# Spin dependent transport through magnetic domain walls in nanowires

## *from channel blocking to adiabatic transmission*

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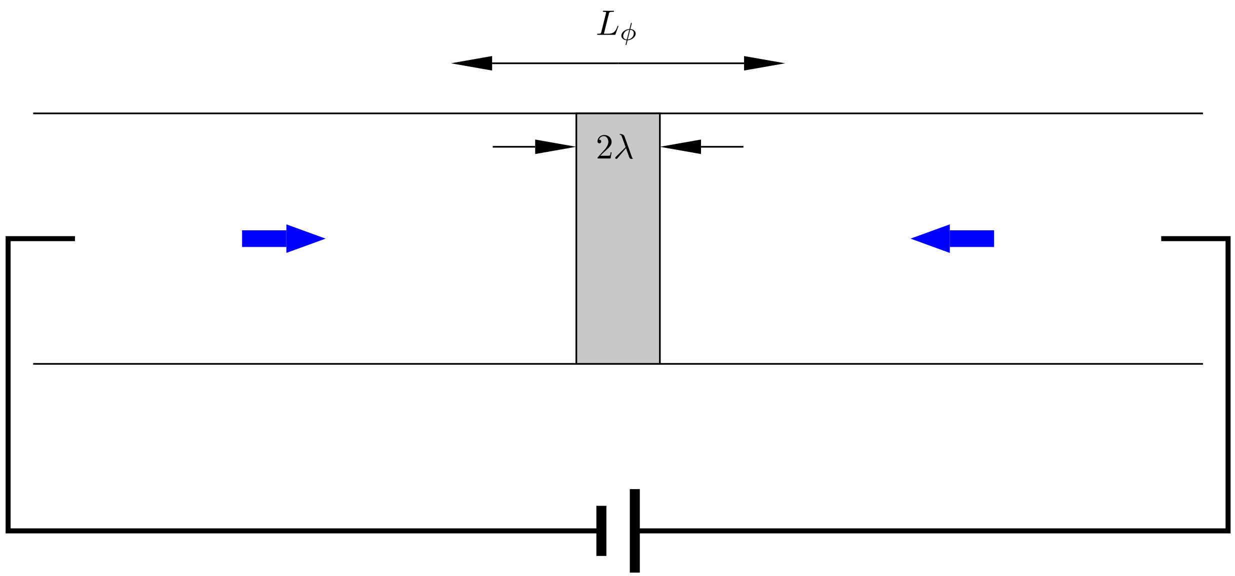
# Ferromagnetic quantum wires




$L_\phi > l \approx 2\lambda$

domain wall:

coherent

ballistic

Experiments:

U. Ebels *et al.*, PRL 84, 983 (2000): Co wires, ∅ 35 nm, single domain wall

G. Dumpich *et al.*, JMMM 248, 241 (2002): polycrystalline Co wires

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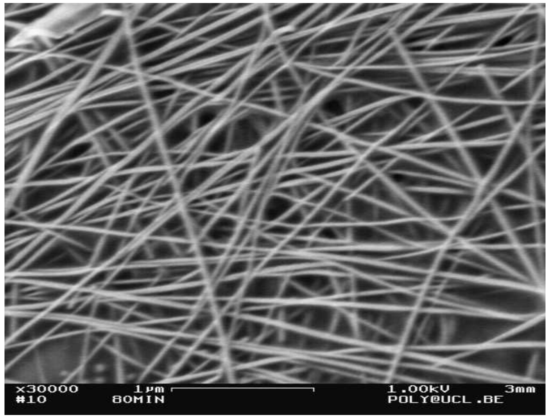
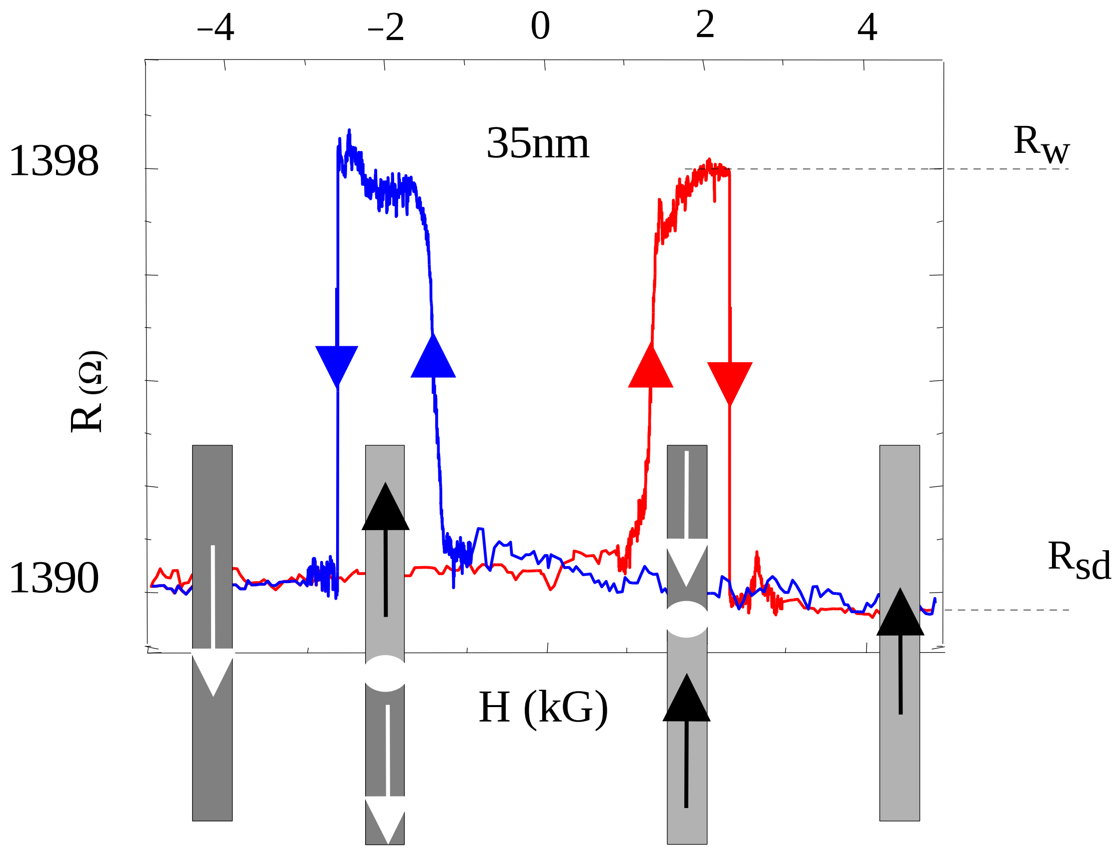
# A single domain wall can increase the resistance




U. Ebels *et al.*,

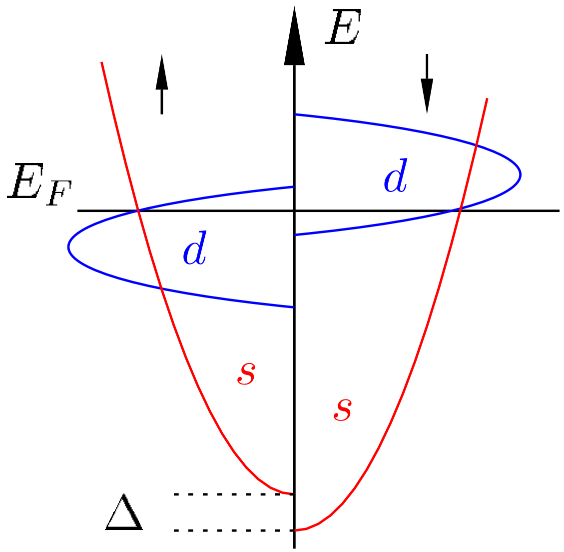
PRL 84, 983 (2000)

Anisotropic Magneto-Resistance: negative contribution

Domain wall scattering: positive contributions

# Model Hamiltonian

Band structure of Co: very complex




Roughly:

$d$ : large effective mass $\rightsquigarrow$ magnetism

$s$ : low effective mass, mobile $\rightsquigarrow$ transport

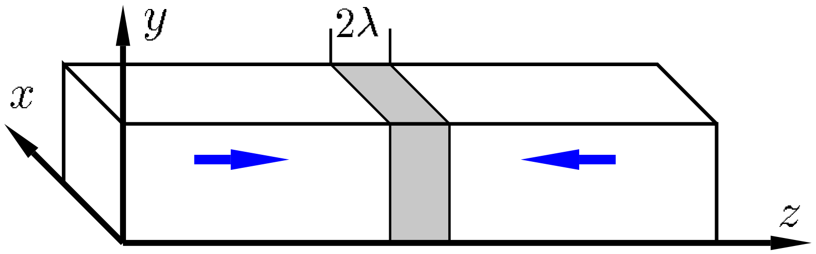
Assumption: $s$-electrons move in a magnetic configuration defined by the static $d$-electrons

Effective Hamiltonian for $s$-electrons $\quad H = -\frac{h^2}{2m}\nabla^2 + \frac{\Delta}{2}\vec{f}(\vec{r})\vec{\sigma}$

$\Delta$: energy difference between $s$-electrons with $\uparrow\uparrow$ and $\downarrow\uparrow$

$\vec{f}(\vec{r})$: local magnetization direction due to the $d$-electrons

# Conductance




$$\vec{f}(\vec{r}) = \vec{f}(z)$$

$H = -\frac{h^2}{2m}\nabla^2 + \frac{\Delta}{2}\vec{f}(z)\vec{\sigma} = H_{\mathrm{t}} + H_z \quad \leadsto \quad$ Transport channels

Leads: $\vec{f}(z)\vec{\sigma} = \pm 1 \quad \leadsto \quad E_\uparrow = E_{\mathrm{t}}(\{n_{\mathrm{t}}\}) + \frac{\hbar^2}{2m}k_z^2 \pm \frac{\Delta}{2}$

Density of $E_{\mathrm{t}}(\{n_{\mathrm{t}}\})$: $\quad \rho = 2\pi m A/h^2 \quad \leadsto \quad N_{\uparrow(\downarrow)} \approx \rho(E_F \mp \Delta/2)$

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Landauer formula $\quad g = \frac{G}{e^2/h} = \sum_{\{n_{\mathrm{t}}\}} \sum_{\sigma,\sigma'} T_{\{n_{\mathrm{t}}\}}^{\sigma\sigma'}(E_{\mathrm{F}})$

constant offset $E_{\mathrm{t}} \quad \leadsto \quad T_{\{n_{\mathrm{t}}\}}^{\sigma\sigma'}(E_{\mathrm{F}}) = T^{\sigma\sigma'}(E_{\mathrm{F}} - E_{\mathrm{t}}(\{n_{\mathrm{t}}\}))$

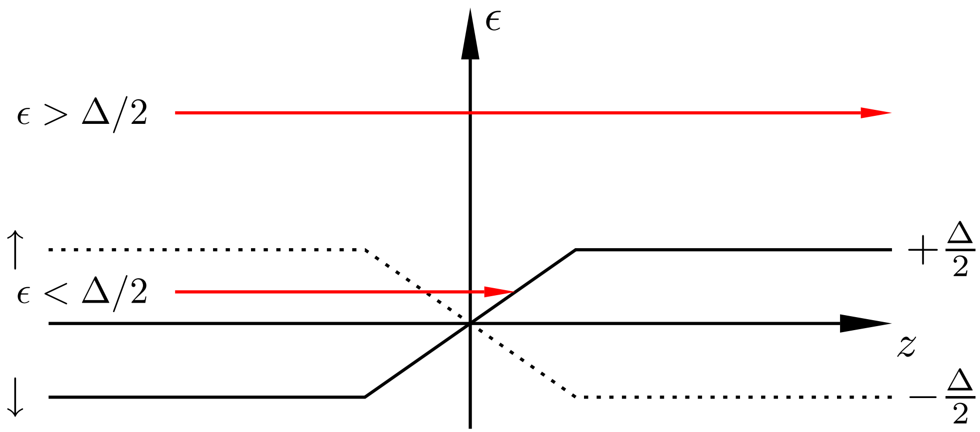
$\leadsto$ effective 1d problem at energy $\epsilon = E_{\mathrm{F}} - E_{\mathrm{t}}(\{n_{\mathrm{t}}\})$

# Channel blocking

No domain wall, single domain: $g_{\text{sd}} = N_\uparrow + N_\downarrow \approx 2\rho E_{\text{F}}$

Domain wall: spin mixing and scattering

$$\vec{f}(z)\vec{\sigma} = \underbrace{f_x(z)\sigma_x + f_y(z)\sigma_y}_{\text{spin-flip}} + \underbrace{f_z(z)\sigma_z}_{\text{potential}}$$




Channel blocking $\rightsquigarrow$ $\dfrac{\delta g}{g_{\text{sd}}} \simeq \dfrac{\Delta}{2E_{\text{F}}}$

Potential only:

step of height $\pm\Delta$

$\epsilon \gg \Delta/2$:

$T$ slightly reduced

$\epsilon < \Delta/2$: $T = 0$

$\rightarrow \rho\Delta$ blocked channels

$\delta g = g_{\text{sd}} - g_{\text{w}} \simeq \rho\Delta$

ok for thin walls $\lambda \rightarrow 0$

$\rightsquigarrow$ atomic size domain walls

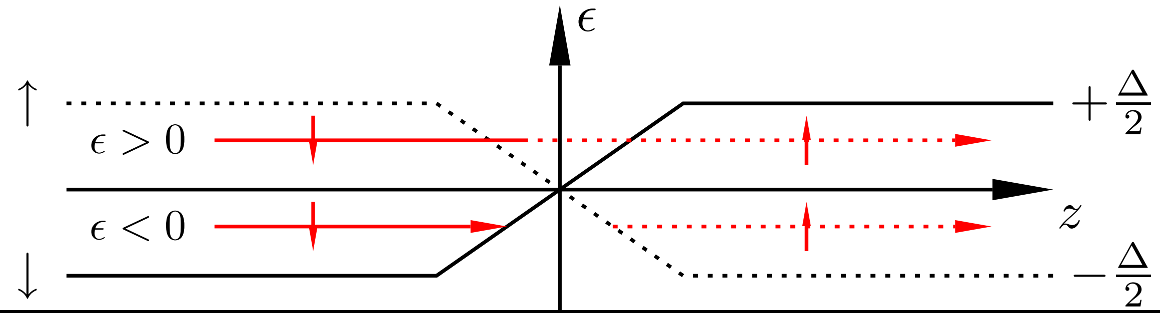
# Transmission with spin-flip ($\lambda > 0$)

$\epsilon \gg \Delta/2$: small correction (Cabrera&Falicov '74)  $\epsilon < \Delta/2$: important?

$s$-electron at $E_{\mathsf{F}}$:

Spinor $(\phi_\uparrow, \phi_\downarrow)$

$\vec{f} = (f_x, 0, f_z)$




$$\left[\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} - \frac{\Delta}{2} f_z + \epsilon\right]\phi_\uparrow = \frac{\Delta}{2} f_x \phi_\downarrow$$

$$\left[\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + \frac{\Delta}{2} f_z + \epsilon\right]\phi_\downarrow = \frac{\Delta}{2} f_x \phi_\uparrow$$

Thin wall

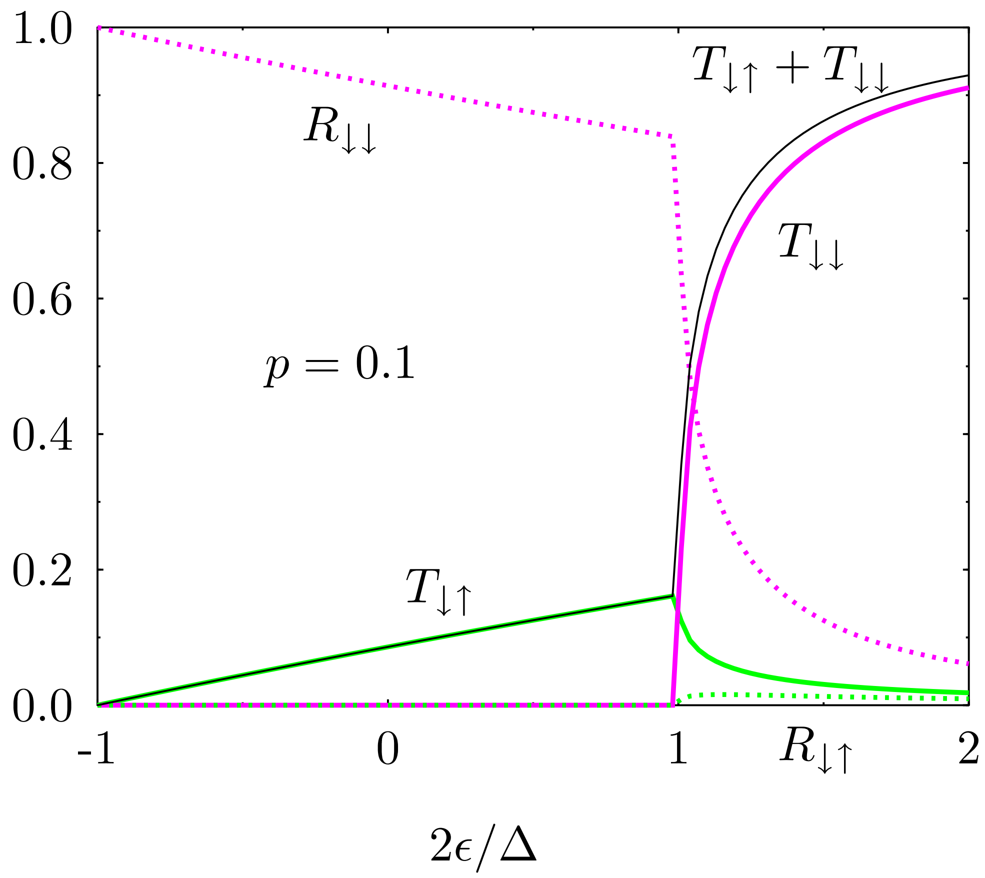
$p = \left(\frac{\Delta}{2E_{\mathsf{F}}}\right)^{1/2} k_{\mathsf{F}}\lambda \ll 1$

perturbation in the spin-flip

$$T_{\downarrow\uparrow}(\epsilon) = (C_{\text{wall}}\, p)^2 \left(1 + \frac{2\epsilon}{\Delta}\right) \rightsquigarrow \frac{\delta g}{g} \simeq \frac{\Delta}{2E_F}\left(1 - (C_{\text{wall}}\, p)^2\right)$$

Shape-dependence $C_{\text{wall}} = \frac{1}{\lambda}\int \mathrm{d}z\, f_x$  at least for linear $f_z = z/\lambda$

# Result for thin domain walls




Different shape:

(Bloch wall)

$f_z = \tanh(z/\lambda)$

Recursive GF

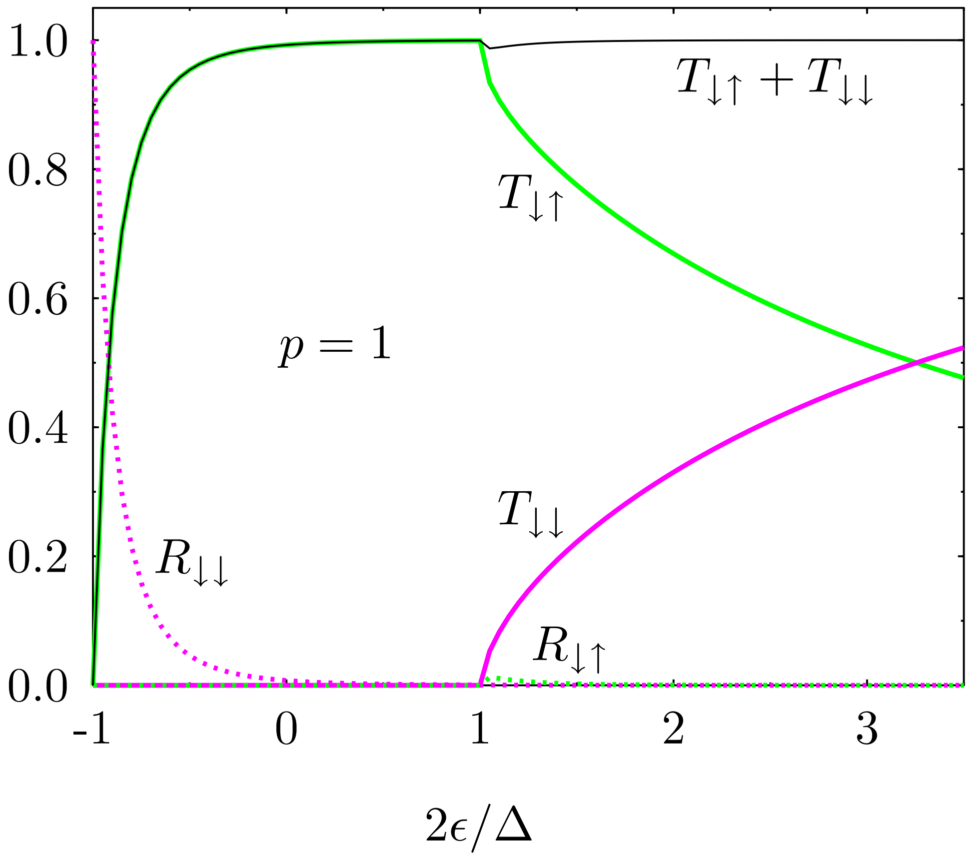
Channel blocking

persists

No spin-flip

at large energies

# Result for thicker domain walls




Channel blocking

suppressed

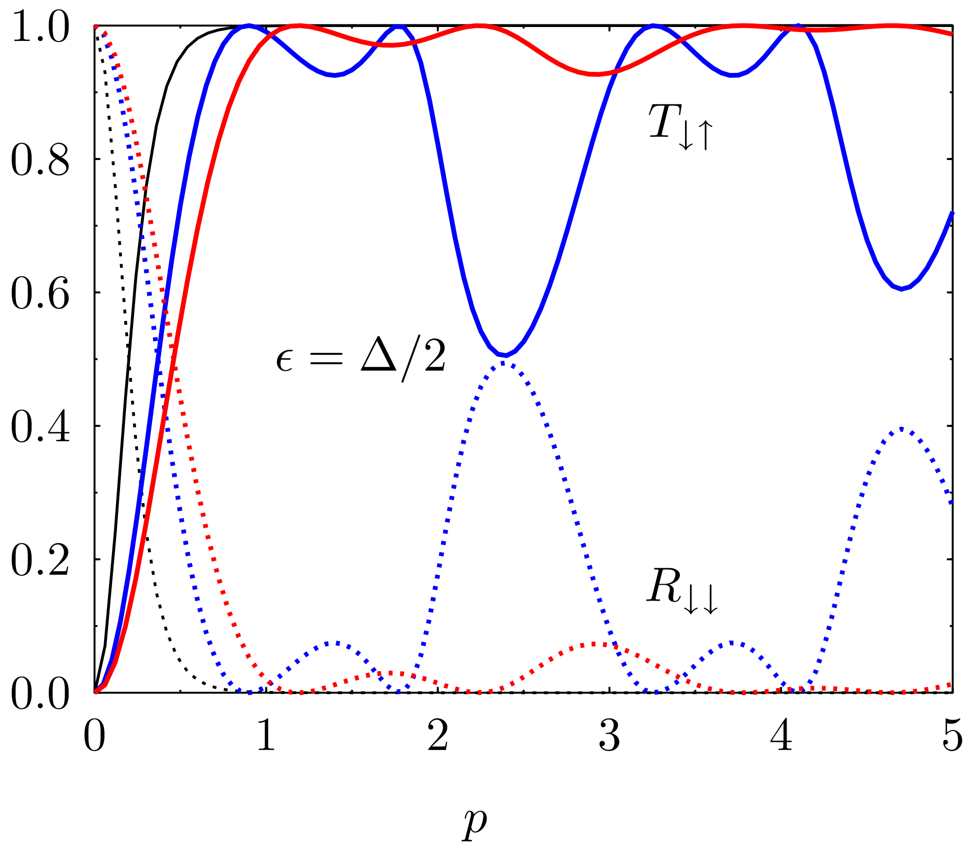
No spin-flip

at large energies

“mistracking”

Very thick walls $p \to \infty$: $T_{\downarrow\uparrow} \to 1$ “adiabatic transport”

# Shape dependence in the intermediate regime




Bloch $f_z = \tanh(z/\lambda)$

linear $f_z = z/\lambda$

trigo $f_z = \sin(\pi z/2\lambda)$

Edges

$\rightsquigarrow$ Fabry-Perot

# Conclusions

Channel blocking in ferromagnetic quantum wires with thin domain walls: important in atomic contacts

Transmission without spin-flip persists in ferromagnetic quantum wires with thicker domain walls at higher energy ("mistracking, non-adiabatic") $\rightsquigarrow$ GMR: relevant except for extremely thick domain walls

# GMR

Example: $L \approx 20\mu$m $> l_{\mathrm{sf}} \approx 60$nm $> L_\phi, l \approx 2\lambda \approx 10$nm