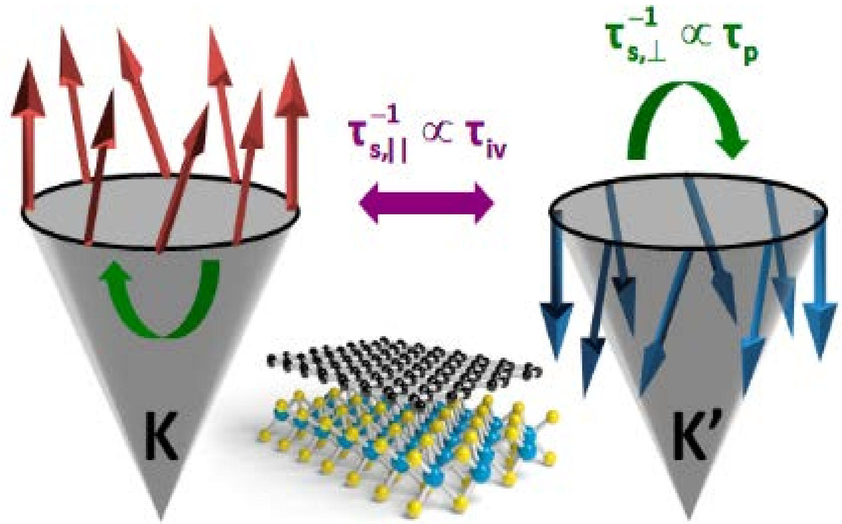
RPGR 2017 SINGAPORE
SEPTEMBER 19-22, 2017 - SINGAPORE
RECENT PROGRESS IN GRAPHENE & 2D MATERIALS RESEARCH

BIST Barcelona Institute of Science and Technology
ICN2 Institut Català de Nanociència i Nanotecnologia

Recent Theoretical Advances in Graphene Spintronics

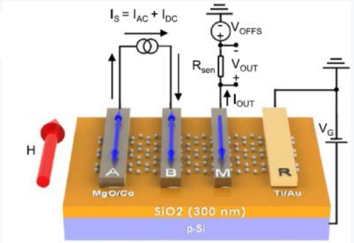
Stephan Roche ICREA



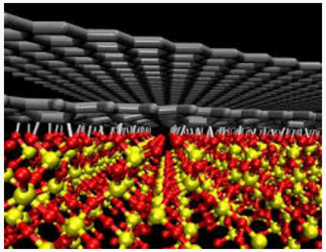
Institució CERCA Centres de Recerca de Catalunya
Generalitat de Catalunya
CSIC Consejo Superior de Investigaciones Científicas
UAB Universitat Autònoma de Barcelona

OUTLINE

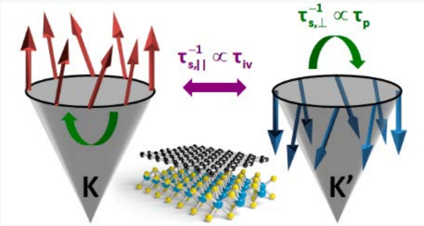
Why Spintronics using 2D Materials ?



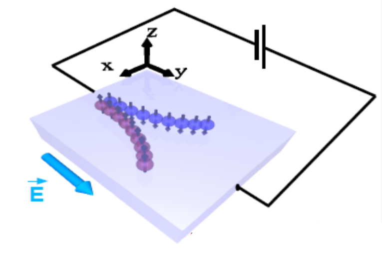
How the substrate controls spin dynamics?



Giant spin transport anisotropy
in graphene induced by strong SOC
Proximity effect

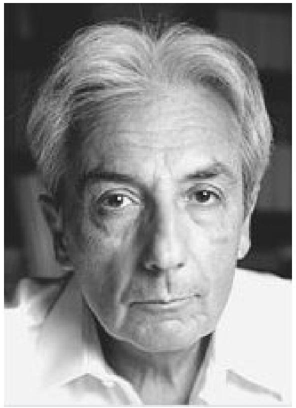


Weak antilocalization & Spin Hall Effect
in Graphene/TMDC

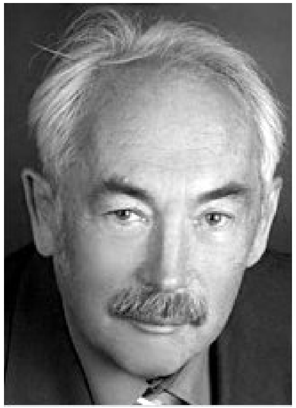


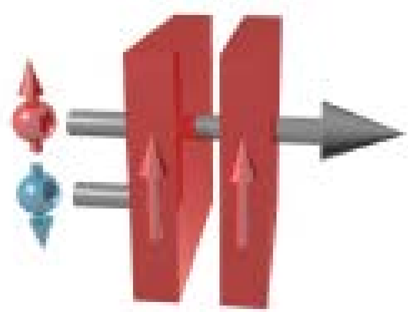
Spintronics and its industrial/Societal impact

Albert Fert

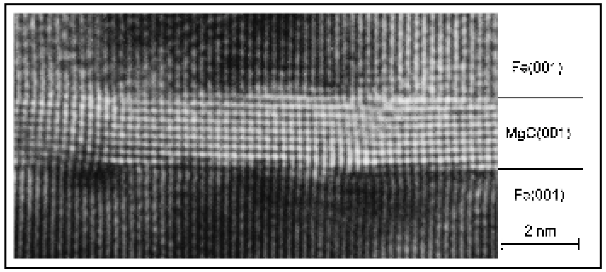


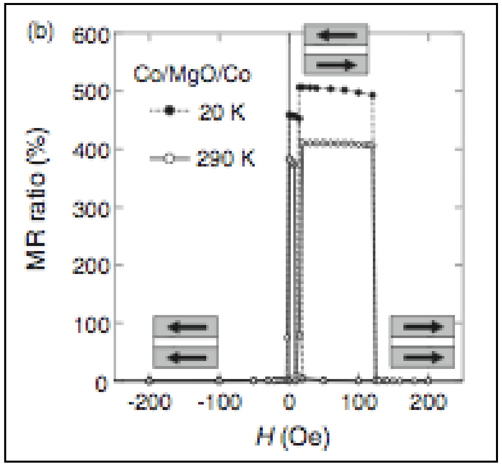
Peter Grünberg





$$MR = \frac{R_{AP} - R_P}{R_P}$$





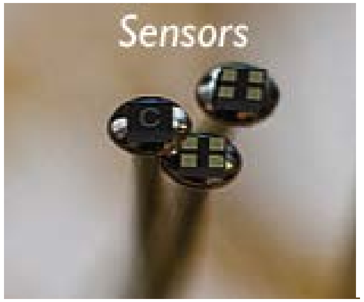
Magnetic field sensors used to read data in hard disk drives,

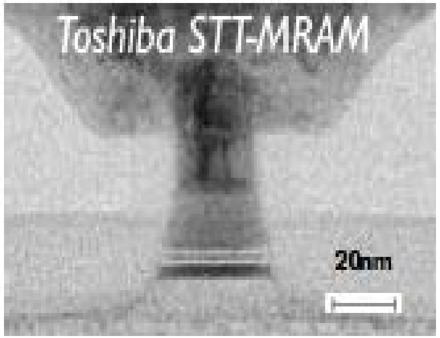
microelectromechanical systems (MEMS), minimally invasive surgery

Automotive sensors for fuel handling system, Anti-skid system, speed control & navigation

***Magnetoresistive random-access memory** (MRAM)*

Spin transfer Torque MRAM

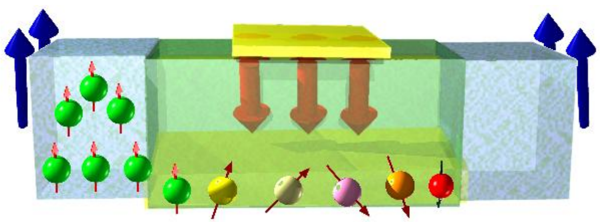




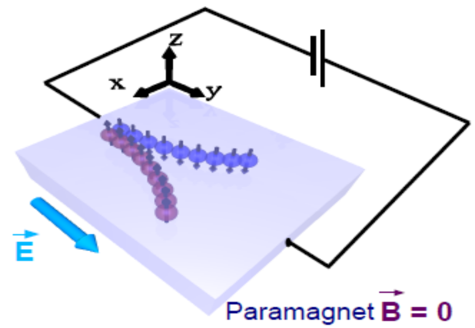
Spin-based information processing ?

Active devices based on **Spin manipulation** ?

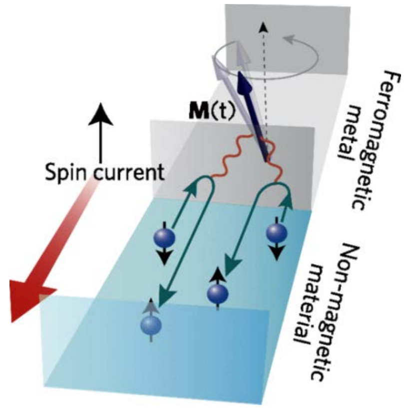
Datta-Das spin transistor



Spin Hall Effect



Spin torques



Need for spin information transport on long distance (room T)
Spin injection and detection (ferromagnets/non magnetic materials)

Metals/semiconductors… short spin diffusion length (spin lifetime 0.1-1ns), 1% (or below) of MR signal

What makes graphene attractive

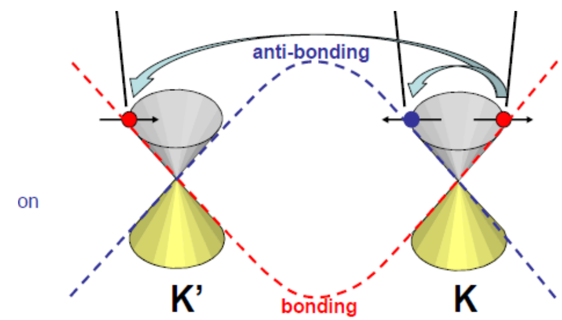
- Ambipolar/tuneable transport

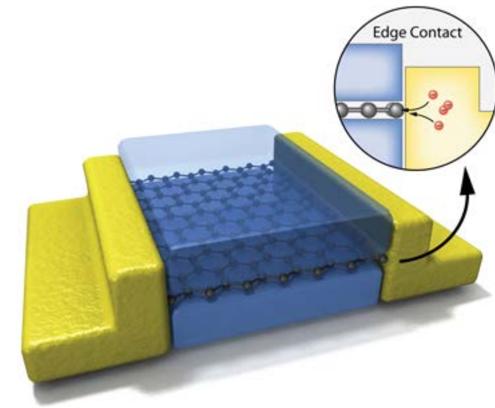
- **Large mobilities**

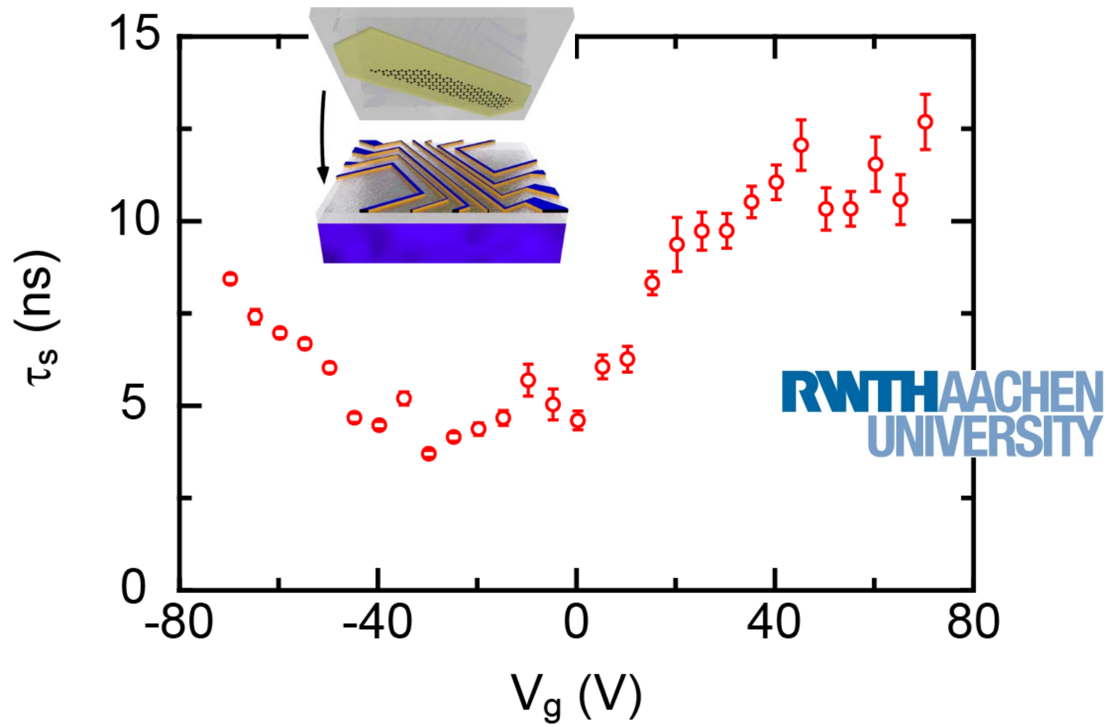
(> 100k cm²/V.s at RT, 1M cm²/V.s at 4K)

- **Low spin-orbit interaction**

- Graphene properties can **be tailored by proximity effects**



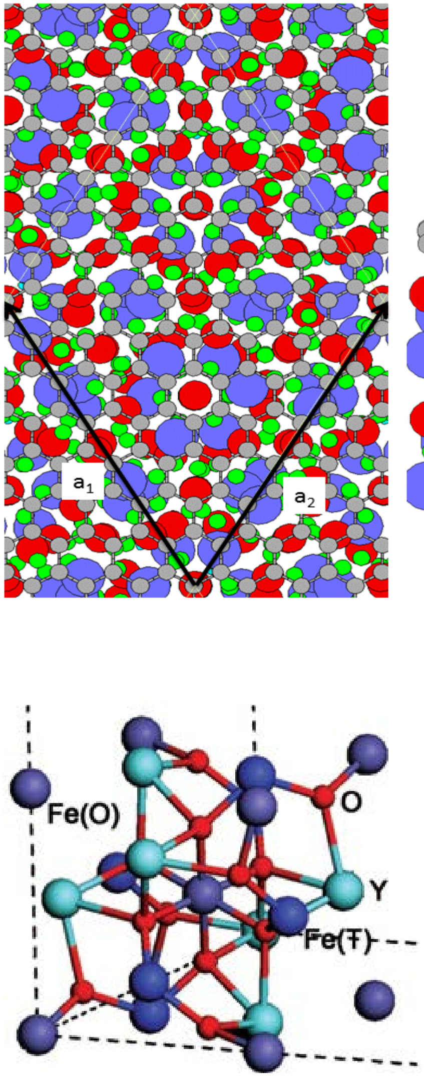




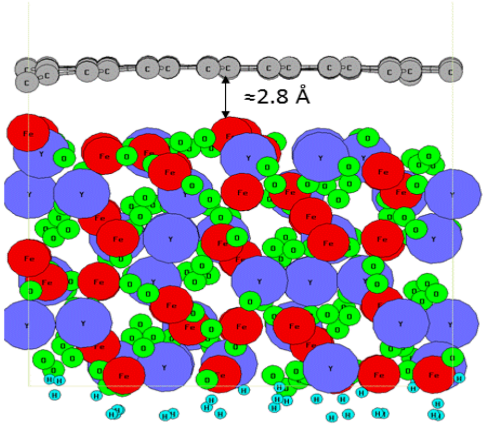
M. Drögeler et al Nano Lett. 16 (6), 3533 (2016)

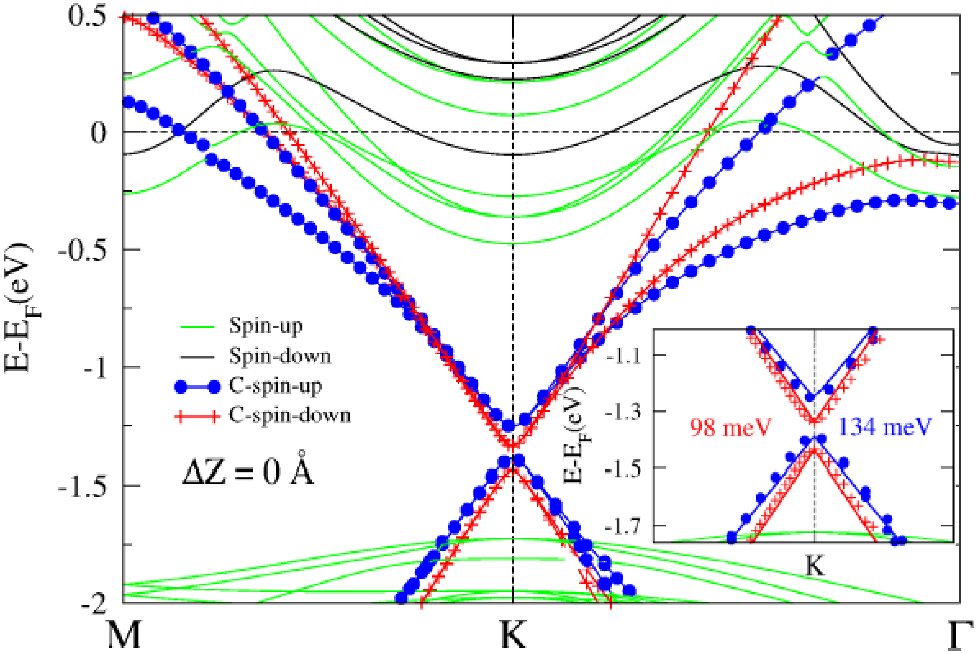
Graphene/Magnetic insulators

Graphene/EuO and Graphene/Y_3Fe_5O



Spin Filtering and Exchange Splitting Gaps



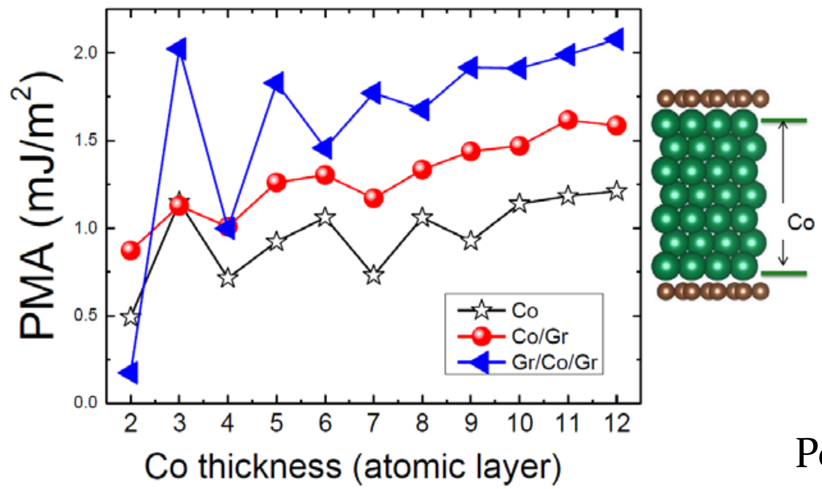


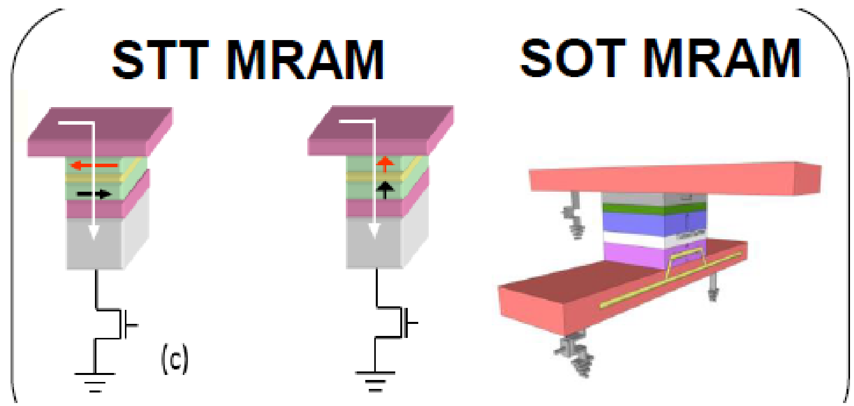
Exchange splitting (G/YIG) = 40 meV

Yang, Hallal, Waintal, Roche, Chshiev, **PRL 110, 046603 (2013)**
Hallal et al. **2D materials 4 , 025074 (2017)**

GRAPHENE FLAGSHIP

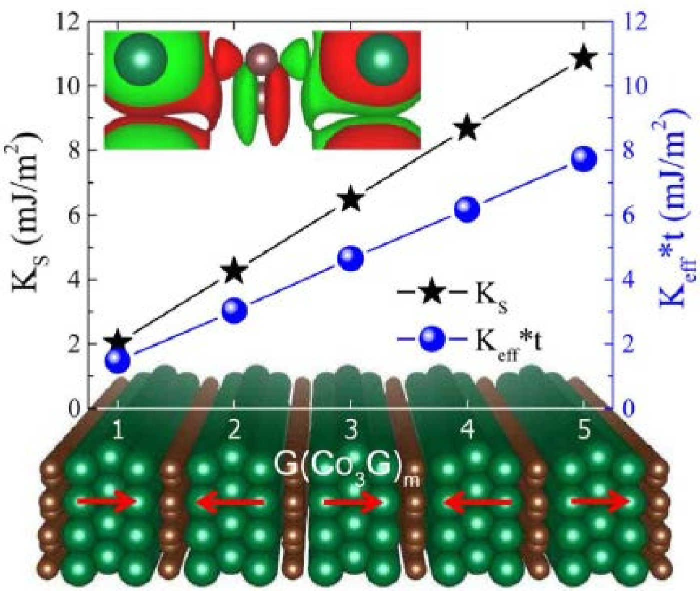
Potential of 2d Materials for STT-MRAM technologies





Perpendicular Magnetic Anisotropy in FM/Ox and FM/Graphene interfaces :
Strongly enhanced PMA of Co realized by graphene coating

Layer and orbital resolved contributions unveil the PMA mechanisms
Superlattice structures to obtain Giant PMA



$$K_{eff} = \frac{K_s}{t_{Co}} - E_{demag}$$

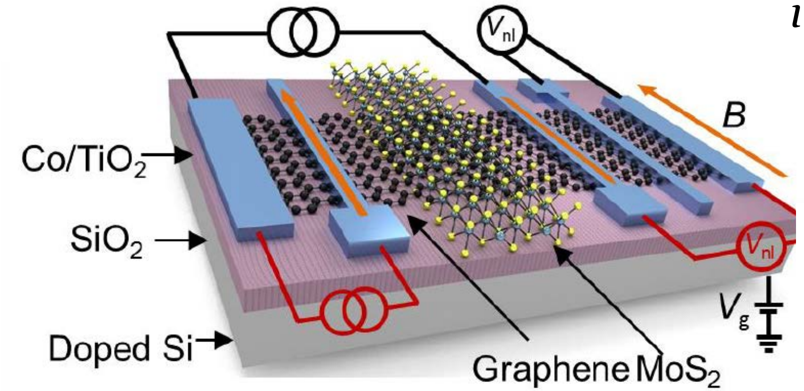
Yang, Chshiev et al, Nano Letters 16, 145 (2015)

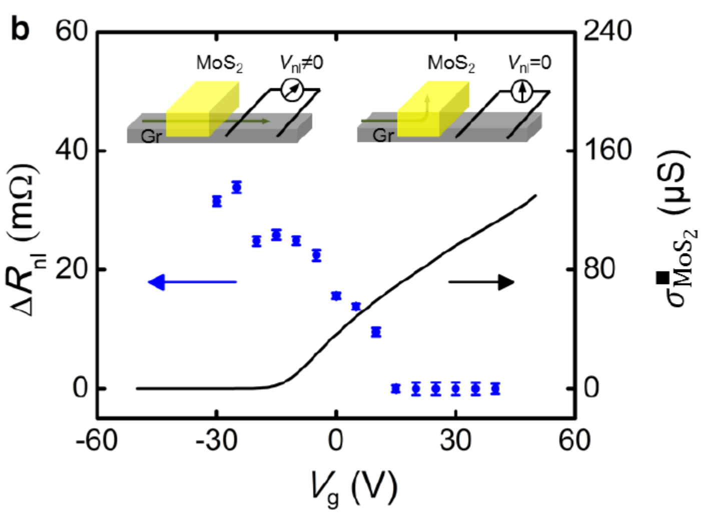
Graphene-based Spintronic logic demonstrators

W. Yan et al.

Nature Comm. 7, 13372 (2016)

SPIN-FET



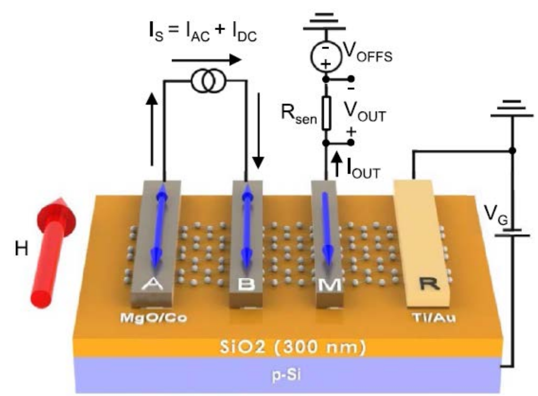


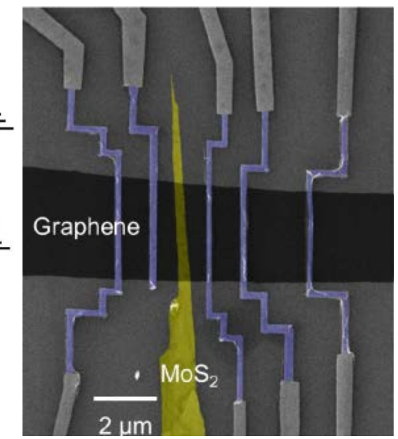
Hua Wen et al.

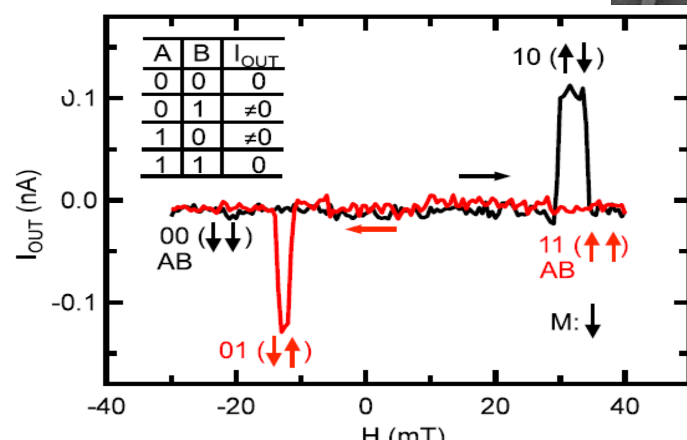
Phys. Rev. Applied **5**, 044003 (2016)

Experimental demonstration of XOR operation

in graphene Magnetologic Gates at room temperature

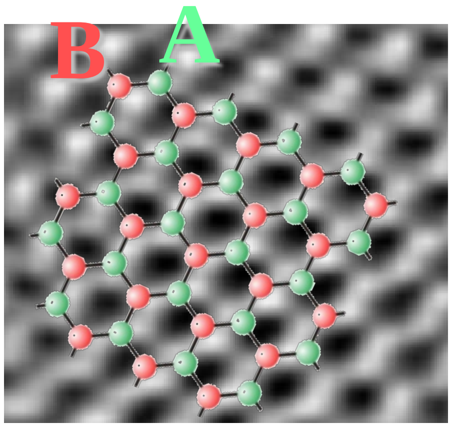


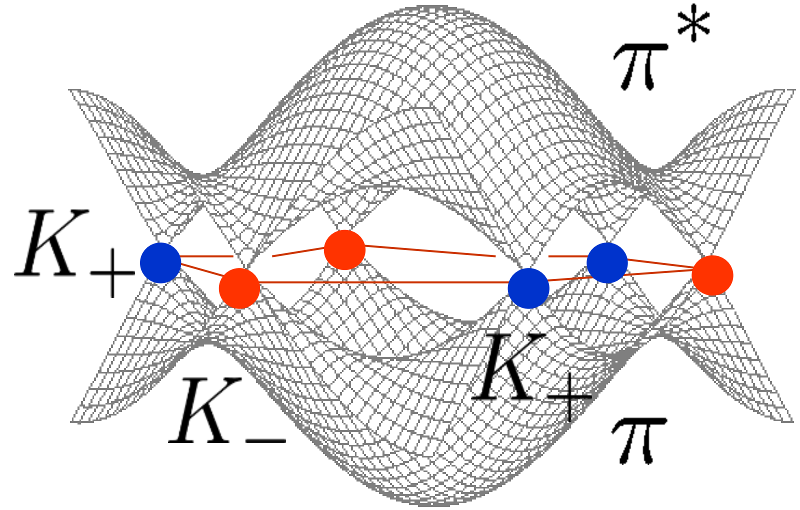




Massless Dirac Fermions in 2D graphene

Sublattice Pseudospin (and valley isospin) & spin quantum degrees of freedom



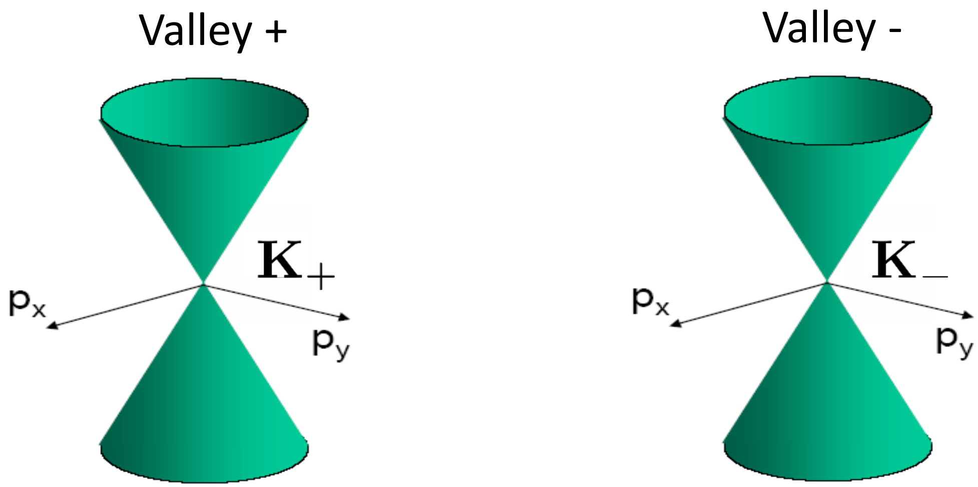


Two valleys -Sublattices A and B - Spin 1/2

Full effective Hamiltonian for low-energy properties
(8-components wavefunction)

$$\begin{pmatrix} 0 & p_x - ip_y & 0 & 0 & 0 & 0 & 0 & 0 \\ p_x - ip_y & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -p_x + ip_y & 0 & 0 & 0 & \\ 0 & 0 & -p_x + ip_y & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & p_x - ip_y & 0 & 0 \\ 0 & 0 & 0 & 0 & p_x - ip_y & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -p_x + ip_y \\ 0 & 0 & 0 & 0 & 0 & 0 & -p_x + ip_y & 0 \end{pmatrix} \begin{pmatrix} \Psi^{\Uparrow}_{A,+} \\ \Psi^{\Uparrow}_{B,+} \\ \Psi^{\Uparrow}_{A,-} \\ \Psi^{\Uparrow}_{B,-} \\ \Psi^{\Downarrow}_{A,+} \\ \Psi^{\Downarrow}_{B,+} \\ \Psi^{\Downarrow}_{A,-} \\ \Psi^{\Downarrow}_{B,-} \end{pmatrix}$$

Massless Dirac Fermions in 2D graphene



$$\vec{Q} = K_+ + \vec{p}/\hbar$$

linearization close to Fermi level

Two valleys -> Dirac cones

$$E(\vec{p}) = v_F|\vec{p}|$$

$$\mathcal{H}_{K_+} = v_F \vec{\sigma}.\vec{p} = v_F(p_x\sigma_x + p_y\sigma_y)$$

Pseudo-spinors are eigenstate of the **helicity operator**

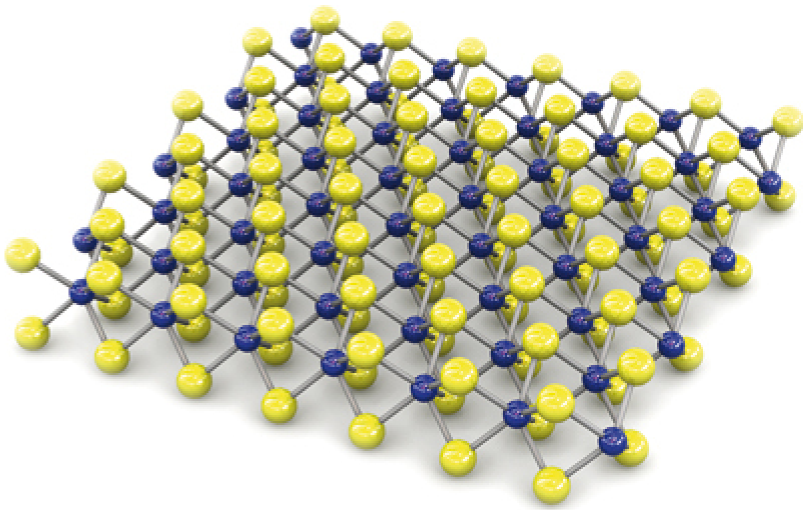
$$\hat{h} = \frac{1}{2}\vec{\sigma}.\frac{\vec{p}}{|\vec{p}|}$$

$$\Psi_{\vec{p}} = \frac{1}{\sqrt{2}}\left(\Psi_{\vec{p}}(A)\begin{pmatrix}1\\0\end{pmatrix} + \Psi_{\vec{p}}(B)\begin{pmatrix}0\\1\end{pmatrix}\right) = \frac{1}{\sqrt{2}}\begin{pmatrix} se^{i\theta_p/2} \\ e^{-i\theta_p/2}\end{pmatrix}$$

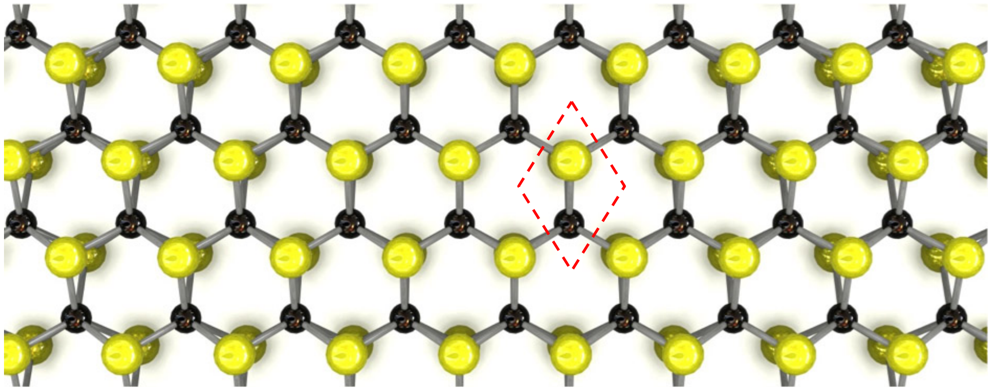
"**pseudospin**"= sublattice index : **up (on A) / down (on B)**

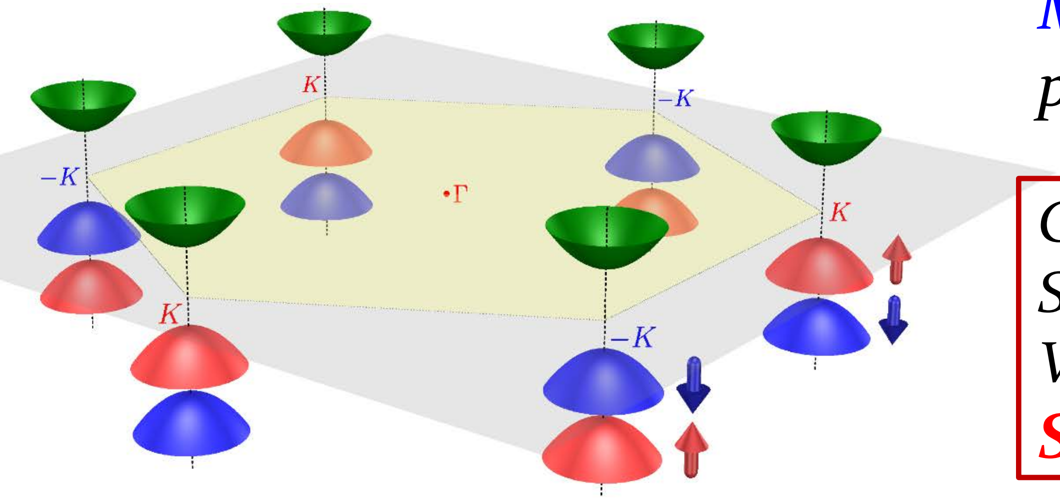
$$\tan\theta_p = \frac{p_y}{p_x}$$

Transition Metal dichalcogenides (monolayer)



Hexagonal lattice structure





Massive Dirac Fermions

partially filled d-orbitals(metal)

Gap ~ 2 eV
Spin-Split vbands $\sim 150 - 400$ meV
Valley pseudospin $\pm K(\tau = \pm 1)$
Spin-valley locking

$$\mathcal{H} = at(\tau_z k_x \hat{\sigma}_x + k_y \hat{\sigma}_y) + \frac{\Delta}{2}\sigma_z + \lambda_{SO}\tau_z \hat{s}_z$$

D. Xiao et al **Phys. Rev. Lett 108, 196802 (2016)**

NANO LETTERS

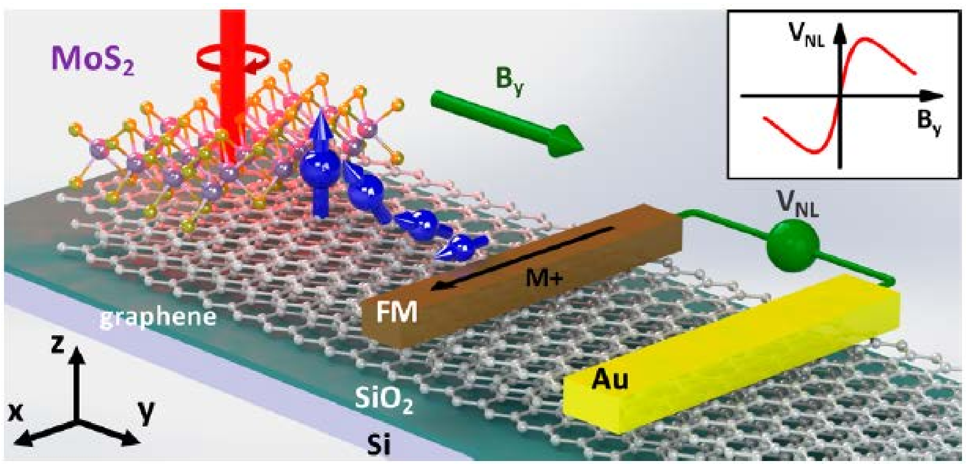
Letter

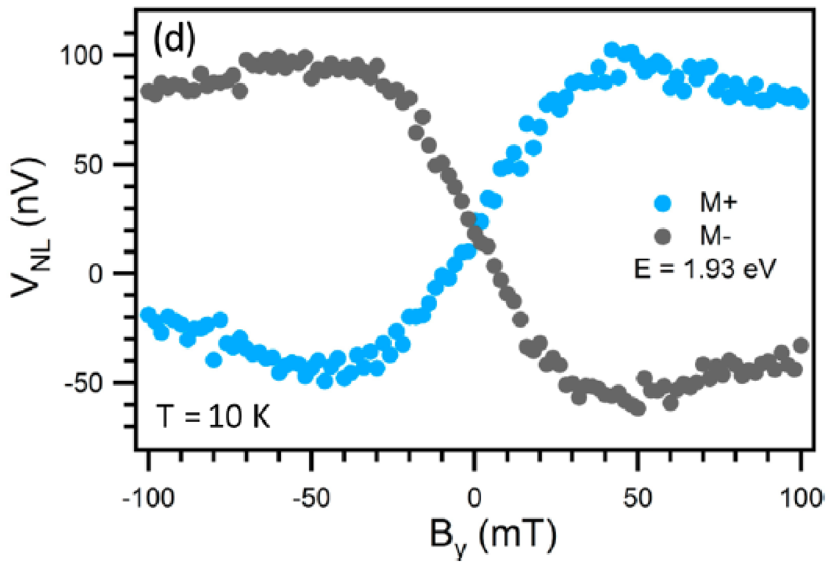
pubs.acs.org/NanoLett

Opto-Valleytronic Spin Injection in Monolayer MoS_2/Few-Layer Graphene Hybrid Spin Valves

Yunqiu Kelly Luo,[†] Jinsong Xu,[†] Tiancong Zhu,[†] Guanzhong Wu,[†] Elizabeth J. McCormick,[†] Wenbo Zhan,[†] Mahesh R. Neupane,[‡] and Roland K. Kawakami[*,†]

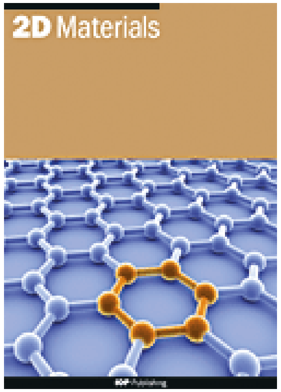
Nano Lett. 17 (6), 3877 (2017)





Multifunctional 2D spintronic/valleytronic devices and applications !

GRAPHENE FLAGSHIP

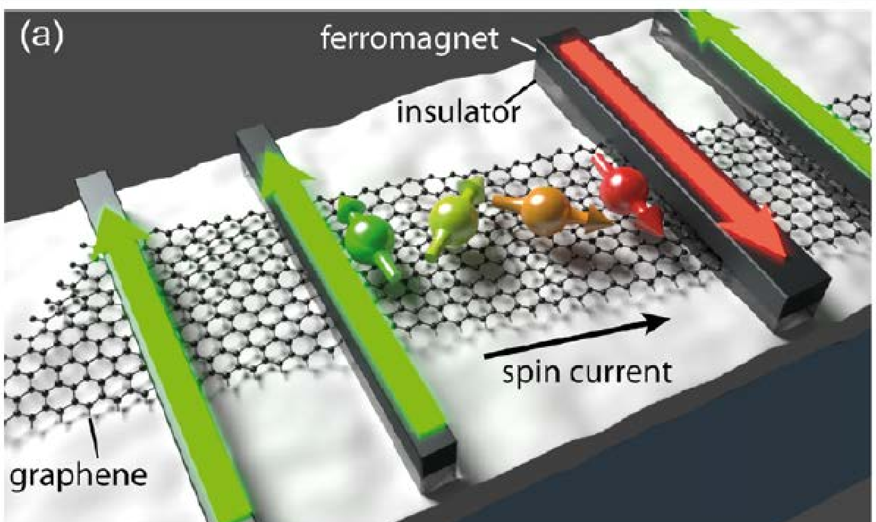


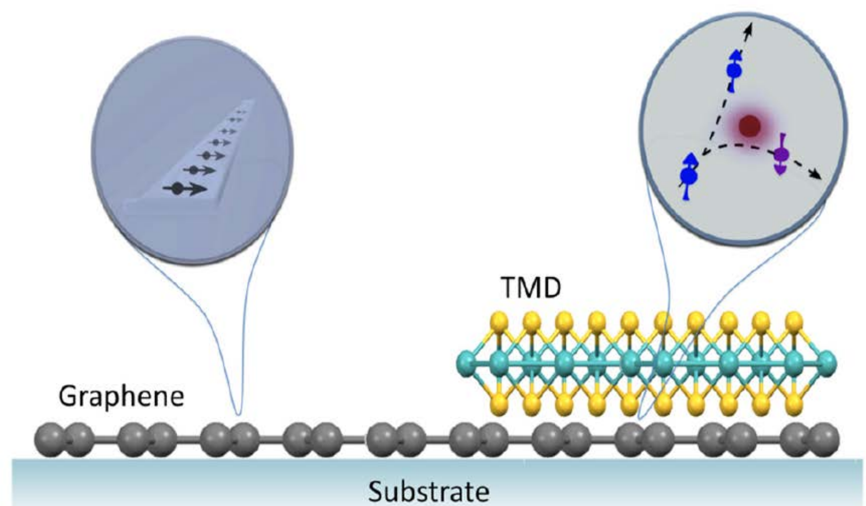
EDITORIAL

Graphene spintronics: the European Flagship perspective

Stephan Roche[1,2], Johan Åkerman[3,4,5], Bernd Beschoten[6], Jean-Christophe Charlier[7], Mairbek Chshiev[8,9], Saroj Prasad Dash[10], Bruno Dlubak[12], Jaroslav Fabian[11], Albert Fert[12], Marcos Guimarães[13,19], Francisco Guinea[14,15], Irina Grigorieva[14], Christian Schönenberger[16], Pierre Seneor[12], Christoph Stampfer[17], Sergio O Valenzuela[1,2], Xavier Waintal[9,18] and Bart van Wees[19]

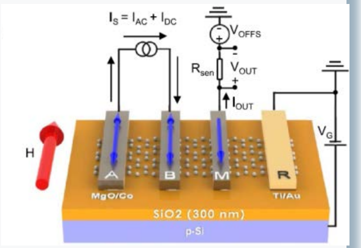
2D Mater. 2 (2015) 030202



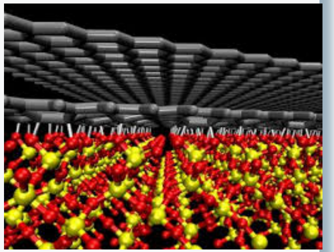


OUTLINE

Why Spintronics using 2D Materials ?



How the substrate controls spin dynamics?



Giant spin transport anisotropy
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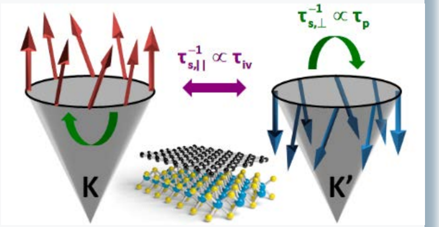
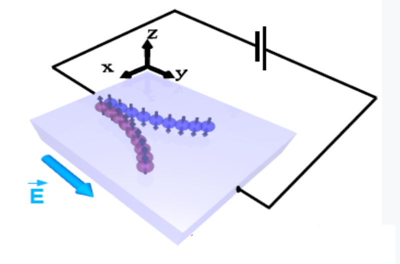
Proximity effect



Spin Hall Effect & Weak antilocalization
in Graphene/TMDC



"Unprecedented spin lifetimes in ultraclean graphene"??

Homogeneous Rashba + disorder (density of impurities)

Numerical calculation of the spin relaxation time by performing Monte Carlo simulations

Along any given classical trajectory $[\mathbf{r}(t), \mathbf{k}(t)]$
the spin dynamics is described by Bloch spin equation

$$\frac{d\mathbf{S}}{dt} = \Omega_R[\mathbf{r}(t)](\mathbf{n}[\mathbf{k}(t)] \wedge \mathbf{S})$$

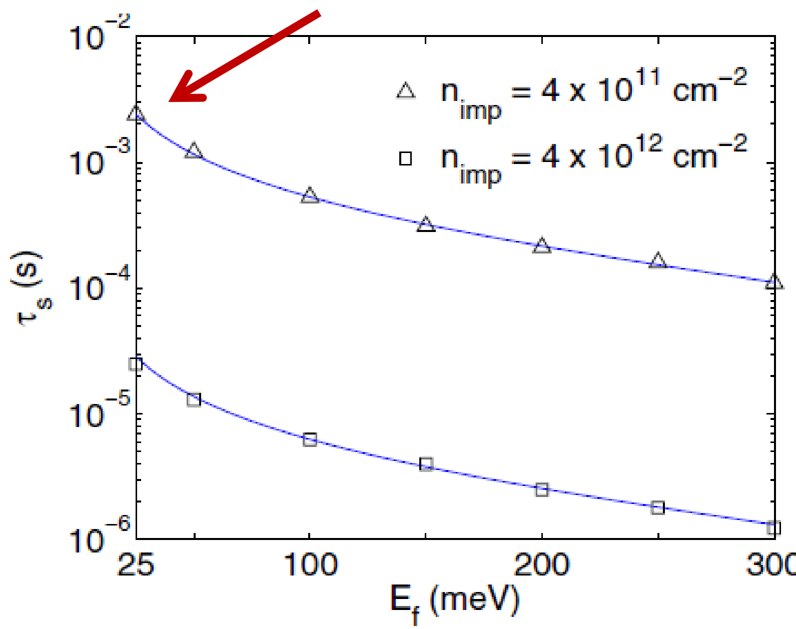
Spin lifetime is calculated by averaging over random trajectories with different initial momenta , assuming

$$t \gg \tau_{tr}$$

$$S_\alpha(t) \sim e^{-t/\tau_\alpha}$$

$$\tau_\alpha \to \mu\mathrm{s} - \mathrm{ms!!!}$$

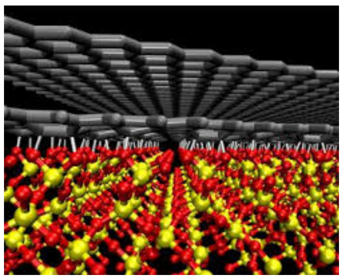
Maximum at Dirac point
Elliot Yaffet



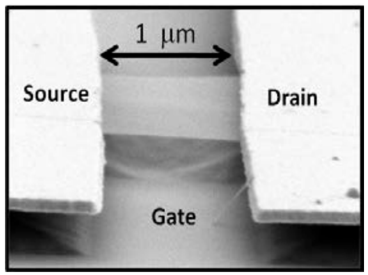
C. Ertler, S. Konschuh, M. Gmitra and J. Fabian, **Phys. Rev. B 80, 041405(R) (2009)**

Experimental spin lifetime features

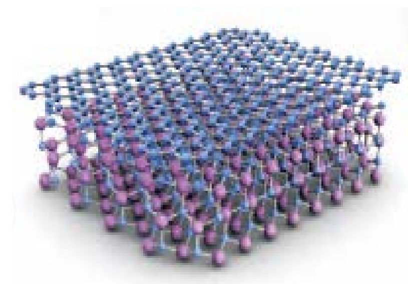
Graphene on SiO2



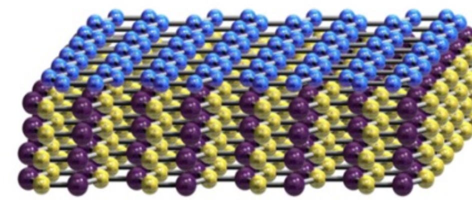
Suspended Graphene



Epitaxial graphene on SiC



Graphene on BN

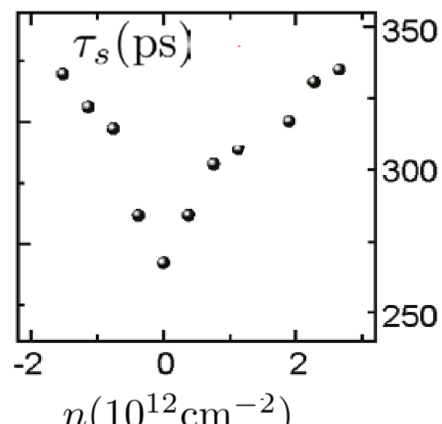


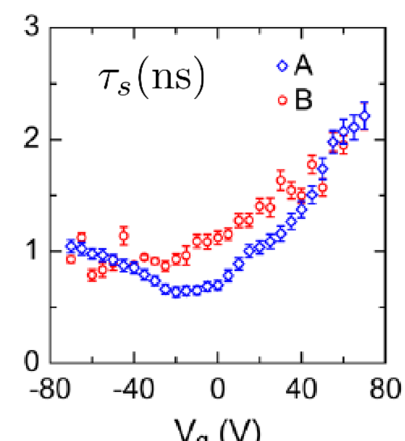
charge mobility $\mu \sim 100 - 100.000\text{cm}^2\text{V}^{-1}\text{s}^{-1}$

Room temperature

$$\tau_s \sim 0.1 - 10 \text{ ns}$$

Avsar et al, Nano Lett. 11, 2363 (2011)
Drögeler et al. Nano Lett. 14, 6050 (2014)
Guimarães et al Phys Rev Lett 113, 086602 (2014)

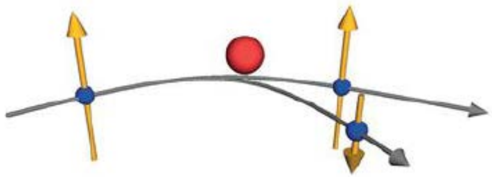




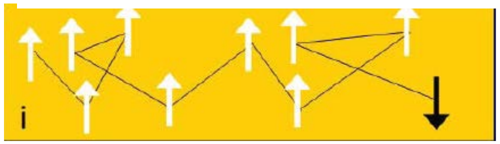
Which relaxation mechanism at play ?

Metals

Eliott-Yafet mechanism



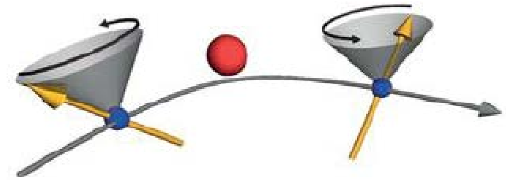
$$\tau_s \sim 10^4 - 10^6 \tau_p$$



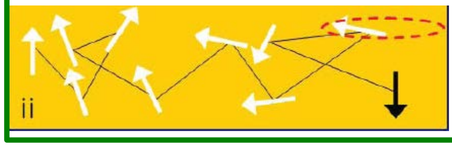
$$\tau_s^{EY} \sim \epsilon_F^2 \tau_p / \lambda_R^2$$

Small gap semiconductor

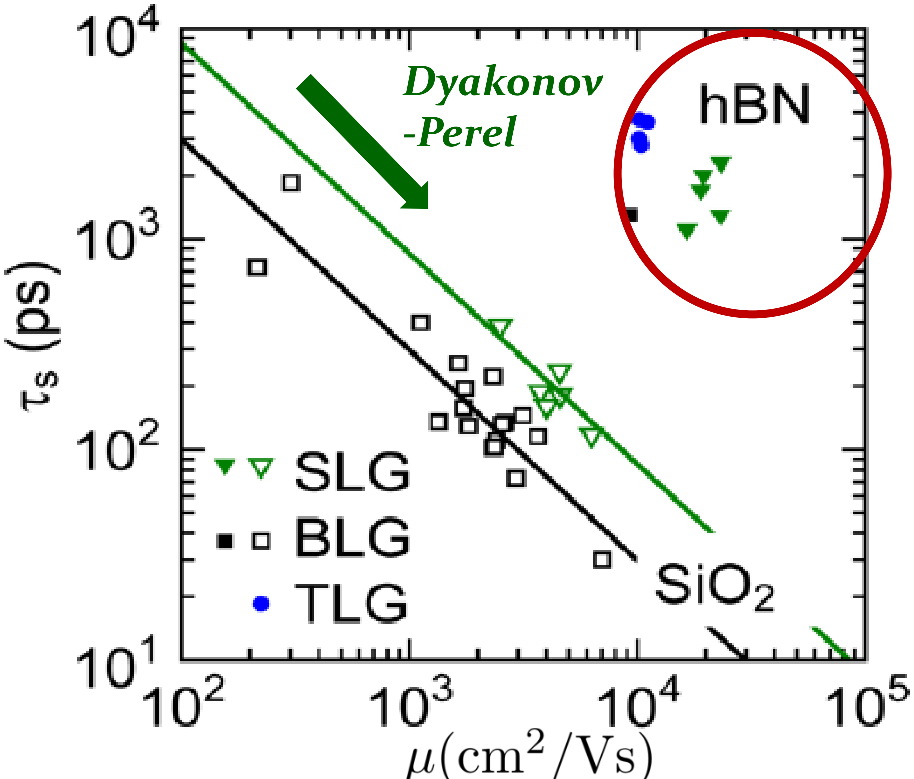
Dyakonov-Perel mechanism



$$\tau_s \sim \frac{1}{\tau_p}$$



$$\tau_s^{DP} \sim \hbar^2 / (\lambda_R^2 \tau_p)$$



Drögeler et al. Nano Lett. 14, 6050 (2014)
Guimarães et al PRL 113, 086602 (2014)

Cleaner samples for SiO2 substrates lead to lower spin lifetime

“opposite trend” for hBN Substrates?

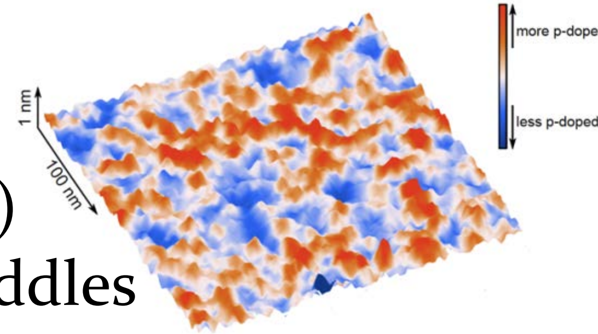
Origin of spin dephasing
Spin-orbit coupling in graphene

“clean limit”

Intrinsic
spin-orbit coupling

⊕

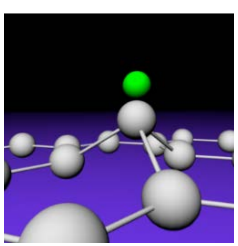
Substrate effects
(Rashba electric field)
and electron-hole puddles



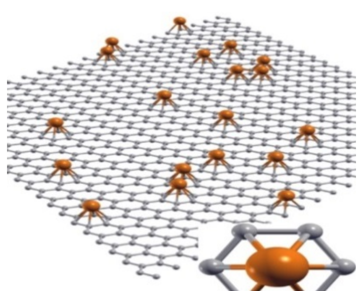
“dirty limit”

Etching transfer processes : contamination with ionic impurities (from metal etchants) or ***metallic residues (from incomplete etching)****,*
+ PMMA residues (transfer)

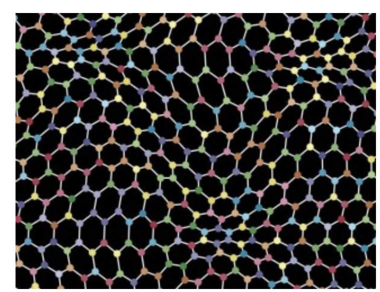
sp³ defects
(σ–π hybridization)
Hydrogen ad-atoms-



Transition- metal adatoms
(Cu, Ni, Au,…)



Deformation fields
(Strain, ripples,bubbles…)

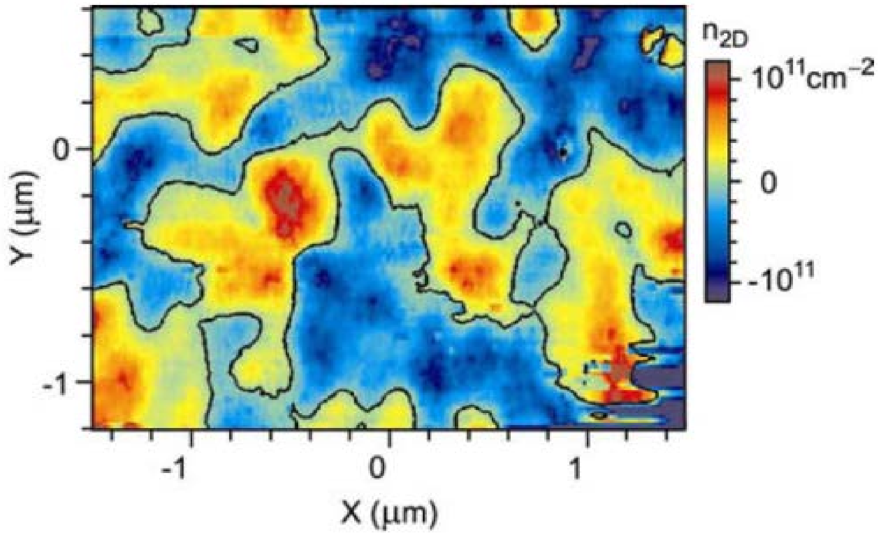


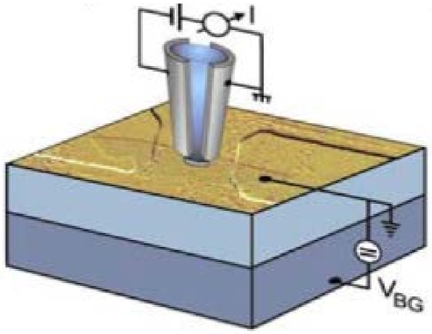
Spin relaxation in supported clean graphene

-beyond semiclassical approximations-

Disorder: Electron-holes puddles

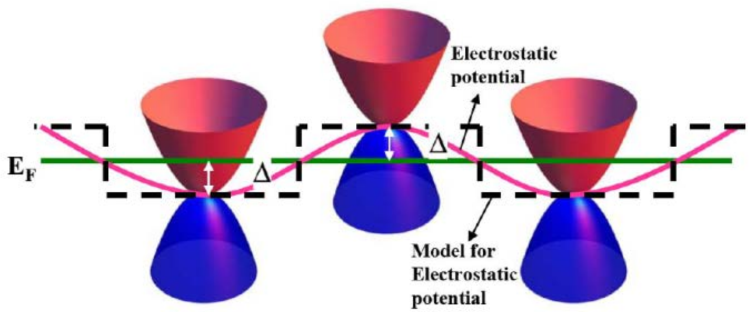
Spatial (long range) charge density fluctuations





Electrons locally screen charged impurities trapped in the substrate

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



Spin-orbit interaction :

Uniform Rashba SOC-field **10 μeV**

(substrate effect/mirror symmetry breaking)

$$\tau_s \sim \mu s - ms \ ???$$

Tight-binding Modelling

$$\mathcal{H} = -\gamma_0 \sum_{\langle ij \rangle} c_i^+ c_j + \sum_{\langle i \rangle} V_i c_i^+ c_i + i V_R \sum_{\langle ij \rangle} c_i^+ \vec{z} \cdot (\vec{s} \times \vec{d}_{ij}) c_j$$

Screened Coulomb potential

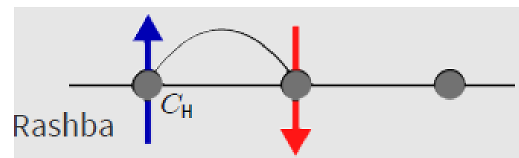
Long range (Gaussian) potential

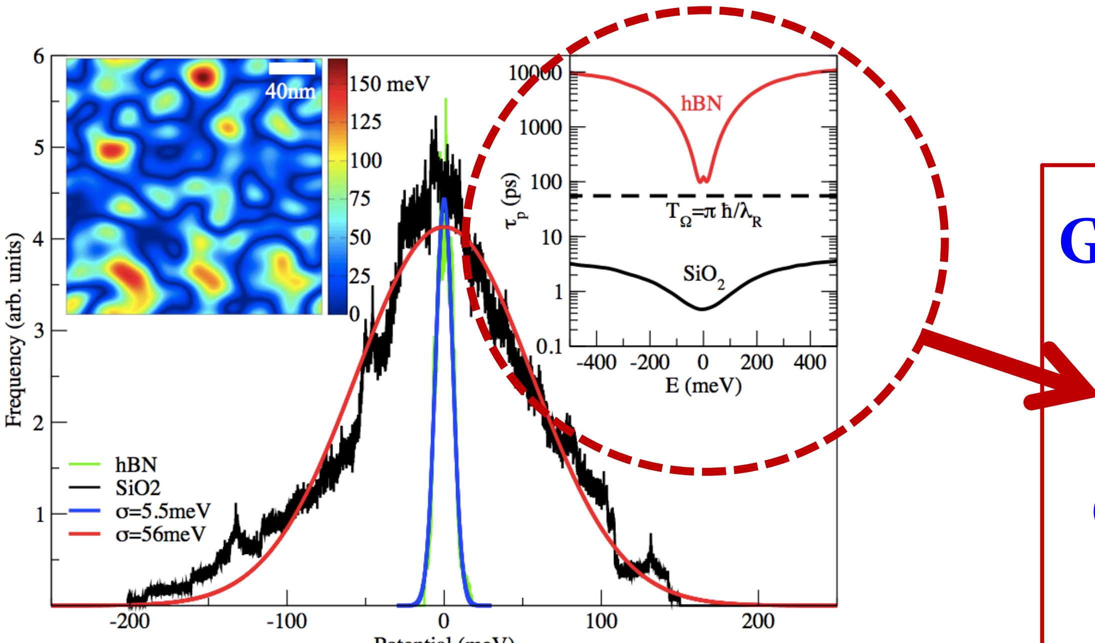
$$V_i = \sum_{\alpha=1}^{N_\alpha} \varepsilon_\alpha \exp(-|\mathbf{r}_\alpha - \mathbf{r}_i|^2/(2\xi^2))$$

Shaffique Adam et al **Phys. Rev. B 84, 235421 (2011)**

Rashba SOC

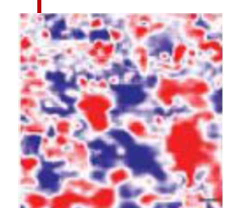
$V_R \sim 20\mu\text{eV}$





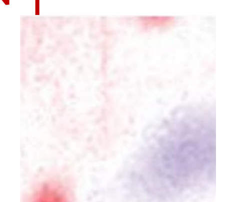
Onsite energy distribution of the π –orbitals with
standard deviation for hBN (5meV) & SiO2 (56meV)

Graphene on SiO2



$$\tau_p^{\mathrm{SiO_2}}/T_\Omega \ll 1$$

Graphene on hBN



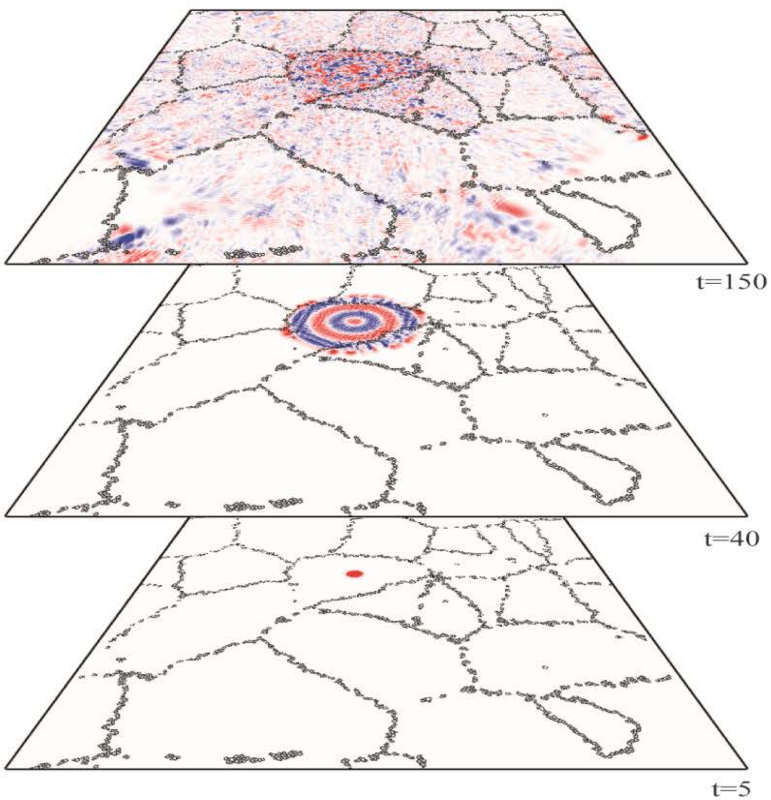
$$\tau_p^{\mathrm{hBN}}/T_\Omega \geq 1$$

Spin dynamics of propagating wavepacket

$$|\Psi_{\perp}(0)\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} |\varphi_{RP}\rangle \quad |\Psi(t)\rangle = e^{-i\hat{\mathcal{H}}t/\hbar}|\Psi(0)\rangle$$

Local spin density in real space

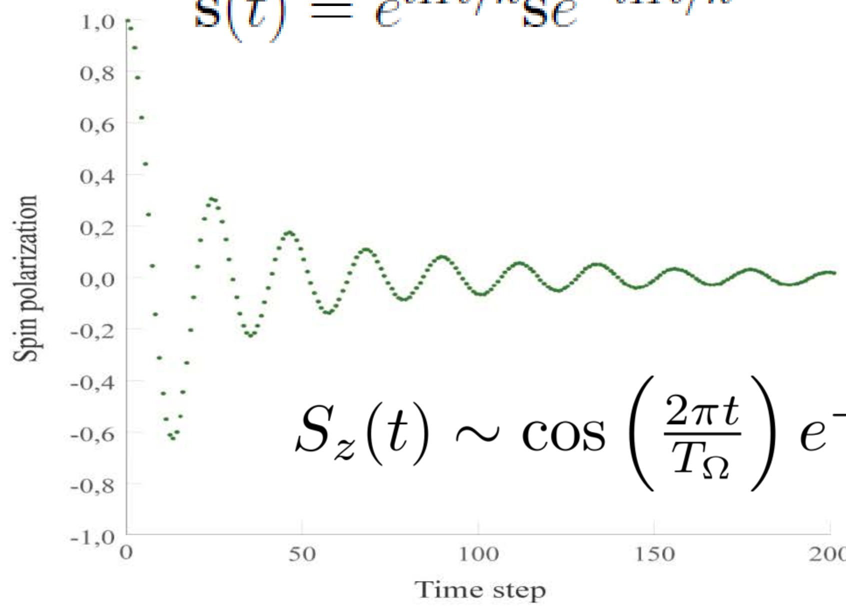
$$s_i(t) = |\Psi_i^{\uparrow}(t)|^2 - |\Psi_i^{\downarrow}(t)|^2$$



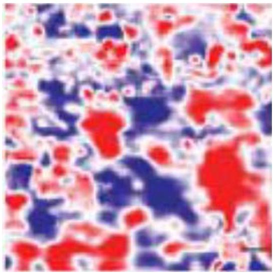
Time evolution of the wavepacket spin polarization

$$\vec{S}(E,t) = \frac{\mathrm{Tr}[\delta(E-H)\hat{\mathbf{s}}(t)]}{\mathrm{Tr}[\delta(E-H)]}$$

$$\hat{\mathbf{s}}(t) = e^{iHt/\hbar}\hat{\mathbf{s}}e^{-iHt/\hbar}$$



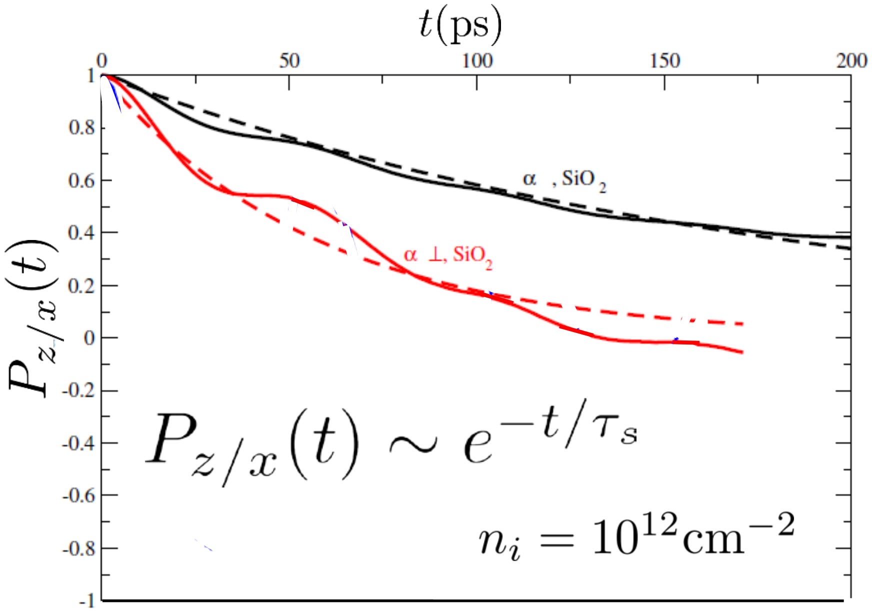
$$S_z(t) \sim \cos\left(\frac{2\pi t}{T_\Omega}\right) e^{-t/\tau_s}$$

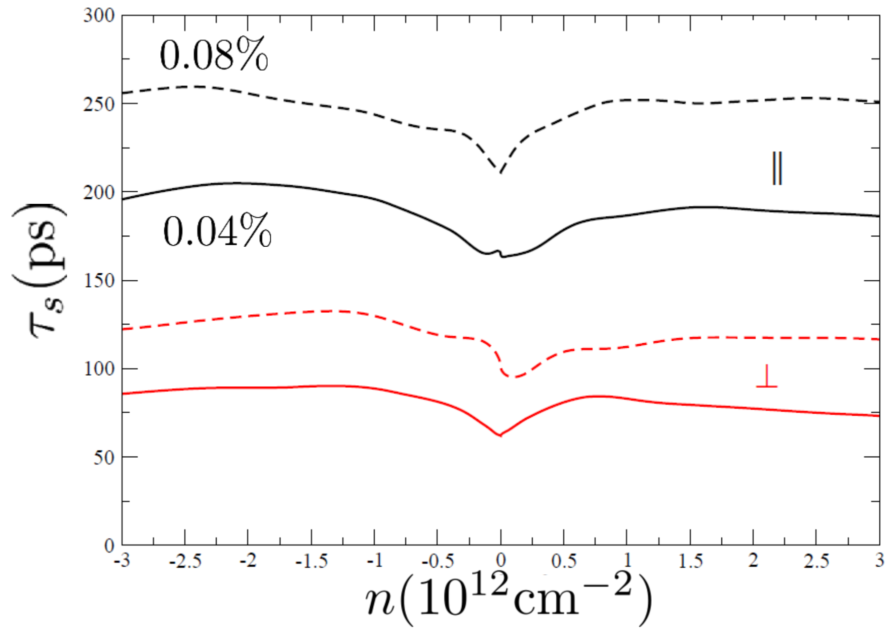


Graphene on SiO2

electron-hole puddles drive the relaxation

$$\tau_p^{\mathrm{SiO_2}}/T_\Omega \ll 1$$





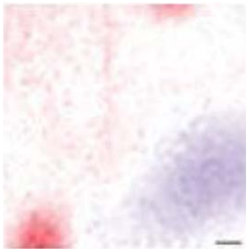
$$\tau_s \sim \frac{1}{n_i}$$

increases with defect density

$$\tau_s^{\perp}/\tau_s^{\parallel} \rightarrow 0.5$$

Dyakonov-Perel

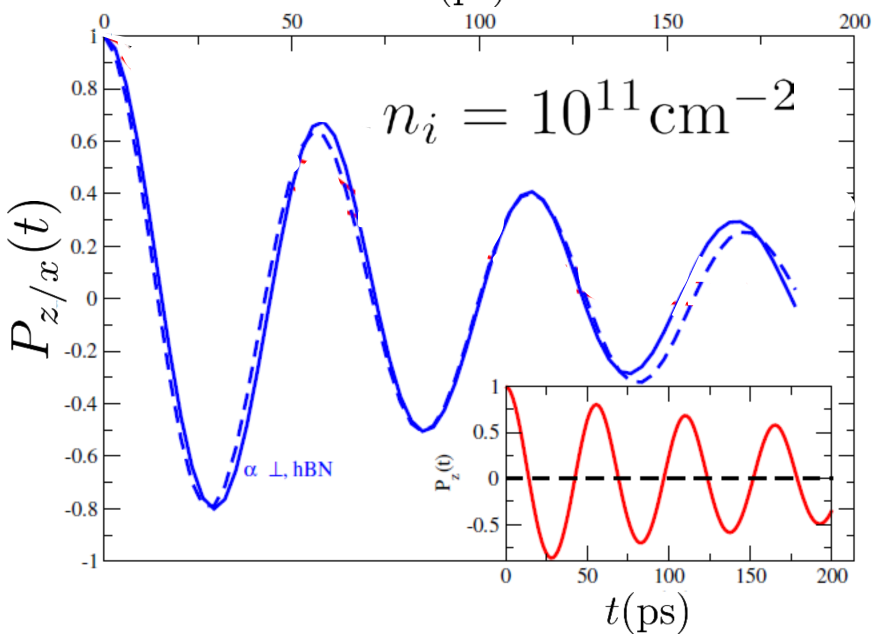
relaxation mechanism



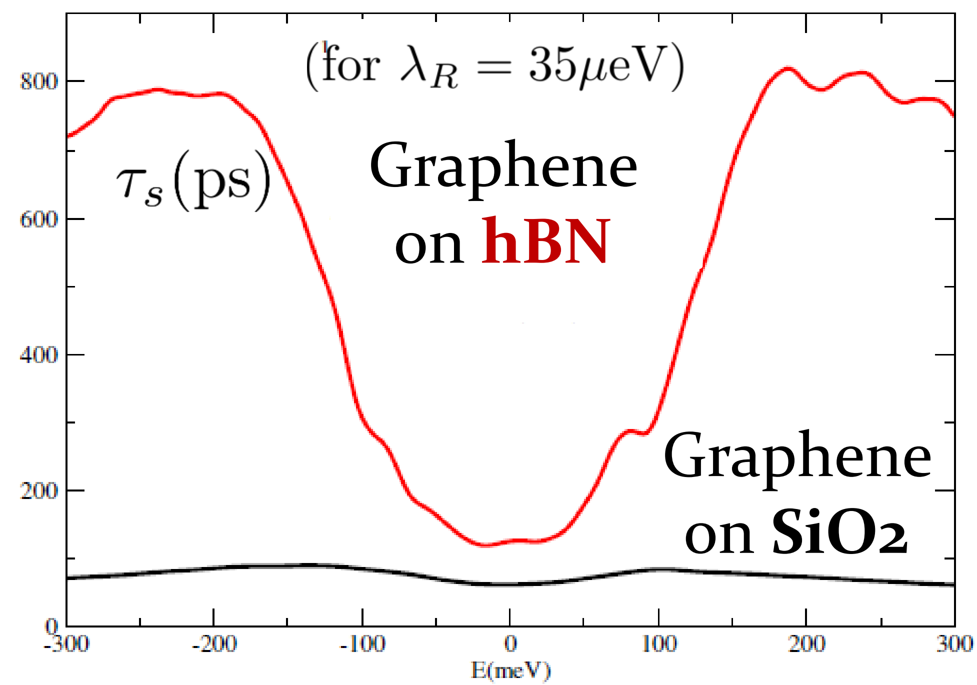
Graphene on hBN

electron-hole puddles drive the relaxation

$$\tau_p^{\mathrm{hBN}}/T_\Omega \geq 1$$



$$P_{z/x}(t) \sim \cos\left(\frac{2\pi t}{T_\Omega}\right) e^{-t/\tau_s}$$



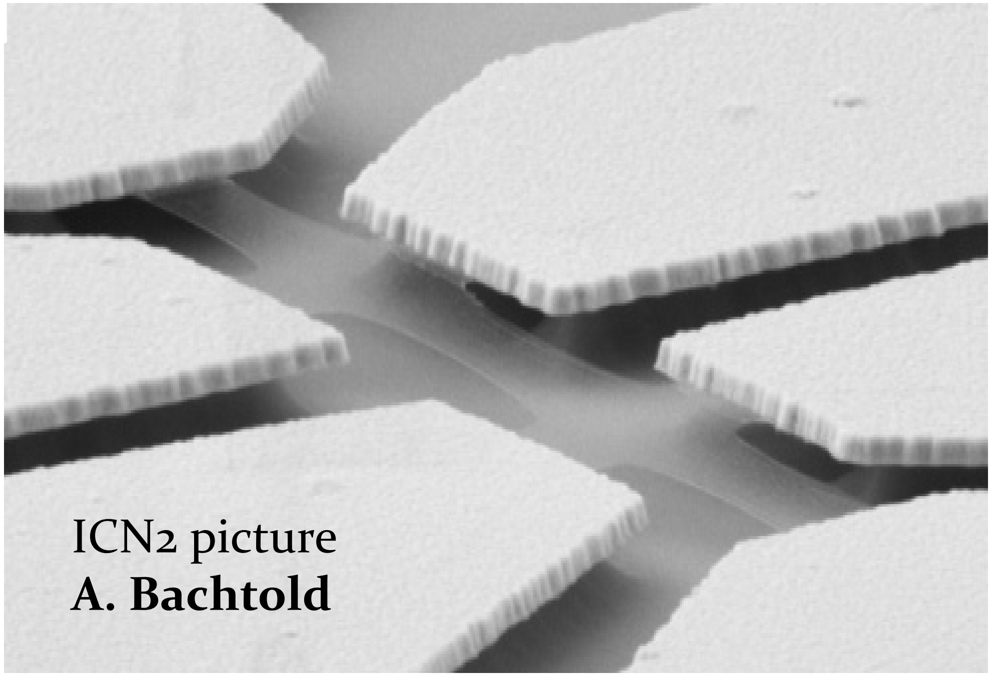
$$\tau_s(E) \approx 4T_\Omega \approx 4\frac{\pi\hbar}{\lambda_R}$$

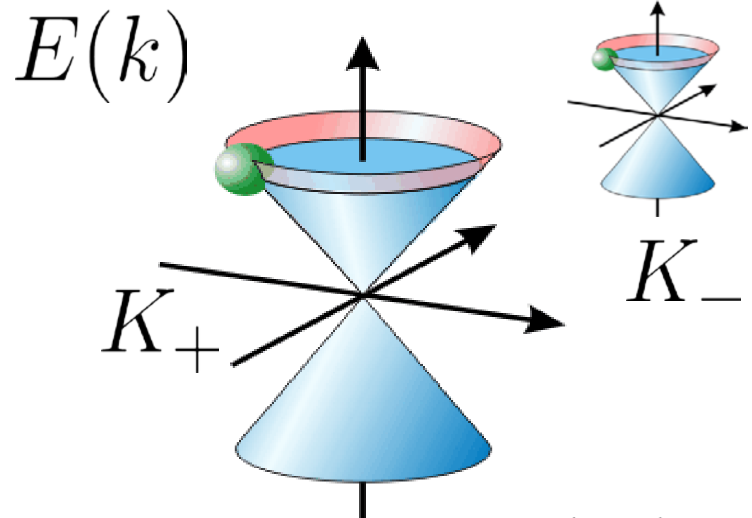
$$\tau_s \simeq 1 - 10 \text{ ns}$$

(for $\lambda_R \to 5\mu\mathrm{eV}$)

What is the origin of dephasing/relaxation mechanism?

"Unique properties of Clean graphene"

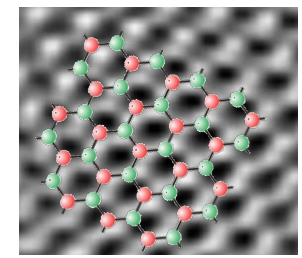




$$\mathcal{H}_{K_+} = v_F \vec{\sigma}.\vec{p}$$

pseudospin

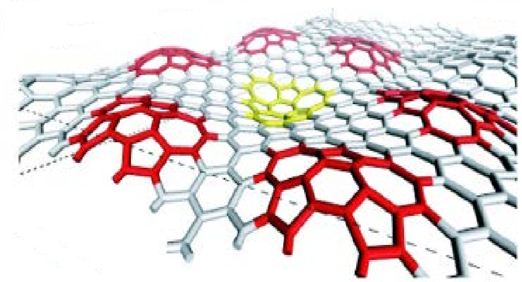
$$|\Downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$



Long range potential

Intravalley scattering

(short momentum transfer)



Anomalous quantum transport

- Ballistic conductivity $\sigma \sim 4e^2/\pi h$
- Klein tunneling
- Diverging zero-energy Mean free path/mobility
- Weak antilocalization (quantum interferences)
- Anomalous vs conventional QHE
- **Spin transport ?**

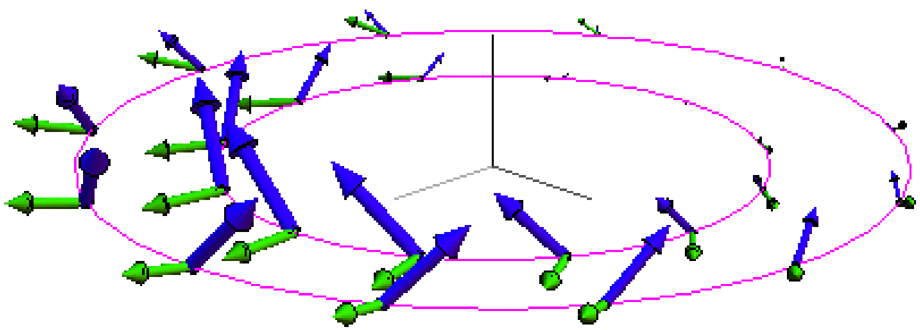
nature physics

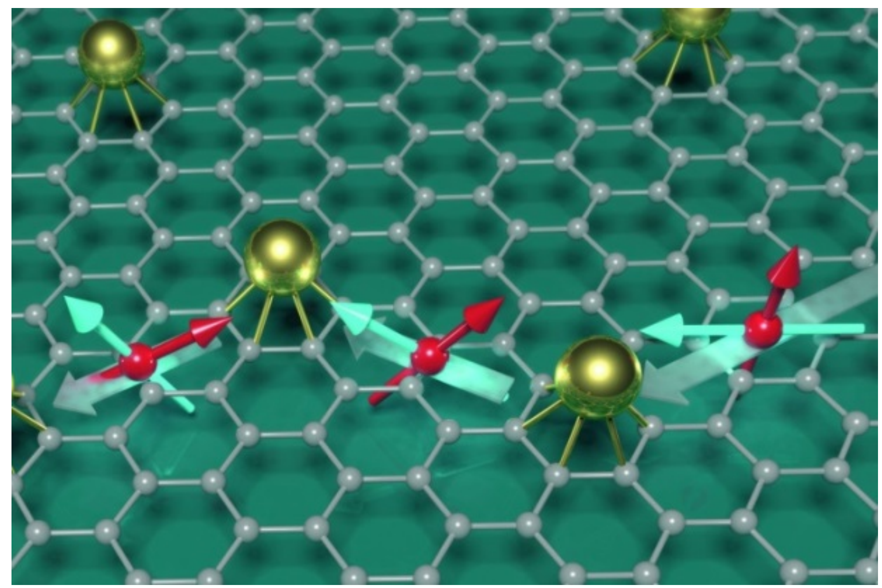
ARTICLES

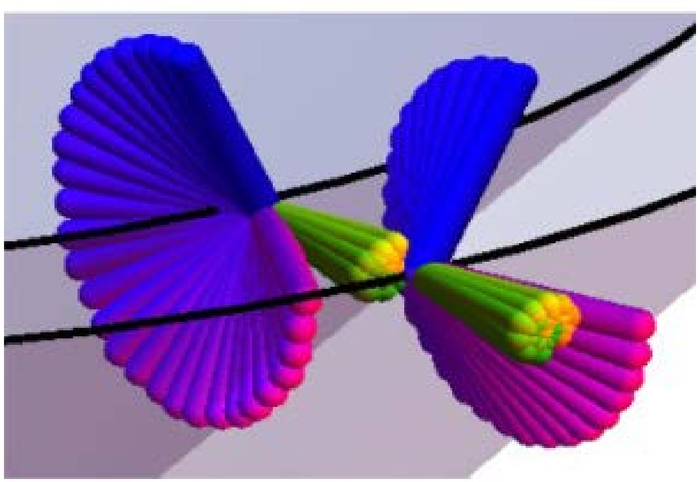
PUBLISHED ONLINE: 14 SEPTEMBER 2014 | DOI: 10.1038/NPHYS3083

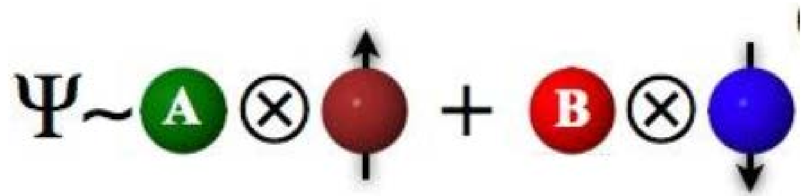
Pseudospin-driven spin relaxation mechanism in graphene

Dinh Van Tuan[1,2], Frank Ortmann[1,3,4], David Soriano[1], Sergio O. Valenzuela[1,5] and Stephan Roche[1,5]*





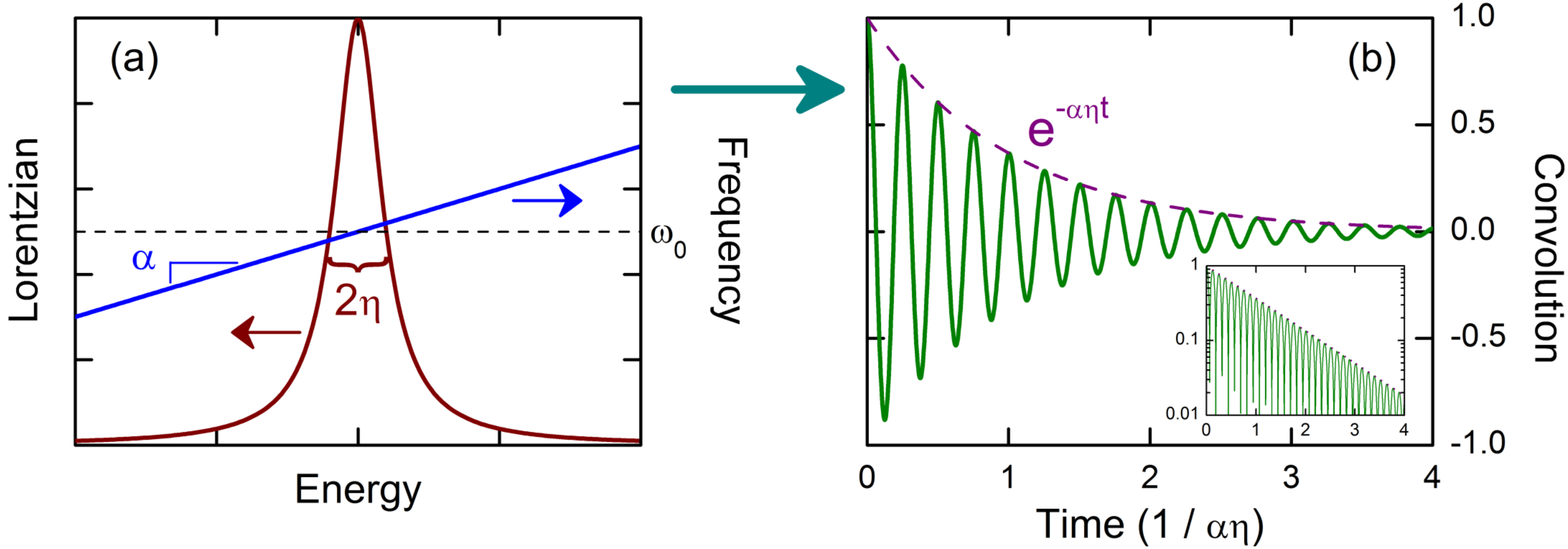




Relaxation in the ultraclean limit....

spin precession frequency varies linearly with energy $\omega(E) = \omega_0 + \alpha E$

charge carriers occupy a Lorentzian distribution in energy $\mathcal{L}(E) = \eta/[\pi \cdot (E^2 + \eta^2)]$

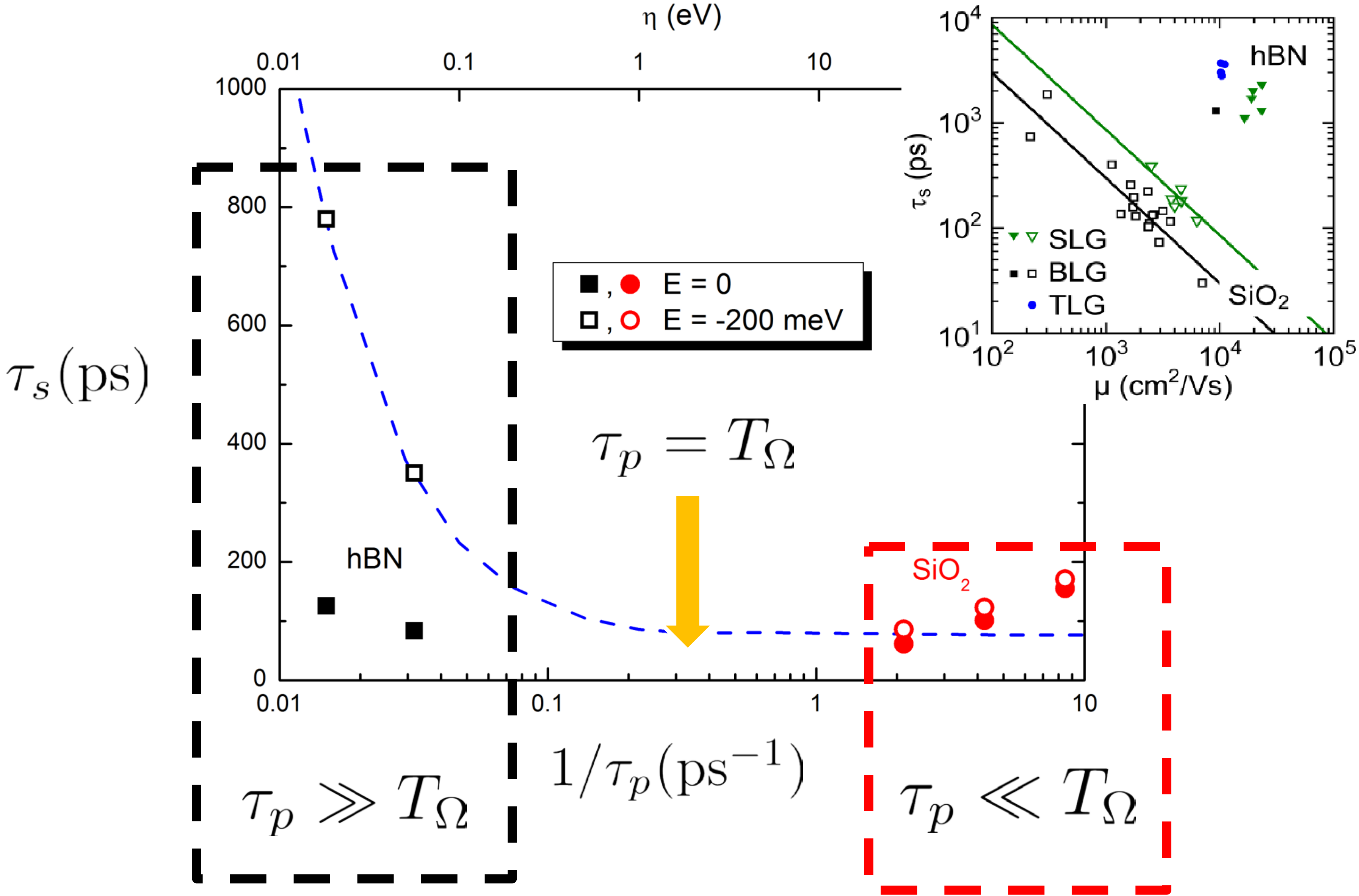


Exponentially-decaying cosine, with frequency ω_0 and decay time $1/\alpha\eta$

$$s(t) = \mathcal{L}(E) \circ \cos(\omega(E)t) = e^{-\alpha\eta t} \cdot \cos(\omega_0 t)$$

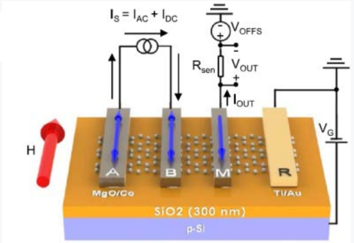
A.W. Cummings and S. Roche , **Phys. Rev. Lett. 116, 086602 (2016)**

Crossover between "pure dephasing" and scattering-induced Dyakonov-Perel

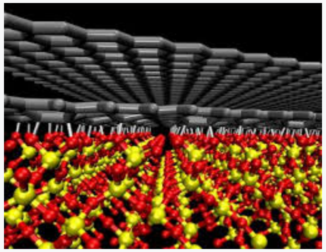


OUTLINE

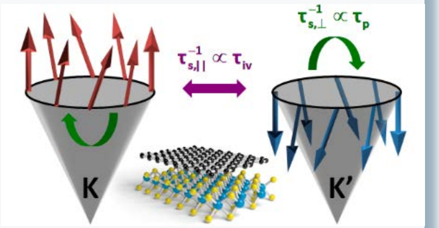
Why Spintronics using 2D Materials ?



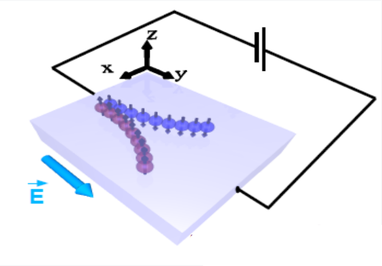
How the substrate controls spin dynamics?



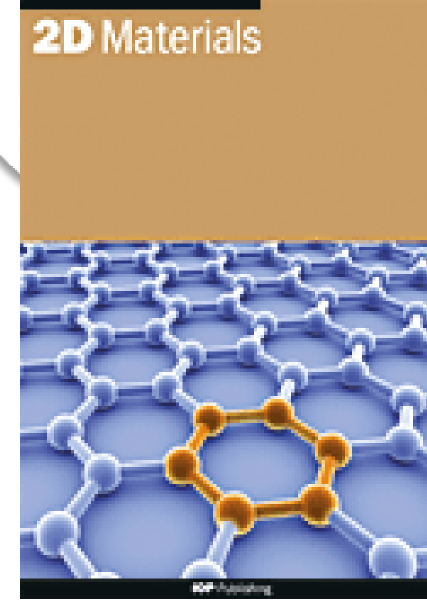
Giant spin transport anisotropy
in graphene induced by strong SOC
Proximity effect

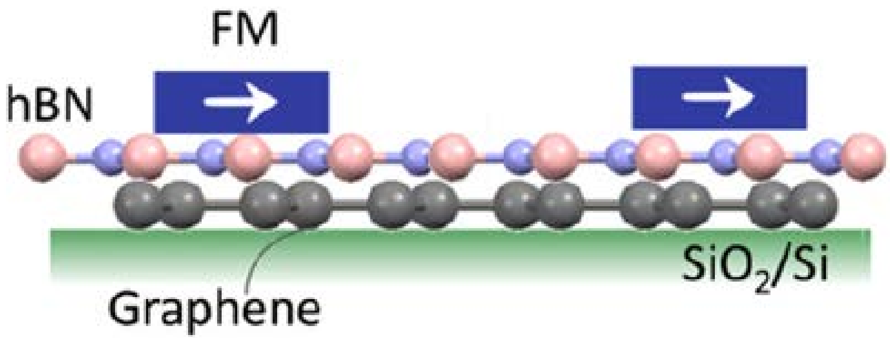


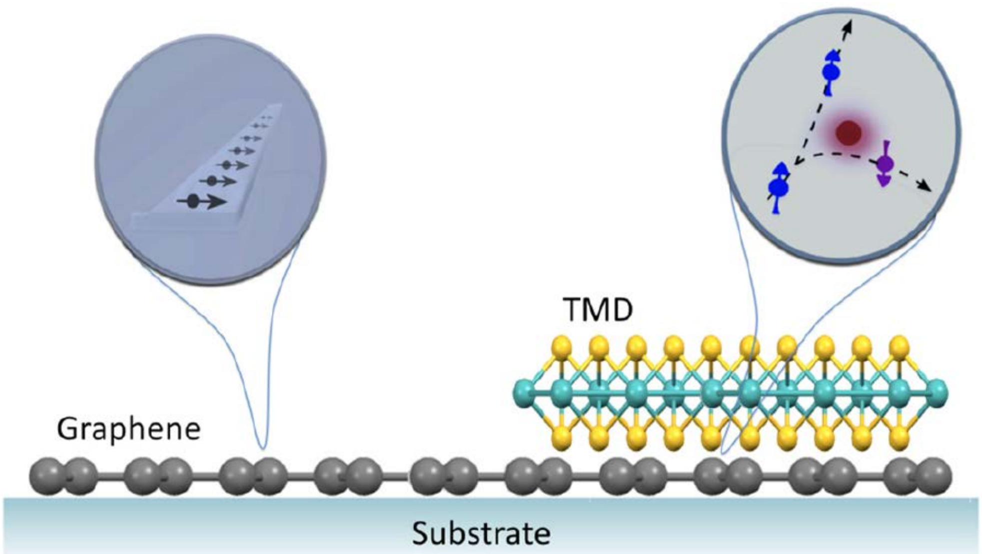
Weak antilocalization & Spin Hall Effect
in Graphene/TMDC



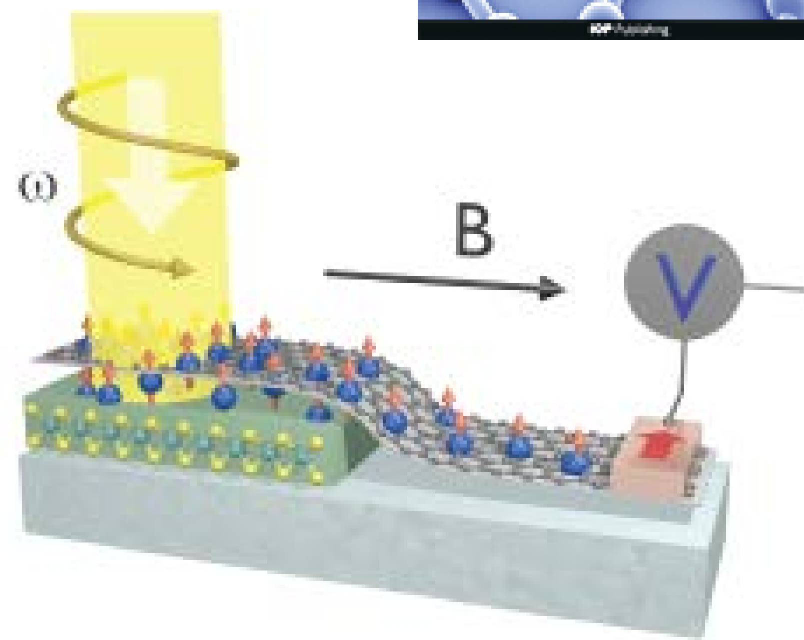
Hybrid devices of graphene and other 2D materials





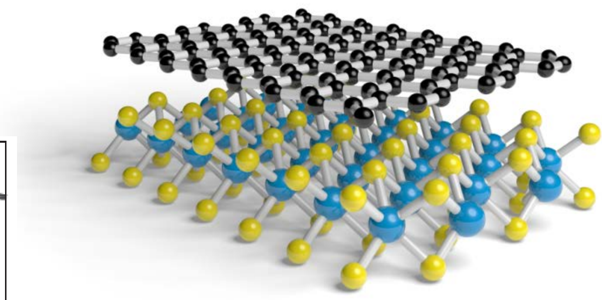


2D Mater. 2 (2015) 030202

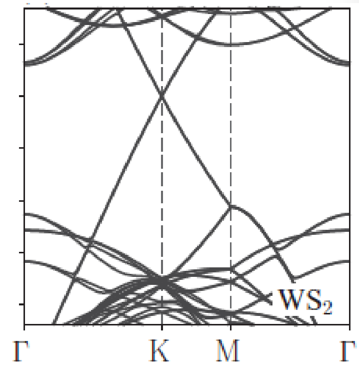


Martin Gmitra and Jaroslav Fabian
Phys. Rev. B **92**, 155403 (2015)

Realistic Model of Graphene/TMDC
with interface disorder



DFT-TB model from
M. Gmitra , D. Kochan, P. Högl, & J.Fabian
PRB **93**, 155104 (2016)

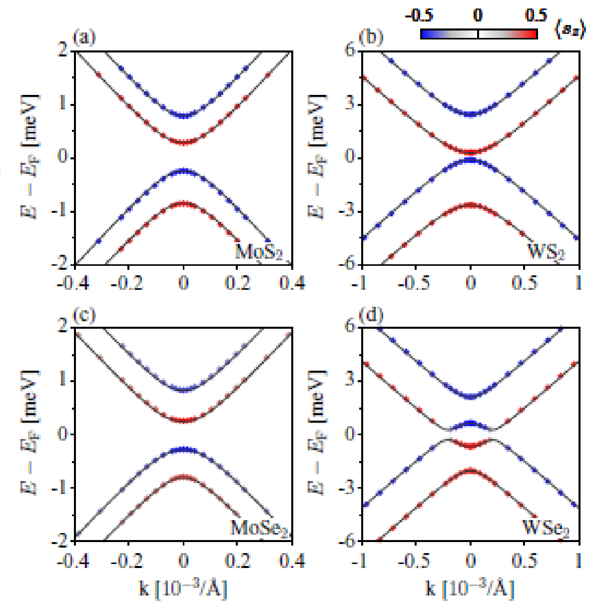


$$H_0 = -t \sum_{\langle i,j \rangle} \left(a_i^\dagger b_j + b_i^\dagger a_i \right) + \frac{\Delta}{2} \sum_i (a_i^\dagger a_i - b_i^\dagger b_i)$$

$$H_{\mathrm{so}} = \frac{2i}{3} \sum_{\langle i,j \rangle, \sigma} (\hat{\boldsymbol{s}} \times \boldsymbol{d}_{i,j})_{z,\sigma,\bar{\sigma}} \; \lambda_{\mathrm{R}} \, a_{i,\sigma}^\dagger \, b_{j,\bar{\sigma}} + h.c$$

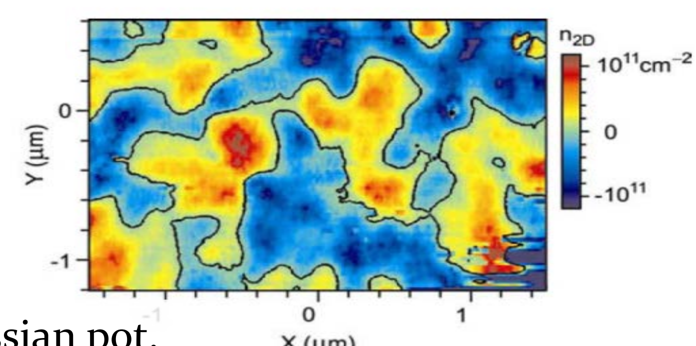
$$+ \frac{2i}{3} \sum_{\langle\langle i,j \rangle\rangle, \sigma} (\hat{\boldsymbol{s}} \times \boldsymbol{D}_{i,j})_{z,\sigma,\bar{\sigma}} \left(\lambda_{\mathrm{PIA}}^{(A)} \, a_{i,\sigma}^\dagger a_{j,\bar{\sigma}} + \lambda_{\mathrm{PIA}}^{(} \, b_{i,\sigma}^\dagger b_{j,\bar{\sigma}} \right)$$

$$+ \frac{i}{3\sqrt{3}} \sum_{\langle\langle i,j \rangle\rangle, \sigma} \nu_{i,j} (\hat{s}_z)_{\sigma,\sigma} \, (\lambda_I^{(A)} a_{i,\sigma}^\dagger a_{j,\sigma} - \lambda_I^{(B)} b_{i,\sigma}^\dagger b_{j,\sigma}),$$



Random distribution of n_p electron-hole puddles

S. Adam et al. PRB 84, 235421 (2011)



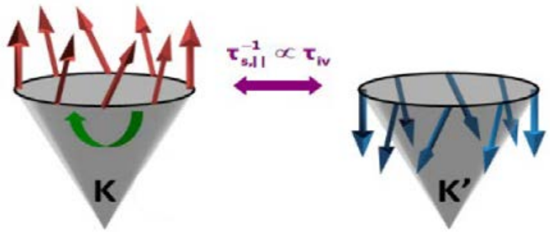
$$U_n(\boldsymbol{r}) = u_n \exp\left(-\frac{(\boldsymbol{r} - \boldsymbol{R}_n)^2}{2\xi_{\mathrm{p}}^2} \right)$$

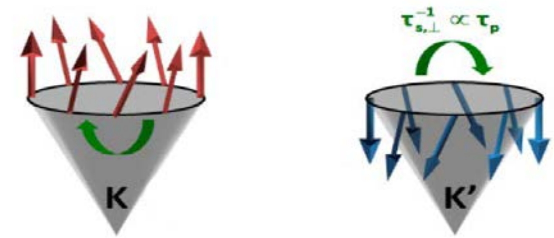
$\xi_{\mathrm{p}} = \sqrt{3}a$ Puddle range

$u_n \in [-U_{\mathrm{p}}, U_{\mathrm{p}}]$ $\boldsymbol{R}_n$ is the position of the center of the Gaussian pot.

Spin dynamics for graphene/TMDC+ el-h puddles

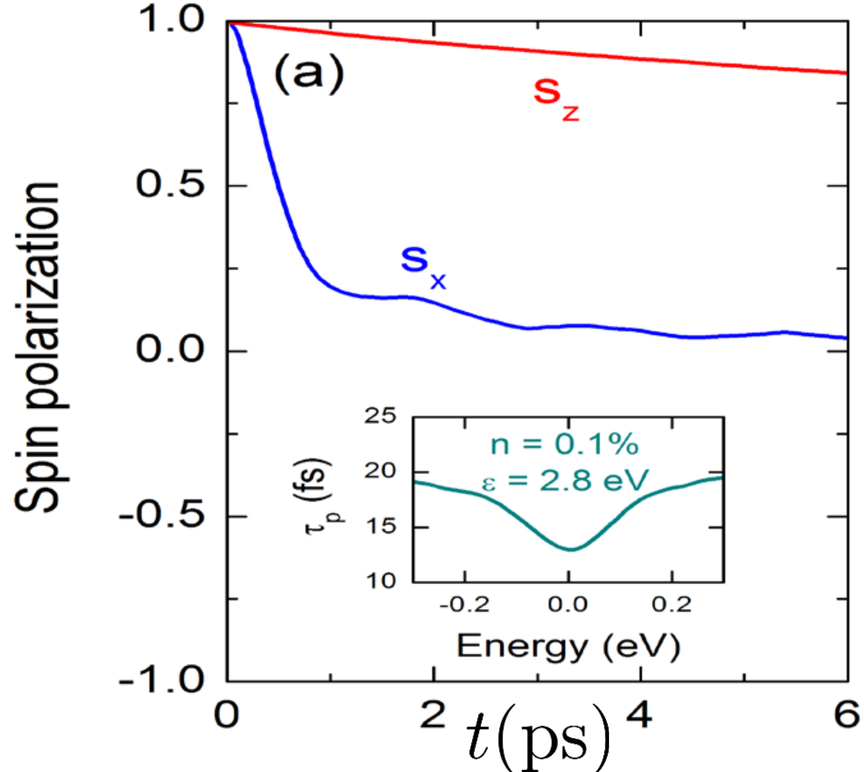
A. W. Cummings, J.H. García, J. Fabian, S. Roche, arXiv:1705.10972

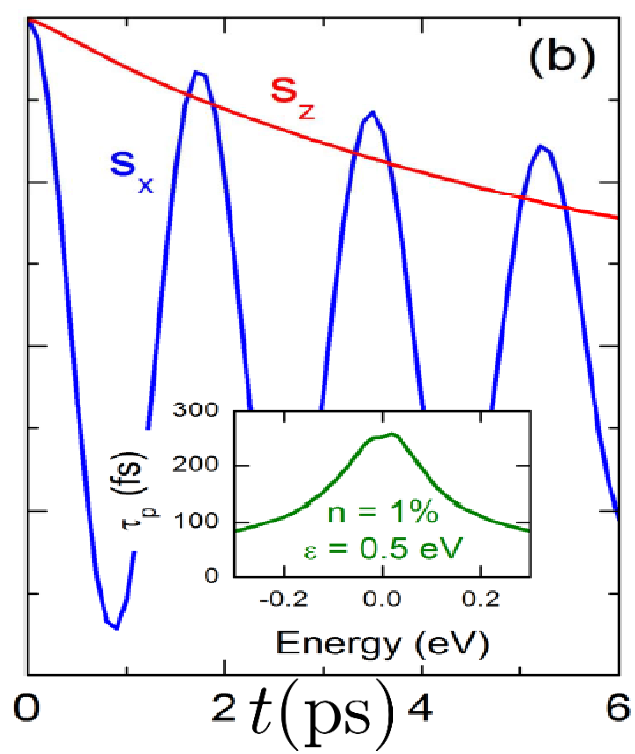




Strong valley mixing

Intravalley scattering

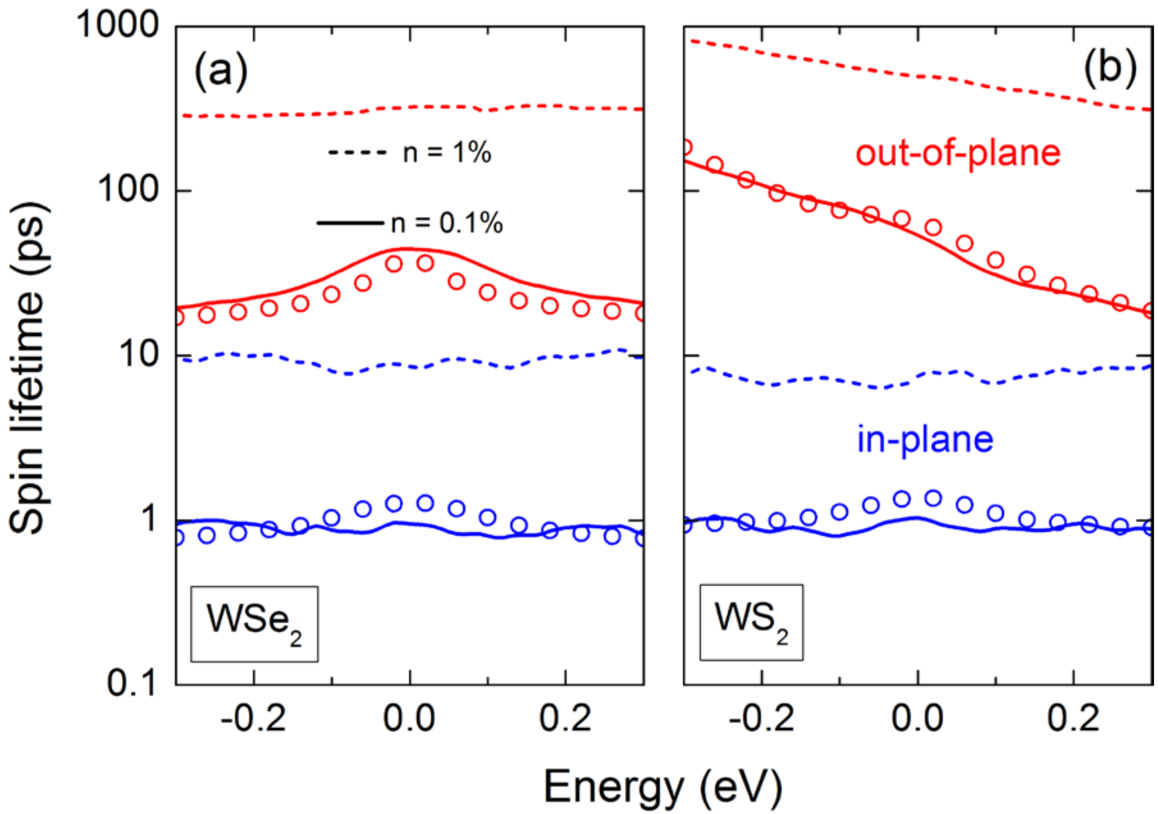




$$S_\alpha \simeq \exp(-t/\tau_{s,\alpha})\cos(\omega_z t)$$

Spin lifetimes in Graphene/TMDC

(strong valley mixing)



Lifetime values

$$\tau_{s,\perp} \in [10, 1000]\text{ps}$$

$$\tau_{s,\parallel} \in [1, 10]\text{ps}$$

Dyakonov-Perel mechanism

$$\tau_{s,\perp} \,\&\, \tau_{s,\parallel} \sim 1/n_p$$

Giant anisotropy

$$\frac{\tau_{s,\perp}}{\tau_{s,\parallel}} = 10 - 100$$

Symbols: Effective spin-orbit fields arising from the SOC terms + equation of motion of density matrix

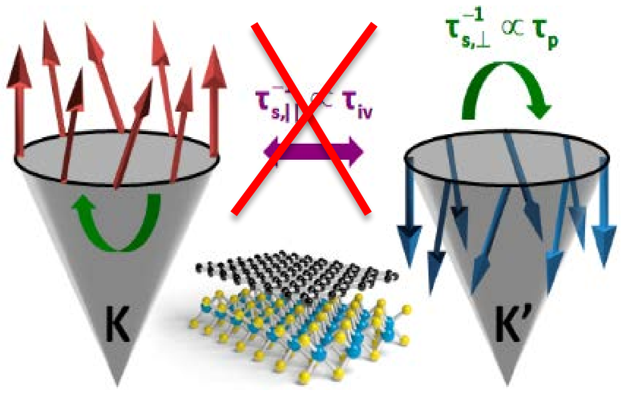
$$H = H_0 + \tfrac{1}{2}\hbar\vec{\omega}(t)\cdot\vec{s} \qquad \overline{\omega_\alpha(t)\omega_\beta(t')} = \delta_{\alpha\beta}\overline{\omega_\alpha^2}\mathrm{e}^{-|t-t'|/\tau_{c,\alpha}},$$

$$\frac{\mathrm{d}\overline{\rho_I(t)}}{\mathrm{d}t} = \left(\frac{1}{i\hbar}\right)^2 \int_0^{t\gg\tau_c} \overline{[V_I(t),[V_I(t'),\overline{\rho_I(t)}]]}\,\mathrm{d}t',$$

$$V_I(t) = \tfrac{1}{2}\hbar\vec{\omega}(t)\cdot\vec{s}_I(t) \text{ and } \vec{s}_I(t) = \mathrm{e}^{iH_0t/\hbar}\vec{s}\mathrm{e}^{-iH_0t/\hbar}$$

Spin transport anisotropy in Graphene/TMDC

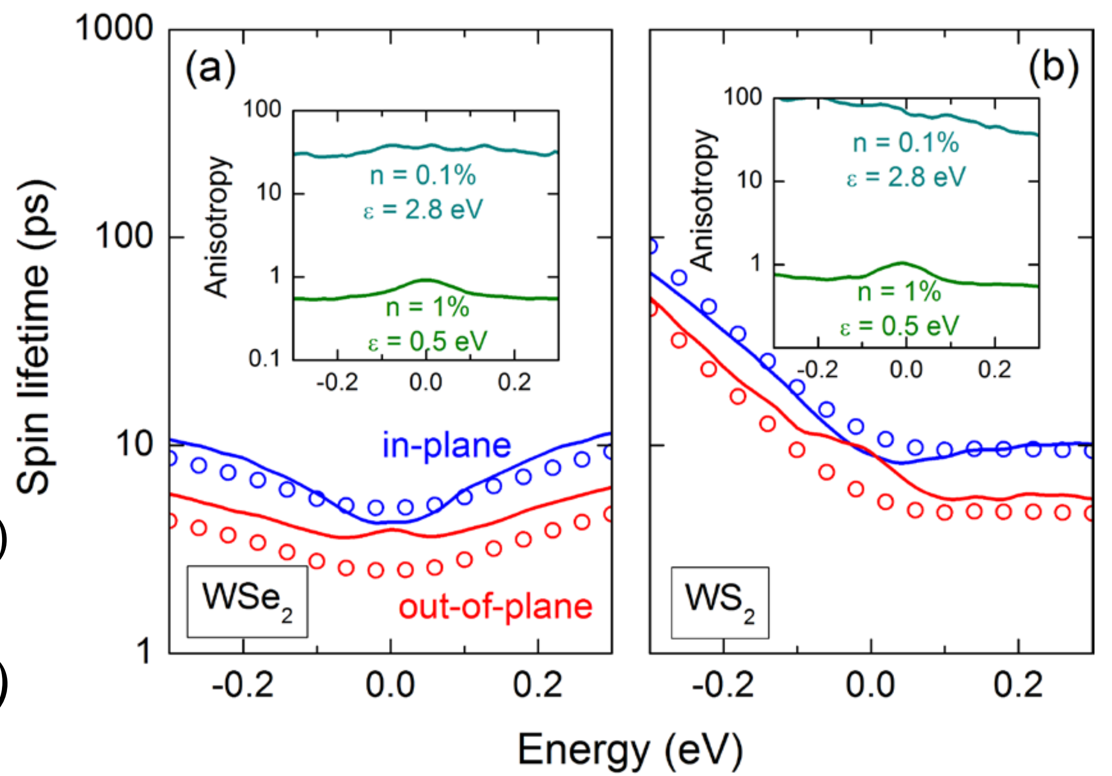
(intravalley scattering only)



higher quality interfaces

Spin lifetimes (**out-of-plane**) **much smaller**

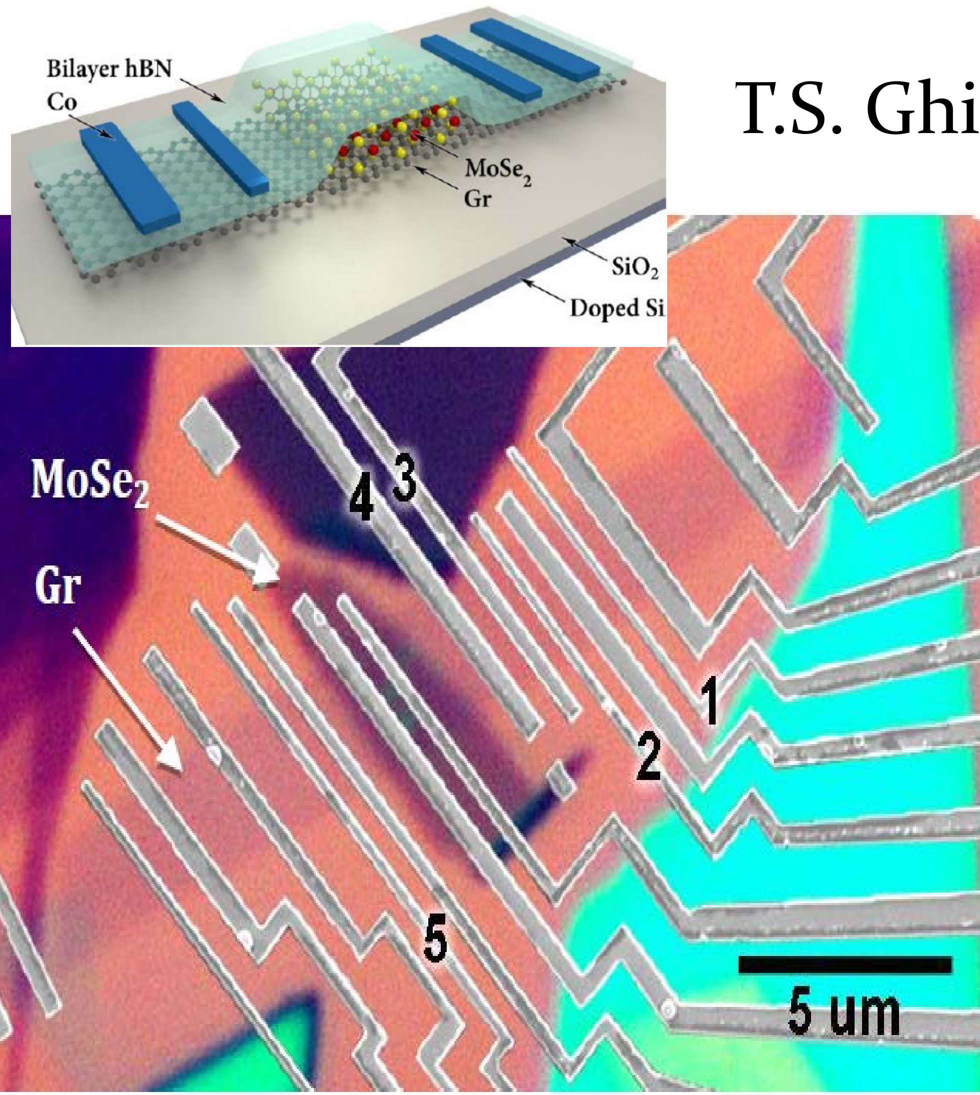
(even smaller than in-plane)



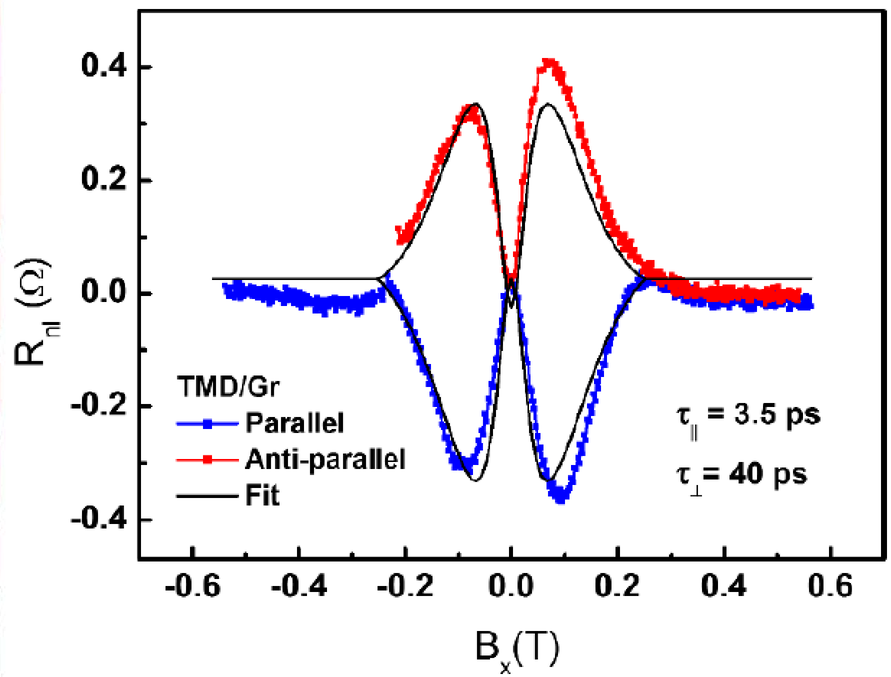
Anisotropy around ½

(as in conventional Rashba disordered systems)

Experimental confirmation
Group of Bart van Wees



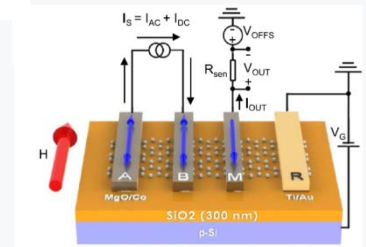
T.S. Ghiasi et al, arXiv:1708.04067



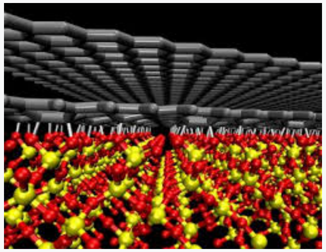
$$\tau_\perp / \tau_{||} \simeq 10\text{–}40$$

OUTLINE

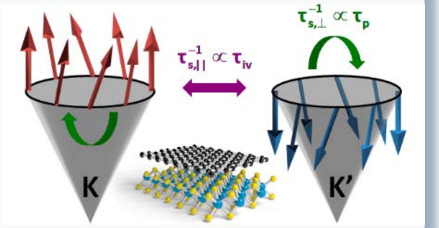
Why Spintronics using 2D Materials ?



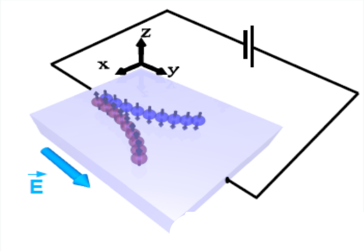
How the substrate controls spin dynamics?



Giant spin transport anisotropy in graphene induced by strong SOC Proximity effect



Spin Hall Effect & Weak antilocalization in Graphene/TMDC

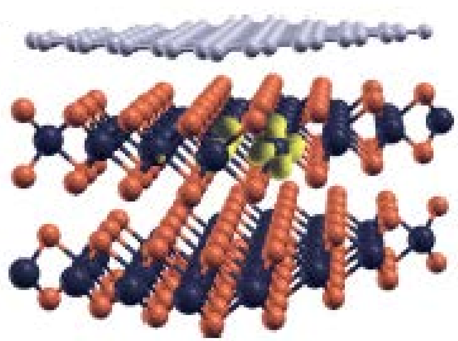


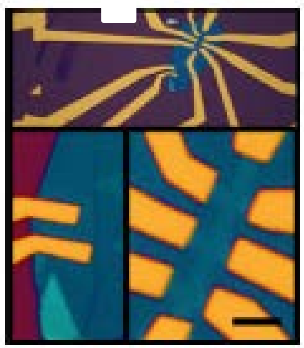
nature COMMUNICATIONS

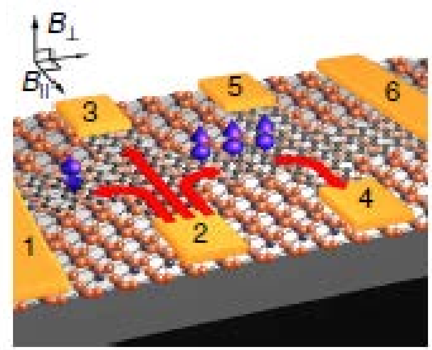
NUS National University of Singapore
Centre for Advanced 2D Materials

Spin-orbit proximity effect in graphene

A. Avsar[1,2], J.Y. Tan[1,2], T. Taychatanapat[1,2], J. Balakrishnan[1,2], G.K.W. Koon[1,2,3], Y. Yeo[1,2], J. Lahiri[1,2], A. Carvalho
A.S. Rodin[4], E.C.T. O'Farrell[1,2], G. Eda[1,2], A.H. Castro Neto[1,2] & B. Özyilmaz[1,2,3]



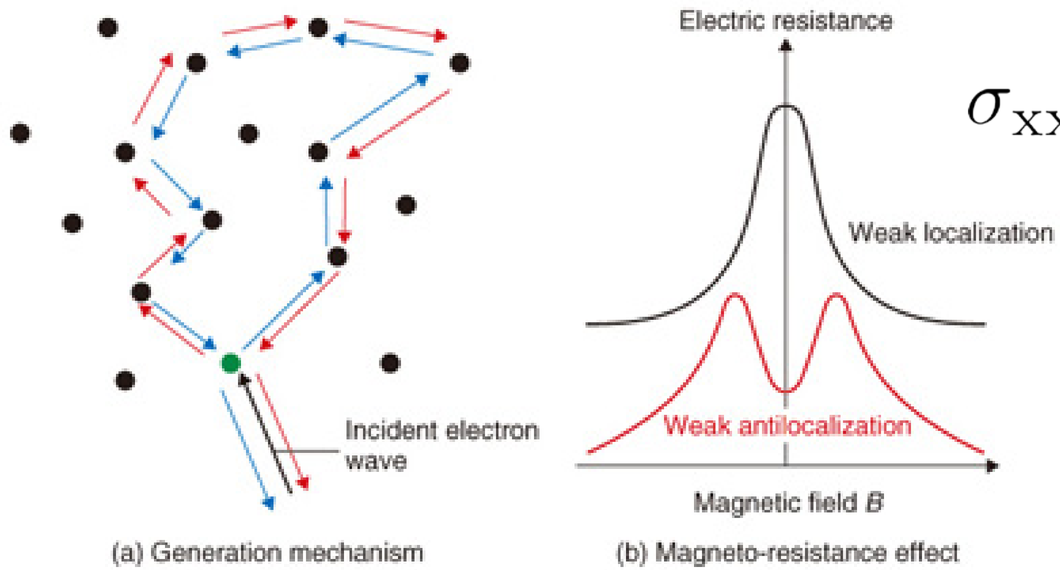




$$\tau_s \simeq 5 - 10\text{ps}$$

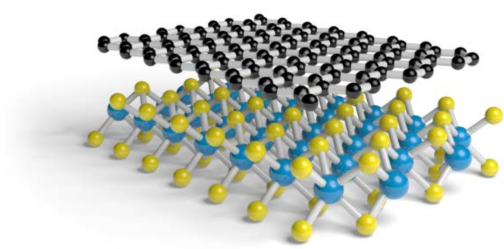
*"Graphene acquires spin–orbit coupling up to **17 meV,** three orders of magnitude higher than its intrinsic value, without modifying the structure of the graphene.*
The proximity SOC leads to the spin Hall effect even at room temperature,
and opens the door to spin field effect transistors"

Weak (anti)-localization by proximity effect

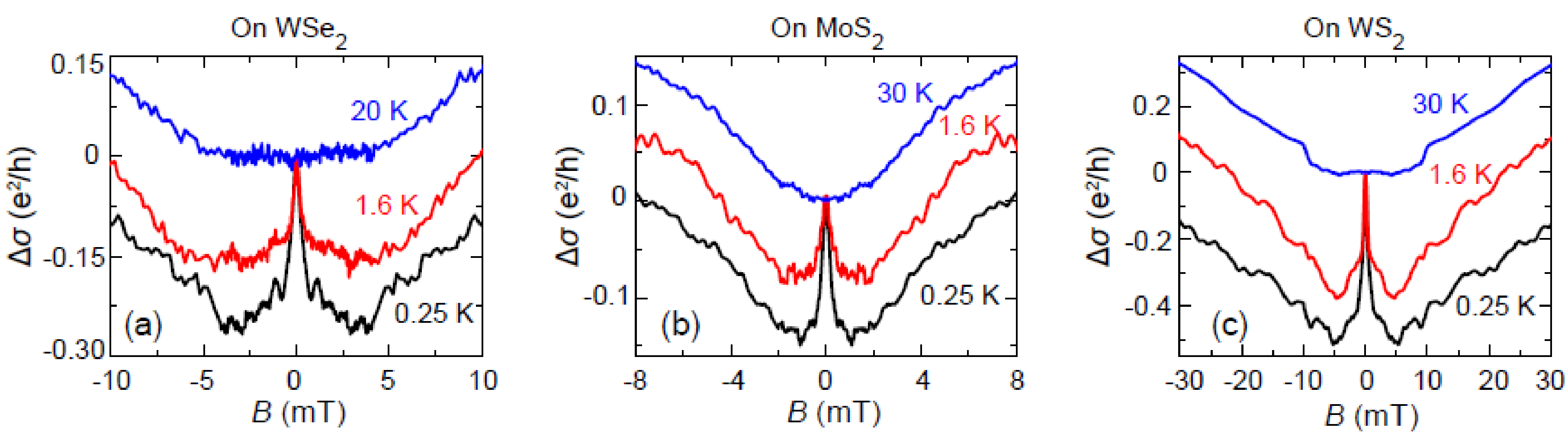


$$\sigma_{\mathrm{xx}}(\varepsilon_F) = \sigma_{\mathrm{sc}}(\varepsilon_F) + \delta\sigma(\varepsilon_F)$$

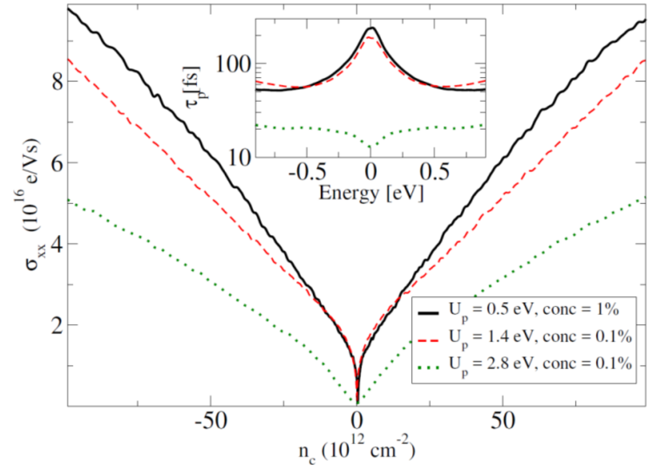
Sign of the **quantum correction** Changes in presence of spin-orbit coupling



Wang et al, PHYSICAL REVIEW X 6, 041020 (2016)

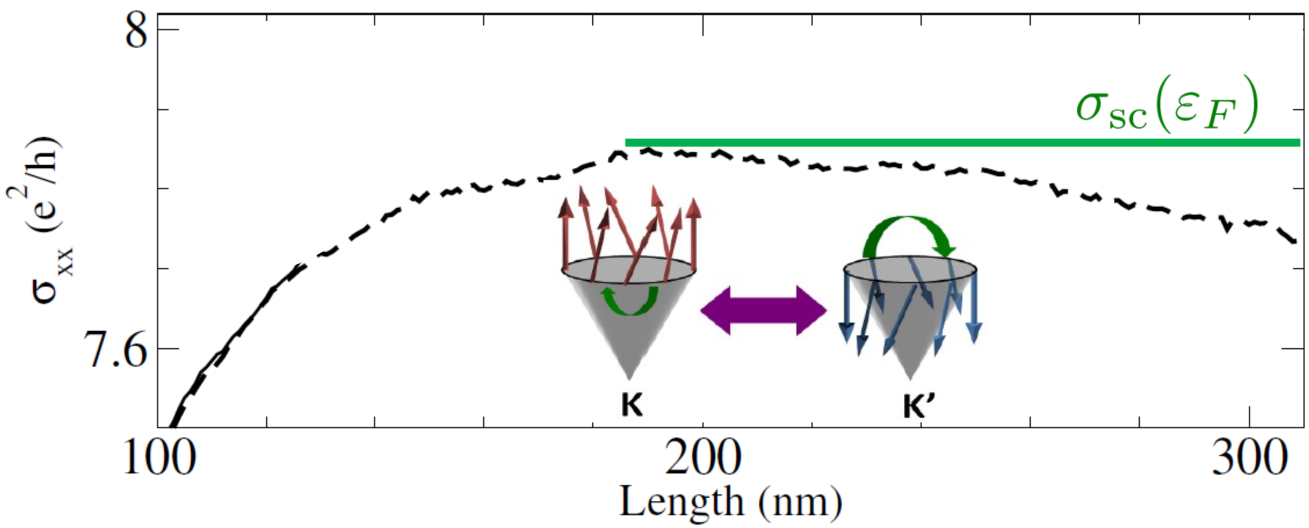


Localization effects for *graphene/WS2 + el-h puddles*



Scaling theory of localization

$$\sigma_{xx}(\varepsilon_F) = \sigma_{sc}(\varepsilon_F) + \delta\sigma(\varepsilon_F)$$



$$\tau_p = \frac{\sigma_{sc}(\varepsilon_F)}{v_F^2 \rho(\varepsilon_F)}$$

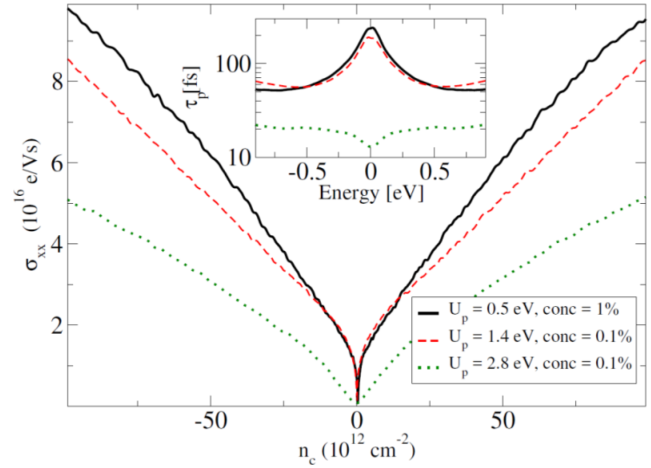
Case of strong scatterers (puddles) and large **intervalley scattering**

SOC switch OFF

$$\delta\sigma = -\frac{2e^2}{\pi h}\log(L/\ell_e)$$

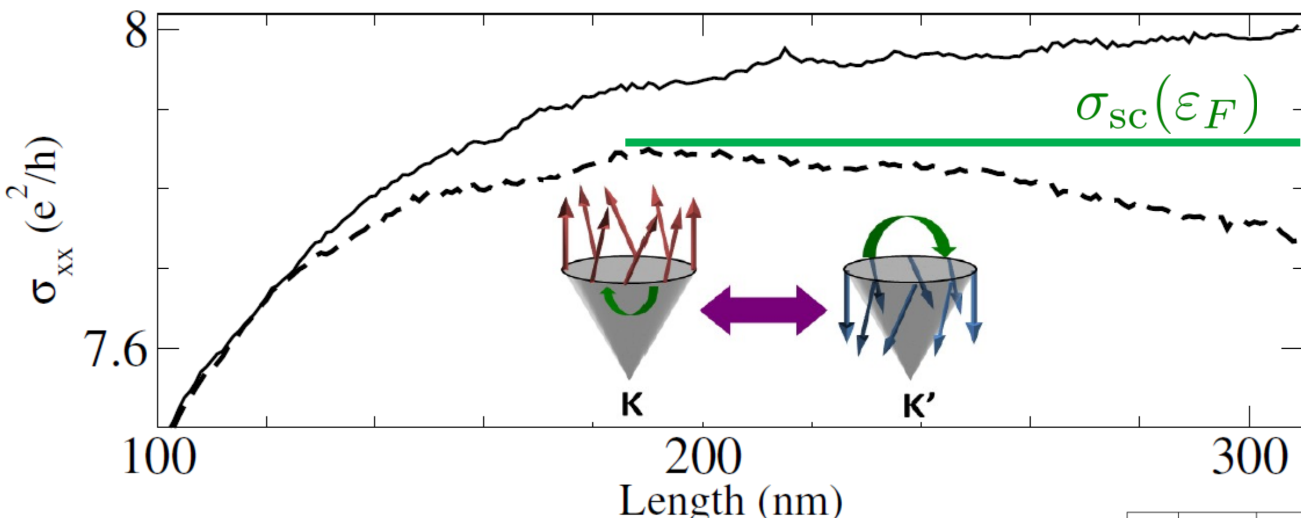
Weak localization

Localization effects for *graphene/WS2 + el-h puddles*



Scaling theory of localization

$$\sigma_{xx}(\varepsilon_F) = \sigma_{sc}(\varepsilon_F) + \delta\sigma(\varepsilon_F)$$

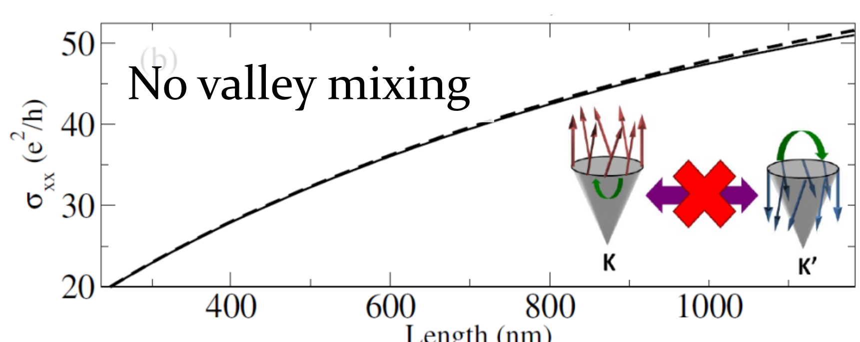


Case of strong scatterers (puddles) and large **intervalley scattering**

SOC switch ON

$$\delta\sigma = +\frac{2e^2}{\pi h}\log(L/\ell_e)$$

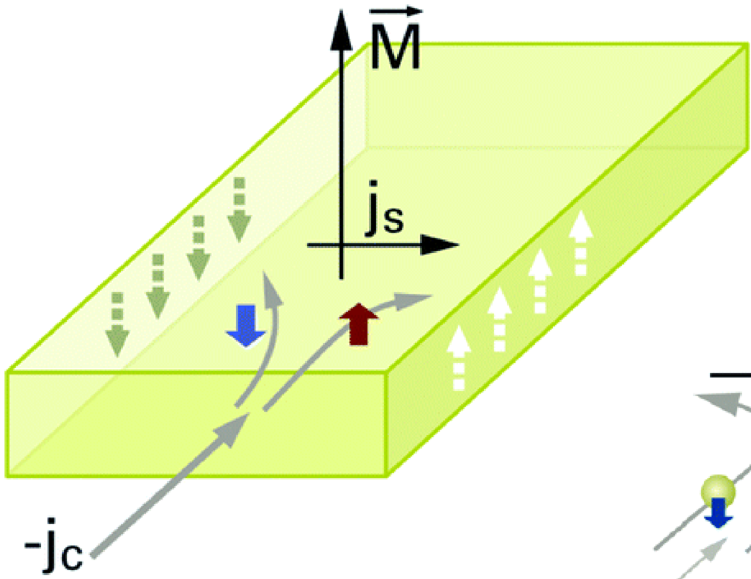
Weak Antilocalization

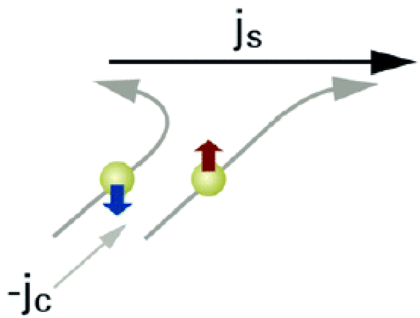


J. García, A. Cummings, S. Roche **Nano Lett. 17, 5078 (2017)**

Spin Hall Effect

Manipulation of spin by electrical means without the use of ferromagnetic materials or magnetic fields

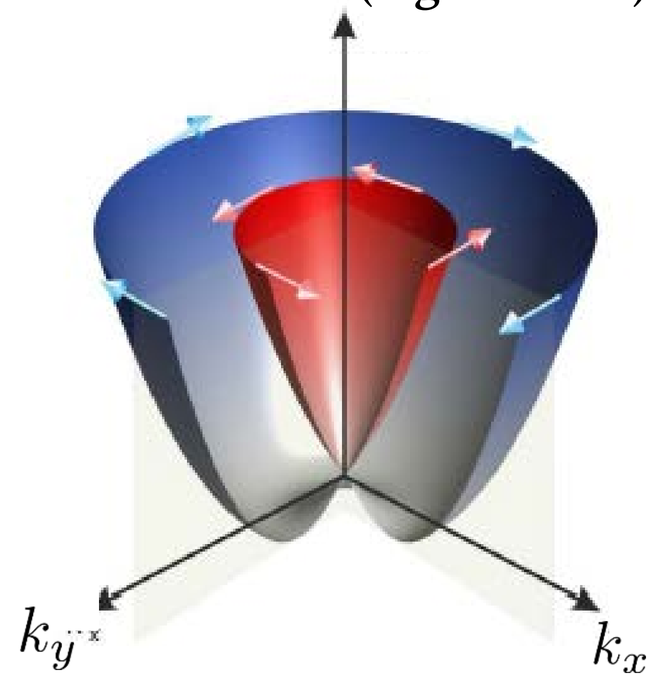




Intrinsic mechanism

Sinova (2005),...

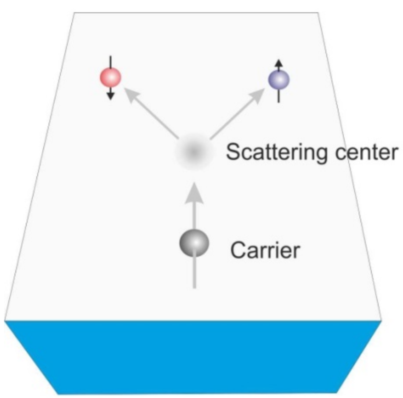
Band Structure (e.g. Rashba)



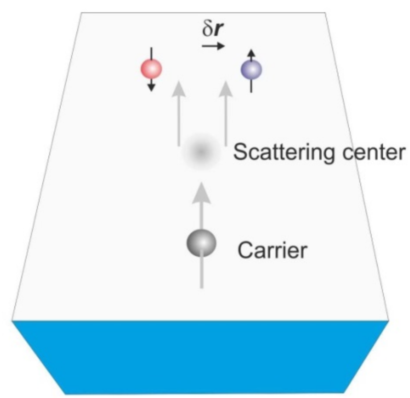
Extrinsic mechanisms

Dyakonov-Perel (1971); Hirsh (1999)

Skew Scattering

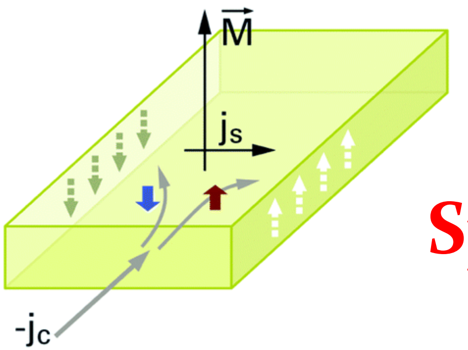


Side-Jump Scattering



Computing SHE figure of merit

in clean/disordered graphene/TMDC interfaces

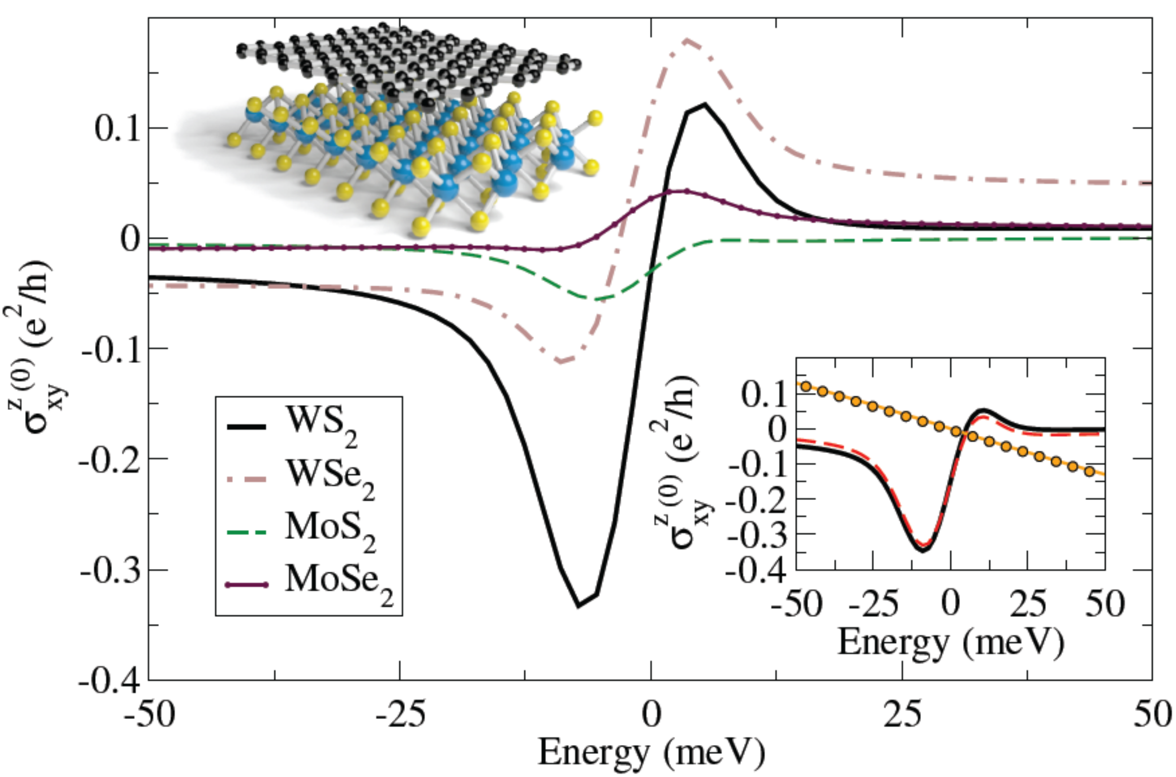


θ_{sH}

Spin Hall angle

measures the efficiency of ***converting charge current to spin current***

$$\theta_{sH} = \frac{|J_s^z|}{|J_c|}$$



Dissipative SHE

$$\theta_{sH} = \frac{\sigma_{xy}^{z}}{\sigma_{xx}}$$

"Clean case" :

"intrinsic SHE"

WS_2 leads to larger Spin Hall conductivity (larger SHA)

Spin Hall Kubo conductivity

in large scale disordered graphene models

$$\sigma_{\mathrm{sH}} = \frac{e\hbar}{\Omega} \sum_{m,n} \frac{f(E_m) - f(E_n)}{E_m - E_n} \frac{\mathcal{I}m[\langle m | J_x^z | n \rangle \langle n | v_y | m \rangle]}{E_m - E_n + i\eta},$$

$J_x^z = \frac{\hbar}{4}\{\sigma_z, v_x\}$ is the spin current operator

real-space formalism

$$\sigma_{\mathrm{sH}} = \frac{e\hbar}{\Omega} \int dudv \frac{f(u) - f(v)}{(u-v)^2 + \eta^2} j(u,v),$$

$$j(u,v) = \sum\nolimits_{m,n} \mathcal{I}m[\langle m | J_x^z | n \rangle \langle n | v_y | m \rangle] \delta(u - E_m) \delta(v - E_n)$$

$$= \sum\nolimits_{m,n}^{M} (4\mu_{mn} g_m g_n T_m(\hat{u}) T_n(\hat{v})) / ((1 + \delta_{m,0})(1 + \delta_{n,0})\pi^2 \sqrt{(1 - \hat{u}^2)(1 - \hat{v}^2)}),$$

$$\mu_{mn} = \frac{4}{\Delta E^2} \mathcal{I}m[Tr[J_x^z T_n(\hat{H}) v_y T_m(\hat{H})]]$$

The trace in μ_{mn} is computed by the average on a small number $R \ll N$ of random phase vectors $|\varphi\rangle$

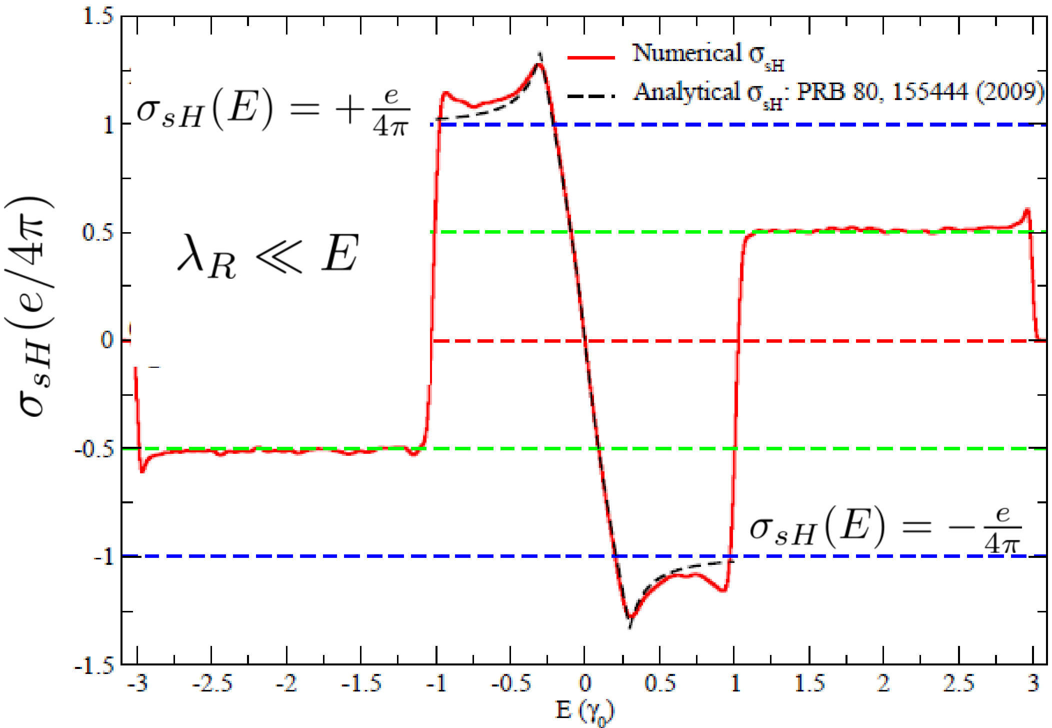
$$\sigma_{xx} = \frac{2\hbar e^2}{\pi\Omega} \sum_{m,n=0}^{M} \mathcal{I}m[g_m(\epsilon + i\eta)] \mathcal{I}m[g_n(\epsilon + i\eta)] \mu_{mn}$$

dc-Kubo conductivity

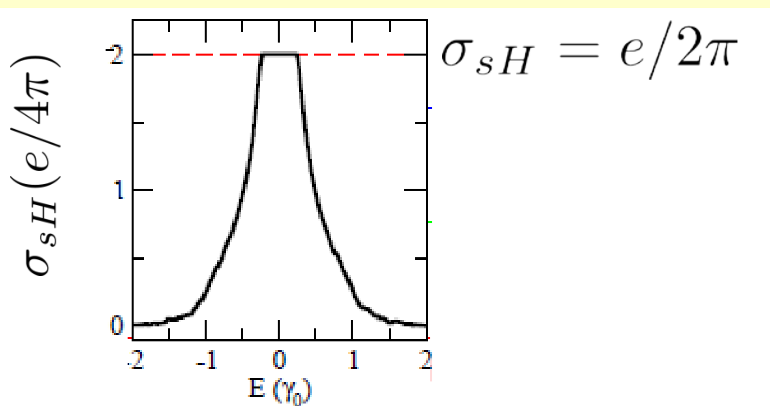
Validation: homogeneous SOCs

Homogeneous Rashba SOC λ_R (no intrinsic SOC)
Analytical result for the spin Hall conductivity
A. Dyrdal, V. K. Dugaev, and J. Barnas, **Phys. Rev. B. 80, 155444 (2009)**

$$\sigma_{sH}(E) = \begin{cases} -\frac{e}{4\pi}\frac{\mathrm{sign}(E)E^2}{(E^2-\lambda_R^2)} & \text{for } |E| \geq 2\lambda_R \\ -\frac{e}{4\pi}\frac{E(E+2\mathrm{sign}(E)\lambda_R)}{2\lambda_R(E+\mathrm{sign}(E)\lambda_R)} & \text{for } |E| < 2\lambda_R \end{cases}$$

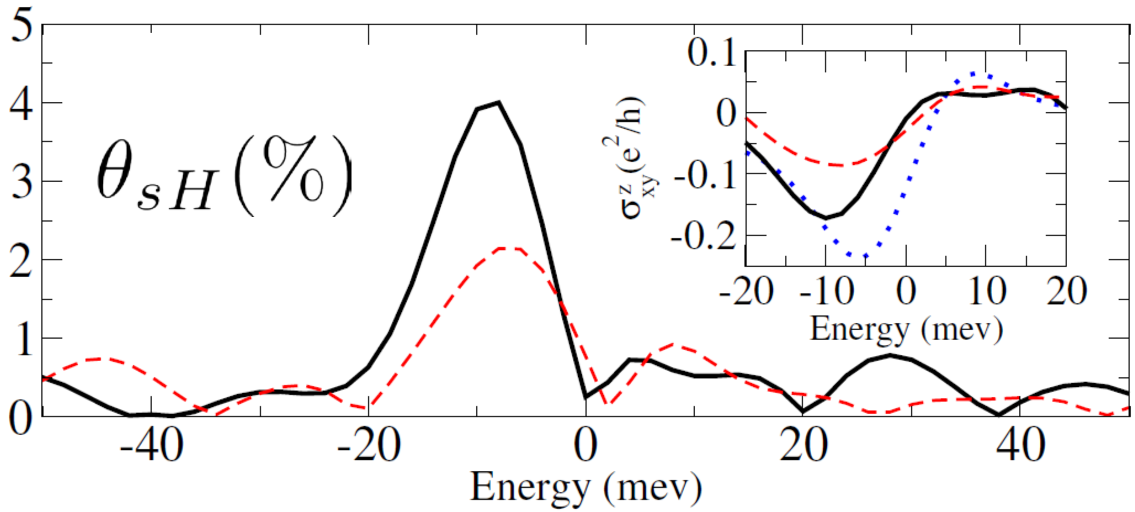


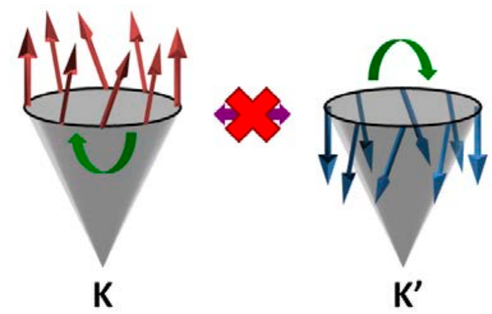
Homogeneous intrinsic SOC
(QSHE)
Plateau in the bulk bandgap
Sheng, Sheng, Ting, Haldane,
Phys. Rev. Lett. 95, 136602 (2005)



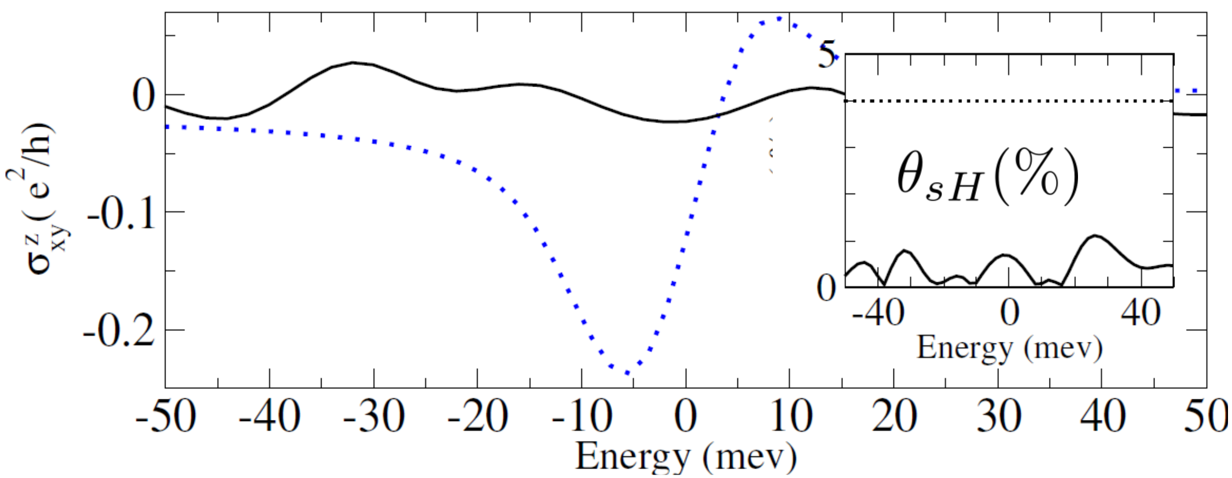
Spin Hall Effect

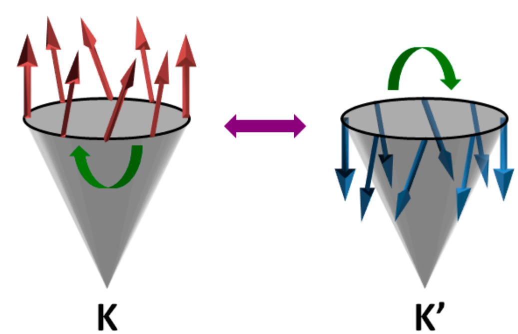
in disordered graphene/TMDC interfaces





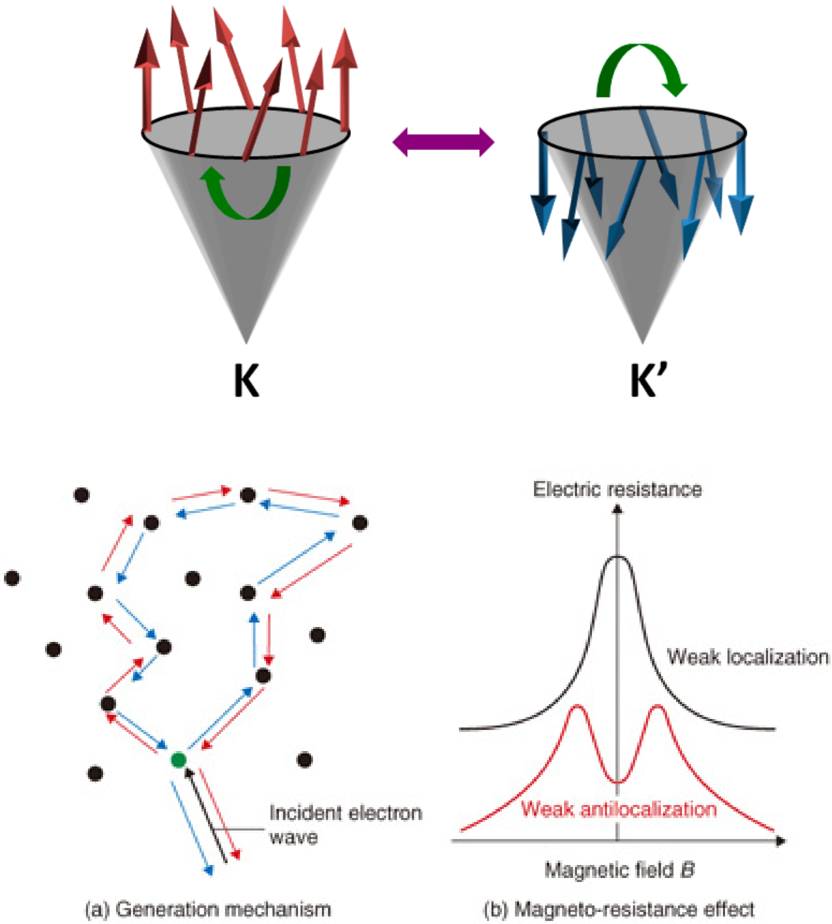
$$\theta_{sH}(\%) \simeq 4\%$$



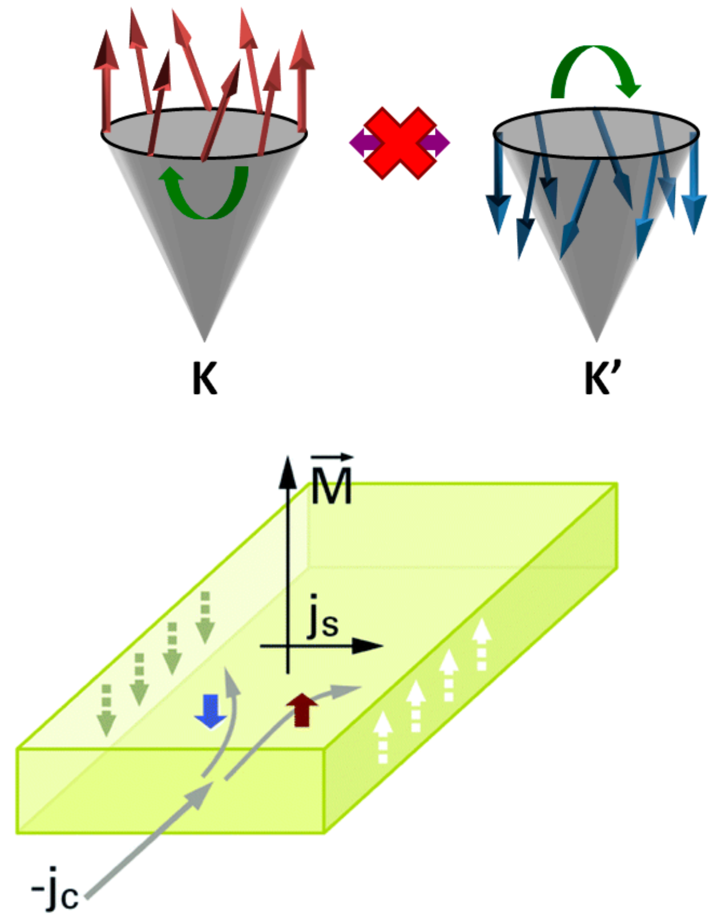


$$\theta_{sH}(\%) \ll 1\%$$

Weak antilocalization vs Spin Hall Effect



$$\frac{\tau_{s,\perp}}{\tau_{s,\parallel}} = 10 - 100$$



$$\frac{\tau_{s,\perp}}{\tau_{s,\parallel}} = 1/2$$

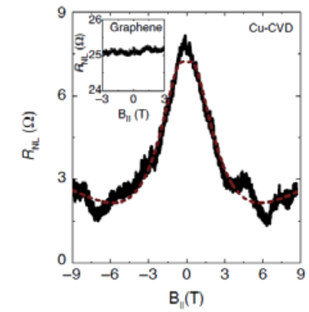
SHE induced
by metallic ad-atoms onto graphene

ARTICLE

Received 17 Apr 2014 | Accepted 18 Jul 2014 | Published 1 Sep 2014

DOI: 10.1038/ncomms5748

Giant spin Hall effect in graphene grown by chemical vapour deposition

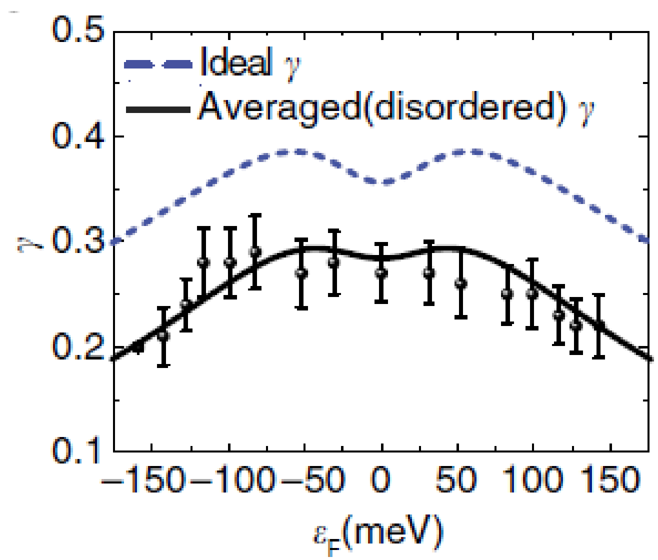


Jayakumar Balakrishnan[1,2,*,†], Gavin Kok Wai Koon[1,2,3,*], Ahmet Avsar[1,2], Yuda Ho[1,3], Jong Hak Lee[1,2], Manu Jaiswal[1,2,†], Seung-Jae Baeck[4], Jong-Hyun Ahn[4], Aires Ferreira[1,2,5], Miguel A. Cazalilla[2,6], Antonio H. Castro Neto[1,2] & Barbaros Özyilmaz[1,2,3]

Table 1 | Graphene decorated with metallic adatoms.

Adatom	Mobility ($cm^2V^{-1}s^{-1}$)	λ_s (μm)	γ	Δ (meV)
Cu-CVD	11,000	1.9	0.17	14.4
Cu-EPG	9,000	1.1	0.27	17.4
Au-EPG	15,000	2.0	0.15	18.0

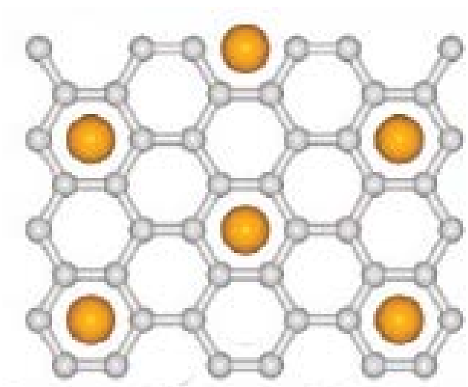
CVD, chemical vapour deposition; EPG, exfoliated pristine graphene.
The extracted values for Δ assume predominant intrinsic SOC (see main text).

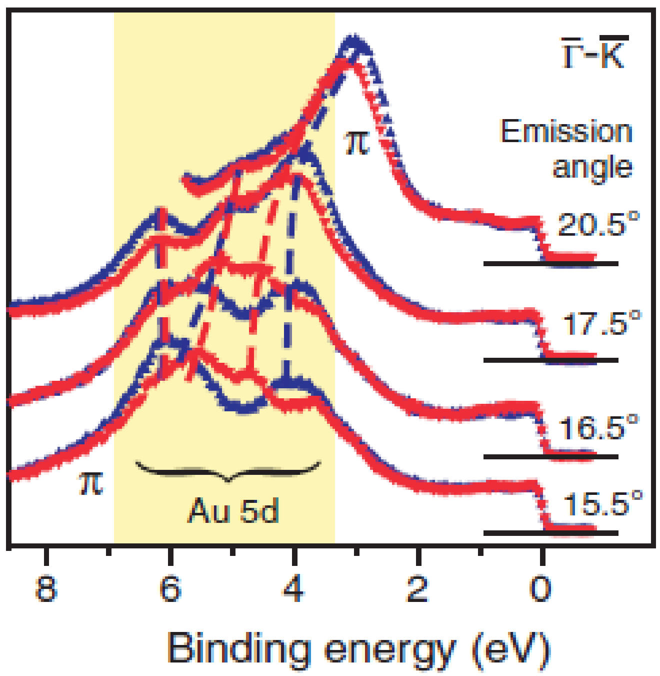


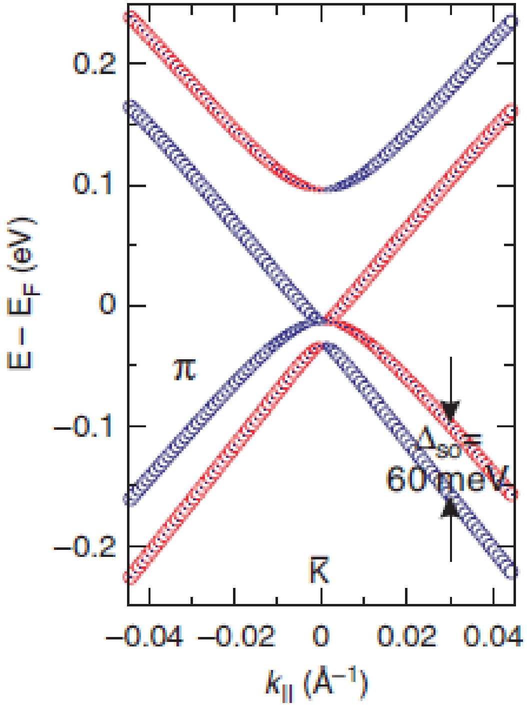
intrinsic-like spin–orbit interaction (20meV), Elliot-Yafet and skew scattering

Giant Rashba Splitting
in graphene hybridized with Au-adatoms

D. Marchenko et al, Nature Comm. 3 (1232), 2012







Au intercalation at the graphene–Ni interface creates a **giant spin–orbit splitting (60 meV)**

Nanoscale

PAPER

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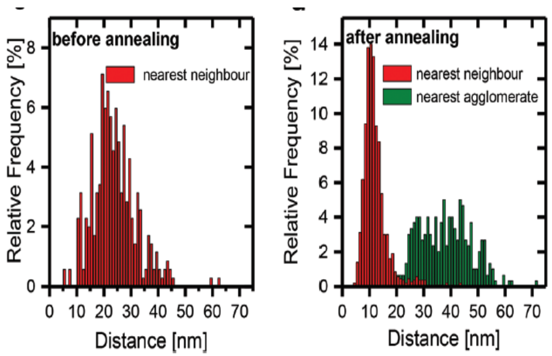
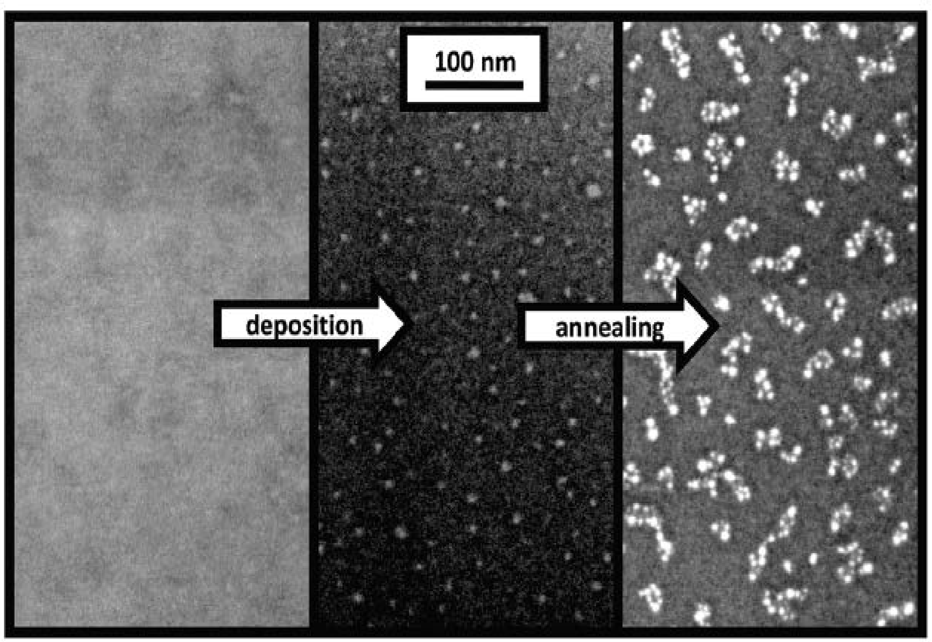
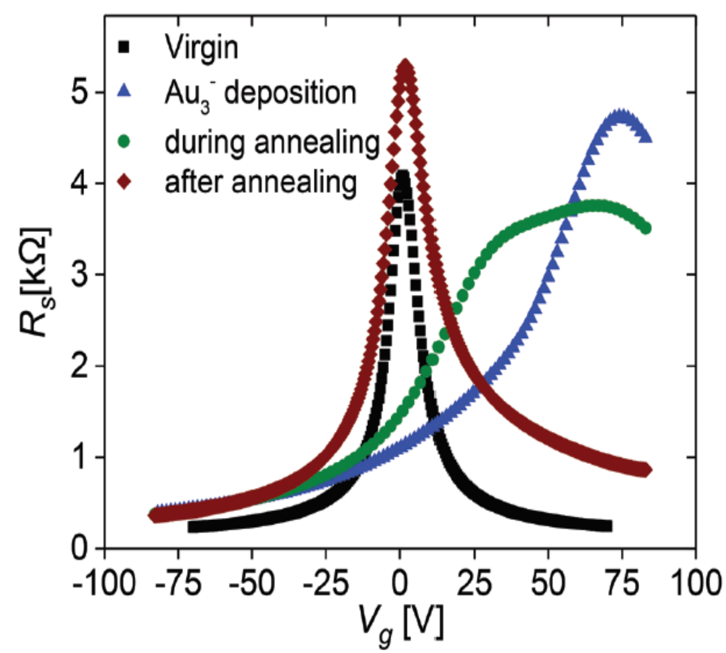


Decorating graphene with size-selected few-atom clusters: a novel approach to investigate graphene–adparticle interactions†

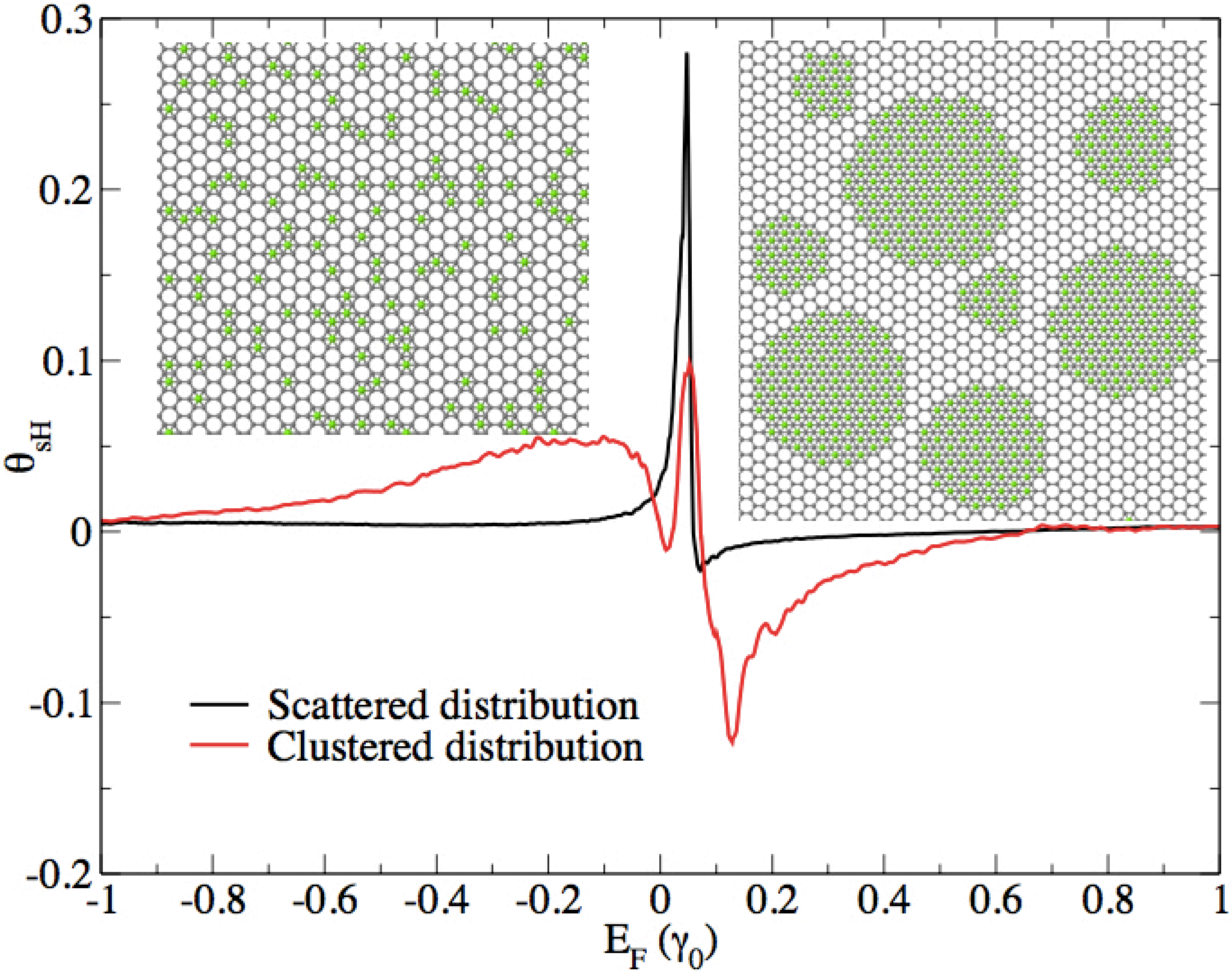
Jeroen E. Scheerder, *[a] Thomas Picot,[a] Nicolas Reckinger,[b] Tomas Sneyder,[a] Vyacheslav S. Zharinov, [a] Jean-François Colomer,[b] Ewald Janssens [a] and Joris Van de Vondel *[a]





Spin Hall angles

$$\theta_{\mathrm{sH}} = \sigma_{\mathrm{sH}} / \sigma_{xx}$$



$\theta_{\mathrm{sH}}^{max} \sim 0.1 - 0.3$

(Zero-temperature)

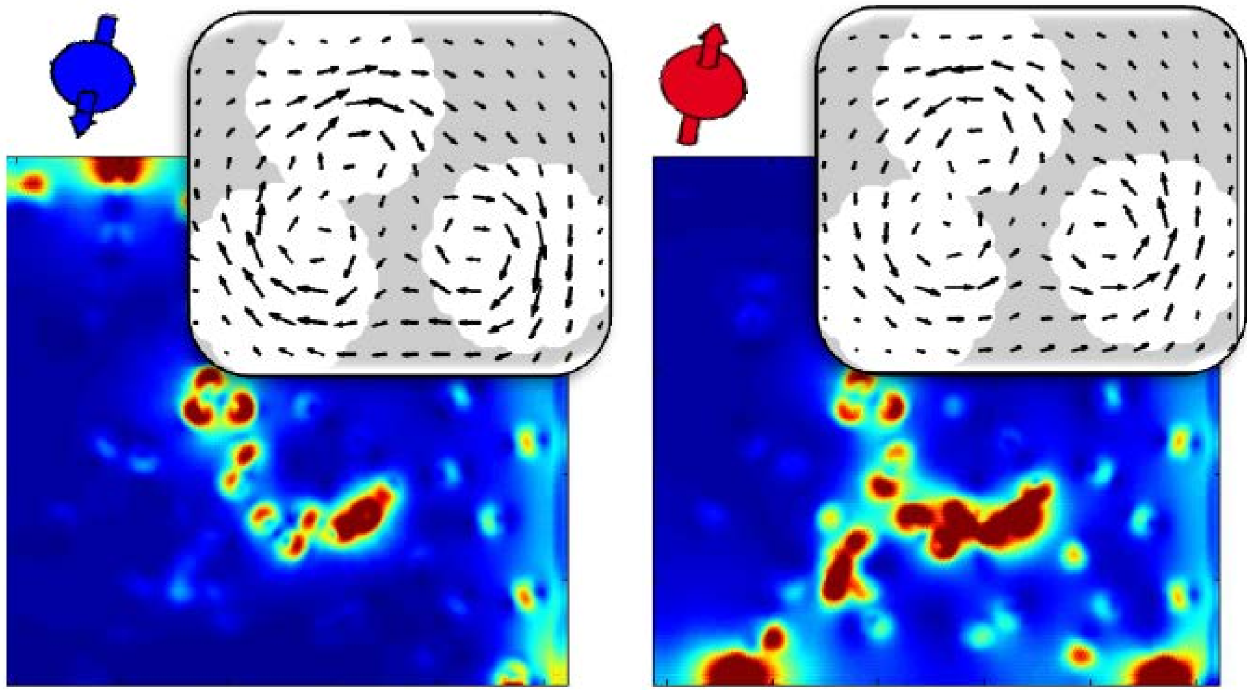
Impact of segregation varies with energy

For same cluster density and distribution ***Intrinsic SOC gives rise to larger SHA than Rashba-SOC***

Far from dilute limit!!! SHA not expected to Be larger for much lower density…

Multiple Quantum Phases in Graphene with Enhanced Spin-Orbit Coupling: From the Quantum Spin Hall Regime to the Spin Hall Effect and a Robust Metallic State

Alessandro Cresti,[1,2] Dinh Van Tuan,[3,4] David Soriano,[3] Aron W. Cummings,[3] and Stephan Roche[3,5]
[1]*Univ. Grenoble Alpes, IMEP-LAHC, F-38000 Grenoble, France*
[2]*CNRS, IMEP-LAHC, F-38000 Grenoble, France*
[3]*ICN2—Institut Catala de Nanociencia i Nanotecnologia, Campus UAB, 08193 Bellaterra (Barcelona), Spain*
[4]*Department of Physics, Universitat Autónoma de Barcelona, Campus UAB, 08193 Bellaterra, Spain*
[5]*ICREA—Institucio Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain*
(Received 21 December 2013; published 9 December 2014)



Non-local transport & topological effects

PRL **117**, 176602 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

Spin Hall Effect and Origins of Nonlocal Resistance in Adatom-Decorated Graphene

D. Van Tuan,[1,2] J. M. Marmolejo-Tejada,[3,4] X. Waintal,[5] B. K. Nikolić,[3,*] S. O. Valenzuela,[1,6] and S. Roche[1,6,†]

[1]*Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and The Barcelona Institute of Science and Technology, Campus UAB, Bellaterra, 08193 Barcelona, Spain*

[2]*Department of Electrical and Computer Engineering, University of Rochester, Rochester, New York 14627, USA*

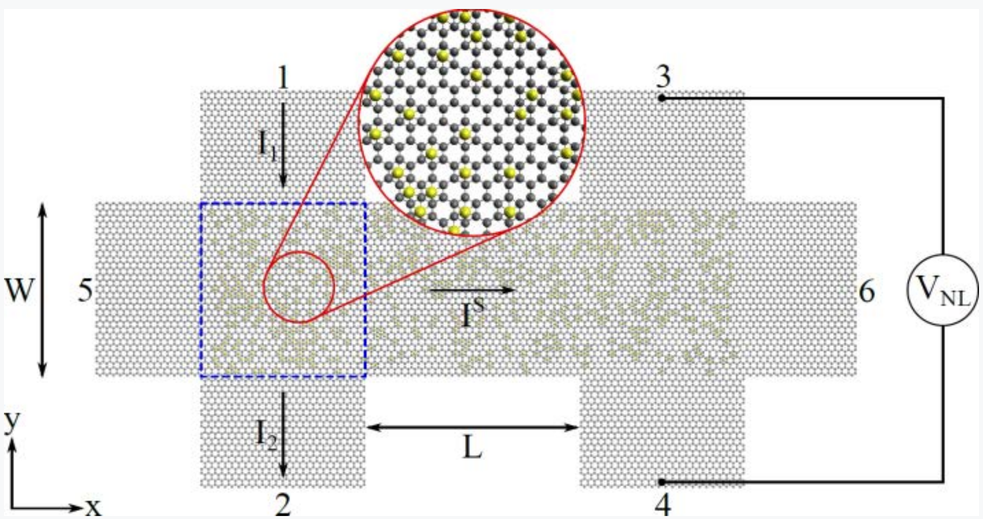
[3]*Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716-2570, USA*

[4]*School of Electrical and Electronics Engineering, Universidad del Valle, Cali AA 25360, Colombia*

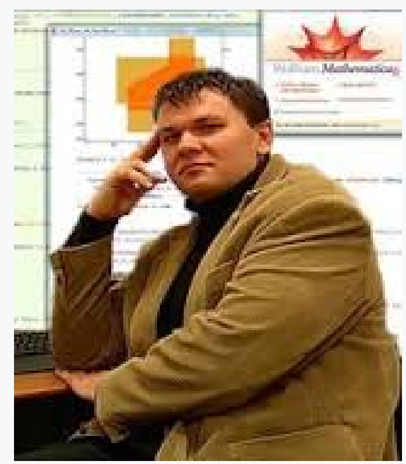
[5]*Univ. Grenoble Alpes, INAC-PHELIQS, F-38000 Grenoble, France and CEA, INAC-PHELIQS, F-38000 Grenoble, France*

[6]*ICREA—Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain*

(Received 19 February 2016; published 20 October 2016)



$$\theta_{\mathrm{sH}} = I_5^{s_z} / I_1$$



Branislav K. Nikolic,
University of Delaware, USA

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ICN2 Institut Català de Nanociència i Nanotecnologia

Group Members

Aron Cummings

José García

D. Van Tuan

David Soriano

Marc Vila

Spintronics Coworkers

Branislav Nikolic
(Univ. Delaware, USA)

Jaroslav Fabian
(Univ. Regensburg)

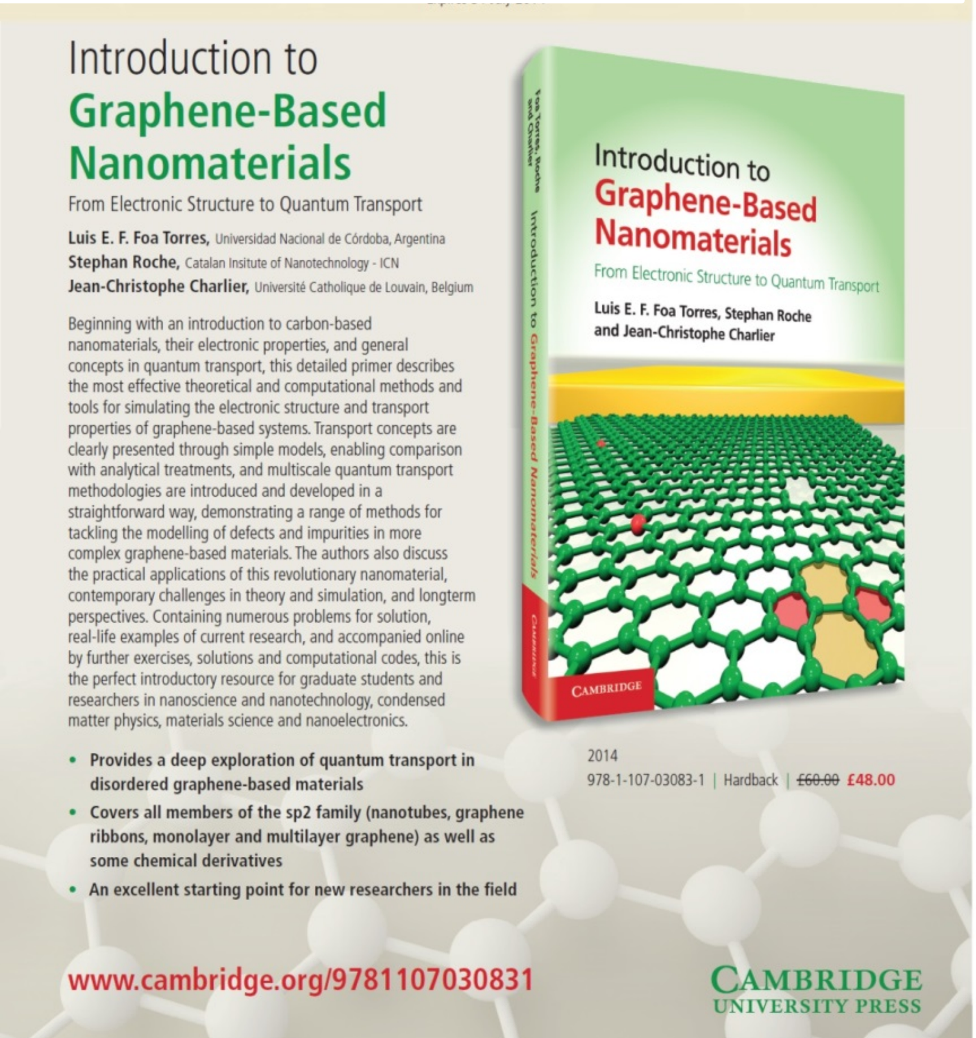
Xavier Waintal
(CEA)

Sergio Valenzuela
(ICN2)

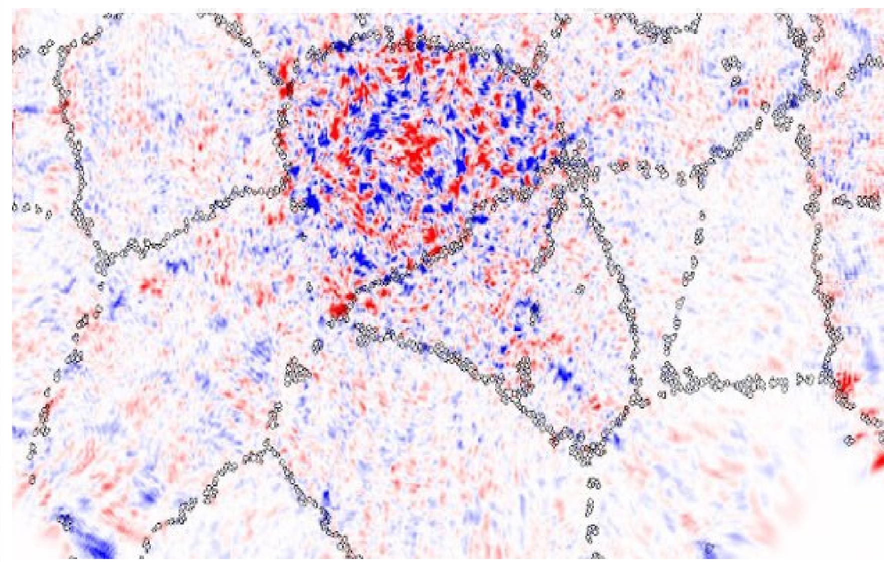
"Introduction to Graphene-Based Nanomaterials From electronic structure to Quantum Transport"

CAMBRIDGE UNIVERSITY PRESS

http://www.introductiontographene.org/



Graphene, ribbons, nanotubes
Concepts /methods
Ab-initio and tight-bindings models
Landauer-Büttiker / Kubo transport



Additional resources

(exercises/solutions, numerical codes,...)


谢谢ありがとう
감사합니다
Thank you~!
धन्यवाद