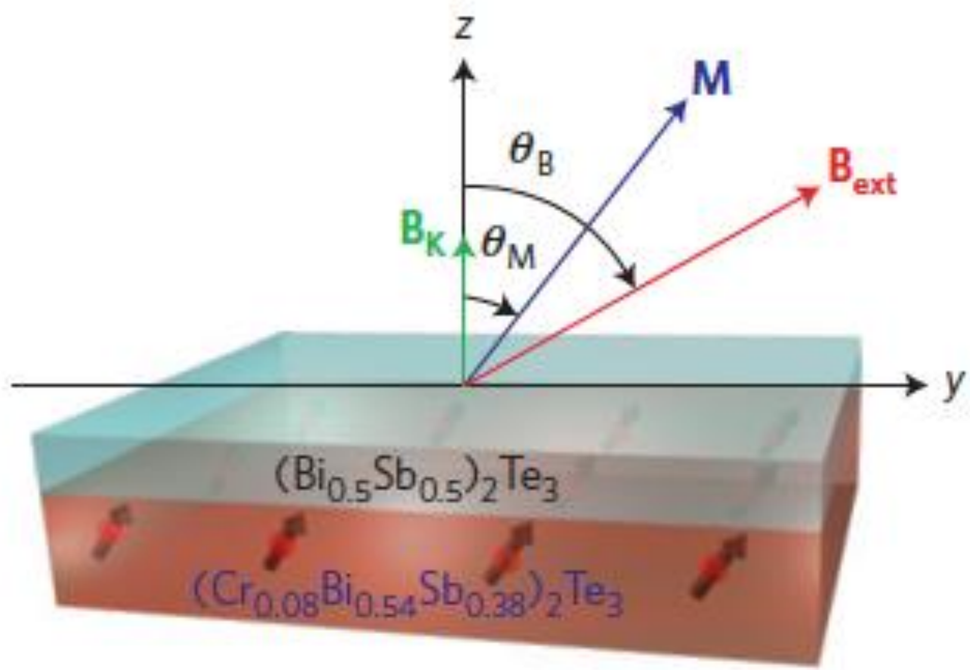
Topological Spintronic Devices

Current-Induced Torques & Topological Insulators

Massoud Masir, Nobu Okuma, Allan MacDonald
UT Austin – SHINES collaboration

Spin-Orbit Torques in TI DMSs



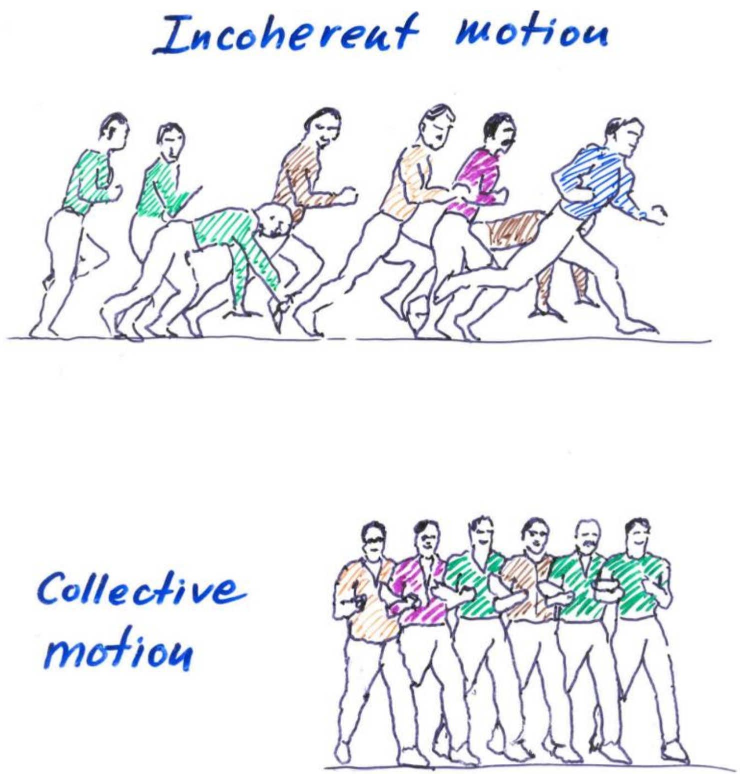
Fan et al., Nature Mat. (2014)
Ndiaye et al. arXiv:1509.06929
Franz and Garate, PRL (2010)

- Theory of Current-Induced Torques

- Resistive Detection of SOTs

- The role of the bulk ?

Emergent Collective DOF

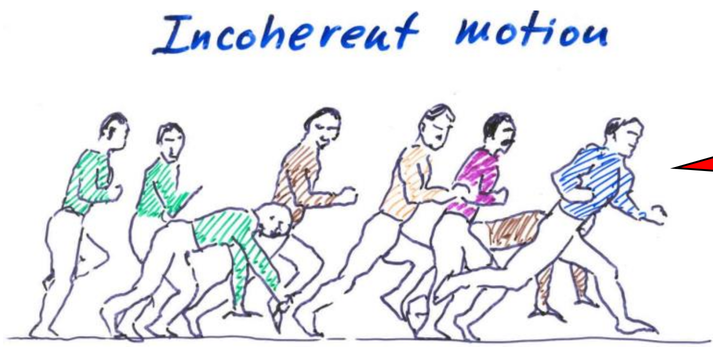


Courtesy Catherine Kallin

Emergent Collective DOF

Ferromagnet

Heavy Metal

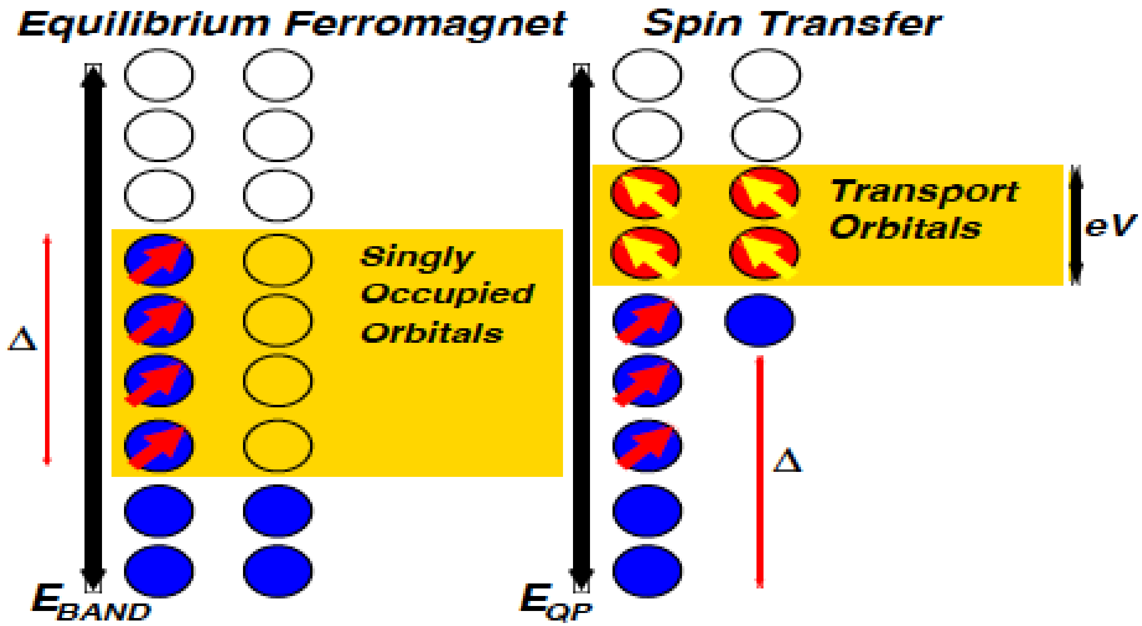


Fermi Liquid Theory

LLG Equation

Courtesy Catherine Kallin

Spin-Torques
Beyond Spin-Transfer

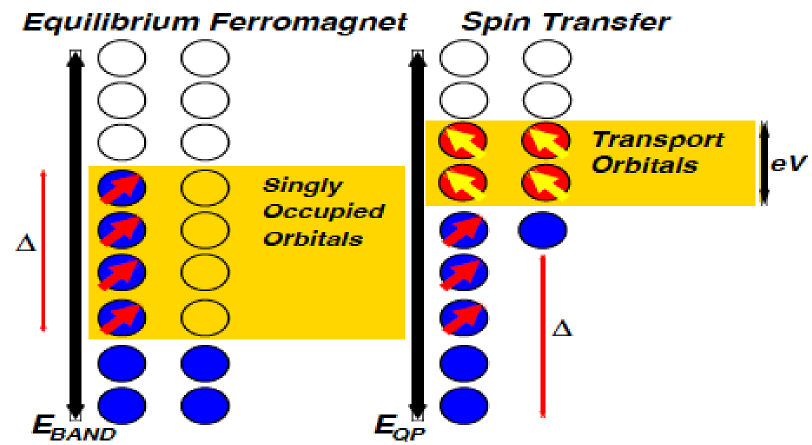


Alvaro Nunez – Ph.D. Thesis (2004)
SSC (2006)

Spin-Torques Beyond Spin-Transfer

$$\delta\vec{H}_{eff} = \Delta(\vec{r})\,\vec{m}_{\perp}$$

$$\vec{T} = (\hat{m}\times\vec{m}_{\perp})\cdot\int d\vec{r}\; m(\vec{r})\,\Delta(\vec{r})$$



Alvaro Nunez – Ph.D. Thesis (2004)
SSC (2006) I. Garate PRB (2009)

Bulk Transport Theory
Relaxation Time Approx

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H, \rho] + \frac{1}{\hbar}\frac{\partial \rho}{\partial \mathbf{k}} \cdot e\mathbf{E} - \frac{\rho - \rho_0}{\tau}$$

Relaxation Time Approximation

Bulk Transport Theory

$$\frac{\partial \rho^{(0)}}{\partial \mathbf{k}} = \sum_m \left\{ \frac{\partial f_{m\mathbf{k}}}{\partial \mathbf{k}} |mk\rangle\langle mk| + \right.$$

$$\left. + f_{m\mathbf{k}} \left| \frac{\partial}{\partial \mathbf{k}} mk \right\rangle \langle mk| + f_{m\mathbf{k}} |mk\rangle \left\langle \frac{\partial}{\partial \mathbf{k}} mk \right| \right\}$$

$$[H,\ \rho]_{nn'} = \left(\varepsilon_{nk} - \varepsilon_{n'k}\right) \rho_{nn'}$$

Off diagonal response is intrinsic when bands are well defined

$$\left| \frac{\partial}{\partial \mathbf{k}} nk \right\rangle = \sum_{m \neq n} \left(\frac{\langle mk| \frac{\partial H}{\partial \mathbf{k}} |nk\rangle}{\varepsilon_{nk} - \varepsilon_{mk}} \right) |mk\rangle$$

Normal Transport
Born Approximation

$$J_d(\langle \rho_{Ed} \rangle)_{\boldsymbol{k}} = D_{d\boldsymbol{k}}$$

$$D_{d\boldsymbol{k}} = \frac{e\boldsymbol{E}}{\hbar} \cdot \frac{\partial \langle \rho^n_{0\boldsymbol{k}} \rangle}{\partial \varepsilon_{n\boldsymbol{k}}}$$

$$J_d(\langle \rho_d \rangle)^{nn}_{\boldsymbol{k}} = \frac{2\pi}{\hbar} \sum_{n'\boldsymbol{k}'} \langle U^{nn'}_{\boldsymbol{k}\boldsymbol{k}'} U^{n'n}_{\boldsymbol{k}'\boldsymbol{k}} \rangle \left(\langle \rho_d \rangle^n_{\boldsymbol{k}} - \langle \rho_d \rangle^{n'}_{\boldsymbol{k}'} \right) \delta(\varepsilon^n_{\boldsymbol{k}} - \varepsilon^{n'}_{\boldsymbol{k}'})$$

Anomalous Transport
Born Approximation

$$\frac{i}{\hbar}[H_{0\boldsymbol{k}}, \langle\rho_{Eod}\rangle_{\boldsymbol{k}}] = D_{od\boldsymbol{k}} - J_{od}(\langle\rho_{Ed}\rangle)_{\boldsymbol{k}}$$

$$D_{od\boldsymbol{k}}^{nn'} \equiv \frac{e\boldsymbol{E}}{\hbar}\cdot\langle u_{\boldsymbol{k}}^{n}|\frac{\partial u_{\boldsymbol{k}}^{n'}}{\partial \boldsymbol{k}}\rangle(\langle\rho_0\rangle_{\boldsymbol{k}}^{n} - \langle\rho_0\rangle_{\boldsymbol{k}}^{n'})$$

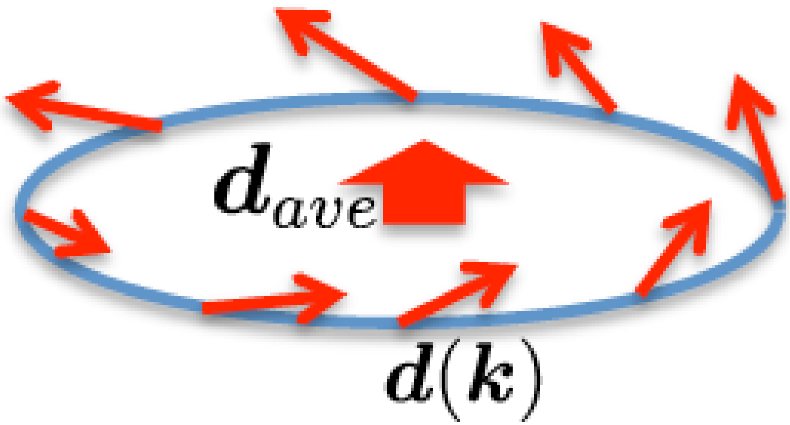
$$D'_{od\boldsymbol{k}} = \frac{e\boldsymbol{E}\tau_p\pi}{\hbar}\cdot\sum_{n'\boldsymbol{k}'}\langle U_{\boldsymbol{k}\boldsymbol{k}'}^{nn'}U_{\boldsymbol{k}'\boldsymbol{k}}^{n'n''}\rangle\{[\boldsymbol{v}_{\boldsymbol{k}}^{n}\delta(\varepsilon_{\boldsymbol{k}}^{n} - \varepsilon_F) - \boldsymbol{v}_{\boldsymbol{k}'}^{n'}\delta(\varepsilon_{\boldsymbol{k}'}^{n'} - \varepsilon_F)]\delta(\varepsilon_{\boldsymbol{k}}^{n} - \varepsilon_{\boldsymbol{k}'}^{n'})$$
$$+ [\boldsymbol{v}_{\boldsymbol{k}}^{n''}\delta(\varepsilon_{\boldsymbol{k}}^{n''} - \varepsilon_F) - \boldsymbol{v}_{\boldsymbol{k}'}^{n'}\delta(\varepsilon_{\boldsymbol{k}'}^{n'} - \varepsilon_F)]\delta(\varepsilon_{\boldsymbol{k}}^{n''} - \varepsilon_{\boldsymbol{k}'}^{n'})\}.$$

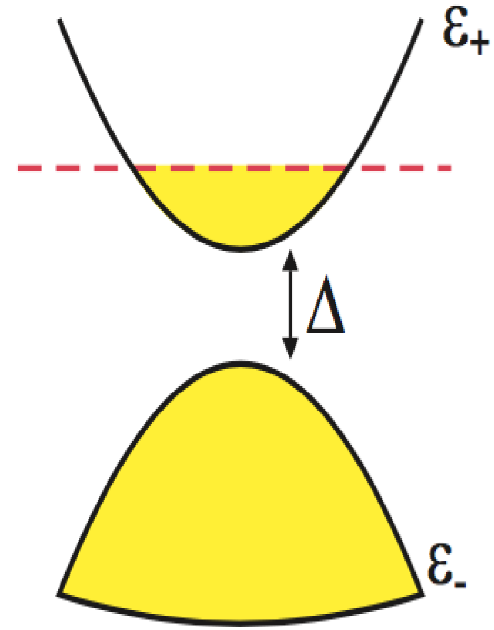
- Theory of Current-Induced Torques

- Resistive Detection of SOTs in TIs

- The role of the bulk ?

Massive Dirac Model for Current-Induced Spin Density





$$2v_D \delta \mathbf{s_k} \times \mathbf{b_k} + \frac{\delta \mathbf{s_k}}{\tau} = -\mathbf{F_k}$$

$$\mathbf{F_k} = \left(\sum_n \langle n, \mathbf{k} | \mathbf{s} | n, \mathbf{k} \rangle \frac{\partial f_{n,\mathbf{k}}}{\partial \mathbf{k}} + \sum_n \sum_{m \neq n} \langle n, \mathbf{k} | \mathbf{s} | m, \mathbf{k} \rangle \left(\frac{f_{n,\mathbf{k}} - f_{m,\mathbf{k}}}{\varepsilon_{n,\mathbf{k}} - \varepsilon_{m,\mathbf{k}}} \right) \langle m, \mathbf{k} | \frac{\partial H}{\partial \mathbf{k}} | n, \mathbf{k} \rangle \right) \cdot \frac{e\mathbf{E}}{\hbar}$$

Magneto-resistance of Massive Dirac Model

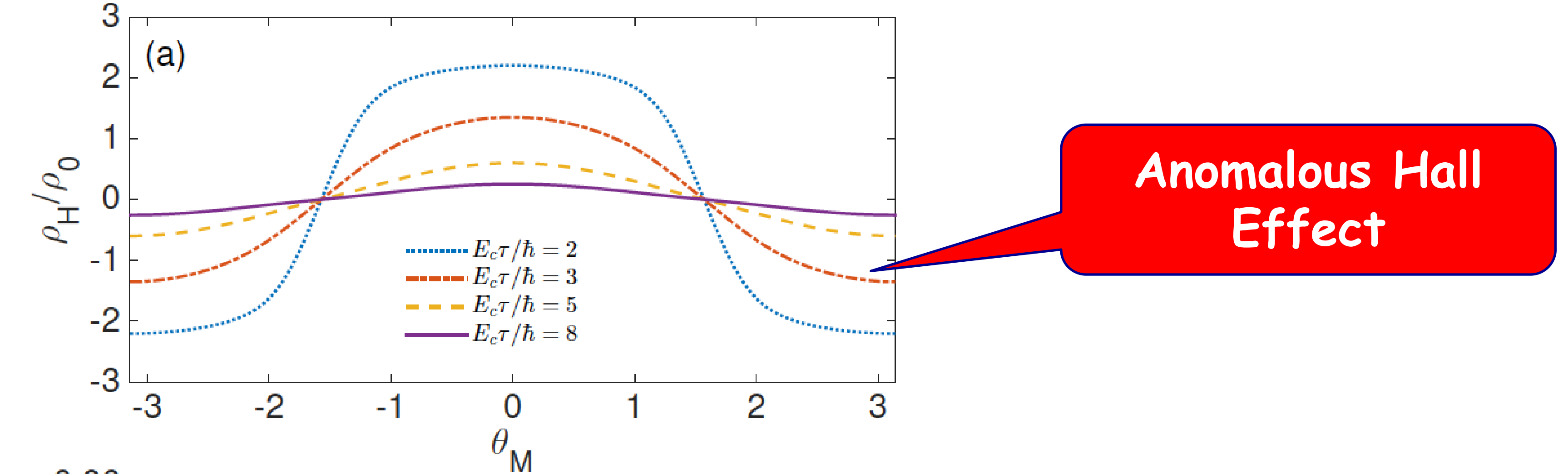
Anomalous Hall Effect

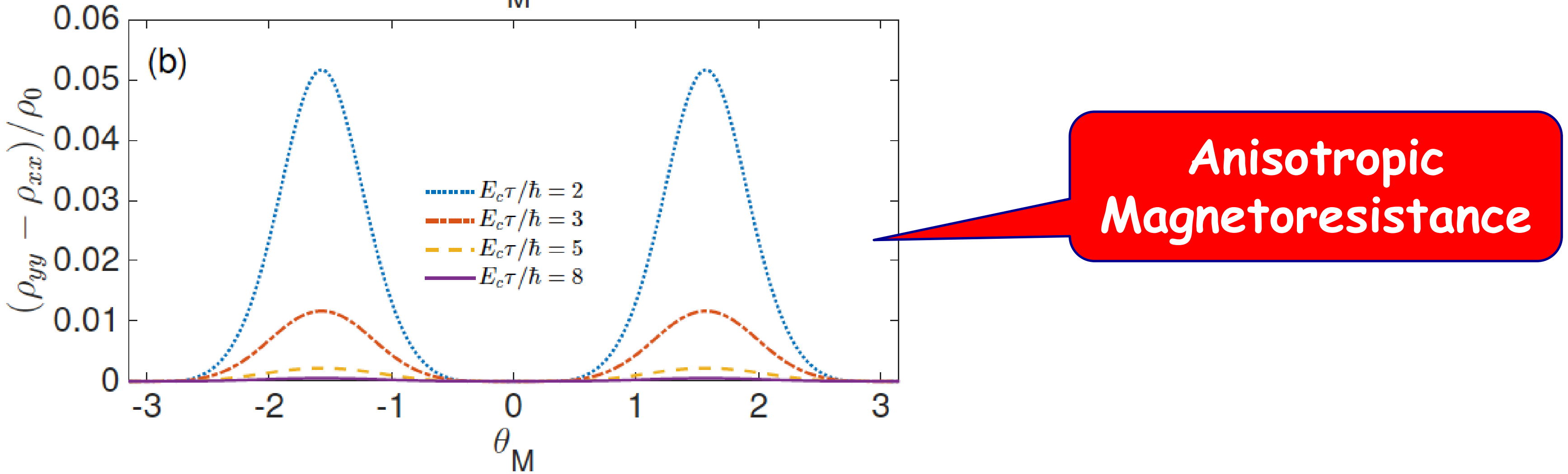
$$\boldsymbol{\rho} = \begin{bmatrix} \rho_\perp \cos^2\varphi_M + \rho_{||}\sin^2\varphi_M & \rho_P \cos\varphi_M \sin\varphi_M + \rho_H \\ \rho_P \cos\varphi \sin\varphi_M - \rho_H & \rho_\perp \sin^2\varphi_M + \rho_{||}\cos^2\varphi_M \end{bmatrix}$$

Anisotropic Magneto-resistance

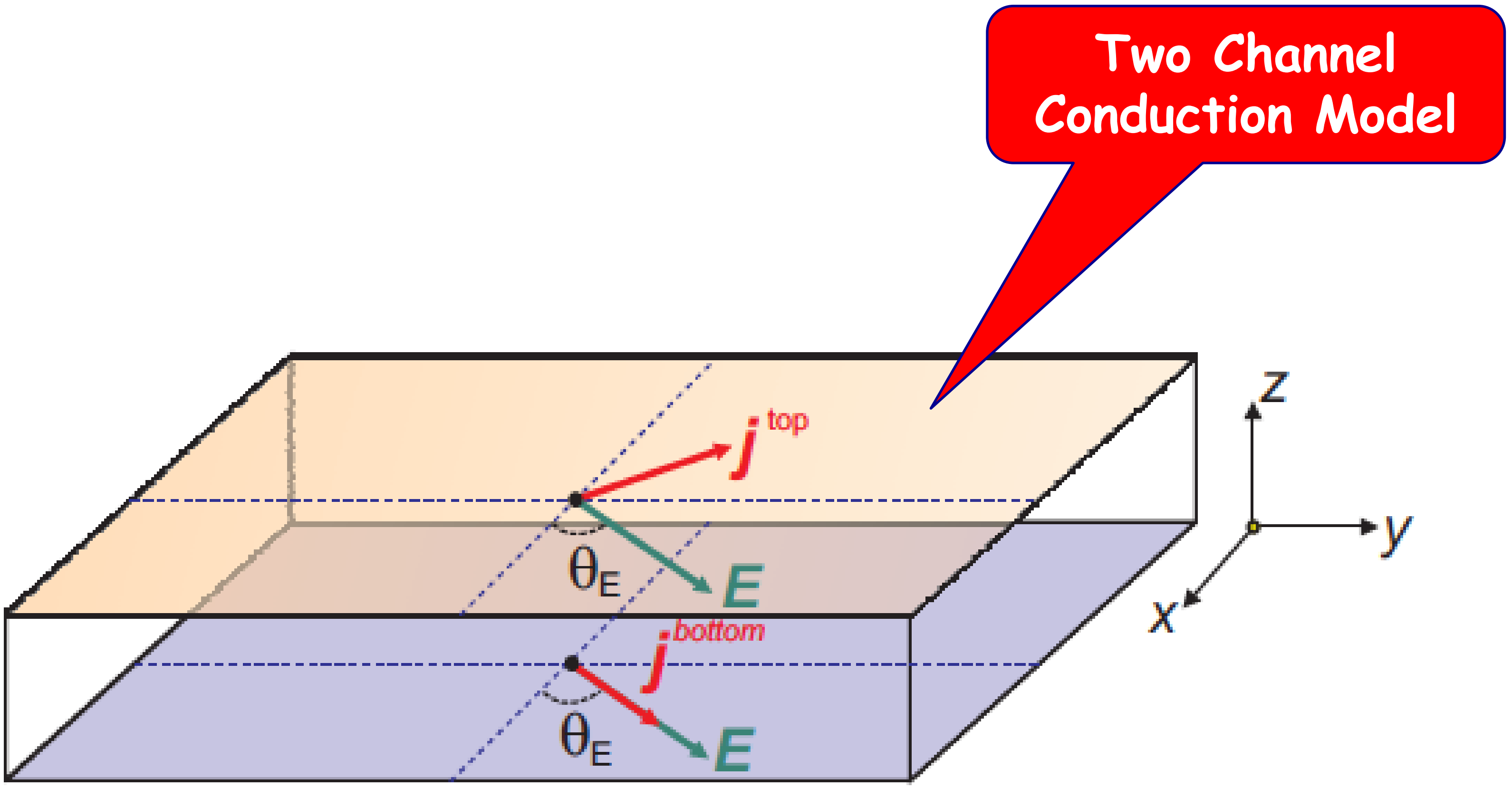
$$\rho_P = \rho_{||} - \rho_\perp$$

Magneto-resistance of Massive Dirac Model

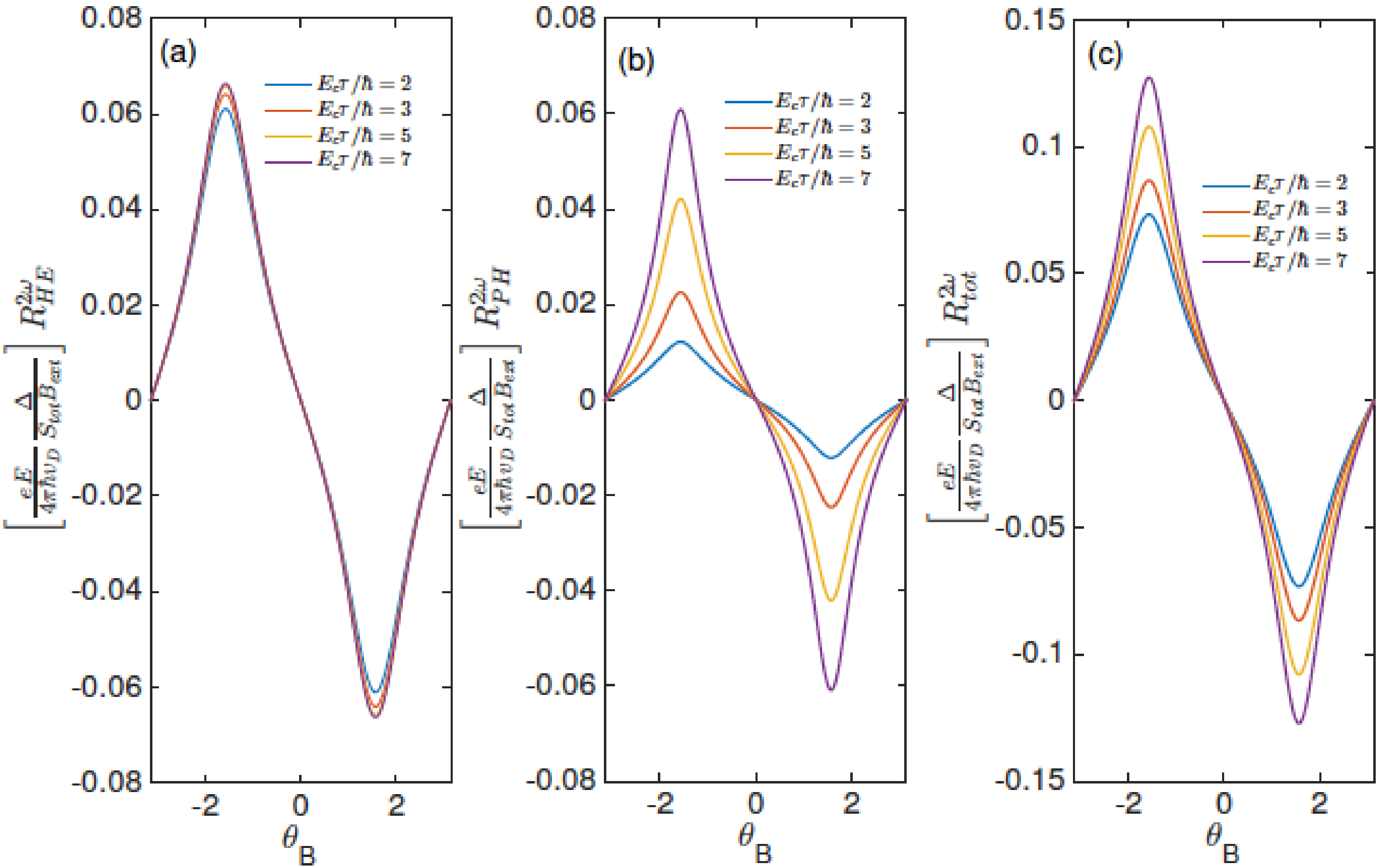




Resistively Detected SOT



Resistively Detected SOT



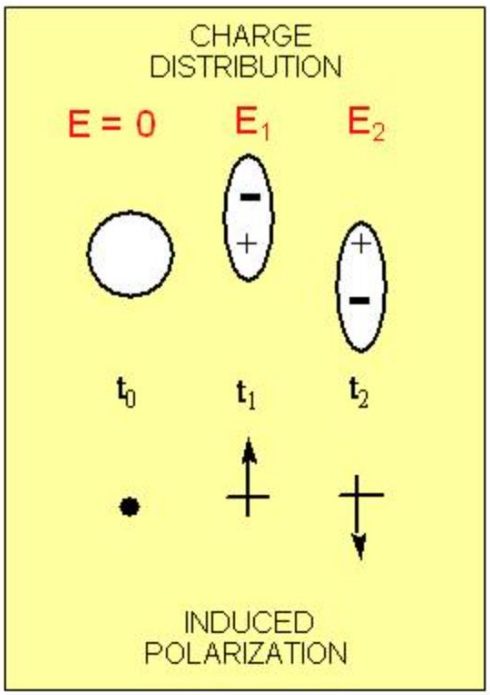
- Theory of Current-Induced Torques: The case of TI DMSs

- Resistive Detection of SOTs

- The role of the bulk ?

Response of Atom to Static Electric Field

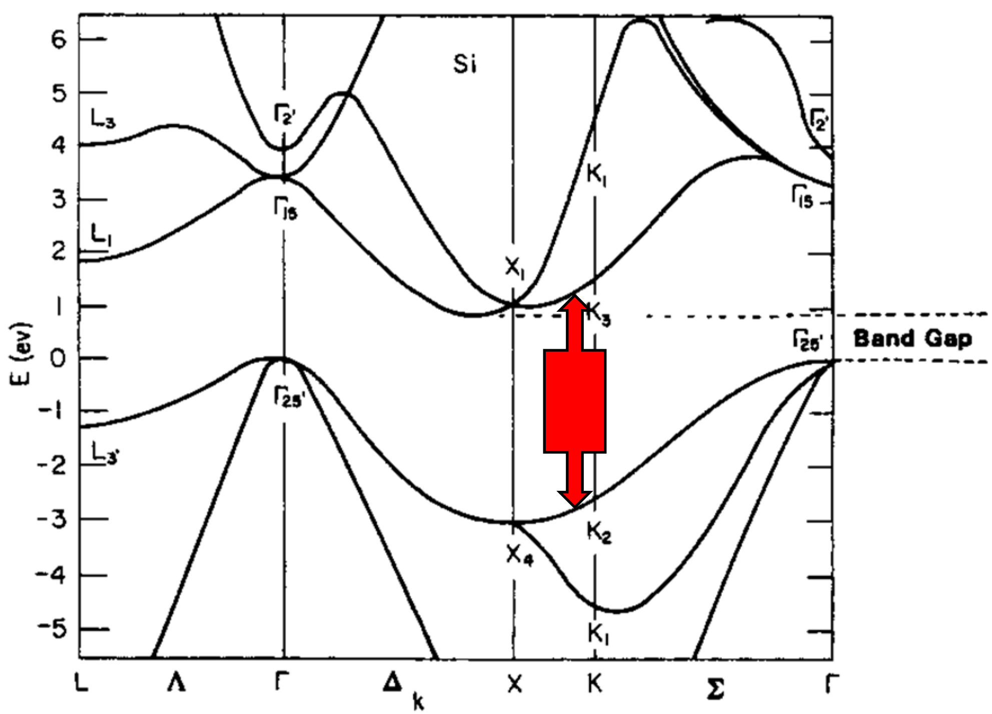
F = qE



$$\Psi_n^{(1)} = \sum_{k \neq n} \Psi_k^{(0)} \frac{V_{kn}}{E_n^{(0)} - E_k^{(0)}}$$

$$\alpha = e^2 \sum_{k \neq n} \frac{\mathbf{r}_{nk}\mathbf{r}_{kn} + \mathbf{r}_{kn}\mathbf{r}_{nk}}{E_k^{(0)} - E_n^{(0)}}$$

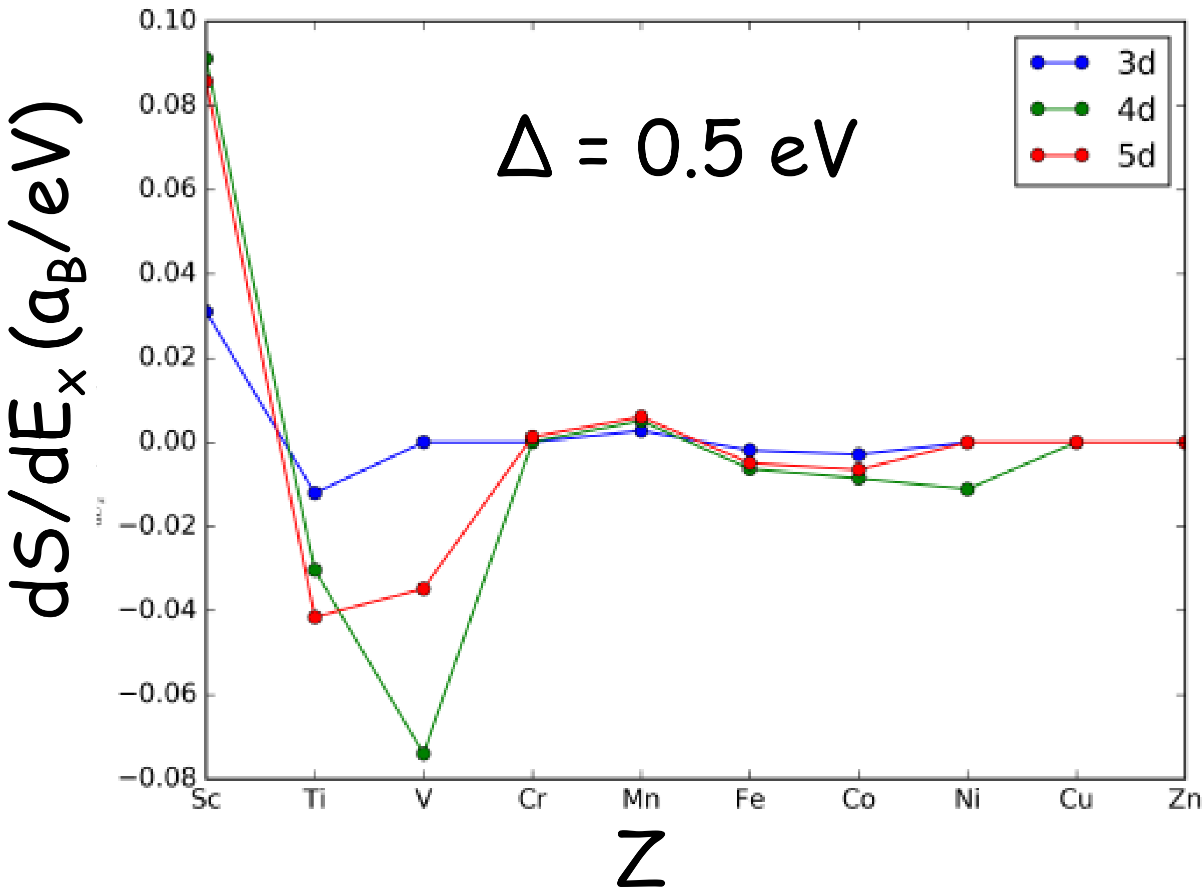
Response of Insulator to static Electric Field



Interband Transitions

$$\rho^{(1)}_{n'n}(\vec{k}) = ieE \, \frac{f_{n',\vec{k}} - f_{n,\vec{k}}}{(E_{n',\vec{k}} - E_{n,\vec{k}})^2} \, \langle \Psi_{n',\vec{k}} | \frac{\partial H}{\partial k_x} | \Psi_{n,\vec{k}} \rangle$$

Atomic Model of Current-Induced Torques



$R^{2\omega}$ signal has both planar Hall and anomalous Hall components

SOTs explained to within factor of a few by massive Dirac surface state model

Bulk of the TI – and bulk of any magnetic insulator – can play a role