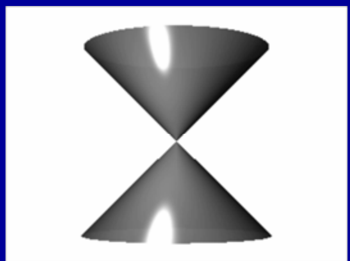
Spin, valley, and exchange proximity effects in graphene van der Waals heterostructures



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www.graphene-flagship.eu
GRAPHENE FLAGSHIP

Elitenetzwerk Bayern

Deutsche Forschungsgemeinschaft DFG

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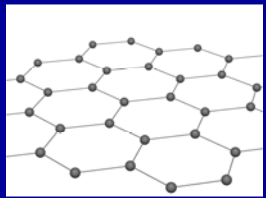
GRK TI

SPP 1666

SFB689

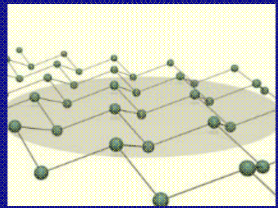
GRK1570

Dresden 27.6.2018

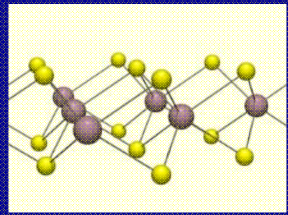


graphene

semimetal

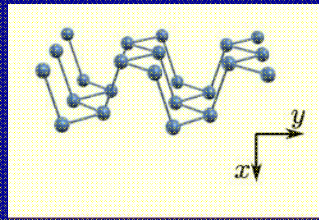


germanene,
silicene

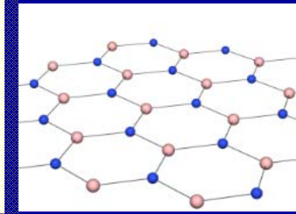


MoS_2

$NbSe_2$

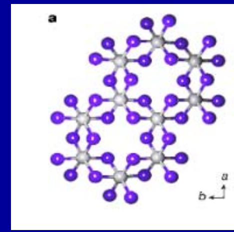


phosphorene



hBN

insulator

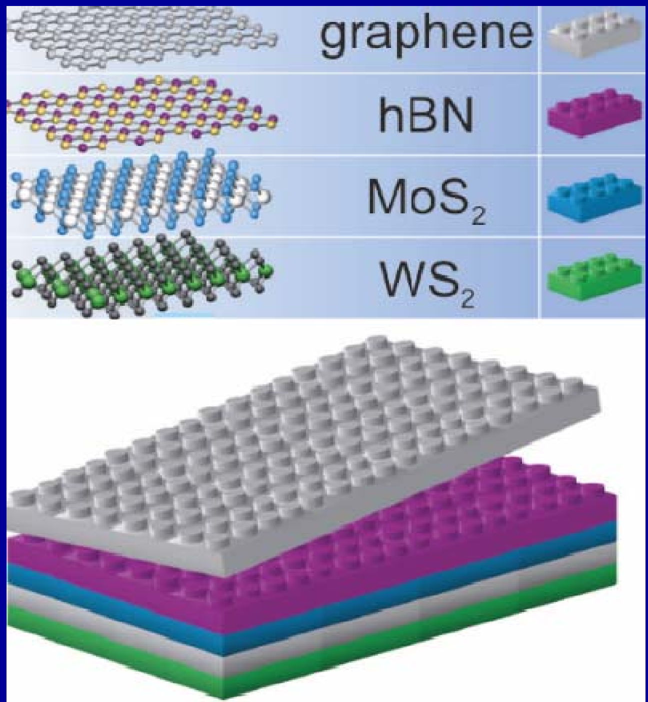


CrI_3

ferromagnet

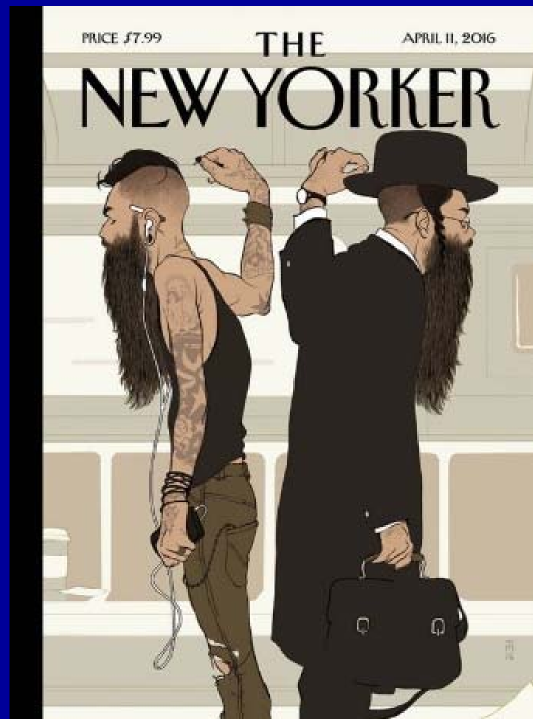
semiconductors

superconductors



heterostructures

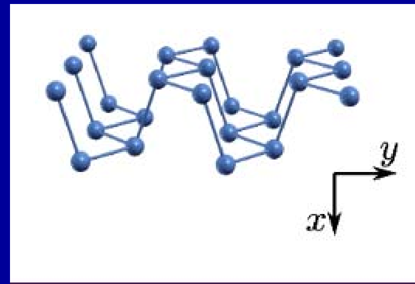
proximity effects?

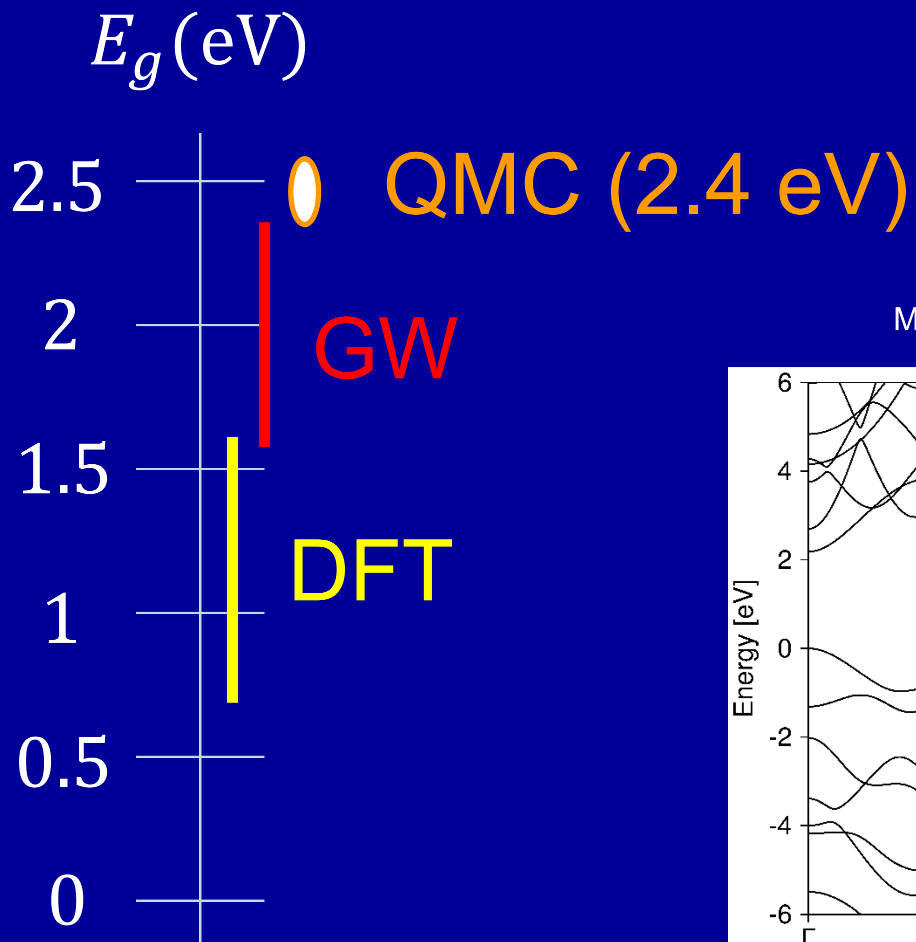


What is the band gap of phosphorene?

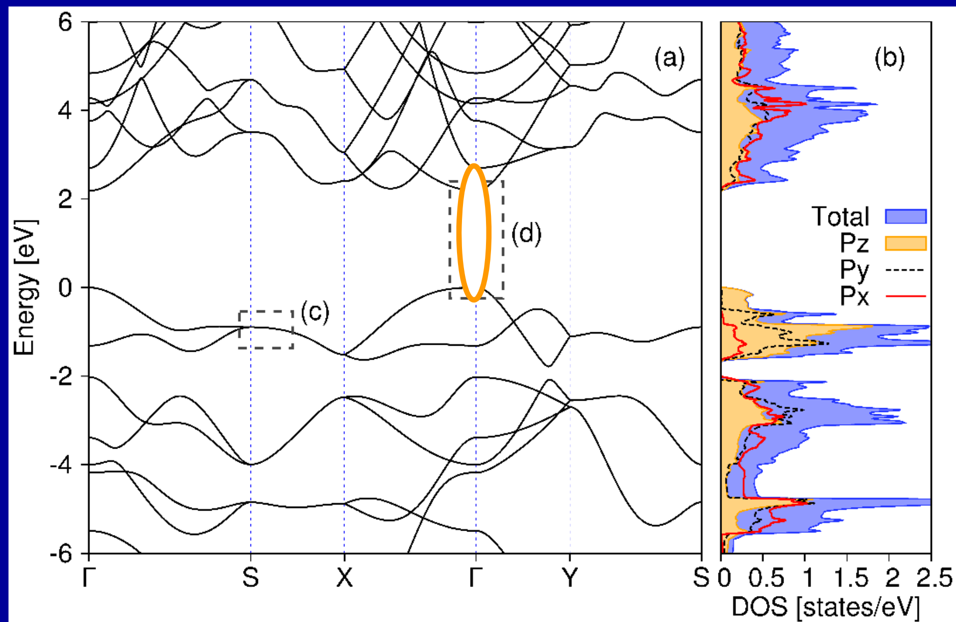
from DFT/GW to QMC

T. Frank et al, arXiv:1805.10823



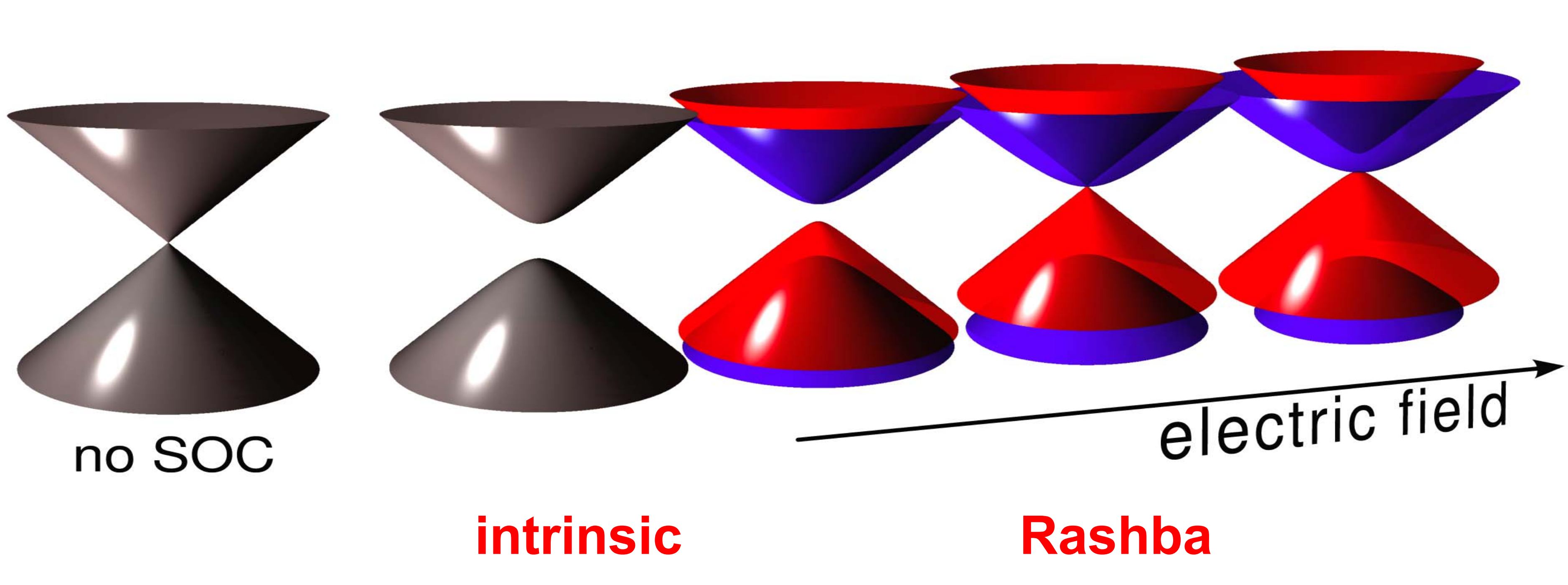


M. Kurpas et al, Phys. Rev. B 94, 155423 (2016)

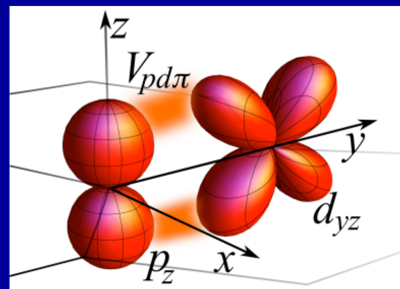


spin-orbit coupling in graphene

band-structure topologies in a transverse E-field



Relativistic interaction (SOC) kills the relativistic massless Dirac band structure!



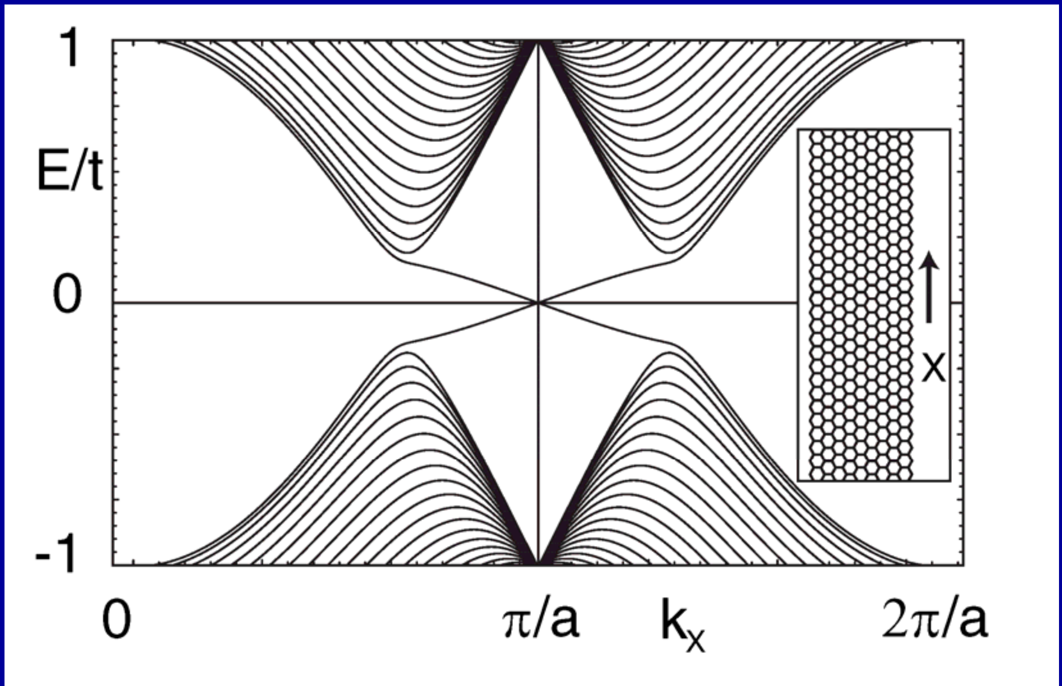
Quantum spin Hall effect

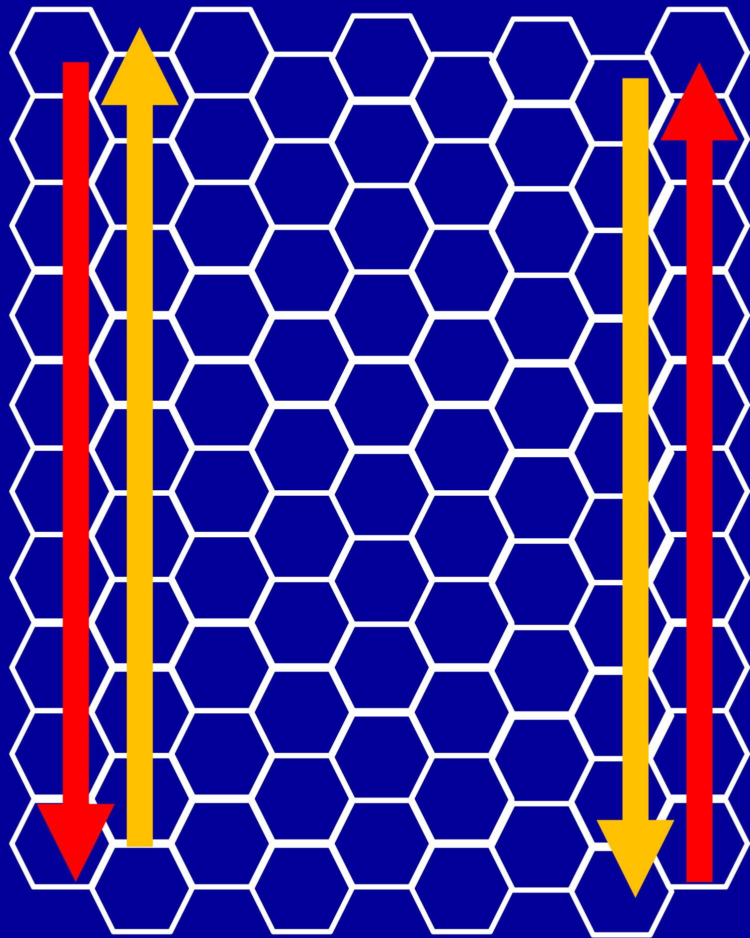
Quantum Spin Hall Effect

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

$$H_I = \lambda_I \sigma_z s_z$$

$$H_R = \lambda_R (\sigma_x s_y - \sigma_y s_x)$$

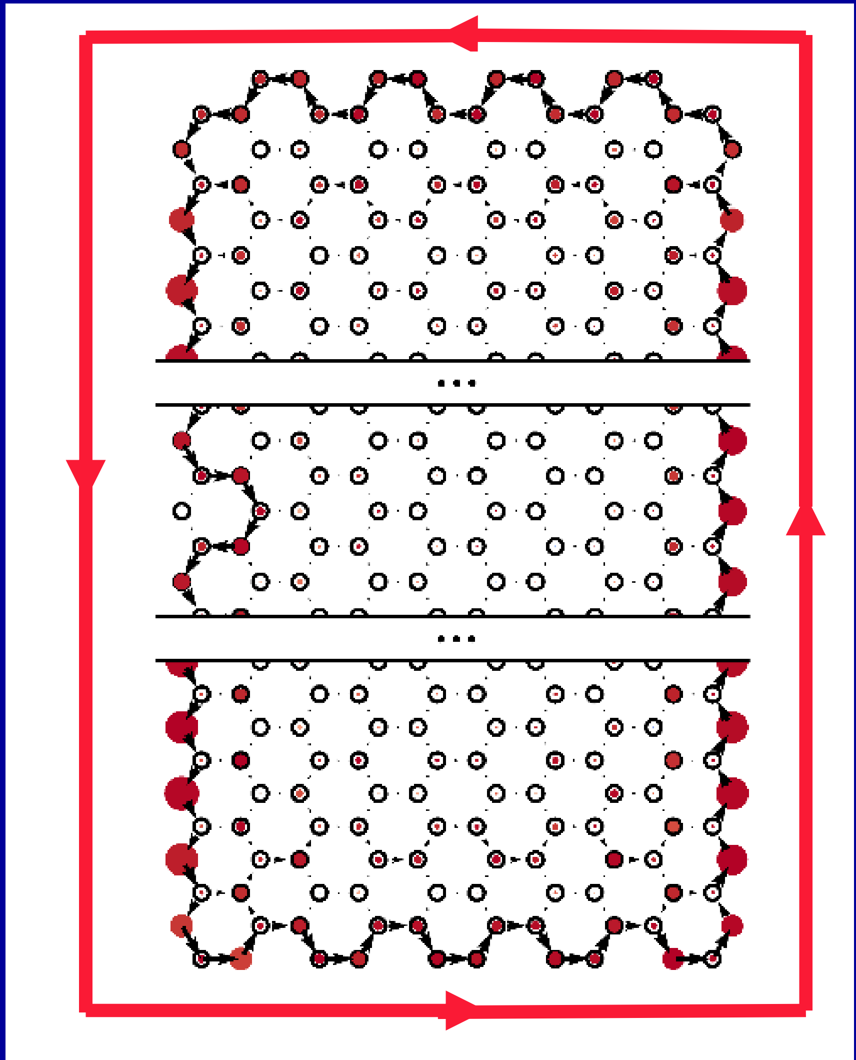




Topological protection

Kane and Mele, QSHE

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



Helical:

spin is locked to momentum

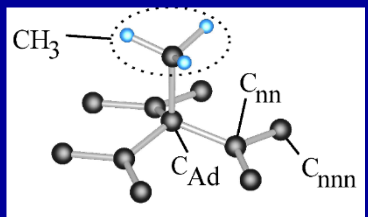
intrinsic graphene:

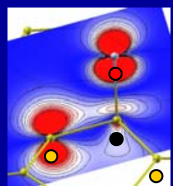
weak SOC gap of 25 μeV

two ways we follow to increase SOC in graphene

functionalizing graphene with adatoms:

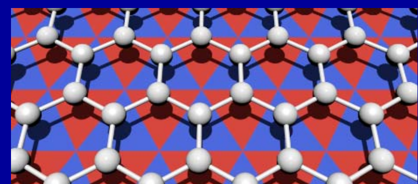
Local *random* SOC





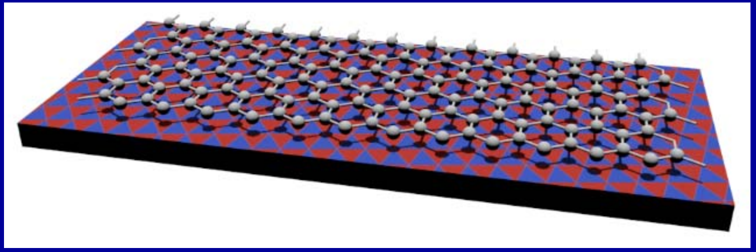
placing graphene on insulating/semiconducting substrates

Uniform *proximity* SOC



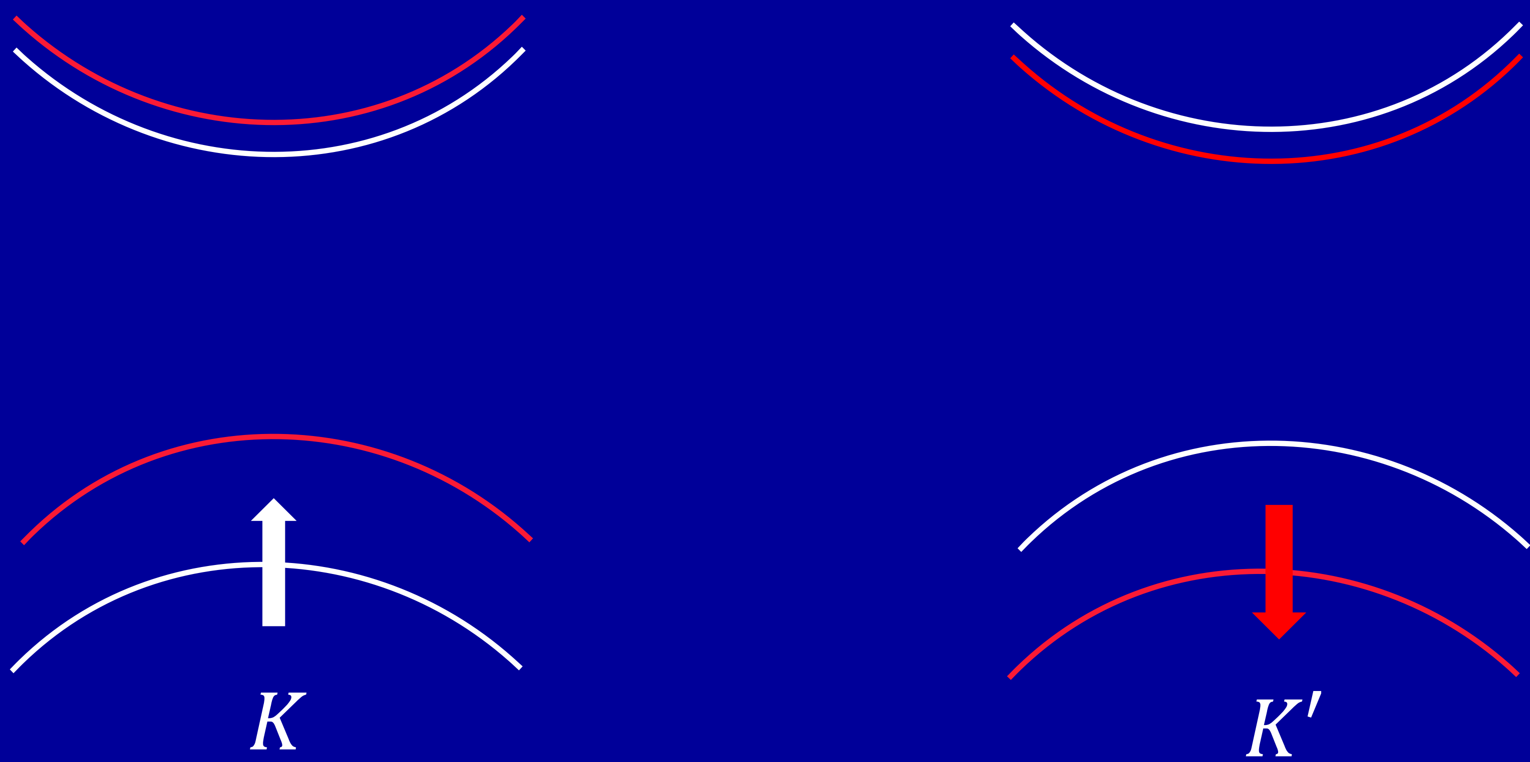
From 10 μeV to 1-10 meV

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



<u>explore proximity physics</u>

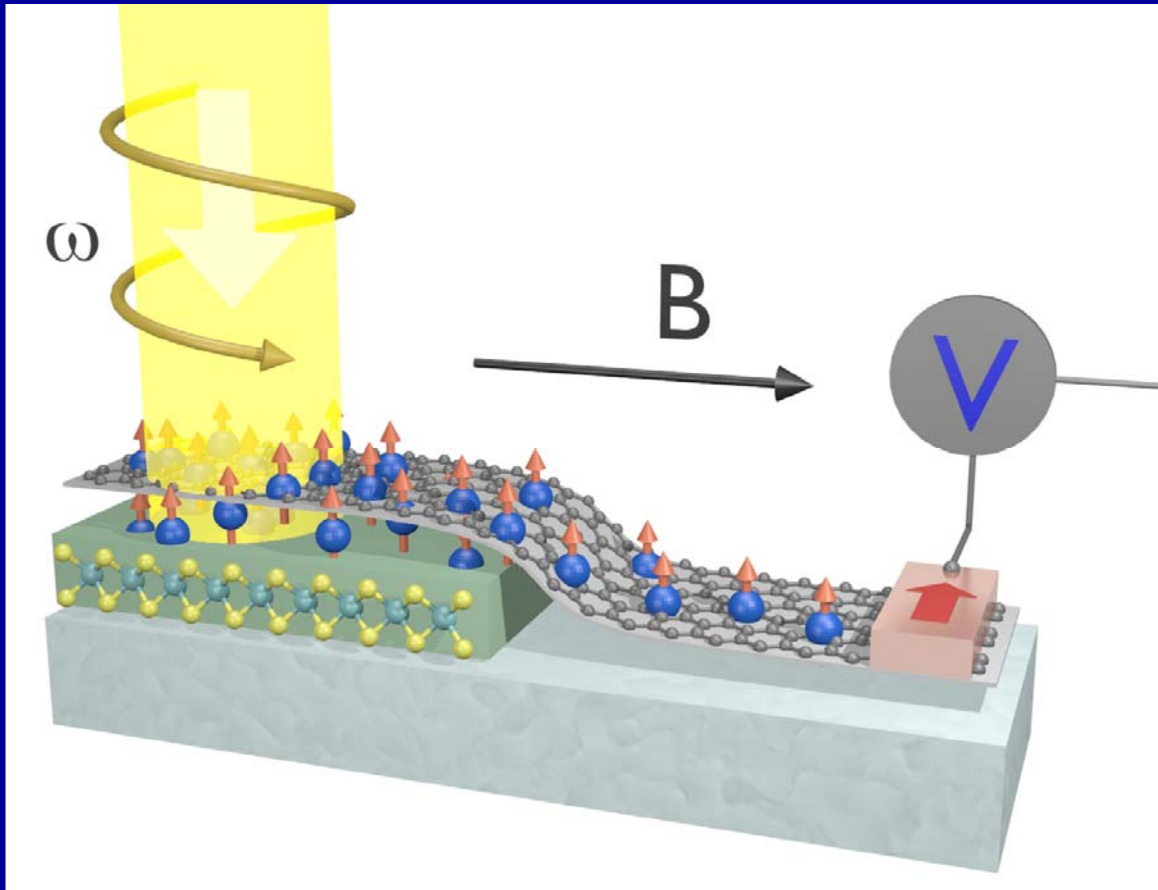
Optical orientation in TMDCs: valley Zeeman effect



optospintronics

graphene on TMDC optical spin injection into graphene

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

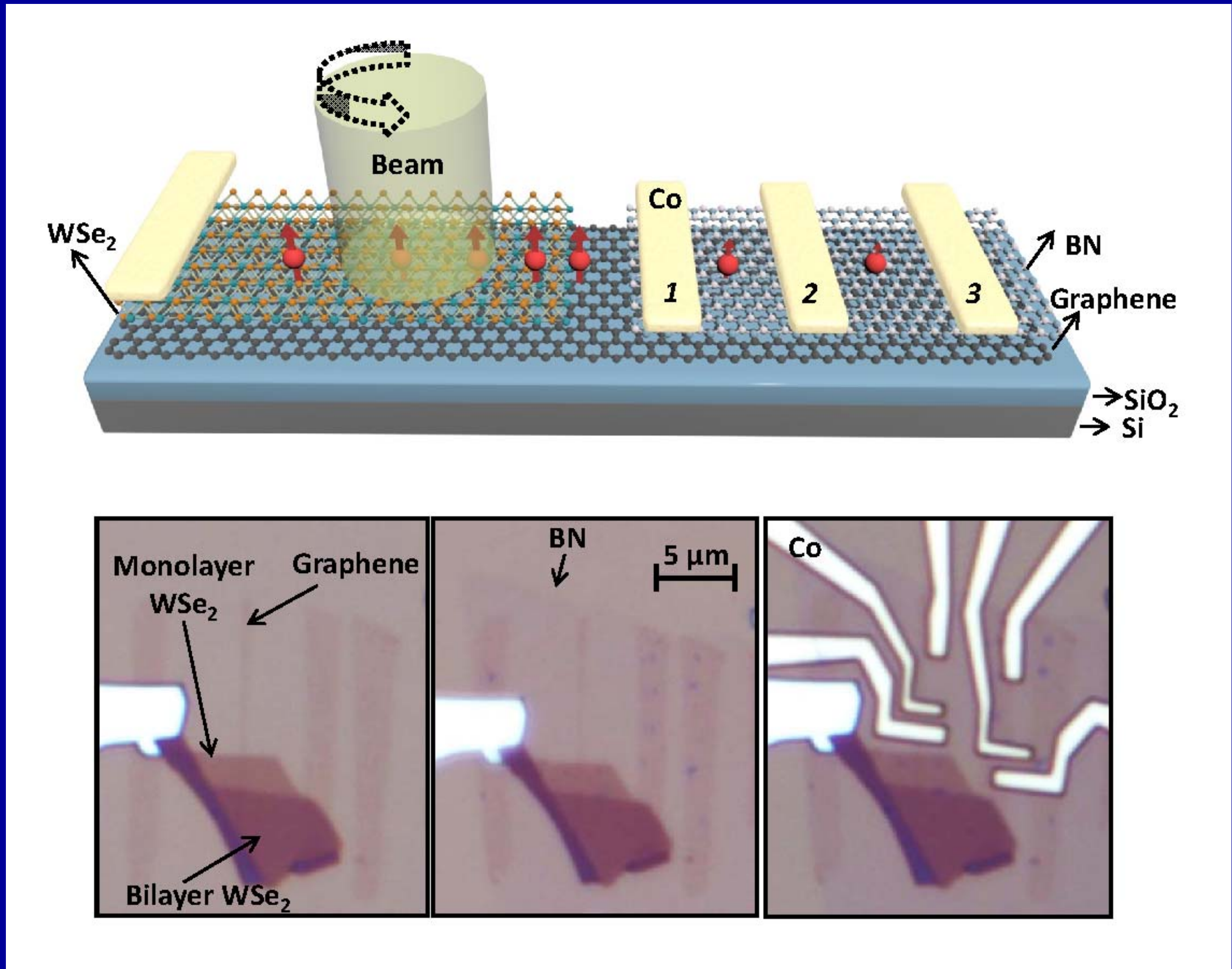


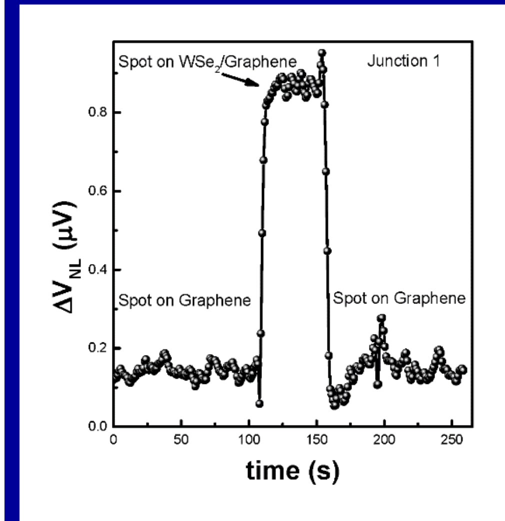
optospintronics

experiment

Luo et al (Kawakami), Nano Letters 17, 3877 (2017)

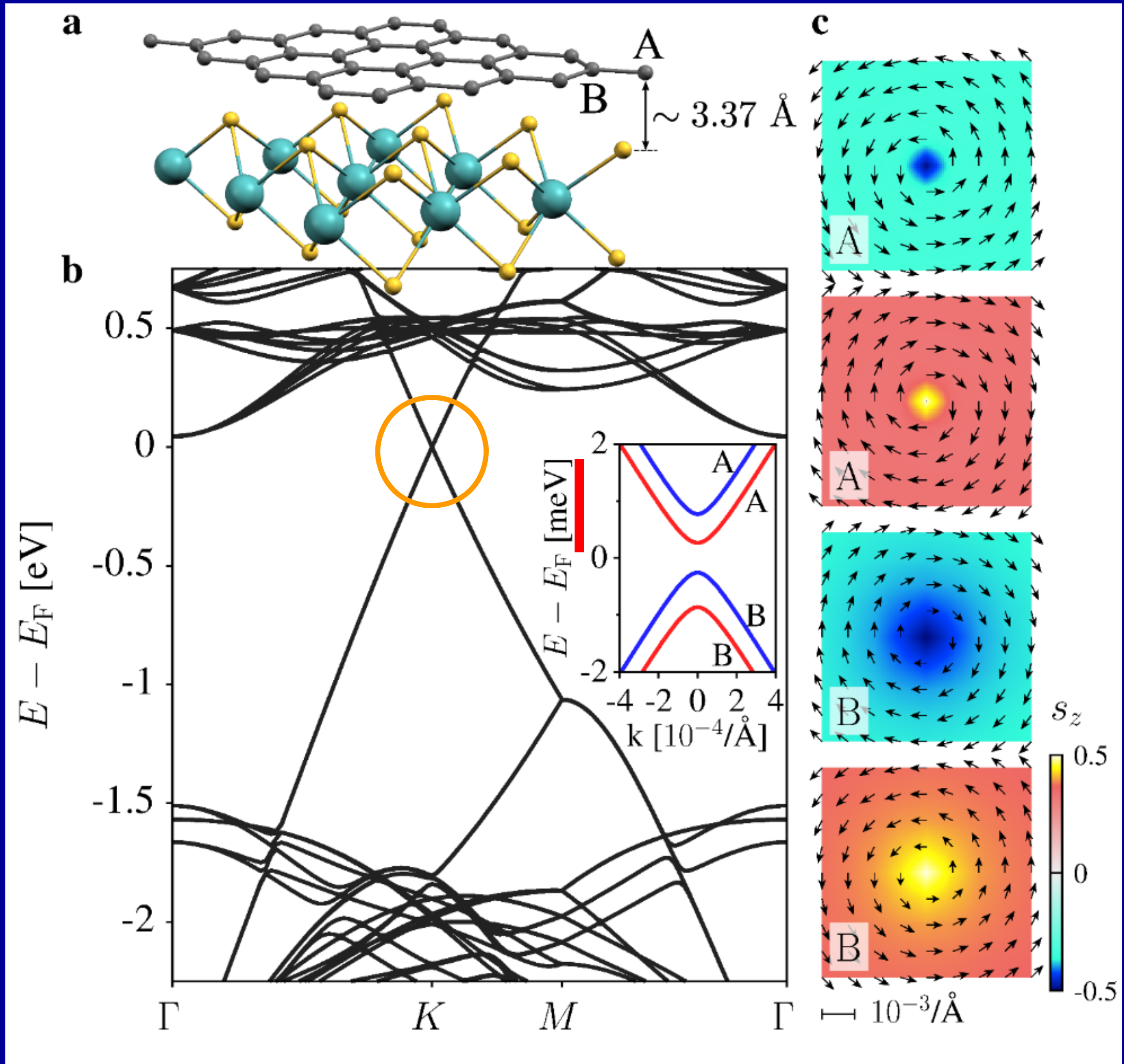
A. Avsar et al (Kis), ACS Nano 11, 11678 (2017)





Graphene on MoS_2: electronic structure

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



$H =$

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

$\Delta\, \sigma_z s_0 +$

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

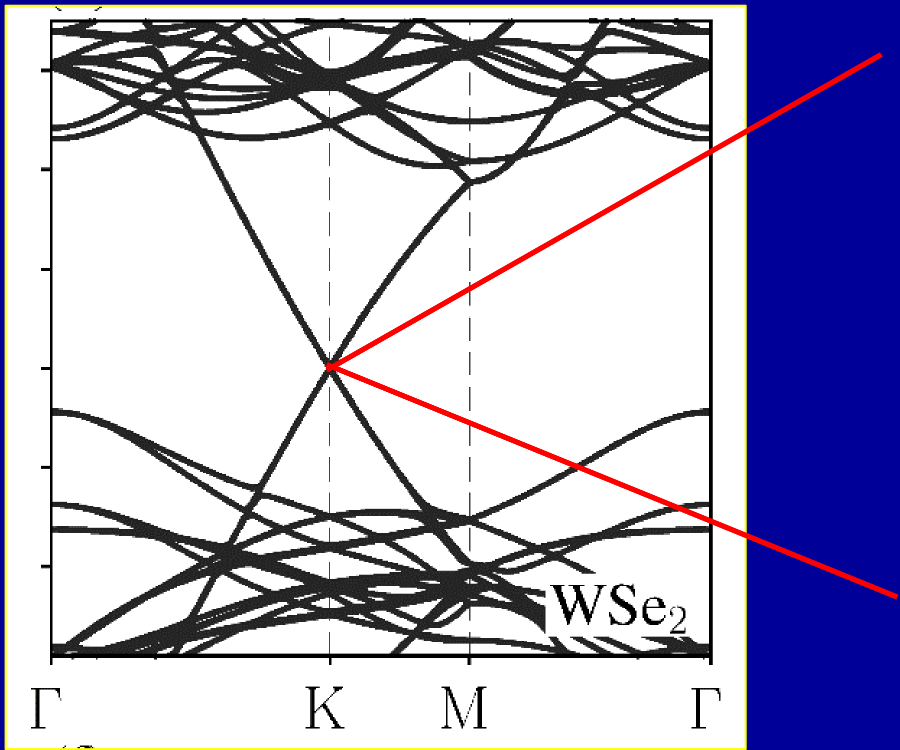
$\Lambda_I^B(\sigma_z - \sigma_0) s_z +$

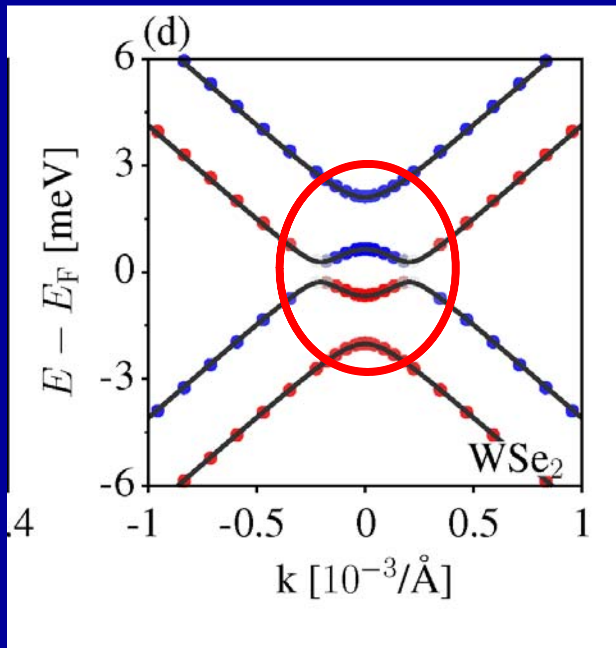
$\Lambda_R(\sigma_x s_y - \sigma_y s_x) +$

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

Quantum valley-spin Hall effect in Gr on WSe_2

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





$H_I = \lambda_I \sigma_z s_z$

intrinsic

$H_I = \lambda_{I\_} \sigma_0 s_z$

Valley Zeeman

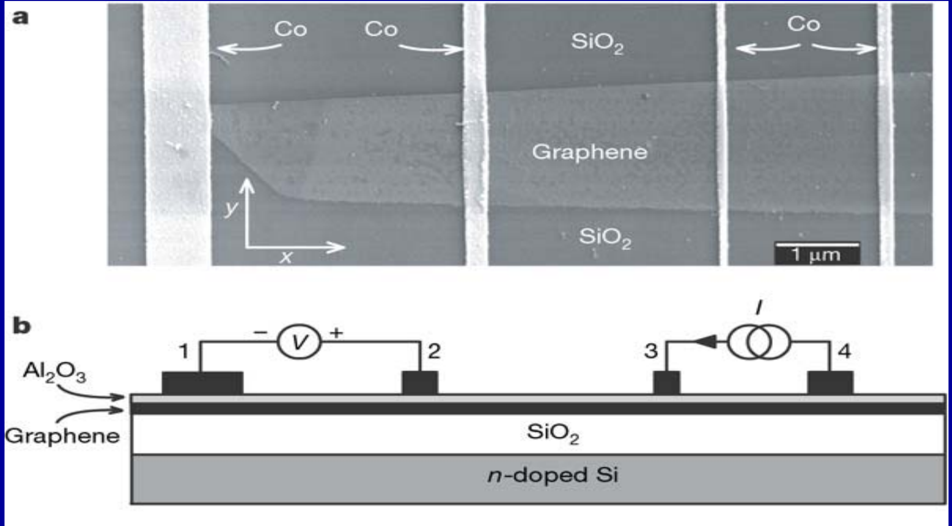
$H_R = \lambda_R(\sigma_x s_y - \sigma_y s_x)$

Rashba

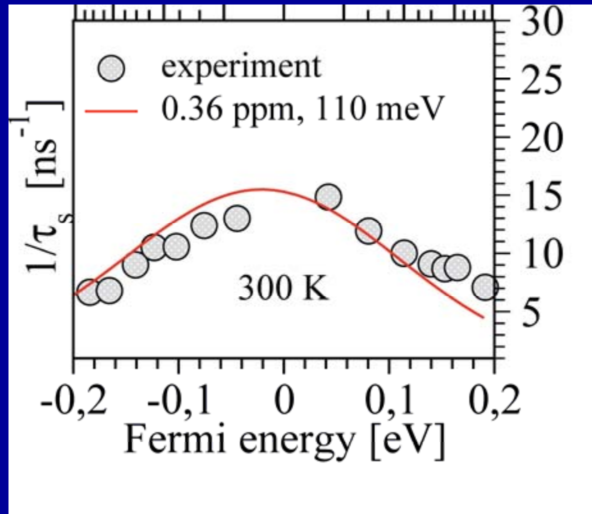
Spin-orbit coupling in spin relaxation in graphene

First generation of graphene devices Gr/SiO_2

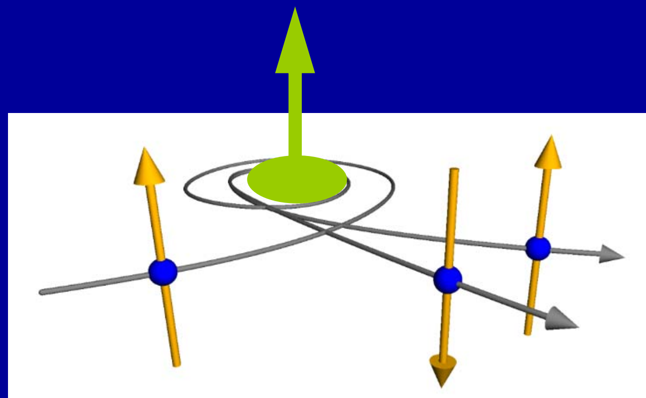
D. Kochan et al, PRL 112, 116602 (2014); PRL 115, 196601 (2015)



N. Tombros et al, Nature 448, 571 (2007)



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

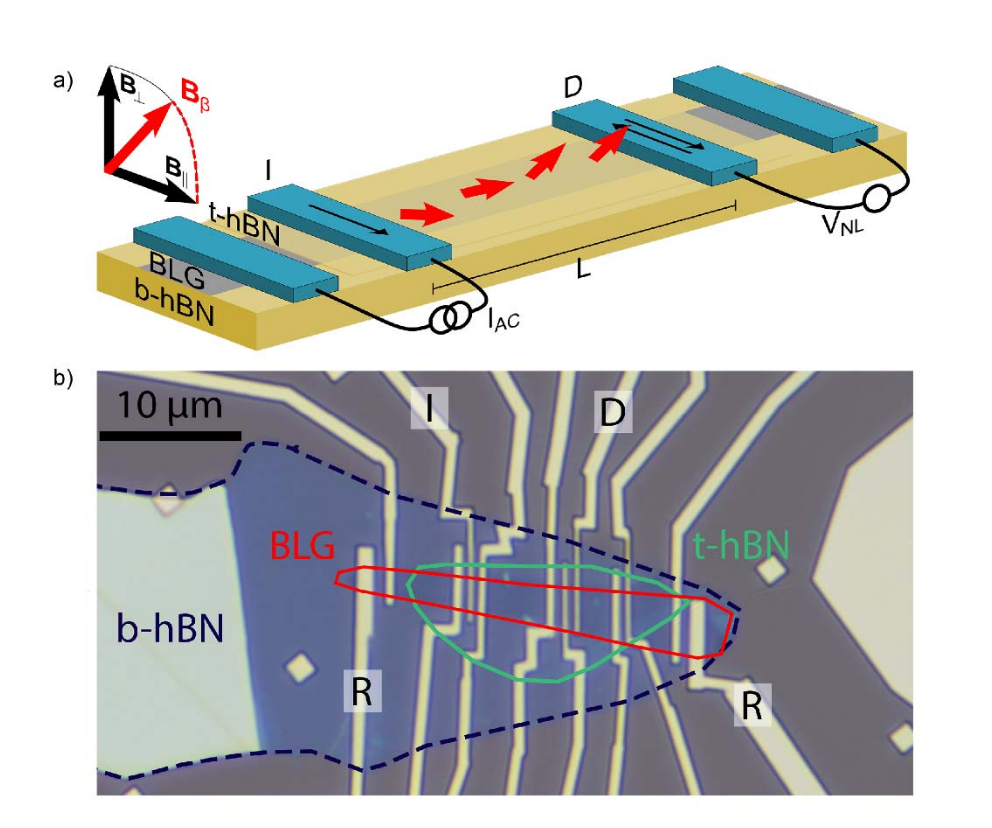


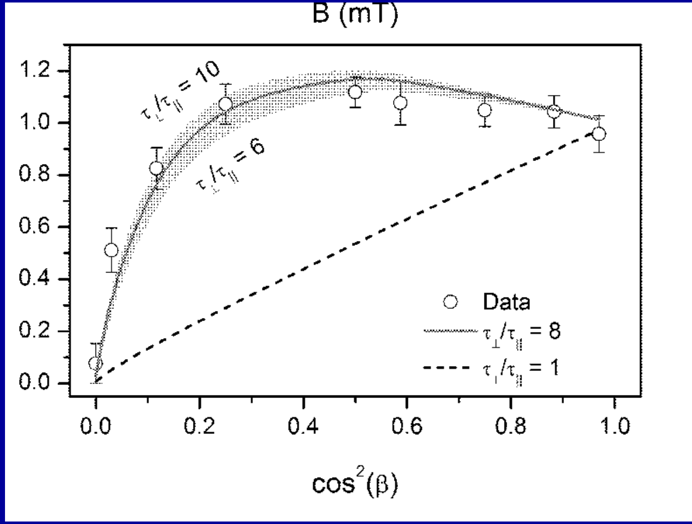
spin relaxation is due to
resonant scattering
off local magnetic moments

exp: no spin anisotropy

Second generation of graphene devices
BGr/hBN

C. Leutenantsmeyer et al, arXiv: 1805.12420





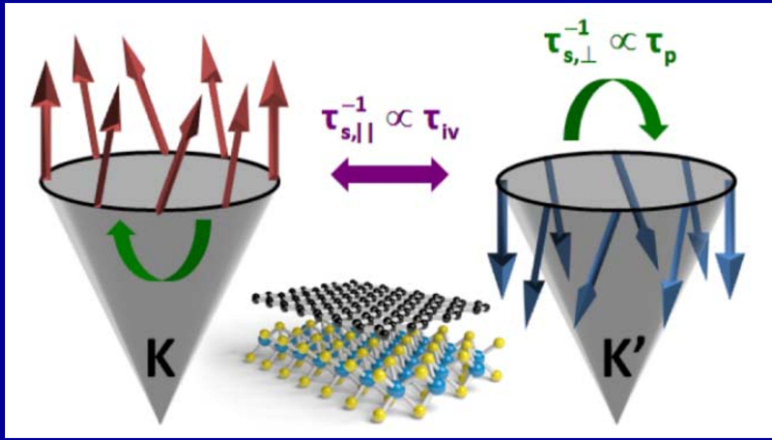
$$\tau_{s\perp} \approx 10\ \tau_{s\parallel}$$

spin relaxation is due to
spin-orbit coupling

Evidence for valley Zeeman effect in proximity graphene on TMDCs

Theoretical prediction for giant spin relaxation anisotropy in graphene on TMDCs

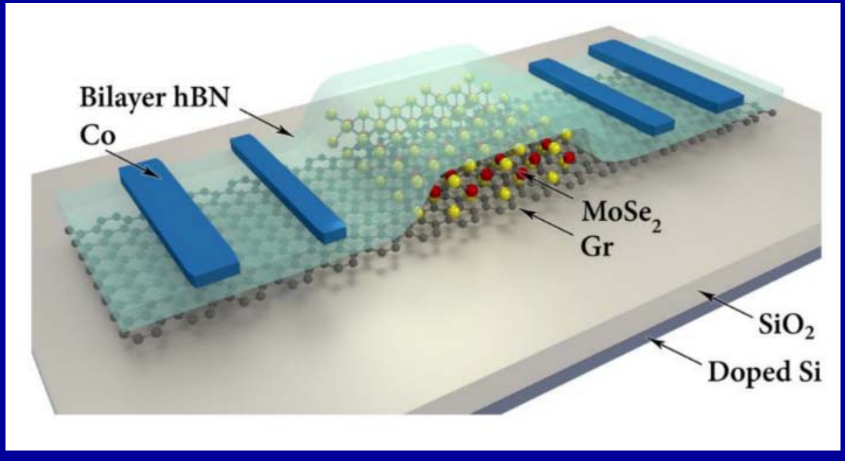
A. Cummigs, J .Garcia, J. Fabian, and S. Roche, Phys. Rev. Lett. 119, 206601 (2017)



$$\tau_{s\perp} = (10 - 100)\,\tau_{s\|}$$

experiment: graphene on MoS_2

T. S. Ghiasi, J. Ingla-Aynés, A. A. Kaverzin, and B. J. van Wees,
Nano Lett. 17, 7528 (2017)

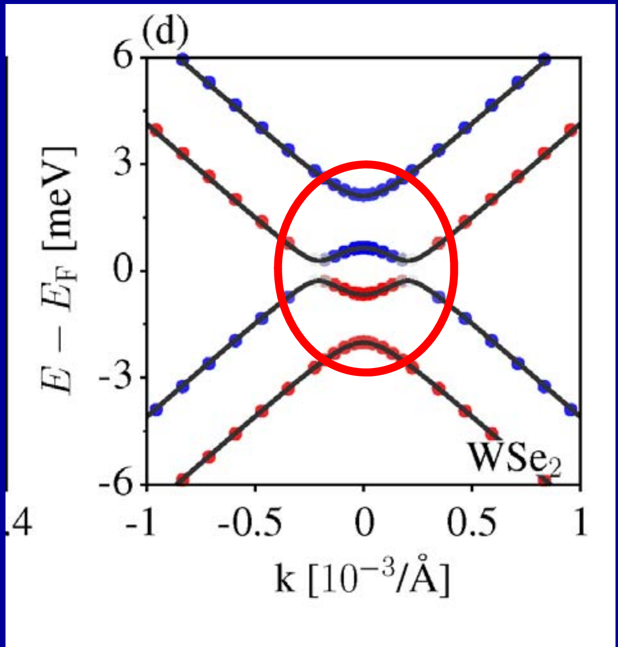


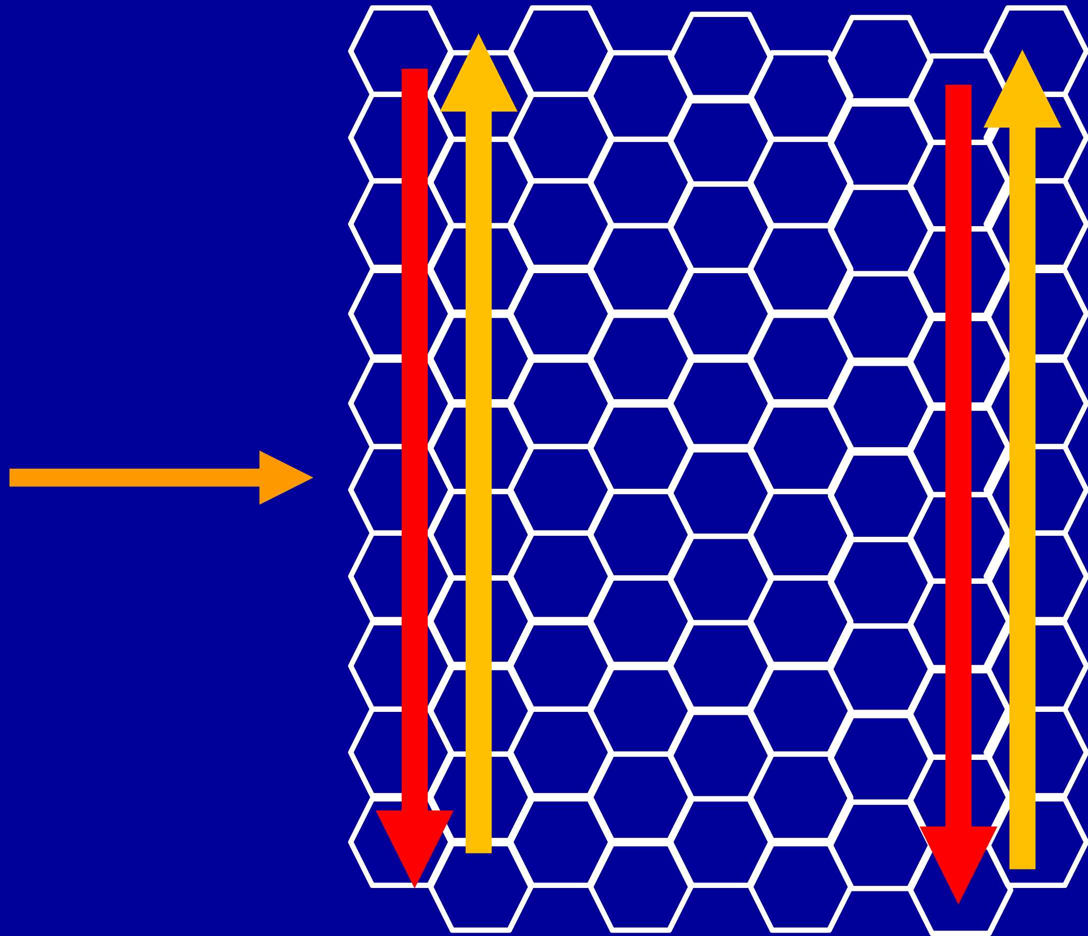
experiment: graphene on WS_2

L. A. Benítez, J. F. Sierra, W. Savero Torres, A. Arrighi, F. Bonell, M. V. Costache, and S. O. Valenzuela, Nature Physics 2017
doi:10.1038/s41567-017-0019-2

Quantum valley-spin Hall effect in Gr on WSe_2

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



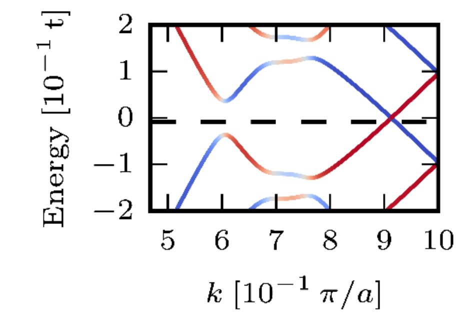


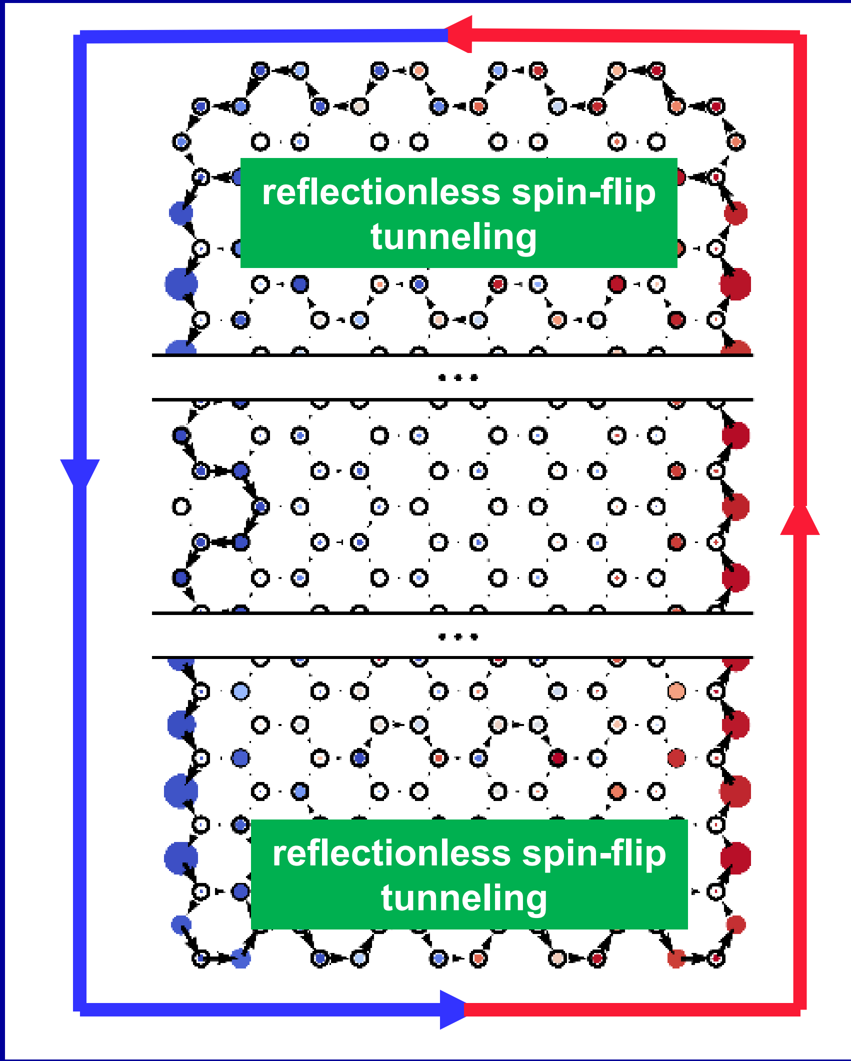
emergence of (pseudo) helical edge states!

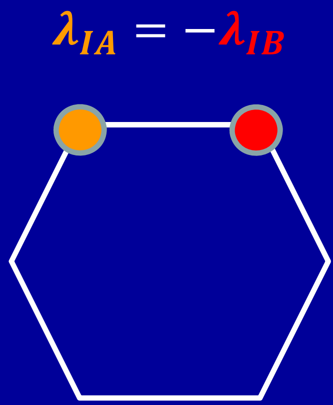
Solution: Flipper Bridge

protected edge states in Z_2=0 (trivial) system

T. Frank, P. Högl. M. Gmitra, D. Kochan, and J. Fabian, PRL 120, 156402 (2018)

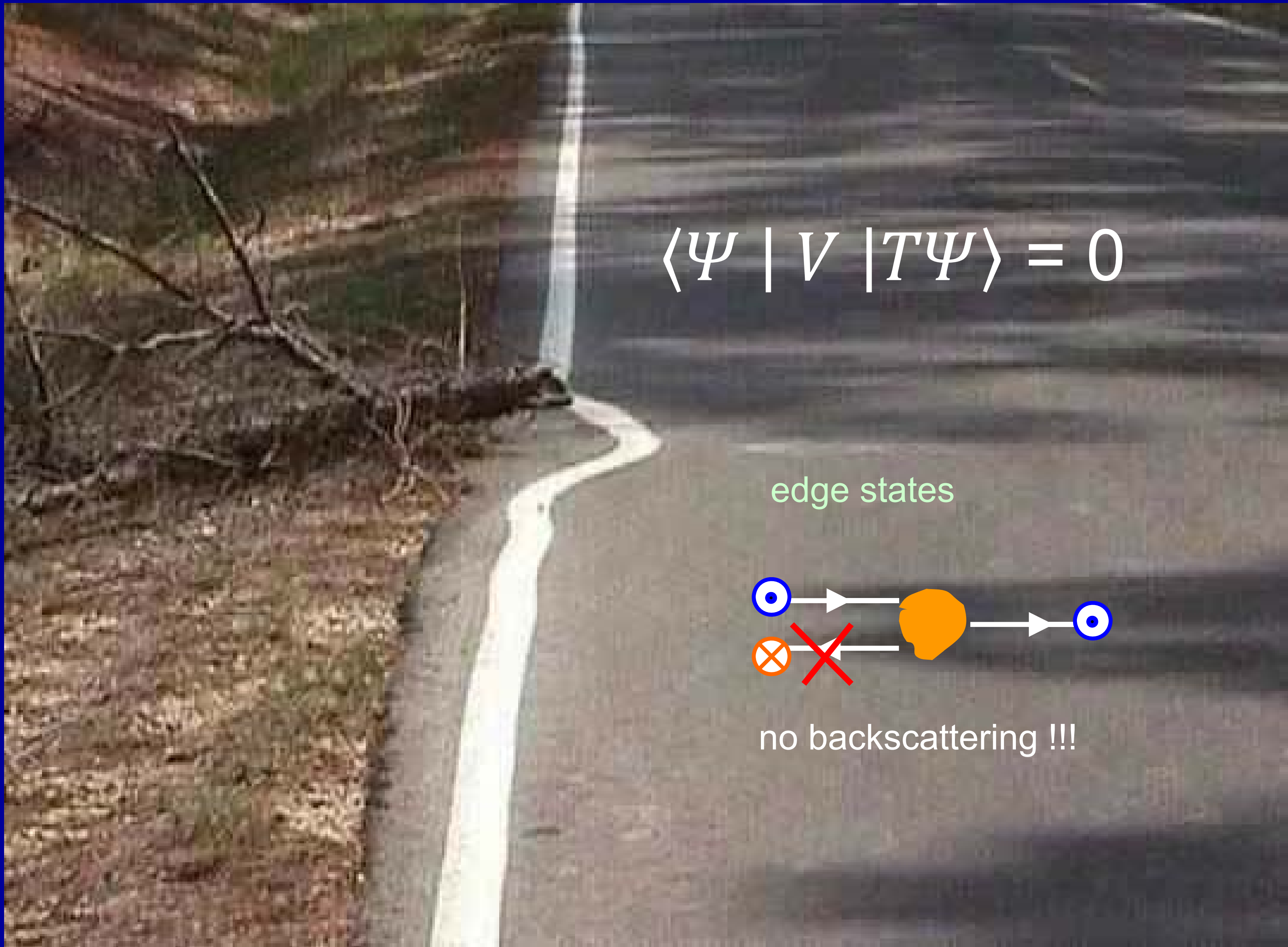






pseudohelical states

Topological protection

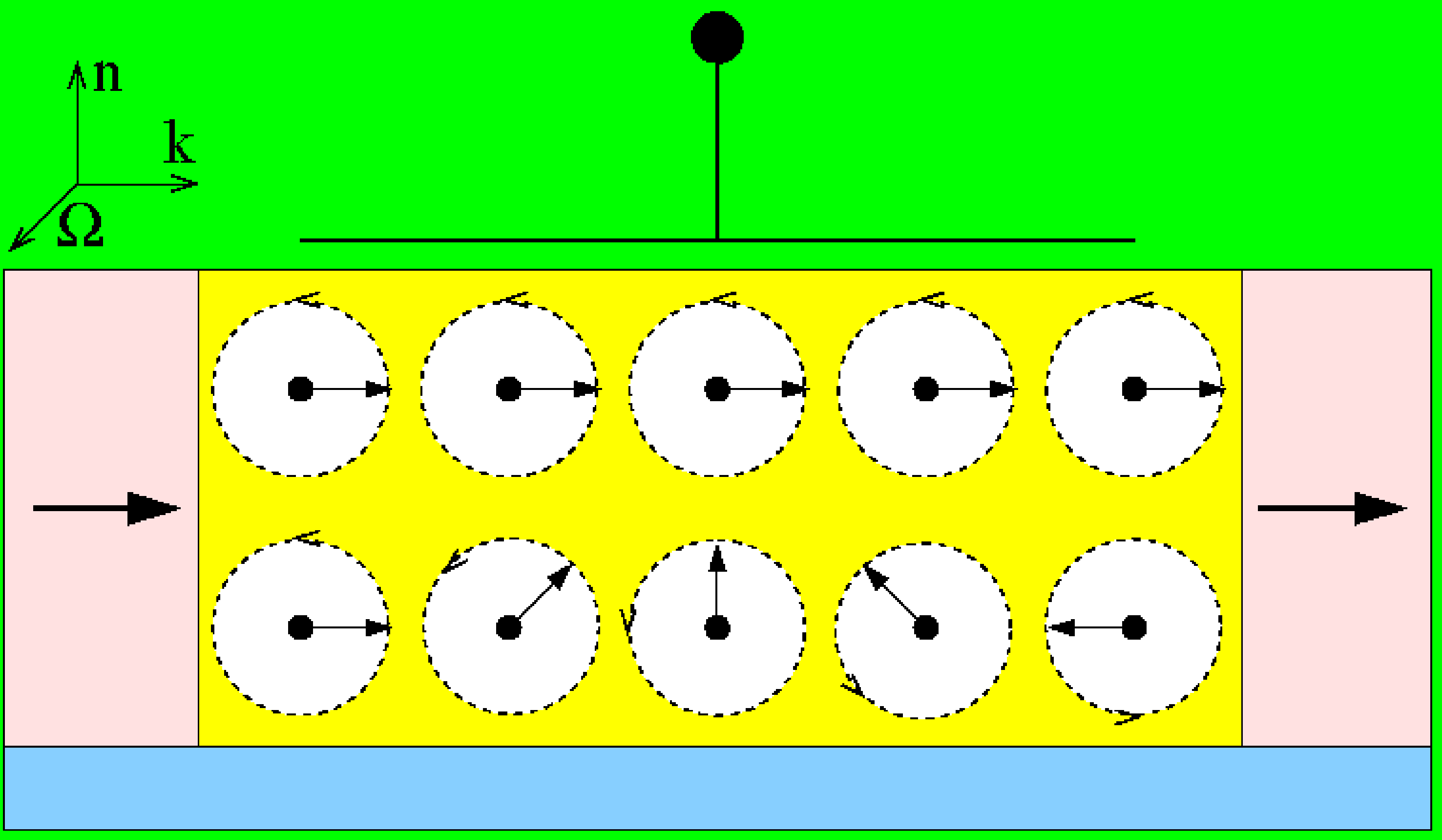


What can we do (spin-wise) with *2D* materials that we cannot do with *conventional* ones?

Field effect spintronics

Electric control of SOC in QWs: Datta-Das transistor

S. Datta and Das, APL 56, 665 (1990)



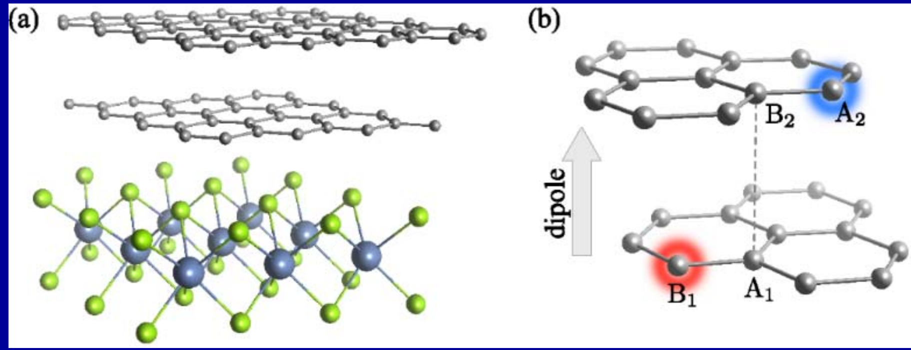
From: I. Zutic, J. Fabian, S. Das Sarma, Rev. Mod. Phys. 76, 323 (2004)

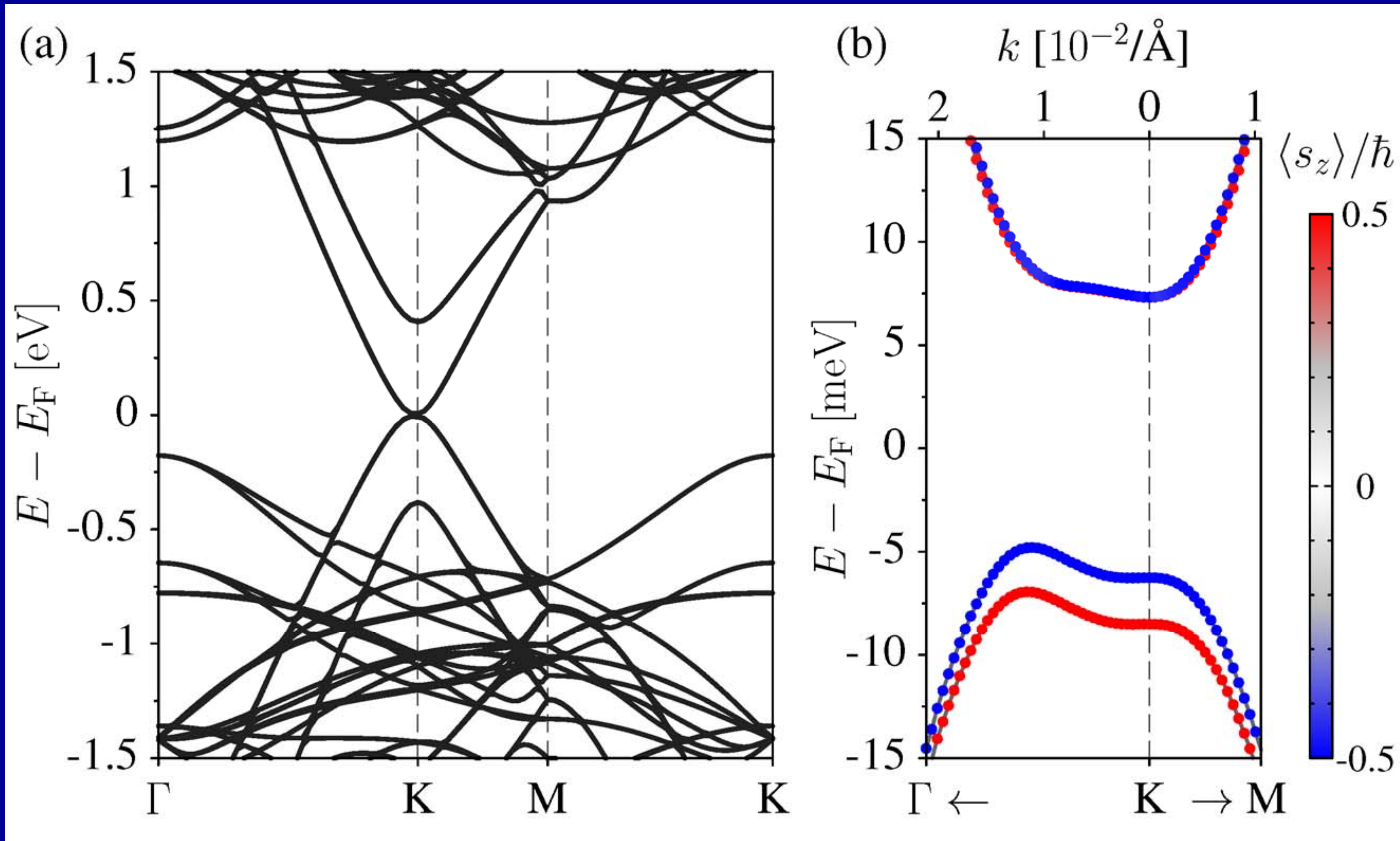
Bilayer Graphene on WSe_2

Field-effect spin-orbit valve

BLG on WSe_2

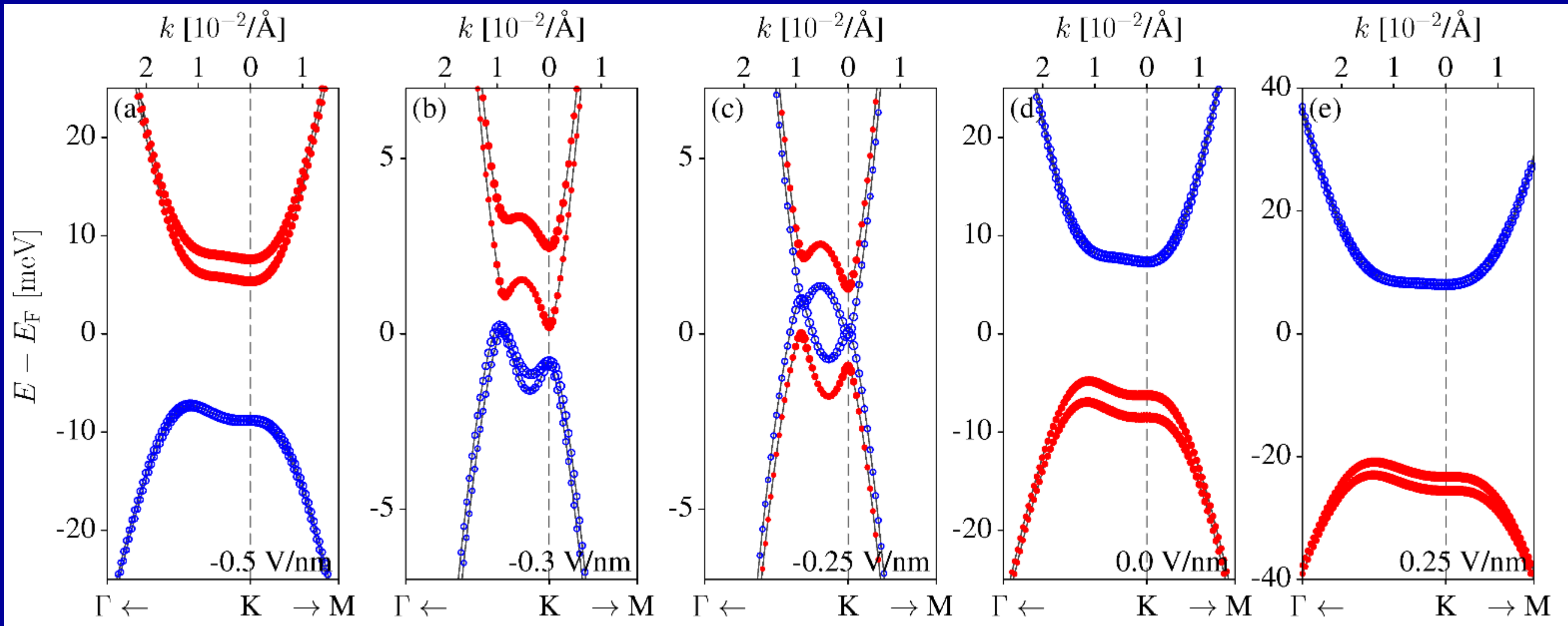
M. Gmitra and J. Fabian,
Phys. Rev. Lett. 119, 146401 (2017)





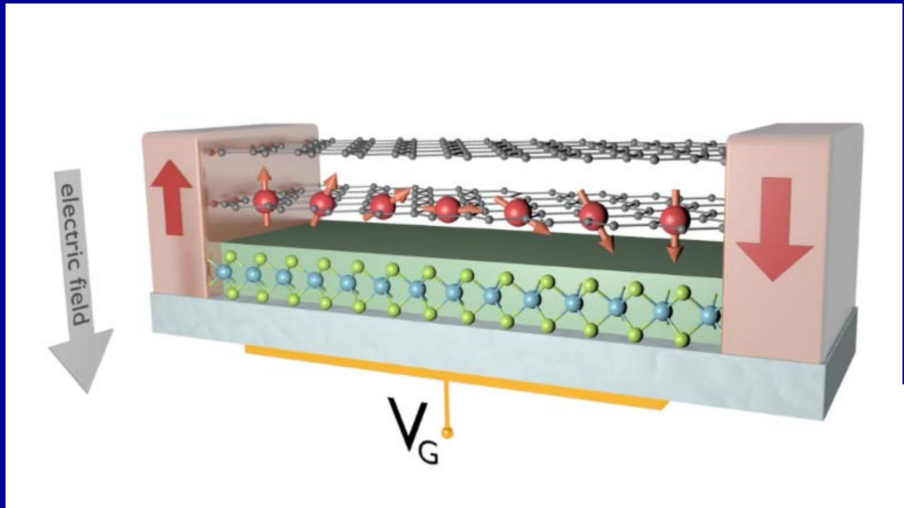
spin-orbit valve

M. Gmitra and J. Fabian,
Phys. Rev. Lett. 119, 146401 (2017)

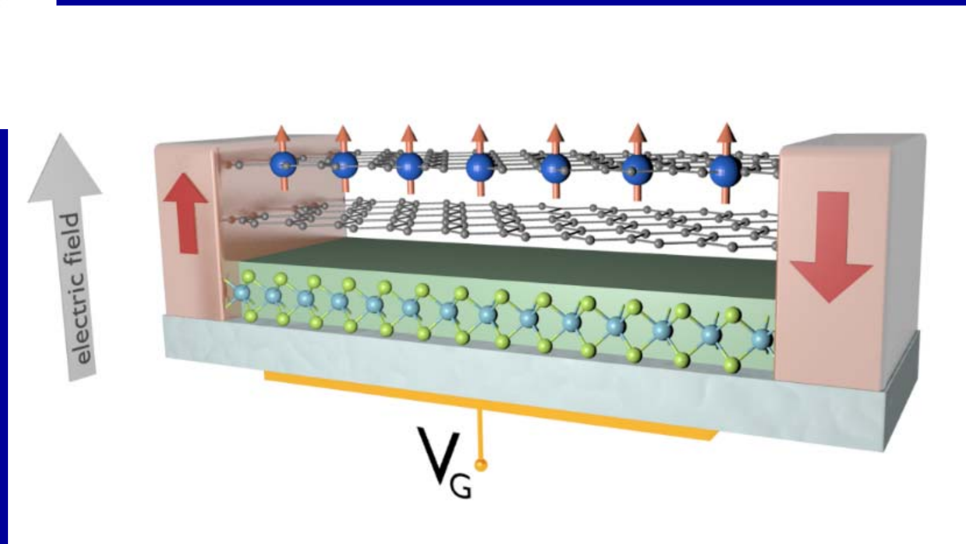


Spin transistor

M. Gmitra and J. Fabian,
Phys. Rev. Lett. 119, 146401 (2017)



ON



OFF

PROXIMITY EXCHANGE

(synthetic magnetic conductors)

Ferromagnetic insulators (YIG, EuO, EuS)

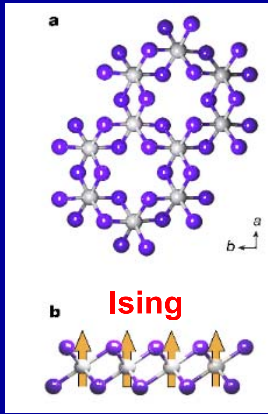
Ferromagnetic metals (Co, Ni) and tunnel barriers (MgO, hBN)

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)

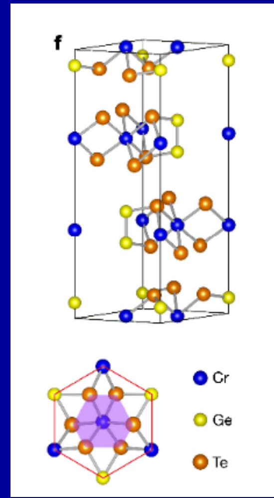
Lazic et al (Zutic), PRB 93, 241401 (2016)
Zollner et al (JF), PRB 94, 155441 (2016)

2D ferromagnets



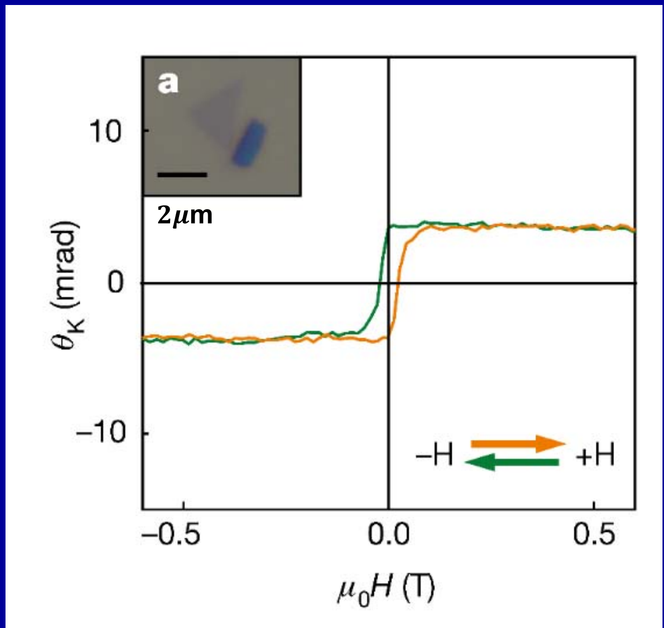
CrI_3

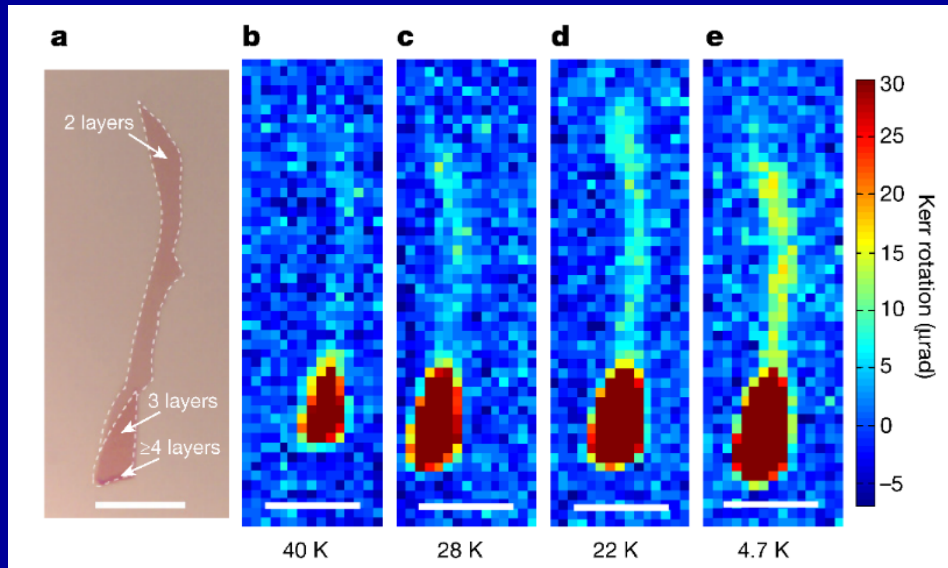
$Cr_2Ge_2Te_6$



B. Huang et al., Nature 546, 270 (2017)

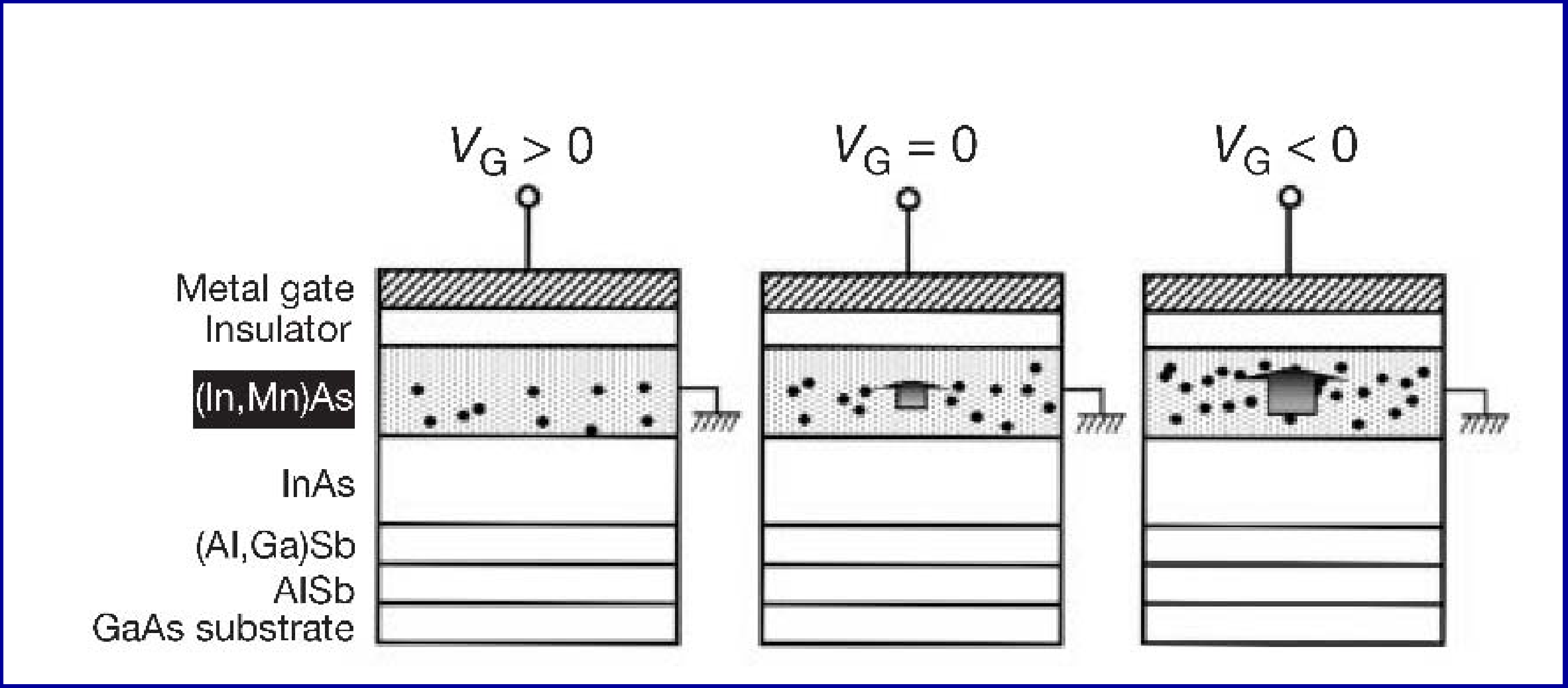
X. Gong et al., Nature 546, 265 (2017)





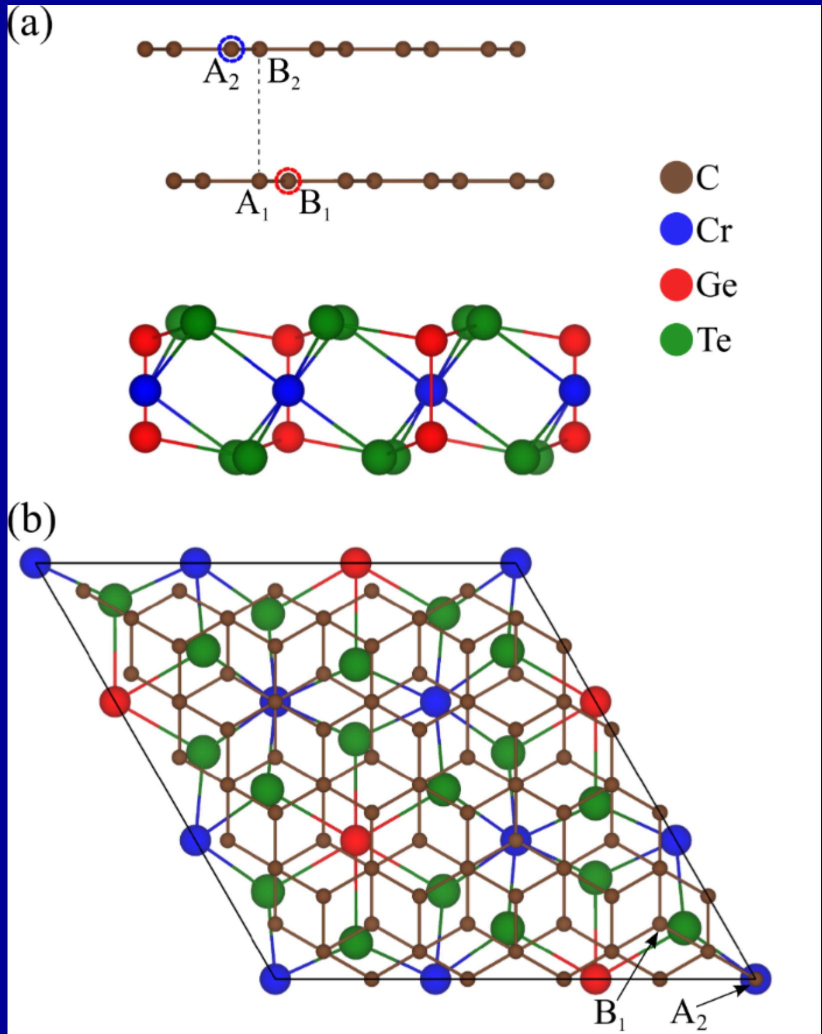
Electric control of magnetization in DMS

H. Ohno et al., Nature 408, 944 (2000)



BLG on $Cr_2 Ge_2Te_6$: gate-controlled exchange

K. Zollner, M. Gmitra, and J. Fabian, arXiv:1710:08117



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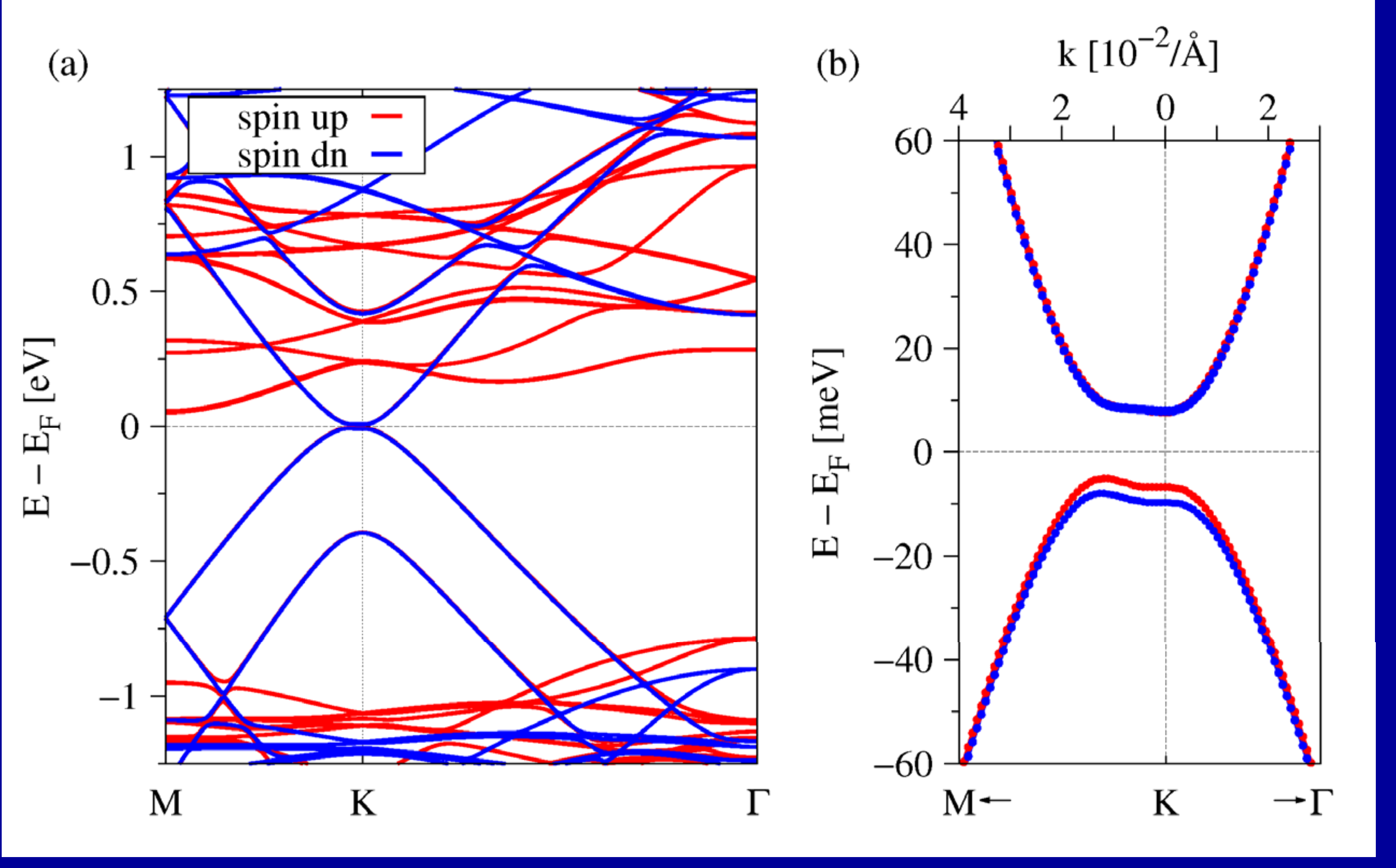
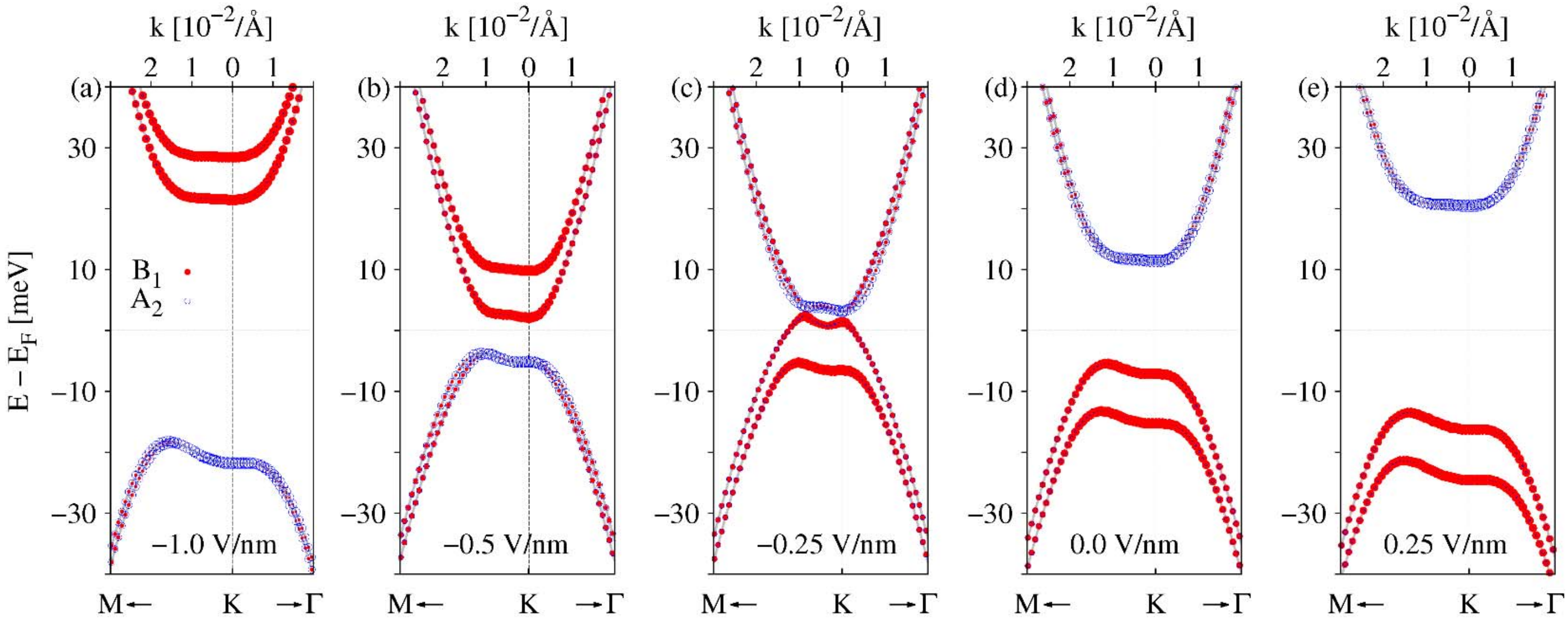


BLG on BLG on $Cr_2Ge_2Te_6$: gate-controlled exchange (turn the exchange on or off)



K. Zollner, M. Gmitra, and J. Fabian, arXiv:1710:08117

Arbeitsgruppe J. Fabian, U Regensburg

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