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Stabilization of the Quantum Spin Hall Effect by Designed Removal of Time-Reversal Symmetry of Edge States

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The quantum spin Hall (QSH) effect is known to be unstable to perturbations violating time-reversal symmetry. We show that creating a narrow ferromagnetic region near the edge of a QSH sample can push one of the counterpropagating edge states to the inner boundary of the ferromagnetic region and leave the other at the outer boundary, without changing their spin polarizations and propagation directions. Since the two edge states are spatially separated into different "lanes," the QSH effect becomes robust against symmetry-breaking perturbations.

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Based on:

Yang *et al.*, PRL **107**, 066602 (2011)

Liu *et al.*, PRL **101**, 146802 (2008)

Franziska Maier

July 09, 2013

Quantum Spin Hall Effect (QSH)

Theory:

Graphene

Kane and Mele, PRL **95**, 226801 (2005)

GaAs with strain gradient

Bernevig and Zhang, PRL **96**, 106802 (2006)

Experiments:

HgTe quantum wells thicker than d_c (band inversion)

Bernevig *et al.*, Science **314**, 1757 (2006)

König *et al.*, Science **318**, 766 (2007)

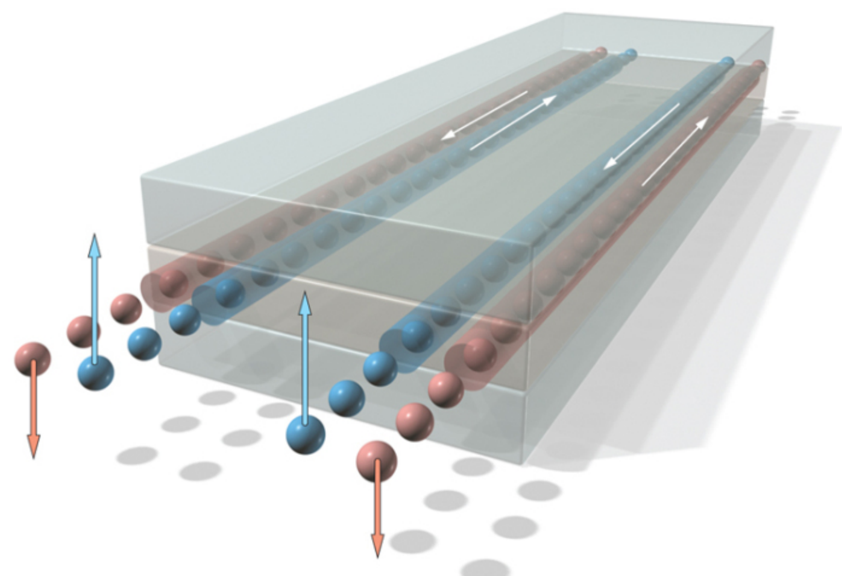
Key ingredient:

Spin orbit interaction (SOI)

Time reversal symmetry (TRS) protected

Immune to non-magnetic scattering, but sensitive to TRS breaking perturbations

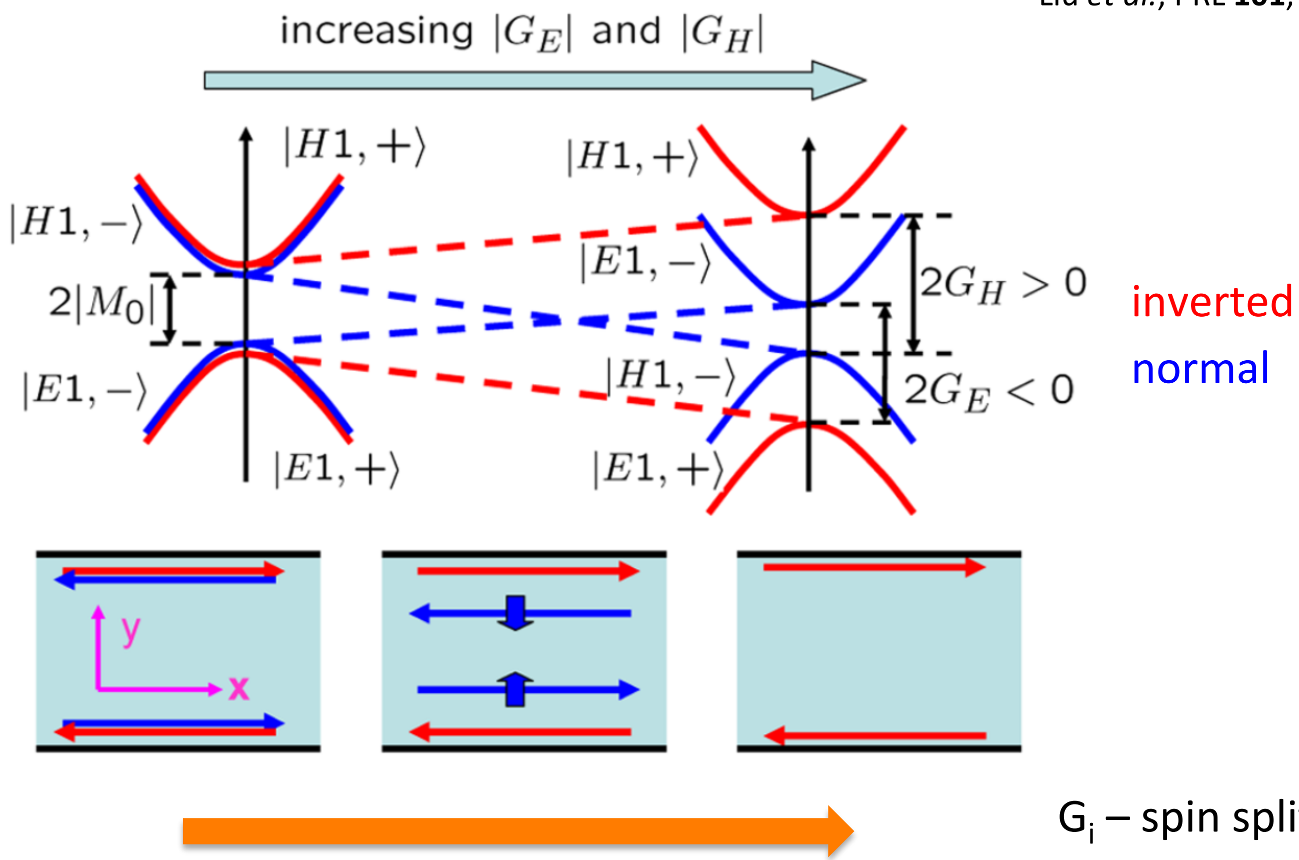
Characterized by spin Chern number $C_{\pm}$



Quantum Anomalous Hall Effect

Quantum Anomalous Hall effect created by TRS breaking due to exchange fields in $Hg_{1-y}Mn_yTe$ quantum wells

Liu *et al.*, PRL **101**, 146802 (2008)



spin down states penetrate deeper and vanish

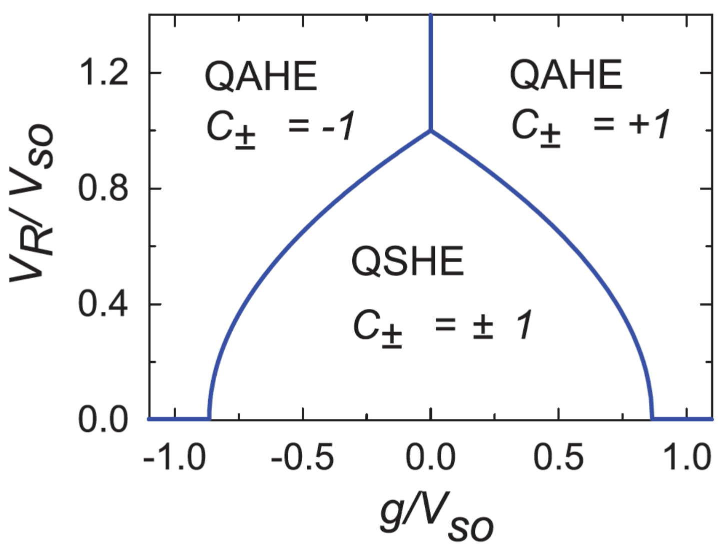
G_i – spin splitting band i

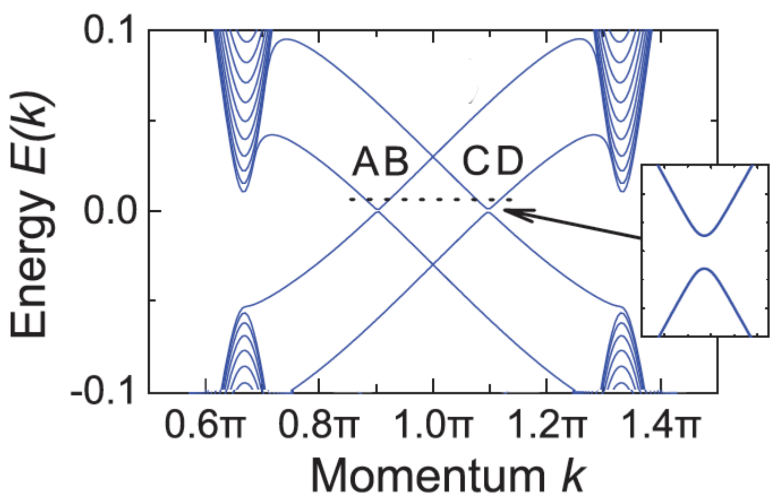
$$G_E G_H < 0$$

QSH with broken TR symmetry

Honeycomb lattice with TRS breaking due to exchange field.
Below a critical value band topology remains intact,
allows for magnetic manipulation of QSH

Yang *et al.*, PRL **107**, 066602 (2011)





g - Exchange field
V_{SO} – intrinsic SOI
V_R – Rashba SOI

Hamiltonian including exchange field

$\hat{\boldsymbol{\tau}}$: spin

$\hat{\boldsymbol{\sigma}}$: e-h bands

$\hbar = 1$

$$H = H_0 + H_1$$

$$H_0 = v_F(\hat{\tau}_z k_x \hat{\sigma}_x + k_y \hat{\sigma}_y) + Dk^2 + (M_0 - Bk^2)\hat{\sigma}_z$$

$$H_1 = (g_0 \hat{\sigma}_z + g_1)\hat{\tau}_z$$

$$g_0 = \frac{1}{2}(G_H - G_E)$$

$$g_1 = \frac{1}{2}(G_H + G_E)$$

Non-zero band gap if

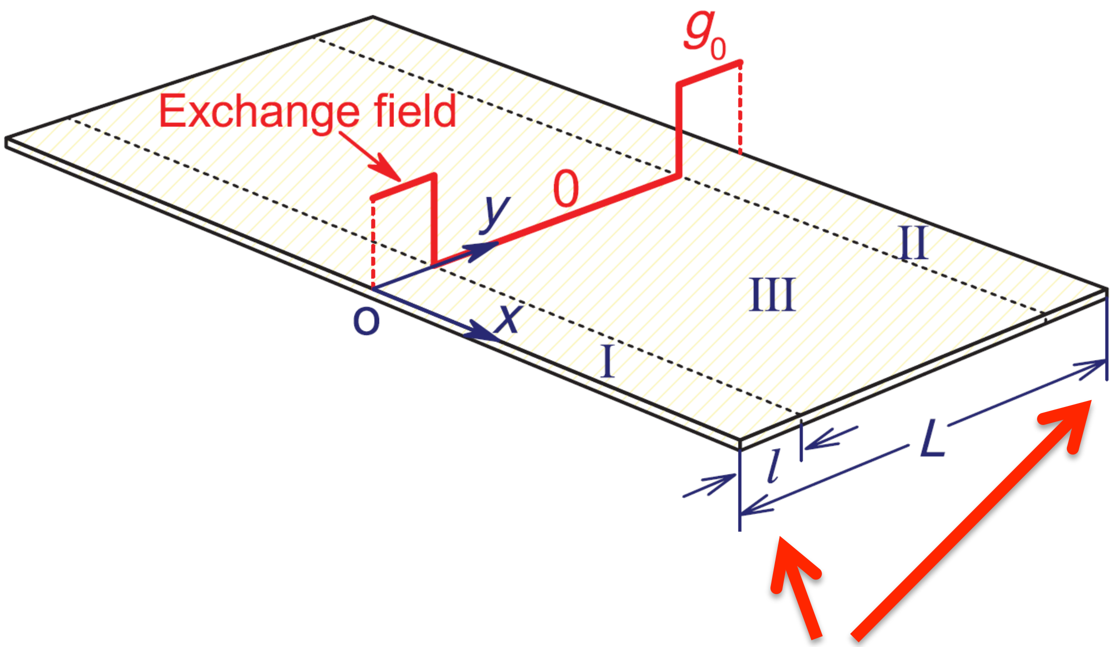
$$|g_1| < \max(|M_0|, |g_0|)$$

Spin Chern number:

$$C_\pm = \pm 1/2[\mathrm{sgn}(B) + \mathrm{sgn}(M_0 \pm g_0)]$$

$$g_0 = 0, \begin{cases} BM_0 > 0 : & C_\pm = \pm\mathrm{sgn}(B) \quad \text{QSH phase} \\ BM_0 < 0 : & C_\pm = 0 \quad \text{insulator} \end{cases}$$

QSH Sample



Mn breaks TRS (backscattering)

Mn-doped

$$g_0 = \frac{1}{2}(G_H - G_E)$$

Edge states I

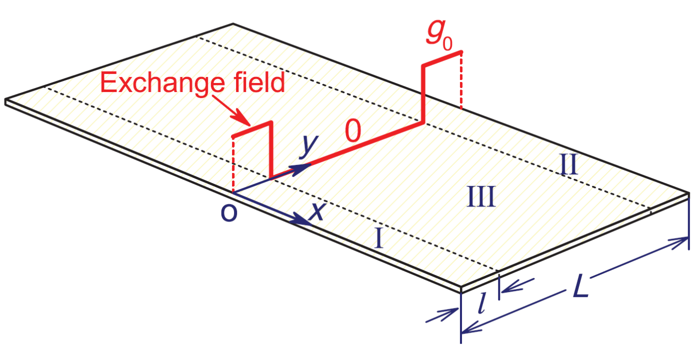
$$D = g_1 = 0$$
$$|\tau_z, \sigma_x\rangle$$

$$E_\pm(k_x) = \pm v_F k_x$$

$$\varphi_+(k_x, y) = |1, 1\rangle\, \phi_+(k_x, y)$$

$$\varphi_-(k_x, y) = |-1, 1\rangle\, \phi_-(k_x, y)$$

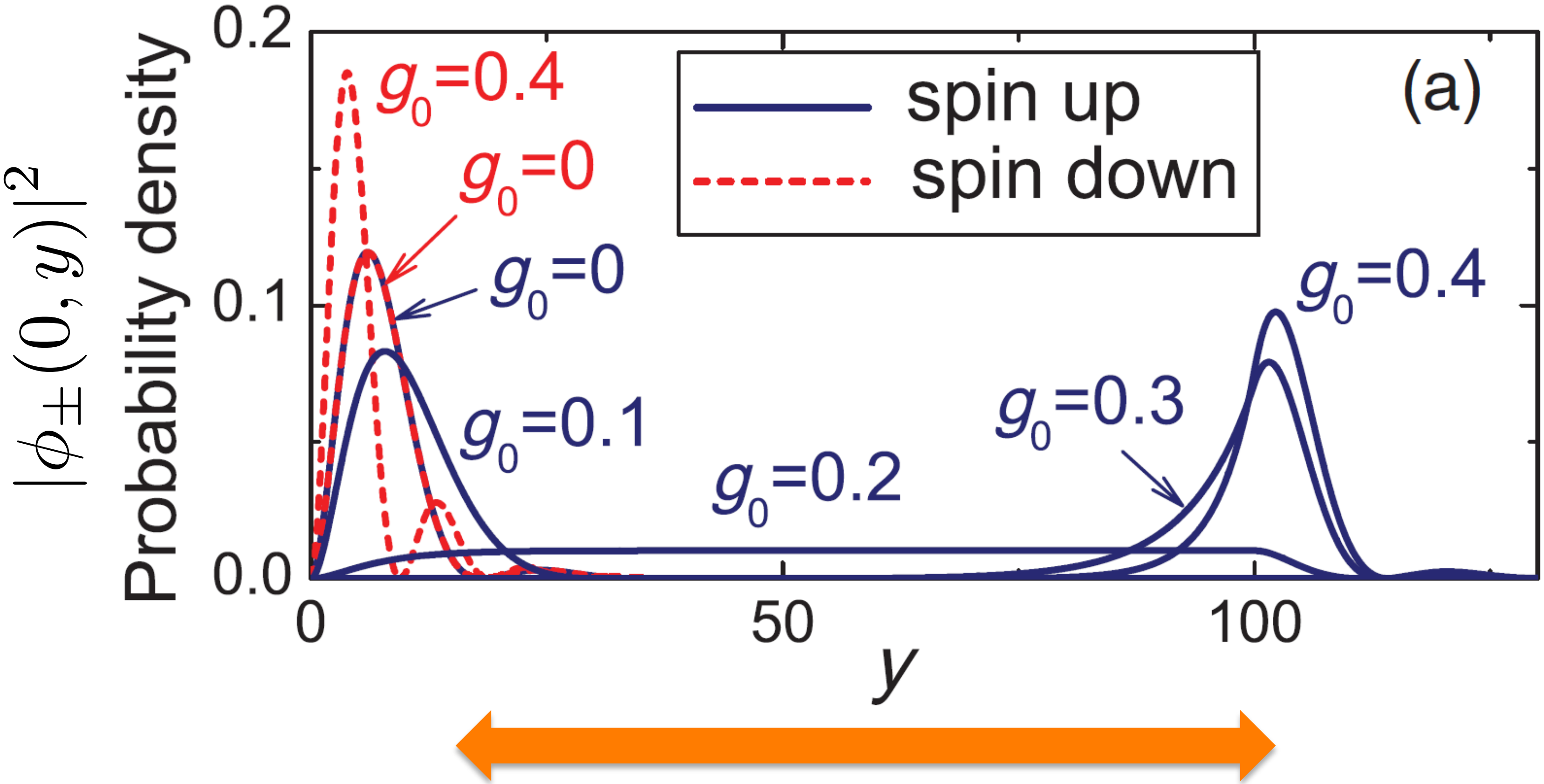
$$\phi_-(k_x, y) \propto \begin{cases} e^{-y/\xi_1(-g_0)} - e^{-y/\xi_2(-g_0)} \\ e^{-(y-l)/\xi_1(0)} - F_- e^{-(y-l)/\xi_2(0)} \end{cases}$$



$$\phi_+(k_x, y) \propto \begin{cases} e^{-y/\xi_1(g_0)} - e^{-y/\xi_2(g_0)} \\ e^{-(y-l)/\xi_1(0)} - F_+ e^{-(y-l)/\xi_2(0)} \end{cases}$$

$$\xi_{1,2}(\epsilon) = \frac{2|B|}{v_F \pm \sqrt{v_F^2 - 4B(M_0 - Bk_x^2 + \epsilon)}}$$

Edge states II



increasing g_0 separates $|\phi_\pm(0,y)|^2$

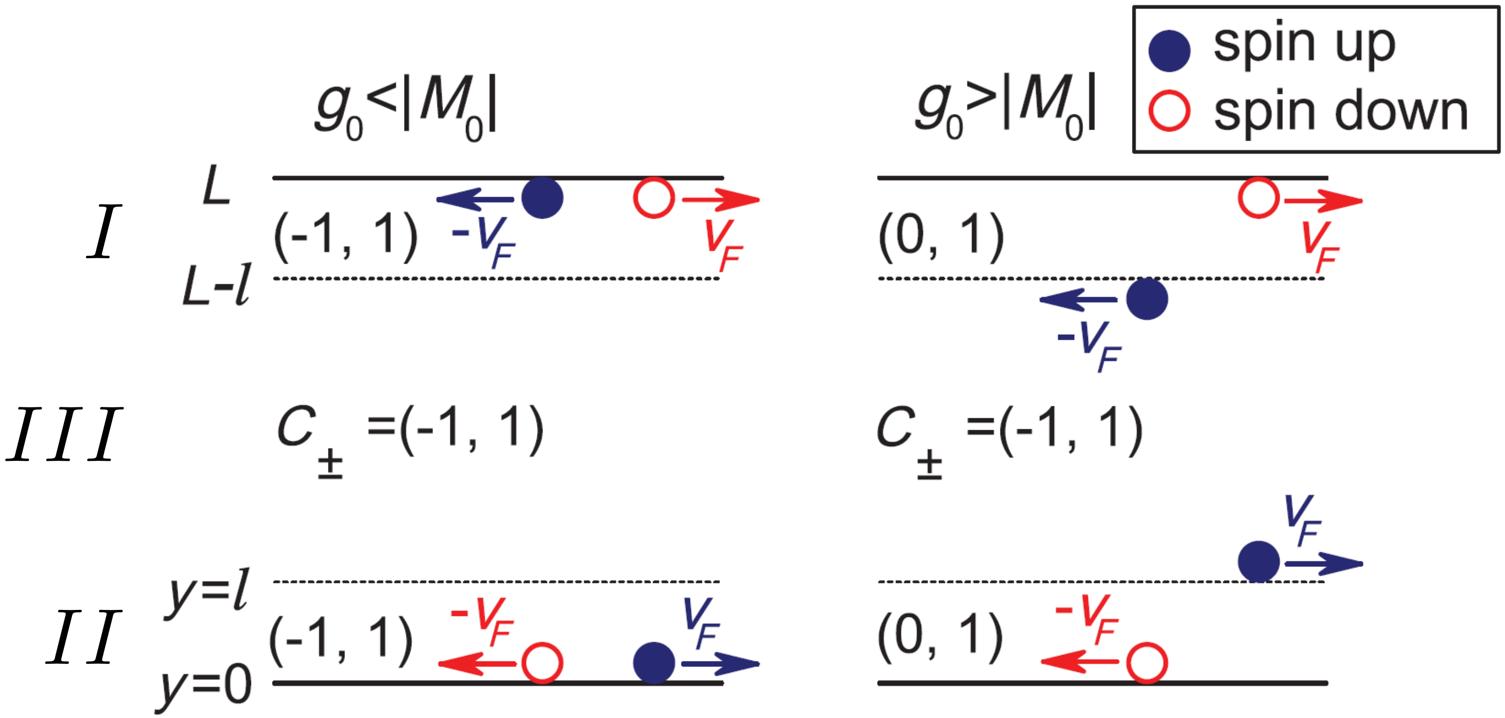
$|\phi_-(0,y)|^2$ spreads out (g_0=0.2) and localizes at y=l

$k_x = 0$

$l = 100$

Edge states III

$$C_\pm = (C_+, C_-)$$



No topological distinction between inner and outer regions

Outer region has C_+=0, i.e. is ordinary insulating for spin up

Separated lanes for + and -, protection against backscattering

Numerical Model – HgTe QW

Randomly distributed Mn atoms, not fully aligned, provides exchange field and scattering potential

$$H_1 = -\frac{1}{\pi\lambda^2}\sum_{\alpha=0}^{N-1}(j_0\hat{\sigma}_z + j_1)\hat{\boldsymbol{\tau}}\cdot\boldsymbol{s}_\alpha e^{-|\boldsymbol{r}-\boldsymbol{R}_\alpha|^2/\lambda^2}$$

Mn spin orientation distribution

$$f(\boldsymbol{s}_\alpha) \propto e^{-\eta\cos\theta_\alpha}$$

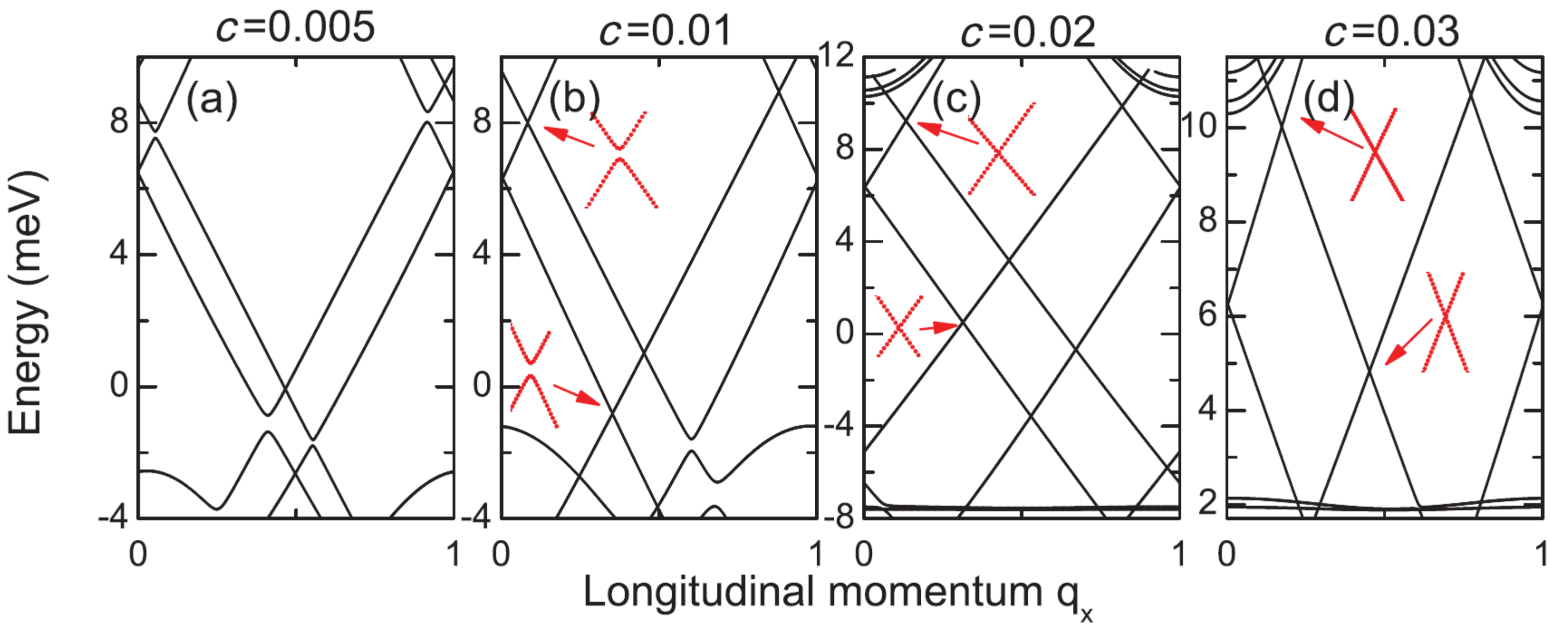
$$M/M_s = -\langle\cos\theta_\alpha\rangle = \coth\eta - 1/\eta$$

Mean field recovers

$$H_1 = (g_0\hat{\sigma}_z + g_1)\hat{\tau}_z$$

$$v_F = 364.5 \text{ meV nm}$$
$$B = -686 \text{ meV nm}^2$$
$$D = -512 \text{ meV nm}^2$$
$$M_0 = 10 \text{ meV}$$

What about backscattering? - Spectrum

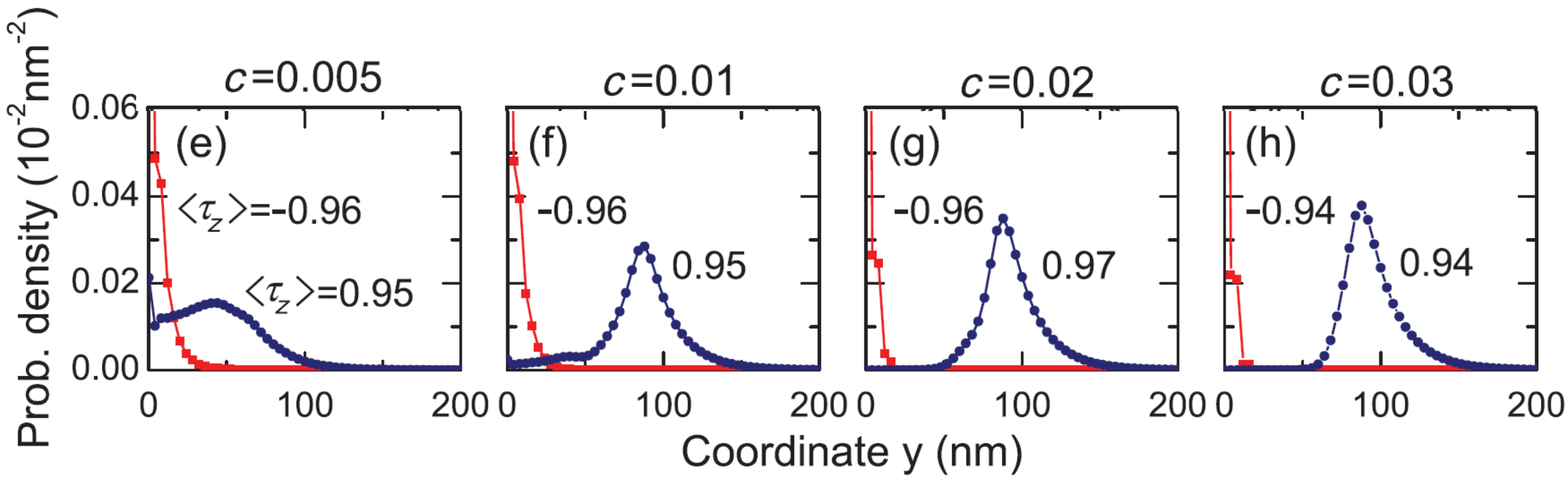


c = doping concentration

Energy gaps vanish
(backscattering is quenched)

$$[q_x] = 2\pi / L_x$$

Numerical Model – Probability density



c = doping concentration

Separation increases

$$E_F = 4 \text{ meV}$$

Conclusions

Use QAH and QSH with broken TRS to separate QSH lanes

Numerical testing shows robustness

- Thank you -