Transport Properties of Spin-polarized Graphene

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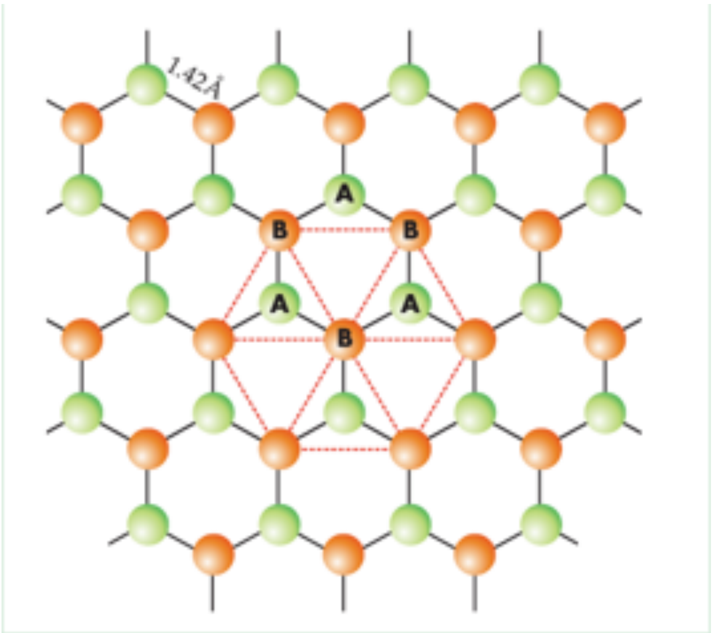
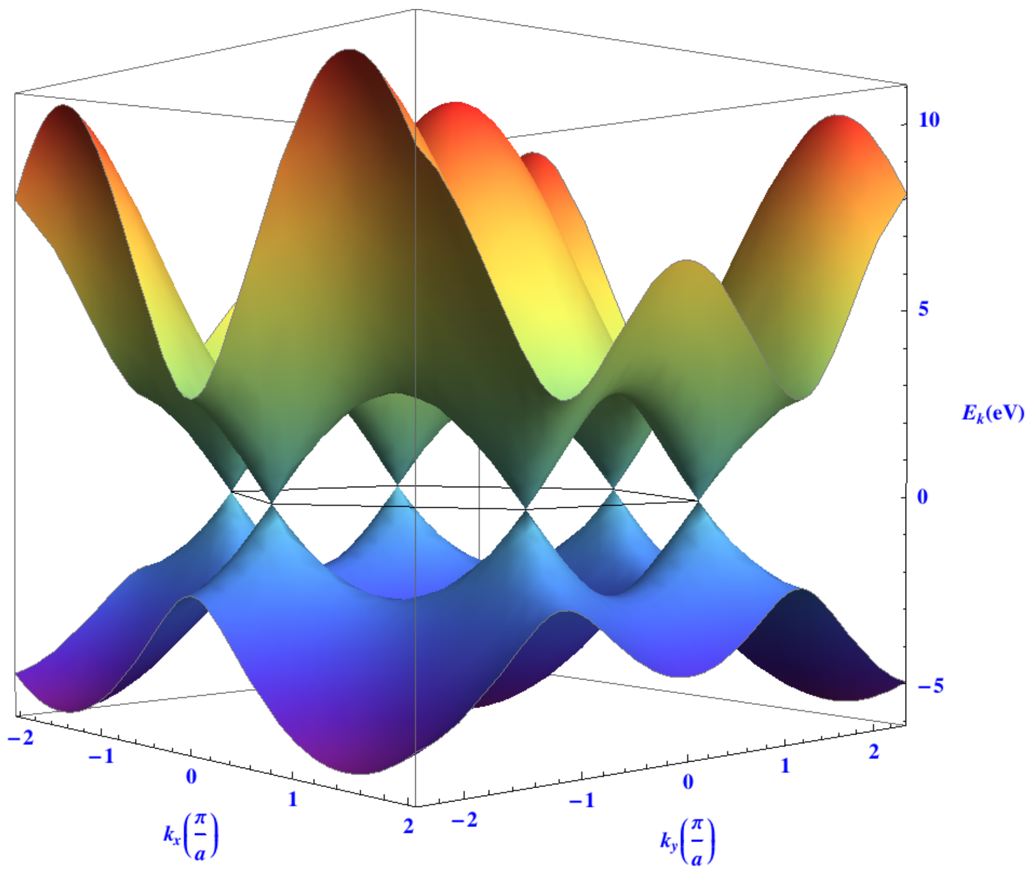
"Quantum transport in graphene", 24 April 2014, School of Physics, IPM
(In memory of Malek Zareyan)

Outline

- Basics of Graphene
- Spin-imbalance in graphene (FM-G)
- Transport in FM-G with magnetic impurities
- Optical Hall conductivity in FM-G
- Spin-Coulomb drag in FM-G!
- Conclusions

Chiral Dirac Fermions in Graphene





http://nobelprize.org/

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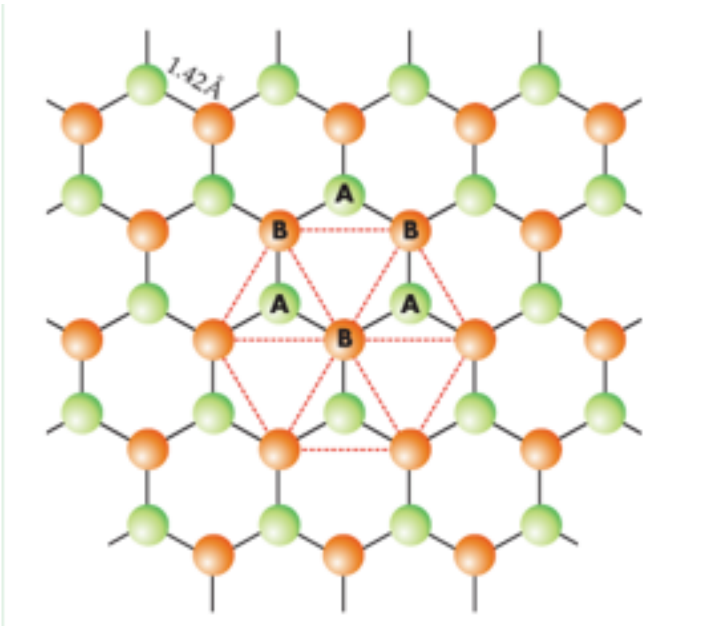

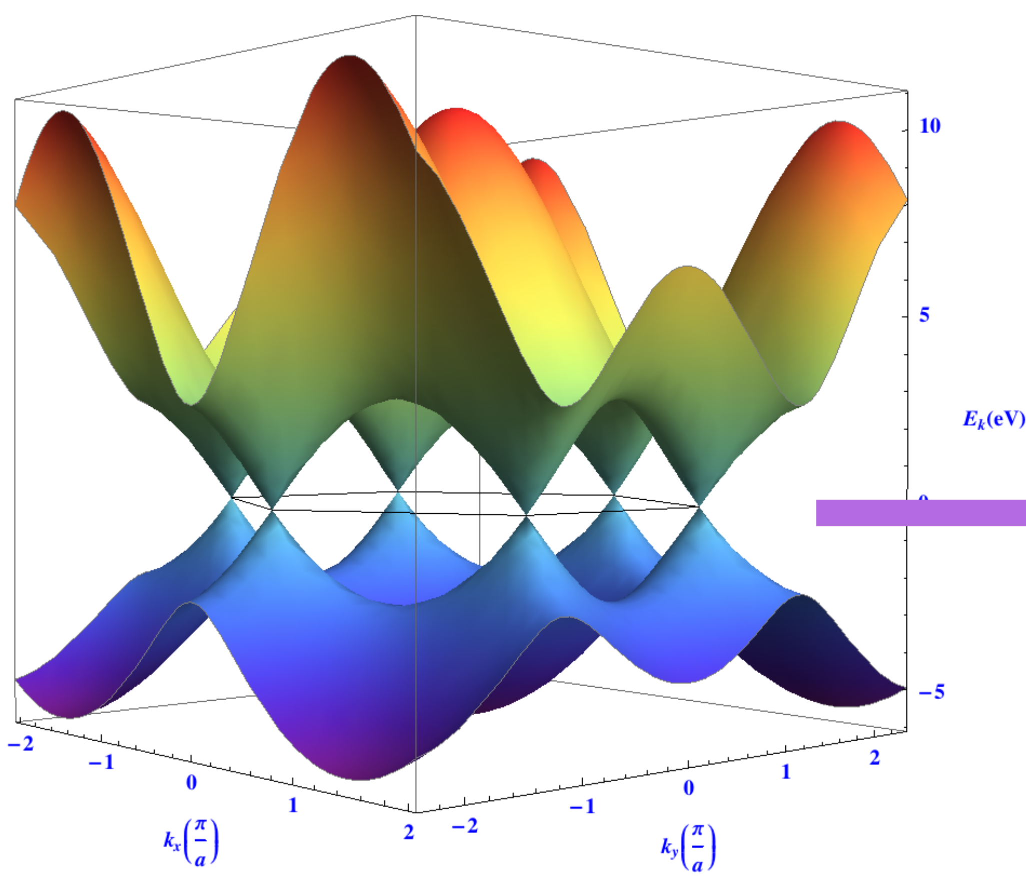

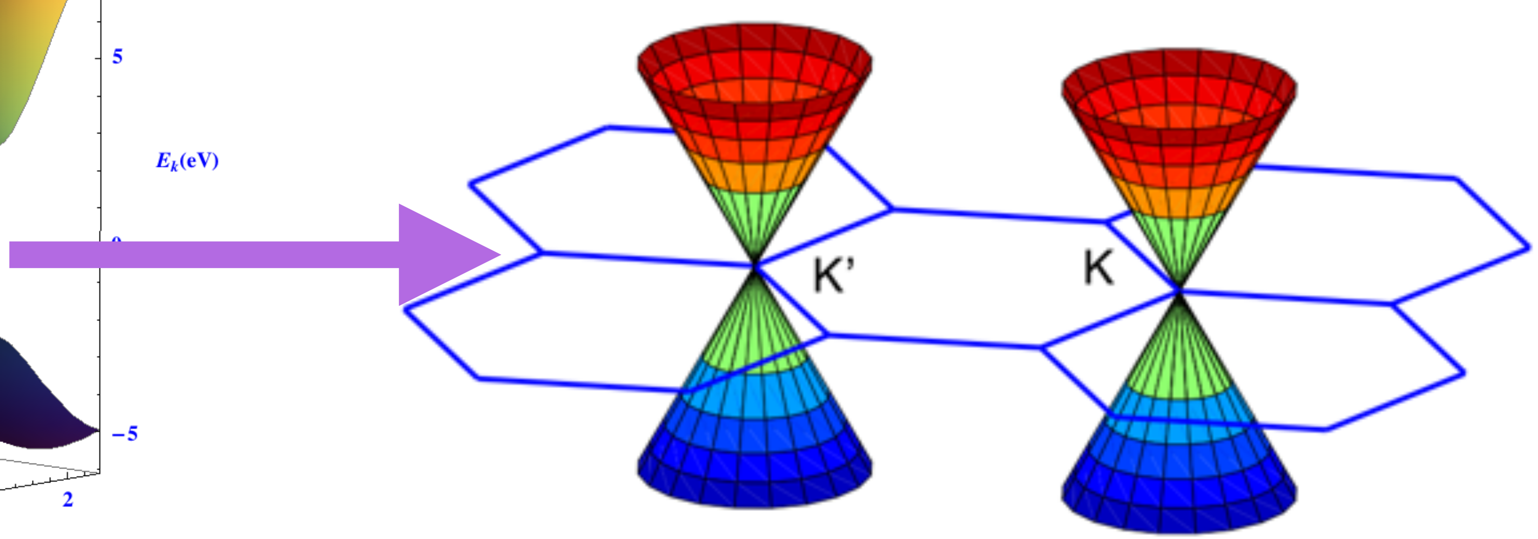

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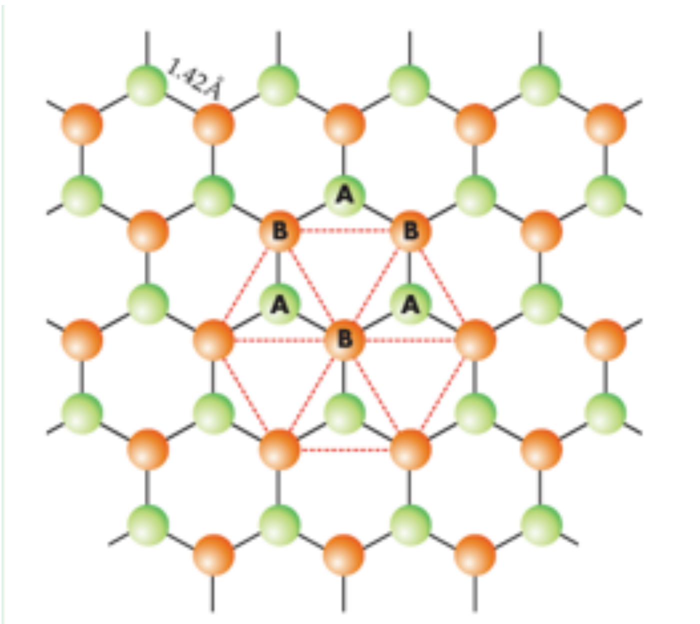

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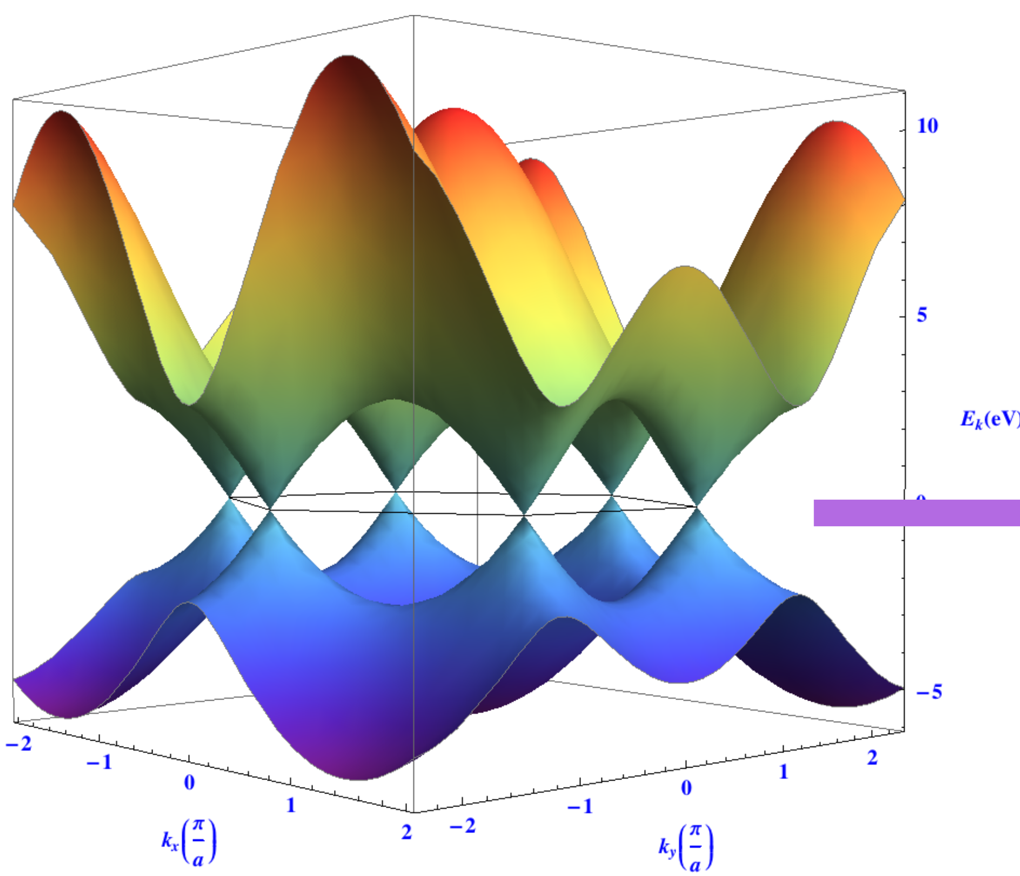

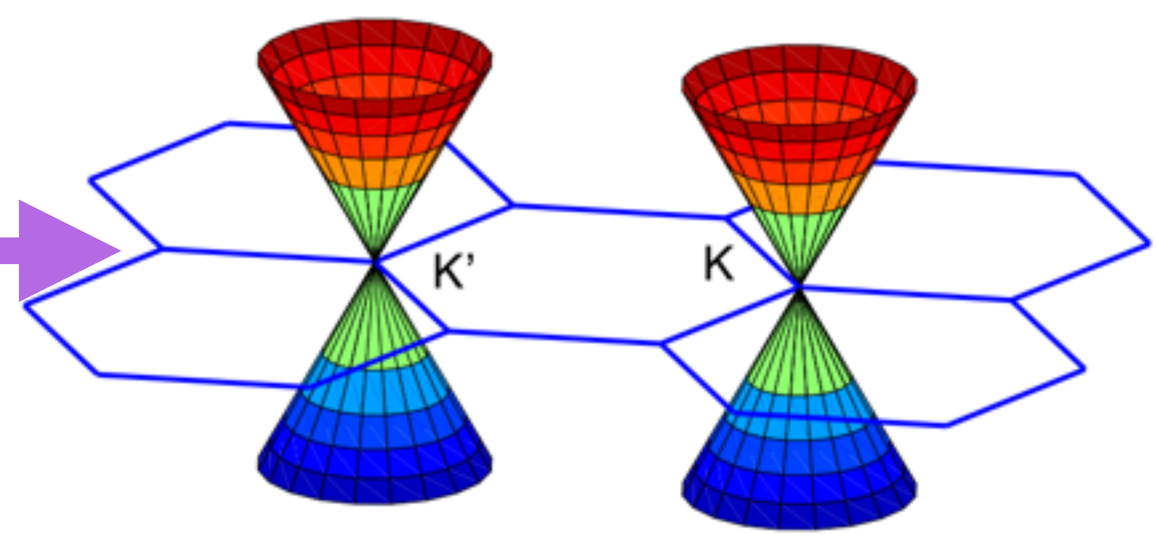

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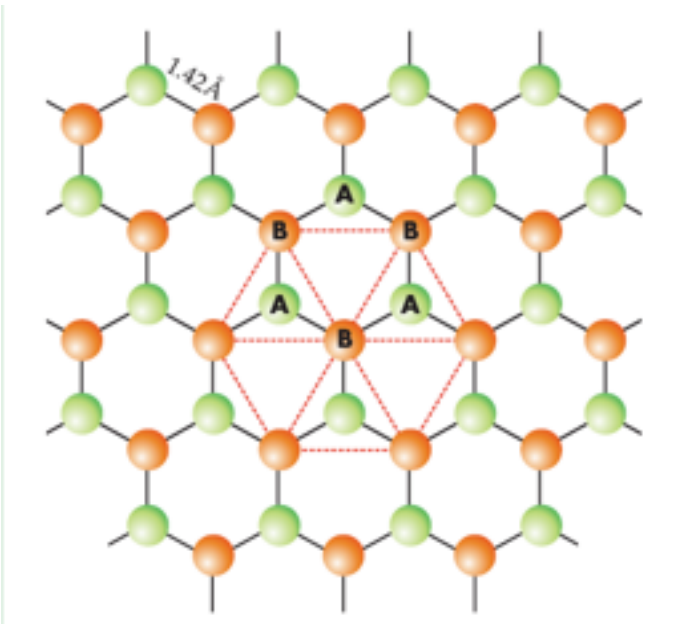

Spin (and valley) degenerate

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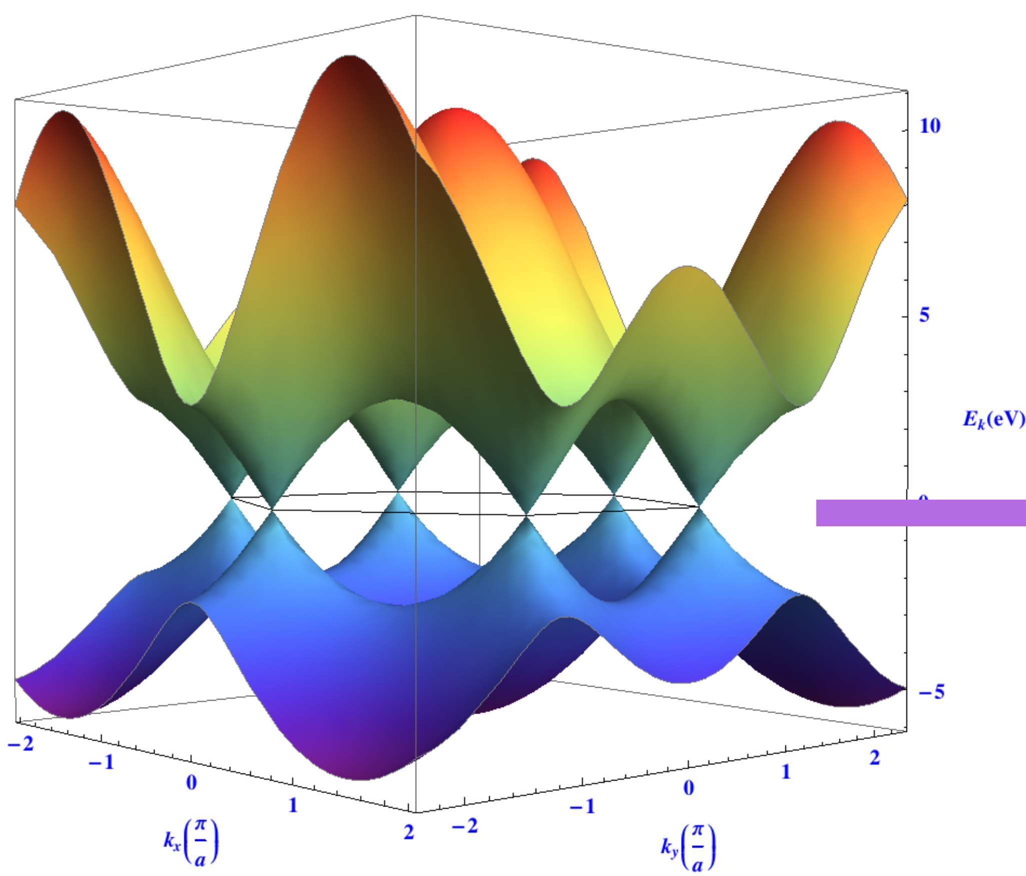

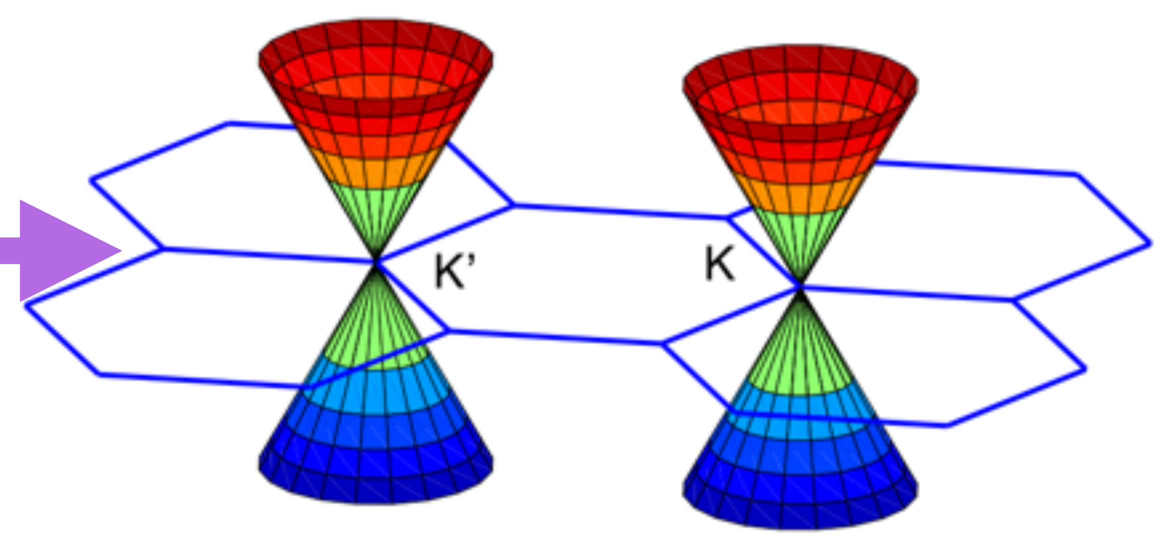

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Tunable electron and hole dopings

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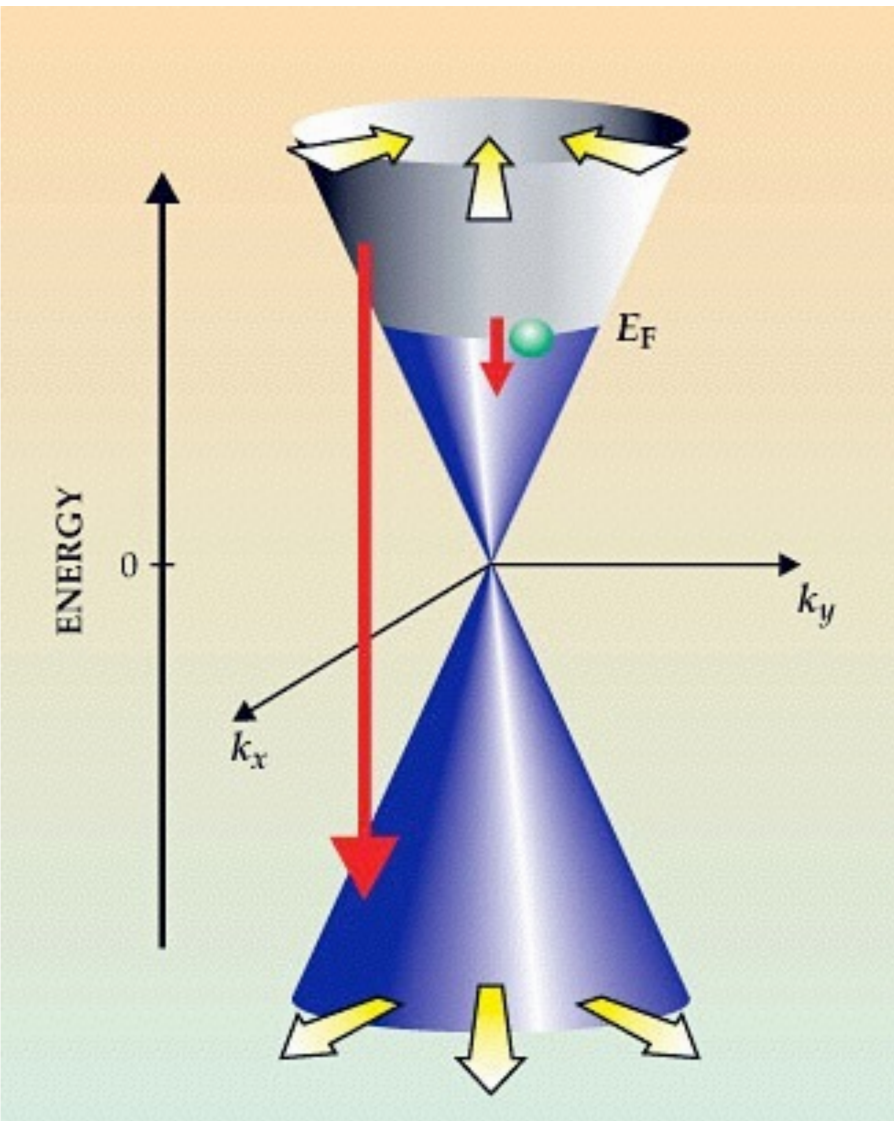

Polini *et al.*, SSC (2007)

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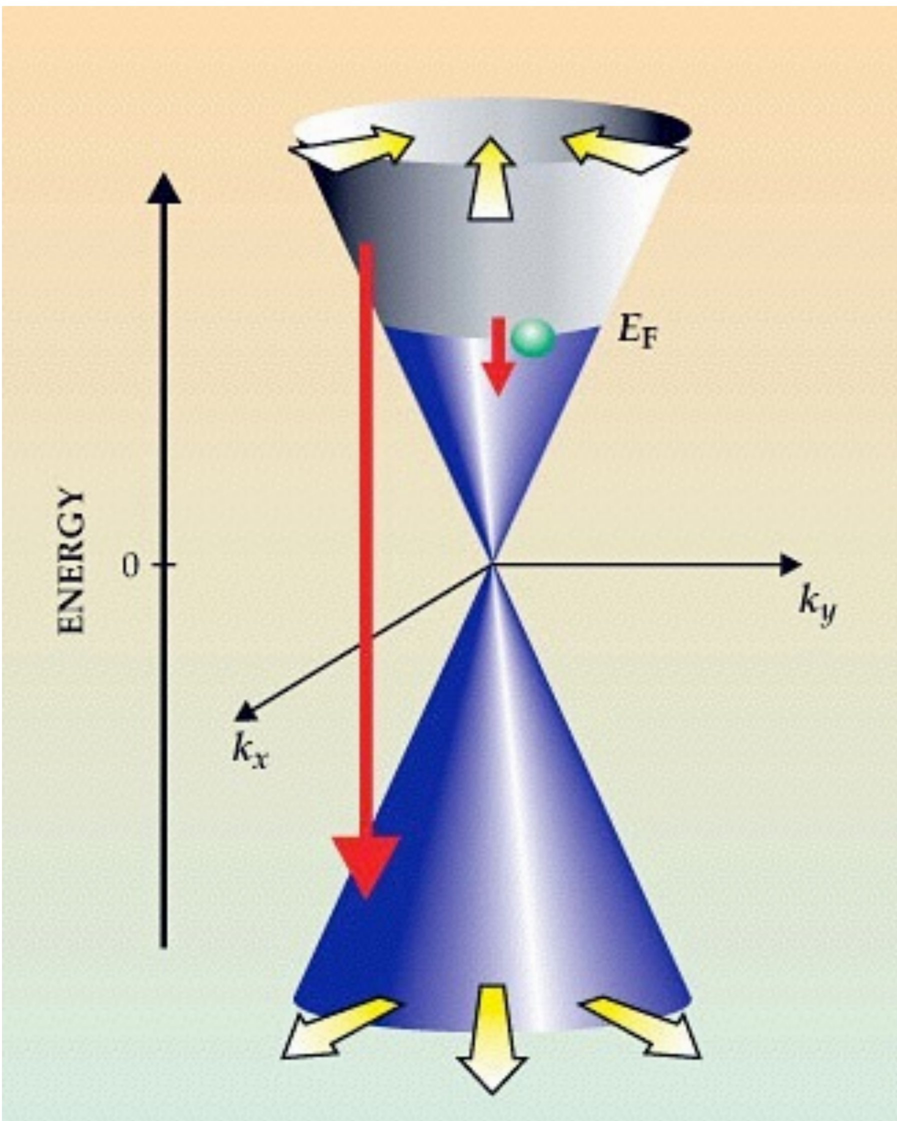
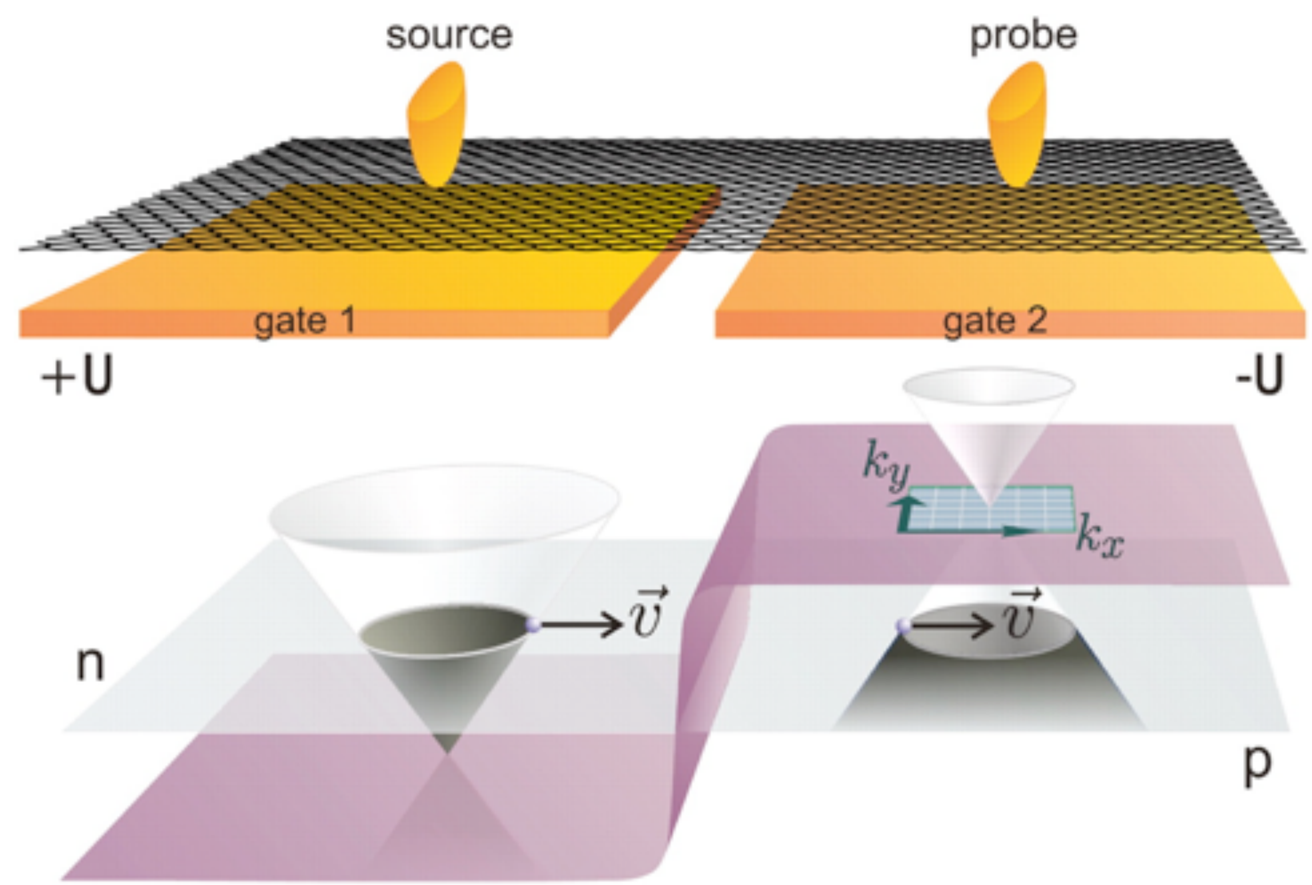


Polini *et al.*, SSC (2007)

graphene p-n junction



Exchange field and spin polarization in graphene

$$\mathcal{H}_K = \hbar v_{\mathrm{F}} \left(k_x \sigma_x + k_y \sigma_y \right) + h \tau_z$$

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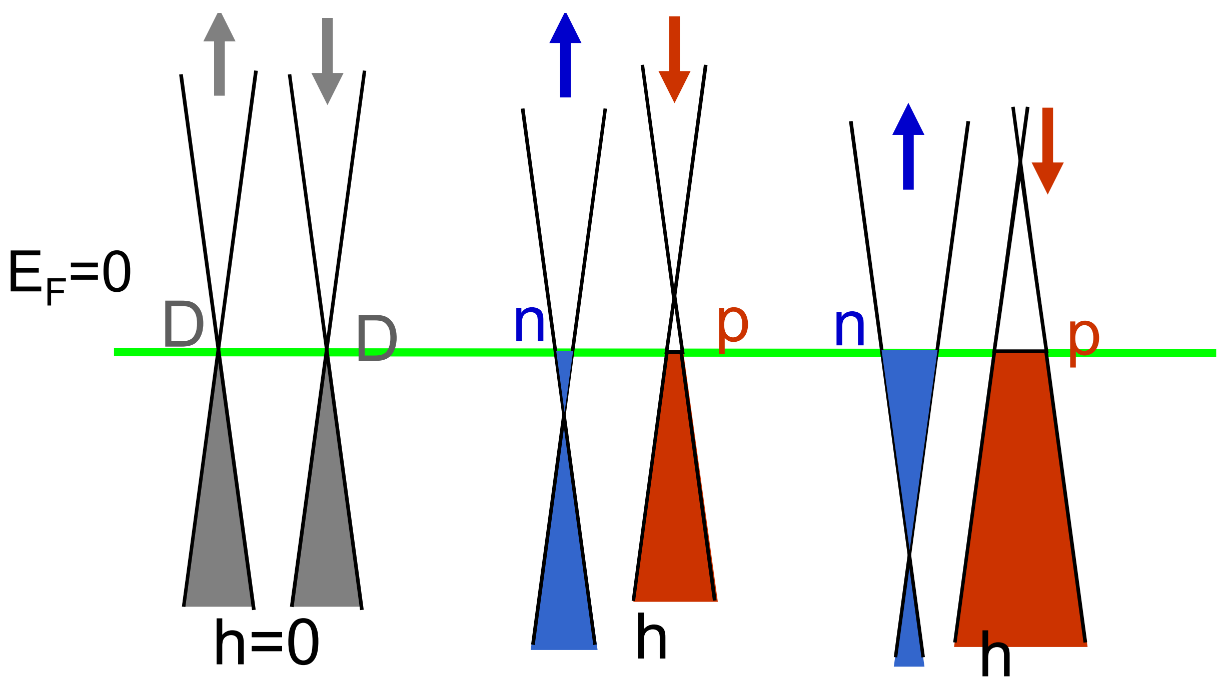

Photo courtesy of M. Zareyan

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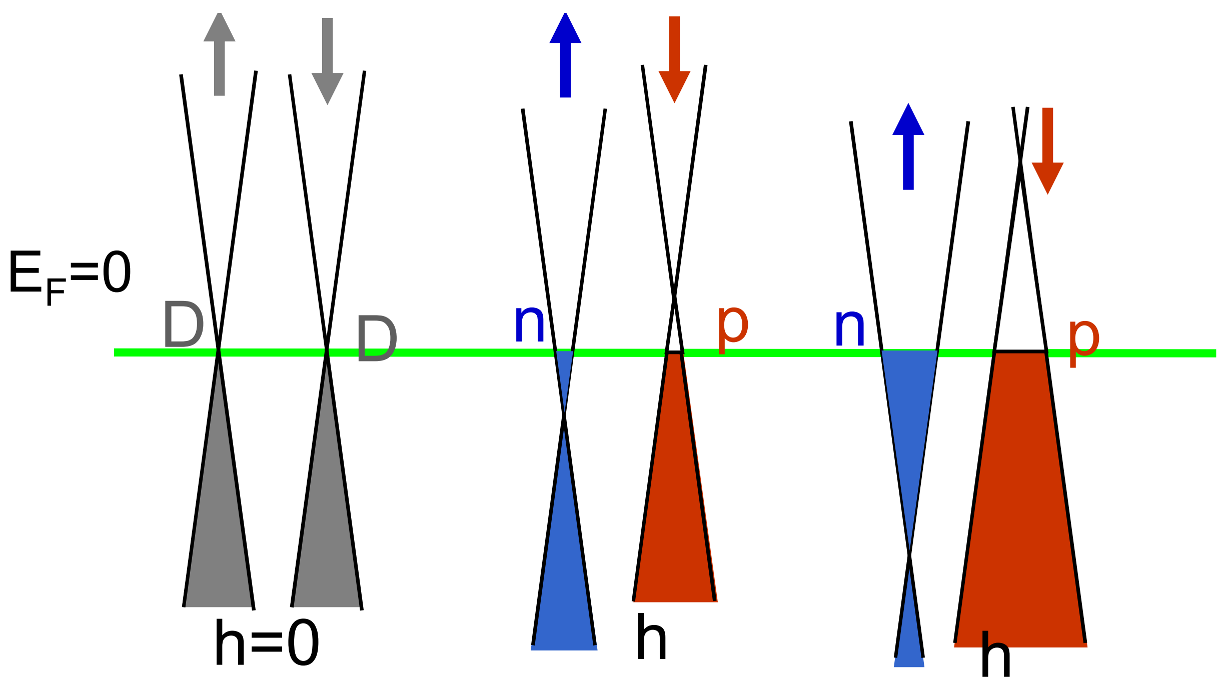
n-type up-spin & p-type down-spin carriers



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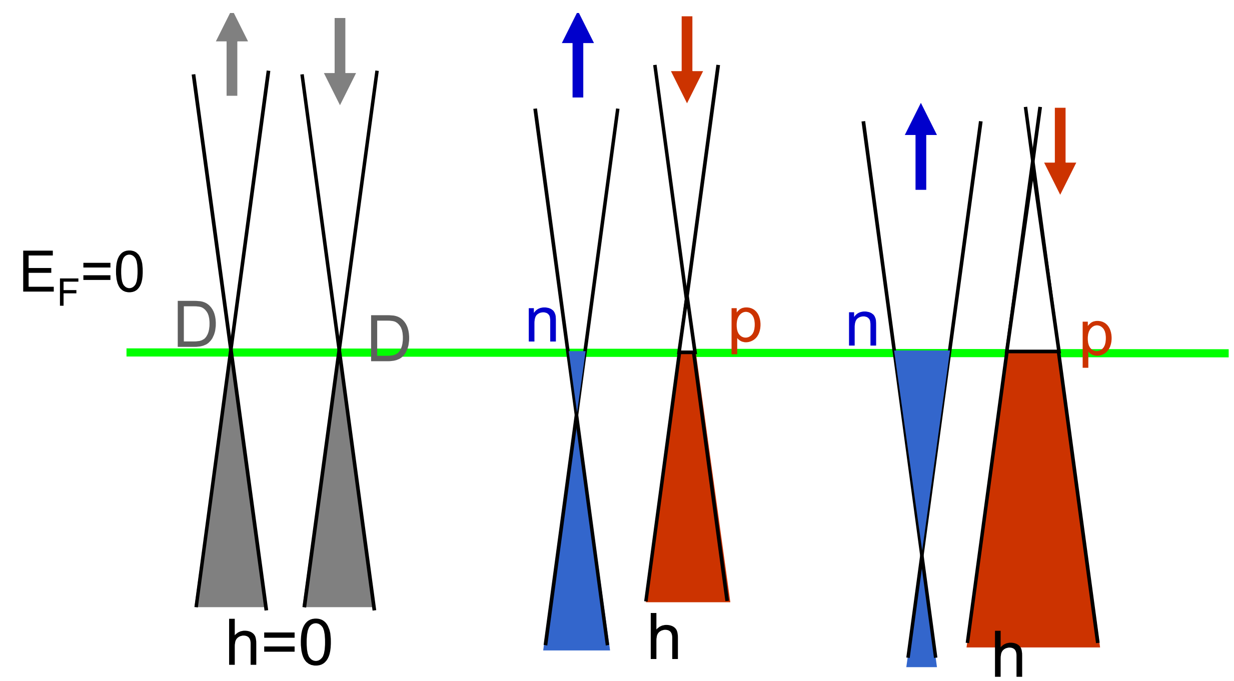


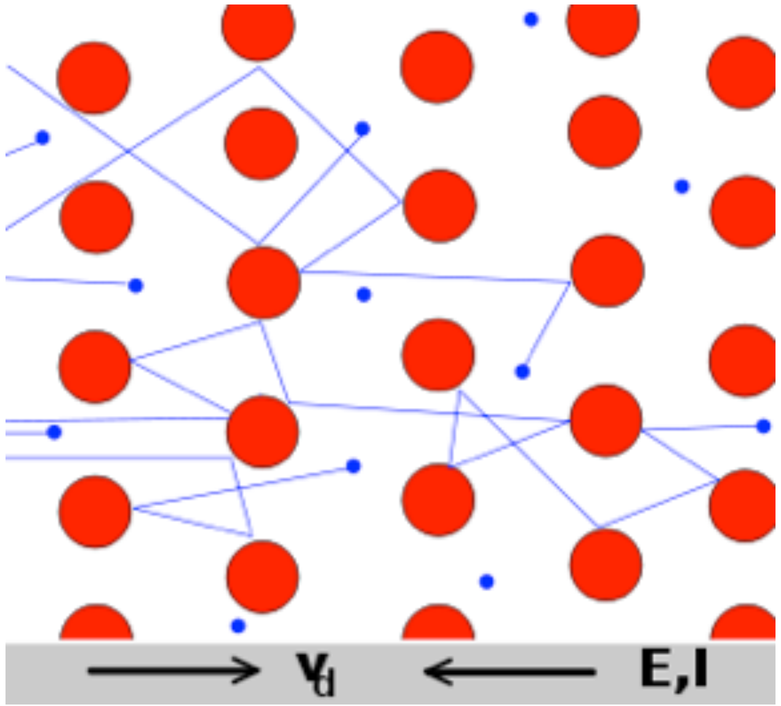
Photo courtesy of M. Zareyan

(Some) exotic properties of spin-polarized graphene:

- Josephson coupling through FM-G: Moghaddam, Zareyan, PRB (2008)
- Andreev-Klein reflection in FM-G: Zareyan, Mohammadpour, Moghadam, PRB (2008)
- Spin-lensing in FM-G: Moghaddam, Zareyan, PRL (2010)
- RKKY interaction in FM-G: Parhizghar, Asgari, SAH, Zareyan, PRB (2013)

Semi-classical theory of charge transport

$$\mathbf{j} = \sigma \mathbf{E}$$



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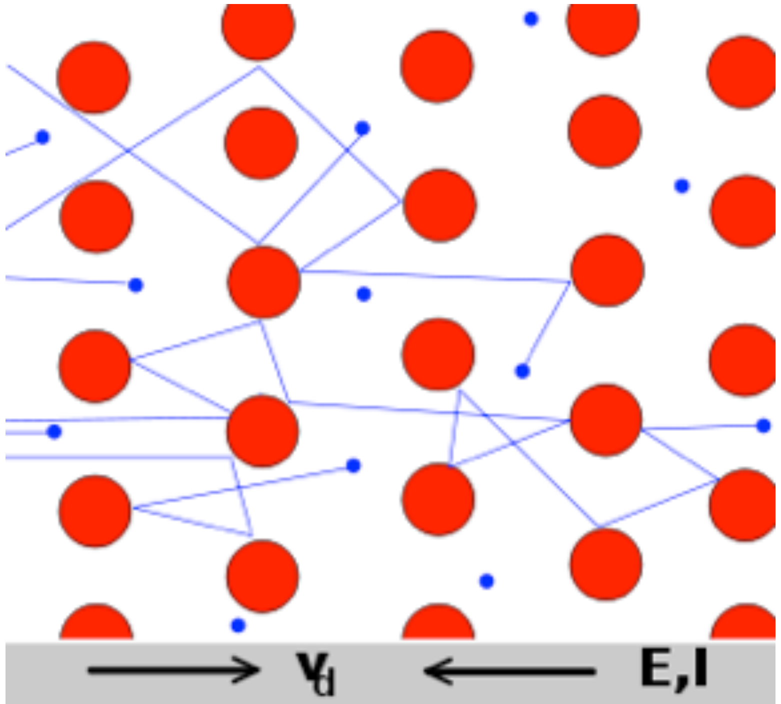

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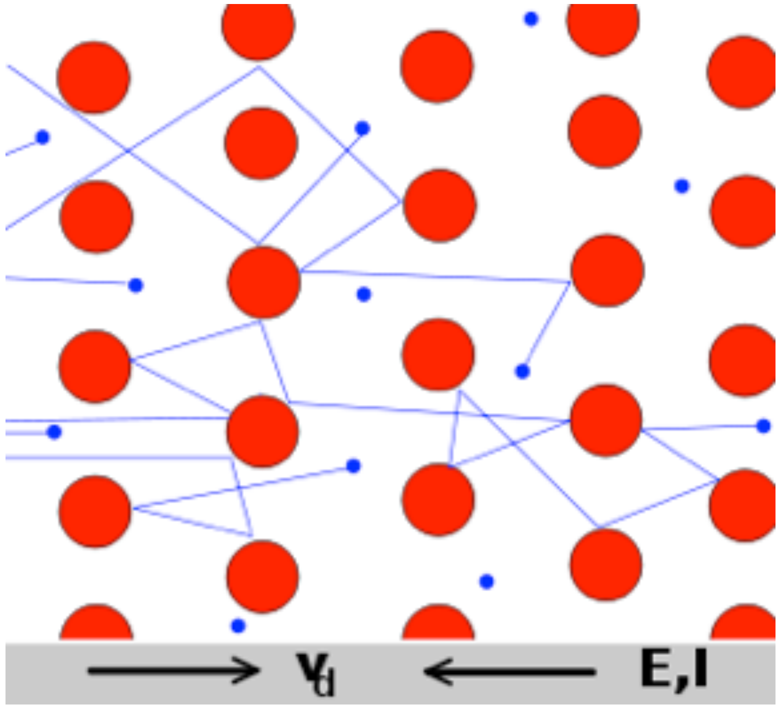

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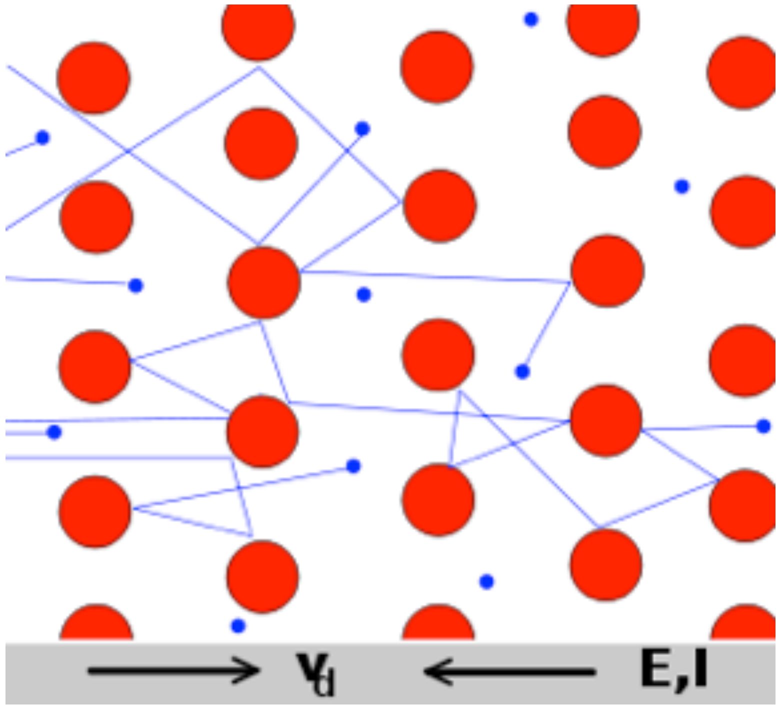

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relaxation time!

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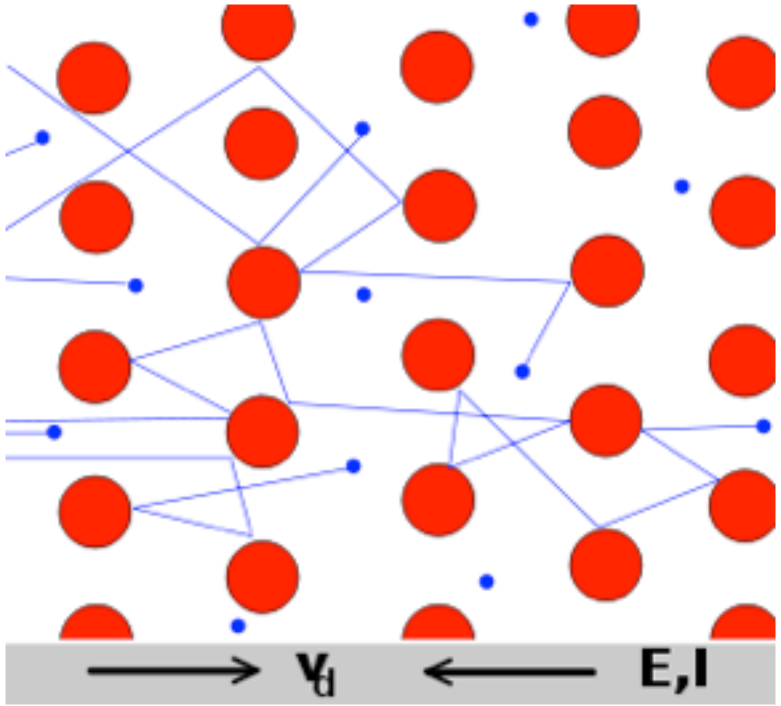

$$\mathbf{j} = e \sum_{\mathbf{k},i} \mathbf{v}_{\mathbf{k},i} f_i(\mathbf{k},\mathbf{r},t)$$

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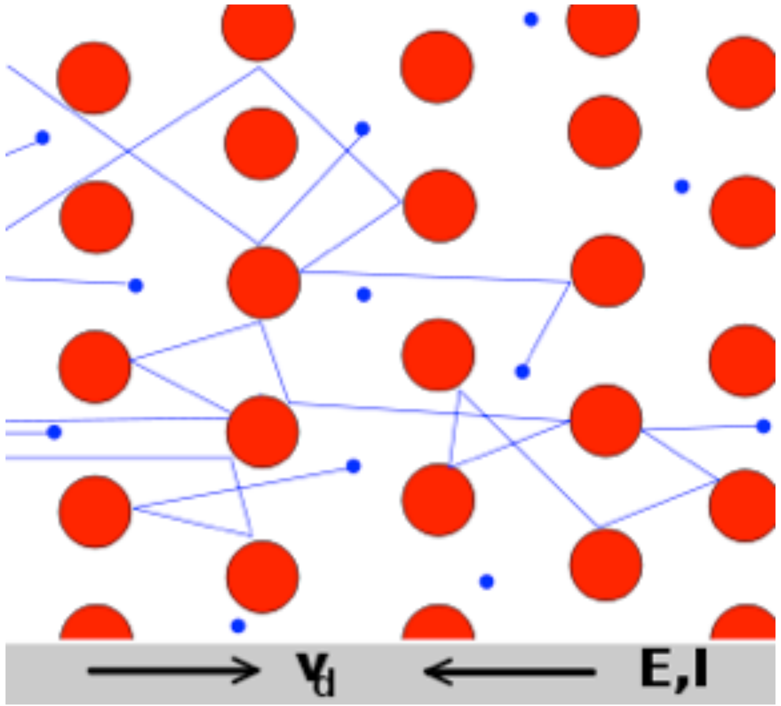

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in equilibrium $f = n_{FD}$
and **j**=0

Semi-classical theory of charge transport (cont.)

out-of-equilibrium: $f(\mathbf{k}) = n_{\mathrm{FD}}(\varepsilon_{\mathbf{k}}) + \delta f(\mathbf{k})$

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Boltzmann & relaxation time approximations:

$$\left(\frac{\partial f}{\partial t}\right)_{\mathrm{scatt}} = e\mathbf{v}_{\mathbf{k}} \cdot \mathbf{E} \left(-\frac{\partial n_{\mathrm{FD}}(\varepsilon)}{\partial \varepsilon}\right) = -\frac{\delta f}{\tau}$$

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scattering rate:
(Fermi's Golden rule)

$$W(k,k') = \frac{2\pi}{\hbar}\,\left|\langle\psi_k|\mathcal{H}_{\rm imp}|\psi_{k'}\rangle\right|^2\,\delta(\varepsilon_{k'}-\varepsilon_k)$$

Transport in spin-polarized graphene with magnetic impurities

$$\mathcal{H}_K = \hbar v_{\mathrm{F}} \left(k_x \sigma_x + k_y \sigma_y \right) + h\tau_z$$

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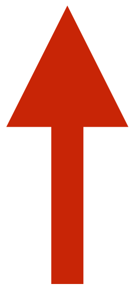

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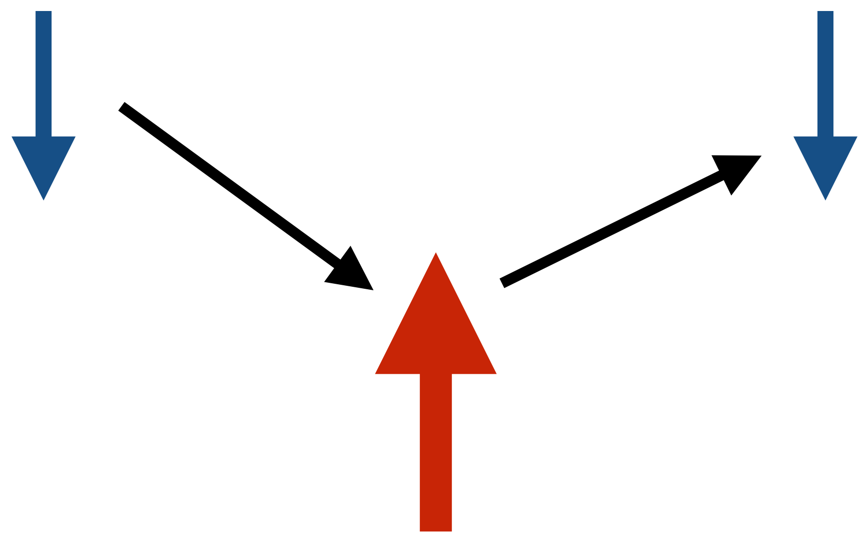

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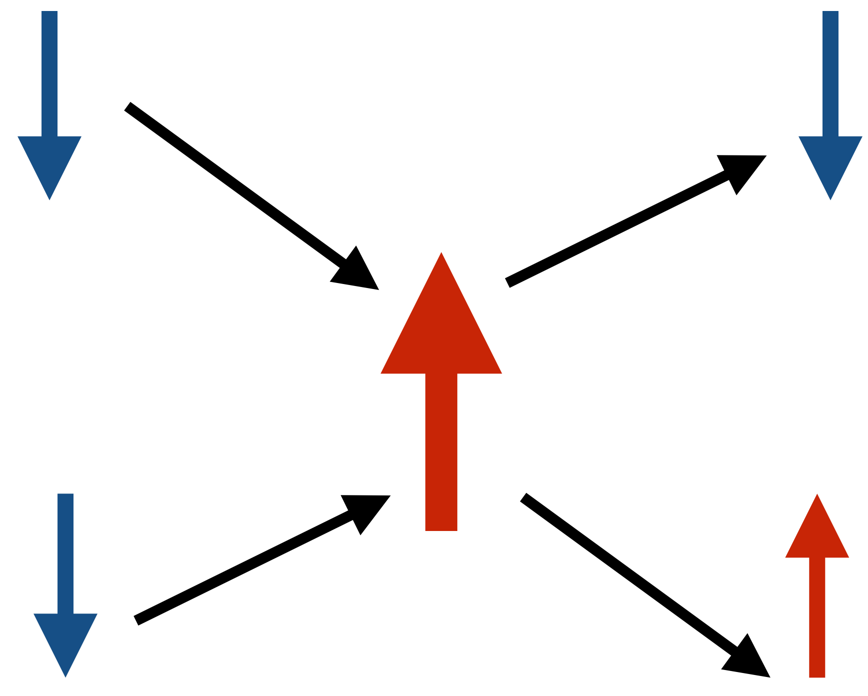

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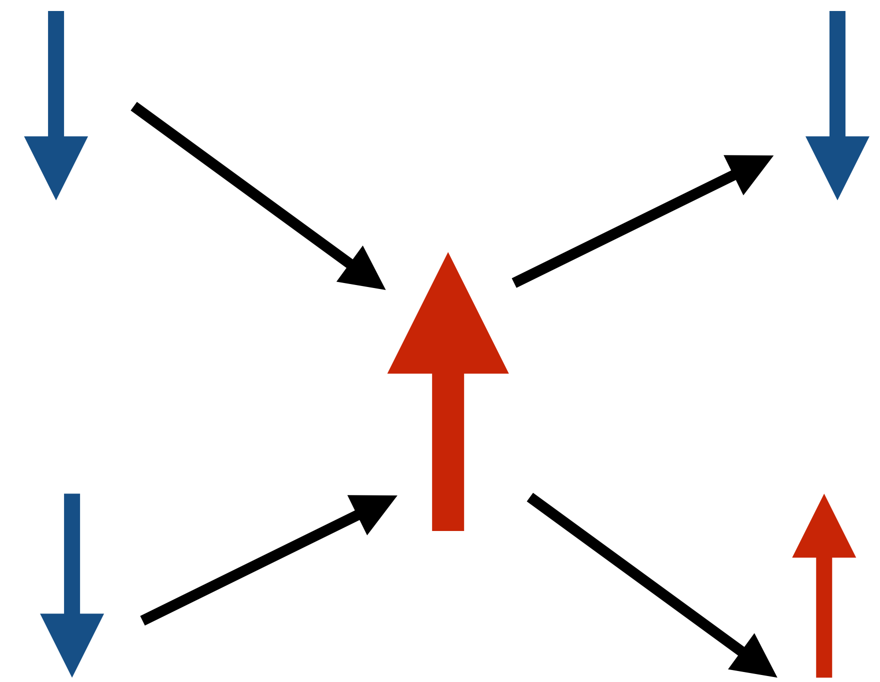


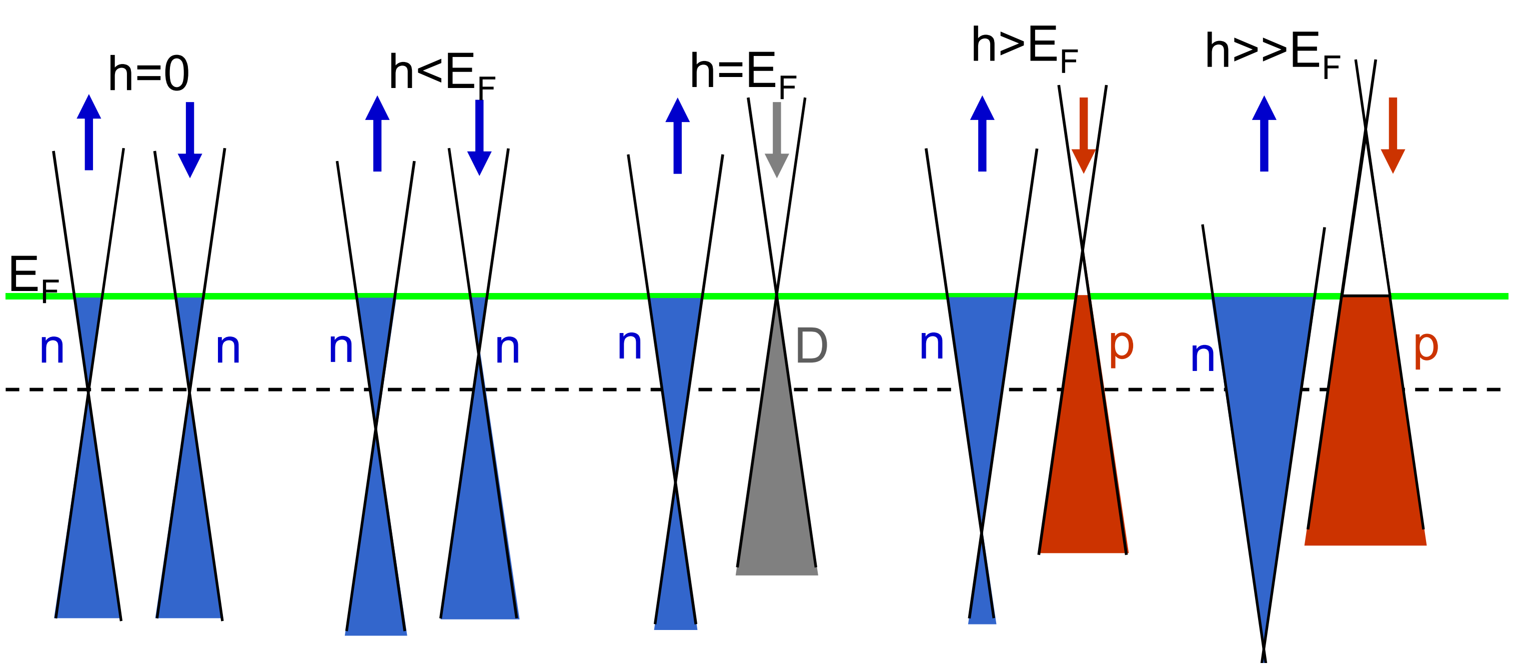
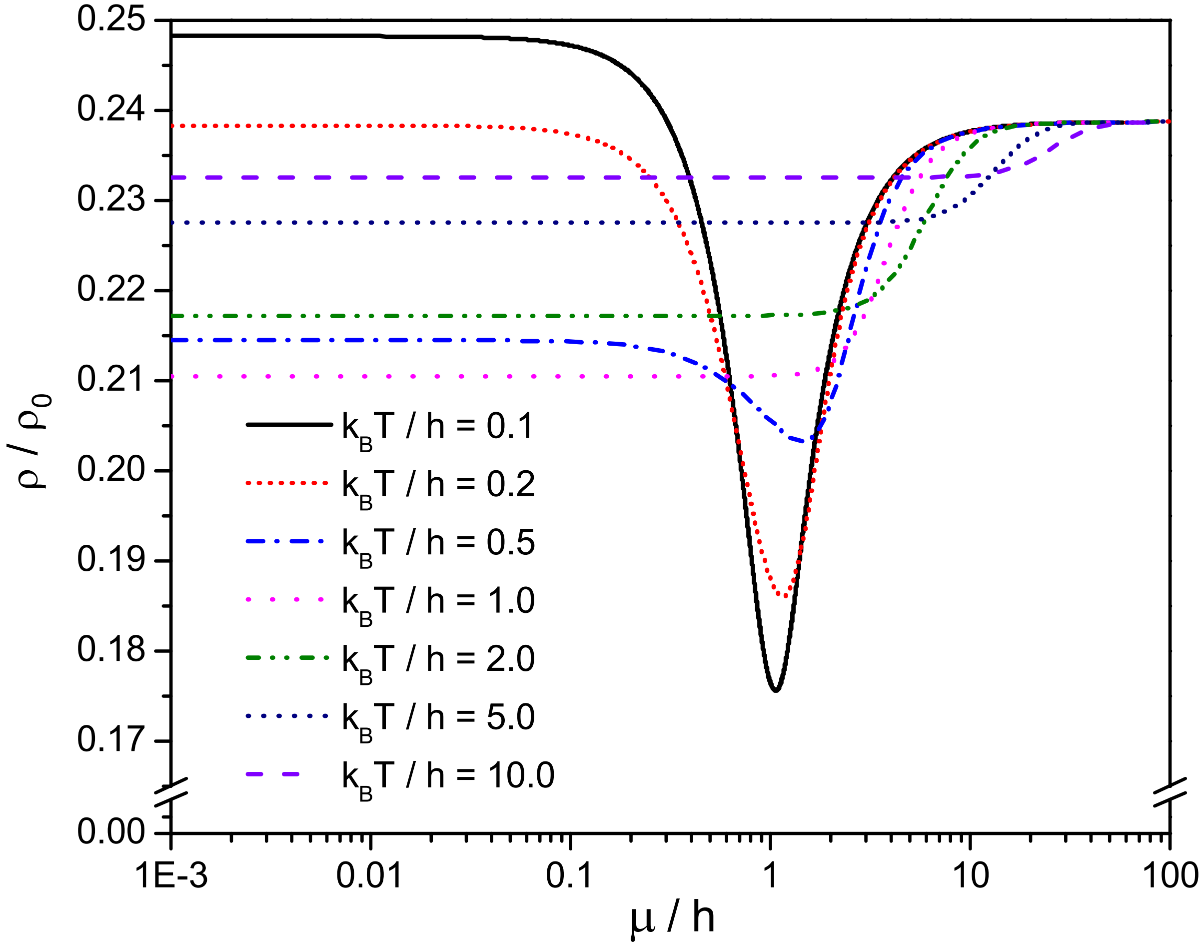
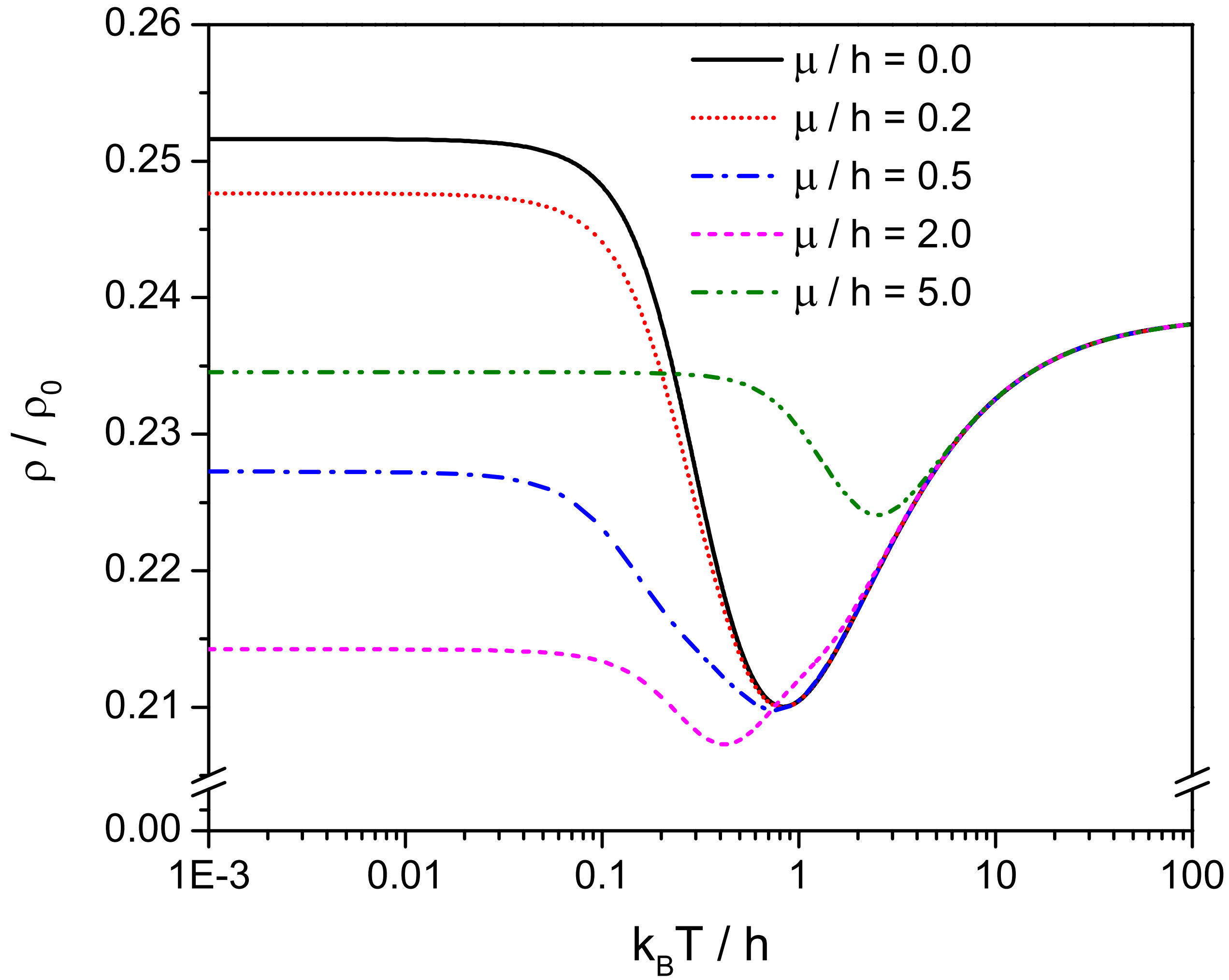


Photo courtesy of M. Zareyan

spin-conserving and spin-flip scatterings from the magnetic impurities

Transport in spin-polarized graphene (cont.)





Zare, Moghaddam, SAH, Abdizadeh, Zareyan, PRB (2013)

Optical Hall conductivity in spin-polarized graphene

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$$\mathcal{H} = v_{\mathrm{F}} \left(\Pi_x \sigma_x + \Pi_y \sigma_y \right) + h\tau_z$$

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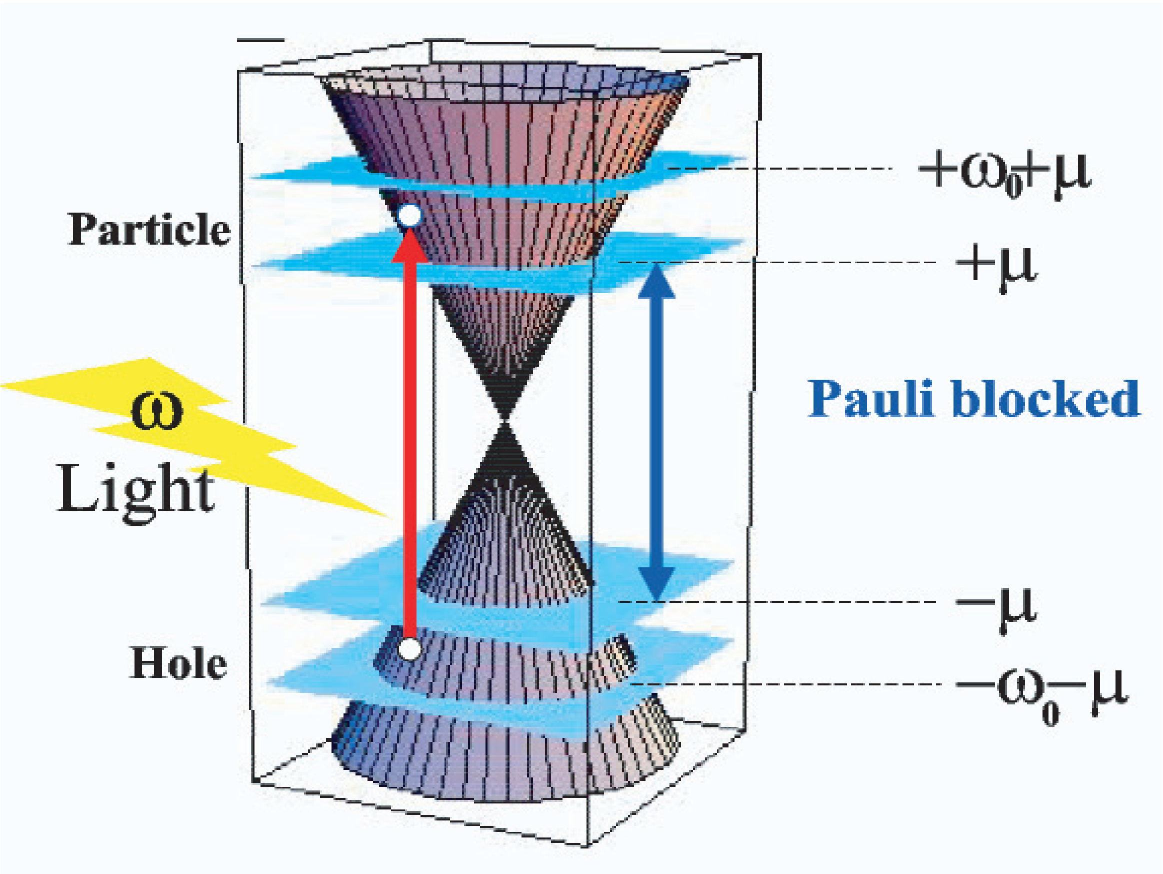
$$\sigma_{xy}(\omega) = \sum_{n,m} \frac{\langle\psi_n|j_x|\psi_m\rangle\langle\psi_m|j_y|\psi_n\rangle}{\omega_{mn}} \frac{n(E_m) - n(E_n)}{\omega_{mn} - \omega}$$

Optical Hall conductivity (cont.)



Peres *et al.*, EPL (2008)

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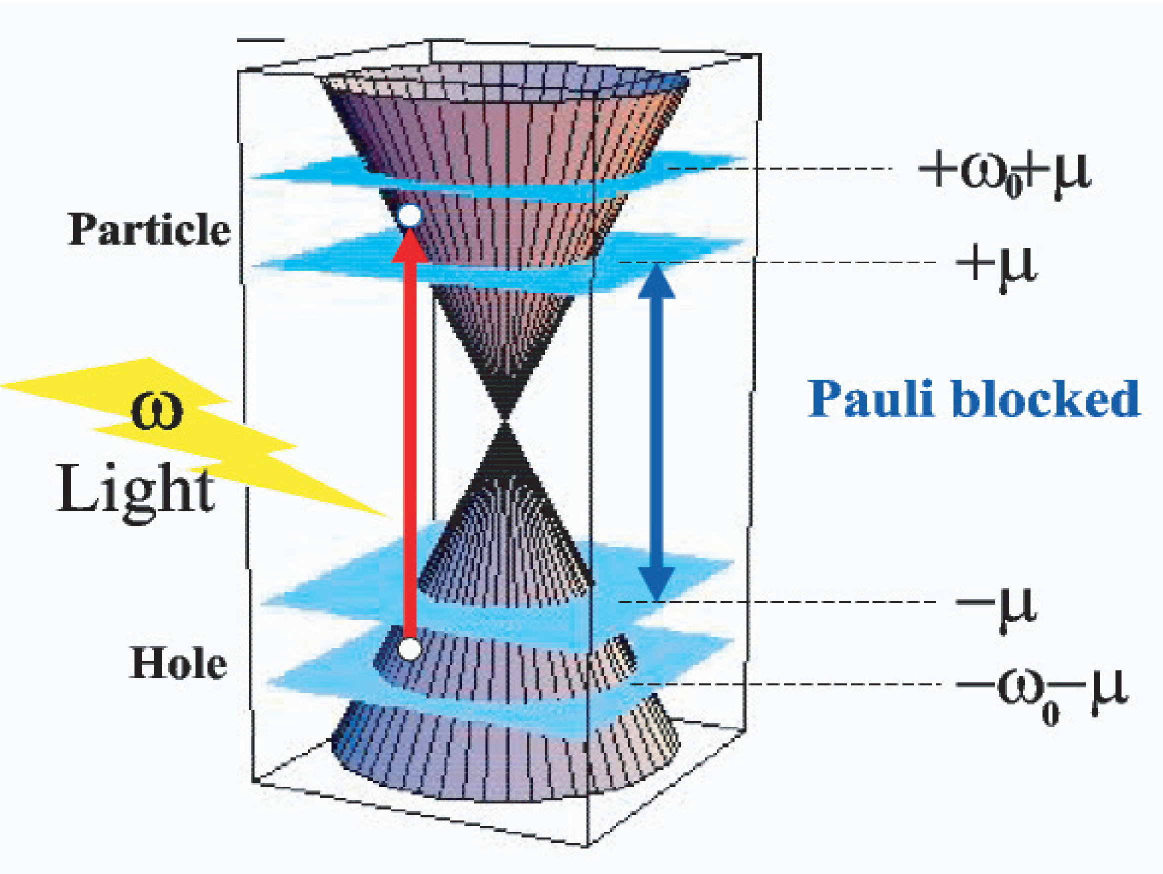

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Optical Hall conductivity (cont.)

Non-zero Hall charge and spin conductivities

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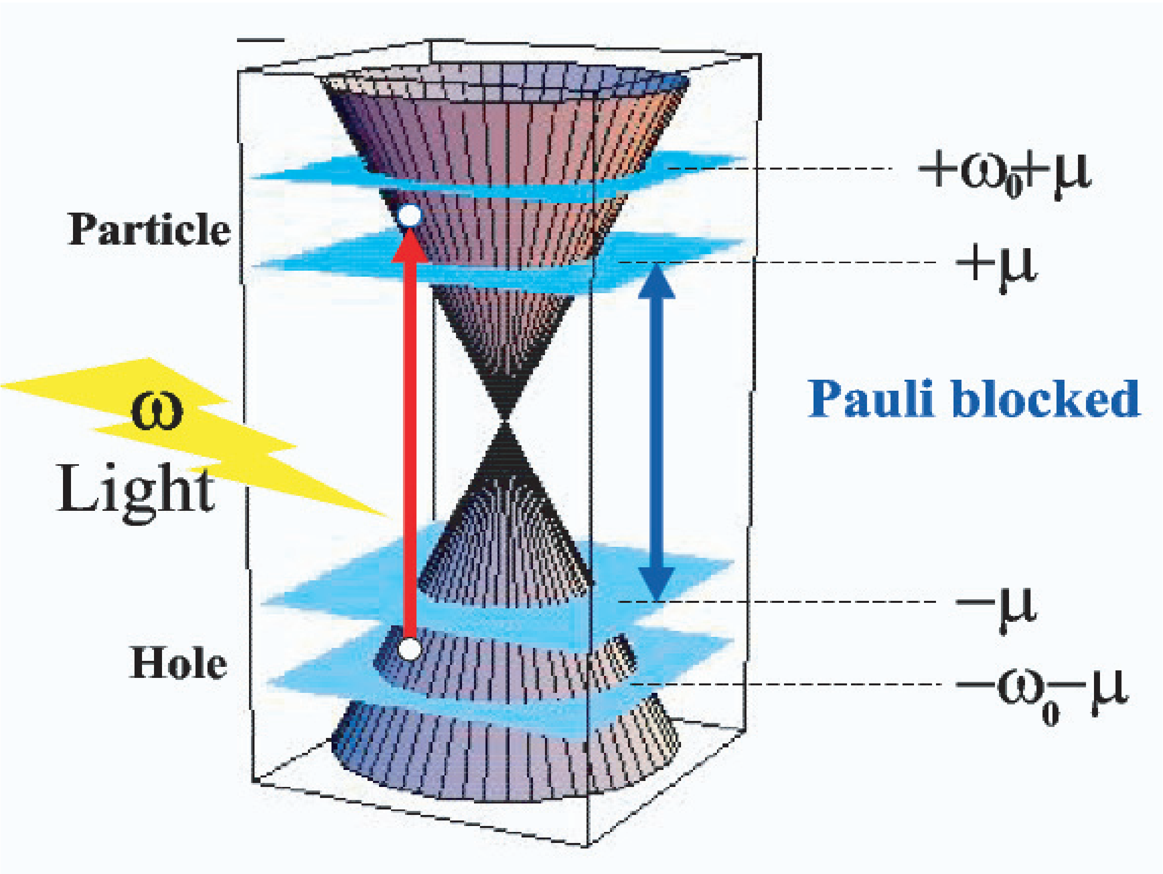

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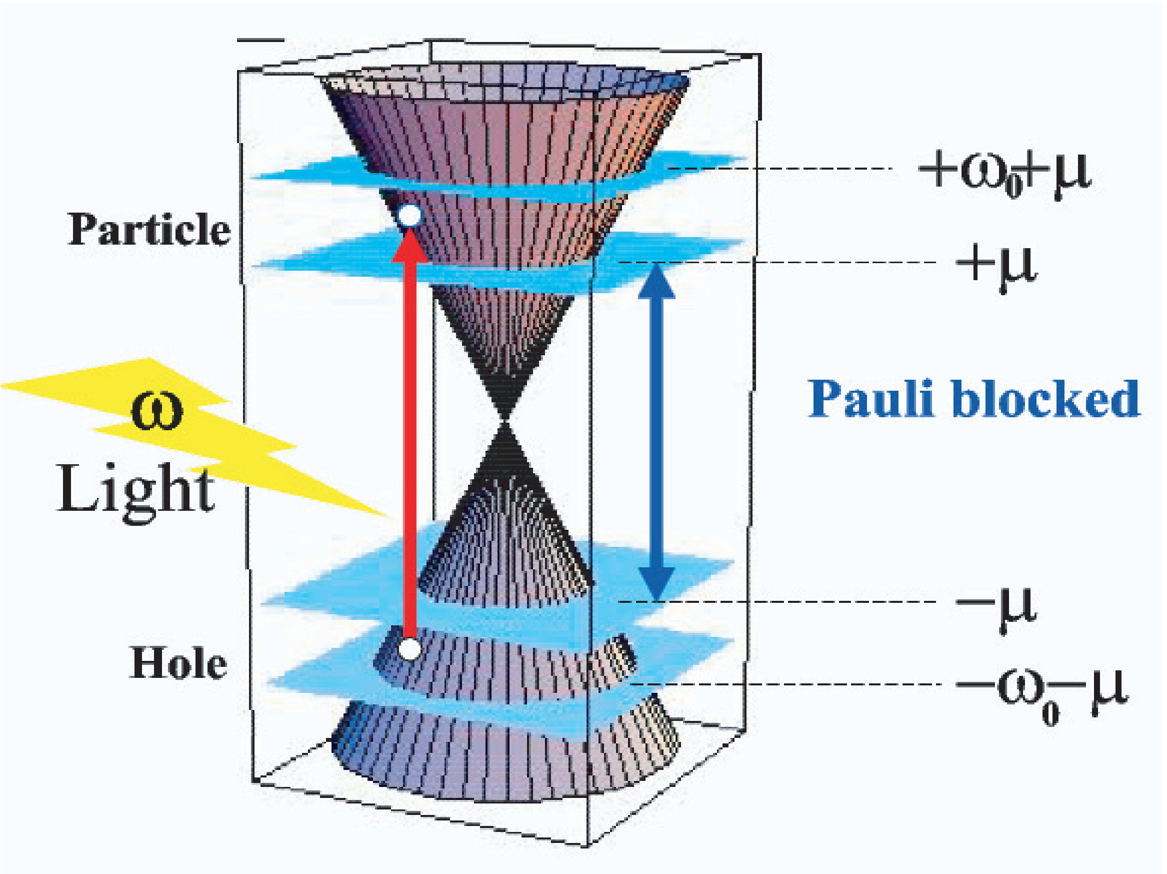

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DC Hall conductivities:

$$\sigma^c_{xy}(\omega \to 0) = \frac{4e^2}{h}$$

$$\sigma^s_{xy}(\omega \to 0) = \frac{8e^2}{h} n_{\mathrm{F}}$$

Barati *et al.*, in preparation

Coulomb drag and spin-Coulomb drag

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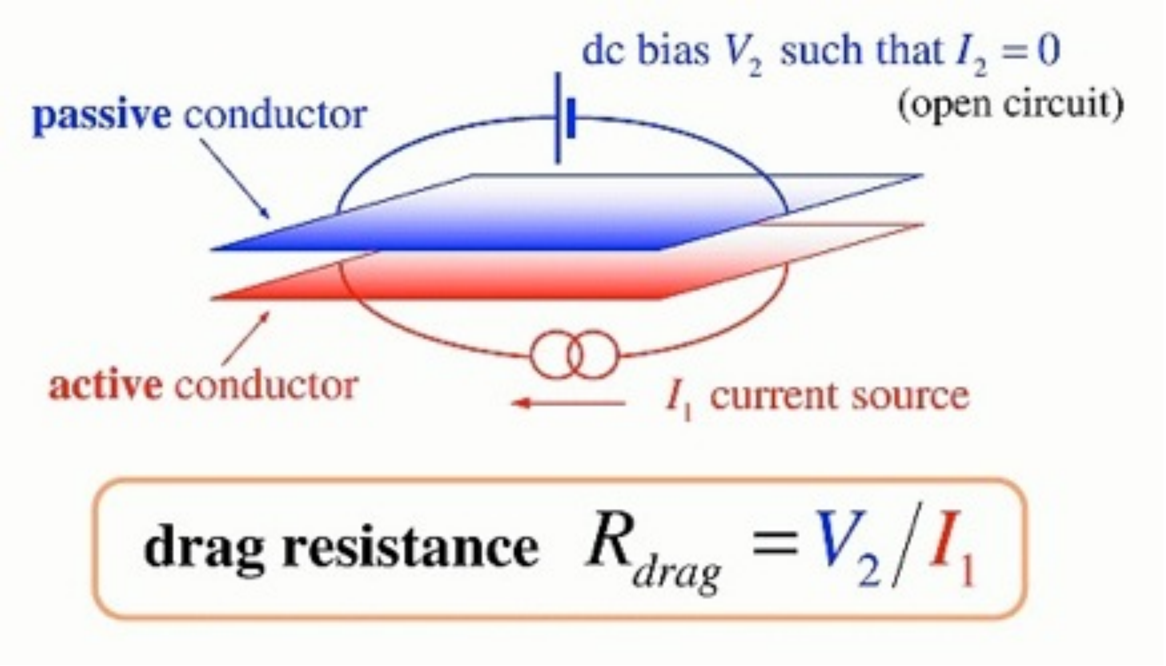
Coulomb drag in
double-layer structures



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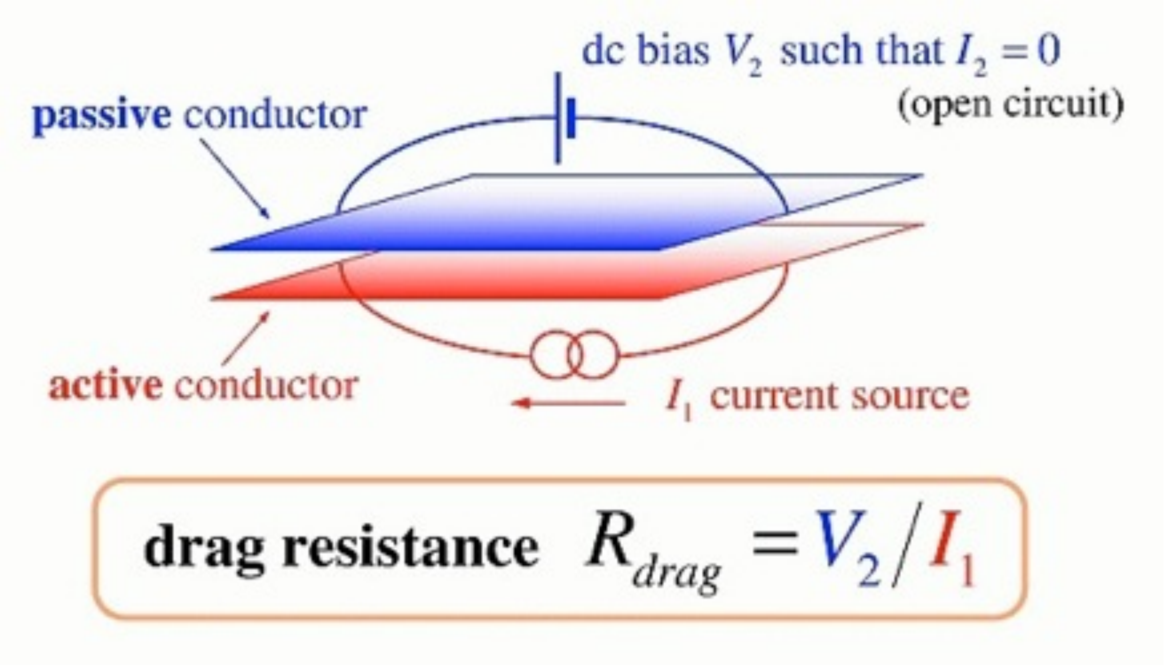

Spin-coulomb drag: intrinsic dissipation of the spin current due to the e-e interaction

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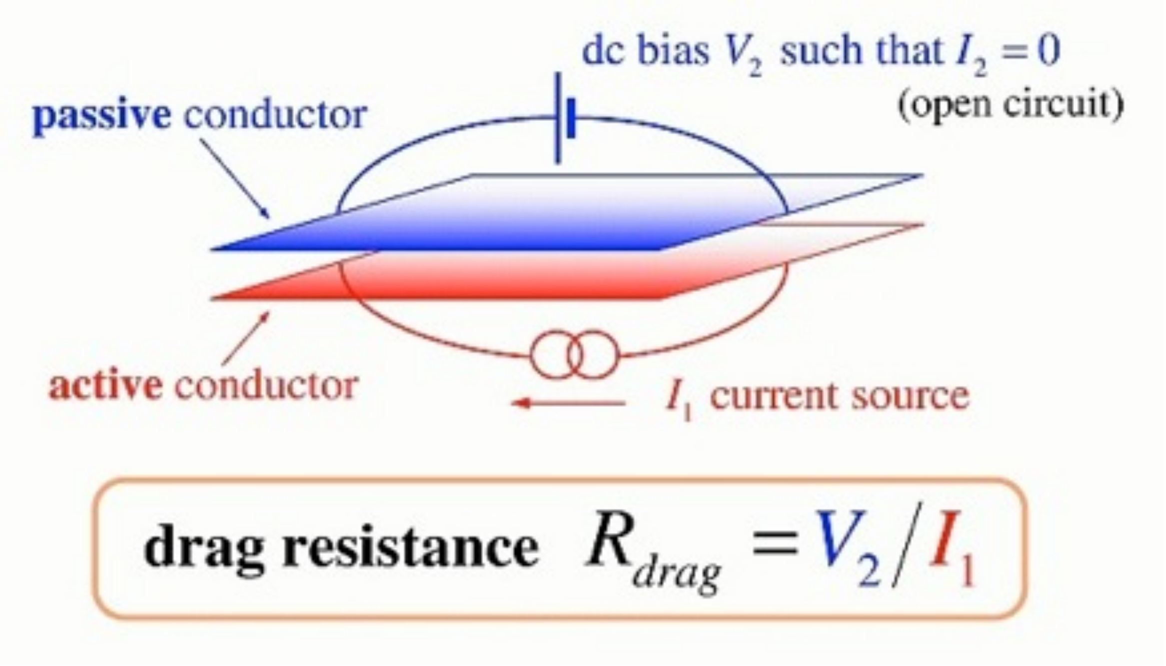

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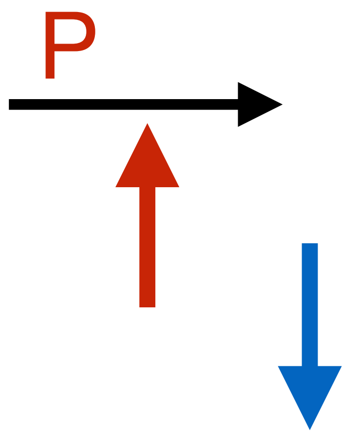

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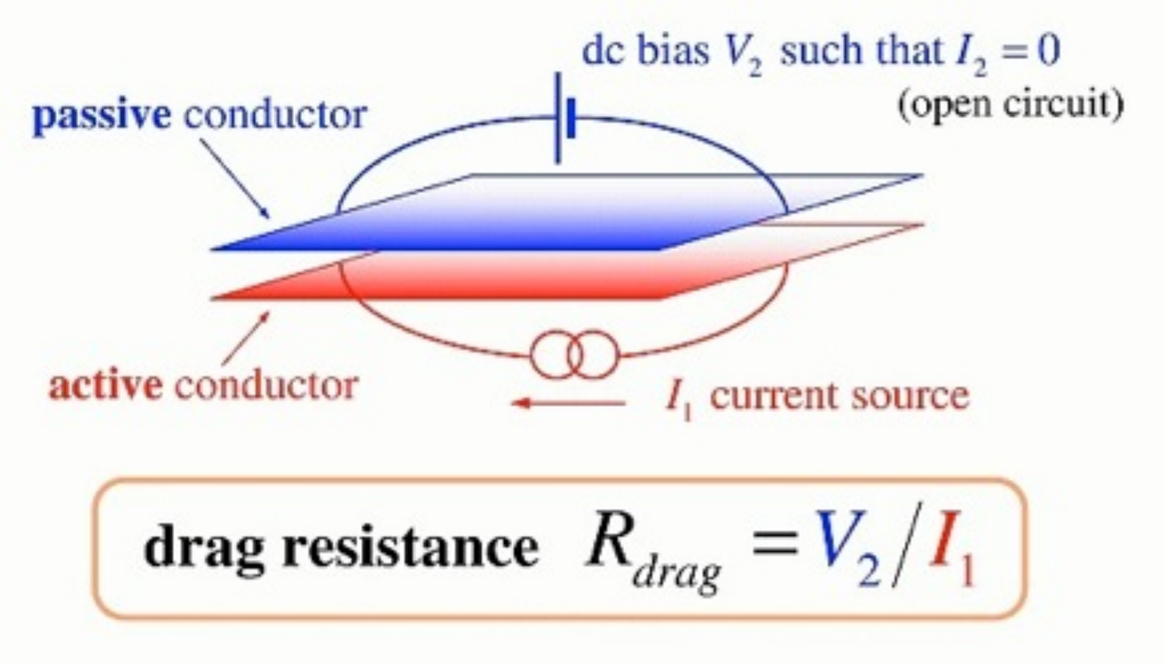

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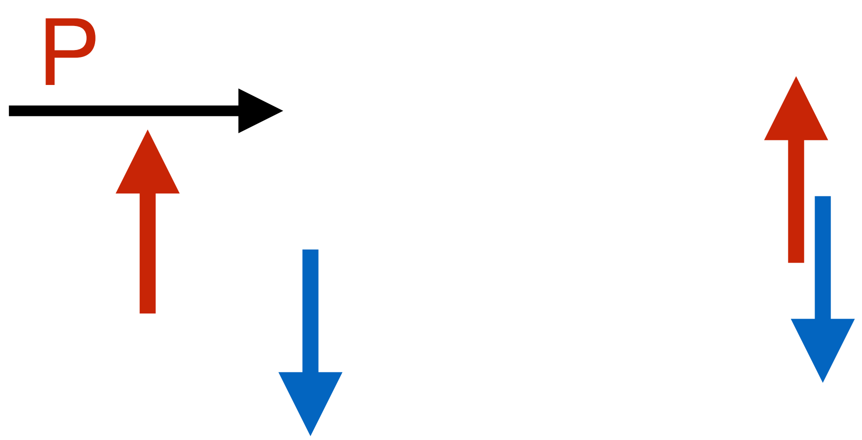

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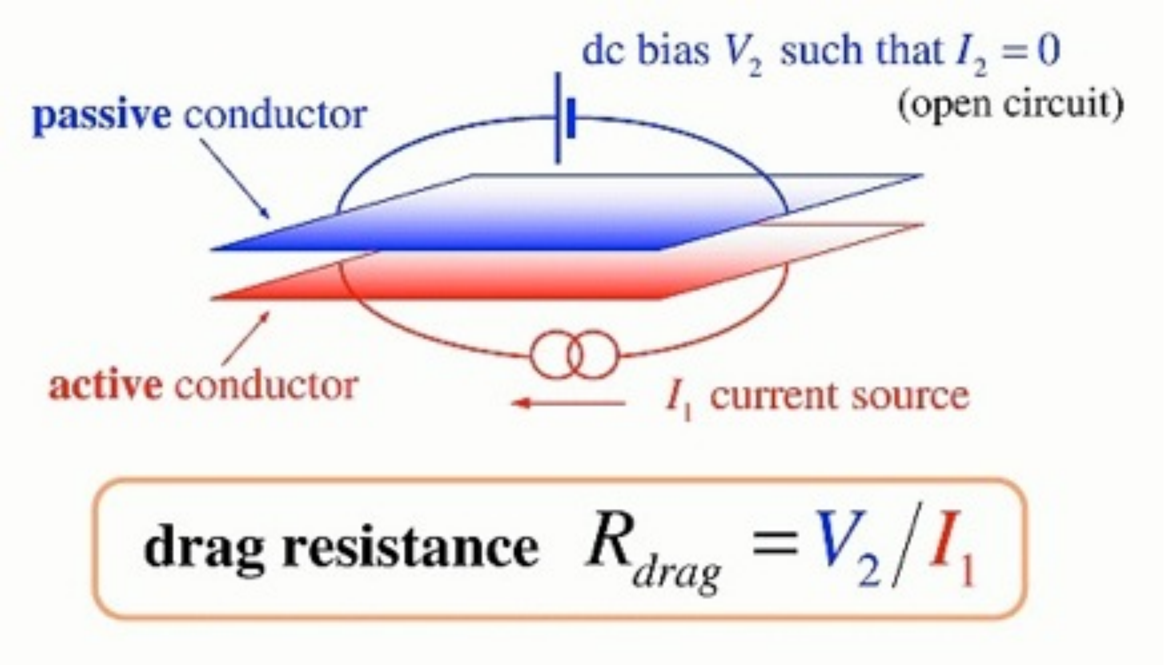

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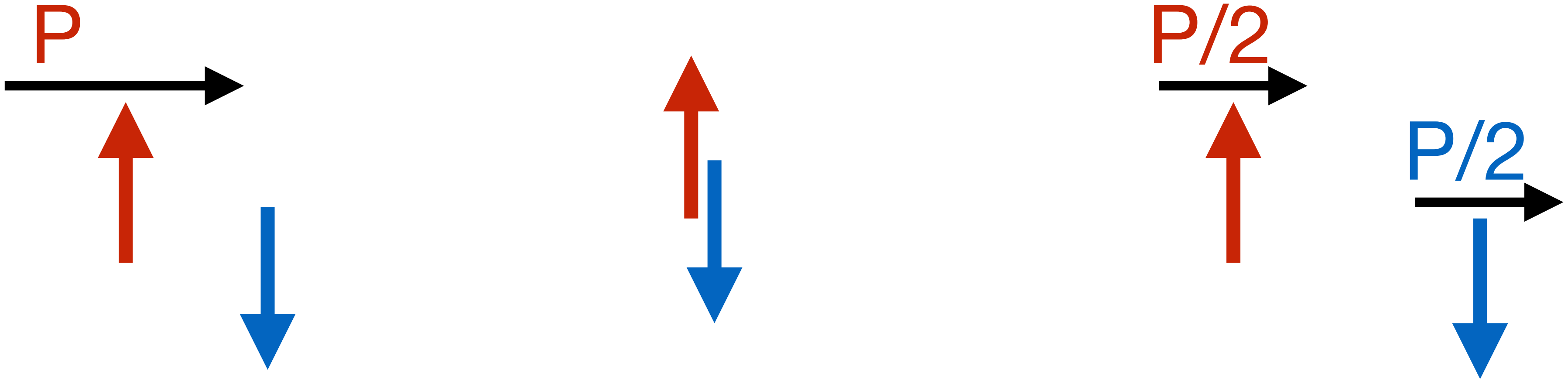

Spin-Coulomb drag in spin-polarized graphene

Rasoulkhani , SAH (in preparation)

Spin-Coulomb drag in spin-polarized graphene

$$\begin{pmatrix} \mathbf{j}_\uparrow \\ \mathbf{j}_\downarrow \end{pmatrix} = \begin{pmatrix} \sigma_{\uparrow\uparrow} & \sigma_{\uparrow\downarrow} \\ \sigma_{\downarrow\uparrow} & \sigma_{\downarrow\downarrow} \end{pmatrix} \begin{pmatrix} \mathbf{E}_\uparrow \\ \mathbf{E}_\downarrow \end{pmatrix}$$

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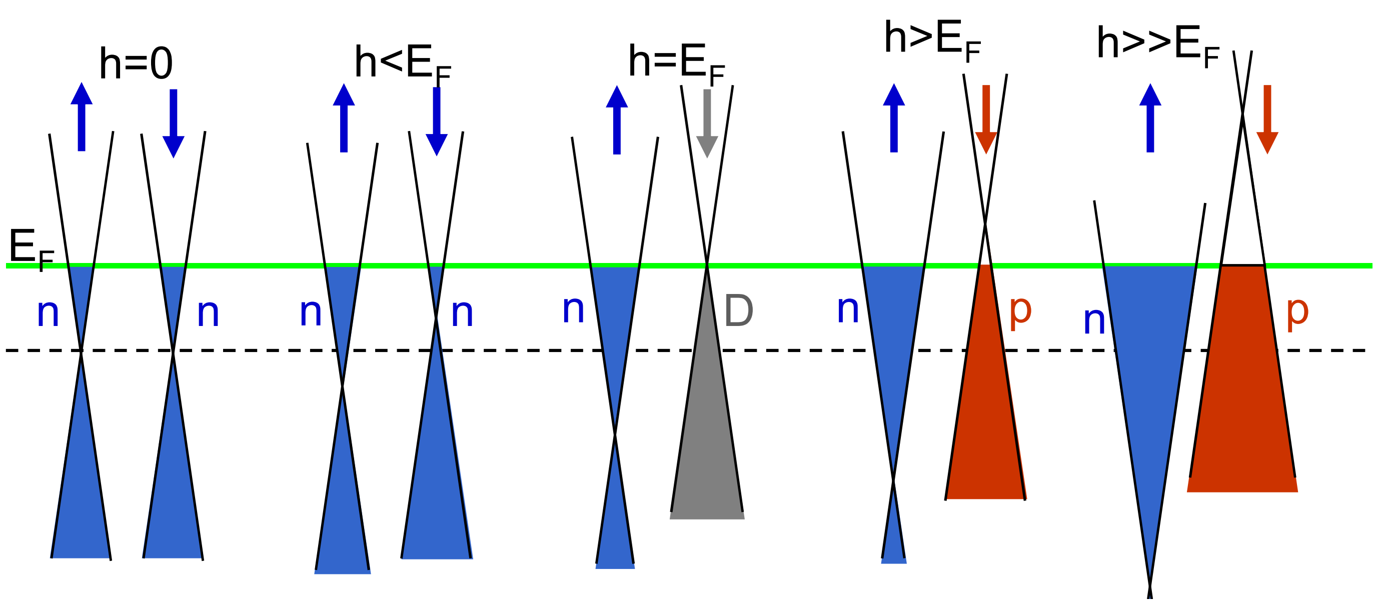

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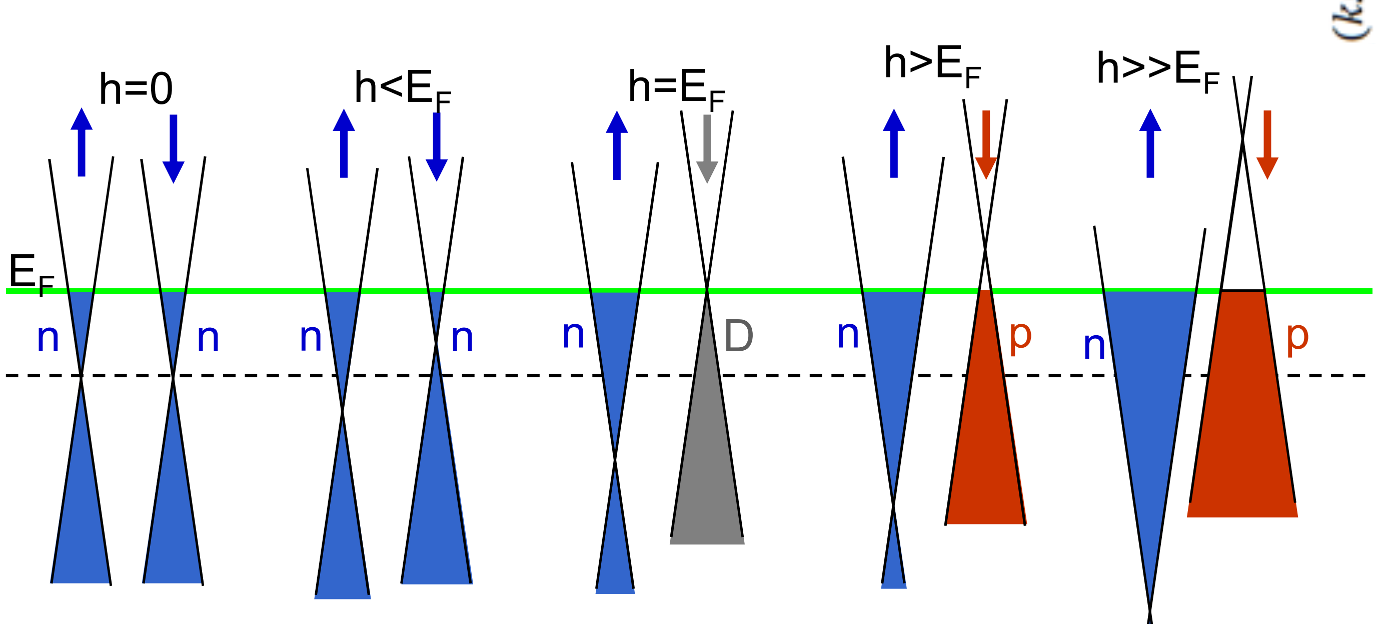

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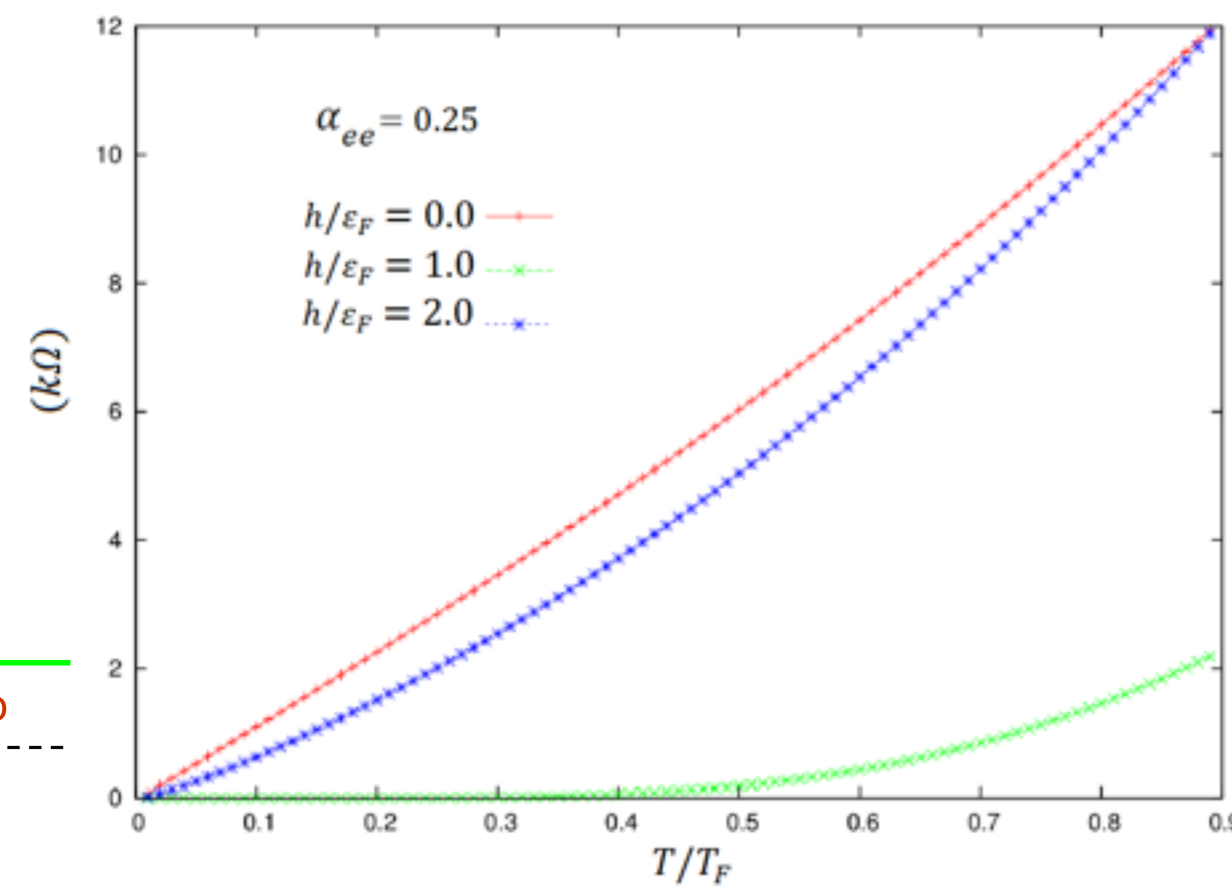

Rasoulkhani , SAH (in preparation)

Conclusions

electron and *hole* like nature of the *up* and *down* spins in graphene results in a bunch of interesting phenomena:

- *spin-flip* scattering from magnetic impurities gives rise to a *Kondo-like* behavior in the electrical conductivity!
- QSH effect! in spin polarized graphene!
- Control of the *spin-Coulomb drag* (spin-current dissipation) with an exchange field!

Thank you for your attention!

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