



Route towards topological antiferromagnetic spin-orbitronics, and Dirac-tronics

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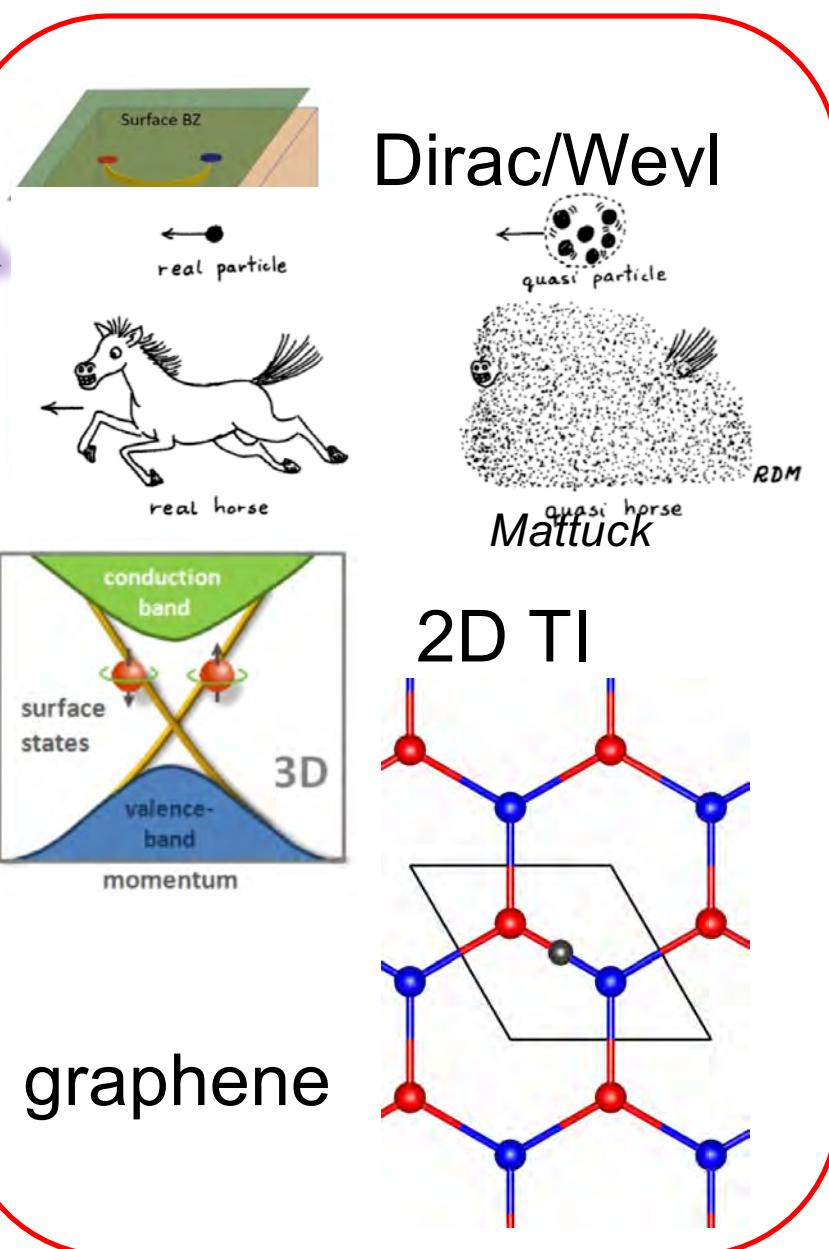
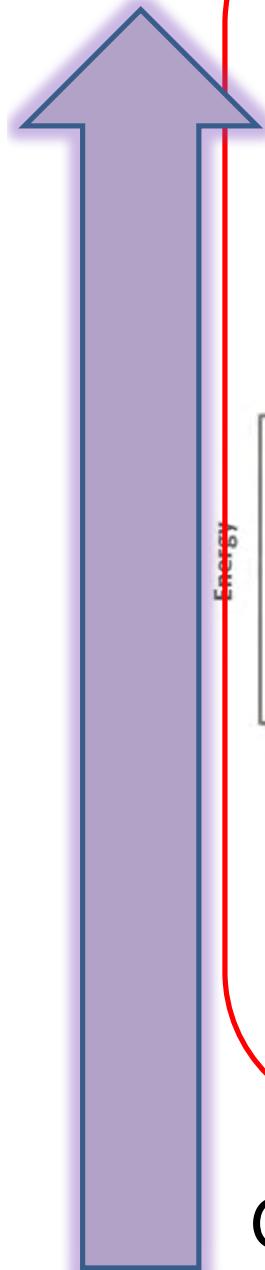
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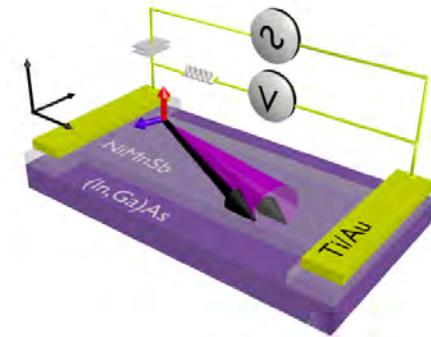
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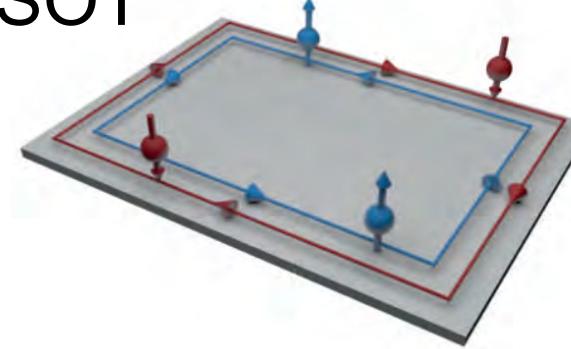
2016



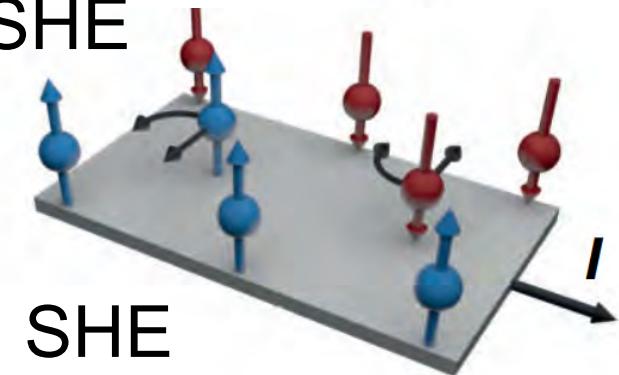
NSOT



SOT



QSHE



SHE

GaMnAs, superconductors (low T_c) \rightarrow emergent effects

2003

<http://www.cpfs.mpg.de/2520384/Weyl-semimetals -Exotic-quantum-materials>

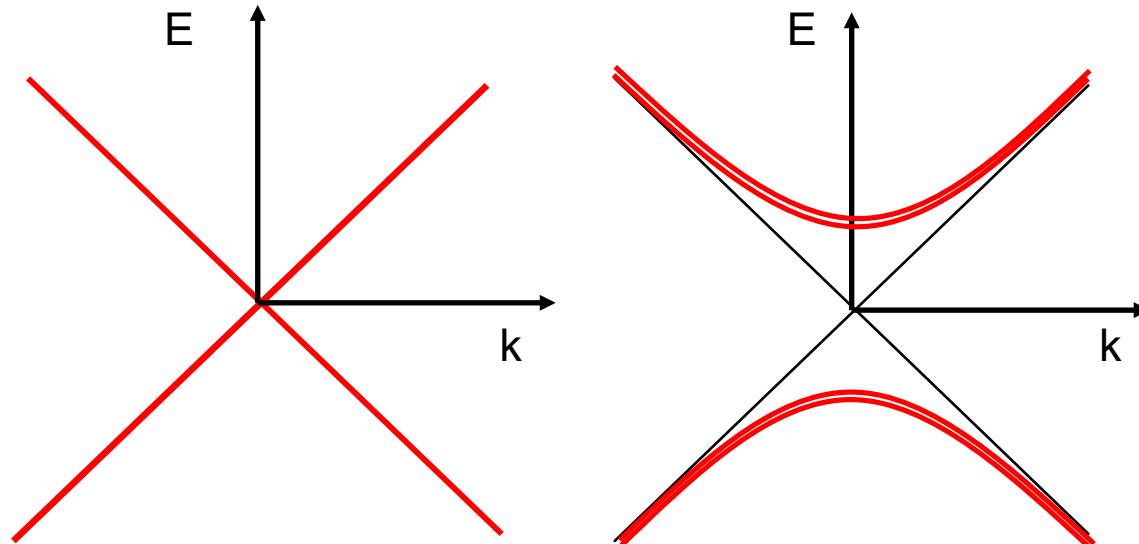
http://www.vi-ti.de/vi-ti/EN/Research/01-Introduction/01-Introduction_node.html, Sinova et al. RMP (2015)

Dirac and Weyl fermions & topological semimetals

Relativistic quantum field theory = spinor fields + Lorentz invariant building blocks

$$\mathcal{L}_D = i\psi_L^\dagger \bar{\sigma}^\mu \partial_\mu \psi_L + i\psi_R^\dagger \sigma^\mu \partial_\mu \psi_R - m(\psi_L^\dagger \psi_R + \psi_R^\dagger \psi_L)$$

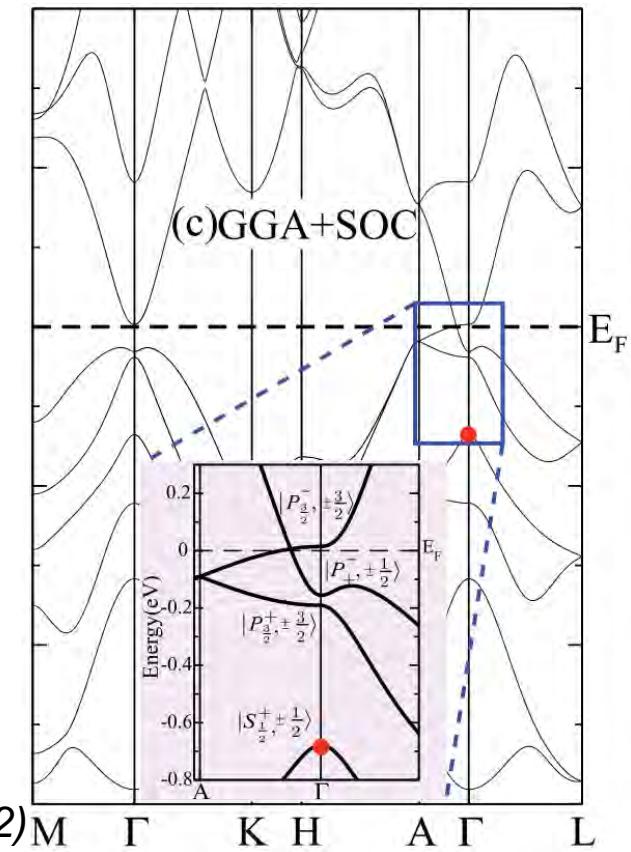
$$(\partial_0 - \sigma^i \partial_i) \psi_L = 0 \quad (i\partial - m) \Psi = 0$$



Mechanism? Suppression of backscattering?

$$E = \sqrt{m^2 c^4 + \mathbf{p}^2 c^2}$$

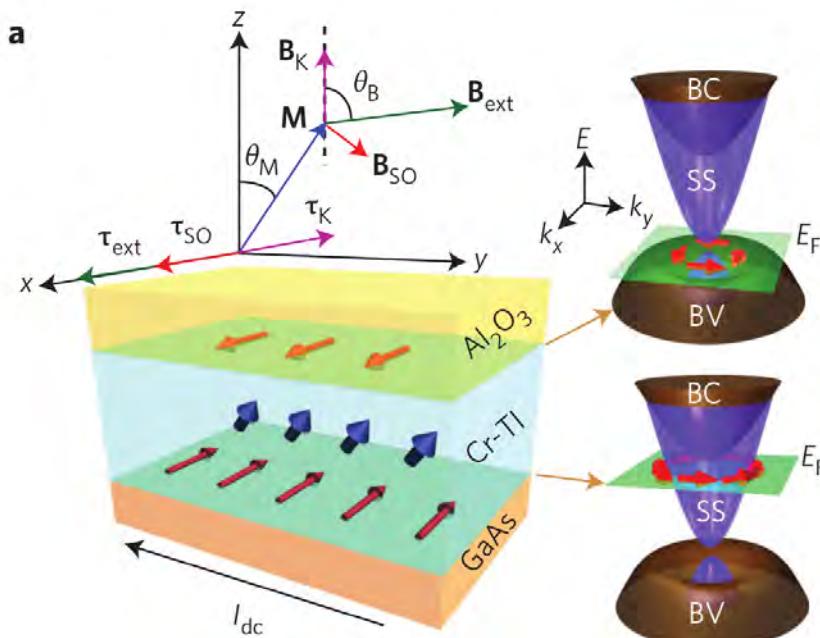
Na₃Bi candidate
Wang Na₃Bi PRB (2012)



Efficient control of Dirac fermions?
Magnetic semimetals, mechanism of low dissipation?

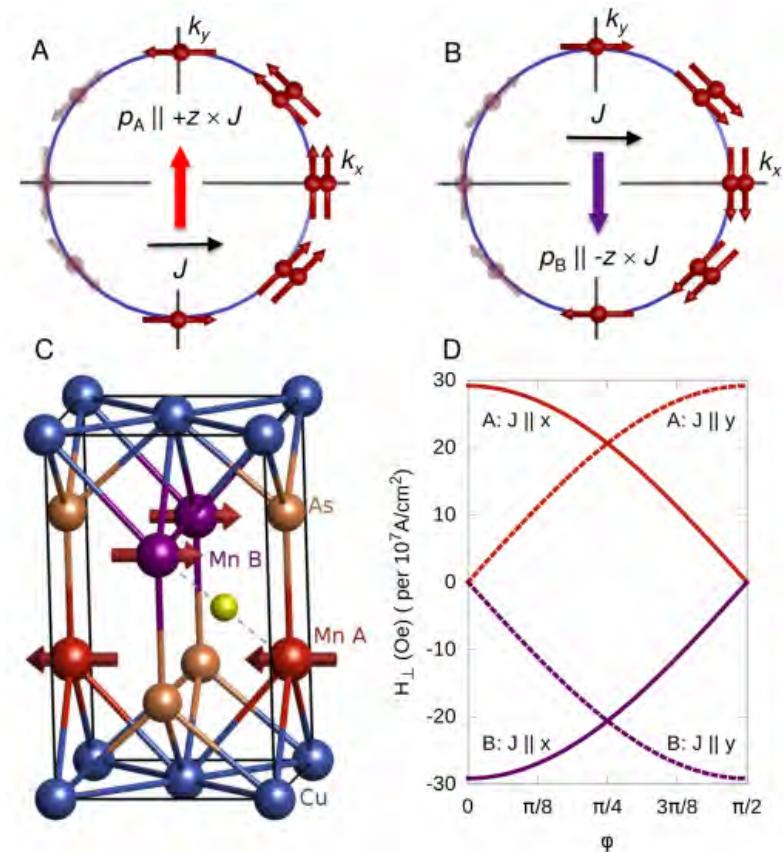
Spin-orbitronics effects

Spin-orbit torque from topological states



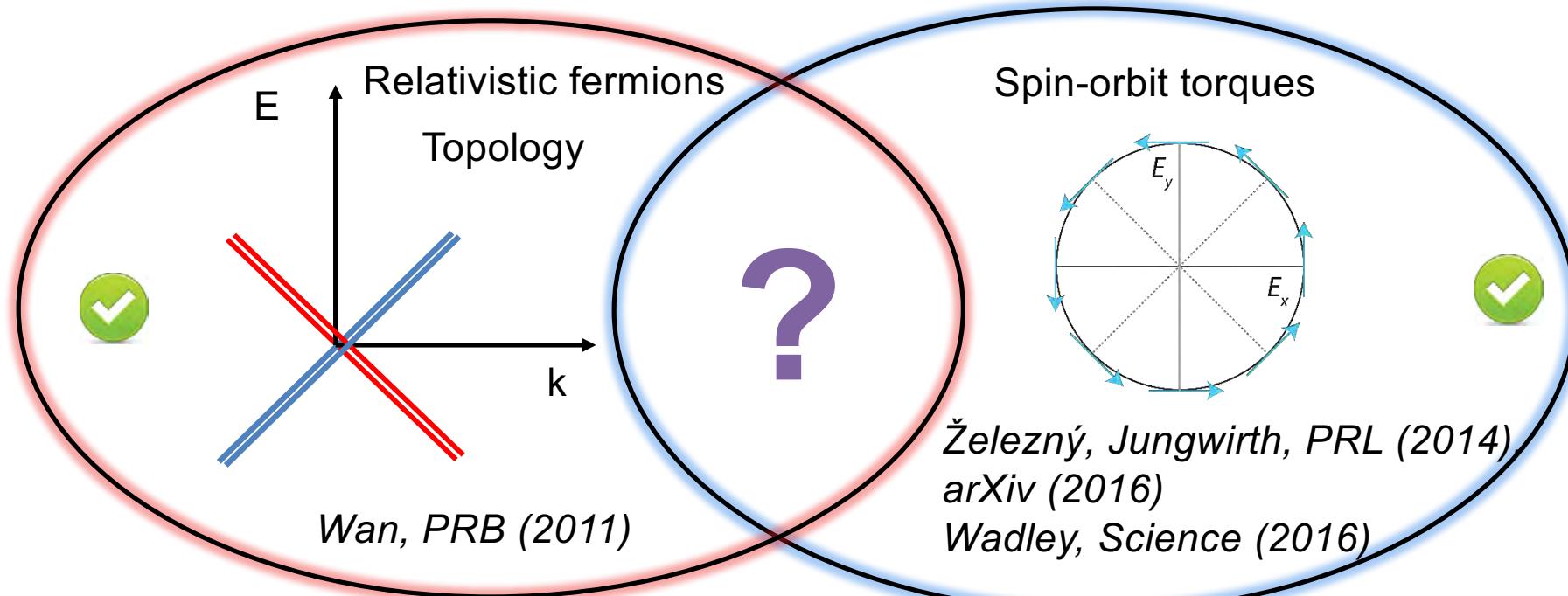
Fan Nature Nanotechnology (2016) :
Electric-field control of spin-orbit torque
in a magnetically doped topological insulator

Spin-orbit torque In antiferromagnets



Enhancement/lower diss.? → topology & Dirac fermions
Fundamental physics of effects (AMR)?

Compatibility of Dirac fermions and NSOT?



External control of Dirac fermions?

Topology/enhancement of spinorbitronics effects?

Diverse symmetries

PT symmetry

Kramers degeneracy *Yang & Nagaosa NC (2014)*

Time reversal T: $E_{n\uparrow}(\mathbf{k})=E_{n\downarrow}(-\mathbf{k})$

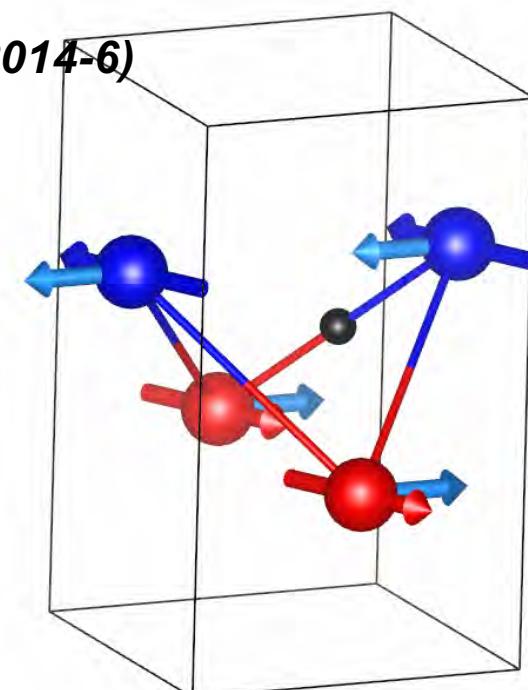
Spatial inversion P: $E_{n\sigma}(\mathbf{k})=E_{n\sigma}(-\mathbf{k})$

$$E_{n\uparrow}(\mathbf{k})=E_{n\downarrow}(\mathbf{k})$$

Néel spin-orbit torque *Železný et al. (2014-6)*

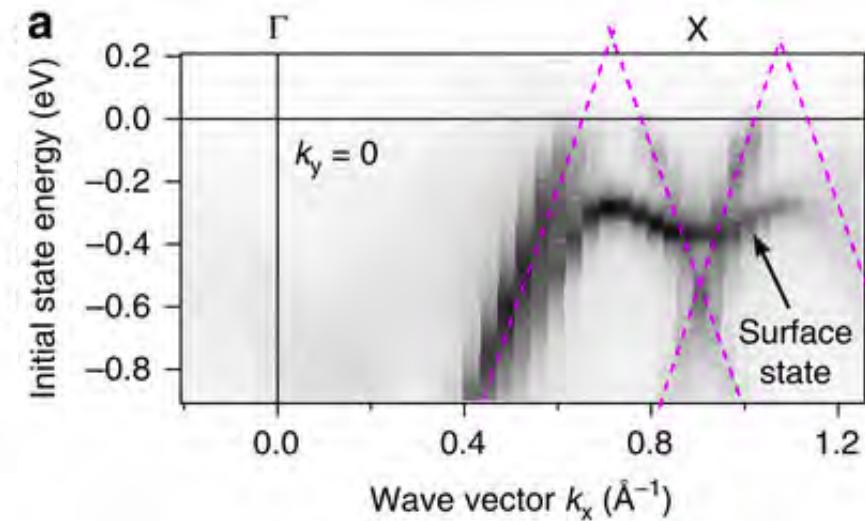
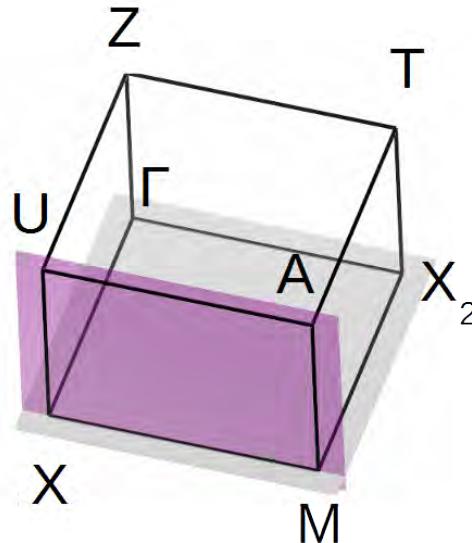
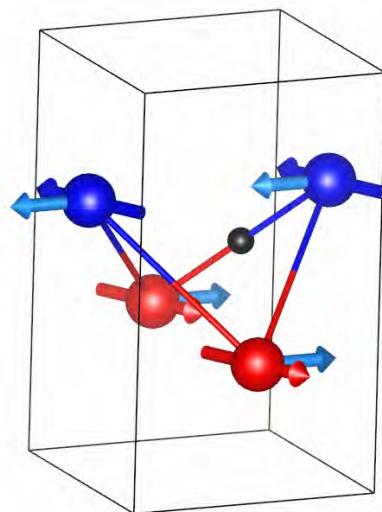
$$\begin{aligned} X^A_{\text{even}} &= -X^B_{\text{even}} & \delta s^A &= \chi^A E \\ X^A_{\text{odd}} &= X^B_{\text{odd}} \end{aligned}$$

+ Noncentrosymmetry



Šmejkal et al., DPG Regensburg (2016)

Nonsymmorphic symmetry $\{g|t\}$ protection



Type I

$$S_x(\mathbf{r}) = \{2_x | (\frac{1}{2}, \frac{1}{2}, 0)\}$$

$$S_x^2 \Psi_{\mathbf{k}} = -e^{-ik_x}$$

Type II

$$G_x(\mathbf{r}) = \{M_x | (\frac{1}{2}, 0, 0)\}$$

$$G_x^2 \Psi_{\mathbf{k}} = -1$$

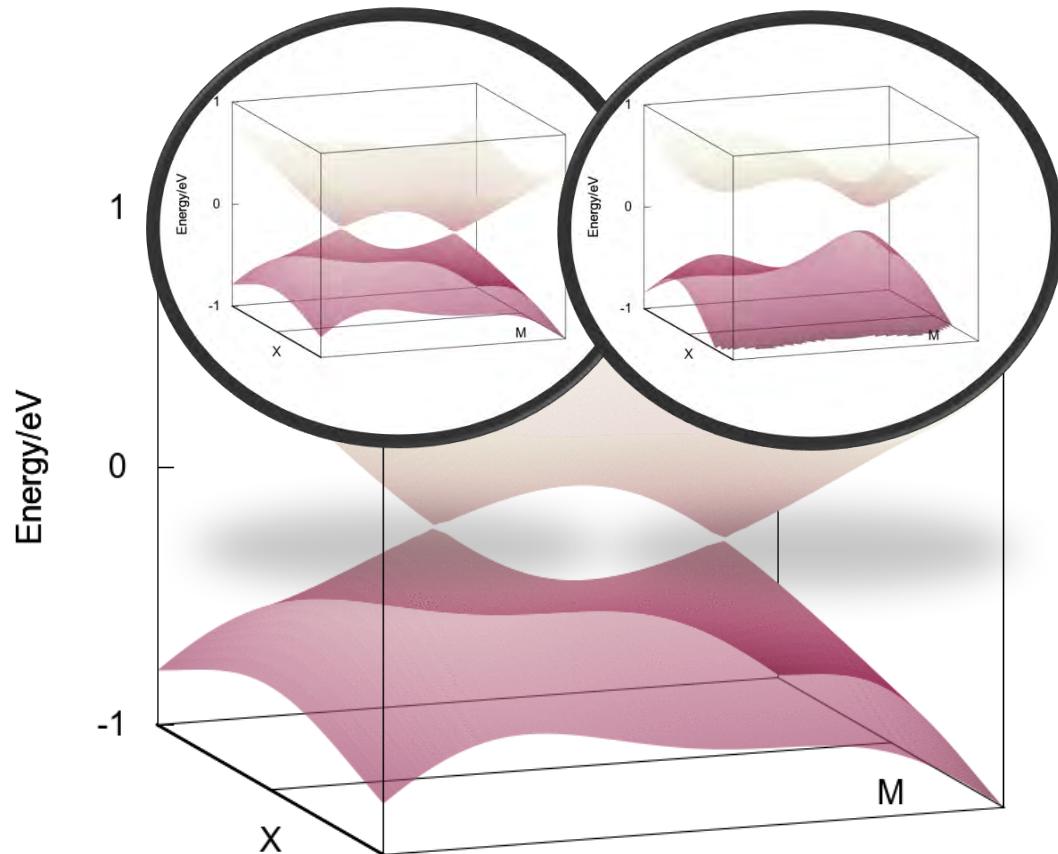
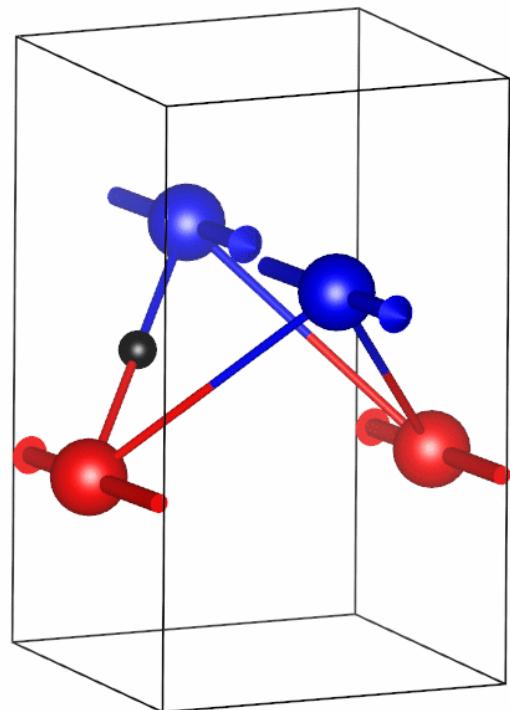
$$S_x P T \Psi_{\mathbf{k}} = e^{-i(k_x + k_y)} P T S_x \Psi_{\mathbf{k}} \quad G_x P T \Psi_{\mathbf{k}} = e^{-i k_x} P T G_x \Psi_{\mathbf{k}}$$

Šmejkal et al., DPG Regensburg (2016)

Identification: Young, Kane PRL (2012, 2015) Classification: Yang, arXiv 2016, experiment Schoop, NC (2016)

Electrical control of Dirac fermions

Serendipitous symmetry overlap



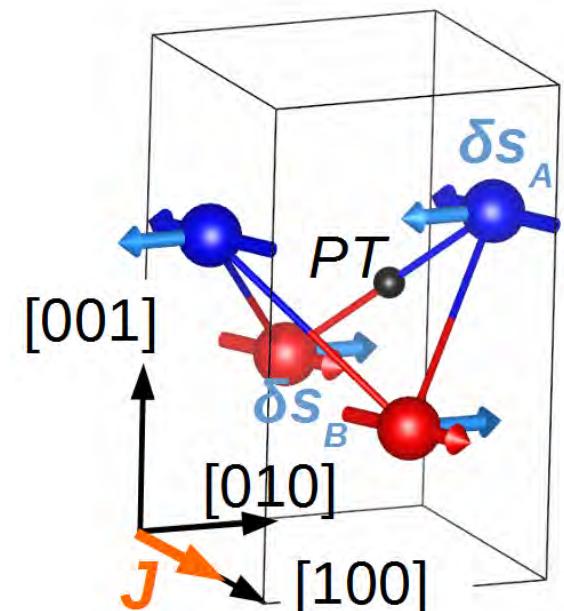
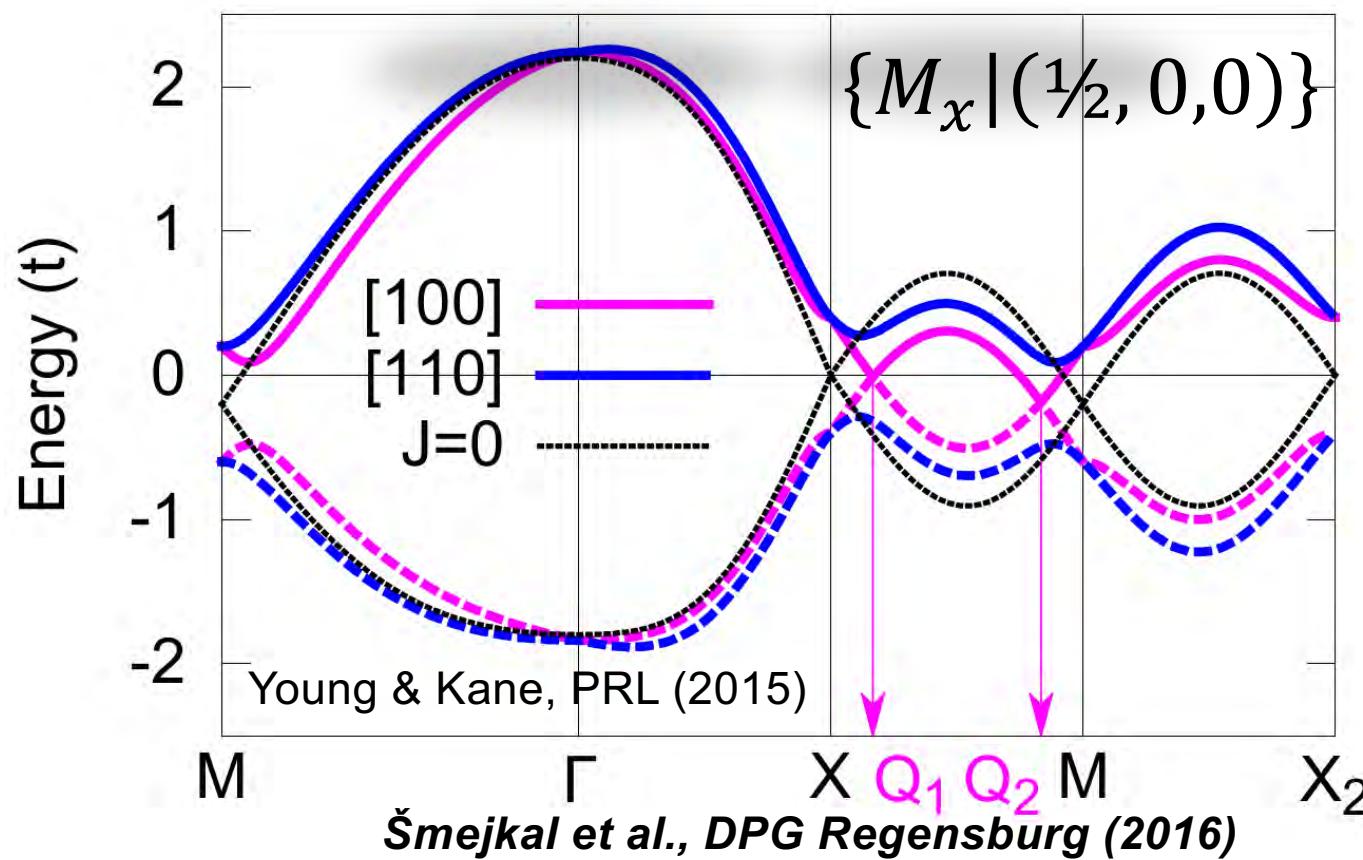
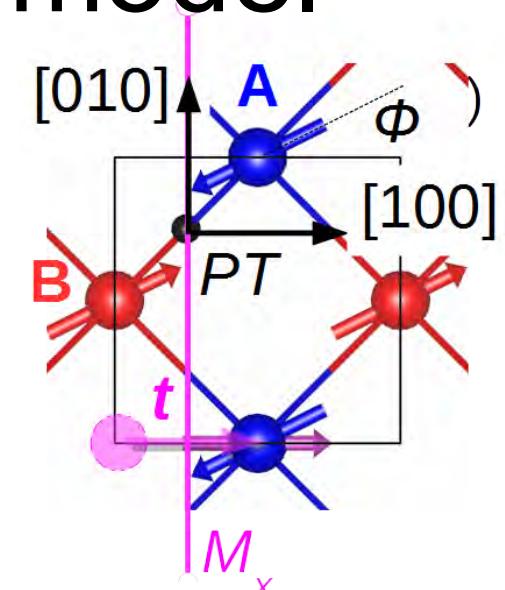
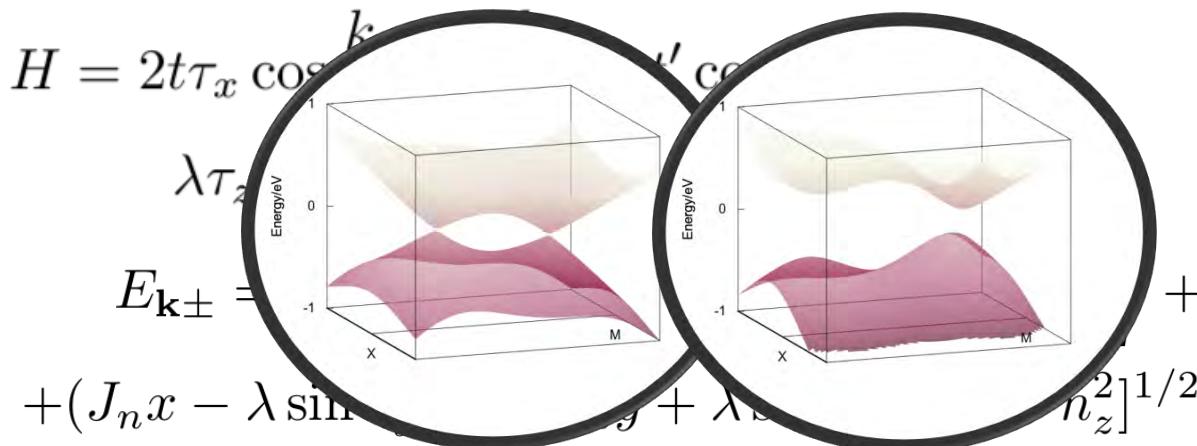
Šmejkal et al., DPG Regensburg (2016)

Antiferromagnetic
topological nonsymmorphic
Dirac semimetal

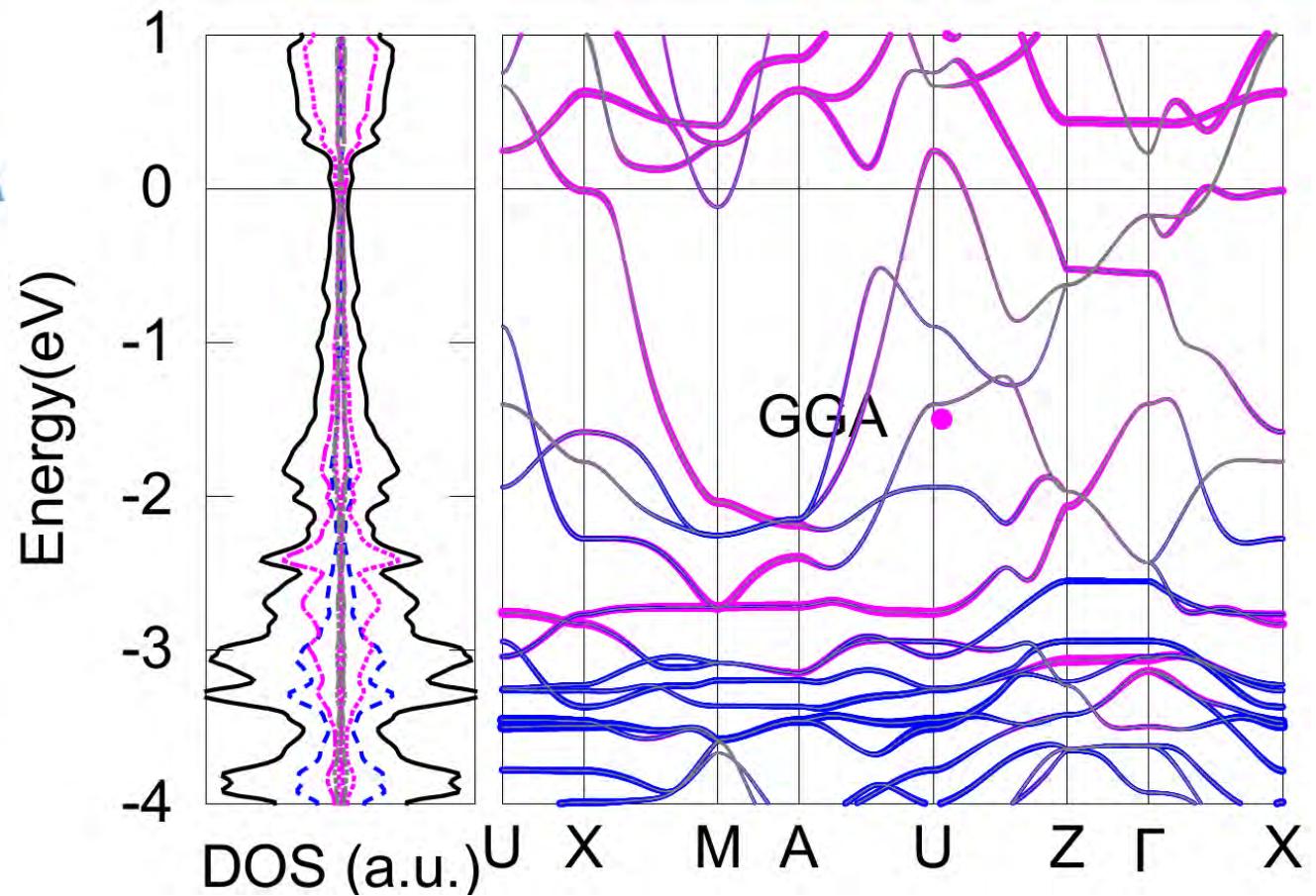
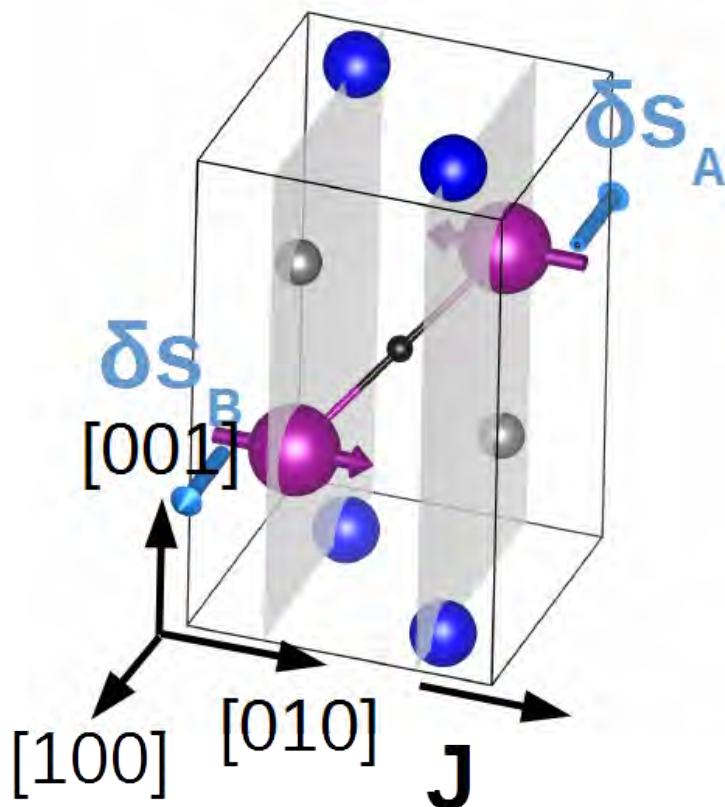
Néel spin-orbit torque
coexistence

Electrical control of Dirac
fermions and topological
metal-insulator transition

Antiferromagnetic minimal model



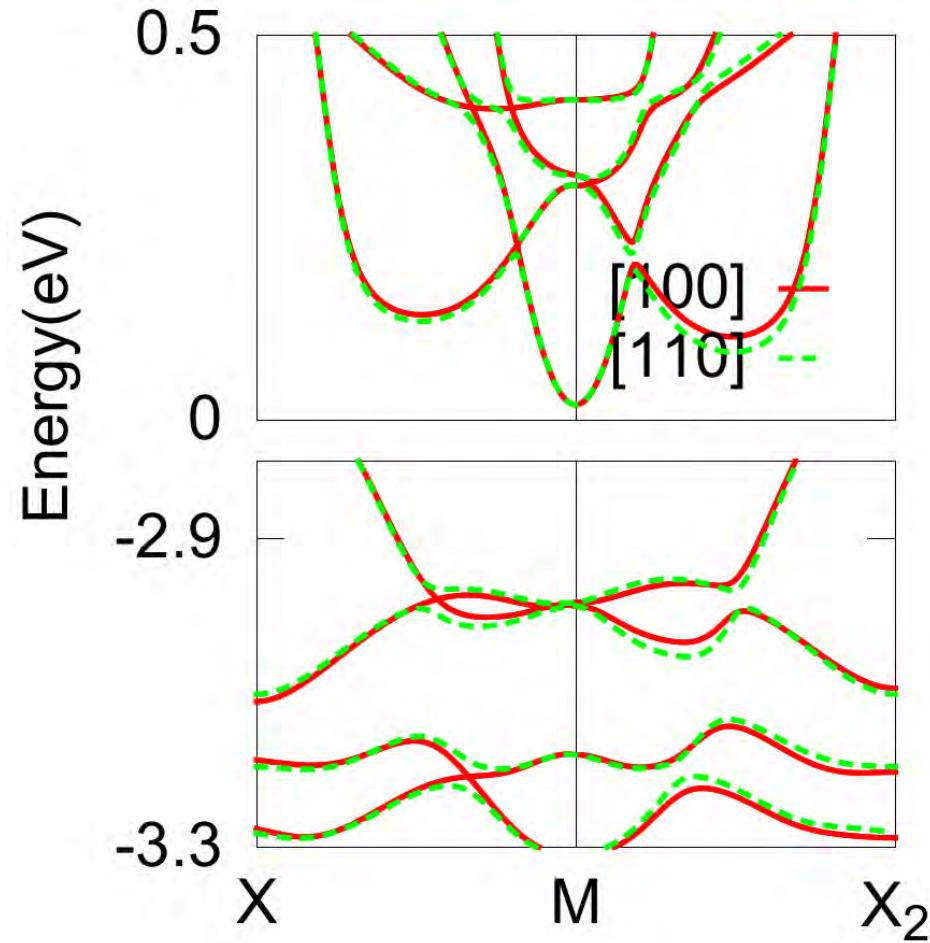
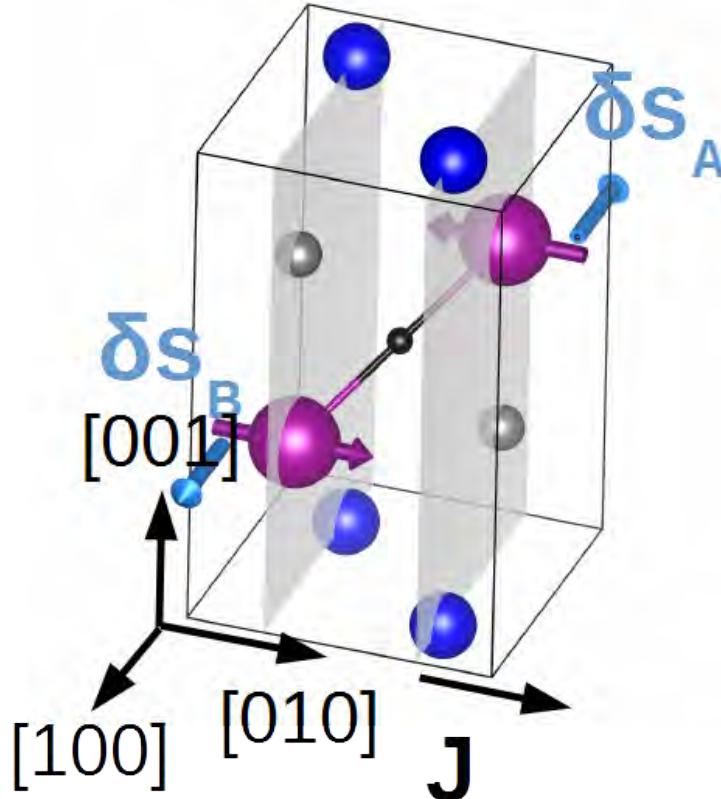
Tetragonal CuMnAs



P4/nmm

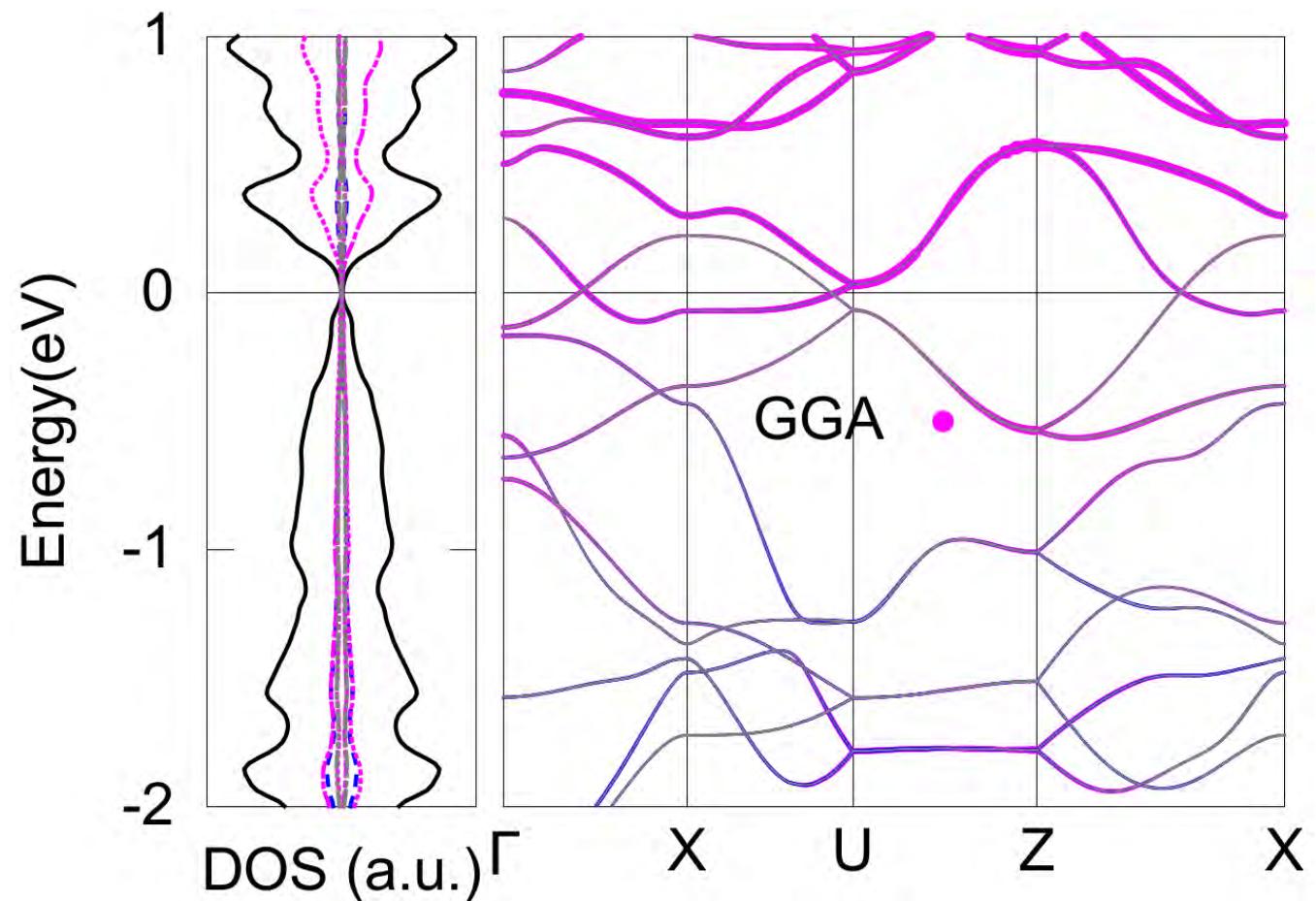
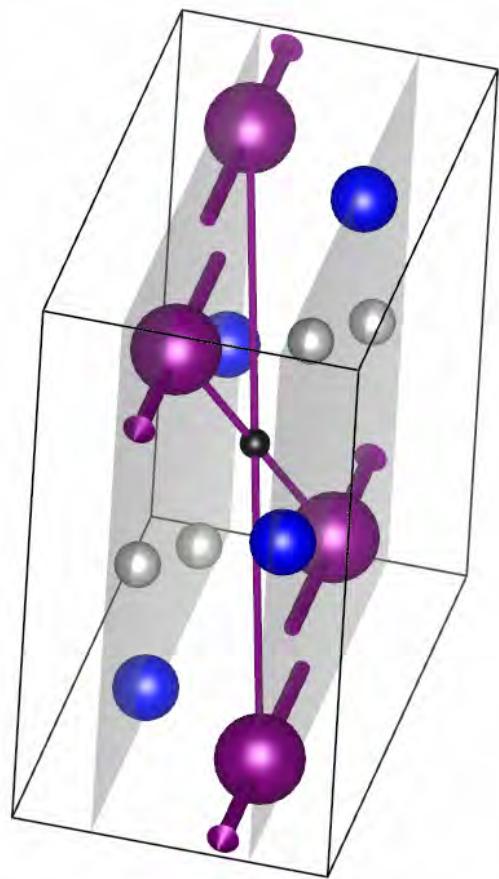
Crossing points interfere with other states.
ELK, FLEUR FLAPW GGA+PBE+U: MAE in-plane in consistent
[*Wadley et al. (2013), (2015), (2016)*]

Electrical control of crossings



Symmetry protection verified by symmetry breaking by staggered order rotations.
Minimal model for tetragonal CuMnAs consistency.
Experimental proof of the microscopic nature of the NSOT.

Orthorhombic CuMnAs



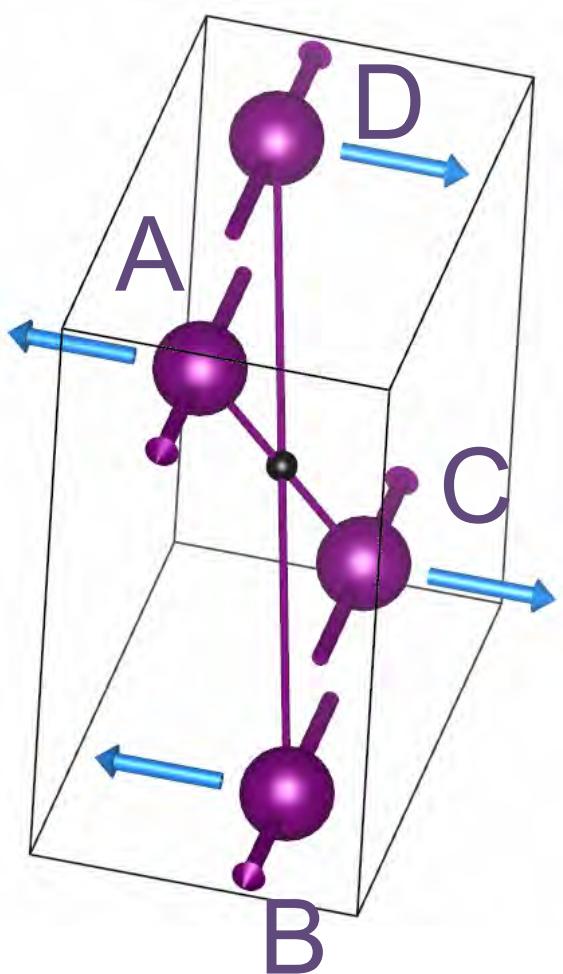
Pnma

PT → AFM 3D graphene

ELK, FLEUR FLAPW GGA+PBE+U: MAE at the resolution limit

Consistent with: *F.Máca, T.Jungwirth et al., JMMM (2012), P.Tang et al., NP (2016)* *Šmejkal et al., DPG Regensburg (2016)*

Neel spin-orbit torque in orthorhombic CuMnAs



PT+noncentrosymmetric → even
Nonsymmorphic symmetry

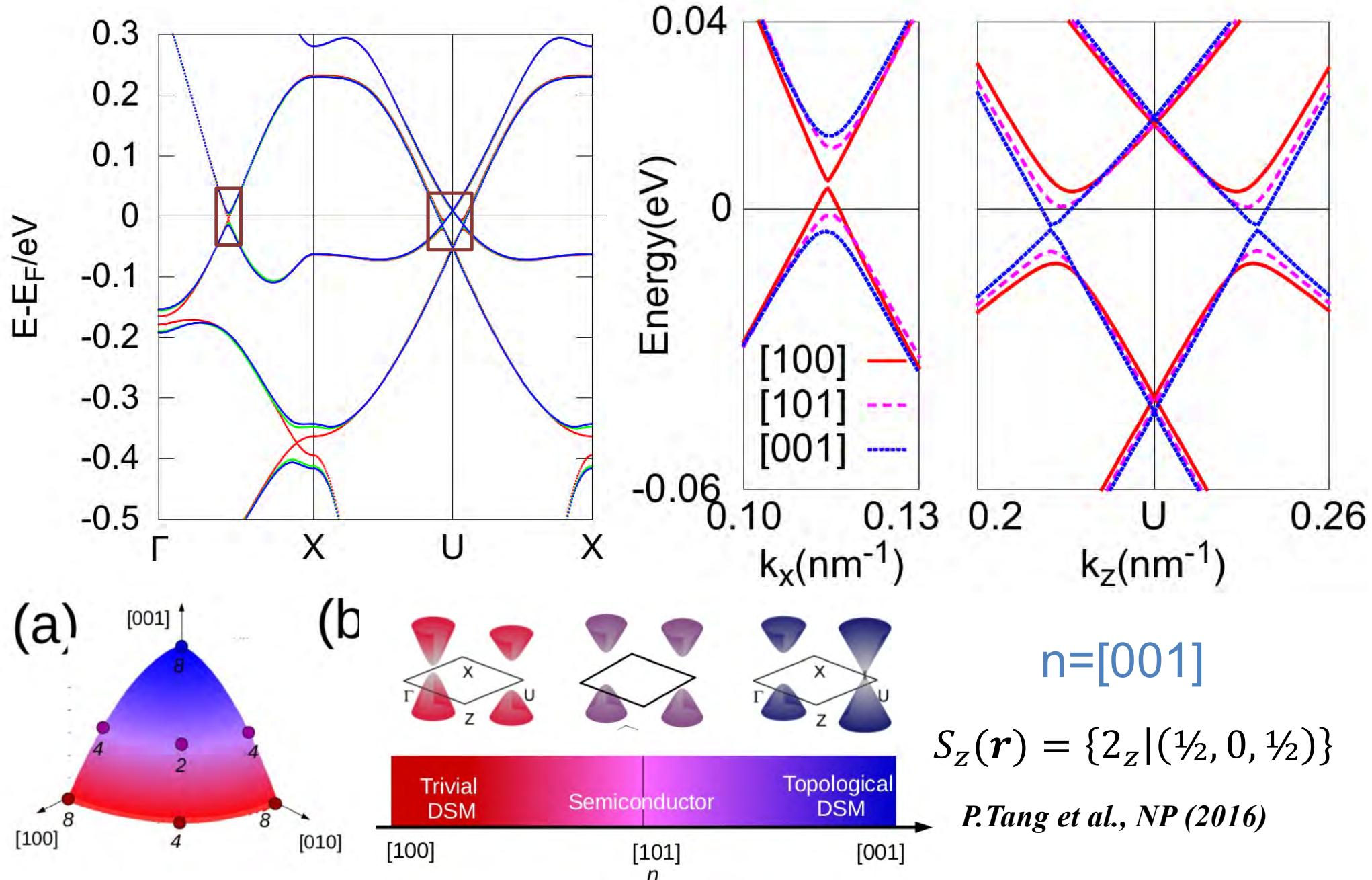
	(s_x, s_y, s_z)	(E_x, E_y, E_z)	δs_{EVEN}	$\chi(001), \chi[001],$
S_z	$(-s_x, -s_y, s_z)$	$(-E_x, -E_y, E_z)$	δs_{EVEN}	$\chi(\mathbf{001}), -\chi[\mathbf{001}]$

$$\chi_A^{(0)} = \begin{pmatrix} 0 & x_{12} & 0 \\ x_{21} & 0 & x_{23} \\ 0 & x_{32} & 0 \end{pmatrix} \quad \chi_B^{(0)} = \begin{pmatrix} 0 & x_{12} & 0 \\ x_{21} & 0 & -x_{23} \\ 0 & -x_{32} & 0 \end{pmatrix}$$

Higher orders for $n=[110]$

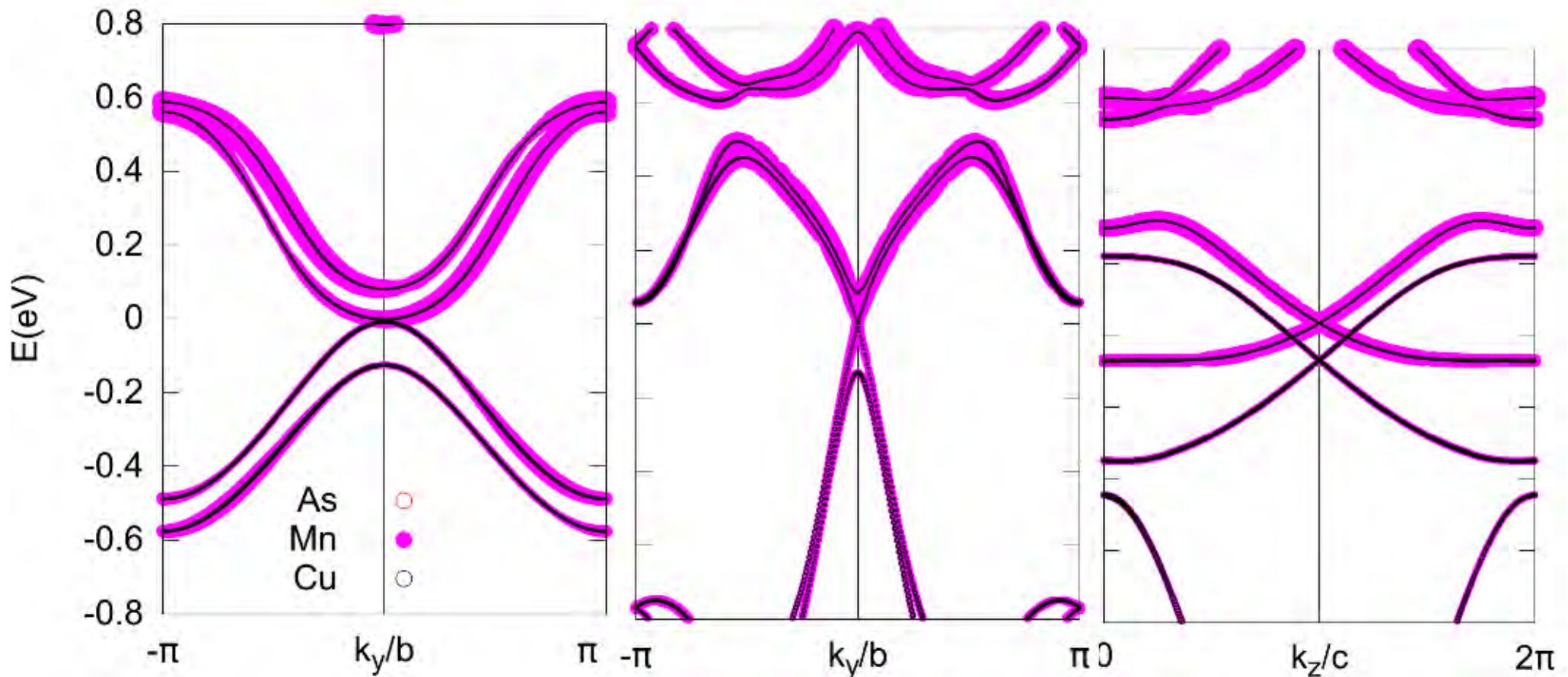
$$\chi_A^{(2)} = \begin{pmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{31} & x_{32} & x_{33} \end{pmatrix} \quad \chi_B^{(2)} = \begin{pmatrix} x_{11} & x_{12} & -x_{13} \\ x_{21} & x_{22} & -x_{23} \\ -x_{31} & -x_{32} & x_{33} \end{pmatrix}$$

Control of Dirac fermions and phase transition



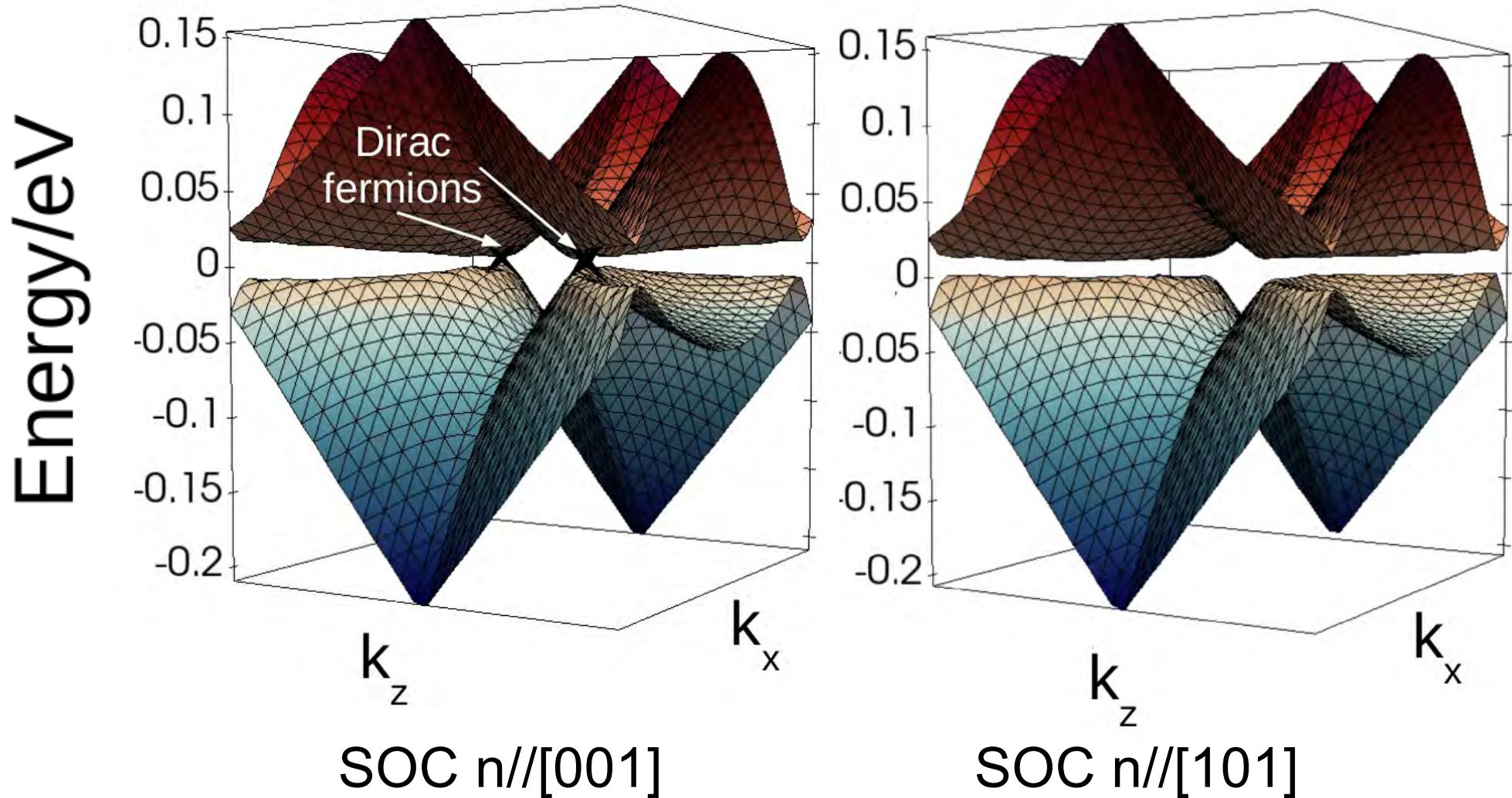
Orbital composition and anisotropic Dirac fermions

SOC n//[001]



$$v_F = 10^5 m/s$$

Topological AMR as a new signature of Dirac fermions



Topological AMR as a new signature of Dirac fermions

Bandstructure + scattering on (magnetic) disorder

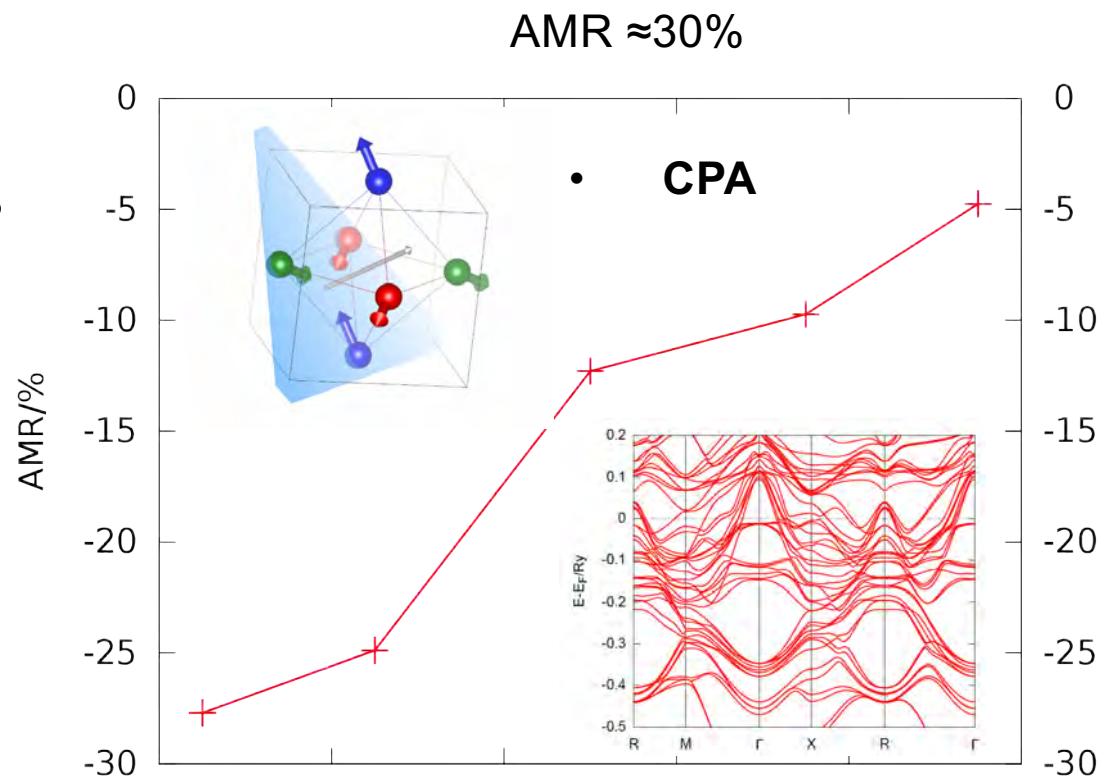
FM: NiMnSb, NiCo, ... 1-40 %

AFM: FeRh, Mn₂Au, collinear IrMn ... 0.1-5 %

NCAFM:

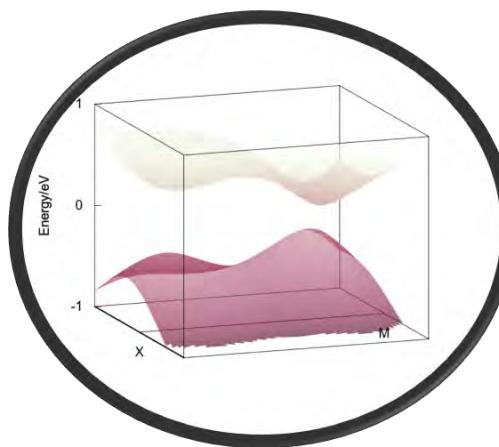
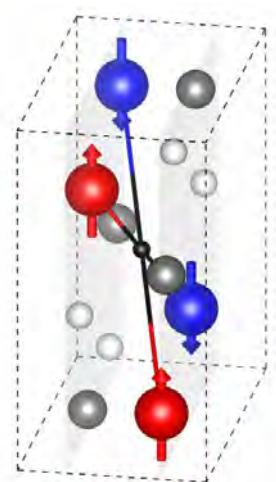
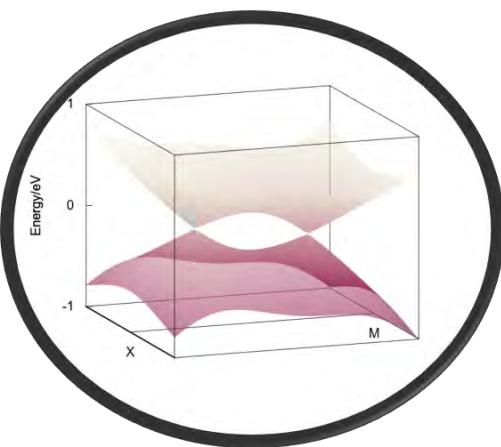
(Ir-derived)Mn₃ alloys

- ‘Decoupling symmetry and disorder’ (GMR)
- **Weyl fermions**



Summary

1. Prediction and classification of Dirac fermions in AFM
2. Electrical control of Dirac fermions
3. Control of electronic/topological phases
4. Topological AMR
5. Bandstructure engineering and the other candidates



Thank you for your attention!

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