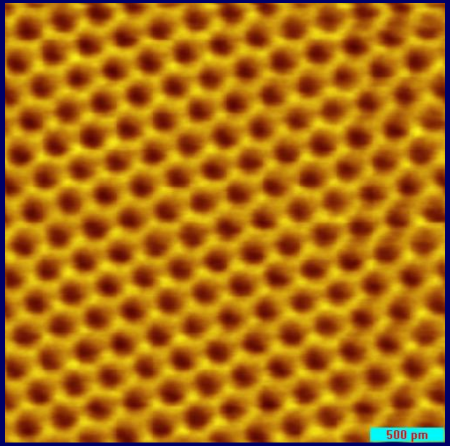
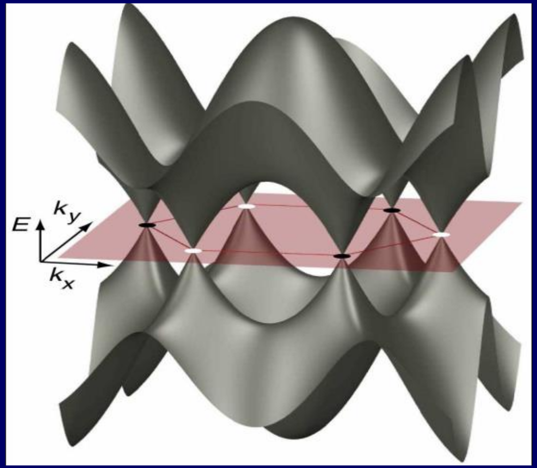
Electronic properties of Graphene and 2-D materials

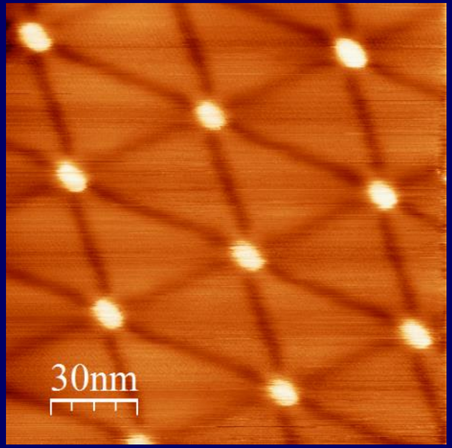
Graphene



Graphene band structure



Twisted Bilayer Graphene



- 2D materials
- Graphene
- STM and transport measurements
- Flat bands and correlations
- Twisted bilayer graphene

Eva Y. Andrei

Rutgers University

2D crystals do not exist in nature

Herbert Wagner

…continuous symmetries cannot be spontaneously broken at finite temperature in systems with sufficiently short-range interactions in dimensions D ≤ 2.

PHYSICAL REVIEW VOLUME 158, NUMBER 2 10 JUNE 1967

Existence of Long-Range Order in One and Two Dimensions

P. C. Hohenberg
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 24 October 1966)

It is pointed out that a rigorous inequality first proved by Bogoliubov may be used to rule out the existence of quasi-averages (or long-range order) in Bose and Fermi systems for one and two dimensions and $T \neq 0$.

Commun. math. Phys. 31, 259—264 (1973)

There are no Goldstone Bosons in Two Dimensions*

Sidney Coleman**

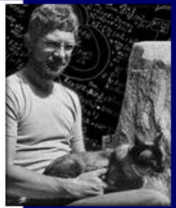
ABSENCE OF FERROMAGNETISM OR ANTIFERROMAGNETISM IN ONE- OR TWO-DIMENSIONAL ISOTROPIC HEISENBERG MODELS*

N. D. Mermin† and H. Wagner‡
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York
(Received 17 October 1966)

J. Phys. C: Solid State Phys., Vol. 6, 1973. Printed in Great Britain. © 1973

Ordering, metastability and phase transitions in two-dimensional systems

J M Kosterlitz and D J Thouless
Department of Mathematical Physics, University of Birmingham, Birmingham B15 2TT, UK

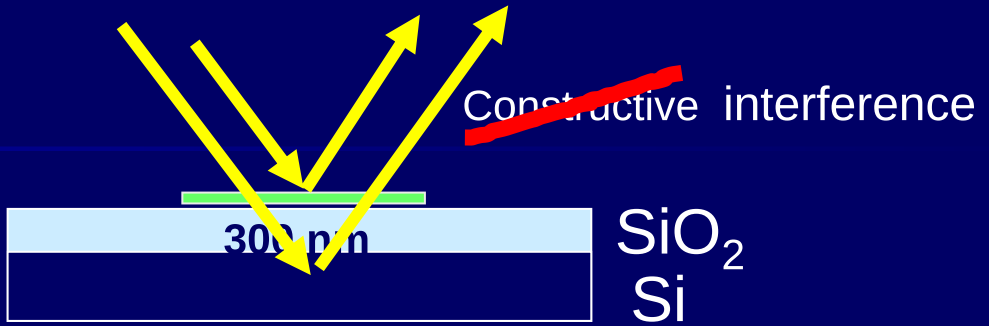


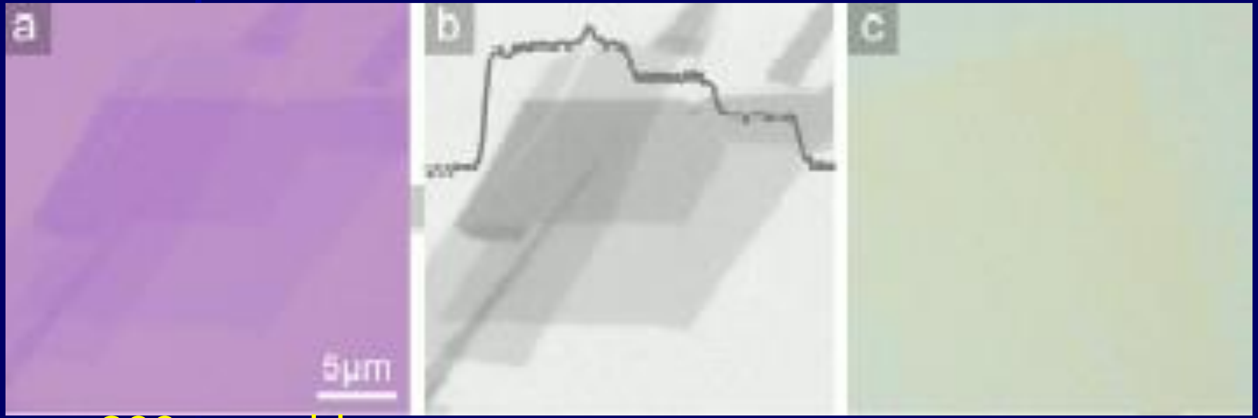
long-range fluctuations can be created with little energy cost and since they increase the entropy they are favored.

No long range order in 2D

… No Magnets
….No superfluids
…No superconductors
… No 2D crystals

How to see an atomically thin layer?

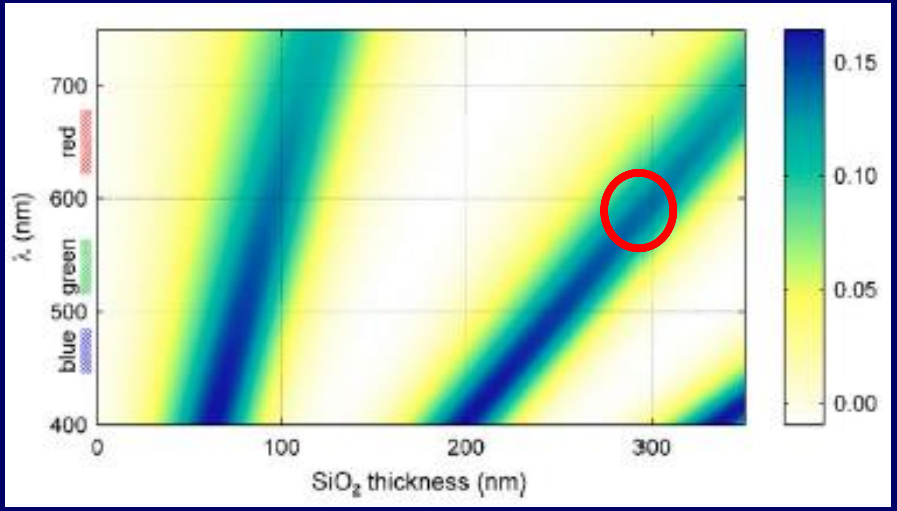




300nm oxide
White light

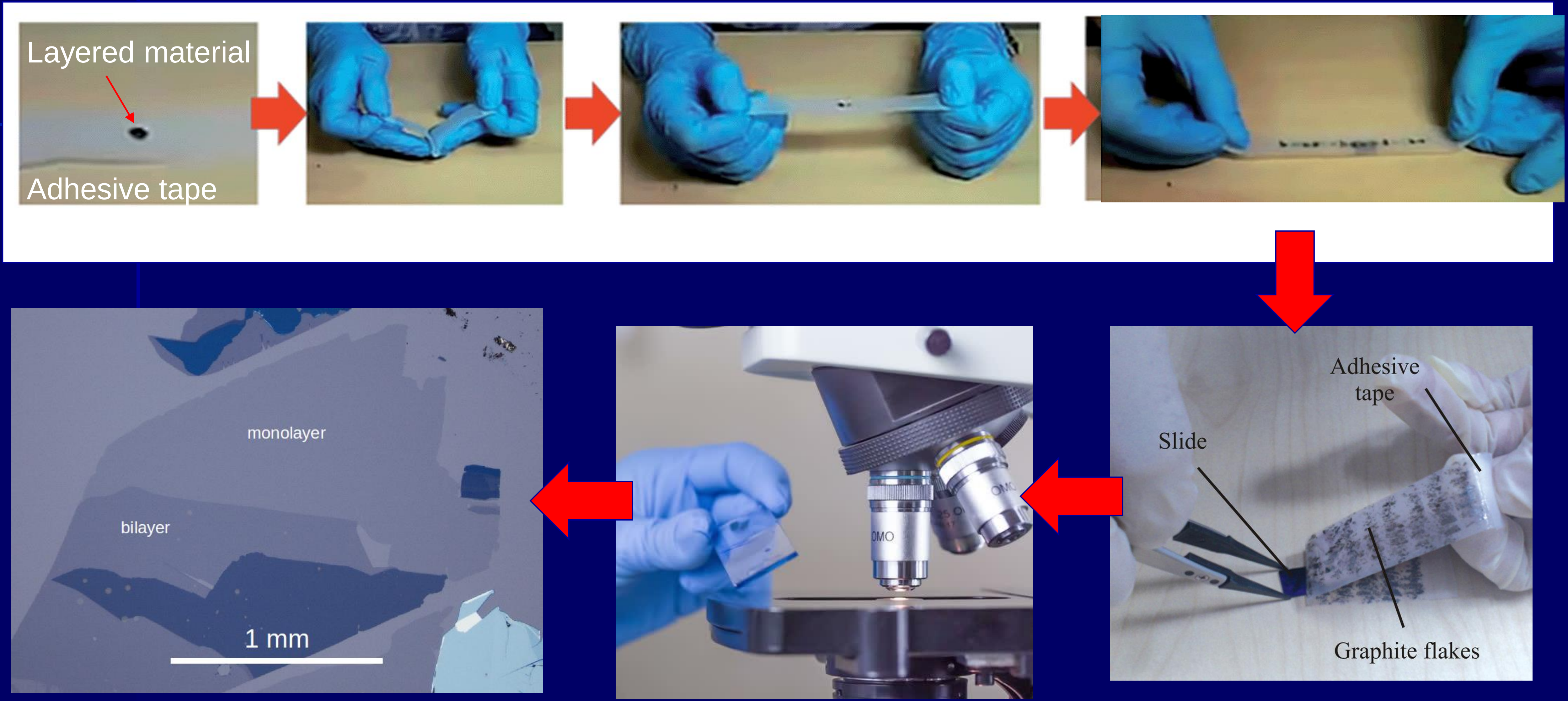
300nm oxide
560nm green light

200nm oxide
White light



P. Blake et.al, APL, 91, 063124 (2007)

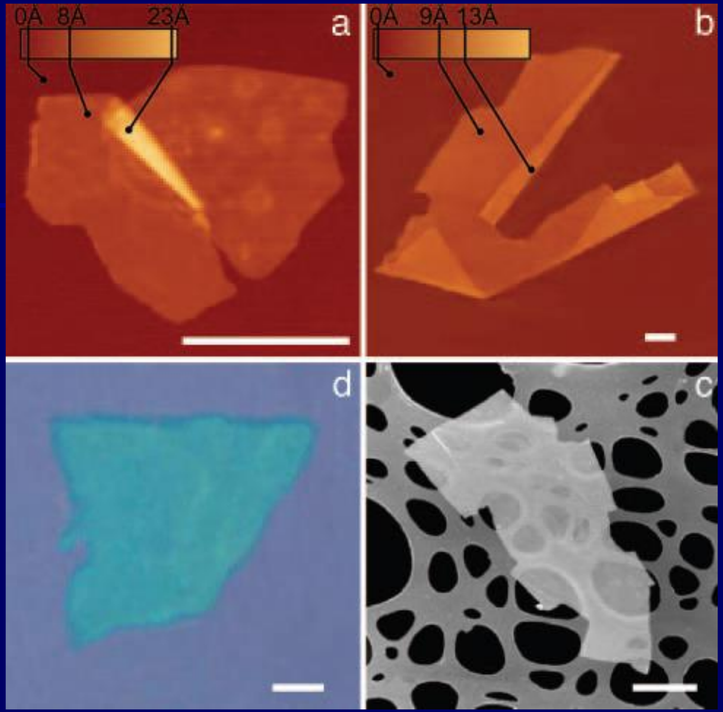
Scotch tape exfoliation



First 2D materials

Andre Geim   Konstantin Novoselov

Graphene, hBN, MoS_2, $NbSe_2$, $Bi_2Sr_2CaCu_2O_x$,



PNAS

Two-dimensional atomic crystals

K. S. Novoselov*, D. Jiang*, F. Schedin*, T. J. Booth*, V. V. Khotkevich*, S. V. Morozov†, and A. K. Geim*‡

*Centre for Mesoscience and Nanotechnology and School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom; and †Institute for Microelectronics Technology, Chernogolovka 142432, Russia

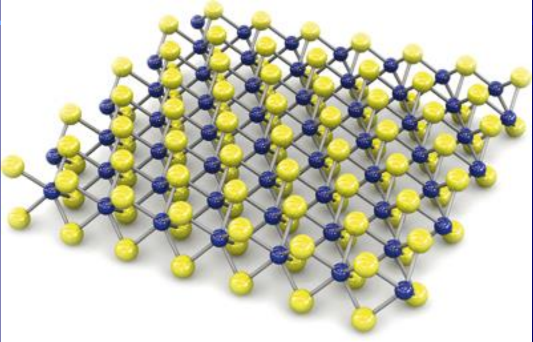
Edited by T. Maurice Rice, Swiss Federal Institute of Technology, Zurich, Switzerland, and approved June 7, 2005 (received for review April 6, 2005)

We report free-standing atomic crystals that are strictly 2D and can be viewed as individual atomic planes pulled out of bulk crystals or as unrolled single-wall nanotubes. By using micromechanical cleavage, we have prepared and studied a variety of 2D crystals including single layers of boron nitride, graphite, several dichalcogenides, and complex oxides. These atomically thin sheets (essentially gigantic 2D molecules unprotected from the immediate environment) are stable under ambient conditions, exhibit high crystal quality, and are continuous on a macroscopic scale.

wafer (Fig. 1*d*), because even a monolayer adds up sufficiently to the optical path of reflected light so that the interference color changes with respect to the one of an empty substrate (phase contrast). The whole procedure takes literally half an hour to implement and identify probable 2D crystallites. Their further analysis was done by atomic force microscopy (AFM), for which single-layer crystals were selected as those exhibiting an apparent (12) thickness of approximately the interlayer distance in the corresponding 3D crystals.

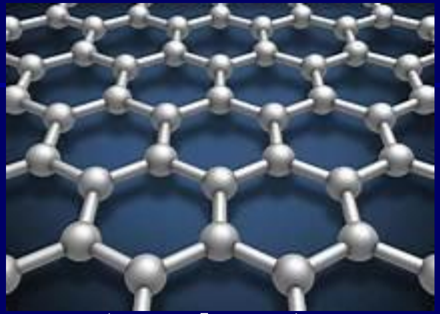
Atomically thin crystals

semiconductor



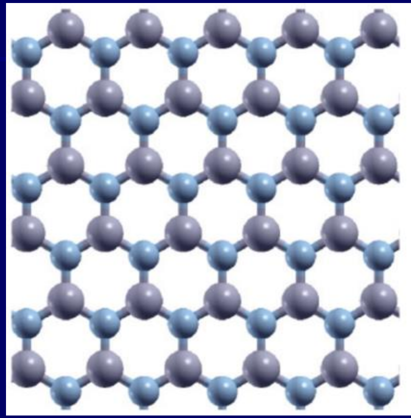
(WSe_2 MoS_2, $MoSe_2$)

Semi-metal

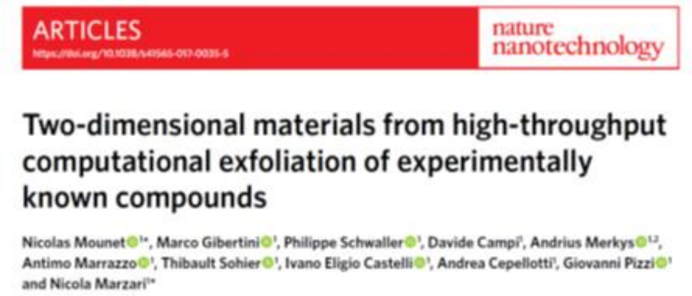


(graphene)

insulator



(boron nitride)



ARTICLES

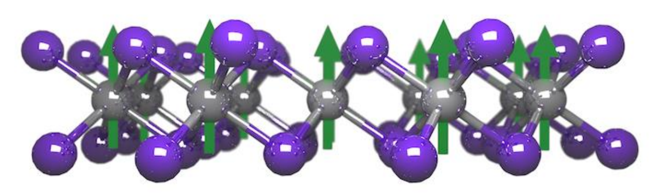
https://doi.org/10.1038/s41565-017-0035-5

nature nanotechnology

Two-dimensional materials from high-throughput computational exfoliation of experimentally known compounds

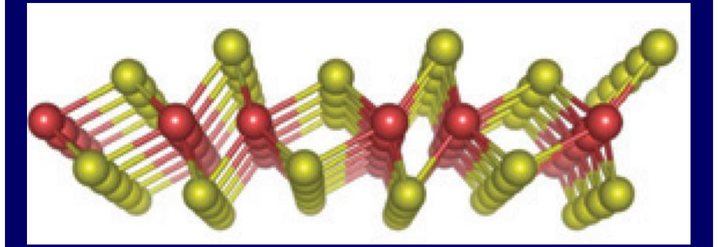
Nicolas Mounet[1*], Marco Gibertini[1], Philippe Schwaller[1], Davide Campi[1], Andrius Merkys[1,2], Antimo Marrazzo[1], Thibault Sohier[1], Ivano Eligio Castelli[1], Andrea Cepellotti[1], Giovanni Pizzi[1] and Nicola Marzari[1*]

magnet



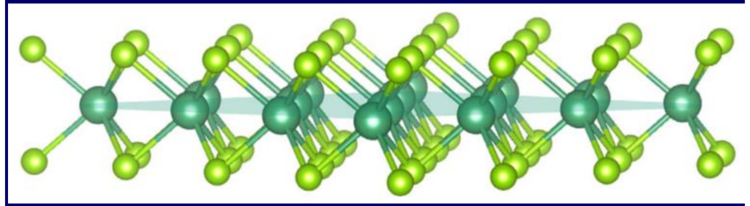
($FeTaS_2$, CrI_3)

topological insulator



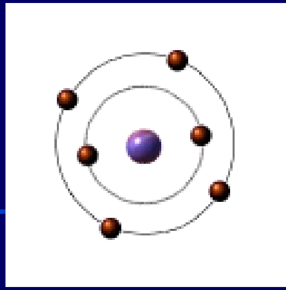
(WTe_2)

superconductor

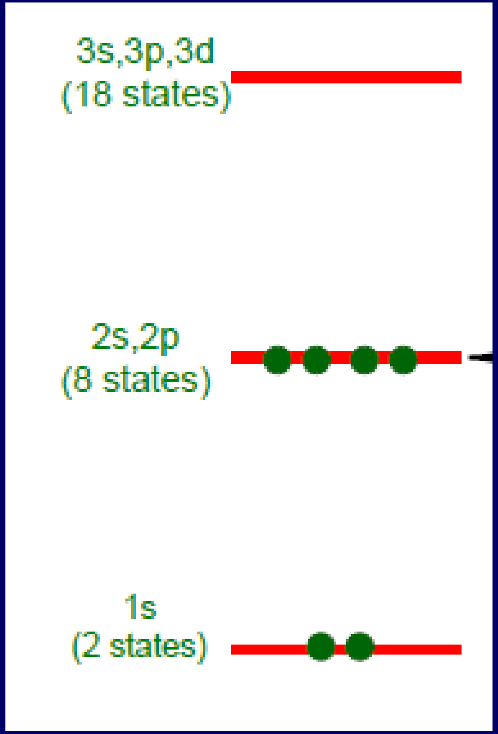


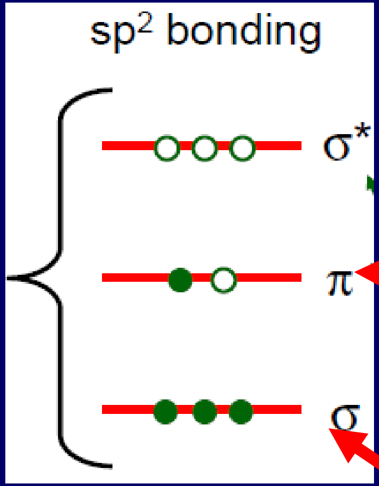
($NbSe_2$ WTe_2, BiSrCaCuO)

Graphitic bond



Carbon: Z=6
4 valence electrons $2s^2 2p^2$

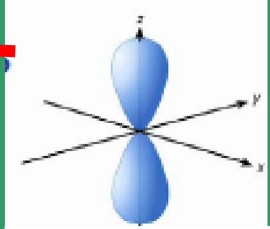




sp^2

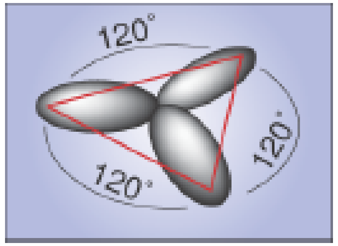
$2S + 2p_x + 2p_y$ hybridize

3 planar σ orbitals: tetragon
1 Out of plane $2p_z$ ["π" orbital]



π orbital (⊥ to plane)

π electrons allow conduction

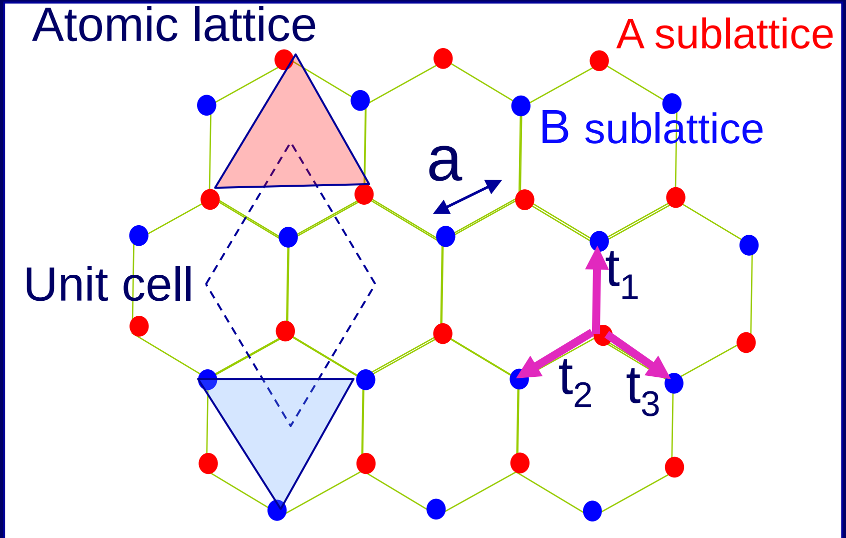


σ orbital (in plane)

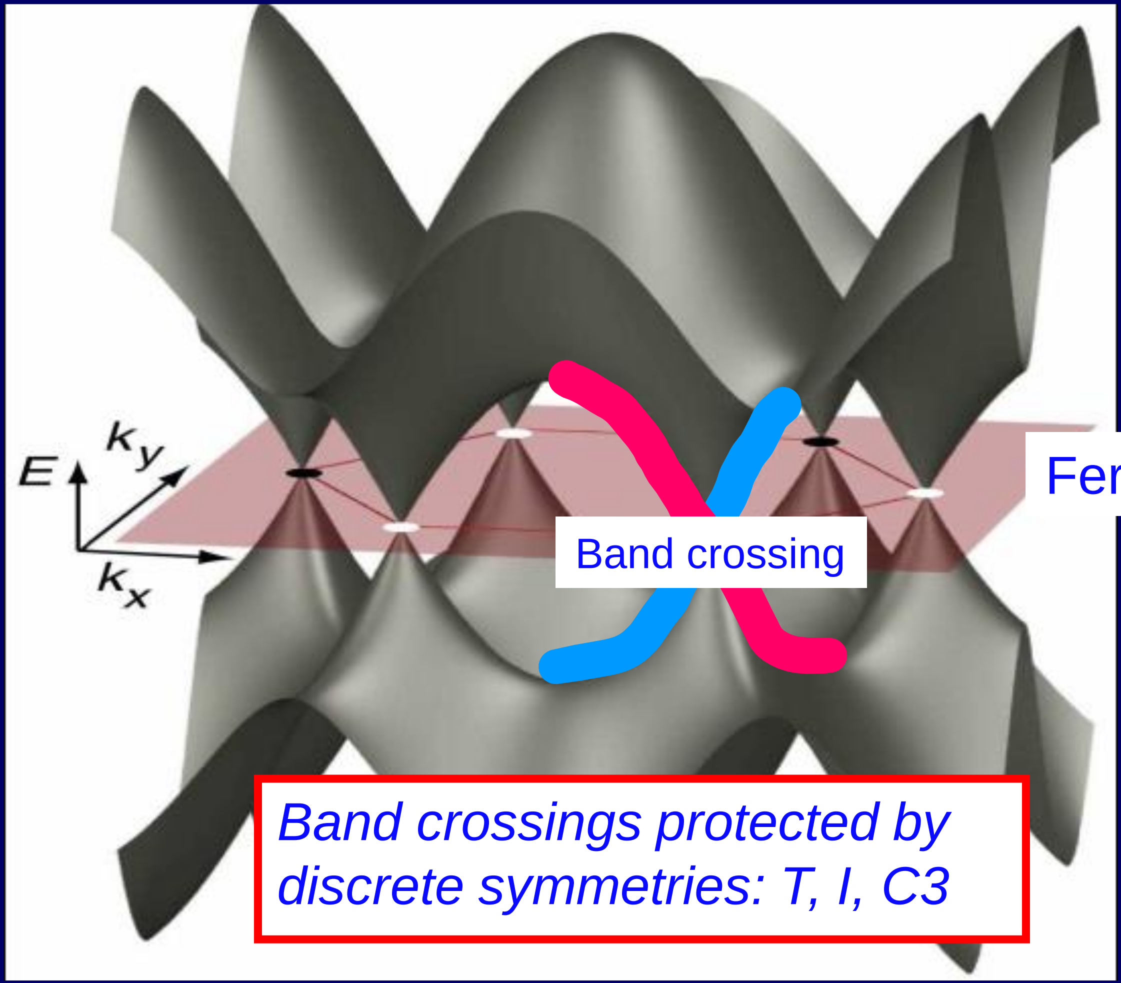
σ bonds: 2D and exceptional rigidity

ei

Graphene: Tight binding model



1. 2D
2. Honeycomb structure (non-Bravais)
3. 2 identical atoms/cell
4. Identical NN hopping



Phys 769: Selected Topics in Condensed Matter Physics — Summer 2010

Lecture 5: Graphene: Electronic band structure and Dirac fermions

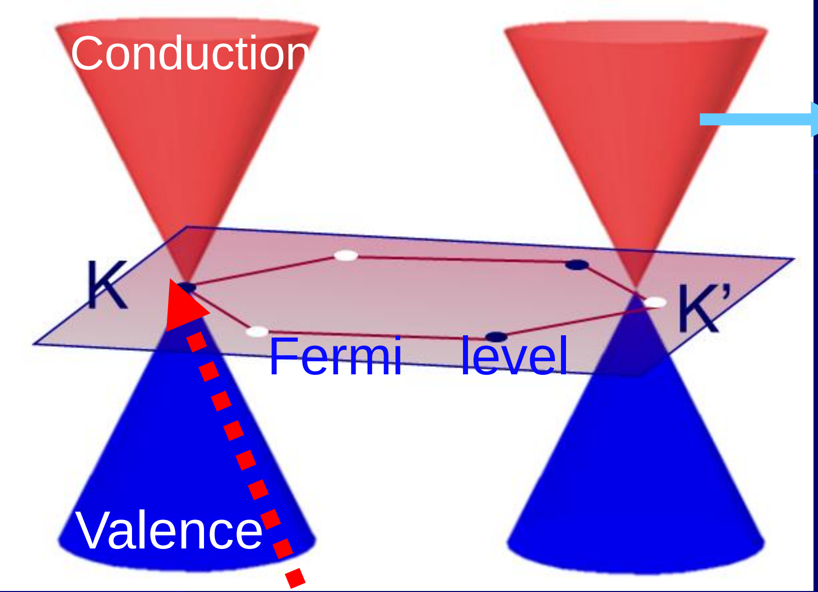
Lecturer: Anthony J. Leggett — *TA: Bill Coish*

Good general references:

CN: A. H. Castro Neto et al., Rev. Mod. Phys., **81**, 109 (2009).

Geim et al., Nature Materials **6** 183 (2007).

Graphene



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

Dirac point

6 Dirac cones, but only 2 independent at K and K' valleys

Dirac Weyl Hamiltonian

$$H = v_F \begin{pmatrix} \vec{\sigma}.\vec{p} & 0 \\ 0 & -\vec{\sigma}^*.\vec{p} \end{pmatrix}$$

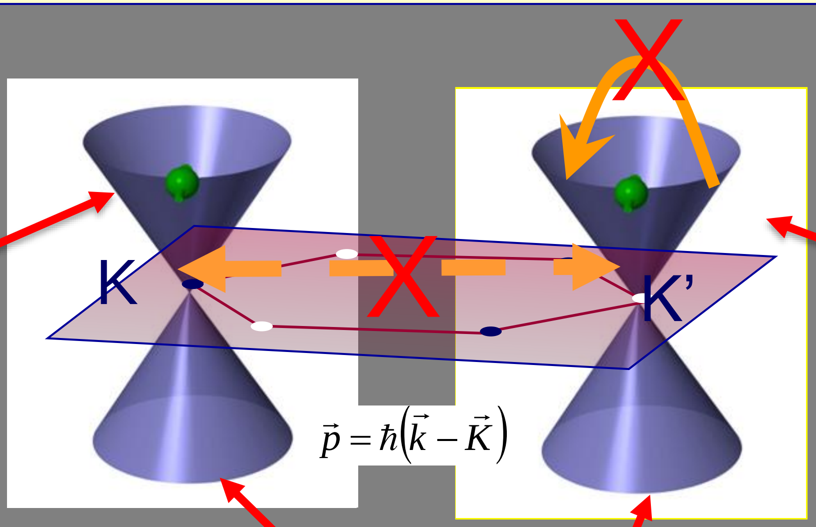
K

K'

p momentum relative to K point

σ Pauli matrices operate on sublattice degree of freedom

No Backscattering



$$\vec{p} = \hbar(\vec{k} - \vec{K})$$

Dirac Weyl Hamiltonian

$$H = v_F \begin{pmatrix} \vec{\sigma}.\vec{p} & 0 \\ 0 & -\vec{\sigma}^*.\vec{p} \end{pmatrix}$$

Helicity $H_K \propto \vec{\sigma}.\vec{p}$

$\mapsto$ projection of pseudospin along momentum conserved

Two massless Dirac fermions with opposite chirality (helicity)

4 flavors: 2 Spin , 2 valley

No backscattering between cones

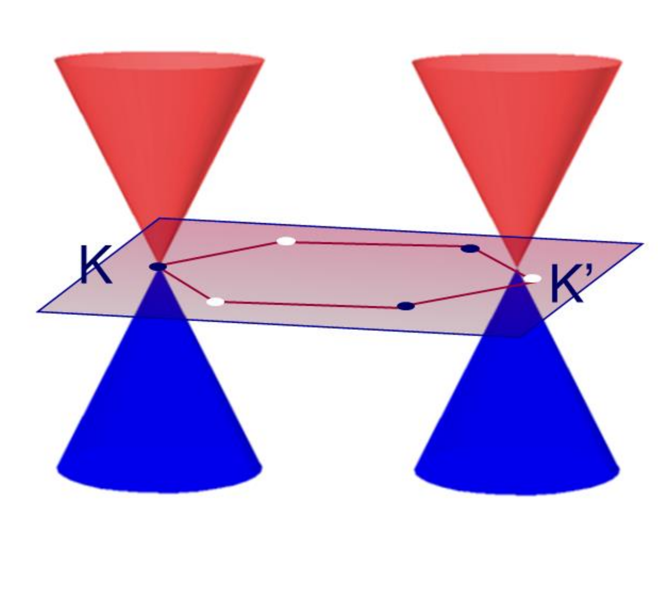
No backscattering within cones

- High carrier mobility

E.Y. Andrei

Density of states

Band structure

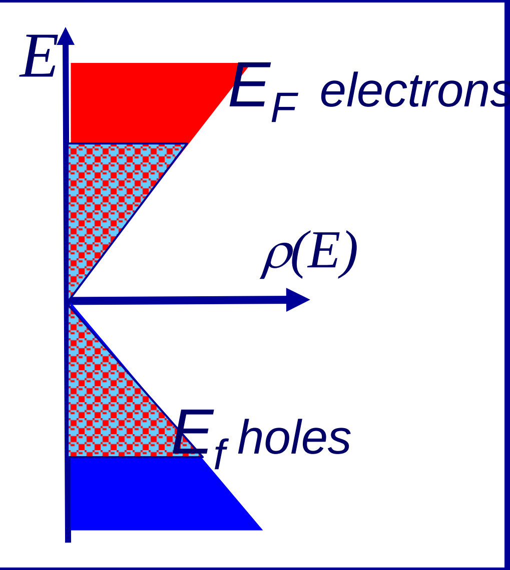


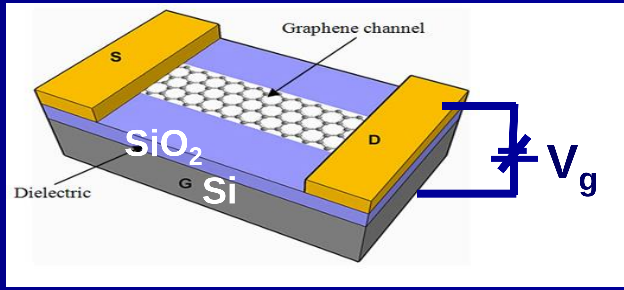
1V ⟼ 7×10^{10} cm^{-2}

$\Delta E \sim 80$meV

Density of states

$$\rho(E) = 3^{3/2} a^2 \frac{|E|}{\pi(\hbar v_F)^2}$$

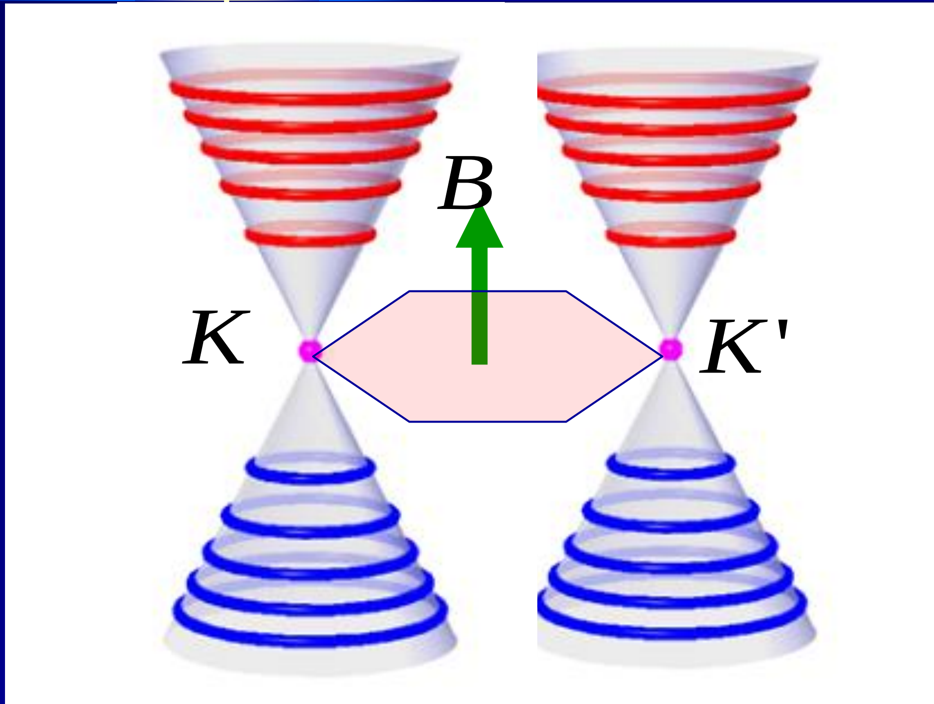




E.Y. Andrei

Landau levels

Band structure



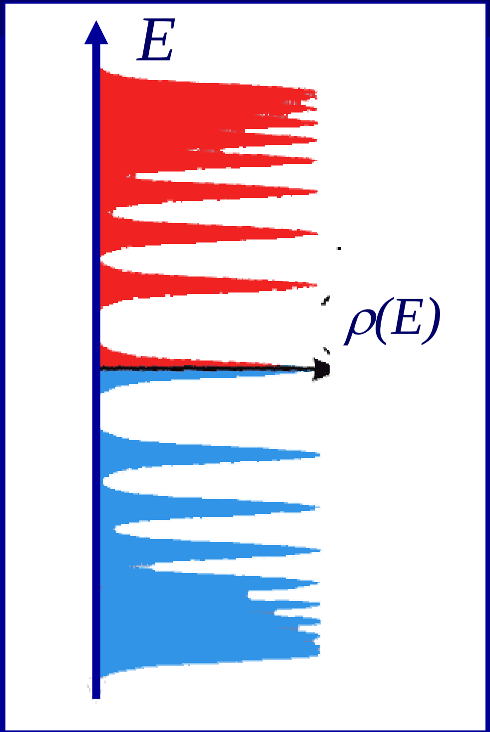
Density of states

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$H_{K.K'} = v_F \begin{pmatrix} \vec{\sigma}.(\vec{p} - e\vec{A}) & 0 \\ 0 & -\vec{\sigma}^*.(\vec{p} - e\vec{A}) \end{pmatrix}$$

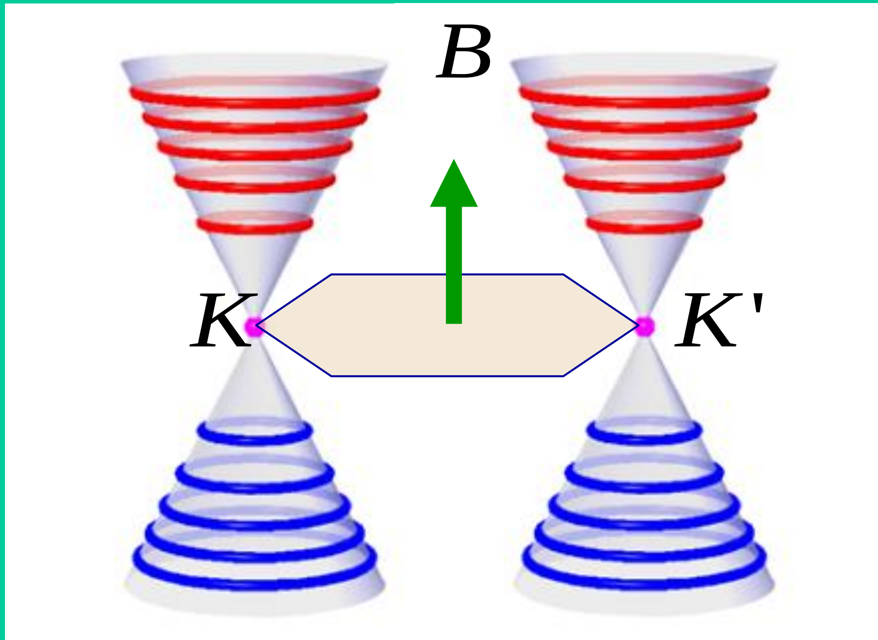
Landau Levels

$$E_N = \pm v_F \sqrt{2e\hbar B|N|} \qquad N = 0, \pm 1, ..$$

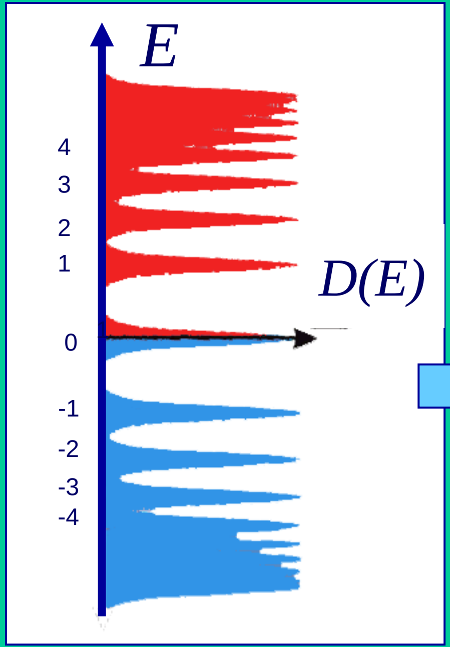


Sublattice Valley locking

Band structure

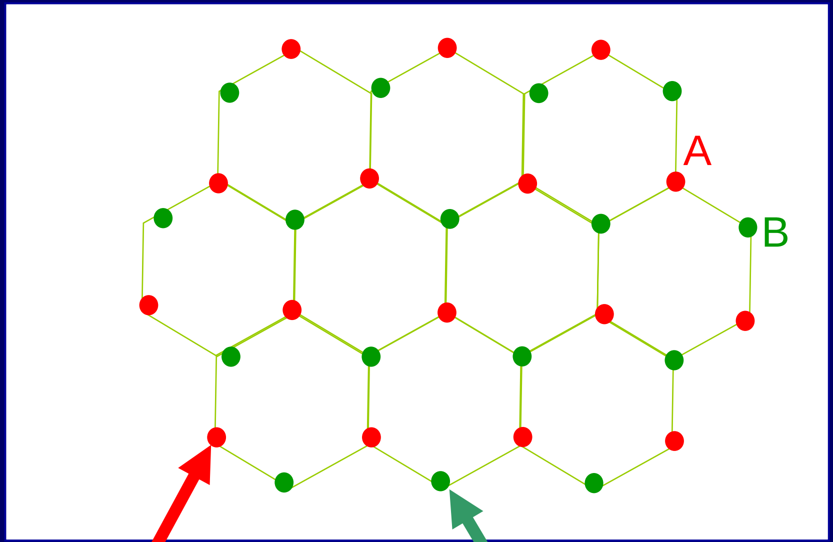


DOS



$$E_N = \pm v_F \sqrt{2e\hbar B|N|} \quad N = 0, \pm 1, ..$$

N=0 Wave function



$\psi^{K}_{N=0}(A)$ $\psi^{K'}_{N=0}(B)$

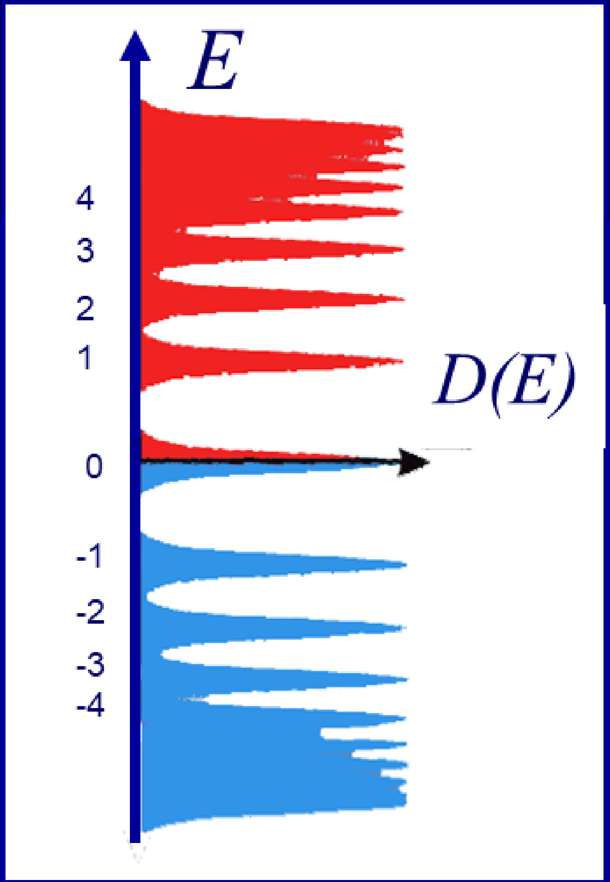
Energy and length scales

$$E_N = \pm v_F \sqrt{2e\hbar B|N|} = \pm \varepsilon_0 \sqrt{2|N|}; \qquad N = 0, \pm 1, ..$$

$$\varepsilon_0 = \hbar v_F / l_B \approx 35\sqrt{\mathrm{B}}\ \mathrm{meV}$$

$$Orbital\ \ Degeneracy\ \ \boldsymbol{g_0} = B/\phi_0 = 2.5\times 10^{14}\ m^{-2} B[T]$$

$$\mathrm{Total}\ Degeneracy: g = 4g_0; \qquad \phi_0 = h/e$$



Compare to non-relativistic electrons

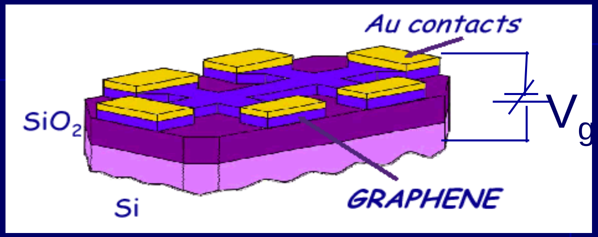
$$E_N = (N + 1/2)\hbar\omega_c$$
$$\hbar\omega_c \approx (0.1B) meV$$

Exquisite sensitivity of 2Dmaterials

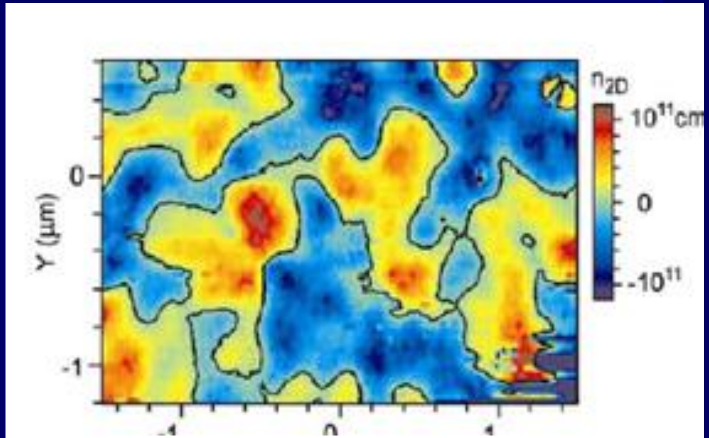
- 2D materials
- Graphene
- Transport and STM
- Flat bands and correlations
- Twisted bilayer graphene

Transport measurements: Substrate trouble

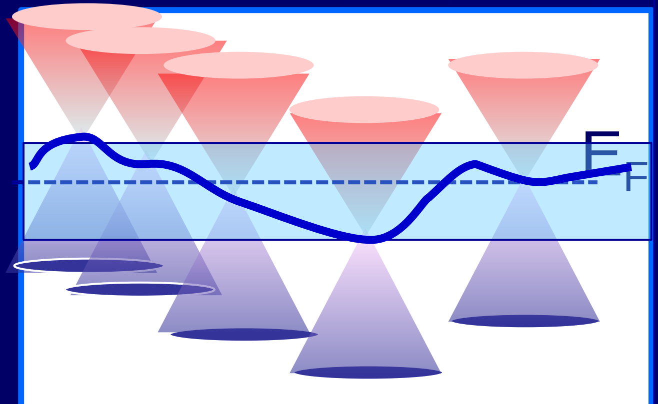
e-h puddles
smeared Dirac point



SET: Local charge density



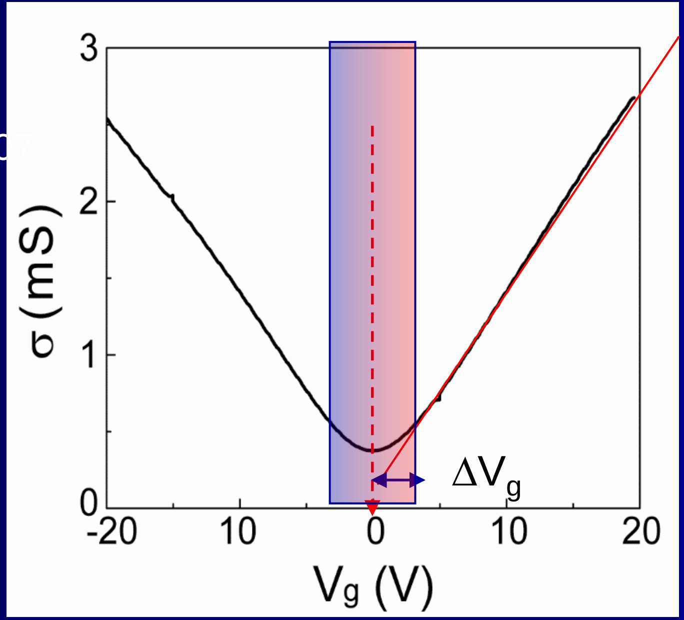
Martin, et.al, Nat. Phys(2008)



STM

- Ishigami et al Nano letters 2007
- Stolyarova et al PNAS 2007
- Geringer et al PRL 2009
- Zhang et al Nat Phys 2009
- Luican et al PRB R 2011
- S. Jung et al Nat Phys 2011

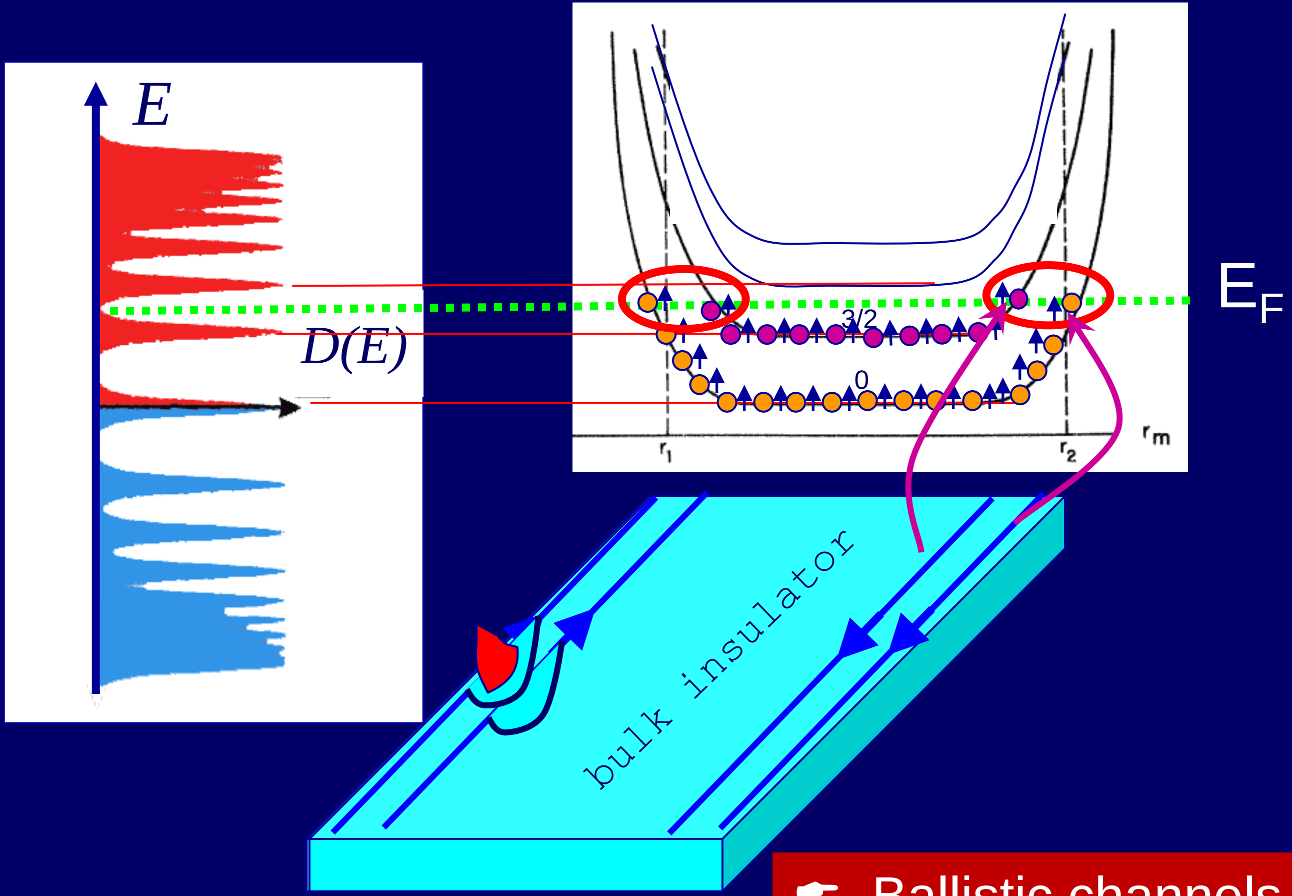
Conductivity



V_{gmin} ~1-10V
n_{min}~ 10^{11} -10^{12} cm $^{-2}$
(ΔE_{RP}~30-100meV)

Quantum Hall Effect

For $E_F \neq E_N$ and sharp edge each filled Landau level contributes *one (g-fold degenerate)* edge state



- ☛ Ballistic channels

 One dimensional edge states

- No backscattering:as long as channels far apart

-Robust against disorder

Prerequisites for QHE in graphene

IQHE

1. Decoupled edges

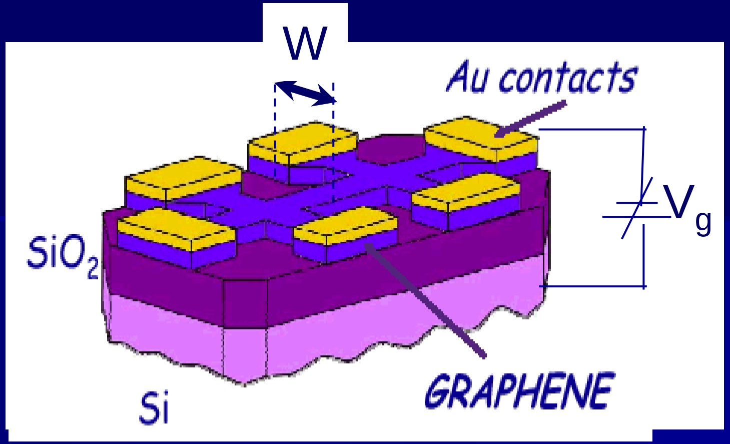
$$l_c = 25nm/(B[T])^{1/2} << W$$

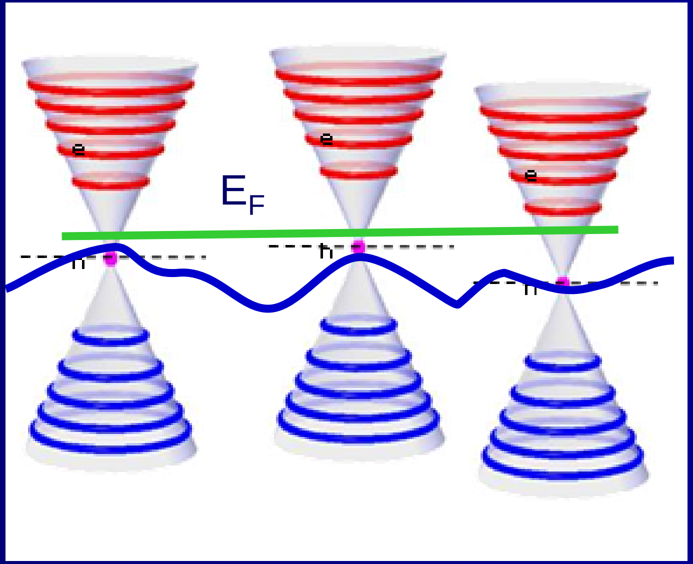
2. Well defined Landau levels

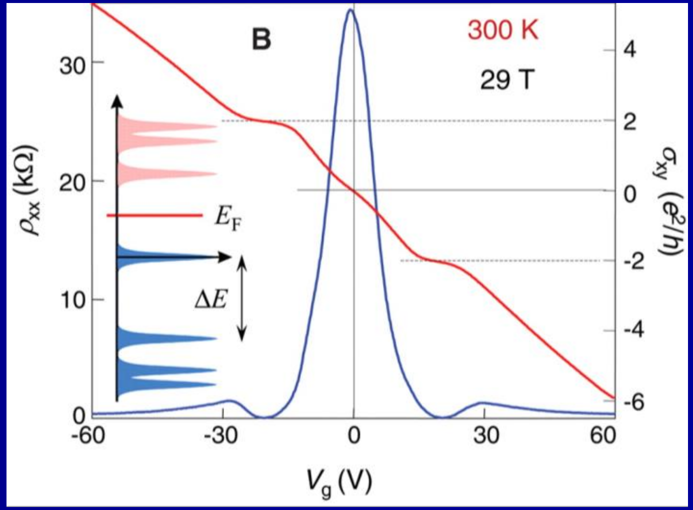
$$E_1 - E_0 = 35meV \cdot (B[T])^{1/2} > \Delta E_{RP}\ , k_B T$$

$\Delta E_{RP} \sim 100\text{meV} \rightarrow \text{IQHE for B} > 10\text{T}$

random potential







Room-Temperature Quantum Hall Effect in Graphene

K. S. NOVOSELOV, Z. JIANG, Y. ZHANG, S. V. MOROZOV, H. L. STORMER, U. ZEITLER, J. C. MAAN, G. S. BOEBINGER, P. KIM, [...] A. K. GEIM +1 authors Authors Inf
Affiliations

SCIENCE • 9 Mar 2007 • Vol 315, Issue 5817 • p. 1379 • DOI: 10.1126/science.1137201

Unteger and fractional QHE in graphene

IQHE

1. Decoupled edges

$$l_c = 25nm/(B[T])^{1/2} << W$$

2. Well defined Landau levels

$$E_1 - E_0 = 35meV \cdot (B[T])^{1/2} > \Delta E_{RP}, k_B T$$

$$\Delta E_{RP} \sim 100\text{meV} \rightarrow \text{IQHE for B} > 10\text{T}$$

random potential

IQHE easily observed in graphene even at room temperature!

FQHE

1. Decoupled edges

$$l_c = 25nm/(B[T])^{1/2} << W$$

2. Well defined "Λ" levels

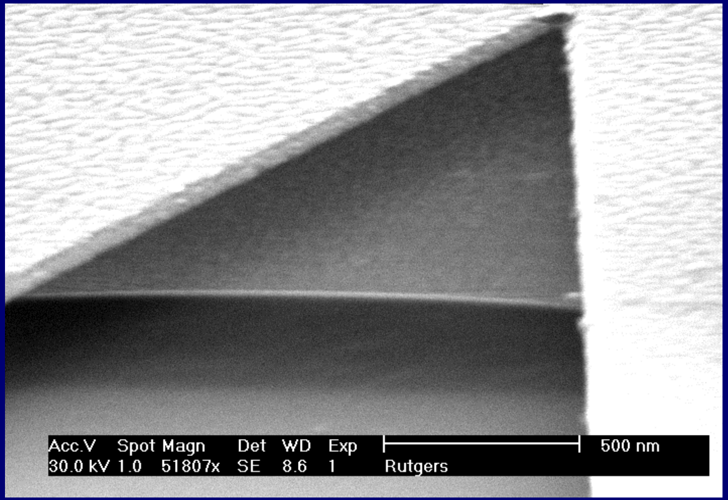
$$E_{\Lambda=1/3} = \nu^2 \frac{e^2}{\kappa l_c} \approx 5meV \frac{(B[T])^{1/2}}{\kappa} > \Delta E_{RP}$$

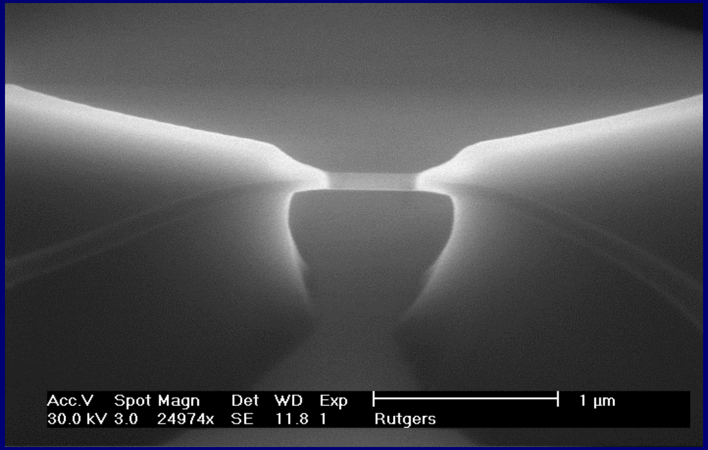
$$\Delta E_{RP} \sim 100meV \Rightarrow B > 6400\,T$$

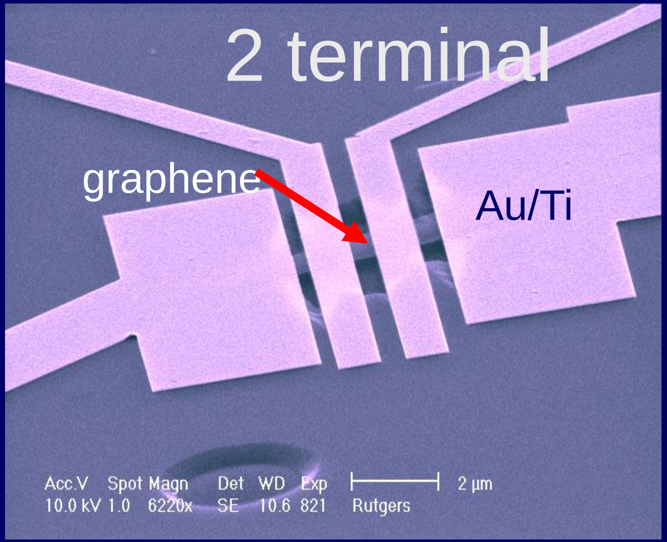
FQHE not observable in graphene on SiO_2 substrates

Suspended Graphene

- X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)
- Bolotin et al , Solid State Communications (2008)

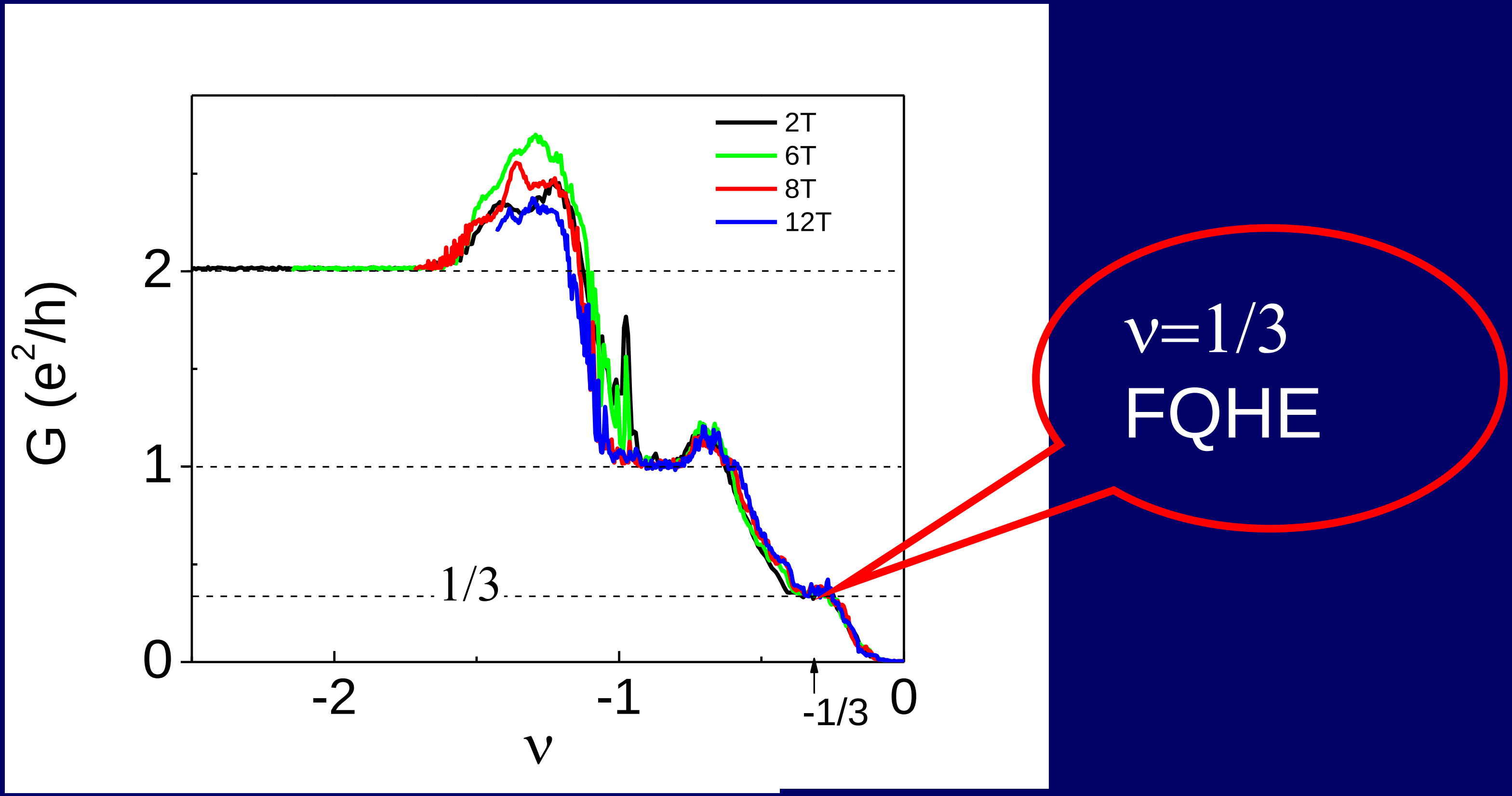






Andrei

X. Du, I. Skachko, F. Duerr, A. Luican, EYA, Nature **462**, 192 (2009)



FQHE in graphene

Seen already at 2T at 0.3K

Persists up to 20K (in 12T)

- Bolotin et al (Columbia) Nature 462 (2009)
- Geim & Novoselov (Manchester)

G/BN C. R. Dean et. al arxiv1010.1179

The magic of hexagonal Boron Nitride (hBN)

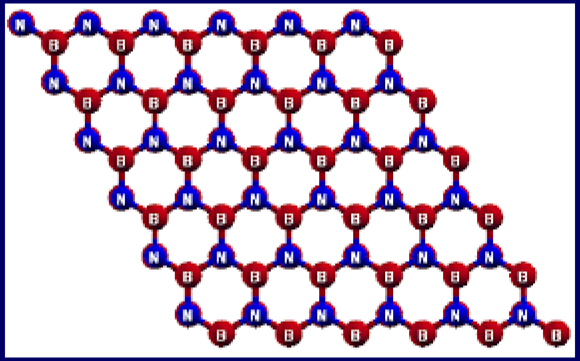
Hexagonal Boron Nitride - hBN

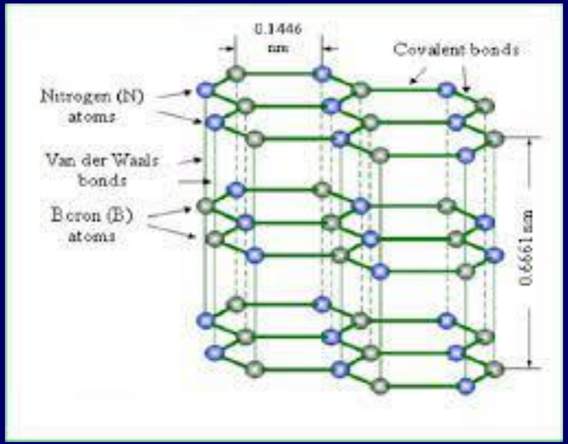
- Honeycomb structure – no dangling bonds, chemically inert.
- Protects graphene from electrical random potential, and chemical contamination

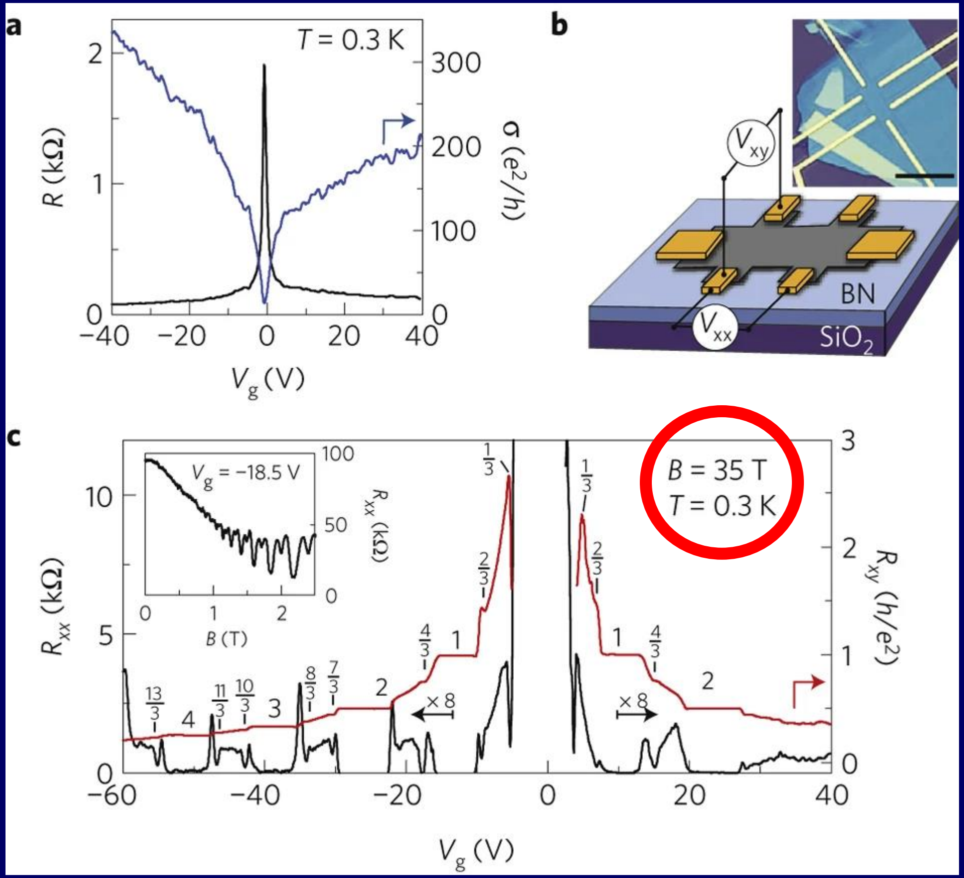
Multicomponent fractional quantum Hall effect in graphene

C. R. Dean, A. F. Young, P. Cadden-Zimansky, L. Wang, H. Ren, K. Watanabe, T. Taniguchi, P. Kim, J. Hone & K. L. Shepard

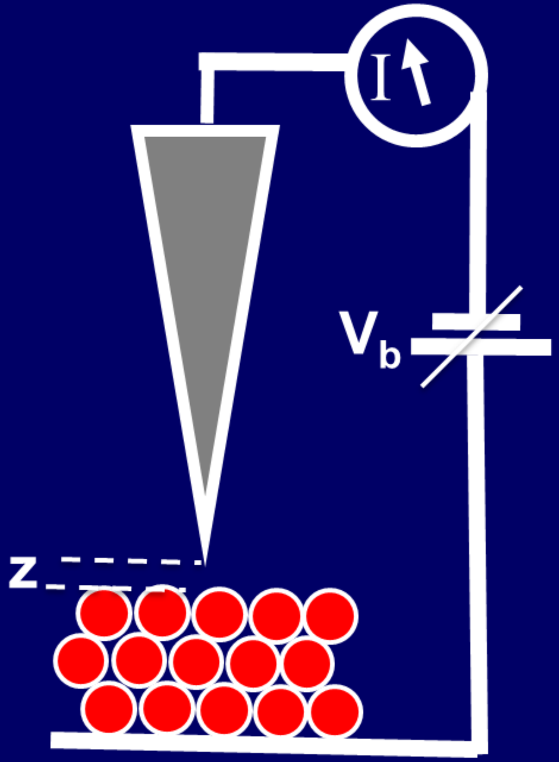
Nature Physics **7**, 693–696 (2011) | Cite this article





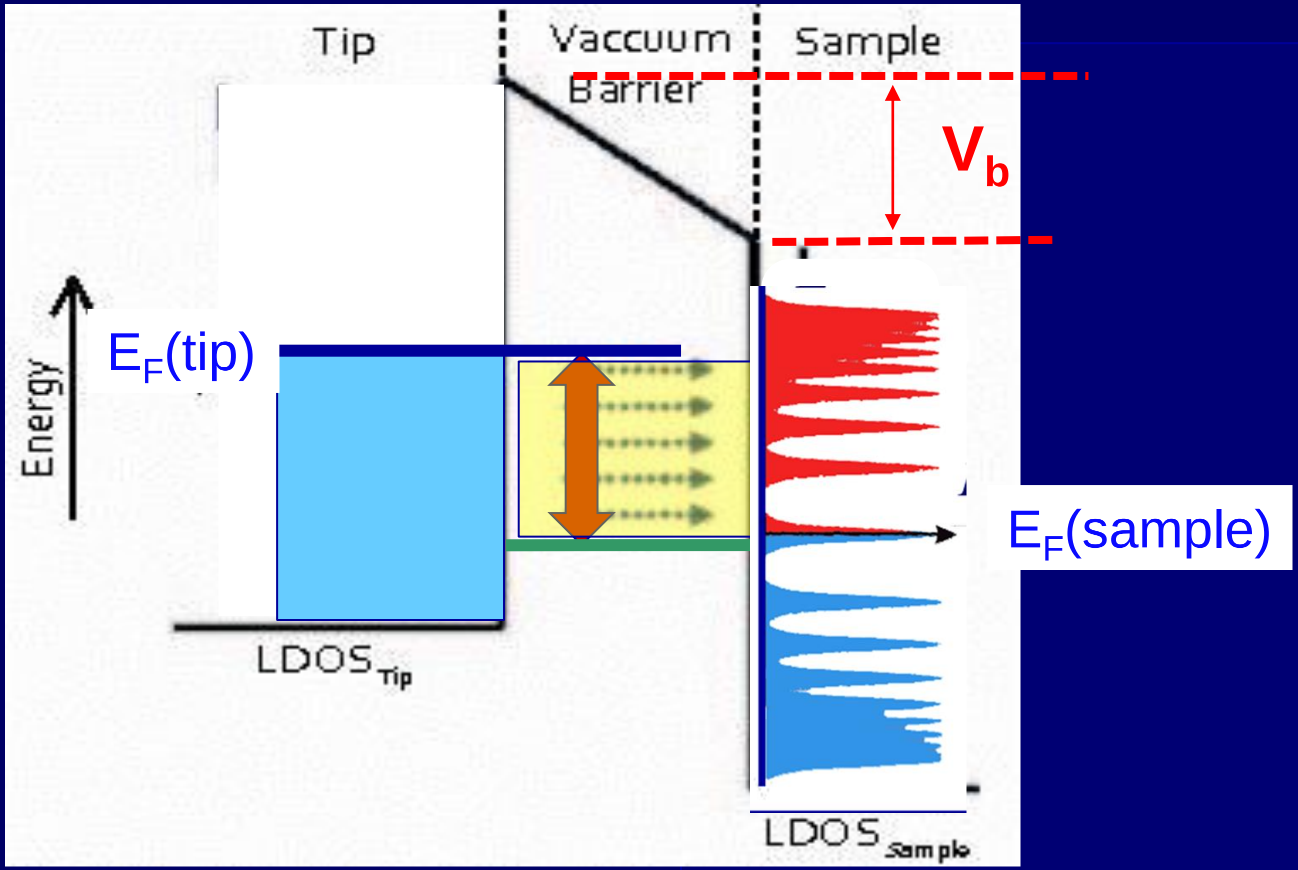


Scanning Tunneling Microscopy (STM



STM measures tunnel current across a vacuum barrier

$$I(r,z,V) \propto \left[\int_0^{eV_b} \rho(r,\varepsilon) d\varepsilon \right] \exp^{-z(r)\kappa}$$



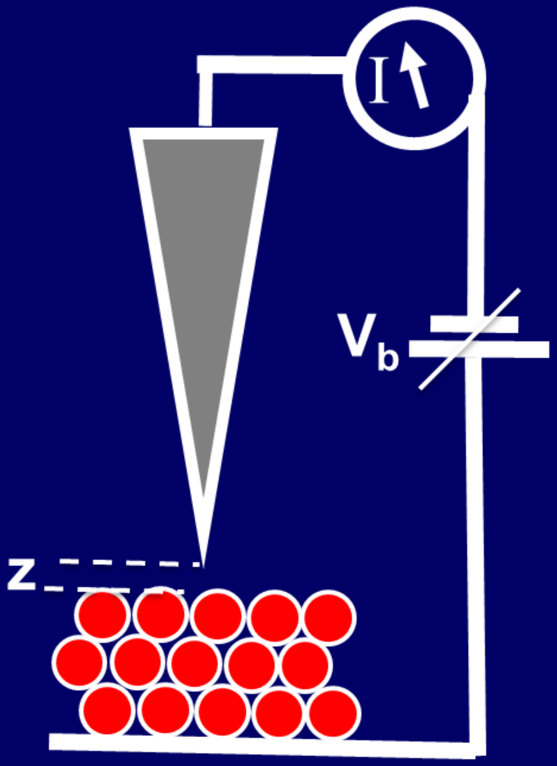
STM probes all states between E_F(tip) and E_F (Sample)

Graphene: STM and STS

Adina Luican

Guohong Li

$$I(r,z,V) \propto \left[\int_0^{eV_b} \rho(r,\varepsilon)\, d\varepsilon \right] \exp^{-z(r)\kappa}$$



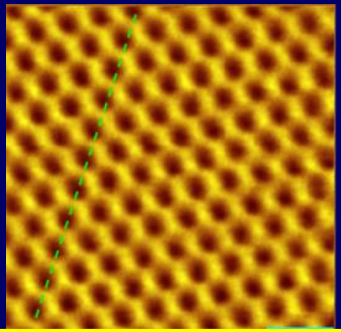
Graphene on graphite

G. Li, A. Luican , E. Y. A
Phys. Rev. Lett 102, 176804 (2009)

I ,V_b constant

Topography:
Imaging Atoms

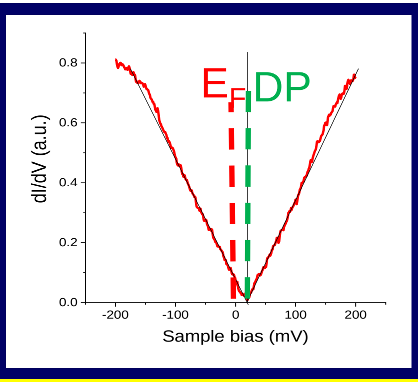
$$I(r,z) \propto \exp^{-z(r)\kappa}$$



z constant

Spectroscopy:
Density of states

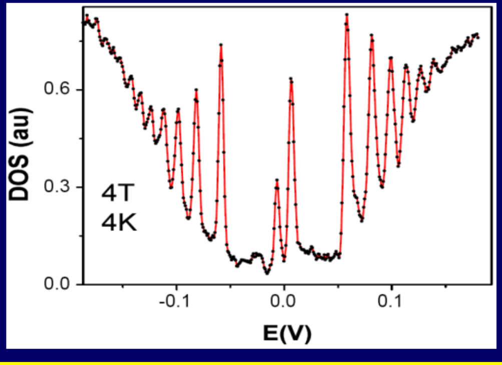
$$dI/dV_b \propto \rho(r,V_b)$$



Landau level Spectroscopy:

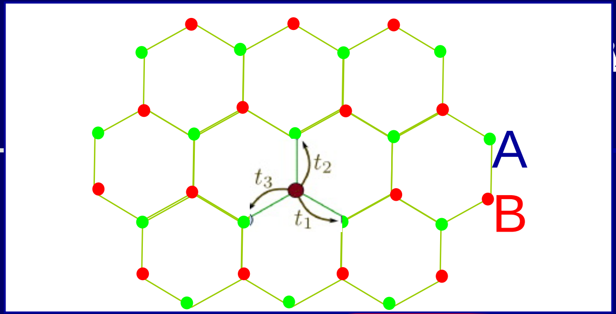
- Local Fermi velocity
- Quasiparticle lifetime
- Coupling to substrate

$$E_N = \pm v_F \sqrt{2e\hbar B|N|}$$

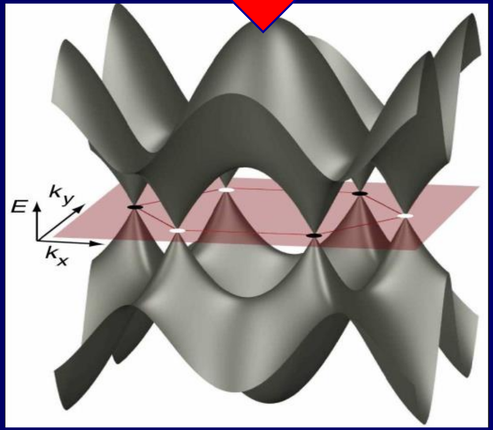


E.Y. Andrei

Controlling the band structure?



1. 2D
2. Honeycomb structure
3. 2 identical atoms/cell
4. $t_1=t_2=t_3= t$



Can one control/manipulate the band structure?

- Relax the condition: $t_1=t_2=t_3$
  - Strain
- Impose external potential
  - Substrate
- Point Defects
- Electrostatic potential
- Magnetic field

2-terminal measurement of QHE

Conformal invariance and shape-dependent conductance of graphene samples

Dmitry A. Abanin and Leonid S. Levitov
Phys. Rev. B **78**, 035416 – Published 10 July 2008

Fractional quantum Hall effect in suspended graphene: Transport coefficients and electron interaction strength

D. A. Abanin, I. Skachko, X. Du, E. Y. Andrei, and L. S. Levitov
Phys. Rev. B **81**, 115410 – Published 8 March 2010

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

Fractional quantum Hall effect in suspended graphene probed with two-terminal measurements

I. Skachko, X. Du, F. Duerr, A. Luican, D. A. Abanin, L. S. Levitov and E. Y. Andrei

Published: 13 December 2010 https://doi.org/10.1098/rsta.2010.0226

Berry phase of π

Electronic properties of graphene: a perspective from scanning tunneling microscopy and magnetotransport

Eva Y Andrei[1], Guohong Li[1] and Xu Du[2]

Published 19 April 2012 • © 2012 IOP Publishing Ltd

Reports on Progress in Physics, Volume 75, Number 5

Onsager: Area of N'th orbit in k space

$$S(k_N) = \pi k_N^2 l_B^2 = 2\pi(N + 1/2 - \gamma/2\pi)$$

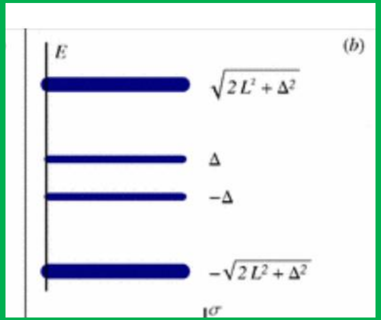
$$\gamma = \text{Berry Phase}$$

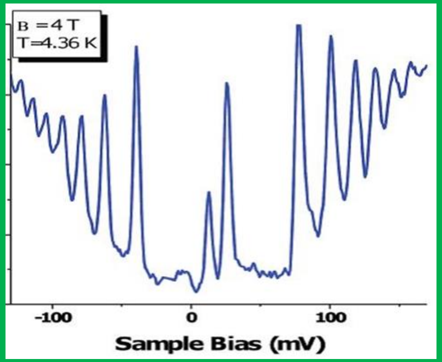
$$\oint_C d\lambda \langle \psi(\lambda) | i(\partial/\partial\lambda) | \psi(\lambda) \rangle$$

Excitonic gap (Magnetic catalysis)

Excitonic gap, phase transition, and quantum Hall effect in graphene

V. P. Gusynin, V. A. Miransky, S. G. Sharapov, and I. A. Shovkovy
Phys. Rev. B **74**, 195429 – Published 22 November 2006





More references

Graphene monolayer and bilayer tutorials

REVIEW ARTICLE

The electronic properties of bilayer graphene

Edward McCann[1] and Mikito Koshino[2]

Published 19 April 2013 • © 2013 IOP Publishing Ltd

Reports on Progress in Physics, Volume 76, Number 5

McCann E 2012 *Graphene Nanoelectronics: Metrology, Synthesis, Properties and Applications* Raza H (ed) (Berlin: Springer-Verlag) 237-275