Shot noise of charge and spin in magnetic nanostructures

Malek Zareyan

وزارت علوم، تحقیقات و فناوری
مرکز تحصیلات تکمیلی در علوم پایه
گاوازنگ - زنجان

Institute for Advanced Studies
in Basic Sciences
Gava Zang, Zanjan, Iran

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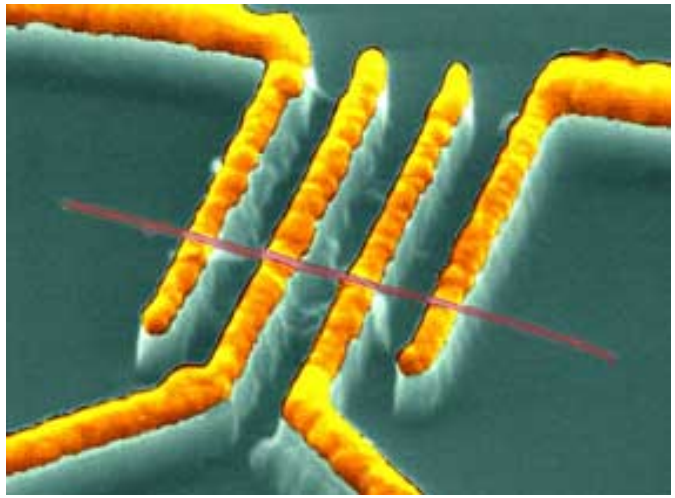
Babak Abdollahipour (PhD, Zanjan)
Moosa Hatami (PhD, Delft)
Wolfgang Belzig (Konstanz)

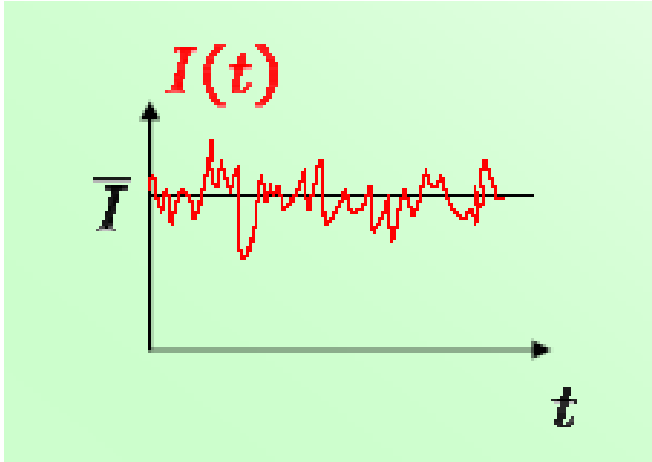
Noise is a signal (Rolf Landauer)

FIG. 1: Whether noise is a nuisance or a signal may depend on whom you ask. (Cartoon by Rand Kruback. Used with permission of Agilent Technologies.)

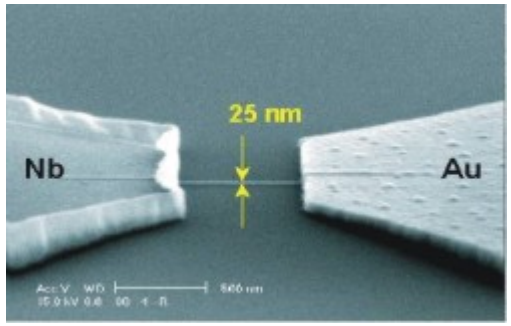
[C. Beenakker and C. Schonenberger, Physics Today, May 2003, page 37]

Noise of electrical current





$$\Delta I(t) = I(t) - \langle I(t) \rangle$$



Noise power:

$$S(\omega) = 2\int_{-\infty}^{\infty} dt e^{-i\omega t} \langle \Delta I(t) \Delta I(0) \rangle,$$

[Mesoscopic physics group, Basel]

Three different types of noise

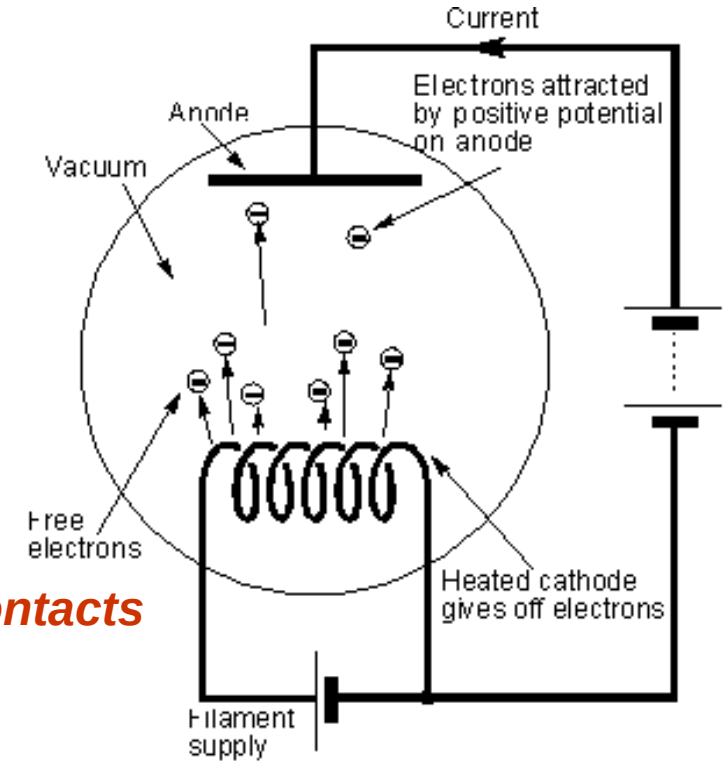
•***Thermal noise*** (Johnson-Nyquist noise, thermal agitations of electrons

•***1/f noise*** (random motion of impurities (time-dependent conductance fluctuations, dominates at low frequency)

•***Shot noise*** (non-equilibrium noise, discreteness of electron Charge, independent of the frequency at low frequencies ,*S* varies linear with mean current)

Shot noise in a vacuum tube (Schottky, 1918)

Electrons are emitted from cathode randomly and independently:
Maximum noise of carriers with charge **e**
(a Poissonian process)



$$S_{\text{Poisson}} = 2e\bar{I}$$

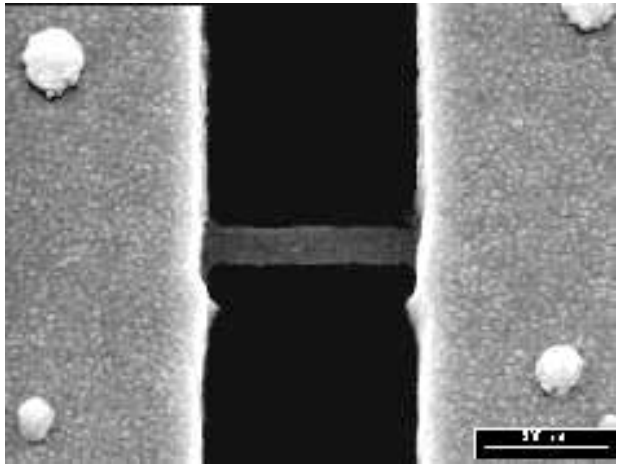
Measuring the unit of charge in tunnel contacts
Fano (1947) factor

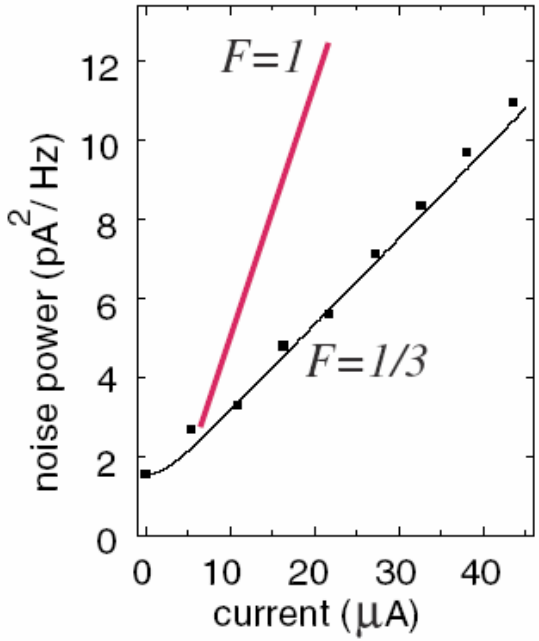
$$F = S/2e\bar{I},$$

$F=1$, **for transfer of electrons (charge e) through a tunnel contact**

F can be different from 1 in presence of correlations and interactions, different charge carriers)

Shot noise suppression in diffusive conductors





Electrons transferring become quite due to the Fermi statistic

F=0, For ballistic contacts

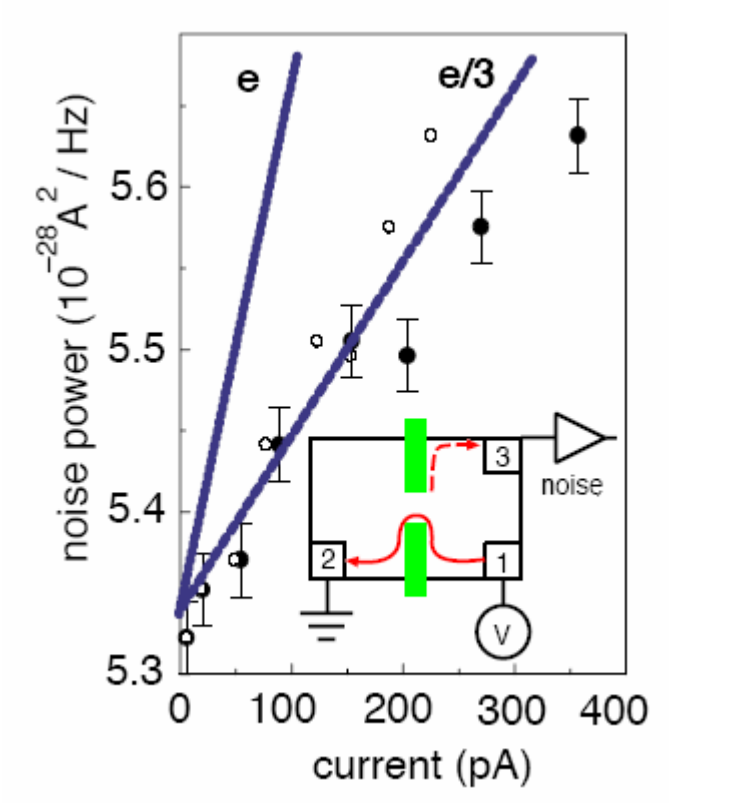
A.H. Steinbach, J.M. Martinis, and M.H. Devoret, Phys. Rev. Lett. **76**, 3806 (1996). More recent experiments include R.J. Schoelkopf, P.J. Burke, A.A. Kozhevnikov, D.E. Prober, and M.J. Rooks, Phys. Rev. Lett. **78**, 3370 (1997); M. Henny, S. Oberholzer, C. Strunk, and C. Schönenberger, Phys. Rev. B **59**, 2871 (1999).

Shot noise of fractional charge

Hall bar on the 1/3 plateau of the fractional quantum Hall effect: p=1 quasiparticle of charge *e/3*

$$q = e/(2p+1)$$

L. Saminadayar, D.C. Glattli, Y. Jin, and B. Etienne, Phys. Rev. Lett. **79**, 2526 (1997); R. de-Picciotto, M. Reznikov, M. Heiblum, V. Umansky, G. Bunin, and D. Mahalu, Nature **389**, 162 (1997); M. Reznikov, R. de-Picciotto, T.G. Griffiths, M. Heiblum, and V. Umansky, Nature **399**, 238 (1999); Y. Chung, M. Heiblum, and V. Umansky, preprint.



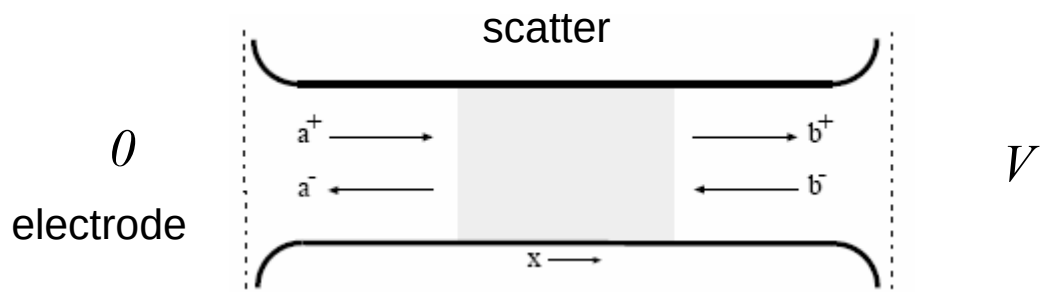
Other example:

Doubled shot noise *(F=2)*, in a tunnel contact between normal metal and superconductor (Cooper pair with *2e* charge tunnelling)[Lefloch et al., 2003]

Landauer-Buttiker formula

Correlations reduces the noise below the Poissonian value

transmission probability T_n



transmission channels

$$\bar{I} = \frac{2e^2}{h} V \sum_{n=1}^{N} T_n.$$

$$S = 2e\frac{2e^2}{h} V \sum_{n=1}^{N} T_n(1 - T_n).$$

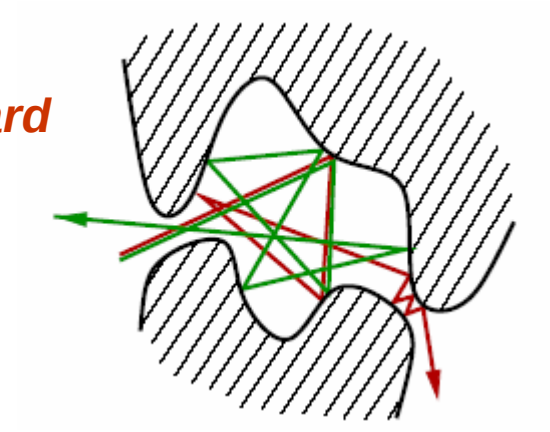
Pauli principal

T_n<<1 tunnel contact $F=1$
$T_n=1$ ballistic contact $F=0$

Tn distribution $p(T)$

Classical to quantum transition in electron billiards

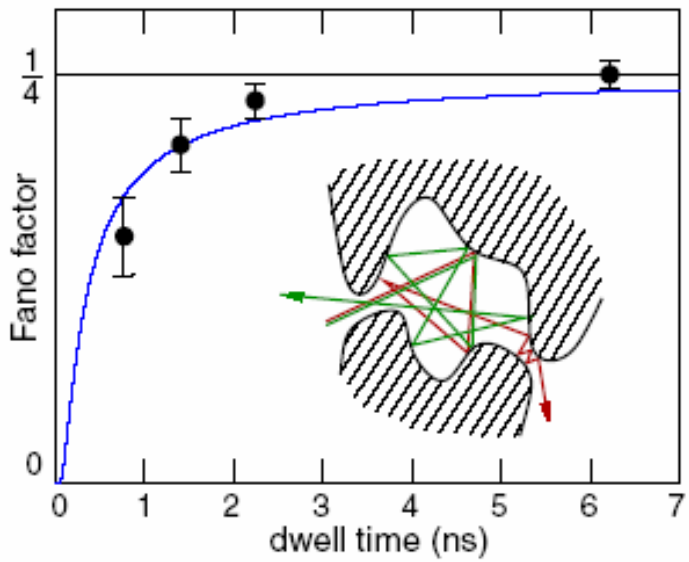
Chaotic billiard



Electron dwell time τ_{dwell} **inside billiard**

Ehrenfest time

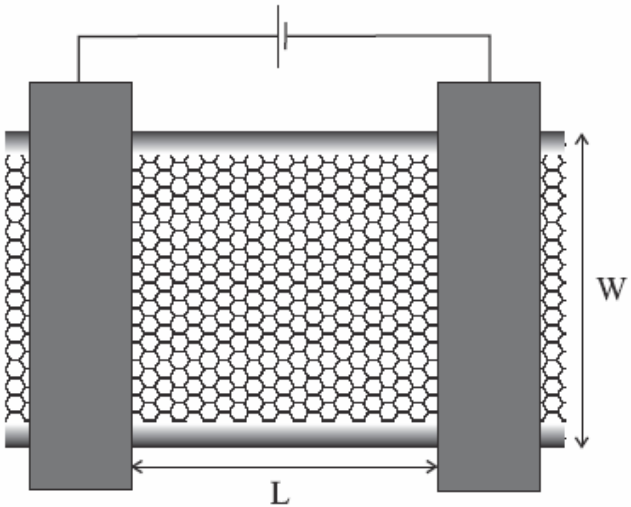
$$\tau_E = \alpha^{-1} \ln(L/\lambda_F)$$

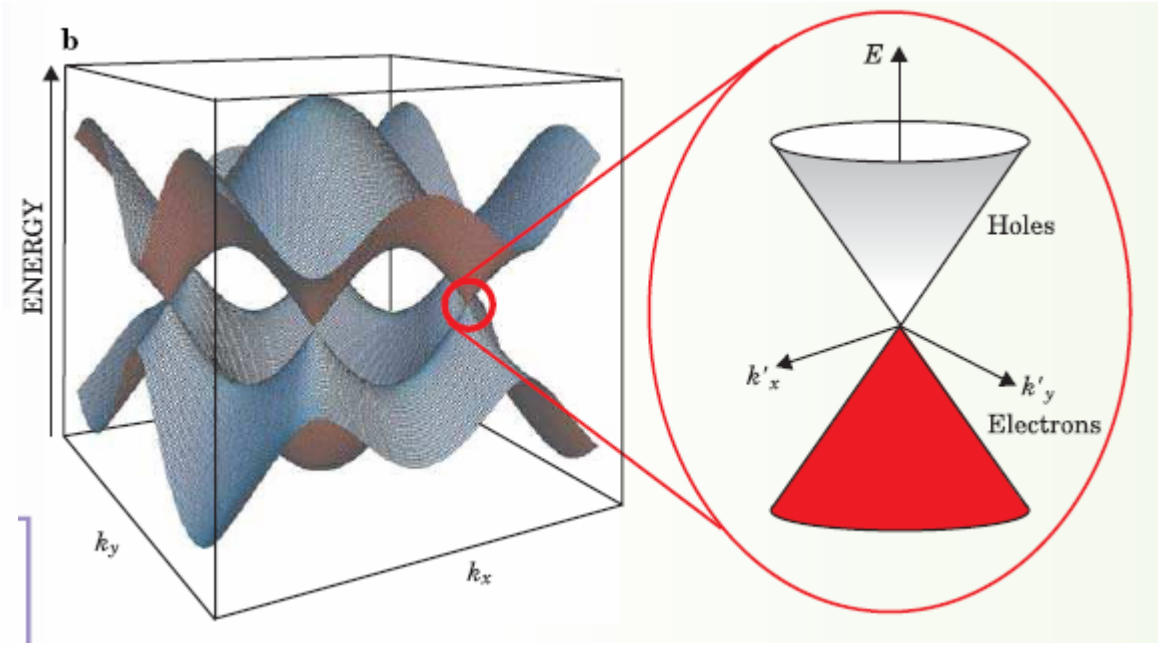


O. Agam, I. Aleiner, and A. Larkin, Phys. Rev. Lett. **85**, 3153 (2000).
S. Oberholzer, E.V. Sukhorukov, and C. Schönenberger, Nature **415**, 765 (2002).

time to initially wave packet of Fermi wave length to spread over size of billiard *L*

Noise of massless Dirac Fermions in graphene





F=1/3, For ballistic (!) graphene

Electrical noise by relativistic dynamics

[Tworzydlo et al, cond-mat/0603315l]

In mesoscopic and nanoscopic N metal, semiconducting, and superconducting Structures including tunnel, diffusive, ballistic contacts: Shot noise provide unique Information about the charge, the statistic and the scattering of the charge carriers.
Ya. M. Blanter and M. Buettiker, Phys. Rep. 336, 1 (2000).

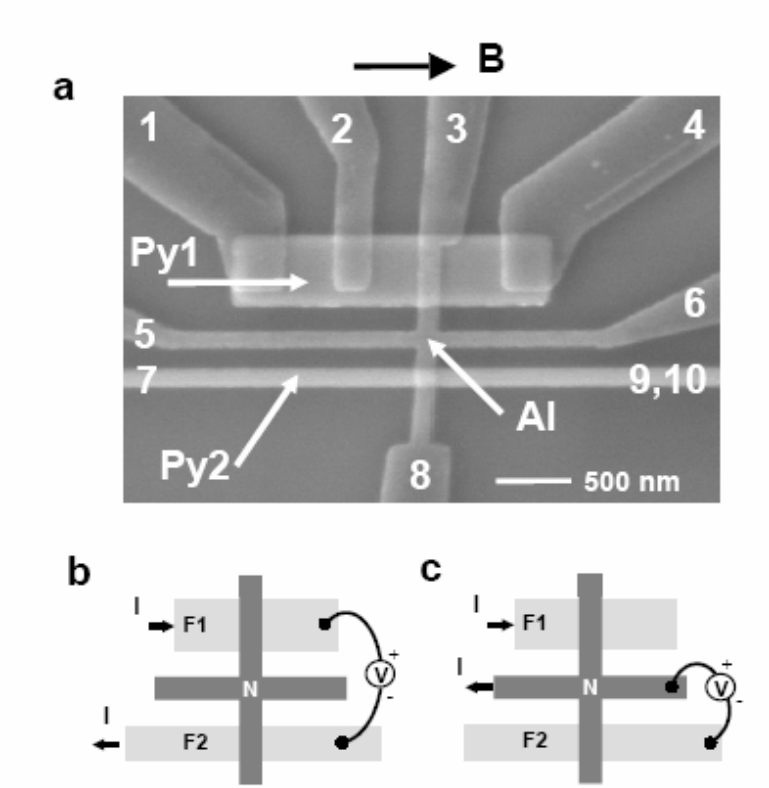
What about spin?

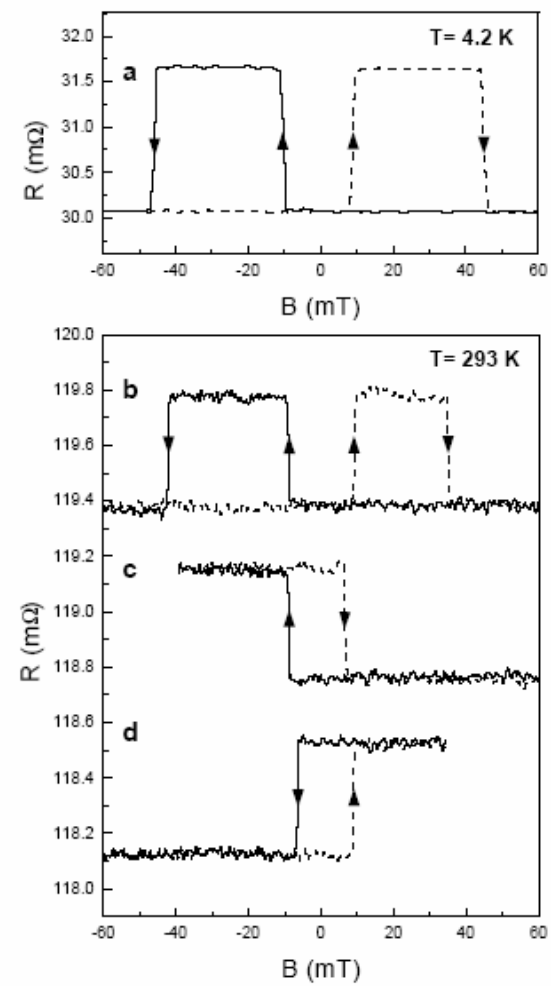
Spintronic: Devices made up ferromagnetic and nonmagnetic materials to:
1-spin control of the currents and voltages
2-currents or voltages control of spin

Spin-polarization injection, relaxation, manipulation, detection: physics of spin and exciting applications

[I. Zutic et al, Rev. Mod. Phys. **76**, 323 (2004); Y. Tserkovnyak et al, cond-mat/0409242]

Spin-valve





Spin injection experiment at room temperature

[Jedema et al., Nature (2001)]

Boltzmann-Langevin equations for spin-polarized currents

Charge

$$f_c(\mathbf{r},E,t) = \bar{f}_c(\mathbf{r},E) + \delta f_c(\mathbf{r},E,t)$$

$$\boldsymbol{j}_c(\mathbf{r},E,t) = \bar{\boldsymbol{j}}_c(\mathbf{r},E) + \delta \boldsymbol{j}_c(\mathbf{r},E,t)$$

$$\nabla \cdot \boldsymbol{j}_c(\mathbf{r},E,t) = 0$$

$$\boldsymbol{j}_c(\mathbf{r},E,t) = -\nabla f_c(\mathbf{r},E,t) + \boxed{\boldsymbol{j}_c^{\mathrm{c}}(\mathbf{r},E,t)}$$

Spin

$$f_s(\mathbf{r},E,t) = \bar{f}_s(\mathbf{r},E) + \delta f_s(\mathbf{r},E,t)$$

$$\boldsymbol{j}_s(\mathbf{r},E,t) = \bar{\boldsymbol{j}}_s(\mathbf{r},E) + \delta \boldsymbol{j}_s(\mathbf{r},E,t)$$

$$\nabla \cdot \boldsymbol{j}_s(\mathbf{r},E,t) = -\frac{\sigma}{\ell_{\mathrm{sf}}^2} f_s(\mathbf{r},E,t) + \boxed{i^{\mathrm{sf}}(\mathbf{r},E,t)}$$

$$\boldsymbol{j}_s(\mathbf{r},E,t) = -\nabla f_s(\mathbf{r},E,t) + \boxed{\boldsymbol{j}_s^{\mathrm{c}}(\mathbf{r},E,t)}$$

Langevin source current fluctuations

Fluctuating spin-flip divergent term

$$\left\langle \boldsymbol{j}_c^{\mathrm{c}}(\mathbf{r},E,t)\boldsymbol{j}_c^{\mathrm{c}}(\mathbf{r}',E',t') \right\rangle =$$

$$\delta(\mathbf{r}-\mathbf{r}')\delta(E-E')\delta(t-t')\sigma \bar{f}_c(\mathbf{r},E)[1-\bar{f}_c(\mathbf{r},E)]$$

[Nagaev (1992)]

Correlation of current fluctuations

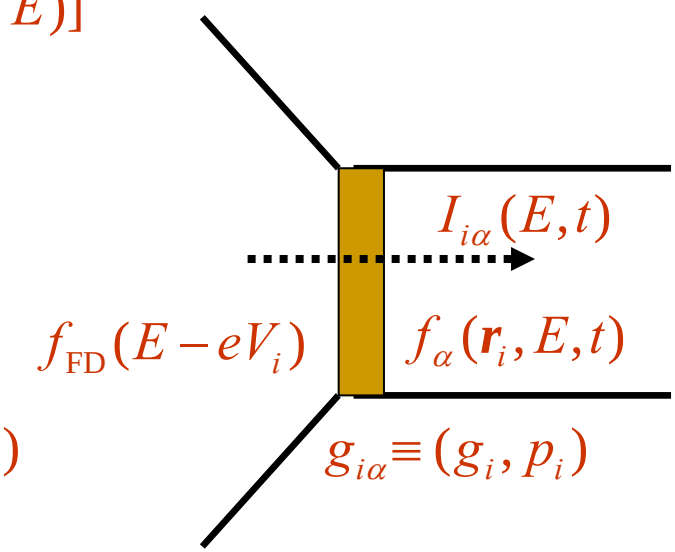
$$\left\langle j_c^{\mathrm{c}}(\mathbf{r},E,t)\, j_c^{\mathrm{c}}(\mathbf{r}',E',t')\right\rangle = \left\langle j_s^{\mathrm{c}}(\mathbf{r},E,t)\, j_s^{\mathrm{c}}(\mathbf{r}',E',t')\right\rangle = \Delta\sigma \sum_{\alpha=\pm} \bar{f}_\alpha(\mathbf{r},E)[1-\bar{f}_\alpha(\mathbf{r},E)]$$

$$\left\langle j_c^{\mathrm{c}}(\mathbf{r},E,t)\, j_s^{\mathrm{c}}(\mathbf{r}',E',t')\right\rangle = \Delta\sigma \sum_{\alpha=\pm} \alpha \bar{f}_\alpha(\mathbf{r},E)[1-\bar{f}_\alpha(\mathbf{r},E)]$$

$$\left\langle i^{\mathrm{sf}}(\mathbf{r},E,t)\, i^{\mathrm{sf}}(\mathbf{r}',E',t')\right\rangle = \Delta \frac{\sigma}{\ell_{\mathrm{sf}}^2} \sum_{\alpha=\pm} \bar{f}_\alpha(\mathbf{r},E)[1-\bar{f}_{-\alpha}(\mathbf{r},E)]$$

$$\left\langle j_c^{\mathrm{c}}(\mathbf{r},E,t)\, i^{\mathrm{sf}}(\mathbf{r}',E',t')\right\rangle = 0$$

Boundary condition:
Temporal current conservation in a tunnel contact

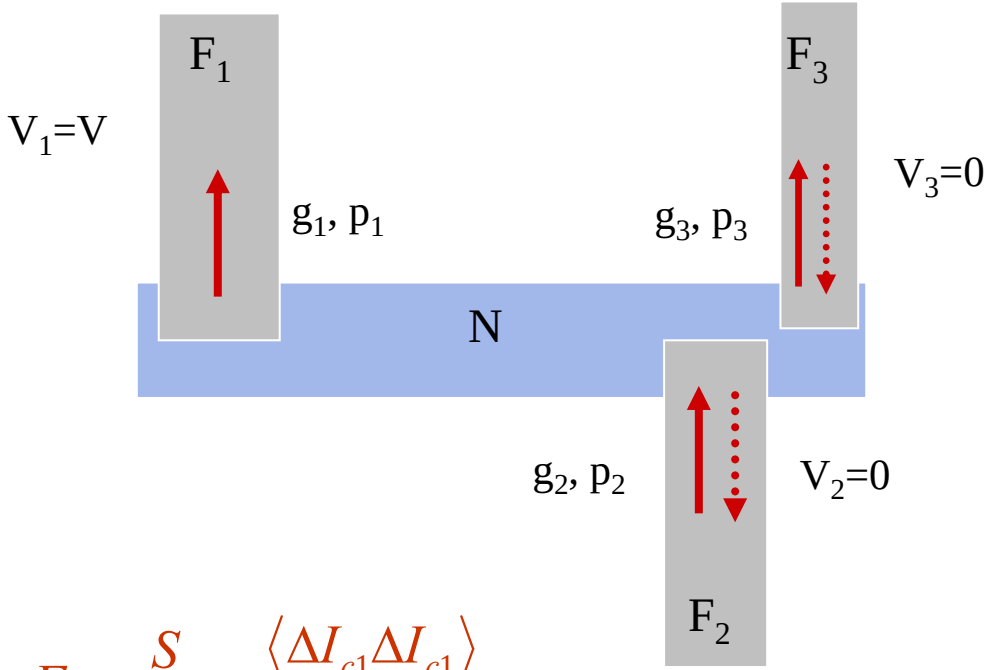


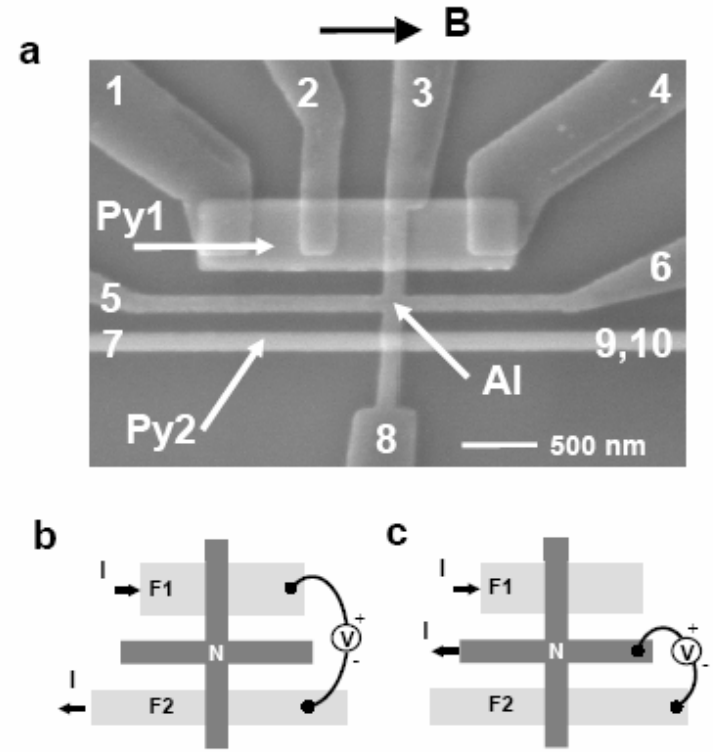
$$I_{i\alpha}(E,t) = g_{i\alpha}[f_{\mathrm{FD}}(E-eV_i) - f_\alpha(\mathbf{r}_i,E,t)] + \delta I_{i\alpha}(E,t)$$

$$\left\langle \delta I_{i\alpha}(E,t)\, \delta I_{i\alpha'}(E,t)\right\rangle = \delta_{\alpha\alpha'}\delta(t-t')2e\bar{I}_{i\alpha}(E)$$

[M. Z. and W. Belzig, PRB (2005)]

Three-terminal spin-valve





$$F = \frac{S}{2eI} = \frac{\langle \Delta I_{c1} \Delta I_{c1} \rangle}{2eI}$$

$$F_{23} = \frac{S_{23}}{2eI} = \frac{\langle \Delta I_{c2} \Delta I_{c3} \rangle}{2eI}$$

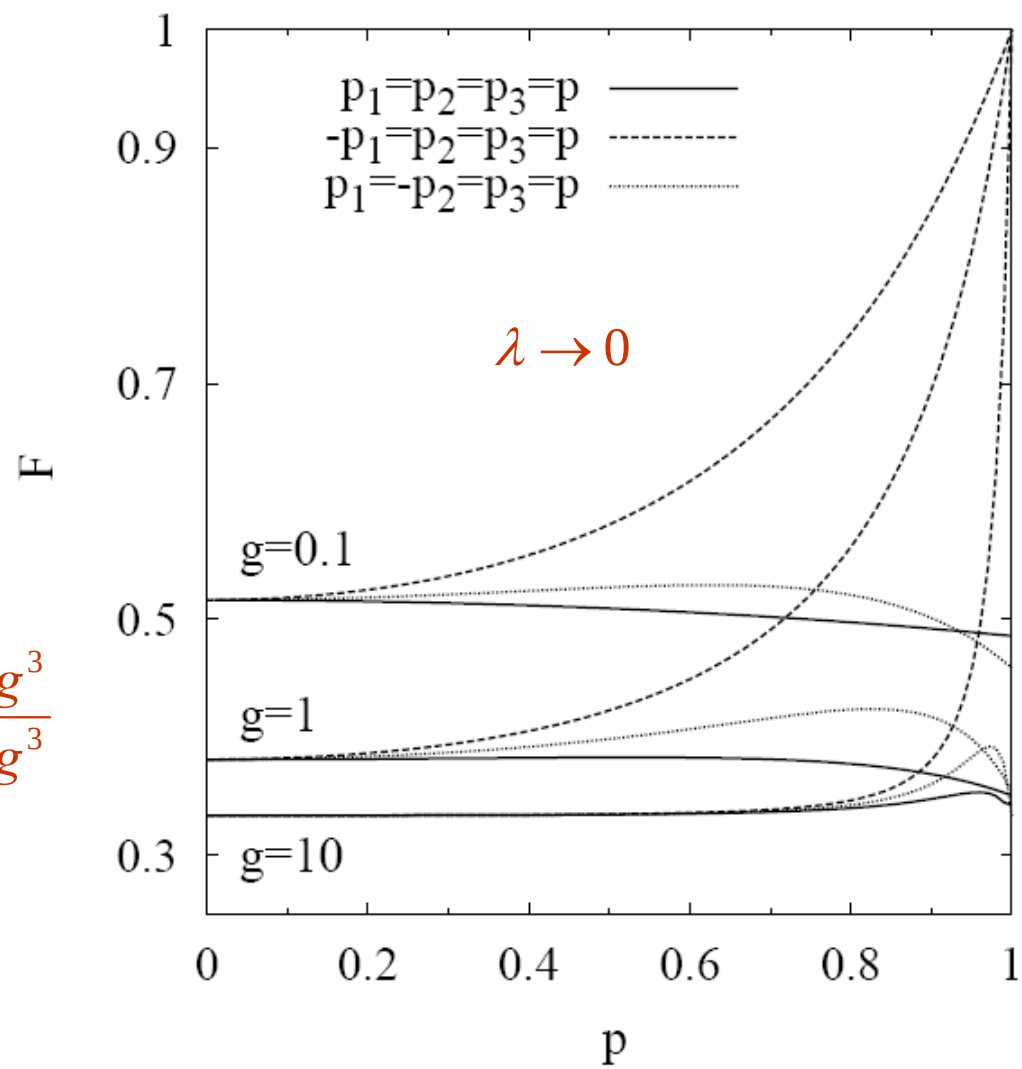
[Jedema et al., (2001)]

Shot noise

$$g = \frac{g_i}{g_N}, |p_i| = p, \lambda = \frac{L}{\ell_{\mathrm{sf}}}$$

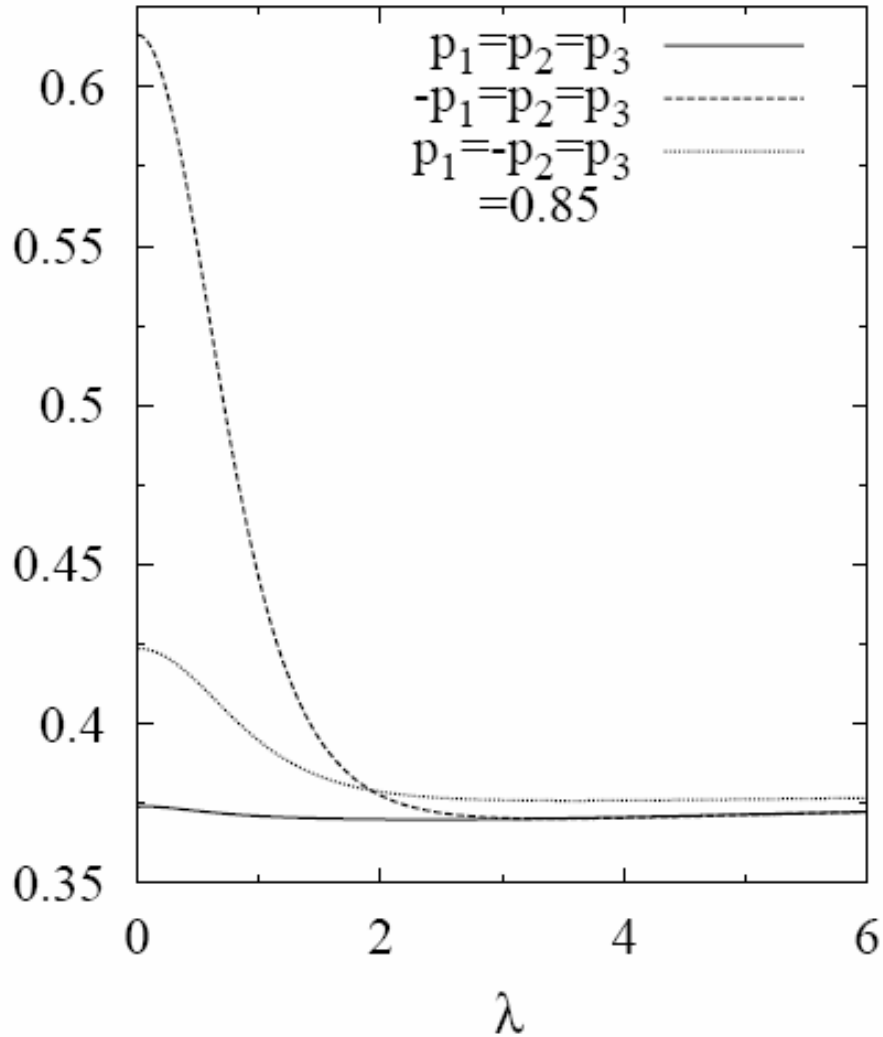
$$F(g, \lambda, \{p_i\}, p)$$

$$F_N = \frac{1}{3}\frac{5 + 6g + 4g^2 + 8/9\, g^3}{3 + 6g + 4g^2 + 8/9\, g^3}$$



Shot noise: effect of spin-flip

$F(g=1,|p|=0.85,\{p_i\},\lambda)$

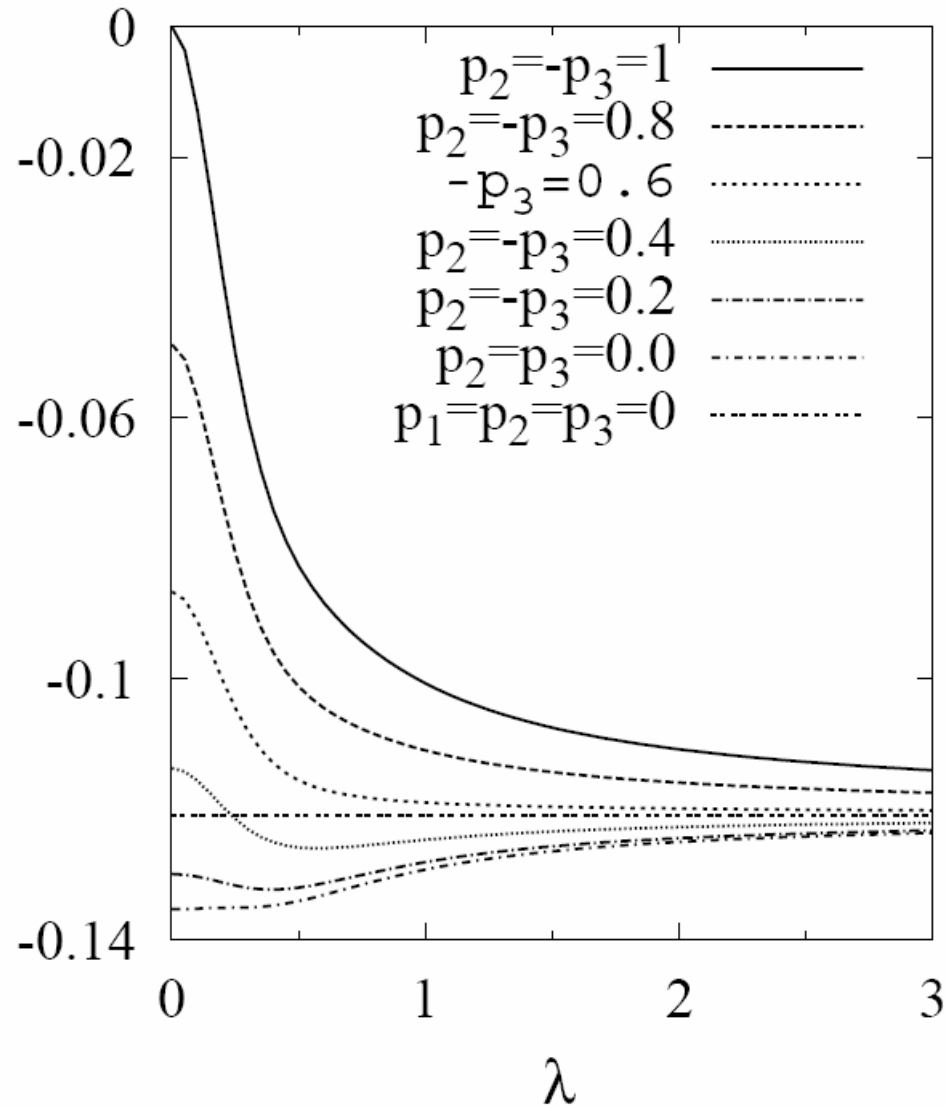


F_N

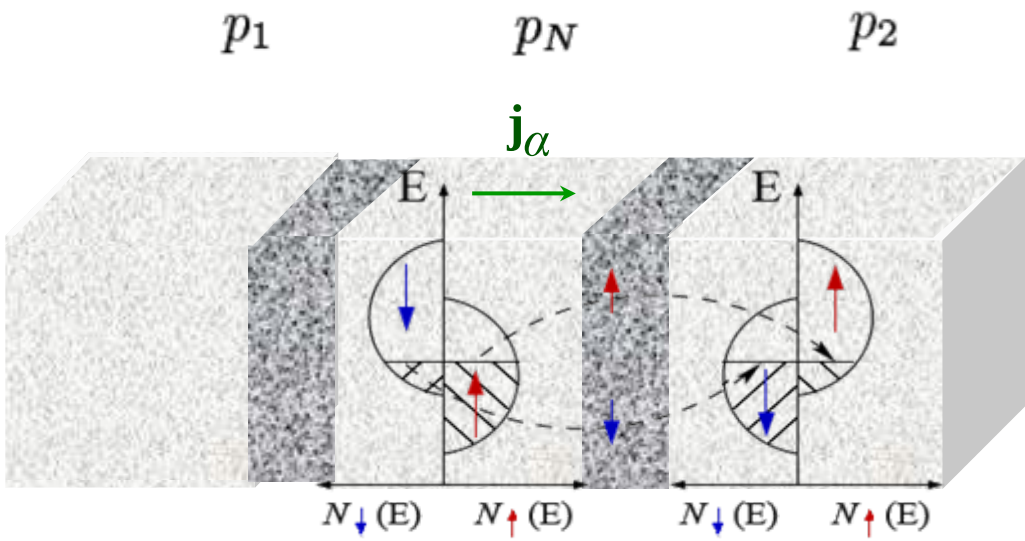
Cross correlations

$$F_{23} = \frac{S_{23}}{2eI} = \frac{\langle \Delta I_{c2} \Delta I_{c3} \rangle}{2eI}$$

$$F_{23}(g = 0.1, p2 = -p3, \lambda)$$



FFF structures: the model



Extended BL theory:

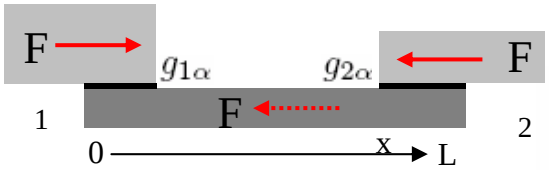
$$p_N = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Polarization of the conductivity

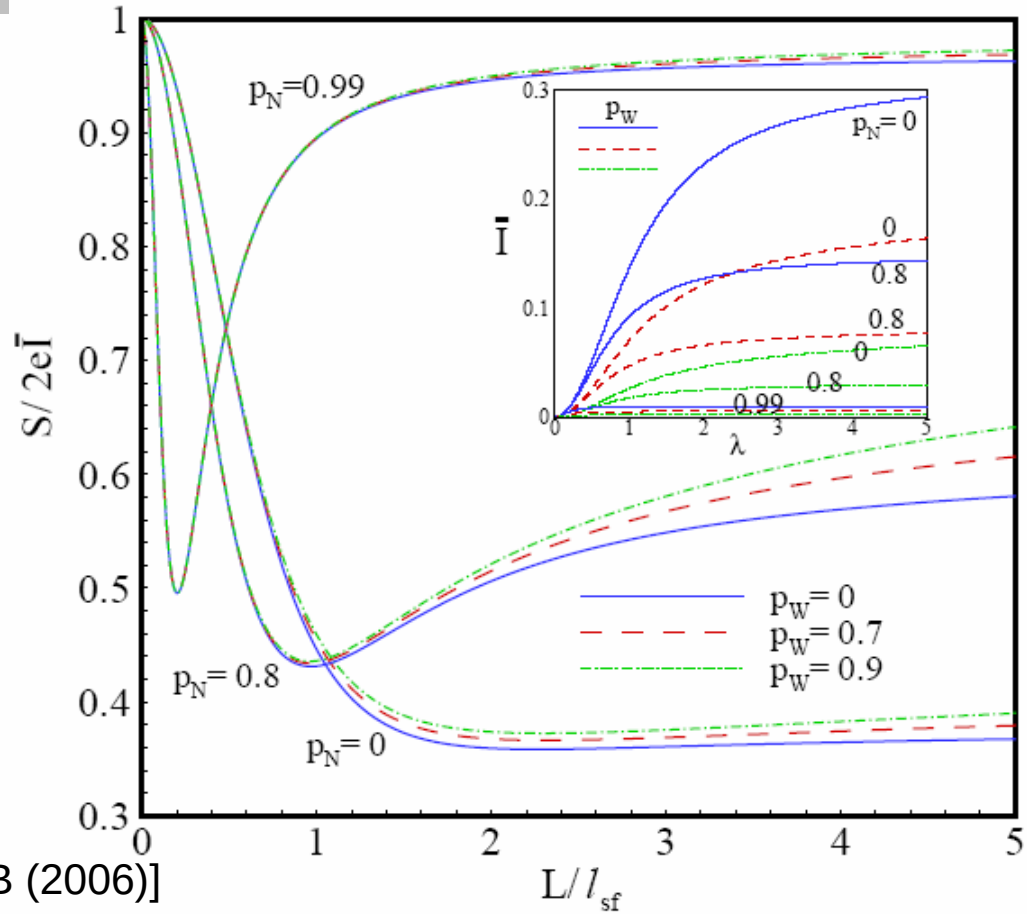
$$p_\sigma = p_\sigma(p_N, p_W, \lambda)$$

$$p_W = \frac{W_\uparrow - W_\downarrow}{W_\uparrow + W_\downarrow}$$

FFF structures: antiparallel

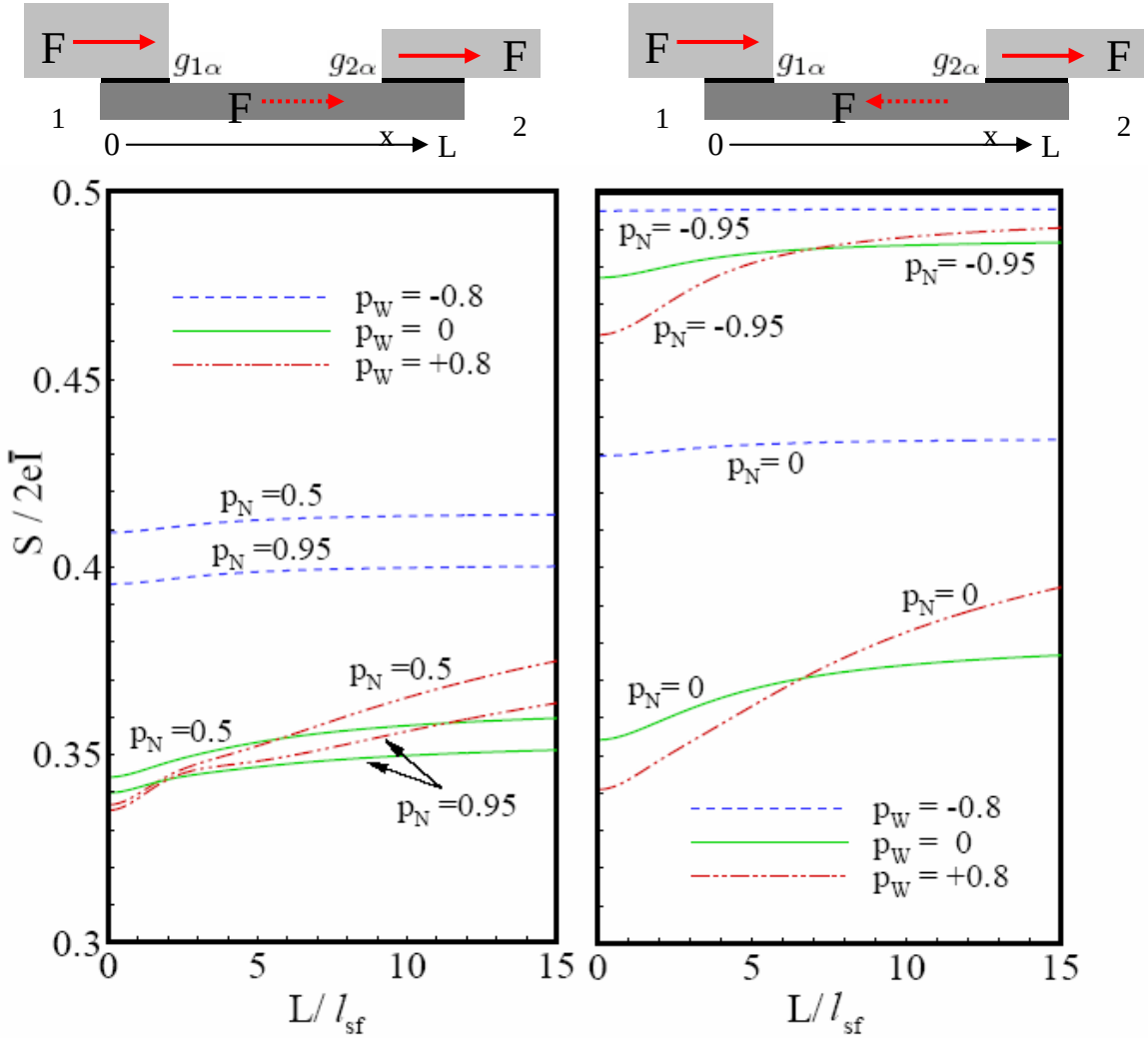


Perfectly polarized terminals



[M. Hatami and M. Z. , PRB (2006)]

FFF structures : parallel



Summary

- **Spin-dependent Boltzman-Langevin theory: collinear magnetizations [M. Z. , W. Belzig (2005)]**
- **Noncollinear BL : Angular magneto shot noise [B. Abdollahipour, M. Z. (2006)]**
- **Shot noise of N spin-valve : strong dependence on the spin-flip rate and the magnetizations configuration**
- **Shot noise of spin current: more sensitive [M. Z. and W. Belzig, (2005)]**
- **Shot noise of FFF structure probe the intrinsic DOS and the extrinsic impurity scattering rate polarizations**
- **Experiments ?**

Mesoscopic physics group at IASBS:
http://www.iasbs.ac.ir/physics/condmat/research/condmatt/mesoscopic.htm