Fluctuations in Mesoscopic Systems

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Outline

- Mesoscopic systems & Noise
- Spin shot noise
- Machine Learning

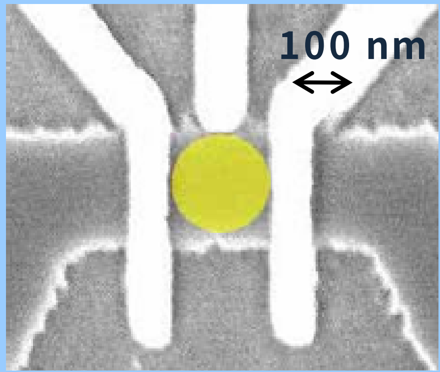
Mesoscopic Systems & Noise

Mesoscopic systems (examples from our works)

Play with quantum physics in a fully tunable way

Quantum Dot

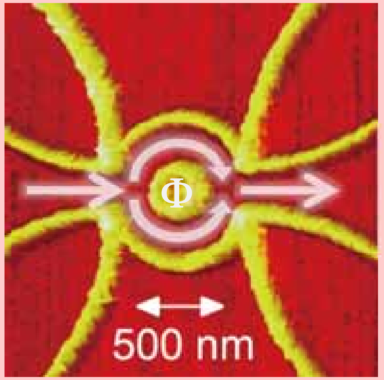
Particle nature



Phys. Rev. Lett. **106**, 176601 (2011);
J. Phys. Soc. Jpn **73,** L3235 (2004)

Electron Interferometer

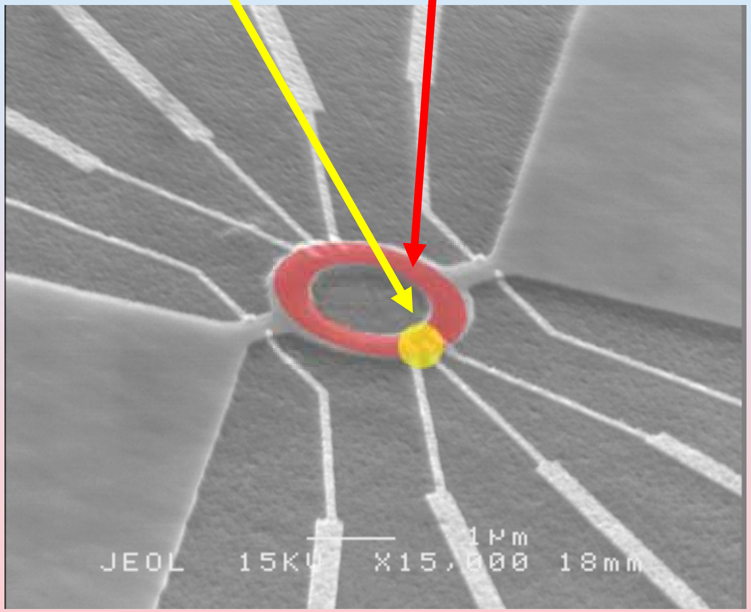
Wave nature



Phys. Rev. Lett **104,** 080602 (2010); Phys. Rev. B **79,** 161306 (R) (2009); **83,** 155431 (2011); J. Phys. Soc. Jpn **71,** L2094 (2002)

QD in Interferometer

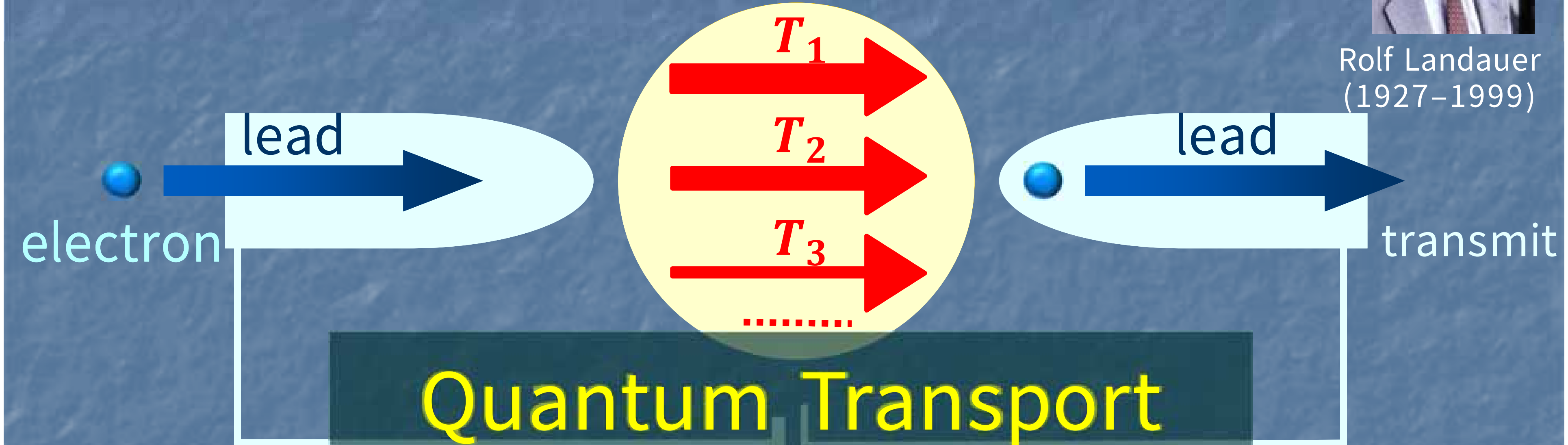
Wave-particle duality



Phys. Rev. Lett. **88,** 256806 (2002); **92,** 176802 (2004); **95,** 066801 (2005); Phys. Rev. B **68,** 235304 (2003); **70,** 035319 (2004); **73,** 195329 (2006).

Electrons flow in mesoscopic systems

Rolf Landauer
(1927–1999)



Quantum Transport as Scattering Problem

Landauer formula

$$G = \frac{2e^2}{h} \sum_n T_n \qquad \frac{2e^2}{h} \sim (12.9\ \mathrm{k}\Omega)^{-1}$$

Conductance tells the electronic properties of single site quantum systems (interference, single-level transport, Kondo physics…).

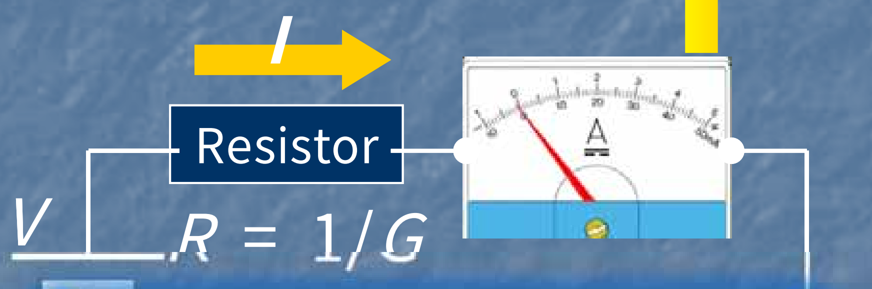
Some electrons cannot transmit…

You can't avoid this.

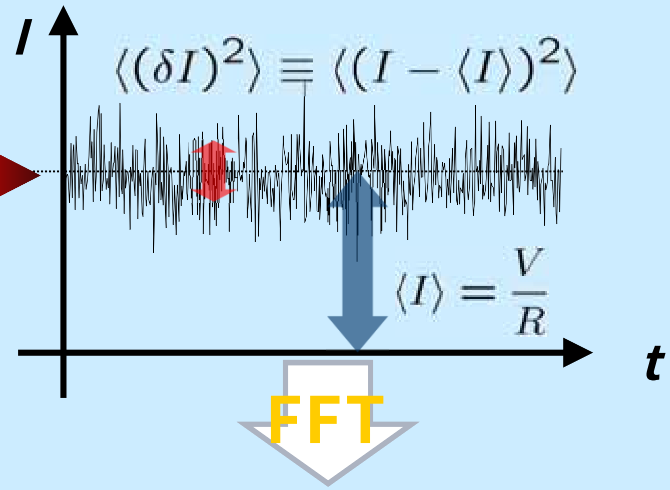
Noise = Current fluctuation

Noise = Variance of # of electrons

Review: Y. M. Blanter and M. Büttiker, *Phys. Rep.* **336**, 1 (2000).



Different unit brings different physics.



Current noise power spectral density $S_I(f)$ $[\mathrm{A}^2/\mathrm{Hz}]$

$$\langle(\delta I(t))^2\rangle \equiv \int_{-\infty}^{\infty} S_I(f)\,df$$

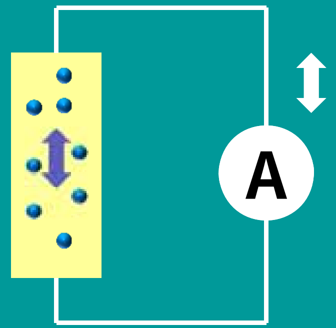
Current: $\langle I\rangle = \frac{\langle Q\rangle}{\tau} = \frac{e\langle N\rangle}{\tau}$ $\quad [\mathrm{A}] = \left[\frac{\mathrm{C}}{\mathrm{s}}\right]$

Noise: $S_\mathrm{I} = \frac{2\langle(\delta Q)^2\rangle}{\tau} = \frac{2e^2\langle(\delta N)^2\rangle}{\tau}$ $\quad \left[\frac{\mathrm{A}^2}{\mathrm{Hz}}\right] = \left[\frac{\mathrm{C}^2}{\mathrm{s}}\right]$

Thermal noise & Shot noise

Thermal noise
(equilibrium noise)

$$S_I = 4k_B T G$$



$\langle I \rangle = 0$
but
$\langle (\delta I)^2 \rangle \neq 0$

✓ Johnson-Nyquist (1928)
✓ Fluctuation-dissipation relations

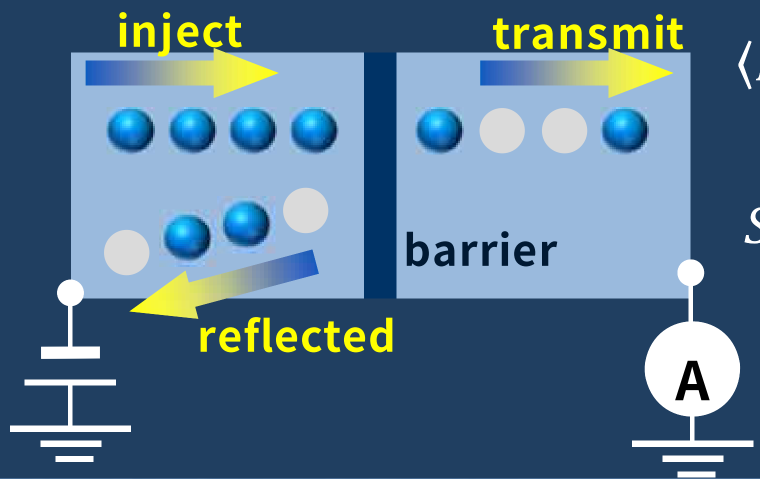
Essentially different.

Nonequilibrium first.

Shot noise
(non-equilibrium noise)

$$S_I = 2e\langle I \rangle$$

✓ Schottky (1918)



$$\langle I \rangle = \frac{\langle Q \rangle}{\tau} = \frac{e\langle N \rangle}{\tau}$$

$$S_I = \frac{2\langle (\delta Q)^2 \rangle}{\tau} = \frac{2e^2\langle (\delta N)^2 \rangle}{\tau} = \frac{2e^2\langle N \rangle}{\tau} = 2e\langle I \rangle$$

(*assume* Poissonian process)

“The noise is the signal.”

R. Landauer, Nature **392,** 658 (1998)

Rolf Landauer
(1927–1999)

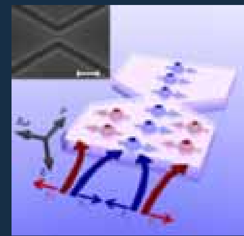
Fluctuation Theorem

Mesoscopic nonequilibrium statistical physics.

Nakamura *et al., PRL* **104,** 080602 (2010);
*PR*B **83,** 155431 (2011)

Spin polarization

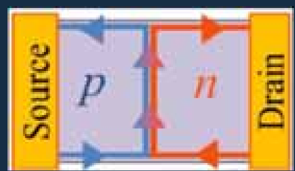
Stern–Gerlach on chip



Kohda *et al. Nature Comm.* **3,** 1082 (2012).
Nishihara *et al. APL* **100,** 203111 (2012).

Edge dynamics

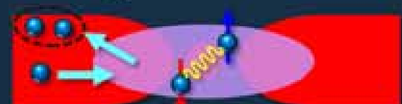
Edge mixing in graphene *pn* junction in QH regime



Matsuo *et al. Sci. Rep.* **5,** 11723 (2015).
Matsuo *et al. et al. Nature Comm.* **6,** 8066 (2015).

Noneq. quantum liquid

Shot noise in Kondo regime.



Yamauchi *et al. PRL* **106,** 176601 (2011); Ferrier *et al. Nature Physics* **12,** 230 (2016); *PRL* **118**, 196803 (2017); Hata *et al. PRL* **121**, 247703 (2018)

Spin Shot Noise

Arakawa *et al.*, *PRL*, **114,** 016601 (2015) [Editors‘ Suggestion]
荒川、小林「スピン流とそのゆらぎ」、日本物理学会誌 **74,** 222 (2019).

Collaborators

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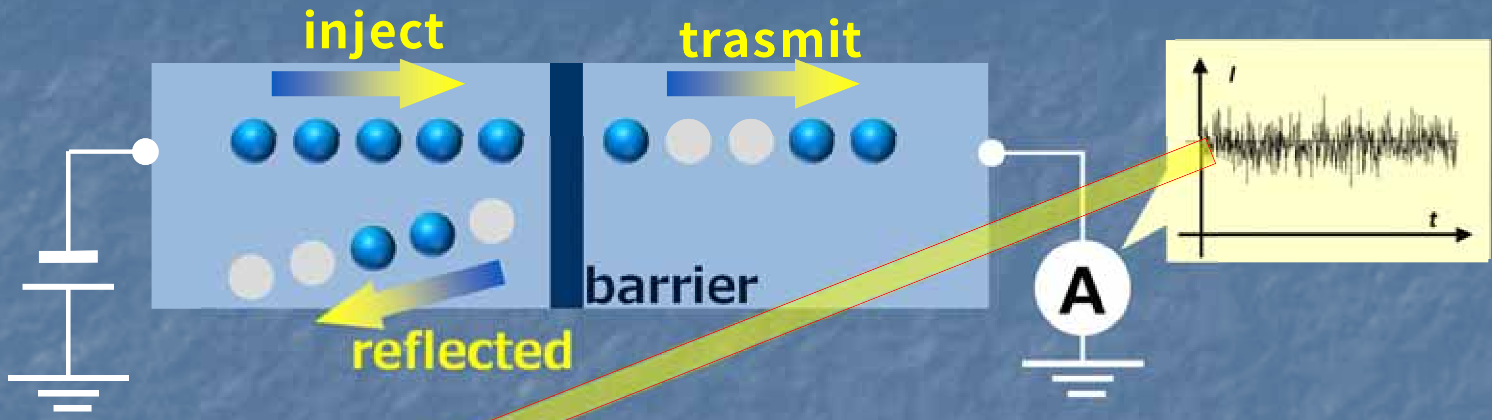
Shot Noise



$$S_{\mathrm{I}} = 2e\langle I\rangle$$

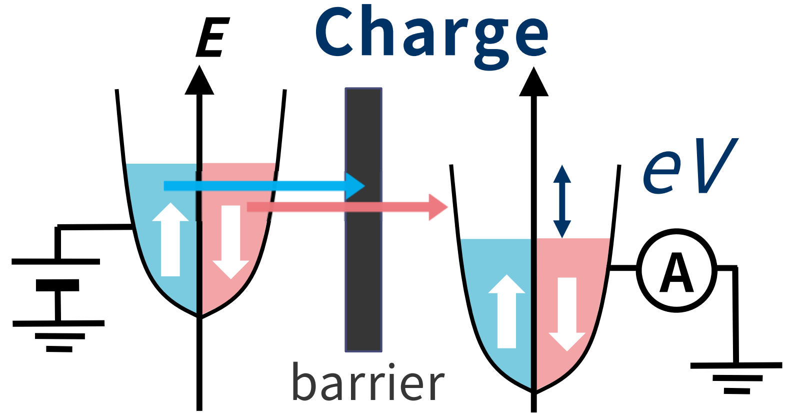
Schottky (1918)

Consequence of discreteness of electric charge.

Walter H. Schottky (1886 –1976)

Not only charge, but also spin is discrete.

Charge & Spin Shot Noise



Current

$I_c = I_\uparrow + I_\downarrow$

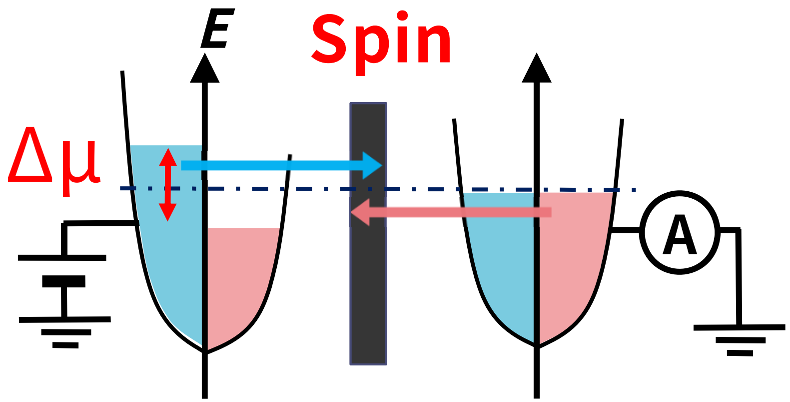
Shot noise

$S_c = 2e|\langle I_c \rangle|$

When $I_\uparrow = -I_\downarrow \neq 0$

$\langle I_c \rangle = 0 \rightarrow S_c = 0$
$\langle I_s \rangle \neq 0 \rightarrow S_s \neq 0$

Non-zero shot noise even for zero-current.



Spin current

$I_s = I_\uparrow - I_\downarrow$

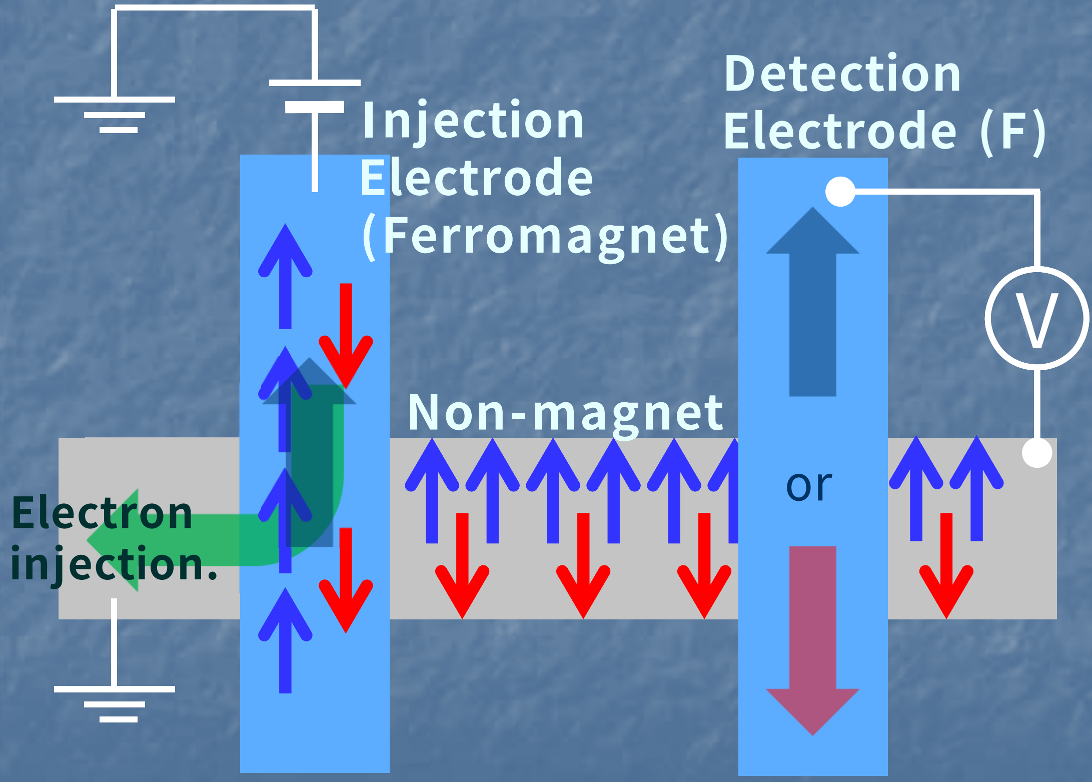
Spin shot noise

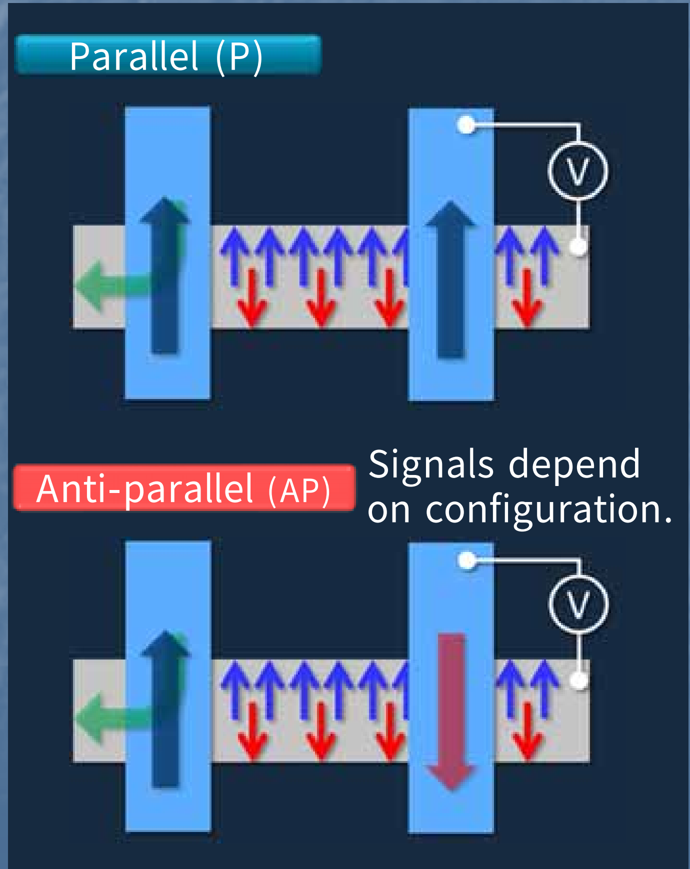
$S_s = 2e|\langle I_s \rangle| = 2e(|\langle I_\uparrow \rangle| + |\langle I_\downarrow \rangle|)$

Spin-dependent energy distribution

Spin accumulation

By injecting spin-polarized electrons from ferromagnet to non-magnet, the non-magnet can be temporarily "magnetized".

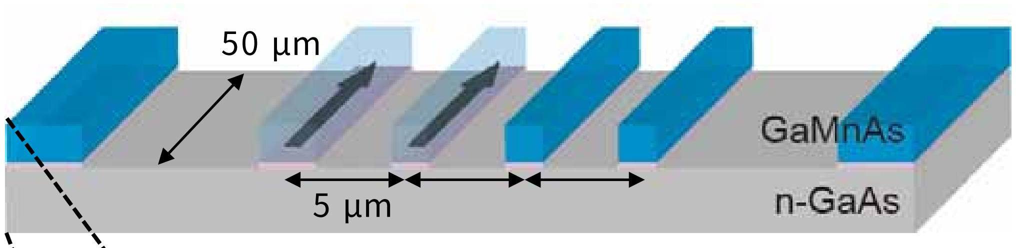




Signals depend on configuration.

F. J. Jedema *et al.*, Nature **410**, 345 (2001).

Device Structure: “Spin valve”



M. Ciorga *et al.*, PRB **79**, 165321 (2009).

J. Shiogai *et al.*, APL **101**, 212402 (2012).

50 nm	$(Ga_{0.945}Mn_{0.055})As$
2.2 nm	$(Al_{0.35}Ga_{0.65})As$
8.0 nm	n^+-GaAs (n^+=5-6×10^{18}cm^{-3})
15 nm	n^+→n-GaAs
1μm	n-GaAs (n=2-4×10^{16}cm^{-3})
500 nm	$[AlGaAs/GaAs]_{50}$
300 nm	GaAs
GaAs substrate	

p-type (Ferromagnet)

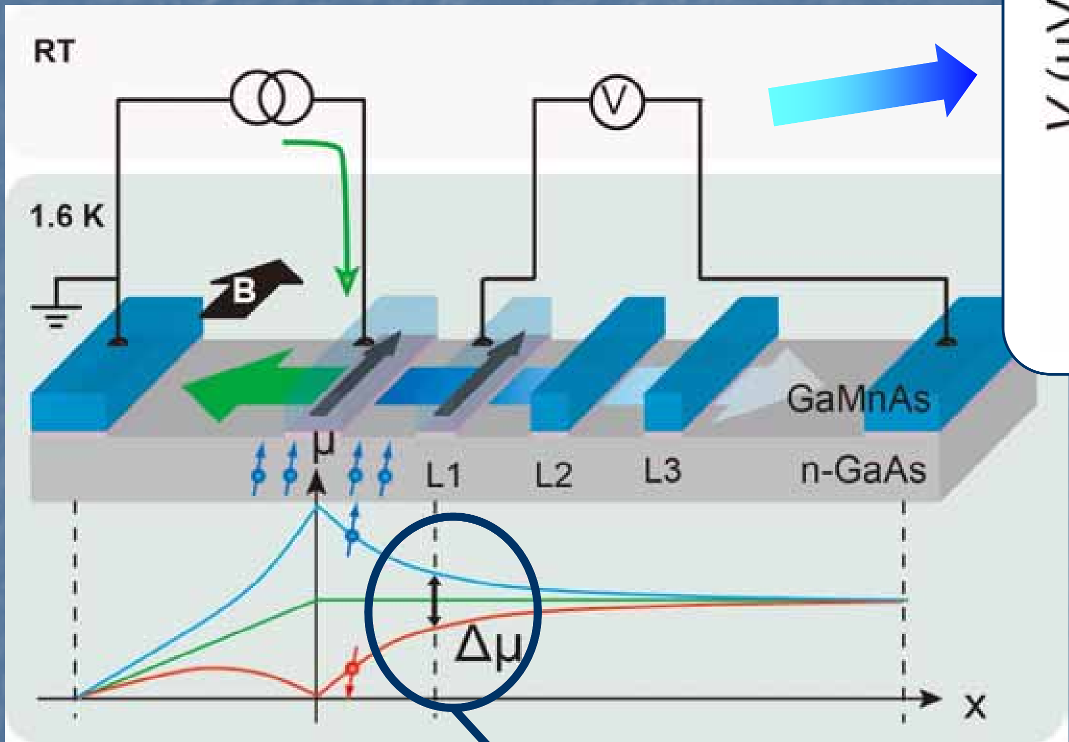
Tunnel barrier

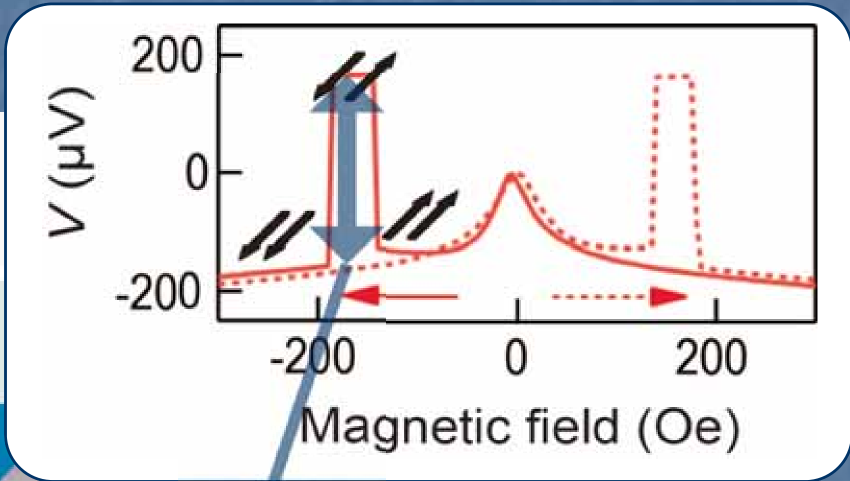
n-type (Non-magnet)

“spin Esaki diode”

M. Kohda, *et al. JJAP,* Part 2, **40,** L1274 (2001).

Spin accumulation



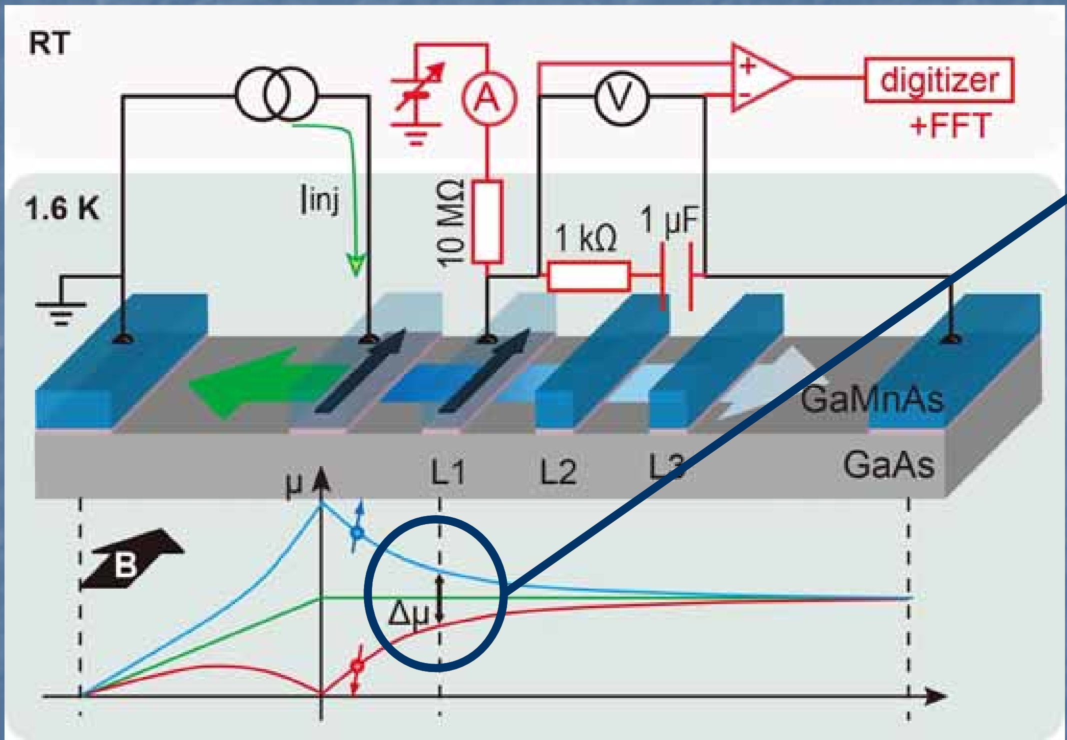


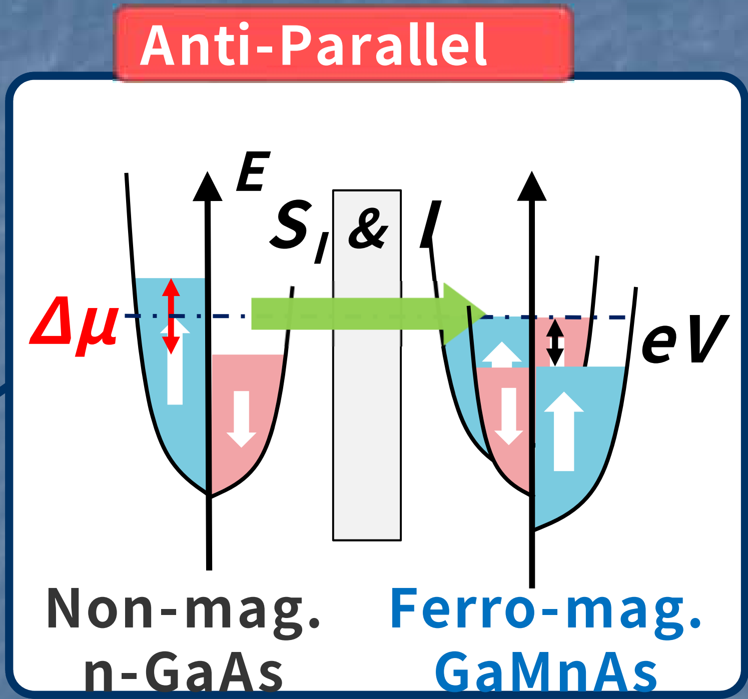
$$e\Delta V = P\Delta\mu = P(\mu_{\uparrow} - \mu_{\downarrow})$$

Nonequilibrium spin accumulation caused by the polarized electrons

F. J. Jedema *et al.*, Nature **410**, 345 (2001).

Noise spectroscopy

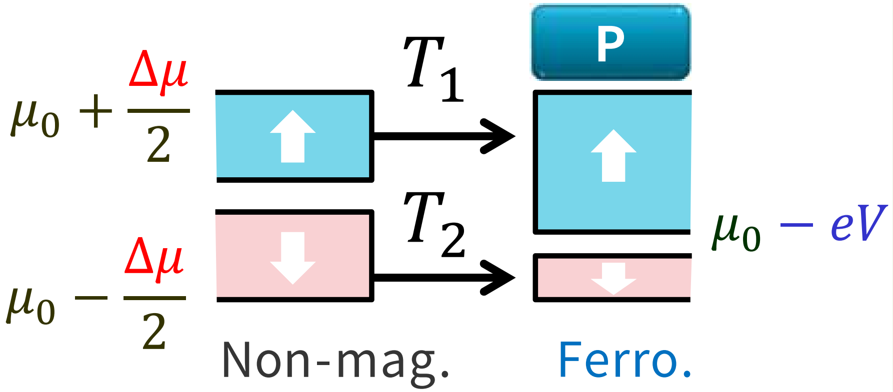




Scheme

1. Spin accumulated by injection
2. Sweep the bias voltage
3. Measure current, voltage & noise
4. Change mag. configuration

Expected shot noise: $S_{\mathrm{I}} = 2e|\langle I \rangle|$



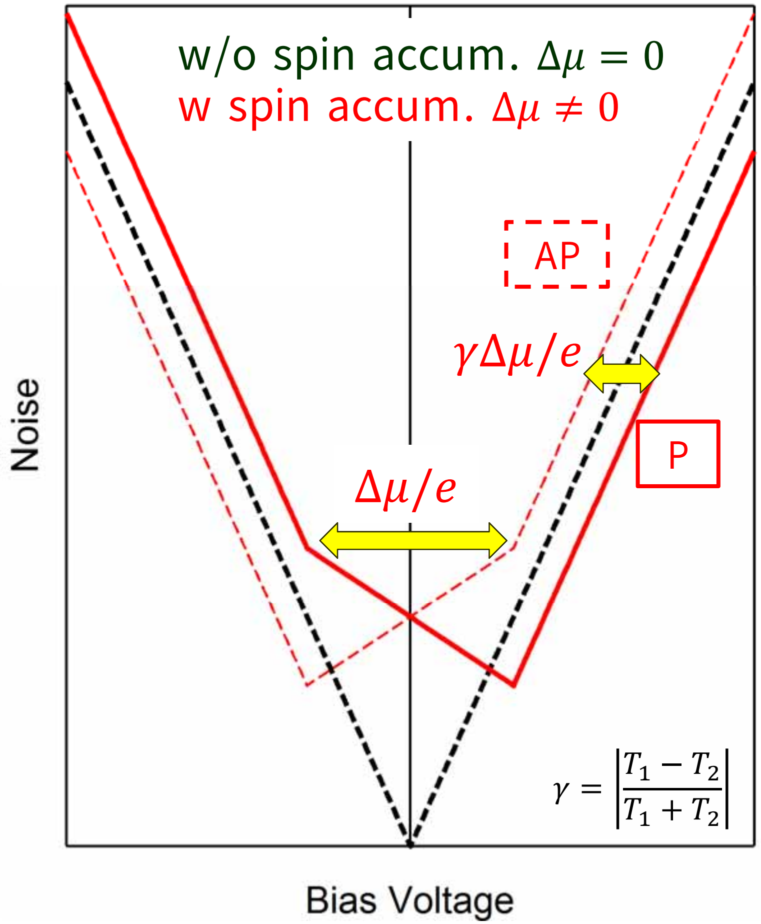
Current (Parallel case)

$$I_P = \frac{e}{h} T_1 \left(eV + \frac{\Delta\mu}{2} \right) + \frac{e}{h} T_2 \left(eV - \frac{\Delta\mu}{2} \right)$$

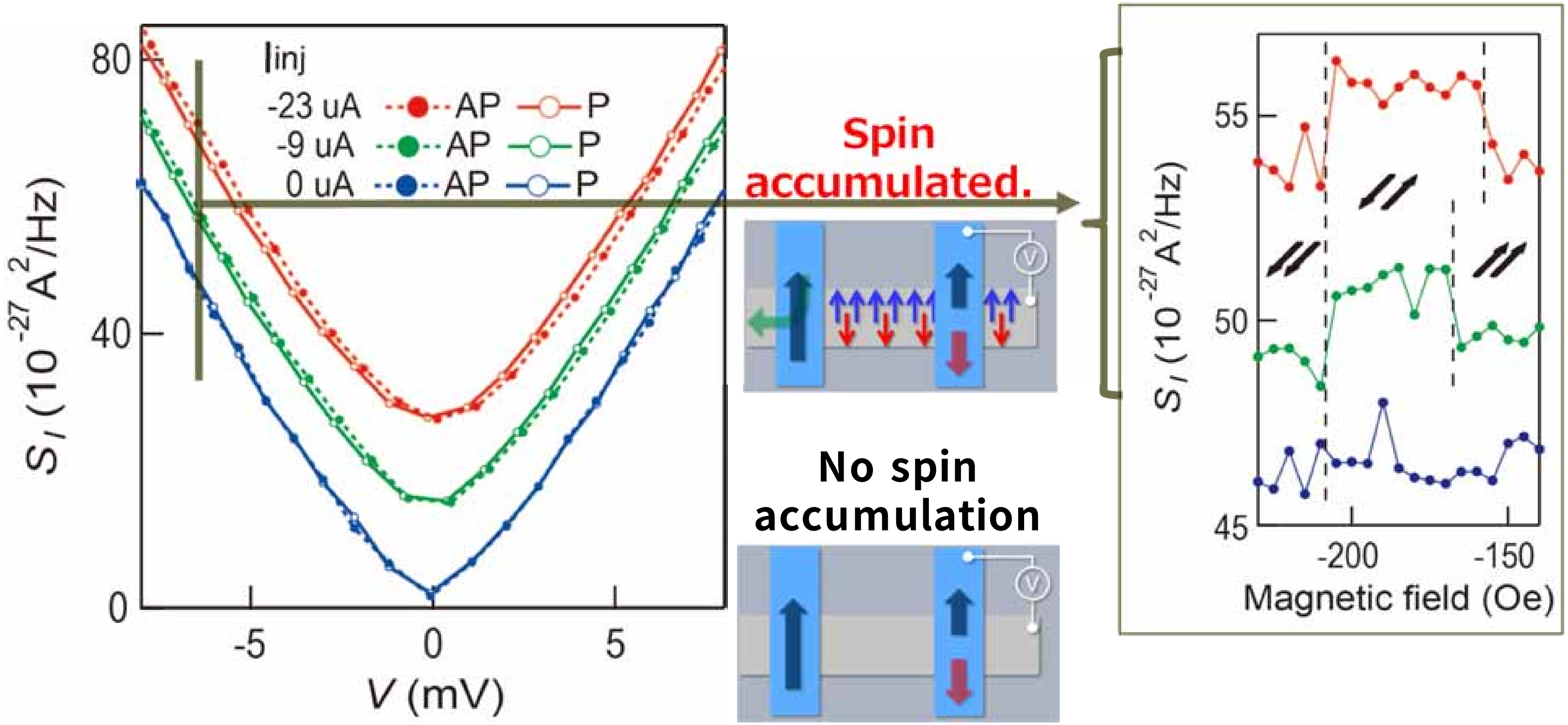
Assume no spin-flip

Shot noise at $T=0$

$$S_P = \frac{2e^2}{h} T_1 \left| eV + \frac{\Delta\mu}{2} \right| + \frac{2e^2}{h} T_2 \left| eV - \frac{\Delta\mu}{2} \right|$$

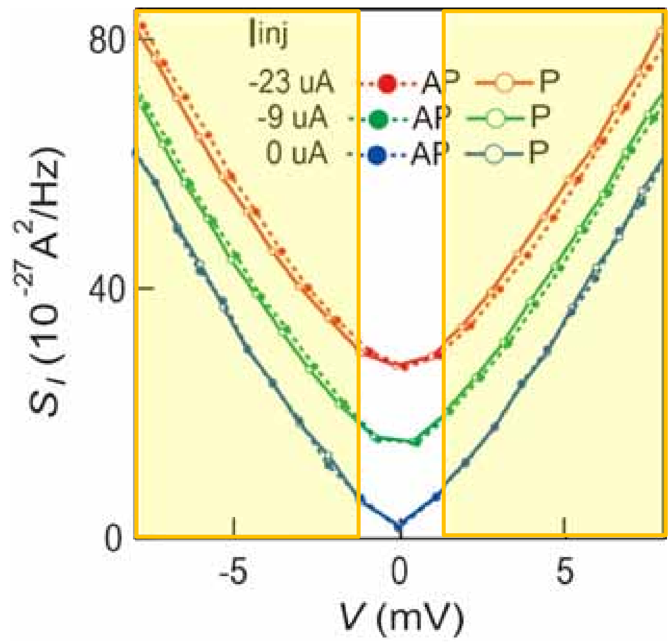


Spin-dependent shot noise

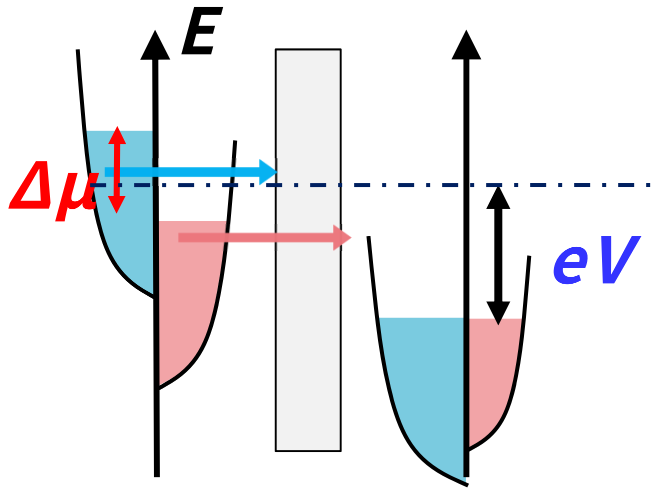


$$S_I = 2eI \coth\left(\frac{eV}{2k_BT}\right)$$

High bias regime



High bias regime
$|eV| \gg \Delta\mu, 4k_BT$



Charge current	Charge shot noise (classical shot noise)
$I_C = \frac{2e}{h}\bar{T}\,eV$	$S_C = 2e\lvert\langle I_C\rangle\rvert = \frac{4e^2}{h}\bar{T}\,eV = \frac{S_P + S_{AP}}{2}$
Spin current	**Spin shot noise**
$I_S = \frac{2e}{h}\bar{T}\,\Delta\mu$	$S_S = 2e\lvert\langle I_S\rangle\rvert = \frac{2e^2}{h}\bar{T}\,\Delta\mu = \frac{\lvert S_P - S_{AP}\rvert}{2\gamma}$

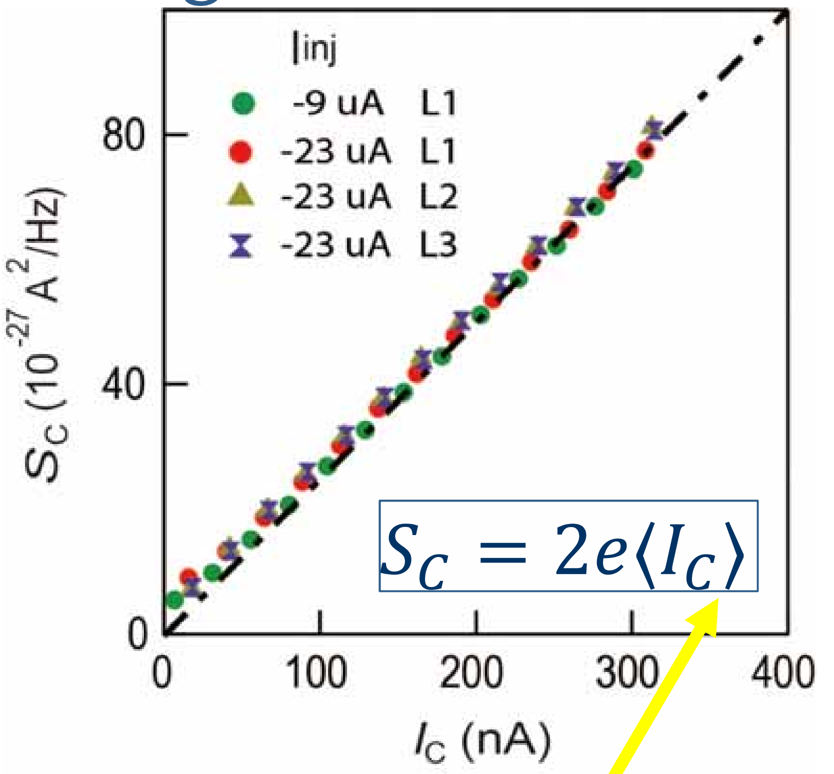
Reconstruct them using measured values.

$$\bar{T} \equiv \frac{T_1 + T_2}{2}$$

$$\gamma \equiv \left|\frac{T_1 - T_2}{T_1 + T_2}\right|$$

Two shot noises

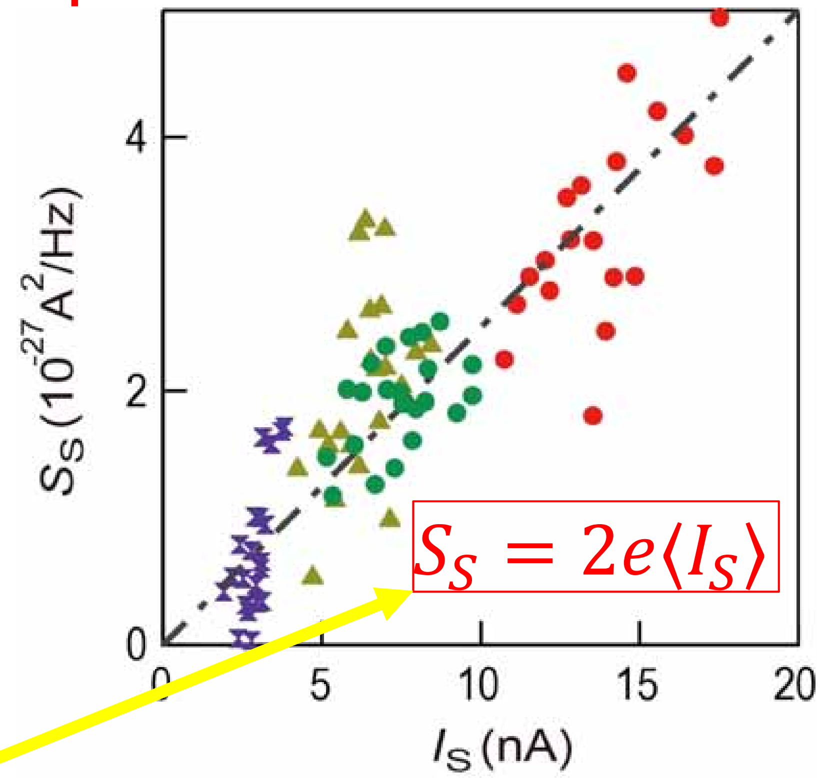
Charge shot noise



$$S_C = 2e\langle I_C \rangle$$

Charge current

Spin shot noise

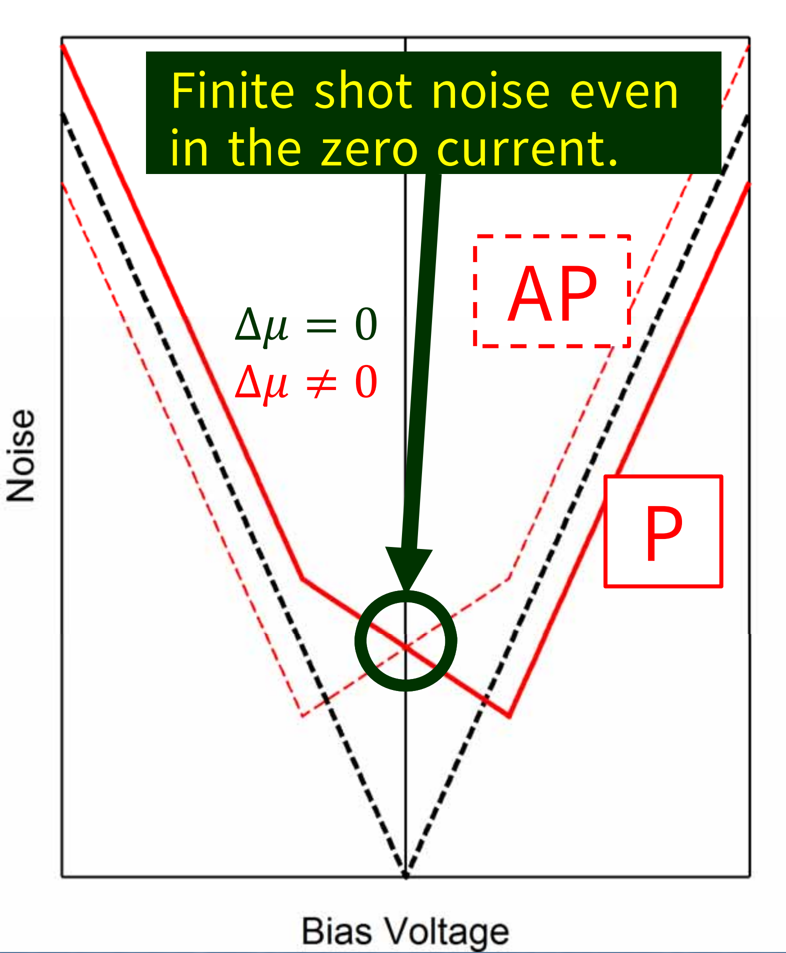


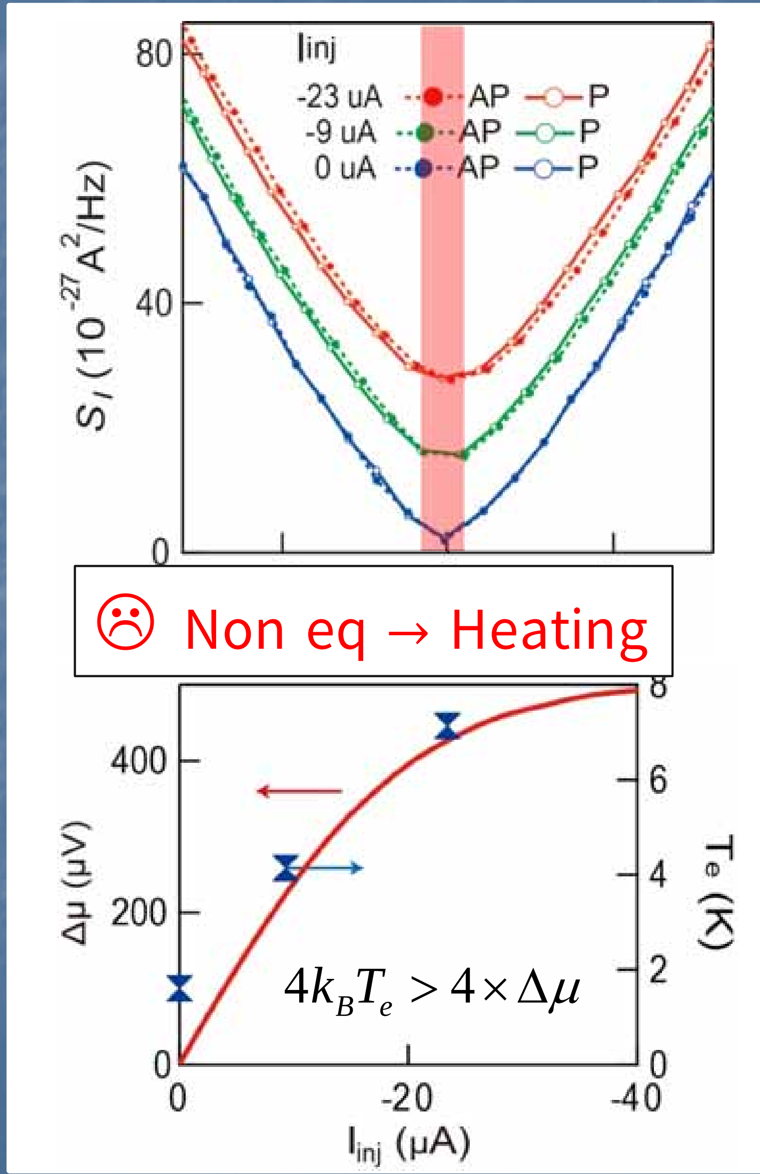
$$S_S = 2e\langle I_S \rangle$$

Spin current

Consistent: spin is preserved in tunneling.
"Spin current" treated by Landauer picture.

Low bias regime: "**pure** spin current"





Conclusion: the noise is the signal.

- Spin current detected by noise.
First observation of spin shot noise.
- Noise tells spin dynamics.
ex: Spin-transfer-torque, edge states in TIs

Arakawa *et al., PRL* **114,** 016601 (2015) [Editors' Suggestion].
Iwakiri, Niimi, Kobayashi, APEX **10,** 053001 (2017).
荒川、小林「スピン流とそのゆらぎ」、日本物理学会誌 **74,** 222 (2019).