Cargèse International School 2013
Topological Phases in Condensed Matter and Cold Atom Systems
June 25, 2013

Kondo Physics in 2D Topological Insulators with Rashba Interactions

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Vetenskapsrådet
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STINT
Stiftelsen för internationalisering av högre utbildning och forskning

Outline

2D topological insulators... some basics

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At the edge: A new kind of electron liquid

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Adding a magnetic impurity...

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... and a Rashba spin-orbit interaction

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Summary and outlook

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... and a Rashba spin-orbit interaction

Electrical control of the Kondo effect!

Summary and outlook

Topological Phases in Condensed Matter and Cold Atom Systems

Topological Phases in Condensed Matter and Cold Atom Systems

”topologically ordered”

FQHE, Z_2 spin liquids,...

”Thouless type”

IQHE,...

”symmetry protected”

topological insulators,...

....

”symmetry protected”

topological insulators

protected by time-reversal invariance

2D topological insulators

F. D. M. Haldane, Phys. Rev. Lett. **61**, 2015 (1988)

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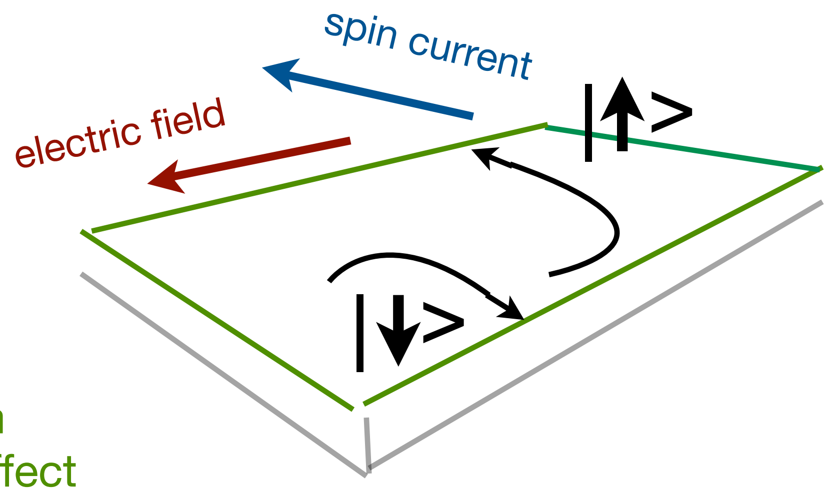

"reference state":
2D bulk insulator
showing quantum
spin Hall (QSH) effect

$$\sigma_{xy}^{s} = \pm\frac{e}{2\pi}$$

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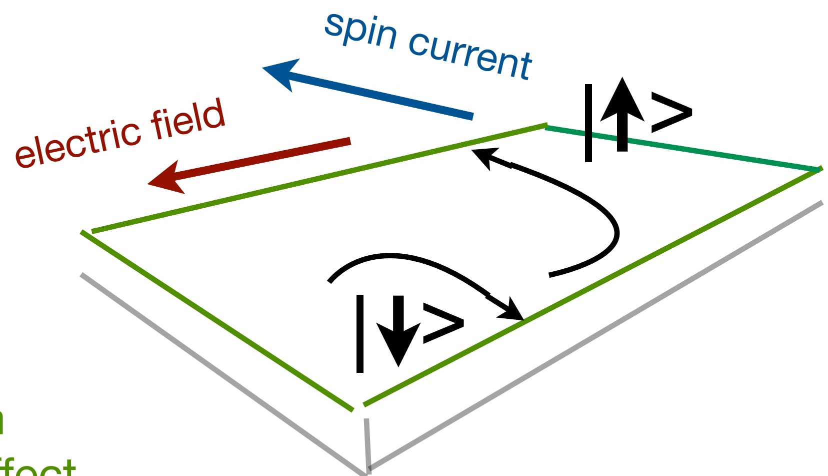

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$$\sigma^s_{xy} = C_s \frac{e}{4\pi}, \quad C_s = \begin{cases} \pm 2 & \text{if QSH insulator} \\ 0 & \text{if ordinary insulator} \end{cases}$$

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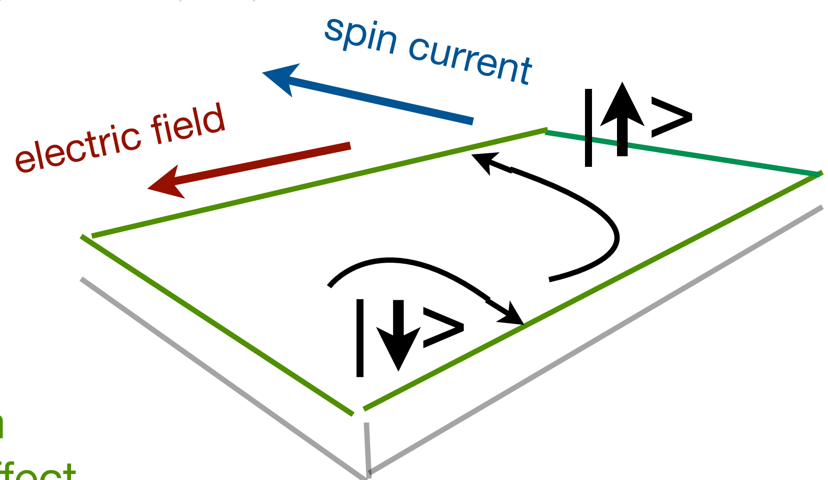
Perturb adiabatically with a time-reversal invariant spin-nonconserving interaction



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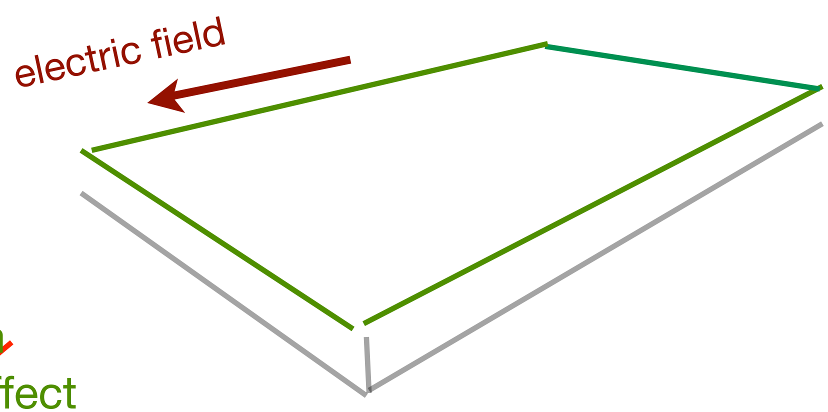

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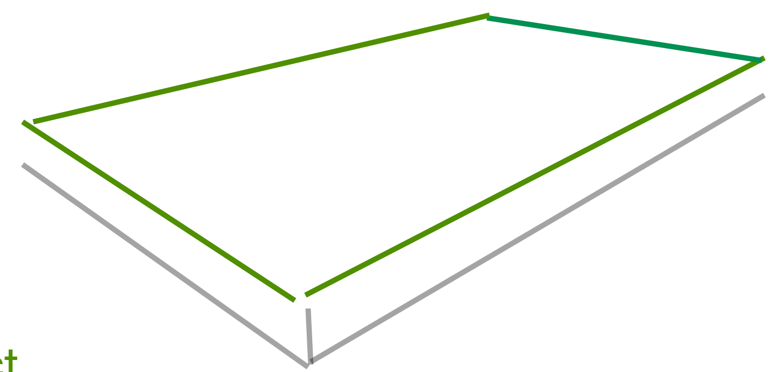

$$\sigma^s_{xy} = C_s \frac{e}{4\pi}, \quad C_s = \begin{cases} \pm 2 & \text{if QSH insulator} \\ 0 & \text{if ordinary insulator} \end{cases}$$

$$\nu = \begin{cases} 1 & \text{"2D topological insulator"} \\ 0 & \text{ordinary insulator} \end{cases}$$

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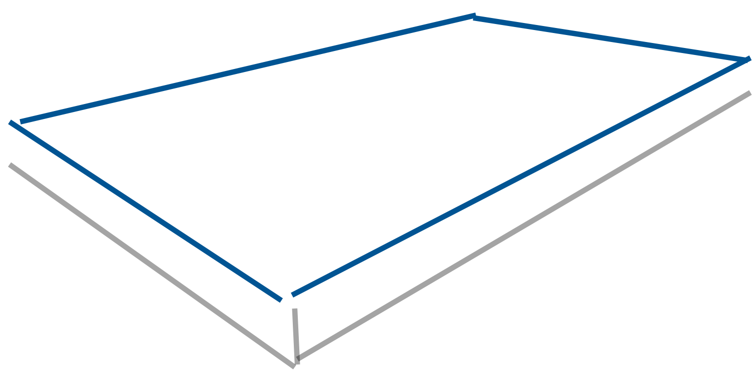
2D topological insulator
"adiabatically connected" to an ideal quantum spin Hall (QSH) insulator



$$\nu = \begin{cases} 1 & \text{"2D topological insulator"} \\ 0 & \text{ordinary insulator} \end{cases}$$

Z_2 topological invariant
encodes Berry curvature structure of the bulk bands

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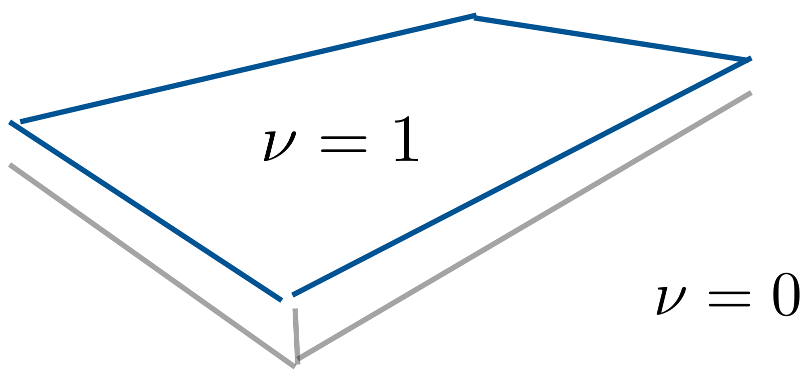

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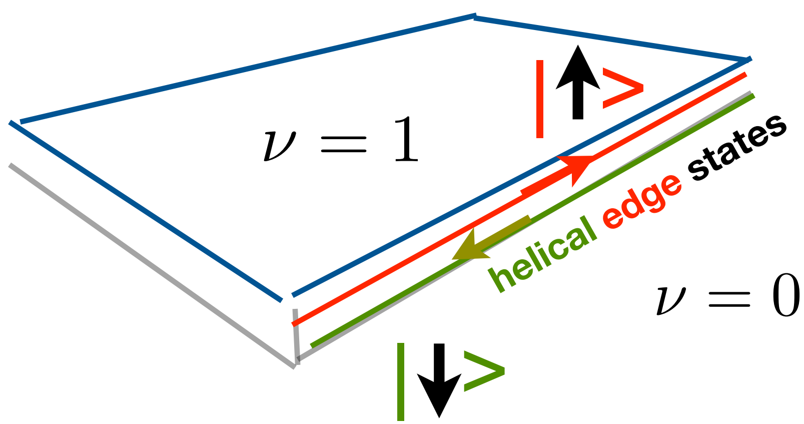

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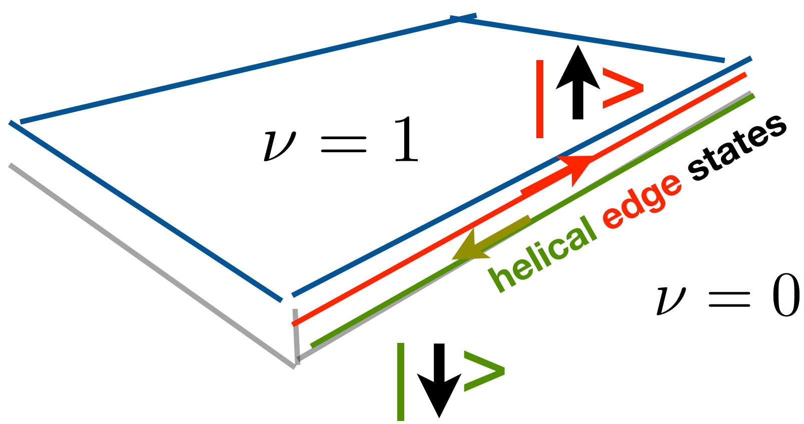

|↑> |↓> are ***pseudospins*** that keep track on the total angular momentum sectors (good quantum numbers in the presence of spin-nonconserving interactions)

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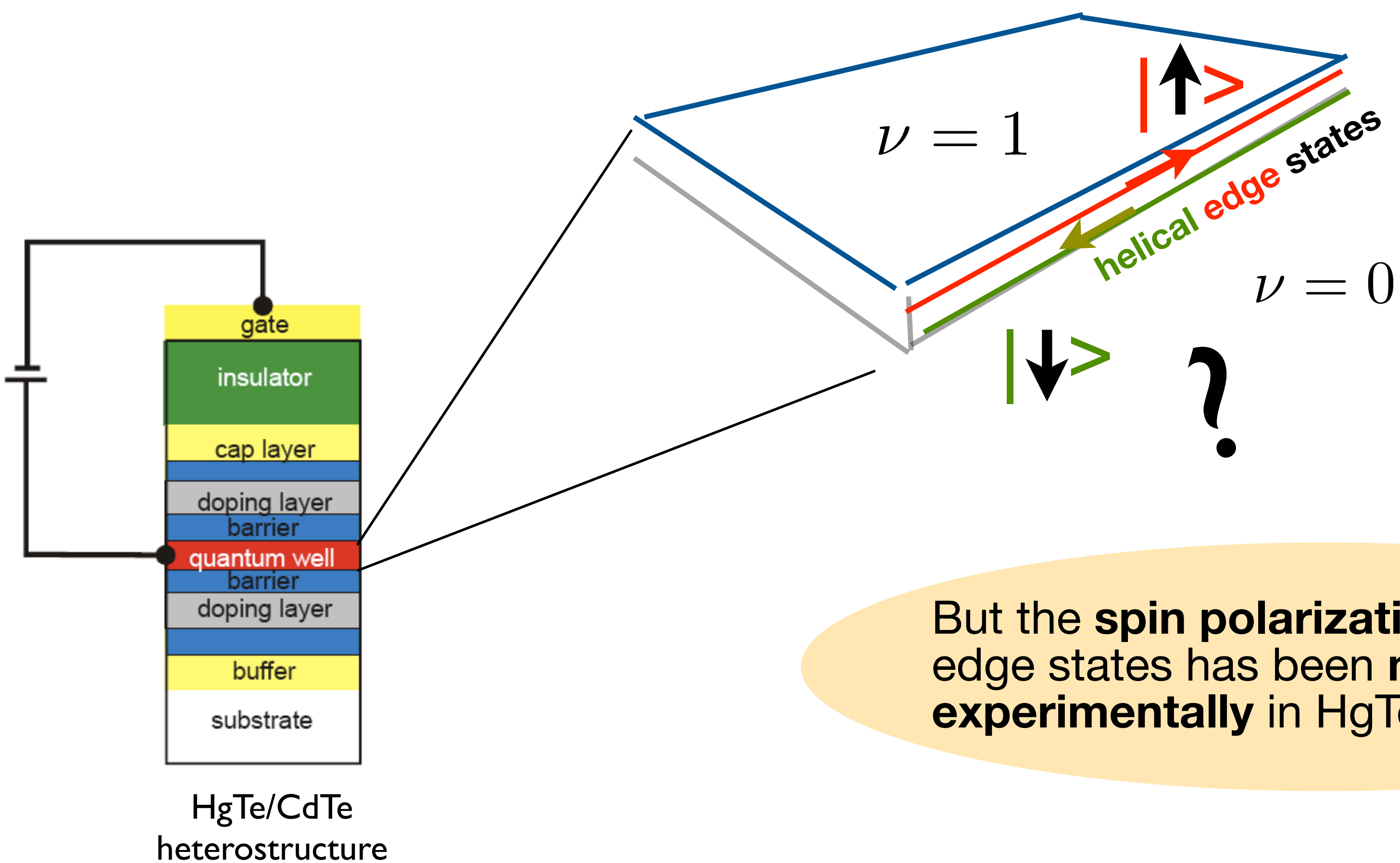

But the **spin polarization** of helical edge states has been **measured experimentally** in HgTe quantum wells!

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"BHZ model"

$|\uparrow>$ $|+\rangle = \Psi_1 |\, E_1 +\rangle + \Psi_2 |\, H_1 +\rangle$

$|\downarrow>$ $|-\rangle = \hat{T}\,|+\rangle = -\Psi_1^* |\, E_1 -\rangle - \Psi_2^* |\, H_1 -\rangle$

$$|E_1 \pm\rangle = \alpha\,|\Gamma_6, \pm\frac{1}{2}\rangle + \beta\,|\Gamma_8, \pm\frac{1}{2}\rangle$$

$$|H_1 \pm\rangle = \alpha\,|\Gamma_8, \pm\frac{3}{2}\rangle$$

$$\begin{aligned}
\langle + |\, \boldsymbol{S}\, | + \rangle &= \frac{\beta}{\sqrt{3}}(\Psi_2^*\Psi_1 + \Psi_1^*\Psi_2)\hat{X} \\
&+ \frac{i\beta}{\sqrt{3}}(-\Psi_2^*\Psi_1 + \Psi_1^*\Psi_2)\hat{Y} \\
&+ (|\Psi_2|^2\,[1 + |\alpha|^2] + \frac{|\Psi_1\beta|^2}{3})\hat{Z} \\
\langle - |\, \boldsymbol{S}\, | - \rangle &= -\langle + |\, \boldsymbol{S}\, | + \rangle
\end{aligned}$$

choose spin quantization axis along $\langle + \mid \boldsymbol{S} \mid + \rangle$

spin-polarized helical edge states for constant $\boldsymbol{\Psi}_{1,2}$

OK in a small energy range!

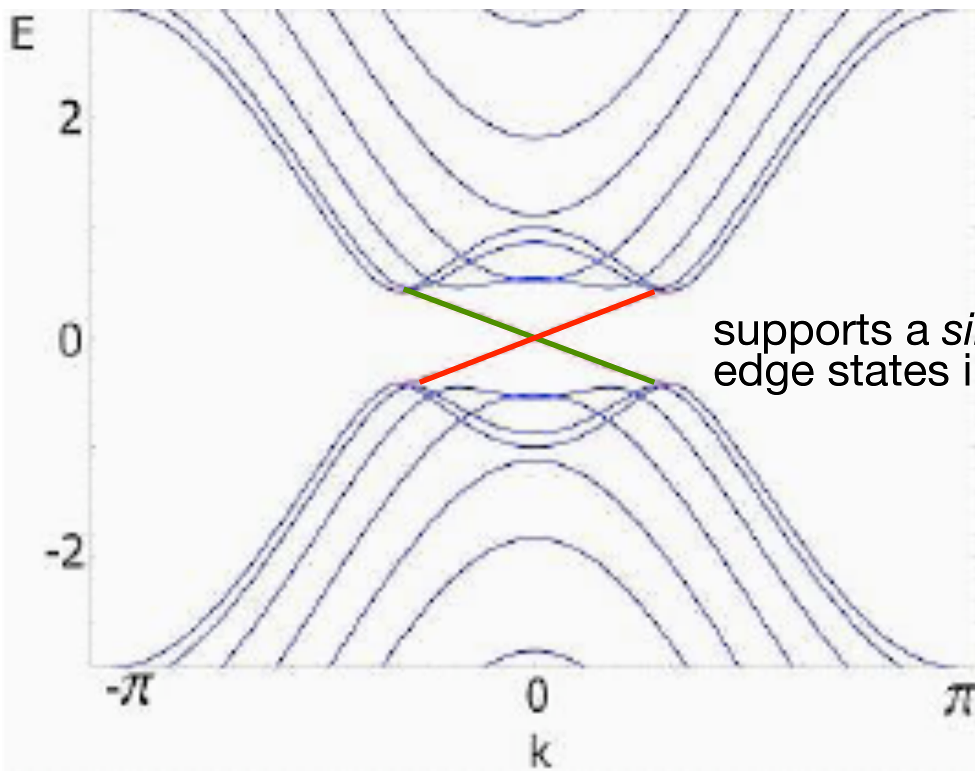
P. Michetti and P. Recher, Phys. Rev. B **83**, 125420 (2011)

What about the ”symmetry protection”
by time-reversal invariance?

What about the ”symmetry protection” by time-reversal invariance?

The helical edge states are stable against time-reversal invariant perturbations!

strong spin-orbit interactions in atomic p-orbitals create an *inverted* band gap (p-band on top of s-band)



B. A. Bernevig *et al.,* PRL **95**, 066601 (2005)

supports a *single* Kramers pair of helical edge states inside the inverted gap

Kramers degeneracy at k=0 protects the stability of the edge states

ballistic transport

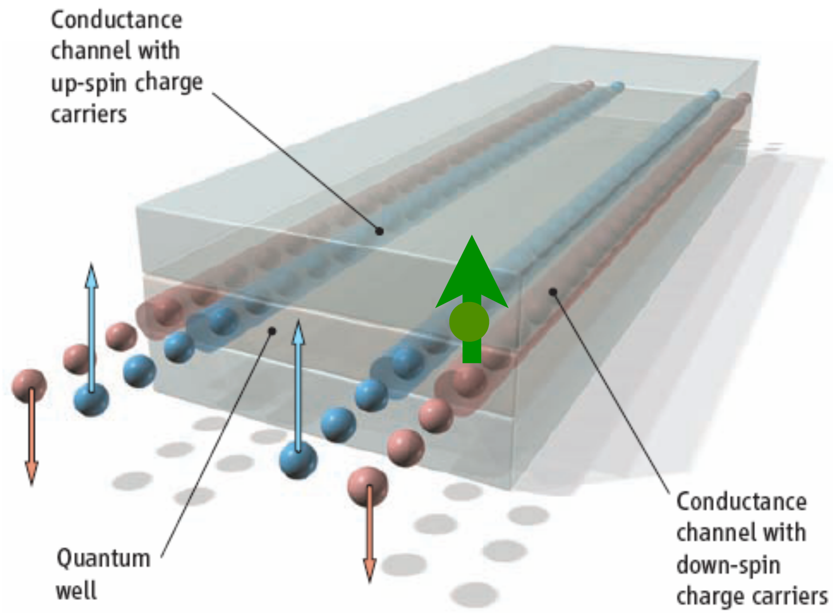
$$G = \frac{2e^2}{h}$$

The helical edge states are stable against time-reversal invariant perturbations!

What about the ”symmetry protection” by time-reversal invariance?

What if time-reversal symmetry gets broken...?

... for example, by putting in a magnetic impurity at the edge?



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

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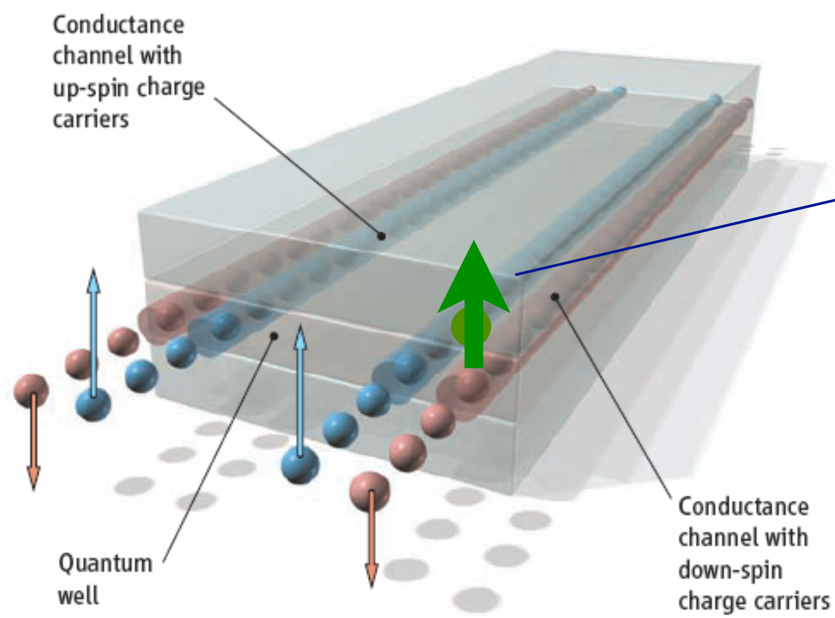

from M. König *et al.*, Science **318**, 766 (2007)

case study:

Mn^{2+}

large and positive single-ion anisotropy $(S^z)^2$

J. K. Furdyna, JAP **64**, R29 (1988)

$$S = 5/2 \underset{\text{low } T}{\longrightarrow} S_{\text{eff}} = 1/2$$

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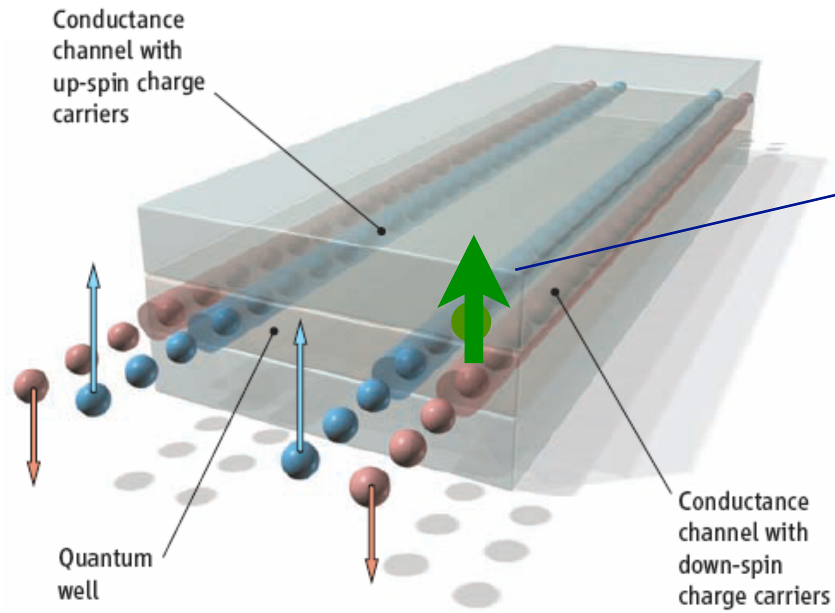

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case study:

Mn^{2+}

large and positive single-ion anisotropy $(S^z)^2$

$$S = 5/2 \xrightarrow[\text{low } T]{} S_{\text{eff}} = 1/2$$

anisotropic spin exchange with the edge electrons

R. Zitko *et al.*, PRB **78**, 224404 (2008)

$$H_K = \Psi^\dagger(0)\left[J_\perp(\sigma^+ S^-_{\text{eff}} + \sigma^- S^+_{\text{eff}}) + J_z \sigma^z S^z_{\text{eff}}\right]\Psi(0)$$

$$\Psi^T = (\psi_\uparrow, \psi_\downarrow)$$

Adding a magnetic impurity...

The Kondo interaction is time-reversal invariant!
Could it still cause a *spontaneous* breaking of time reversal invariance and localize the edge states?

Adding a magnetic impurity...

Recall the Kondo effect

One-loop RG equations:

P. W. Anderson, J. Phys. C **3**, 2436 (1970)

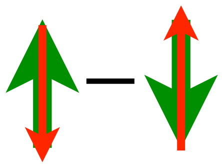
$$\frac{\partial J_\perp}{\partial D} = -\nu J_\perp J_z + \ldots$$
$$\frac{\partial J_z}{\partial D} = -\nu J_\perp^2 + \ldots$$

strong-coupling physics for $T << T_K$

$$T_K = D_0 \exp(-\text{const.}/J_0)$$

$$J_0 \equiv \max(J_\perp, J_z)_{D=D_0}$$

formation of impurity-electron singlet **("Kondo screening")**



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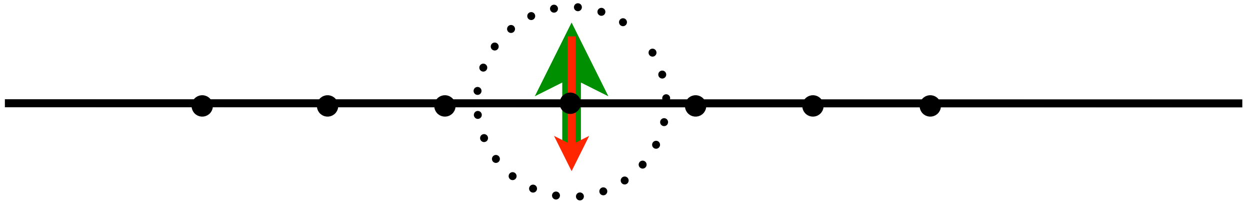

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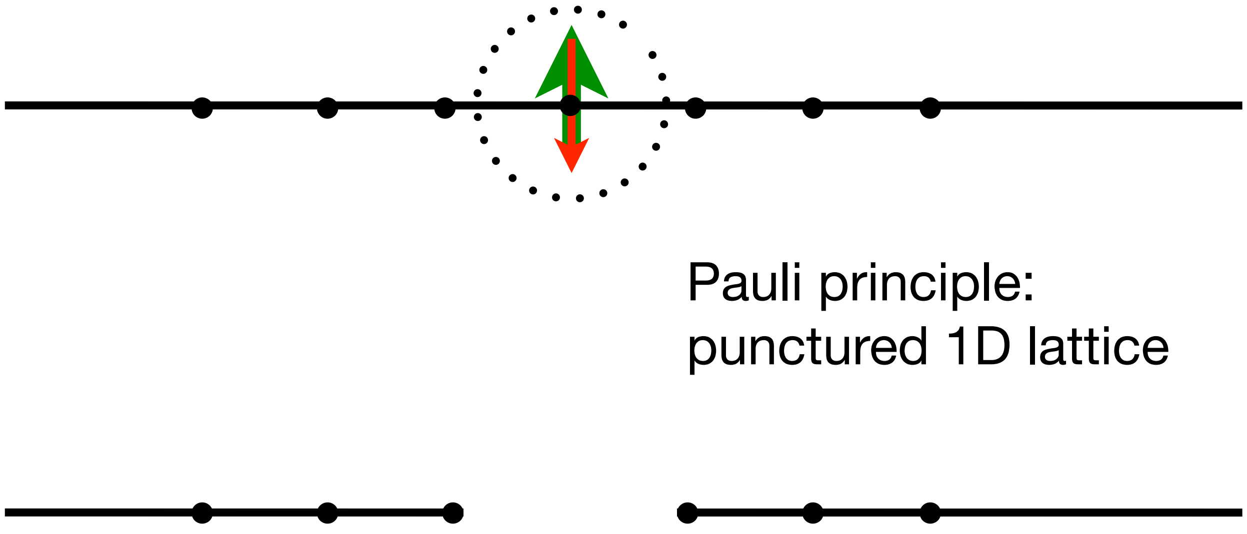
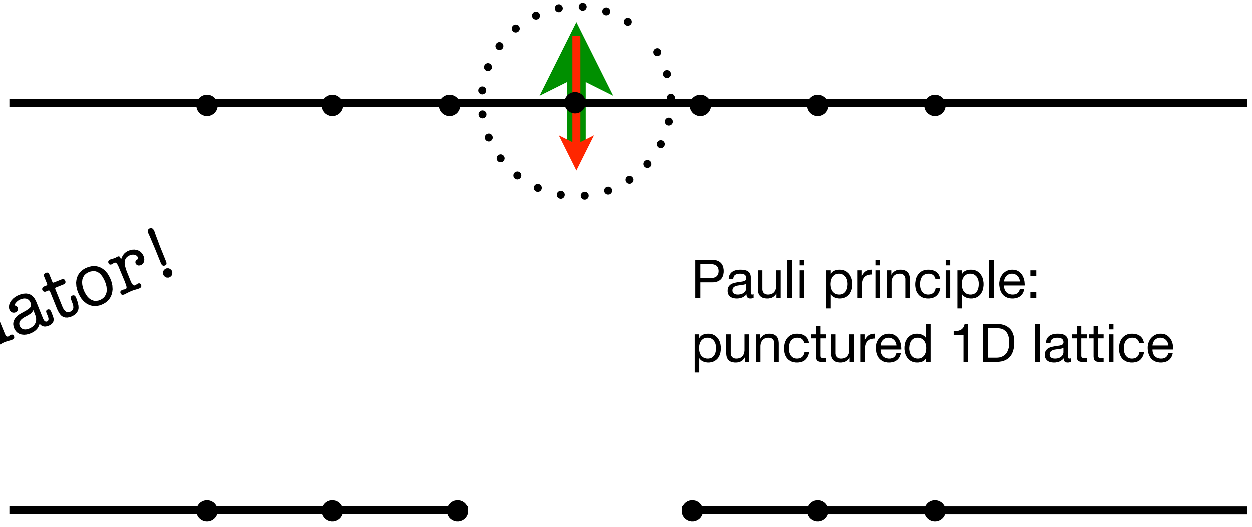


Pauli principle:
punctured 1D lattice

Adding a magnetic impurity...



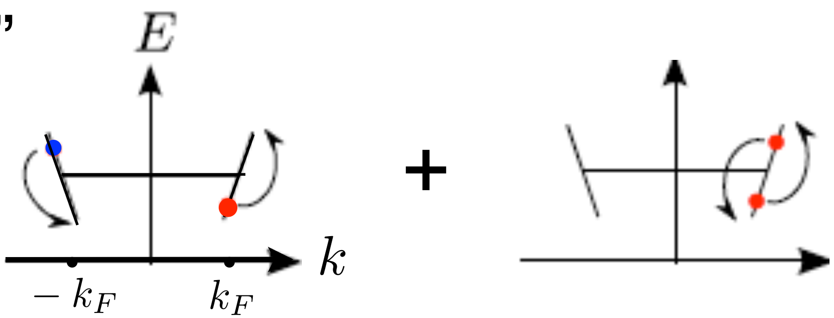
T=0 insulator!

Pauli principle:
punctured 1D lattice

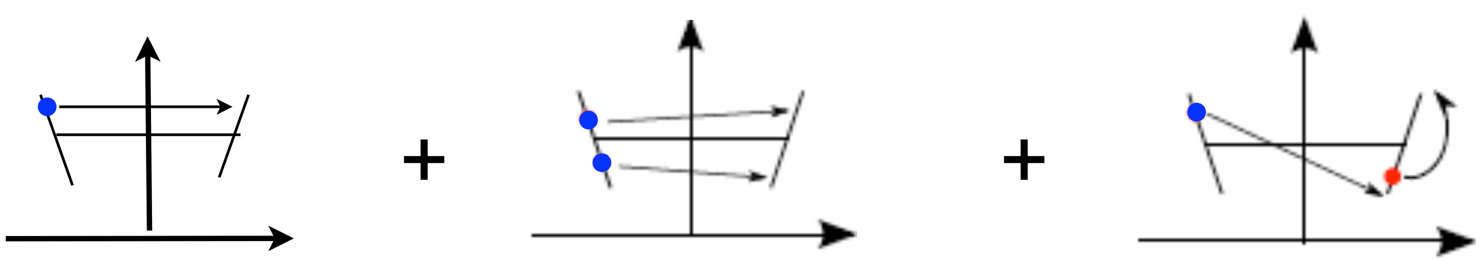
Adding a magnetic impurity...

Does this really happen for the helical liquid?
To find out, first add e-e interactions.... important in 1D!

"bulk"



local (at impurity site)



from Kondo

Adding a magnetic impurity...

Adding the kinetic energy and bosonizing...

$$
\begin{aligned}
H &= (v/2)\int \mathrm{d}x\big((\partial_x\varphi)^2 + (\partial_x\vartheta)^2\big) \\
&+ \frac{A}{\kappa}\cos(\sqrt{4\pi K}\varphi) + \frac{B}{\kappa}\sin(\sqrt{4\pi K}\varphi) + \frac{C}{\sqrt{K}}\partial_x\vartheta \\
&+ \frac{g_U}{2(\pi\kappa)^2}\cos(\sqrt{16\pi K}\varphi) \\
&+ \frac{g_{ie}}{2\pi^2\sqrt{K}} :(\partial_x^2\vartheta)\cos(\sqrt{4\pi K}\varphi):
\end{aligned}
$$

Kondo

local Umklapp

local 1-particle inelastic term

Adding a magnetic impurity...

Bosonization...

"Luttinger liquid parameter"

$$\begin{aligned} H &= (v/2)\int \mathrm{d}x\big((\partial_x\varphi)^2 + (\partial_x\vartheta)^2\big) \\ &+ \frac{A}{\kappa}\cos(\sqrt{4\pi K}\varphi) + \frac{B}{\kappa}\sin(\sqrt{4\pi K}\varphi) + \frac{C}{\sqrt{K}}\partial_x\vartheta \\ &+ \frac{g_U}{2(\pi\kappa)^2}\cos(\sqrt{16\pi K}\varphi) \\ &+ \frac{g_{ie}}{2\pi^2\sqrt{K}} :(\partial_x^2\vartheta)\cos(\sqrt{4\pi K}\varphi): \end{aligned}$$

Adding a magnetic impurity...

Bosonization...

"Luttinger liquid parameter"

functions of Kondo couplings

$$
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H &= (v/2)\int \mathrm{d}x\left((\partial_x\varphi)^2 + (\partial_x\vartheta)^2\right) \\
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\end{aligned}
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Adding a magnetic impurity...

Bosonization...

"Luttinger liquid parameter"

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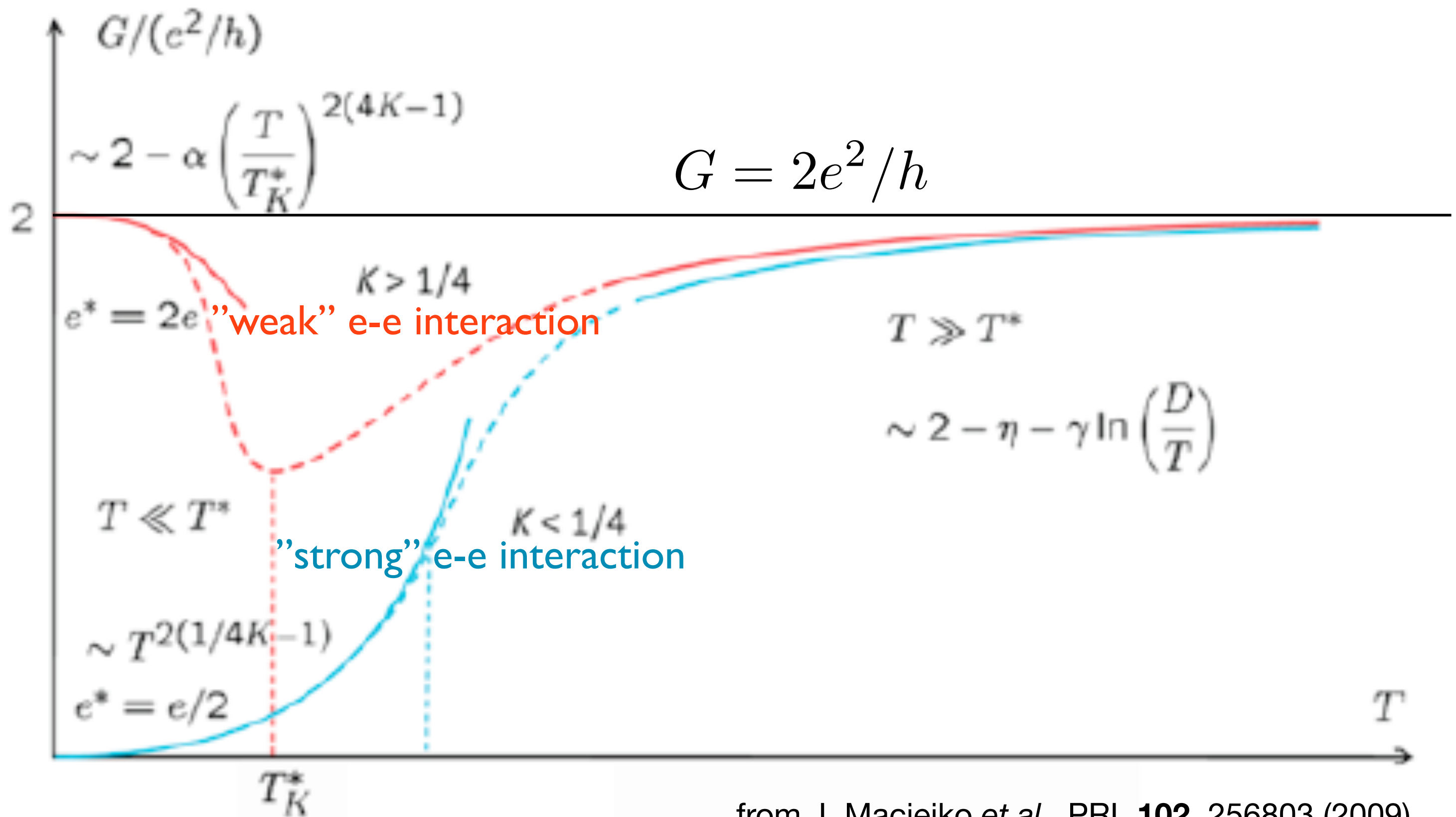
&+\frac{g_{ie}}{2\pi^2\sqrt{K}}:(\partial_x^2\vartheta)\cos(\sqrt{4\pi K}\varphi):
\end{aligned}
$$

...perturbative RG and linear response

J. Maciejko *et al.*, PRL **102**, 256803 (2009)

Adding a magnetic impurity...



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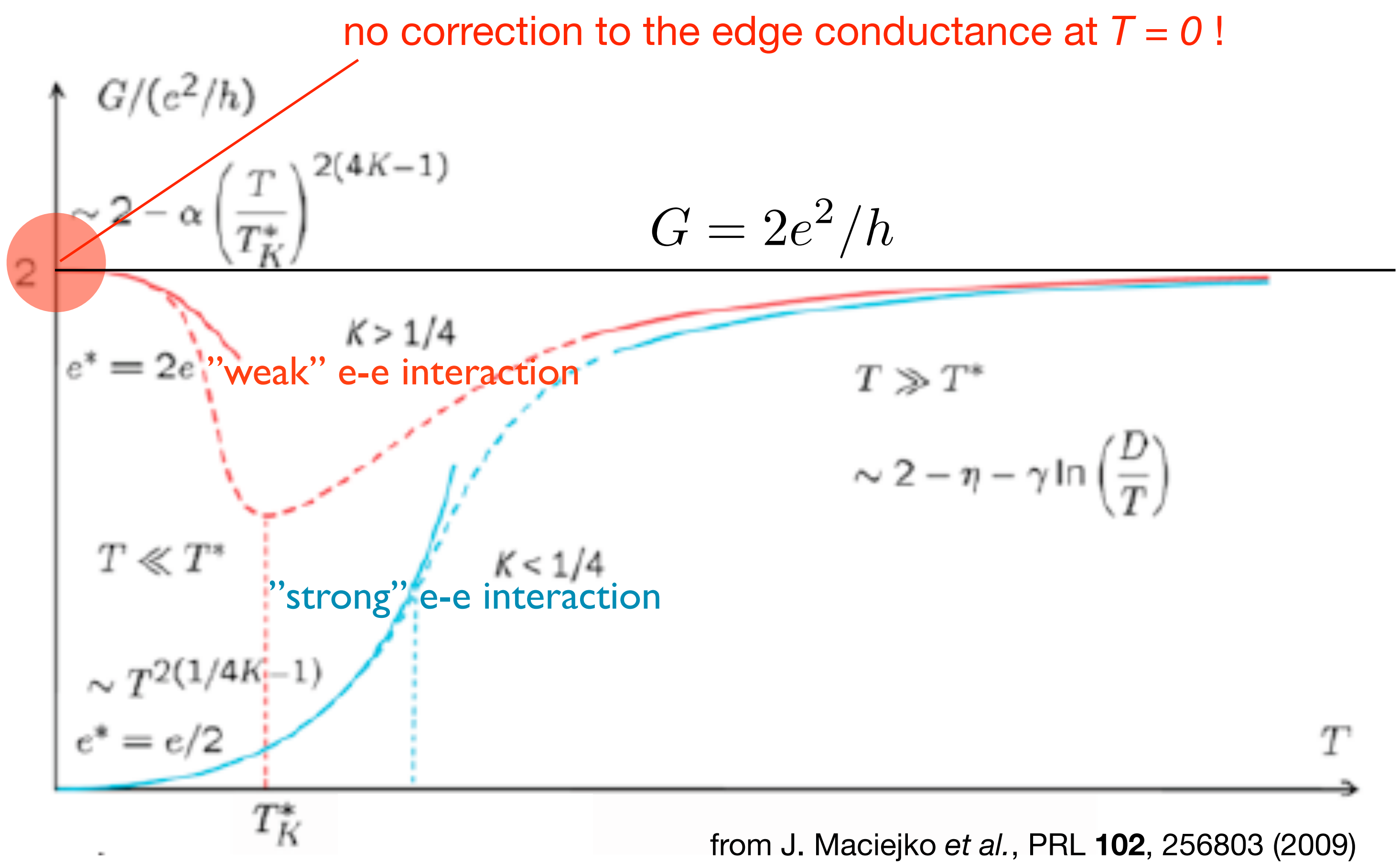

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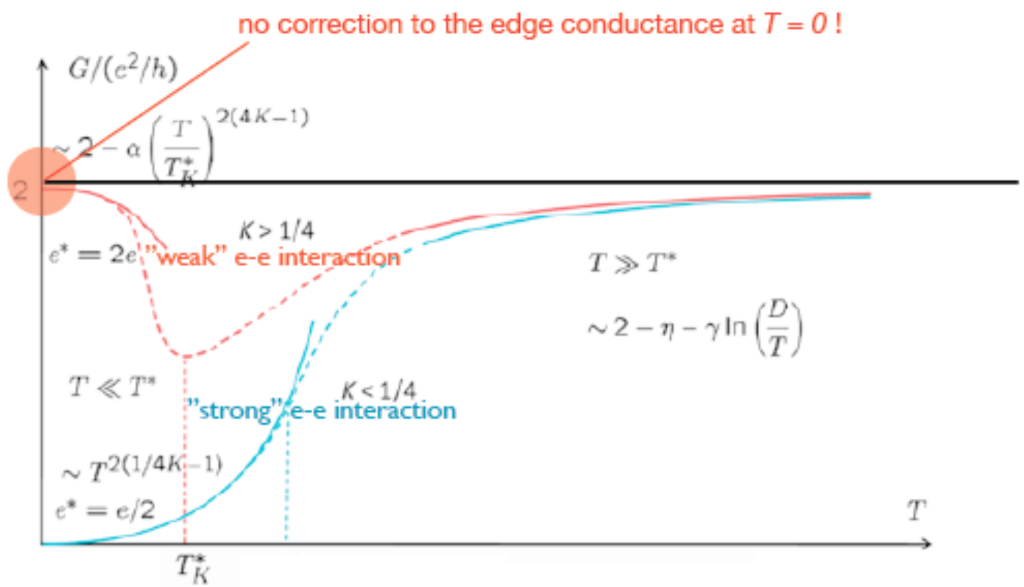

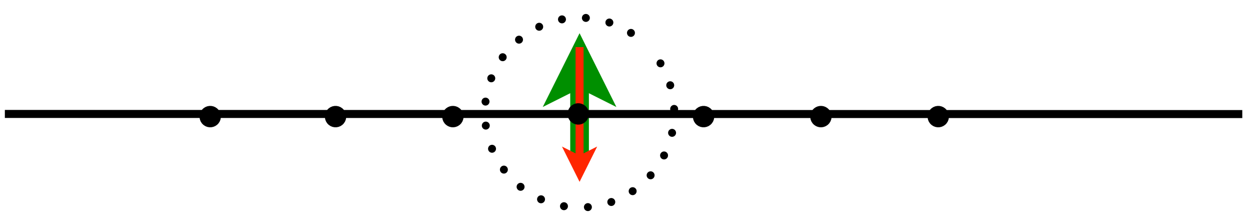

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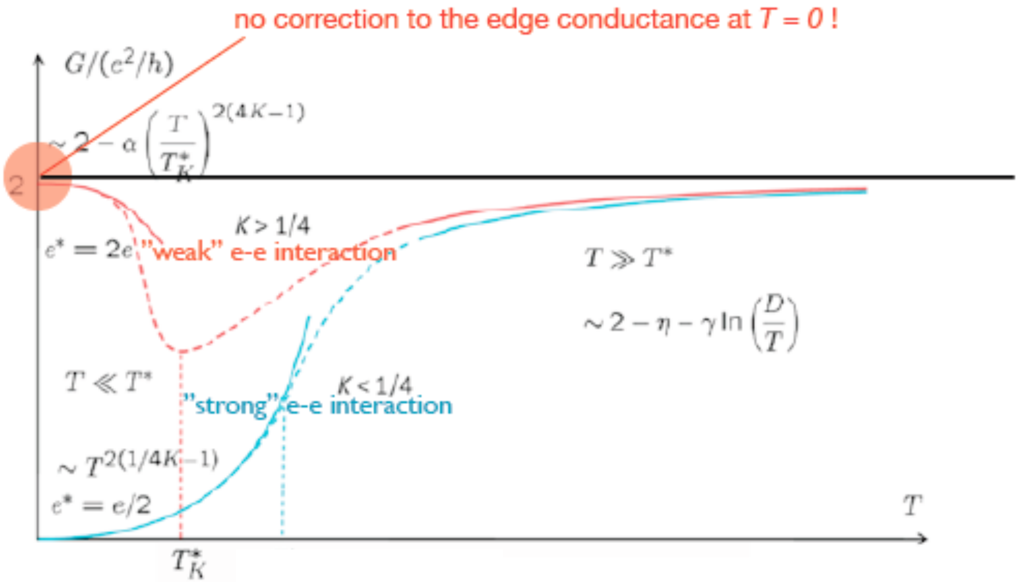

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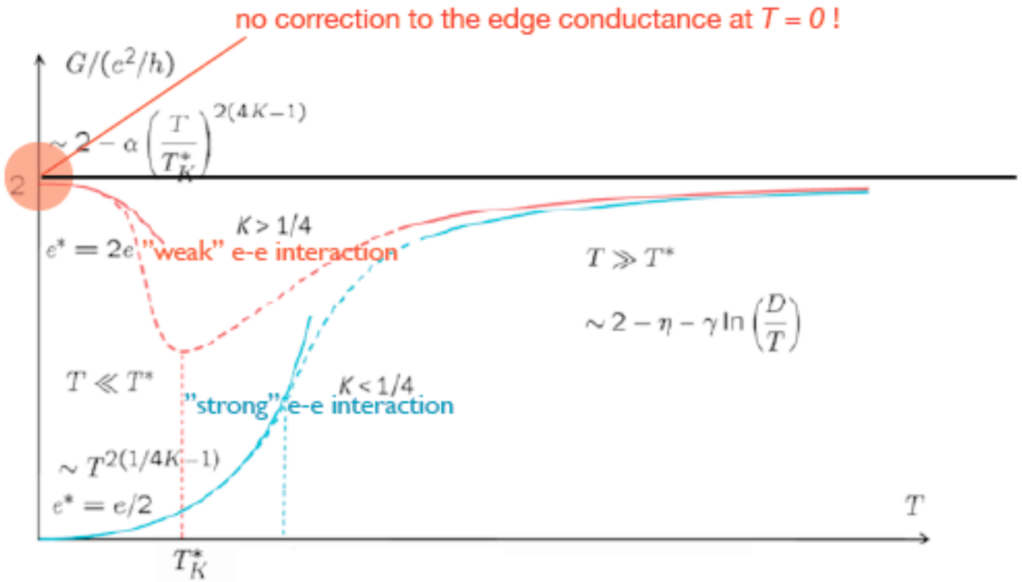
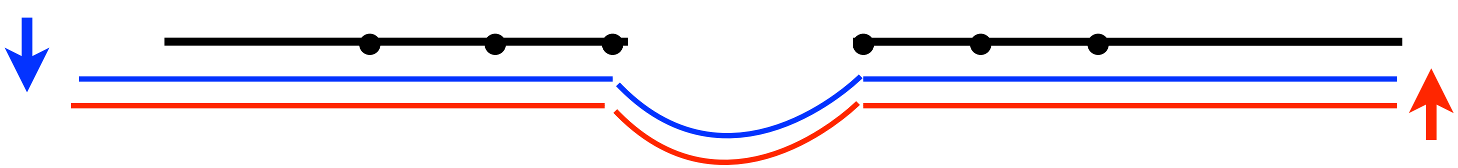


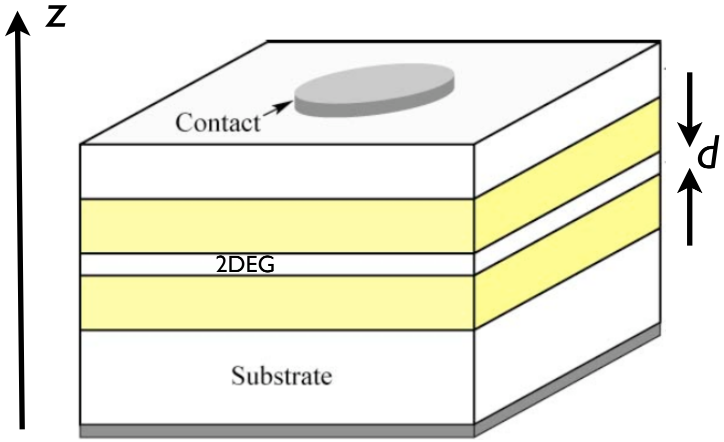


Due to its topological nature, the edge states follow the new shape of the edge.
Weak coupling helical edge states are robust against spontaneous breaking of time-reversal symmetry!

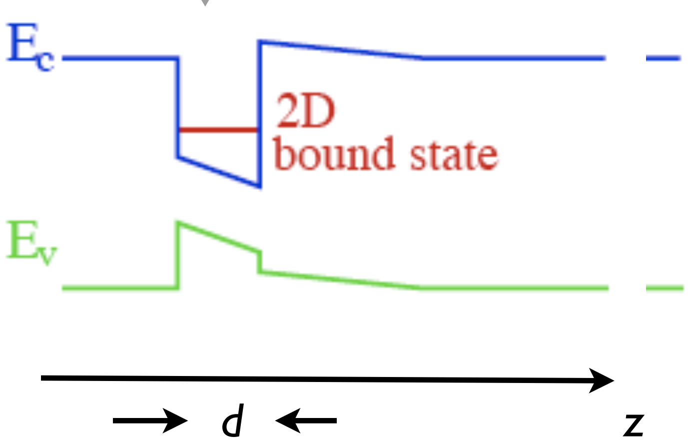
J. Maciejko *et al.*, PRL **102**, 256803 (2009)

But... one important thing is missing from the analysis!

Rashba spin-orbit interaction!



semiconductor heterostructure

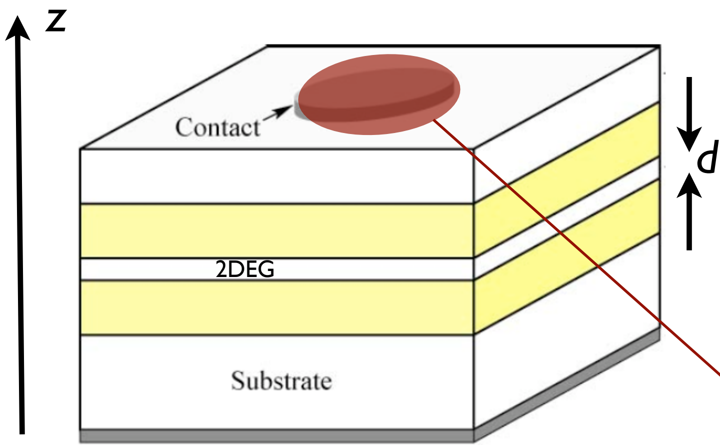


Spatial asymmetry of
band edges mimics an
E-field in the *z*-direction

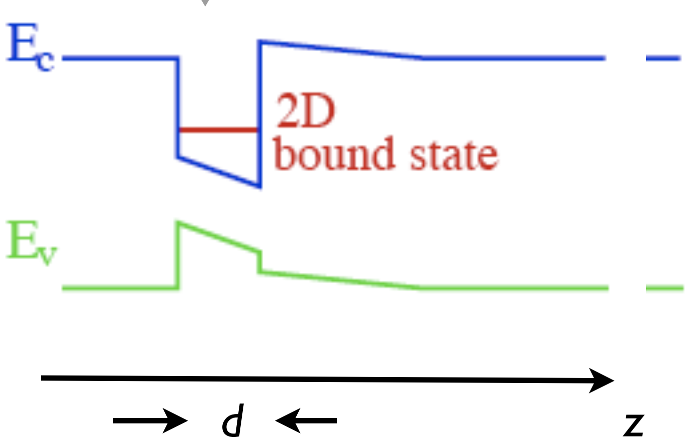
$$H_R = \alpha(k_x\sigma^y - k_y\sigma^x)$$

Yu. A. Bychkov and E. I. Rashba,
J. Phys. C **17**, 6039 (1984)

Rashba spin-orbit interaction



semiconductor heterostructure



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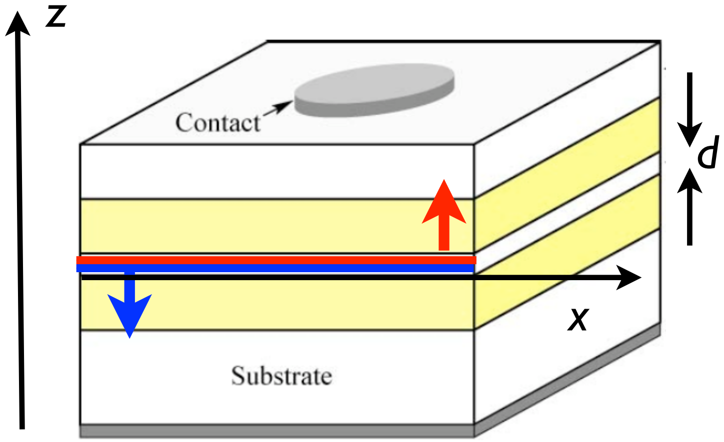
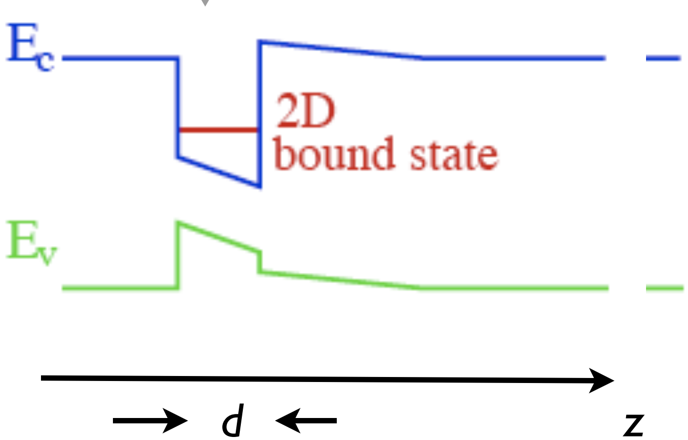
Yu. A. Bychkov and E. I. Rashba, J. Phys. C **17**, 6039 (1984)

Spatial asymmetry of band edges mimics an ***E***-field in the *z*-direction, **tunable by gate voltage**

Rashba spin-orbit interaction



semiconductor heterostructure



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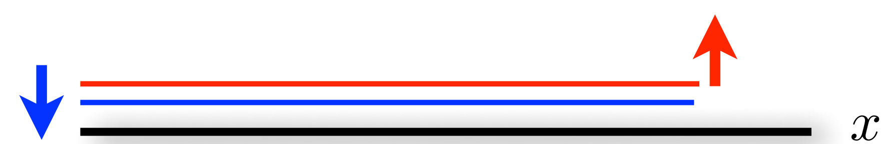

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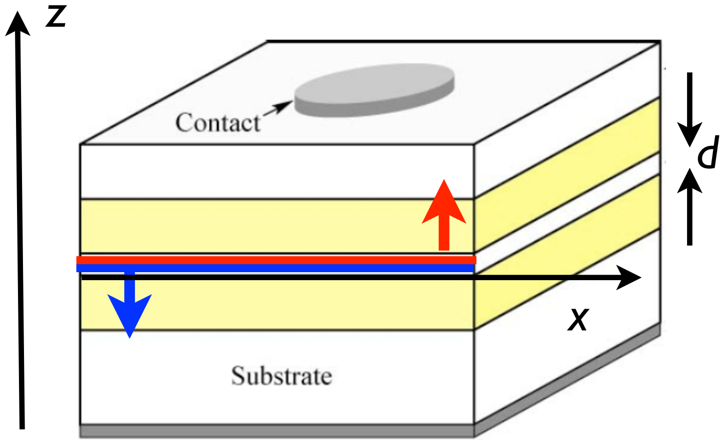
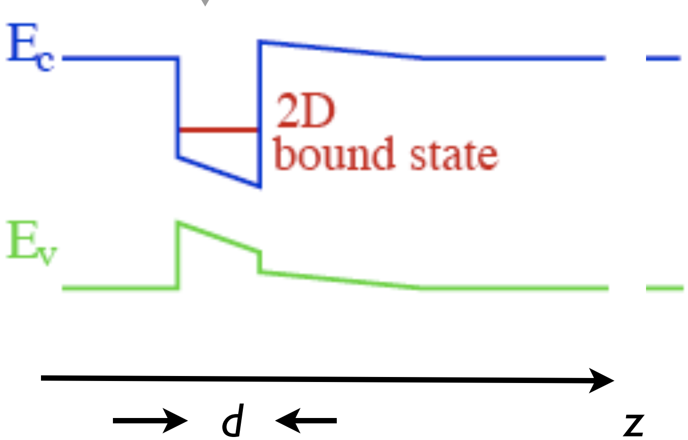
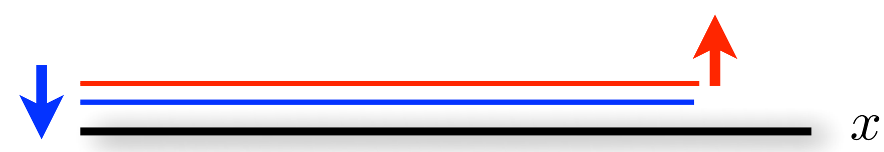


semiconductor heterostructure

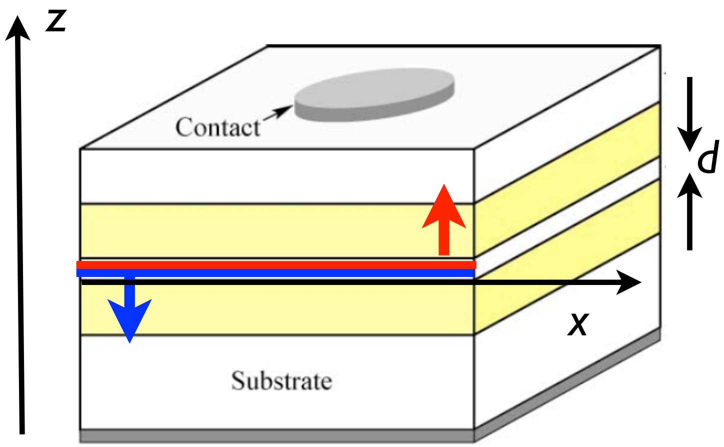


HgTe quantum well:
weaker-amplitude k_x^3 corrections
D.G. Rothe *et al.*, New J. Phys. **12**, 065012 (2010)

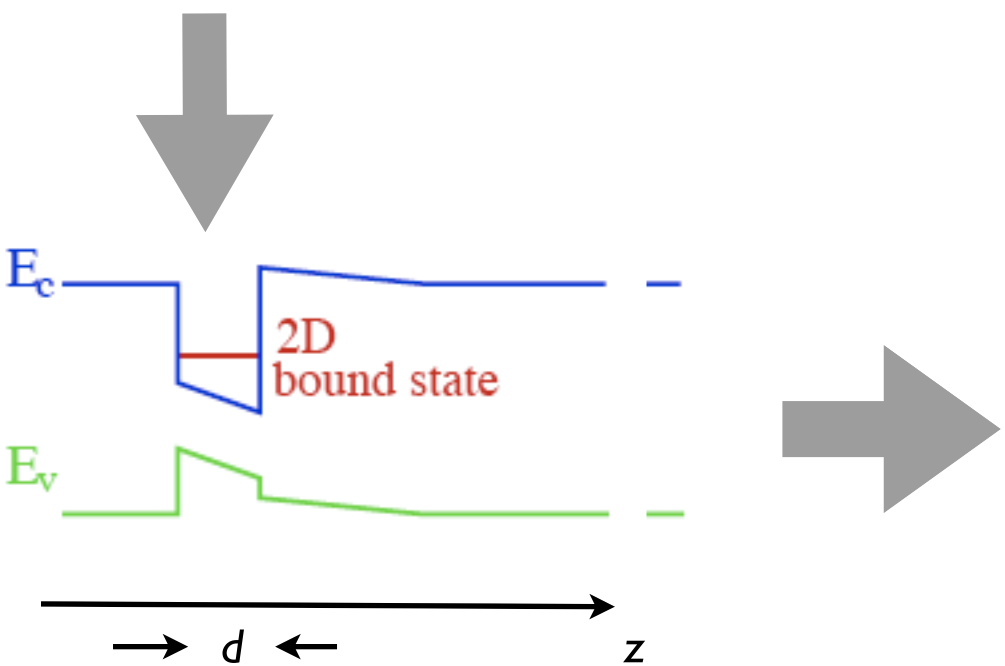
$$H_R = \alpha\, k_x \sigma^y + \ldots\ldots$$



Rashba spin-orbit interaction

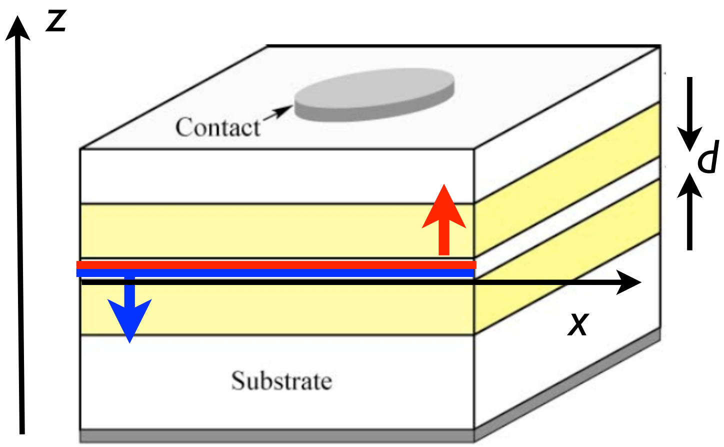


semiconductor heterostructure

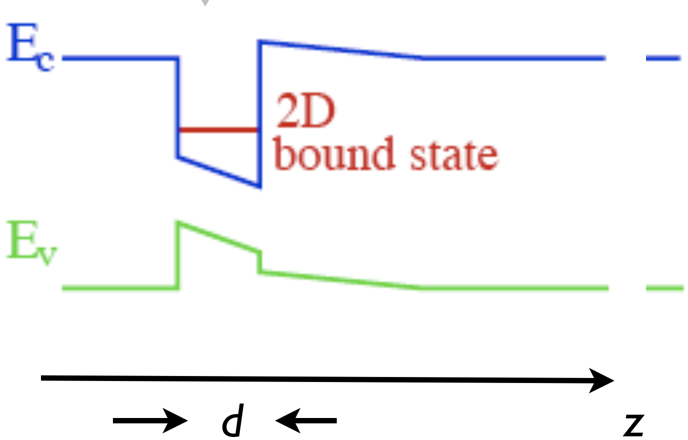


$$H_R = \alpha\, k_x \sigma^y$$

Rashba spin-orbit interaction



semiconductor heterostructure



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Adding the Rashba interaction...

... breaks the locking of spin to momentum. However, there is still a single Kramers pair on the edge, and this is all that matters!

Adding the Rashba interaction...

... breaks the locking of spin to momentum. However, there is still a single Kramers pair on the edge, and this is all that matters!

In fact, we can recover helicity by rotating the spin quantization axis:

kinetic term Rashba

$$H = v_F \int \mathrm{d}x \ \Psi^\dagger(x) \left[-\mathrm{i}\sigma^z \partial_x\right] \Psi(x) + \alpha \int \mathrm{d}x \ \Psi^\dagger(x) \left[-\mathrm{i}\sigma^y \partial_x\right] \Psi(x)$$

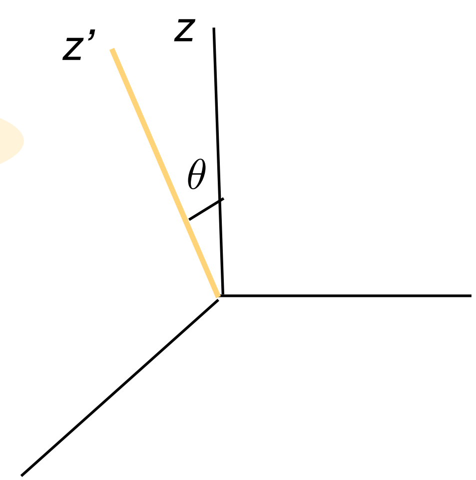
$$\Psi^T = (\psi_\uparrow, \psi_\downarrow)$$

$$\Psi' = \mathrm{e}^{-\mathrm{i}\sigma^x \theta/2} \Psi$$

$$\cos\theta = v_F / v_\alpha \qquad v_\alpha = \sqrt{v_F^2 + \alpha^2}$$

$$H' = v_\alpha \int \mathrm{d}x \ \Psi'^\dagger(x) \left[-\mathrm{i}\sigma^{z'} \partial_x\right] \Psi'(x)$$

$$\Psi'^T = (\psi_{\uparrow'}, \psi_{\downarrow'})$$



Adding the Rashba interaction...

e-e interaction is invariant under $\Psi \to \Psi'$

Kondo interaction $H_{\mathrm{K}} \; = \; \Psi^\dagger(0) \left[J_\perp(\sigma^+ S^-_{\mathrm{eff}} + \sigma^- S^+_{\mathrm{eff}}) + J_z \sigma^z S^z_{\mathrm{eff}} \right] \Psi(0)$

$$\Psi' = \mathrm{e}^{-\mathrm{i}\sigma^x\theta/2}\Psi$$
$$\boldsymbol{S}' = \mathrm{e}^{-\mathrm{i}S^x\theta/2}\boldsymbol{S}\mathrm{e}^{\mathrm{i}S^x\theta/2}$$

$$H'_K = \Psi'^\dagger(0)[J_x\sigma^x S^x + J'_y\sigma^{y'}S^{y'} + J'_z\sigma^{z'}S^{z'} + J_{\mathrm{NC}}(\sigma^{y'}S^{z'} + \sigma^{z'}S^{y'})]\Psi'(0)$$

Adding the Rashba interaction...

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XYZ Kondo

Non-Collinear term

depend on the Rashba coupling α

controllable by a gate voltage

Adding the Rashba interaction...

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XYZ Kondo

Non-Collinear term

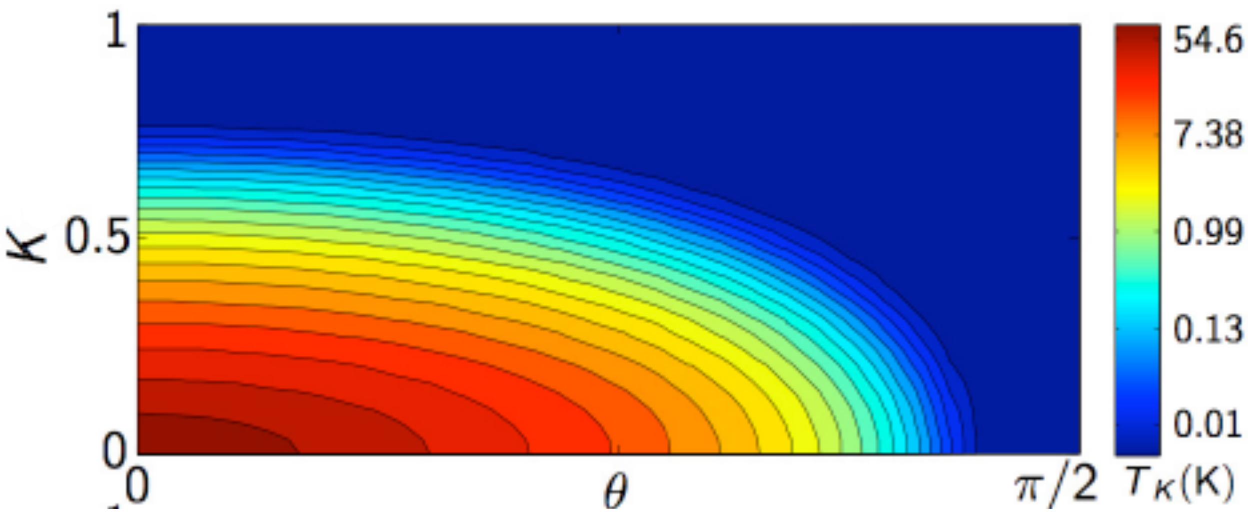
depend on the Rashba coupling α
controllable by a gate voltage

...bosonization and perturbative RG

E. Eriksson, A. Ström, G. Sharma, H.J., PRB **86**, 161103(R) (2012)

Electrical control of the Kondo temperature

via the ”Rashba angle” θ ~ gate voltage



easy-plane Kondo

$J_x = J_y = 20 \text{ meV}, \; J_z = 10 \text{ meV}$

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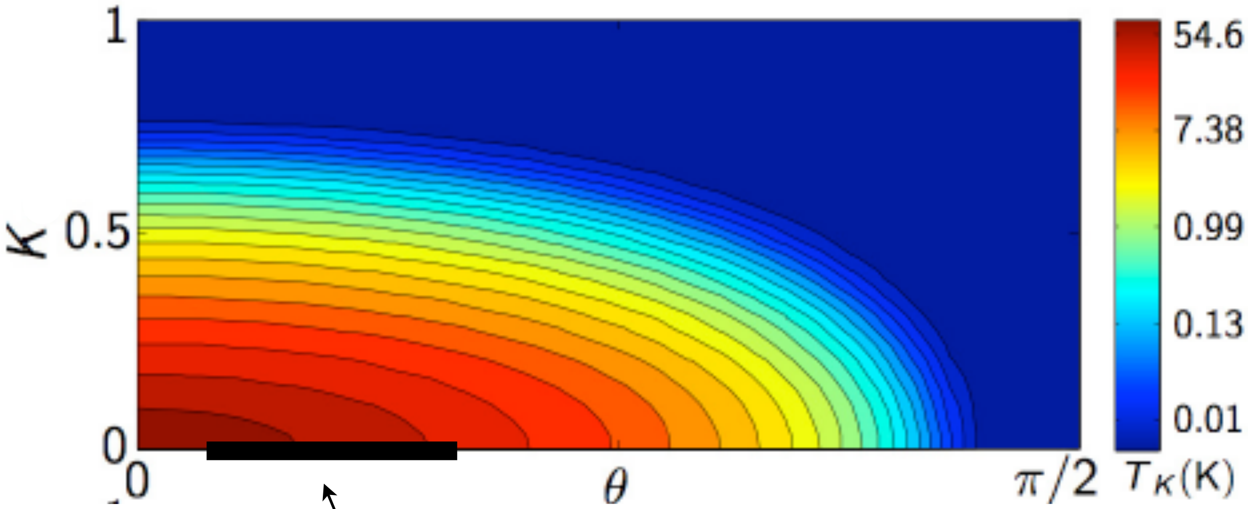

experimentally probed range in a HgTe quantum well
by tuning the bias of a top gate from -2V to 2V
J. Hinz *et al.*, Semicond. Sci. Technol. **21**, 501 (2006)

easy-plane Kondo

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$$\mathrm{Mn}^{2+}$$

J.K. Furdyna, J. Appl. Phys. **64**, R29 (1988)

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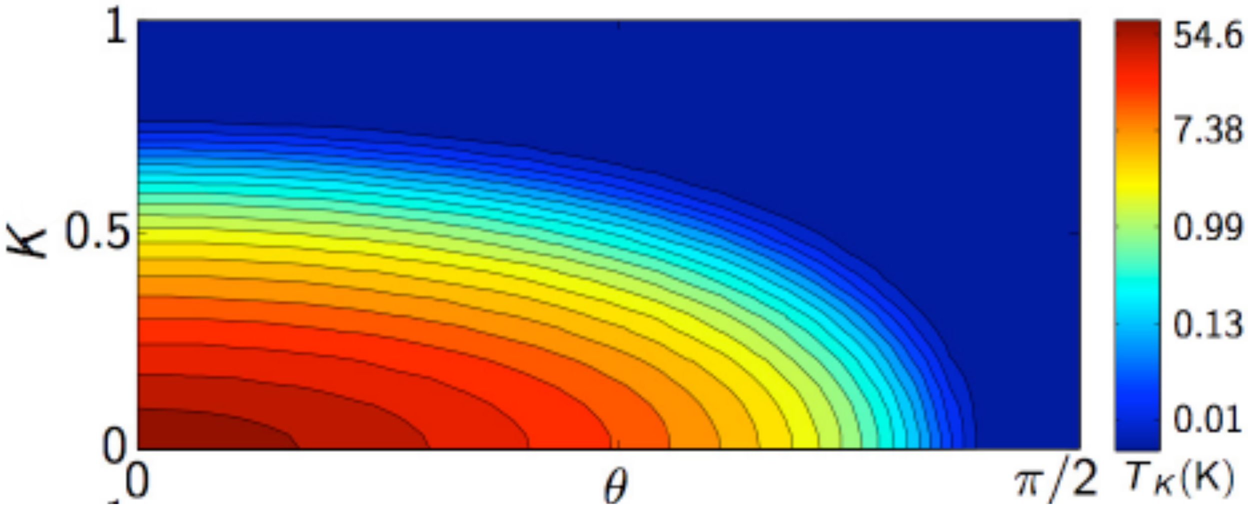

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Note: Kondo temperatures modified by spin-orbit interactions or spin-dependent hopping have been proposed also for ordinary (non-helical) conduction electrons:

M. Pletyukhov and D. Schuricht, PRB **84,** 041309(R) (2011)
X.-Y. Feng and F.-C. Zhang, J. Phys.: Cond. Matt. **23**, 105602 (2011)
R. Zitko and J. Bonca, PRB **84**, 193411 (2011)
M. Zarea, S. E. Ulloa, and N. Sandler, PRL **108**, 046601 (2012)
L. Isaev, L. Agterberg, and I. Vekhter, PRB **85**, 081107 (2012)

Electrical control of the Kondo temperature

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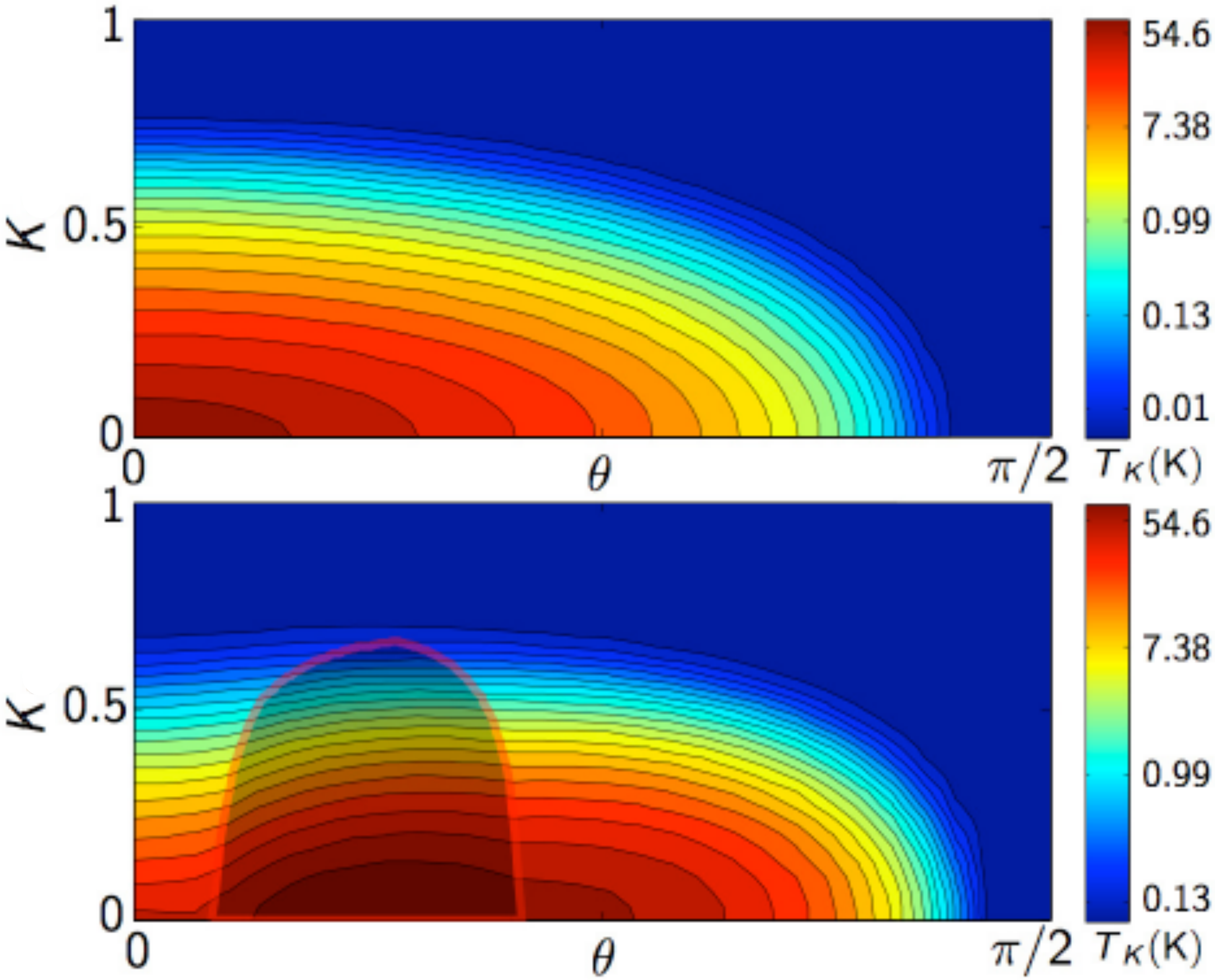

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$J_x = J_y = 20\ \mathrm{meV},\ J_z = 10\ \mathrm{meV}$

easy-axis Kondo

$J_x = J_y = 5\ \mathrm{meV},\ J_z = 50\ \mathrm{meV}$

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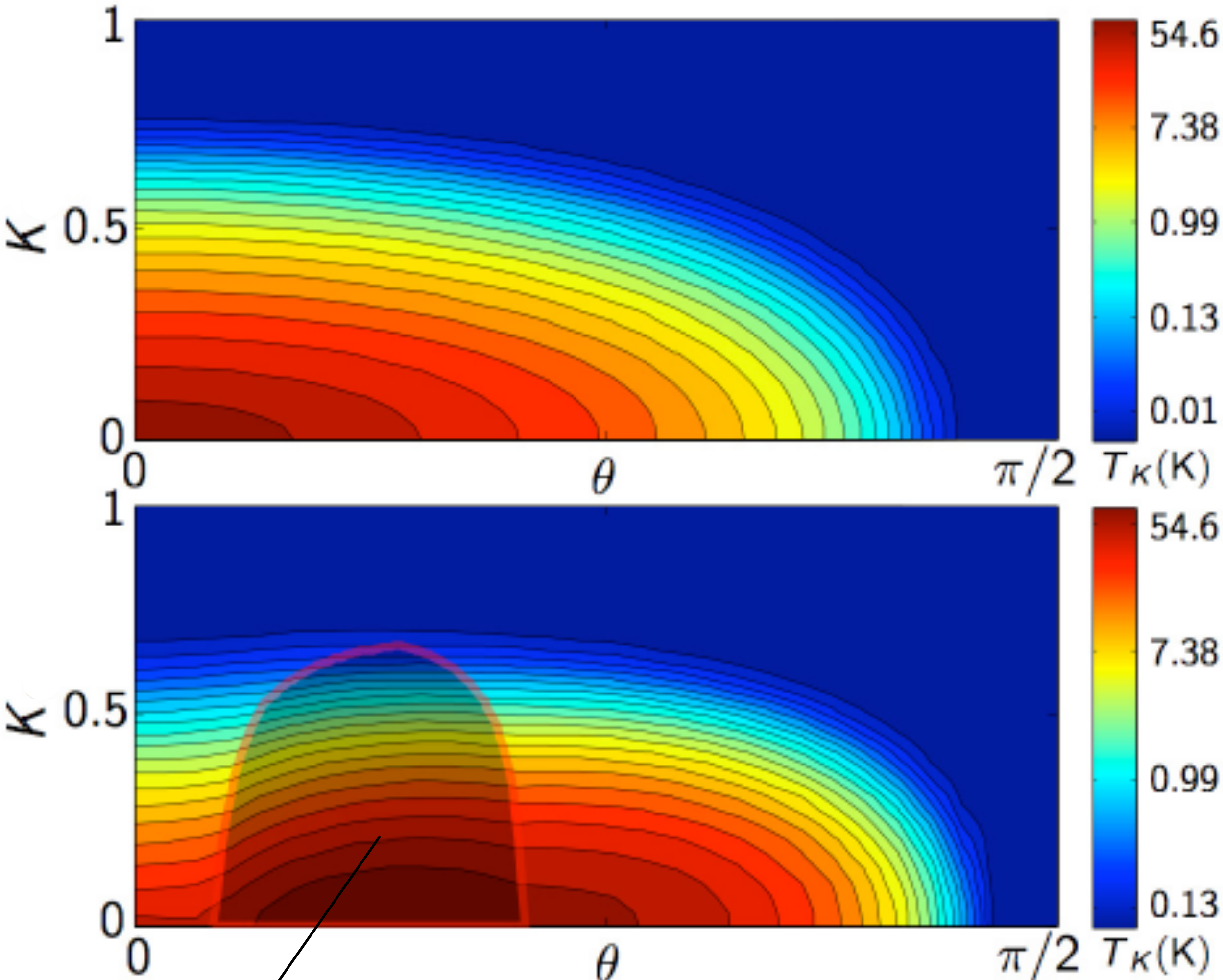

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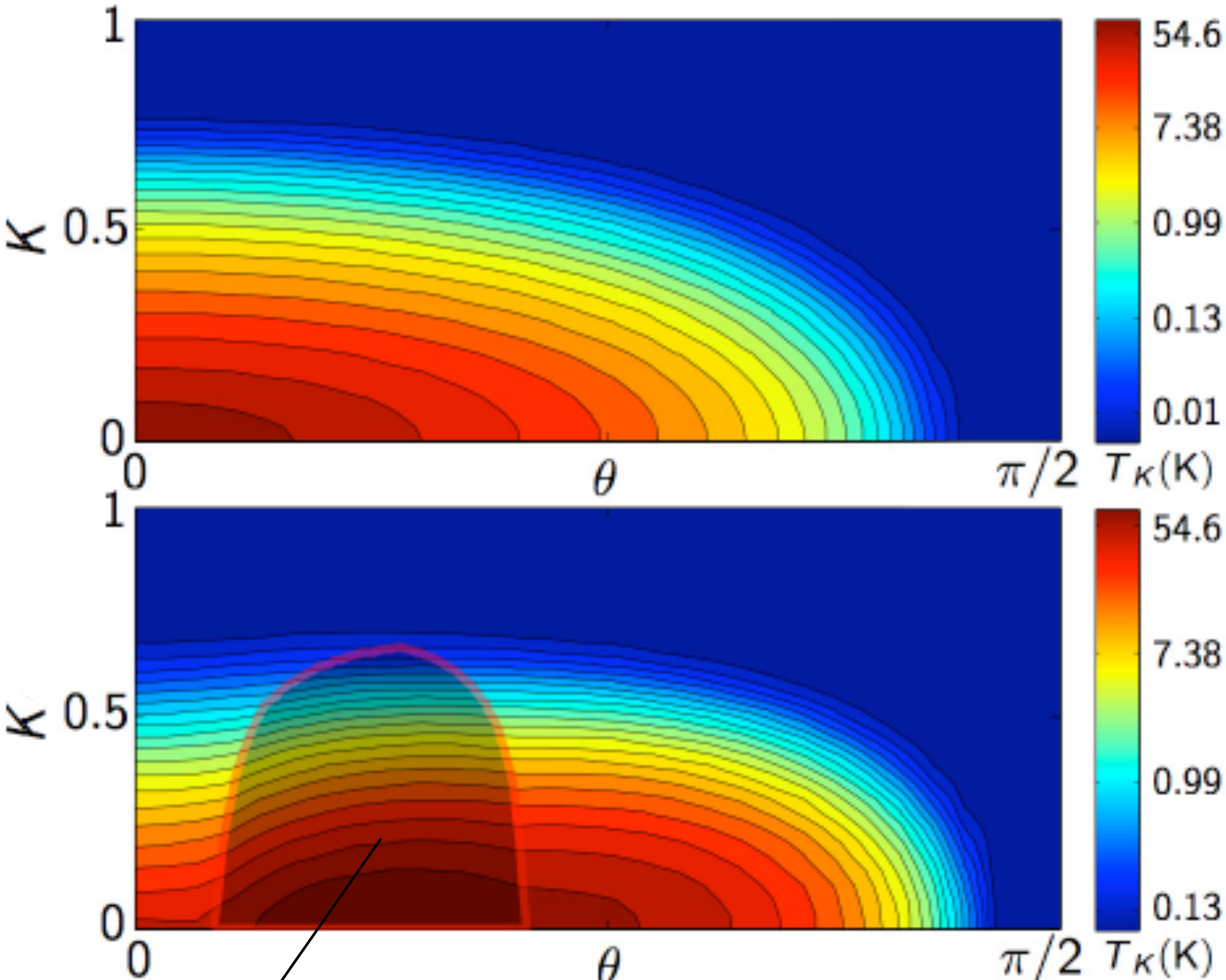
Region where J_{NC} dominates the RG flow

⟶ obstruction of Kondo screening**!**

Electrical control of the Kondo temperature

via the "Rashba angle" θ ~ gate voltage



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Region where J_{NC} dominates the RG flow

→ obstruction of Kondo screening**!**

challenges "conventional wisdom" that Kondo screening cannot be killed off by time-reversal invariant perturbations!

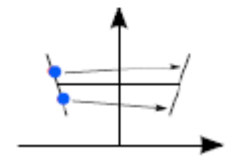
drawn from

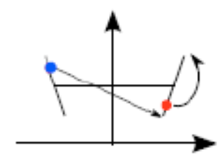
Y. Meir and N.S. Wingreen, PRB **50**, 4947 (1994)

Low-temperature transport, $T \ll T_K$ (away from the "dome")

"weak" e-e interaction

$$G = \frac{2e^2}{h} - \delta G \quad \begin{cases} \sim (T/T_K)^{8K-2} & 1/4 < K < 2/3 \\ \sim (T/T_K)^{2K+2} & K > 2/3 \end{cases}$$





no signature of Rashba

"strong" e-e interaction $K < 1/4$

$\mathrm{G} \sim (T/T_K)^{2(1/4K-1)}$ from instanton processes

J. Maciejko *et al.*, PRL **102**, 256803 (2009)
J. Maciejko, PRB B **85**, 245108 (2012)

"High-temperature" transport, $T \gg T_K$

$$\delta I = I - I_0$$

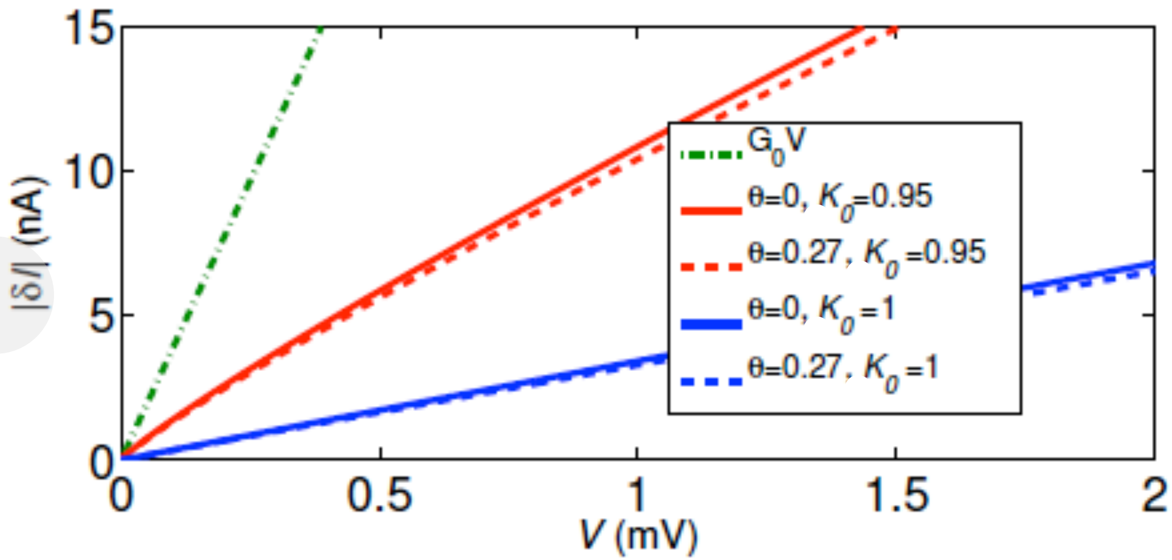


FIG. 2: The RG-improved current correction (12) at $T = 30$ mK as a function of applied voltage, for different values of K_0 and θ. The dashed lines represent $\theta \approx 0.27$, corresponding to $\hbar\alpha = 10^{-10}$ eVm. $J_x = J_y = 3J_z = 30$ meV, $a_0 = 0.5$ nm, $v_F = 5 \times 10^5$ m/s, and $D = 300$ meV.

"High-temperature" transport, $T \gg T_K$

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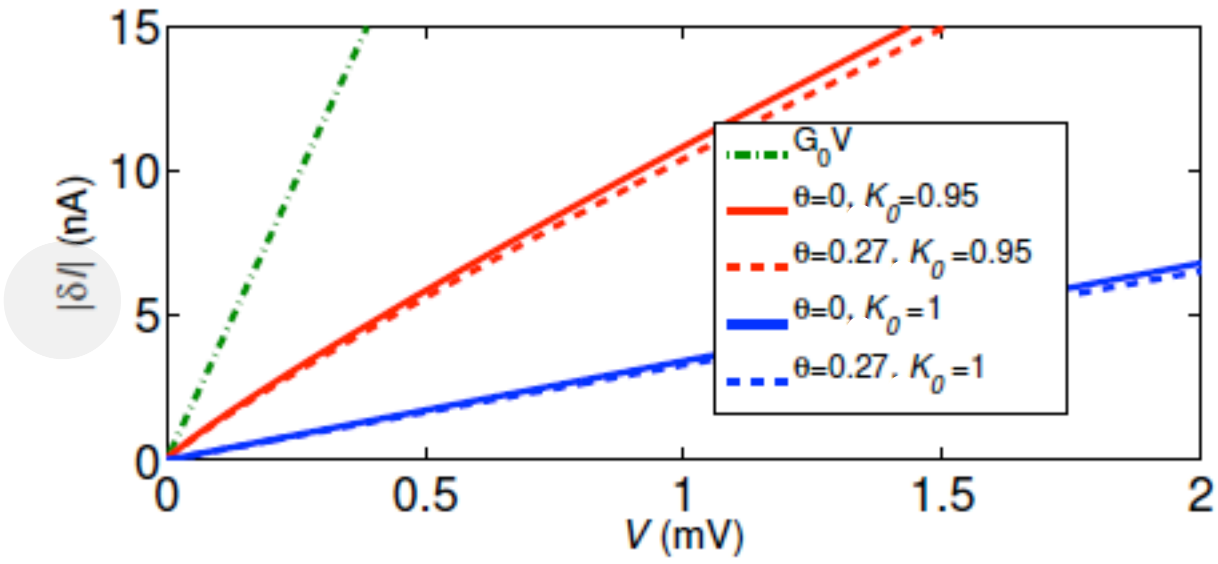

The Rashba-driven correction for a fixed voltage increases with the e-e interaction. Estimated values of *K* for the HgTe quantum wells used in the Würzburg experiments range from K = 0.55 to K = 0.98.

"High-temperature" transport, $T \gg T_K$

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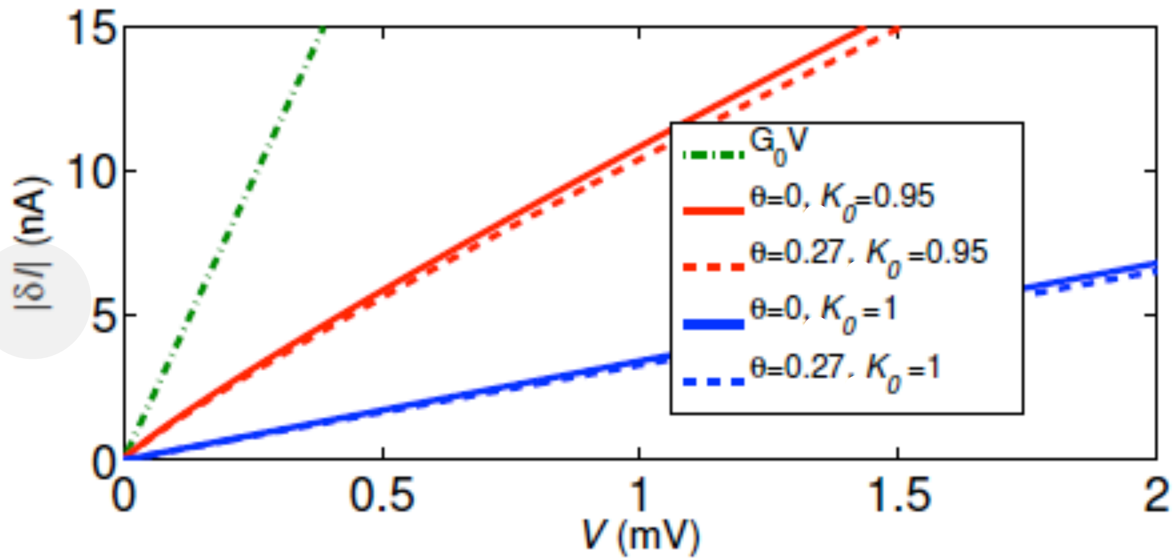
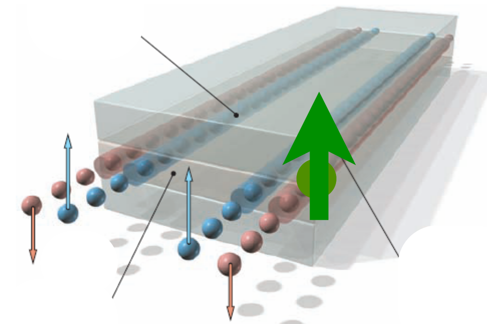


For more results on transport, see

E. Eriksson *et al.*, PRB **86**, 161103(R) (2012);
PRB **87**, 079902(E) (2013)

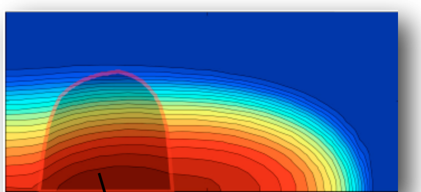
Summary

E. Eriksson *et al.*, PRB **86**, 161103(R) (2012)
PRB **87**, 079902(E) (2013)

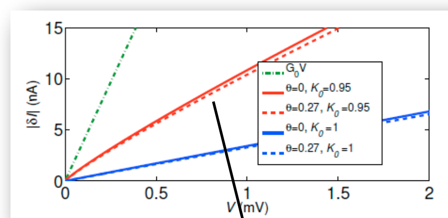


from M. König *et al.*, Science **318**, 766 (2007)

Magnetic impurity in a helical edge liquid:
Rashba coupling allows electrical "control" of **Kondo temperature** and **IV-characteristics**



blocking of Kondo screening
(one-loop RG)



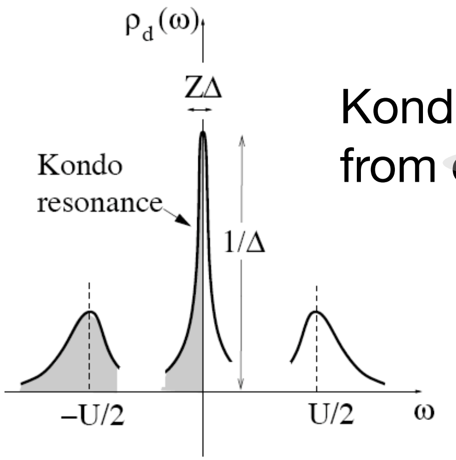
Rashba-induced
impurity correction,
accessible in experiment?

More results:

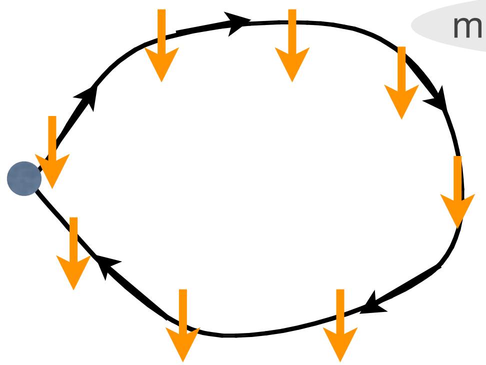
Current fluctuations, thermal transport, effects from Dresselhaus interactions,...
E. Eriksson, PRB **87**, 235414 (2013)

Addendum...

Conventional picture...

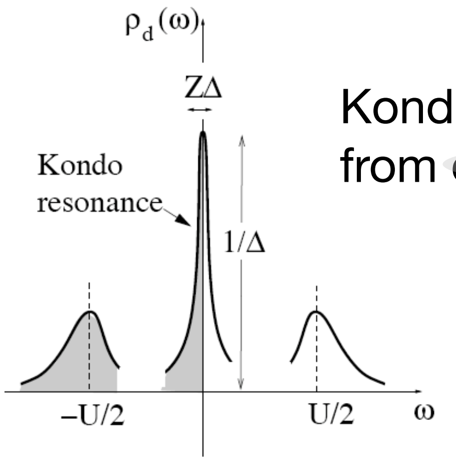


Kondo resonance at the Fermi level
from divergence in the electron self-energy



multiple electron-impurity scattering

Conventional picture...



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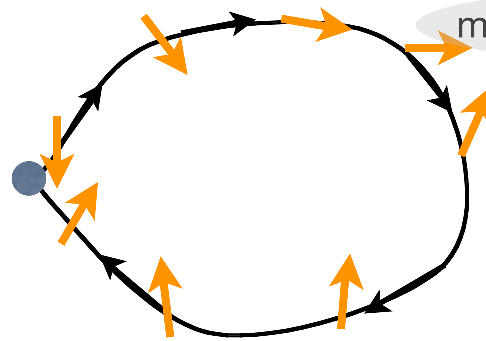
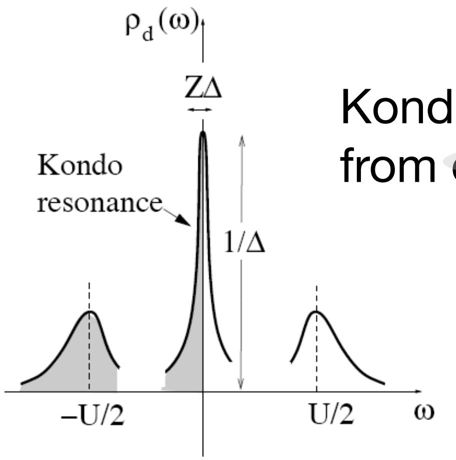


multiple electron-impurity scattering

non-conservation of electron spin in the presence of spin-orbit interactions

Conventional picture...



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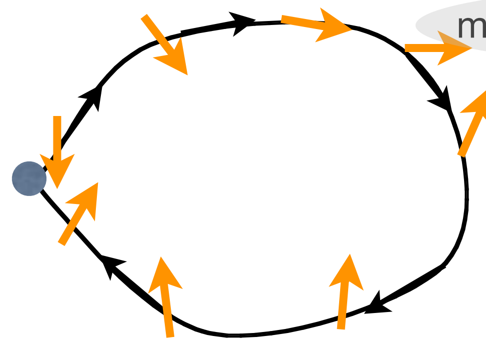


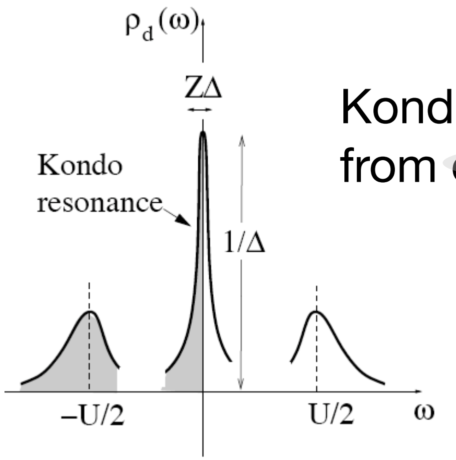
multiple electron-impurity scattering

non-conservation of electron spin in the presence of spin-orbit interactions!

But,... experiments show that the Kondo effect is insensitive to spin-orbit scattering...

G. Bergmann, PRL 57, 1460 (1986)

Conventional picture...



Kondo resonance at the Fermi level
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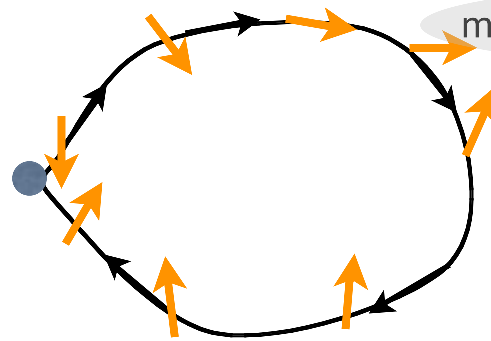
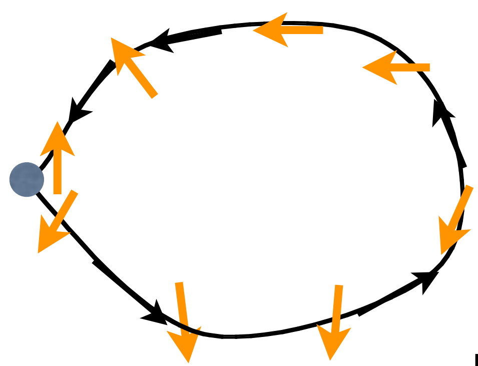
+



multiple electron-impurity scattering

non-conservation of electron spin in the presence of spin-orbit interactions!

-



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G. Bergmann, PRL **57**, 1460 (1986)

= 0

...protected by time-reversal invariance

Y. Meir and N.S. Wingreen, PRB **50**, 4947 (1994)