Electrons in One-Dimension
Spin-Charge Separation and Localization

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Collaboration:

Experiment: Bell Labs, Lucent Technologies.
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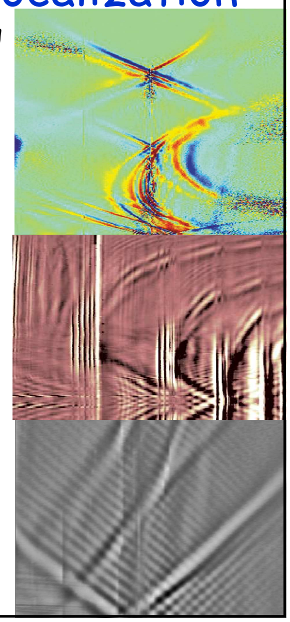
H. L. Stormer

Theory: Harvard University.
B. I. Halperin,
Y. Tserkovnyak, G. Fiete, J. Qian



Mapping the dispersion of elementary excitations
- Momentum conserving tunneling
- spin-charge separation

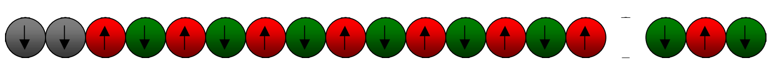
Spontaneous breaking of translation invariance
- Localization

Finite size effects – Interference.
- Soft confinement
- Two velocities – Spin – Charge

Spin – Charge Separation

Strong interactions order electrons anti-ferromagnetically

Ground State has zero spin



Extract an electron

Motion of electrons create spin and charge excitations

Spin excitation

Weakly affected through Exchange Interaction $\upsilon_\sigma = \upsilon_F$

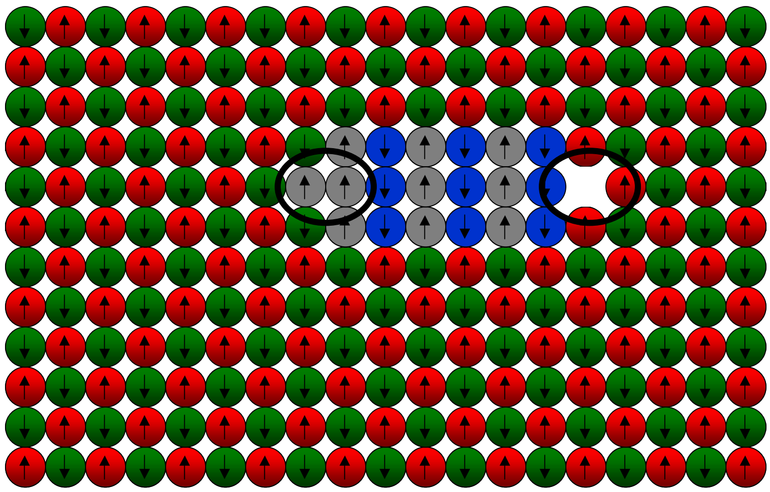
Charge excitation

Affected by Interactions

$$\upsilon_\rho = \upsilon_F / g$$

$$g \approx \frac{1}{\sqrt{1+\frac{U}{2E_F}}} < 1$$

Spin – Charge Separation in 2D

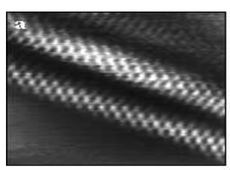


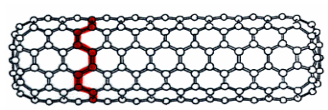
Energy increases with spatial separation

→ Force that binds spin and charge

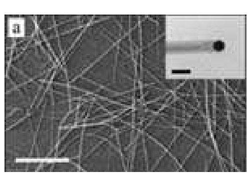
1D-Systems

1D systems – Carbon Nanotubes





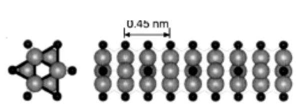
Semiconducting Nanowires



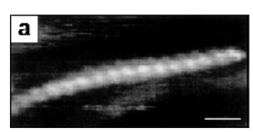
GaAs GaP InP InAs ZnS ZnSe CdS CdSe

$GaAs_{0.6}P_{0.4}$ $InAs_{0.5}P_{0.5}$ GaN(Fe)

Single molecules

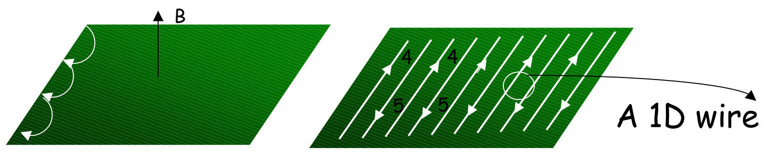


Mo_6Se_6(MoSe)

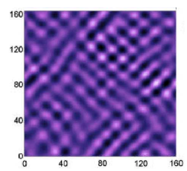


Other Systems Showing 1D Physics

2D systems – Chiral edges of the QH and FQHE
Striped phase at high Landau levels



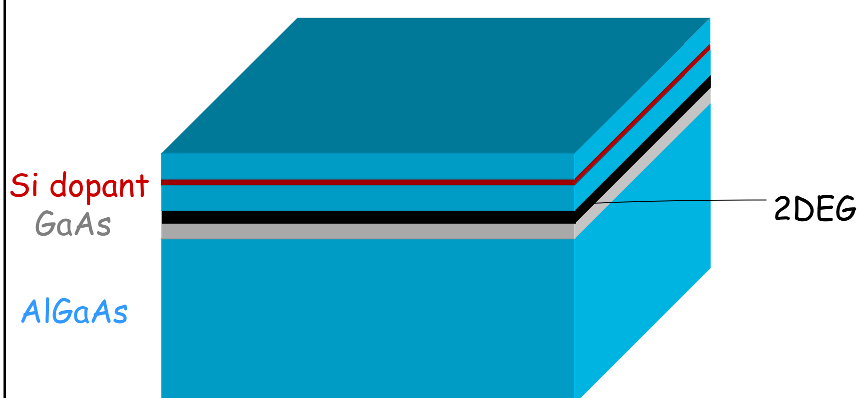
3D systems – Crystals of 1D molecules - Polyacetelene
Stripes in High Tc superconductors



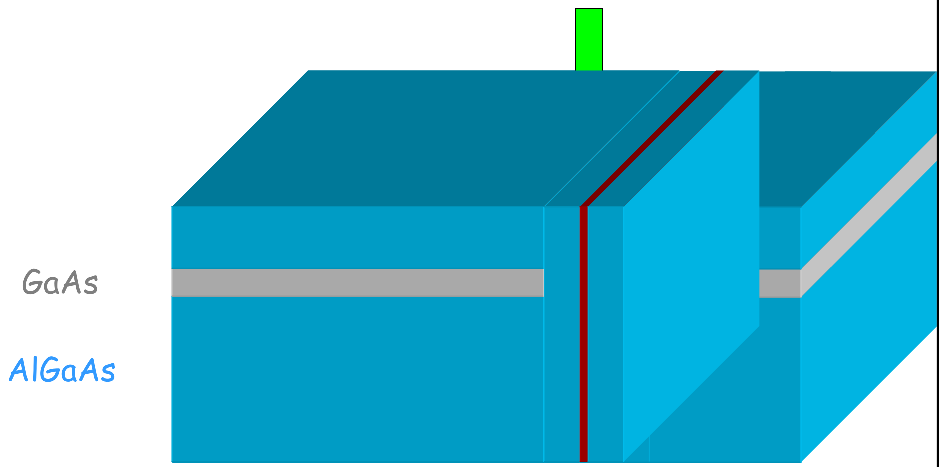
A. Kapitulnik

Coupled wires systems

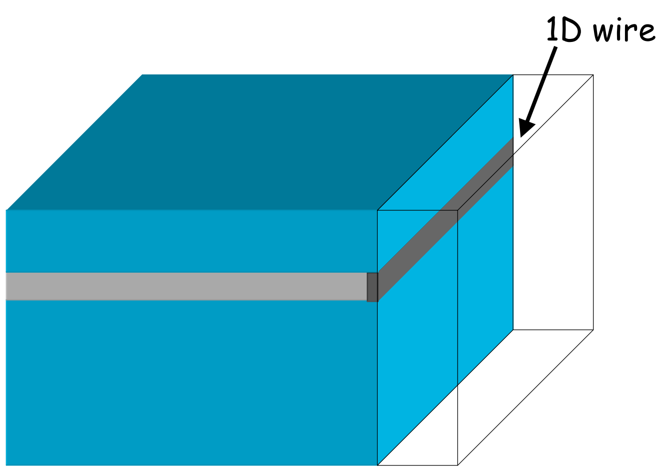
Cleaved Edge Overgrowth



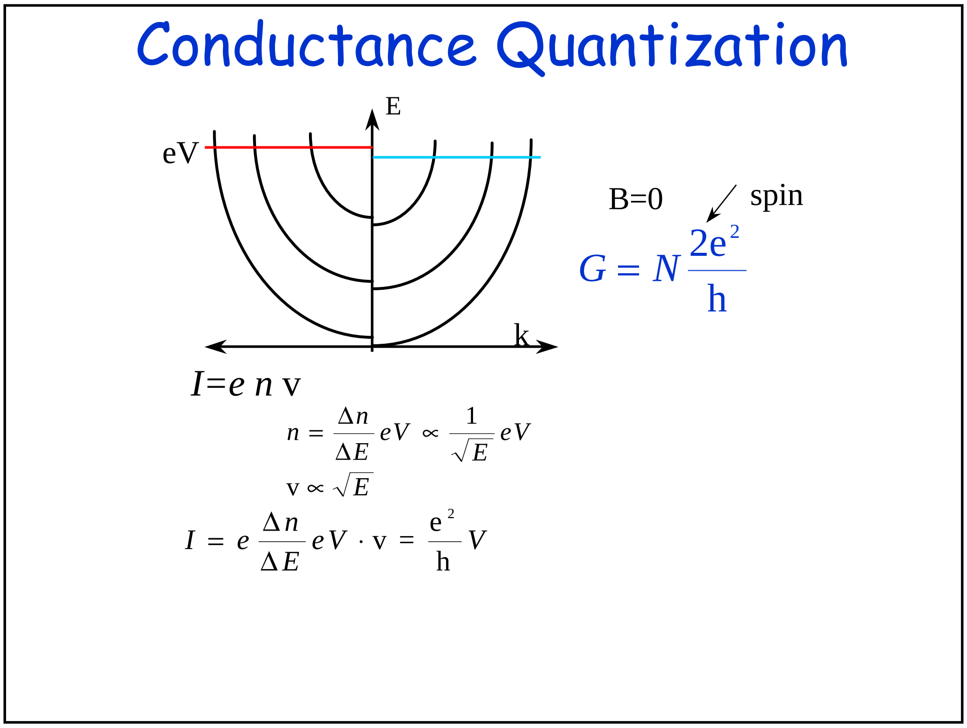
Cleaved Edge overgrowth

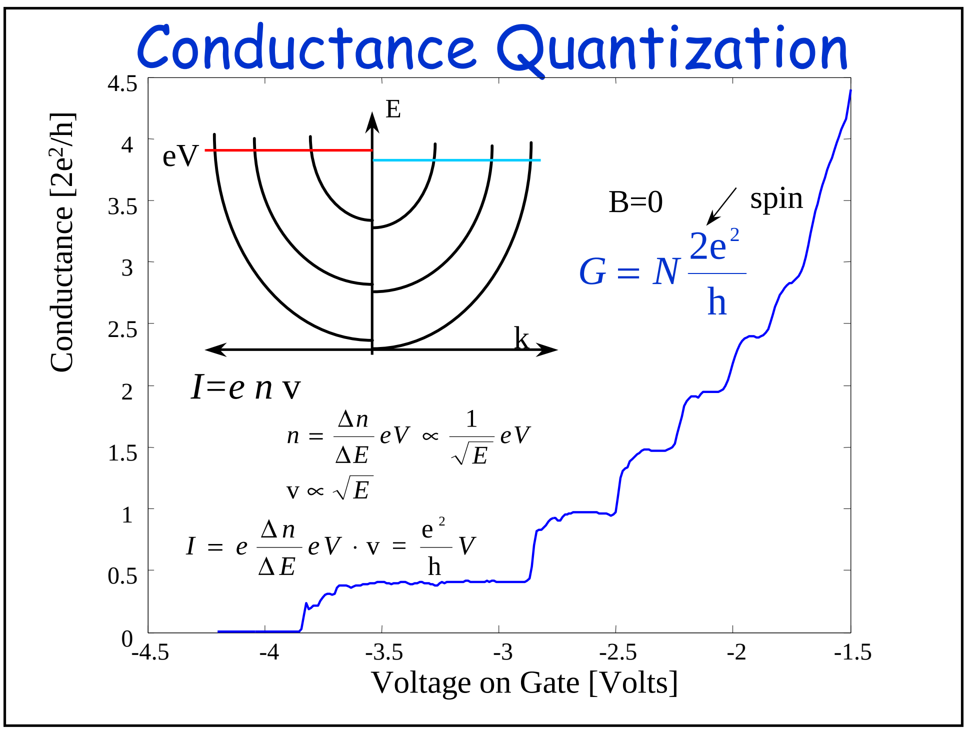


Cleaved Edge overgrowth



Very clean wires with mean free path of tens of microns


Conductance Quantization
E
eV
k
B=0
spin
$G = N\frac{2e^2}{h}$
$I = e\,n\,v$
$n = \frac{\Delta n}{\Delta E} eV \propto \frac{1}{\sqrt{E}} eV$
$v \propto \sqrt{E}$
$I = e\frac{\Delta n}{\Delta E} eV \cdot v = \frac{e^2}{h} V$


Conductance Quantization
E
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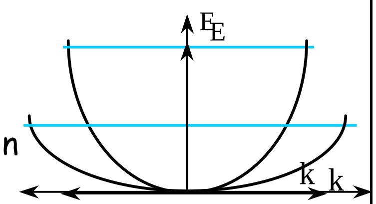
$G = N\frac{2e^2}{h}$
$I = e\,n\,v$
$n = \frac{\Delta n}{\Delta E} eV \propto \frac{1}{\sqrt{E}} eV$
$v \propto \sqrt{E}$
$I = e\frac{\Delta n}{\Delta E} eV \cdot v = \frac{e^2}{h} V$
Conductance [$2e^2/h$]
Voltage on Gate [Volts]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5

Conductance Quantization

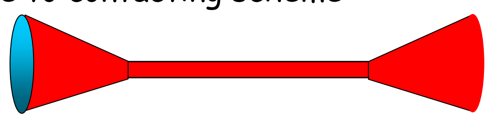
Universal : $G = \frac{e^2}{h}$

Independent of dispersion and density



Independent of geometry

Weakly sensitive to contacting scheme



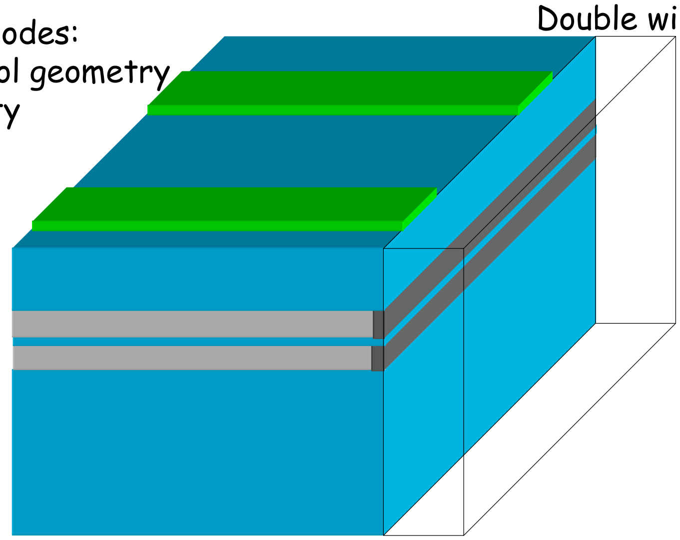
Independent of Coulomb Interaction

→ Tunneling between parallel wires

Cleaved Edge overgrowth

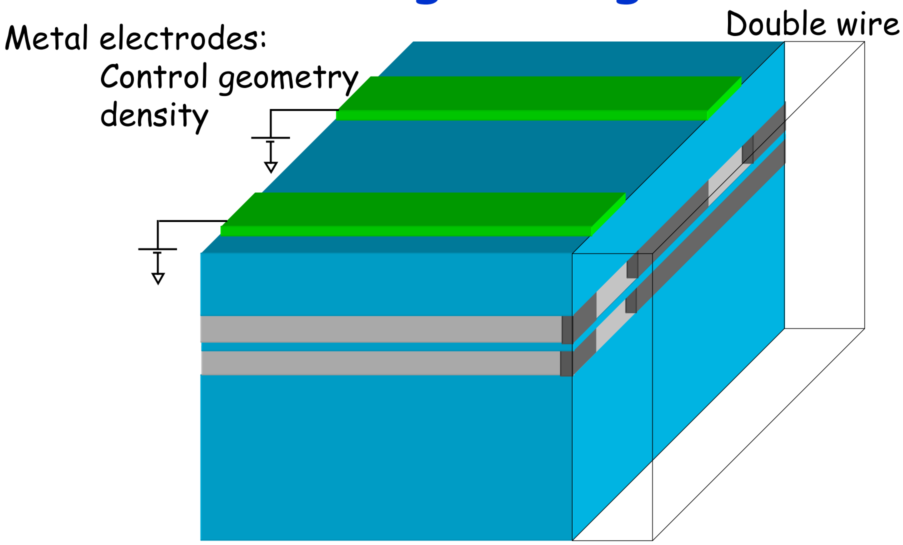
Metal electrodes:
Control geometry
density

Double wire



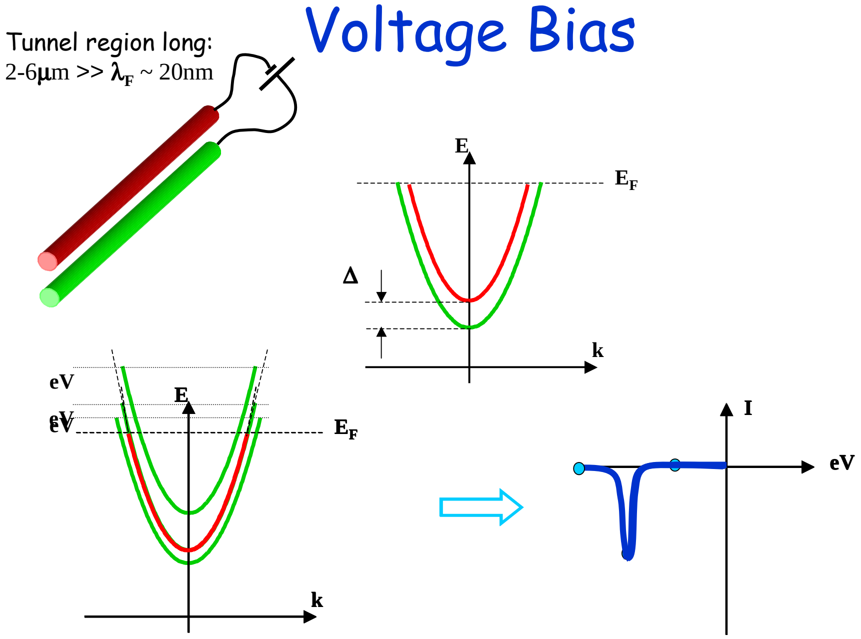
- Distance between wires is 6nm with atomic precision
- Tunneling preserves energy and momentum

Cleaved Edge overgrowth



- Distance between wires is 6nm with atomic precision
- Tunneling preserves energy and momentum

Voltage Bias

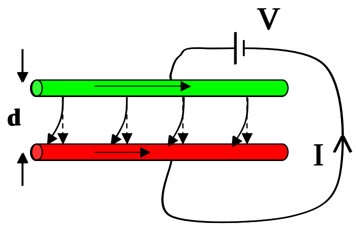


Voltage shifts dispersions vertically

Tunneling in a magnetic field

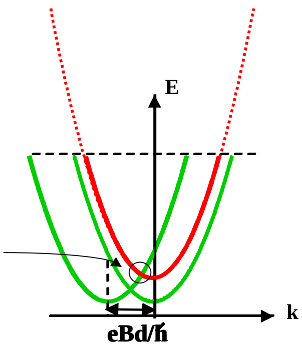
To first order in B:

$E_U(k,B) \sim E_U(k - eBd/h)$ $B \neq 0$

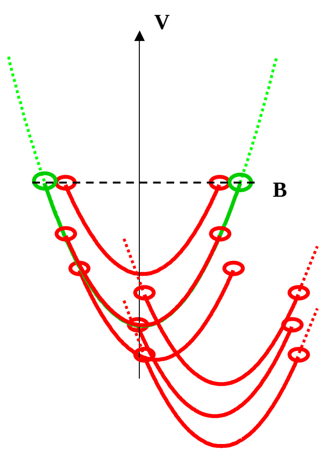


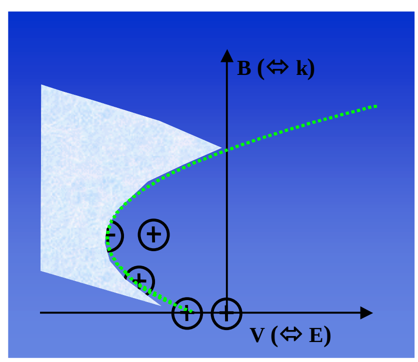
The Lorentz force shifts the momentum of the tunneling electron

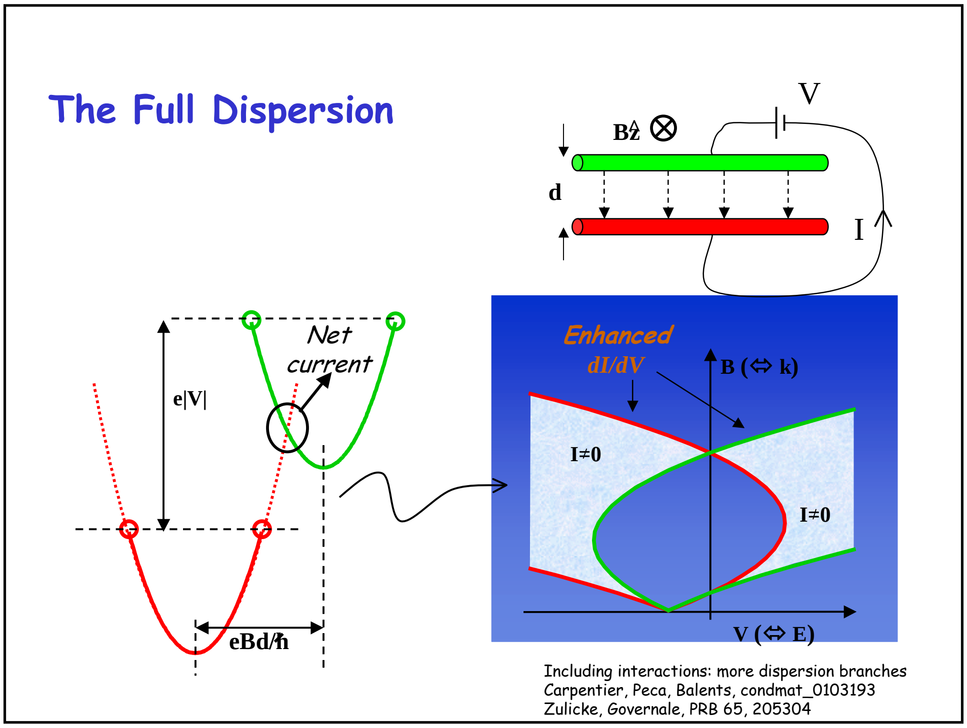
Momentum and energy conservation satisfied at crossing points

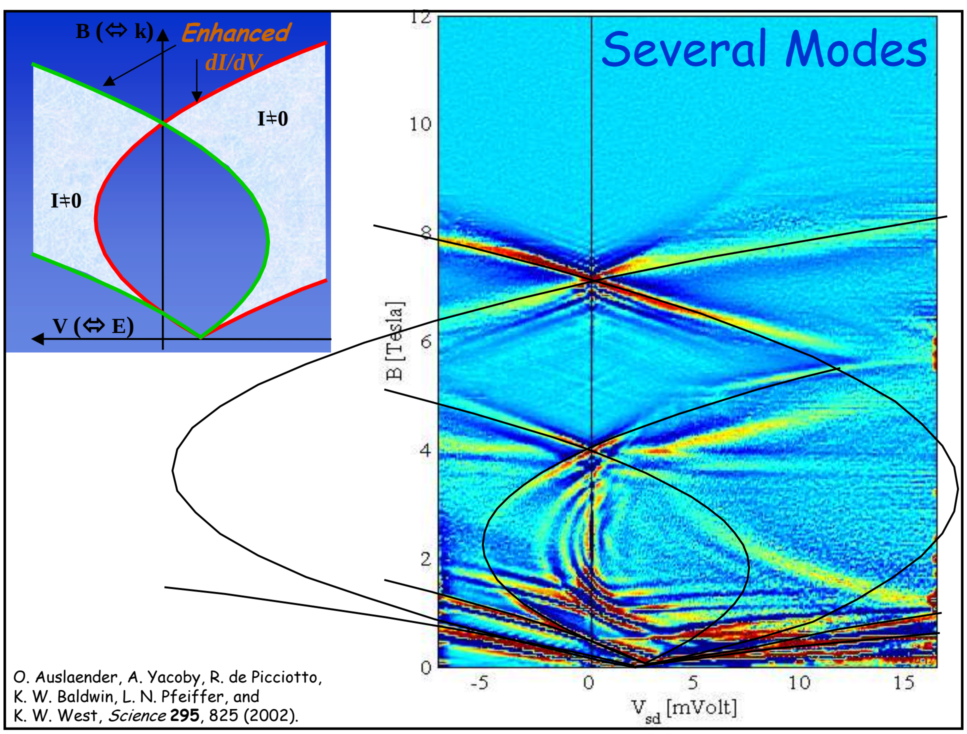


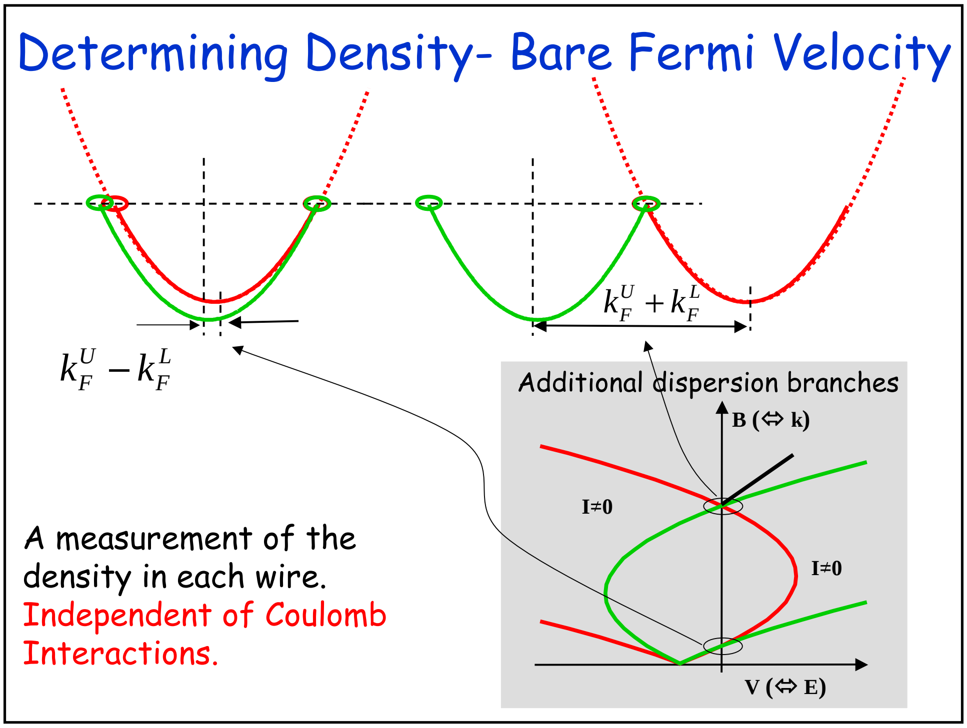
Mapping the dispersion

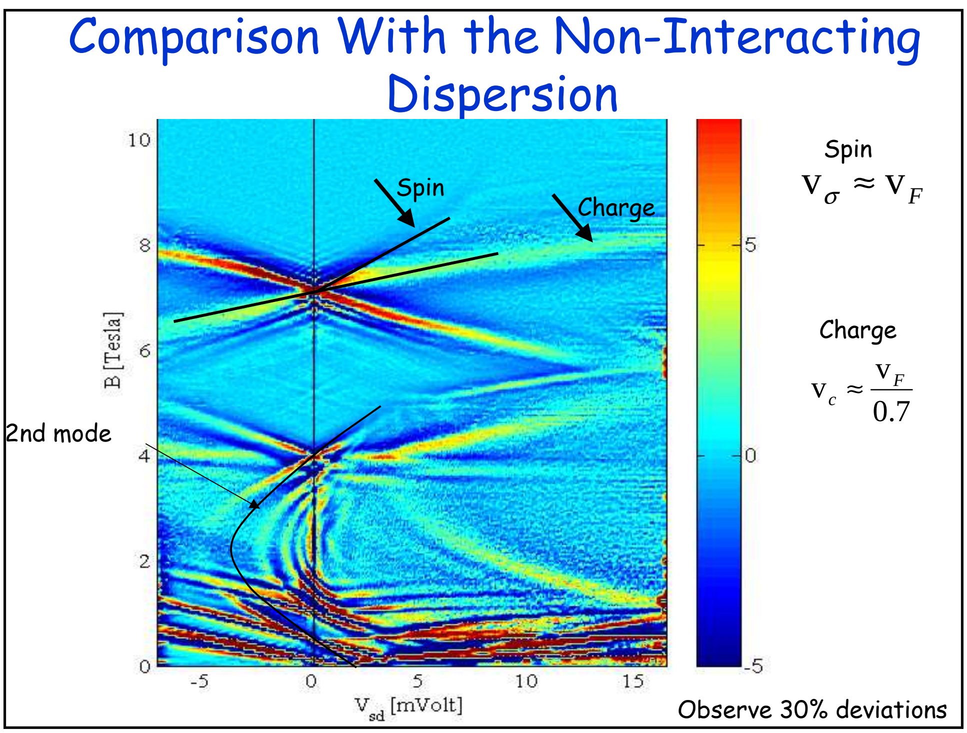





The Full Dispersion
V
Bẑ ⊗
d
I
Net
current
e|V|
eBd/ħ
Enhanced
dI/dV
B (⇔ k)
I≠0
I≠0
V (⇔ E)
Including interactions: more dispersion branches
Carpentier, Peca, Balents, condmat_0103193
Zulicke, Governale, PRB 65, 205304


B (⇔ k)
Enhanced
dI/dV
I≠0
I≠0
V (⇔ E)
Several Modes
B [Tesla]
V_sd [mVolt]
O. Auslaender, A. Yacoby, R. de Picciotto,
K. W. Baldwin, L. N. Pfeiffer, and
K. W. West, Science 295, 825 (2002).

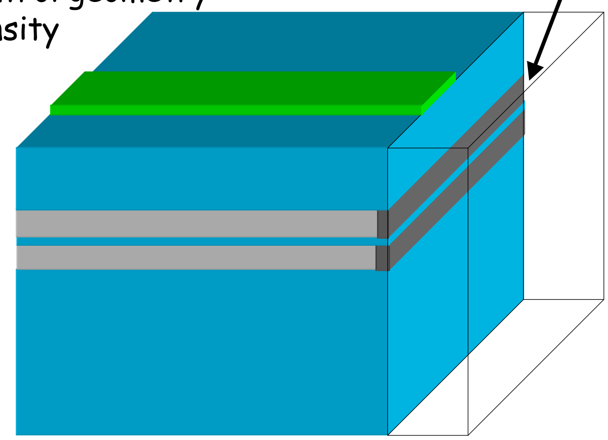

Determining Density- Bare Fermi Velocity
$k_F^U + k_F^L$
$k_F^U - k_F^L$
Additional dispersion branches
B (⇔ k)
I≠0
I≠0
V (⇔ E)
A measurement of the density in each wire.
Independent of Coulomb Interactions.


Comparison With the Non-Interacting Dispersion
Spin
Charge
2nd mode
B [Tesla]
V_{sd} [mVolt]
Spin
$V_\sigma \approx V_F$
Charge
$V_c \approx \frac{V_F}{0.7}$
Observe 30% deviations

Tunneling vs Density

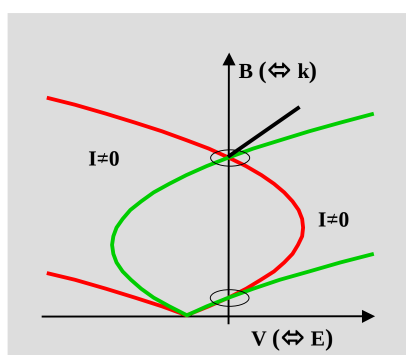
Metal electrodes:
Control geometry
density

Double wire



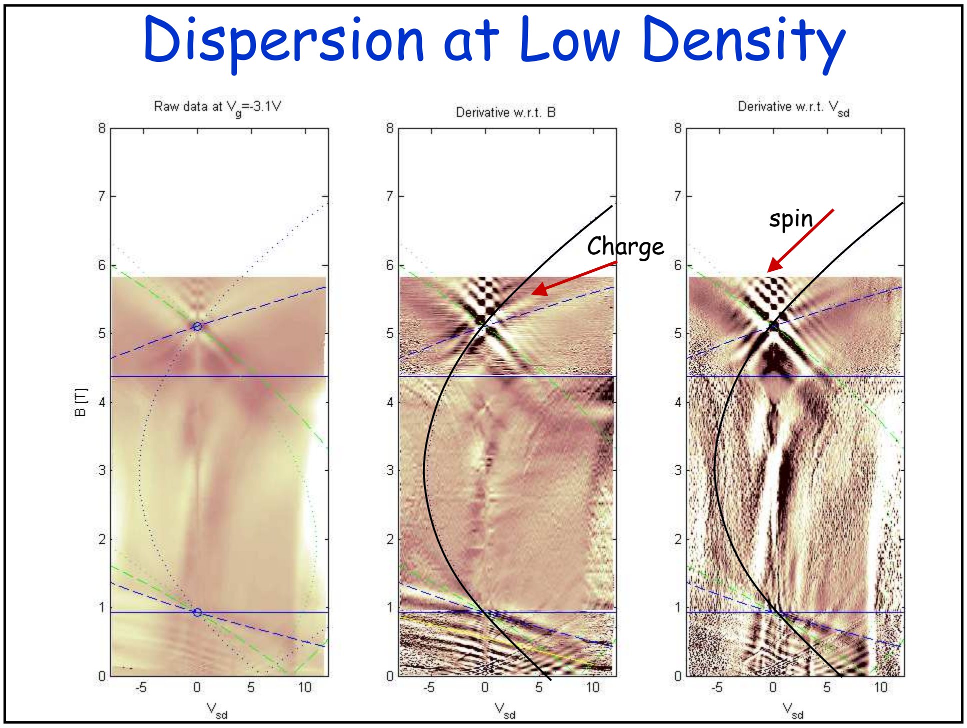
Varying Density

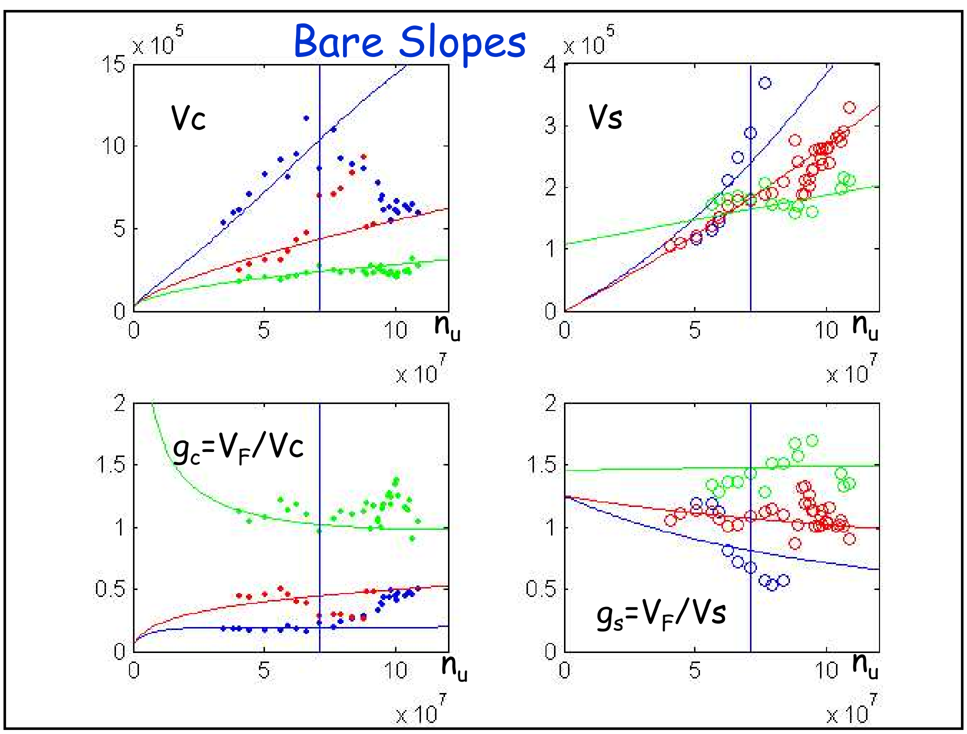
Extract density from crossing points - V_F



Extract spin and charge excitation velocities – V_S ; V_C

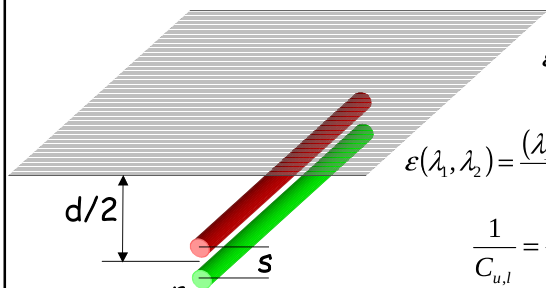
Carpentier, Peca, Balents, condmat_0103193
Zulicke, Governale, PRB 65, 205304


Dispersion at Low Density
Raw data at V_g=-3.1V
Derivative w.r.t. B
Derivative w.r.t. V_sd
B [T]
V_sd
Charge
spin


Bare Slopes
Vc
Vs
x 10^5
n_u
x 10^7
g_c=V_F/Vc
g_s=V_F/Vs

Model- Effects of Electrostatic Charging

Zulicke, Governale PRB 65,205304



d=1μm
r=10nm
s=30nm

$$\varepsilon(\lambda_1,\lambda_2)=\frac{\lambda_1^2}{2C_1}+\frac{\lambda_2^2}{2C_2}+\frac{\lambda_1\lambda_2}{C_{12}}+V\lambda_2$$

$$\varepsilon(\lambda_1,\lambda_2)=\frac{(\lambda_1+\lambda_2)^2}{2C_+}+\frac{(\lambda_1-\lambda_2)^2}{2C_-}+V\lambda_2+\frac{\lambda_1^2}{2C_u}+\frac{\lambda_2^2}{2C_l}$$

$$\frac{1}{C_{u,l}}=\frac{\hbar\pi}{2e^2}v_{F_{u,l}}$$

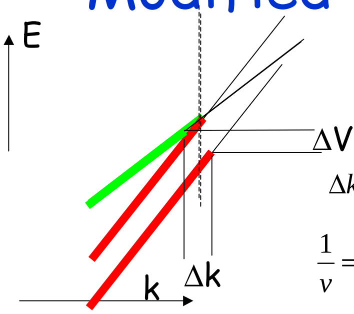
$$\frac{1}{C_+}=\frac{1}{4\pi\varepsilon\varepsilon_0}\ln\left(\frac{d}{r}\right)+\frac{1}{4\pi\varepsilon\varepsilon_0}\ln\left(\sqrt{1+\left(\frac{d}{s}\right)^2}\right)$$

$$\frac{1}{C_-}=\frac{1}{4\pi\varepsilon\varepsilon_0}\ln\left(\frac{d}{r}\right)-\frac{1}{4\pi\varepsilon\varepsilon_0}\ln\left(\sqrt{1+\left(\frac{d}{s}\right)^2}\right)$$

calculate $\lambda_1=\kappa_1 V$

$\lambda_2=\kappa_2 V$

Modified Dispersion



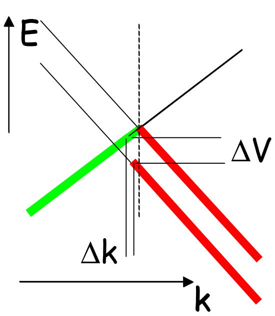
<u>Lower cross</u>

$$\Delta k=\Delta B+\frac{\pi}{2e}(\lambda_1-\lambda_2)=\Delta B+\frac{\pi}{2e}(\kappa_1-\kappa_2)\Delta V$$

$$\frac{1}{v}=\frac{\Delta k}{\Delta V}$$ ⇨True velocity

$$\frac{1}{v_{\exp}}=\frac{\Delta B}{\Delta V}$$ ⇨ Measured velocity

$$\frac{1}{v}=\frac{1}{v_{\exp}}+\frac{\pi\hbar}{2e^2}(\kappa_1-\kappa_2)$$



<u>Upper cross</u>

$$\frac{1}{v}=\frac{1}{v_{\exp}}+\frac{\pi\hbar}{2e^2}(\kappa_1+\kappa_2)$$

Slopes Recalculated

$n \propto k_F$

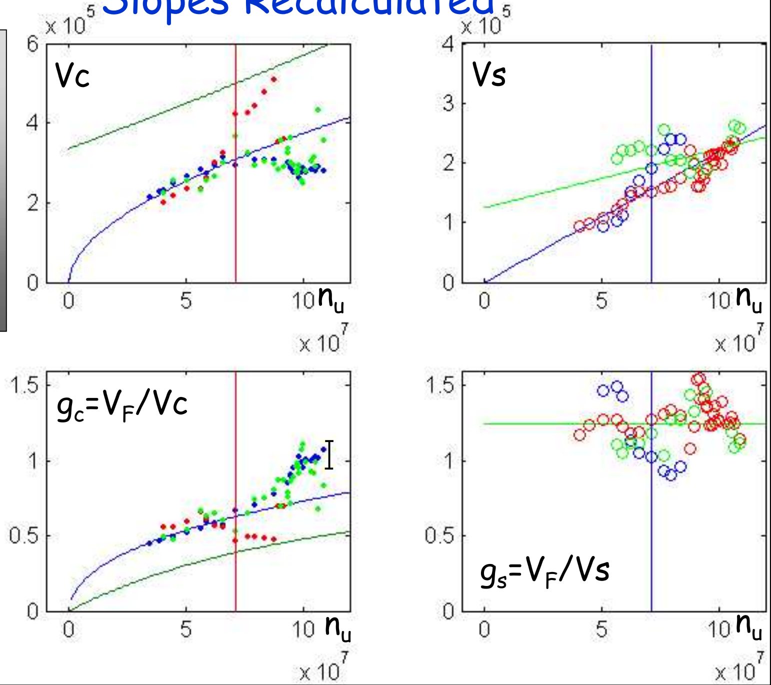
$E_F \propto k_F^2 \propto n^2$

$U_{e-e} \propto \frac{e^2}{r} \propto n$

$g = \frac{1}{\sqrt{1 + \frac{U_{e-e}}{2E_F}}}$

For g=0.4

$\frac{U_{e-e}}{E_F} = 10$



Expected Excitation Velocities

Focusing on the charge sector

Matveev, Glazman, PRL 93'

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

Elementary velocities obtained given by square root of eigenvalues of :

$$\sqrt{v_i v_j \hat{C}_{ij}^{-1}}$$

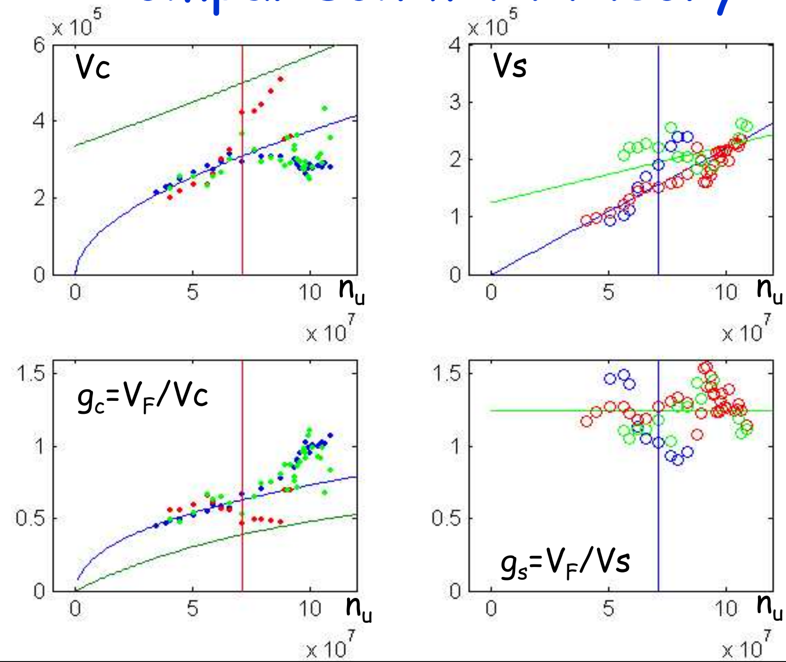
For N=1

$$v_c^2 = \frac{2e^2 v_F}{\pi C} \quad ; \quad \frac{1}{C} = \frac{\pi v_F}{2e^2} + \frac{1}{C_{electro}}$$

For N=2

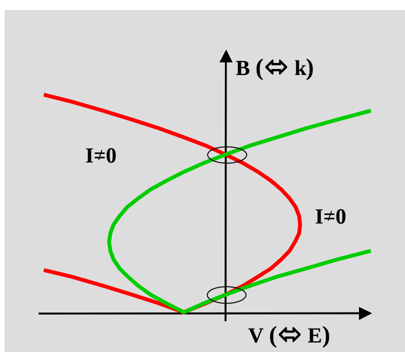
$$v_{c\pm}^2 = \frac{e^2}{\pi}\left[\left(\frac{v_{F1}}{C_1} + \frac{v_{F2}}{C_2}\right) \pm \sqrt{\left(\frac{v_{F1}}{C_1} - \frac{v_{F2}}{C_2}\right)^2 + 4\frac{v_{F1} v_{F2}}{C_{12}^2}}\right]$$

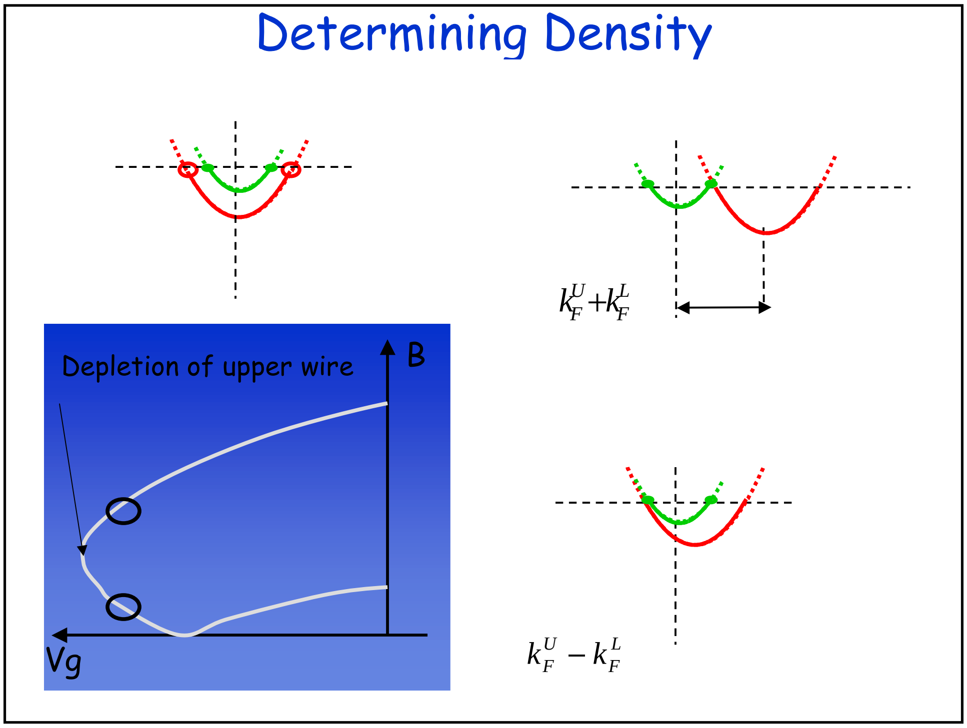
Comparison with theory

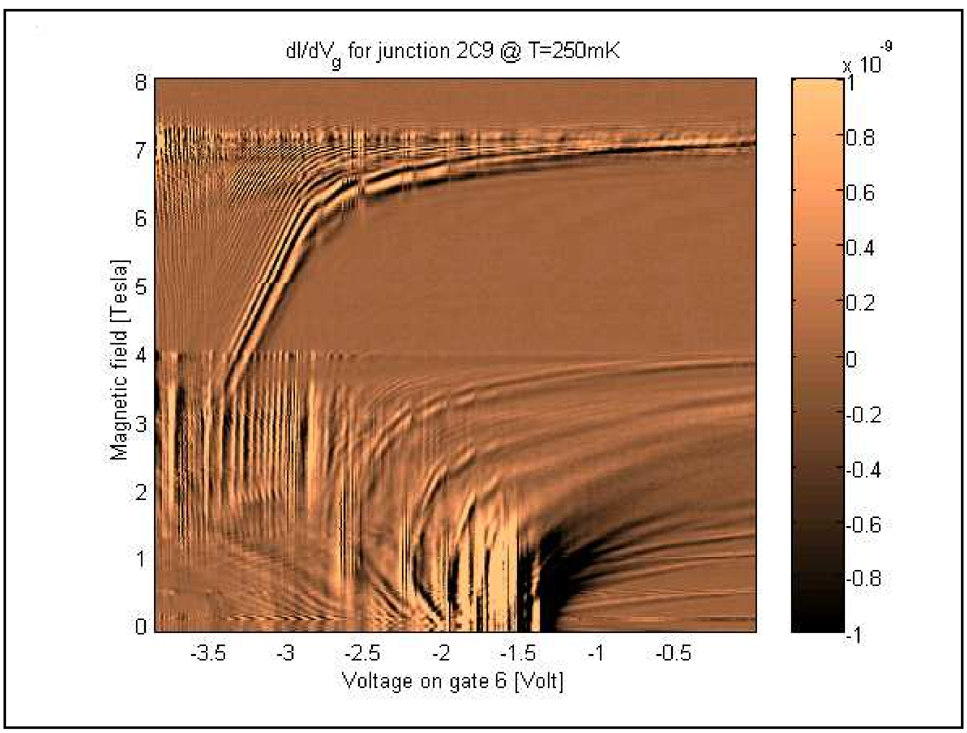


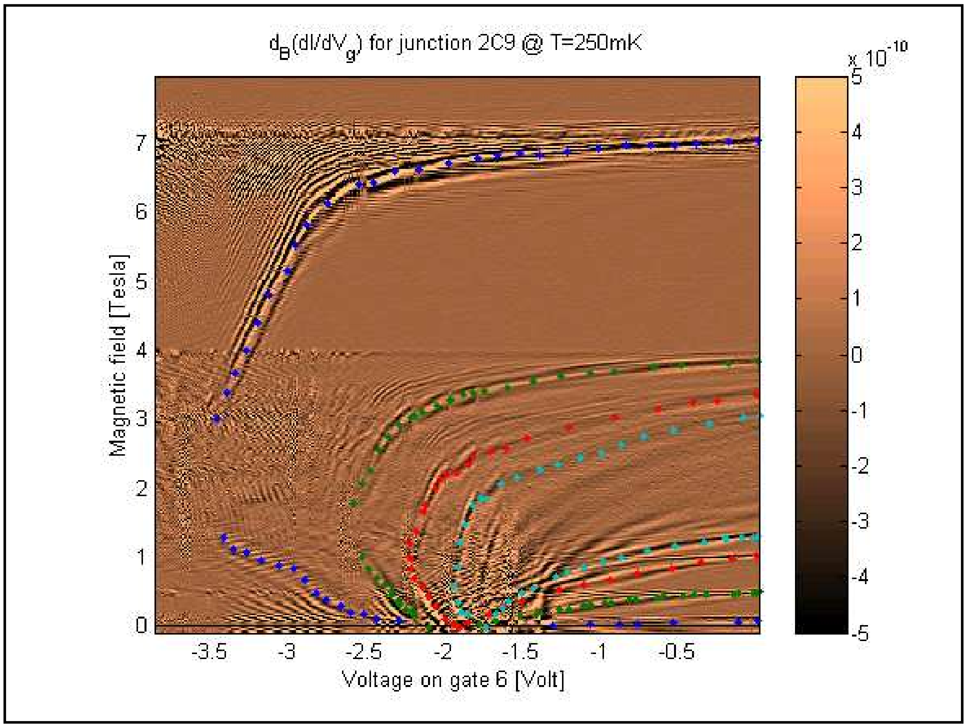
Reduce density further

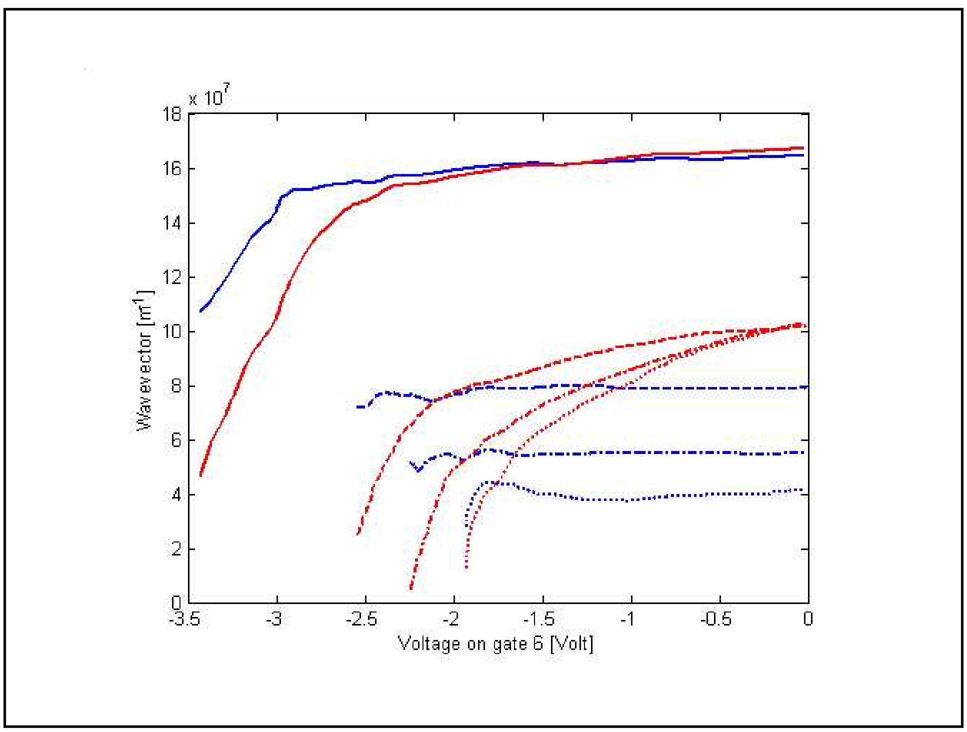
Focus on crossing points



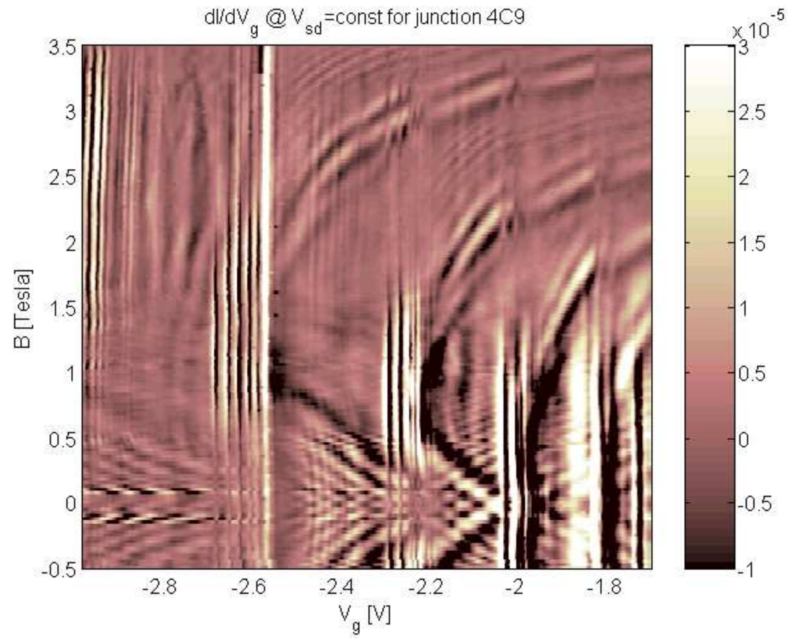

Determining Density
$k_F^U + k_F^L$
Depletion of upper wire
B
Vg
$k_F^U - k_F^L$


dI/dV$_g$ for junction 2C9 @ T=250mK
Magnetic field [Tesla]
Voltage on gate 6 [Volt]
x 10^{-9}

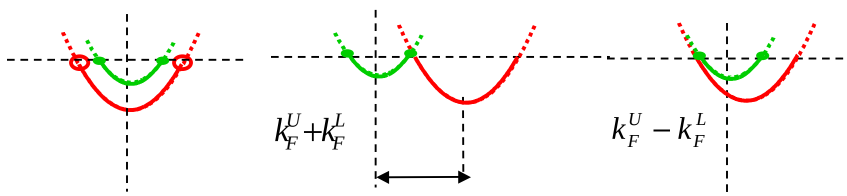

$d_B(dI/dV_g)$ for junction 2C9 @ T=250mK
x 10^-10
5
4
3
2
1
0
-1
-2
-3
-4
-5
Magnetic field [Tesla]
7
6
5
4
3
2
1
0
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
Voltage on gate 6 [Volt]

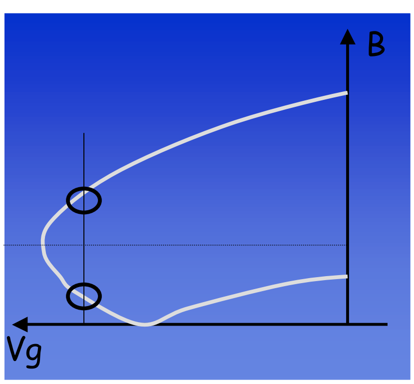

x 10^7
18
16
14
12
10
8
6
4
2
0
Wavevector [m^-1]
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
Voltage on gate 6 [Volt]

Low Densities



What's Being Measured?

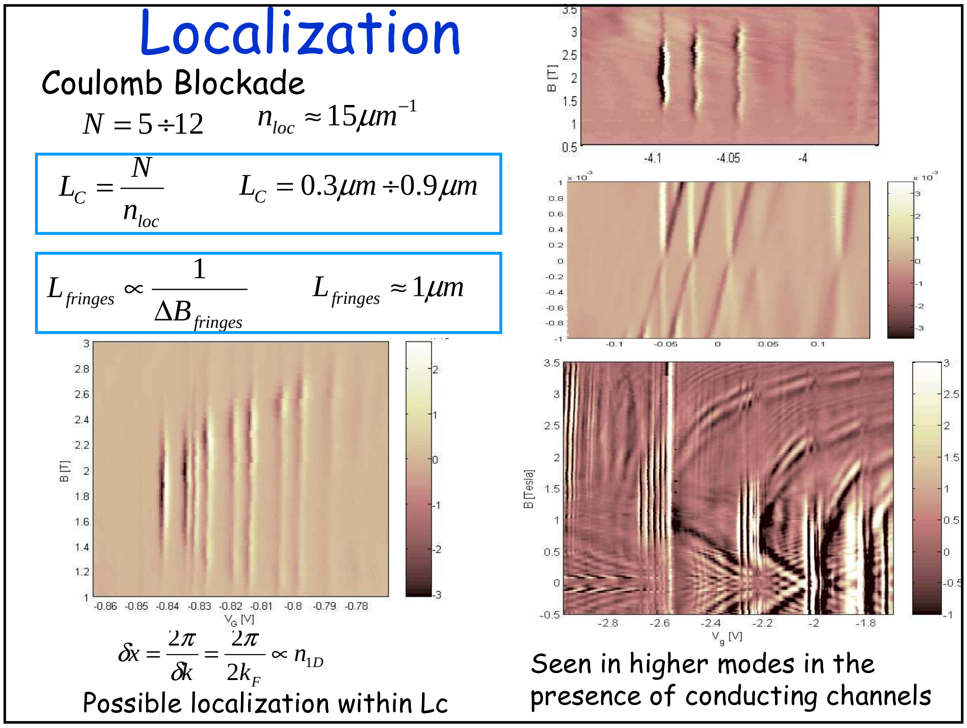




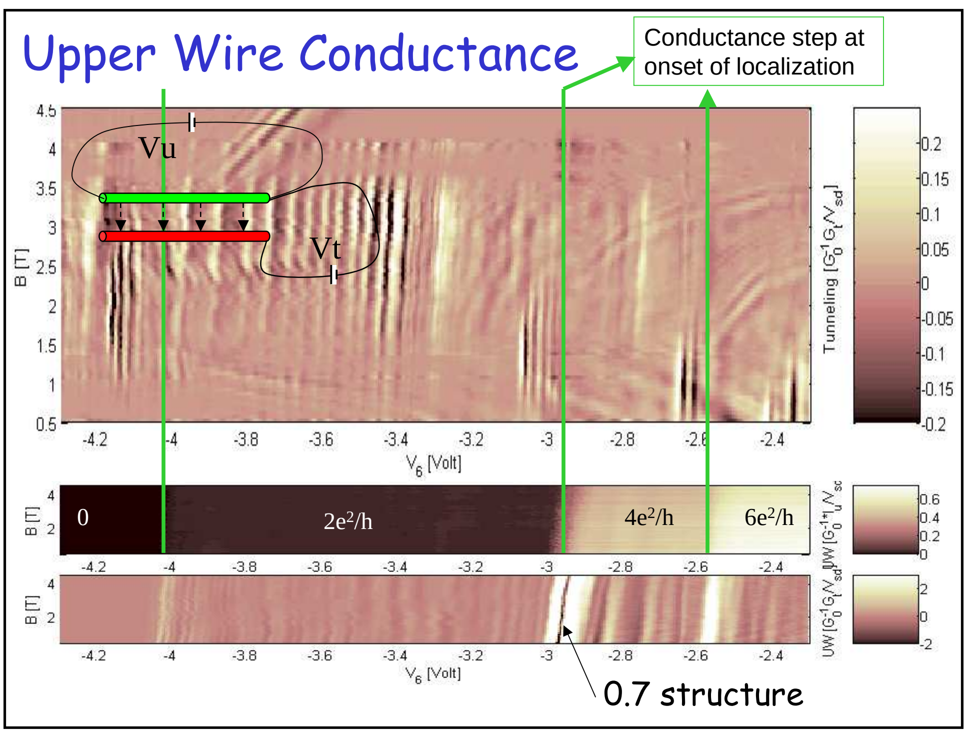
$$I \propto \left|\langle \Psi_u | M | \Psi_l \rangle\right|^2 = \left| \int e^{ik_l x + i\frac{ed}{\hbar}Bx} \cdot M \cdot \Psi_u dx \right|^2$$

$$I(B) \propto \left| \int e^{ik_l x + i\frac{ed}{\hbar}Bx} \Psi_u dx \right|^2 = \left| FT(\Psi_u) \right|^2$$

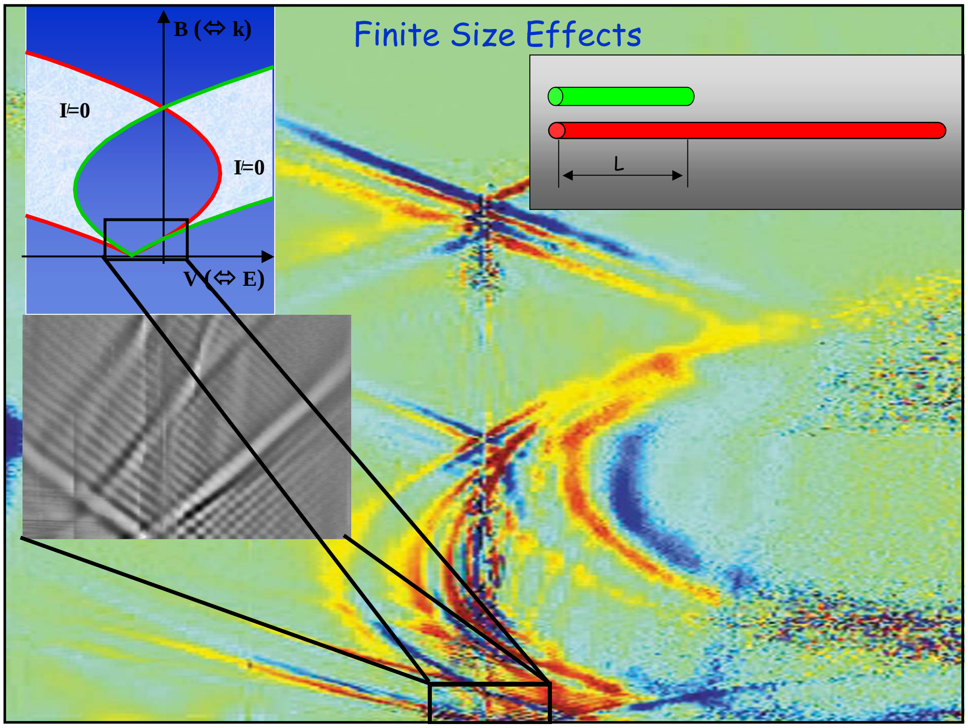
FT centered around k_l

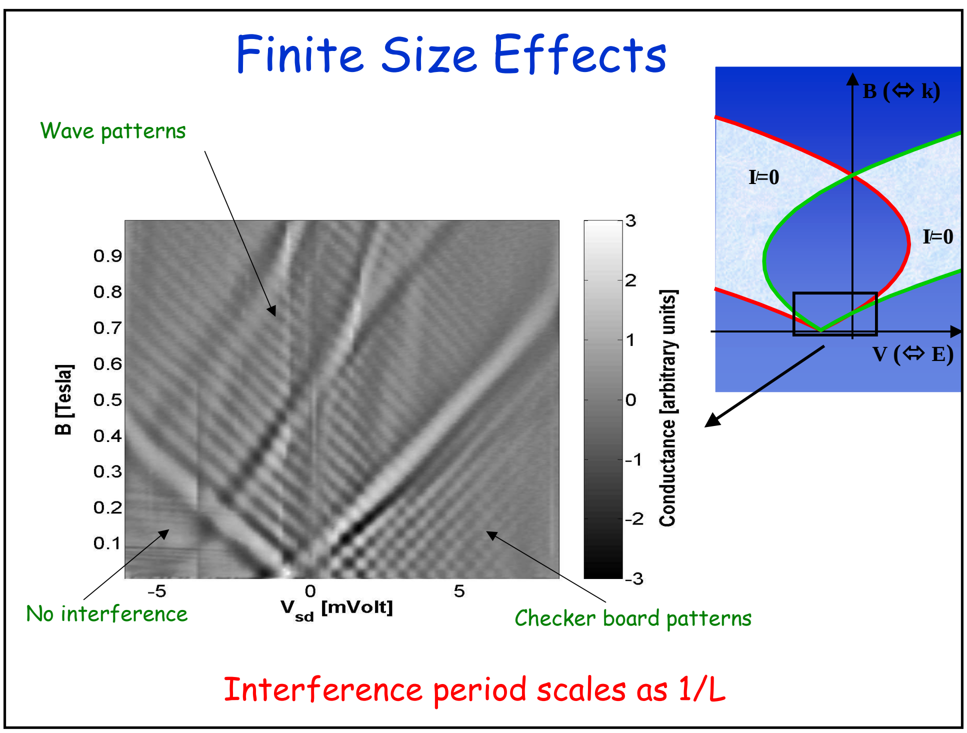


Localization
Coulomb Blockade
$N = 5 \div 12$ $n_{loc} \approx 15\mu m^{-1}$
$L_C = \frac{N}{n_{loc}}$ $L_C = 0.3\mu m \div 0.9\mu m$
$L_{fringes} \propto \frac{1}{\Delta B_{fringes}}$ $L_{fringes} \approx 1\mu m$
B [T]
B [Tesla]
V_g [V]
$\delta x = \frac{2\pi}{\delta k} = \frac{2\pi}{2k_F} \propto n_{1D}$
Possible localization within Lc
Seen in higher modes in the presence of conducting channels

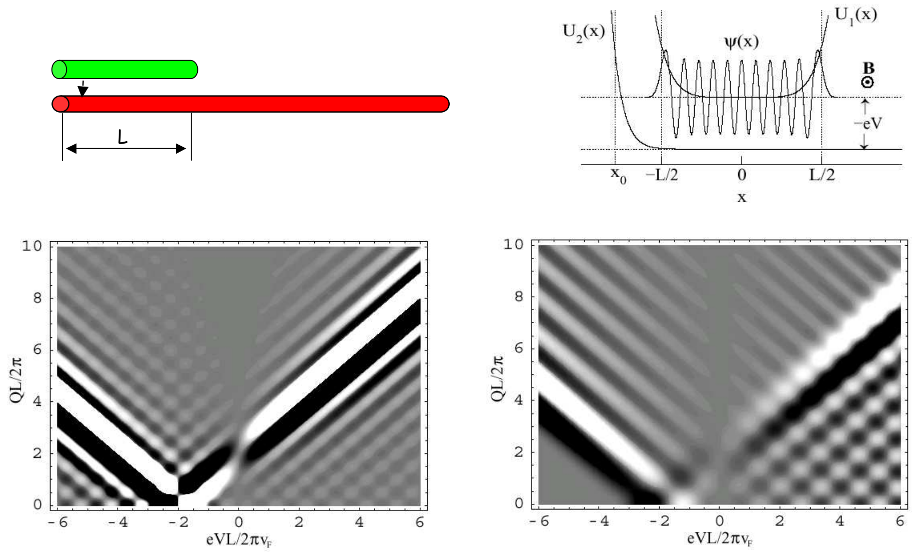


Upper Wire Conductance
Conductance step at onset of localization
Vu
Vt
B [T]
V_6 [Volt]
Tunneling $[G_0^{-1} G_t / V_{sd}]$
0
$2e^2/h$
$4e^2/h$
$6e^2/h$
0.7 structure


Finite Size Effects
B (⇔ k)
I=0
I=0
V (⇔ E)
L

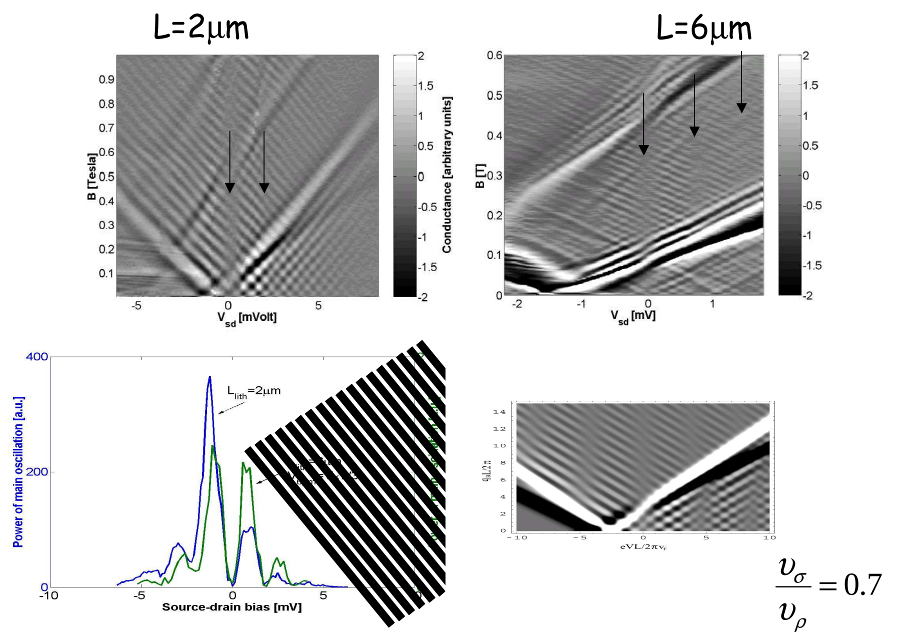

Finite Size Effects
Wave patterns
B [Tesla]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-5
0
5
V_sd [mVolt]
3
2
1
0
-1
-2
-3
Conductance [arbitrary units]
B (⇔ k)
I=0
I=0
V (⇔ E)
No interference
Checker board patterns
Interference period scales as 1/L

Finite Tunneling Junction



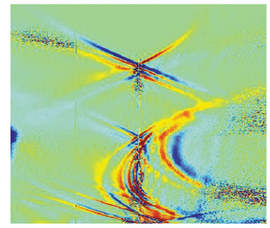
Y. Tserkovnyak, B. I. Halperin, O. M. Auslaender and A. Yacoby, Phys. Rev. Lett. 89 136805 (2002)

Two Velocities – Spin Charge Separation

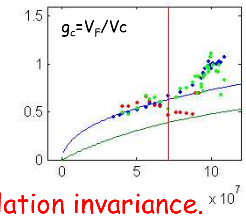


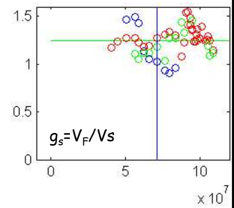
$$\frac{v_\sigma}{v_\rho} = 0.7$$

Main Results



- Momentum resolved tunneling
  - Dispersion of elementary excitations.
  - Spin-Charge Separation.
- Study density dependence
  - Observe anti-symmetric charge mode
  - Spin velocity slower than Fermi velocity.





- Spontaneous breaking of translation invariance.
  - Measurement of densities in each 1D mode
  - Coulomb blockade
  - Localization length corresponds to inter particle separation
  - Seen in higher modes