Spin and orbital magnetic response on the surface of a topological insulator

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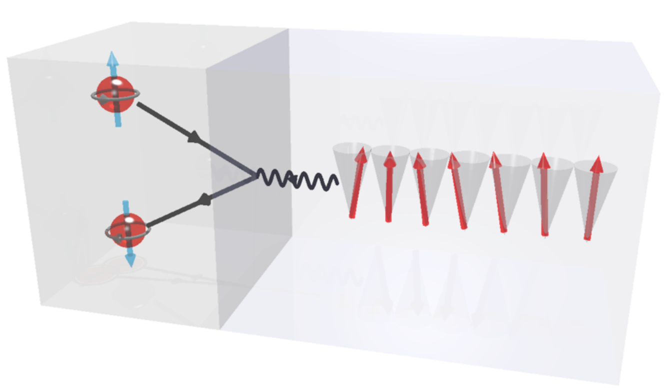
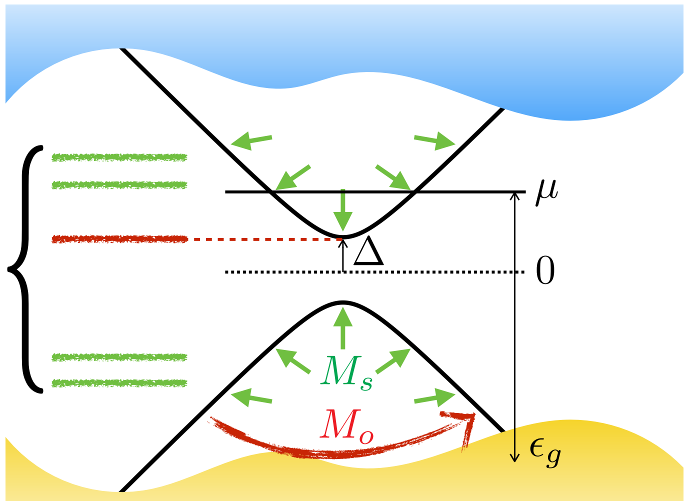
in collaboration with D. Loss (Basel), D. Pesin (Utah), S. Bender and K. Wang (UCLA)



YT and Loss, *PRL* (2012)
Pesin and MacDonald, *PRL* (2013)
YT and Bender, *PRB* (2014)
Fan *et al.*, *Nature Mat.* (2014)
YT, Pesin, and Loss, *PRB* (2015)

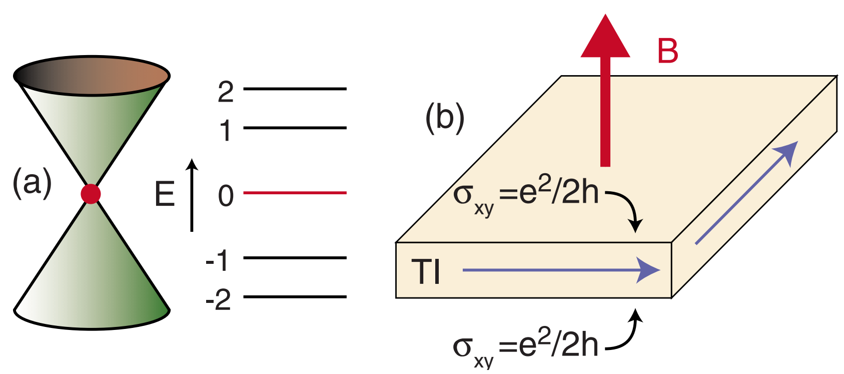


Outline

- Equilibrium spin and orbital magnetic response of Dirac electrons
- Spin Hall phenomenology of out-of-equilibrium dynamics
- UCLA experiments on Cr-doped (magnetic) BiSbTe
- Dynamics (theory) of a domain-wall/chiral-mode composite

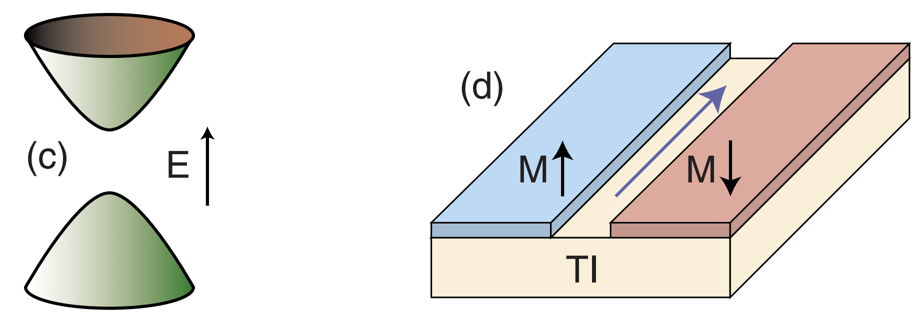
Overview (magnetoelectric phenomena)

- Magnetic field



0th Landau level

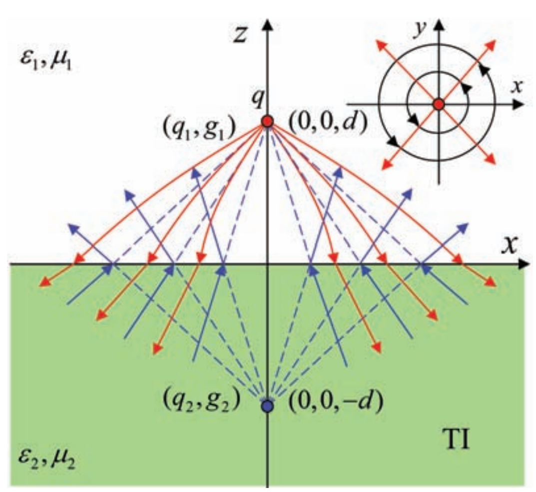
- Magnetic exchange



chiral "anomaly"

Hasan and Kane, *RMP* (2010)

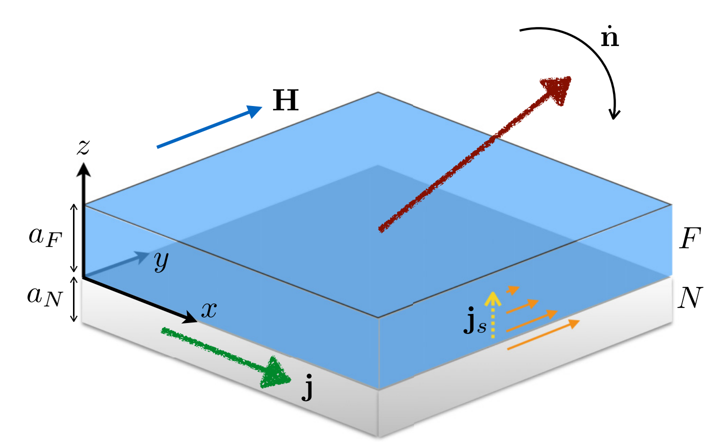
- Equilibrium



axion electrodynamics

Qi *et al.*, *Science* (2009)

- Nonequilibrium



spin Hall phenomenology

YT and Bender, *PRB* (2014)

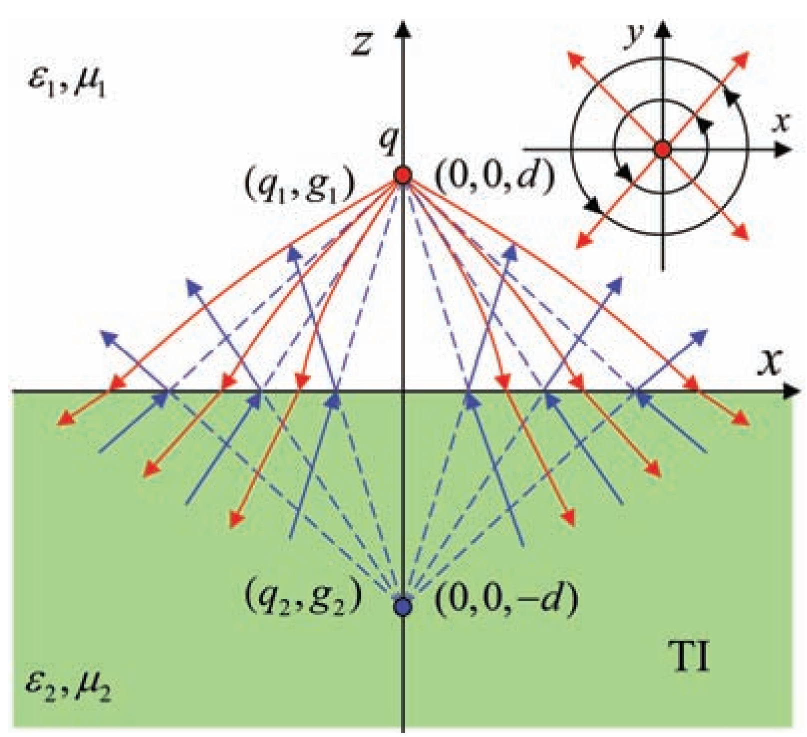
Topological magnetoelectric effect

- Axion electrodynamics: $\Delta\mathcal{L} = \theta \mathbf{E}\cdot\mathbf{B}$ $\theta = \pm e^2/2h \rightarrow \sigma_{xy}$

(sign determined by the magnetically induced gap)

Wilczek, *PRL* (1987)

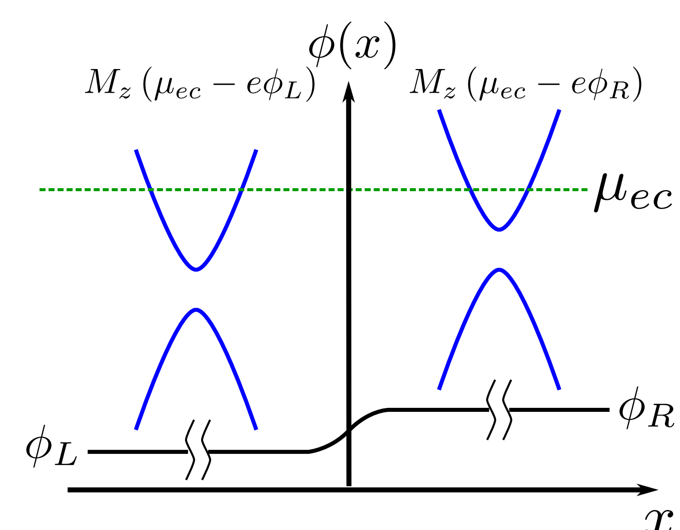
- dyonic screening:



Qi *et al.*, *Science* (2009)

- longitudinal conductance leads to a receding monopole

- no monopoles in equilibrium for a metallic surface



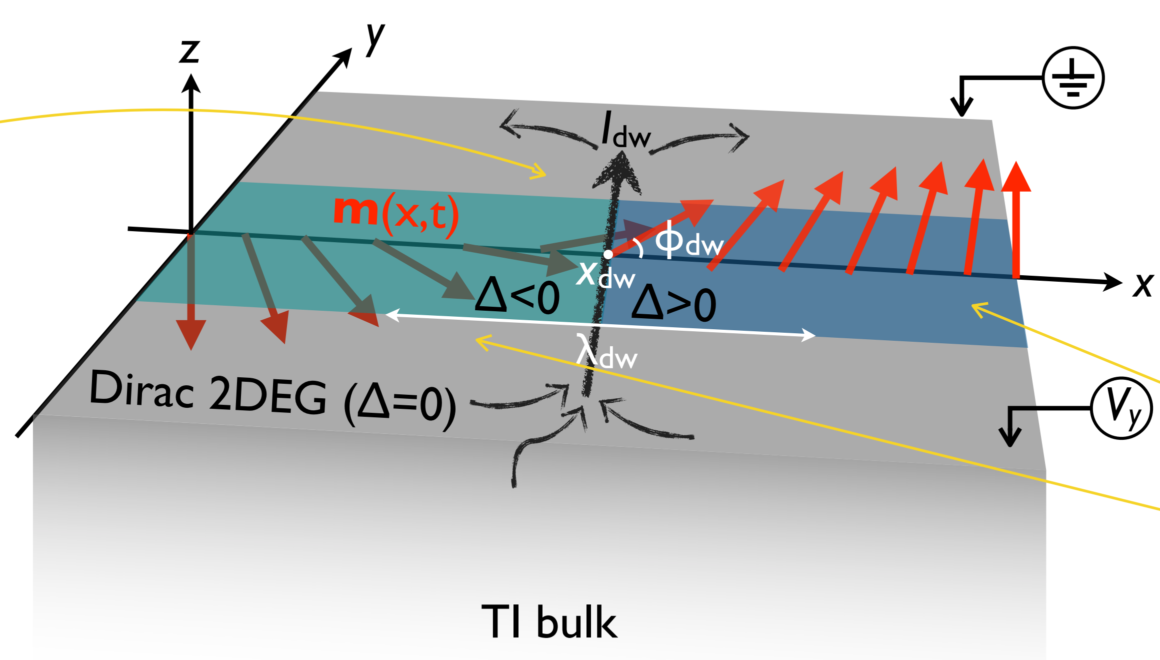
Pesin and MacDonald, *PRL* (2013)

no direct correspondence between Hall effect and equilibrium currents

Beyond axion electrodynamics

- TI in proximal coupling to a ferromagnetic texture
- In general, we have inhomogeneities in the electrical potential and magnetic exchange field
- What is the nature of the magnetic (spin and orbital) response of the TI surface?
- What is the feedback to (and coupling with) the magnetic layer?

chiral mode



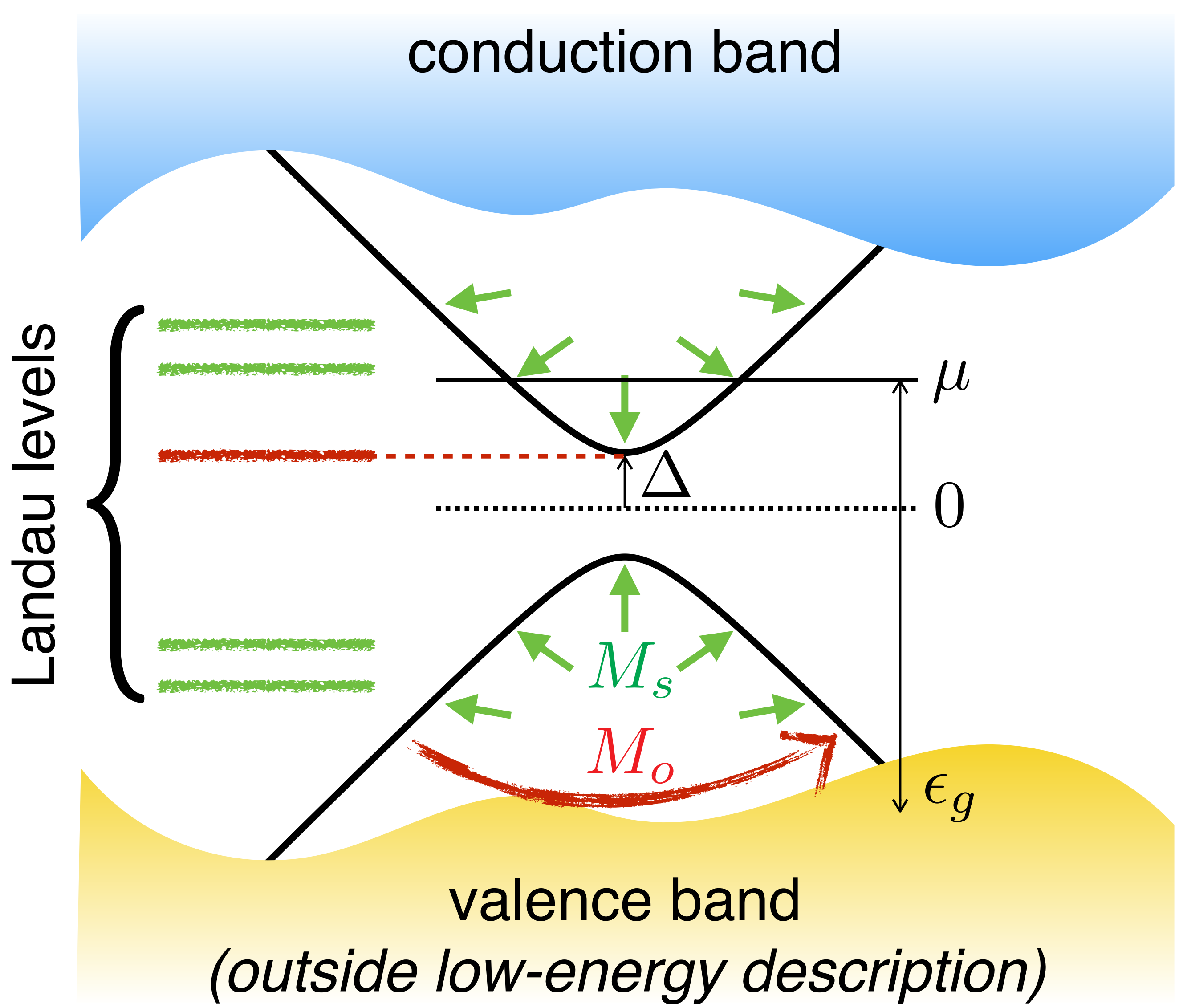
gapped regions

YT and Loss, *PRL* (2012)

Effective theory for magnetic response

- Peierls-substituted Dirac equation with Zeeman coupling:

$$H_0 = v\left(\mathbf{p} + \frac{e}{c}\mathbf{A}\right)\cdot \mathbf{z}\times\hat{\boldsymbol{\sigma}} - e\varphi + \frac{g}{2}\mu_B \mathbf{B}\cdot\hat{\boldsymbol{\sigma}}$$



Landau levels

$$\epsilon_0 = -\mathrm{sgn}(B)\Delta$$

$$\epsilon_n = \mathrm{sgn}(n)\sqrt{2(\hbar v/l)^2|n| + \Delta^2}$$

Pankratov, *PLA* (1987)

$$M = -\partial_B \Omega(\mu, T, B)$$

the thermodynamic potential Ω
is dominated by the 0th LL at low fields

(orbital) persistent current:

$$\mathbf{j} = -c\mathbf{z}\times\boldsymbol{\nabla} M_o$$

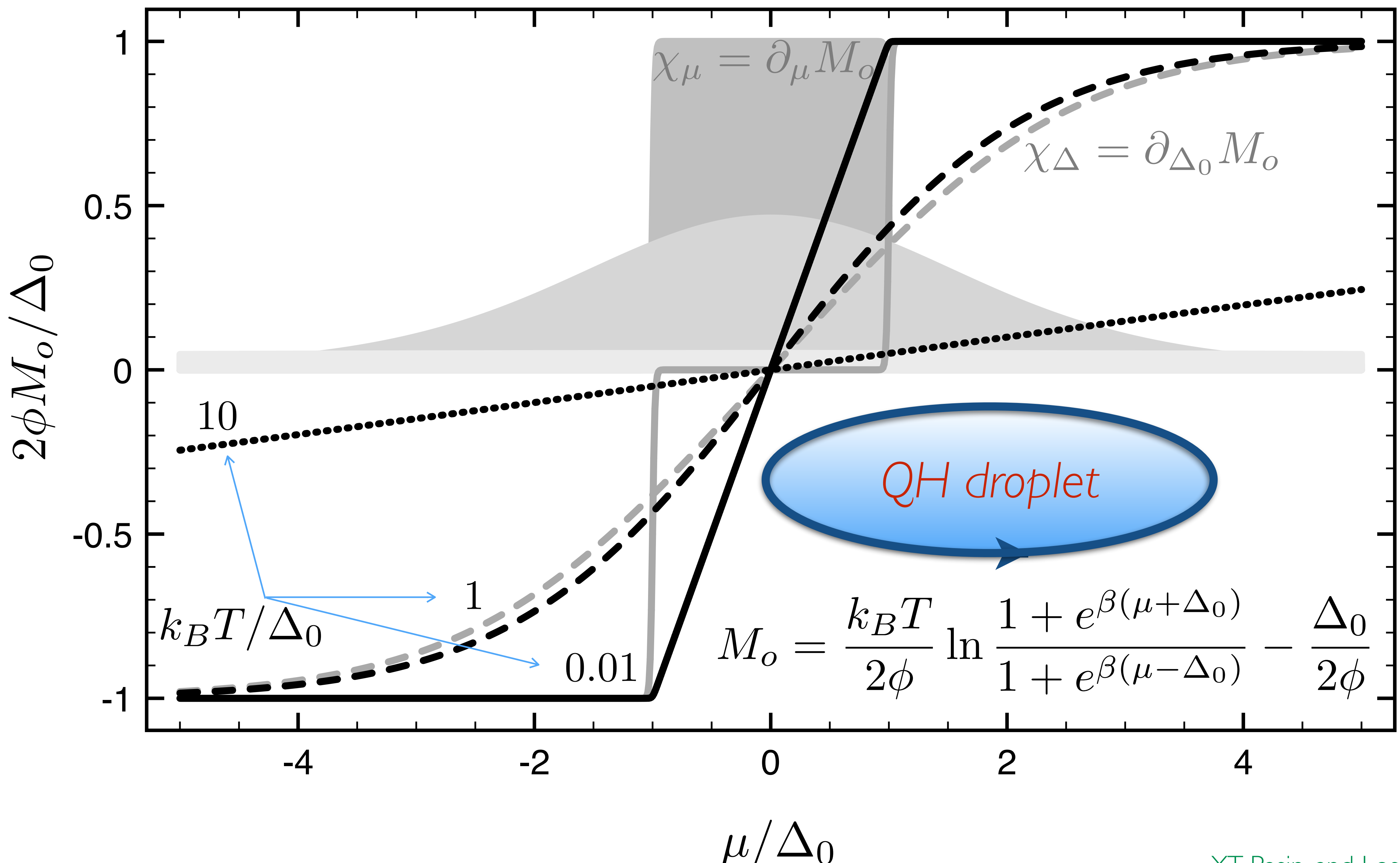
(helical) planar spin density:

$$\boldsymbol{\rho}\times\mathbf{z} = -\frac{c}{ev}\delta_{\mathbf{A}} H = \frac{\mathbf{j}}{ev}$$

Magnetic response

- Spin/orbital contributions to the (local) out-of-plane magnetization:

$$M = M_s + M_o \qquad M_s = \Delta_0 \frac{g}{4m\phi}\frac{\epsilon_g}{v^2}$$



YT, Pesin, and Loss, *PRB* (2015)

Exchange coupling and local spin density

- The local exchange interaction has the general form

$$H' = J(n_x\hat{\sigma}_x + n_y\hat{\sigma}_y) + J_\perp n_z \hat{\sigma}_z$$

$\mathbf{n}$ - magnetic order (direction) $\hat{\boldsymbol{\sigma}}$ - electron spin

- We are thus tasked with calculating the out-of-plane and planar components of the spin density

- Due to the electronic helicity, the out-of-plane orbital magnetization has the full information about the planar spin density $\boldsymbol{\rho}_{\|}$:

$$\boxed{\boldsymbol{\rho}_{\|} \equiv \mathbf{z} \times \boldsymbol{\rho} \times \mathbf{z} = \frac{\mathbf{z}\times\mathbf{j}}{ev} = \frac{J_\perp \chi_\Delta \boldsymbol{\nabla} n_z - e\chi_\mu \mathbf{E}}{4\pi\hbar v}}$$

$$\chi_\Delta \equiv 2\phi\partial_{\Delta_0} M_o = \frac{\sinh(\beta\mu)}{\cosh(\beta\Delta_0)+\cosh(\beta\mu)} \qquad \chi_\mu \equiv 2\phi\partial_\mu M_o = \frac{\sinh(\beta\Delta_0)}{\cosh(\beta\Delta_0)+\cosh(\beta\mu)}$$

- universal scaling functions

YT, Pesin, and Loss, *PRB* (2015)

Feedback on the magnetization

- Landau-Lifshitz equation:

$$s(1+\alpha\mathbf{n}\times)\partial_t\mathbf{n} = \mathbf{n}\times\Big(\mathbf{H}_{\mathrm{eff}} - \underbrace{J\boldsymbol{\rho}_{\parallel} - J_\perp\rho_z\mathbf{z}}_{\text{spin torque}}\Big) = \mathbf{n}\times\mathbf{H}^*$$

$$\mathbf{H}^* \equiv -\delta_{\mathbf{n}}(\Omega_0 + \Omega')$$

(intrinsic) magnetic free energy   TI feedback (spin torque)

- The TI feedback is obtained by integrating electrons out:

$$\Omega' = \int d^2\mathbf{r}\,\mathcal{F}'[\mathbf{n}] \qquad \mathcal{F}'[\mathbf{n}] = -\frac{Kn_z^2}{2} - \frac{\Gamma_{\mathrm{DM}}}{2}(\underbrace{n_z\boldsymbol{\nabla}\cdot\mathbf{n} - \mathbf{n}\cdot\boldsymbol{\nabla}n_z}_{\text{DMI}}) - \Gamma_{\mathrm{ME}}\underbrace{\mathbf{E}\cdot\mathbf{n}}_{\text{ME effect}}$$

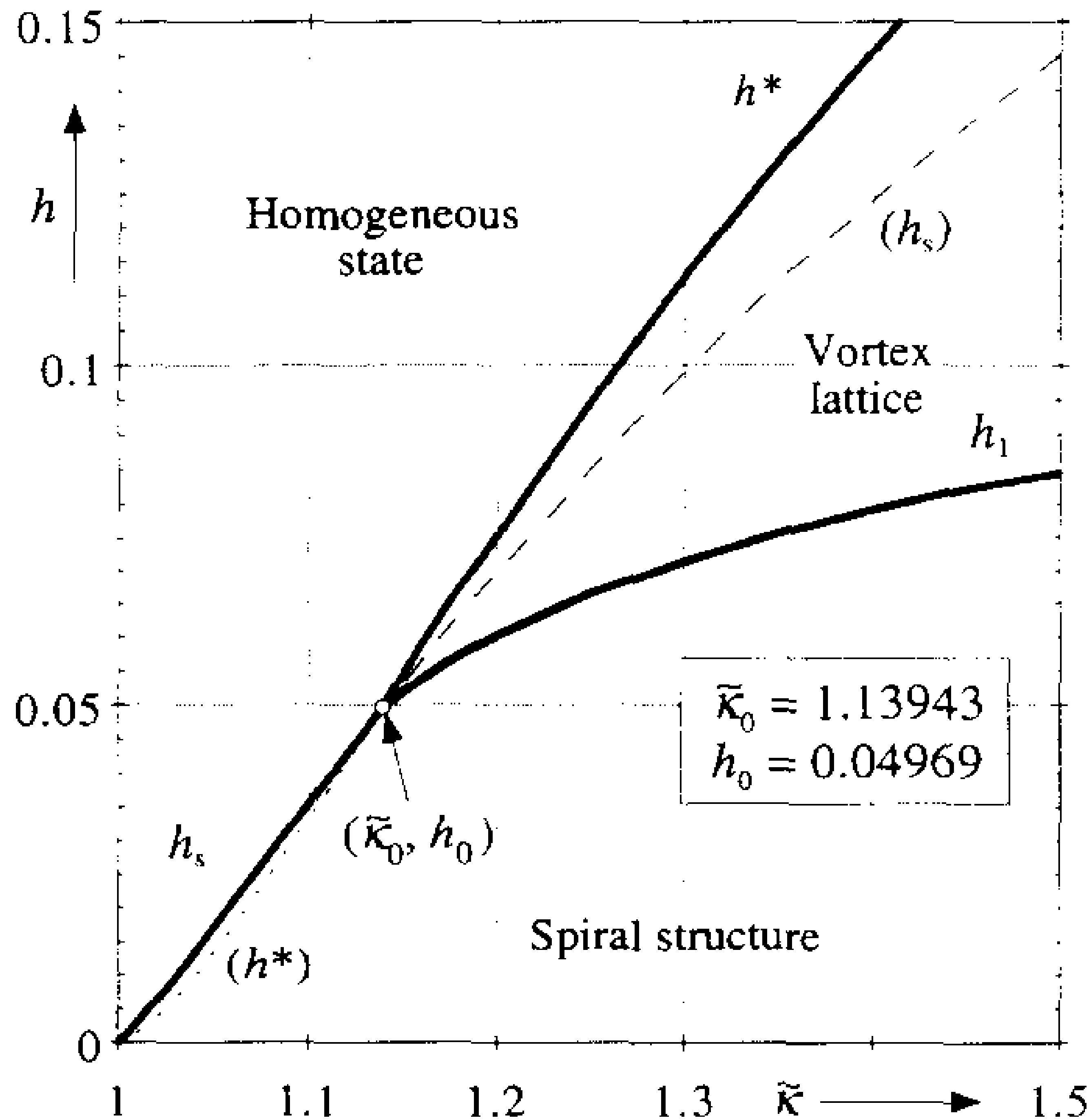
Magnetic free energy, with universal scaling of the DMI and magnetoelectric coefficients with the exchange-induced gap, temperature, and chemical potential:

$$\Gamma_{\mathrm{DM}} = (JJ_\perp/4\pi\hbar v)\chi_\Delta$$
$$\Gamma_{\mathrm{ME}} = (Je/4\pi\hbar v)\chi_\mu$$

YT, Pesin, and Loss, *PRB* (2015)

Skyrmionic lattice

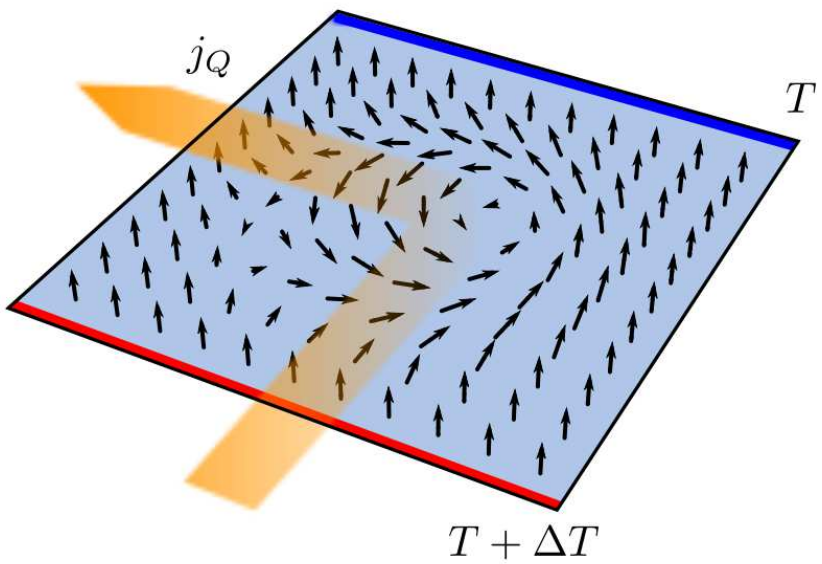
- Phase diagram engendered by the DMI:



Bogdanov and Hubert, *JMMM* (1994)

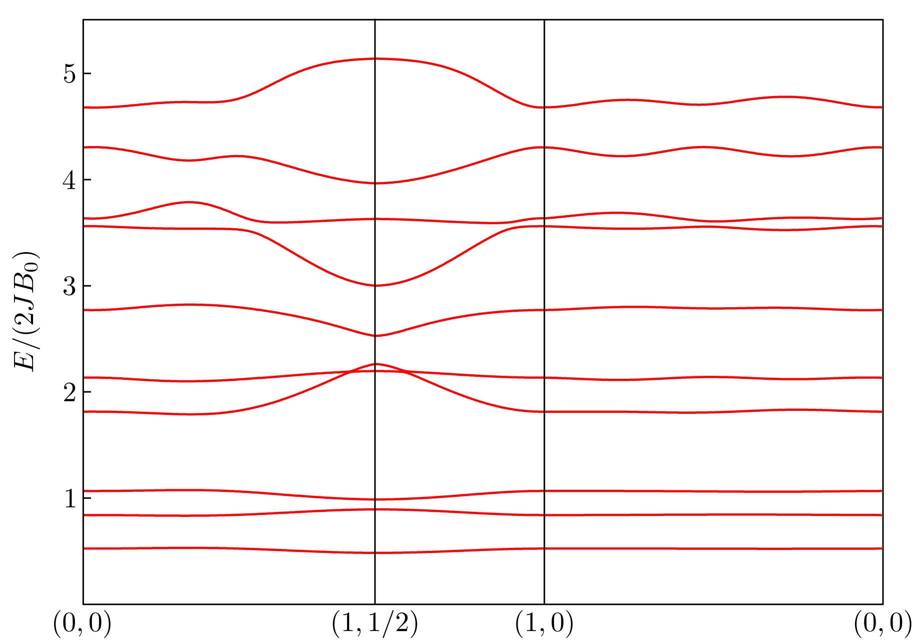
Thermal Hall effect

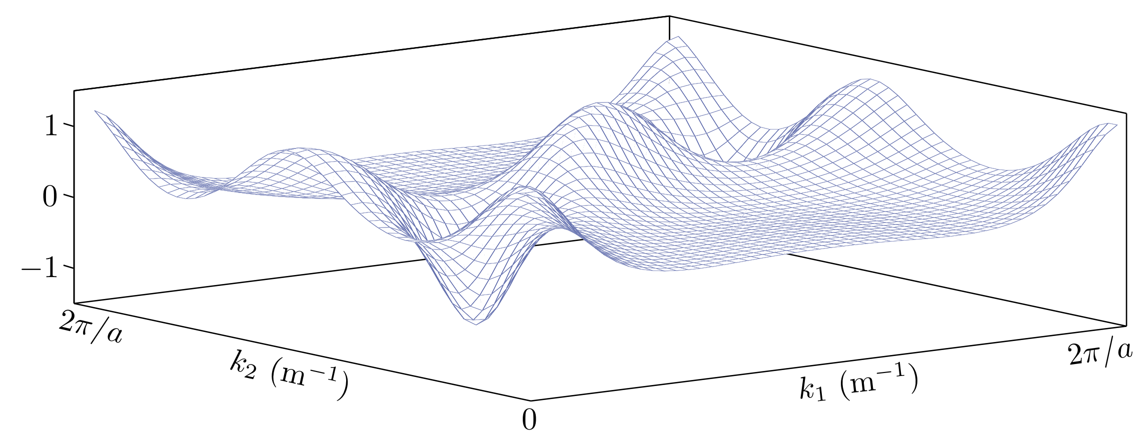
- The magnetic texture fomented by the DM interaction can produce Landau-level-like magnonic Chern bands, which harbor magnonic chiral edge states and induce a thermal Hall effect:

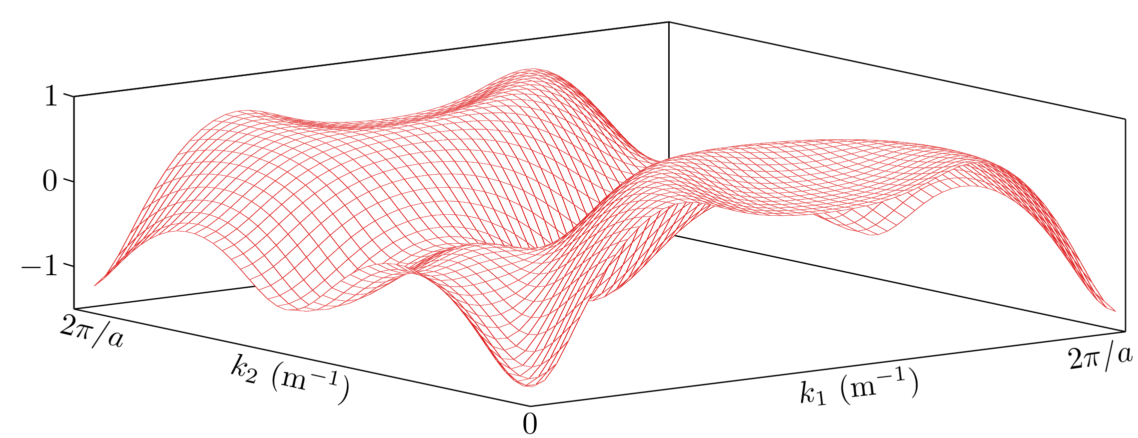


$$i\hbar\partial_t m_+ = A(\boldsymbol{\nabla}/i+\boldsymbol{\alpha})^2 m_+$$

$$\boldsymbol{\alpha} = \hat{R}^{-1}\left(\boldsymbol{\nabla} - \frac{JJ_\perp}{vA}\hat{\mathbf{I}}\right)\hat{R}\bigg|_{12}$$







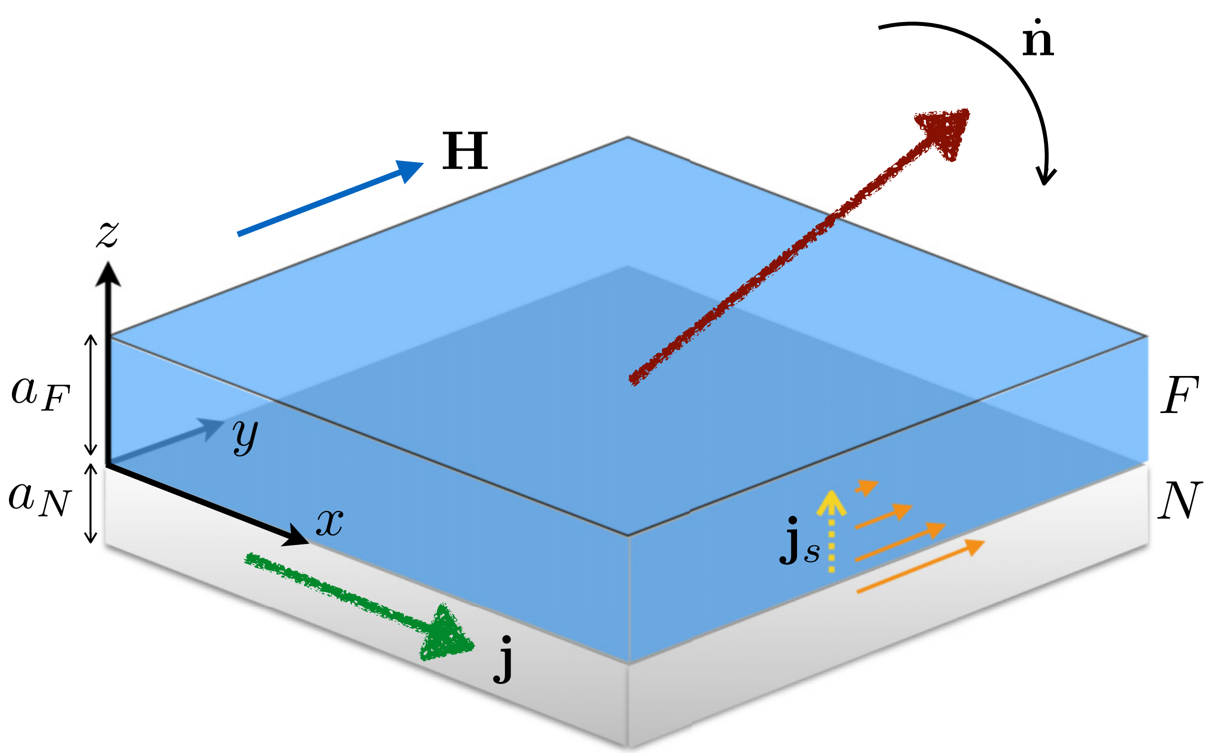
cf. Katsura *et al.*, *PRL* (2010); Onose *et al.*, *Science* (2010)

Hoogdalem, YT, and Loss, *PRB* (2013)

Spin Hall phenomenology of magnetic dynamics

- Our understanding of the interaction between electric (transport) currents and magnetic dynamics at magnetic/nonmagnetic interfaces is based on the phenomenological theory according to:

  - Structural/crystalline symmetries
  - Onsager reciprocity
  - Nonequilibrium thermodynamics



$$s(\dot{\mathbf{n}} + \mathbf{n} \times \hat{\alpha}\dot{\mathbf{n}}) = \mathbf{H}^* \times \mathbf{n} + \boxed{\boldsymbol{\tau}} \quad \textit{torque}$$

$$L\dot{\mathbf{j}} + \hat{\varrho}\mathbf{j} = \mathbf{E} + \boxed{\boldsymbol{\epsilon}} \quad \textit{motive force}$$

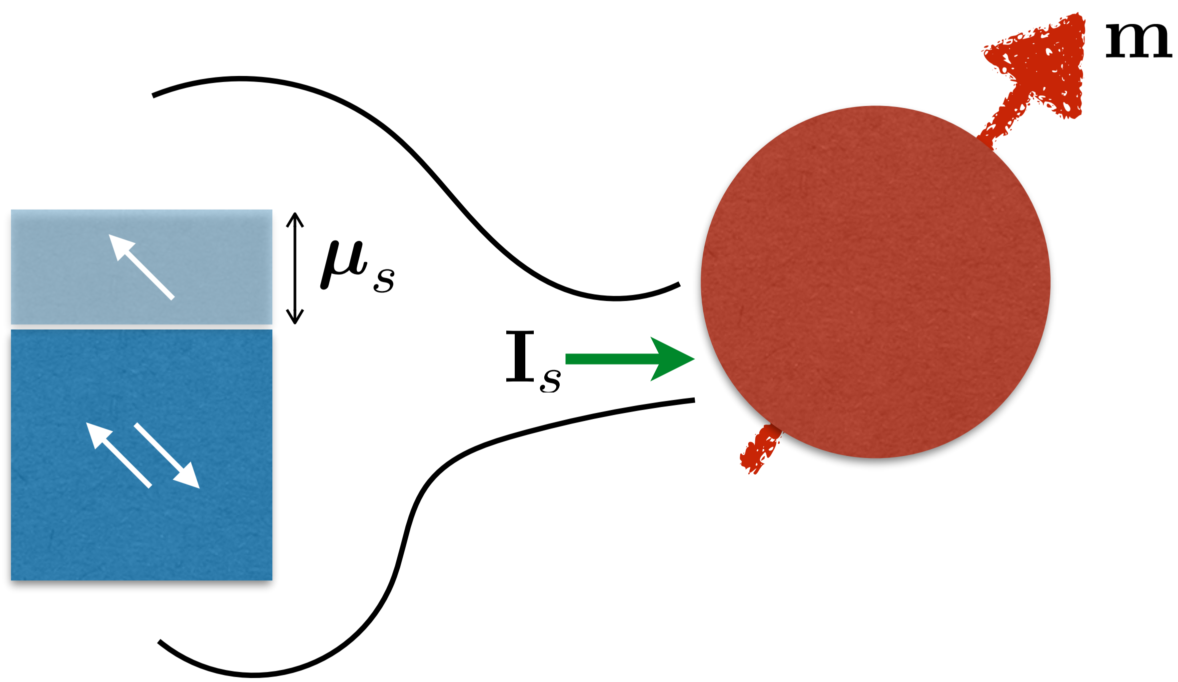
$$\boldsymbol{\tau} = (\eta + \vartheta\mathbf{n}\times)(\mathbf{z} \times \mathbf{j}) \times \mathbf{n}$$

$$\boldsymbol{\epsilon} = [(\eta + \vartheta\mathbf{n}\times)\dot{\mathbf{n}}] \times \mathbf{z}$$

YT and Bender, *PRB* (2014)

Towards magnetic insulators and extreme SOI

- For the ferromagnetic metals where the exchange interaction is strong and normal metals where spin-orbit coupling is weak:



$$-\frac{d\boldsymbol{\mu}_s}{dt} \leftarrow \mathbf{I}_s \equiv \boldsymbol{\tau} \rightarrow \frac{d\mathbf{m}}{dt}$$

spin-transfer torque/pumping

YT *et al.*, *RMP* (2005)

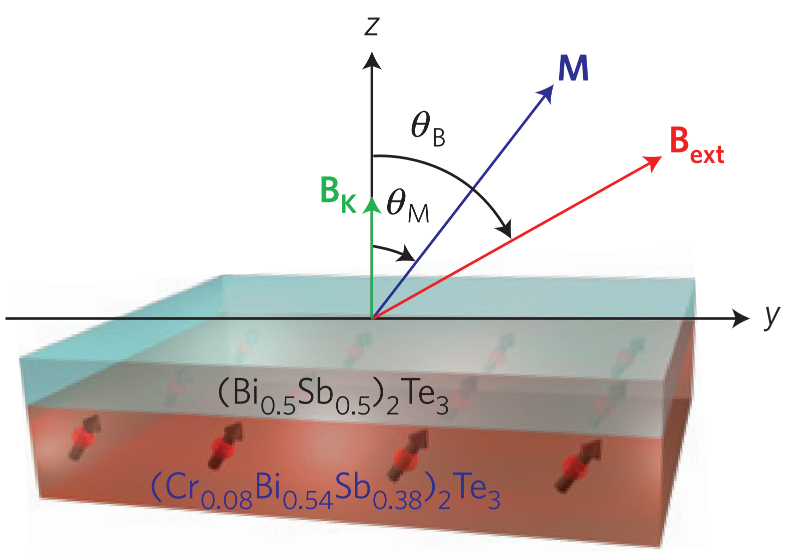
- Recently: growing interest toward replacing ferromagnetic metals with insulators and normal metals with conductors exhibiting strong spin-orbit interactions

  - Direct/inverse *spin Hall effects*
  - Spin transport via magnetic dynamics (e.g., magnons, domain walls)

TI-based magnetic heterostructures

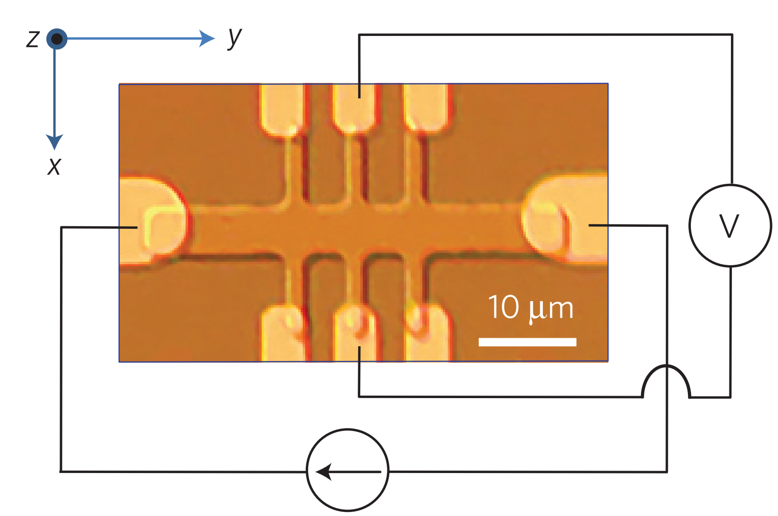
- Perhaps the most dramatic magnetoelectric phenomena can be expected at the interfaces between magnetic and topological insulators:

  - Electric current is localized at the interface, where the magnetic proximity effects are strongest



  - The spin-orbit interactions constitute the dominant contribution to the electronic Hamiltonian: This limit is opposite to the nonrelativistic regime

  - If the Dirac electrons are gapped by the ferromagnet, the bilayer provides an essentially nondissipative magnetoelectric compound

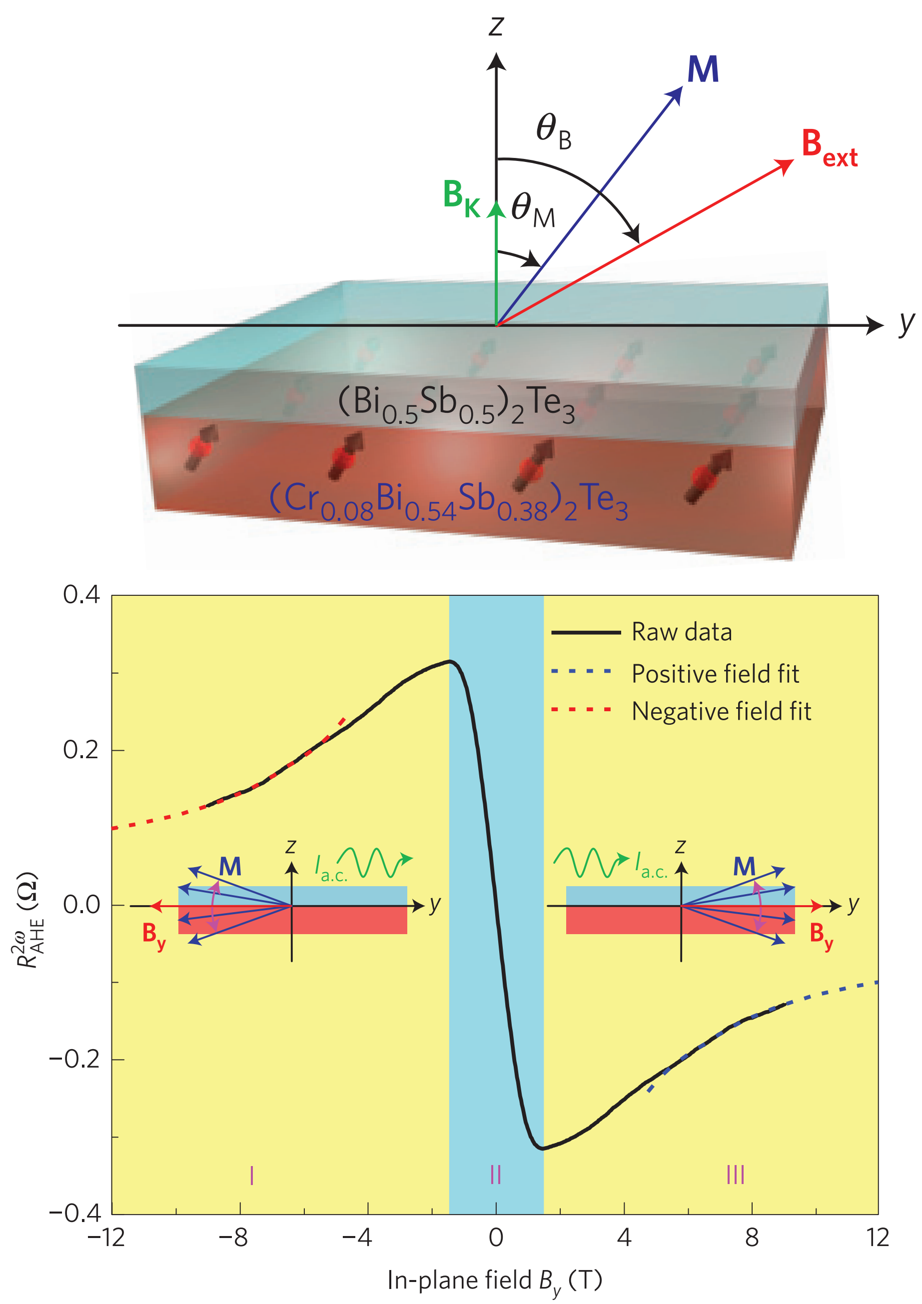


Mellnik *et al.*, *Nature* (2014)

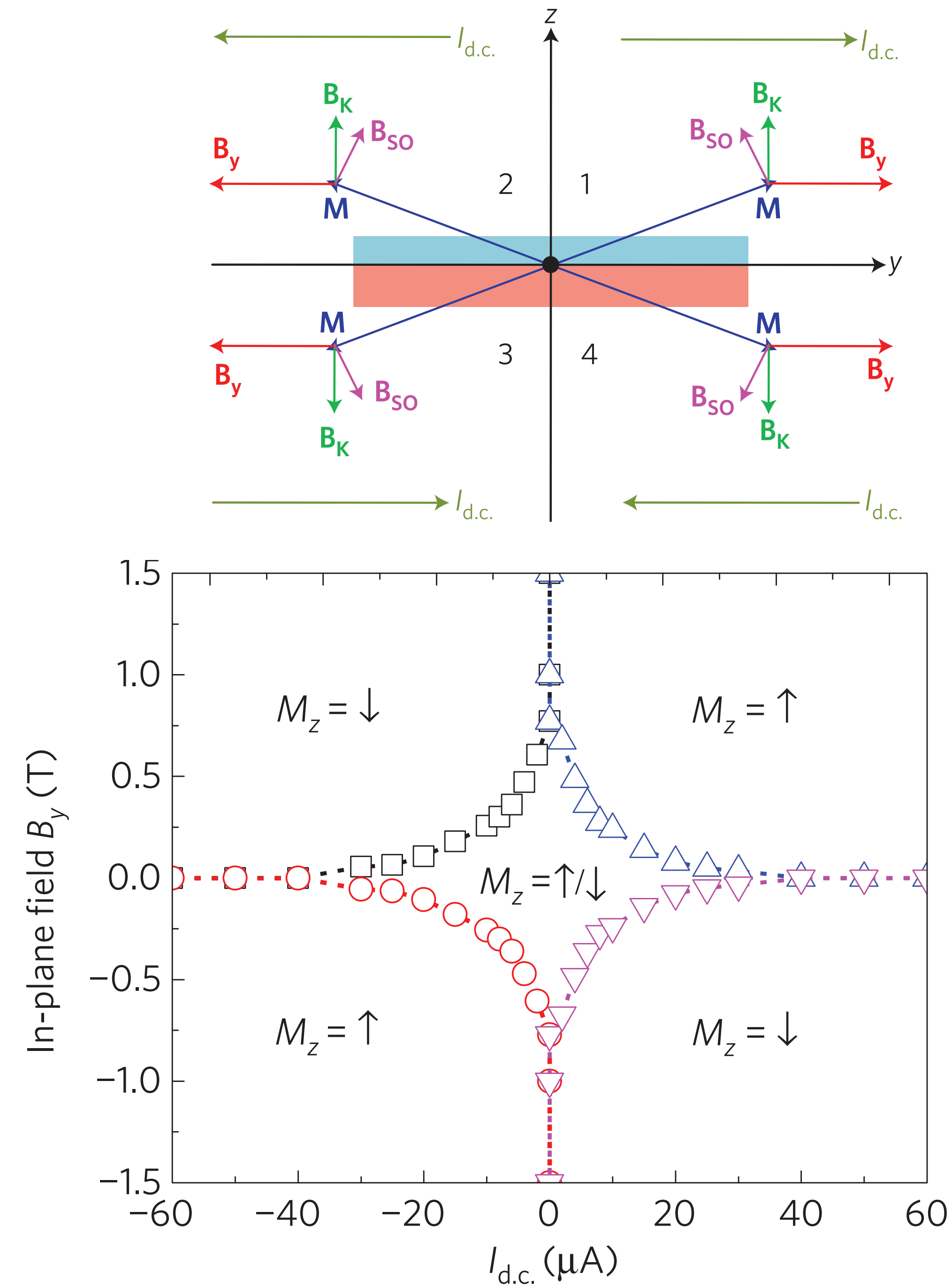
Fan *et al.*, *Nature Mat.* (2014)

Magnetically-doped topological insulators

- Our phenomenology can be applied to analyze current-driven dynamics in magnetically-doped TI's:



2nd-harmonic AHE measurement of the effective spin Hall angle: $\tan\theta_{SH} > 10^2$



Deterministic current-induced switching

Fan *et al.*, *Nature Mat.* (2014)

Electronic chiral mode bound to a magnetic DW

- Free-energy density

$$\mathcal{F}_0 = \frac{A}{2}[(\partial_x \mathbf{n})^2 + (\partial_y \mathbf{n})^2] - \frac{K}{2} n_z^2$$

- Domain-wall profile

$$\theta(\mathbf{r}) = 2\tan^{-1} e^{-(x-x_{\rm dw})/\lambda_{\rm dw}}$$

$$\phi(\mathbf{r}) = \phi_{\rm dw}$$

- Soft variables are provided by the zero-mode amplitudes $x_{\rm dw}$ and $\phi_{\rm dw}$

- Dirac Hamiltonian

$$H_0 = v\,(\mathbf{p} + e\mathbf{A}/c)\cdot\mathbf{z}\times\hat{\boldsymbol{\sigma}} - e\varphi + \Delta\hat{\sigma}_z$$

- Charge response

$$\rho = -\sigma_{xy} B_z\,,\quad \mathbf{j} = \sigma_{xy}\mathbf{z}\times\mathbf{E}$$

- Hall conductance

$$\sigma_{xy} = \mathrm{sgn}(\Delta)\frac{e^2}{2h}$$

Redlich, *PRL* (1984); Jackiw, *PRD* (1984)

- Local exchange coupling:

$$H' = J(n_x\hat{\sigma}_x + n_y\hat{\sigma}_y) + J_\perp n_z\hat{\sigma}_z$$

- Charge pumping by magnetic dynamics:

$$\beta_z = \frac{J}{ev}\boldsymbol{\nabla}\cdot\mathbf{n}\,,\quad \boldsymbol{\epsilon} = -\frac{J}{ev}\mathbf{z}\times\partial_t\mathbf{n}$$

Garate and Franz, *PRL* (2010); Nomura, and Nagaosa, *PRB* (2010)

Magnetic torques

- Torque is governed by the helical locking of spin and current:

$$\boldsymbol{\tau} = (J\boldsymbol{\rho}_{||} + J_\perp \rho_z \mathbf{z}) \times \mathbf{n} \qquad \text{where} \qquad \boldsymbol{\rho}_{||} = \frac{\mathbf{z} \times \mathbf{j}}{ev}$$

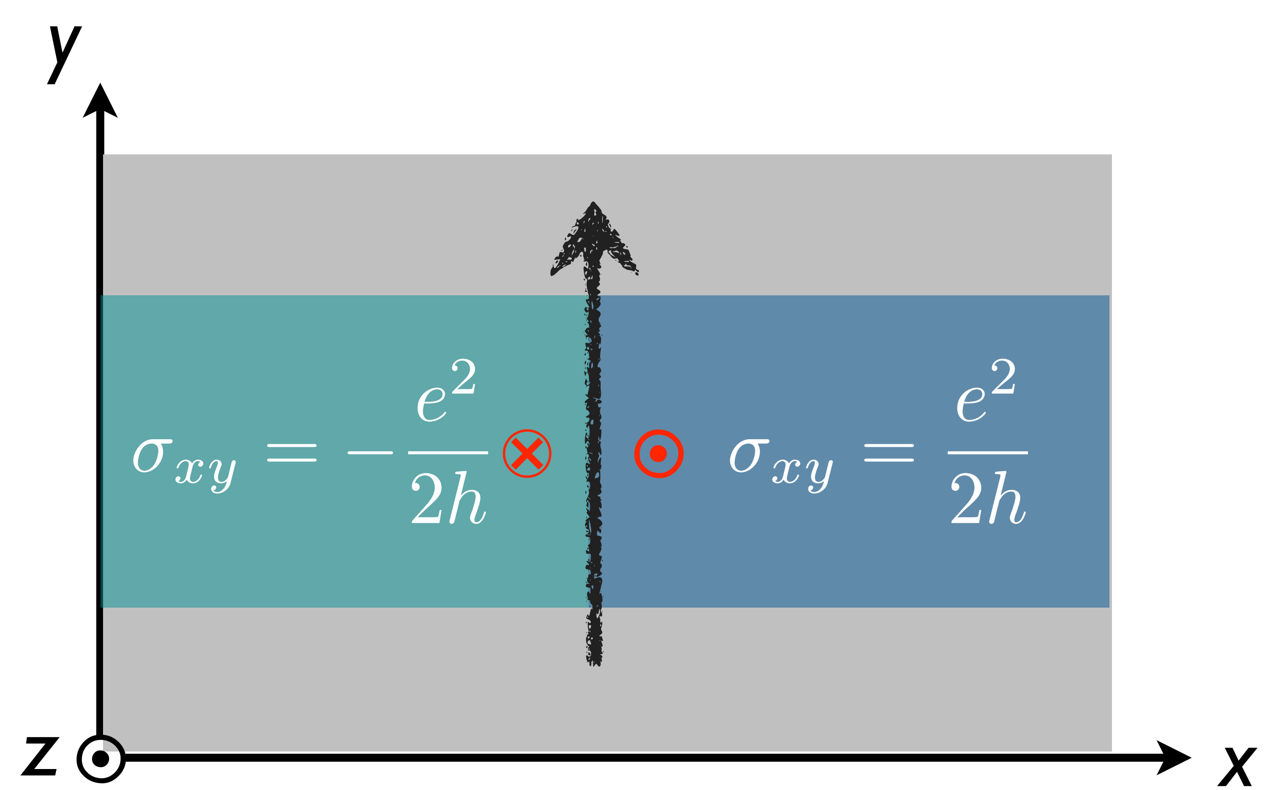
which precisely reproduces the nondissipative sector of the Onsager-reciprocal torque/pumping structure

- The total current $\mathbf{j}$ consists of the dynamics-induced transport (Hall) and texture-induced equilibrium (persistent) contributions:

$$\mathbf{j} = \sigma_{xy}\frac{J}{ev}\underbrace{\mathbf{z} \times \partial_t \mathbf{n} \times \mathbf{z}}_{\text{pumping}} - \underbrace{c\mathbf{z} \times \boldsymbol{\nabla} M_o}_{\text{DM/ME}}$$

spin Hall phenomenology

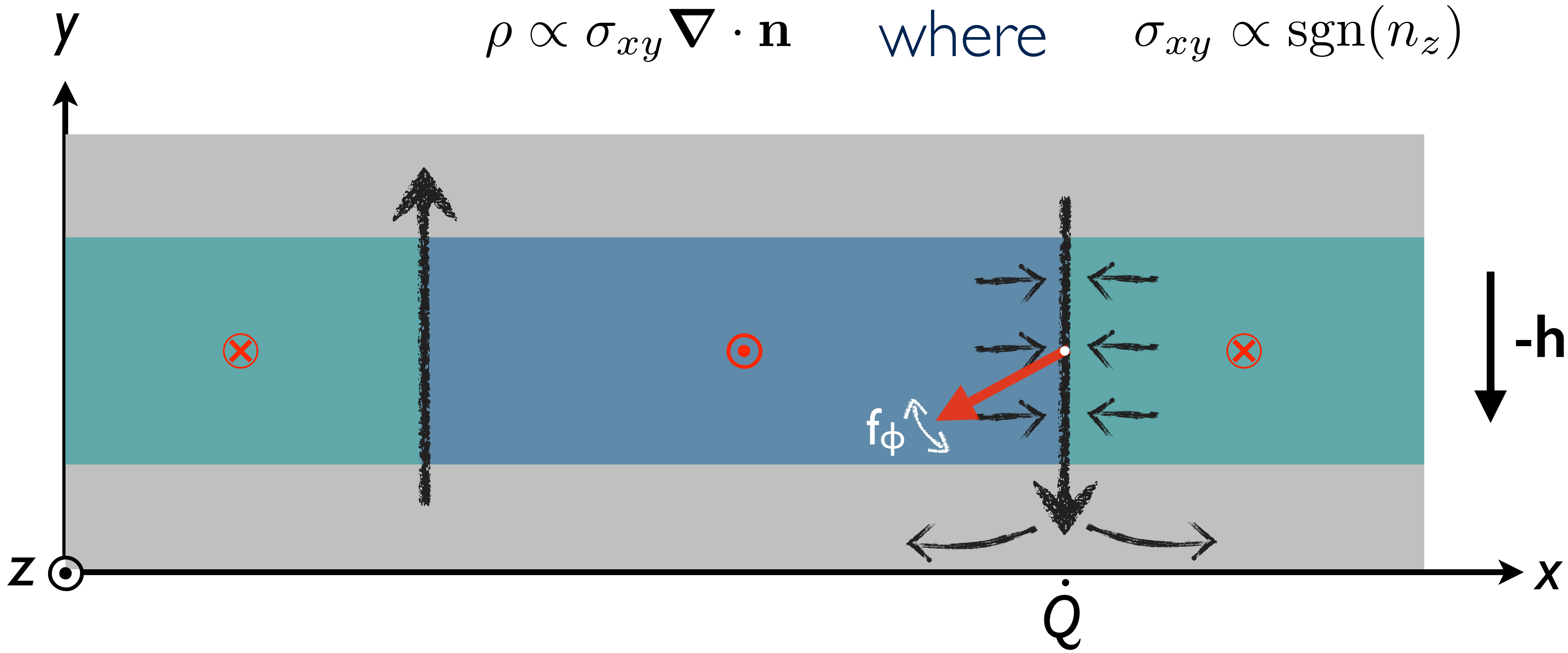
0th Landau level



Charge pumping along a domain wall

- The magnetic dynamics redistributes charges between the gapless chiral modes and the adjacent gapped regions:

$$\rho \propto \sigma_{xy} \boldsymbol{\nabla} \cdot \mathbf{n} \quad \text{where} \quad \sigma_{xy} \propto \mathrm{sgn}(n_z)$$

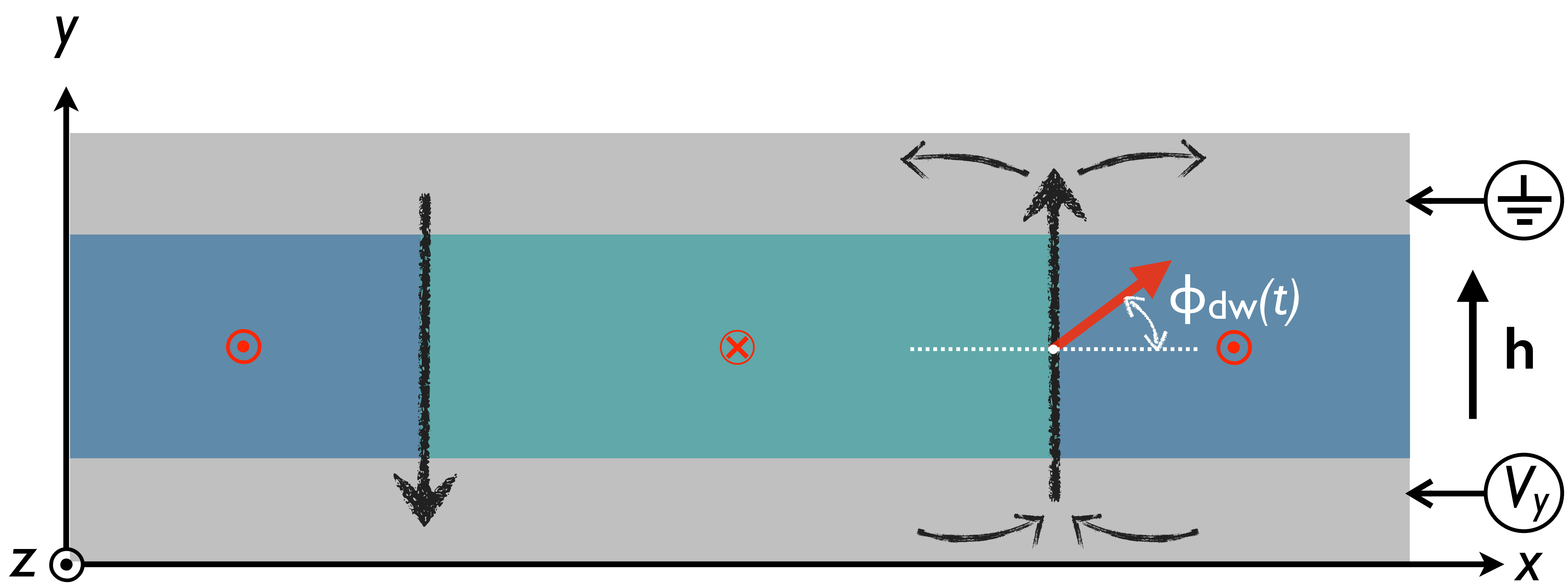


$$\boldsymbol{\epsilon} \propto \mathbf{z} \times \partial_t \mathbf{n} \to \mathbf{y} \sin \phi_{\mathrm{dw}} \dot{\phi}_{\mathrm{dw}}$$

- The domain-wall dynamics thus pumps current along the chiral mode ("squeezing" it out of the gapped quantum-Hall regions)

Onsager-reciprocal torque

- The coupled dynamics of the canonically conjugate pair $(x_{\rm dw}, \phi_{\rm dw})$



realizes a damped analog of the Josephson junction, whose equilibrium phase can be arbitrarily controlled by the applied voltage and magnetic field:

$$\dot{x}_{\rm dw} \propto (f_\phi + j \sin\phi_{\rm dw})\,, \quad \dot{\phi}_{\rm dw} \propto \frac{\alpha}{\lambda_{\rm dw}} \dot{x}_{\rm dw}$$

Onsager

$$\epsilon \propto \sin\phi_{\rm dw} \dot{\phi}_{\rm dw}$$

$$f_\phi \equiv -\partial_{\phi_{\rm dw}} F \propto J J_\perp \sin\phi_{\rm dw} + h\lambda_{\rm dw} \cos\phi_{\rm dw}$$

YT and Loss, *PRL* (2012)

Summary

- Universal scaling functions for the orbital magnetization (the three spin components are contained in the out-of-plane spin and orbital magnetizations), leading to DMI and $\mathbf{E} \cdot \mathbf{n}$ ME effect

- Zeroth Landau level and spin Hall phenomenology encapsulate the essential equilibrium and nonequilibrium magnetoelectric properties

- Magnetic domain walls bind electronic chiral modes, thus imprinting reconfigurable interconnects, which could be "loaded" by a voltage bias, microwaves, and thermal gradients

YT and Loss, *PRL* (2012)
Pesin and MacDonald, *PRL* (2013)
YT and Bender, *PRB* (2014)
Fan *et al.*, *Nature Mat.* (2014)
YT, Pesin, and Loss, *PRB* (2015)

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