UNIVERSITY OF BATH

Graphene 2018
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Dresden (Germany)

MANCHESTER 1824
The University of Manchester
National Graphene Institute

Superconductivity-induced features in the electronic Raman spectrum of monolayer graphene

Raman scattering minds the gap

Aitor García-Ruiz

Supervisor: Marcin Mucha-Kruczynski

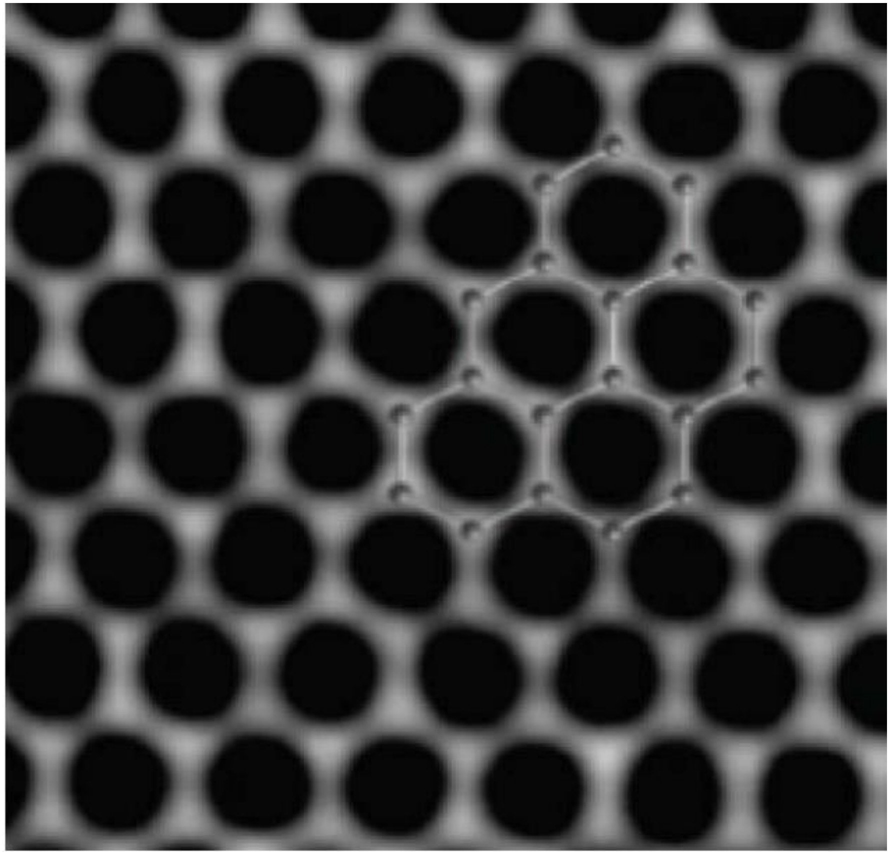
Collaborators: Joshua Thompson, Vladimir Falko

Image from “Raman Spectroscopy in Graphene Related Systems” Ado Jorio et al.

Outline

- ERS in graphene
  - Graphene
  - Raman in graphene
  - Electronic Raman scattering in graphene
- ERS in superconducting graphene
  - Superconducting graphene
  - Electronic Raman scattering in superconducting graphene

Outline



- **ERS in graphene**
  - **Graphene**
  - **Raman Scattering in graphene**
  - **Electronic Raman scattering in graphene**
- ERS in superconducting graphene
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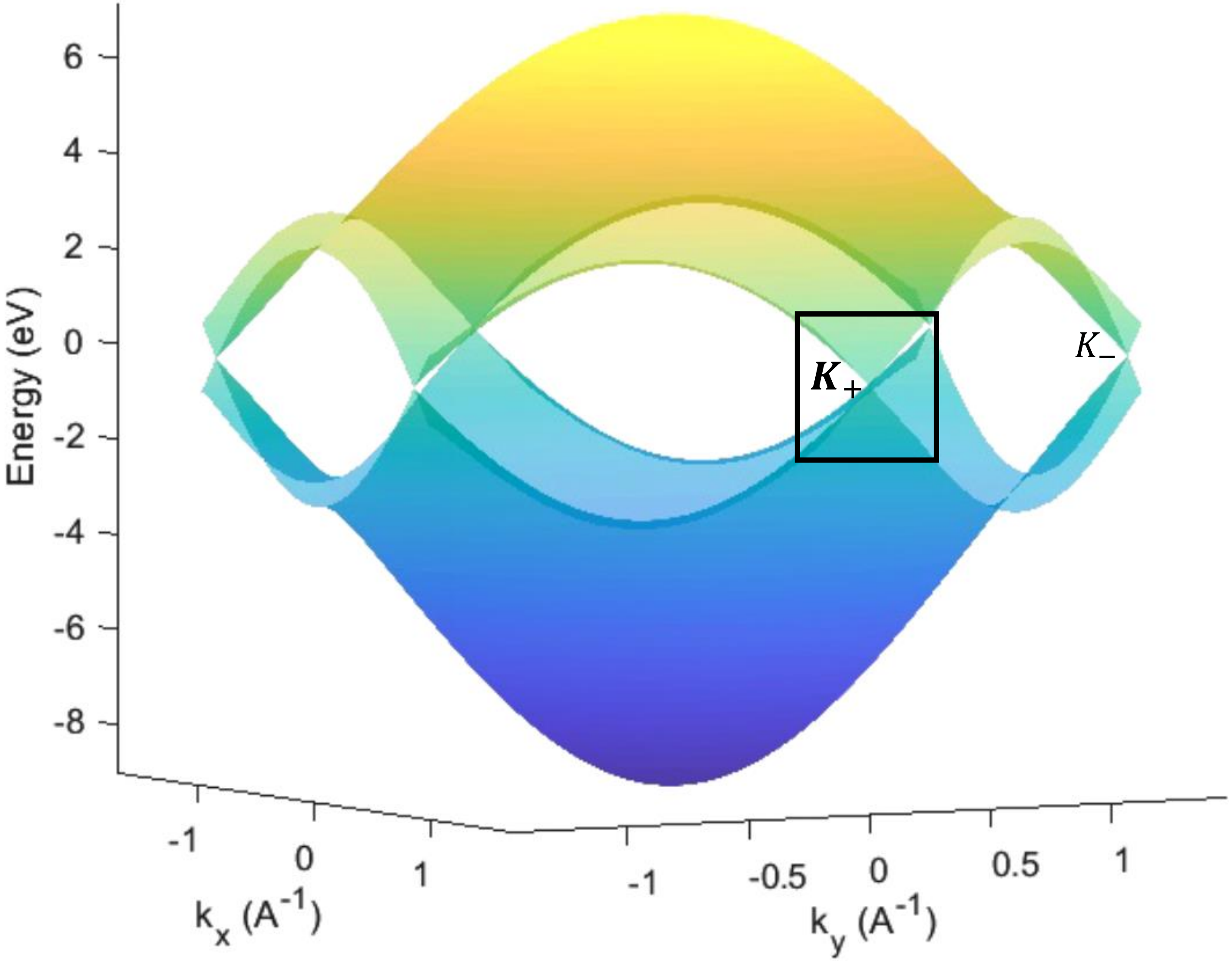
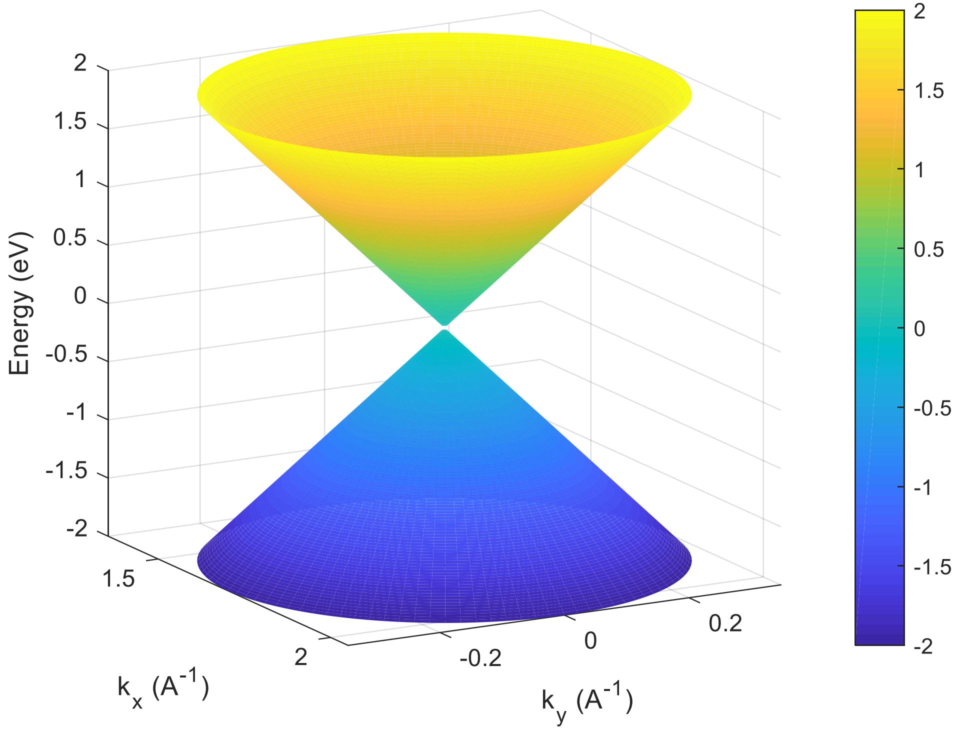
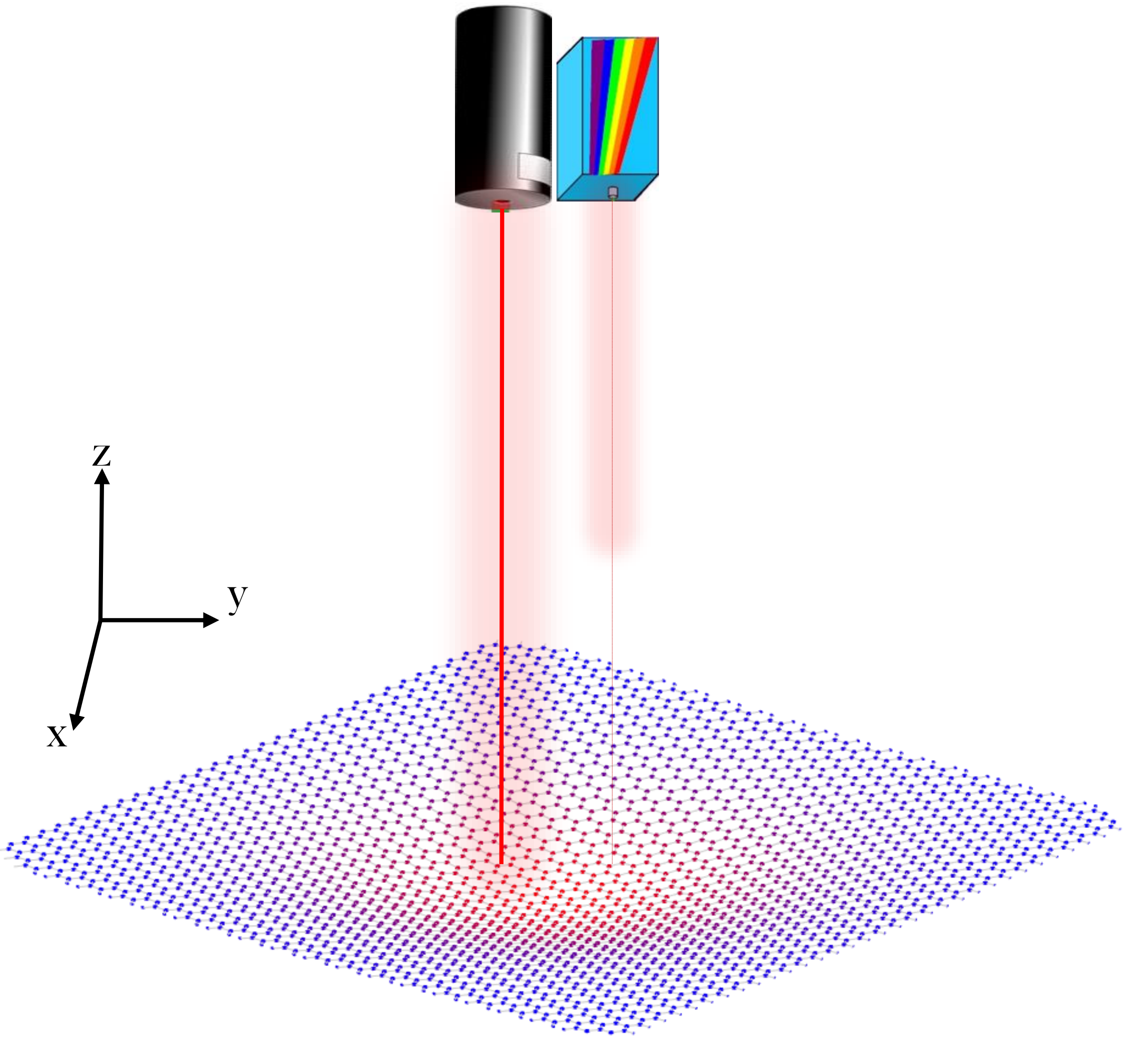
Graphene: dispersion relation



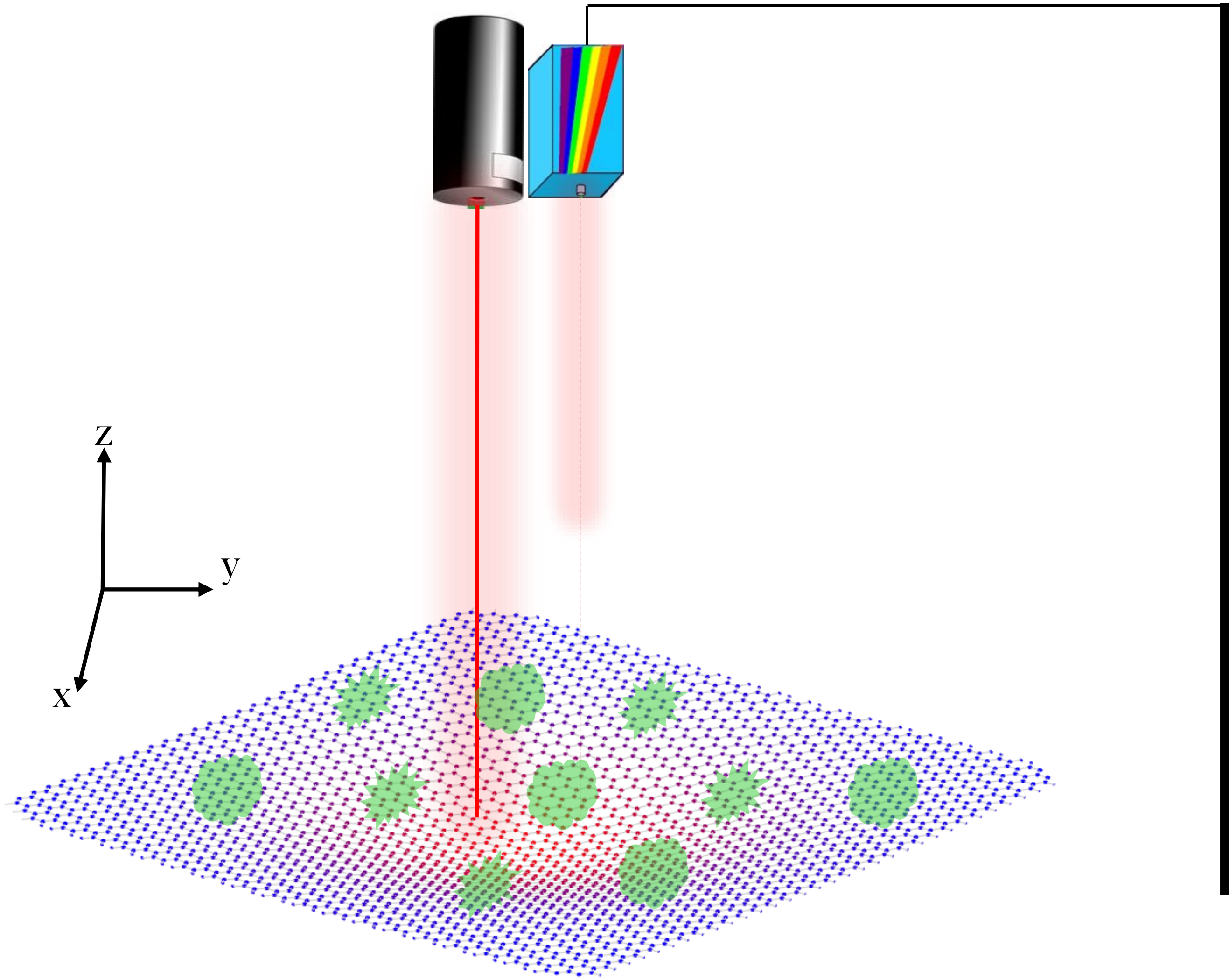
Linear dispersion $\mathcal{H}_{gr}^{lin}$

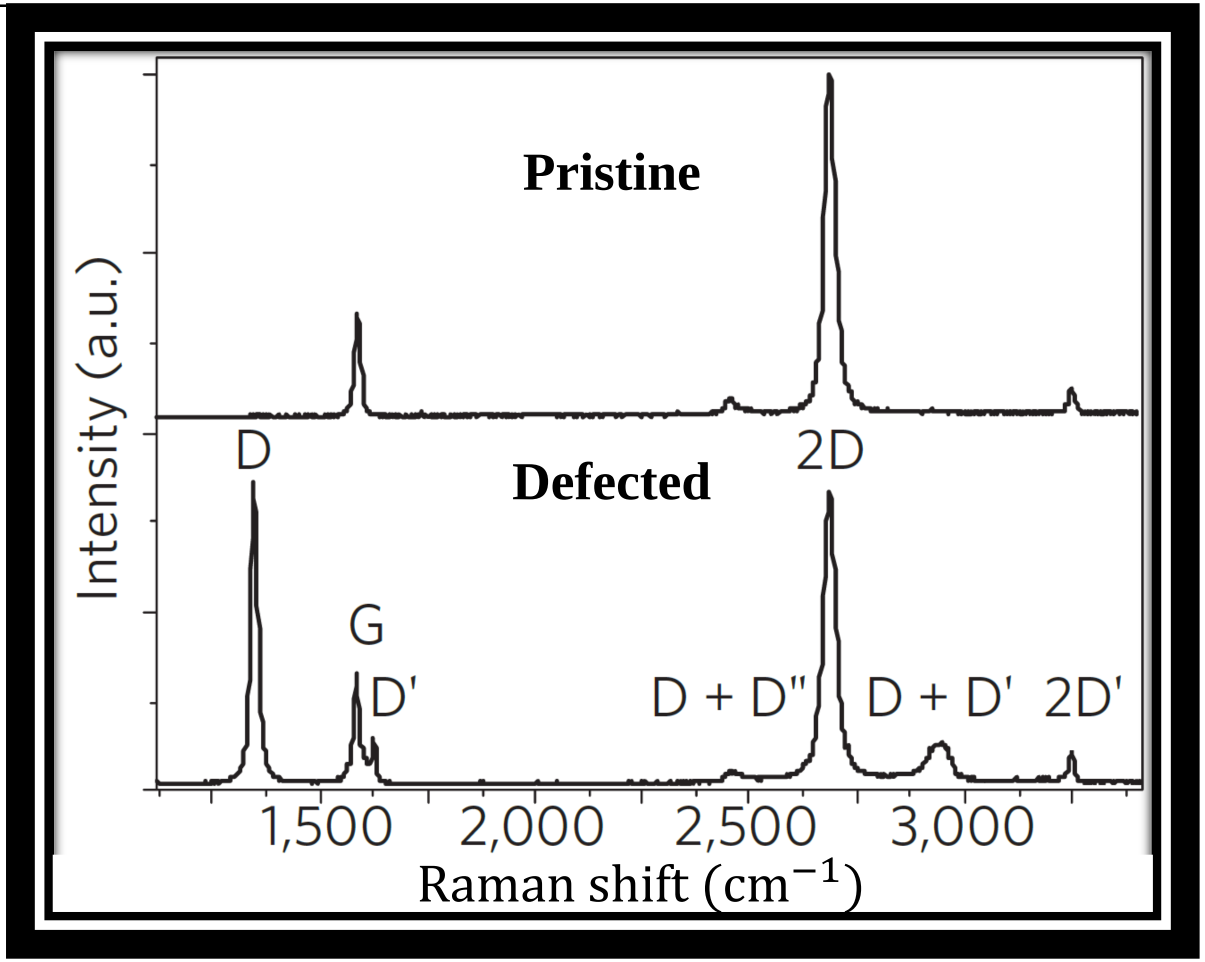


Raman scattering in graphene



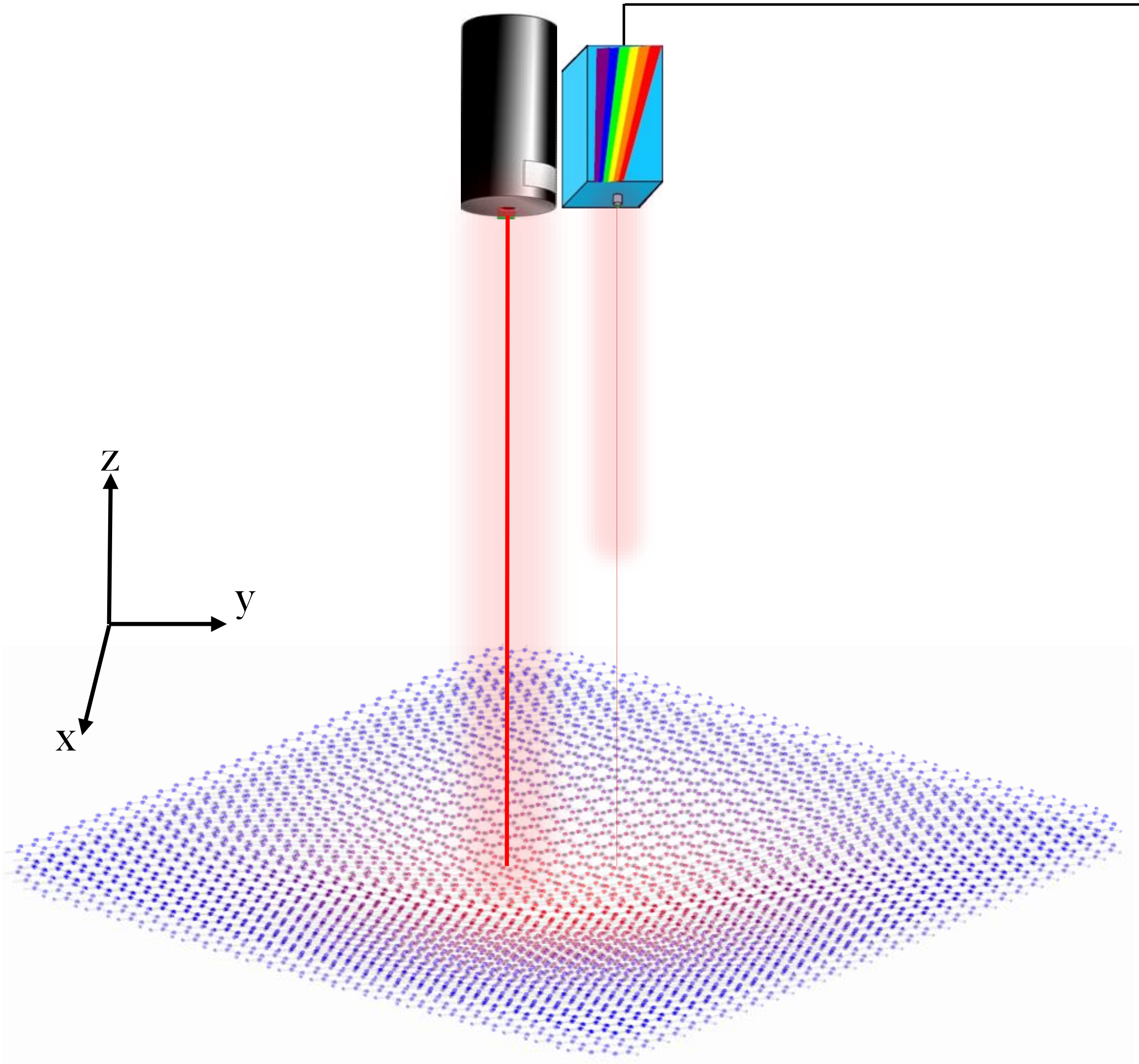
Raman scattering in graphene: defects

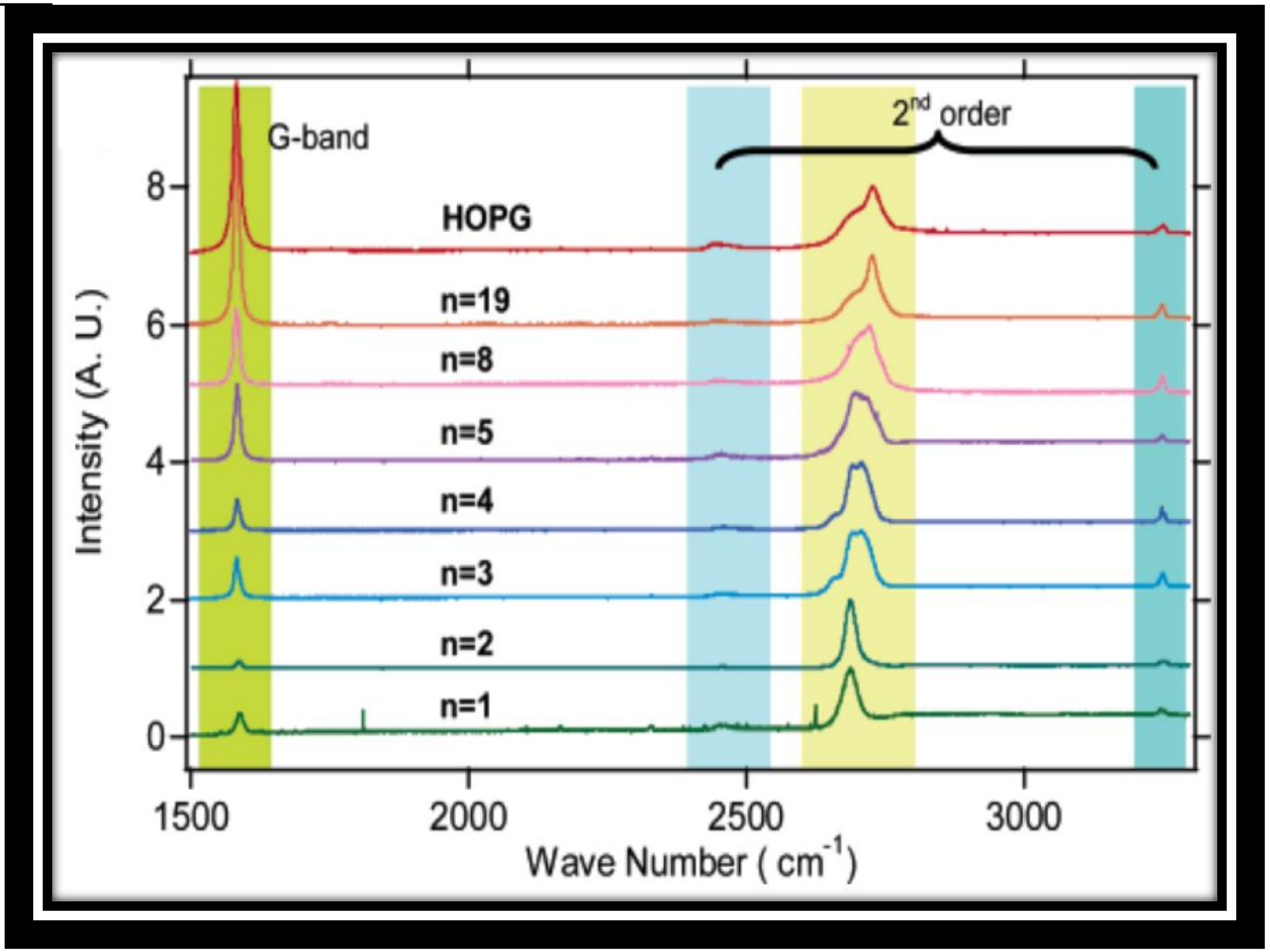




A.C. Ferrari et al., Nature Nanotechnology, **8** 235 (2013)

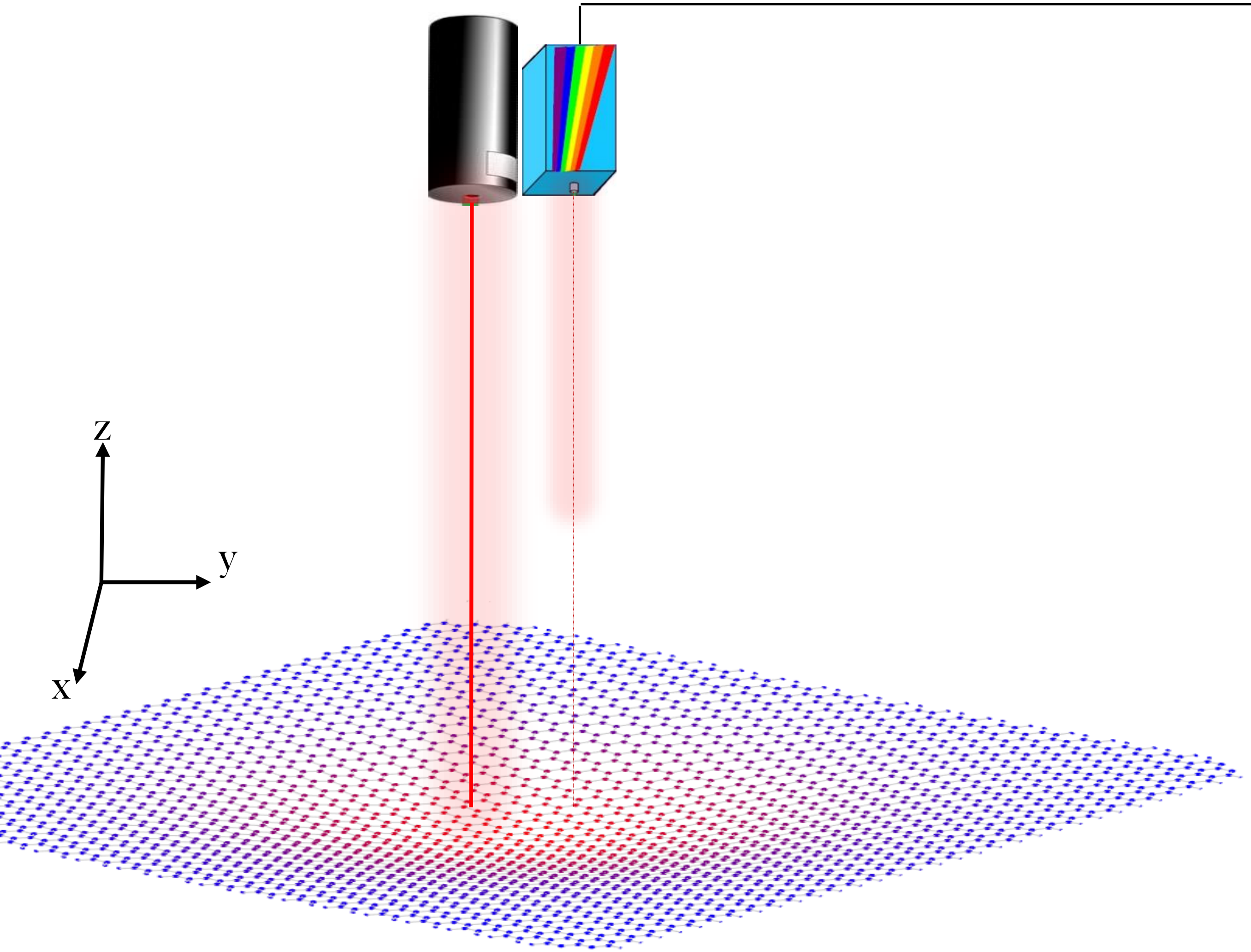
Raman scattering in graphene: layers

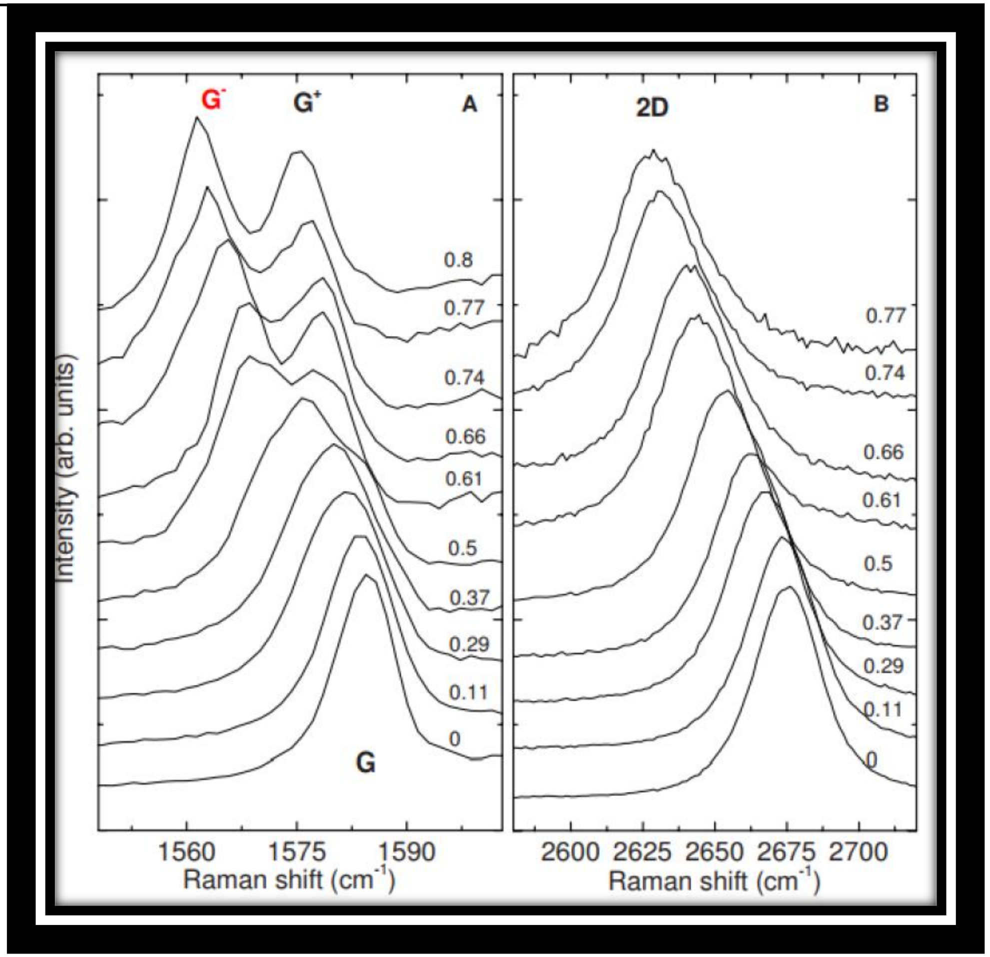




A. Gupta, et al., Nano Lett. **6**, 12, 2667-2673 (2006)

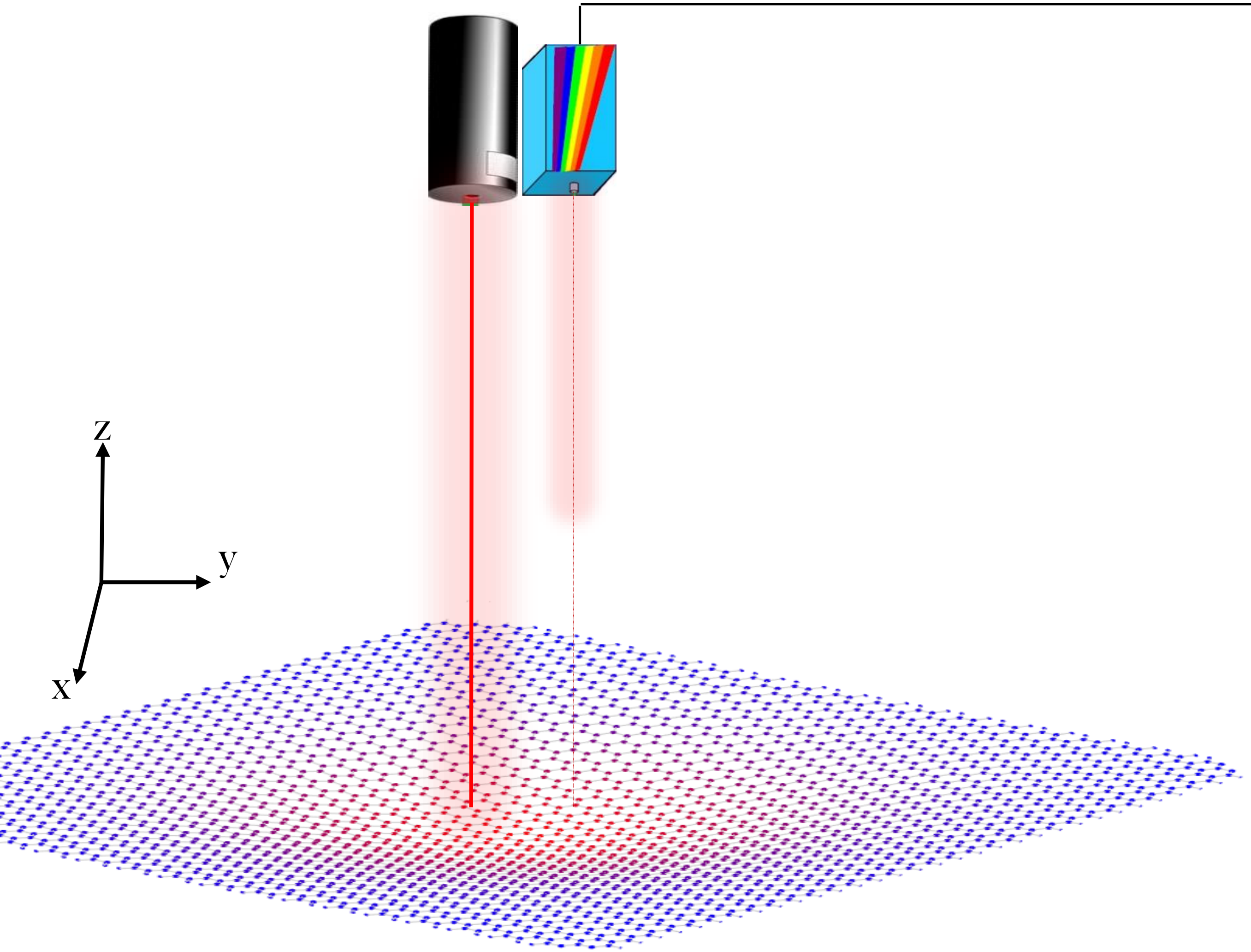
Raman scattering in graphene: strains





T. M. G. Mohiuddin et al. , Phys. Rev. B **79**, 205433 (2009)

Raman scattering in graphene: strains



Are there purely electronic excitations?

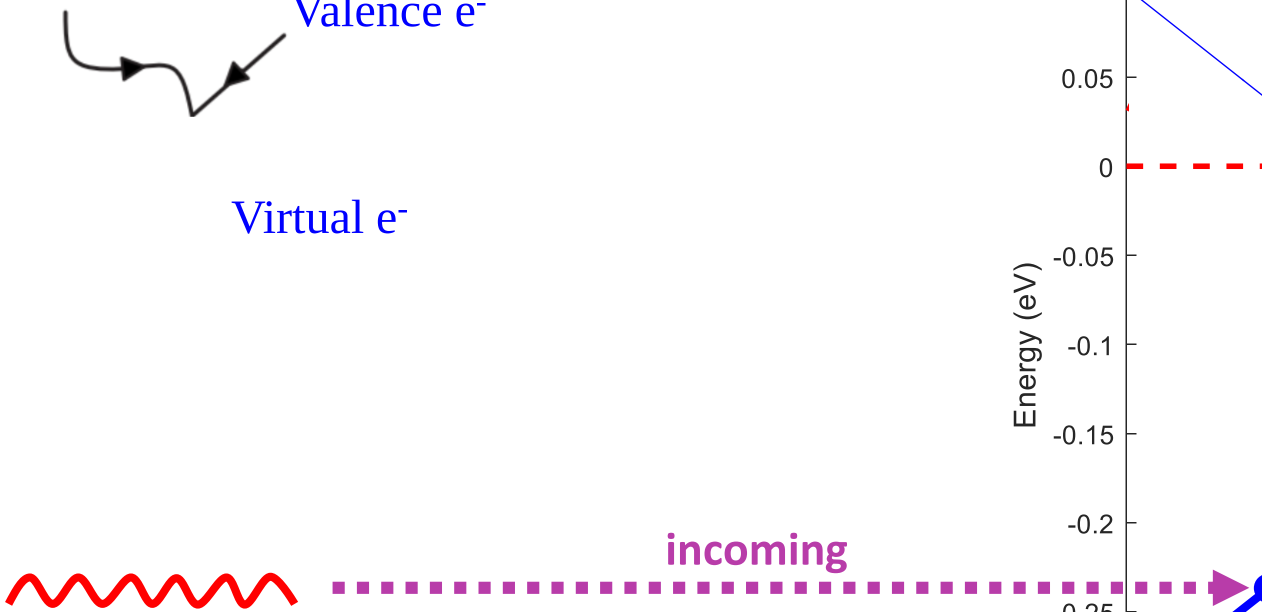
ERS in graphene: the picture

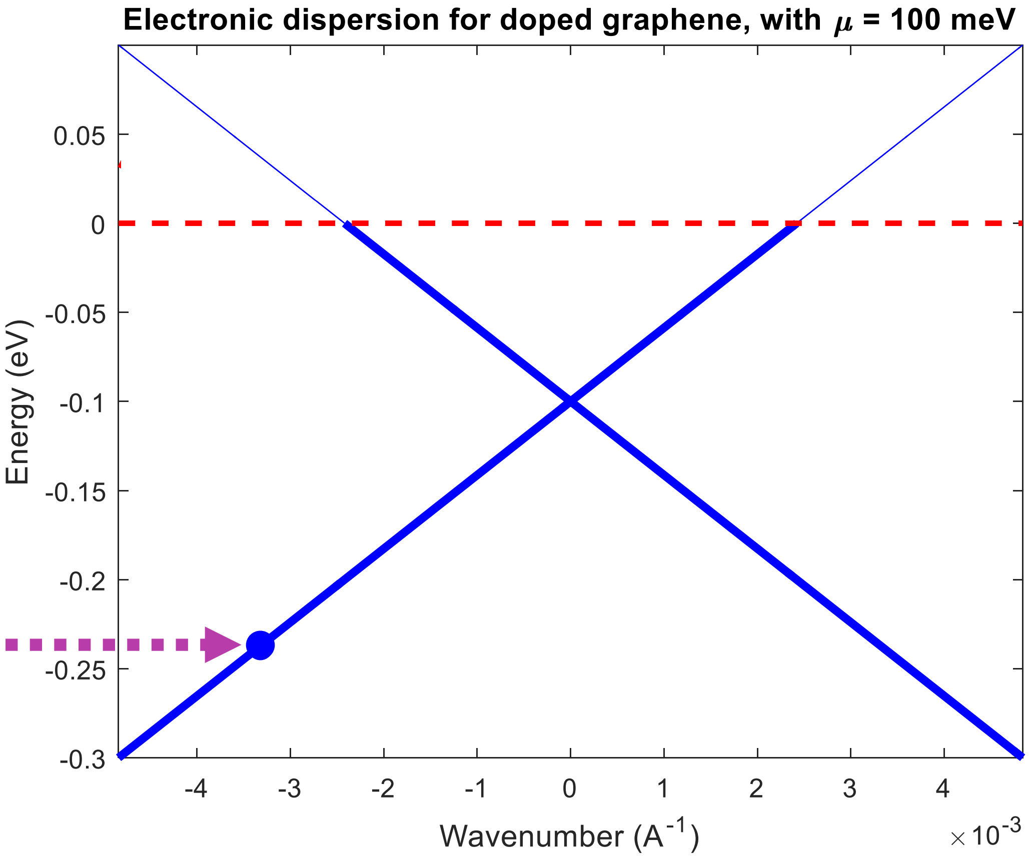
Virtual state

Incoming γ

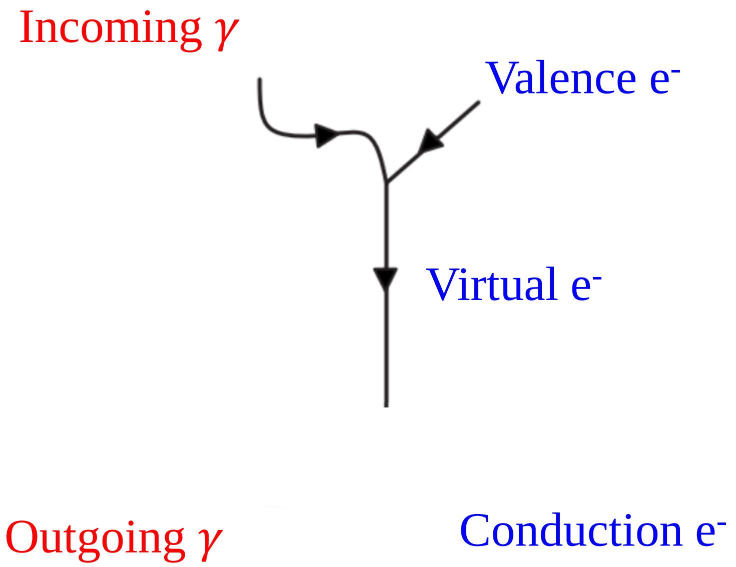
Valence e$^-$

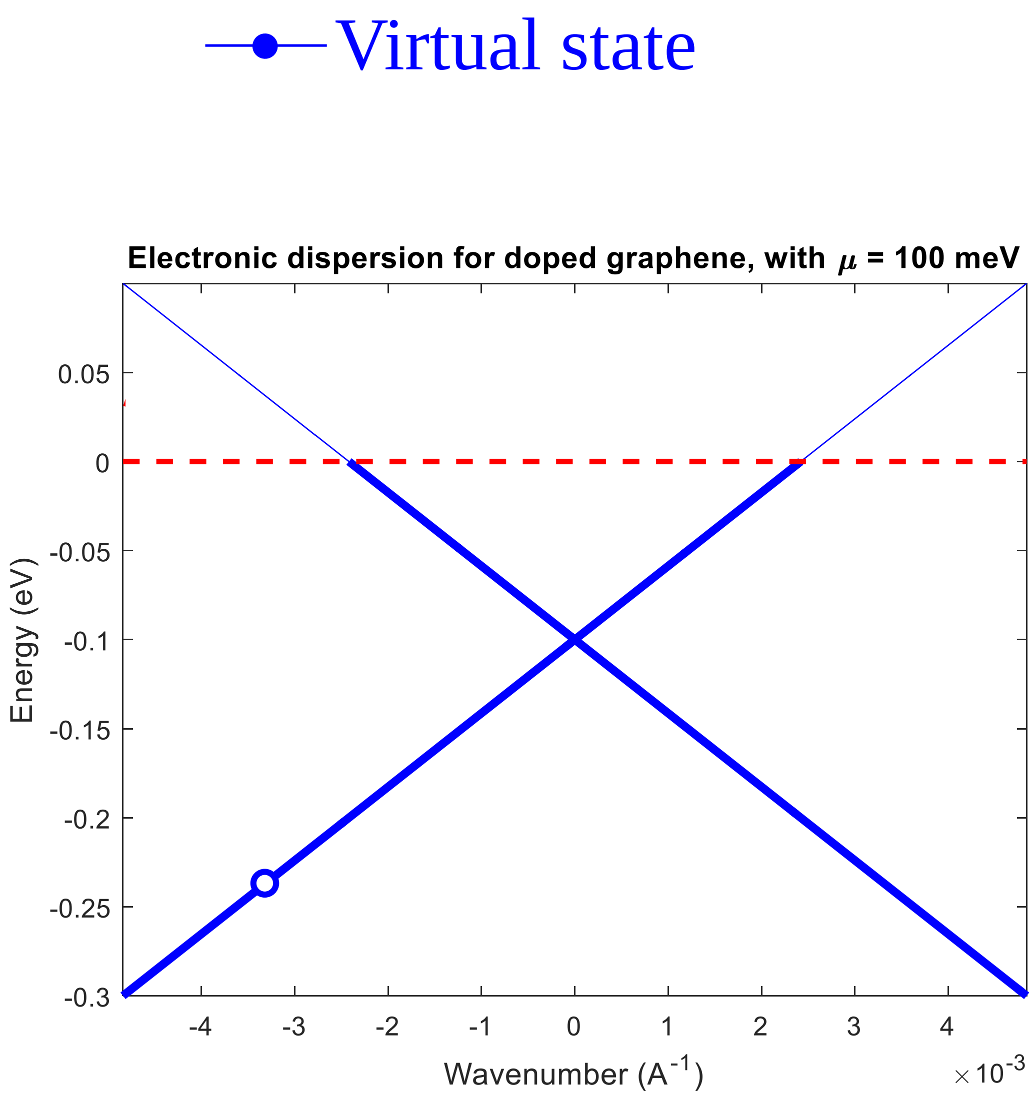
Virtual e$^-$





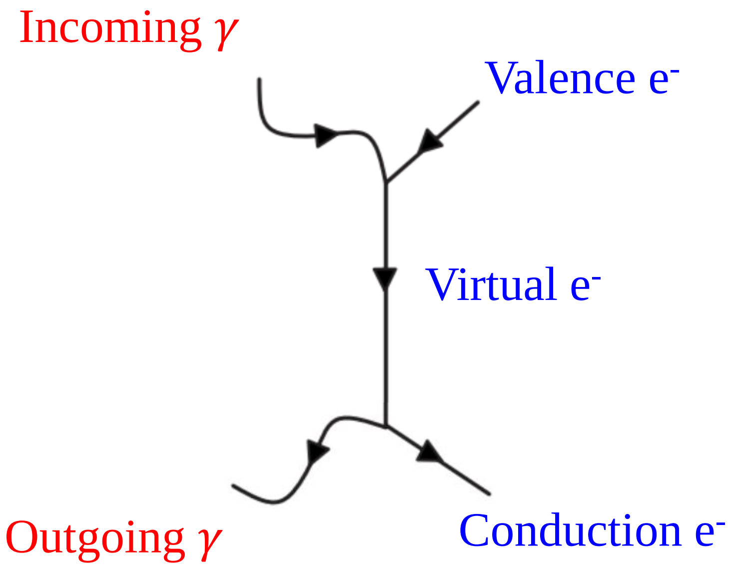
ERS in graphene: the picture

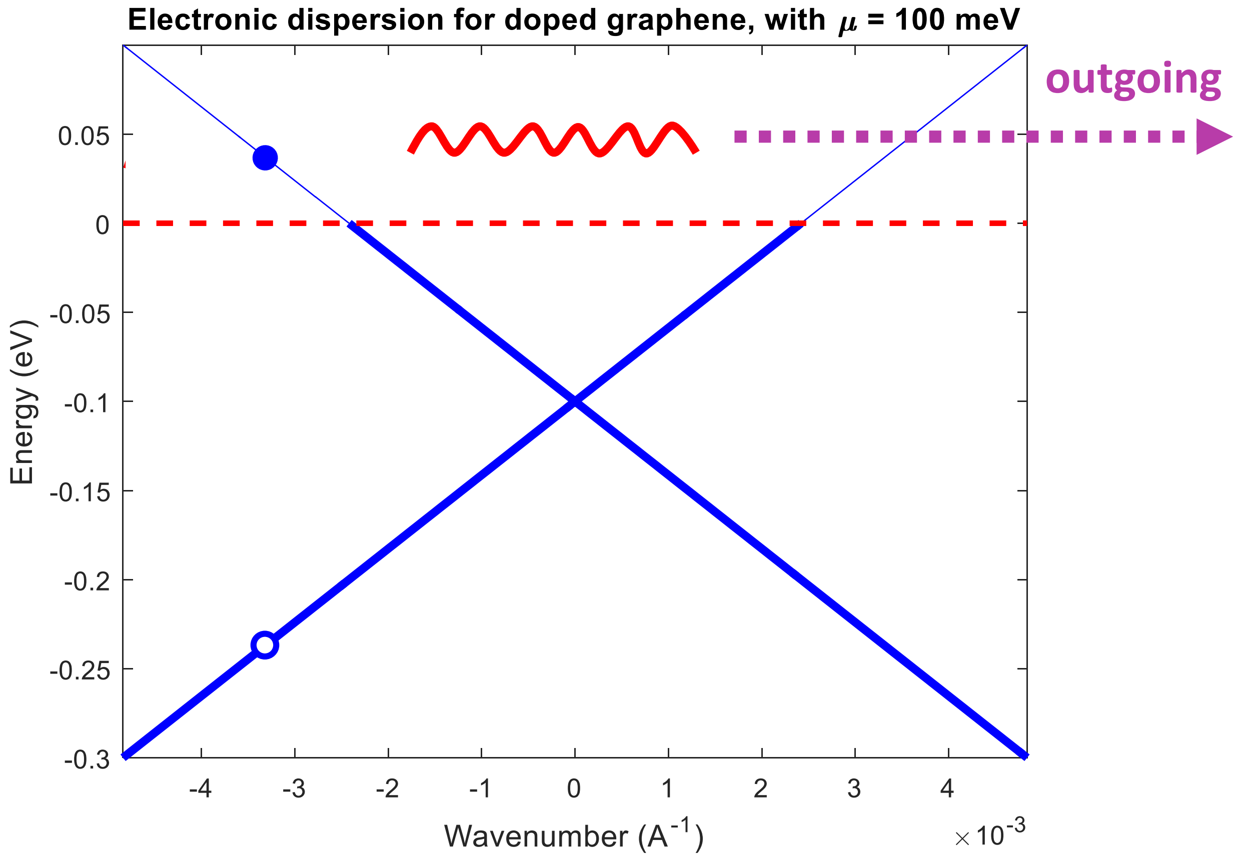




ERS in graphene: the picture

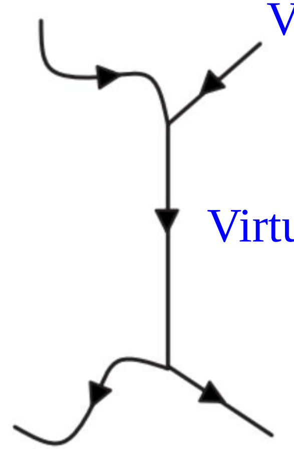
Virtual state

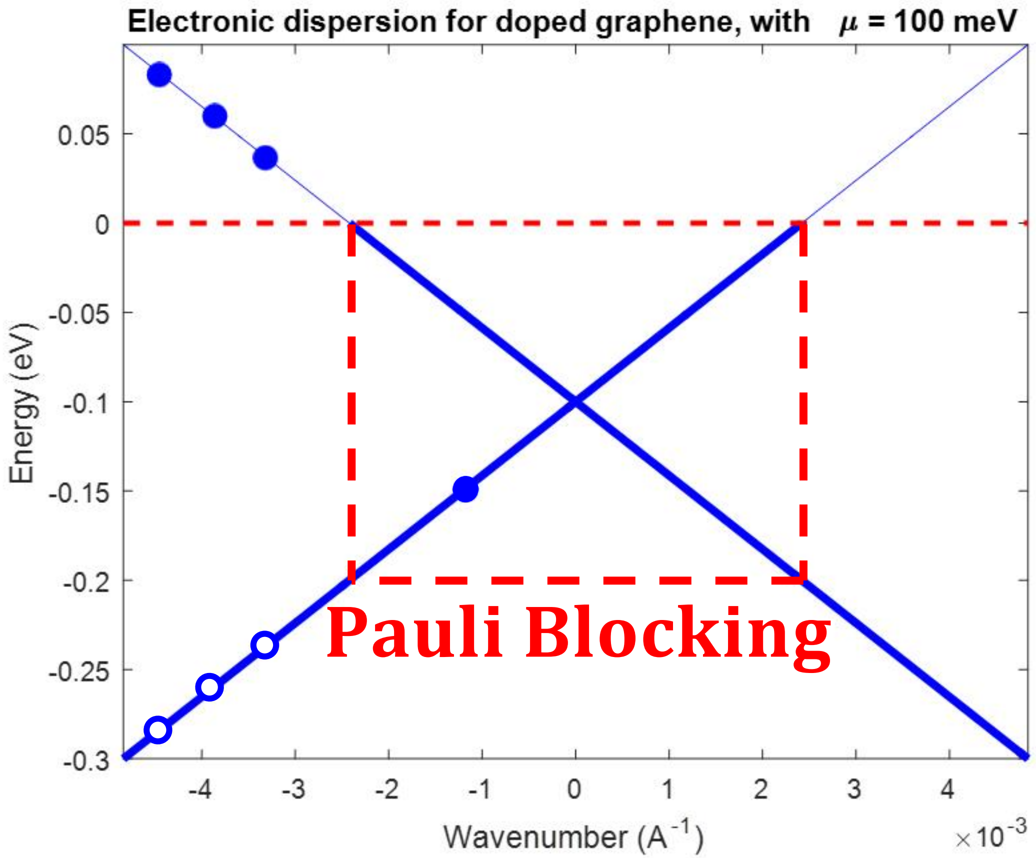




ERS in graphene: the picture

Virtual state





ERS in graphene: the theory

Light-matter interaction

$\vec{P} \longrightarrow \vec{p} - \frac{e}{c}\vec{A}$

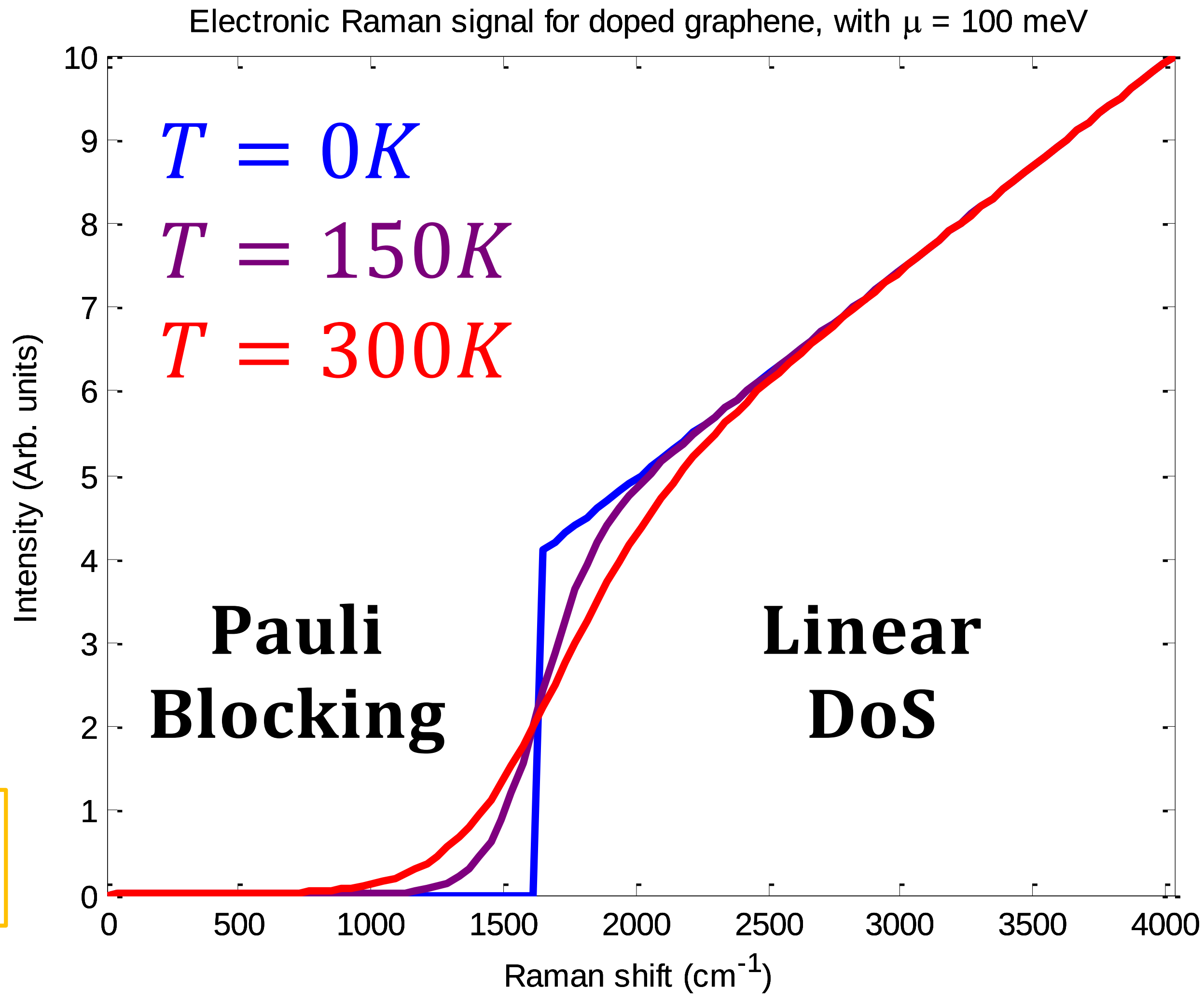
$\mathcal{H}_{gr}^{lin}$

$$w(\omega) = \int \frac{dp}{2\pi\hbar^3} \left| \langle c | \mathcal{V}_{lin} | v \rangle \right|^2 \delta(\epsilon_c - \epsilon_v + \omega)$$

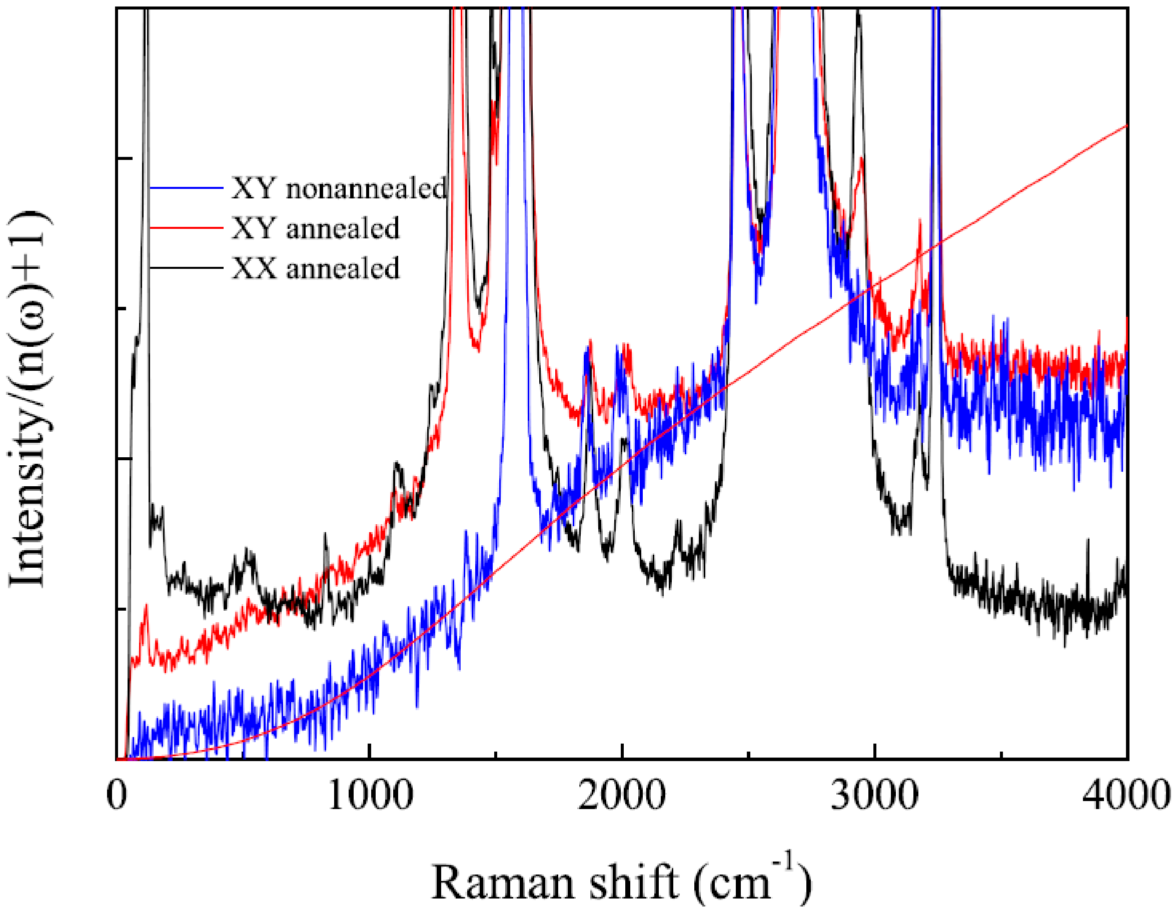
O. Kashuba and V. I. Fal'ko, Phys. Rev. B **80**, 241404 (2009)

$w(\omega) =$ Polarization factor (XY) · Linear DoS · Pauli Blocking

XY – configuration

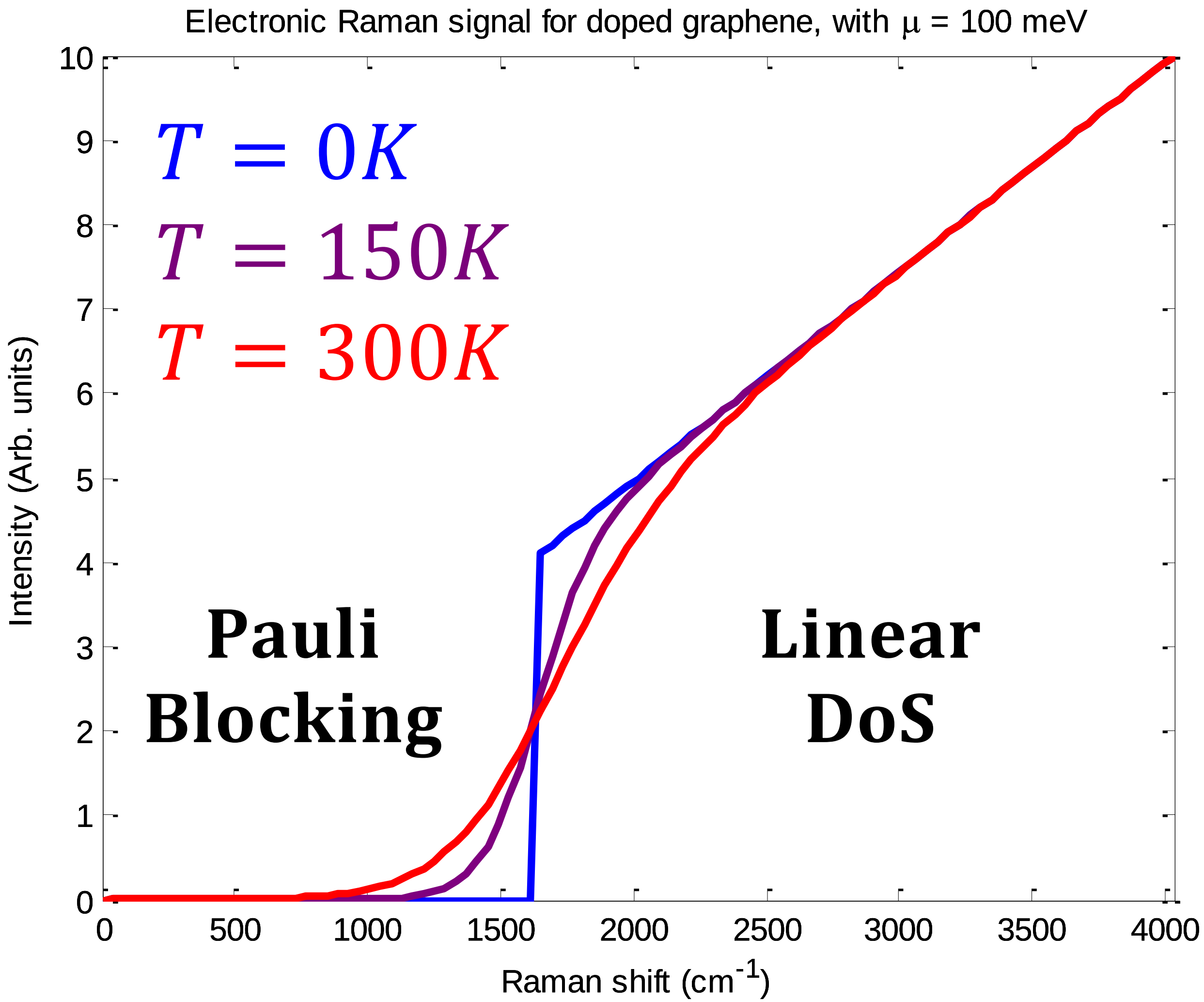


ERS in graphene: the experiment

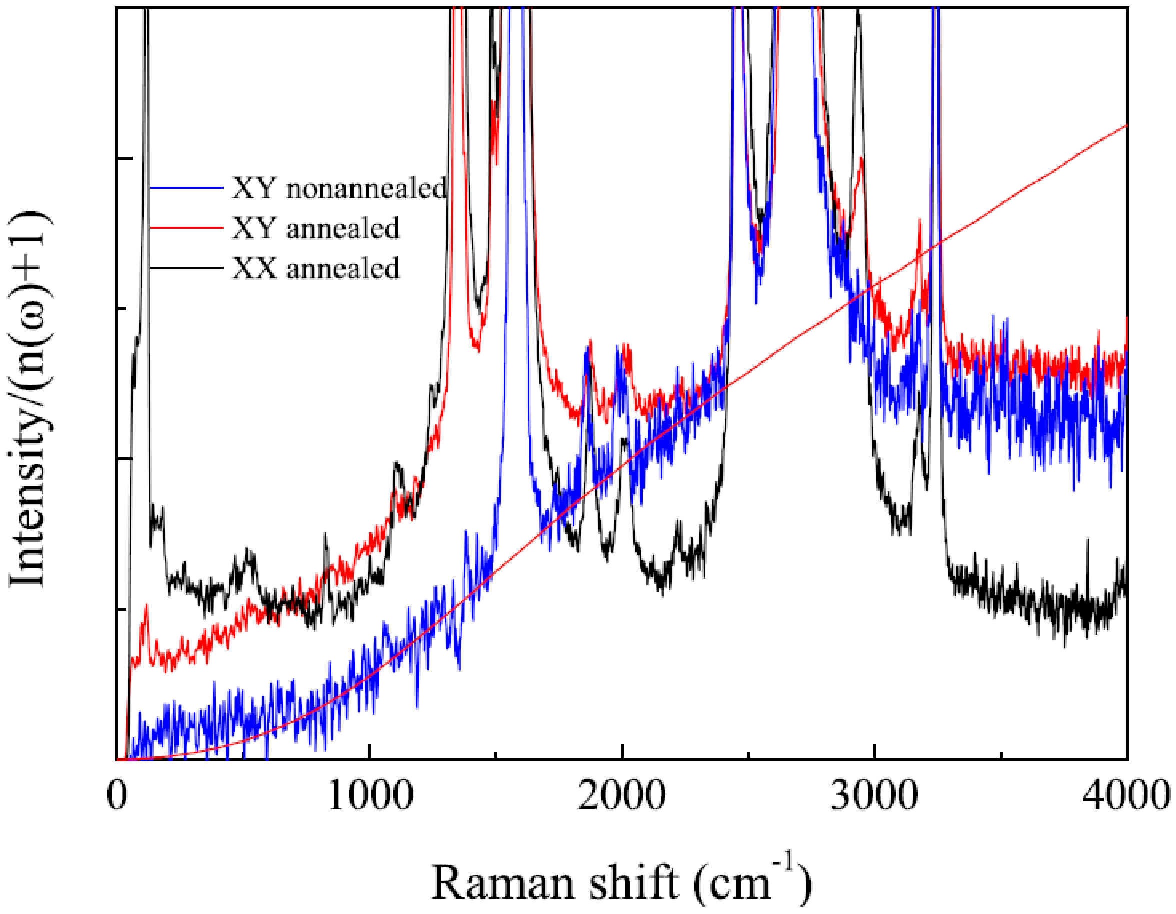


Y. S. Ponosov, et al., Phys. Rev. B **91**, 195435 (2015).

XY – configuration



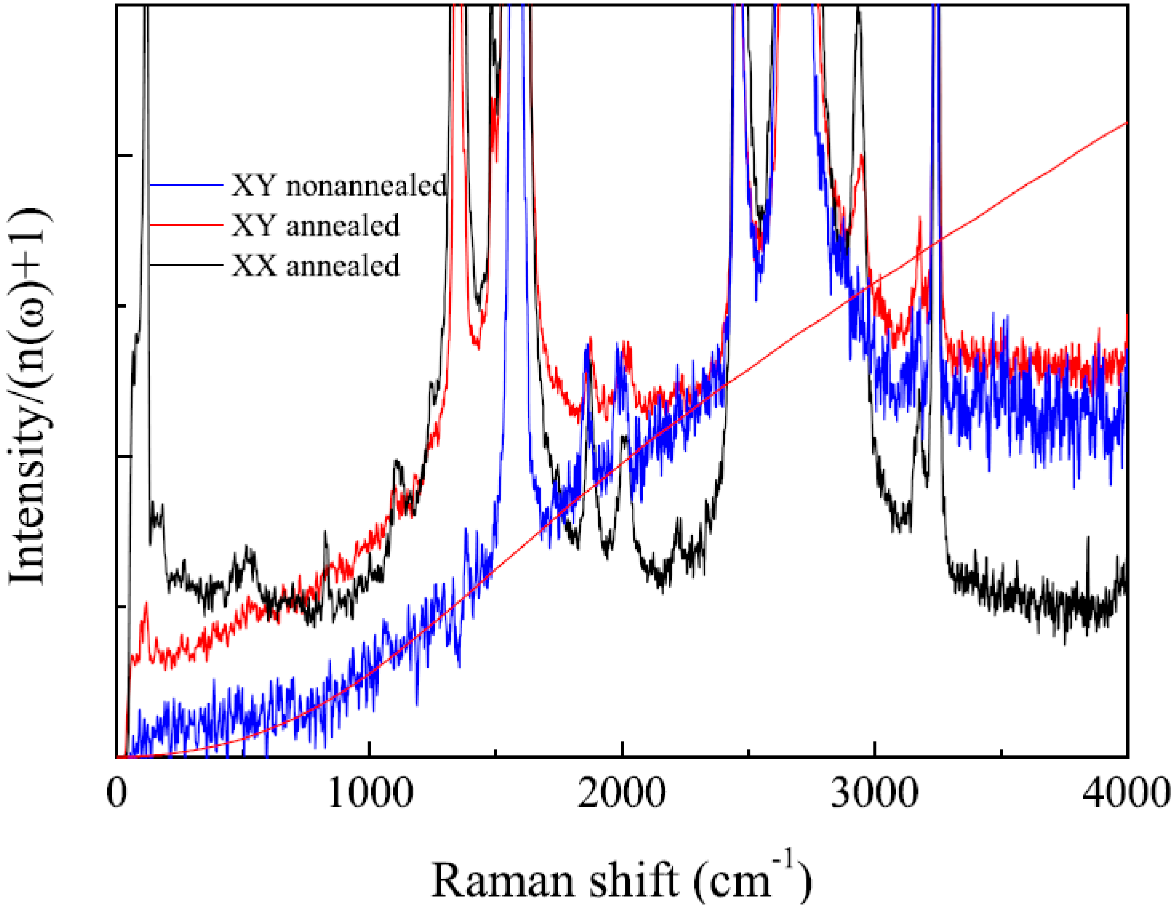
ERS in graphene: the experiment



Y. S. Ponosov, et al., Phys. Rev. B **91**, 195435 (2015).

“ Thus one can see that electronic Raman scattering at zero magnetic field is a sensitive tool for probing the low-energy electronic structure and pseudospin symmetry in pure and doped graphitic structures, and it has a potential for studying gapped structures formed by different methods.

ERS in graphene: the experiment

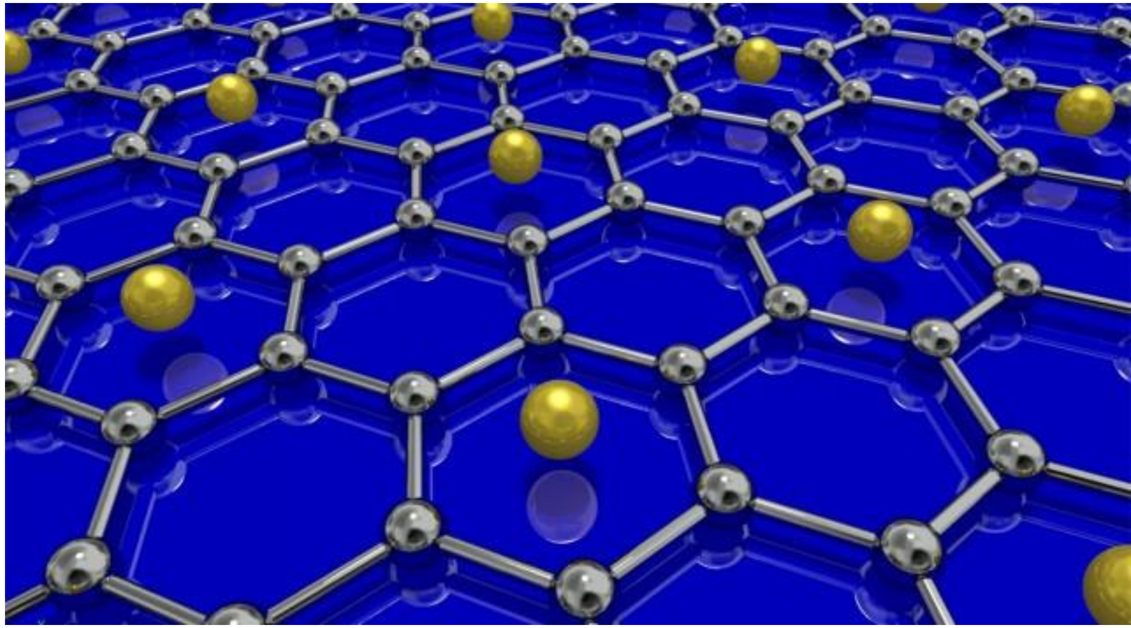


Y. S. Ponosov, et al., Phys. Rev. B **91**, 195435 (2015).

“ n Raman scattering
m i d s the
gap
”

What if we induce superconductivity?

Outline



- ERS in graphene
  - Graphene
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  - Electronic Raman scattering in graphene
- **ERS in superconducting graphene**
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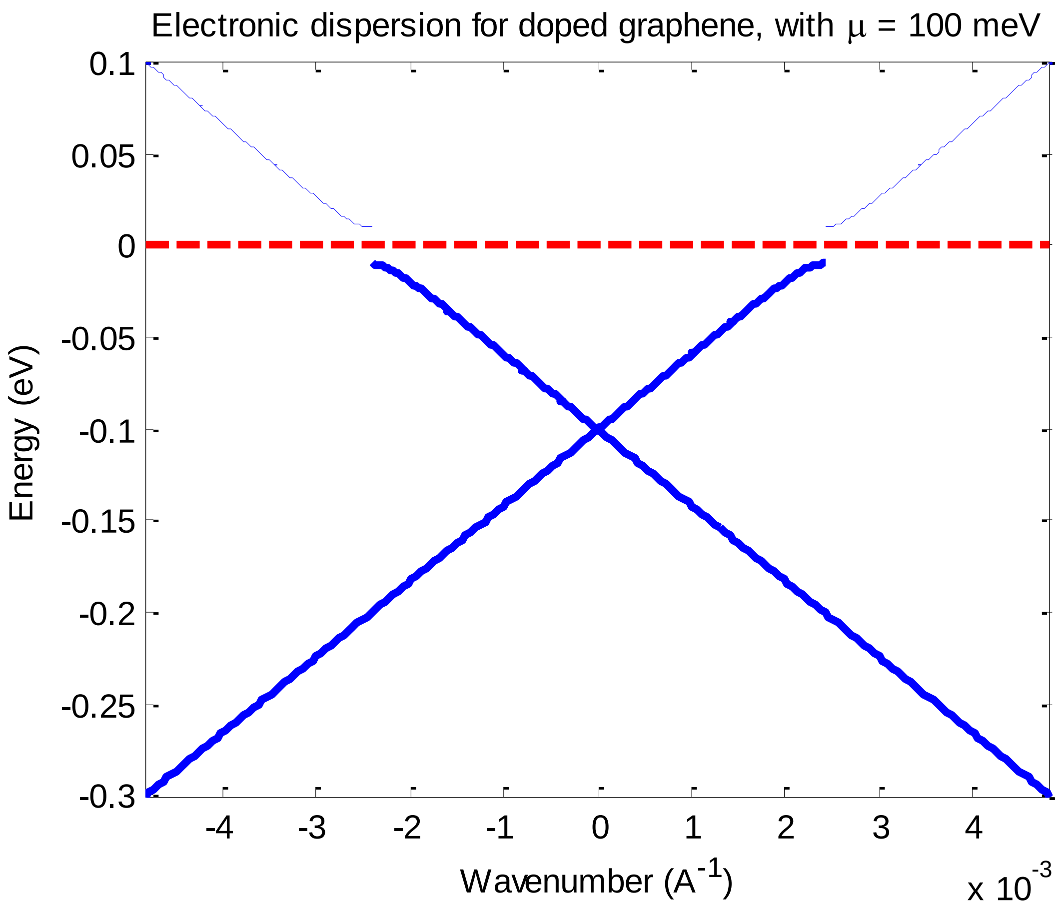
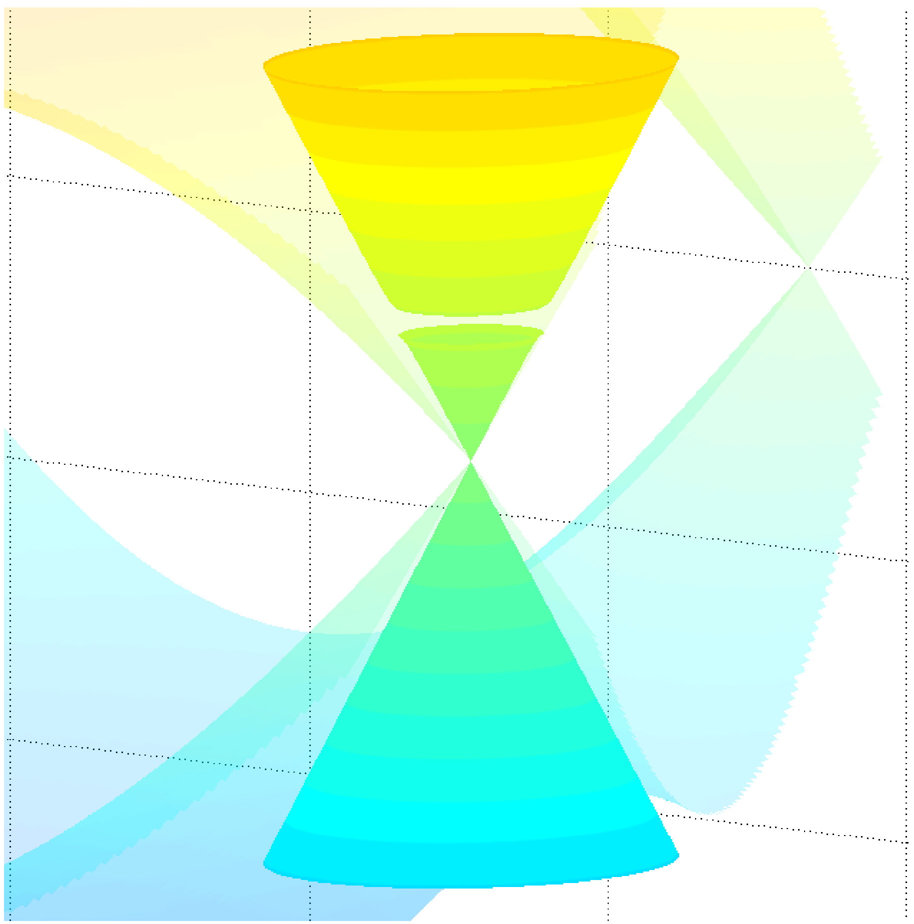
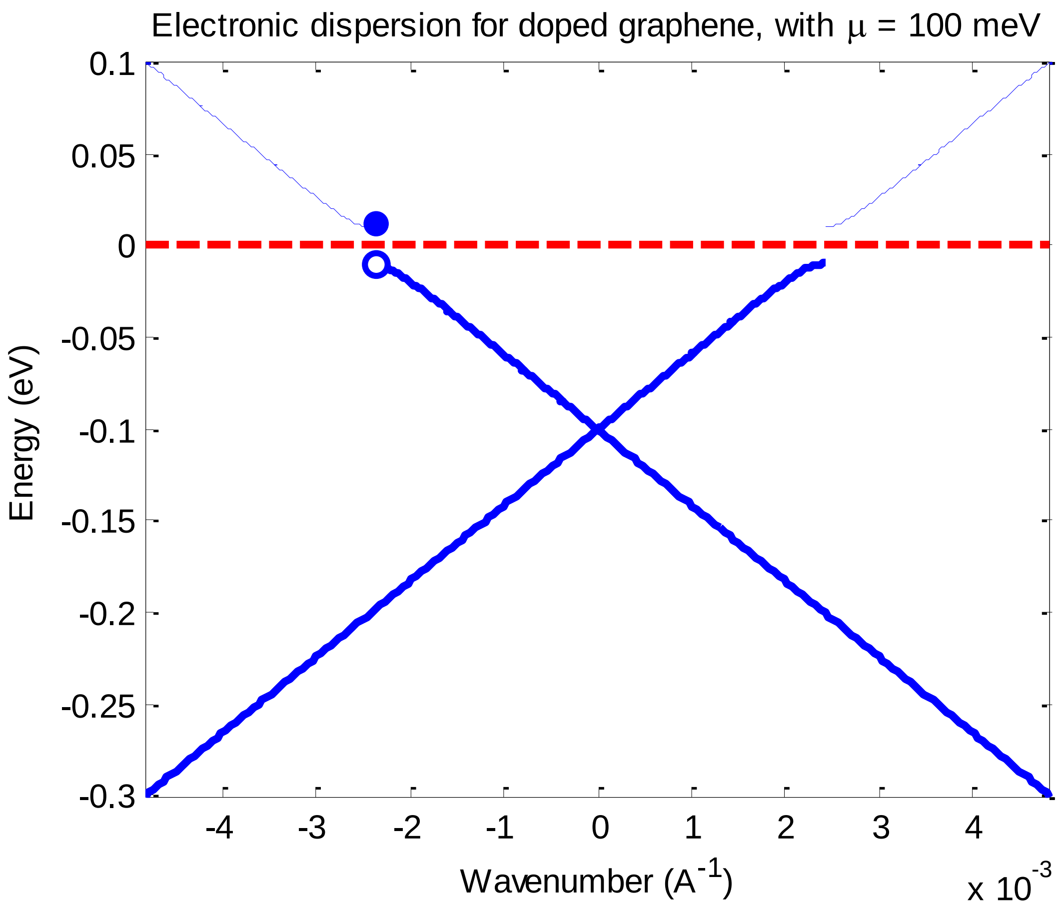
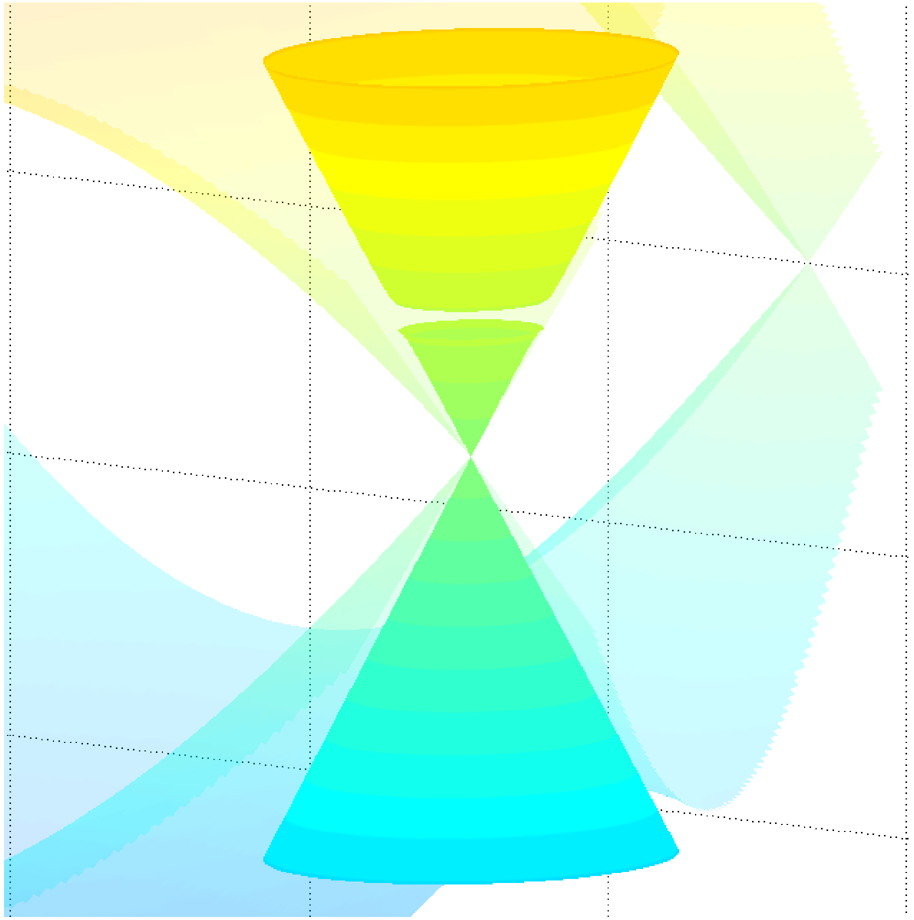
ERS in superconducting graphene: the picture





ERS in superconducting graphene: the picture



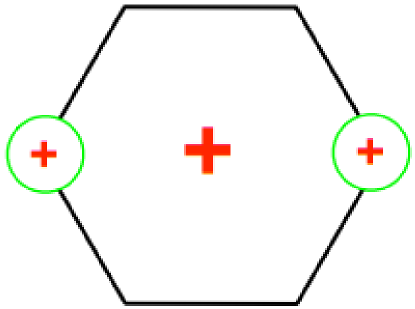


ERS in superconducting graphene: the theory

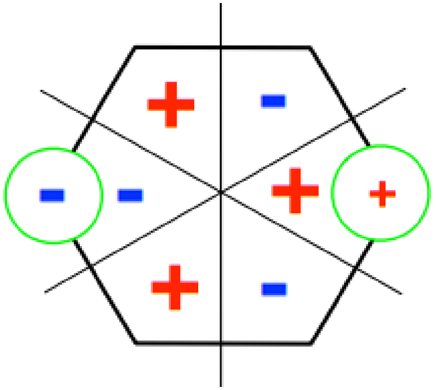
$\Psi_k = \boxed{\text{Spin}} \otimes \text{momentum}$

Order parameter

$$\Delta_k \equiv \langle GS|\Psi_k|GS\rangle$$

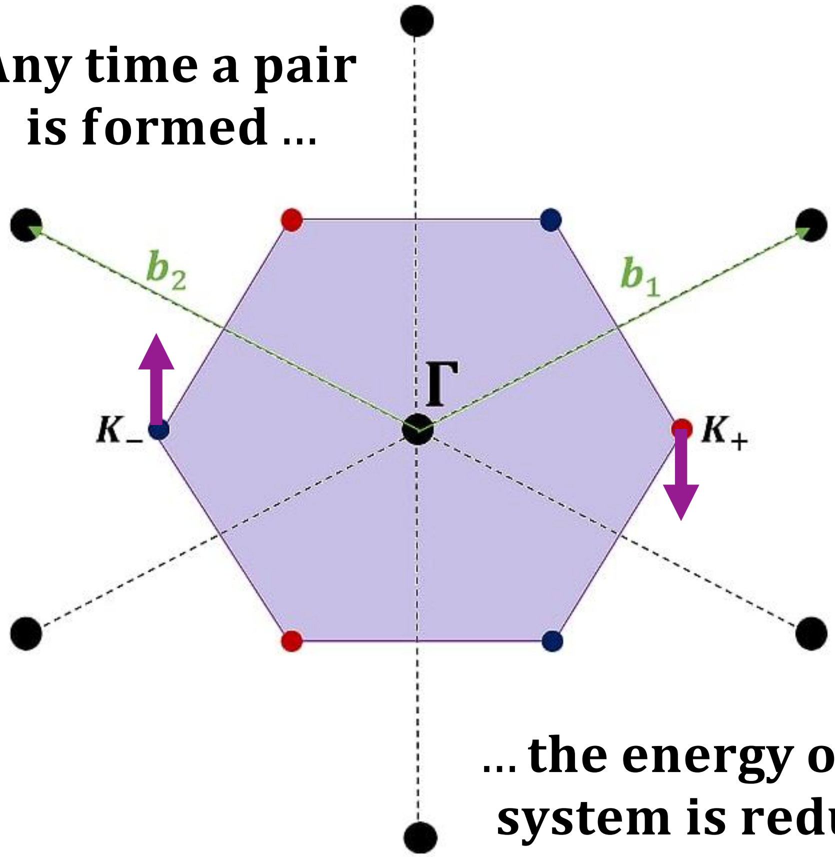
$\Delta_k =$ 

Singlet



Triplet

Any time a pair is formed …



… the energy of the system is reduced

ERS in superconducting graphene: the theory

Light-matter interaction

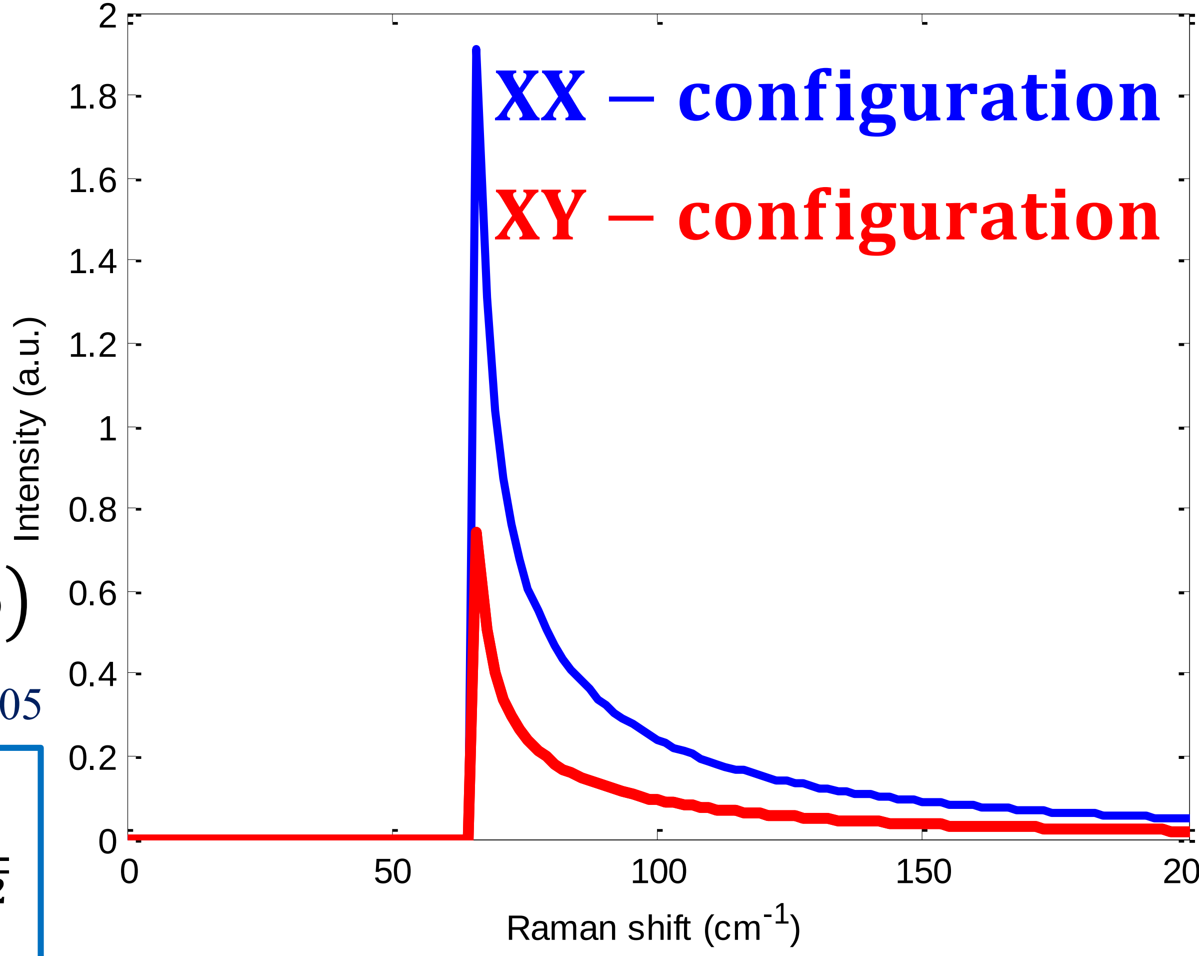
$$\vec{P} \longrightarrow \vec{p} - \frac{e}{c}\vec{A}$$

$$\mathcal{H}_{gr}^{lin}$$

$$w(\omega) = \int \frac{dp}{2\pi\hbar^3} \left| \langle c_2 | \mathcal{V}_{lin} | c_1 \rangle \right|^2 \delta(\epsilon_f - \epsilon_i + \omega)$$

A. García−Ruiz, M. Mucha−Kruczyński, and V. I. Fal′ko, PRB **97**, 155405

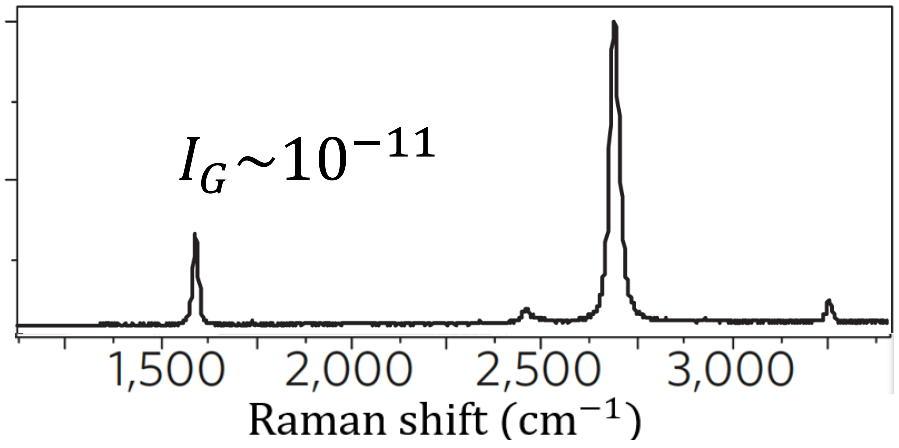
$$w(\omega) = \frac{8\hbar e^4 v^2 \mu}{\Omega^2} \left(\left(\frac{\mu}{\Omega^2} - \frac{\gamma_n}{2\gamma_0^2} \right)^2 \Xi_s' + \frac{\mu^2}{2\Omega^4} \Xi_o \right) \frac{4\Delta}{\omega\sqrt{\omega^2 - 4\Delta^2}}$$



ERS in superconducting graphene: the theory

The challenge: Is this feature measurable?

$$\text{Quantum efficiency} = \int d\omega \int d\binom{scattered}{angles} w(\omega) \quad {\sim}10^{-14}$$



Marcin Mucha-Kruczynski

Stephen Clark

Joshua Thompson

Vladimir Falko

#148

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Superconductivity-induced features in the electronic Raman spectrum of monolayer graphene

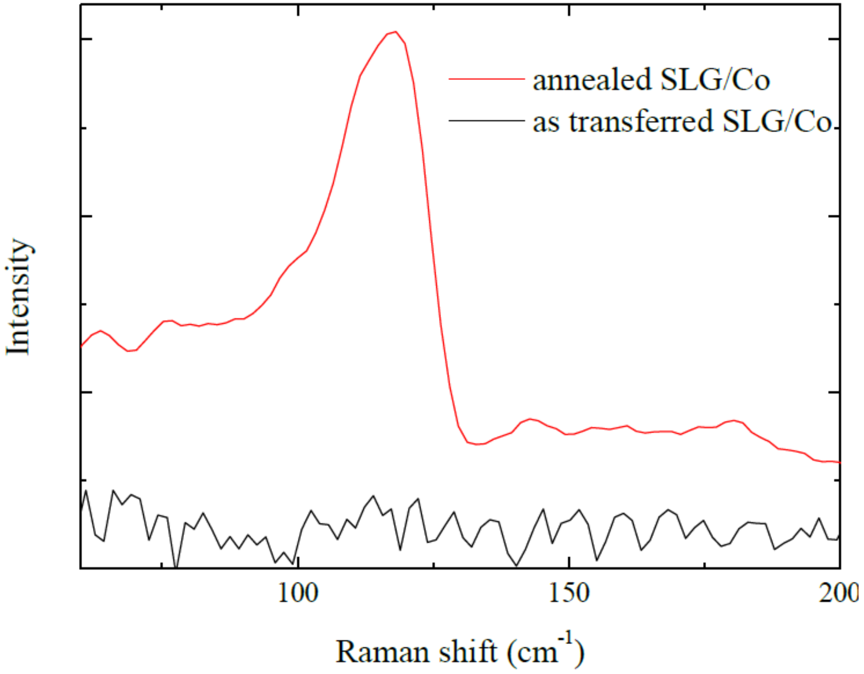
Raman scattering minds the gap

Image from "Raman Spectroscopy in Graphene Related Systems" Ado Jorio et al.

Extra slide: peak at 117cm^{-1}

Phys. Rev. B **91**, 195435 (2015)

[…] the *XX* spectrum of the annealed sample demonstrates a surprising appearance of the narrow intense band at 117 cm^{-1} (see Fig. S3 in [30]). Its line shape is very asymmetric, showing the well-known Breit-Wigner-Fano (BWF) interference between the phonon and continuum [33]. This implies the **appearance of the defect-induced low-energy electronic excitations, perhaps of the intraband type discussed in [16,17].**



Supplementary information

The heat treatment results in a strong intensity increase of the D mode at 1346 cm^{-1} and an appearance of asymmetric low-frequency peak at 117 cm^{-1}. This implies a growth of the defect density leading to selection rules violation and Raman activity of layer-breathing mode at 117 cm^{-1}.

ERS in superconducting graphene: the theory

Light-matter interaction

$\vec{P} \rightarrow \vec{p} - \frac{e}{c}\vec{A}$

$\mathcal{H}_{gr}^{lin} \rightarrow \mathcal{V}_{lin}$

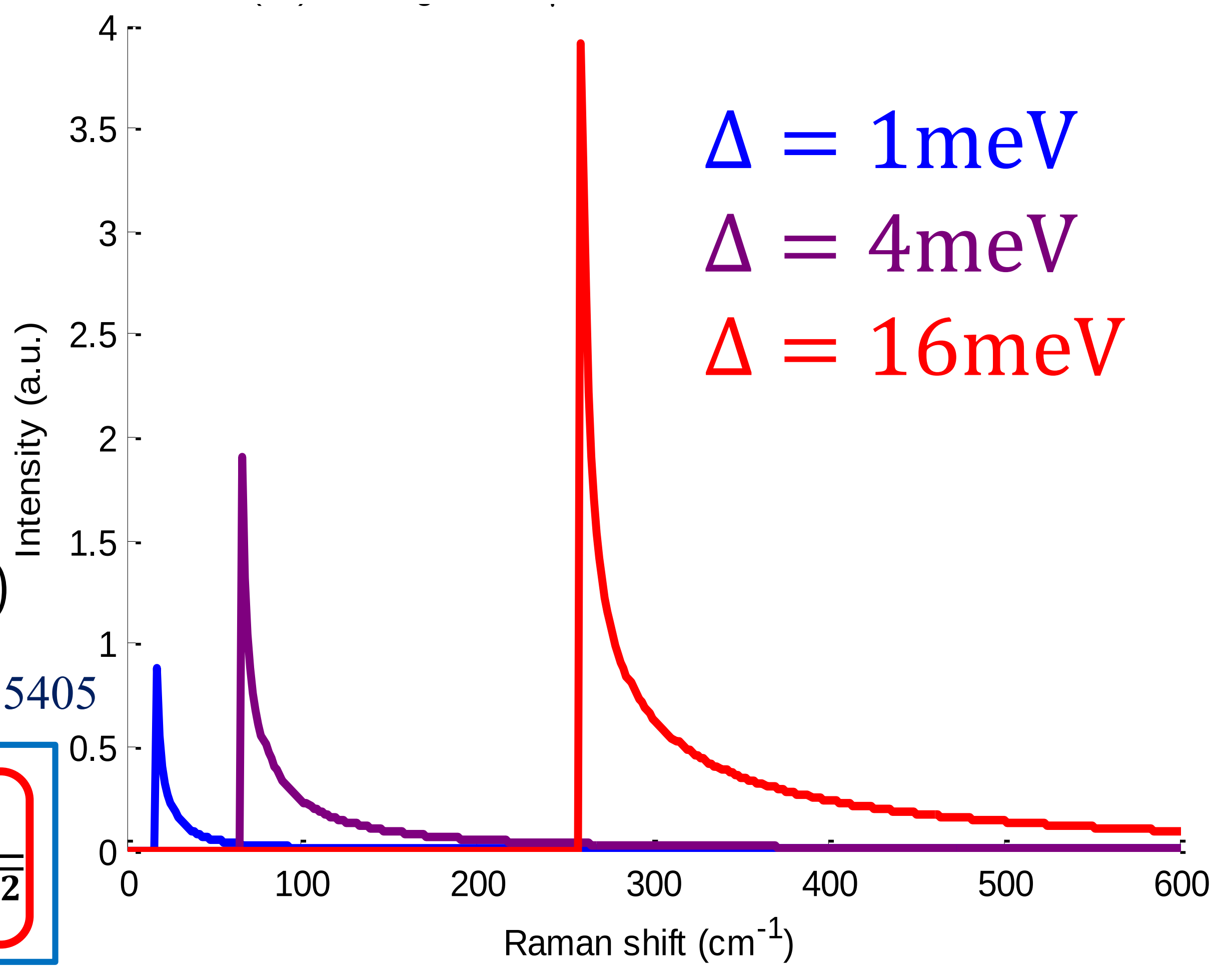
$\mathcal{H}_{gr}^{TW} \rightarrow \mathcal{V}_{TW}$

$\mathcal{H}_{gr}^{nnn} \rightarrow \mathcal{V}_{nnn}$

$$w(\omega) = \int \frac{dp}{2\pi\hbar^3} \left| \langle f | \mathcal{V}_{lin} + \mathcal{V}_{TW} + \mathcal{V}_{nnn} | i \rangle \right|^2 \delta(\epsilon_f - \epsilon_i + \omega)$$

A. García−Ruiz, M. Mucha−Kruczyński, and V. I. Fal′ko, PRB **97**, 155405

$$w(\omega) = \frac{8\hbar e^4 v^2 \mu}{\Omega^2} \left(\left(\frac{\mu}{\Omega^2} - \frac{\gamma_n}{2\gamma_0^2} \right)^2 \Xi_s' + \frac{\mu^2}{2\Omega^4} \Xi_o \right) \boxed{\frac{4\Delta}{\omega\sqrt{\omega^2 - 4\Delta^2}}}$$



ERS in superconducting graphene: the theory

Light-matter interaction

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$$\mathcal{H}_{gr}^{lin} \rightarrow \mathcal{V}_{lin} \qquad \mathcal{H}_{gr}^{TW} \rightarrow \mathcal{V}_{TW} \qquad \mathcal{H}_{gr}^{nnn} \rightarrow \mathcal{V}_{nnn}$$

$$w(\omega) = \int \frac{dp}{2\pi\hbar^3} \left| \langle f | \mathcal{V}_{lin} + \mathcal{V}_{TW} + \mathcal{V}_{nnn} | i \rangle \right|^2 \delta(\epsilon_f - \epsilon_i + \omega)$$

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