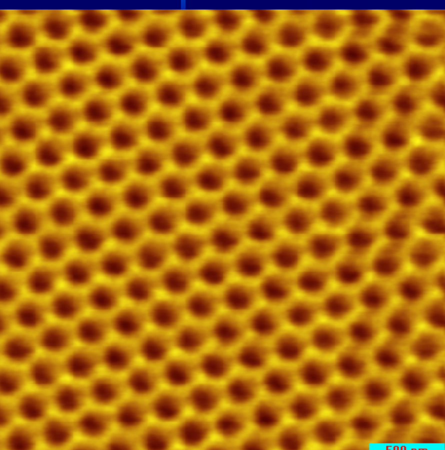
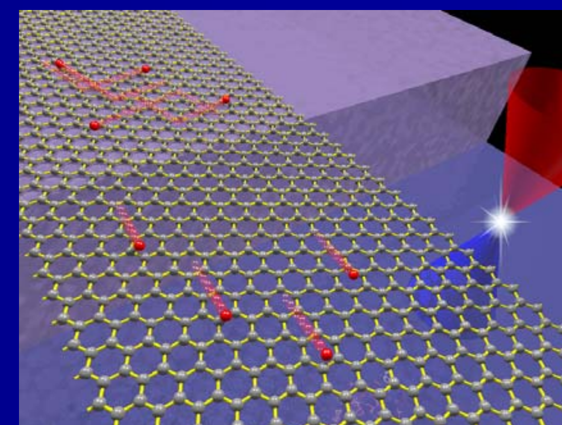
Graphene viewed through STM and transport

- STM graphene on graphite
  - Structure
  - Density of States
  - Landau levels
    - *Fermi Velocity*
    - *e-ph interactions*
    - *Quasiparticle lifetime*
    - *Gap*





- Transport
  - Suspended graphene
    - *Ballistic transport*
    - *Dirac point*
    - *Quantum Hall effect*

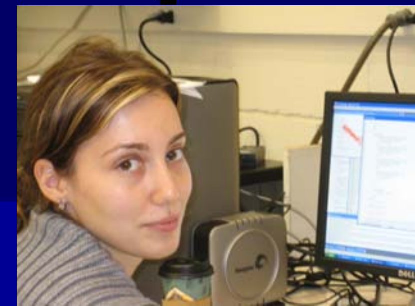
Eva Y. Andrei
Rutgers

Rutgers Graphene Group



STM - Guohong Li
Adina Luican

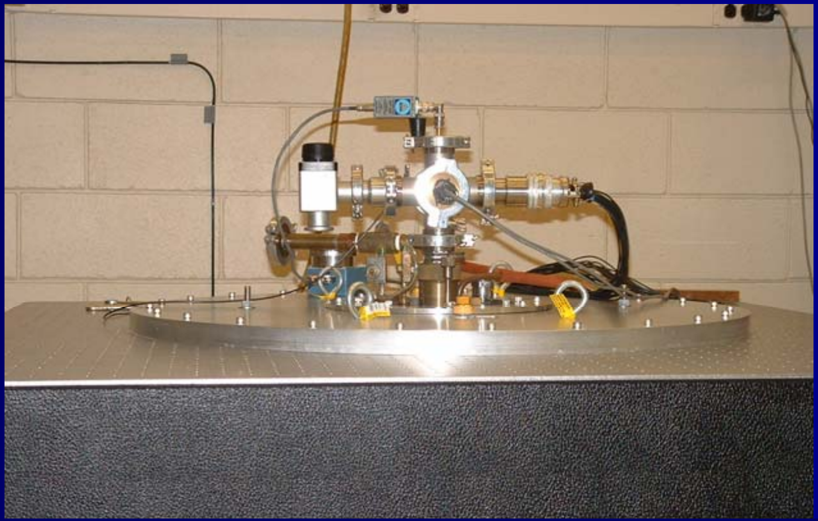
Transport - Xu Du
Ivan Skachko
Anthony Barker
Alex Archer



- *G. Li , E.Y. A - Nature Physics, 3, 623 (2007)*
- *X. Du, G. Li, A. Barker, E. Y. A, Nature Nano 3, 491 (2008); arxiv:0802.2933*
- *G. Li, A. Luican, E. Y. A., arXiv:0803.4016*
- *X. Du, I. Skachko, E.Y. A. PRB* ***77****,184507 (2008) arxiv:0710.4984*

Graphene on graphite: STM

- Temperature T=4 (2K)
- Magnetic field B=13 (15T)
- Scanning range 10^{-10} -10^{-3} m



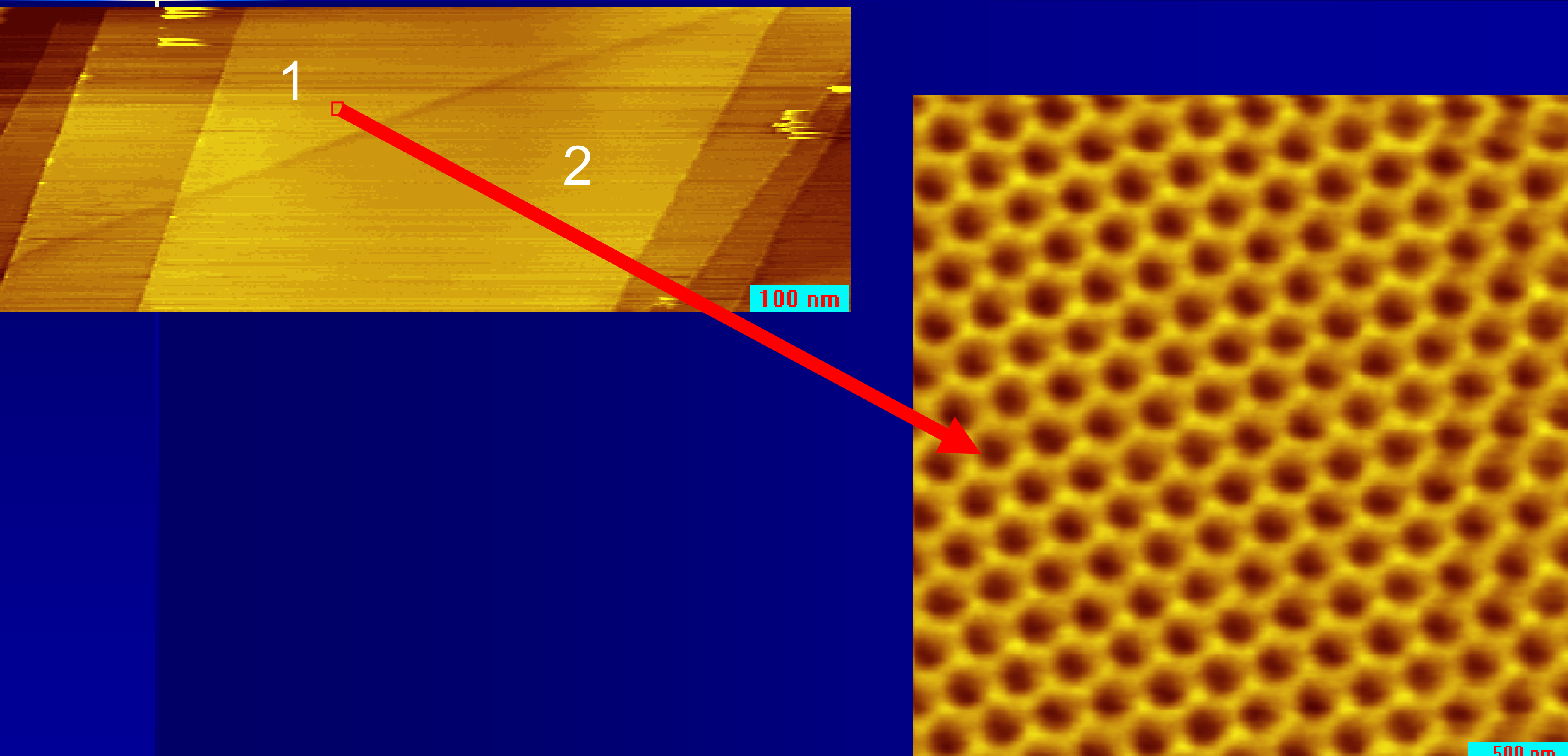
- ➢Topography
- ➢Spectroscopy B=0
- ➢Spectroscopy B>0

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

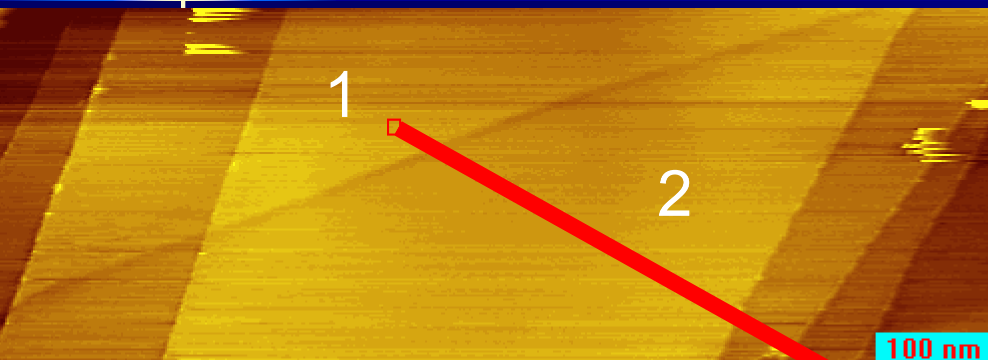
✓ *G. Li, A. Luican, E. Y. A., arXiv:0803.4016*

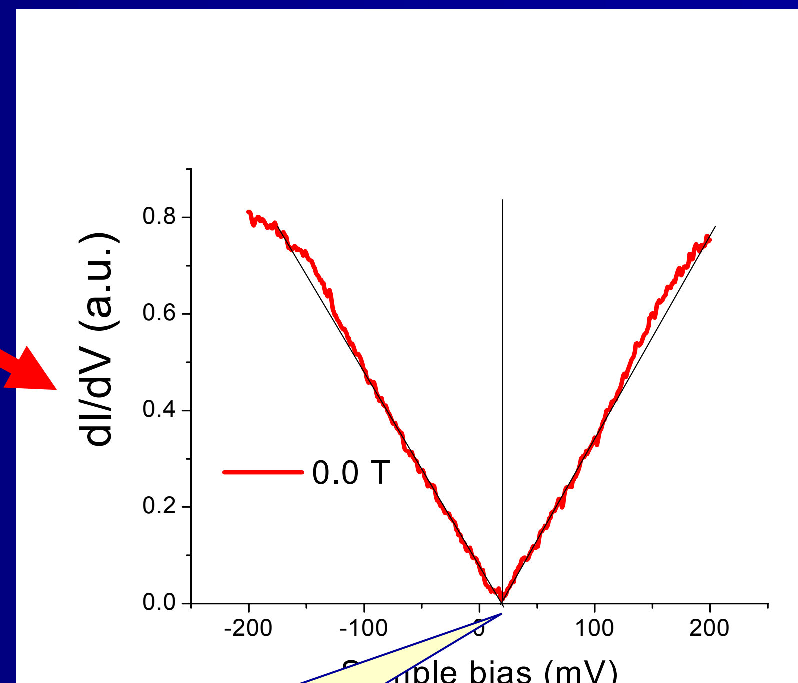
Rutgers

Topography - honeycomb



Spectroscopy B=0





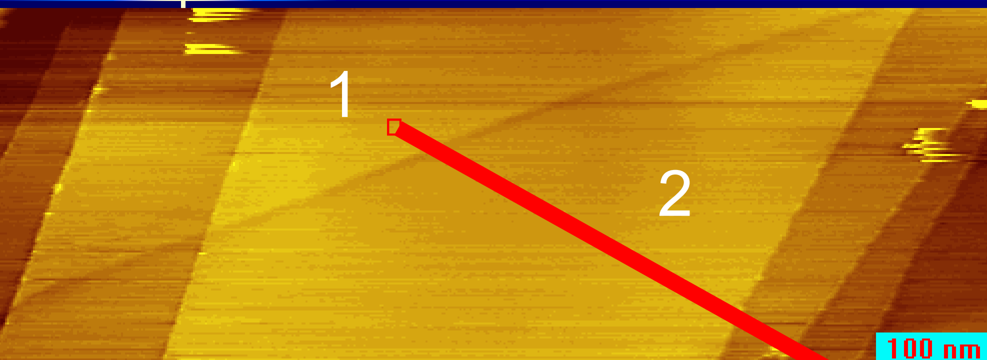
dI/dV ~ DOS

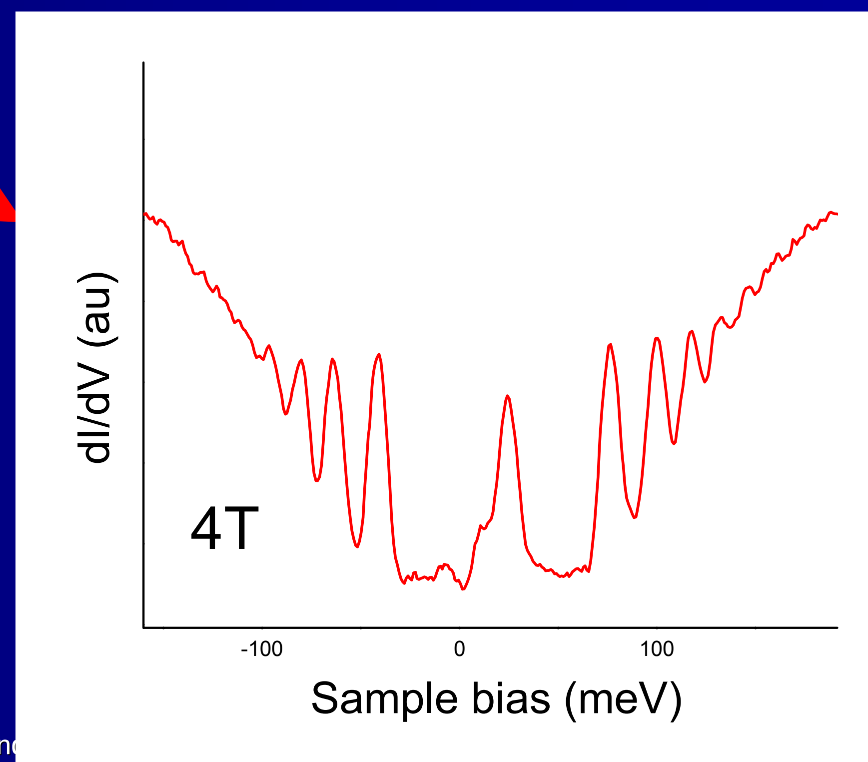
- Linear in E
- Vanishes at Dirac point
- ➢ Massless DF

Unintentional hole doping

$$n_h = 3\times10^{10}\ \mathrm{cm}^{-2}$$

B>0 Landau level spectroscopy

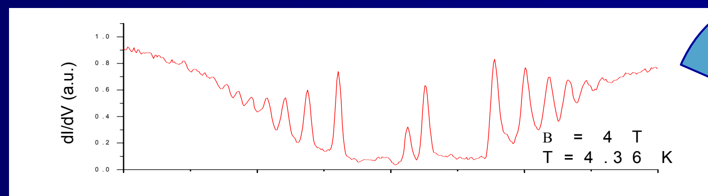




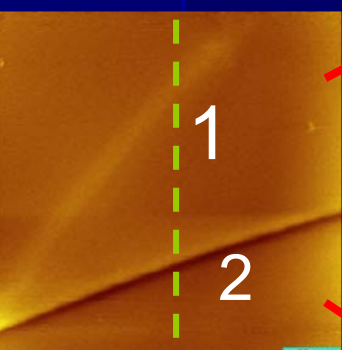
Interlayer coupling

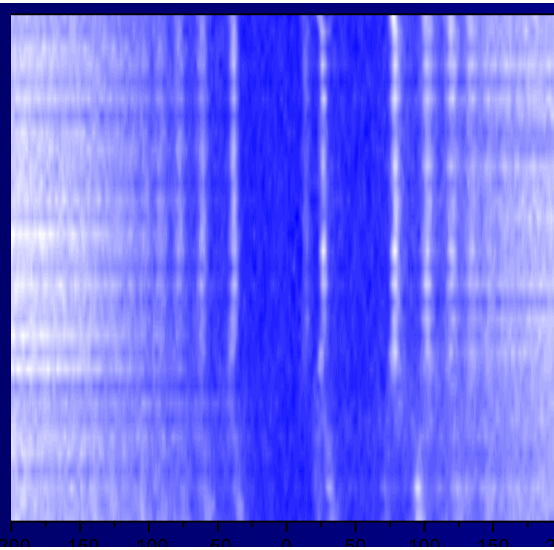
Pereira et al (PRB,2007)
LL vs interlayer coupling parameter

Region 1
No coupling – single layer graphene t=0

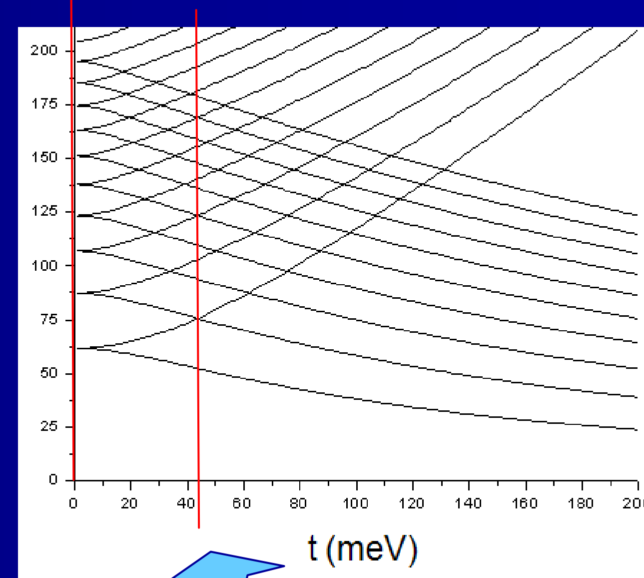


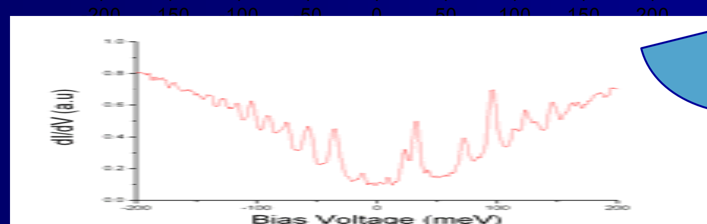
t=0





t=45meV



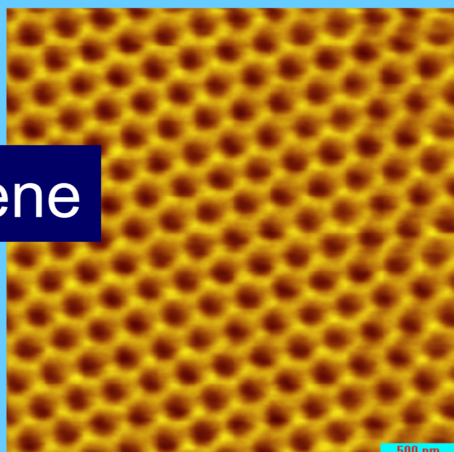


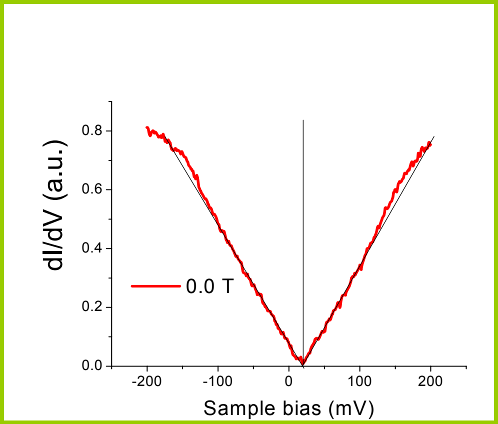
Region 2
Coupled layer t=0.045eV
Compare to $\gamma_1=0.3$ eV

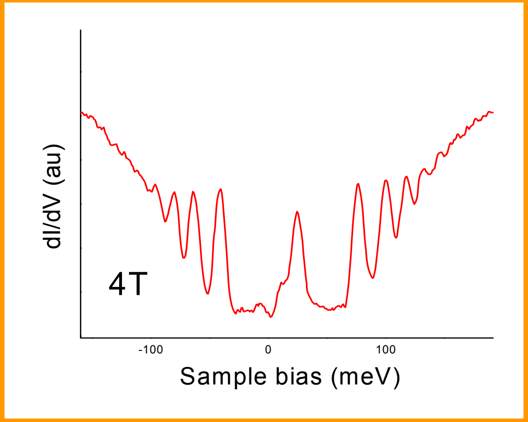
Graphene vs graphite

topography | B=0 spectroscopy | B>0 spectroscopy

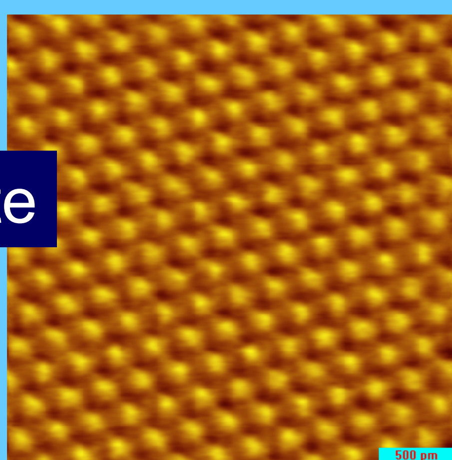
Graphene

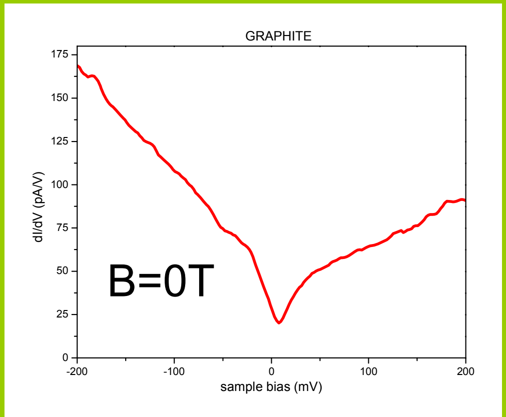


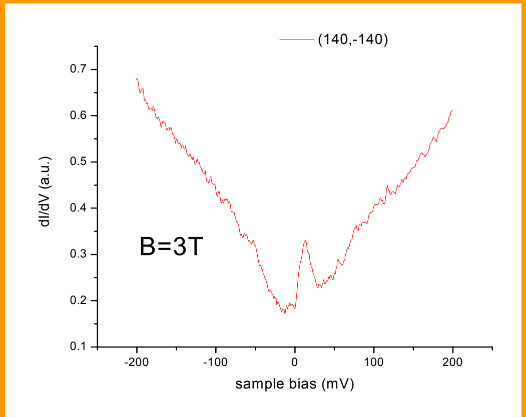




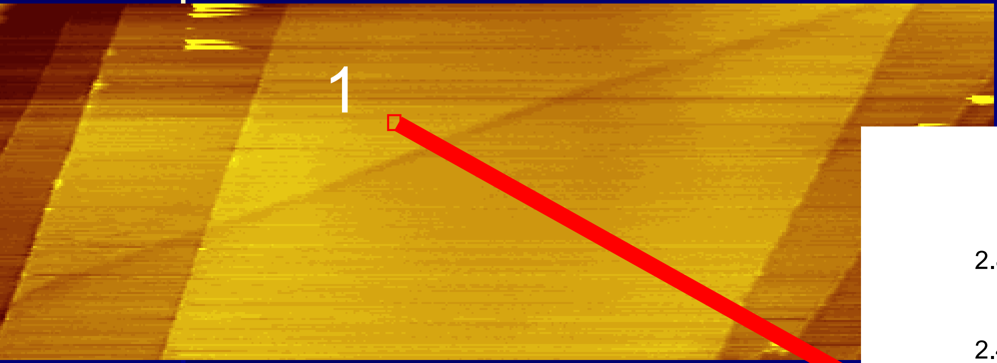
Graphite

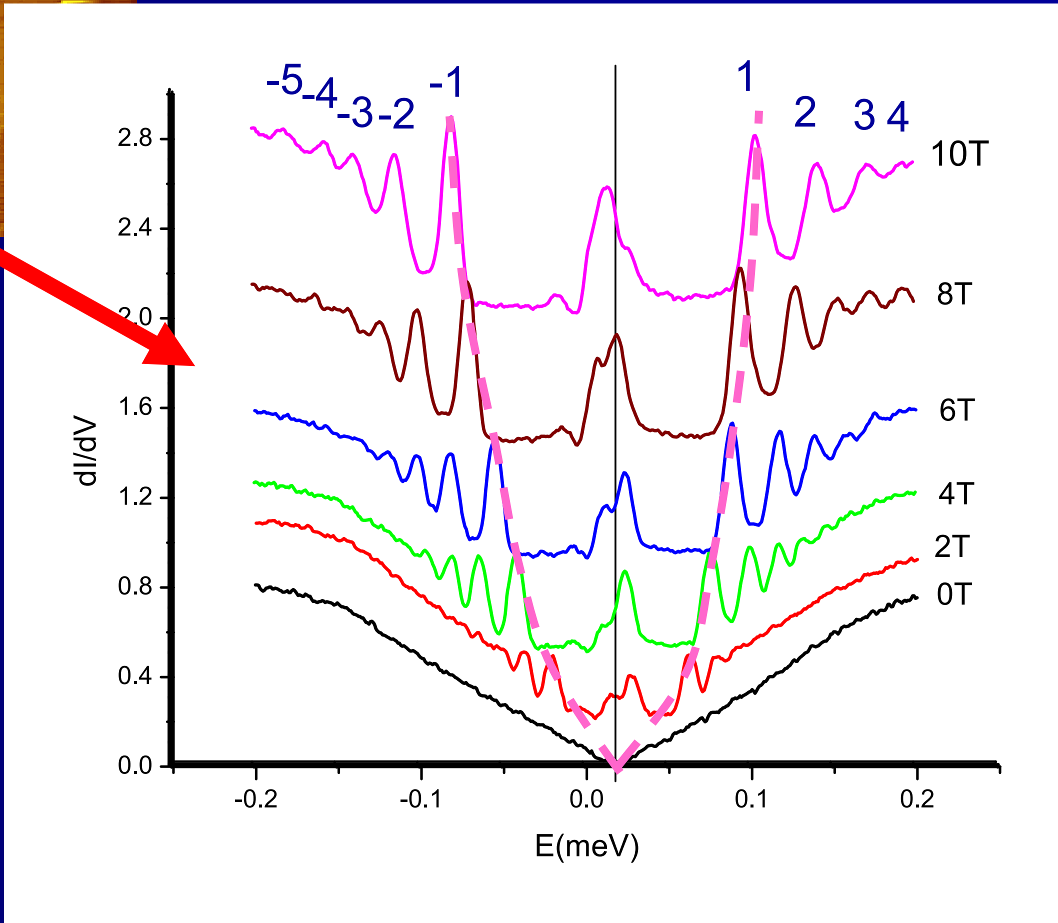






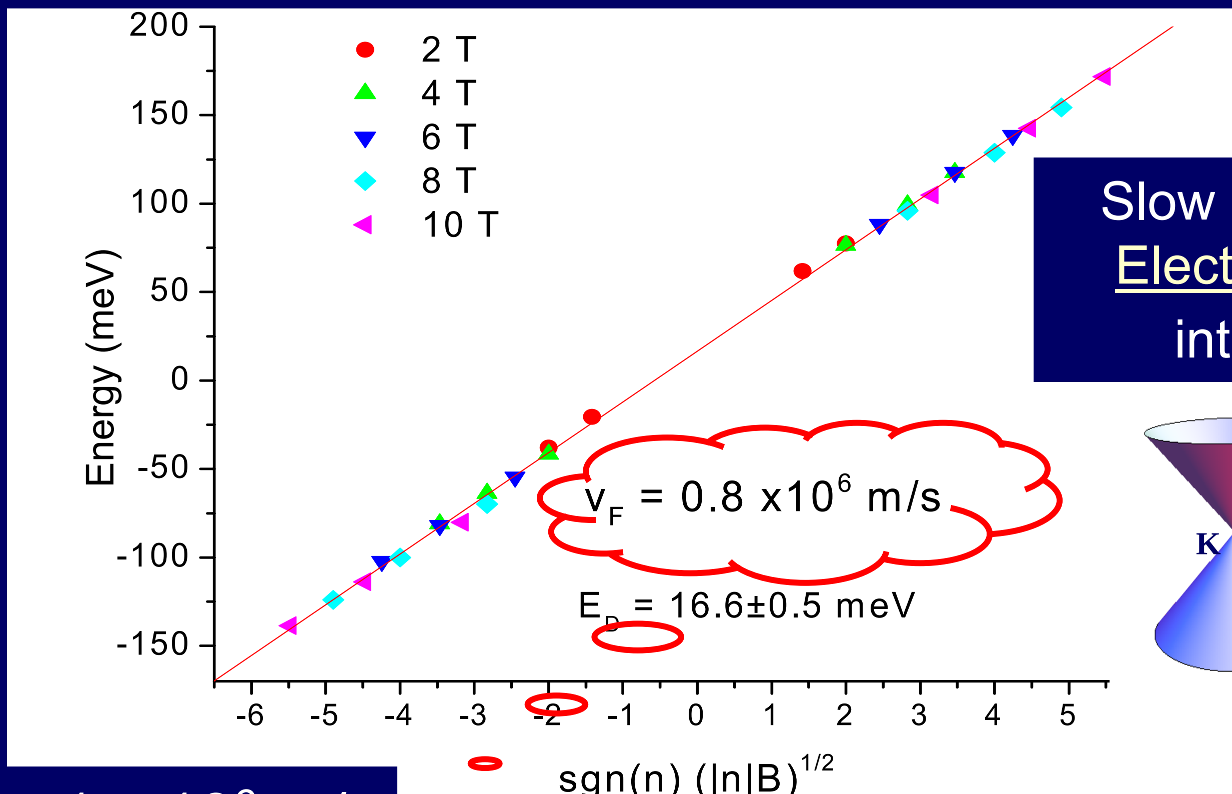
Landau level spectroscopy



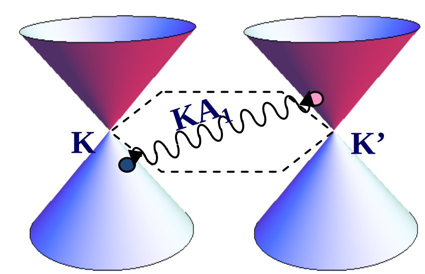


Massless Dirac Fermions

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



Slow down due to
Electron-phonon
interactions



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

skip

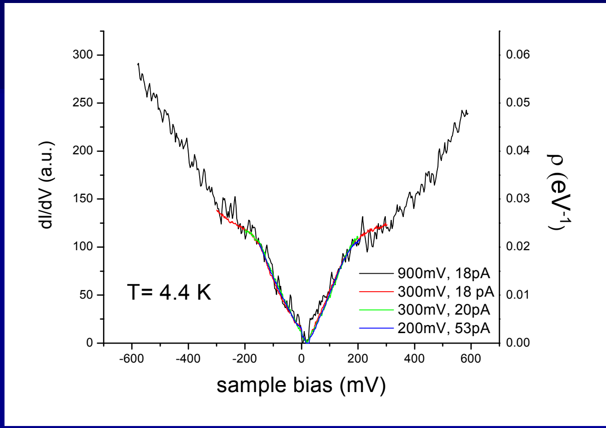
Fermi Velocity

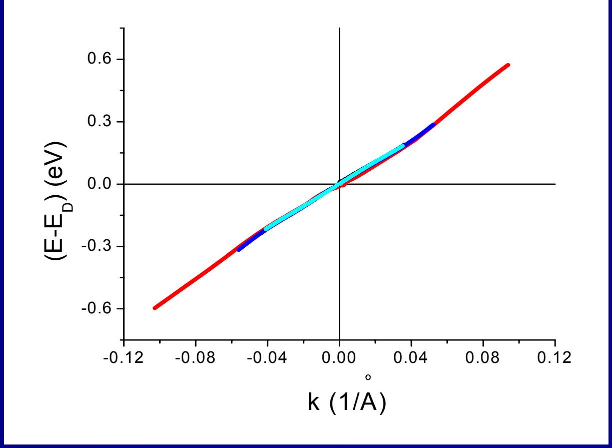
- 2D (isotropic)

  Number of states /cell

$$N(E)=\int_0^E \rho(E')dE' = A_c \frac{1}{\pi} k^2$$

$$k(E)=\pm\left(\frac{\pi}{A_c}\int_0^E \rho(E')dE'\right)^{1/2}$$





- Fermi Velocity

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

Electron phonon coupling

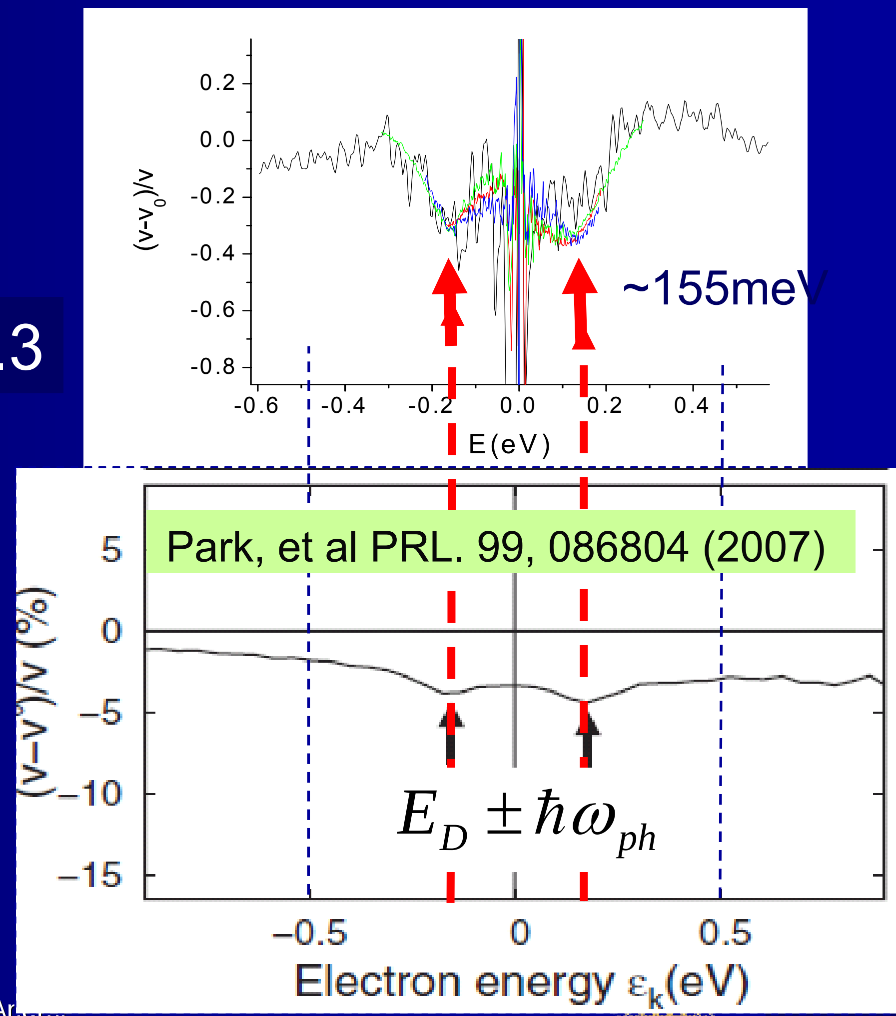
E-ph coupling strength

$$\lambda_{k_F} = -\frac{\partial \operatorname{Re}\sum_k(E)}{\partial E}\bigg|_{E=E_F}$$

$$\lambda_{k_F} = -\frac{v_F(E_F) - v_F^0(E_F)}{v_F(E_F)}$$

$\lambda \sim 0.2$ -0.3

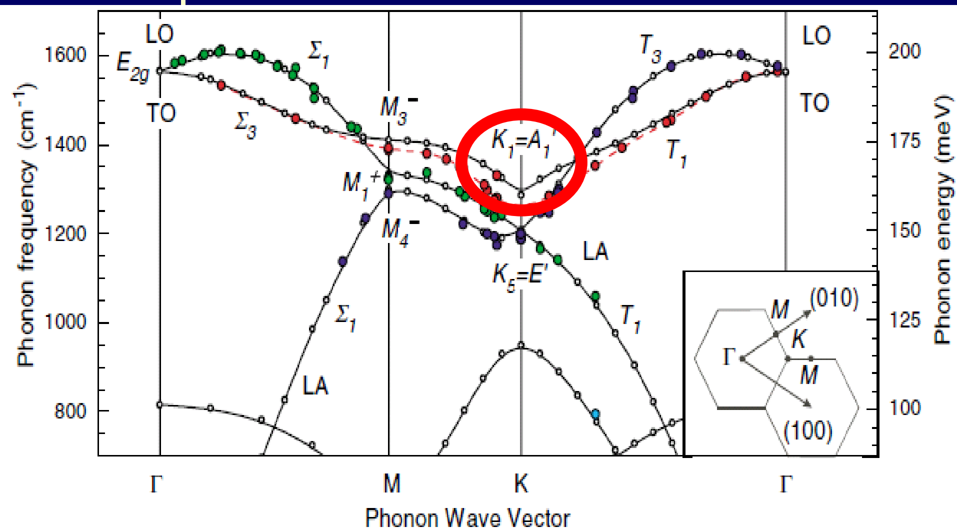
S. Nakajima and M. Watabe 1963
G. Grimvall 1981



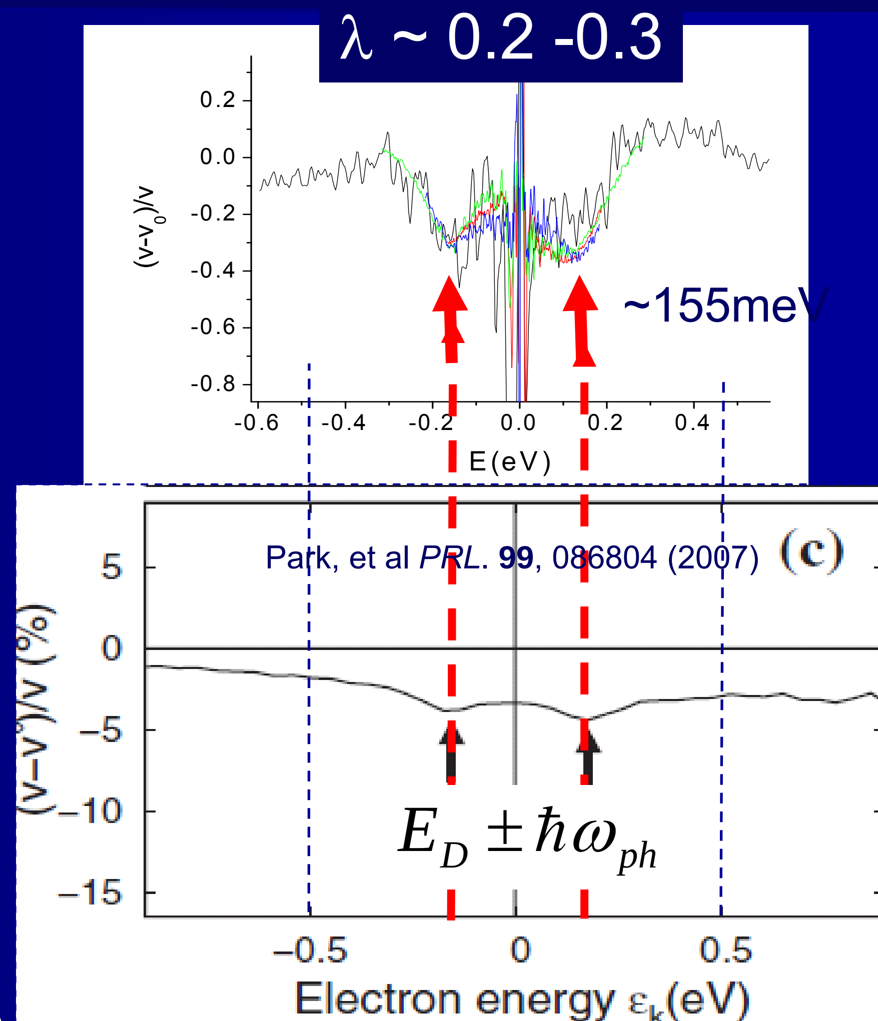
Bostwick et al Nature Physics (2007)

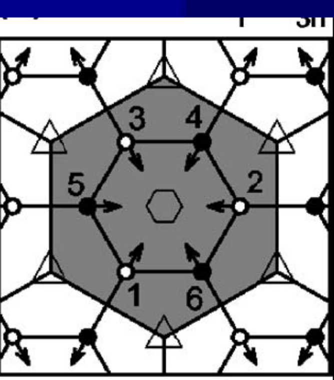
Zhou et al (2008) preprint

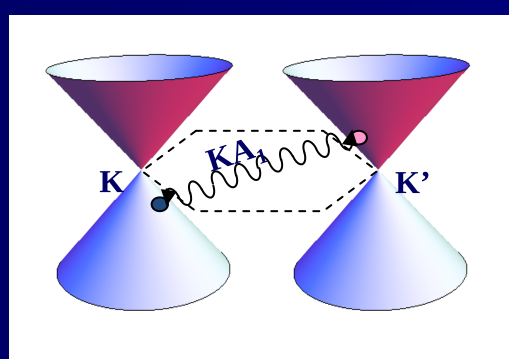
Electron phonon coupling



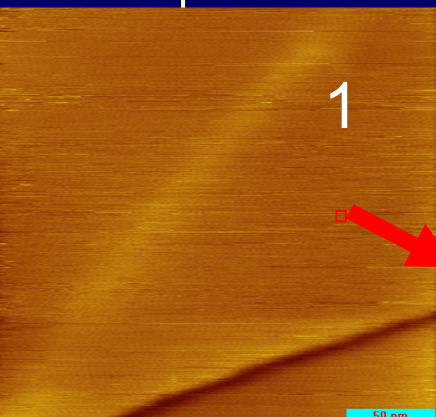
IXS data
J. Maultzsch et al. PRL. 92, 075501 (2004)

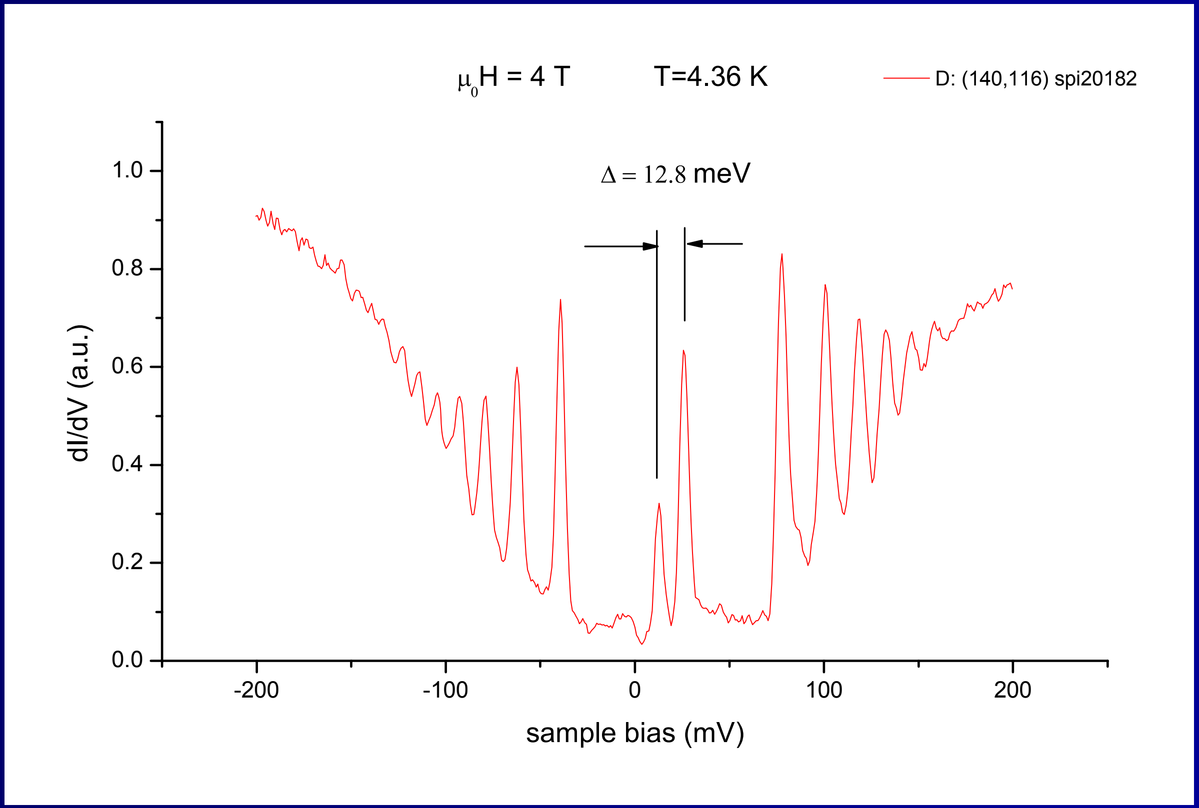






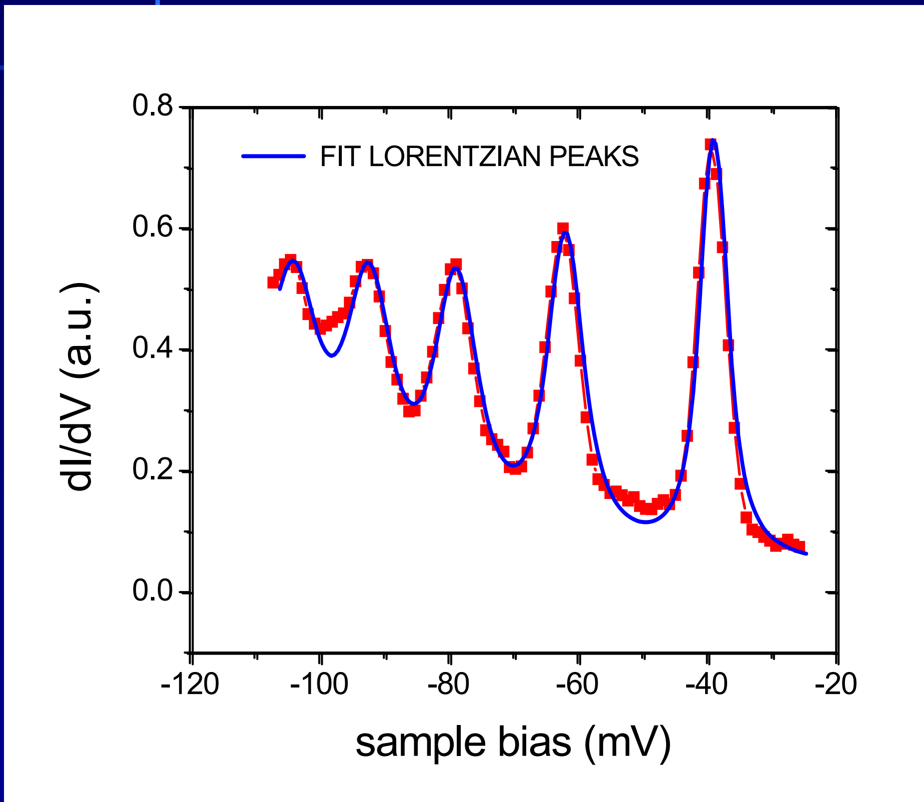
High resolution STS – 4T



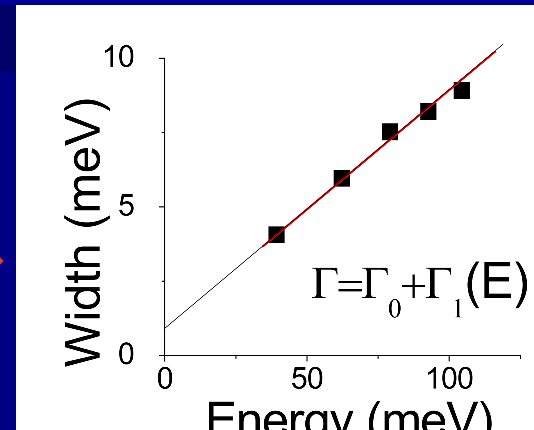


16 resolved LL

Quasiparticle lifetime



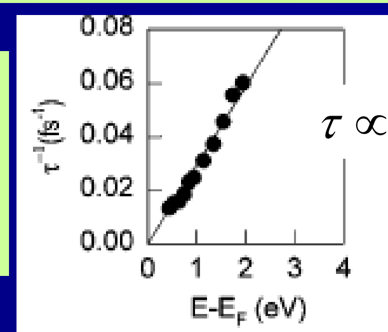
Line-width ~ E



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

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

Phemtosecond photoemission on Graphite, B=0
Xu et al PRL (1996)

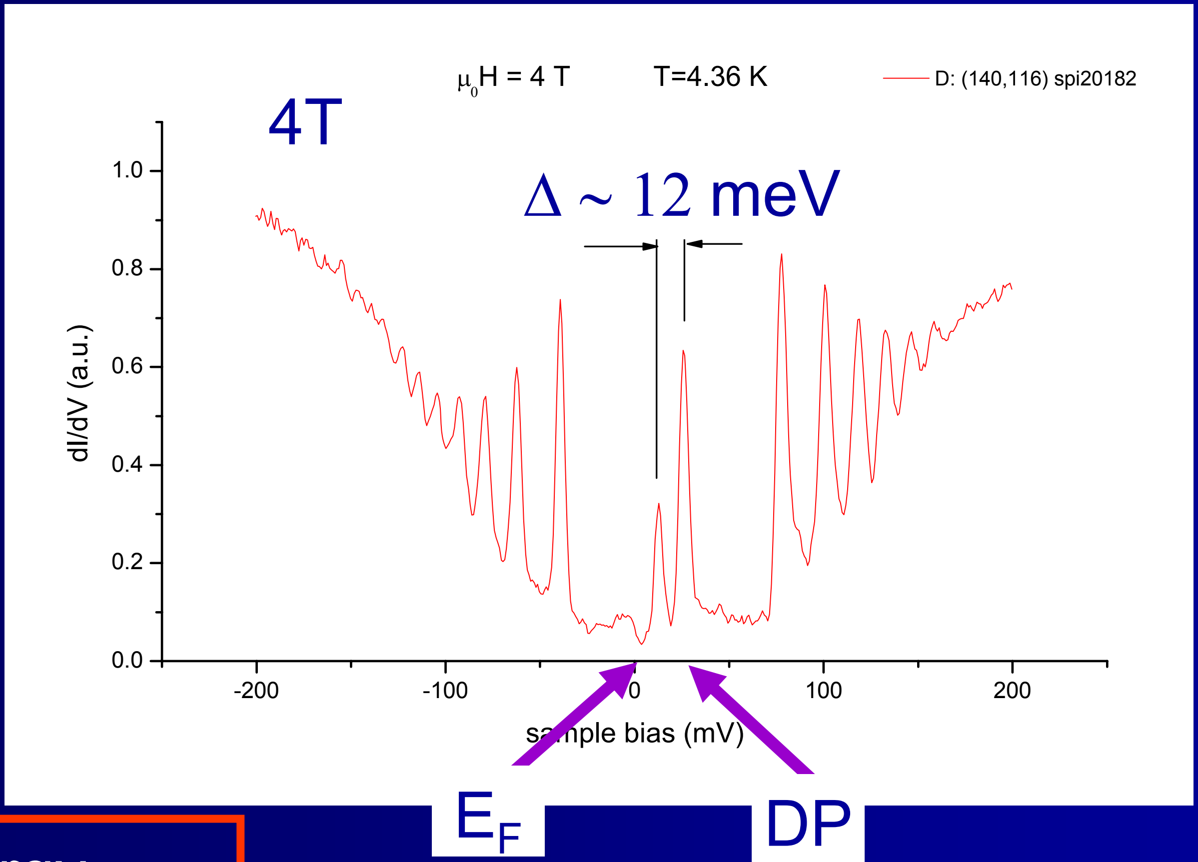


$$\tau \propto E^{-1} \approx 30\,ps/meV$$

Gonzalez et al (96) (B=0)
Inelastic e-e interactions
$\tau \sim E^{-1} \sim 18$ ps/meV

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

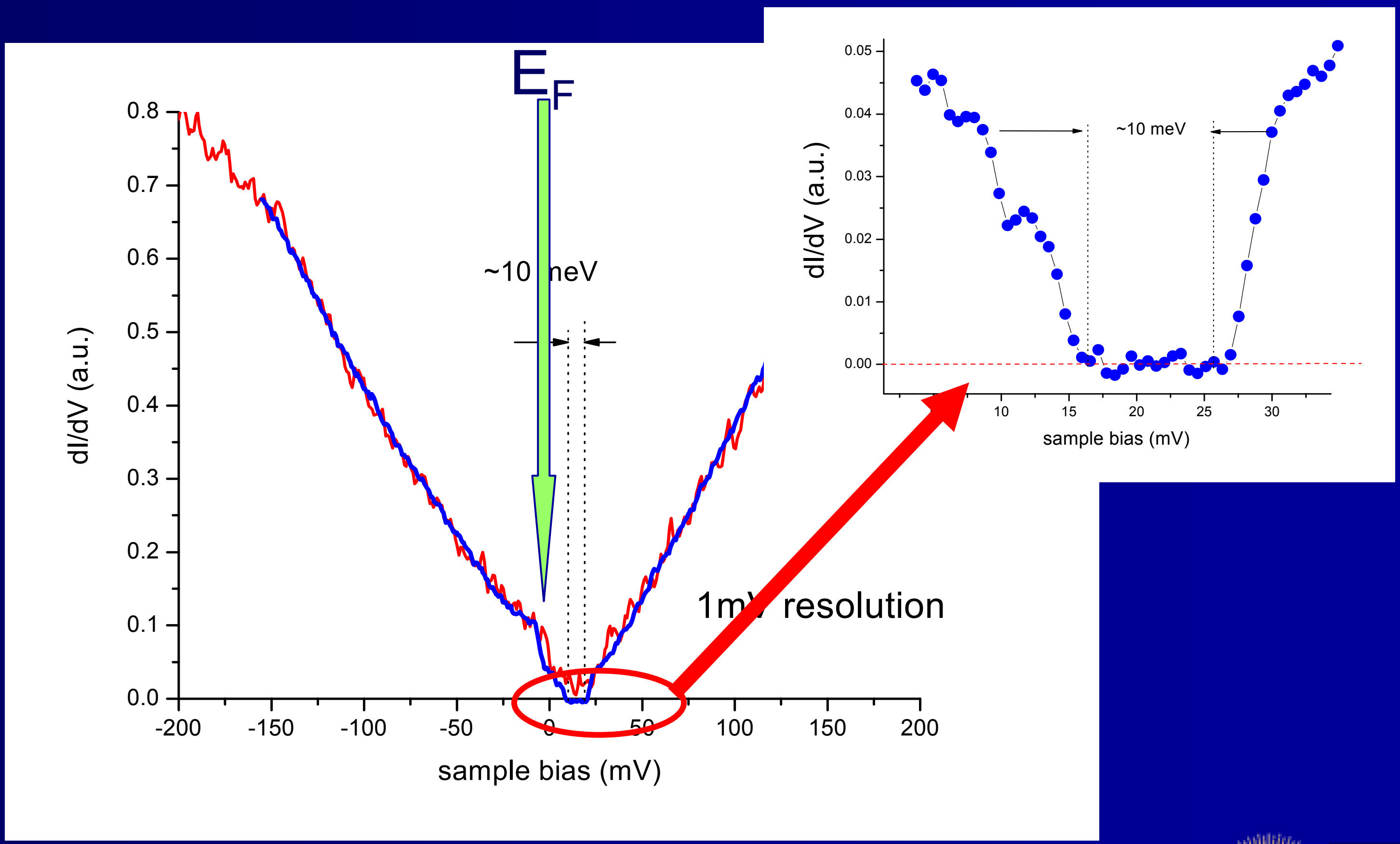
High resolution STS (B>0) SPLITTING of n=0 LL



Zeeman energy
$g^*\mu_B$ ~ 0.17 meV/T

- Splitting at DP!

STS (B = 0)

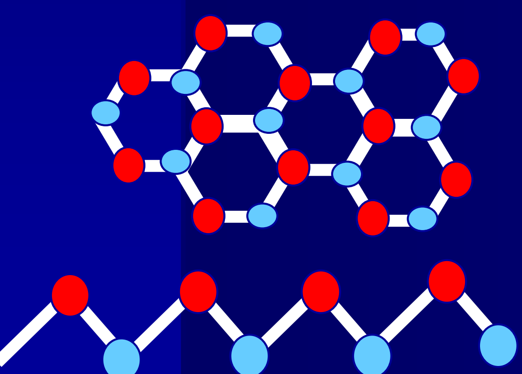

E_F
~10 meV
dI/dV (a.u.)
sample bias (mV)
1mV resolution
~10 meV
dI/dV (a.u.)
sample bias (mV)

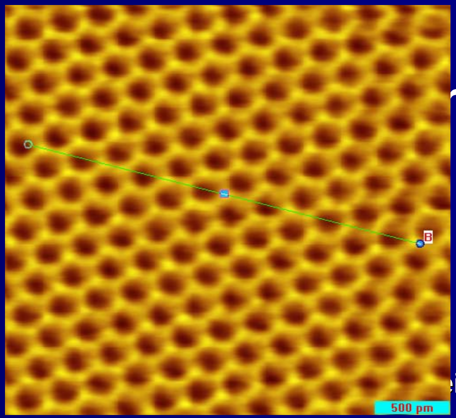
GAP at Dirac Point B=0

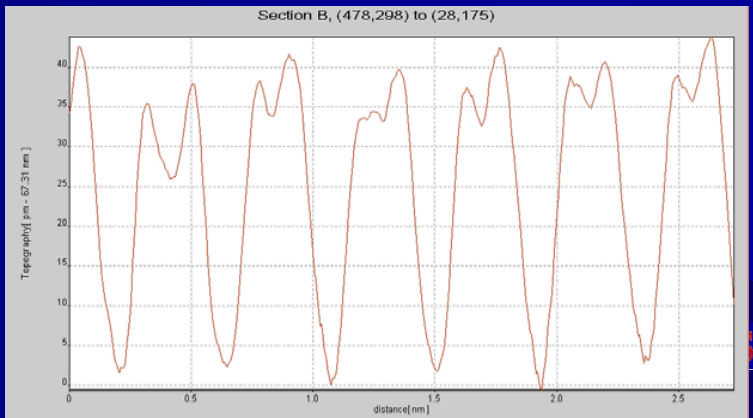
- Gap at DP (not E_F)
  - Broken AB symmetry

$$E_{k,\pm} = \pm\sqrt{(v_F k)^2 + \Delta^2}; \quad \Delta = m v_F^2$$
$$\Rightarrow m = 0.002 m_e$$

- Spontaneously broken symmetry CDW?
- Substrate induced potential modulation



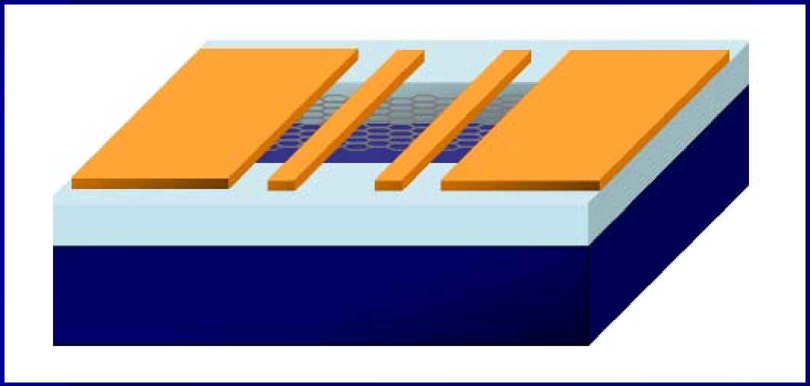


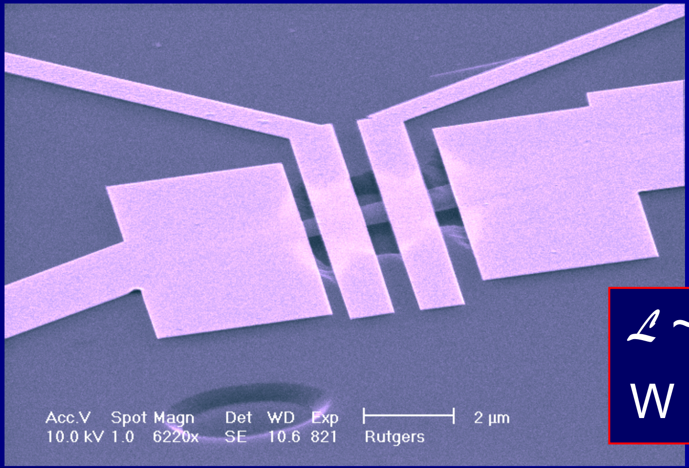


Suspended graphene

- Substrate roughness
- Trapped charges
- Quench condensed ripples

→ Eliminate substrate!



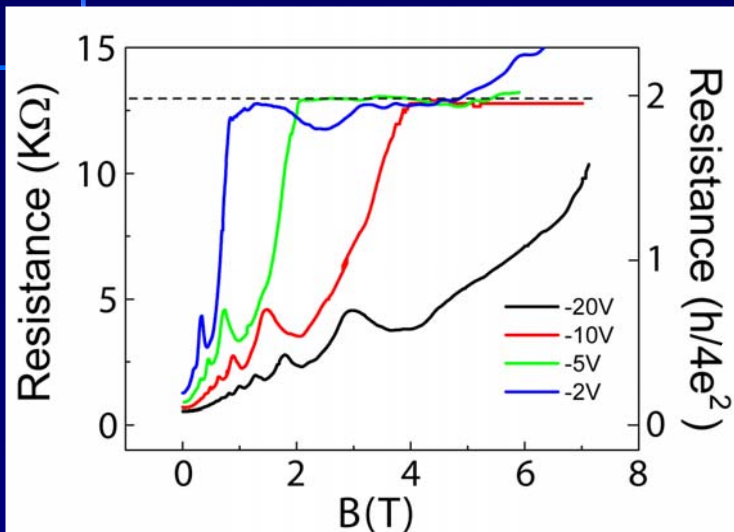


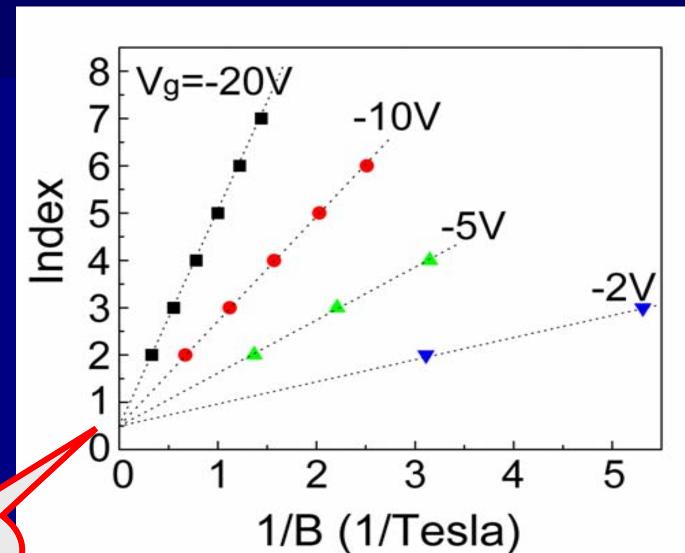
$\mathcal{L} \sim 600$ nm
W = 1.6 μm

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

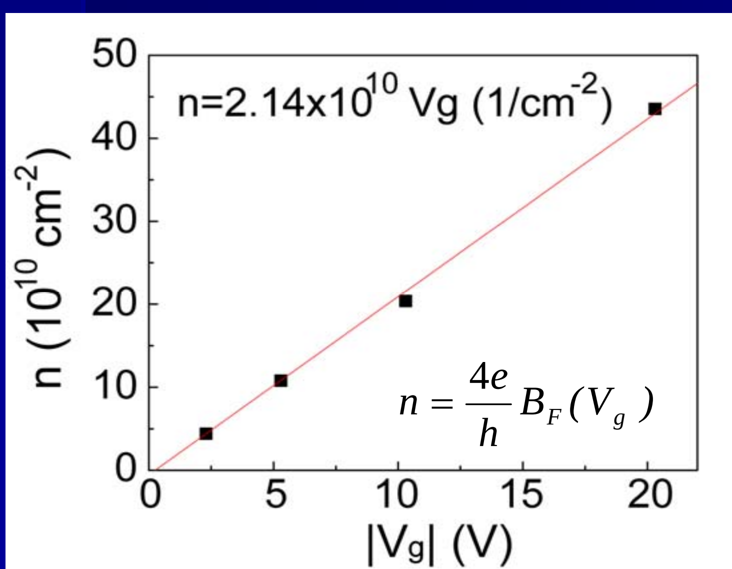
$\alpha_{SG} = n / V_g$

ShdH Oscillations





1/2



- Single layer

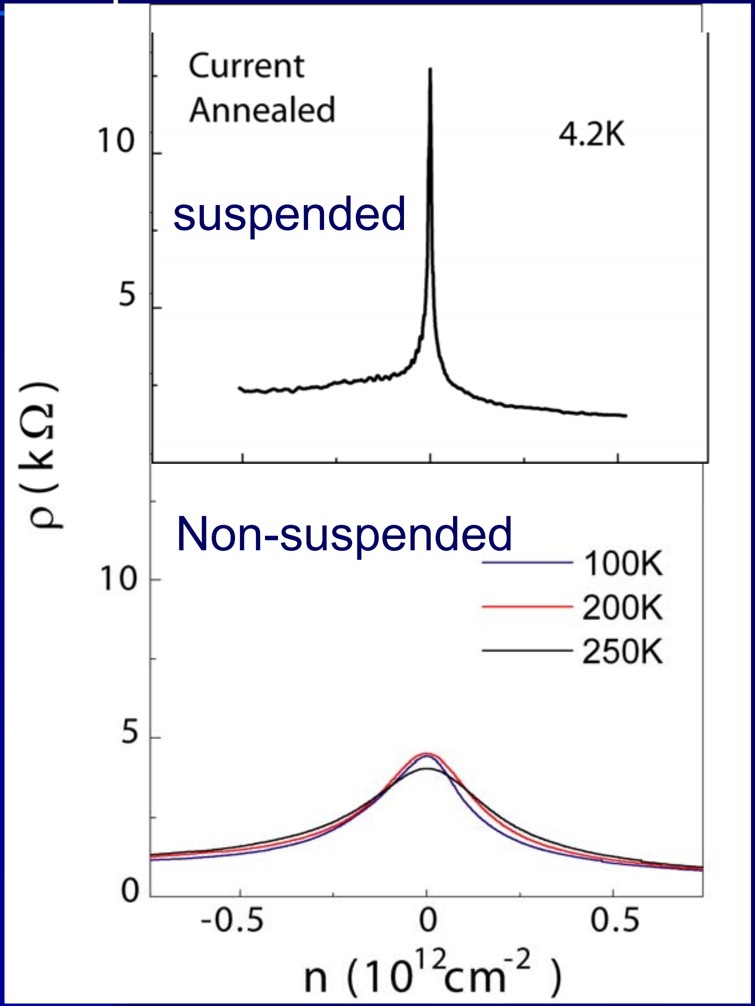
$$\alpha_{SG} = n / V_g = 2.14 \times 10^{10} cm^{-2} V^{-1}$$

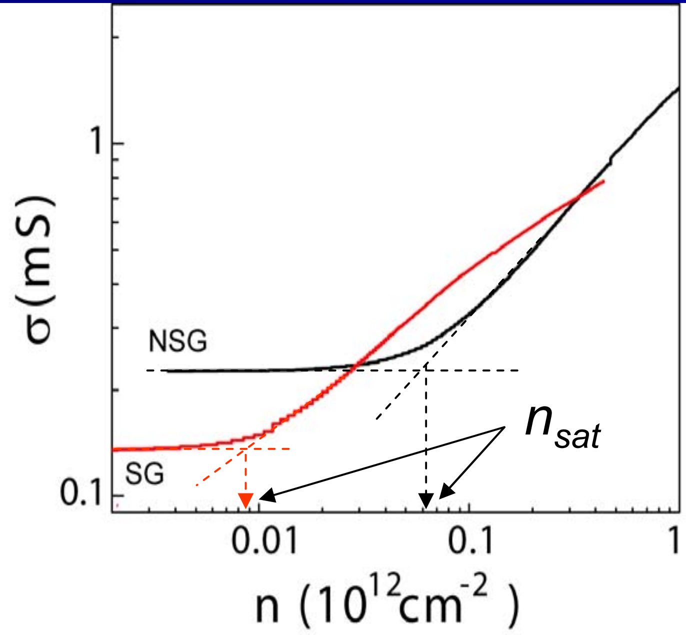
$$\alpha_{SG} / \alpha_{NSG} \approx \varepsilon_{SiO_2}$$

- Suspended

Eva Andrei

Substrate induced Potential fluctuations





reduced potential fluctuations

Substrate induced Potential fluctuations

suspended

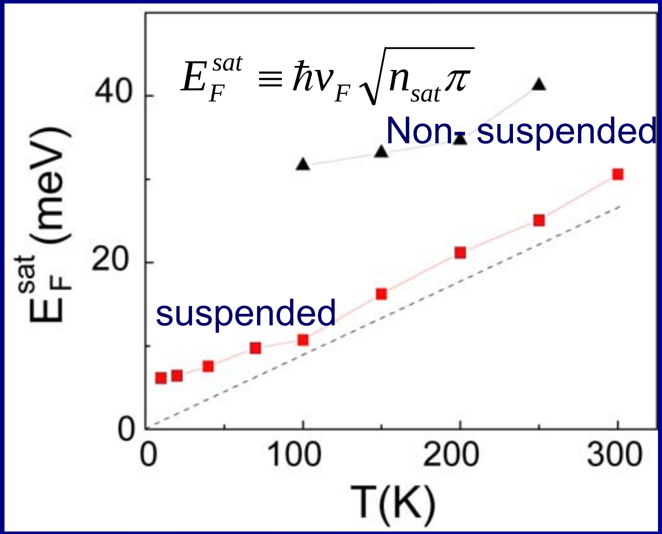
Residual carriers
$n_{sat} \sim 4\ 10^9 cm^{-2}$

Mobility ~ 200,000 $cm^2/V\ s$

Non suspended

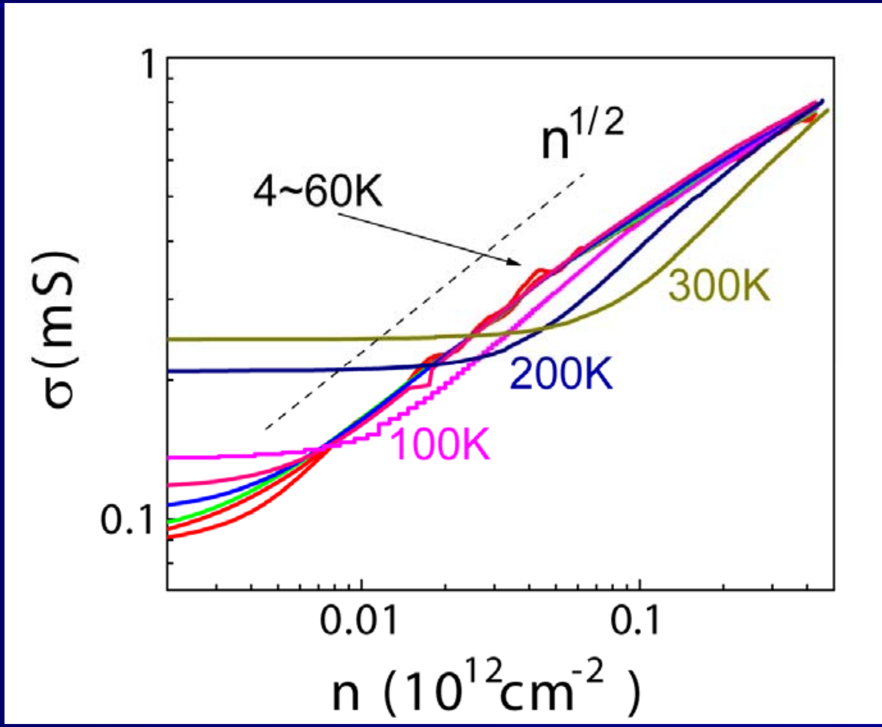
Residual carriers
$n_{sat} \sim 10^{11} cm^{-2}$

Mobility ~ 20,000 $cm^2/V\ s$



reduced potential fluctuations

Ballistic transport

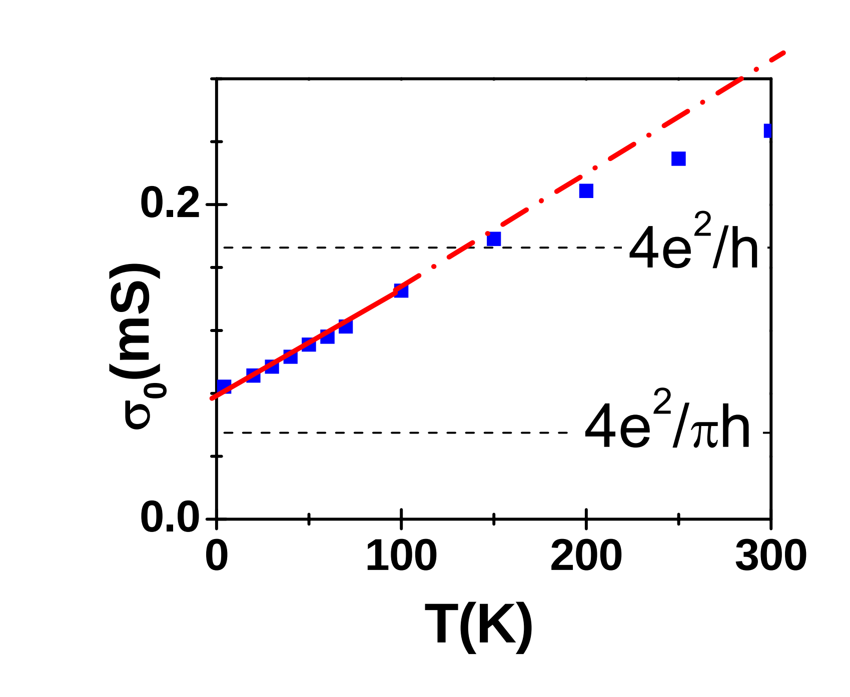


T<100K:

At low densities: $\sigma \sim n^{1/2} \sim E_F$

Approaching Ballistic transport!

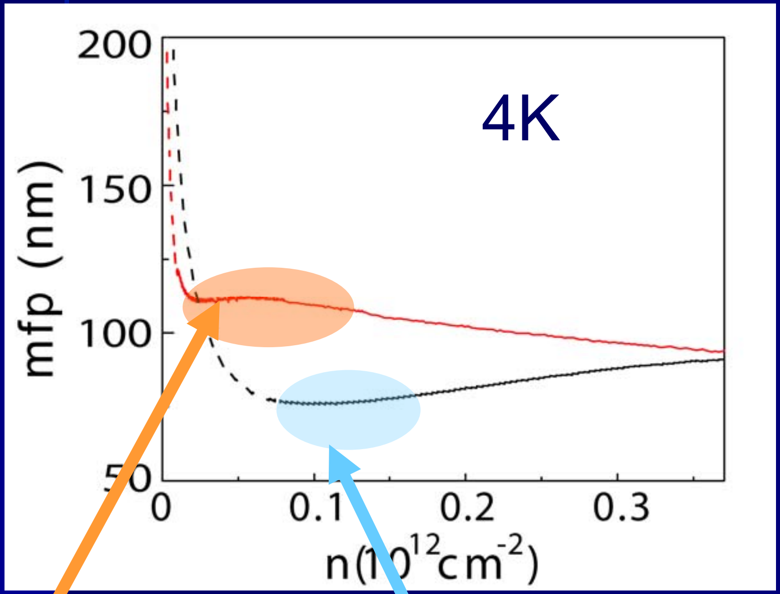
Temperature dependence of minimum conductivity



- $\sigma_{min} \sim T$ for T<150K
- Slope – sample dependent

Mean-free-path

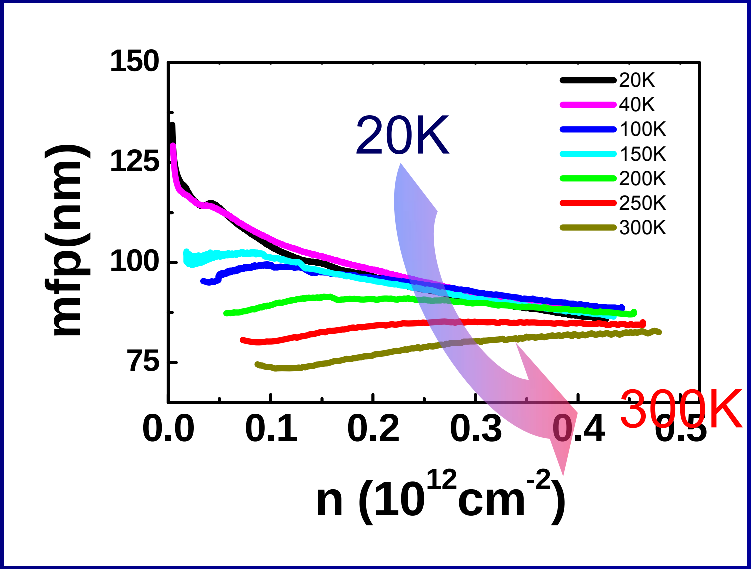
suspended vs non-suspended graphene



Suspended Short range scattering

Non-suspended Long range scattering

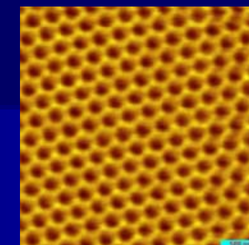
Temperature dependence of suspended graphene

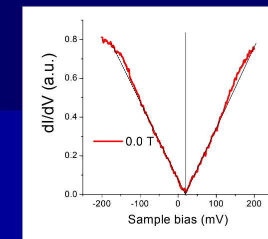


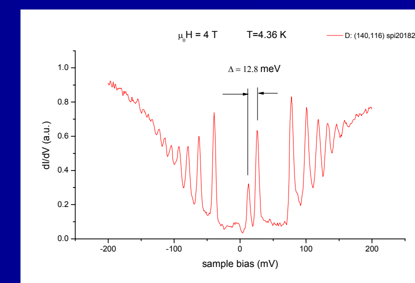
T>100K: Onset of long-range scattering:

Summary

- Graphene on graphite
  - Honeycomb structure
  - Direct observation of Landau levels
  - Dirac fermions
    - Linear Density of states
    - Well defined Dirac point
  - Long lived
  - Slow down by interactions with lattice
  - Mass ~ $0.002m_e$?







- Suspended graphene
  - Well defined Dirac point
  - Ballistic transport on micron scales
  - Quantum Hall effect
  - ν=0 Insulating