# Local injection of pure spin current generates electric current vortices

Yaroslaw Bazaliy [1], Revaz Ramazashvili [2]

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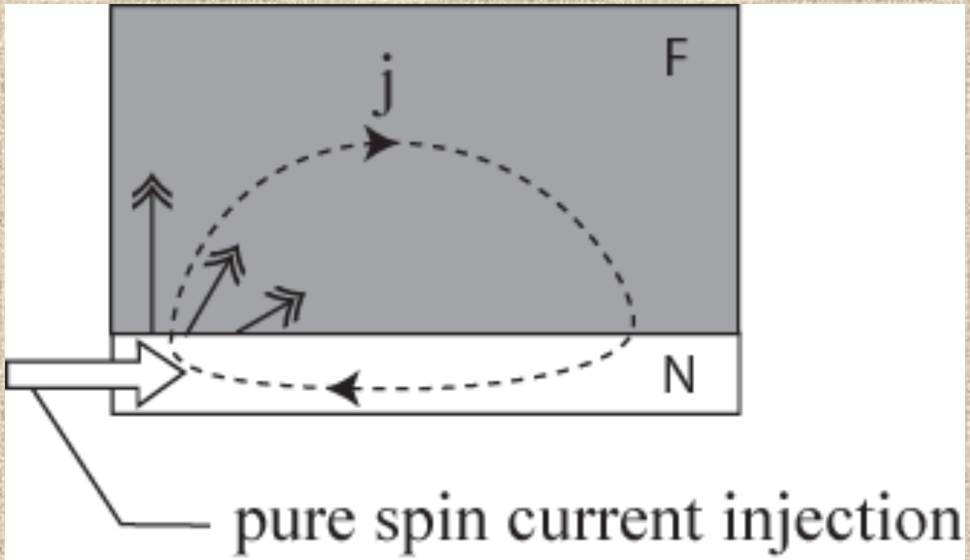
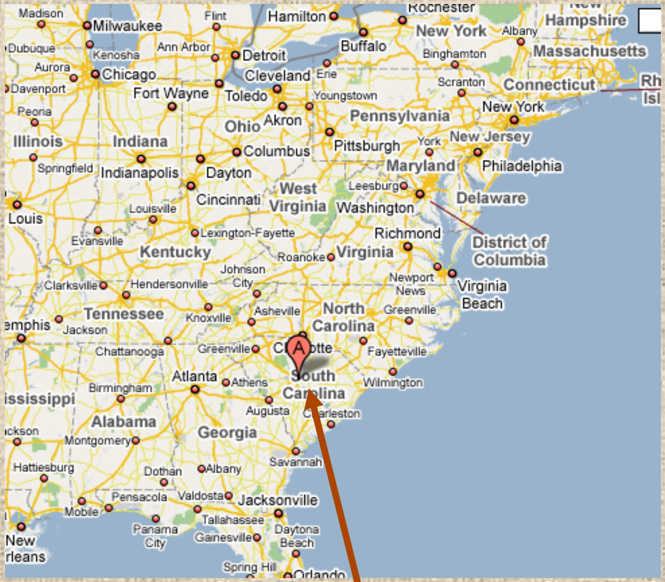
**ECRYS-2017**

# Generation of electric vortices :




**An electric current loop in an electrically disconnected device !**

Bazaliy, Ramazashvili, arXiv:1607.06385 = APL **110**, 092405 (2017)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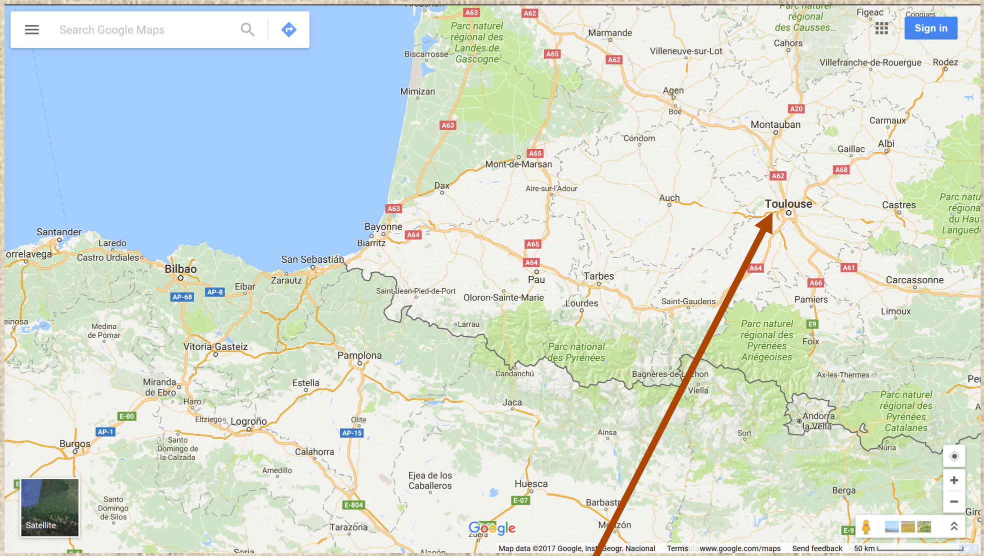
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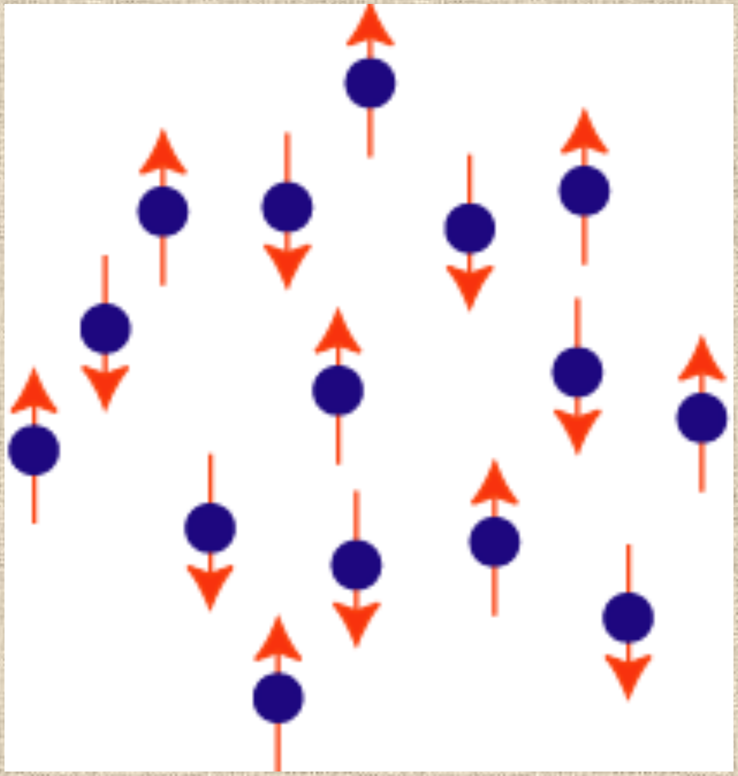
ИЗБИРАТЕЛЬНЫЙ ПУНКТ № 51
12

# Plan of the talk

1. Electric and spin currents
2. Generation of spin current and its non-conservation
3. The model
4. Johnson-Silsbee experiment with non-local injection
5. Problem of wide electrode
6. Electric current loops
7. Conclusions

# Microscopic (purely classical !) picture of electrons in a metal :

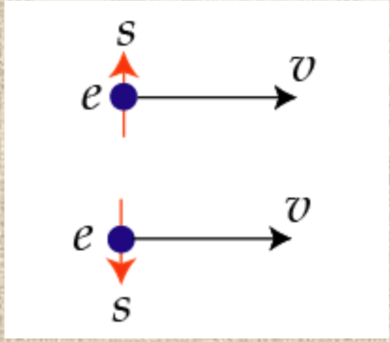


# Electric and spin currents

| | |
|---|---|
| $j_i^e = e\langle v_i \rangle$ | electric current |
| $s_\alpha = \langle \sigma_\alpha \rangle$ | average spin |
| $j_{\alpha,i}^s = \langle \sigma_\alpha v_i \rangle$ | spin current |

# Electric and spin currents

Non-magnetic metal: pure electric current




$$j_i^e = e\langle v_i \rangle \quad \text{electric current}$$

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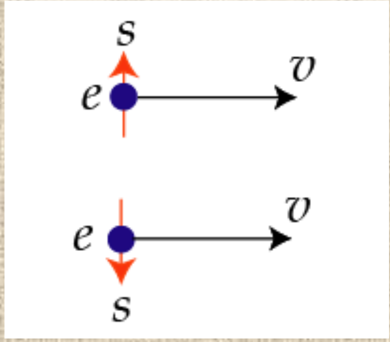


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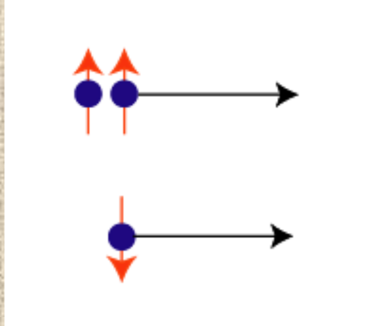
Ferromagnetic metal: electric and spin currents



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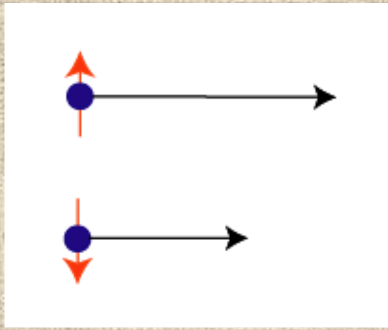

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# Electric and spin currents

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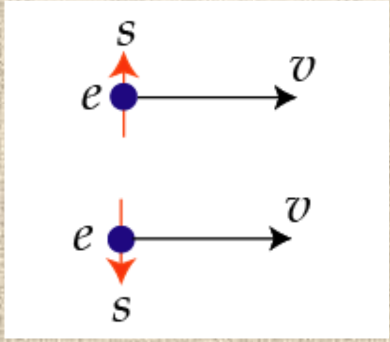


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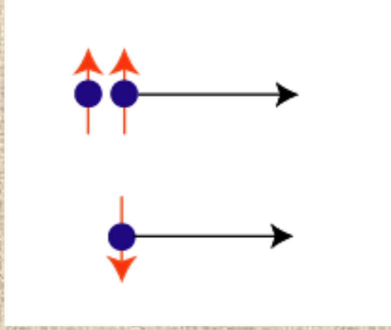

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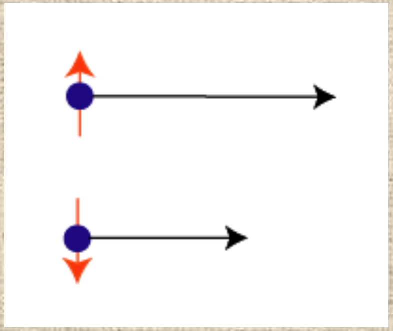

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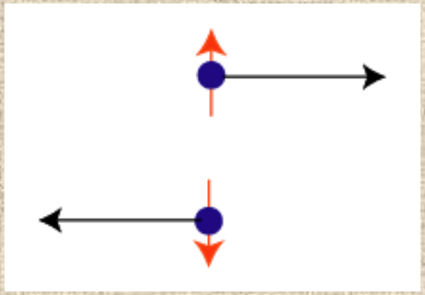
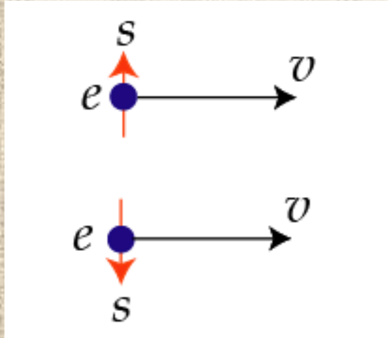
Pure spin current



# Electric and spin currents

Non-magnetic metal: pure electric current

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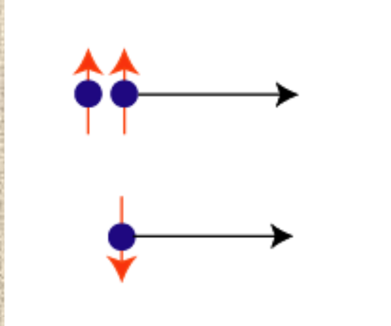

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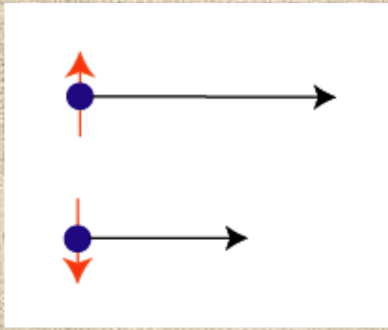

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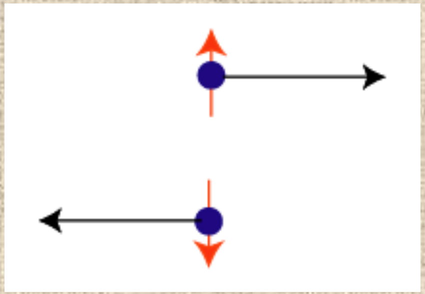
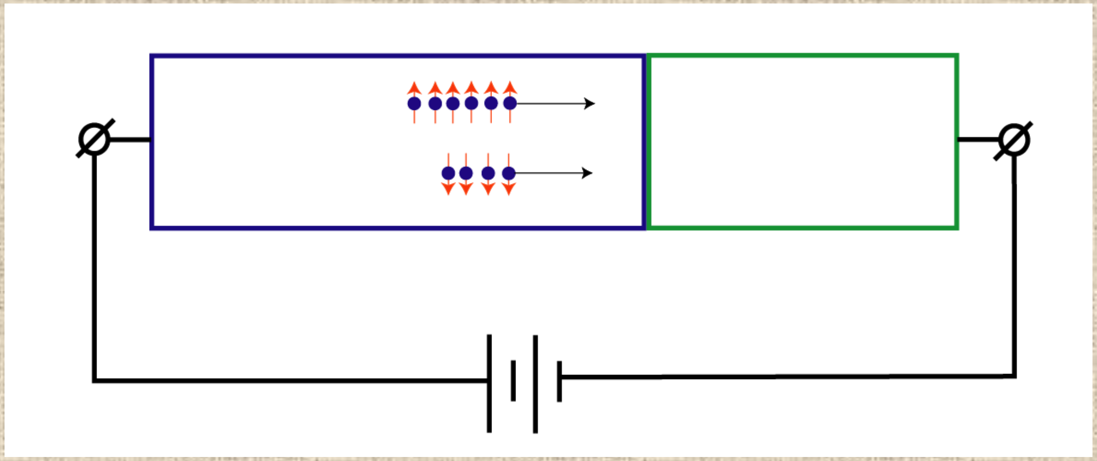


**How can one ever produce a pure spin current?**
**Or at least some spin current in a normal metal?**

# … Injection from a ferromagnet !

*F* *N*



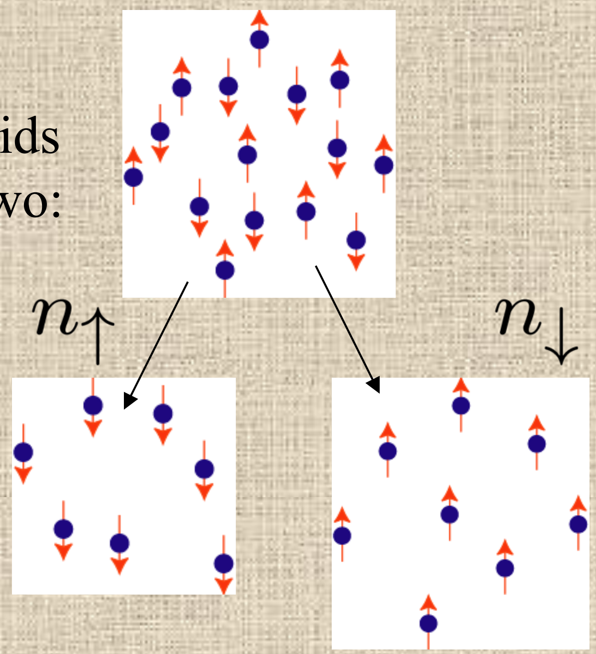
- Naturally, the excess of spin-up will drift from F into N
- But ... one needs a well-defined model.

# Diffusion model :

Campbell, Fert, and Pomeroy, Philos.Mag. **15**, 977 (1967)
Valet and Fert, Phys. Rev. B **48**, 7099 (1993).

a) Short electron mean free path => diffusive regime
b) It takes much longer to flip spin than to scatter momentum

$\uparrow$ and $\downarrow$ electrons form two separate fluids
with slow equilibration between the two:




$$n_\uparrow + n_\uparrow = n = const$$

**Non-equilibrium :** $\mu_\uparrow \neq \mu_\downarrow$ **!**

# The equations:

$$
\begin{aligned}
j_\uparrow &= -(\sigma_\uparrow/e^2)\nabla\mu_\uparrow \\
j_\downarrow &= -(\sigma_\downarrow/e^2)\nabla\mu_\downarrow
\end{aligned}
$$

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$$
\boxed{
\begin{aligned}
\dot{n}_\uparrow + \mathrm{div} j_\uparrow &= -q_{flip} \\
\dot{n}_\downarrow + \mathrm{div} j_\downarrow &= +q_{flip}
\end{aligned}
}
$$

$$
q_{flip} \sim (n_\uparrow - n_\downarrow) \sim (\mu_\uparrow - \mu_\downarrow)
$$

# The equations:

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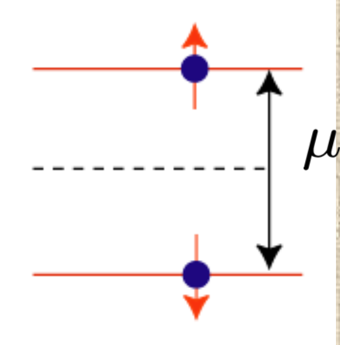
$$q_{flip} \sim (n_\uparrow - n_\downarrow) \sim (\mu_\uparrow - \mu_\downarrow)$$

**Deviation from equilibrium :** $\mu_\uparrow \neq \mu_\downarrow$ **!**

# Separation into electric and spin parts :

voltage $\frac{\mu_\uparrow + \mu_\downarrow}{2} = \mu$



$\mu_s = \mu_\uparrow - \mu_\downarrow$ non-equilibrium spin accumulation

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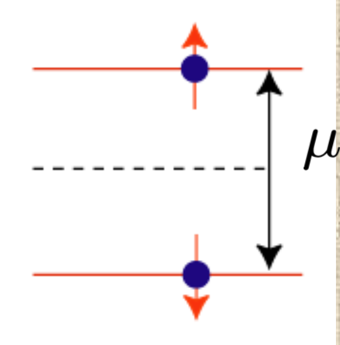

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**Electric and spin currents:**

$$\begin{aligned} j &= j_\uparrow + j_\downarrow \\ j_s &= j_\uparrow - j_\downarrow \end{aligned}$$

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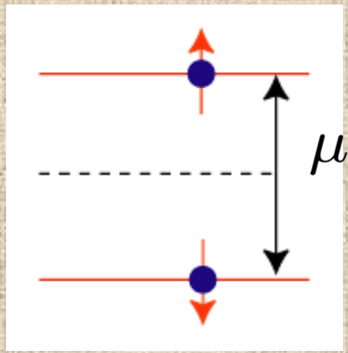

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**Electric and spin currents:**

$$\begin{aligned} j &= j_\uparrow + j_\downarrow \\ j_s &= j_\uparrow - j_\downarrow \end{aligned}$$

$$\begin{cases} j = -\frac{\sigma}{e^2}\left[\nabla\mu + p\left(\frac{\nabla\mu_s}{2}\right)\right] \\ j_s = -\frac{\sigma}{e^2}\left[\left(\frac{\nabla\mu_s}{2}\right) + p\nabla\mu\right] \end{cases}$$

$$p \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

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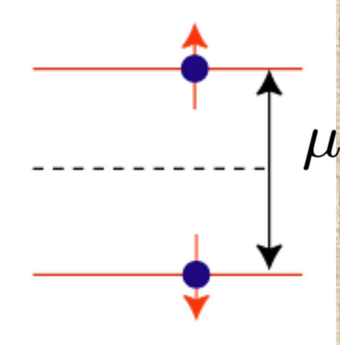

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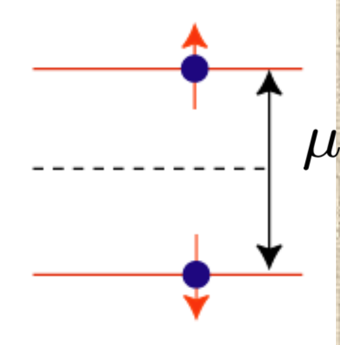

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**Electric and spin currents:**

$$
\begin{aligned}
j &= j_\uparrow + j_\downarrow \\
j_s &= j_\uparrow - j_\downarrow
\end{aligned}
$$

- effective EMF developed in the ferromagnet
- electric current couples to spin !

$$
\begin{cases}
j = -\frac{\sigma}{e^2}\left[\nabla\mu + p\left(\frac{\nabla\mu_s}{2}\right)\right] \\
j_s = -\frac{\sigma}{e^2}\left[\left(\frac{\nabla\mu_s}{2}\right) + p\nabla\mu\right]
\end{cases}
$$

$$
p \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}
$$

# Stationary regime :

$$j = -\frac{\sigma}{e^2}\left[\nabla\mu + p\left(\frac{\nabla\mu_s}{2}\right)\right]$$

$$j_s = -\frac{\sigma}{e^2}\left[\left(\frac{\nabla\mu_s}{2}\right) + p\nabla\mu\right]$$

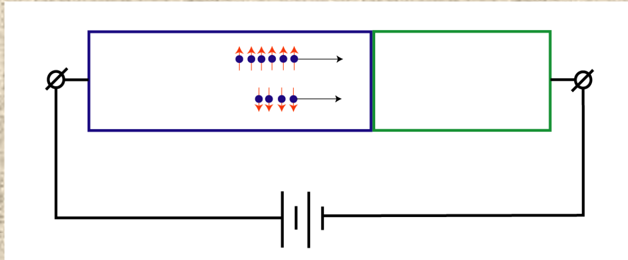
$$\begin{aligned}\dot{n}_\uparrow + \mathrm{div} j_\uparrow &= -q_{flip} \\ \dot{n}_\downarrow + \mathrm{div} j_\downarrow &= +q_{flip}\end{aligned} \quad \Longrightarrow \quad \begin{aligned}&\mathrm{div} j = 0 \\ &\mathrm{div} j_s = -\frac{\mu_s}{\tau_s}\end{aligned}$$

$$q_{flip} \sim \mu_s = \mu_\uparrow - \mu_\downarrow$$

$$\dot{n}_\uparrow = \dot{n}_\downarrow = 0$$

$$\boxed{\lambda^2 \begin{vmatrix} 2 & p \\ 2p & 1 \end{vmatrix} \begin{pmatrix} \Delta\mu \\ \Delta\mu_s \end{pmatrix} = \begin{pmatrix} 0 \\ \mu_s \end{pmatrix}}$$

# Spin injection :



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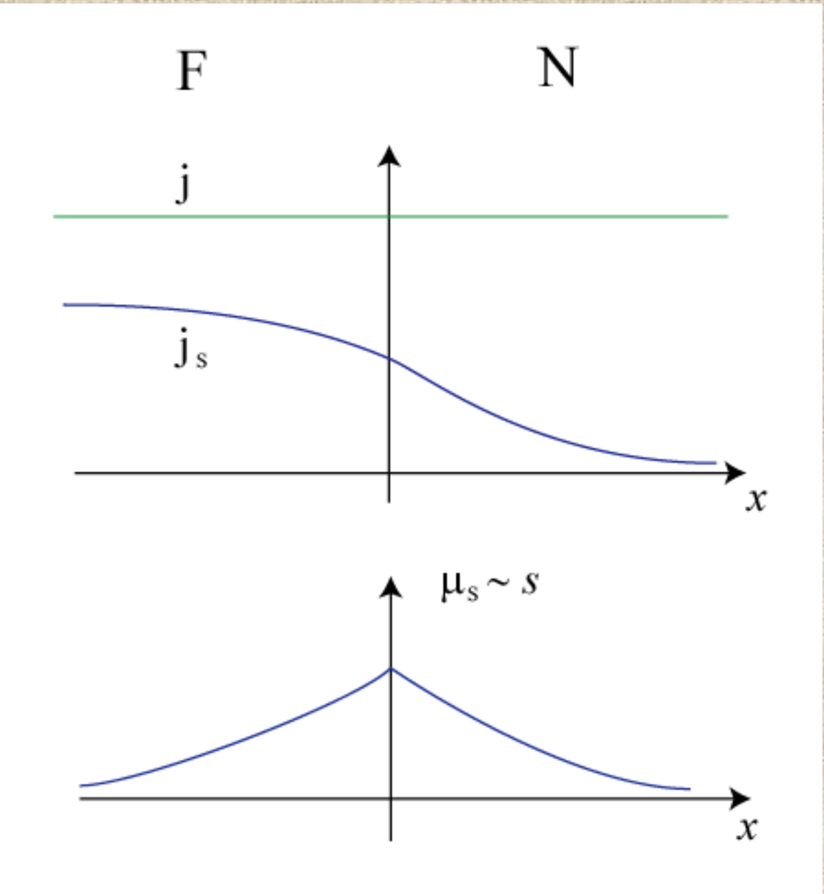
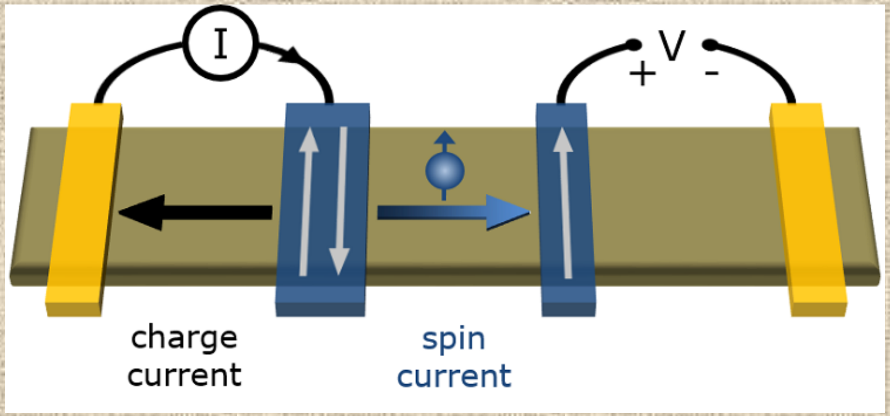



Spin current is *not* conserved
(spin relaxation)

Spin accumulation
occurs near the boundaries

# Non-local spin injection




"Non-local resistance"

M. Johnson and R. H. Silsbee, PRL **55**, 1790 (1985) .

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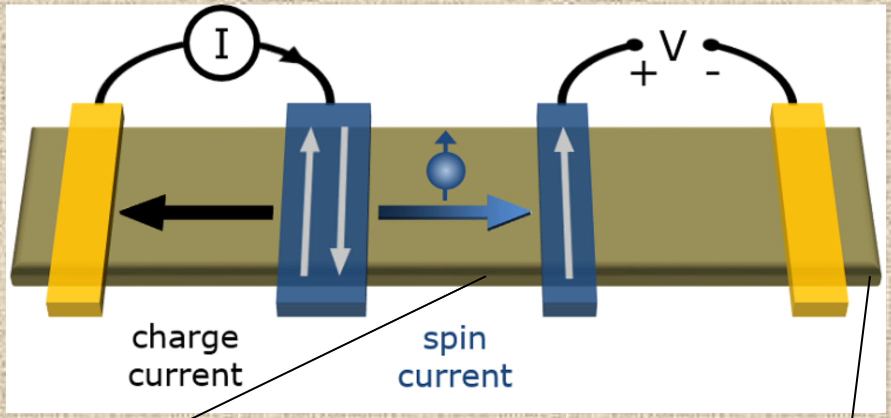


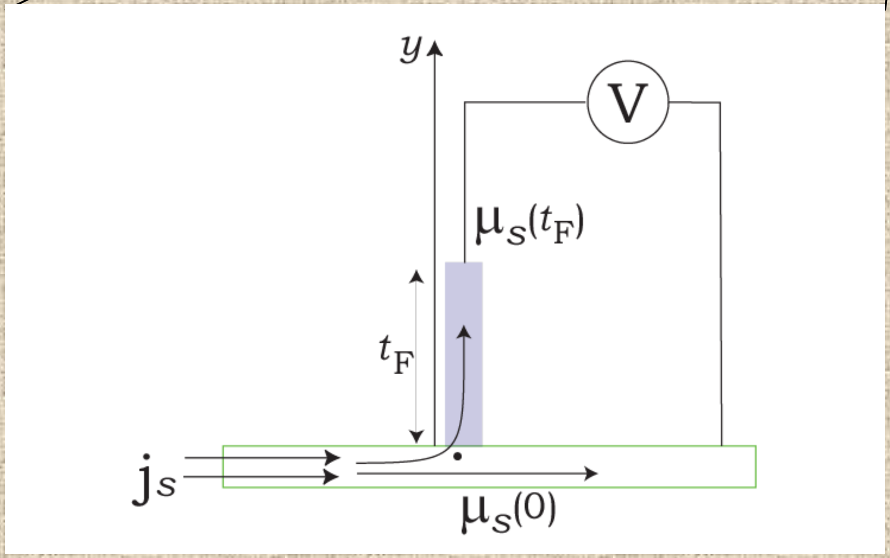


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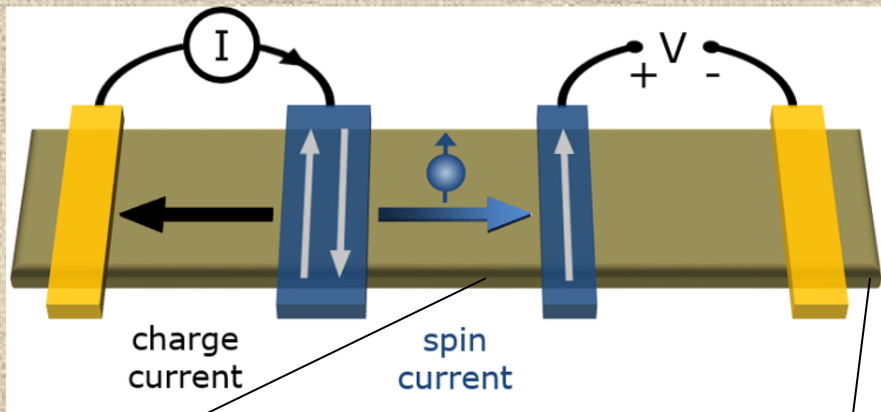


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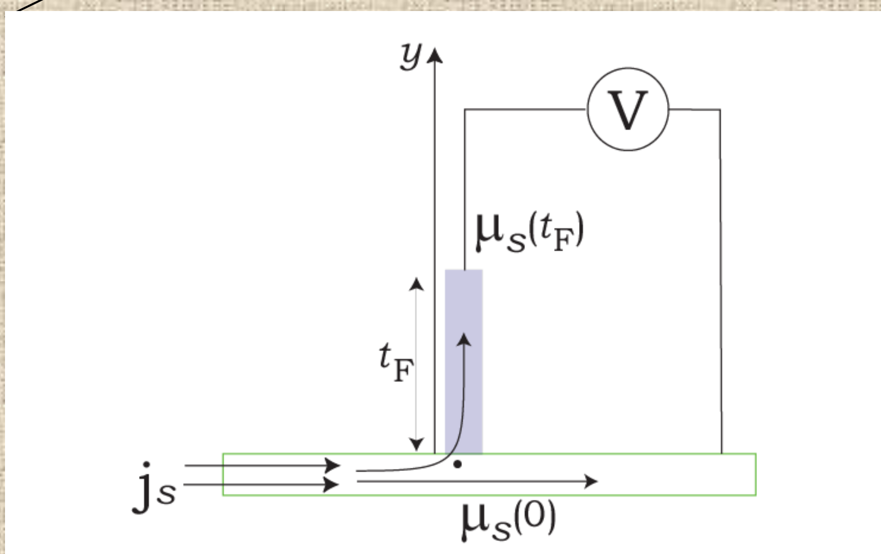
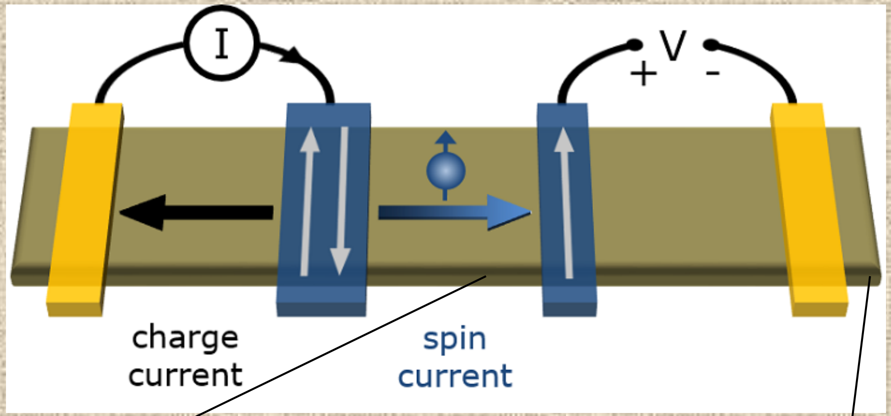



$$j = -\frac{\sigma}{e^2}\left[\nabla\mu + \frac{p}{2}\nabla\mu_s\right] = 0 \Rightarrow V = \frac{p}{2}\left[\mu_s(0) - \mu_s(t_F)\right]$$

# Non-local spin injection




"Non-local resistance"

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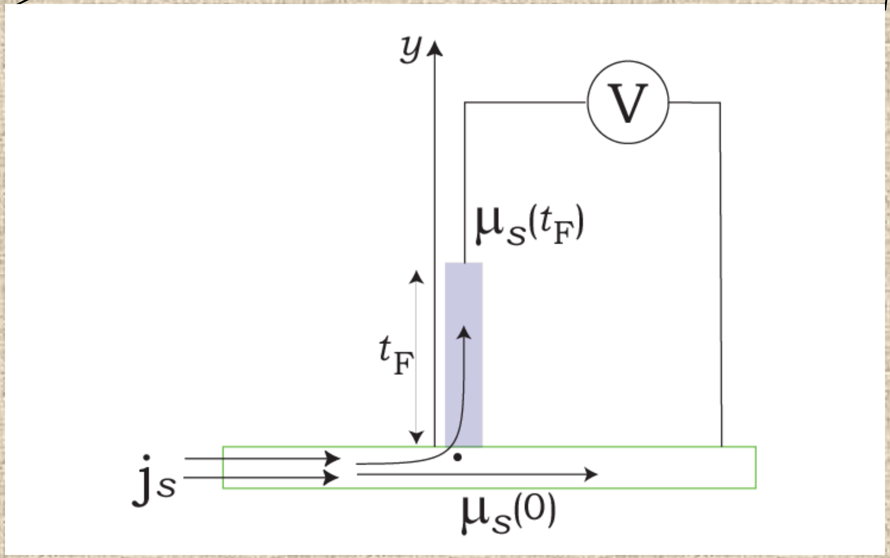
$$\mu_s(t_F) \rightarrow 0$$




$$\boxed{V = \frac{p}{2}\mu_s(0)}$$

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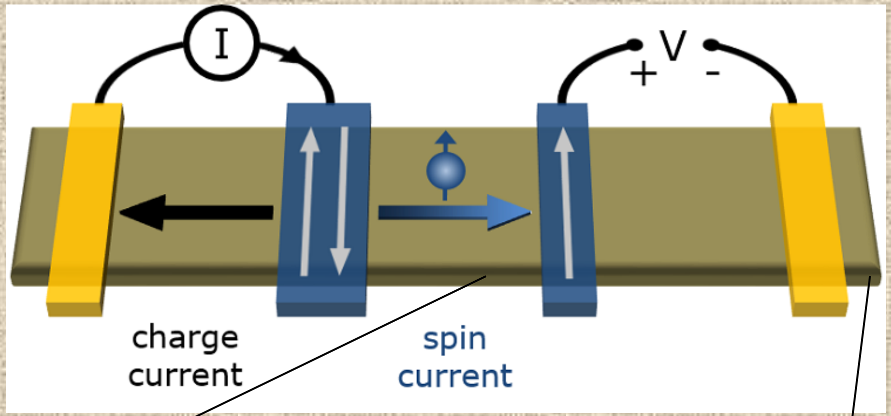


"Non-local resistance"

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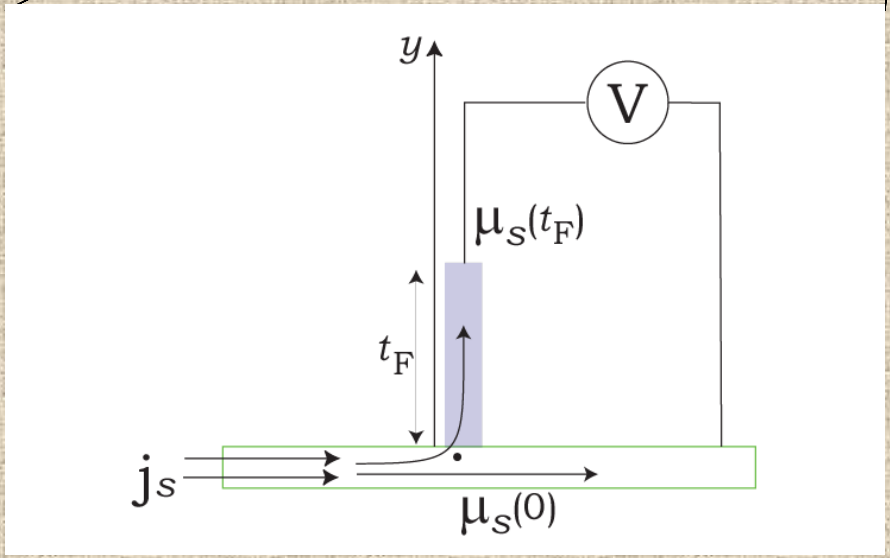
$$\mu_s(t_F) \to 0$$

$$\Downarrow$$

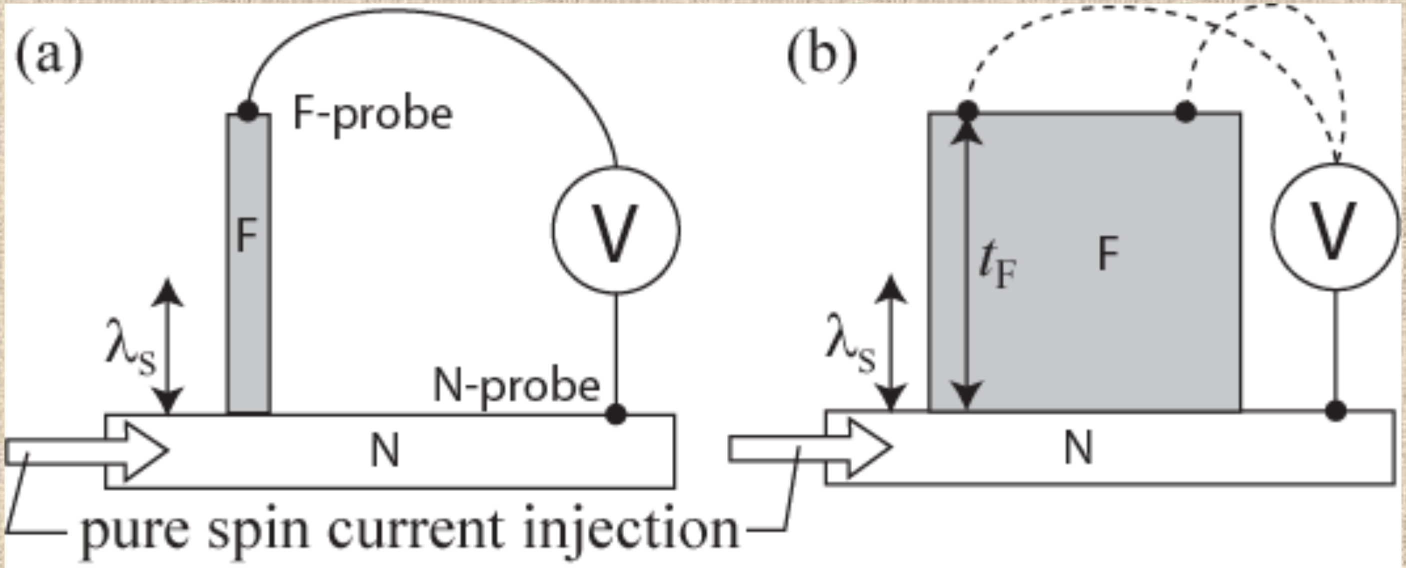



$$!! \quad V = \frac{p}{2}\mu_s(0) \quad !!$$

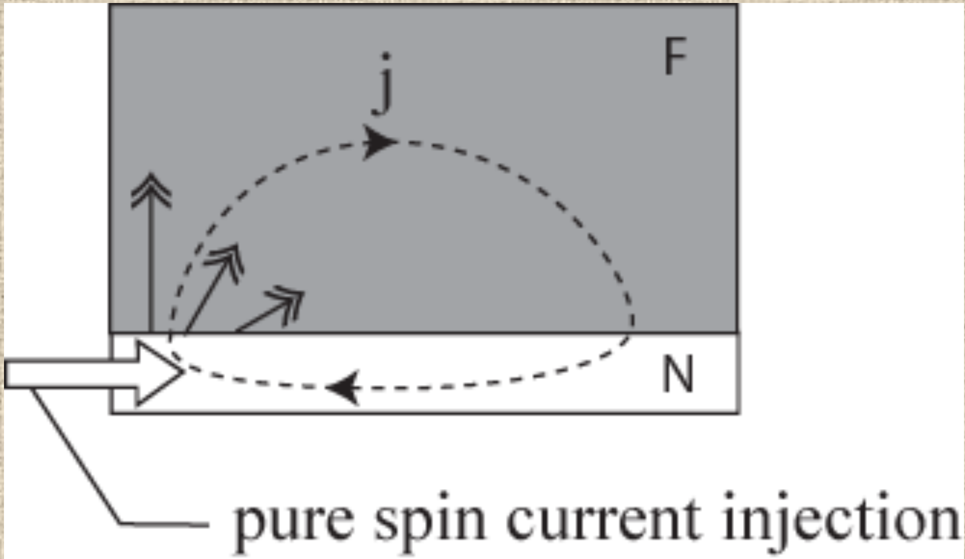
$$j = -\frac{\sigma}{e^2}\left[\nabla\mu + \frac{p}{2}\nabla\mu_s\right] = 0 \Rightarrow V = \frac{p}{2}\left[\mu_s(0) - \mu_s(t_F)\right]$$

# Problem of a wide measuring contact

When $\mu_s$ varies along the interface,
which $\mu_s$ should be substituted into $V = \dfrac{p\mu_s(0)}{2e}$ ?



# Generation of electric current loops :




Bazaliy, Ramazashvili, arXiv:1607.06385 = APL **110**, 092405 (2017)

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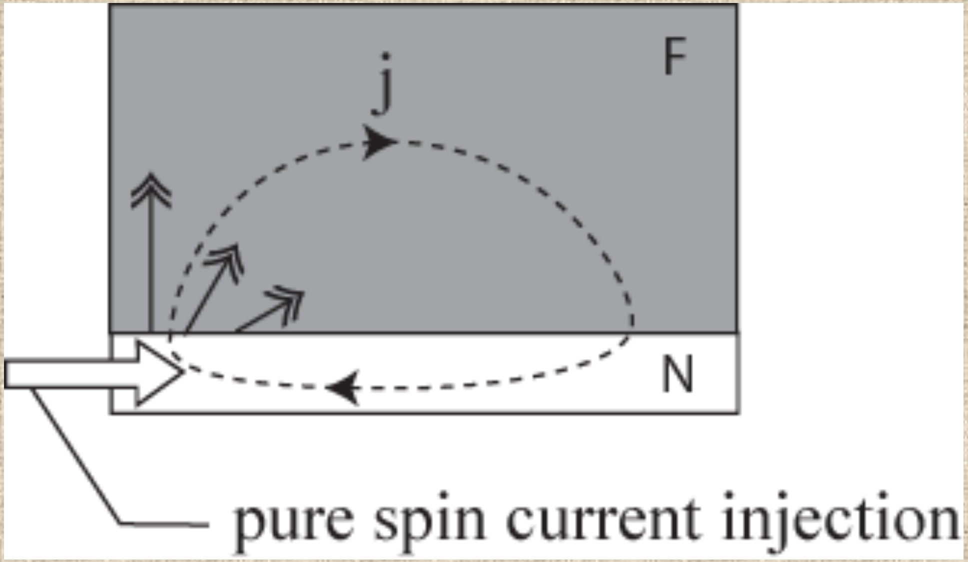


$$j = -\frac{\sigma}{e^2}\left[\nabla\mu + \frac{p}{2}\nabla\mu_s\right]$$

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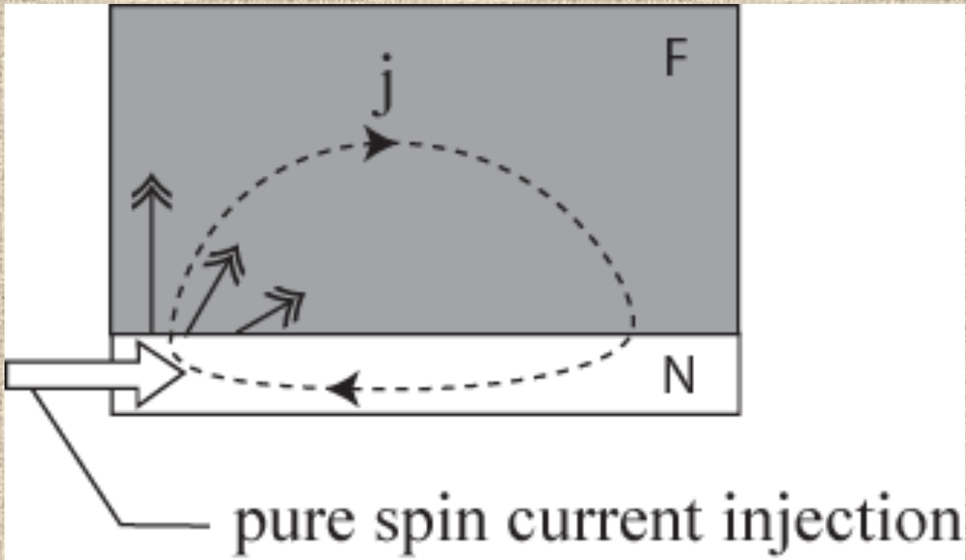


$$j = -\frac{\sigma}{e^2}\left[\nabla\mu + \frac{p}{2}\nabla\mu_s\right]$$

$$\Downarrow$$

$$\boxed{\mathrm{curl}\left(\frac{\mathbf{j}}{\sigma}\right) = \frac{1}{2}\nabla p \times \nabla\mu^s \ .}$$

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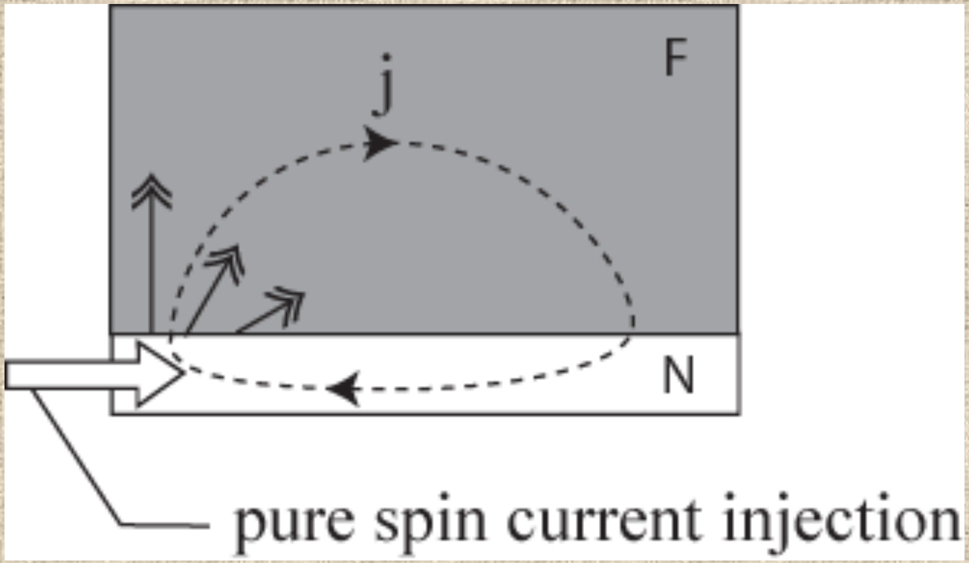


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$$\boxed{\mathrm{curl}\left(\frac{\mathbf{j}}{\sigma}\right) = \frac{1}{2}\nabla p \times \nabla\mu^s \ .}$$

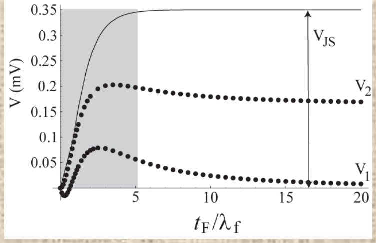
**An electric current loop in an electrically disconnected device !**

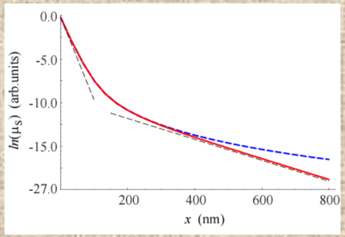
Bazaliy, Ramazashvili, arXiv:1607.06385 = APL **110**, 092405 (2017)

# Conclusions

***1. Local*** injection of pure spin current into an electrically disconnected device produces electric current loops. (Normally, if there is no current flowing into or out of the device, then there is no current anywhere inside it.)

2. These electric loops lead to long-range spin propagation along the F/N interface and substantially modify the voltage distribution in the device.



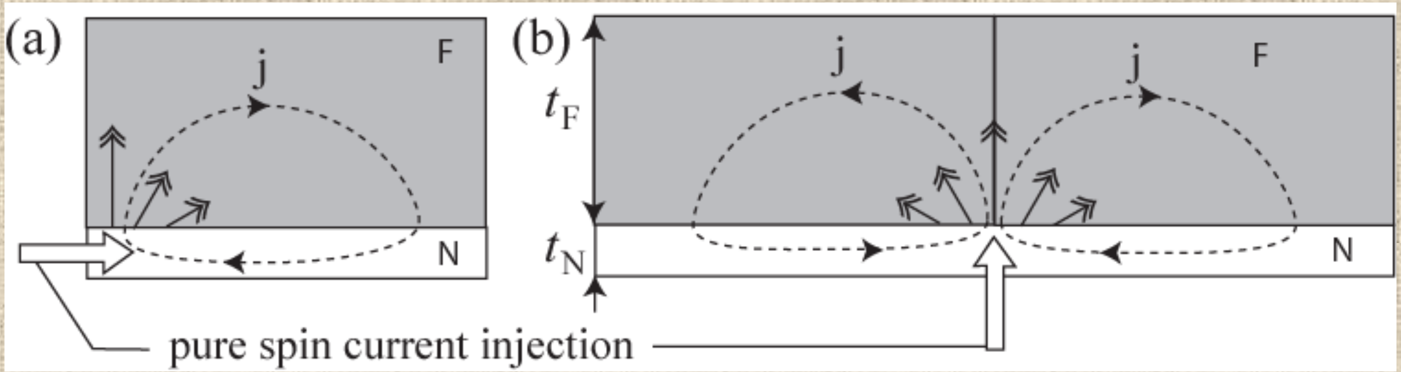




3. Generally, passing the signal via spin without perturbing the charge is an iffy proposition.

Bazaliy, Ramazashvili, arXiv:1607.06385 = APL **110**, 092405 (2017)

# Consequence #1

Voltage depends on the thickness of the F-layer, and on the measurement point




"spin fountain"

Bazaliy, Ramazashvili, arXiv:1607.06385 = APL **110**, 092405 (2017)

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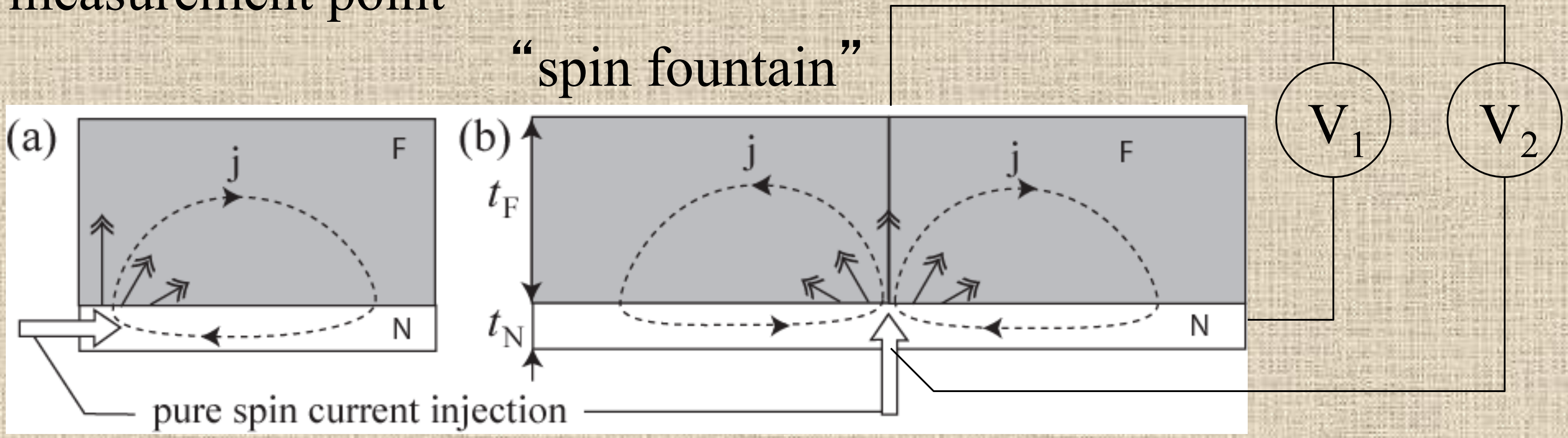


Bazaliy, Ramazashvili, arXiv:1607.06385 = APL **110**, 092405 (2017)

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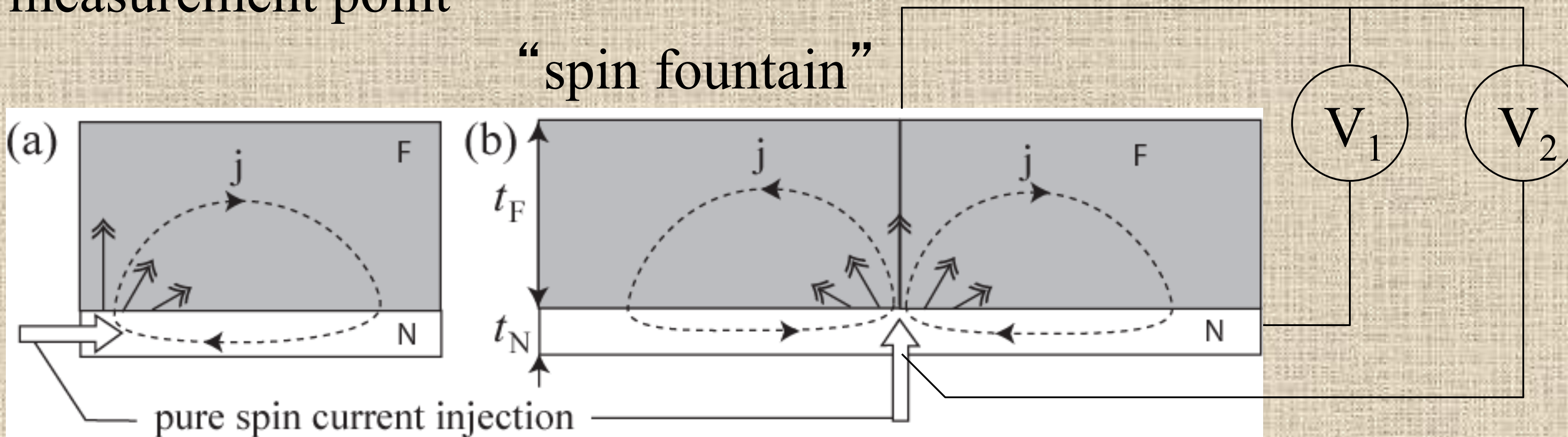


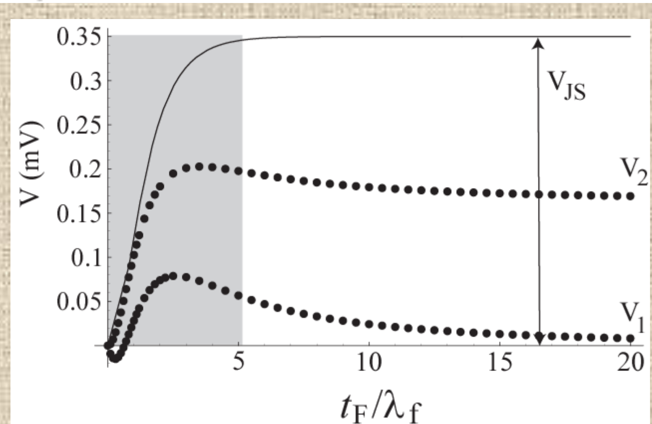


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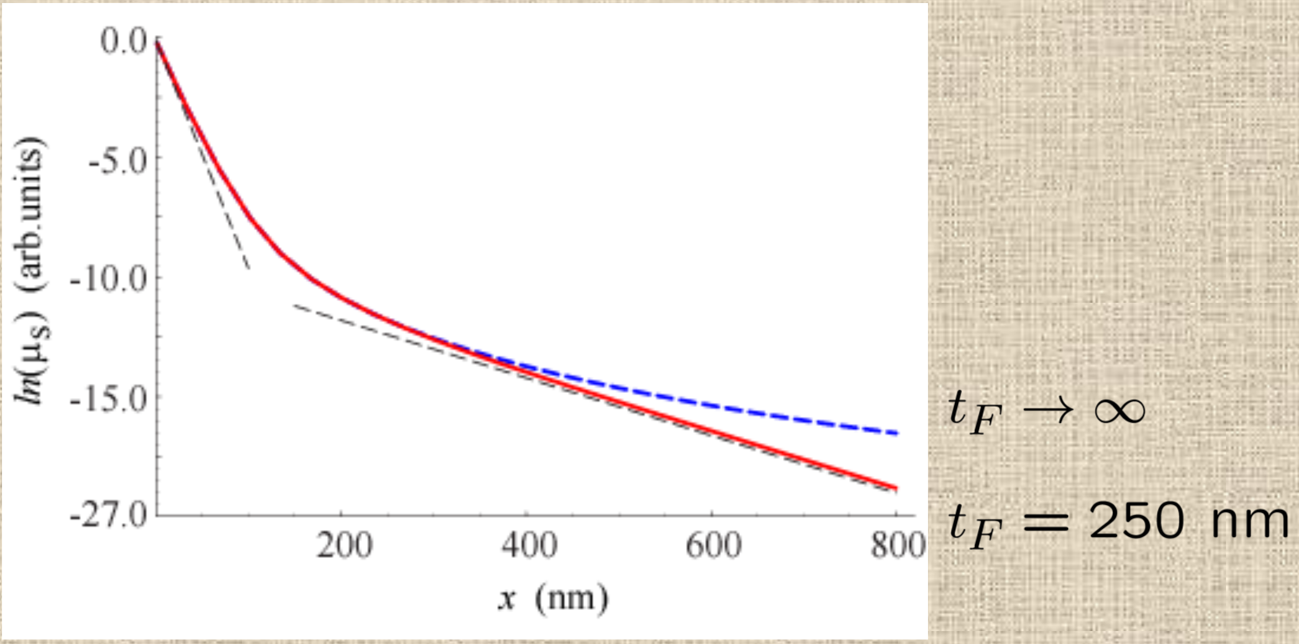
# Consequence #2

How far do the spins propagate along the F/N interface?

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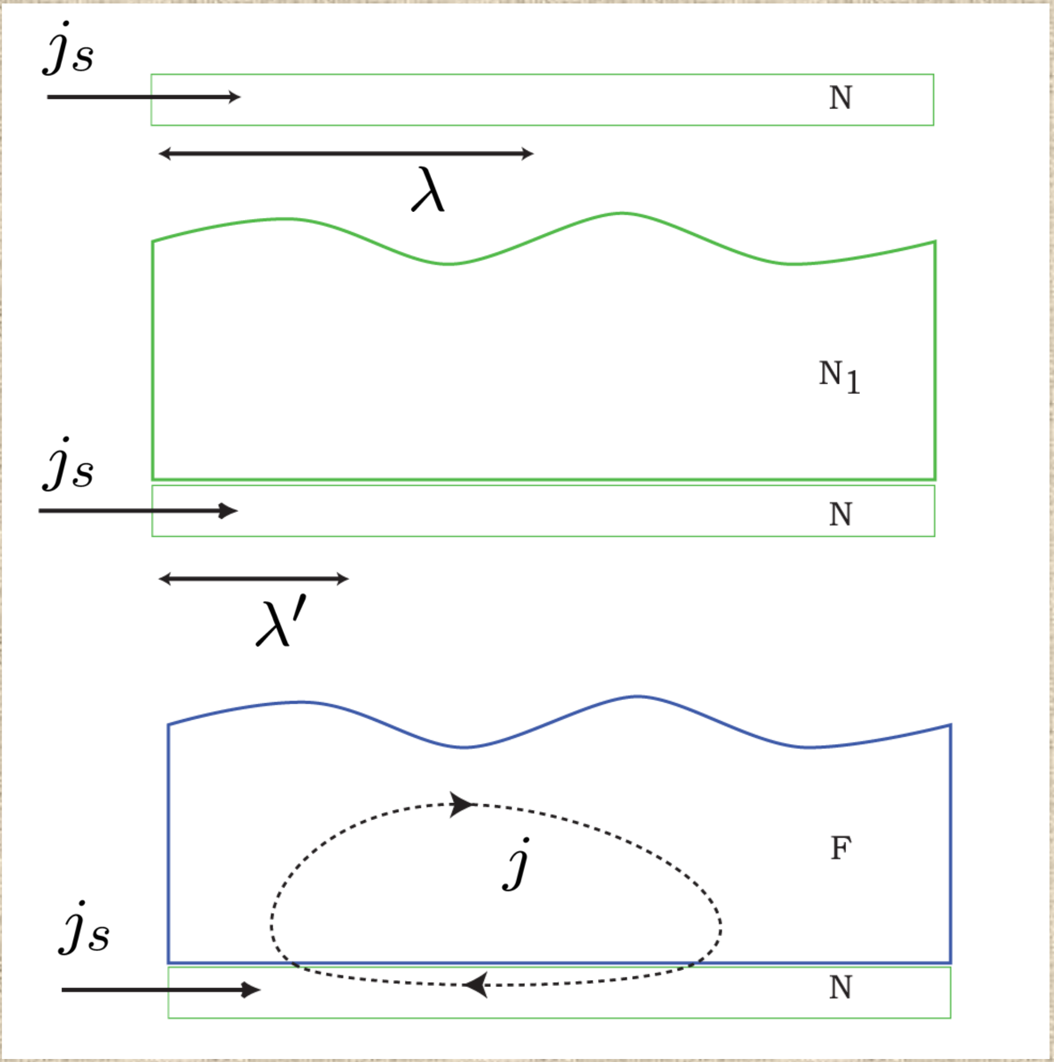
# Long-range spin propagation




$\mu_s(x) \sim \exp(-x/\lambda)\ (x \to \infty)$

$\mu_s(x) \sim \exp(-x/\lambda')\ (x \to \infty)$

$\mu_s(x) \sim x^{-4}\ (x \to \infty)$