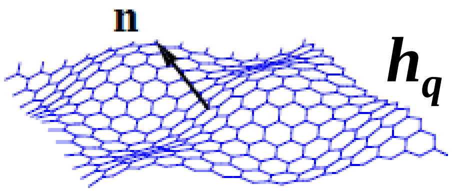
Spintronics in 2D hexagonal crystals

Vladimir Falko



- **2DHC band structure, SPD *kp* theory, *z->-z* symmetry and spin-lattice relaxation due to flexural deformations in 2DHCs**

Ochoa, Guinea, VF - PRB 88, 195417 (2013); Ochoa, Castro Neto, Guinea, VF – PRB 86, 245411 (2012)
Kormányos, Zólyomi, Drummond, Rakyta, Burkard, VF - PRB 88, 045416 (2013)

- **SO coupling and WL/WAL in graphene** McCann and VF, PRL 108, 166606 (2012)
- **spin-flip processes and spin ½ defects in graphene shown by WL**

Kashuba, VF + NPL + Chalmers + Vancouver (2013)

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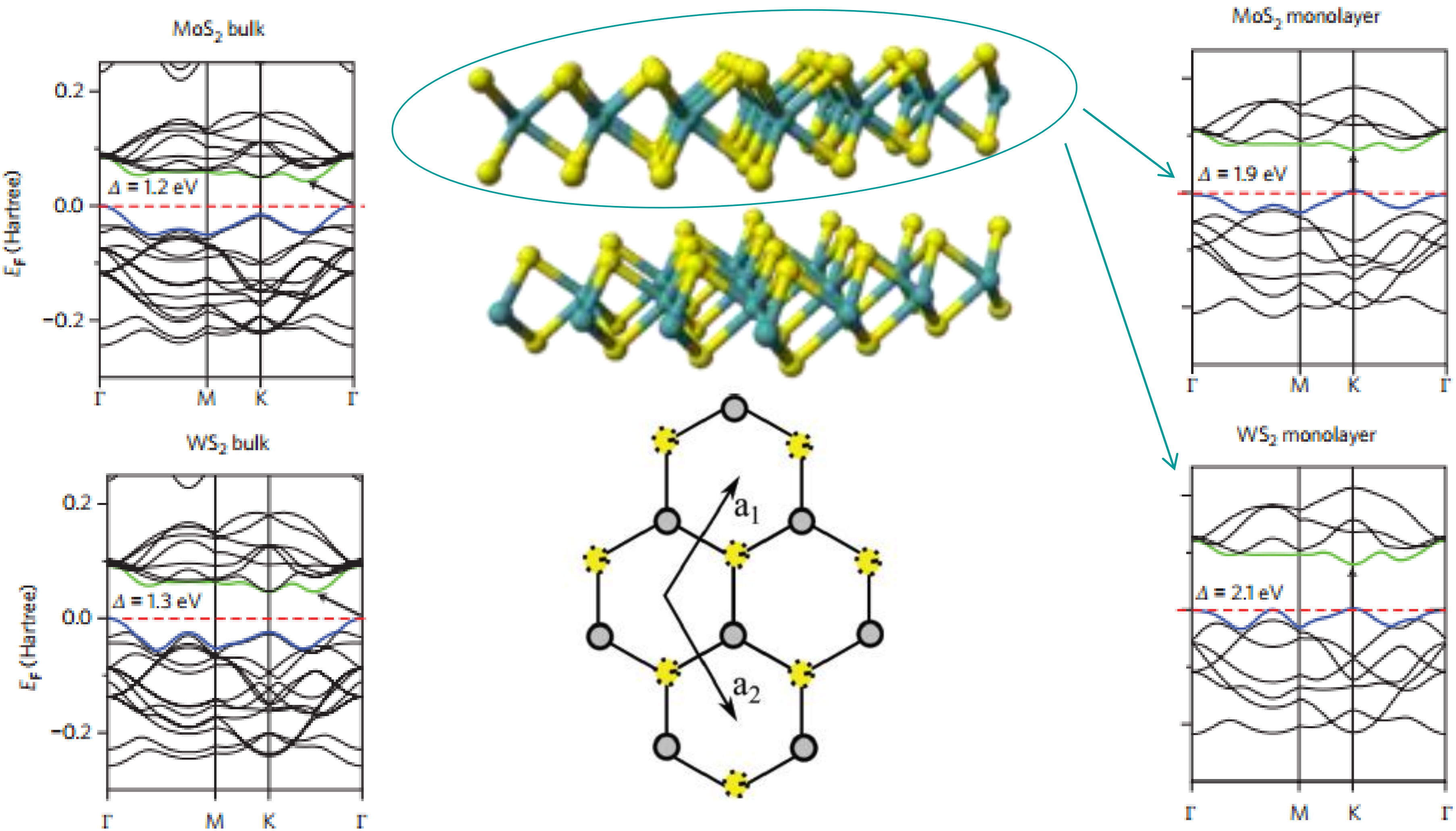
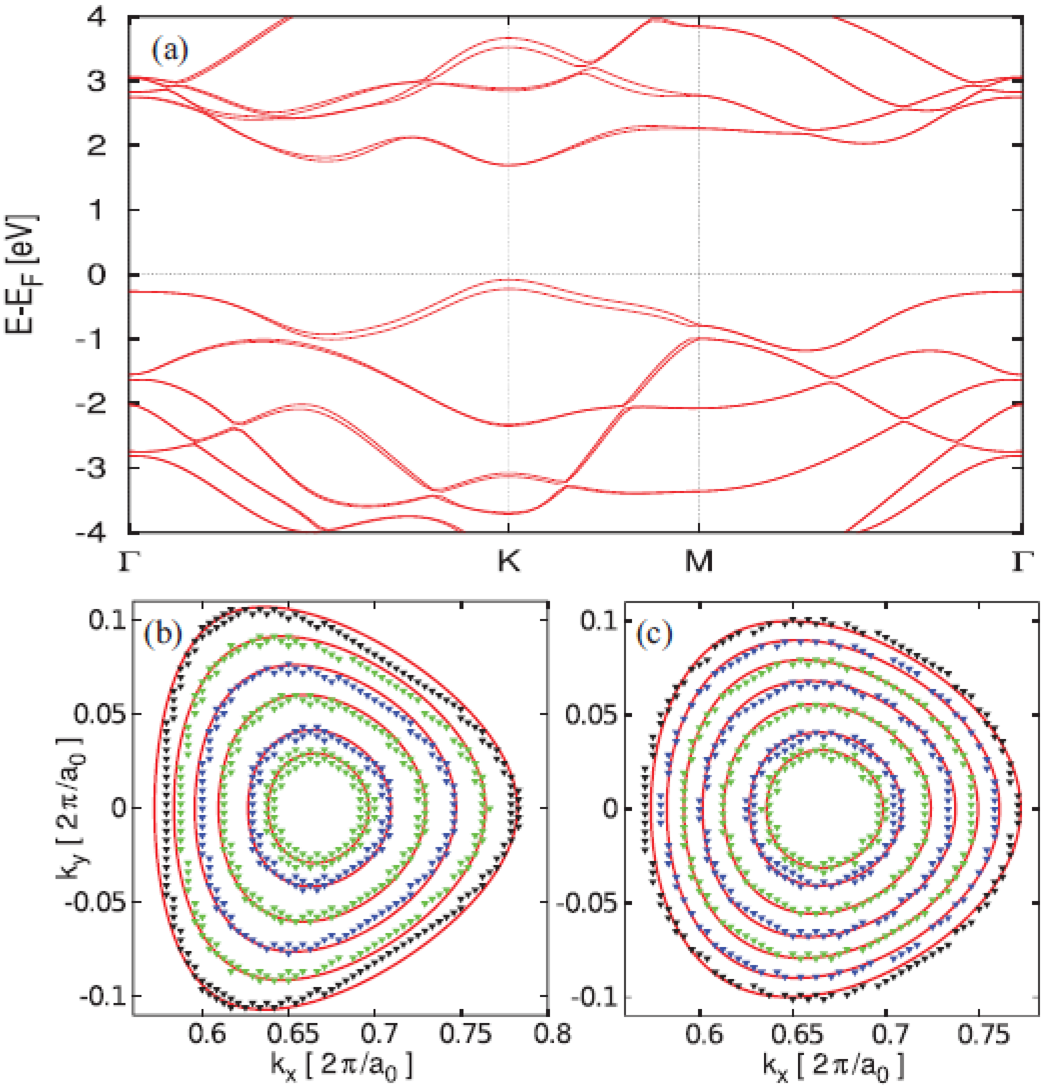
Transition metal dichalcogenides: MoS_2, $MoSe_2$, WSe_2



Bromley, Murray, Yoffe – JP-C 5, 759 (1972)
Mattheis - PRB 8, 3719 (1973)

Kuc, Zibouche, Heine - PRB 83, 245213 (2011)
Zhu, Cheng, Schwingenschlogl - PRB 84, 153402 (2011)

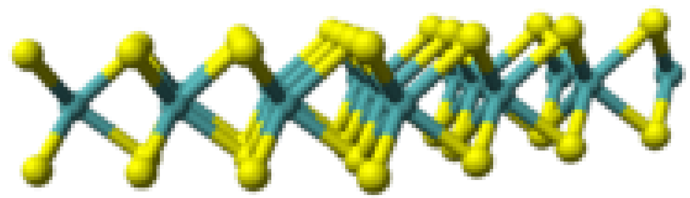
Transition metal dichalcogenide MoS_2



Kormányos, Zólyomi, Drummond, Rakyta, Burkard, VF - PRB 88, 045416 (2013)

Transition metal dichalcogenides: MoS_2, $MoSe_2$, WSe_2

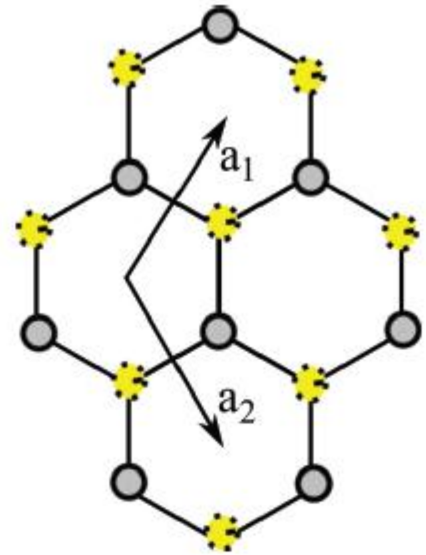
Material	ϵ_z (meV)
e-MoS_2	3
h-MoS_2	140
h-WS_2	430
h-$MoSe_2$	180
h-WSe_2	460



$z \longrightarrow -z$

symmetric

~~$S_{x,y}$~~



± 1 for

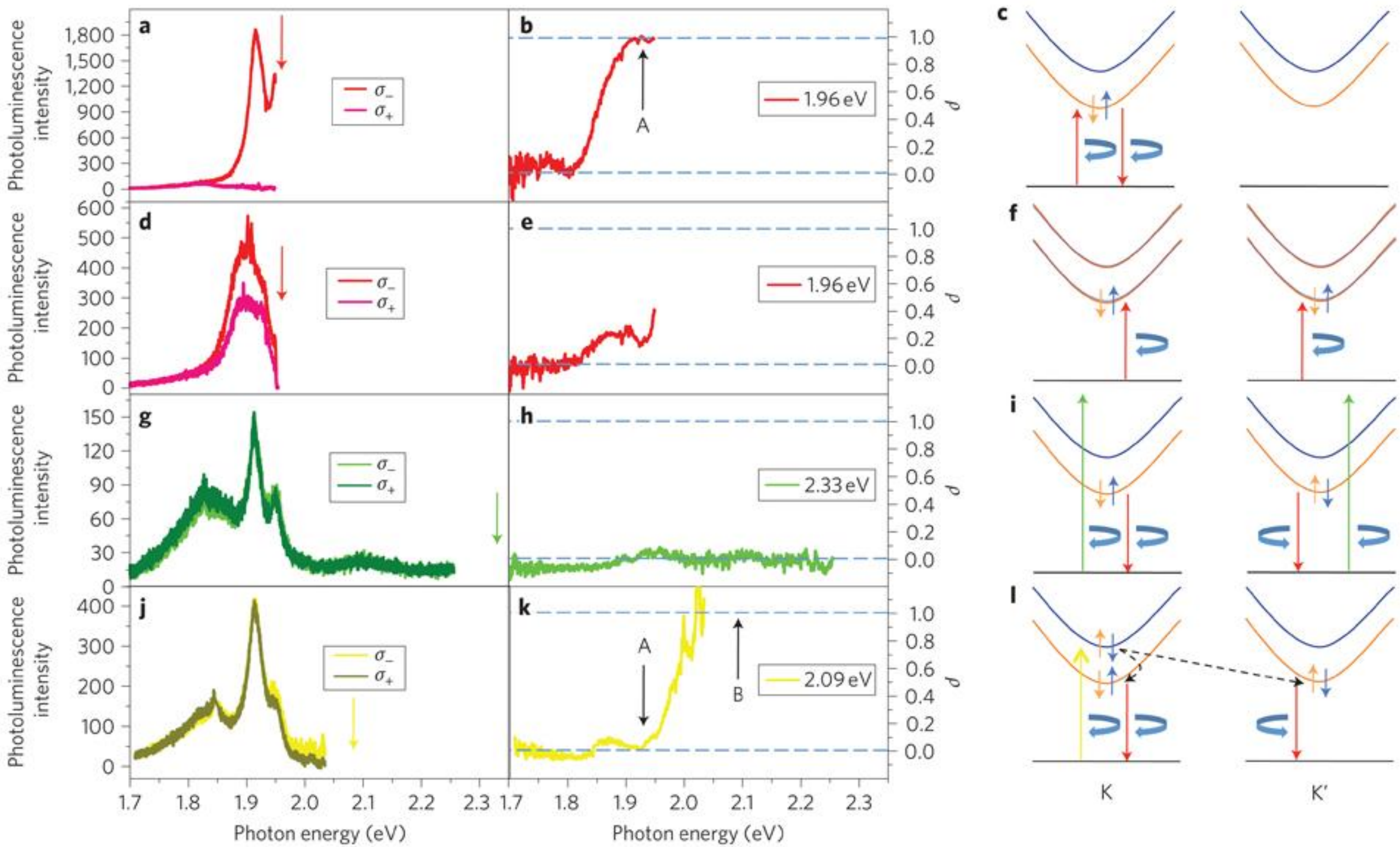
$\pm K$ valleys

$$\mathcal{H}(\pm\mathbf{K}+\mathbf{p}) = \mathcal{H}_{\text{band}}(\pm\mathbf{K}+\mathbf{p}) + \epsilon_z(\mathbf{p})\hat{\mathcal{L}}_z\hat{s}_z$$

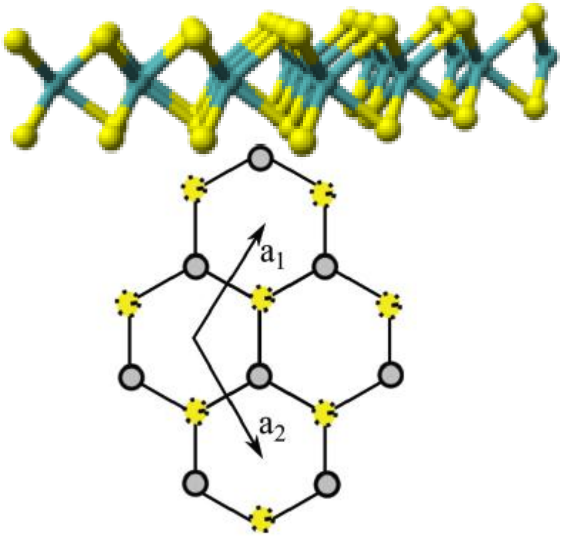
s_z conserves

Nanoseconds-long spin memory of optically excited carriers, observed in MoS_2, $MoSe_2$, WSe_2

Mak, He, Sahn, Heinz, Nature Nanotechnol. 7, 494 (2012)
Zeng, Dai, Yao, Xiao, Cui, Nature Nanotechnol. 7, 490 (2012)
Cao, et al., Nature Commun. 3, 887 (2012)

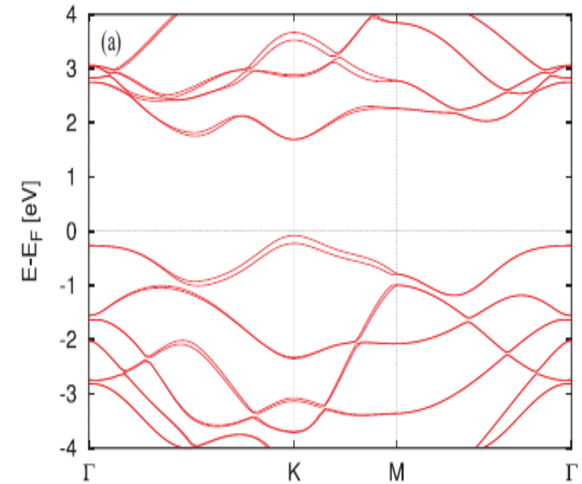


KP model for transition metal dichalcogenides (MoS_2)



$\lvert\Psi^{\mathrm{Mo}}_{2,-2}\rangle,\ \frac{1}{\sqrt{2}}\left(\lvert\Psi^{\mathrm{S1}}_{1,-1}\rangle + \lvert\Psi^{\mathrm{S2}}_{1,-1}\rangle\right)$	VB
$\lvert\Psi^{\mathrm{Mo}}_{2,1}\rangle,\ \frac{1}{\sqrt{2}}\left(\lvert\Psi^{\mathrm{S1}}_{1,-1}\rangle - \lvert\Psi^{\mathrm{S2}}_{1,-1}\rangle\right)$	$\mathrm{CB}+1$
$\lvert\Psi^{\mathrm{Mo}}_{2,0}\rangle,\ \frac{1}{\sqrt{2}}\left(\lvert\Psi^{\mathrm{S1}}_{1,1}\rangle + \lvert\Psi^{\mathrm{S2}}_{1,1}\rangle\right)$	CB
$\lvert\Psi^{\mathrm{Mo}}_{2,2}\rangle,\ \frac{1}{\sqrt{2}}\left(\lvert\Psi^{\mathrm{S1}}_{1,0}\rangle - \lvert\Psi^{\mathrm{S2}}_{1,0}\rangle\right)$	VB-3
	$\mathrm{CB}+2$
$\lvert\Psi^{\mathrm{Mo}}_{1,0}\rangle,\ \frac{1}{\sqrt{2}}\left(\lvert\Psi^{\mathrm{S1}}_{1,1}\rangle - \lvert\Psi^{\mathrm{S2}}_{1,1}\rangle\right)$	VB-2
$\lvert\Psi^{\mathrm{Mo}}_{2,-1}\rangle,\ \frac{1}{\sqrt{2}}\left(\lvert\Psi^{\mathrm{S1}}_{1,0}\rangle + \lvert\Psi^{\mathrm{S2}}_{1,0}\rangle\right)$	VB-1

$$H_{\mathbf{kp}} = \begin{pmatrix} \varepsilon_v & \gamma_3 q_- & \gamma_2 q_+ & \gamma_4 q_+ \\ \gamma_3 q_+ & \varepsilon_c & \gamma_5 q_- & \gamma_6 q_- \\ \gamma_2 q_- & \gamma_5 q_+ & \varepsilon_{v-3} & 0 \\ \gamma_4 q_- & \gamma_6 q_+ & 0 & \varepsilon_{c+2} \end{pmatrix}$$

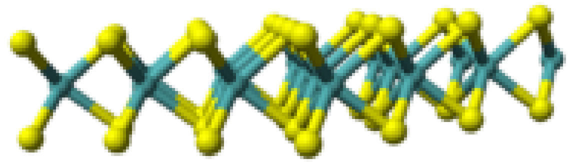


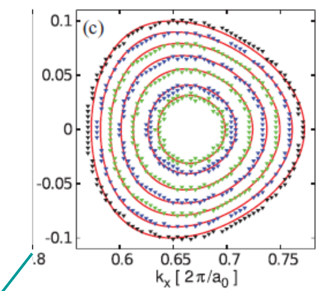
Kormányos, Zólyomi, Drummond, Rakyta, Burkard, VF - PRB 88, 045416 (2013)

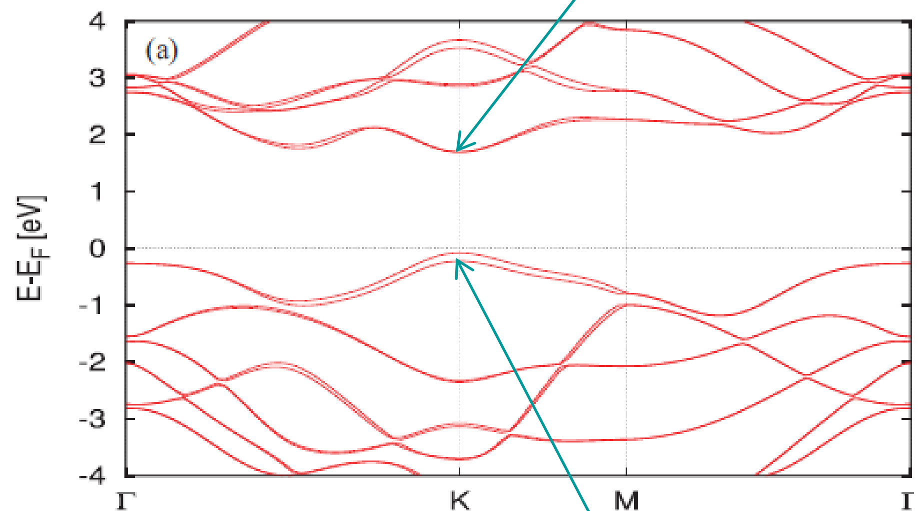
KP model for transition metal dichalcogenides (MoS_2)

Kormányos, Zólyomi, Drummond, Rakyta, Burkard, VF - PRB 88, 045416 (2013)

$$\left|\Psi^{Mo}_{2,0}\right\rangle, \ \frac{1}{\sqrt{2}}\left(\left|\Psi^{S1}_{1,1}\right\rangle + \left|\Psi^{S2}_{1,1}\right\rangle\right)$$





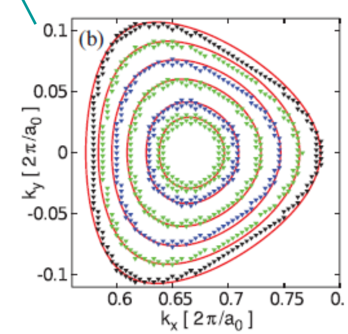


$$H_{\text{eff}} = H_0 + H_{\text{as}} + H_{3w} + H_{\text{cub}},$$

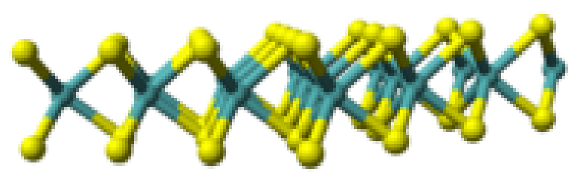
$$H_0 + H_{\text{as}} = \begin{pmatrix} \varepsilon_v & \tau\,\gamma_3 q_- \\ \tau\,\gamma_3\, q_+ & \varepsilon_c \end{pmatrix} + \begin{pmatrix} \alpha q^2 & 0 \\ 0 & \beta q^2 \end{pmatrix}$$

$$H_{3w} = \kappa \begin{pmatrix} 0 & (q_+)^2 \\ (q_-)^2 & 0 \end{pmatrix}$$

$$H_{\text{cub}} = -\tau\,\frac{\eta}{2} q^2 \begin{pmatrix} 0 & q_- \\ q_+ & 0 \end{pmatrix}$$



$$\left|\Psi^{Mo}_{2,-2}\right\rangle, \ \frac{1}{\sqrt{2}}\left(\left|\Psi^{S1}_{1,-1}\right\rangle + \left|\Psi^{S2}_{1,-1}\right\rangle\right)$$



± for ± *K* valleys

KP model for transition metal dichalcogenides (MoS_2)

Kormányos, Zólyomi, Drummond, Rakyta, Burkard, VF - PRB 88, 045416 (2013)

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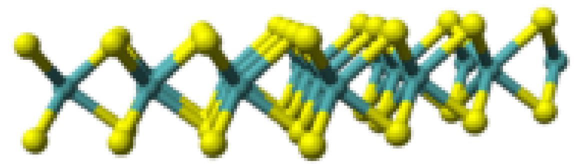

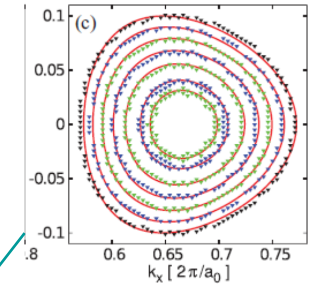

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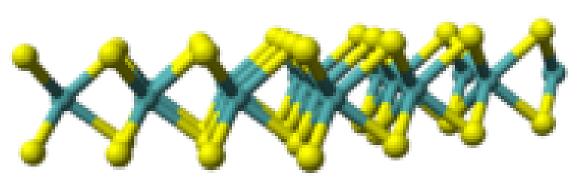
$$H_{3w} = \kappa \begin{pmatrix} 0 & (q_+)^2 \\ (q_-)^2 & 0 \end{pmatrix}$$

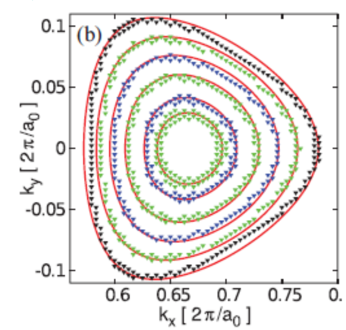
$$H_{\mathrm{cub}} = -\tau\,\frac{\eta}{2} q^2 \begin{pmatrix} 0 & q_- \\ q_+ & 0 \end{pmatrix}$$

	LDA	HSE06
α	1.73 eV Å^2	1.57 eV Å^2
β	−0.13 eV Å^2	0.1 eV Å^2
γ_3	3.82 eV Å	4.13 eV Å
κ	−1.02 eV Å^2	−1.12 eV Å^2
η	8.53 eV Å^3	7.87 eV Å^3
m^c_{eff}/m_e	0.48	0.43
m^v_{eff}/m_e	−0.62	−0.53

$$\left|\Psi^{\mathrm{Mo}}_{2,-2}\right\rangle,\ \frac{1}{\sqrt{2}}\left(\left|\Psi^{S1}_{1,-1}\right\rangle + \left|\Psi^{S2}_{1,-1}\right\rangle\right)$$

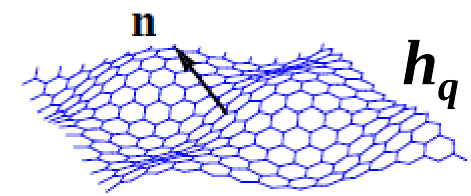


± for ± K valleys



Spin-lattice coupling and relaxation due to ripples

$$\mathcal{H}\left(\pm\mathrm{K}+\mathrm{p}\right)=\mathcal{H}_{band}\left(\pm\mathrm{K}+\mathrm{p}\right)+\epsilon_{z}\left(\mathrm{p}\right)\hat{\mathcal{L}}_{z}\hat{s}_{z}$$



short-range wrinkles $q \gg \epsilon_z / v$

$$H_{SO}=\epsilon_{z}\hat{\mathcal{L}}_{z}\hat{\mathbf{s}}\cdot\mathbf{n}\approx\epsilon_{z}\hat{\mathcal{L}}_{z}\hat{s}_{z}+\delta H_{g}$$

$$\delta H_{g}=-\epsilon_{z}\hat{\mathcal{L}}_{z}\left(\partial_{x}h\hat{s}_{x}+\partial_{y}h\hat{s}_{y}\right)$$

$$\tau_b^{-1}=\frac{2\pi}{N\hbar}\sum_{\mathbf{q}}e^{-\frac{1}{q\ell}}|\langle\mathbf{p}+\mathbf{q}\uparrow|\delta H_g|\mathbf{p}\downarrow\rangle|^2\delta(\varepsilon^{\uparrow}_{\mathbf{p}+\mathbf{q}}-\varepsilon^{\downarrow}_{\mathbf{p}})$$

spin relaxation in ballistic propagation

long-range wrinkles $q < \epsilon_x / v$

$$\hat{U}\mathcal{H}_{band}\left(\pm\mathbf{K}+\mathbf{p}\right)\hat{U}^{\dagger}\approx\mathcal{H}_{band}\left(\pm\mathbf{K}+\mathbf{p}\right)+\delta\tilde{H}_{g}$$

$$\delta\tilde{H}_{g}=\frac{1}{2}\left\{\frac{\partial\mathcal{H}_{band}}{\partial\mathbf{p}},\hat{U}\left(-i\hbar\partial\right)\hat{U}^{\dagger}\right\}$$
$$=\frac{\hbar}{2}\left[\hat{v}_{y}\hat{s}_{x}\partial_{y}^{2}h-\hat{v}_{x}\hat{s}_{y}\partial_{x}^{2}h+\left(\hat{v}_{x}\hat{s}_{x}-\hat{v}_{y}\hat{s}_{y}\right)\partial_{x}\partial_{y}h\right]$$

requires spin-diffusion theory

IrRep	$D_{3h} = D_3 \times \sigma_h$	
A_1'	$\mathcal{L}_z \hat{s}_z$	
A_2'		$\mathcal{L}_z, \hat{s}_z$
A_1''	$\hat{\mathbf{v}} \cdot \hat{\mathbf{s}}$	
A_2''	$\nabla^2 h, (\hat{\mathbf{v}} \times \hat{\mathbf{s}})_z$	
E'		$\begin{pmatrix} \hat{v}_x \\ \hat{v}_y \end{pmatrix}$
E''	$\begin{pmatrix} \partial_x^2 h - \partial_y^2 h \\ 2\partial_x \partial_y h \end{pmatrix}$, $\begin{pmatrix} \hat{v}_x \hat{s}_y + \hat{v}_y \hat{s}_x \\ \hat{v}_y \hat{s}_y - \hat{v}_x \hat{s}_x \end{pmatrix}$	$\begin{pmatrix} \hat{s}_x \\ \hat{s}_y \end{pmatrix}$
$t \to -t$	even	odd

$$\delta H_o = \lambda_{\parallel}[2h''_{xy}\hat{s}_x + (h''_{yy} - h''_{xx})\hat{s}_y]\hat{\mathcal{L}}_z + \hbar\beta(\mathbf{v} \times \mathbf{s})_z \nabla^2 h$$
$$+ \hbar\tilde{\beta}[(\hat{v}_x\hat{s}_y + \hat{v}_y\hat{s}_x)(h''_{xx} - h''_{yy}) + (\hat{v}_y\hat{s}_y - \hat{v}_x\hat{s}_x)2h''_{xy}]$$

Ochoa, Guinea, VF - PRB 88, 195417 (2013)

Spin-lattice coupling and relacxation due to ripples

$$\delta H_o = \lambda_{\parallel}[2h''_{xy}\hat{s}_x + (h''_{yy} - h''_{xx})\hat{s}_y]\hat{\mathcal{L}}_z + \hbar\beta(\mathbf{v}\times\mathbf{s})_z\nabla^2 h$$
$$+\hbar\tilde{\beta}[(\hat{v}_x\hat{s}_y + \hat{v}_y\hat{s}_x)(h''_{xx} - h''_{yy}) + (\hat{v}_y\hat{s}_y - \hat{v}_x\hat{s}_x)2h''_{xy}]$$

geometrical limit

(dominant for the valence band)

Ochoa, Guinea, VF - PRB 88, 195417 (2013)

$$\tilde{\beta} = \beta = -\frac{1}{4}$$

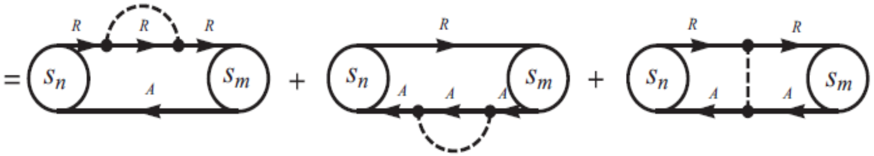
$$\hat{U}\mathcal{H}_{band}(\pm\mathbf{K}+\mathbf{p})\hat{U}^\dagger \approx \mathcal{H}_{band}(\pm\mathbf{K}+\mathbf{p}) + \delta\tilde{H}_g$$

$$\delta\tilde{H}_g = \frac{1}{2}\left\{\frac{\partial\mathcal{H}_{band}}{\partial\mathbf{p}}, \hat{U}(-i\hbar\partial)\hat{U}^\dagger\right\}$$

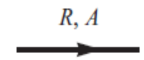
$$= \frac{\hbar}{2}\left[\hat{v}_y\hat{s}_x\partial_y^2 h - \hat{v}_x\hat{s}_y\partial_x^2 h + (\hat{v}_x\hat{s}_x - \hat{v}_y\hat{s}_y)\partial_x\partial_y h\right]$$

$$\left[\partial_t - D\nabla^2 + \hat{\Pi}^{(2)}\right]\vec{\rho}(t) = \vec{\rho}(0)\delta(t)$$

$\prod^{(2)}_{\mathrm{nm}} =$



$G^{R,A}(\omega, \vec{p}) =$



$$= \frac{(\omega - \varepsilon_p \pm i\hbar/2\tau) + \epsilon_z/2\, s_z}{(\omega - \varepsilon_p \pm i\hbar/2\tau)^2 - \epsilon_z^2/4}$$

$$= \begin{cases} \beta_{so}^2\, \hbar^2\, v^2 \langle |h_q|^2 \rangle & \text{if } q < \epsilon_z/\hbar v \\ \epsilon_z^2 \langle |h_q|^2 \rangle & \text{if } q > \epsilon_z/\hbar v \end{cases}$$

$$\tau_d^{-1} = \sum_{\mathbf{q}} \mathcal{M}(q) \frac{\tau q^2}{N} \langle |h_{\mathbf{q}}|^2 \rangle \times \begin{cases} q^2 \beta_{\mathrm{SO}}^2 v^2 & q < \frac{\epsilon_z}{\hbar v} \\ \epsilon_z^2/\hbar^2 & q > \frac{\epsilon_z}{\hbar v} \end{cases}$$

$$\mathcal{M}(q) = \frac{1 + \ell^2 q^2 + \frac{\tau^2 \epsilon_z^2}{\hbar^2}}{1 + 2\left(\ell^2 q^2 + \frac{\tau^2 \epsilon_z^2}{\hbar^2}\right) + \left(\ell^2 q^2 - \frac{\tau^2 \epsilon_z^2}{\hbar^2}\right)^2},$$

$$\beta_{\mathrm{SO}}^2 \equiv \beta^2 + \tilde{\beta}^2 + \frac{\lambda_\parallel^2}{\hbar^2 v^2}.$$

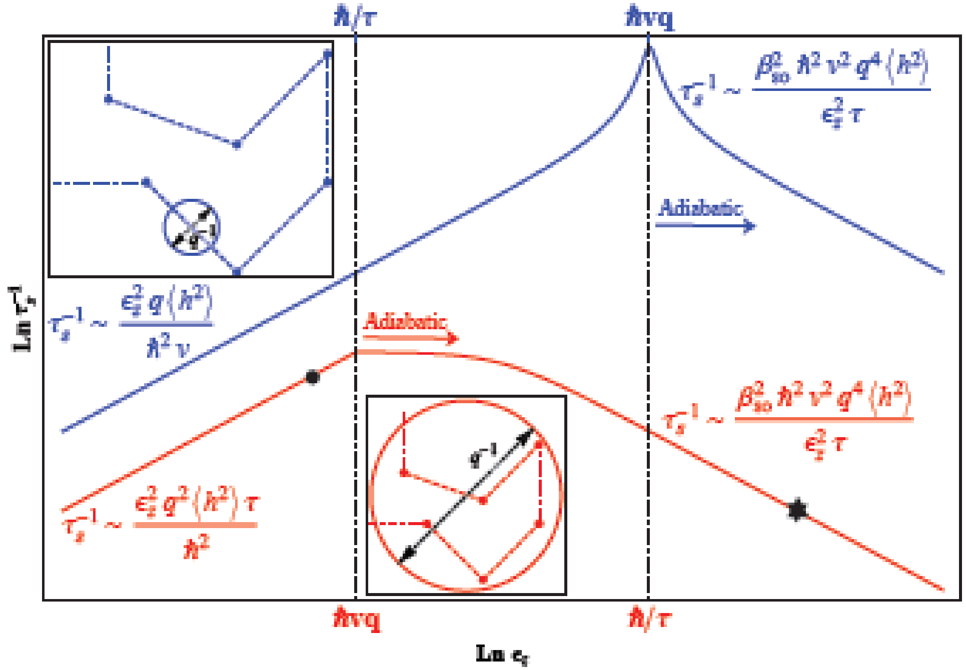
$$[\partial_t - D\nabla^2]\vec{\rho}_\pm \pm \lambda_{Z_2} \mathbf{n}_z \times \vec{\rho}_\pm + \tau_d^{-1}\vec{\rho} = \vec{\rho}_\pm(0)\delta(t)$$

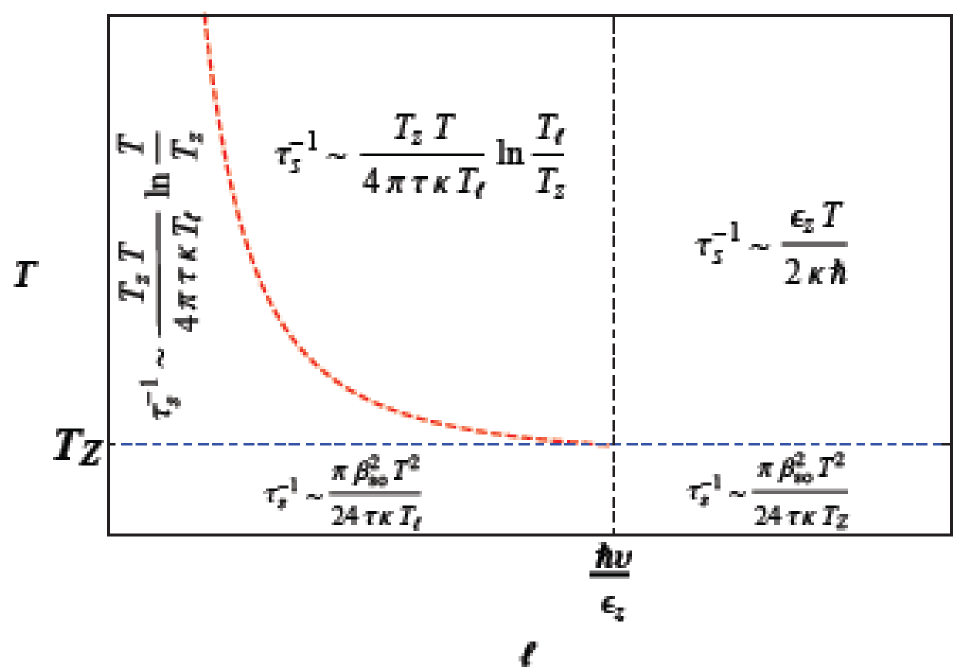
spin-lattice relaxation due to ripples in 2DHCs

assisted by flexural phonons

$$T_Z \equiv \sqrt{\kappa/\rho}\,\epsilon_z^2/\hbar v^2$$

$$T_\ell \equiv \ell^{-2}\hbar\sqrt{\kappa/\rho}$$





Ochoa, Guinea, VF - PRB 88, 195417 (2013)

MoS_2 at room temperature

for electrons at $10^{13}cm^{-2}$: 5ns

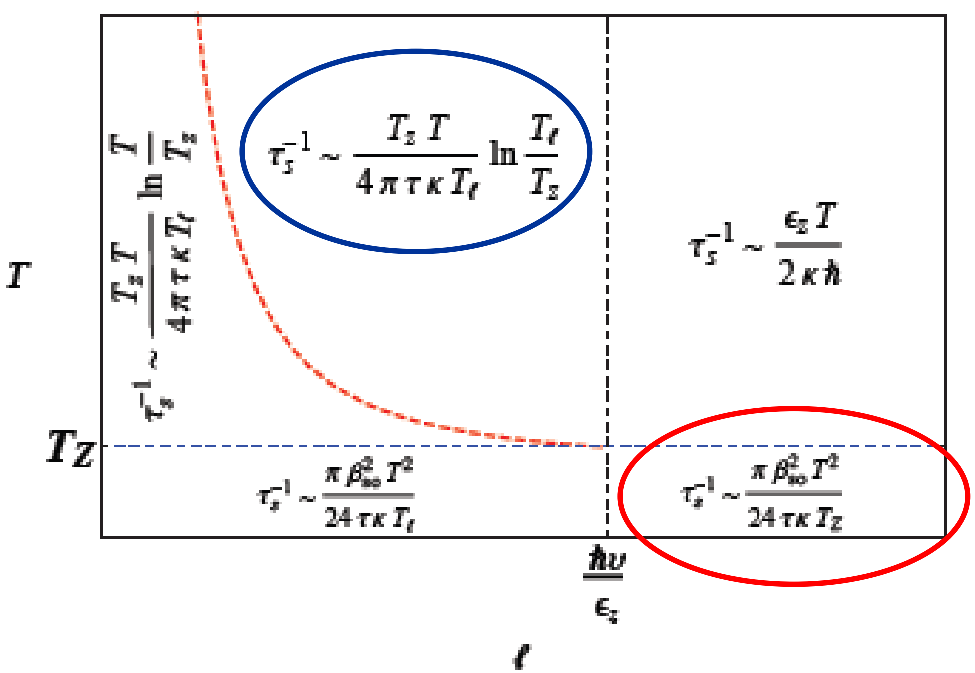
for holes $10^{13}cm^{-2}$: 20ns

(atomically flat substrate quenches bending modes, longer lifetimes –> even better for spintronics!)

assisted by flexural phonons

$$T_Z \equiv \sqrt{\kappa/\rho}\epsilon_z^2/\hbar v^2$$

$$T_\ell \equiv \ell^{-2}\hbar\sqrt{\kappa/\rho}$$

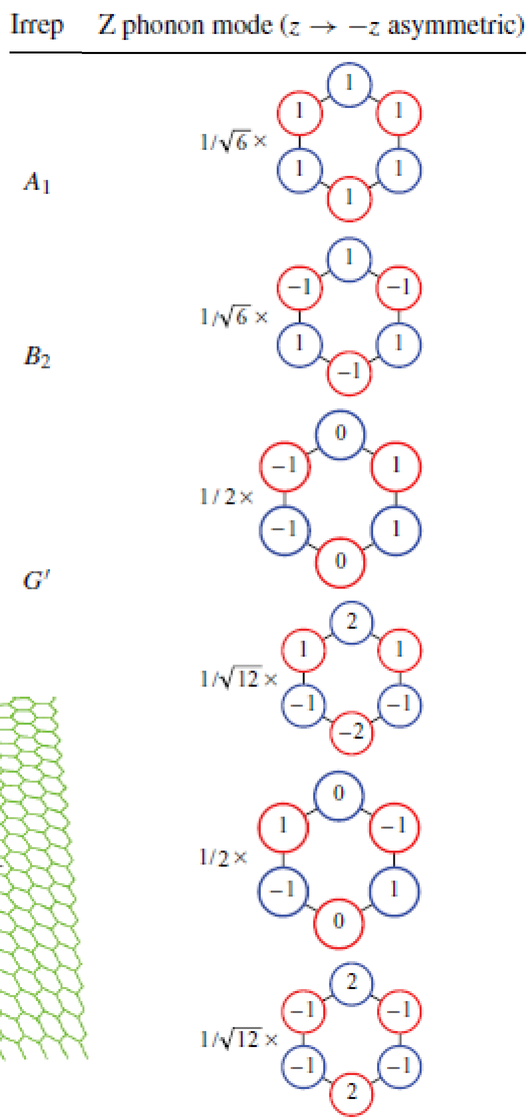


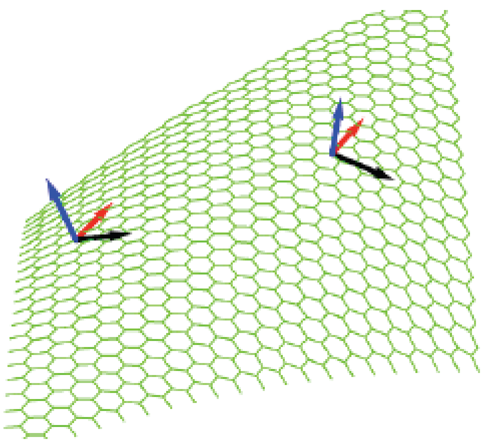
Ochoa, Guinea, VF - PRB 88, 195417 (2013)

SO coupling and flexural deformations in graphene

$$
\begin{aligned}
\mathcal{H}_{A_1} = {} & g_1(\Sigma_x \otimes s_y - \Sigma_y \otimes s_x)\partial_i \partial^i u_{A_1} \\
& + g_2\left[-\Lambda_z \otimes s_y\left(\partial_x^2 u_{A_1} - \partial_y^2 u_{A_1}\right) + 2\Lambda_z \otimes s_x \partial_x \partial_y u_{A_1}\right] \\
& + g_3\left[(\Sigma_x \otimes s_y + \Sigma_y \otimes s_x)\left(\partial_x^2 u_{A_1} - \partial_y^2 u_{A_1}\right)\right. \\
& \left. + 2(\Sigma_x \otimes s_x - \Sigma_y \otimes s_y)\partial_x \partial_y u_{A_1}\right]
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{H}_{G'} = {} & g_5[(\Lambda_x \otimes s_x)u_1 + (\Lambda_x \otimes s_y)u_2 \\
& -(\Lambda_y \otimes s_y)u_3 - (\Lambda_y \otimes s_x)
\end{aligned}
$$

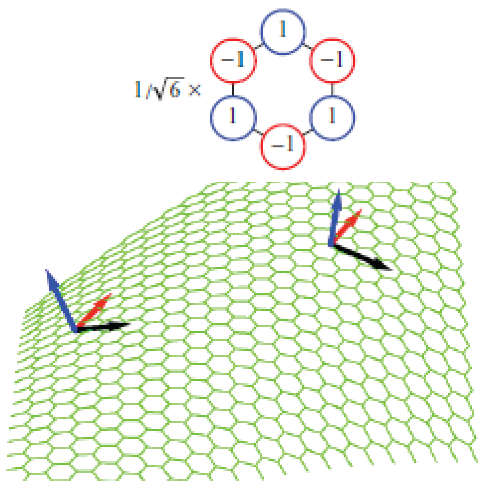




…. a very slow S_z relaxation at any temperature

Ochoa, Castro Neto, Guinea, VF – PRB 86, 245411 (2012)

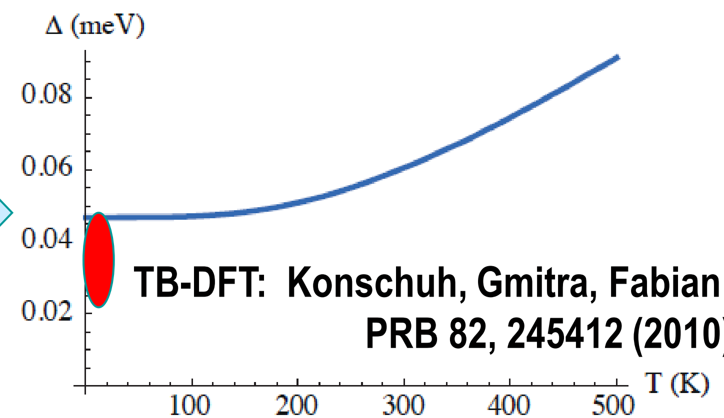
Enhancement of SO Kane-Mele coupling (splitting) by zero-mode & thermal out-of-plane diplacements



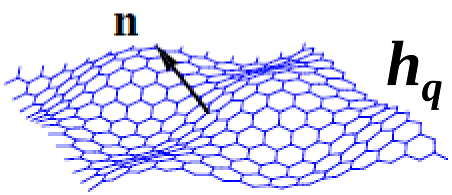
$$\mathcal{H} = -i v_F \vec{\Sigma} \cdot \vec{\partial} + \Delta_I \Sigma_z \otimes s_z$$

$$\mathcal{H}_{B_2} = g_4 \Sigma_z \otimes s_z (u_{B_2})^2$$

Ochoa, Castro Neto, Guinea, VF – PRB 86, 245411 (2012)



TB-DFT: Konschuh, Gmitra, Fabian
PRB 82, 245412 (2010)



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- spin-flip processes and spin ½ defects in graphene shown by WL

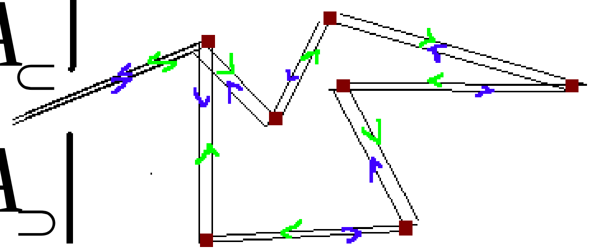
Kashuba, VF + NPL + Chalmers + Vancouver (2013)

Interference correction to conductivity in MLG: WAL *versus* WL.

$$w \sim |A_{\subset} + A_{\supset}|^2 = |A_{\subset}|^2 + |A_{\supset}|^2 + [A_{\subset}^* A_{\supset} + A_{\subset} A_{\supset}^*]$$

$A_{\subset}|$

$A_{\supset}|$



WL = enhanced backscattering for non-chiral electrons in time-reversal-symmetric systems

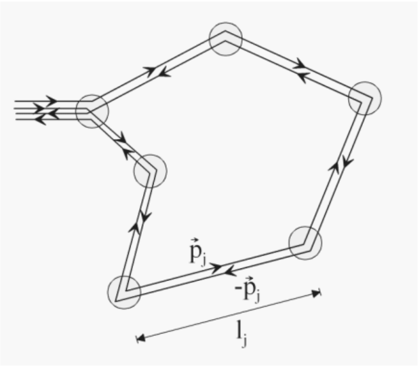
$$\sigma = \sigma_{cl} + \frac{e^2}{2\pi h} \ln\left(\min[\tau_{\varphi}, \tau_B]/\tau\right)$$

WAL = suppressed backscattering for Berry phase π electrons in MLG

chiral electrons $\psi_{out} = e^{-i\phi(\sigma_z/2)}\psi_{in}$

$$A_{\subset} A_{\supset}^* = e^{-i2\pi(\sigma_z/2)} |A_{\subset}|^2 = -|A_{\subset}|^2 < 0$$

... however, **bond disorder (riples, epoxy-bonded adatoms) leads to a valley-dependent effective 'magnetic field'.**

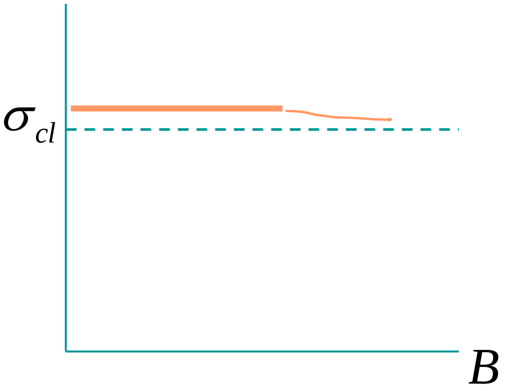


$$A^K_{\supset} \neq A^K_{\subset}$$

$$\hat{H} = v\vec{\sigma}\cdot\vec{p} + \hat{I}U(r) + \hat{V}(\vec{r})$$

Foster, Ludwig - PRB 73, 155104 (2006)
Morpurgo, Guinea - PRL 97, 196804 (2006)

$$\sigma = \sigma_{cl} + \frac{e^2}{2\pi h}\ln\left(\min[\tau_\varphi, \tau_B]/\tau\right)$$

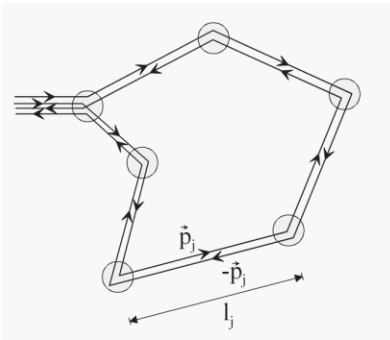


chiral electrons $\psi_{out} = e^{-i\phi(\sigma_z/2)}\psi_{in}$

$$A_{\subset}A^*_{\supset} = e^{-i2\pi(\sigma_z/2)}|A_{\subset}|^2 = -|A_{\subset}|^2 < 0$$

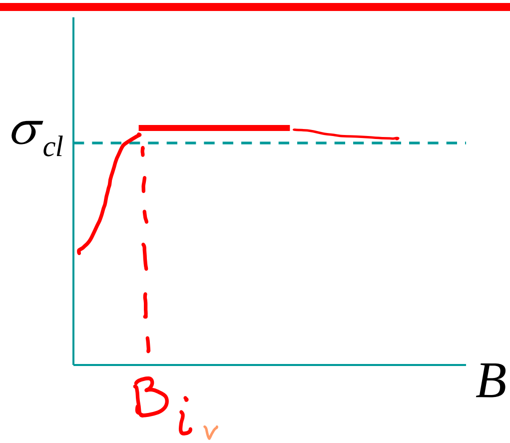
McCann, Kechedzhi, VF, Suzuura, Ando, Altshuler - PRL 97, 146805 (2006)

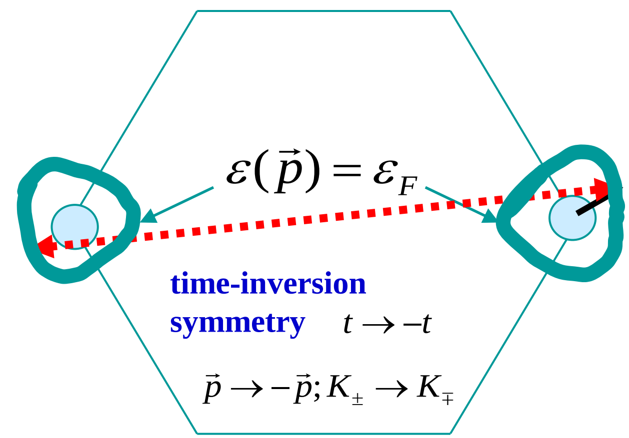
... but bond disorder has the opposite effect on electrons in K and K' valleys, so that the true time-reversal symmetry is preserved, and the inter-valley scattering restores the WL behaviour typical for electrons in time-inversion symmetric systems.



$$A_{\supset}^{K_{\pm}} = A_{\subset}^{K_{\mp}}$$

$$\sigma = \sigma_{cl} - \frac{e^2}{2\pi h} \ln\left(\min[\tau_{\varphi}, \tau_B] / \tau_{iv}\right)$$





McCann, Kechedzhi, VF, Suzuura, Ando, Altshuler - PRL 97, 146805 (2006)
for bilayers: Kechedzhi, McCann, VF, Altshuler – PRL 98, 176806 (2007)

$$\hat{H} = v\vec{\Sigma}\cdot\vec{p} + \hat{I}\,u(\vec{r}) + \sum_{\sigma=x,y,z} u_{\sigma z}(\vec{r})\Sigma_\sigma\Lambda_z + \sum_{\substack{\sigma=x,y,z\\ l=x,y}} u_{\sigma l}(\vec{r})\Sigma_\sigma\Lambda_l$$

only SU_2^Σ singlet survives diffusion

$z\longrightarrow -z$ symmetric. Conserves s_z but breaks time-inversion for the orbital motion of spin-up/down electrons.

$$+\ \alpha_{KM}\Sigma_z s_z + \sum_{l=x,y,z} a_{lz}(\vec{r})s_z\Lambda_l$$

$$+\ \alpha_{BR}\vec{\Sigma}\cdot(\vec{s}\times\vec{l}_z) + \sum_{\substack{s=x,y\\ l=x,y,z}} a_{sl}(\vec{r})s_s\Lambda_l$$

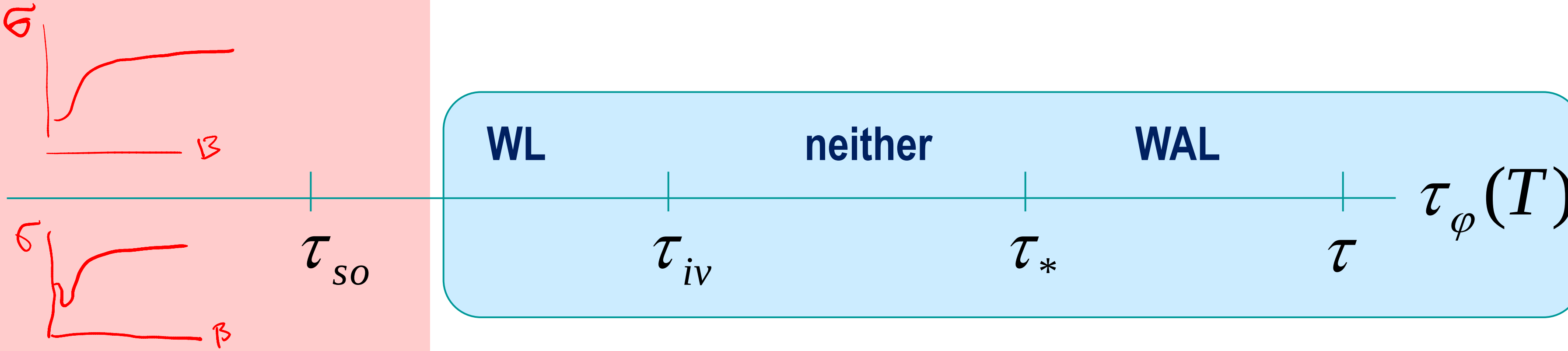
$z\longrightarrow -z$ asymmetric. Relaxes all spin components

McCann and VF, PRL 108, 166606 (2012)

Spin, $z \to -z$ symmetry and weak localisation in graphene

In $z \to -z$ symmetric MLG, SO coupling breaks time inversion for the orbital motion of spin-up/down electrons.

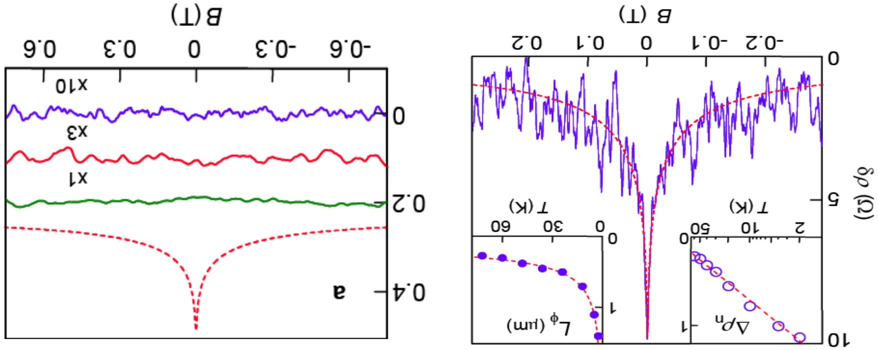
$$\sigma = \sigma_{cl} - \frac{e^2}{\pi h} \ln \frac{\min[\tau_\varphi, \tau_{so}, \tau_B]}{\tau_{iv}}$$



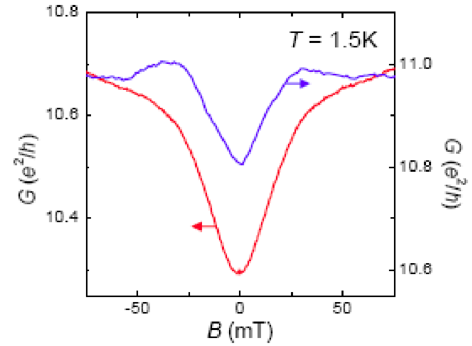
WAL, in $z \to -z$ asymmetric MLG

$$\sigma = \sigma_{cl} + \frac{e^2}{2\pi h} \ln \frac{\min[\tau_\varphi, \tau_B]}{\tau_{iv}} - \frac{3e^2}{2\pi h} \ln \frac{\min[\tau_\varphi, \tau_{so}, \tau_B]}{\tau_{iv}}$$

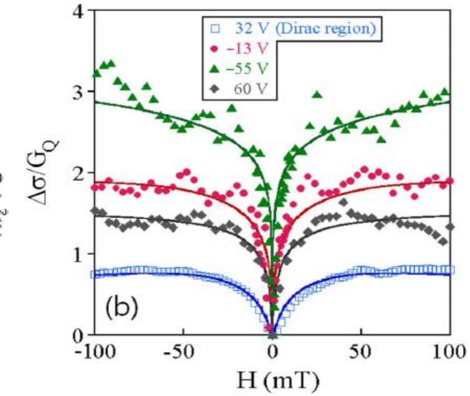
McCann and VF, PRL 108, 166606 (2012)



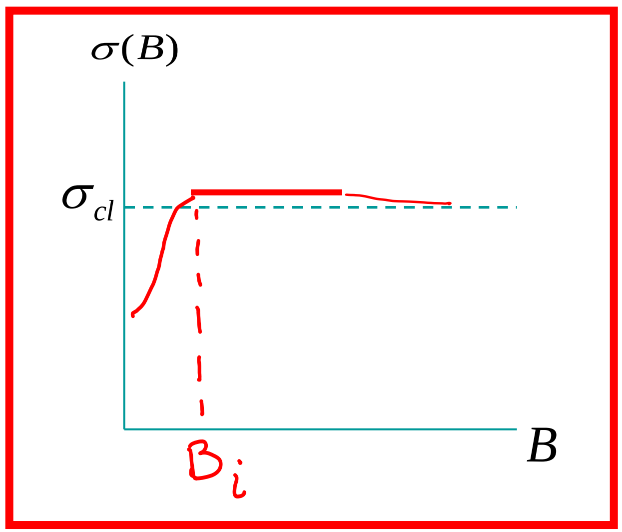
Morozov et al, PRL 97, 016801 (2006)



Heersche et al,
Nature 446, 56-59 (2007)



Ki et al,
PR B 78, 125409 (2008)

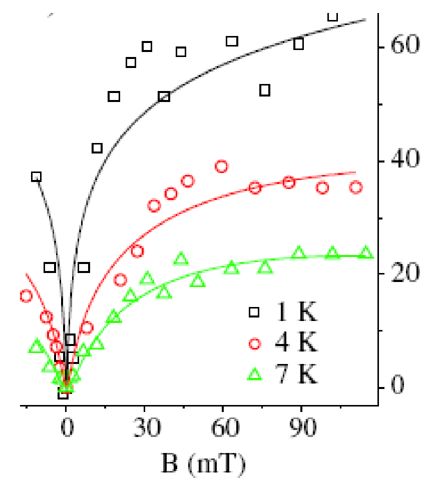


$$\tau_* << \tau_{iv} < \tau_\varphi$$

$$\Delta\sigma \sim \frac{e^2}{\pi h}\left(F\left(\tfrac{B}{B_\varphi+2B_{iv}}\right)+2F\left(\tfrac{B}{B_\varphi+B_*}\right)-F\left(\tfrac{B}{B_\varphi}\right)\right)$$

$$F(z)=\ln z+\psi\left(\tfrac{1}{2}+z^{-1}\right)$$

McCann, Kechedzhi, VF, Suzuura, Ando, Altshuler, PRL 97, 146805 (2006)



Tikhonenko *et al*
PRL 100, 056802 (2008)

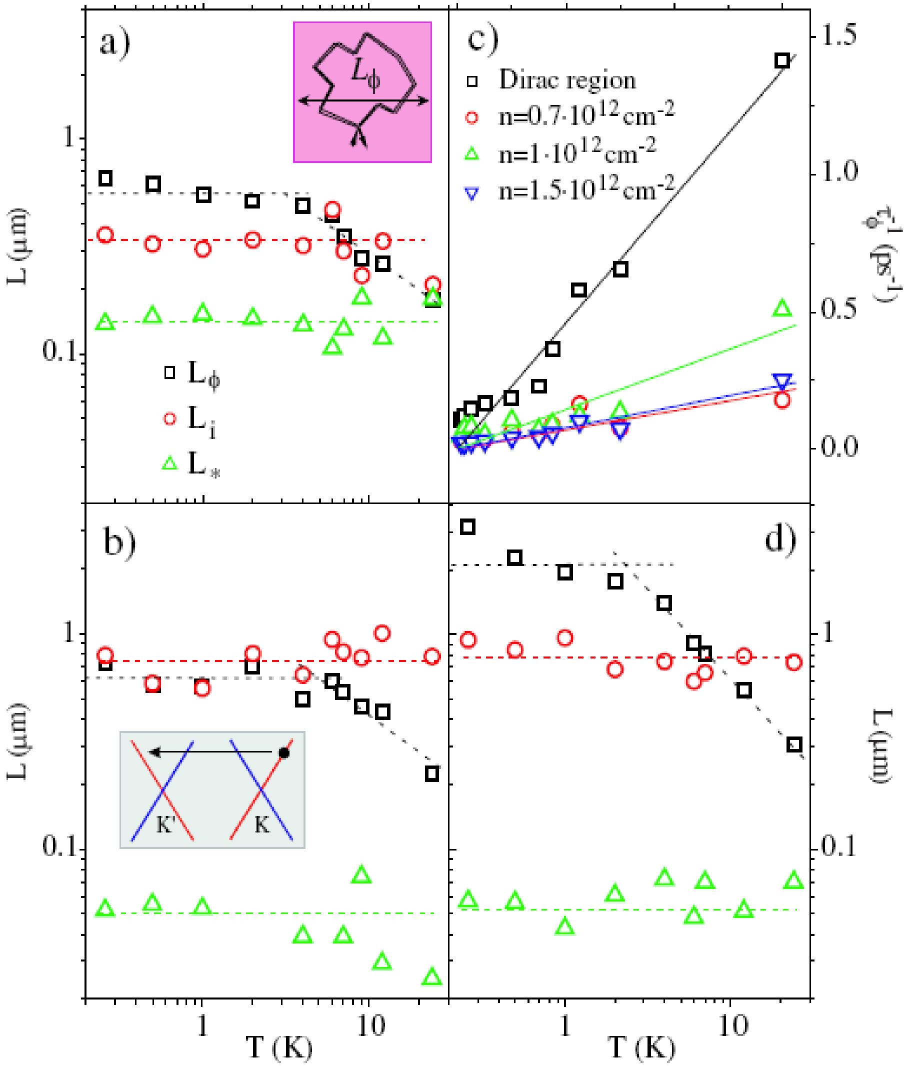
PRL **100,** 056802 (2008) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2008

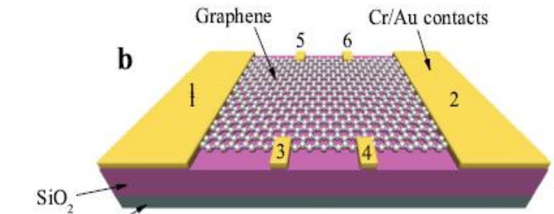
Weak Localization in Graphene Flakes

F. V. Tikhonenko, D. W. Horsell, R. V. Gorbachev, and A. K. Savchenko
School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, United Kingdom

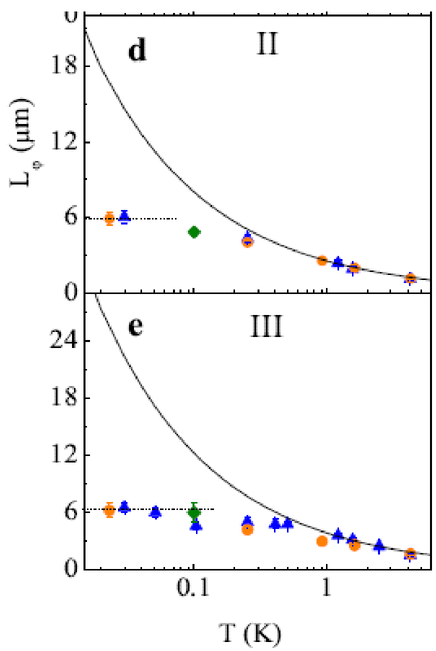
WL was used to test 'what type' of disorder:

$$L_i = \sqrt{\tau_{iv} D} >> l$$

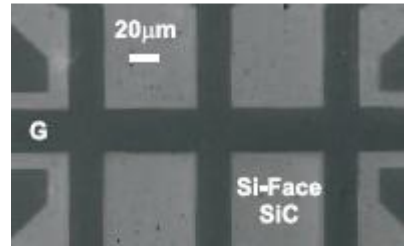


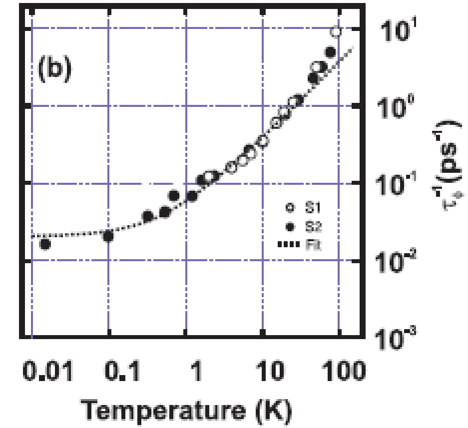


Sample	Size L×W	Mobility I	II	III
S1	41×18	13400	9800	7700

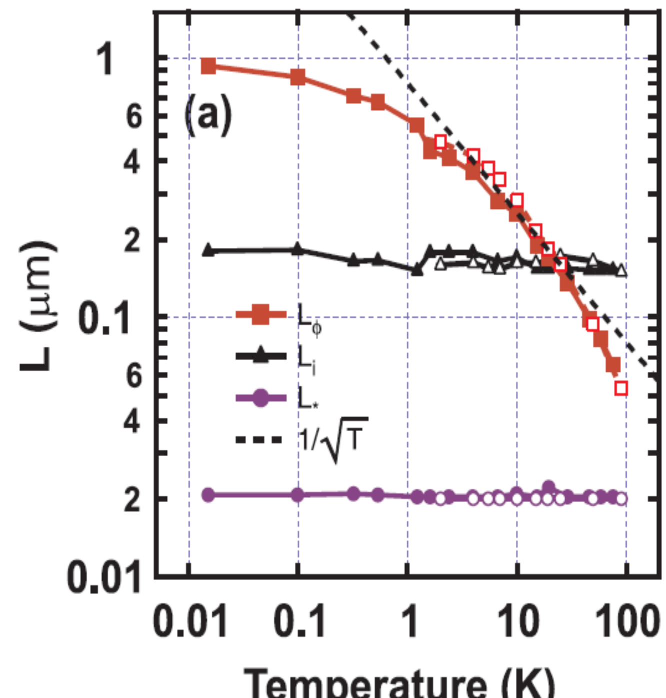


SiC/MLG





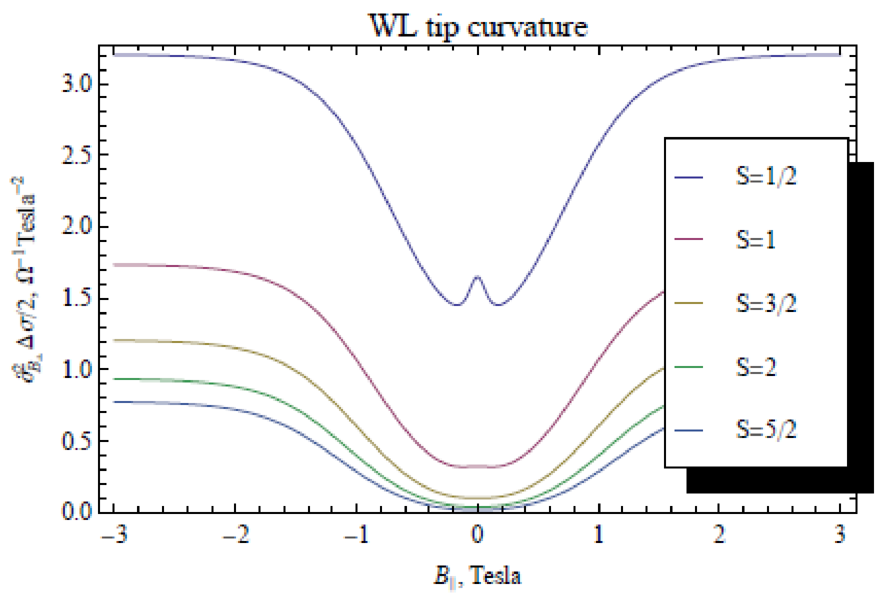
saturated WL (not WAL), possibly due to flip-flops with local magnetic moments of defects, or maybe SO scattering

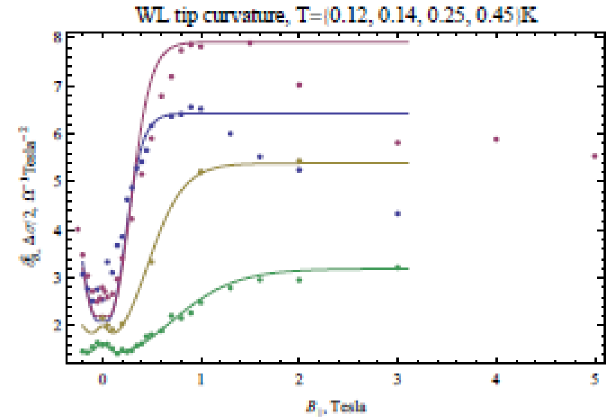


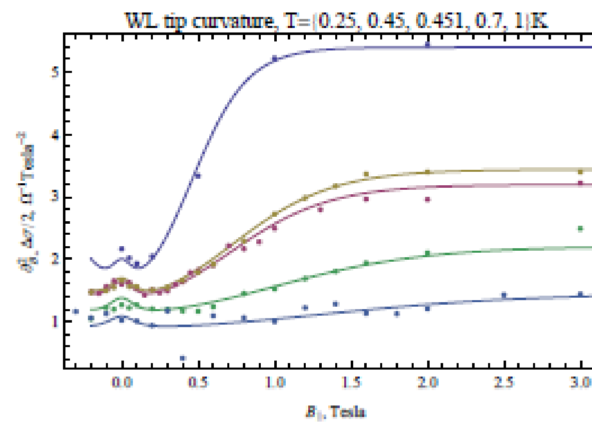
Kozikov, Horsell, McCann, VF
Phys. Rev. B 86, 045436 (2012)

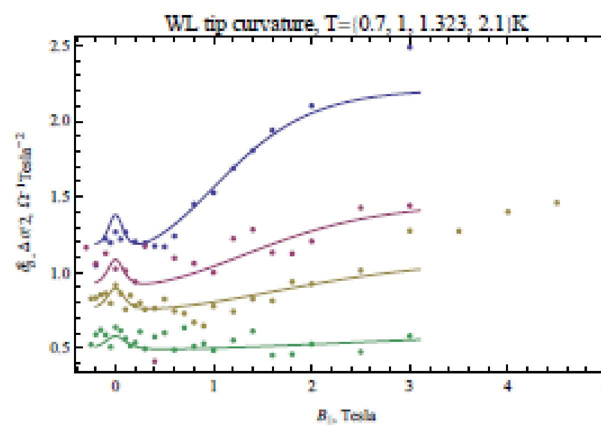
Lara-Avila, Tzalenchuk, Kubatkin, Yakimova, Janssen, Cedergren, Bergsten, VF – PRL 107, 166602 (2011)

decoherence rate detected by the curvature of magnetoconductance minimum





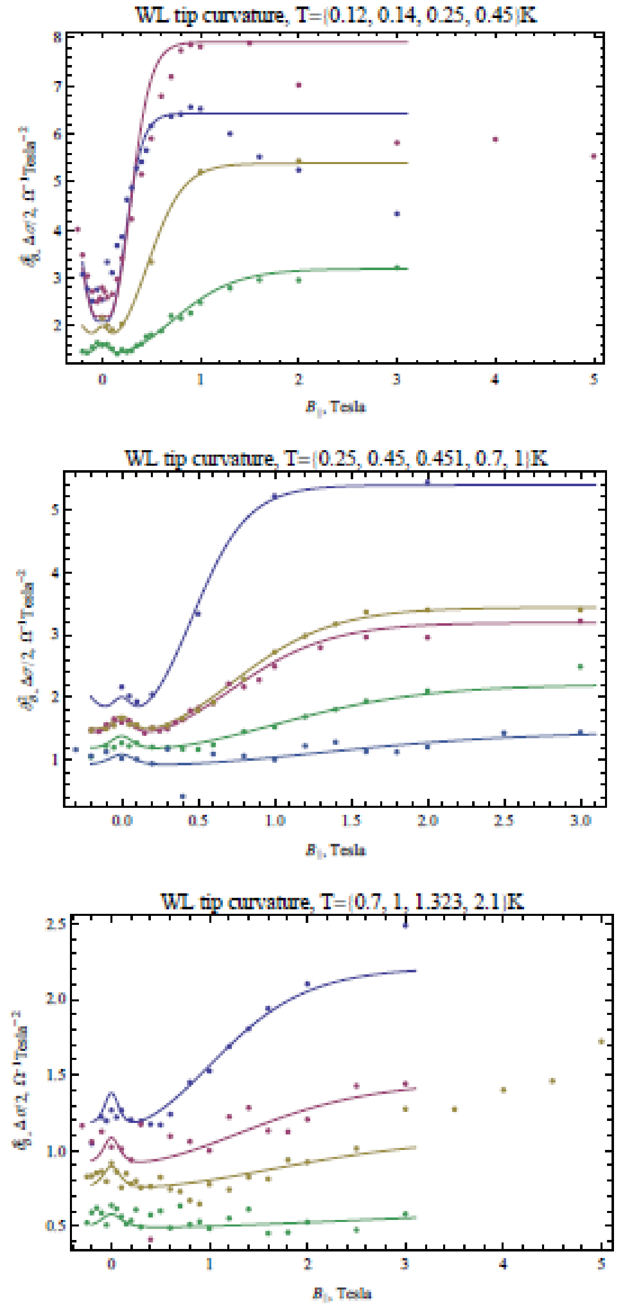




Non-monotonic behaviour only for spin ½!

Kashuba, VF + NPL + Chalmers + Vancouver (2013)

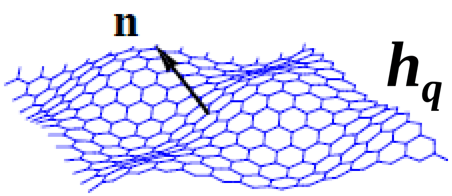
Non-monotonic dependence of the curvature of magnetoconductance minimum on the in-plane magnetic field: evidence of spin ½ defects (vacancies?)



Kashuba, VF + NPL + Chalmers + Vancouver (2013)

Spintronics in 2D hexagonal crystals

Vladimir Falko



- 2DHC band structure, SPD *kp* theory, *z->-z* symmetry and spin-lattice relaxation due to flexural deformations in 2DHCs

Ochoa, Guinea, VF - PRB 88, 195417 (2013); Ochoa, Castro Neto, Guinea, VF – PRB 86, 245411 (2012)
Kormányos, Zólyomi, Drummond, Rakyta, Burkard, VF - PRB 88, 045416 (2013)

- SO coupling and WL/WAL in graphene McCann and VF, PRL 108, 166606 (2012)
- spin-flip processes and spin ½ defects in graphene shown by WL

Kashuba, VF + NPL + Chalmers + Vancouver (2013)

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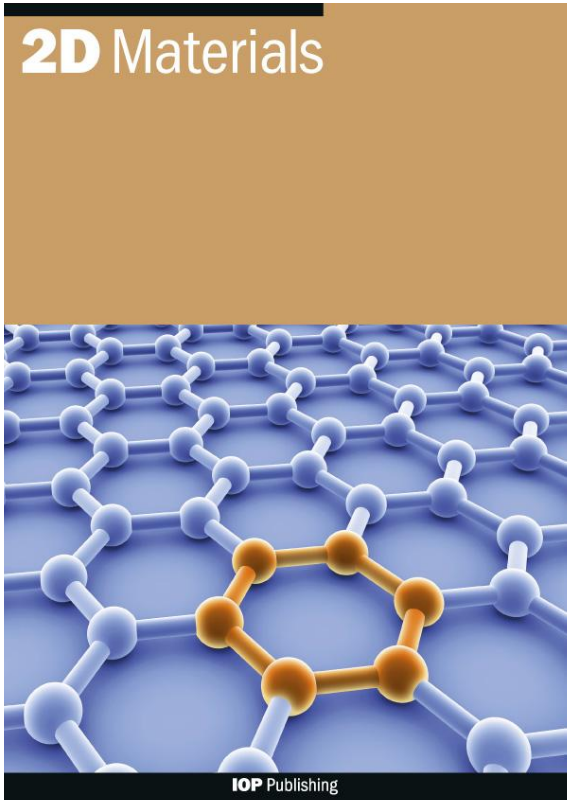

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