Electronic spin transport and spin precession in single graphene layers at room temperature

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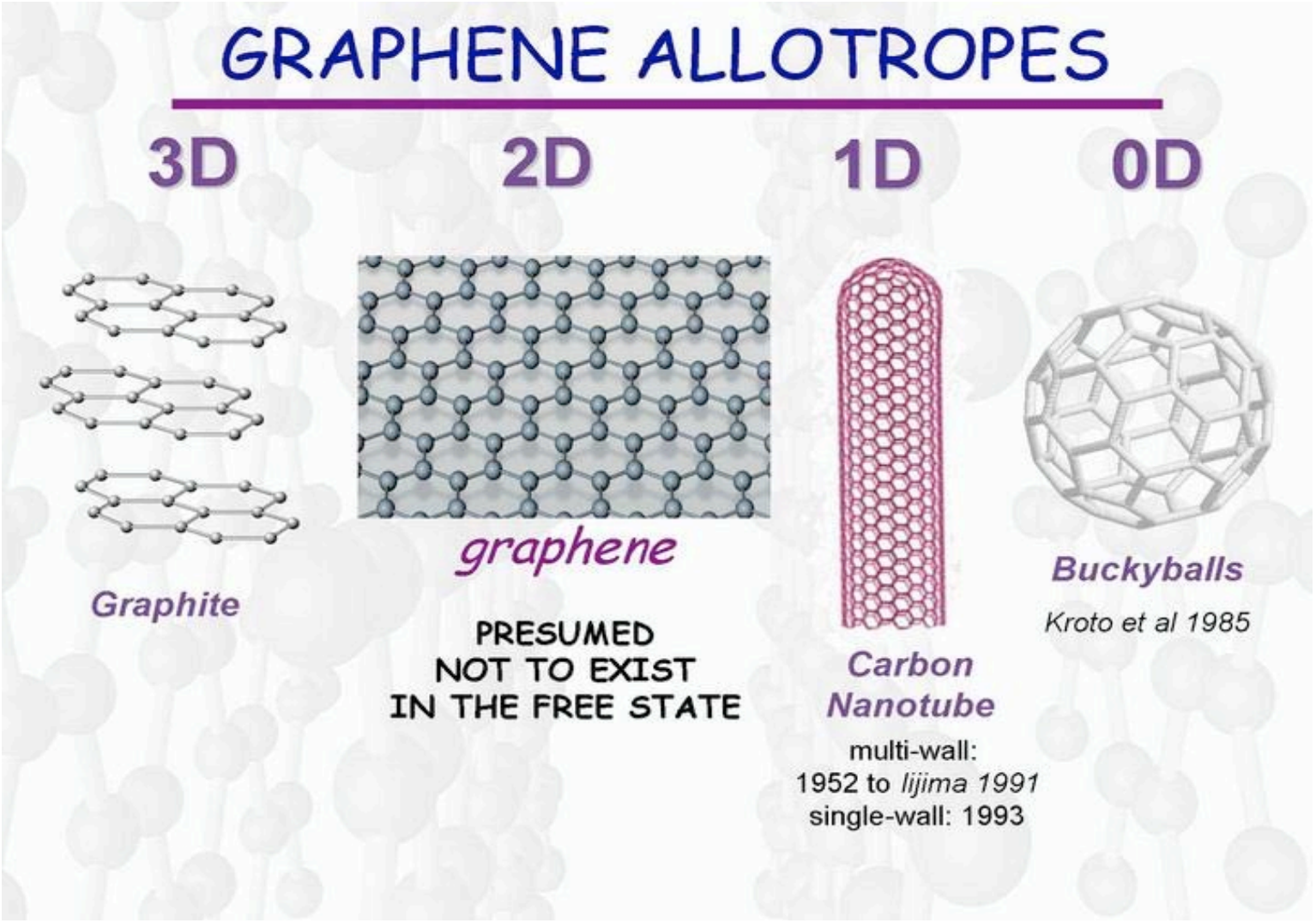
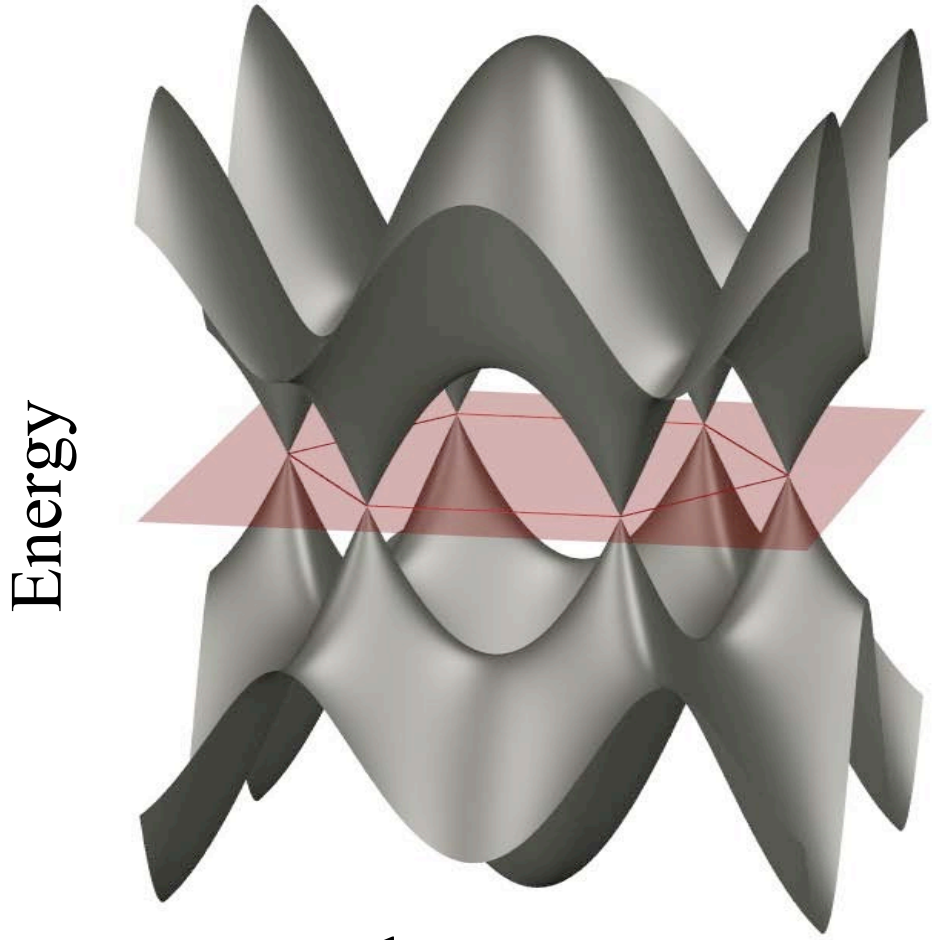
Carbon comes in different shapes



Graphene bandstructure

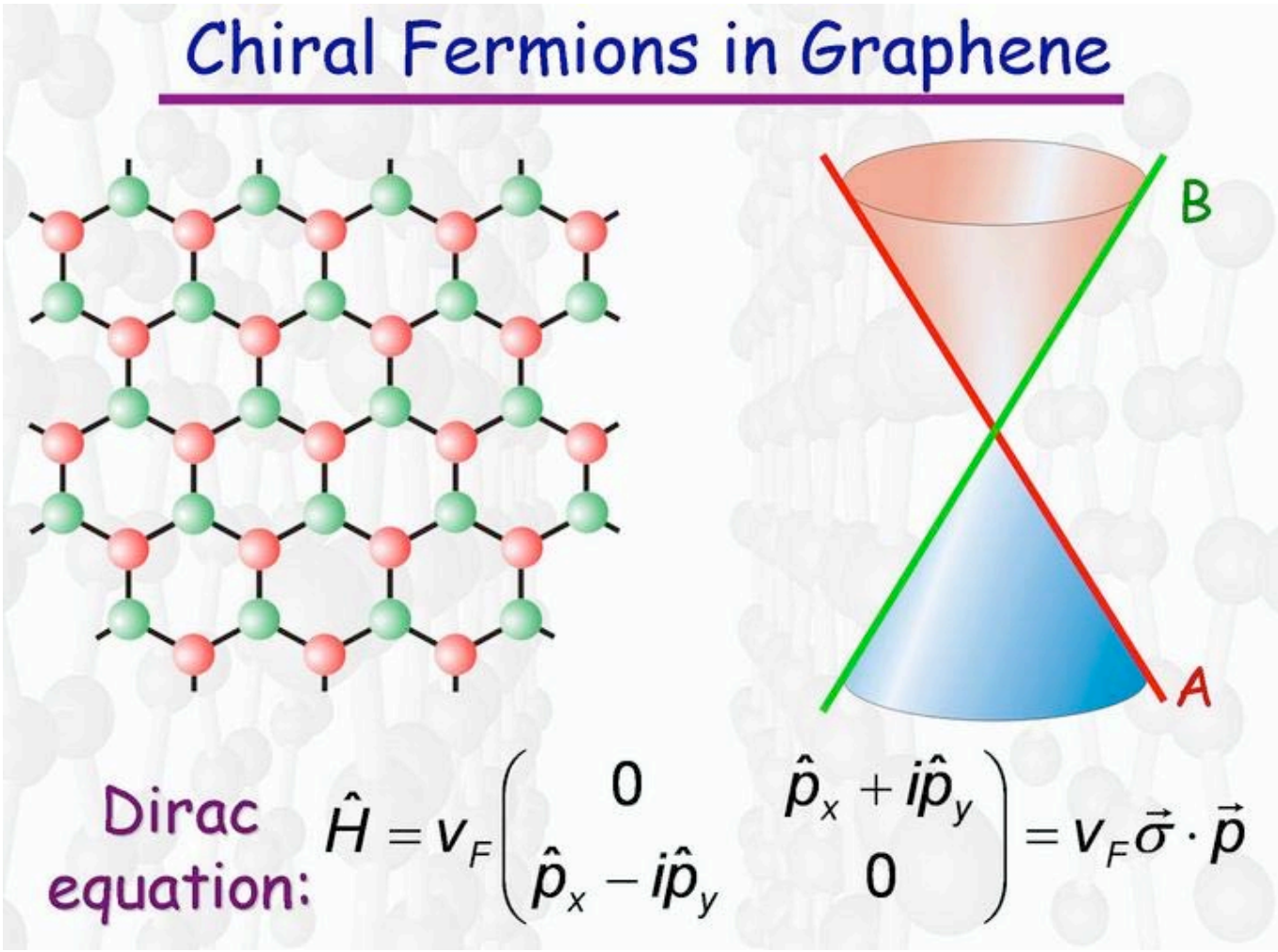


electron states

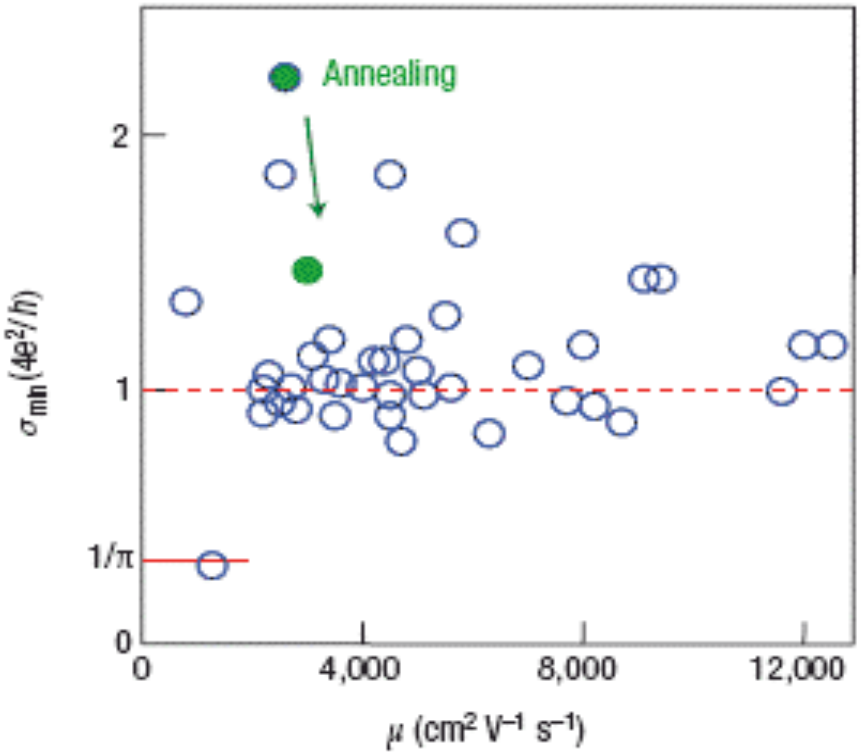
Dirac neutrality points

hole states

Graphene bandstructure



“Quantized” minimum conductivity

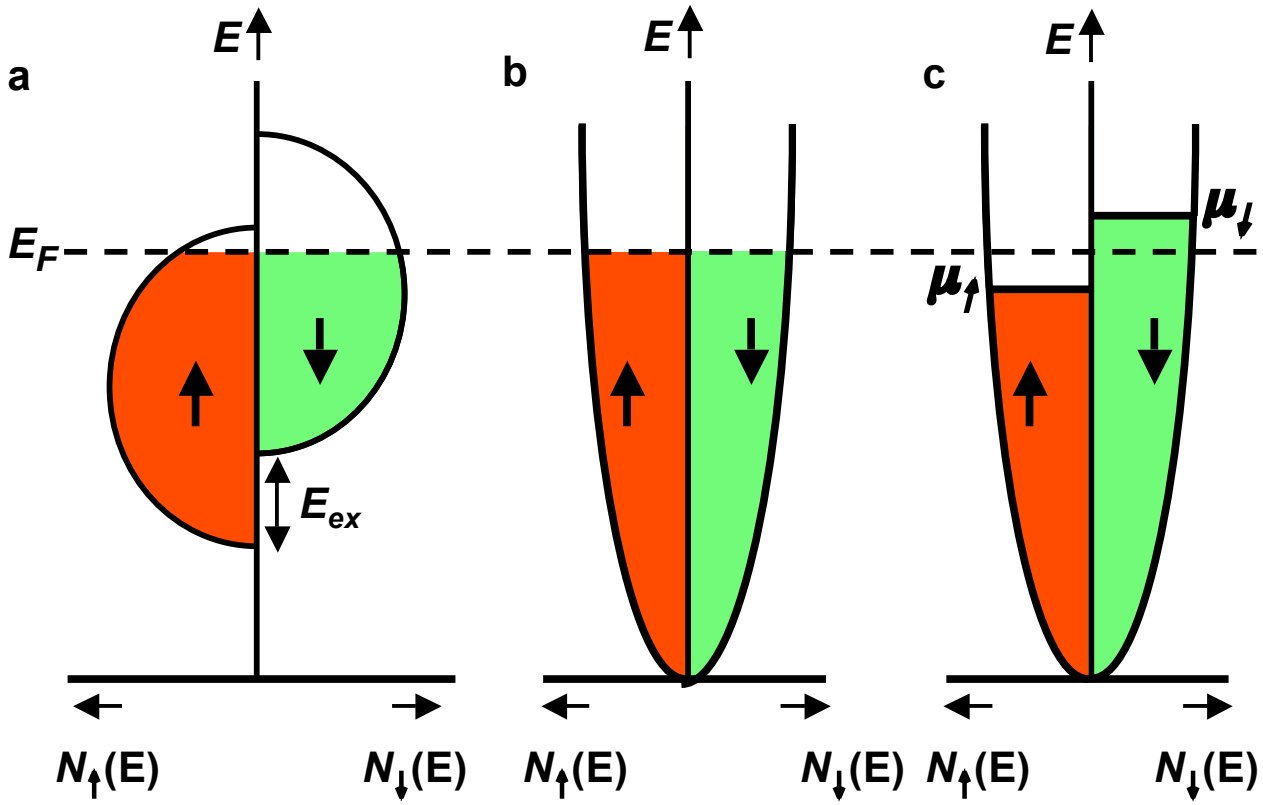


A.K. Geim, K. S. Novoselov, Nature Materials 6, 183 (2007)

Spin dynamics in graphene

- Weak SO interaction in clean graphene
- Weak hyperfine interactions
- Long T_1 and T_2 times ?
- Role of various types of (disorder) scattering

Spin injection: The basic picture



Bloch equations for spin accumulation

$$\frac{\partial \vec{\mu}}{\partial t} = D\nabla^2 \vec{\mu} - \frac{\vec{\mu}}{\tau} + \left(\frac{g\mu_B}{\hbar} \vec{B} \times \vec{\mu} \right)$$

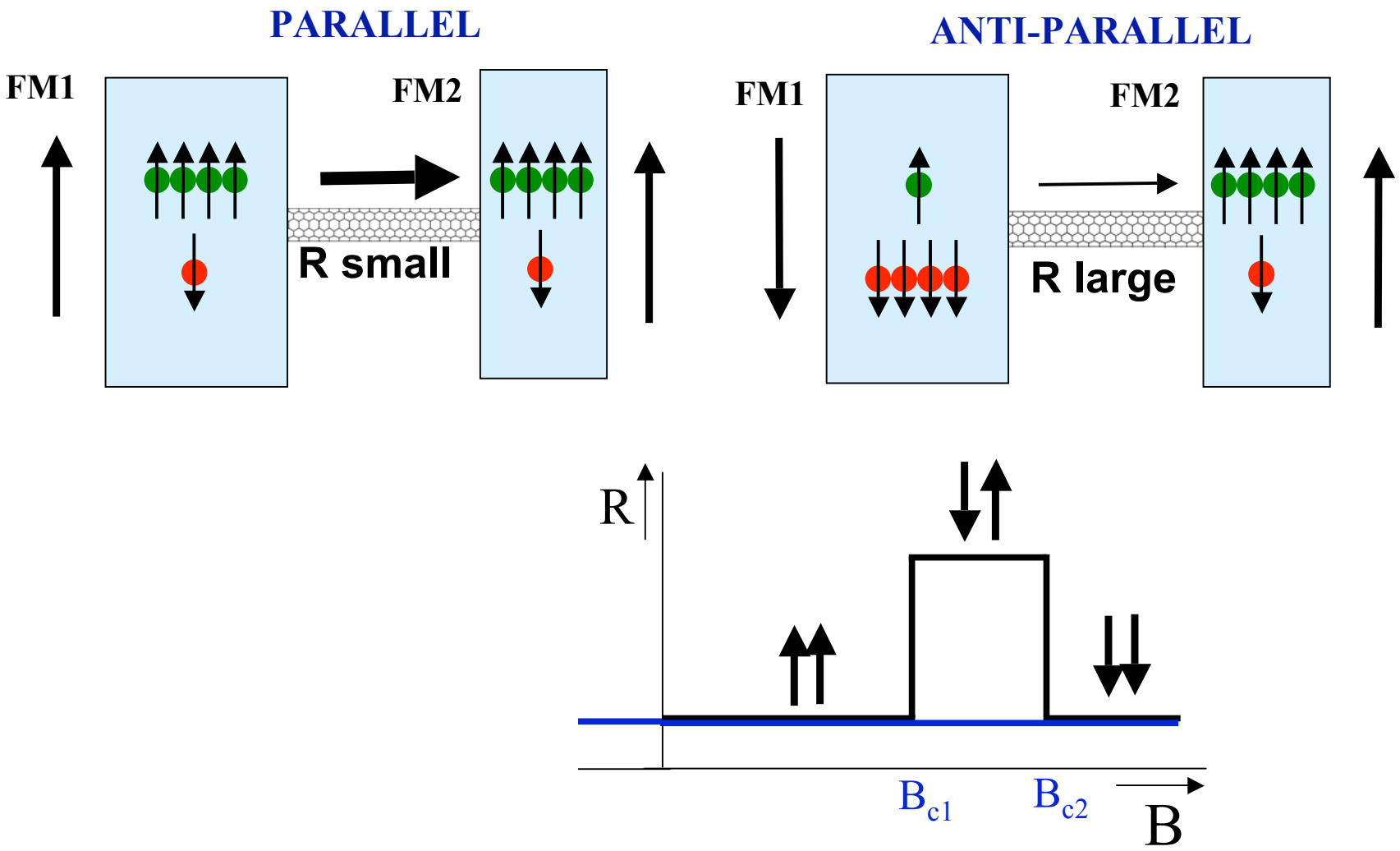
1) Diffusion D : diffusion constant

2) Relaxation τ_{sf} : relaxation time

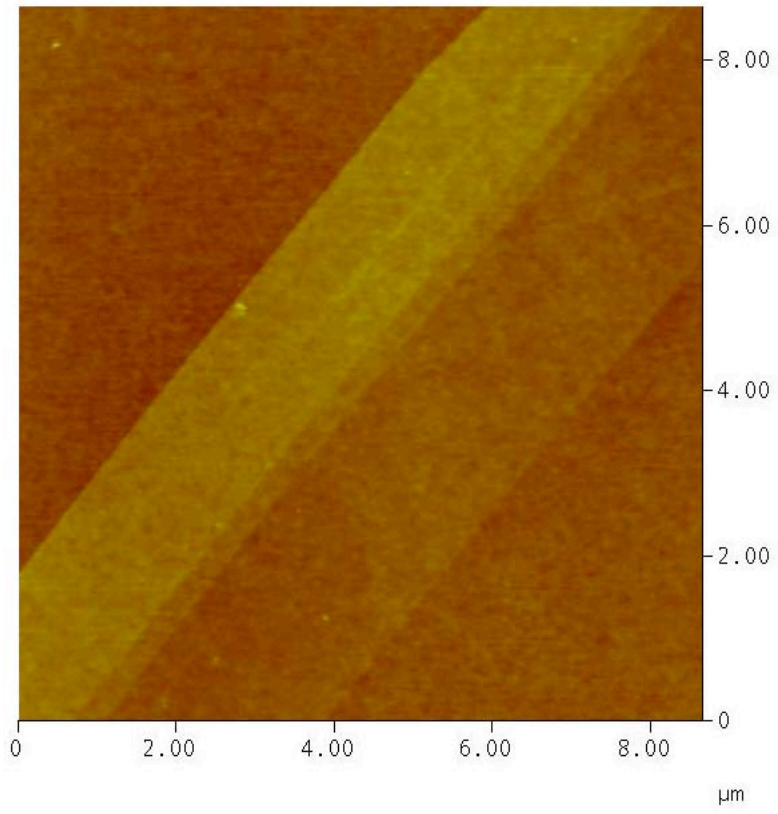
3) Precession g ~ 2

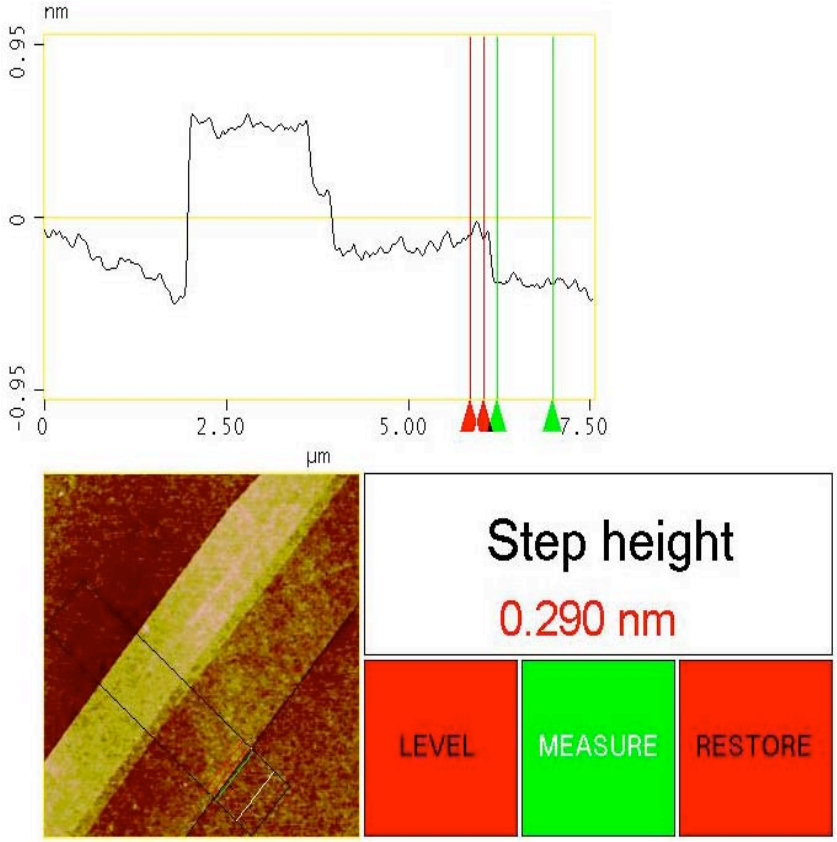
Spin relaxation length: $\lambda = \sqrt{D\tau}$

Two-terminal Spin Valve

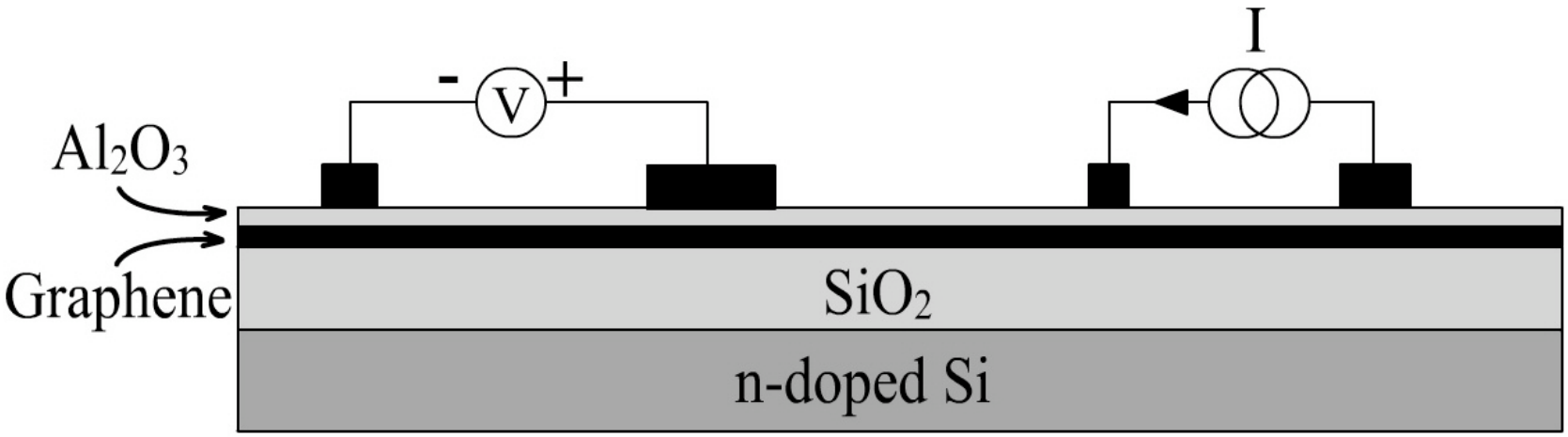


Single graphene layers





Device cross section



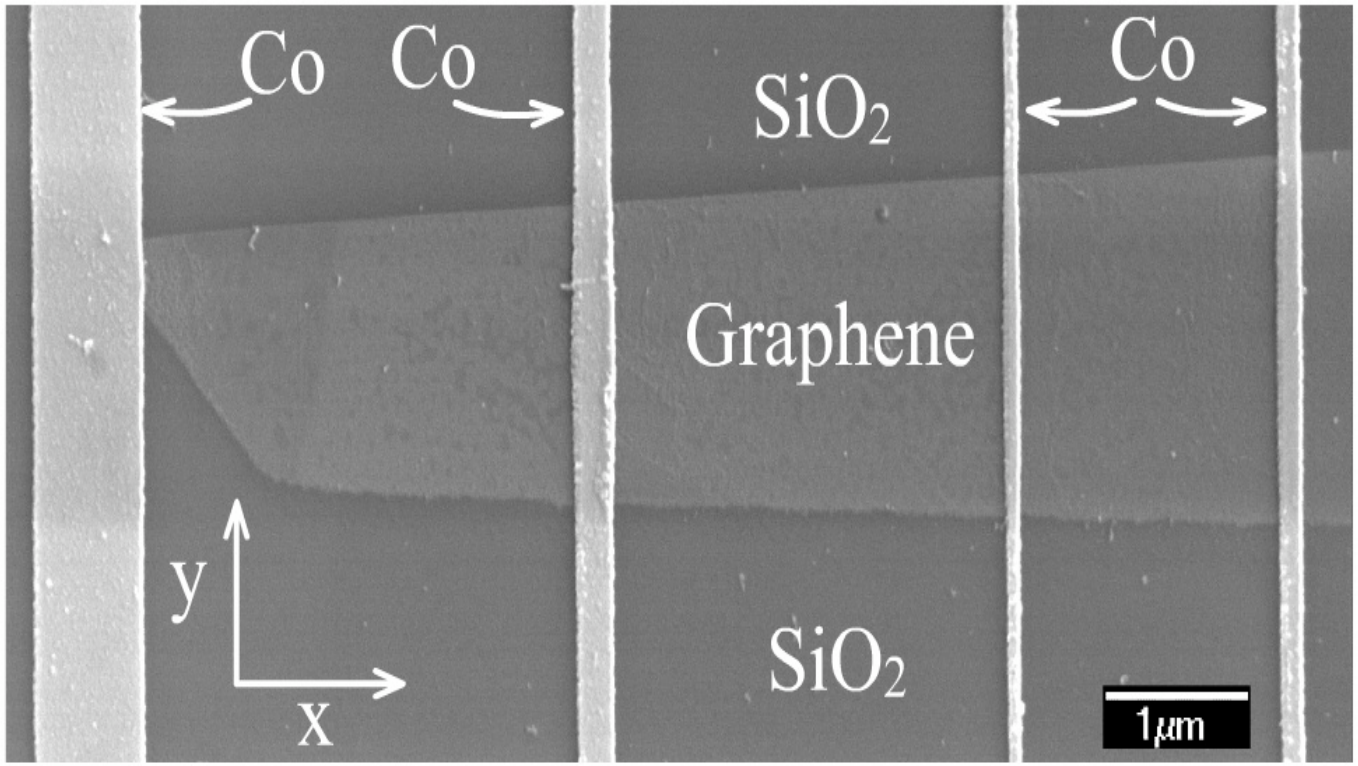
Conductivity mismatch: 1 nm Al_2O_3 tunnel barrier

Current contacts: inject spin current

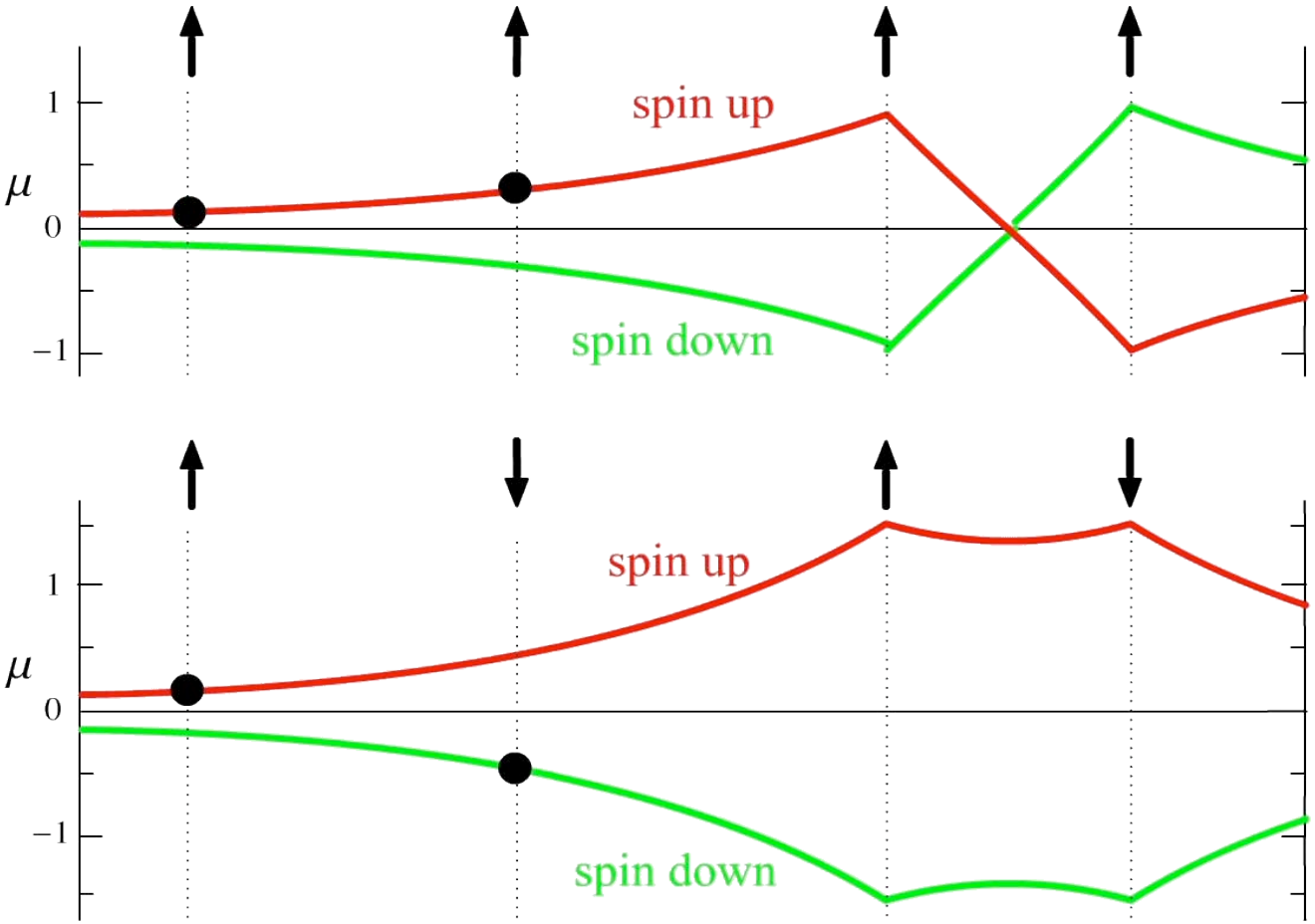
Voltage contacts: measure spin dependent voltage

Gate voltage: applied between graphene and n-doped Si

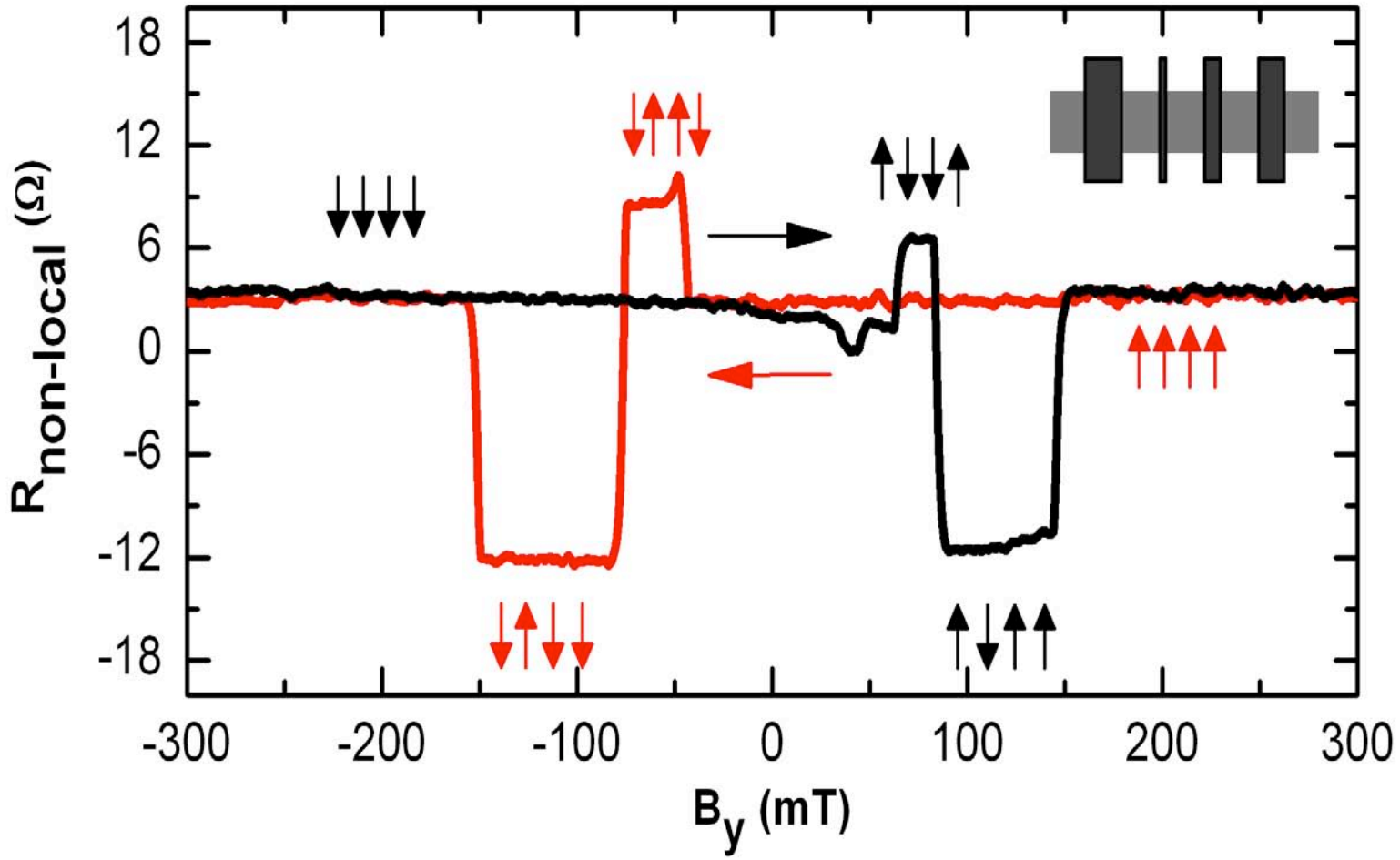
Device preparation



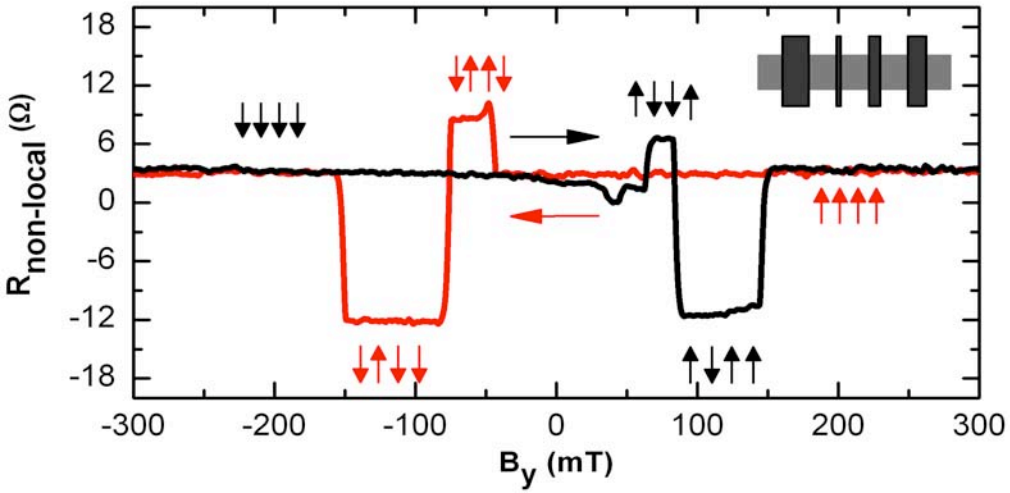
Spin injection/detection

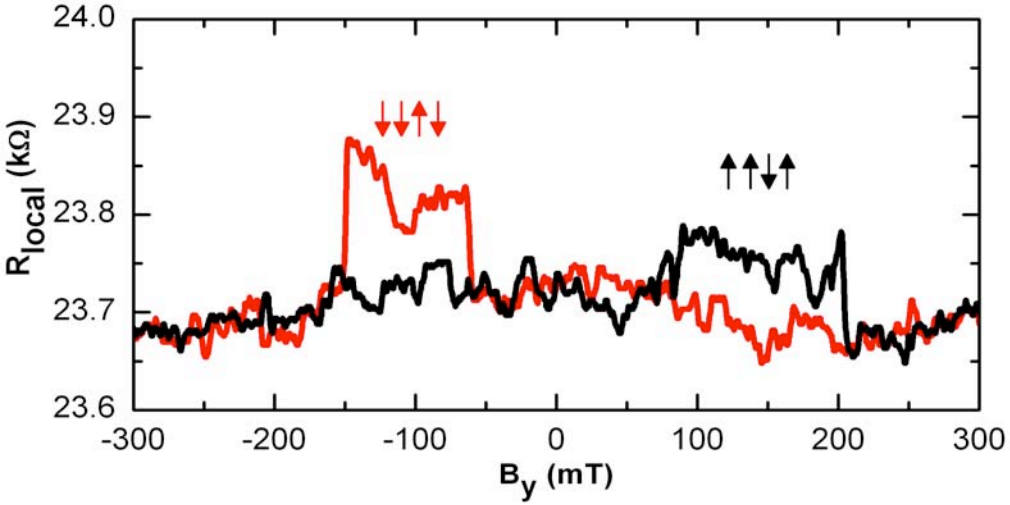


Spin injection in graphene at 4.2 K

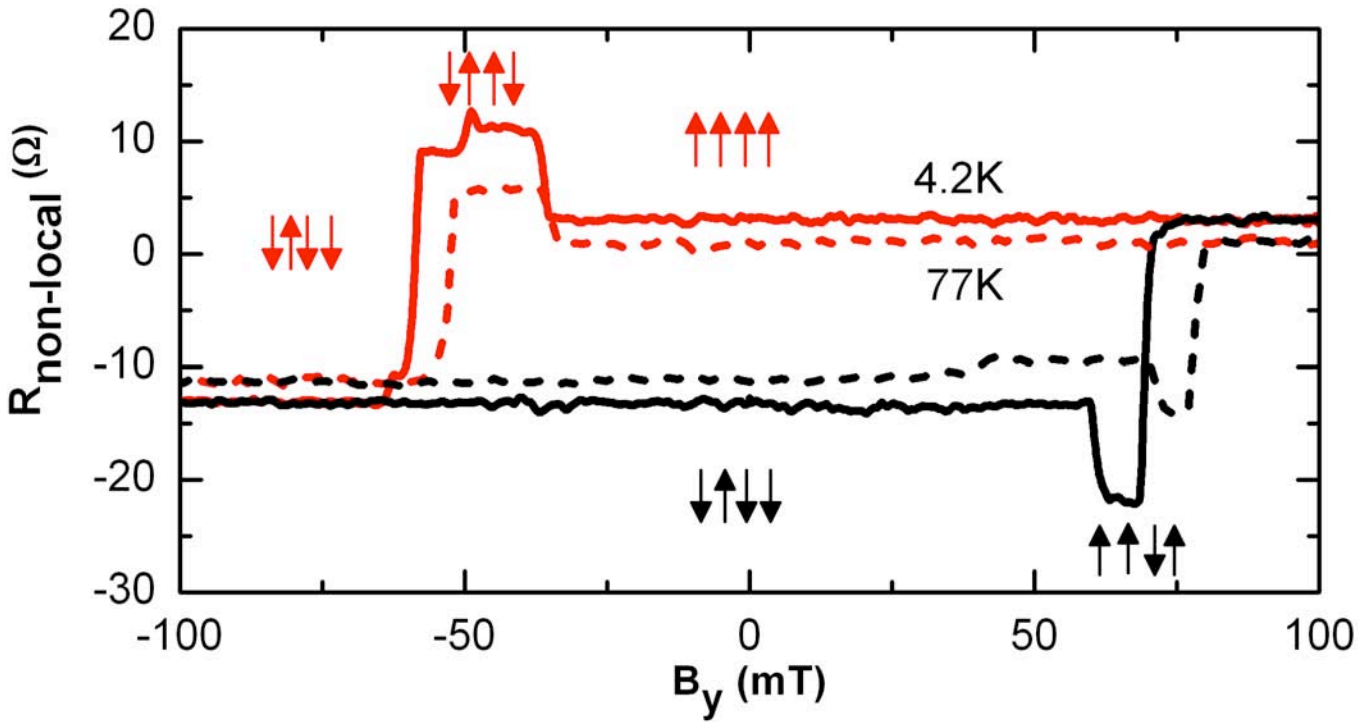


Comparison “local” vs. “nonlocal”

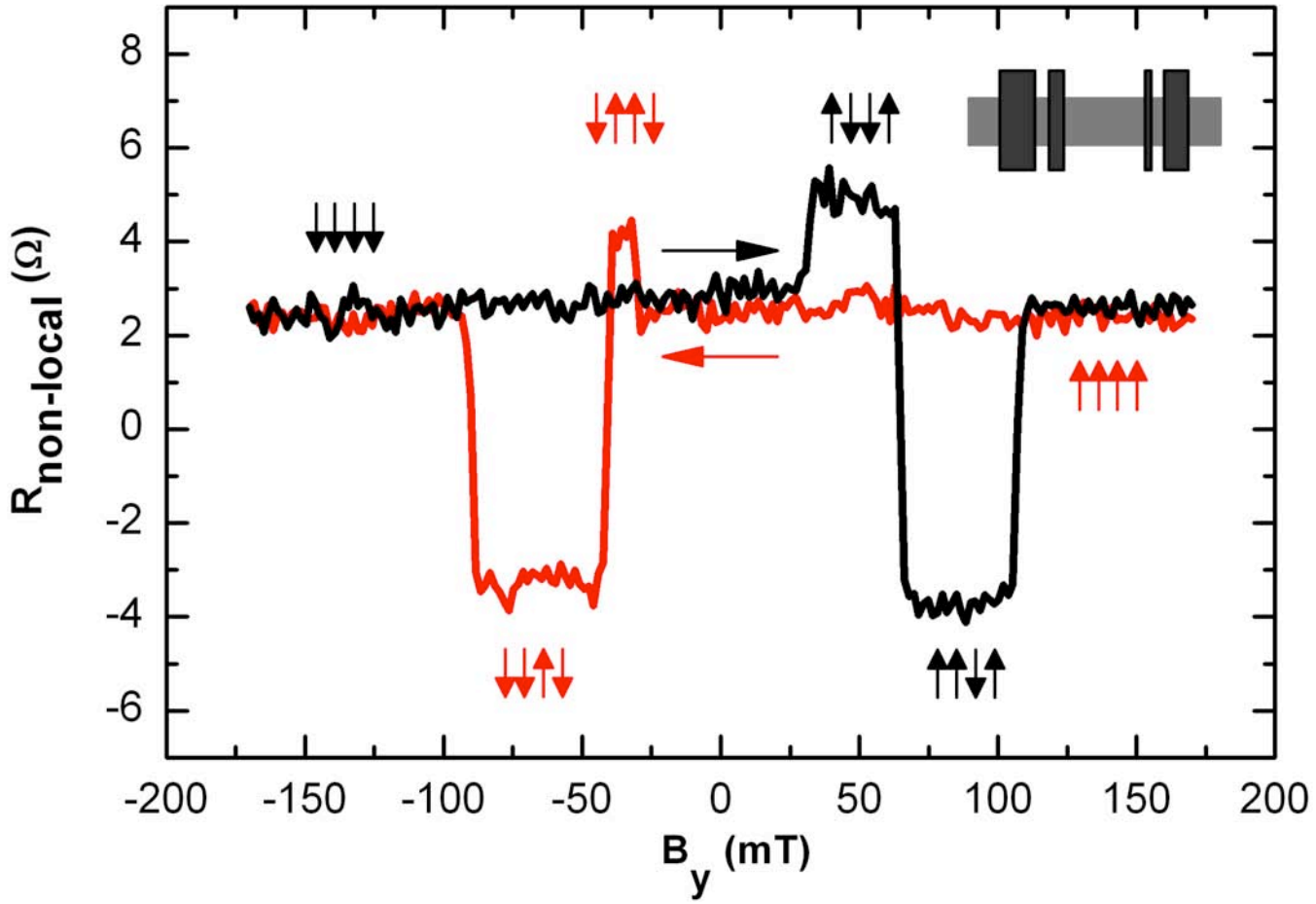




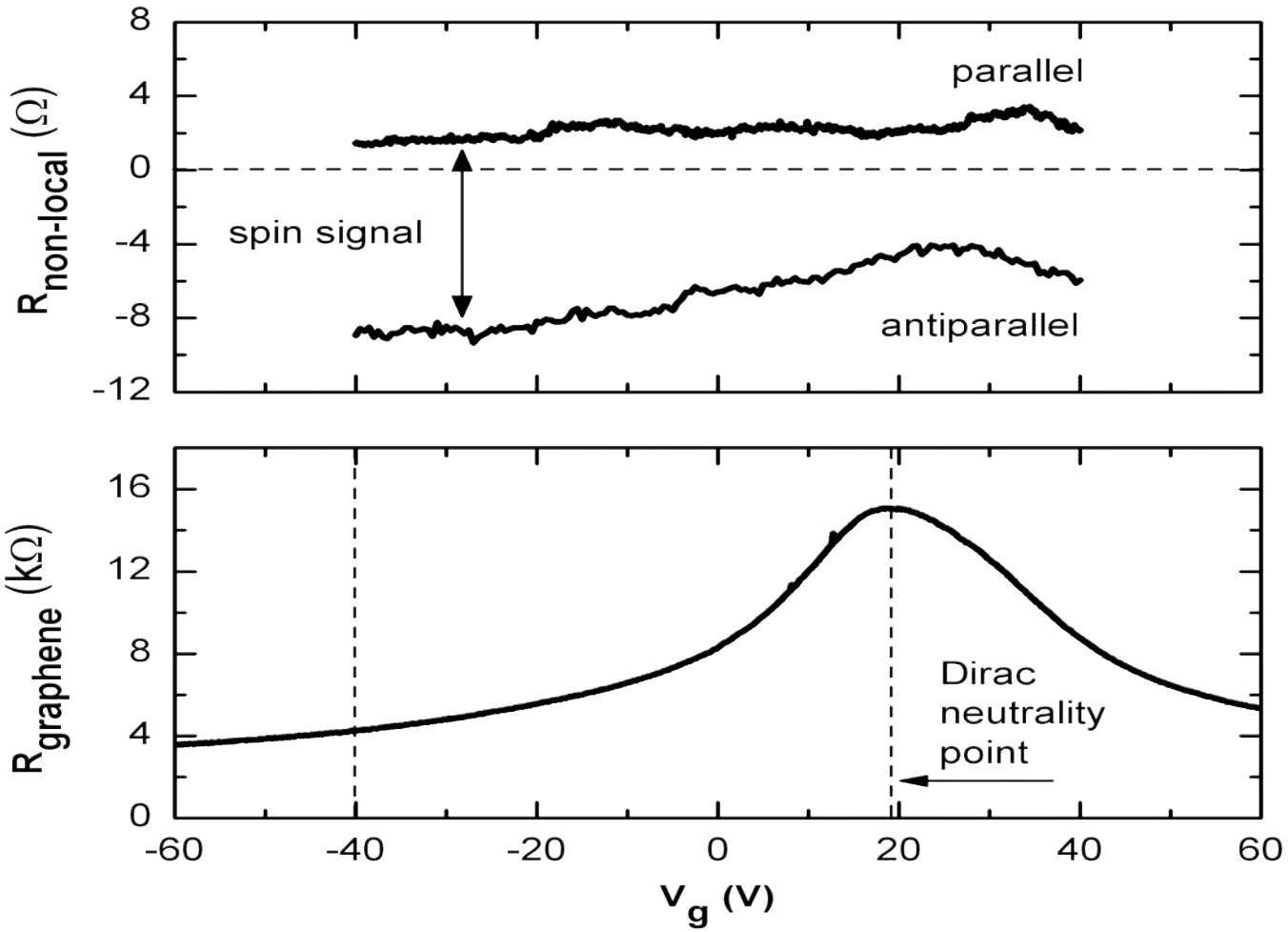
Comparison 4.2 K and 77 K



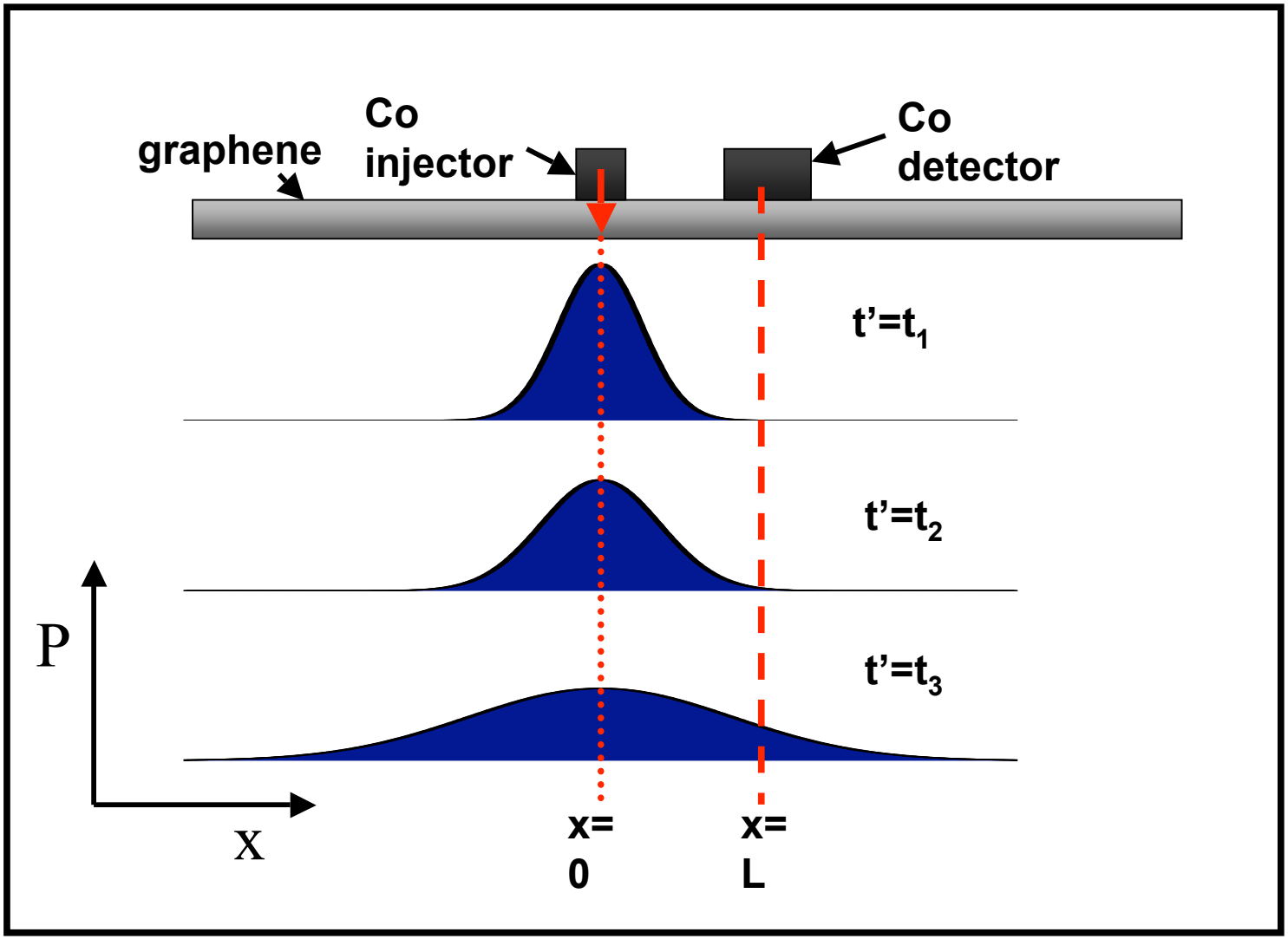
Room temperature spin transport



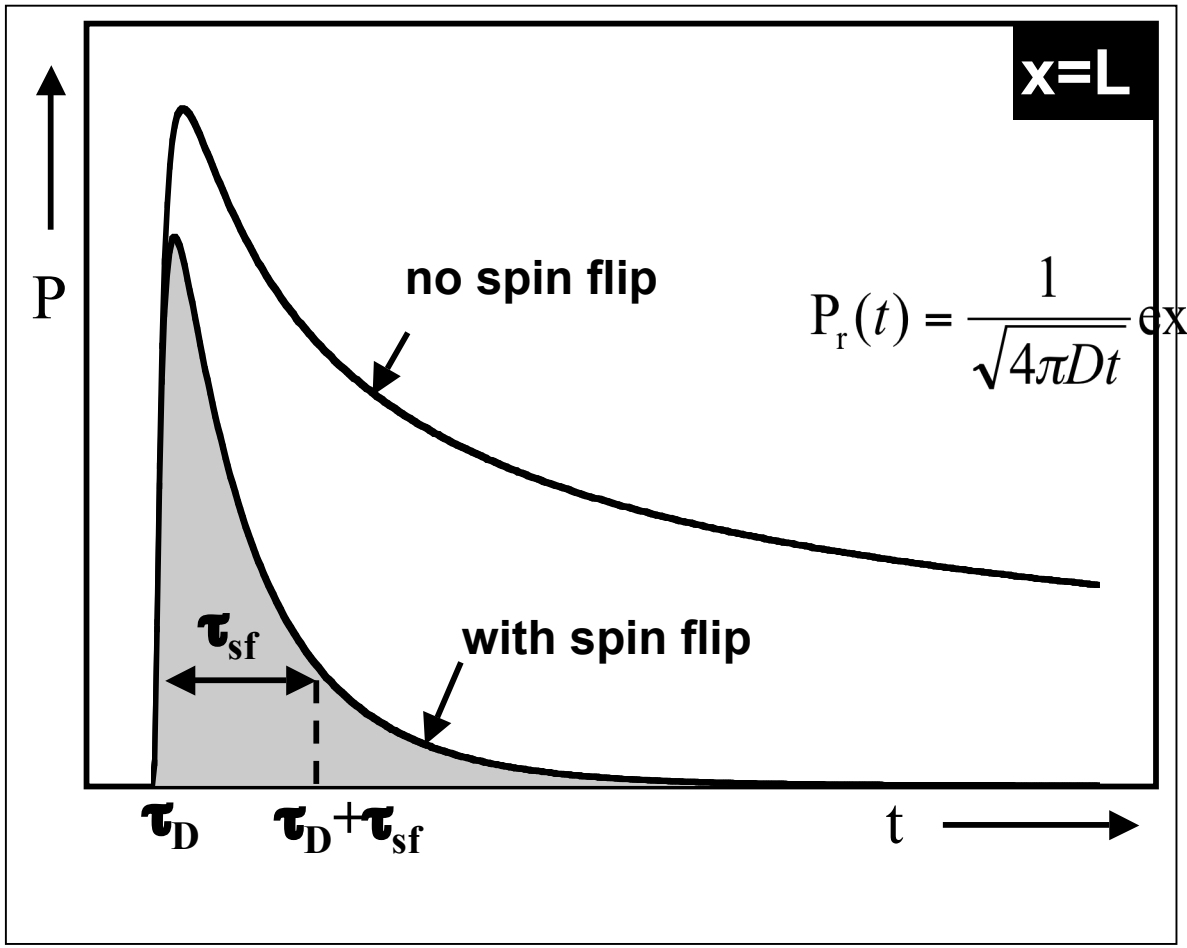
Gate voltage dependence



Spin diffusion



Distribution of arrival times

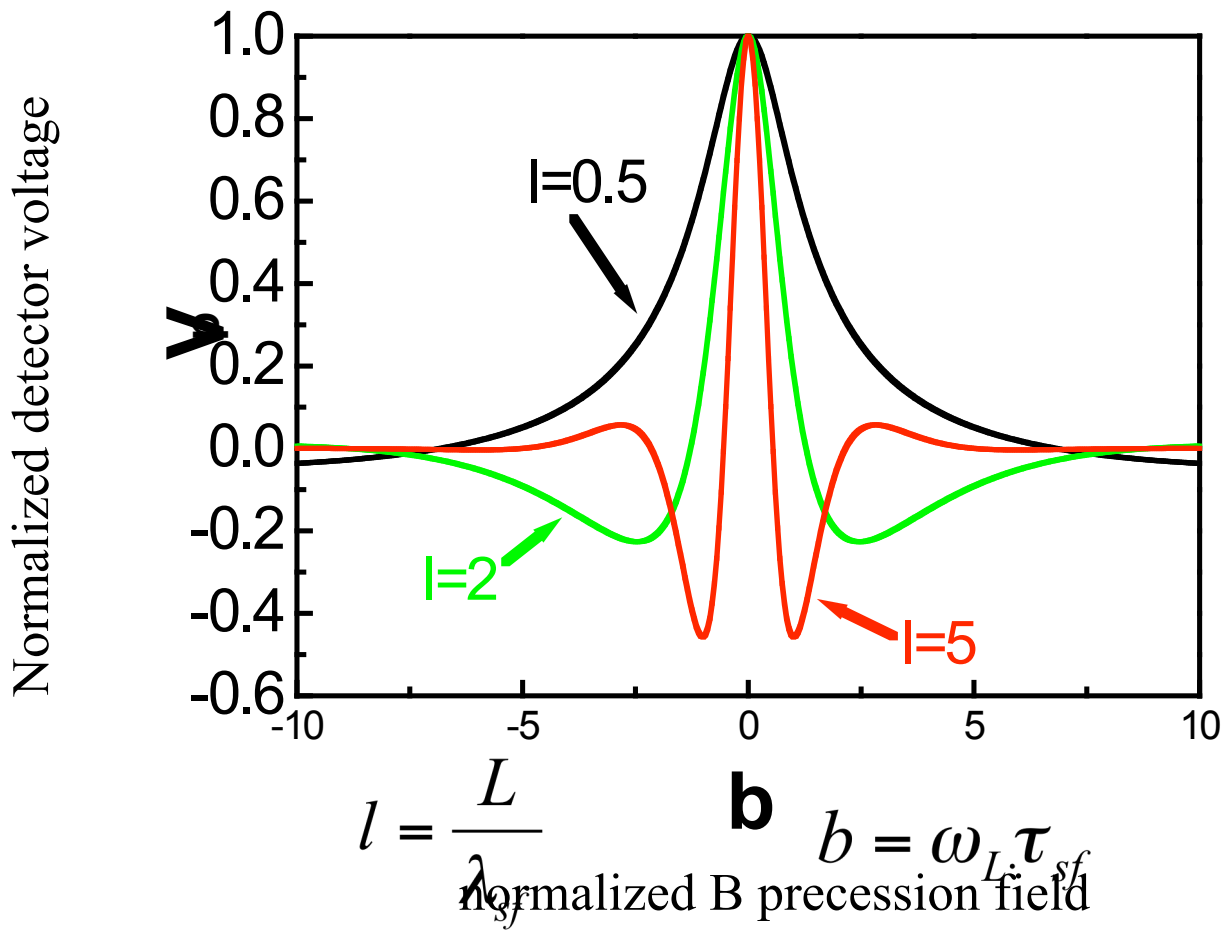


$$P_r(t) = \frac{1}{\sqrt{4\pi D t}} \exp\left(-\frac{L^2}{4Dt}\right) \exp\left(-\frac{t}{\tau_{sf}}\right)$$

Diffusion time:

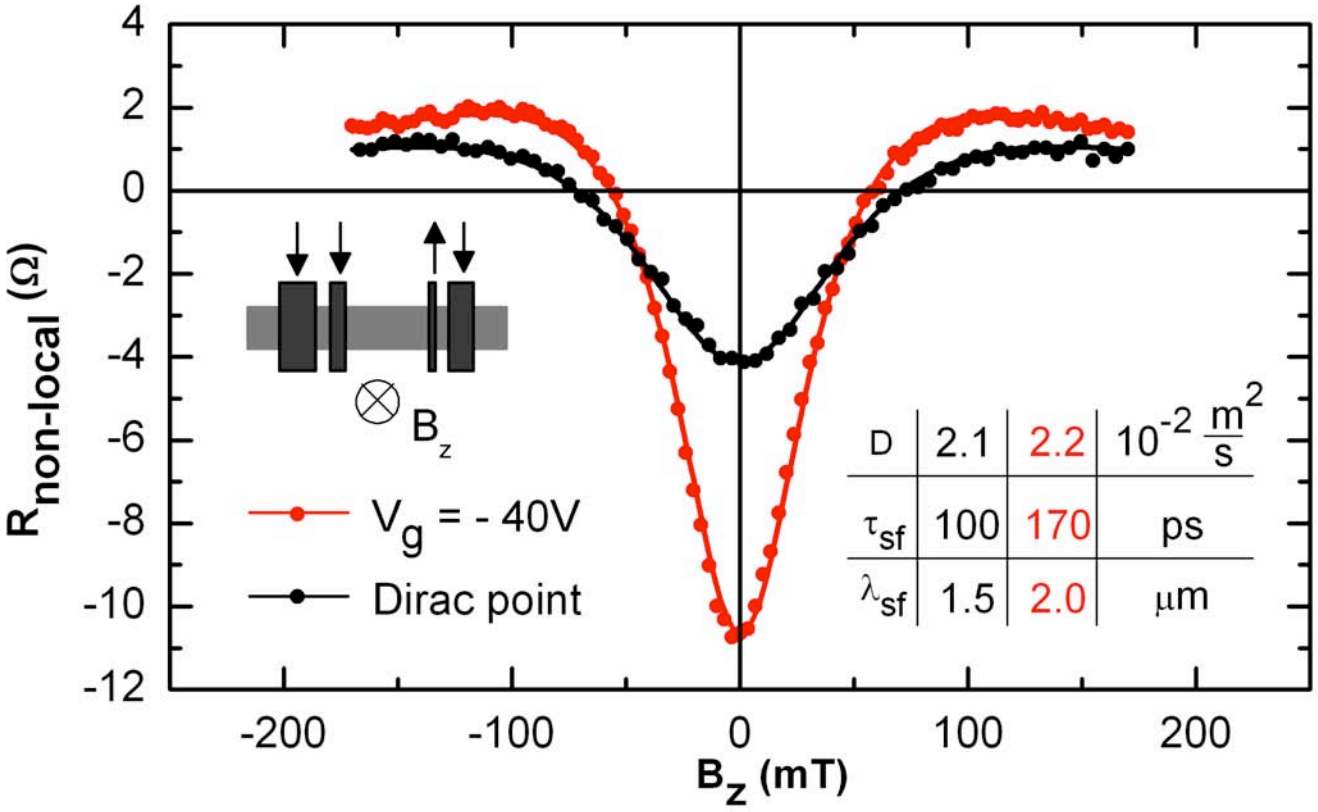
$\tau_D = D/L^2$

Spin precession (theory)

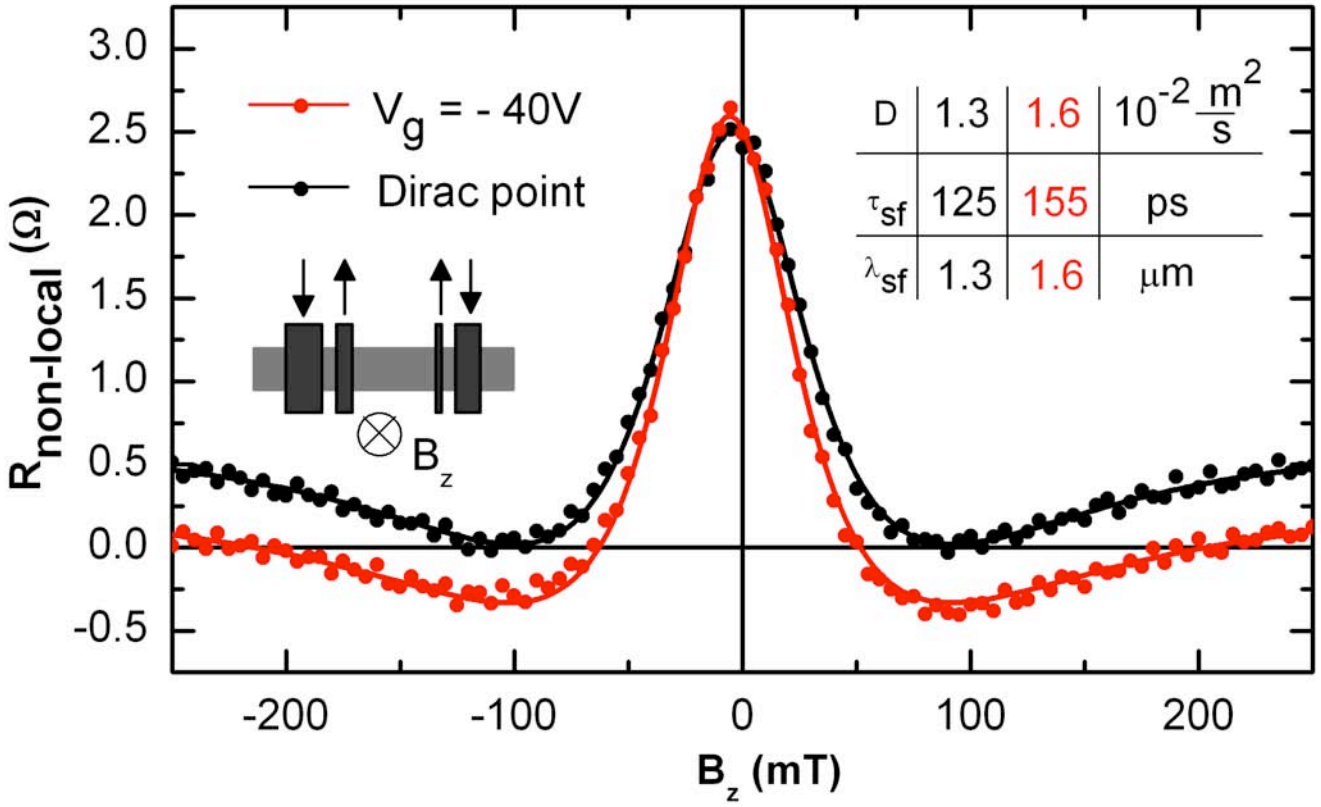


$l = L/\lambda_{sf}$

Spin precession (antiparallel state)



Spin precession (parallel state)



Analysis

Density of states:

Metallic regime: $\nu(\varepsilon)=g_v\, g_s\, 2\,\pi\,\varepsilon/(h^2 v_F^2)$

Close to Dirac point: $\nu(\varepsilon\sim 0) = 4\,\pi\,/h\, v_F\, l$

Einstein relation for degenerate electron systems:

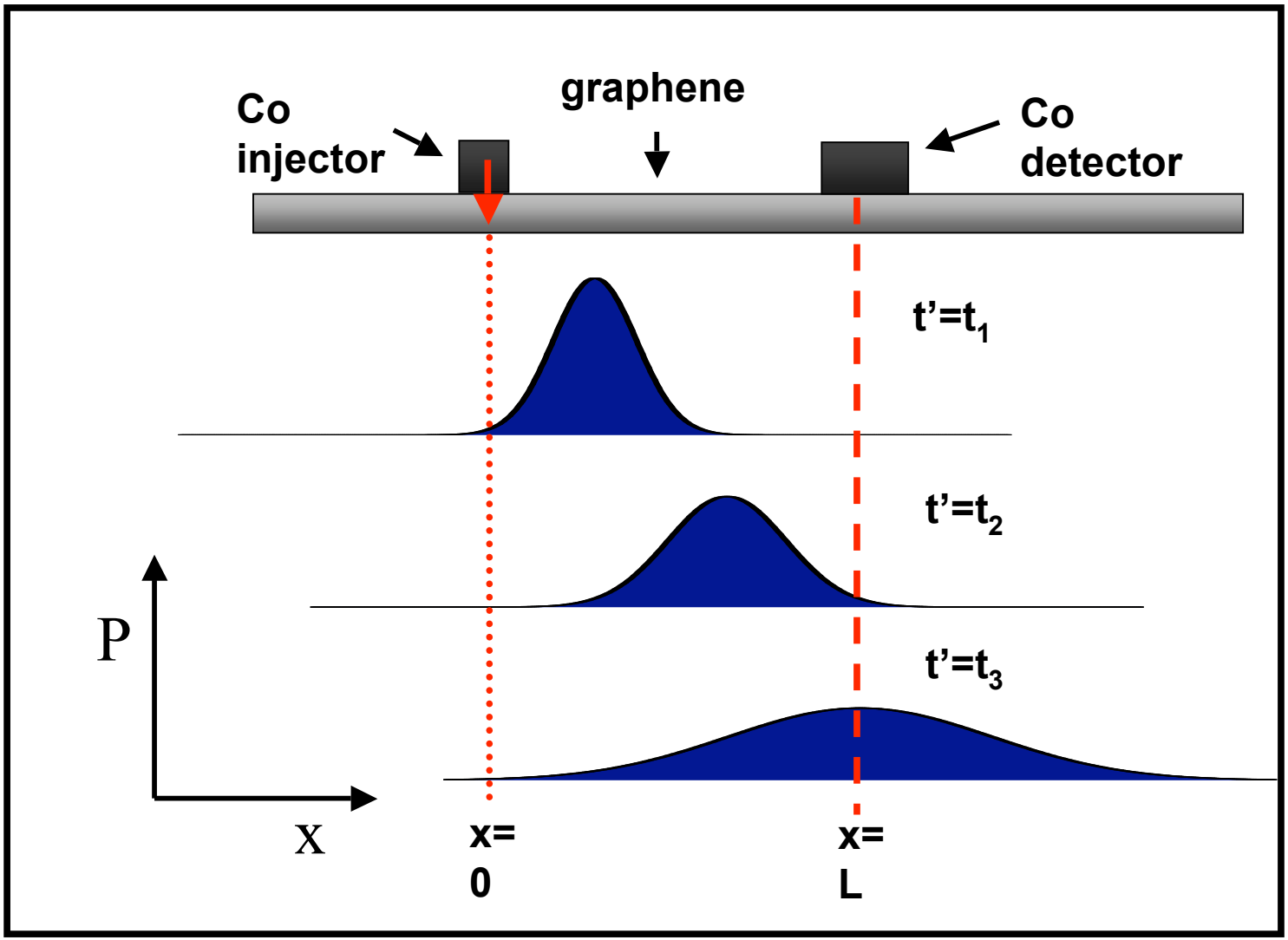
$\sigma(\varepsilon) = \nu(\varepsilon)\, e^2\, D(\varepsilon)$

Diffusion constants from conductivity measurements:

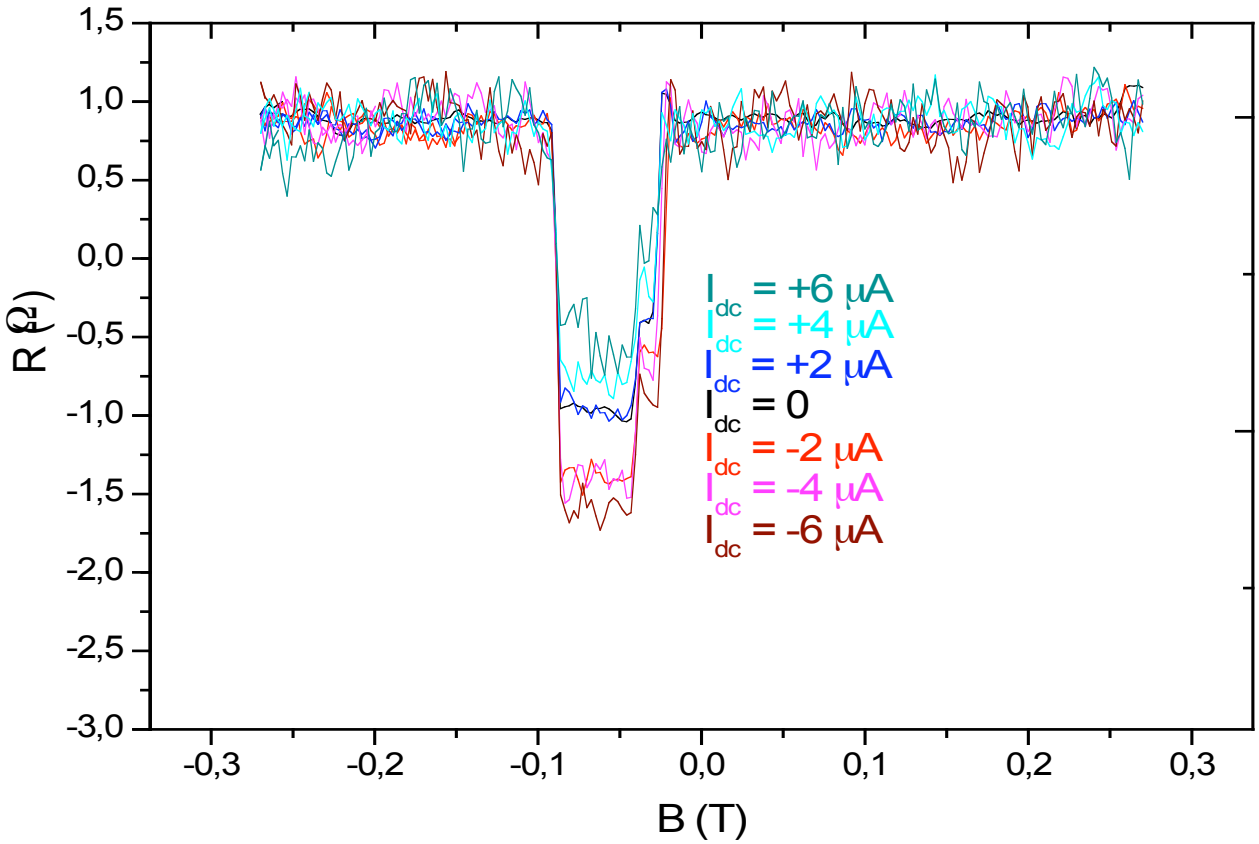
$D= 1.8\ 10^{-2}\ m^2/s$ (Vg=-40V)

$D= 2.2\ 10^{-2}\ m^2/s$ (Dirac point)

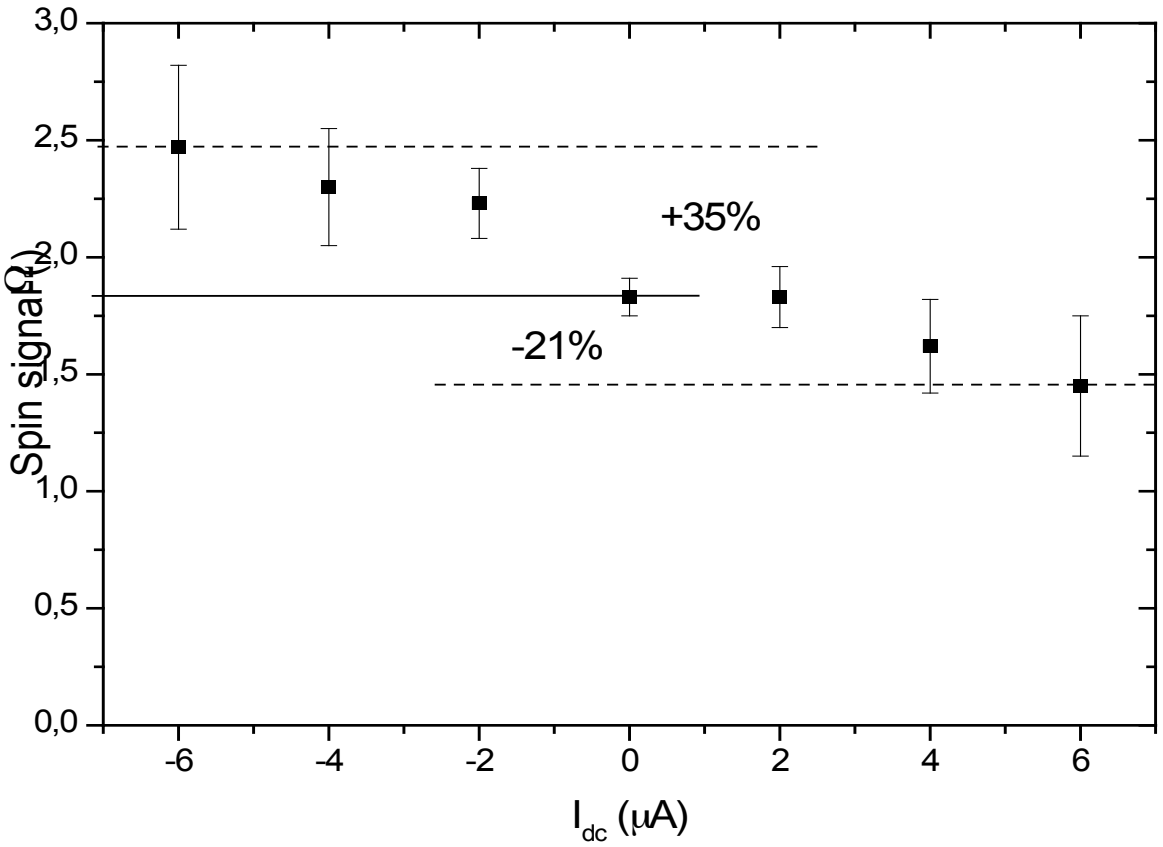
Spin drift



Spin drift (typical E~10^4 V/m)



Spin drift



drift velocity ~ 10^4 m/s

Conclusions

* Spin transport in single graphene layers

* Spin relaxation time (~150 ps) and length (~ 1.5 - 2 μm)

* Limited by impurity potential scattering

* Role of electron phonon scattering

* Cleaner systems

* Role of quantum confinement

• Anisotropic spin relaxation

• Spin drift, p-n junctions.