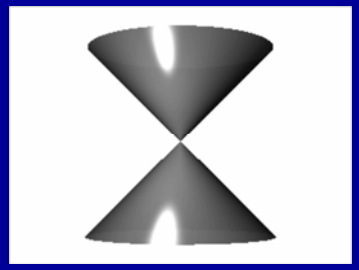
Hvar, 4.10.2017

Spin-orbit proximity effects in graphene on TMDCs



Jaroslav Fabian

Institute for Theoretical Physics
University of Regensburg

SFB1277

GRK TI

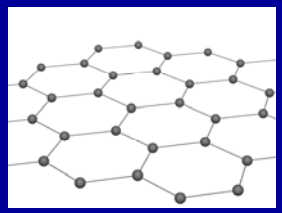
SPP 1666

SFB689

GRK1570

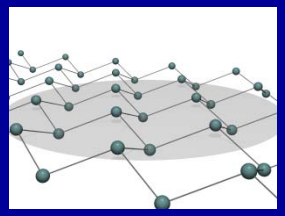
SPP 1538

Arbeitsgruppe J. Fabian, U Regensburg



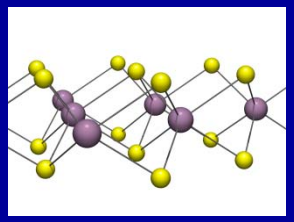
graphene

semimetal



germanene,
silicene

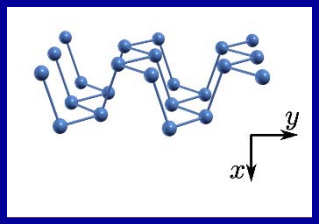
semiconductor



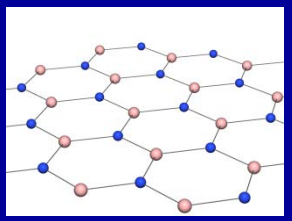
MoS_2
$NbSe_2$

semiconductor

superconductor



phosphorene



hBN

insulator

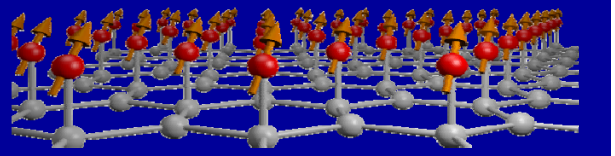
2d materials ZOO:

we discover QM in 2 dimensions

2D SPINTRONICS?

Proximity materials

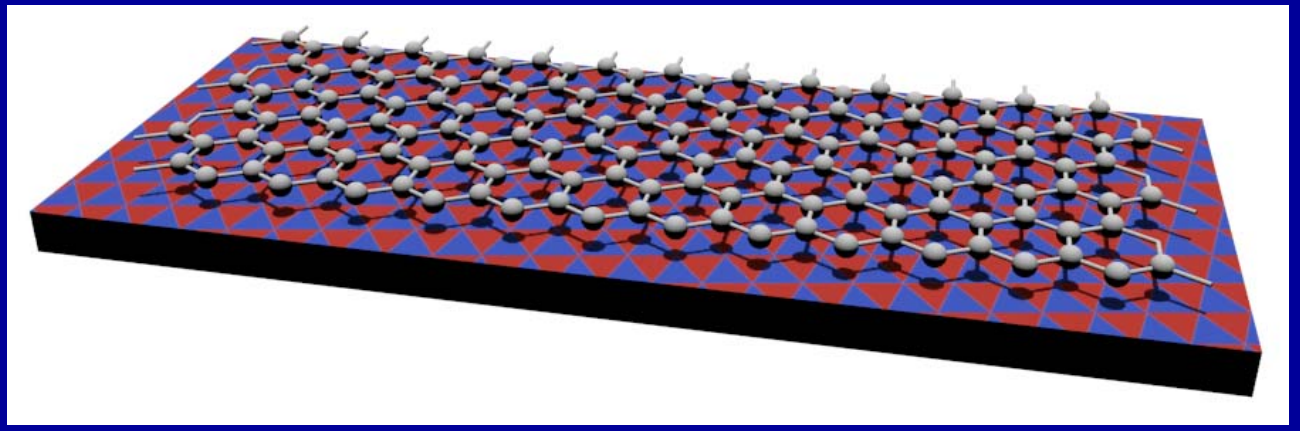
optospintronics



2D magnets

spin transistor

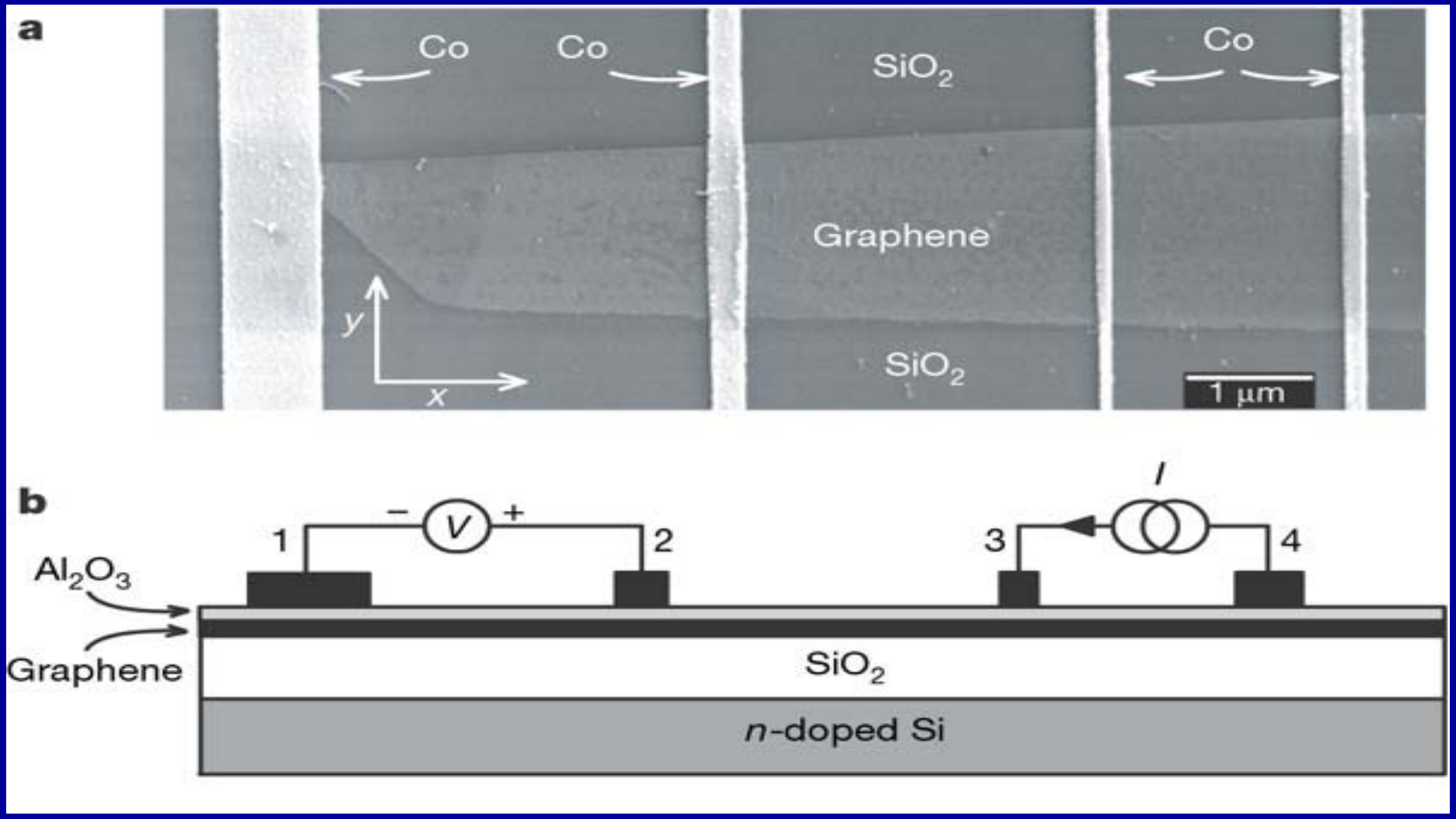
topological states



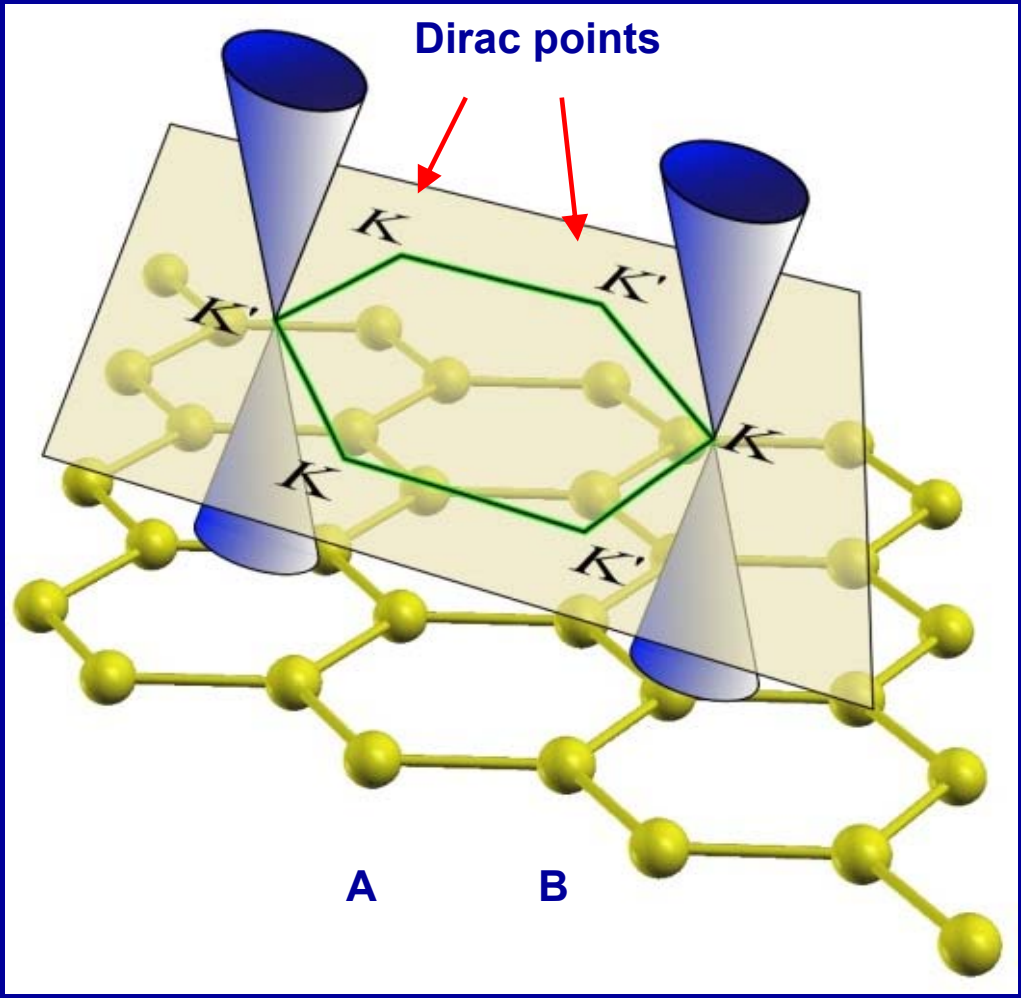
What do we know about spins in graphene?

Spin injection into graphene

van Wees group,
Electronic spin transport and spin precession in single graphene layers at room temperature,
Nature 448, 571 (2007)



:electronic states in graphene:

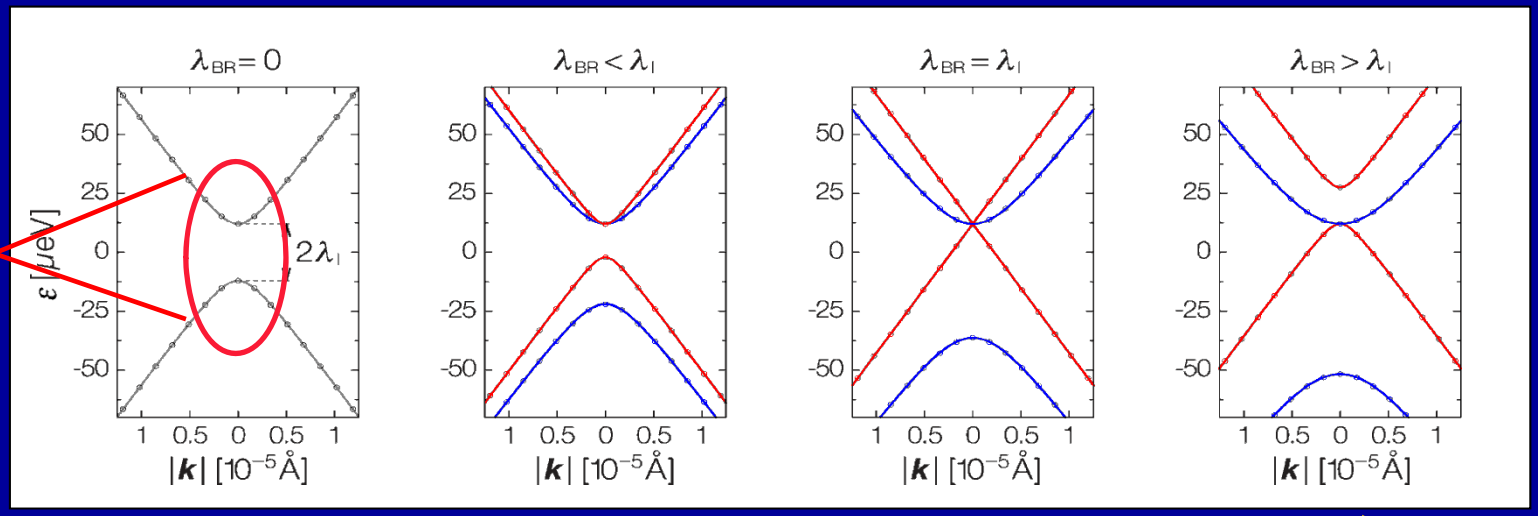


$$H = v_F \, \boldsymbol{\sigma} \cdot k$$

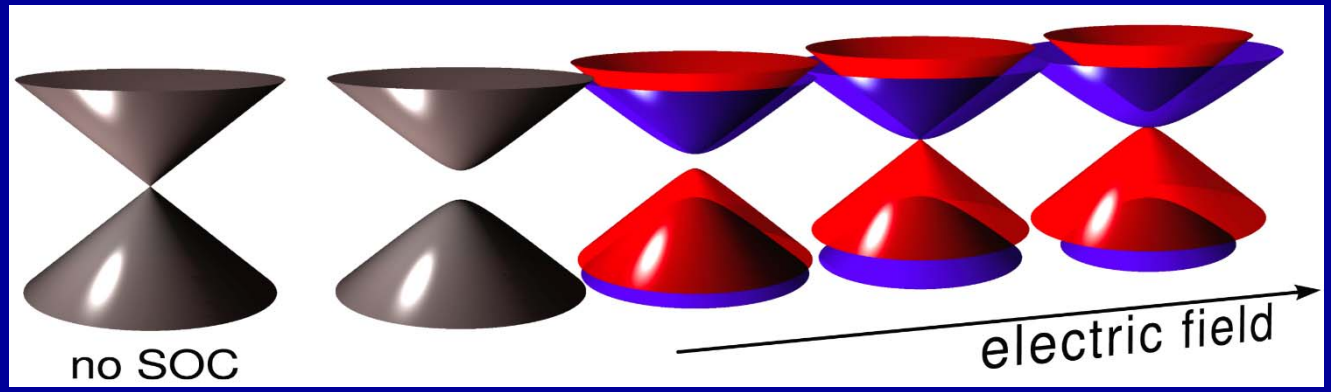
Spin-orbit coupling is weak,

M. Gmitra, S. Konschuh, C. Ertler, C. Ambrosch-Draxl, and J. Fabian, Phys. Rev. B 80, 235431 (2009)
S. Konschuh, M. Gmitra, and J. Fabian, Phys. Rev. B 82, 245412 (2010)

24 μev

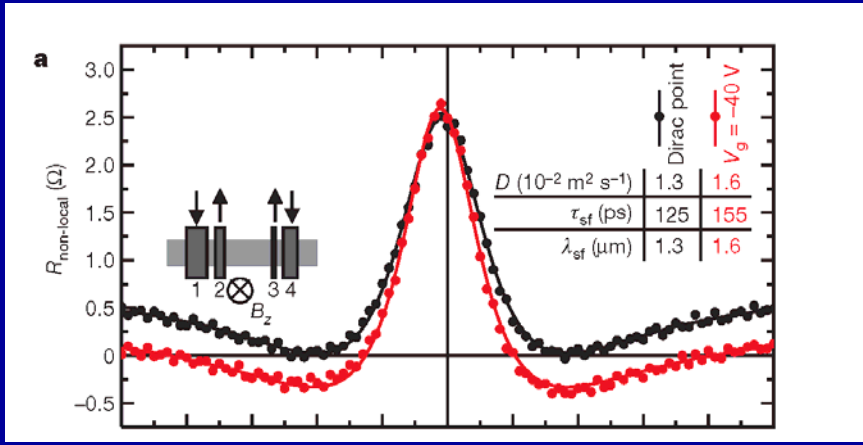


0 transverse E-field

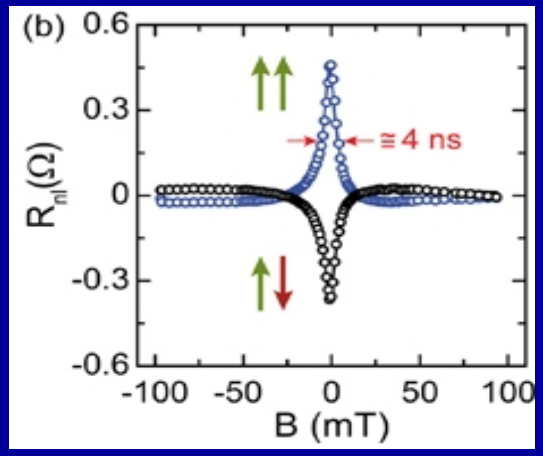


but spin relaxation is ultrafast

$$\tau_s \approx 100 \text{ ps}, \quad L_s = \sqrt{D\tau_s} \approx 1\,\mu\text{m}$$



Gr on SiO_2

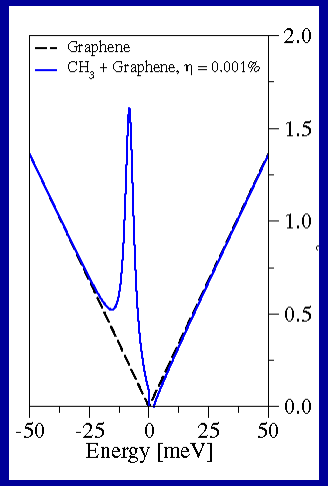


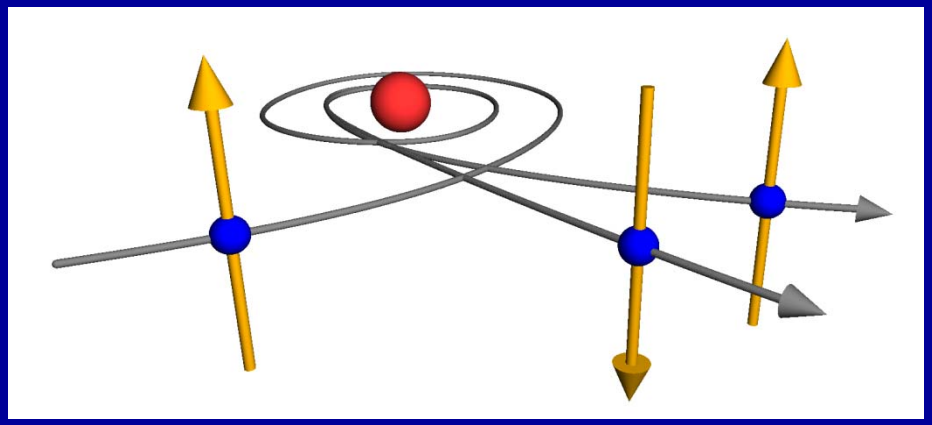
Gr on/in hBN

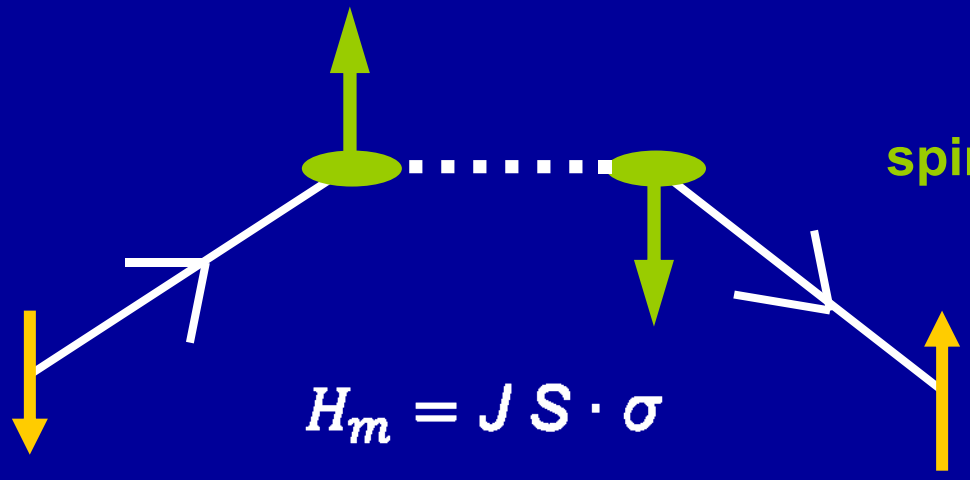
Reason: resonant scattering off magnetic impurities

D. Kochan, M. Gmitra, and J. Fabian, PRL 112, 116602 (2014),
D. Kochan, M. Gmitra, S. Irmer and J. Fabian, PRL 115, 196601 (2015)

Resonant scattering off magnetic impurities



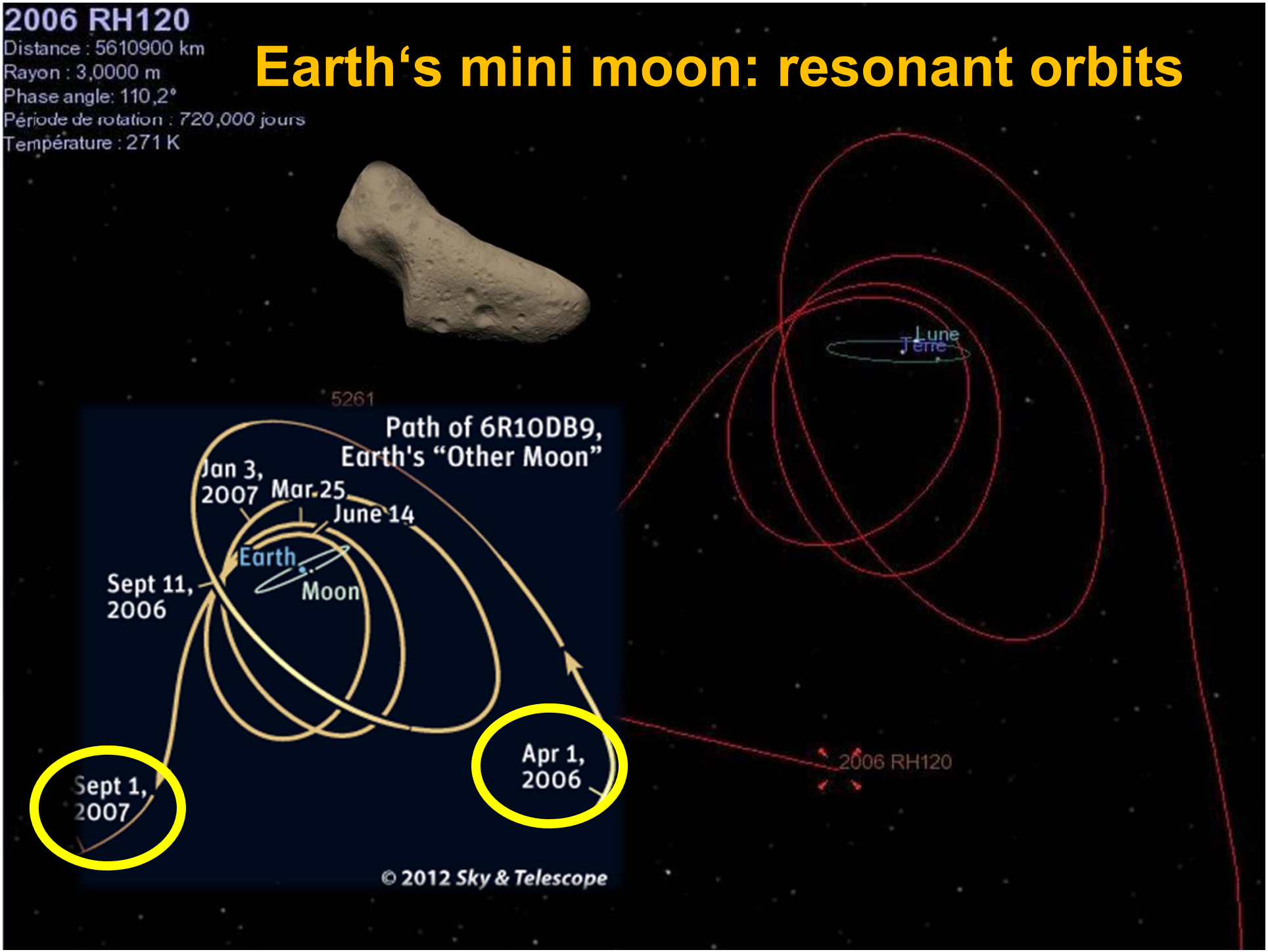




if larmor period $\geq T_r$

spin flip as likely as spin conserving scattering

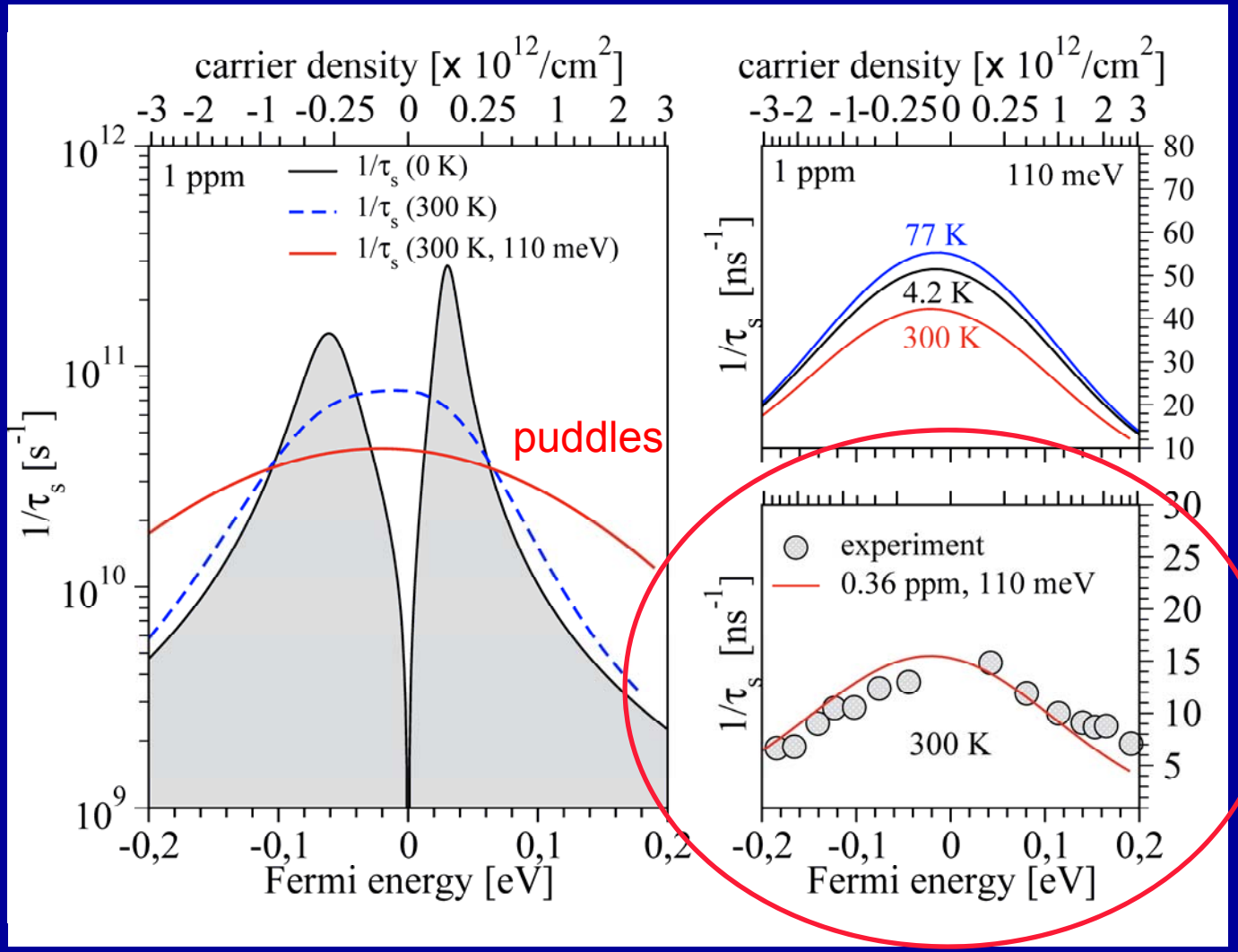
Earth‘s mini moon: resonant orbits



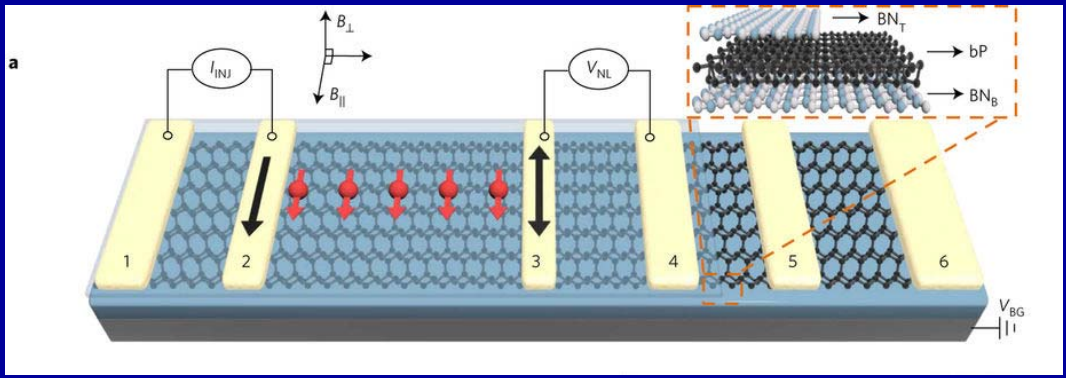
Resonant spin-flip scattering by local moments

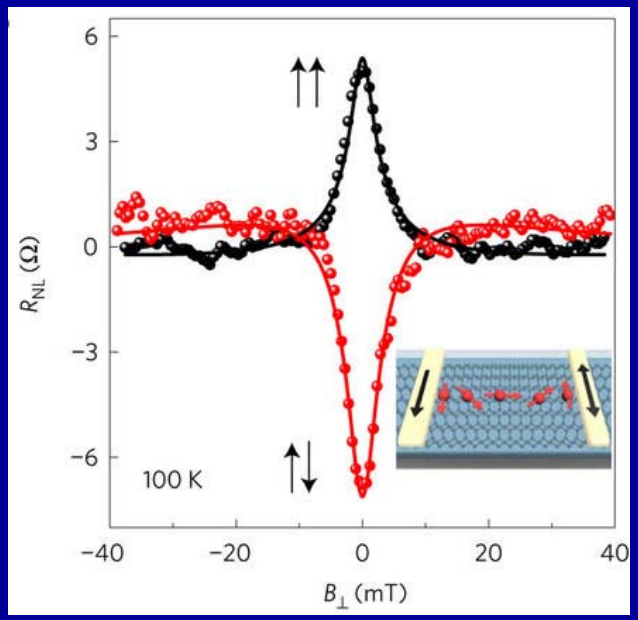
D. Kochan, M. Gmitra, and J. Fabian, PRL 112, 116602 (2014)

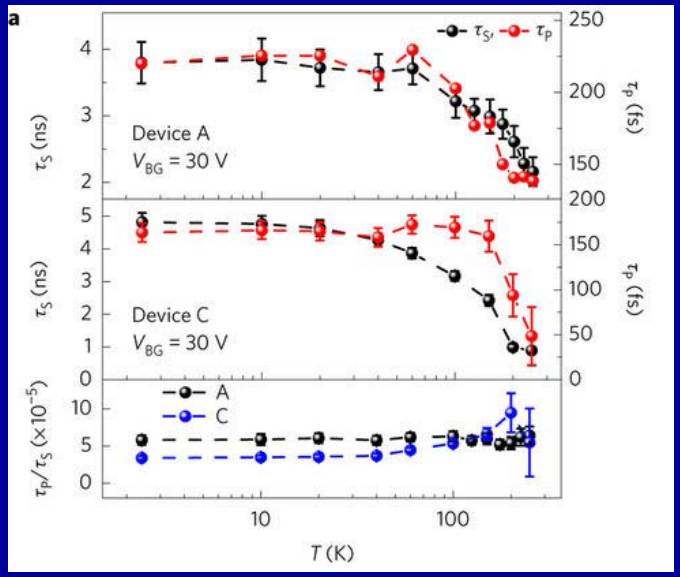
D. Kochan, M. Gmitra, S. Irmer and J. Fabian, PRL 115, 196601 (2015)



Spin injection and relaxation in BP







Elliot-Yafet Mechanismen

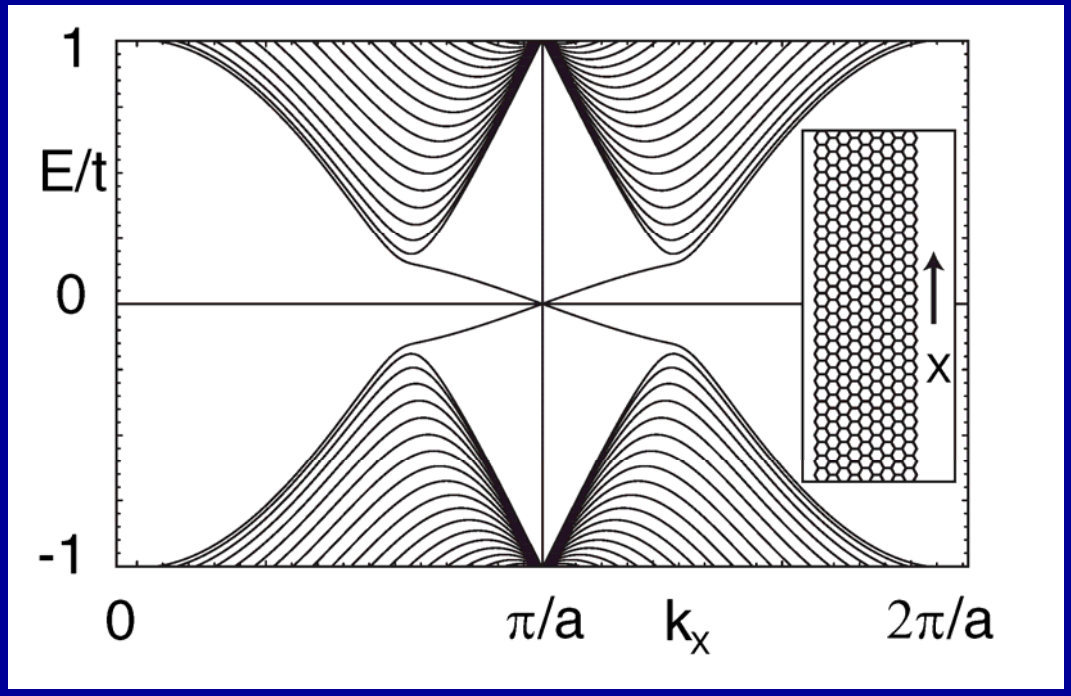
A. Avsar, M. Kurpas, et al (Singapore-UR col.), Nature Physics, 13, 888 (2017)
M. Kurpas, M. Gmitra, and J. Fabian, PRB 94, 155423 (2016)

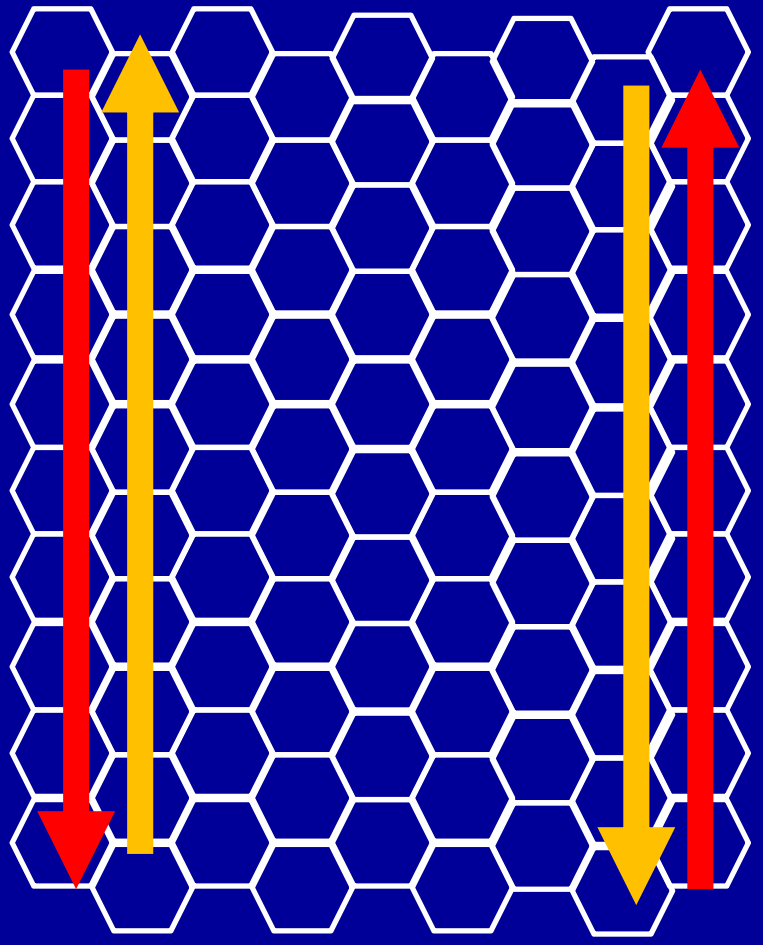
We want greater spin-orbit coupling!

Why?

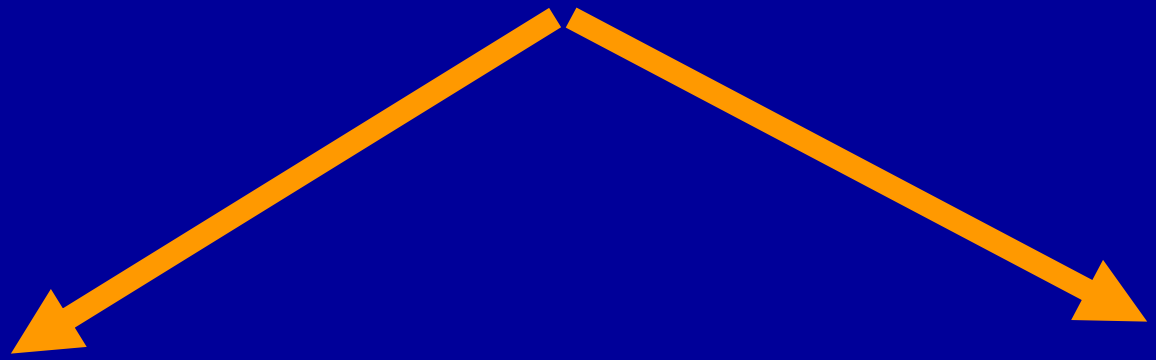
Quantum Spin Hall Effect

Kane and Mele, Phys. Rev. Lett. 95, 226801 (2005)





two ways to increase SOC in graphene



functionalizing graphene with adatoms:

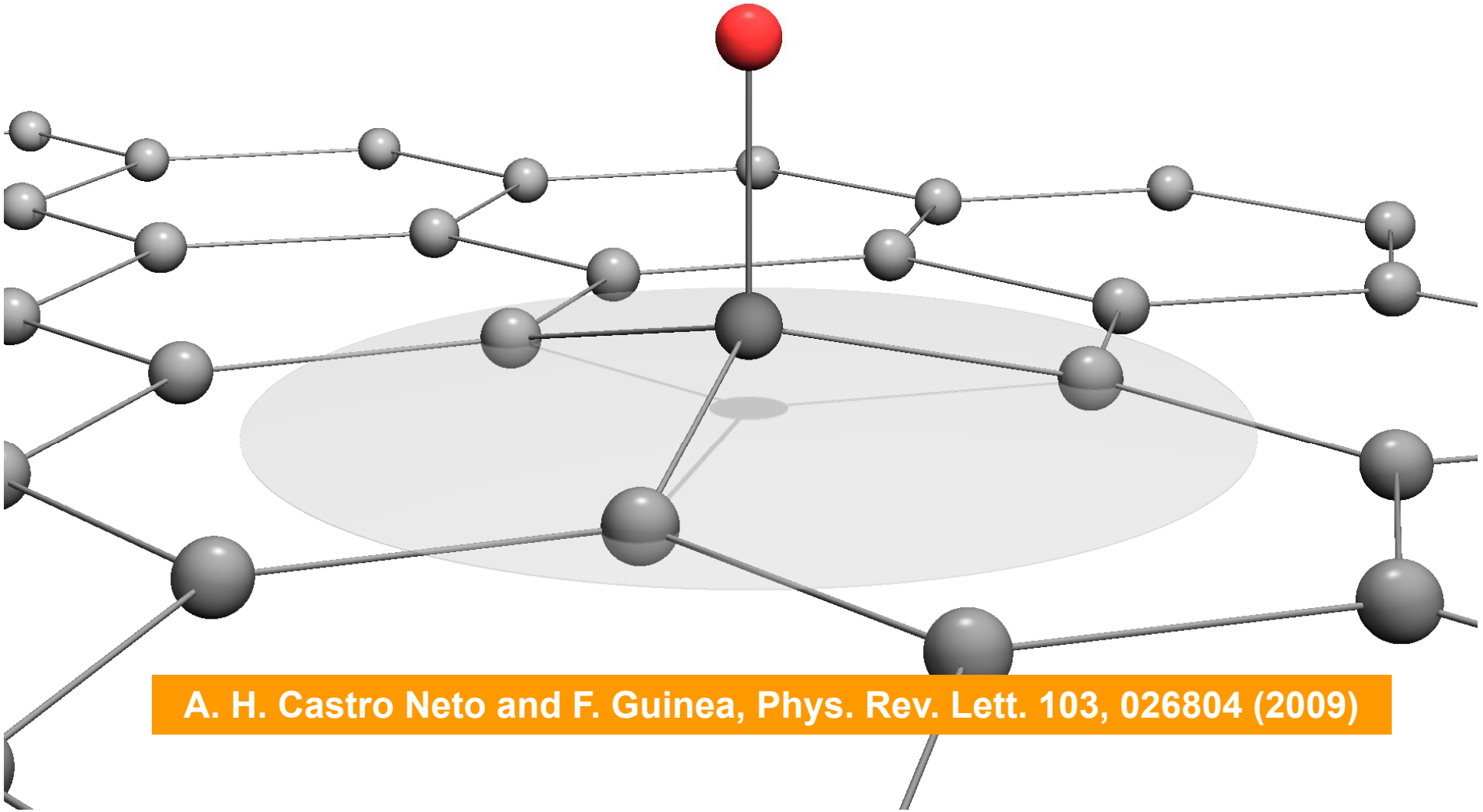
Local *random* SOC

placing graphene on insulating substrates

Uniform *proximity* SOC

From 10 μeV to 1-10 meV

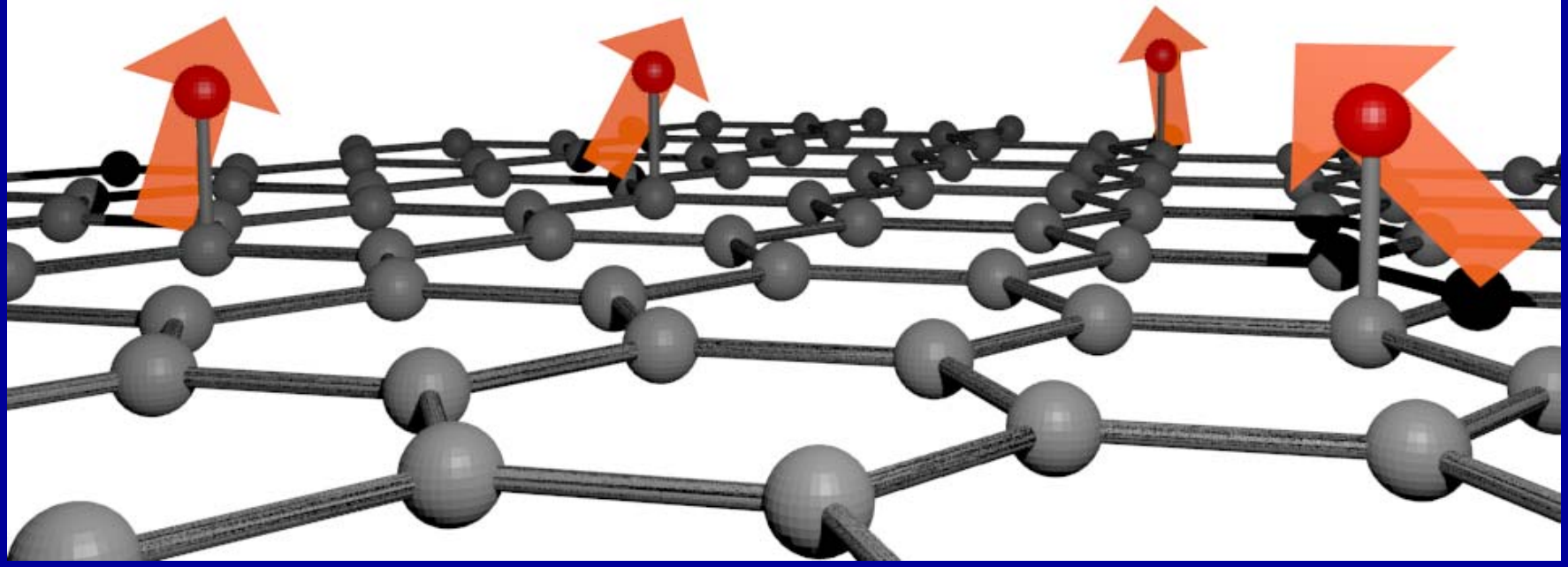
Spin-orbit coupling induced by ad-ons (H, F, Cu, CH_3,…)



A. H. Castro Neto and F. Guinea, Phys. Rev. Lett. 103, 026804 (2009)

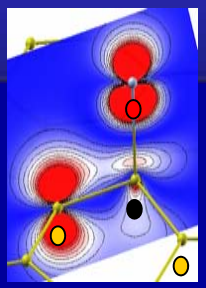
Functionalized graphene

$$H, F, Cu, CH_3 \ \ldots$$

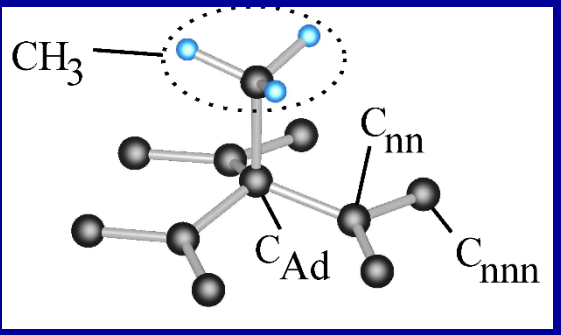


Courtesy Martin Gmitra

H, F, Cu,CH_3 on graphene



M. Gmitra, D. Kochan, and JF, PRL 110, 246602 (2013)
S. Irmer, T. Frank, S. Putz, M. Gmitra, D. Kochan, and JF, PRB 91, 115141 (2015)
K. Zollner, T. Frank, S. Irmer, M. Gmitra, D. Kochan, and JF, PRB 93, 045423 (2016)
T. Frank, S. Irmer, M. Gmitra, D. Kochan, and JF, PRB 95, 035402 (2017)



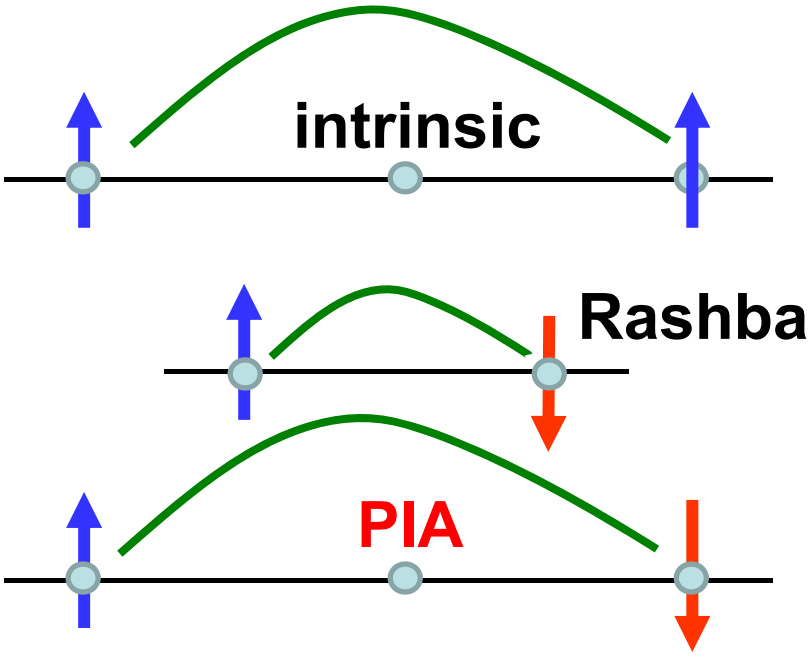
adatom	H	CH_3	F	Cu
SOC	1 meV	1 meV	10 meV	10 meV
cause	sp^3	sp^3	p-orb	p, d - orb
resonant	✓	✓	✗ ✓	✓

$$\mathcal{H}_{\rm so} = \frac{i}{3}\sum_{\langle\langle i,j\rangle\rangle}{}' c^\dagger_{i\sigma}\, c_{j\sigma'}\left[\frac{\lambda_{\rm I}}{\sqrt{3}}\,\nu_{ij}\,\hat{s}_z\right]_{\sigma\sigma'}$$

$$+\frac{i}{3}\sum_{\langle\langle {\rm C_H},j\rangle\rangle} A^\dagger_\sigma\, c_{j\sigma'}\left[\frac{\Lambda_{\rm I}}{\sqrt{3}}\,\nu_{{\rm C_H},j}\,\hat{s}_z\right]_{\sigma\sigma'} + {\rm h.c.}$$

$$+\frac{2i}{3}\sum_{\langle {\rm C_H},j\rangle} A^\dagger_\sigma\, B_{j\sigma'}\left[\Lambda_{\rm BR}\left(\hat{\boldsymbol{s}}\times\mathbf{d}_{{\rm C_H},j}\right)_z\right]_{\sigma\sigma'} + {\rm h.c.}$$

$$+\frac{2i}{3}\sum_{\langle\langle i,j\rangle\rangle} B^\dagger_{i\sigma}\, B_{j\sigma'}\left[\Lambda^{\rm B}_{\rm PIA}\left(\hat{\boldsymbol{s}}\times\mathbf{D}_{ij}\right)_z\right]_{\sigma\sigma'}.$$



Giant enhancement of SOC by H adatoms

M. Gmitra, D. Kochan, and J. Fabian, Phys. Rev. Lett 110, 246602 (2013)

nature physics

LETTERS

PUBLISHED ONLINE: 17 MARCH 2013 | DOI: 10.1038/NPHYS2576

Colossal enhancement of spin–orbit coupling in weakly hydrogenated graphene

Jayakumar Balakrishnan[1,2†], Gavin Kok Wai Koon[1,2,3†], Manu Jaiswal[1,2‡], A. H. Castro Neto[1,2,4] and Barbaros Özyilmaz[1,2,3,4★]

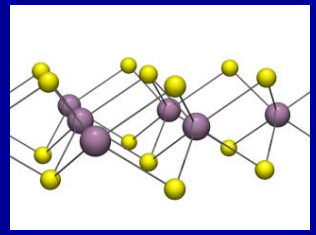
SHE exp: SOC = 1.25 meV

theory: $\Lambda_I = 0.21$ meV

$\Lambda_{BR} = 0.33$ meV

$\Lambda_{PIA} = 0.77$ meV

Graphene on transition-metal dichalcogenides (MoS_2, WSe_2, …):



explore proximity physics

Graphene on transition-metal dichalcogenides (TMDCs)

optospintronics
(bipolar spintronics?)

uniform proximity SOC

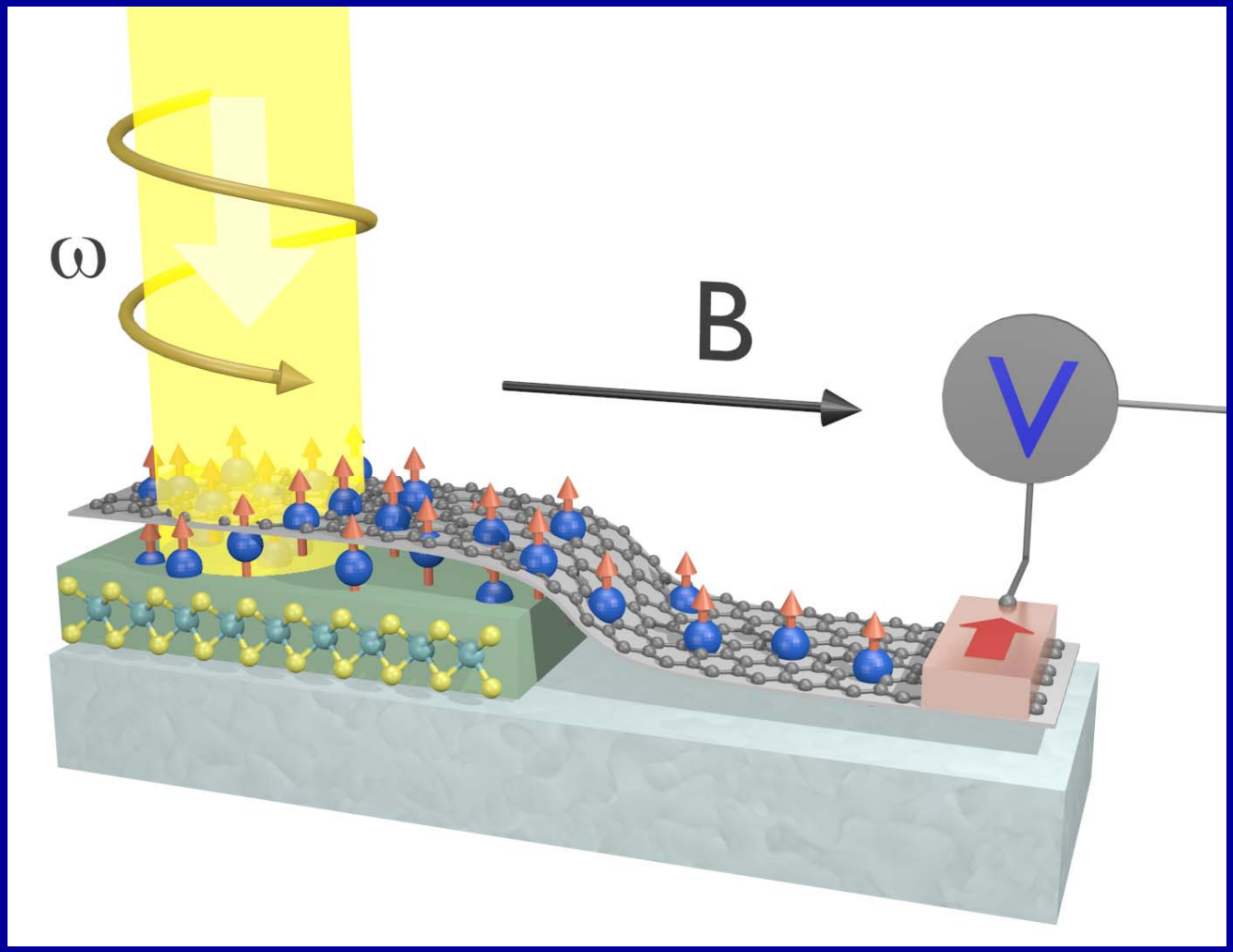
giant spin relaxation anisotropy
(theory prediction A. Cummings et al, arxiv.1705.10972, experimental confirmation van Wees group, arxiv.1708.04067)

quantum spin Hall physics

optospintronics

graphene on TMDC optical spin injection into graphene

M. Gmitra, and J. Fabian, Phys. Rev. B 92, 155403 (2015)

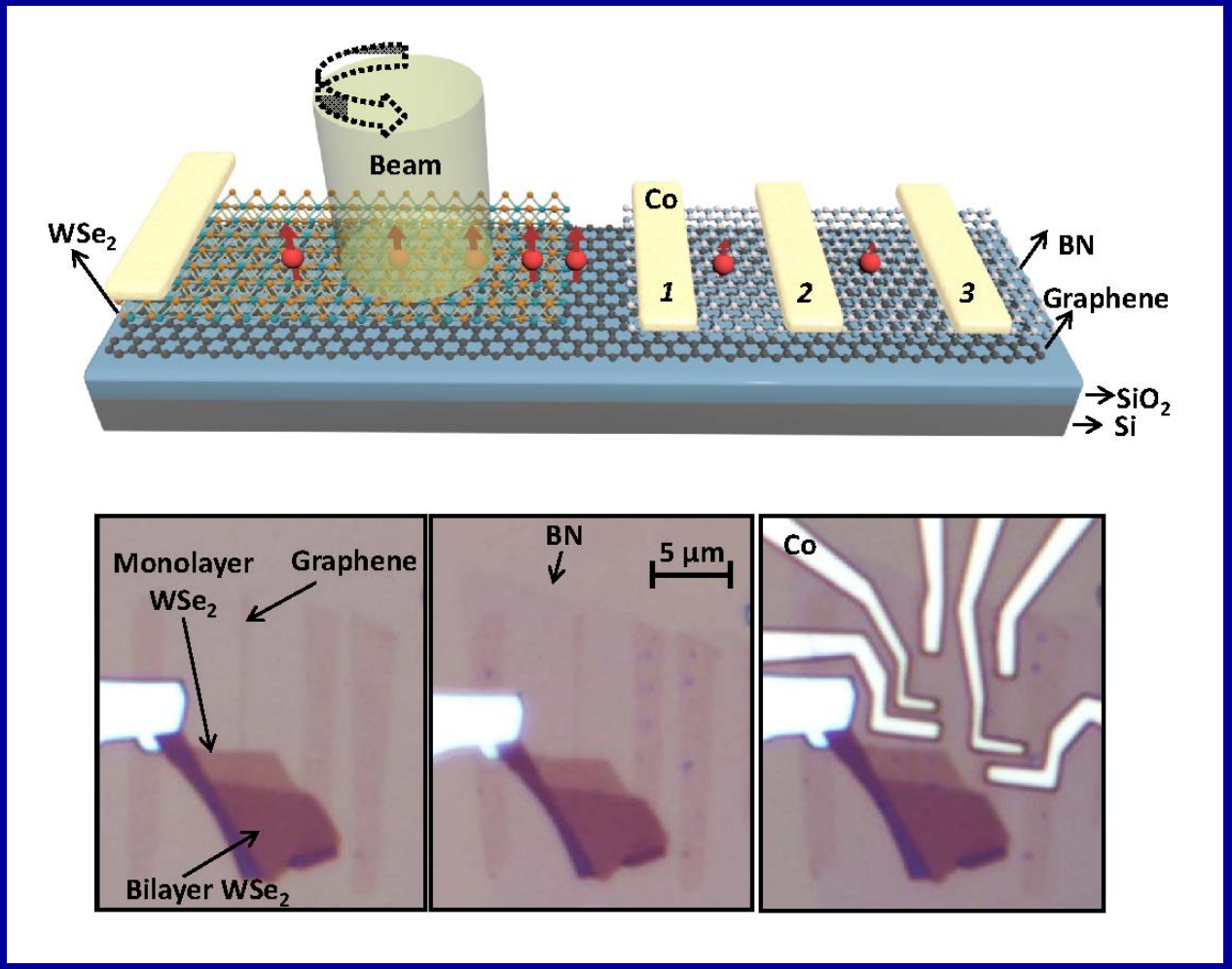


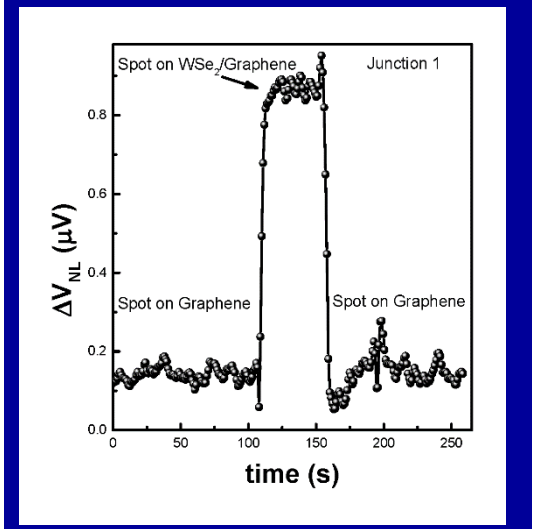
optospintronics

experiment

Luo et al (Kawakami) Nano Letters, 10.1021/acs.nanolett.7b01393

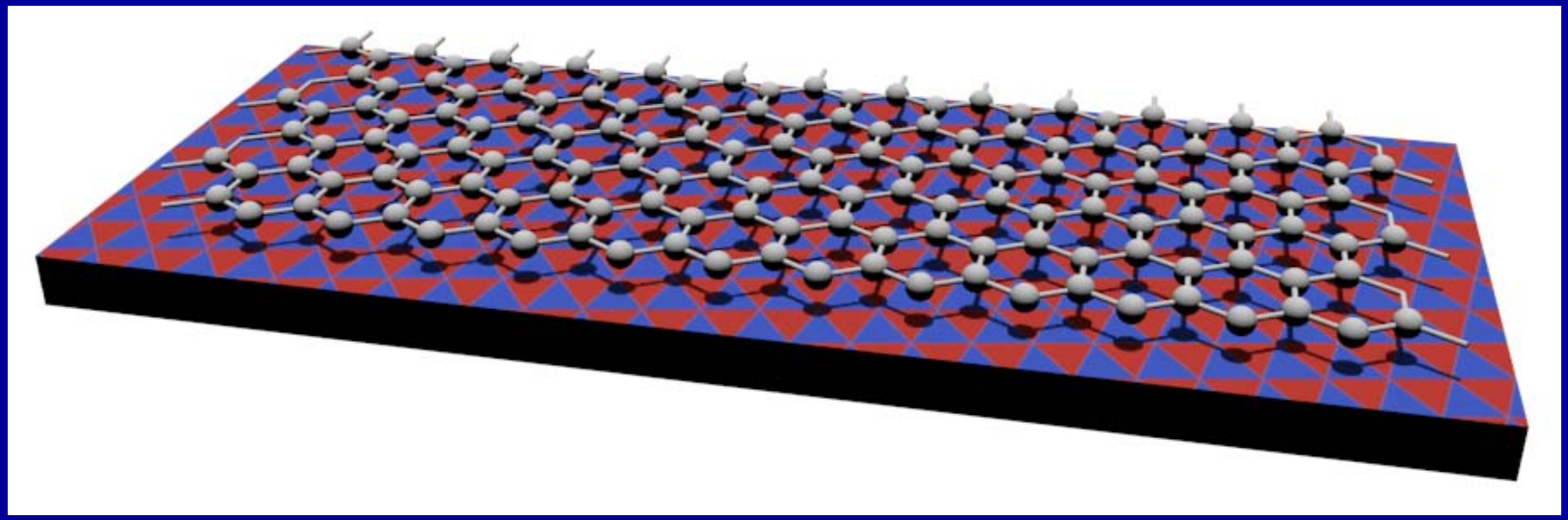
A. Avsar et al (Lausanne), arxiv:1705.10267





graphene on transition-metal dichalcogenides (TMDCs)

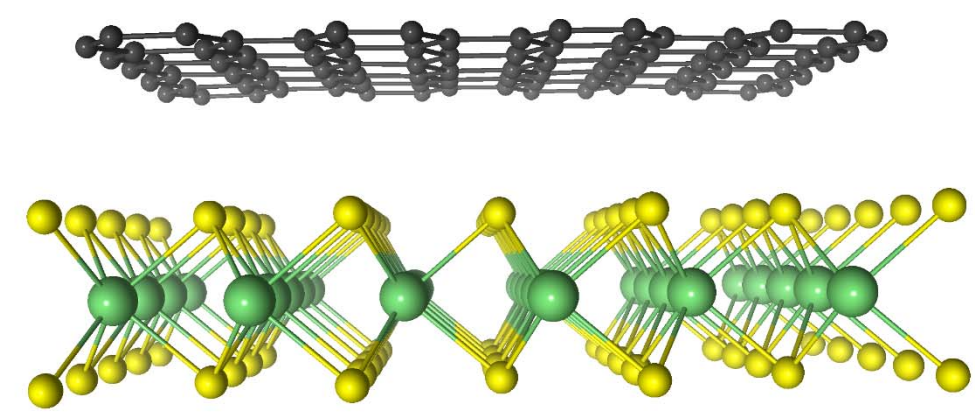
proximity *uniform* SOC of 1 meV

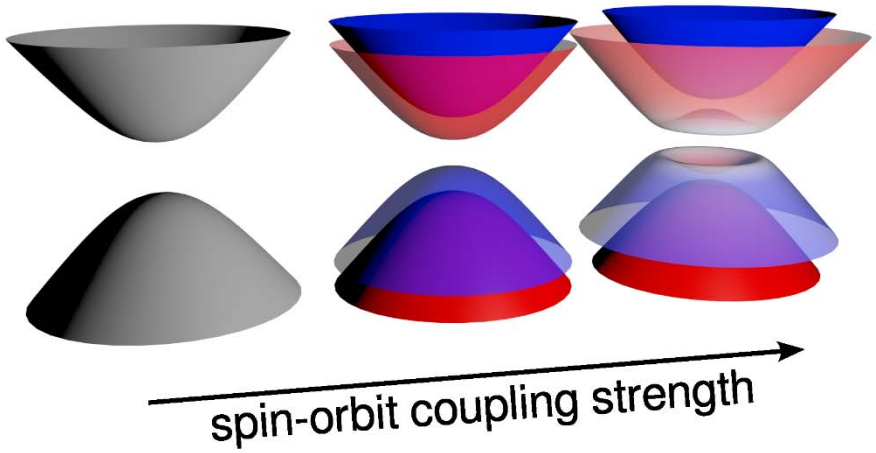


Graphene on TMDCs:
from normal to inverted bands

M. Gmitra, and J. Fabian, Phys. Rev. B 92, 155403 (2015)

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





Also: Kaloni et al (Schwingenschlögl), APL 105, 233112 (2014) …. DFT Theory (1 meV)
A. Alsharari et al (Ulloa), PRB 94, 241106 (2016) … TB modeling

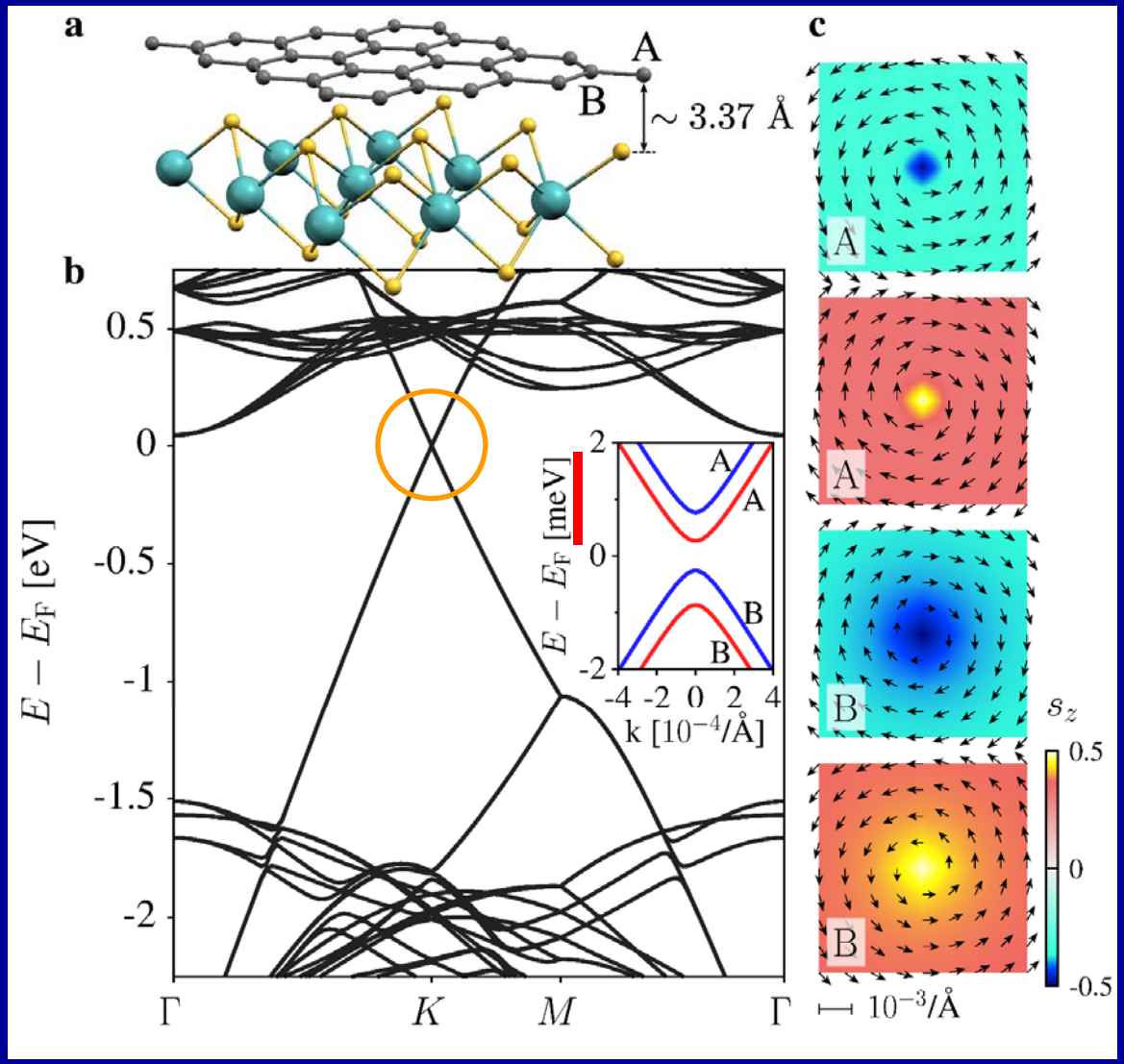
A. Avsar et al. (Özyilmaz)Nature Communications (2014) …. Spin Hall …. (17 meV)

Wang et al (Morpurgo), Nature Comm. 6, 8339 (2015) (Gr/WS2) 2-5 ps ….WL
Yang et al (Shi), 2D Mater. 3, 031012 (2016) (Gr/WS2) 5 ps

S. Omar and B. J. van Wees, PRB 95, 081404(R) (Gr/WS2) 20 ps …. Spin injection
A. Dankert and S Dash, Nature Comm. 8, 16093 (2017) (Gr/MoS2) 40 ps

Graphene on MoS_2: electronic structure

M. Gmitra, and J. Fabian, Phys. Rev. B 92, 155403 (2015)



$$H =$$

$$\hbar v_F(k_x\sigma_y + k_y\sigma_x) +$$

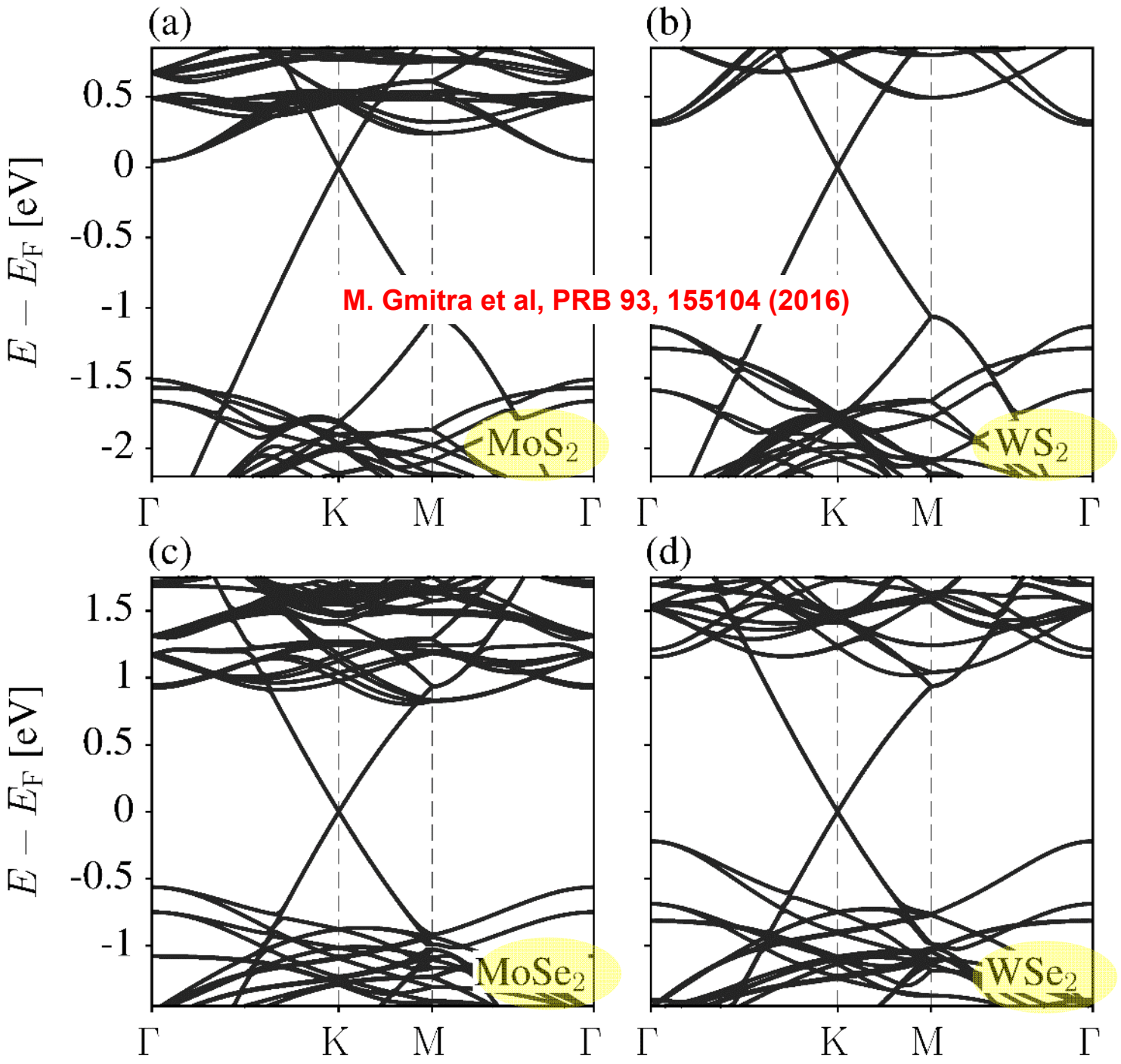
$$\Delta\,\sigma_z\, s_0 +$$

$$\Lambda_I^A(\sigma_z + \sigma_0)sz +$$

$$\Lambda_I^B(\sigma_z - \sigma_0)sz +$$

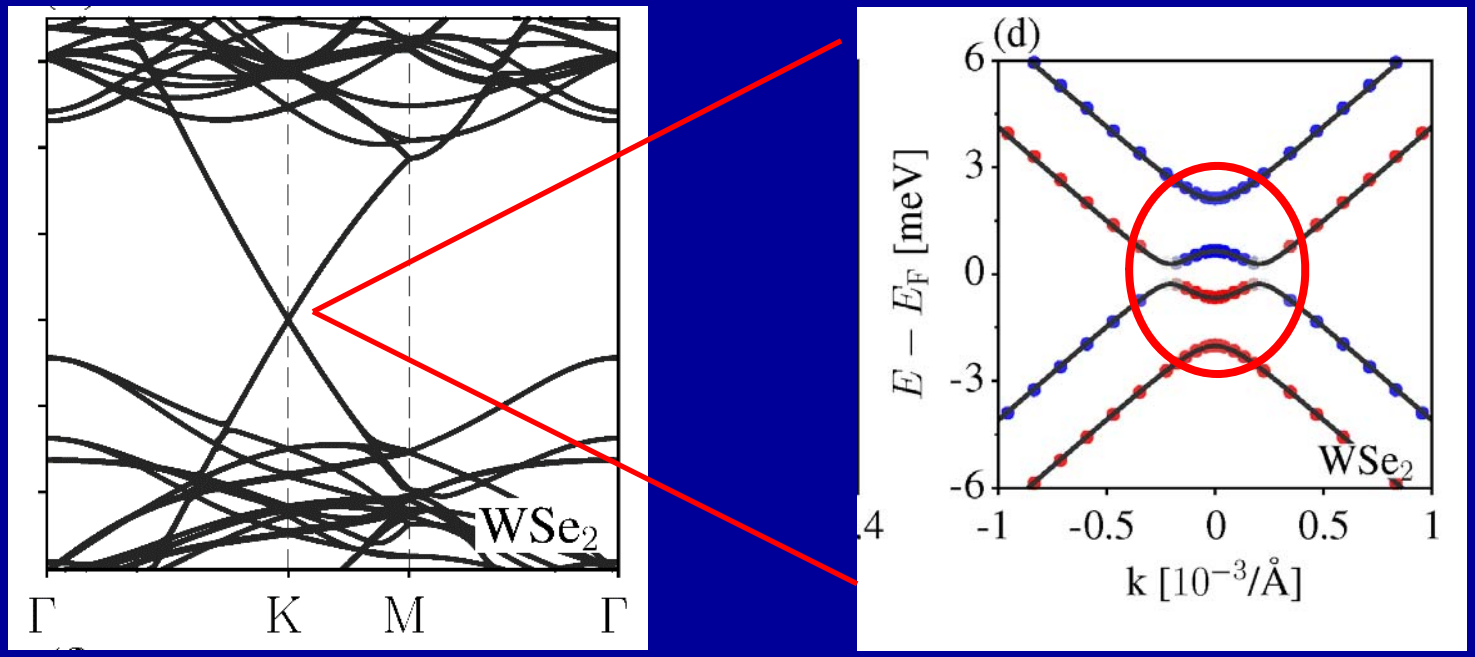
$$\Lambda_R(\sigma_x\, sy - \sigma_y\, s_x) +$$

$$\Lambda_{PIA}\sigma_z\,(k_x\, sy - k_y\, s_x)$$


(a)
(b)
(c)
(d)
$E - E_F$ [eV]
0.5
0
-0.5
-1
-1.5
-2
1.5
1
Γ
K
M
Γ
MoS_2
WS_2
$MoSe_2$
WSe_2
M. Gmitra et al, PRB 93, 155104 (2016)

Quantum valley-spin Hall effect in Gr on WSe_2

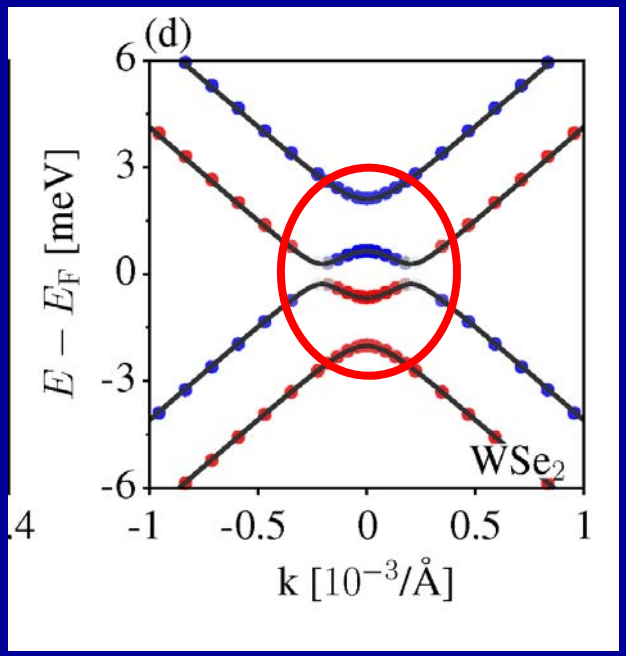
M. Gmitra, D Kochan, P. Högl, and J. Fabian, PRB 93, 155104 (2016)

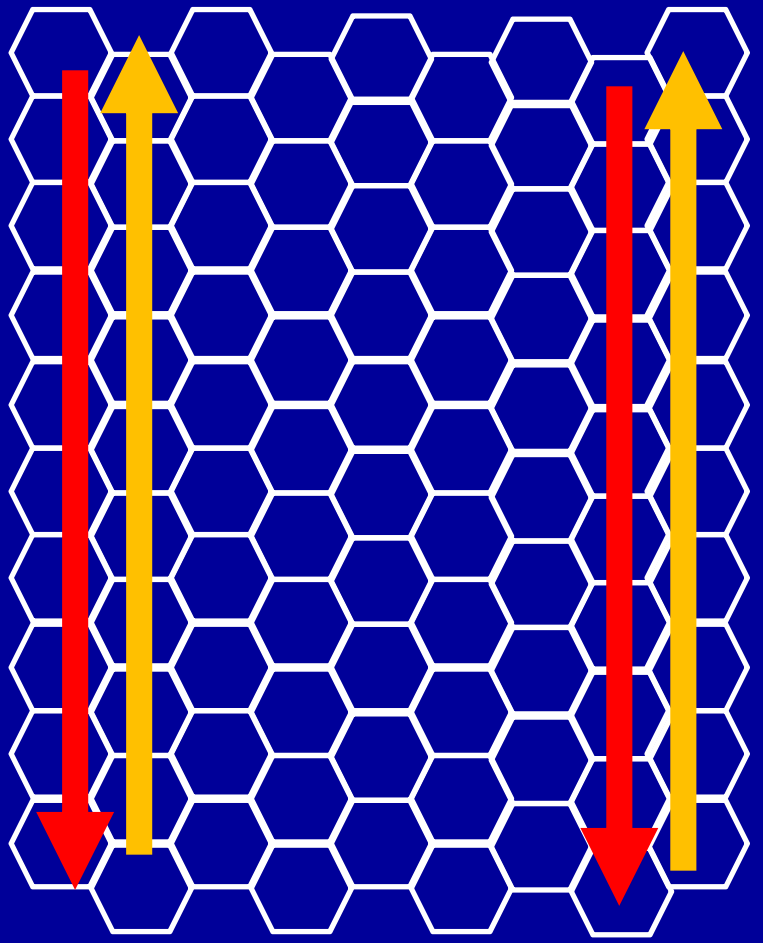


$$H_R = \alpha(k_x \sigma_x + k_y \sigma_y) + \lambda_{I+} s_z \sigma_z + \lambda_{I-} s_z \sigma_0 + \lambda_R(s_x \sigma_y - s_y \sigma_x)$$

Quantum valley-spin Hall effect in Gr on WSe_2

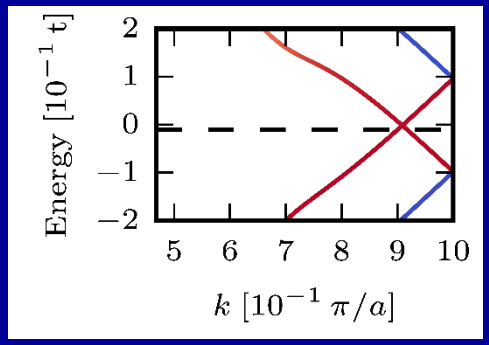
M. Gmitra, D Kochan, P. Högl, and J. Fabian, PRB 93, 155104 (2016)



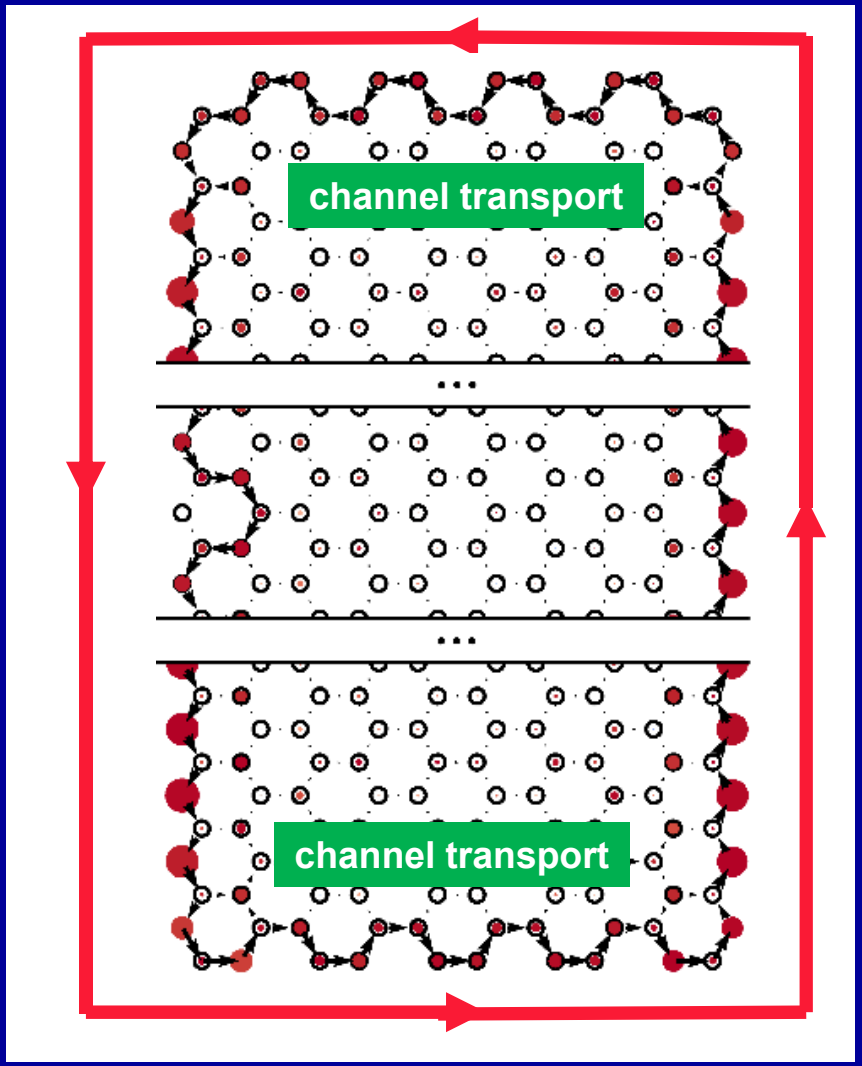


emergence of helical edge states!

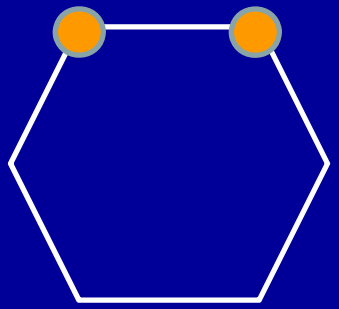
Topological protection



Kane and Mele,
Phys. Rev. Lett. 95, 226801 (2005)

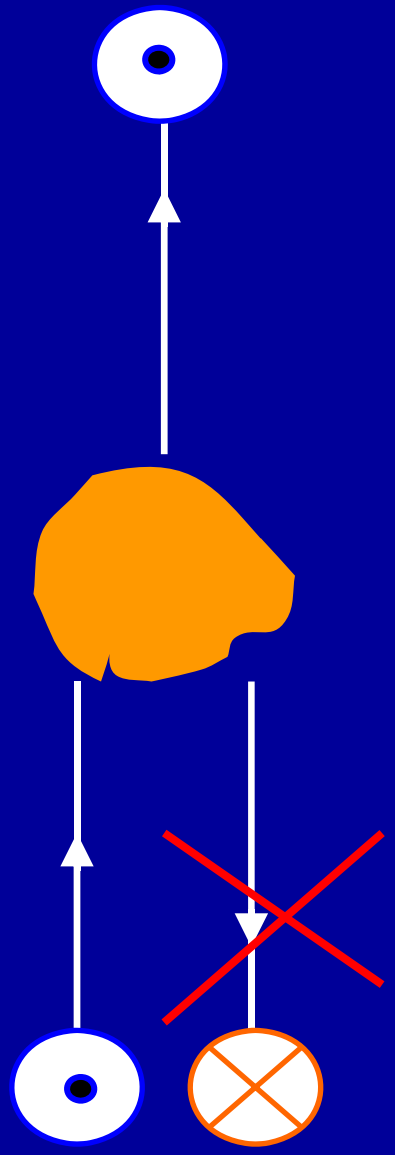


$\lambda_{IA} = \lambda_{IB}$



helical

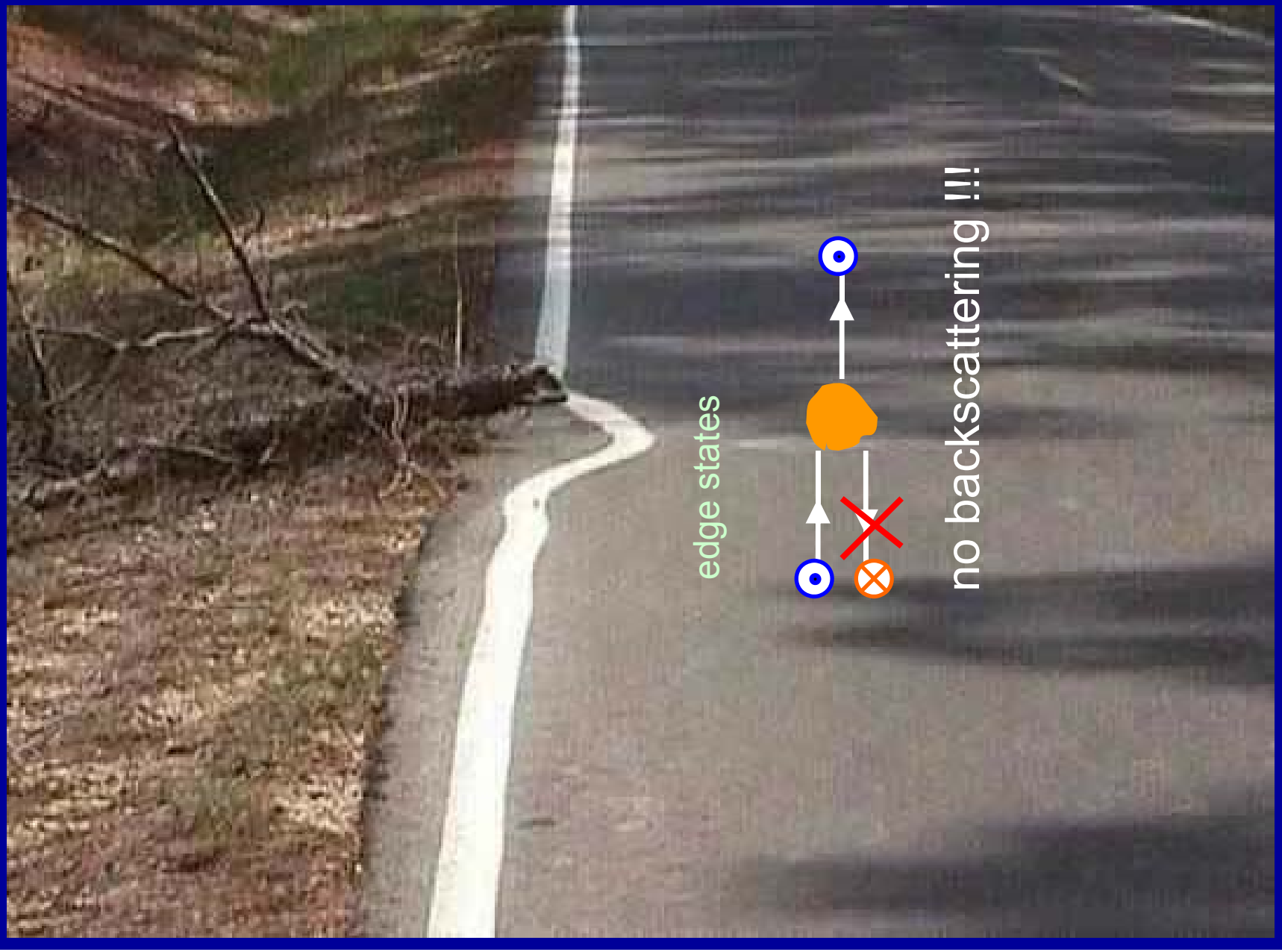
protected edge states against backscattering



$$\langle \Psi \mid V \mid T\Psi \rangle = 0$$

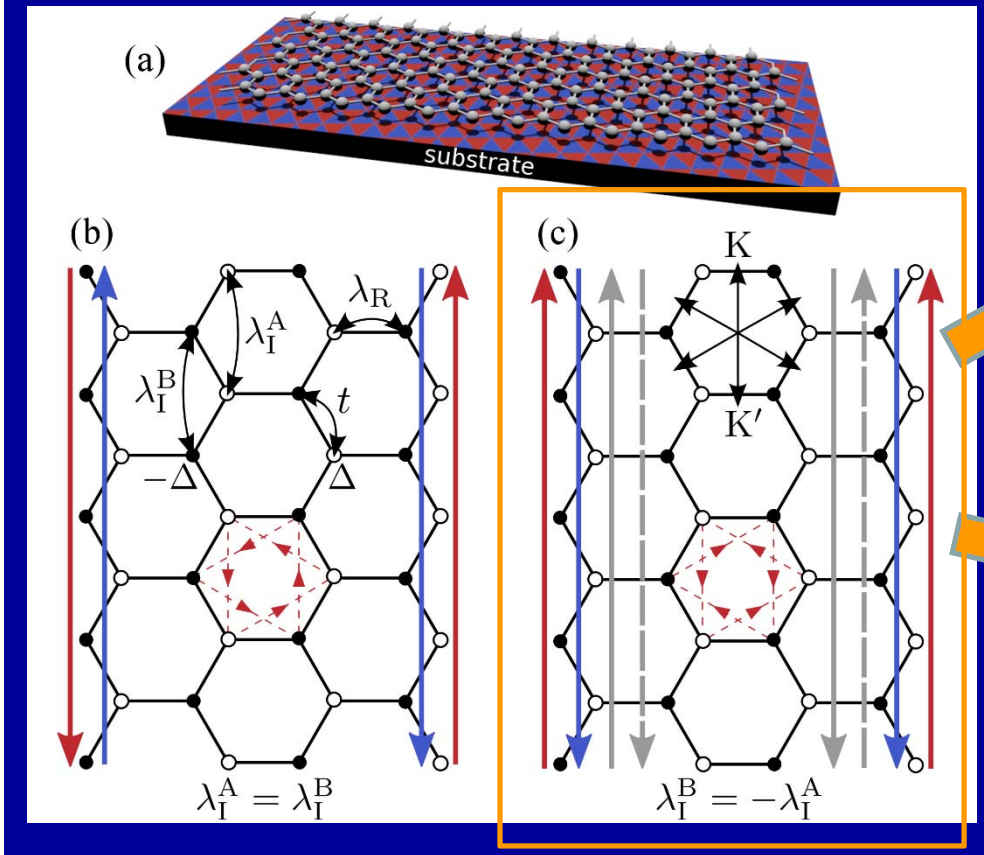
no backscattering !!!

Topological protection

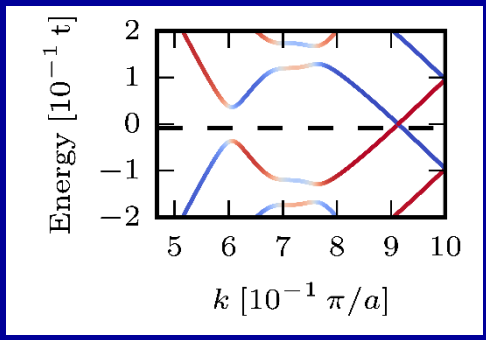


protected edge states in Z_2=0 (trivial) system

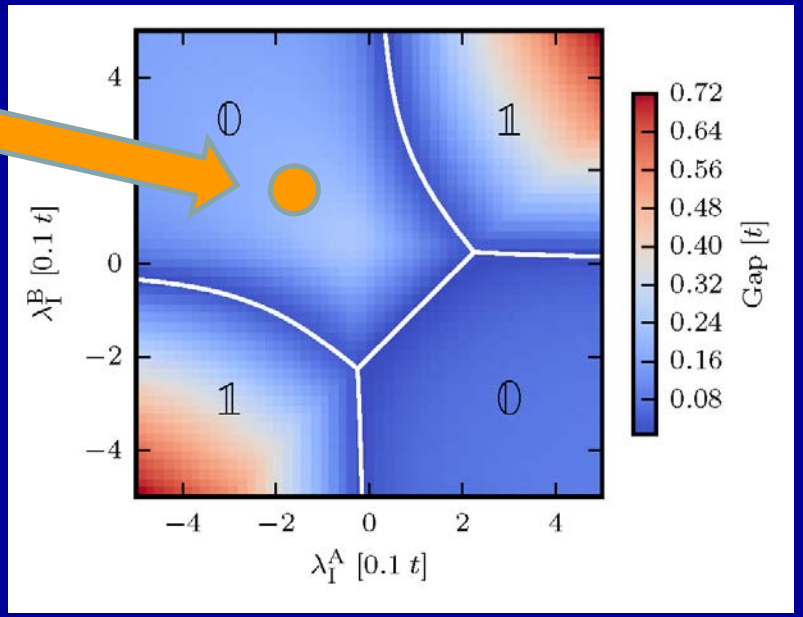
T. Frank, P. Högl. M. Gmitra, D. Kochan, and J. Fabian, arXiv:1707.02124



finite ZZ ribbon

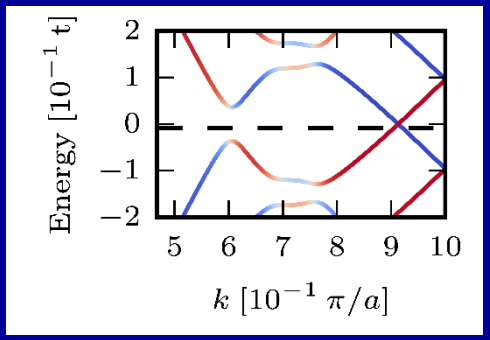


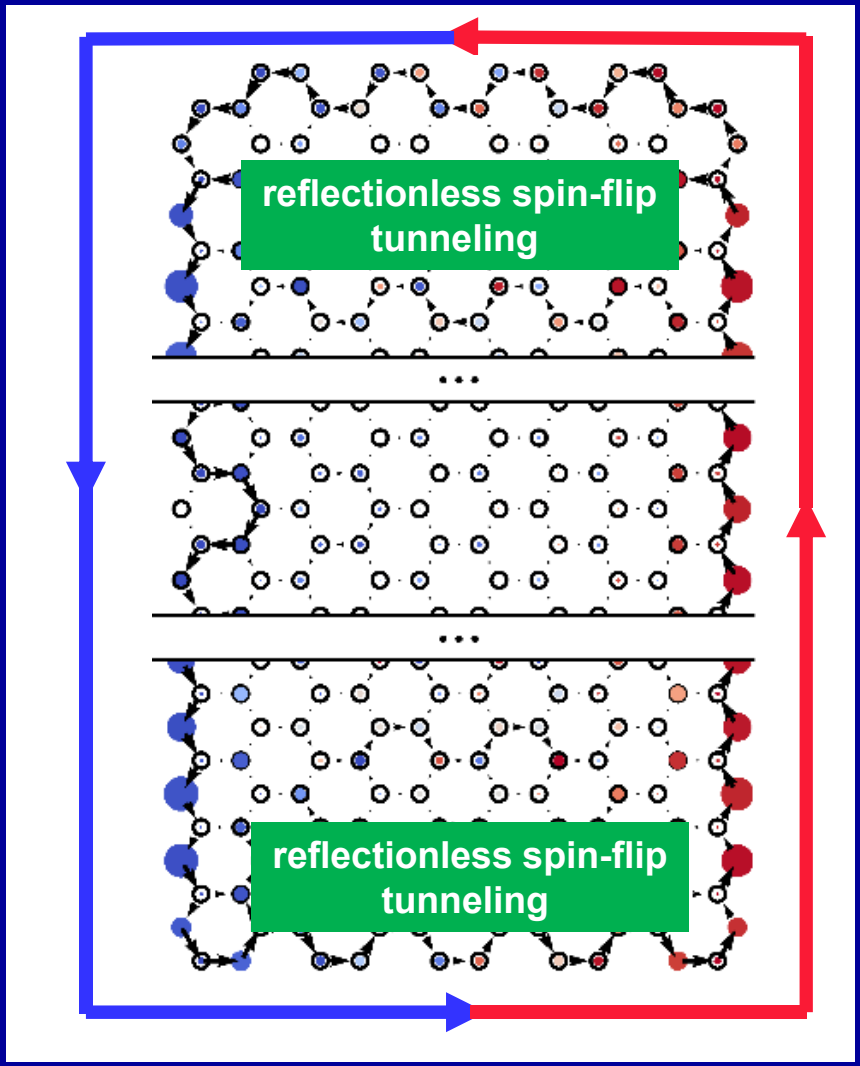
Z_2 map



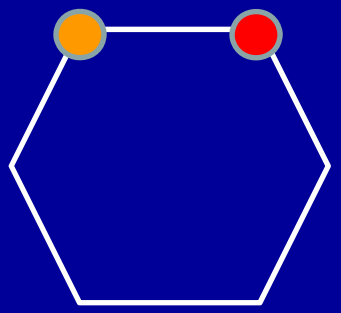
protected edge states in Z_2=0 (trivial) system

T. Frank, P. Högl. M. Gmitra, D. Kochan, and J. Fabian,
arXiv:1707.02124





$\lambda_{IA} = -\lambda_{IB}$



pseudohelical states

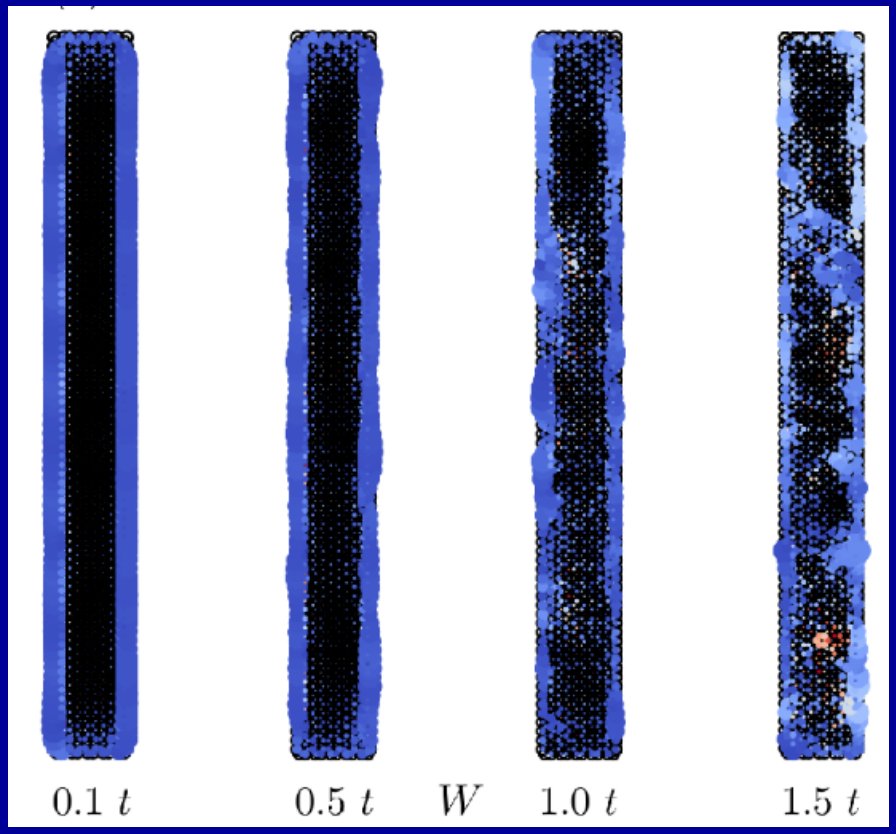
Topological protection

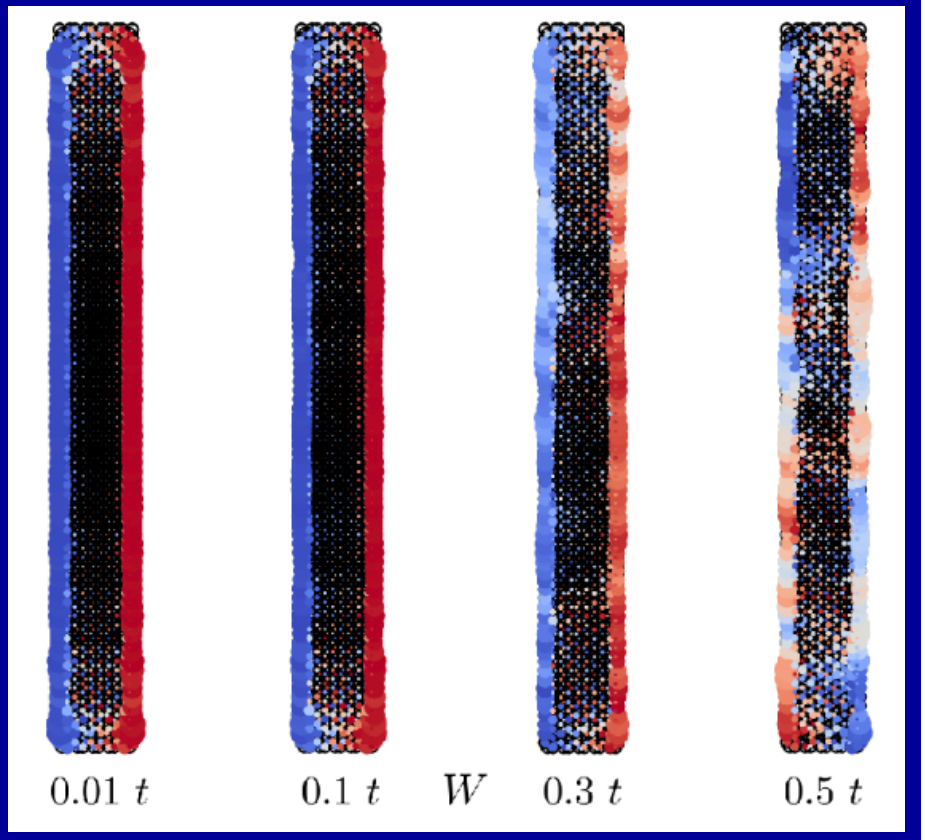
T. Frank, P. Högl. M. Gmitra, D. Kochan, and J. Fabian,
arXiv:1707.02124

$\lambda_{IA} = \lambda_{IB}$

Kane-Mele

$\lambda_{IA} = -\lambda_{IB}$



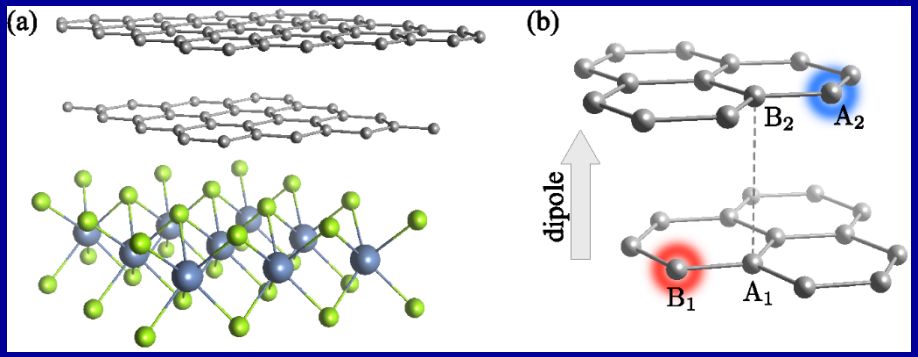


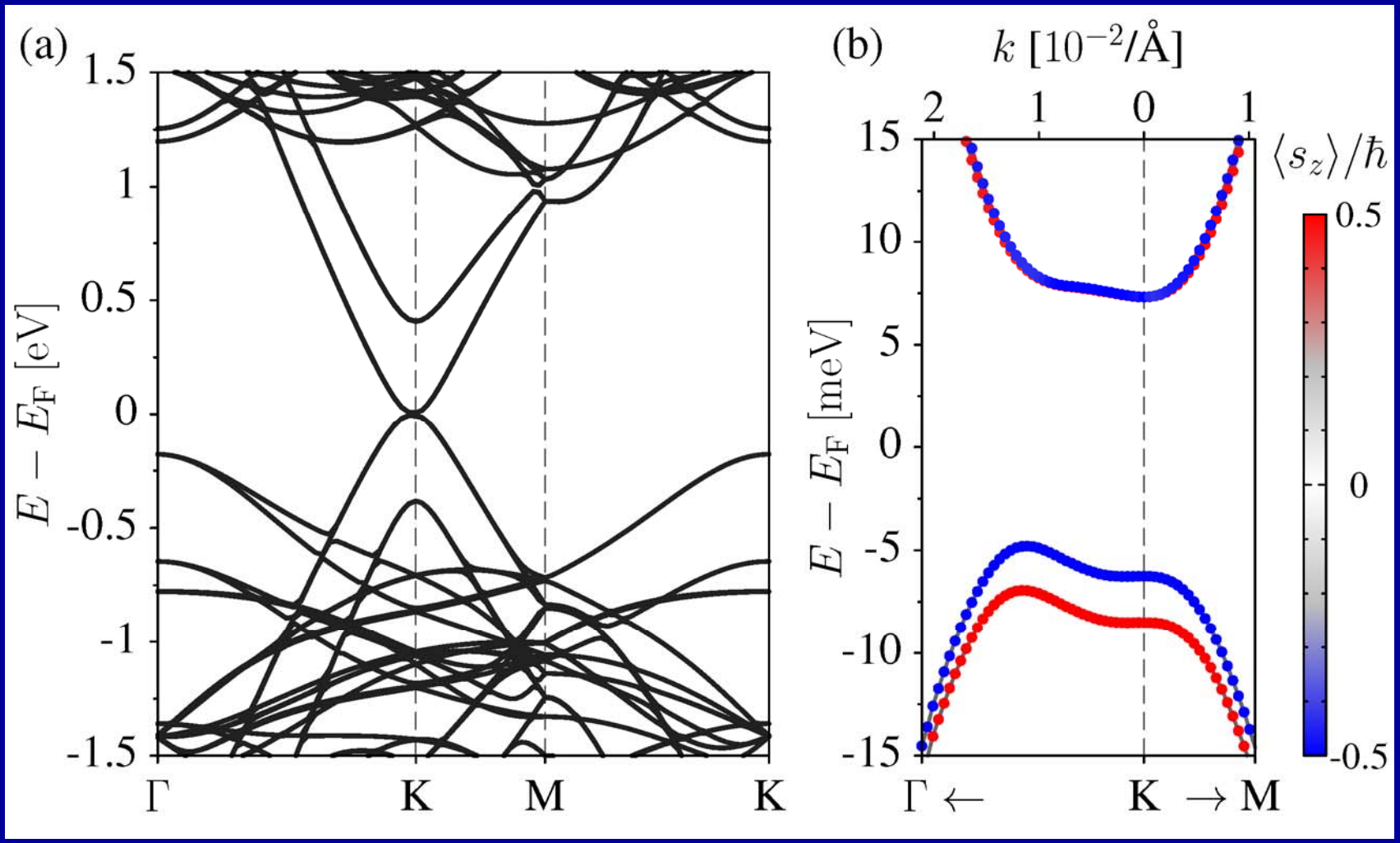
Bilayer Graphene on WSe_2

spin-orbit valve and spin transistor

BLG on WSe_2

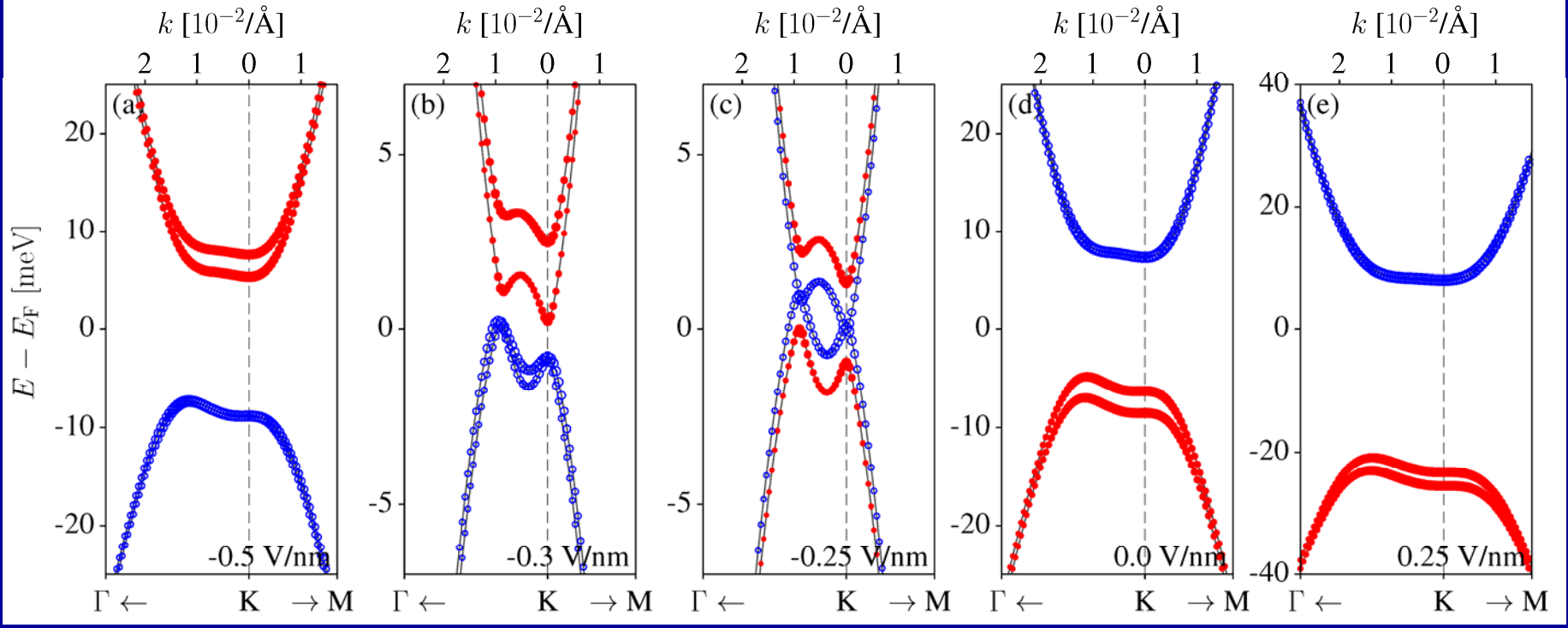
M. Gmitra and J. Fabian, arXiv1706.06149, PRL in press





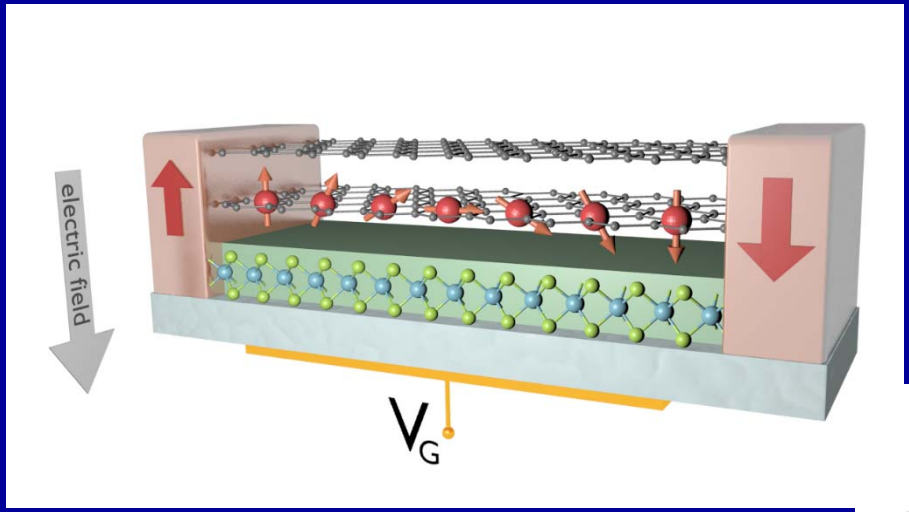
spin-orbit valve

M. Gmitra and J. Fabian, arXiv1706.06149 , PRL in press

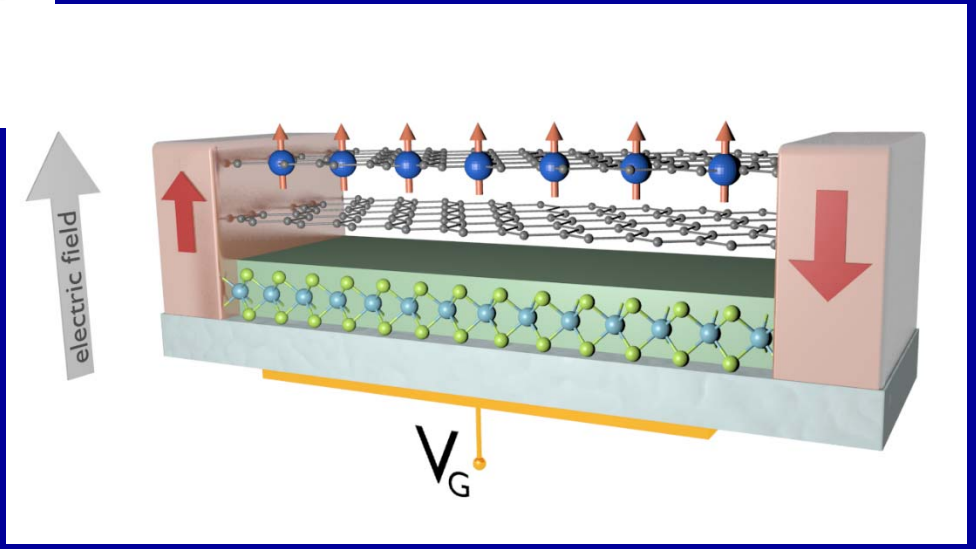


Spin transistor

M. Gmitra and J. Fabian, arXiv1706.06149, PRL in press
based on spin transistor design of Hall and Flatte, APL 88, 162503 (2006)

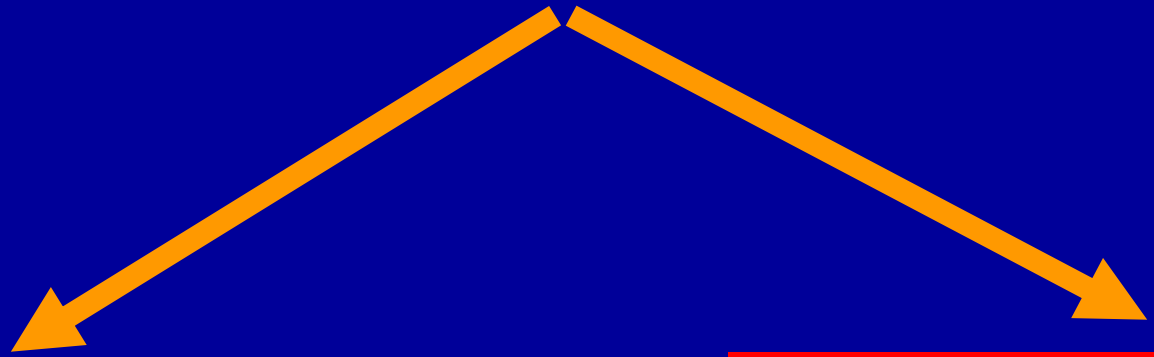


ON



OFF

PROXIMITY EXCHANGE



Ferromagnetic insulators (YIG, EuO, EuS)

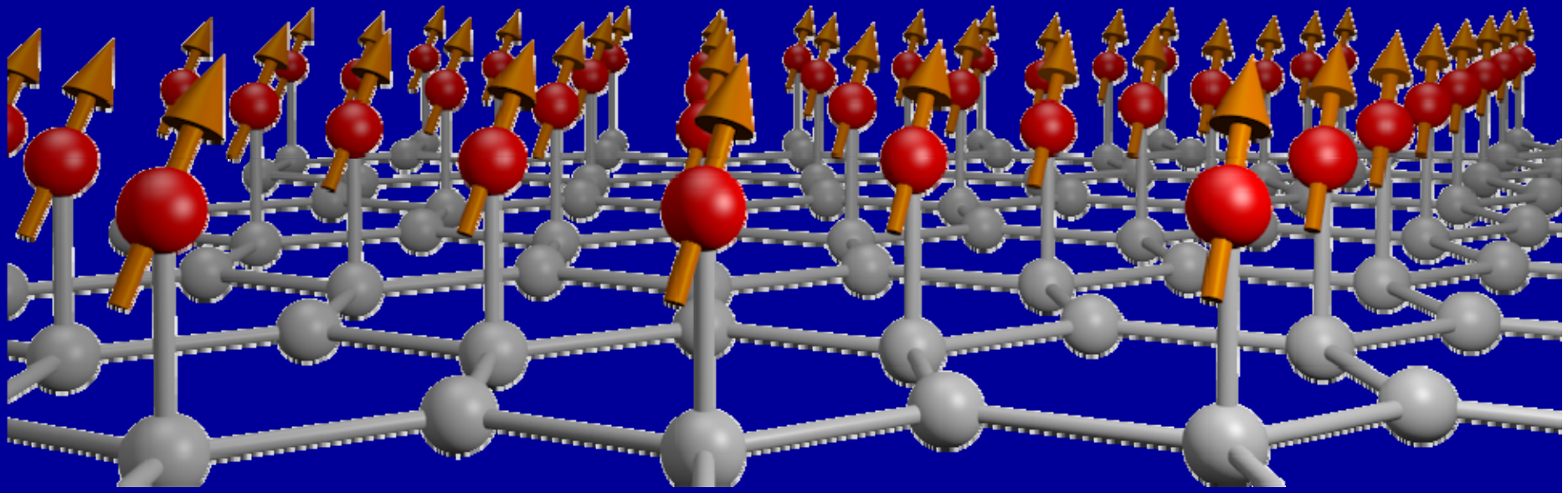
Yang et al (Chshiev), PRL 110, 046603 (2013)

Wang et al (Shi), PRL 114, 016603 (2015)
Leutenantsmeyer et al (van Wees), 2D Materials 4, 014001 (2017)

Ferromagnetic metals (Co, Ni) and tunnel barriers (MgO, hBN)

Lazic et al (Zutic), PRB 93, 241401 (2016)
Zollner et al (JF), PRB 94, 155441 (2016)

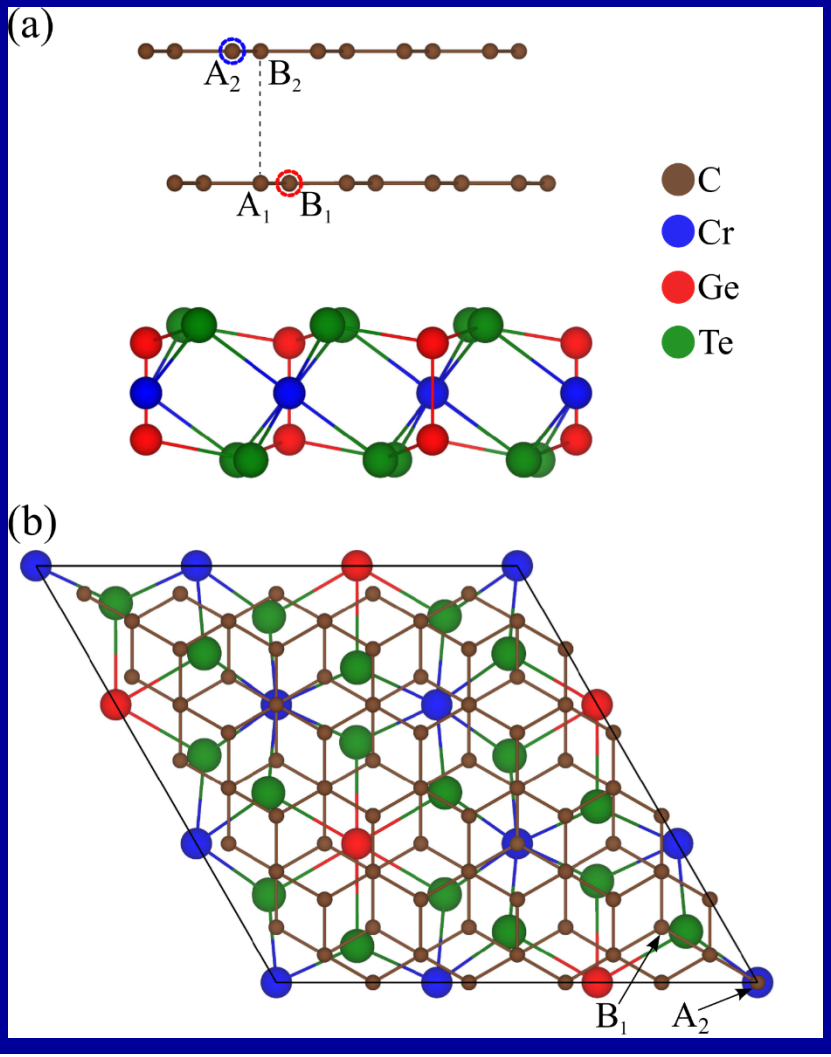
Thinnest ferromagnet?



Courtesy Martin Gmitra

BLG on $CrSi(Ge)Te_3$: gate-controlled exchange

K. Zollner, M. Gmitra, and J. Fabian, preprint



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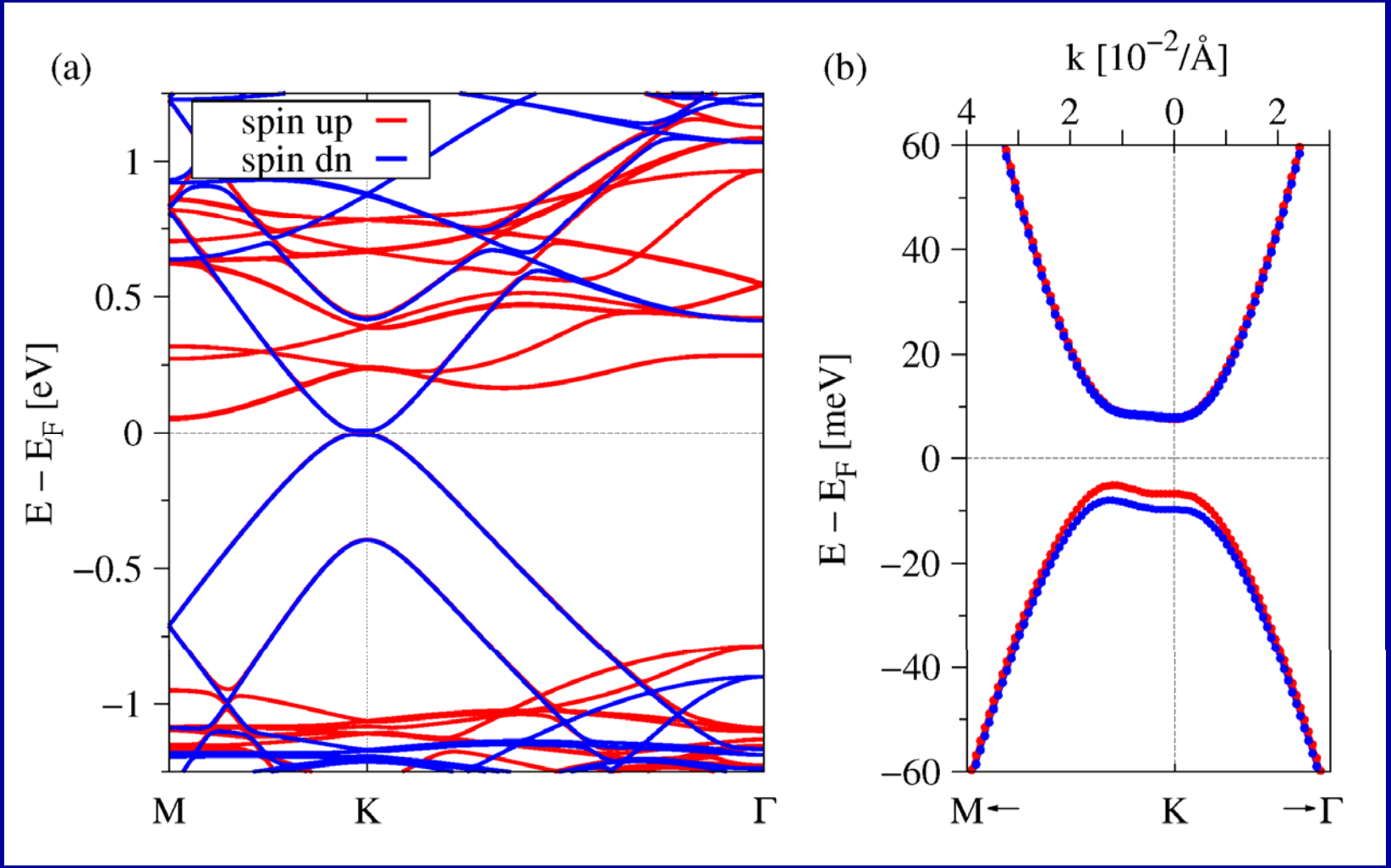

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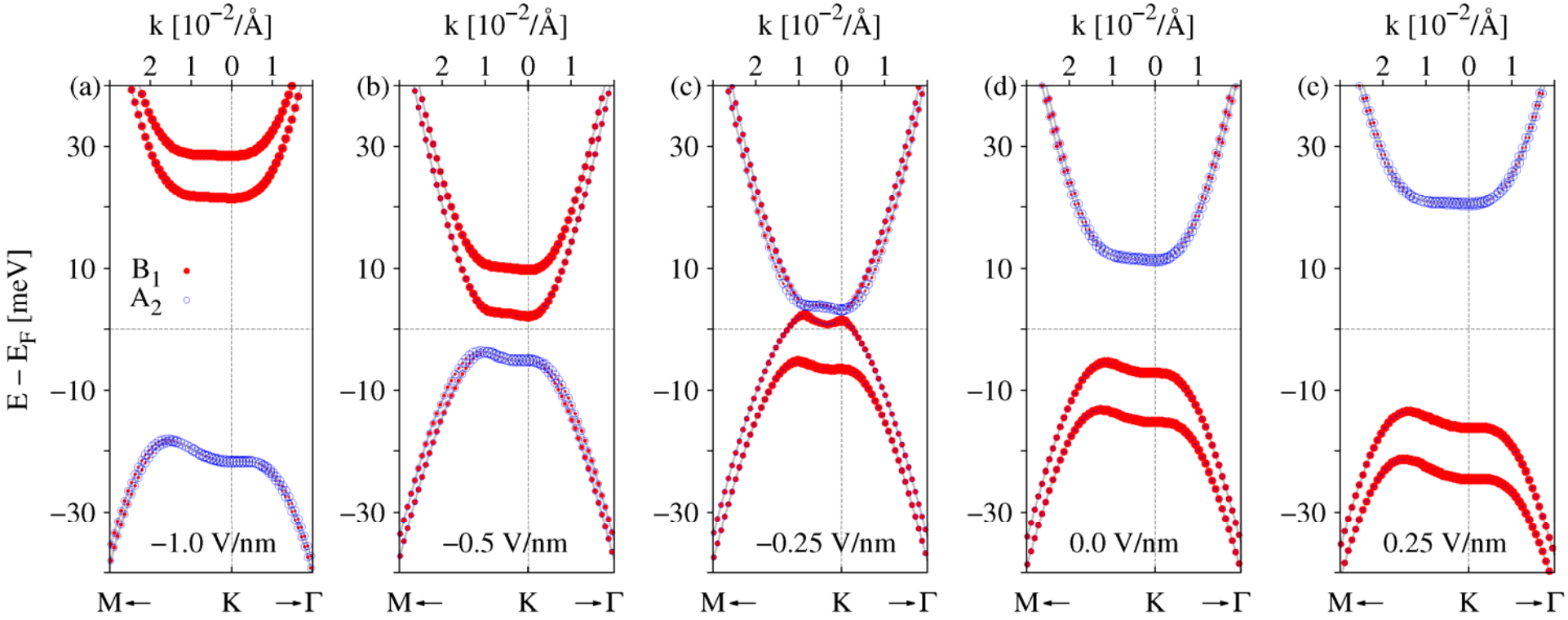

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nature nanotechnology

Graphene spintronics

Wei Han[1,2,3], Roland K. Kawakami[4,5]*, Martin Gmitra[6] and Jaroslav Fabian[6]*

The isolation of graphene has triggered an avalanche of studies into the spin-dependent physical properties of this material and of graphene-based spintronic devices. Here, we review the experimental and theoretical state-of-art concerning spin injection and transport, defect-induced magnetic moments, spin–orbit coupling and spin relaxation in graphene. Future research in graphene spintronics will need to address the development of applications such as spin transistors and spin logic devices, as well as exotic physical properties including topological states and proximity-induced phenomena in graphene and other two-dimensional materials.