New Perspectives in Spintronic and Mesoscopic Physics
at ISSP University of Tokyo 6/12/2015

Coupled charge and magnetization in a Weyl semimetal

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in collaboration with
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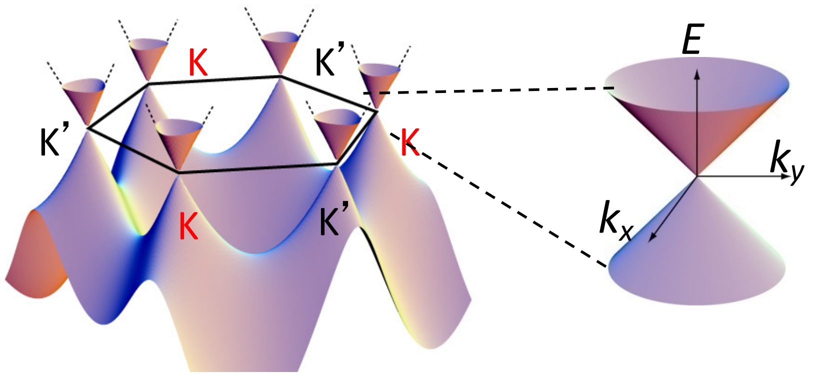
Coupled charge and magnetization in a Weyl semimetal

outline

Introduction: What is a Weyl semimetal
1. Weyl semimetal in a magnetic Topological insulator
2. Magnetization-dynamics-induced charge pumping
3. Charge-induced spin torque

What is a Weyl semimetal?

A Weyl semimetal is three-dimensional analogue of graphene



$$H^{2D} = v_F \begin{pmatrix} m_0 & p_x - ip_y \\ p_x + ip_y & -m_0 \end{pmatrix}$$

$$H^{3D} = v_F \begin{pmatrix} p_z & p_x - ip_y \\ p_x + ip_y & -p_z \end{pmatrix}$$

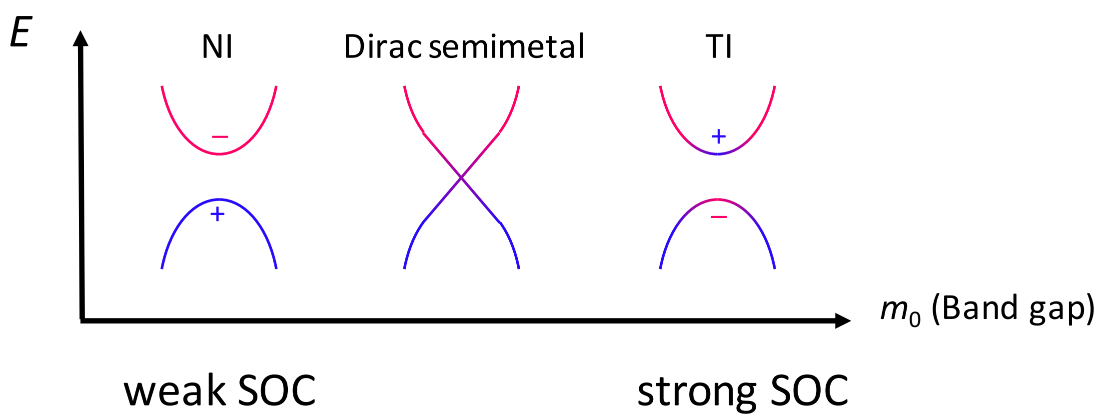
$m_0 = 0$ (for massless)

Dirac cone is stable in 3D

Topological states of matters

Spin-orbit coupling ➡ Topologically nontrivial states

Kane & Mele (2005)



- Topological insulators (gapped)
- Topological semimetals (gapless)

Dirac-Weyl semimetals

Dirac semimetals

degenerate

2D (graphene)

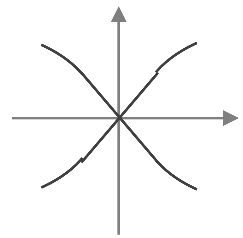
Wallace (1947), ...

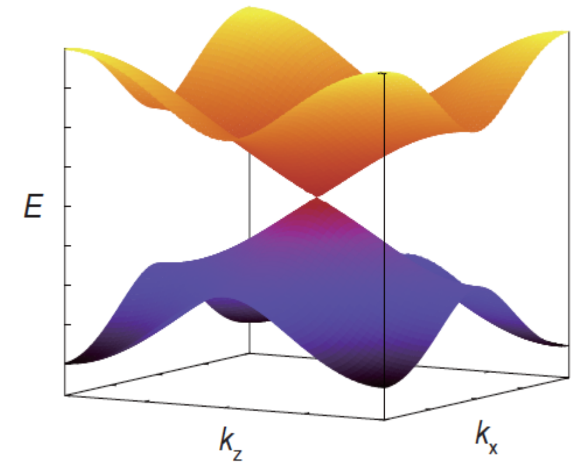
3D (accidental)

Herring (1937), ...

(symmetry protected)

Wang et al., Young et al.(2012),..





Weyl semimetals

non-degenerate

3D (I-symmetry broken)

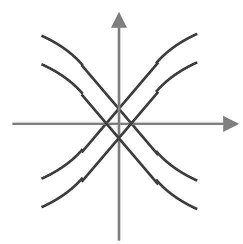
Murakami (2007)

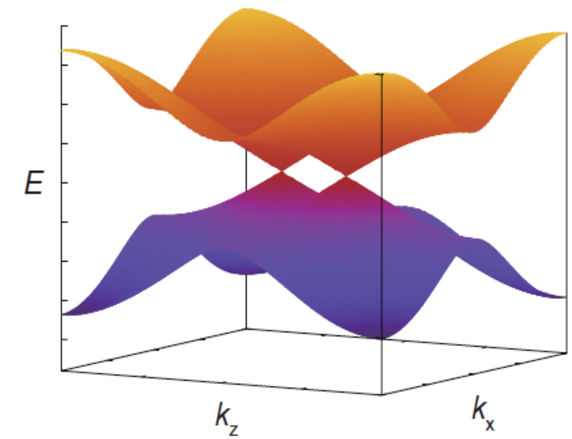
Halasz&Balents (2012), ..

3D (T-symmetry broken)

Wan et al. (2011)

Burkov&Balents (2012), ..





Dirac-Weyl semimetals

Dirac semimetals

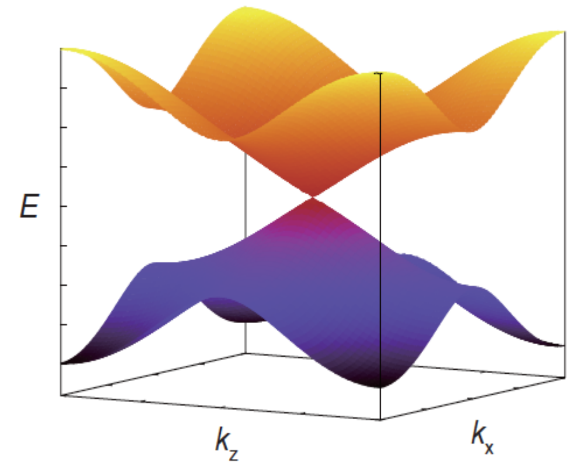
degenerate

$$H_{Dirac} = k_x\alpha_1 + k_y\alpha_2 + k_z\alpha_3 + m_0\alpha_4$$

m_0=0 (massless)

a_i: 4x4 Dirac matrix

$$\{\alpha_i, \alpha_j\} = 2\delta_{ij}$$

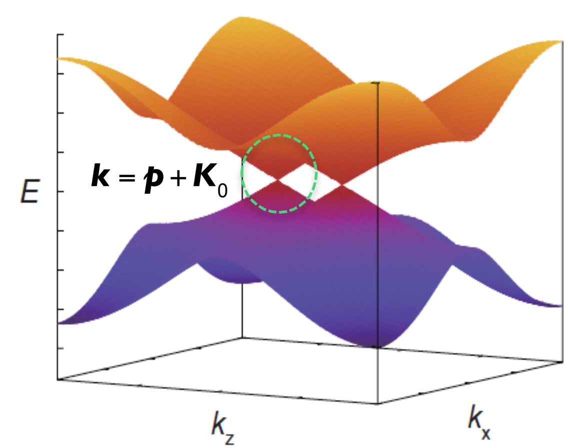


Weyl semimetals

non-degenerate

$$H_{Weyl} = p_x\sigma_1 + p_y\sigma_2 + p_z\sigma_3$$

s_i: 2x2 Pauli matrix

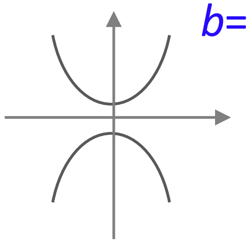


Symmetry breaking

Dirac hamiltonian

degenerate

$$H_{Dirac} = k_x\alpha_1 + k_y\alpha_2 + k_z\alpha_3 + m_0\alpha_4$$



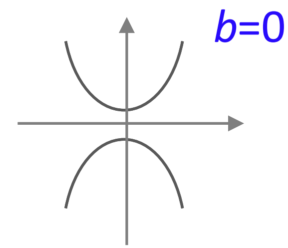
$$\begin{cases} \Theta^{-1}H_{Dirac}(\boldsymbol{k})\Theta = H_{Dirac}(-\boldsymbol{k}) & \text{T-symmetry} \\ \Pi^{-1}H_{Dirac}(\boldsymbol{k})\Pi = H_{Dirac}(-\boldsymbol{k}) & \text{I -symmetry} \end{cases}$$

$$\alpha_i = \begin{bmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{bmatrix}, \qquad \alpha_4 = \begin{bmatrix} I & 0 \\ 0 & -I \end{bmatrix}$$

Symmetry breaking

Dirac hamiltonian

degenerate



$$H_{Dirac} = k_x\alpha_1 + k_y\alpha_2 + k_z\alpha_3 + m_0\alpha_4 + bS_z$$

$$\begin{cases} \Theta^{-1}H_{Dirac}(\boldsymbol{k})\Theta \neq H_{Dirac}(-\boldsymbol{k}) & \text{T-symmetry} \\ \Pi^{-1}H_{Dirac}(\boldsymbol{k})\Pi = H_{Dirac}(-\boldsymbol{k}) & \text{I -symmetry} \end{cases}$$

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$$\Sigma_i = \begin{bmatrix} \sigma_i & 0 \\ 0 & \sigma_i \end{bmatrix}$$

spin of electrons

Symmetry breaking

Dirac hamiltonian

$$H_{Dirac} = k_x\alpha_1 + k_y\alpha_2 + k_z\alpha_3 + m_0\alpha_4 + bS_z$$

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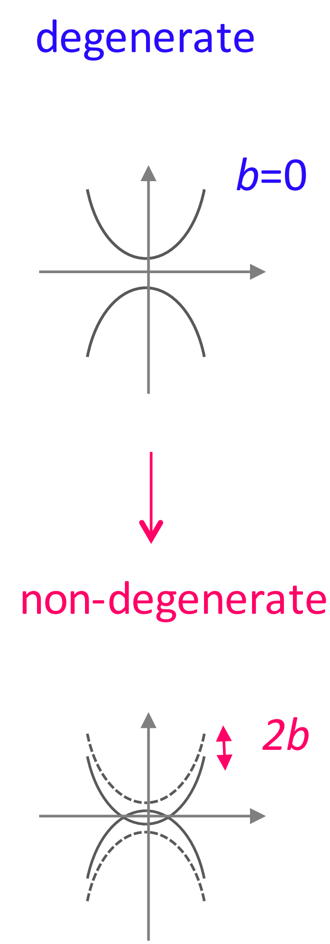
spin of electrons



Symmetry breaking

Dirac hamiltonian

$$H_{Dirac} = k_x\alpha_1 + k_y\alpha_2 + k_z\alpha_3 + m_0\alpha_4 + bS_z$$

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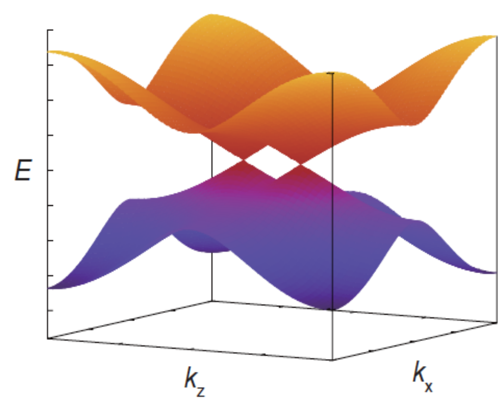
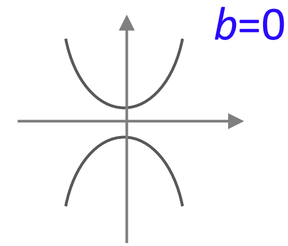
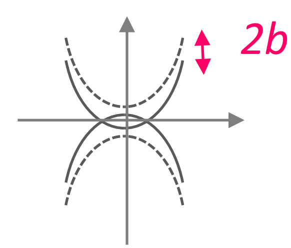
spin of electrons



degenerate



non-degenerate

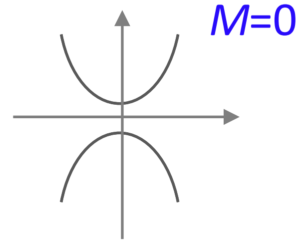


Symmetry breaking

Dirac hamiltonian

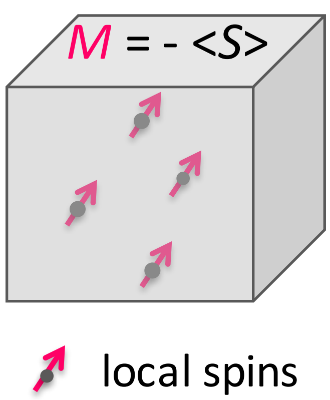
degenerate

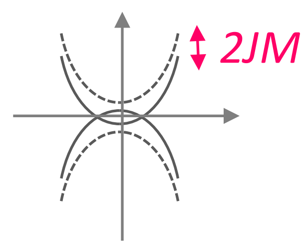
$$H_{Dirac} = k_x\alpha_1 + k_y\alpha_2 + k_z\alpha_3 + m_0\alpha_4 + JMS_z$$



$$H_{sd} = J\sum_{i=1}^{N_{imp}} \boldsymbol{S}(\boldsymbol{R}_i)\cdot\Sigma$$

non-degenerate



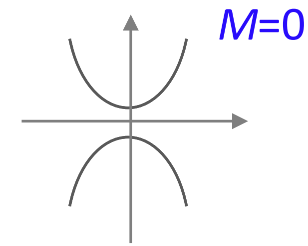


Symmetry breaking

Dirac hamiltonian

degenerate

$$H_{Dirac} = k_x\alpha_1 + k_y\alpha_2 + k_z\alpha_3 + m_0\alpha_4 + JMS_z$$



local spin ↓   electron spin ↓

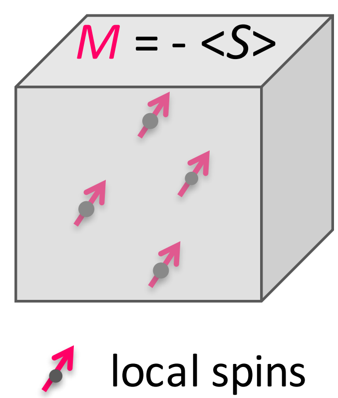
$$F = \frac{1}{2\chi_s}M^2 + \frac{1}{2\chi_e}m^2 - JMm$$

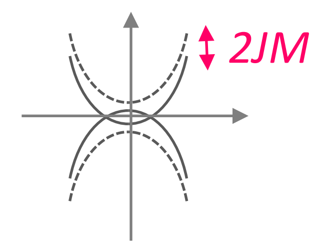
$$= \frac{1}{2\chi_s}\left(1 - J^2\chi_e\chi_s\right)M^2$$

$$+ \frac{1}{2\chi_e}\left(m - \chi_e JM\right)^2$$

$$H_{sd} = J\sum_{i=1}^{N_{imp}} \boldsymbol{S}(\boldsymbol{R}_i)\cdot\Sigma$$

non-degenerate





Symmetry breaking

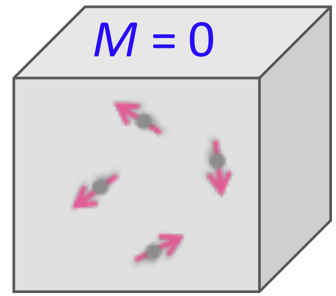
“Van Vleck ferromagnetism”

local spin $\downarrow$ electron spin $\downarrow$

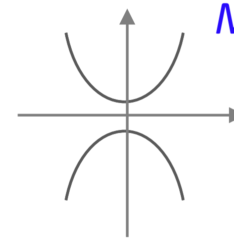
$$F = \frac{1}{2\chi_s} M^2 + \frac{1}{2\chi_e} m^2 - JMm$$

$$= \frac{1}{2\chi_s}\left(1 - J^2 \chi_e \chi_s\right) M^2 + \frac{1}{2\chi_e}\left(m - \chi_e J M\right)^2$$

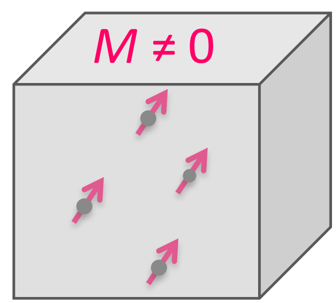
$1 - J^2 \chi_s \chi_e > 0$



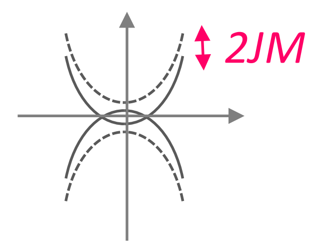
degenerate



$1 - J^2 \chi_s \chi_e < 0$



non-degenerate



local spins

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outline

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1. Weyl semimetal in a magnetic TI
2. Magnetization-dynamics-induced charge pumping
3. Charge-induced spin torque

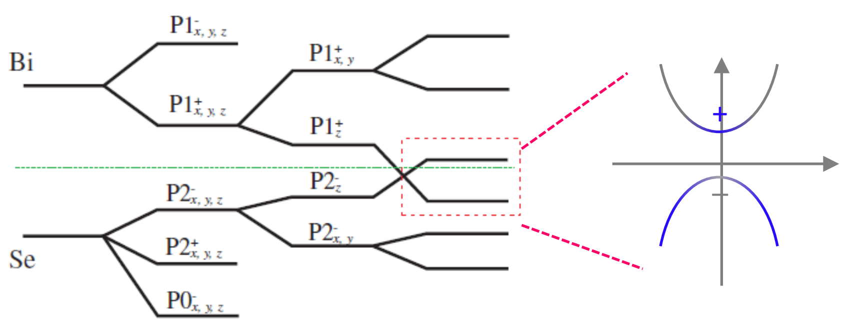
Self-consistent theory

Kurebayashi, KN
JPSJ 83 (2014) 063709.

$$H_{\mathrm{total}} = H_e^{\mathrm{MF}} + H_s^{\mathrm{MF}} - N_{imp} J\, Mm$$

Electrons

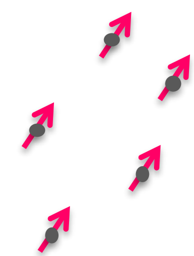
$$H_e^{MF} = \sum_{\boldsymbol{k}} c_{\boldsymbol{k}}^{+} \left[H_0(\boldsymbol{k}) + xJM\Sigma_z \right] c_{\boldsymbol{k}}$$



$$H_0(\boldsymbol{k}) = \sum_{i=1}^{3} R_i(\boldsymbol{k})\alpha_i + m_0(\boldsymbol{k})\alpha_4 + \varepsilon(\boldsymbol{k}) I$$

local spins

$$H_S^{MF} = Jm \sum_{l=1}^{N_{imp}} S_z(\boldsymbol{r}_l)$$



local spins

Virtual crystal approximation

Self-consistent theory

Kurebayashi, KN
JPSJ 83 (2014) 063709.

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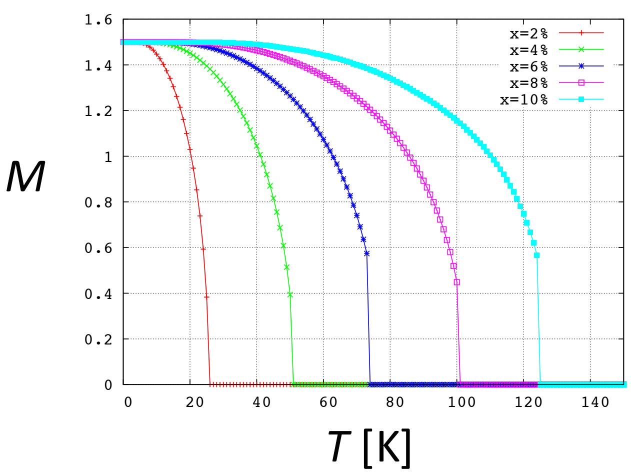
Electrons

$$H_e^{MF} = \sum_{\boldsymbol{k}} c_{\boldsymbol{k}}^{+}\left[H_0(\boldsymbol{k}) + xJM\Sigma_z\right]c_{\boldsymbol{k}}$$

local spins

$$H_S^{MF} = Jm \sum_{l=1}^{N_{imp}} S_z(\boldsymbol{r}_l)$$



$$m = \frac{1}{N}\sum_{i=1}^{N}\langle c_i^{+}\Sigma_z c_i\rangle, \qquad M = \frac{1}{N_i}\sum_{l=1}^{N_{imp}}\langle S_z(\vec{R}_l)\rangle$$

Virtual crystal approximation

Self-consistent theory

Kurebayashi, KN
JPSJ 83 (2014) 063709.

$$H_{\text{total}} = H_e^{\text{MF}} + H_s^{\text{MF}} - N_{imp} J\, Mm$$

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local spins

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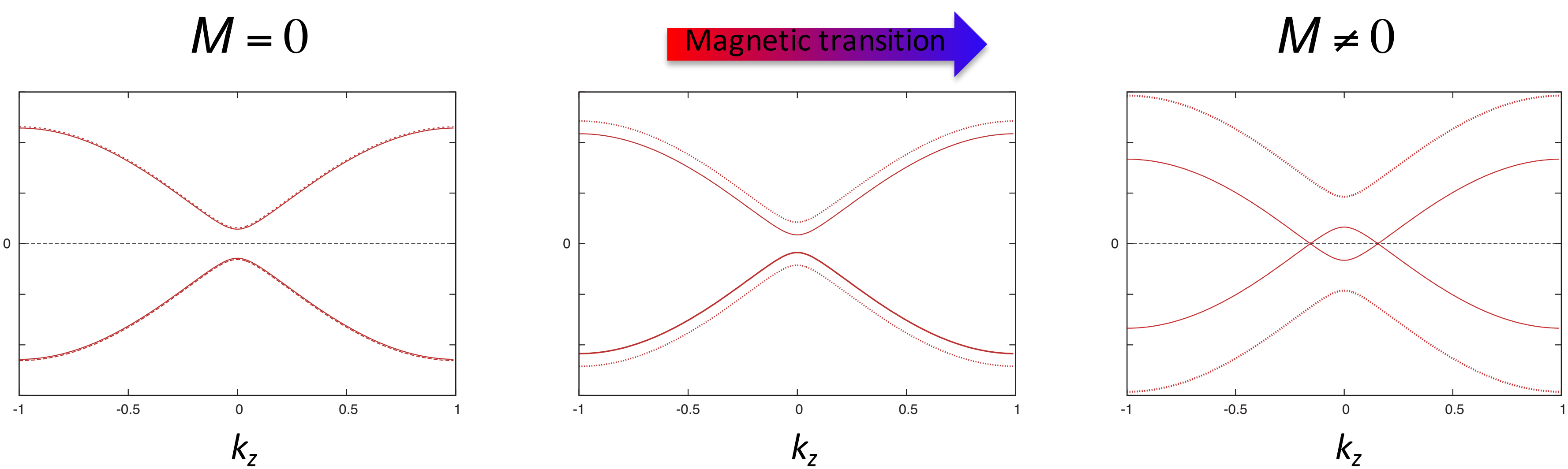
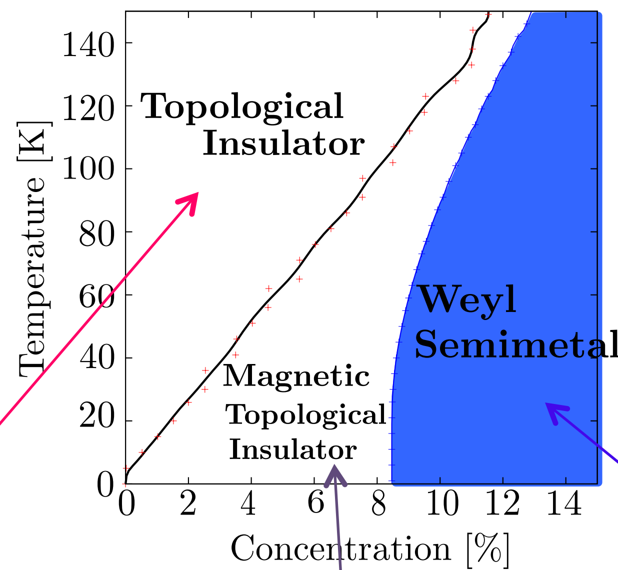
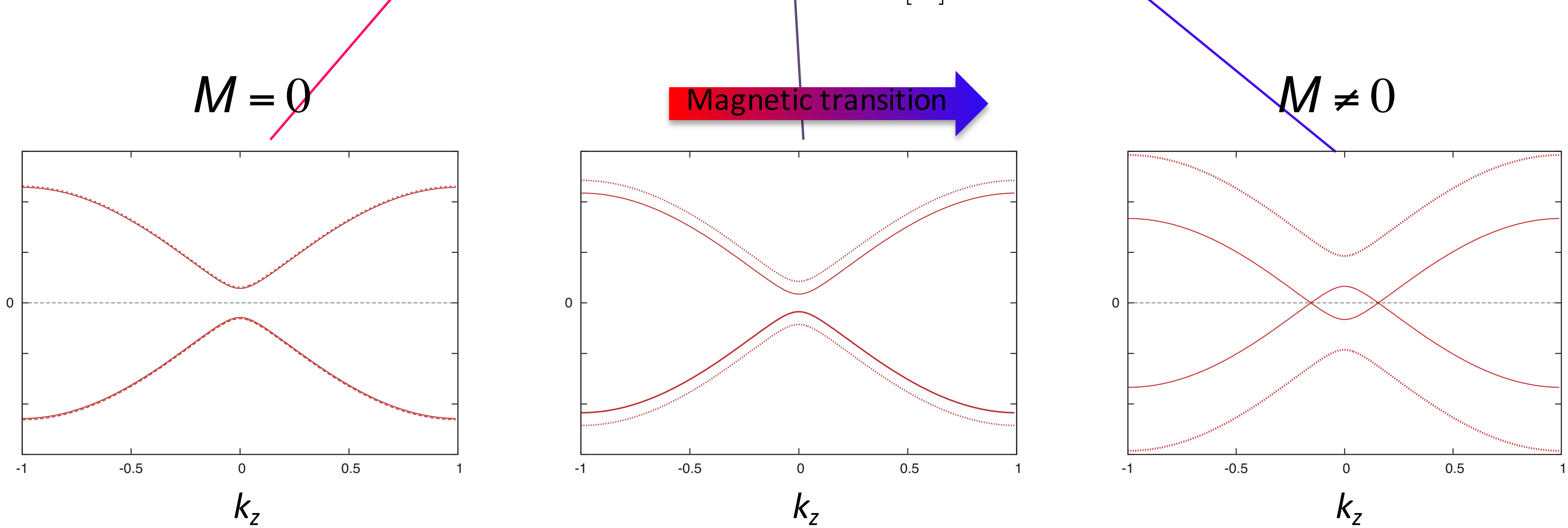


Weyl semimetal in a magnetic TI

Kurebayashi, KN
JPSJ 83 (2014) 063709.

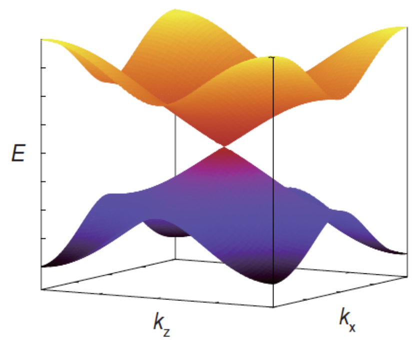


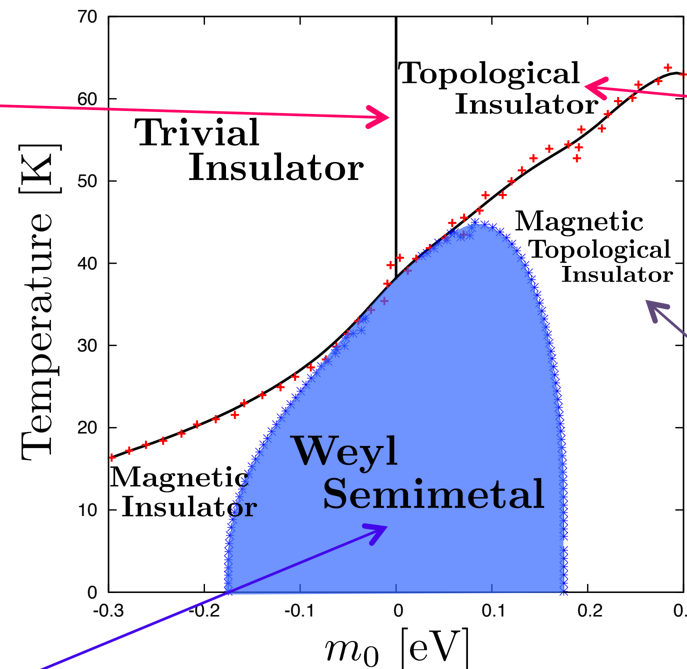


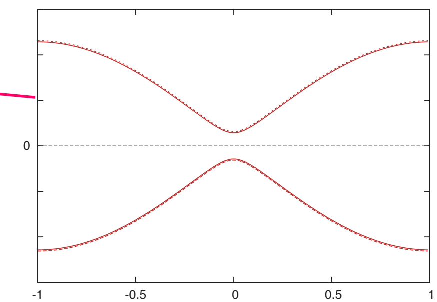
Phase diagram

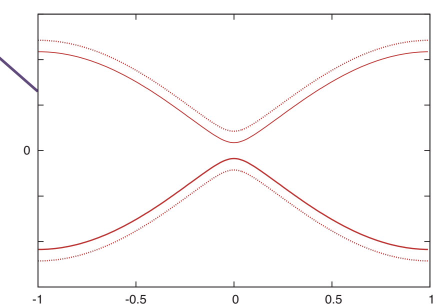
Kurebayashi, KN
JPSJ 83 (2014) 063709.

Dirac semimetals

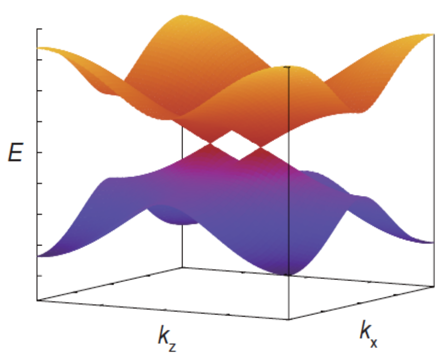








Weyl semimetals



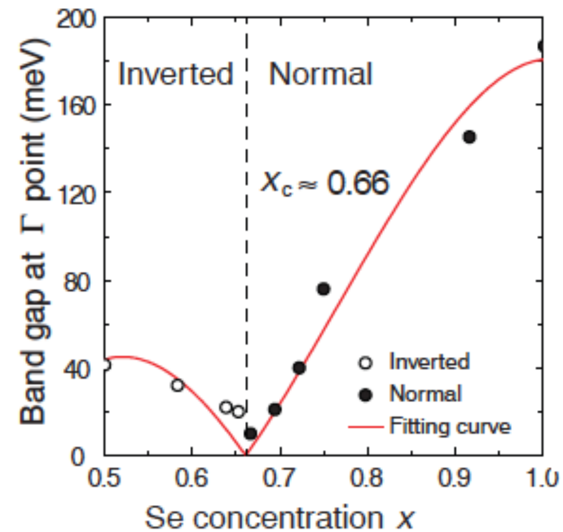
weak SOC ⟷ strong SOC

Experiments of magnetic TIs

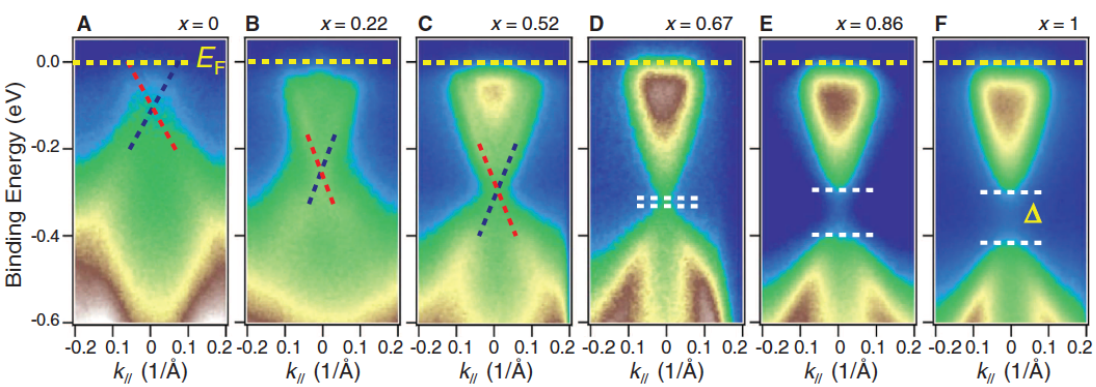
Science 339, 1582 (2013)

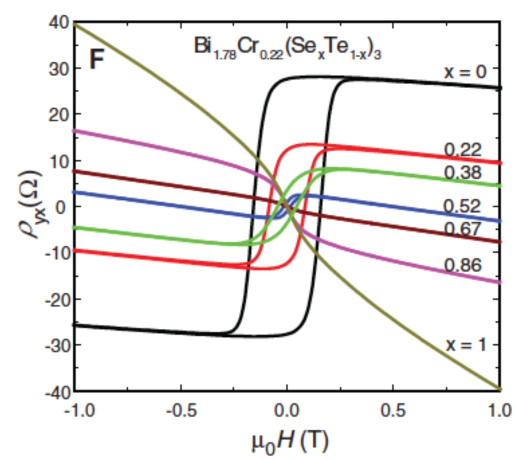
Topology-Driven Magnetic Quantum Phase Transition in Topological Insulators

Jinsong Zhang,[1*] Cui-Zu Chang,[1,2*] Peizhe Tang,[1*] Zuocheng Zhang,[1] Xiao Feng,[2] Kang Li,[2] Li-li Wang,[2] Xi Chen,[1] Chaoxing Liu,[3] Wenhui Duan,[1] Ke He,[2†] Qi-Kun Xue,[1,2] Xucun Ma,[2] Yayu Wang[1†]



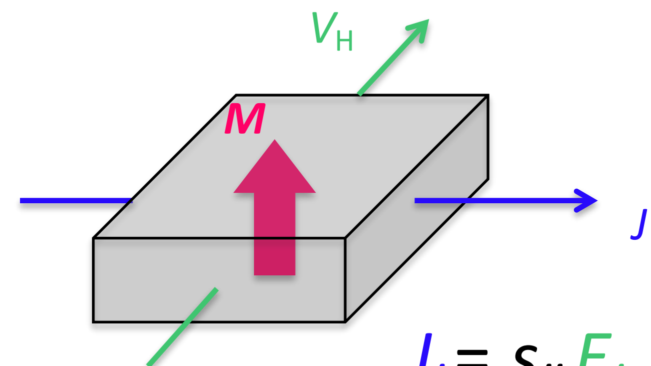
$Bi_{2-y}Cr_y(Se_x\ Te_{1-x})_3$





Anomalous Hall effect

The Hall effect in materials with
- ferromagnetic order
- spin-orbit coupling

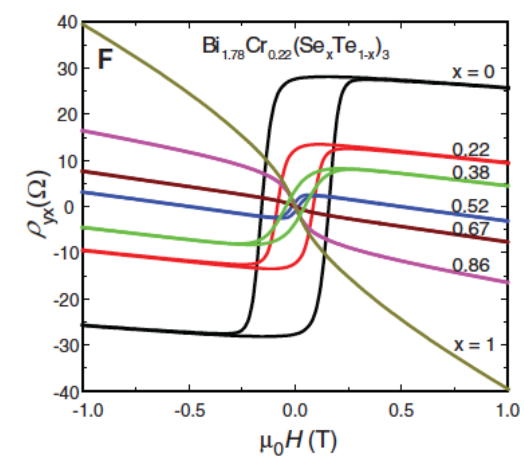


$$J_i = s_{ij} E_j$$

$$\rho_{xy} = R_0 B + R_s M$$

$$\rho_{xy} \propto M \quad (B \to 0)$$

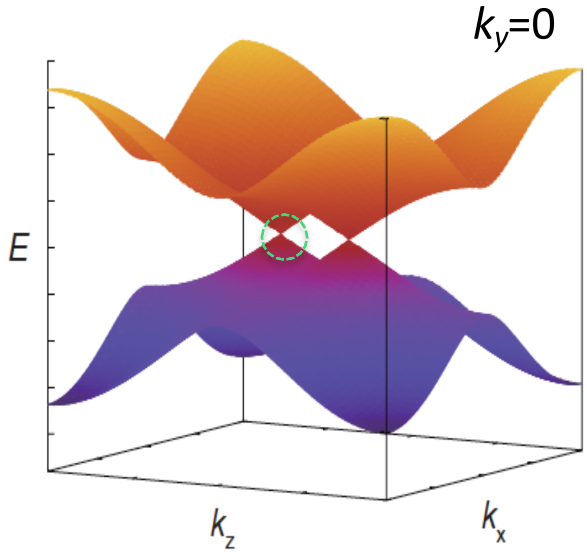
$Bi_{2-y}Cr_y(Se_x\ Te_{1-x})_3$

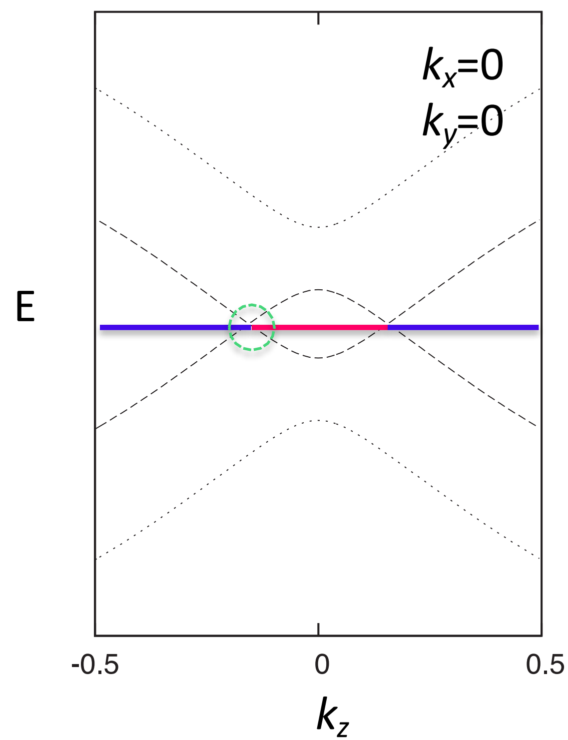


Anomalous Hall effect

$$H_{weyl}(k_x, k_y, k_z) = k_x s_1 + k_y s_2 + D_m(k_z) s_3$$

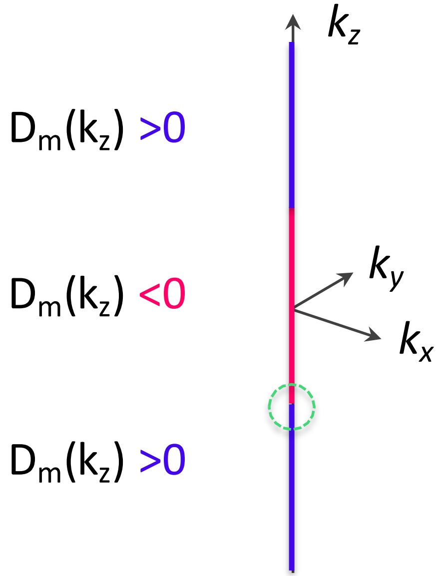
3d Weyl SM

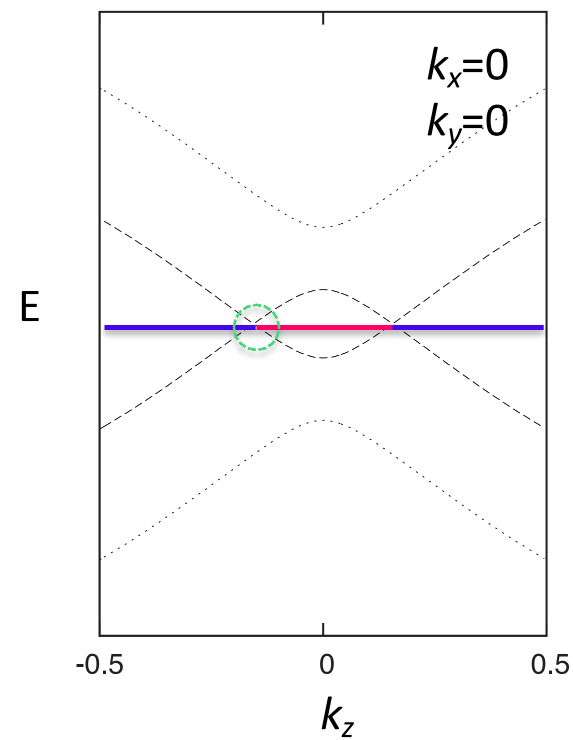




Anomalous Hall effect

$$H_{weyl}(k_x,k_y,k_z) = k_x s_1 + k_y s_2 + D_m(k_z) s_3$$

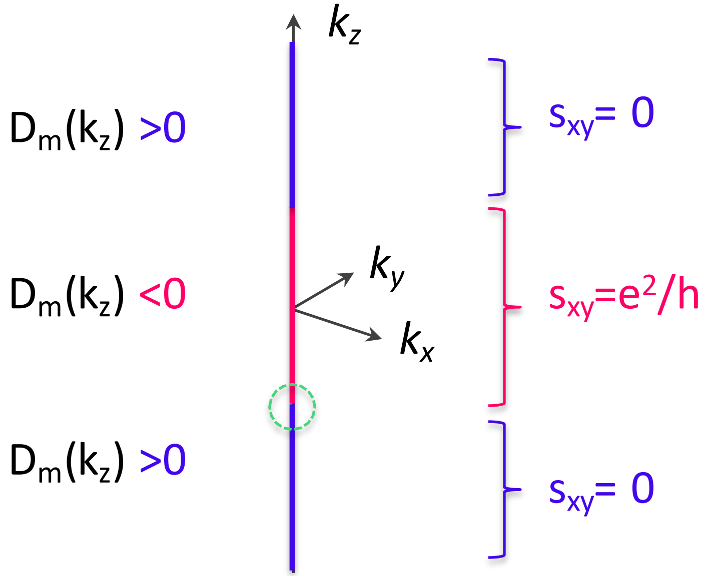




Anomalous Hall effect

$$H_{weyl}(k_x,k_y,k_z) = k_x s_1 + k_y s_2 + D_m(k_z) s_3$$

$$\sigma_{xy}^{2D}(k_z) = \frac{e^2}{2h}[1 - \mathrm{sgn}(\Delta_m(k_z))]$$



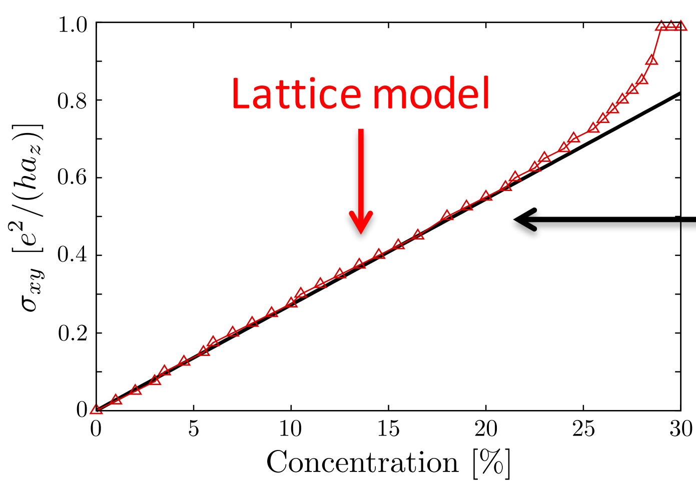
$$\sigma_{xy}^{3D} = \int \frac{dk_z}{2\pi} \sigma_{xy}^{2D}(k_z)$$

$$= \frac{e^2}{2\pi h} 2K_{Weyl}$$

Anomalous Hall effect

$$H_{weyl}(k_x, k_y, k_z) = k_x s_1 + k_y s_2 + D_m(k_z) s_3$$

$$\sigma_{xy}^{2D}(k_z) = \frac{e^2}{2h}[1 - \mathrm{sgn}(\Delta_m(k_z))]$$



$$\sigma_{xy}^{3D} = \int \frac{dk_z}{2\pi} \sigma_{xy}^{2D}(k_z)$$

$$= \frac{e^2}{2\pi h} 2K_{Weyl}$$

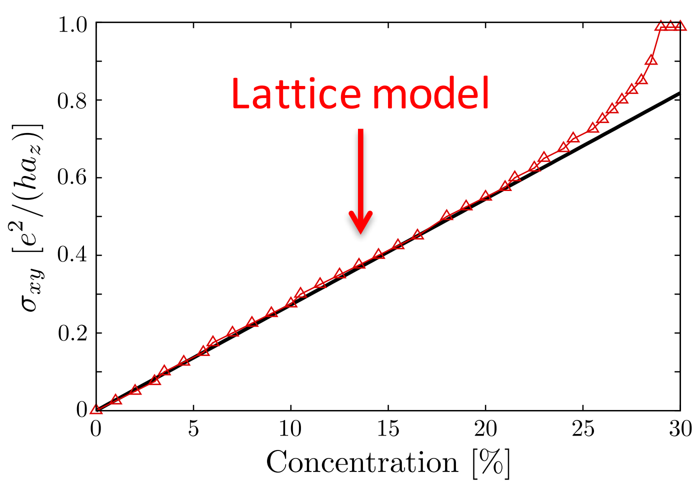
$2JM$

Kubo formula by D. Kurebayashi

Remarks

Magnetic order in TI as “Van Vleck ferromagnetism”.

Weyl semimetal can be realized in magnetic TIs.
(Cr-doped $Bi_2(Se_xTe_{1-x})_3$)
Anomalous Hall effect is a signature of the Weyl semimetal.



Kubo formula by D. Kurebayashi