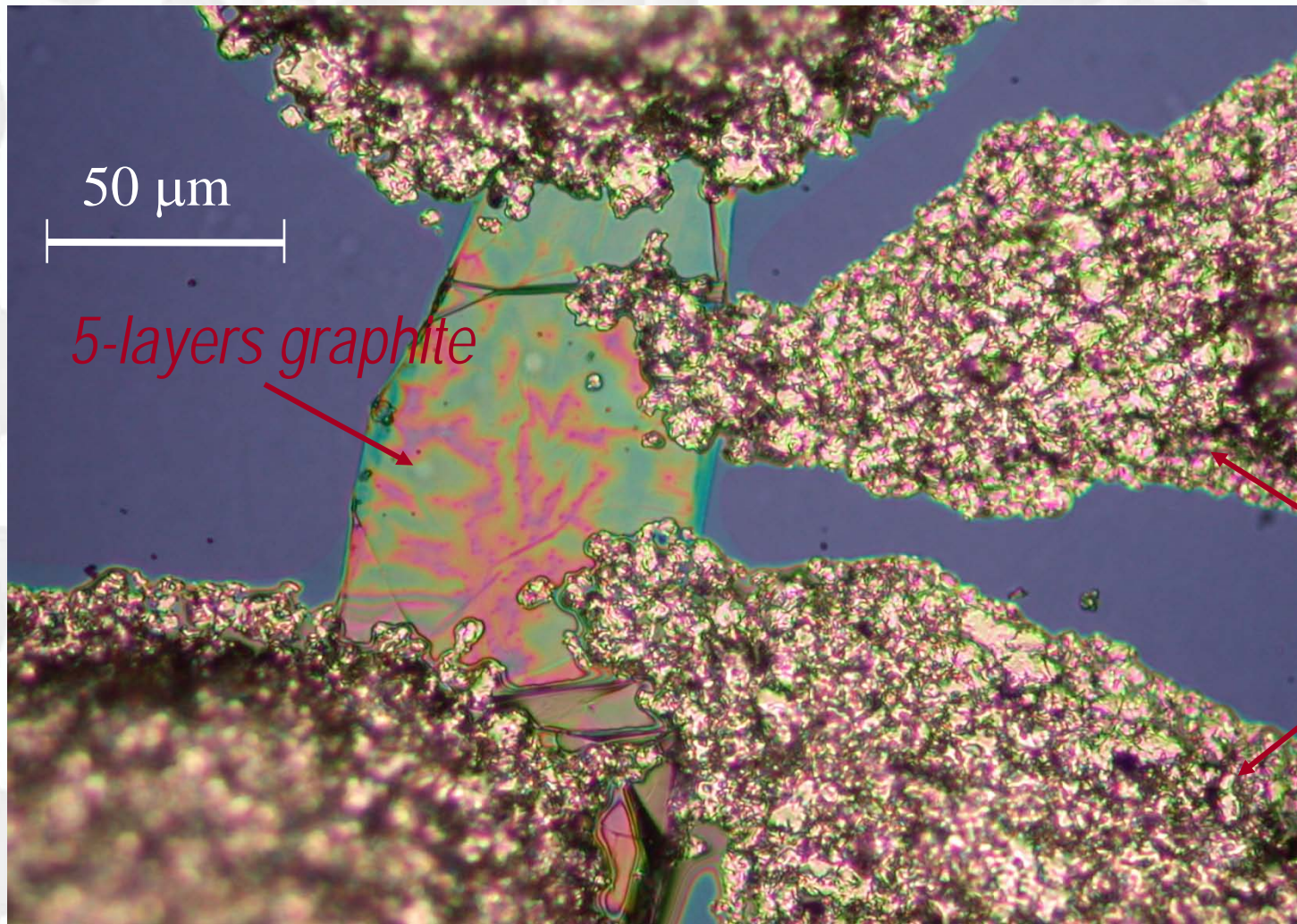


QHE@300

Graphene FET



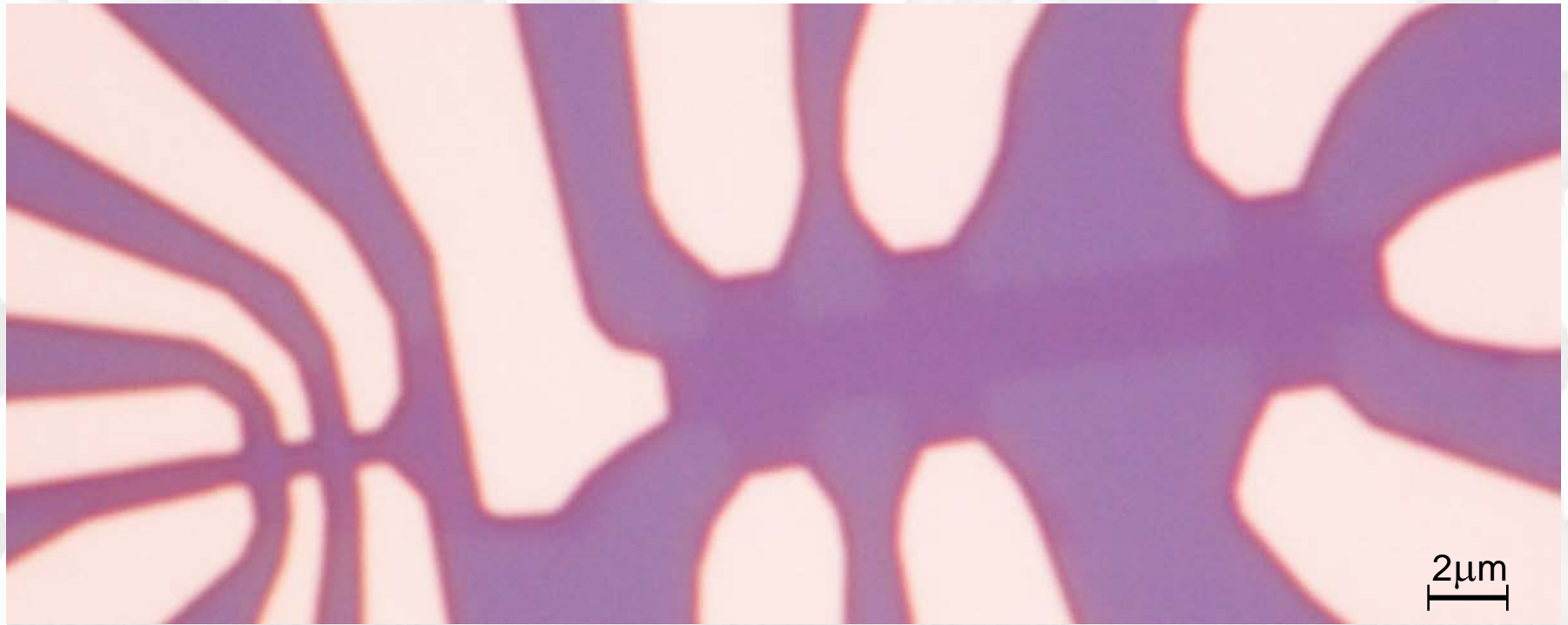
5-layers graphite

*Contacts
formed by
silver epoxy*

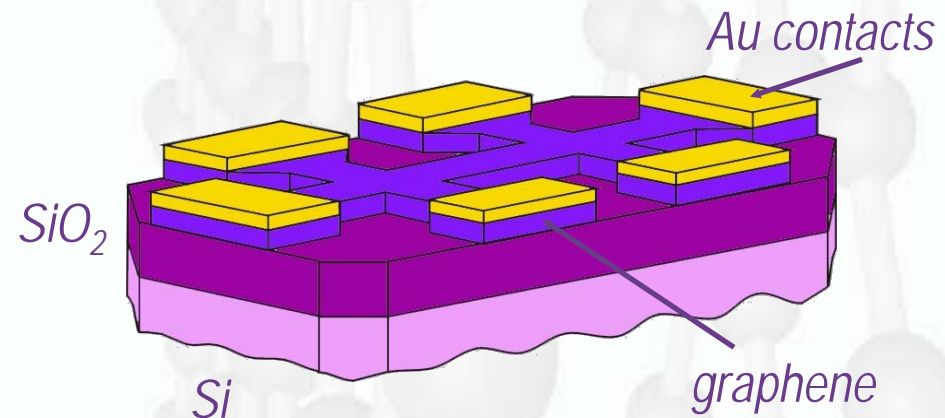
First graphitic FET

No clean room facilities required

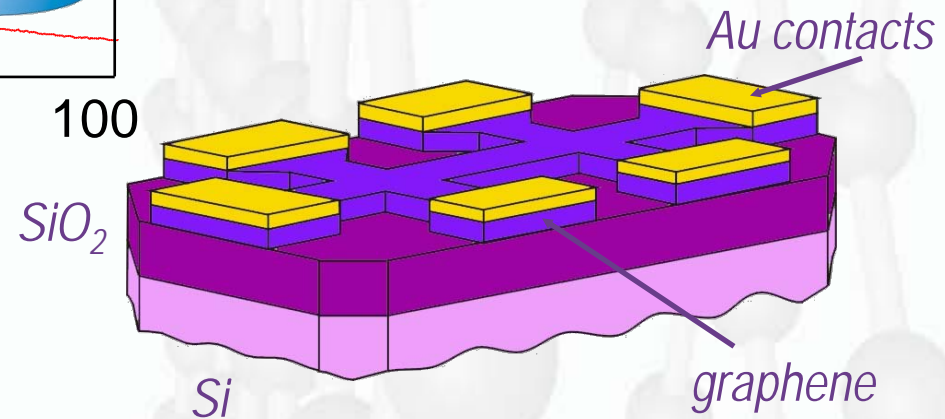
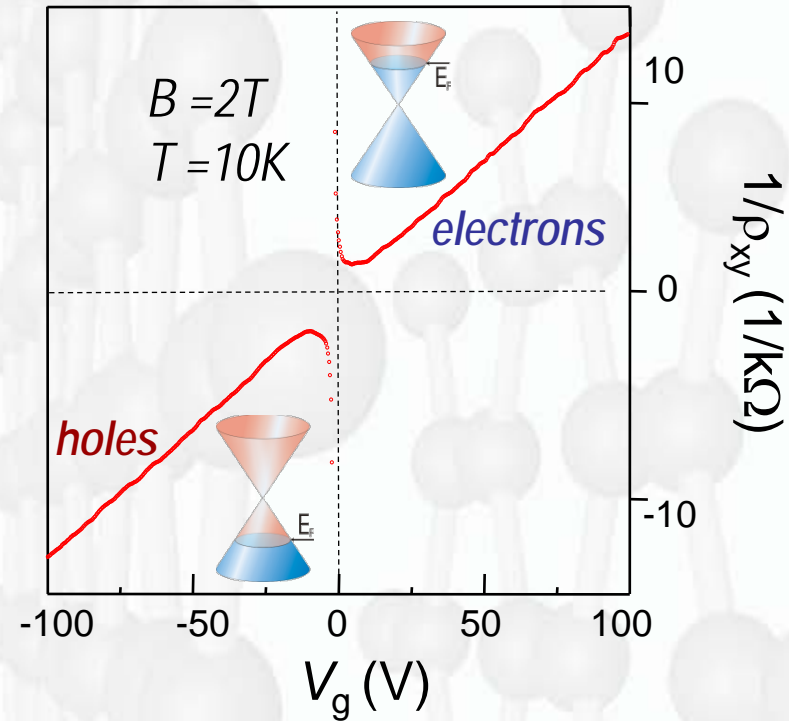
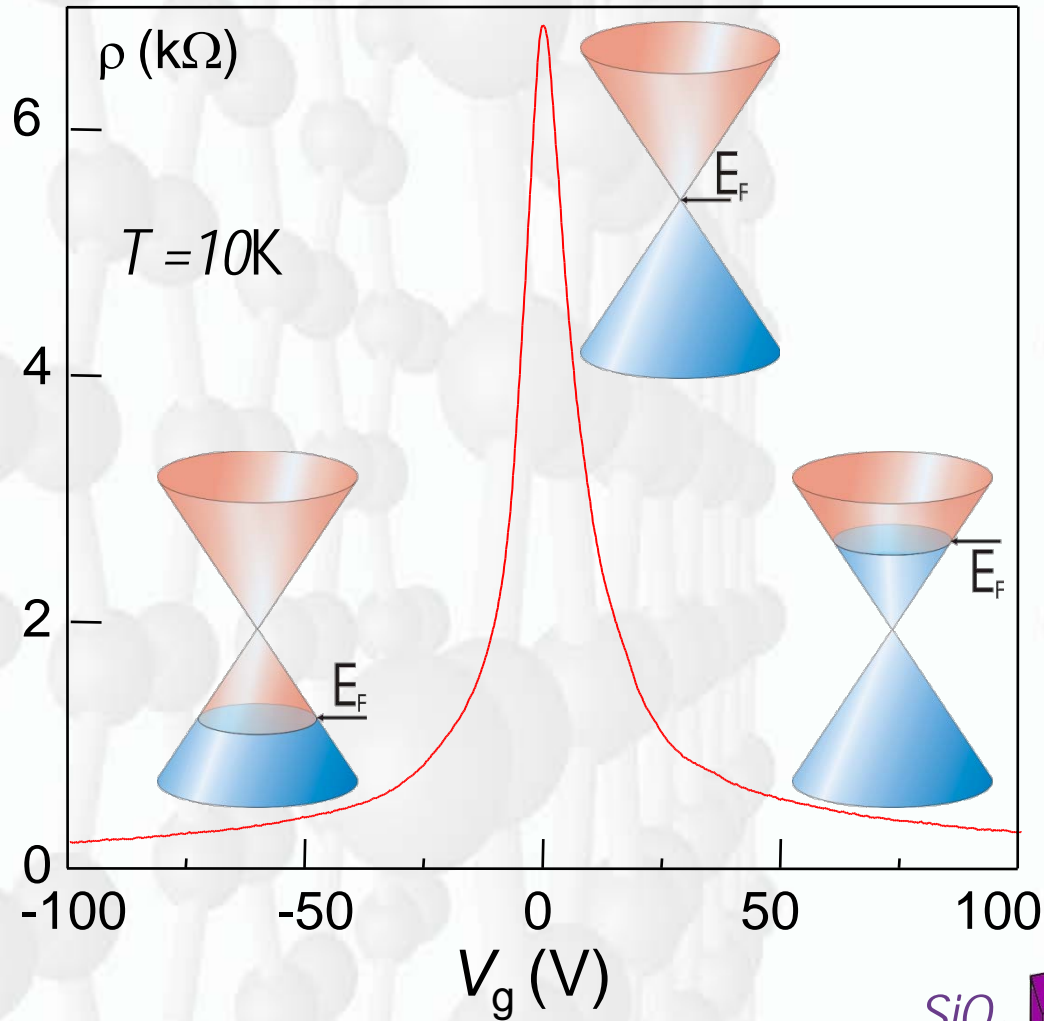
Graphene Devices



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



Graphene Field Effect Transistors

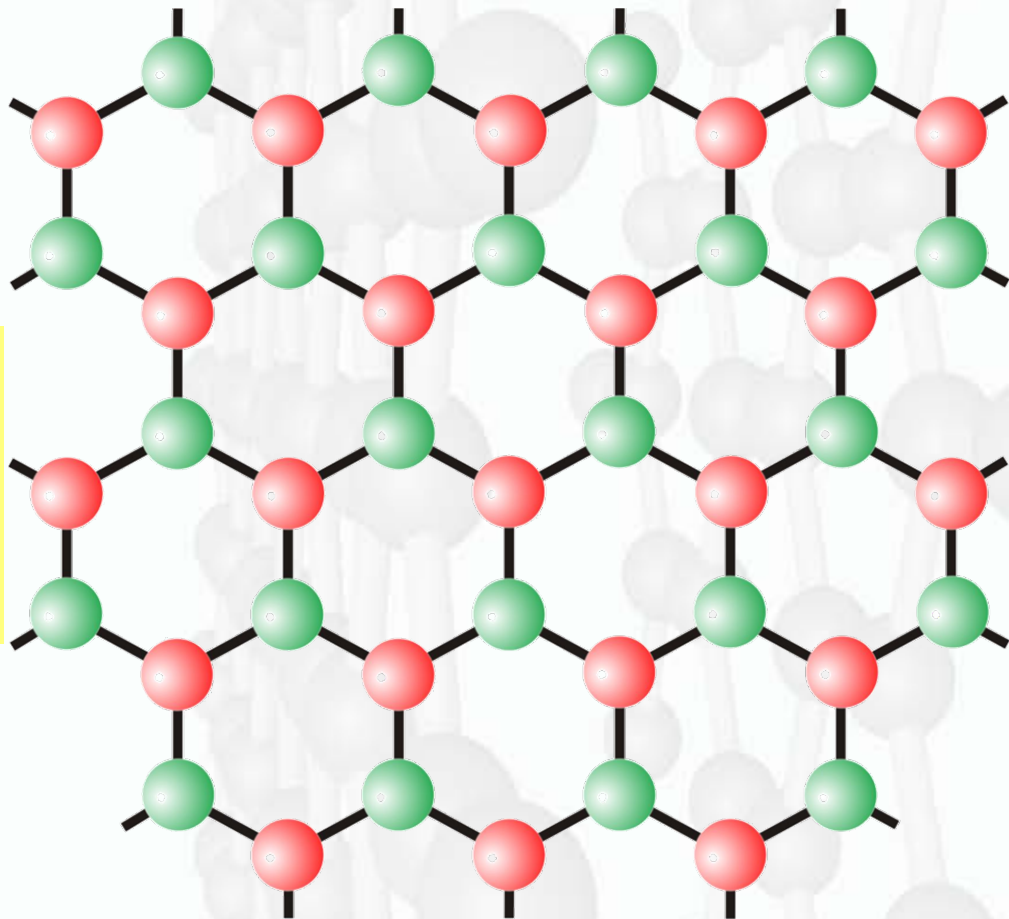
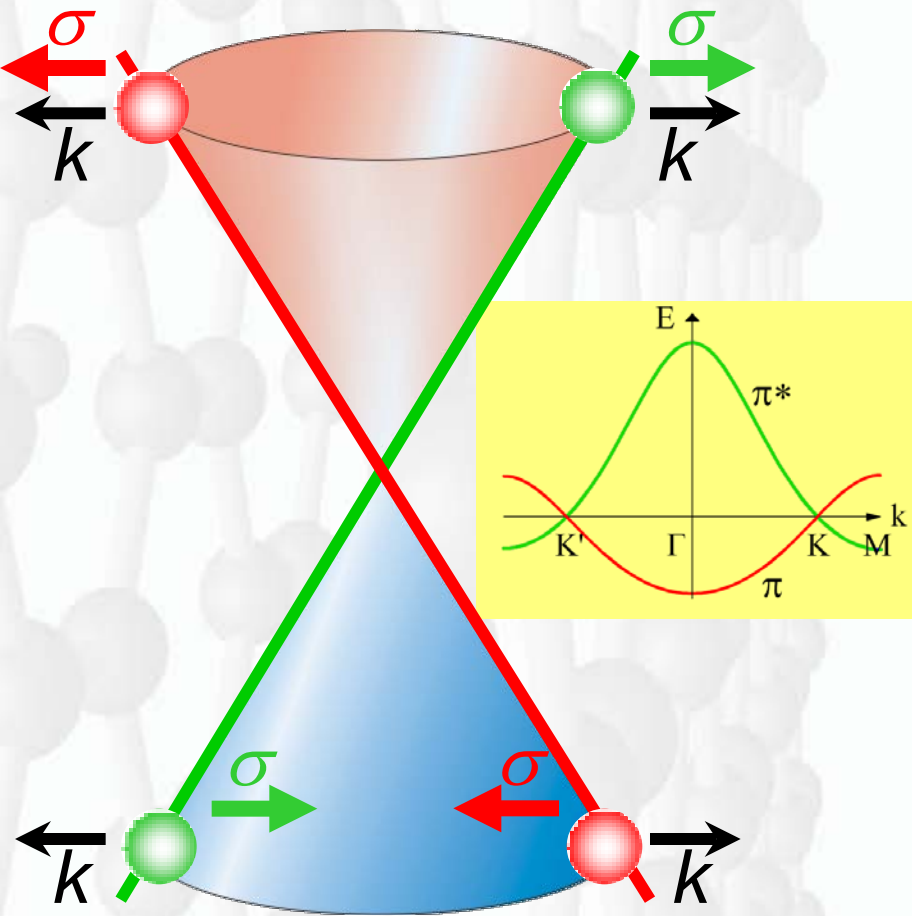


Chiral Dirac Fermions

2 equivalent sublattices



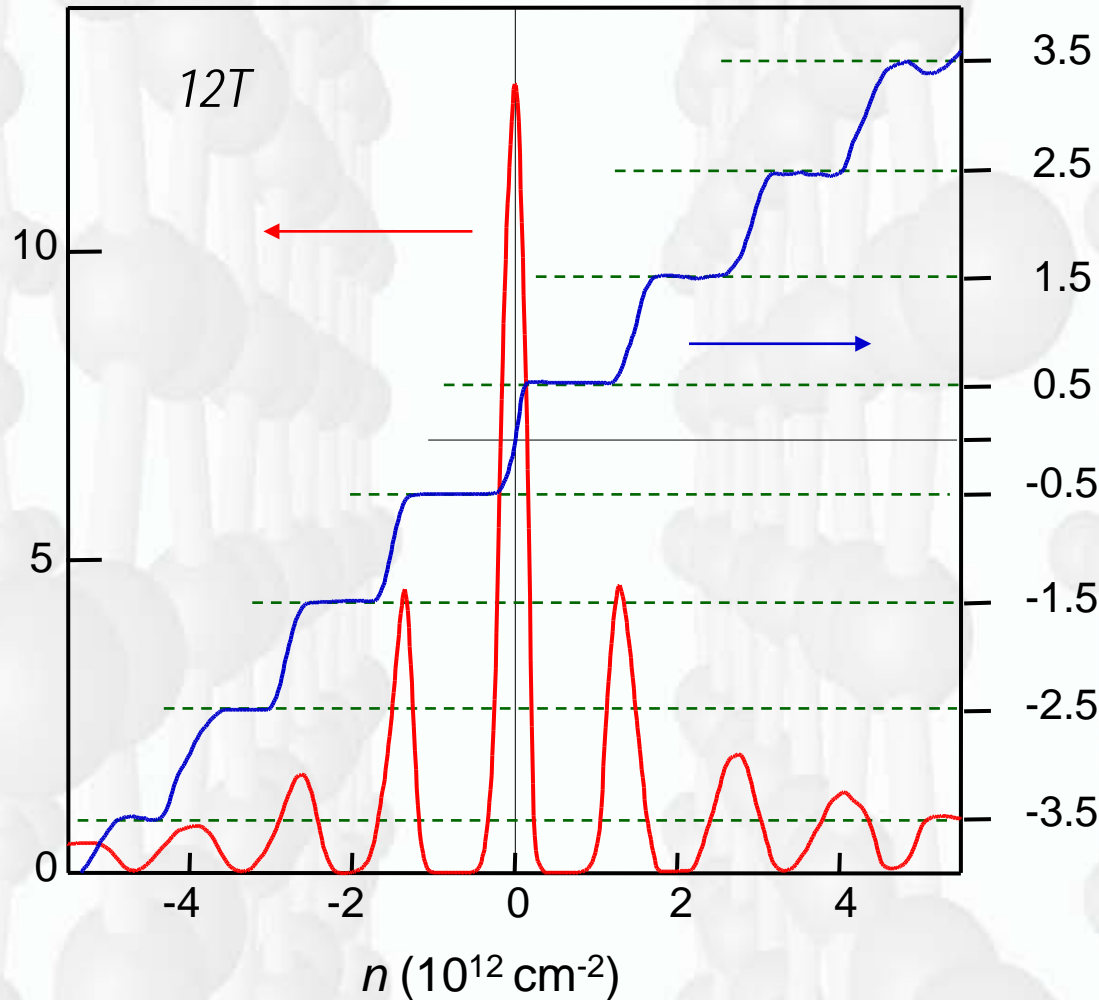
pseudospin index



Half-Integer Quantum Hall Effect

ρ_{xx} (k Ω)

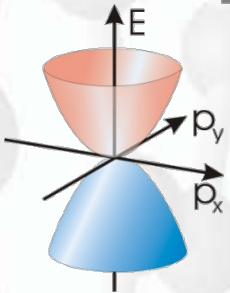
σ_{xy} (4e²/h)



Quantisation at $\nu = N + 1/2$

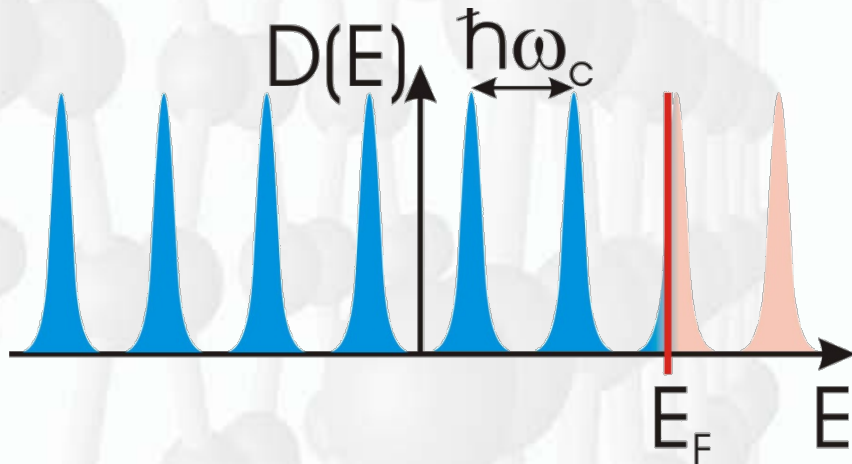
Novoselov et al, Nature (2005)
Zhang et al, Nature (2005)

2-DEG in Magnetic Field



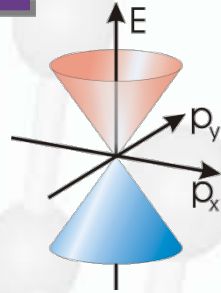
Parabolic Dispersion

$$E_{LL} = \pm \hbar \omega_c \left(n + \frac{1}{2} \right)$$



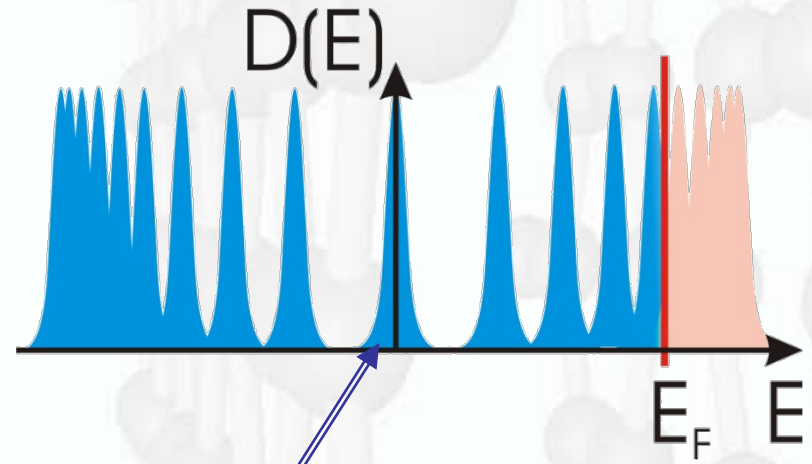
Each level has a degeneracy

$$g_v g_s \frac{eB}{h} = 4 \frac{eB}{h}$$



Linear Dispersion

$$E_{LL} = \pm c_* \sqrt{2e\hbar B} \sqrt{n}$$



Shared equally between holes and electrons

New Types of Quasiparticles

"Schrödinger fermions"

$$\hat{H} = \hat{p}^2 / 2m^*$$

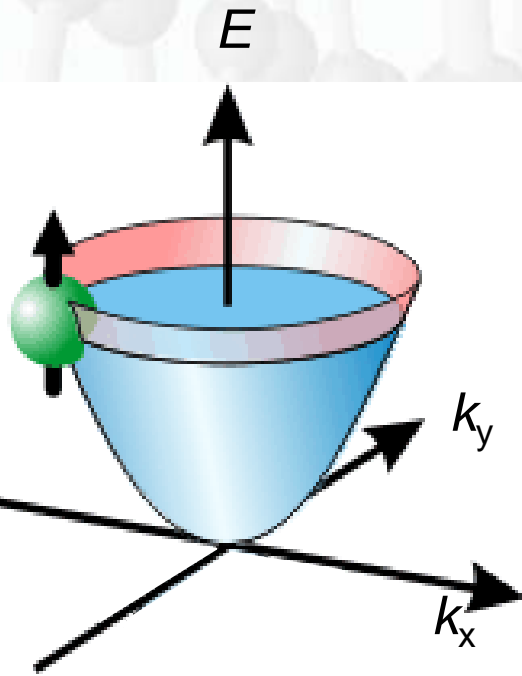
real Dirac fermions

$$\hat{H} = c \vec{\sigma} \cdot \hat{p}$$

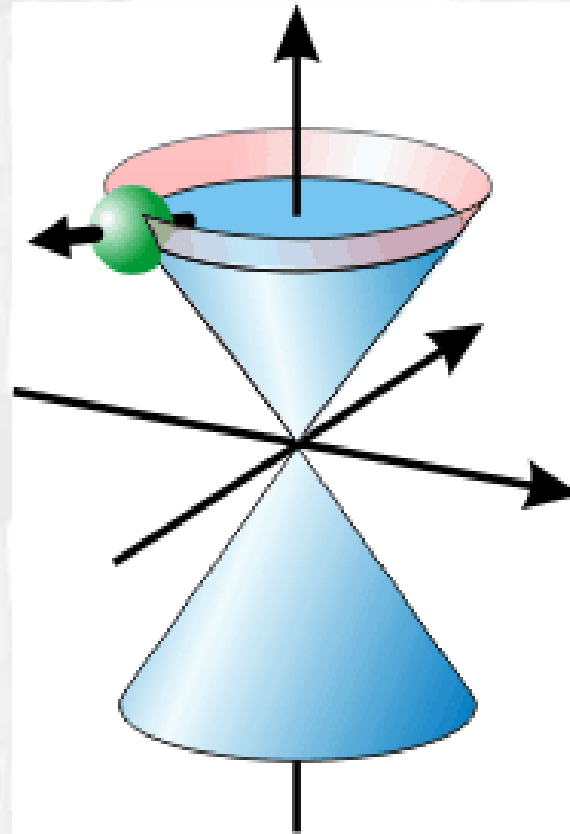
massless Dirac fermions

$$\hat{H} = v_F \vec{\sigma} \cdot \hat{p}$$

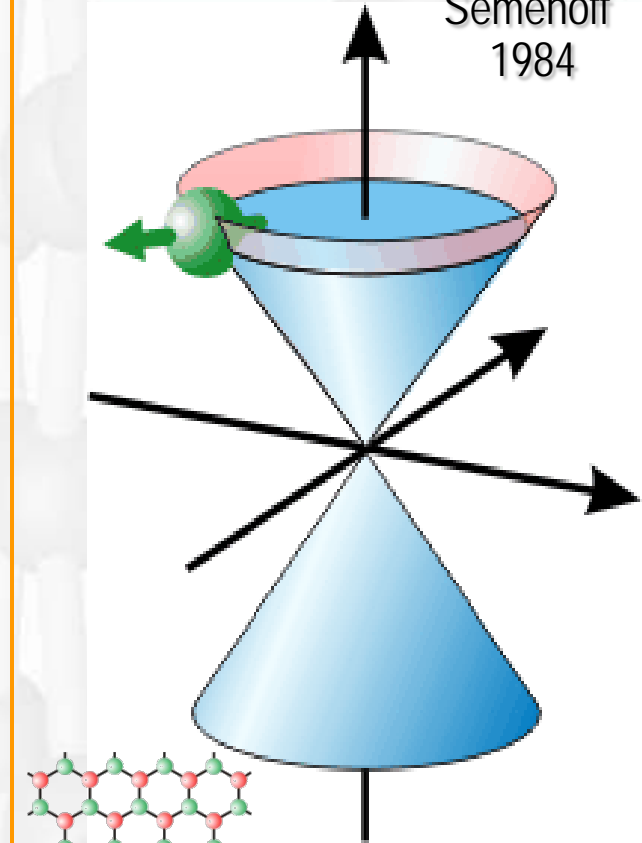
Semenoff
1984



metals
and
semiconductors

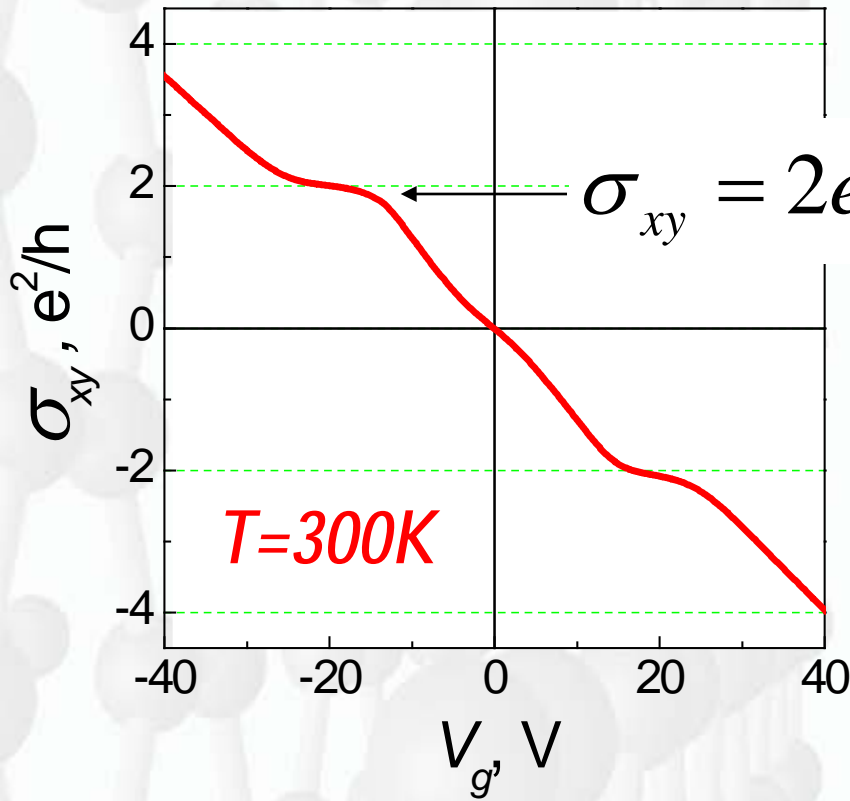


neutron stars
and
accelerators



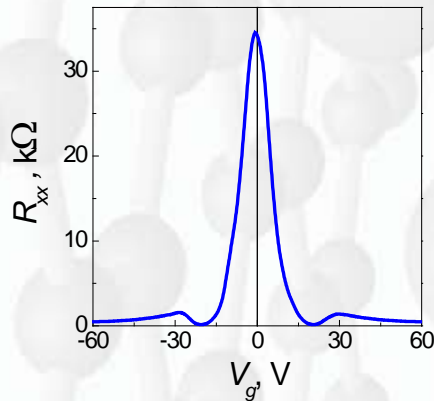
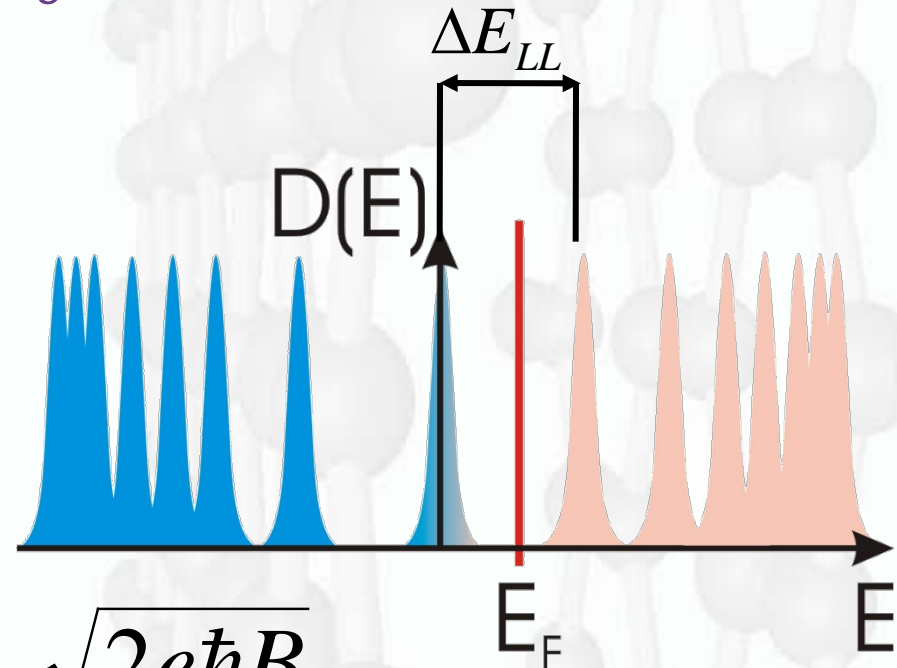
monolayer graphene

Room Temperature Quantum Hall Effect



Quantization at room temperature

➤ Large inter-Landau level distance

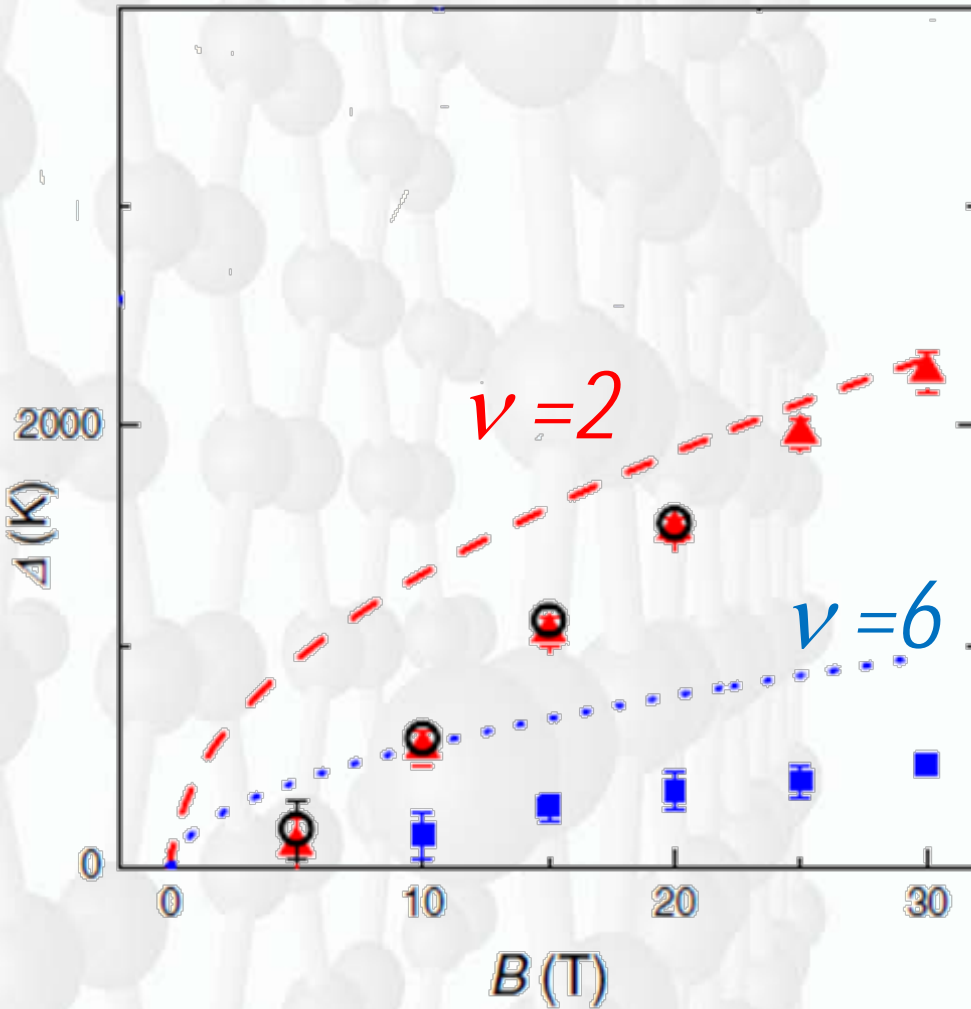


$$\Delta E_{LL} = c_* \sqrt{2e\hbar B}$$

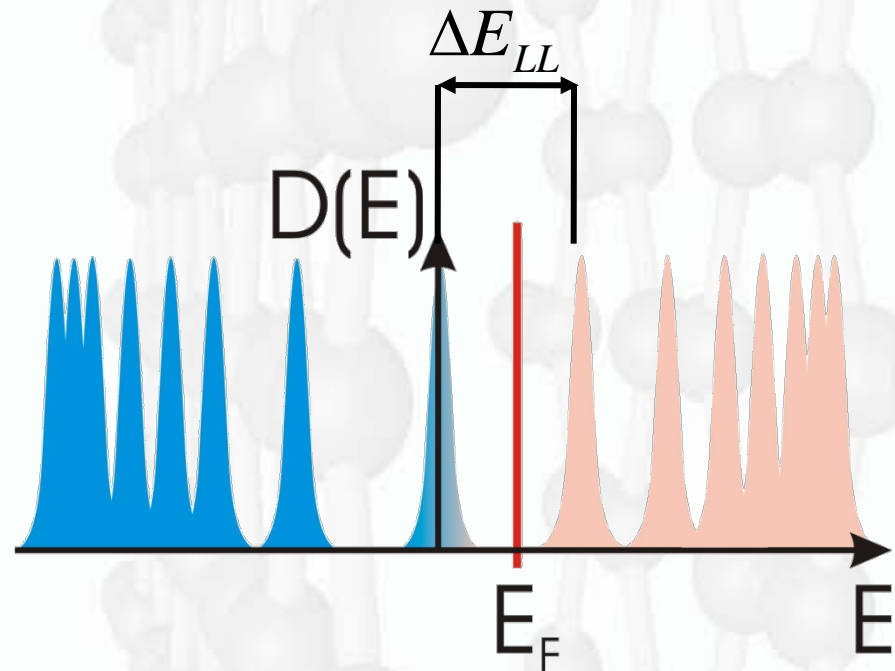
$$\Delta E_{LL} = 400 \left[\frac{K}{\sqrt{T}} \right] \sqrt{B}$$

Novoselov et al, Science (2007)

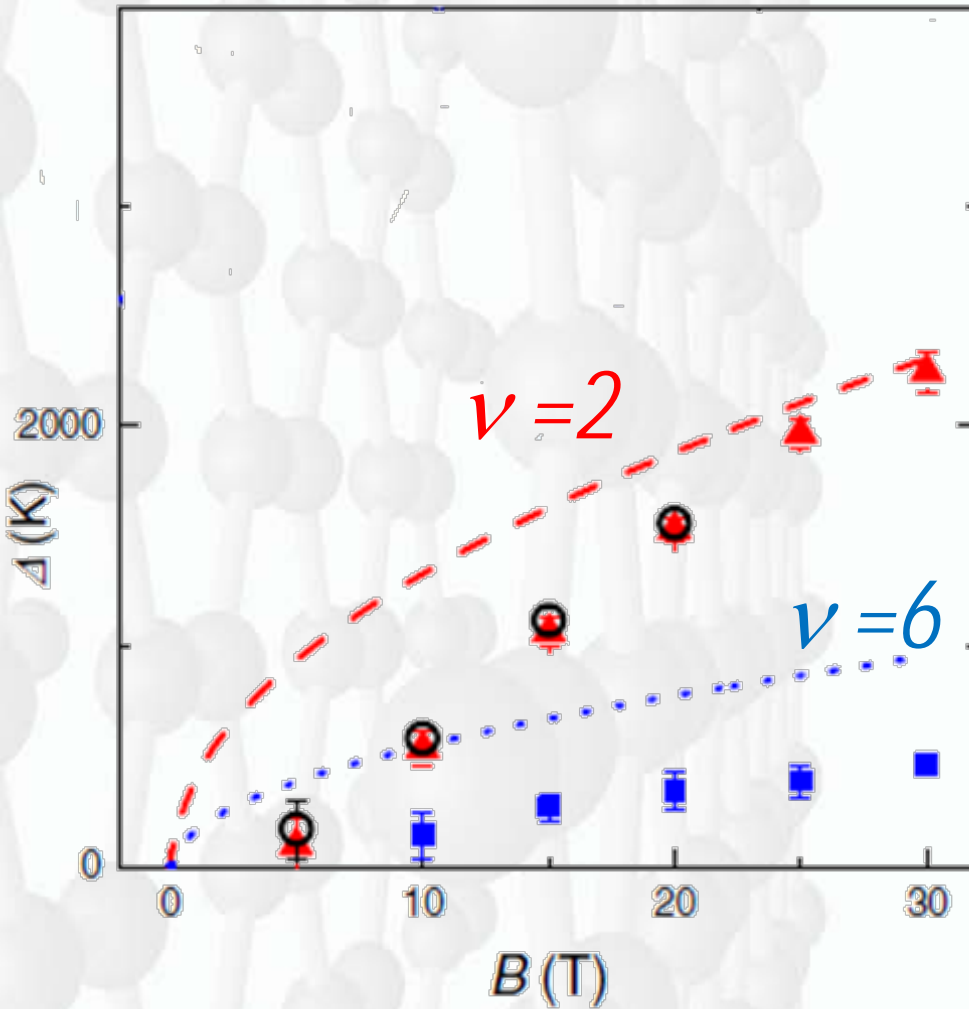
$\nu = 0$ level



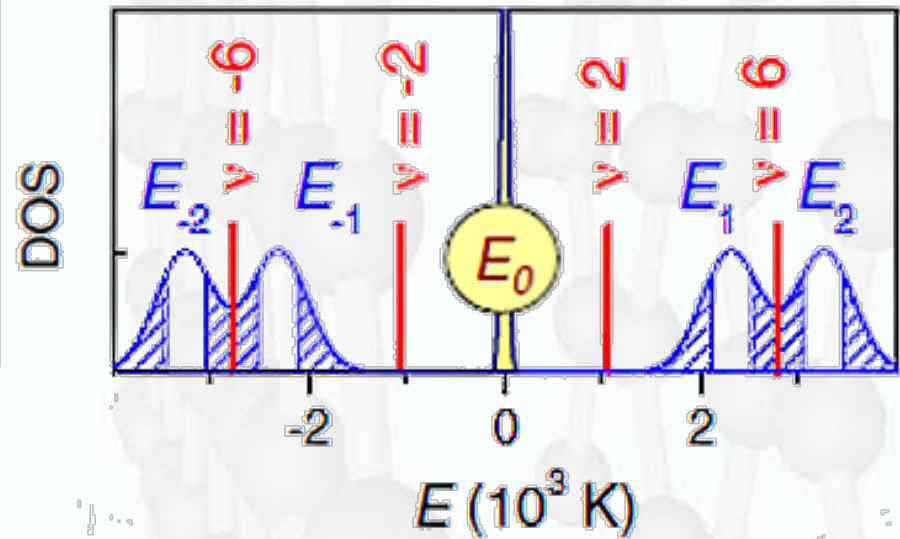
Quantization at room temperature



$\nu = 0$ level

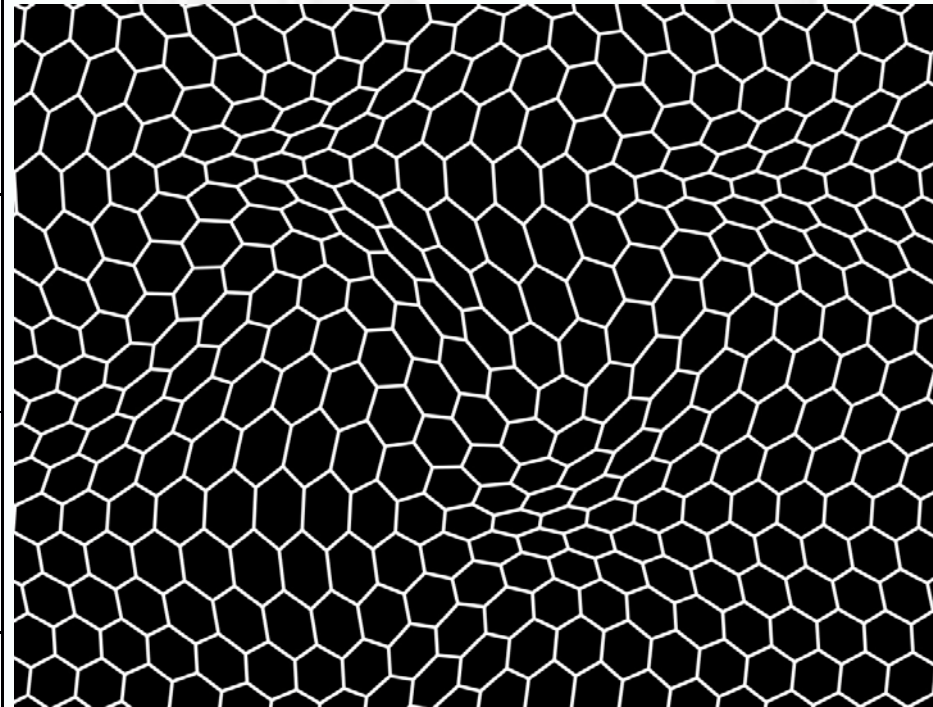
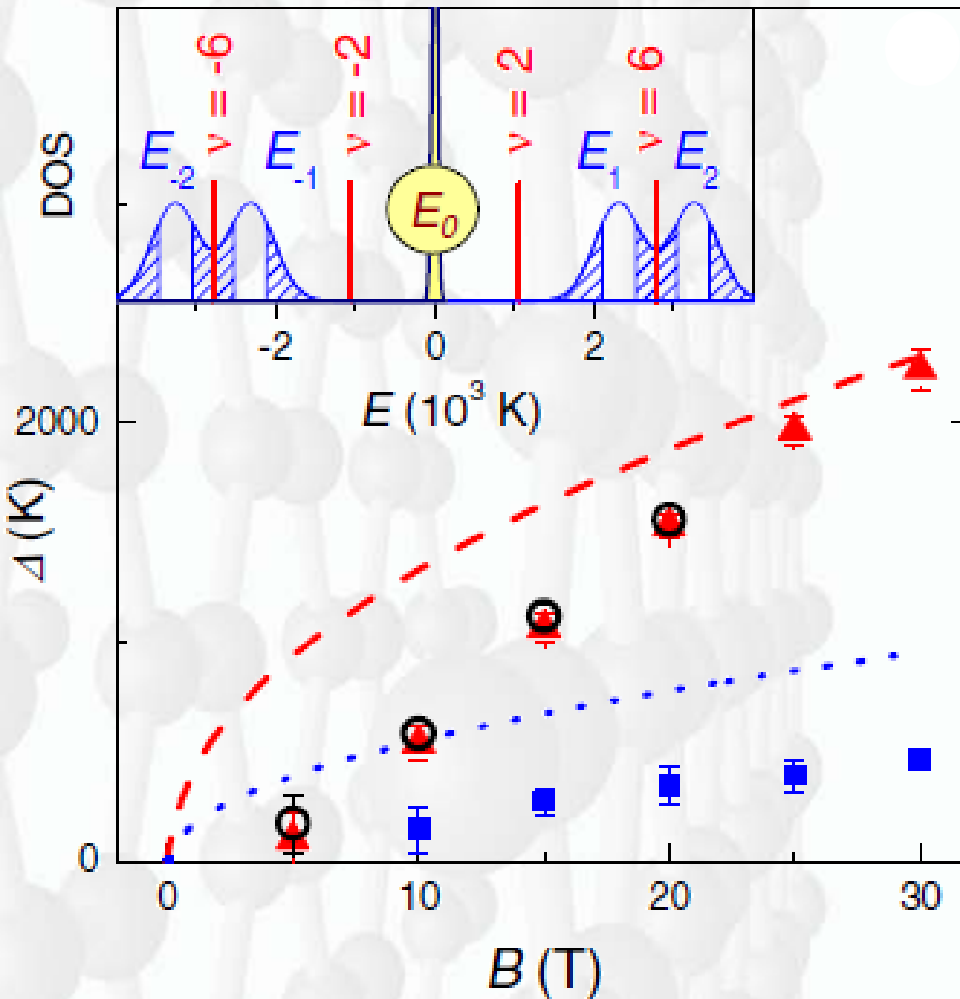


Quantization at room temperature



Extremely narrow $\nu = 0$ level

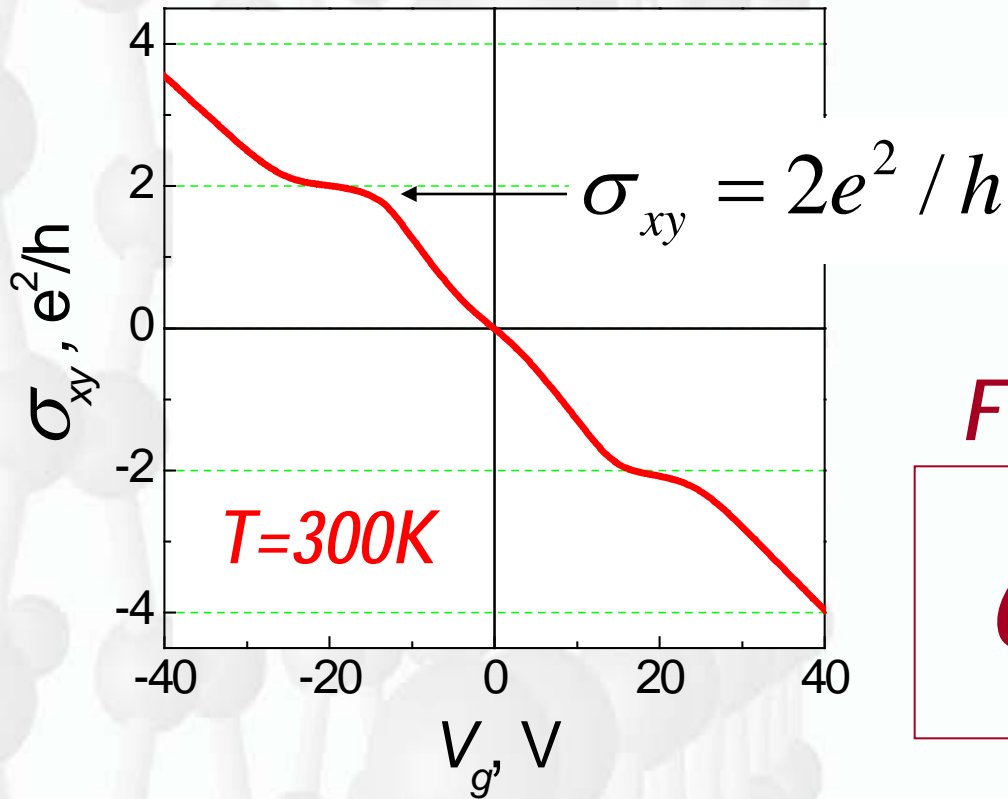
$\nu = 0$ level



*Gauge Field Disorder:
doesn't broaden $\nu = 0$ level*

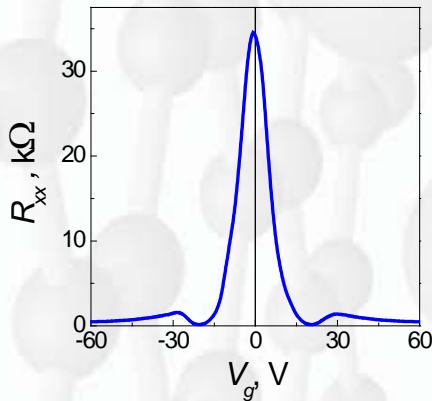
Extremely narrow $\nu = 0$ level

Room Temperature Quantum Hall Effect



Fine Structure Constant

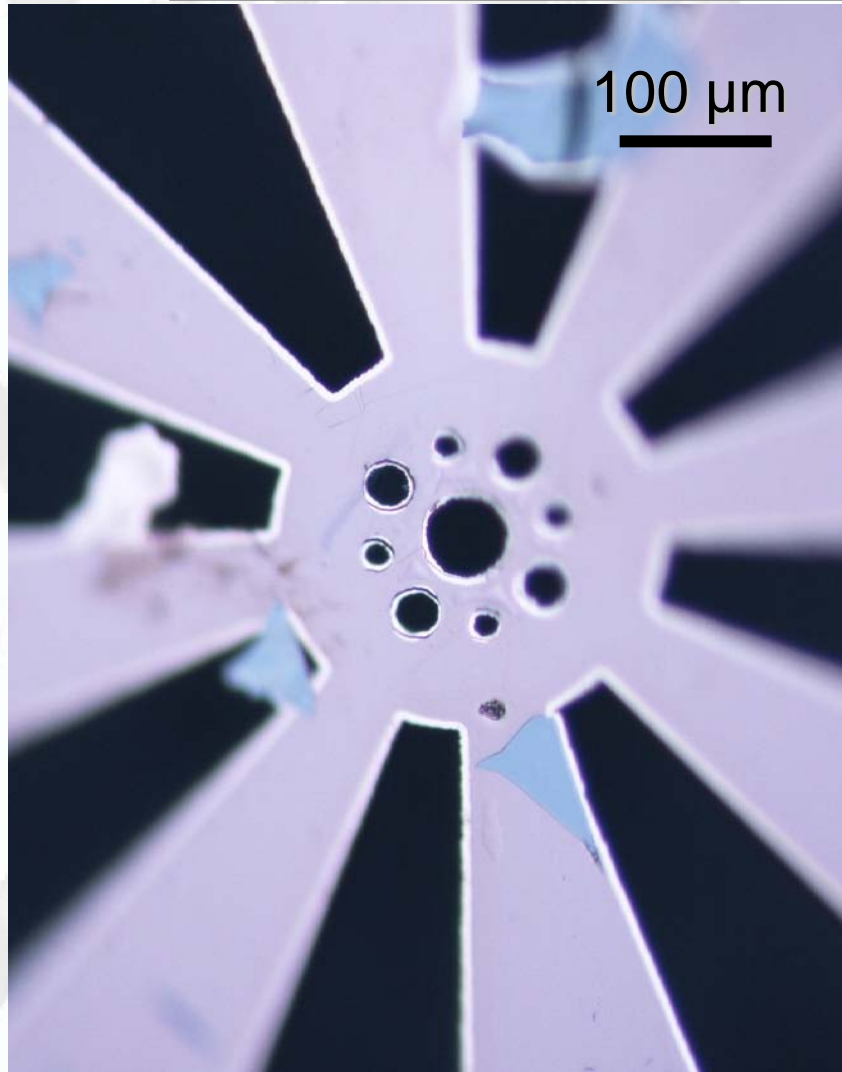
$$\alpha = \sigma_{xy} / 4\pi\epsilon_0$$



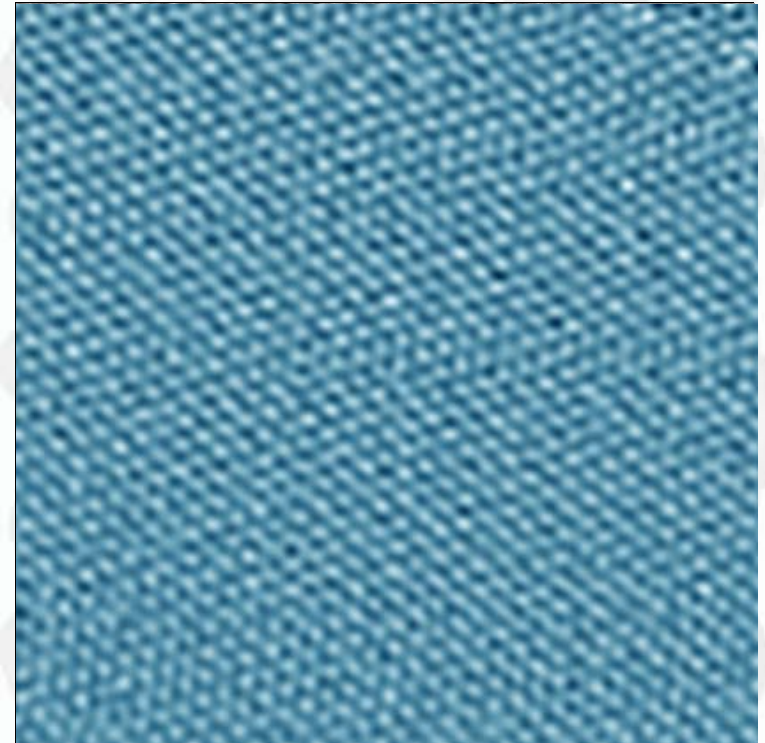
*Other
Fundamental Constants
with Graphene*

(how to measure π)

Current State of the Art



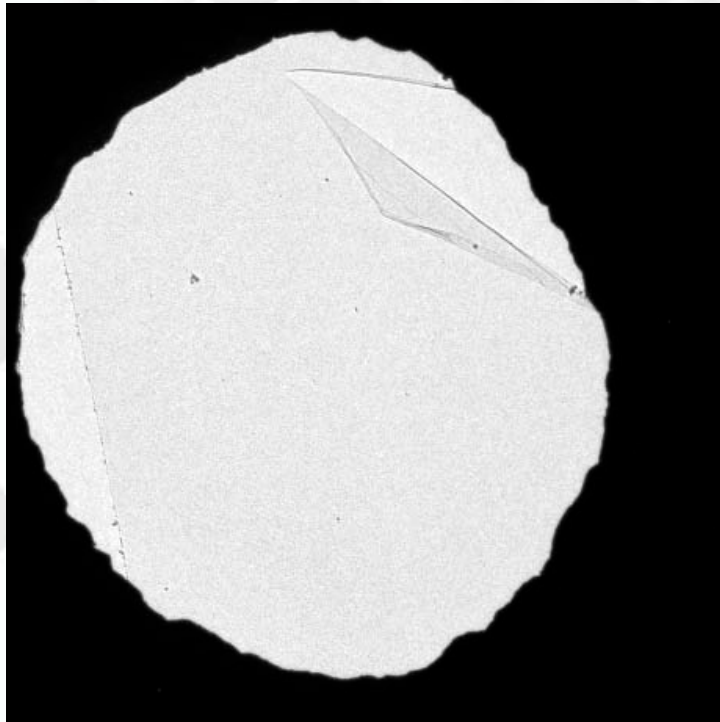
*graphene lattice
in SuperSTEM*



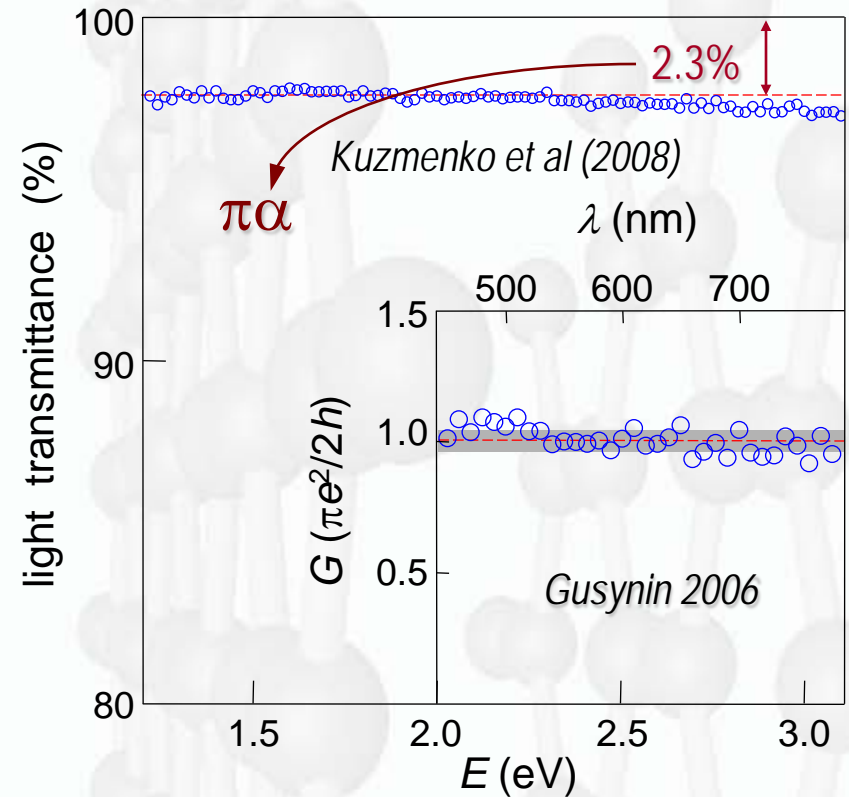
*one-atom-thick
single-crystal membranes*

Meyer et al Nature '07

Graphene Optics

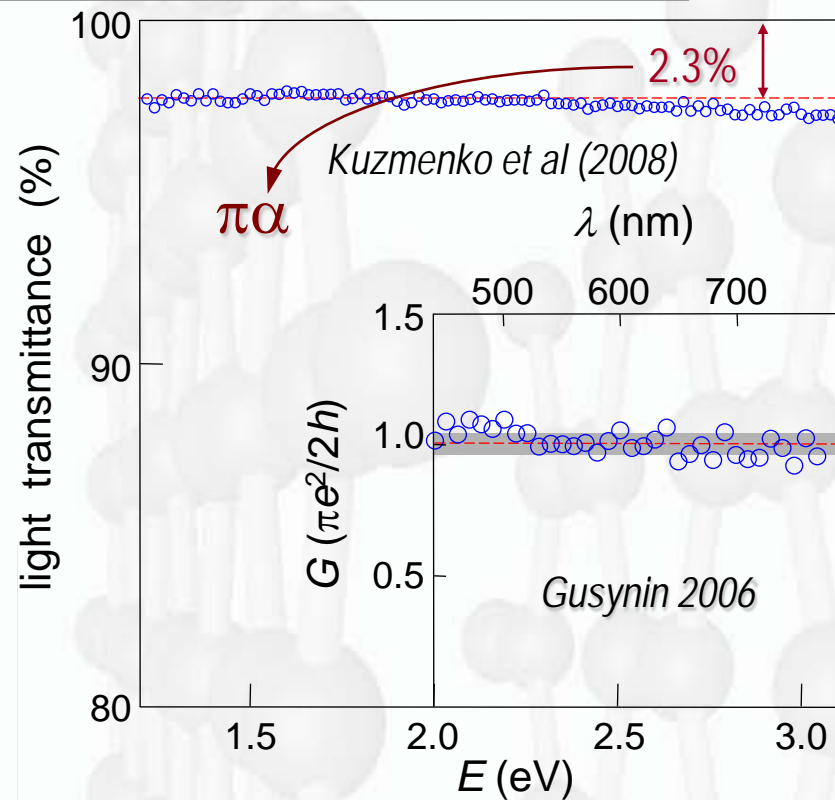
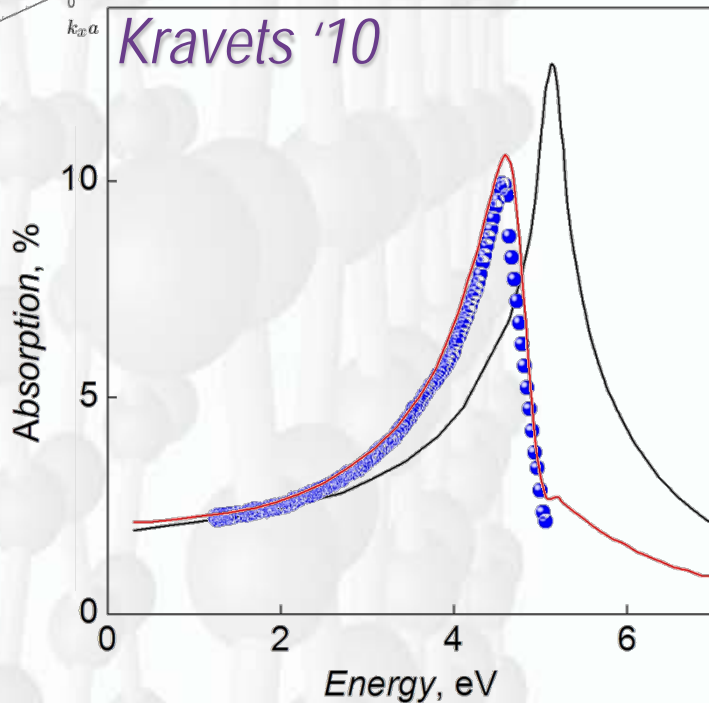
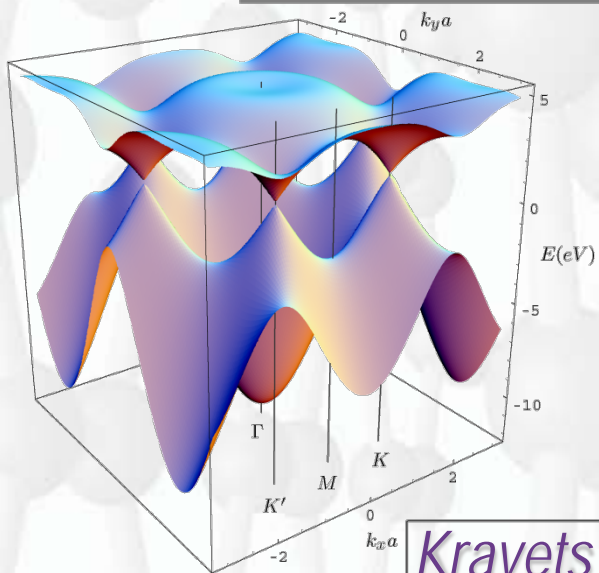


50 μm



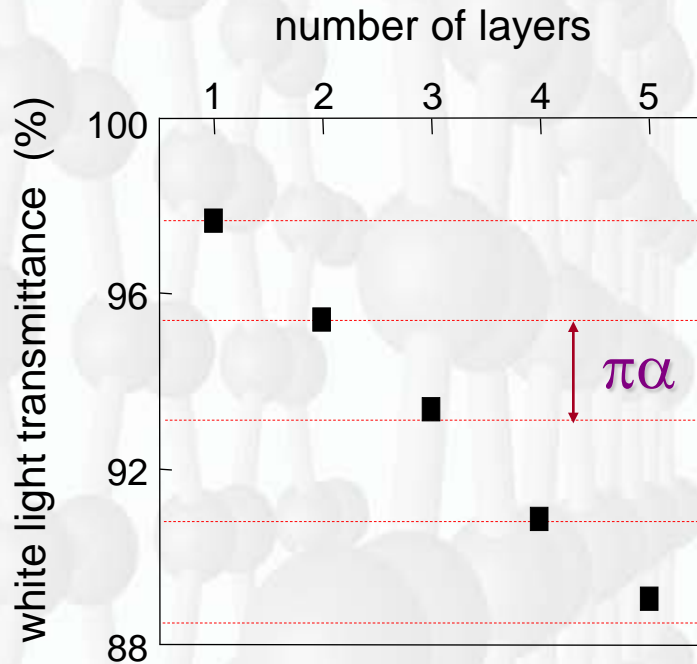
coupling interaction of electromagnetic waves with quasi-relativistic 2D charges should be described by coupling constant α

Graphene Optics

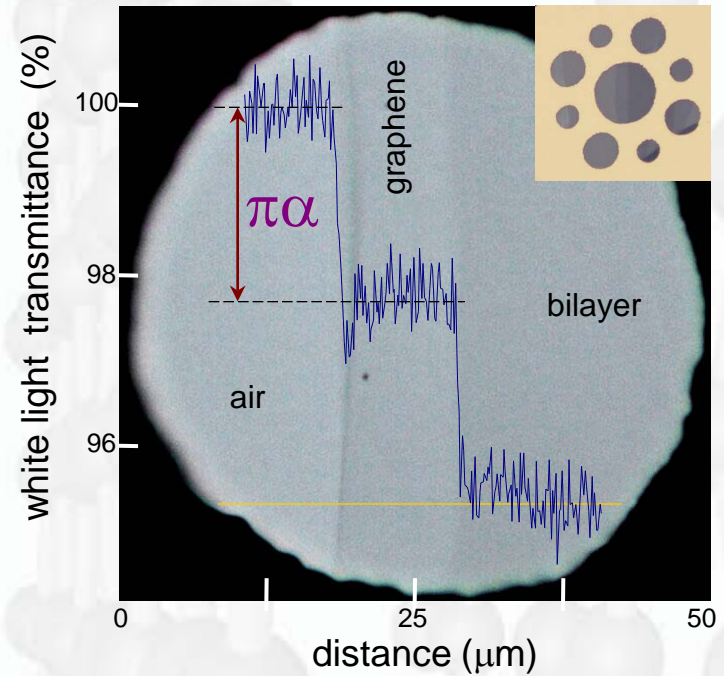


theory, non-interactive
 theory, e-e interaction
 Louie '09

Visualisation of Fine Structure Constant



*the fine structure constant
observed
"with a naked eye"
 $\alpha = 1/137 (\pm 2\%)$*



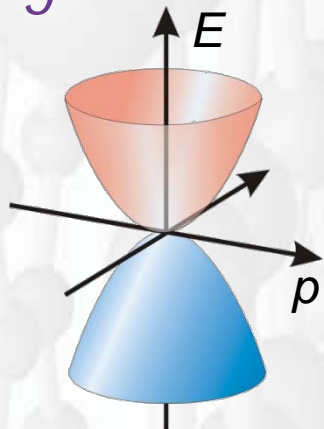
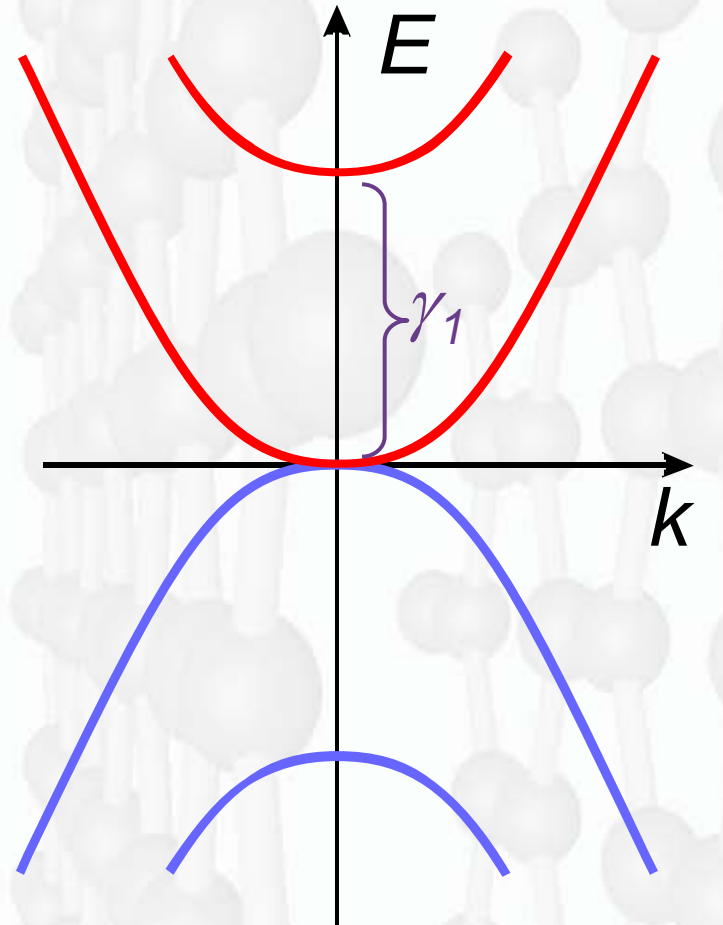
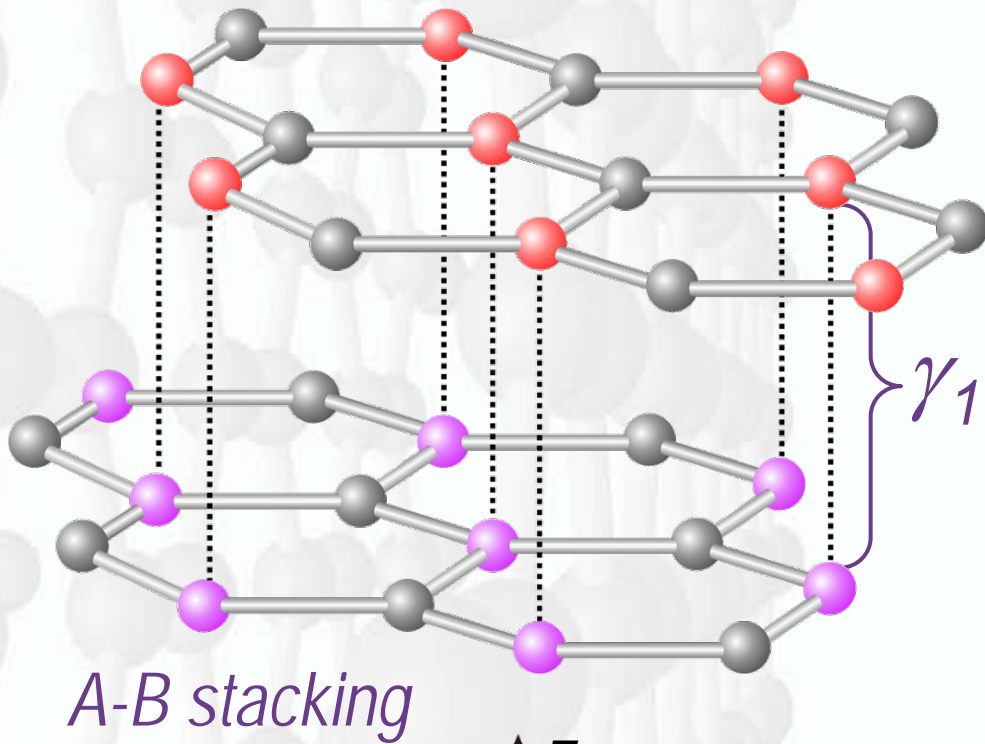
$$\pi = \frac{t}{\alpha}$$

if we know α from the Quantum Hall Effect



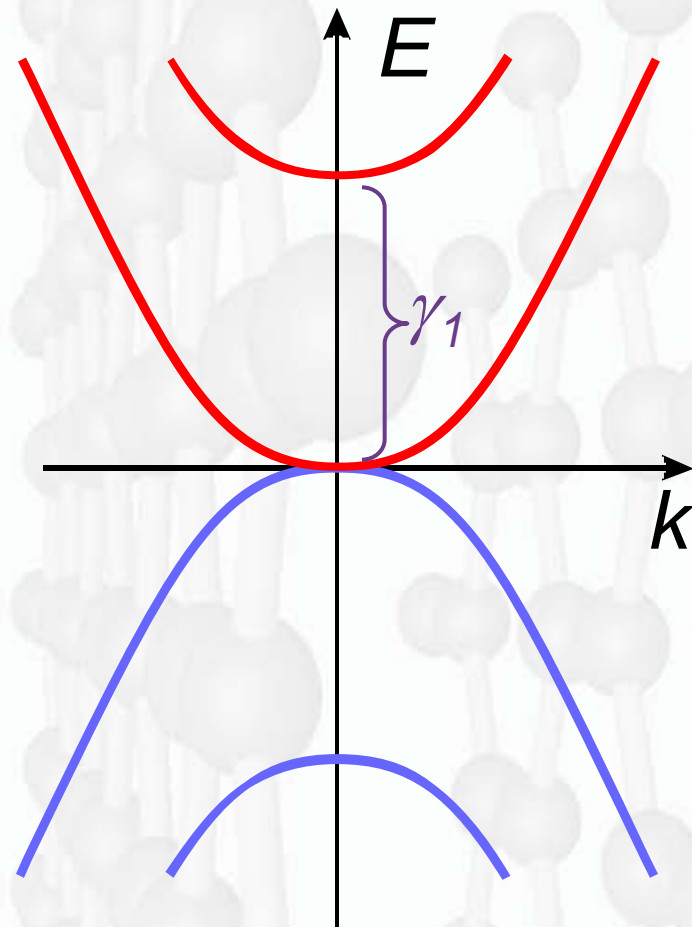
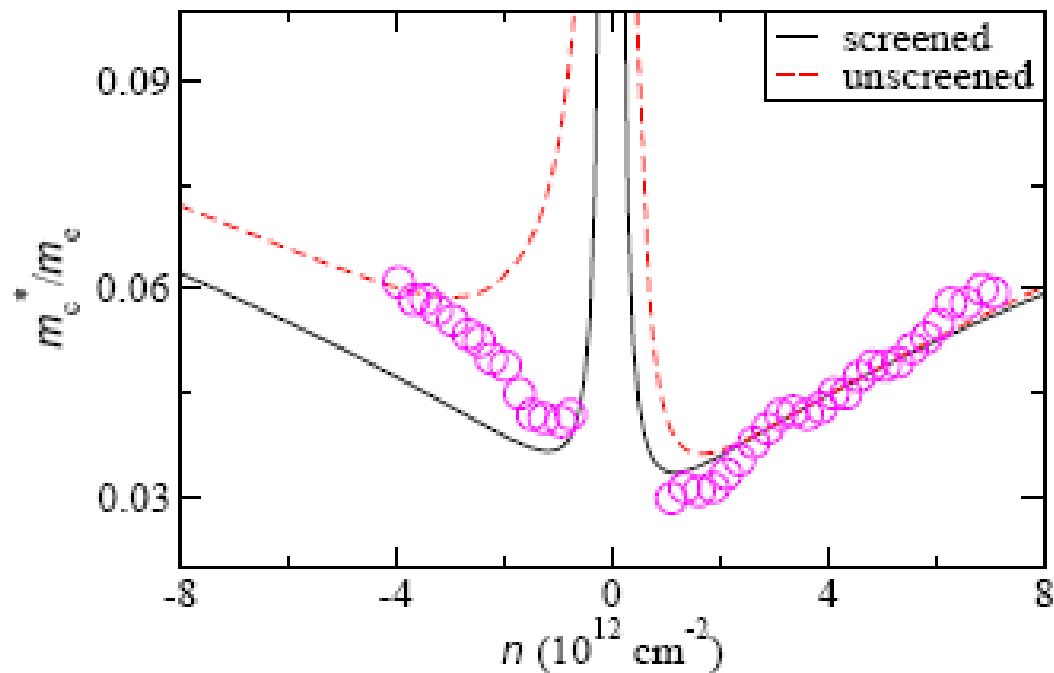
More Chiral Particles

Bilayer Graphene

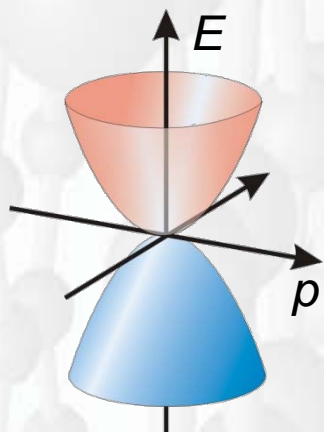


$$E(p) = \pm \frac{1}{2} \gamma_1 \pm \sqrt{\frac{1}{4} \gamma_1^2 + v_F^2 p^2}$$

Bilayer Graphene



E. V. Castro et al PRL 2007

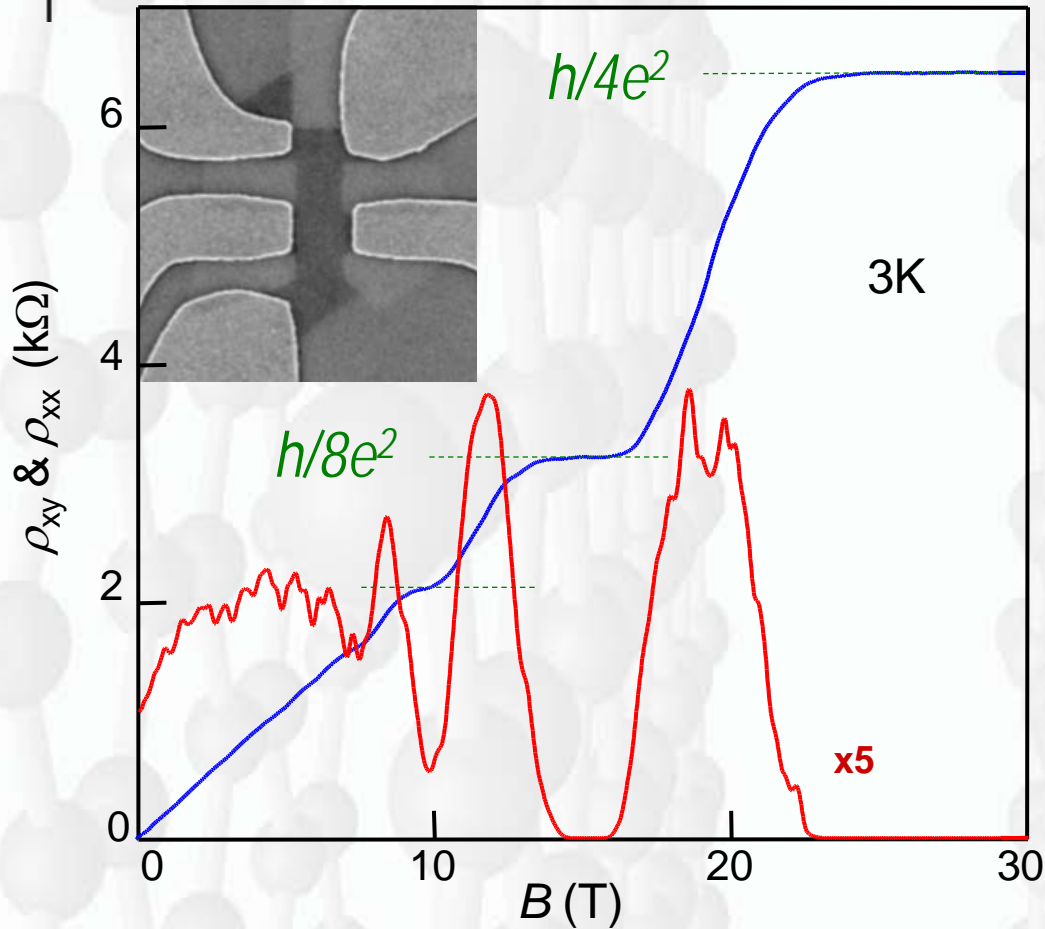
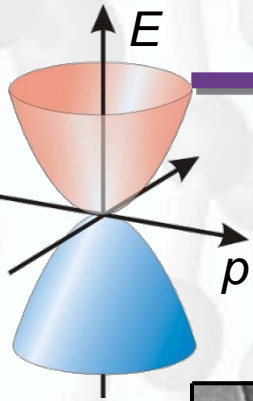


$$E(p) = \pm \frac{1}{2} \gamma_1 \pm \sqrt{\frac{1}{4} \gamma_1^2 + v_F^2 p^2}$$

QHE in Bilayer Graphene

quadruple degeneracy:
plateaus are expected at

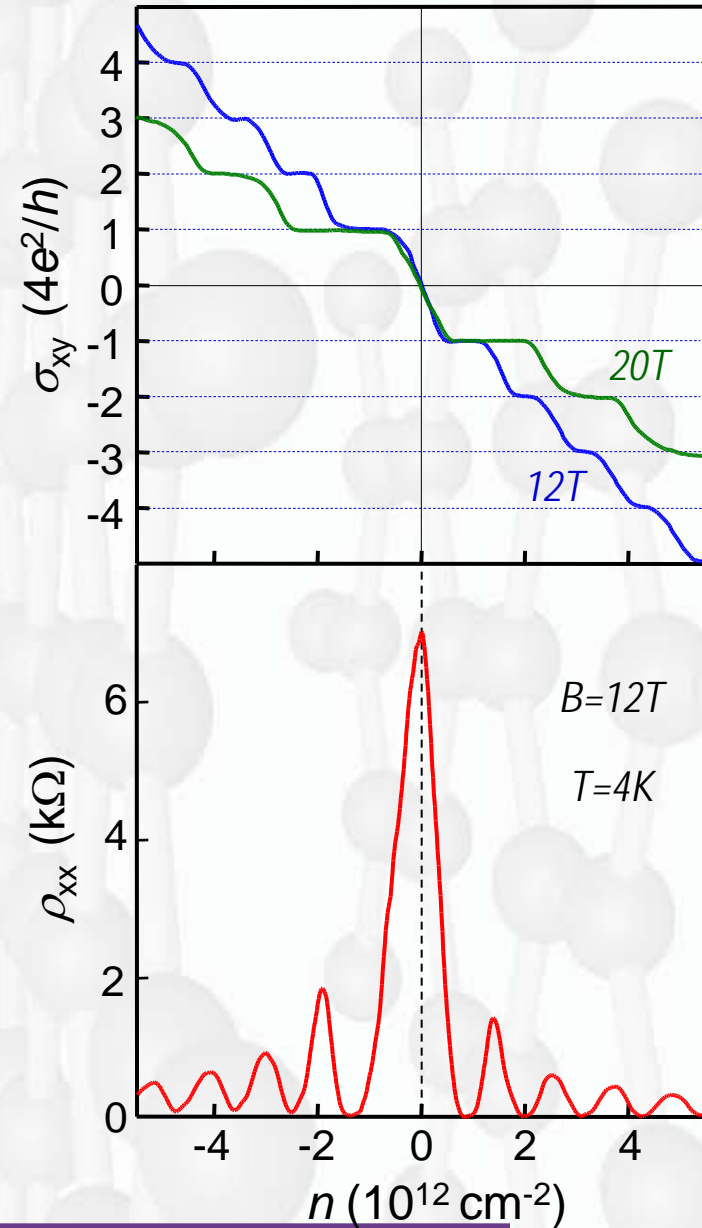
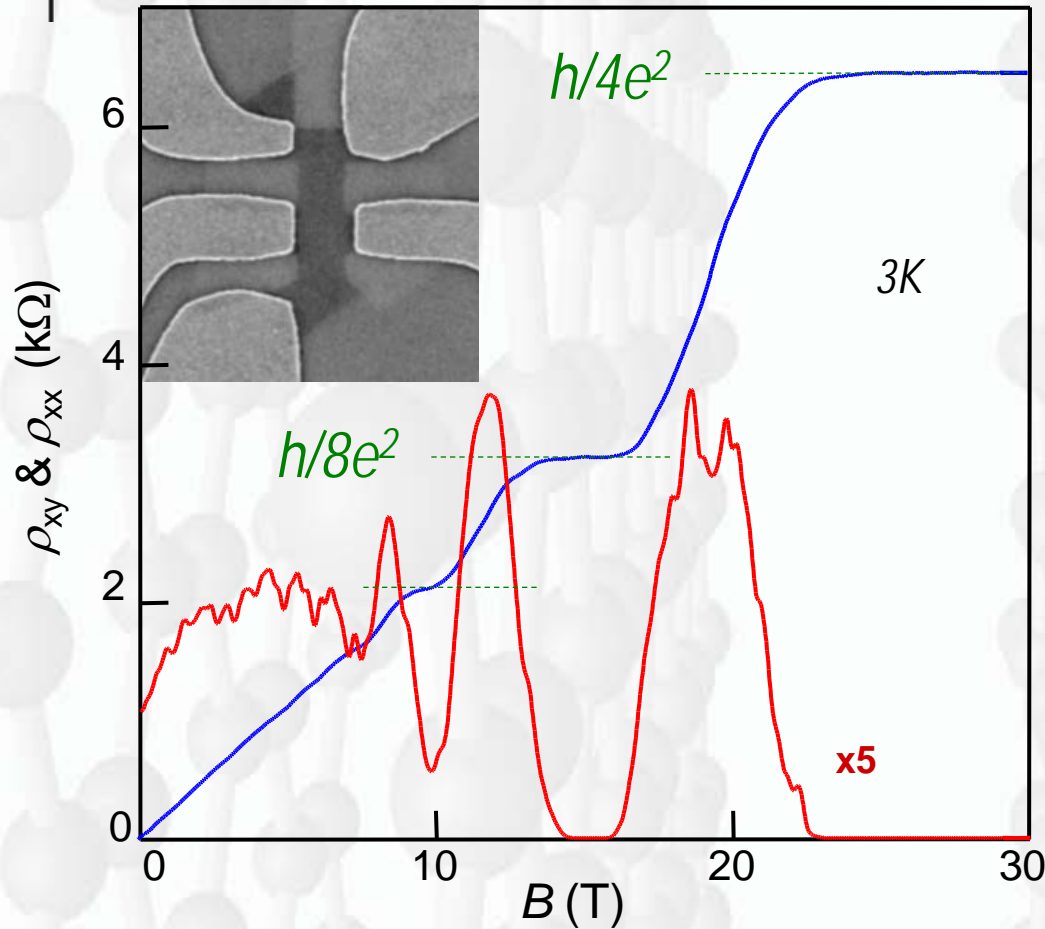
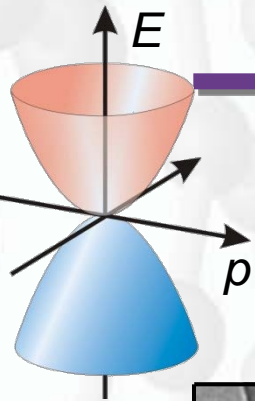
$$(h/4e^2)N^{-1}$$



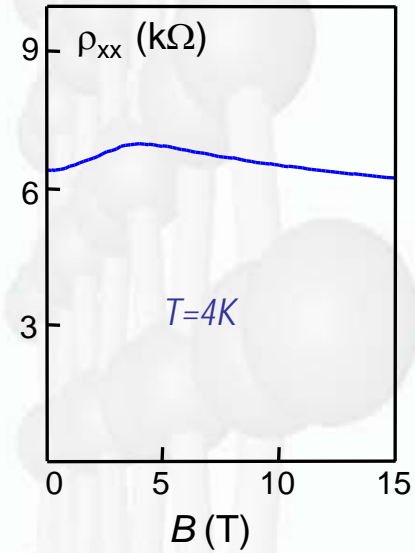
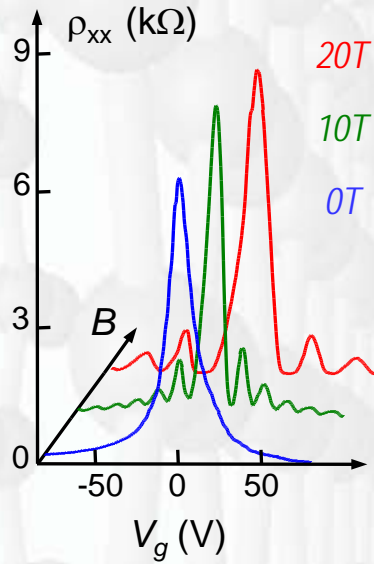
QHE in Bilayer Graphene

quadruple degeneracy:
plateaus are expected at

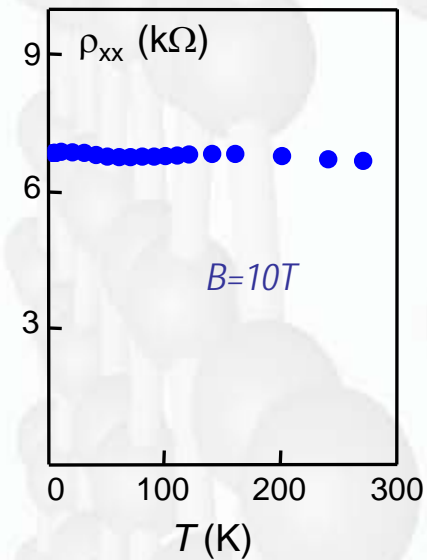
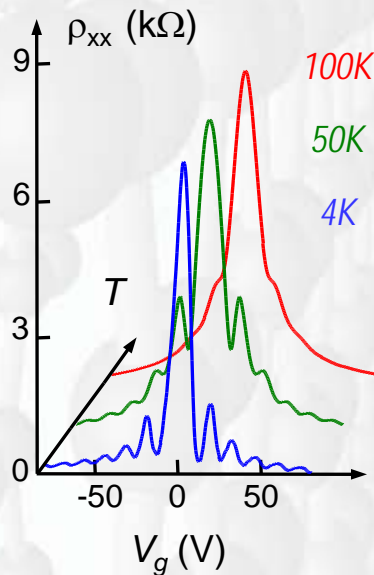
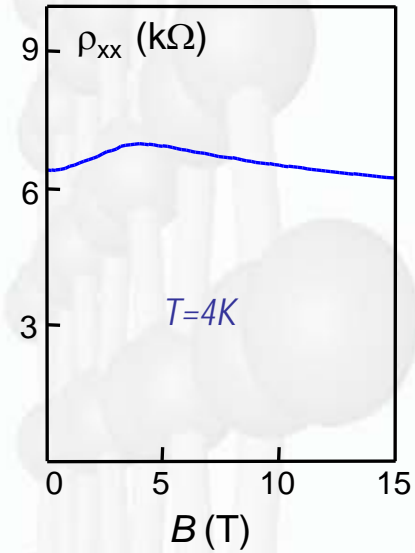
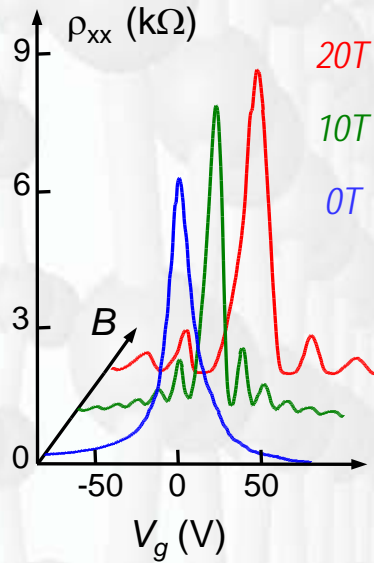
$$(h/4e^2)N^{-1}$$



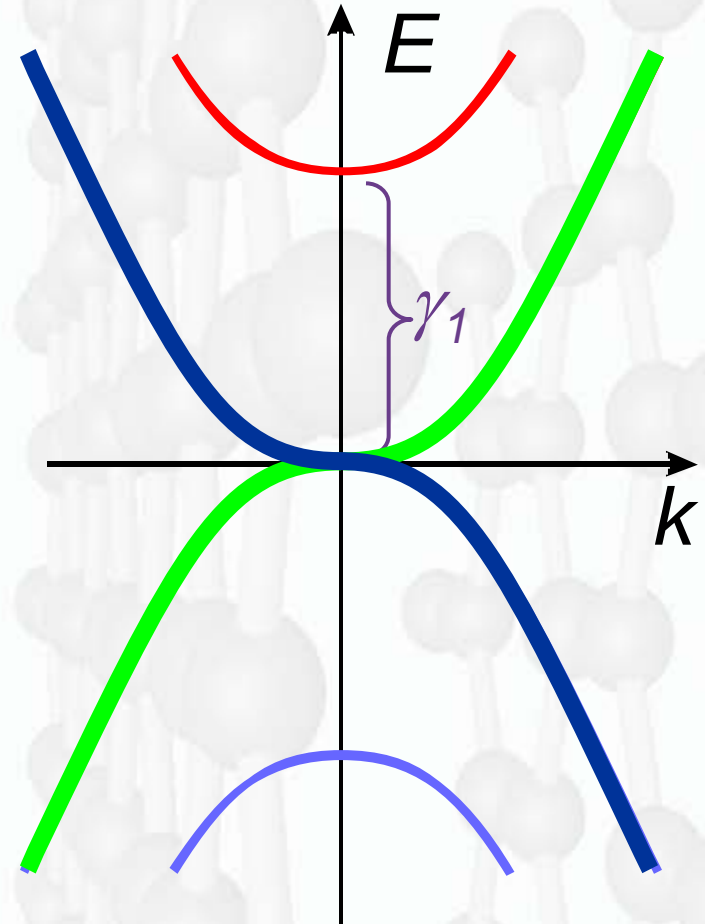
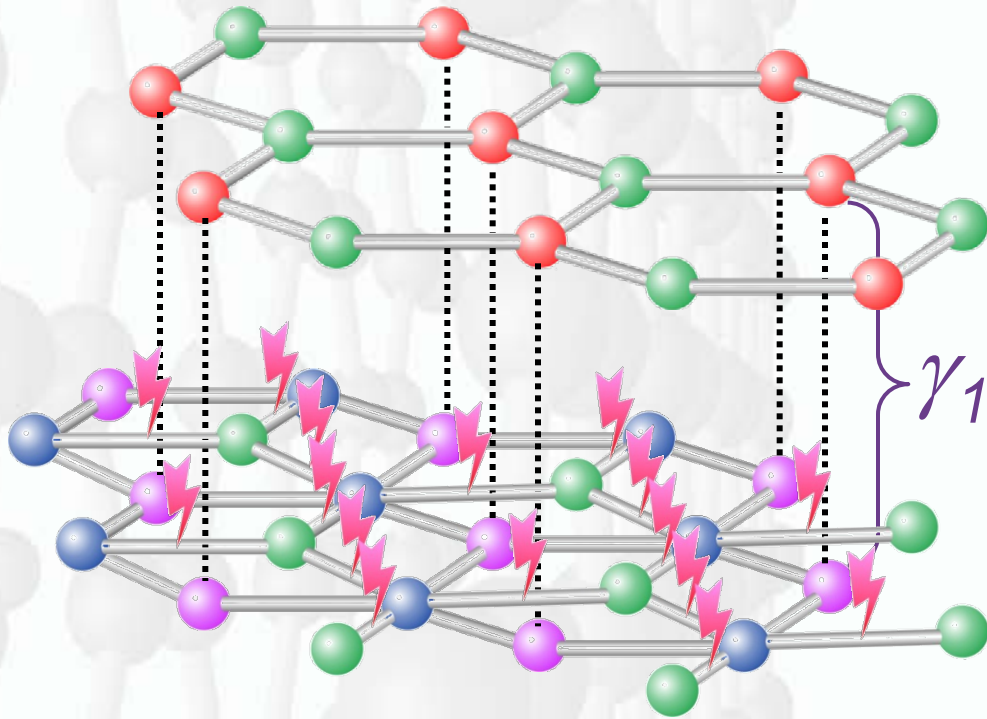
Metallic Behaviour at $\nu = 0$



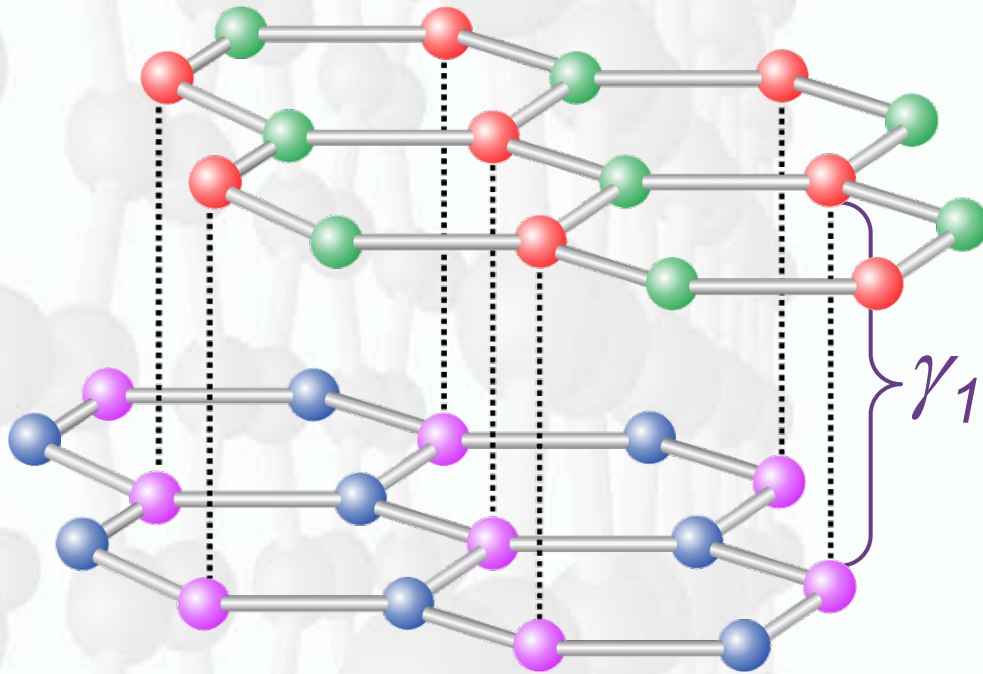
Metallic Behaviour at $\nu = 0$



Chiral Massive Fermions

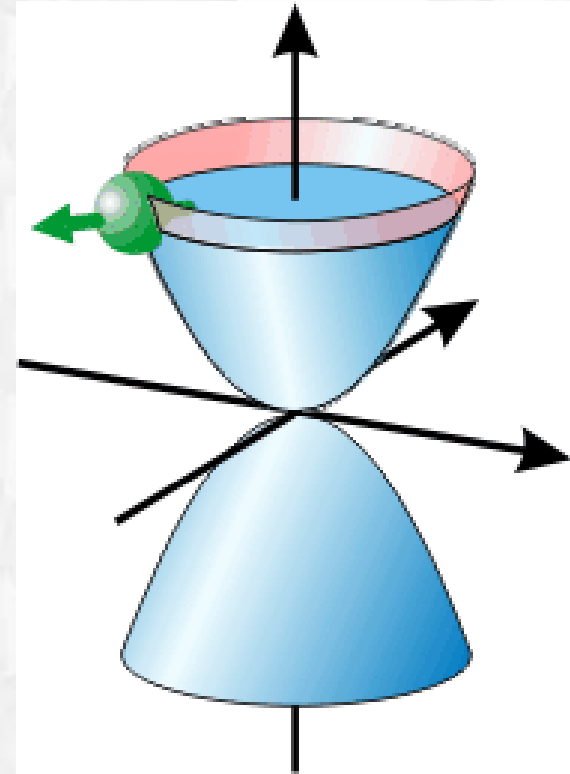


Chiral Massive Fermions



*topological (Berry)
phase of 2π*

Novoselov et al, Nature Phys 2006

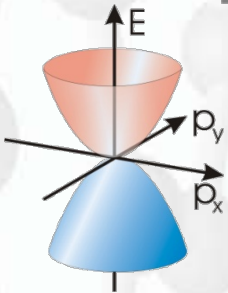


$$E_N = \pm \hbar \omega_c \sqrt{N(N-1)}$$

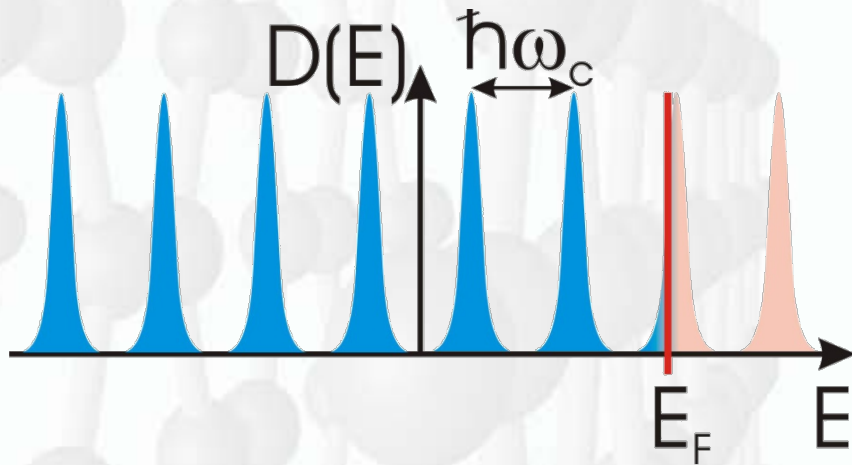
McCann & Falco, PRL 2006

2-DEG in Magnetic Field

Normal electrons



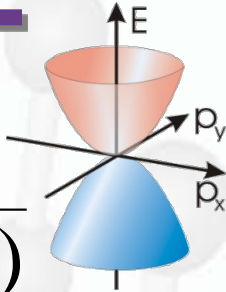
$$E_{LL} = \pm \hbar \omega_c \left(n + \frac{1}{2} \right)$$



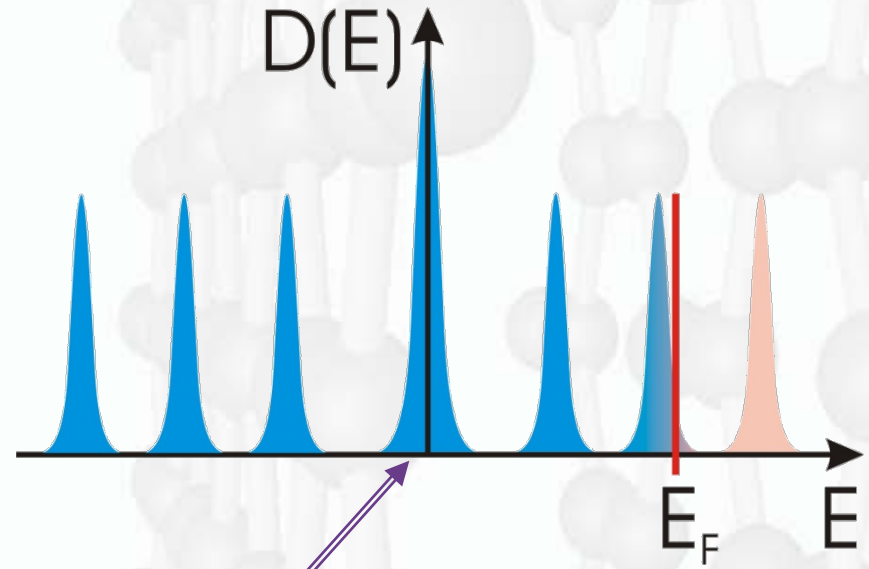
Each level has a degeneracy

$$g_v g_s \frac{eB}{h} = 4 \frac{eB}{h}$$

Chiral Massive Fermions



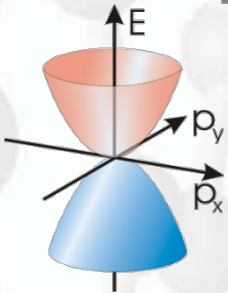
$$E_{LL} = \pm \hbar \omega_c \sqrt{n(n-1)}$$



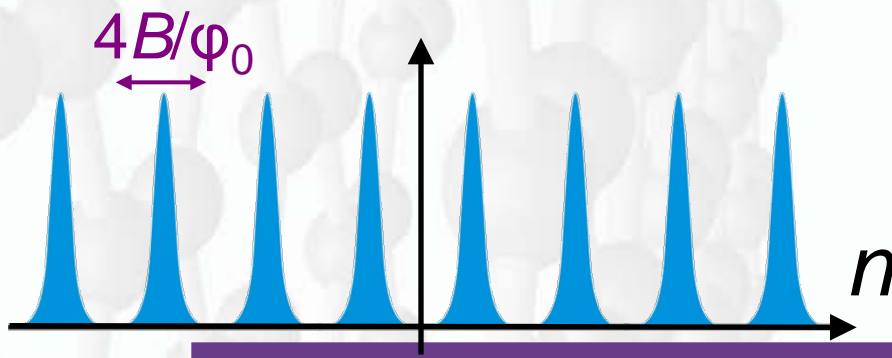
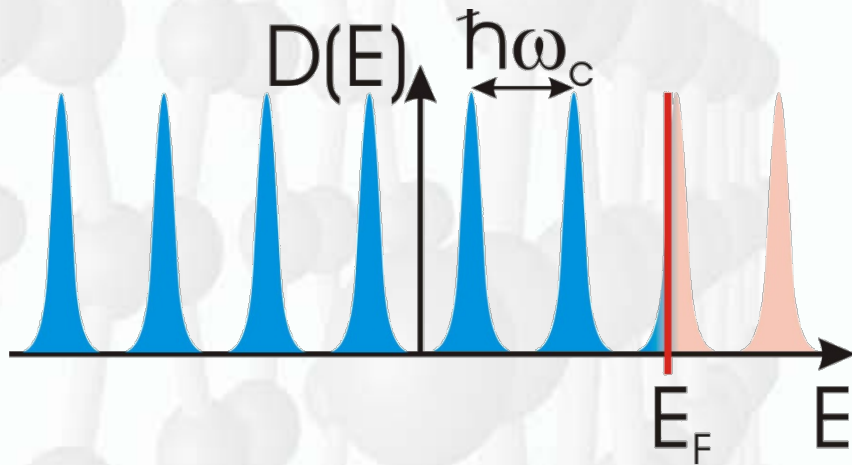
Shared equally between holes and electrons and has **double** degeneracy

2-DEG in Magnetic Field

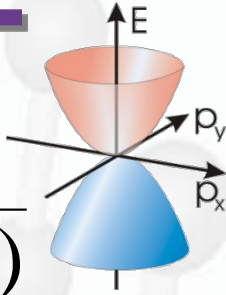
Normal electrons



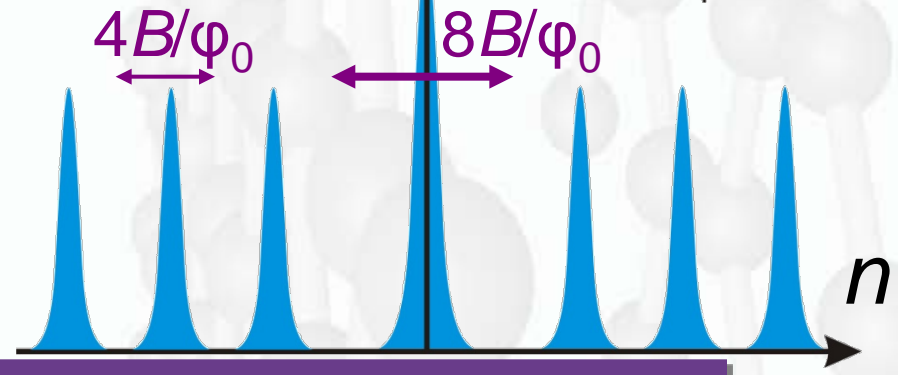
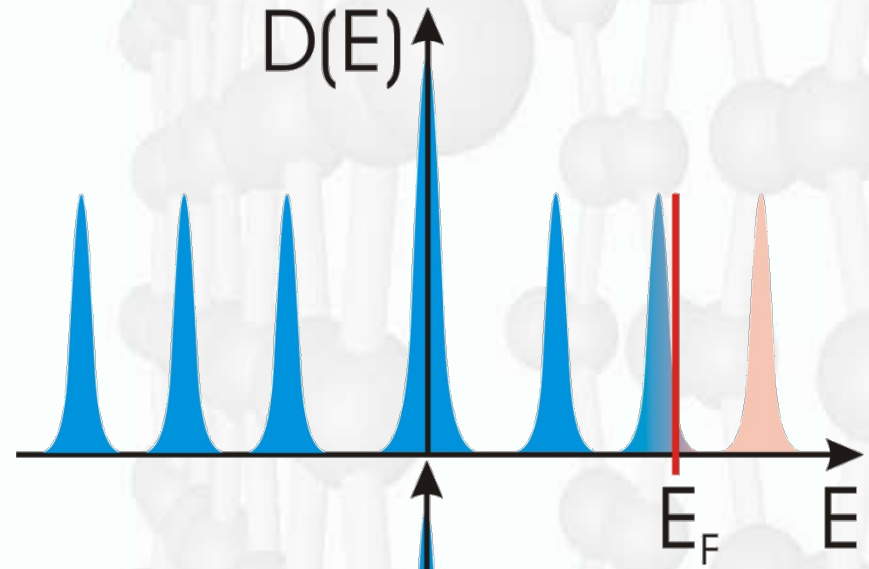
$$E_{LL} = \pm \hbar \omega_c (n + \frac{1}{2})$$



Chiral Massive Fermions



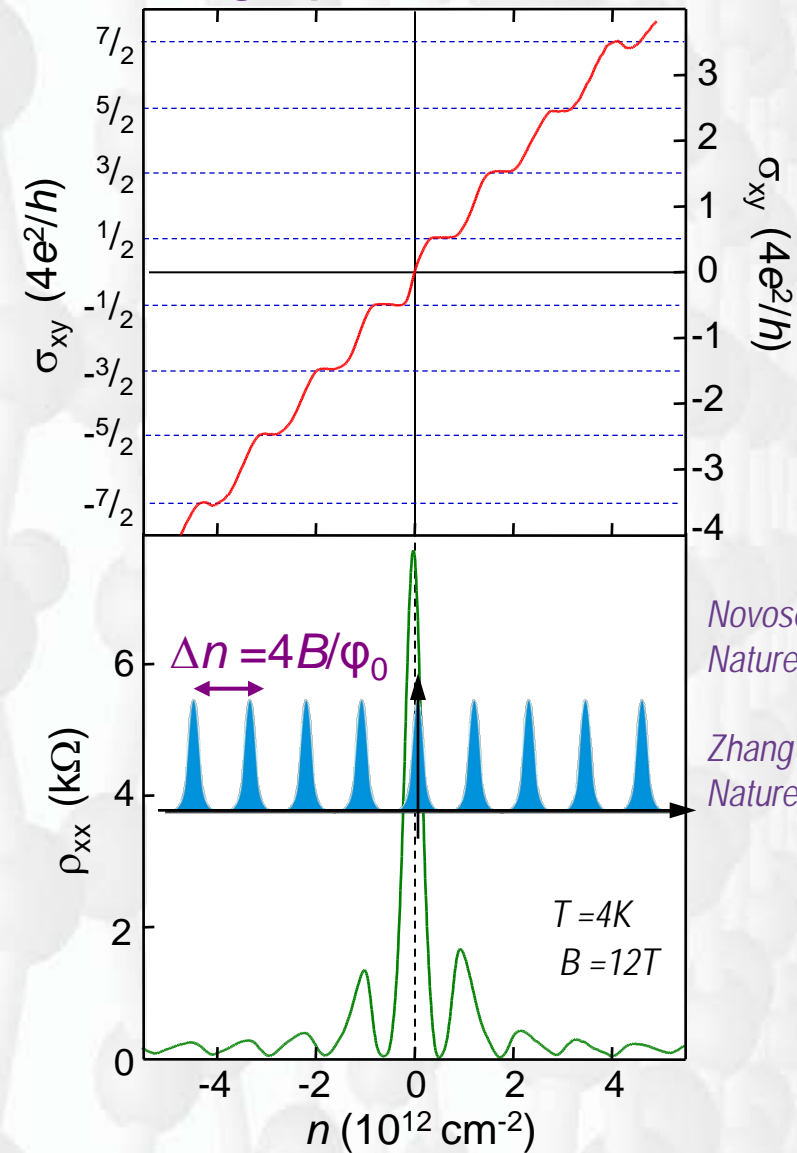
$$E_{LL} = \pm \hbar \omega_c \sqrt{n(n-1)}$$



Chiral Quantum Hall Effects

graphene $\nu = N + 1/2$

bilayer graphene $\nu = N$

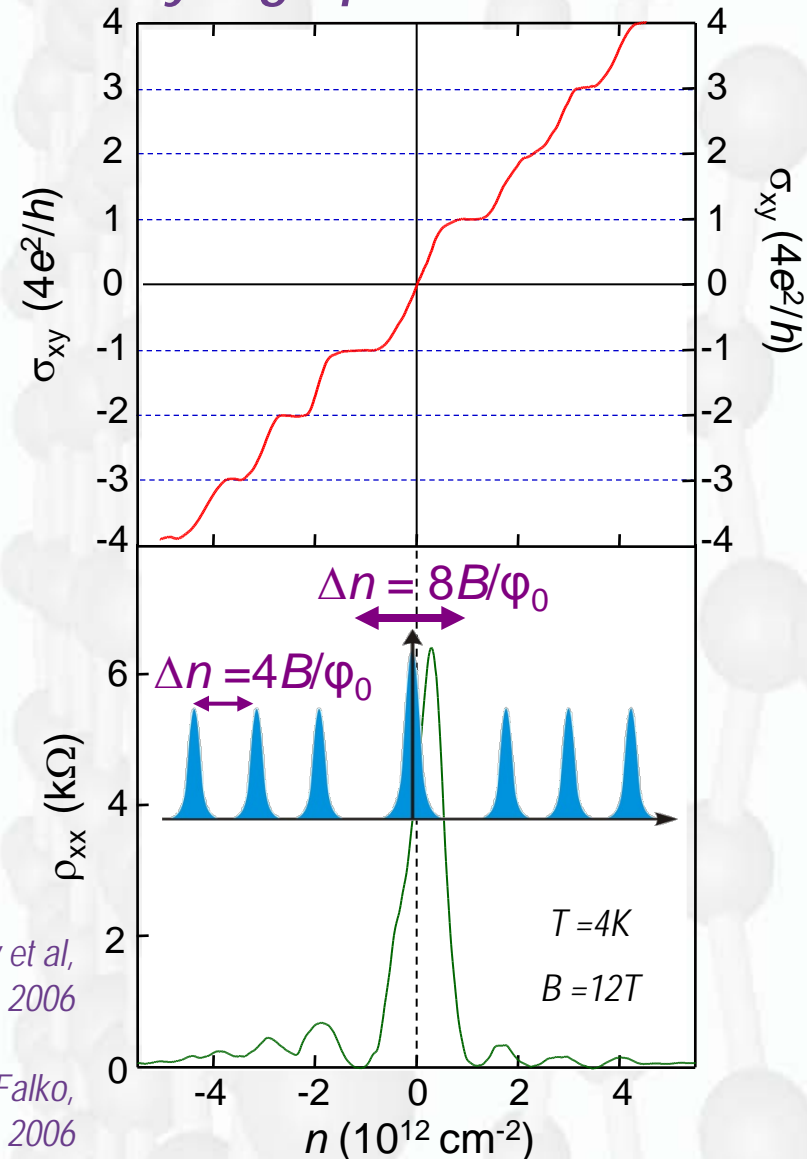


Novoselov et al,
Nature 2005

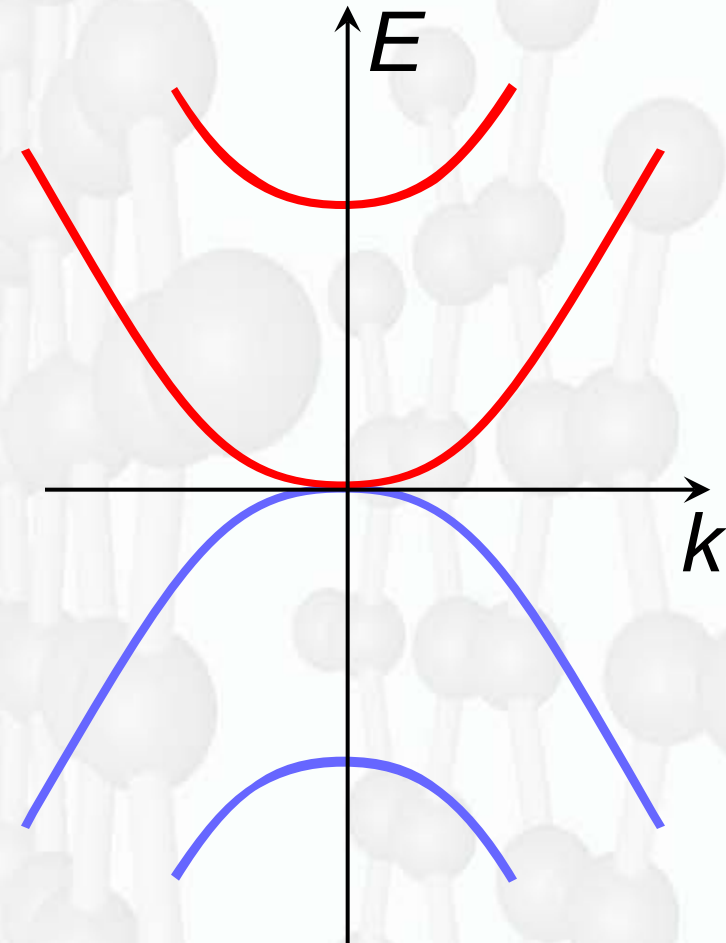
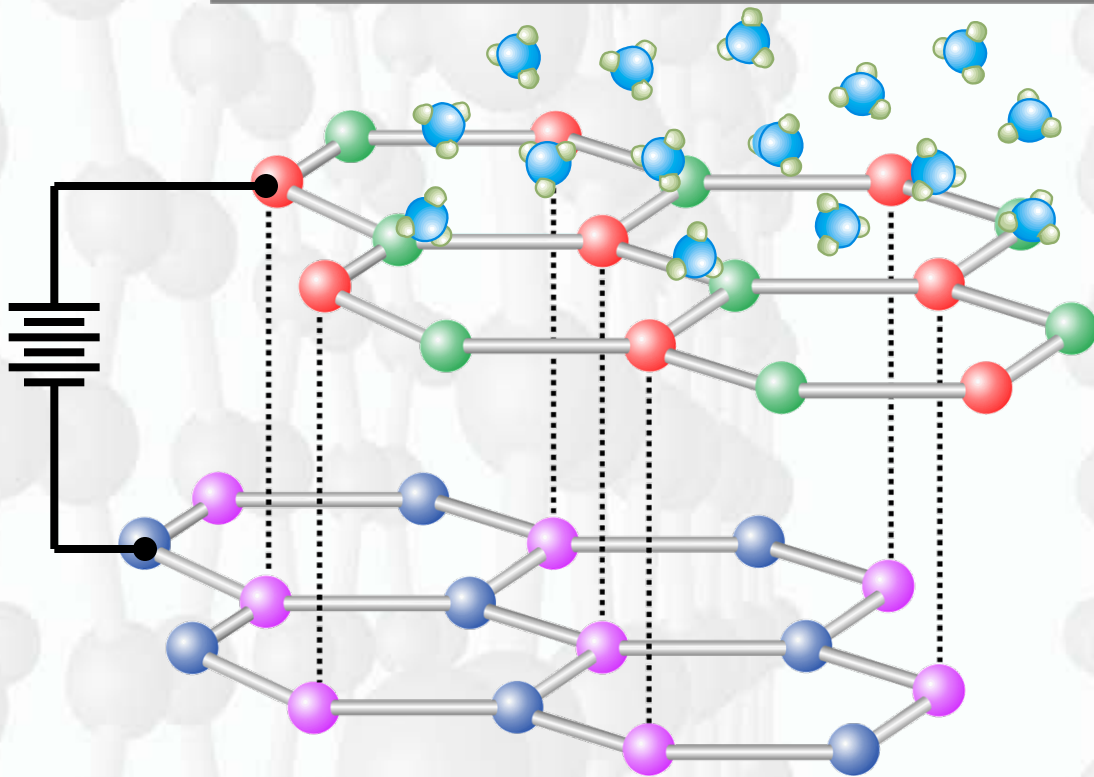
Zhang et al,
Nature 2005

Novoselov et al,
Nature Phys. 2006

McCann & Falco,
PRL 2006

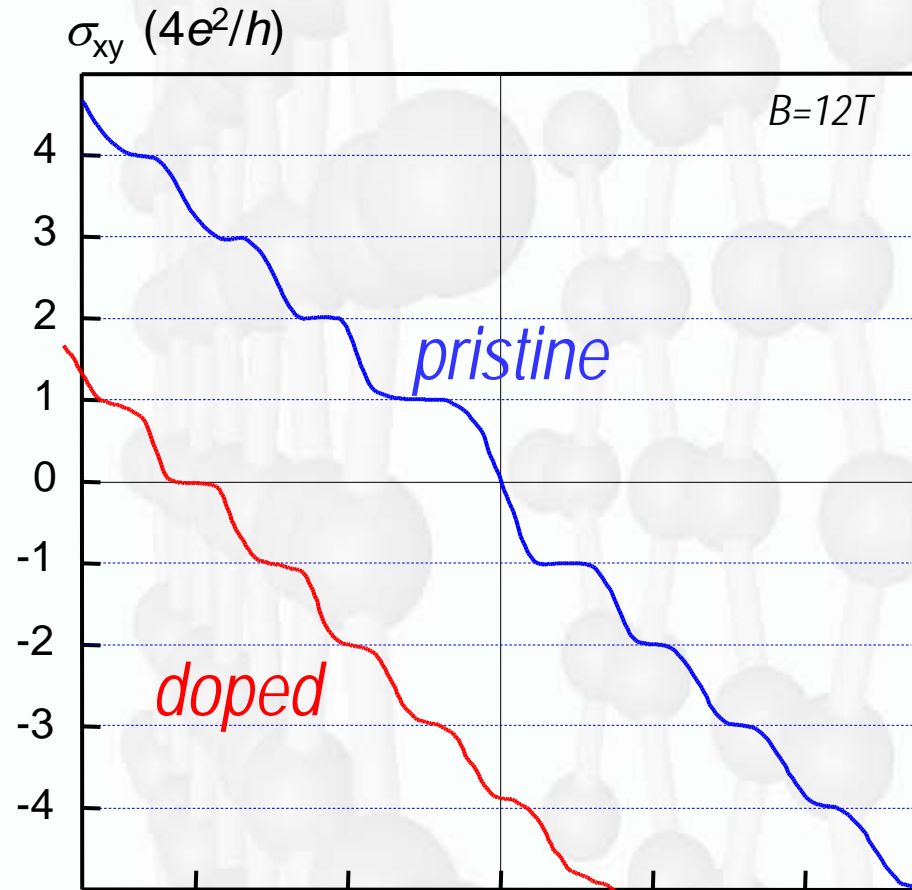
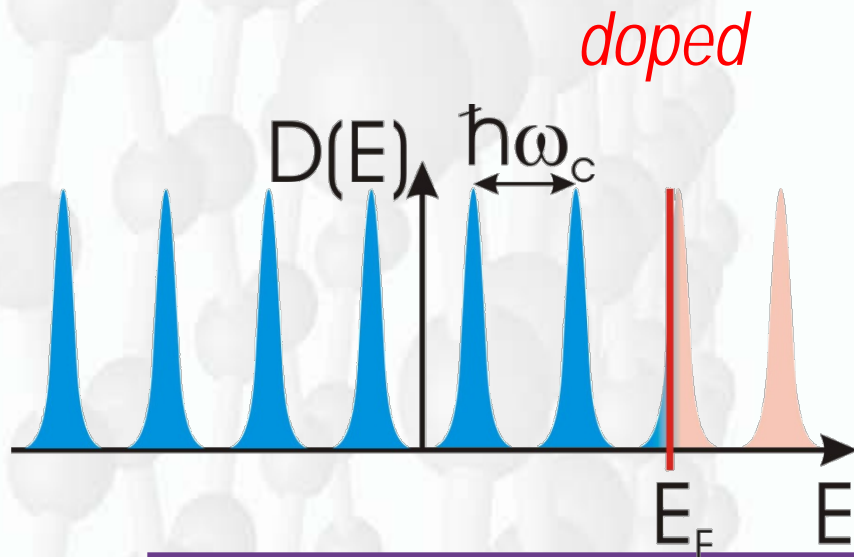
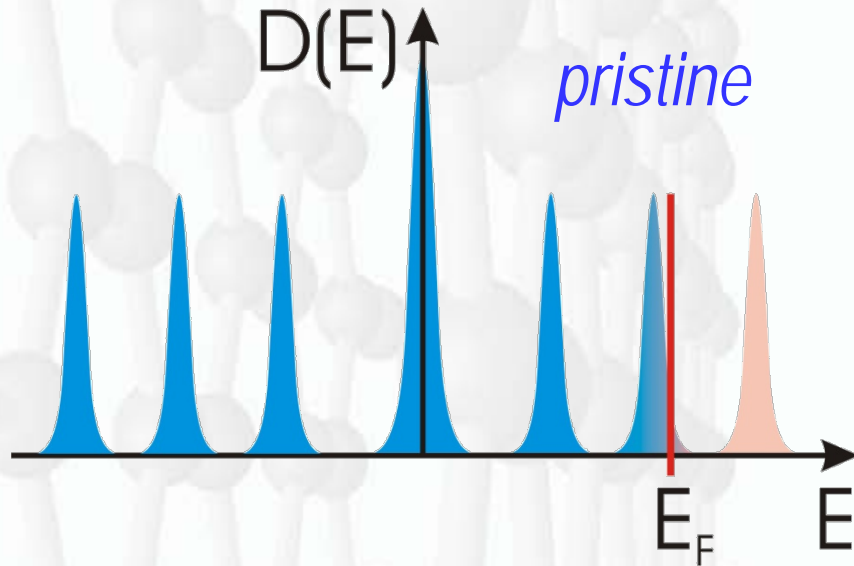


QHE in Bilayer Graphene

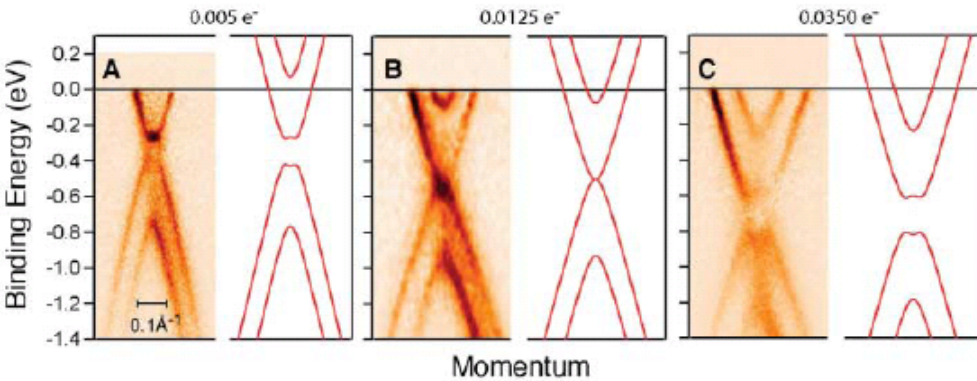


Electronically controlled gap

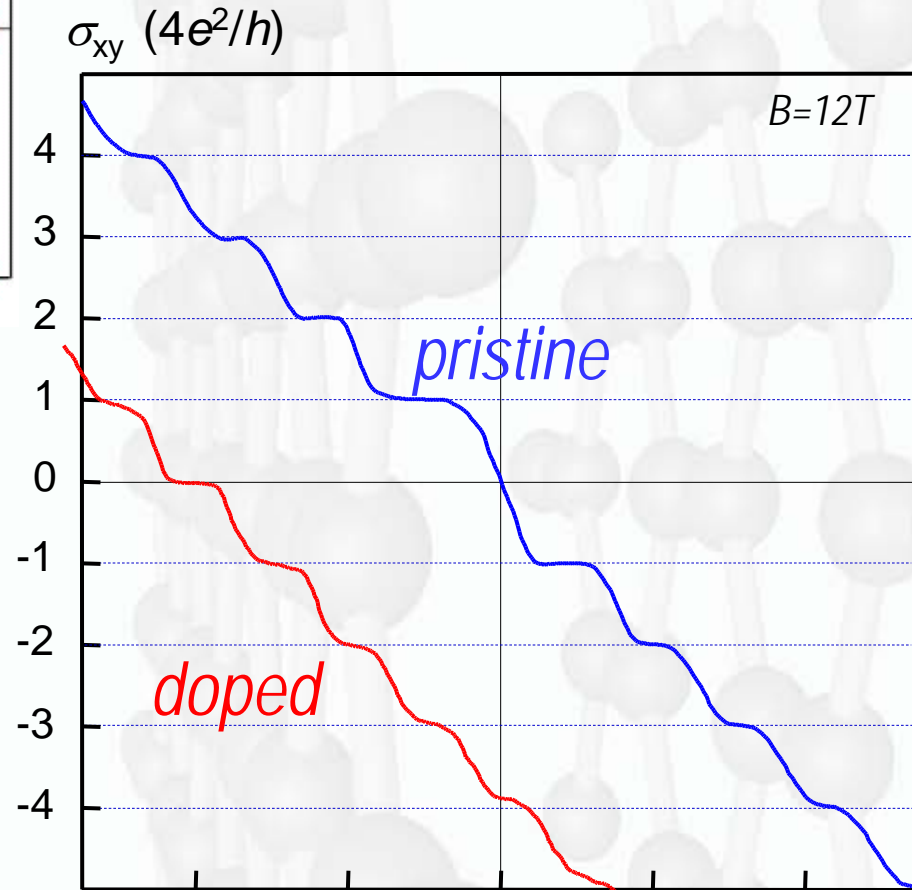
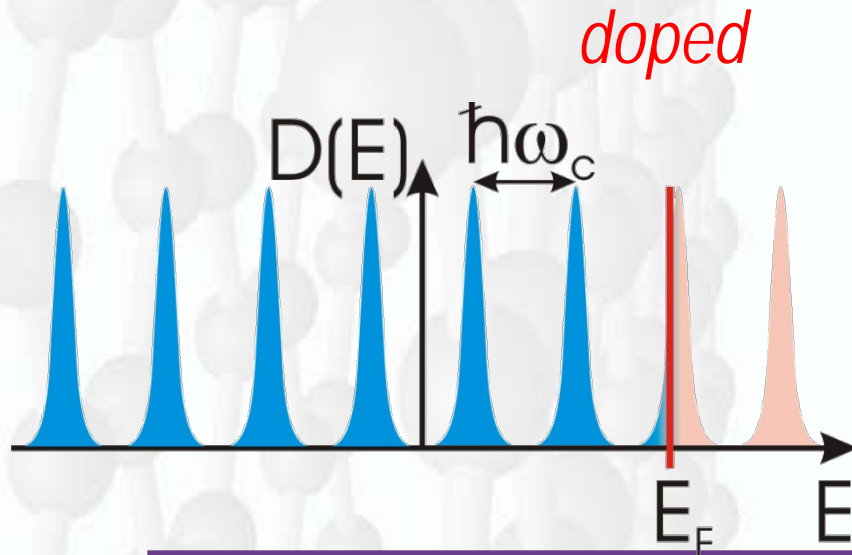
QHE in Bilayer Graphene



QHE in Bilayer Graphene

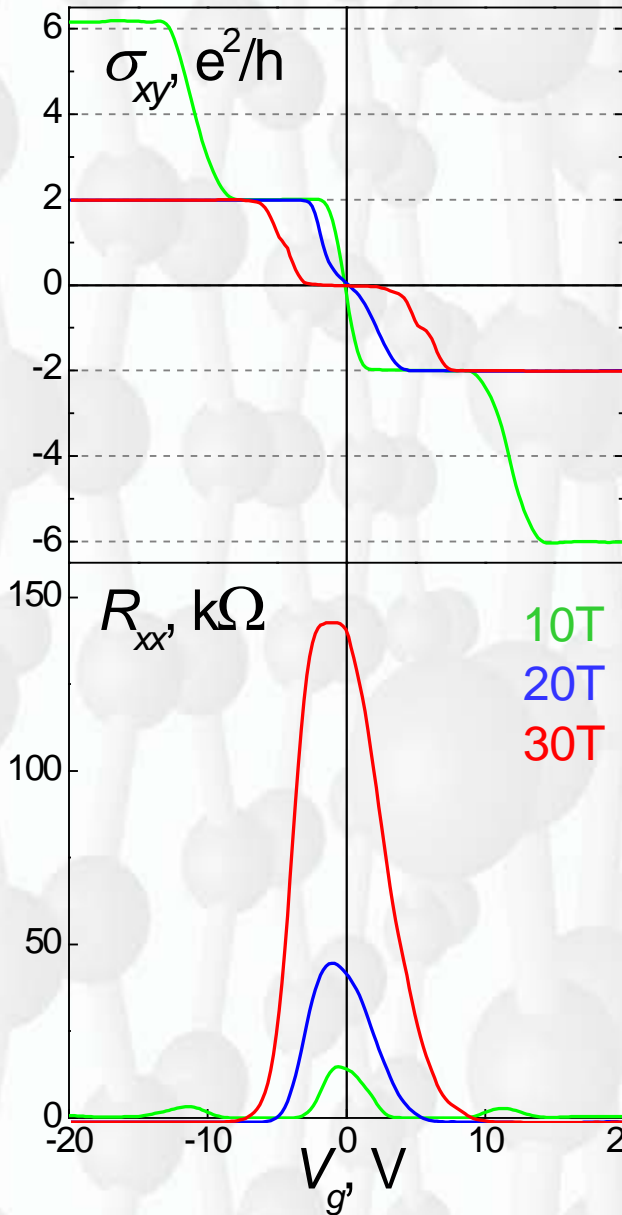


Taisuke Ohta, Aaron Bostwick, Thomas Seyller,
 Karsten Horn, and Eli Rotenberg
Science 18 August 2006 313: 951-954



E. V. Castro et al PRL 2007

Lifting Degeneracy

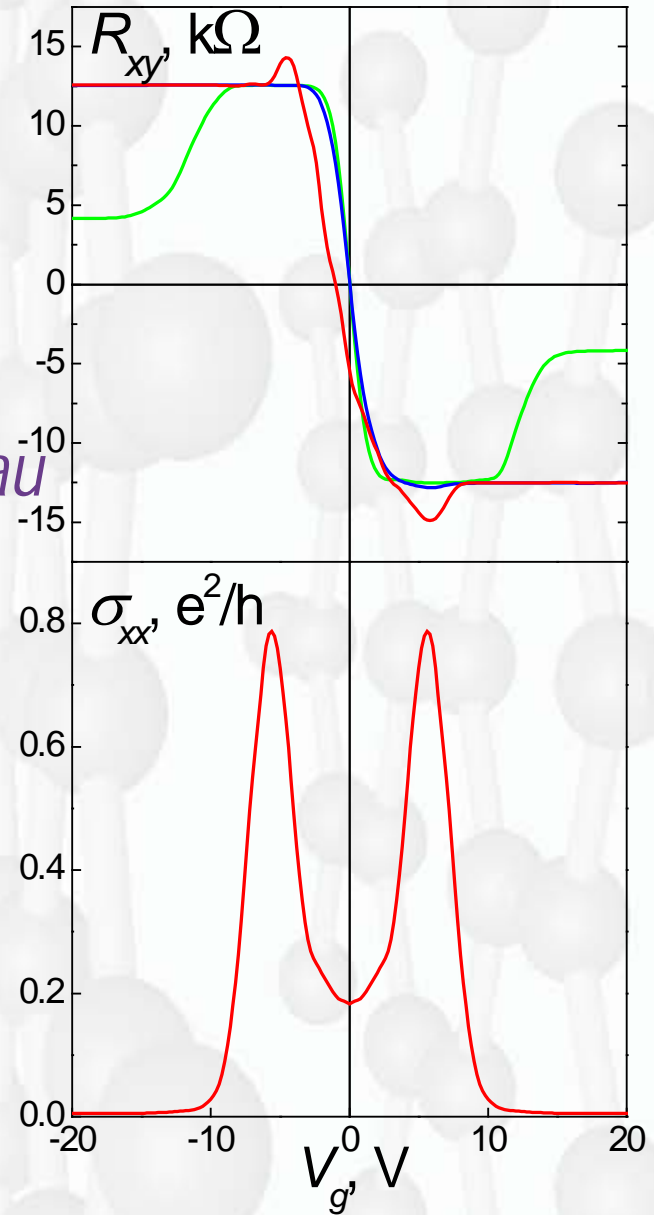


*additional plateau
at $\nu=0$*

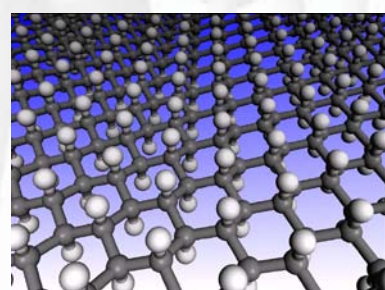
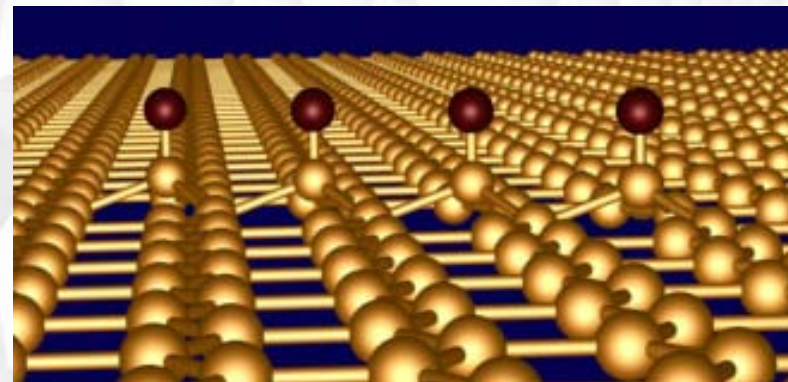
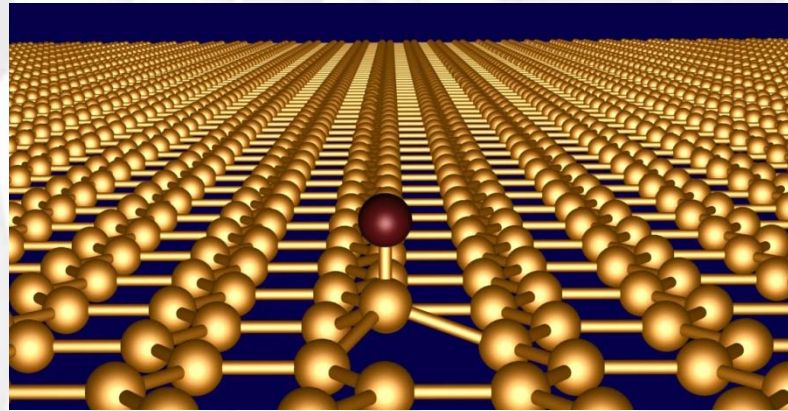
(also at $\nu=\pm 1$)

R_{xy} - no plateau

σ_{xx} - no plateau

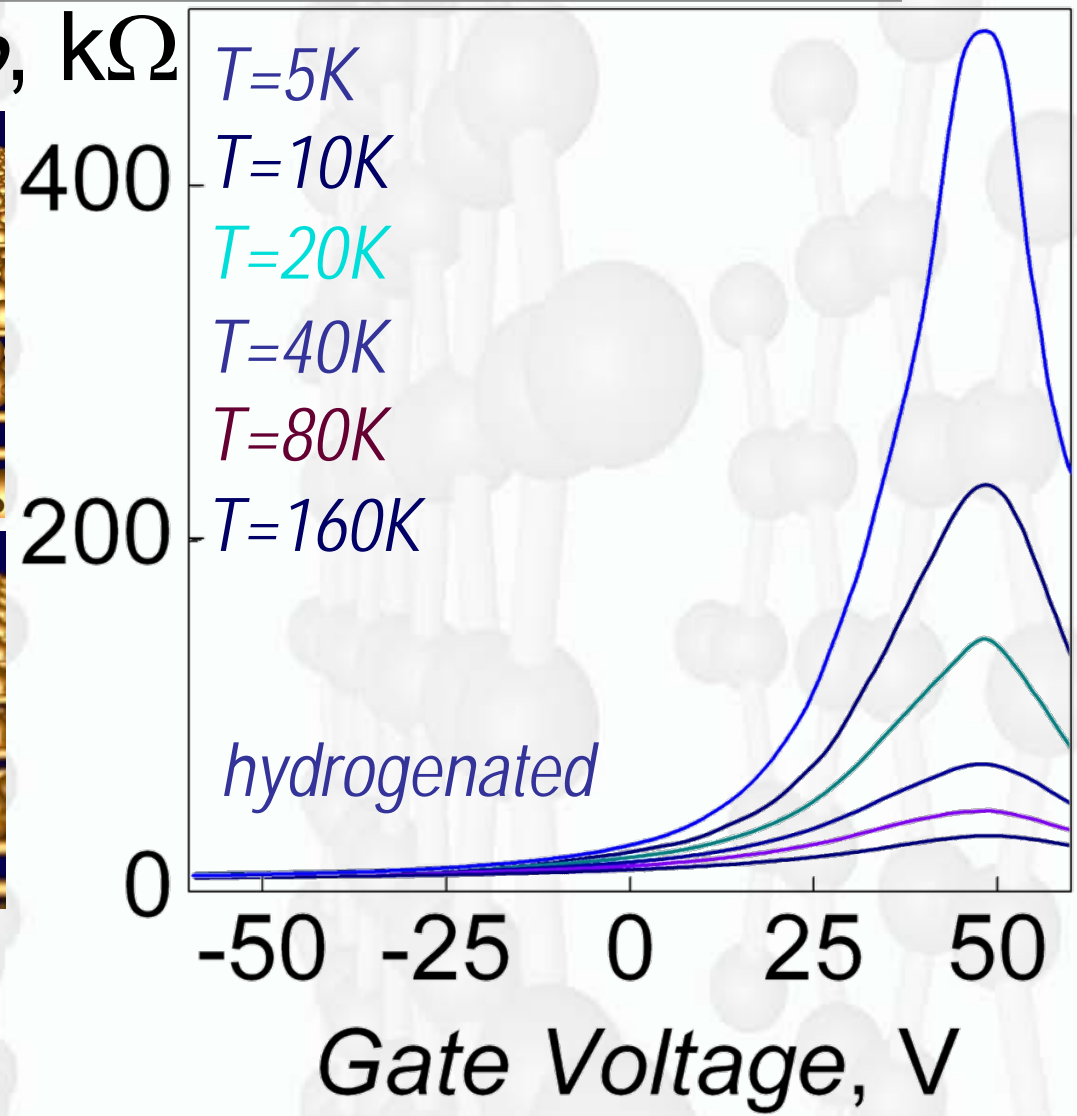


Introducing Resonant Scatterers

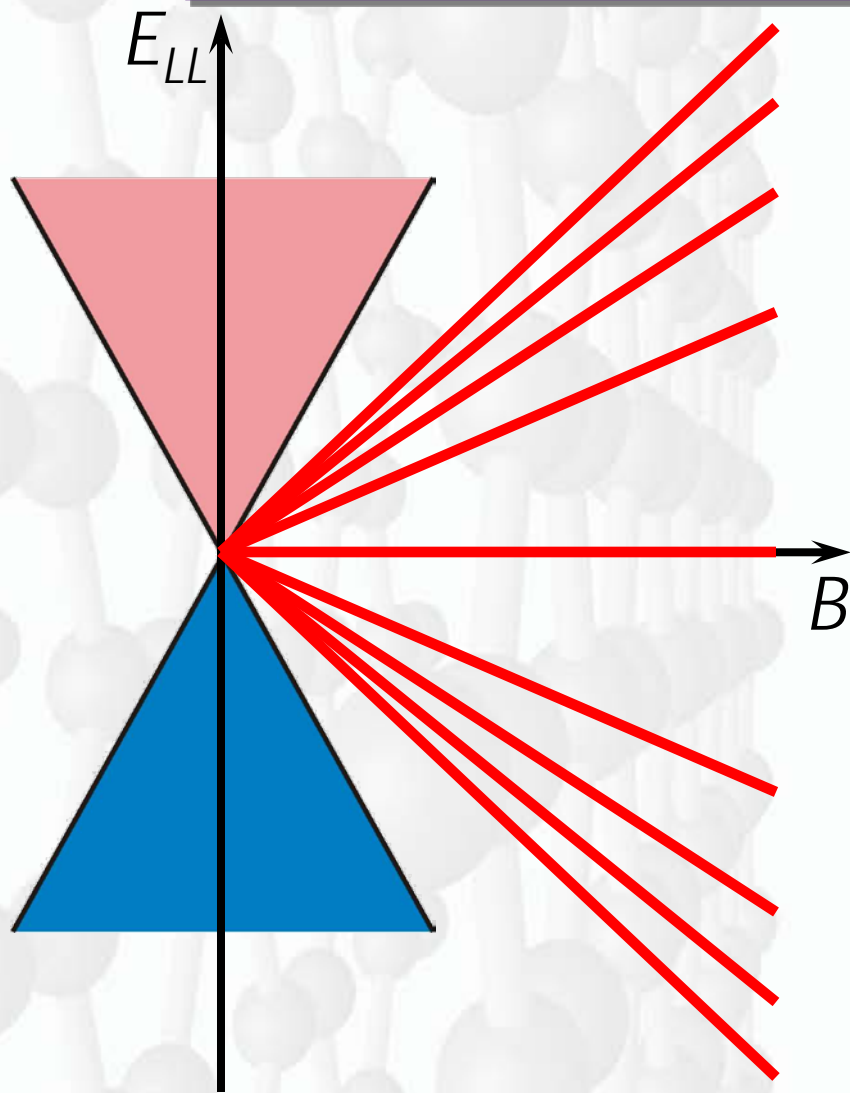


graphane

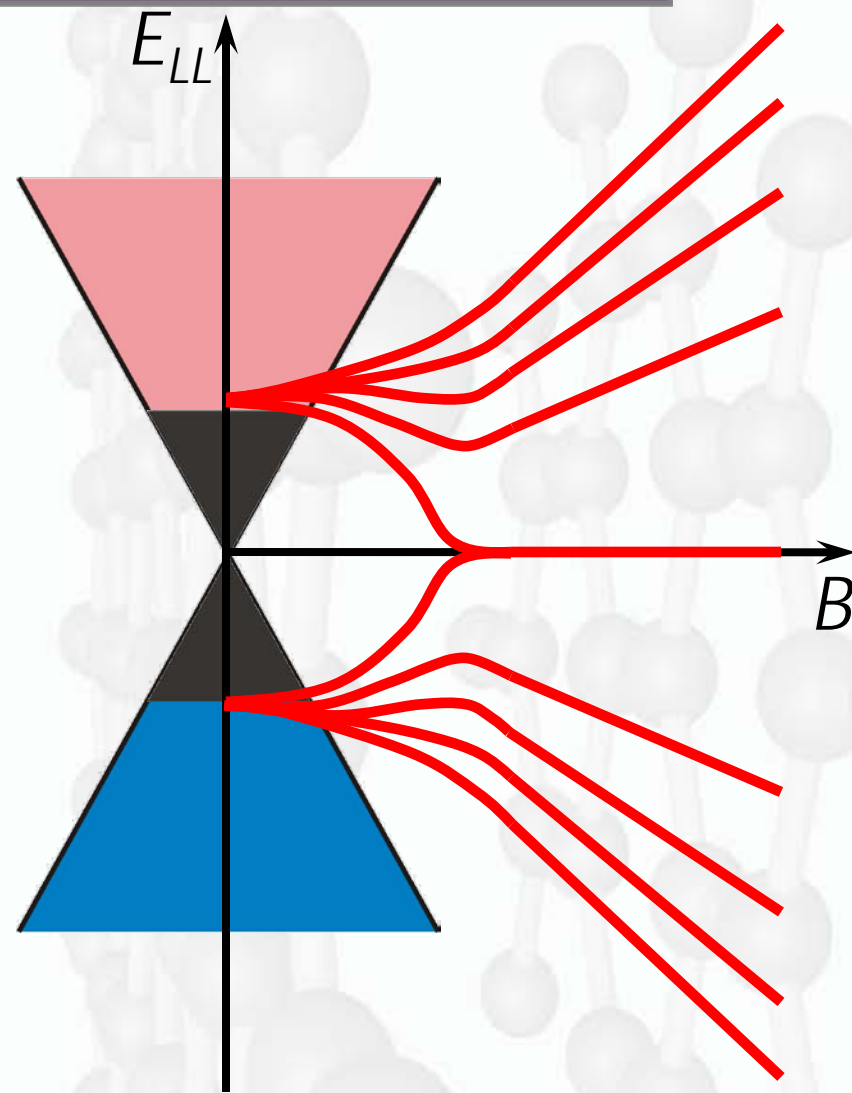
ρ , $k\Omega$



Floating of the Energy Levels

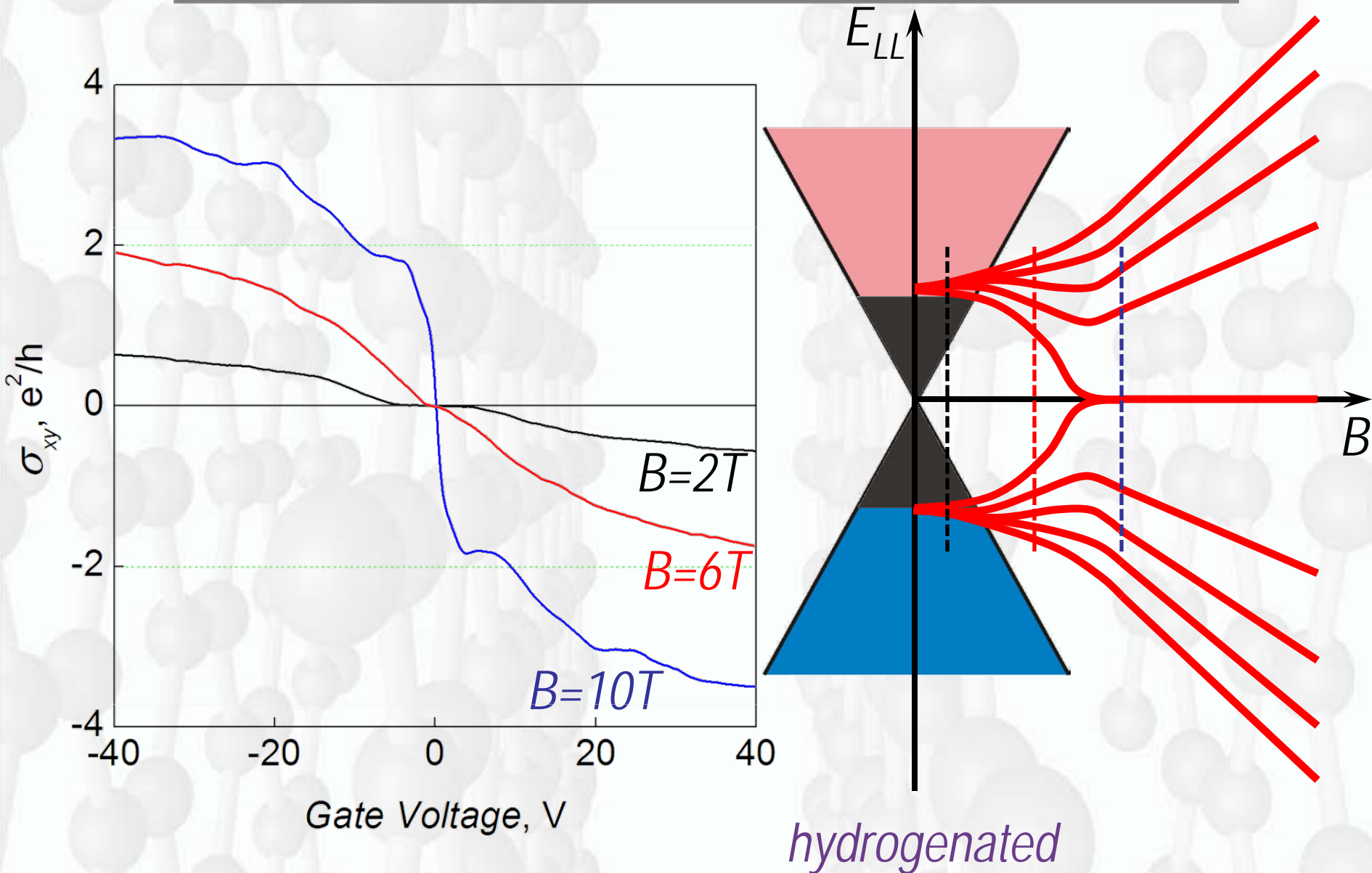


pristine



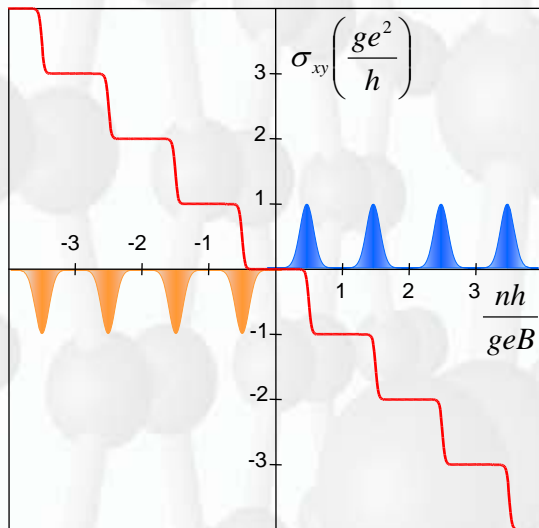
hydrogenated

QHE in Hydrogenated Graphene



Three types of IQHE

conventional IQHE

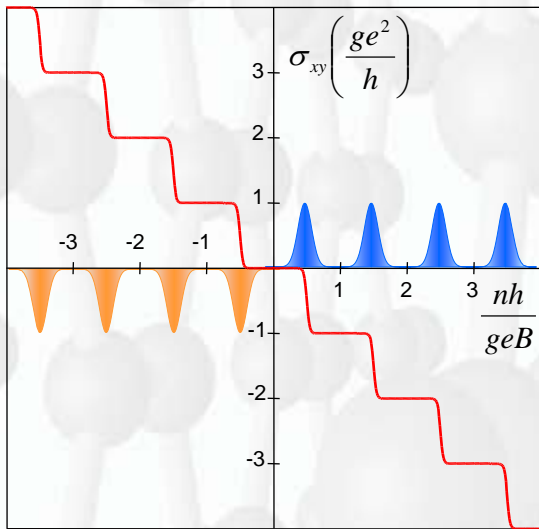


*all LL at non-zero E
zero Berry phase
insulator at $\nu \rightarrow 0$*

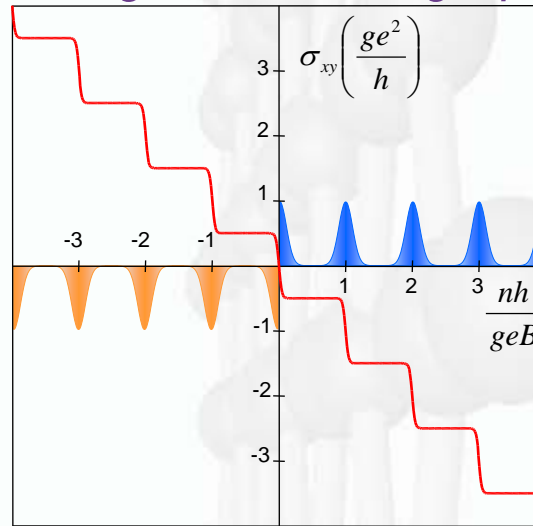
Three types of IQHE

"half-integer" QHE in graphene

conventional IQHE



*all LL at non-zero E
zero Berry phase
insulator at $\nu \rightarrow 0$*

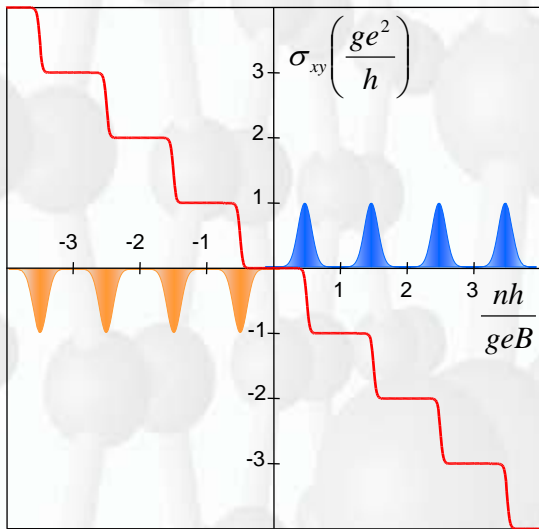


*one LL at zero E
Berry phase π
metallic at $\nu \rightarrow 0$*

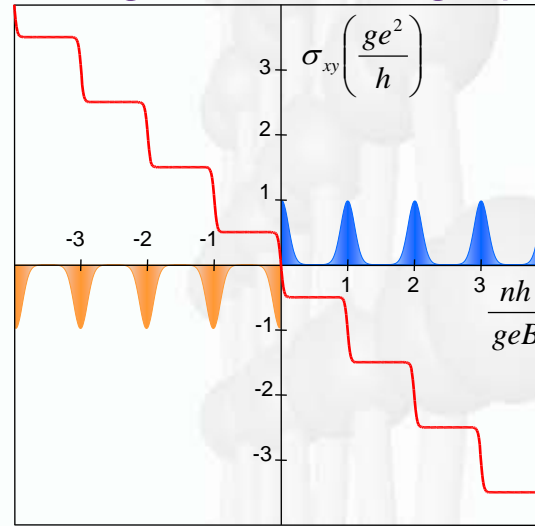
Three types of IQHE

"half-integer" QHE in graphene

conventional IQHE

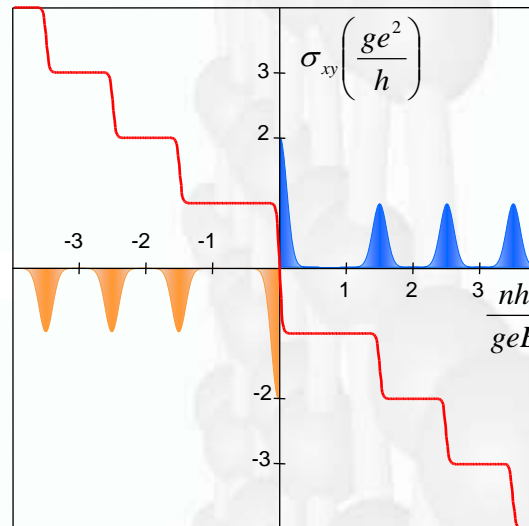


*all LL at non-zero E
zero Berry phase
insulator at $\nu \rightarrow 0$*



*one LL at zero E
Berry phase π
metallic at $\nu \rightarrow 0$*

chiral IQHE in bilayer graphene

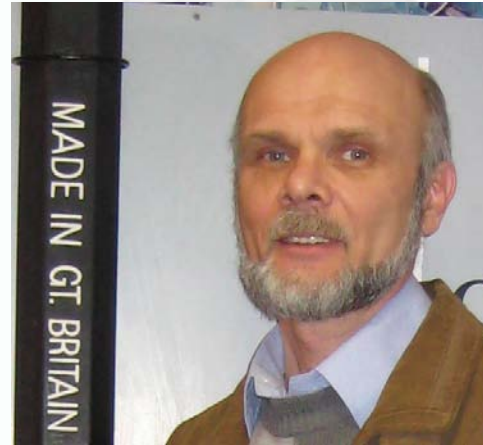


*two LLs at zero E
Berry phase 2π
metallic at $\nu \rightarrow 0$*

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