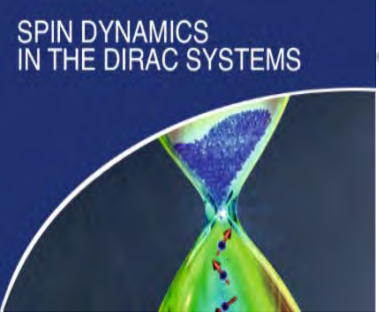


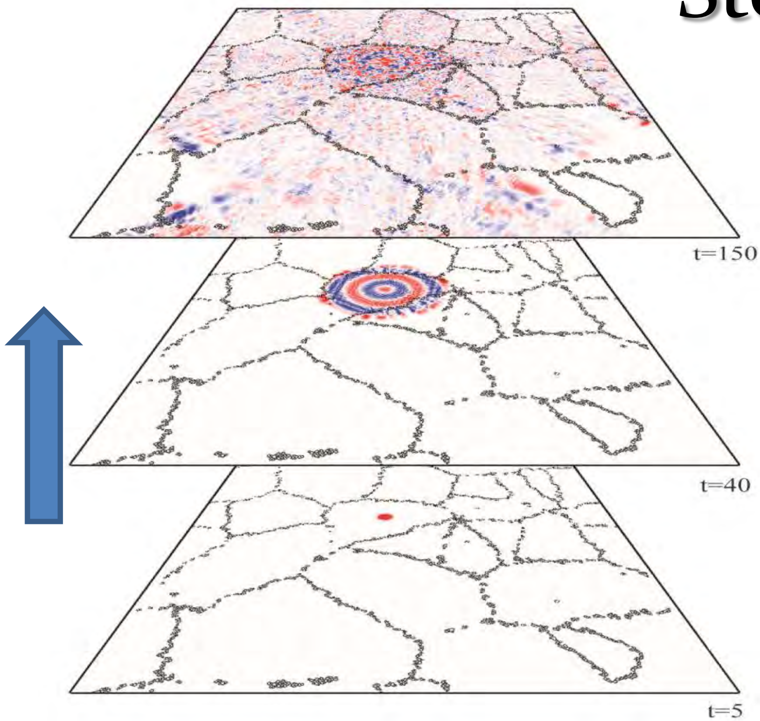
Proximity effects and Spin dynamics in Dirac Matter?

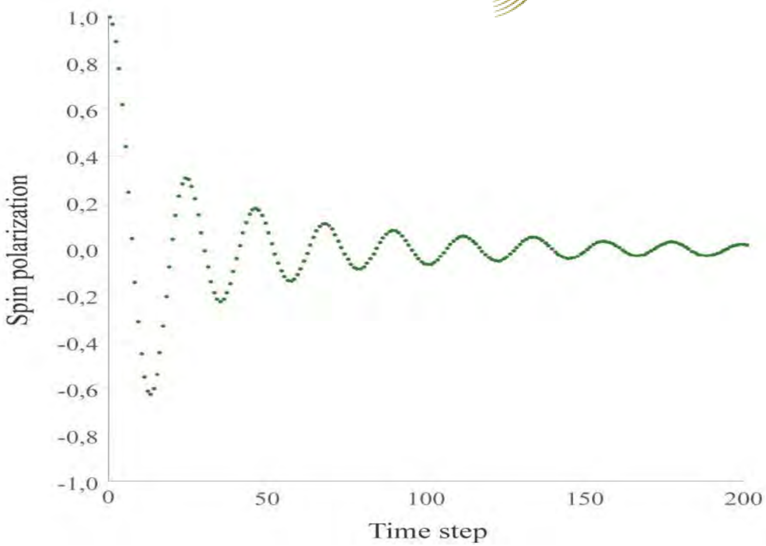
Stephan Roche

ICN2 Institut Català de Nanociència i Nanotecnologia

BIST Barcelona Institute of Science and Technology

ICREA





Institució CERCA Centres de Recerca de Catalunya

Generalitat de Catalunya

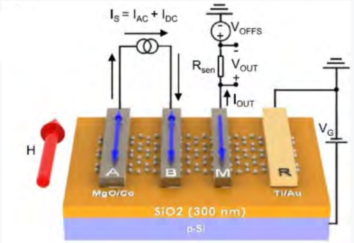
CSIC Consejo Superior de Investigaciones Científicas

UAB Universitat Autònoma de Barcelona

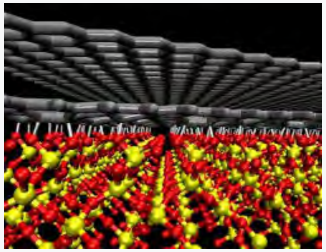
OUTLINE

Institut Català de Nanociència i Nanotecnologia

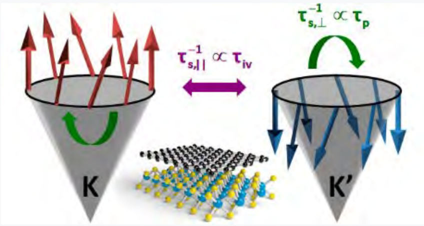
Why Spintronics using 2D Materials ?



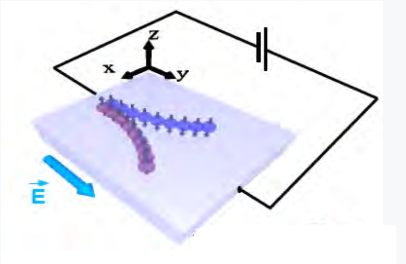
How the substrate controls spin dynamics?



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



Weak antilocalization & Spin Hall Effect
in Graphene/TMDC



Institut Català de Nanociència i Nanotecnologia

Acknowledgements

Group Members

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D. Van Tuan

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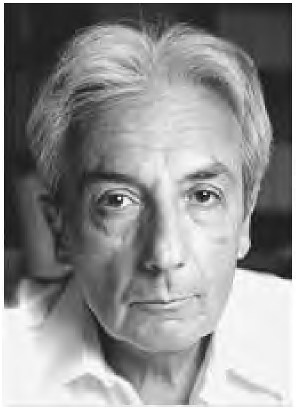
(Univ. Regensburg)

Xavier Waintal
(CEA)

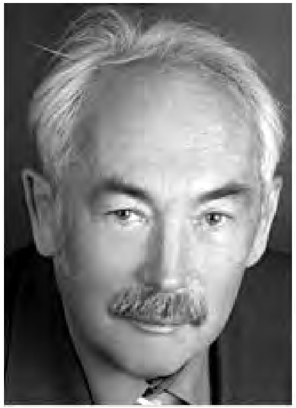
Sergio Valenzuela
(ICN2)

Spintronics and its industrial/Societal impact

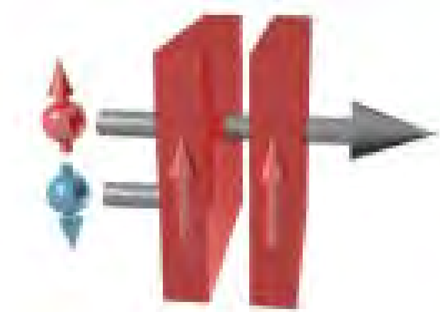
Albert Fert

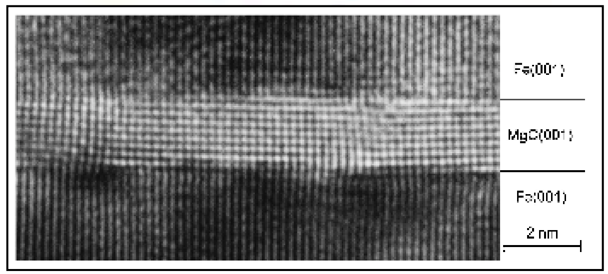


Peter Grünberg

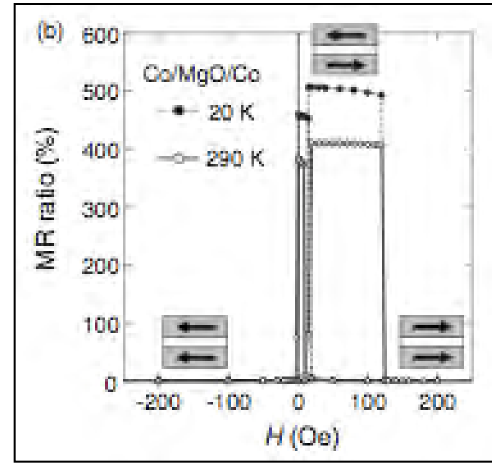


2007 Physics Nobel Laureates





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



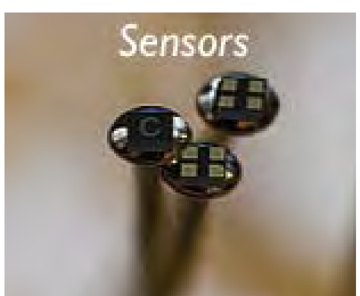
Magnetic field sensors used to read data in hard disk drives,

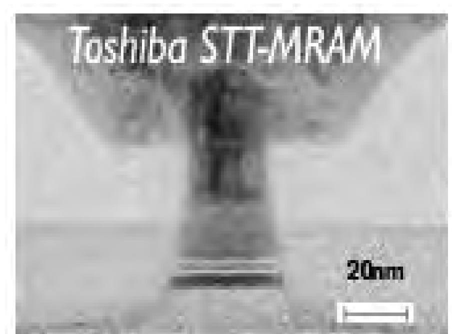
microelectromechanical systems (MEMS), minimally invasive surgery

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

Magnetoresistive random-access memory *(MRAM)*

Spin transfer Torque MRAM

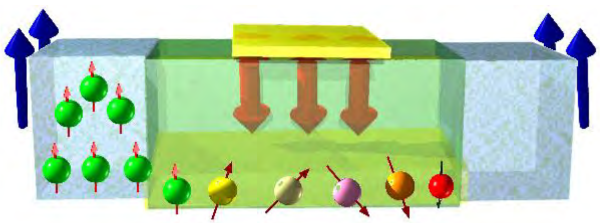




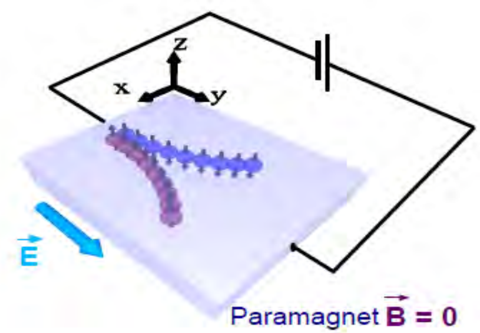
Spin-based information processing ?

Active devices based on **Spin manipulation** ?

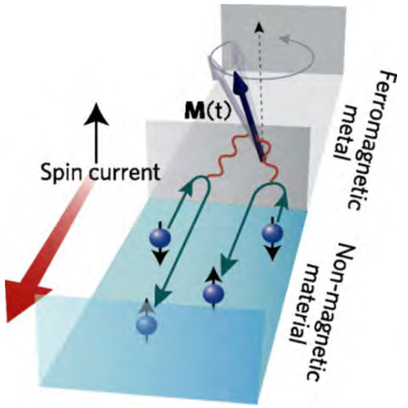
Datta-Das spin transistor



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

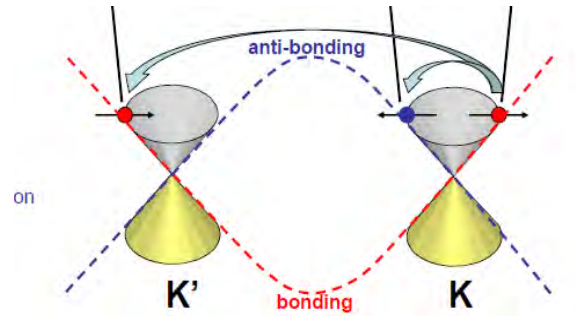
What makes graphene attractive

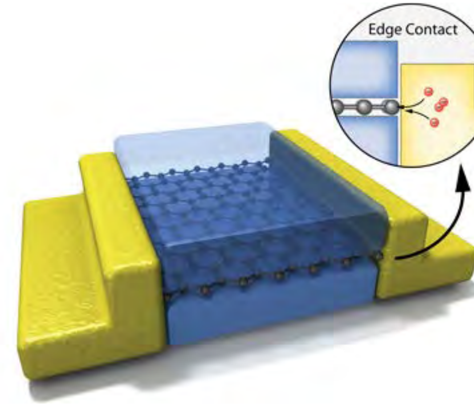
- Ambipolar/tuneable transport

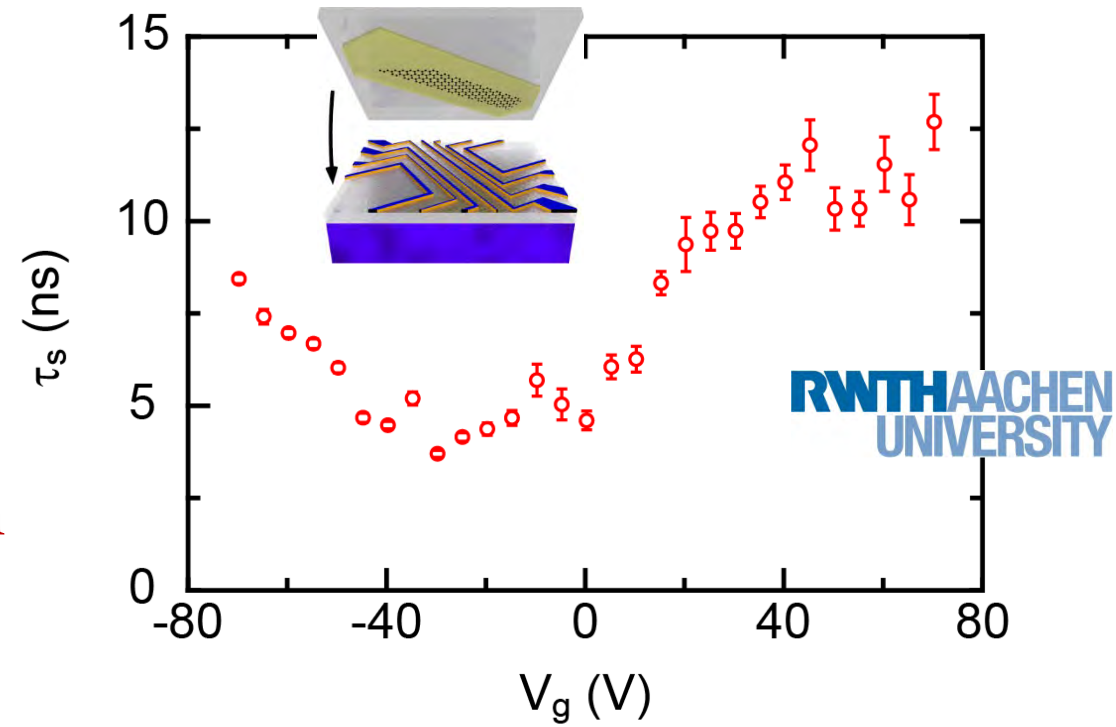
- **Large mobilities**
(> 100k cm²/V.s at RT, 1M cm²/V.s at 4K)

- **Low spin-orbit interaction**

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







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

Magnetic oxides induce spin filtering/gap

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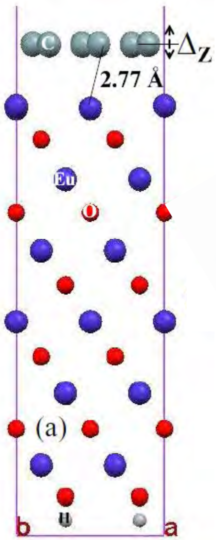
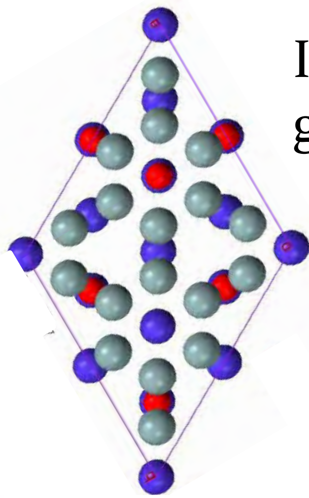
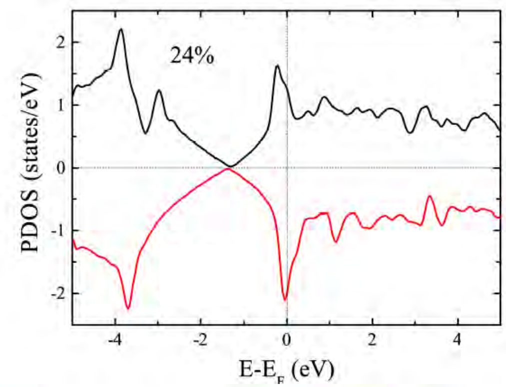
Spin Filtering and Exchange Splitting Gaps

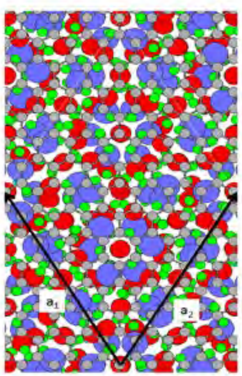




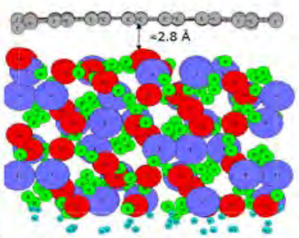
Induced spin polarization in graphene by EuO

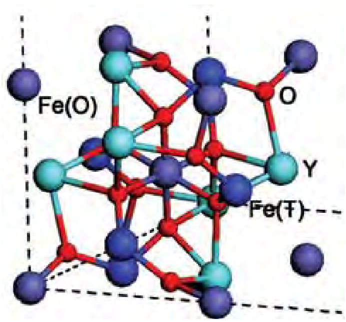
$$\mathcal{P} = \frac{n^{\downarrow} - n^{\uparrow}}{n^{\downarrow} + n^{\uparrow}}$$

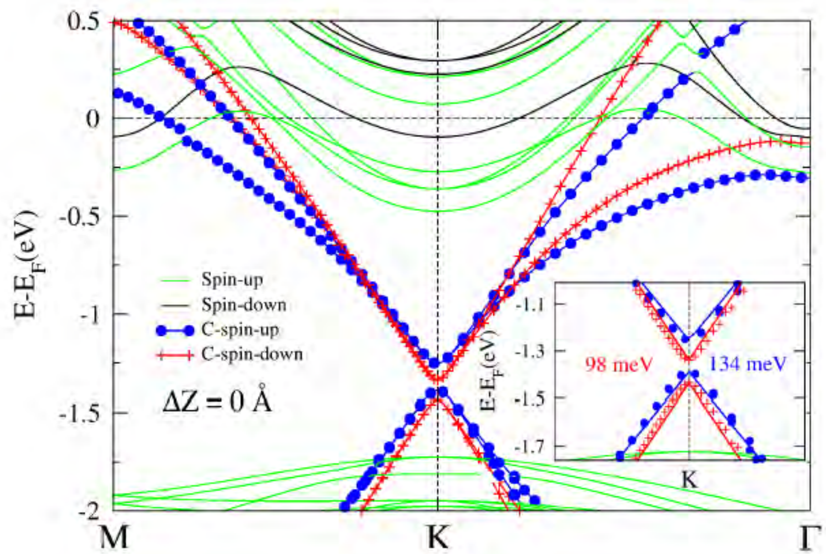




Gr/Y_3Fe_5O



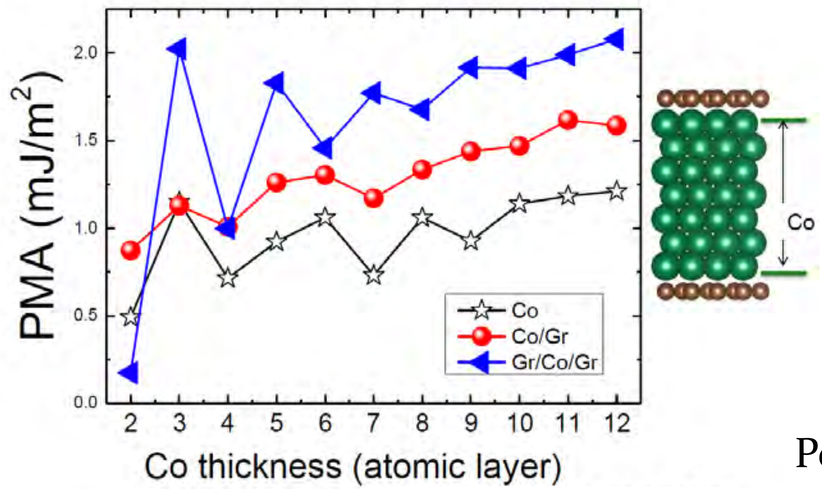


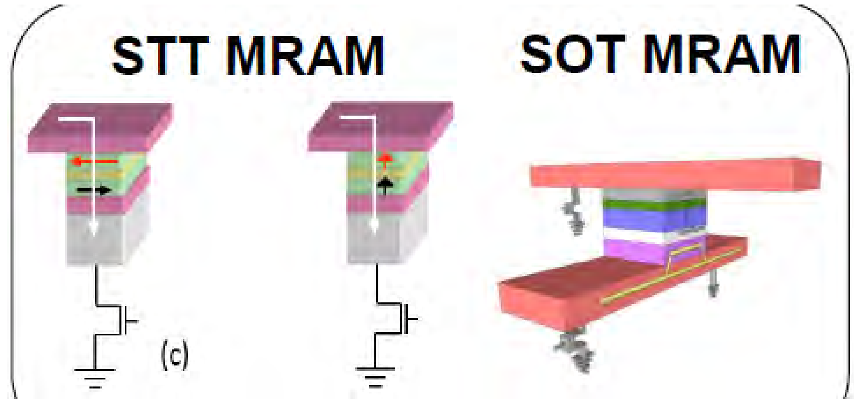


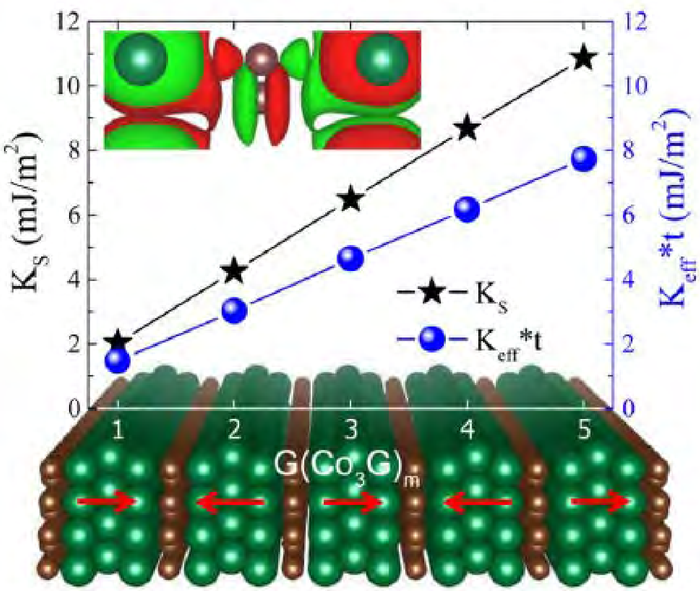
Yang, Hallal, Terrade, Waintal, Roche, Chshiev, PRL 110, 046603 (2013)
Hallal et al. 2D materials 4 , 025074 (2017)

Exchange splitting (G/YIG) = 40 meV

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)

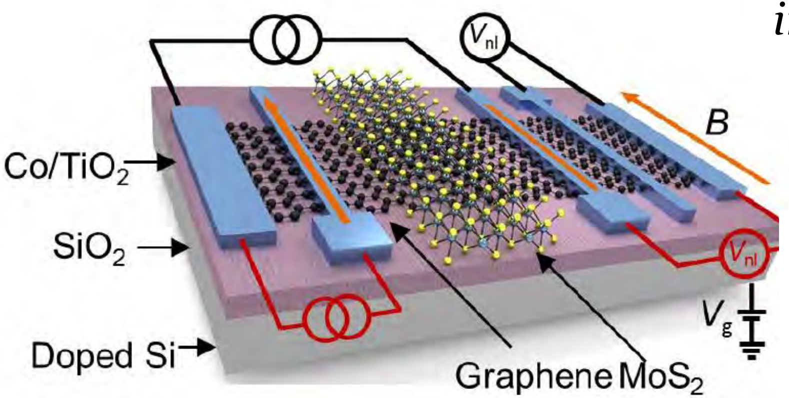
Graphene-based Spintronic logic demonstrators

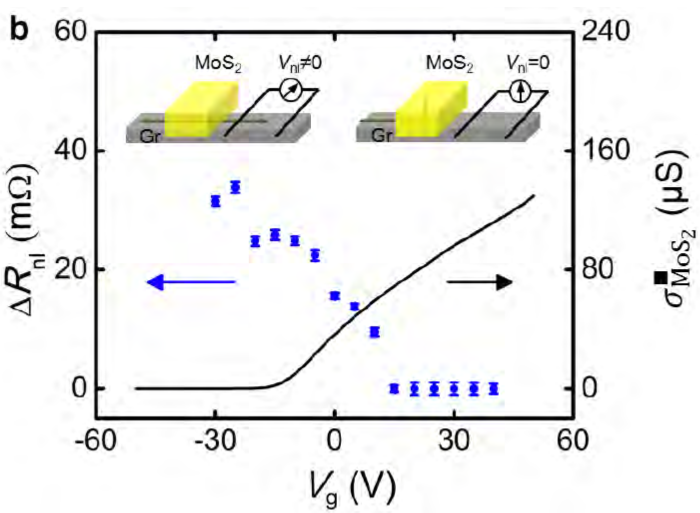
ICN2 Institut Català de Nanociència i Nanotecnologia

W. Yan et al.

Nature Comm. 7, 13372 (2016)

SPIN-FET



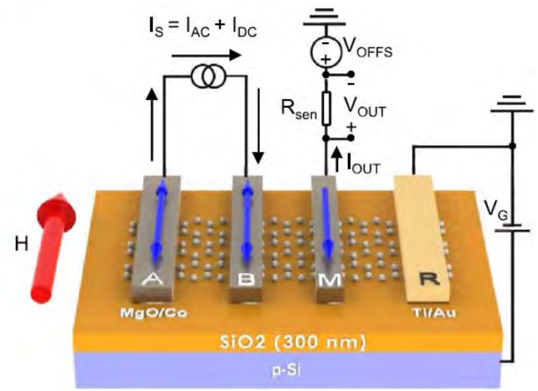


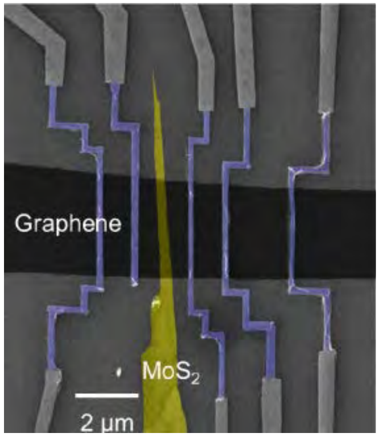
Hua Wen et al.

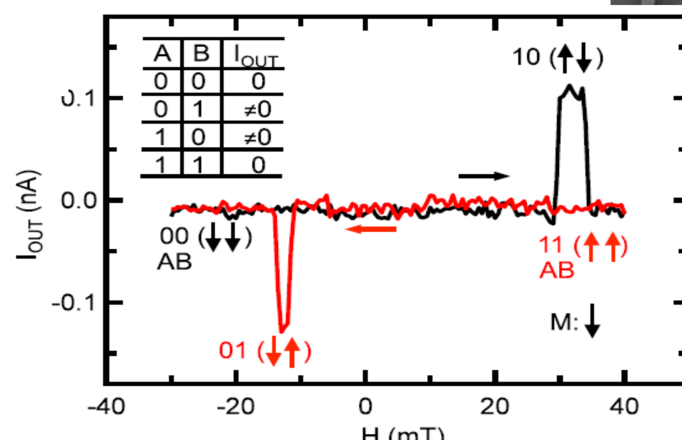
Phys. Rev. Applied **5**, 044003 (2016)

Experimental demonstration of XOR operation

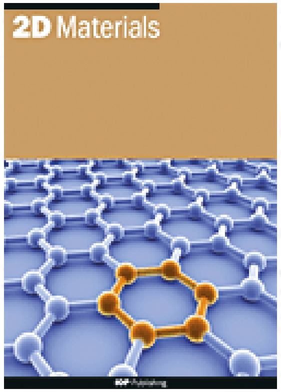
in graphene Magnetologic Gates at room temperature







GRAPHENE FLAGSHIP

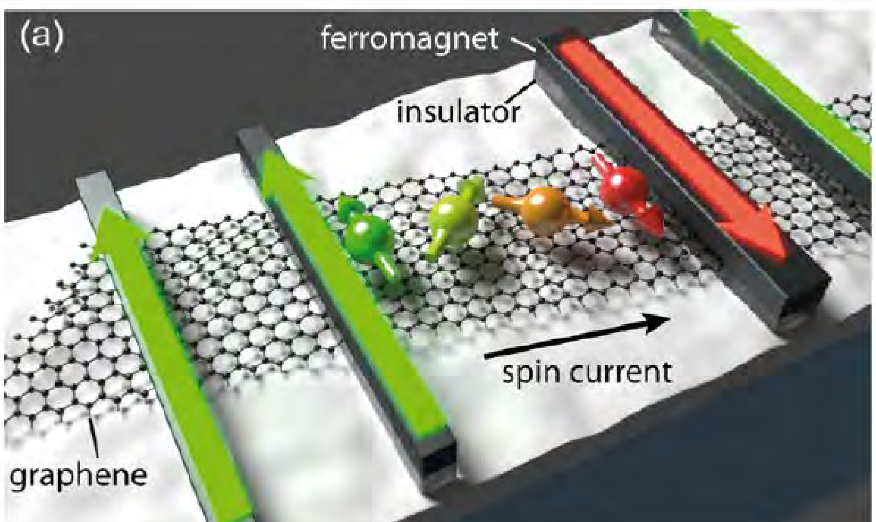


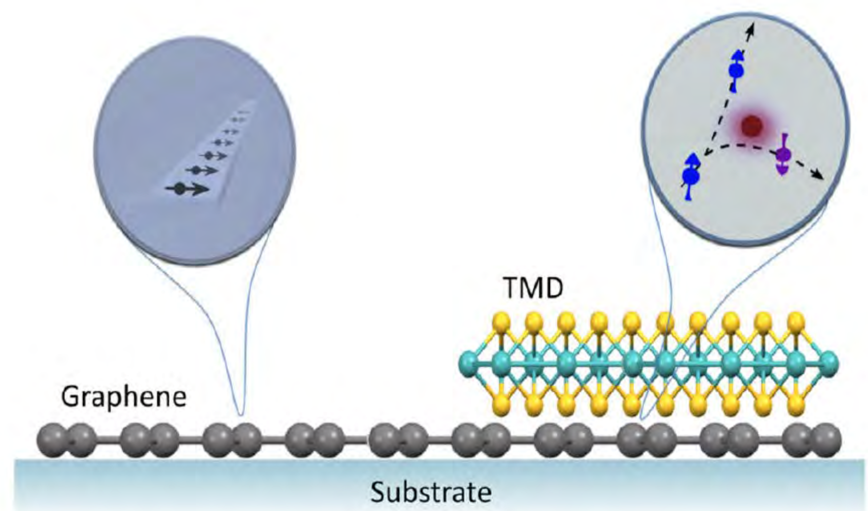
EDITORIAL

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]

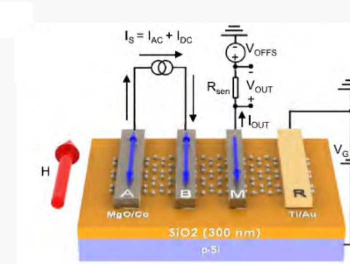
2D Mater. 2 (2015) 030202



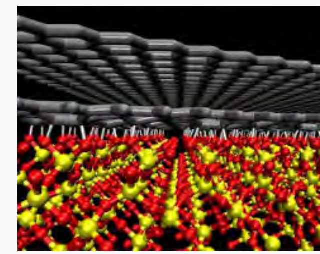


OUTLINE

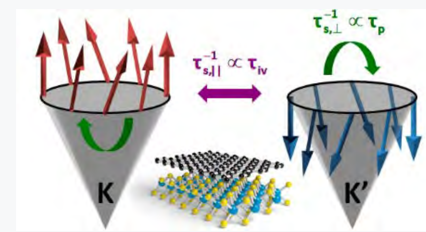
Why Spintronics using 2D Materials ?



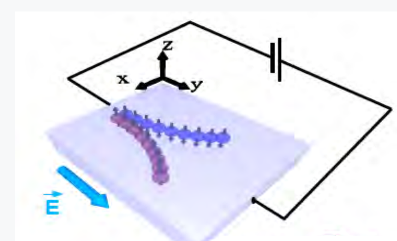
How the substrate controls spin dynamics?



Giant spin transport anisotropy
in graphene induced by strong SOC
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

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

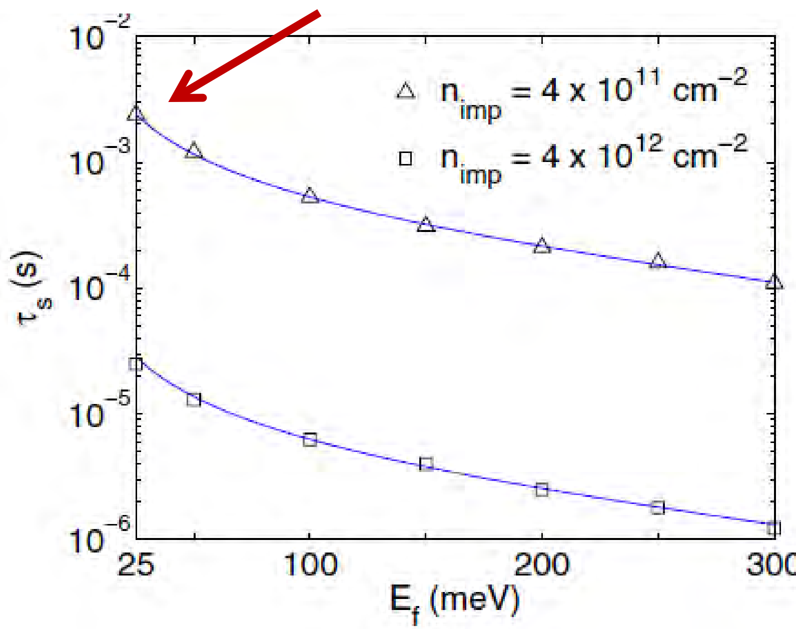
Spin lifetime is calculated by averaging over random trajectories with different initial momenta , assuming

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

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

$$\tau_\alpha \rightarrow \mu s - ms!!!$$

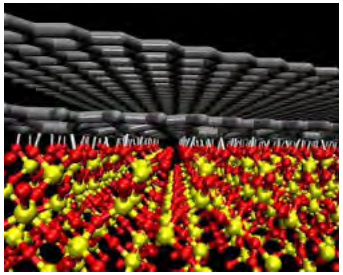
Maximum at Dirac point
Elliot Yaffet



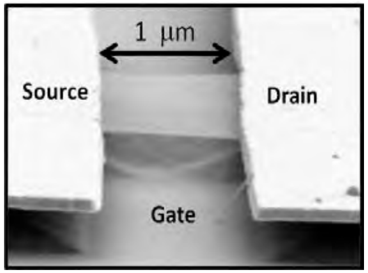
C. Ertler, S. Konschuh, M. Gmitra and J. Fabian, **Phys. Rev. B 80, 041405(R) (2009)**

Experimental spin lifetime features

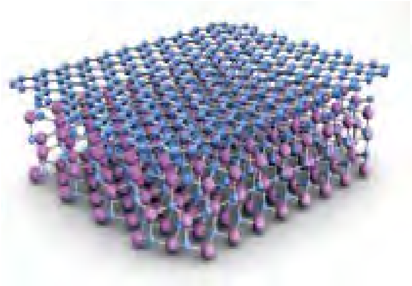
Graphene on SiO2



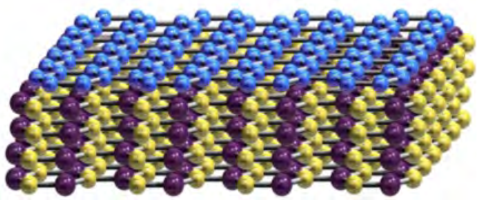
Suspended Graphene



Epitaxial graphene on SiC



Graphene on BN

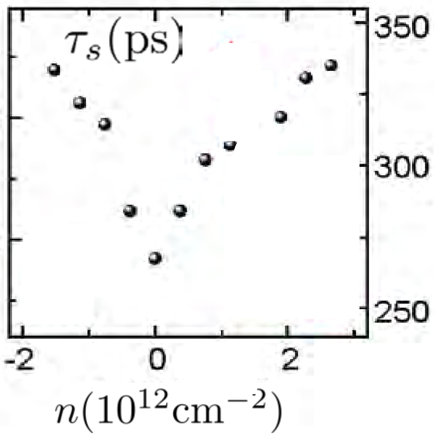


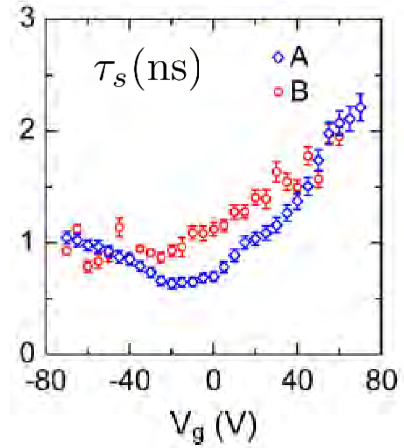
charge mobility $\mu \sim 100 - 100.000 \mathrm{cm}^2 \mathrm{V}^{-1} \mathrm{s}^{-1}$

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)

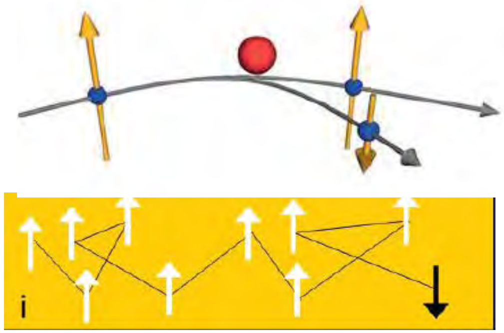




Which relaxation mechanism at play ?

Metals

Eliott-Yafet mechanism

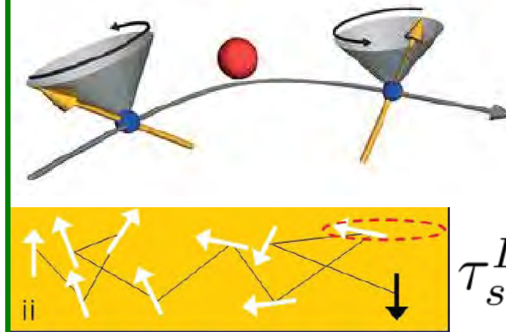


$$\tau_s \sim 10^4 - 10^6 \tau_p$$

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

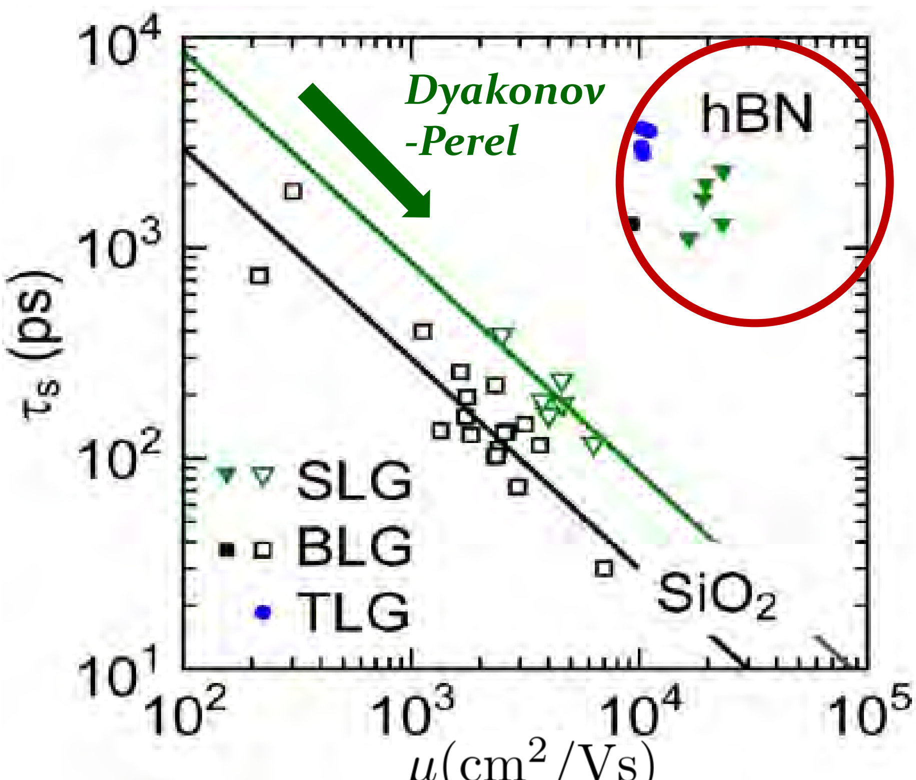
Small gap semiconductor

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)

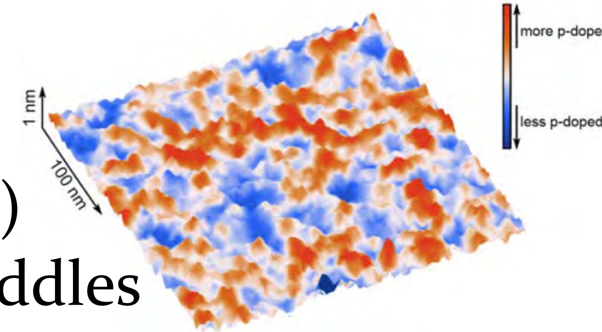
Cleaner samples for SiO2 substrates lead to lower spin lifetime

“opposite trend” for hBN Substrates?

Origin of spin dephasing
Spin-orbit coupling in graphene

"clean limit"

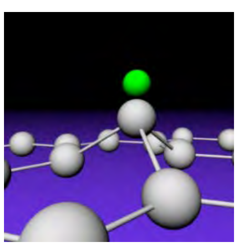
Intrinsic spin-orbit coupling ⊕ Substrate effects (Rashba electric field) and electron-hole puddles



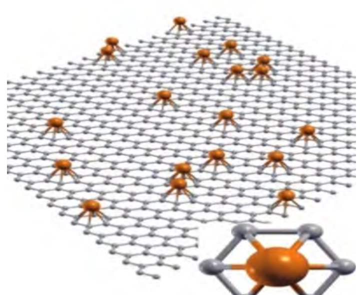
"dirty limit"

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

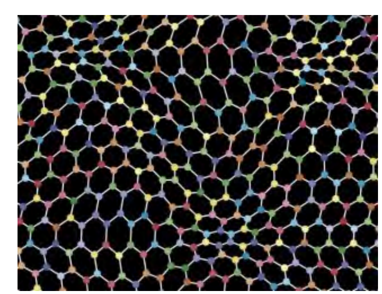
sp^3 defects
($\sigma-\pi$ hybridization)
Hydrogen ad-atoms-



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



Deformation fields
(Strain, ripples,bubbles...)

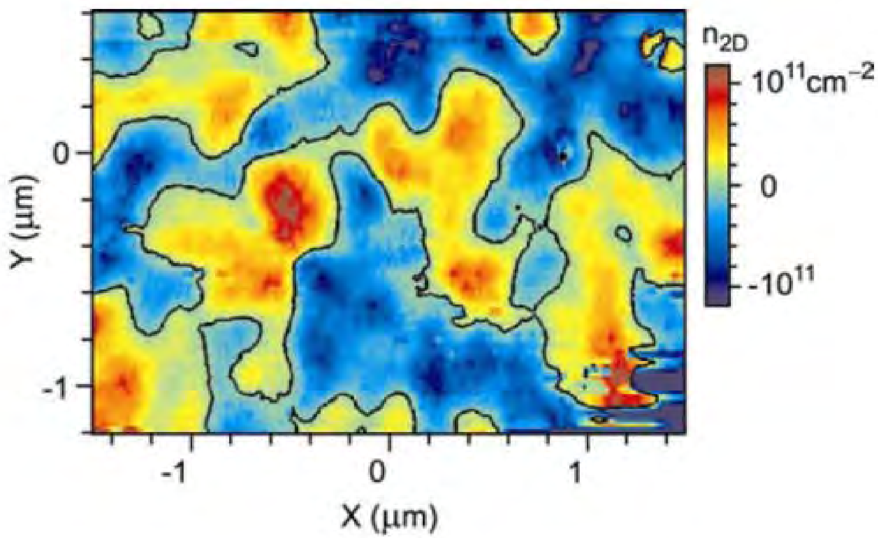


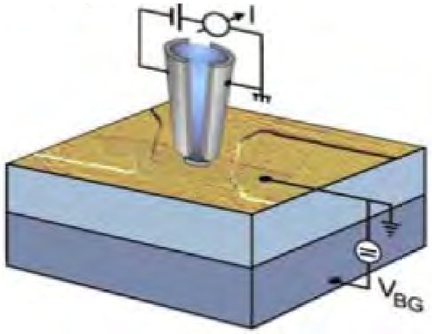
Spin relaxation in supported clean graphene

-beyond semiclassical approximations-

Disorder: Electron-holes puddles

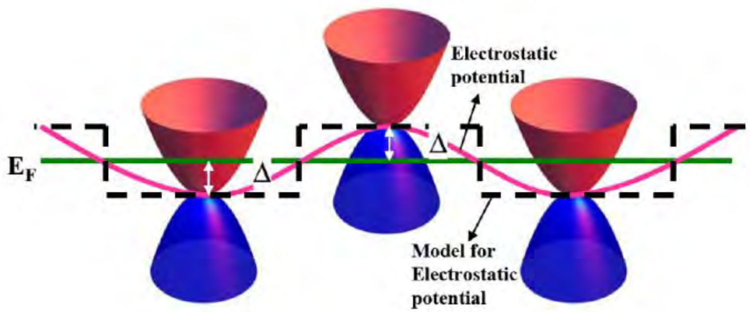
Spatial (long range) charge density fluctuations





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

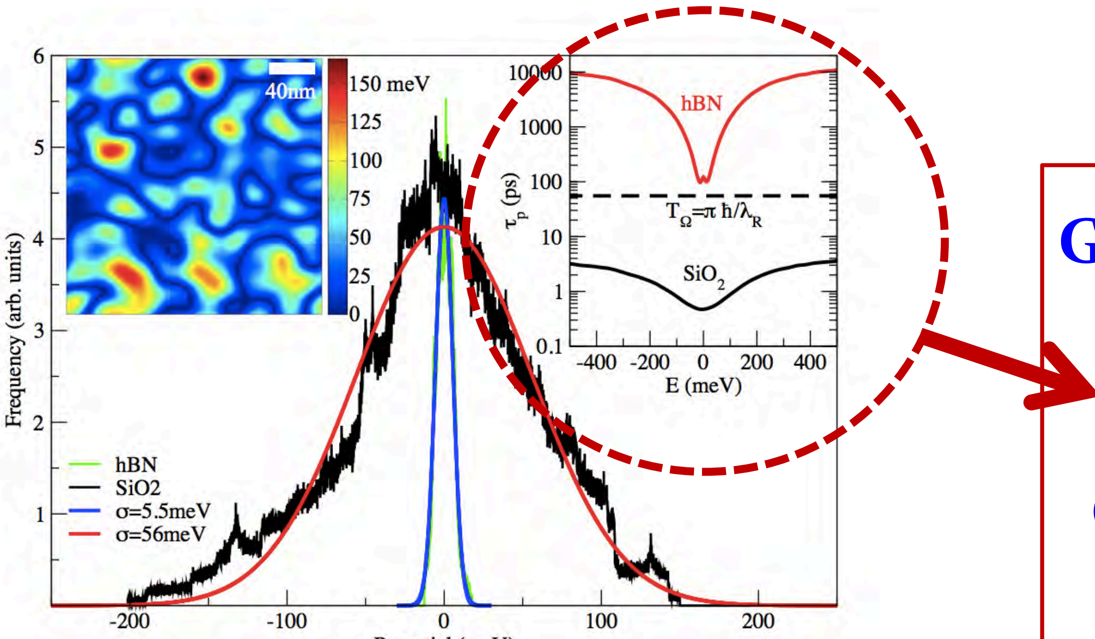
Long range (Gaussian) potential

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

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

Rashba SOC

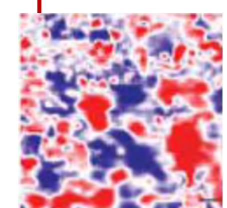
$$V_R \sim 20\mu\text{eV}$$



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

Graphene on SiO2

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



Graphene on hBN

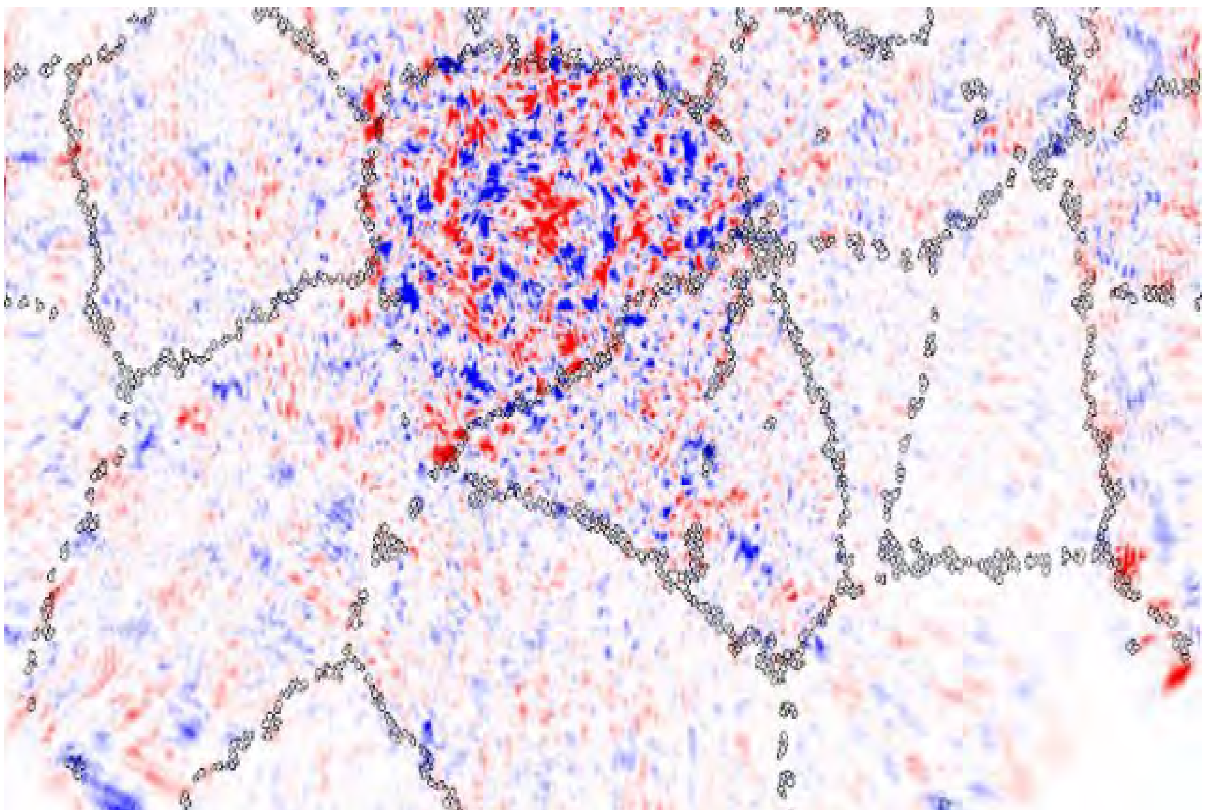
$$\tau_p^{hBN}/T_\Omega \geq 1$$

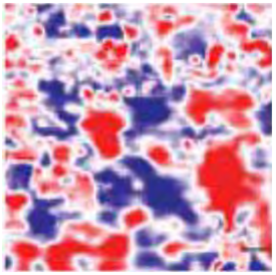
Spin dynamics of propagating wavepacket

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

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

(time-dependent)
Local spin density in real space

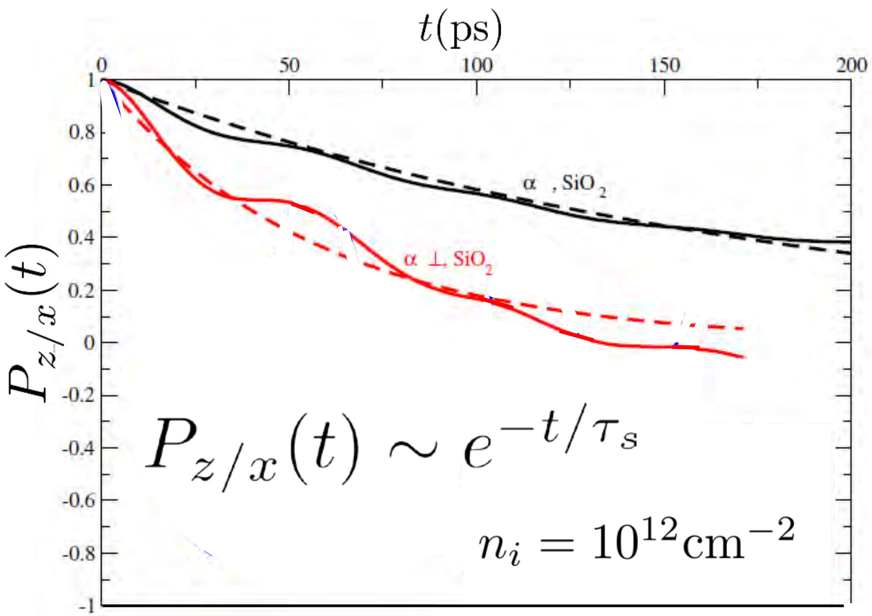


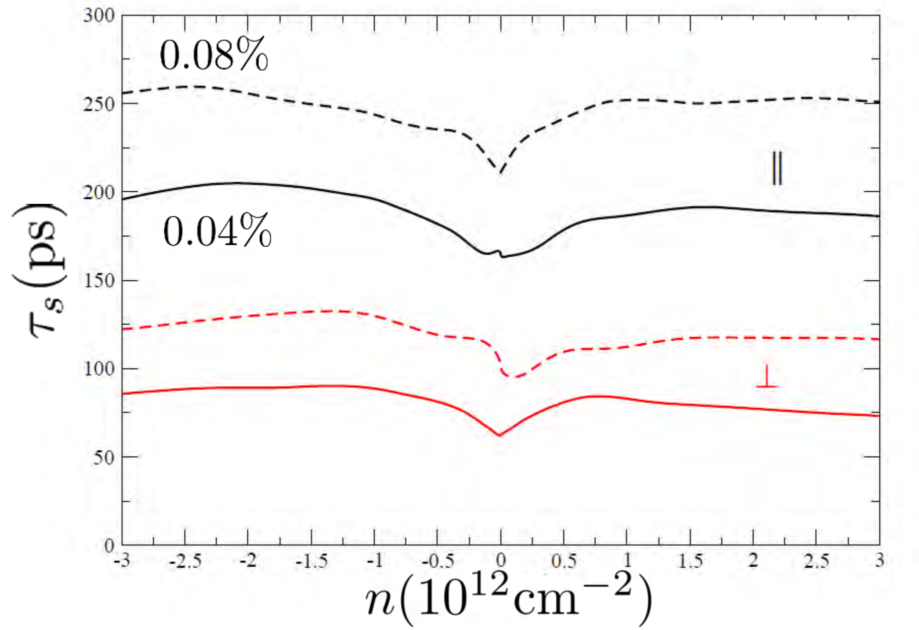


Graphene on SiO_2

electron-hole puddles drive the relaxation

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





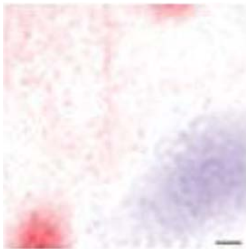
$$\tau_s \sim \frac{1}{n_i}$$

increases with defect density

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

Dyakonov-Perel

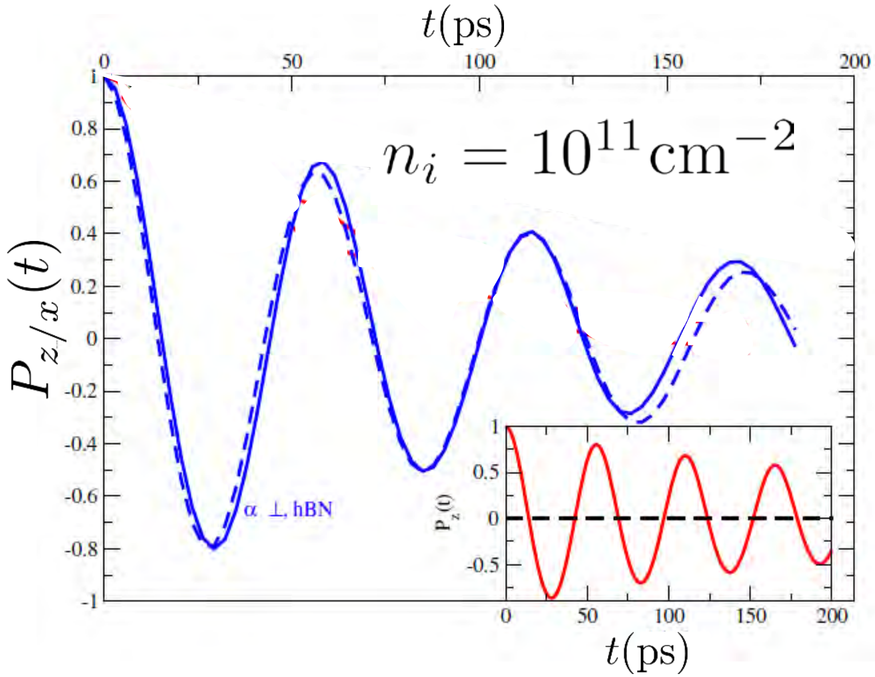
relaxation mechanism



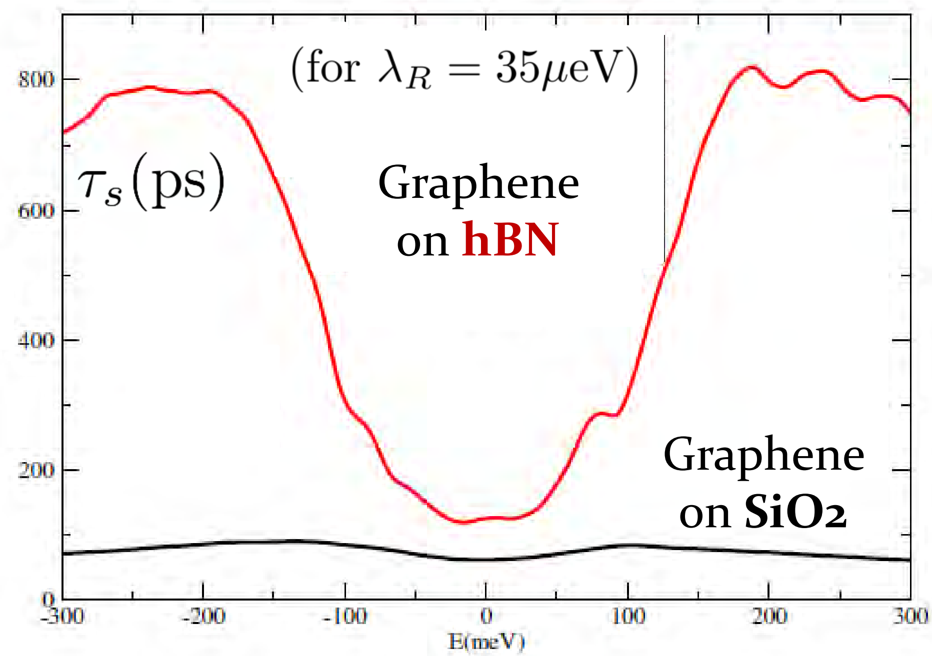
Graphene on hBN

electron-hole puddles drive the relaxation

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



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



Dephasing driven by an
entangled dynamics between spin and pseudospin

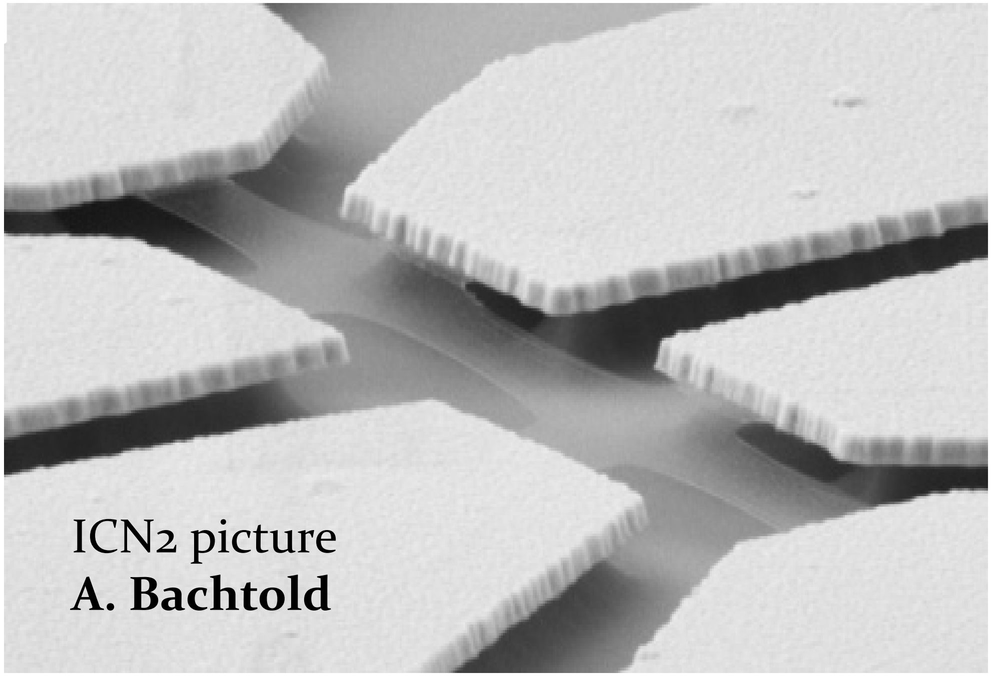
$$\tau_s(E) \approx 4T_\Omega \approx 4\frac{\pi\hbar}{\lambda_R}$$

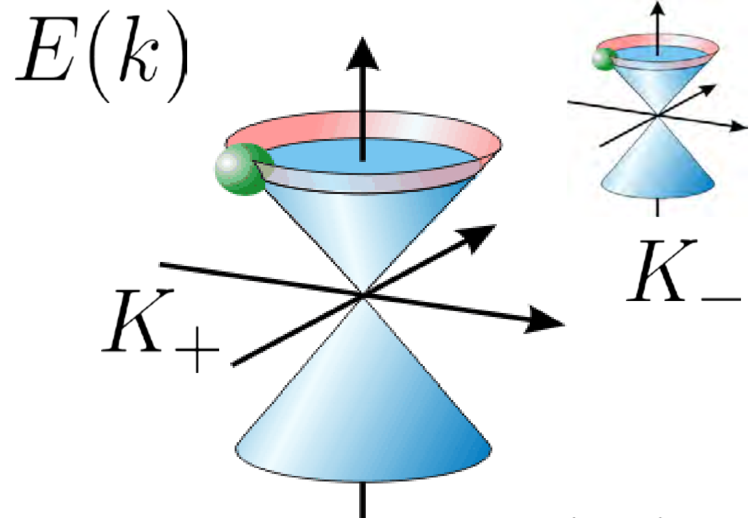
$$\boxed{\tau_s \simeq 1 - 10\ \mathrm{ns}}$$

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

D. Van Tuan et al, **Nature Physics 10, 857 (2014)**
,, **Sci. Reports 6, 21046 (2016)**
A.W. Cummings and SR, **PRL 116, 086602 (2016)**

"Unique properties of Clean graphene"

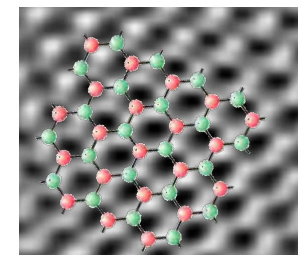




$$\mathcal{H}_{K_+} = v_F \vec{\sigma}.\vec{p}$$

pseudospin

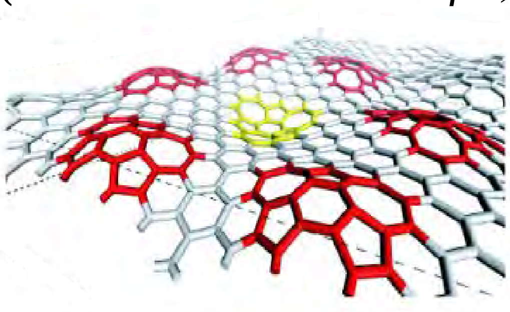
$$|\Downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$



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 ?**

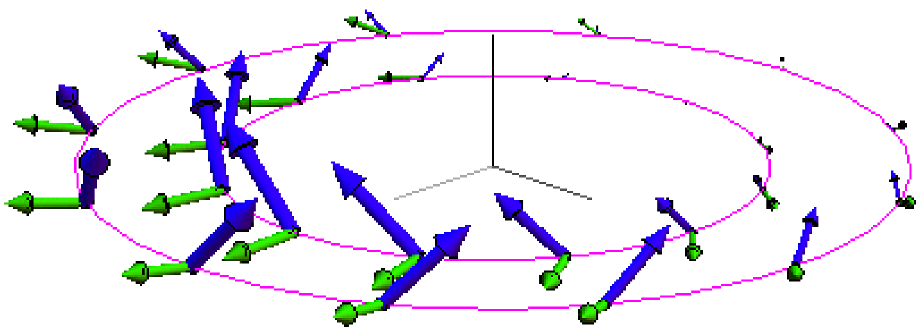
nature physics

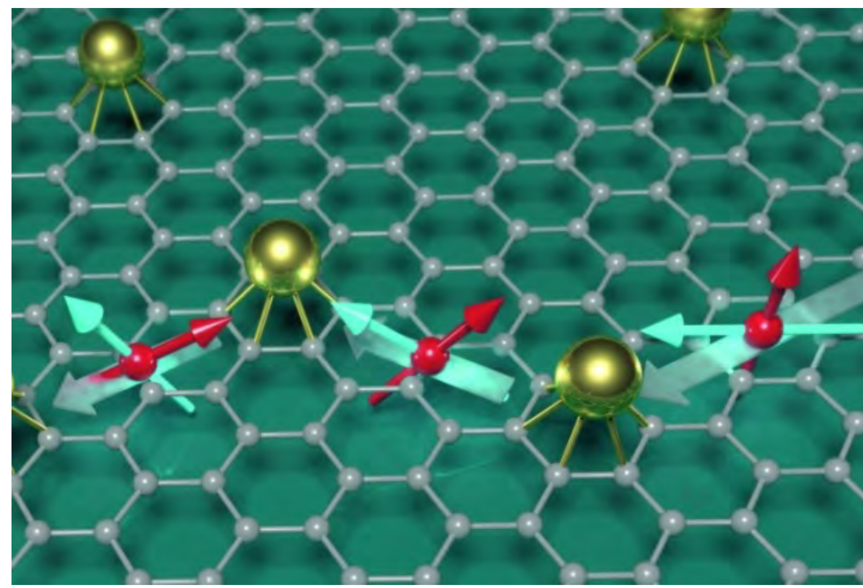
ARTICLES

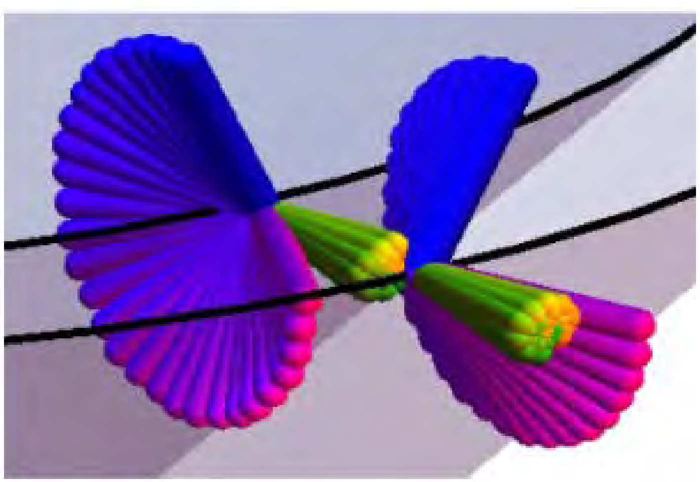
PUBLISHED ONLINE: 14 SEPTEMBER 2014 | DOI: 10.1038/NPHYS3083

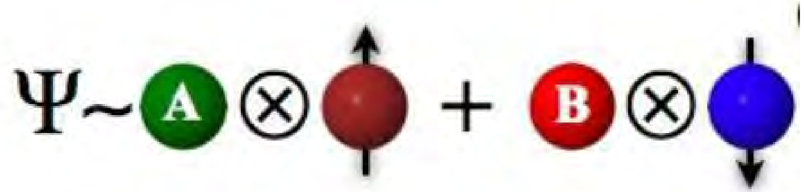
Pseudospin-driven spin relaxation mechanism in graphene

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





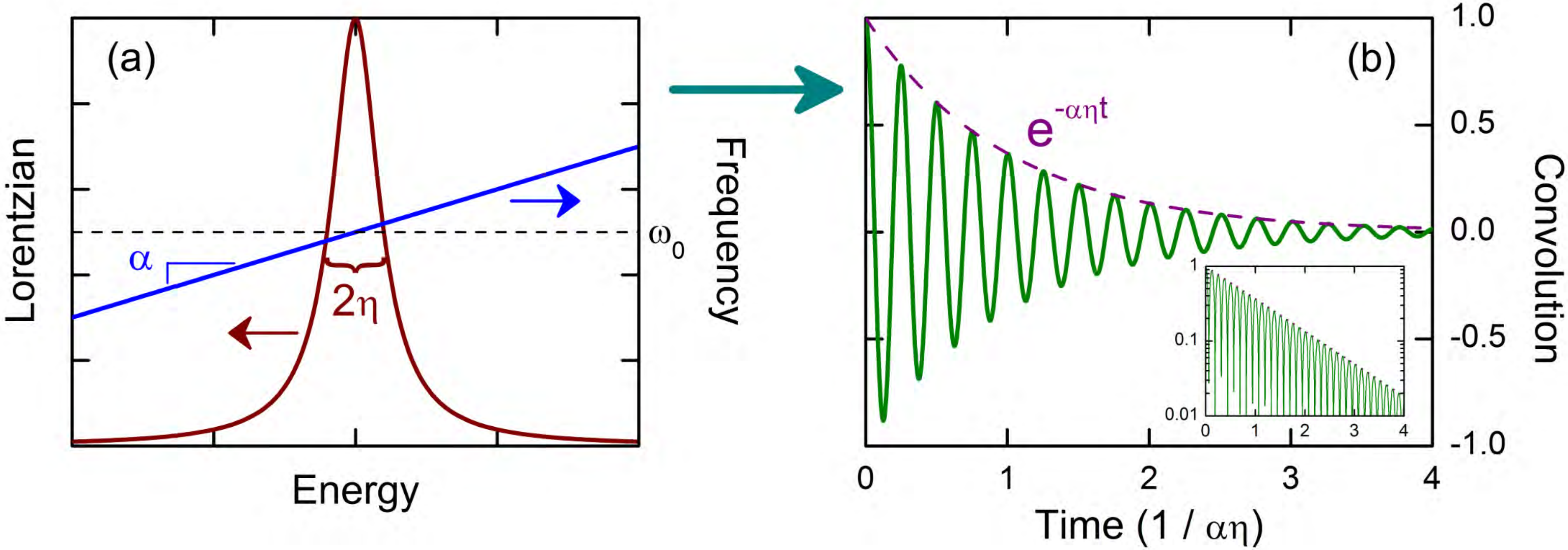




Relaxation in the ultraclean limit....

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

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

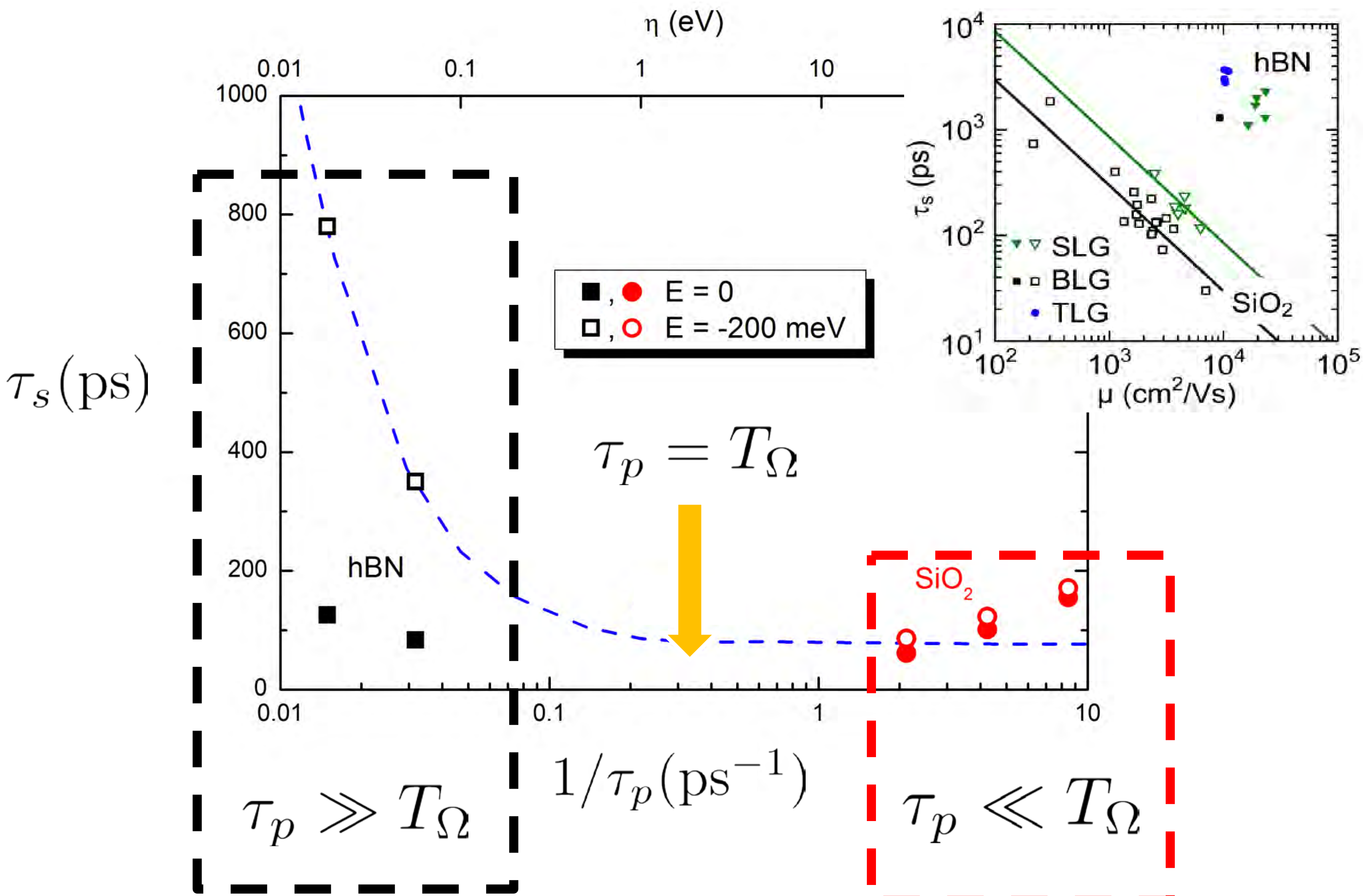


Exponentially-decaying cosine, with frequency ω_0 and decay time $1/\alpha\eta$

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

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

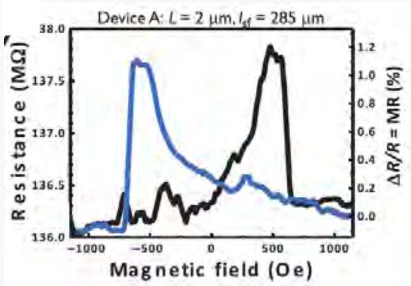
Crossover between "pure dephasing" and scattering-induced Dyakonov-Perel



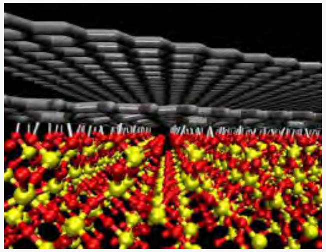
OUTLINE

ICN2
Institut Català de Nanociència i Nanotecnologia

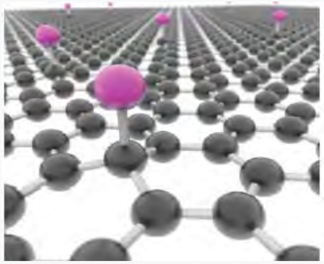
Why Spintronics using 2D Materials ?



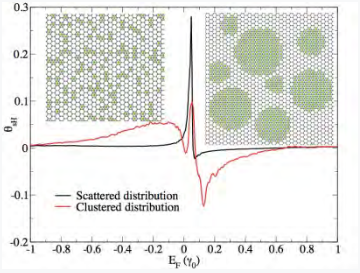
How the substrate controls spin dynamics?



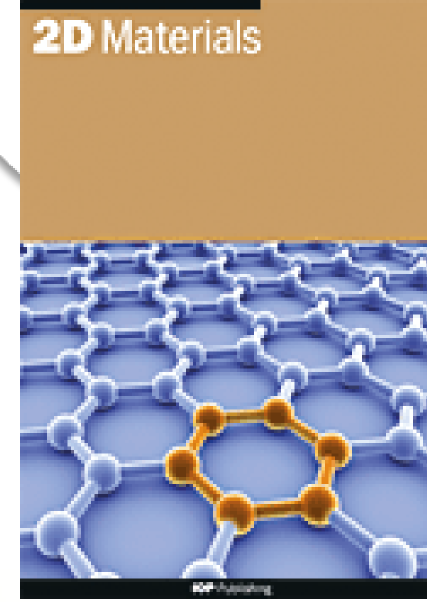
Giant spin transport anisotropy in graphene induced by strong SOC 2D materials

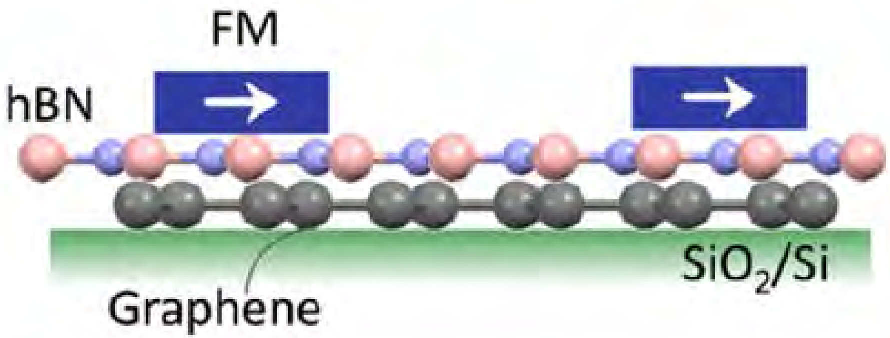


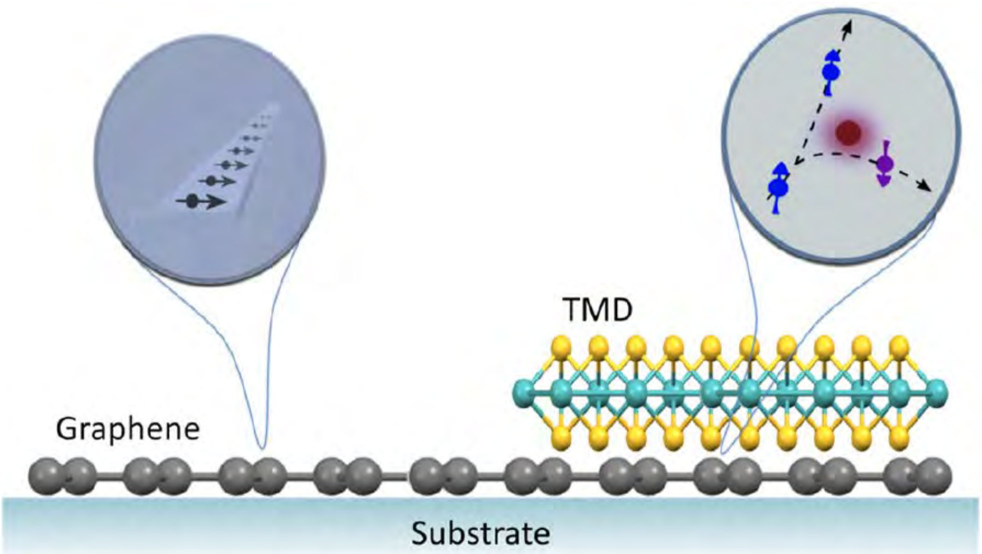
Spin Hall Effect and Weak antilocalization in Graphene/TMDC



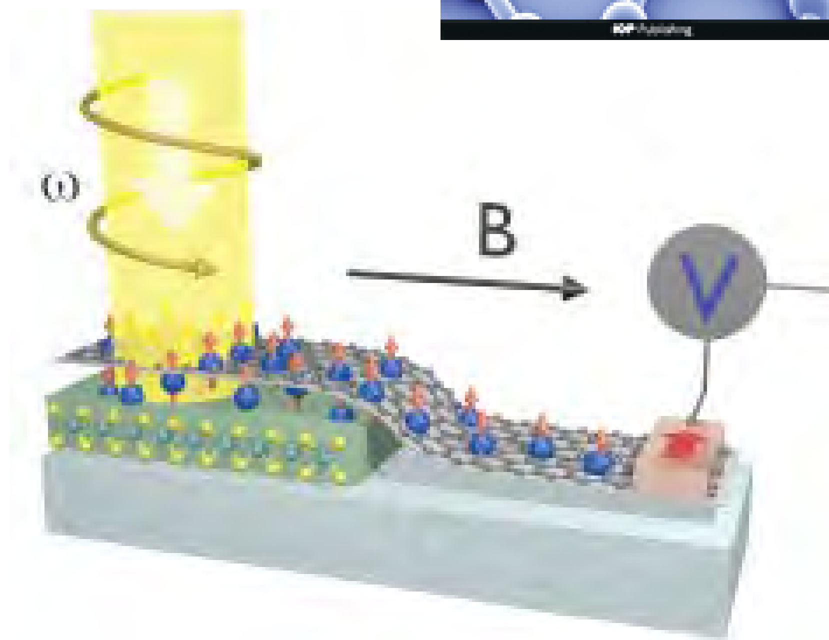
Hybrid devices of graphene and other 2D materials





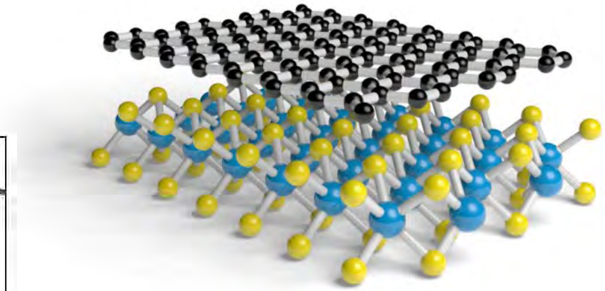


2D Mater. 2 (2015) 030202



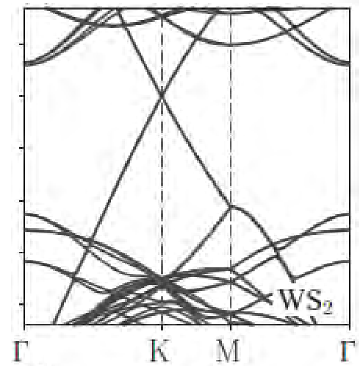
Martin Gmitra and Jaroslav Fabian
Phys. Rev. B **92**, 155403 (2015)

Realistic Model of Graphene/TMDC
with interface disorder



DFT-TB model from

M. Gmitra , D. Kochan, P. Högl, & J.Fabian
PRB **93**, 155104 (2016)

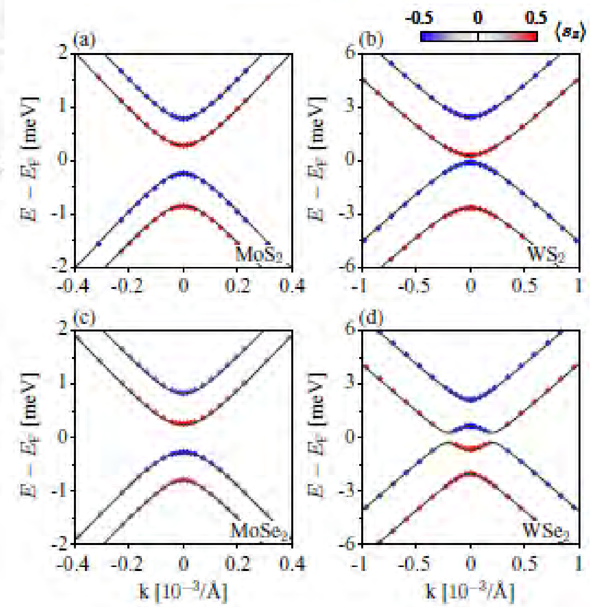


$$H_0 = -t \sum_{\langle i,j \rangle} \left(a_i^\dagger b_j + b_i^\dagger a_i \right) + \frac{\Delta}{2} \sum_i (a_i^\dagger a_i - b_i^\dagger b_i)$$

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

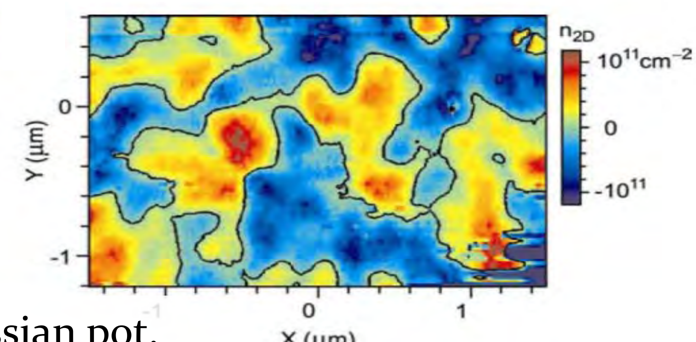
$$+ \frac{2i}{3} \sum_{\langle\langle i,j \rangle\rangle, \sigma} (\hat{\boldsymbol{s}} \times \boldsymbol{D}_{i,j})_{z,\sigma,\bar{\sigma}} \left(\lambda_{\rm PIA}^{(A)} \, a_{i,\sigma}^\dagger a_{j,\bar{\sigma}} + \lambda_{\rm PIA}^{(} \, b_{i,\sigma}^\dagger b_{j,\bar{\sigma}} \right)$$

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



Random distribution of n_p electron-hole puddles

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

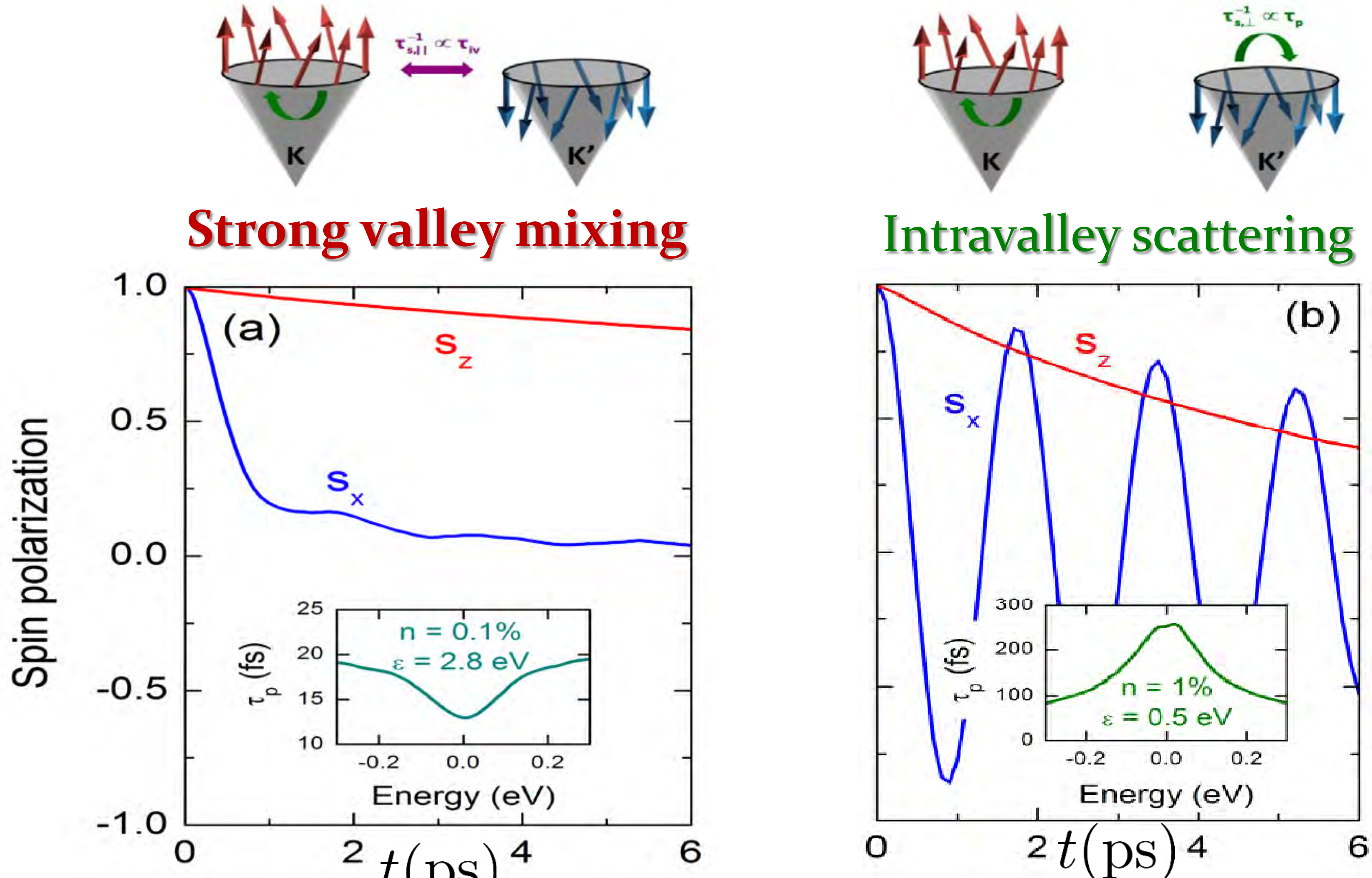


$$U_n(\boldsymbol{r}) = u_n \exp\left(-\frac{(\boldsymbol{r} - \boldsymbol{R}_n)^2}{2\xi_{\rm p}^2} \right) \qquad \xi_{\rm p} = \sqrt{3}a \quad \text{Puddle range}$$

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

Spin dynamics for graphene/TMDC+ el-h puddles

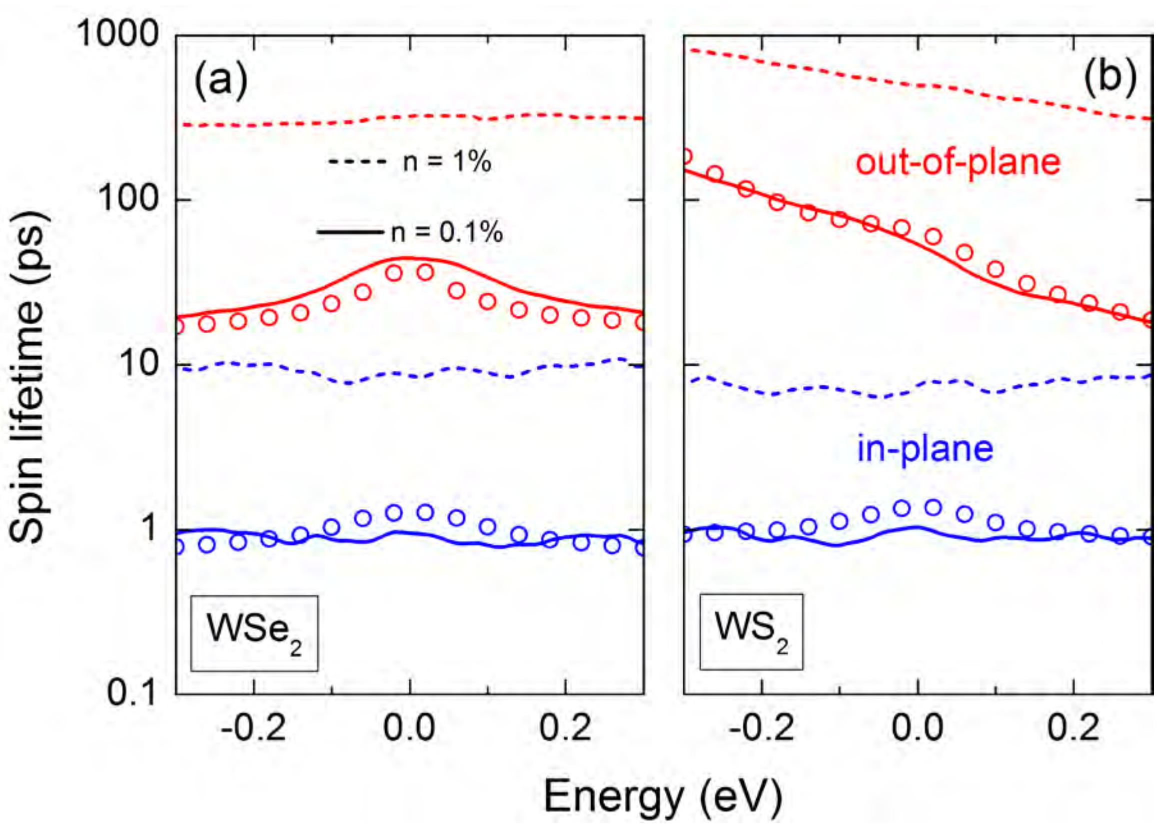
A. W. Cummings, J.H. García, J. Fabian, S. Roche, arXiv:1705.10972



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

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

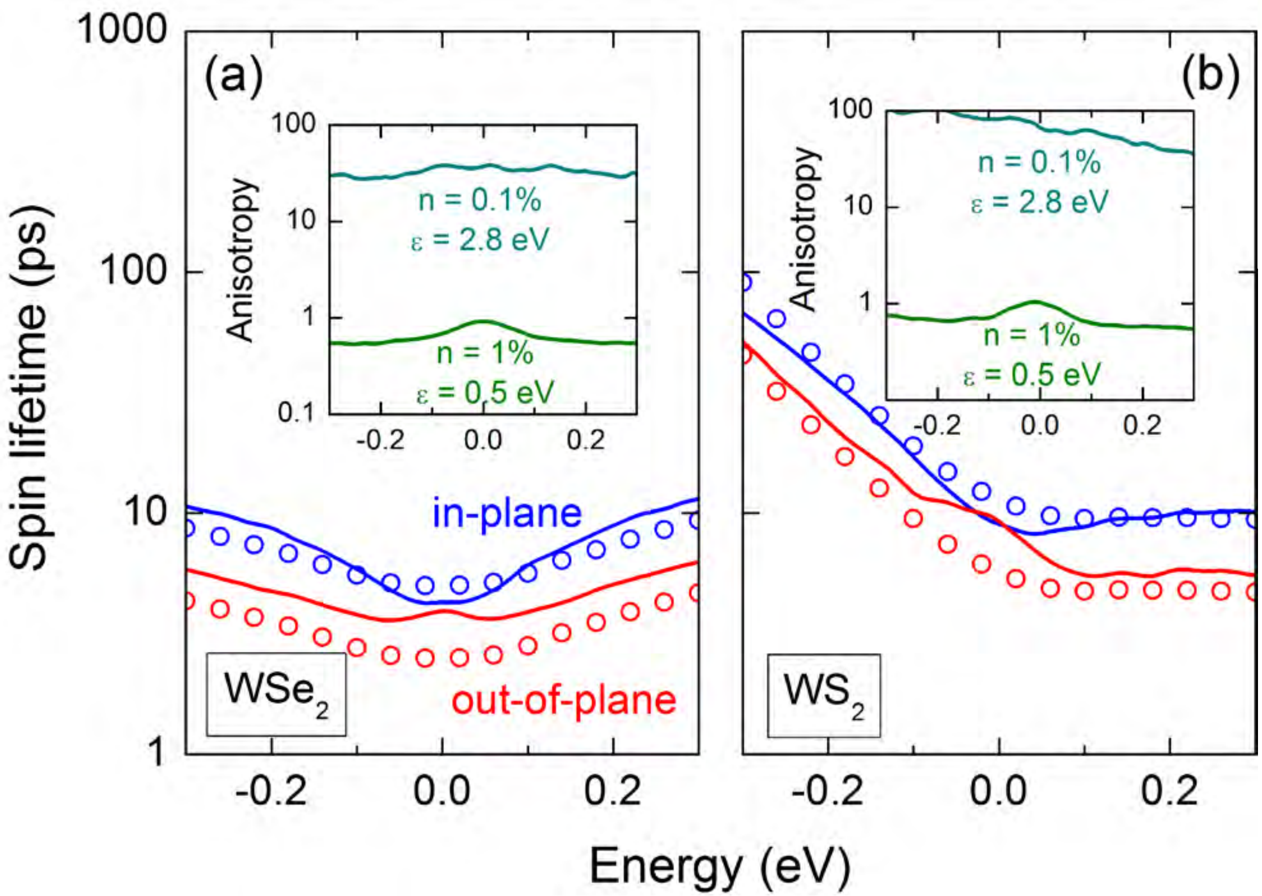
$$H = H_0 + \frac{1}{2}\hbar\vec{\omega}(t)\cdot\vec{s} \qquad \overline{\omega_\alpha(t)\omega_\beta(t')} = \delta_{\alpha\beta}\overline{\omega_\alpha^2}\mathrm{e}^{-|t-t'|/\tau_{c,\alpha}},$$

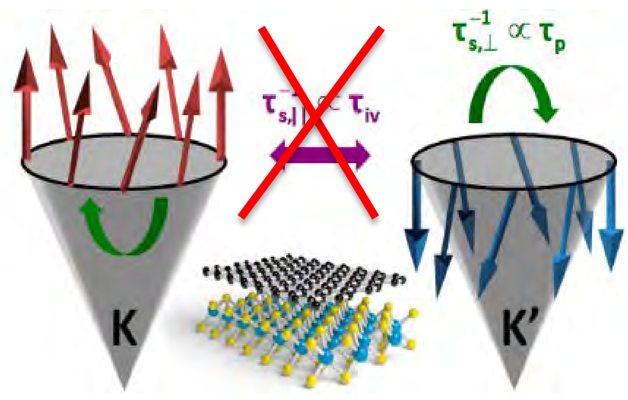
$$\frac{\mathrm{d}\overline{\rho_I(t)}}{\mathrm{d}t} = \left(\frac{1}{i\hbar}\right)^2 \int_0^{t\gg\tau_c} \overline{[V_I(t),[V_I(t'),\overline{\rho_I(t)}]]}\,\mathrm{d}t',$$

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

Spin transport anisotropy in Graphene/TMDC

(intravalley scattering only)



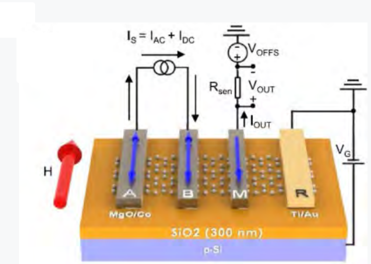


For higher quality interfaces
Spin lifetimes (**out-of-plane**)
Much smaller

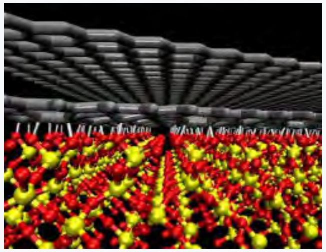
Anistropy around ½
as in conventional Rashba
Disordered systems

OUTLINE

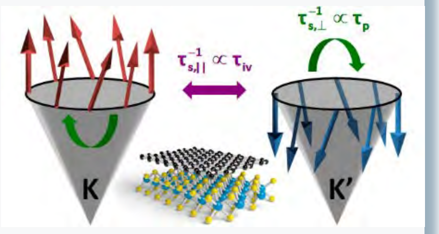
Why Spintronics using 2D Materials ?



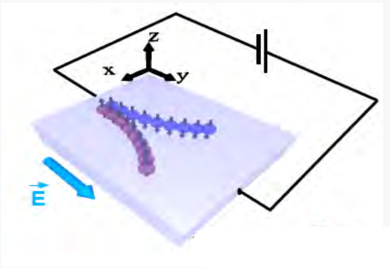
How the substrate controls spin dynamics?



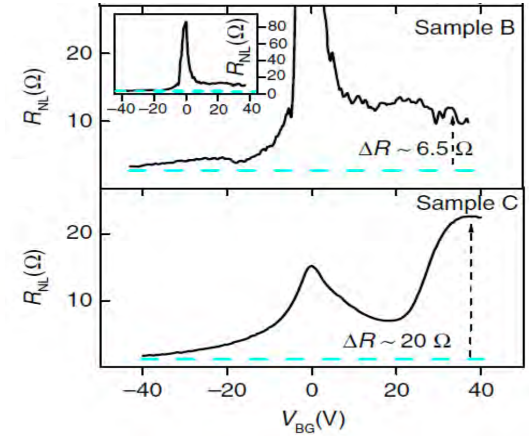
Giant spin transport anisotropy
in graphene induced by strong SOC
Proximity effect



Spin Hall Effect & Weak antilocalization
in Graphene/TMDC



nature COMMUNICATIONS

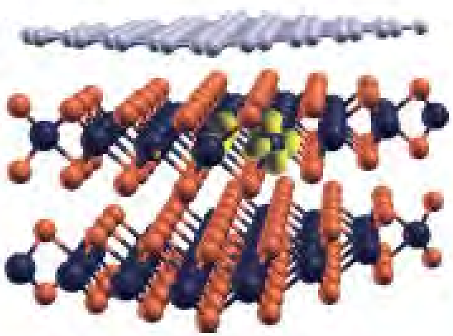


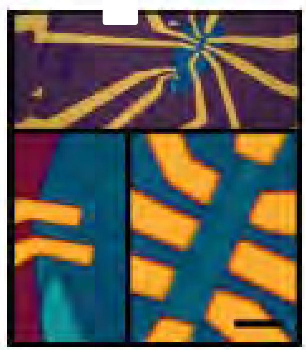
ARTICLE

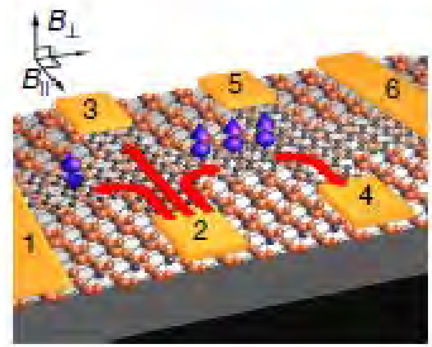
Received 10 Mar 2014 | Accepted 31 Jul 2014 | Published 26 Sep 2014

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. Carval
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]







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

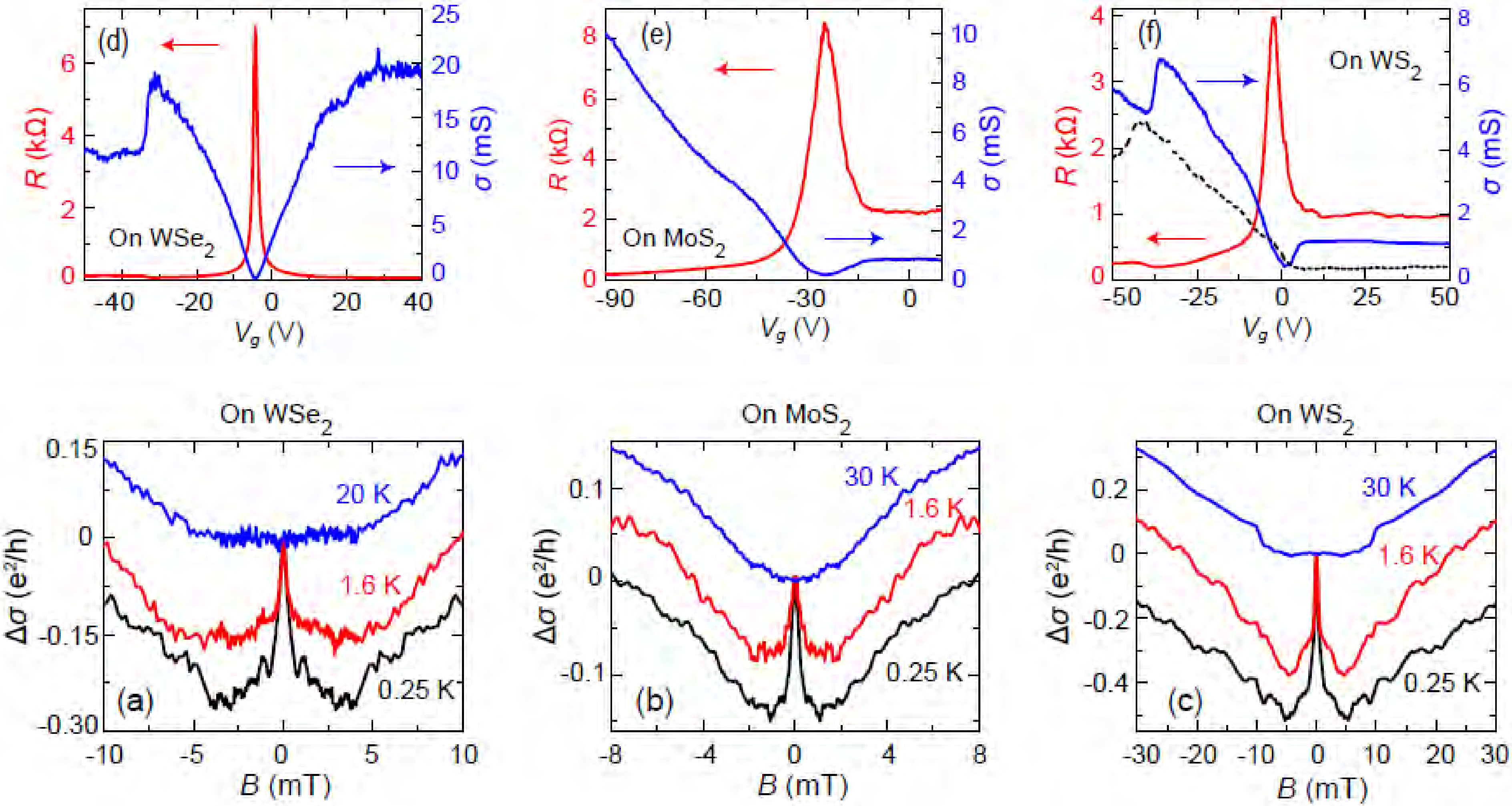
"Graphene acquires spin–orbit coupling up to ***17 meV,*** *three orders of magnitude higher than its intrinsic value, without modifying the structure of the graphene.*

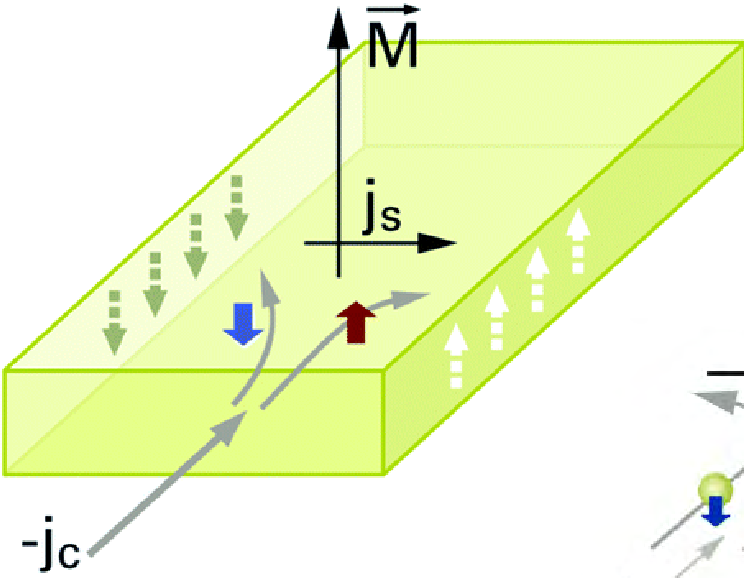
The proximity SOC leads to the spin Hall effect even at room temperature,

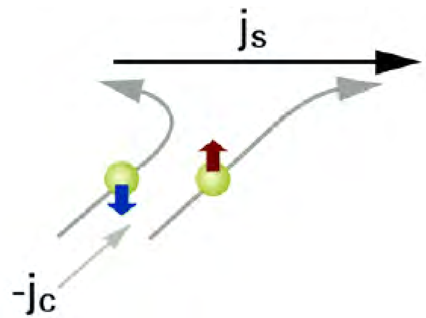
and opens the door to spin field effect transistors"

Weak antilocalization by proximity effect

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







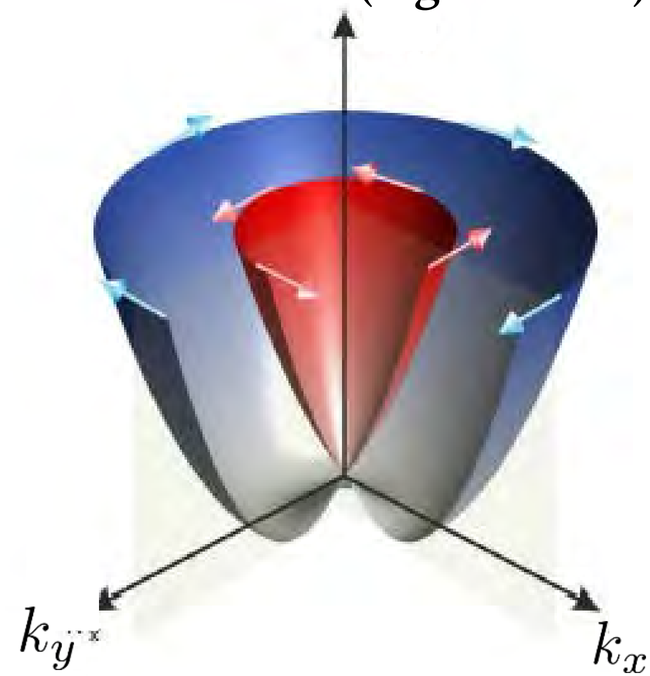
Spin Hall Effect

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

Intrinsic mechanism

Sinova (2005),...

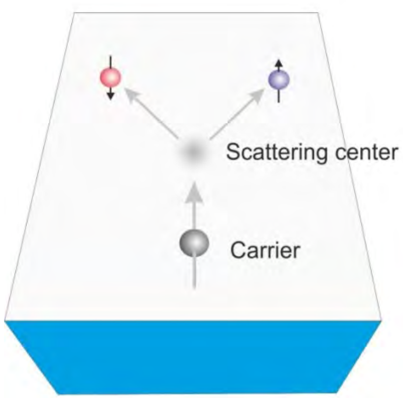
Band Structure (e.g. Rashba)



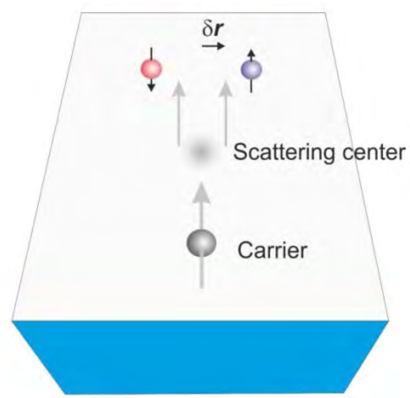
Extrinsic mechanisms

Dyakonov-Perel (1971); Hirsh (1999)

Skew Scattering



Side-Jump Scattering



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

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

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

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

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

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

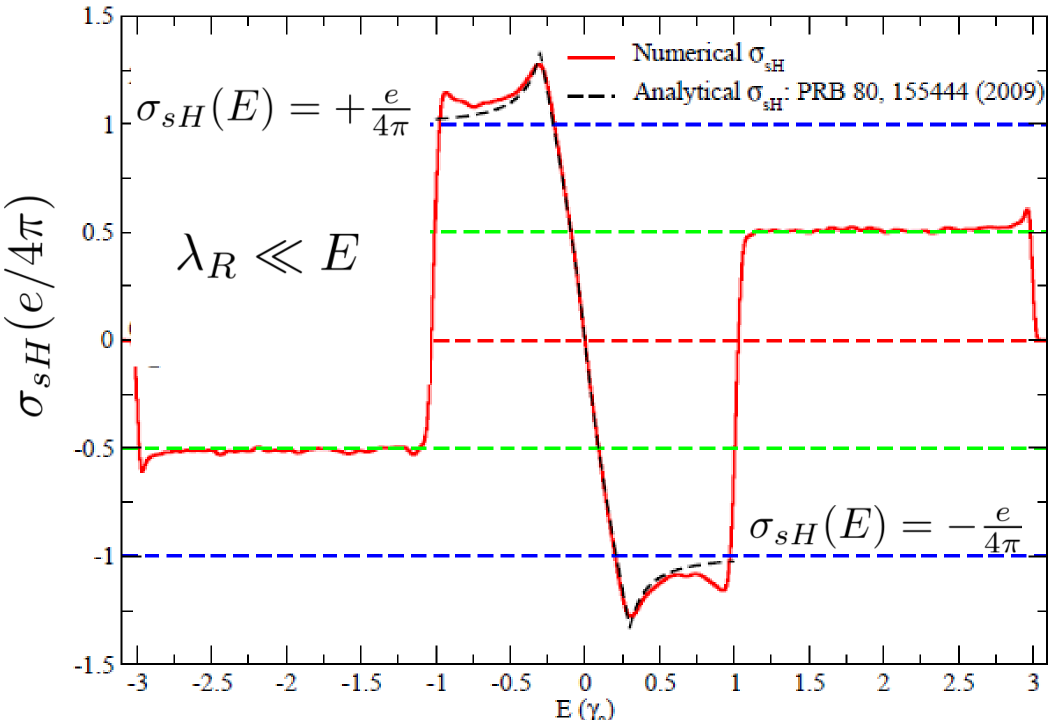
$$\sigma_{xx} = \frac{2\hbar e^2}{\pi \Omega} \sum_{m,n=0}^{M} \mathcal{I}m[g_m(\epsilon + i\eta)] \mathcal{I}m[g_n(\epsilon + i\eta)] \mu_{mn}$$

dc-Kubo conductivity

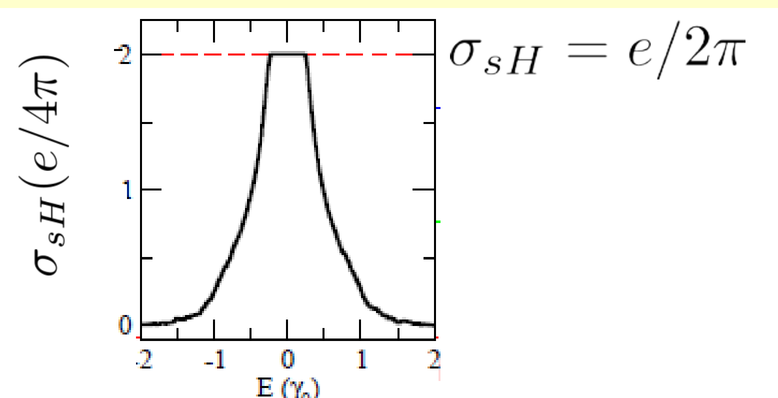
Validation: homogeneous SOCs

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)



SHE induced
by metallic ad-atoms onto graphene

ARTICLE

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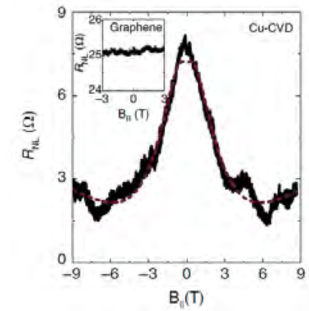
DOI: 10.1038/ncomms5748



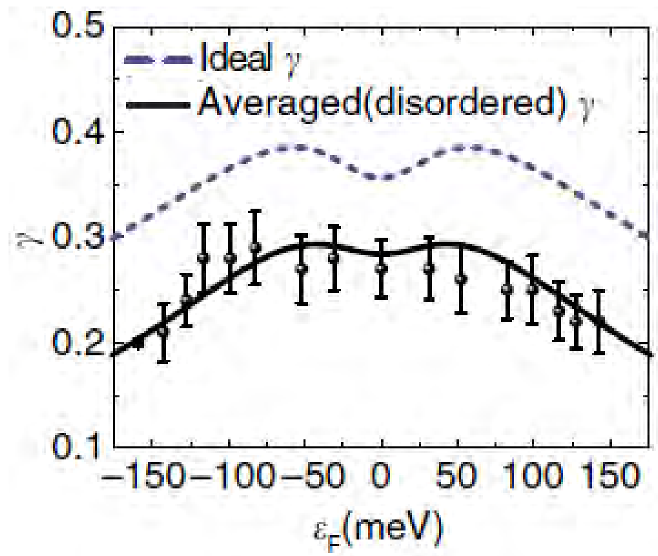
Giant spin Hall effect in graphene grown by chemical vapour deposition

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

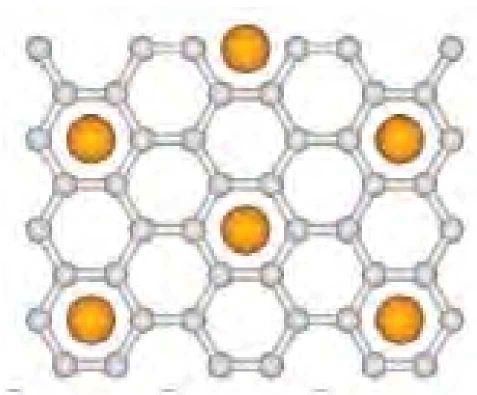
CVD, chemical vapour deposition; EPG, exfoliated pristine graphene.
The extracted values for Δ assume predominant intrinsic SOC (see main text).

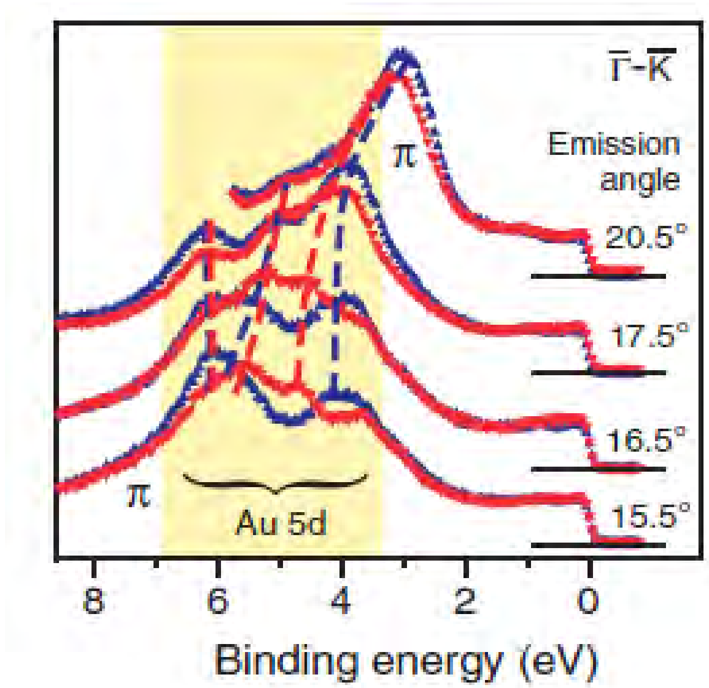


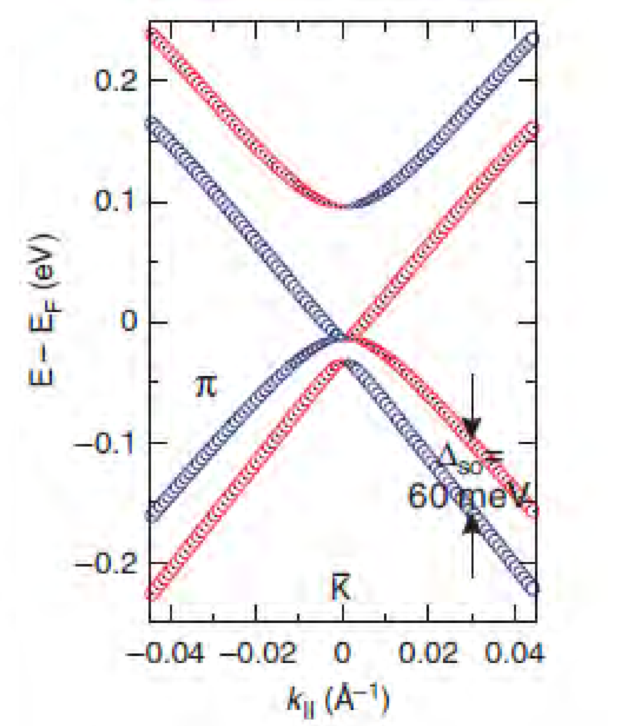
intrinsic-like spin–orbit interaction (20meV), Elliot-Yafet and skew scattering

Giant Rashba Splitting in graphene hybridized with Au-adatoms

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



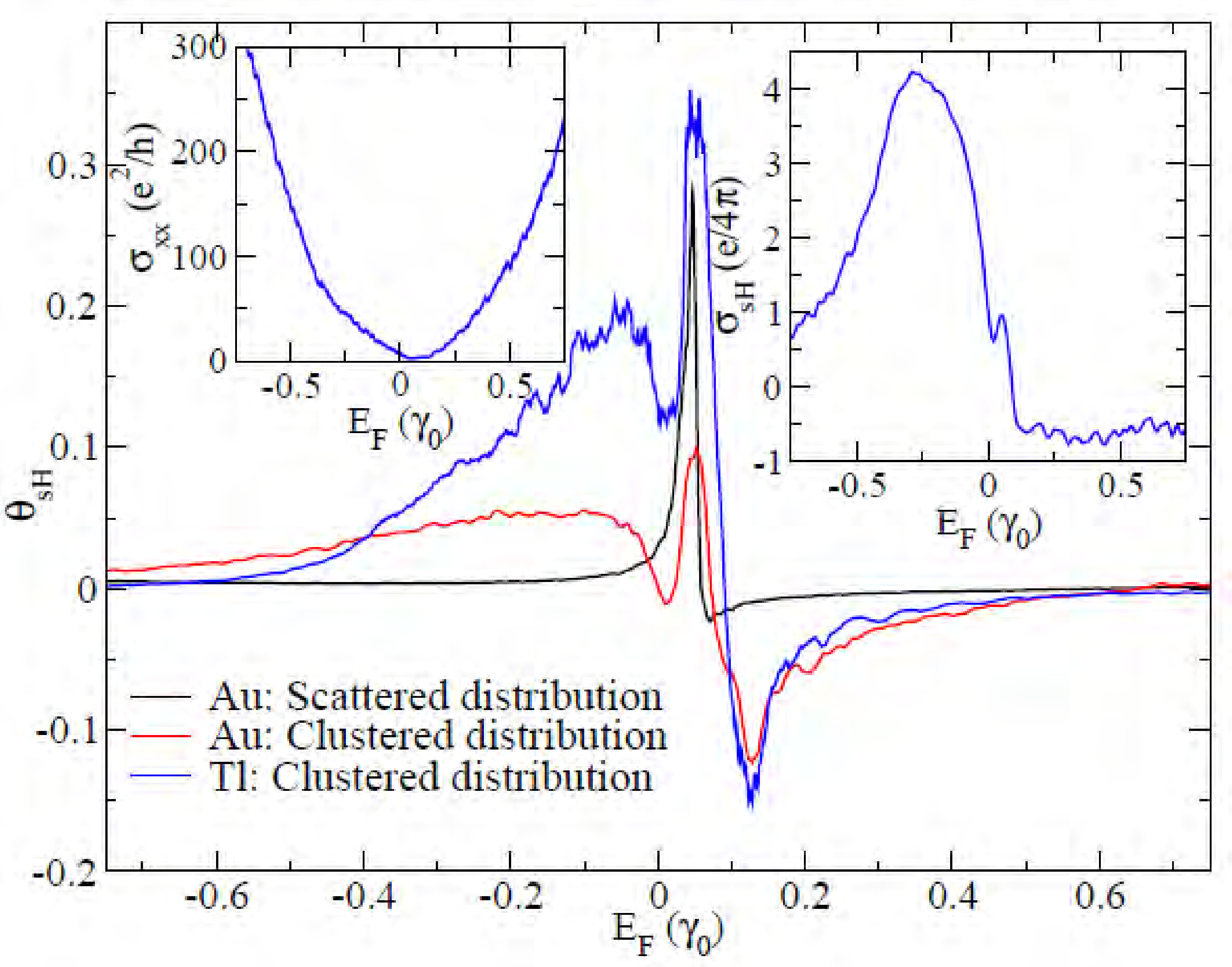




Au intercalation at the graphene–Ni interface creates a **giant spin–orbit splitting (60 meV)**

Spin Hall angles

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



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

(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...

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

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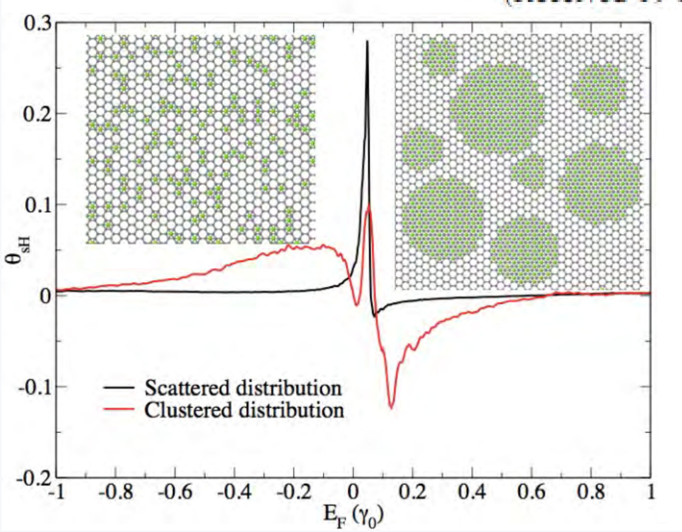

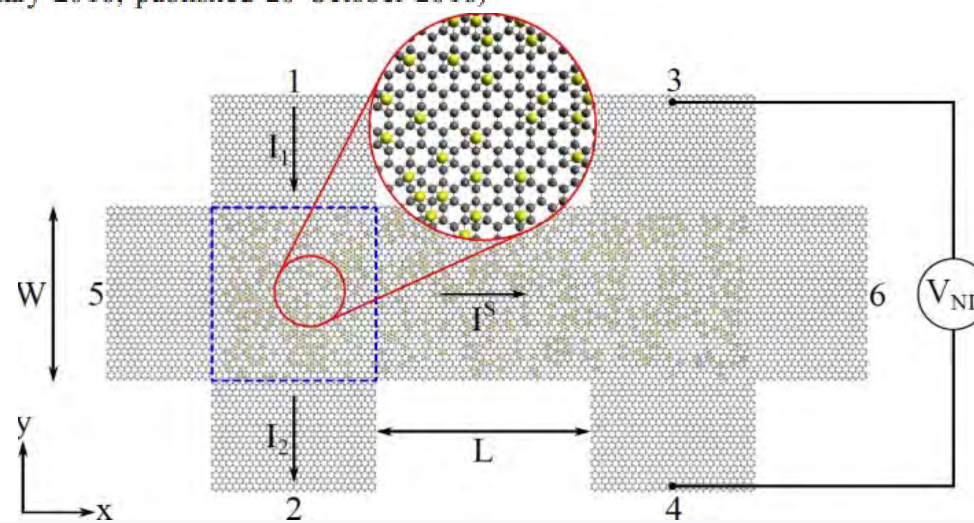

$$\theta_{\rm sH} = \sigma_{\rm sH}/\sigma_{xx}$$

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

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]
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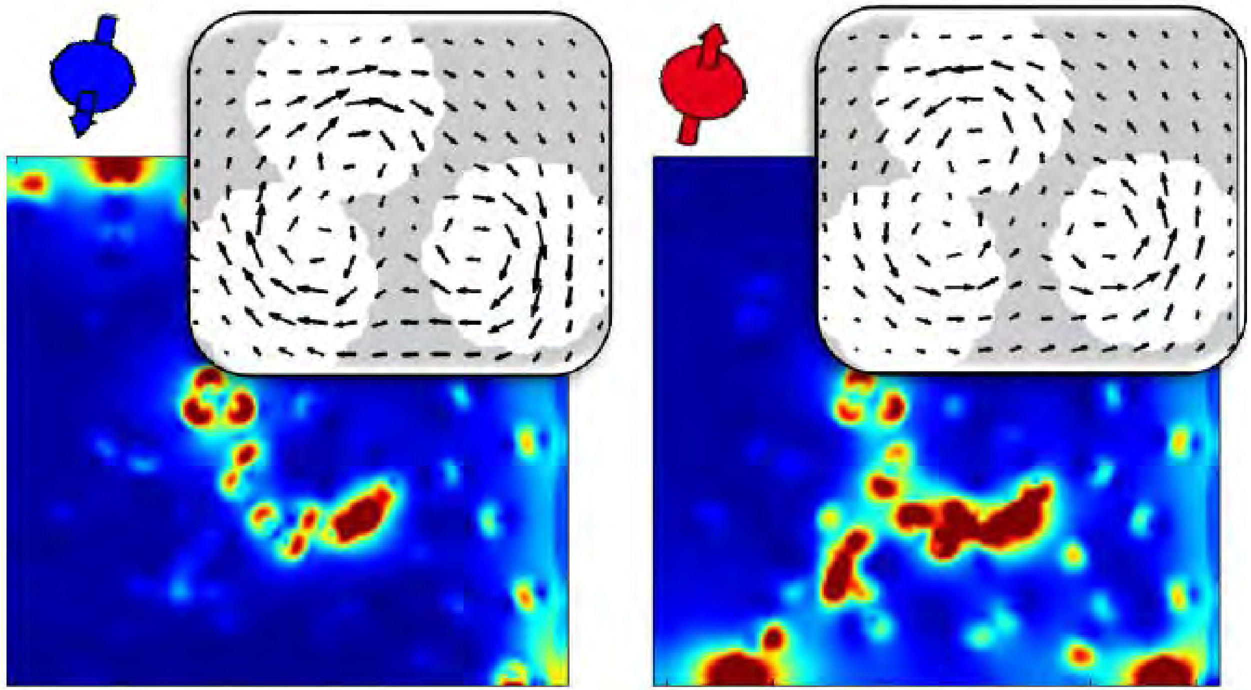
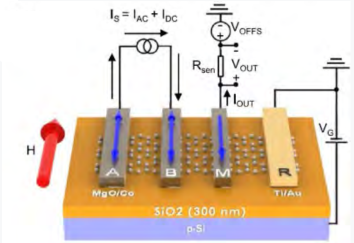
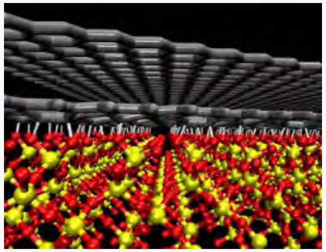


THANK YOU FOR YOUR ATTENTION

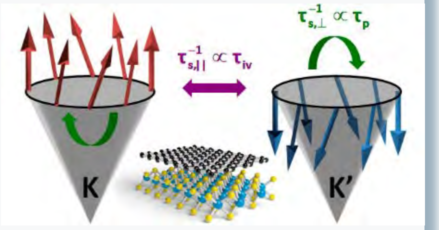
Why Spintronics using 2D Materials ?



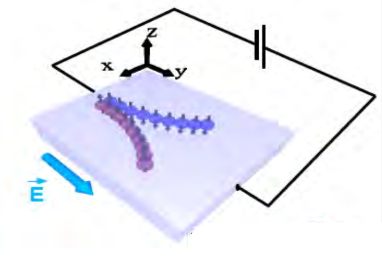
How the substrate controls spin dynamics?



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



Spin Hall Effect & Weak antilocalization
in Graphene/TMDC



Related Publications

- D. Van Tuan, F. Ortmann, D. Soriano, S.O. Valenzuela, S. Roche,
  Pseudospin-driven spin relaxation mechanism in graphene',
  Nature Physics, 10, 857-863 (2014)
- A. Cresti, D. Van Tuan, D. Soriano, A. W. Cummings, S. Roche 2014, *'Multiple Quantum Phases in Graphene with Enhanced Spin-Orbit Coupling : from Quantum Spin Hall Regime to Spin Hall Effect and Robust Metallic State*',
  Physical Review Letters, 113, 246603 (2014).
- A.W. Cummings and S. Roche , *′Effects of Dephasing on Spin Lifetime in Ballistic Spin-Orbit Materials′*,
  Physical Review Letters 116, 086602 (2016)
- D. Van Tuan and S. Roche, *′Spin manipulation in graphene by chemically induced pseudospin polarization′*,
  Physical Review Letters 116, 106601 (2016)
- D. Van Tuan, J. M. Marmolejo-Tejada, X. Waintal, B.K. Nikolic, S. Roche,
  Physical Review Letters 117176602 (2016)
- D. Van Tuan, F. Ortmann, A.W. Cummings, D. Soriano, S. Roche,
  ′Spin dynamics and relaxation in graphene dictated by el-h puddle
  Scientific Reports 6, 21046 (2016)
- A. W. Cummings, J.H. García and S. Roche, ‘
  Giant Spin Lifetime Anisotropy in Graphene Induced by Proximity Effects
  Physical Review Letters (submitted)