Unveiling the Landau Levels Structure of Graphene Nanoribbons

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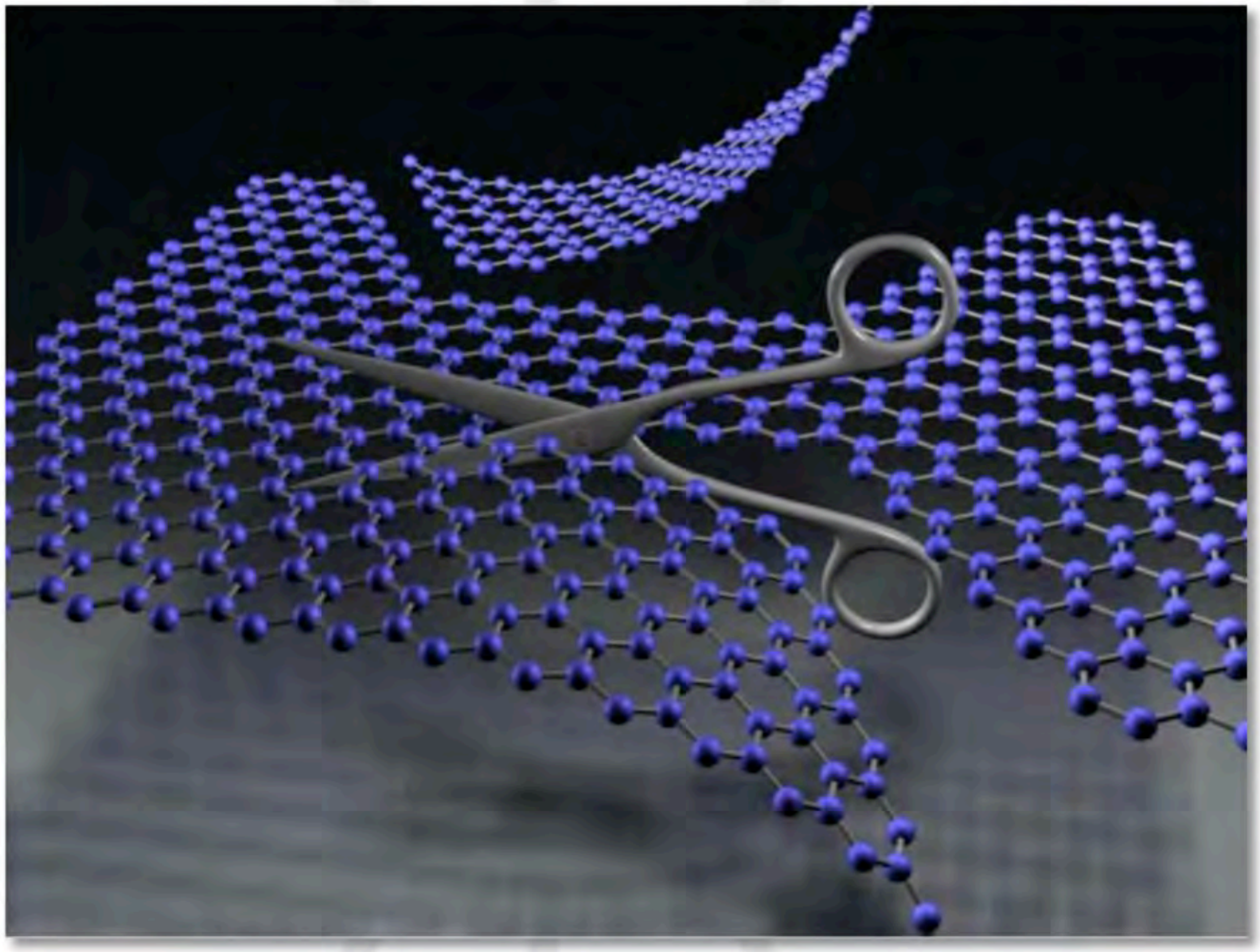
Outline

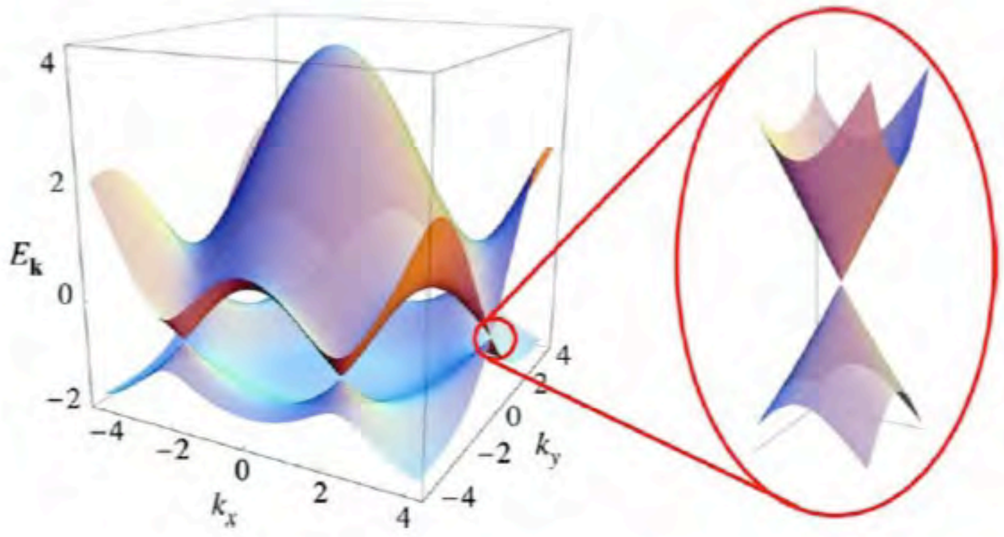
- **Motivation**
- **Sample fabrication and standard characterization.**
- **Measurements under high magnetic field.**
- **Effects of the electronic confinement on the Landau levels formation.**

Motivation

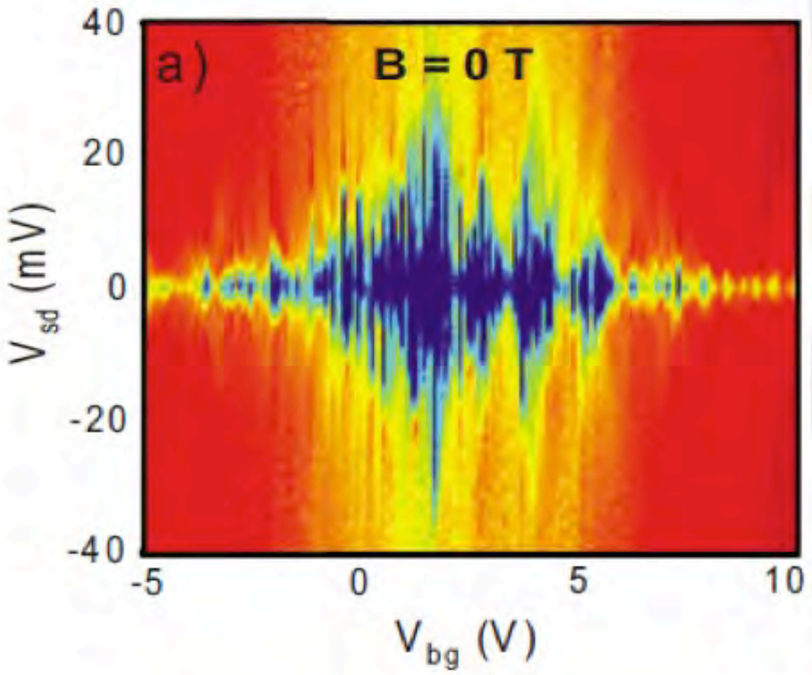


What if we decided to cut the graphene into nanoribbons?

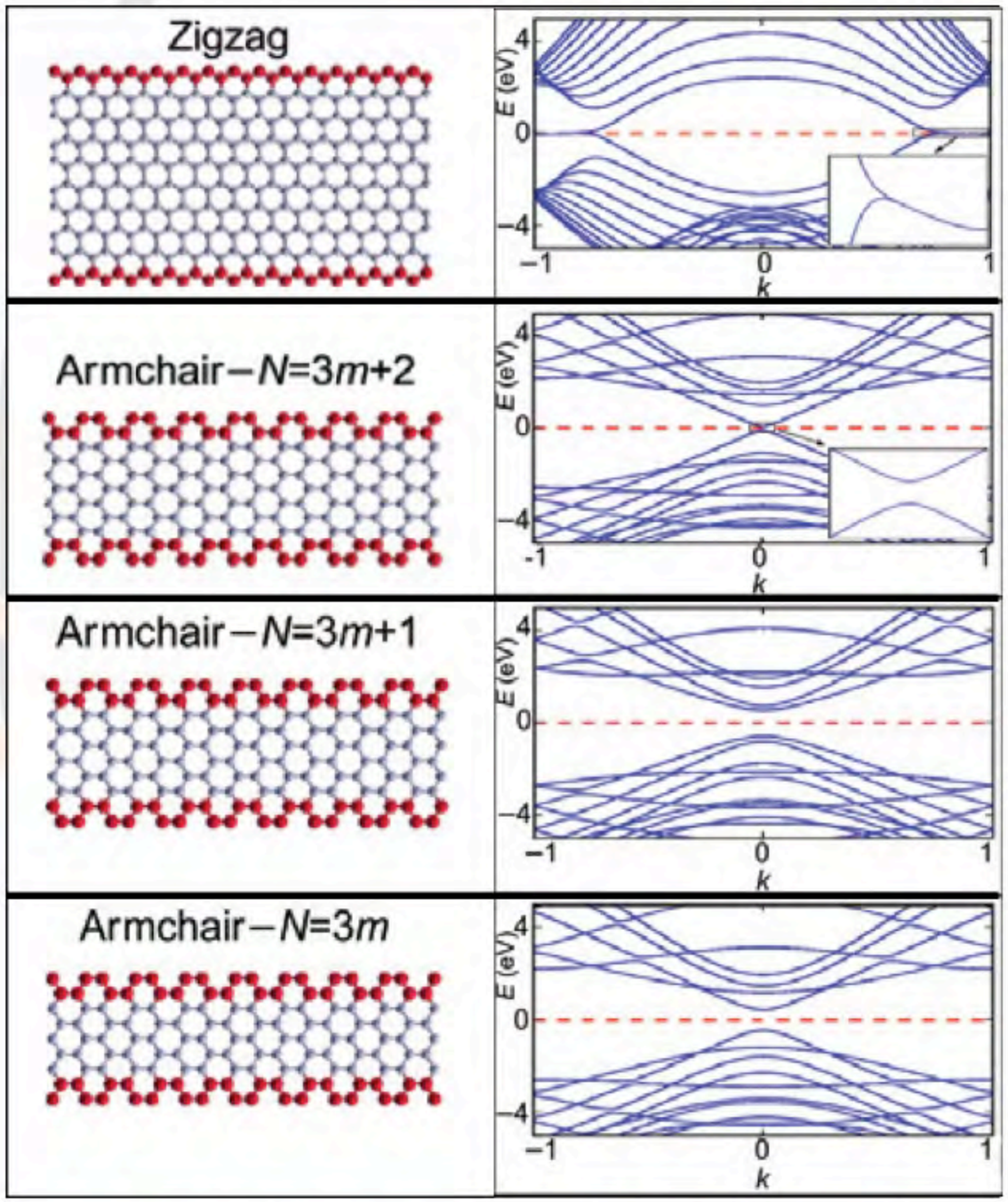
Motivation



Graphene's band structure



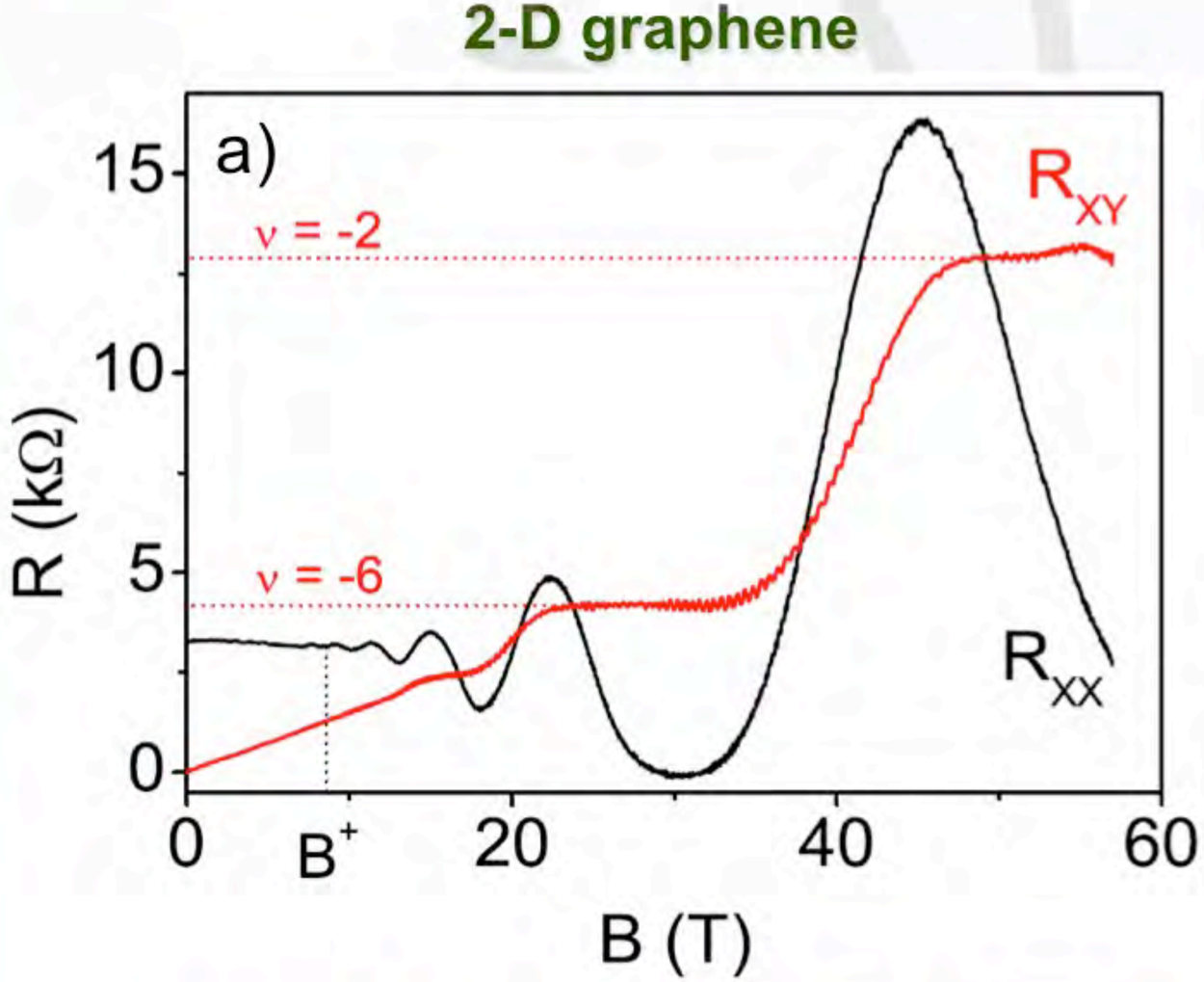
Energy gap for a ribbon of 50 nm**

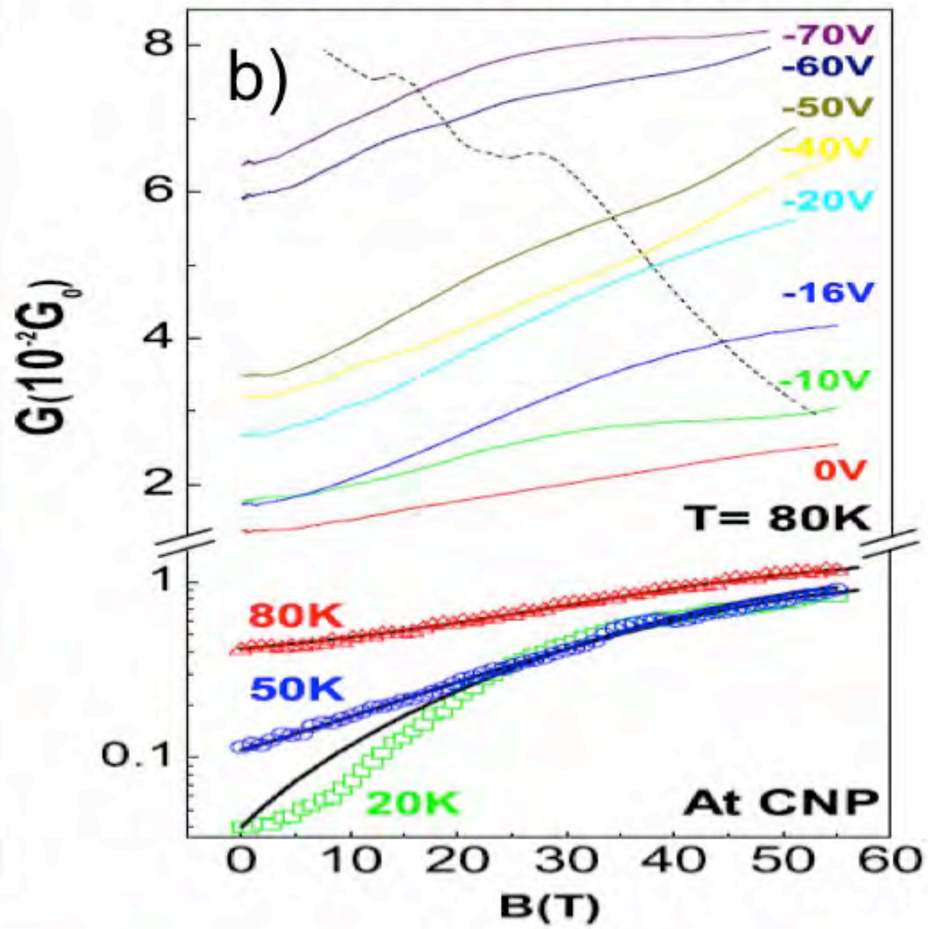


Graphene nanoribbons band structure*

[*] Cresti et al. Nano Res. (2008) [**] Oostinga et al. PRB (2010)

Motivation

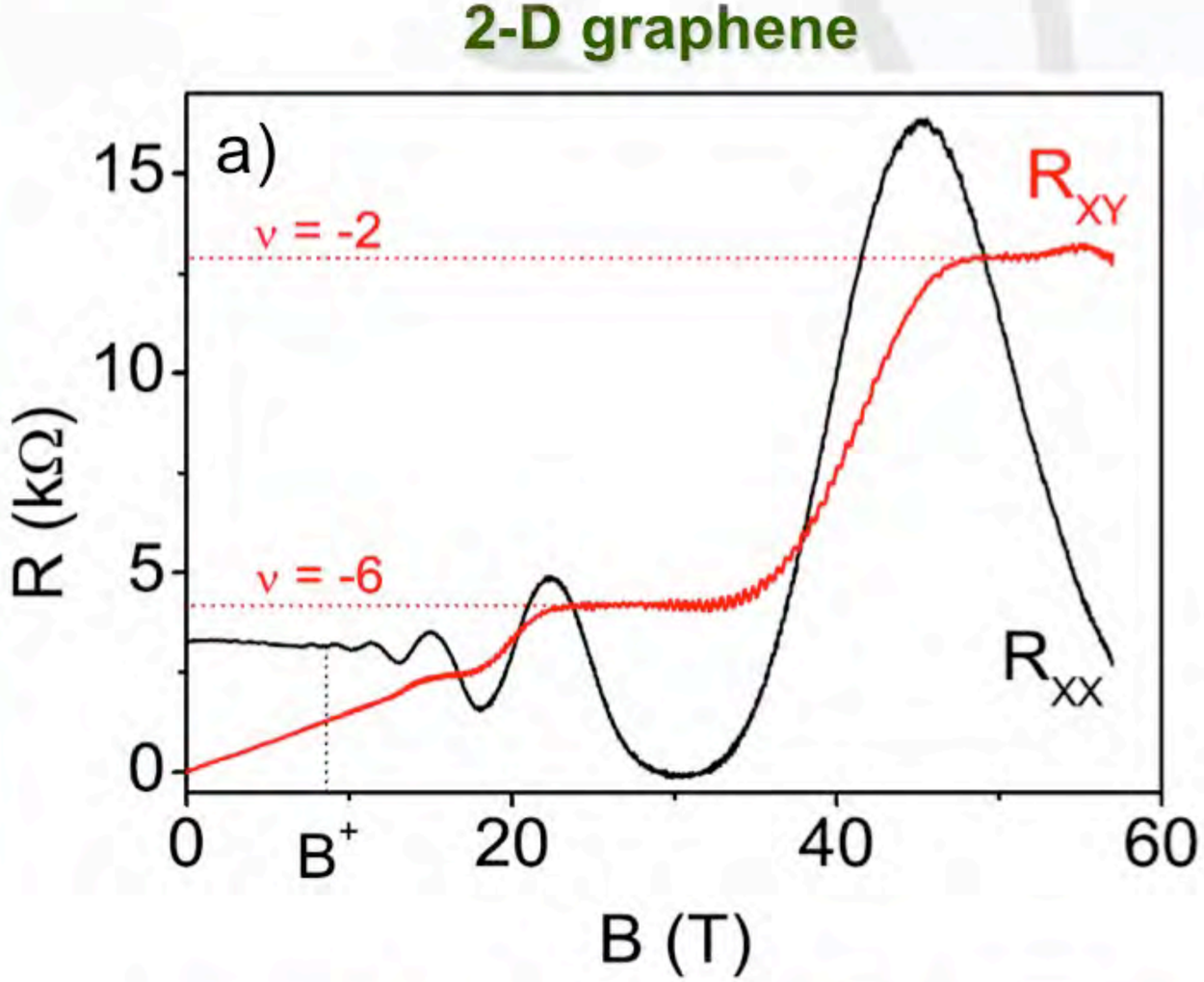


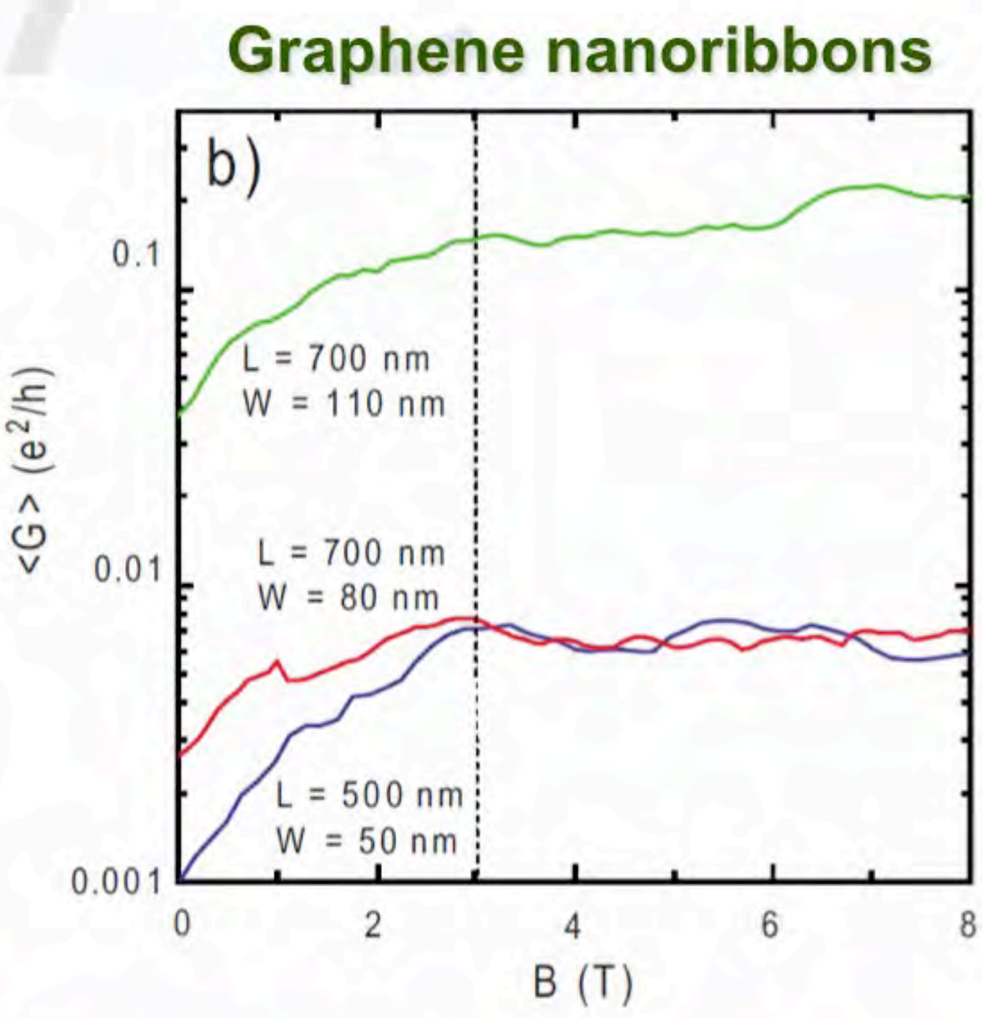


a) Hall (red) and longitudinal resistance (black) of single layer graphene as a function of magnetic field* b) Magneto conductance for GNR of 11 nm.**

[*] Poumirol et al. NJP (2010) [**] Poumirol et al. PRB (2010)

Motivation





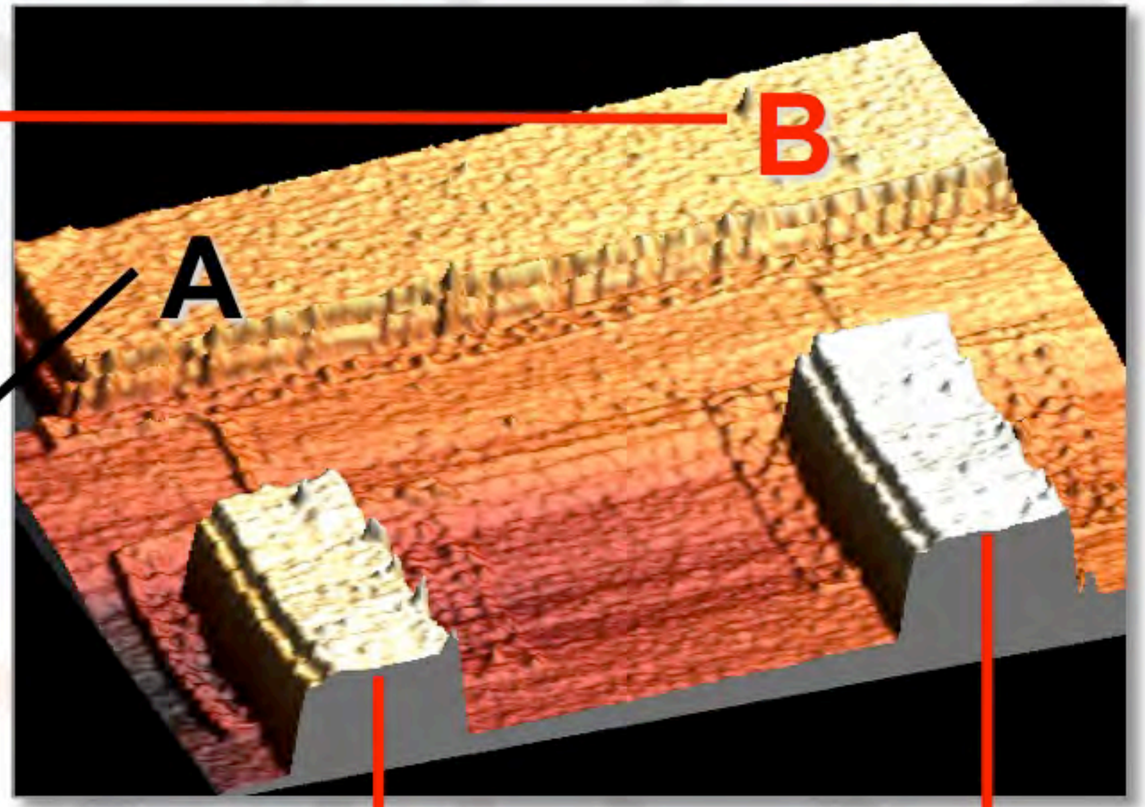
a) Hall (red) and longitudinal resistance (black) of single layer graphene as a function of magnetic field* b) Magneto conductance for GNR of 110 nm, 80 nm and 50 nm.**

[*] Poumirol et al. NJP (2010) [**] Oostinga et al. PRB (2010)

Standard Characterization

W=70 nm

L=750 nm



W=100 nm

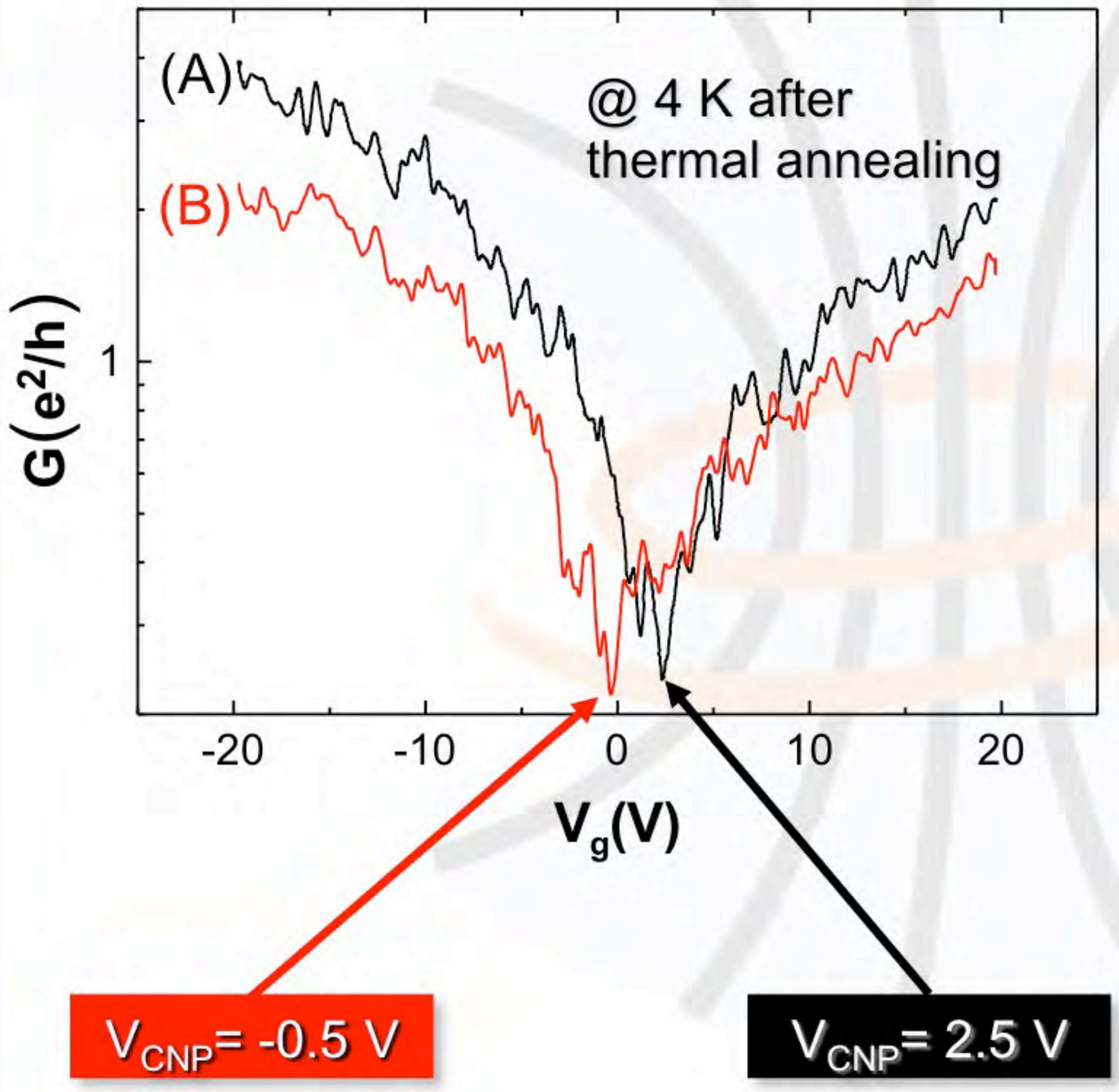
L=350 nm

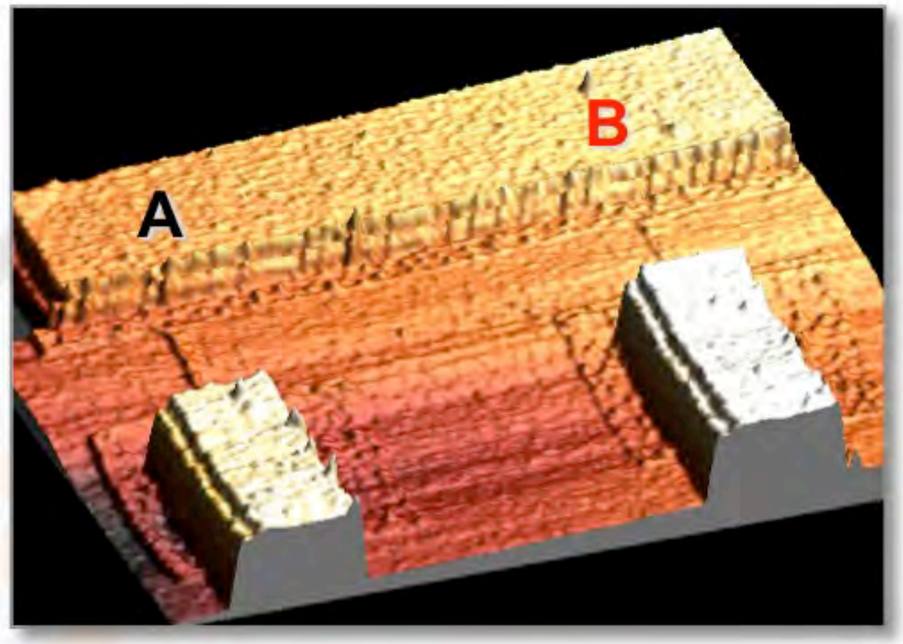
LAAS-CNRS

Ti/Pd/Au electrodes

Lithographically patterned graphene nanoribbons obtained by oxygen plasma etching

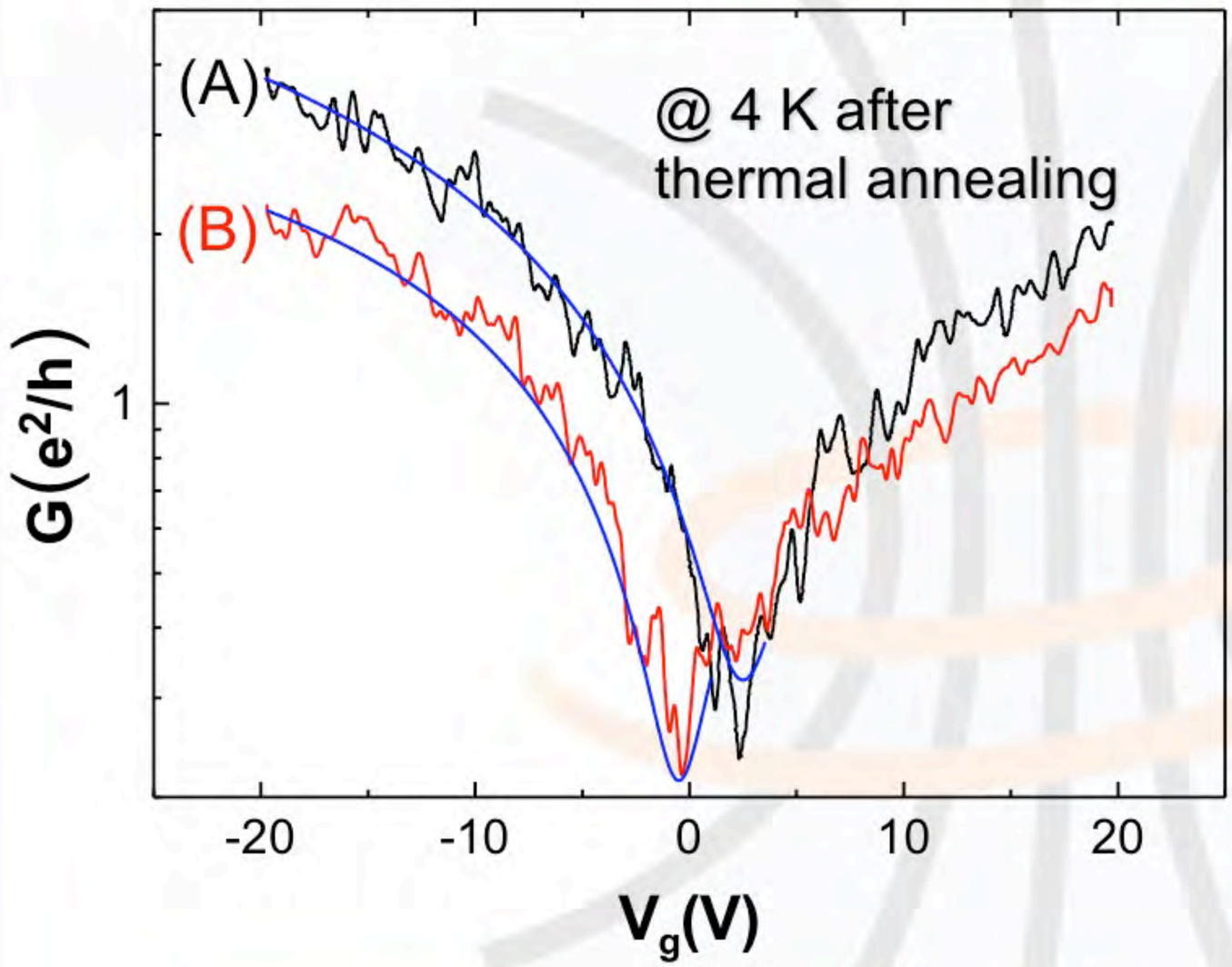
Standard Characterization

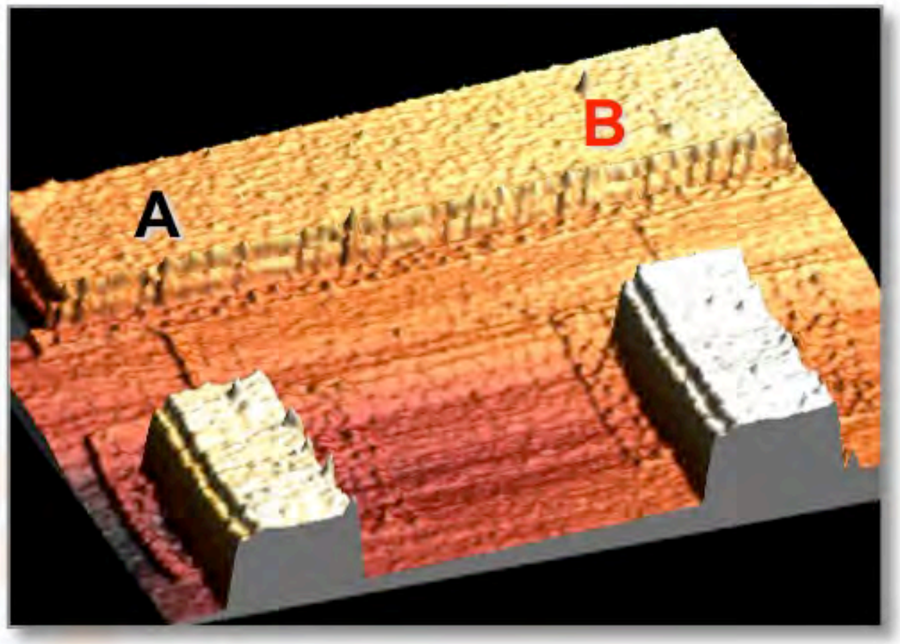




Negligible residual doping !

Standard Characterization





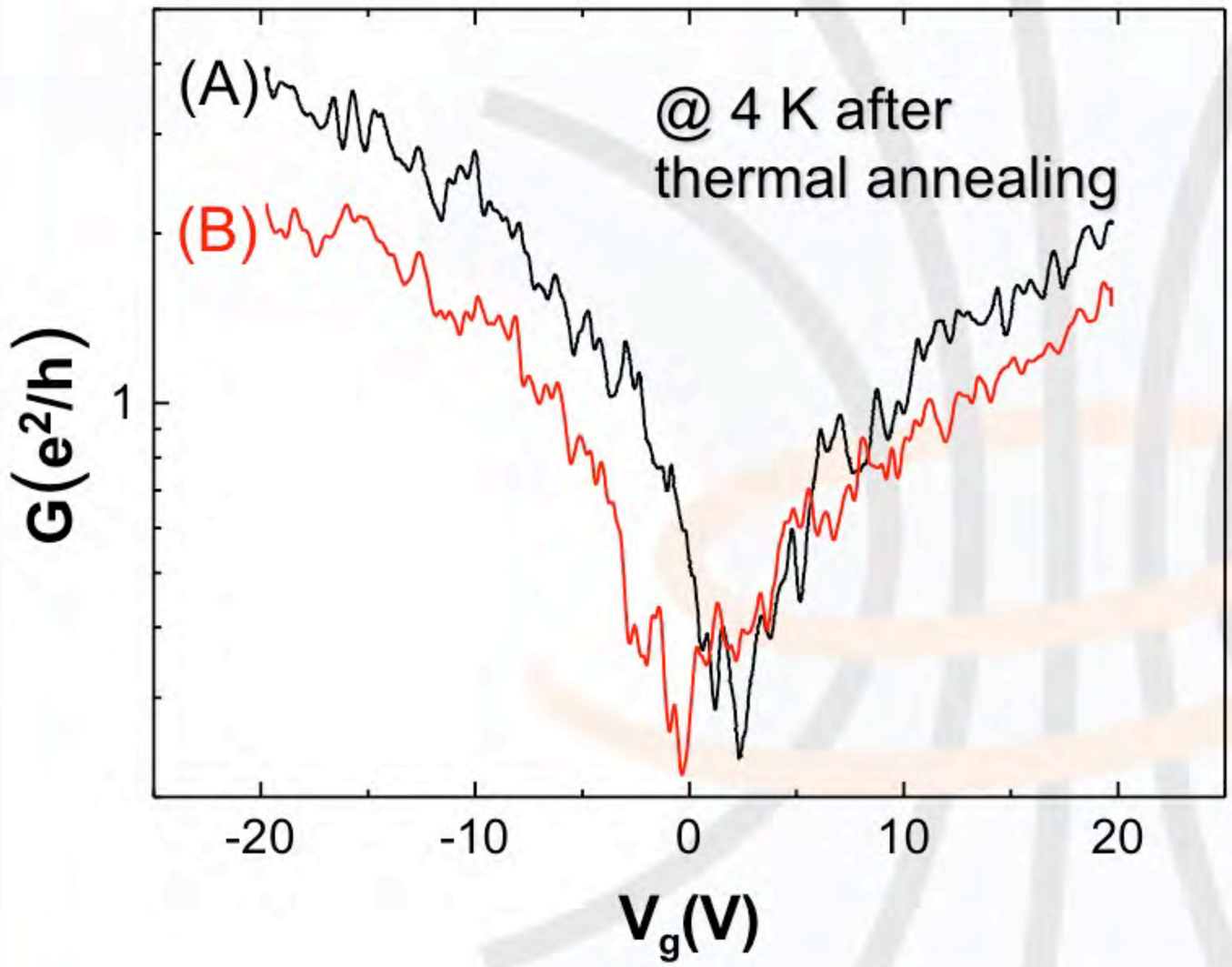
μ = 1200 cm²/ Vs*

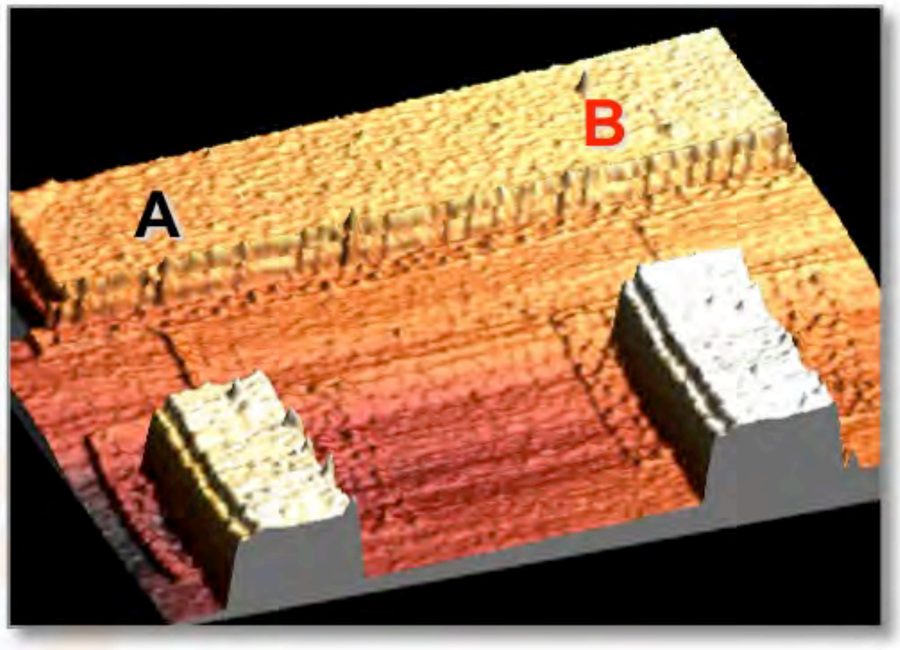
μ = 3500 cm²/ Vs

10 time higher than the reported mobility in GNR on SiO_2 !**

[*] Farmer et al. Nano Letters (2009) [**] Oostinga et al. PRB (2010)

Standard Characterization

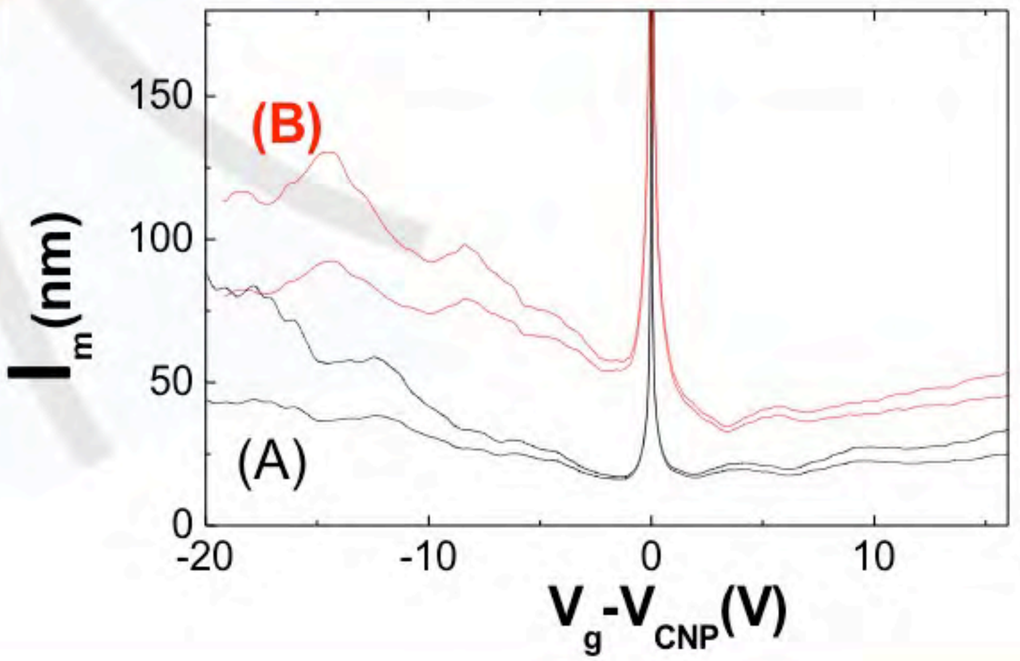




Mean free path of the order of the GNR width!

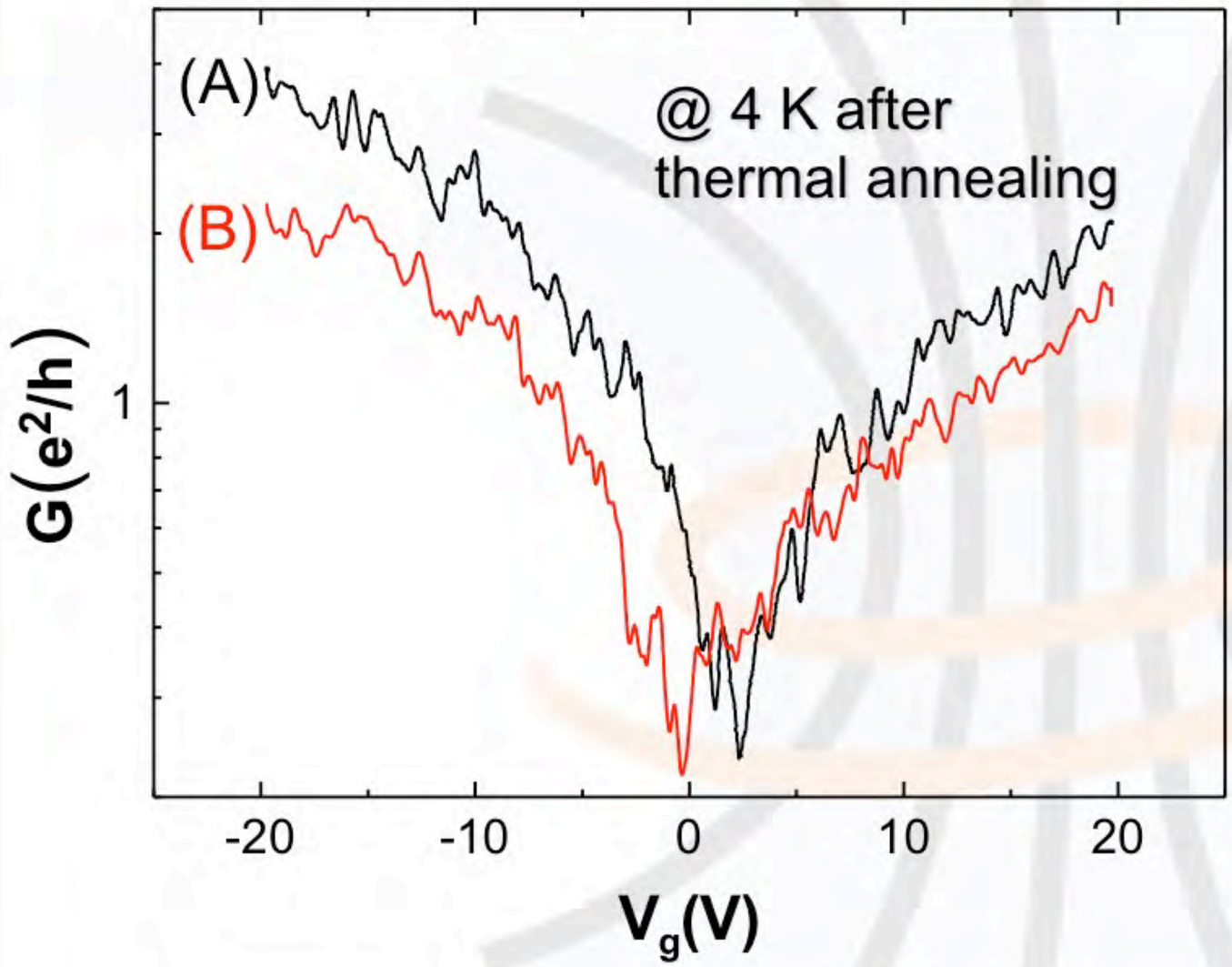
l=50-120 nm*

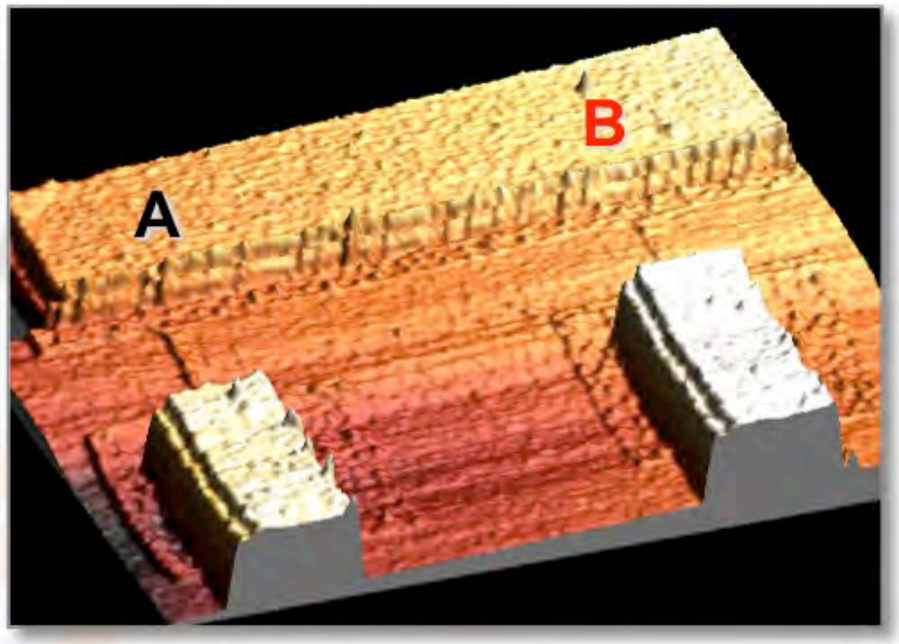
l=80-120 nm



[*] Cresti et al. NJP (2009)

Standard Characterization





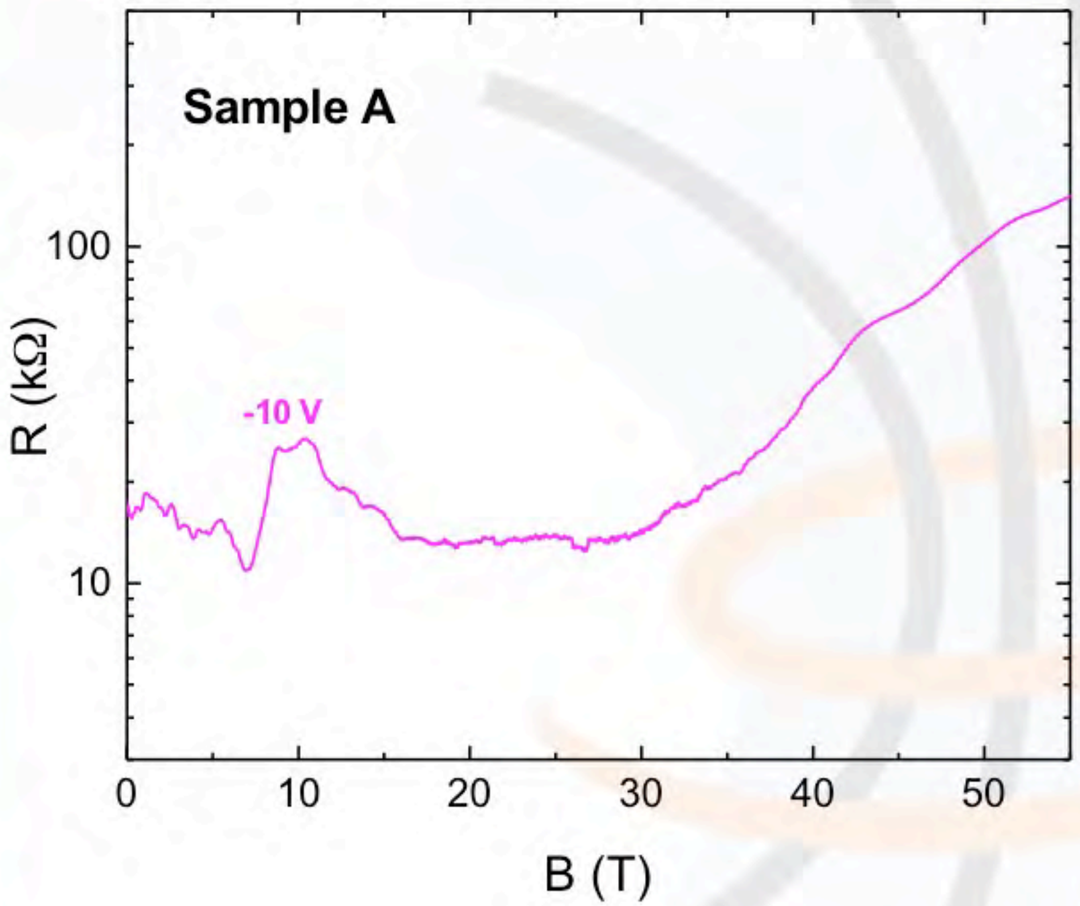
μ = 1200 cm²/ Vs*; l=50-120 nm**

μ = 3500 cm²/ Vs; l=80-120 nm

Quasi-ballistic transport regime !

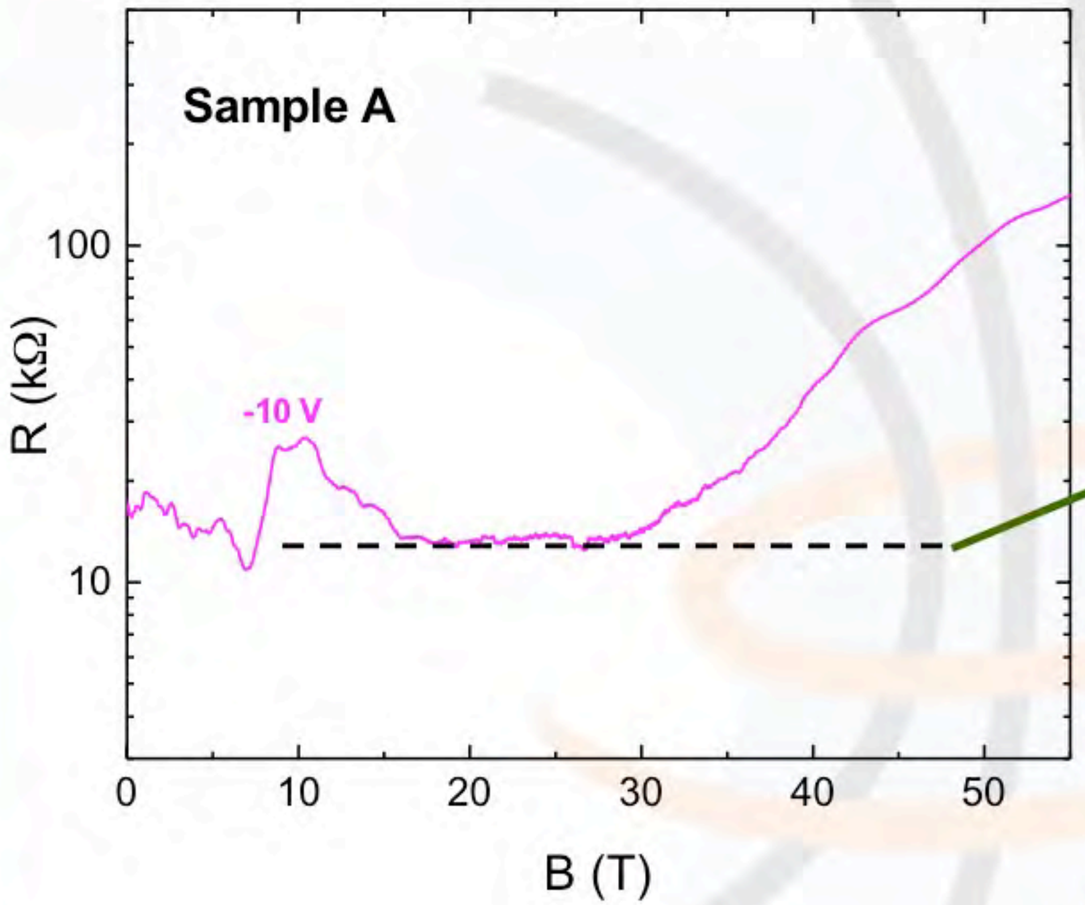
[*] Farmer et al. Nano Letters (2009) [**] Cresti et al. NJP (2009)

High Magnetic Field



Magneto-resistance measurements for different V_g at 4 K.

High Magnetic Field

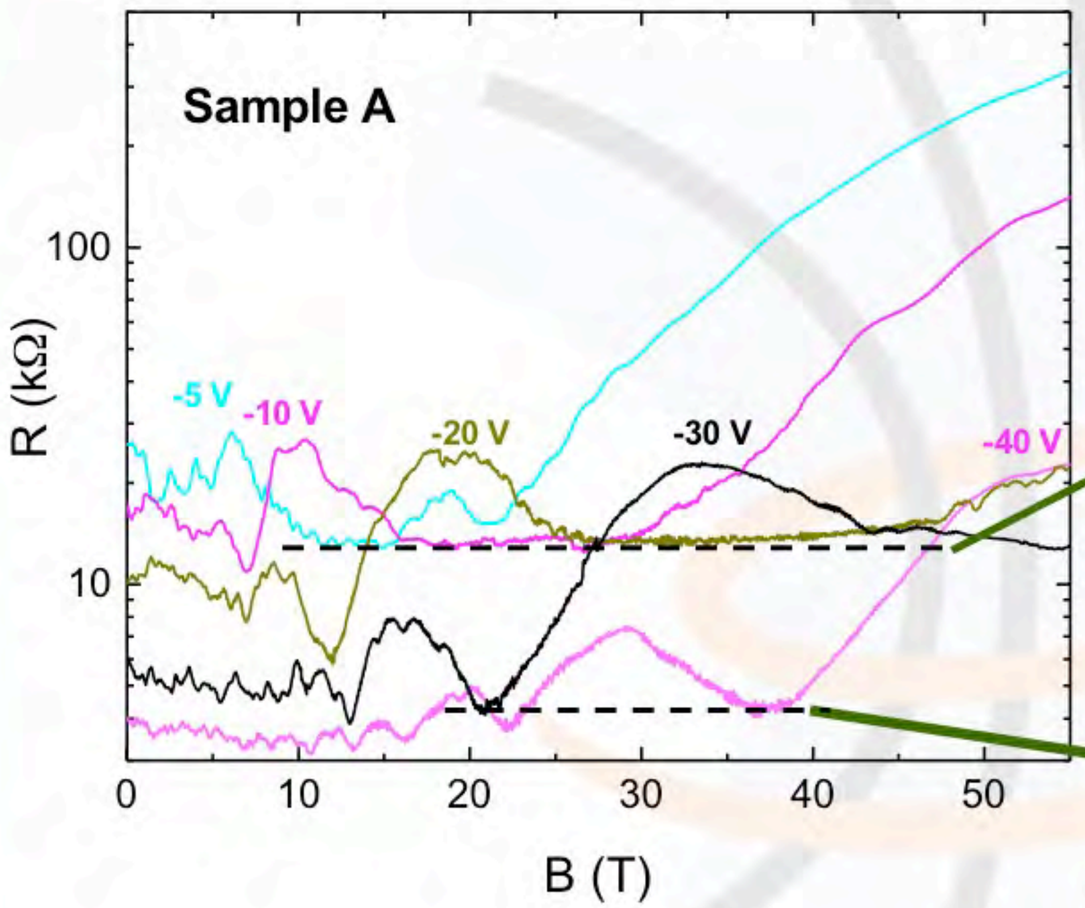


Magneto-resistance measurements for different V_g at 4 K.

Quantization plateau around 13 kΩ

($h/2e^2$)

High Magnetic Field



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Quantization minimum around 4,3 kΩ

($h/6e^2$)

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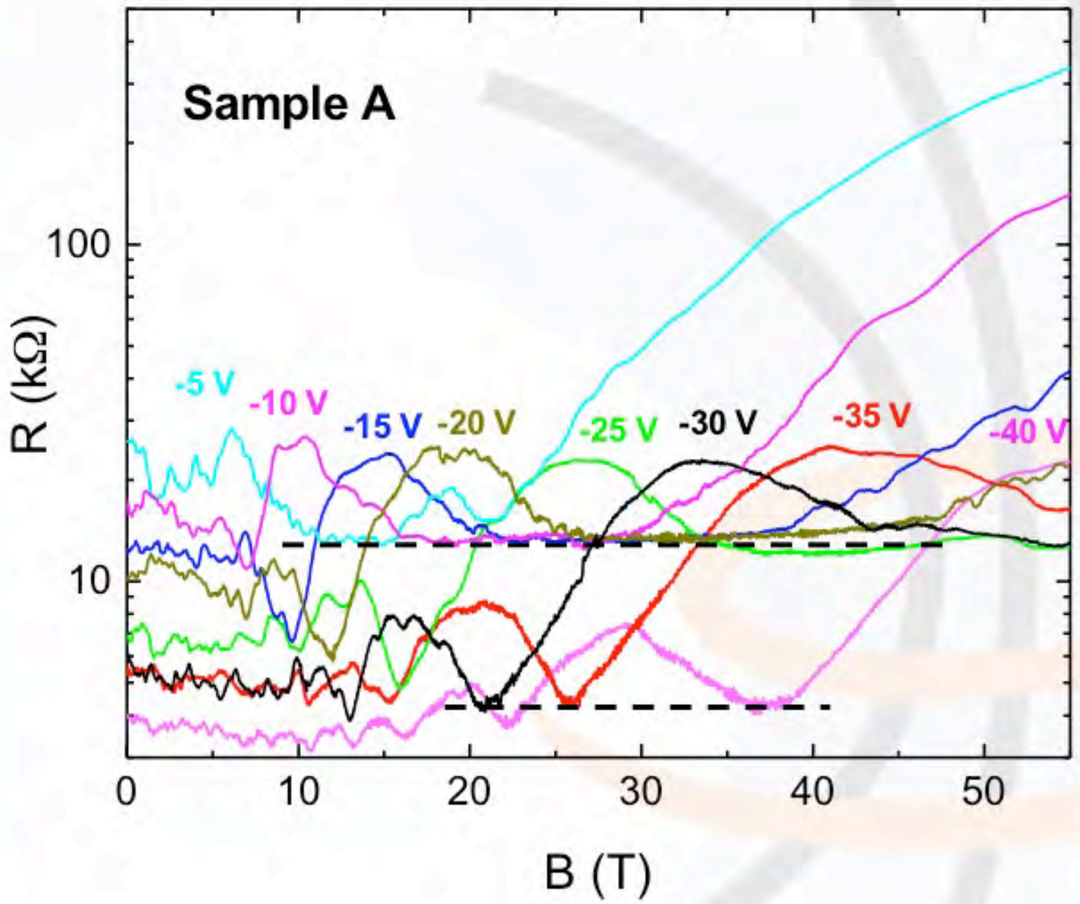

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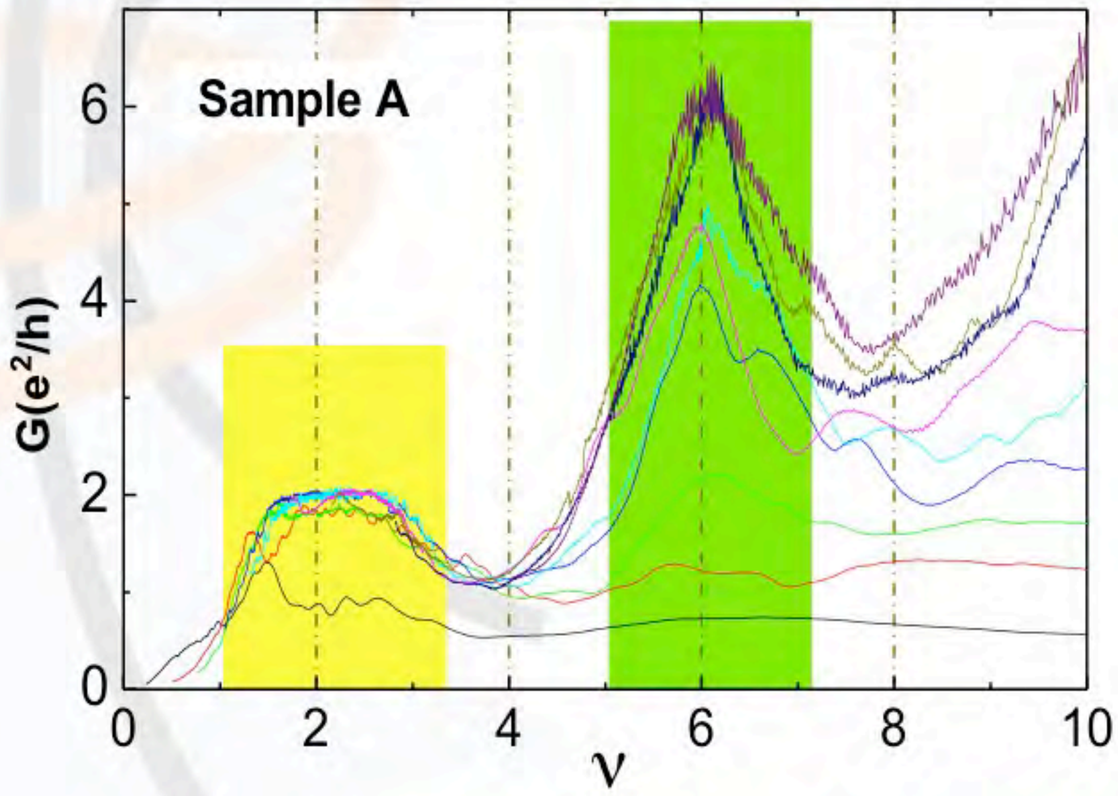
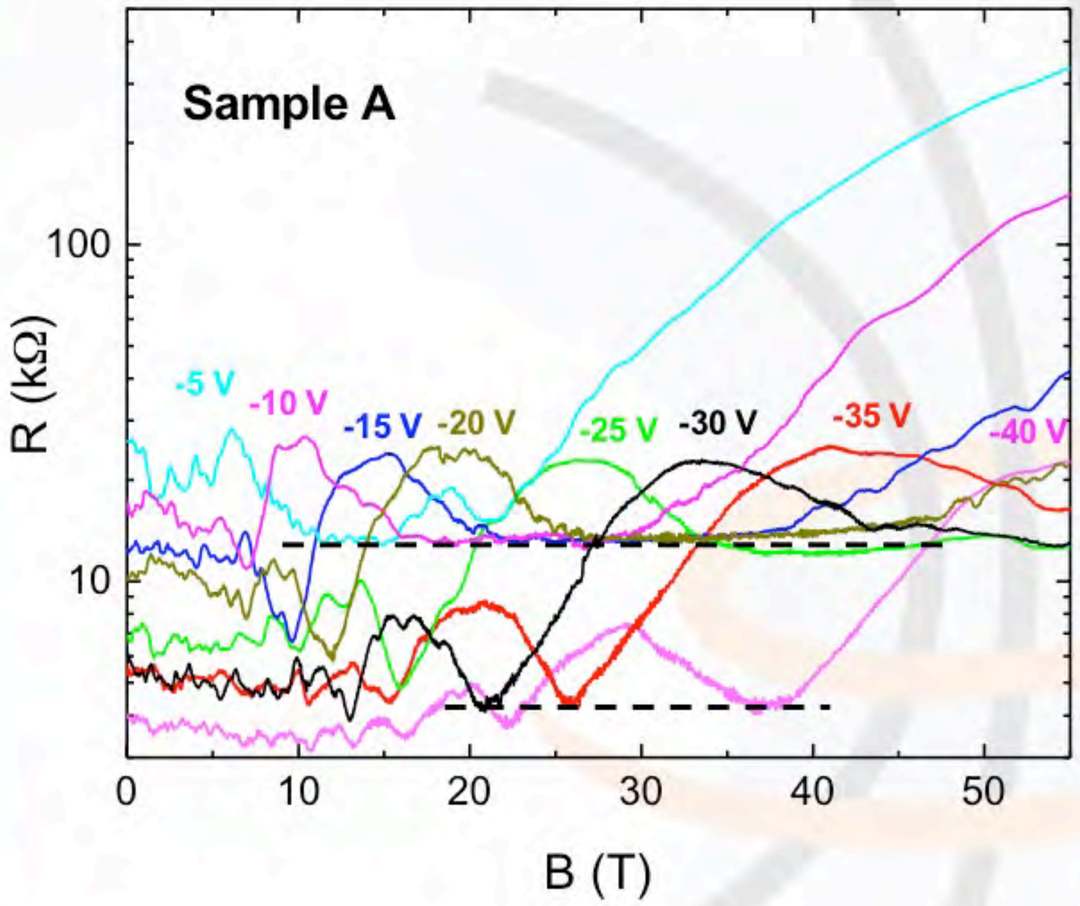


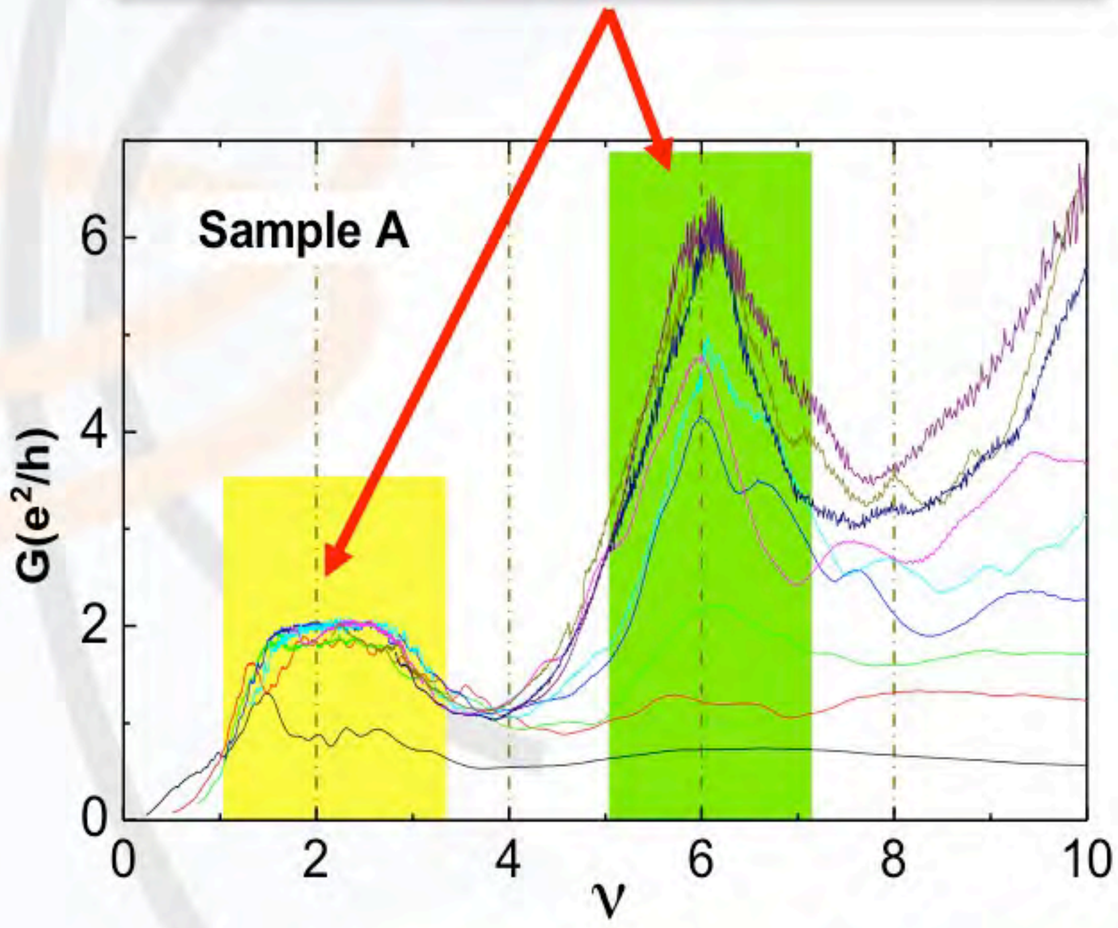
Conductance as a function of filling factor for several V_g.

High Magnetic Field



Magneto-resistance measurements for different V_g at 4 K.

Evidence of single-layer Graphene



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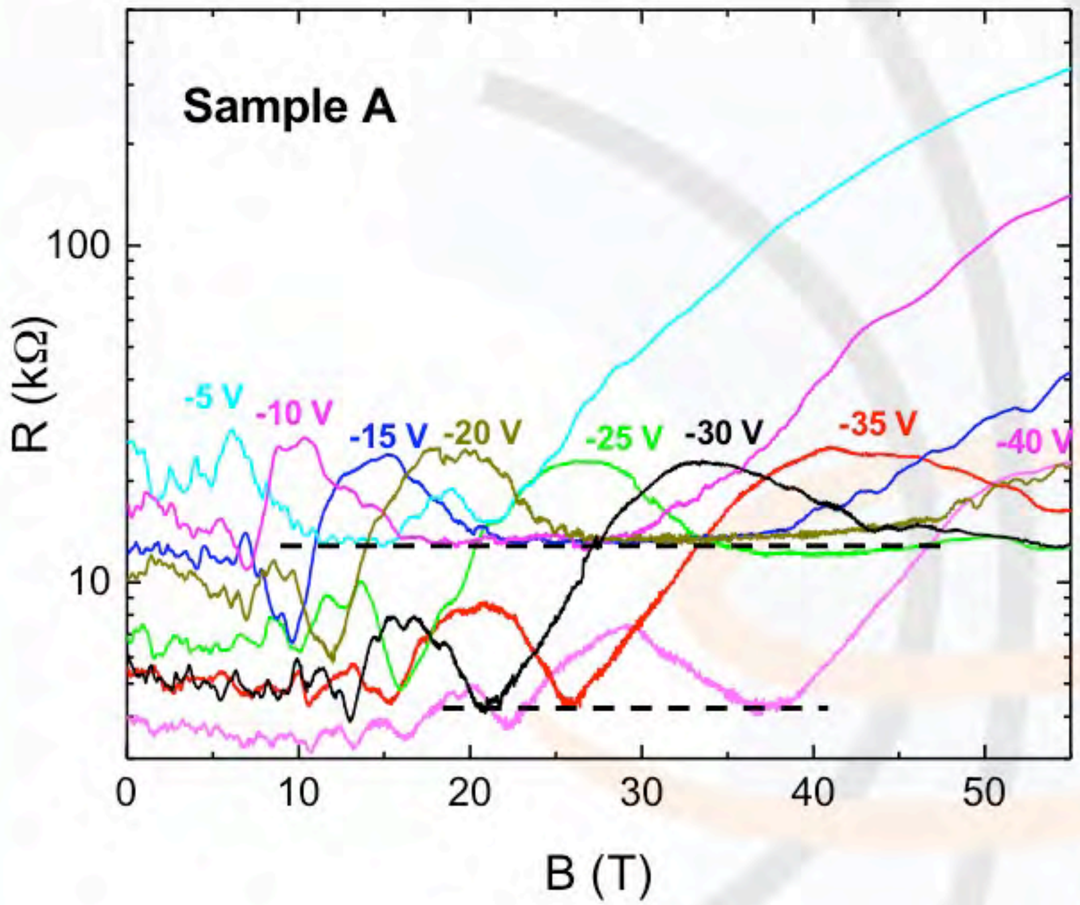
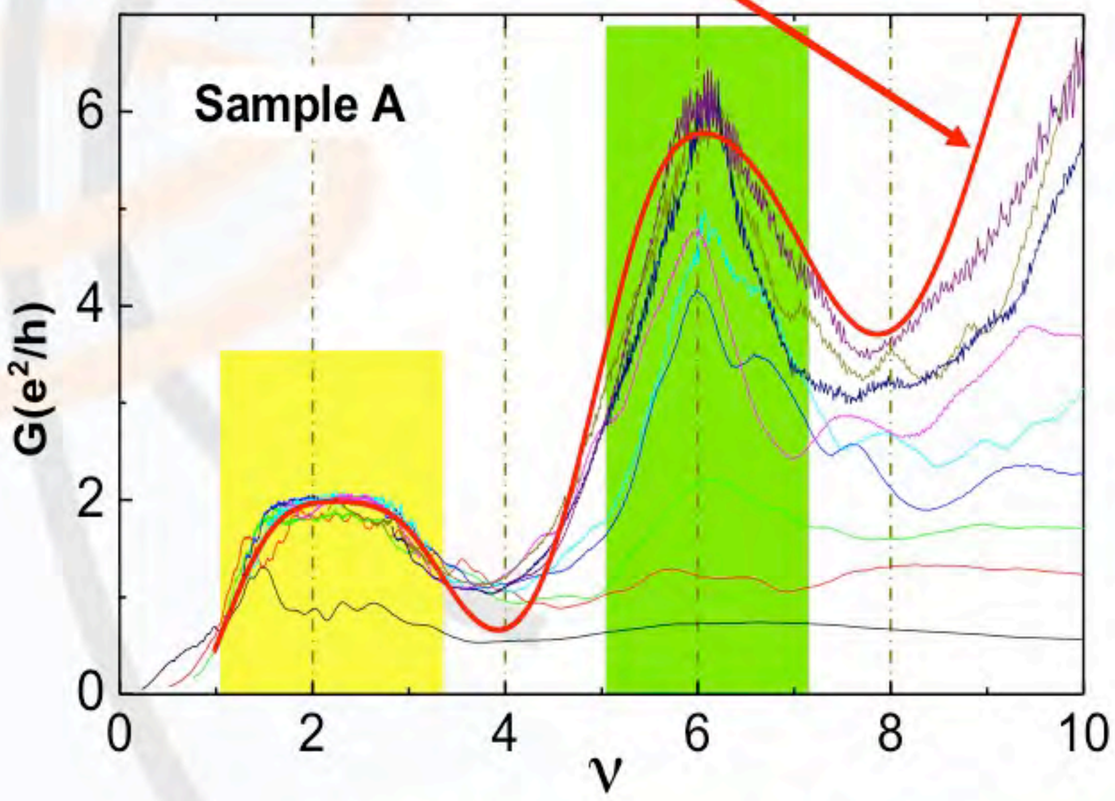


Magneto-resistance measurements for different V_g at 4 K.

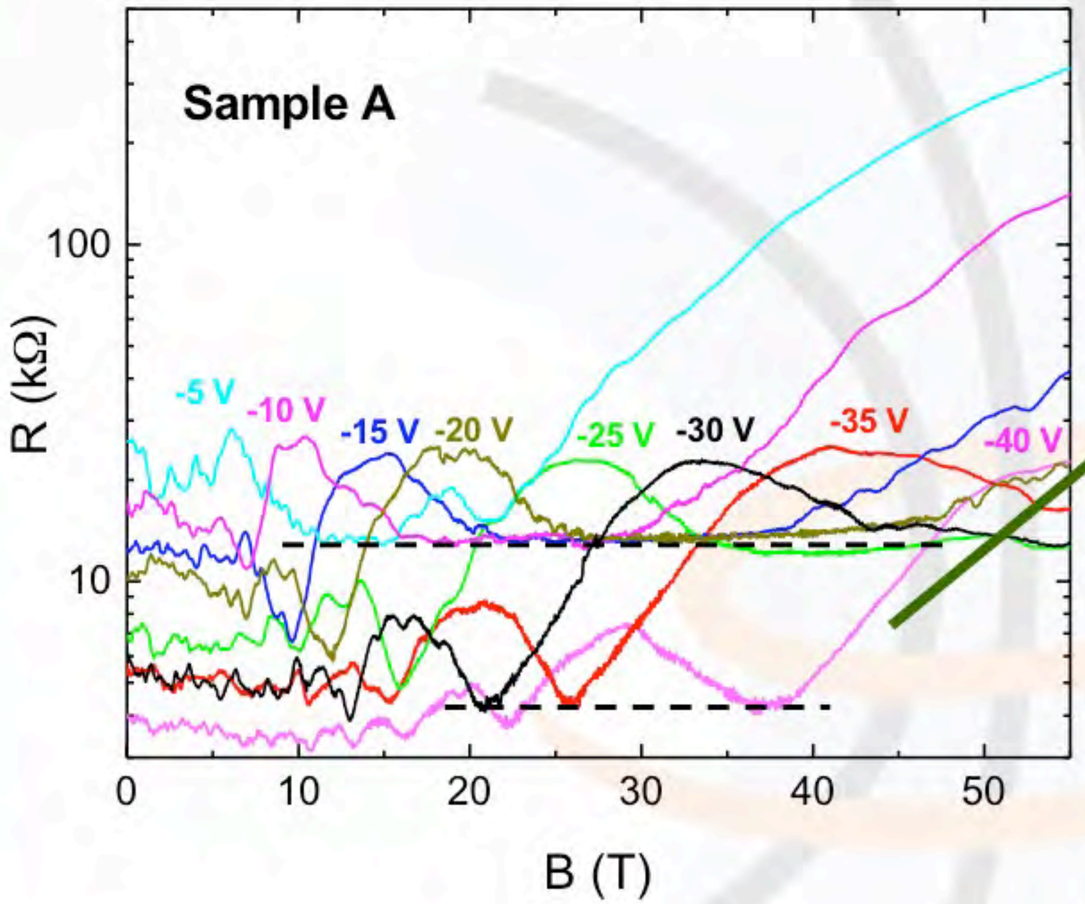
Numerical simulation* of conductance for two terminal measurement with a specific geometry



Conductance as a function of filling factor for several V_g.

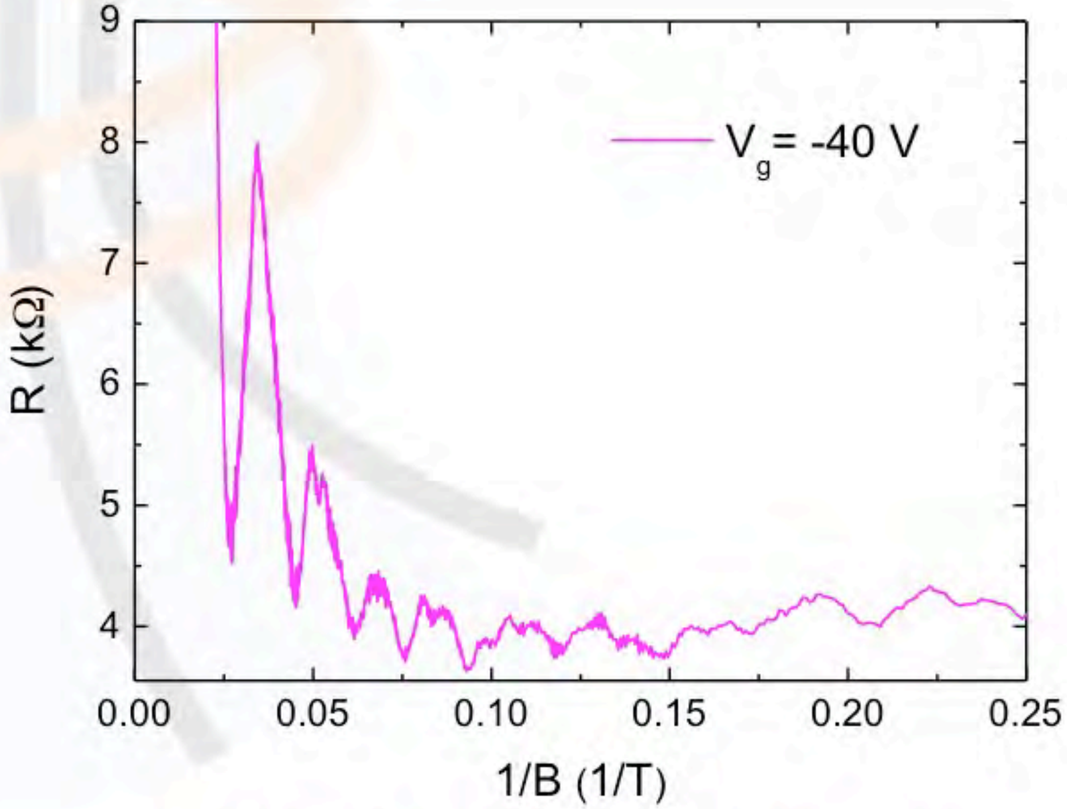
[*] Williams et al. Phys. Rev. B (2009)

High Magnetic Fields



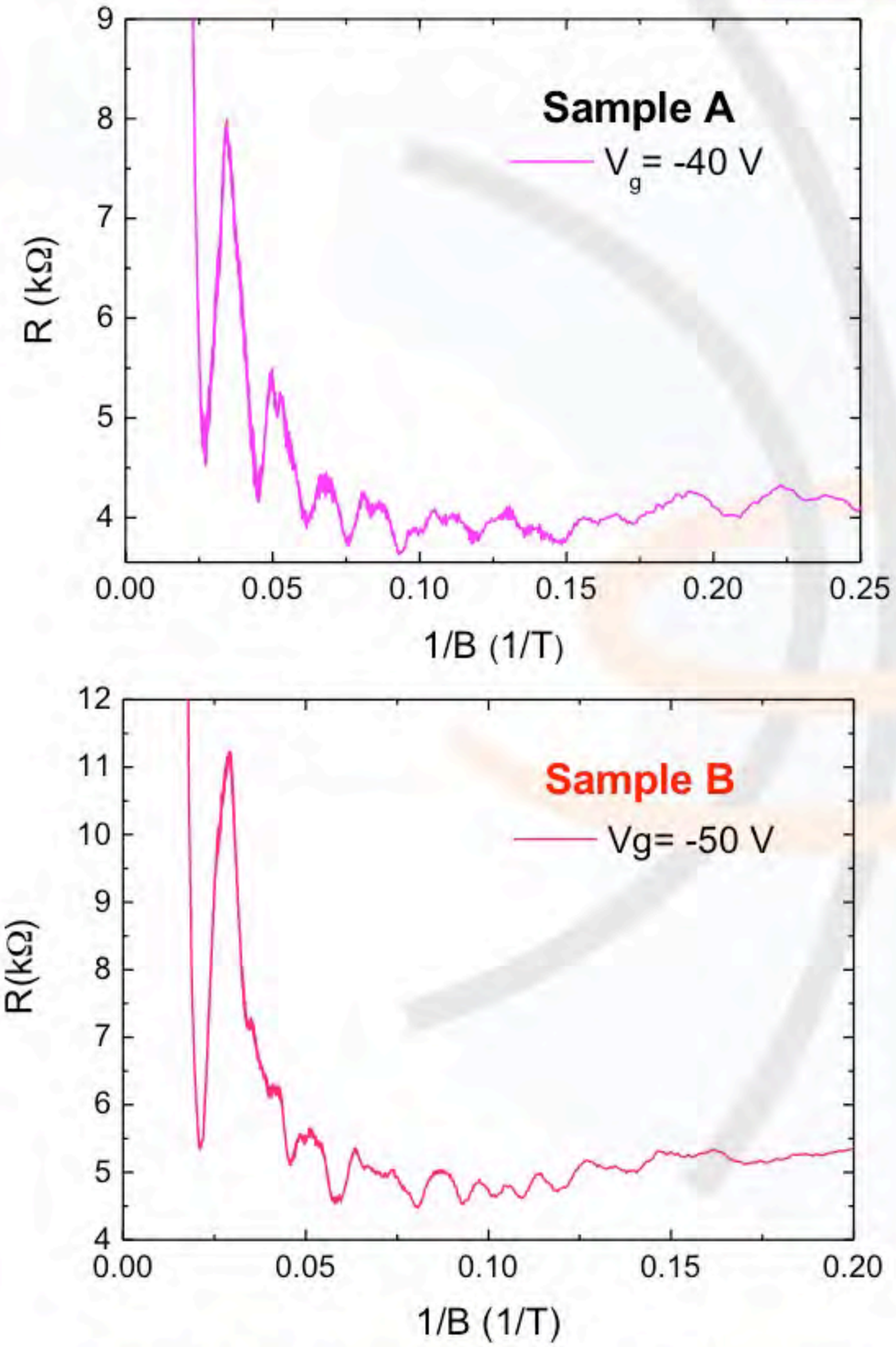
Magneto-resistance measurements for different V_g at 4 K.

Anomalous Shubnikov-deHaas oscillations



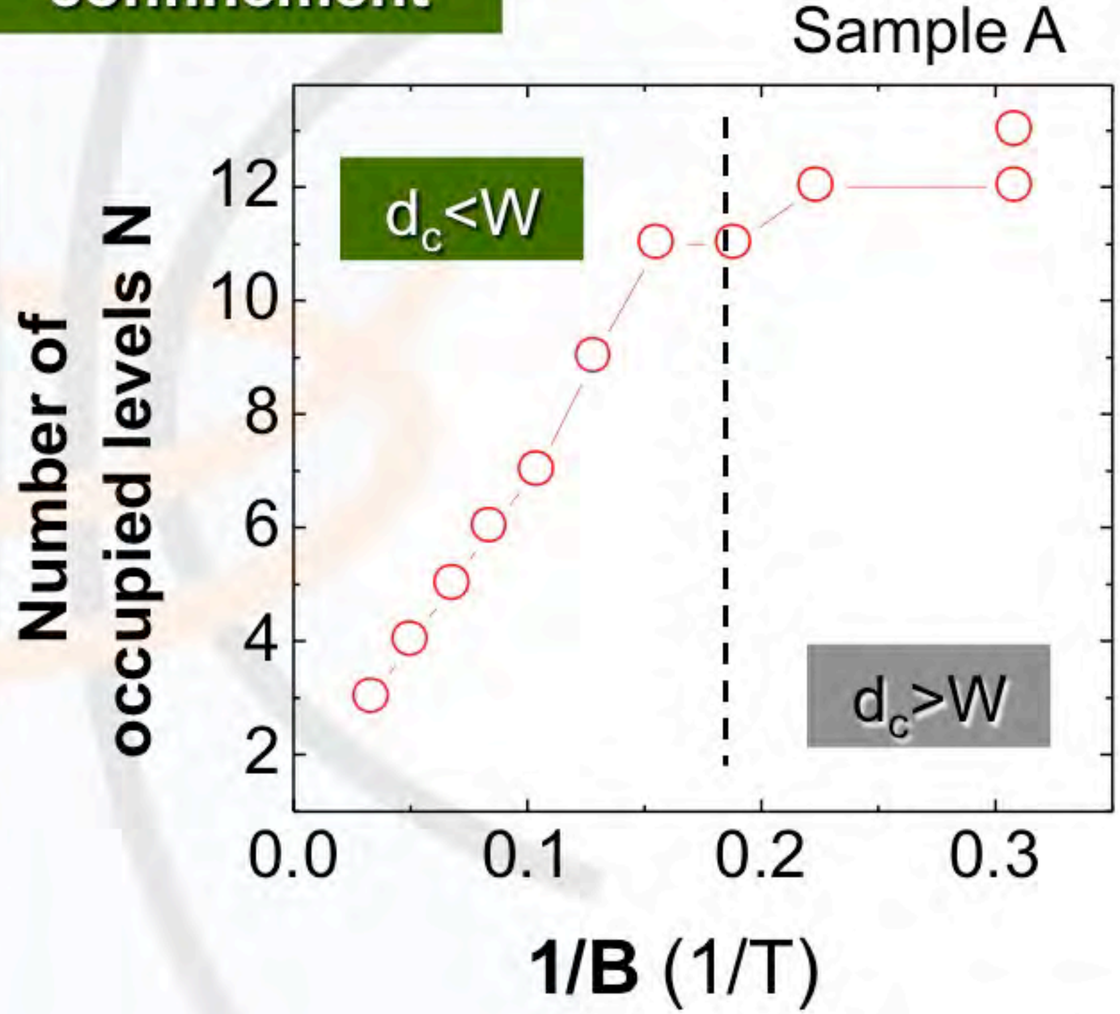
Shubnikov-deHaas oscillations

Electronic Confinement



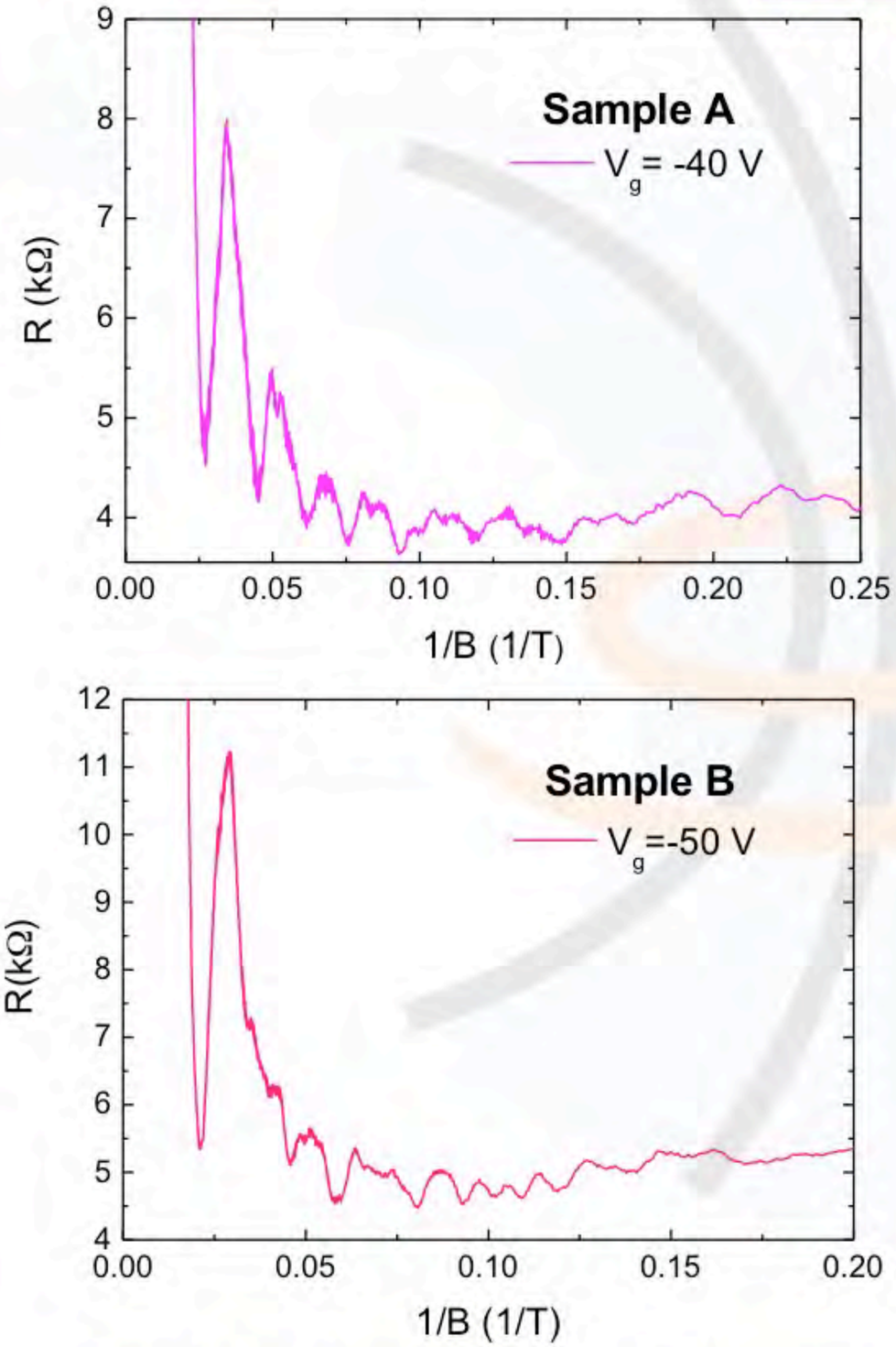
Shubnikov-deHaas oscillations

Magnetic confinement



Electronic confinement

Electronic Confinement



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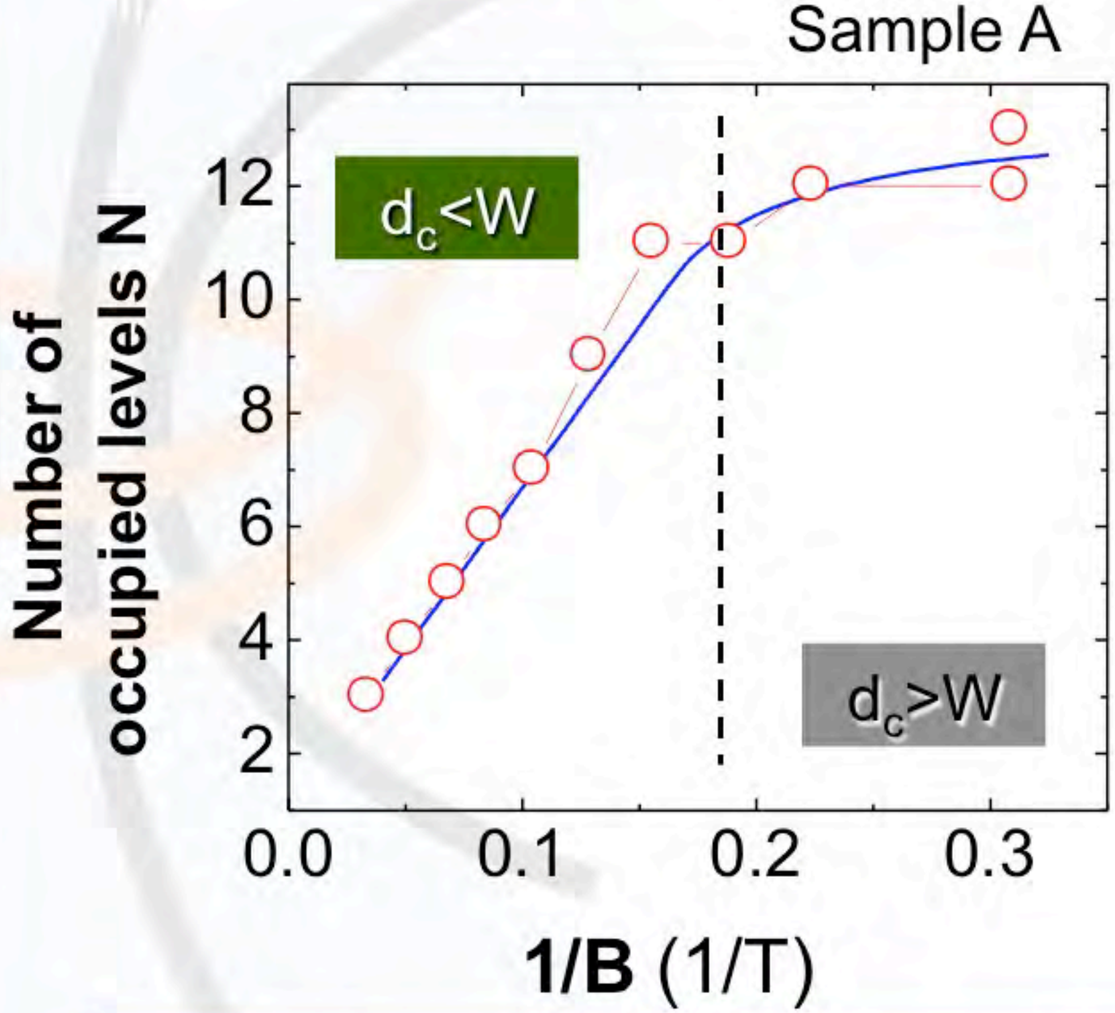
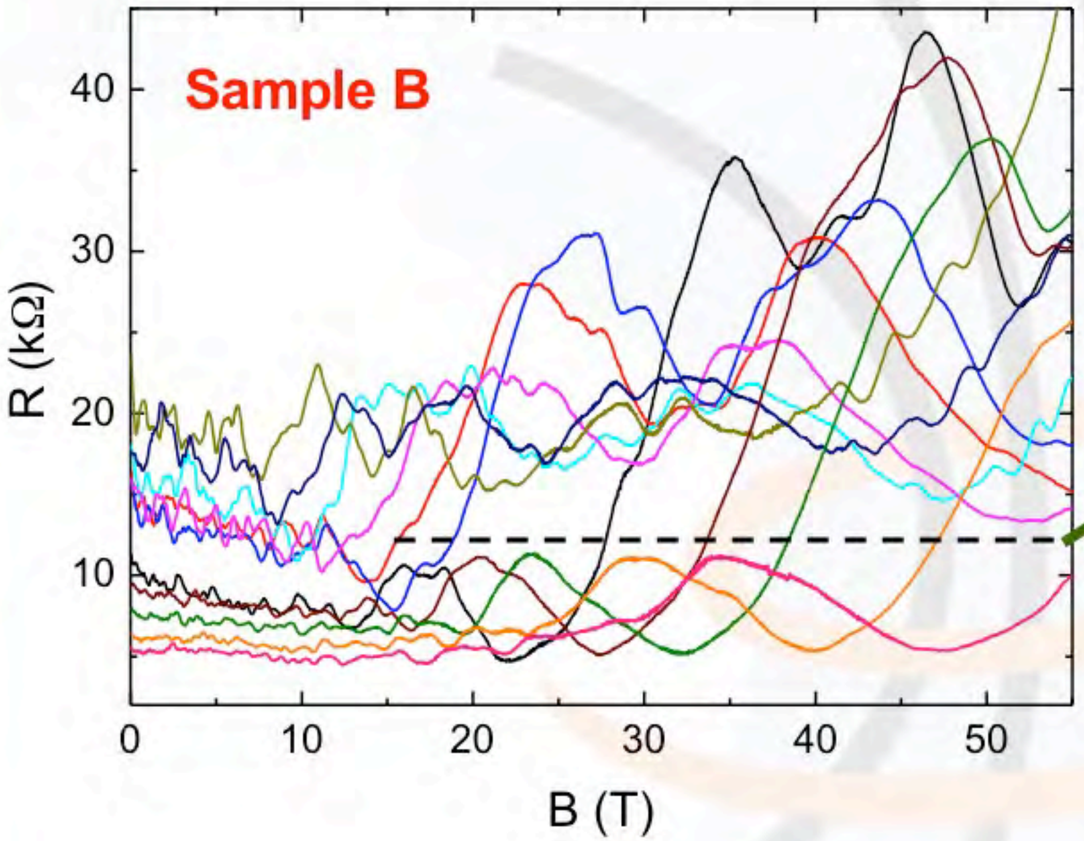


Semiclassical Bohr-Sommerfeld quantization rule*
Using as a fit parameter W=94 nm

[*] Beenakker and van Houten, Solid State Physics (1991)

High Magnetic Field

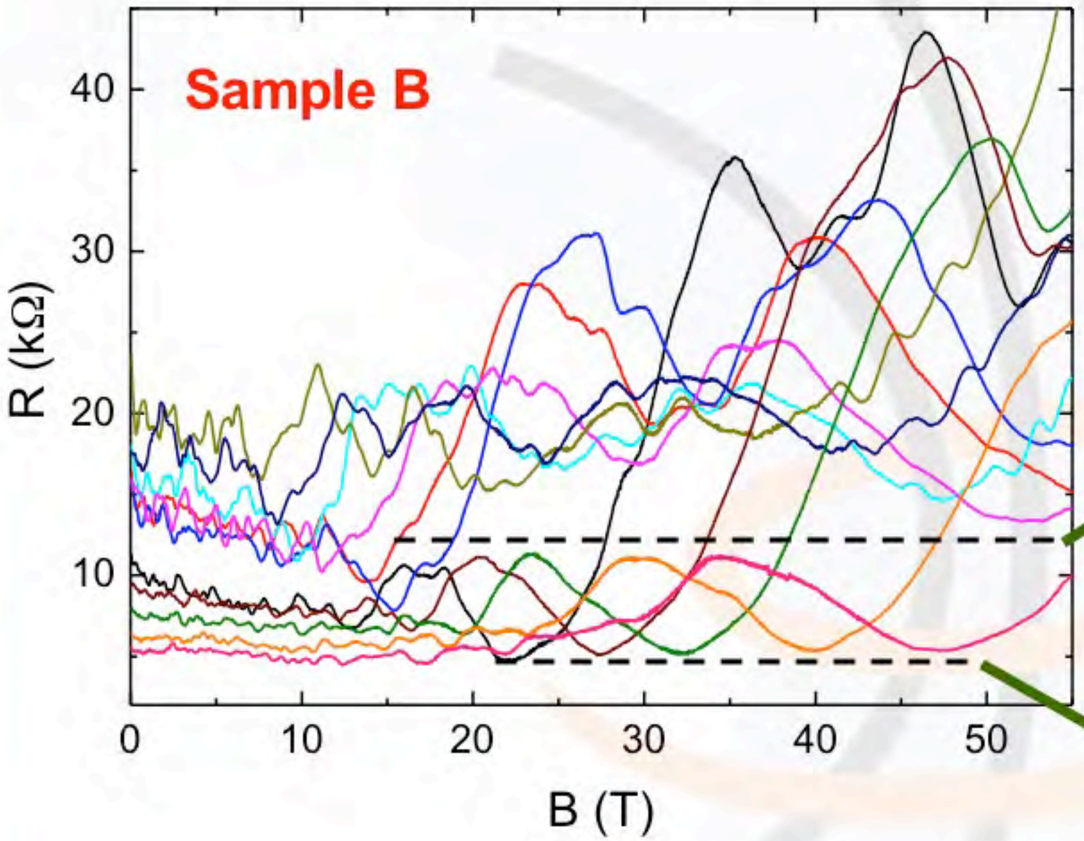


NO Quantization plateau around 13 kΩ

($h/2e^2$)

Magneto-resistance measurements for different V_g at 4 K. From left (-5 V) to right (-40 V) in steps of 5V.

High Magnetic Field



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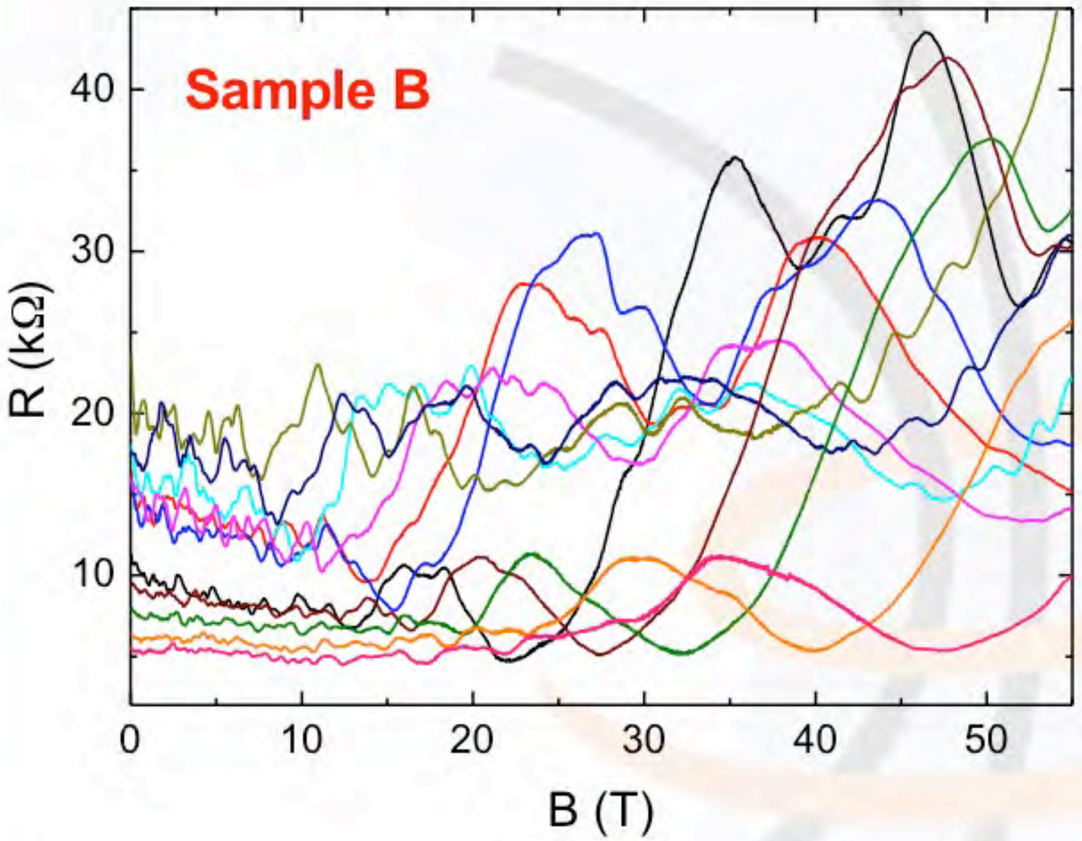
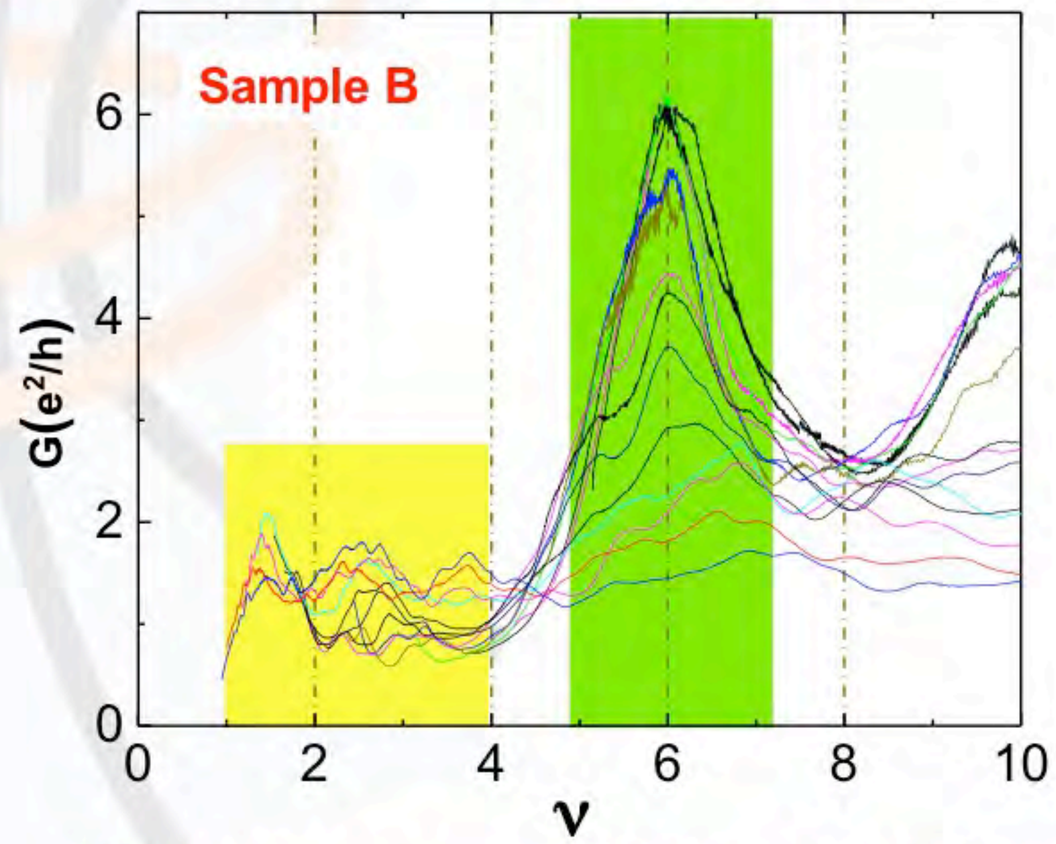


Magneto-resistance measurements for different V_g at 4 K.

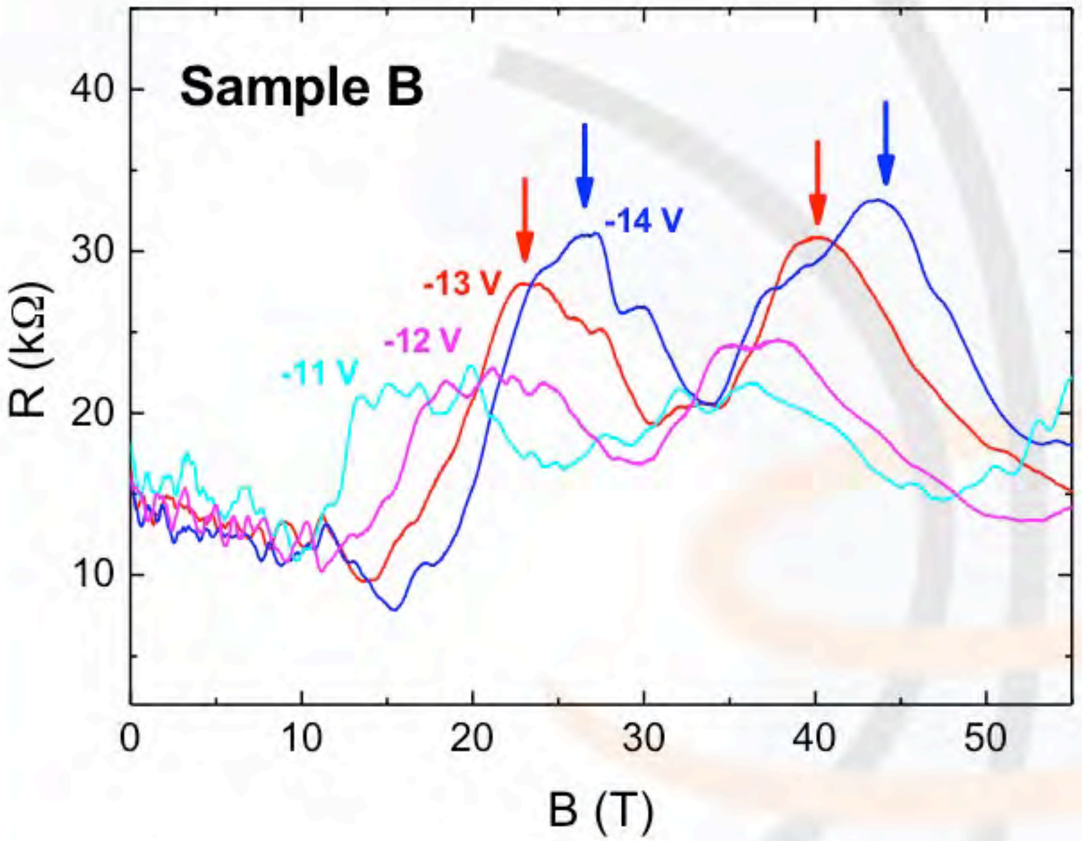
No quantization for ν=2 even when we have quantization for ν=6



Conductance as a function of filling factor for several V_g.

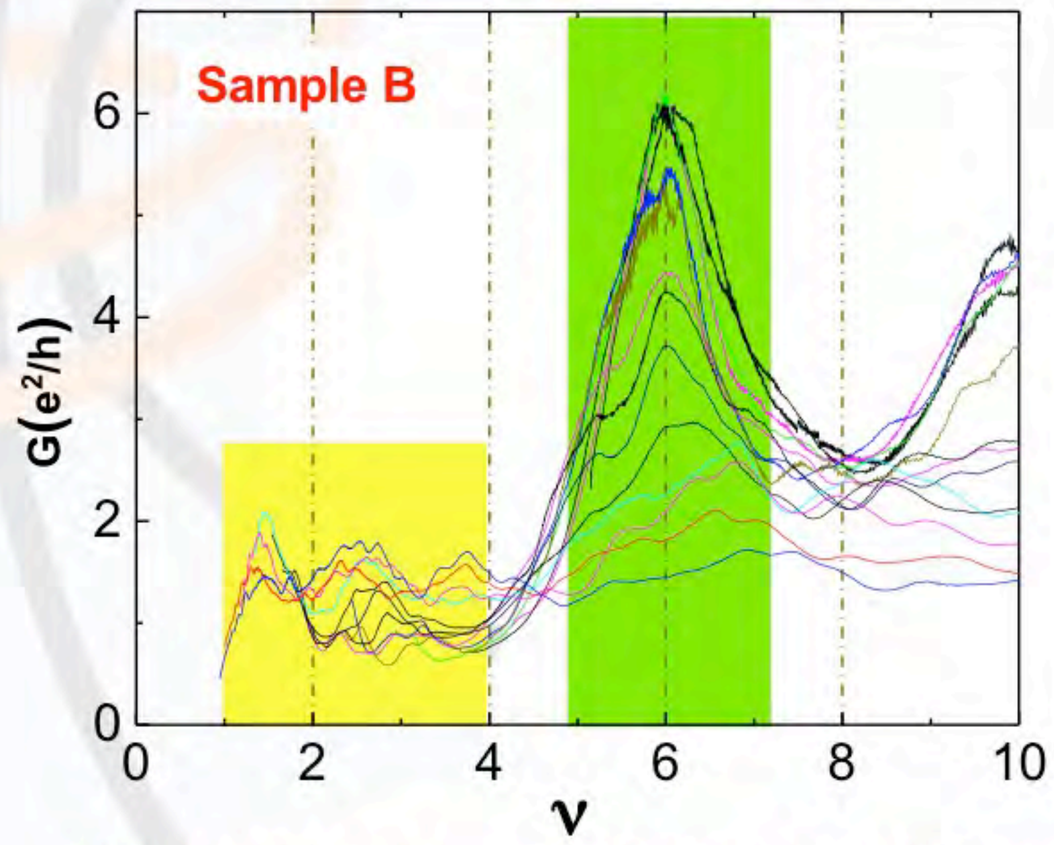
[*] Cresti et al.

High Magnetic Field



Magneto-resistance measurements for different V_g at 4 K.

Impossibile visualizzare l'immagine. La memoria del computer potrebbe essere insufficiente per aprire l'immagine oppure l'immagine potrebbe essere danneggiata. Riavviare il computer e aprire di nuovo il file. Se viene visualizzata di nuovo la x rossa, potrebbe essere necessario eliminare l'immagine e inserirla di nuovo.



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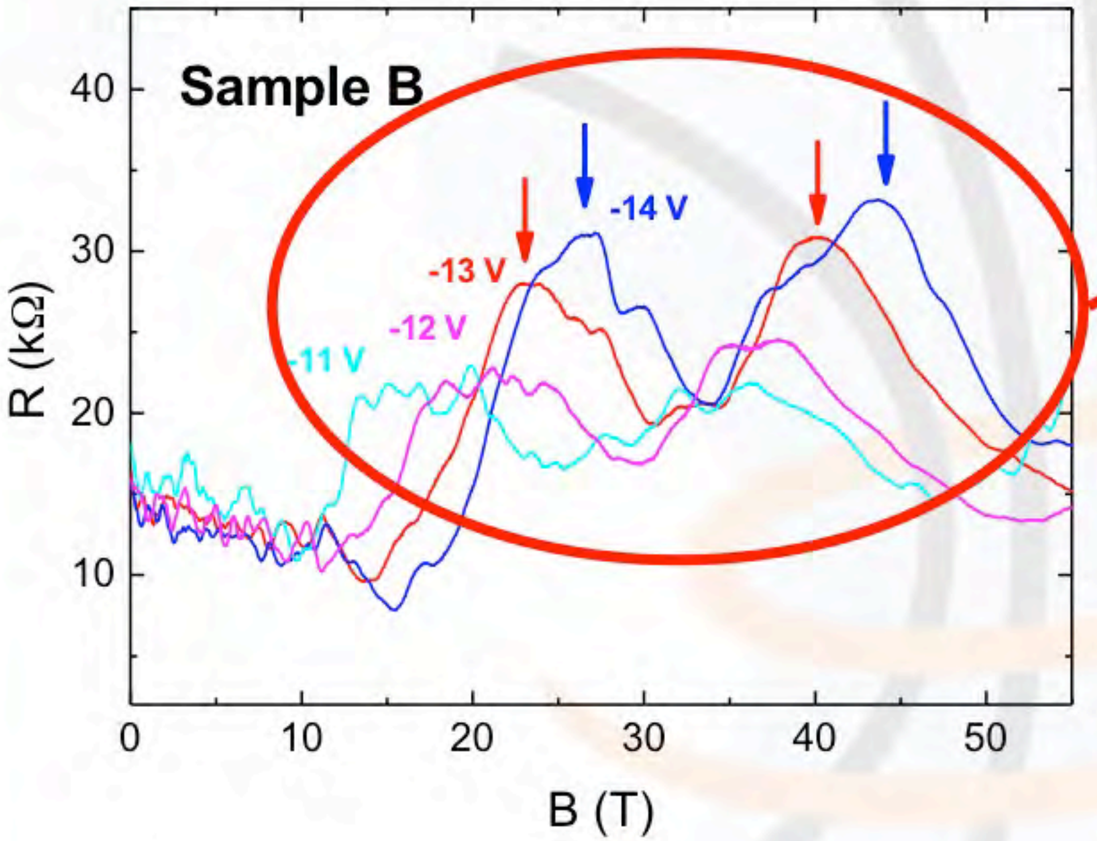
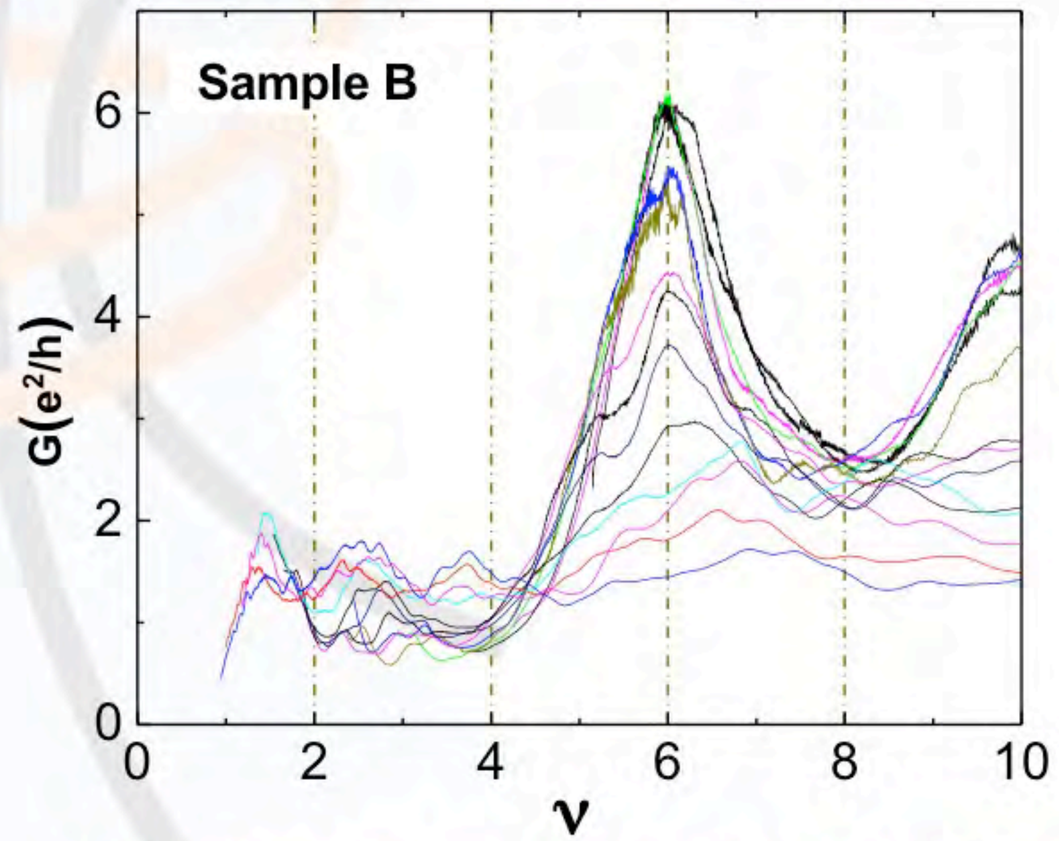


Magneto-resistance measurements for different V_g at 4 K.

Double peak formation instead of the expected peak which precede the quantization plateau



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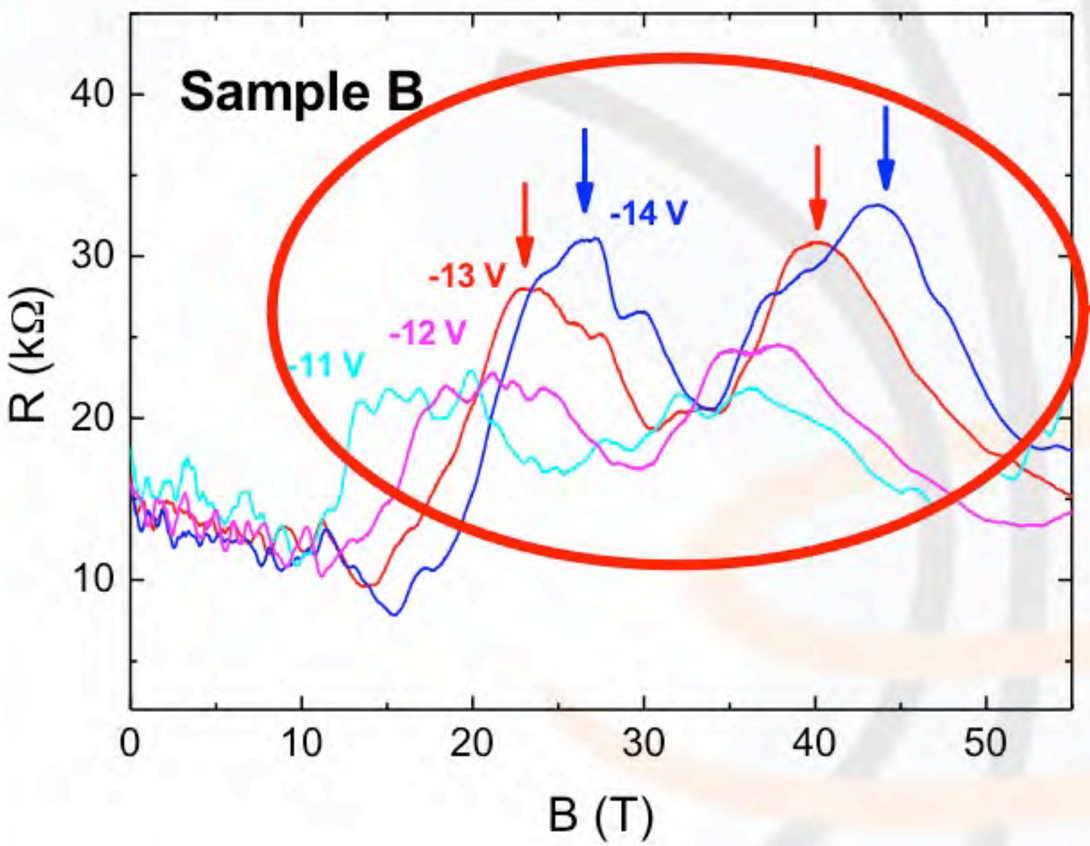
High Magnetic Field



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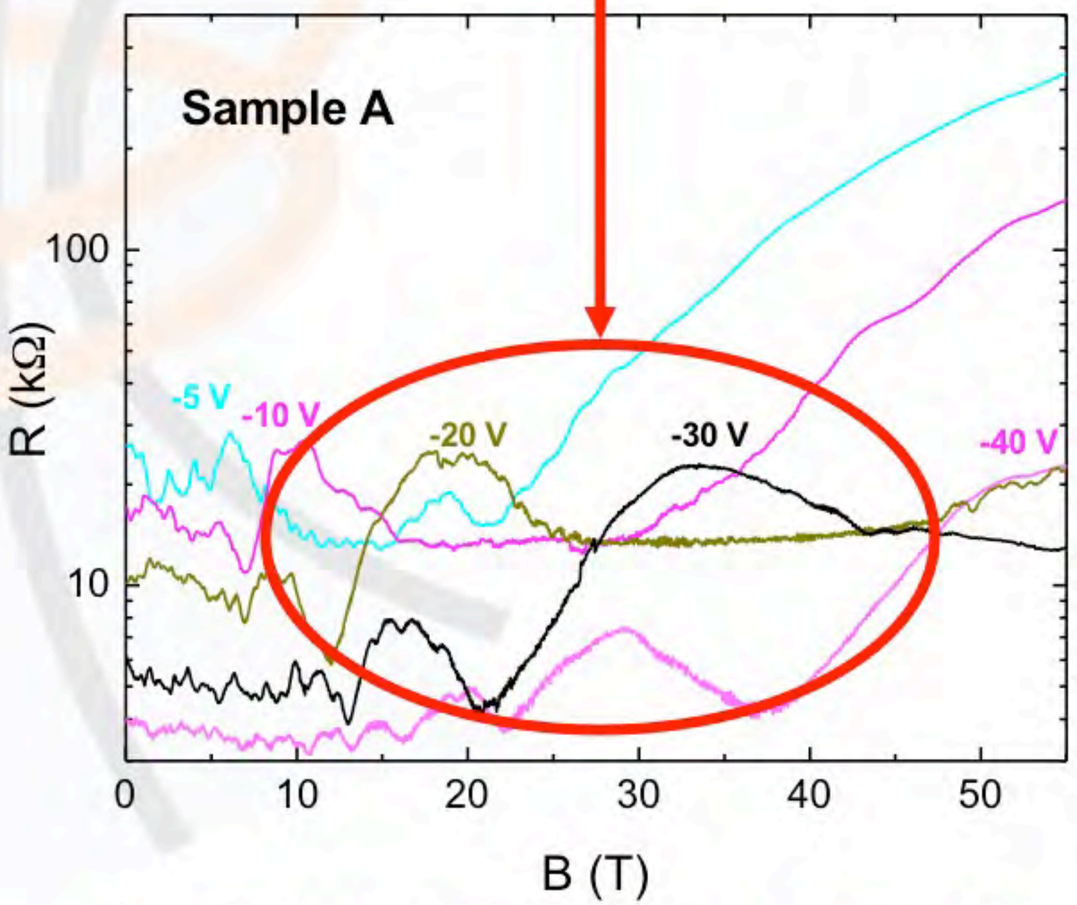
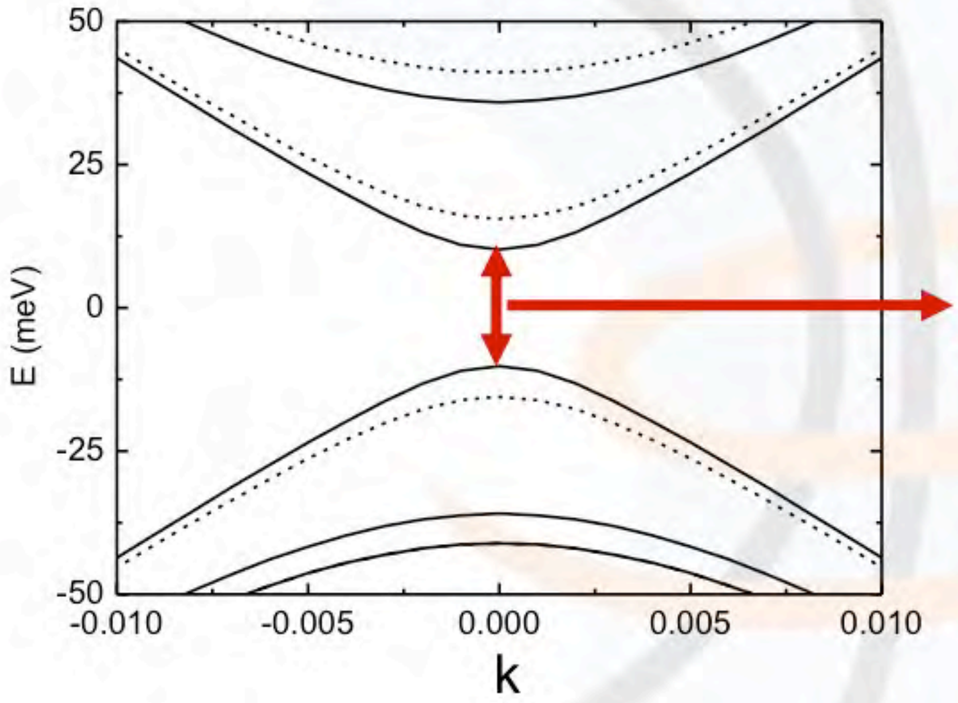


Magneto-resistance for several V_g.

Electronic Confinement

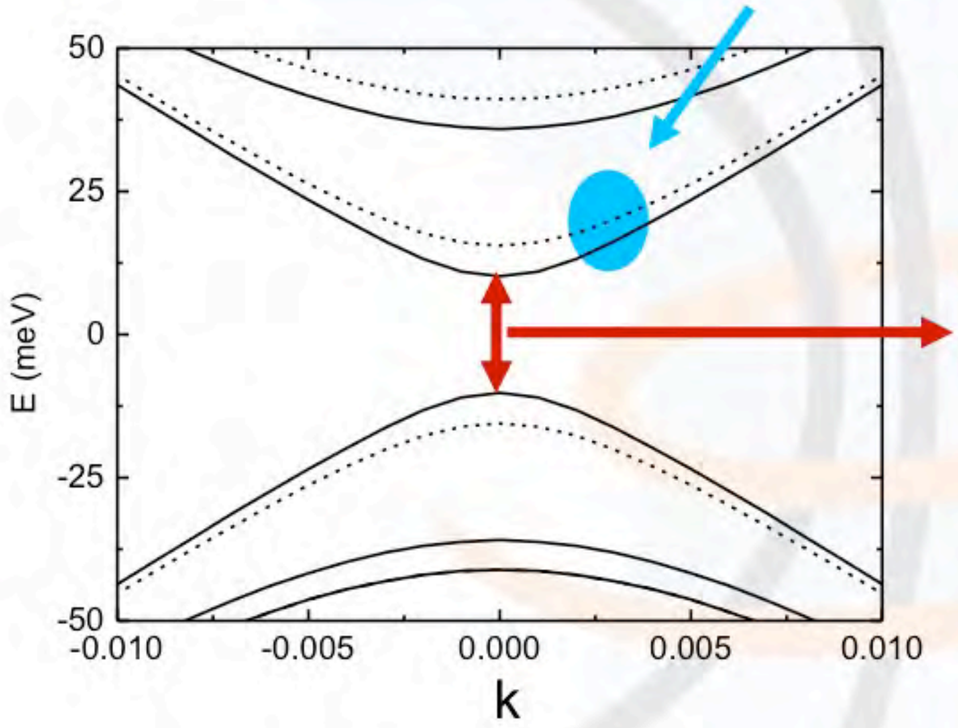


Energy gap

Band structure for a armchair GNR of 70 nm at 0 T.

Electronic Confinement

Degeneracy lifting due to edge configuration



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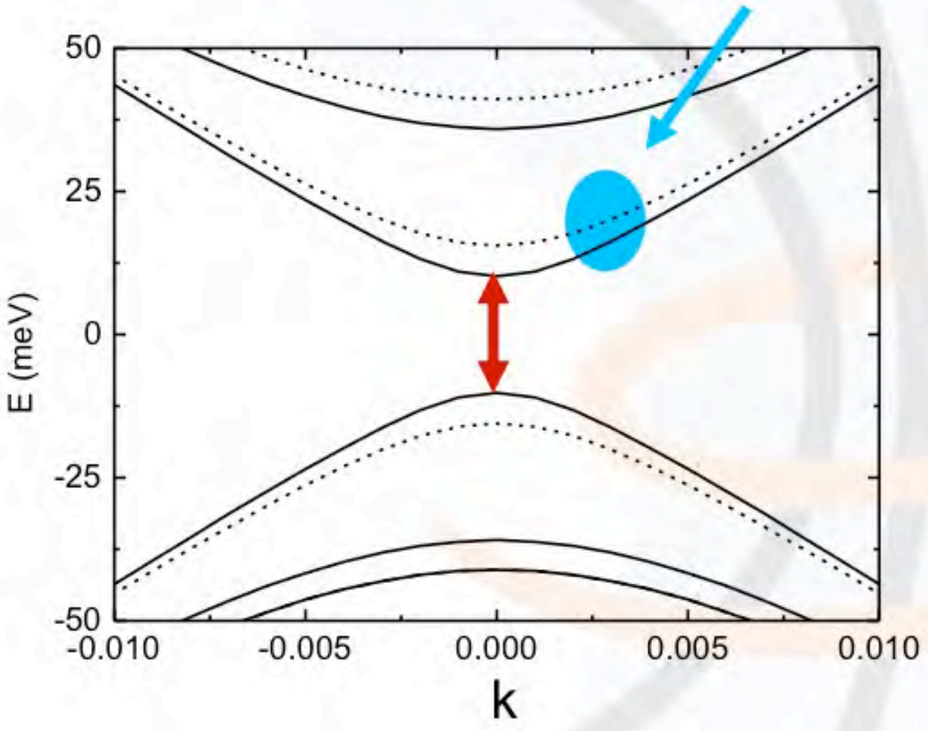
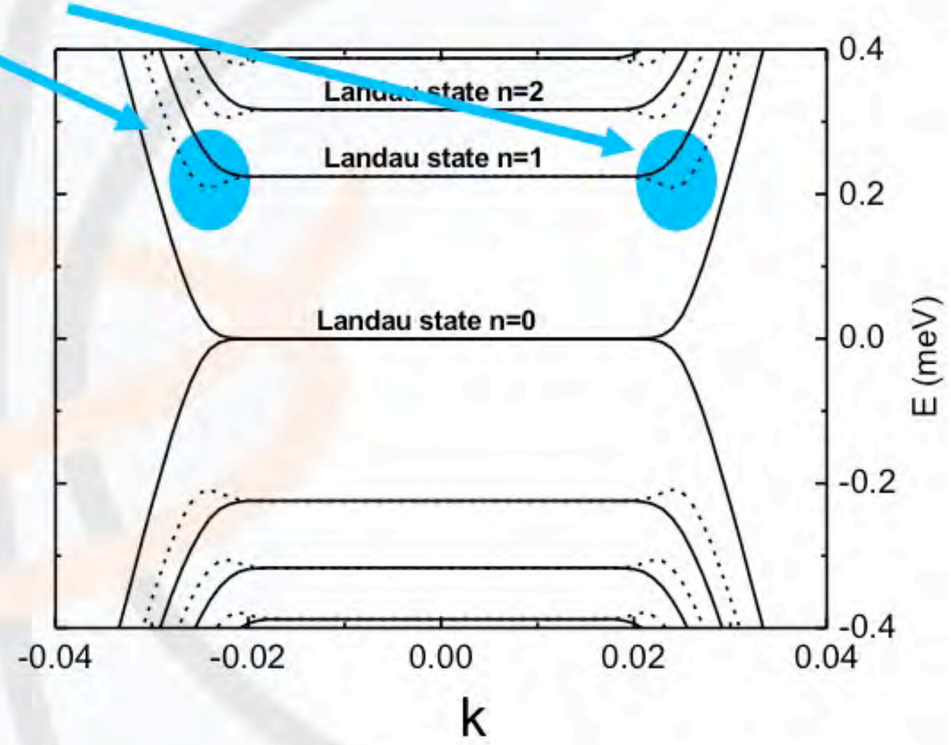


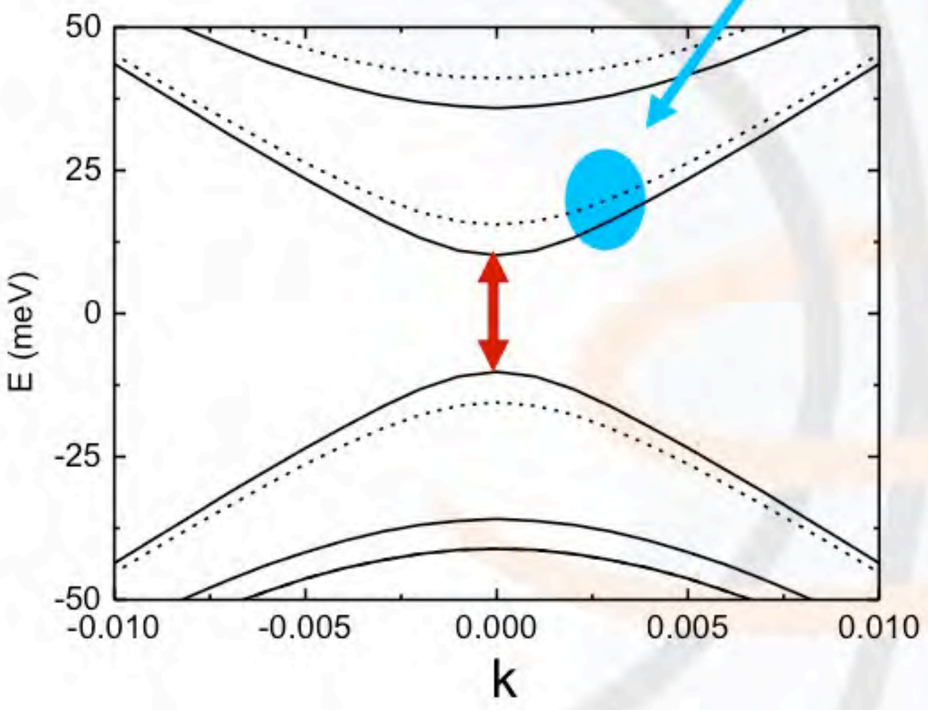
Band structure for a armchair GNR of 70 nm at 0 T.



Band structure for a armchair GNR of 70 nm at 50 T.

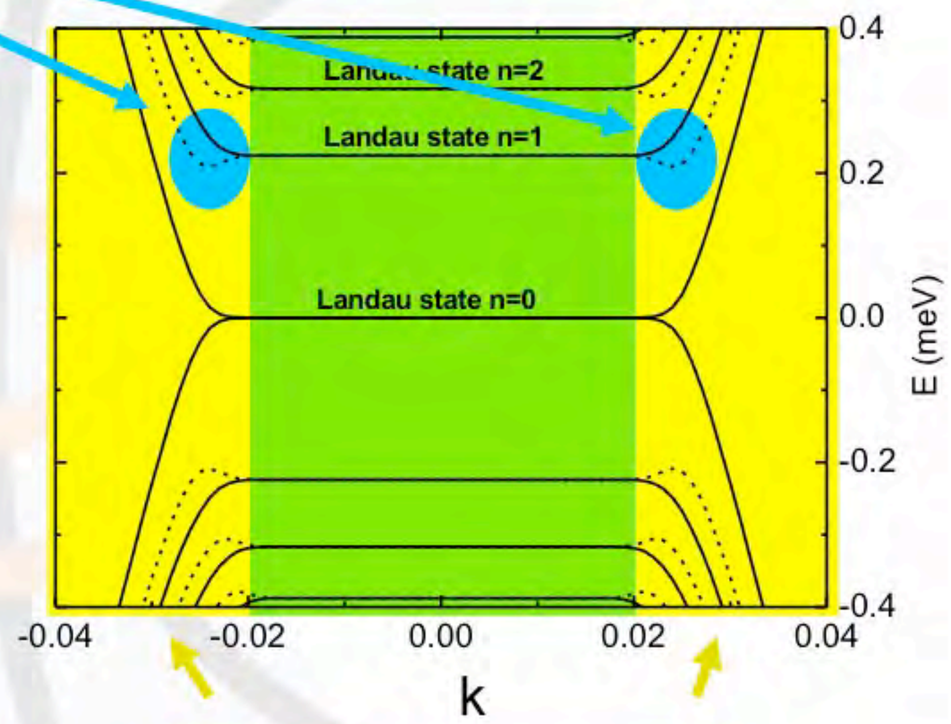
Electronic Confinement

Degeneracy lifting due to edge configuration



Band structure for a armchair GNR of 70 nm at 0 T.

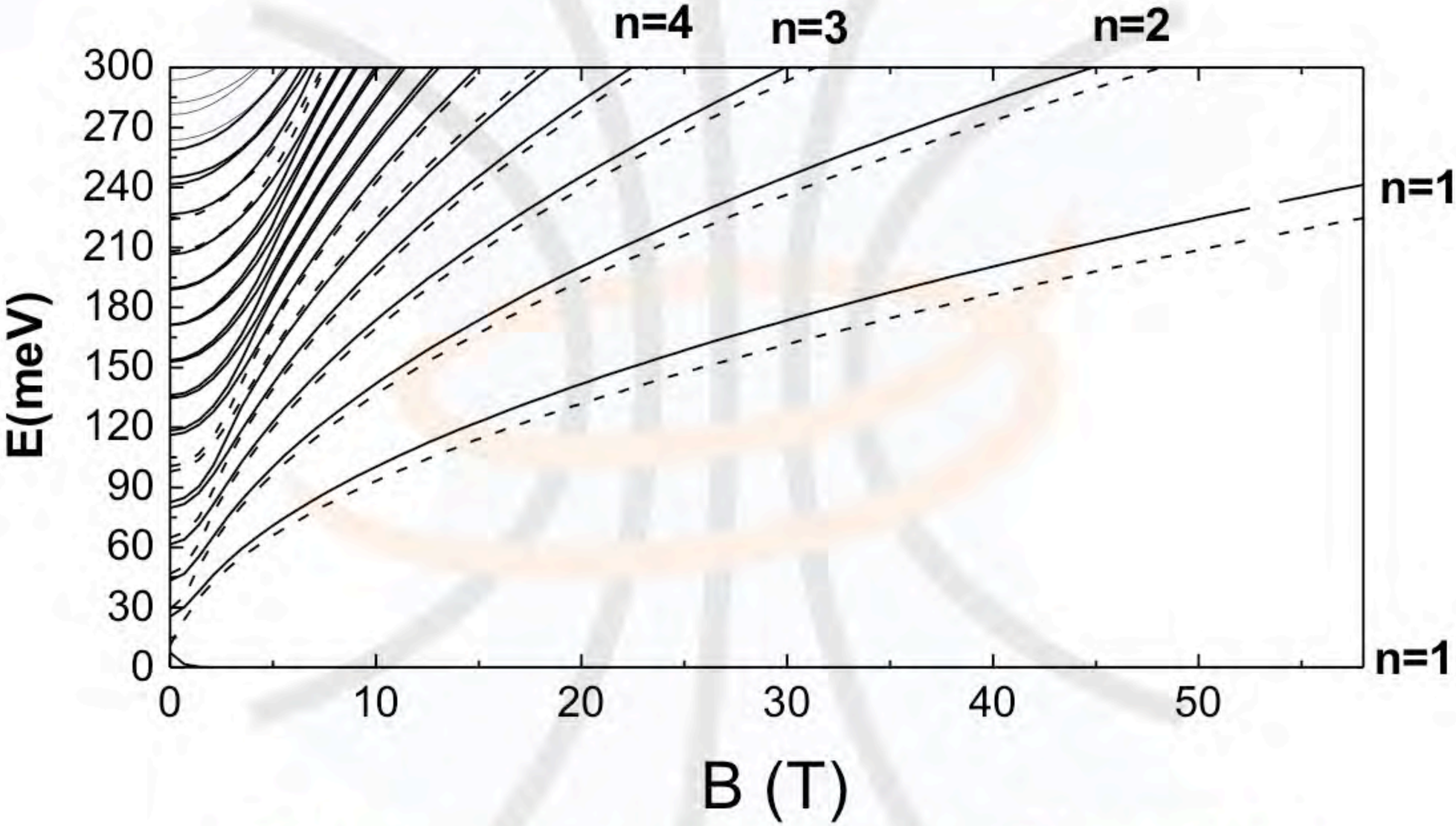
Bulk region



Edge region

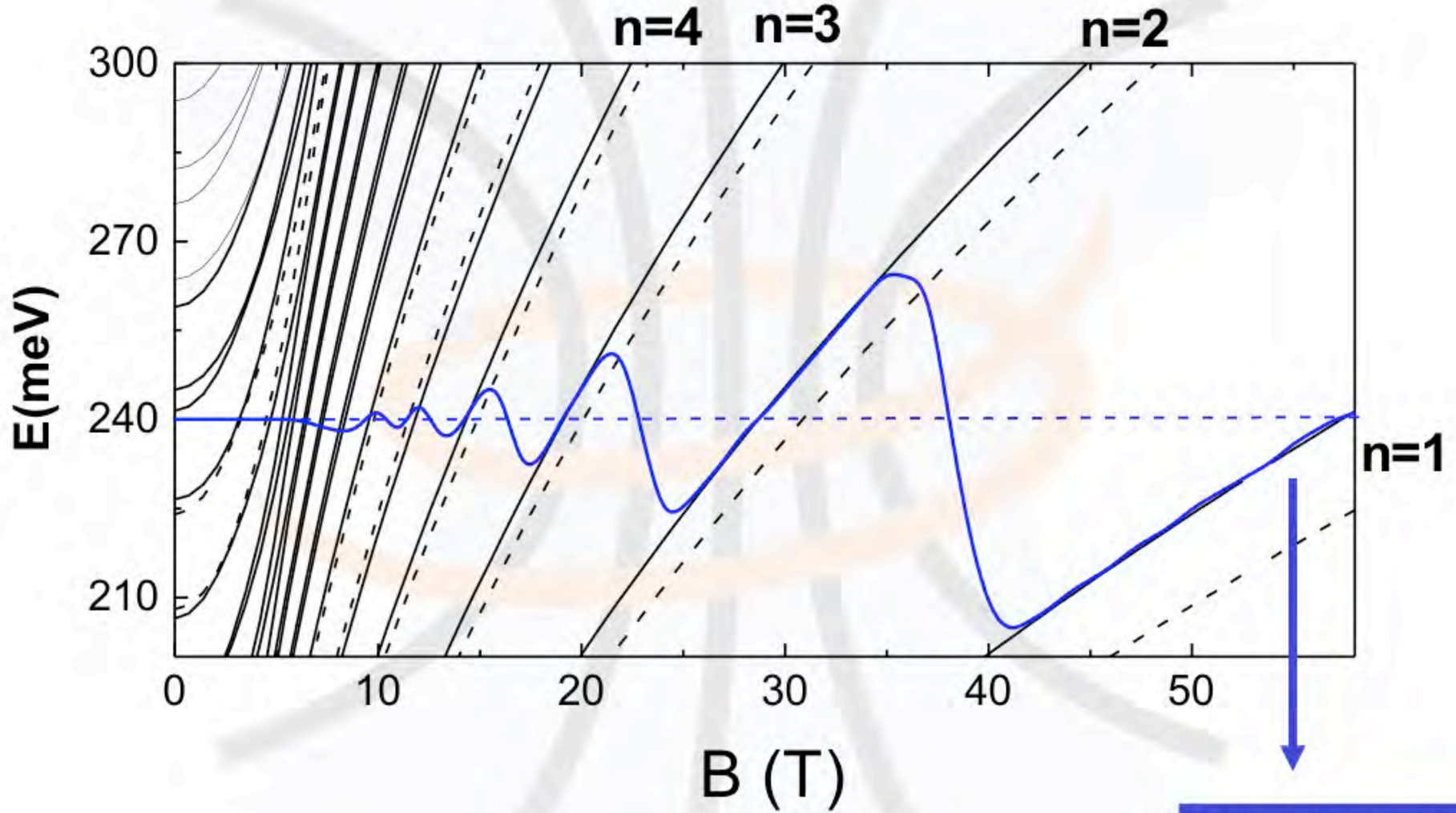
Band structure for a armchair GNR of 70 nm at 50 T.

Electronic Confinement



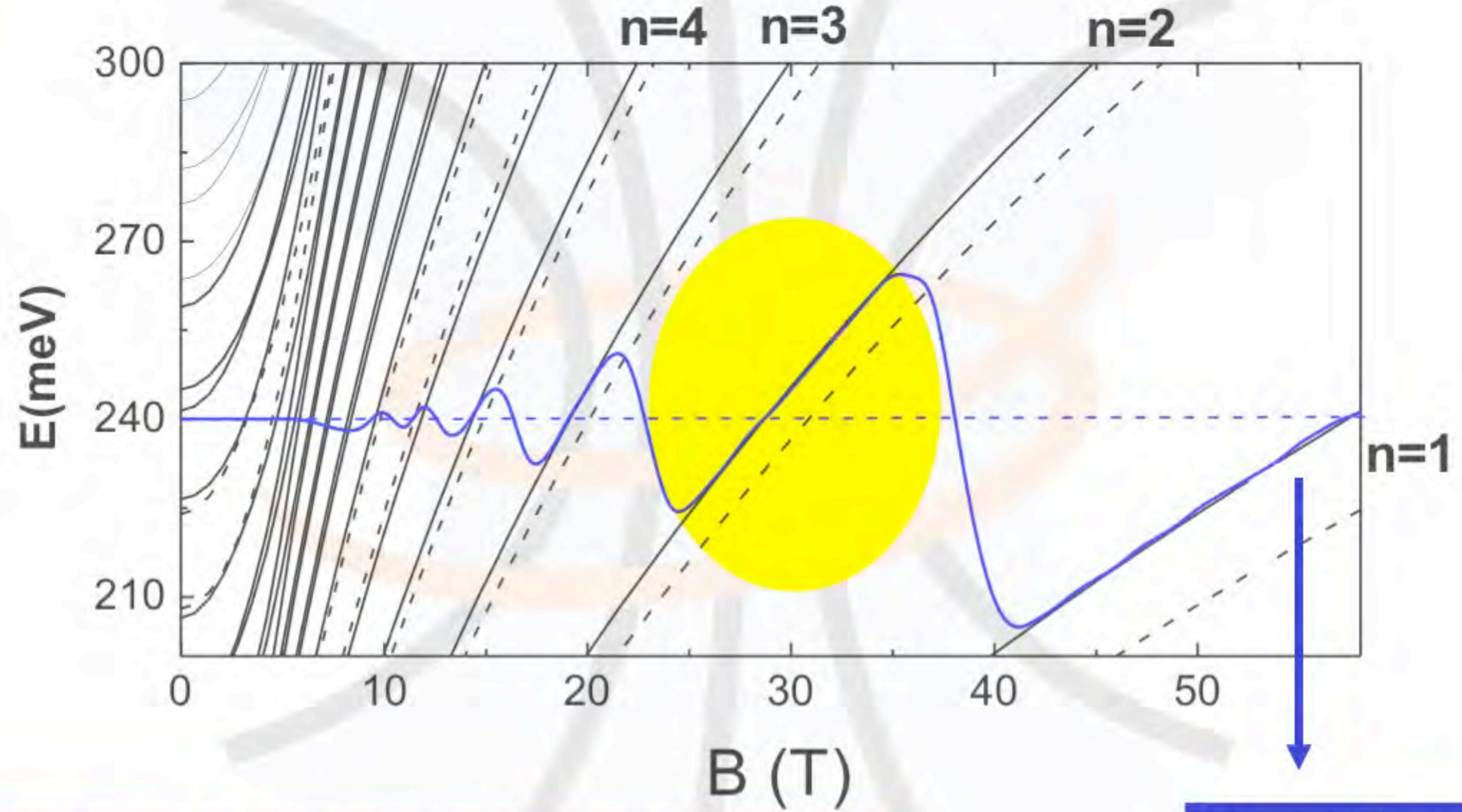
Evolution of the band structure for a 70 nm width aGNR as a function of the magnetic field

Electronic Confinement



Numerical simulation of the charge density as a function of magnetic field

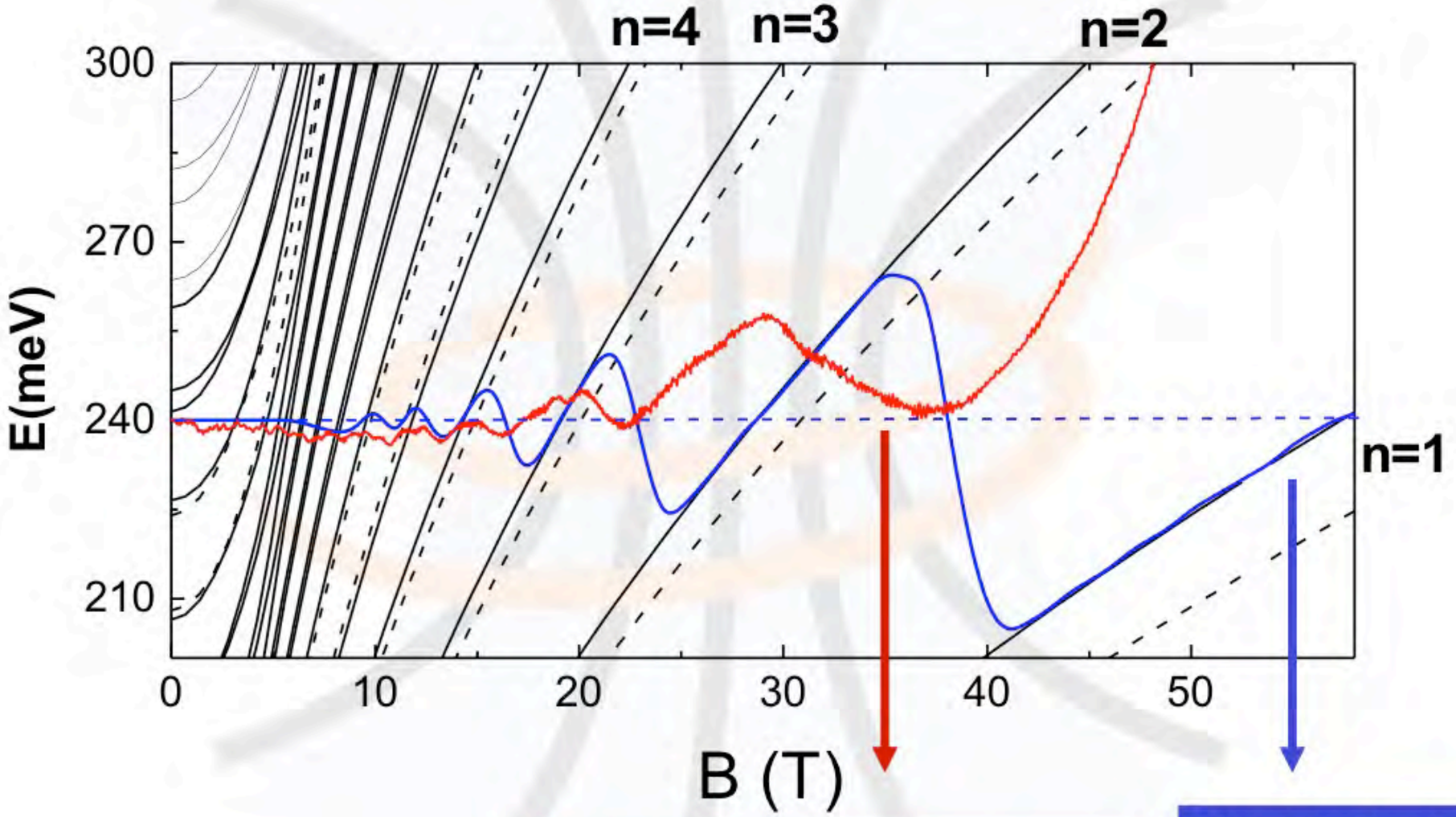
Electronic Confinement



The pinning of the Fermi energy becomes more important for low Landau level index

Numerical simulation of the charge density as a function of magnetic field

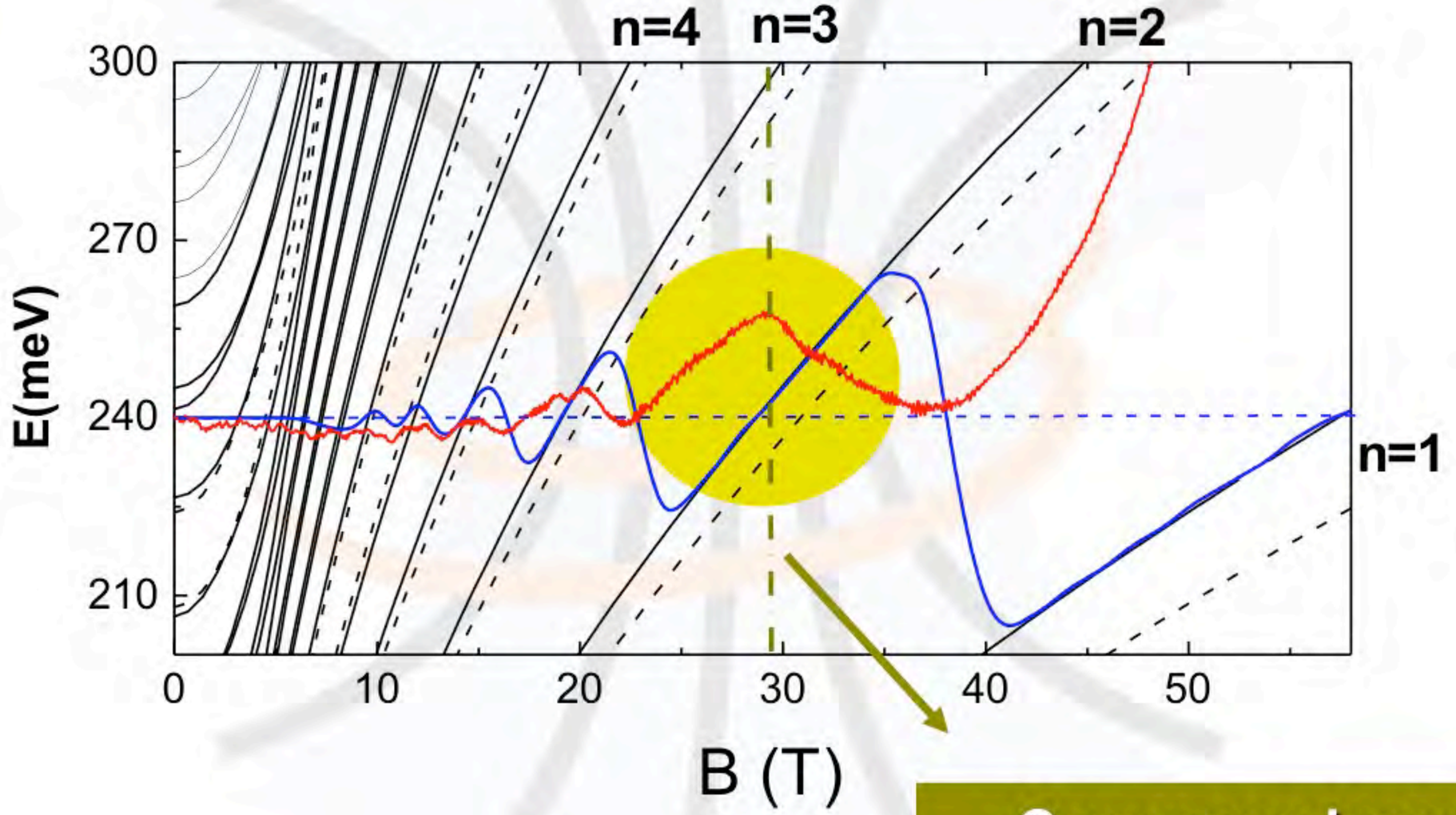
Electronic Confinement



Magneto-resistance measurement for V_g=40 V (E_F≈240 meV)

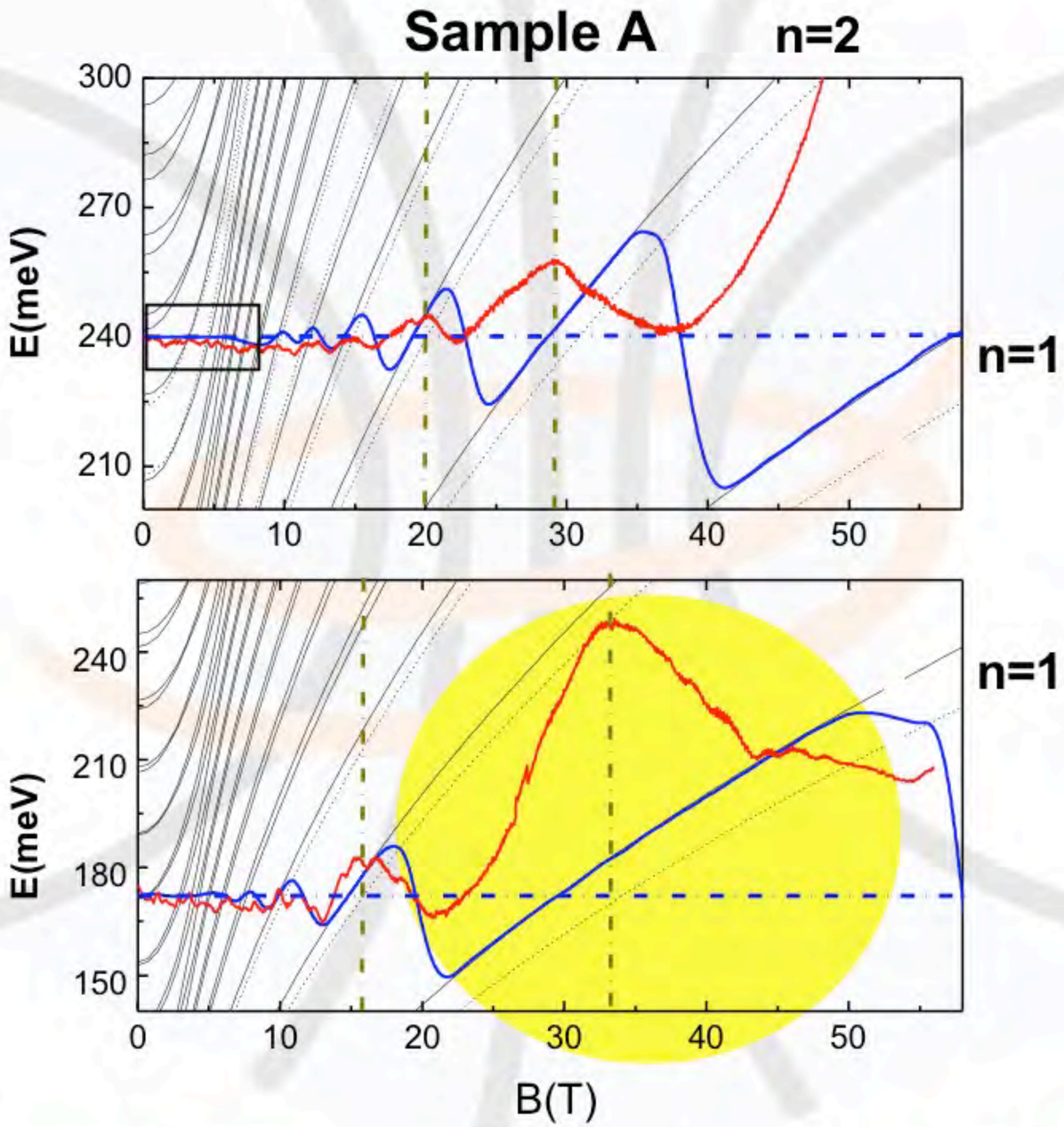
Numerical simulation of the charge density as a function of magnetic field

Electronic Confinement



Correspondence of the resistance broadening with the Fermi energy pinning

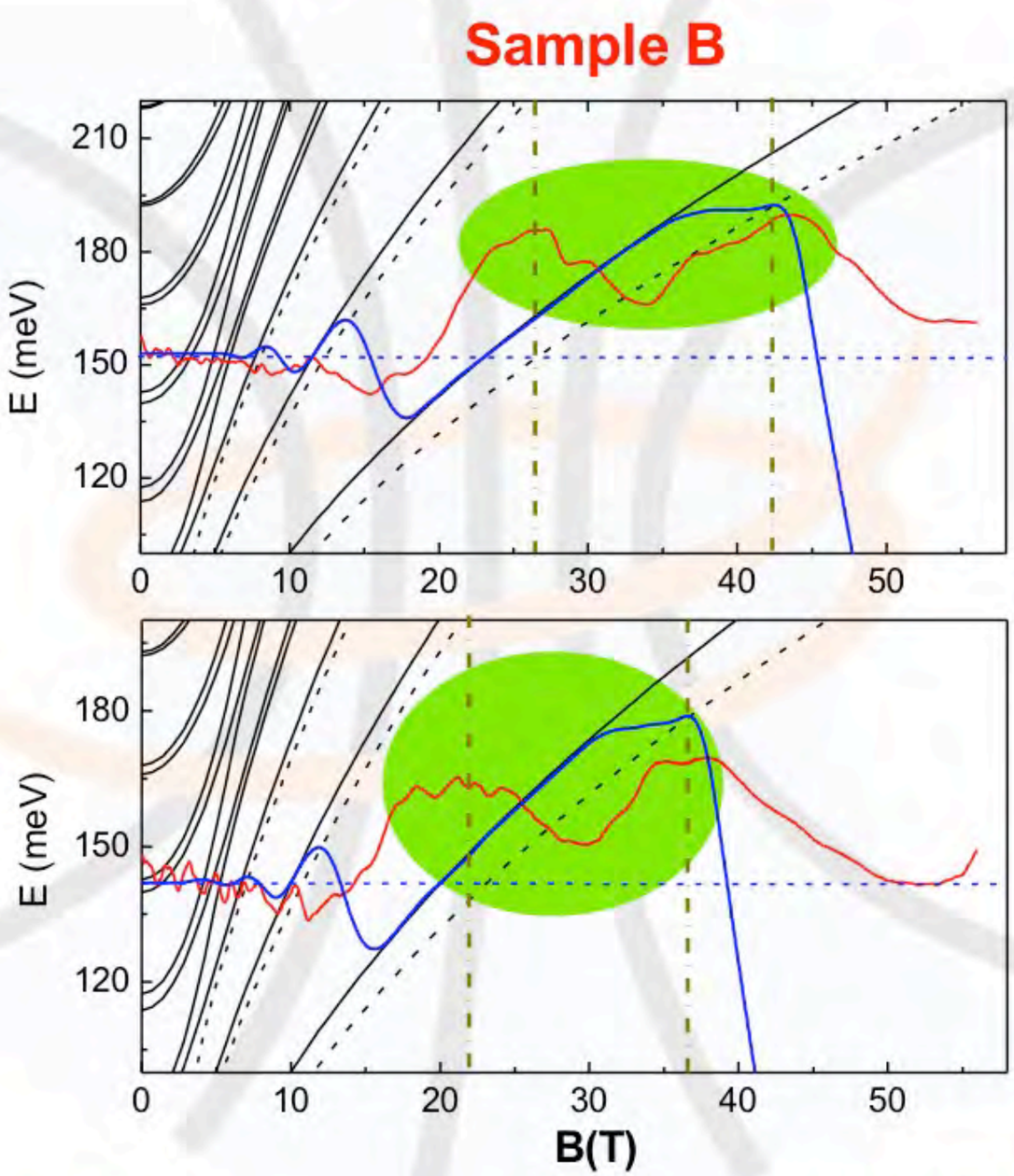
Electronic Confinement



Broadening on the resistance maximum consistent with the pinning of the Fermi energy larger for low energies

Band structure evolution in magnetic field for a aGNR of 100 nm and a direct comparation with MR measurements (red) for Vg= -40 V (up) and -30 V (down)

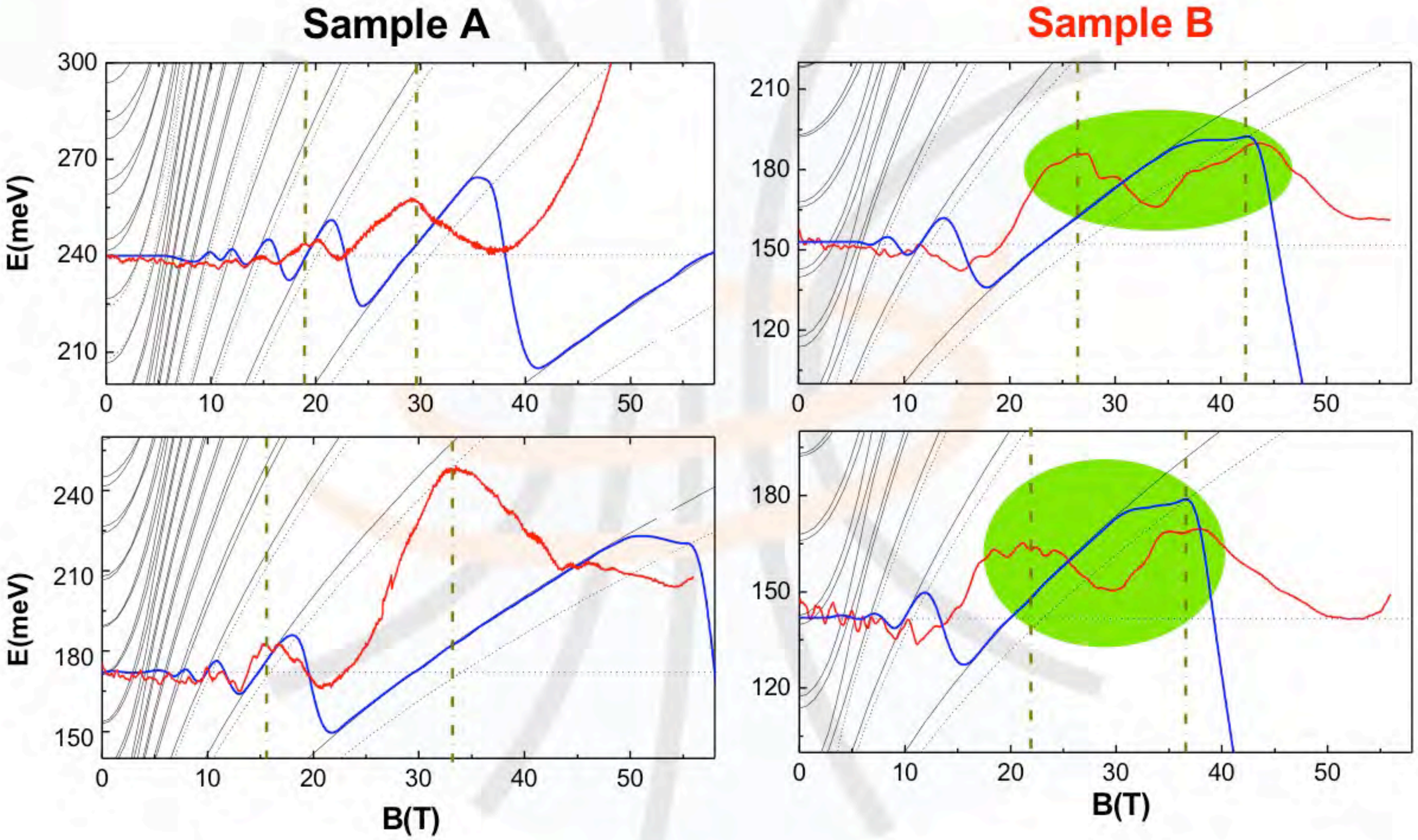
Electronic Confinement



Double peak due to the degeneracy lifting and to the pinning of the Fermi energy in the second 1-D subband

Band structure evolution in magnetic field for a aGNR of 70 nm and a direct comparation with MR measurements (red) for Vg= -13 V (up) and -12 V (down)

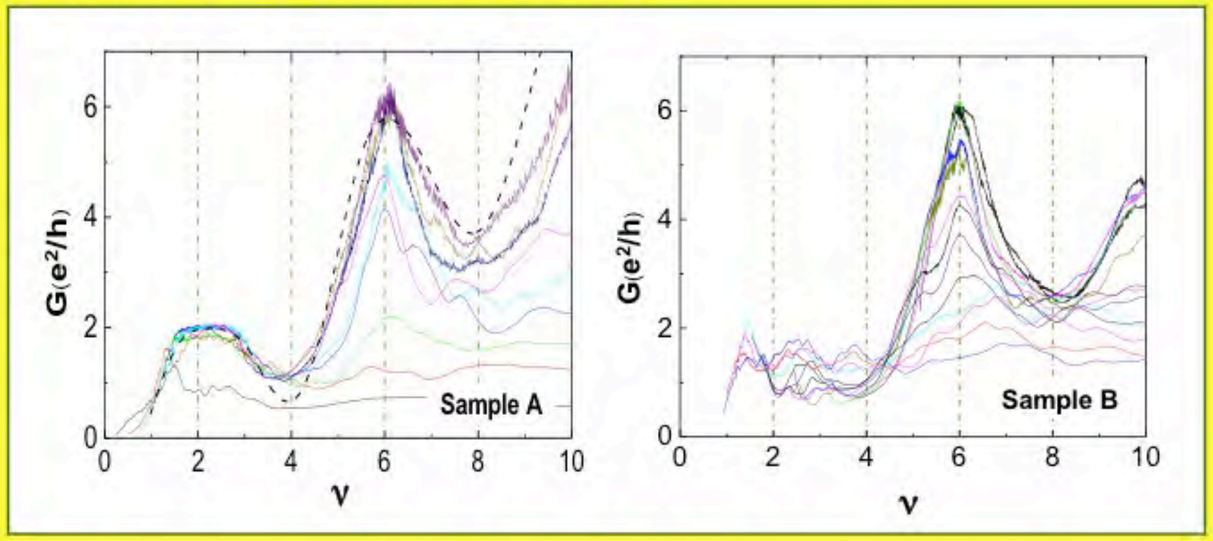
Electronic Confinement



Band structure evolution in magnetic field for several energies

Conclusions

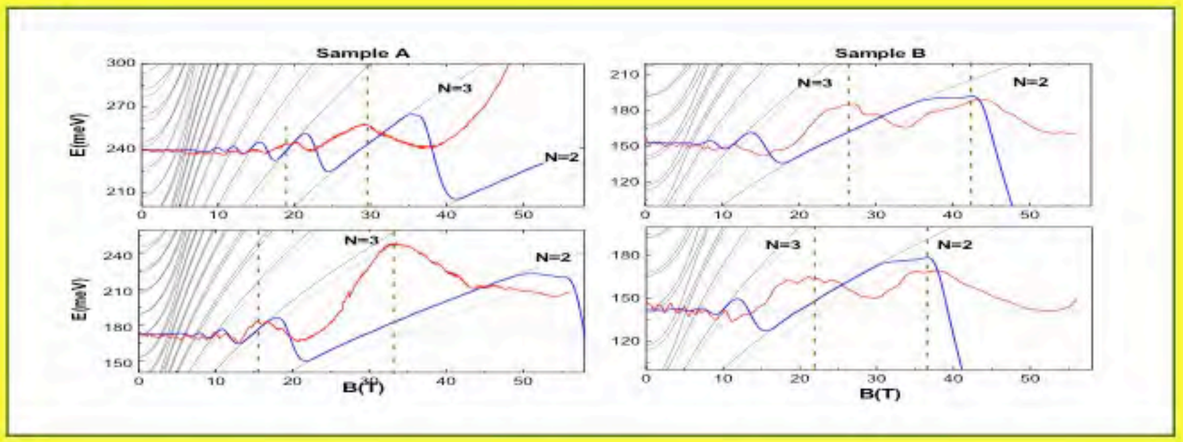
- First experimental observation of Landau quantization in GNR.



Conclusions

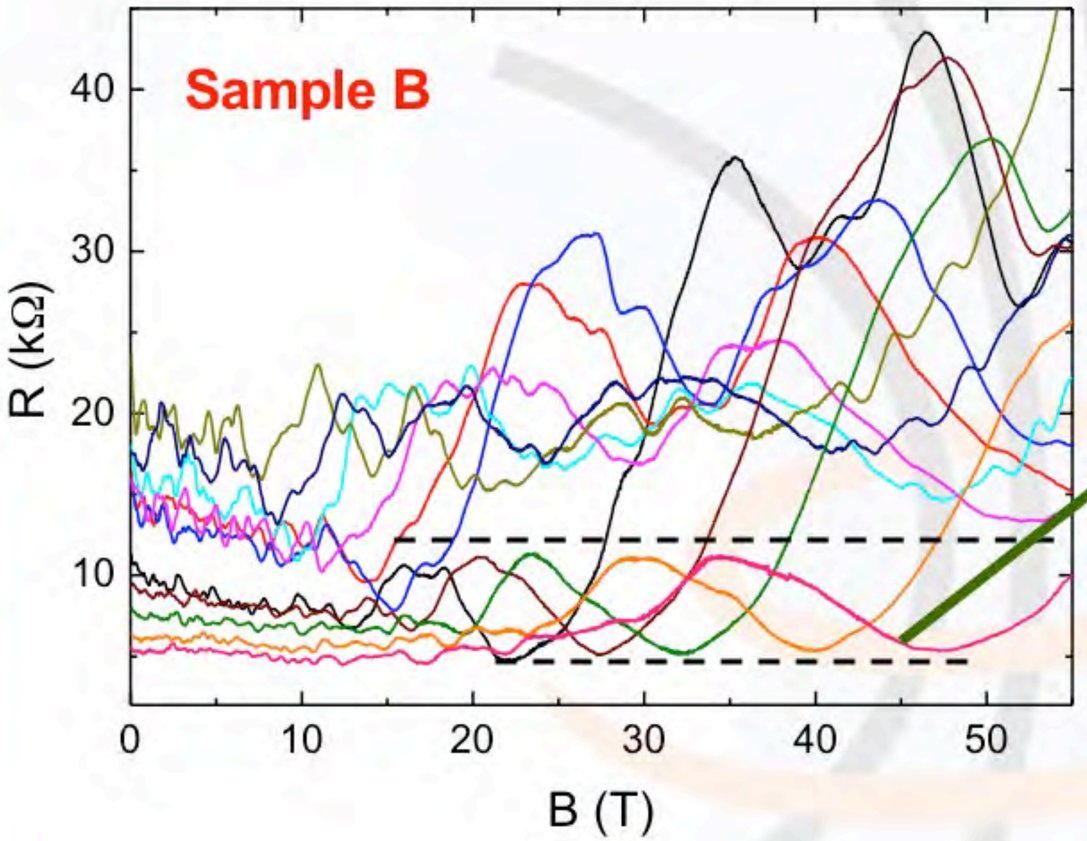
- First experimental observation of Landau quantization in GNR.

- Observation of the orbital degeneracy lifting due to confinement in armchair structure.



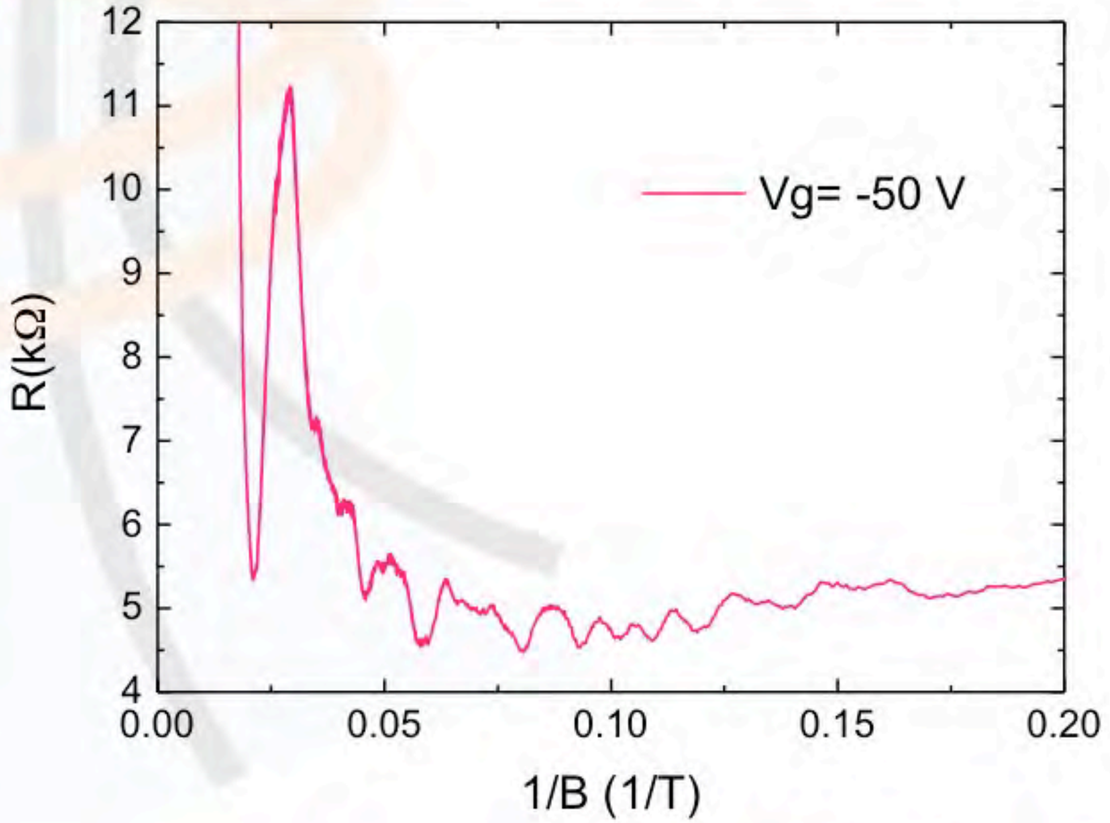
Thanks for your attention!

Electronic Transport



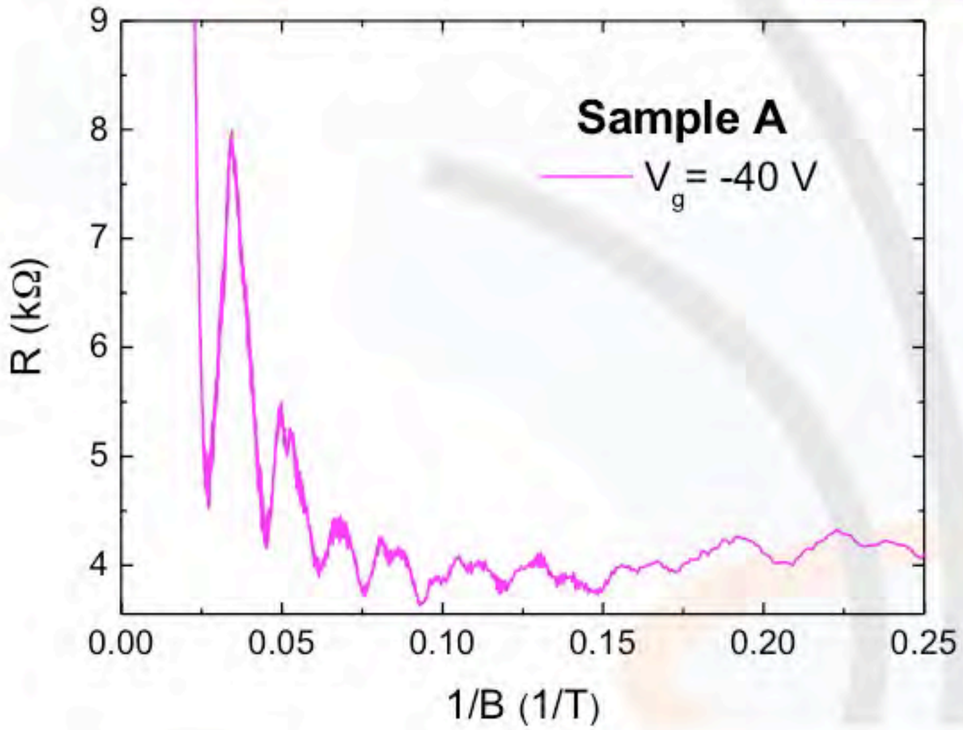
Magneto-resistance measurements for different V_g at 4 K. From left (-5 V) to right (-40 V) in steps of 5V.

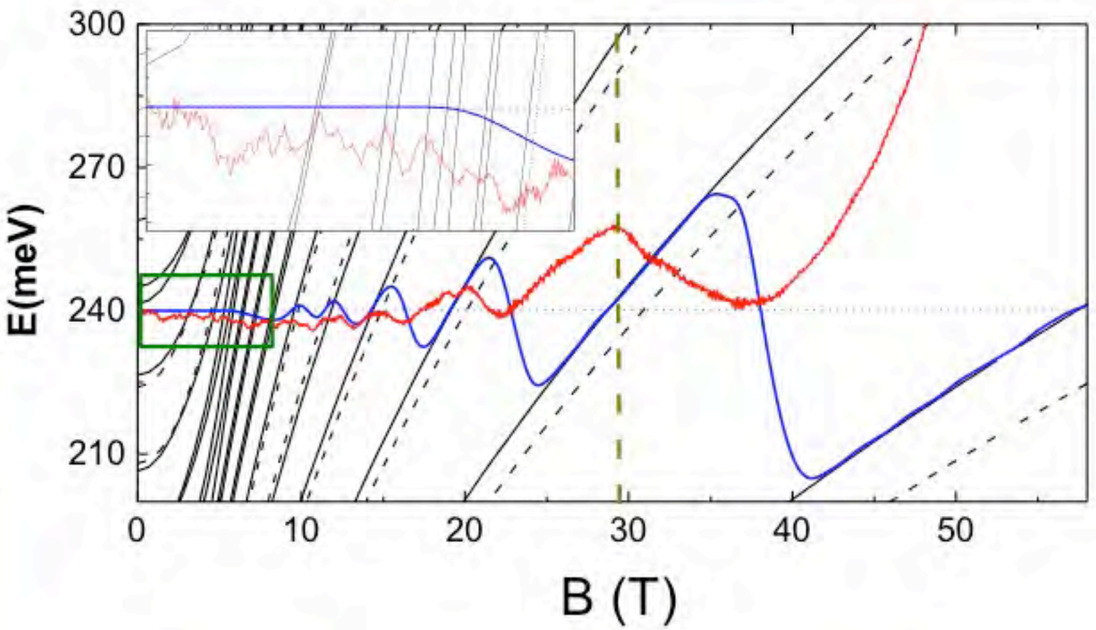
Anomalous Shubnikov-deHaas oscillations



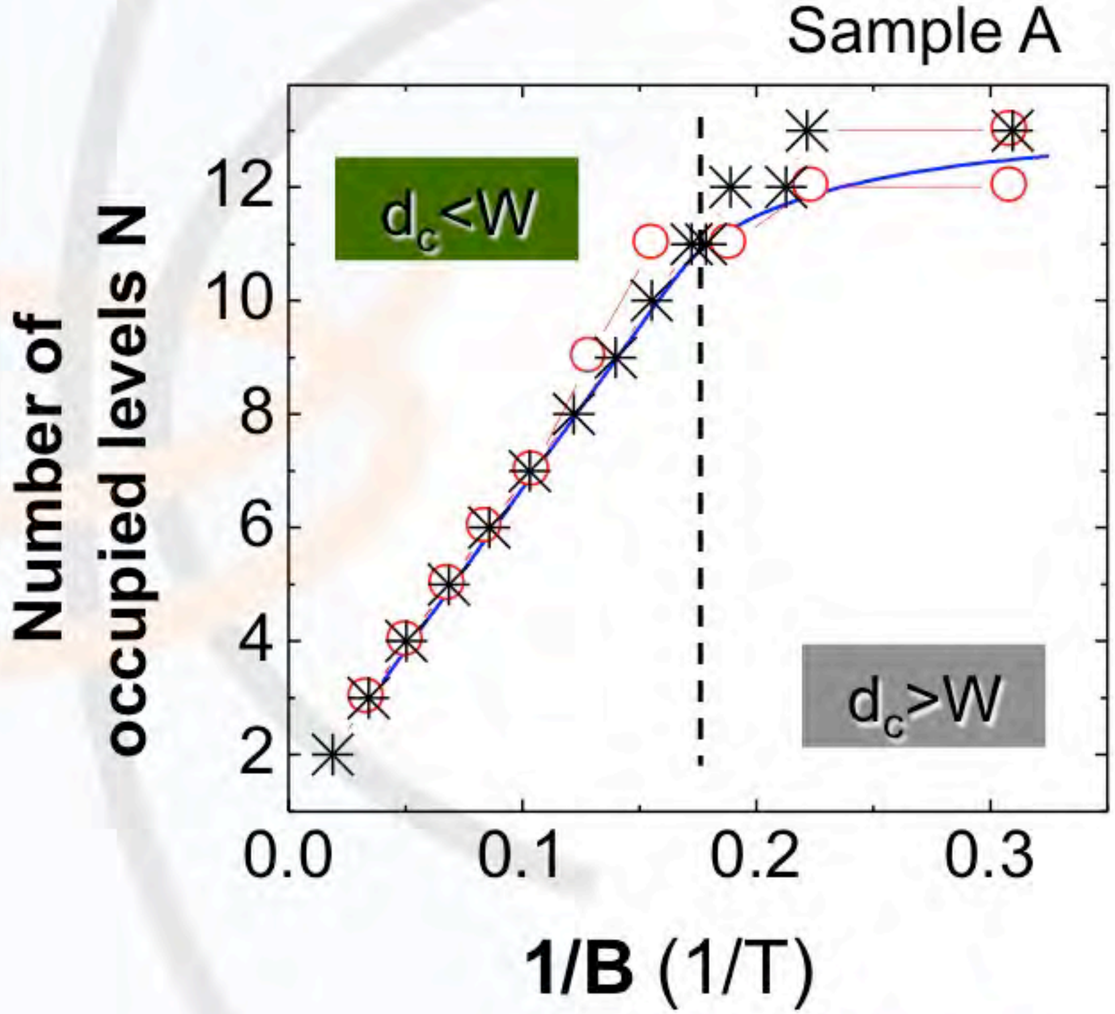
Shubnikov-deHaas oscillations

Electronic Confinament



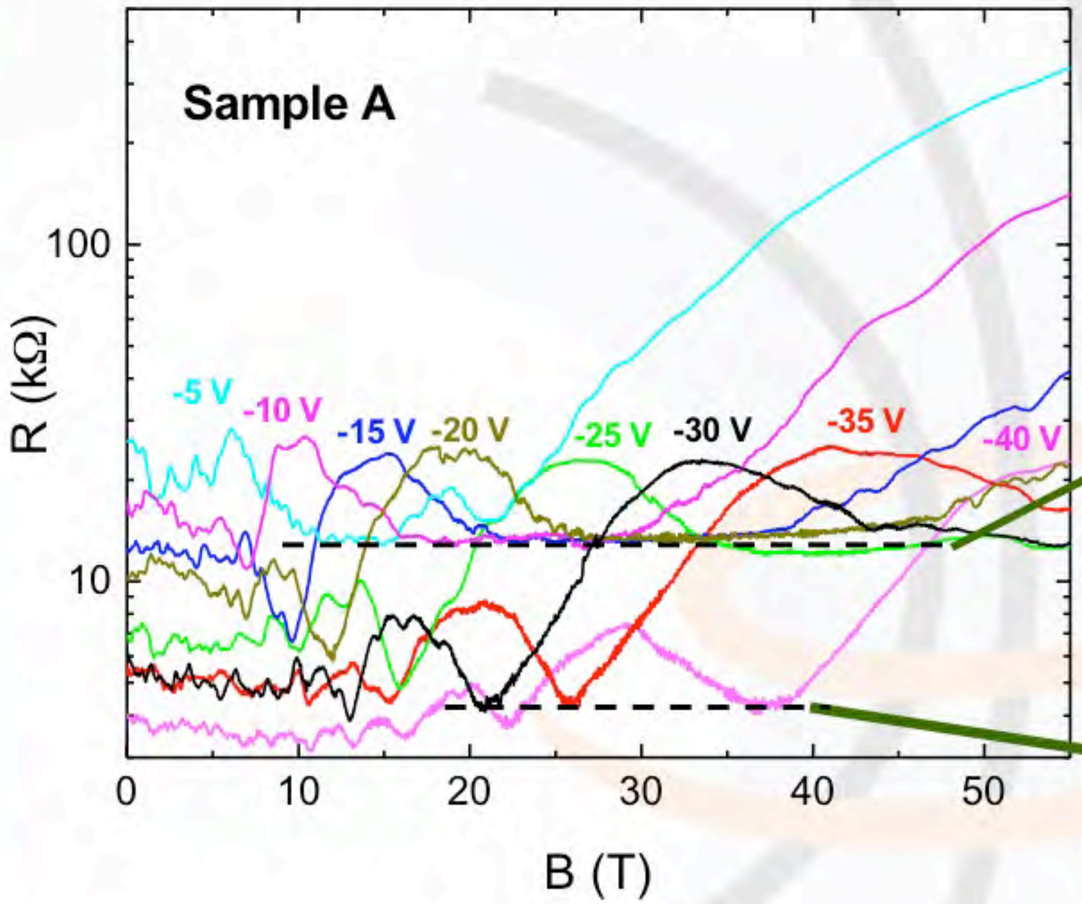


Shubnikov-deHaas oscillations



Shubnikov-deHaas oscillations

High Magnetic Field



Magneto-resistance measurements for different V_g at 4 K.

Quantization plateau at $h/2e^2$

Quantization minimum at $h/6e^2$