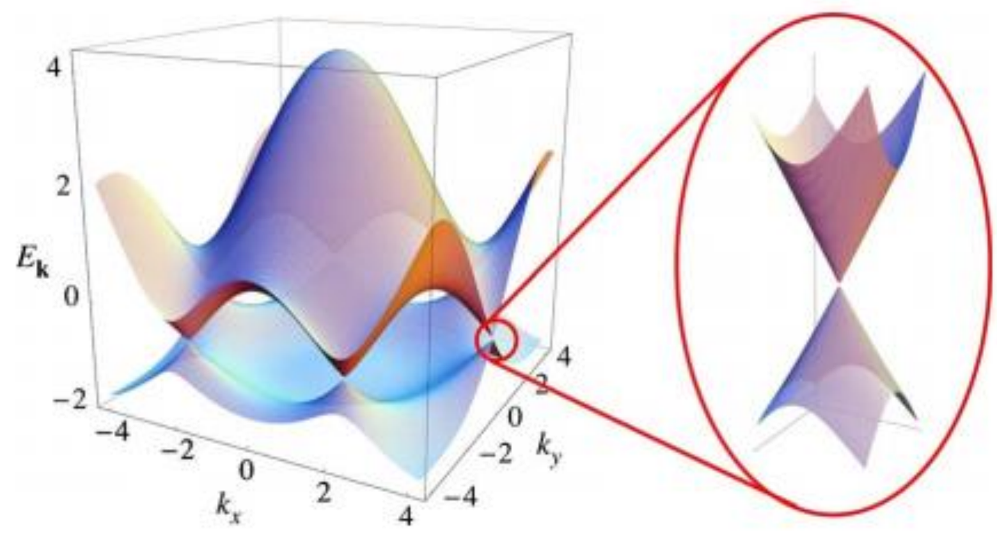
Fantastic and Physically Appealing: the Electronic Structure and Properties of Graphene

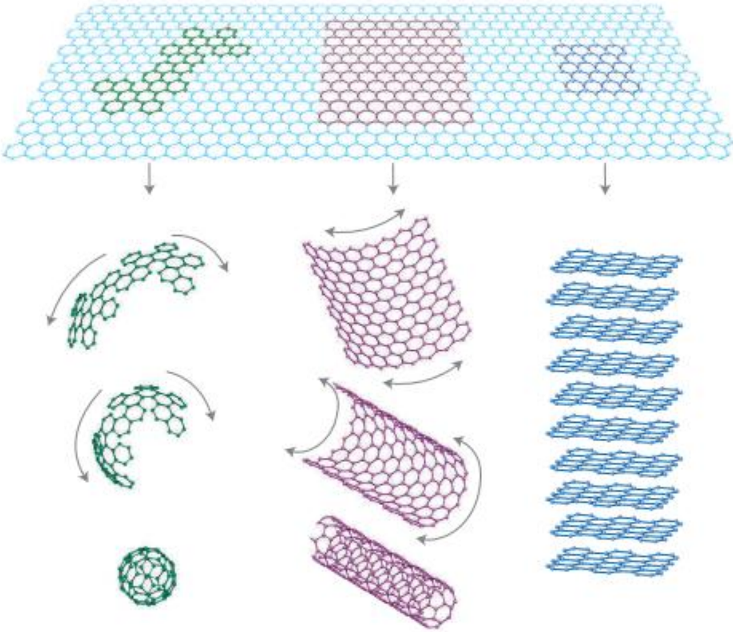
燕保明（Speaker） 章亮 、 胡蕊、李彩珍、牛晶晶、周旭、柳晨、杨传剑、
汤宏建、陈志超



Outline

- Elementary Introduction
- Electronic Structure
- Disorder of Graphene
- Transport (Near and far from Dirac Cone)
- Quantum Hall Effect
- Summary

Elementary Introduction



- Strictly 2D crystals were thermodynamically unstable and could not exist.(Landau& Peierls)
- Theorical study: Electronic structure(Philip Wallace,1947) name ‘graphene’(S.Mouras,1987)
- Experiment seeking:

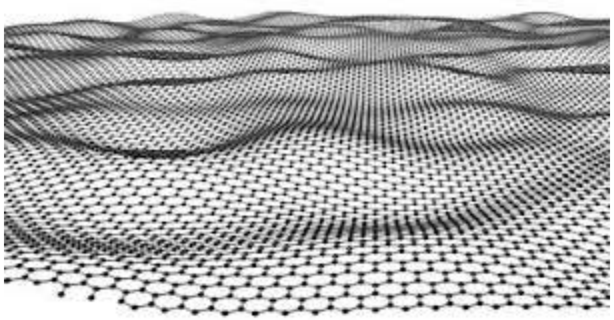
  Extract by AFM (P.Kim Group, Columbia University)

  Epitaxy on SiC (Walt A. de Heer Group,Georgia Institute of Technology)
- Success:

  Scotch tape technique(Andre Geim and Kostya Novoselov, Manchester University)

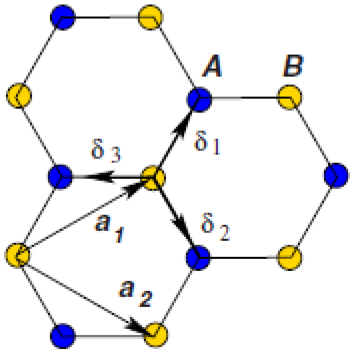
  Nobel Prize 2010!
- Ripples made graphene possible

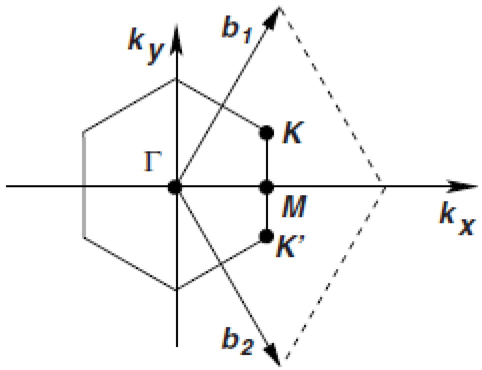
  (~1nm height ,~10nm in planar)



Nature Materials, 6,183(2007)

Electronic Structure





Above left: **lattice structure of graphene**
Above right: **corresponding Brillouin zone.**
Below: **Band structure of graphene**

Band (Tight-binding approach)

$$E_{\pm}(\mathbf{q}) \simeq 3t' \pm v_F|\mathbf{q}| - \left(\frac{9t'a^2}{4} \pm \frac{3ta^2}{8}\sin(3\theta_{\mathbf{q}})\right)|\mathbf{q}|^2,$$

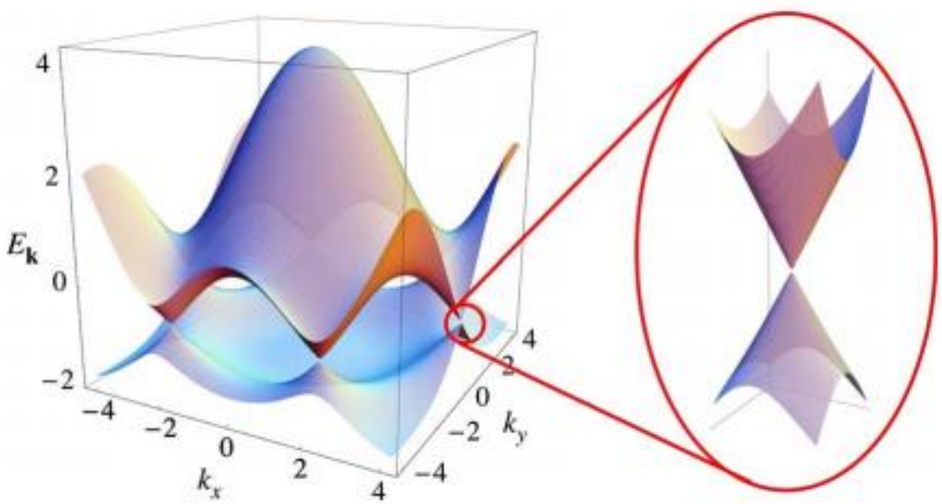
where

$$\theta_{\mathbf{q}} = \arctan\left(\frac{q_x}{q_y}\right)$$

Considering t(≈2.5eV)>>t'(≈0.1eV)

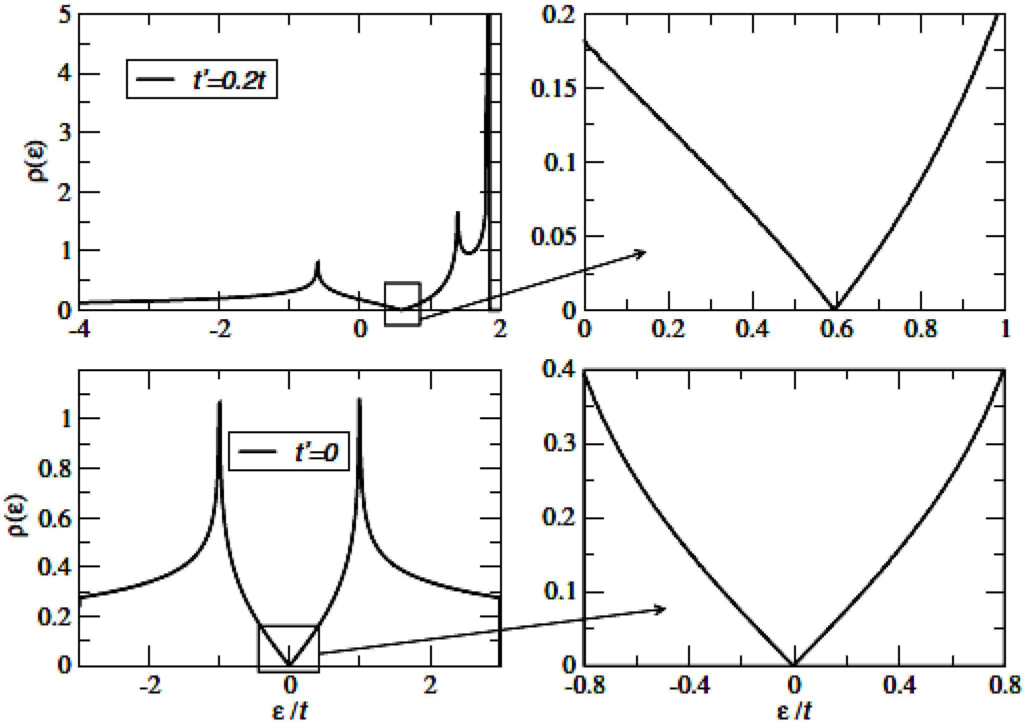
$$E_{\pm}(q) = \pm\hbar v_F q + O(q / k)^2$$

q is the momentum measured relatively to the Dirac points and V_f is the Fermi velocity, with a value $V_f \approx 10^6$ m/ s.(c/300)



Rev. Mod. Phys. 81, 109–162 (2009)

Density of States



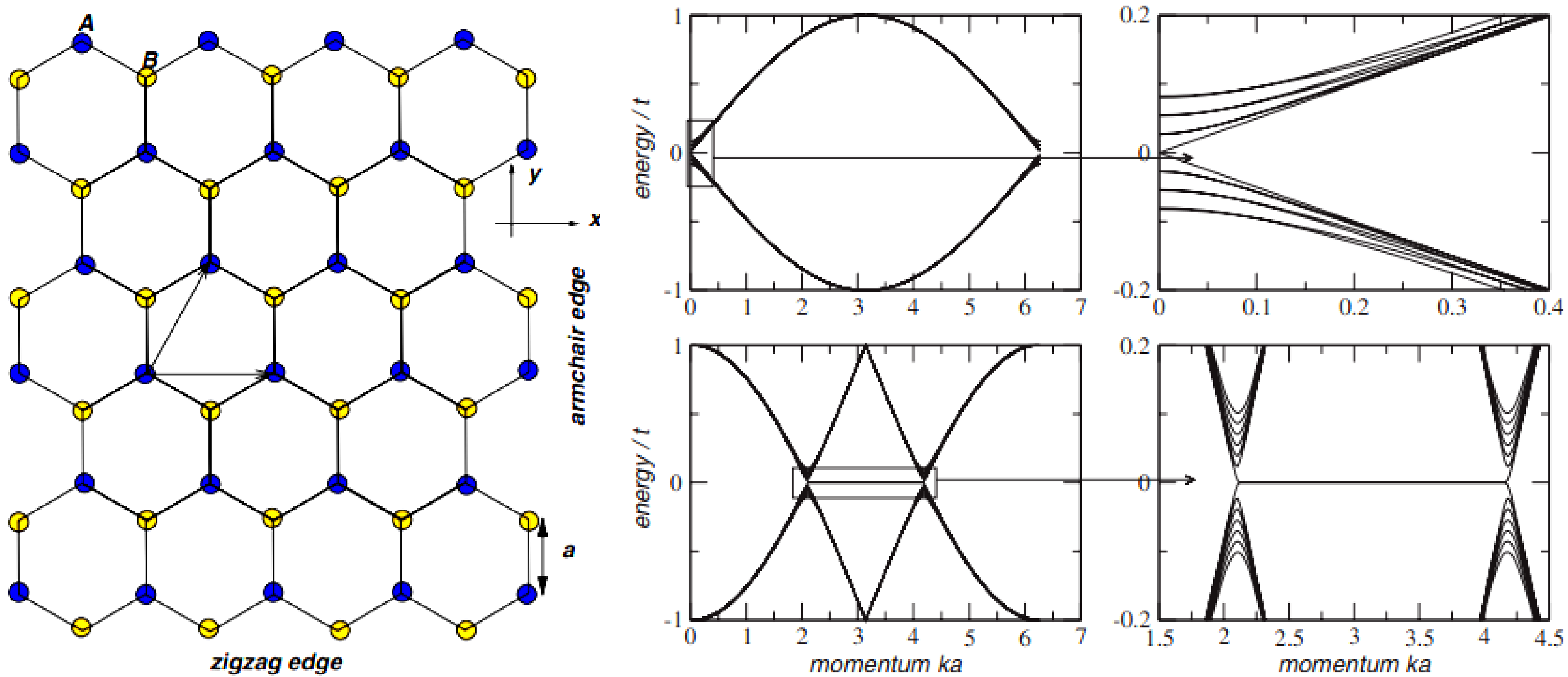
- **Considering the degeneracy is four, (spin&valley),**

$$\rho(E) = \frac{2A_c}{\pi}\frac{|E|}{v_F^2},$$

where A_c is the unit cell area given by $A_c = 3\sqrt{3}a^2/2$.

Wallace, 1947;Rev. Mod. Phys. 81, 109–162 (2009)

Surface(Edge) State & Nanoribbon

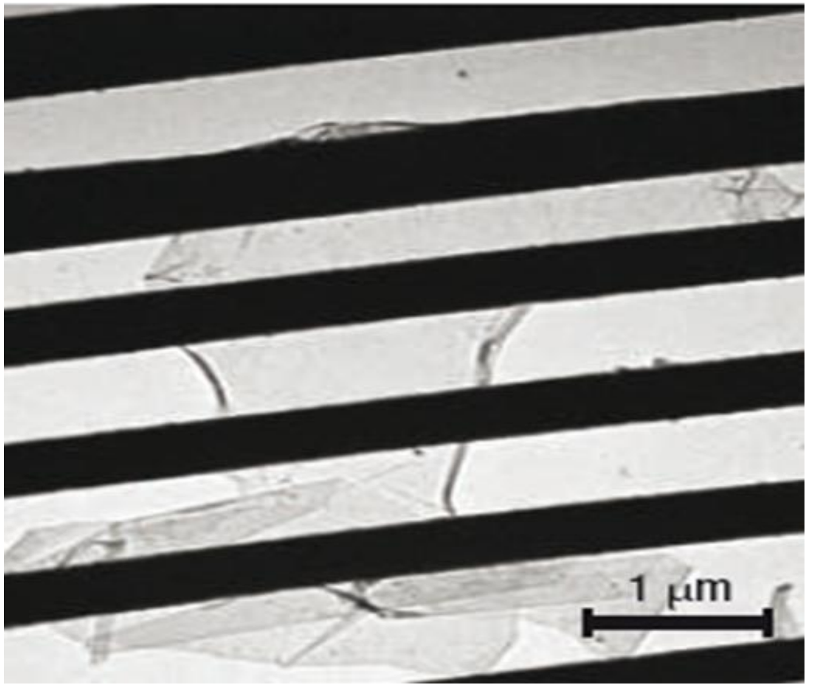


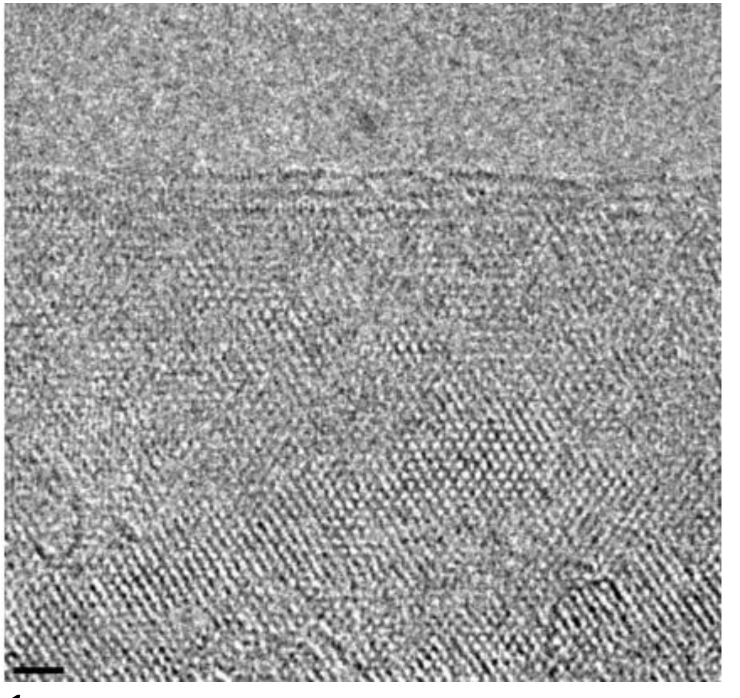
- **Armchair nanoribbons:**
  zero or no-zero gap， based on width(N), no edge state
- **Zigzag nanoribbons:**
  zero gap, exist localized edge state(near fermion energy)

Brey and Fertig, 2006a , 2006b; Rev. Mod. Phys. 81, 109–162 (2009)

Disorder in Graphene

- Ripples
- Topological defects
- Impurities
- Ad-atoms
- Cracks
- Edges





1nm

Meyer J C, et al. Nature, 2007, 446(7131): 60-63.

Why Ripples

- **Number of flexural modes per unit of area at a certain temperature T**

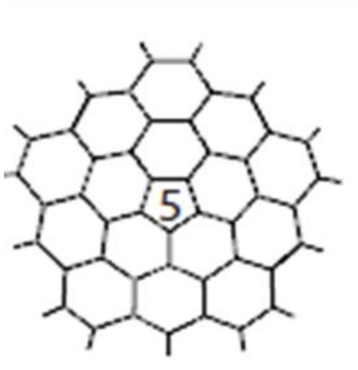
$$N_{\mathrm{ph}} \approx \frac{2\pi}{L_T^2} \ln\left(\frac{L}{L_T}\right), \qquad L_T = \frac{2\pi}{\sqrt{k_B T}}\left(\frac{\kappa}{\sigma}\right)^{1/4}$$

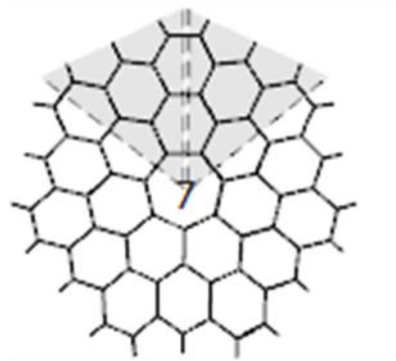
$L_{T,}$ is the thermal wavelength of flexural modes

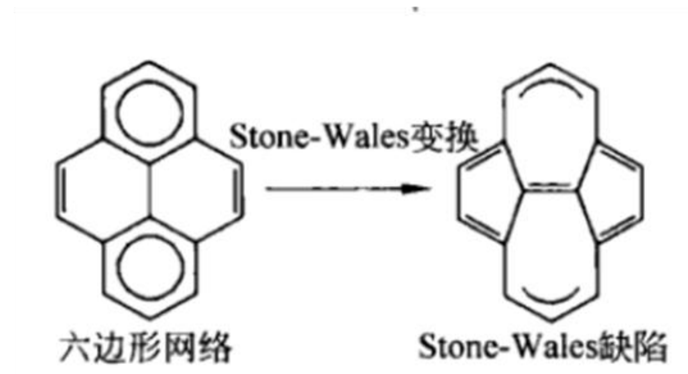
- **At T=300K,L~1** Å
- **Indicating that free-floating graphene should always crumple at room temperature due to thermal fluctuations associated with flexural phonons**

Rev. Mod. Phys. 81, 109–162 (2009)

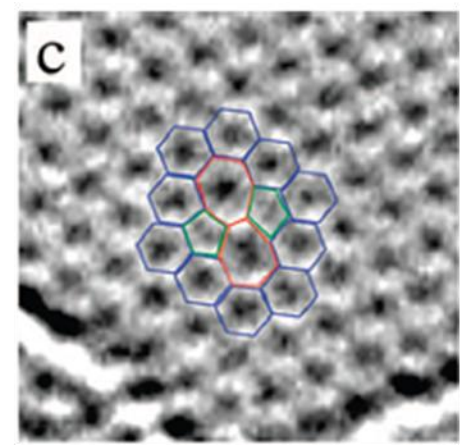
Topological Lattice Defects





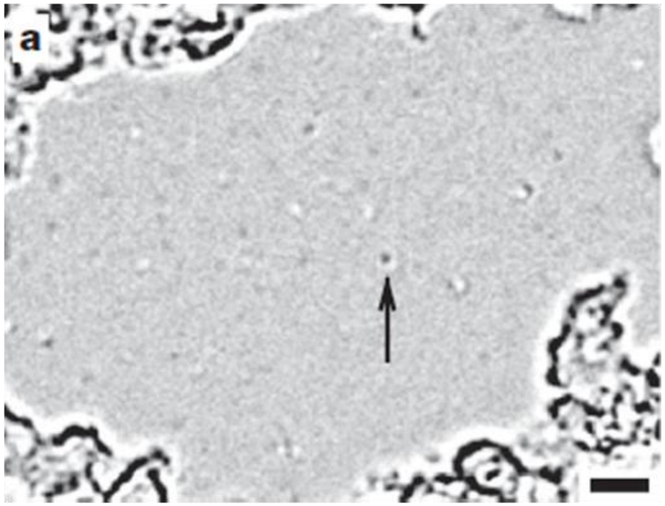


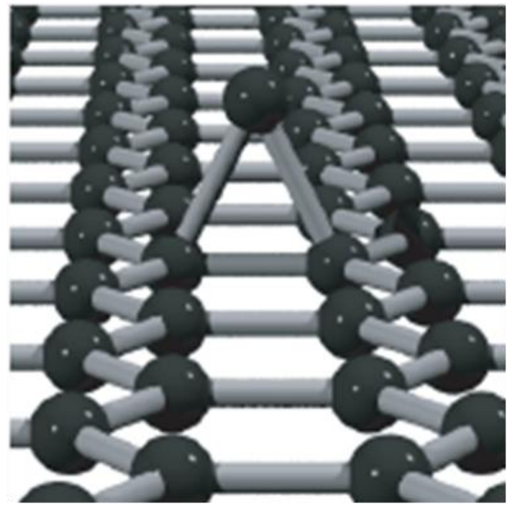
- Structural defects of the honeycomb lattice like **pentagons**, **heptagons**, and their combination such as **Stone-Wales defect** are named **topological lattice defect**.



*Oleg V. Yazyev et al. PHYSICAL REVIEW B **81**, 195420 2010;*
zhiyong wang et al. Acta Phys. Sin. Vol. 60，No. 1 (2011) 017102;
Jannik C. Meyer et al. 2008 Vol. 8, No. 11 3582-3586

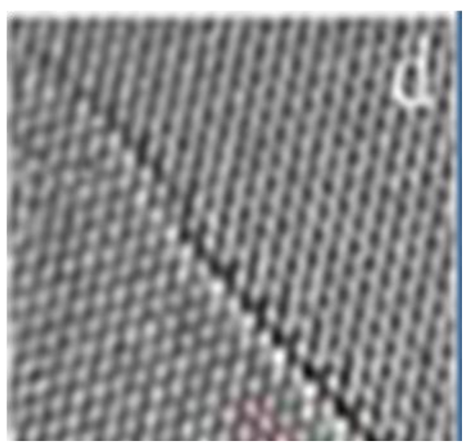
Ad-atoms& Cracks & Edges

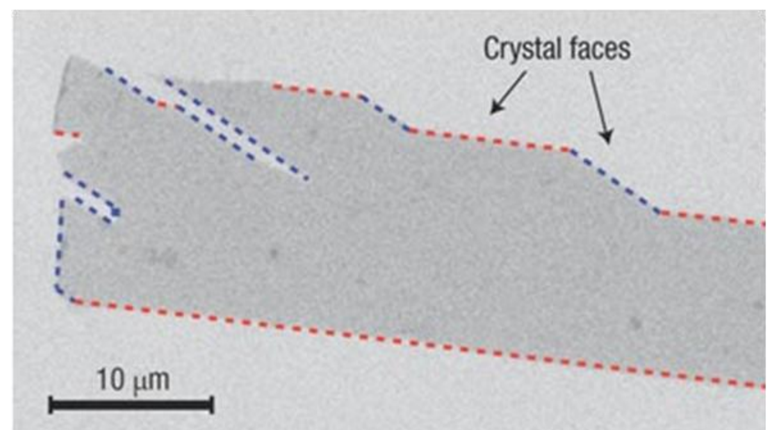




Above: ad-atoms.

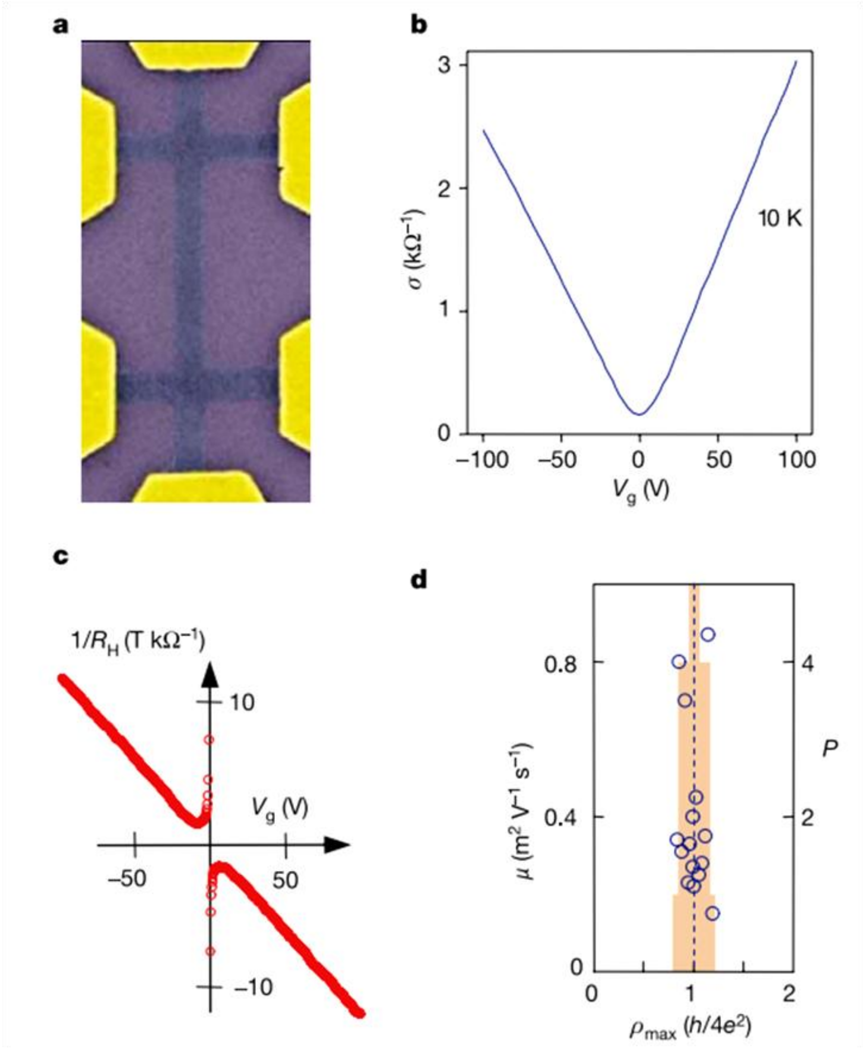
Below: left(cracks)
right(edges)





Meyer, Jannik C., et al. "Imaging and dynamics of light atoms and molecules on graphene." Nature 454.7202 (2008): 319-322.

Transport of Graphene



- **Conductance increases linearly with increasing carrier concentration. ($n = V_g \varepsilon_0 \varepsilon / te$)**
- **Asymmetry of electron and hole**
- **Minimum conductivity near Dirac cone $\sim 4e^2/h$**

Novoselov, K. S. et al. Two-dimensional gas of massless Dirac fermions in graphene.Nature438, 197–200 (2005).

Far From the Dirac Cone

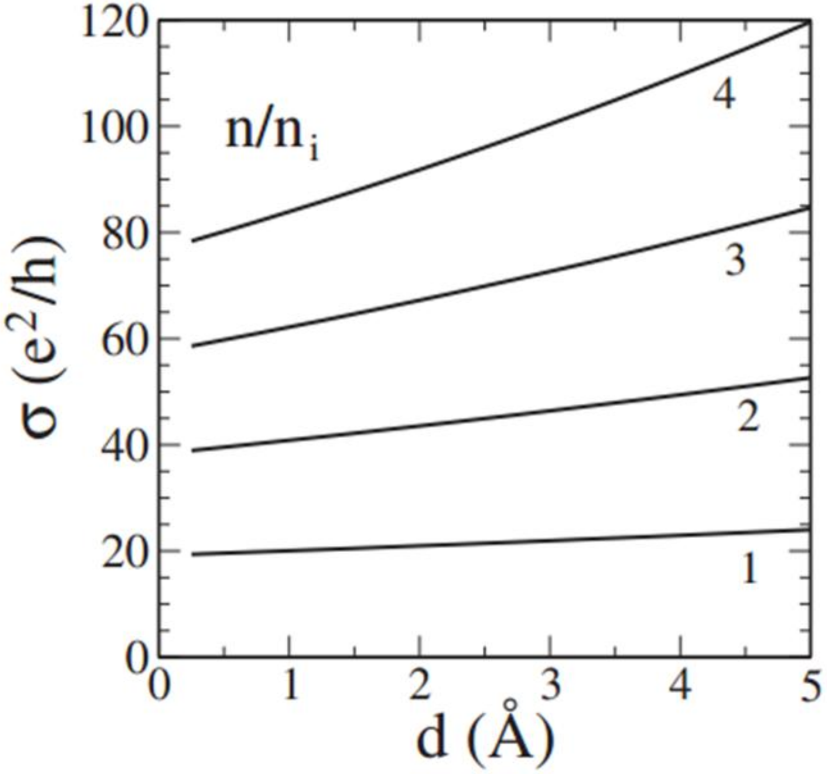
- **Scattering mechanics**
  - random charged impurity centers (long range scattering)
  - short-range scattering (e.g. defects).
  - Phonon (no need considering)
- **Boltzmann transport theory**
  - **For $n >> n_i$,**

$$-\boldsymbol{v}_{\boldsymbol{k}} \cdot \boldsymbol{\nabla}_{\boldsymbol{r}} f(\epsilon_{\boldsymbol{k}}) - e(\boldsymbol{E} + \boldsymbol{v}_{\boldsymbol{k}} \times H) \cdot \nabla_{\boldsymbol{k}} f(\epsilon_{\boldsymbol{k}}) = -\left.\frac{\partial f_{\boldsymbol{k}}}{\partial t}\right|_{\text{scatt}}.$$

  - **Coulomb potential scattering** $\sigma_{xx} = 2\frac{e^2}{h}\frac{\mu^2}{u_0^2} = 2\frac{e^2}{h}\frac{\pi v_F^2}{u_0^2}n,$
  - **Short-range scattering** $\sigma = C$ **So, impurity scattering!**

Hwang, E. H., S. Adam, & S. Das Phys. Rev. Lett.98, 186806 (2007).
Nomura K et.al. Phys. Rev. Lett, 2007, 98(7): 076602.

Asymmetry of Electron and Hole



- **Approximate:**
  - **The impurities are confined in a 2D plane located at distance d from the interface.**
  - **A small shift of d~1-2** Å
  - **Approximate that the impurities are confined in a 2D plane located at distance d from the interface**

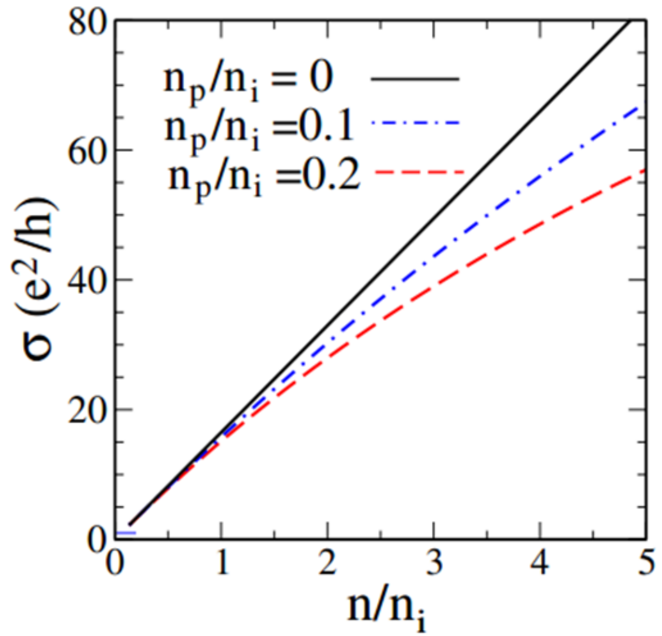
Hwang, E. H., S. Adam, & S. Das Sarma.Carrier transport in two-dimensional graphene layers. Phys. Rev. Lett.98, 186806 (2007).

Sublinear for High Mobility Sample

- For high mobility sample, charged Impurity concentration n_i is small, the point defect play a more dominar role.

- Conductance corresponding to defec constant.

- For most sample $n_p/n_i \ll 1$, for highe mobility samples, $n_p/n_i \sim 0.2$



Hwang, E. H., S. Adam, & S. Das Sarma.Carrier transport in two-dimensional graphene layers. Phys. Rev. Lett.98, 186806 (2007).

Near Dirac Cone: Minimum Conductivity

- **Theoretically Prediction:** $\sigma = \frac{4e^2}{\pi h}$
- **Experiment :** $\sigma = \frac{4e^2}{h}$
- Intrinsic or extrinsic property of graphene?
- **Extrinsic** :
- **2D electrons and hole conducting puddles caused by impurities**
- **Considering screened impurity scattering,**

$$\sigma = \frac{e^2}{h}\frac{n}{n_{\mathrm{imp}}}\frac{2}{G[2r_s]},$$

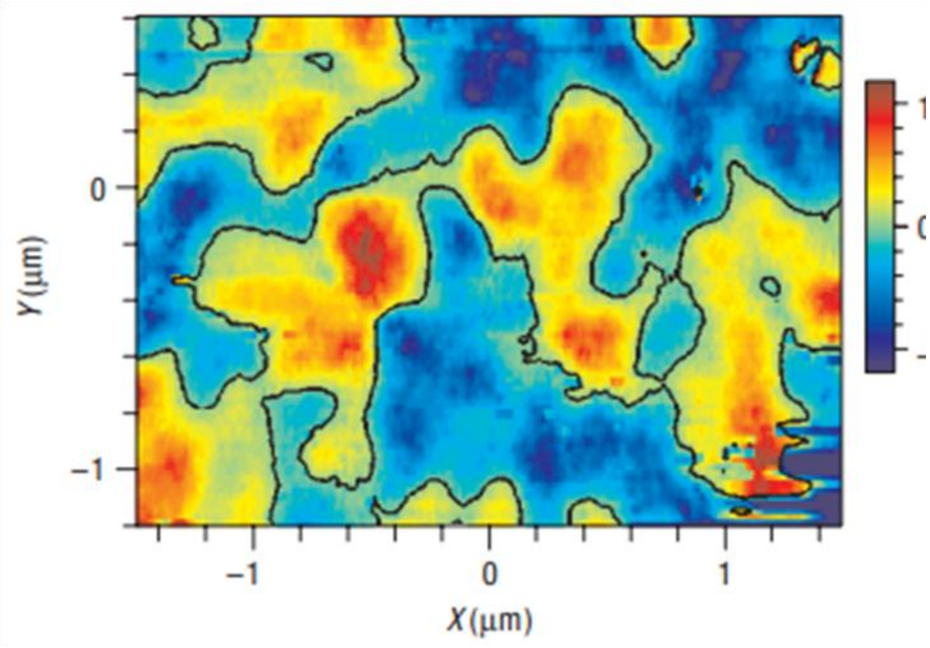
$$\frac{G[x]}{x^2} = \frac{\pi}{4} + 3x - \frac{3\pi x^2}{2} + \frac{x(3x^2-2)\arccos[1/x]}{\sqrt{x^2-1}},$$

- **For Graphene on SiO_2:** $\sigma = 20(e^2/h)(n/n_{imp})$

S. Adam.et .al. PNAS, 104, 18392 (2007). Nomura K et.al. Phys. Rev. Lett, 2007, 98(7): 076602.

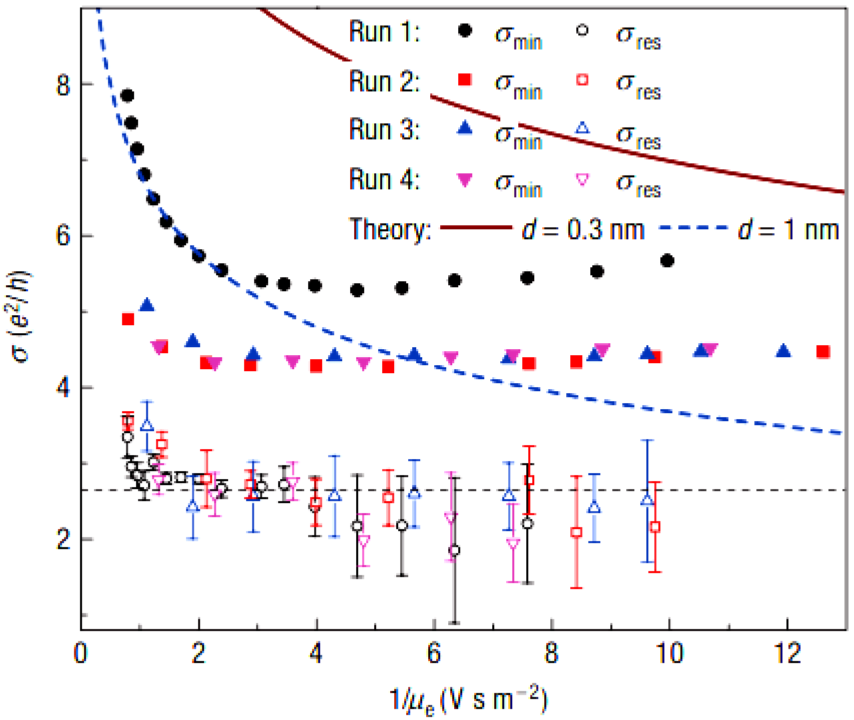
Near Dirac Cone: Minimum Conductivity

- **Observation of electron–hole puddles in graphene using a scanning single-electron transistor**



J. Martin.et.al. Nature Physics,4,144(2007).

- **Experimental Verification**



Chen J H, et al. Nature Physics, 2008, 4(5): 377-381.

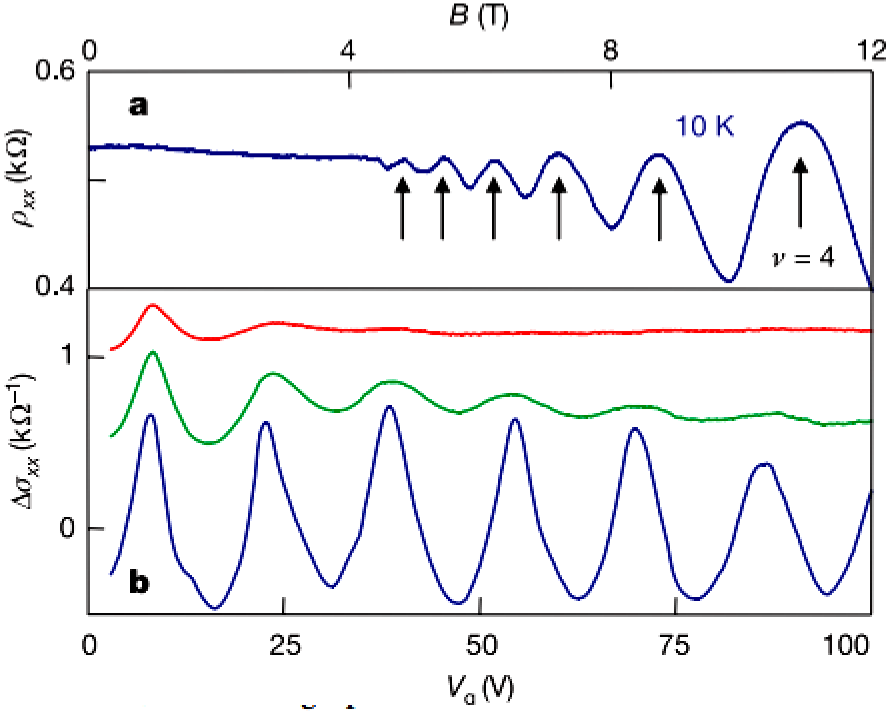
Quantum Hall Effect

- **Half-integer Quantum Hall Effect (SDH Oscillation)**
- **Landau-Level Splitting in High Magnetism**
- **Fractional Quantum Hall Effect**

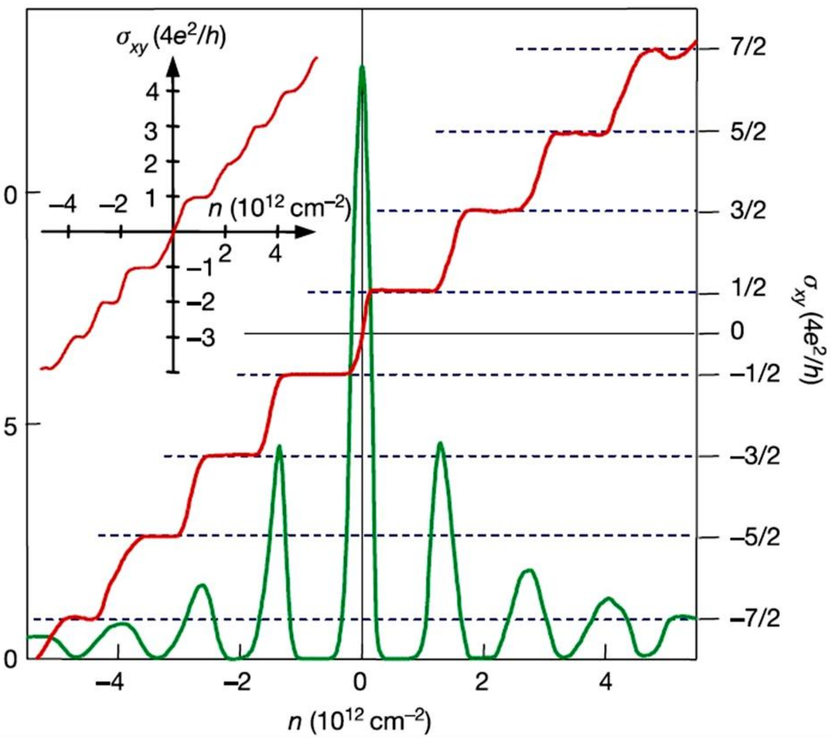
Half-integer Quantum Hall Effect (SdHO)

Two-dimensional gas of massless Dirac fermions in graphene

K. S. Novoselov[1], A. K. Geim[1], S. V. Morozov[2], D. Jiang[1], M. I. Katsnelson[3], I. V. Grigorieva[1], S. V. Dubonos[2] & A. A. Firsov[2]



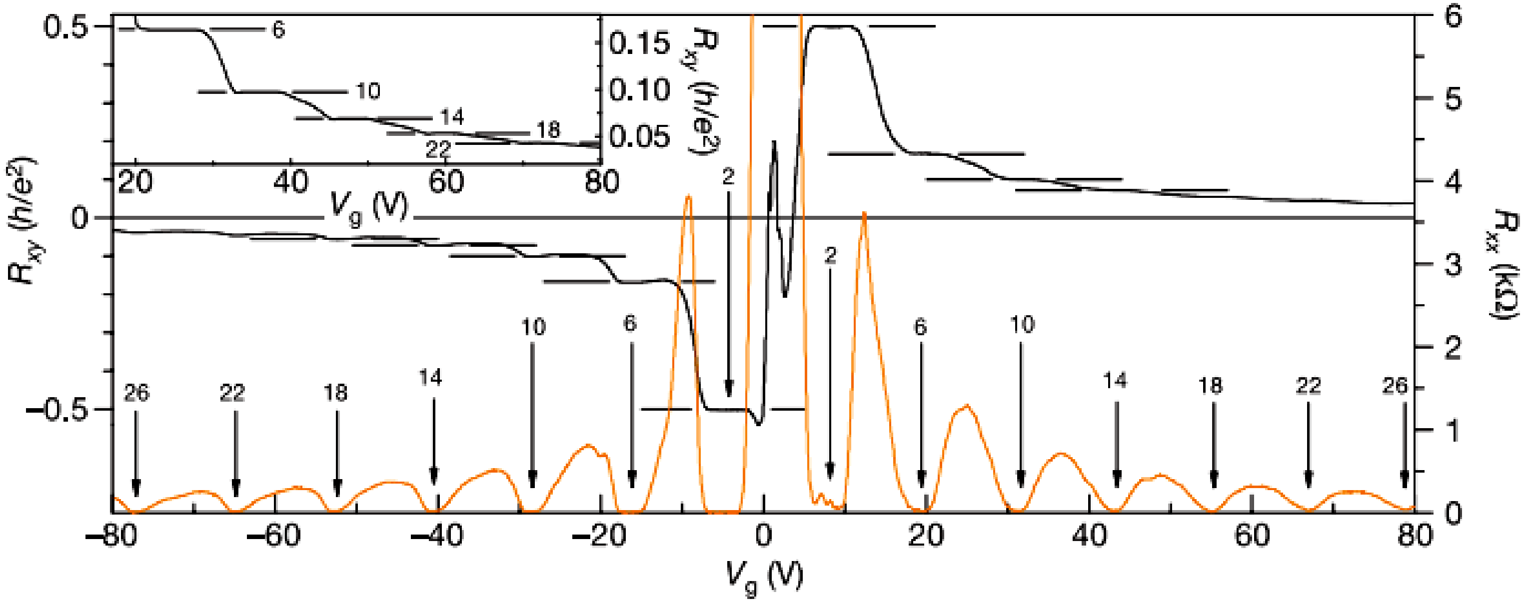
blue, $T = 20$ K; green, $T = 80$ K; red, $T = 140$ K.



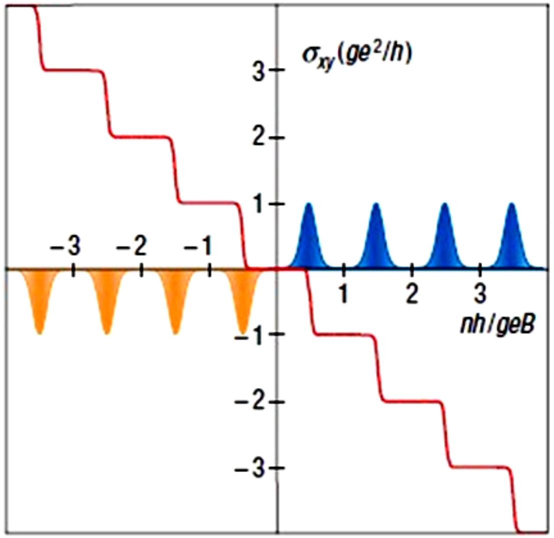
Half-integer Quantum Hall Effect (SdHO)

Experimental observation of the quantum Hall effect and Berry's phase in graphene

Yuanbo Zhang[1], Yan-Wen Tan[1], Horst L. Stormer[1,2] & Philip Kim[1]

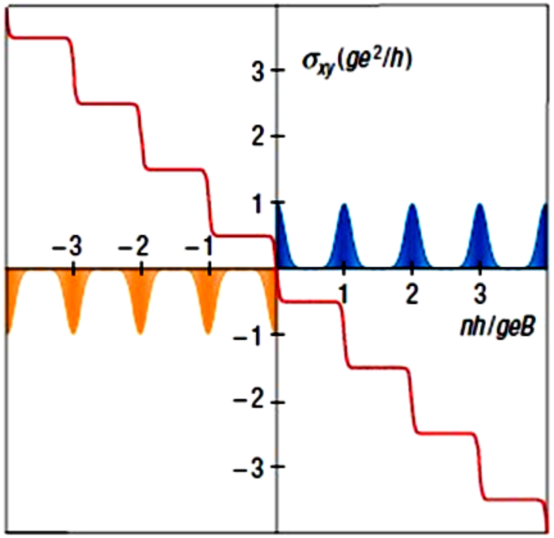


Different Types of Landau quantization



2DEG

$$\sigma_{xy} = gn\frac{e^2}{h}$$



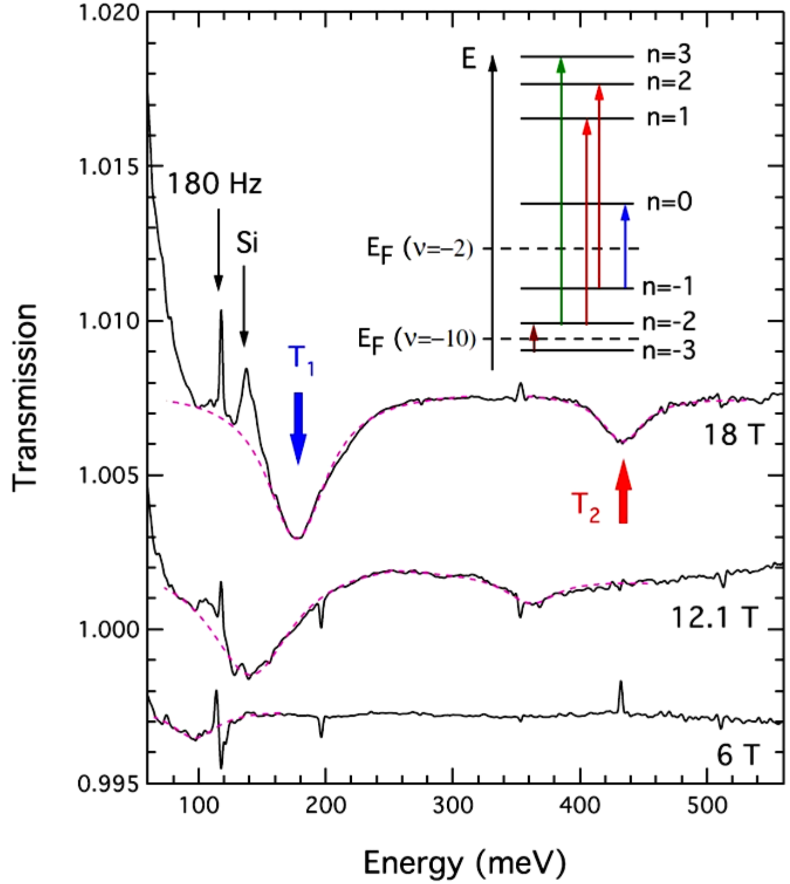
MLG $\upsilon = \pm 2, \pm 6, \ldots$

$$\sigma_{xy} = g(n + \frac{1}{2})\frac{e^2}{h}$$

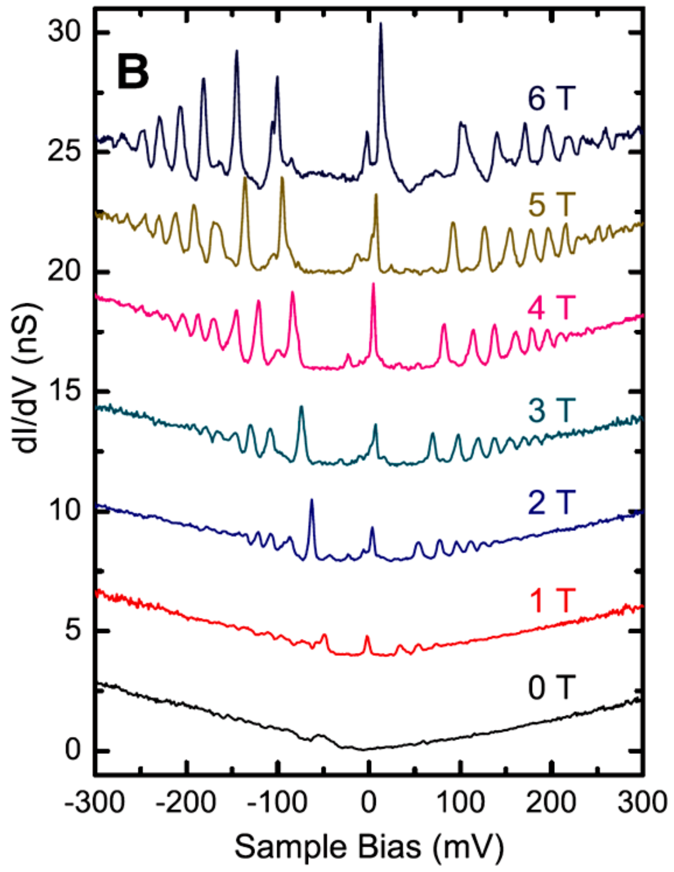
Landau Level:

$$E_n = sgn(n) v_F \sqrt{2e\hbar B|n|}$$

Observation of Landau Level in Graphene

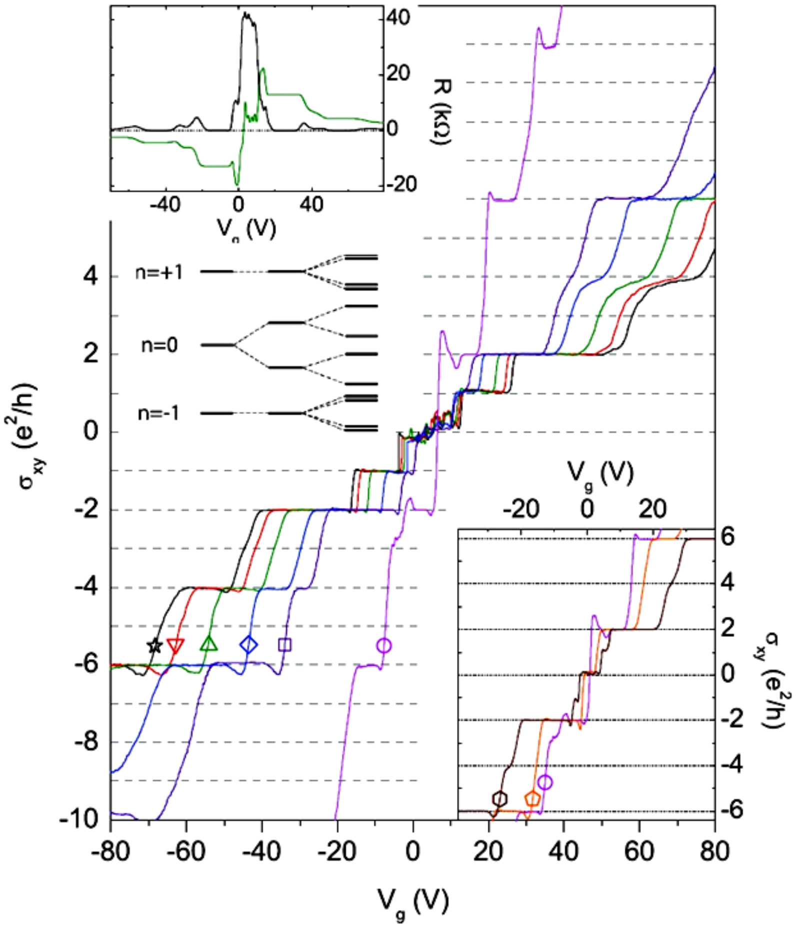


Infrared Spectroscopy of Landau Levels
PRL 98, 197403 (2007)



STM Observation of LLs
Miller et al., Science 324, 924 (2009)

Symmetry Breaking: Landau-Level Splitting



- **New sets:** $\upsilon = 0, \pm 1, \pm 4$
- **n=0 LL splits into four sublevels, lifting spin and sub-lattice degeneracy**
- **n=1 LL, only the spin degeneracy is lifted**

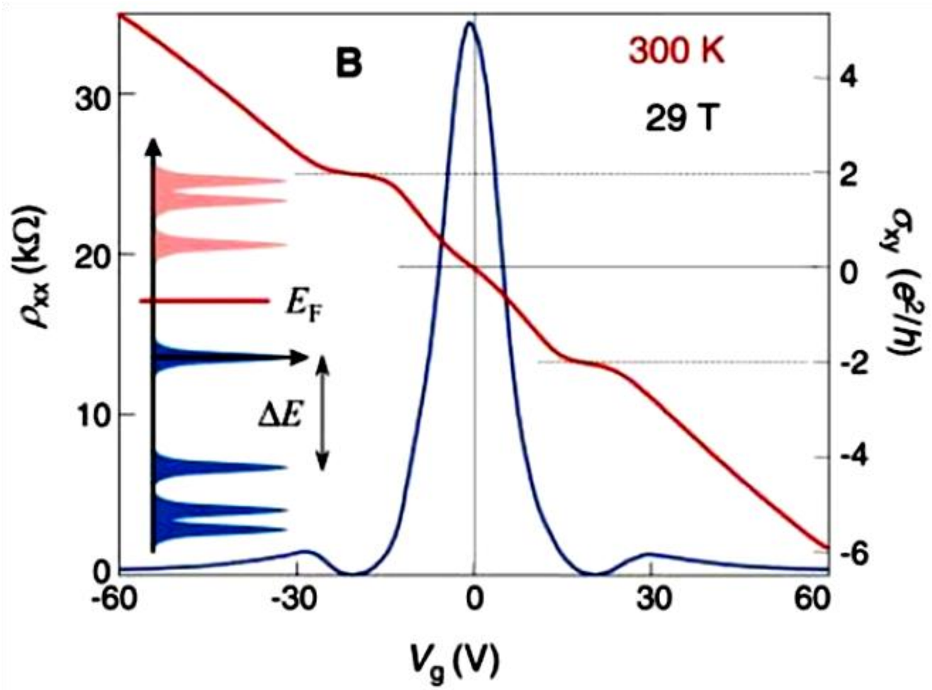
Zhang Y, Jiang Z, Small J P, et al. Physical review letters, 2006, 96(13): 136806.

Room-Temperature QHE

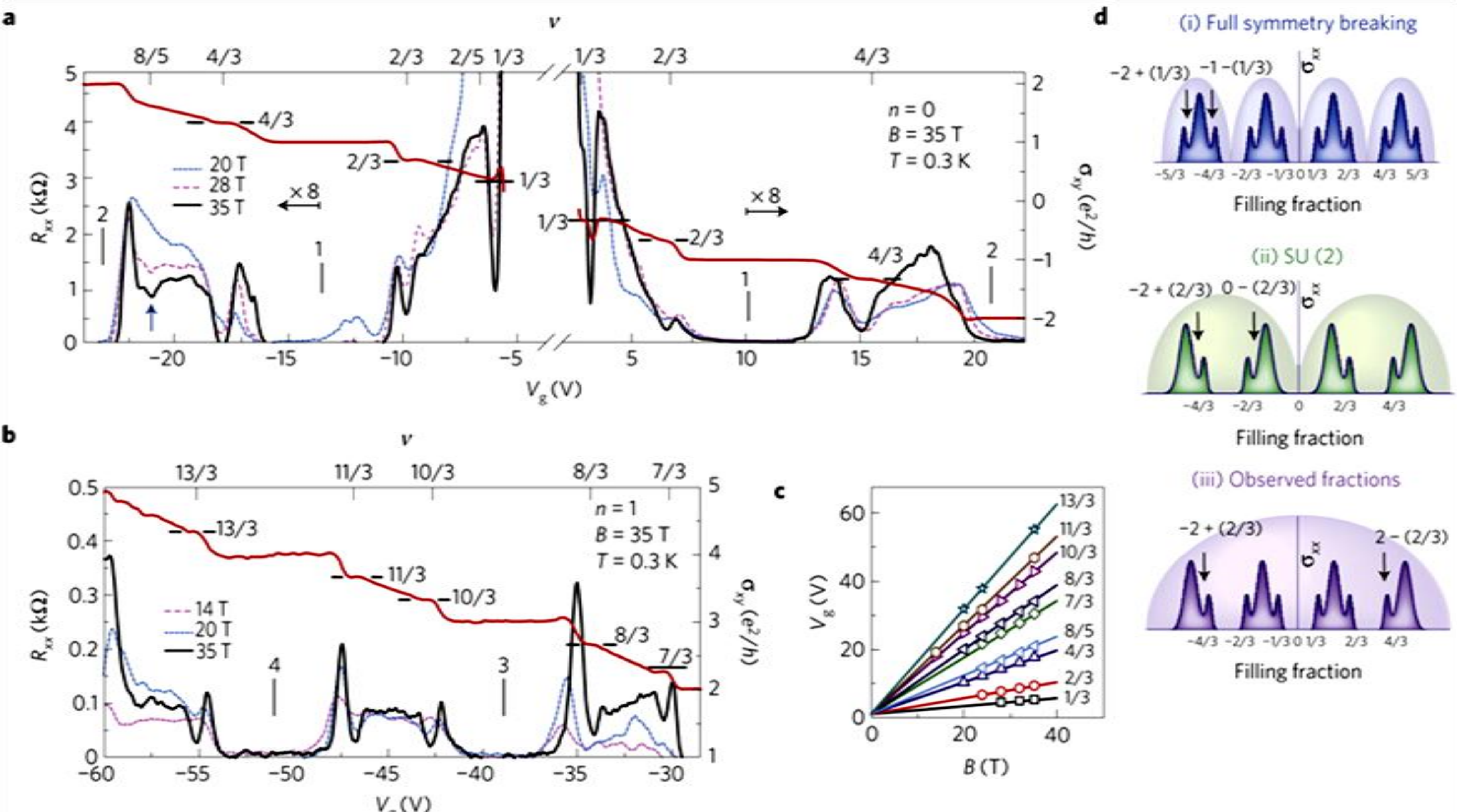
At 10T,cyclotron gaps~1000K for graphene ,~10K (2DEG)

Room-Temperature Quantum Hall Effect in Graphene

K. S. Novoselov,[1] Z. Jiang,[2,3] Y. Zhang,[2] S. V. Morozov,[1] H. L. Stormer,[2] U. Zeitler,[4] J. C. Maan,[4]
G. S. Boebinger,[3] P. Kim,[2]* A. K. Geim[1]*



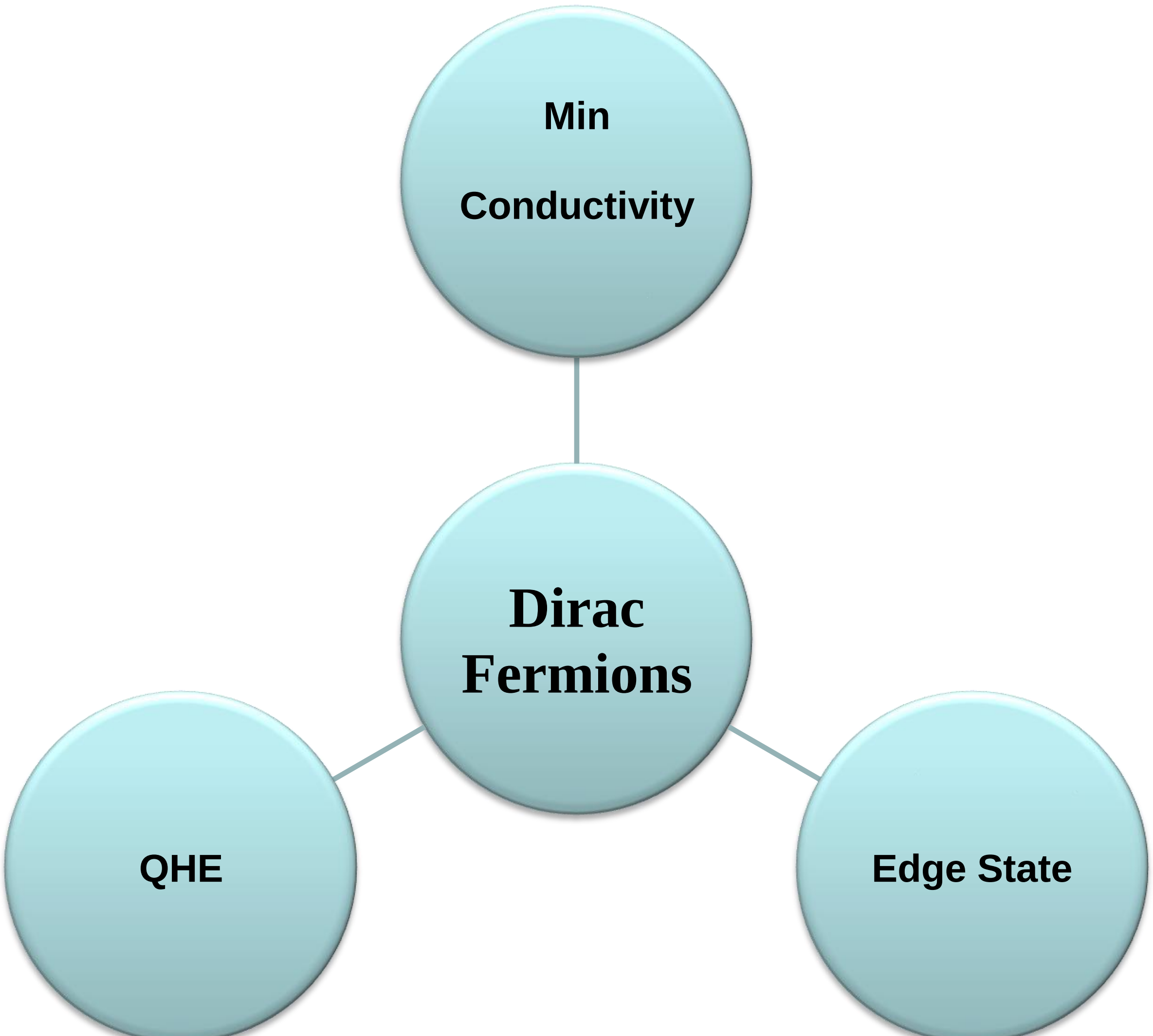
Fractional Quantum Hall Effect



Suspended graphene:
Nature 462, 196(2009) ;Nature 462, 192(2009)

BN substrate:
Nature Physics ,7,693(2011)

Summary



Thank you!