MANCHESTER 1824

The University of Manchester

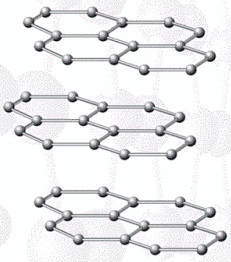
QED in a Pencil Trace

Andre Geim

in collaboration with
K. Novoselov, S. Morozov, F. Schedin, D. Jiang, T. Booth,
M. Katsnelson, J. Meyer & I. Grigorieva

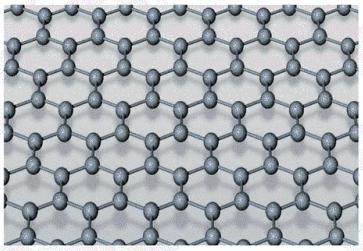
GRAPHENE ALLOTROPES

3D



Graphite

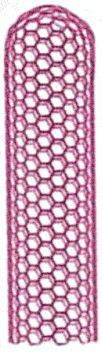
2D



graphene

PRESUMED
NOT TO EXIST
IN THE FREE STATE

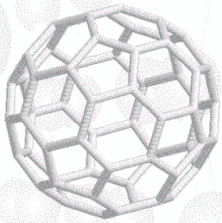
1D



Carbon Nanotube

multi-wall:
1952 to *Iijima 1991*
single-wall: 1993

0D

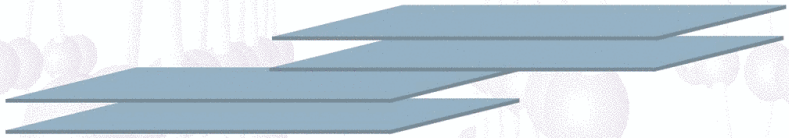


Buckyballs

Kroto et al 1985

Extracting a Single Plane

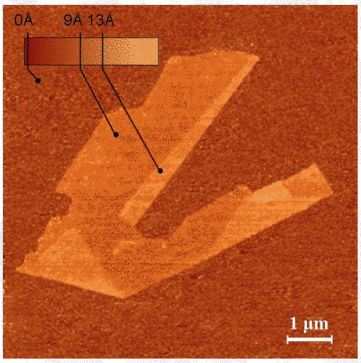
GRAPHITE IS
STRONGLY LAYERED



SLICE DOWN TO
ONE ATOMIC PLANE

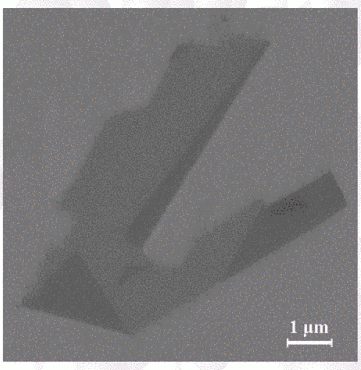
individual atomic sheets: do they exist?

Free-Standing Graphene



AFM

low throughput

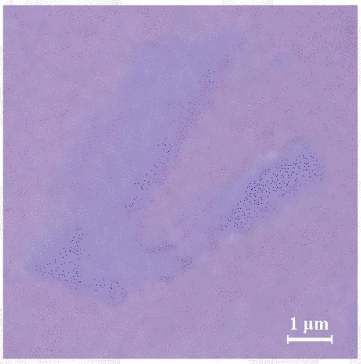


SEM

no clear signatures

Key: Visual Identification

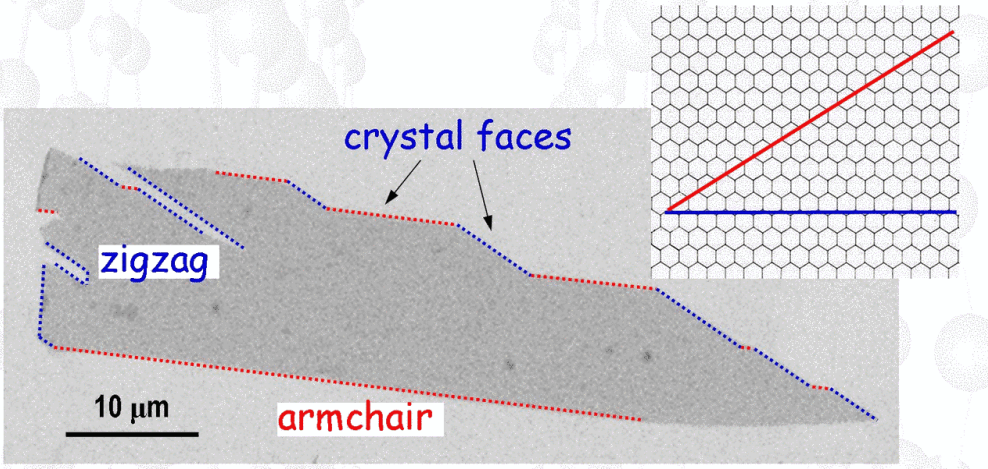
OPTICS



single layer of atoms visible by "naked" eye

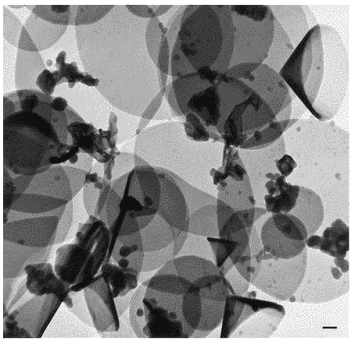
5% change in SiO_2 thickness important

Two Dimensional Crystallites

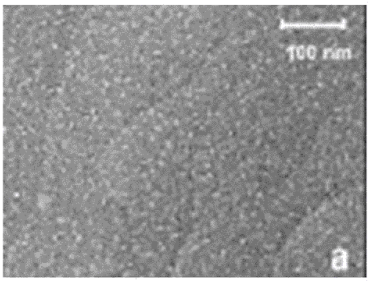


not just flakes
but graphene crystallites

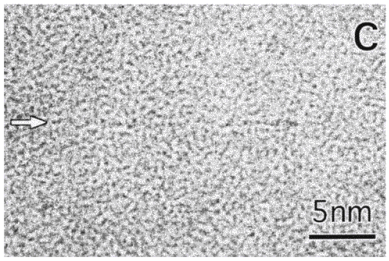
No Free Standing Monolayers Known



CHEMICAL DECOMPOSITION
up to Ø 2μm; > 80 layers; Krishnan 1998



EPITAXIAL GROWTH
McConville 1986 (on Ni); Land *1992* (on Pt)
Affoune 2001 (on HOPG); Nagashima 1993 (on TiC)
quality & continuity (?)



SiC: Bommel 1975; Forbeaux 1998; Charrier 2002;
Berger 2004-2006; *Rotenberg 2006*

CHEMICAL EXFOLIATION
Dresselhauses (2002 review)
restacked and scrolled SOOT
individual folds: Horiuchi 2004

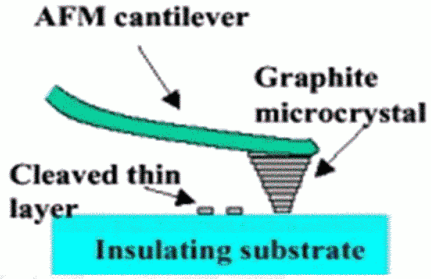
mechanical cleavage in retrospect

Ohashi (*Tanso* 1997, 2000)
from 1000 down to 50 layers

our work (Science 2004): single layer

Philip Kim's & Paul McEuen's groups
(*PRL* 2005 & *Nanoletters* 2005) down to 35 layers

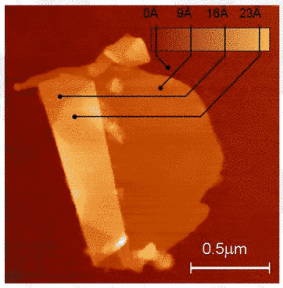
Nanopencil



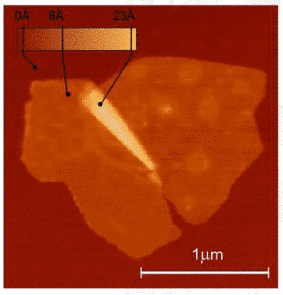
for >10 layers,
electronic structure
of bulk graphite
(*Partoens 2006*)

Other 2D Atomic Crystals

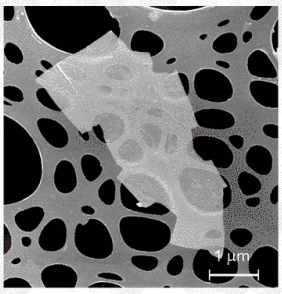
2D boron nitride in AFM



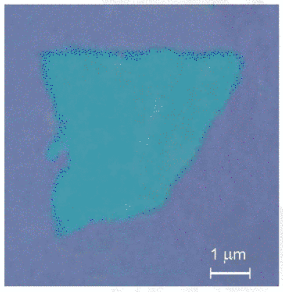
2D $NbSe_2$ in AFM



also,
2,3,4... layers



2D $Bi_2Sr_2CaCu_2O_x$ in SEM



2D MoS_2 in optics

PNAS **102**, 10451 (2005)

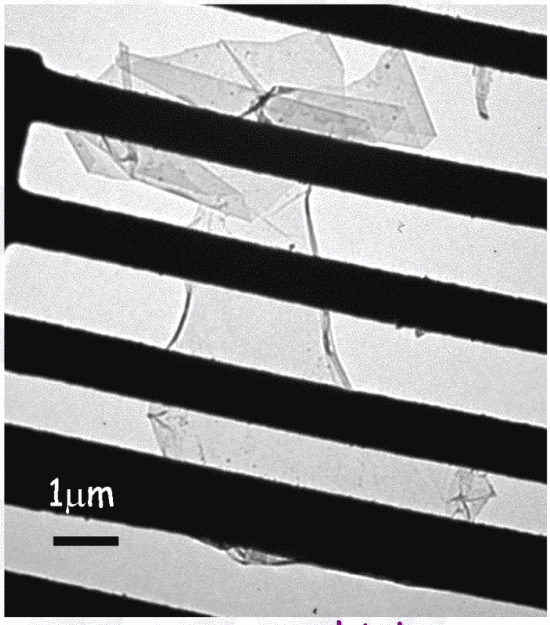
2D ATOMIC CRYSTALS
a new kind of materials
wide choice of materials properties
(electronic, mechanical, chemical, etc.)

Why 2D Crystals Exist ?

- *stabilizing influence of substrate*
- *extracted from 3D, remain (meta)stable*
- *something else*

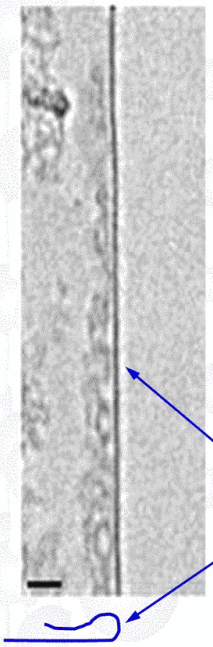
Jannik Meyer, AKG et al

"Free-Hanging" Graphene



one-atom-thick
single-crystal fabric

TEM confirms single layer



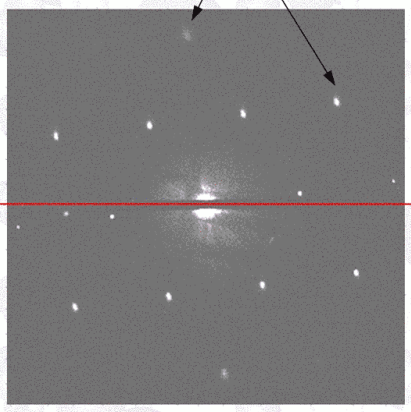
single fold
at the edge

Structure Of Suspended Graphene

local electron diffraction
(beam Ø 250 nm)

normal incidence

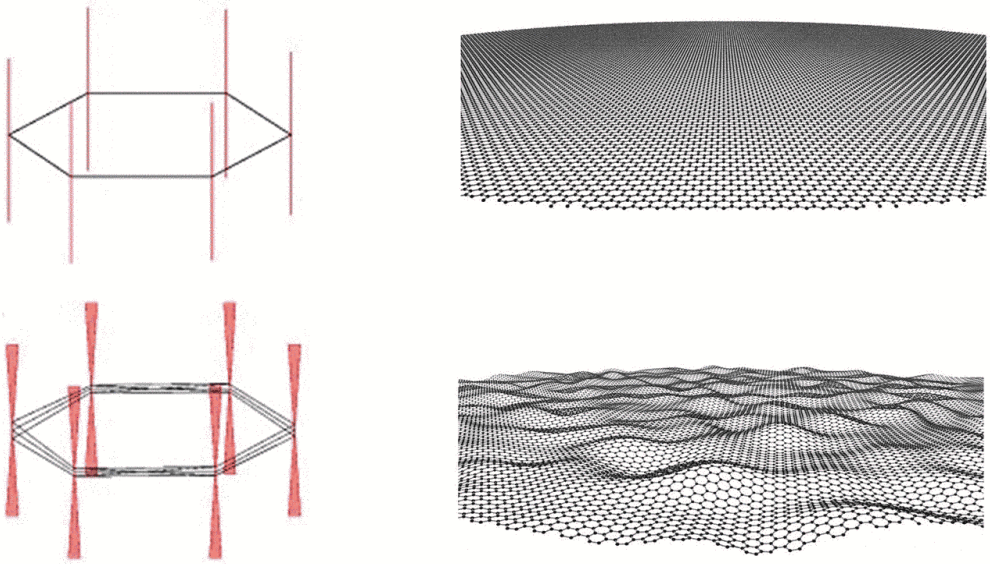
diffraction peaks
away from tilt axis
become blurred



26° tilt

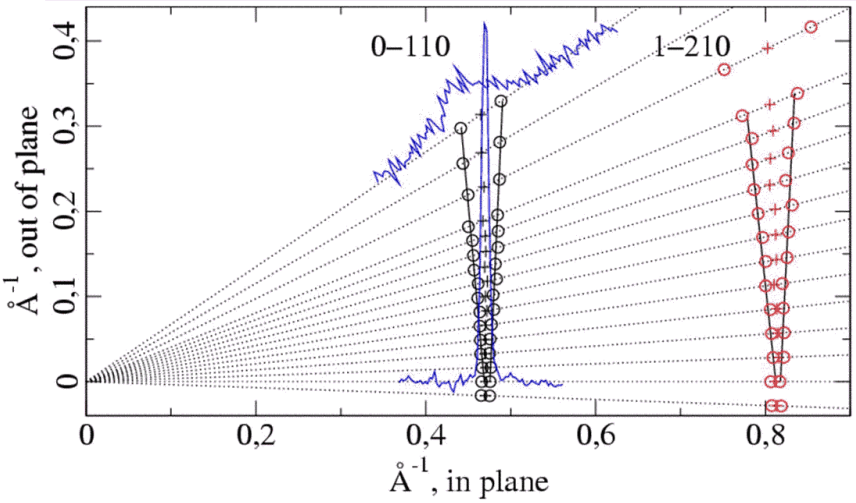
Structure Of Suspended Graphene

reciprocal space *real space*



cones in Fourier space rather than rods

Intrinsic Microscopic Crumpling

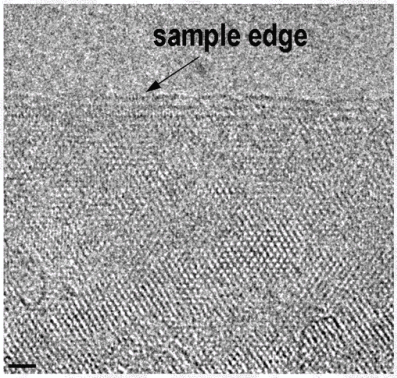


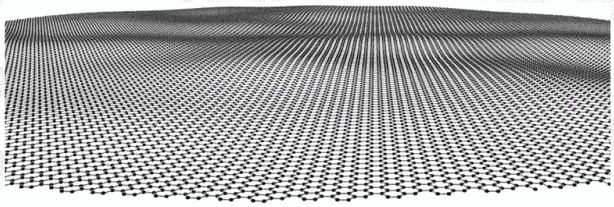
5° angle, and highly reproducible for different samples
twice smaller (≈2°) for bilayer graphene
disappears for few-layer samples

isotropic: local strain up to 1%

Intrinsic Microscopic Crumpling

atomic resolution TEM
ripple contrast appears for >1 layer



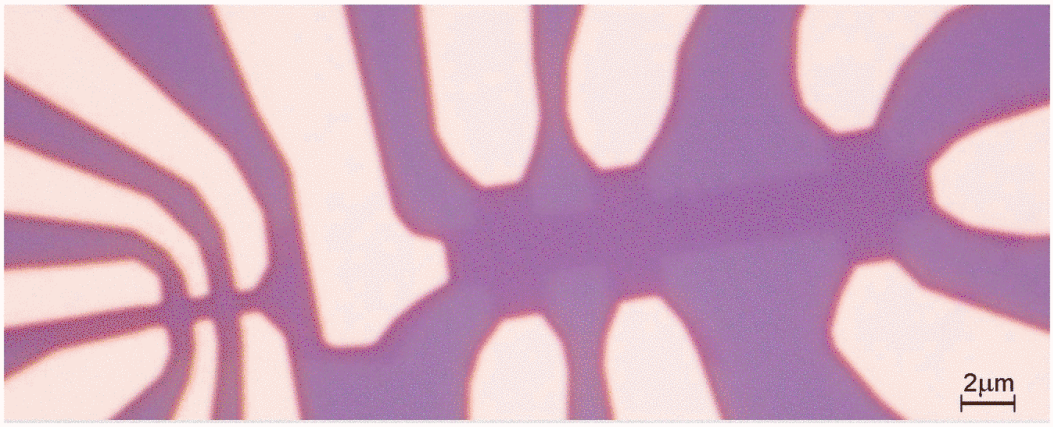


height ≈5Å; size ≈5nm;
elastic energy
few kT per ripple

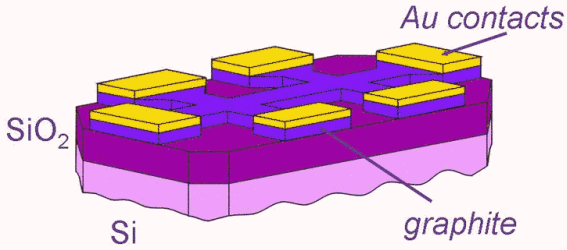
- ***crumpling in third-D may stabilize 2D sheet***
  loose in elastic energy but gain in entrophy; Nelson (1987)

ELECTRON TRANSPORT IN GRAPHENE

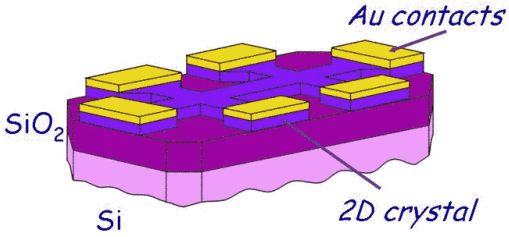
Graphene Devices

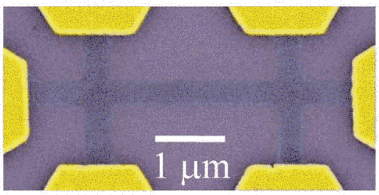


- optical image
- SEM image
- design
- contacts and mesa



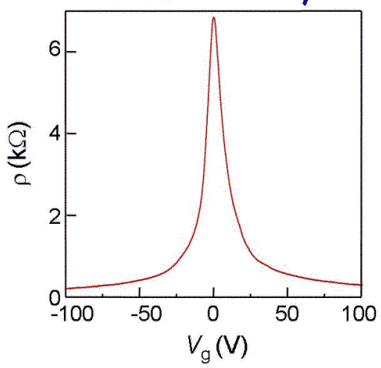
Electric Field Effect in Graphene





SEM in false colour

resistivity



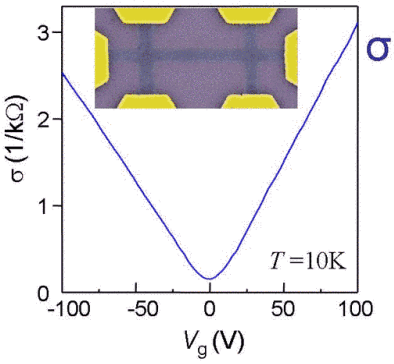
graphene: currently
up to 10,000 $cm^2/V \cdot s$ at 300K

ballistic transport on submicron scale

under ambient conditions

Electric Field Effect in Graphene

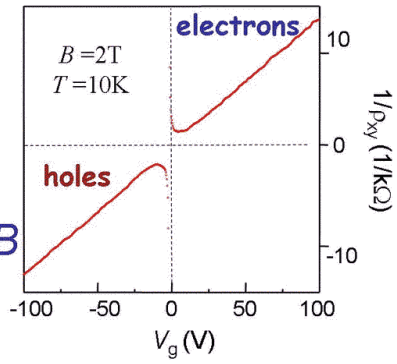
conductivity



$\sigma = n(V_g)e\mu$

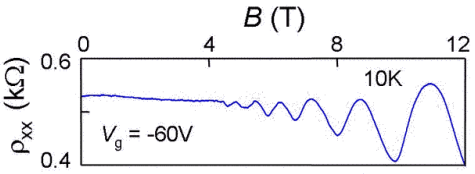
$1/\rho_{xy} = ne/B$

Hall effect

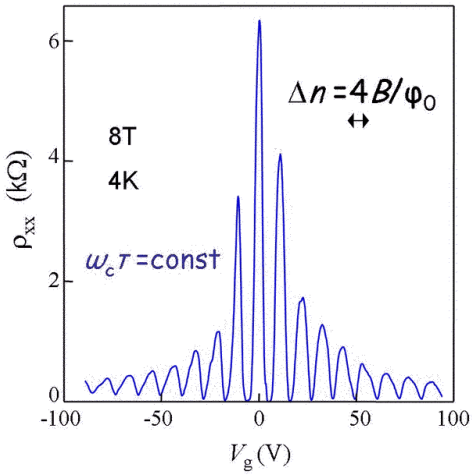


simple behaviour;
practically constant mobility;
no trapped carriers

Quantum Oscillations in Graphene



degeneracy $f = 4$
two spins & two valleys



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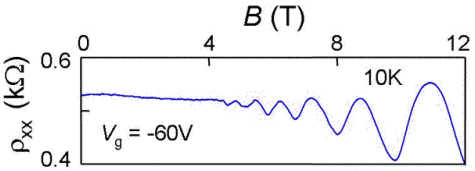

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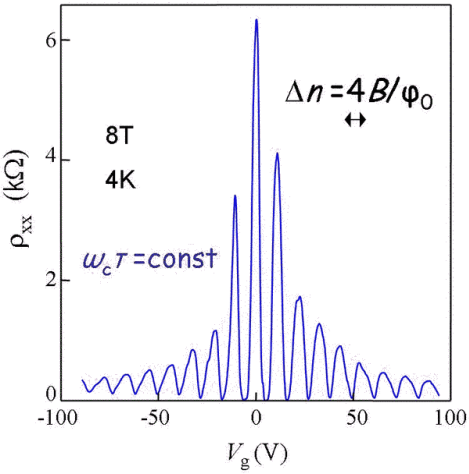
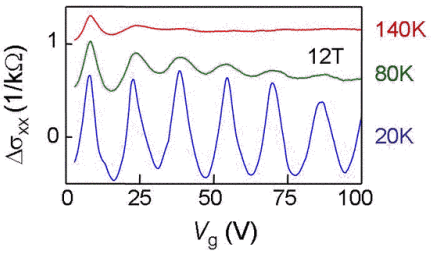
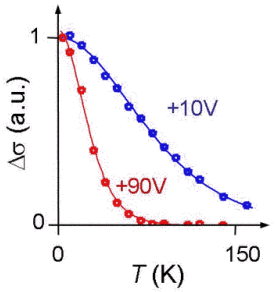


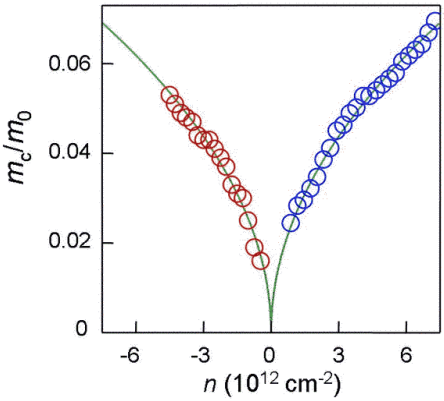




$$\Delta\sigma_{xx} \propto T_i \sinh\left(\frac{2\pi^2 k_B T m_c}{\hbar e B}\right)$$

Band Structure of Graphene

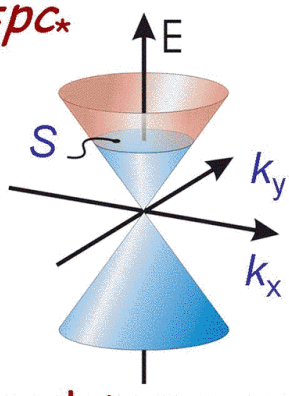
cyclotron mass strongly depends on concentration



$B_F = (\hbar/2\pi e)S$ and $m_c = (\hbar^2/2\pi)\partial S/\partial E$

experimental dependences
$B_F \sim n$ and $m_c \sim n^{1/2}$
necessitates $S \sim E(k)^2$ or $E \sim k$

$E = pc^*$



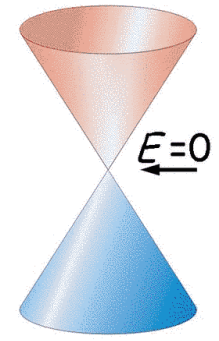
cyclotron mass
$E = m_c v_F^2$

$v_F = 10^6$ m/s ±5%

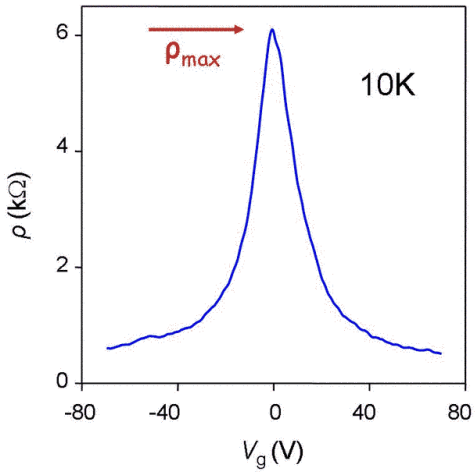
previously seen in
zero-gap 3D semiconductors
(Zawadzki 1974)

CONDUCTIVITY "WITHOUT" CHARGE CARRIERS

Minimum Quantum Conductivity

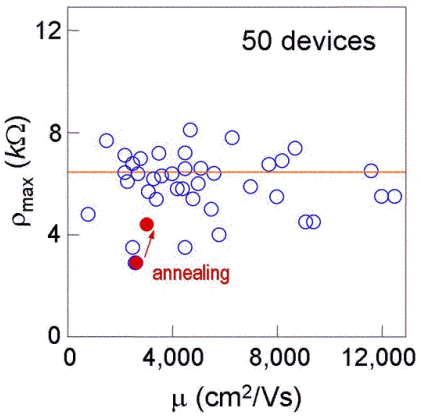


zero-gap semiconductor



no temperature dependence in the peak from 3 to 100K

Minimum Quantum Conductivity



$h/4e^2$

most theories predict
π-times larger value

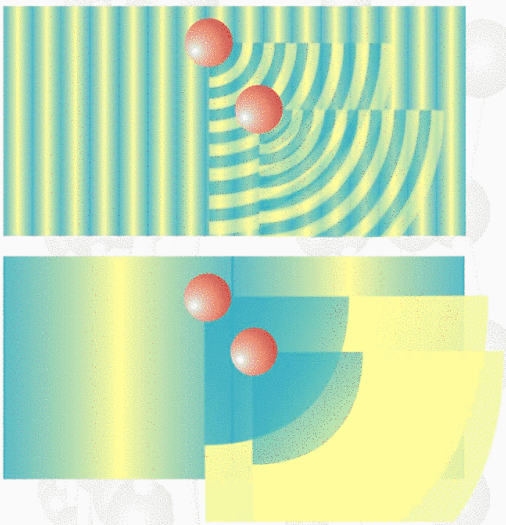
Fradkin 1986
Lee 1993
Ludwig 1994
Morita 1997
Ziegler 1998
Peres 2005
Gusynin 2005
Katsnelson 2006
Tworzydlo 2006
Cserti 2006
Ostrovsky 2006
.....
.....

quantized resistivity NOT resistance
(h/e^2 per spin and valley)

Minimum Quantum Conductivity

Mott's argument: $l \geq \lambda_F$

$$\sigma = ne\mu = \frac{e^2}{h} k_F l \geq \frac{e^2}{h}$$



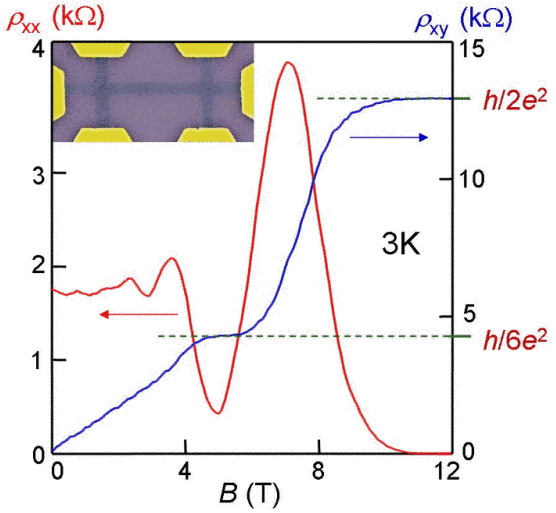
NO LOCALIZATION

as observed in graphene

CHIRAL Quantum Hall Effects

Quantum Hall Effect in Graphene

quadruple degeneracy:
plateaus are expected at $h/4Ne^2$



Quantum Hall Effect in Graphene

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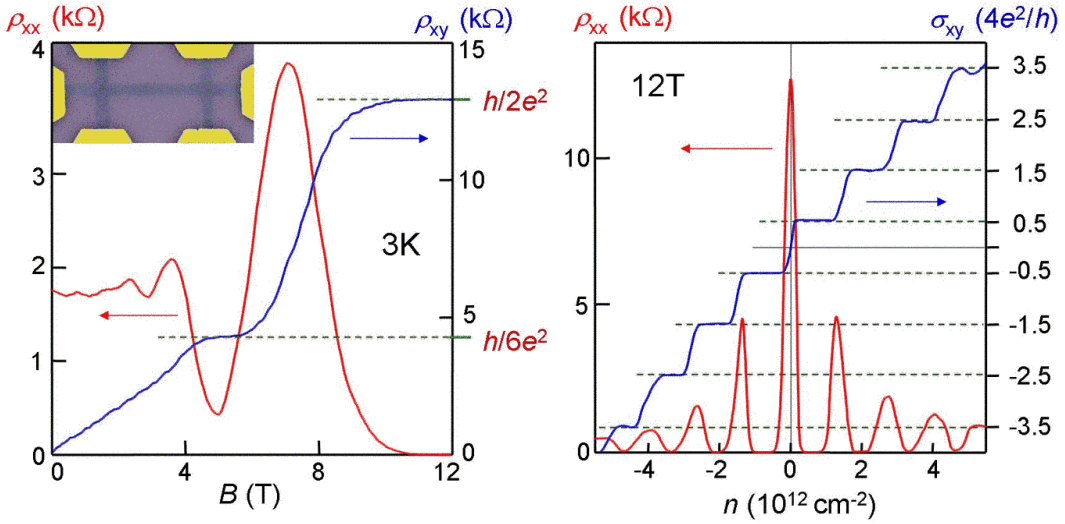
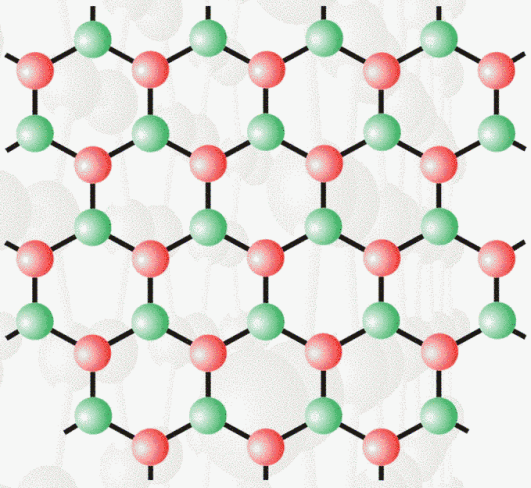
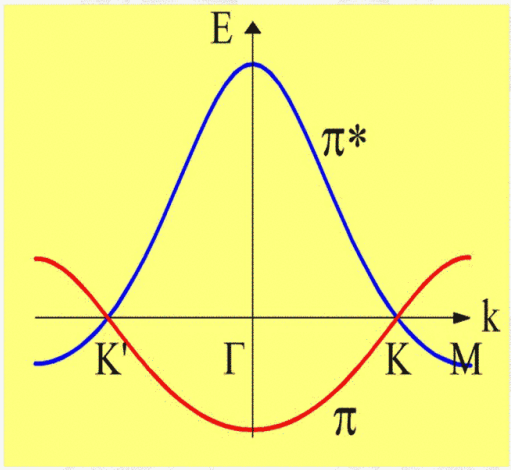


"half-integer" QHE

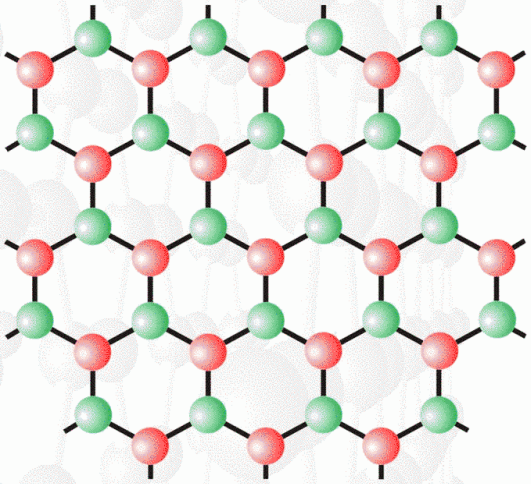
Chiral Fermions in Graphene

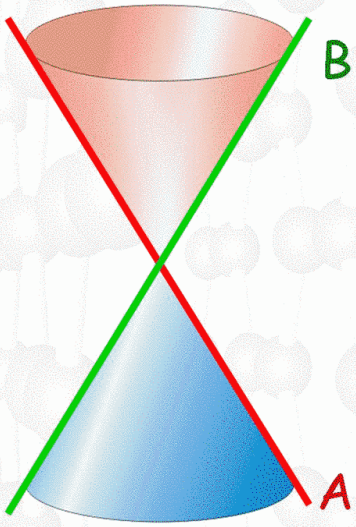




two sublattices ⇒ superposition of their wavefunctions ⇒ spinors (2 projections of pseudospin)

Chiral Fermions in Graphene



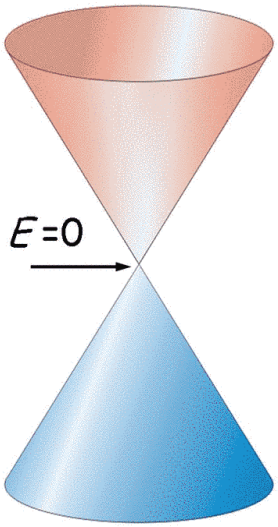


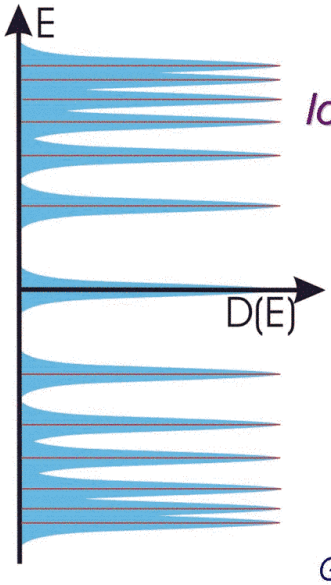
Dirac equation: $\hat{H} = v_F \begin{pmatrix} 0 & \hat{p}_x + i\hat{p}_y \\ \hat{p}_x - i\hat{p}_y & 0 \end{pmatrix} = v_F \vec{\sigma} \cdot \vec{p}$

quantization of Dirac fermions

$E = \pm\sqrt{2\hbar v_F{}^2 eBN}$

$E = \hbar v_F k$

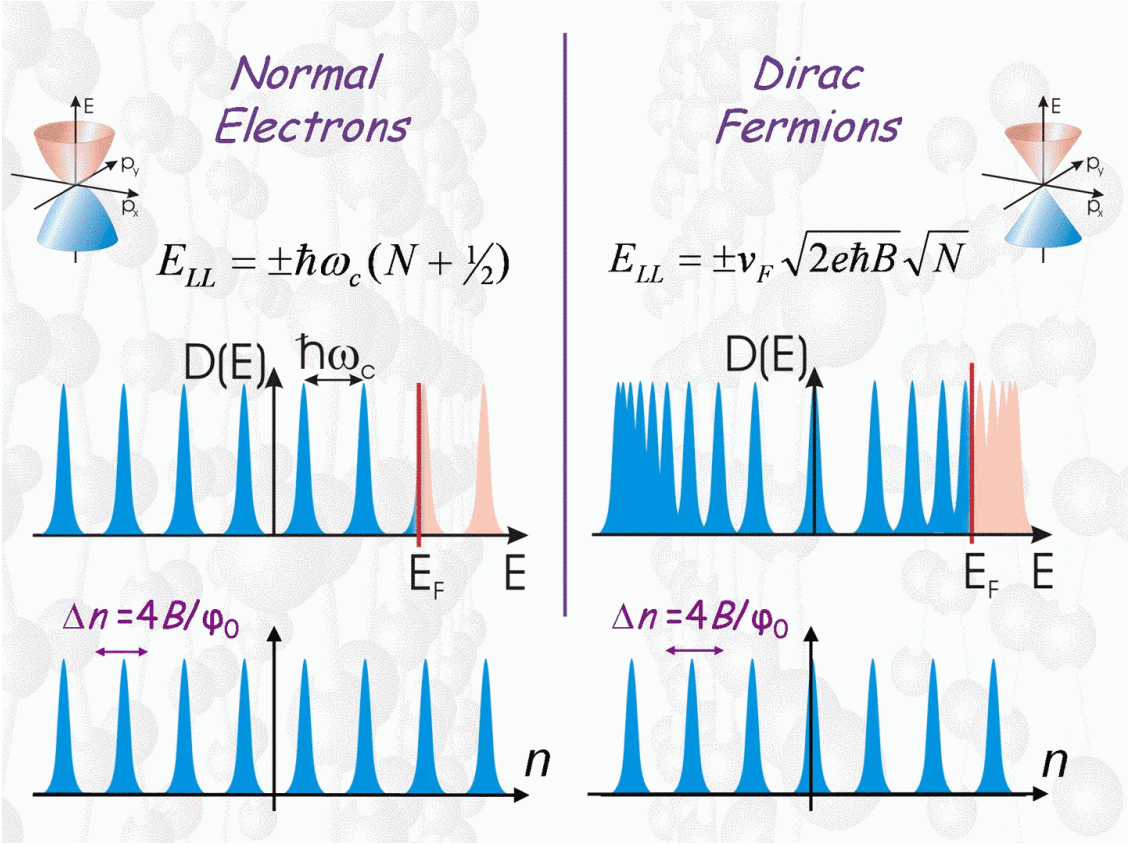




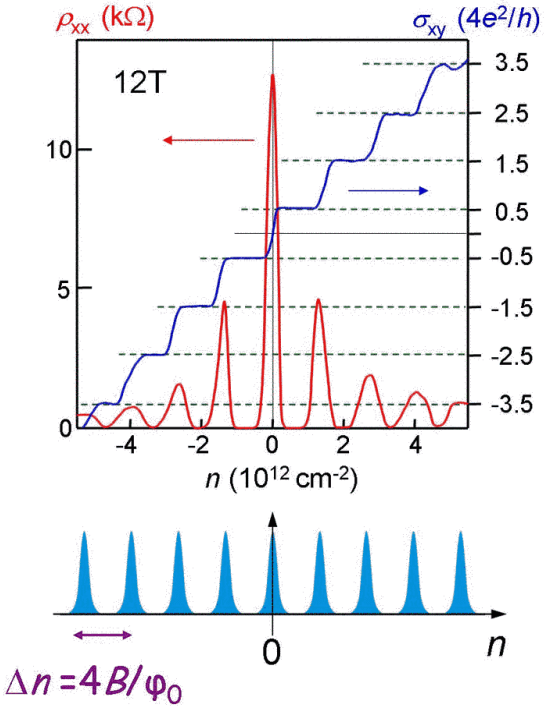
lowest Landau level at ZERO energy

$\Delta n = 4B/\varphi_0$

McClure 1956
Semenoff 1984
Haldane 1988
Gonzalez 1993
.....
Gusynin 2005; Peres 2006
.....



half-integer quantum Hall effect

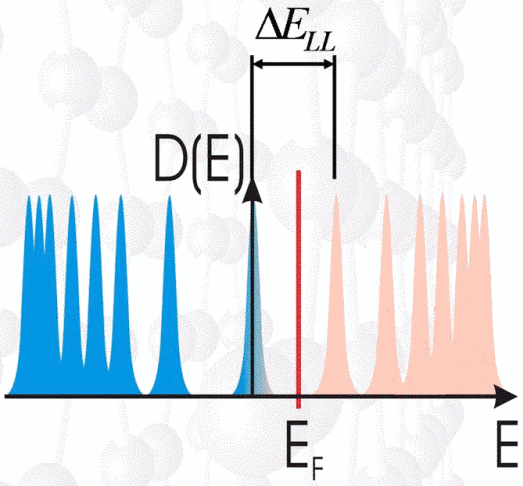


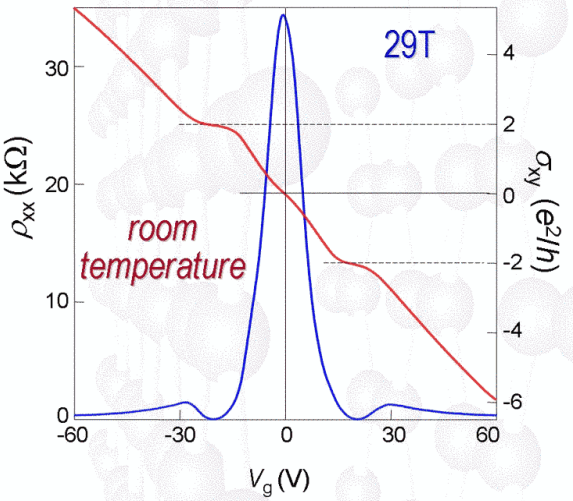
relativistic analogue of the integer QHE

Nature **438**, 197 (2005)

also Zhang *et al*, *ibid* 201 (2005)

room-temperature QHE



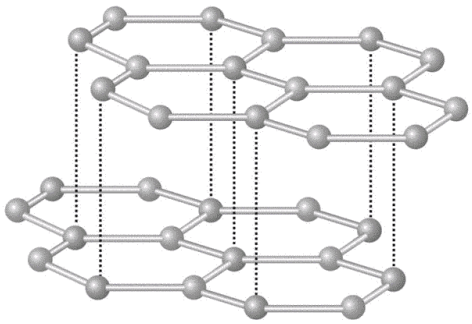


$$\Delta E_{LL} = v_F \sqrt{2e\hbar B}$$

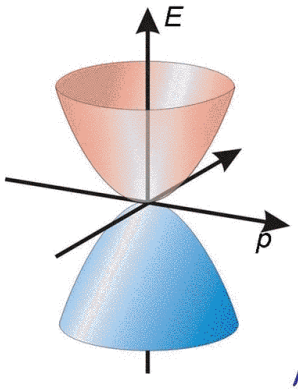
$$\Delta E_{LL}(K) = 420\sqrt{B(T)}$$

previously, only below 30K

BILAYER GRAPHENE

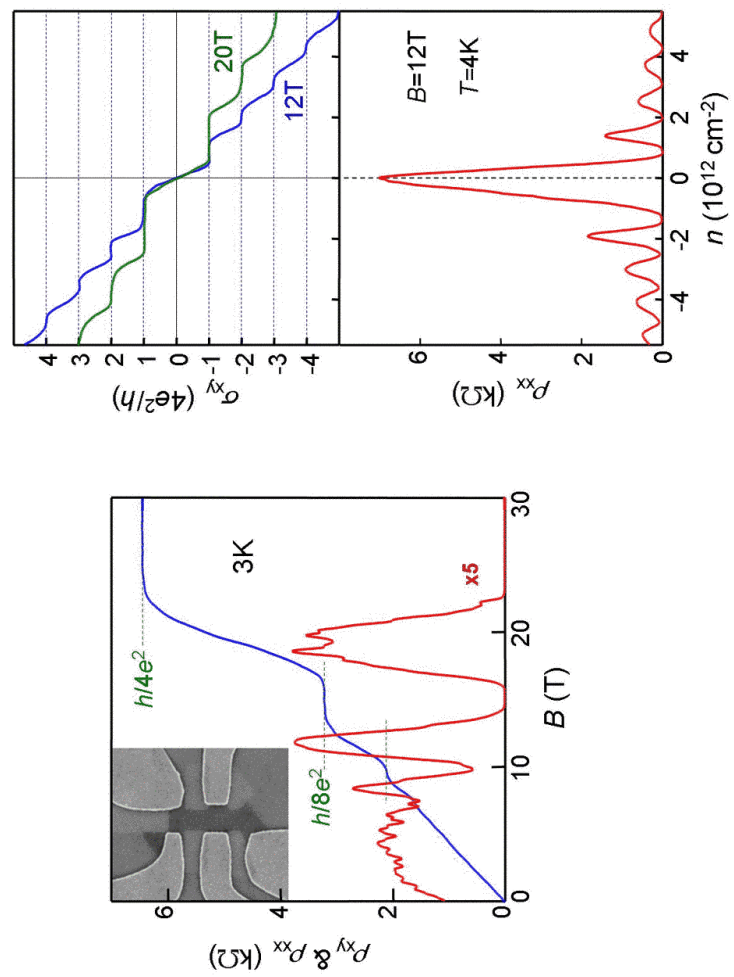


$$E(p) = \pm\tfrac{1}{2}\gamma_1 \pm \sqrt{\tfrac{1}{4}\gamma_1^2 + v_F^2 p^2}$$

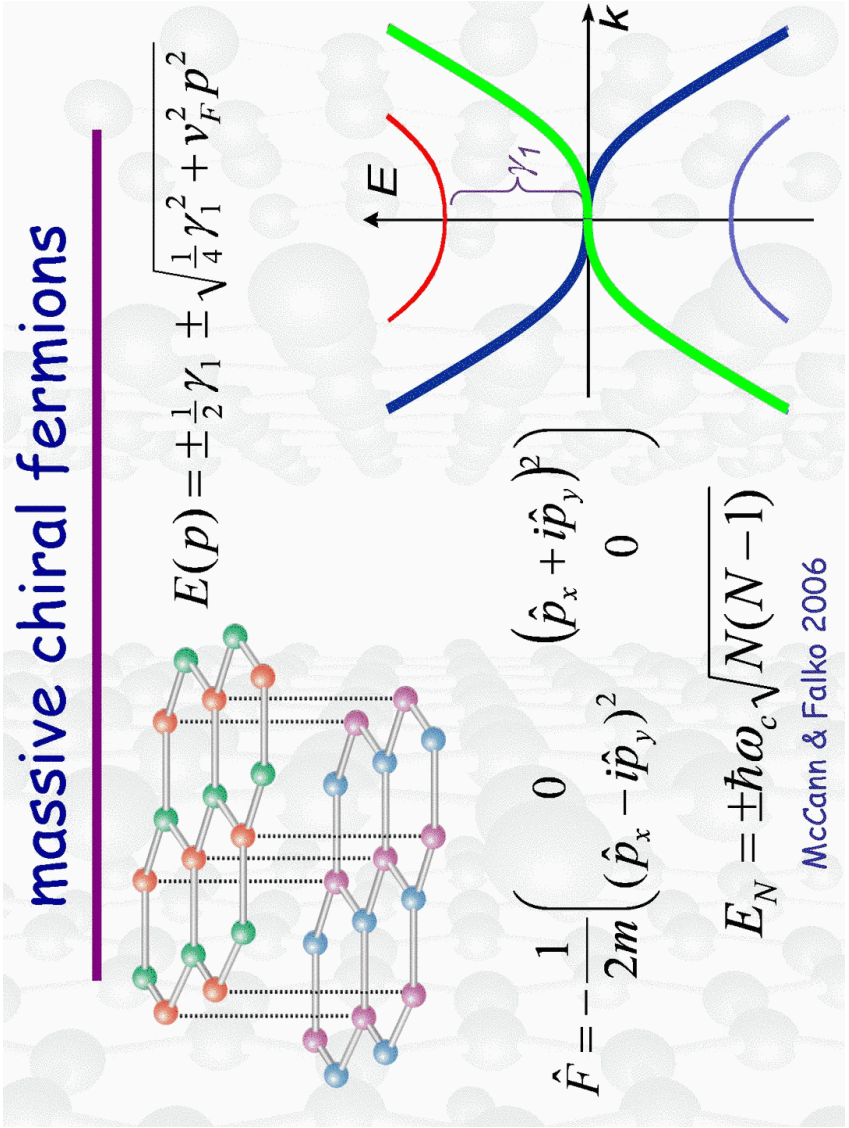


Nature Phys **2**, 177 (2006)

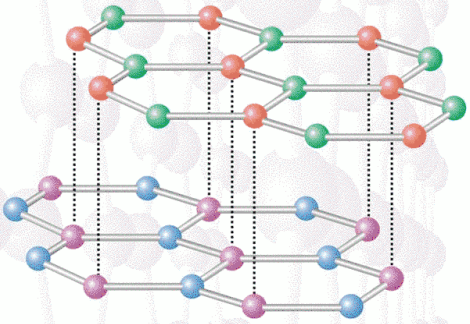
QHE in bilayer graphene



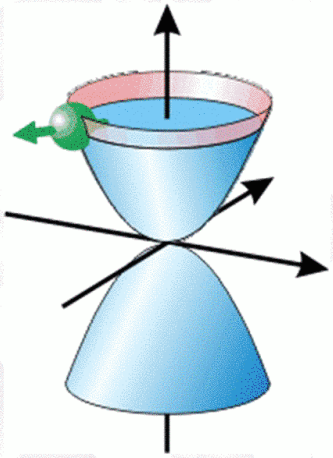
massive chiral fermions



massive chiral fermions



$$E(p) = \pm\tfrac{1}{2}\gamma_1 \pm \sqrt{\tfrac{1}{4}\gamma_1^2 + v_F^2 p^2}$$



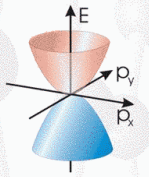
$$\hat{F} = -\frac{1}{2m}\begin{pmatrix} 0 & (\hat{p}_x + i\hat{p}_y)^2 \\ (\hat{p}_x - i\hat{p}_y)^2 & 0 \end{pmatrix}$$

$$E_N = \pm\hbar\omega_c\sqrt{N(N-1)}$$

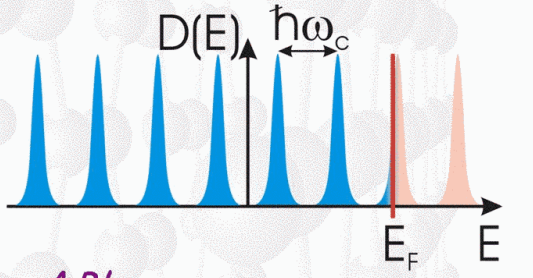
McCann & Falko, *PRL* 2006

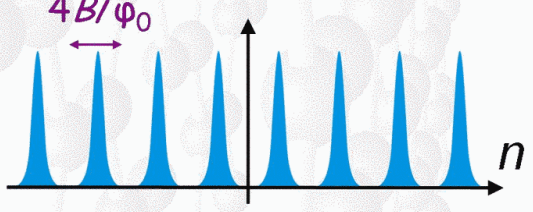
topological phase of 2π

Normal Electrons

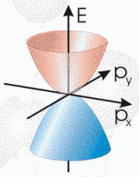


$$E_{LL} = \pm\hbar\omega_c(N + \tfrac{1}{2})$$

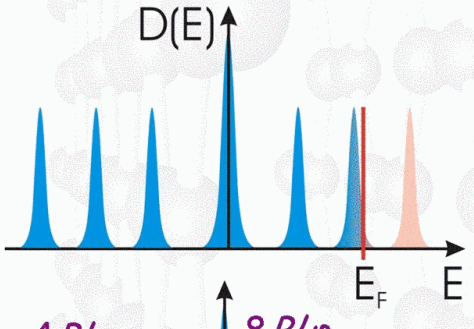


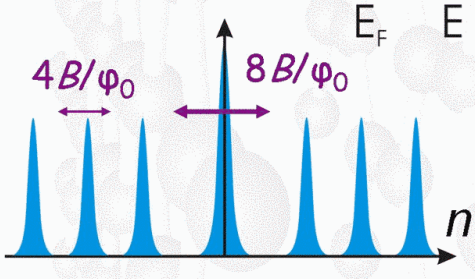


Massive Dirac Fermions

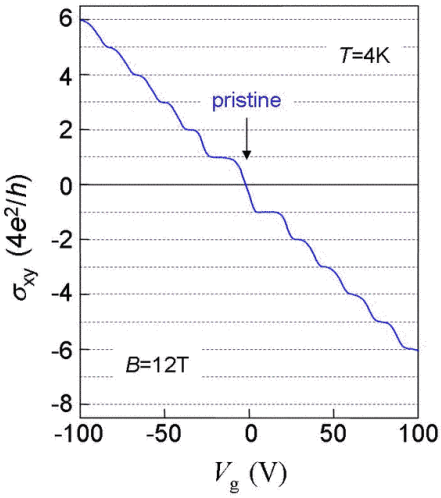


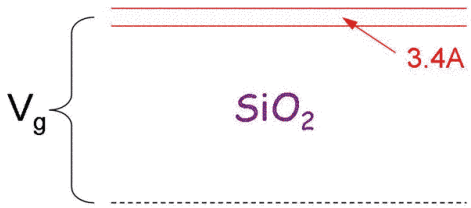
$$E_{LL} = \pm\hbar\omega_c\sqrt{N(N-1)}$$

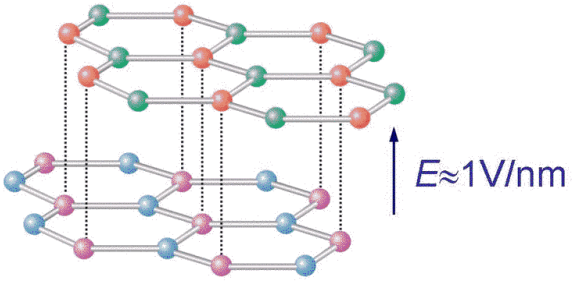




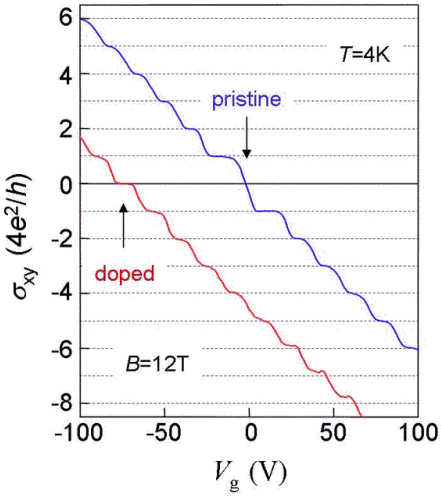
Tuneable-Gap Semiconductor

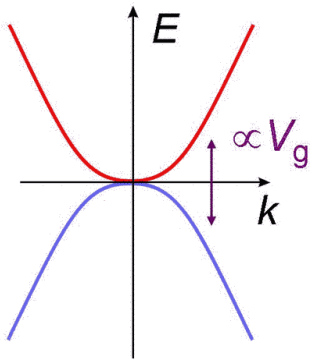






Tuneable-Gap Semiconductor

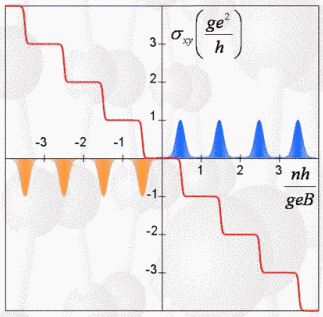




semiconductor with
electrically controlled gap
up to 0.3 eV

three types of IQHE

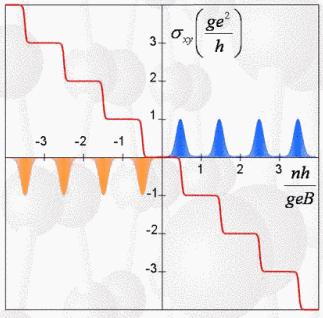
conventional IQHE



all LL at non-zero E
zero Berry phase

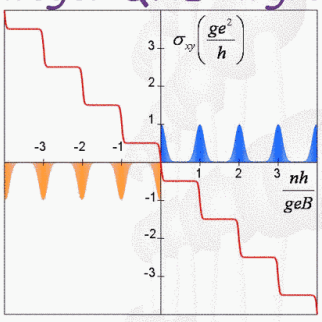
three types of IQHE

conventional IQHE



all LL at non-zero E
zero Berry phase

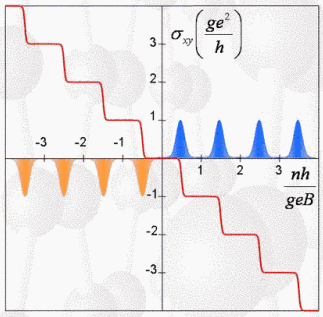
half-integer QHE in graphene



Dirac fermions
one LL at zero E
Berry phase π
metallic at ν□0

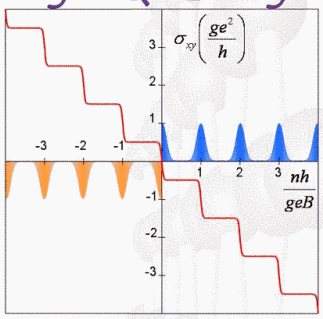
three types of IQHE

conventional IQHE



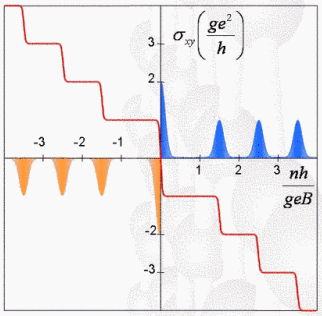
all LL at non-zero E
zero Berry phase

half-integer QHE in graphene



Dirac fermions
one LL at zero E
Berry phase π
metallic at ν□0

chiral IQHE in bilayer graphene



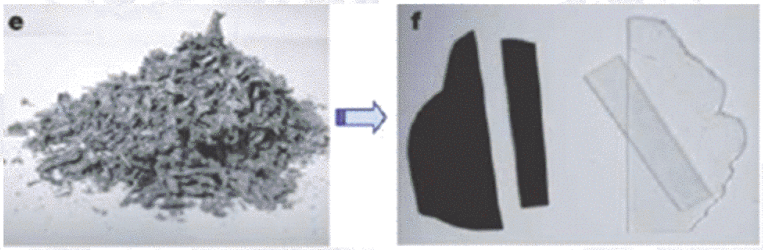
massive Dirac fermions
two LLs at zero E
Berry phase 2π
metallic at ν□0

POTENTIAL APPLICATIONS

just think of carbon nanotubes
but … in large wafers
with fully reproducible properties

unless specifically 1D phenomena

composite materials

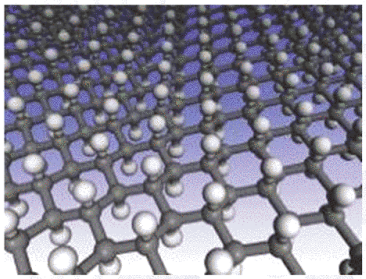


graphene-based composite Ruoff 2006

field-emitters

very thin graphite flakes (already used; *PFE Ltd*)

hydrogen storage



"GRAPHANE"

electrical batteries

GRAPHENE-BASED ELECTRONICS

✓ *ballistic field-effect transistor*

⌖ THz-frequency operation

(despite low on-off ratio ~10 at room T)

✓ *chemical sensors*

(detection of a single gas molecule!)

✓ *superconducting FETs*

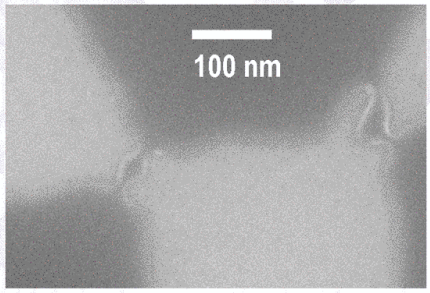
(Delft group)

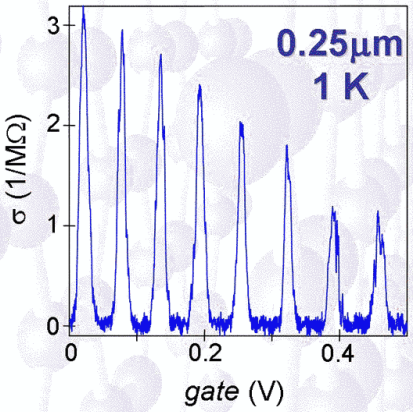
⌖ *spintronics with gate control*

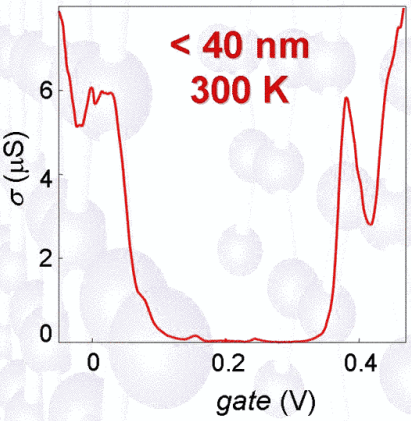
GRAPHENE DREAMS

entire SET-like circuitry carved in graphene

stable down to a single benzene ring
molecular electronics
but with the top-down approach





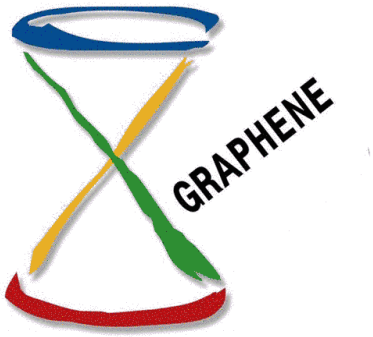


CONCLUSIONS

strictly-2D crystals do exist

"relativistic"
condensed matter
physics

(addressing QED phenomena such as zitterbewegung, Klein paradox, etc)



REALISTIC POSSIBILITY
OF VARIOUS APPLICATIONS