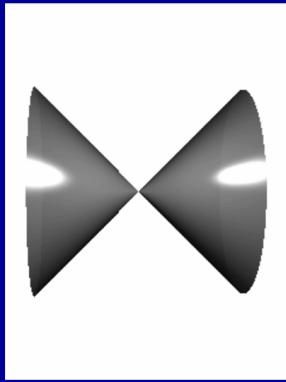


Proximity spin-orbit and

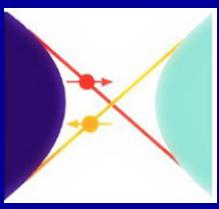
exchange coupling in vdW

heterostructures

Jaroslav Fabian



Institute for Theoretical Physics
University of Regensburg



Deutsche
Forschungsgemeinschaft
DFG

Elitenetzwerk
Bayern



Spintronics
Research Group
Jaroslav Fabian

Spintronics: Fundamentals and applications

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(Published 23 April 2004)

acta physica slovaca

Acta Physica Slovaca 57, No.4&5, 565-907 (2007) (342 pages)

Semiconductor Spintronics

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Outline

- Spin-orbit coupling in graphene: basics
- Proximity spin-orbit coupling in graphene/TMD/C
- Ramifications of valley Zeeman SOC in graphene
- Proximity exchange coupling
- Towards multifunctional vdW heterostructures

spin-orbit coupling

in graphene
(SOC)

soc in elemental 2D materials

For hydrogen-like atoms:

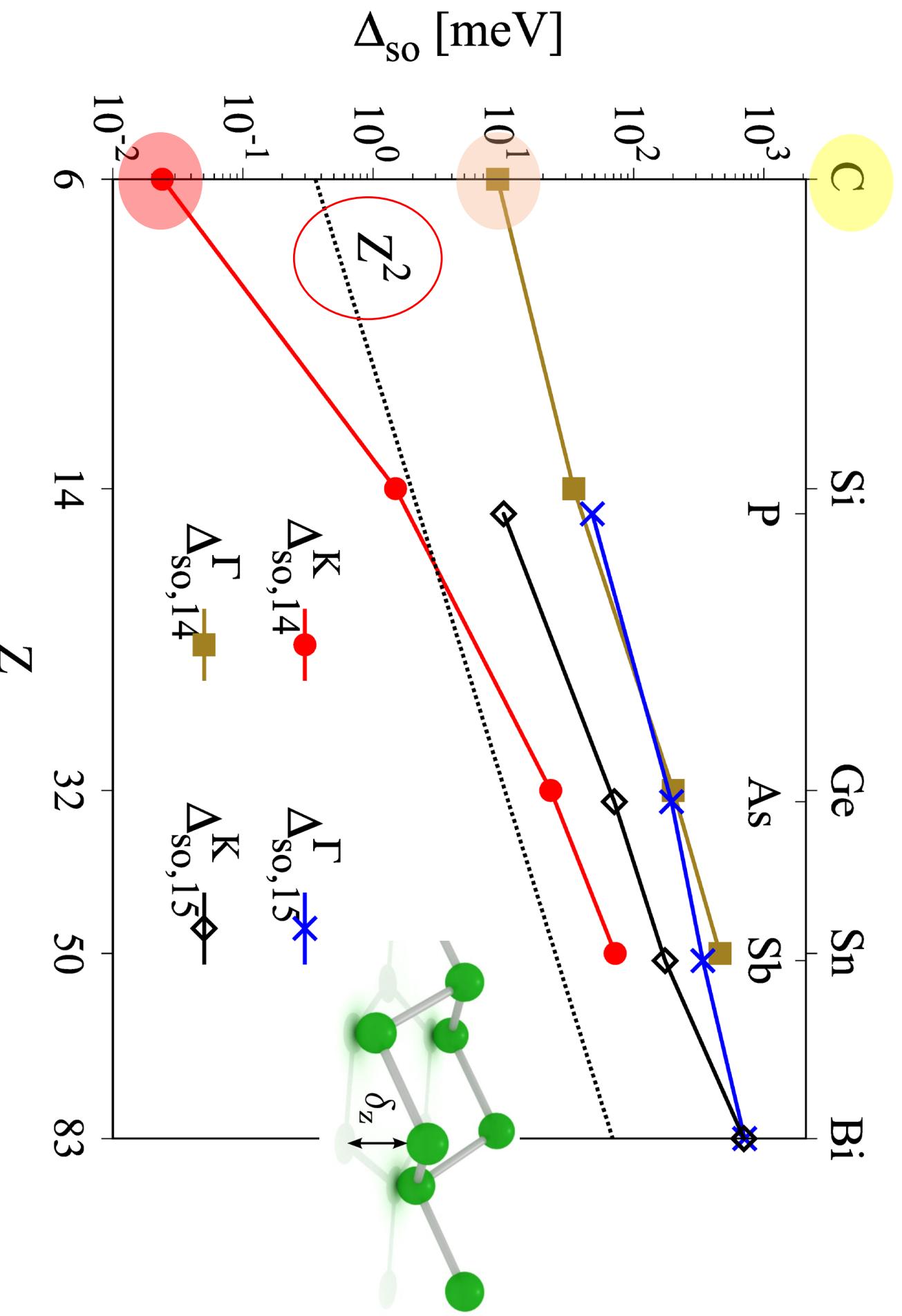
$$E_{\text{SOC}} \sim Z^4$$

For atoms:

$$E_{\text{SOC}} \sim Z^2$$

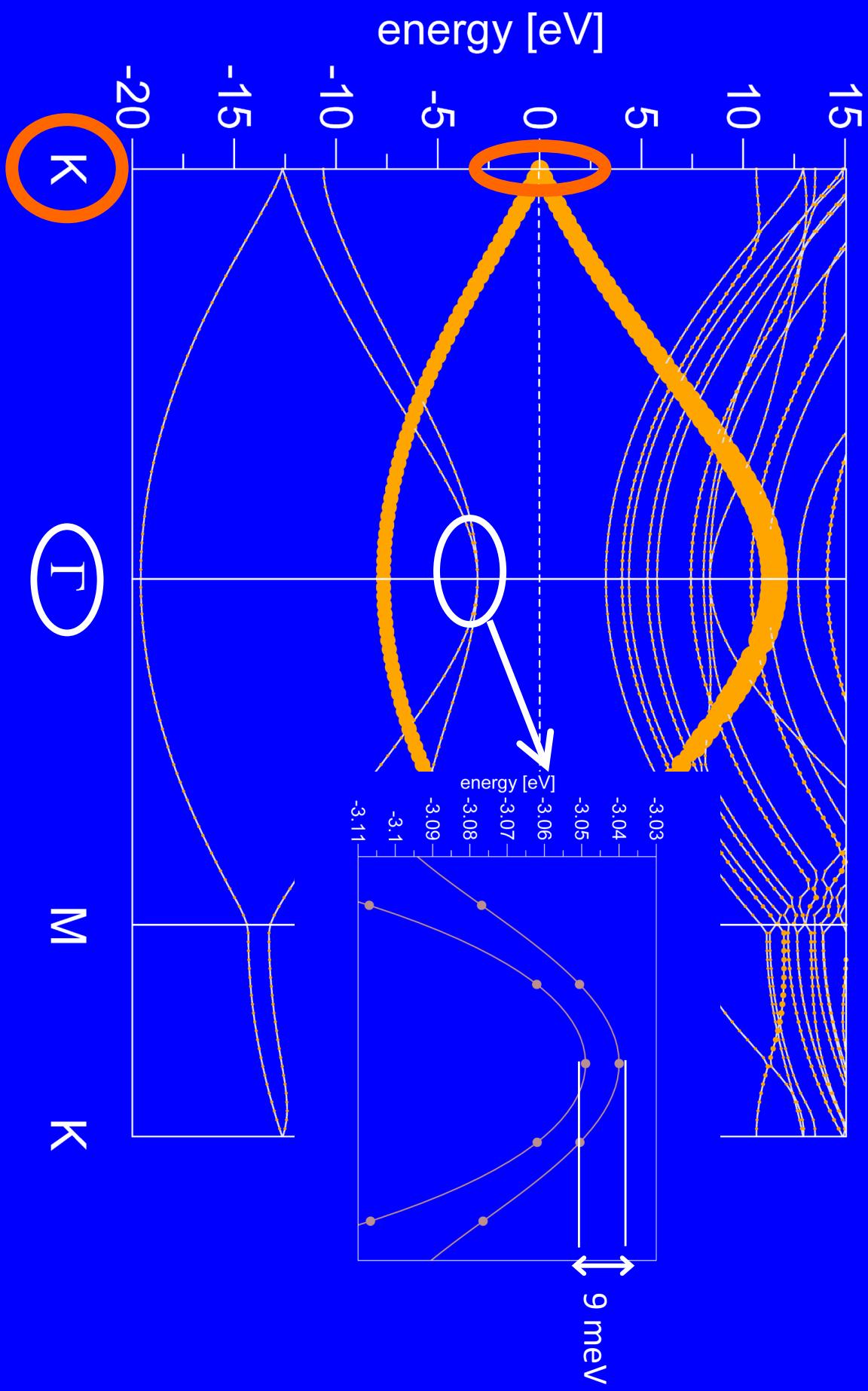
SOC in elemental 2D materials

M Kurpas et al, PRB 100, 125422 (2019)



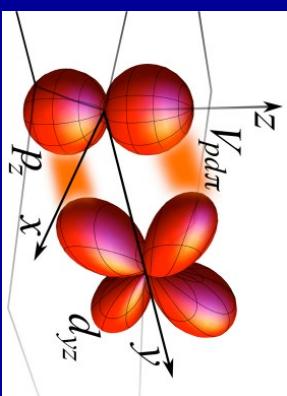
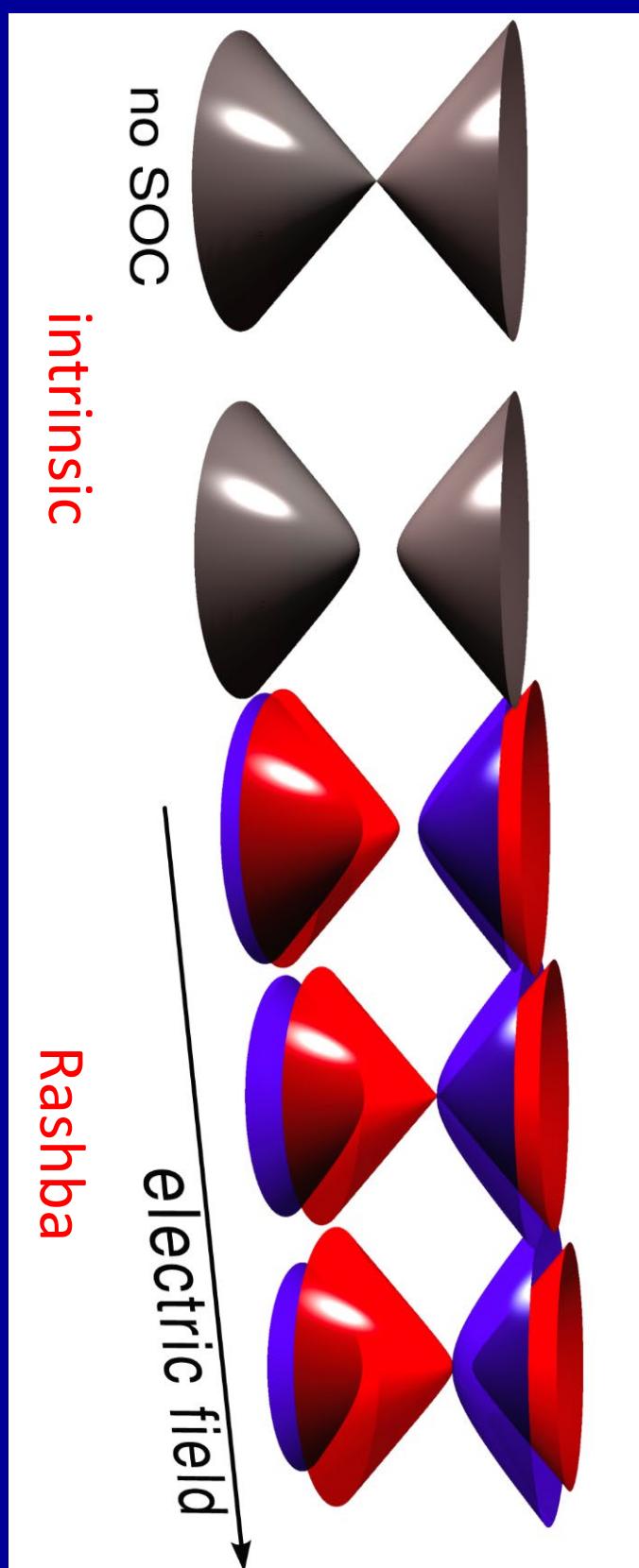
SPIN-ORBIT COUPLING in graphene

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



SPIN-ORBIT COUPLING in graphene

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



physical origin: hybridization of p_z and d orbitals

d -orbitals contribute almost 100%

intrinsic SOC in graphene

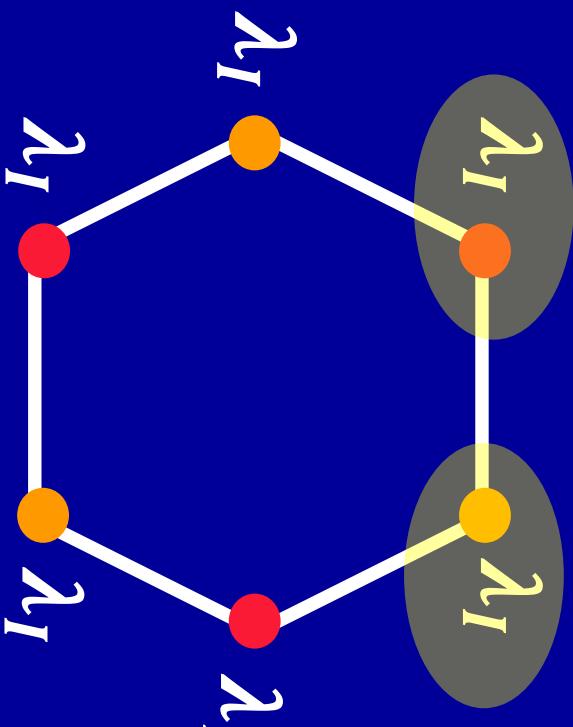
McClore-Yafet-Kane-Mele

J. W. McClure and Y. Yafet, *Theory of the g-factor of the current carriers in graphite single crystals*, Proceedings of the 5th conference on carbon, 1, 22 (1962)

$$\mathcal{H}(\kappa) = \begin{pmatrix} -\alpha(\lambda s_z + \beta H) & i p_0 \mathbf{k}_\perp \\ -i p_0 \mathbf{k}_\perp & + \alpha(\lambda s_z + \beta H) \end{pmatrix}$$

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

$$H = -p_0 (k_y \sigma_x + k_x \sigma_y) - \lambda_I s_z \sigma_z$$



$$H_I = \lambda_I \sigma_z s_z$$
$$\lambda_I \approx 12 \mu eV$$

SOC in graphene is

too small!!

let us increase it!

two ways we follow to increase SOC
in graphene

From 10 μ eV to 1-10 meV

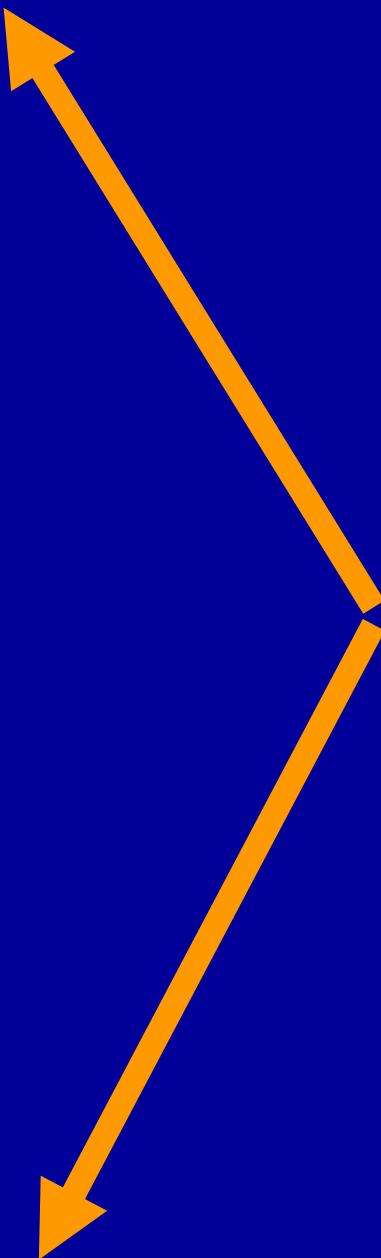
functionalizing graphene

with adatoms:

Local random SOC

placing graphene on
insulating/semiconducting
substrates

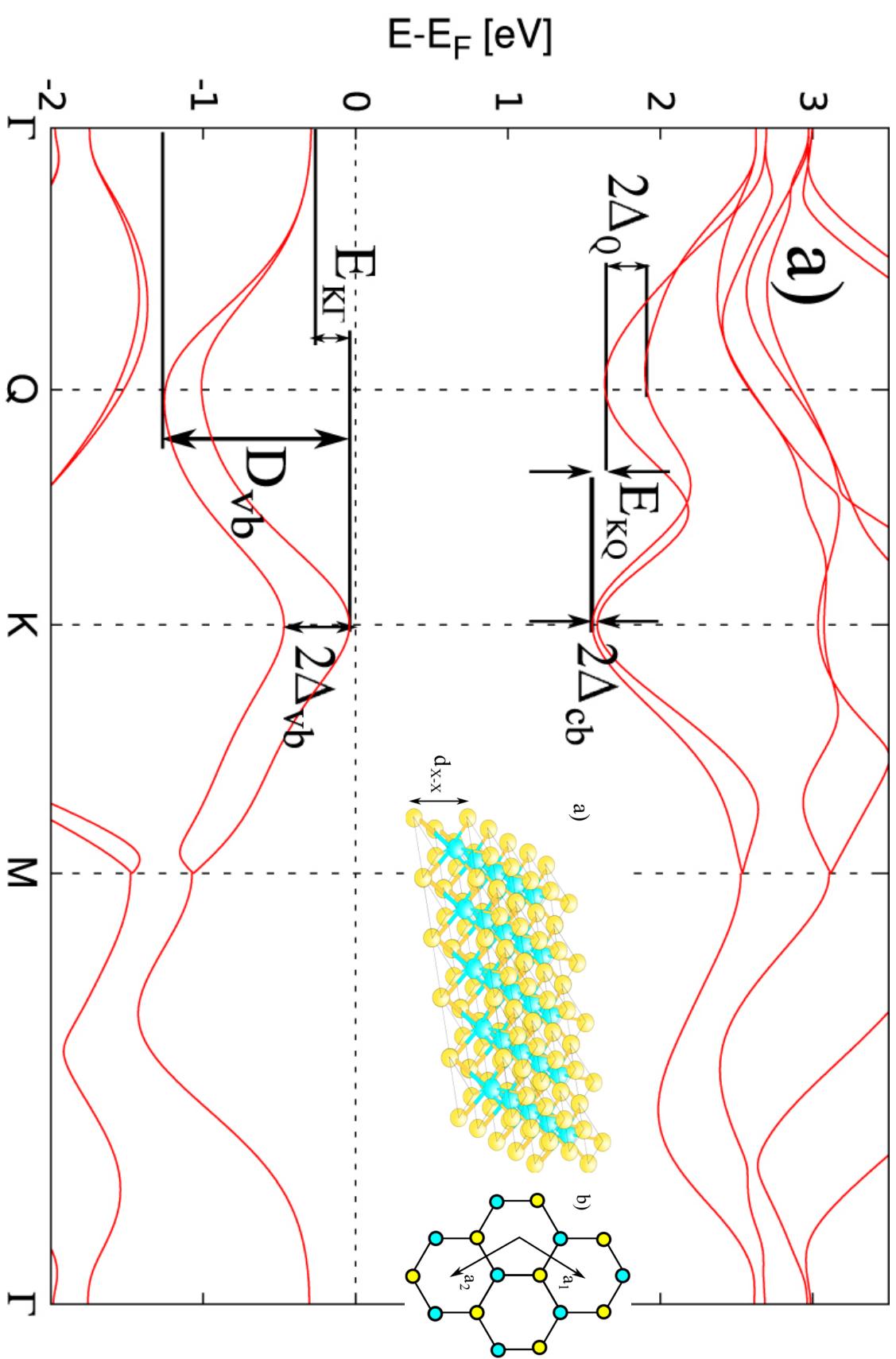
Uniform proximity SOC



Proximity SOC:
graphene/TMDC

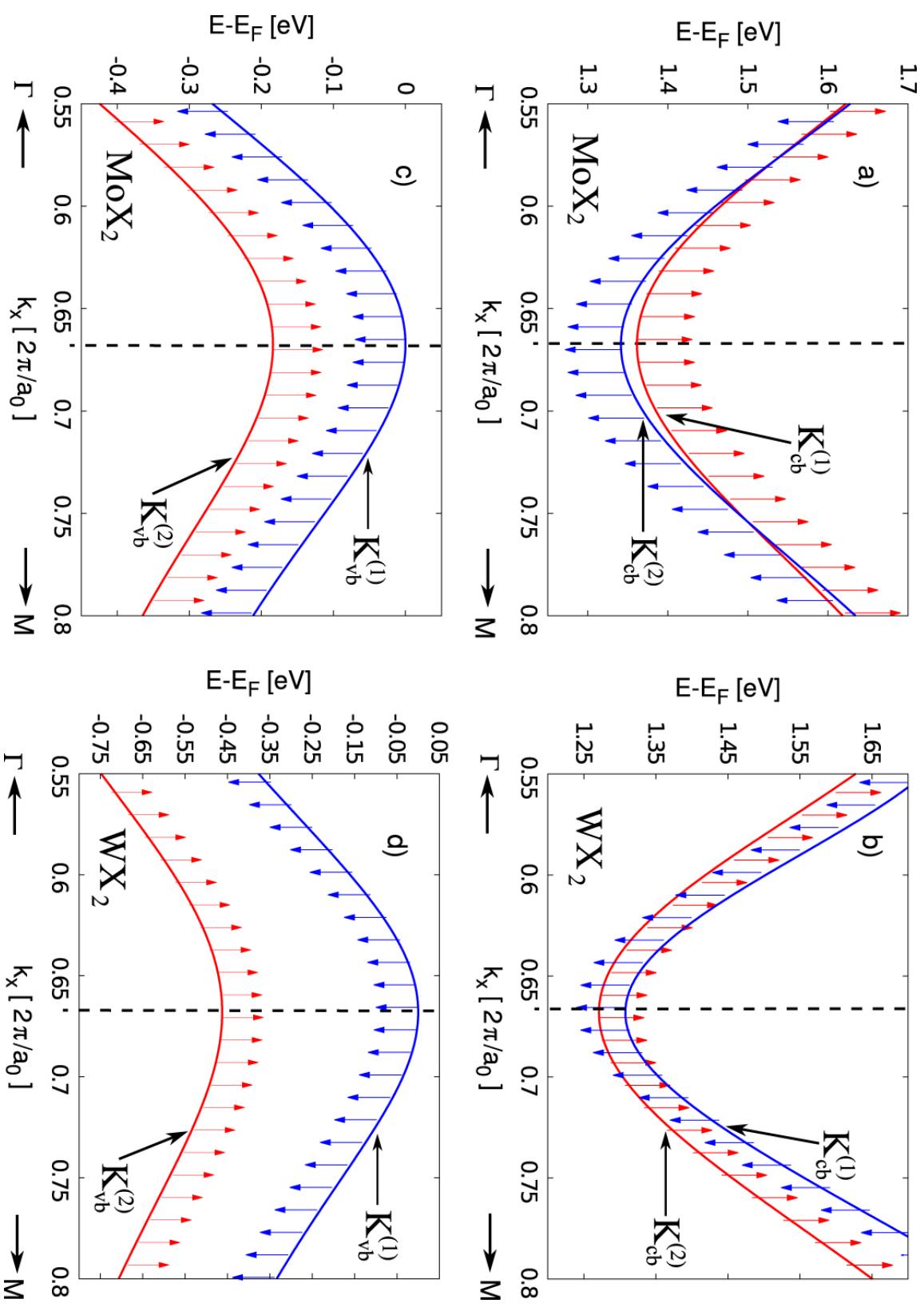
Why TMDC?

stable, large gap at K, huge SOC, valley Zeeman SOC

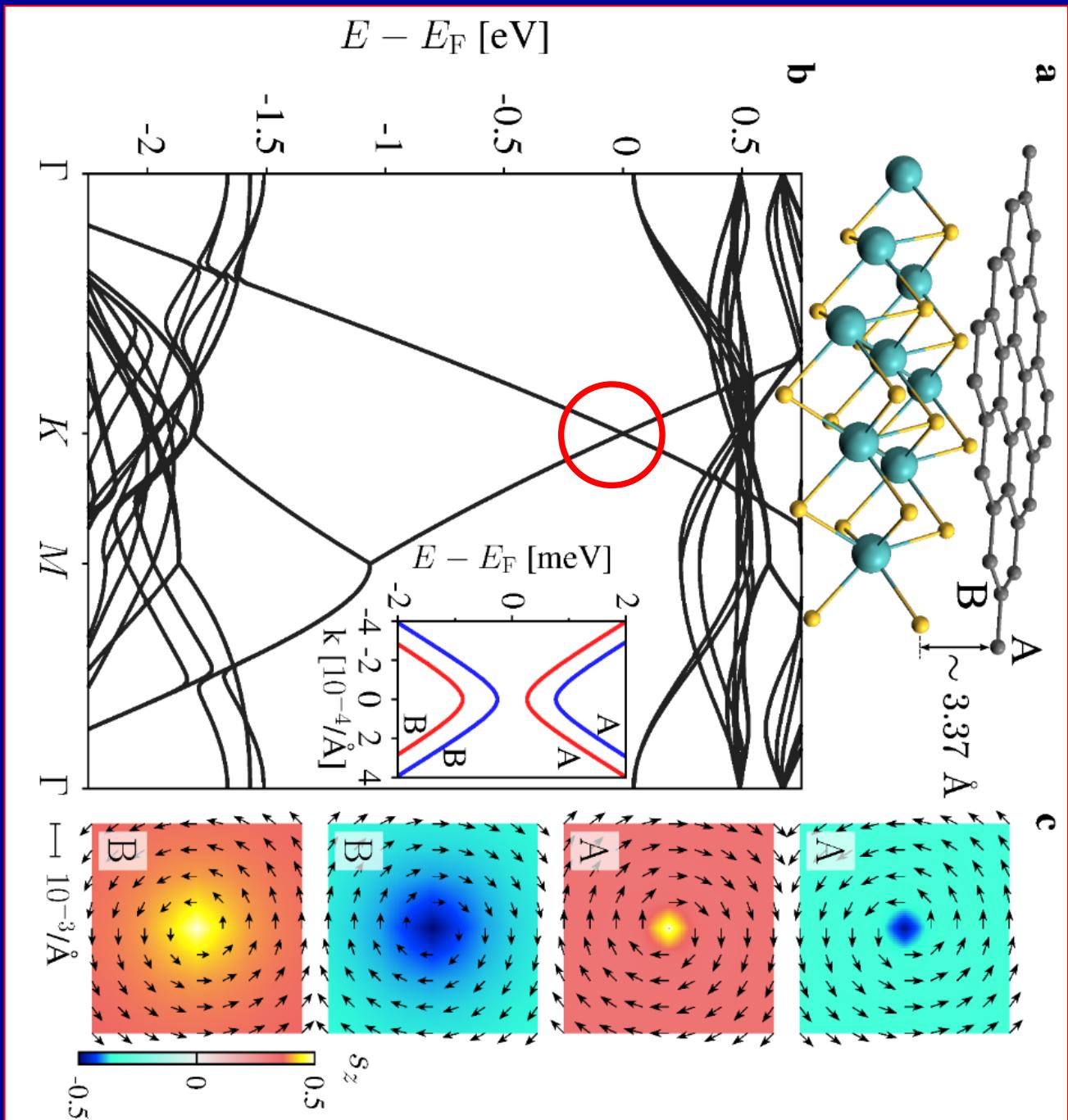


Why TMDC?

stable, large gap at K, huge SOC, valley Zeeman SOC



Graphene on TMDC (MoS_2)



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

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

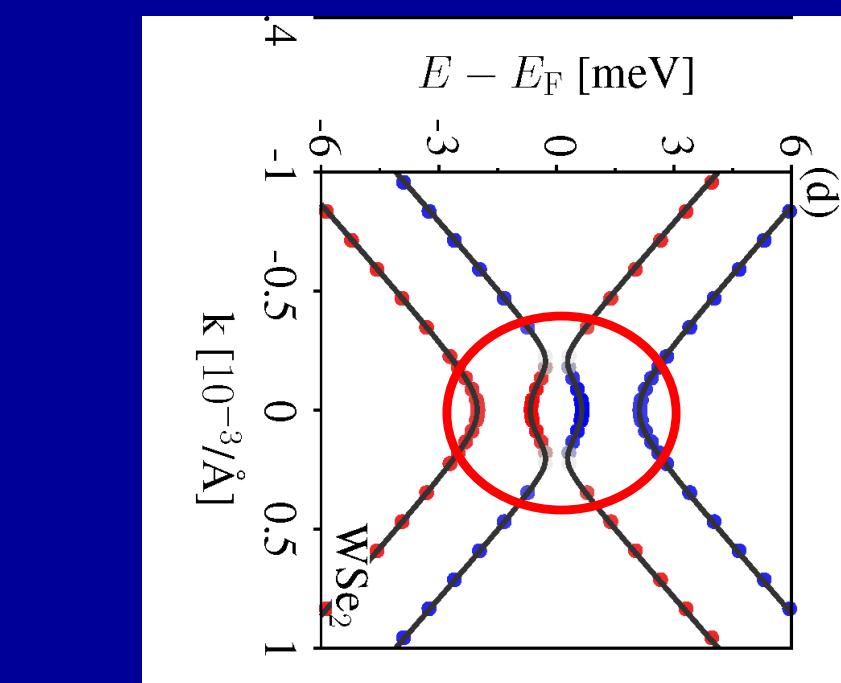
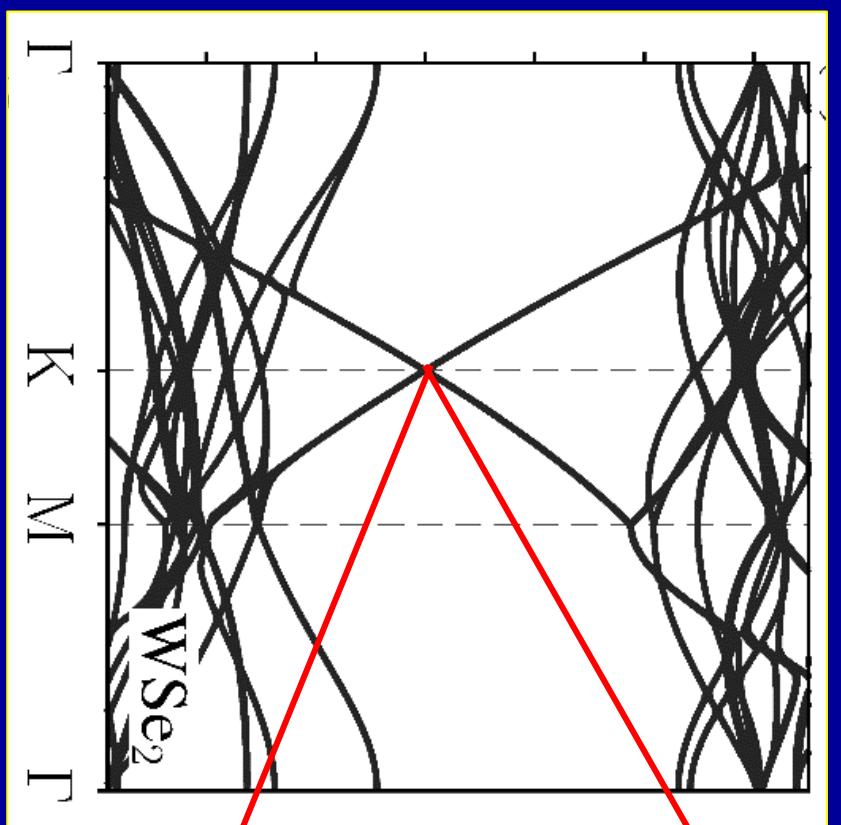
$$\Delta \sigma_z S_0 +$$

$$\Lambda_{PIA}^A \sigma_z (k_x S_y - k_y S_x) +$$

$$\Lambda_R^B (\sigma_x S_y - \sigma_y S_x) +$$

Quantum valley-spin Hall effect in Gr on WSe₂

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



$$H_R = \lambda_R(\sigma_x S_y - \sigma_y S_x)$$

$$H_{VZ} = \lambda_{VZ}\sigma_0 S_z$$

$$H_I = \lambda_I \sigma_z S_z$$

intrinsic

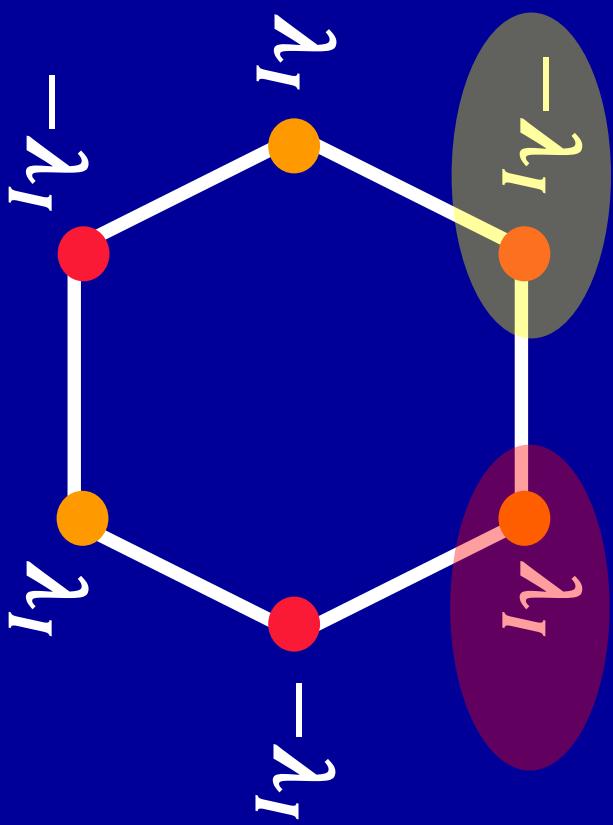
Valley Zeeman

Rashba

valley-Zeeman spin-Orbit

coupling

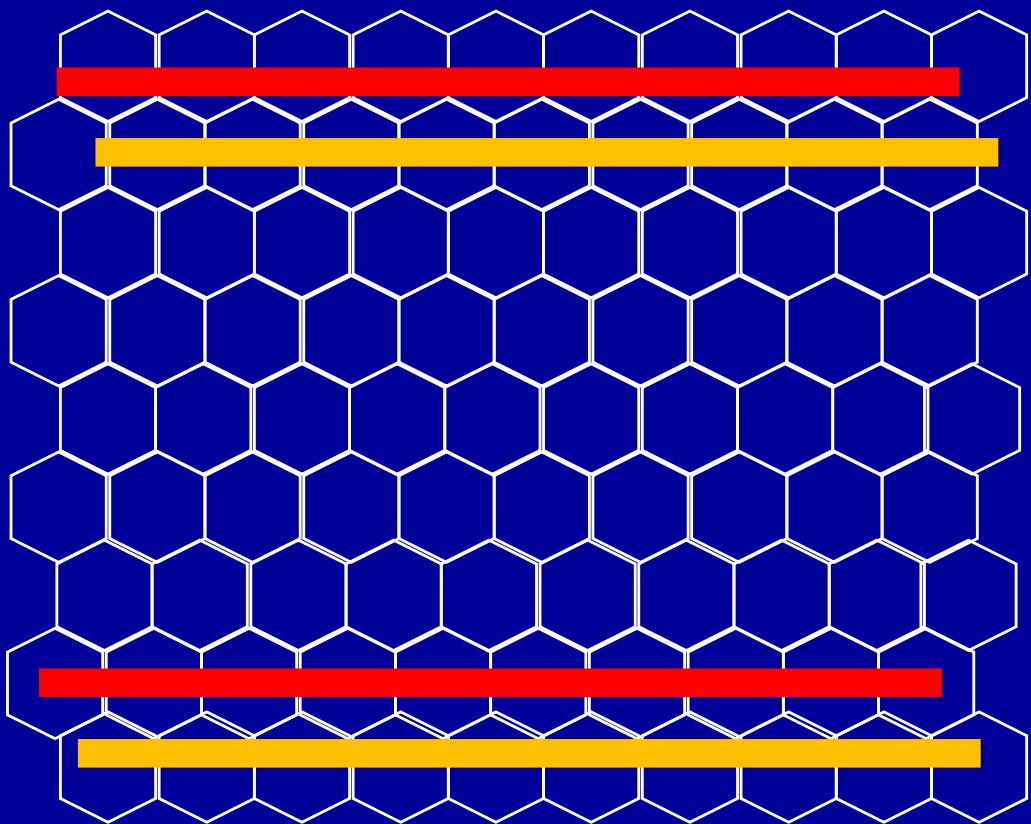
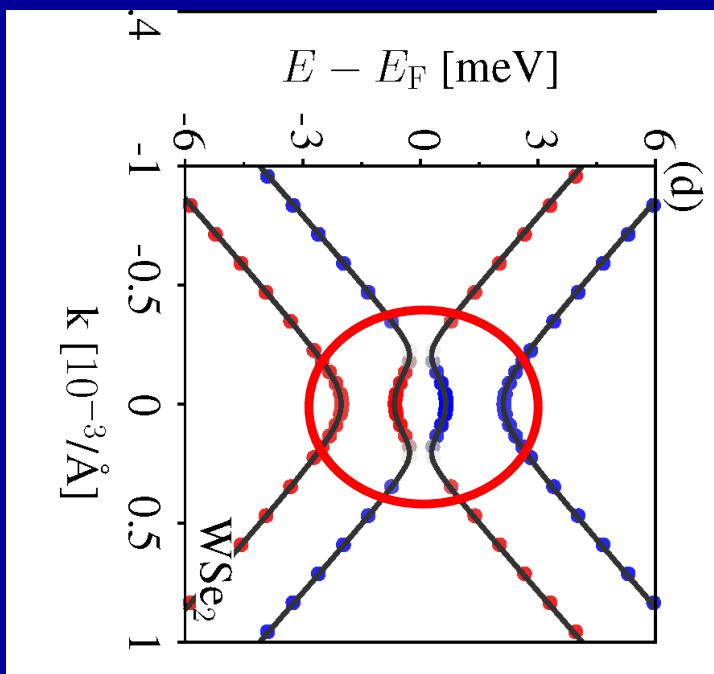
in graphene



pseudohelical edge
states

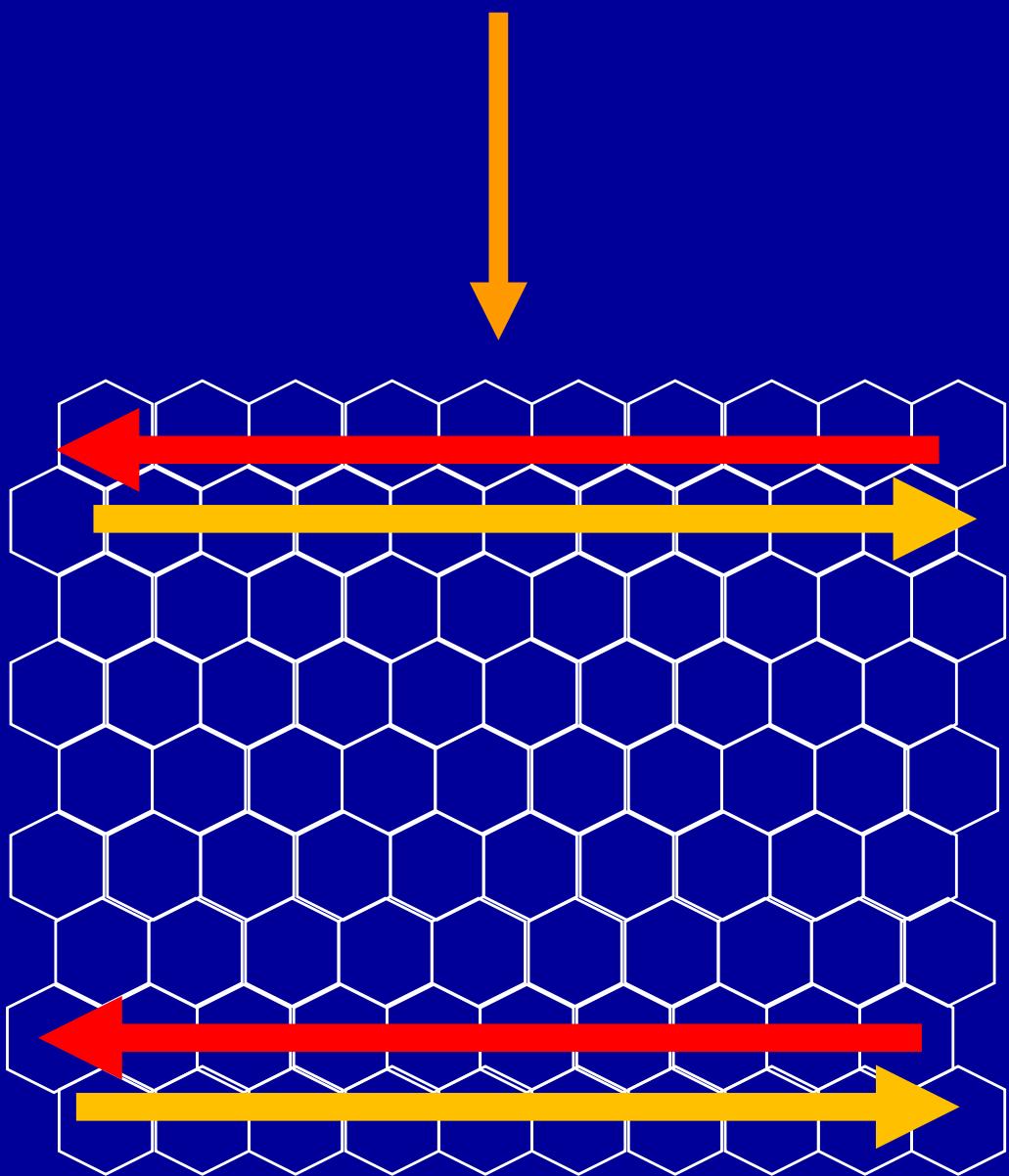
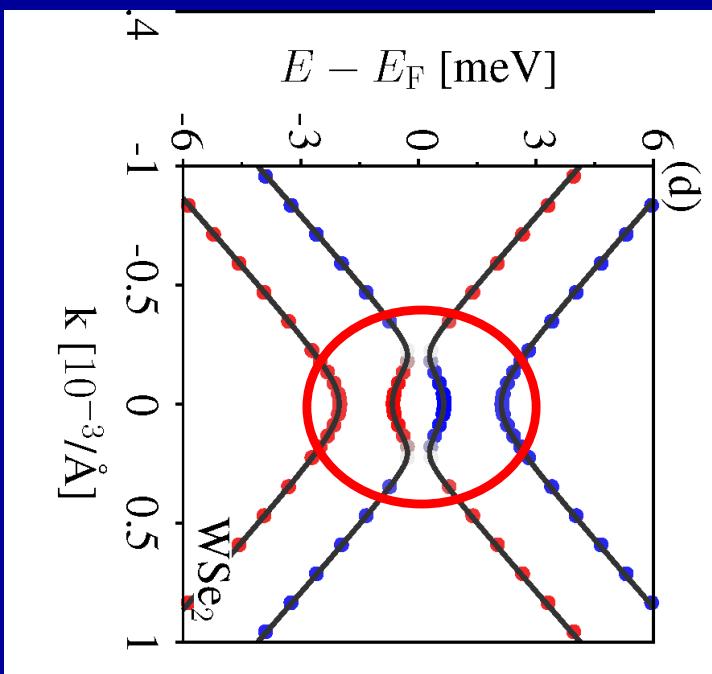
Quantum valley-spin Hall effect in Gr on WSe₂

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Quantum valley-spin Hall effect in Gr on WSe₂

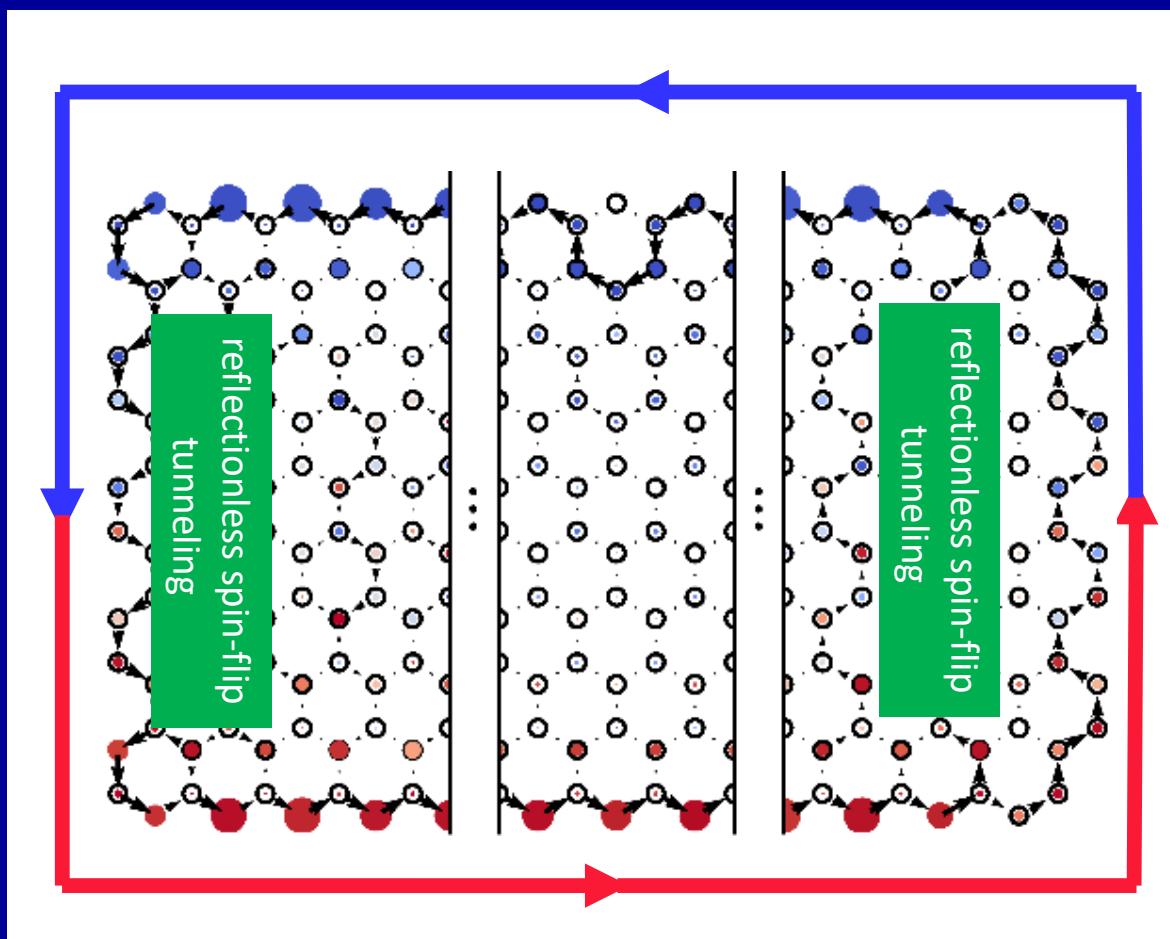
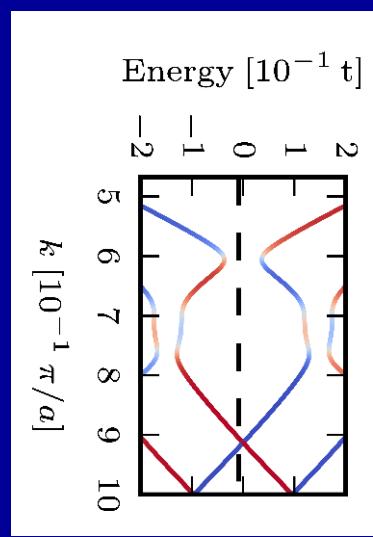
M. Gmitra, D Kochan, P. Högl, and J. Fabian, PRB 93, 155104 (2016)



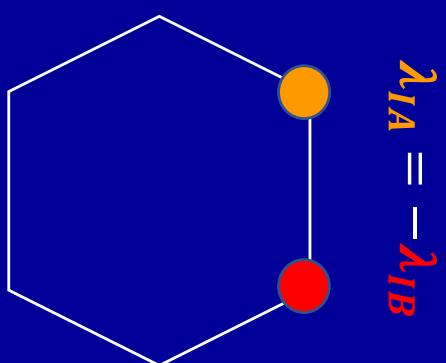
emergence of (pseudo) helical edge states!

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



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

Topological protection

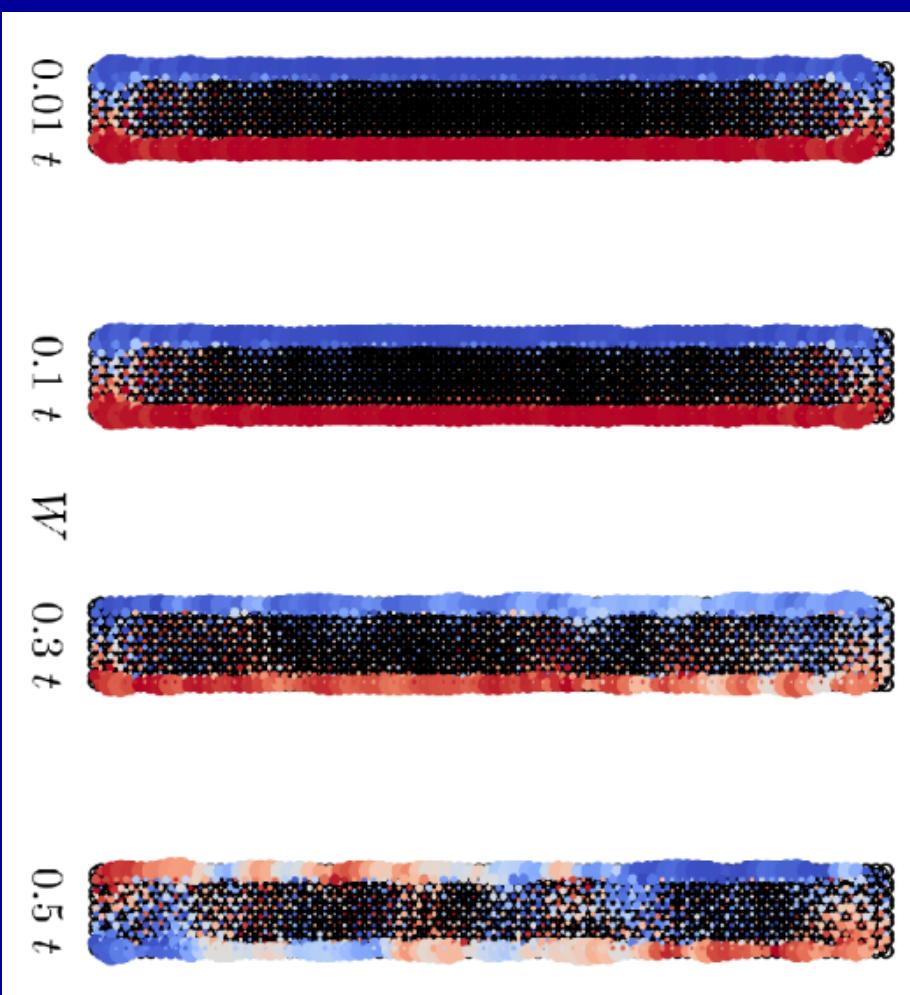
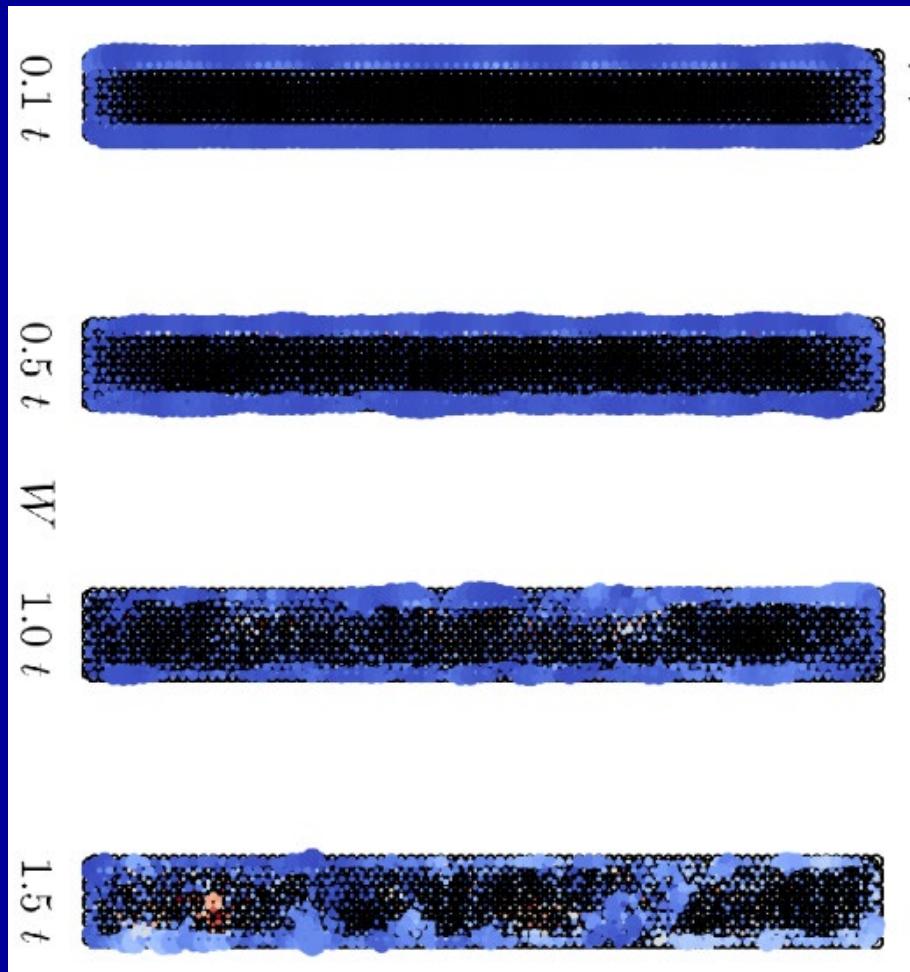
T. Frank, P. Högl, M. Gmitra, D. Kochan, and J. Fabian, PRL 120, 156402 (2018)

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

Kane-Mele

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

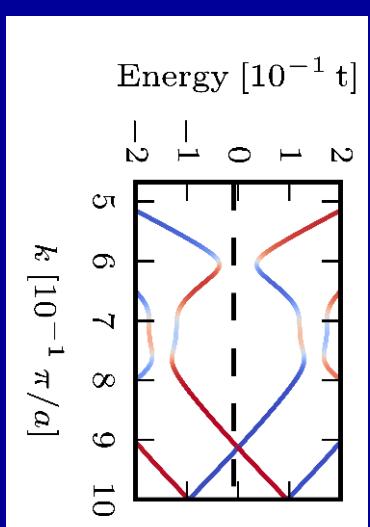
valley Zeeman



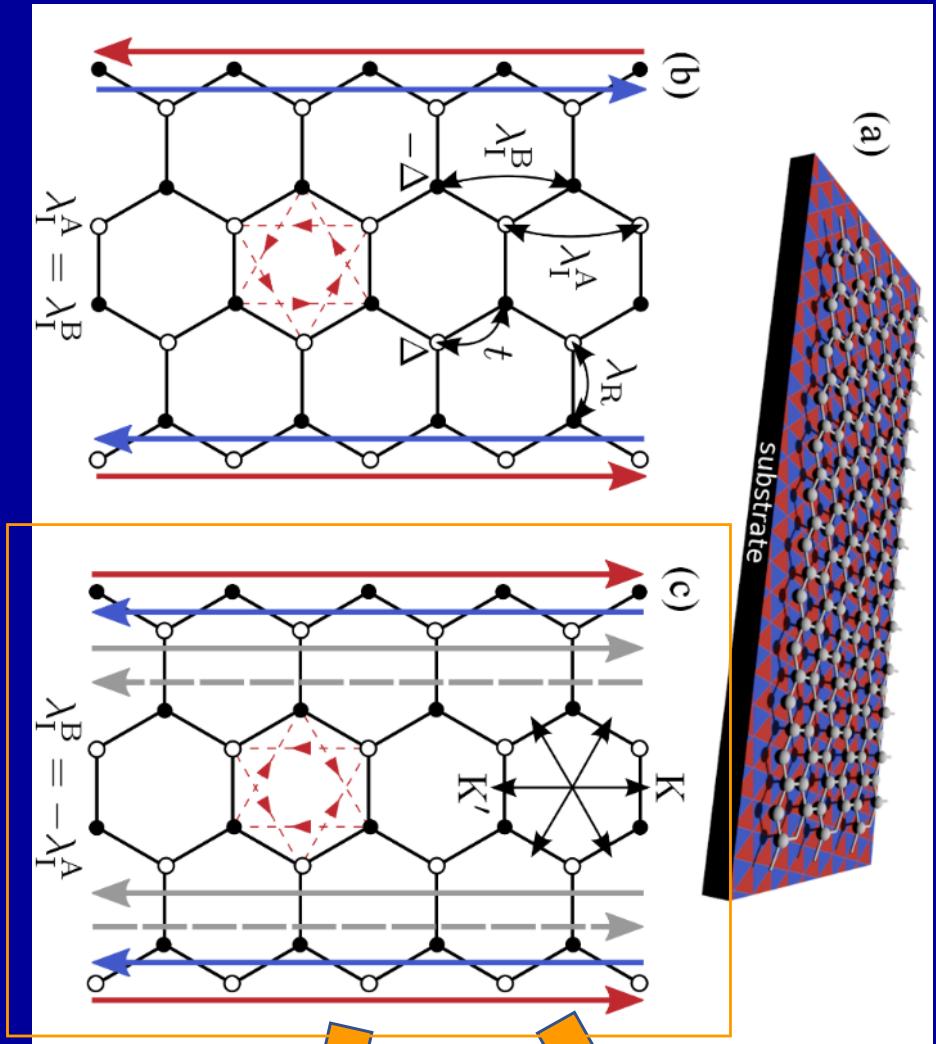
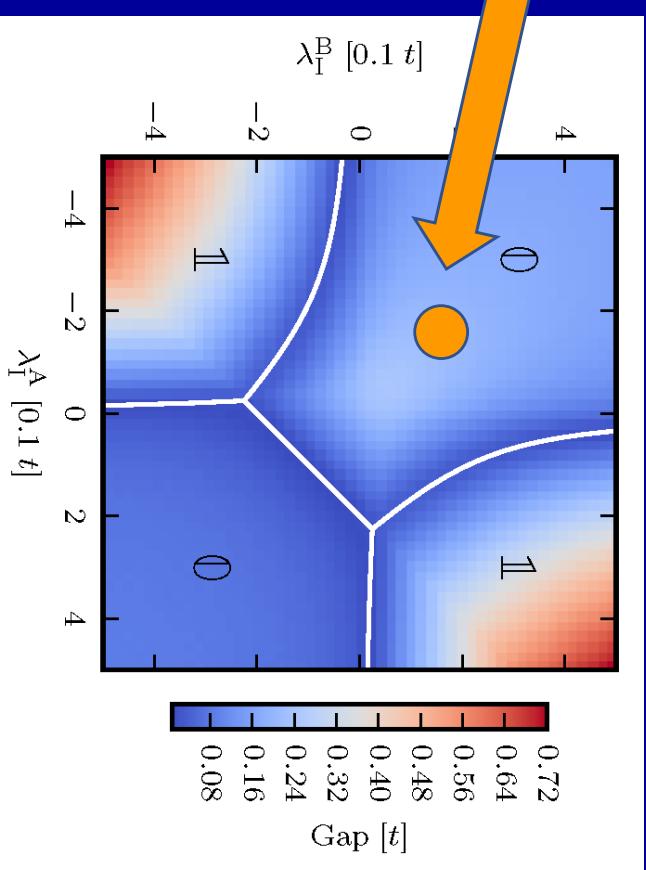
protected edge states in $Z_2=0$ (trivial) system

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

finite ZZ ribbon



Z_2 map

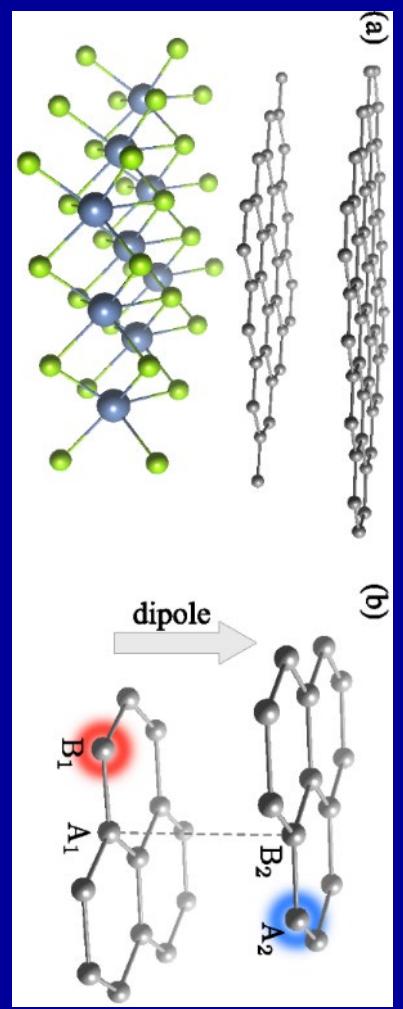
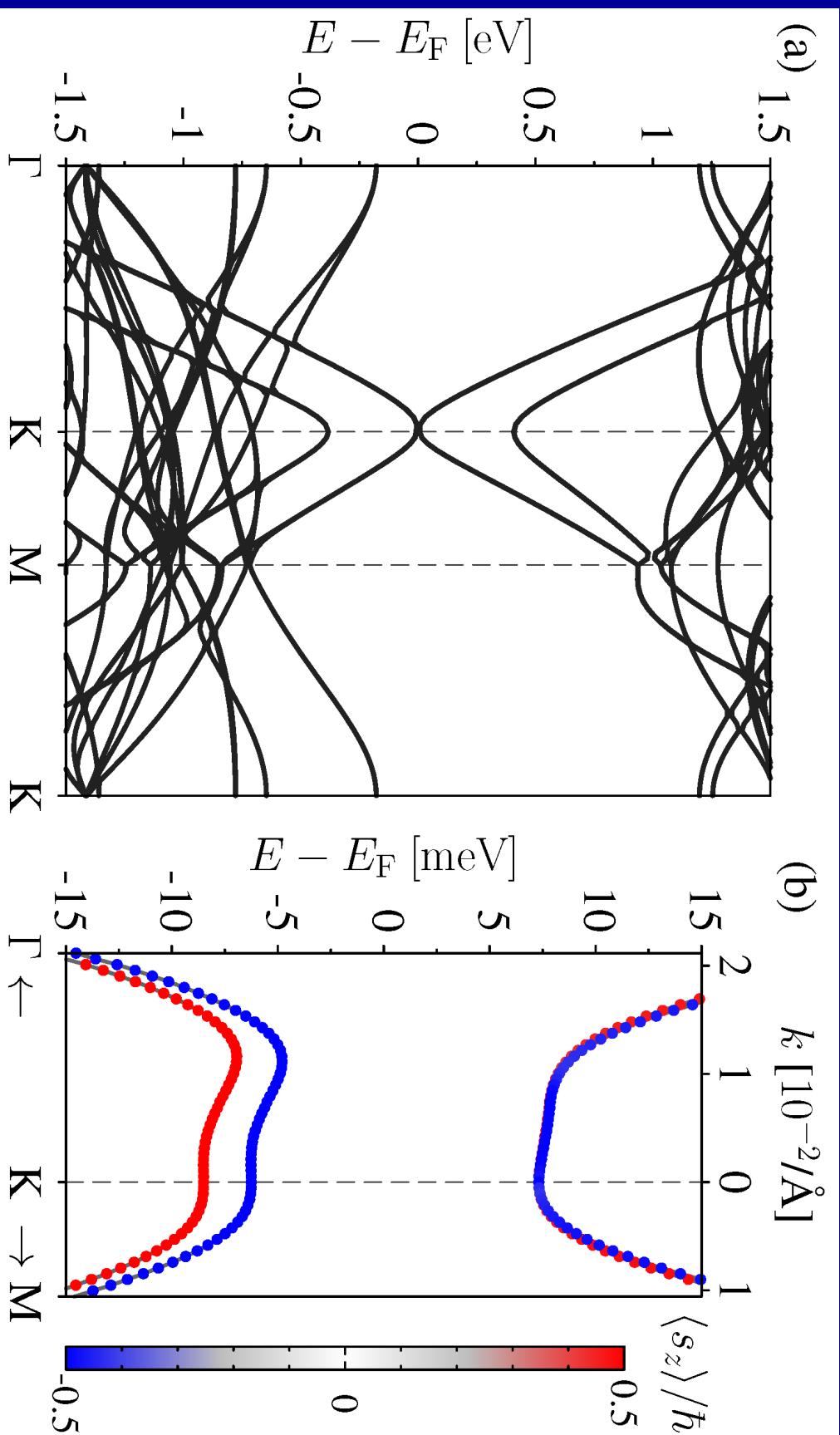


spin-orbit valve

BLG on WSe₂

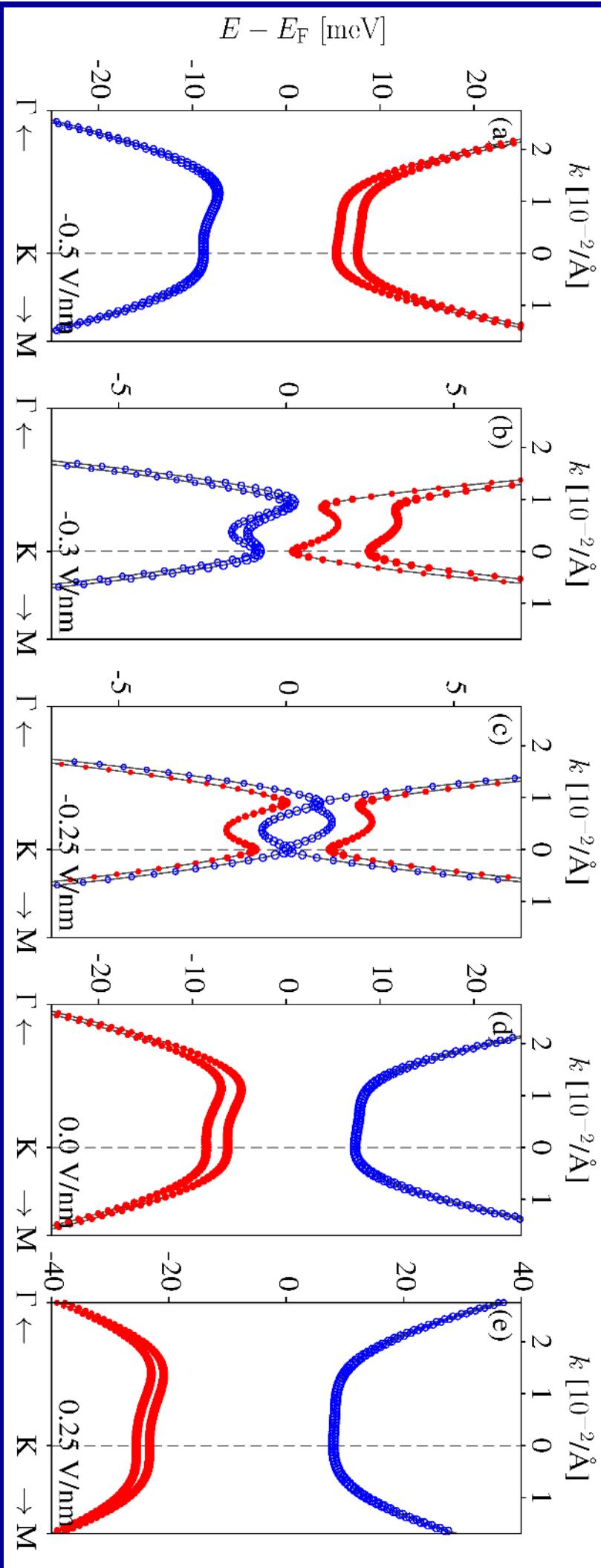
M. Gmitra and J. Fabian,
Phys. Rev. Lett. 119, 146401 (2017)

J. Khoo, A. Morpurgo, and L. Levitov,
Nano Lett. 17 (11), pp 7003-7008 (2017)



spin-orbit valve

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

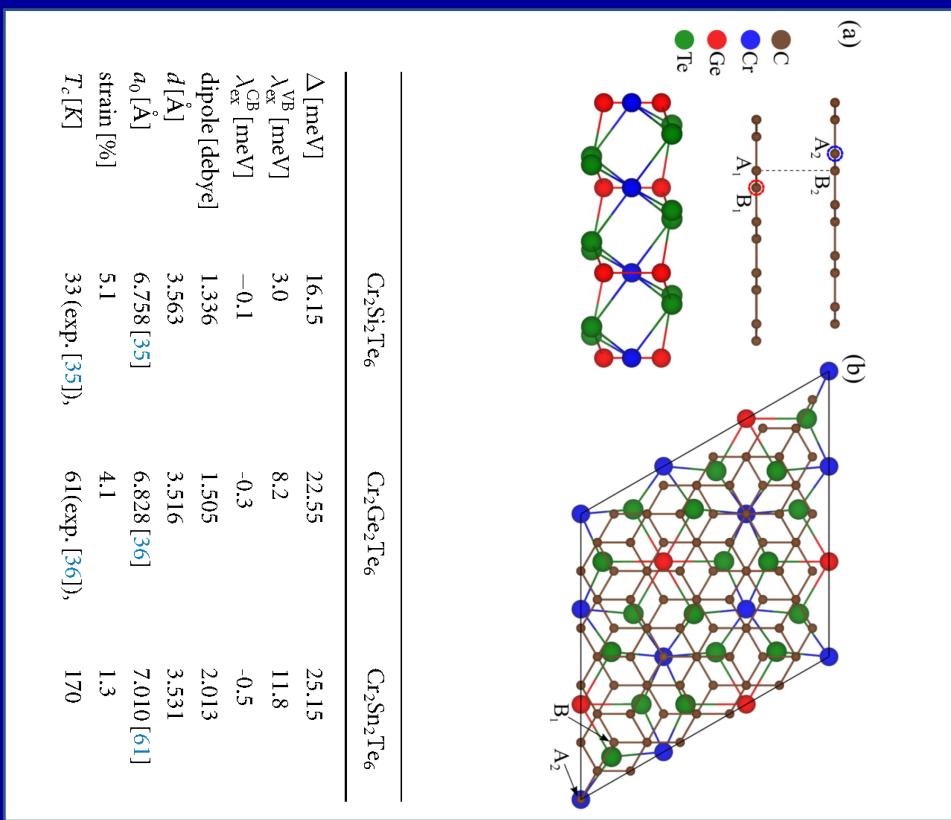
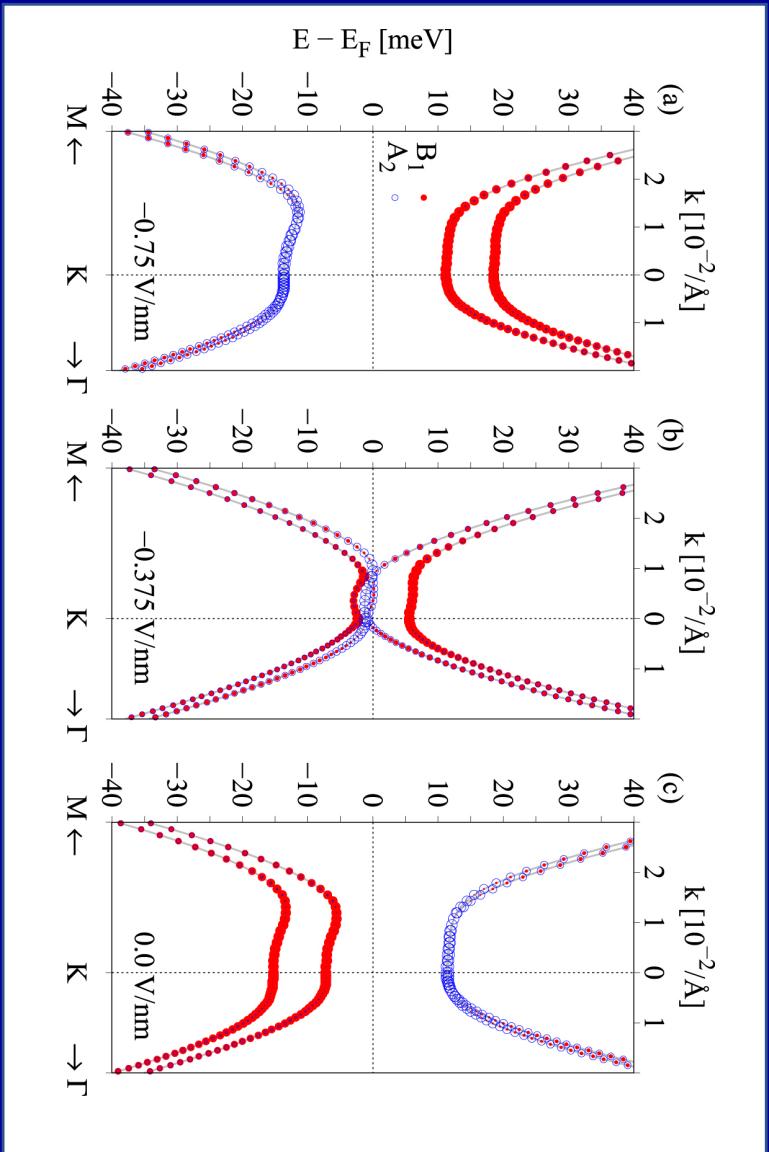


Proximity exchange

coupling in 2D
materials

exchange valve in BLG/CGT slabs

K. Zollner and J. Fabian, NJP 20, 073007 (2018)

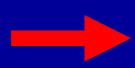


ex-SO-tic vdW heterostructures

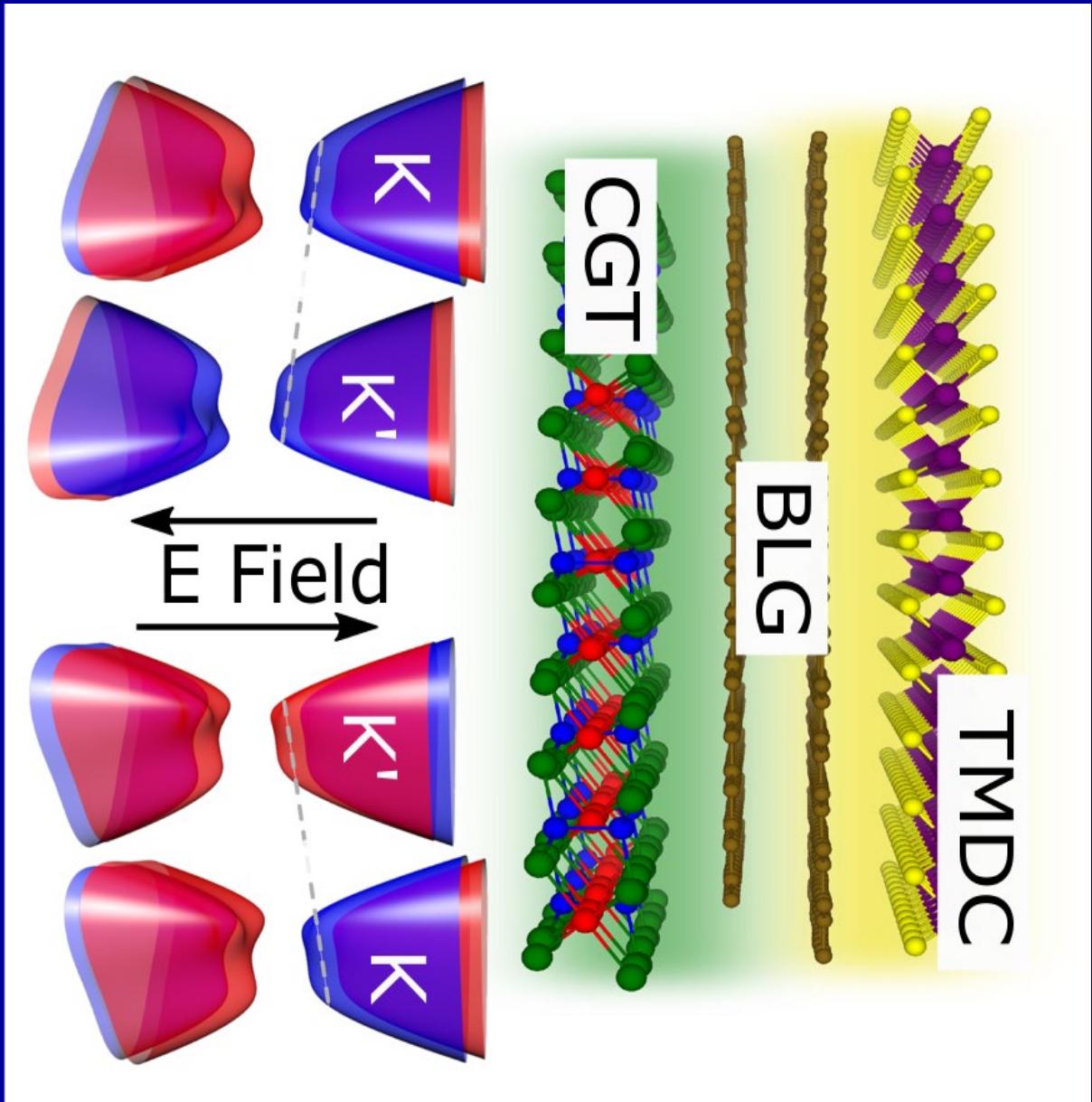
K Zollner, M Gmitra, JF , Phys. Rev. Lett. 125, 196402 (2020)

strong SOC
material

platform 2D
material

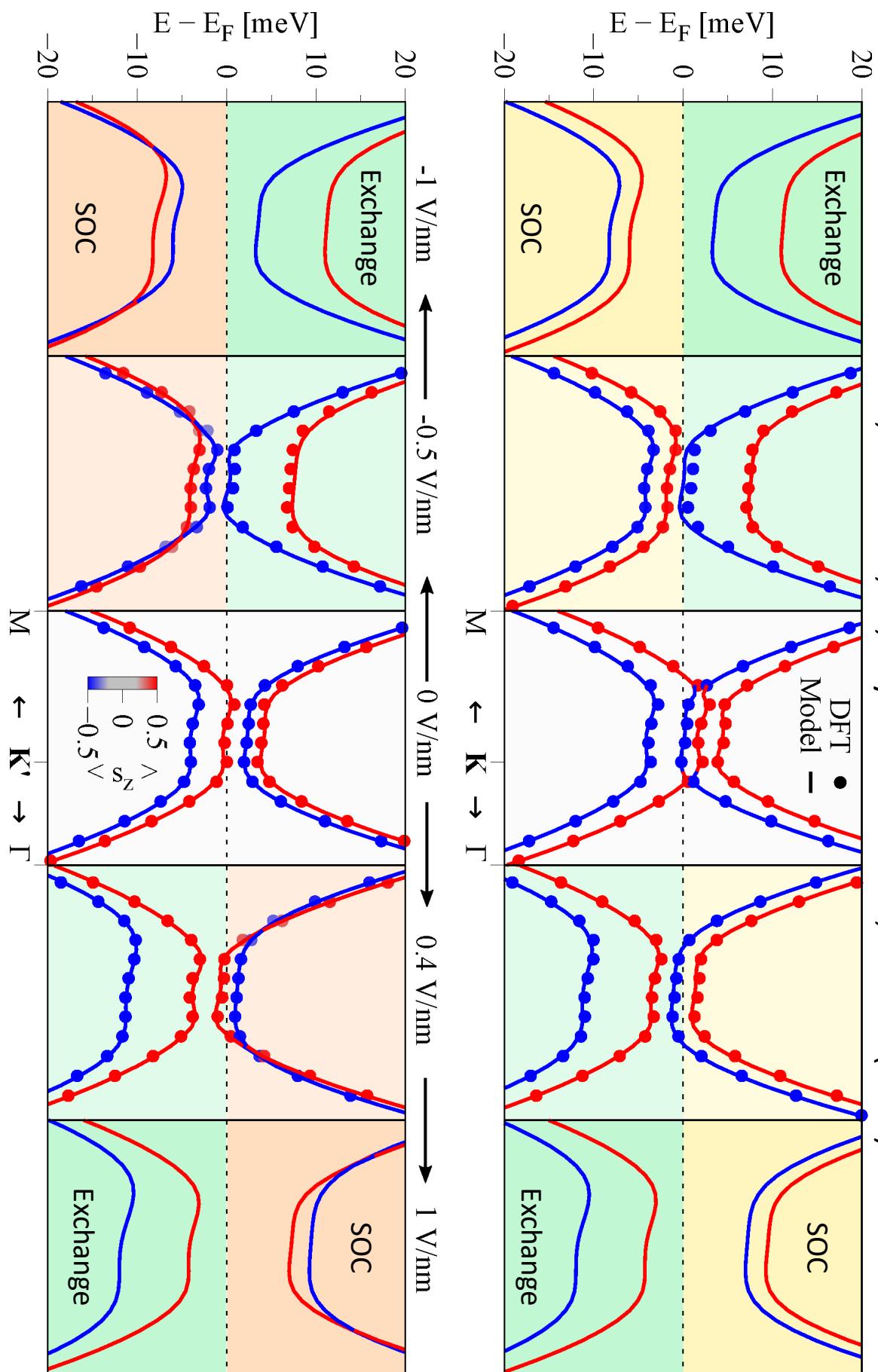


magnet



ex-SO-tic vdW heterostructures swapping SOC and exchange in BLG

K Zollner, M Gmitra, JF , Phys. Rev. Lett. 125, 196402 (2020)

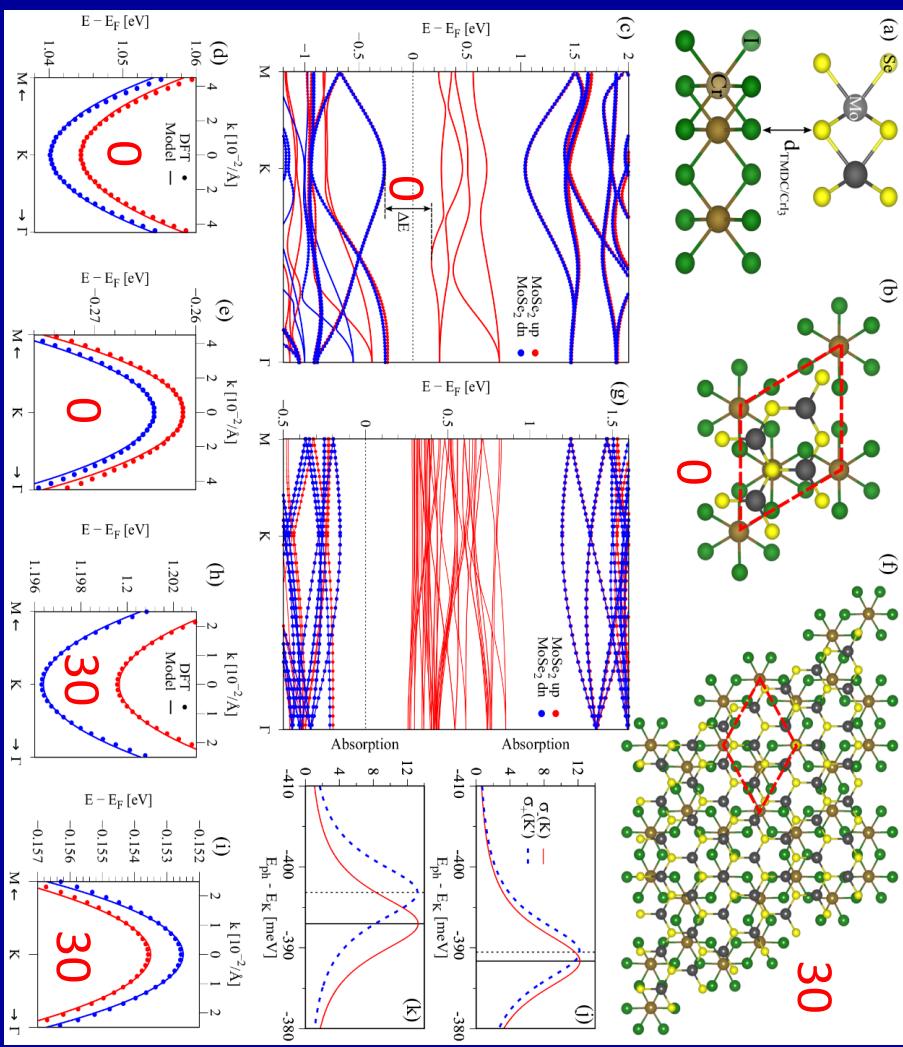
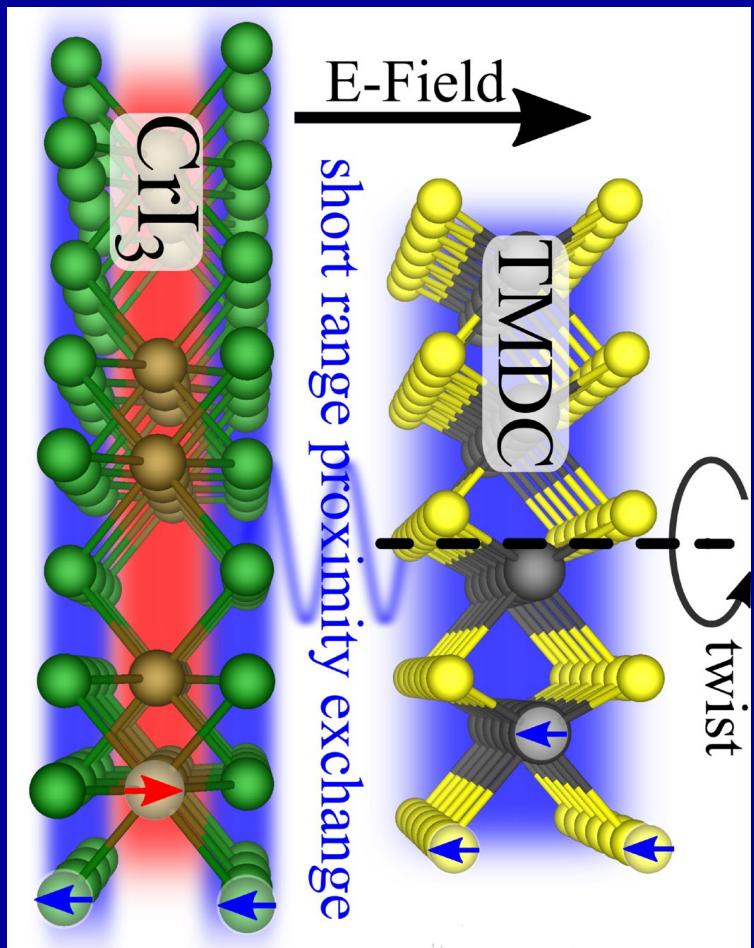


What next?

- Twist-angle control of proximity effects
- Other proximity effects, different materials
- Ramifications in transport, topology, magnetism
- Spin-orbit torques driven by proximity effects
(see talk by B. Nikolic on Wednesday)
- Proximity effects and strong correlations at *magic angle*
- *rainbow-cake* vdW heterostructures

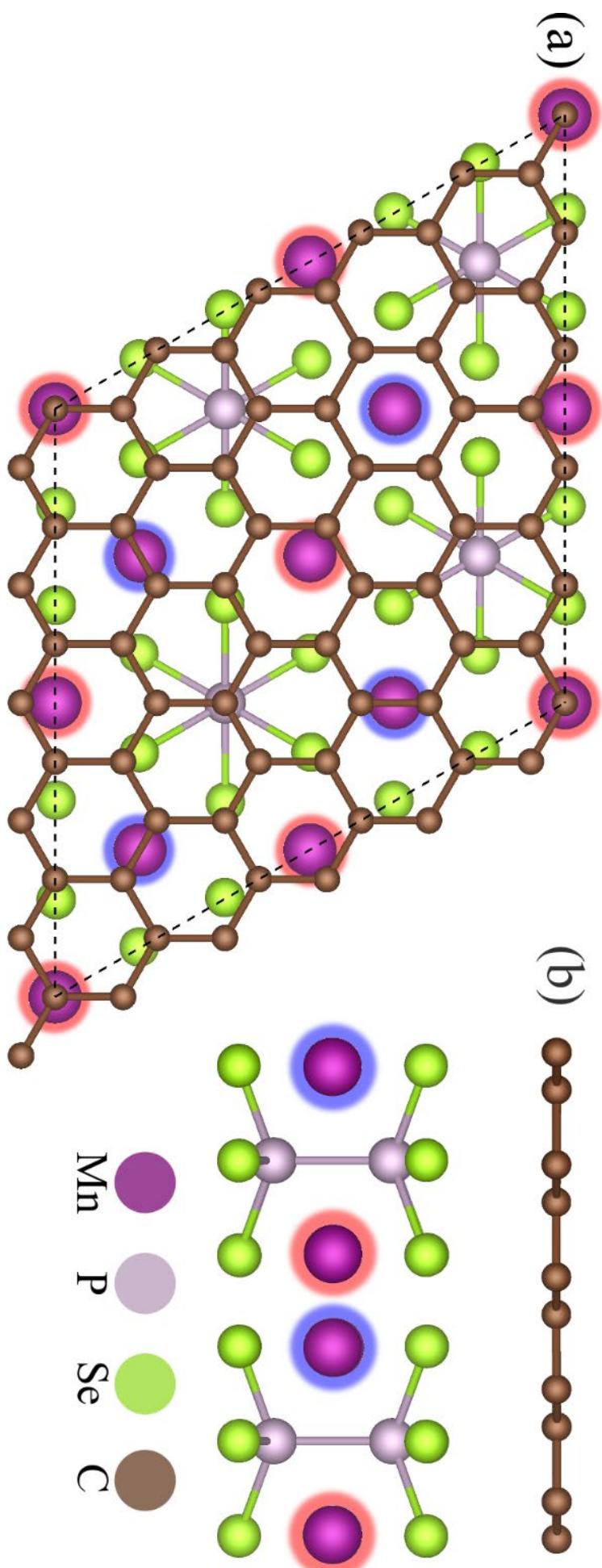
Twist-angle control of exchange proximity effects

K Zollner, PEF Junior, J Fabian, Phys. Rev. B 100, 085128 (2019)



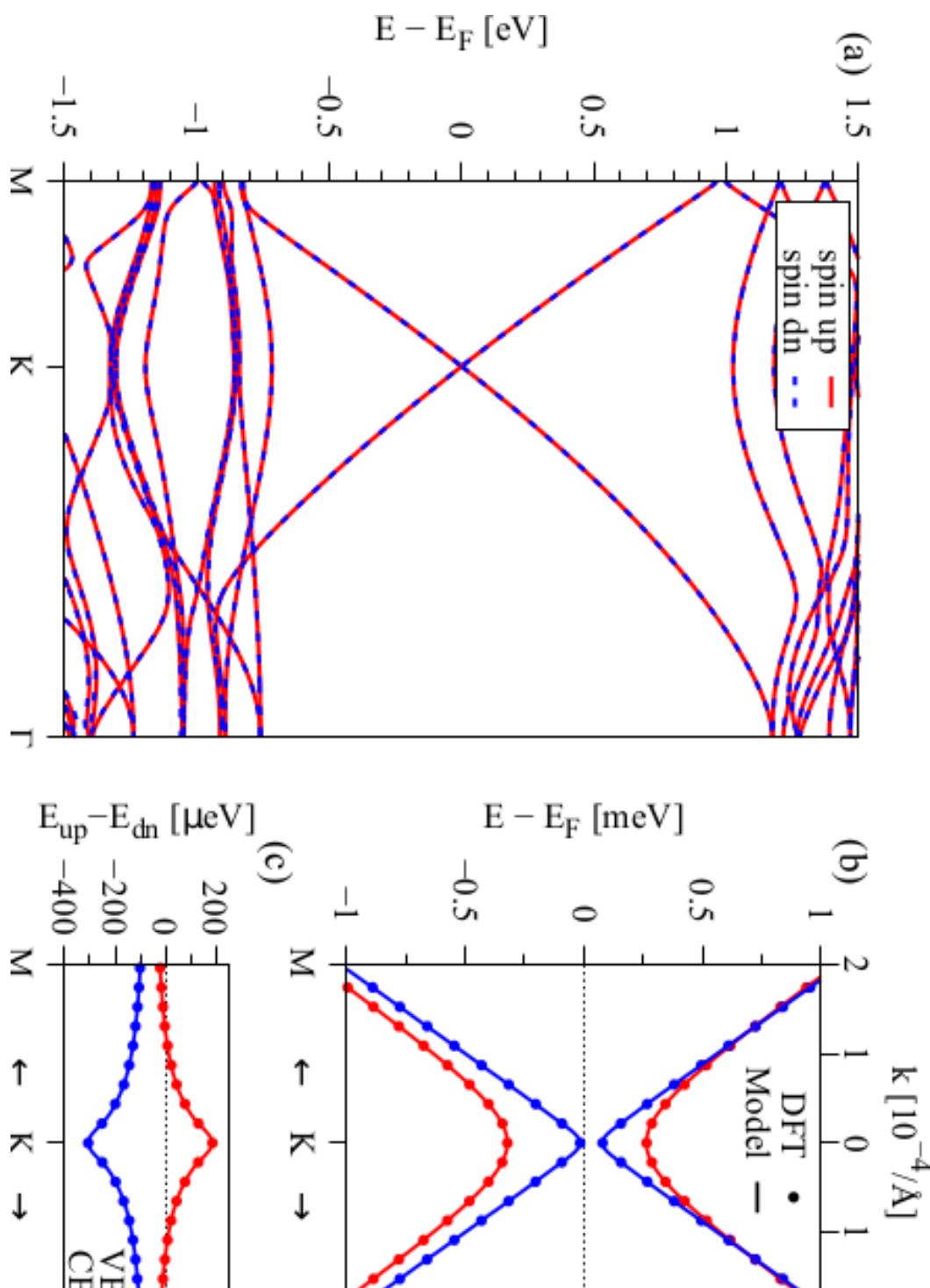
Making Graphene antiferromagnetic: graphene on MnPSe_3

P Högl et al, Phys. Rev. Lett. 124, 136403 (2020)



Making Graphene antiferromagnetic: graphene on MnPSe₃

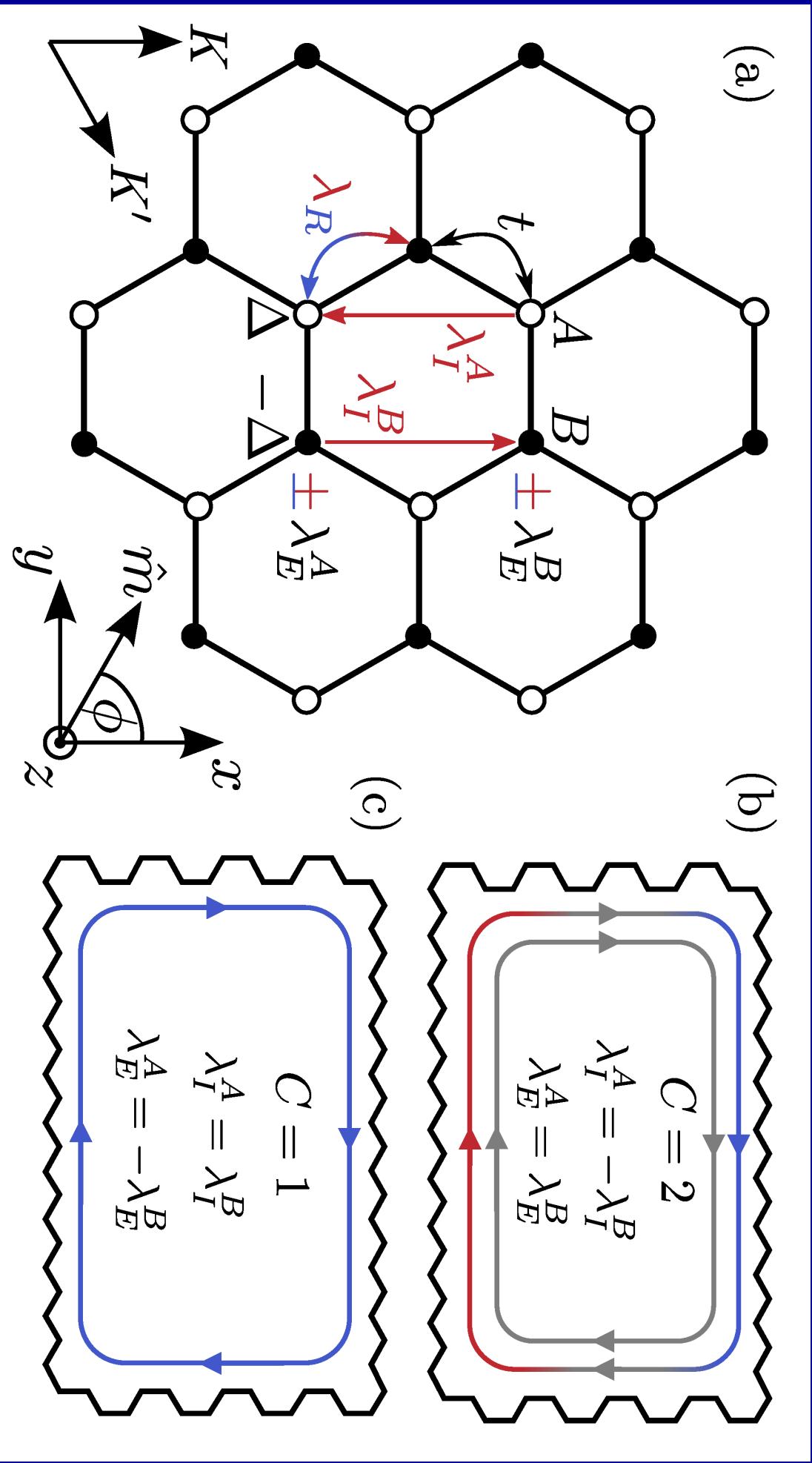
P Högl et al, Phys. Rev. Lett. 124, 136403 (2020)



QAHE in graphene

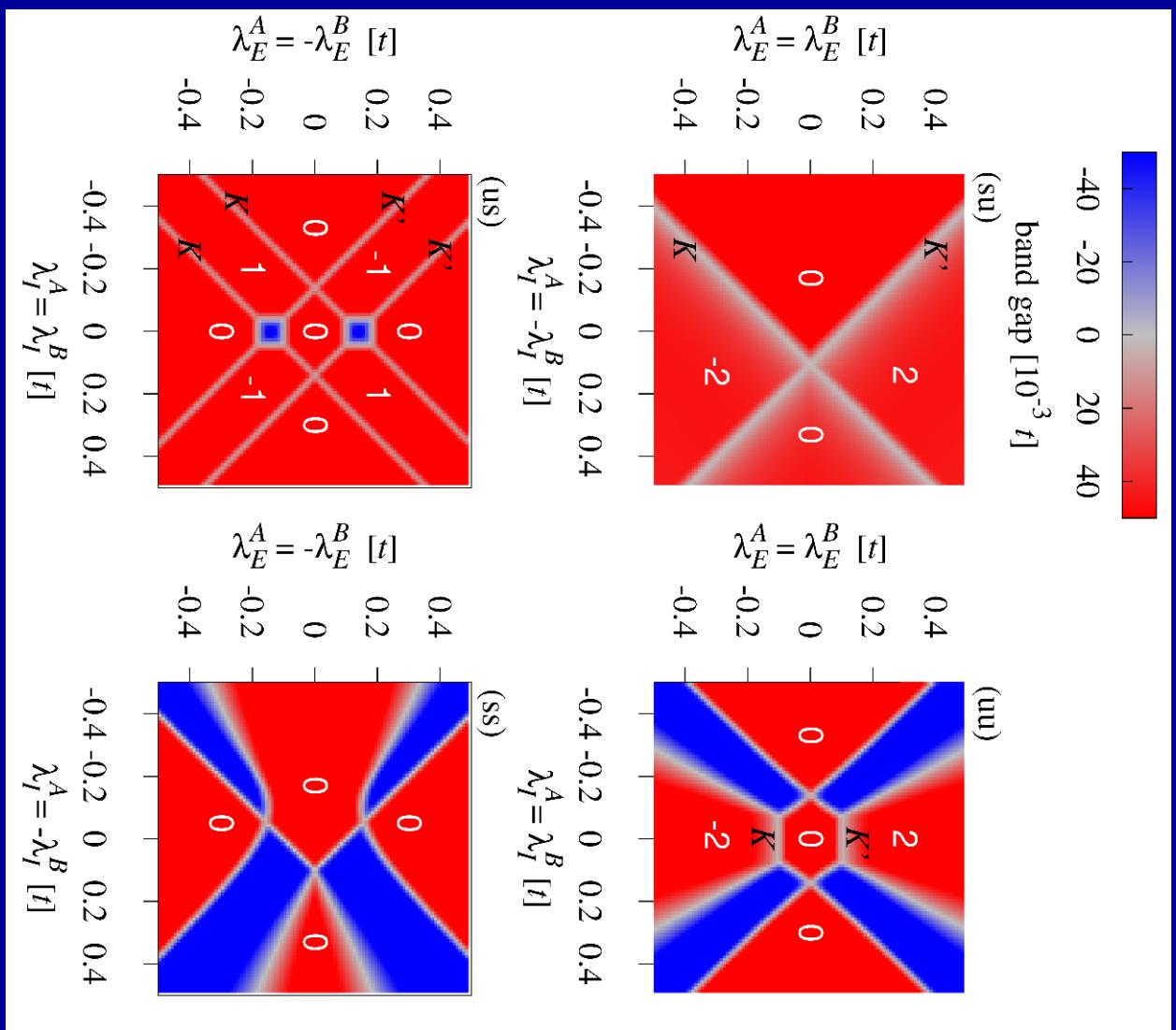
P Högl et al, Phys. Rev. Lett. 124, 136403 (2020)

pseudohelical states become topological



QAHE in graphene

P Högl et al, Phys. Rev. Lett. 124, 136403 (2020)



SOC:

- uniform (intrinsic)
- staggered (valley Zeeman)

Exchange:

- uniform (ferromagnetic)
- staggered (antiferromagnetic)

Colloquium: Spintronics in graphene and other two-dimensional materials

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REVIEW ARTICLE | FOCUS

PUBLISHED ONLINE: 6 OCTOBER 2014 | DOI: 10.1038/NNANO.2014.214

nature
nanotechnology

Graphene spintronics

Wei Han^{1,2,3}, Roland K. Kawakami^{4,5*}, Martin Gmitra⁶ 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.

Materials Today 22 January/February (2019)

Proximity-induced materials

Igor Žutić^{1,*}, Alex Matos-Abiague², Benedikt Scharf³, Hanan Dery⁴,
Kirill Belashchenko⁵