KEK連携コロキウム･研究会エディション
「量子多体系の素核･物性クロスオーバー」
1.15 .2019

ワイル半金属における軸性アノマリーと磁化ダイナミクス

Kentaro Nomura
(IMR, Tohoku University)

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ワイル半金属における
軸性アノマリーと磁化ダイナミクス

Collaborators

Daichi Kurebayashi
(RIKEN)

Yasu Araki
(JAEA)

Outline

- Introduction – Spintronics and Weyl fermions
- Chiral anomaly and magnetization dynamics
- Axial Hall effect and domain-wall dynamics

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- Introduction – Spintronics and Weyl fermions
- Chiral anomaly and magnetization dynamics
- Axial Hall effect and domain-wall dynamics

Spintronics

Main purpose:

Electrical control of spin magnetization

Spintronics

Topological materials for spintronics

↓

- ✓ Robust against perturbations
- ✓ Less-dissipation devices
- ✓ Strong spin-orbit coupling

What is a Weyl semimetal?

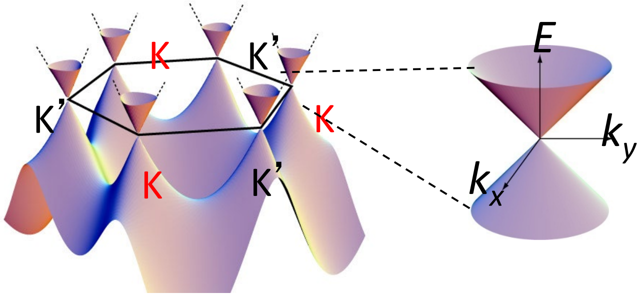
3-dimensional analogue of graphene

2D (Graphene)

$$H^{2D} = p_x\sigma_x + p_y\sigma_y$$

$$E(p) = \pm v_F\sqrt{p_x^2 + p_y^2}$$

Wallace (1947)



3D (Weyl semimetal)

$$H^{3D} = p_x\sigma_x + p_y\sigma_y + p_z\sigma_z$$

$$E(p) = \pm v_F\sqrt{p_x^2 + p_y^2 + p_z^2}$$

Murakami (2007)
Wan et al. (2011)
Burkov&Balents (2012)
Halasz&Balents (2012)
....

What is a Weyl semimetal?

3-dimensional analogue of graphene

2D (Graphene)

$$H^{2D} = p_x\sigma_x + p_y\sigma_y$$

σ_i : pseudo-spin

sublattice degrees of freedom

(Weak SOC)

3D (Weyl semimetal)

$$H^{3D} = p_x\sigma_x + p_y\sigma_y + p_z\sigma_z$$

σ_i : real-spin

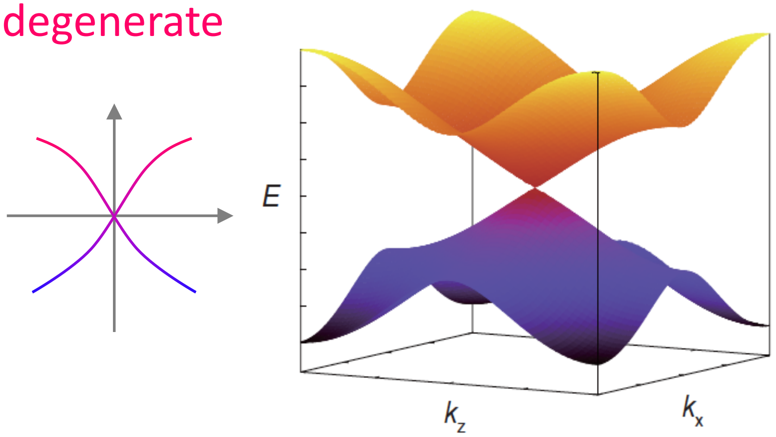
magnetic degrees of freedom

(Strong SOC)

Dirac-Weyl semimetals

- Dirac semimetals

degenerate

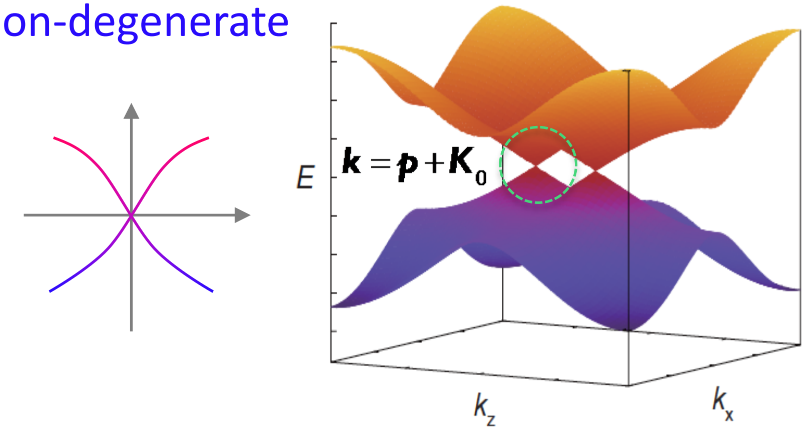


$$H = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3$$

α_i : 4x4 Dirac matrix

- Weyl semimetals

non-degenerate



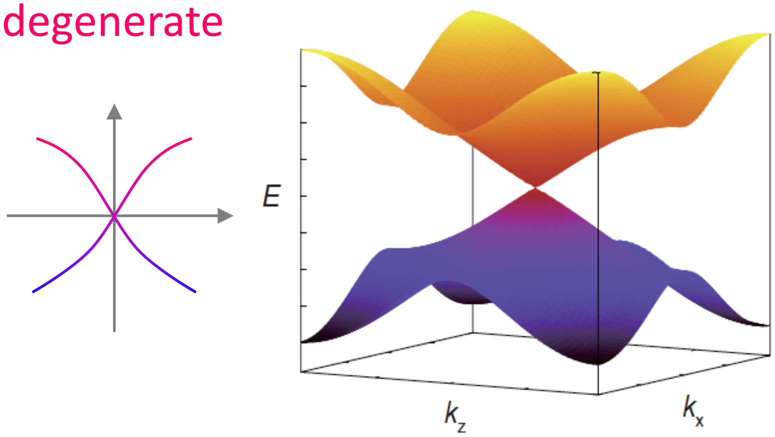
$$H = p_x\sigma_1 + p_y\sigma_2 + p_z\sigma_3$$

σ_i : 2x2 Pauli matrix

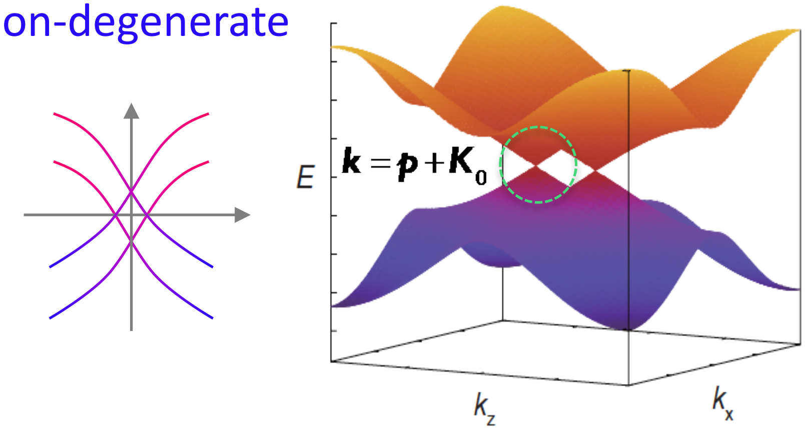
Dirac-Weyl semimetals

- Dirac semimetals
- Weyl semimetals

degenerate



non-degenerate



$H = p_x\alpha_1 + p$ … $_1 + p_y\sigma_2 + p_z\sigma_3$

Breaking of

- Inversion symmetry
- Time-reversal symmetry

α_i : 4x … σ_i : 2x2 Pauli matrix

Weyl semimetals

Weyl semimetals

with broken inversion sym.

TaAs, TaP, NbAs, NbP

(Non-magnetic)

Weyl semimetals

with broken time-reversal sym.

$A_2Ir_2O_7$

Magnetically doped TI

Mn_3Sn, $Co_3Sn_2S_2$

(magnetic)

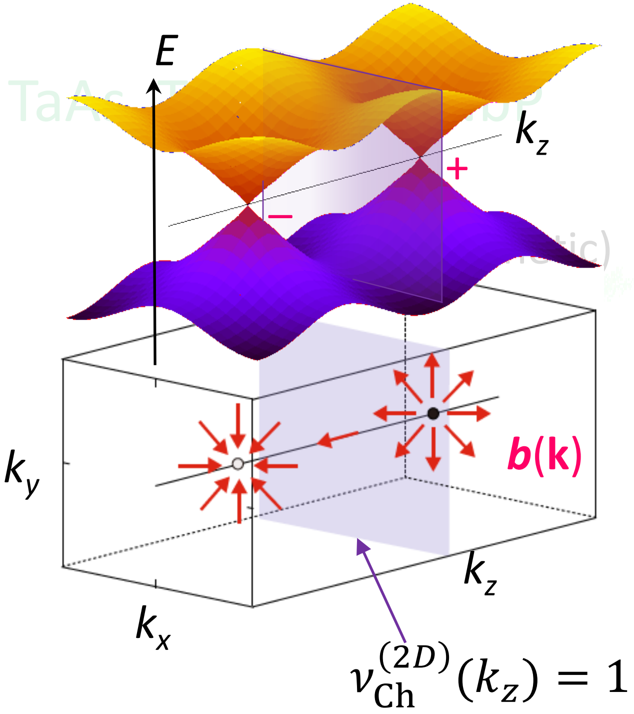
Breaking of

- Inversion symmetry
- Time-reversal symmetry

Weyl semimetals

Weyl semimetals

with broken inversion sym.



Weyl semimetals

with broken time-reversal sym.

$A_2Ir_2O_7$

Magnetically doped TI

Mn_3Sn, $Co_3Sn_2S_2$

(magnetic)

$\boldsymbol{b}(\boldsymbol{k})$: Berry curvature

Weyl points = “magnetic monopoles”

$$\sigma_{xy}^{\mathrm{AHE}} = \frac{e^2}{4\pi^2\hbar}\Delta K_z$$

Weyl semimetals

Weyl semimetals

with broken inversion sym.

TaAs, TaP, NbAs, NbP

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Weyl semimetals

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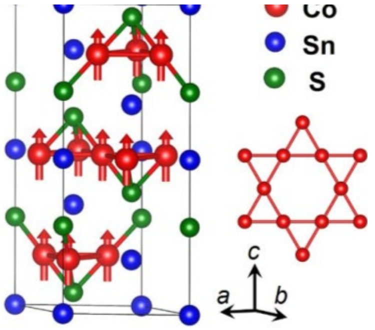
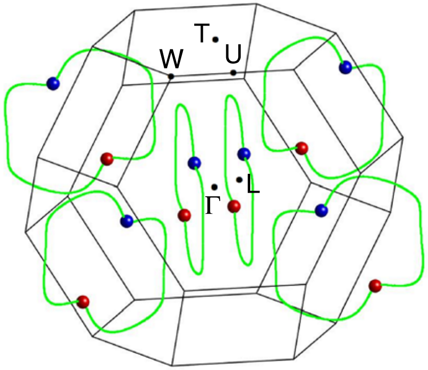
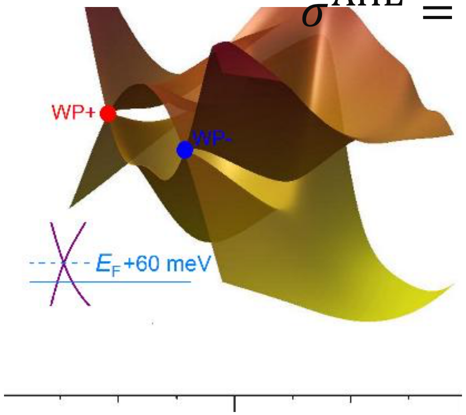
$Co_3Sn_2S_2$



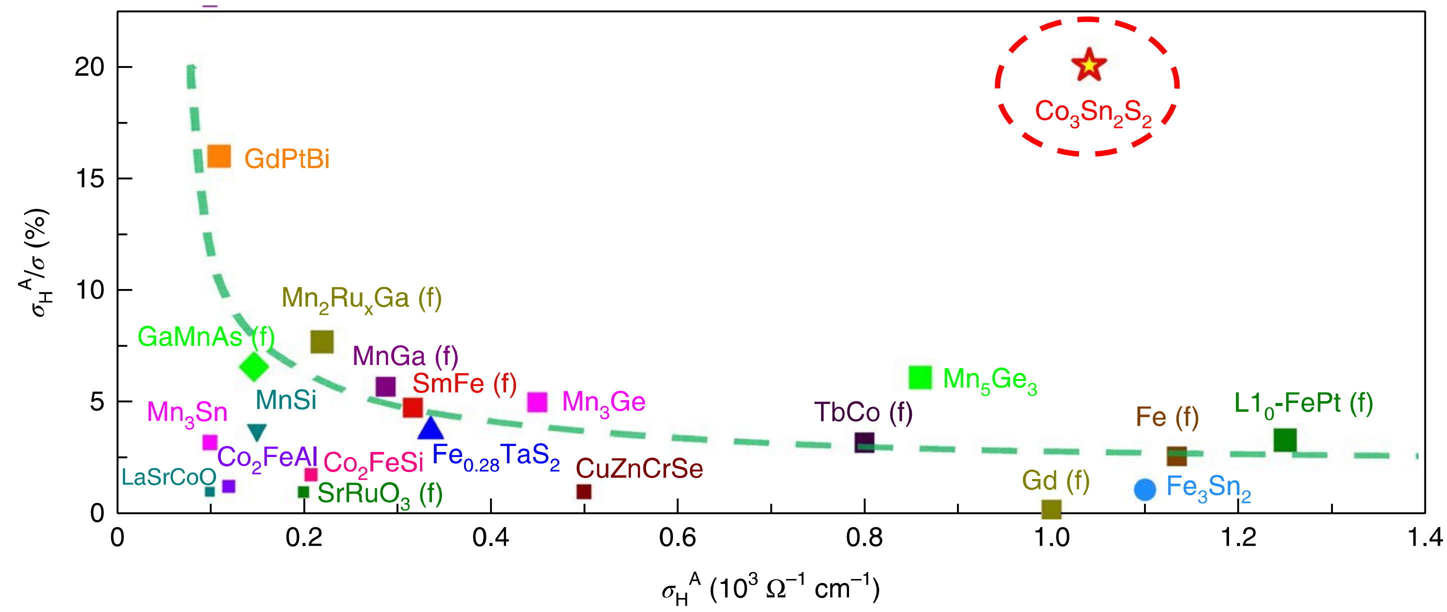


$$\sigma^{\text{AHE}} = \frac{e^2}{4\pi^2\hbar}\Delta Q$$

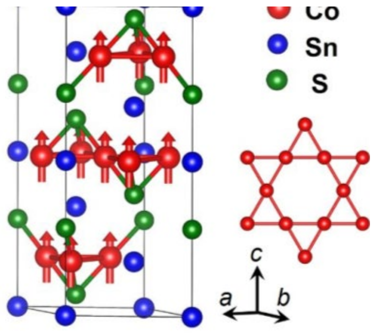


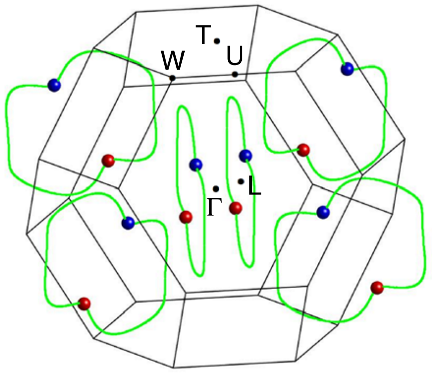
Liu et al. (2018)

Weyl semimetals



$Co_3Sn_2S_2$





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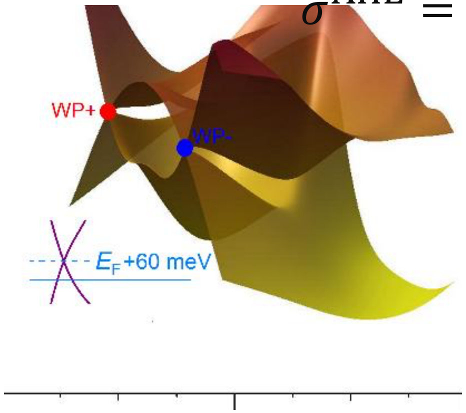
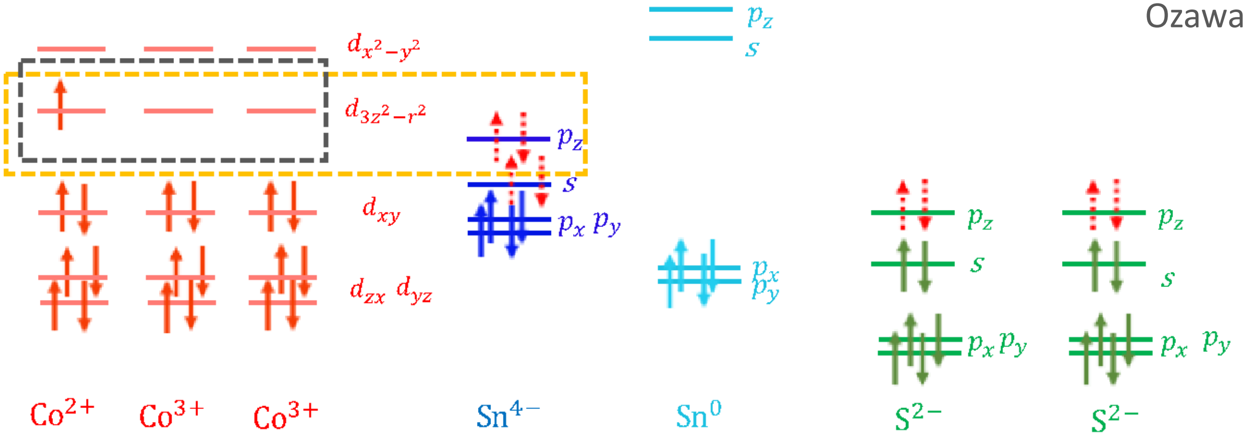


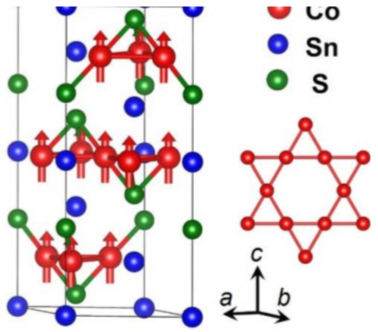
Liu et al. (2018)

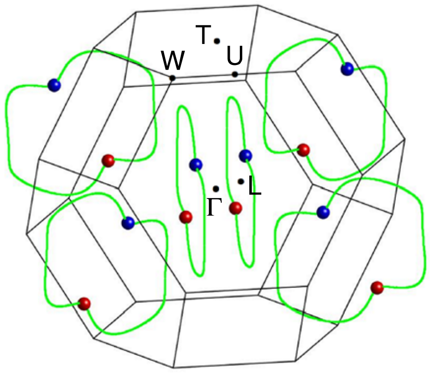
Weyl semimetals

Ozawa, KN. (2018)



$Co_3Sn_2S_2$





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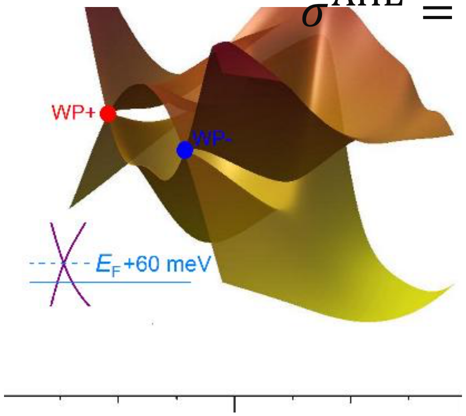

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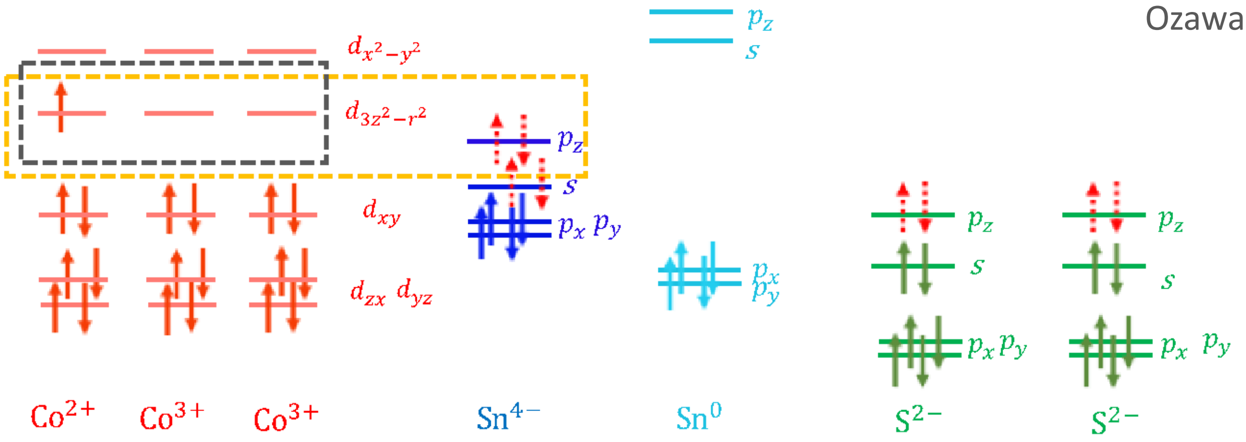
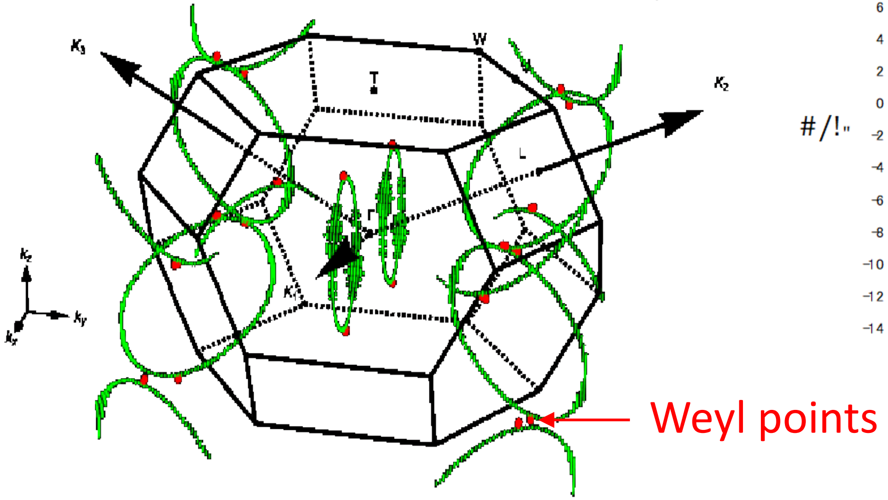
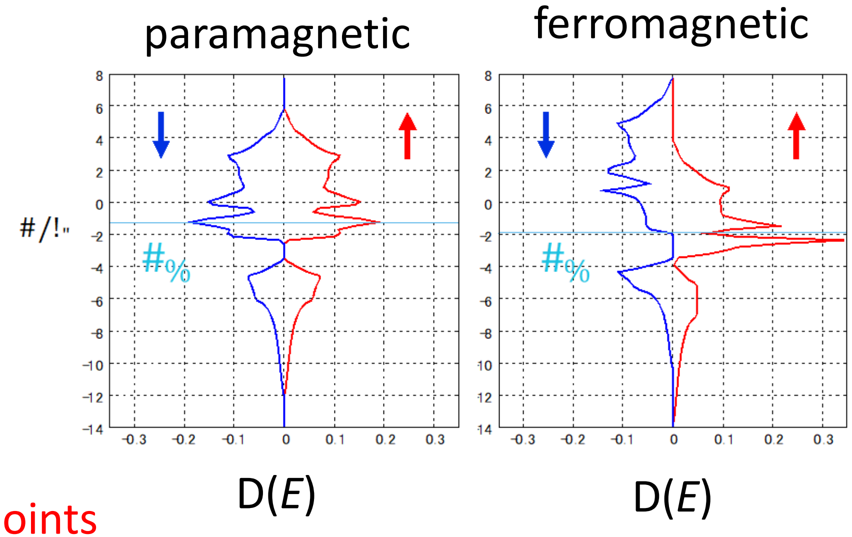


$H = H_{dp} + H_{exc} + H_{so} + H_U$

momentum space



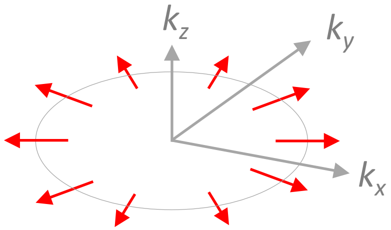


Types of spin-orbit coupling

Weyl-type

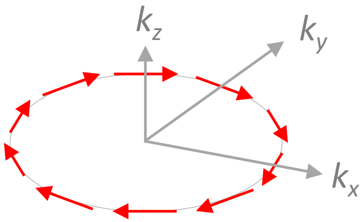
$$k_x\sigma_x\tau_z + k_y\sigma_y\tau_z + k_z\sigma_z\tau_z$$

σ: spin



Rashba-type

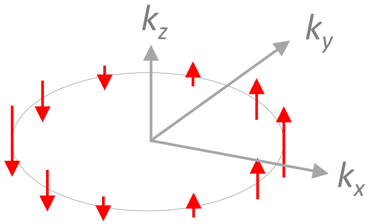
$$k_x\sigma_y\tau_x - k_y\sigma_x\tau_x + k_z\tau_y$$



Topological insulator
(Bi_2Se_3, Bi_2Te_3, etc)

BHZ-type

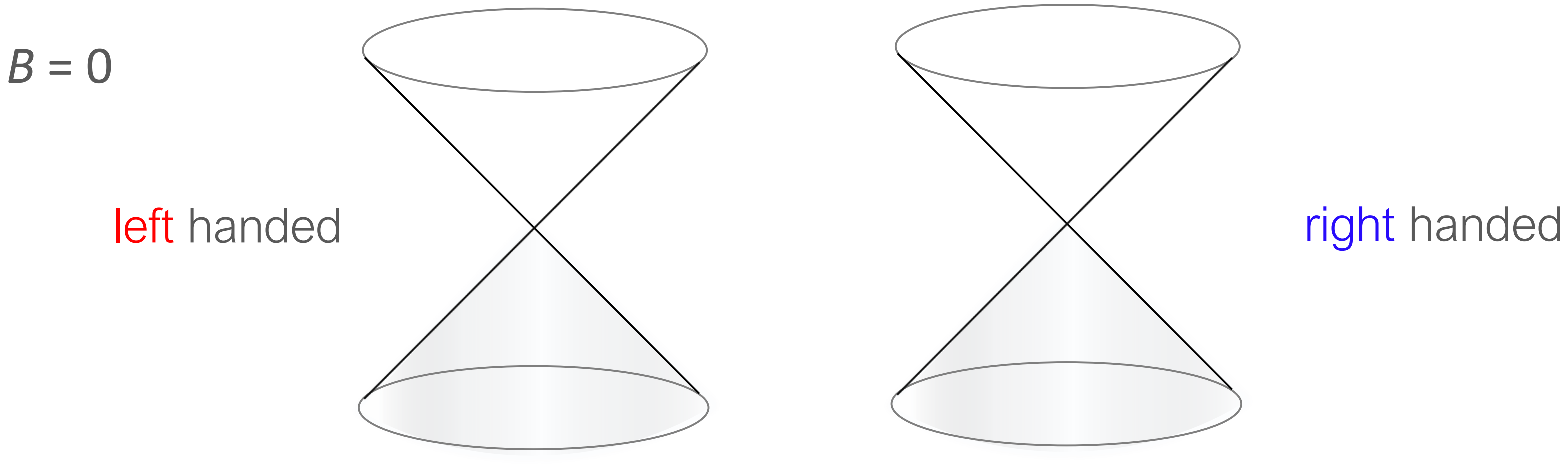
$$k_x\sigma_z\tau_x - k_y\tau_y + k_z\tau_z$$



HgTe/CdTe, Cd_3As_2 , $Co_3Sn_2S_2$

Chiral anomaly

Chiral anomaly

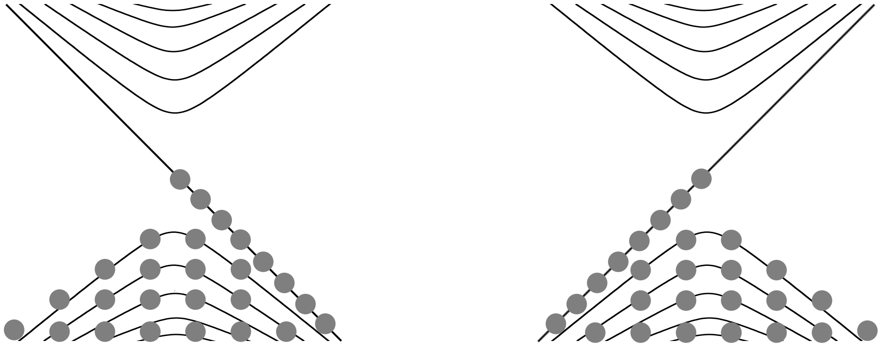


$$H = \begin{pmatrix} H_R & 0 \\ 0 & H_L \end{pmatrix}$$

$$H_L = -\boldsymbol{\sigma} \cdot (\boldsymbol{p} + e\boldsymbol{A} + J\boldsymbol{M}) \qquad H_R = +\boldsymbol{\sigma} \cdot (\boldsymbol{p} + e\boldsymbol{A} - J\boldsymbol{M})$$

Chiral anomaly

$B \neq 0$



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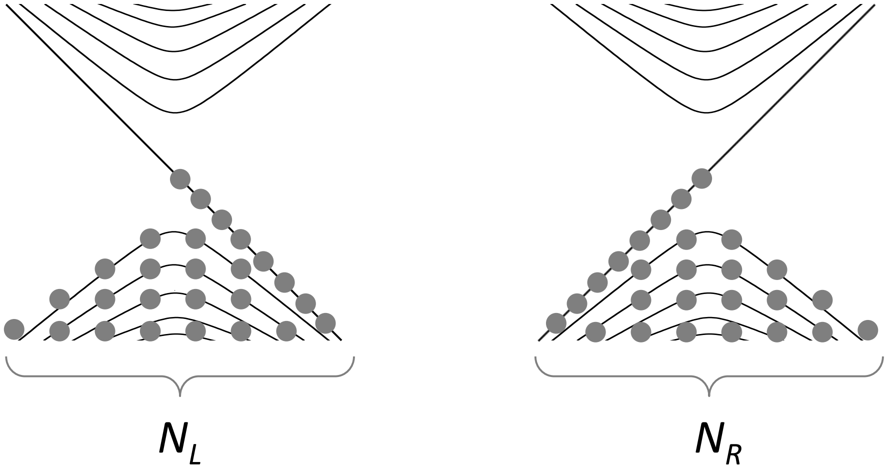


$$n_\Phi = \frac{BL_xL_y}{\phi_0}$$

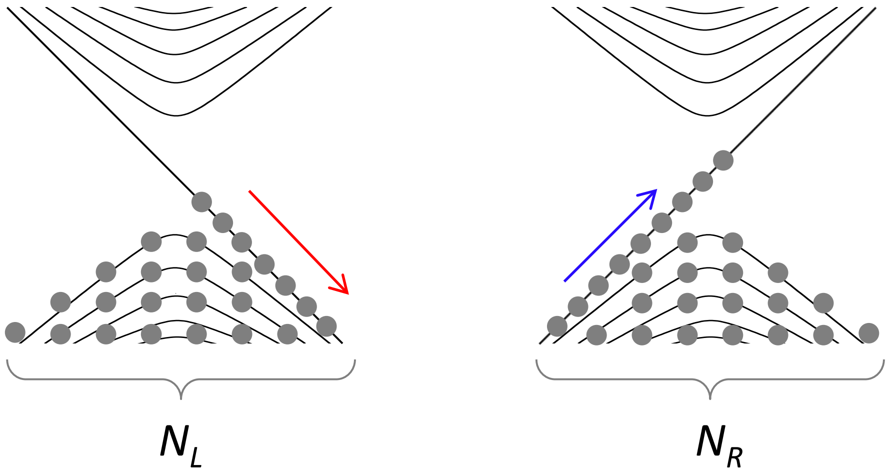
Landau level degeneracy

Chiral anomaly

$B \neq 0$

$E \neq 0$

$\dot{k} = eE$



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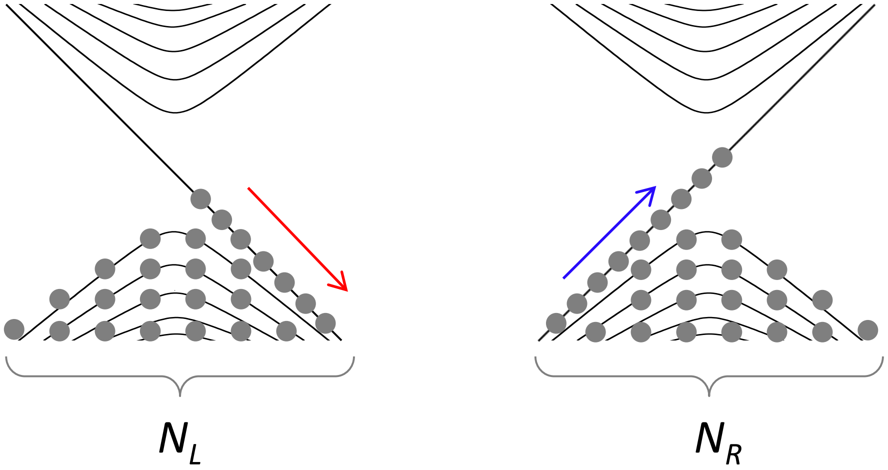


$$n_\Phi = \frac{BL_xL_y}{\phi_0}$$

Landau level degeneracy

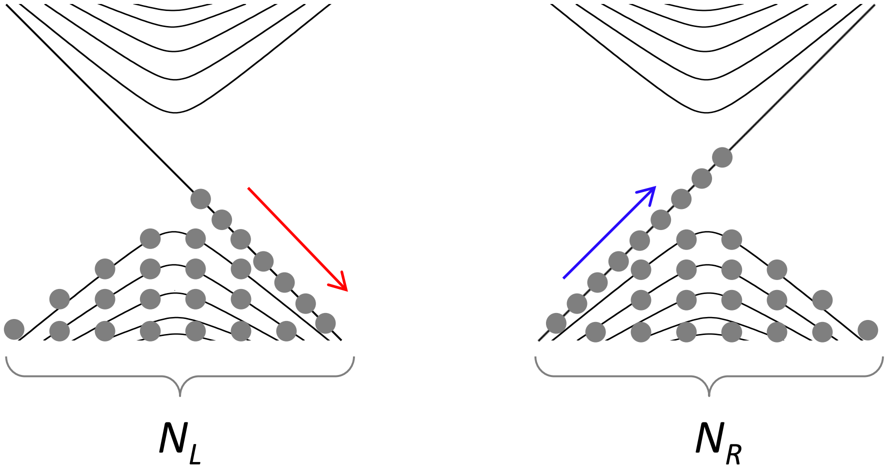
$$\frac{dN_L}{dt} = -n_\Phi \frac{L}{2\pi} eE \qquad \frac{dN_R}{dt} = +n_\Phi \frac{L}{2\pi} eE$$

Chiral anomaly

$B \neq 0$

$E \neq 0$

$$\dot{k} = eE$$



$$n_\Phi = \frac{BL_xL_y}{\phi_0}$$

Landau level degeneracy

$$\frac{dN_L}{dt} = -n_\Phi \frac{L}{2\pi} eE = -\frac{L^3}{(2\pi)^2} e^2 \boldsymbol{E} \cdot \boldsymbol{B}$$

$$\frac{dN_R}{dt} = +n_\Phi \frac{L}{2\pi} eE = +\frac{L^3}{(2\pi)^2} e^2 \boldsymbol{E} \cdot \boldsymbol{B}$$

Chiral anomaly

$B \neq 0$

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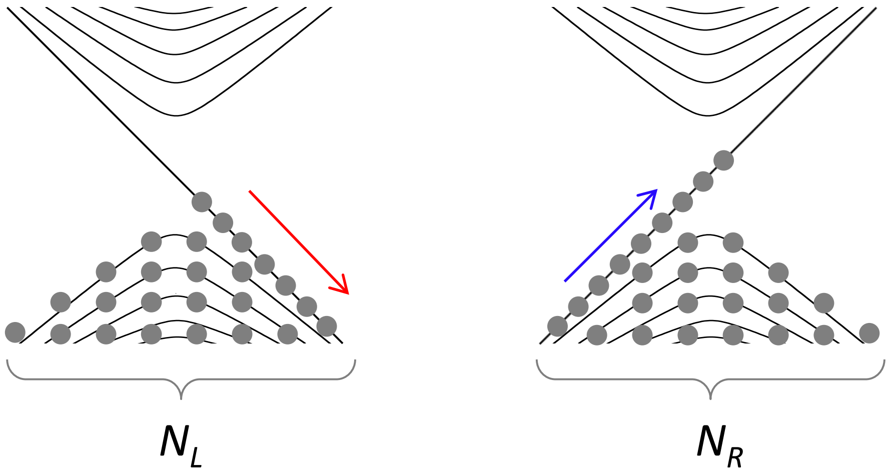


$$n_\Phi = \frac{BL_xL_y}{\phi_0}$$

Landau level degeneracy

$$\frac{dN_L}{dt} = -n_\Phi \frac{L}{2\pi} eE$$
$$= -\frac{L^3}{(2\pi)^2} e^2 \boldsymbol{E} \cdot \boldsymbol{B}$$

$$\frac{dN_R}{dt} = +n_\Phi \frac{L}{2\pi} eE$$
$$= +\frac{L^3}{(2\pi)^2} e^2 \boldsymbol{E} \cdot \boldsymbol{B}$$

total charge

$$\frac{d(N_R + N_L)}{dt} = 0$$

axial charge

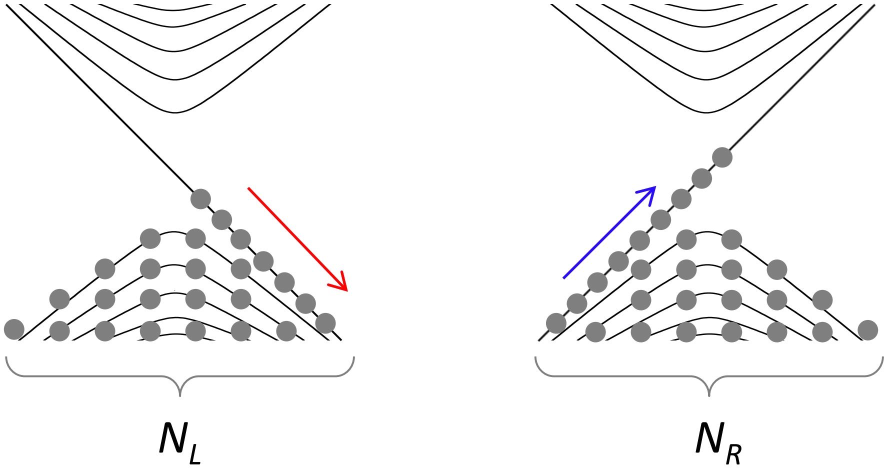
$$\frac{d(N_R - N_L)}{dt} = \int d^3x \frac{e^2}{2\pi^2} \boldsymbol{E} \cdot \boldsymbol{B}$$

Chiral anomaly

$B \neq 0$

$E \neq 0$

$$\dot{k} = eE$$



$$n_\Phi = \frac{BL_xL_y}{\phi_0}$$

Landau level degeneracy

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$$= +\frac{L^3}{(2\pi)^2} e^2 \boldsymbol{E} \cdot \boldsymbol{B}$$

total charge

$$\partial_\mu j^\mu = 0$$

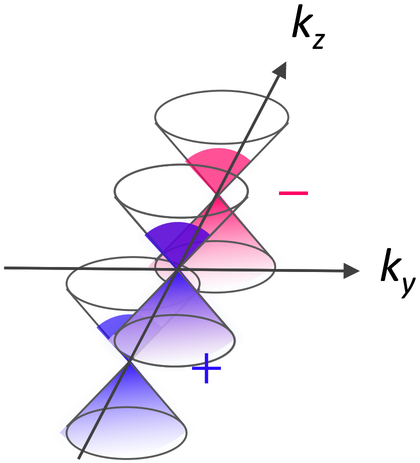
axial charge

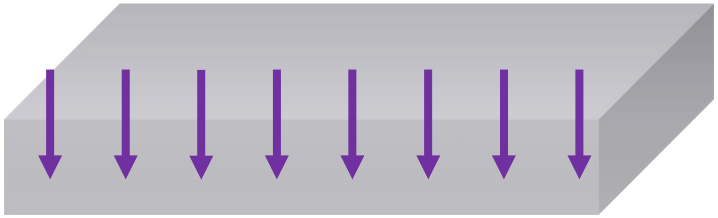
$$\partial_\mu j_5^\mu = \frac{e^2}{2\pi^2} \boldsymbol{E} \cdot \boldsymbol{B}$$

Chiral anomaly

Dirac fermions + exchange interaction

$$H = \begin{pmatrix} \boldsymbol{\sigma}\cdot(\boldsymbol{p}+e\boldsymbol{A}+J\boldsymbol{M}) & 0 \\ 0 & -\boldsymbol{\sigma}\cdot(\boldsymbol{p}+e\boldsymbol{A}-J\boldsymbol{M}) \end{pmatrix}$$





total charge

$$\partial_\mu j^\mu = 0$$

axial charge

$$\partial_\mu j_5^\mu = \frac{e^2}{2\pi^2}\boldsymbol{E}\cdot\boldsymbol{B}$$

Chiral anomaly

Dirac fermions + exchange interaction

$$H = \begin{pmatrix} \boldsymbol{\sigma}\cdot(\boldsymbol{p} + e\boldsymbol{A} + J\boldsymbol{M}) & 0 \\ 0 & -\boldsymbol{\sigma}\cdot(\boldsymbol{p} + e\boldsymbol{A} - J\boldsymbol{M}) \end{pmatrix}$$

$$= \tau_z\, \boldsymbol{\sigma}\cdot\boldsymbol{p} + \boldsymbol{j}\cdot\boldsymbol{A} + \boldsymbol{j}_5\cdot\boldsymbol{A}_5$$

total charge

$$\partial_\mu j^\mu = 0$$

axial charge

$$\partial_\mu j_5^\mu = \frac{e^2}{2\pi^2}\boldsymbol{E}\cdot\boldsymbol{B}$$

Chiral anomaly

Dirac fermions + exchange interaction

$$H = \begin{pmatrix} \boldsymbol{\sigma}\cdot(\boldsymbol{p}+e\boldsymbol{A}+J\boldsymbol{M}) & 0 \\ 0 & -\boldsymbol{\sigma}\cdot(\boldsymbol{p}+e\boldsymbol{A}-J\boldsymbol{M}) \end{pmatrix}$$

$$= \tau_z\,\boldsymbol{\sigma}\cdot\boldsymbol{p}+\boldsymbol{j}\cdot\boldsymbol{A}+\boldsymbol{j}_5\cdot\boldsymbol{A}_5$$

$$\boldsymbol{E}_5 = -\dot{\boldsymbol{A}}_5 \qquad \boldsymbol{B}_5 = \nabla\times\boldsymbol{A}_5$$

total charge

$$\partial_\mu j^\mu = \frac{e^2}{2\pi^2}(\boldsymbol{E}_5\cdot\boldsymbol{B}+\boldsymbol{E}\cdot\boldsymbol{B}_5)$$

axial charge

$$\partial_\mu j_5^\mu = \frac{e^2}{2\pi^2}(\boldsymbol{E}\cdot\boldsymbol{B}+\boldsymbol{E}_5\cdot\boldsymbol{B}_5)$$

Anomalous transport phenomena

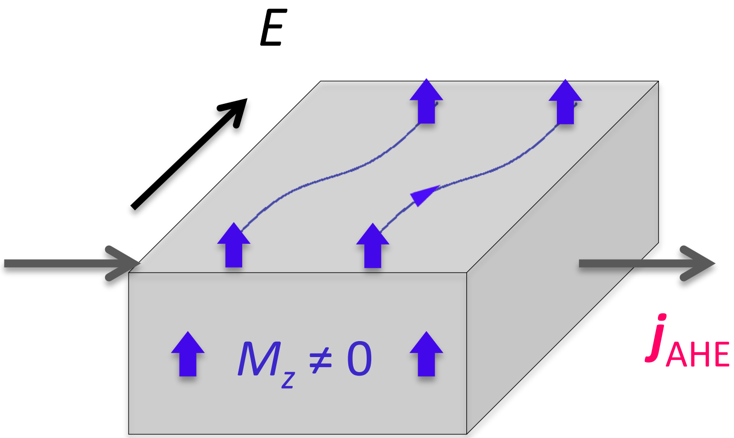
$$\partial_\mu j^\mu = \underbrace{\frac{e^2}{2\pi^2}(\boldsymbol{E}_5 \cdot \boldsymbol{B} + \boldsymbol{E} \cdot \boldsymbol{B}_5)}_{-\partial_\mu j^\mu_{\text{anomaly}}}$$

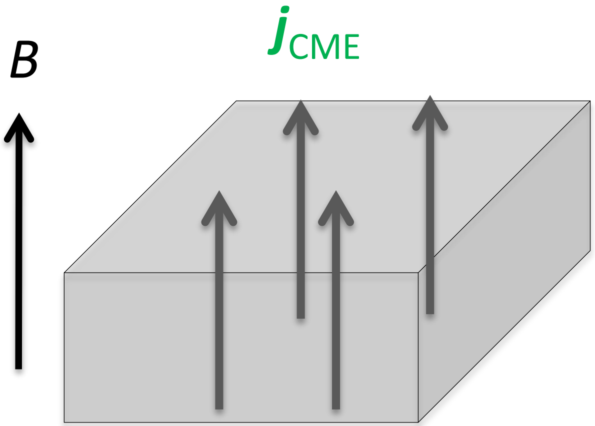
$$\boldsymbol{E}_5 = -\dot{\boldsymbol{A}}_5 - \boldsymbol{\nabla}\mu_5/e \qquad \boldsymbol{B}_5 = \boldsymbol{\nabla} \times \boldsymbol{A}_5$$

$$\boldsymbol{j}_{\text{anomaly}} = \underset{\substack{\uparrow \\ \text{Anomalous Hall effect}}}{\frac{e^2}{2\pi^2}\boldsymbol{A}_5 \times \boldsymbol{E}} + \underset{\substack{\uparrow \\ \text{Chiral magnetic effect}}}{\frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B}}$$

$$\rho_{\text{anomaly}} = \frac{e^2}{2\pi^2}\boldsymbol{A}_5 \cdot \boldsymbol{B}$$

Anomalous transport phenomena





Fukushima, Kharzeev, and Warringa (2008)

$$\boldsymbol{j}_{\text{anomaly}} = \frac{e^2}{2\pi^2}\boldsymbol{A}_5 \times \boldsymbol{E} + \frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B}$$

Anomalous Hall effect

Chiral magnetic effect

$$\rho_{\text{anomaly}} = \frac{e^2}{2\pi^2}\boldsymbol{A}_5 \cdot \boldsymbol{B}$$

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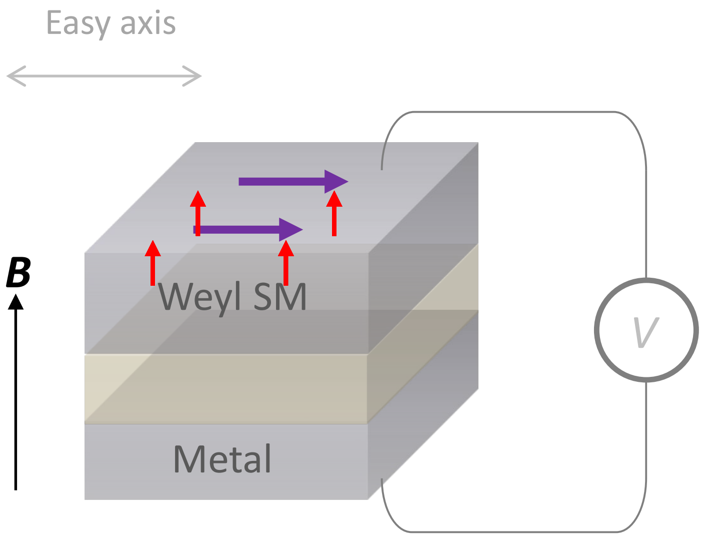
Voltage induced spin torque



$\hat{\boldsymbol{M}}$: local magnetization

$\boldsymbol{\sigma}$: spin of Weyl electrons

Kurebayashi, KN (2016)

$$H_{\mathrm{exc}} = J\hat{\boldsymbol{M}} \cdot \boldsymbol{\sigma}$$

$$\langle \boldsymbol{\sigma} \rangle = \frac{e^2}{2\pi^2 \hbar^2 v_F} V\boldsymbol{B}$$

Voltage induced spin torque

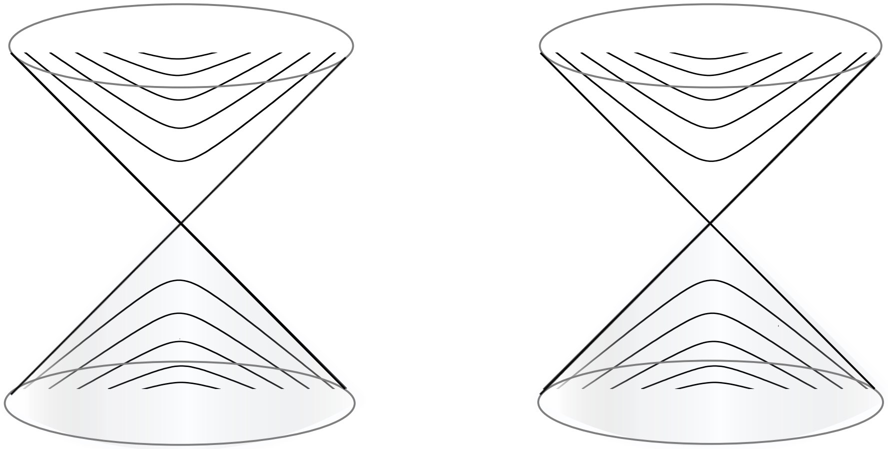
$$\langle \boldsymbol{\sigma} \rangle = \frac{e^2}{2\pi^2 \hbar^2 v_F} V \boldsymbol{B}$$

Weyl fermions in B field

$$H = \begin{pmatrix} H_R & 0 \\ 0 & H_L \end{pmatrix}$$

$$H_L = -\boldsymbol{\sigma} \cdot (\boldsymbol{p} + e\boldsymbol{A} + J\boldsymbol{M}) \qquad H_R = +\boldsymbol{\sigma} \cdot (\boldsymbol{p} + e\boldsymbol{A} - J\boldsymbol{M})$$

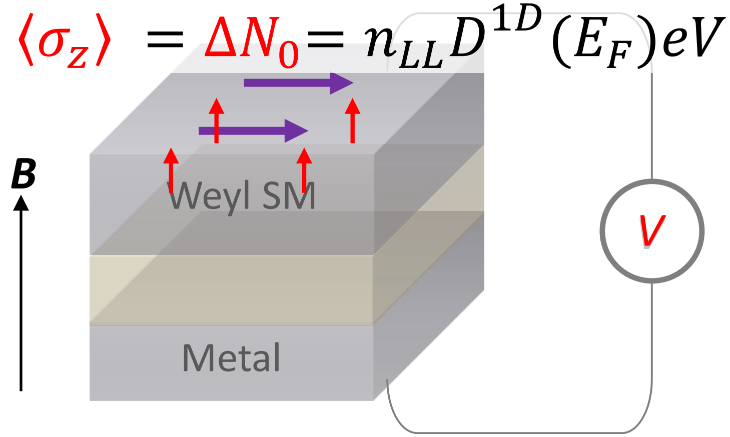
$B \neq 0$



$$\langle \boldsymbol{\sigma} \rangle = \frac{e^2}{2\pi^2 \hbar^2 v_F} V\boldsymbol{B}$$

Weyl fermions in *B* field

$$\langle\sigma_z\rangle = \Delta N_0 = n_{LL} D^{1D}(E_F) eV$$



$$\frac{d\hat{\boldsymbol{M}}}{dt} = -\gamma \hat{\boldsymbol{M}} \times \boldsymbol{H}_{\text{eff}} + \alpha \hat{\boldsymbol{M}} \times \frac{d\hat{\boldsymbol{M}}}{dt} + J \hat{\boldsymbol{M}} \times \langle\boldsymbol{\sigma}\rangle$$

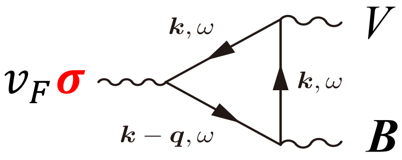
$$\boxed{\langle\boldsymbol{\sigma}\rangle = \frac{e^2}{2\pi^2\hbar^2 v_F} V\boldsymbol{B}}$$

Relation to chiral anomaly

Anomaly equation of the axial current

$$\boldsymbol{\nabla} \cdot \boldsymbol{j}_5 = \frac{e^2}{2\pi^2 \hbar^2} (-\boldsymbol{\nabla} V) \cdot \boldsymbol{B}$$

$$\boldsymbol{j}_5 = \frac{\partial H}{\partial \boldsymbol{A}_5} = -e v_F \boldsymbol{\sigma}$$



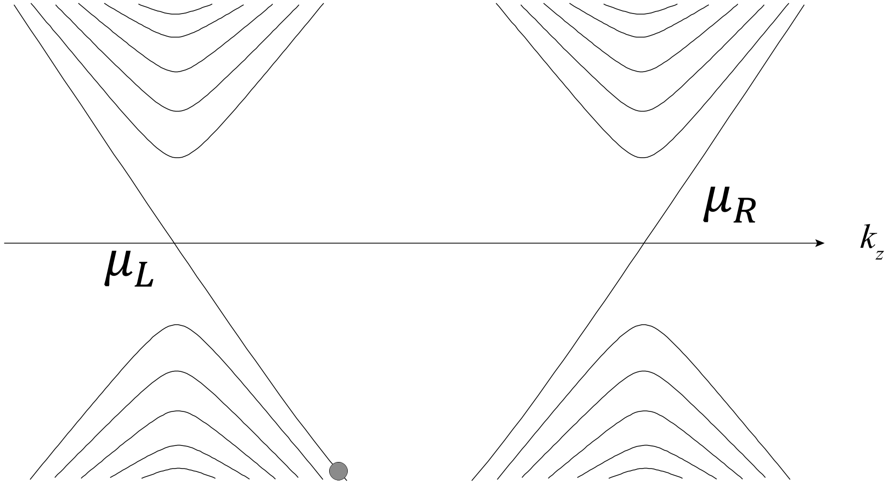
$$\boxed{\langle \boldsymbol{\sigma} \rangle = \frac{e^2}{2\pi^2 \hbar^2 v_F} V \boldsymbol{B}}$$

Chiral magnetic effects

$$\boldsymbol{j}_L = -\frac{e^2}{2\pi^2}\mu_L \boldsymbol{B}_L \qquad \boldsymbol{j}_R = +\frac{e^2}{2\pi^2}\mu_R \boldsymbol{B}_R$$

$$\begin{cases} \boldsymbol{B}_{R/L} = \boldsymbol{B} \pm \boldsymbol{B}_5 \\ \mu_{R/L} = \mu \pm \mu_5 \end{cases}$$

Fukushima, Kharzeev, and Warringa (2008)



Chiral magnetic effects

$$\boldsymbol{j}_L = -\frac{e^2}{2\pi^2}\mu_L \boldsymbol{B}_L \qquad \boldsymbol{j}_R = +\frac{e^2}{2\pi^2}\mu_R \boldsymbol{B}_R$$

$$\begin{cases} \boldsymbol{B}_{R/L} = \boldsymbol{B} \pm \boldsymbol{B}_5 \\ \mu_{R/L} = \mu \pm \mu_5 \end{cases}$$

$$\boldsymbol{j} = \boldsymbol{j}_R + \boldsymbol{j}_L$$

Fukushima, Kharzeev, and Warringa (2008)

Electrical current

$$\boldsymbol{j} = \frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B}$$

$$\boldsymbol{j} = \frac{e^2}{2\pi^2}\mu \boldsymbol{B}_5$$

Chiral magnetic effects

$$\boldsymbol{j}_L = -\frac{e^2}{2\pi^2}\mu_L \boldsymbol{B}_L \qquad \boldsymbol{j}_R = +\frac{e^2}{2\pi^2}\mu_R \boldsymbol{B}_R$$

$$\begin{cases} \boldsymbol{B}_{R/L} = \boldsymbol{B} \pm \boldsymbol{B}_5 \\ \mu_{R/L} = \mu \pm \mu_5 \end{cases}$$

$$\boldsymbol{j} = \boldsymbol{j}_R + \boldsymbol{j}_L$$

Electrical current

$$\boldsymbol{j} = \frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B}$$

$$\boldsymbol{j} = \frac{e^2}{2\pi^2}\mu \boldsymbol{B}_5$$

$$\boldsymbol{j}_5 = \boldsymbol{j}_R - \boldsymbol{j}_L$$

Axial current

$$\boldsymbol{j}_5 = \frac{e^2}{2\pi^2}\mu \, \boldsymbol{B}$$

Chiral magnetic effects

Axial current

$$\boldsymbol{j}_5 = \frac{e^2}{2\pi^2}\,\mu\,\boldsymbol{B}$$

Chiral magnetic effects

$$H = \begin{pmatrix} H_+ & 0 \\ 0 & H_- \end{pmatrix}$$

$$H_{\pm} = \pm v\, \boldsymbol{\sigma} \cdot (\boldsymbol{p} + e\boldsymbol{A} \pm e\boldsymbol{A}_5) + eA^0 \pm eA_5^0$$

$$\boldsymbol{j}_5 = -\frac{\partial H}{\partial \boldsymbol{A}_5} = -ev\boldsymbol{\sigma}$$

Spin density

$$\langle \boldsymbol{\sigma} \rangle = \frac{-e}{2\pi^2 v}\, \mu\, \boldsymbol{B}$$

⟷

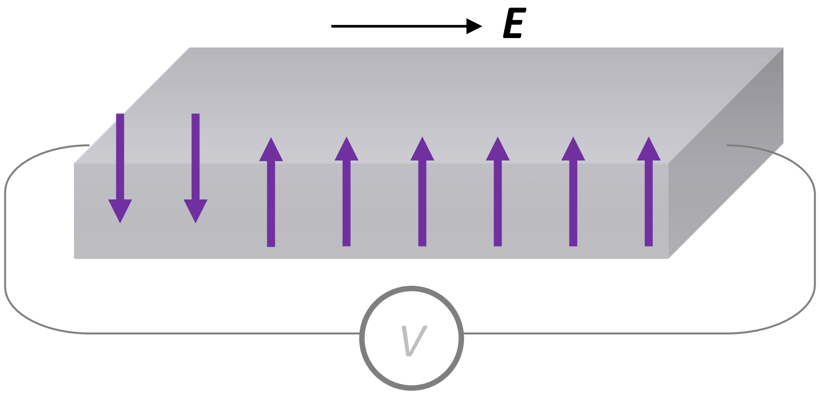
Axial current

$$\boldsymbol{j}_5 = \frac{e^2}{2\pi^2}\, \mu\, \boldsymbol{B}$$

Outline

- Introduction – Spintronics and Weyl fermions
- Chiral anomaly and magnetization dynamics
- Axial Hall effect and domain-wall dynamics

Domain wall in Weyl semimetal



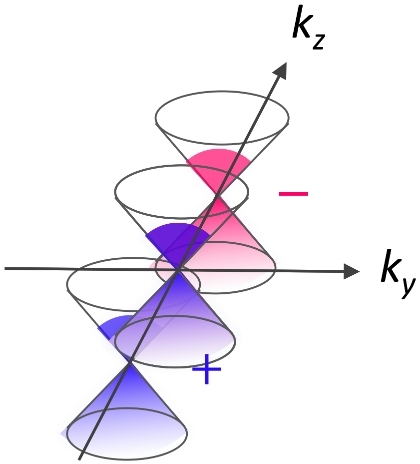
Spin torques in conventional metals

$$\boldsymbol{T}_E = (\boldsymbol{\nabla}\cdot\boldsymbol{v}_s)\widehat{\boldsymbol{M}} + \beta\,\widehat{\boldsymbol{M}}\times(\boldsymbol{\nabla}\cdot\boldsymbol{v}_s)\widehat{\boldsymbol{M}}$$

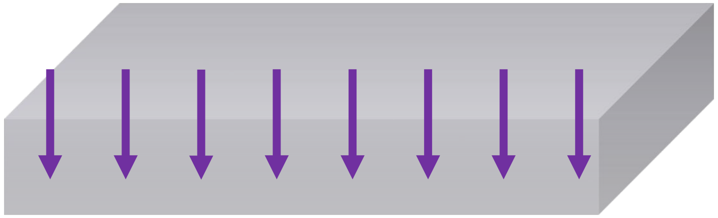
adiabatic

non-adiabatic ($\beta\sim 0.01$)

Domain wall in Weyl semimetal



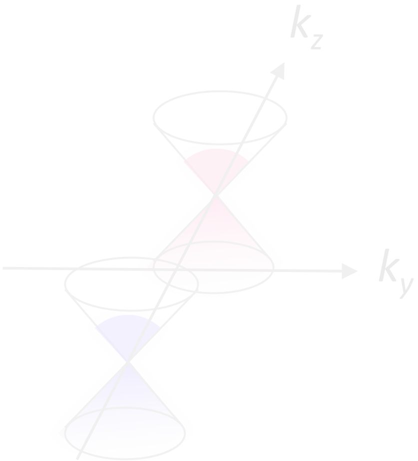
$$
\begin{aligned}
H_{\pm} &= \pm\boldsymbol{\sigma}\cdot\boldsymbol{p} + J\boldsymbol{M}\cdot\boldsymbol{\sigma} \\
&= \pm\boldsymbol{\sigma}\cdot(\boldsymbol{p} \pm e\boldsymbol{A}_5)
\end{aligned}
$$

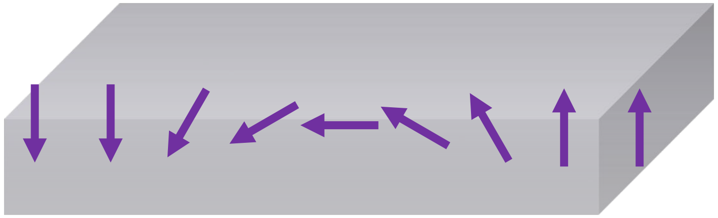


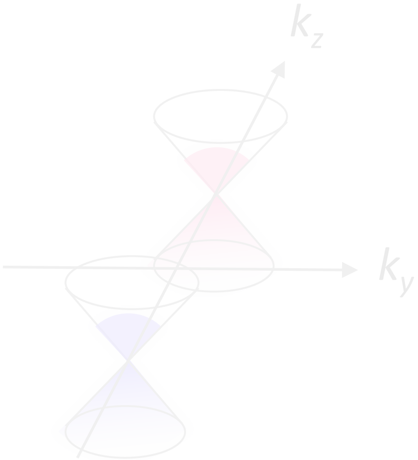
Magnetic Weyl semimetal

Domain wall in Weyl semimetal

$$\begin{aligned} H_{\pm} &= \pm \boldsymbol{\sigma} \cdot \boldsymbol{p} + J\boldsymbol{M} \cdot \boldsymbol{\sigma} \\ &= \pm \boldsymbol{\sigma} \cdot \boldsymbol{p} + \boldsymbol{A}_5 \cdot \boldsymbol{j}_5 \end{aligned}$$







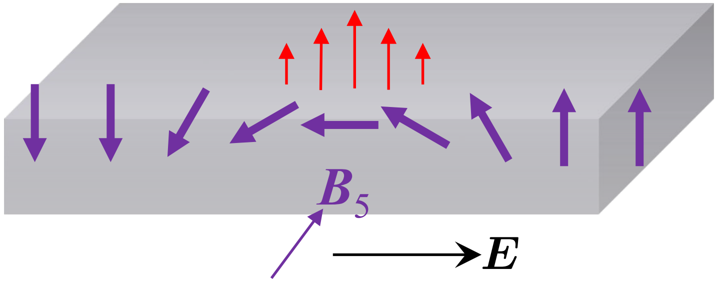
$$\boldsymbol{B} = \nabla \times \boldsymbol{A}$$

$$\boldsymbol{B}_5 = \nabla \times \boldsymbol{A}_5 \propto \nabla \times \boldsymbol{M}$$

Domain wall in Weyl semimetal

$$H_{\pm} = \pm \boldsymbol{\sigma} \cdot \boldsymbol{p} + J\boldsymbol{M} \cdot \boldsymbol{\sigma}$$

$$= \pm \boldsymbol{\sigma} \cdot \boldsymbol{p} + \boldsymbol{A}_5 \cdot \boldsymbol{j}_5$$

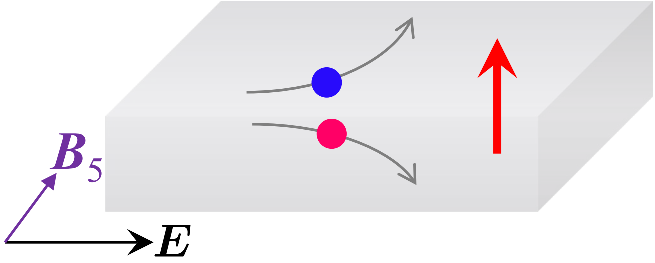


$$\boldsymbol{j}_5 = \sigma_H \hat{\boldsymbol{B}}_5 \times \boldsymbol{E}$$

$$= \frac{\sigma_H}{e v_F} \frac{\nabla \times \hat{\boldsymbol{M}}}{|\nabla \times \hat{\boldsymbol{M}}|} \times \boldsymbol{E}$$

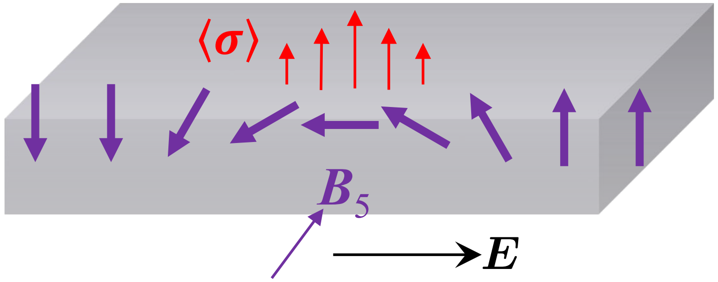
$$\boldsymbol{B}_5 = \boldsymbol{\nabla} \times \boldsymbol{A}_5 \propto \boldsymbol{\nabla} \times \boldsymbol{M}$$

$$\boldsymbol{j}_5 = \boldsymbol{j}_+ - \boldsymbol{j}_- \propto \boldsymbol{\sigma}$$



Domain wall in Weyl semimetal

$$\frac{d\hat{\boldsymbol{M}}}{dt} = -\gamma\hat{\boldsymbol{M}} \times \boldsymbol{H}_{\mathrm{eff}} + \alpha\hat{\boldsymbol{M}} \times \frac{d\hat{\boldsymbol{M}}}{dt} + \underbrace{J\hat{\boldsymbol{M}} \times \frac{\sigma_H}{ev_F}\frac{\nabla \times \hat{\boldsymbol{M}}}{|\nabla \times \hat{\boldsymbol{M}}|} \times \boldsymbol{E}}$$



$$\propto \quad \hat{\boldsymbol{M}} \times (\boldsymbol{E} \cdot \nabla)\hat{\boldsymbol{M}}$$

non-adiabatic STT

$$\langle\boldsymbol{\sigma}\rangle = \frac{\boldsymbol{j}_5}{ev_F} = \frac{\sigma_H \hat{\boldsymbol{B}}_5 \times \boldsymbol{E}}{ev_F}$$

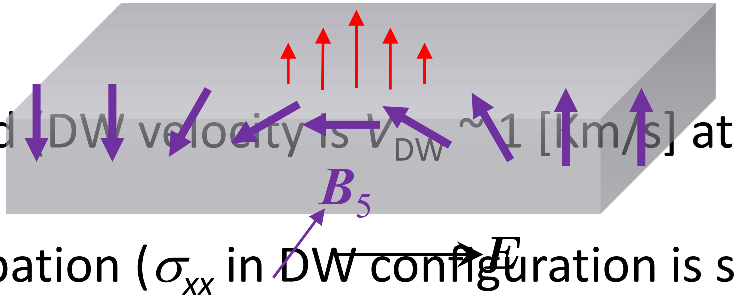
$$= \frac{\sigma_H}{ev_F}\frac{\nabla \times \hat{\boldsymbol{M}}}{|\nabla \times \hat{\boldsymbol{M}}|} \times \boldsymbol{E}$$

Domain wall in Weyl semimetal

$$\frac{d\widehat{\boldsymbol{M}}}{dt} = -\gamma \widehat{\boldsymbol{M}} \times \boldsymbol{H}_{\mathrm{eff}} + \alpha \widehat{\boldsymbol{M}} \times \frac{d\widehat{\boldsymbol{M}}}{dt} + J \widehat{\boldsymbol{M}} \times \underbrace{\frac{\sigma_H}{e v_F} \frac{\nabla \times \widehat{\boldsymbol{M}}}{|\nabla \times \widehat{\boldsymbol{M}}|} \times \boldsymbol{E}}$$

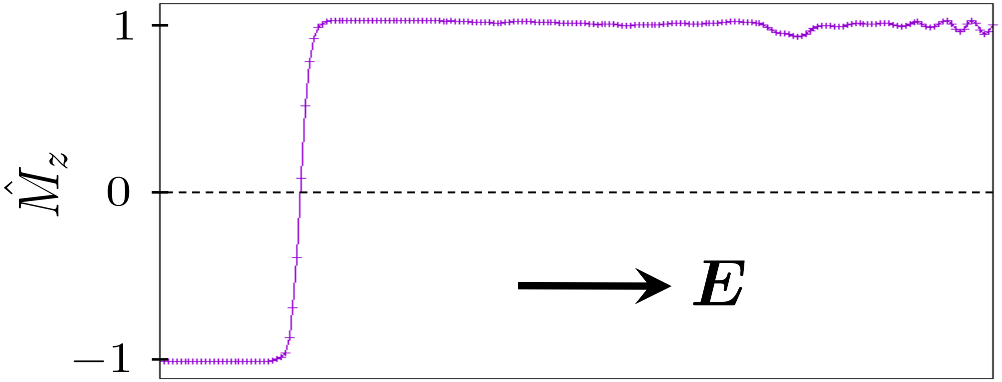
$$\propto \quad \widehat{\boldsymbol{M}} \times (\boldsymbol{E} \cdot \nabla) \widehat{\boldsymbol{M}}$$

non-adiabatic STT



✓High speed (DW velocity is V_{DW} ~1 [km/s] at E=10[illegible] [V/m])

✓Less dissipation (σ_{xx} in DW configuration is suppressed)

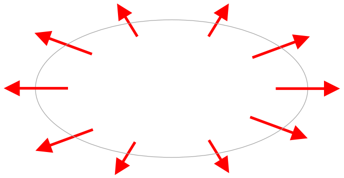


Daichi Kurebayashi

Types of SO coupling

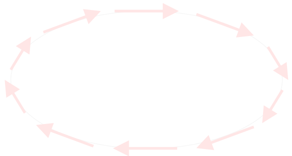
Weyl-type SOC

$p_x\tau_z\sigma_x + p_y\tau_z\sigma_y + p_z\tau_z\sigma_z$



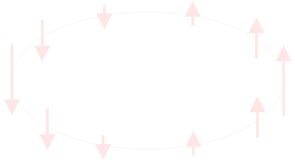
Rashba-type SOC

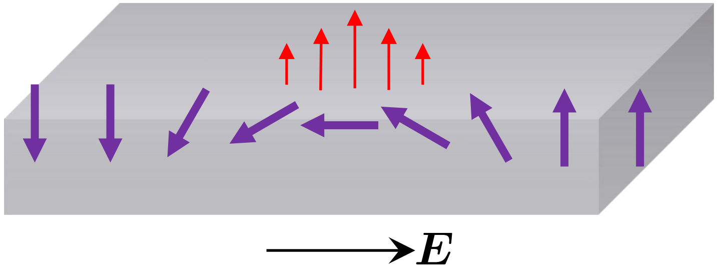
$p_x\tau_x\sigma_y - p_y\tau_x\sigma_x + p_z\tau_y$



BHZ-type SOC

$p_x\tau_x\sigma_z - p_y\tau_y + p_z\tau_z$





Daichi Kurebayashi

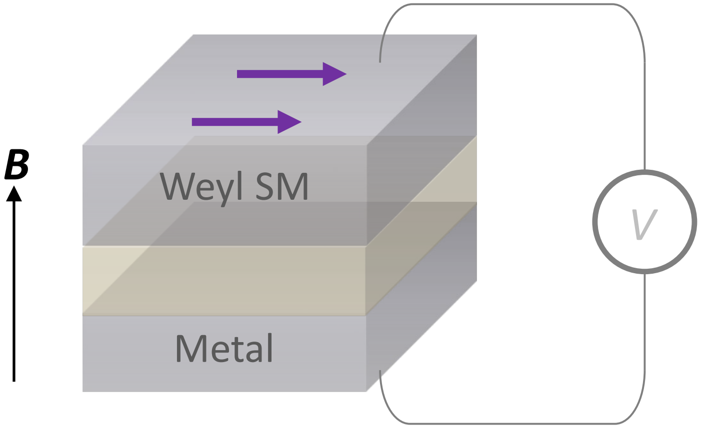
Spin torque is <u>insensitive to the type of SOC</u>

Summary

- Voltage induced spin switching

$$\langle \boldsymbol{\sigma} \rangle = \frac{e^2}{2\pi^2\hbar^2 v_F} V\boldsymbol{B}$$

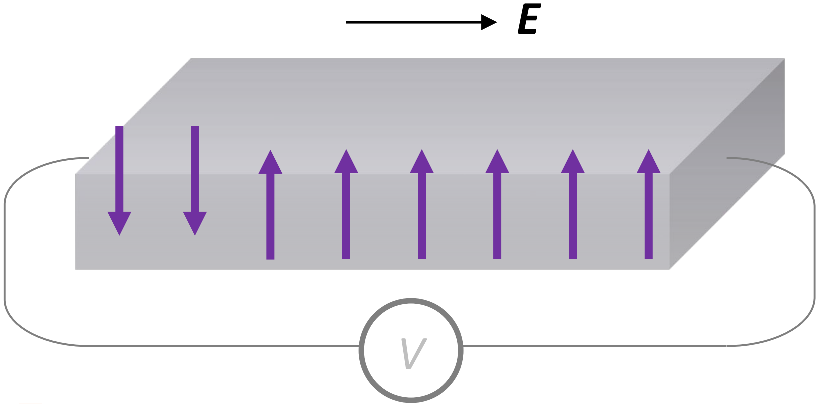
Axial anomaly $\nabla \cdot \boldsymbol{j}_5 \propto \boldsymbol{E} \cdot \boldsymbol{B}$



$$\boldsymbol{T}_{\text{exc}} = J\widehat{\boldsymbol{M}} \times \langle \boldsymbol{\sigma} \rangle$$

- Current induced domain-wall motion

$$\langle \boldsymbol{\sigma} \rangle = \frac{\sigma_H \widehat{\boldsymbol{B}}_5 \times \boldsymbol{E}}{e v_F}$$



Axial Hall effect $\boldsymbol{j}_5 = \sigma_H \widehat{\boldsymbol{B}}_5 \times \boldsymbol{E}$