Momentum-resolved tunneling into a short cleaved-edge wire

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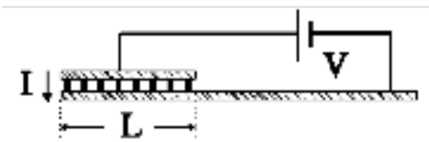
Motivation

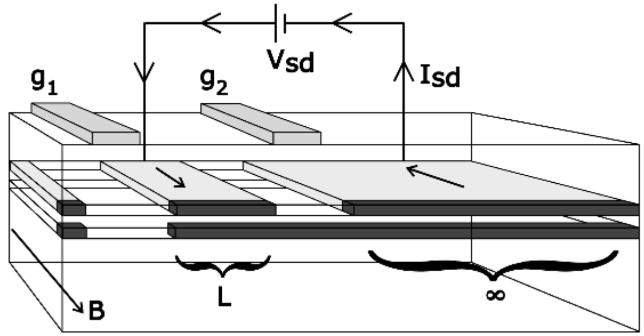
- One-dimensional physics has attracted a tremendous amount of theorists' attention in the past several decades, because of solvable models and powerful exact methods (Bethe ansatz, Bosonization) as well as rich physics
- To a large degree, it became a paradigm for thinking of interacting electron systems in general (in the same league as fractional quantum Hall physics)
- But only recently mesoscopic physics created a gateway for experimental exploration of 1D physics (carbon nanotubes, organic conductors, cleaved-edge wires)
- Naturally, new questions were raised by trying to apply old theory to new systems which led to a renewed interest in 1D physics
- As a starting point, we have to find a solid common ground between the established theory and recent measurements

Outline

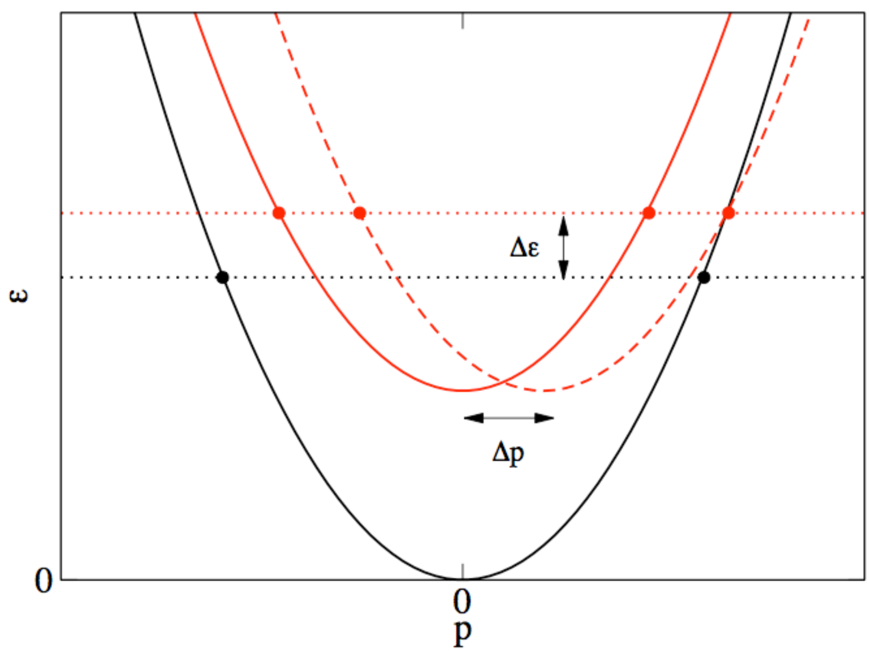
- Probing elementary excitations by momentum-resolved tunneling
- <u>Top-gate density control</u>
- Extracting charge/spin velocities
- Localization
- Quasi-wavefunction, Wigner-crystal limit, and free-spin regime

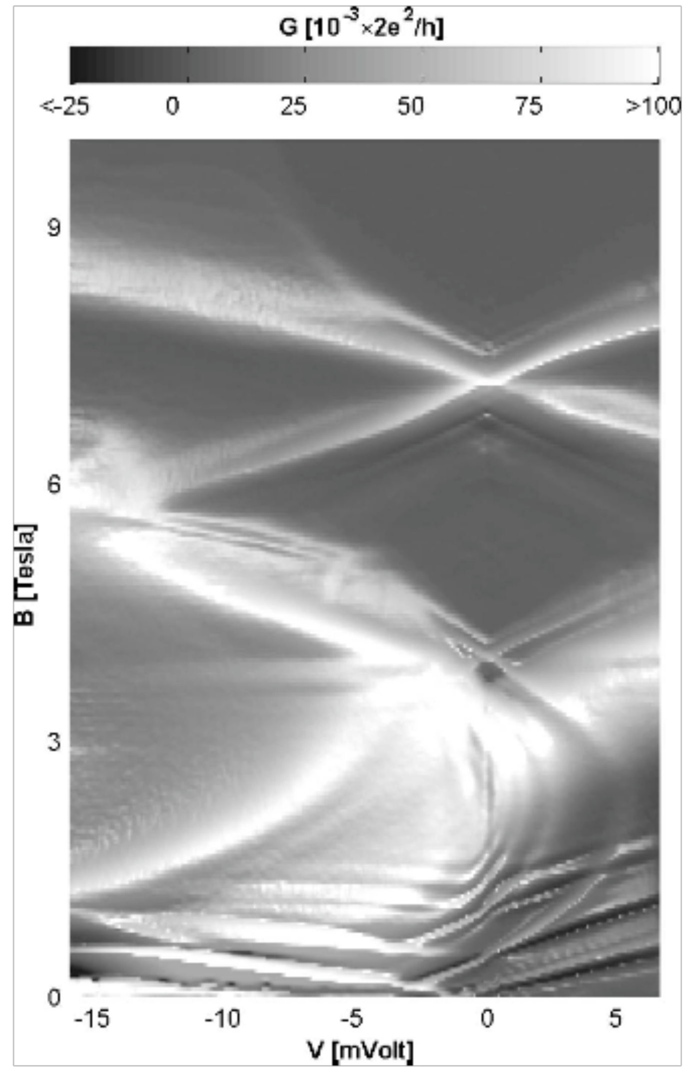
Momentum-resolved tunneling





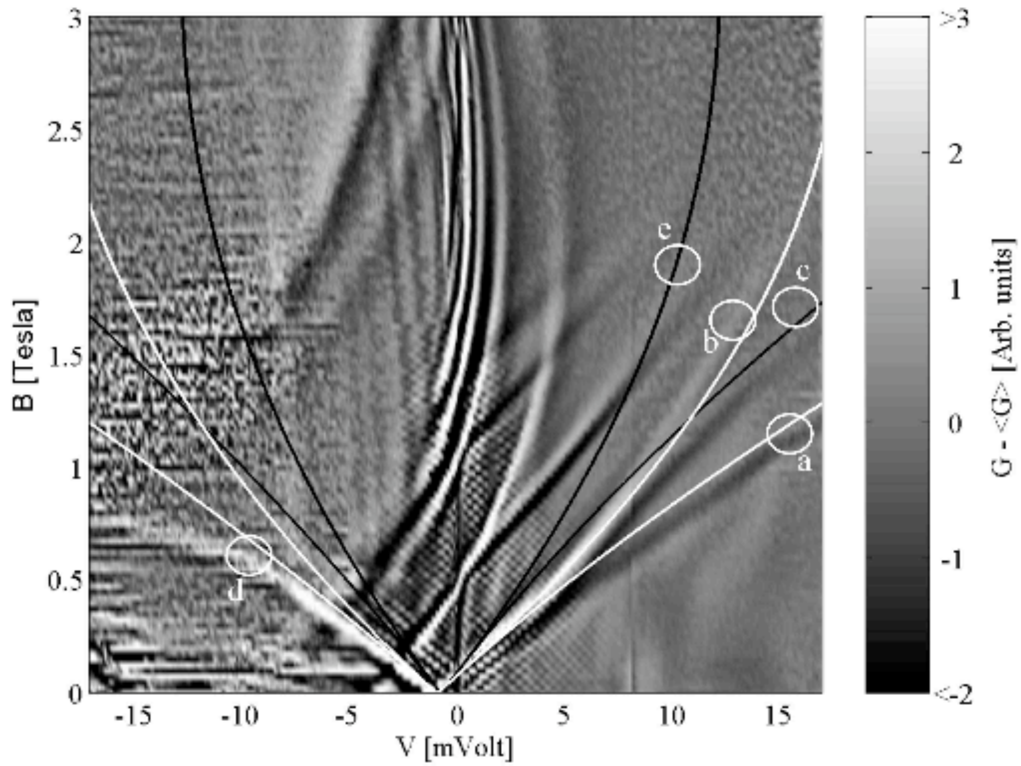
$$\Delta p = edB \qquad \Delta\varepsilon = eV_{sd}$$





Auslaender, Yacoby, de Picciotto, Baldwin, Pfeiffer, and West, Science **295**, 825 (2002)

Zoom into lower crossing point

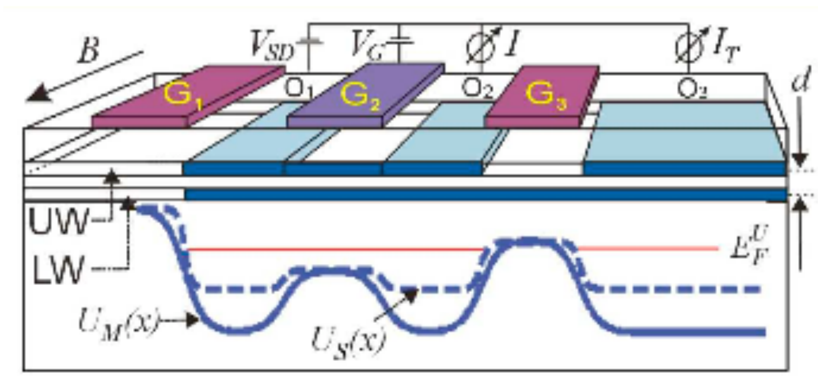


Spin-charge separation:

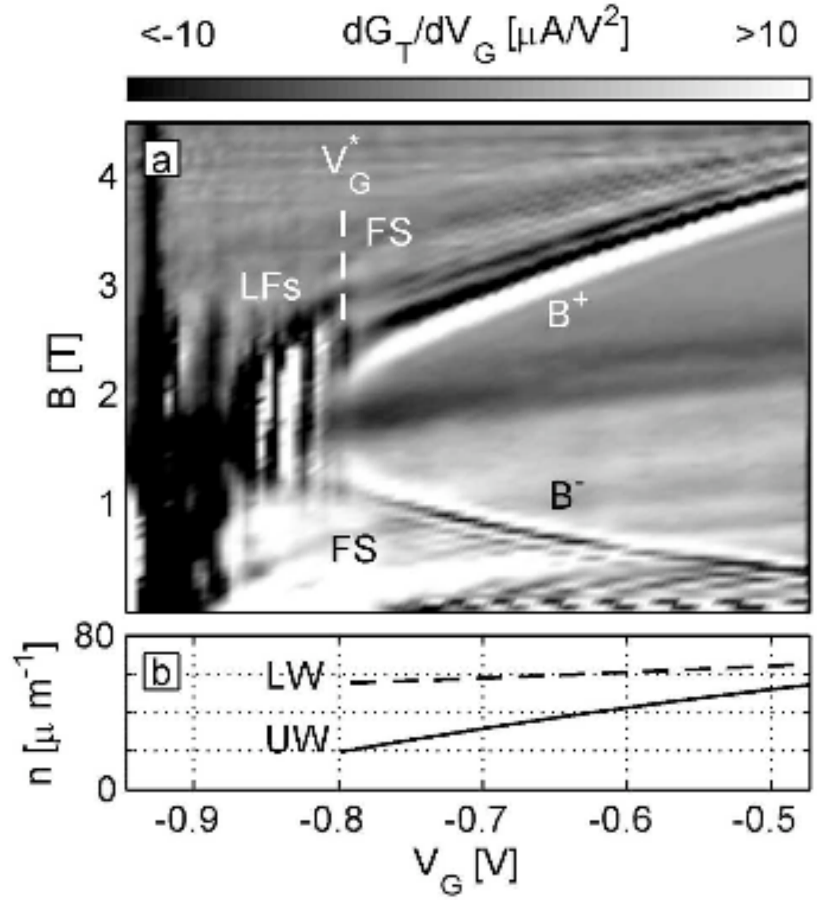
- crossing points
- diffraction pattern
- zero-bias anomaly

YT, Halperin, Auslaender, and Yacoby, PRL **89**, 136805 (2002); PRB **68**, 125312 (2003)

Top-gate density control



$$B_{\pm} = \frac{\hbar}{ed}|k_{\mathrm{FU}} \pm k_{\mathrm{FL}}|$$



Auslaender, Steinberg, Yacoby, YT, Halperin, Baldwin, Pfeiffer, and West, Science **308**, 88 (2005)

N coupled spin-degenerate modes

Hamiltonian for the charge sector

$$H_\rho = \sum_{i=1}^{N} \int dx \frac{\pi v_{Fi}}{2} \Pi_i^2 + \sum_{i,j=1}^{N} \left(\frac{e}{\pi}\right)^2 \hat{C}_{ij}^{-1} \int dx (\partial_x \phi_i)(\partial_x \phi_j)$$

ϕ_i is displacement operator for charge density

Π_i canonically-conjugate momentum-density operator

$$[\phi_i(x), \Pi_{i'}(x')] = i\delta_{ii'}\delta(x - x')$$

can be diagonalized by a unitary transformation

Elementary charge velocities are then given by eigenvalues of

$$\frac{2e^2}{\pi} \sqrt{\hat{v}_F} \hat{C}^{-1} \sqrt{\hat{v}_F}$$

Double-wire estimates

$$N=1: \qquad v_c^2 = \frac{2e^2 v_F}{\pi C}, \quad \frac{1}{C} = \frac{\pi v_F}{2e^2} + \frac{1}{C_{\text{electrost.}}}$$

$$N=2: \qquad v_{c\pm}^2 = \frac{e^2}{\pi}\left[\left(\frac{v_{F1}}{C_1}+\frac{v_{F2}}{C_2}\right) \pm \sqrt{\left(\frac{v_{F1}}{C_1}-\frac{v_{F2}}{C_2}\right)^2 + 4\frac{v_{F1}v_{F2}}{C_{12}^2}}\right]$$

Two cylindrical wires of radius r, center-to-center distance s, screened by a 2D plate at distance $d/2 \gg s \gg r$:

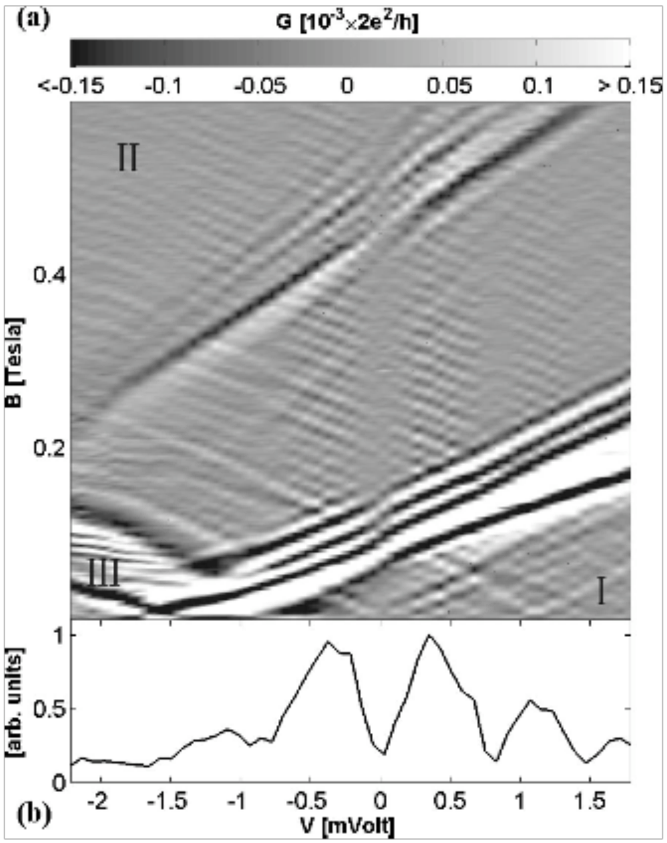
$$\frac{1}{C_i} = \frac{\pi v_F}{2e^2} + \frac{2}{\epsilon}\ln\frac{d}{r}, \qquad \frac{1}{C_{12}} = \frac{2}{\epsilon}\ln\frac{d}{s}$$

$$v_{c\pm}^2 = v_F^2 + \frac{4e^2}{\pi\epsilon}v_F\left(\ln\frac{d}{r} \pm \ln\frac{d}{s}\right)$$

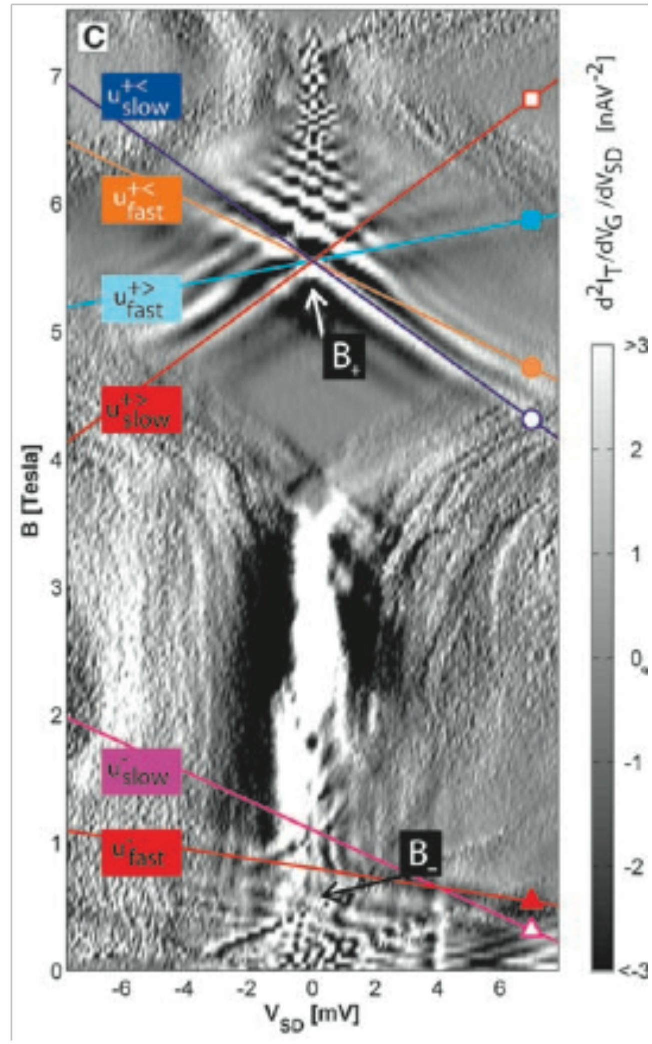
$$n = 100\ \mu\text{m}^{-1}, \quad d = 1\ \mu\text{m}, \quad s = 30\ \text{nm}, \quad r = 10\ \text{nm}, \quad \epsilon = 13$$

$v_F/v_{c+} \approx 0.4$ and $v_F/v_{c-} \approx 0.7$

Extracting velocities

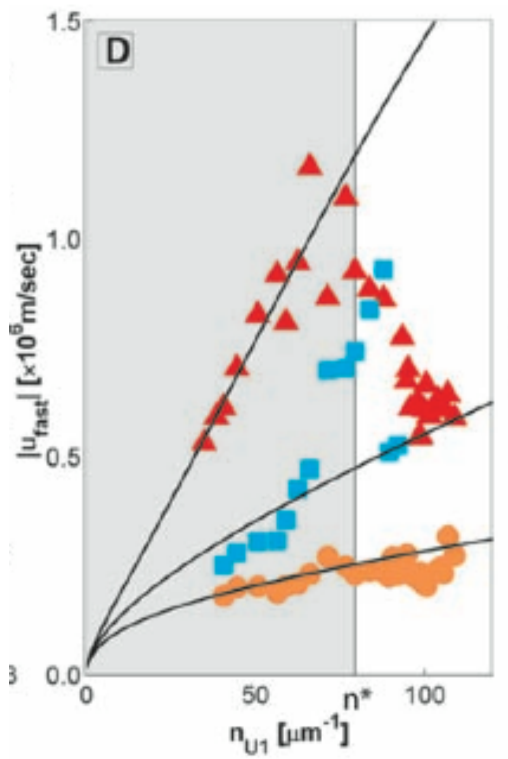


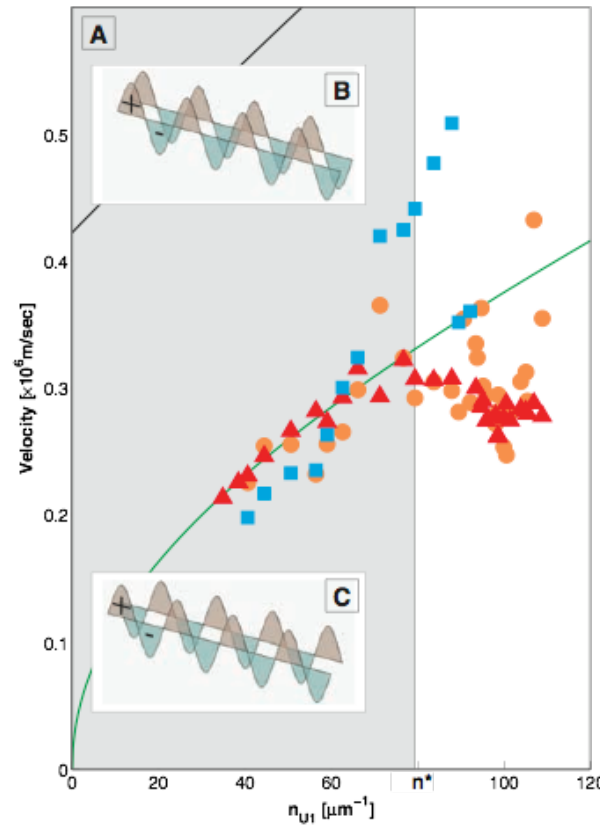
$v_F/v_{c-} \approx 0.7$



YT, Halperin, Auslaender, and Yacoby, PRB **68**, 125312 (2003)

Charging correction to the slopes



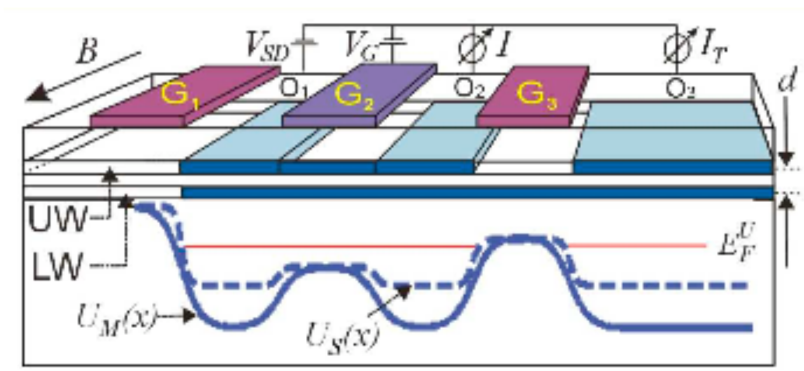


Actual velocity is $v = \dfrac{|u^{\pm}|}{1 \pm \gamma_{\pm} u^{\pm}}$ in terms of "slope" velocity $u^{\pm}$

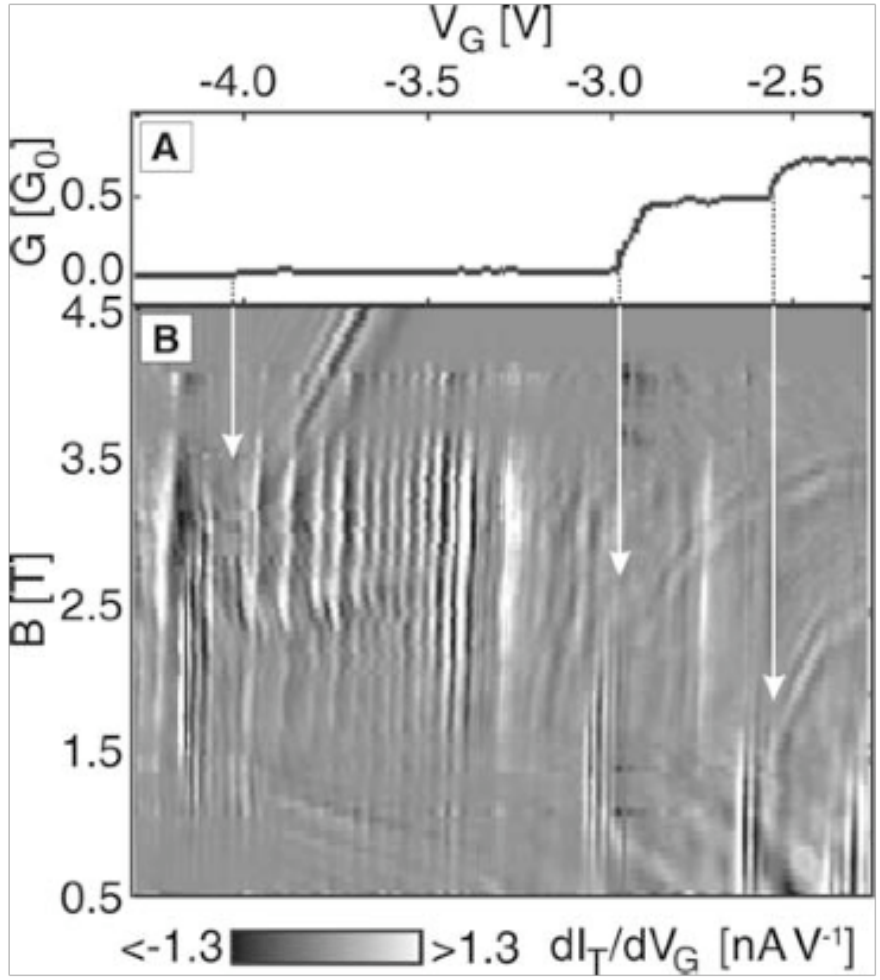
$$\gamma_{\pm} = \frac{\pi\hbar}{e^2}\left[c_{\pm}c_{\mathrm{U}}\left(c_{\mathrm{L}} + c_{\mp}/2\right)\right]\left[\left(c_{+} + c_{-}\right)\left(c_{\mathrm{L}} + c_{\mathrm{U}}\right) + c_{+}c_{-} + 4c_{\mathrm{L}}c_{\mathrm{U}}\right]^{-1}$$

Auslaender, Steinberg, Yacoby, YT, Halperin, Baldwin, Pfeiffer, and West, Science **308**, 88 (2005)

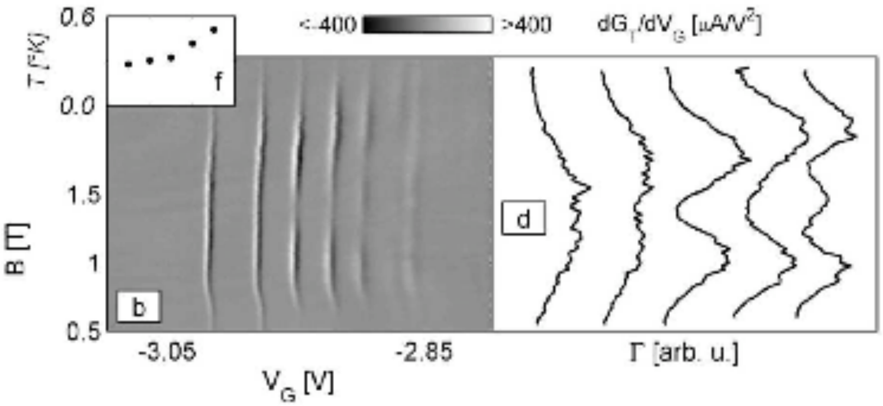
Localization

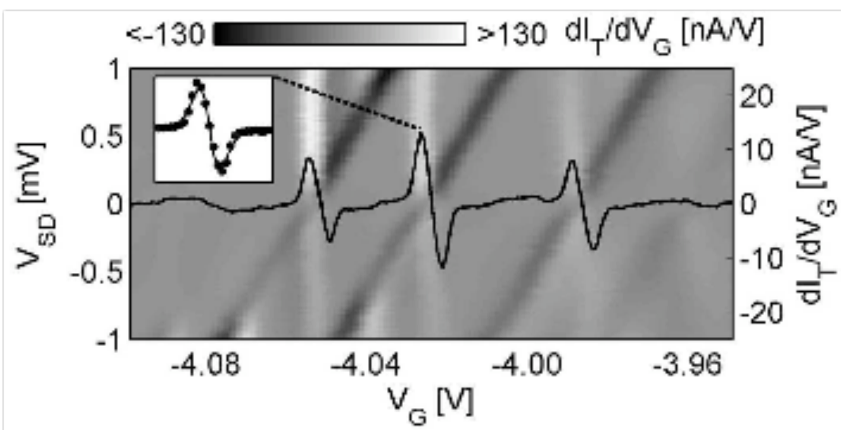


Localization features are concurrent with conductance steps



Momentum-resolved structure





Magnetic-field dependence of tunneling probes one-electron spectral function, which can be described by quasi-wavefunction:

$$\Psi^N_{\text{eff}}(x) \equiv \langle \Psi^{N-1}_\gamma | \psi_\sigma(x) | \Psi^N_\alpha \rangle$$

$$M(k) = \int dx e^{ikx} \Psi^{N*}_{\text{eff}}(x) / \sqrt{L}$$

$$G_\pm \propto |M(k_\pm)|^2$$

$$k_\pm = \pm k^l_F + eBd/\hbar$$

Fiete, Qian, YT, and Halperin, PRB 72, 045315 (2005)

Steinberg, Auslaender, Yacoby, Qian, Fiete, YT, Halperin, Baldwin, Pfeiffer, and West, cond-mat/0506812

Few-electron limit

$N=1$ $\quad M(k) = \int dx \frac{e^{ikx}}{\sqrt{L}} \Psi^*(x)$ $\quad |M(k)|$ has its maximum when $k=0$ for $N=1$

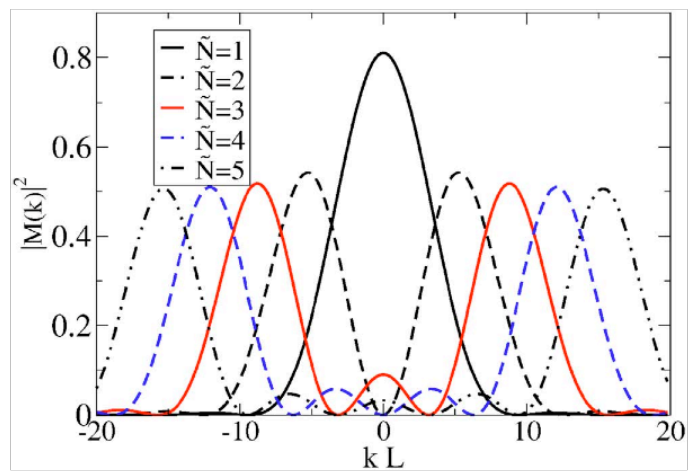
$N=2$ $\quad |\Phi\rangle = f(x_1,x_2)\chi_0(\sigma_1,\sigma_2)$ (singlet)

$$M(k) = \int dx_1 dx_2 \frac{e^{ikx_2}}{\sqrt{L}} \Psi(x_1) f(x_1,x_2)$$ has its maximum at $k=0$.

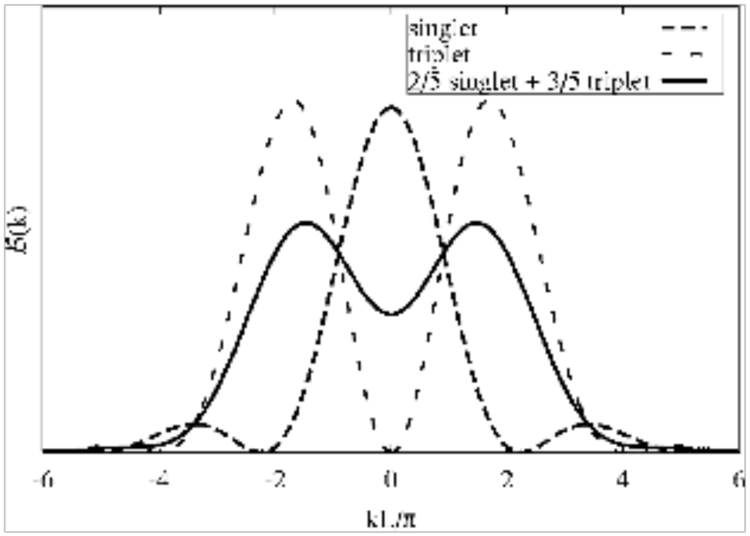
$|\Phi\rangle = g(x_1,x_2)|\uparrow\uparrow\rangle$ (triplet)

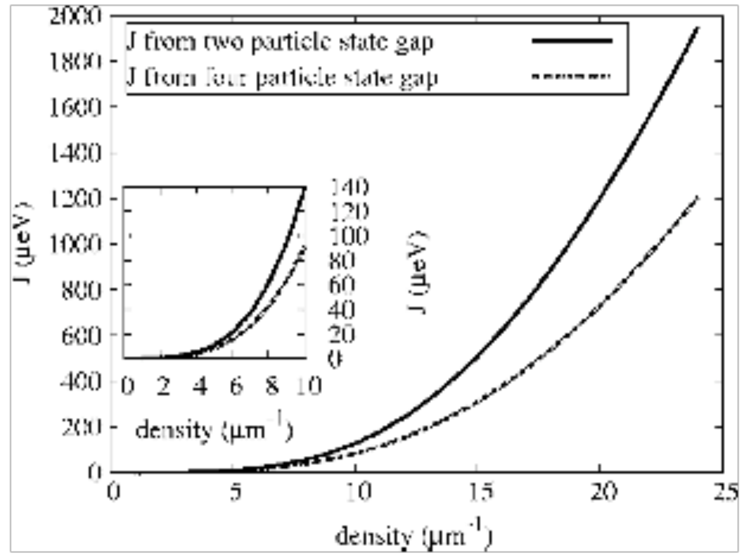
$$M(k) = \sqrt{2}\int dx_1 dx_2 \frac{e^{ikx_2}}{\sqrt{L}} \Psi(x_1) g(x_1,x_2)$$ $M=0$ at $k=0$

In general, *M=0* when parity is changed upon addition of electron. For not too strong interactions, the parity must be the same as for noninteracting states.



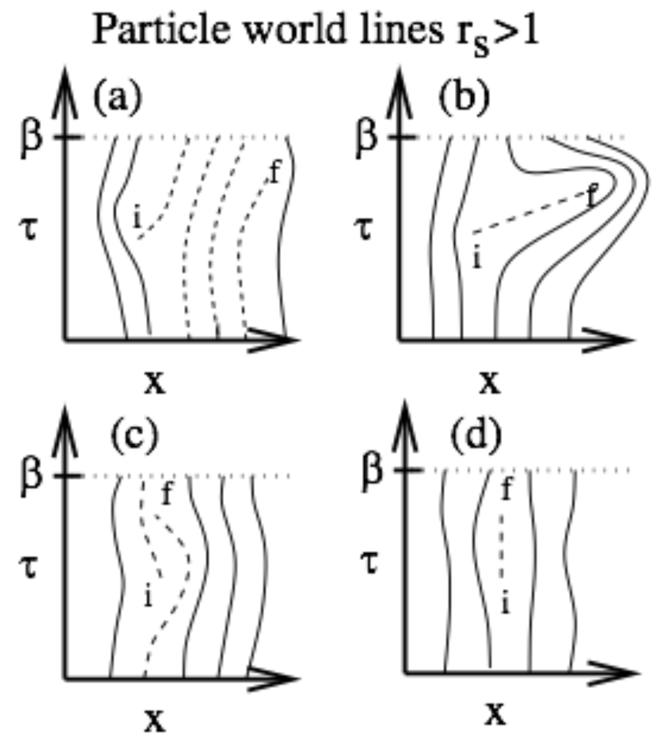
Wigner-crystal exchange coupling





The relevant tunneling transitions are determined by three energy scales: temperature, Heisenberg exchange, and Zeeman energy

“Free-spin” Luttinger liquids



$$\mathcal{G}(x,\tau) \sim \left\langle \left(-\frac{1}{2}\right)^{N(x,\tau)} e^{i\frac{\pi}{\sqrt{2}}\left[\int_{-\infty}^{x} dx'\Pi_\rho(\tau) - \int_{-\infty}^{0} dx'\Pi_\rho(0)\right]} \right\rangle$$

$$N(x,\tau) = \bar{n}x + \frac{\sqrt{2}}{\pi}\left[\phi_\rho(x,\tau) - \phi_\rho(0,0)\right]$$

Fiete and Balents, PRL **93**, 226401 (2004); Cheianov and Zvonarev, PRL **92**, 176401 (2004); Matveev, PRL **92**, 106801 (2004)

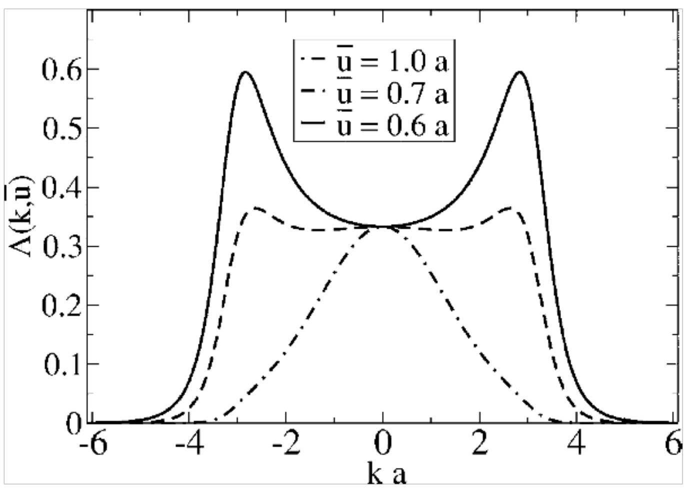
Spectral function

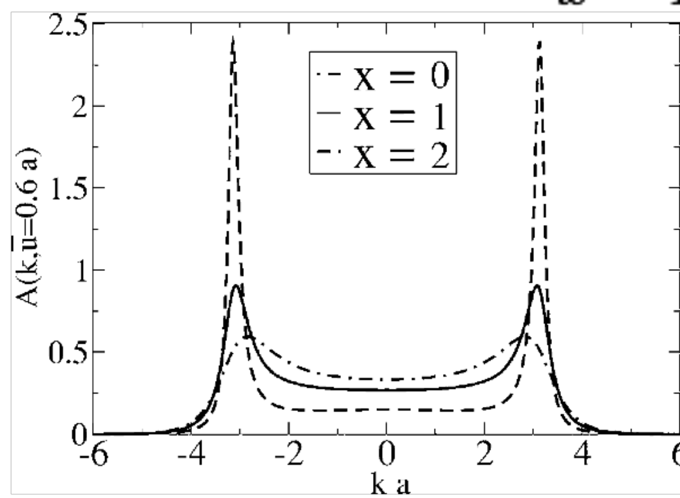
$$\mathcal{G}(k,\tau) \sim a\left(\frac{a}{v_c\tau}\right)^{1/(4g)} A(k,\bar{u}(\tau)) \qquad A(k,\bar{u}) \equiv e^{-(k^2\bar{u}^2/2)}\left[\frac{3}{5+4\cos(ka)}\right]$$

$\bar{u}(\tau) = \frac{a}{\pi}\sqrt{2g\ln(v_c\tau/a)}$ electron displacement

$\tau \sim L/v_c$ cutoff

$x = E_Z/k_BT$





$\mathcal{A}(\omega) \approx \tau\mathcal{G}(z=0,\tau)$, with $\tau = \omega^{-1}$

$$\tilde{\alpha} = \frac{1}{4g} - 1 \qquad \tilde{\alpha}_{\text{end}} = \frac{1}{2g} - 1$$

Fiete, Qian, YT, and Halperin, PRB 72, 045315 (2005)

Summary

- Finite size and temperature lead to an emergence of interesting states of "conventional" 1D metals which were not explored until recently
- Deacreasing density of a short interacting wire drives the system into a localized state where electrons cannot penetrate each other and form a crystal (Electron fluctuations diverge logarithmically in time)
- We have explored the structure of such states in two limits: Small particle number (numerical diagonalization as well as simple parity arguments) and many-electron limit (based on the bosonic Luttinger-liquid picture)