Pauli-blockaded spin transport across coupled quantum magnets

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collaborator & acknowledgment

- PhD student:

Joshua Aftergood

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- summary and outlook

spin Hall phenomena

- experimental evidence for macroscopic coupling between electrical currents and magnetization dynamics in normal metal-magnet bilayers

manipulation of magnetization with electrical currents

- spin transfer torque

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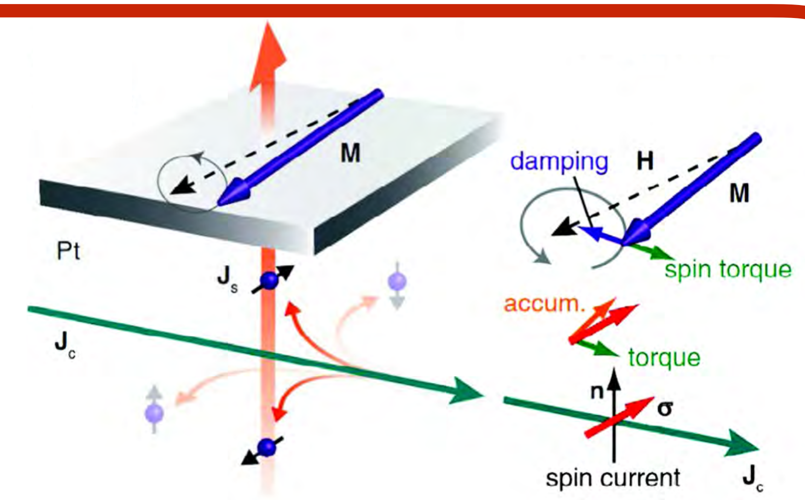

- inverse spin galvanic effect

A. Manchon, J. Appl. Phys. **104**, 043914 (2008)
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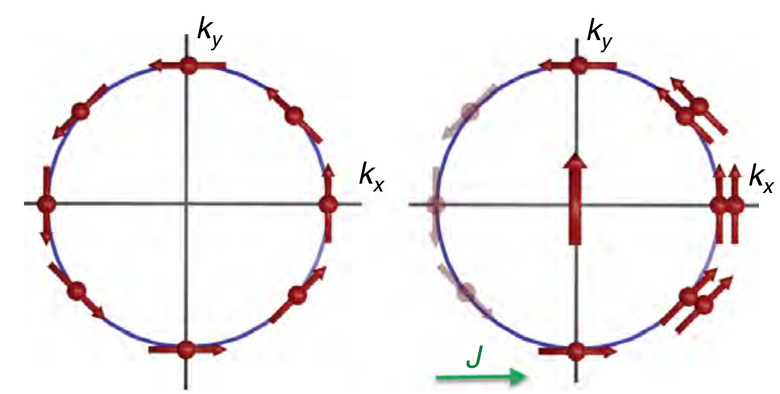

electrical detection of spin current

- spin pumping/inverse spin Hall effect

S. Mizukami *et al*., J. Magn. Magn. Mater. **226–230**, 1640 (2001)
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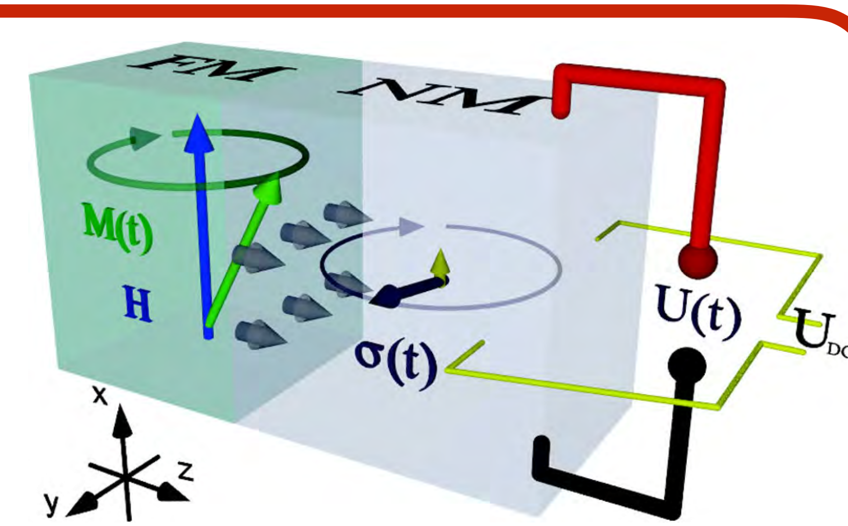
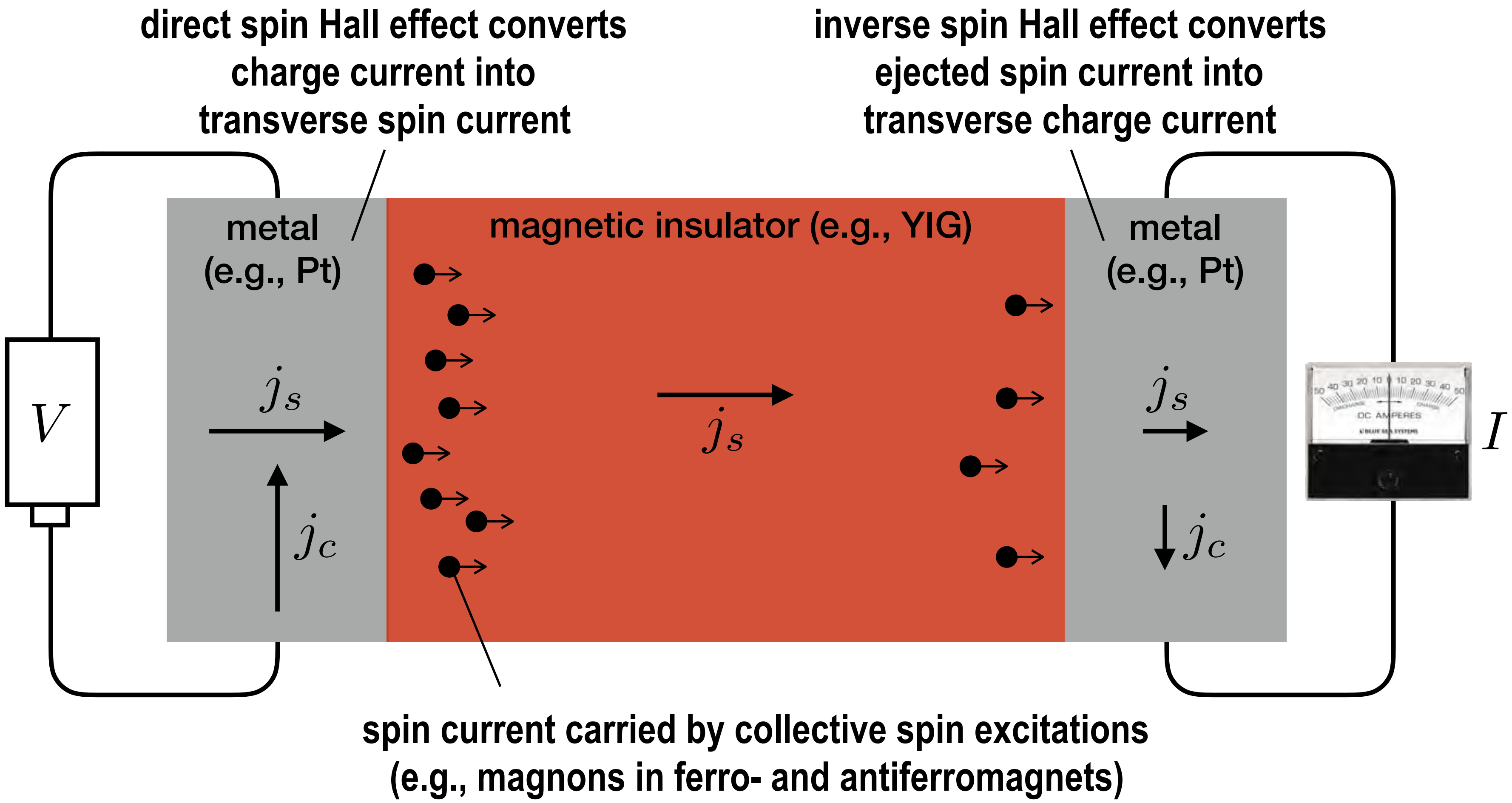


J. Sinova *et al*., Rev. Mod. Phys. **87**, 1213 (2015)

two-terminal spin transport through insulators

- nonlocal current drag mediated by diffusing magnons in a magnetic insulator
- e.g., yttrium iron garnet-platinum heterostructure (Pt|YIG|Pt)
  - YIG: Curie temperature 560K, very low magnetic damping (magnon spin diffusion length ~ 9μm @ room temperature — ~ 47 - 73μm @ 23K)
  - Pt: strong spin-orbit coupling facilitates spin-to-charge interconversion



what can we learn from the noise in the spin current?

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S. B. Gönnenwein *et al.*, App. Phys. Lett. **107**, 172405 (2015)
B. L. Giles *et al.*, Phys. Rev. B **92**, 224415 (2015)
J. Li *et al.*, Nature Comm. **7**, 10858 (2016)

spin current noise

- spin-dependent charge current noise:

E. G. Mishchenko, Phys. Rev. B **68**, 100409 (2003)
R. Guerrero, F. G. Aliev, Y. Tserkovnyak, T. S. Santos, and J. S. Moodera, Phys. Rev. Lett. **97**, 266602 (2006)
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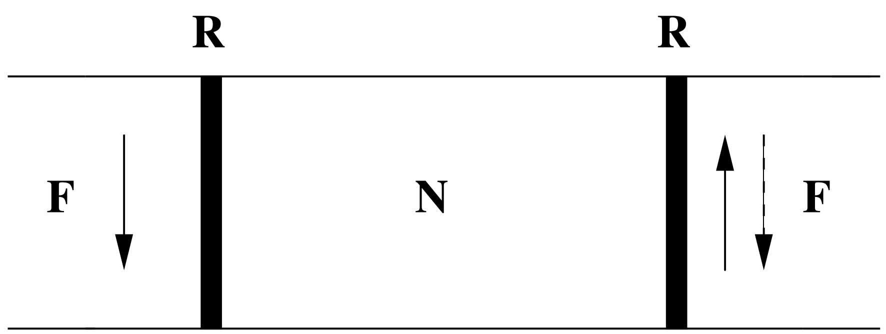
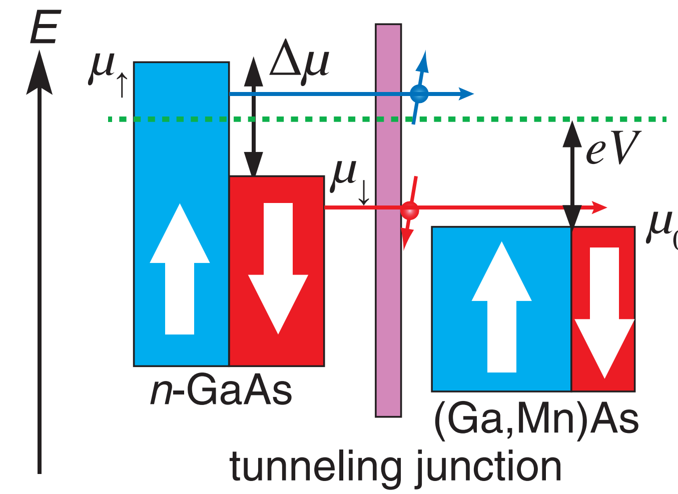
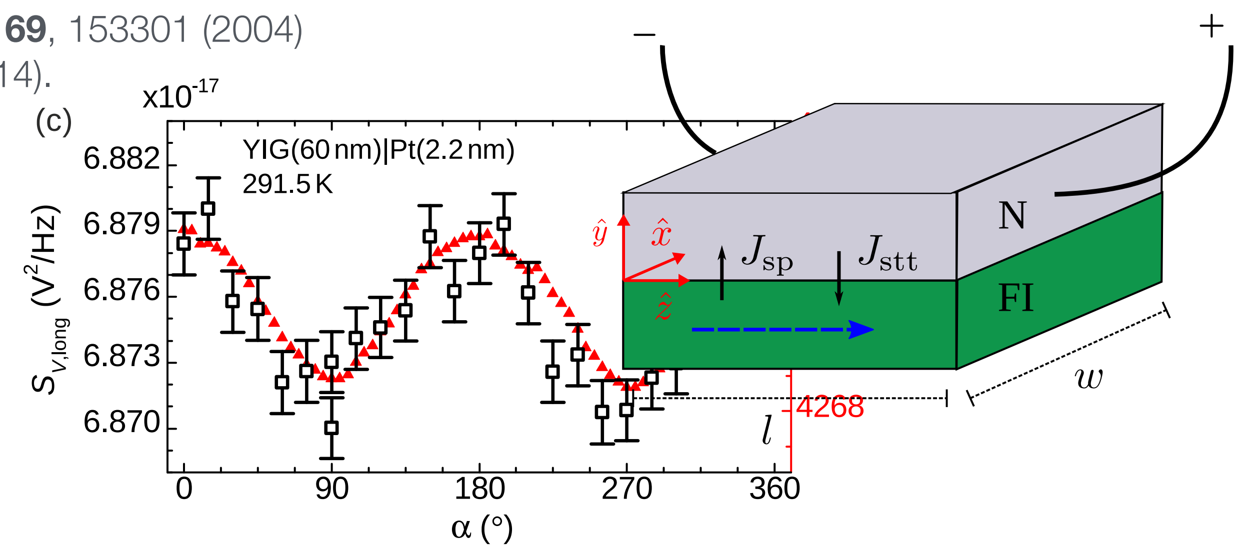




- noise in pure spin current in conductors:

B. Wang, J. Wang, and H. Guo, Phys. Rev. B **69**, 153301 (2004)
A. Kamra *et al.*, Phys. Rev. B **90**, 214419 (2014).



- noise in spin current pumped by a ferromagnetic (ferrimagnetic) insulator:

A. Kamra and W. Belzig, Phys. Rev. Lett. **116**, 146601 (2016)
A. Kamra and W. Belzig, arXiv:1706.07118. ← **Akash's talk**

Focus: spin current and its noise in 1d quantum magnets

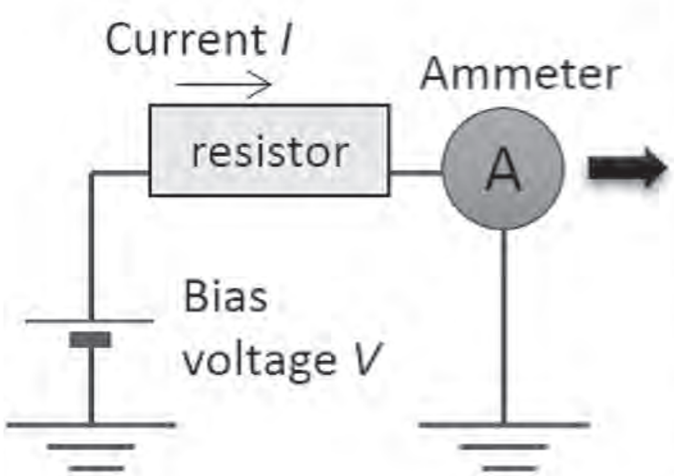
(charge) current noise in mesoscopic systems

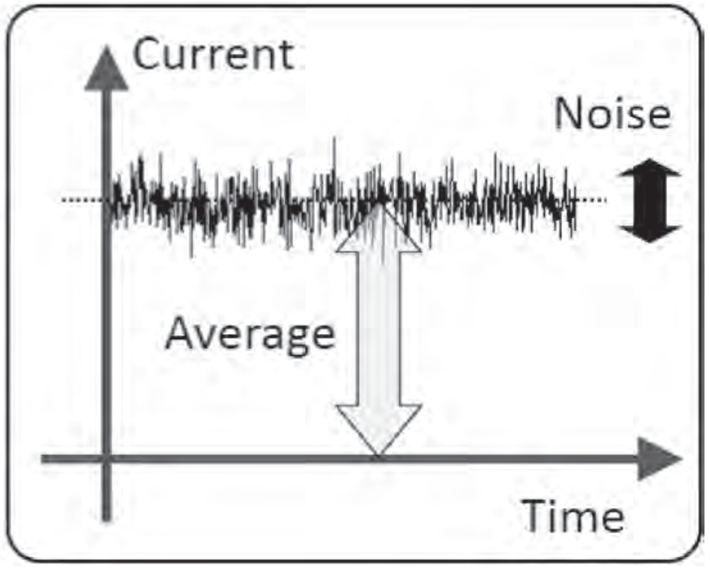
- a resistor biased by voltage and ammeter measuring current:
  - time-averaged value: $\langle I \rangle$
  - noise (fluctuations about the mean value):

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

  - noise spectral density:

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





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Ya. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000)
K. Kobayashi, Proc. Jpn. Acad. B **92**, 204 (2016)

- consider zero voltage case: $V = 0$
  - time-averaged value: $\langle I \rangle = 0$
  - noise spectral density at finite temperature: $S_{\rm th}(\omega) = 2k_B T G$
  - G quantifies **response** of the resistor to external voltage: $I = GV$

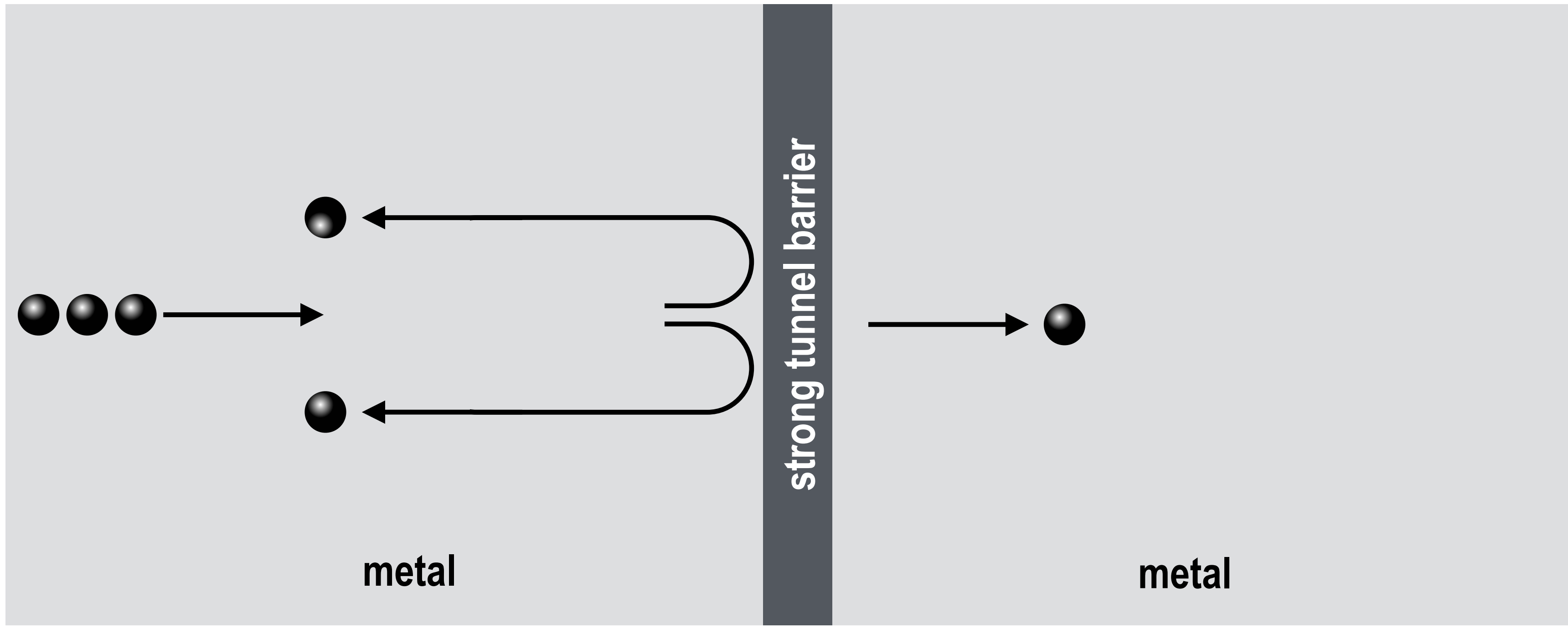
- first measured in an electrical conductor by Johnson in 1928 and theoretical explained by Nyquist in the same year.

Equilibrium noise is a manifestation of fluctuation-dissipation theorem that dictates a relationship between the fluctuations and the response of a system.

J. B. Johnson, Phys. Rev. **32**, 97 (1928)
H. Nyquist, Phys. Rev. **32**, 110 (1928)

(nonequilibrium) shot noise

- a metal-insulator-metal trilayer under a finite voltage: $V \neq 0$



- stochastic tunneling of electrons gives rise to noise in the transmitted current (due to Schottky in 1918):

$$S_{\text{shot}} = e \langle I \rangle$$

assume tunneling events are uncorrelated so that the tunneling process obeys the Poissonian distribution

current $$\langle I \rangle = \frac{e \langle N \rangle}{\tau} \quad \longrightarrow \quad \left\langle (\delta N)^2 \right\rangle = \langle N \rangle$$

noise $$\left\langle (\delta I)^2 \right\rangle = \frac{e^2 \left\langle (\delta N)^2 \right\rangle}{\tau} = \frac{e^2 \langle N \rangle}{\tau} = e \langle I \rangle$$

W. Schottky, Ann. Phys. **362**, 541 (1918)

fermionic statistics

- incorporate fermionic statistics (ignore interactions)
- consider with mesoscopic conductor with *n* conducting channels:

  - conductance: $$G = \frac{2e^2}{h}\sum_n T_n$$ **"Landauer formula"**
  - noise spectral density for low-frequencies:

$$S = 2k_BTG + e\langle I\rangle F\left[\coth\left(\frac{eV}{2k_BT}\right) - \frac{2k_BT}{eV}\right]$$

  - Fano factor:

$$F = \frac{\sum_n T_n(1-T_n)}{\sum_n T_n}$$

$$\frac{eV}{k_BT} \ll 1$$

$$S \rightarrow S_{\text{th}} = 2k_BTG$$

thermal noise recovered

$$\frac{eV}{k_BT} \gg 1$$

$$S \rightarrow FS_{\text{shot}} = Fe\langle I\rangle$$

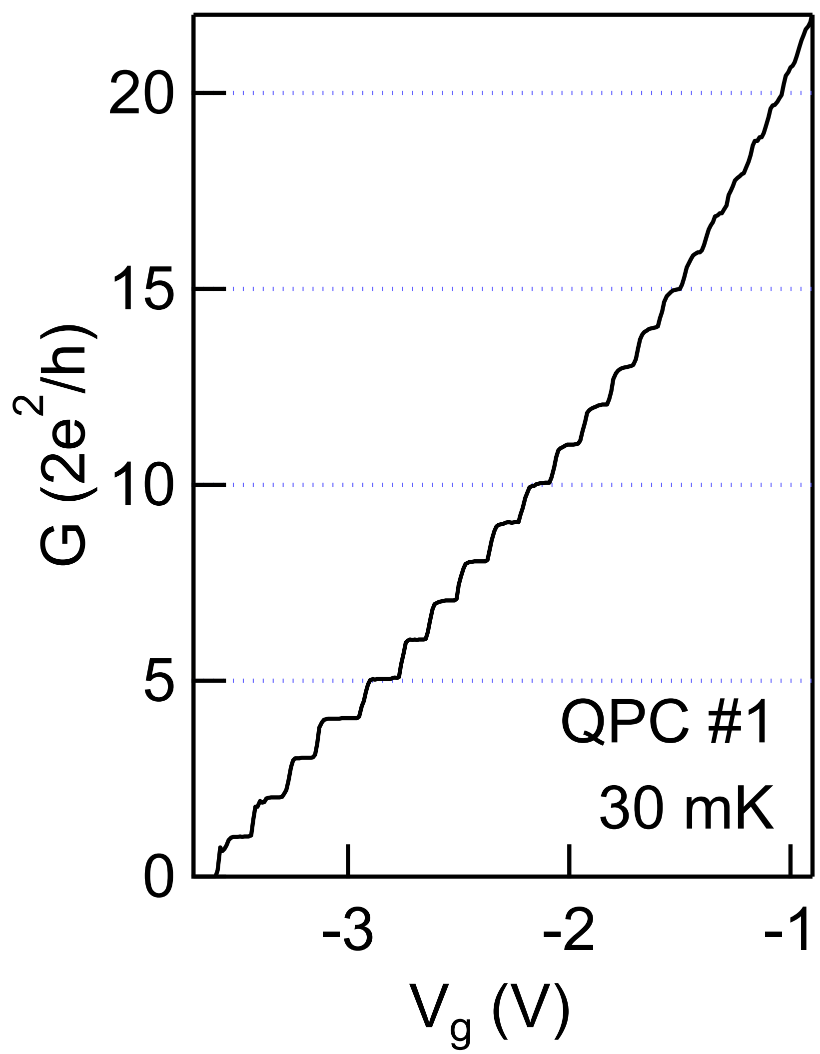
$F \rightarrow 1$: **low transmission limit (shot result recovered)**

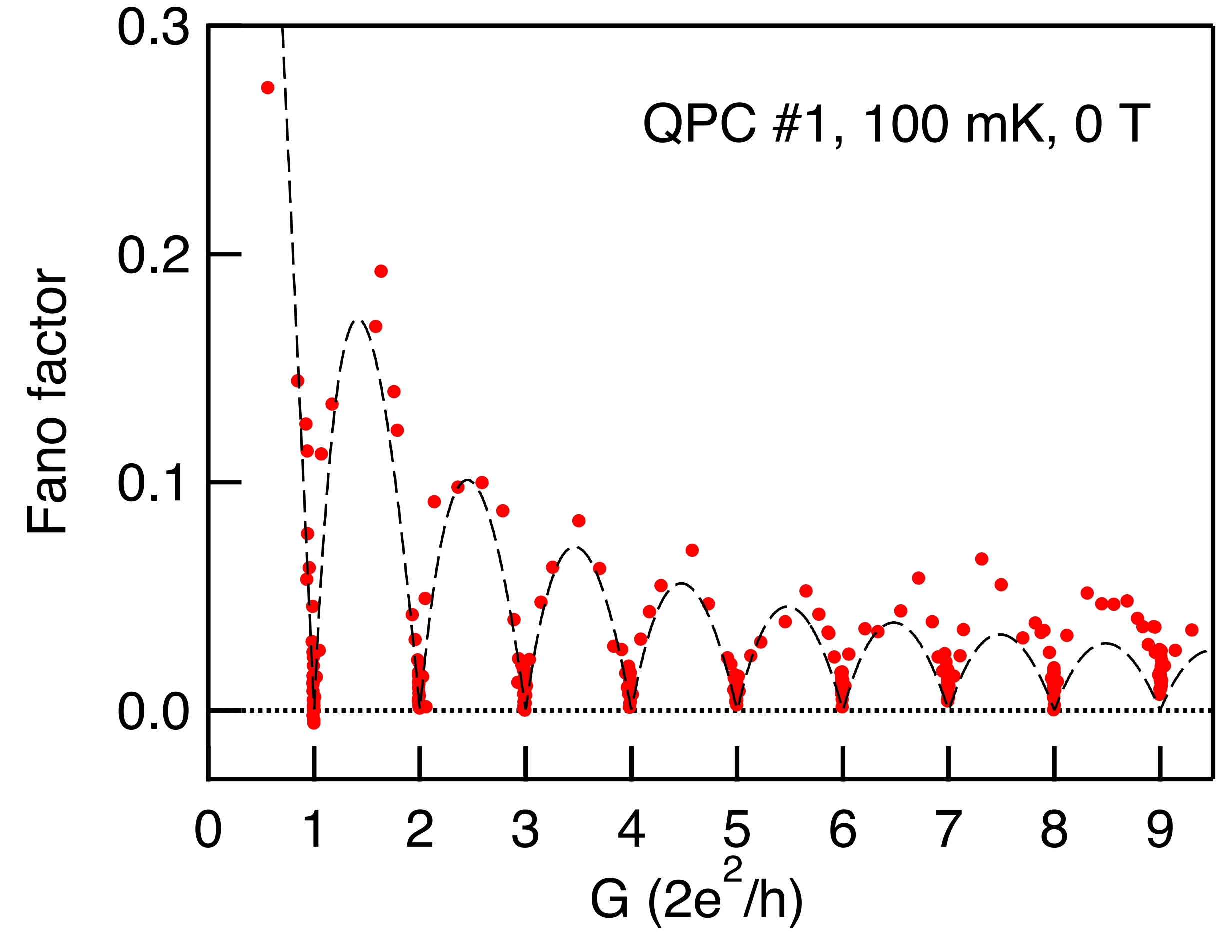
S. Datta, "Electronic Transport in Mesoscopic Systems" (Cambridge University Press, New York, 1997)
Ya. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000)
Y. Imry, "Introduction to Mesoscopic Physics" (Oxford University Press, New York, 2002)

revealing particle statistics

- Pauli principle reduces the shot noise from Schottky result for high transmission:

$$F = \frac{\sum_n T_n(1-T_n)}{\sum_n T_n}$$





T. Muro *et al.*, Phys. Rev. B **93**, 195411 (2016)

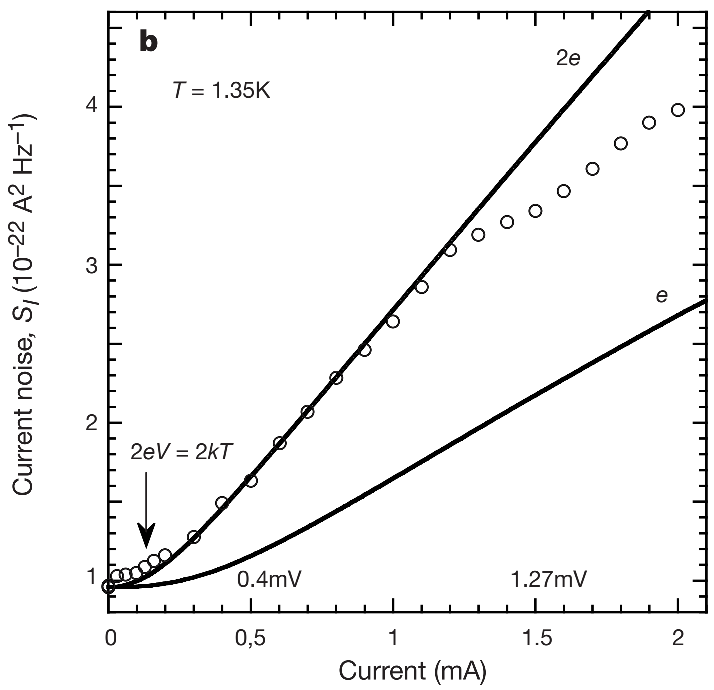
revealing charge unit of charge carriers

- for low transmission: $T_n \ll 1$

$$F = \frac{\sum_n T_n(1 - T_n)}{\sum_n T_n} \to 1 \quad \Rightarrow \quad S = e\langle I \rangle \qquad \frac{eV}{k_B T} \gg 1$$

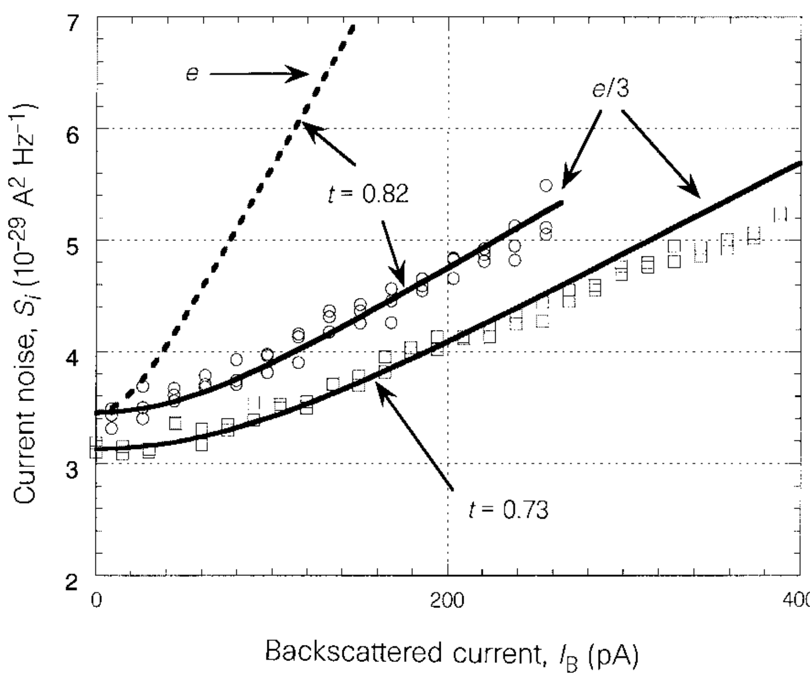
Detection of doubled shot noise in short normal-metal/superconductor junctions

X. Jehl*, M. Sanquer*, R. Calemczuk* & D. Mailly†



Direct observation of a fractional charge

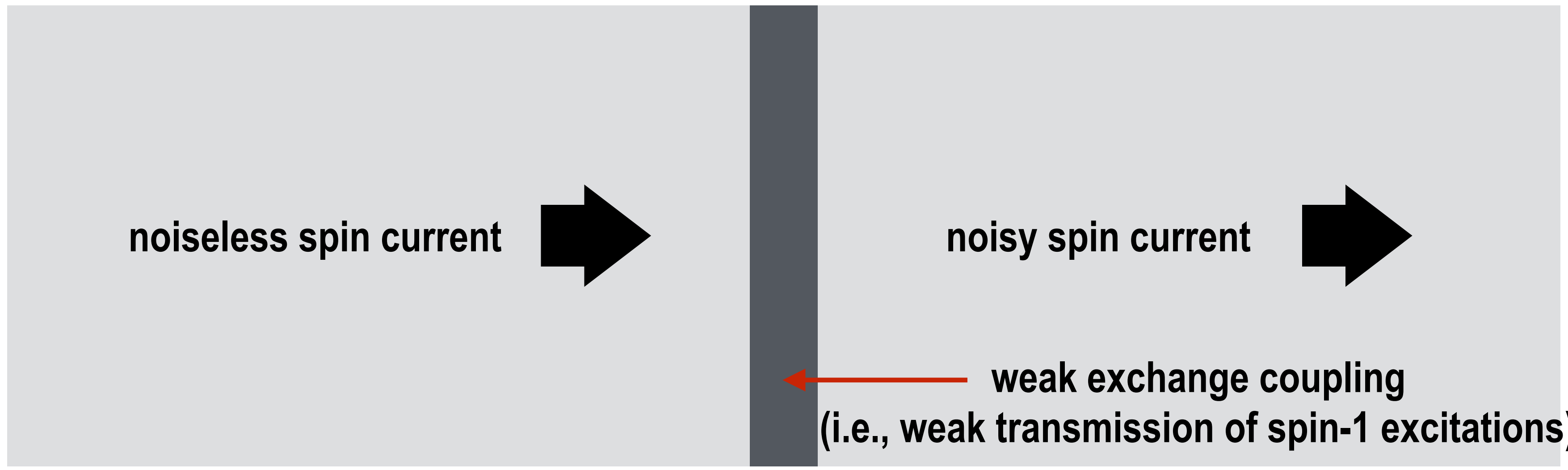
R. de-Picciotto, M. Reznikov, M. Heiblum, V. Umansky, G. Bunin & D. Mahalu



X. Jehl *et al.*, Nature **405**, 50 (2000)
R. de-Picciotto *et al*,, Nature **389**, 162 (1997)

spin current noise

- noise in spin current tunneling between two weakly coupled quantum magnets (i.e., low transmission limit):



- consider two quantum magnets coupled weakly via exchange interaction

What are the consequences of quantized spin transmission on the spin current noise: spin Fano factor?

- consider tunneling spin excitations with different statistics:
    - **large-s magnon system**: multiple spin-1 excitations can be injected simultaneously into a single site ➜ theoretical description of the injection process in terms of tunneling bosonic quasiparticles, i.e., magnon (the "Holstein-Primakoff paradigm").
    - **s=1/2 quantum magnet:** cannot inject two or more spin-1 excitations into a single site at a time ➜ theoretical description of the injection process in terms of tunneling fermions ➜ injection process subject to Pauli blockade

what are the consequences of this crossover from boson-like to fermion-like spin injection physics as *s* approaches the quantum limit?

s=1/2 one-dimensional quantum magnet

- xxz quantum antiferromagnet chain:

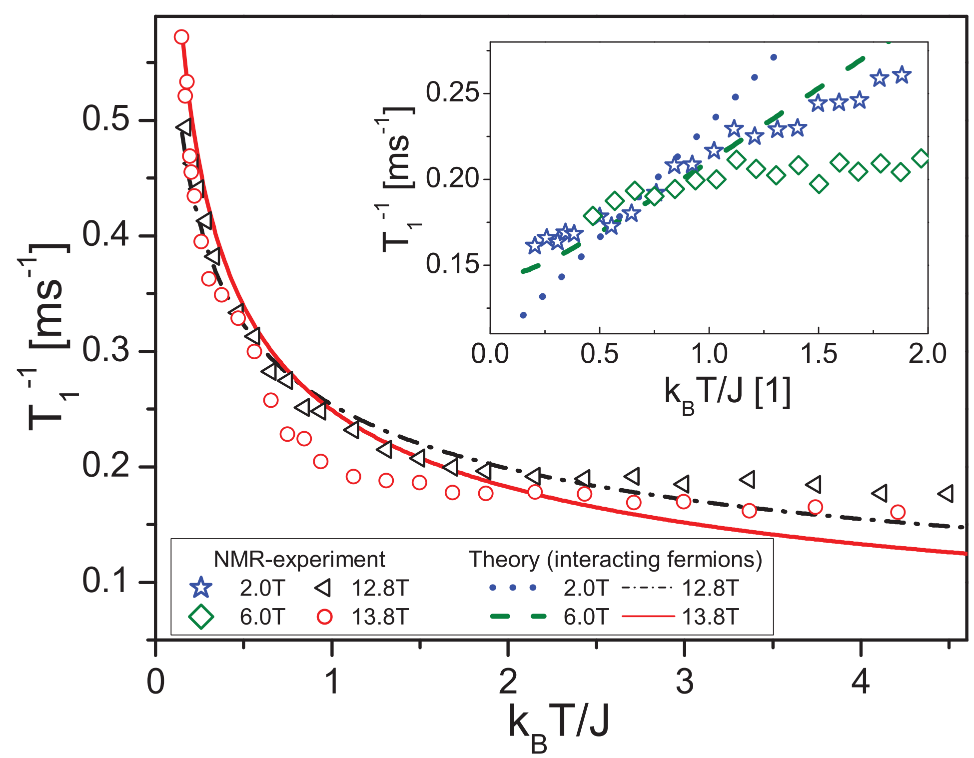
$$\hat{H}_{xxz} = J \sum_j \left\{ \hat{S}^x_{\nu,j}\hat{S}^x_{\nu,j+1} + \hat{S}^y_{\nu,j}\hat{S}^y_{\nu,j+1} + \Delta \hat{S}^z_{\nu,j}\hat{S}^z_{\nu,j+1} \right\}$$

- amenable to rigorous theoretical analysis: Bethe ansatz, bosonization, DMRG, exact diagonalization, QMC, etc.

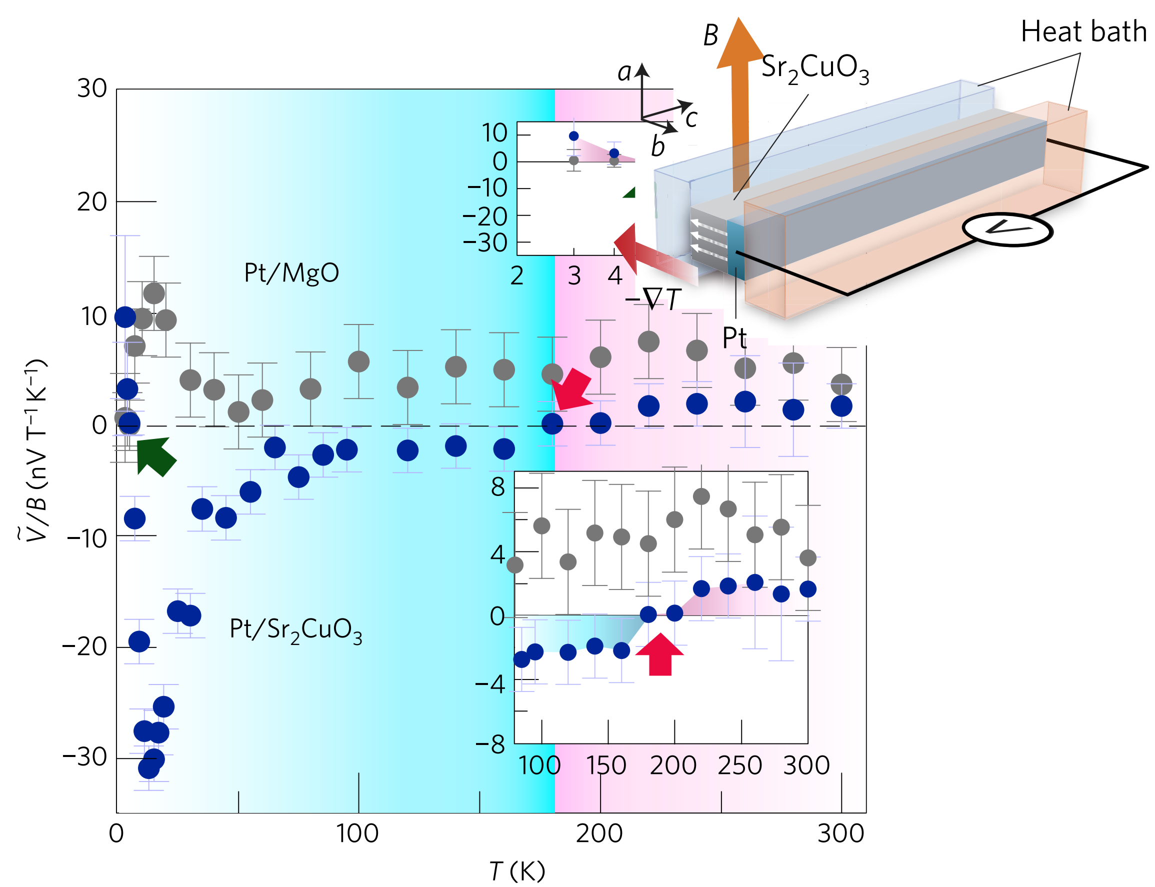
A. Klümper, *Quantum Magnetism*, (Springer Berlin Heidelberg, Berlin, Heidelberg, 2004), pp. 349–379.
H.-J. Mikeska and A. K. Kolezhuk, *Quantum Magnetism*,(Springer Berlin Heidelberg, Berlin, Heidelberg, 2004), pp. 1– 83.

- relevance to experiments:

spin dynamics in s=1/2 AF chain probed via NMR relaxation rate and showing excellent agreement with field theoretical methods



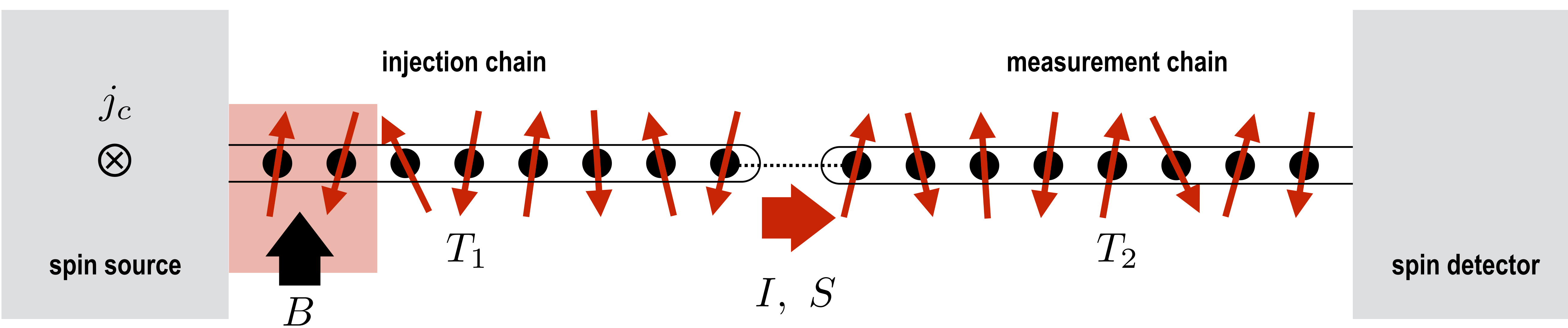
negative inverse spin Hall signal attributed to spin injection from s=1/2 AF chain into Pt



D. Hirobe *et al.*, Nature Pays. **13**, 30 (2016)
H. Kühne *et al.*, Phys. Rev. B **83**, 100407(R) (2011)

quantum spin limit (fermionic)

- two weakly coupled semi-infinite ***s*** **= 1/2 xxz antiferromagnet chains**
- axial symmetry about z axis: spin current = z polarized spin current
- two types of biases (**chemical bias** and **thermal bias**):
  - spin current driven into the injection chain by spin Hall effect and magnetic field bias.
  - temperature T_1 of injection chain elevated above temperature T_2 of measurement chain.
- focus on tunneling $\underbrace{\textbf{spin current}}_{I}$ between chains, its $\underbrace{\textbf{dc noise}}_{S}$ and $\underbrace{\textbf{spin Fano factor}}_{F = \frac{S}{I}}$



model

- two semi-infinite spin chains (injection chain: ν = 1; measurement chain: ν = 2):

$$\hat{H}_\nu = J \sum_j \left\{ \hat{S}^x_{\nu,j} \hat{S}^x_{\nu,j+1} + \hat{S}^y_{\nu,j} \hat{S}^y_{\nu,j+1} + \Delta \hat{S}^z_{\nu,j} \hat{S}^z_{\nu,j+1} \right\}$$

- coupling @ $j = 0$:

$$\hat{H}_c = J_c \hat{\boldsymbol{S}}_{1,j=0} \cdot \hat{\boldsymbol{S}}_{2,j=0}$$

- long-wavelength description (gapless regime: Δ < 1):

$$\hat{H}_\nu = \frac{\hbar u}{4\pi K} \int_0^\infty dx \{[\partial_x \hat{\varphi}_{\nu,R}(x)]^2 + [\partial_x \hat{\varphi}_{\nu,L}(x)]^2\} + \hat{H}_{\rm irr}$$

$$[\hat{\varphi}_{\nu,R}(x), \hat{\varphi}_{\nu',R}(x')] = -[\hat{\varphi}_{\nu,L}(x), \hat{\varphi}_{\nu',L}(x')] = i\pi K \delta_{\nu\nu'} \,\mathrm{sgn}(x - x')$$

  - chiral mode speed: $u = \pi v_F \sqrt{1-\Delta^2}/2 \cos^{-1}(\Delta)$
  - Luttinger parameter: $K = [2 - (2/\pi) \cos^{-1}(\Delta)]^{-1}$

- semi-infinite boundary conditions: $\hat{\varphi}_{\nu,R}(x,t) = -\hat{\varphi}_{\nu,L}(-x,t)$
- magnetic-field bias Hamiltonian:

chemical bias

$$\hat{H}_b = \hbar\gamma B \int_{-\infty}^{-x_0} dx \; \hat{S}^z_1(x) = \frac{\mu}{2\pi} \int_{-\infty}^{-x_0} dx \; \partial_x (\hat{\varphi}_{1,R} + \hat{\varphi}_{1,L})$$

theory and results

- tunneling spin current (outflow of spin current from injection chain):

$$\hat{I}(t) = -\hbar\partial_t \sum_j \hat{S}^z_{1,j}(t)$$

- Keldysh calculation for weak-coupling:
  - thermal averages in chain 1 with respect to $\hat{H}_1 + \hat{H}_b,\ T_1$
  - thermal averages in chain 2 with respect to $\hat{H}_2,\ T_2$

$$I = \langle \hat{I}(0) \rangle = \frac{-i}{\hbar} \int dt' \theta(-t') \langle [\hat{I}(0), \hat{H}_c(t')] \rangle_0 \qquad S = \int dt\ \langle \hat{I}(0)\hat{I}(t) \rangle_0$$

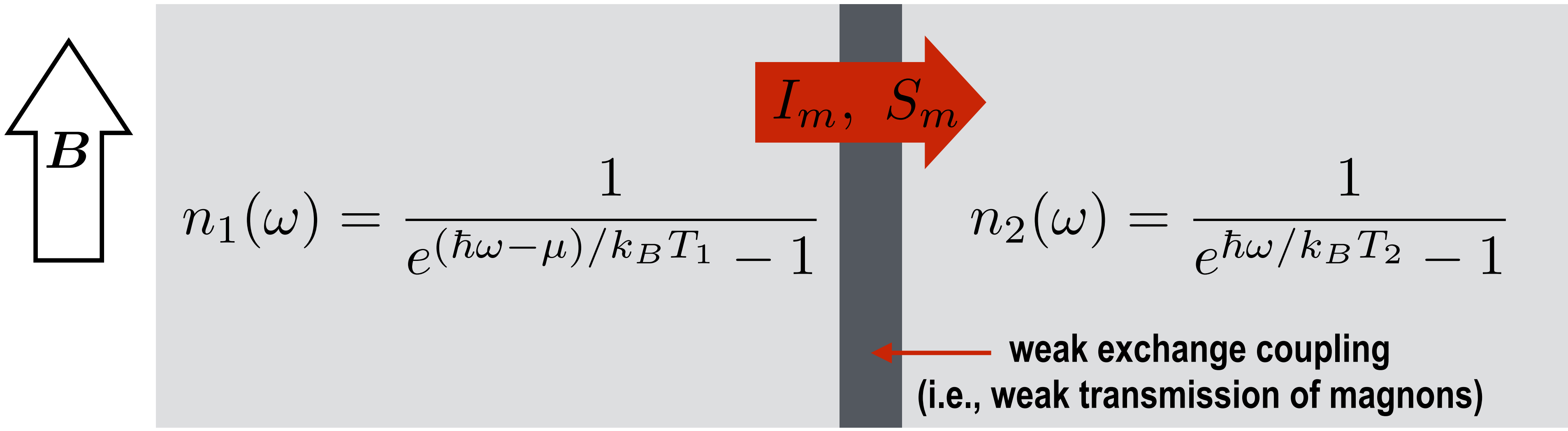
- spin current and dc noise:

$$I = \frac{iJ_c^2}{32\hbar\pi^2} \int dt\ \sin\left(\frac{\mu t}{2\hbar}\right) \left[\frac{\frac{\pi k_B T_1 \alpha}{u\hbar}}{\sin \frac{\pi k_B T_1 (iut+\alpha)}{u\hbar}}\right]^{\frac{1}{K}} \left[\frac{\frac{\pi k_B T_2 \alpha}{u\hbar}}{\sin \frac{\pi k_B T_2 (iut+\alpha)}{u\hbar}}\right]^{\frac{1}{K}}$$

$$S = \frac{J_c^2}{32\pi^2} \int dt\ \cos\left(\frac{\mu t}{2\hbar}\right) \left[\frac{\frac{\pi k_B T_1 \alpha}{u\hbar}}{\sin \frac{\pi k_B T_1 (iut+\alpha)}{u\hbar}}\right]^{\frac{1}{K}} \left[\frac{\frac{\pi k_B T_2 \alpha}{u\hbar}}{\sin \frac{\pi k_B T_2 (iut+\alpha)}{u\hbar}}\right]^{\frac{1}{K}}$$

classical (large-S) limit

- magnon flow across two weakly coupled magnon baths:



- two **large-*s*** Heisenberg ferromagnets in a uniform magnetic field (e.g., YIG can be modeled with *s* = 14, a = 12Å):

$$\hat{H}^m_\nu = -\frac{J}{2}\sum_{\boldsymbol{j},\boldsymbol{\delta}} \hat{\boldsymbol{S}}_{\nu,\boldsymbol{j}} \cdot \hat{\boldsymbol{S}}_{\nu,\boldsymbol{j}+\boldsymbol{\delta}} + \hbar\gamma B \sum_{\boldsymbol{j}} \hat{S}^z_{\nu,\boldsymbol{j}} \approx \sum_{\boldsymbol{k}} \varepsilon_{\boldsymbol{k}} \hat{b}^\dagger_{\nu,\boldsymbol{k}} \hat{b}_{\nu,\boldsymbol{k}}$$

  - magnon dispersion: $\varepsilon_{\boldsymbol{k}} = -2Js[\cos(k_x a) + \cos(k_y a) + \cos(k_z a) - 3] + \hbar\gamma B$

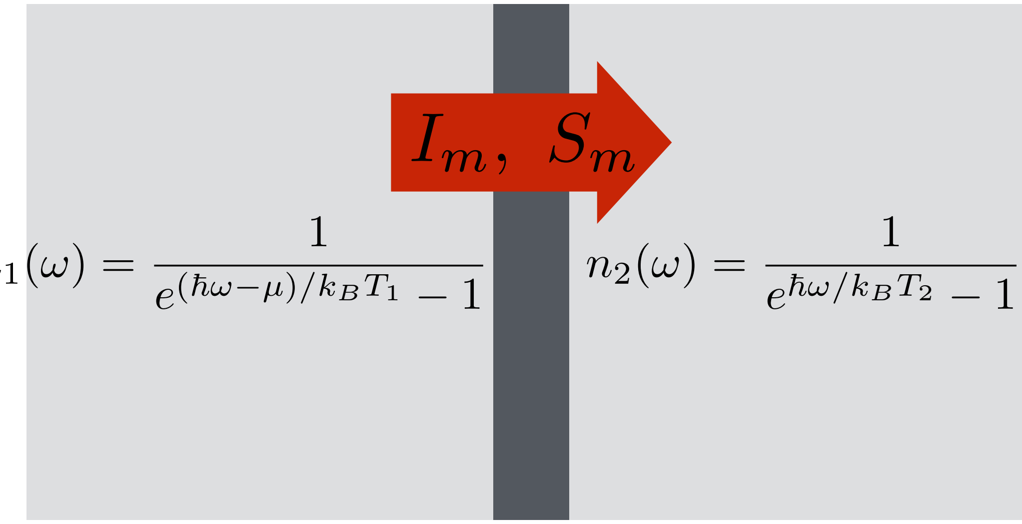
- interface coupling:

$$\hat{H}^m_c = s \sum_{\boldsymbol{k},\boldsymbol{p}} J_{c\boldsymbol{k}\boldsymbol{p}} b^\dagger_{\boldsymbol{k},1} b_{\boldsymbol{p},2} + h.c.$$

theory and results

- spin current (outflow of spin current from bath 1):

$$\hat{I}_m(t) = -\hbar \partial_t \sum_{\boldsymbol{j}} \hat{S}^z_{1,\boldsymbol{j}}$$



$$n_1(\omega) = \frac{1}{e^{(\hbar\omega - \mu)/k_B T_1} - 1} \qquad n_2(\omega) = \frac{1}{e^{\hbar\omega/k_B T_2} - 1}$$

- Keldysh calculation for weak coupling:

$$I_m = \frac{1}{\hbar} \int_{\gamma B}^{\infty} d\omega \; g(\omega)[n_1(\omega) - n_2(\omega)]$$

$$S_m = \int_{\gamma B}^{\infty} d\omega \; g(\omega)[n_1(\omega) + 2n_1(\omega)n_2(\omega) + n_2(\omega)]$$

  - magnon tunneling density of states

$$g(\omega) = J_c^2 s^2 \left(\frac{2}{N_x}\right)^2 \sum_{k_x, k'_x, \boldsymbol{k}_\perp} A_{k_x \boldsymbol{k}_\perp}(\omega) A_{k'_x \boldsymbol{k}_\perp}(\omega)$$

$$A_{\boldsymbol{k}}(\omega) = 2\pi\delta(\omega - \varepsilon_{\boldsymbol{k}})$$

magnon spectral function

spin Fano factor — magnon case

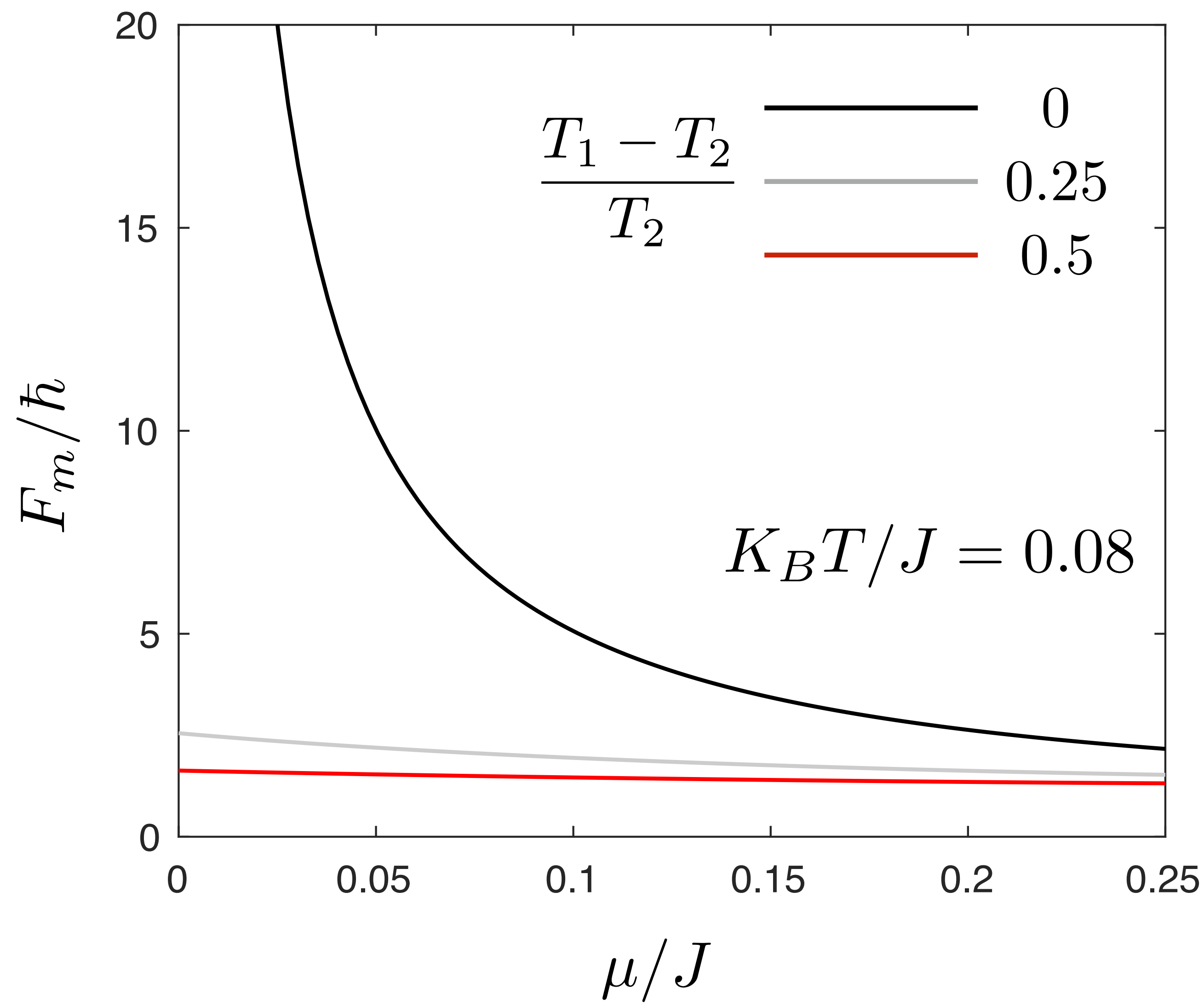
- nonzero chemical bias, equal temperature

$$\mu \gg k_B T_2 \longrightarrow F_m \to \hbar$$

- zero chemical bias, unequal temperature

$$\tau \equiv \frac{T_1 - T_2}{T_2} \gg 1 \longrightarrow F_m \to \hbar$$

Poissonian tunneling of magnons, each carrying a spin quantum $\hbar$



spin Fano factor — quantum chain case

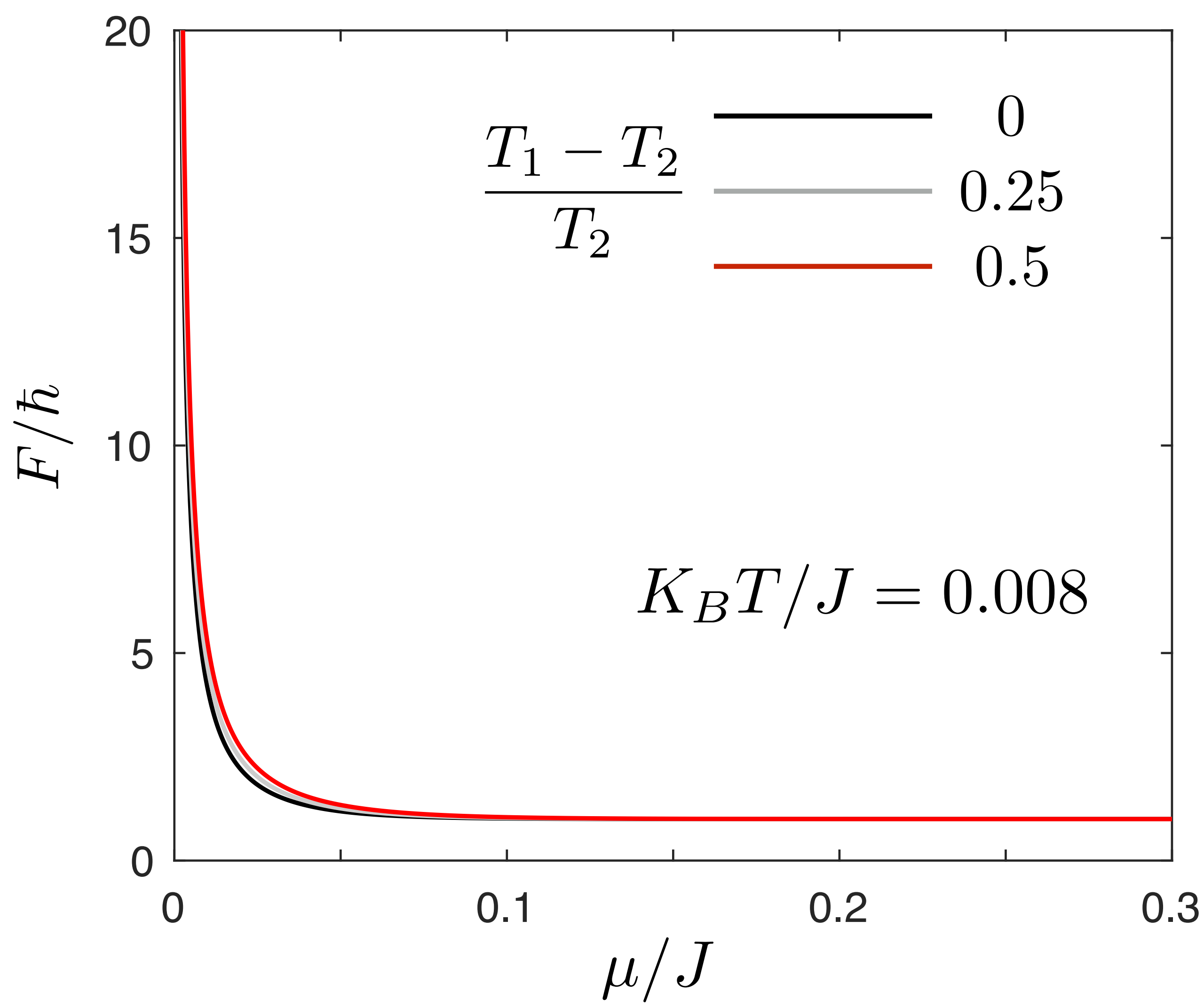
- nonzero chemical bias, equal temperature

$$\mu \gg k_B T_2 \longrightarrow F \to \hbar$$

Bunched Poissonian tunneling of spin-1 excitations

- zero chemical bias, unequal temperature

$$\tau \equiv \frac{T_1 - T_2}{T_2} \gg 1 \longrightarrow F \to \infty$$



spin Fano factor — quantum chain case

- in the low-energy long-wavelength limit in which spin chain is well-described by the (gaussian) Tomonaga-Luttinger model, spin current vanishes for any T_1 and T_2 if chemical bias is zero.
- noise does not vanish for zero chemical bias ➜ Fano factor diverges.

chemical bias effects **thermal effects**

$$I = \frac{iJ_c^2}{32\hbar\pi^2} \int dt \boxed{\sin\left(\frac{\mu t}{2\hbar}\right)} \boxed{\left[\frac{\frac{\pi k_B T_1 \alpha}{u\hbar}}{\sin \frac{\pi k_B T_1 (iut+\alpha)}{u\hbar}}\right]^{\frac{1}{K}} \left[\frac{\frac{\pi k_B T_2 \alpha}{u\hbar}}{\sin \frac{\pi k_B T_2 (iut+\alpha)}{u\hbar}}\right]^{\frac{1}{K}}}$$

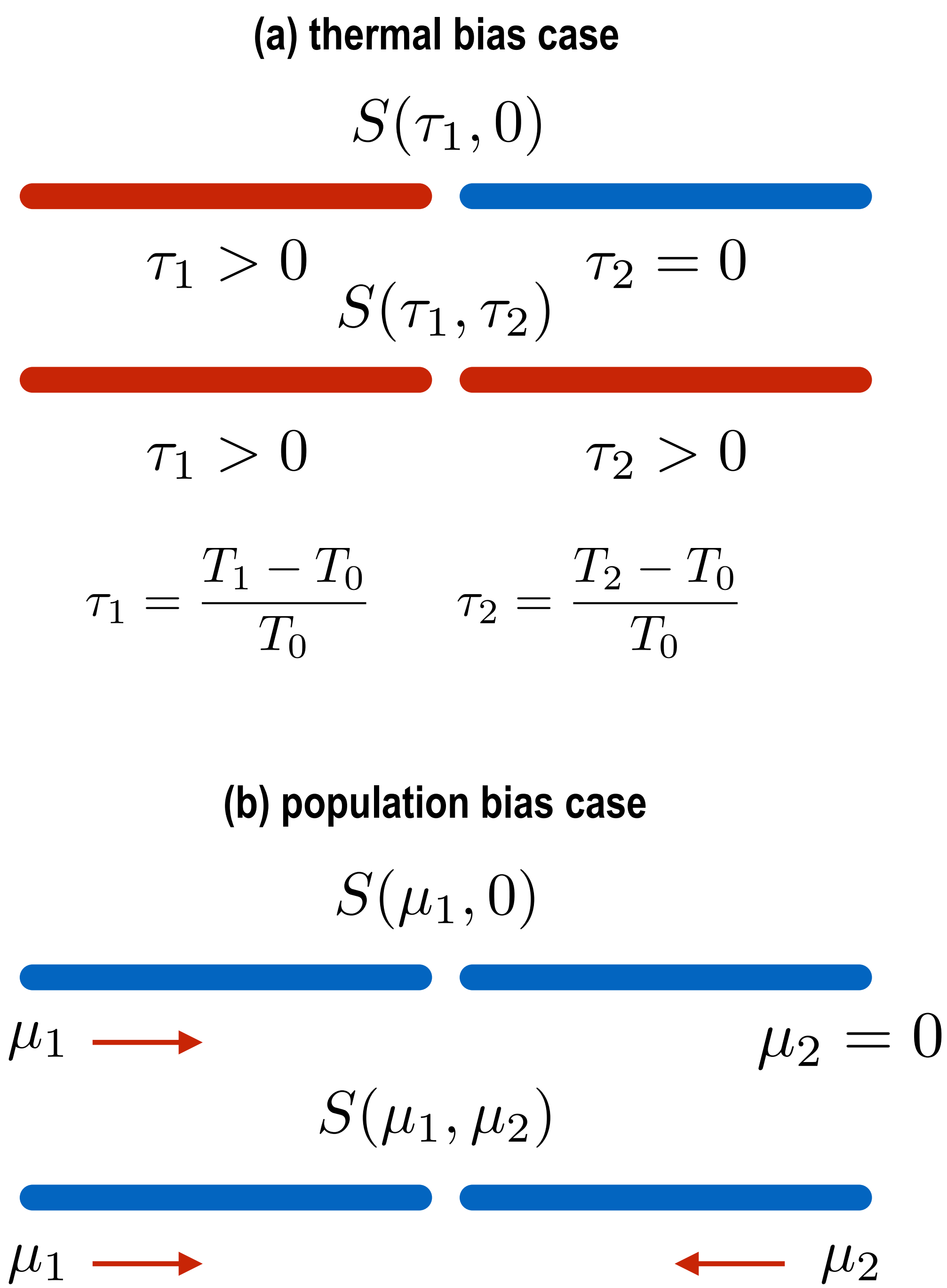
chemical bias effects **thermal effects**

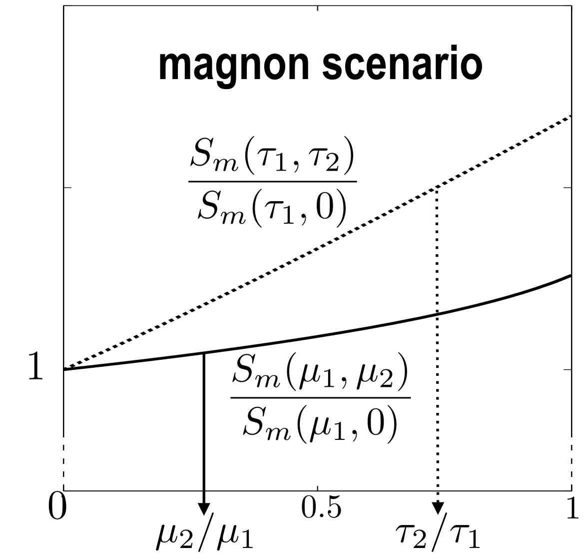
$$S = \frac{J_c^2}{32\pi^2} \int dt \boxed{\cos\left(\frac{\mu t}{2\hbar}\right)} \boxed{\left[\frac{\frac{\pi k_B T_1 \alpha}{u\hbar}}{\sin \frac{\pi k_B T_1 (iut+\alpha)}{u\hbar}}\right]^{\frac{1}{K}} \left[\frac{\frac{\pi k_B T_2 \alpha}{u\hbar}}{\sin \frac{\pi k_B T_2 (iut+\alpha)}{u\hbar}}\right]^{\frac{1}{K}}}$$

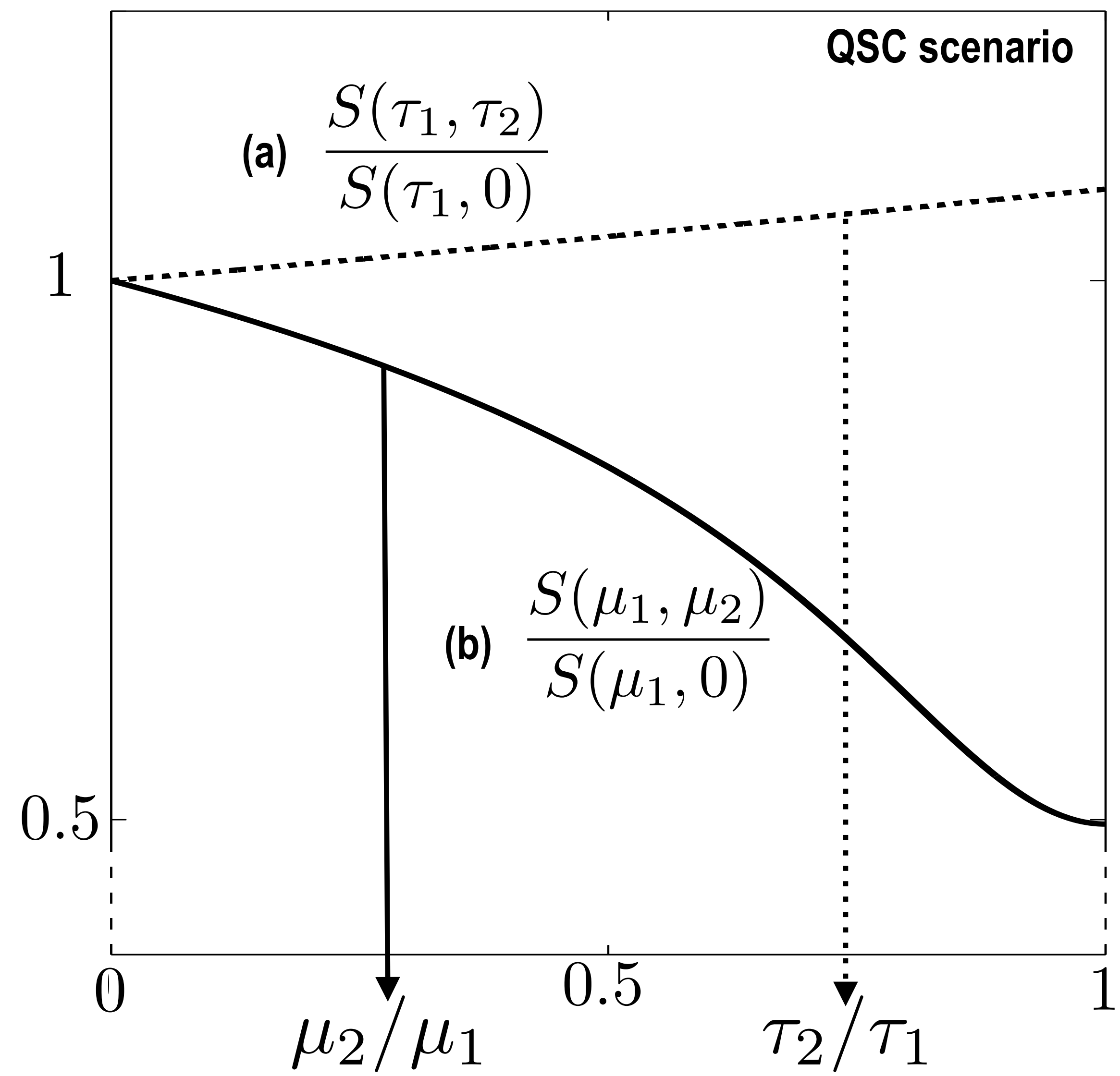
Irrelevant terms (e.g., umklapp term, band curvature, etc.) may give rise to a finite current.
How does the Fano factor change in that case?

Pauli blockade in noise — quantum chain case

- manifestation of Pauli statistics of spin-1/2 operators in the dc spin current noise:





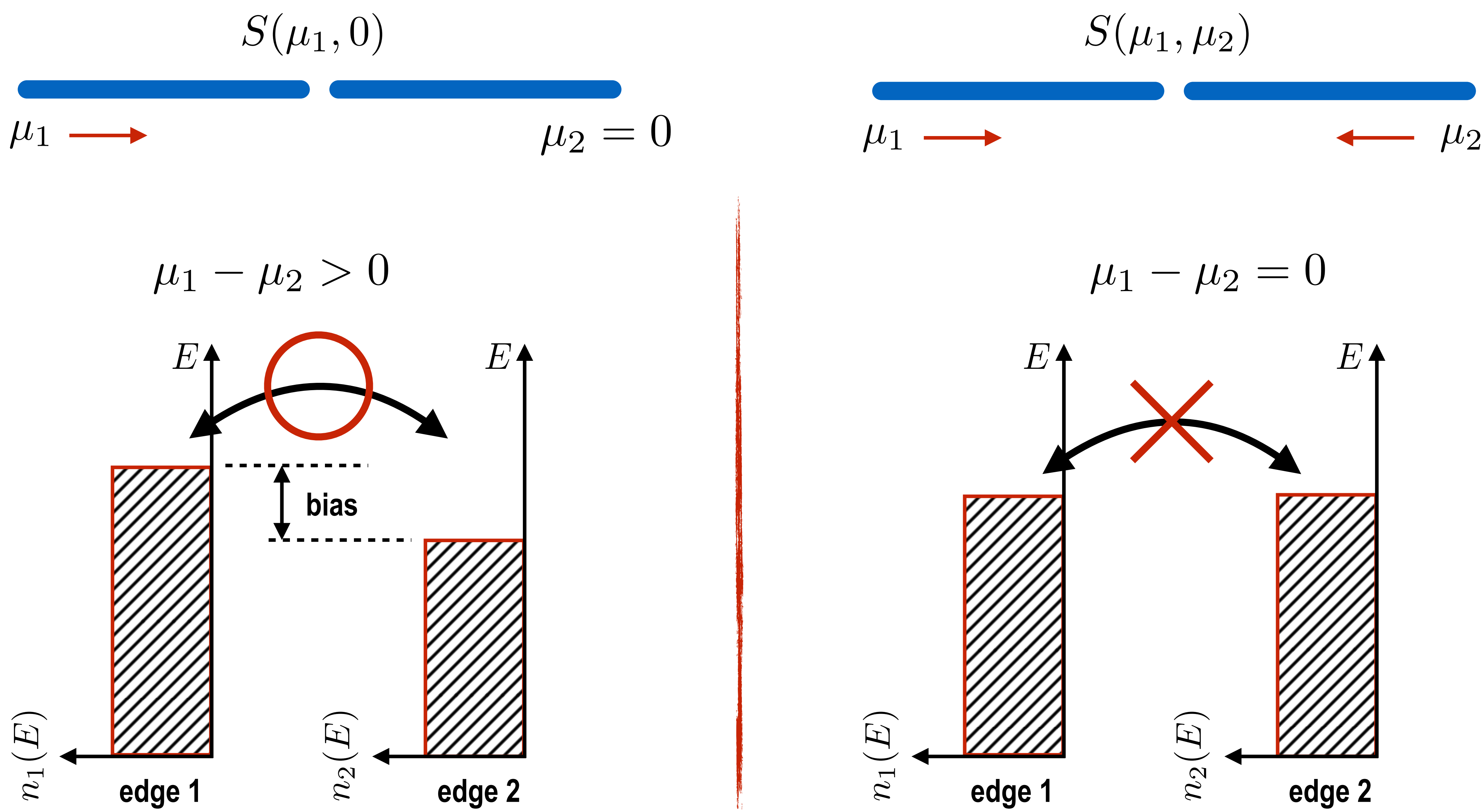


Pauli blockade in noise — quantum chain case

- exchange coupling is hopping of fermionic quasiparticles:

$$\hat{H}_c = J_c \hat{\boldsymbol{S}}_{1,j=0} \cdot \hat{\boldsymbol{S}}_{2,j=0} \sim \hat{c}^{\dagger}_{1,j=0} \hat{c}_{2,j=0} + h.c.$$

Jordan-Wigner fermions



experimental extraction of noise

- **spin current noise in the detector metal**: if no additional noise is generated when impinging spin current flows into the detector metal:

$$S_{\text{tot}} = \underbrace{S_n^{\text{eq}} + S_c^{\text{eq}}}_{\text{equilibrium noise}} + S$$

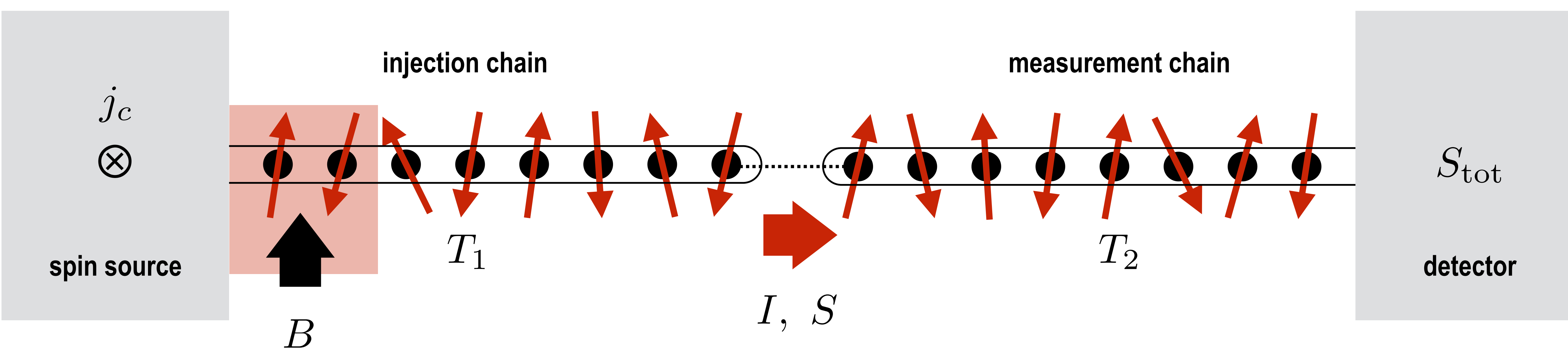
noise generated by bias

- excess spin current noise:

$$S = S_{\text{tot}} - \underbrace{S_{\text{tot}}|_{\mu=\tau=0}}_{\text{equilibrium noise}}$$

- **excess charge current noise** generated via inverse spin Hall effect:

$$S^e_{\text{excess}} \equiv S^e_{\text{tot}} - S^e_{\text{tot}}|_{\mu=\tau=0} = \tilde{\Theta} S$$



experimental extraction of spin Fano factor

- charge current generated by injected spin current:

$$I^e = \Theta I$$

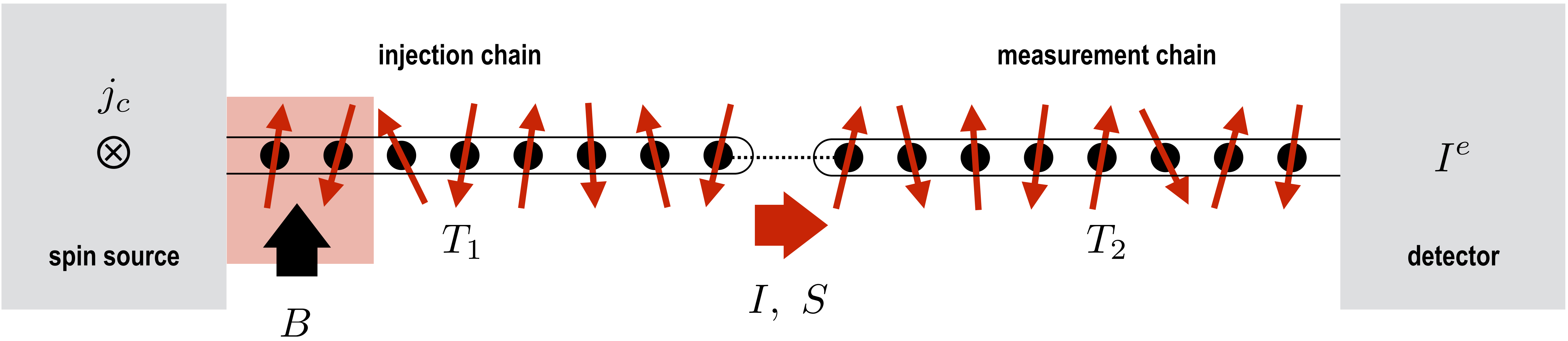
- charge Fano factor:

$$F^e = \frac{S^e_{\text{excess}}}{I^e} = \frac{\tilde{\Theta} S}{\Theta I}$$

- obtain the unknown pre-factor first in the limit of strong chemical bias: $\mu \gg k_B T_2$

$$\frac{S}{I} \to \hbar \qquad\qquad \frac{\tilde{\Theta}}{\Theta} = \frac{F^e}{\hbar}$$

- obtain Fano factor from the measurable charge Fano factor: $F = \frac{\Theta}{\tilde{\Theta}} F^e$



summary and outlook

- spin current noise can reveal underlying quantum statistics of tunneling spin excitations: crossover from bosonic tunneling physics to fermion tunneling physics as spin quantum number approaches quantum limit.
- **spin Fano factor** reveals the spin unit of tunneling spin excitations
- additional noise generated during measurement process? A quantitative theory of conversion between spin current noise and measured charge current noise is necessary.
- effects of irrelevant operators?