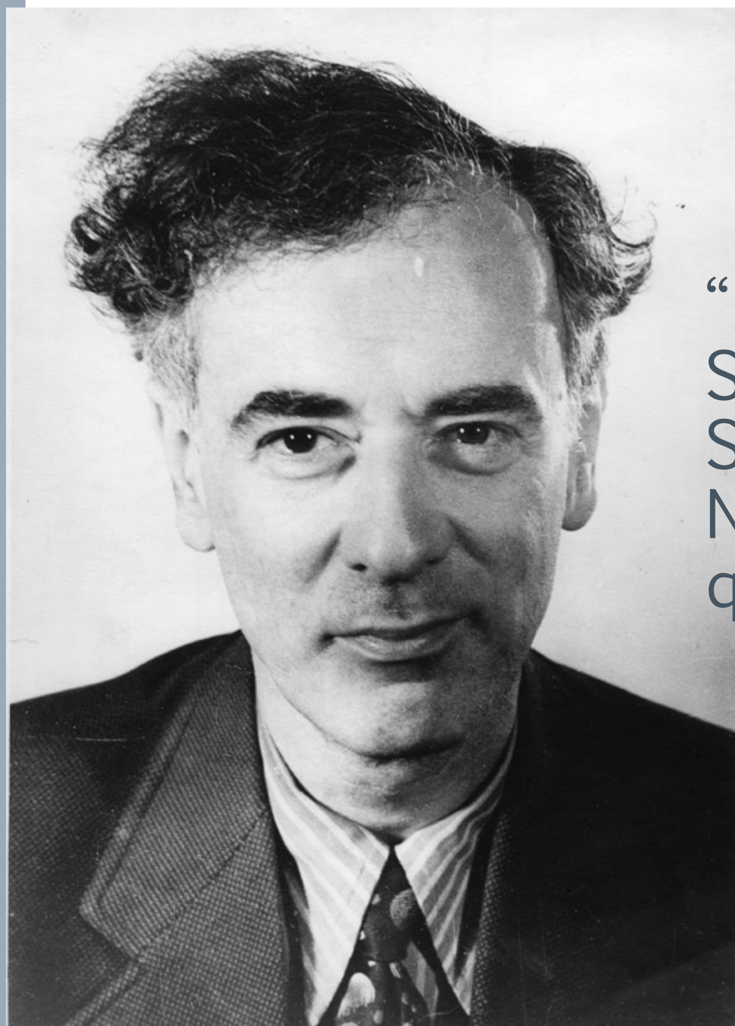




$$c_L^{\text{Pauli}} = \frac{\pi}{3} k_B \left(\frac{k_B T}{\hbar v_F} \right),$$

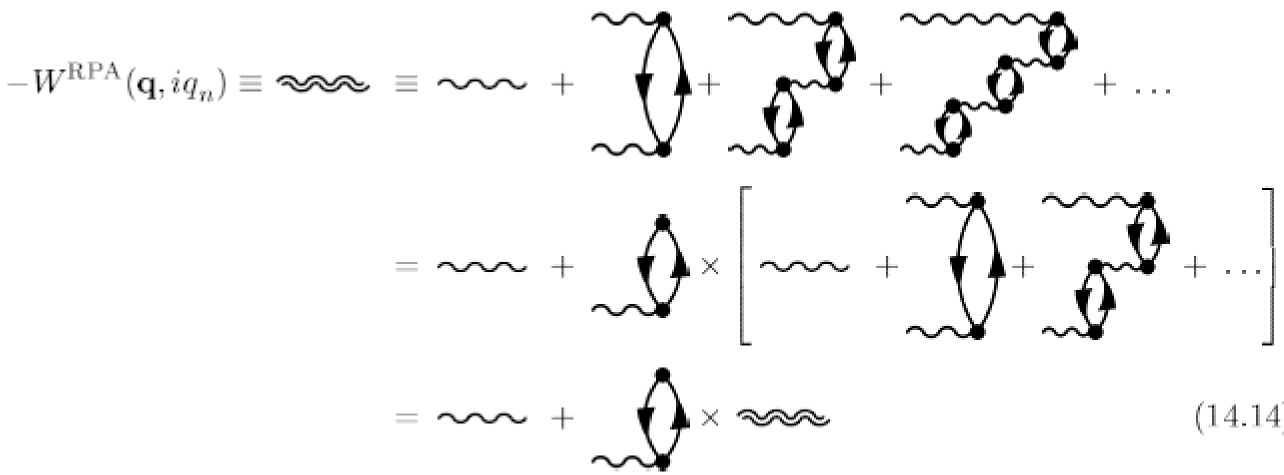
As interações elétron-elétron são importantes.
Por quê, se são depreciadas, o modelo ainda funciona?

Lev Landau (1957)



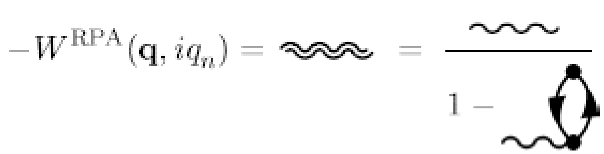
"Um sistema de interações
Suficientemente fracas. Pode
Ser modelado como um sistema
Não interagente mas de
quase-partículas."

Aproximação RPA. Criação par elétron-buraco



(14.14)

In $(\mathbf{q}, iq_n)$-space this is an algebraic equation with the solution



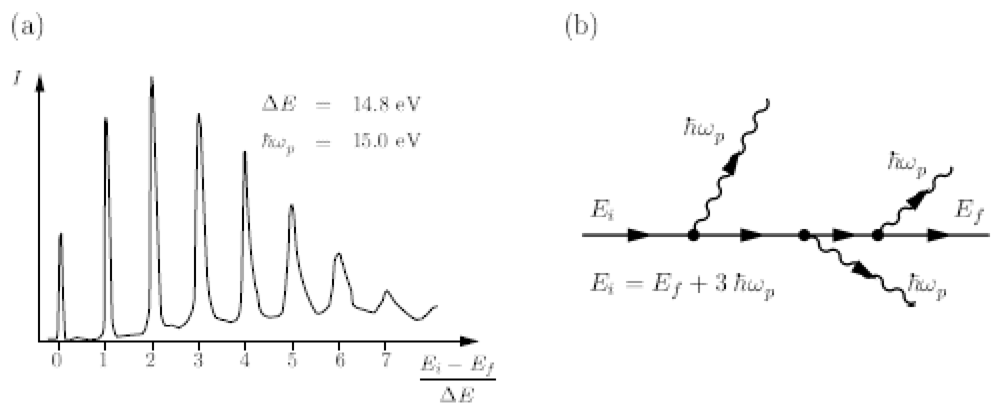
$$= \frac{-W(\mathbf{q})}{1 - W(\mathbf{q})\,\chi_0(\mathbf{q}, iq_n)}. \qquad (14.15)$$

$$\mathrm{Re}\,\chi_0^R(\mathbf{q}, \omega) = \frac{n}{m}\frac{q^2}{\omega^2}\Big[1 + \frac{3}{5}\big(\frac{qv_{\mathrm{F}}}{\omega}\big)^2\Big],$$

$$\varepsilon^{\mathrm{RPA}}(\mathbf{q}, \omega) = 1 - \frac{\omega_p^2}{\omega^2}\Big[1 + \frac{3}{5}\big(\frac{qv_{\mathrm{F}}}{\omega}\big)^2\Big],$$

Plasmons

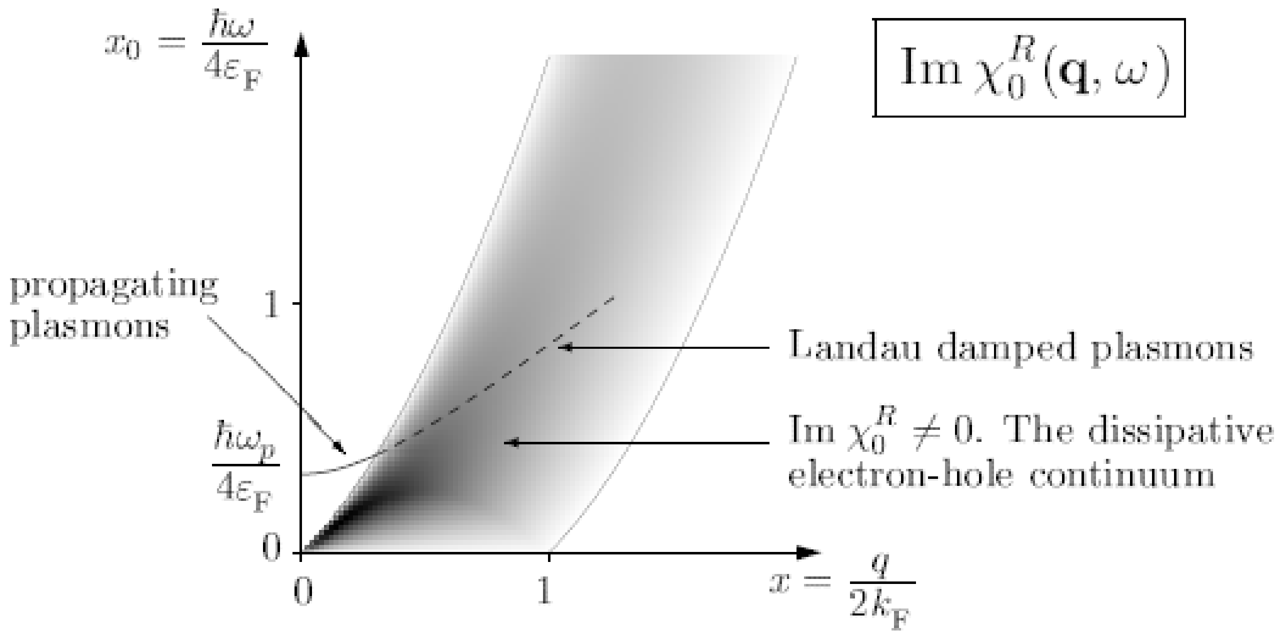
$$\varepsilon^{\mathrm{RPA}}(\mathbf{q},\omega)=0 \quad\Rightarrow\quad \omega^2 \approx \omega_p^2+\frac{3}{5}\,(qv_{\mathrm{F}})^2 \quad\Rightarrow\quad \omega\,(q)\approx \omega_p+\frac{3}{10}\,\frac{v_{\mathrm{F}}^2}{\omega_p}\,q^2.$$



Ocorrem oscilações para Re(e) aprox zero

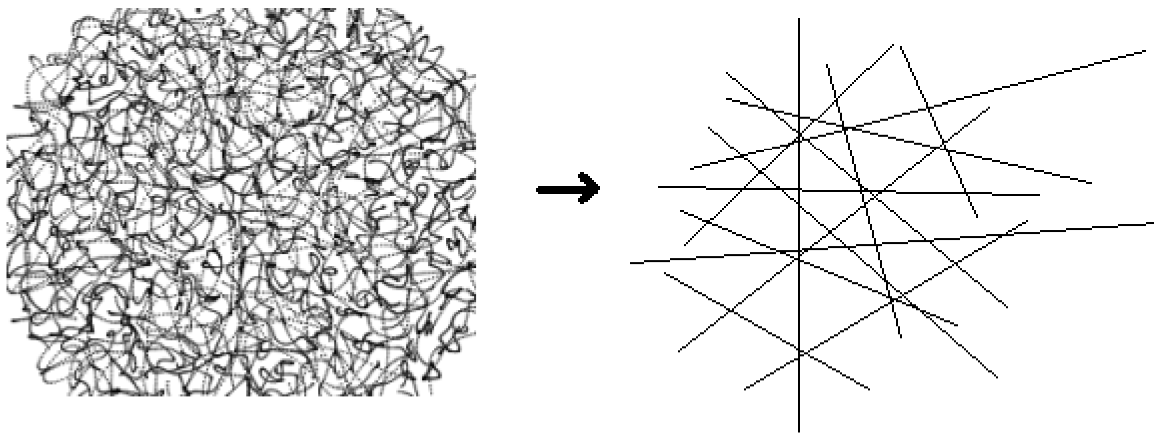
$$\mathrm{Im}\,\chi_0^R(\mathbf{q},\omega)=-d(\varepsilon_{\mathrm{F}})\begin{cases}\frac{\pi}{8x}\Big[1-\big(\frac{x_0}{x}-x\big)^2\Big], & \text{for } |x-x^2|<x_0<x+x^2\\ \frac{\pi}{2}\,\frac{x_0}{x}, & \text{for } 0<x_0<x-x^2\\ 0, & \text{for other } x_0\geq 0.\end{cases}$$

Landau Damping



Quase-particulas

$$H_\zeta = H_0 + H_{\rm int} e^{-\zeta|t|}$$



$$\tau_{\rm life}^{-1} \ll \zeta \ll k_B T.$$

Método semi-clasico de Landau

Considerando uma distribuição de Fermi de não equilibrio
mas que conserva a quantidade total de particulas.

$$\dot{n}_{\mathbf{k}} + \nabla_r \mathbf{j}_k = \partial_t(n_k) + \dot{k} \cdot \nabla_k n_k + v_k \cdot \nabla_r n_k = 0$$

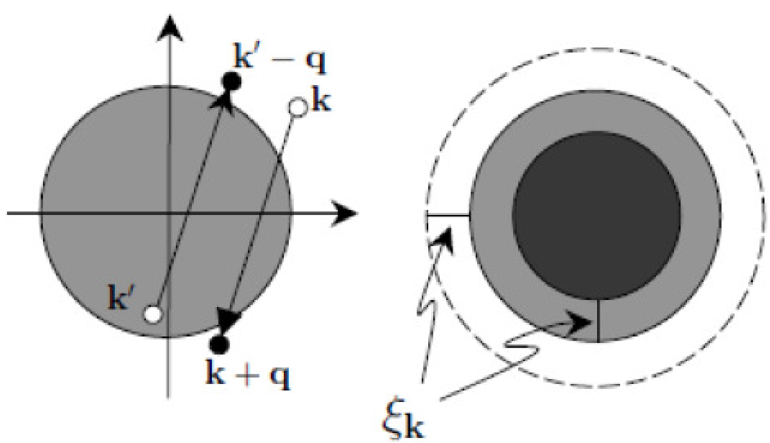
$$\varepsilon(\mathbf{q}) \approx 1 - \frac{W(\mathbf{q})}{\omega^2} \frac{2}{V} \sum_k (\mathbf{q} \cdot \mathbf{v}_k)^2 \left(-\frac{\partial n_F(\xi_k)}{\partial \xi_k} \right) = 1 - \left(\frac{\omega_p}{\omega} \right)^2$$

Tempo de vida medio

A transição pode-se modelar por a regra de ouro de Fermi

$$\frac{1}{\tau_k} = \sum_{k',q} |\langle k+q, k'-q|W(q)|k', k\rangle|^2 \delta(\xi_k + \xi_{k'} - \xi_{k+q} - \xi_{k'-q})$$

Maximum phase space = $(4\pi k_F^2 \xi_{\mathbf{k}})^2$



$$\frac{1}{\tau_k} \sim |W|^2 [D(\varepsilon_F)]^3 \xi_k^2 / 2$$

$$\frac{1}{\tau} \propto T^2$$

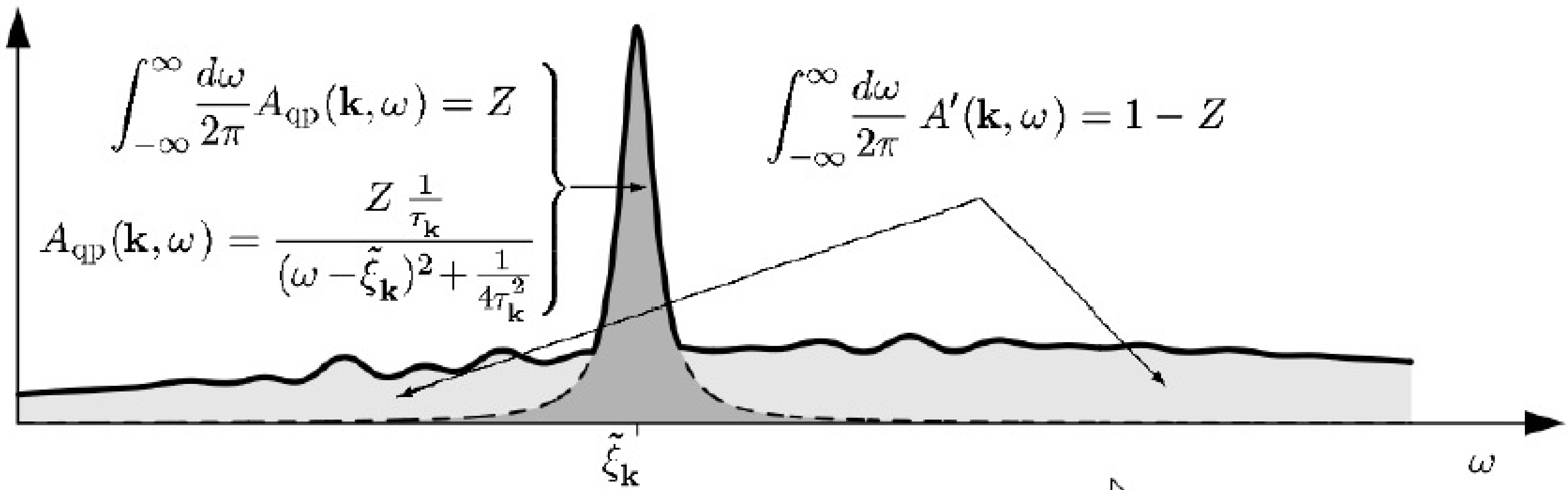
Função de Green renormalizada

$$G^R(k,\omega) = \frac{1}{\omega - \xi_k - \Sigma^R(k,\omega)}$$

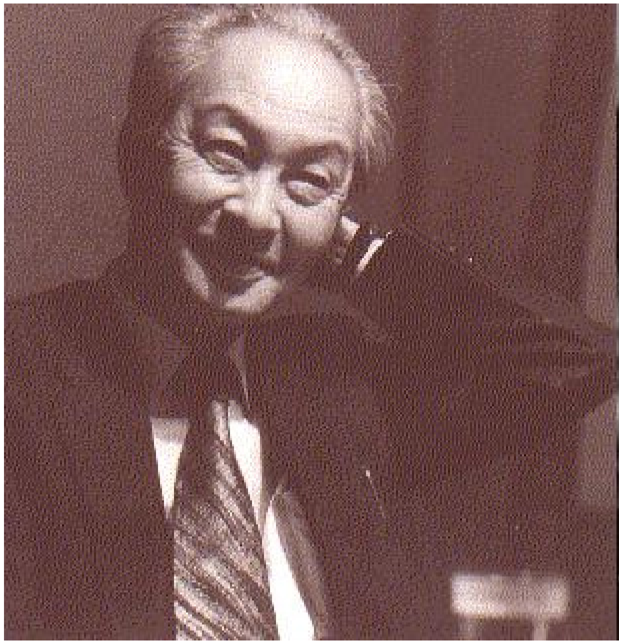
$$\frac{1}{\tilde{\tau}_k(\omega)} = -2 Z Im \Sigma^R$$

$$A(k,\omega) = -2 Im G^R(k,\omega) \approx 2\pi Z \delta(\omega - \tilde{\xi}_k)$$

$$A(\mathbf{k},\omega) = A_{qp}(\mathbf{k},\omega) + A'(\mathbf{k},\omega)$$



LIQUIDO EM 1 DIMENSÃO



1950

1963

Possíveis candidatos

Figure 1: Atomic arrangement of self-organized gold chains on Ge(001).

From

Atomically controlled quantum chains hosting a Tomonaga–Luttinger liquid

C. Blumenstein, J. Schäfer, S. Mietke, S. Meyer, A. Dollinger, M. Lochner, X. Y. Cui, L. Patthey, R. Matzdorf & R. Claessen

Nature Physics **7**, 776–780 (2011) | doi:10.1038/nphys2051

Figure 1: Atomic arrangement of self-organized gold chains on Ge(001).

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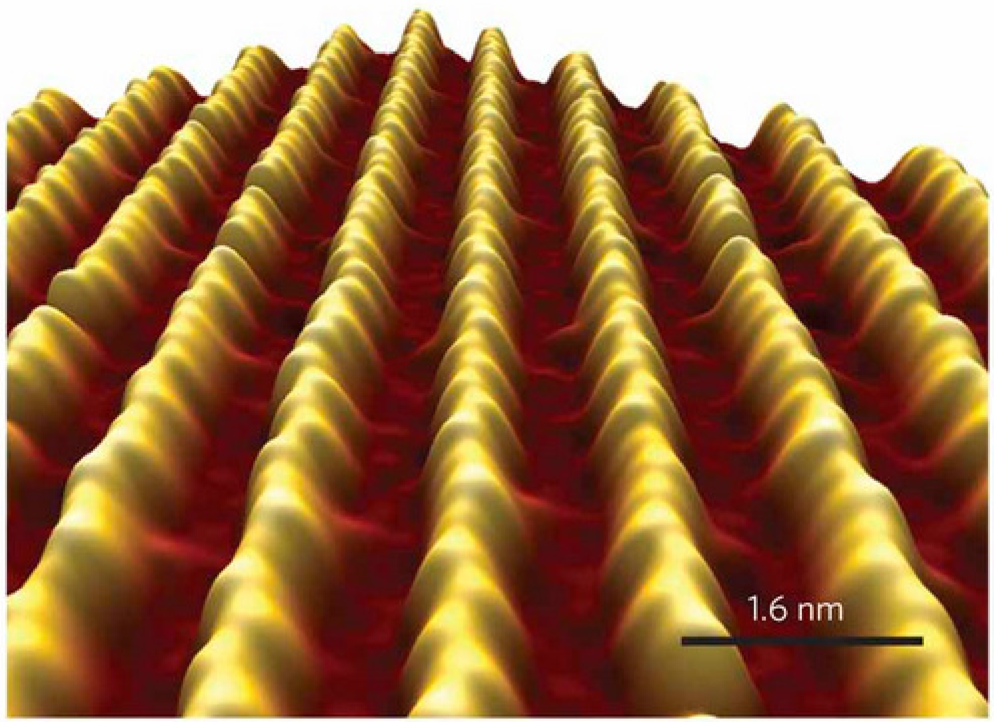
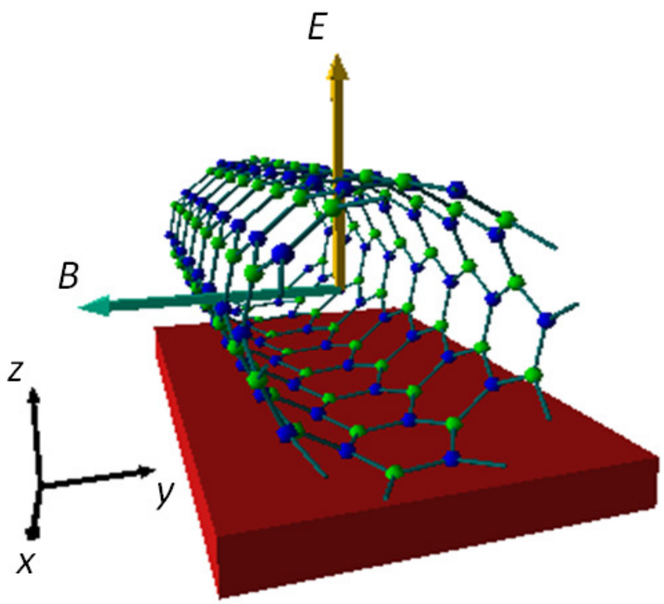


Carbon nanotubes



Luttinger-liquid behaviour in carbon nanotubes

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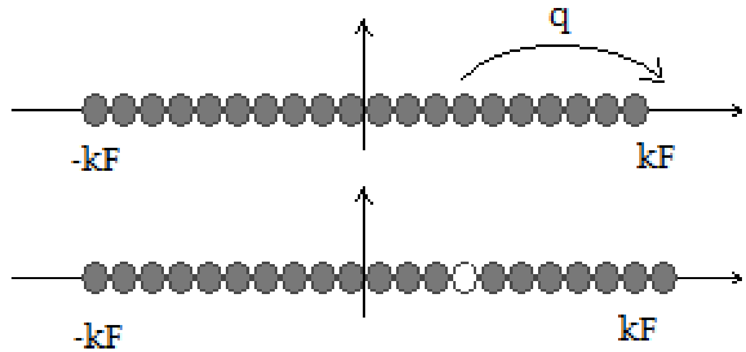
Electron transport in conductors is usually well described by Fermi-liquid theory, which assumes that the energy states of the electrons near the Fermi level E_F are not qualitatively altered by Coulomb interactions. In one-dimensional systems, however, even weak Coulomb interactions cause strong perturbations.

Excitações em 1D

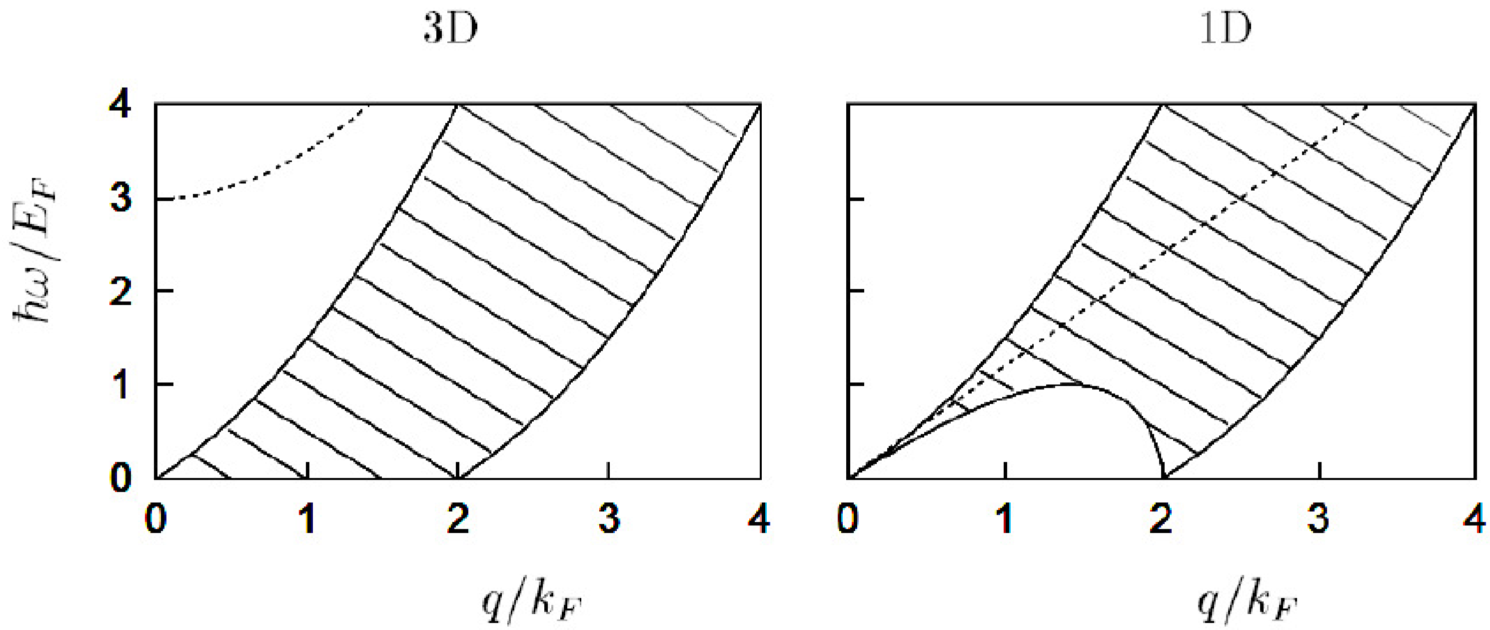


As excitações são sempre coletivas.
Um operador de partícula única não faz sentido

$$\rho_R(q) = \sum_{k>0} c^\dagger_{k+q} c_q$$
$$\rho_L(q) = \sum_{k<0} c^\dagger_{k+q} c_q$$

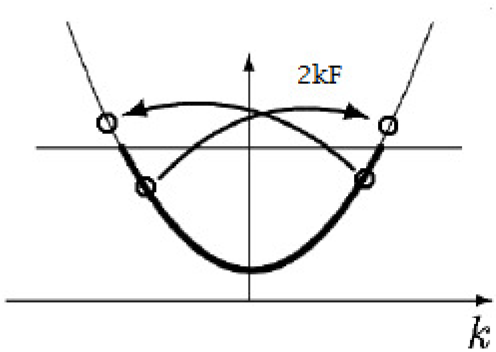
Considerações

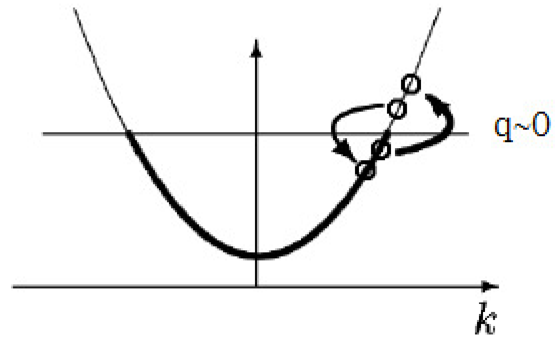
$$\omega_{pl} \propto q.$$

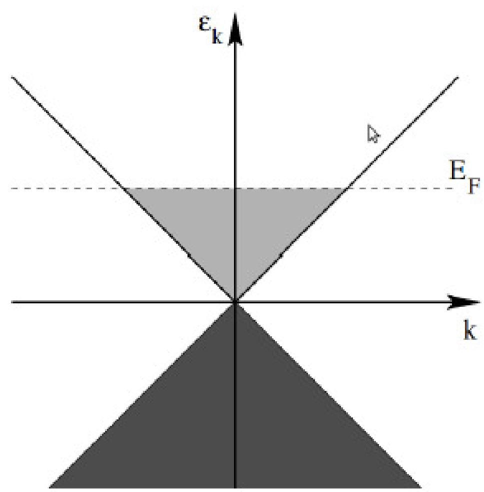


$$\tau^{-1} \propto \xi_k$$

Linearização







$$\rho_R(q) = \sum_{k>0} c^\dagger_{k+q} c_q$$

$$\rho_L(q) = \sum_{k<0} c^\dagger_{k+q} c_q$$

π

Construção do hamiltoniano

$$[\rho_r(q), \rho_{r'}(-q')] = 2\sum_k (n_r(k) - n_r(k+q)) \approx \delta_{r,r'}\delta_{q,q'}\frac{rLq}{2\pi}$$

$$[H_0, \rho_r(q)] = -rqv_F\rho(q)$$

$$H_0 = \frac{2\pi v_F}{L}\sum_{q>0}[\rho_R(-q)\rho_R(q) + \rho_L(q)\rho_L(-q)]$$

$$\begin{aligned} H_{I,1} &= \frac{1}{2L}\sum_q V_q(\rho_R(q) + \rho_L(q))(\rho_R(-q) + \rho_L(-q)) \\ H_{I,2} &= -\frac{1}{2L}\sum_q V_{2k_F}(\rho_R(-q)\rho_L(q) + \rho_R(q)\rho_L(-q)) \end{aligned}$$

“Bosonização”

$$b_{R,q} = \rho_R(q)\sqrt{\frac{2\pi}{qL}}, \qquad b^\dagger_{R,q} = \rho_R(-q)\sqrt{\frac{2\pi}{qL}}$$

$$b_{L,q} = \rho_L(-q)\sqrt{\frac{2\pi}{qL}}, \qquad b^\dagger_{L,q} = \rho_L(q)\sqrt{\frac{2\pi}{qL}}$$

Fazendo uma transformação de Bogoliunov

$$E_q = q\tilde{v}, \quad \tilde{v} = v_F\sqrt{1 + \frac{V_0 - V_{2k_F}}{\pi v_F}}$$

Formulação no espaço real

$$[\hat{A}(x), \rho_{x'}] = i\delta(x - x')$$

$$e^{i\hat{A}(x_0)}|0\rangle = |x_0\rangle$$

$$\rho_r(x) = \frac{1}{L}\sum_q e^{iqx}\rho_r(q)$$

$$[\rho_r(x), \rho_r'(x')] = \frac{r}{2\pi i}\delta_{rr'}\frac{\partial}{\partial x}\delta(x - x')$$

$$A(x) = \int_{-\infty}^{x} \rho_r(x')dx'$$

$$\psi_r(x) \propto U_r e^{\int_{-\infty}^{x} \rho(x')dx'}$$

Separação Carga-espin

$$H_0 = \frac{2\pi v_F}{L} \sum_{q>0,s} [\rho_{R,s}(-q)\rho_{R,s}(q) + \rho_{L,s}(q)\rho_{L,s}(-q)]$$

$$H_{int} = \frac{V}{L} \sum_{q} \sum_{s,s'} [(\rho_{R,s}(q) + \rho_{L,s}(q))(\rho_{R,s'}(-q)\rho_{L,s'}(-q)]$$

Com a transformação

$$\rho = \rho_\downarrow + \rho_\uparrow, \quad \sigma = \rho_\downarrow - \rho_\uparrow,$$

$$\begin{aligned} H_0 &= \frac{2\pi v_F}{L} \sum_{q} [\rho_R(-q)\rho_R(q) + \rho_L(q)\rho_L(-q) + \sigma_R(-q)\sigma_R(q) + \sigma_L(q)\sigma_L(-q)] \\ H_{int} &= \frac{V}{L} \sum_{q} [(\rho_R(q) + \rho_L(q))(\rho_R(-q)\rho_L(-q)] \end{aligned}$$

$$v_F^2 = v_\sigma v_\rho$$

OBRIGADO