Integer Quantum Hall Effect in trilayer graphene

W. Escoffier, A. Kumar, J.M. Poumirol, C. Faugeras, D. Arovas, M. Fogler, F. Guinea, S. Roche, M. Goiran and B. Raquet

graphene 2011

LNCMI

Université de Toulouse

UCSD

ICMM

UAB Universitat Autònoma de Barcelona

AGENCE NATIONALE DE LA RECHERCHE ANR

cnrs advancing the frontiers

OUTLINE…

1980 Conventional Integer Quantum Hall Effect in 2D semiconductor heterojunctions

2005 Anomalous Integer Quantum Hall Effect in 2D graphene monolayer

K.Novoselov et. al. Nature 438, 197 (2005) ; Y. Zhang et. al., Nature 438, 201 (2005)

2006 Another form of Integer Quantum Hall Effect in 2D graphene bilayer

K.Novoselov et. al. Nature Physics 2, 177 (2006)

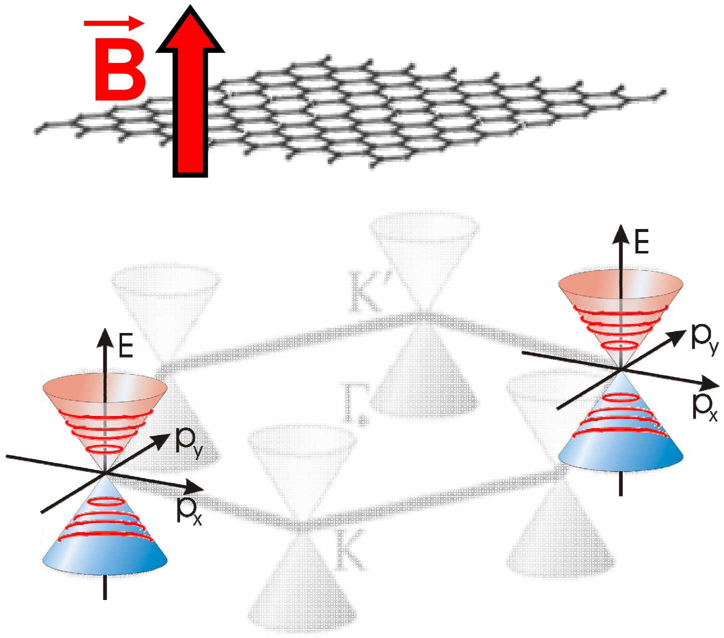
2011 Again another form of Integer Quantum Hall Effect in (2D ?) graphene trilayer

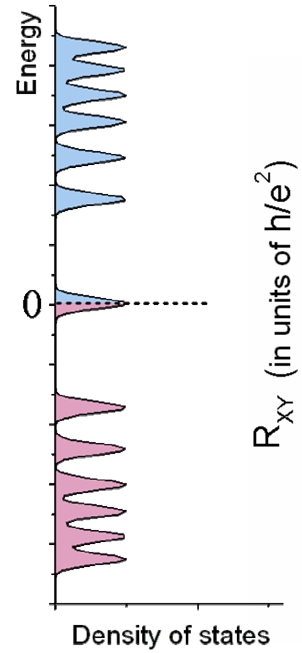
Expected …!

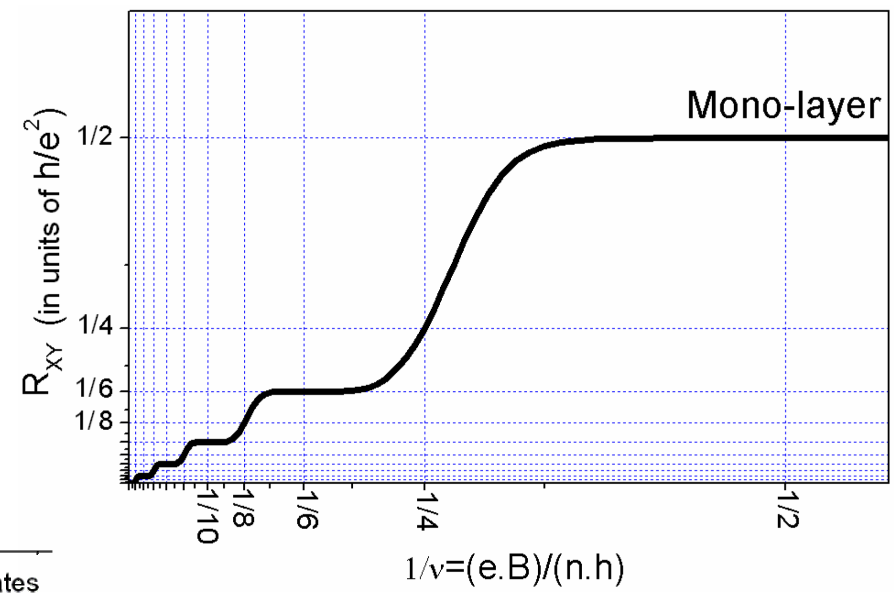
Several issues :

- Mobility of SiO_2 - supported graphene trilayer is low (<2000 cm^2 / V.s)
- The QHE is predicted to depend on the (unknown) stacking order

IQHE in graphene monolayer…

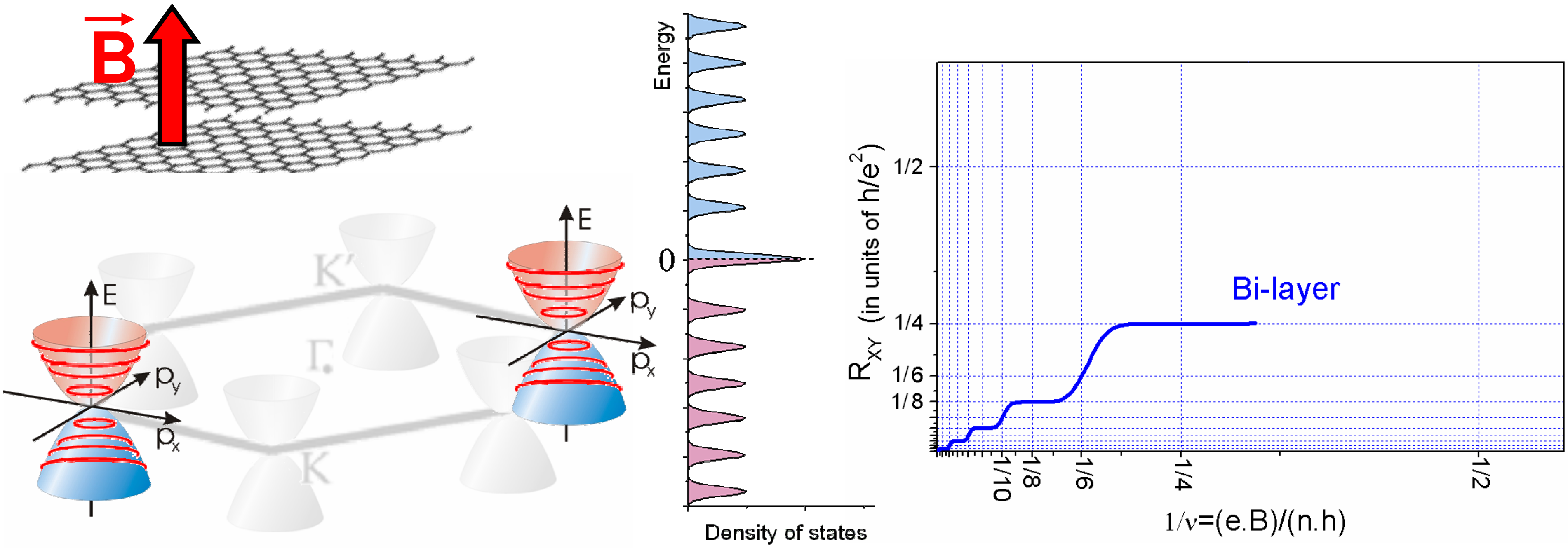






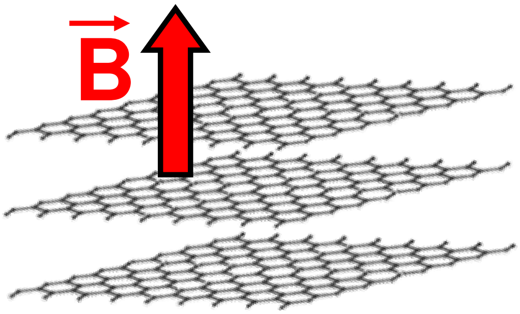
- The n=0 Landau level is 4-fold degenerate and equally shared by electrons and holes
- Other Landau levels are 4-fold degenerate
- Hall resistance plateaus at $\nu = 4.n + 2$

IQHE in graphene bilayer…

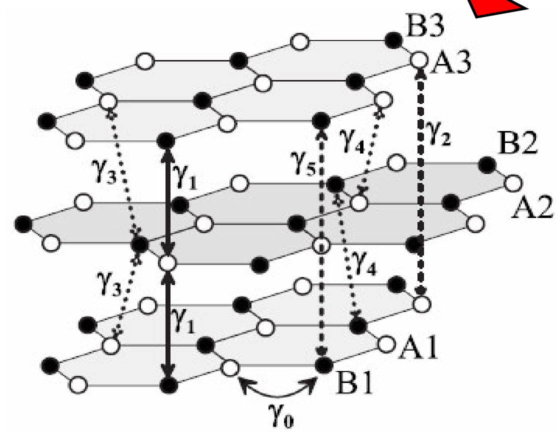


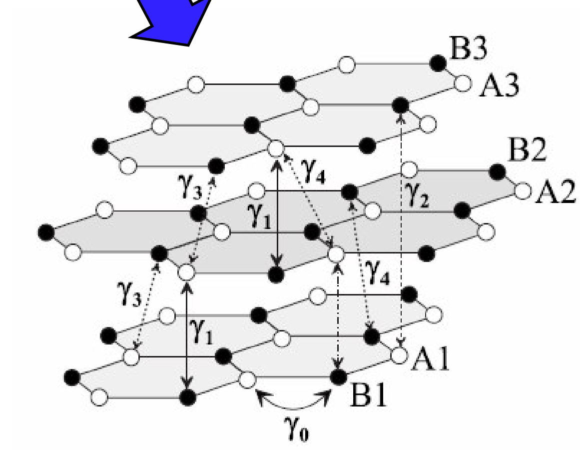
- The n=0 Landau level is 4-fold degenerate and equally shared by electrons and holes
- Other Landau levels are 4-fold degenerate
- Hall resistance plateaus at $\nu = 4.n + 4$

IQHE in graphene trilayer…



Stacking of the graphene layers can be
Bernal (ABA) or rhombohedral (ABC)

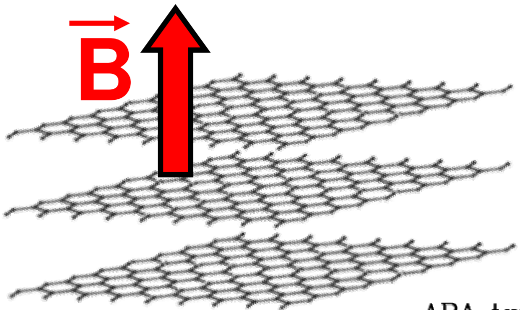




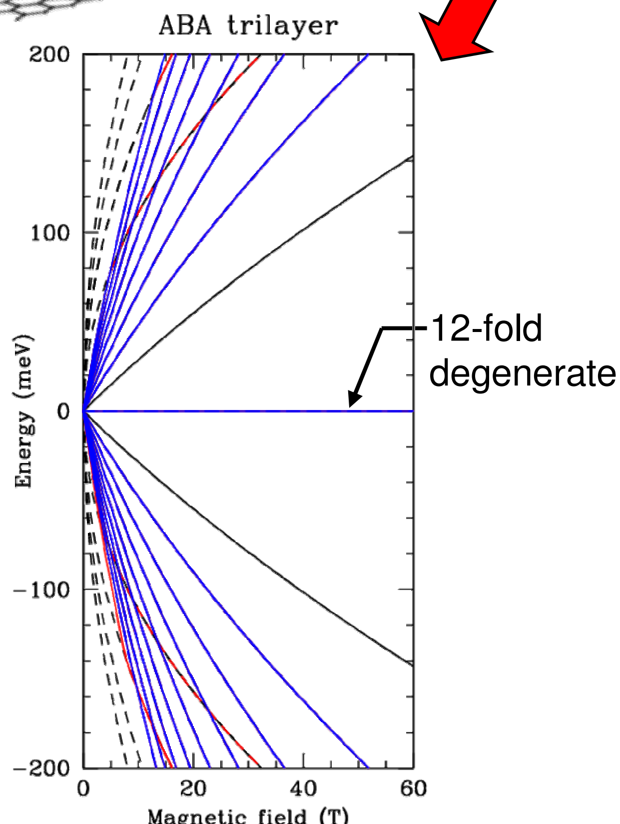
Slonczewski-Weiss-McClure parametrization of tight-bonding couplings :

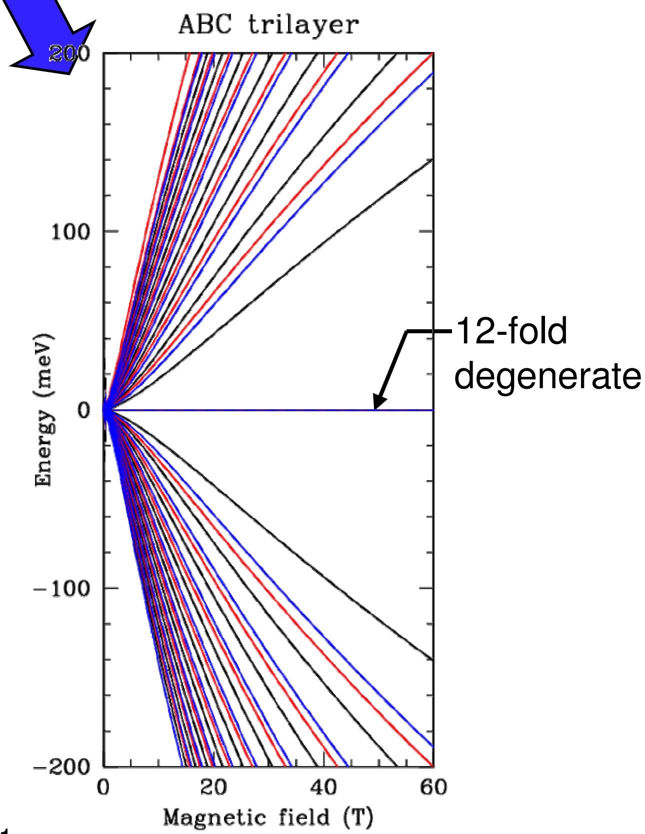
γ_0 and γ_1 : strong nearest-neighbor coupling
~~γ_3~~ and ~~γ_4~~ : weak nearest-layer coupling
~~γ_2~~ and ~~γ_5~~ : weak next-layer coupling
~~δ~~ : on-site energy for each site which has a pair of nearest-neihbors along the c-axis

IQHE in graphene trilayer…

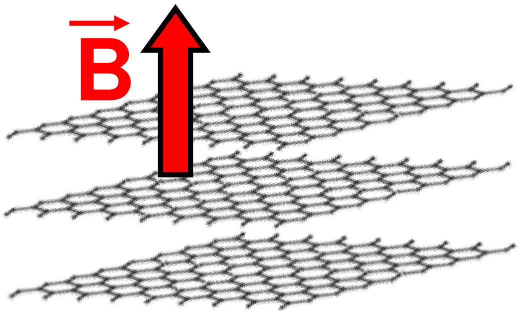


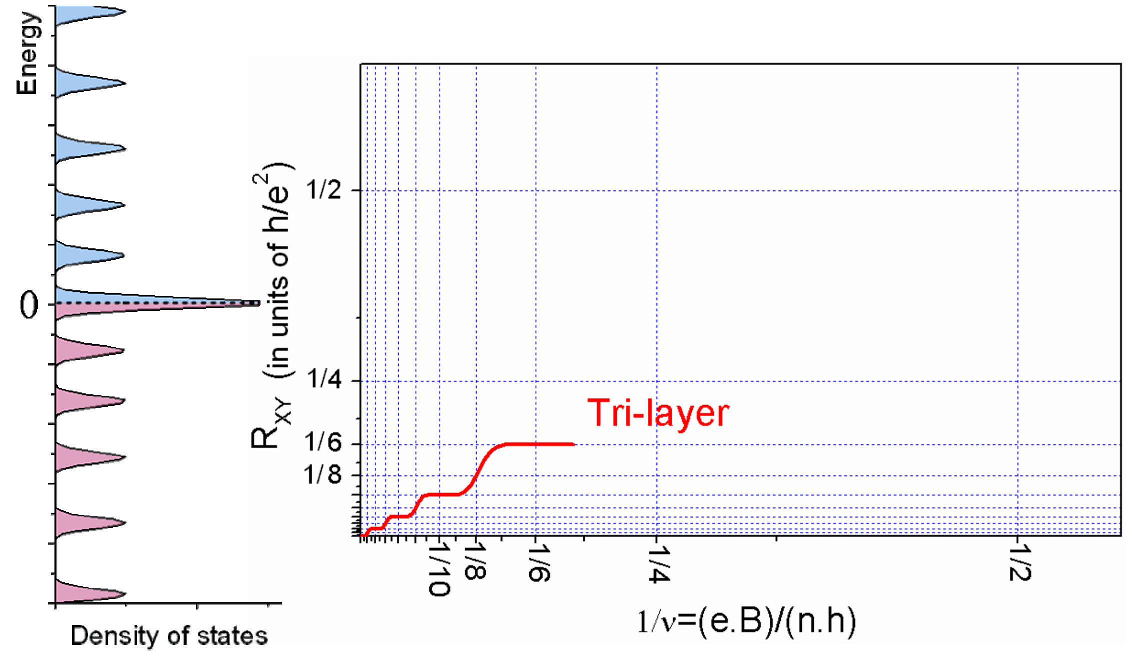
Stacking of the graphene layers can be
Bernal (ABA) or rhombohedral (ABC)





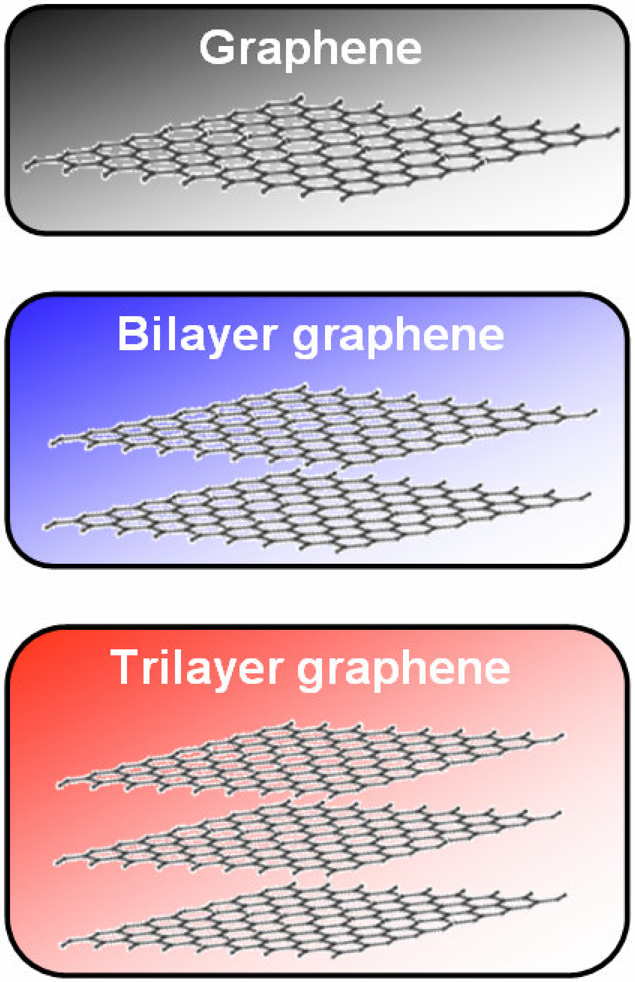
IQHE in graphene trilayer…

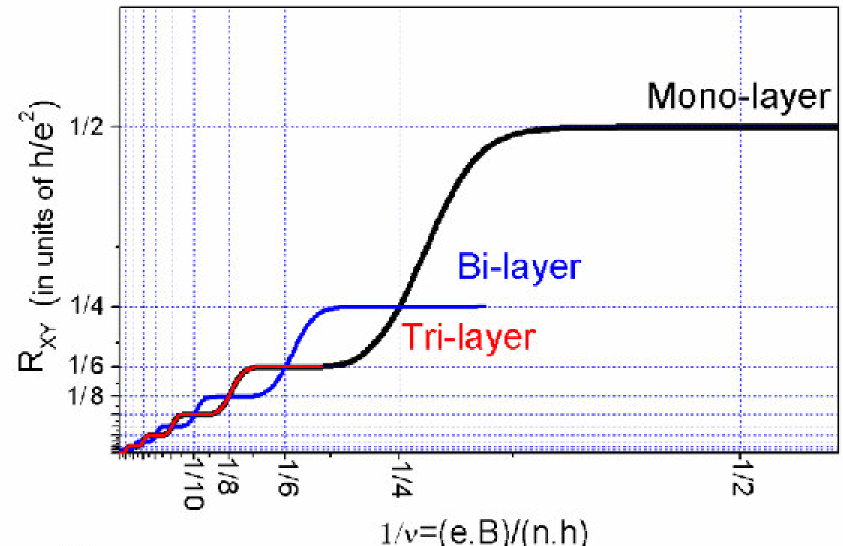


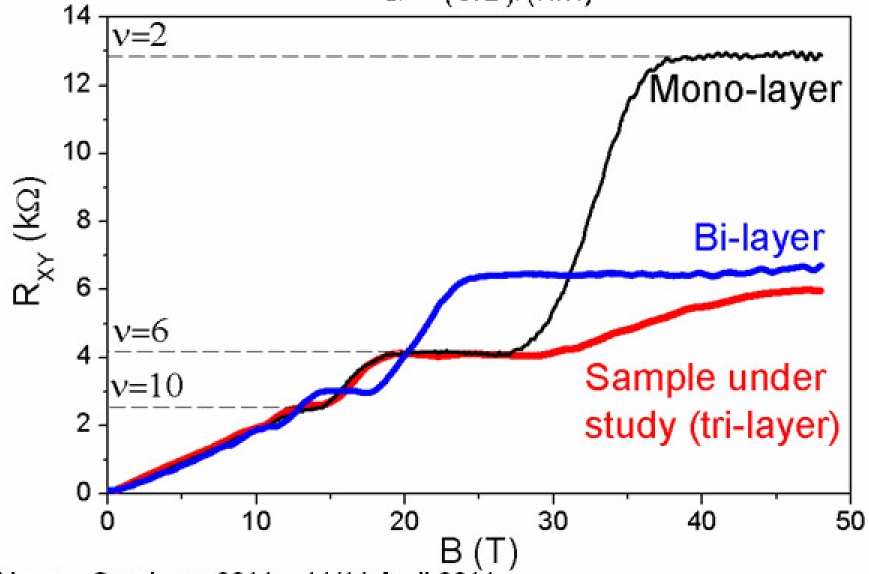


- The n=0 Landau level is 12-fold degenerate and equally shared by electrons and holes
- Other Landau levels are 4-fold degenerate
- Hall resistance plateaus at $\nu = 4.n + 6$

Overview of IQHE in graphene(s)…







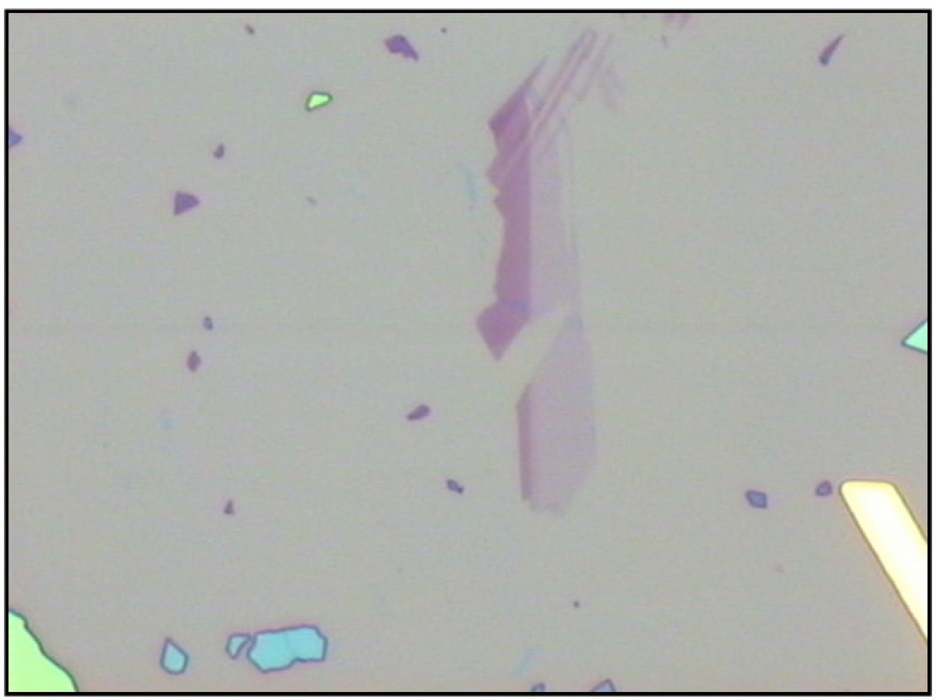
Carrier density $n = 3.4 \times 10^{12}\ cm^{-2}$

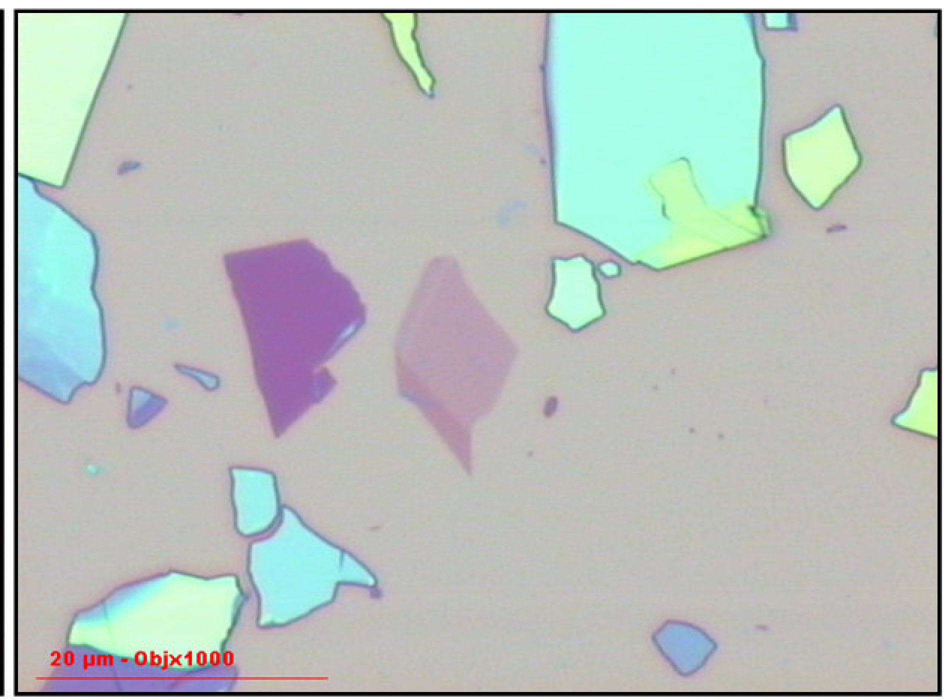
Mobility $\mu = 1500\ cm^2/V.s$

The sample IS a trilayer graphene

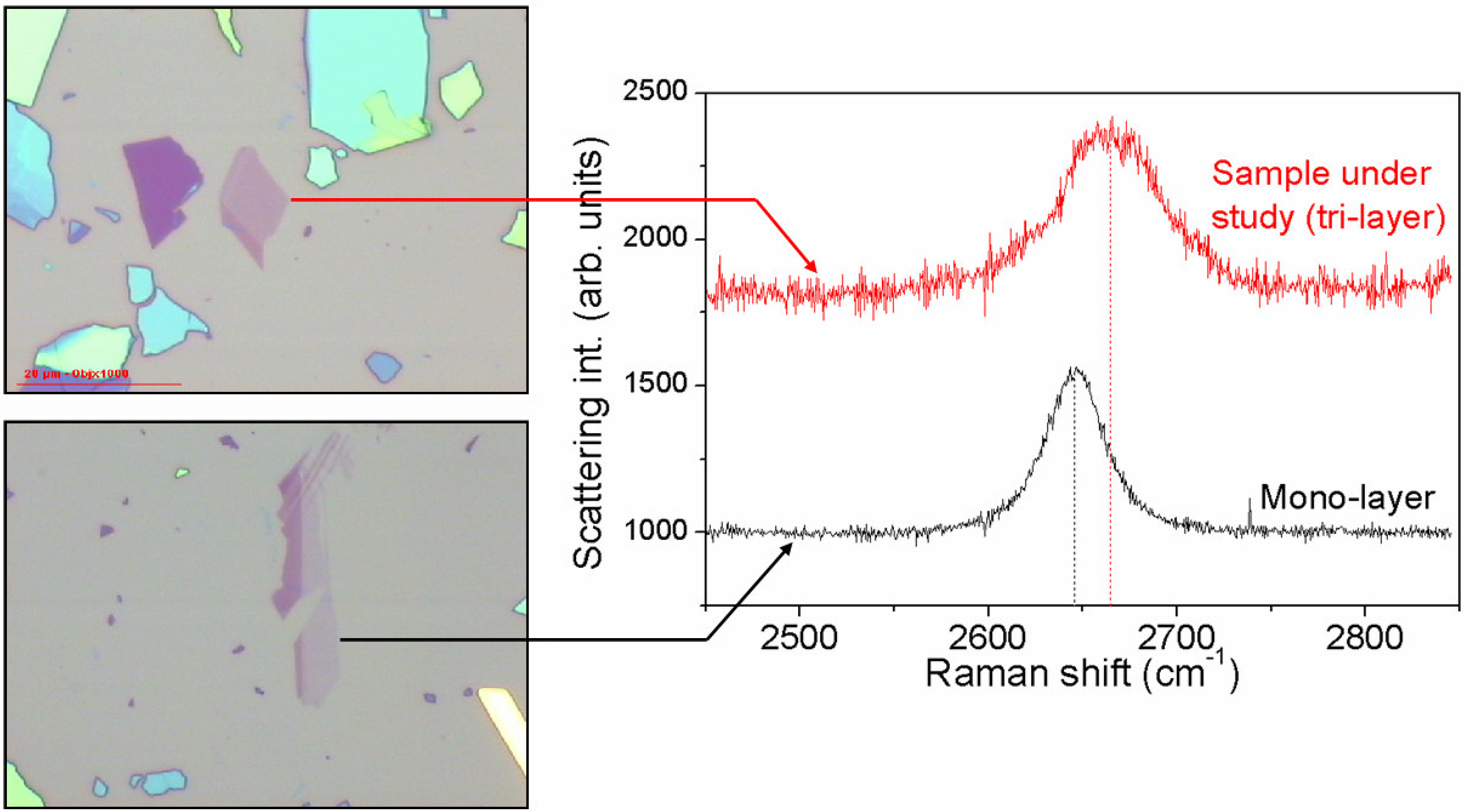
- Micro-mechanical cleavage of natural graphite onto Si/SiO_2 substrate
- Optical microscope observation

- Same substrate
- Same illumination conditions

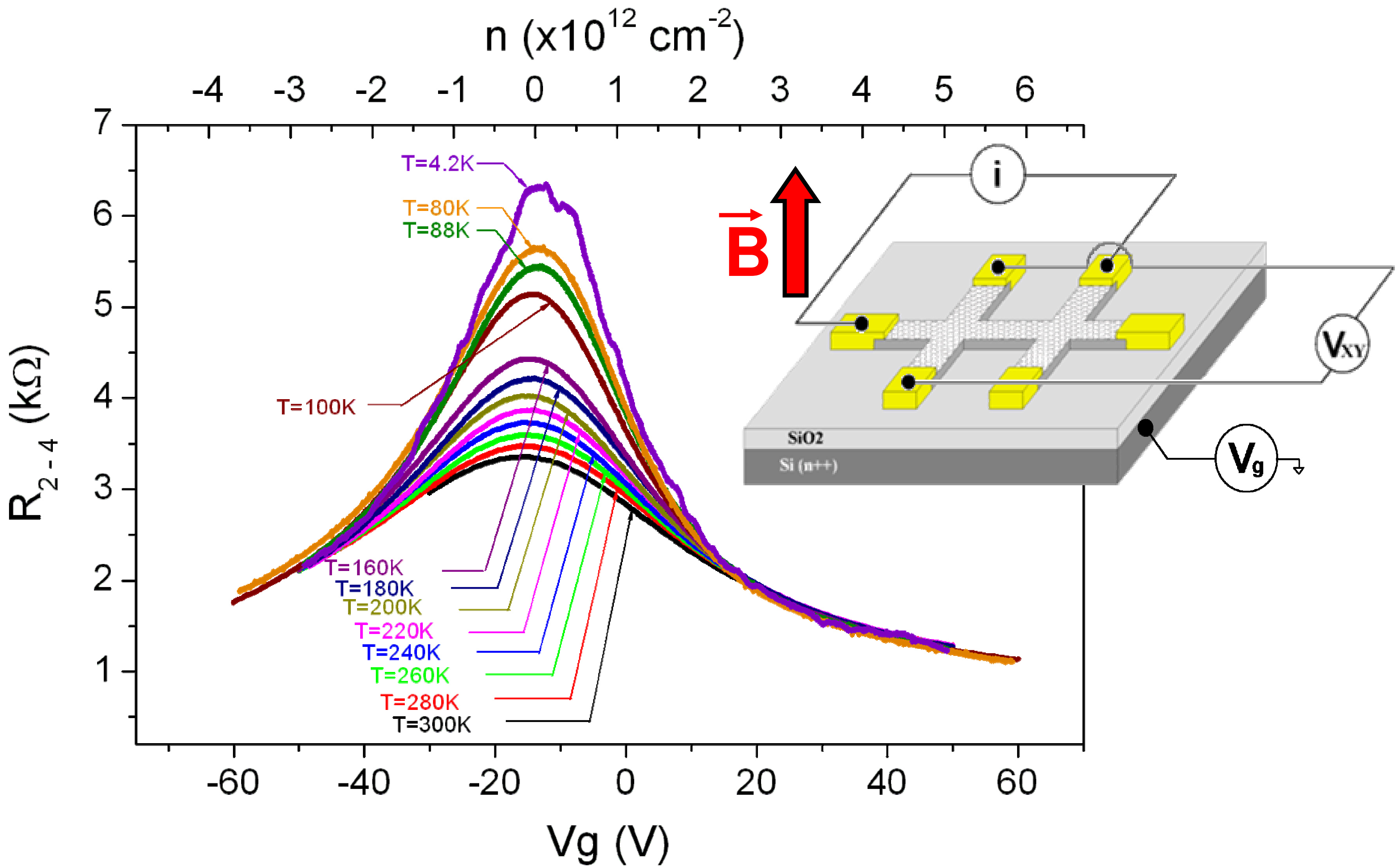




The sample IS a trilayer graphene



Zero-field analysis



Zero-field analysis

- We assume the presence of electron and hole puddles close to CNP

- At CNP, conductivity results from both metallic and activated transport

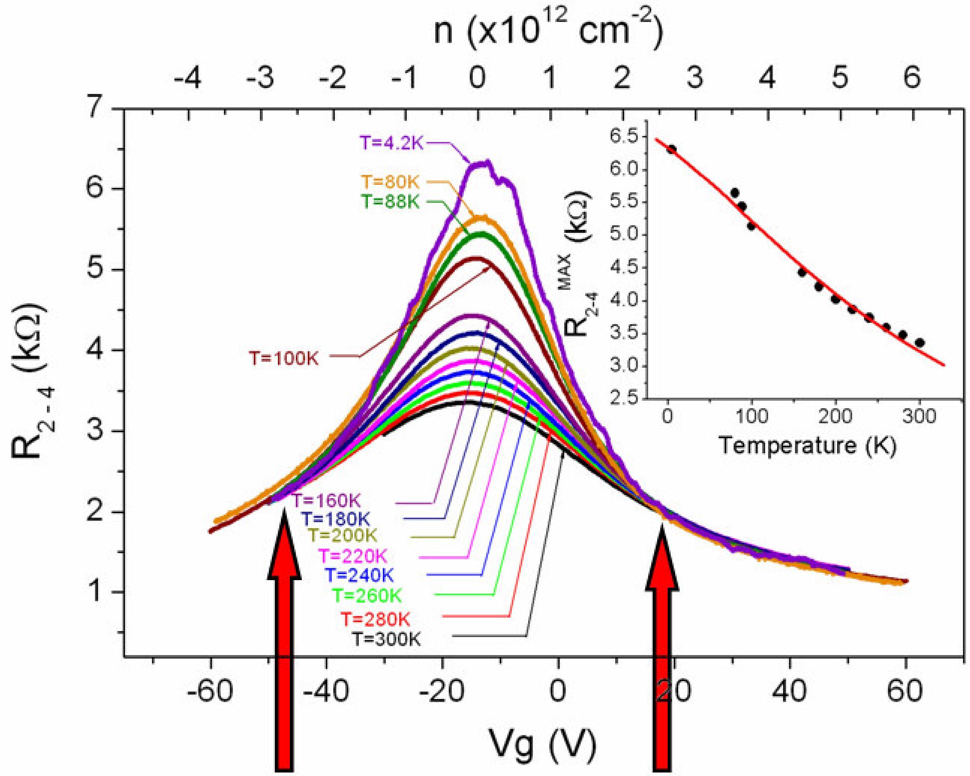
  E.H. Hwang, Phys. Rev. B 82, 081409 (2010)

- We extract $R^{MAX}(T)$ and fit with equation

$$R = \frac{L}{W}.\sigma^{-1} = \frac{L}{W}.(n.e.\mu)^{-1}$$

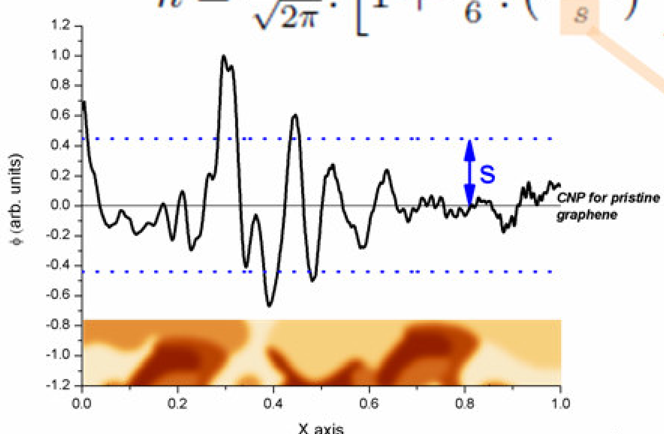
with

$$n = \frac{DoS}{\sqrt{2\pi}}.\left[1+\frac{\pi^2}{6}.\left(\frac{k_B T}{s}\right)^2\right]$$



Close to CNP

R ↗ when T ↘



Two adjustable parameters:

μ = 1150 cm² / V.s

s = 58 meV

- Field effect mobility :

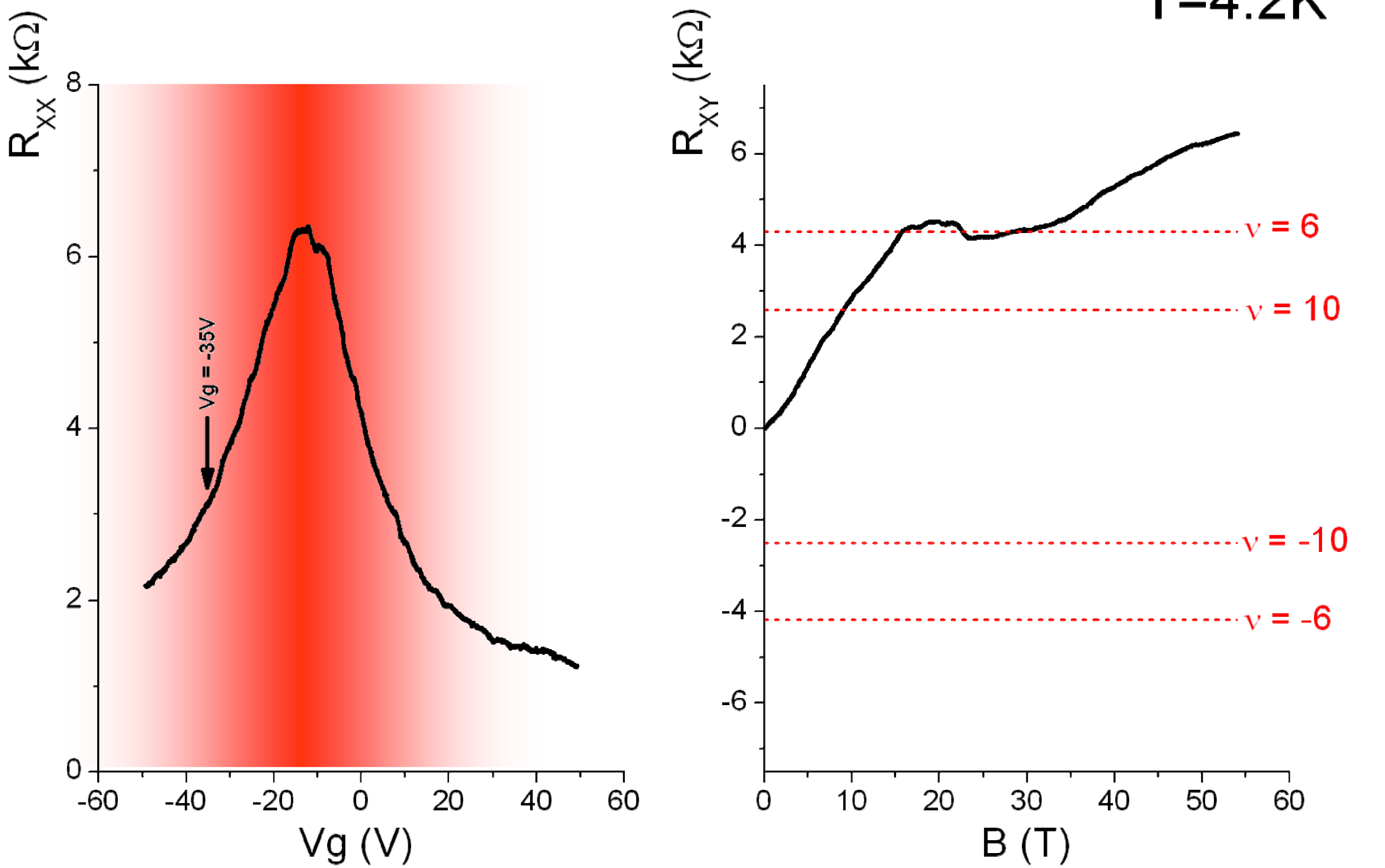
  μ ≈ 1100 cm² / V.s

- Hall mobility :

  μ ≈ 1300 cm2 / V.s

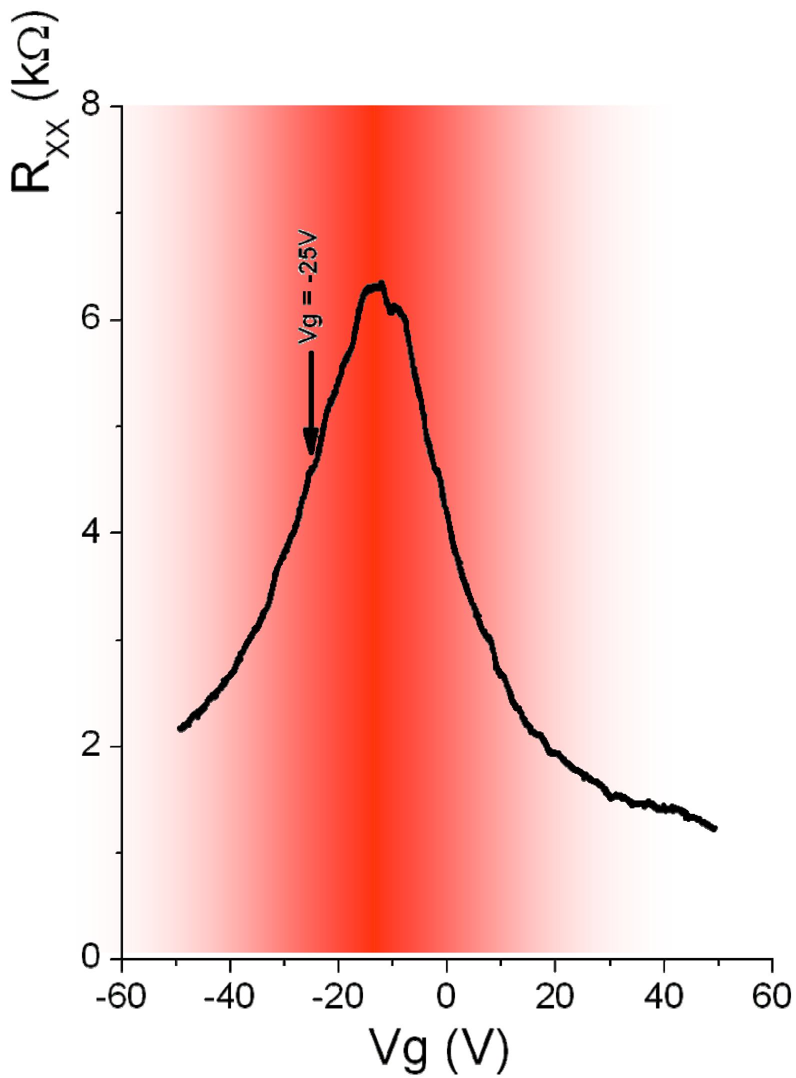
IQHE in graphene trilayer

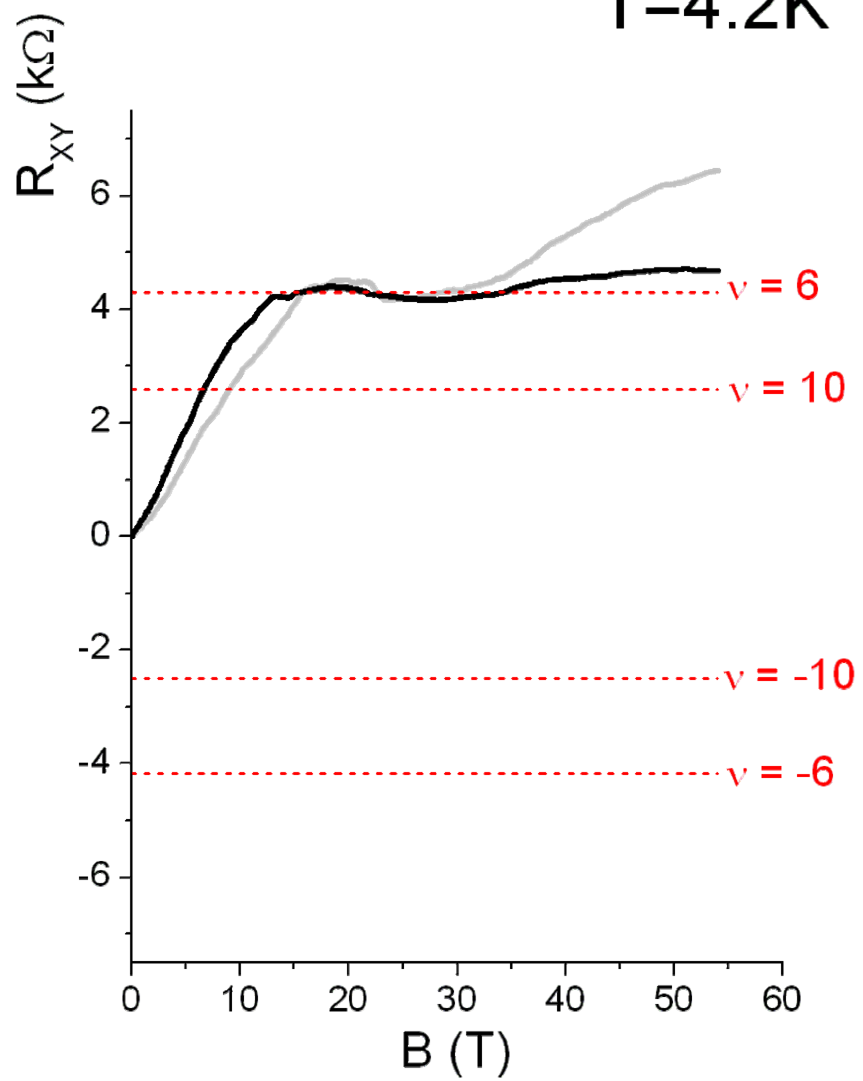
T=4.2K



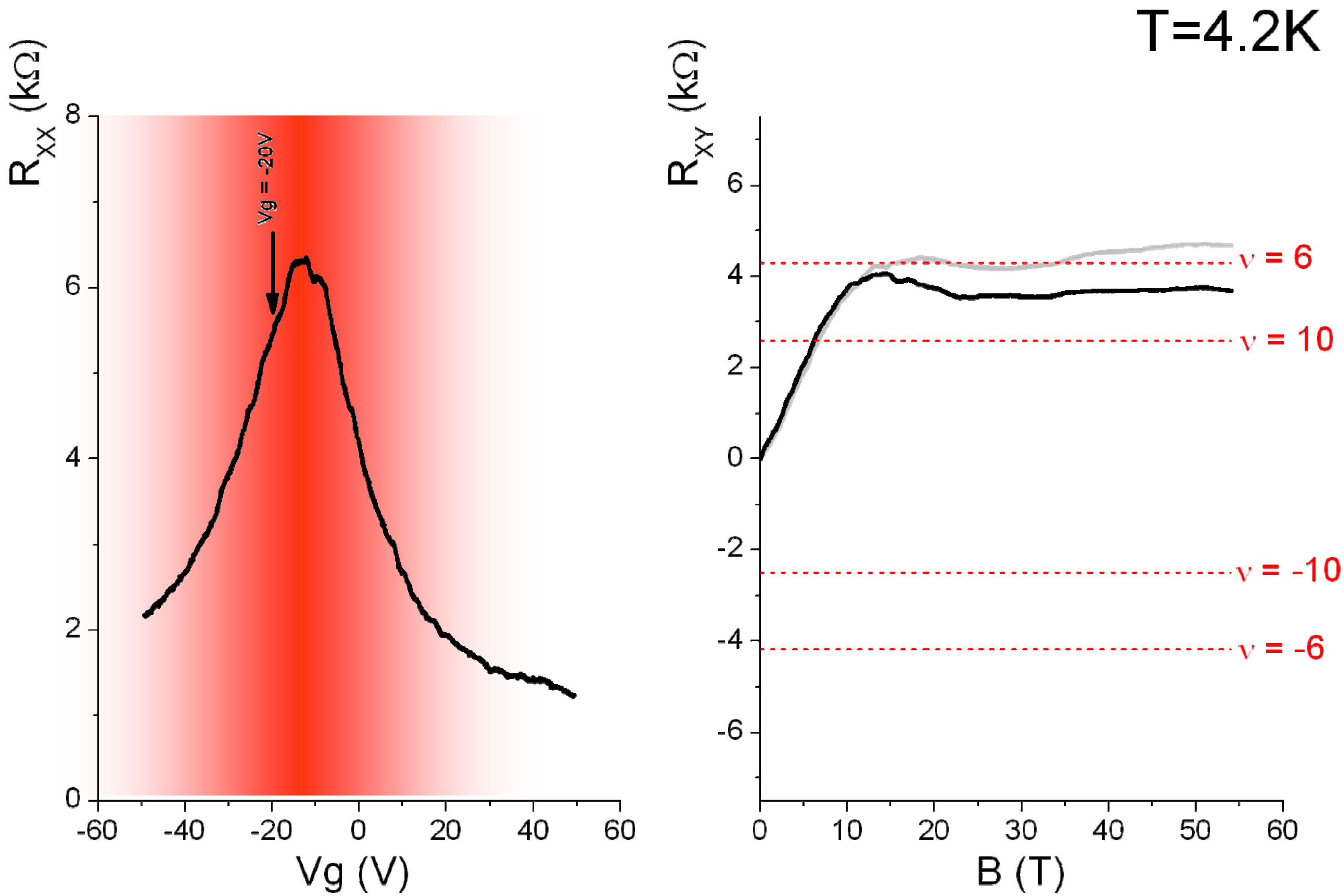
IQHE in graphene trilayer

T=4.2K



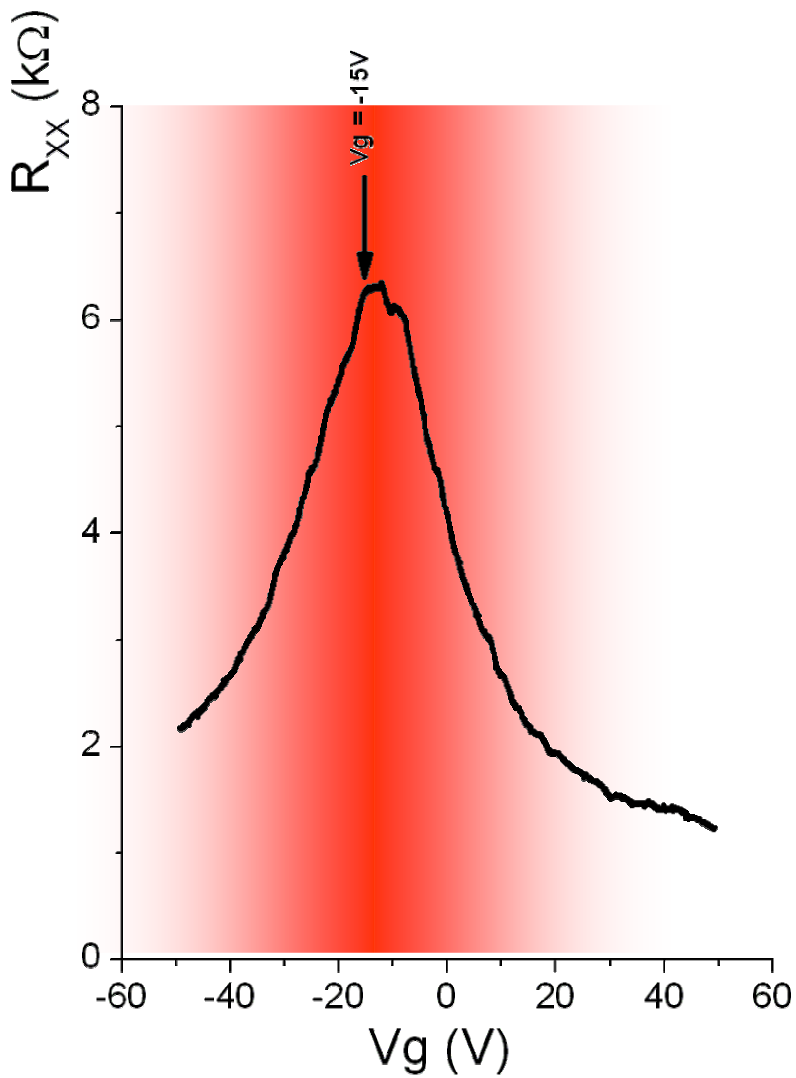


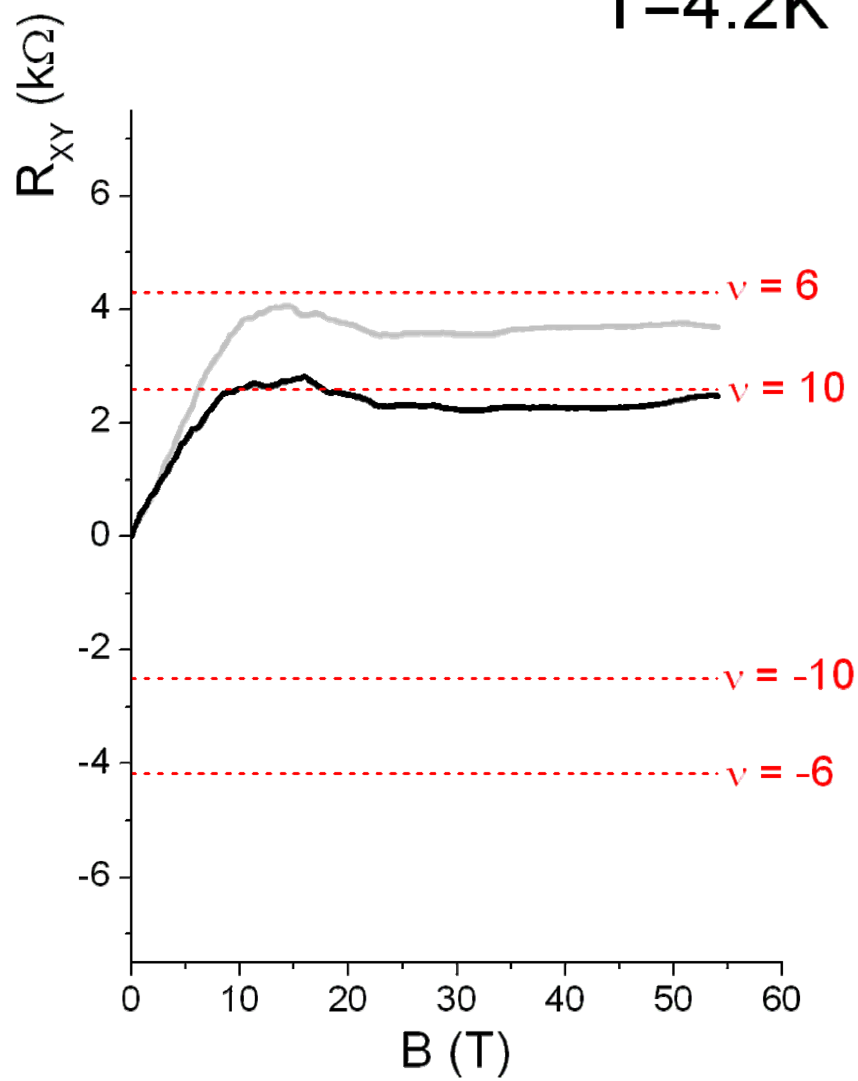
IQHE in graphene trilayer



IQHE in graphene trilayer

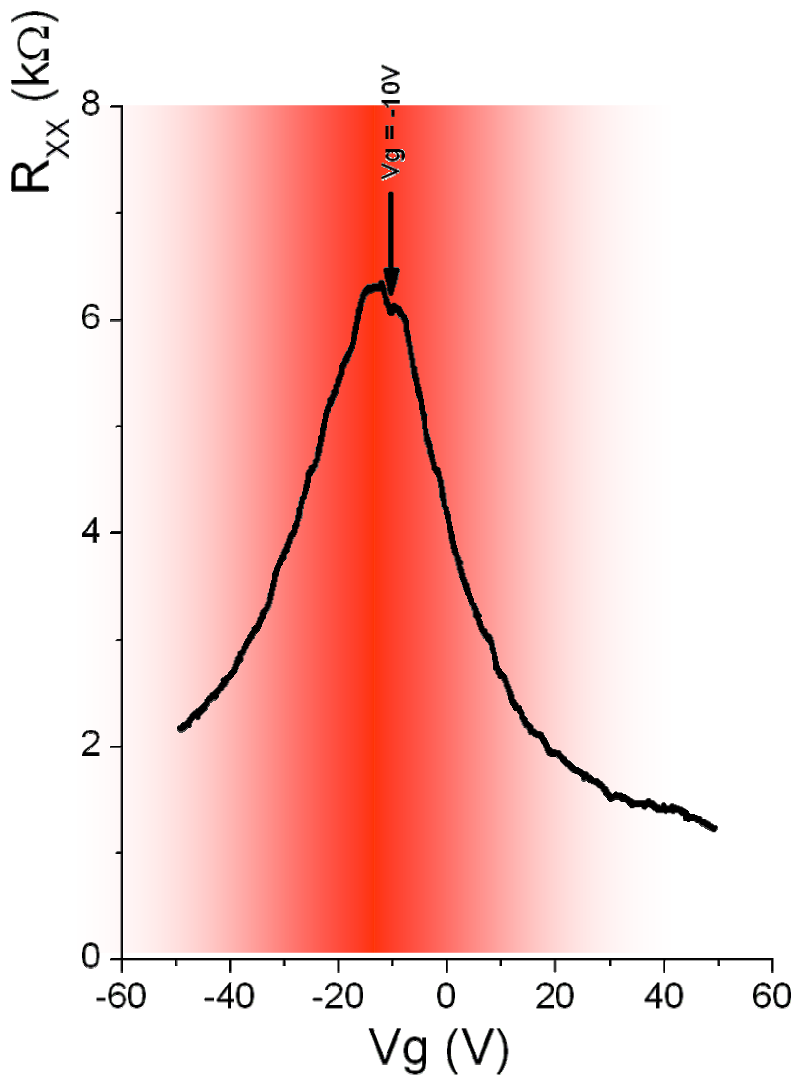
T=4.2K

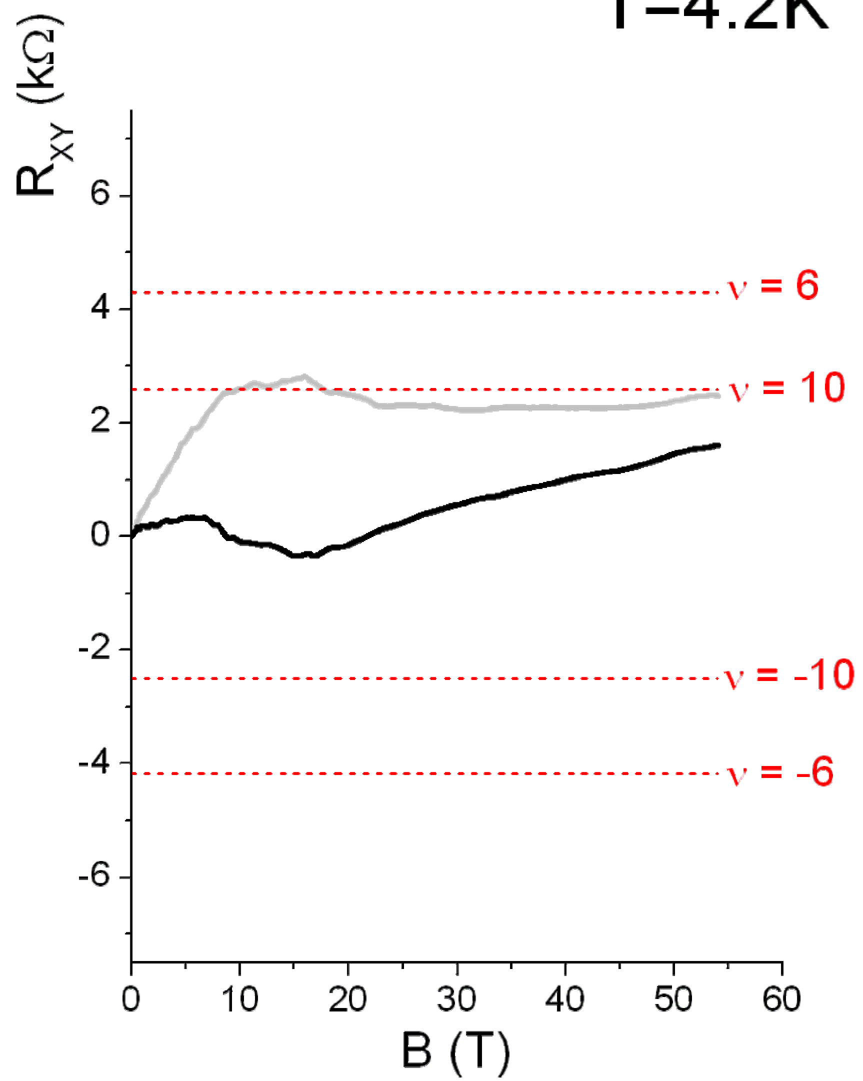




IQHE in graphene trilayer

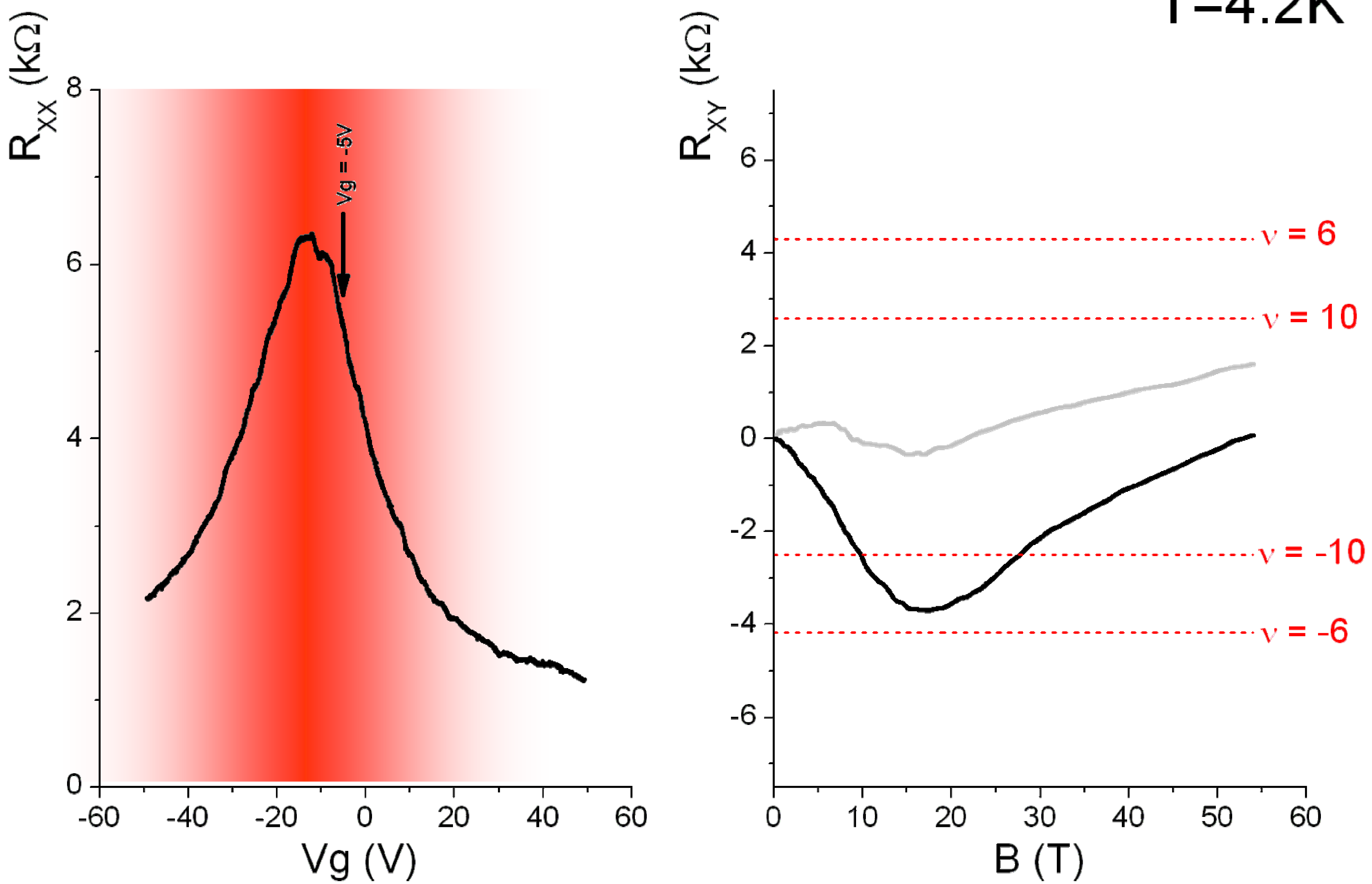
T=4.2K





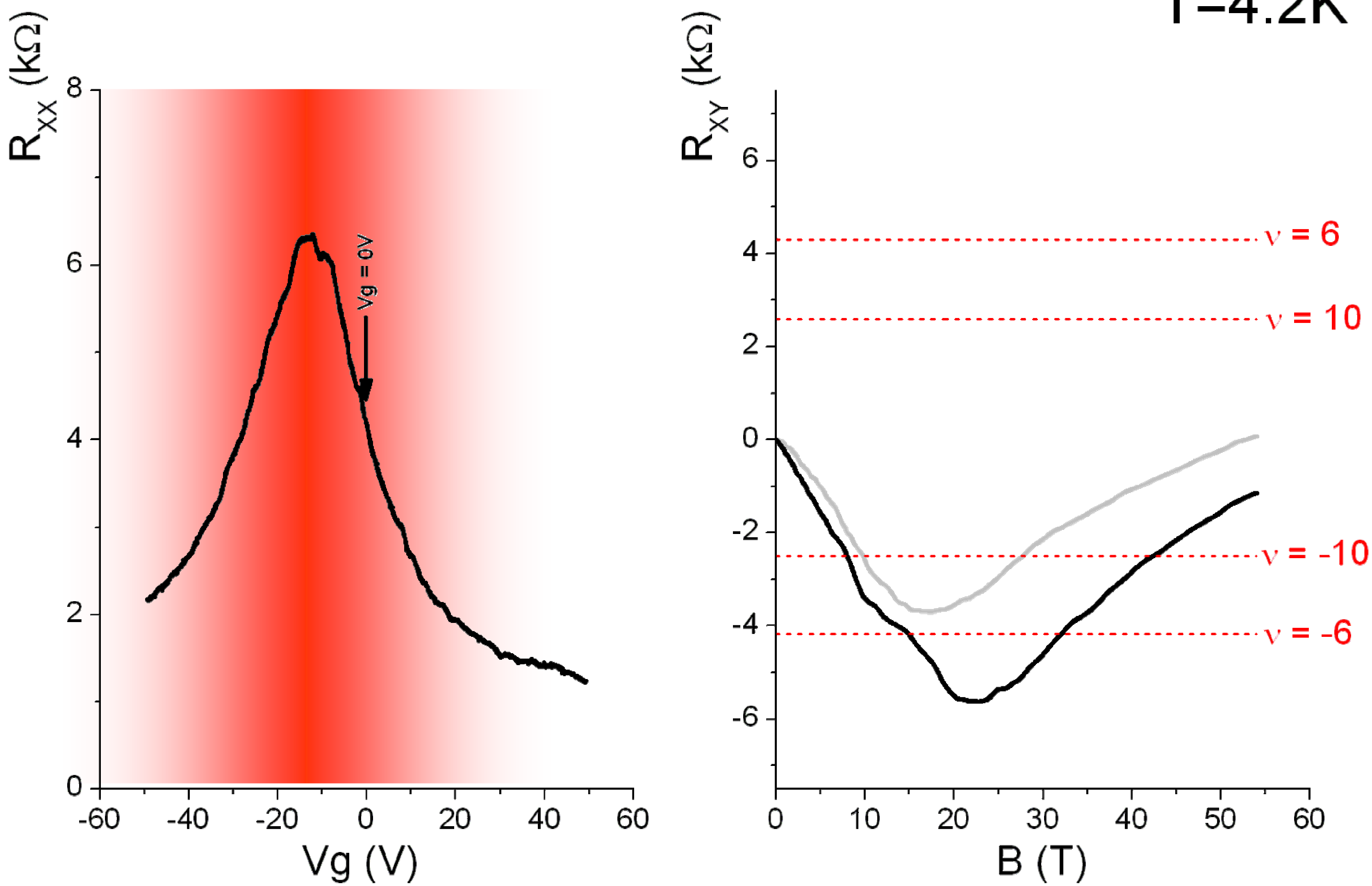
IQHE in graphene trilayer

T=4.2K



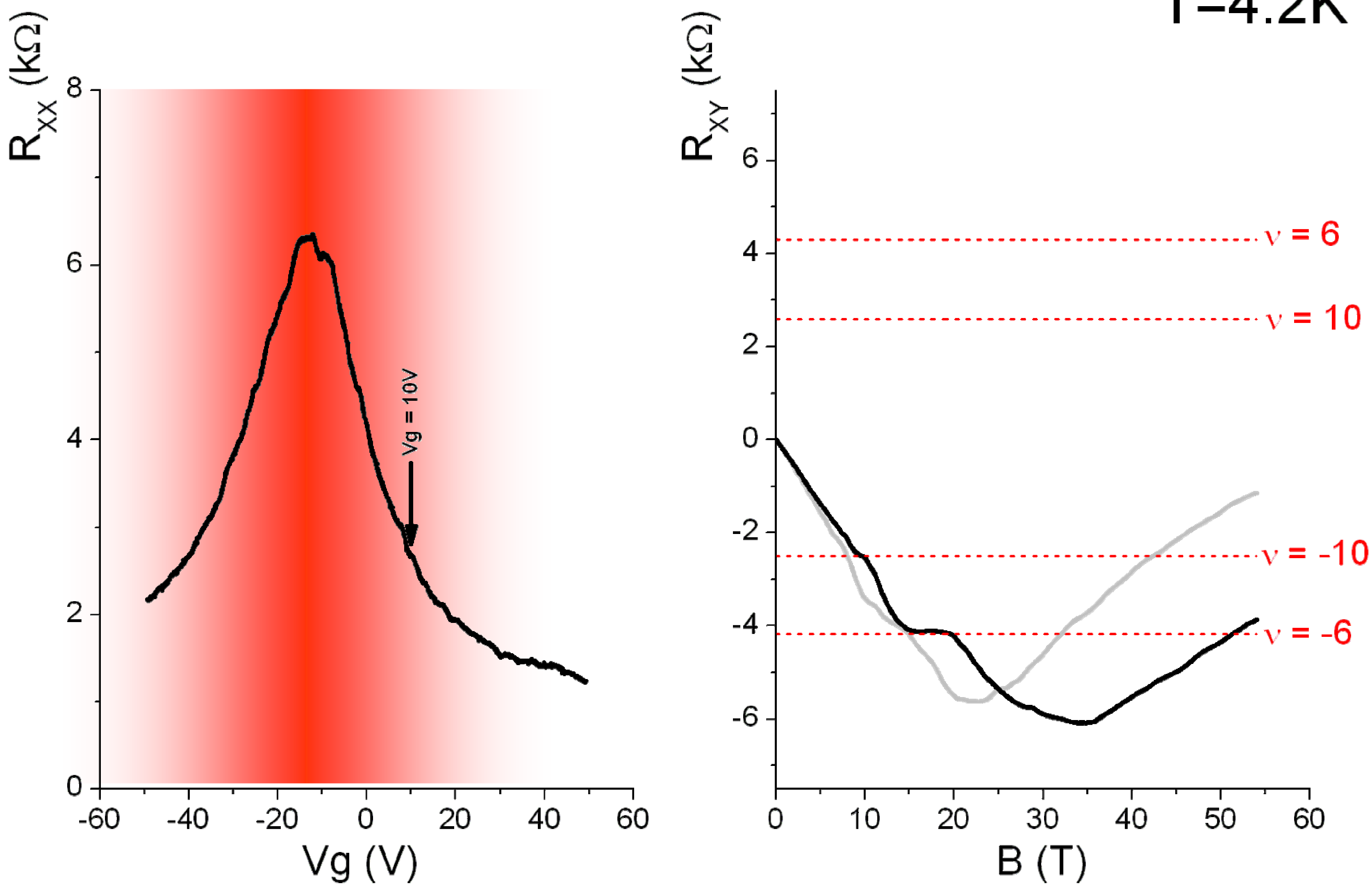
IQHE in graphene trilayer

T=4.2K

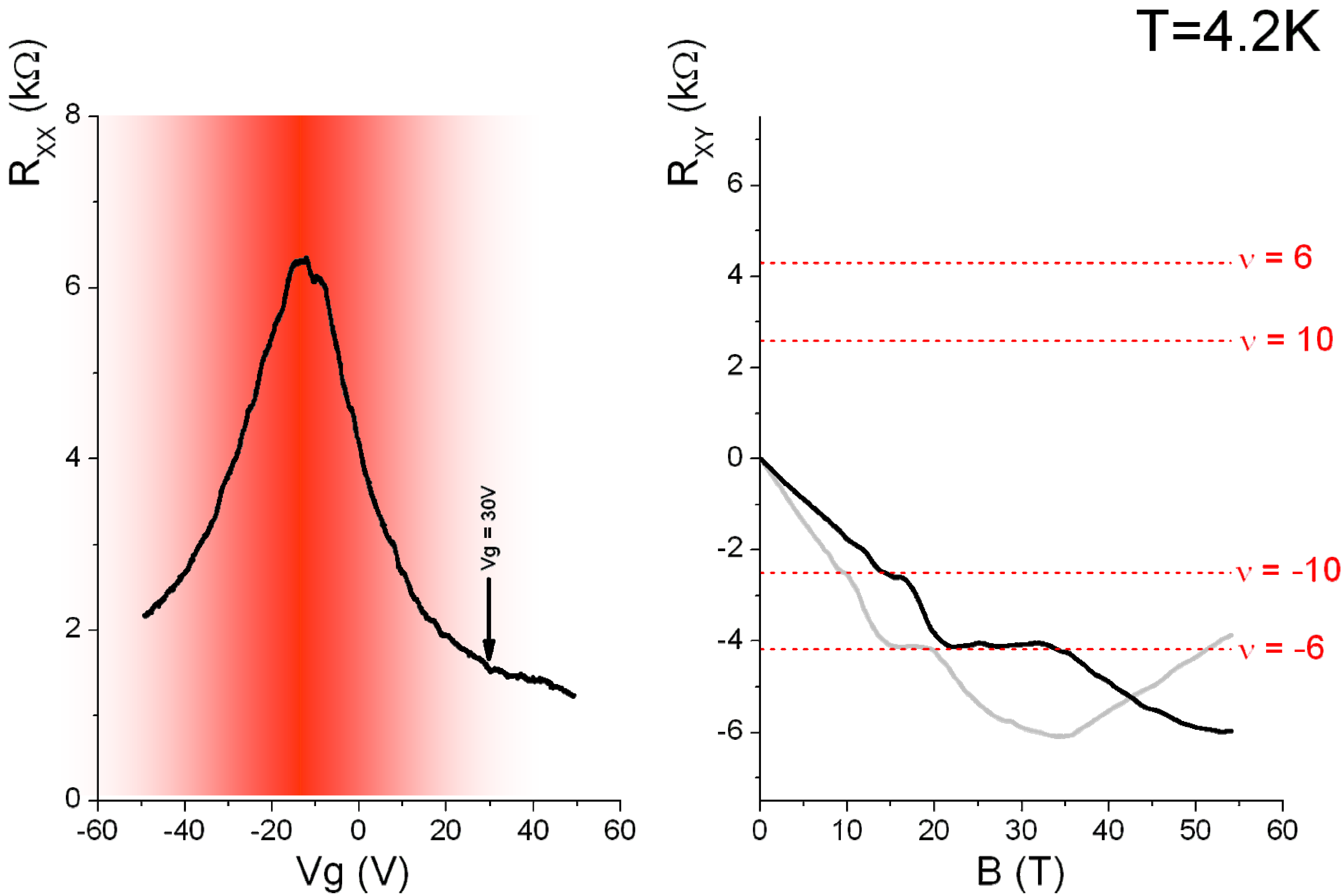


IQHE in graphene trilayer

T=4.2K

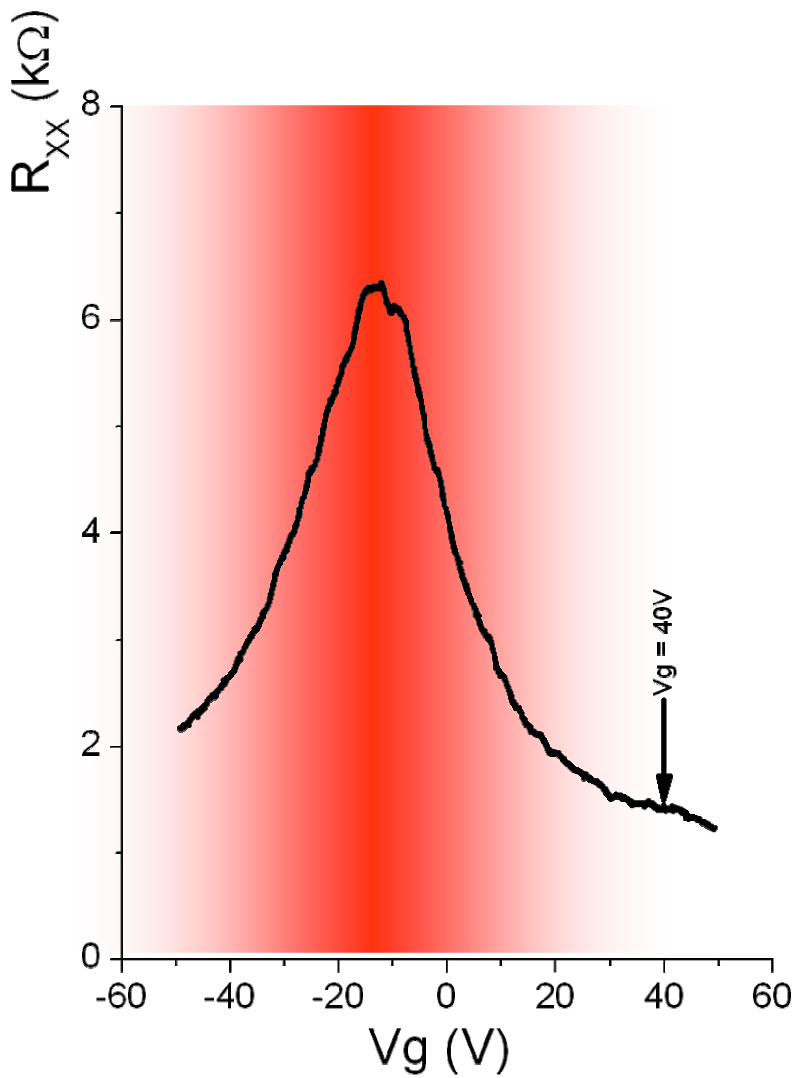


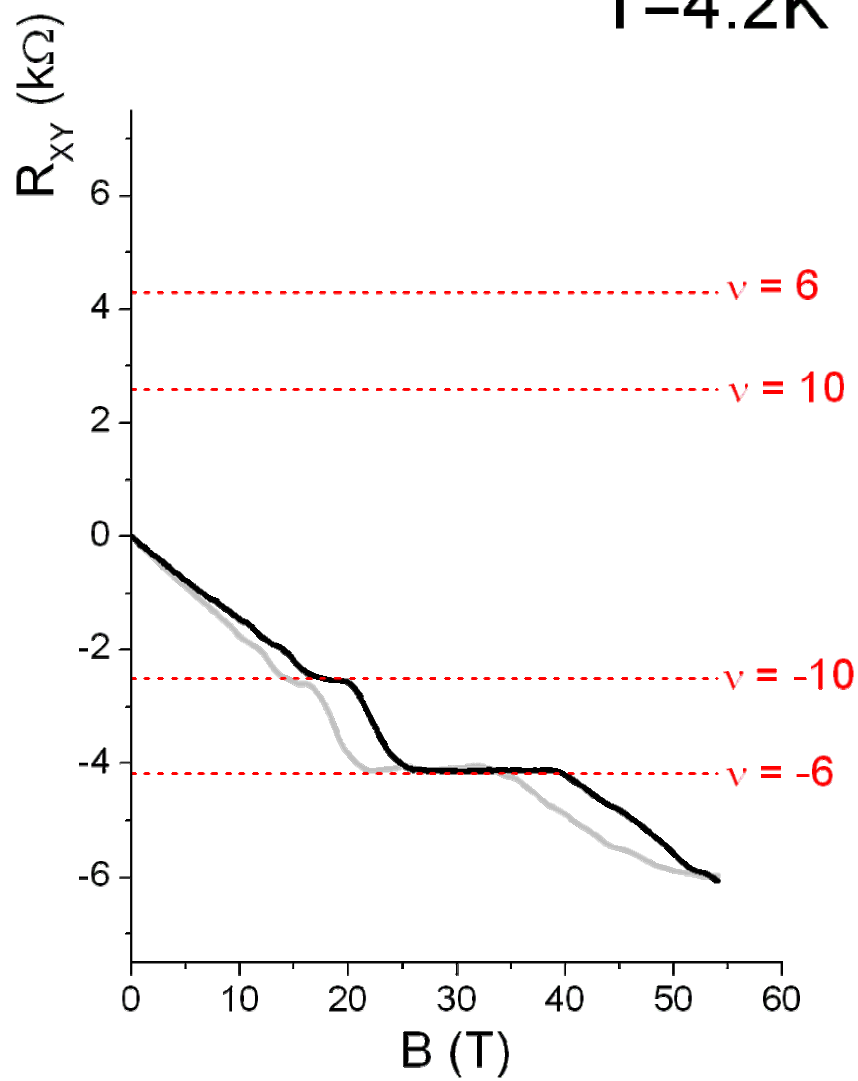
IQHE in graphene trilayer



IQHE in graphene trilayer

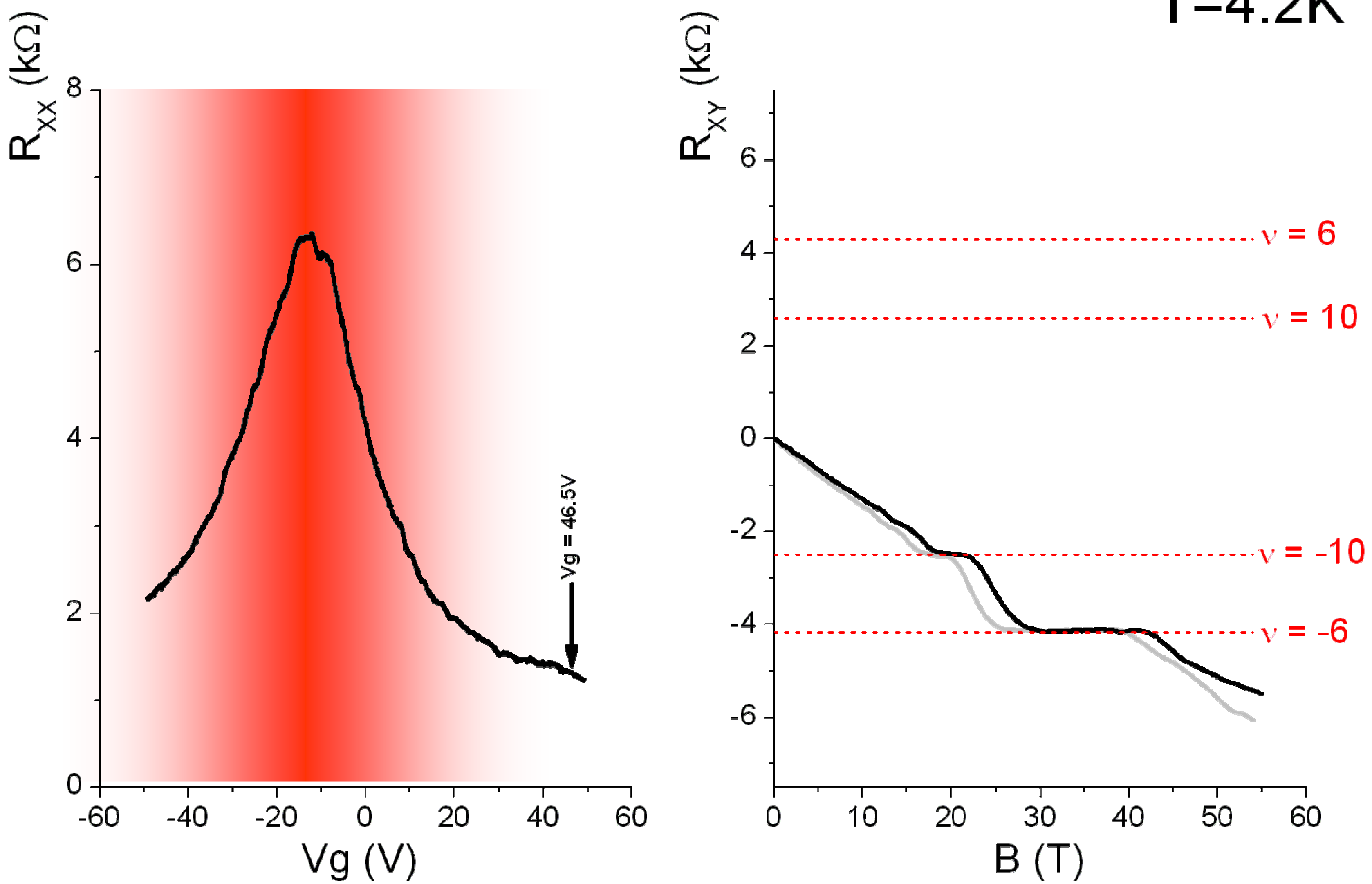
T=4.2K





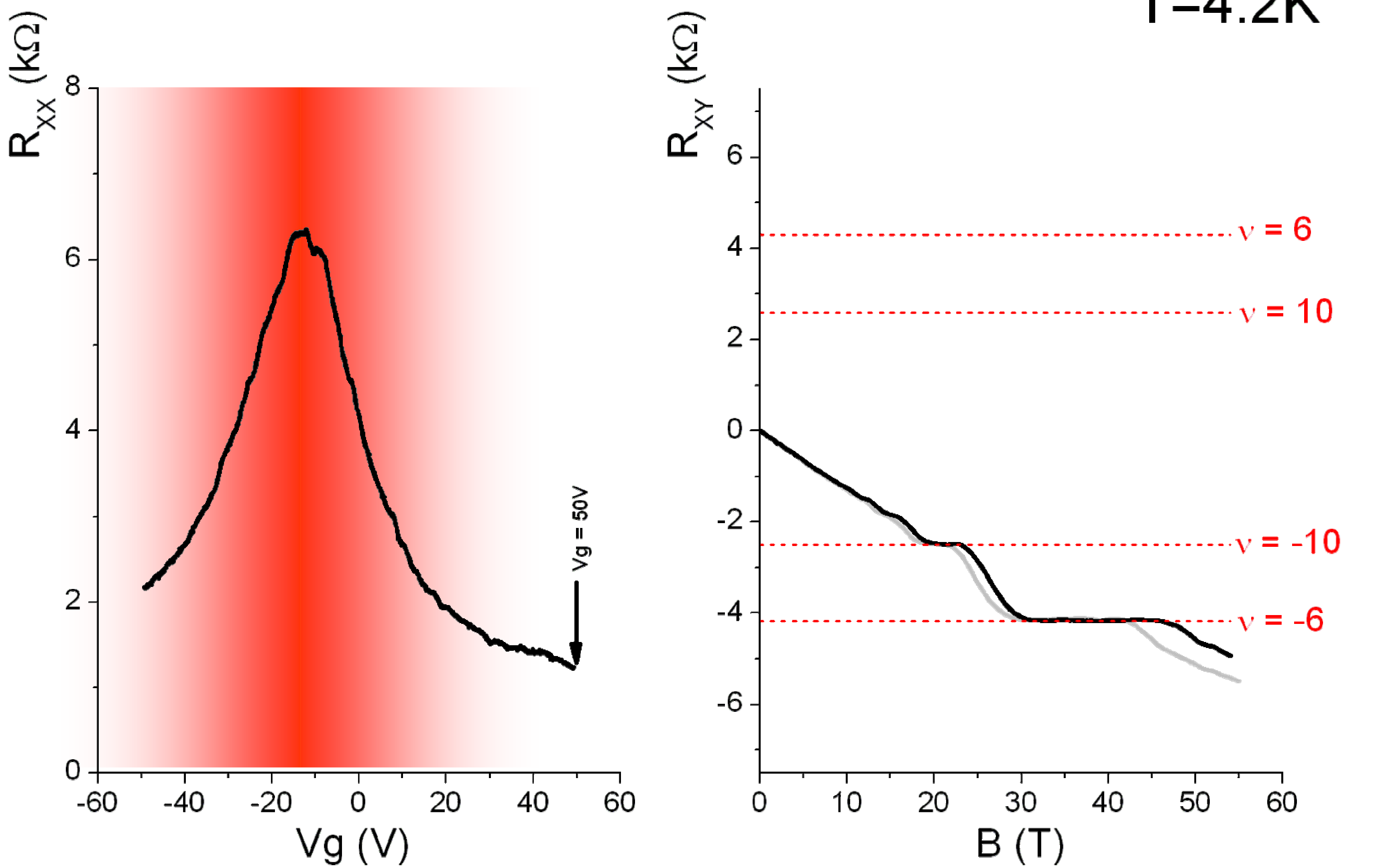
IQHE in graphene trilayer

T=4.2K



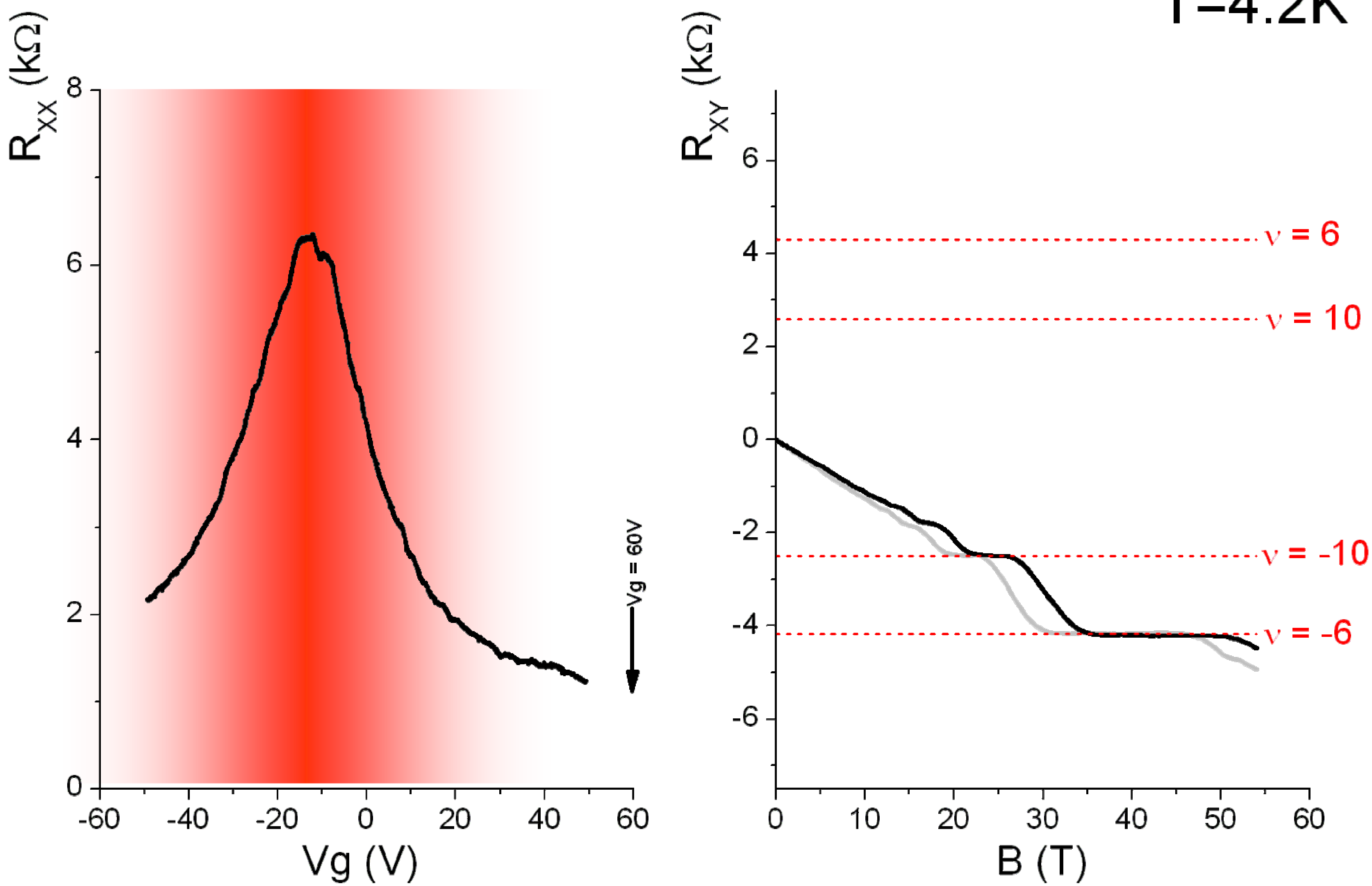
IQHE in graphene trilayer

T=4.2K

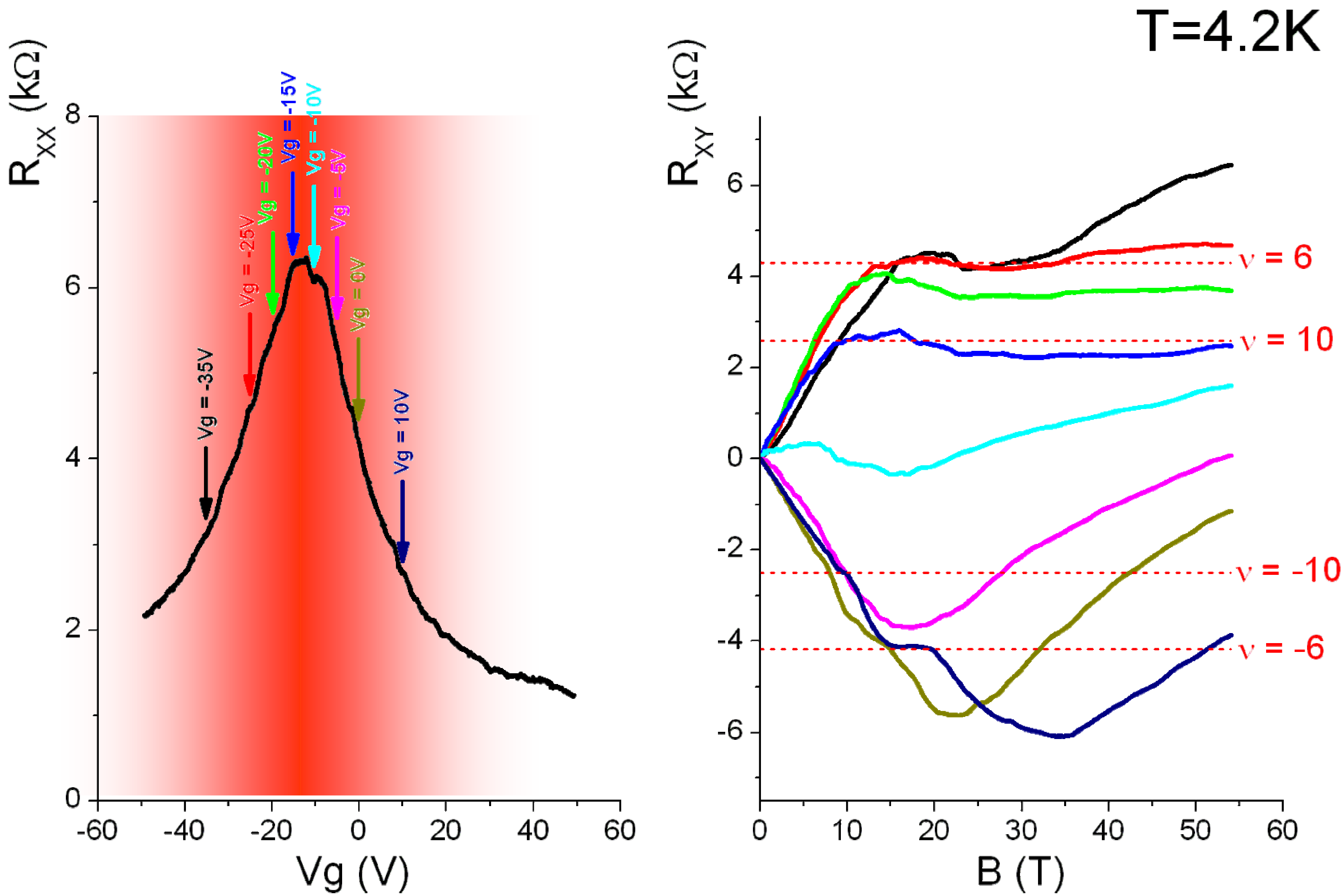


IQHE in graphene trilayer

T=4.2K

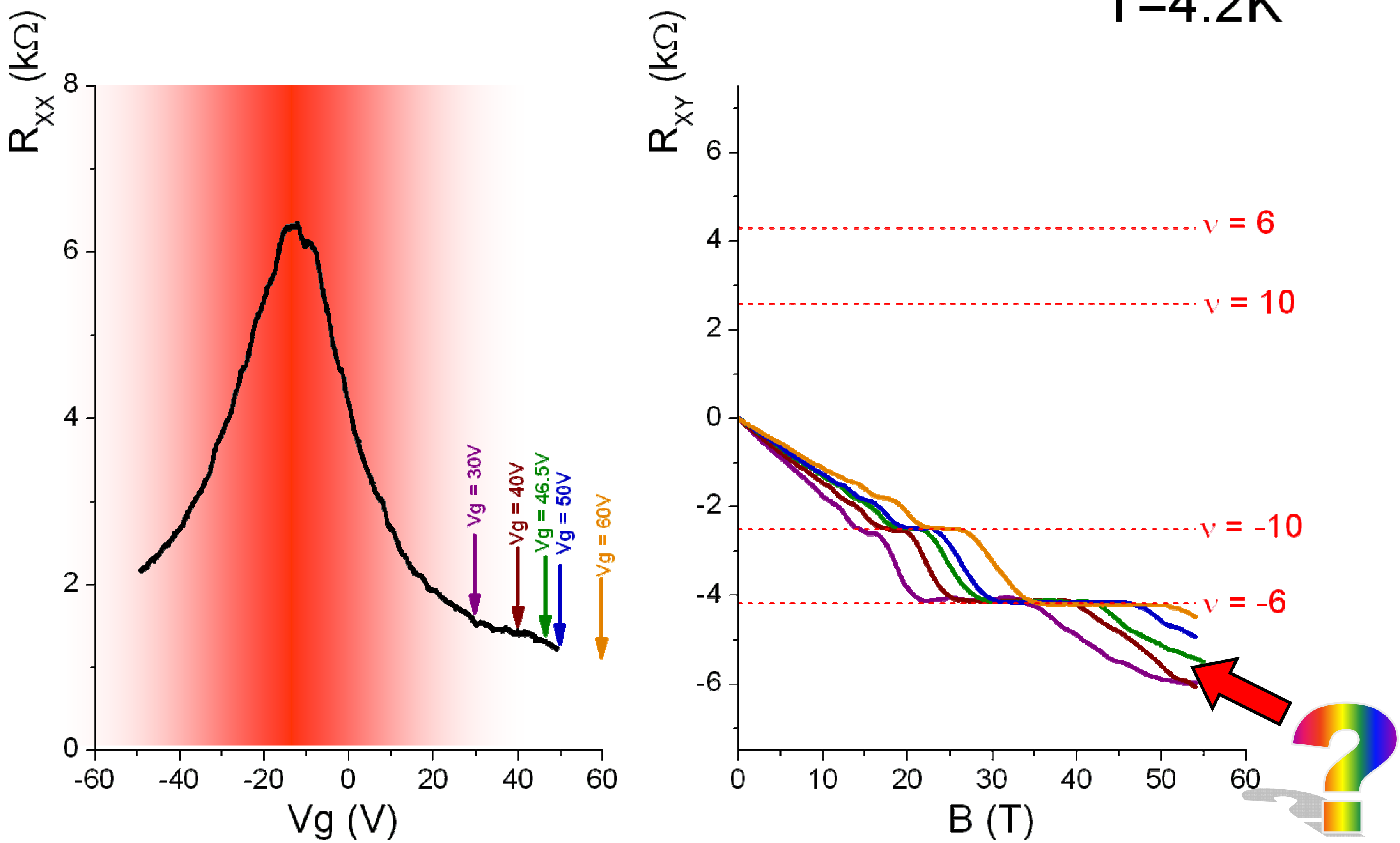


IQHE in graphene trilayer



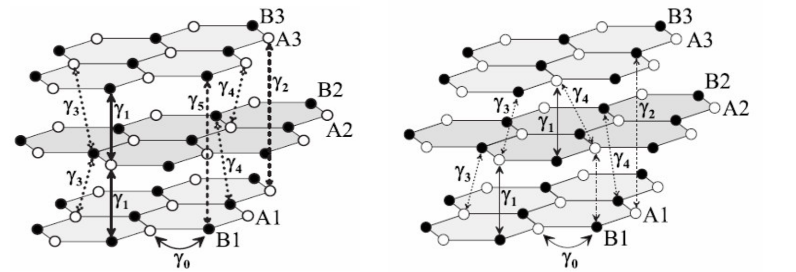
IQHE in graphene trilayer

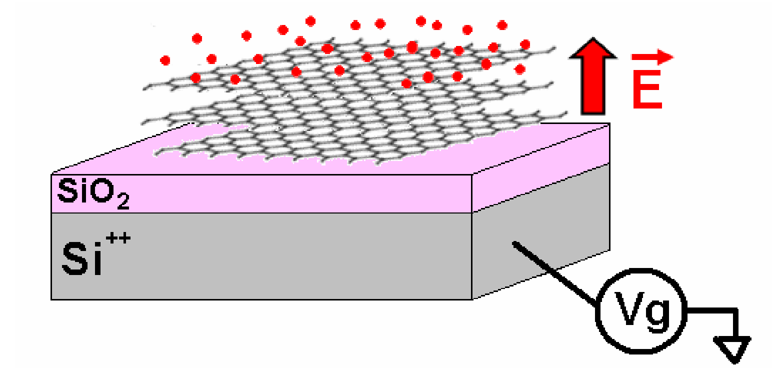
T=4.2K



The model for IQHE

- Band-structure calculations for both ABA and ABC stacking order
- Full set of tight-binding coupling parameters (Slonczewski-Weiss-McClure model)
- The back-gate voltage changes the carrier density and charge distribution among the layers, which is calculated self consitently
- Stray charges on the top layer to account for V_{CNP} = -13.75 V
- The Fermi energy is computed self-consistently with increasing magnetic field
- We assume the g-factor with g=2





- Broadening of the LL

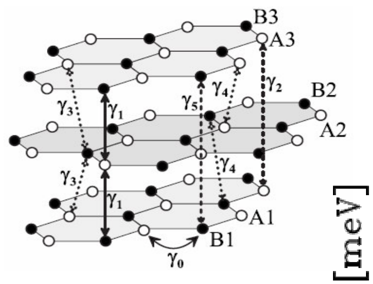
$$\Delta E \sim \frac{\hbar}{\tau} \text{ with } \tau = \frac{\mu . m^*}{e}$$

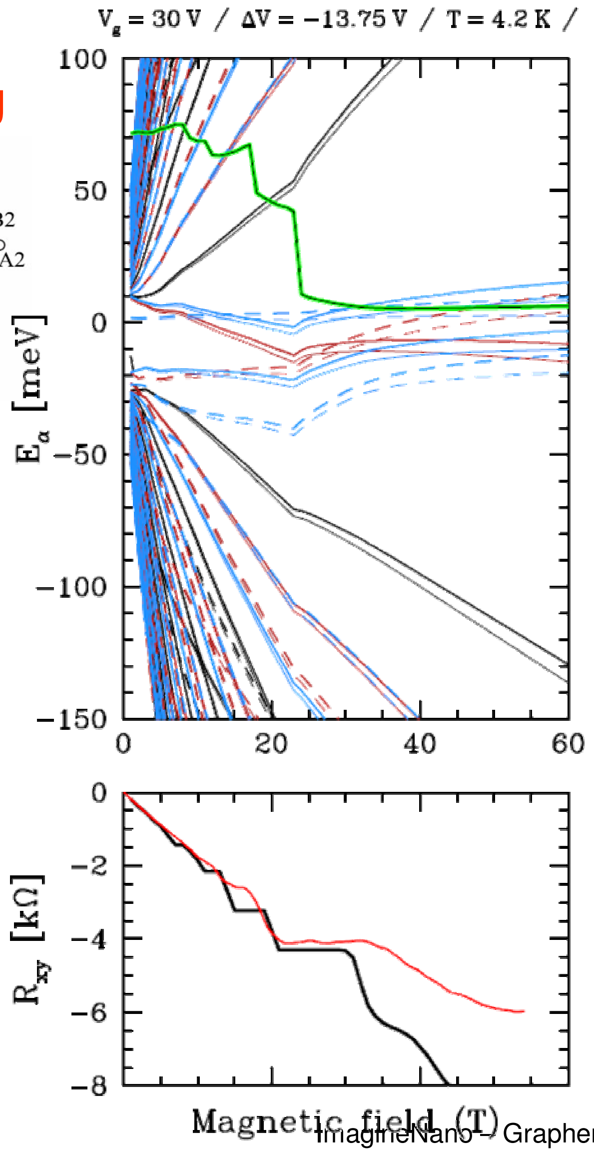
$$\text{Using} \begin{cases} \mu \sim 1000 cm^2/V.s \\ m^* = 0.054 . m_e \end{cases}$$

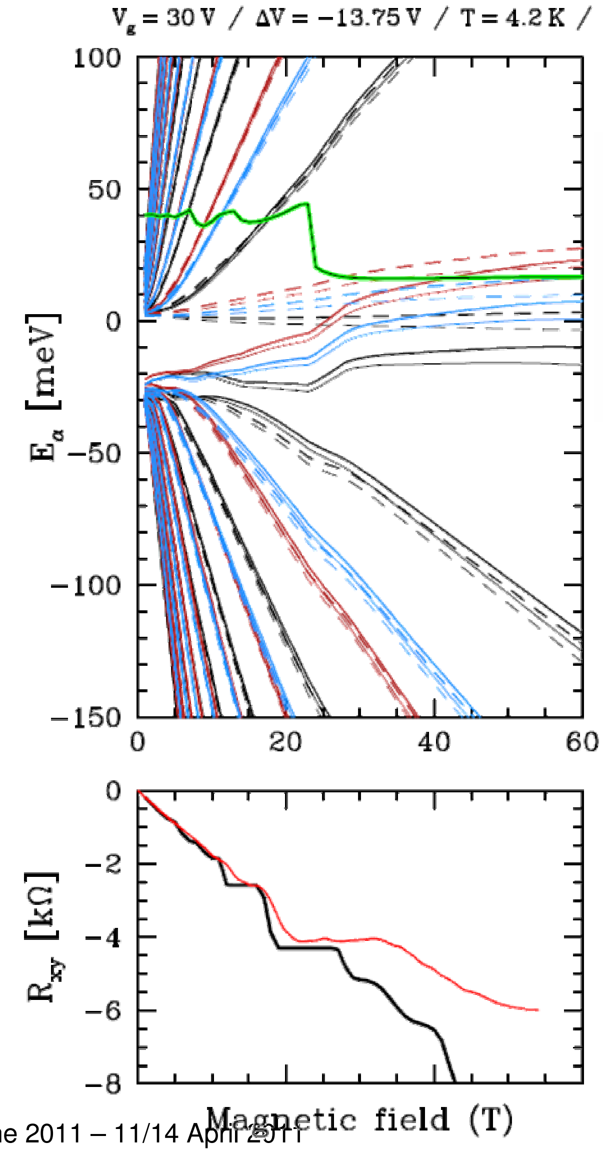
$$\text{we get } \Delta E \approx 20\text{meV}$$

The model for IQHE

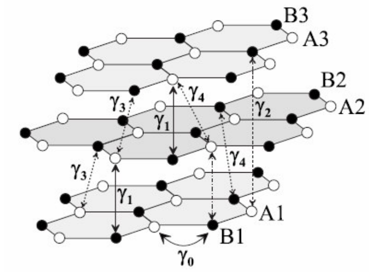
ABA stacking





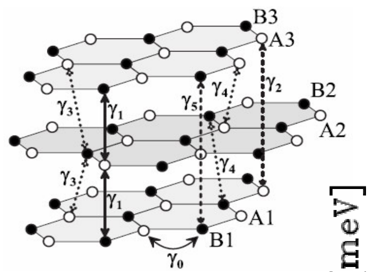


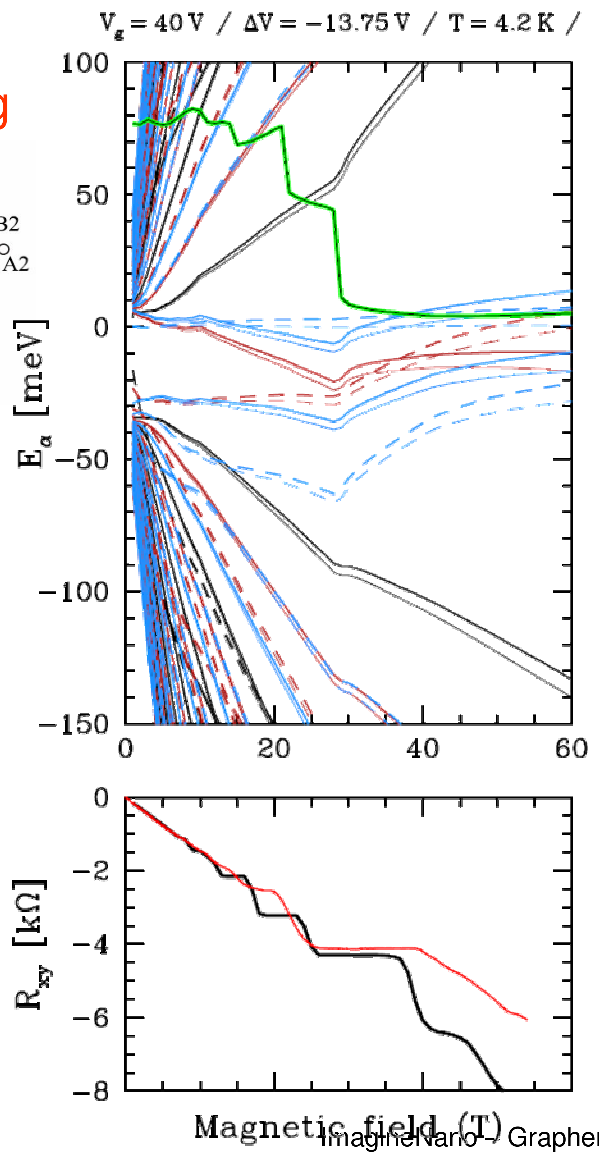
ABC stacking

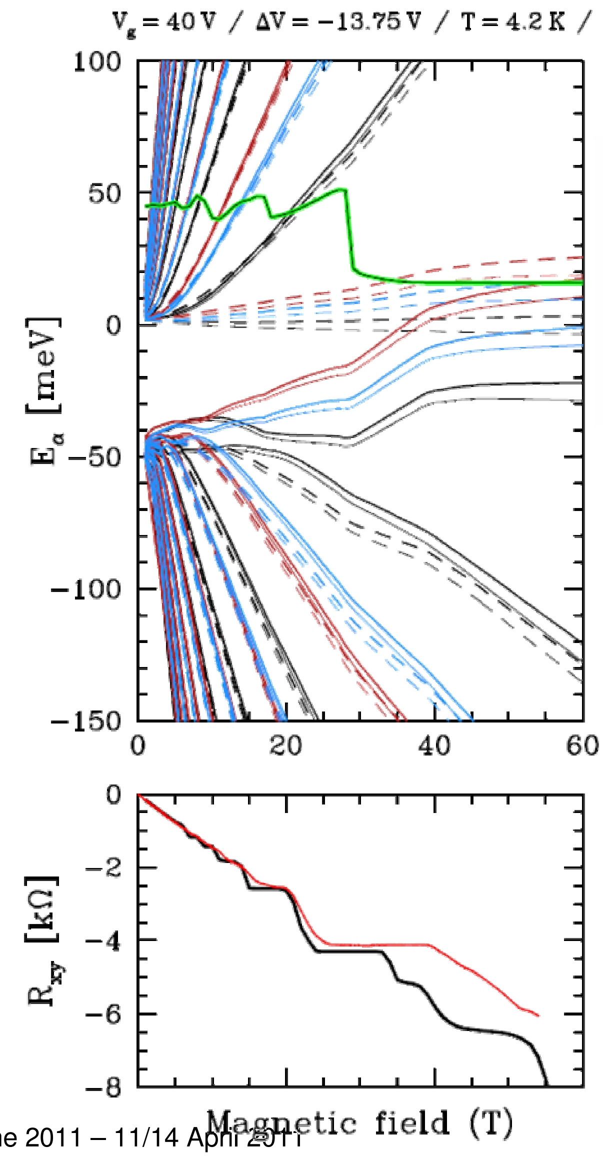


The model for IQHE

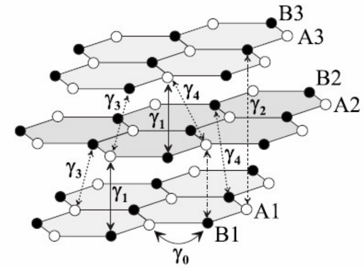
ABA stacking





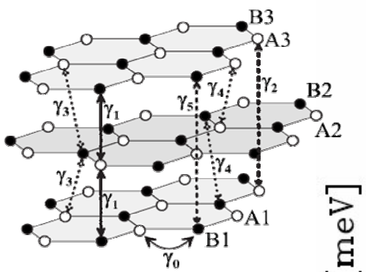


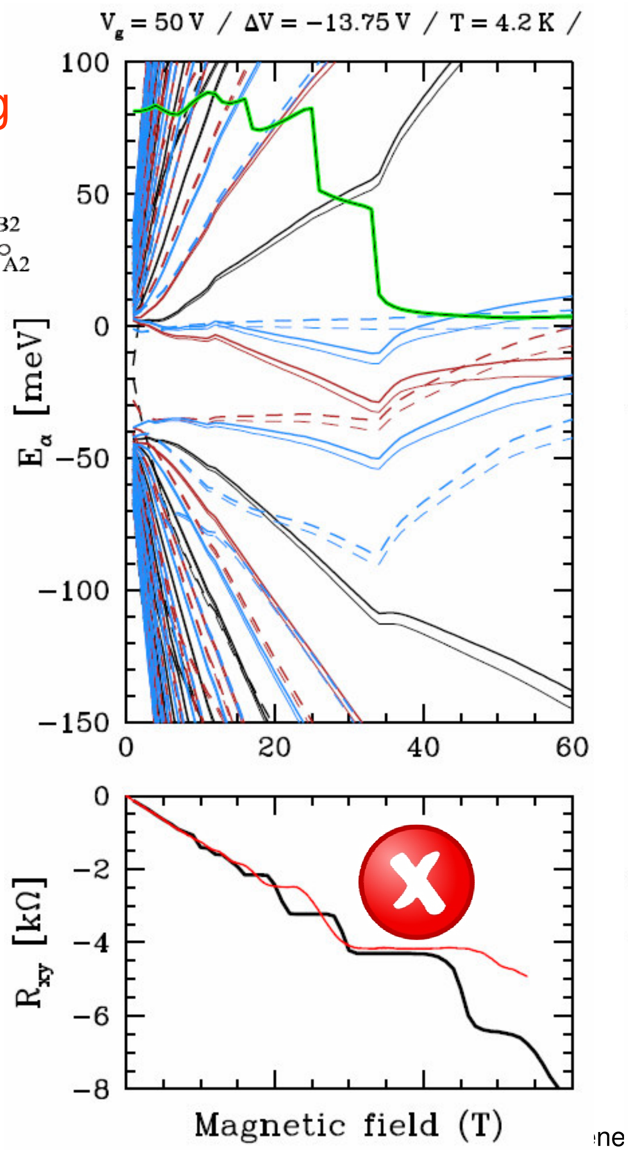
ABC stacking

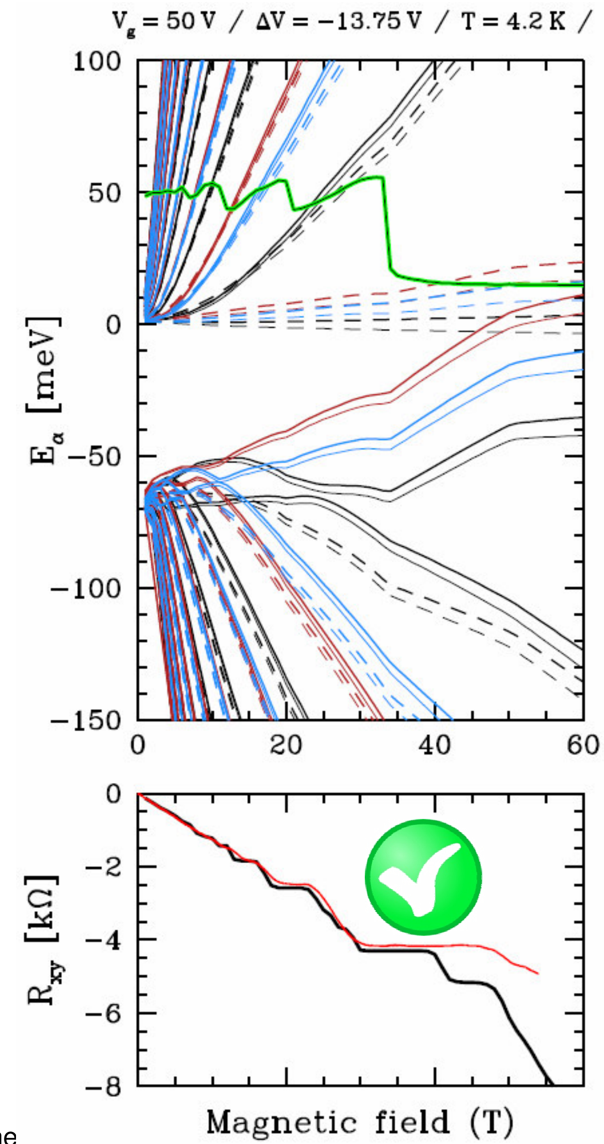


The model for IQHE

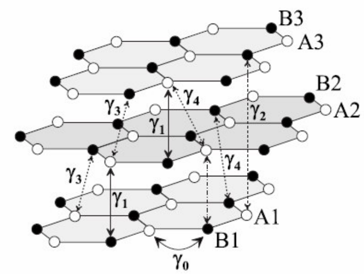
ABA stacking





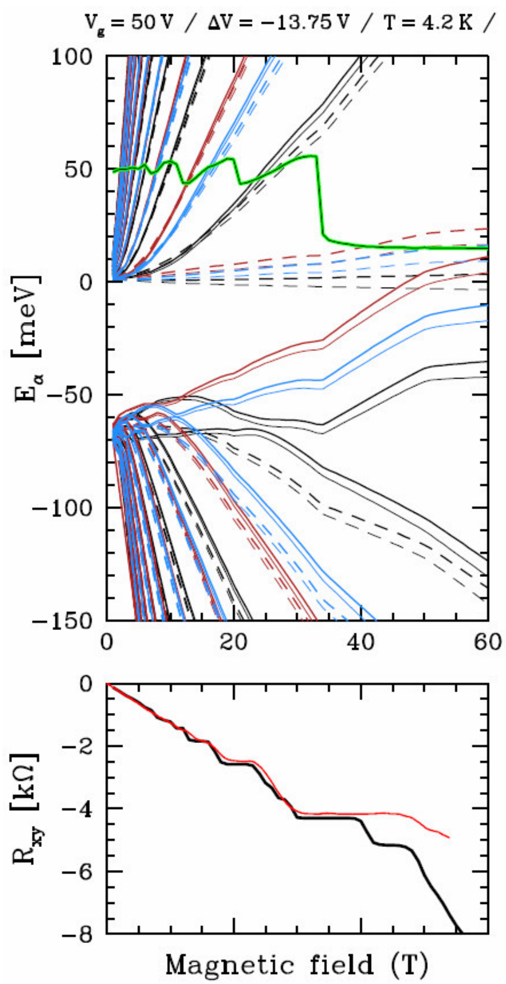


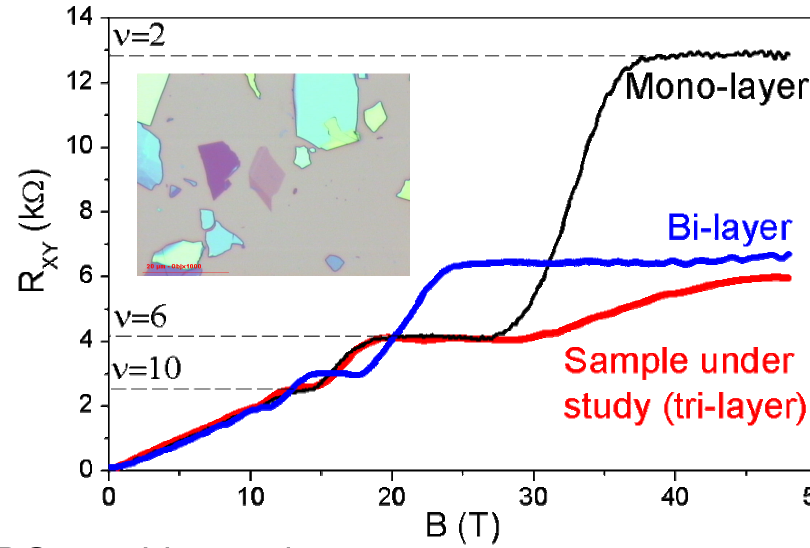
ABC stacking



Conclusion

- Experimental observation of QHE in trilayer graphene using high magnetic field





- Determination of the ABC stacking order
  (based on comparison of experimental
  data with advanced numerical analysis)

Last week on Arxiv …

Quantum Hall effect and Landau level crossing of Dirac fermions in trilayer graphene
Thiti Taychatanapat, Kenji Watanabe, Takashi Taniguchi, Pablo Jarillo-Herrero

Stacking-Dependent Band Gap and Quantum Transport in Trilayer Graphene
W. Bao, L. Jing, Y. Lee, J. Velasco Jr., P. Kratz, D. Tran, B. Standley, M. Aykol *et. al.*

The experimental observation of quantum Hall effect of l = 3 chiral charge carriers in trilayer
Liyuan Zhang, Yan Zhang, J. Camacho, M. Khodas, I. A. Zaliznyak