Massless fermion in Graphene

Habib Rostami

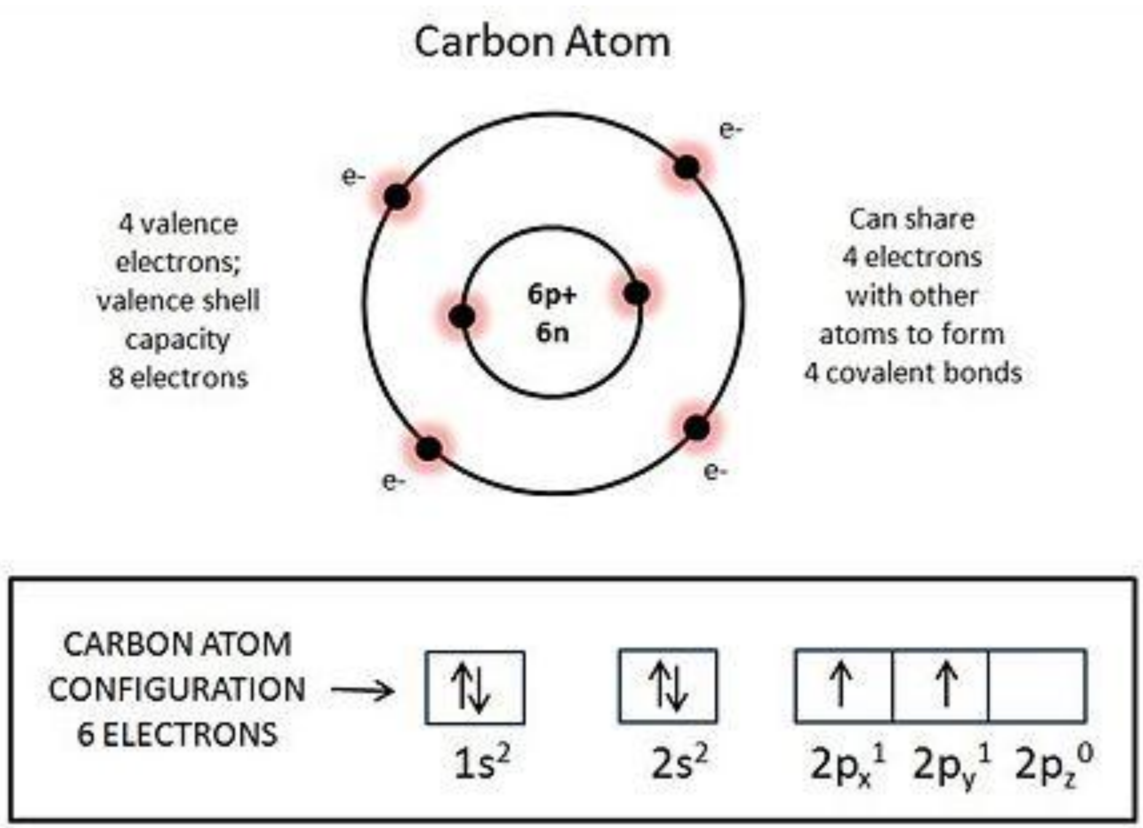
IPM

December 18,2011

Outline

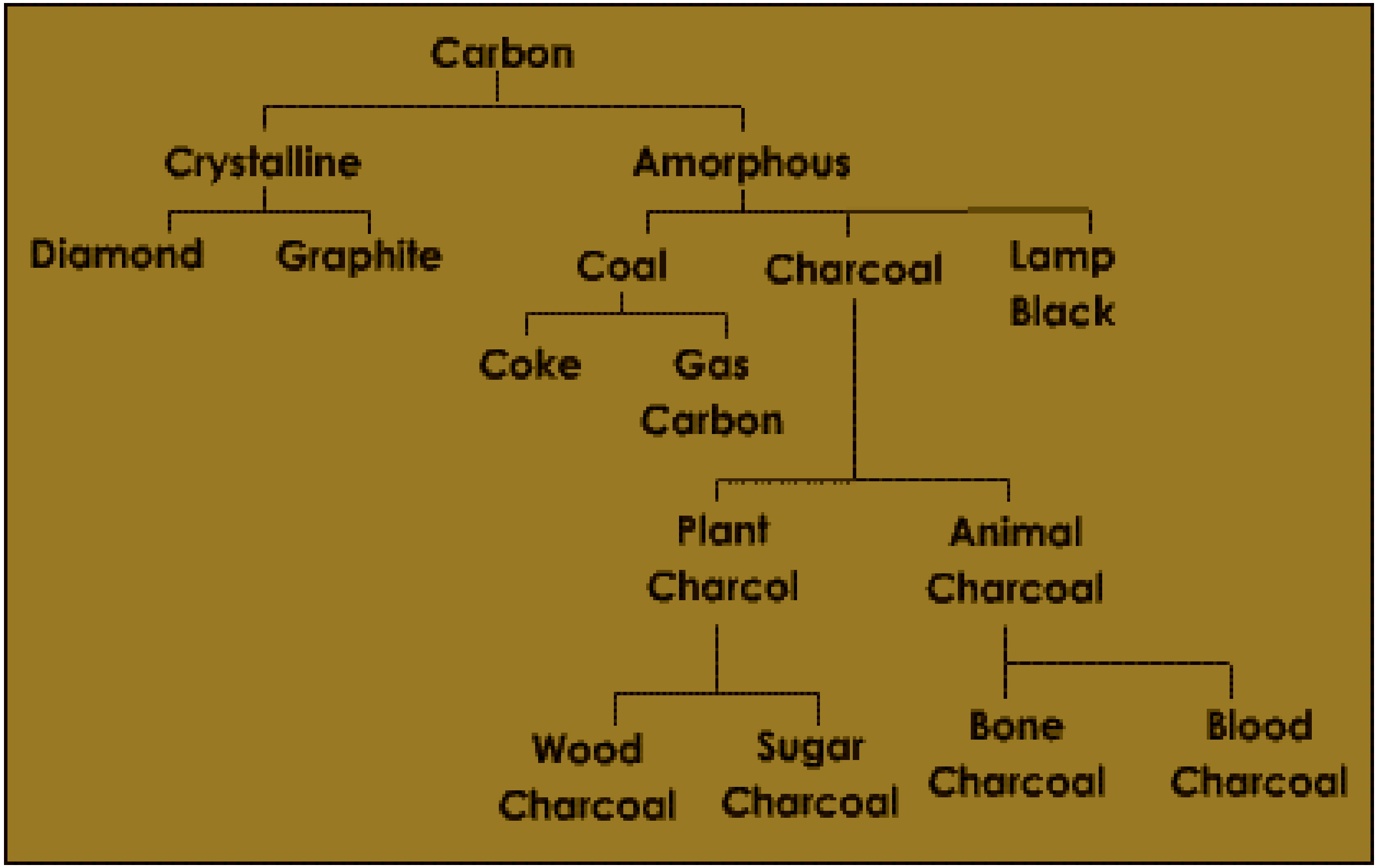
- allotropes of Carbon
- Two dimensional lattice stability
- Electronic structure of Graphene
- Experimental evidences for massless fermions in graphene

Carbon



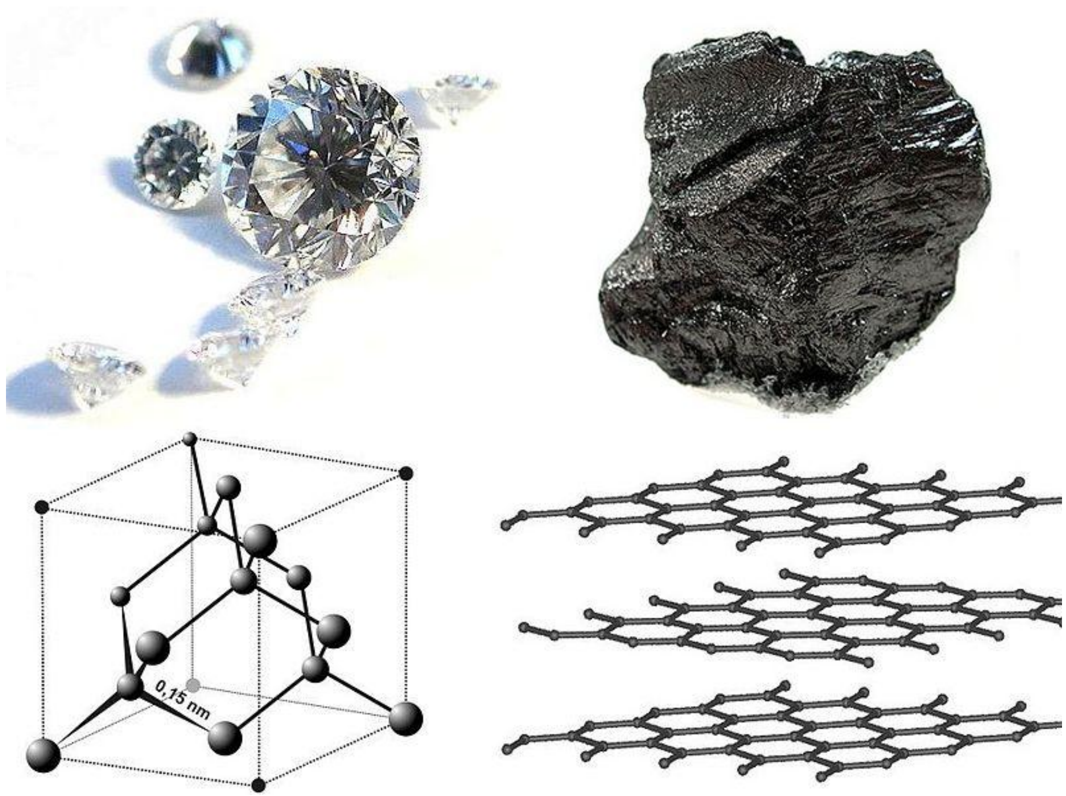
http://en.citizendium.org/wiki/life

The allotropes of Carbon



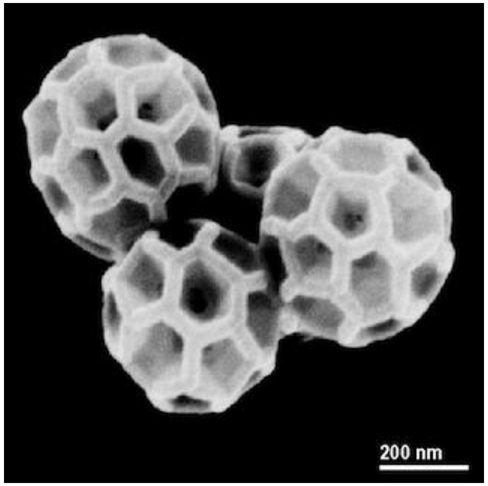
http://chemistry.tutorvista.com/inorganic-chemistry/allotropes-of-carbon.html

Diamond And Graphite



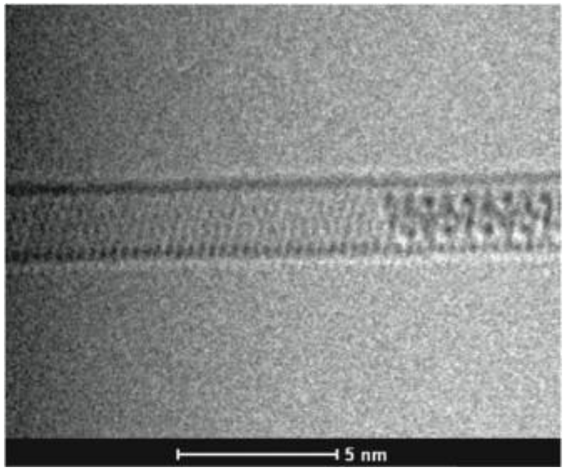
http://en.wikipedia.org/wiki/File:Diamond_and_graphite2.jpg

New allotropes of Carbon



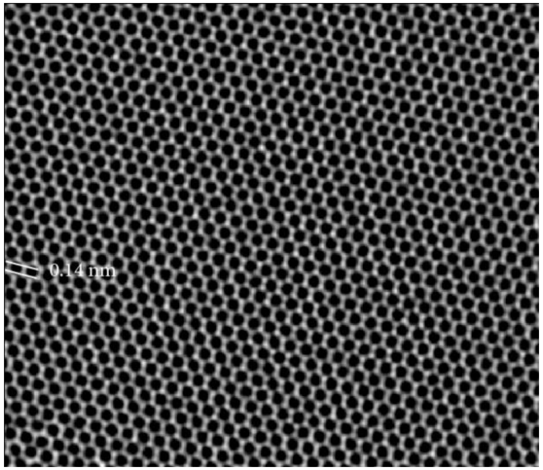
Fullerene

Harold Kroto, et al
1986



Carbon nanotube

Sumio Iijima
1991



Graphene

2004

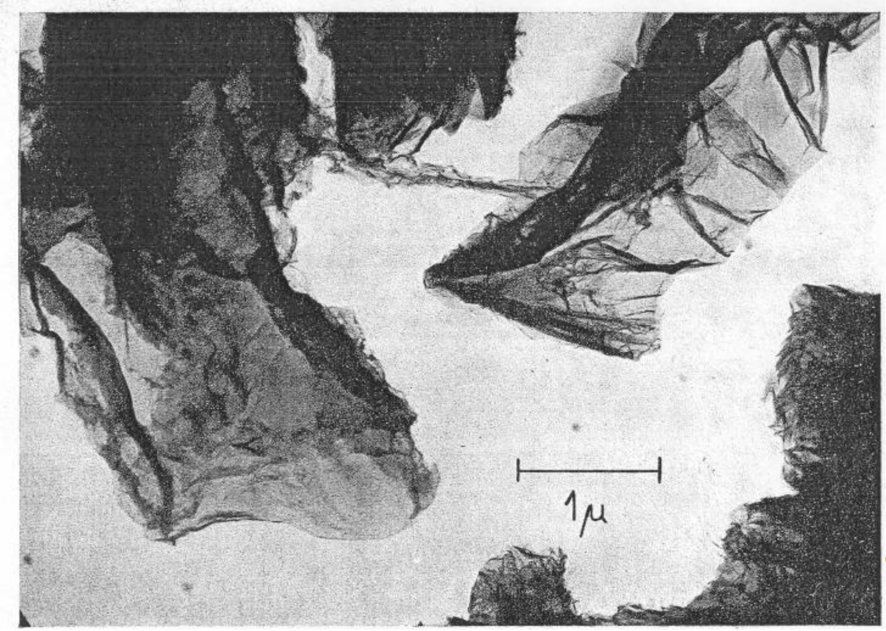
Graphene for the first time!!!

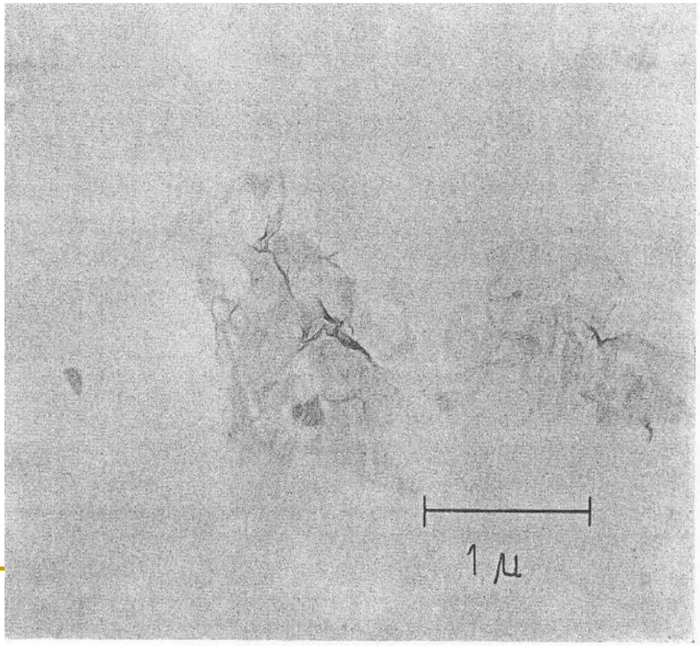
Reprinted from "Proceedings of the Fifth Conference on Carbon"
PERGAMON PRESS
OXFORD . LONDON . NEW YORK . PARIS
1962

SURFACE PROPERTIES OF EXTREMELY THIN GRAPHITE LAMELLAE

H. P. BOEHM, A. CLAUSS, G. FISCHER and U. HOFMANN
Anorganisch-Chemisches Institut der Universität, Heidelberg, Germany

(Manuscript received September 15, 1961)





Graphene for the first time

19912 *J. Phys. Chem. B* **2004,** *108,* 19912−19916

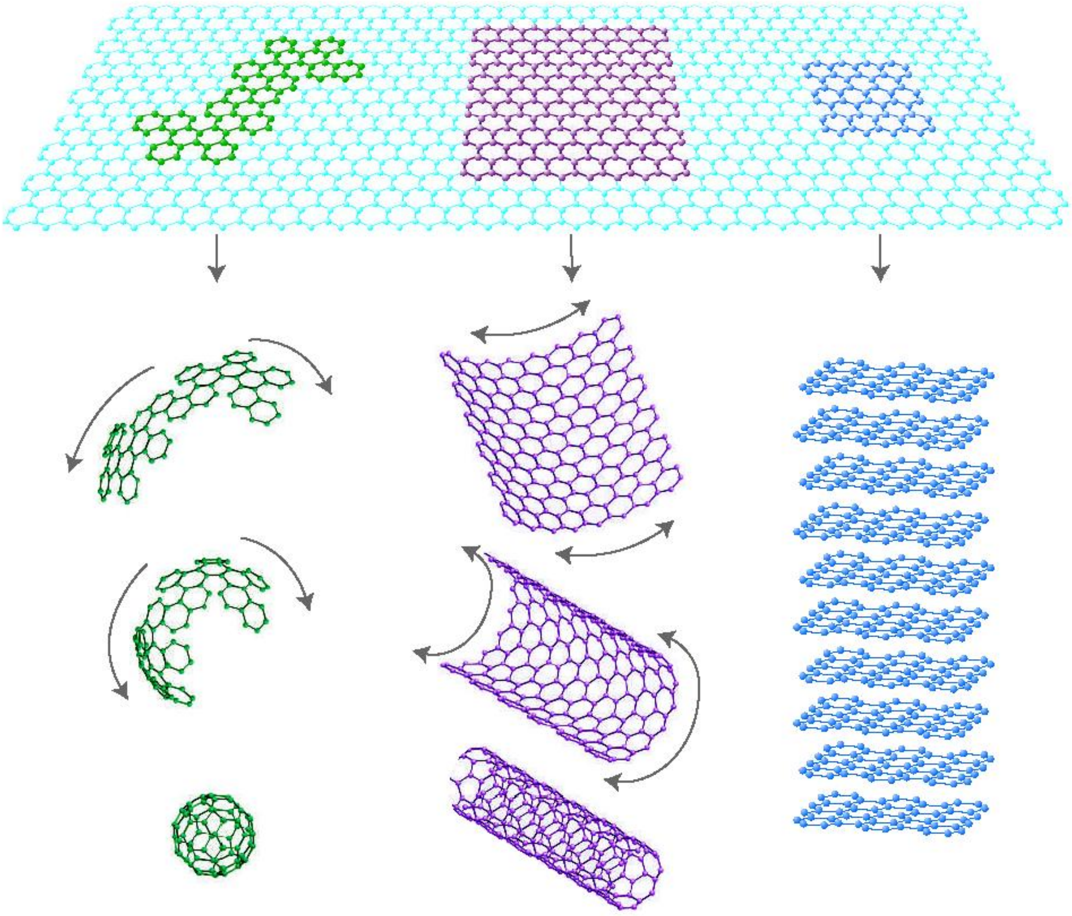
Ultrathin Epitaxial Graphite: 2D Electron Gas Properties and a Route toward Graphene-based Nanoelectronics

Claire Berger,† Zhimin Song, Tianbo Li, Xuebin Li, Asmerom Y. Ogbazghi, Rui Feng, Zhenting Dai, Alexei N. Marchenkov, Edward H. Conrad, Phillip N. First, and Walt A. de Heer*

Science AAAS

Electric Field Effect in Atomically Thin Carbon Films
K. S. Novoselov, *et al.*
Science **306**, 666 (2004);
DOI: 10.1126/science.1102896

Graphene



THE RISE OF GRAPHENE

A.K. Geim and K.S. Novoselov

2D!

In harmonic approximation

$$F = \frac{\gamma}{2}\int |\nabla h|^2 \; ds + \frac{\kappa}{2}\int (\nabla^2 \mathrm{h})^2 \, ds$$

$$\langle h^2 \rangle \propto T \; Log[L/a] \quad , \;\; L \gg a$$

D=2

Logarithmic Divergence

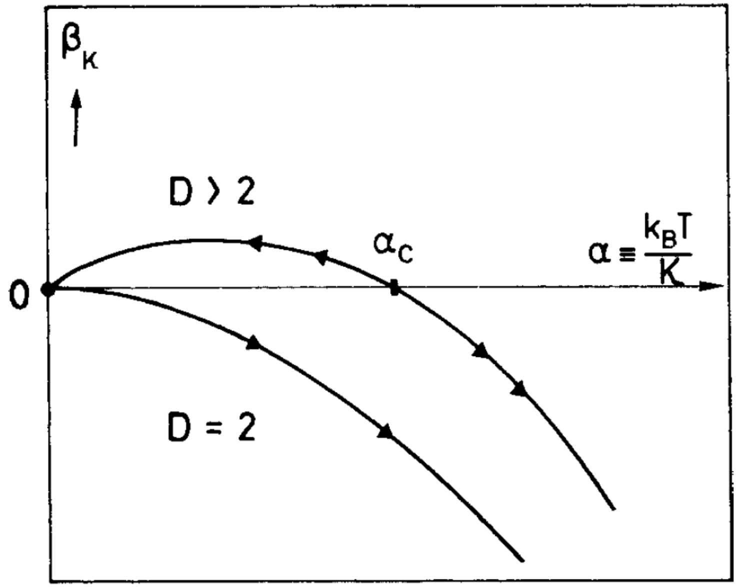
Peierls(1934), Landau(1937) ,Mermin&Wagner(1966)

Anharmonic terms

$$F = \frac{\gamma}{8}\int |\nabla h|^4 \; ds + \frac{\kappa}{4}\int \left(\nabla^2 h\right)^2 |\nabla h|^2 \, ds + \frac{\bar{\kappa}}{2}\int \nabla^2 h \, \nabla h . \nabla |\nabla h|^2 \, ds$$

$$\beta_\kappa = \mu \left.\frac{d\kappa}{d\mu}\right|_{\kappa_0}$$

$$\frac{\kappa}{\kappa_0} \sim L^{|\epsilon|}, \qquad D = 2 + |\epsilon|$$



Statistical Mechanics of Membranes and Surfaces

by: David Nelson, Steven Weinberg, T Piran

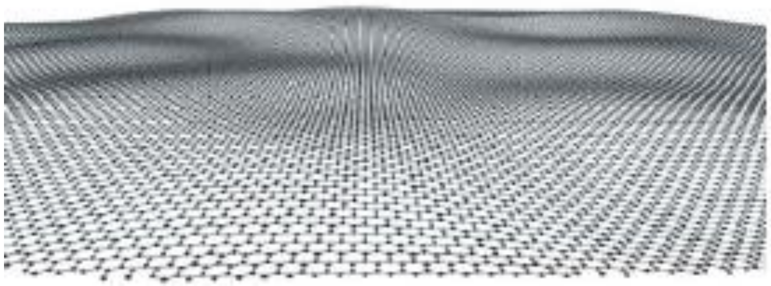
nature
Vol 446|1 March 2007|doi:10.1038/nature05545

LETTERS

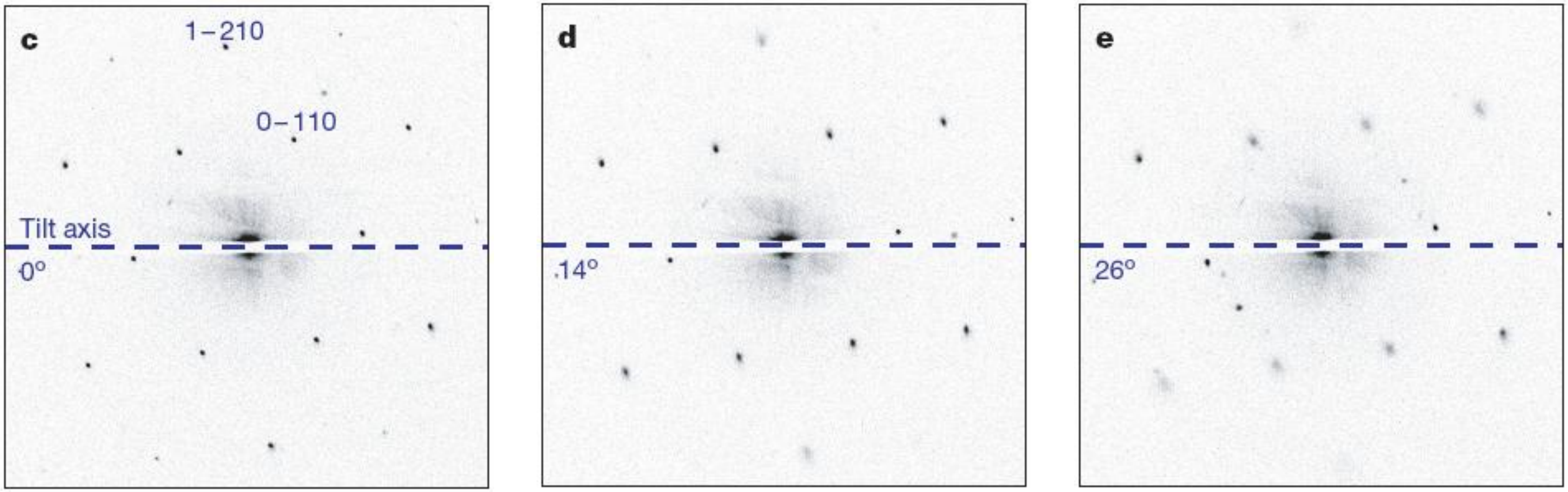
The structure of suspended graphene sheets

Jannik C. Meyer[1], A. K. Geim[2], M. I. Katsnelson[3], K. S. Novoselov[2], T. J. Booth[2] & S. Roth[1]

Scale bar, 500 nm



Ripple in Graphene



Electron diffraction pattern

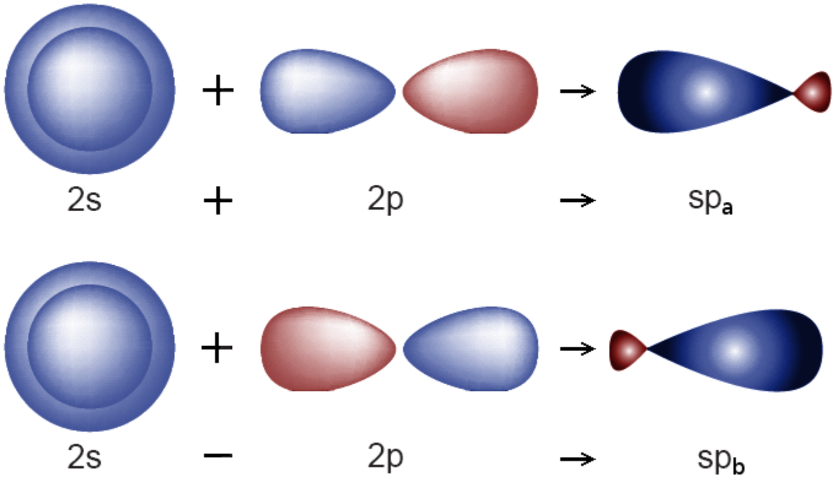
The fabrication of Graphene

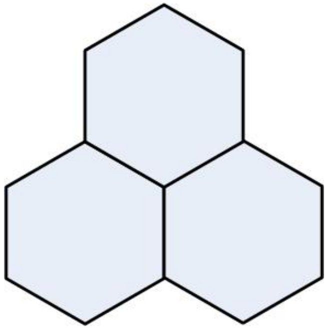
Mechanical cleavage

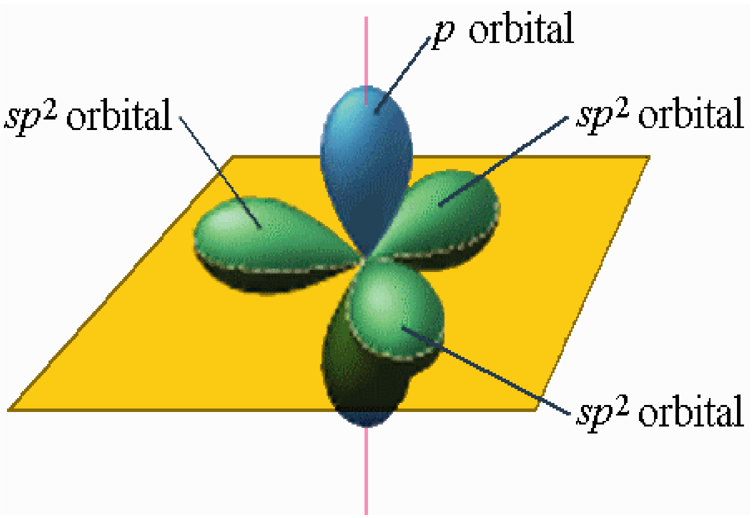
silicon carbide is heated up to 1100 °C

Epitaxial growth on metal substrates

Carbon atoms in Graphene





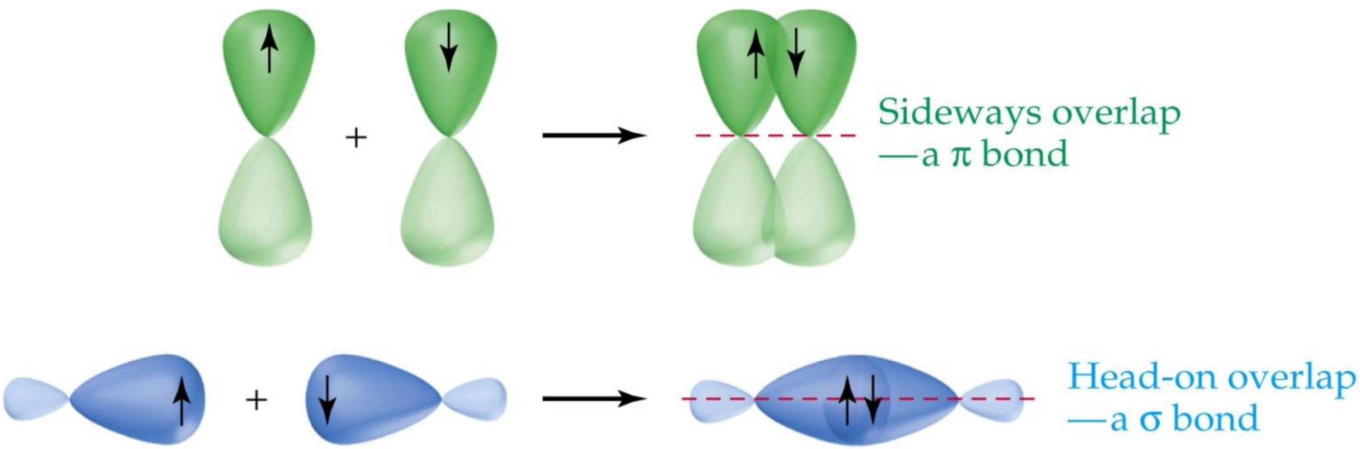


C:1s^2 2s^2 2p^2 →1s^2 2s^1 2p^3

→(two)1s^2 +(three)sp^2 + (one)p$_z$

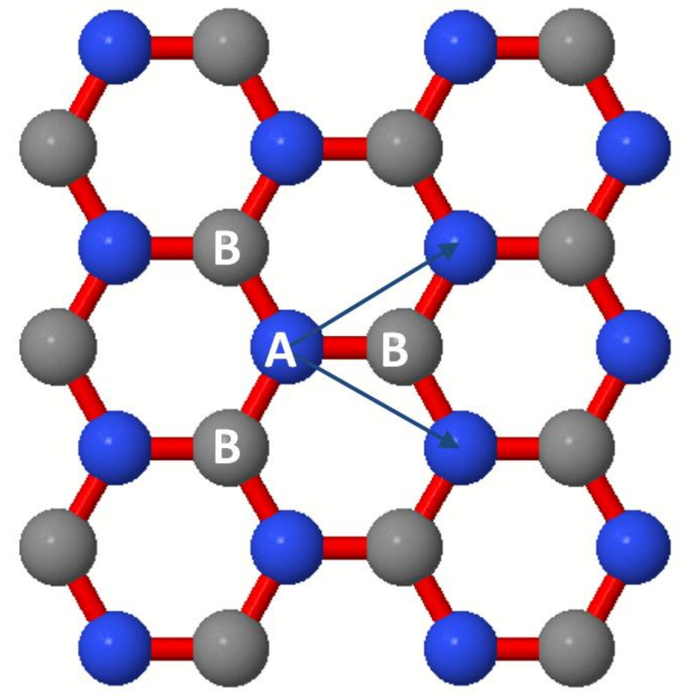
1-S. Thompson and J. Staley. *Orbitals and Molecular Representation*
2-Jason E. Hill's presentation

σ-bond and π-bond



McMurray and Fay. Chemistry 4th ed., Prentice-Hall, 2004.

Tight-Binding Model



$$\mathcal{H} = -t \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \, \hat{b}_j + H.c. \qquad t \approx 3eV$$

arXiv:1110.6557v1, Daniel R. Cooper,2011 ,Experimental review of graphene

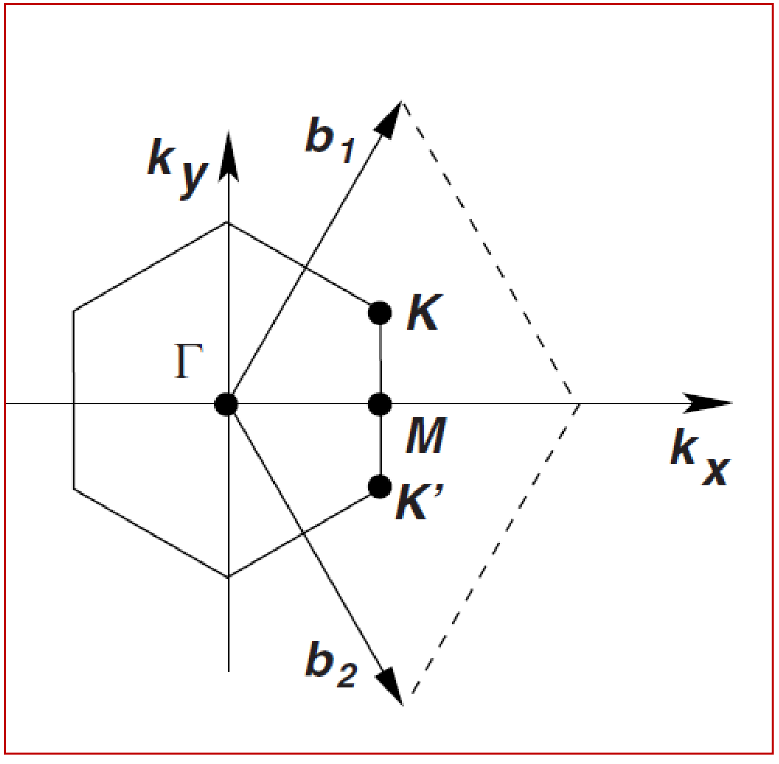
Tight-Binding Model

$$H = \sum_{q} \psi^{\dagger} \begin{pmatrix} 0 & f(q)^{*} \\ f(q) & 0 \end{pmatrix} \psi$$

$$f(q) = -t \sum_{\delta_i} e^{iq.\delta_i} \qquad \psi = \begin{pmatrix} \hat{a}_q \\ \hat{b}_q \end{pmatrix}$$

Sublattice=Pseudospin

Tight-Binding Model



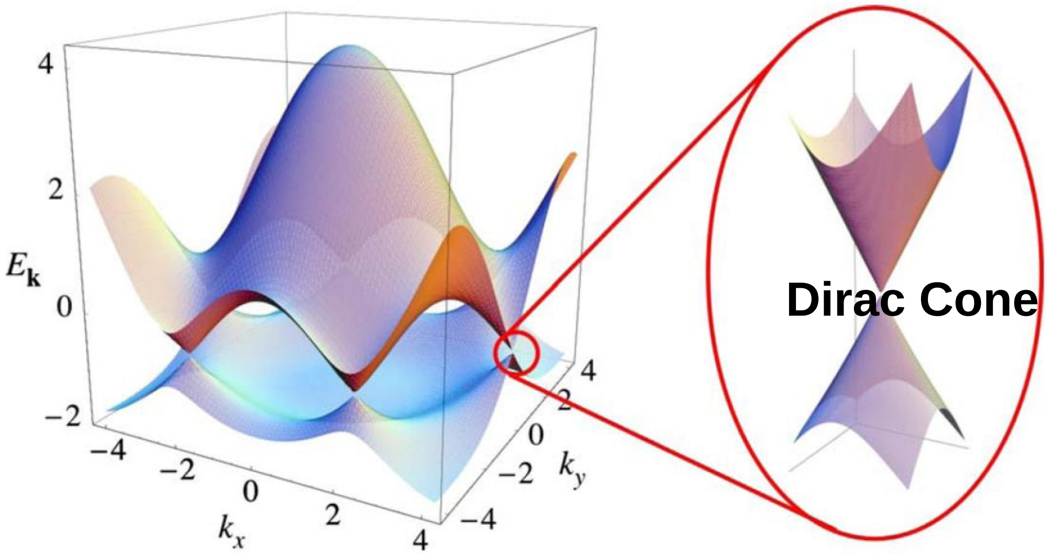
$$k = K + q$$

$$q = q_x + iq_y$$

$$H^K = \hbar v_F \begin{pmatrix} 0 & q^* \\ q & 0 \end{pmatrix}$$

$$v_F = \frac{3}{2\hbar} at \sim 10^6 m/s$$

Massless Quasiparticle



$$H = v_F\, \vec{\sigma}.\vec{p}$$

$$E_{c,v} = \pm \hbar v_F |q|$$

$$\psi_{c,v} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm e^{i\varphi_q} \end{pmatrix}$$

Each state is 4-fold degenerate, 2 for spin and 2 for valley

The electronic properties of graphene, REVIEWS OF MODERN PHYSICS, 81,2009

What we expect?

Linear Dispersion relation

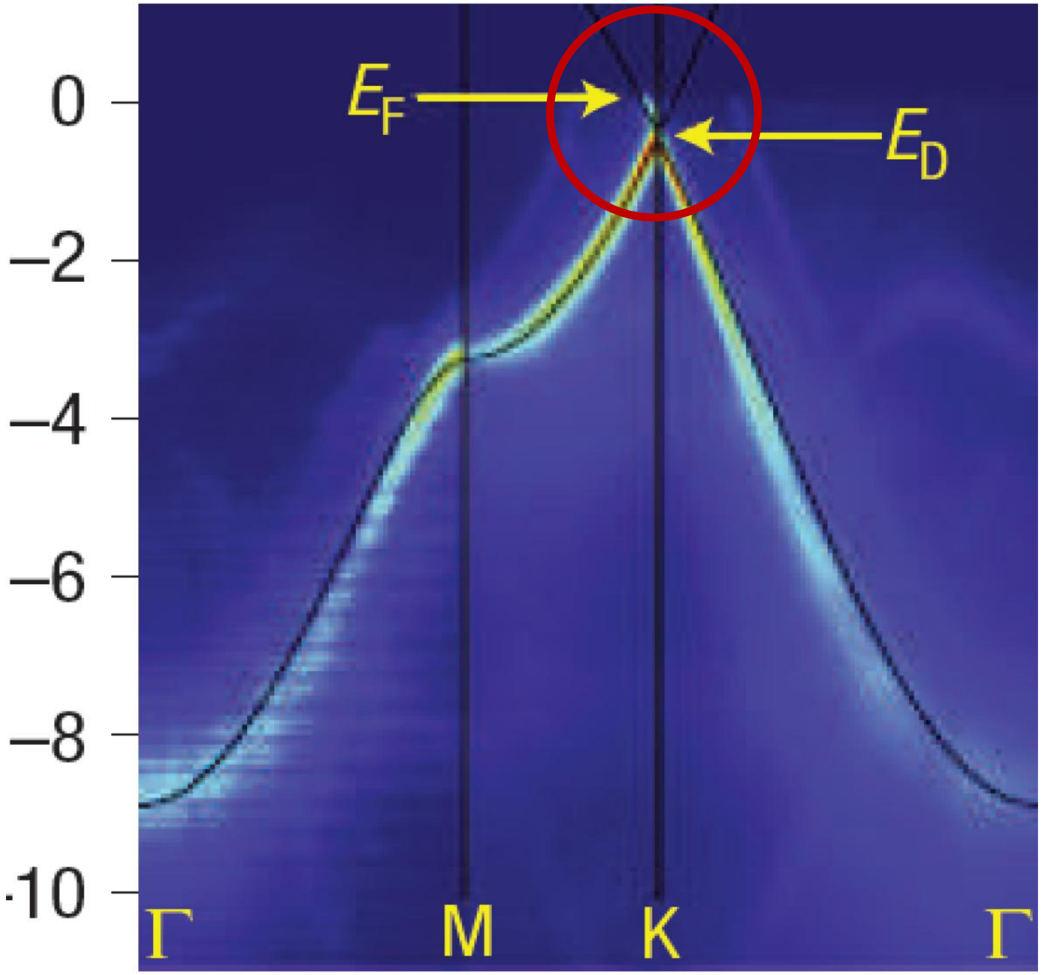
New Landau levels

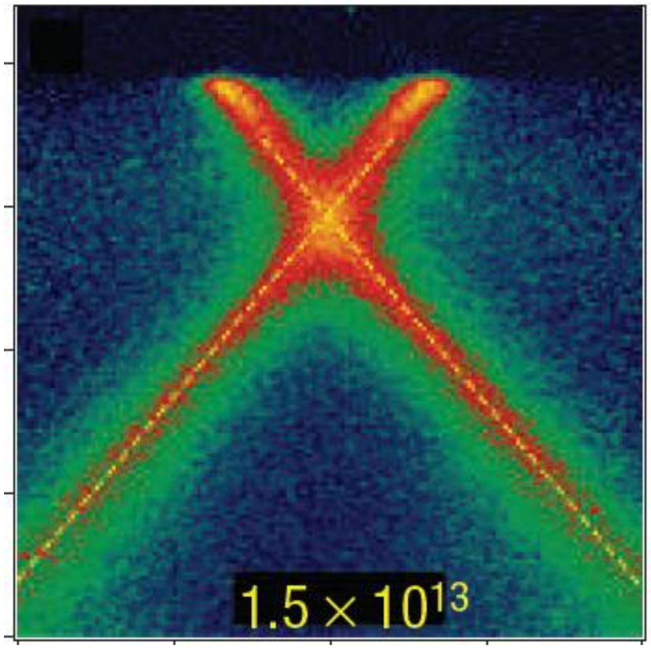
Cyclotron mass

Chirality and Kelin tunneling

Anomalous QHE

Linear Dispersion relation





Angle-resolved photoemission spectroscopy (ARPES)

Bostwick, A., T. Ohta, T. Seyller, K. Horn, and E. Rotenberg,2007, Nature Physics 3(1), 36.

The Landau levels of Massless particles

$$H = v_F\, \vec{\sigma}.\, (\vec{p} + e\vec{A})$$

$$E_n = \hbar v_F \frac{\sqrt{2}}{l_B} \sqrt{n} \sim 400 k_B \sqrt{B[Tesla]n}$$

Observation of Landau levels of Dirac fermions in graphite

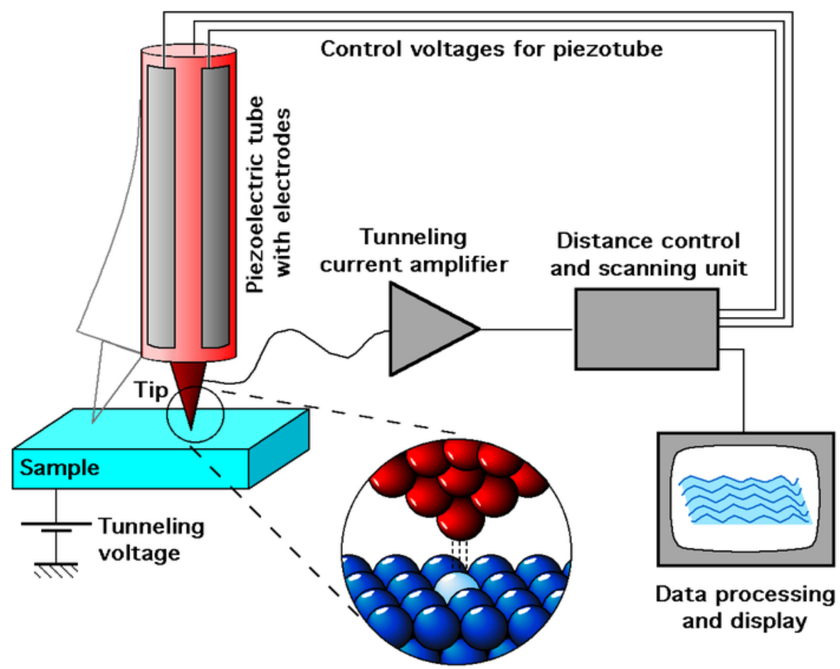
GUOHONG LI AND EVA Y. ANDREI*
Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA
*e-mail: eandrei@physics.rutgers.edu

STM

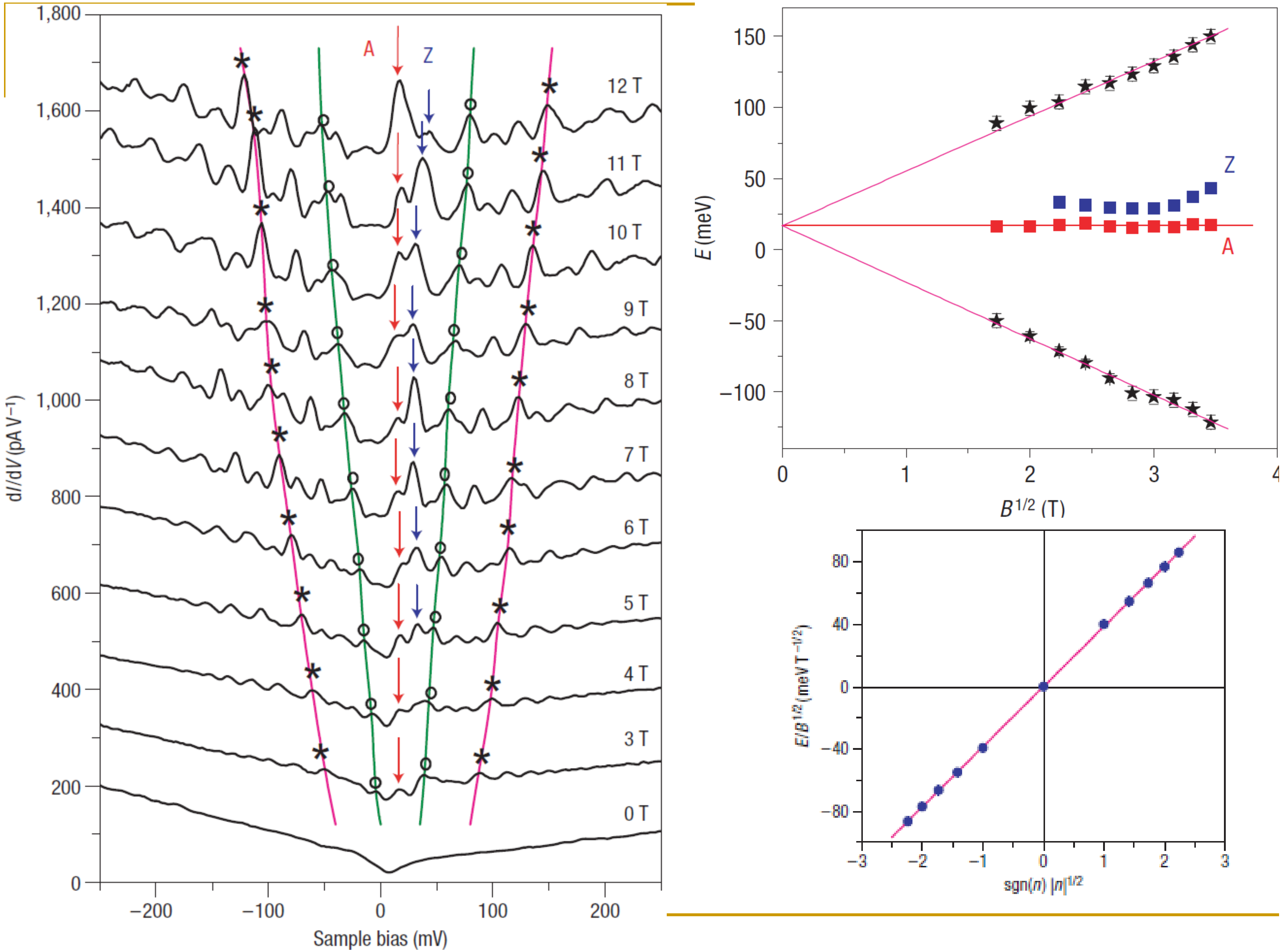
$$I \propto \sum_{E_f - eV}^{E_f} |\psi_n(0)|^2 e^{-2\kappa W}$$

$$\rho_s(z, E) = \frac{1}{\epsilon} \sum_{E-\epsilon}^{E} |\psi_n(z)|^2$$

$$I \propto V \rho_s(0, E_f) e^{-2\kappa W}$$



http://en.wikipedia.org/wiki/Scanning_tunneling_microscope



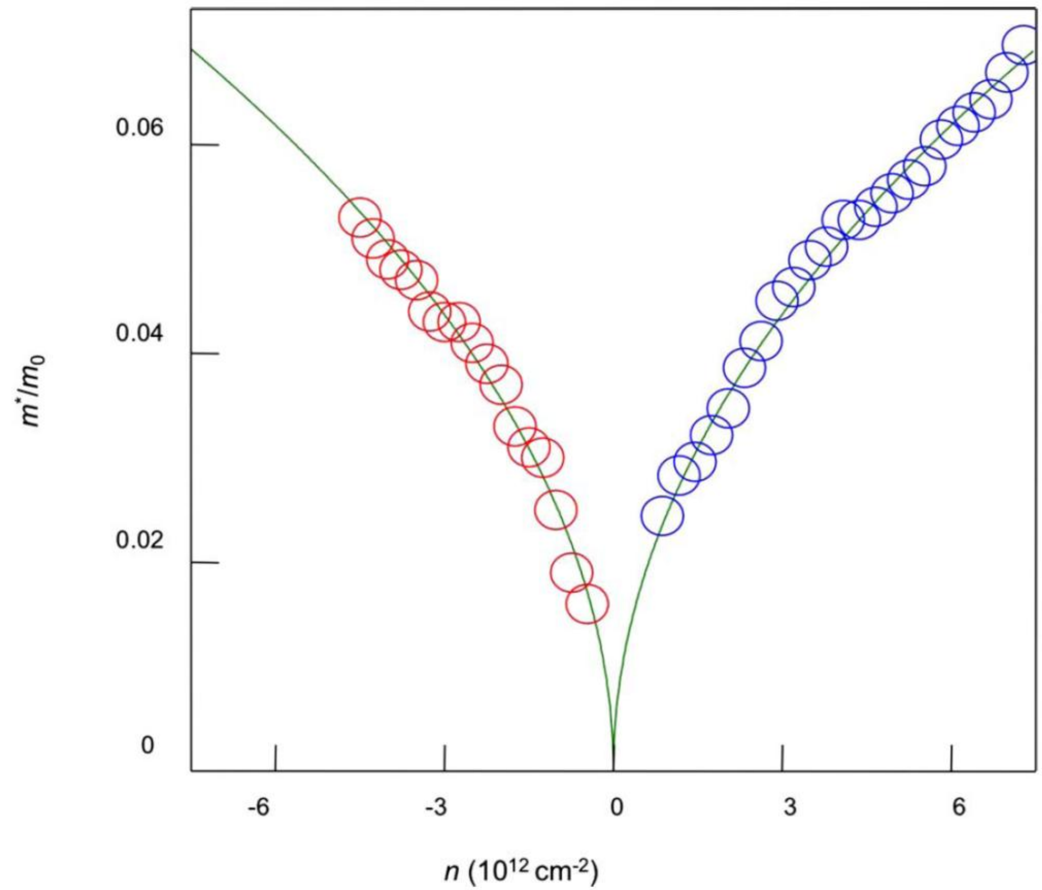
A
Z
12 T
11 T
10 T
9 T
8 T
7 T
6 T
5 T
4 T
3 T
0 T
dI/dV (pA V−1)
Sample bias (mV)
E (meV)
B1/2 (T)
Z
A
E/B1/2 (meV T−1/2)
sgn(n) |n|1/2

The Landau level Massless Dirac particle

$$m^* = \frac{1}{2\pi}\left[\frac{\partial A(E)}{\partial E}\right]_{E=E_F}$$

$$A(E) = \pi q(E)^2$$

$$m^* = \frac{\sqrt{\pi}}{v_F}\sqrt{n}$$



Two-dimensional gas of massless Dirac fermions in graphene

nature

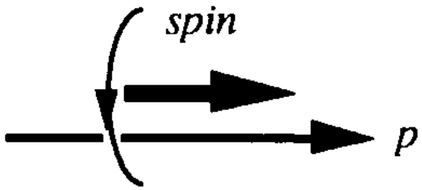
LETTERS

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]

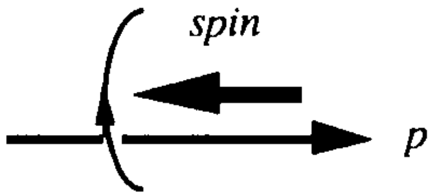
ARTICLES

Chiral tunnelling and the Klein paradox in graphene

M. I. KATSNELSON[1]*, K. S. NOVOSELOV[2] AND A. K. GEIM[2]*



positive helicity:
clockwise (right-handed) spin

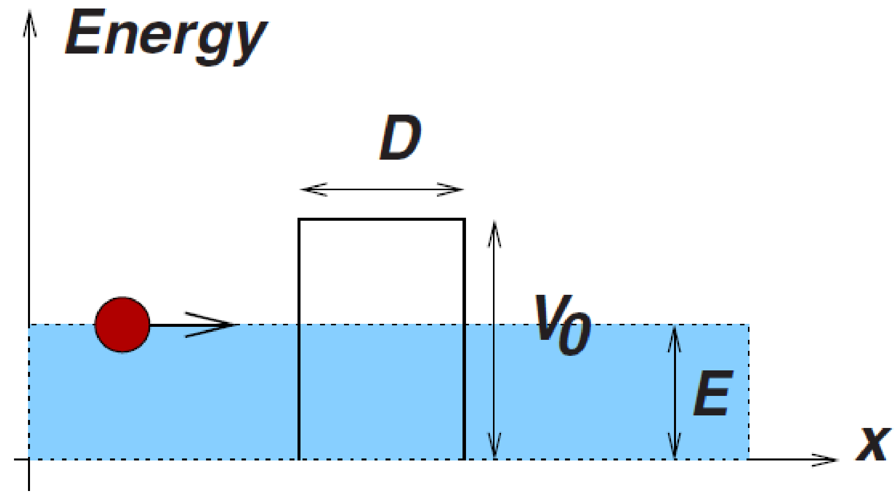


negative helicity:
counter-clockwise (left-handed) spin

Is Pseudospin a real parameter?

Are quasiparticles of Graphene Chiral?

$$\psi_s = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ s e^{i\varphi_q} \end{pmatrix} e^{iq.r}$$

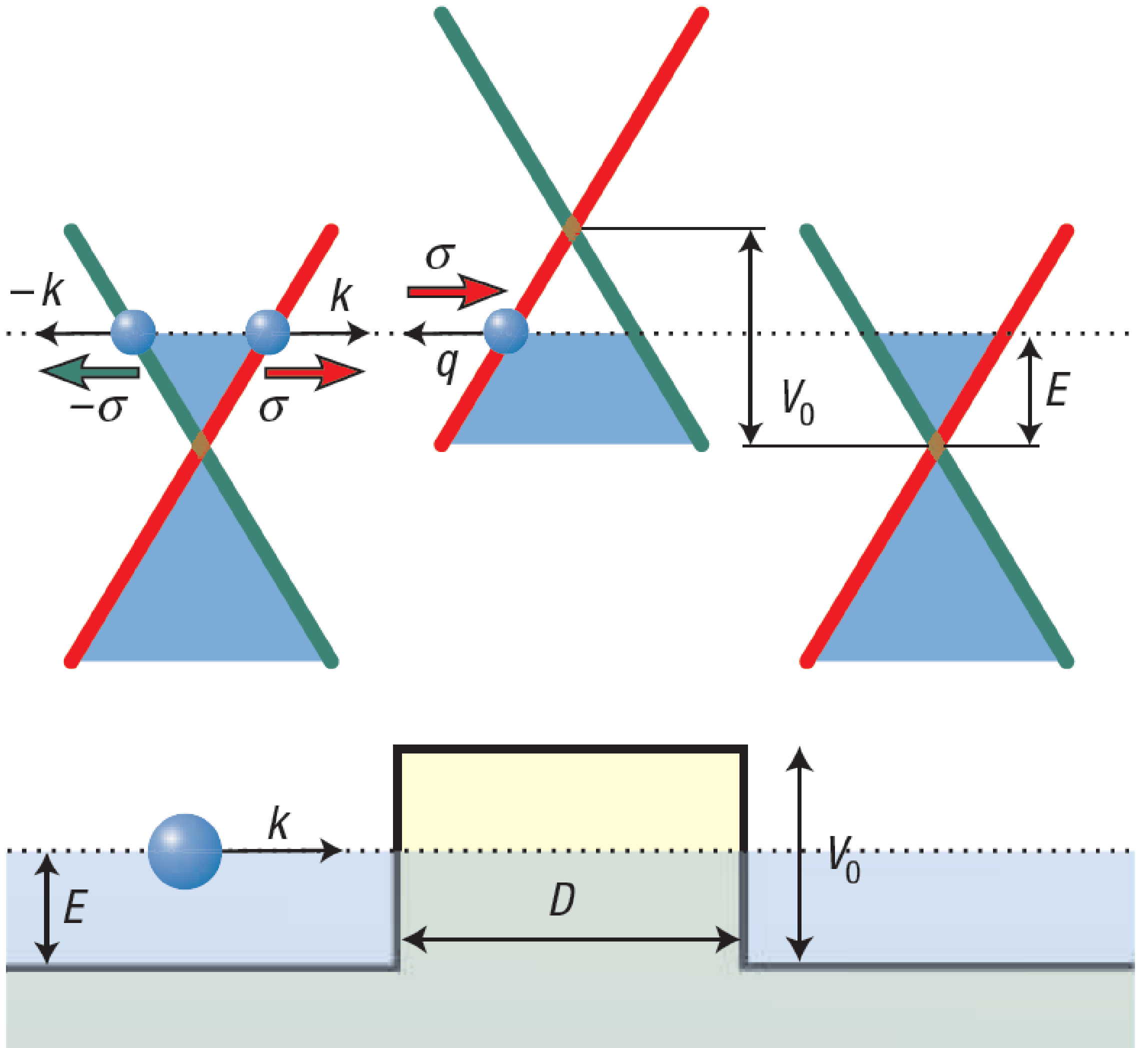


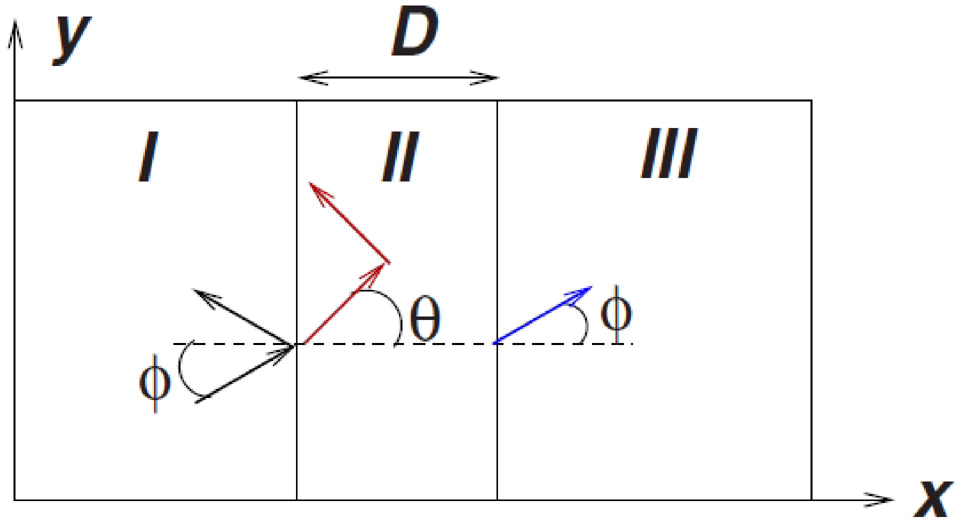
$s = +(\text{conduction band or electron}), -(\text{valence band or hole})$

$$P = |\langle \psi_{s'} | V | \psi_s \rangle|^2 = |V_{q-q'}|^2 \frac{(1 + ss' \cos(\Delta\varphi))}{2}$$

$$\Delta\varphi = \varphi_q - \varphi_{q'}$$

$\text{if } s = s' \text{ and } \Delta\varphi = \pi \rightarrow P = 0$


−k
k
−σ
σ
σ
q
V_0
E
k
E
D
V_0

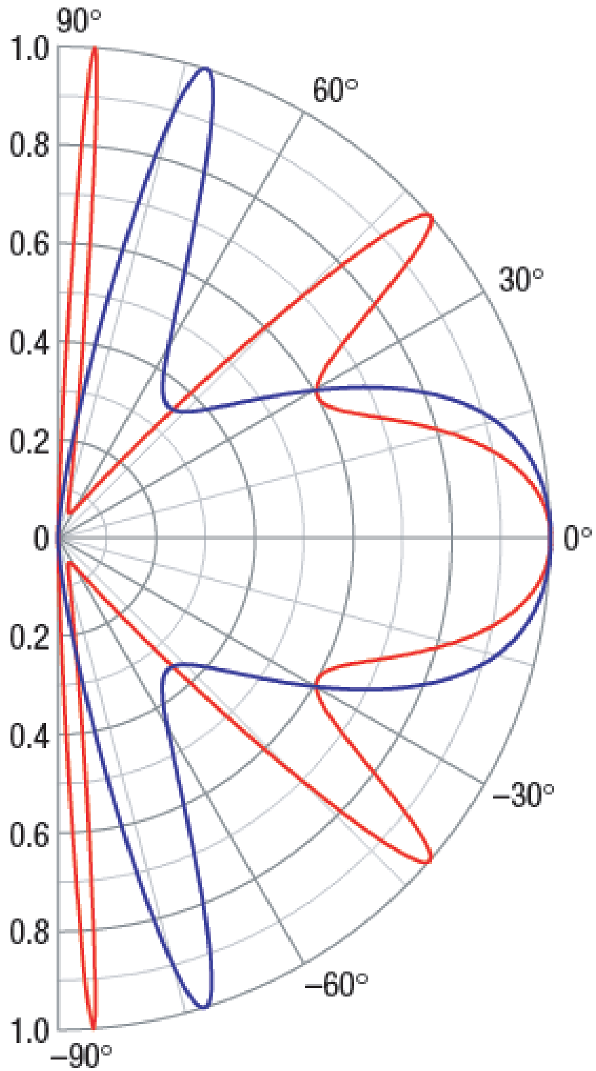


$$\psi_I(\boldsymbol{r}) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ s e^{i\phi} \end{pmatrix} e^{i(k_x x + k_y y)} + \frac{r}{\sqrt{2}}\begin{pmatrix} 1 \\ s e^{i(\pi-\phi)} \end{pmatrix} e^{i(-k_x x + k_y y)}$$

$$\psi_{\mathrm{II}}(\boldsymbol{r}) = \frac{a}{\sqrt{2}}\begin{pmatrix} 1 \\ s' e^{i\theta} \end{pmatrix} e^{i(q_x x + k_y y)} + \frac{b}{\sqrt{2}}\begin{pmatrix} 1 \\ s' e^{i(\pi-\theta)} \end{pmatrix} e^{i(-q_x x + k_y y)}$$

$$\psi_{\mathrm{III}}(\boldsymbol{r}) = \frac{t}{\sqrt{2}}\begin{pmatrix} 1 \\ s e^{i\phi} \end{pmatrix} e^{i(k_x x + k_y y)}$$

The electronic properties of graphene, REVIEWS OF MODERN PHYSICS, 81,2009



$$T(\phi) \simeq \frac{\cos^2 \phi}{1 - \cos^2(Dq_x)\sin^2 \phi},$$

$$|V_0| \gg |E|$$

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*]

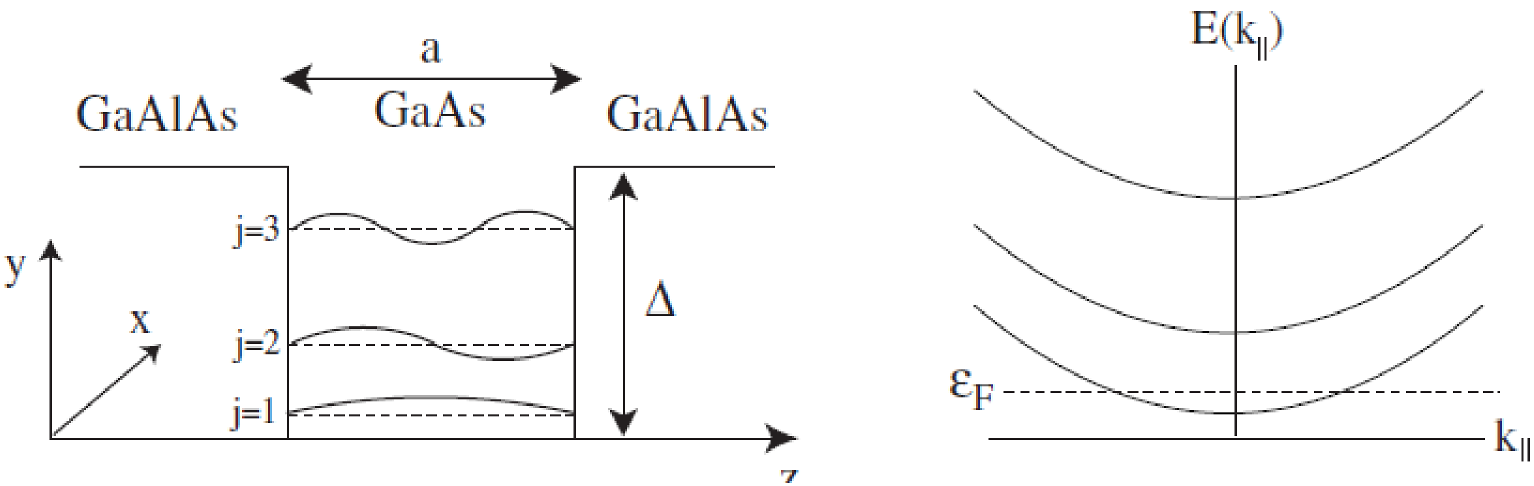
$$E_n = \hbar v_F \frac{\sqrt{2}}{l_B}\sqrt{n} \sim 400 k_B \sqrt{B[Tesla]n}$$

$$\boldsymbol{n^* = g\,\frac{A}{2\pi\, l_B^2}\,,\quad l_B = \sqrt{\frac{\hbar}{eB}}}$$

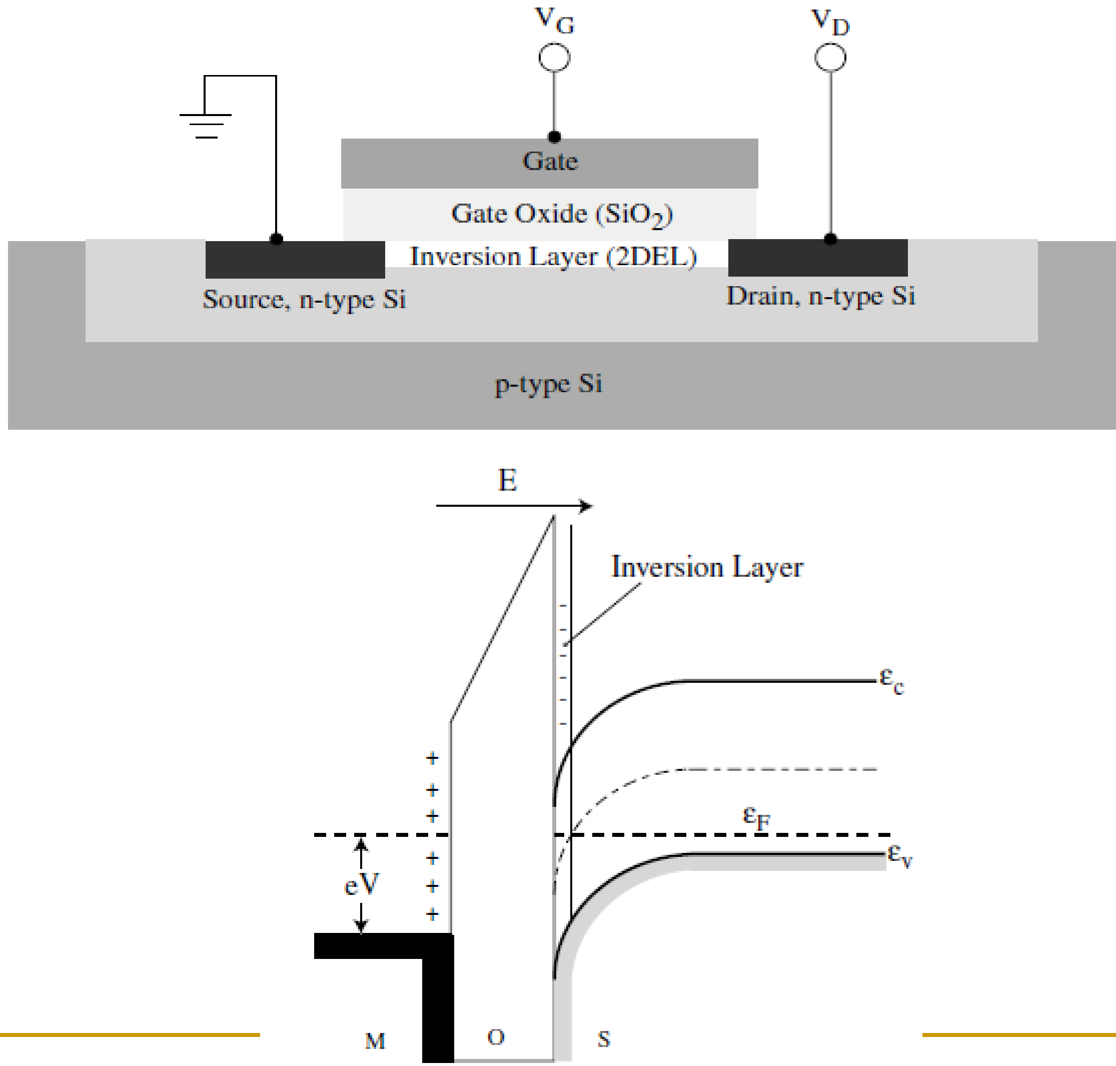
$$\boldsymbol{g = internal\ degeneracy}$$

$$\boldsymbol{N = \nu n^*\,,\ \ \nu\text{: } filling\ factor}$$

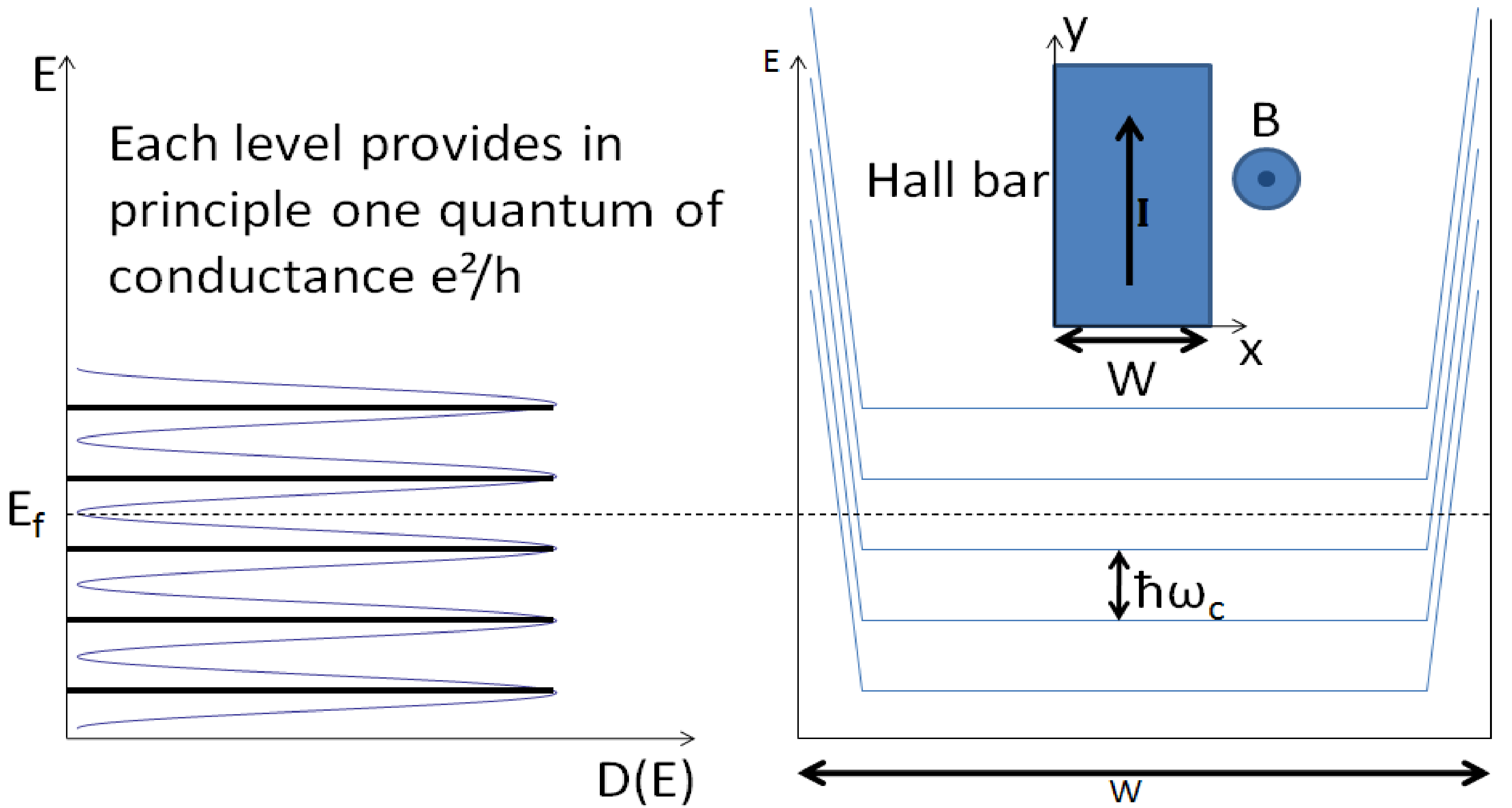
Two dimensional electron gas



Two dimensional electron gas

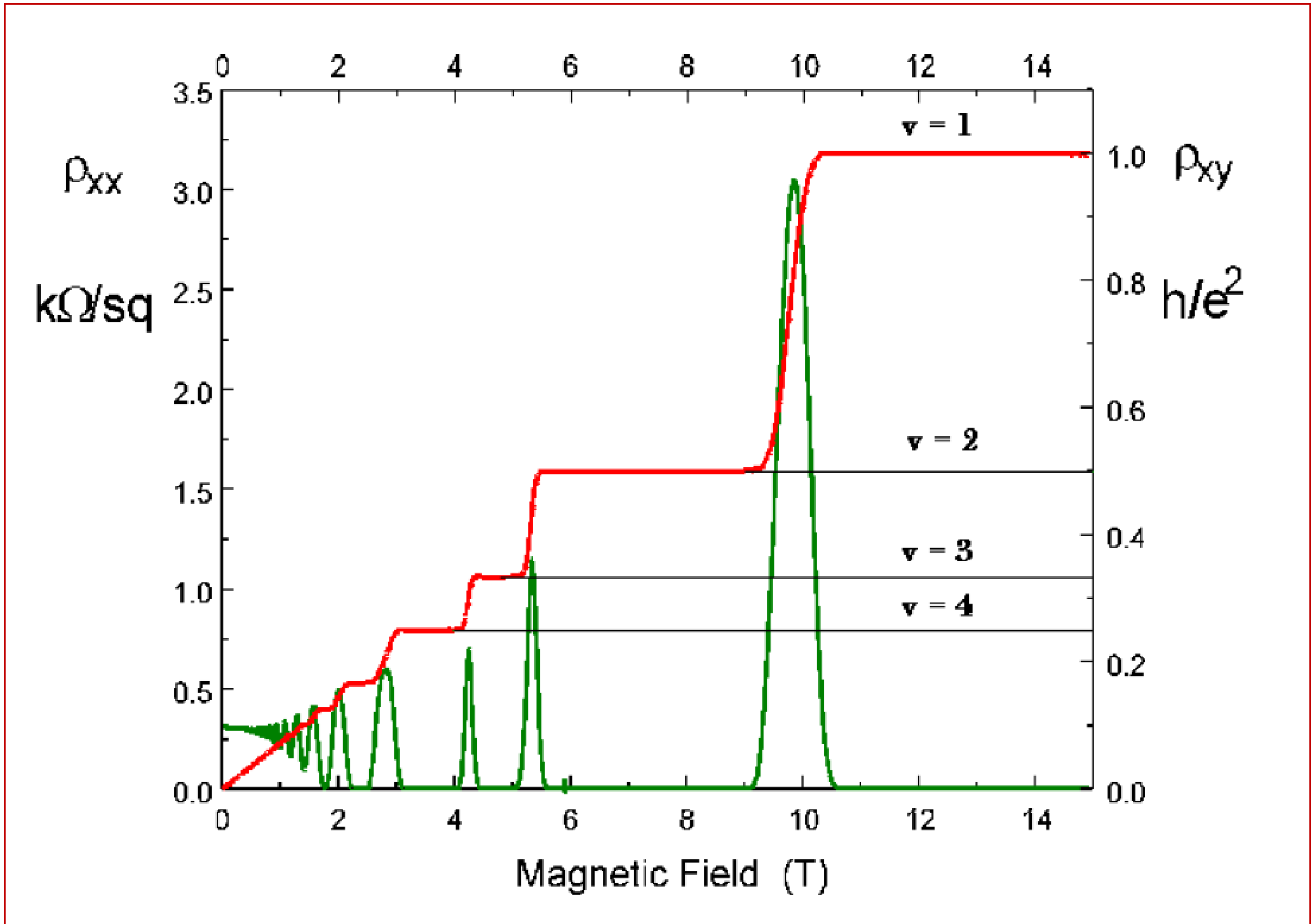


Integer Quantum Hall effect



$$\rho_{xx} = 0\ , E_F \neq E_n \qquad\qquad \sigma_{xy} = gv\left(\frac{e^2}{h}\right)$$

arXiv:1110.6557v1, Daniel R. Cooper,2011 ,Experimental review of graphene

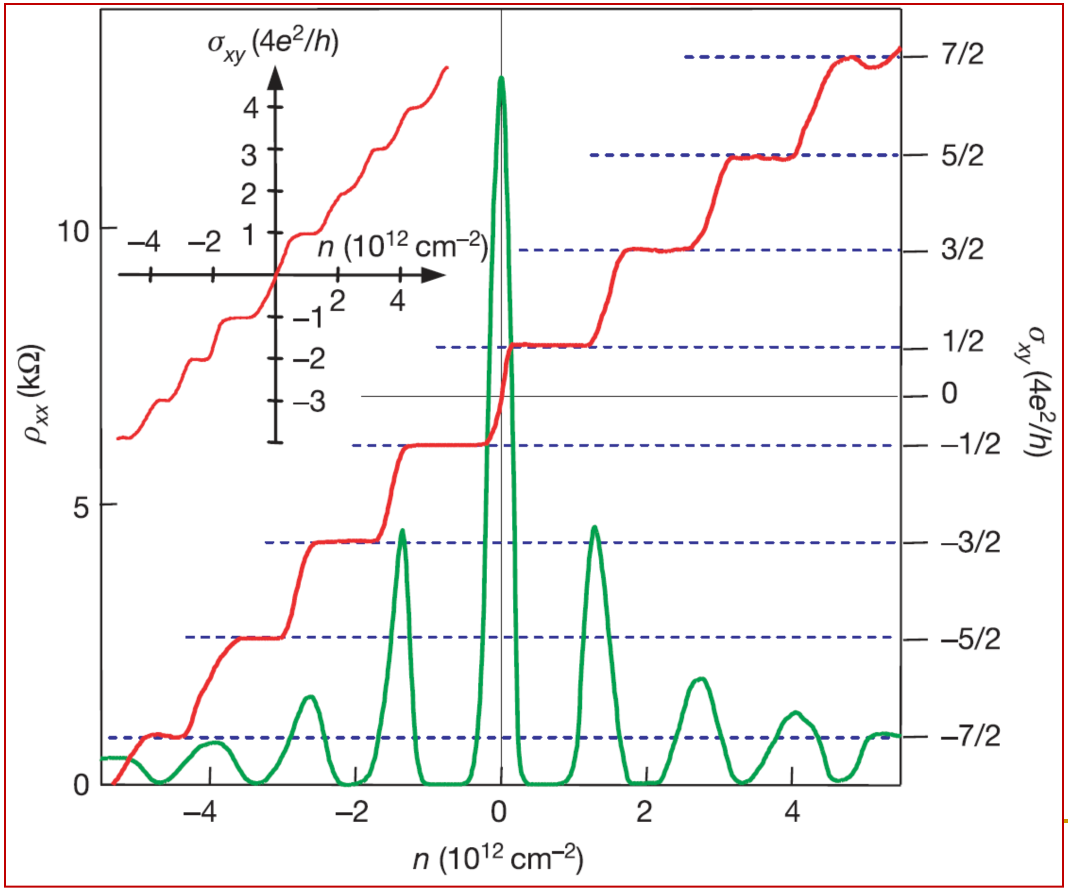


$$\sigma_{xy} = n\left(\frac{2e^2}{h}\right)$$

arXiv:1110.6557v1, Daniel R. Cooper,2011 ,Experimental review of graphene

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]



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

$$\sigma_{xy} = 4(v-1)\left(\frac{e^2}{h}\right) + 2\left(\frac{e^2}{h}\right)$$

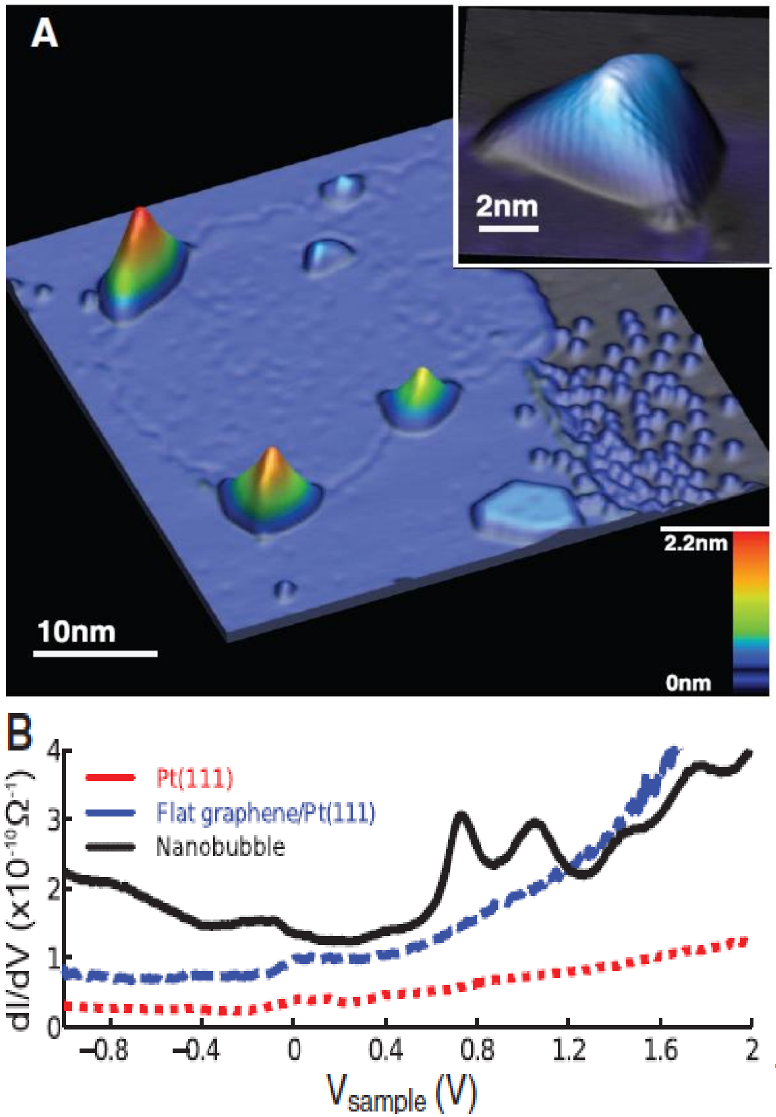
$$\xrightarrow{v-1=n} (2n+1)\left(\frac{2e^2}{h}\right)$$

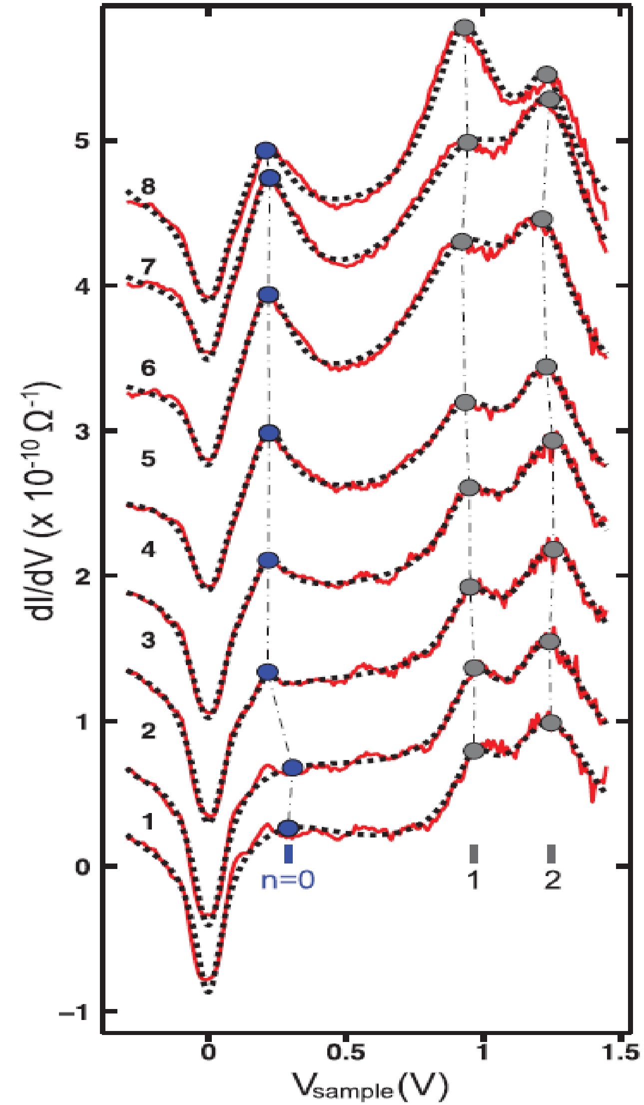
Science
AAAS

Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles

N. Levy, *et al.*

Science **329**, 544 (2010);
DOI: 10.1126/science.1191700

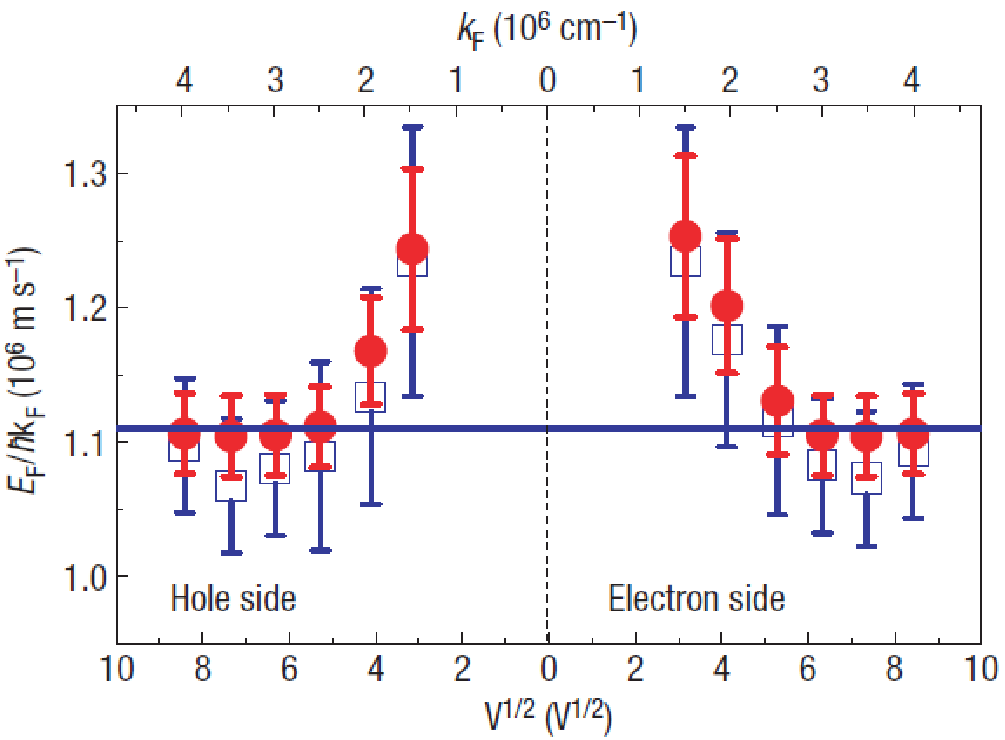




Interactions and disorders

Interactions and disorders can destroy our massless fermin

for example:



Dirac charge dynamics in graphene by infrared spectroscopy nature physics, vol 4 ,2008

So that they are massless fermion

Thanks for your attention