Current-induced gap opening of topological insulator surface states

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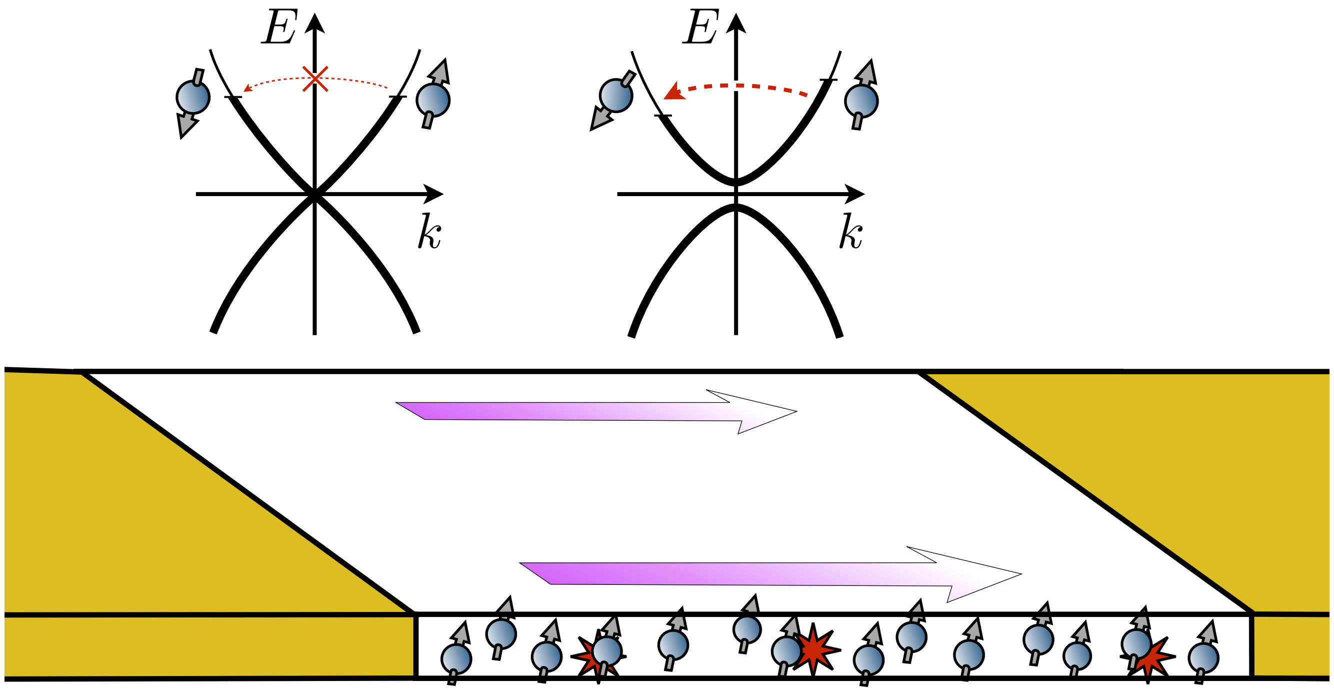

Balram, Flensberg, Paaske, and MR, PRL (2019).

In collaboration with: Ajit Balram, Karsten Flensberg, and Jens Paaske

Support provided by:

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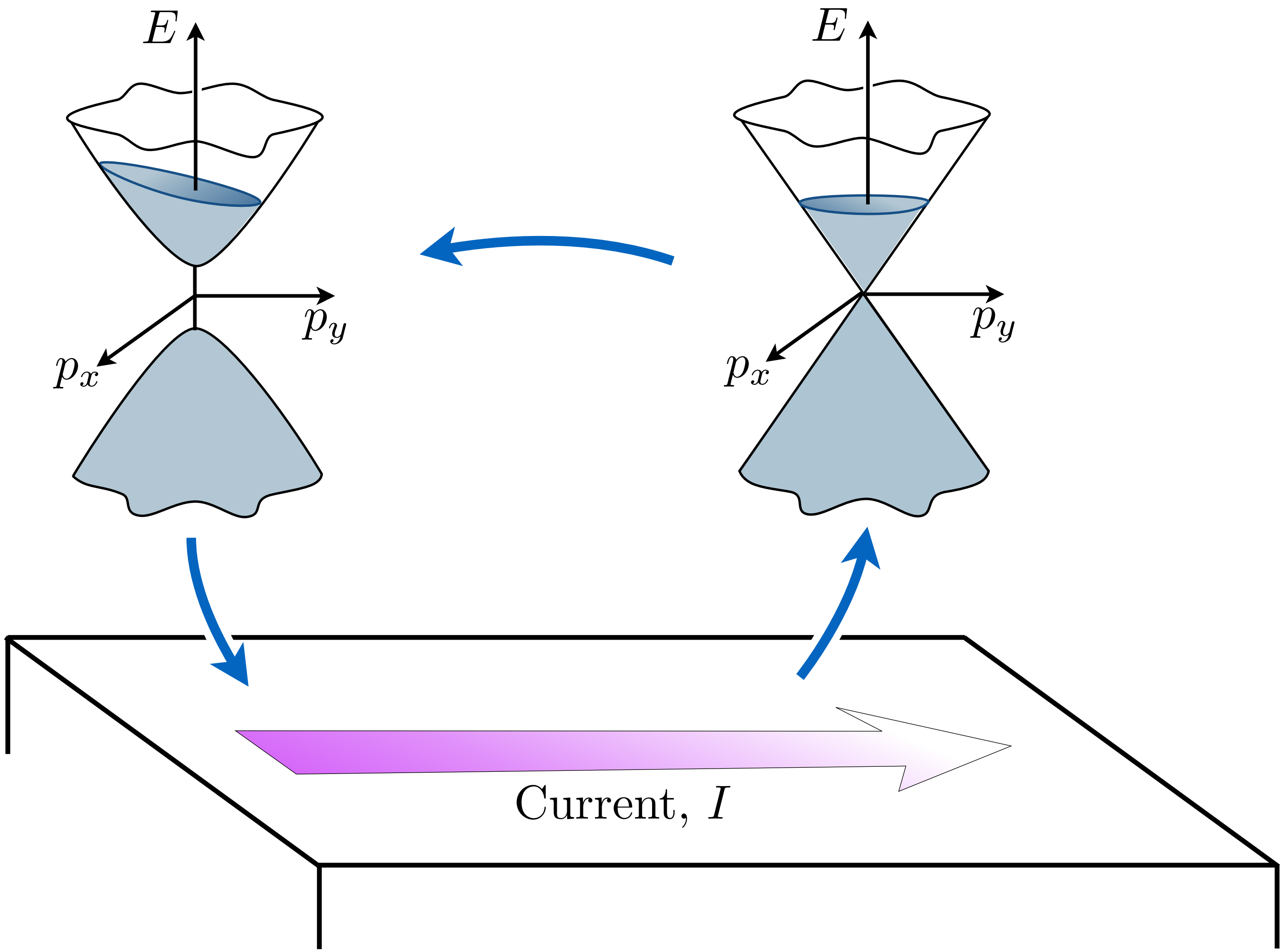
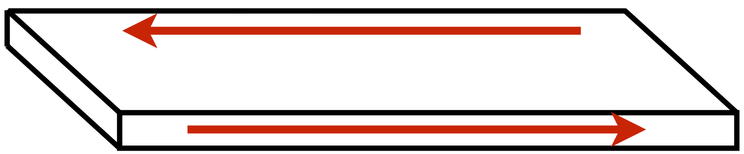
Out-of-equilibrium internal fields may lead to interesting nonlinear phenomena, dynamical phase transitions

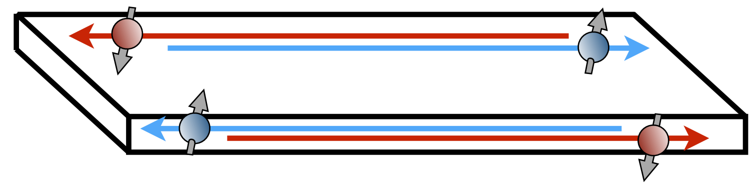


The Plan

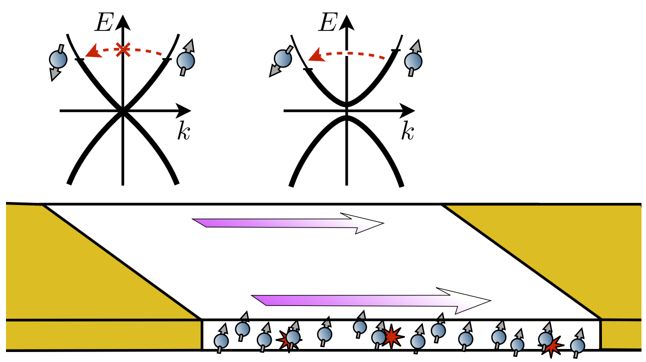
I. Robust (and not-as-robust) topological transport



vs.

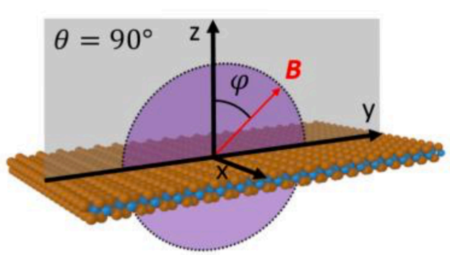


II. Current-induced gap opening in 1D helical edge modes

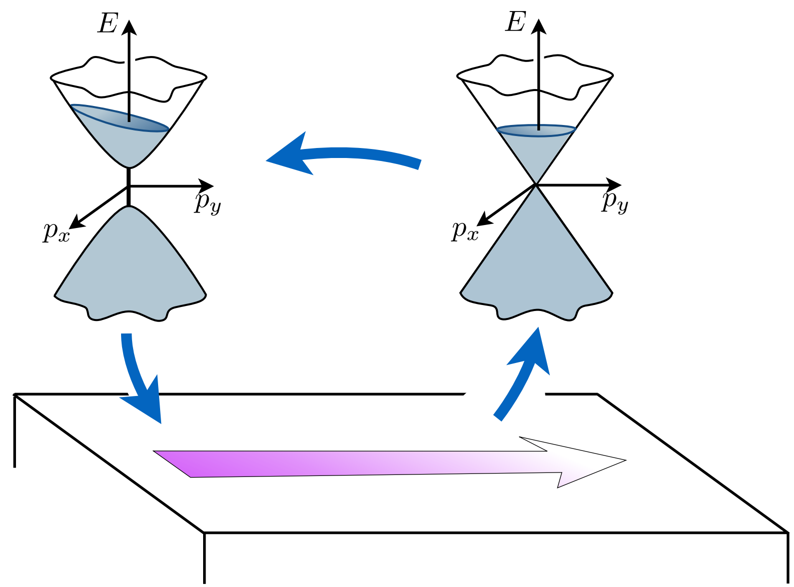


Balram, Flensberg, Paaske, and MR, PRL (2019).

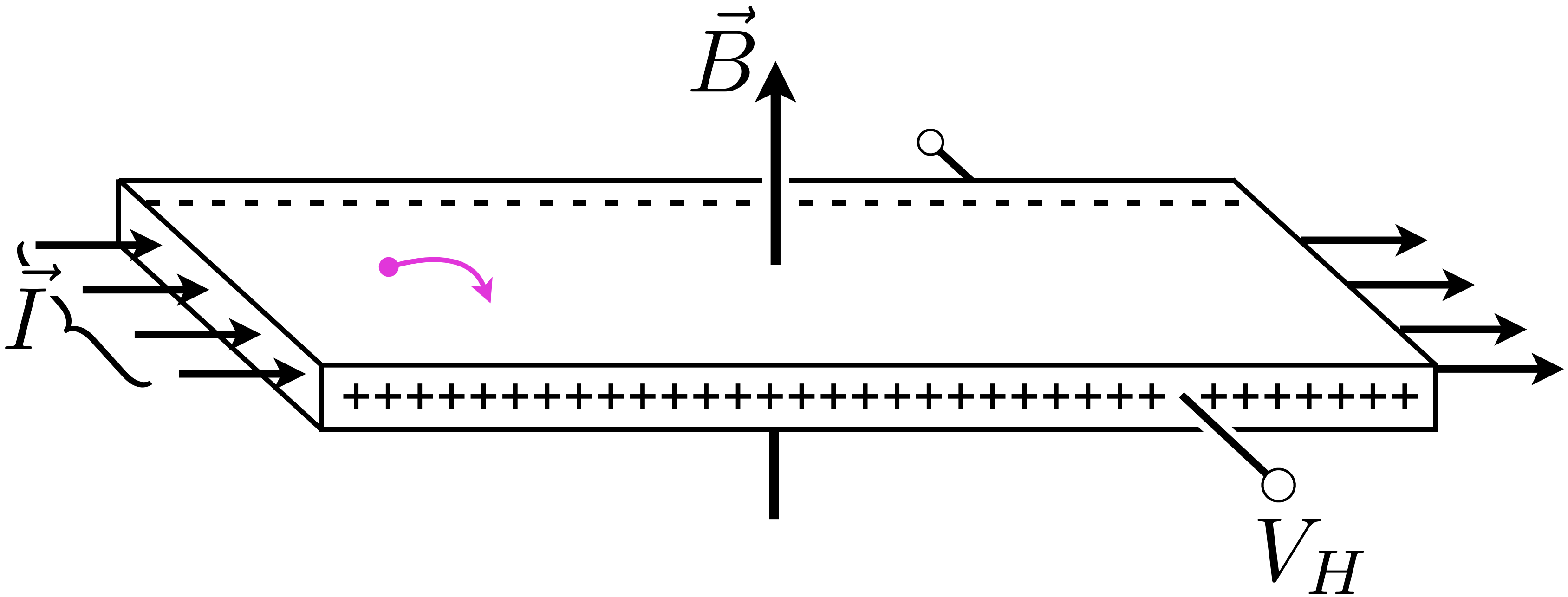
III. Extensions and connections



Zhao et al., arXiv (2020).

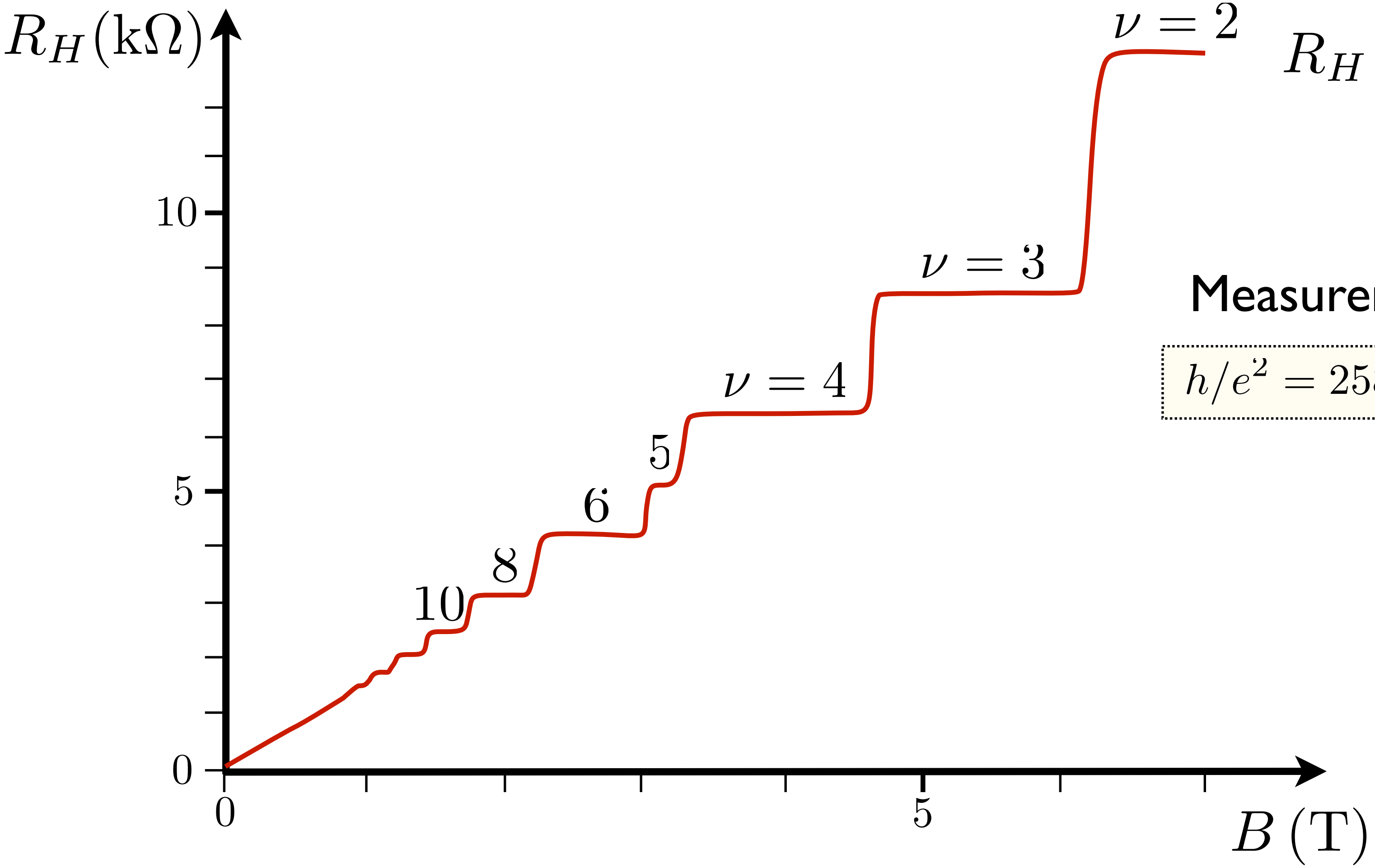


Hall resistance relates transverse voltage to applied current



$$R_H \equiv V_H / I$$

Hall resistance features extremely flat stapes at low T, high B



$$R_H = h/\nu e^2$$

Measurement Standard

$$h/e^2 = 25812.807557(18)\,\Omega$$

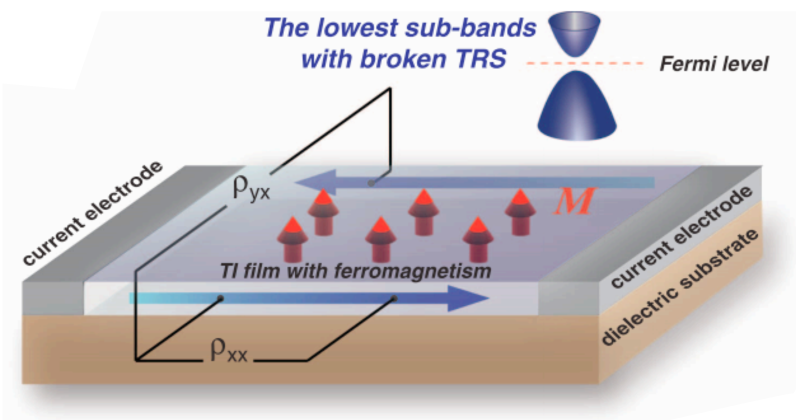
Figure adapted from nobelprize.org

Key theoretical insights:

Thouless, Kohmoto, Nightingale, and den Nijs, PRL (1982).

Avron, Seiler, and Simon, PRL (1983). Haldane, PRL (1988).

Quantum anomalous Hall effect: robust quantization at H = 0



$Cr_{0.15}(Bi_{0.1}Sb_{0.9})_{1.85}Te_3$

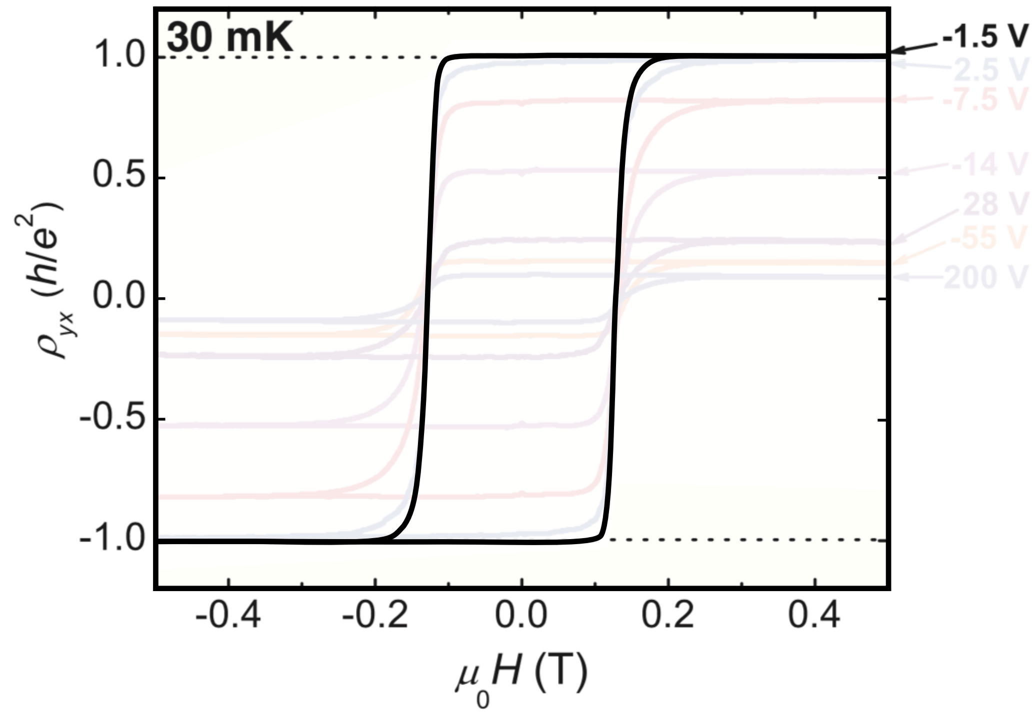


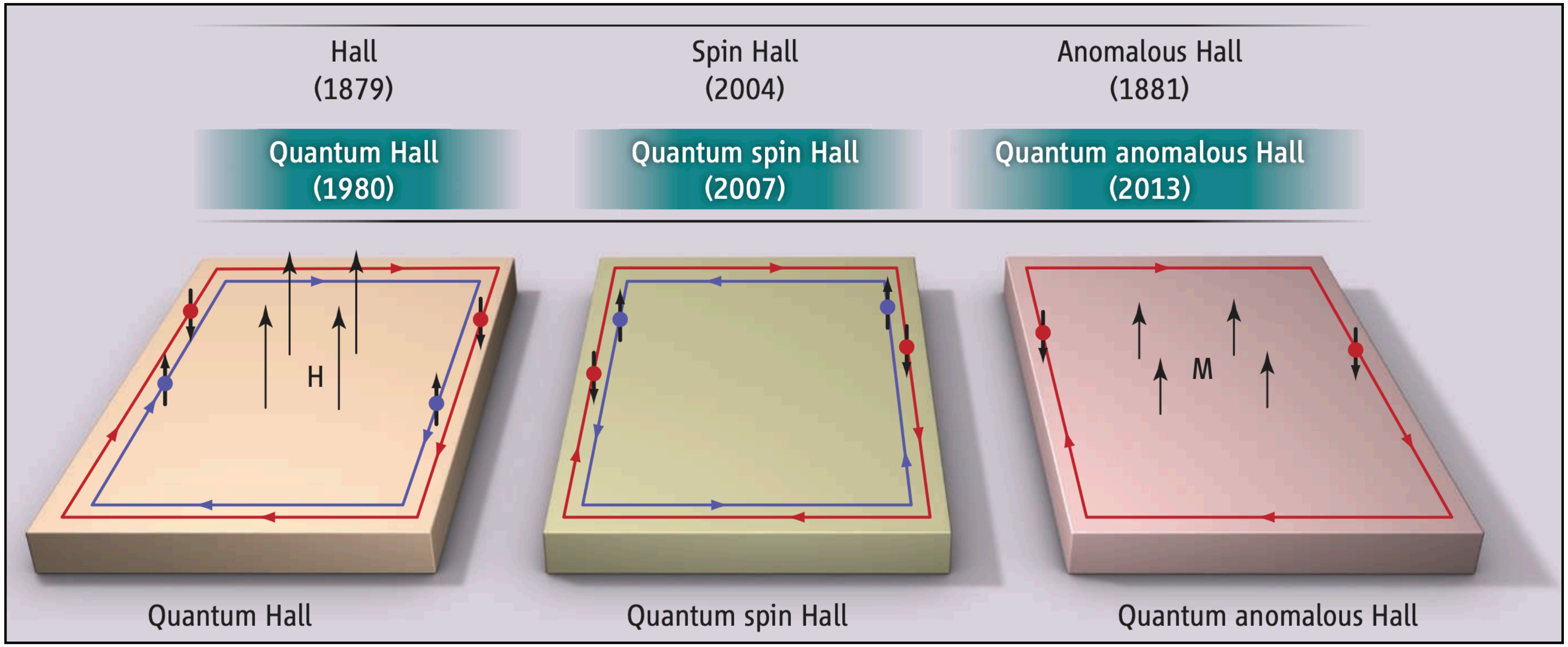
Figure adapted from:

Chang et al., Science (2013).

Part-per-million quantization in QAH effect:

Fox et al., PRB (2018).

2D topological insulator hosts "helical" edge states



S. Oh, Science (2013).

* TRS : backscattering is forbidden

Theoretical prediction:

Kane and Mele, PRL (2005).

Bernevig, Hughes and Zhang, Science (2006).

Quantum spin Hall effect: robust quantization at H = 0?

HgTe quantum well

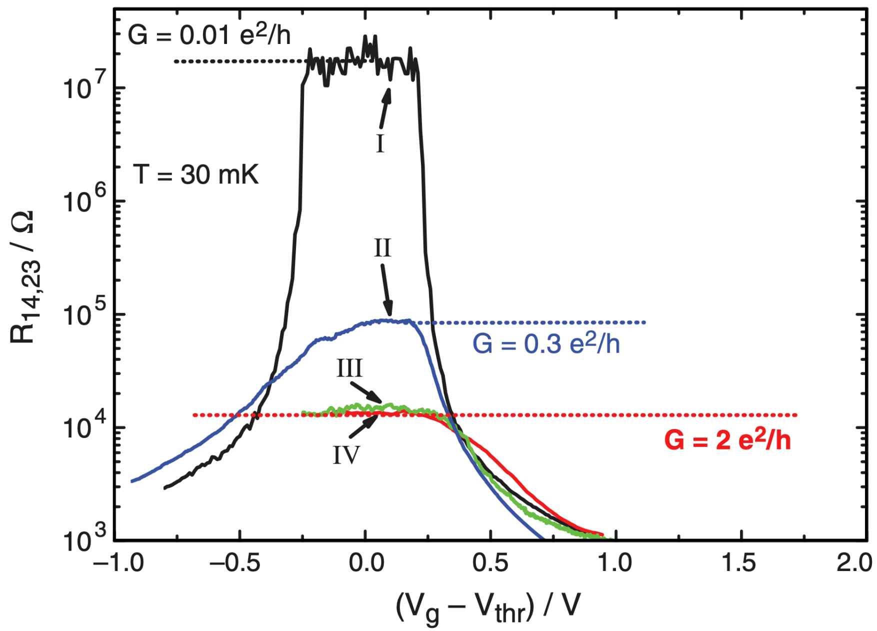


Figure adapted from:

König et al., Science (2007).

Quantum spin Hall effect: robust quantization at H = 0?

HgTe quantum well

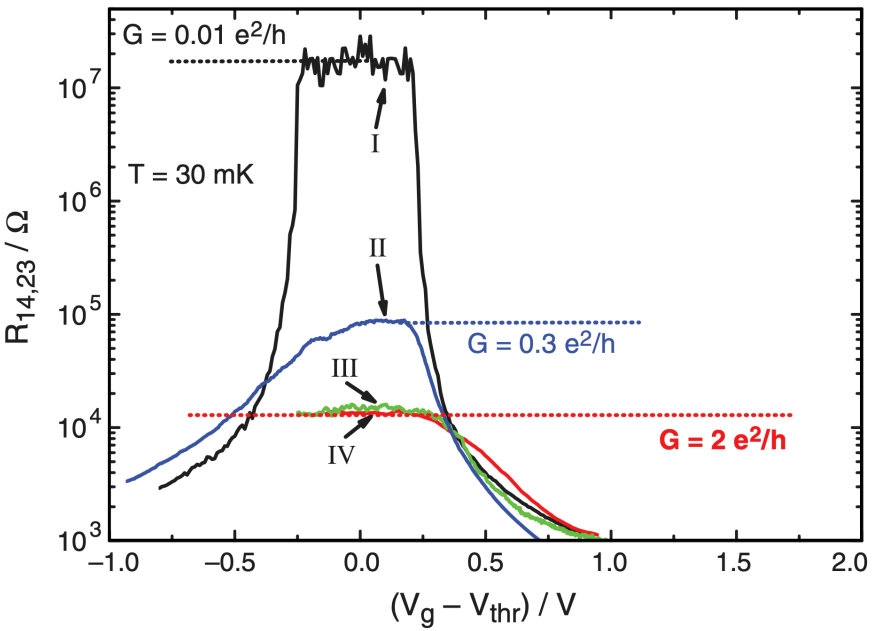


Figure adapted from:
König et al., Science (2007).

WTe_2 monolayer

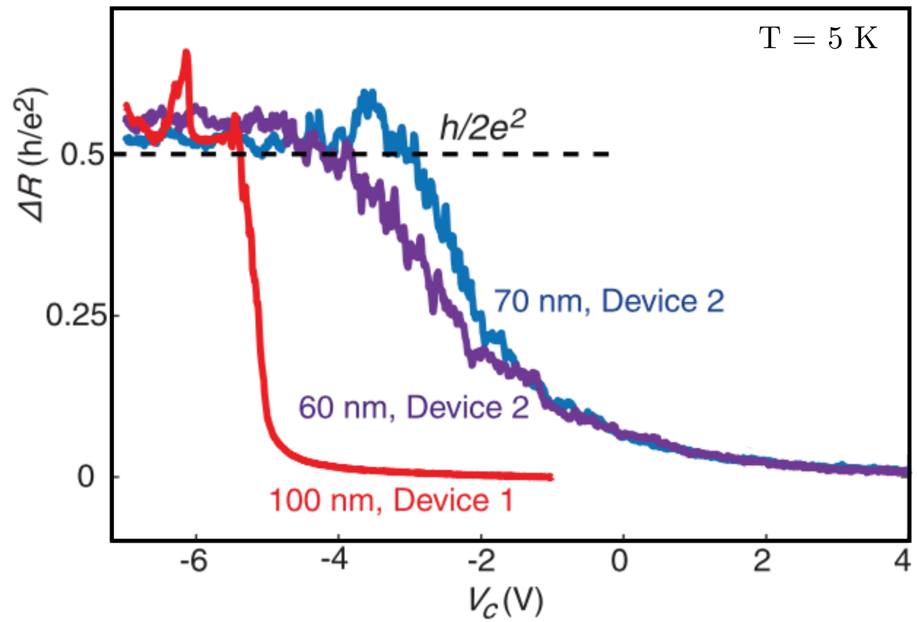
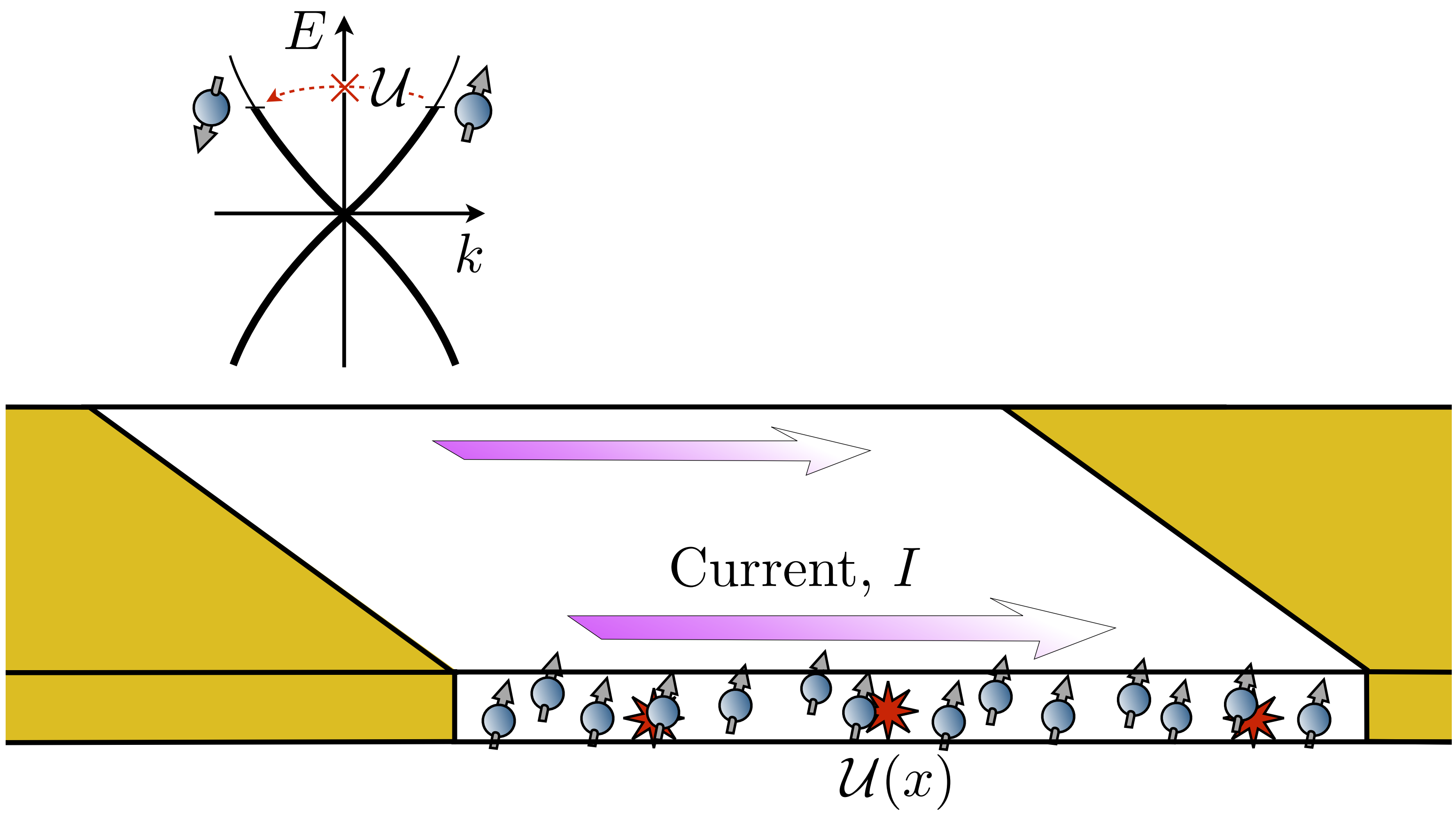


Figure adapted from:
Wu et al., Science (2018).

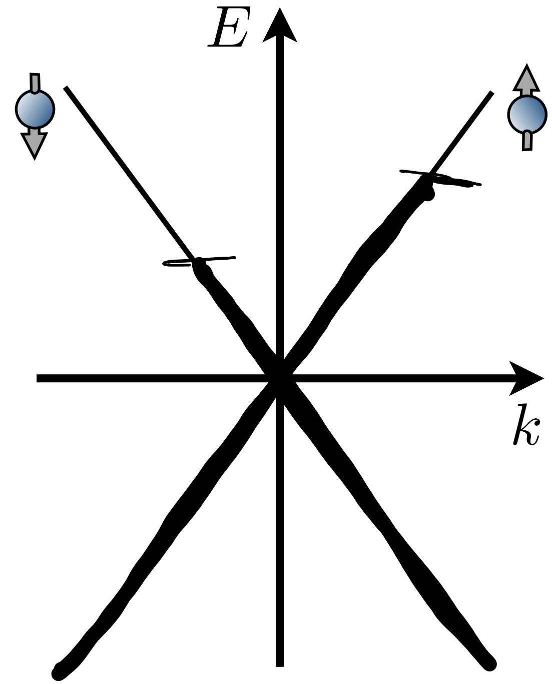
Part II

Current-induced gap opening in 1D helical edge modes

TRS: matrix element for elastic backscattering vanishes



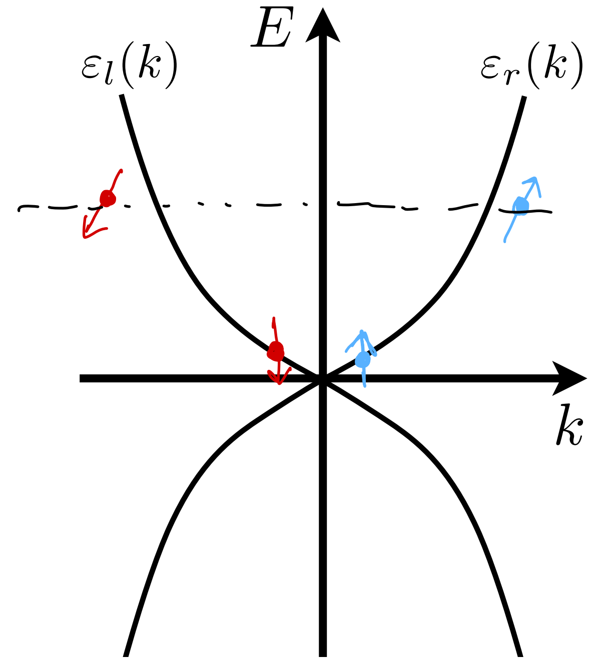
Flowing current breaks time-reversal symmetry…



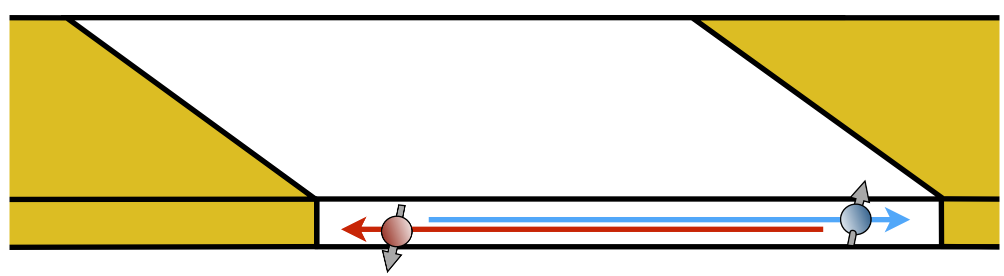
* Feedback (e-e interactions)

* relax S_z conservation

Generically, spin quantization axis is *energy dependent*



$$H_{1\mathrm{D}}(k) = \hbar v k \sigma_z + \lambda k^3 \sigma_x$$

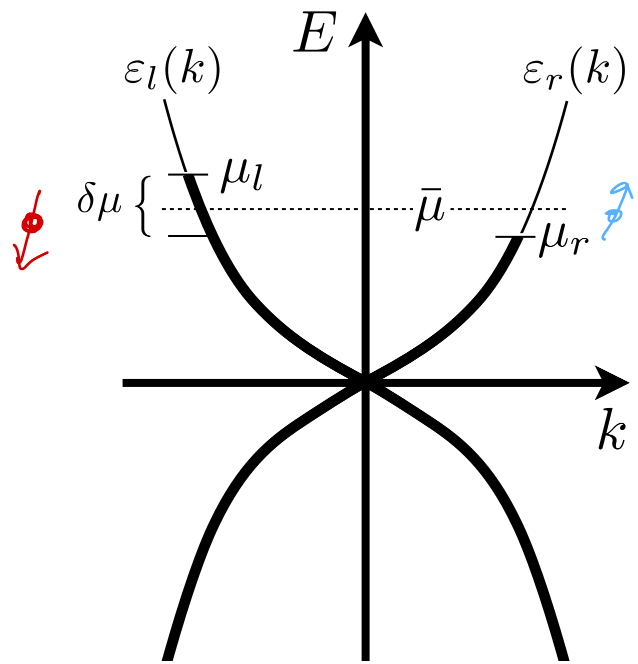


See, for example:

Schmidt, Rachel, von Oppen, and Glazman, PRL (2012).

Ortiz, Molina, Platero, and Lunde, PRB (2016).

Due to spin-orbit coupling, current induces *spin polarization*



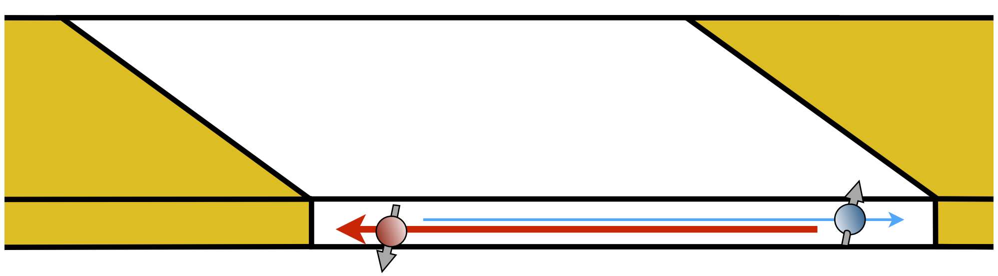
Current-induced spin density:

$$\langle s_z \rangle \approx -\frac{\delta\mu}{4\pi v}$$

$$\langle s_x \rangle \approx -\alpha \frac{\delta\mu}{4\pi v}$$

small parameter

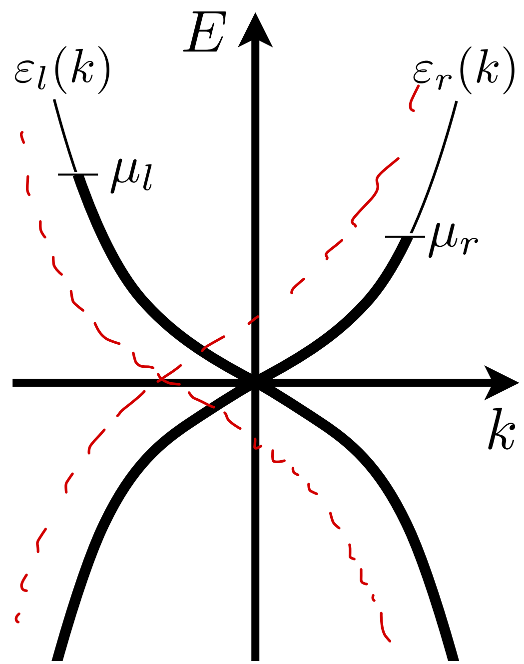
$$H_{1D}(k) = \hbar v k \sigma_z + \lambda k^3 \sigma_x$$



Dimensionless S.O.C.:

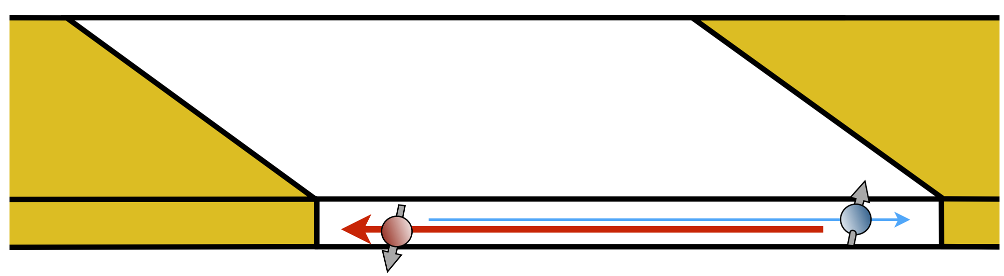
$$\alpha = \frac{\lambda \bar{\mu}^2}{\hbar^3 v^3}$$

Through e-e interaction, spin-polarization makes exchange field

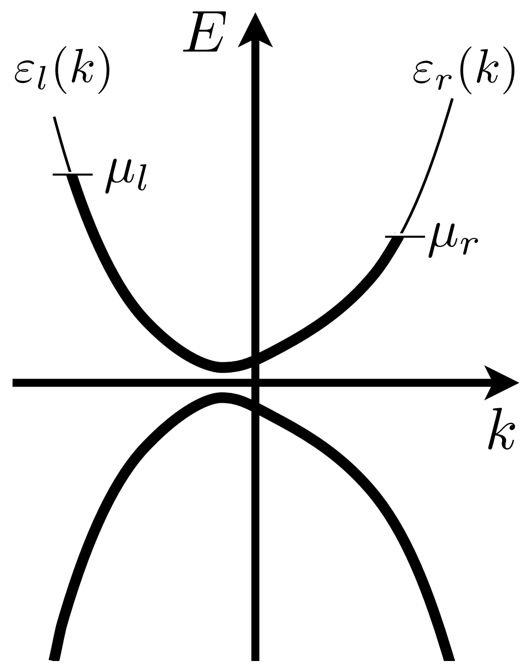


$$H_{1D}^{MF}(k) = [\hbar v k - g\langle s_z \rangle/\hbar]\,\sigma_z + \left[\lambda k^3 - g\langle s_x \rangle/\hbar\right]\sigma_x$$

contact interaction strength



Gap proportional to current, interaction and SOC strength



Minimal splitting between bands:

$$\Delta \approx \frac{\alpha}{2\pi}\left|\frac{g\delta\mu}{\hbar v}\right|$$

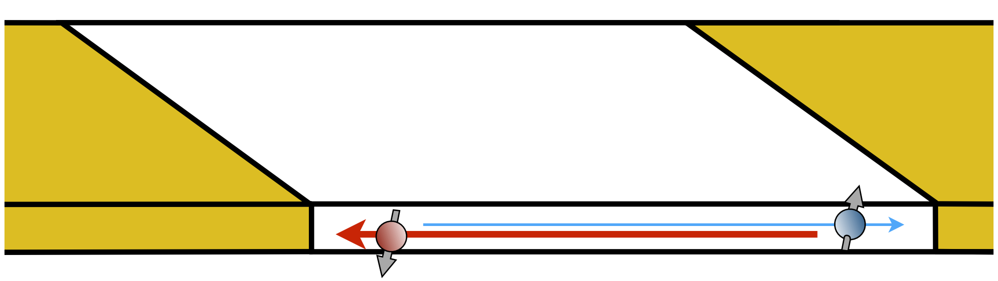
Weak interaction, small current:

$$\frac{g}{\hbar v}\frac{\delta\mu}{\bar{\mu}} \ll 1$$

Weak spin-orbit:

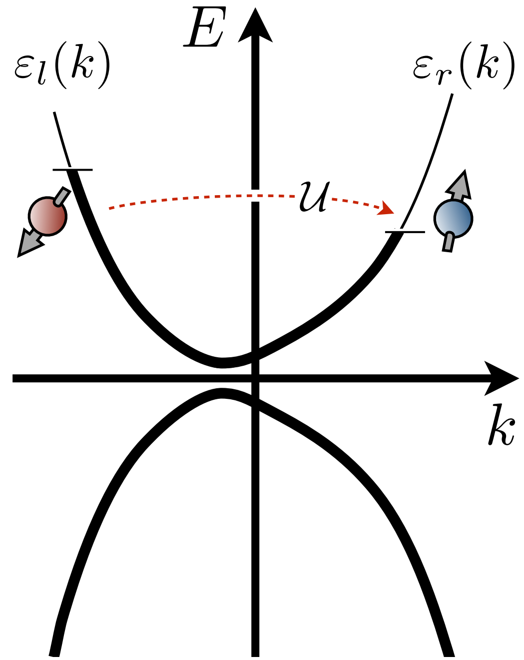
$$\alpha = \frac{\lambda\bar{\mu}^2}{\hbar^3 v^3} \ll 1$$

$$H_{1\mathrm{D}}^{\mathrm{MF}}(k) = \left[\hbar v k - g\langle s_z\rangle/\hbar\right]\sigma_z + \left[\lambda k^3 - g\langle s_x\rangle/\hbar\right]\sigma_x$$



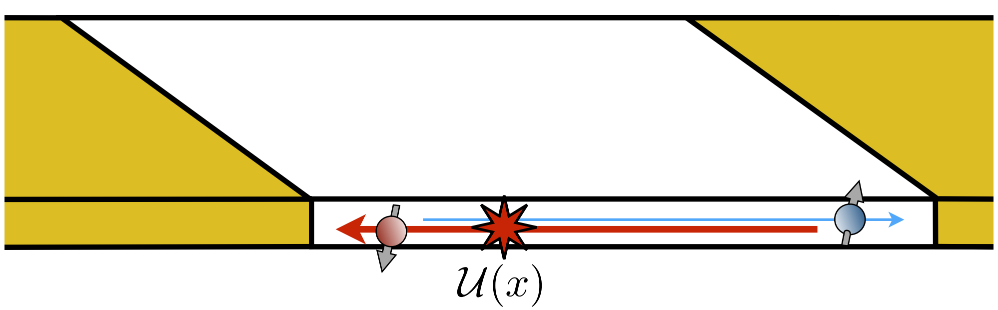
Balram, Flensberg, Paaske, and MR, PRL (2019).

Current-induced band modification enables backscattering



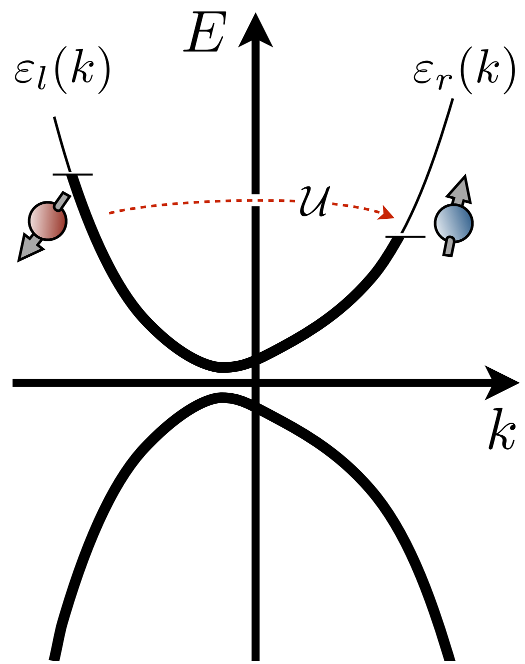
<u>Elastic</u> backscattering matrix element:

$$\langle \psi_r^{\mathrm{MF}} | \psi_l^{\mathrm{MF}} \rangle \approx \frac{g\langle s_x \rangle}{\hbar \bar{\mu}}$$



Balram, Flensberg, Paaske, and MR, PRL (2019).

Backscattering rate ~ (current)², (interaction)², (SOC)²



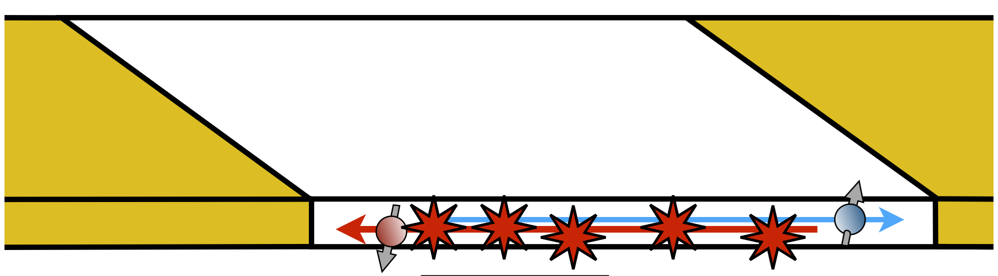
<u>Elastic</u> backscattering matrix element:

$$\langle \psi_r^{\mathrm{MF}} | \psi_l^{\mathrm{MF}} \rangle \approx \frac{g \langle s_x \rangle}{\hbar \bar{\mu}}$$

Elastic backscattering rate:

$$\frac{1}{\tau} \propto \alpha^2 \left(\frac{g}{\hbar v} \frac{\delta \mu}{\bar{\mu}} \right)^2$$

$$\frac{1}{\tau} \sim I^2$$



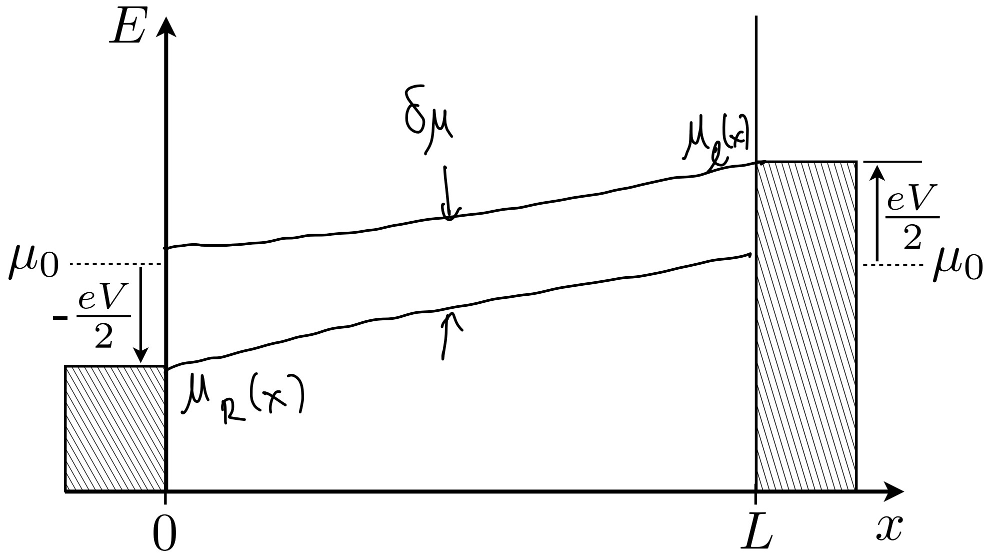
$$\overline{\mathcal{U}(x)\mathcal{U}(x')} \propto \delta(x - x')$$

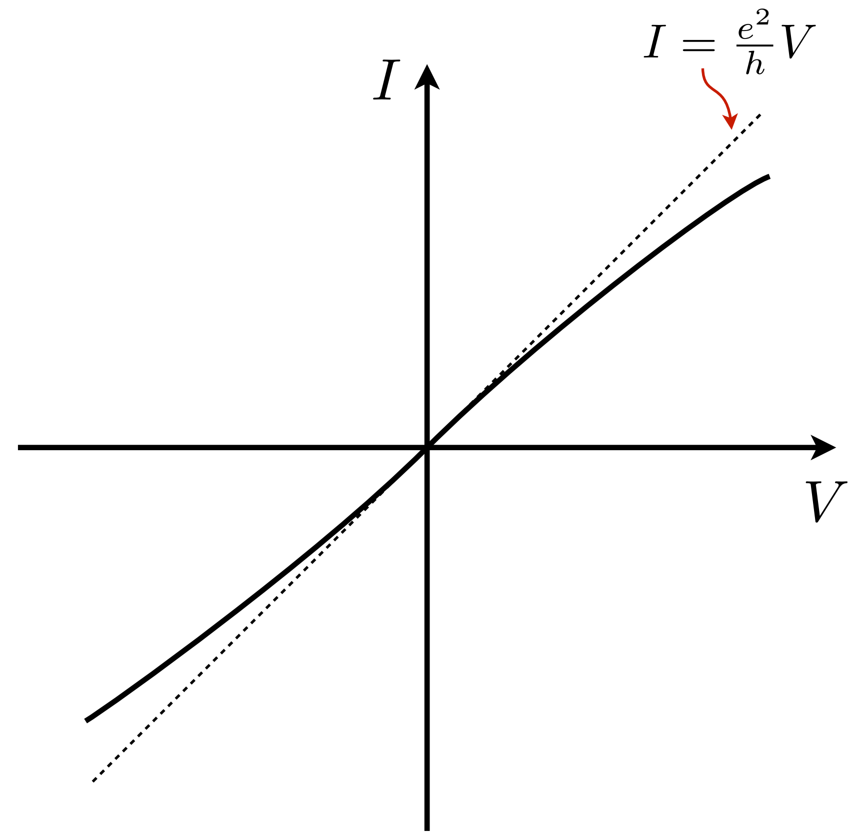
Dimensionless S.O.C.:

$$\alpha = \frac{\lambda \bar{\mu}^2}{\hbar^3 v^3}$$

Balram, Flensberg, Paaske, and MR, PRL (2019).

Current-induced edge state breakdown reflected in nonlinear I-V characteristic





Balram, Flensberg, Paaske, and MR, PRL (2019).

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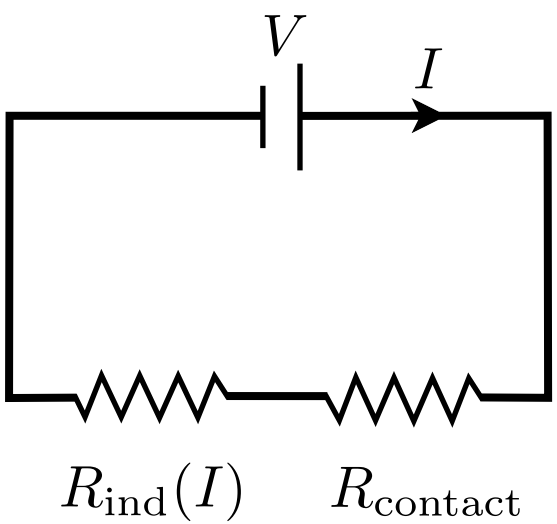
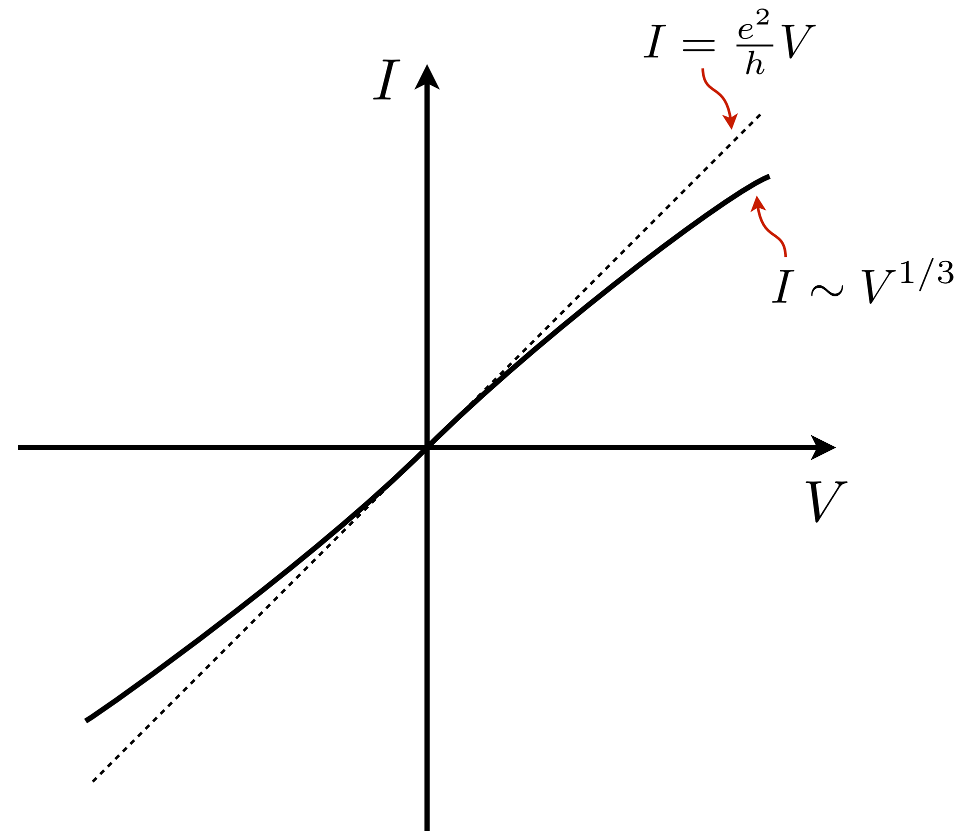


$R_{\text{contact}} = h/e^2$

$R_{\text{ind}}(I) \propto I^2$



$$I = \frac{V}{R_{\text{contact}} + R_{\text{ind}}(I)}$$

$I \simeq \frac{V}{R_{\text{contact}}} \Rightarrow I = \frac{e^2}{h}(V - \# V^3)$

$I^3 \sim V$

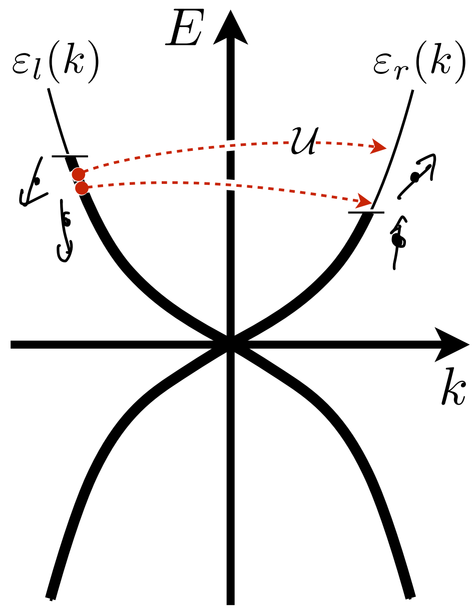
Balram, Flensberg, Paaske, and MR, PRL (2019).

Part III

Extensions and connections

Interactions can "break" QSHE in a variety of ways

Disorder-assisted two-particle backscattering



Correction to *linear* conductance:

$$\delta G \sim T^4$$

temperature

Schmidt, Rachel, von Oppen, and Glazman, PRL (2012).

Spontaneous breaking of TRS:

Wu, Bernevig, and Zhang, PRL (2006).

Xu and Moore, PRB (2006).

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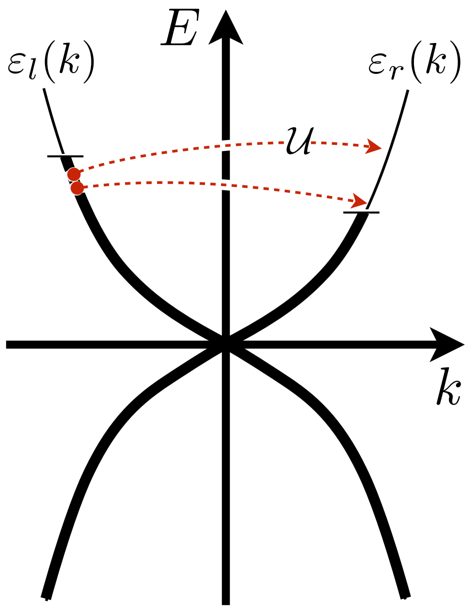
Disorder-assisted two-particle backscattering



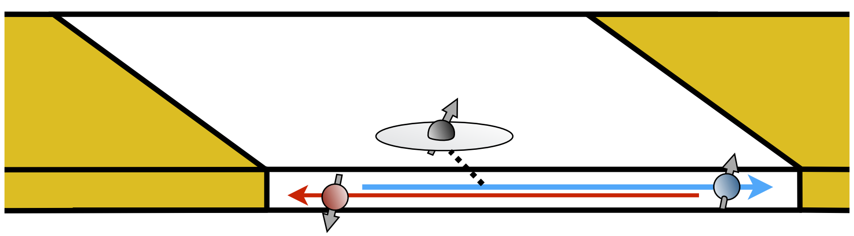
Correction to *linear* conductance:

$$\delta G \sim T^4$$

temperature

Schmidt, Rachel, von Oppen, and Glazman, PRL (2012).

Impurity spin *polarized* by current-induced spin polarization



Correction to *linear* conductance:

$$\delta G \sim (\delta J_{\text{aniso}})^2$$

anisotropic exchange

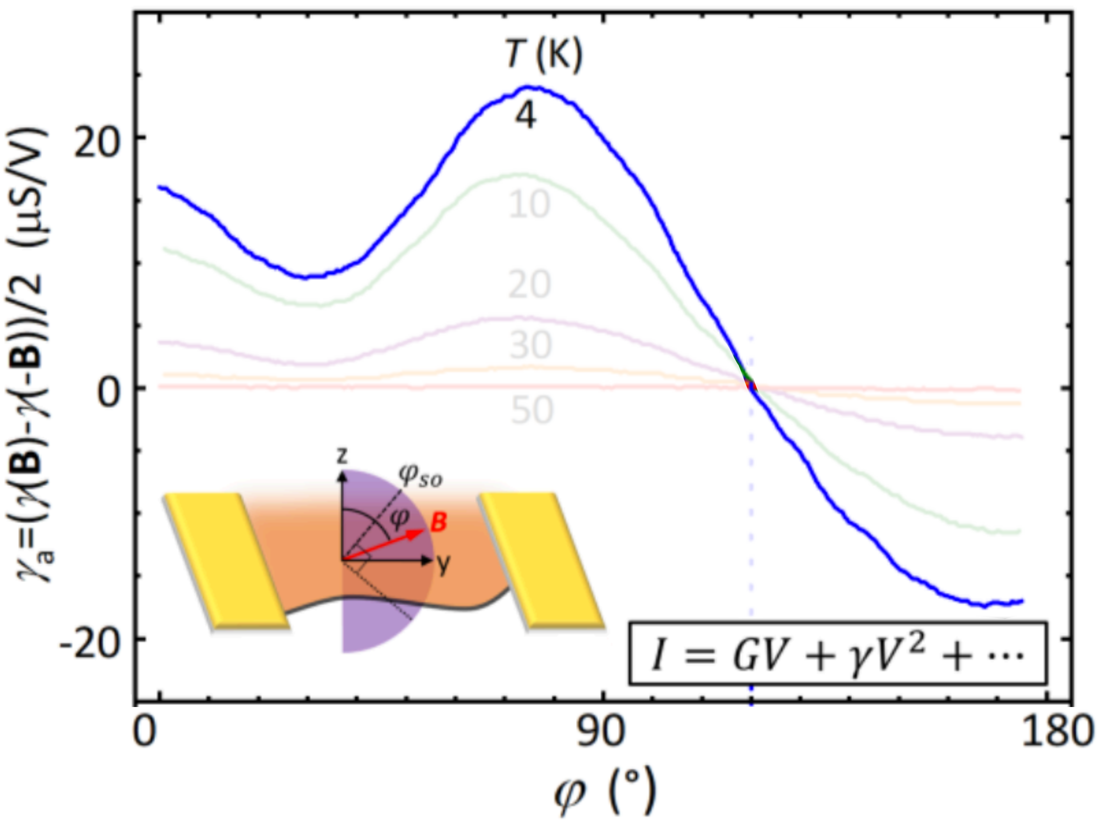
Väyrynen, Goldstein, Gefen, and Glazman, PRB (2014).

Spontaneous breaking of TRS:

Wu, Bernevig, and Zhang, PRL (2006).

Xu and Moore, PRB (2006).

Signatures of current-induced spin polarization observed in nonlinear magnetotransport in monolayer WTe_2



Nonlinear conductance:

$$\gamma = 2I_{2f}/V_f^2$$

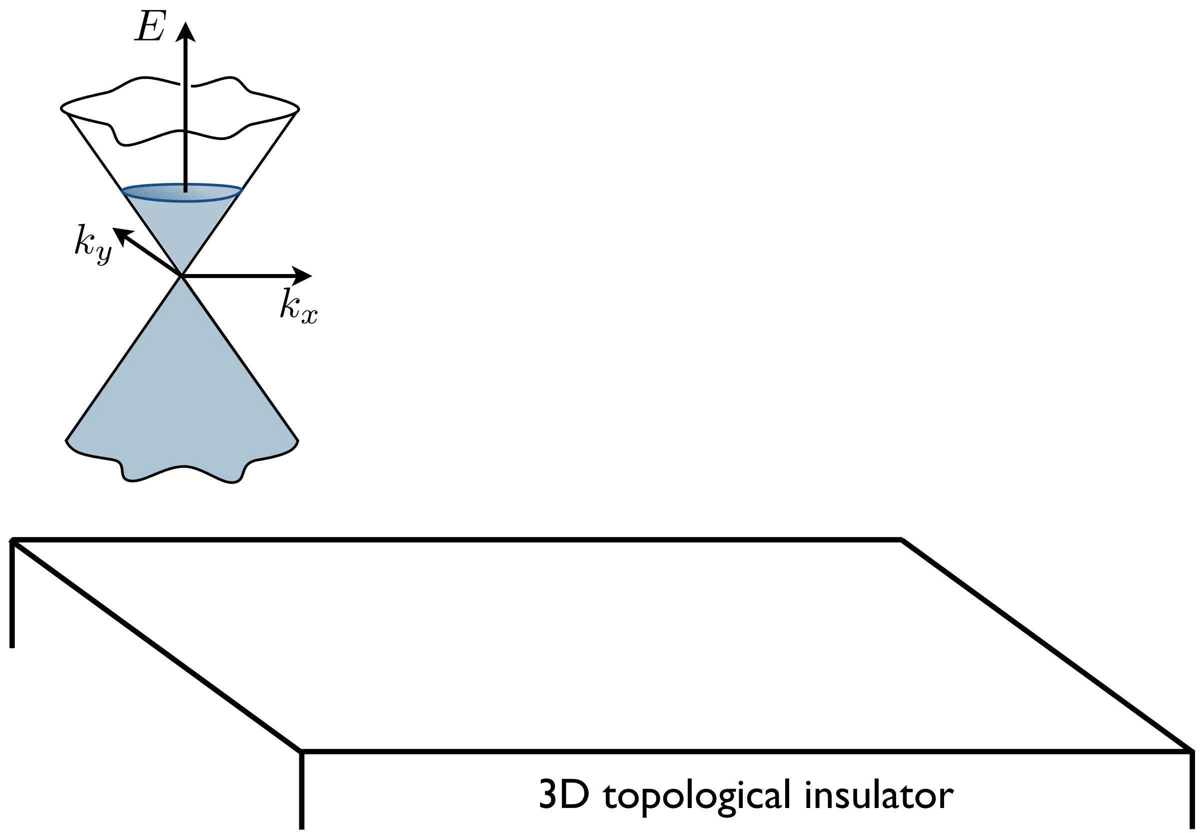
second harmonic current signal

ac voltage

Figure adapted from:

Zhao et al., arXiv:2010.09986.

Current-induced spin polarization opens gap in 3D TI surface state



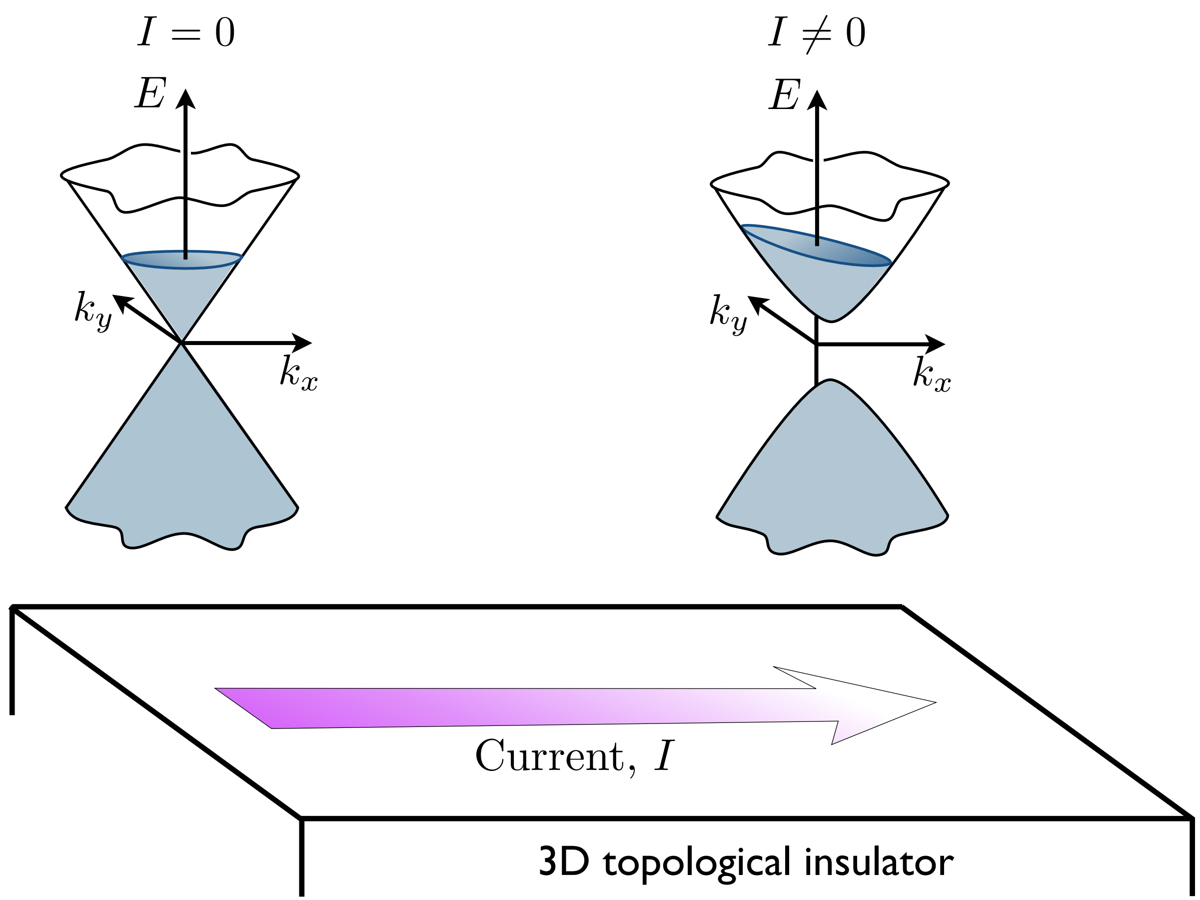
$$H_{2\mathrm{D}}(\mathbf{k}) = \hbar v(\mathbf{k} \times \boldsymbol{\sigma}) \cdot \hat{\mathbf{z}} + \lambda k^3 \cos(3\phi_{\mathbf{k}})\sigma_z$$

angle from $\Gamma - K$

Hexagonal warping, Bi_2Te_3 surface states:

Fu, PRL (2009).

Current-induced spin polarization opens gap in 3D TI surface state



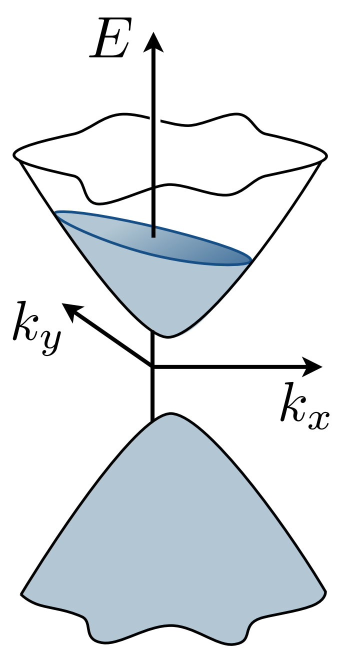
$$H_{\mathrm{2D}}^{\mathrm{MF}}(\mathbf{k}) = \hbar v(\mathbf{k} \times \boldsymbol{\sigma}) \cdot \hat{\mathbf{z}} + \lambda k^3 \cos(3\phi_{\mathbf{k}})\sigma_z - g\langle \mathbf{s} \rangle \cdot \boldsymbol{\sigma}$$

internal exchange field

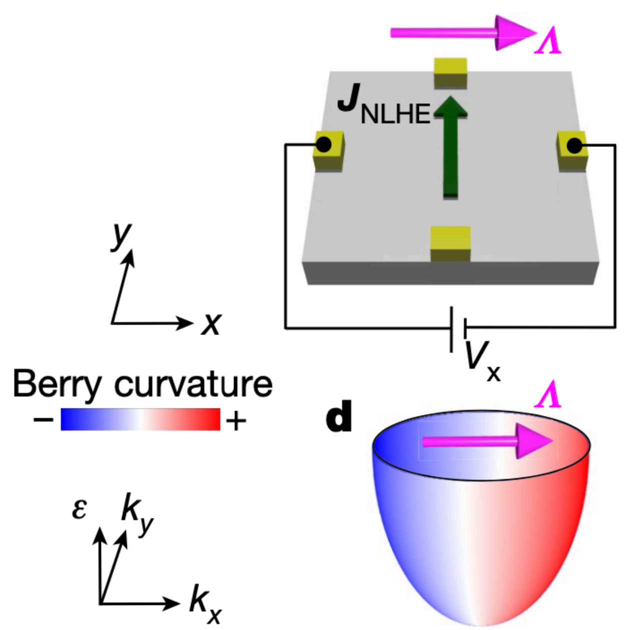
Balram, Flensberg, Paaske, and MR, PRL (2019).

Current-induced gap opening yields nonlinear Hall effect

Current-induced Berry monopole



Nonlinear Hall effect from (equilibrium) Berry dipole



Experiment: bilayer WTe_2

Ma et al., Nature (2019).

Theory of nonlinear Hall effect due to Berry curvature dipole, application to TMDs:

Sodemann and Fu, PRL (2015).

You, Fang, Xu, Kaxiras, and Low, PRB (2018).

Summary

* Electron-electron interactions and current-induced spin polarization can alter the underlying "electronic fabric" of material

* Picture reveals new mechanisms for nonlinear transport phenomena

* Similar ideas may apply to variety of materials, nonequilibrium internal fields

* Questions to explore: search for favorable materials, mechanisms to boost size of effects, signatures of current-induced Berry monopole, …

In collaboration with: Ajit Balram, Karsten Flensberg, and Jens Paaske

Balram, Flensberg, Paaske, and MR, PRL (2019).

Support provided by:

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