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# Landau Level Spectroscopy of Multilayer Epitaxial Graphene in the Immediate Vicinity of the Dirac Point

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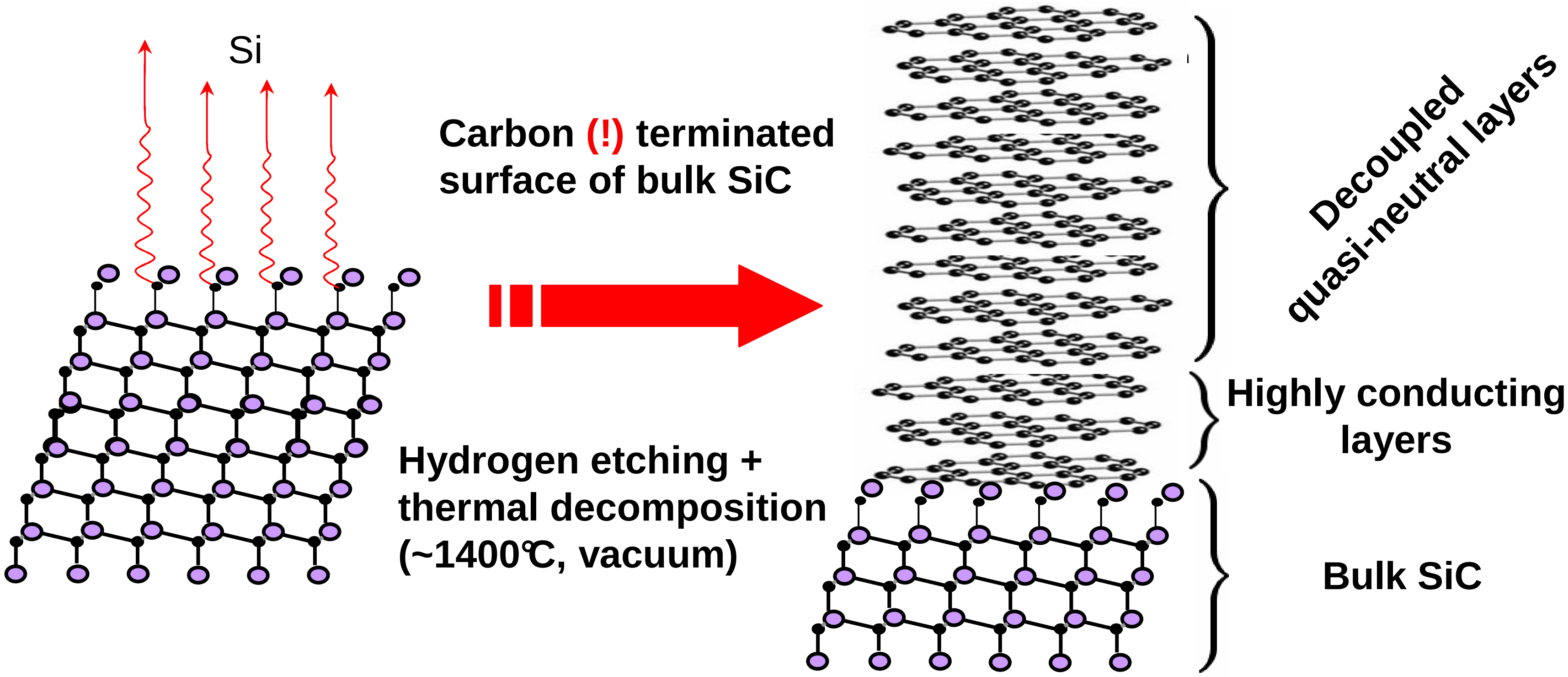
Trieste, 29 August 2008

# Outline:

- Multilayer epitaxial graphene
- Experimental details
- Cyclotron resonance at low magnetic fields
- Cyclotron resonance at elevated temperature
- Conclusions

# Multilayer epitaxial graphene on SiC substrate




**Relatively simple preparation of macroscopic samples with practically decoupled and undoped graphene layers (up to ~100 layers)**

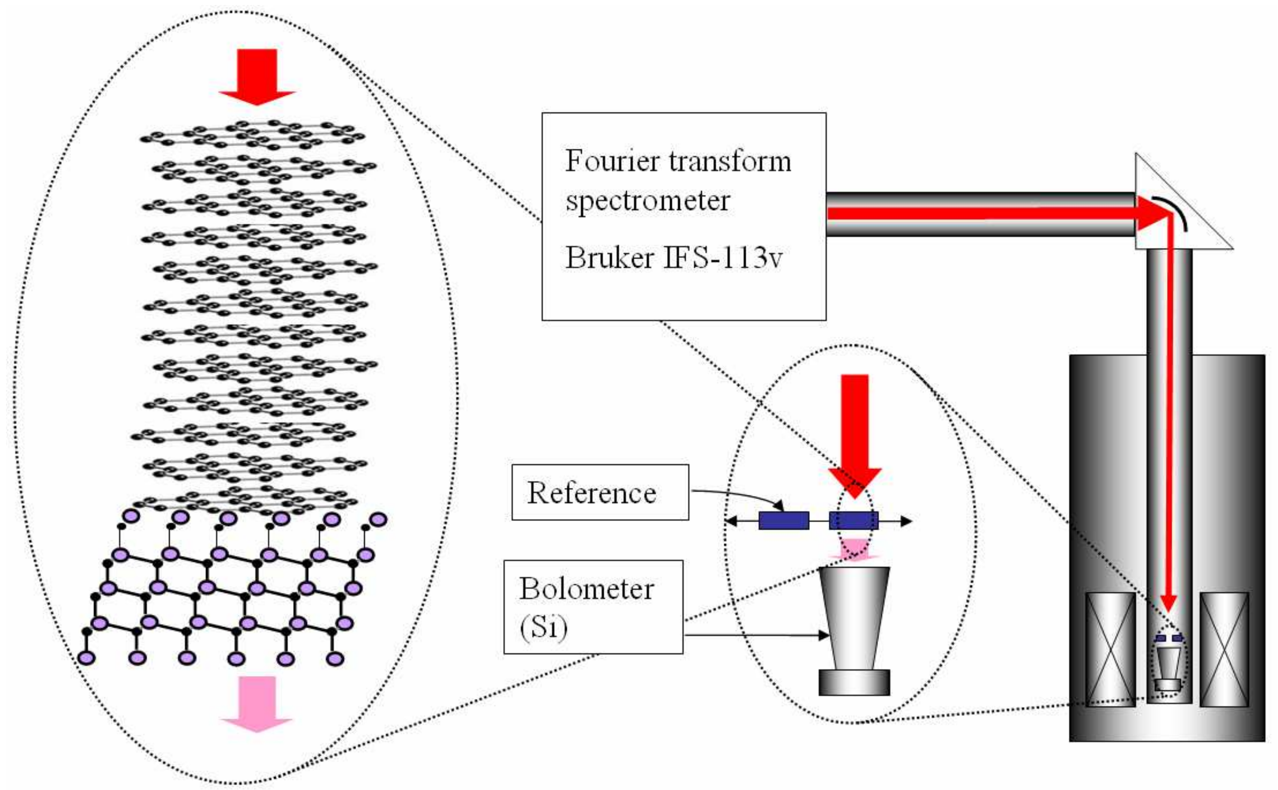
Sadowski PRL (2006), Hass PRL (2008), Lopes dos Santos PRL (2008)

**Significant difference from epitaxial graphene grown on Si terminated surface of SiC, where Bernal stacked layers are present**

Ohta PRL (2007), Bostwick Nature Phys. (2007), Zhou Nature Mat. (2008)

# Experimental setup

**Far infrared transmission (FIR) spectroscopy in magnetic fields (Landau level spectroscopy)**

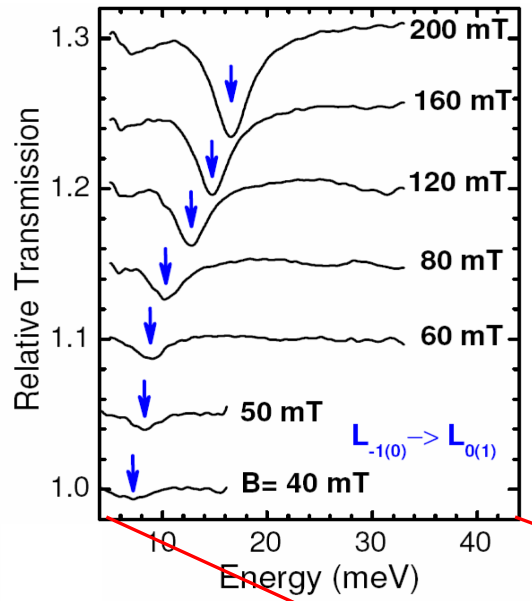


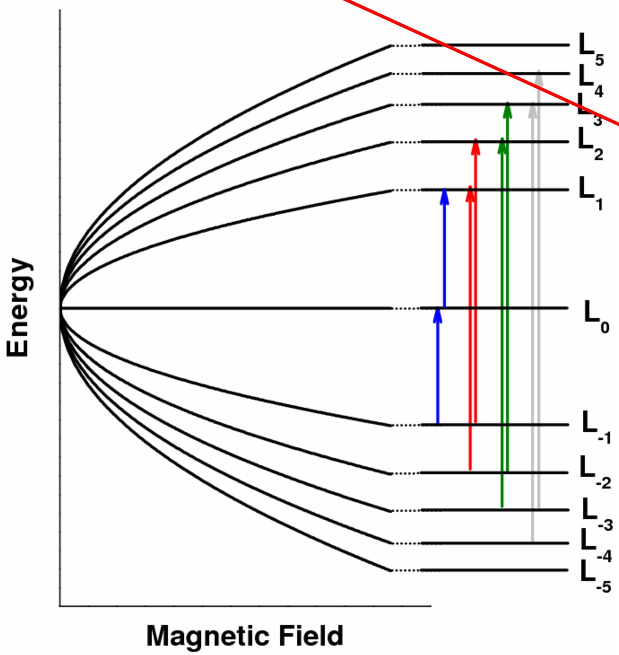

**Transmission experiment probes all graphene layers simultaneously**

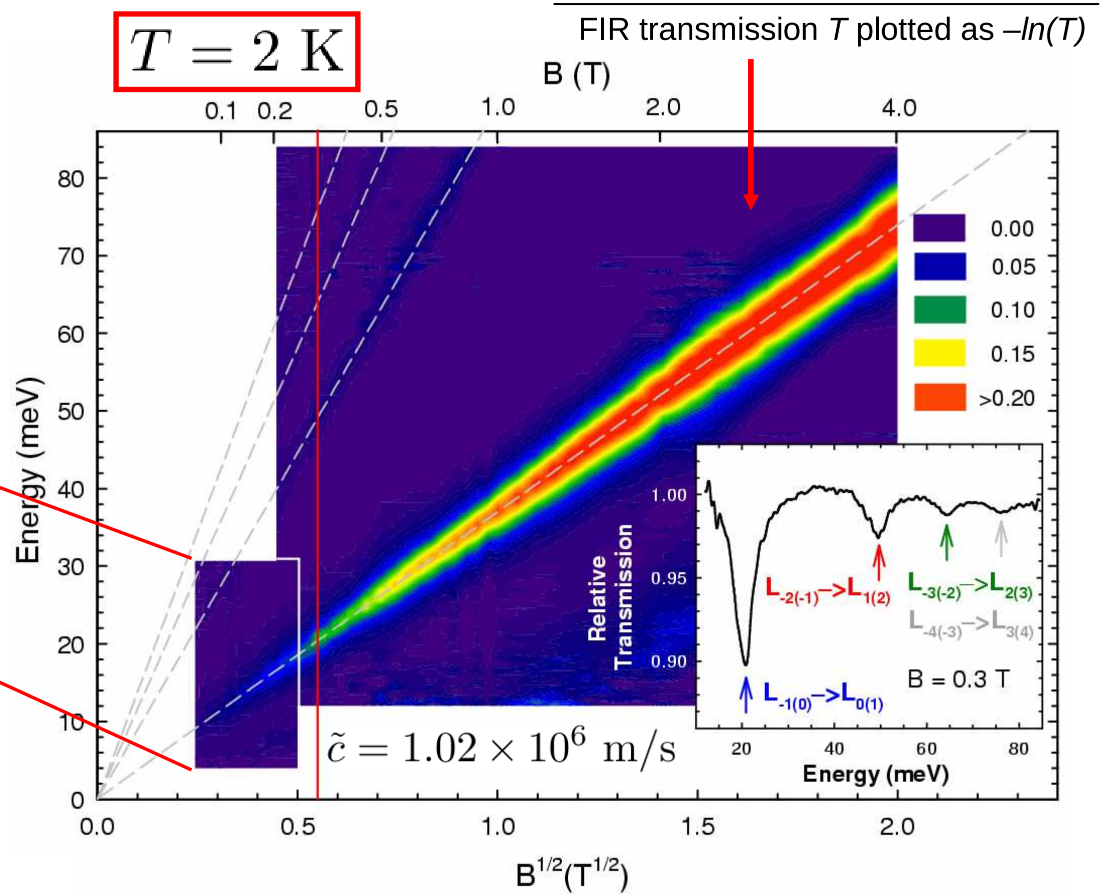
**Relative change of the sample transmission at finite magnetic field:**

$$\frac{T(B)}{T(B=0)}$$

# Cyclotron resonance at low magnetic fields




**Energy spectrum:**

$$E_n = \text{sgn}(n)\tilde{c}\sqrt{2e\hbar B|n|}$$

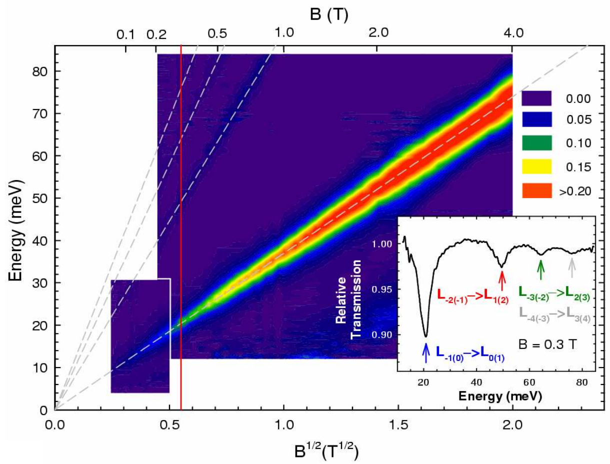
**Selection rules for dipole-allowed transitions in graphene:**

$$|n| \to |n| \pm 1$$

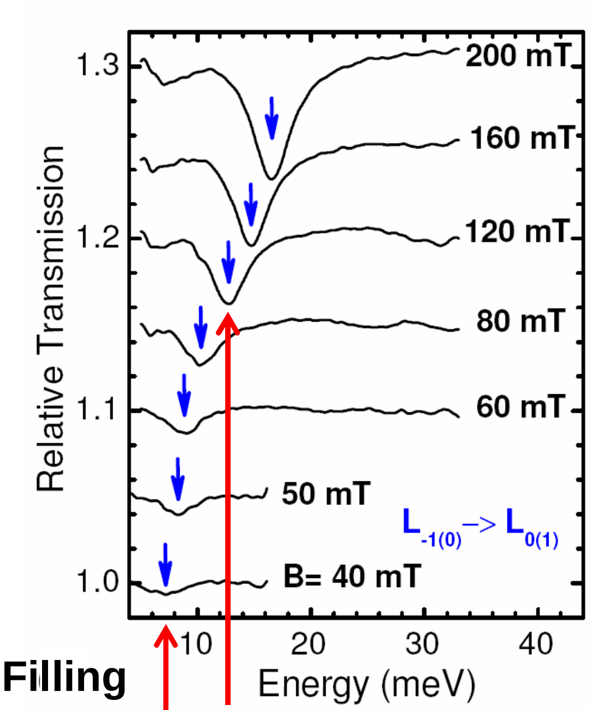
M. Sadowski et al., Phys. Rev. Lett. 97, 266405 (2006)
Z. Jiang et al., Phys. Rev. Lett. 98, 197403 (2007)

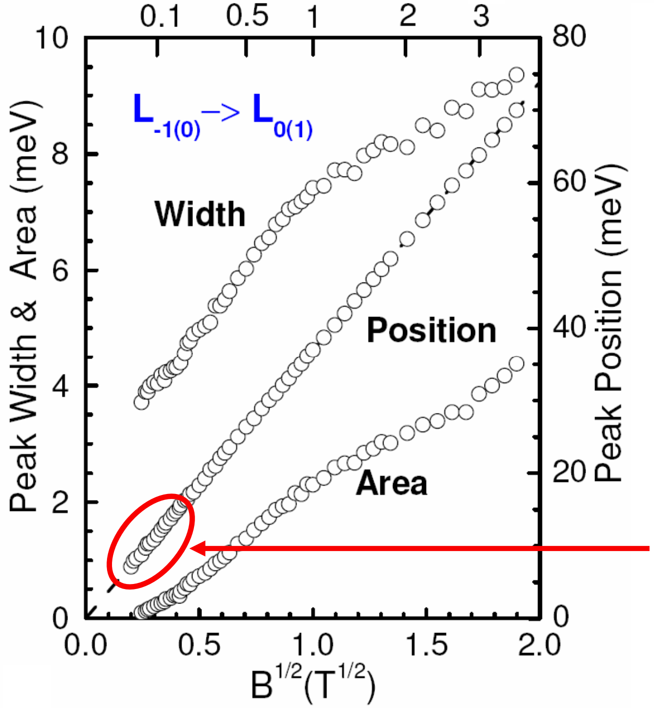
# Analysis of low magnetic field data

Focus on $L_{-1(0)} \rightarrow L_{0(1)}$ line representing transitions from/to the vicinity of the Fermi level.




Well-defined line followed down to $B \sim 40$ mT at the energy of $\sim 7$ meV




No signs of any gap opened at the Dirac point ($\Delta \lesssim 1$ meV)

No direct signs of e-e interaction in spectra when 1st Landau level is gradually (de)populated

Filling factor

$\nu \approx 2$

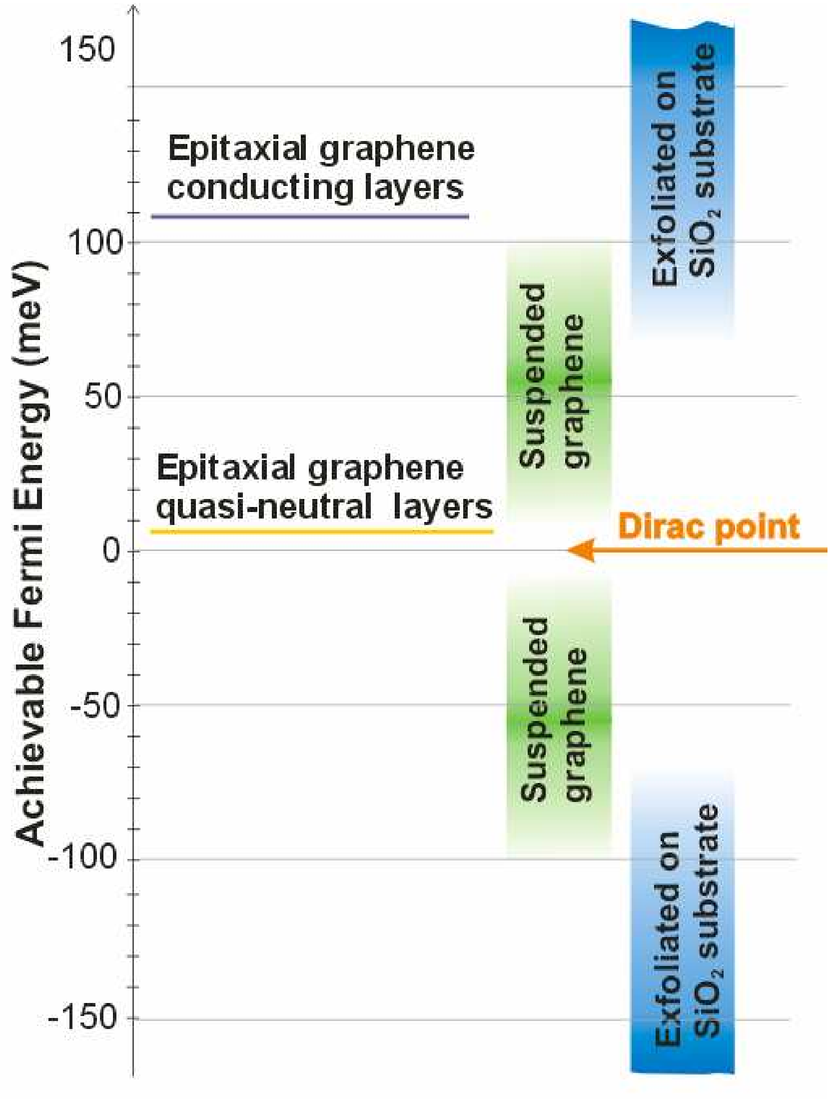
$\nu \approx 6$

Estimation of the carrier density in quasi-neutral graphene layers

$$n_0 \approx 5 \times 10^9 \text{ cm}^{-2}$$

$$\varepsilon_F = \tilde{c}\hbar\sqrt{\pi n_0} \approx 8 \text{ meV}$$

## Achievable Fermi level (density) in current graphene systems




**Inaccessibility of the Dirac point in current exfoliated graphene due to electron and hole puddles**

J. Martin et al., Nature Phys. 4, 144 (2008)

**Exfoliated graphene on $SiO_2$/Si substrate** $n_0 \gtrsim 5 \times 10^{11}\ \mathrm{cm}^{-2}$

K. S. Novoselov et al., Nature 438, 197 (2005)
Y. B. Zhang et al., Nature 438, 201 (2005)
Y.-W. Tan, et al., Phys. Rev. Lett. 99, 246803 (2007)

**Epitaxial graphene (conducting layers)**

$$n_0 \sim 10^{12}\ \mathrm{cm}^{-2}$$

C. Berger et al., J. Phys. Chem. B 108, 19912 (2004)
C. Berger et al., Science 312, 1191 (2006)

**Suspended graphene** $n_0 \gtrsim 10^{10}\ \mathrm{cm}^{-2}$

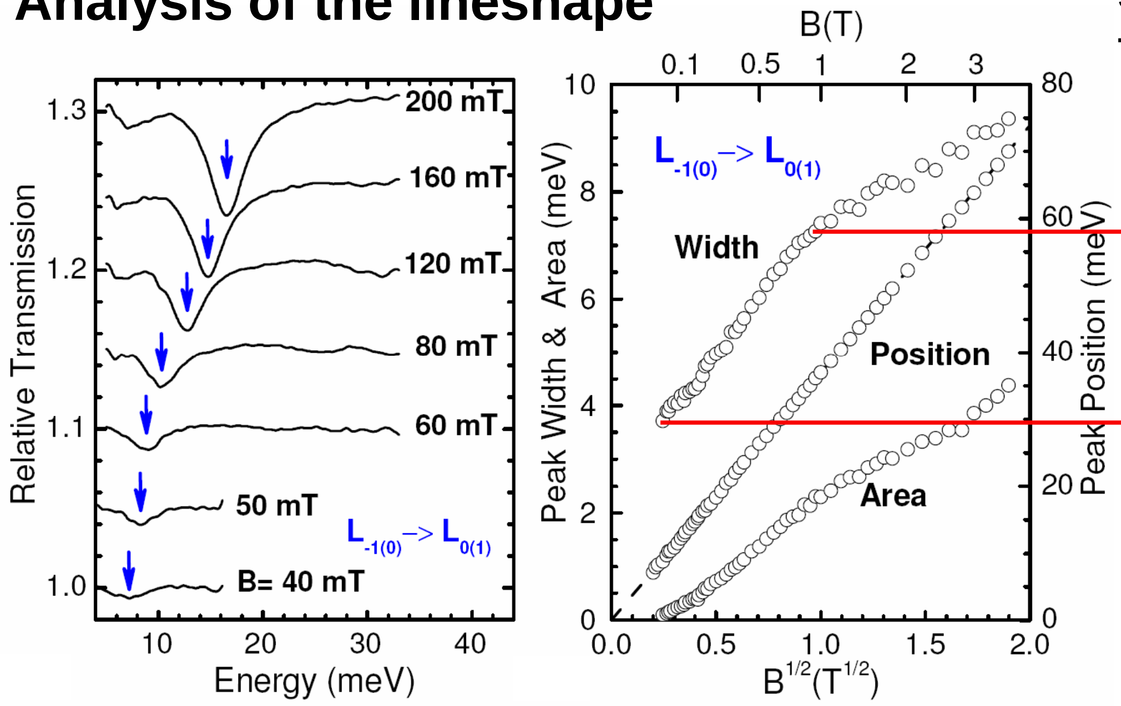
K. I. Bolotin et al., Solid State Commun. 146, 351 (2008)
X. Du et al., Nature Nanotechnology 3, 491 - 495 (2008)

**Epitaxial graphene (quasi-neutral layers)**

$$n_0 = 5 \times 10^{9}\ \mathrm{cm}^{-2}$$

M. Orlita et al., arXiv:0808.3662 (2008)

# Analysis of the lineshape




**Scattering time from the linewidth**

$$\tau = 2\hbar/\delta E$$

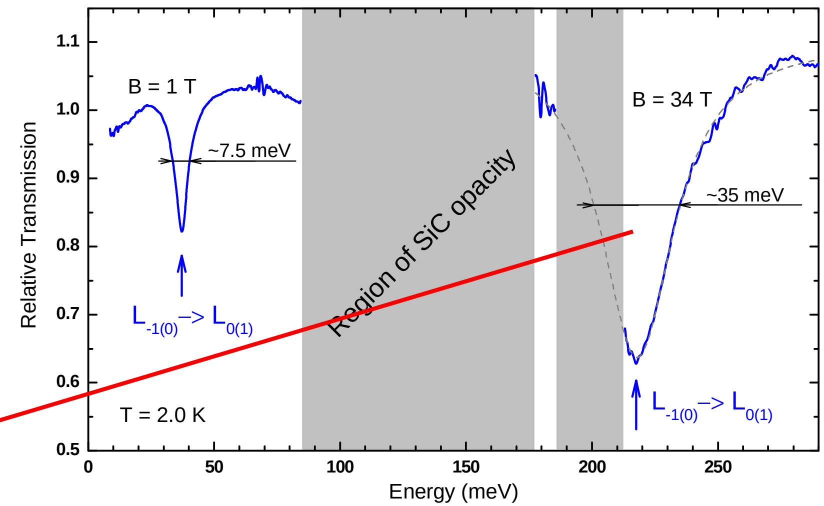
$$\tau \sim 150 \text{ fs}$$

$$\tau \sim 300 \text{ fs}$$

**….at extremely low and homogeneous carrier density….**

**Linewidth nearly increases as $\sqrt{B}$ predicted for short-range scattering (independent of the carrier density)**

N. H. Shon and T. Ando, J. Phys. Soc. Jap. 67, 2421 (1998)



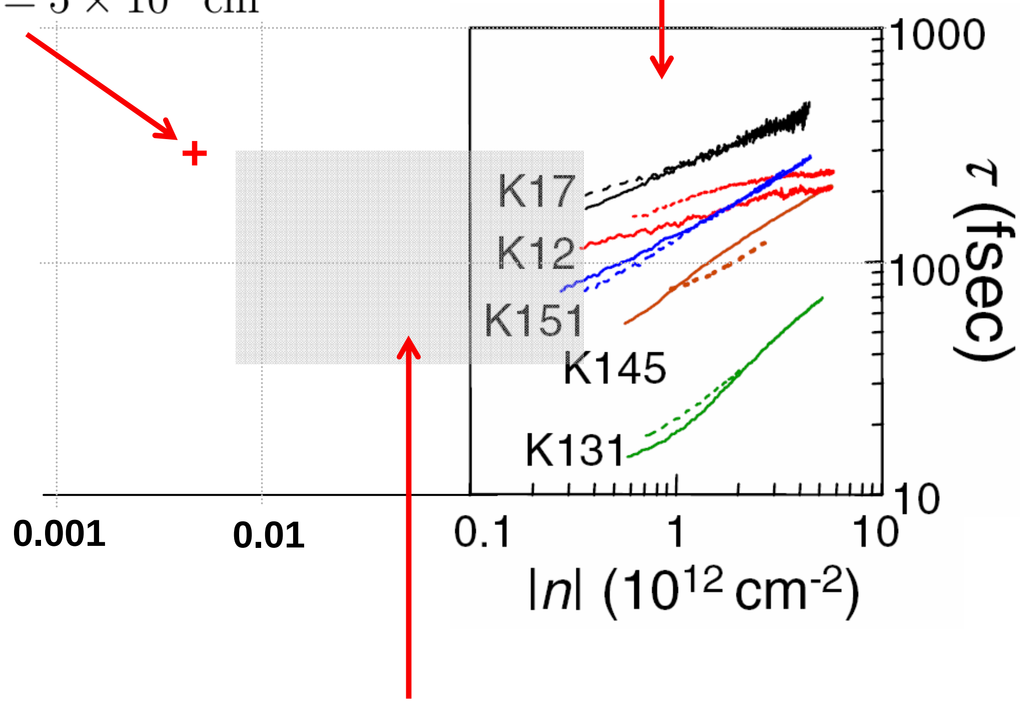

**Nearly $\sqrt{B}$-scaled increase of the linewidth continues up to very high magnetic fields….**

# Comparison of scattering times in different graphene systems

Y.-W. Tan et al., Phys. Rev. Lett. 99, 246803 (2007)

Orlita et al., arXiv:0808.3662 (2008)

300 fs @ $n_0 = 5 \times 10^9$ cm$^{-2}$




**Short-range scatterers likely dominate in epitaxial graphene giving scattering time independent of carrier density**

**Strong dependence of scattering time on carrier density in exfoliated graphene is given by dominant scattering on ionized impurities**

**Recent results on suspended graphene**

K. I. Bolotin et al., Solid State Commun. 146, 351 (2008)
X. Du et al., Nature Nanotechnology 3, 491 (2008)
K. I. Bolotin et al., Phys. Rev. Lett., to be published (2008)

# Transport properties from optical data (?)

**Estimation of the zero field conductivity from Boltzmann transport theory…..**

e.g. K. Nomura, A. H. MacDonald, Phys. Rev. Lett. 98, 076602 (2007)

$$\sigma = \frac{e^2}{\pi\hbar^2}(\varepsilon_F \cdot \tau) \approx 10\frac{e^2}{h}$$

$$\varepsilon_F = \tilde{c}\hbar\sqrt{\pi n_0} \approx 8 \text{ meV}$$

$$\delta E = 2\hbar/\tau \rightarrow \approx 3 \text{ meV}$$

**Close to values of minimum conductivity in clean samples….**

J.-H. Chen et al., Nature Physics 4, 377 (2008)

**Mobility from the conductivity (i.e. from linewidth)**

$$\frac{\sigma(\varepsilon)}{e n_0} = \mu \approx 500.000 \text{ cm}^2/(\text{V.s})$$ **?**

**Mobility from the semiclassical condition for quantization into Landau levels (i.e. from appearance of the line in the spectrum)**

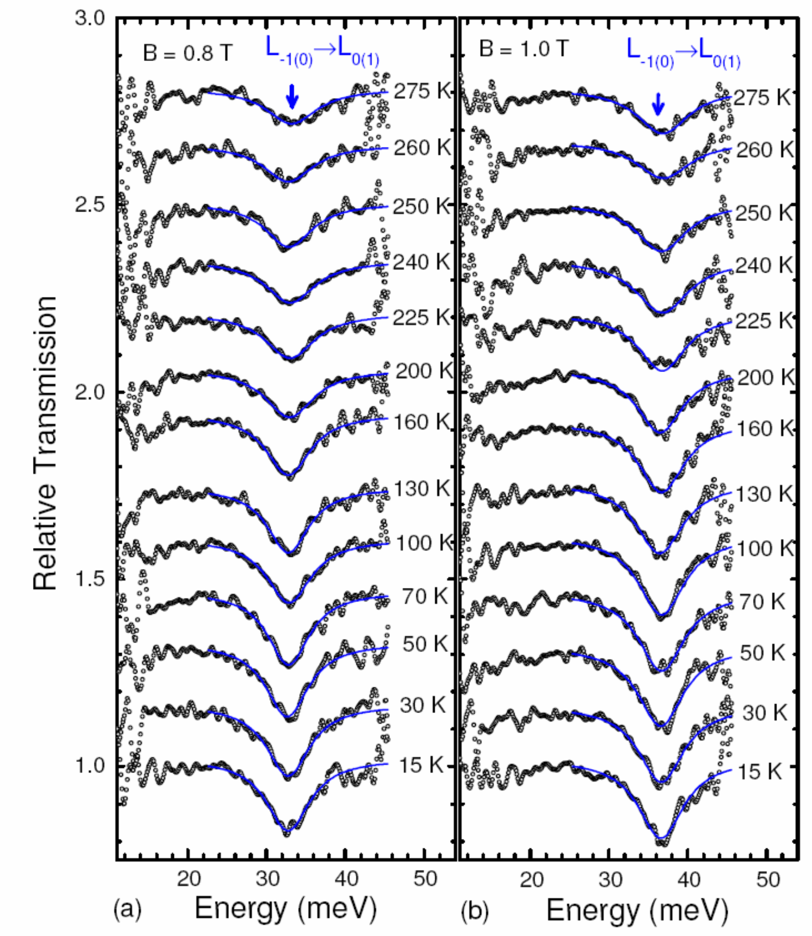
$$\omega_c \tau > 1 \quad \Rightarrow \quad \mu B > 1 \quad \Rightarrow \quad \mu > 250.000 \text{ cm}^2/(\text{V.s})$$

**Main line observed down to** $B = 40 \text{ mT}$

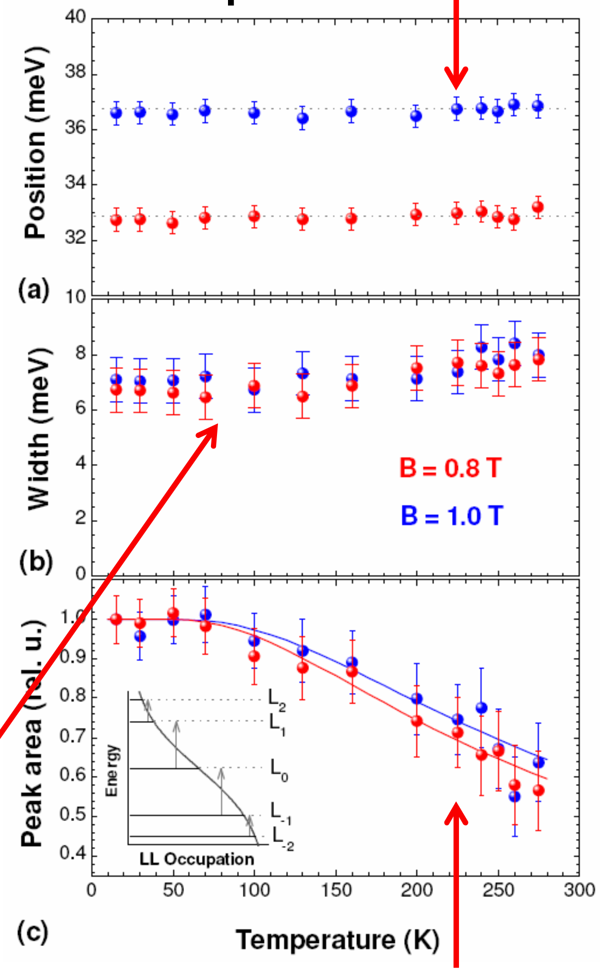
**However….** **No varification in transport experiment currently possible**

**Unknown behaviour of mobility with increasing carrier density**

# Temperature dependence




**Fermi velocity independent of temperature**




**No scattering process activated up to room temperature. No decrease of the mobility expected!!! (Record at RT?)**

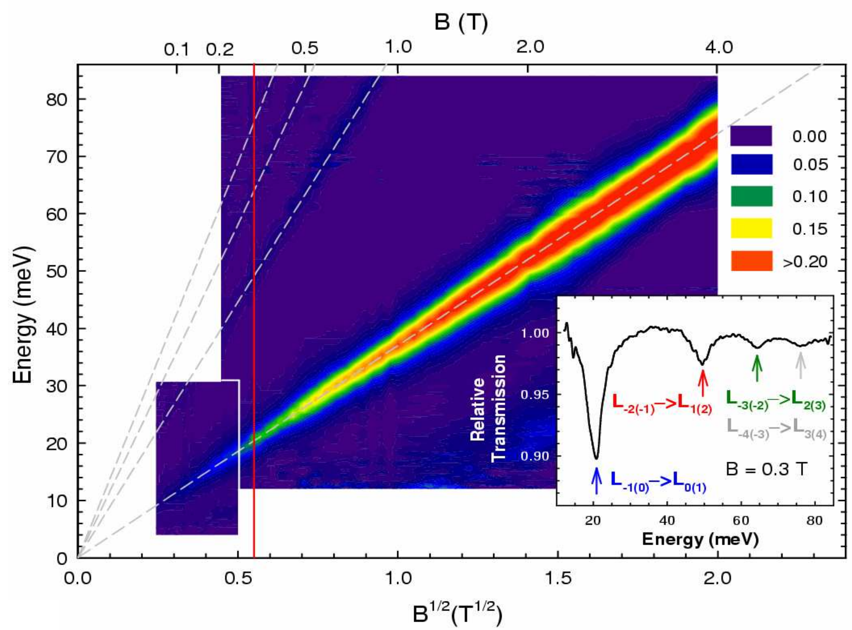
**Decrease of the line intensity due to occupation effect**

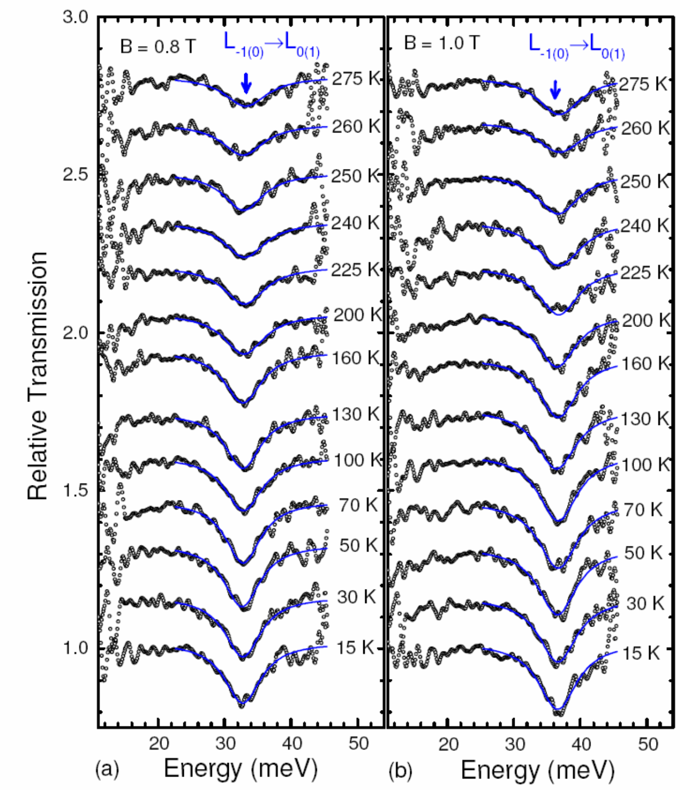
$$I(T) = 1 - 2f_1 = 1 - \frac{2}{1 + \exp(E_1/k_B T)}$$

S. V. Morozov et al., Phys. Rev. Lett. 100, 016602 (2008)

# Conclusions

**Multilayer epitaxial graphene is a well-defined system of Dirac fermions with the extremelly low carrier density allowing to investigate the immediate vicinity of the Dirac point (few meV)**




**Mobility deduced from optical data exceeds** $250.000\ \mathrm{cm}^2/(\mathrm{V.s})$ **and survices up to room temperature**

**Quantized motion of carriers in multilayer graphene surprisingly survives up to room temperature at magnetic field well below 1 T**

M. Orlita et al., arXiv:0808.3662 (2008)