Seminar at JAEA, 23rd Jan. 2017

Topological Materials for Spintronis

トポロジカル物質におけるスピントロニクス現象

Kentaro Nomura (IMR, Tohoku University)

Seminar at JAEA, 23rd Jan. 2017

Topological Materials for Spintronis

トポロジカル物質におけるスピントロニクス現象

Collaborators

Yasufumi Araki, Gerrit Bauer,
Koji Kobayashi, Daichi Kurebayashi,
Ryota Nakai, Yuya Ominato, Akihiko Sekine,
Nobuyuki Okuma(Tokyo)
Yuki Shiomi (Tohoku), Eiji Saitoh (Tohoku),
Yoichi Ando (Cologne)

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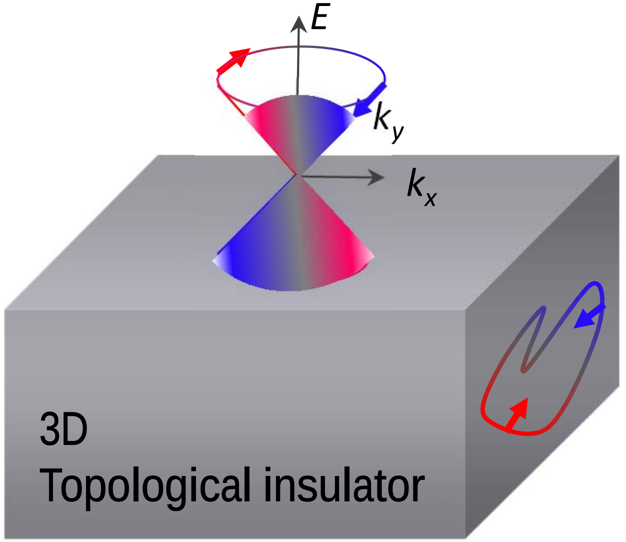
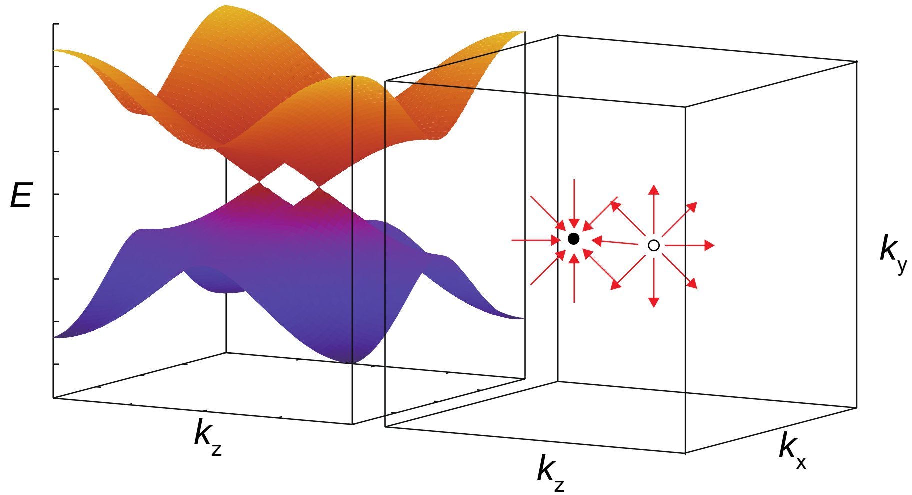
Topological Materials for Spintronis

トポロジカル物質におけるスピントロニクス現象

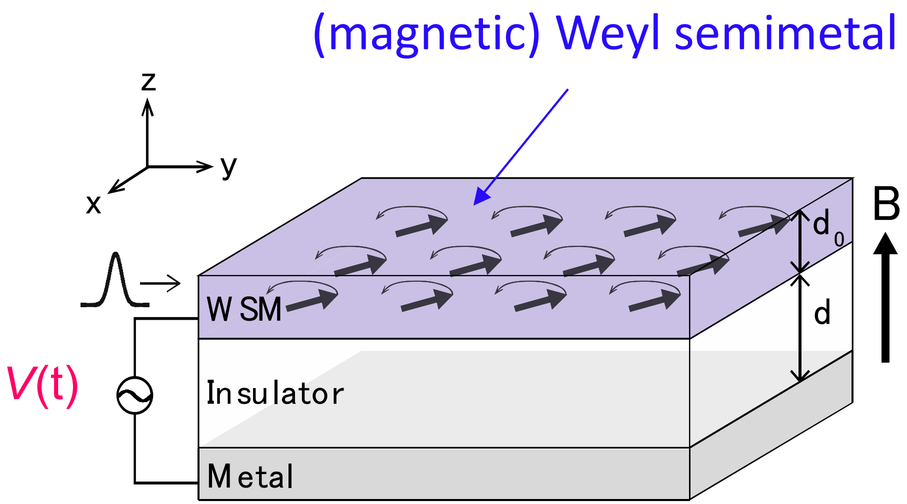
- Topological insulators



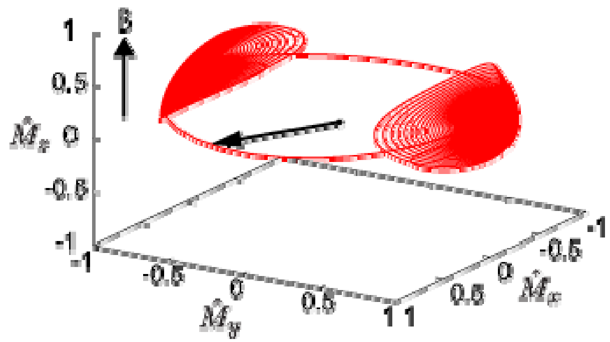
- Weyl semimetals



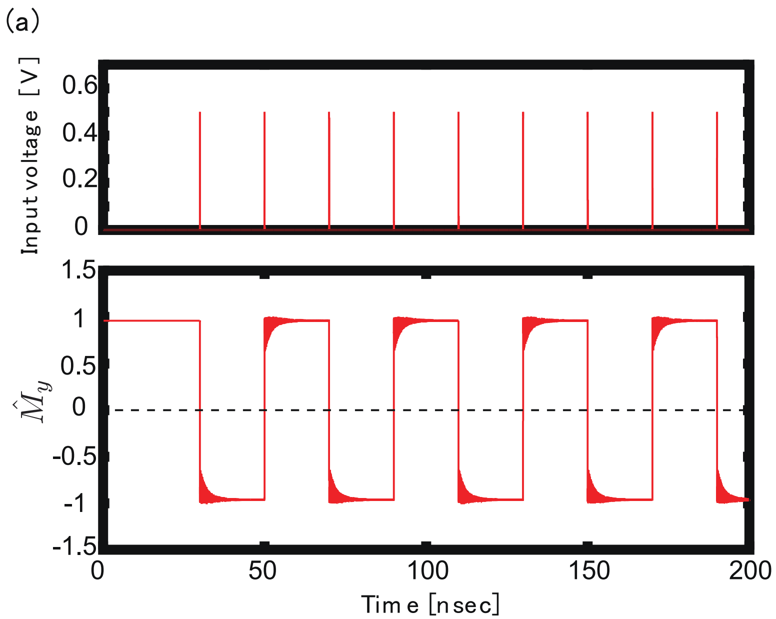
Take home message



$$\boldsymbol{T}_{\mathrm{CS}} = \sigma_{\mathrm{AHE}} V(t) \widehat{\boldsymbol{M}} \times \boldsymbol{B}$$



Kurebayashi, KN 2016



Magnetization switching via electric voltage

Outline

Part I

- Spin-Electricity conversion in topological insulators

Part II

- Introduction: What is a Weyl semimetal?
- Magnetization dynamics in Weyl semimetals

Outline

Part I

- Spin-Electricity conversion in topological insulators

Part II

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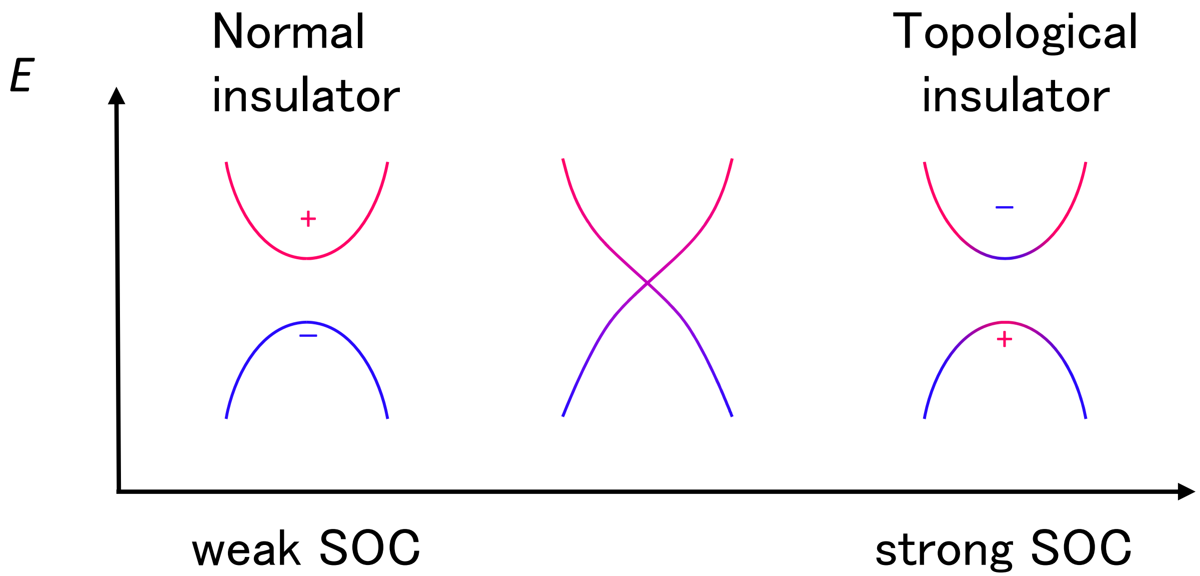
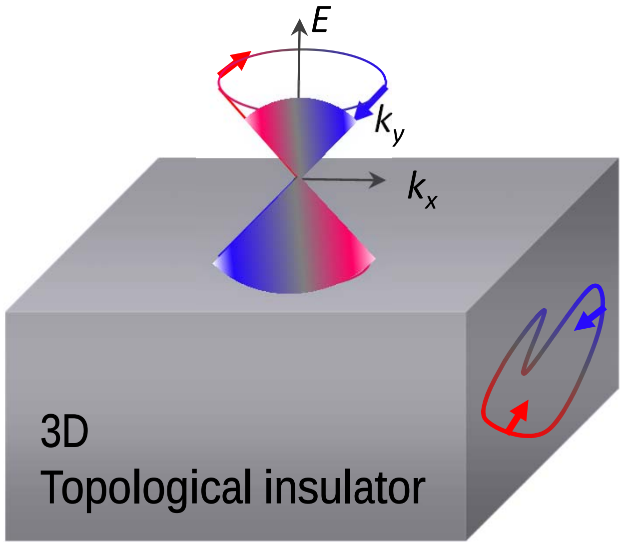
- Magnetization dynamics in Weyl semimetals

Topological insulators

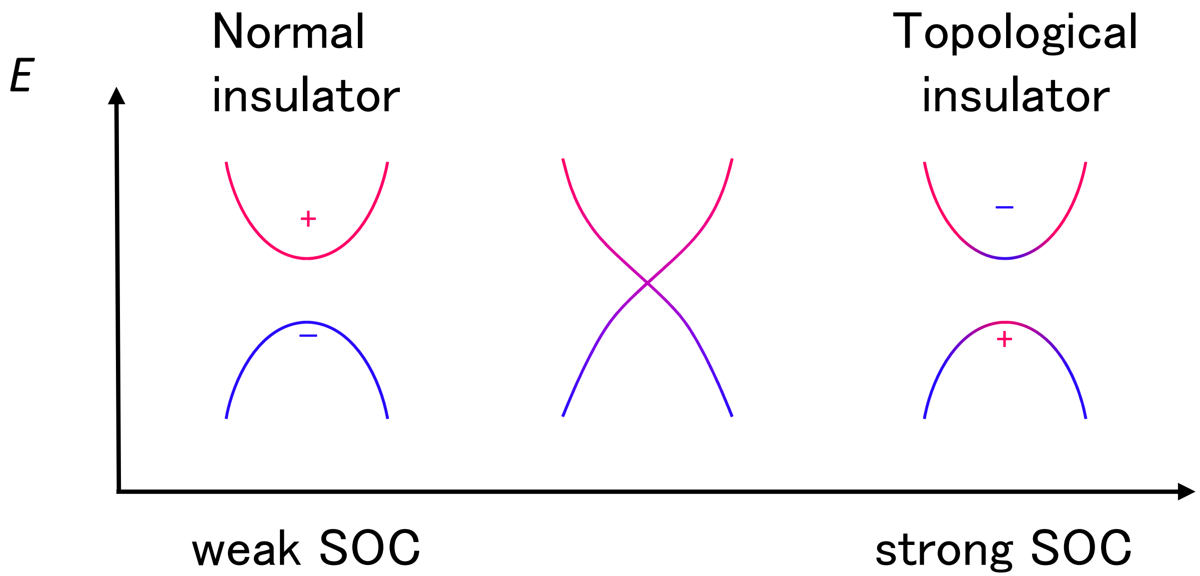


$$H_{2D} = p_y \sigma_x - p_x \sigma_y$$



Kane-Mele, Bernevig-Hughes-Zhang,
Moore-Balents, Roy, Fu-Kane-Mele, …

Topological insulators



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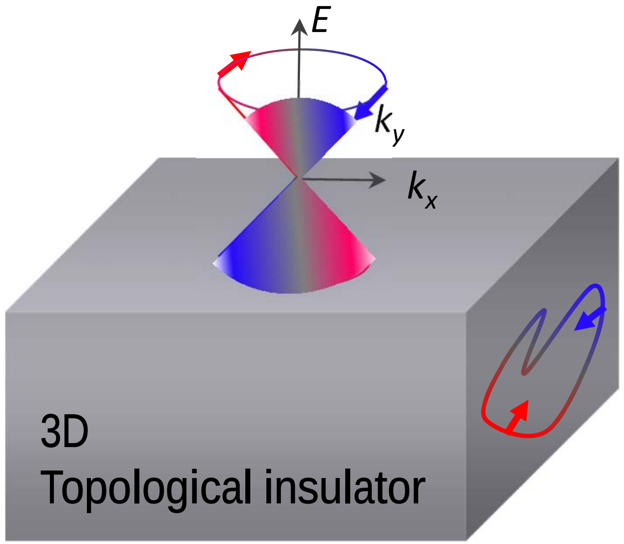


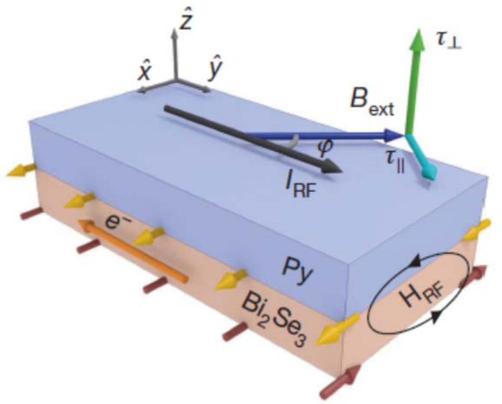
3d Topological insulator materials

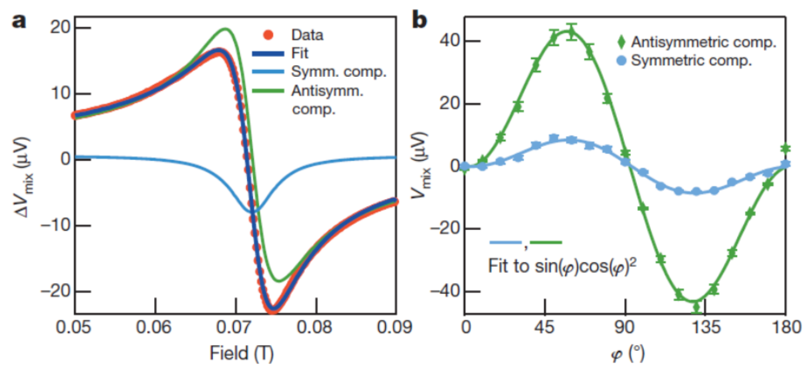
- $Bi_{1-x}Sb_x$
- Bi_2Se_3, Bi_2Te_3
- Bi-Sb-Te-Se (BSTS)

Spintronics phenomena on TI surface

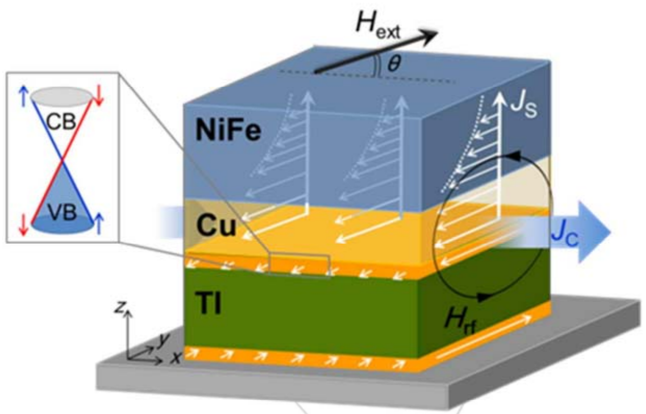
Experimental studies

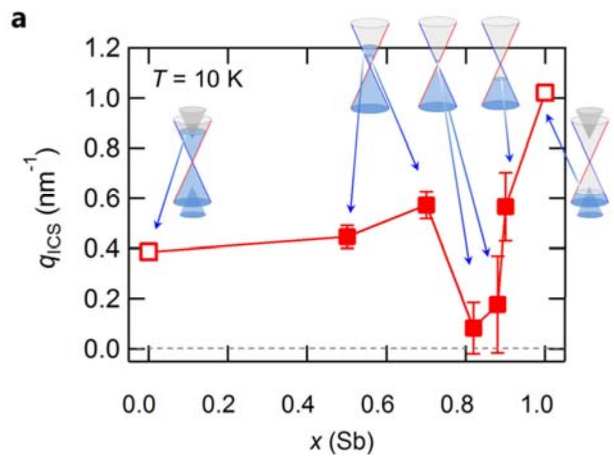
A.R.Mellnik, et al. Nature 511, 449-451 (2014)





Shiomi, et al. Phys. Rev. Lett. 113, 196601 (2004)
C.H.Li, et al. Nature Nano. 9, 218-224 (2014)
Y. Fan, et al. Nature Materials 13, 699 (2014)
Kondo et al. Nature Phys. 3833 (2016)





Spintronics phenomena on TI surface

Experimental studies

PRL **113,** 196601 (2014) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2014

Spin-Electricity Conversion Induced by Spin Injection into Topological Insulators

Y. Shiomi,[1] K. Nomura,[1] Y. Kajiwara,[1] K. Eto,[2] M. Novak,[2] Kouji Segawa,[2] Yoichi Ando,[2] and E. Saitoh[1,3,4,5]

[1]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[2]*Institute of Scientific and Industrial Research, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[3]*WPI Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[4]*CREST, Japan Science and Technology Agency, Tokyo 102-0076, Japan*
[5]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan*

(Received 11 May 2014; published 3 November 2014)

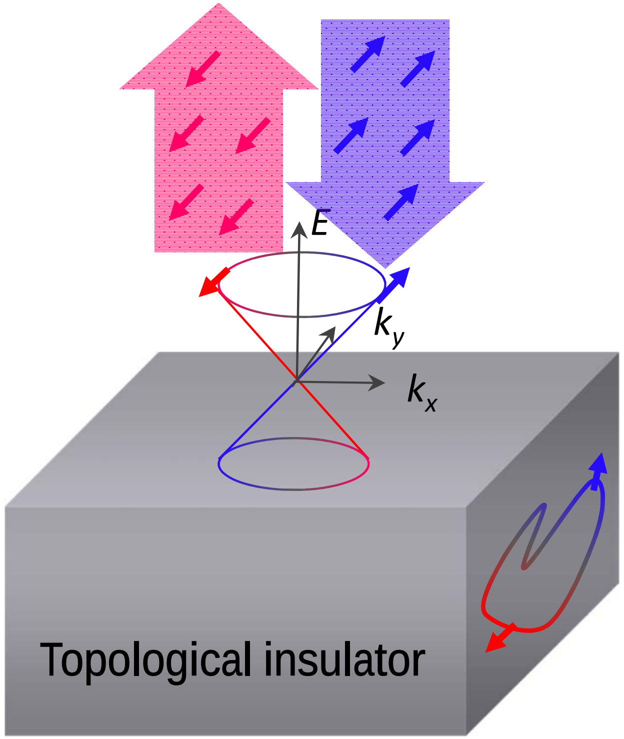
We report successful spin injection into the surface states of topological insulators by using a spin pumping technique. By measuring the voltage that shows up across the samples as a result of spin pumping, we demonstrate that a spin-electricity conversion effect takes place in the surface states of bulk-insulating topological insulators $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ and Sn-doped Bi_2Te_2Se. In this process, the injected spins are converted into a charge current along the Hall direction due to the spin-momentum locking on the surface state.

Spin injection experiments

spin-momentum locking

Voltage difference between left and right

spin-electricity conversion



$$H_{surface} = k_y \sigma_x - k_x \sigma_y$$

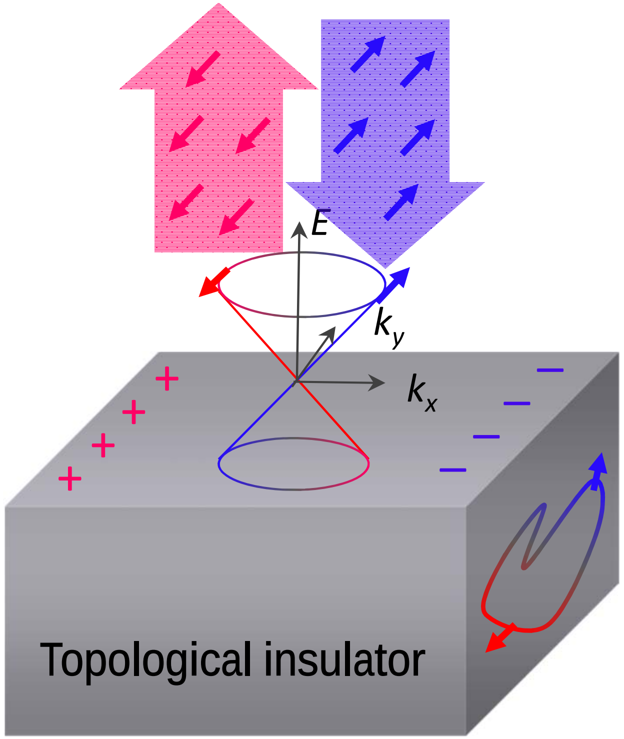
σ_z : ↑,↓ real spin

Spin injection experiments

spin-momentum locking

Voltage difference between left and right

spin-electricity conversion



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Spin injection experiments

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⬇

Voltage difference between left and right

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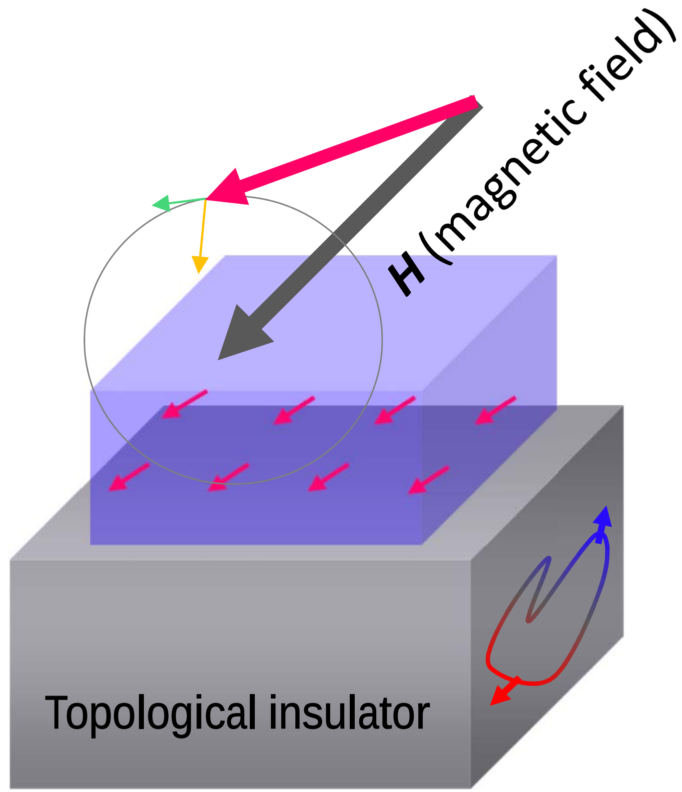
Y. Shiomi, et al. PRL 113, 196601 (2014)



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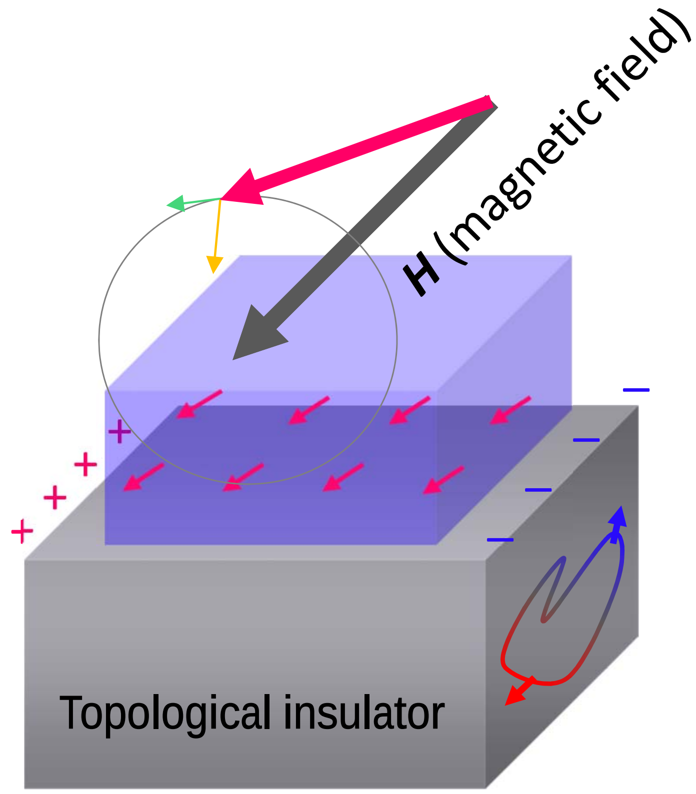

$$H_{surface} = k_y \sigma_x - k_x \sigma_y$$

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Spin injection experiments

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↓

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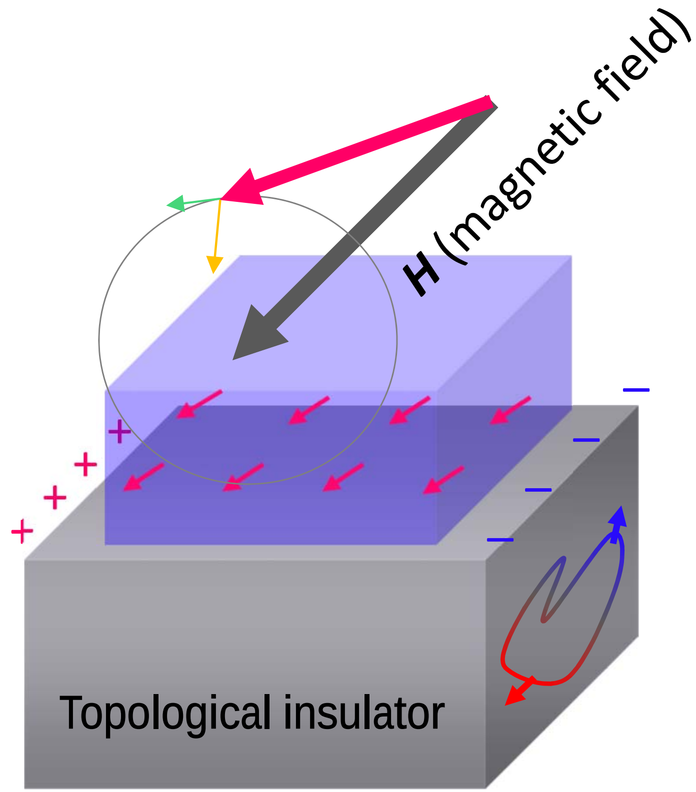
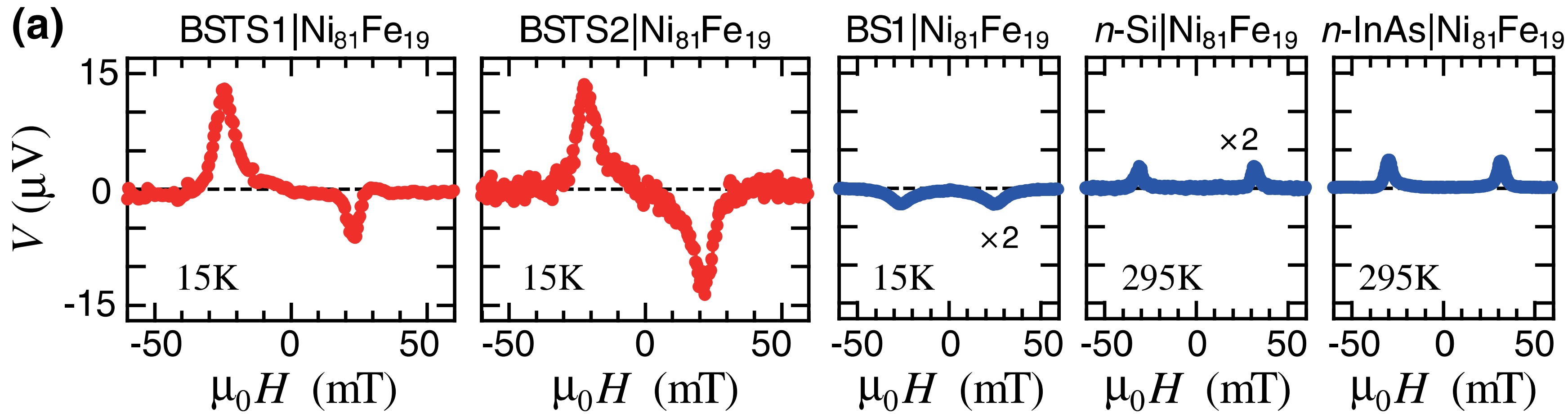
Y. Shiomi, et al. PRL 113, 196601 (2014)



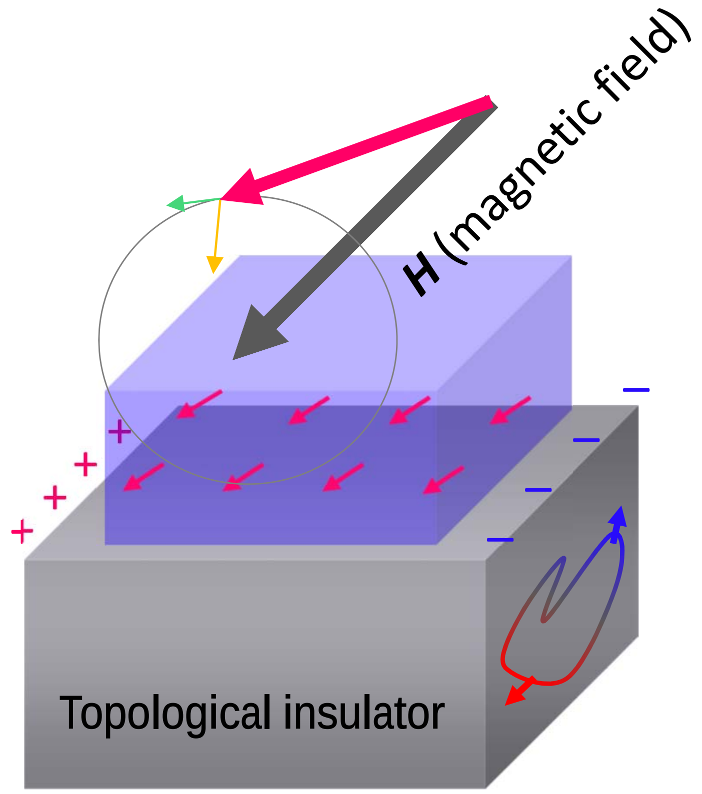


Dumping enhancement

- Local spins

$$\frac{d\boldsymbol{S}}{dt} = \boldsymbol{H}_{eff} \times \boldsymbol{S} + \alpha_0 \boldsymbol{S} \times \frac{d\boldsymbol{S}}{dt} + \dot{\boldsymbol{S}}_{surface}$$

$$\dot{\boldsymbol{S}}_{surface} = -J\, \boldsymbol{S} \times \langle \vec{\sigma} \rangle$$



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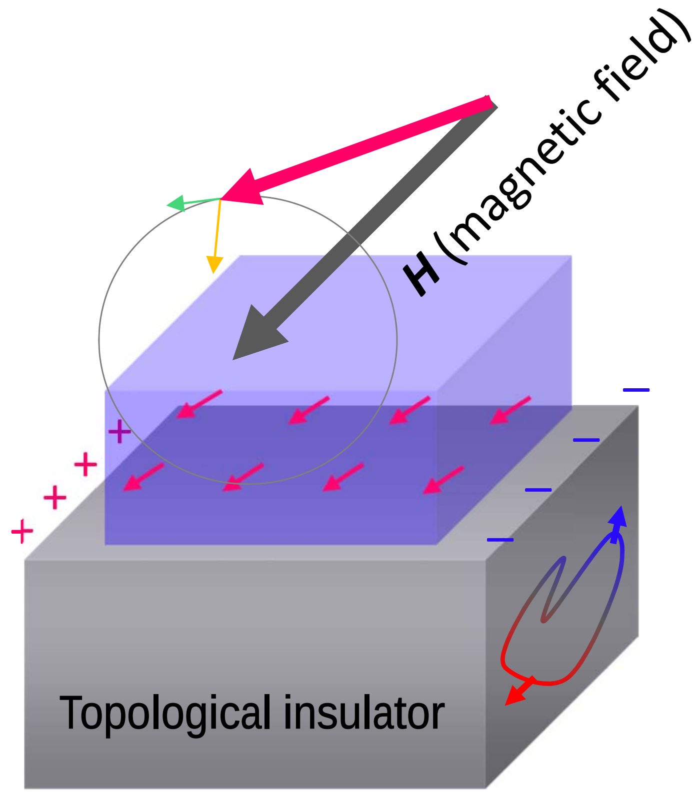
$$\dot{\boldsymbol{S}}_{surface} = -J\, \boldsymbol{S} \times \langle \vec{\sigma} \rangle$$

- Surface electrons

$$\begin{aligned} H_{Dirac} + H_{exc} &= v_F \hat{\mathbf{z}} \times \vec{\sigma} \cdot \boldsymbol{p} + J\boldsymbol{S} \cdot \vec{\sigma} \\ &= v_F \hat{\mathbf{z}} \times \vec{\sigma} \cdot \left(\boldsymbol{p} + e\boldsymbol{a} \right) + JS_z \sigma_z \end{aligned}$$



$$\boldsymbol{a} = \frac{J}{ev_F} \hat{\mathbf{z}} \times \mathbf{S}$$

Dumping enhancement

- Local spins

$$\frac{d\boldsymbol{S}}{dt} = \boldsymbol{H}_{eff} \times \boldsymbol{S} + \alpha_0 \boldsymbol{S} \times \frac{d\boldsymbol{S}}{dt} + \dot{\boldsymbol{S}}_{surface}$$

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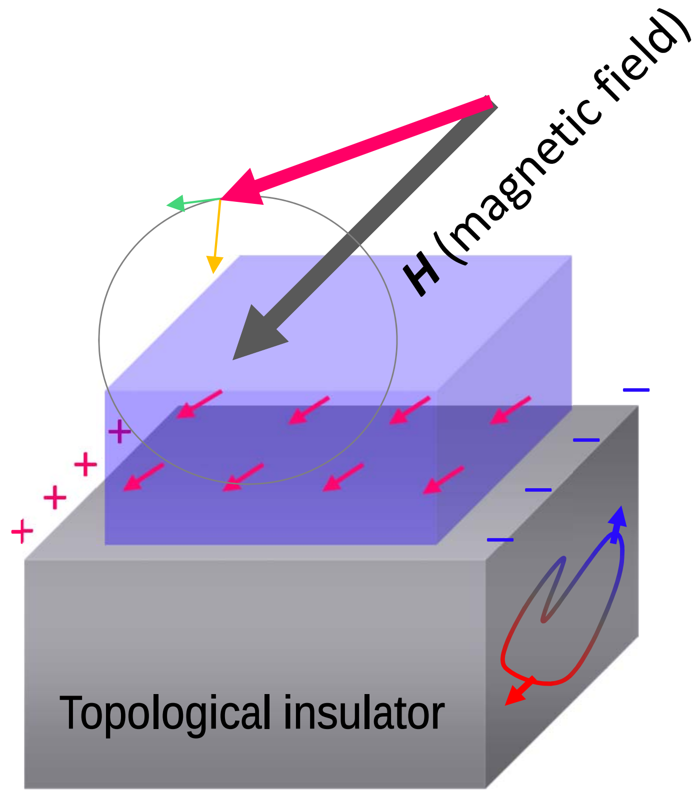


- Surface electrons

$$H_{Dirac} + H_{exc} = v_F \hat{\boldsymbol{z}} \times \vec{\sigma} \cdot \boldsymbol{p} + J\boldsymbol{S} \cdot \vec{\sigma}$$
$$= v_F \hat{\boldsymbol{z}} \times \vec{\sigma} \cdot \left(\boldsymbol{p} + e\boldsymbol{a} \right) + J S_z \sigma_z$$

$$\boldsymbol{a} = \frac{J}{ev_F} \hat{\boldsymbol{z}} \times \boldsymbol{S}$$

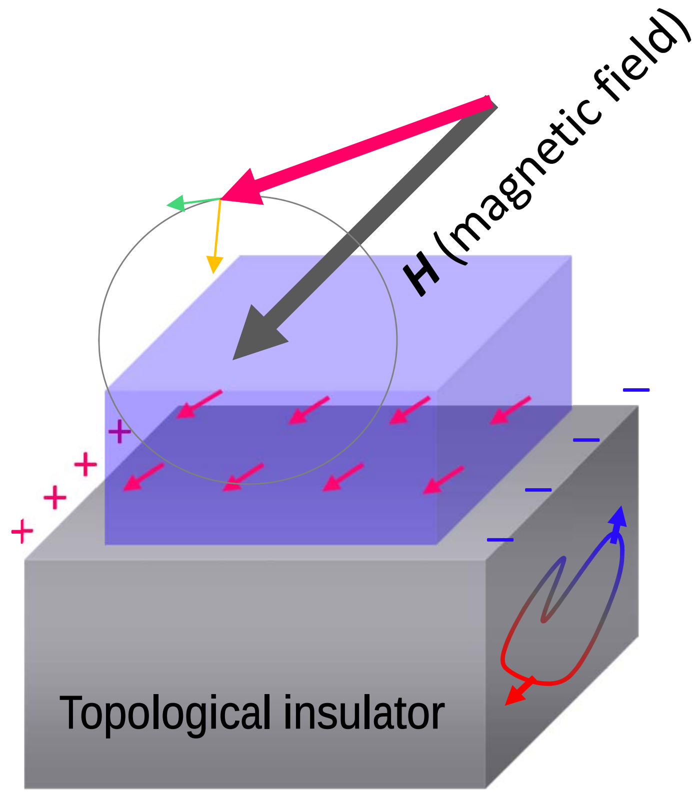
$$\left.\begin{aligned} \boldsymbol{j} &= -ev_F \hat{\boldsymbol{z}} \times \langle \vec{\sigma} \rangle \\ \boldsymbol{j} &= \sigma_{xx}(-\dot{\boldsymbol{a}}) = \frac{\sigma_{xx} J}{ev_F} \hat{\boldsymbol{z}} \times \dot{\boldsymbol{S}} \end{aligned}\right\} \quad \langle \vec{\sigma} \rangle = -\frac{\sigma_{xx} J}{(ev_F)^2} \dot{\boldsymbol{S}}$$

Dumping enhancement

- Local spins

$$\frac{d\boldsymbol{S}}{dt} = \boldsymbol{H}_{eff} \times \boldsymbol{S} + \alpha_0 \boldsymbol{S} \times \frac{d\boldsymbol{S}}{dt} + \dot{\boldsymbol{S}}_{surface}$$

$$\dot{\boldsymbol{S}}_{surface} = -J\, \boldsymbol{S} \times \langle \vec{\sigma} \rangle$$



$$\boldsymbol{a} = \frac{J}{ev_F} \hat{\boldsymbol{z}} \times \boldsymbol{S}$$

$$\frac{d\boldsymbol{S}}{dt} = \boldsymbol{H}_{eff} \times \boldsymbol{S} + (\alpha_0 + \delta\alpha) \boldsymbol{S} \times \frac{d\boldsymbol{S}}{dt}$$

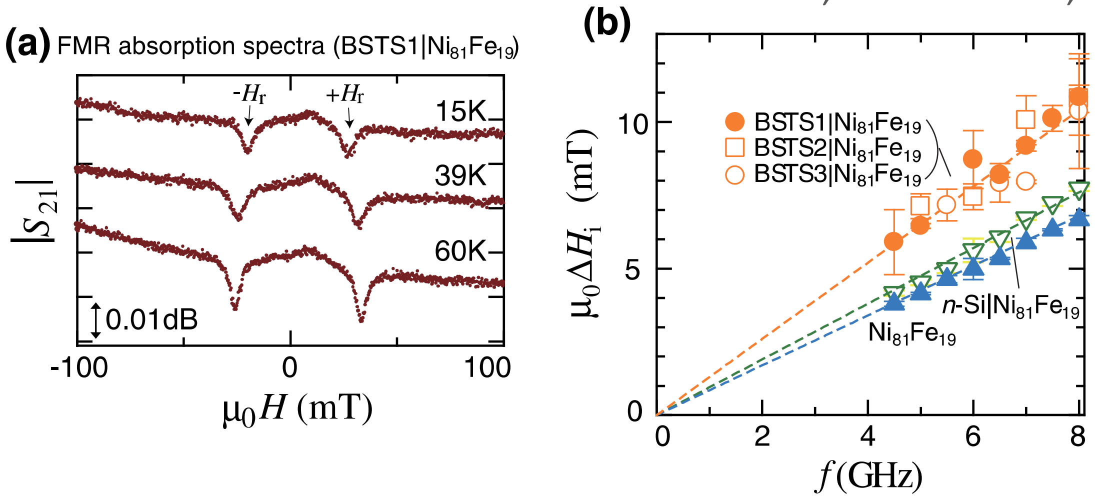
The enhanced dumping factor

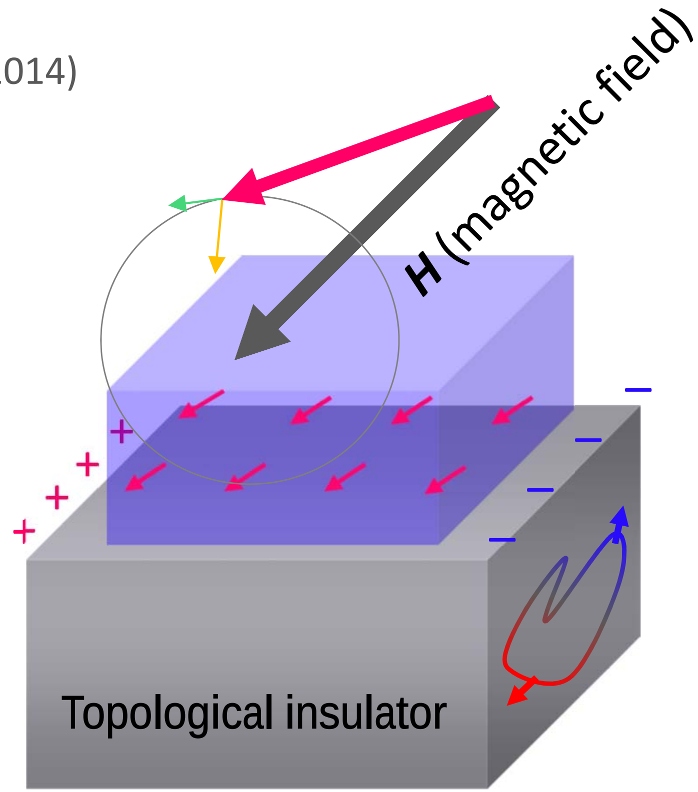
$$\delta\alpha = \frac{\mu_H J^2}{\hbar e v_F^2}$$

$$\langle \vec{\sigma} \rangle = -\frac{\sigma_{xx} J}{(ev_F)^2} \dot{\boldsymbol{S}}$$

Dumping enhancement

Y. Shiomi, et al. PRL 113, 196601 (2014)





$$\delta\alpha = \frac{\gamma}{2\omega}(\mu_0 \Delta H_{\mathrm{BSTS|Py}} - \mu_0 \Delta H_{\mathrm{Py}})$$
$$\sim 7.8\times 10^{-3}$$

$$\boldsymbol{a} = \frac{J}{ev_F}\hat{\boldsymbol{z}} \times \boldsymbol{S}$$

$$\frac{d\boldsymbol{S}}{dt} = \boldsymbol{H}_{eff} \times \boldsymbol{S} + \underline{(\alpha_0 + \delta\alpha)}\boldsymbol{S} \times \frac{d\boldsymbol{S}}{dt}$$

The enhanced dumping factor

$$\delta\alpha = \frac{\mu_H J^2}{\hbar e v_F^2}$$

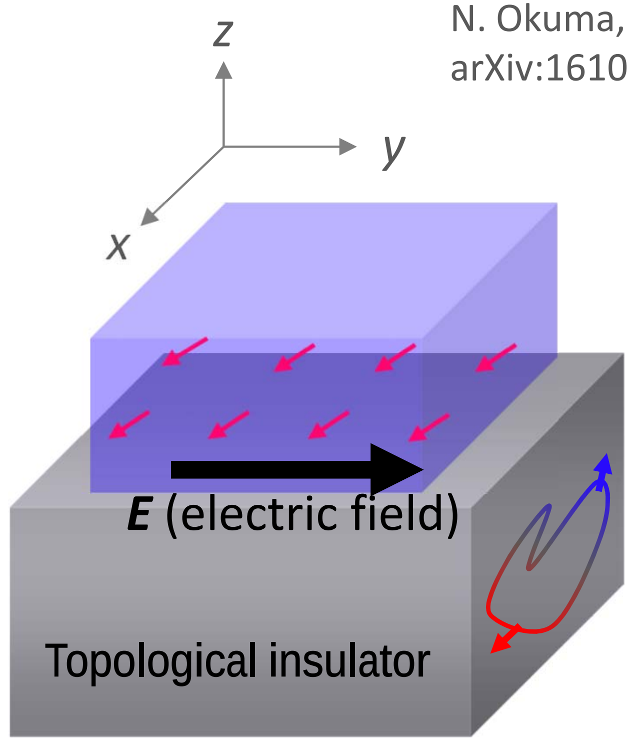
$J \cong 10$ meV

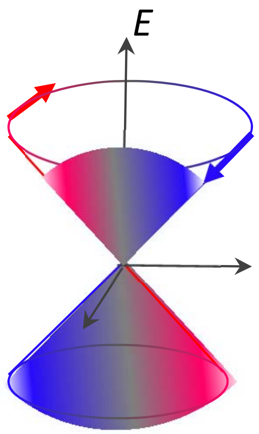
Microscopic theory of spin torque

Relation between

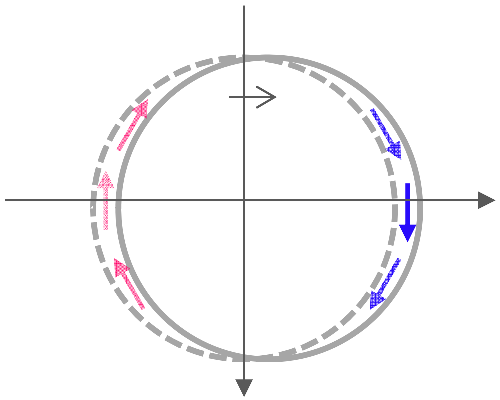
$$J^{S_x}(=\dot{S}^x{}_{surface}) \quad \text{and} \quad E_y$$

N. Okuma, KN
arXiv:1610.05236





Edelstein effect



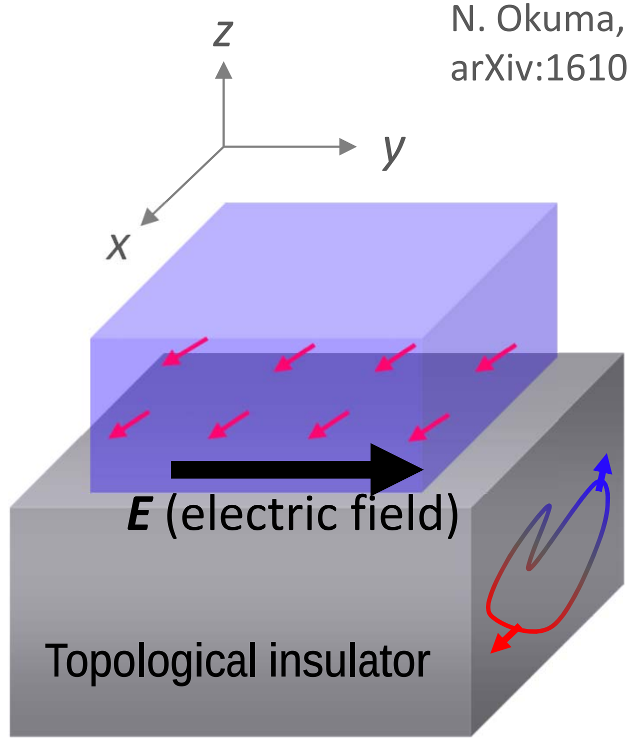
$\langle\sigma_x\rangle$ exert a spin torque on the local spin magnetization

Microscopic theory of spin torque

Relation between

$$J^{S_x} (= \dot{S}^x{}_{surface}) \quad \text{and} \quad E_y$$

N. Okuma, KN
arXiv:1610.05236



Torque at the surface

$$\dot{\boldsymbol{S}}_{surface} = \frac{1}{i\hbar}[\boldsymbol{S}_{total}, H_{exc}]$$

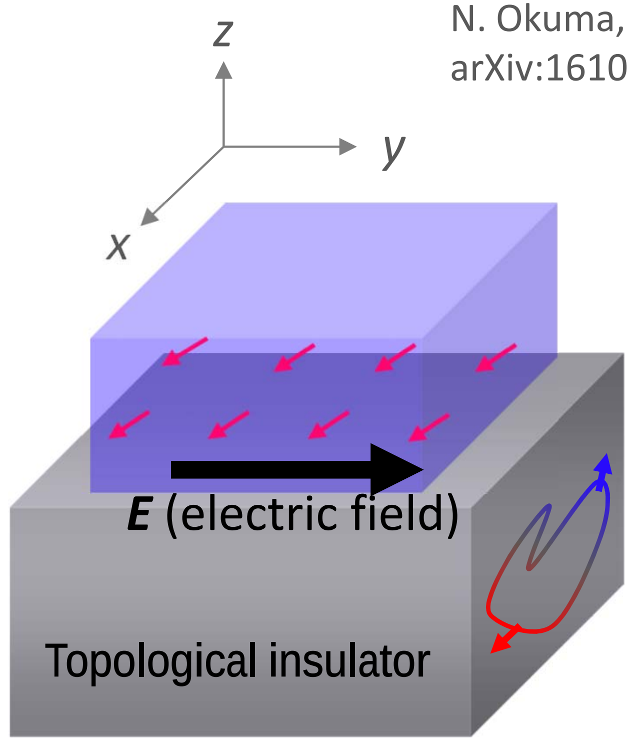
$$\dot{\boldsymbol{S}}_{surface} = -J \sum_{\boldsymbol{k},\boldsymbol{q}_{\parallel},q_z} \boldsymbol{S}(\boldsymbol{q}_{\parallel}, q_z) \times c^{+}_{\boldsymbol{k}+\boldsymbol{q}_{\parallel}} \vec{\sigma} c_{\boldsymbol{k}}$$

Microscopic theory of spin torque

N. Okuma, KN
arXiv:1610.05236

$$H_{Dirac} = \sum_{\boldsymbol{k}} c_{\boldsymbol{k}}^{+} \left(v_F \hat{\boldsymbol{z}} \times \vec{\sigma} \cdot \boldsymbol{k} - \mu_F \right) c_{\boldsymbol{k}}$$

$$H_{exc} = -\sum_{\boldsymbol{q}_{\parallel}, q_z} J\, \boldsymbol{S}(\boldsymbol{q}_{\parallel}, q_z) \cdot c_{\boldsymbol{k}+\boldsymbol{q}_{\parallel}}^{+} \vec{\sigma} c_{\boldsymbol{k}}$$



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$$\dot{\boldsymbol{S}}_{surface} = \frac{1}{i\hbar} [\boldsymbol{S}_{total}, H_{exc}]$$

$$\dot{\boldsymbol{S}}_{surface} = -J \sum_{\boldsymbol{k}, \boldsymbol{q}_{\parallel}, q_z} \boldsymbol{S}(\boldsymbol{q}_{\parallel}, q_z) \times c_{\boldsymbol{k}+\boldsymbol{q}_{\parallel}}^{+} \vec{\sigma} c_{\boldsymbol{k}}$$

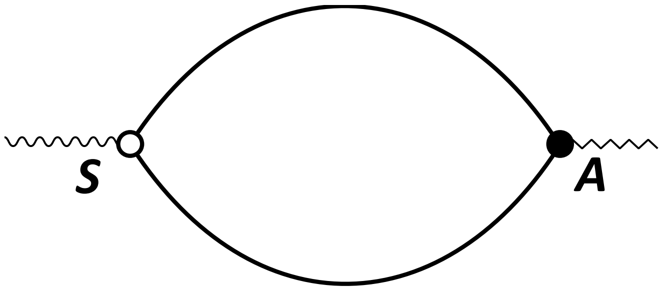
Microscopic theory of spin torque

Linear response theory

N. Okuma, KN
arXiv:1610.05236

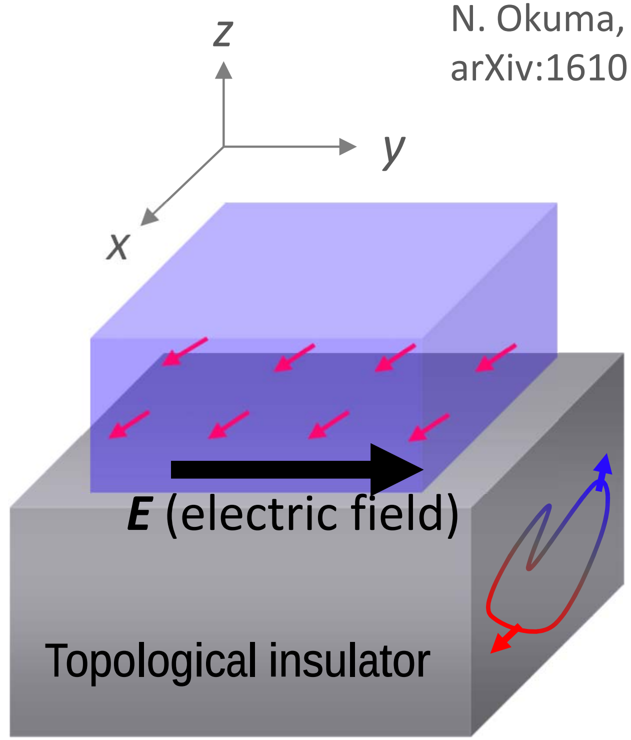
$$\left\langle \dot{S}^x_{surface} \right\rangle = -\frac{i}{\hbar}\int dt'\, e^{\eta t} \left\langle [\dot{S}^x_{surface}(t), j_y(t')] \right\rangle A_y(t')$$

=



+

$$\langle S^y \rangle = \langle S^z \rangle = 0$$



$$\dot{\boldsymbol{S}}_{surface} = -J \sum_{\boldsymbol{k},\boldsymbol{q}_{\parallel},q_z} \boldsymbol{S}(\boldsymbol{q}_{\parallel}, q_z) \times c^{+}_{\boldsymbol{k}+\boldsymbol{q}_{\parallel}} \vec{\sigma} c_{\boldsymbol{k}}$$

Microscopic theory of spin torque

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$$\left\langle \dot{S}^{x}_{surface} \right\rangle = -\frac{i}{\hbar}\int dt'\ e^{\eta t}\left\langle [\dot{S}^{x}_{surface}(t), j_y(t')] \right\rangle A_y(t')$$

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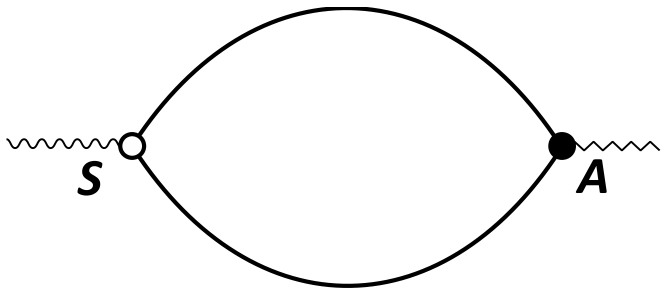

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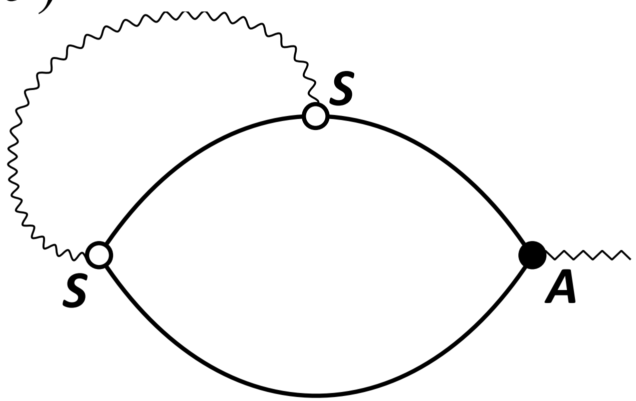

+

$$\dot{\boldsymbol{S}}_{surface} = -J\sum_{\boldsymbol{k},\boldsymbol{q}_{\parallel},q_z} \boldsymbol{S}(\boldsymbol{q}_{\parallel}, q_z)\times c^{+}_{\boldsymbol{k}+\boldsymbol{q}_{\parallel}}\vec{\sigma}c_{\boldsymbol{k}}$$

Microscopic theory of spin torque

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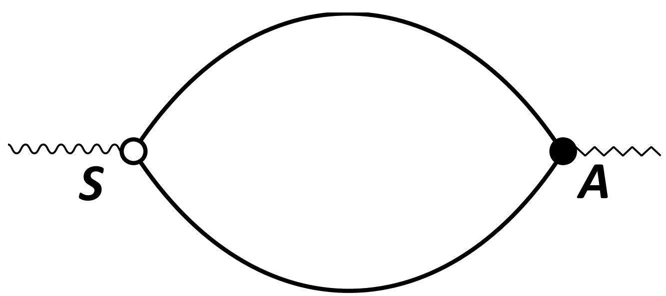
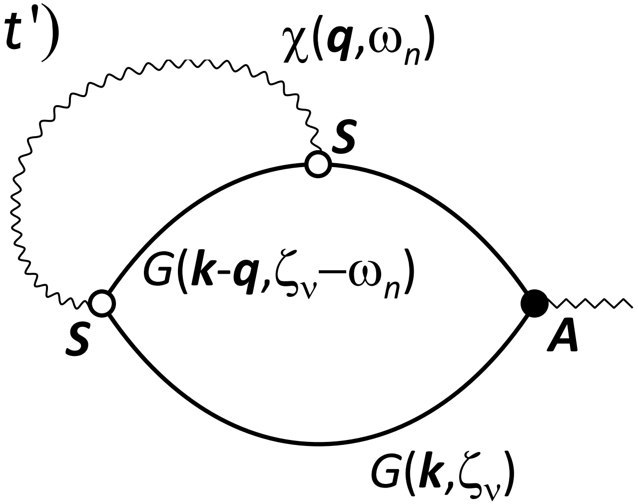
Linear response theory

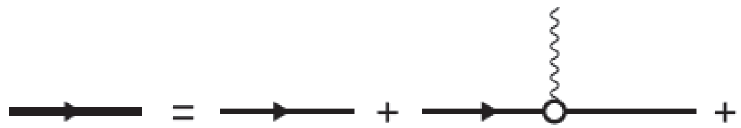
$$\left\langle \dot{S}^x_{surface} \right\rangle = -\frac{i}{\hbar}\int dt' \; e^{\eta t} \left\langle [\dot{S}^x_{surface}(t), j_y(t')] \right\rangle A_y(t')$$

$=$ 

$+$ 

$+$

$$\left\langle c^+_{\boldsymbol{k}} c_{\boldsymbol{k}} \right\rangle = G(\boldsymbol{k}) =$$



$$\left\langle S^i_{-\boldsymbol{q}} S^j_{\boldsymbol{q}} \right\rangle = \chi^{ij}(\boldsymbol{q}) =$$

Microscopic theory of spin torque

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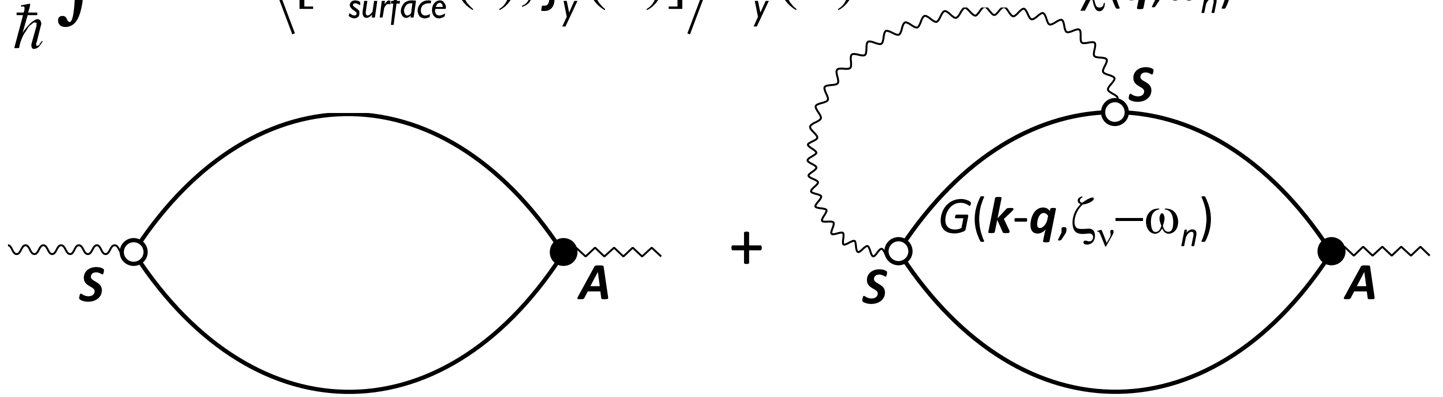
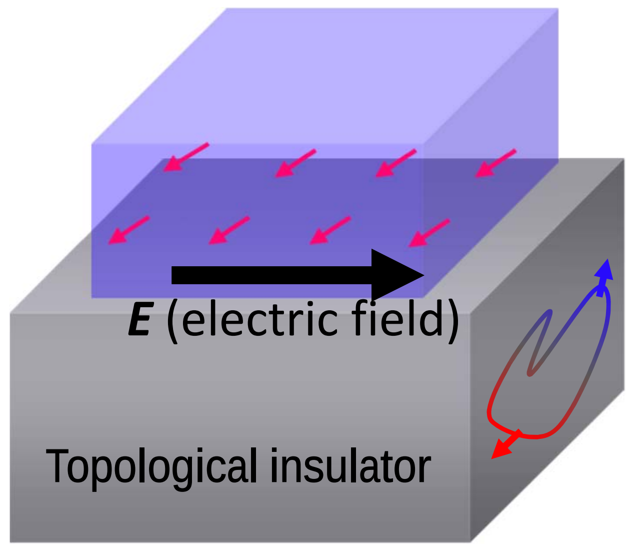
$=$



$+$

$$\cong \langle S_x \rangle \frac{a^3 k_B T}{\hbar^3 v^2 D}\varepsilon_F \tau e E_y$$

$$\frac{J^{S_x}}{E_y} \cong 10 \left(\frac{\hbar}{e}\right) [\Omega^{-1}\mathrm{cm}^{-1}]$$



Short summary

N. Okuma, KN
arXiv:1610.05236

Part I

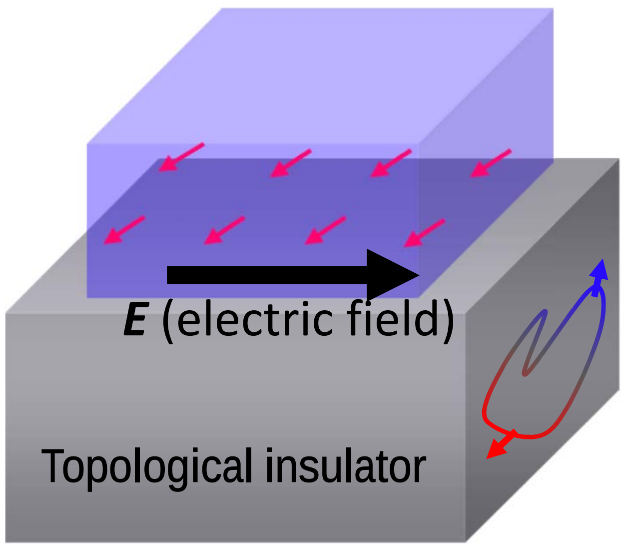
- Spin-Electricity conversion in topological insulators

The enhanced dumping factor

$$\delta\alpha = \frac{\mu_H J^2}{\hbar e v_F^2}$$

Electrically induced spin current

$$\frac{J^{S_x}}{E_y} \cong 10 \left(\frac{\hbar}{e}\right) [\Omega^{-1}\mathrm{cm}^{-1}]$$



Outline

Part I

- Spin-Electricity conversion in topological insulators

Part II

- Introduction: What is a Weyl semimetal?
- Magnetization dynamics in Weyl semimetals

What is Weyl a semimetal?

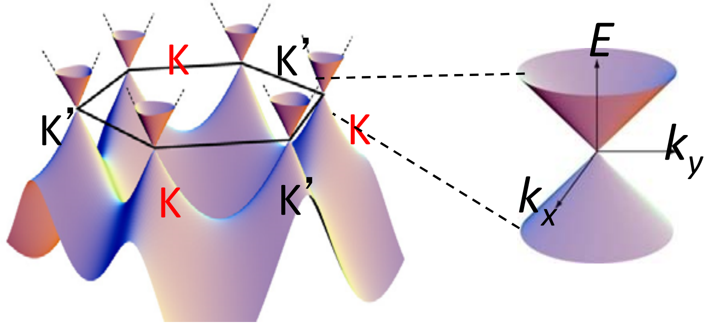
3-dimensional analogue of "graphene"

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 Weyl a semimetal?

Differences

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)

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

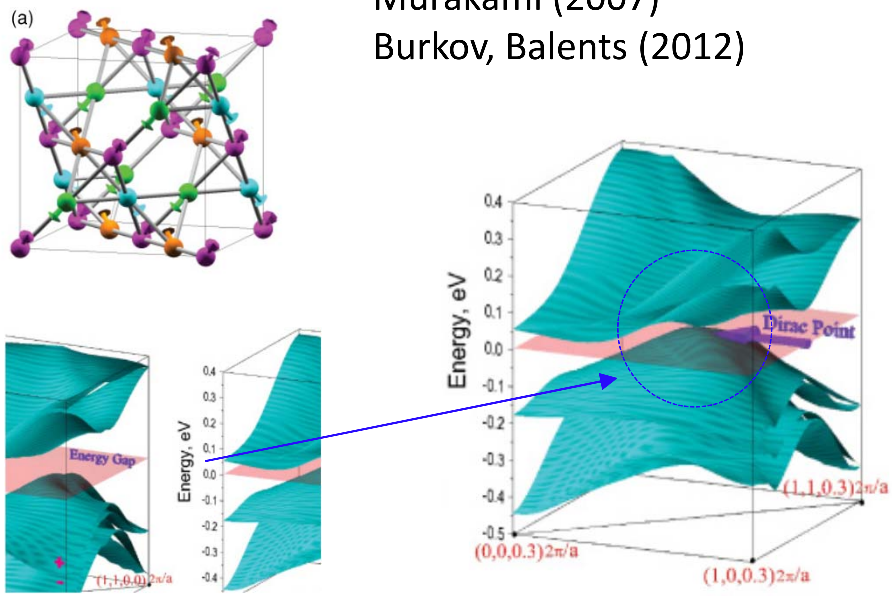
σ_i : real-spin

magnetic degrees of freedom

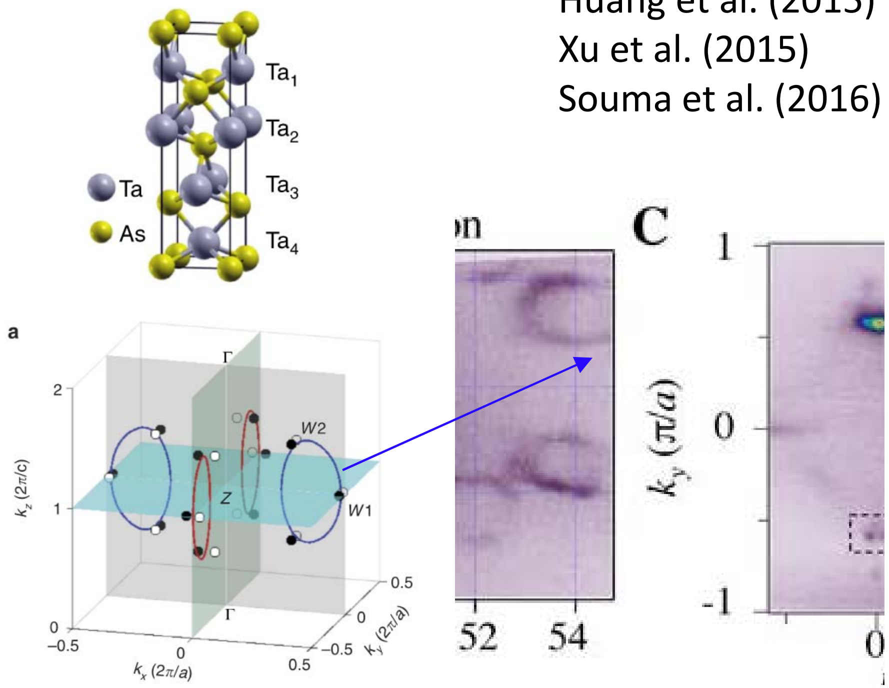
(Strong SOC)

Theory and Experiment

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



Huang et al. (2015)
Xu et al. (2015)
Souma et al. (2016)



3D (Weyl semimetal)

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

σ_i : real-spin

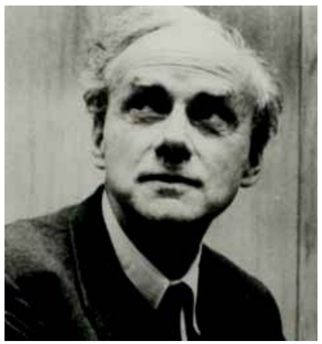
magnetic degrees of freedom

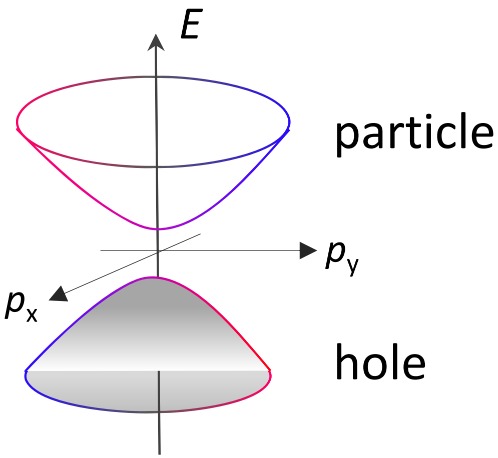
(Strong SOC)

Relativistic quantum mechanics

- Dirac theory

$$H = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4 \quad \Longleftrightarrow \quad E^2 = p_x^2 + p_y^2 + p_z^2 + m_0^2$$





Relativistic quantum mechanics

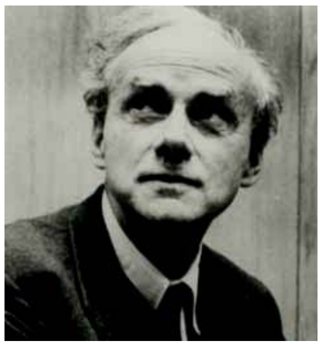
- Dirac theory

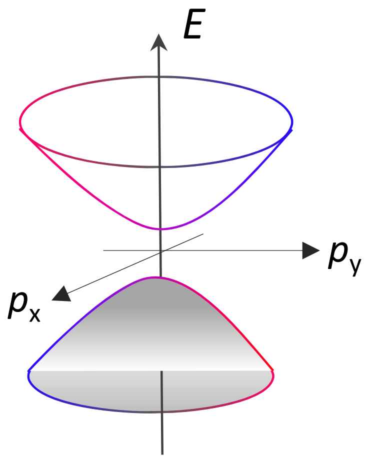
$$H = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4 \quad \Longleftrightarrow \quad E^2 = p_x^2 + p_y^2 + p_z^2 + m_0^2$$

matrices

$$H^2 = \left(\sum_i p_i\alpha_i + m_0\alpha_4\right)^2$$
$$= \sum_{i,j} p_i p_j \alpha_i\alpha_j + \sum_i p_i m_0(\alpha_i\alpha_4 + \alpha_4\alpha_i) + m_0^2\alpha_4\alpha_4$$

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





Relativistic quantum mechanics

- Dirac theory

$$H = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4 \quad \Longleftrightarrow \quad E^2 = p_x^2 + p_y^2 + p_z^2 + m_0^2$$

σ_x σ_y σ_z

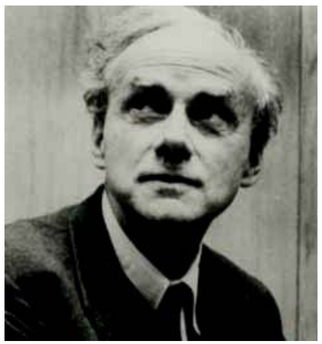
matrices

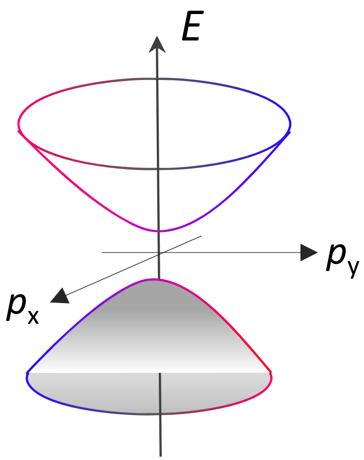
$$H^2 = \left(\sum_i p_i\alpha_i + m_0\alpha_4\right)^2$$

$$= \sum_{i,j} p_i p_j \alpha_i\alpha_j + \sum_i p_i m_0(\alpha_i\alpha_4 + \alpha_4\alpha_i) + m_0^2\alpha_4\alpha_4$$

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

$$\sigma_x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad \sigma_y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad \sigma_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$





Relativistic quantum mechanics

- Dirac theory

$$H = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4 \quad \Leftarrow \quad E^2 = p_x^2 + p_y^2 + p_z^2 + m_0^2$$

$\alpha_1 \quad \alpha_2 \quad \alpha_3 \quad \alpha_4$

α_i: 4x4 Dirac matrices

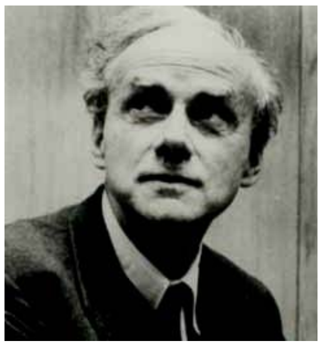
$$H^2 = \left(\sum_i p_i\alpha_i + m_0\alpha_4\right)^2$$

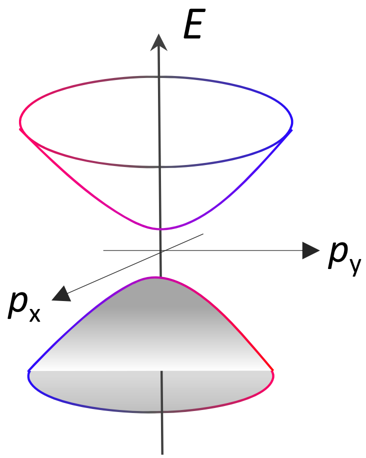
$$= \sum_{i,j} p_i p_j \alpha_i\alpha_j + \sum_i p_i m_0(\alpha_i\alpha_4 + \alpha_4\alpha_i) + m_0^2\alpha_4\alpha_4$$

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

$$\alpha_1 = \begin{bmatrix} 0 & \sigma_x \\ \sigma_x & 0 \end{bmatrix}, \alpha_2 = \begin{bmatrix} 0 & \sigma_y \\ \sigma_y & 0 \end{bmatrix},$$

$$\alpha_3 = \begin{bmatrix} 0 & \sigma_z \\ \sigma_z & 0 \end{bmatrix}, \alpha_4 = \begin{bmatrix} +I & 0 \\ 0 & -I \end{bmatrix}$$



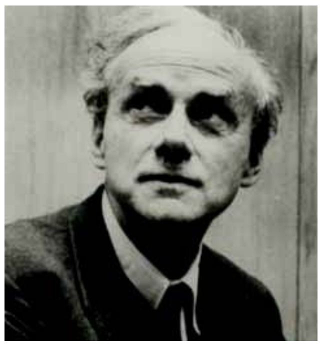


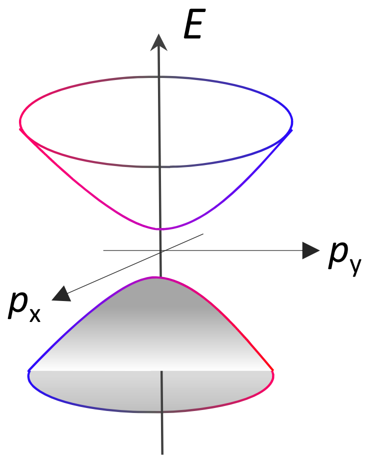
Relativistic quantum mechanics

・Dirac theory

$$H = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4$$

α_i: 4x4 Dirac matrices



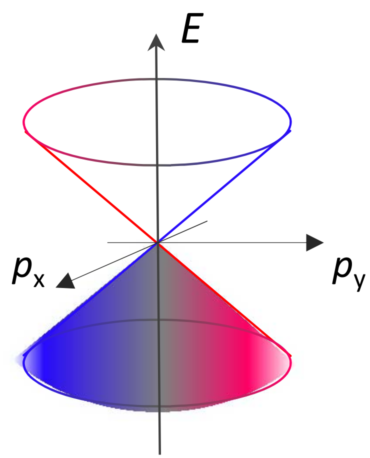


・Weyl theory

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

σ_i: 2x2 Pauli matrices

massless



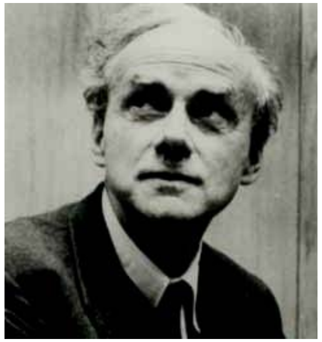
Relativistic quantum mechanics

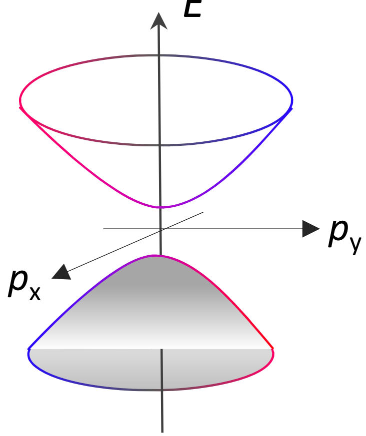
- Dirac theory

$$H = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4$$

α_i: 4x4 Dirac matrices

degenerate





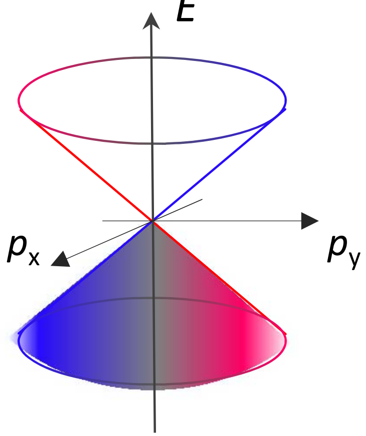
- Weyl theory

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

σ_i: 2x2 Pauli matrices

massless

non-degenerate



Dirac–Weyl semimetals

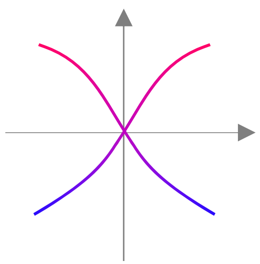
・Dirac semimetal

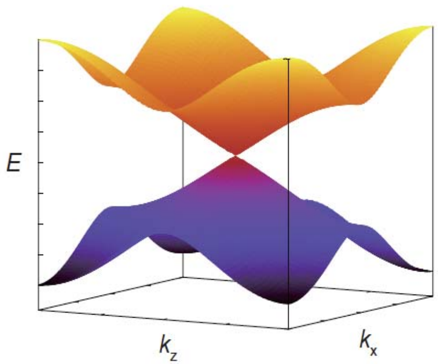
$$H = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4$$

α_i: 4x4 Dirac matrices

m_0=0 (massless)

degenerate





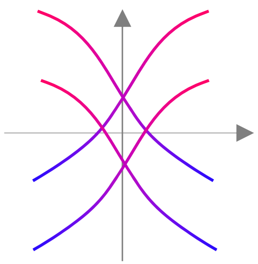
・Weyl semimetal

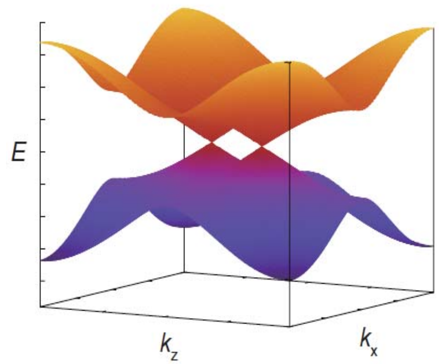
$$H = p_x\sigma_1 + p_y\sigma_2 + p_z\sigma_3$$

σ_i: 2x2 Pauli matrices

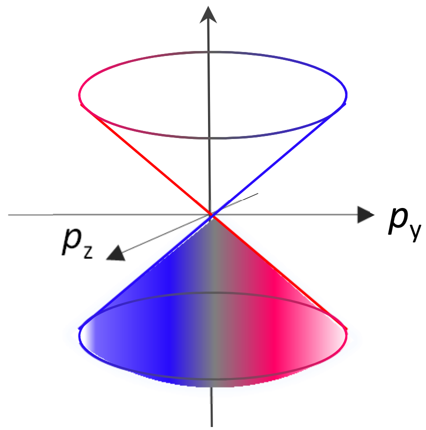
massless

non-degenerate





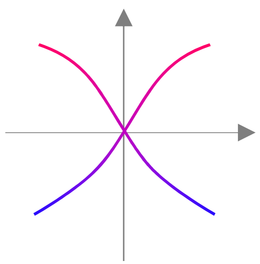
Dirac–Weyl semimetals

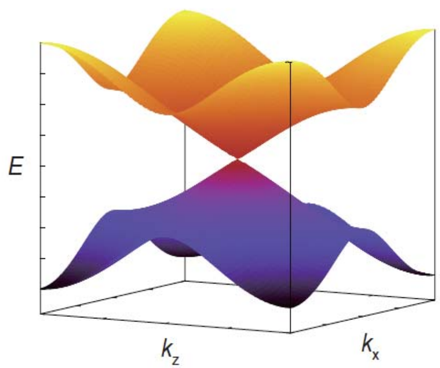


symmetry breaking

・Dirac semimetal

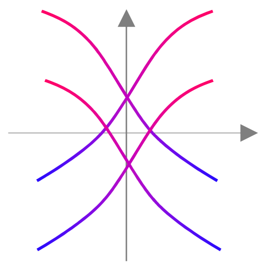
degenerate

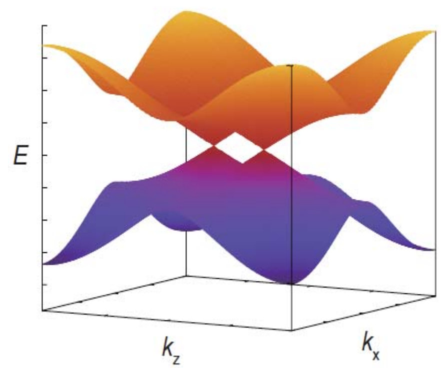




・Weyl semimetal

non–degenerate





Two types of Weyl semimetals

- Weyl semimetal with *broken* space-inversion symmetry

Non-magnetic $M=0$

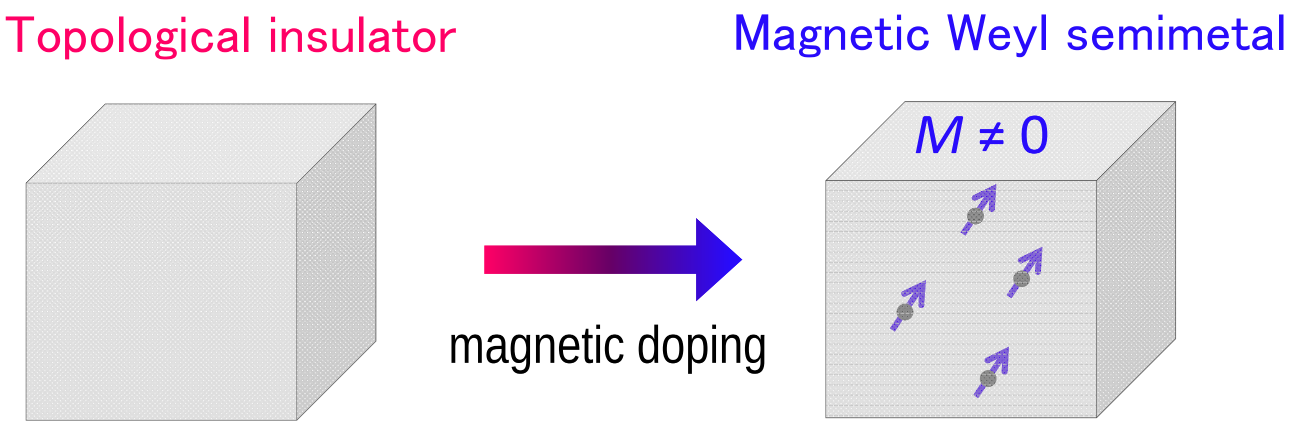
-Materials: TaAs , NbAs, NbP, TaP, ..

- Weyl semimetal with *broken* time-reversal symmetry

Ferromagnetic $M \neq 0$

-Only theoretical proposals so far

From TI to Weyl SM



- Weyl semimetal with *broken* time-reversal symmetry

Ferromagnetic $M \neq 0$

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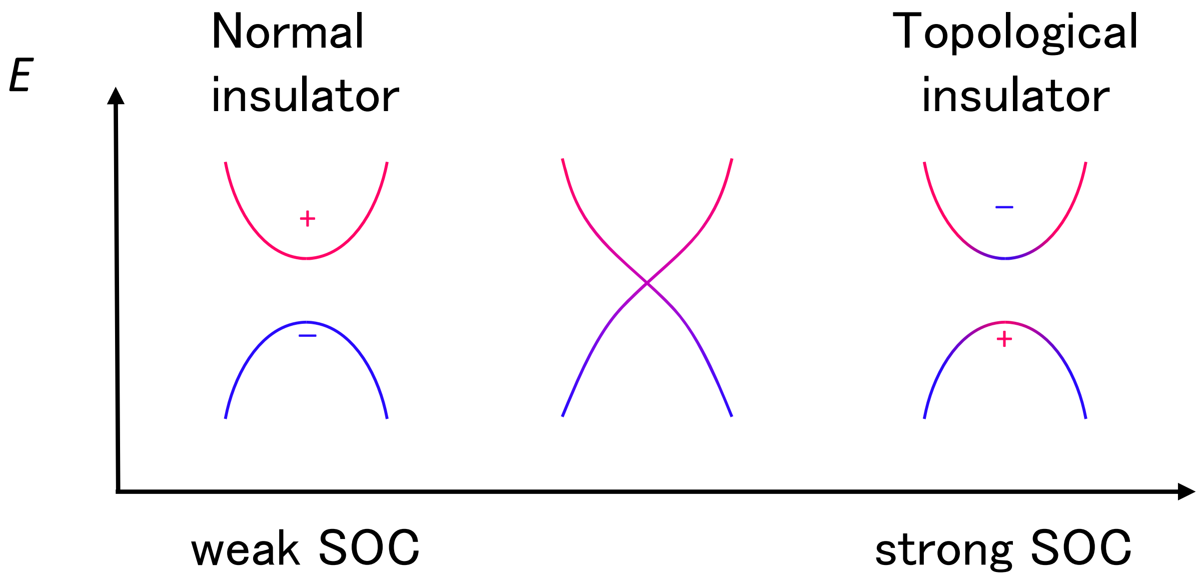
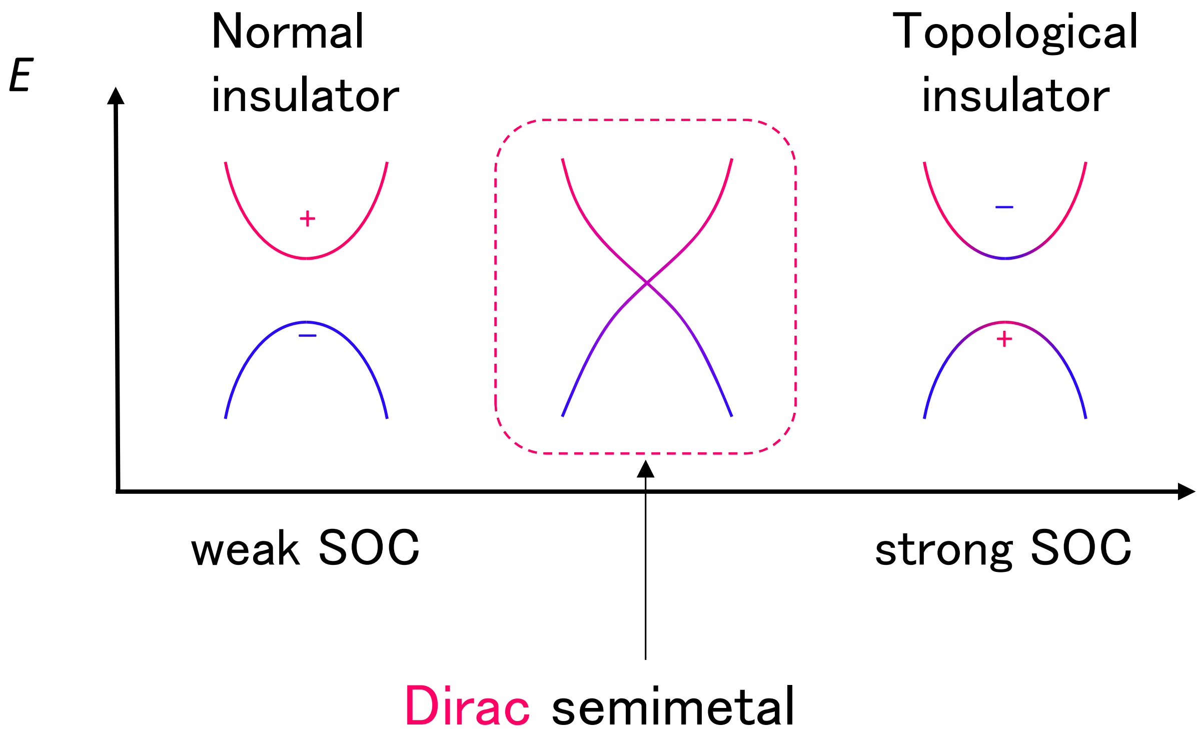
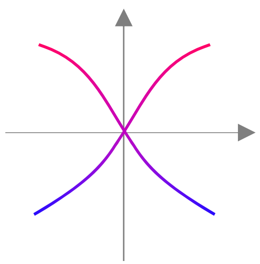
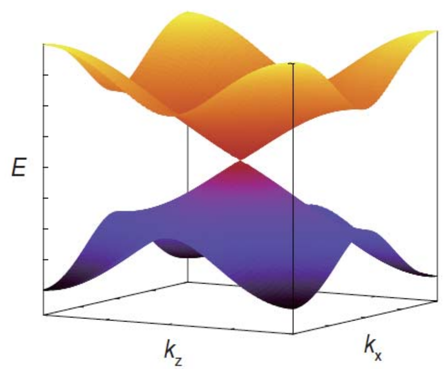
From TI to Weyl SM



From TI to Weyl SM

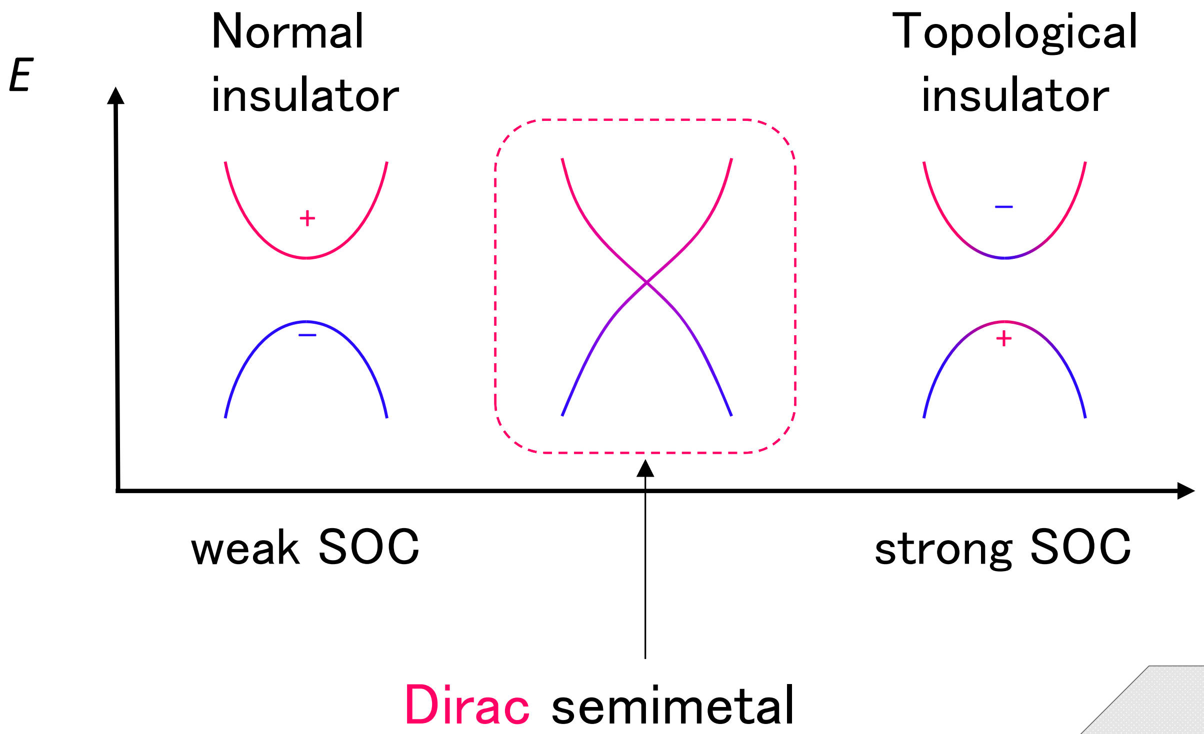


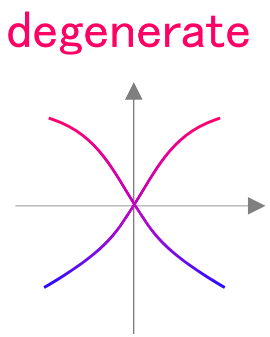


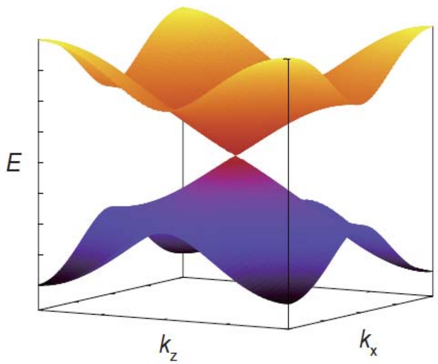


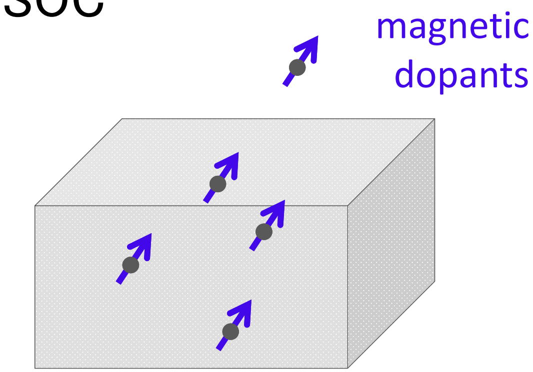
$$H_{4\times4}^{\mathrm{Dirac}} = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4$$

From TI to Weyl SM





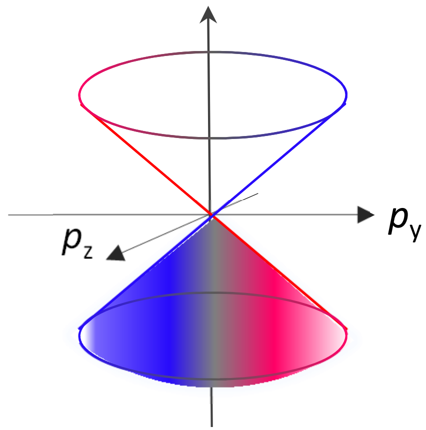




$$H^{\mathrm{Dirac}}_{4\times4} = p_x\alpha_1 + p_y\alpha_2 + p_z\alpha_3 + m_0\alpha_4$$

From TI to Weyl SM

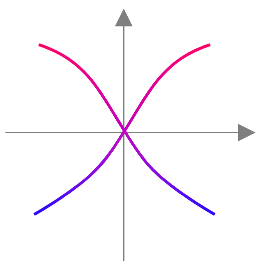
Burkov, Balents 2011

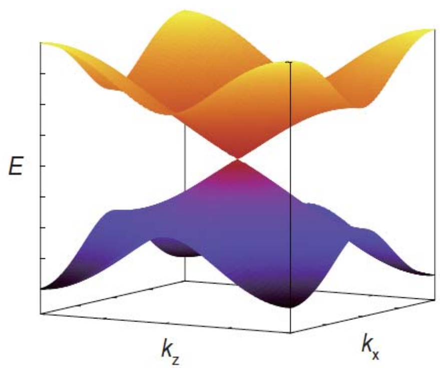


magnetic doping

- Dirac semimetals

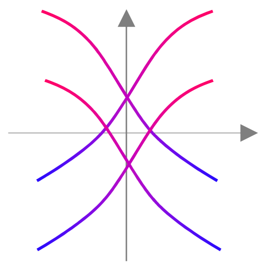
degenerate

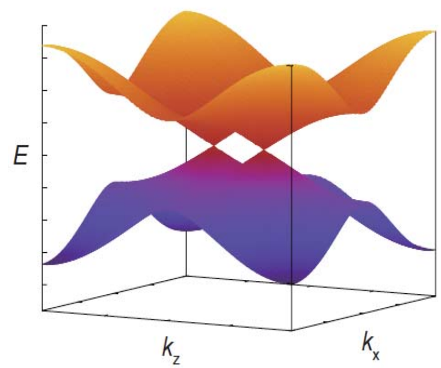




- Weyl semimetals

non−degenerate



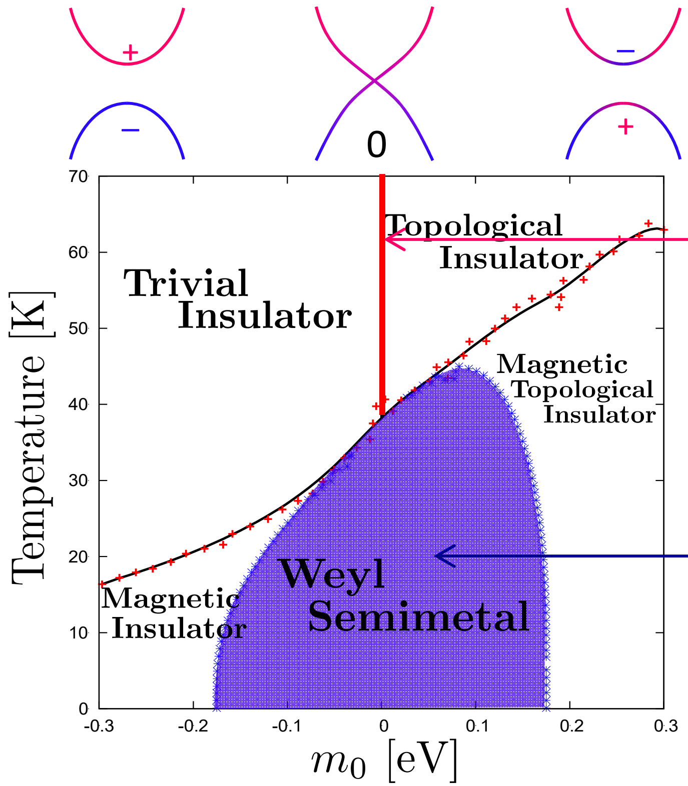


Magnetic ordering

Theory
Kurebayashi, KN. (2014)

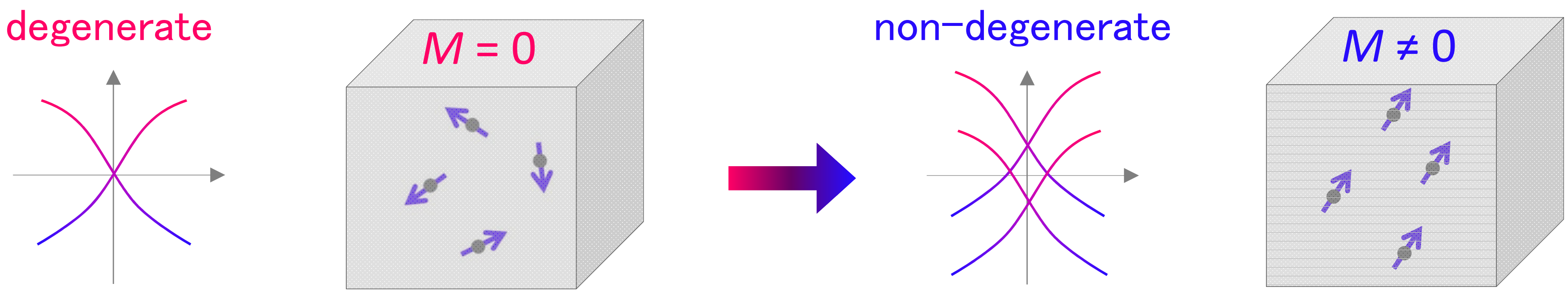
high T

low T



Dirac semimetal

Weyl semimetal



paramagnetic

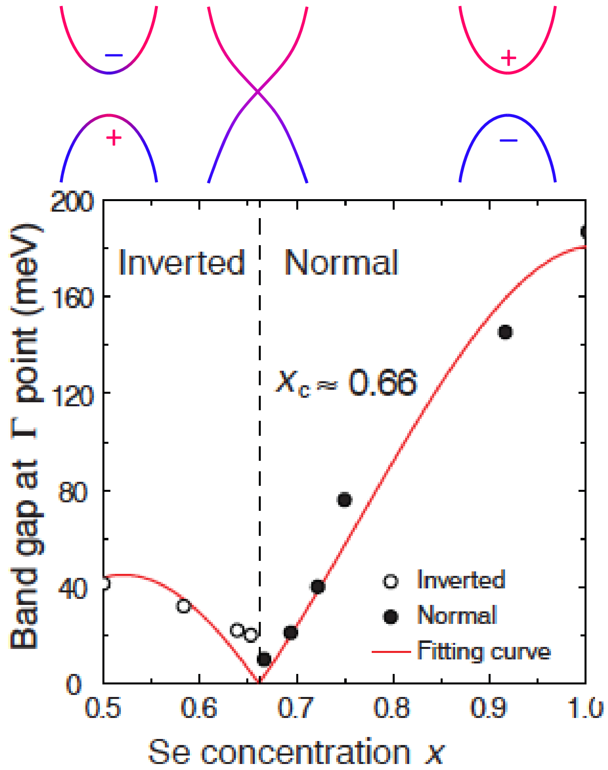
ferromagnetic

Experiment

Science 339, 1582 (2013)

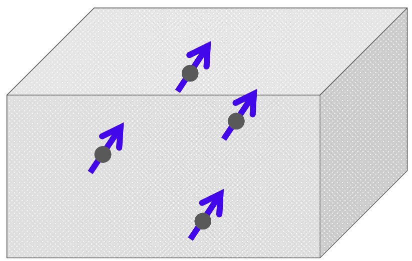
Topology-Driven Magnetic Quantum Phase Transition in Topological Insulators

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†]

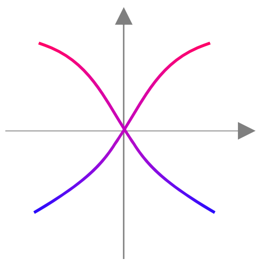


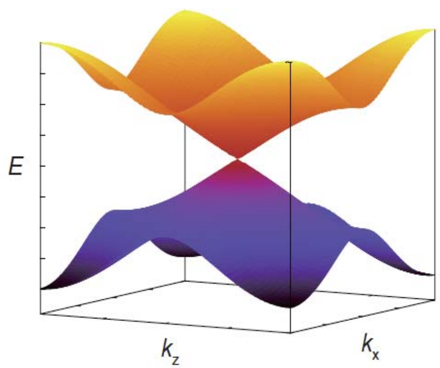
$Bi_{2-y}Cr_y(Se_{1-x}Te_x)_3$

 Cr

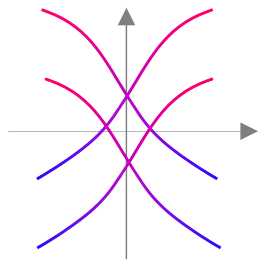


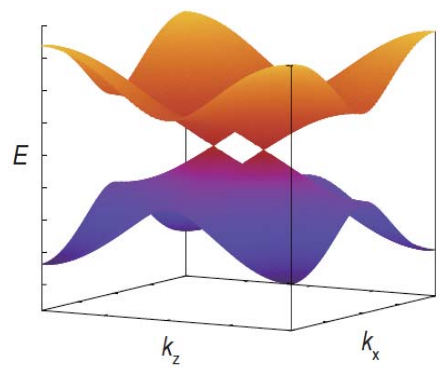
degenerate





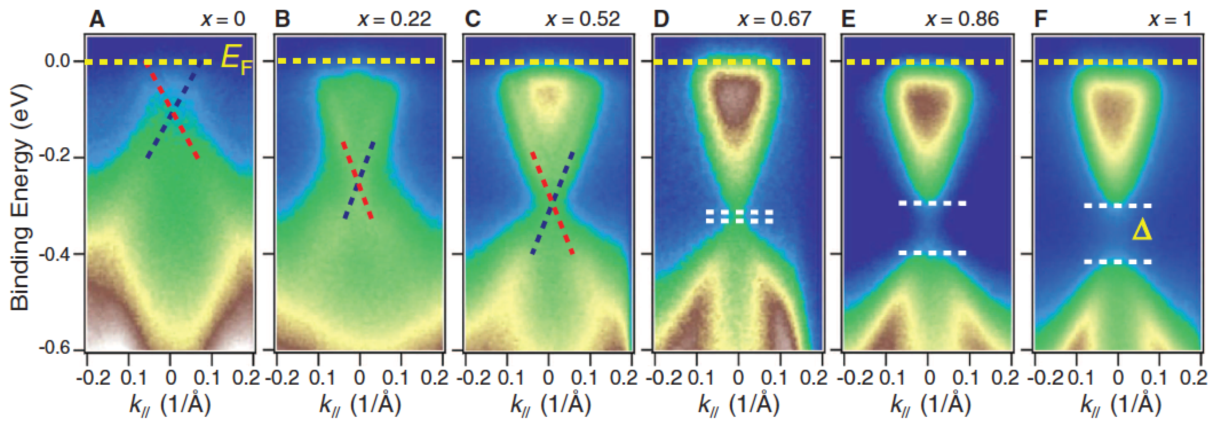
non−degenerate

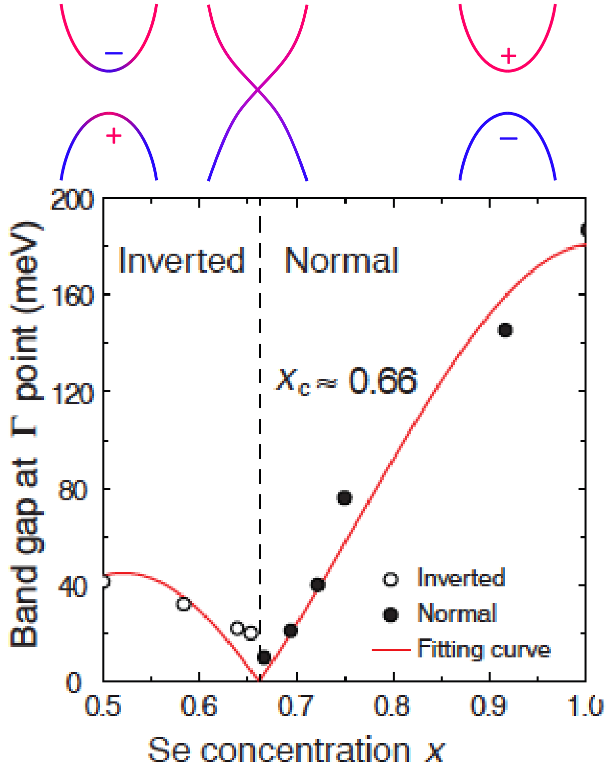




Experiment

Science 339, 1582 (2013)





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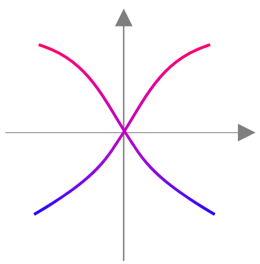
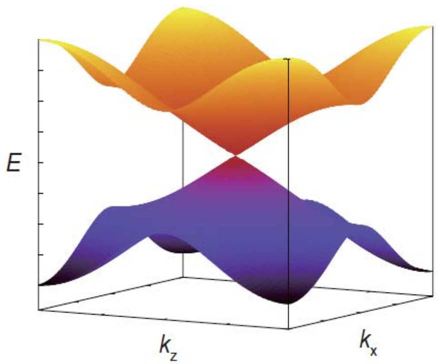
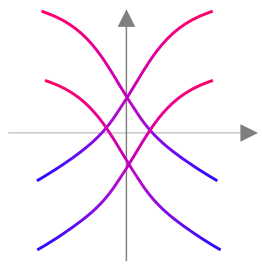
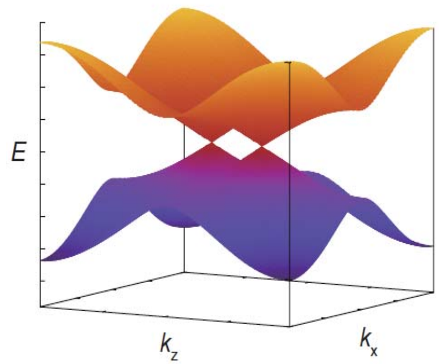




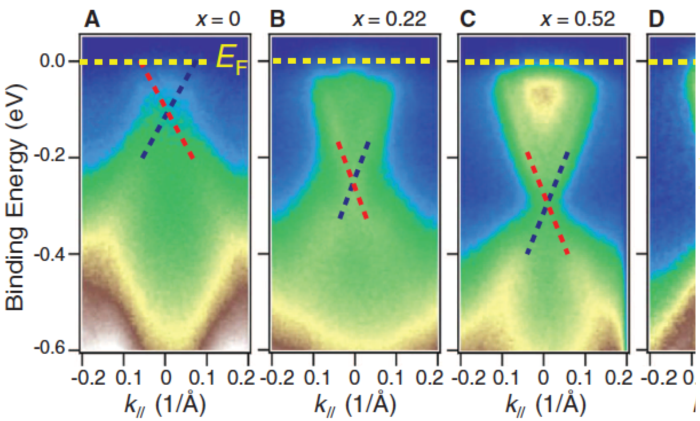
non−degenerate

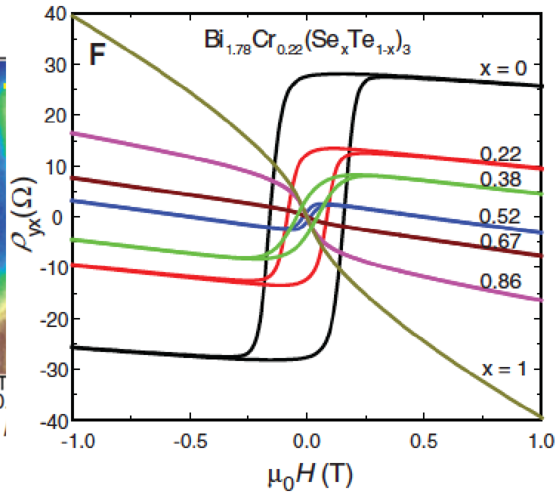


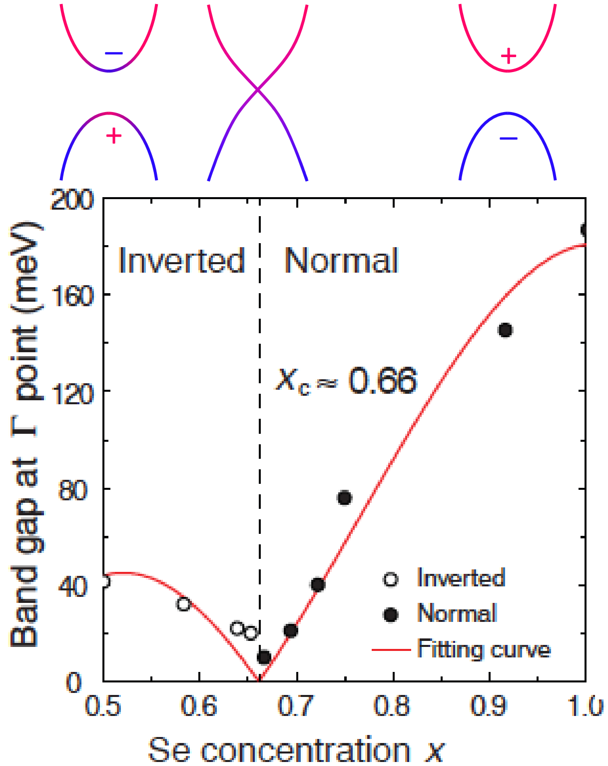


Experiment

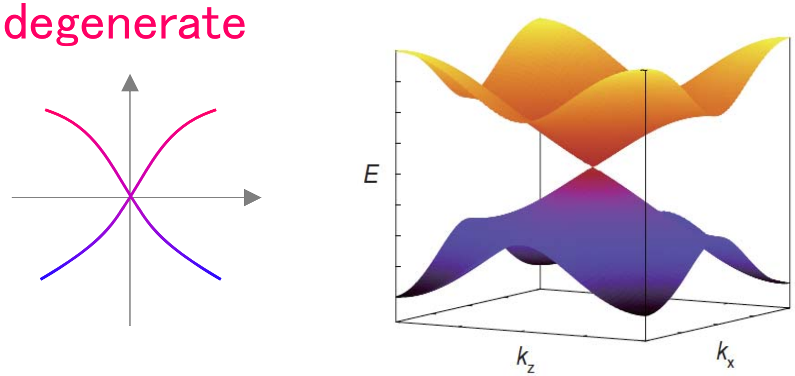
Science 339, 1582 (2013)



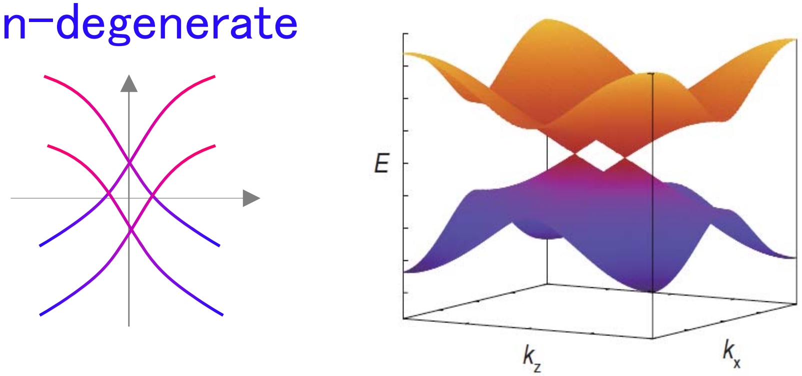




degenerate

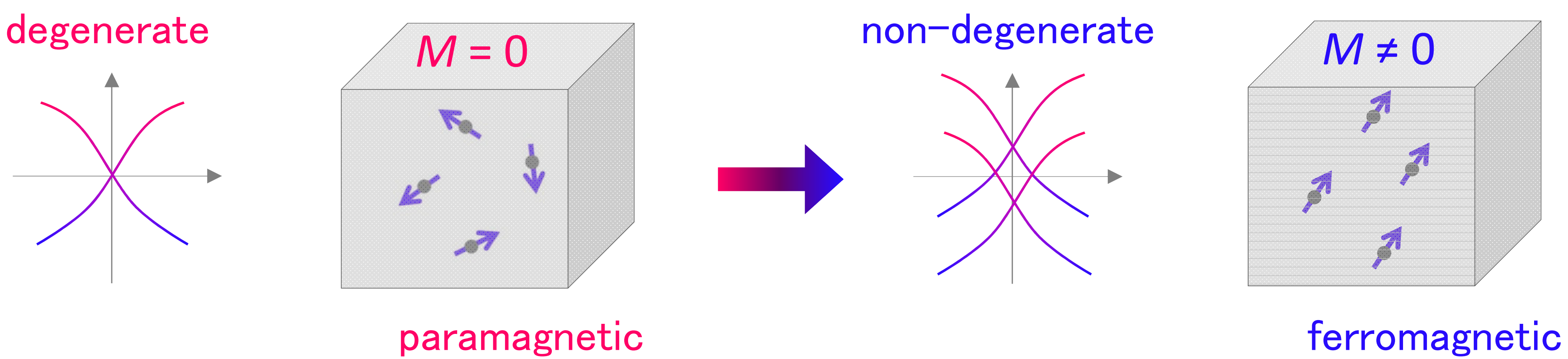


non-degenerate



Magnetic ordering

$$F = \overset{\text{local spin}}{\overset{\downarrow}{\frac{1}{2\chi_s}}} M^2 + \overset{\text{electron spin}}{\overset{\downarrow}{\frac{1}{2\chi_e}}} m^2 - JMm$$

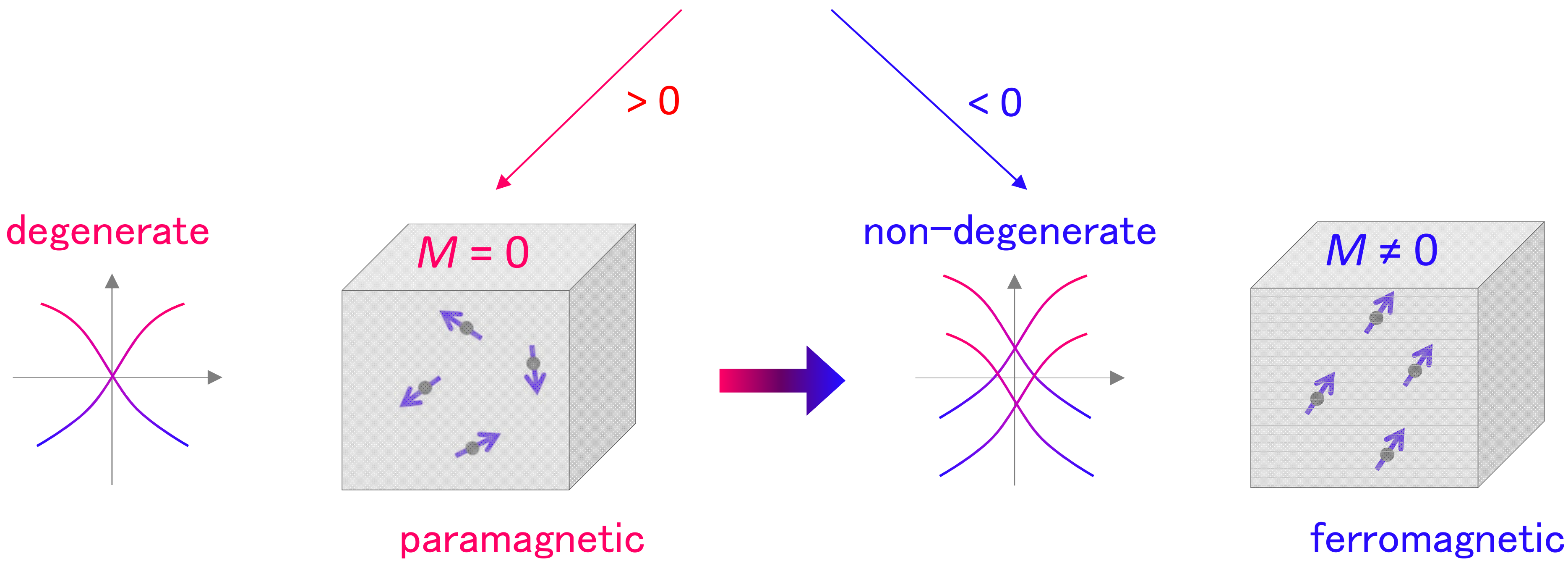


Magnetic ordering

local spin　　electron spin

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

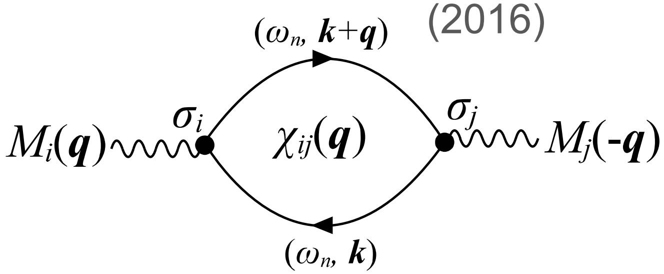
$$= \frac{1}{2}\left(\frac{1}{\chi_s} - J^2\chi_e\right)M^2 + \frac{1}{2\chi_e}\left(m - \chi_e JM\right)^2$$



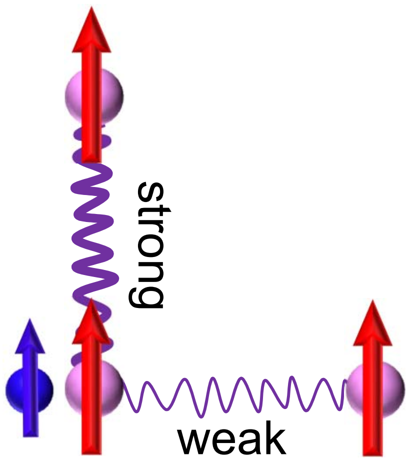
GL & gradient expansion

$$F_{\mathrm{GL}}[\boldsymbol{M}] = \int d^3\boldsymbol{r}\left[\frac{1}{2}\left(\frac{1}{\chi_s} - J^2\chi_e\right)|\boldsymbol{M}|^2 + J_H[\boldsymbol{\nabla}\,\boldsymbol{M}]^2 + J_K[\boldsymbol{\nabla}\times\,\boldsymbol{M}]^2\right]$$

Araki, KN, PRB 93, 094438 (2016)

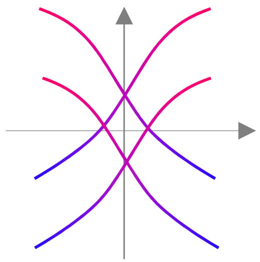


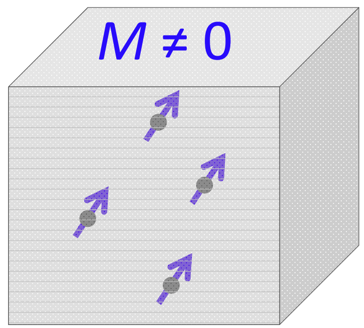
$$\mathrm{H}_{\mathrm{Weyl}} = \pm\,\boldsymbol{\sigma}\cdot\boldsymbol{k}$$



$$\mathrm{H}_{\mathrm{exc}} = J\boldsymbol{\sigma}\cdot\boldsymbol{M}$$

non-degenerate





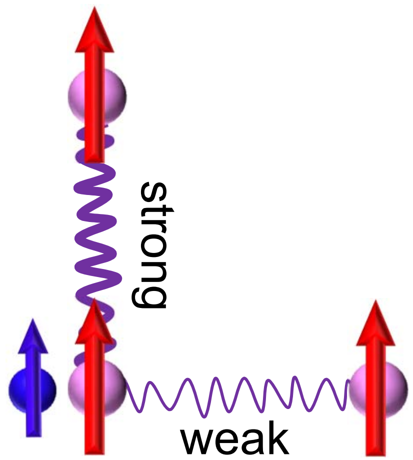
ferromagnetic

GL & gradient expansion

$$F_{\mathrm{GL}}[\boldsymbol{M}] = \int d^3\boldsymbol{r}\left[\frac{1}{2}\left(\frac{1}{\chi_s} - J^2\chi_e\right)|\boldsymbol{M}|^2 + J_H[\boldsymbol{\nabla}\,\boldsymbol{M}]^2 + J_K[\boldsymbol{\nabla}\times\ \boldsymbol{M}]^2\right]$$

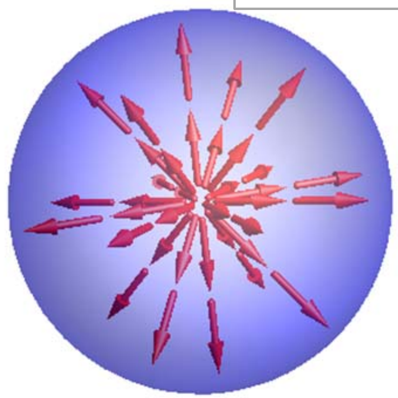
Araki, KN, PRB 93, 094438 (2016)

$\mathrm{H}_{\mathrm{Weyl}} = \pm\,\boldsymbol{\sigma}\cdot\boldsymbol{k}$



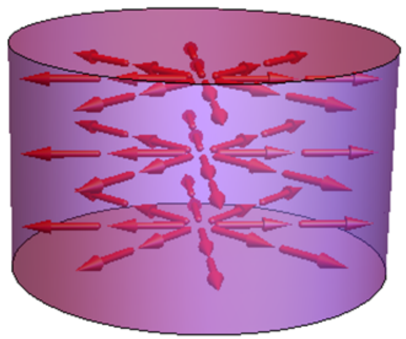
$\mathrm{H}_{\mathrm{exc}} = J\boldsymbol{\sigma}\cdot\boldsymbol{M}$

Excited states



Hedgehog

$\nabla\boldsymbol{M}\neq 0,\ \nabla\times\boldsymbol{M}=0$



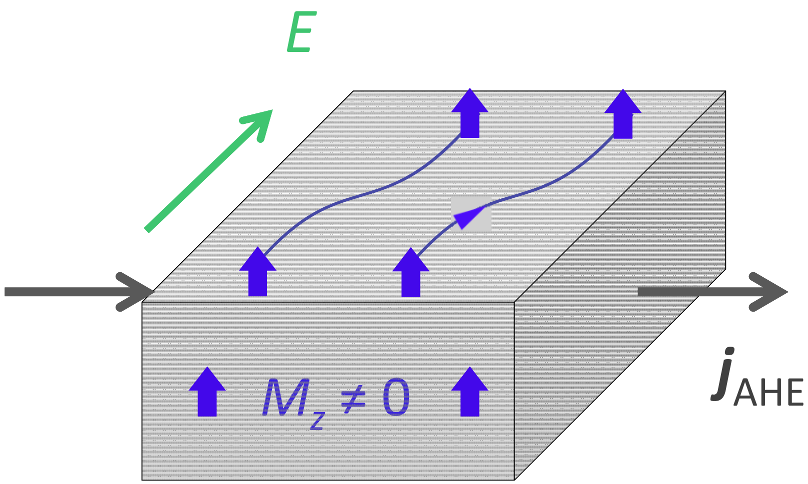
Radial vortex

$\nabla\boldsymbol{M}\neq 0,\ \nabla\times\boldsymbol{M}=0$

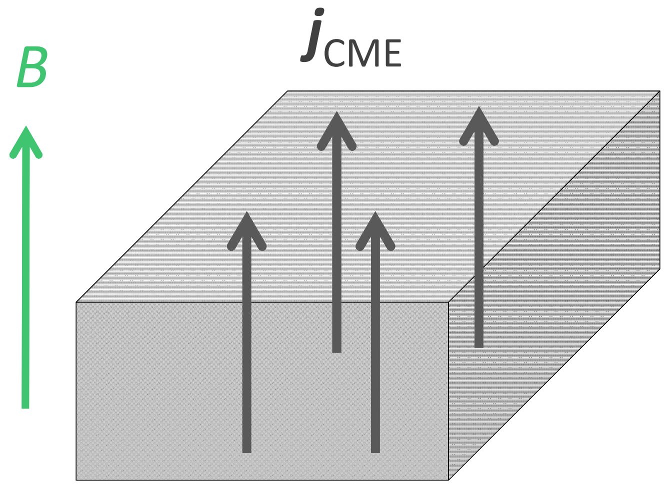
Anomalous transport phenomena

in magnetic Weyl semimetals

- Anomalous Hall effect



- Chiral magnetic effect

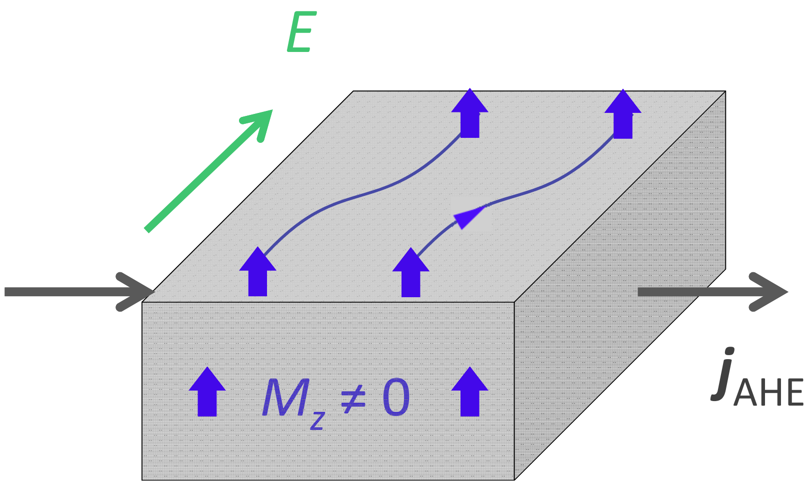


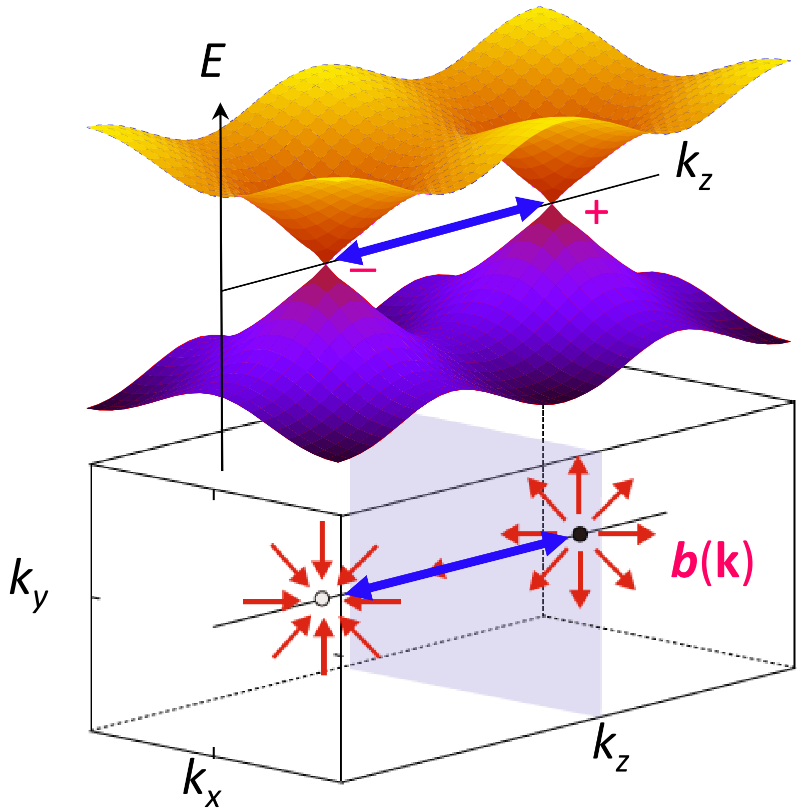
Fukushima, Kharzeev, and Warringa (2008)

Anomalous Hall responses

$$\boldsymbol{j}_{\text{anomaly}} = \sigma_{\text{AHE}}\, \widehat{\boldsymbol{M}} \times \boldsymbol{E}$$

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



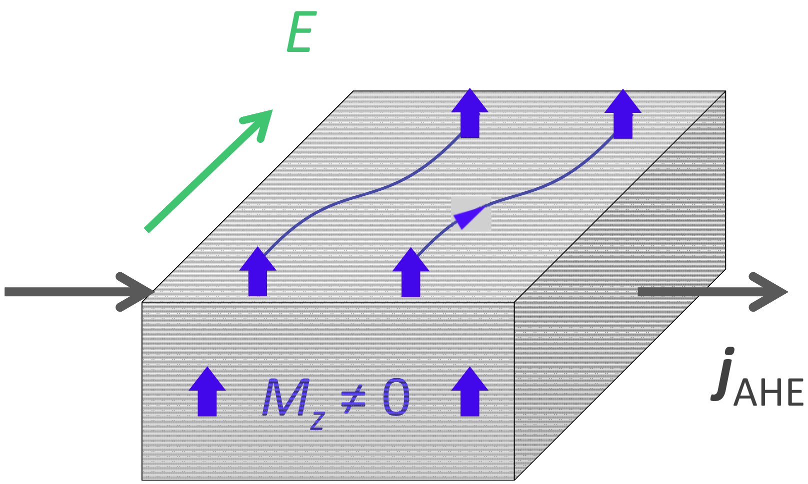


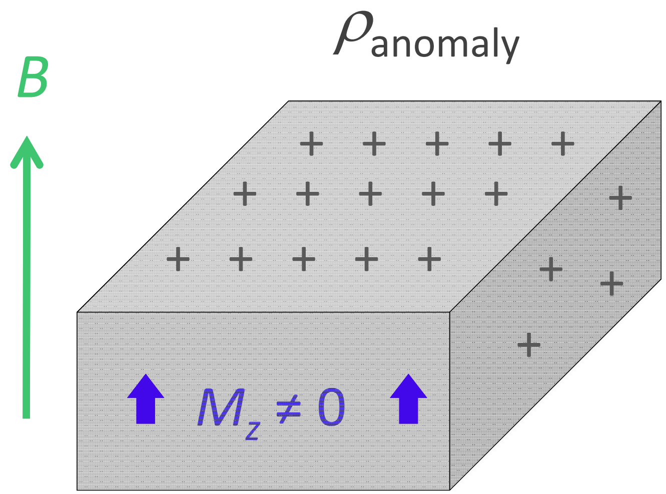
$$\sigma_{\text{AHE}} = \frac{e^2}{\hbar}\int_{BZ}\frac{d^3k}{(2\pi)^3}\, b_z(\boldsymbol{k}) = \frac{e^2}{2\pi h}\left(\frac{2JM_z}{v}\right)$$

Anomalous Hall responses

$$\boldsymbol{j}_{\text{anomaly}} = \sigma_{\text{AHE}} \widehat{\boldsymbol{M}} \times \boldsymbol{E}$$

$$\rho_{\text{anomaly}} = \sigma_{\text{AHE}} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}$$



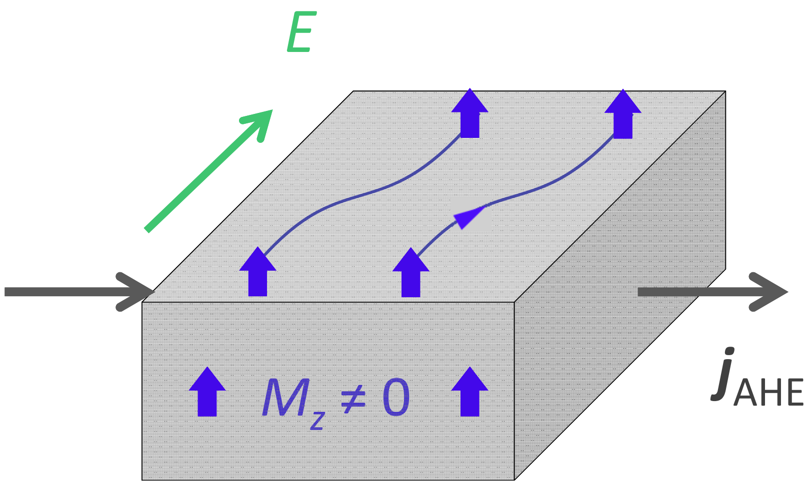


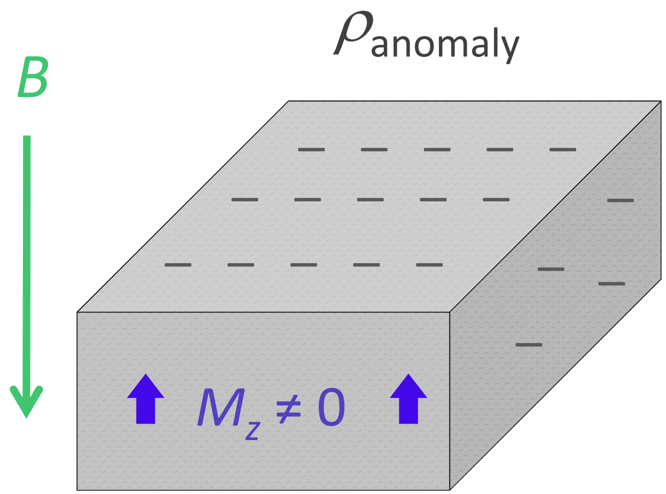
$$\frac{\partial}{\partial t}\rho_{\text{anomaly}} + \boldsymbol{\nabla} \cdot \boldsymbol{j}_{\text{anomaly}} = 0$$

Anomalous Hall responses

$$\boldsymbol{j}_{\text{anomaly}} = \sigma_{\text{AHE}} \widehat{\boldsymbol{M}} \times \boldsymbol{E}$$

$$\rho_{\text{anomaly}} = \sigma_{\text{AHE}} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}$$





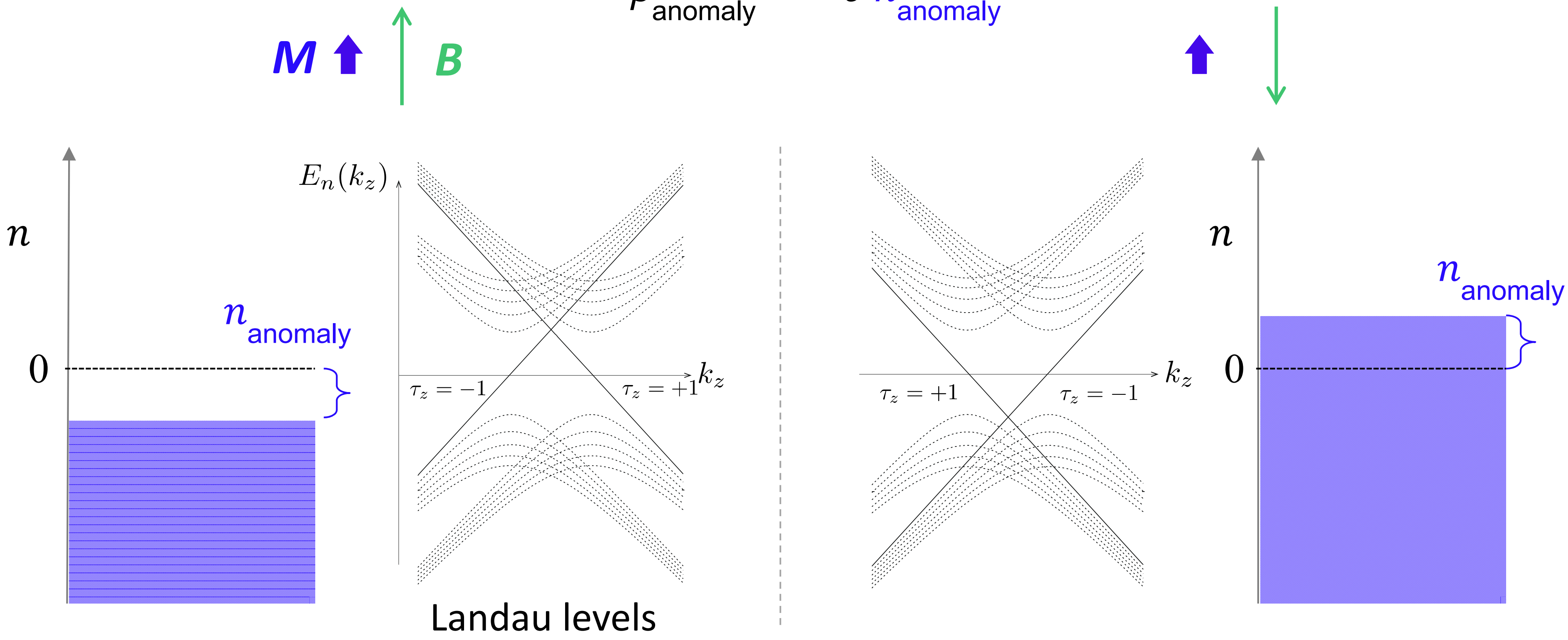
$$\frac{\partial}{\partial t} \rho_{\text{anomaly}} + \boldsymbol{\nabla} \cdot \boldsymbol{j}_{\text{anomaly}} = 0$$

Anomalous Hall responses

$$\boldsymbol{j}_{\text{anomaly}} = \sigma_{\text{AHE}}\,\widehat{\boldsymbol{M}}\times\boldsymbol{E}$$

$$\rho_{\text{anomaly}} = \sigma_{\text{AHE}}\,\widehat{\boldsymbol{M}}\cdot\boldsymbol{B}$$

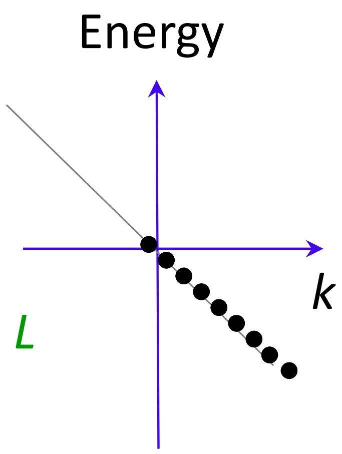
$$\rho_{\text{anomaly}} = -e\,n_{\text{anomaly}}$$

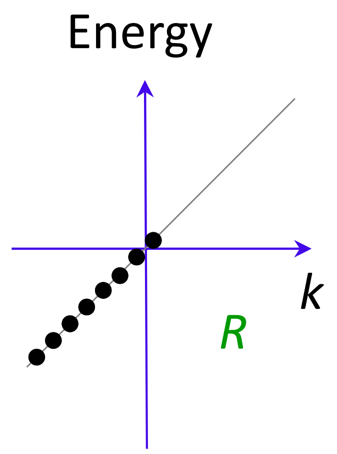


Chiral anomaly

1D Weyl fermions

$$H_{1D} = \int dx \; \psi_R^{+}\left(-i\partial_x + eA_x\right)\psi_R - \psi_L^{+}\left(-i\partial_x + eA_x\right)\psi_L$$





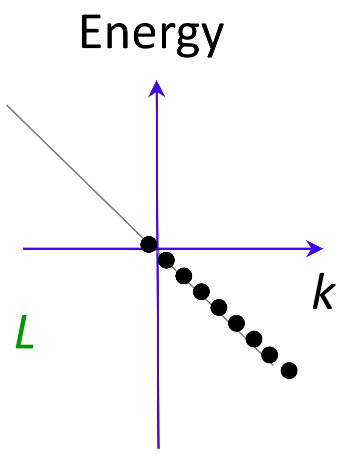
$$\frac{dk}{dt} = -eE$$

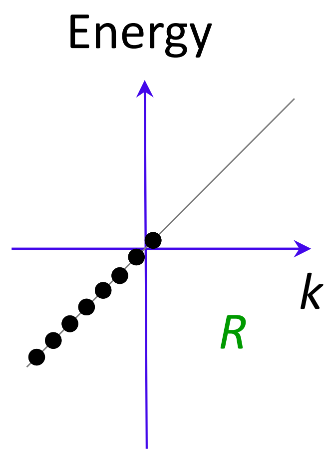
Chiral anomaly

1D Weyl fermions

$$H_{1D} = \int dx \; \psi_R^{+}\left(-i\partial_x + eA_x\right)\psi_R - \psi_L^{+}\left(-i\partial_x + eA_x\right)\psi_L$$

$$\frac{dN_L}{dt} = -\int dx \frac{-e}{2\pi} E \qquad \frac{dN_R}{dt} = +\int dx \frac{-e}{2\pi} E$$





$$\frac{dk}{dt} = -eE$$

Chiral anomaly

1D Weyl fermions

$$H_{1D} = \int dx\ \psi_R^{+}\left(-i\partial_x + eA_x\right)\psi_R - \psi_L^{+}\left(-i\partial_x + eA_x\right)\psi_L$$

$$\frac{dN_L}{dt} = -\int dx \frac{-e}{2\pi} E \qquad \frac{dN_R}{dt} = +\int dx \frac{-e}{2\pi} E$$

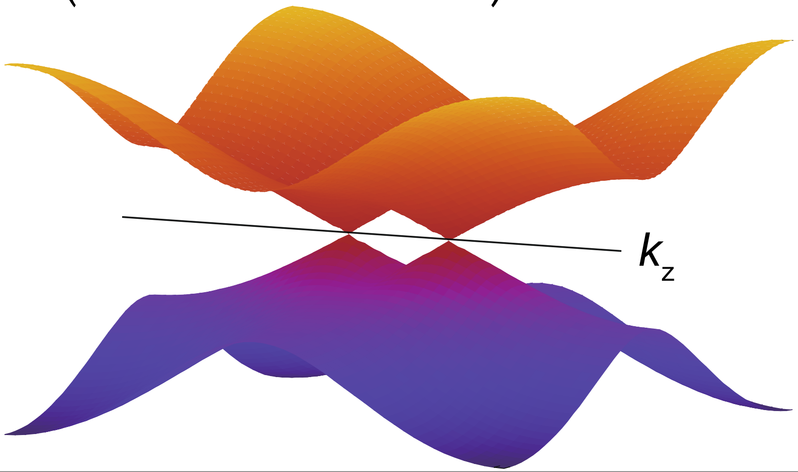
$$\frac{d(N_R + N_L)}{dt} = 0$$ total charge

$$\frac{d(N_R - N_L)}{dt} = \int dx \frac{-e}{\pi} E$$ axial charge

Chiral anomaly

3D Weyl fermions

$$H_{3D} = \int d^3x \;\; \psi_R^{+}\vec{\sigma}\cdot\left(-i\vec{\nabla}+e\boldsymbol{A}+J\boldsymbol{M}\right)\psi_R - \psi_L^{+}\vec{\sigma}\cdot\left(-i\vec{\nabla}+e\boldsymbol{A}-J\boldsymbol{M}\right)\psi_L$$



$B = 0$

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

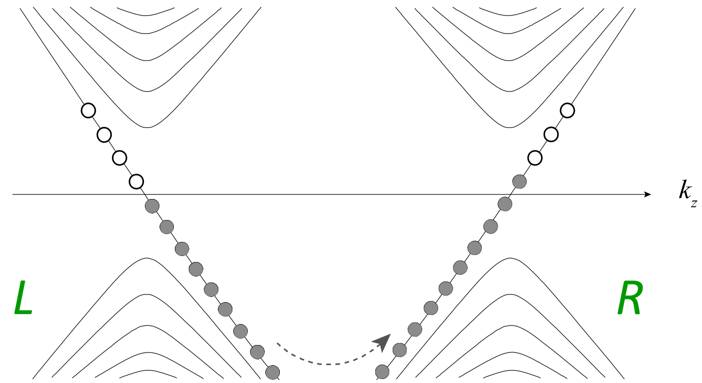
$$\frac{d(N_R-N_L)}{dt} = \int dx \frac{-e}{\pi}E$$ axial charge

for 1D

Chiral anomaly

3D Weyl fermions

$$H_{3D} = \int d^3x \ \psi_R^{+}\vec{\sigma}\cdot\left(-i\vec{\nabla}+e\boldsymbol{A}+J\boldsymbol{M}\right)\psi_R - \psi_L^{+}\vec{\sigma}\cdot\left(-i\vec{\nabla}+e\boldsymbol{A}-J\boldsymbol{M}\right)\psi_L$$



$B \neq 0$

$$N_{LL} = \frac{BL_xL_y}{hc/e}$$

$$\frac{d(N_R+N_L)}{dt} = \quad 0 \qquad \text{total charge}$$

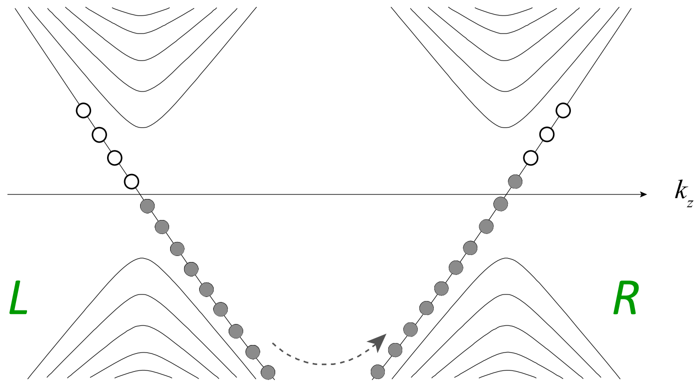
$$\frac{d(N_R-N_L)}{dt} = \int dx \frac{-e}{\pi}E \qquad \text{axial charge}$$

for 1D

Chiral anomaly

3D Weyl fermions

$$H_{3D} = \int d^3x \;\; \psi_R^{+}\vec{\sigma}\cdot\left(-i\vec{\nabla} + e\boldsymbol{A} + J\boldsymbol{M}\right)\psi_R - \psi_L^{+}\vec{\sigma}\cdot\left(-i\vec{\nabla} + e\boldsymbol{A} - J\boldsymbol{M}\right)\psi_L$$



$B \neq 0$

$$N_{LL} = \frac{BL_xL_y}{hc/e}$$

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

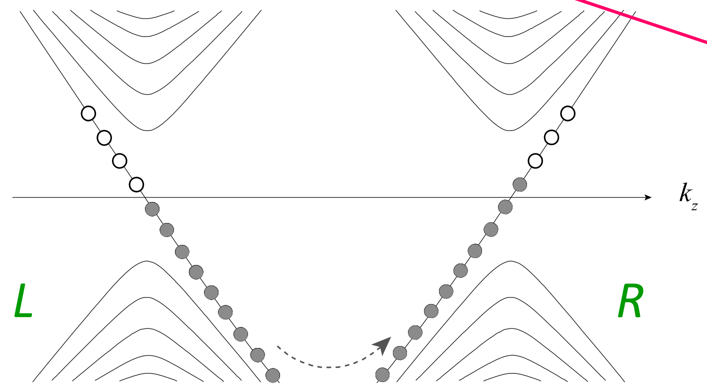
$$\frac{d(N_R-N_L)}{dt} = \int d^3x \frac{2e^2}{(2\pi)^2}\boldsymbol{E}\cdot\boldsymbol{B}$$ axial charge

Chiral anomaly

3D Weyl fermions

$$H_{3D} = \int d^3x \;\; \psi_R^{+}\vec{\sigma}\cdot\left(-i\vec{\nabla} + e\boldsymbol{A} + \underline{J\boldsymbol{M}}\right)\psi_R - \psi_L^{+}\vec{\sigma}\cdot\left(-i\vec{\nabla} + e\boldsymbol{A} - \underline{J\boldsymbol{M}}\right)\psi_L$$

$\boldsymbol{a} = J\boldsymbol{M}$
"chiral vector potential"



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

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

Chiral anomaly

3D Weyl fermions

$$H_{3D} = \int d^3x \;\; \psi_R^\dagger \vec{\sigma}\cdot\left(-i\vec{\nabla} + e\boldsymbol{A} + \underline{J\boldsymbol{M}}\right)\psi_R - \psi_L^\dagger \vec{\sigma}\cdot\left(-i\vec{\nabla} + e\boldsymbol{A} - \underline{J\boldsymbol{M}}\right)\psi_L$$

$\boldsymbol{a} = J\boldsymbol{M}$
"chiral vector potential"

$$\begin{cases} \boldsymbol{b} = \nabla \times \boldsymbol{a} = \nabla \times J\boldsymbol{M} \\ \boldsymbol{e} = -\dot{\boldsymbol{a}} = -J\dot{\boldsymbol{M}} \end{cases}$$

Zyusin & Burkov (2012), Liu, Ye, Qi (2013)

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

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

Chiral anomaly

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

$$\left\{\begin{array}{ll} \boldsymbol{b} = \nabla\times\boldsymbol{a} & = \nabla\times J\boldsymbol{M} \\ \boldsymbol{e} = -\dot{\boldsymbol{a}} & = -J\dot{\boldsymbol{M}} \end{array}\right.$$

Zyusin & Burkov (2012), Liu, Ye, Qi (2013)

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

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

Chiral anomaly

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

$$\begin{cases} \boldsymbol{b} = \nabla\times\boldsymbol{a} = \nabla\times J\boldsymbol{M} \\ \boldsymbol{e} = -\dot{\boldsymbol{a}} = -J\dot{\boldsymbol{M}} \end{cases}$$

Zyusin & Burkov (2012), Liu, Ye, Qi (2013)

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

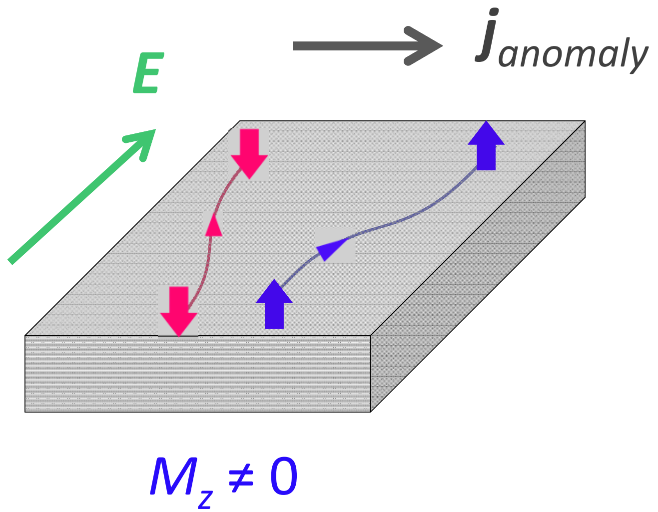
$$\frac{d(N_R-N_L)}{dt} = \int d^3x \frac{2e^2}{(2\pi)^2}(\boldsymbol{E}\cdot\boldsymbol{B}+\boldsymbol{e}\cdot\boldsymbol{b})$$

Chiral anomaly

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

$$\begin{cases} \boldsymbol{b} = \nabla\times\boldsymbol{a} = \nabla\times J\boldsymbol{M} \\ \boldsymbol{e} = -\dot{\boldsymbol{a}} = -J\dot{\boldsymbol{M}} \end{cases}$$

Zyusin & Burkov (2012), Liu, Ye, Qi (2013)



$$\boldsymbol{j}_{anomaly} = \frac{e^2}{2\pi^2} J\boldsymbol{M}\times\boldsymbol{E}$$

$$\rho_{anomaly} = \frac{e^2}{2\pi^2} J\boldsymbol{M}\cdot\boldsymbol{B}$$

Weyl fermions in B field

n^{th} Landau level :

$$E_n(k_z) = \pm\hbar v_F \sqrt{\left(k_z + \frac{xJS}{\hbar v_F}\tau_z \hat{M}_z\right)^2 + \frac{2eB_z}{\hbar c}|n|}$$

$(n=\pm1, \pm2, \pm3, \cdots)$

0^{th} Landau level :

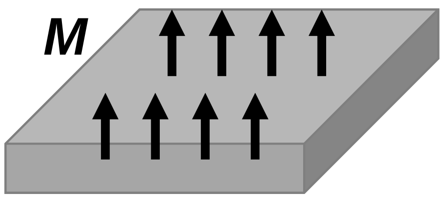
$$E_0(k_z) = -\tau_z \hbar v_F k_z - xJS\hat{M}_z$$

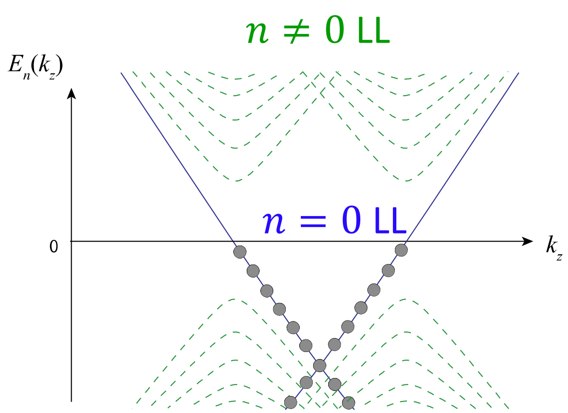
charge density

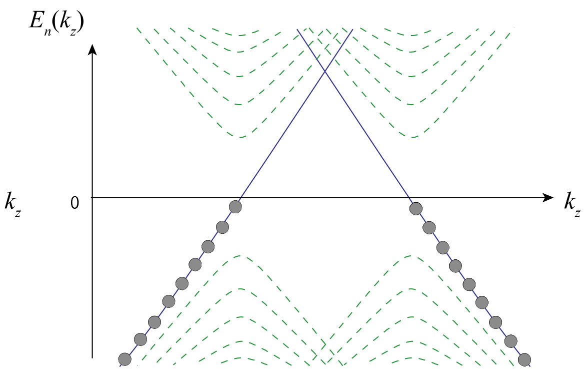
$$\rho_{AHE} = \sigma_{AHE} \hat{\boldsymbol{M}} \cdot \boldsymbol{B}$$

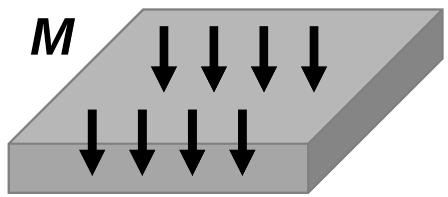
(not resistivity)

$$N_{LL} = \frac{BL_x L_y}{hc/e}$$

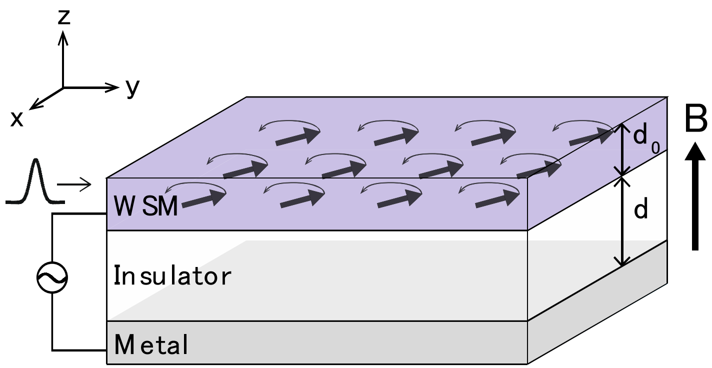








Gate-tuned magnetization dynamics

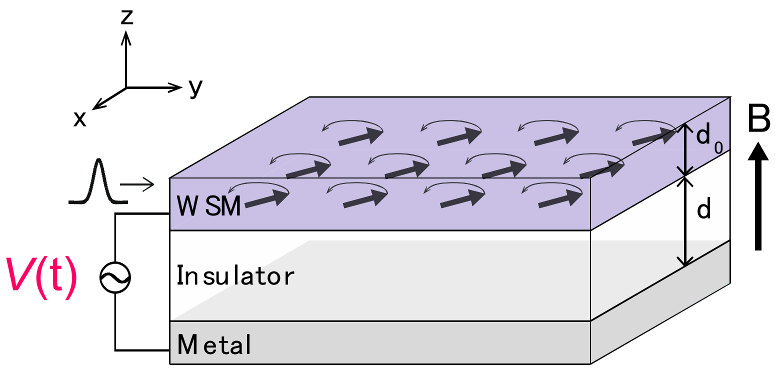


$$\rho_{\text{anomaly}} = \sigma_{\text{AHE}} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}$$

Zeeman Anisotropy

$$E(\widehat{\boldsymbol{M}}) = -g\mu_B S\, \widehat{\boldsymbol{M}} \cdot \boldsymbol{B} - K M_y^2$$

Gate-tuned magnetization dynamics



Kurebayashi, KN 2016

$$\rho_{\text{anomaly}} = \sigma_{\text{AHE}} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}$$

charge density

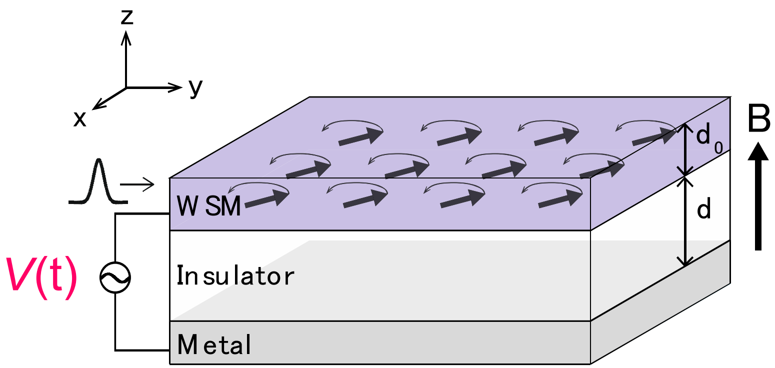
Zeeman Anisotropy

$$E(\widehat{\boldsymbol{M}}) = -g\mu_B S\, \widehat{\boldsymbol{M}} \cdot \boldsymbol{B} - KM_y^2 + \frac{1}{2C}\left(\sigma_{AHE}\widehat{\boldsymbol{M}} \cdot \boldsymbol{B}\right)^2 + V\,\sigma_{AHE}\widehat{\boldsymbol{M}} \cdot \boldsymbol{B}$$

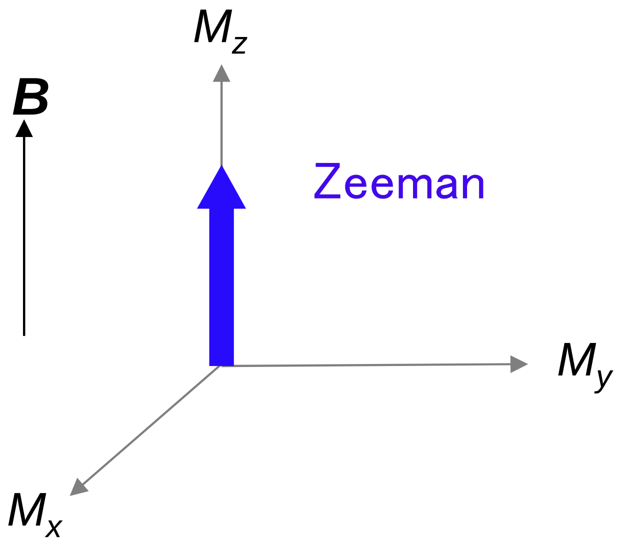
Charging Gate voltage

$\frac{1}{2C}\rho^2$ $V\rho$

Gate-tuned magnetization dynamics



Kurebayashi, KN 2016



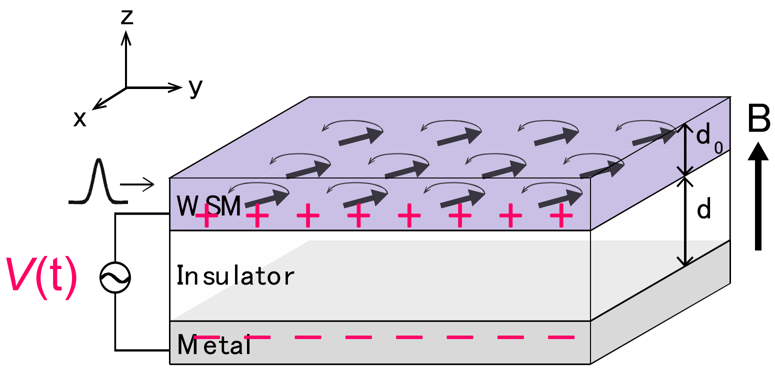
Zeeman Anisotropy

$$E(\widehat{\boldsymbol{M}}) = -g\mu_B S\,\widehat{\boldsymbol{M}}\cdot\boldsymbol{B} - KM_y^2 + \frac{1}{2C}\left(\sigma_{AHE}\widehat{\boldsymbol{M}}\cdot\boldsymbol{B}\right)^2 + V\,\sigma_{AHE}\widehat{\boldsymbol{M}}\cdot\boldsymbol{B}$$

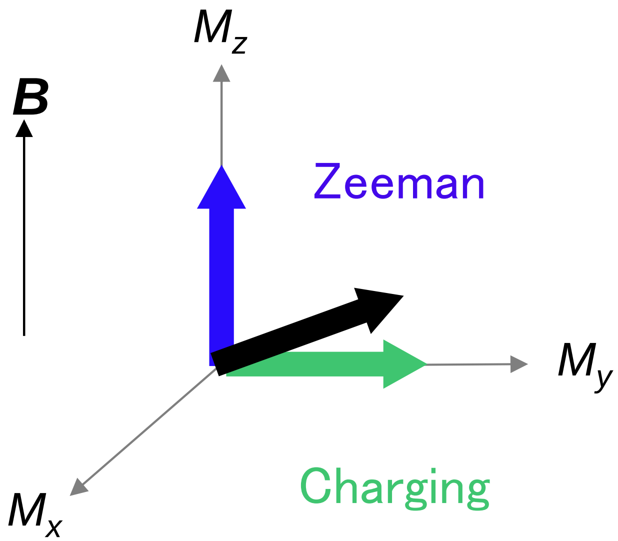
Charging Gate voltage

$\frac{1}{2C}\rho^2$ $V\rho$

Gate-tuned magnetization dynamics



Kurebayashi, KN 2016



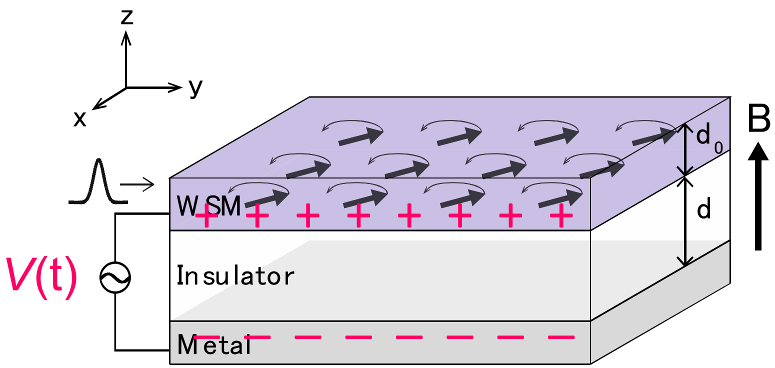
Zeeman Anisotropy

$$E(\widehat{\boldsymbol{M}}) = -g\mu_B S\,\widehat{\boldsymbol{M}}\cdot\boldsymbol{B} - KM_y^2 + \frac{1}{2C}\left(\sigma_{AHE}\widehat{\boldsymbol{M}}\cdot\boldsymbol{B}\right)^2 + V\,\sigma_{AHE}\widehat{\boldsymbol{M}}\cdot\boldsymbol{B}$$

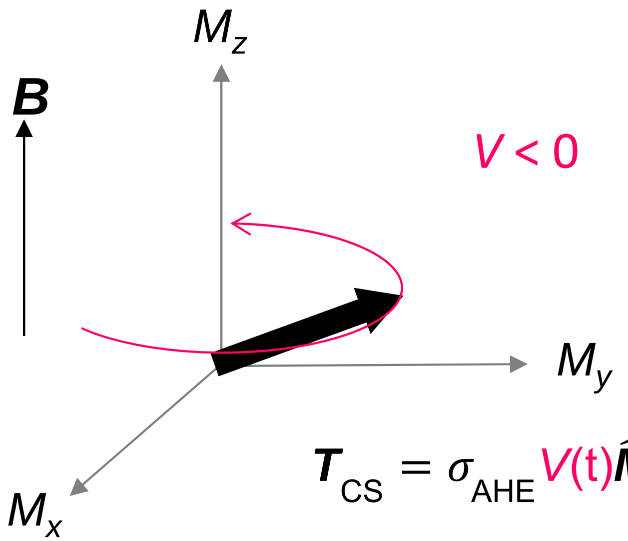
Charging Gate voltage

$\frac{1}{2C}\rho^2$ $V\rho$

Gate-tuned magnetization dynamics



Kurebayashi, KN 2016



$$\boldsymbol{T}_{\mathrm{CS}} = \sigma_{\mathrm{AHE}} V(t) \widehat{\boldsymbol{M}} \times \boldsymbol{B}$$

Charge-induced spin torque

KN, Kurebaashi, 2015

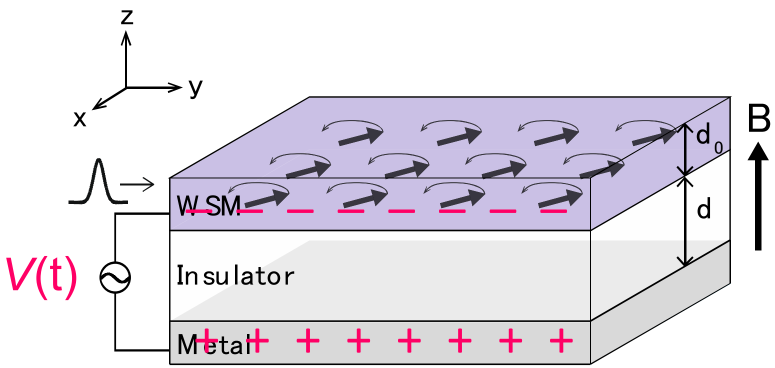
Zeeman   Anisotropy

$$E(\widehat{\boldsymbol{M}}) = -g\mu_B S\, \widehat{\boldsymbol{M}} \cdot \boldsymbol{B} - KM_y^2 + \frac{1}{2C}\left(\sigma_{AHE} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}\right)^2 + V\, \sigma_{AHE} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}$$

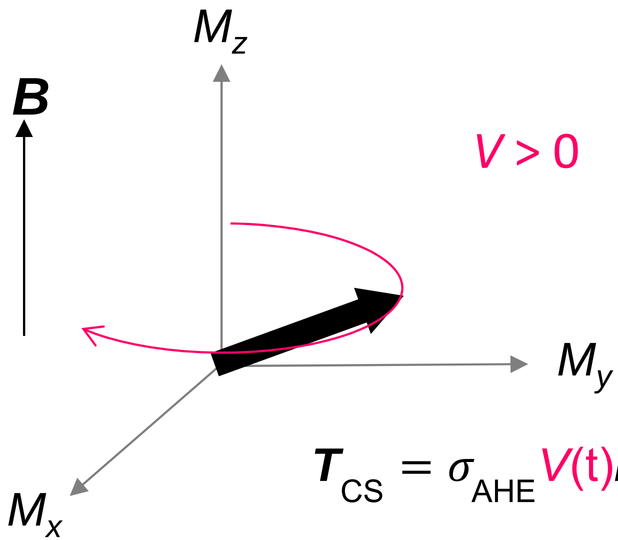
Charging   Gate voltage

$\frac{1}{2C}\rho^2$ $V\rho$

Gate-tuned magnetization dynamics



Kurebayashi, KN 2016



$$\boldsymbol{T}_{\mathrm{CS}} = \sigma_{\mathrm{AHE}} V(t) \widehat{\boldsymbol{M}} \times \boldsymbol{B}$$

Charge-induced spin torque

KN, Kurebaashi, 2015

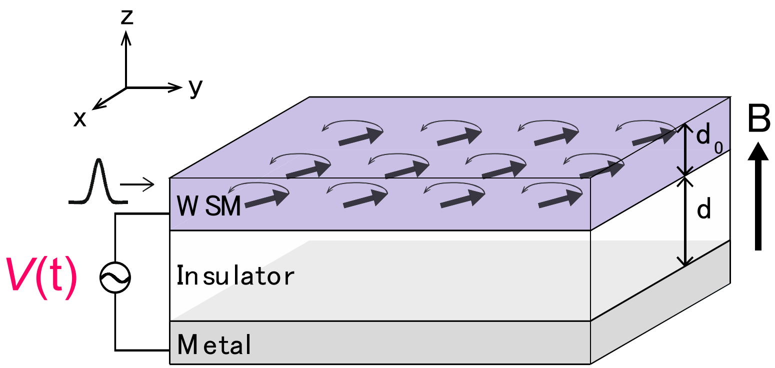
Zeeman Anisotropy

$$E\left(\widehat{\boldsymbol{M}}\right) = -g\mu_B S\, \widehat{\boldsymbol{M}} \cdot \boldsymbol{B} - K M_y^2$$
$$+ \frac{1}{2C}\left(\sigma_{AHE} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}\right)^2 + V\, \sigma_{AHE} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}$$

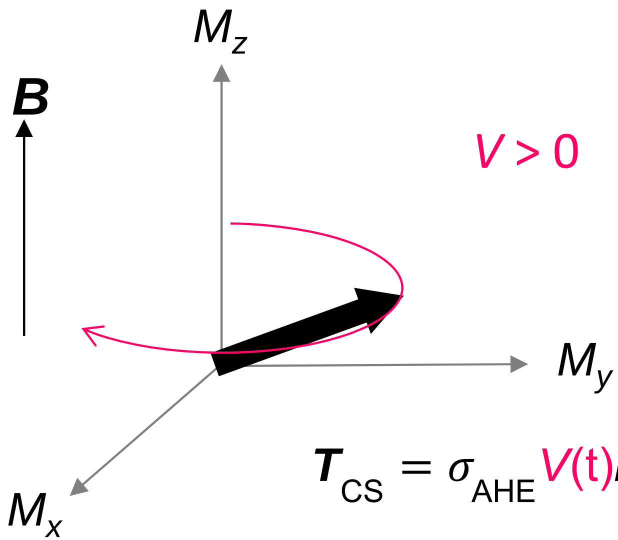
Charging Gate voltage

$\frac{1}{2C}\rho^2$ $V\rho$

Gate-tuned magnetization dynamics



Kurebayashi, KN 2016



$$\boldsymbol{T}_{\mathrm{CS}} = \sigma_{\mathrm{AHE}} V(t) \widehat{\boldsymbol{M}} \times \boldsymbol{B}$$

$$\boldsymbol{B}_{eff} = \frac{\delta E(\widehat{\boldsymbol{M}})}{\delta \widehat{\boldsymbol{M}}}$$

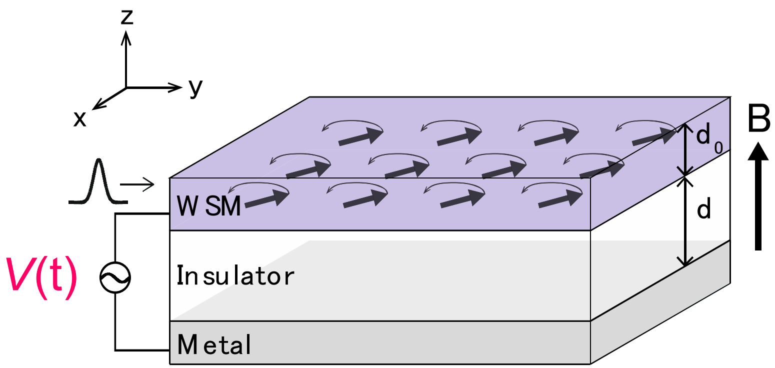
Zeeman Anisotropy

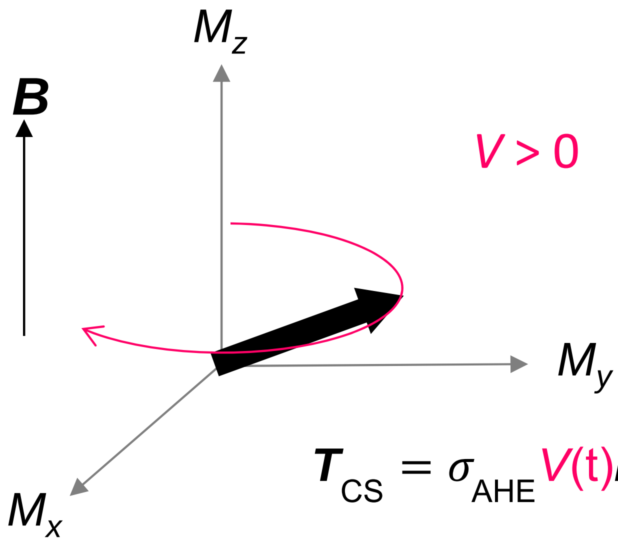
$$E(\widehat{\boldsymbol{M}}) = -g\mu_B S\, \widehat{\boldsymbol{M}} \cdot \boldsymbol{B} - K M_y^2 + \frac{1}{2C}\left(\sigma_{AHE} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}\right)^2 + V\, \sigma_{AHE} \widehat{\boldsymbol{M}} \cdot \boldsymbol{B}$$

Charging Gate voltage

$\frac{1}{2C}\rho^2$ $V\rho$

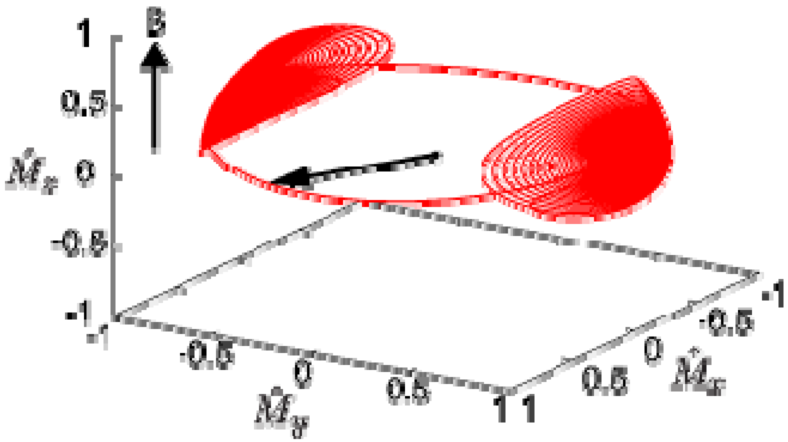
Gate-tuned magnetization dynamics





$$\boldsymbol{T}_{\mathrm{CS}} = \sigma_{\mathrm{AHE}} V(\mathrm{t}) \widehat{\boldsymbol{M}} \times \boldsymbol{B}$$

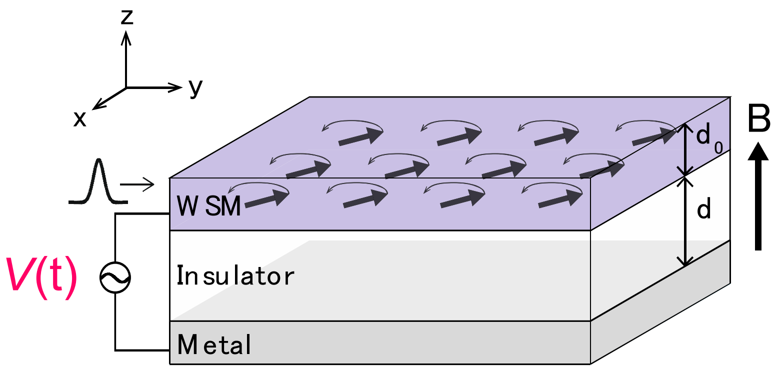
Kurebayashi, KN 2016



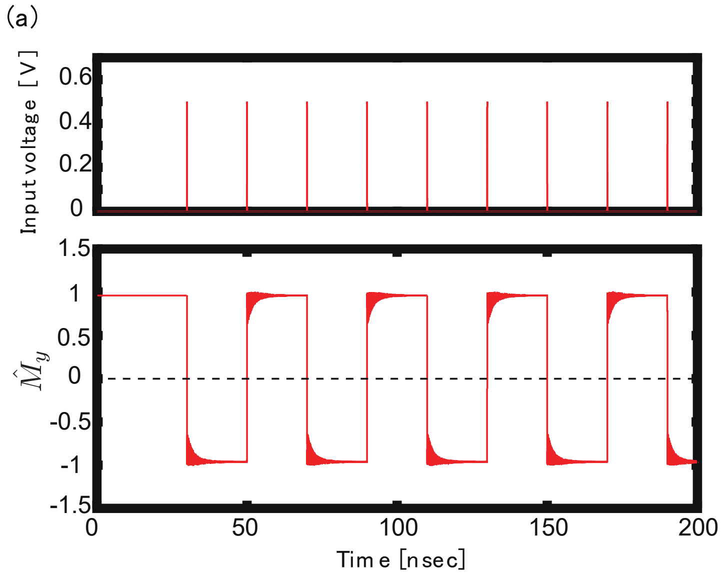
$$\boldsymbol{B}_{eff} = \frac{\delta E\left(\widehat{\boldsymbol{M}}\right)}{\delta \widehat{\boldsymbol{M}}}$$

$$\frac{d\widehat{\boldsymbol{M}}}{dt} = -\gamma \widehat{\boldsymbol{M}} \times \boldsymbol{B}_{eff} + \alpha \widehat{\boldsymbol{M}} \times \frac{d\widehat{\boldsymbol{M}}}{dt}$$

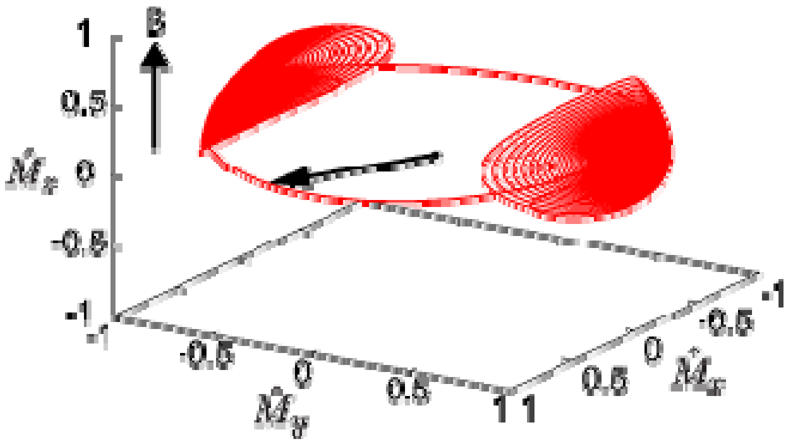
Gate-tuned magnetization dynamics



Kurebayashi, KN 2016

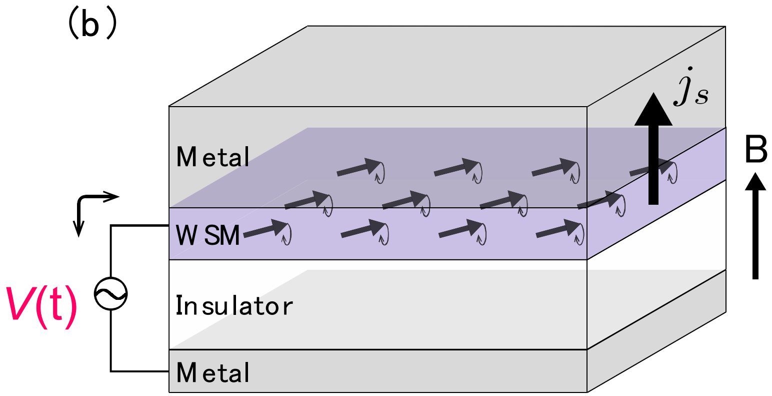


$$\boldsymbol{T}_{\mathrm{CS}} = \sigma_{\mathrm{AHE}} V(t) \widehat{\boldsymbol{M}} \times \boldsymbol{B}$$

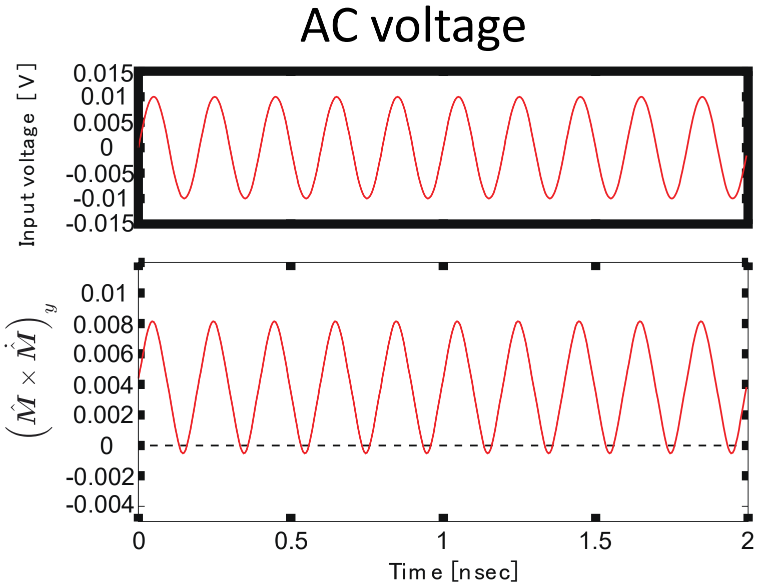


$$\frac{d\widehat{\boldsymbol{M}}}{dt} = -\gamma \widehat{\boldsymbol{M}} \times \boldsymbol{B}_{eff} + \alpha \widehat{\boldsymbol{M}} \times \frac{d\widehat{\boldsymbol{M}}}{dt}$$

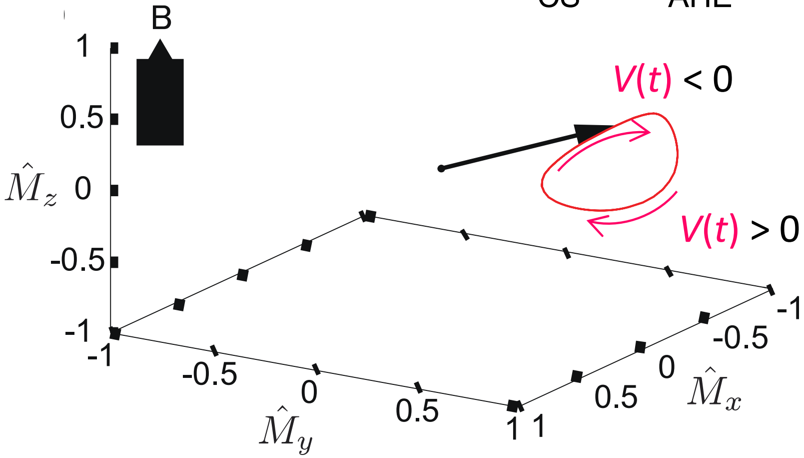
Gate-tuned magnetization dynamics



Kurebayashi, KN 2016



$$\boldsymbol{T}_{\rm CS} = \sigma_{\rm AHE} V(t) \hat{\boldsymbol{M}} \times \boldsymbol{B}$$



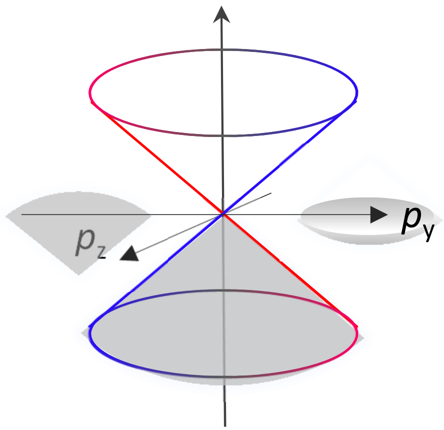
spin current

$$\boldsymbol{j}_{spin} = \left(\frac{g_r^{\uparrow\downarrow}}{4\pi}\right) \hat{\boldsymbol{M}} \times \frac{d\hat{\boldsymbol{M}}}{dt}$$

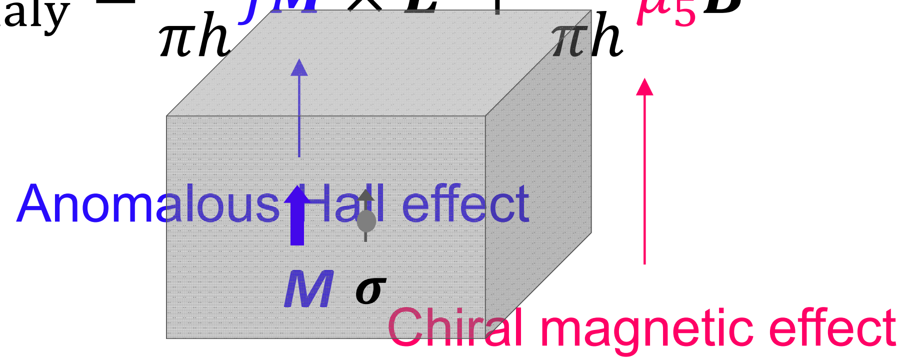
Tserkovnyak et al. (2003)

Chiral magnetic effect

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



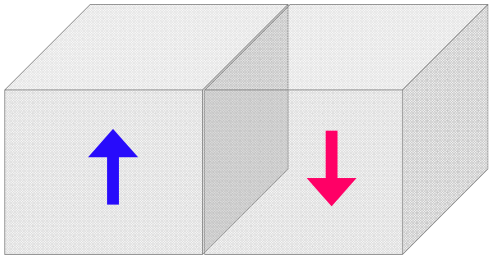
$$\boldsymbol{j}_{\mathrm{anomaly}} = \frac{e^2}{\pi h} J\boldsymbol{M} \times \boldsymbol{E} + \frac{e^2}{\pi h} \mu_5 \boldsymbol{B}$$



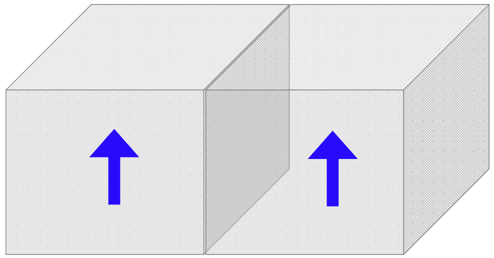
Chiral magnetic effect vanishes in equilibrium

Inhomogeneous Weyl semimetal

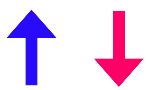
real space



antiparallel



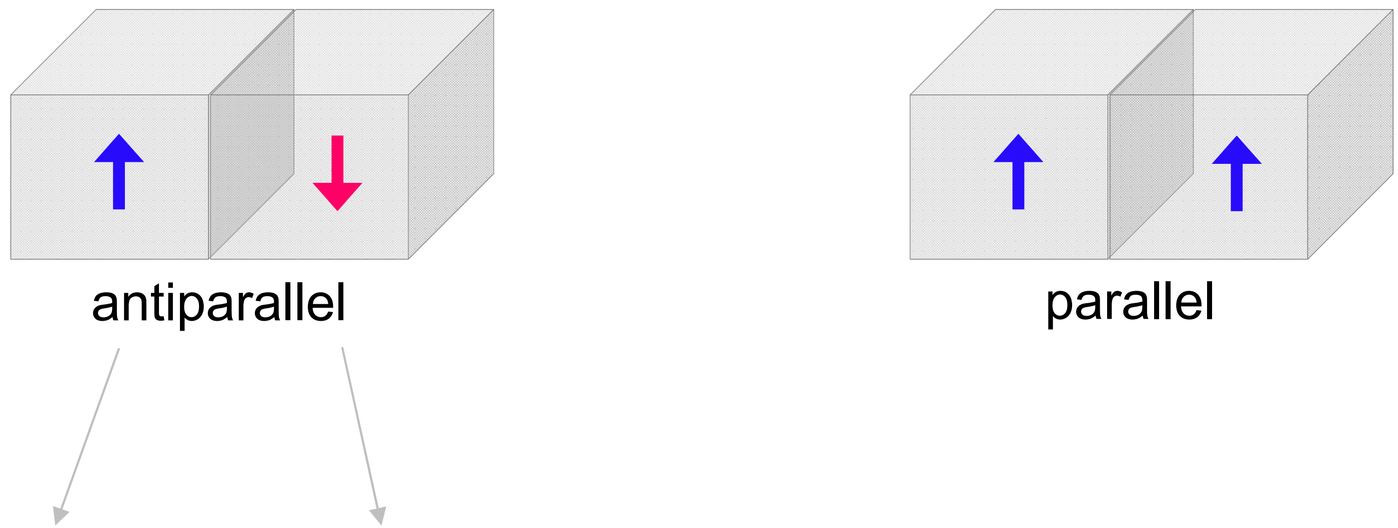
parallel



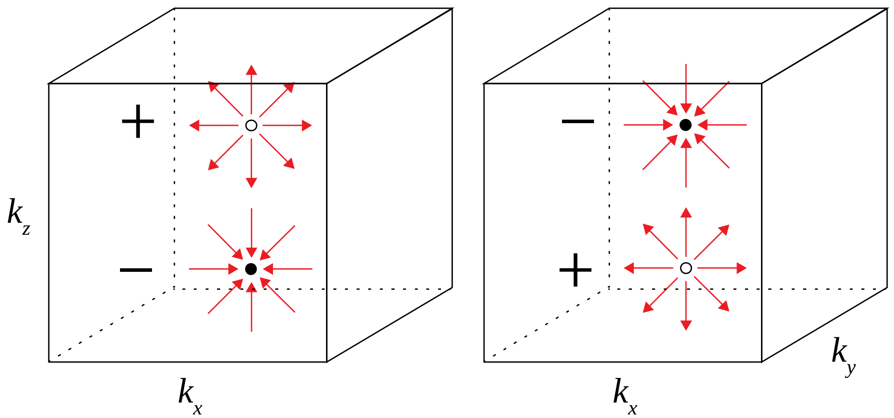
Doped local spins

Inhomogeneous Weyl semimetal

real space

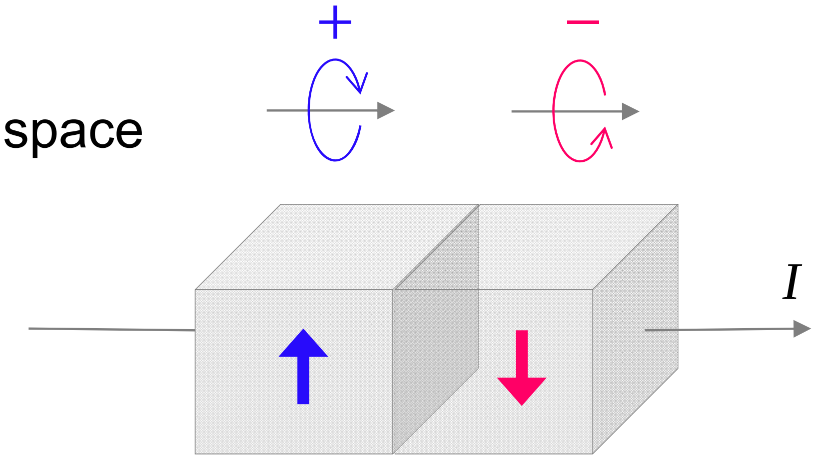


k space

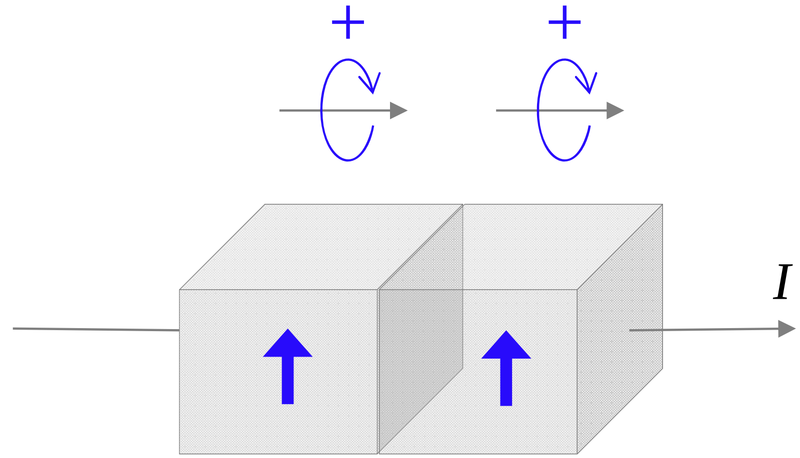


Magnetotransport in Weyl semimetal

real space

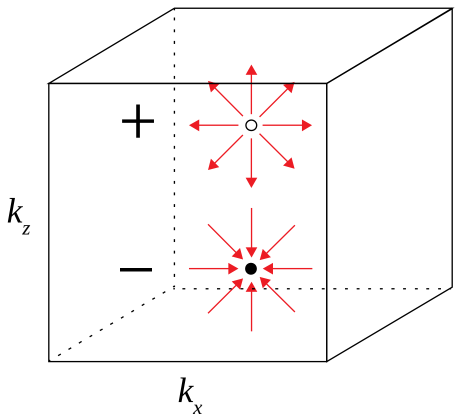


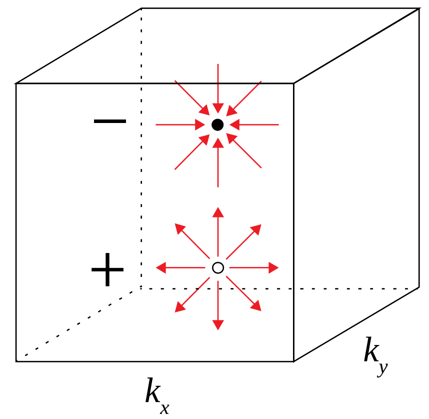
antiparallel



parallel

k space





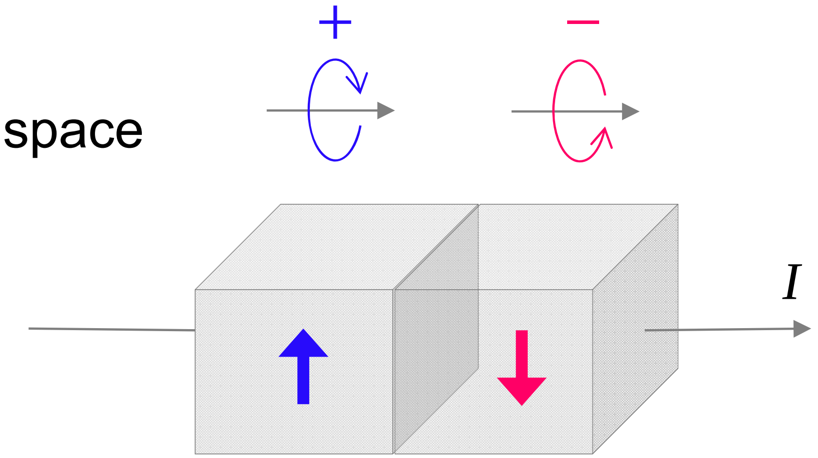
$G_{\uparrow\downarrow} = 0 \qquad G_{\uparrow\uparrow} \neq 0$

Ideal magnetotransport!

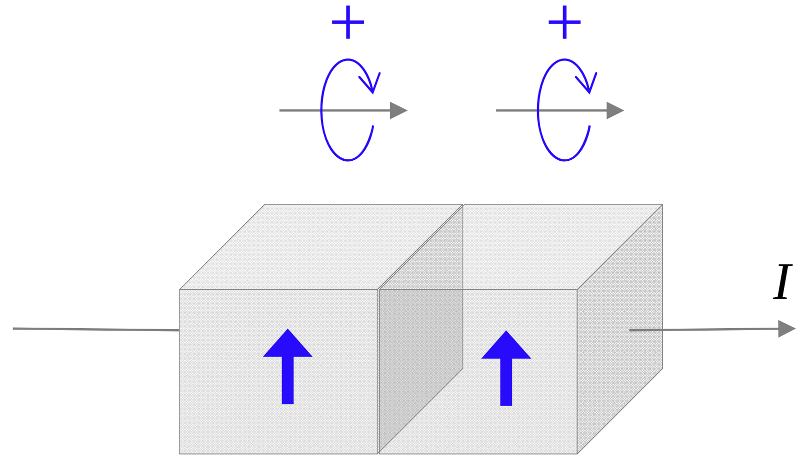
Transmission probability from left to right is
zero

Magnetotransport in Weyl semimetal

real space

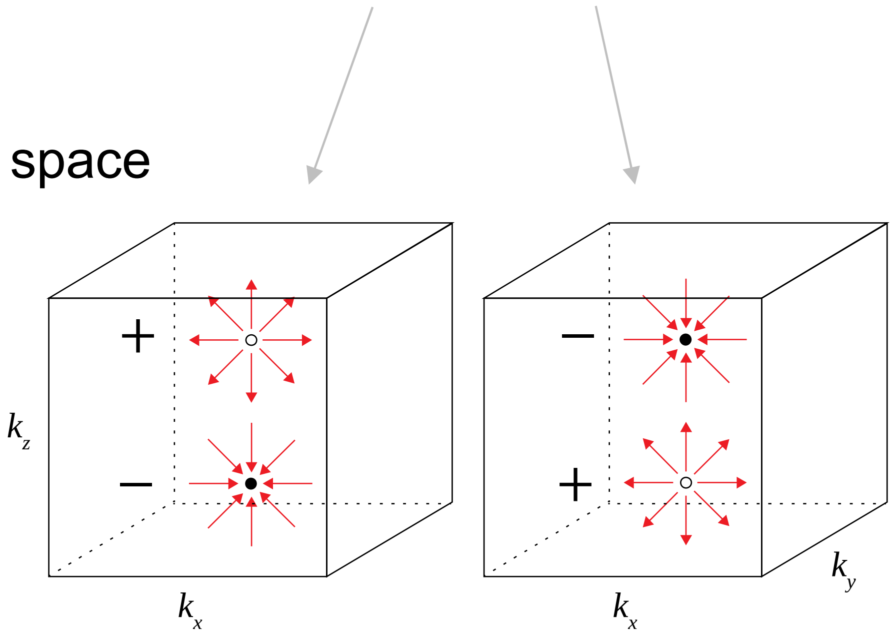


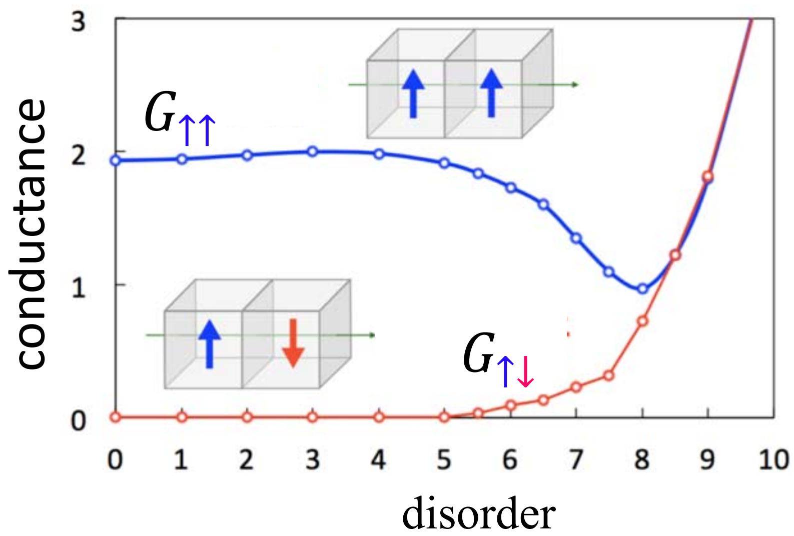
antiparallel



parallel

k space



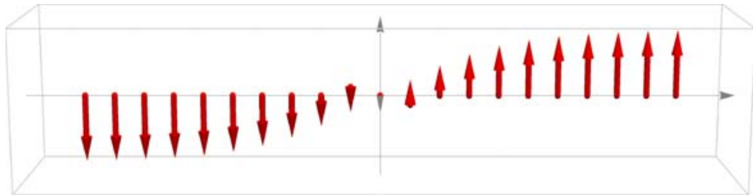


K. Kobayashi

Domain wall in Weyl semimetal

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

Axial vector potential



$$\boldsymbol{B}_5 \neq 0$$

Axial magnetic field

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

Y. Araki

A. Yoshida

Domain wall in Weyl semimetal

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Axial vector potential

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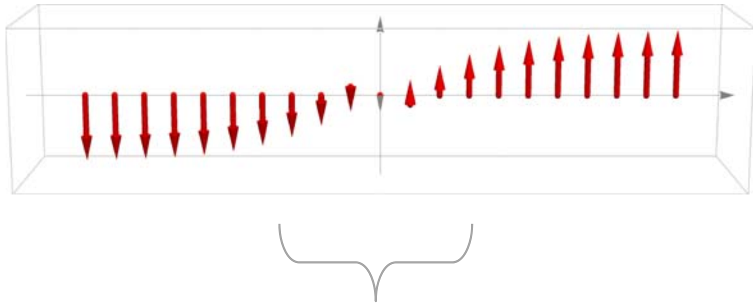

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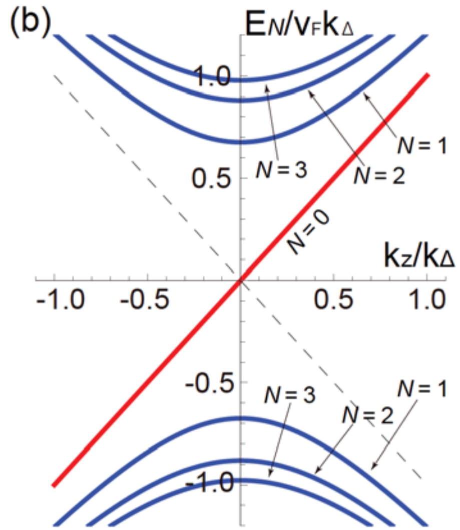
Axial magnetic field



Y. Araki

A. Yoshida

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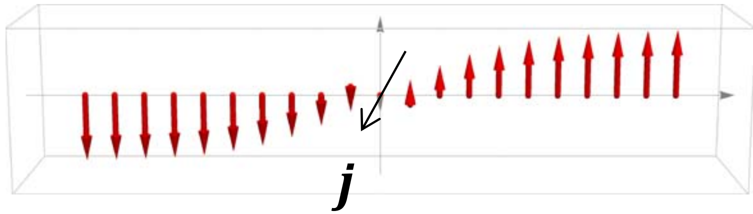
$$= \pm\boldsymbol{\sigma}\cdot(\boldsymbol{p} \pm e\boldsymbol{A}_5)$$

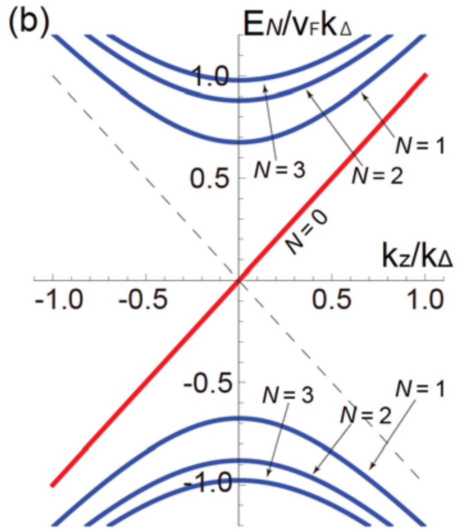
Axial vector potential

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



$$\boldsymbol{B}_5 \neq 0$$

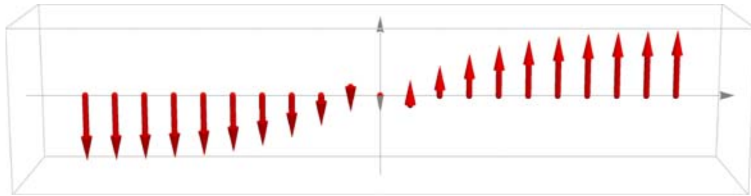
Axial magnetic field



Equilibrium current

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

Domain wall in Weyl semimetal



$$\boldsymbol{B}_5 \neq 0$$

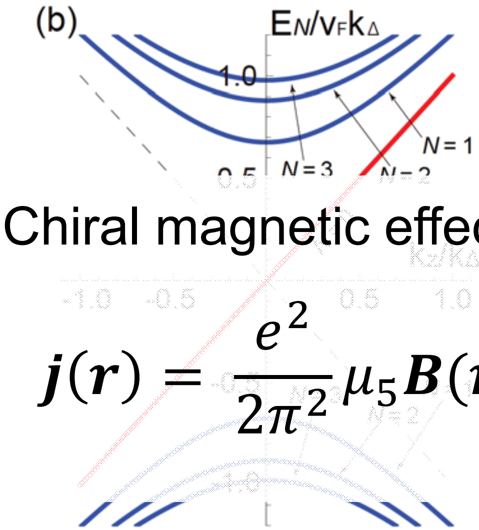
$$H_{\pm} = \pm\boldsymbol{\sigma}\cdot\boldsymbol{p} + J\boldsymbol{M}\cdot\boldsymbol{\sigma}$$
$$= \pm\boldsymbol{\sigma}\cdot(\boldsymbol{p} \pm e\boldsymbol{A}_5)$$

Axial vector potential

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

Equilibrium current

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



c.f. Chiral magnetic effect

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

Domain wall in Weyl semimetal

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

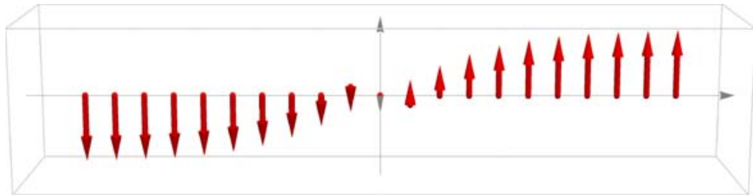
Axial vector potential

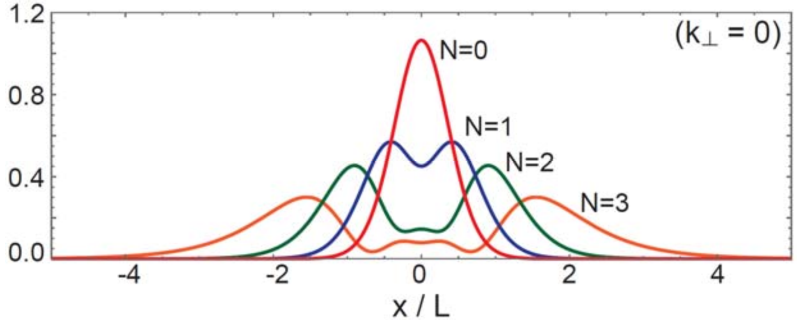
$$\boldsymbol{B}_5 = \boldsymbol{\nabla} \times \boldsymbol{A}_5$$

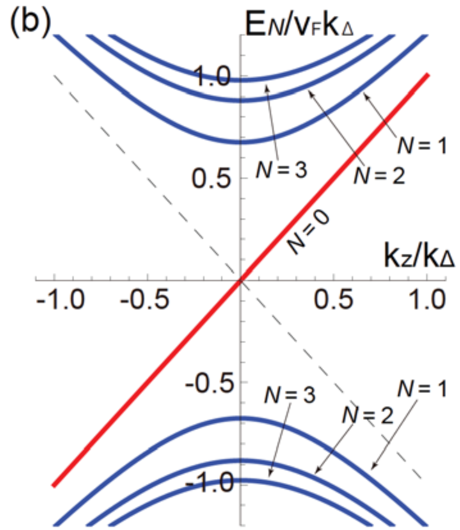
Yasufumi Araki et al. (2016)

Electric charge on the domain wall

$$Q = \frac{e^2}{\pi^2} \frac{k_\Delta}{v_F} \mu$$



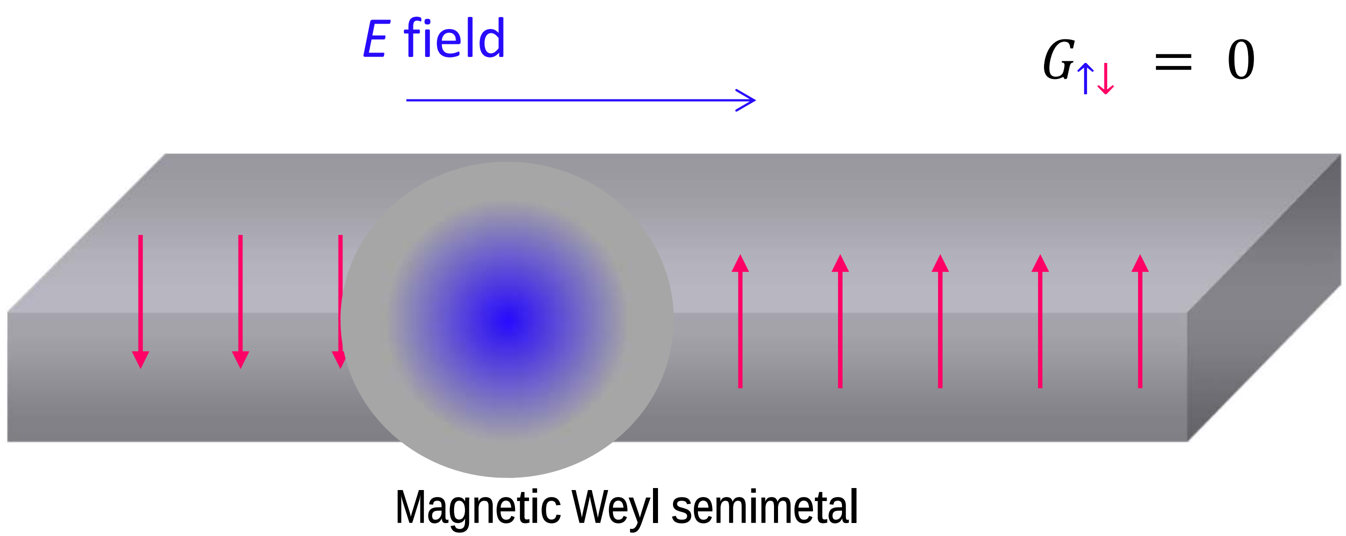




Electrical domain wall motion

Electric charge on the domain wall

$$Q = \frac{e^2}{\pi^2}\frac{k_\Delta}{v_F}\mu$$

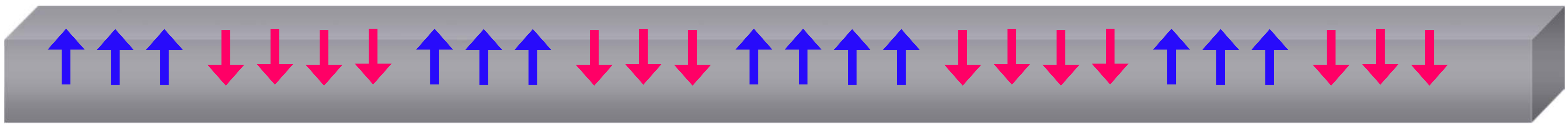


Electrical domain wall motion

Electric charge on the domain wall

$$Q = \frac{e^2}{\pi^2} \frac{k_\Delta}{v_F} \mu$$

$\boldsymbol{E}(t)$



Magnetic Weyl semimetal

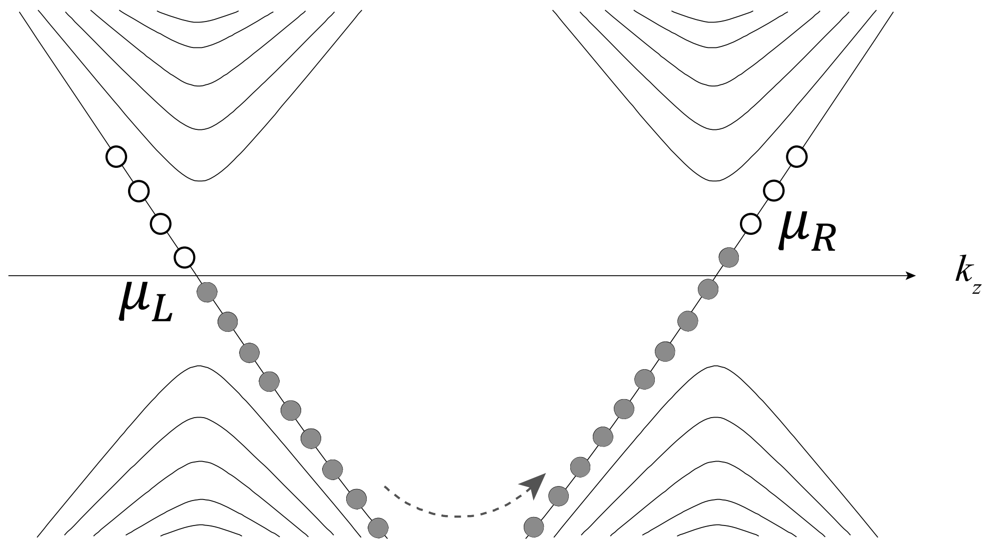
A less-dissipation spintronics device

Chiral magnetic effects

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

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

$B \neq 0$



Chiral magnetic effects

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

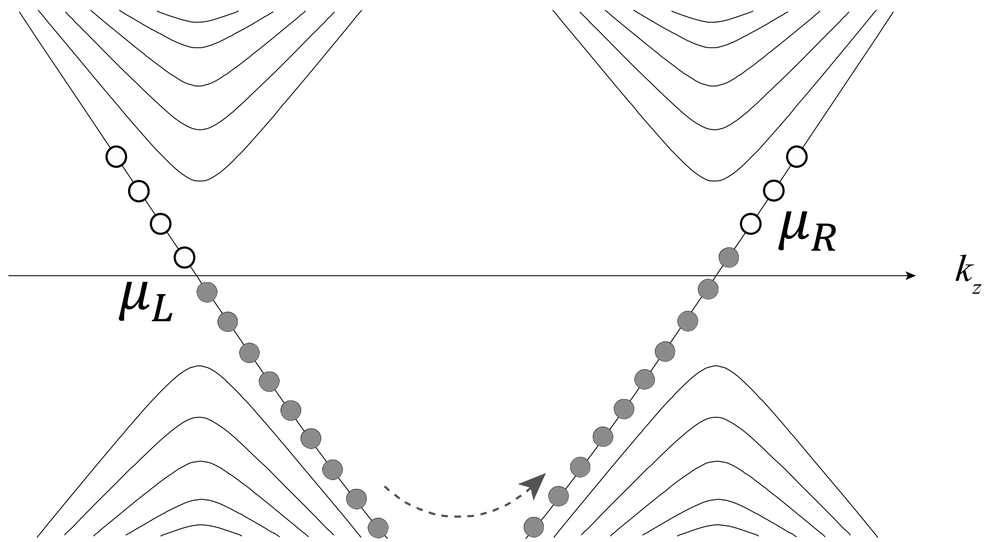
$$\begin{cases} \boldsymbol{B}_{R/L} = \boldsymbol{B} \pm \boldsymbol{B}_5 \\ \mu_{R/L} = \mu \pm \mu_5 \end{cases}$$

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

Electrical current

$$\boxed{\begin{aligned} \boldsymbol{j} &= \frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B} \\ \boldsymbol{j} &= \frac{e^2}{2\pi^2}\mu \boldsymbol{B}_5 \end{aligned}}$$

$B \neq 0$



Chiral magnetic effects

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

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

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

Electrical current

$$\boxed{\begin{aligned} \boldsymbol{j} &= \frac{e^2}{2\pi^2}\mu_5 \boldsymbol{B} \\ \boldsymbol{j} &= \frac{e^2}{2\pi^2}\mu \boldsymbol{B}_5 \end{aligned}}$$

Axial current

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

Chiral magnetic effects

$$H = \begin{pmatrix} H_+ & 0 \\ 0 & H_- \end{pmatrix} \qquad H_{\pm} = \pm v\,\boldsymbol{\sigma} \cdot (\boldsymbol{p} + e\boldsymbol{A} \pm e\boldsymbol{A}_5) + eA^0 \pm eA_5^0$$

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

Spin density

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

$\Longleftrightarrow$

Axial current

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

D. Kurebayashi

Chiral magnetic effects

Local spin magnetization

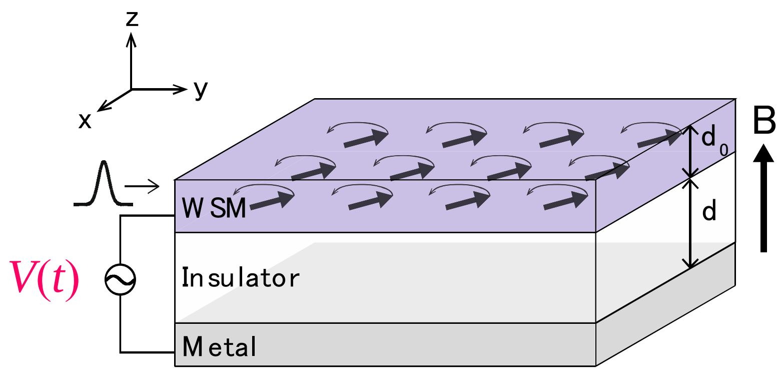
$$\frac{d\hat{\boldsymbol{M}}}{dt} = -\gamma\hat{\boldsymbol{M}} \times \boldsymbol{H}_{\text{eff}} + \alpha\hat{\boldsymbol{M}} \times \frac{d\hat{\boldsymbol{M}}}{dt} + J\hat{\boldsymbol{M}} \times \langle\boldsymbol{\sigma}\rangle$$

$$\boldsymbol{T}_{\text{cs}} = \sigma_{\text{AHE}}\, \mu\, \hat{\boldsymbol{M}} \times \boldsymbol{B}$$

Charge-induced spin torque

Spin density

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



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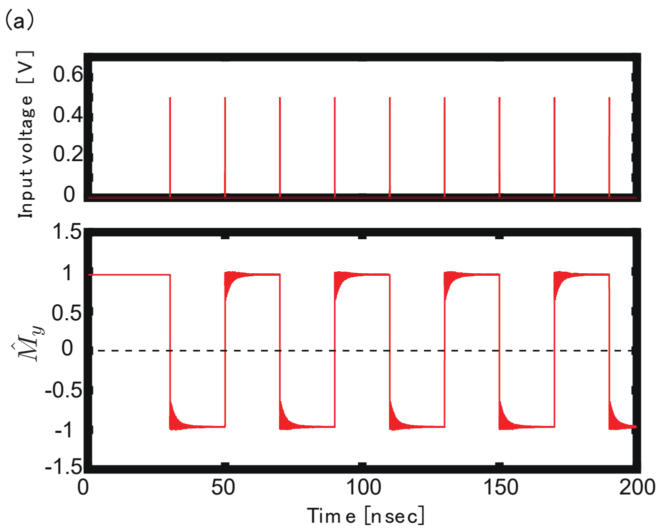
Chiral magnetic effects

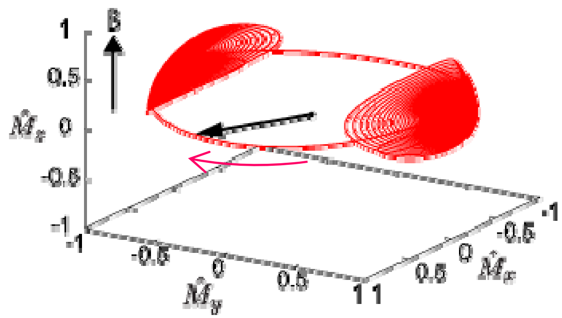
Local spin magnetization

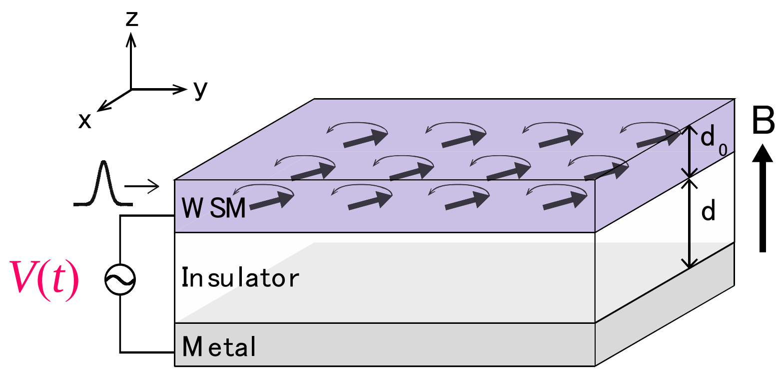
$$\frac{d\widehat{\boldsymbol{M}}}{dt} = -\gamma\widehat{\boldsymbol{M}} \times \boldsymbol{H}_{\text{eff}} + \alpha\widehat{\boldsymbol{M}} \times \frac{d\widehat{\boldsymbol{M}}}{dt} + J\widehat{\boldsymbol{M}} \times \langle\boldsymbol{\sigma}\rangle$$

$$\boldsymbol{T}_{\text{cs}} = \sigma_{\text{AHE}}\, \mu\, \widehat{\boldsymbol{M}} \times \boldsymbol{B}$$

Charge-induced spin torque







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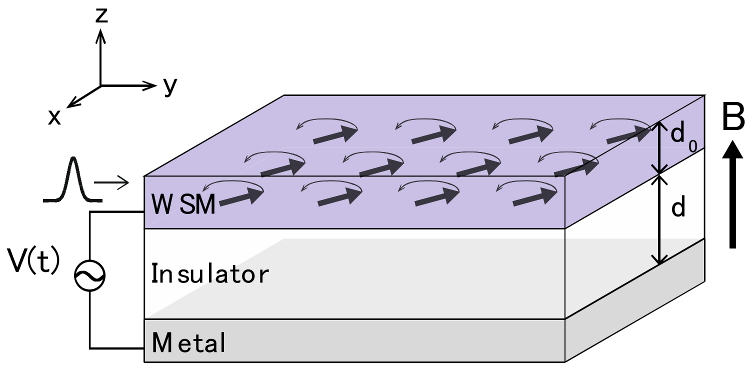
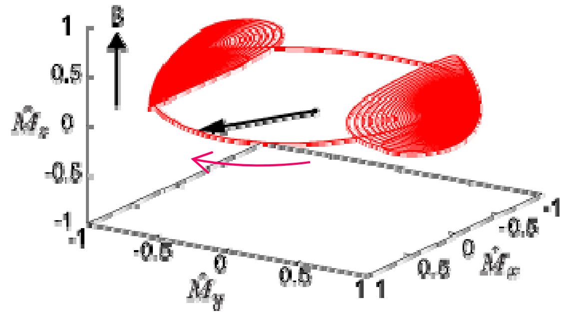
Summary

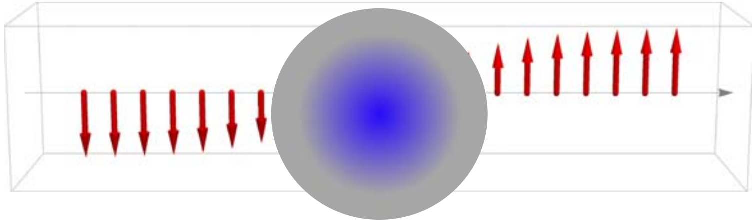
- We demonstrated *magnetization switching* and *spin pumping* by the charge-induced torque



$$\boldsymbol{T}_{\mathrm{CS}} = \sigma_{\mathrm{AHE}} V(t)\, \hat{\boldsymbol{M}} \times \boldsymbol{B}$$



- Helicity-induced magnetoresistence and domain wall motion in Weyl semimetals



$$Q = \frac{e^2}{\pi^2} \frac{k_\Delta}{v_F} \mu$$

Acknowledgement

Collaborators

IMR theory group

Yasufumi Araki(Ass. Prof.)
Daichi Kurebayashi(D2)
Koji Kobayashi(PD)
Yuya Ominato(PD)
Akihide Yoshida(M1)

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