2D electron interferometer : interaction and temperature effects

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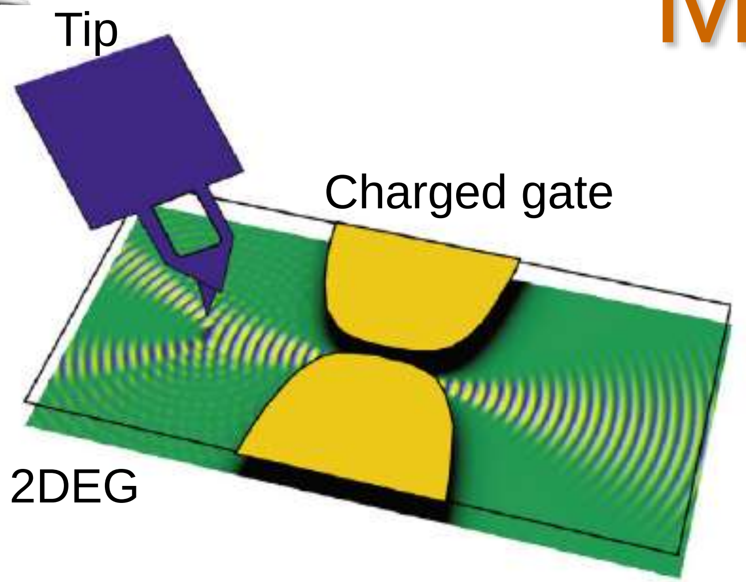
Outline

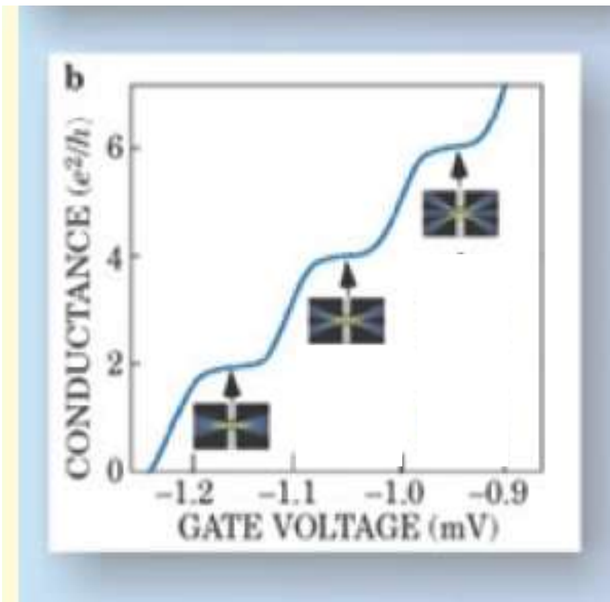
- Motivation
- Quantum point contact and resonance level model
- Conductance and transmission, Hartree-Fock approximation
- Regimes of the Anderson model
- Enhancement of the fringes with interaction

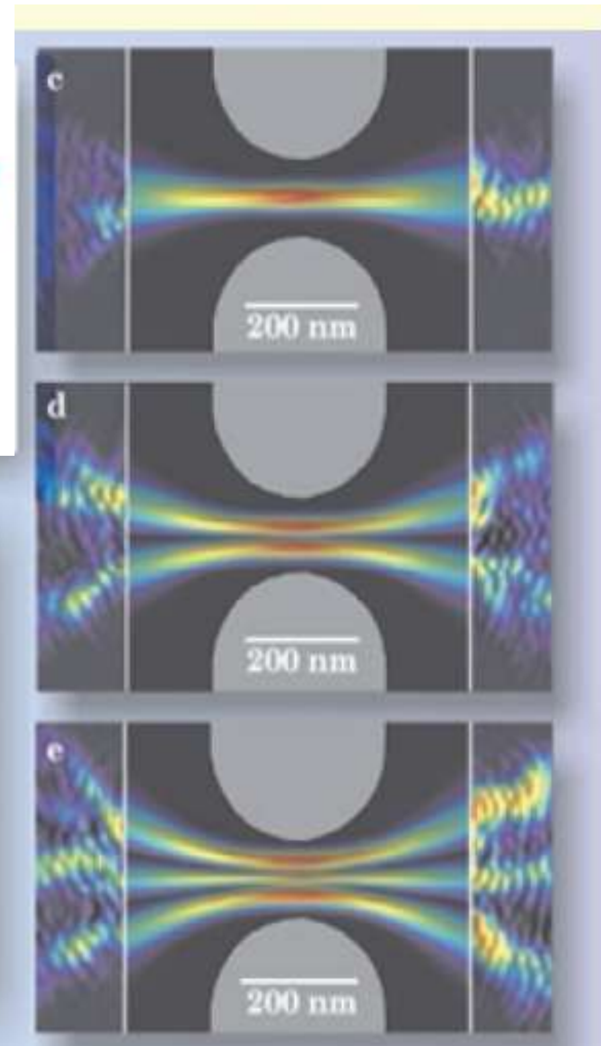
 (weak coupling regime)
- Conductance as a function of the tip position

(local moment regime)
- Summary

Motivation



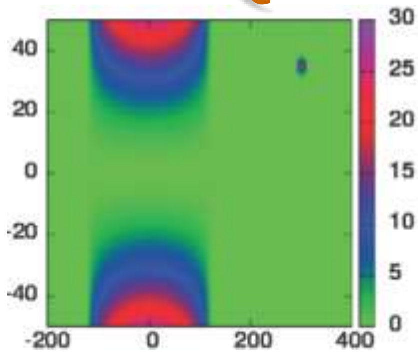




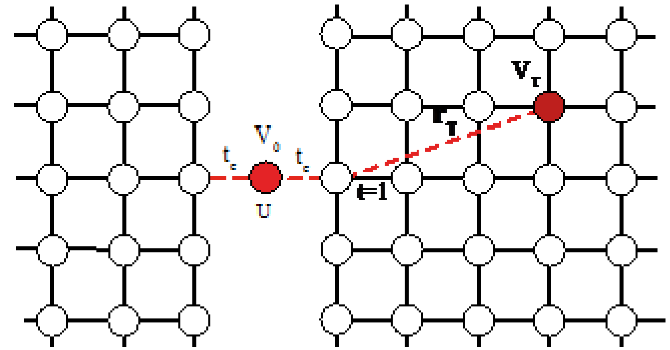
Topinka et al, Nature (2001)

- scanning gate microscopy
- electron-electron interaction inside QPC
- thermoelectric materials and promising fabrication technologies

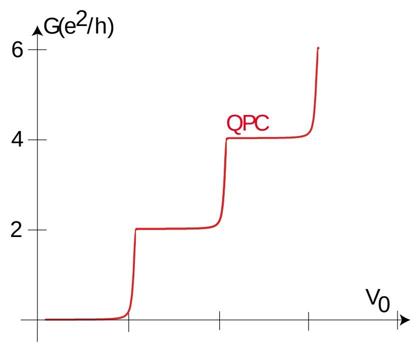
Real QPC

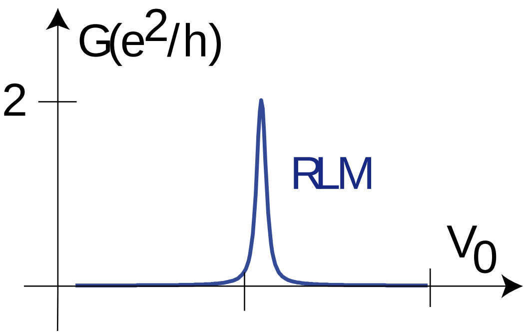


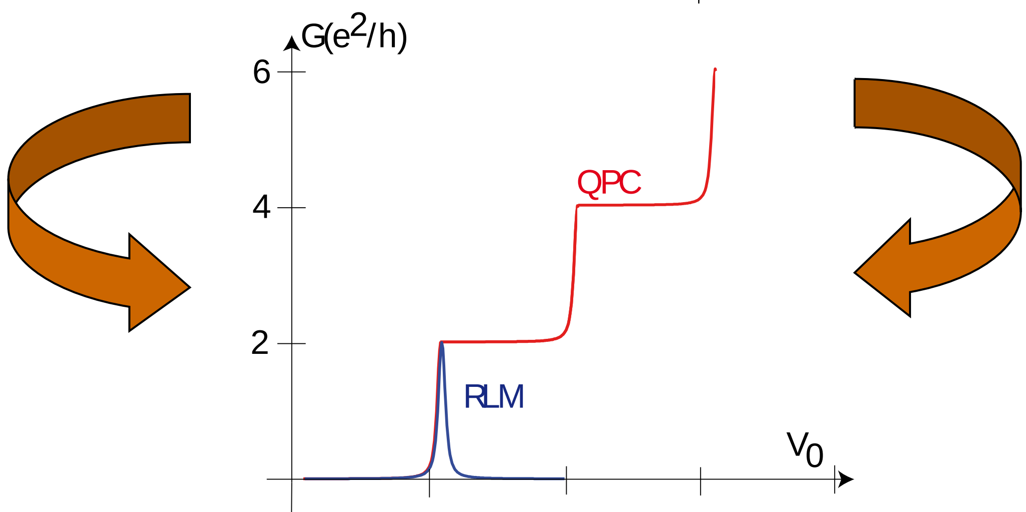
RLM



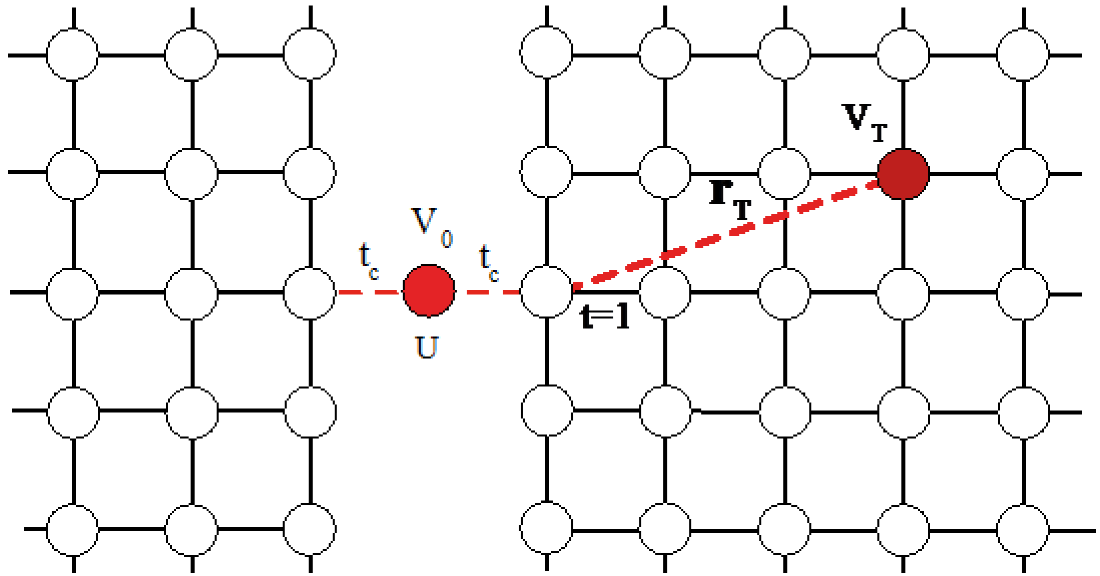
conductance







Resonance Level Model



$$H = \sum_{\sigma}\left(H_0 + H_c + H_L + H_{R+T}\right) + H_U$$ – Hamiltonian of the system

$$H_0 = V_0 |0\rangle\langle 0|$$ – Hamiltonian of the quantum impurity located at (0,0)

$$H_C = -t_c\left(|-1,0\rangle\langle 0| + |1,0\rangle\langle 0| + H.C.\right)$$ – coupling between the leads and site (0,0)

$$H_L = \sum_{x_i<0} v|i\rangle\langle i| - t_h \sum_{x_i,x_j<0} |j\rangle\langle i|$$ – left lead

$$H_{R+T} = \sum_{x_i>0} v|i\rangle\langle i| - t_h \sum_{x_i,x_j<0} |j\rangle\langle i| + V_T|x_T, y_T\rangle\langle x_T, y_T|$$ – right lead with a tip on the site (x_T,y_T)

$$H_U = U n_{\downarrow} n_{\uparrow}$$ – Hubbard interaction on the site (0,0)

Transmission and conductance

$\tau(E) = \mathrm{Tr}\left(G^R \Gamma_L G^A \Gamma_{R+T}\right)$ – transmission expressed with the Fisher-Lee formula

$\Gamma_L = -2\,\mathrm{Im}(\Sigma_L),\quad \Gamma_{R+T} = -2\,\mathrm{Im}(\Sigma_{R+T})$ – broadenings due to the left and right leads

$\Gamma \sim t_c^2$

$$G_{\text{sys}} = \begin{pmatrix} G_\uparrow & 0 \\ 0 & G_\downarrow \end{pmatrix} = \begin{pmatrix} (E - H_C - \Sigma_L - \Sigma_R - \Sigma_\uparrow^H)^{-1} & 0 \\ 0 & (E - H_C - \Sigma_L - \Sigma_R - \Sigma_\downarrow^H)^{-1} \end{pmatrix}$$

– green function of the system that consists of electron with spin up and spin down green functions

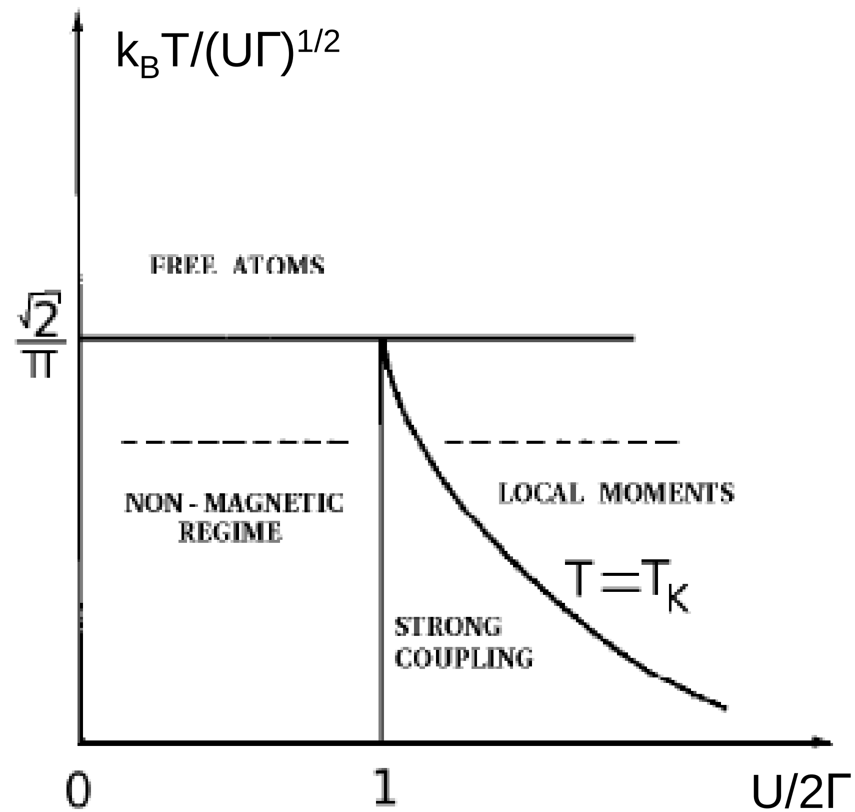
$\Sigma_{\uparrow,\downarrow}^H = -\dfrac{U}{\pi}\displaystyle\int dEf\,(E - E_F)\,\mathrm{Im}\left(G_{\downarrow,\uparrow}(E)\right)$ – Hartree self-energy

$G = \dfrac{2e^2}{h}\displaystyle\int \tau(E) F_T(E - E_F)\,dE$ – conductance of the system at T≠0

$F_T(E - E_F) = -\dfrac{d}{dE}\left(f(E)\right) = \dfrac{1}{4k_B T}\mathrm{sech}^2\left(\dfrac{E - E_F}{2k_B T}\right)$ – thermal broadening

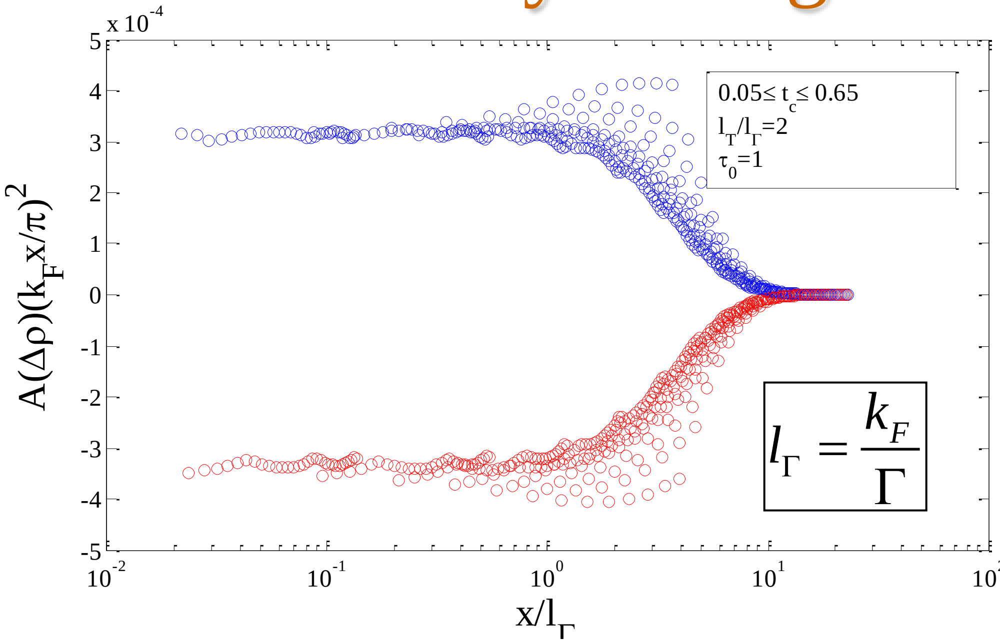
Energy scales of the Anderson model

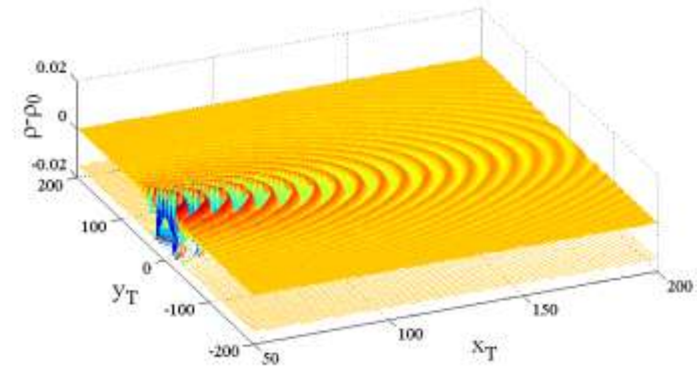
- $T \gg (U\,\Gamma)^{1/2}$ – free atom limit
- $U \ll \Gamma$ – non-magnetic regime
- V_0, $U \gg \Gamma$, $T > T_k$ – local moment regime
- V_0, $U \gg \Gamma$, $T < T_k$ – strong coupling (Kondo) regime
- $\Gamma \geq V_0$ – mixed valence regime



Tsvelick A. M., Wiegmann P. B., Advances in Physics (1983)

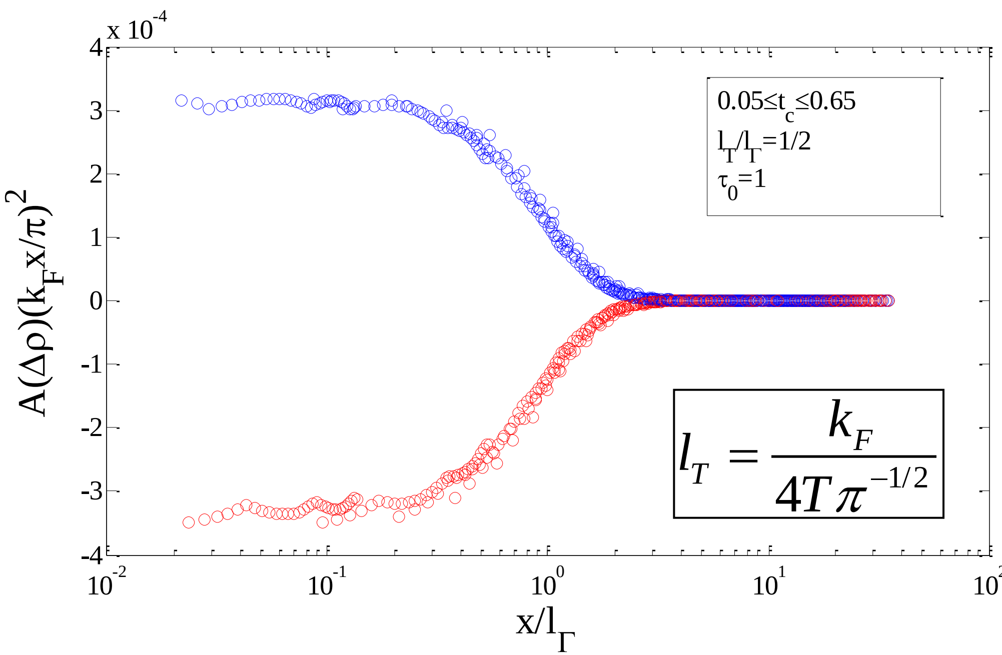
Density scaling without interaction





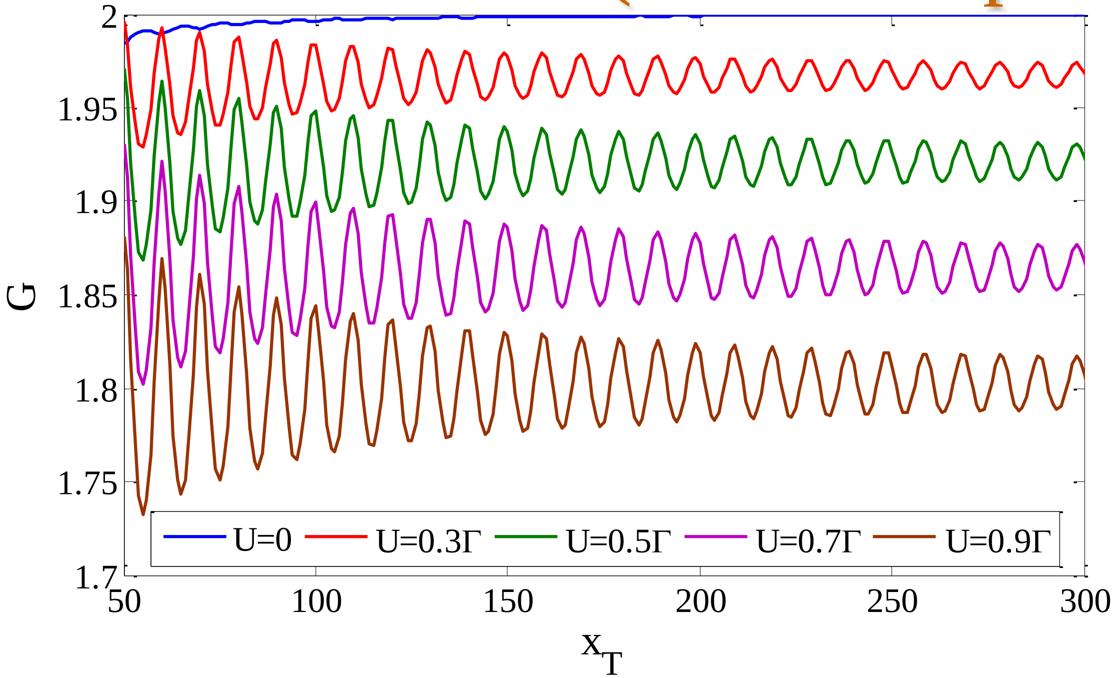
$$\Delta\rho = \rho(\text{with tip}) - \rho_0(\text{without tip})$$

$$\Delta\rho \sim \frac{1}{x^2}\exp(-x/l)$$



Scaling of the density amplitude for different values of $0.05<t_c<0.65$ for $l_T/l_\Gamma=2$ and $l_T/l_\Gamma=0.5$

Enhancement of the fringes due to the interaction at U<Γ<T (1-st order perturbation)



Oscillation are falling of with distance as

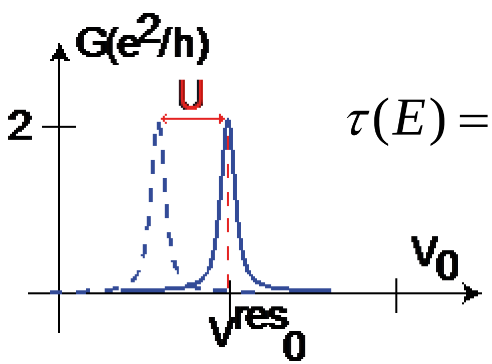
$$G \propto \frac{\exp(-x/l_\Gamma)}{x}$$

with a decay scale

$$l_\Gamma = \frac{k_F}{\Gamma}$$

spaced by $\lambda_F/2$.

Parameters: E_F=0.1, t_c=0.2, y_T=0, T=1e-3, $V_0=V^{res}_0$, V_T=-2.

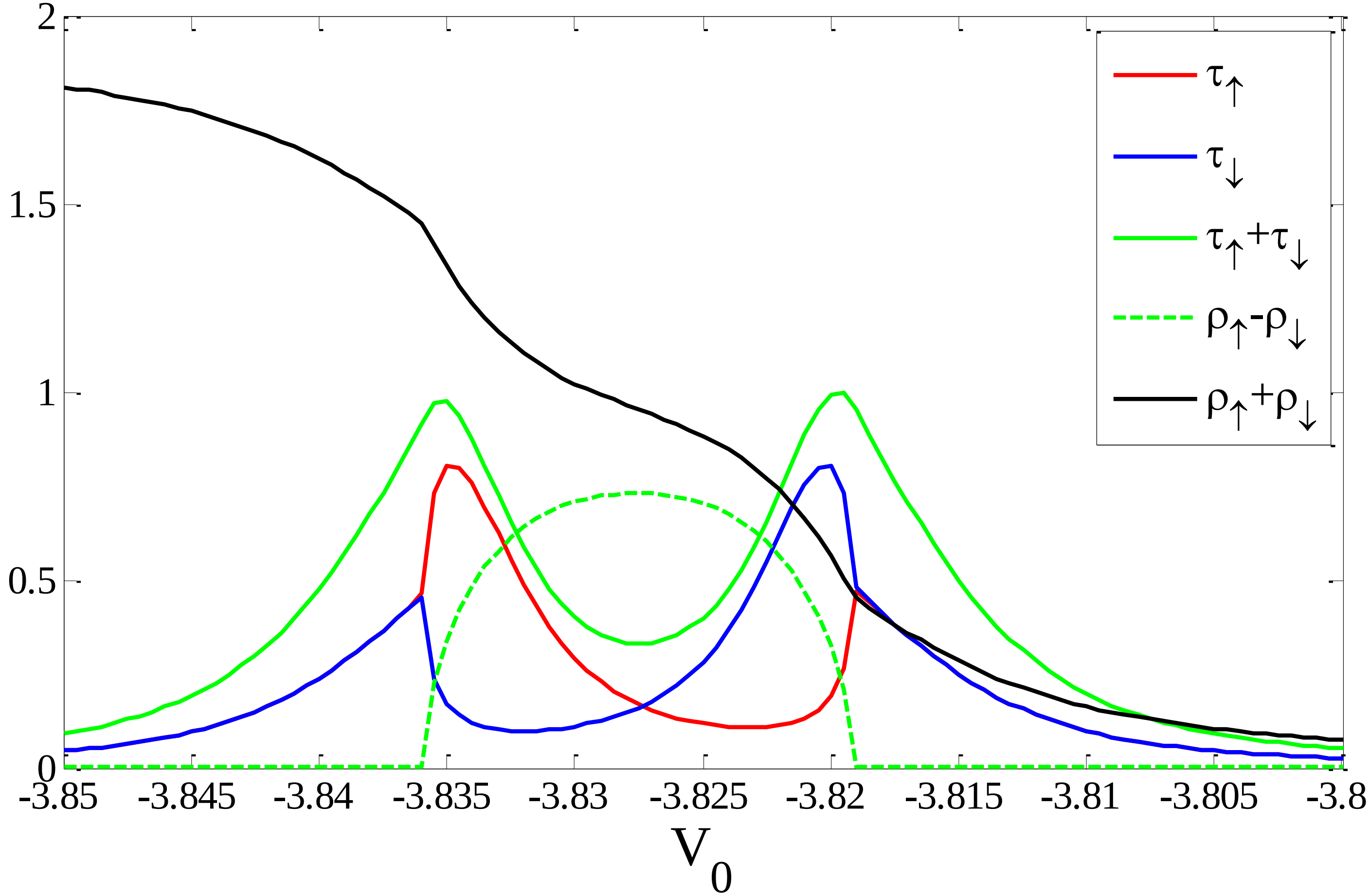


$$\tau(E) = \frac{4 I_L I_R}{\left(E - H_C - R_R - R_L - \Sigma^H\right)^2 + \left(I_R + I_L\right)^2}$$

$$\Sigma_{R,L} = R_{R,L} + i I_{R,L}$$

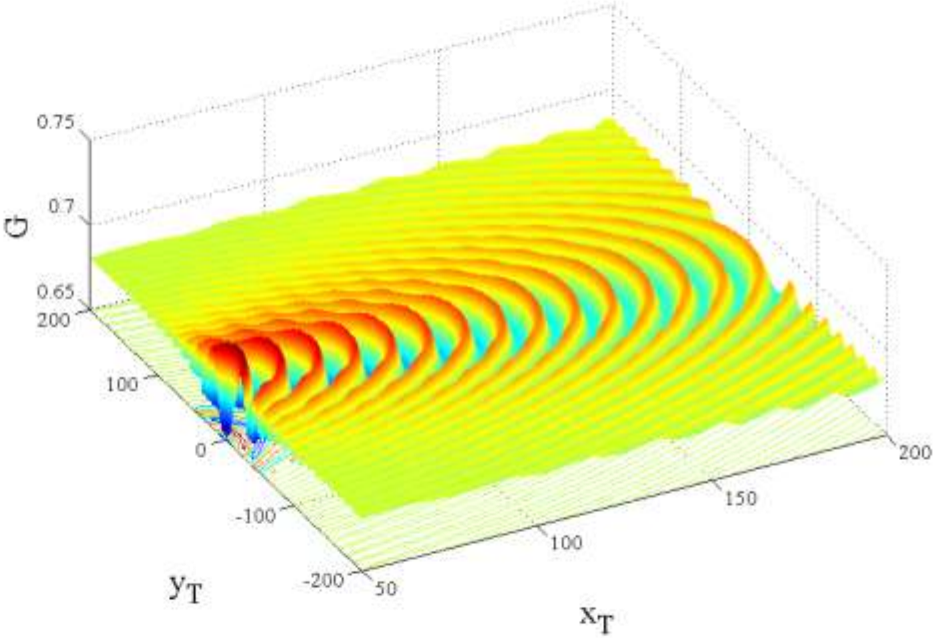
– transmission without a tip has Loretzian form of width Γ if t_c<<1.

Transmission and density without a tip at U>Γ, T>T_K Hartree-Fock study (local moment regime)

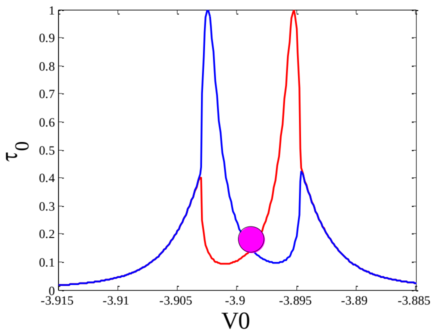


Parameters: E_F=0.15, t_c=0.2, T=1e-3, U=0.02

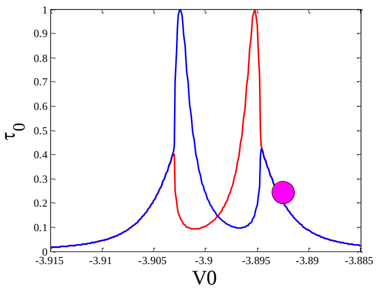
Conductance modulated by the tip

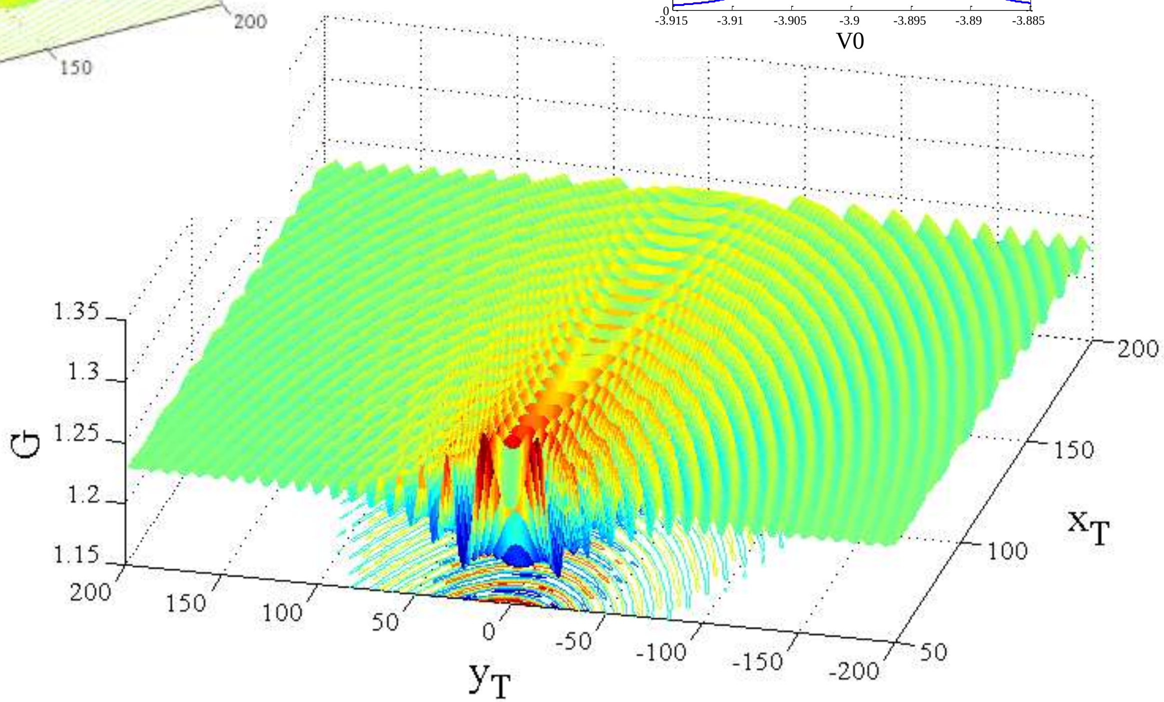


two modes regime

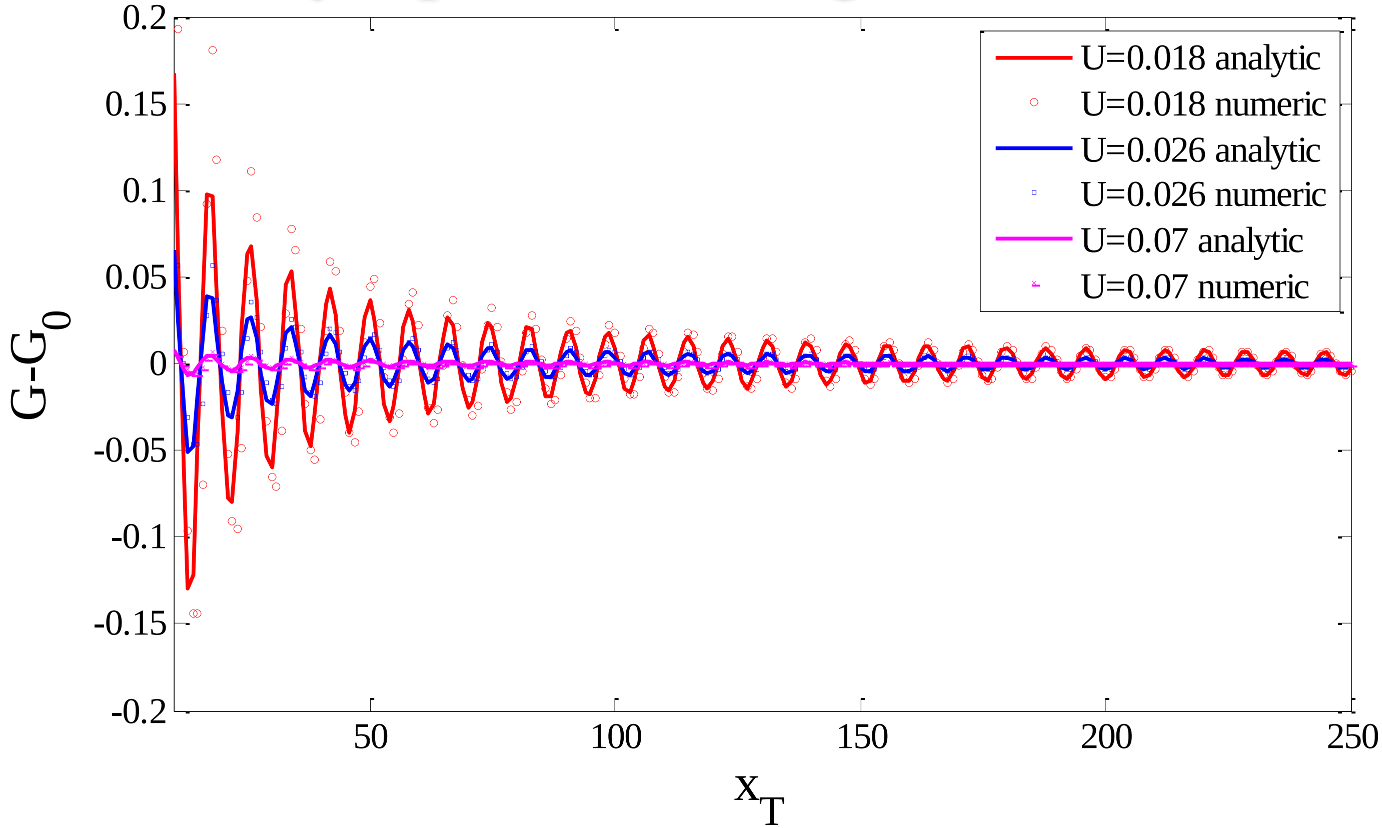


one mode regime





Conductance as a function of the tip position: asymptotic at long distances



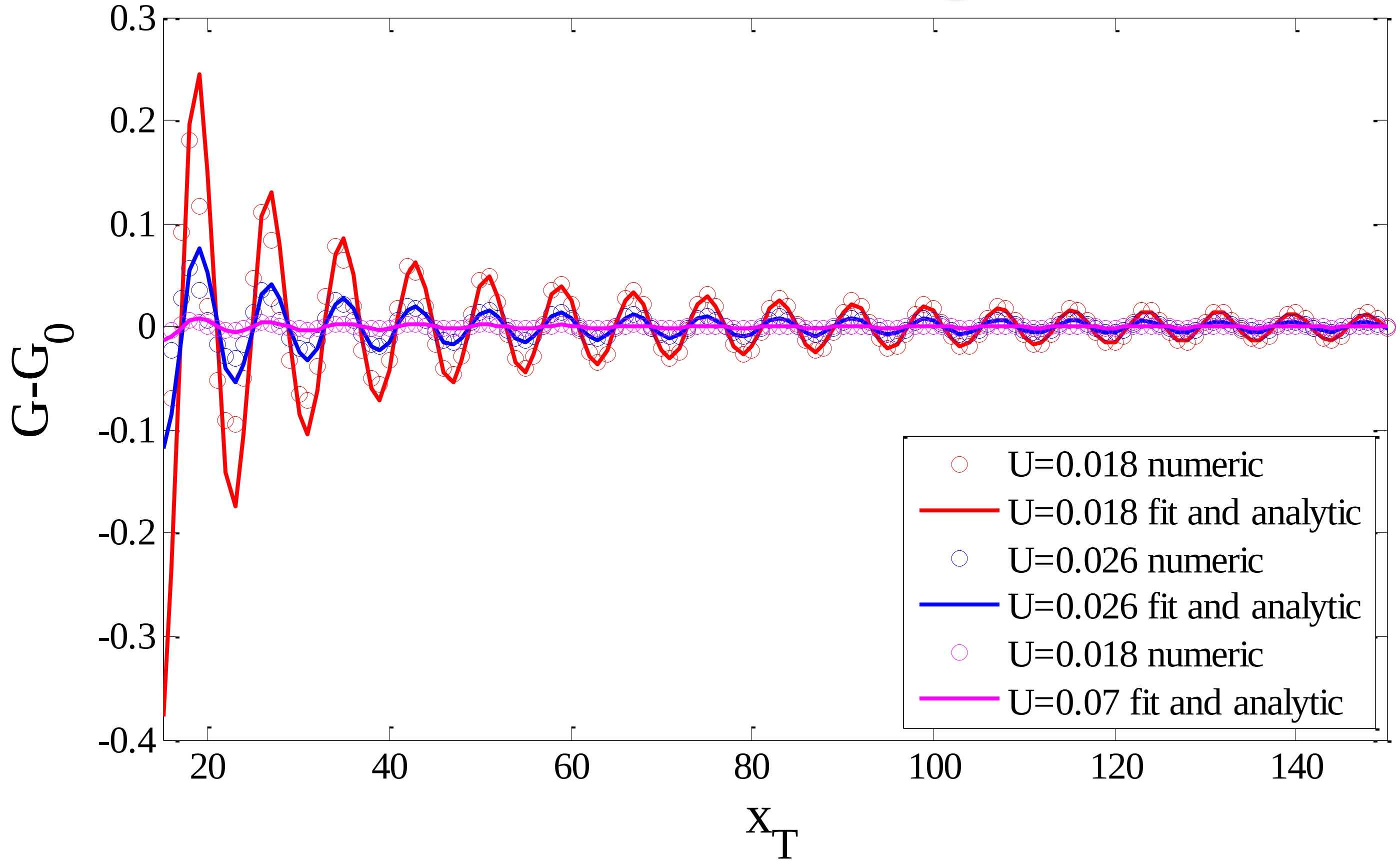
Parameters: E_F=0.15, t_c=0.2, T=1e-3, y_T=0 V_T=-2.

$$\Delta G \propto \frac{1}{k_F}\frac{1}{x_T}\left(1-\tau_0(U)\right)\tau_0(U)\cos\left(2k_F x_T+\varphi\right)\exp\left(-\left(x_T/2l_T\right)^2\right)$$

asymptotic $r \gg \lambda_F$

if $T \ll U/2$

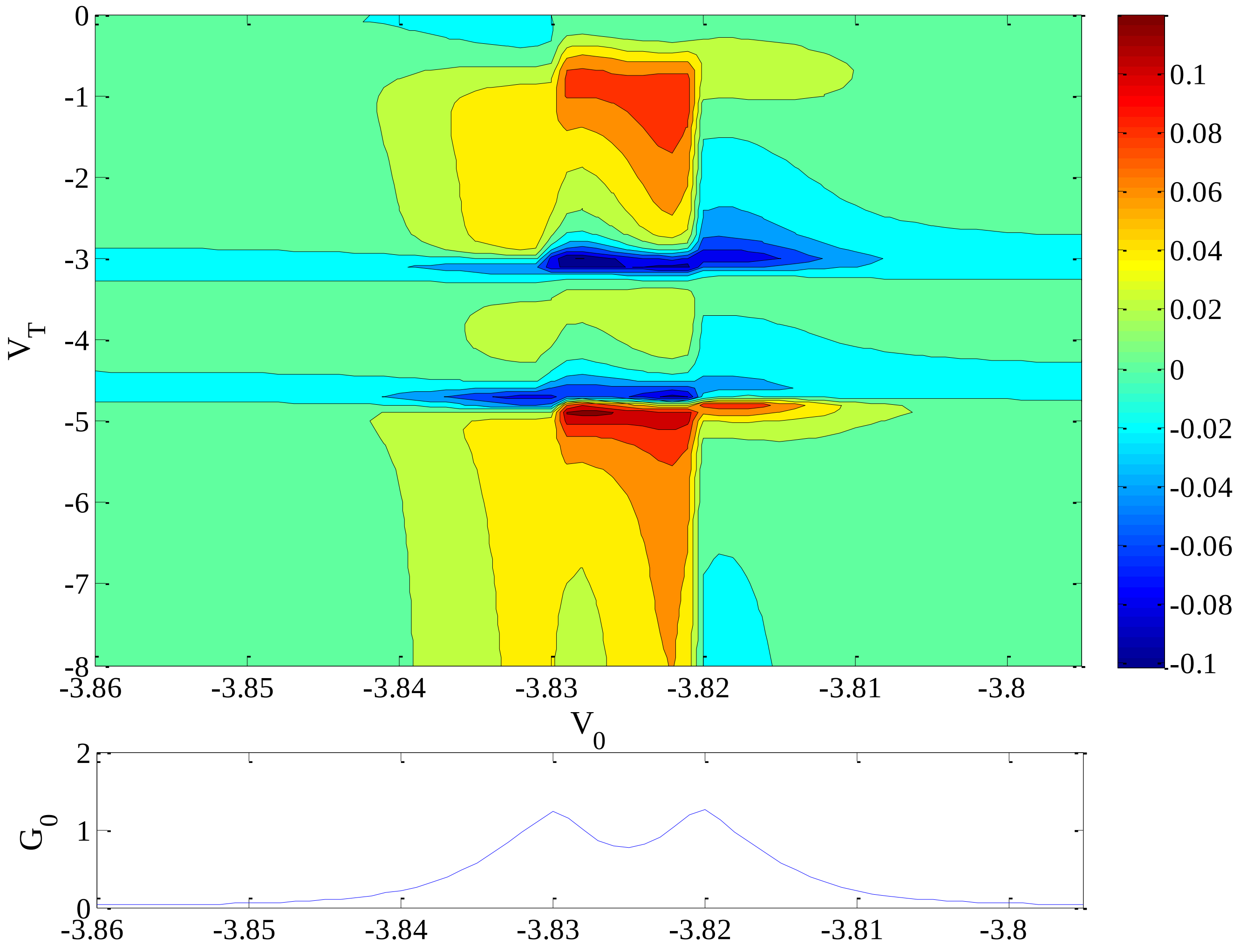
Conductance as a function of the tip position, short distance fitting



$$\Delta G \approx A(U)\frac{\cos\left(2k_F x_T+\varphi_1\right)}{x_T^2}+\frac{\cos\left(2k_F x_T+\varphi_2\right)}{x_T}\exp\left(-\left(x_T/2l_T\right)^2\right)$$

$$A(U)\approx e^{-\sqrt{\Gamma U}}$$

Conductance as a function of the site and tip potential at the fixed position of the tip



Parameters: E_F=0.15, t_c=0.2, T=1e-3, y_T=0, x_T=80.

Summary

•One can "read" temperature, broadening and interaction from the interference pattern.

•Interaction can enhance conductance fringes at non-magnetic regime.

•Conductance in the local moment regime can be described with two terms:

$$\Delta G \propto \frac{A}{x_T^2} + \frac{B}{x_T} \exp\left(-\left({x_T}/{2l_T} \right)^2 \right)$$

$1/x^2$ term arises due to density oscillations inside QPC.

$\exp(-(x/l_T)^2)/x$ term results from the detuning of the resonance due to interaction.

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