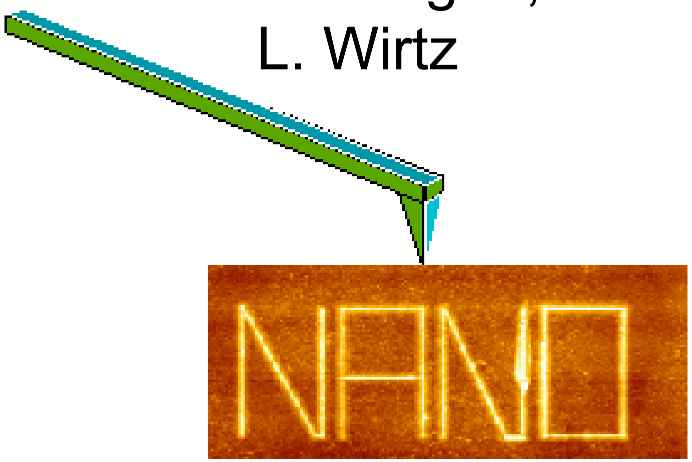
Raman imaging of graphene

Klaus Ensslin

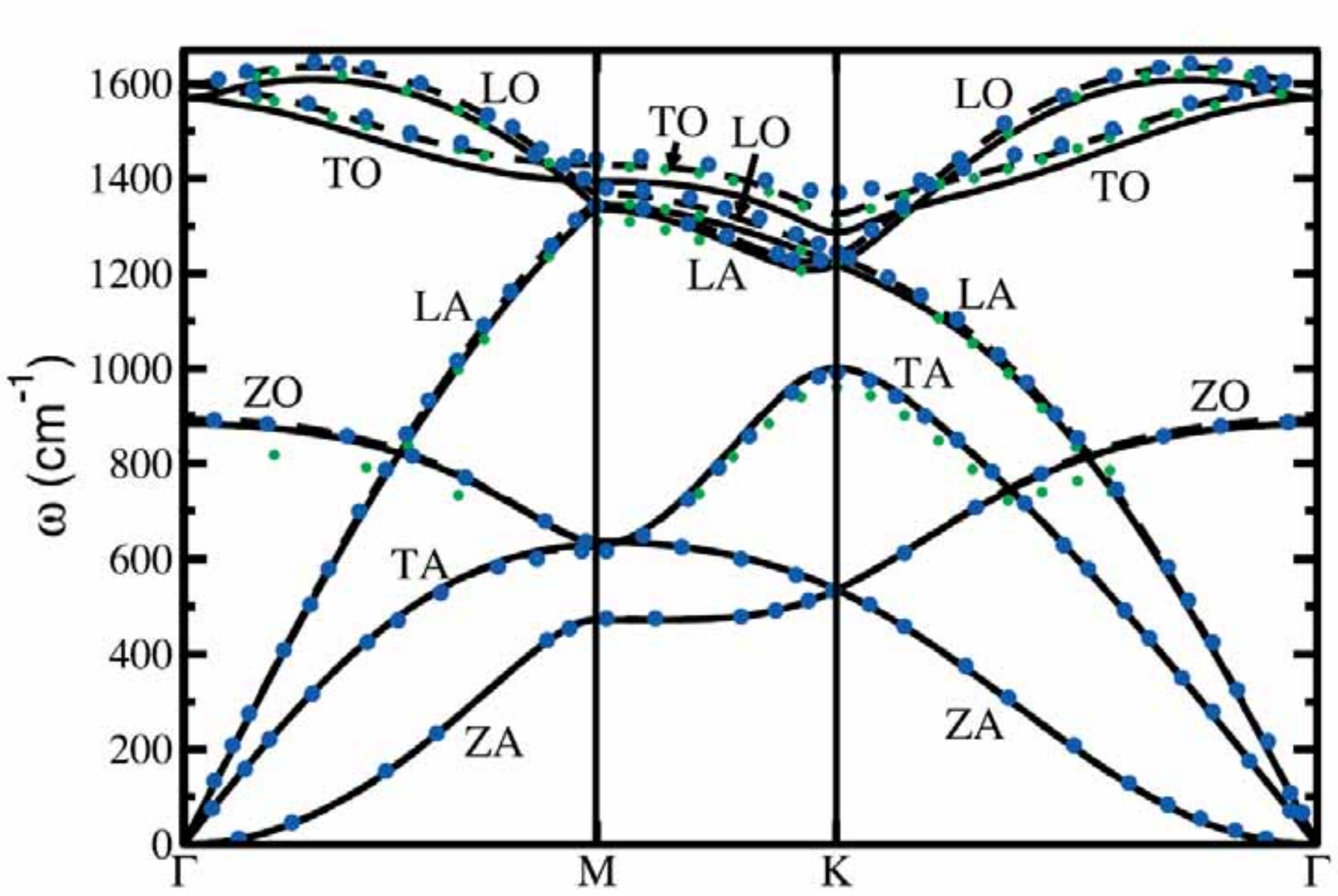
Solid State Physics ETH Zürich

D. Graf, F. Molitor, C. Stampfer, T. Ihn	ETH Zürich
A. Jungen, and C. Hierold	ETH Zürich
L. Wirtz	Lille



- Raman on graphene
- Spectral and spatial resolution
- Transport

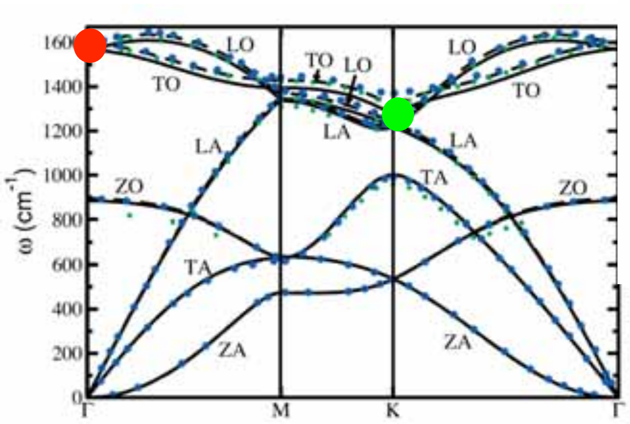
Phonon spectrum of graphite

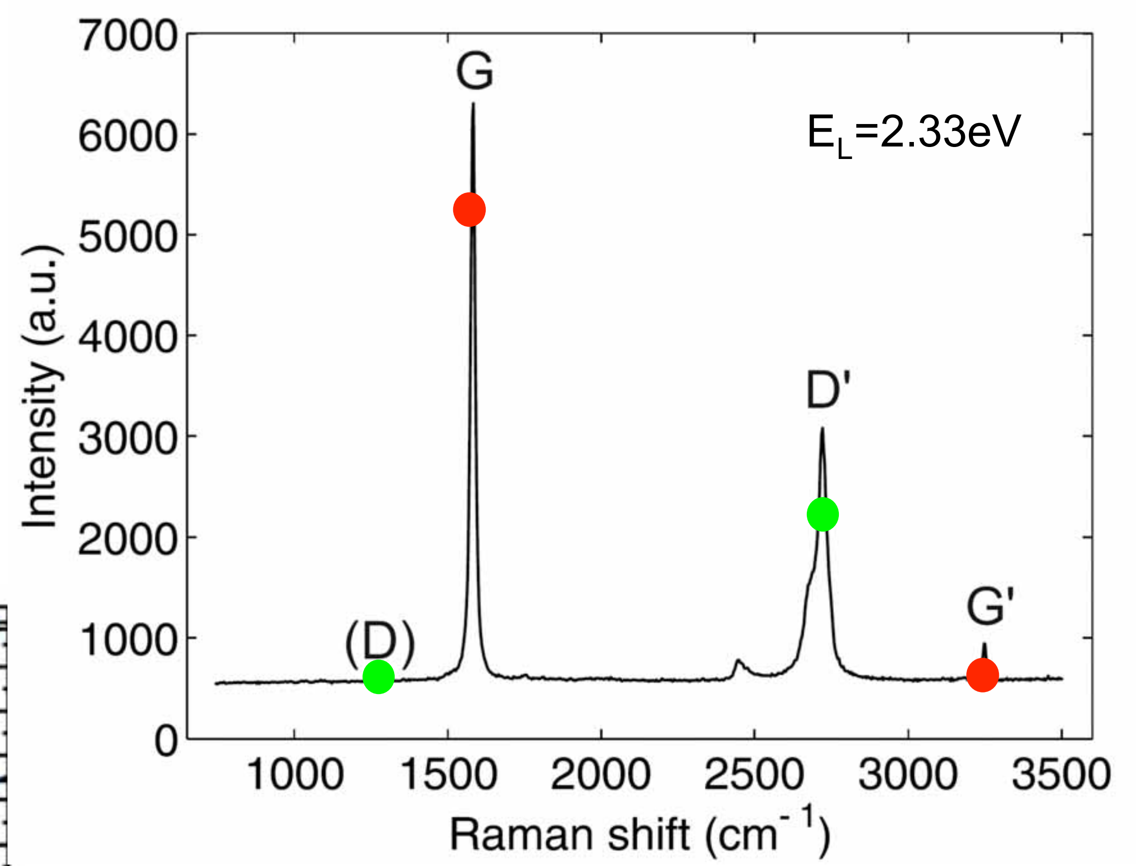


Ref.: Ludger Wirtz and Angel Rubio, Solid State Communications **131**, 141 (2004)

- does the phonon spectrum depend on the number of layers ?

Raman spectrum of graphite

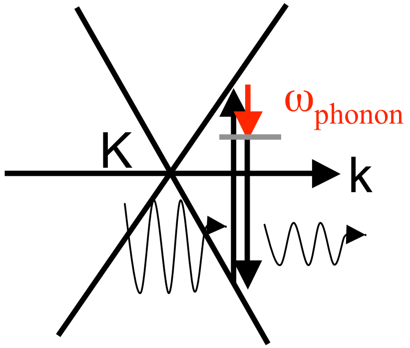




- does the phonon spectrum depend on the number of layers ?

Raman spectrum of graphite

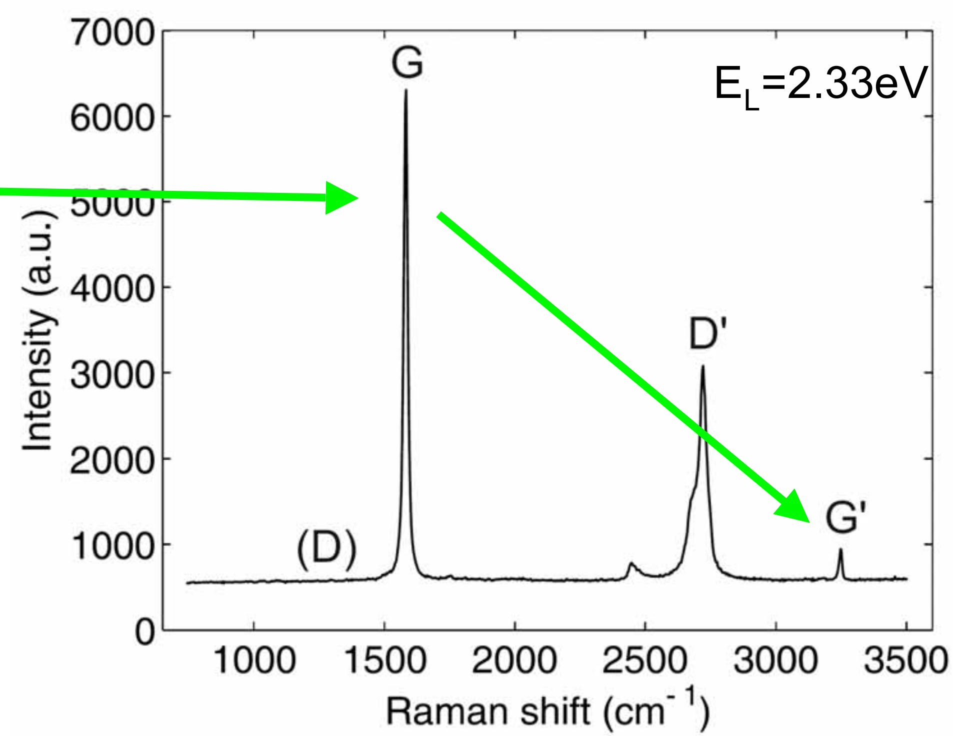
Single-resonant

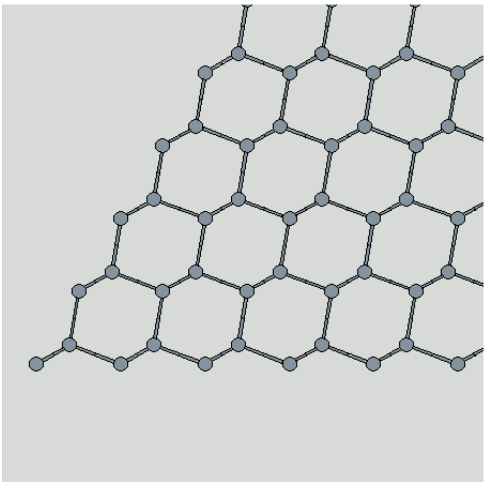


at Γ point, k~0

→ **G, (1582 cm^{-1})**

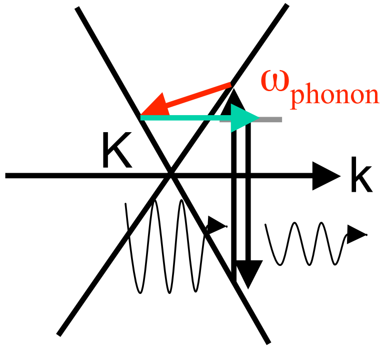
overtone G'





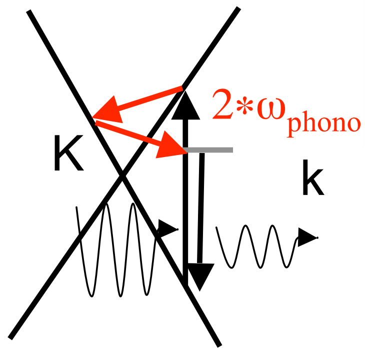
G- line

Raman spectrum of graphite

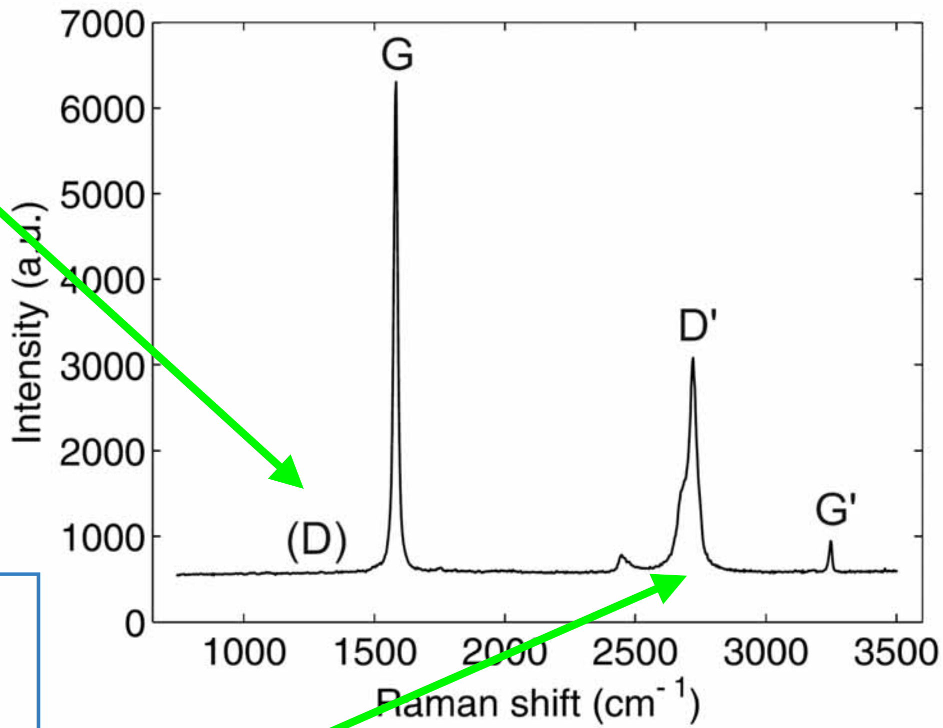


close to K point, k>0
elastic scattering → **D**
(~1350 cm^{-1})

Double-resonant

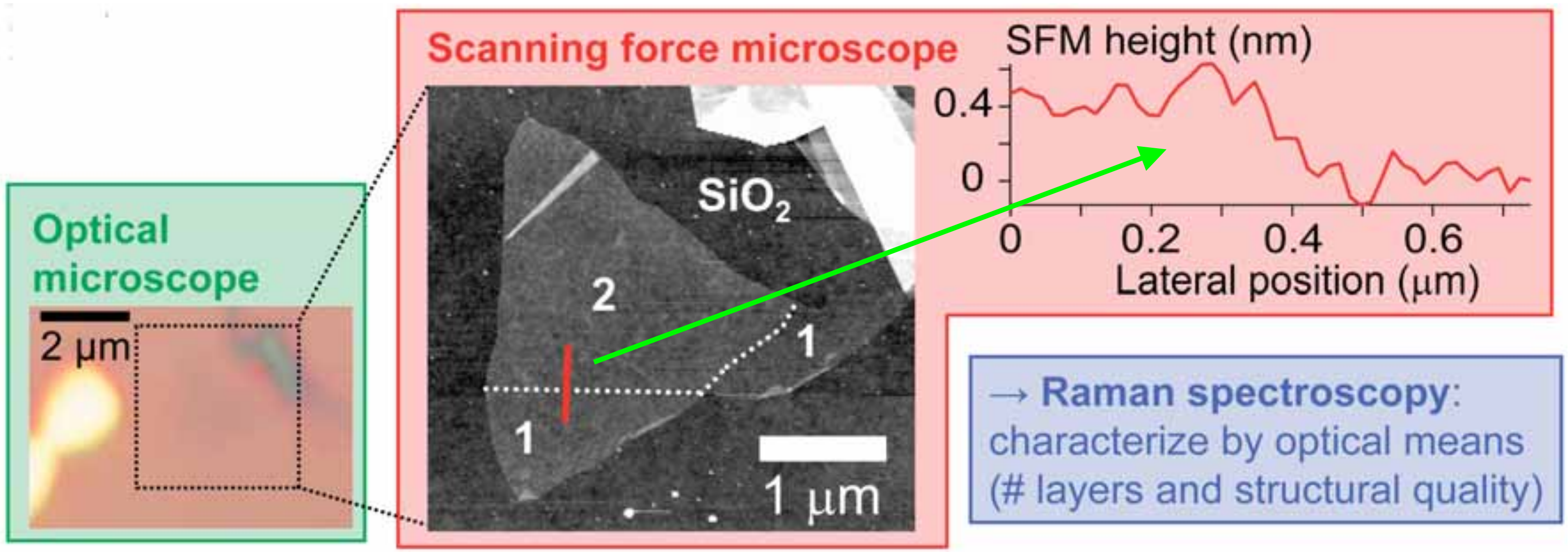


close to K point, k>0
→ **D‘ (~2700 cm^{-1})**



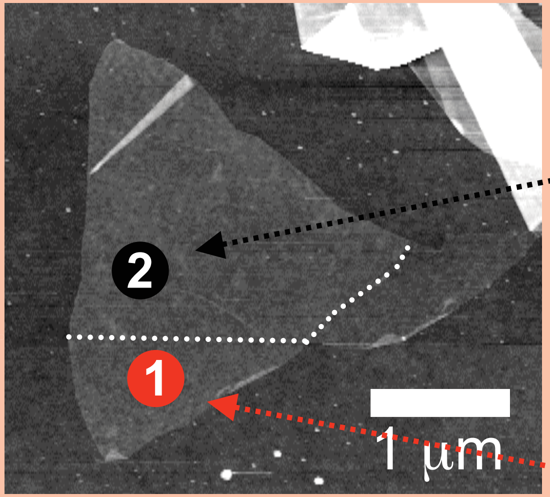
double-resonant Raman model
C. Thomsen and S. Reich
PRL 85, 5214 (2000)

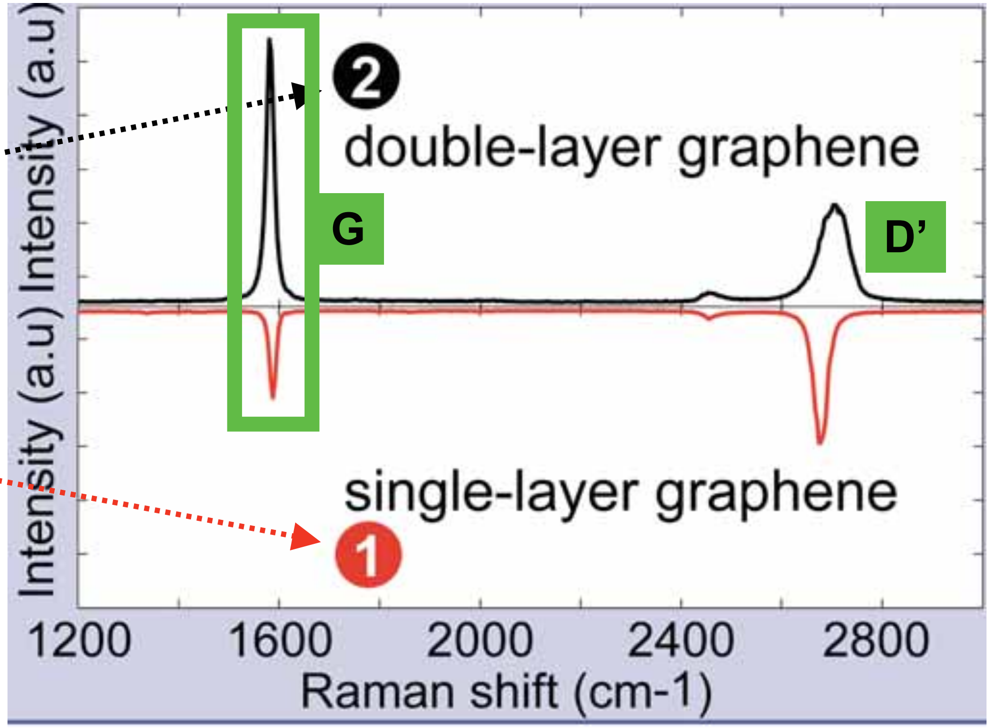
Spatial resolution: AFM



Raman spectra of single- and double layer graphene

Scanning force microscope



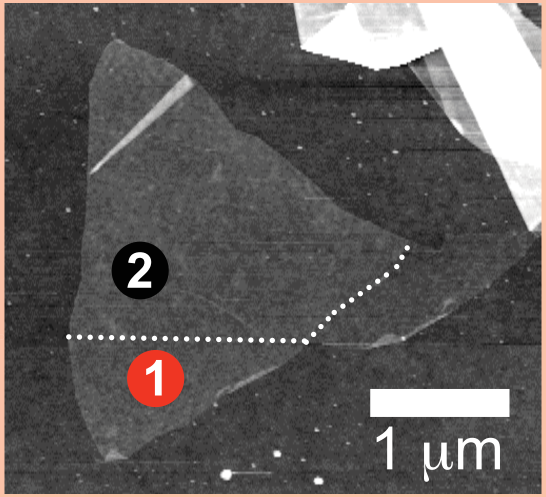


Scanning confocal Raman spectroscopy:

- Laser excitation of 532 nm/ 2.33 eV
- Spot size:

Raman mapping: intensity of G-line

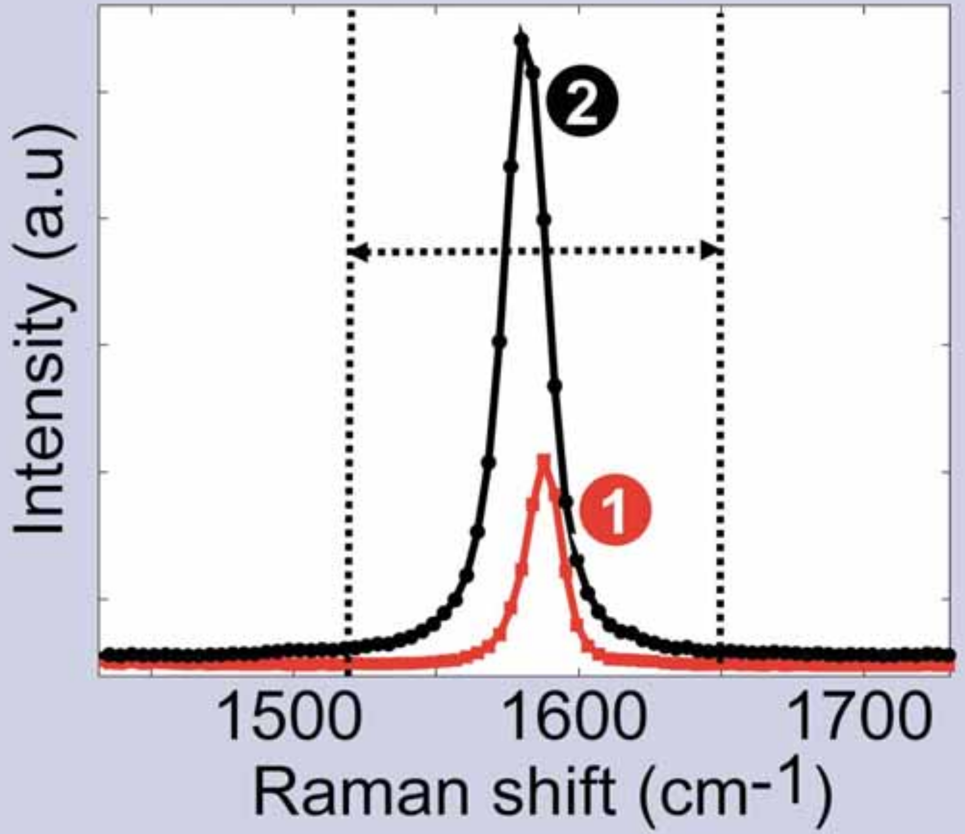
Scanning force microscope



Scanning confocal Raman spectroscopy:

- Laser excitation of 532 nm/ 2.33 eV
- Spot size:

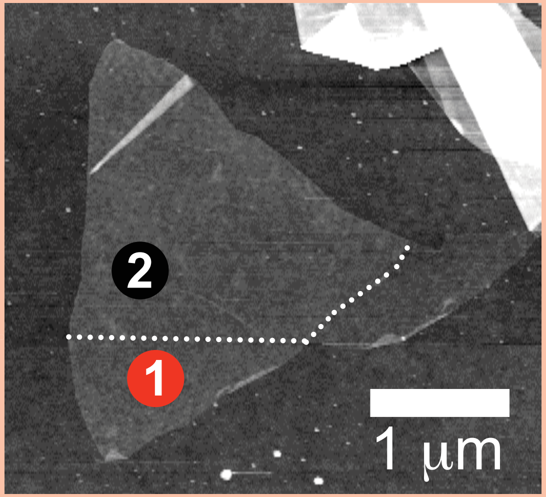
Raman: G line intensity



two layers have higher G-line intensity, slightly different peak position

Raman mapping: intensity of G-line

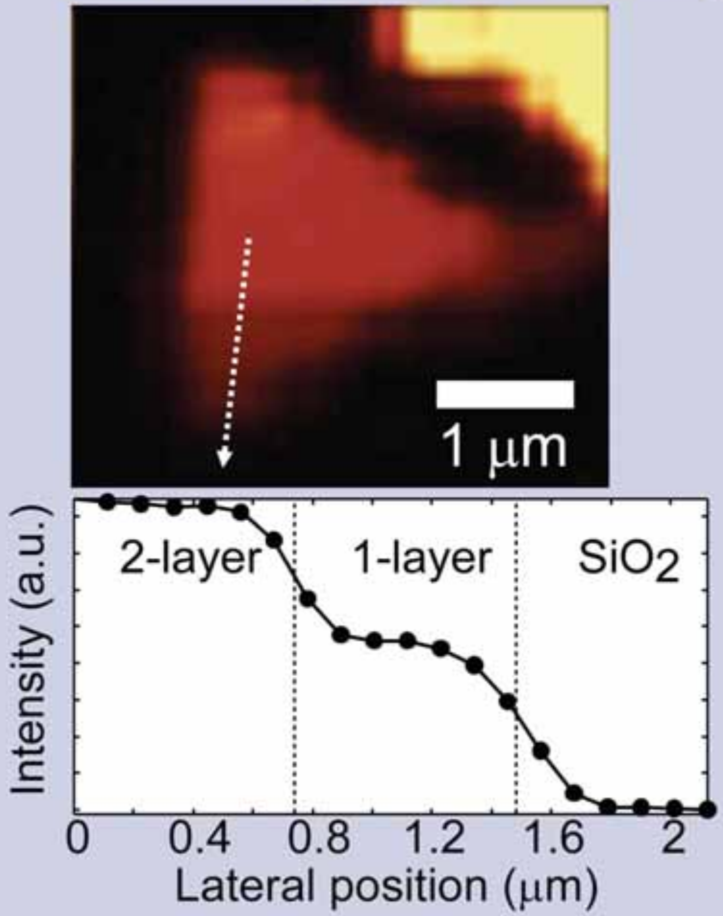
Scanning force microscope



Scanning confocal Raman spectroscopy:

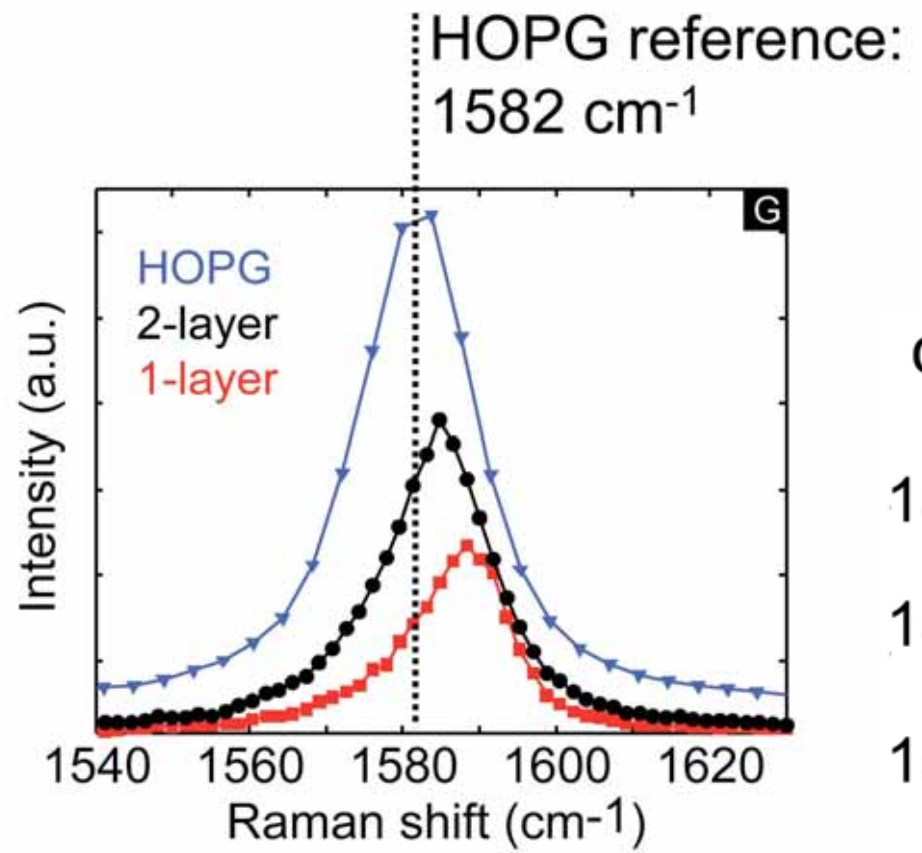
- Laser excitation of 532 nm/ 2.33 eV
- Spot size:

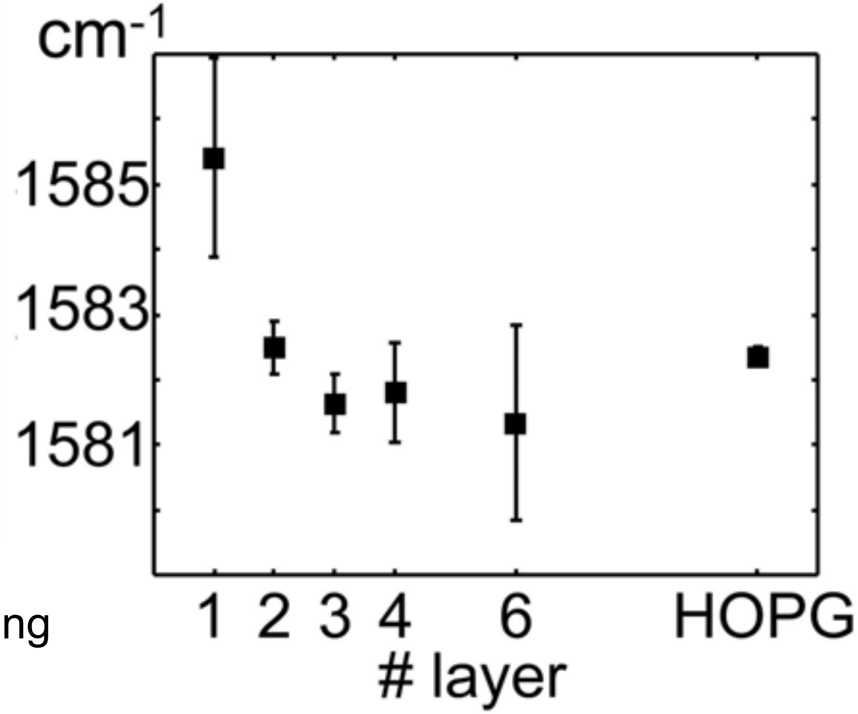
Raman: Integrated G line intensity



intensity increases with layer thickness

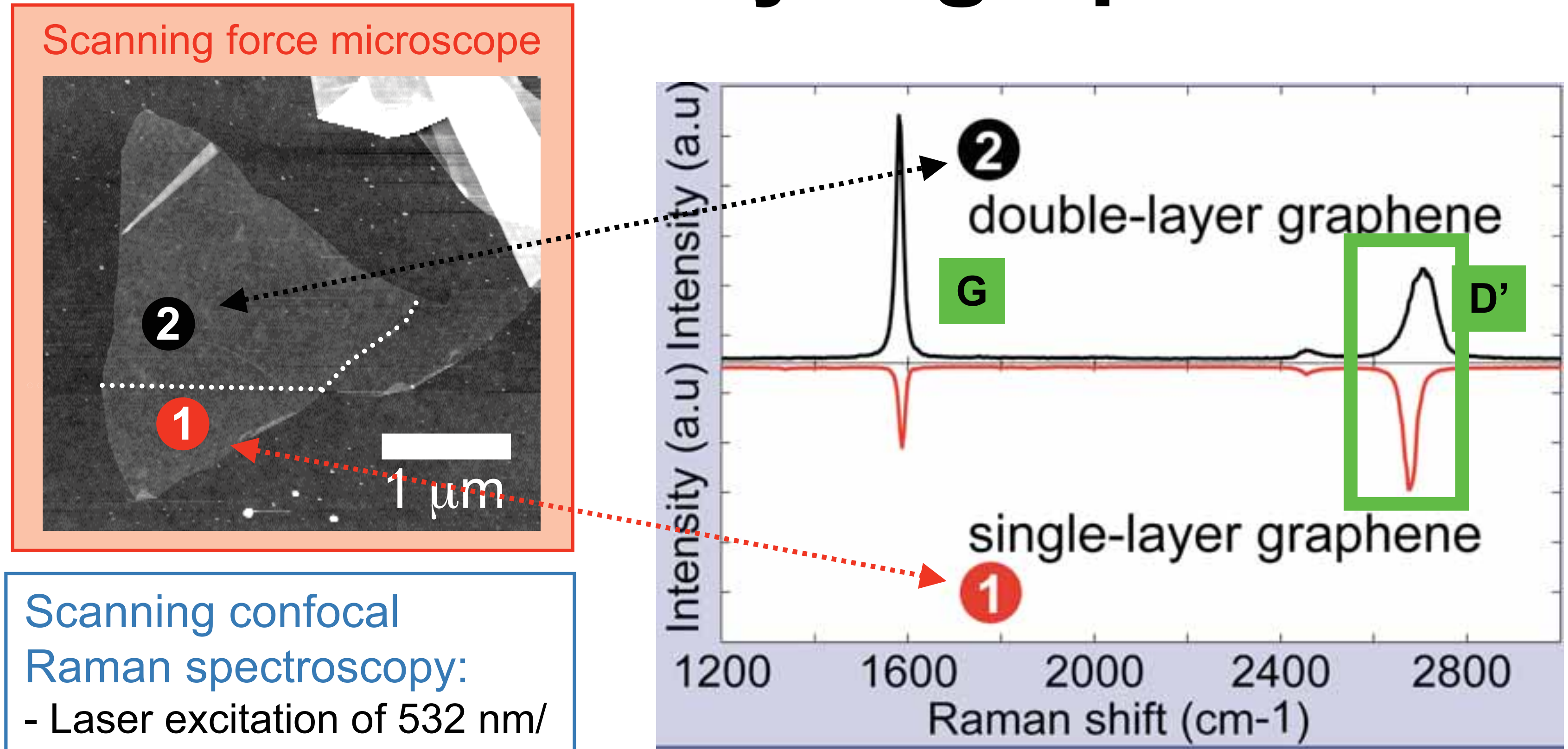
Raman mapping: position of G-line





shift of resonance presumably due to doping
-> variations across a flake

Raman spectra of single- and double layer graphene

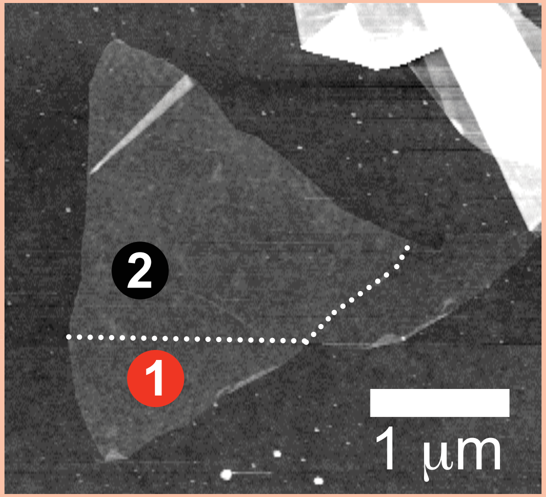


Scanning confocal Raman spectroscopy:

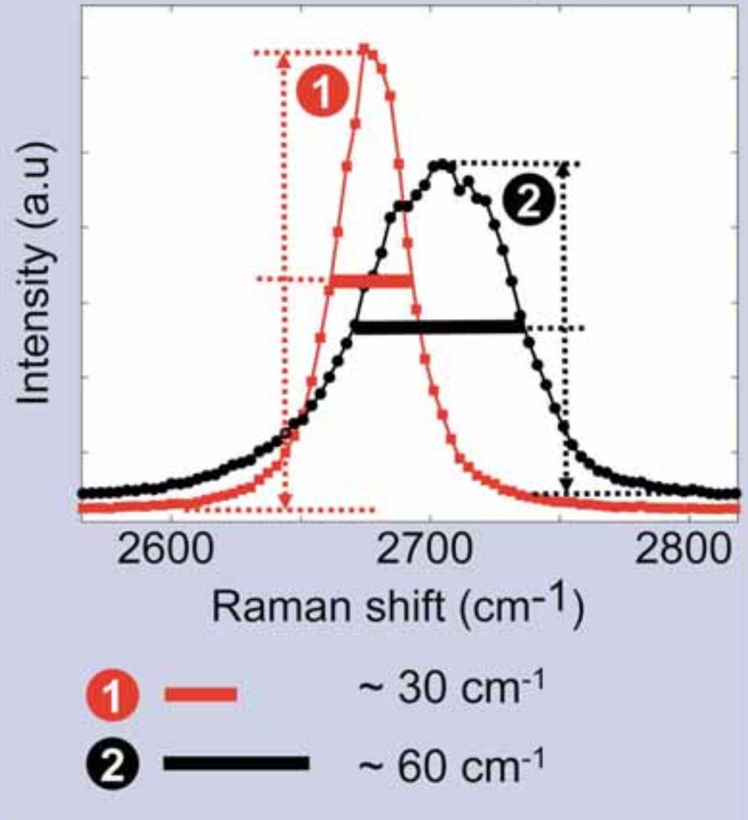
- Laser excitation of 532 nm/ 2.33 eV
- Spot size:

Raman mapping: FWHM of the D‘ line

Scanning force microscope



Raman: D‘ line intensity



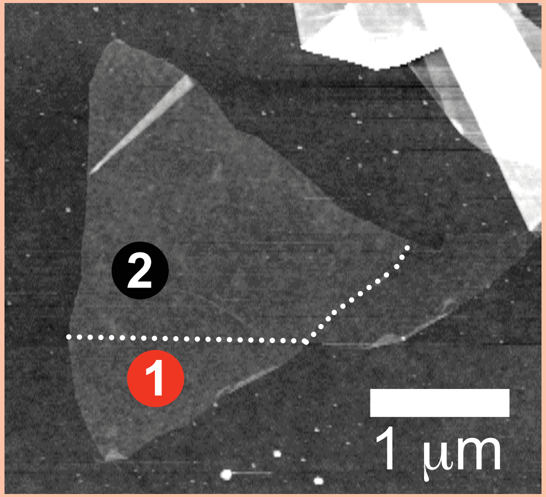
Scanning confocal Raman spectroscopy:

- Laser excitation of 532 nm/ 2.33 eV
- Spot size:

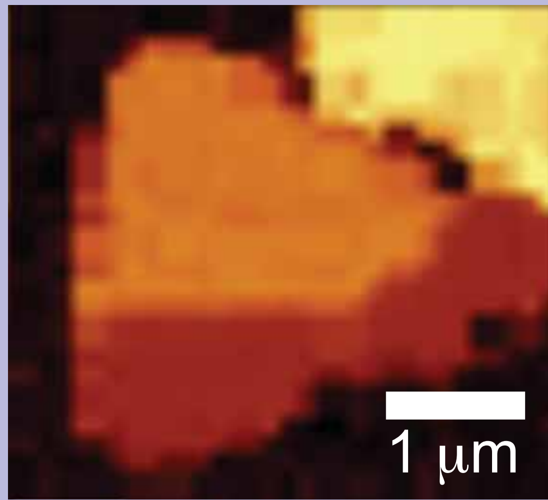
two layers have broader D’-line, different peak position

Raman mapping: FWHM of the D‘ line

Scanning force microscope



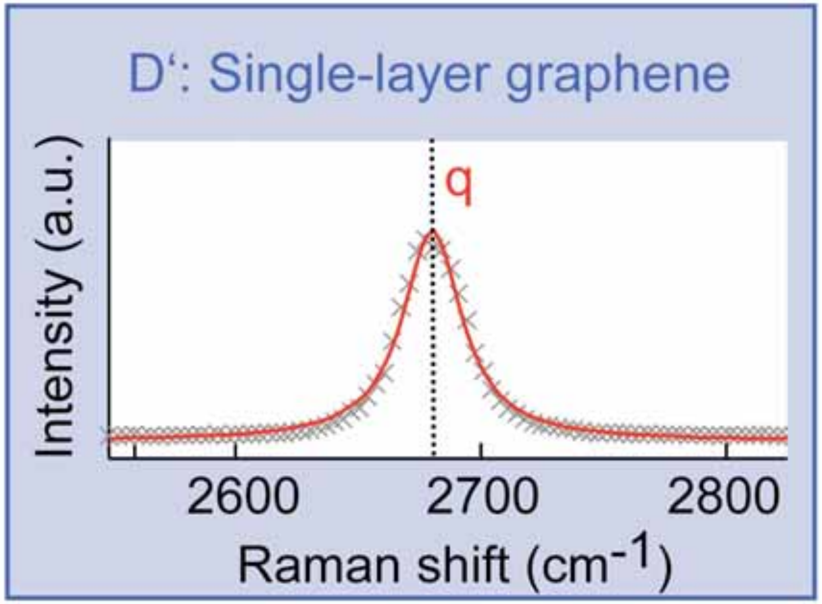
Raman: FWHM of D‘ line

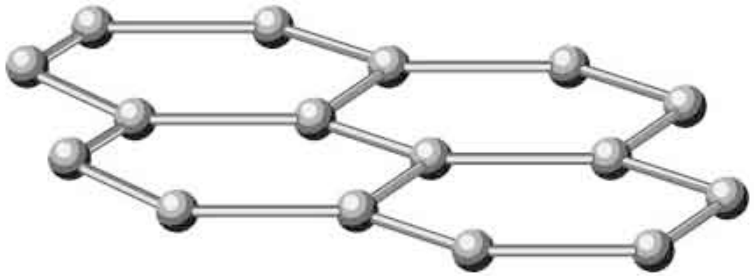


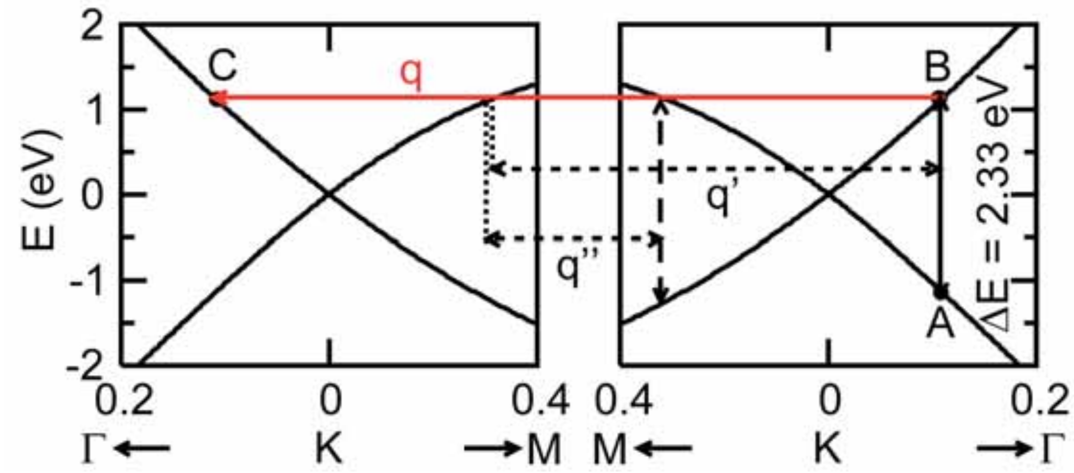
Scanning confocal Raman spectroscopy:
- Laser excitation of 532 nm/ 2.33 eV
- Spot size:

two layers have broader D'-line, different peak position

D‘ line for <u>single</u> layer graphene

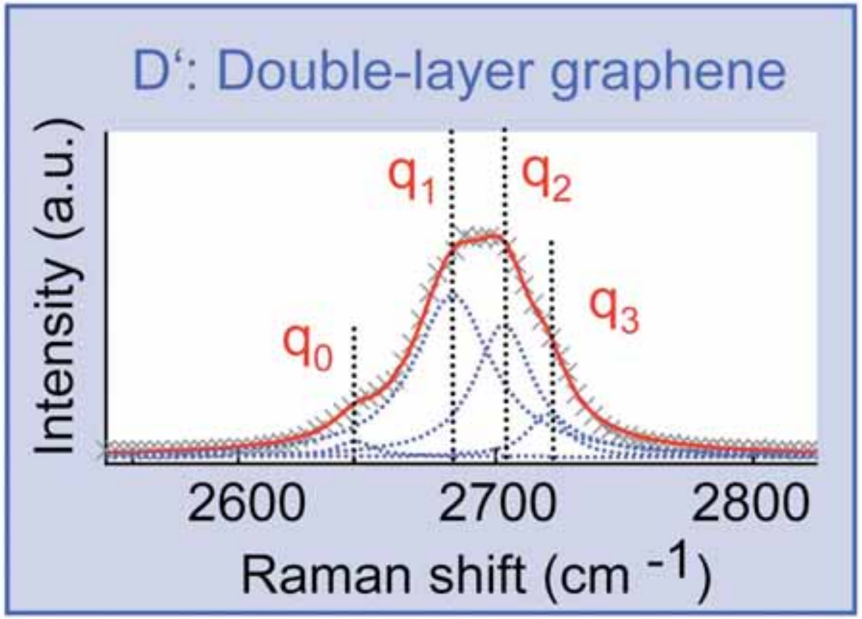


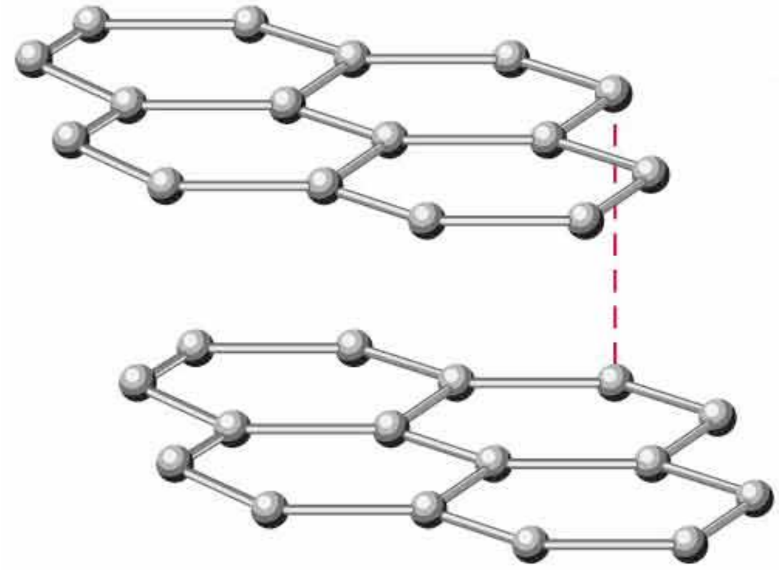


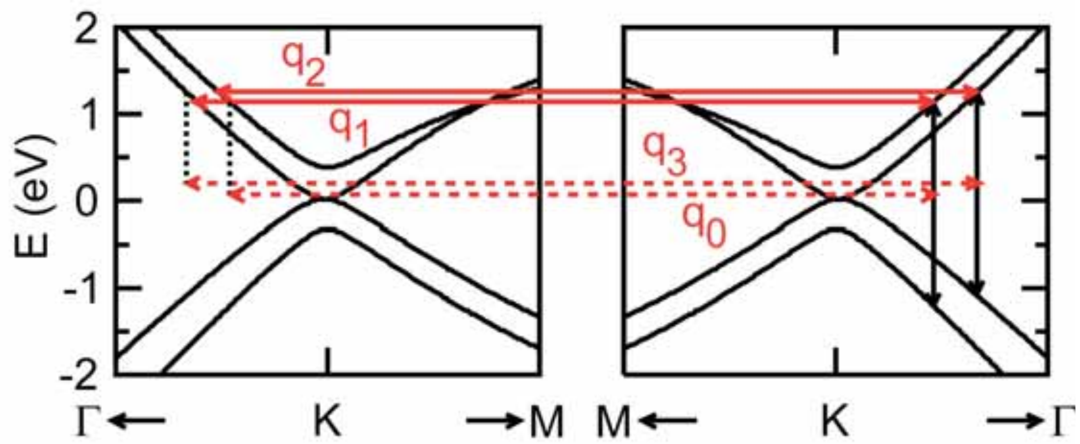


Related work: A.C. Ferrari et al., *PRL* ***97***, 187401 (2006)

D‘ line for <u>double</u> layer graphene

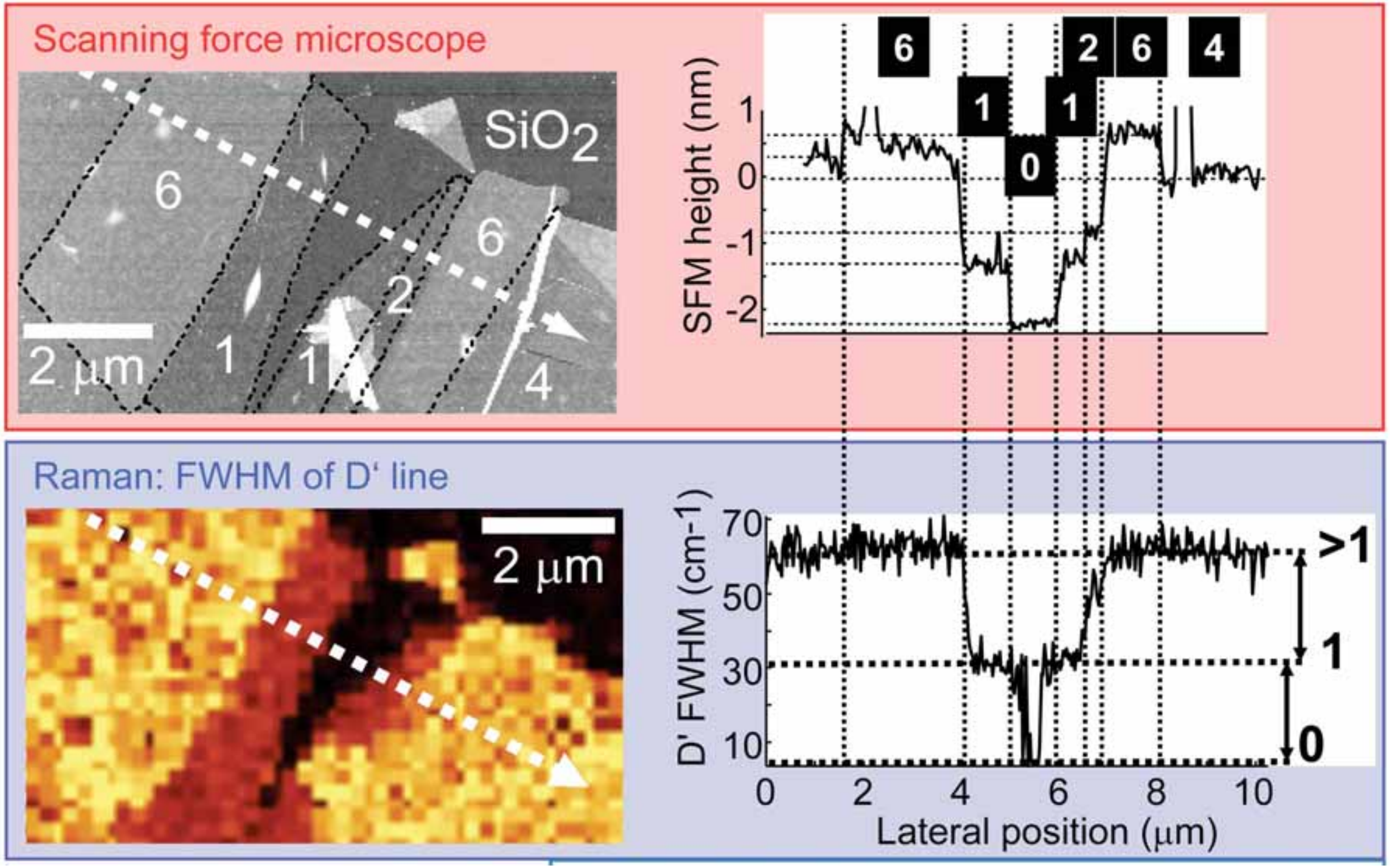






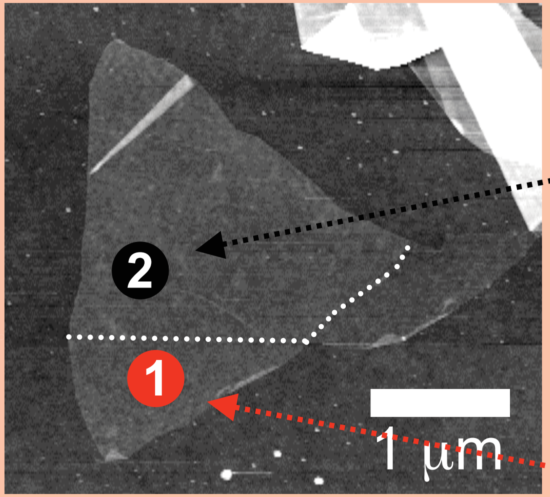
Related work: A.C. Ferrari et al., *PRL* ***97***, 187401 (2006)

Detecting single layer graphene



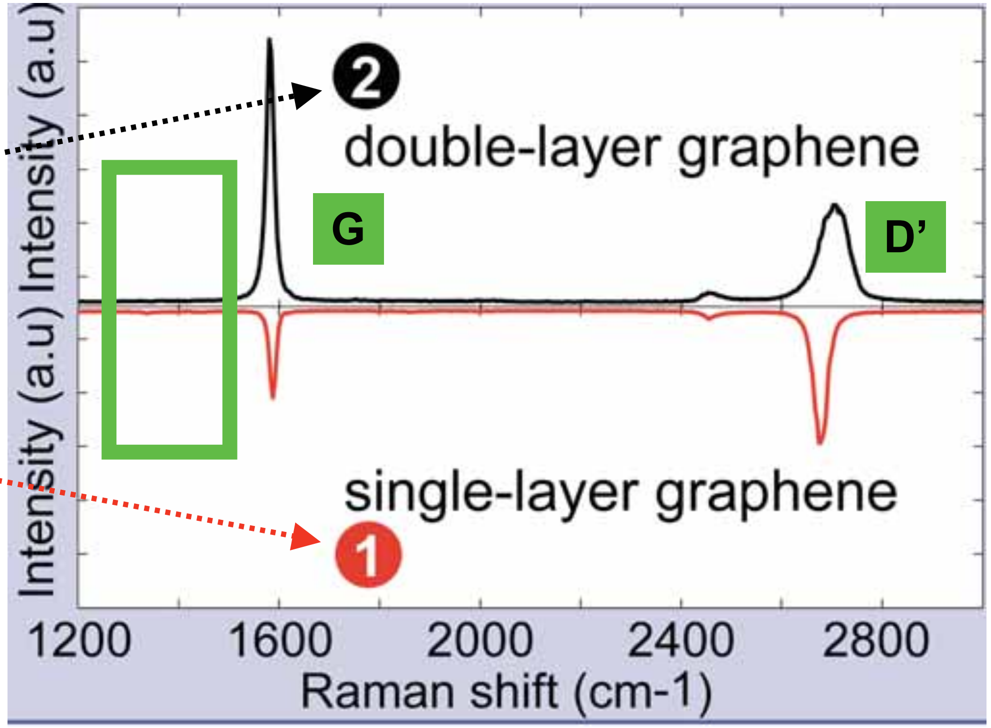
What about the D-line?

Scanning force microscope

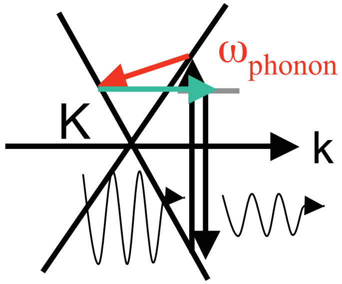


Scanning confocal Raman spectroscopy:

- Laser excitation of 532 nm/ 2.33 eV
- Spot size:



Raman mapping: intensity of the D line

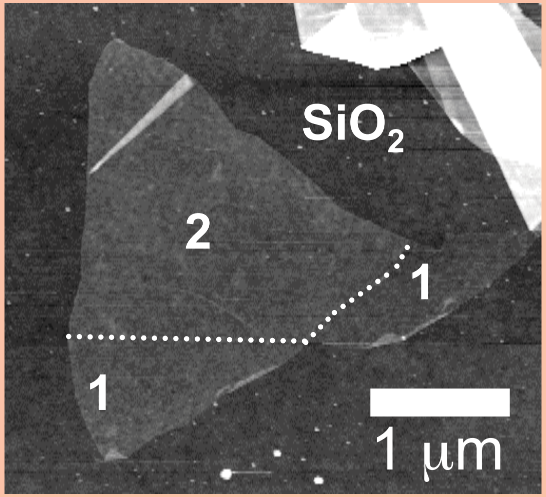


Double-resonant

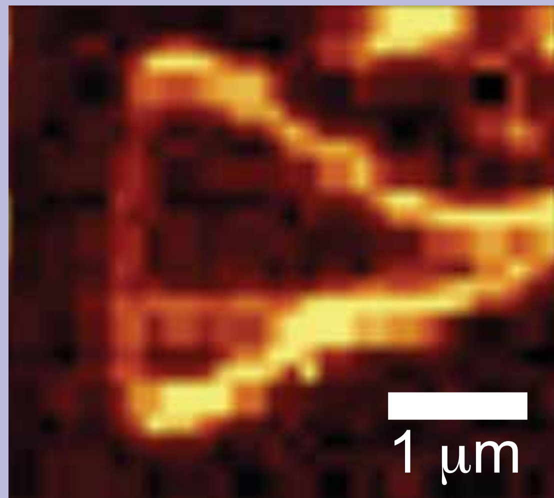
close to K, M point, k>0
Momentum restoring:
elastic scattering → **D**

1) **Crystallite grain size, symmetry breaking** [Tuinstra and Koenig, 1970]
2) **Defects, disorder in general** [Y. Wang et al, 1990]

Scanning force microscope



Raman: Integrated D line intensity



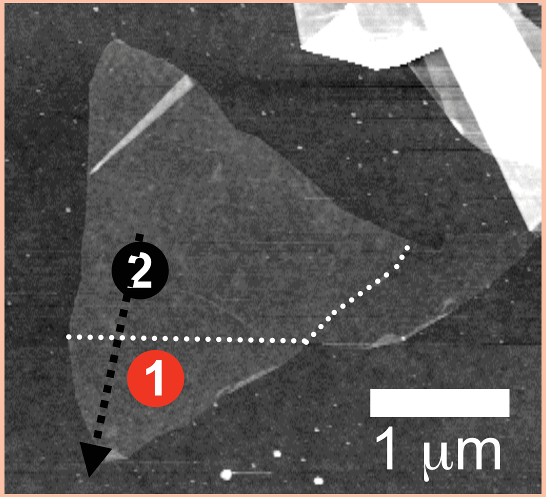
Symmetry breaking and defects

at edges and boundaries,

not within the flake.

Raman mapping: intensity of D-line

Scanning force microscope



Scanning confocal Raman spectroscopy:

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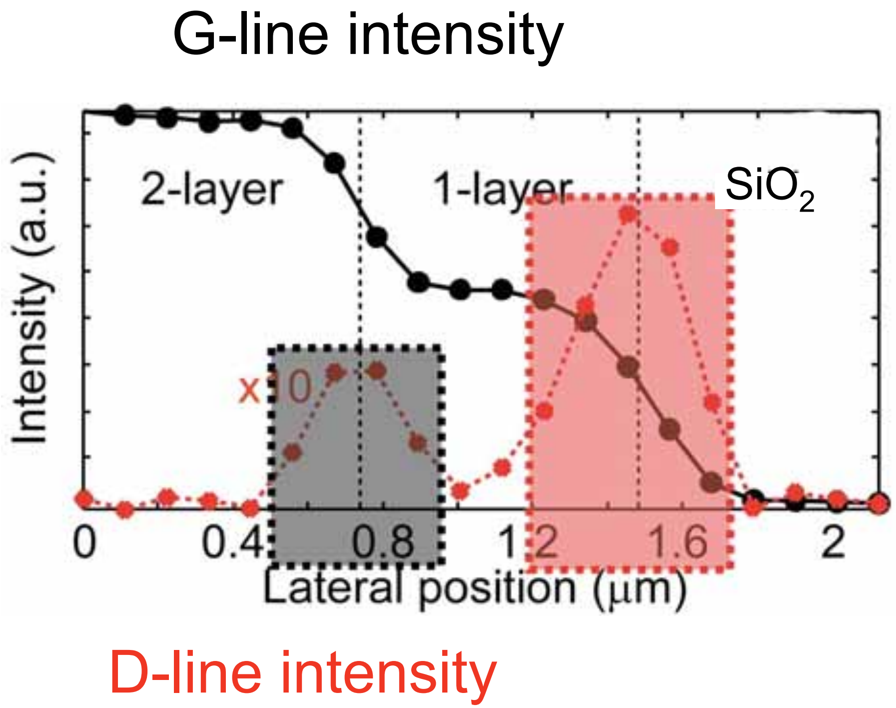
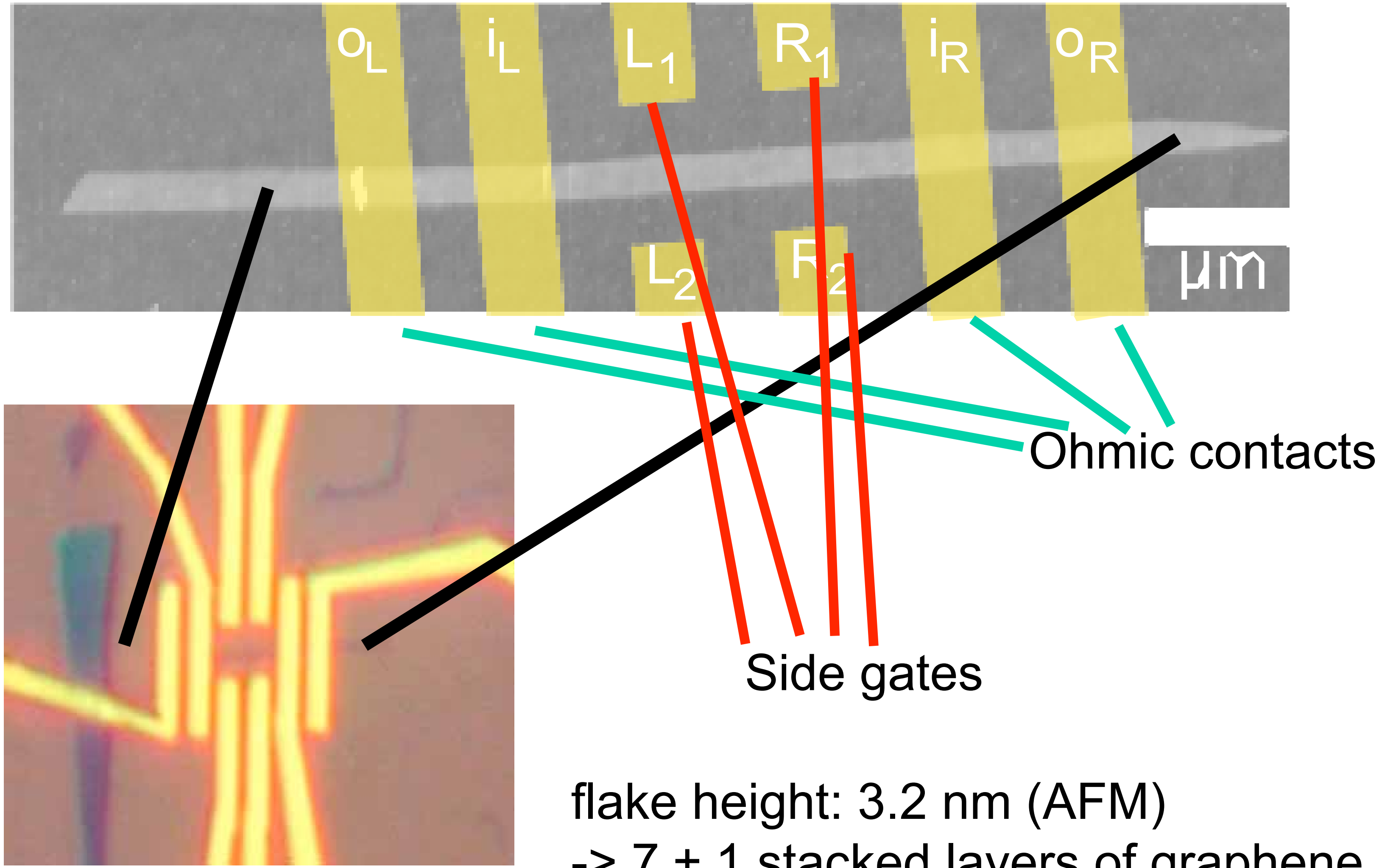
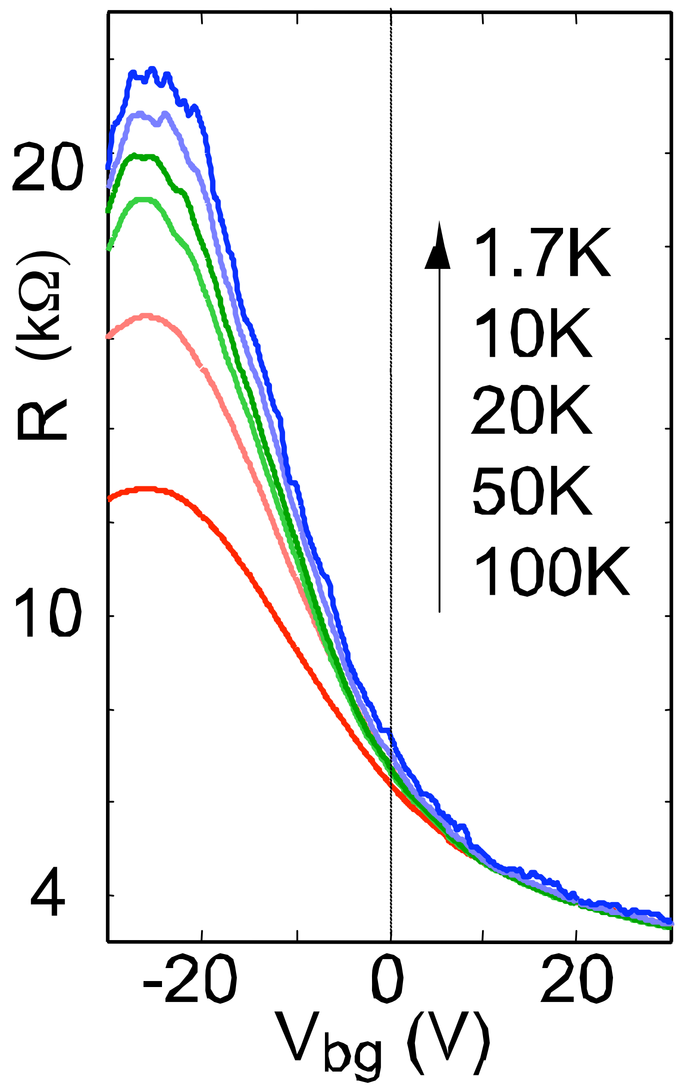


Sample for transport expts.



flake height: 3.2 nm (AFM)
-> 7 ± 1 stacked layers of graphene

Electronic properties



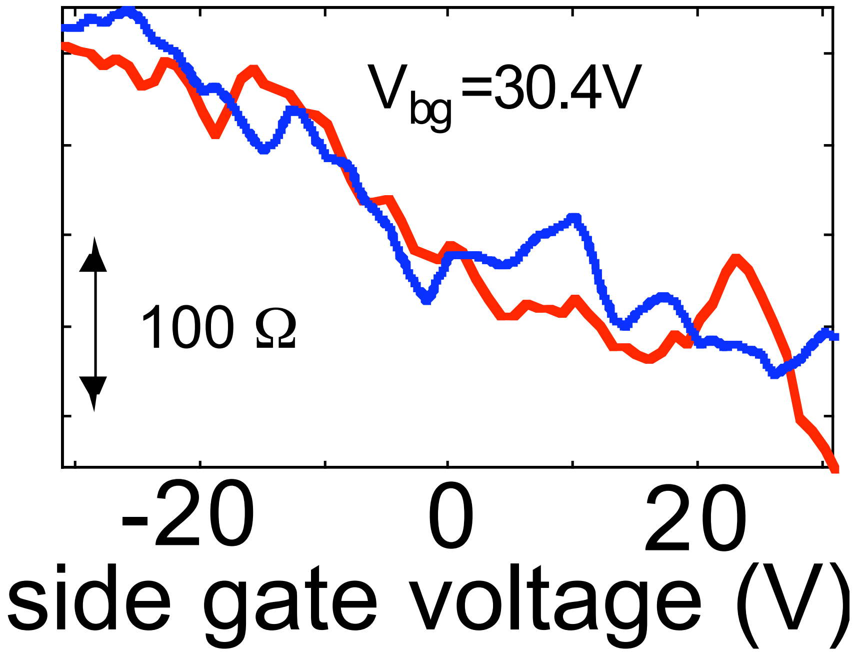
sample is n-doped

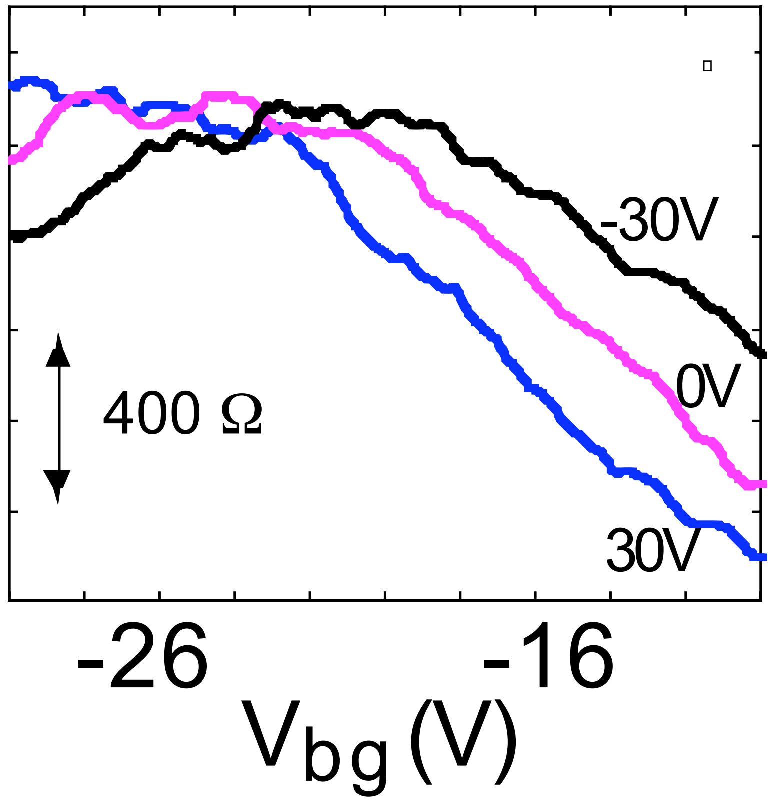
Carrier density can be tuned by back gate

$\mu \approx 3000\ cm^2/Vs$

fluctuations at low temperatures are reproducible

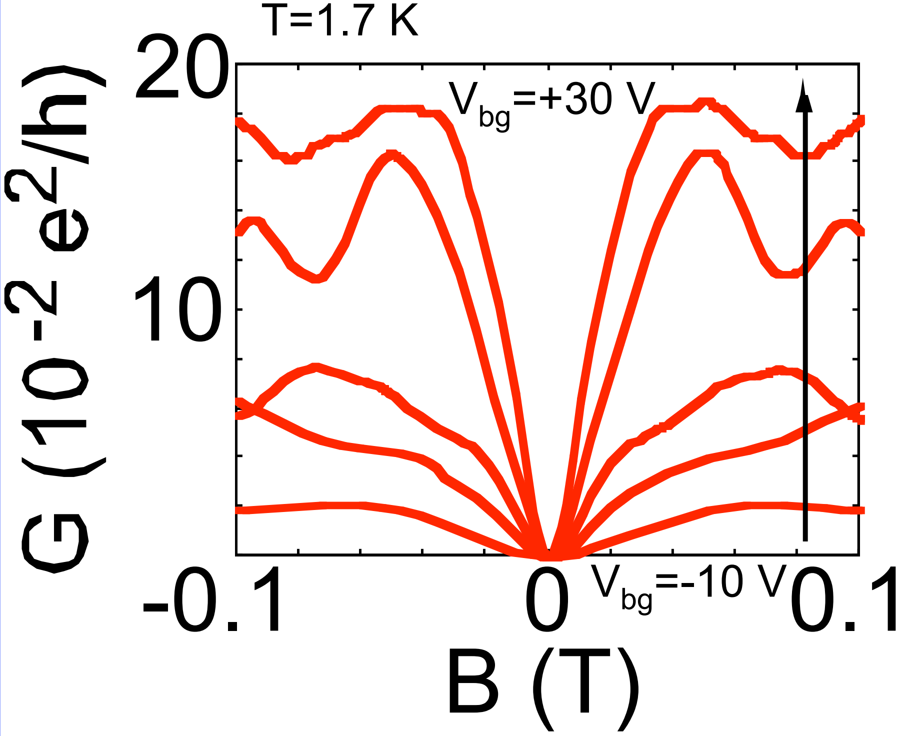
side gate vs. back gate





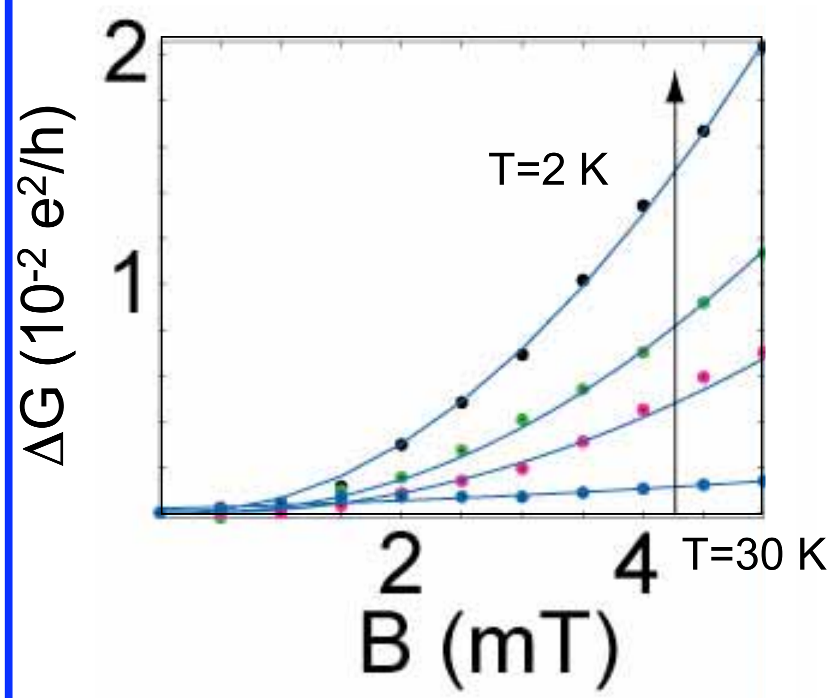
$$\frac{\text{lever arm side gate}}{\text{lever arm back gate}} \approx \frac{1}{10}$$

Weak localization



gate voltage dependence

temperature dependence



Weak localization

$$\delta G^{1D}_{loc}(B) = -\frac{2e^2}{h}\frac{1}{L}\left(\frac{1}{D\tau_\phi} + \frac{1}{D\tau_B}\right)^{\frac{1}{2}}$$

one-dimensional expression in the dirty metal regime

$$l_e << W << l_\varphi$$

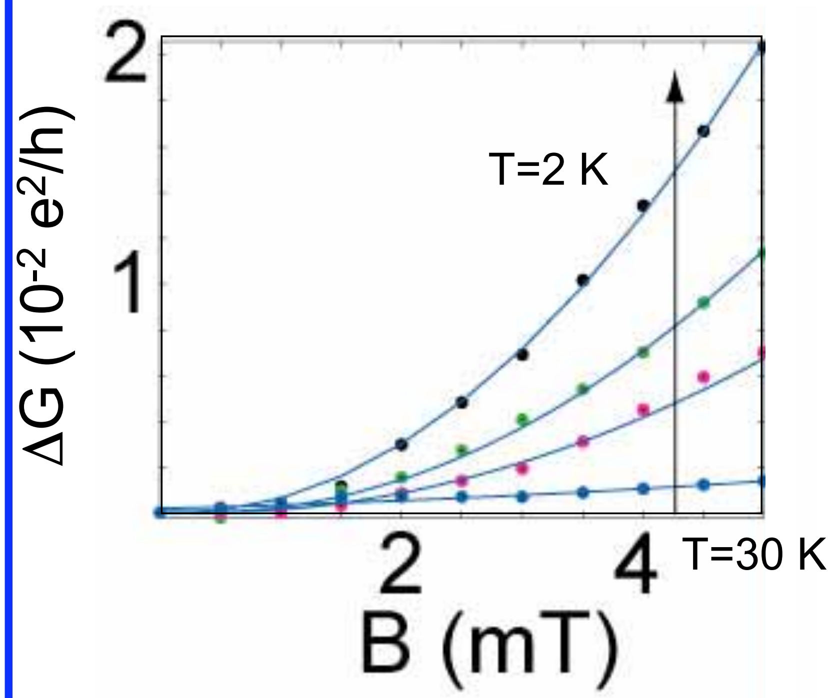
$$\tau_B \approx {l_m}^4/(DW^2)$$

$$l_m = (\hbar/eB)^{1/2}$$

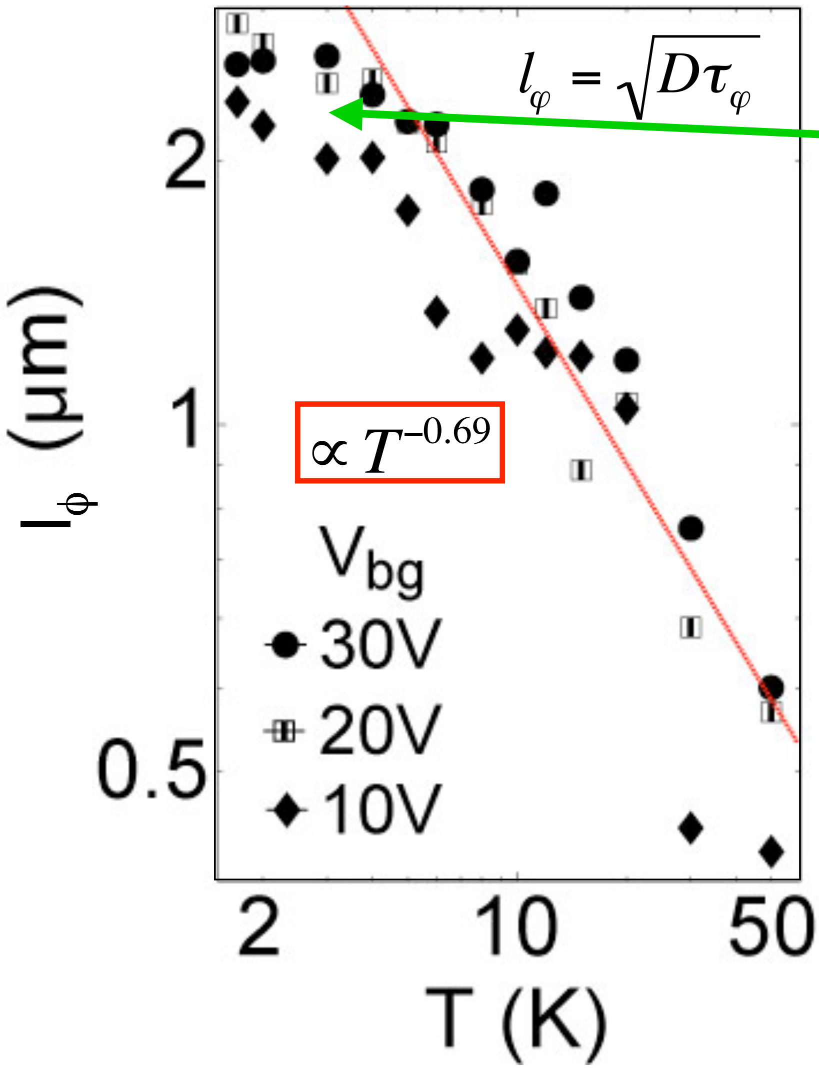
W, L: wire width, length

D: diffusion constant

temperature dependence

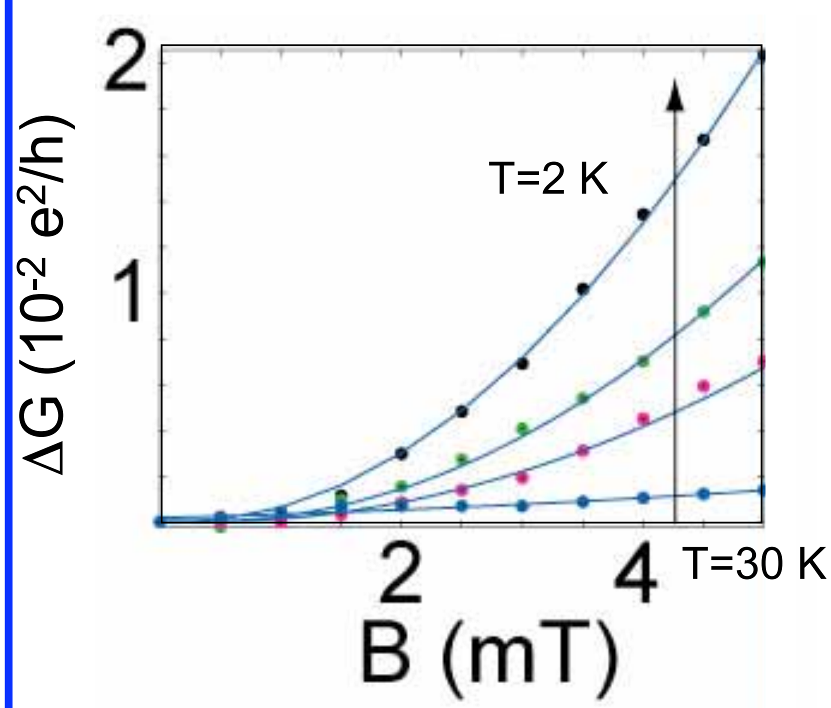


Weak localization

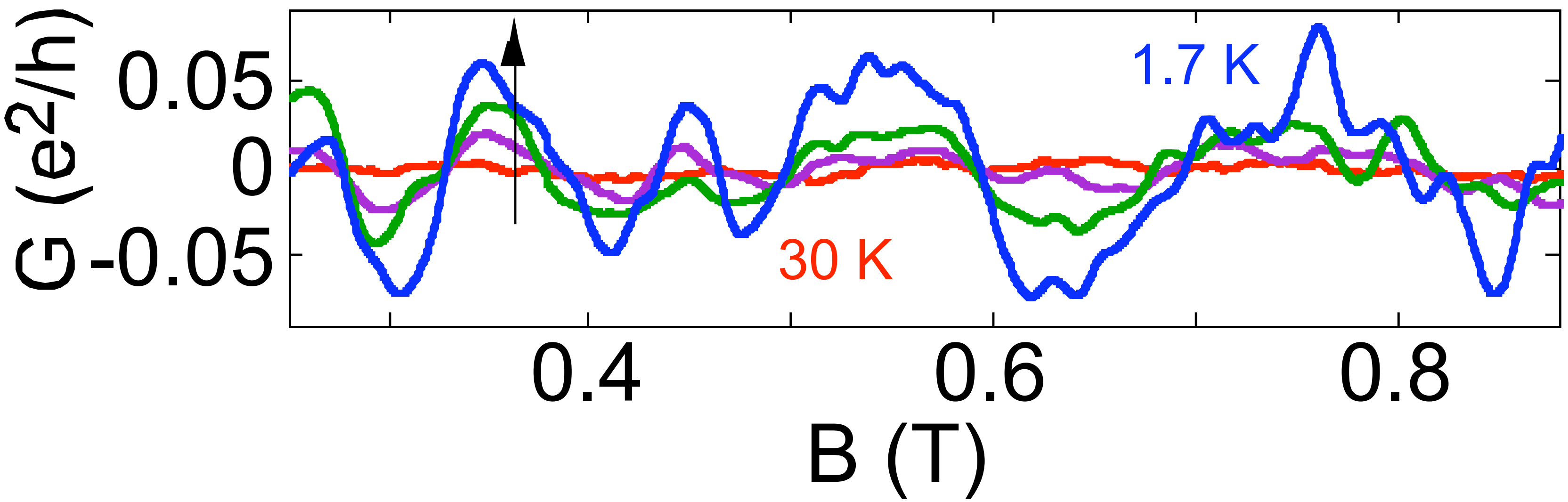


saturation:
l_Φ approaches wire length

temperature dependence

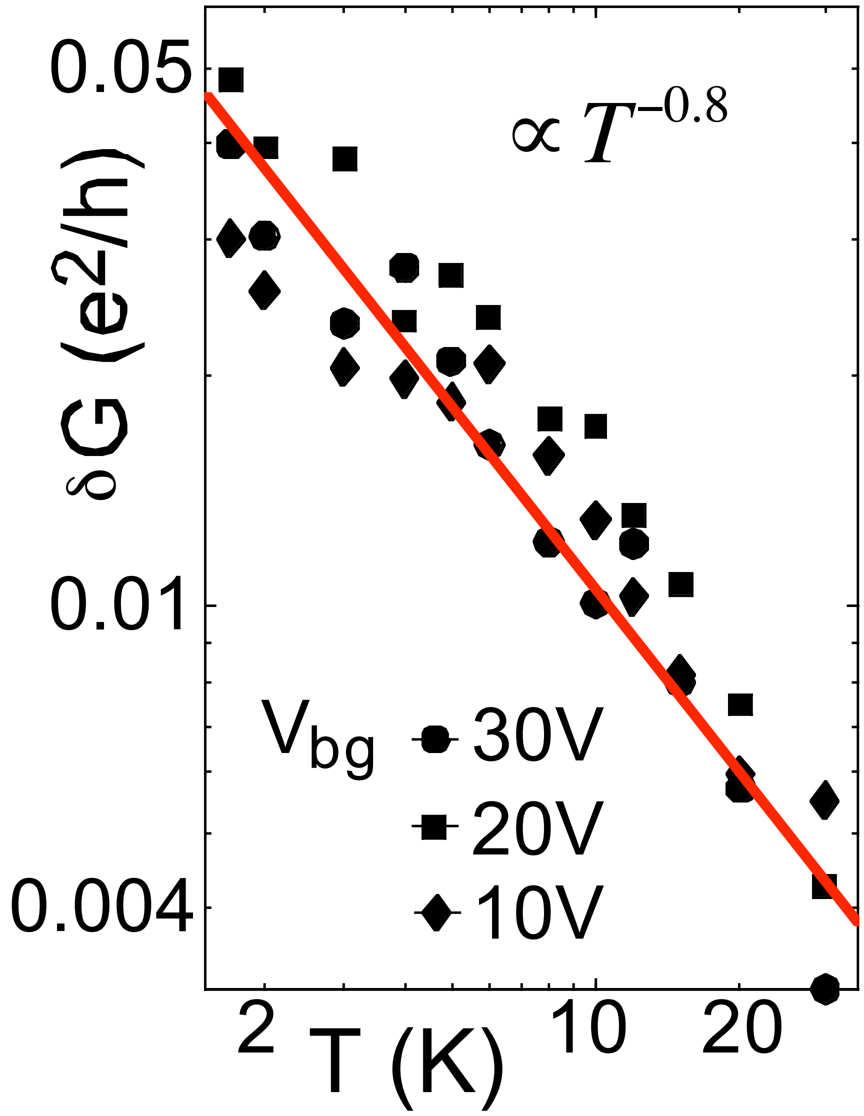


Universal conductance fluctuations



linear background subtracted

Universal conductance fluctuations

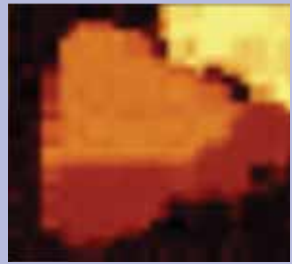


δG:
magnetoconductance
fluctuation amplitude

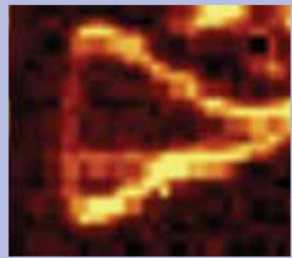
Conclusions

- Raman spectroscopy: an alternative to scanning force microscopy
- Monolayer sensitivity (single to double layer)
- Defects/symmetry breaking at the edge (not within the flakes)

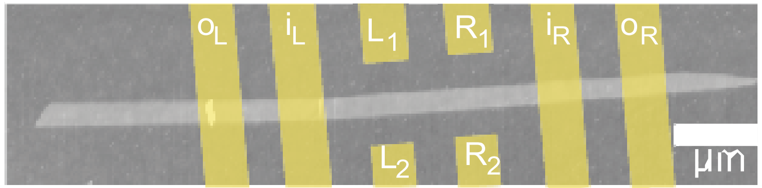
Raman: FWHM D'



Raman: Intensity D



thank you:
Davy Graf
Francoise Molitor
Christoph Stampfer
Thomas Ihn



l_ϕ (T=1.7K) > 2 μm
E_F can be tuned by side gates

Raman data:
D. Graf *et al.*, Nano Letters **7**, 238 (2007)
Related work: A.C. Ferrari *et al.*, *PRL* ***97***, 187401 (2006)
A. Gupta *et al.*, Nano Letters **6**, 2667 (2006)