CARLSBERGFONDET

Current-induced magnetization in a two-dimensional topological insulator coupled to an environment of localized spins

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Center for Quantum Devices

Ref.: - Phys. Rev. B **86**, 035112 (2012)

- Phys. Rev. B **88**, 115411 (2013)

SUGGESTION

Outline

- Introduction:
  -What is a 2D topological insulator?
  -Solid state experiments

- A 2D Topological insulator coupled to a spin bath

- Summary

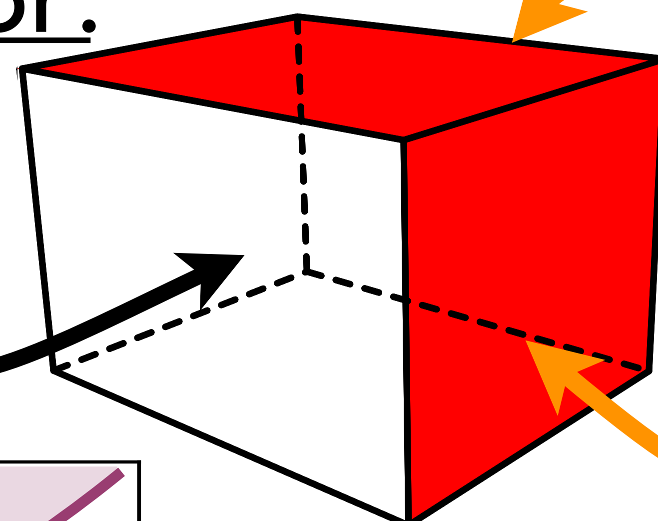
What is a Topological insulator?

Minimal answer:

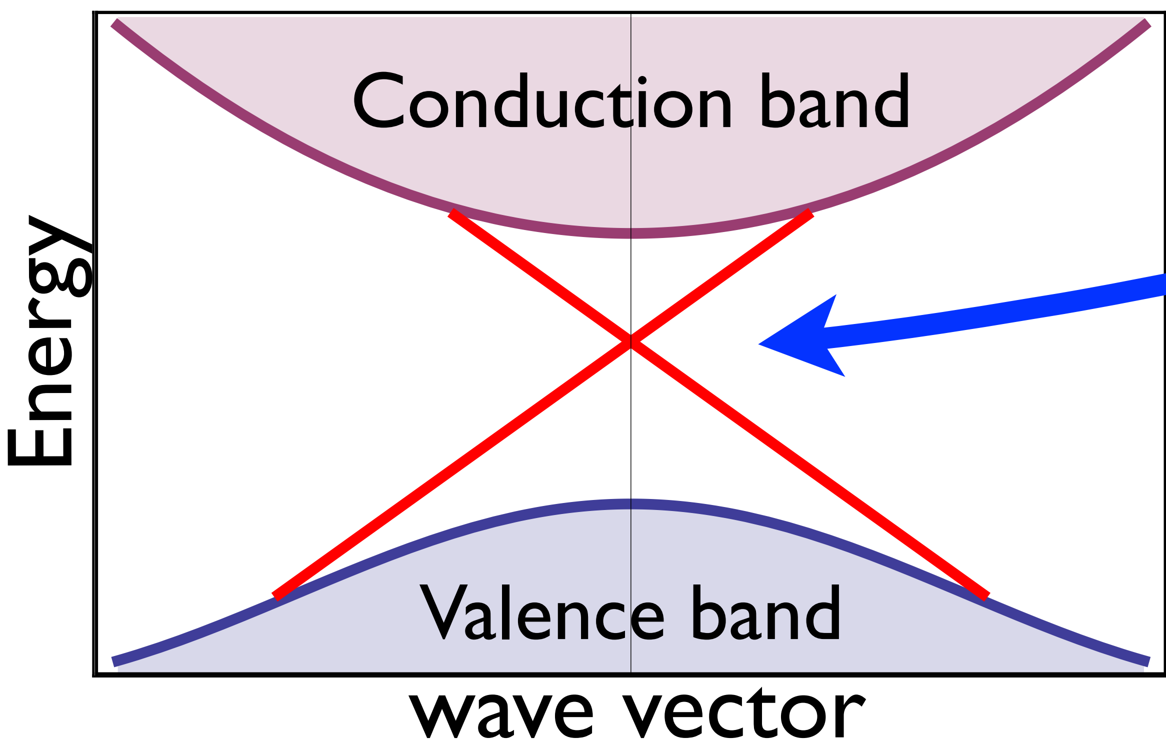
A material with an ***insulating bulk*** and
metallic states at the boundary

3D Topological Insulator:

Insulating bulk energy band gap



2D surface states:
Massless Dirac Fermions



Solid state materials:

Bi_2Se_3, Bi_2Te_3, HgTe, BiSb alloys, etc.

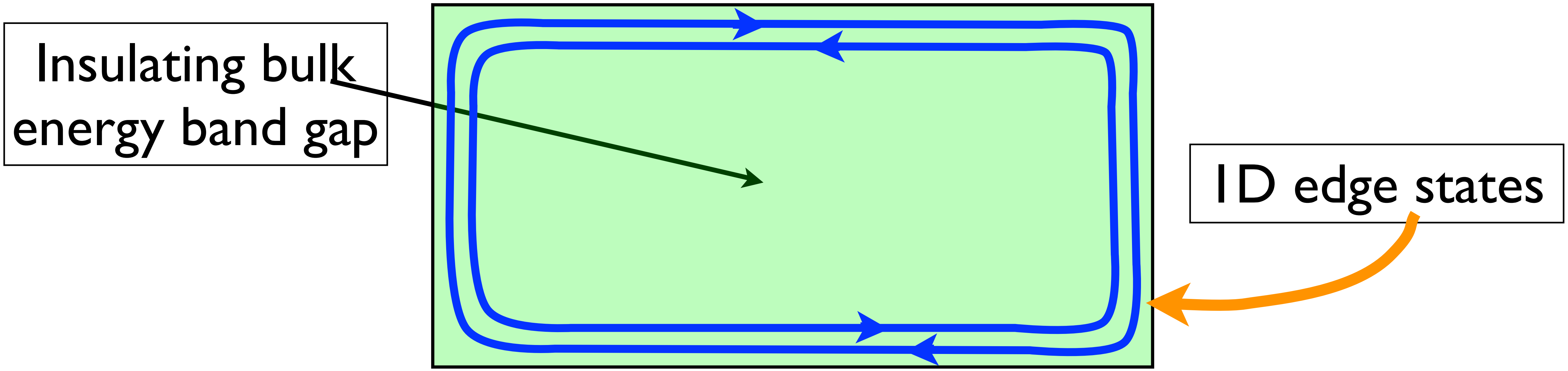
Review:
Qi and Zhang, Rev. Mod. Phys. **83**, 1057 (2011)

What is a Topological insulator?

Minimal answer:

A material with an *insulating bulk* and *metallic states at the boundary*

2D Topological Insulator:



Proposed in Graphene!

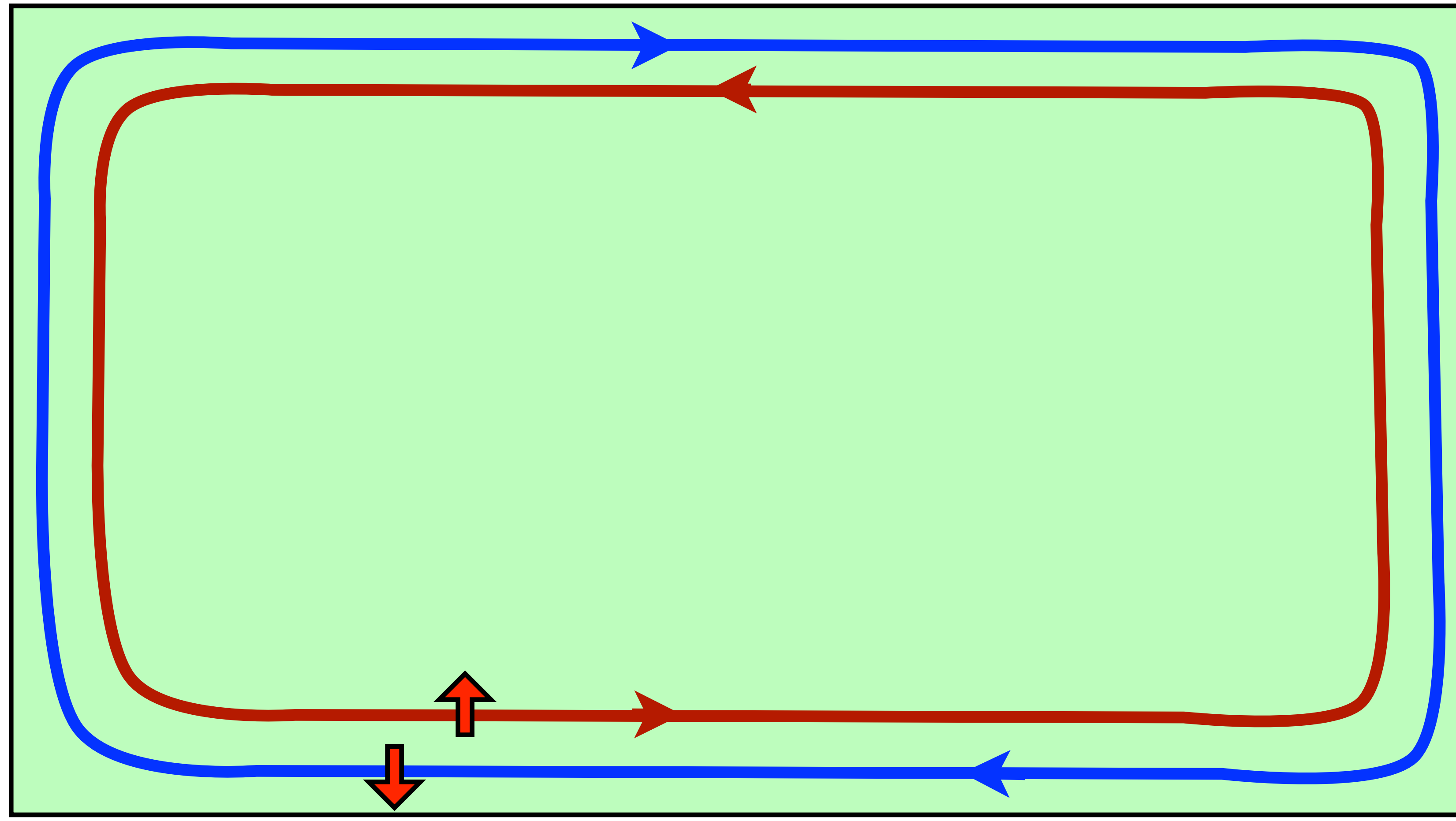
Problem: The spin-orbit coupling seems two small experimentally!

Kane and Mele, **95** Phys. Rev. Lett 2005

Only a few Solid state materials: HgTe and InAs/GaSb quantum wells.

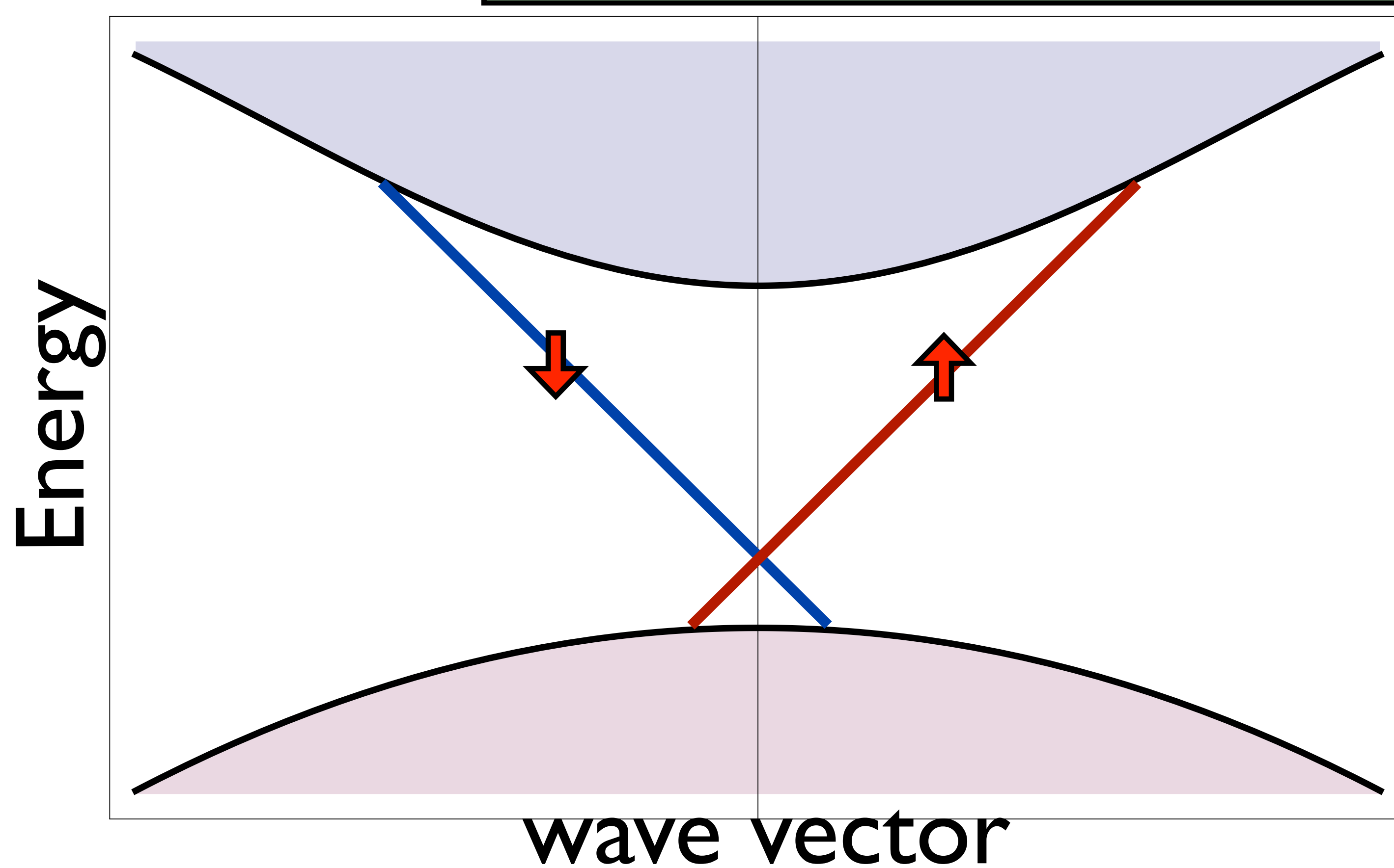
Review: Qi and Zhang, Rev. Mod. Phys. **83**, 1057 (2011)

Spin-momentum locking in topological insulators



Helical edge states:

-Spin *up* and *down* are counterpropagating



Time-reversal invariance in topological insulators

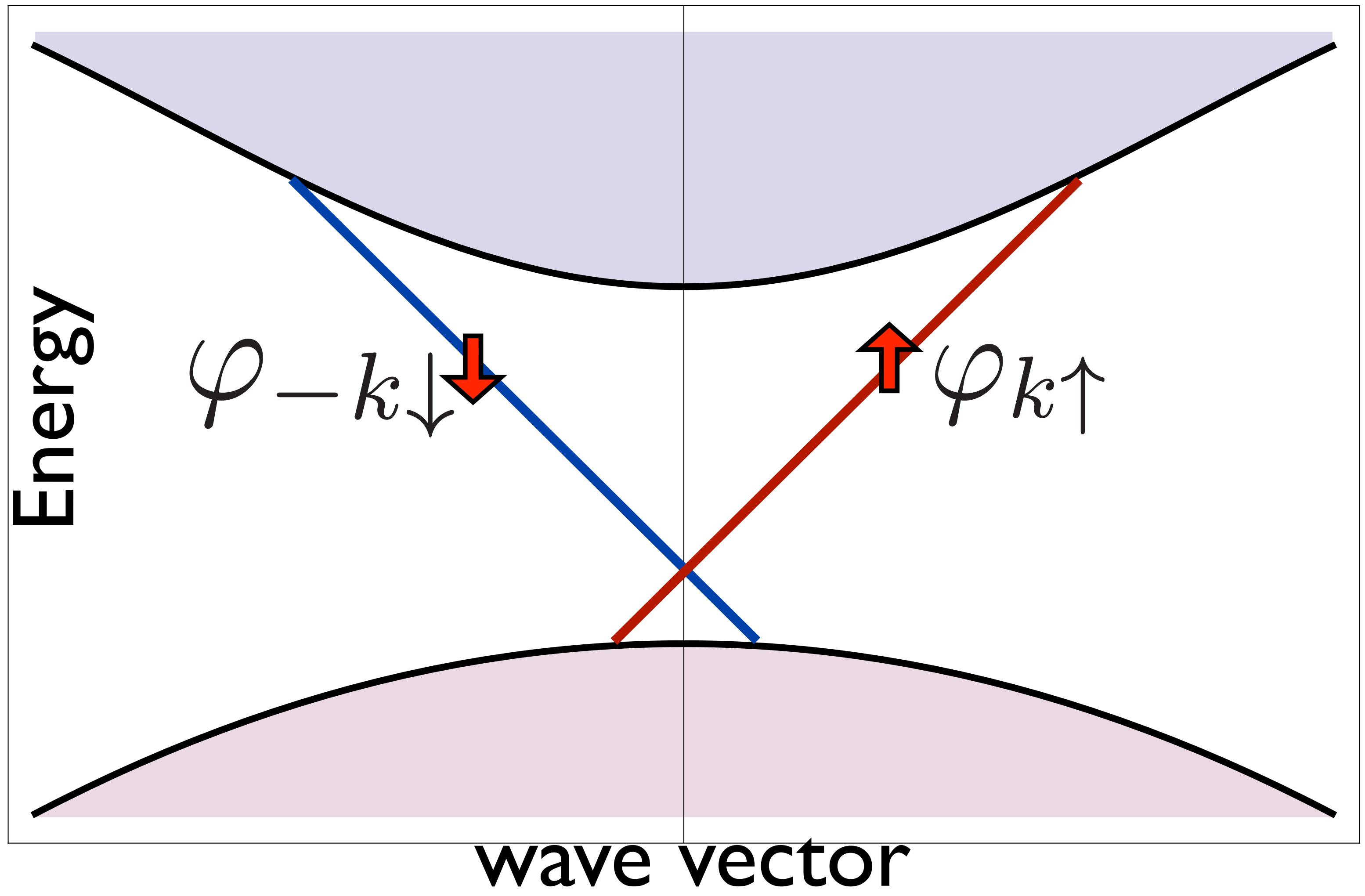
Generally:

Time-reversal symmetry

$\Downarrow$

Kramers degeneracy: Energy levels doubly degenerate

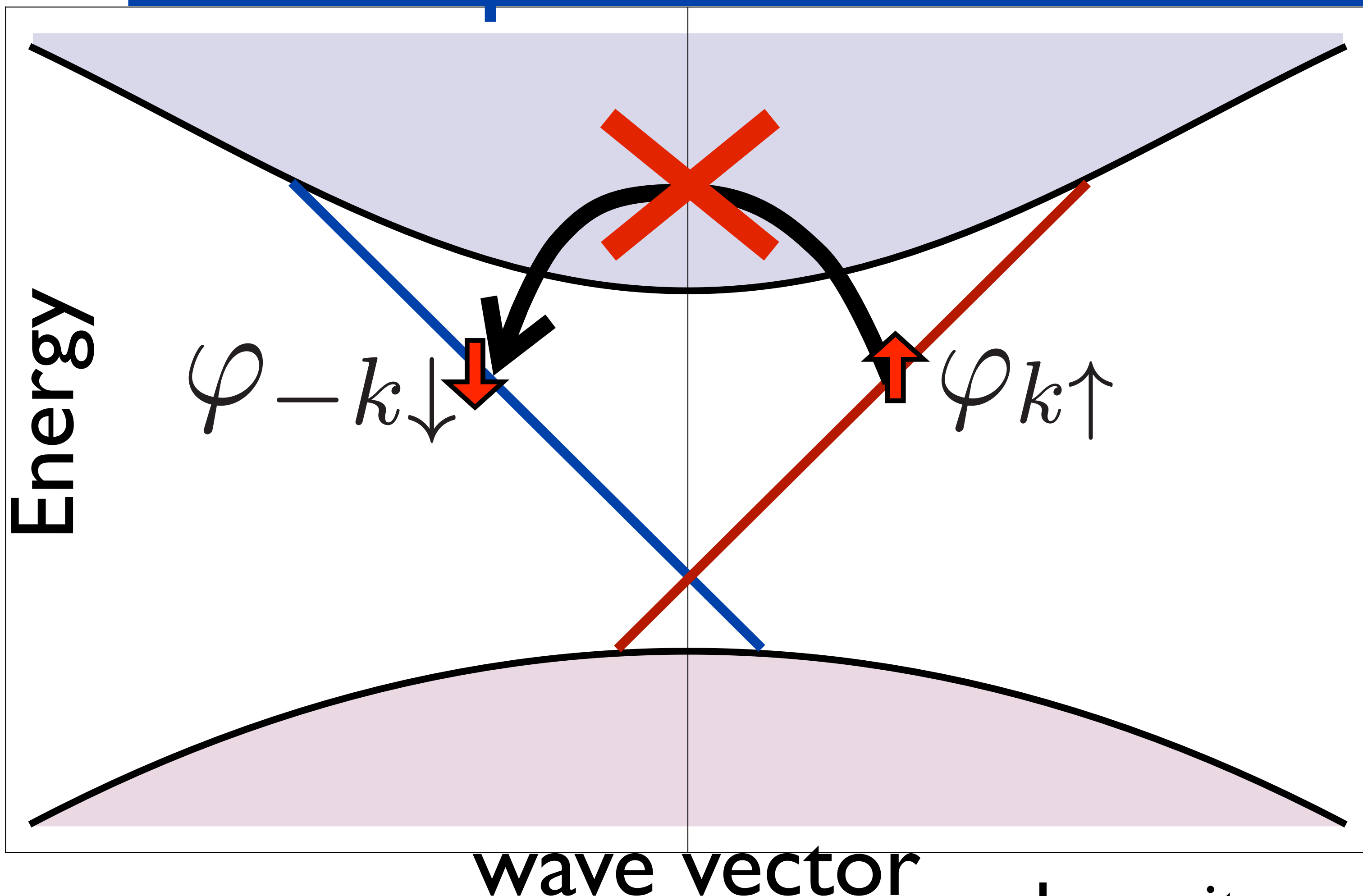
In 2D topological insulators:



Helical edge states appear in Kramers pairs:

$$\varepsilon_{k\uparrow} = \varepsilon_{-k\downarrow}$$

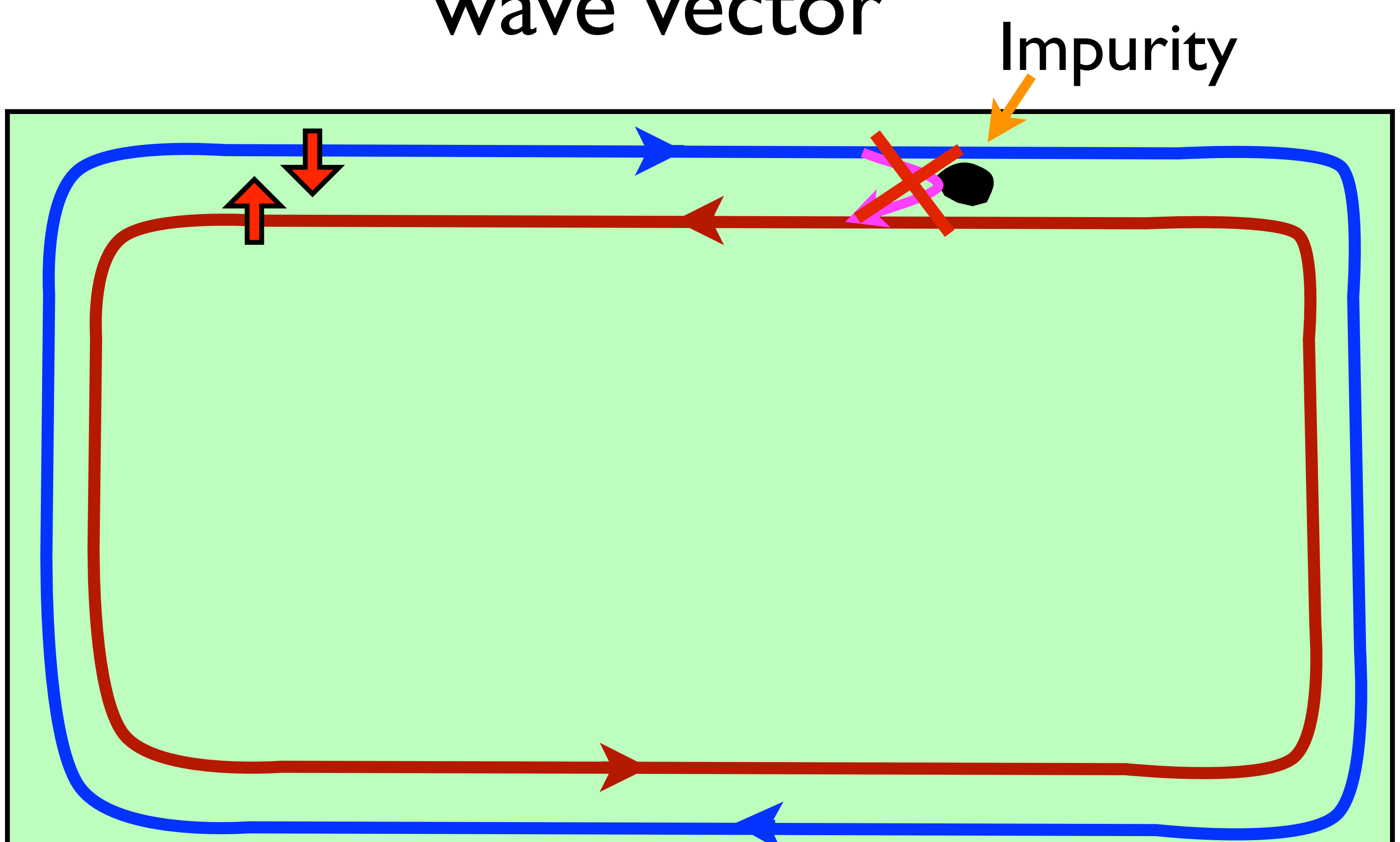
The importance of Time-reversal invariance



No scattering between Kramers pairs:

$$\langle \varphi_{k\uparrow} | V | \varphi_{-k\downarrow} \rangle = 0$$

by time-reversal invariant potentials $\Theta V \Theta^{-1} = V$

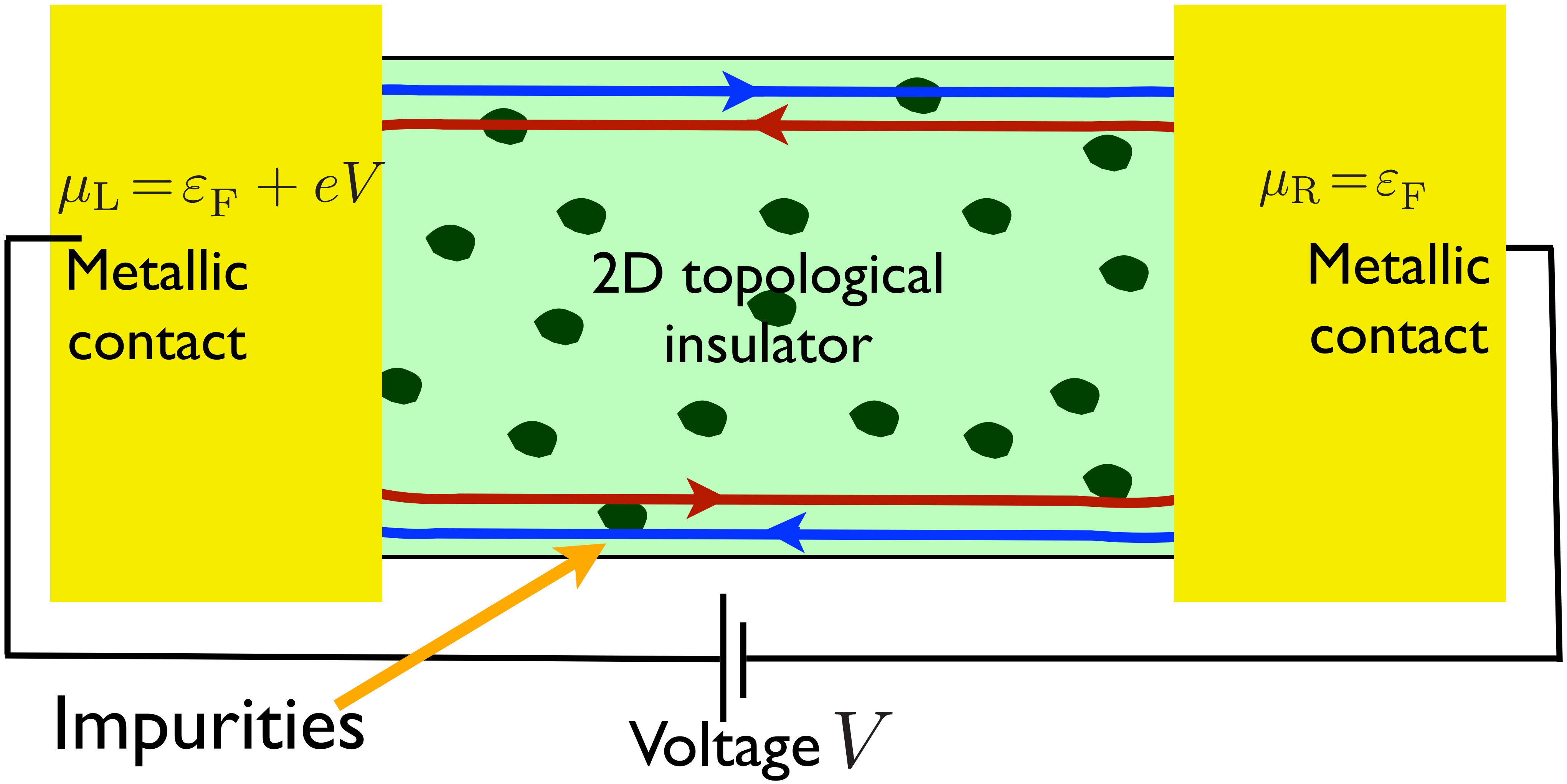


NO elastic backscattering by impurities etc.

***But* In**elastic backscattering is possible!

- Phonon + spin-orbit: Budich, Dolcini, Recher, Trauzettel PRL (2012);
- e-e interactions + impurity + Spin-orbit: Schmidt, Rachel, von Oppen, Glazman PRL (2012)

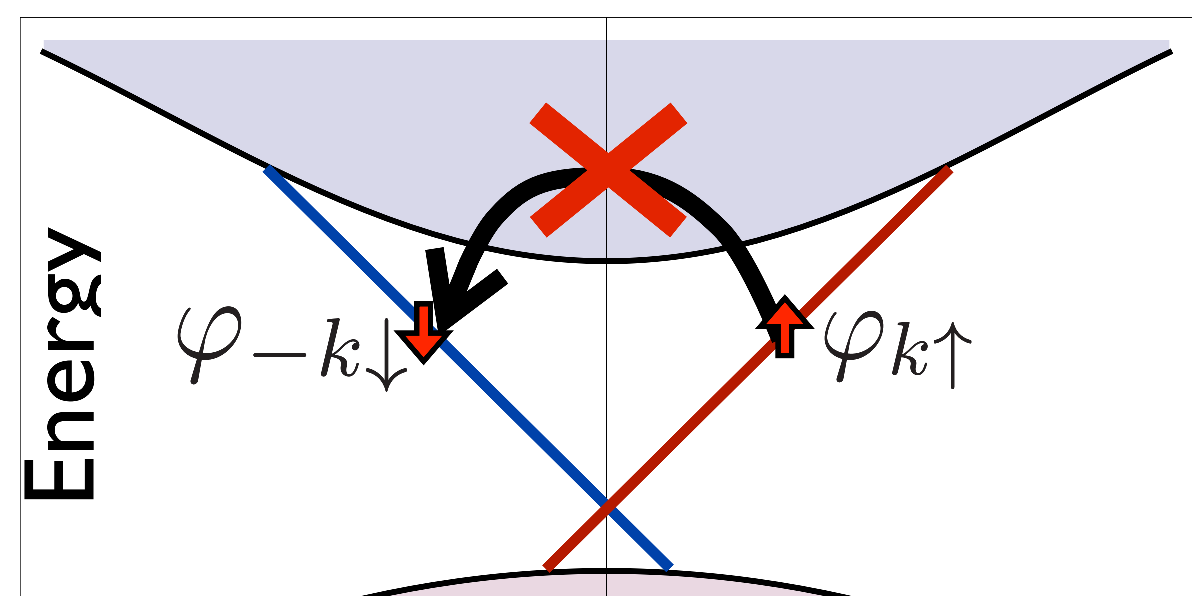
The importance of Time-reversal invariance



Quantized conductance:

$$G = \frac{2e^2}{h}$$

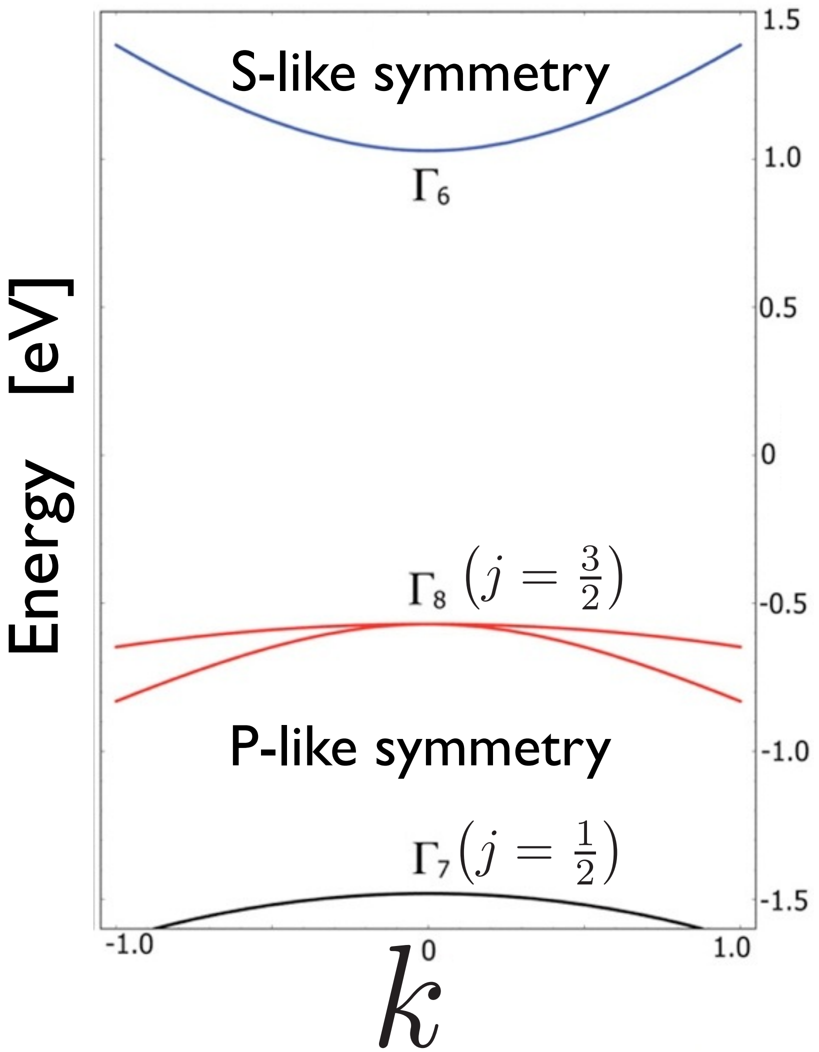
Also including disorder!



Spin-flip + momentum-reversal needed to backscatter elastically!!

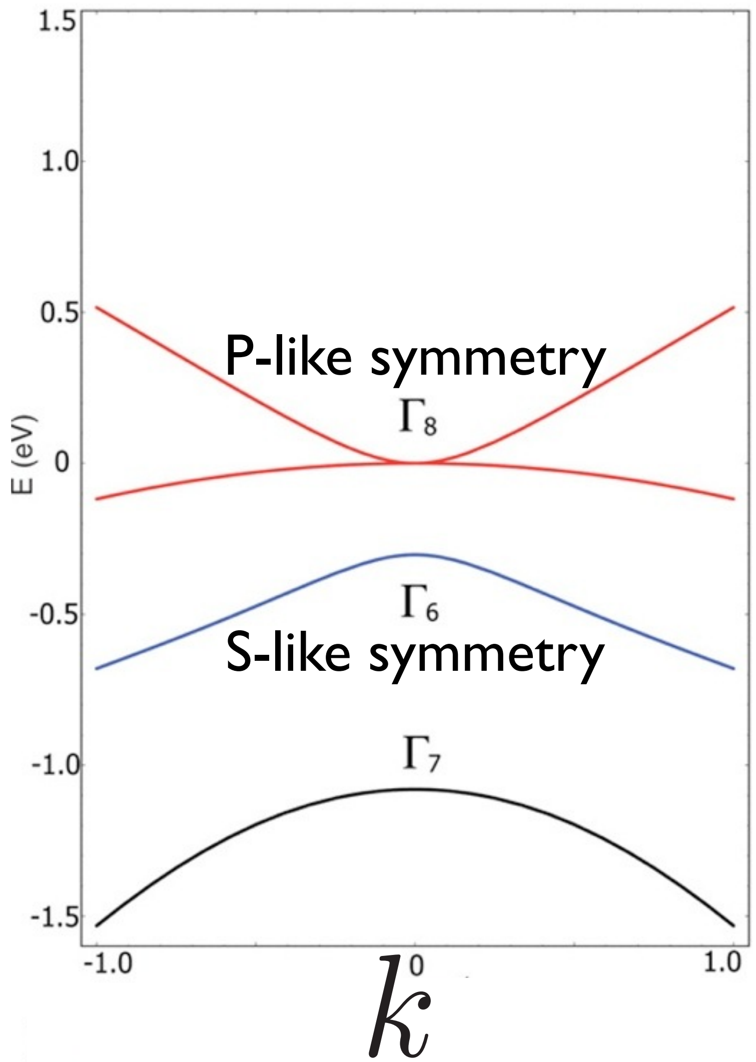
Intuitive explanation for appearance of edge states

Normal
band structure



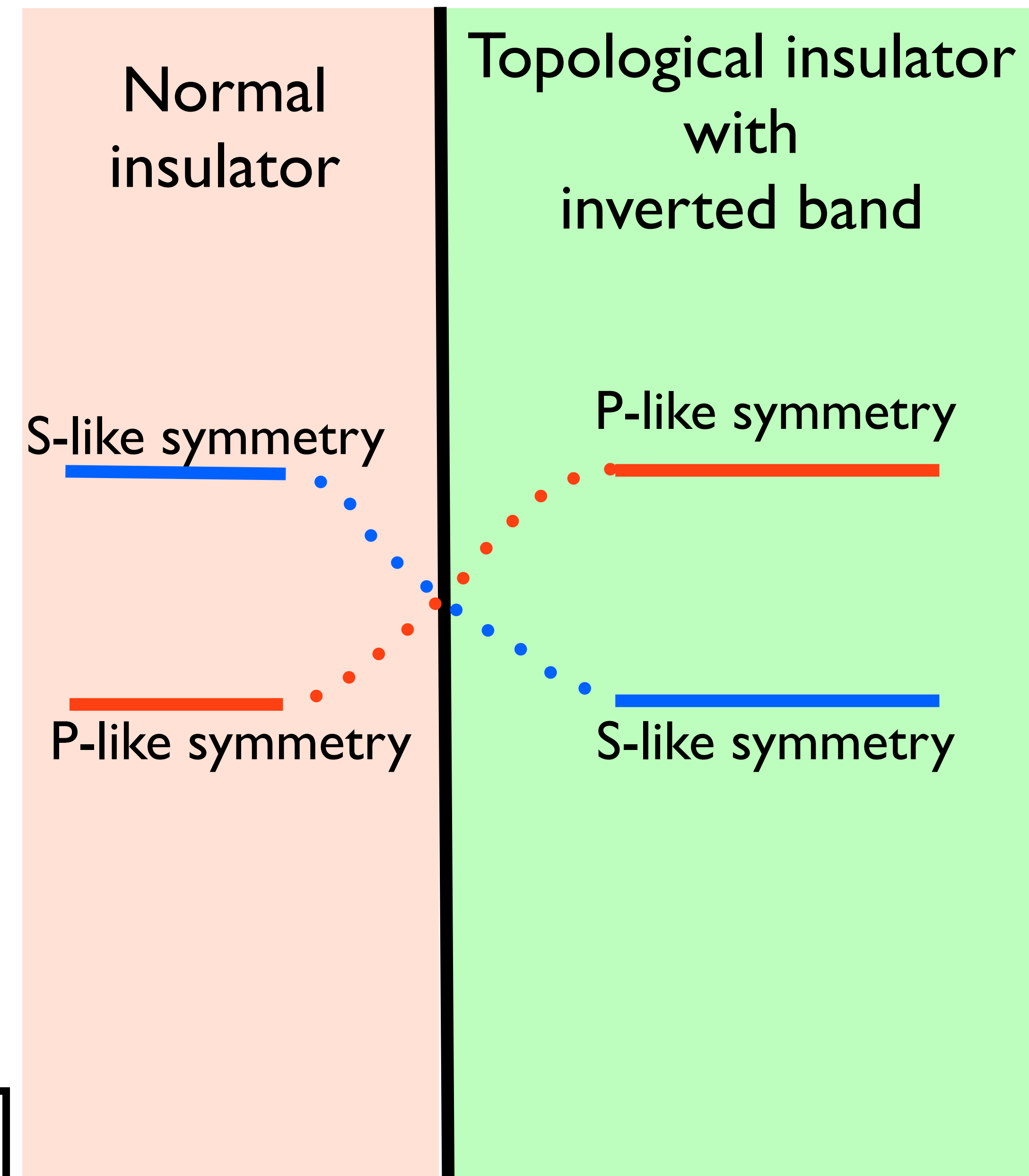
(III-V semiconductor)

Inverted
band structure



Strong spin-orbit splitting

HgTe in 3D



States appear at the Interface

Bernevig, Hughes and Zhang, Science **314**, 1757 (2006)

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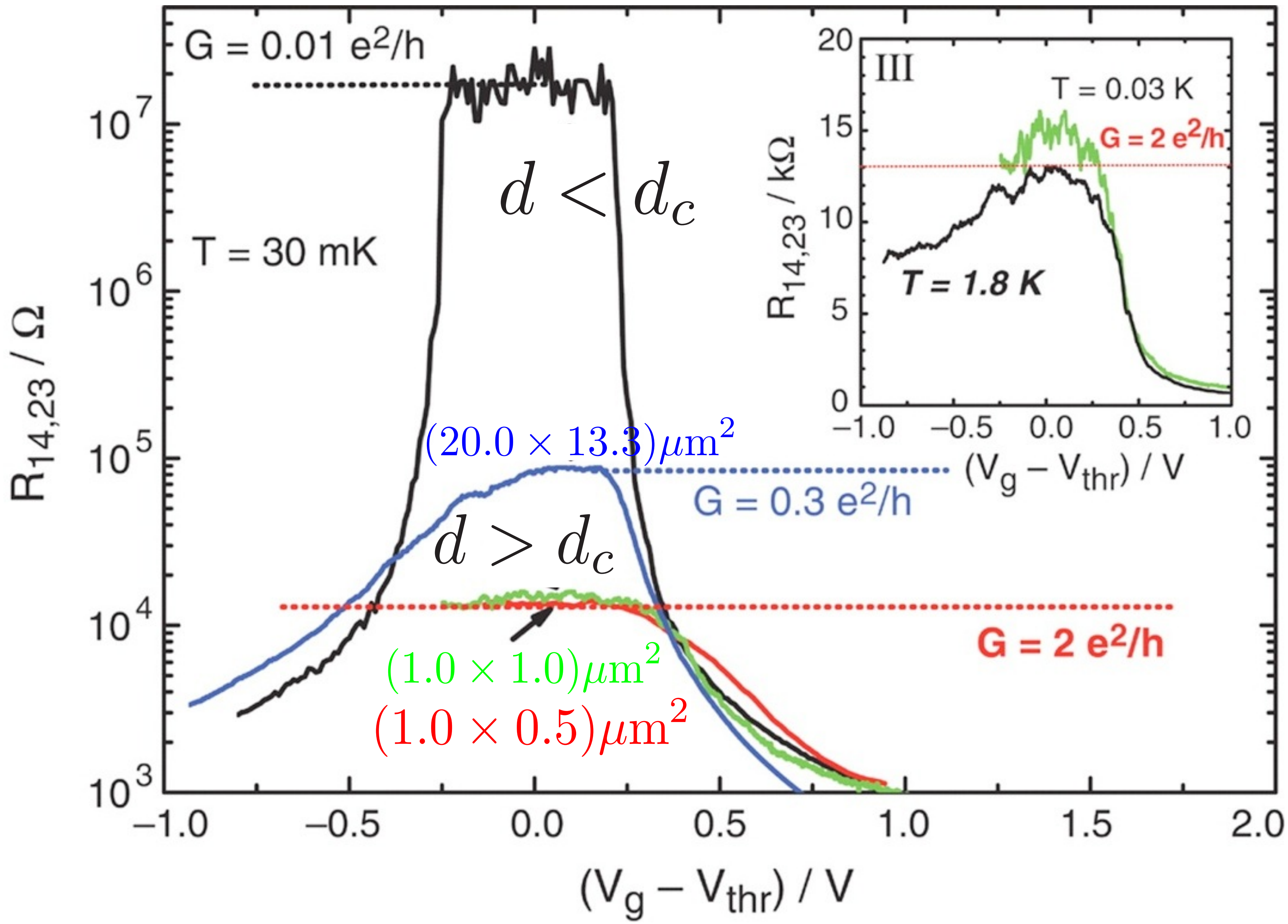
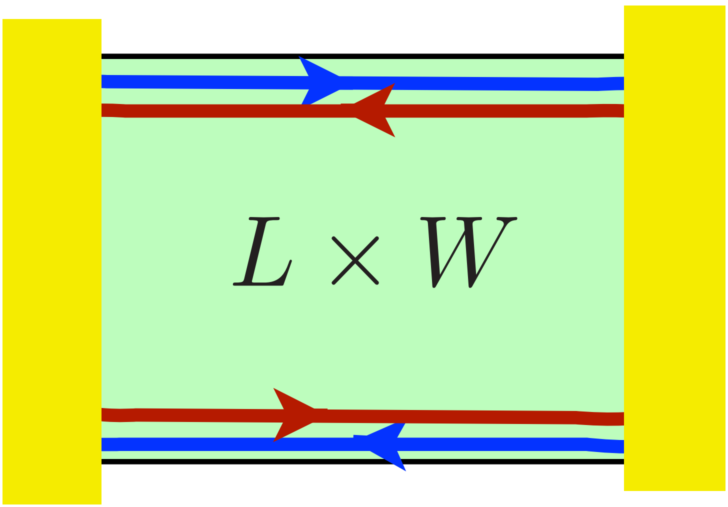
Experiments in HgTe quantum wells

Molenkamp's group, Science **318**, 5851 (2007)





- Further evidence for edge state transport from Hall bar geometry

  Molenkamp's group, Science (2009)

- Better conductance quantization in InAs/GaSb quantum wells

  Du´s group, PRL (2011) + (2014)

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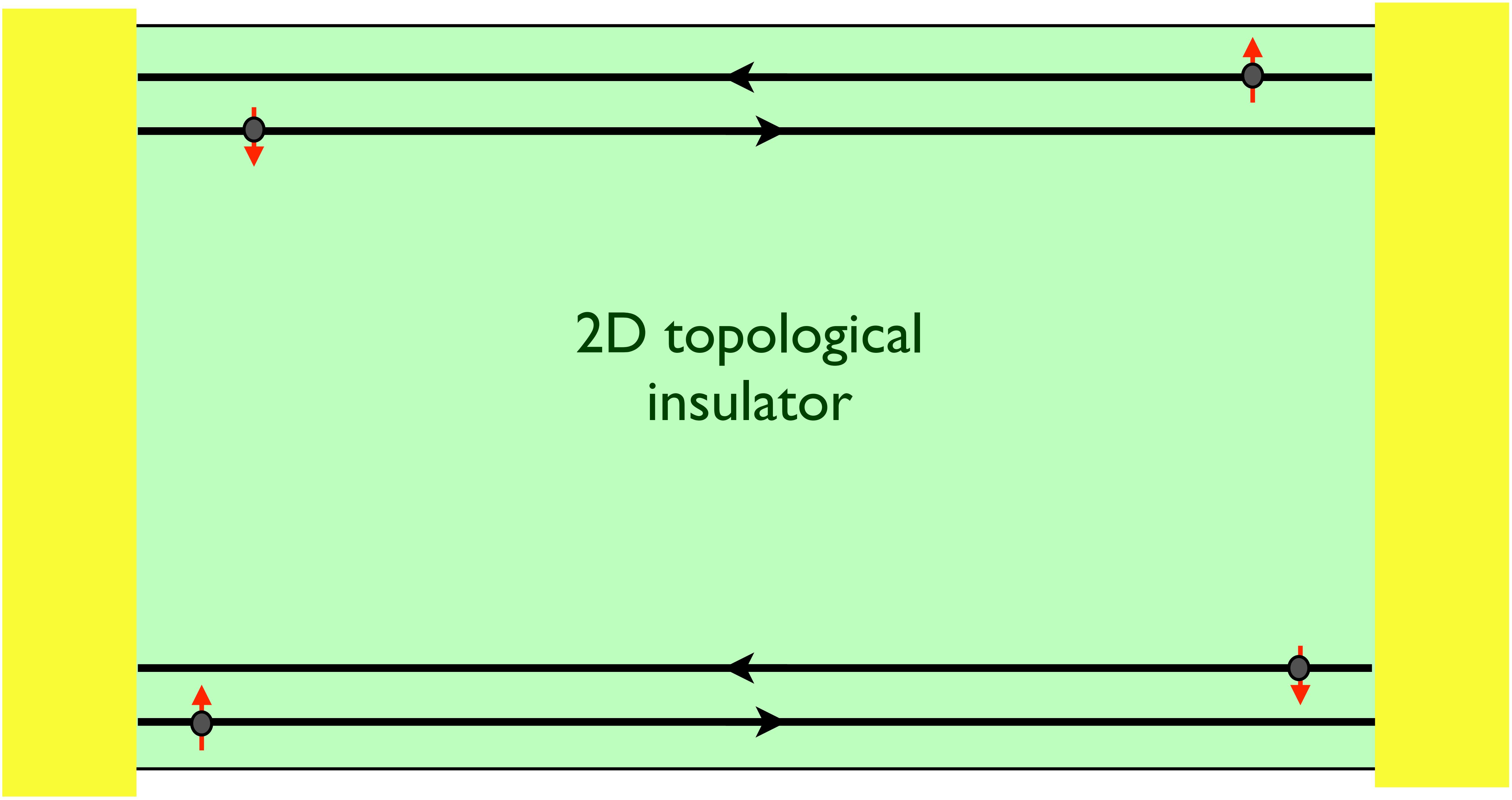
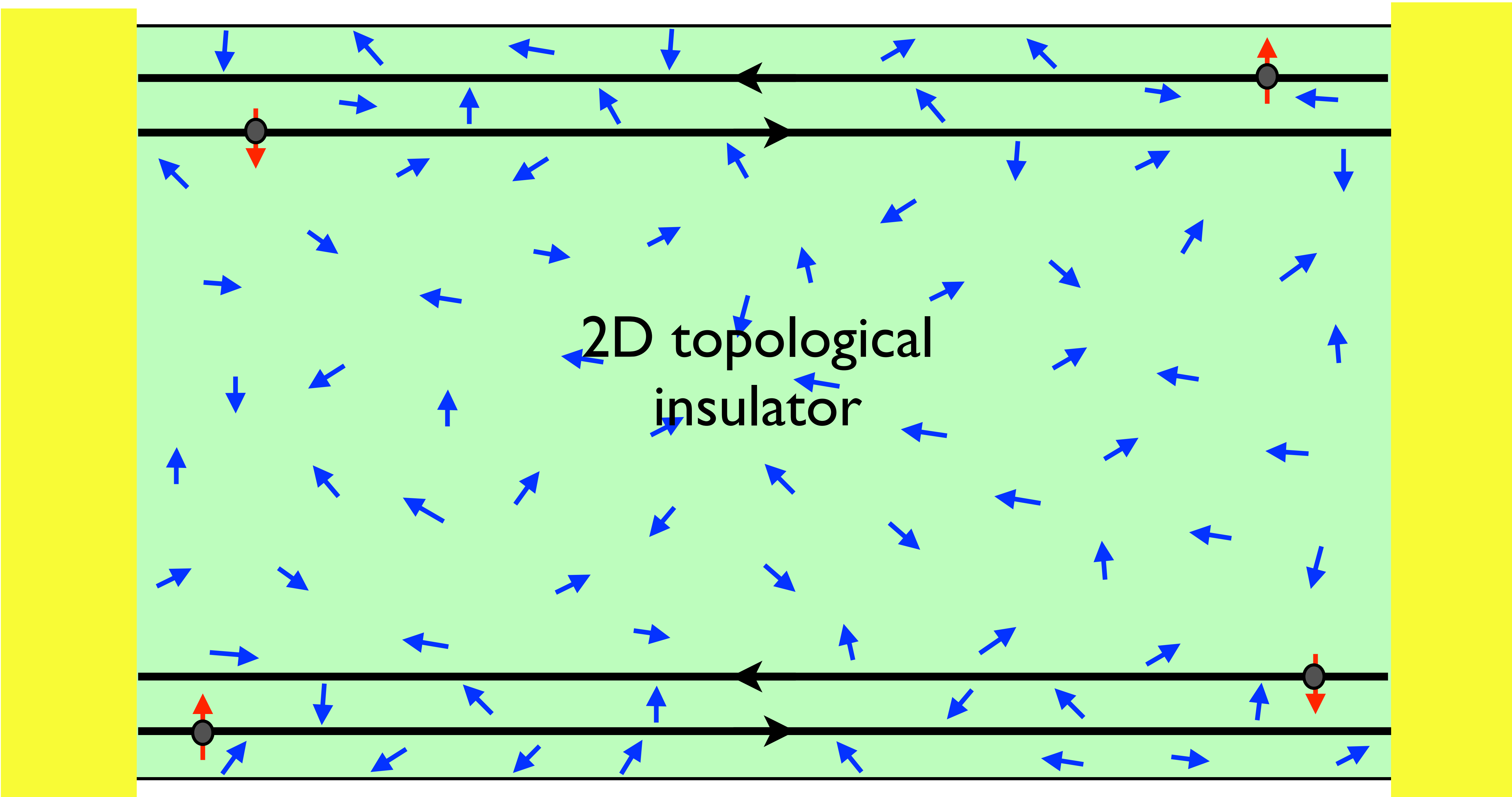
Setup



Setup

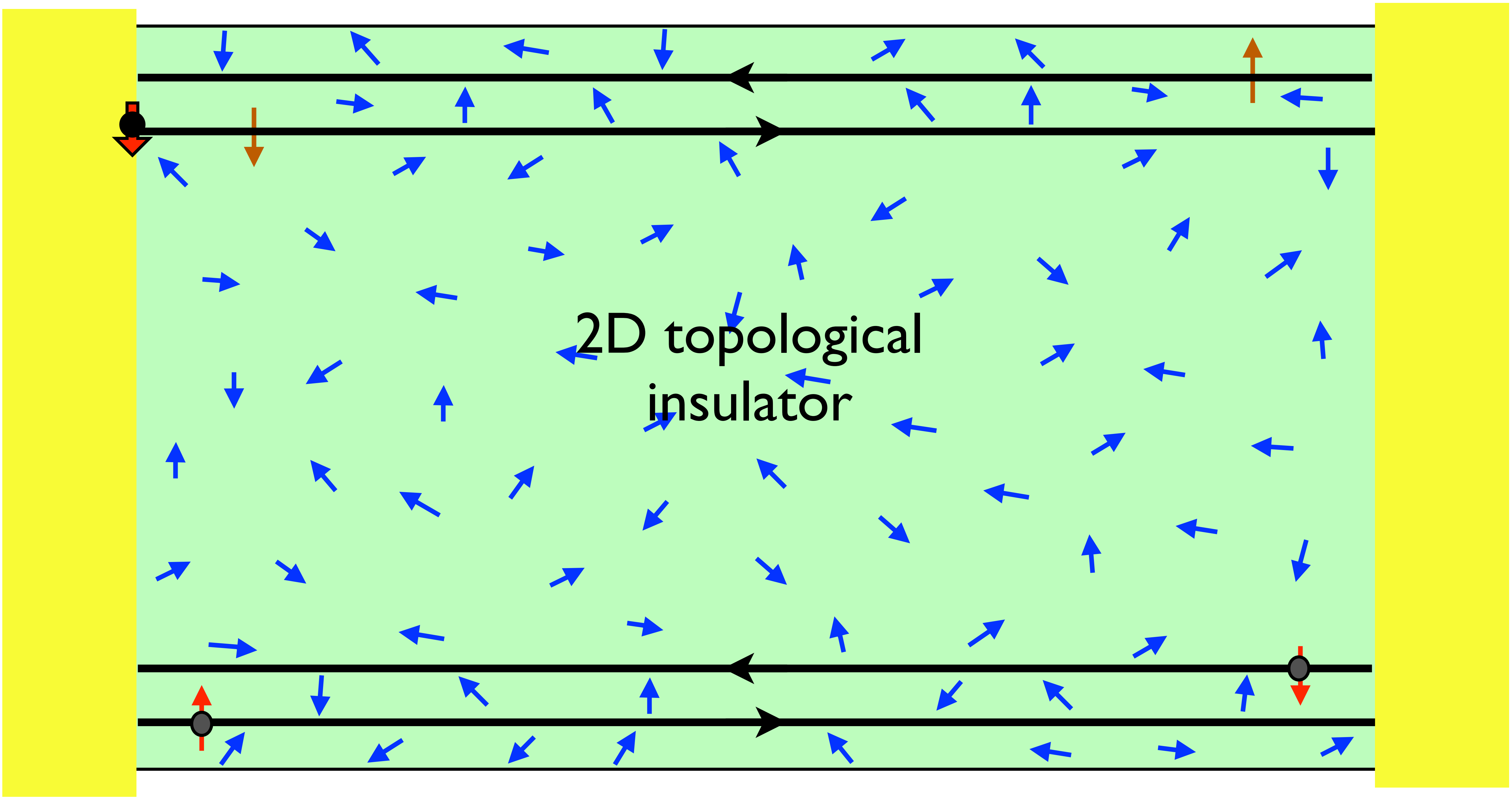


Realizations:

-Magnetic impurities

-Nuclear spins A.M. Lunde and Platero PRB (2013)

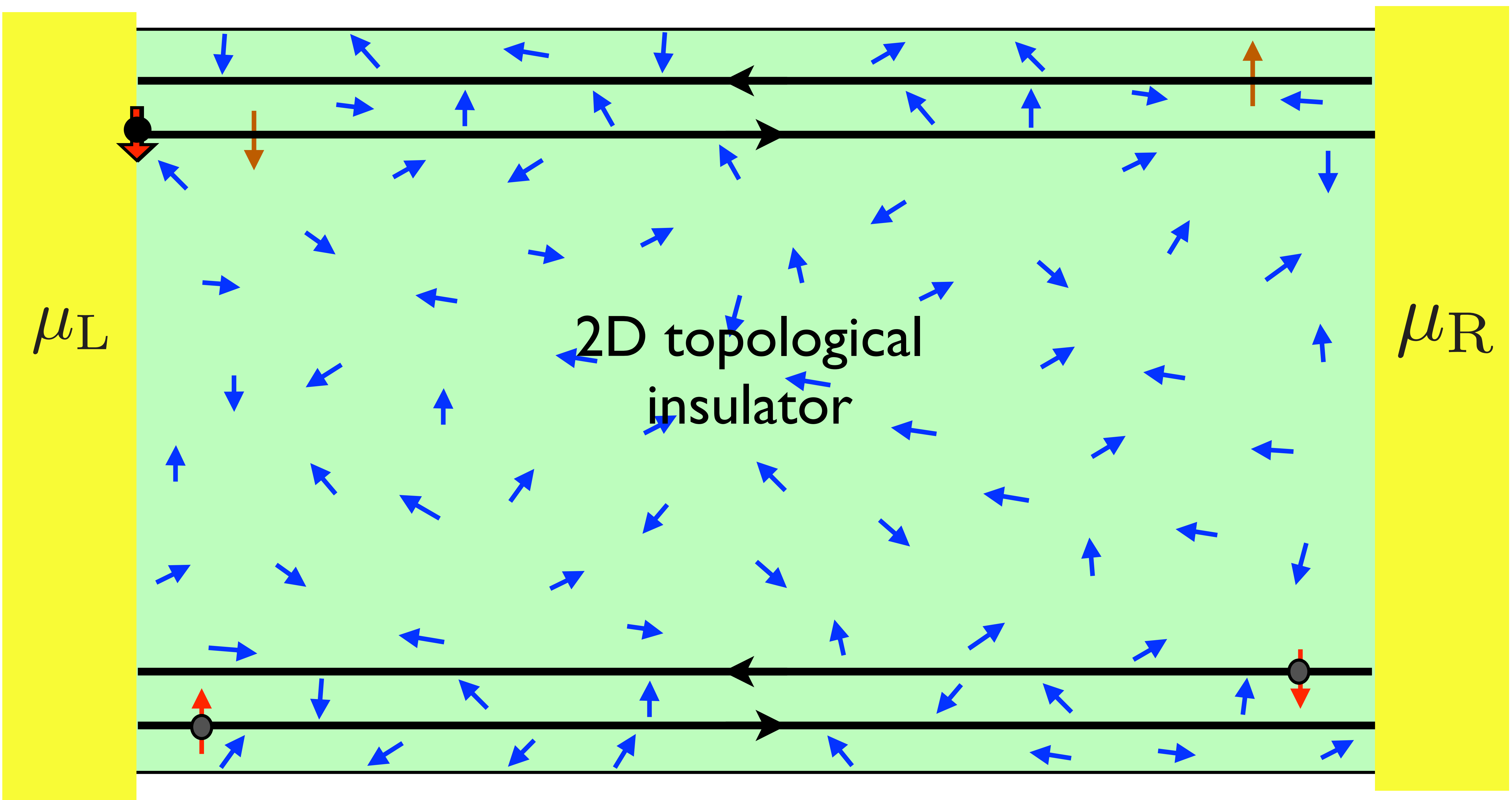
Idea



Fixed spins $\Rightarrow$ spin-flip + momentum-reversal
$\Rightarrow$ Backscattering!

Voltage induce magnetization at edges

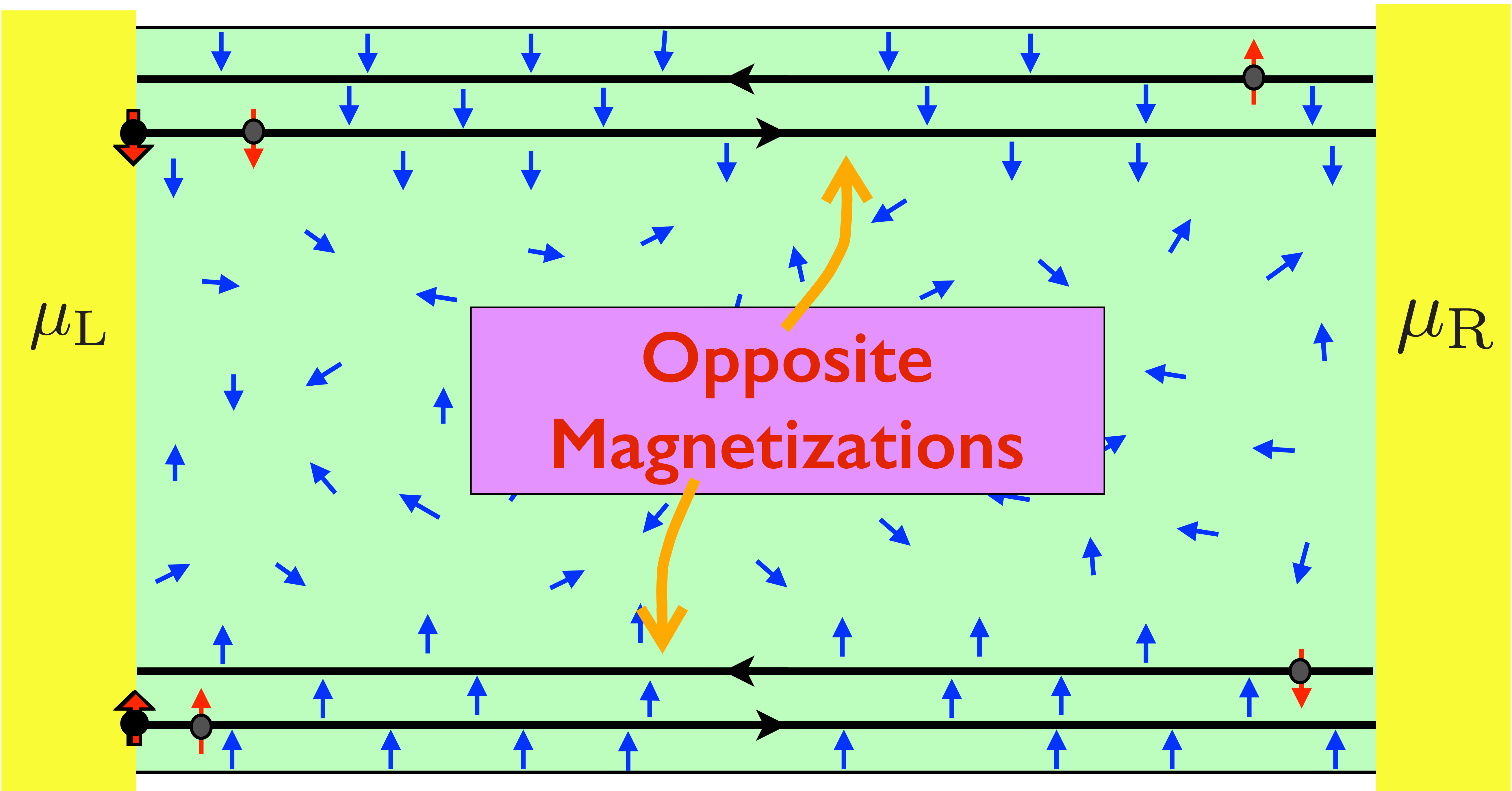
High bias limit: $\mu_{\mathrm{L}} - \mu_{\mathrm{R}} \gg k_{\mathrm{B}} T$ (or low temperature)



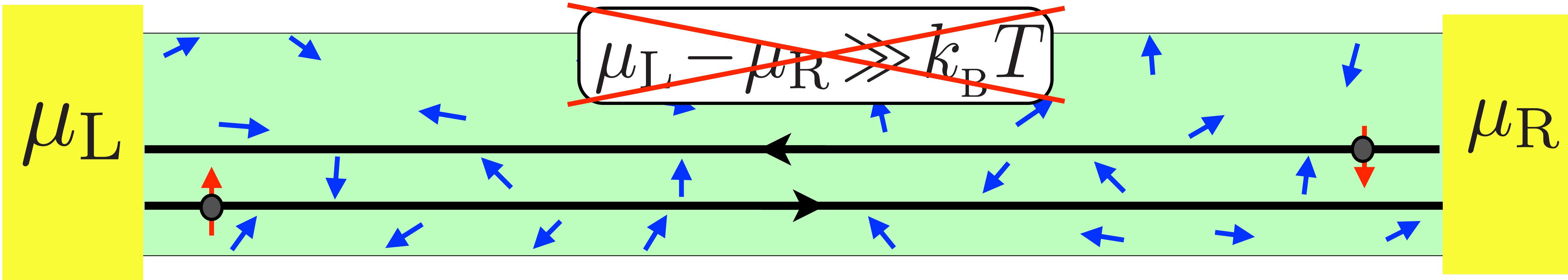
Voltage induce magnetization at edges

High bias limit: $\mu_L - \mu_R \gg k_B T$ (or low temperature)

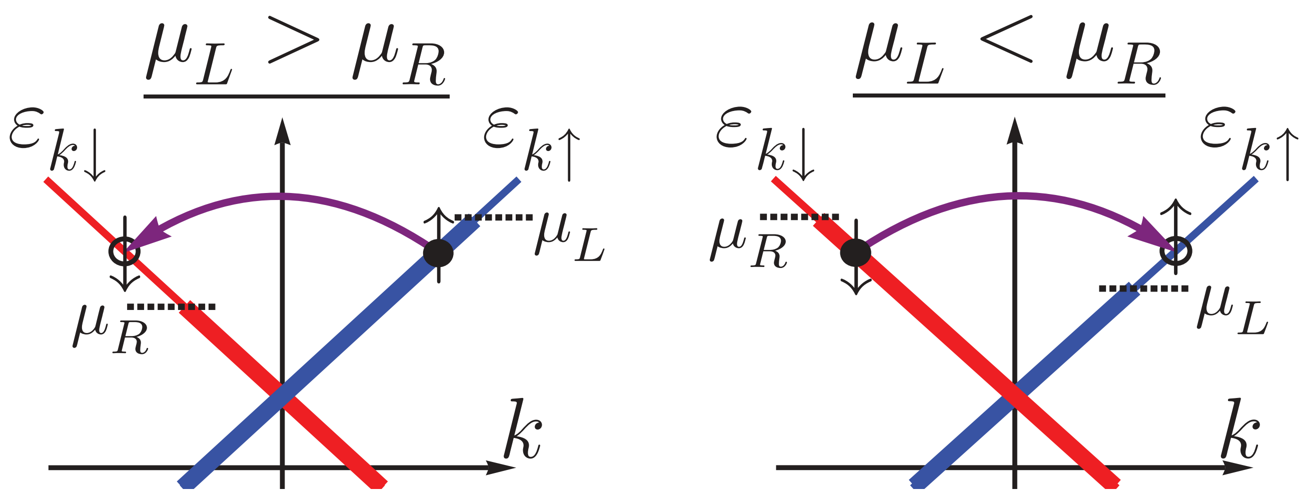
No steady state conductance change!! $G = \frac{2e^2}{h}$



Voltage induced magnetization: Temperature effects



Scattering processes for unmagnetized bath

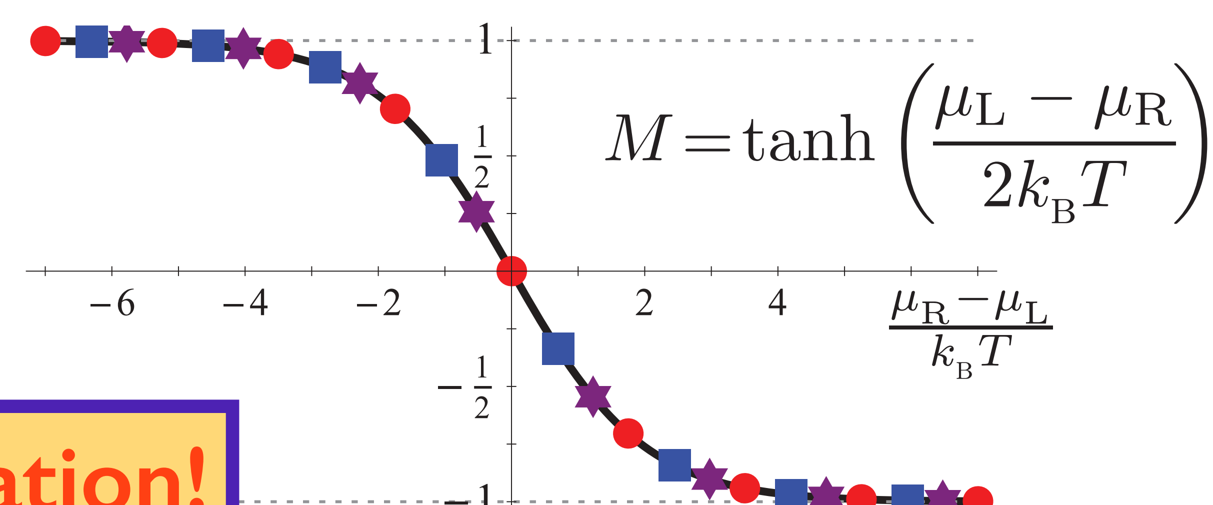


Current: $I = \frac{2e^2}{h} V + \delta I$

$$\delta I = (-e)(\Gamma_{\uparrow\leftarrow\downarrow} - \Gamma_{\downarrow\leftarrow\uparrow})$$

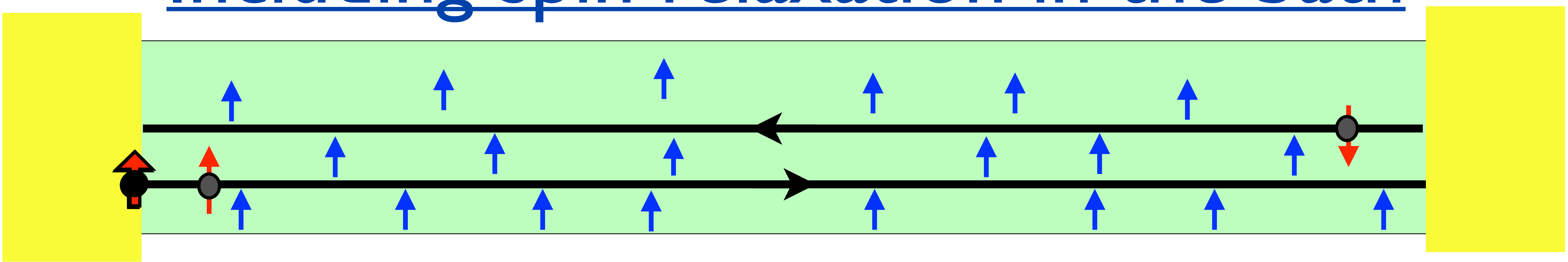
Stationary Magnetization: $\frac{dM}{dt} = \frac{2}{N_s}(\Gamma_{\downarrow\leftarrow\uparrow} - \Gamma_{\uparrow\leftarrow\downarrow}) \implies \Gamma_{\downarrow\leftarrow\uparrow} = \Gamma_{\uparrow\leftarrow\downarrow} \implies \delta I = 0$

$$\left.\begin{aligned} \Gamma_{\uparrow\leftarrow\downarrow} &\propto \frac{N_\uparrow}{N_s} \int dk\, f_R^0(\varepsilon_{k\uparrow})[1 - f_L^0(\varepsilon_{k\uparrow})] \\ \Gamma_{\downarrow\leftarrow\uparrow} &\propto \frac{N_\downarrow}{N_s} \int dk\, f_L^0(\varepsilon_{k\uparrow})[1 - f_R^0(\varepsilon_{k\uparrow})] \end{aligned}\right\} \implies$$



Electrically controllable magnetization!

Including spin relaxation in the bath



Possible mechanism: Spin-phonon relaxation

Current: $I = \frac{2e^2}{h} V + \delta I$

$$\delta I = (-e)(\Gamma_{\uparrow\leftarrow\downarrow} - \Gamma_{\downarrow\leftarrow\uparrow})$$

Stationary Magnetization and current change:

Spin-relaxation

$$\frac{dM}{dt} = \frac{2}{N_s}(\Gamma_{\downarrow\leftarrow\uparrow} - \Gamma_{\uparrow\leftarrow\downarrow}) - \frac{\Gamma_r}{N_s} M$$

$$\Downarrow$$

$$M = \frac{\mu_\mathrm{L} - \mu_\mathrm{R}}{(\mu_\mathrm{L} - \mu_\mathrm{R}) \coth\left(\frac{\mu_\mathrm{L} - \mu_\mathrm{R}}{2k_\mathrm{B} T}\right) + \frac{\hbar}{2\eta}\Gamma_r}$$

and $\delta I \neq 0$ where $\eta \propto J^2$

$$G = \frac{e^2}{h} - \frac{e^2}{h} \frac{\pi\hbar\Gamma_r}{2k_\mathrm{B} T + \frac{\hbar}{2\eta}\Gamma_r}$$

Summary

- 2D topological insulators exist in the solid state

- 2D topological insulator + spin-bath = Magnetization at the edge, but no current change!!

- Spin-relaxation in spin-bath gives a small current change.

Ref.: - Phys. Rev. B **86**, 035112 (2012)

- Phys. Rev. B **88**, 115411 (2013)

SUGGESTION

Thank you
for your attention!