Observation of Fractional Quantum Hall effect in suspended graphene

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Eva Y. Andrei

- 1'st report: May, 2009 (Science brevia submission)
- reported June 25, 09, EPQHS3 Lucca, Italy
- reported July 1,09, "Recent Progress in Graphene", Seoul, Korea
- reported July 28, 09 "Graphene 2009" , Benasque, Spain

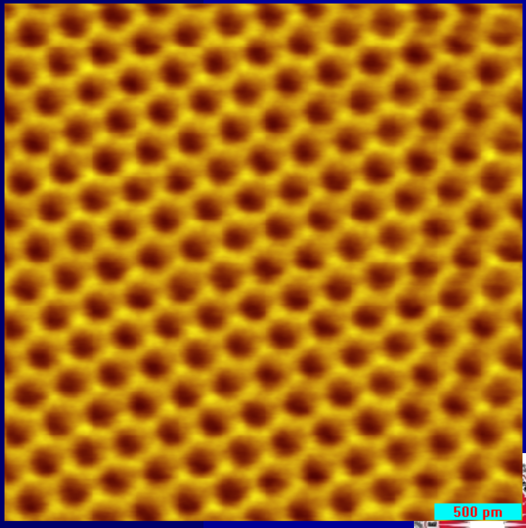
Interaction and correlation effects in suspended graphene using STM and Transport

- Transport in Suspended graphene
  - Reduced potential fluctuations
  - B finite
    - Quantum Hall effect
    - ν=0 insulating phase

IQHE ν=1,3,4

FQHE ν=1/3

- STM in suspended graphene
  - Structure
  - Density of States
  - B finite
    - Landau levels
    - Fermi Velocity
    - e-ph interactions
    - e-e interactions

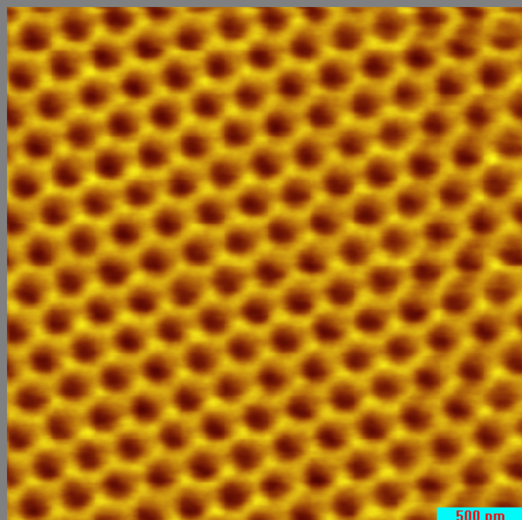


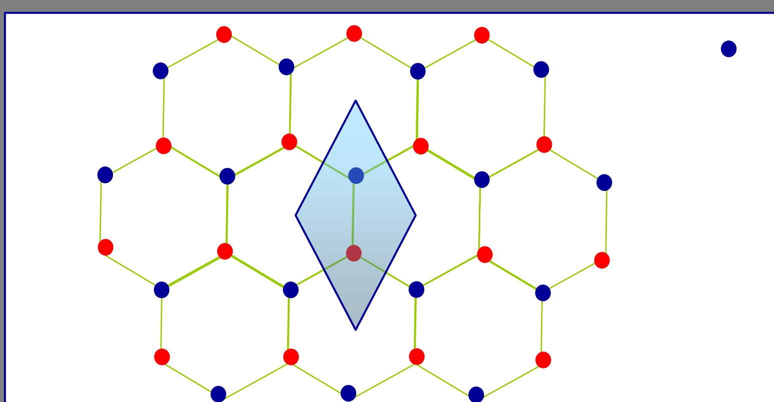
- Rotated graphene
  - Tunable Van-Hove singularities

see talk by J. Lopes dos Santos

Graphene – the hallmarks

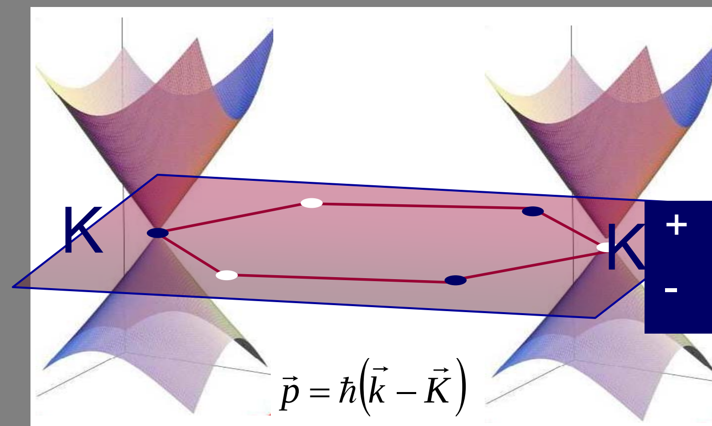
Structure: honeycomb





$$\Psi_{\vec{k}}(\vec{r}) = c_A|\bigcirc_A\rangle + c_B|\bullet_B\rangle = \begin{pmatrix} c_A \\ c_B \end{pmatrix}$$

Band structure



\+ electrons
\- holes

Degeneracy 2-spin x 2-valley

$$H_K^{eff} = v_F \vec{\sigma}.\vec{p}$$

Dirac-Weyl

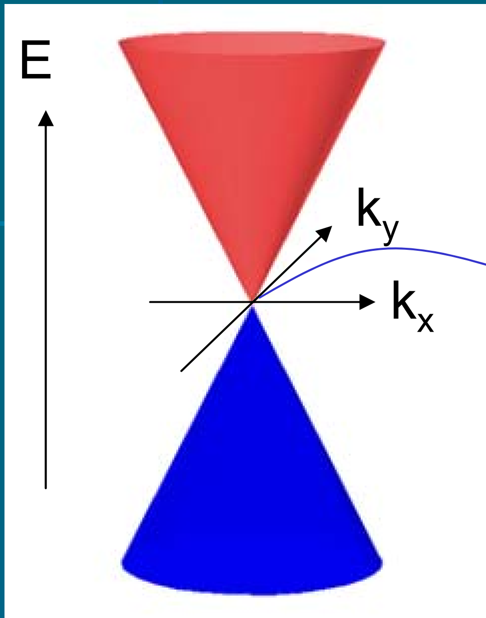
$$E = \pm v_F |\vec{p}|$$

Zero mass
$v_f \sim 10^6$ m/s

$$\psi = \begin{pmatrix} c_A \\ c_B \end{pmatrix} = \frac{1}{\sqrt{2}} e^{i\vec{k}\vec{r}} \begin{pmatrix} e^{-i\varphi/2} \\ e^{i\varphi/2} \end{pmatrix}$$

spinor

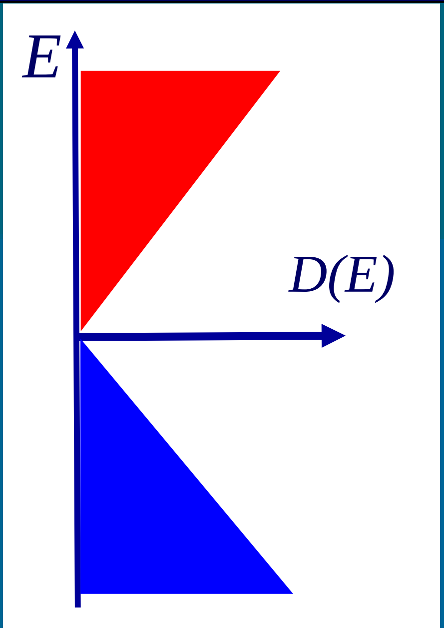
Density of states

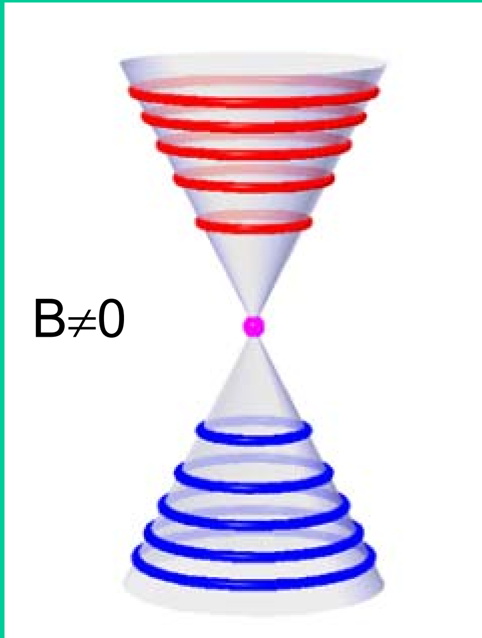


$$E(k) = v_F \hbar k$$

Dirac Point

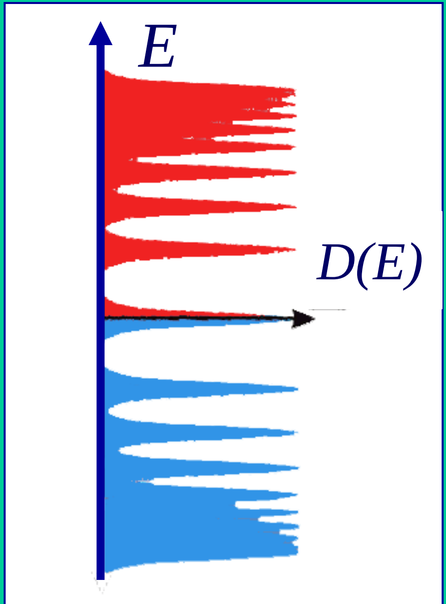
$$D(E) = \frac{2}{\pi\hbar^2}\frac{1}{v_F^2}|E|$$





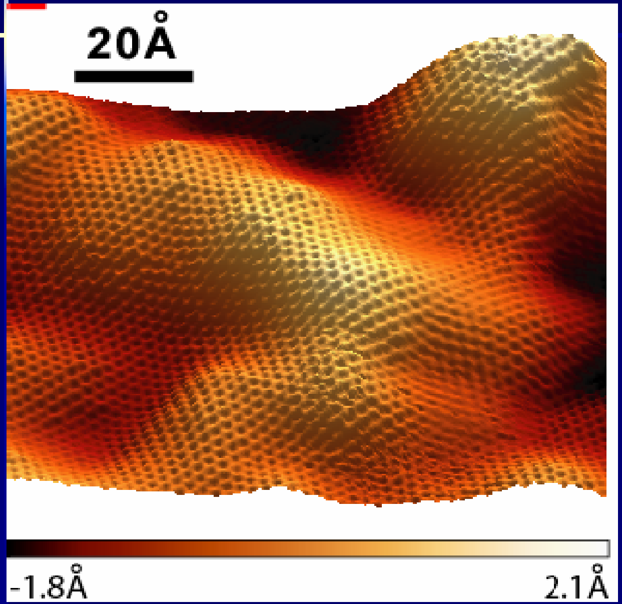
Landau Levels

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

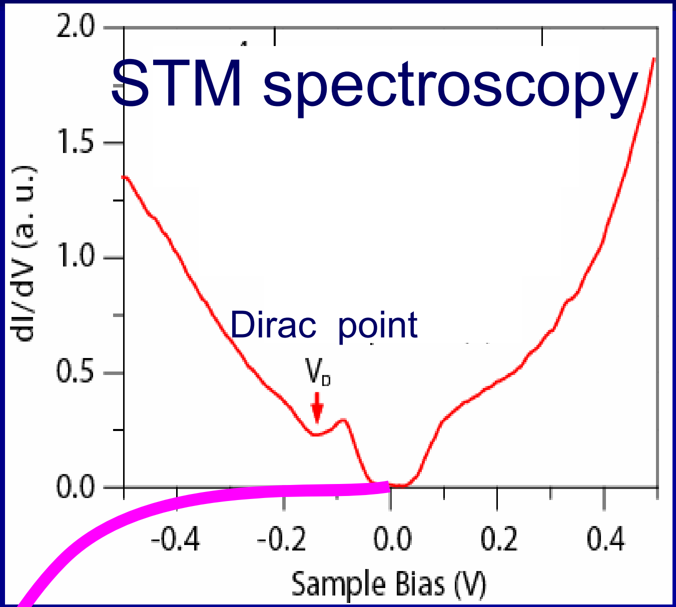


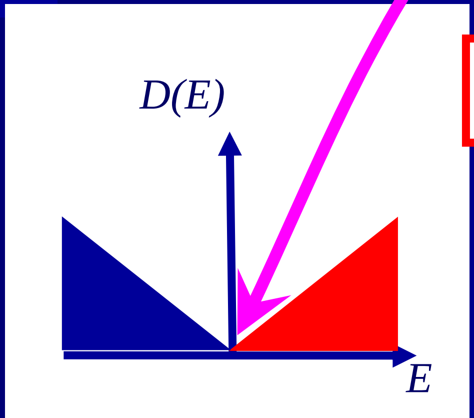
STM - Graphene on insulating substrates (SiO_2 , SiC)

STM topography



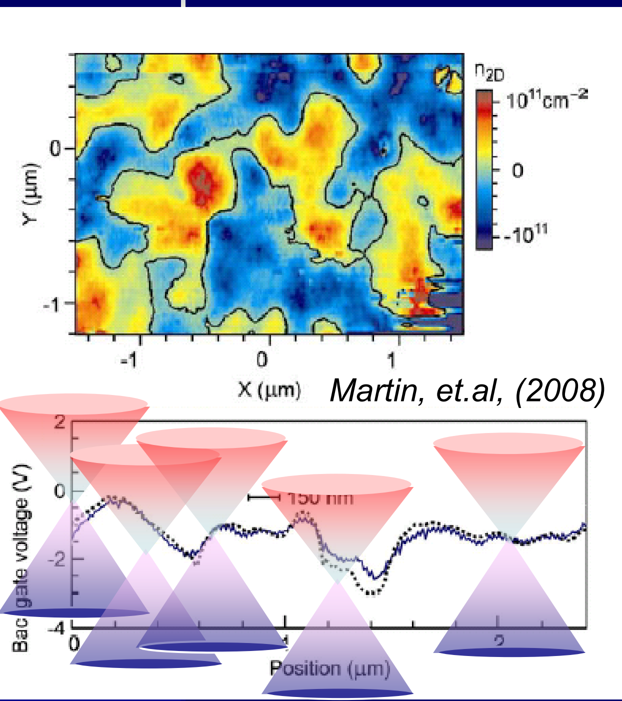
W. Brar, et al arxiv:0802.4315

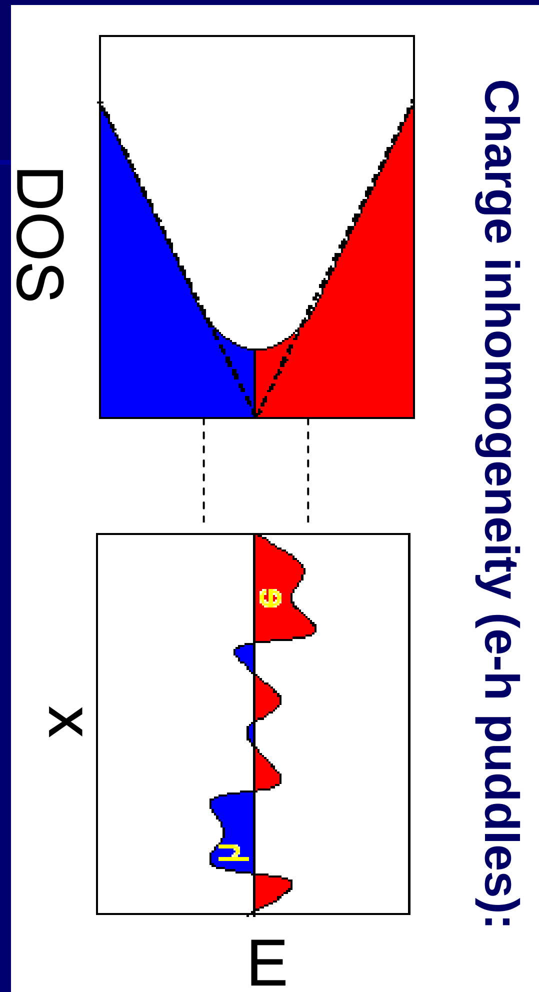


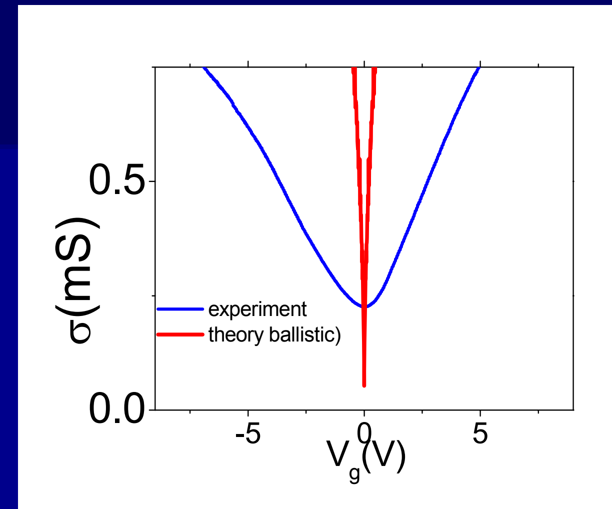


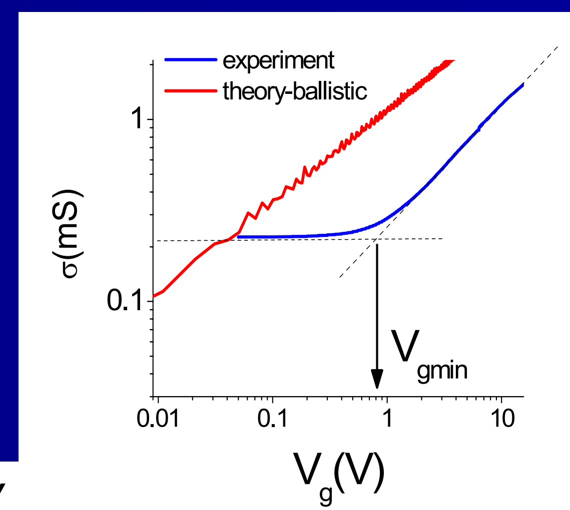
No Dirac cone

Graphene on SiO_2 : e-h puddles and









e-h puddles : smeared Dirac point

➡ n_{min} minimum carrier density

ΔV_g ~1-10V
n_{min}~ 10^{11}- $10^{12}cm^{-2}$
(ΔE_F~30-100meV)

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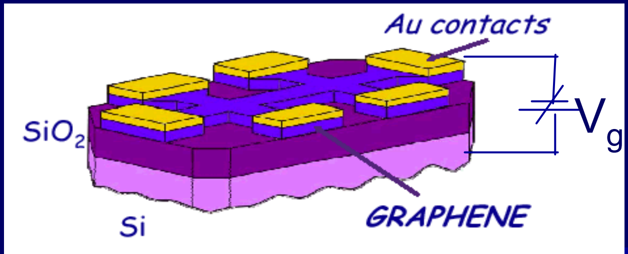
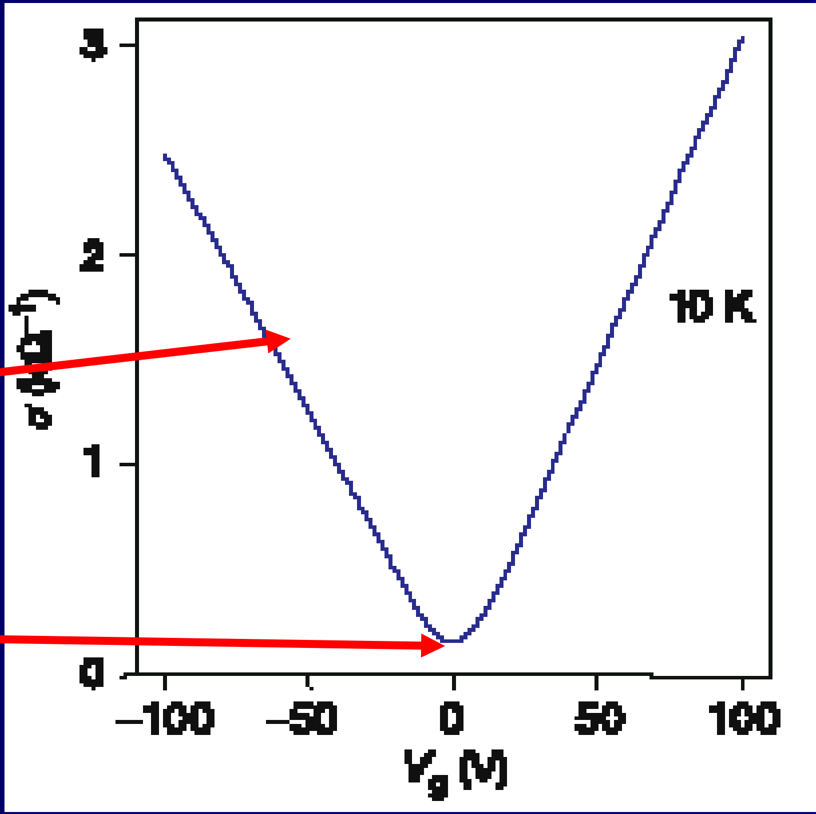
  - Tunable Van Hove singularities

Transport: graphene on SiO_2

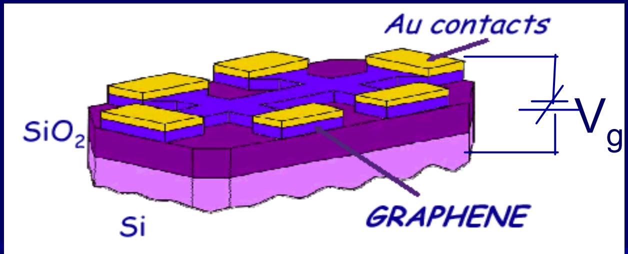


	Experiment
Far from Dirac point	$\sigma \propto n$
At Dirac point	$\sigma_{\min} = \frac{4e^2}{h}$

Novoselov et al, Nature 2005
Y.W. Tan et al 2007



Transport: graphene on SiO_2



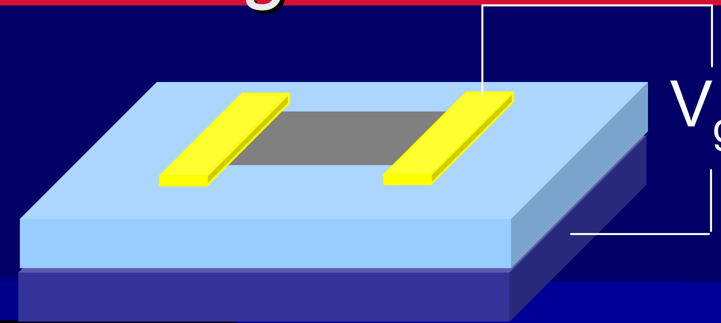
	Experiment	Theory: Ballistic transport $G(\mu) = \frac{4e^2}{h} \sum_n t_n(\mu)$
Far from Dirac point	$\sigma \propto n$	$\sigma \propto n^{1/2}$ $n \gg 10^8\ cm^{-2}$
At Dirac point	$\sigma_{\min} = \frac{4e^2}{h}$	$\sigma_{\min} = \frac{4e^2}{\pi h}$ (L<<W)

Novoselov et al, Nature 2005
Y.W. Tan et al 2007

Tworzydło et al PRL 2006
Katsnelson et.al, 2006

Conductivity and scattering

$$\sigma = \frac{e^2 v_F^2 N(E_F)\tau(k_F)}{2}$$



scattering	Source	Contributions
Long range	Charged impurities	$\sigma \sim n$ μ~const $l_m \sim n^{1/2}$
Short-range	atomic roughness Neutral impurities	$\sigma \sim$ const $\mu \sim n^{-1}$ $l_m \sim n^{-1/2}$
Midgap states	Vacancies boundaries corrugations	$\sigma \sim n\,[\ln(n^{1/2}R_0)]^2$ $\mu \sim [\ln(n^{1/2}R_0)]^2$ $l_m \sim n^{1/2}[\ln(n^{1/2}R_0)]^2$
Ballistic		$\sigma \sim n^{1/2}$ $\mu \sim n^{-1/2}$ $l_m = L/2$

S. Adam et al 2007

$$E_F = \hbar v_F k_F \sim n^{1/2}$$
$$\sigma = ne\mu$$
$$l = v_F \tau$$

Peres et al PRB 2006
T. Stauber, et al (2007).

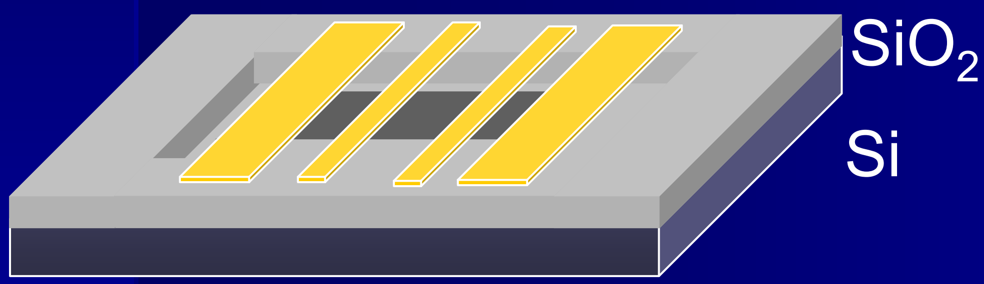
Suspended Graphene

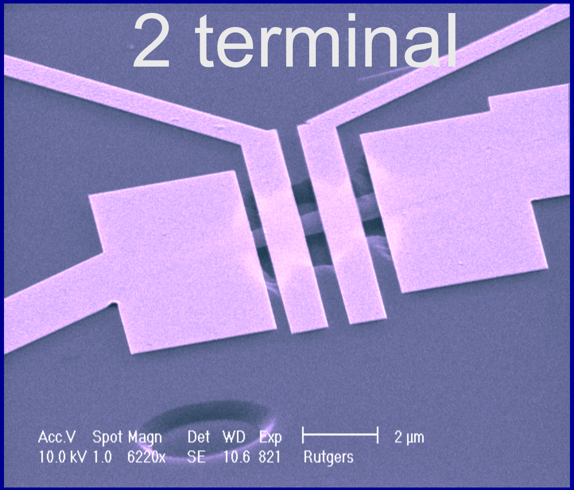
2-terminal technique :

X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)

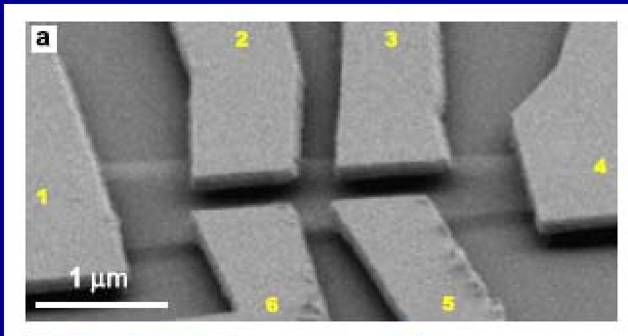
- Substrate roughness
- Trapped charges
- Quench condensed ripples

Get rid of the substrate!





4-terminal (Hall bar)

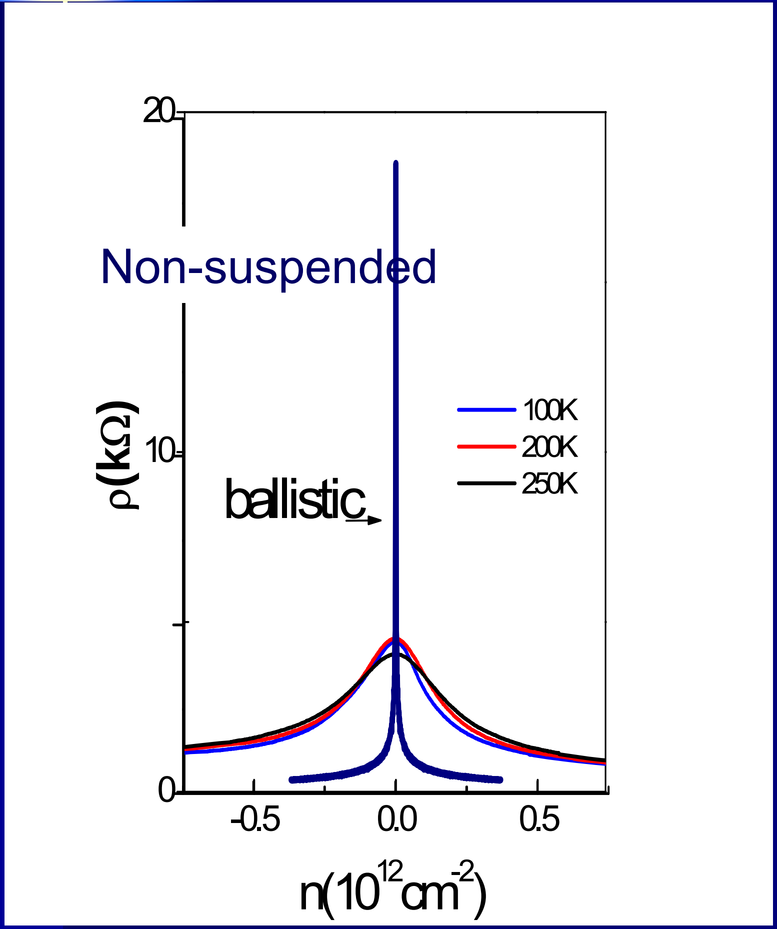


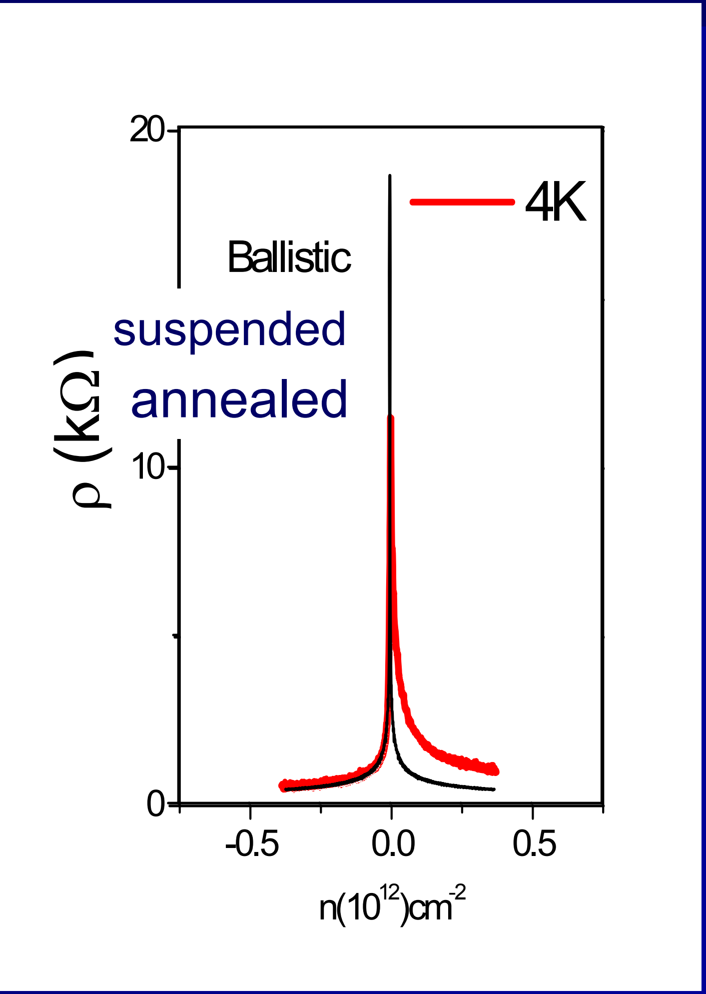
4-terminal

Bolotin et al , Solid State Communications (2008)

Suspended Graphene: T dependence

2-terminal technique :
X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)

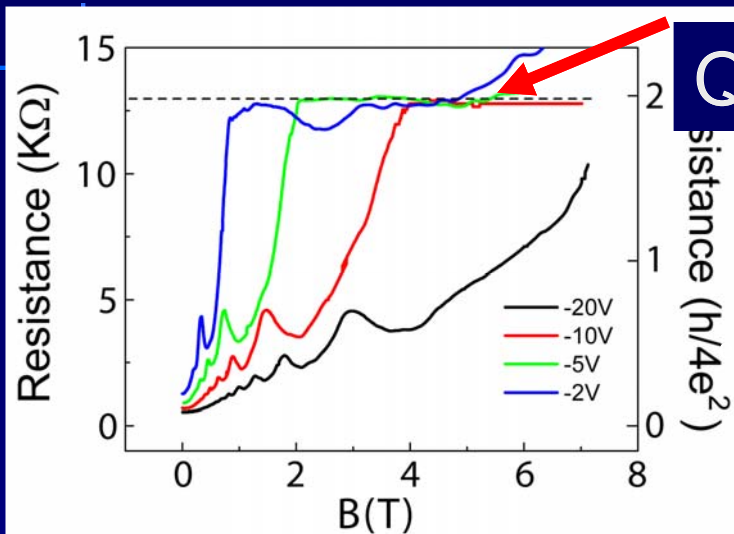


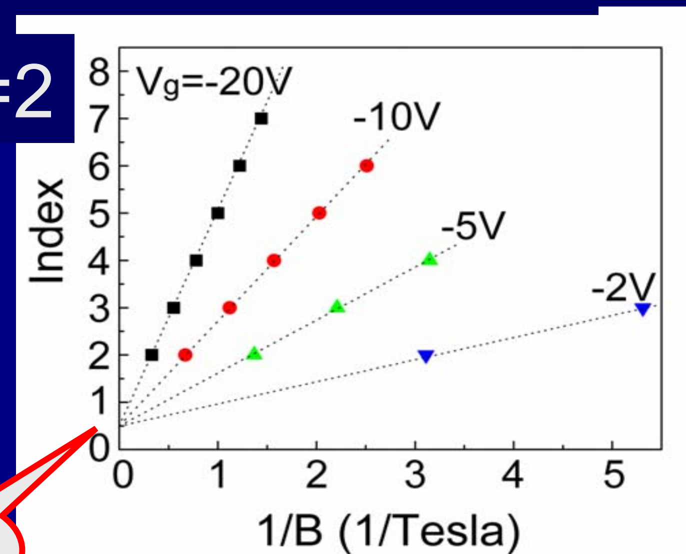


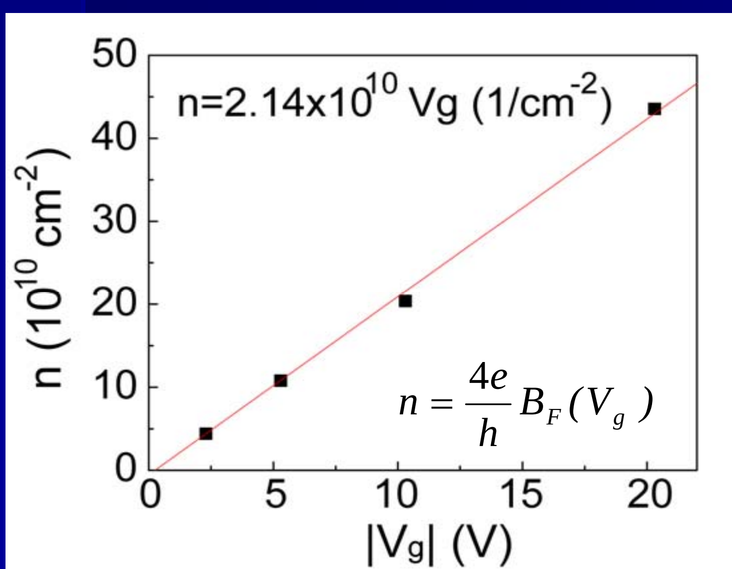
$\alpha_{SG} = n/V_g$

ShdH and QHE – density calibration

2-terminal technique X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)







$$n = \frac{4e}{h} B_F(V_g)$$

- Single layer

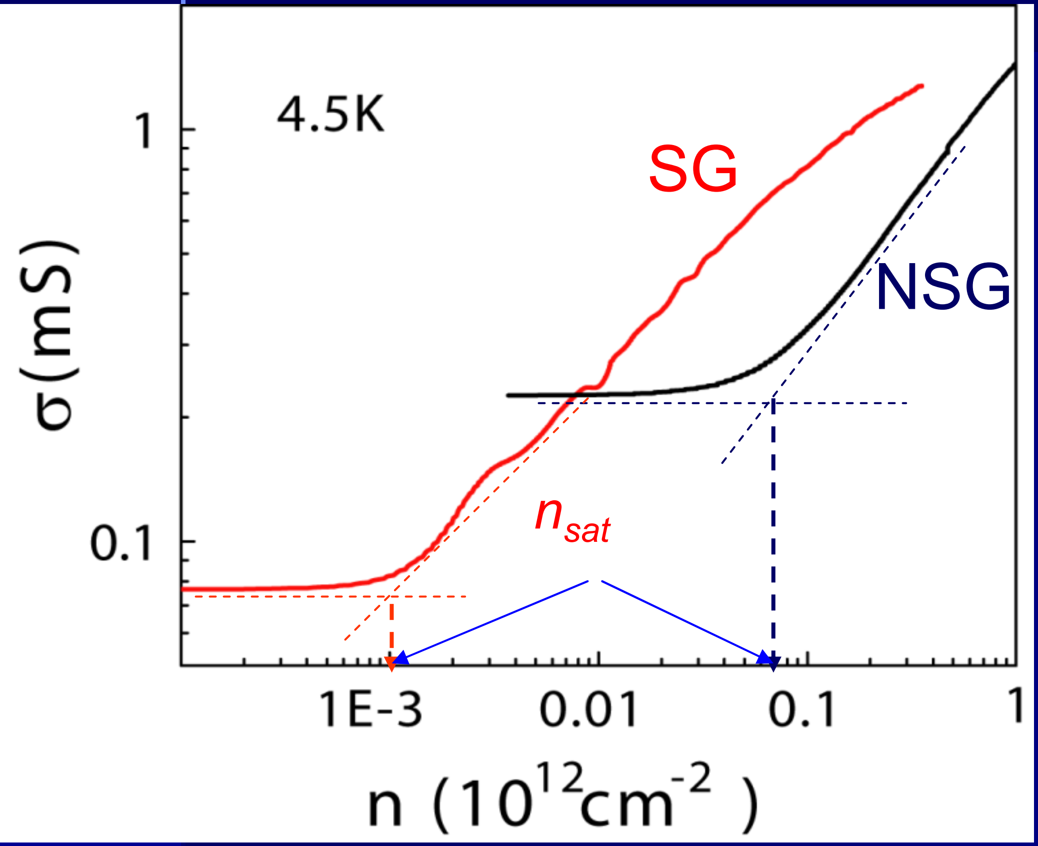
$$\alpha_{SG} = n/V_g = 2.14\times10^{10}\, cm^{-2} V^{-1}$$

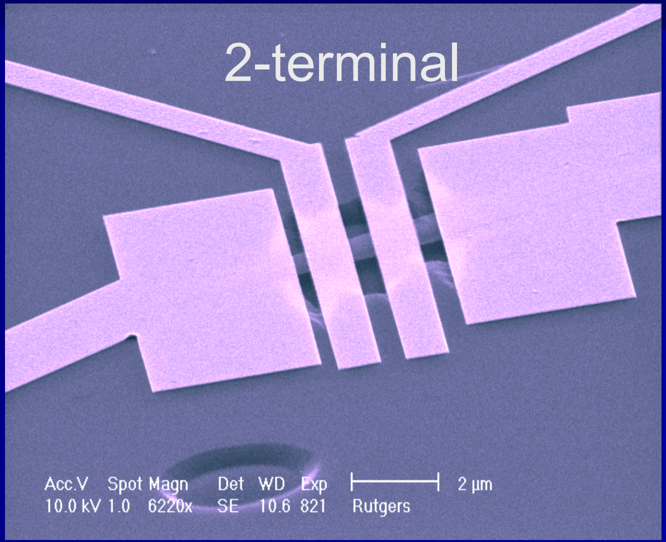
$$\alpha_{SG}/\alpha_{NSG} \approx \varepsilon_{SiO_2}$$

- Suspended

Suspended Graphene: reduced residual carriers

2-terminal technique :
X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)





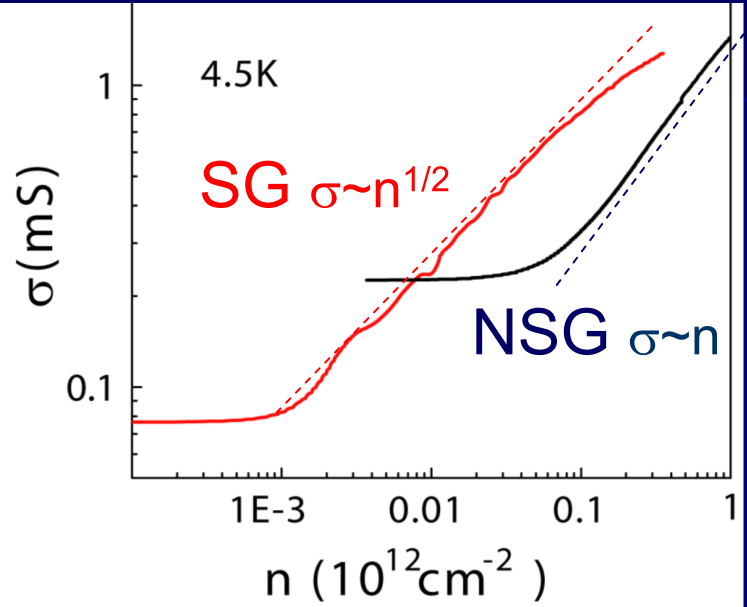
NSG: n_{sat}~ 10^{10} -10^{11} cm^{-2}

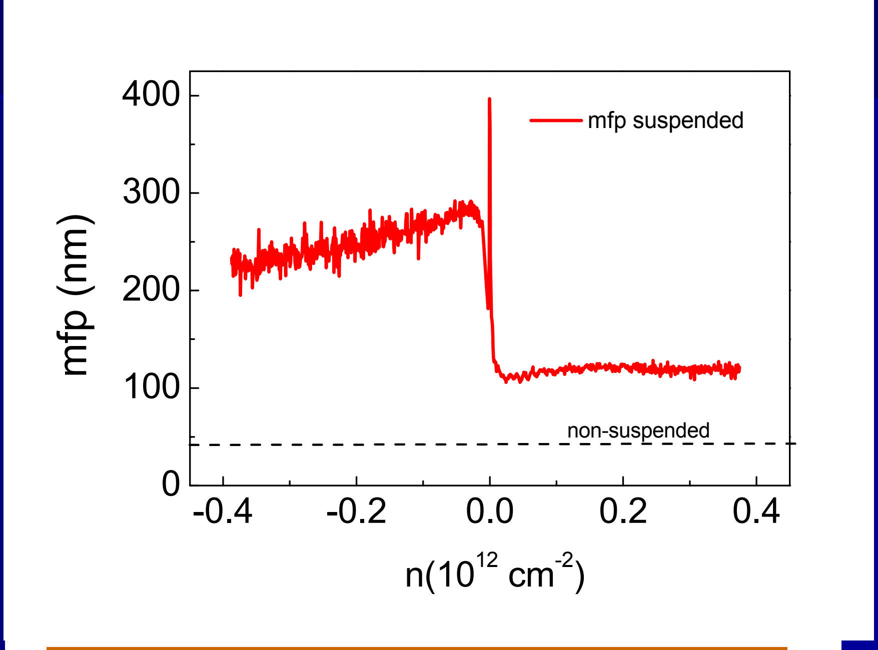
SG: n_{sat}~ 10^9 cm^{-2}

Suspended Graphene: approaching ballistic transport

2-terminal technique :

X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)





suspended

$n_{sat} \sim 10^9\ cm^{-2}$

$\sigma \sim n^{1/2}$ **Ballistic**

$\mu \sim n^{-1/2}$

$\mu_{sat} \sim 2 \times 10^5 - 10^6\ cm^2/V\ s$

Non suspended

$n_{sat} \sim 10^{11}\ cm^{-2}$

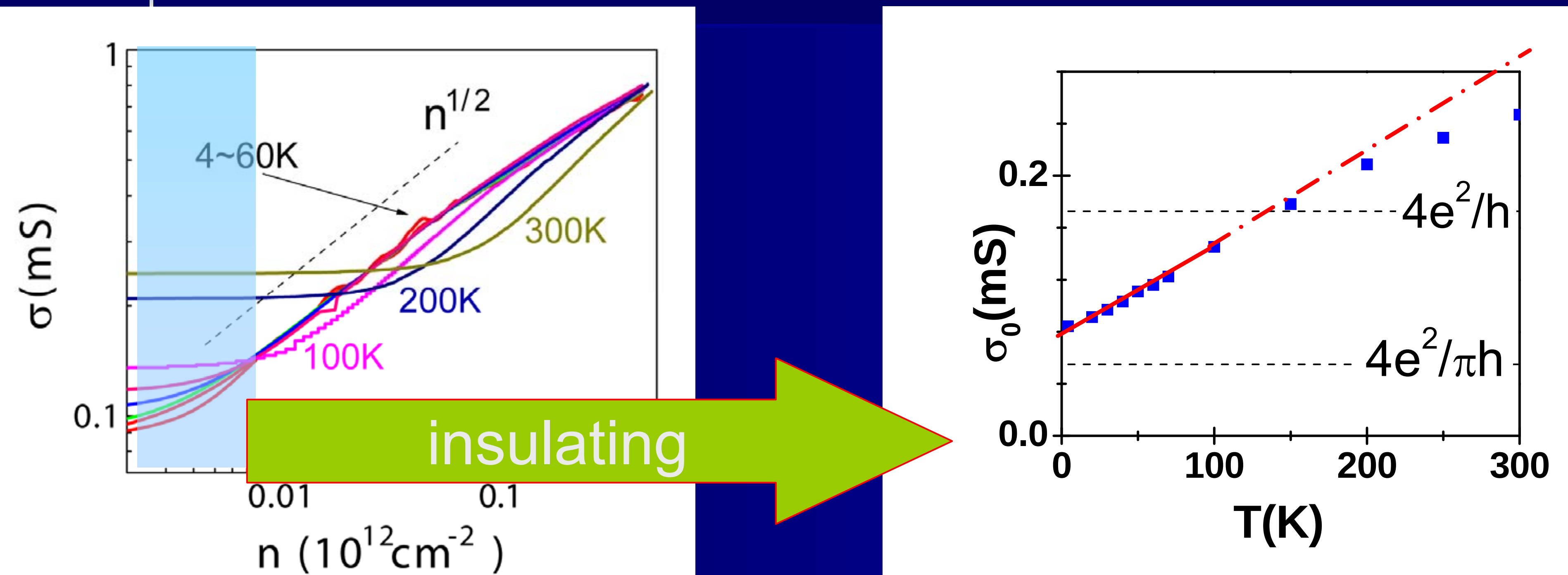
$\sigma \sim n$ – Long range scatterers

$\mu \sim 1\text{-}2 \times 10^4\ cm^2/V\ s$

B

Suspended Graphene: T dependence

2-terminal technique :
X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)



T<100K: Approaching Ballistic
$\sigma \sim n^{1/2} \sim E_F$

T>100K:
Long-range scattering, ripples?

- $\sigma_{min} \sim T$ for T<150K

Interaction and correlation effects in suspended graphene using STM and Transport

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  - Fractional Quantum Hall effect
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  - e-e interactions

- Rotated graphene

Quantum Hall Effect

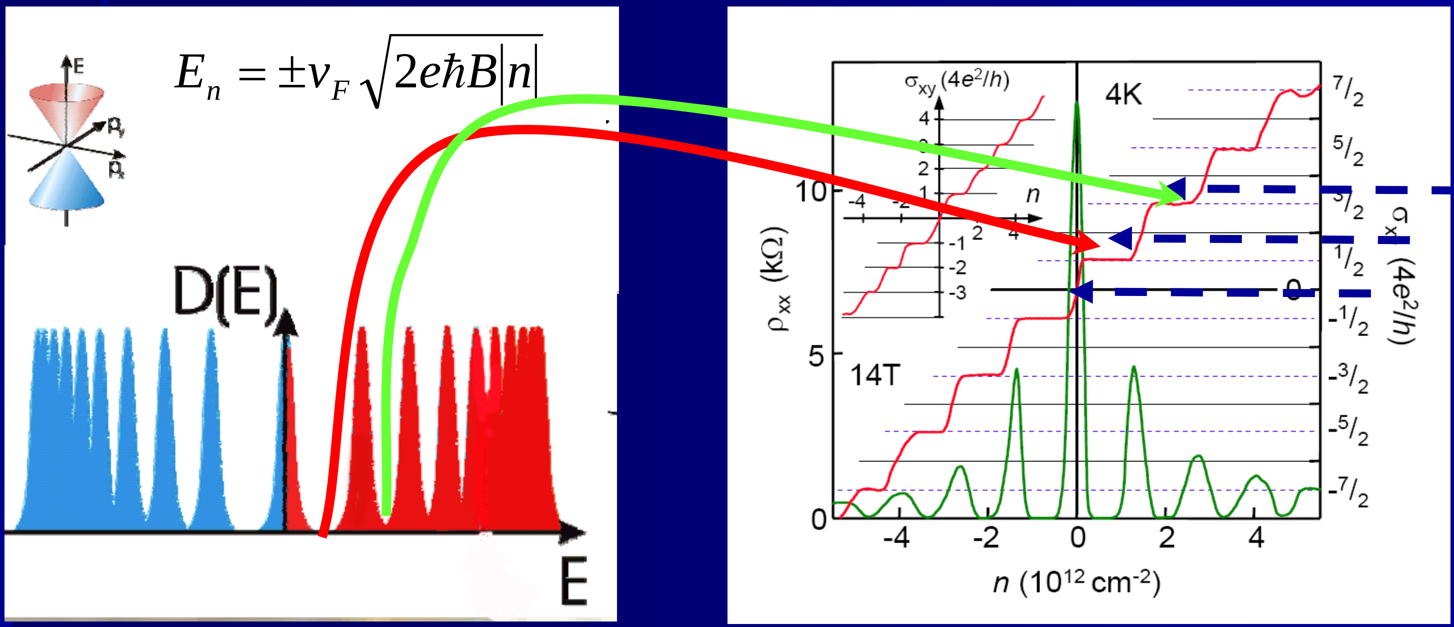
Each filled Landau level contributes *g* quanta of Hall conductance
(g = degeneracy)

$$\sigma_{xy} = \nu \frac{e^2}{\hbar}$$

$$\nu = g_s g_v (n + 1/2) = \pm 2, \pm 6$$
$$g = 4$$

non-interacting sequence

$$E_n = \pm v_F \sqrt{2e\hbar B|n|}$$



$$non-relativistic$$
$$\nu = 2n \quad n = 0,1..$$
$$g = 2$$

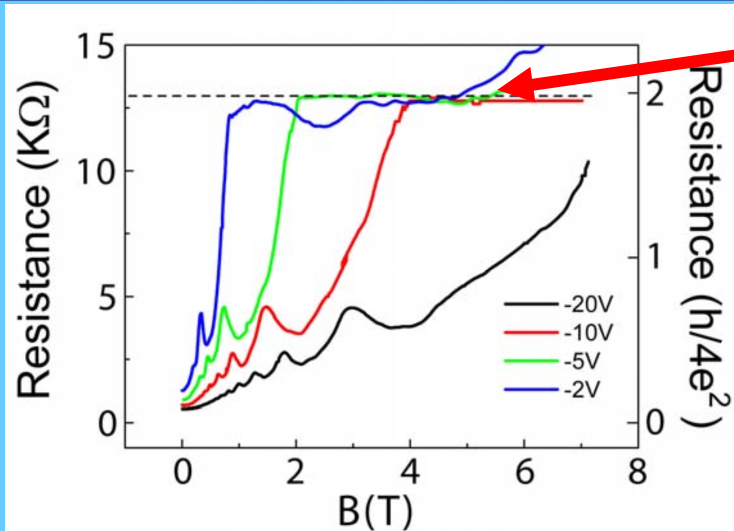
Landau level at E=0 :
no QHE plateau at 0.

Novoselev et al Nature 2005
Zhang et al Nature 2005

$\alpha_{SG} = n / V_g$

QHE: 2-terminal versus 4-terminal

supended graphene with 2-terminal technique
X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)

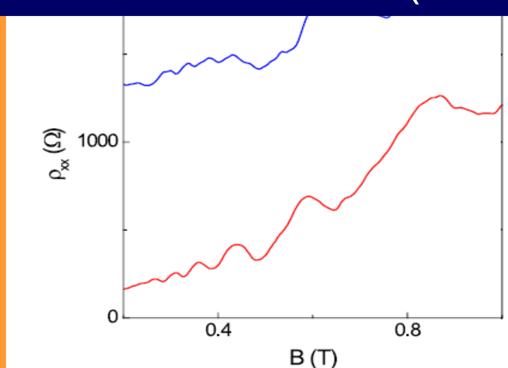


QHE: ν=2

- well defined QHE plateaus clearly visible at low density n ~ 2 x10^{10} cm^{-2}.

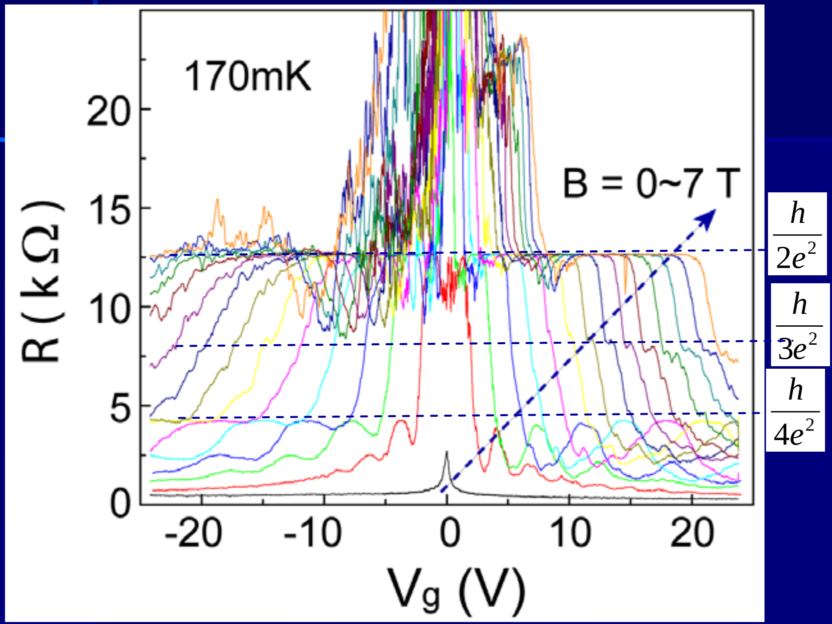
compare:

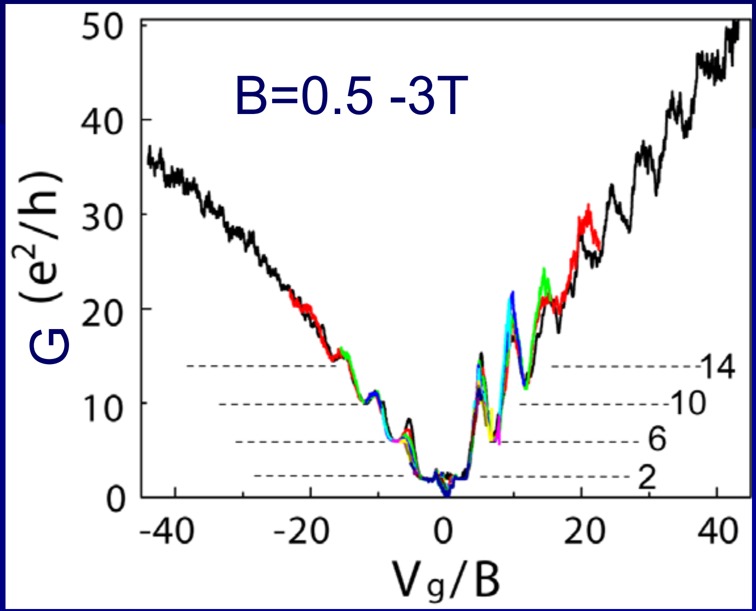
supended graphene with 4-terminal technique Bolotin et al , Solid State Communications (2008)

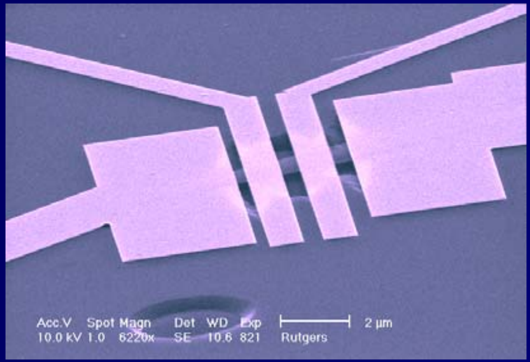


- No evidence of QHE plateaus!
- even at higher density n ~ 10^{11} cm^{-2}. !

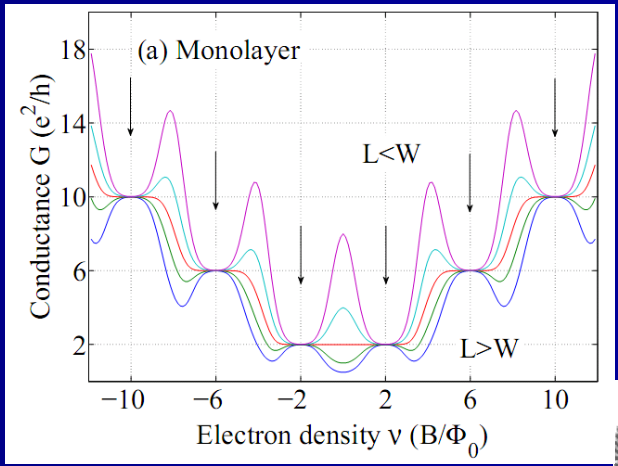
Suspended Graphene: QHE 2-terminal measurement







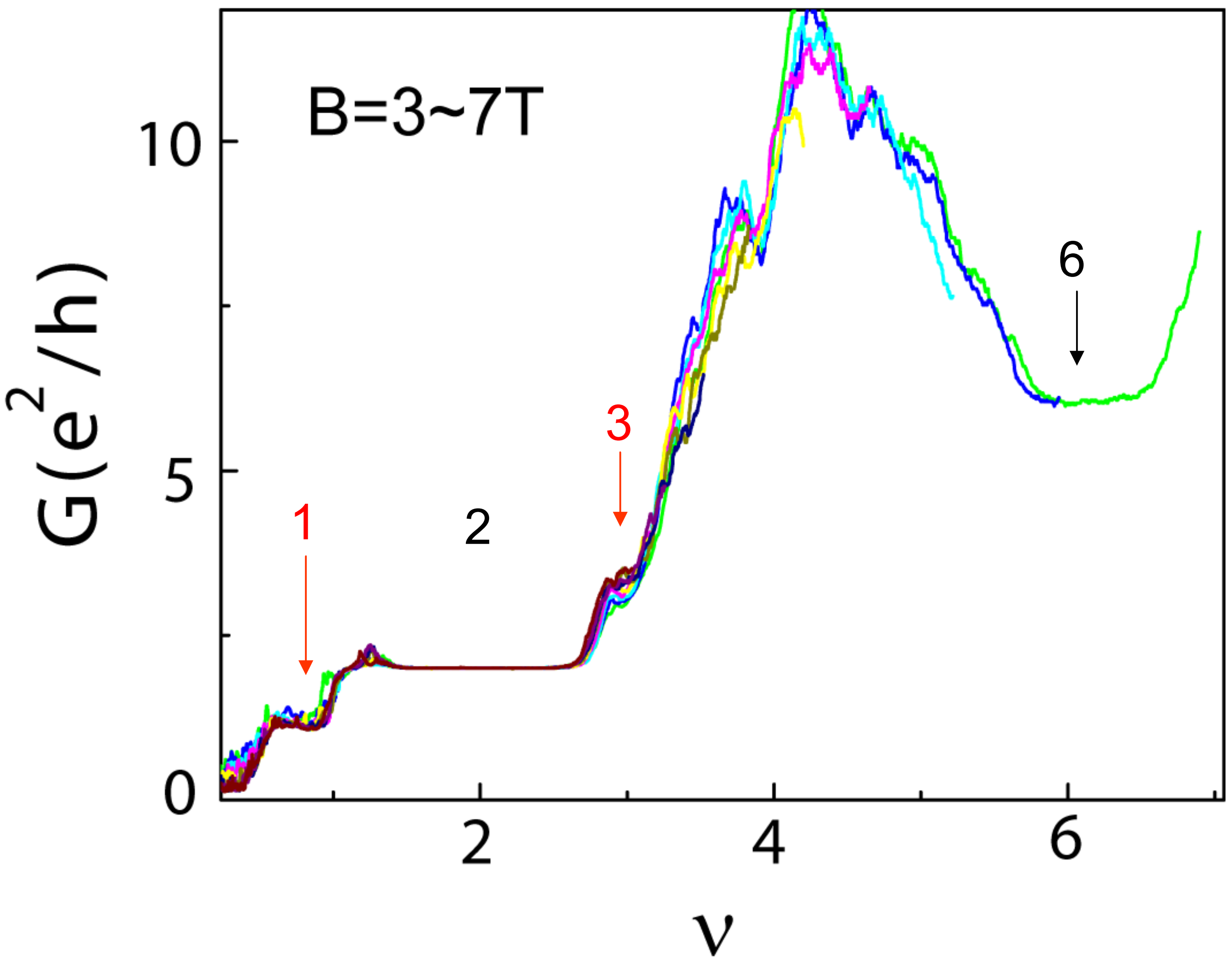
L / W~2-3



QHE in 2-terminal device:

Abanin & Levitov, PRB (2008)

Suspended Graphene: QHE 2-terminal measurement



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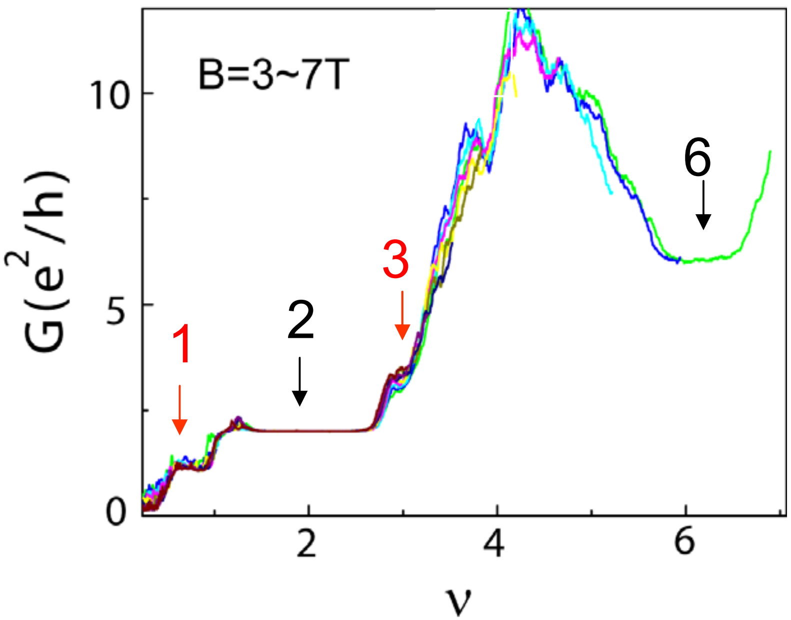
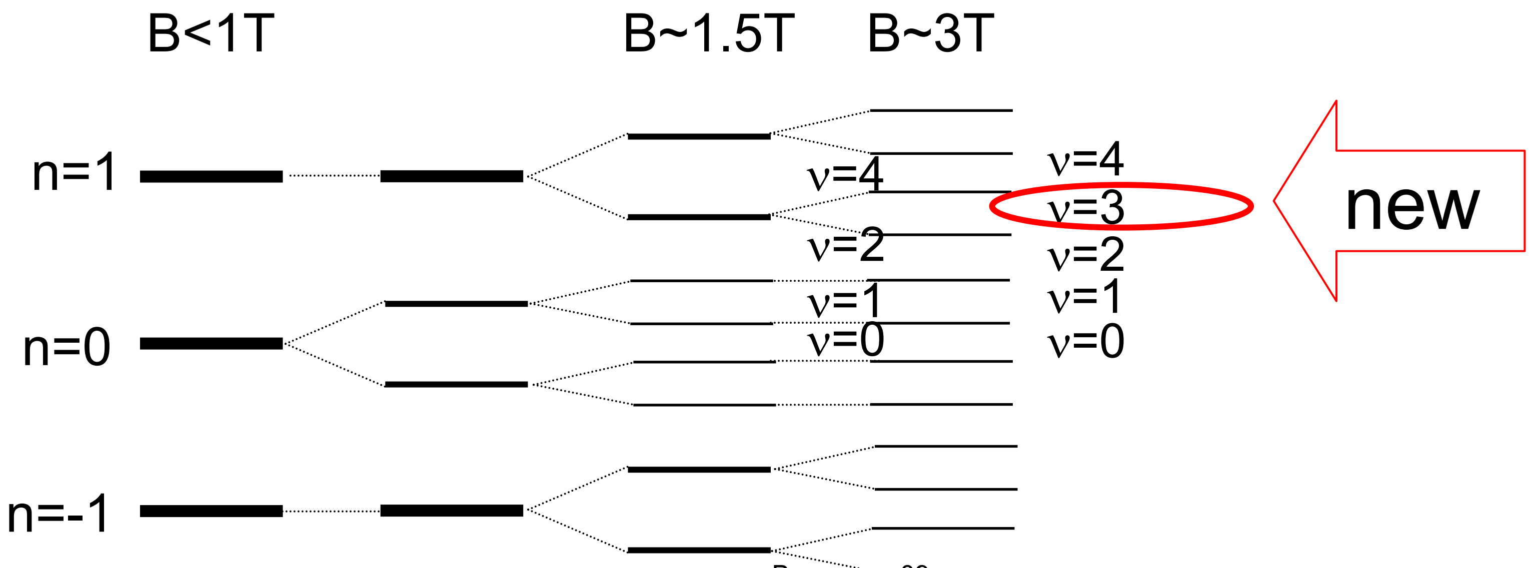
Suspended Graphene: QHE 2-terminal measurement





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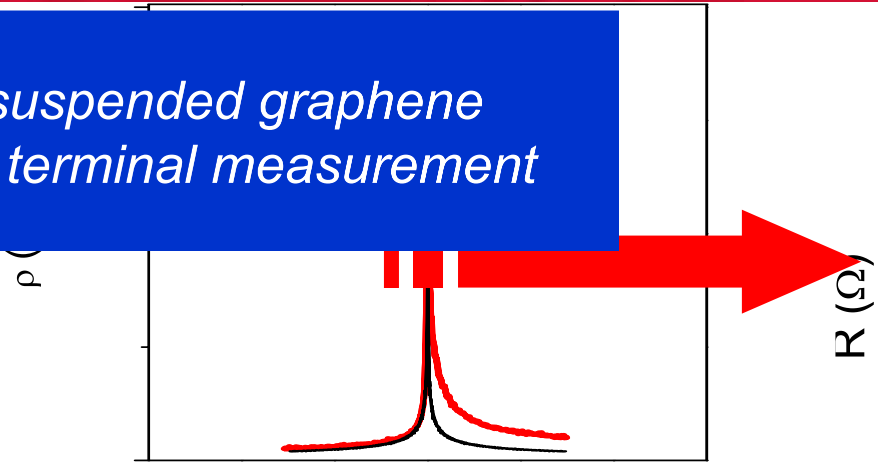
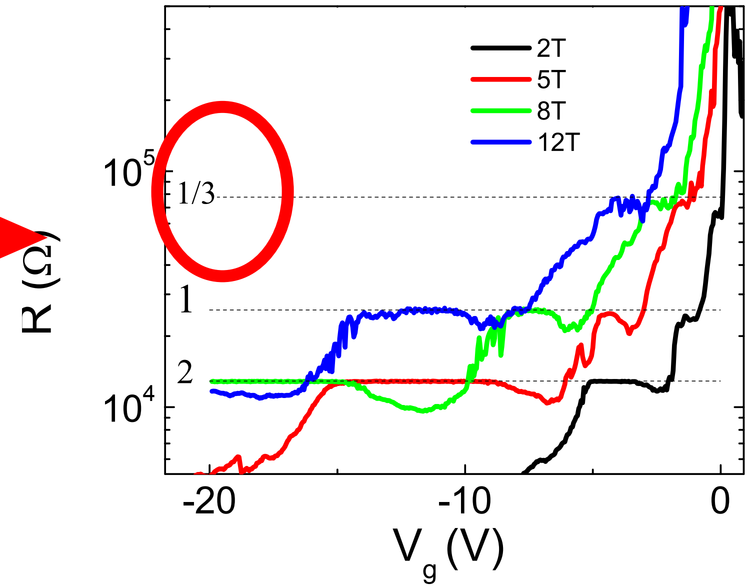
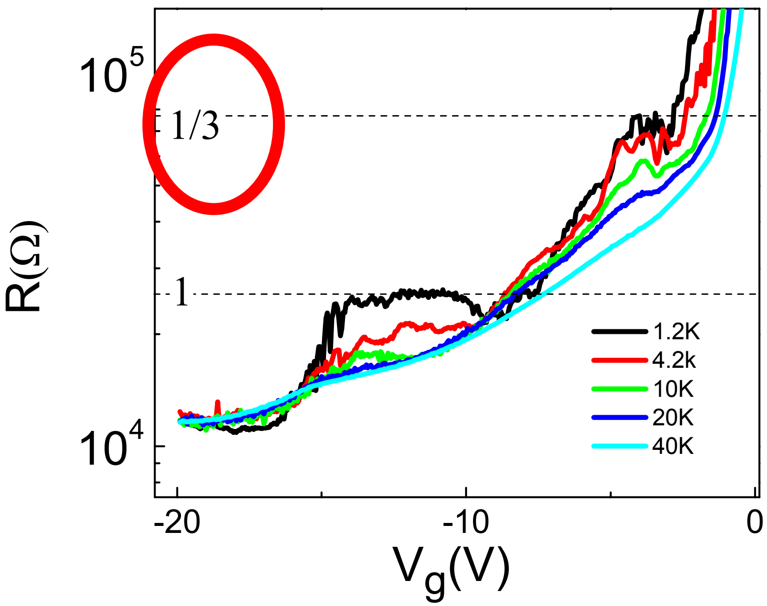
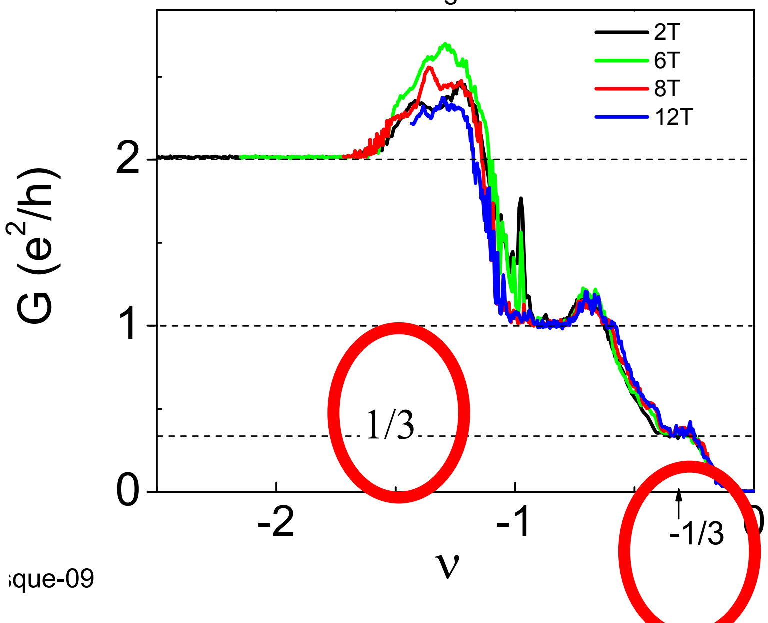
1'st observation of Fractional QHE in graphene

suspended graphene
2 - terminal measurement





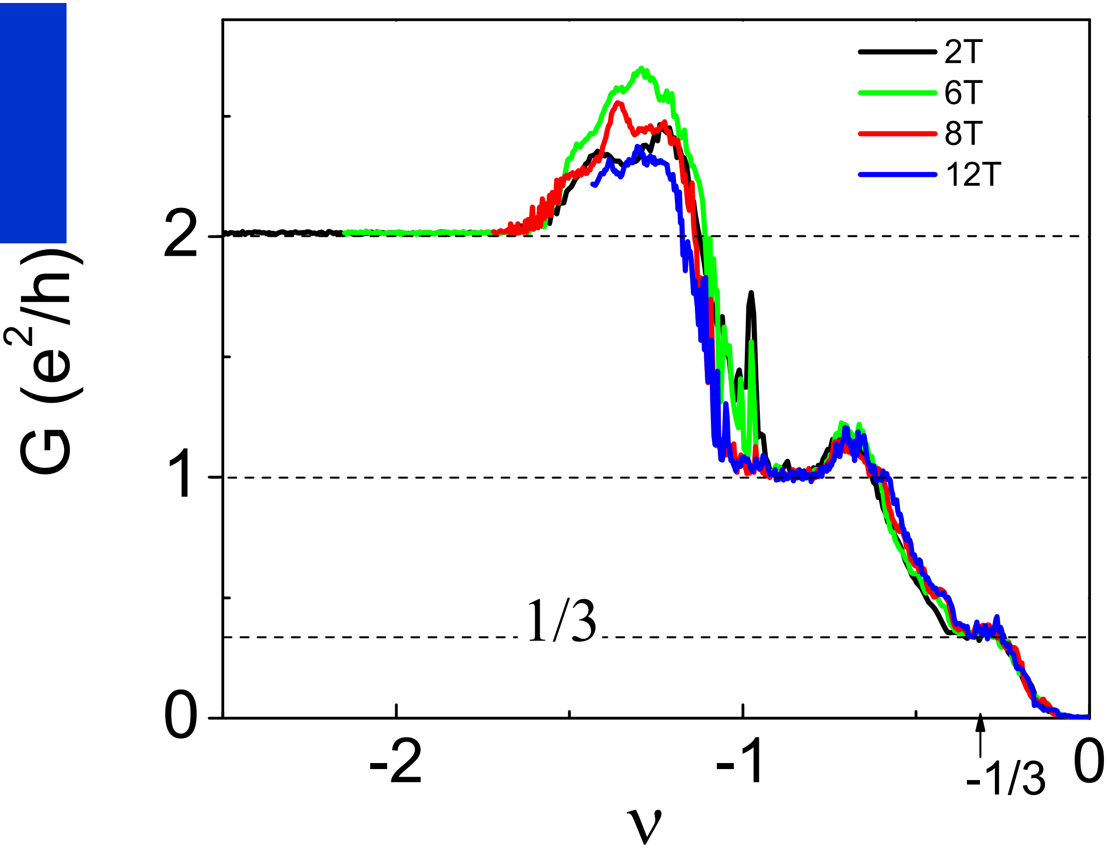




que-09

1'st observation of Fractional QHE in graphene

suspended graphene
2 - terminal measurement



FQHE ***not*** *seen in 4-terminal measurements !!*

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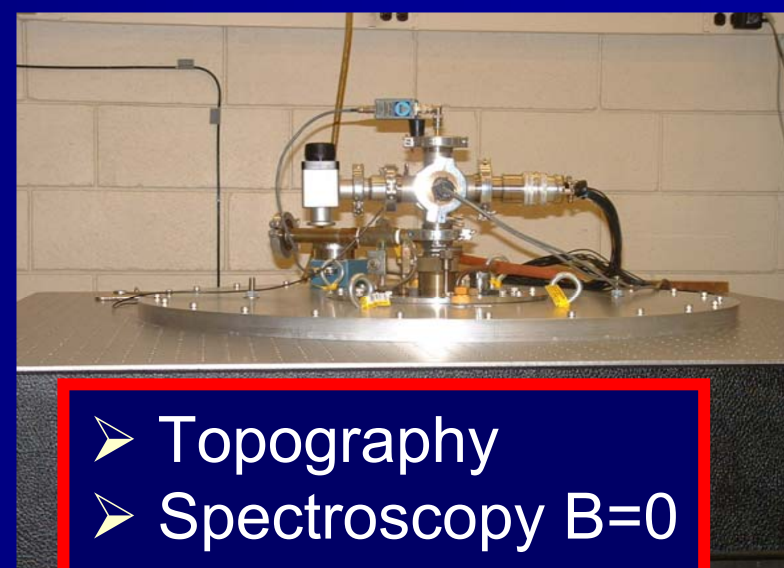
"New" Substrate - Graphite

G. Li, A. Luican, E. Y. A., PRL (2009)
G. Li , E.Y. A - Nature Physics, 3, 623 (2007)

graphene

- Clean
- Lattice matched
- Conductor

- STM –
  - T=4 (2K)
  - B=13 (15T)
  - 10^{-10} -10^{-3} m



- Topography
- Spectroscopy B=0
- Spectroscopy B>0

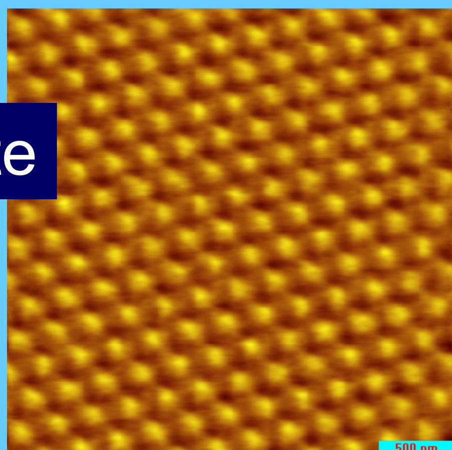
STM: Graphene on Graphite

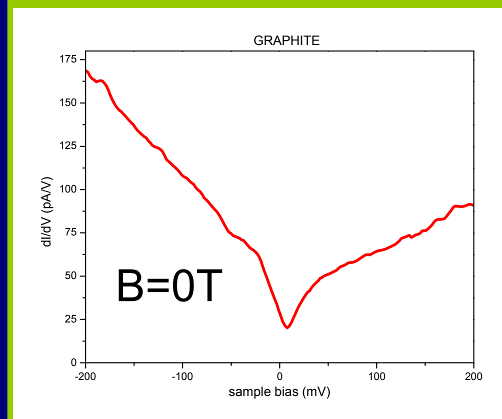
topography

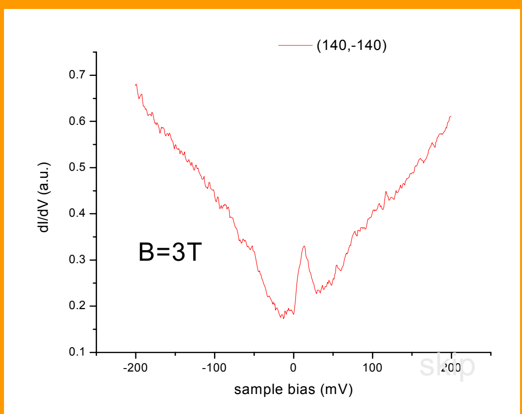
B=0 spectroscopy

B>0 spectroscopy

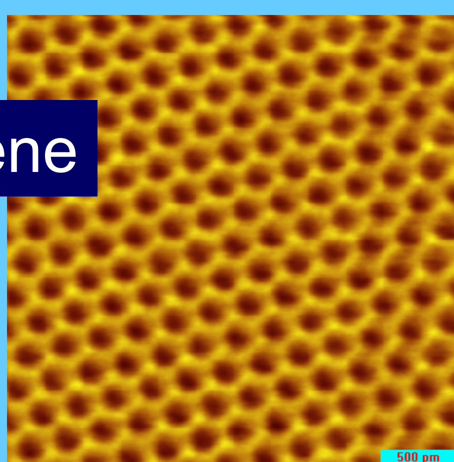
Graphite

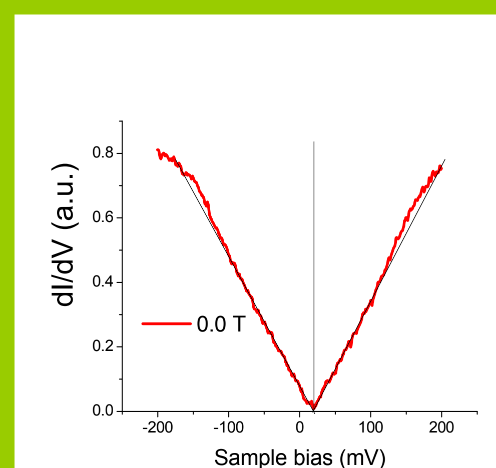


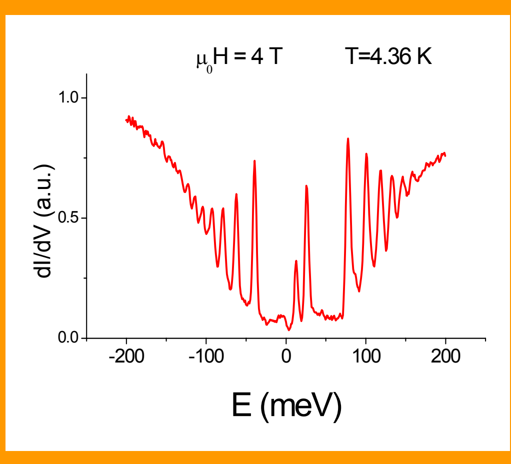




Graphene







Finding graphene on graphite

- Search on graphite surface

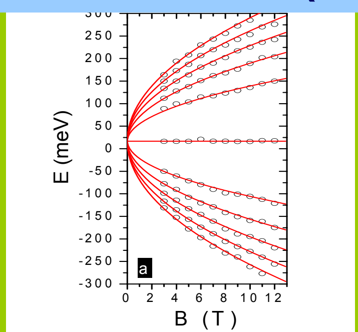
  Macroscopic defects – Terraces, ribbons
- Characterize: Landau level spectroscopy
- Coupling strength and Landau levels

Decoupled graphene layer

Single massless sequence

$E_n \sim (nB)^{1/2}$

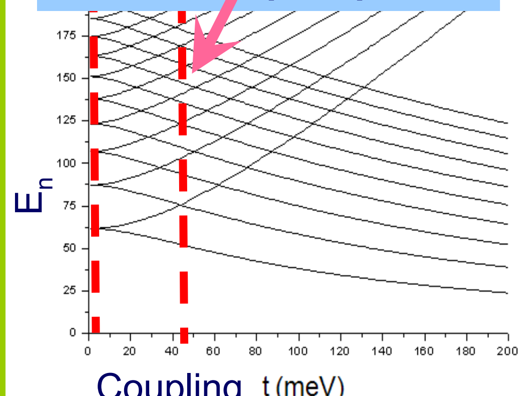
G. Li , A. Luican, E.Y. A
PRL102, 176804 (2009)



Weakly coupled layer

crossing levels

A. Luican, G. Li , E.Y. A
S. S. Com (2009)

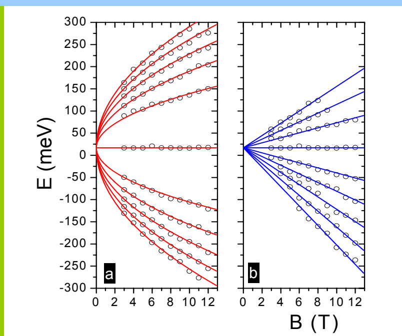


3-10 coupled layers

2 LL sequences:

massless and massive

G. Li , E.Y. A
Nature Physics, 3, 623 (2007)

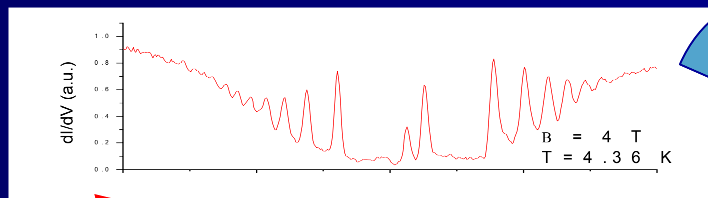


Interlayer coupling

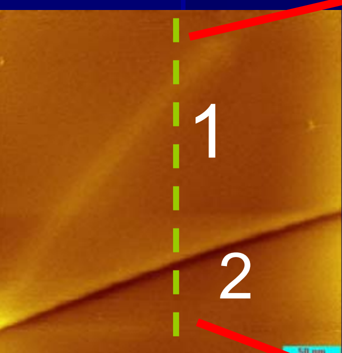
A. Luican, G. Li , E.Y. A , Solid State Com (2009)

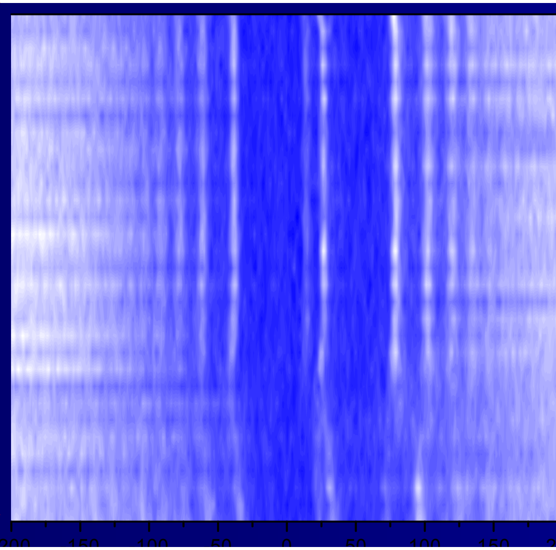
Pereira et al (PRB,2007)
LL vs interlayer coupling parameter

Region 1
No coupling – single layer graphene t=0

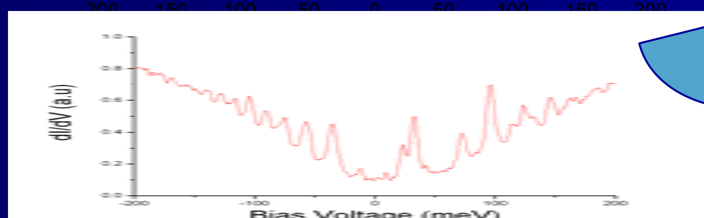


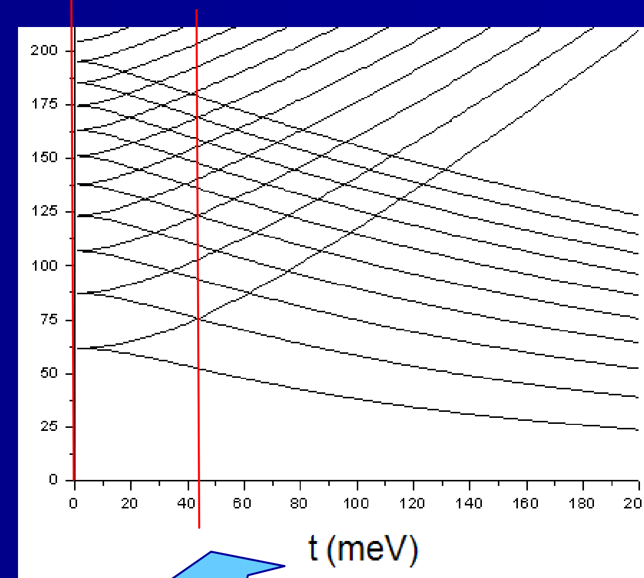
t=0





t=45meV

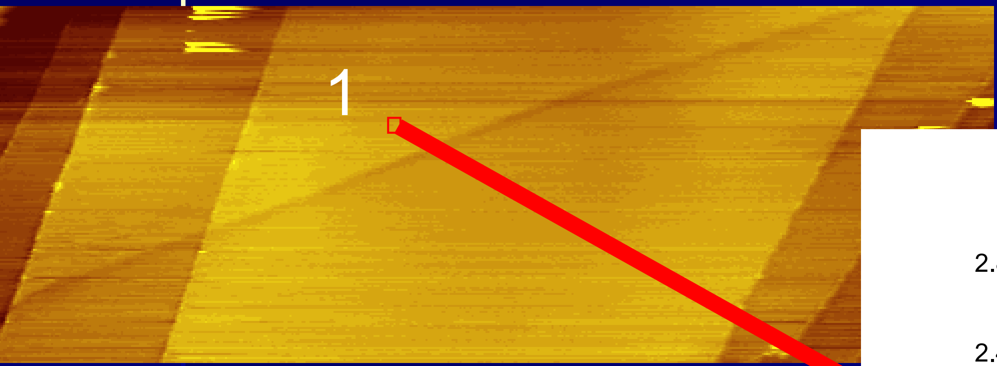


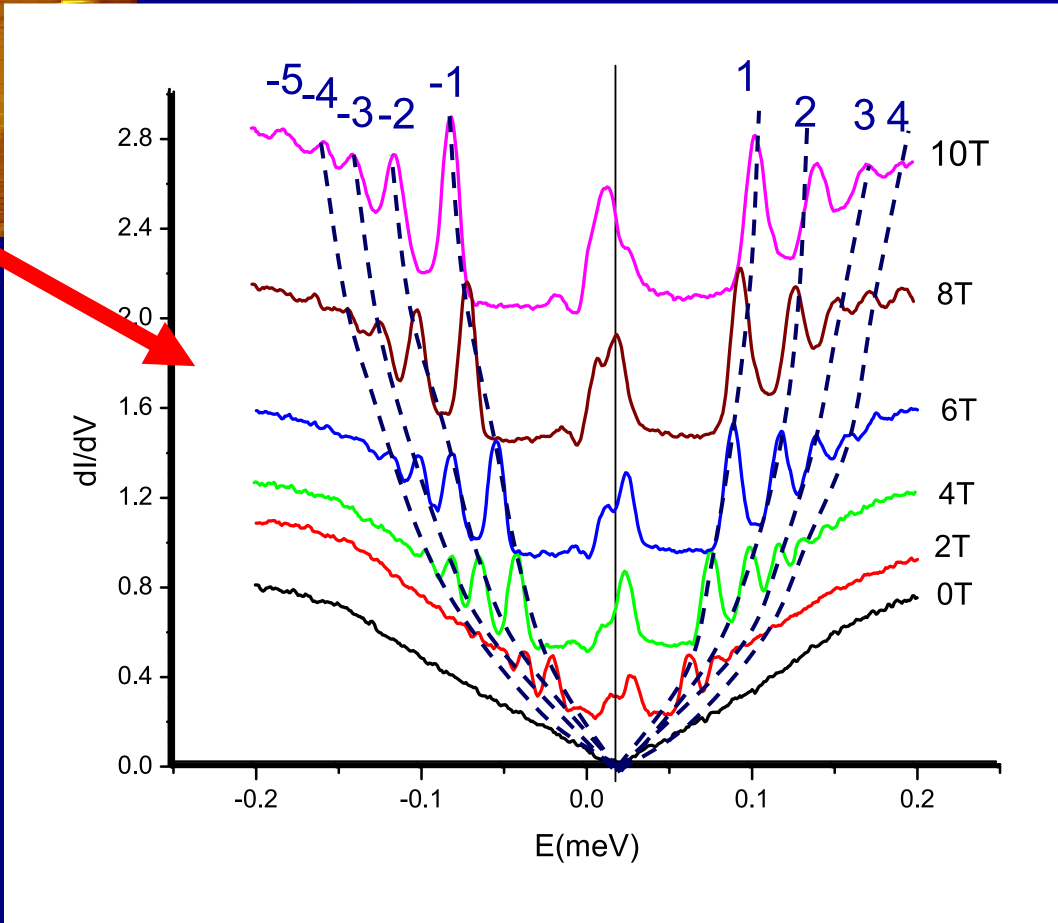


Region 2
Coupled layer t=0.045eV
Compare to $\gamma_1=0.3$ eV

Landau level spectroscopy

G. Li, A. Luican, E. Y. A., PRL (2009)
G. Li , E.Y. A - Nature Physics, 3, 623 (2007)

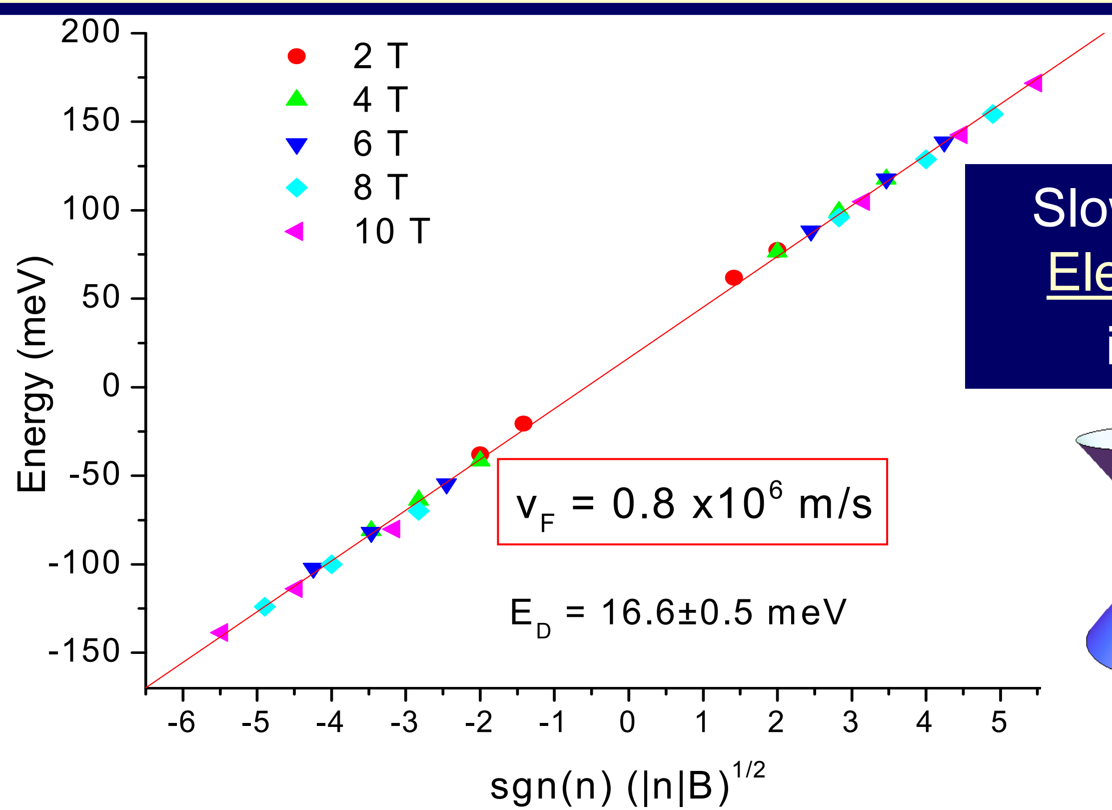




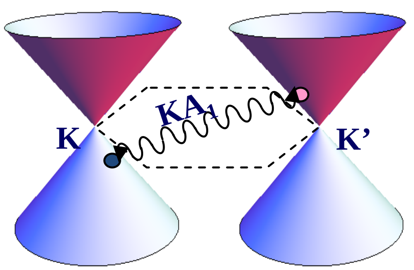
Massless Dirac Fermions

G. Li, A. Luican, E. Y. A., PRL (2009)
G. Li , E.Y. A - Nature Physics, 3, 623 (2007)

$$E_j = \pm v_F \sqrt{2e\hbar |n| B}, \quad n = 0, \pm 1, \ldots$$



Slow down due to Electron-phonon interactions

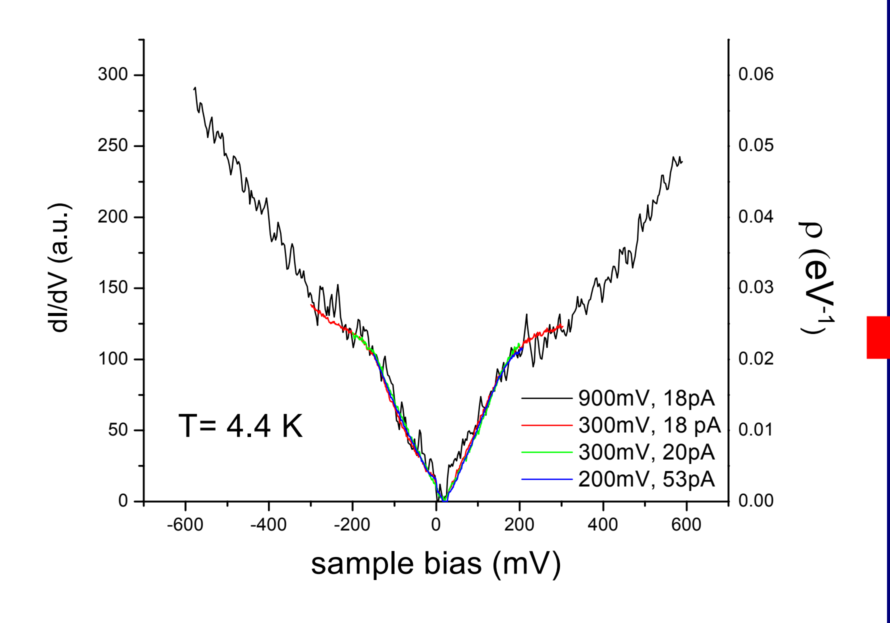


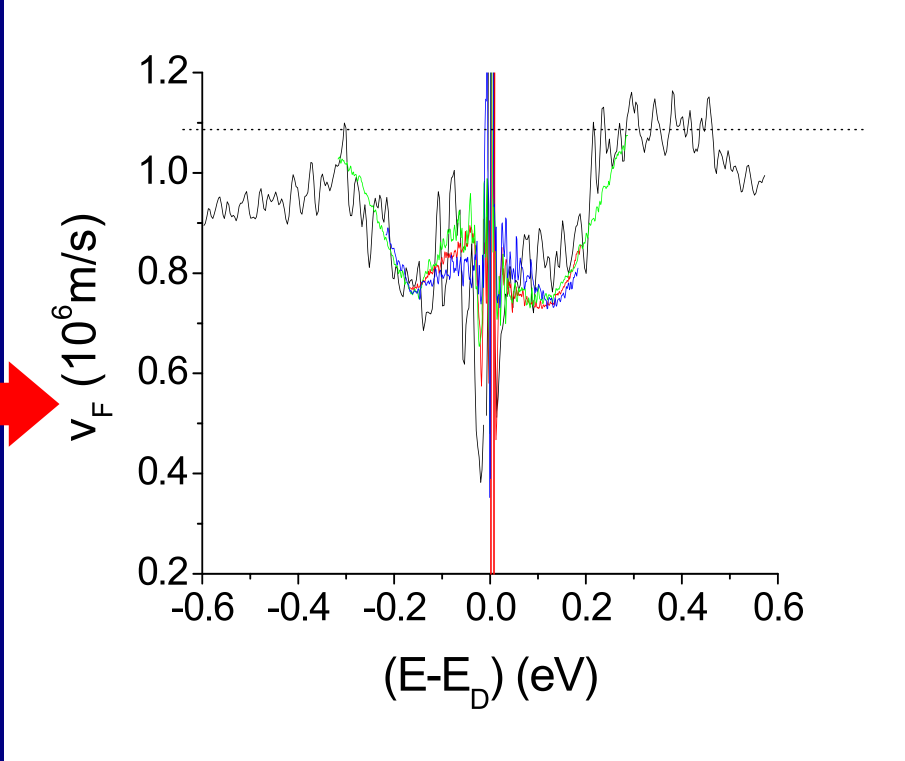
Expect: $V_F = 1 \times 10^6$ m/s

skip

Velocity normalization

- Zero field density of states

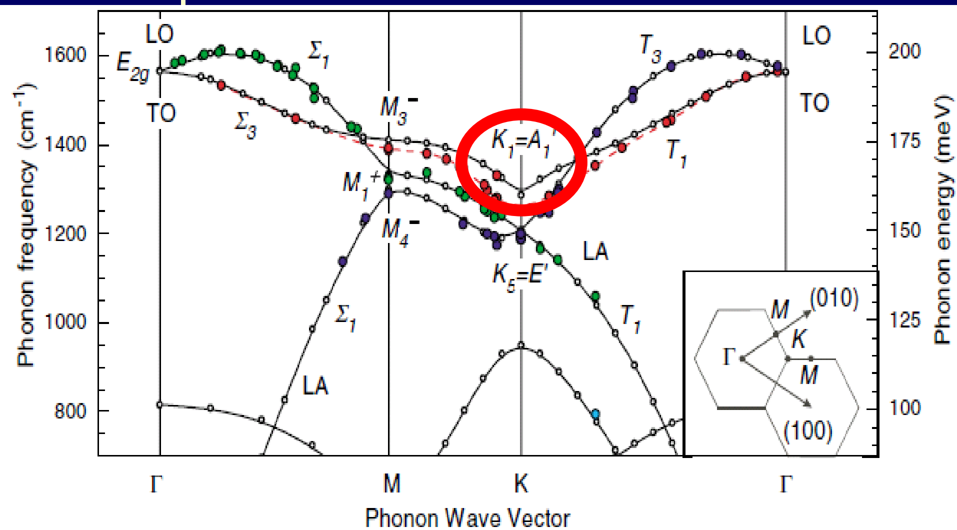


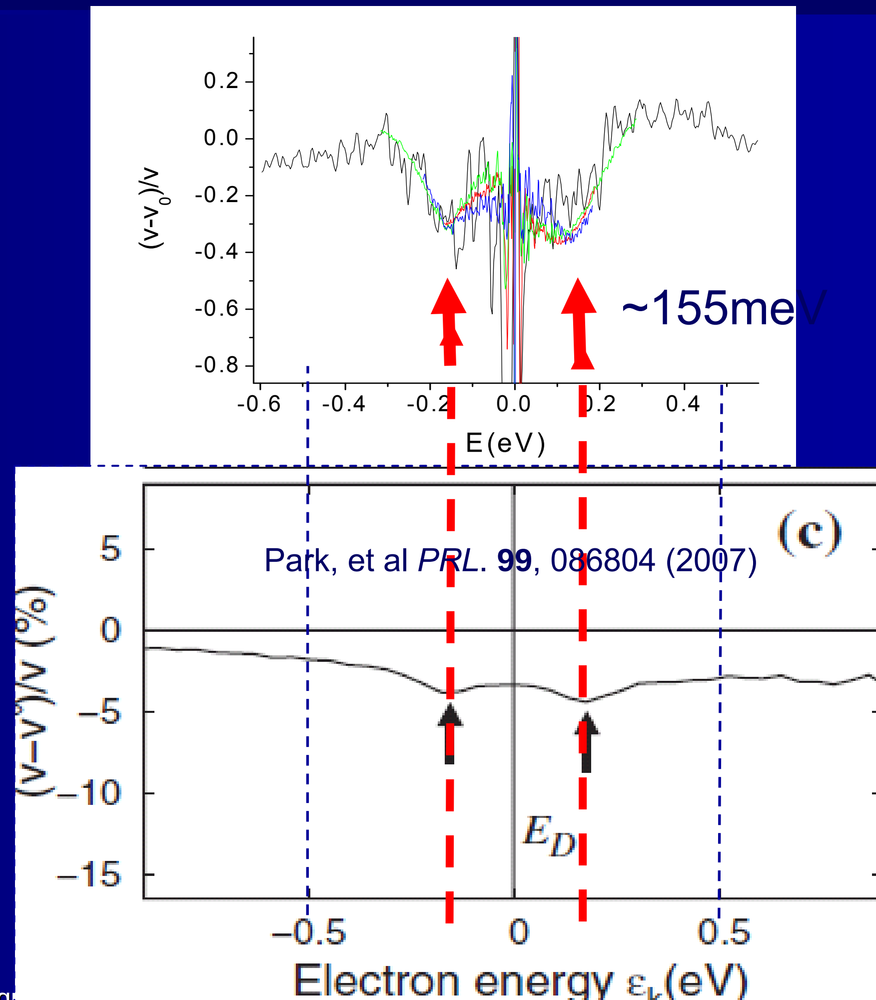


$$v_F \equiv \frac{dE}{\hbar dk} = \frac{2}{\hbar}\sqrt{\frac{A_c}{\pi}}\left(\int_0^E \rho(E')dE'\right)^{1/2} / \rho(E)$$

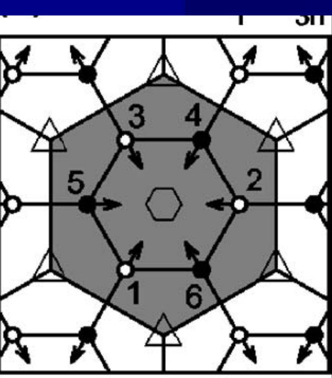
$A_c = 3\sqrt{3}a^2/2$

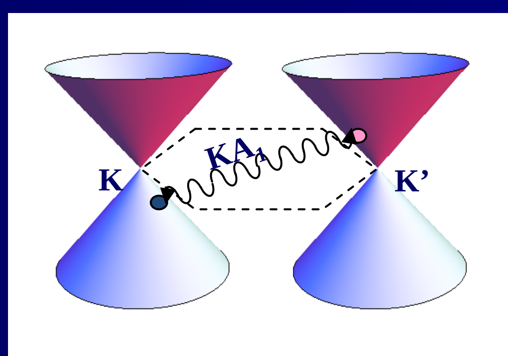
Electron phonon coupling





Park, et al *PRL*. **99**, 086804 (2007)

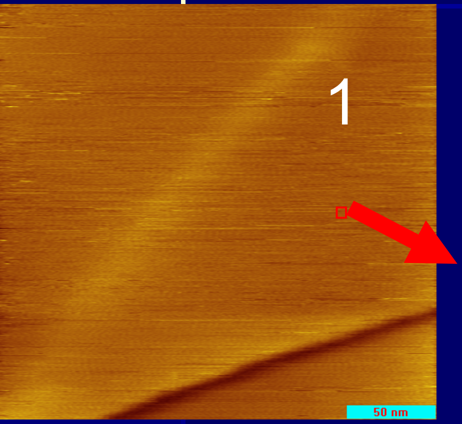


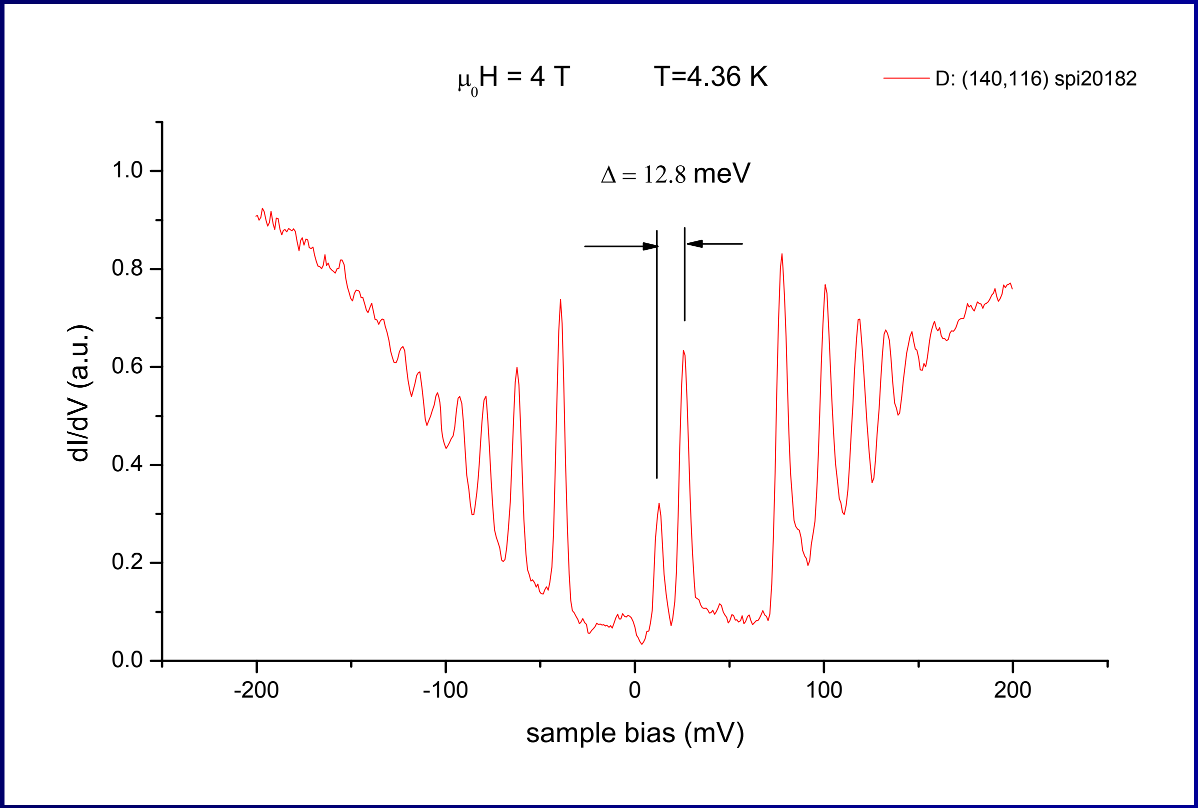


Benasq

High resolution STS – 4T

G. Li, A. Luican, E. Y. A., PRL (2009)
G. Li , E.Y. A - Nature Physics, 3, 623 (2007)

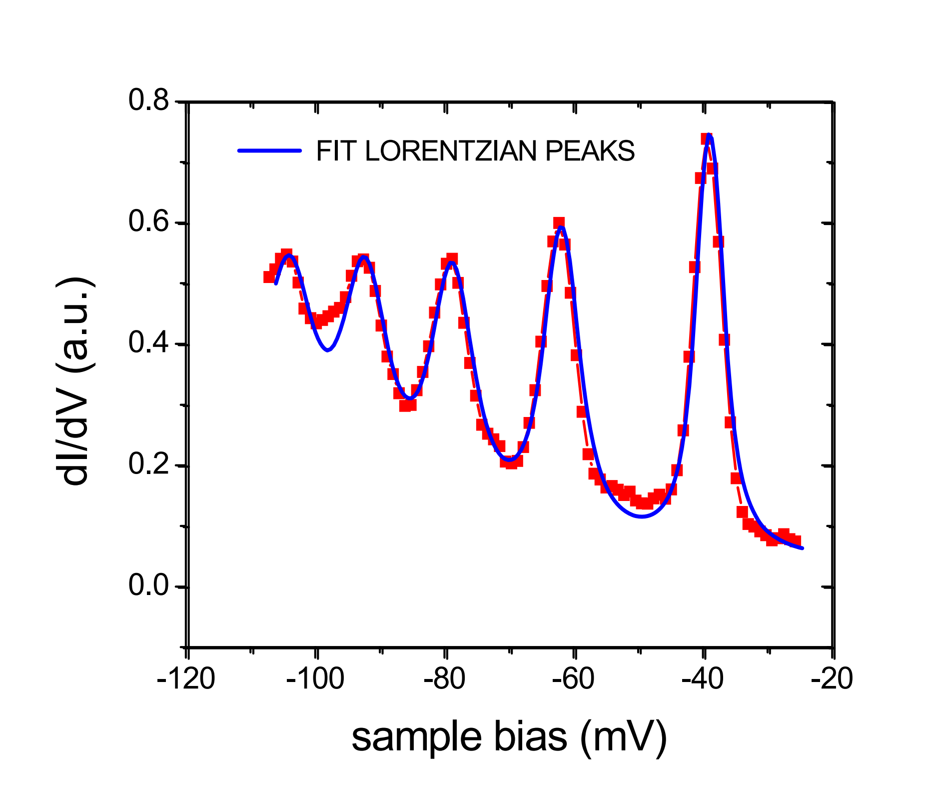




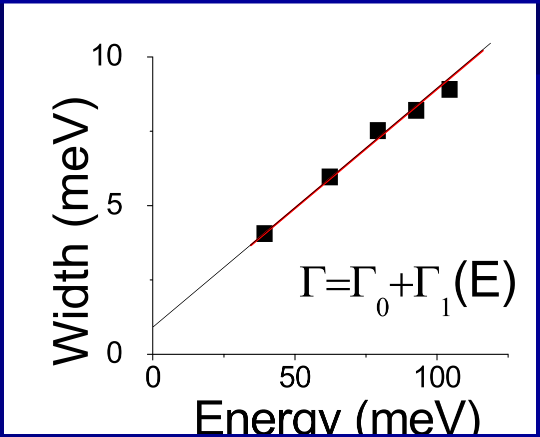
16 resolved Landau Levels

Quasiparticle lifetime

G. Li, A. Luican, E. Y. A., PRL (2009)
G. Li , E.Y. A - Nature Physics, 3, 623 (2007)



Line-width ~ E



$$\tau_0 = 0.7\,ps \Rightarrow l_{mfp} \sim v_F \tau_0 = 700\,nm$$

$$\tau \propto E^{-1} \approx 9\,ps\,/\,meV$$

Inelastic e-e interactions
$\tau \sim E^{-1} \sim 18$ ps/meV

$$\mu = \frac{e v_F l_{mfp}}{E_F} = 220{,}000\ cm^2 / V \cdot \sec$$

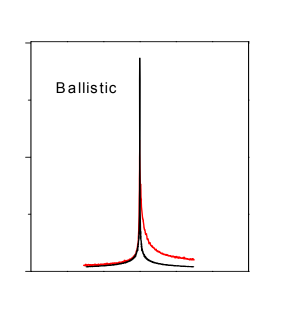
$$n = 3\times 10^{10}\ cm^{-2}$$

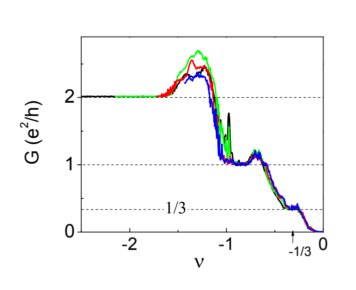
Gonzalez et al 1993
Castro Neto al PRB 2006
Fritz et al arXiv:0802.4289

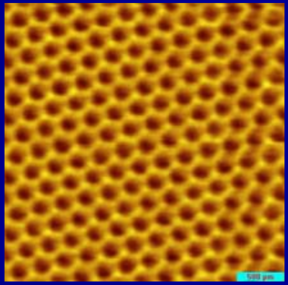
Summary

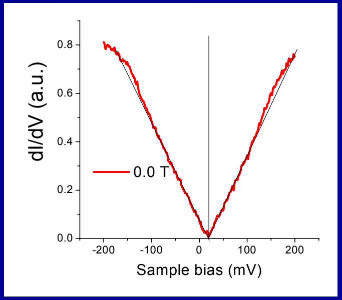
- Graphene without insulating substrate: Intrinsic properties

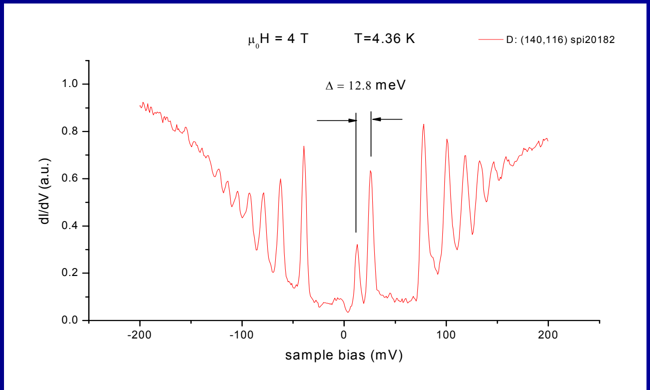
- Transport – 2-terminal
  - Ballistic transport on micron length scales
  - IQHE ν=1,2,3,4
  - FQHE ν=1/3
  - ν=0 insulator
- STM
  - Honeycomb structure
  - Spectroscopy
    - Linear Density of states
    - Well defined Dirac point
  - Direct observation of Landau levels
    - Fermi velocity
    - e-phonon interactions
    - e-e interactions













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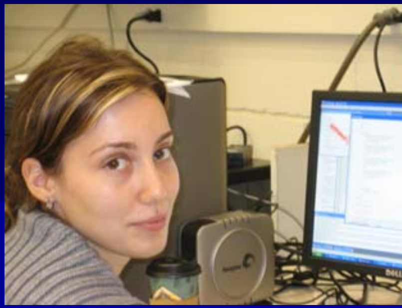
Fabian Duerr



Eva Y. Andrei

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