

Evolution of the Kondo effect in a quantum dot probed by shot noise

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T. Machida (IIS, University of Tokyo)

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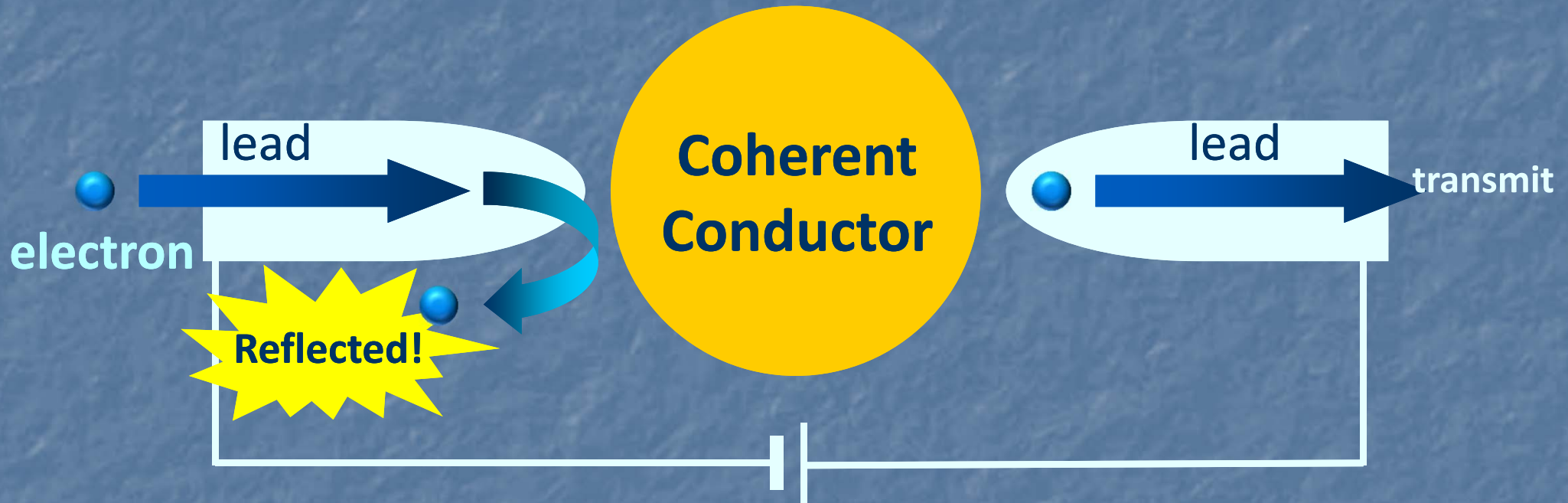
Outline

- Introduction: Noise in mesoscopic systems
- Electron bunching effect in **Kondo** correlated state
- **Spin polarization** deduced by shot noise
- Conclusion

Shot noise in spin-dependent transport

Mesoscopic Transport

Imry & Landauer, *Rev. Mod. Phys.* **71**, S306 (1999).
Blanter & Büttiker, *Phys. Rep.* **336**, 1 (2000).



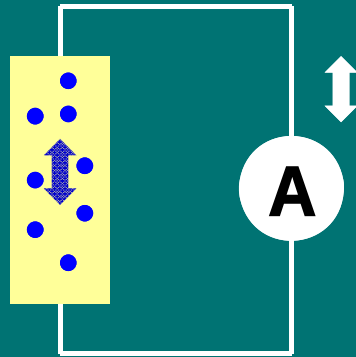
Landauer Formula = “Conductance is transmission.”

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

Conductance measurements give you information on the electronic properties of single site quantum systems (interference, single-level transport, Kondo physics...).

Thermal noise & Shot noise

Thermal noise $S_I = 4k_B T G$



$$\langle I \rangle = 0$$

Essentially different!

Johnson-Nyquist (1928)



Gas molecules in a tube with temperature T

Black-body radiation

Nyquist, Phys. Rev. **32**, 110 (1928).

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

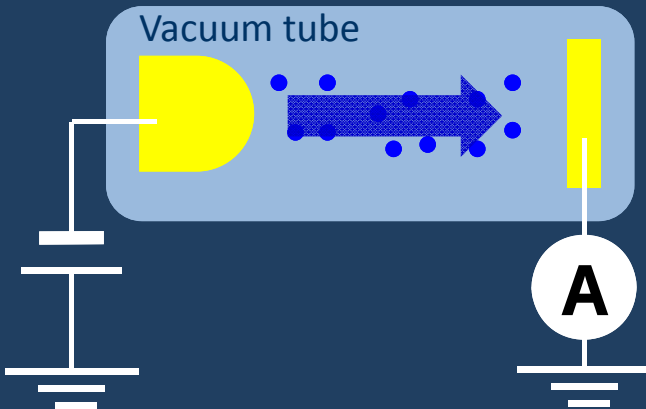
(non-equilibrium noise)

Schottky (1918)

$$\langle I \rangle = e\langle N \rangle \quad \text{*assume Poissonian process}$$

$$\langle (\delta I)^2 \rangle = e^2 \langle (\delta N)^2 \rangle = e^2 \langle N \rangle = e\langle I \rangle$$

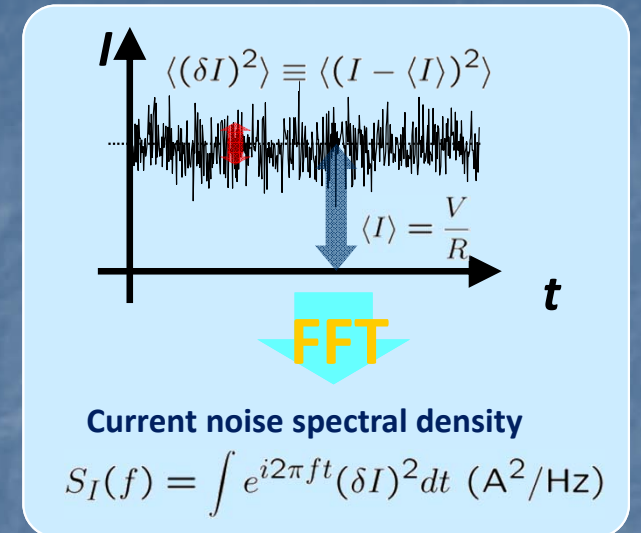
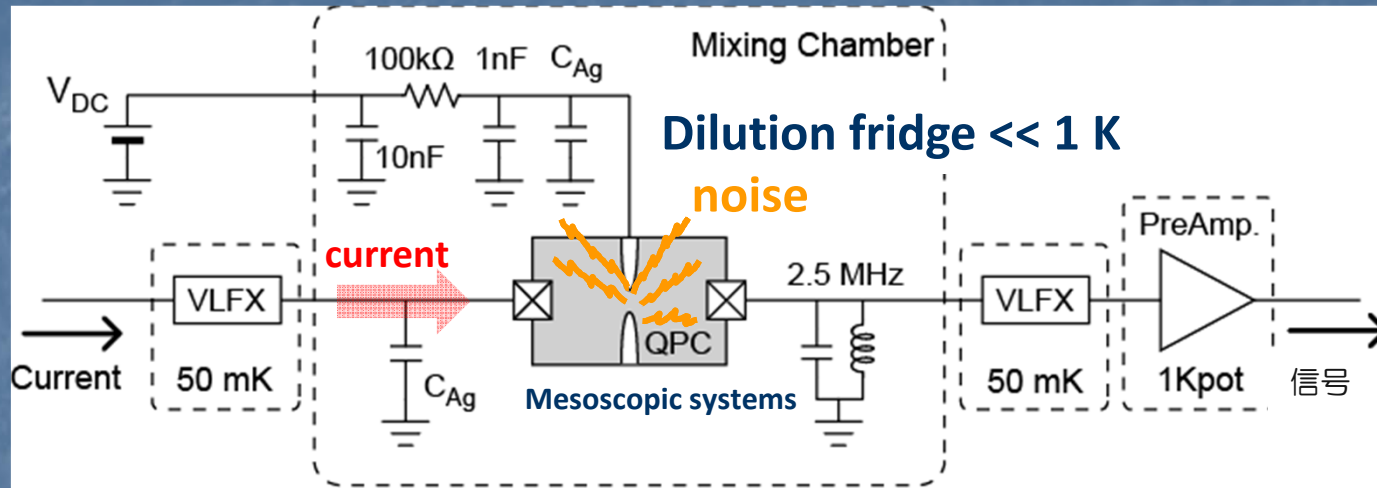
Quantum transport



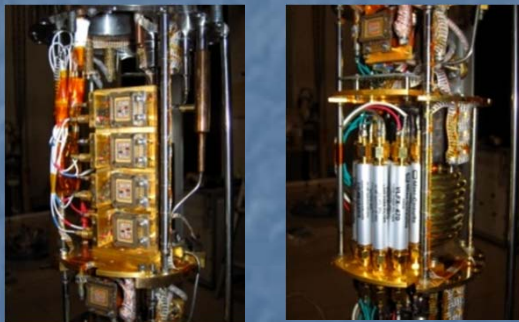
➡ Effective charge $S_I = 2e^* \langle I \rangle$

➡ Fano factor $F \equiv \frac{S_I}{2e\langle I \rangle} = \frac{\langle (\delta N)^2 \rangle}{\langle N \rangle}$

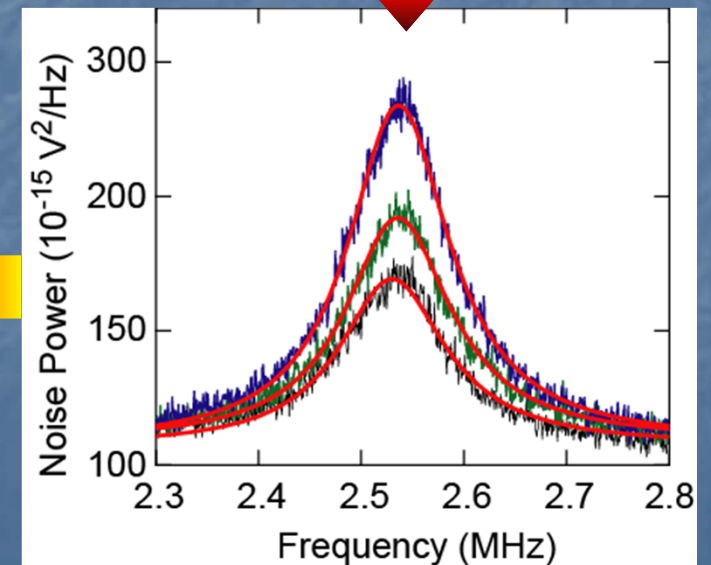
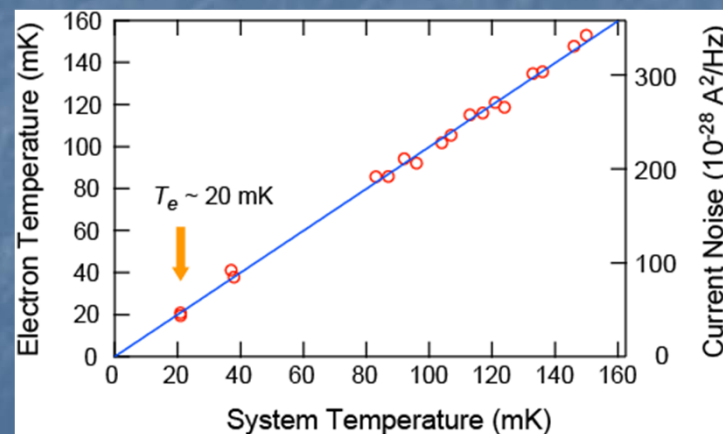
Noise measurement



Cryogenic amplifiers & Cold filters



Sensitivity $\sim 10^{-29} \text{ A}^2/\text{Hz}$
Electron temperature $\sim 20 \text{ mK}$



Our Noise Study

- Bolometric detection of **quantum noise**

Hashisaka *et al.* PRB **78**, 241303(R)(2008).

- **Coherent transport** in magnetic tunnel junctions

Arakawa *et al.* APL **98**, 202103 (2011); Tanaka *et al.* APEX **5**, 053003 (2012).

- Experimental test of **quantum fluctuation theorem**

Nakamura *et al.* PRL **104**, 080602 (2010); PRB **83**, 155431 (2011) [*Editors' suggestion*]

- **Electron-nuclear spin** scattering in quantum wire

Chida *et al.* PRB **85**, 041309(R)(2012) [*Editors' suggestion*]

- Shot noise in the **Kondo regime**

Yamauchi *et al.* PRL **106**, 176601 (2011).

- Electron **spin polarization** due to correlation or SOI

Nakamura *et al.* PRB **79**, 201308(R) (2009); Kohda *et al.* Nature Comm. (to appear).

Evolution of the Kondo effect in a quantum dot probed by shot noise

Yamauchi, *et al. Phys. Rev. Lett.* **106**, 176601 (2011).

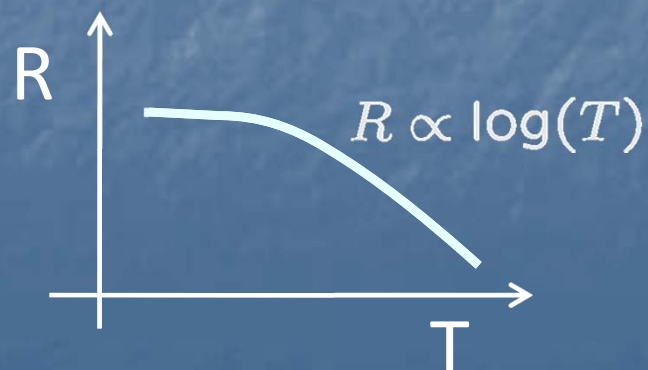
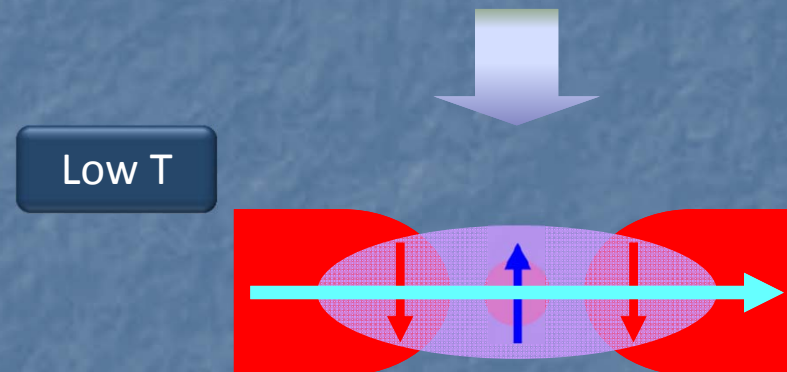
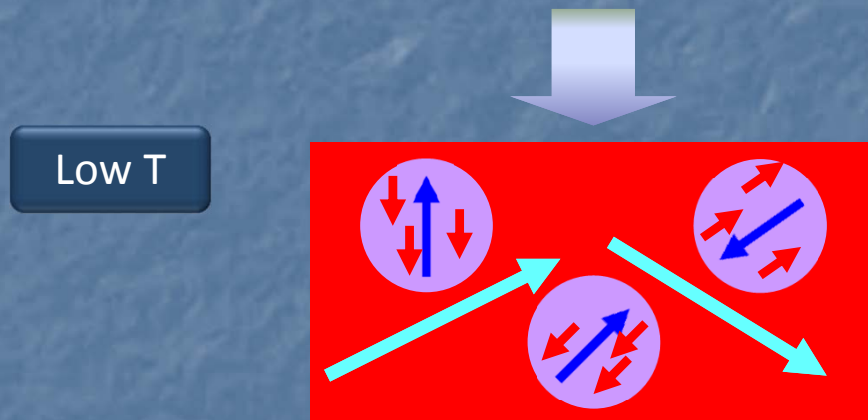
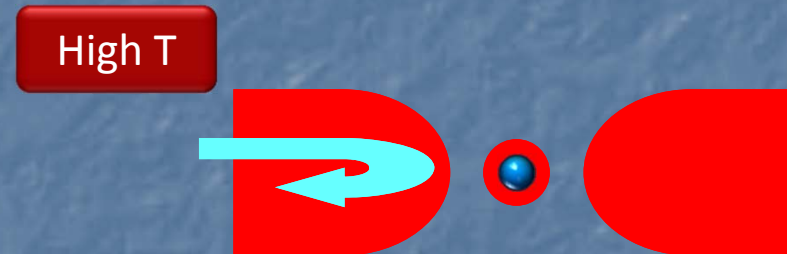
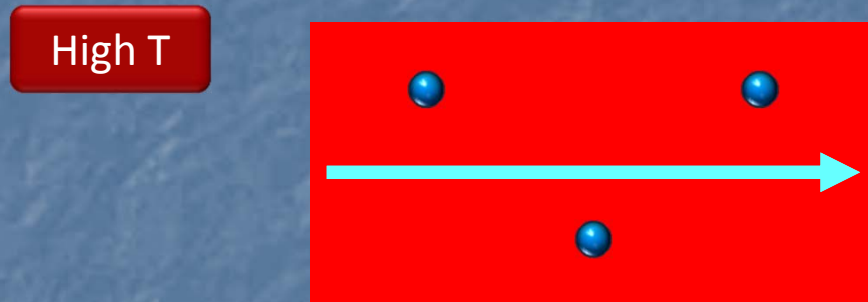
Kondo effect 1964



J. Kondo 1930-

Magnetic impurity in metals

QD



Kondo QD

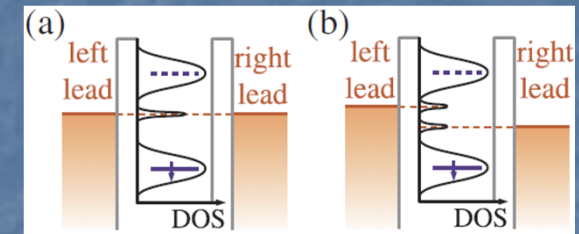
Gordhaber-Gordon *et al.* Nature **391**, 156 (1998);
Cronenwett *et al.*, Science **281**, 540 (1998); J.
Schmid *et al.* Physica B 256-258, 182 (1998). van
der Wiel *et al.*, Science **289**, 2105 (2000).

Realization of Kondo effect in a QD

→ Ideal stage for experiments to test theories on nonequilibrium interacting systems

■ “Three terminal” Kondo effect

S. De Franceschi *et al.*, PRL **89**, 156801 (2002);
R. Leturcq *et al.*, *ibid.* **95**, 126603 (2005).

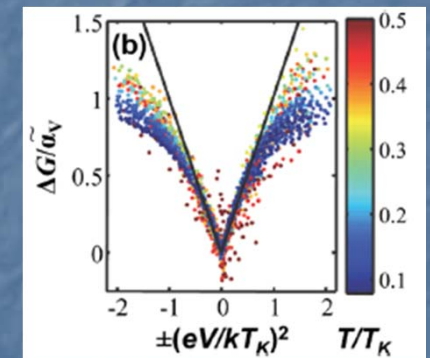


■ Scaling of the differential conductance

Grobis *et al.*, PRL **100**, 246601 (2008); Delattre *et al.*, Nat. Phys. **5**, 208 (2009); Kretinin *et al.* PRB **84**, 245316 (2011).

■ Shot noise / quantum noise

Zarchin *et al.* PRB **77**, 241303(R) (2008); Delattre *et al.*, Nat. Phys. **5**, 208 (2009); Basset *et al.*, PRL **108**, 046802 (2012)...

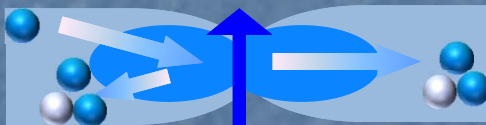


Shot noise in Kondo regime

Theory

Enhanced shot noise due to two-particle back scattering

Kondo state “fractional” charge

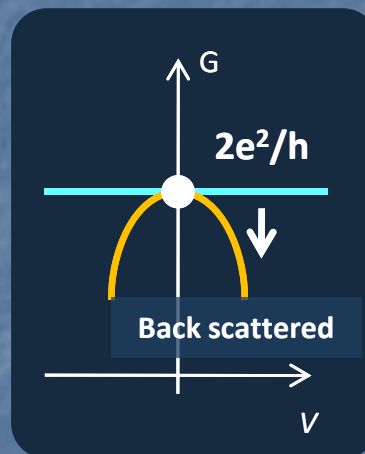


$$e^* = \frac{5}{3}e$$

Free electron model



$$e^* = e$$



Theory

Meir and Golub, PRL **88**, 116802 (2002).

Gogolin and Komnik, PRL **97**, 016602 (2006) .

Sela, Oreg, von Oppen, and Koch, PRL **97**, 086601 (2006).

Golub, PRB **73**, 233310 (2006).

Mora, Leyronas, and Regnault PRL **100**, 036604 (2008).

Mora, et al., PRB **80**, 155322 (2009).

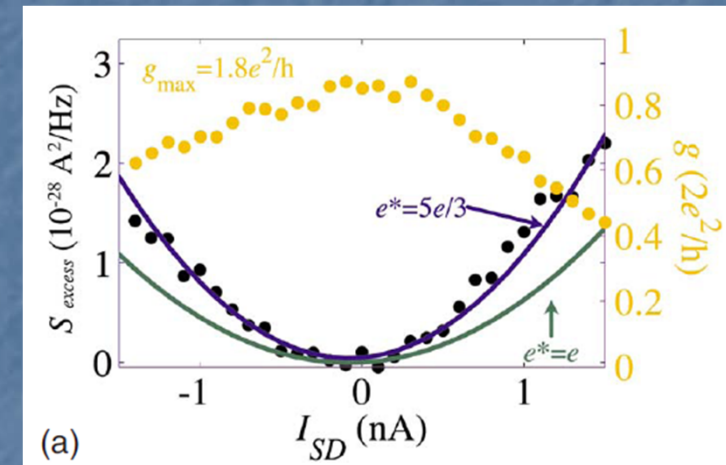
Fujii, JPSJ **79**, 044714 (2010).

Sela and Malecki, PRB **80**, 233103 (2010).

Sakano, Fujii, Oguri, PRB **83**, 075440 (2011). etc...

Experiment

Theory was confirmed.



Zarchin, Zaffalon, Heiblum, Mahalu, and Umansky, PRB **77**, 241303(R) (2008)

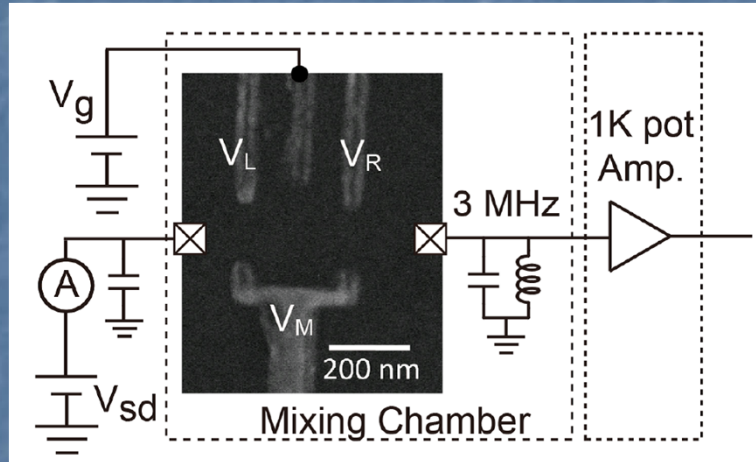
Still to be addressed...

Temperature dependence?

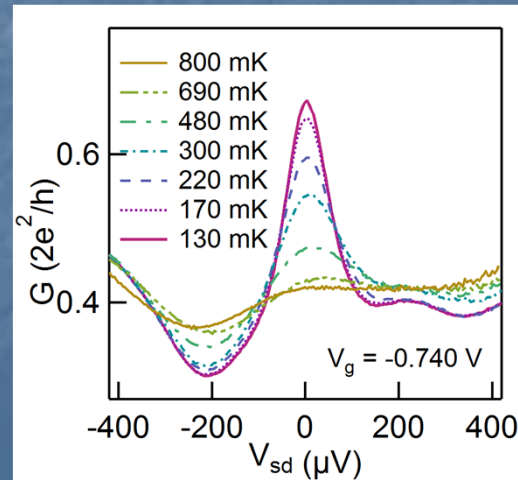
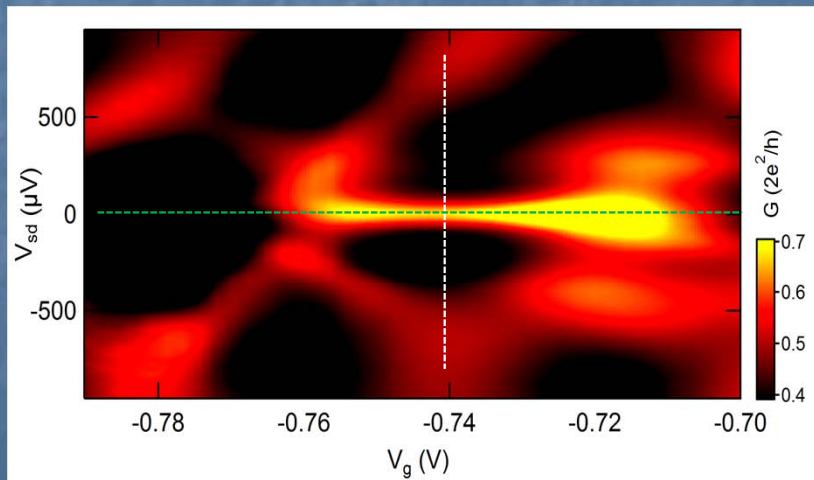
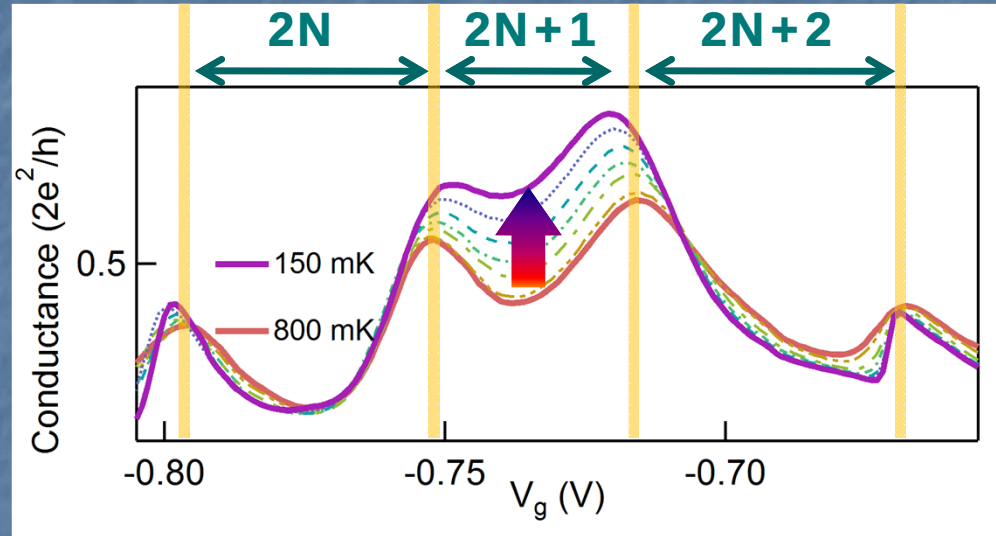
Kondo temperature?

Free particle picture validated?

Kondo state

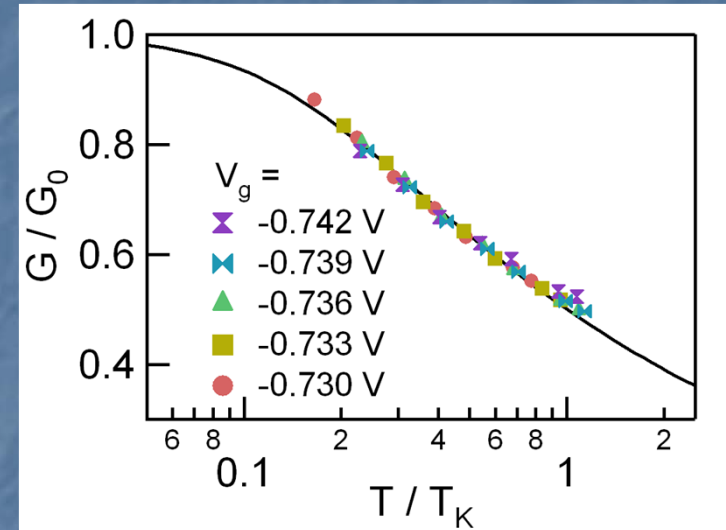
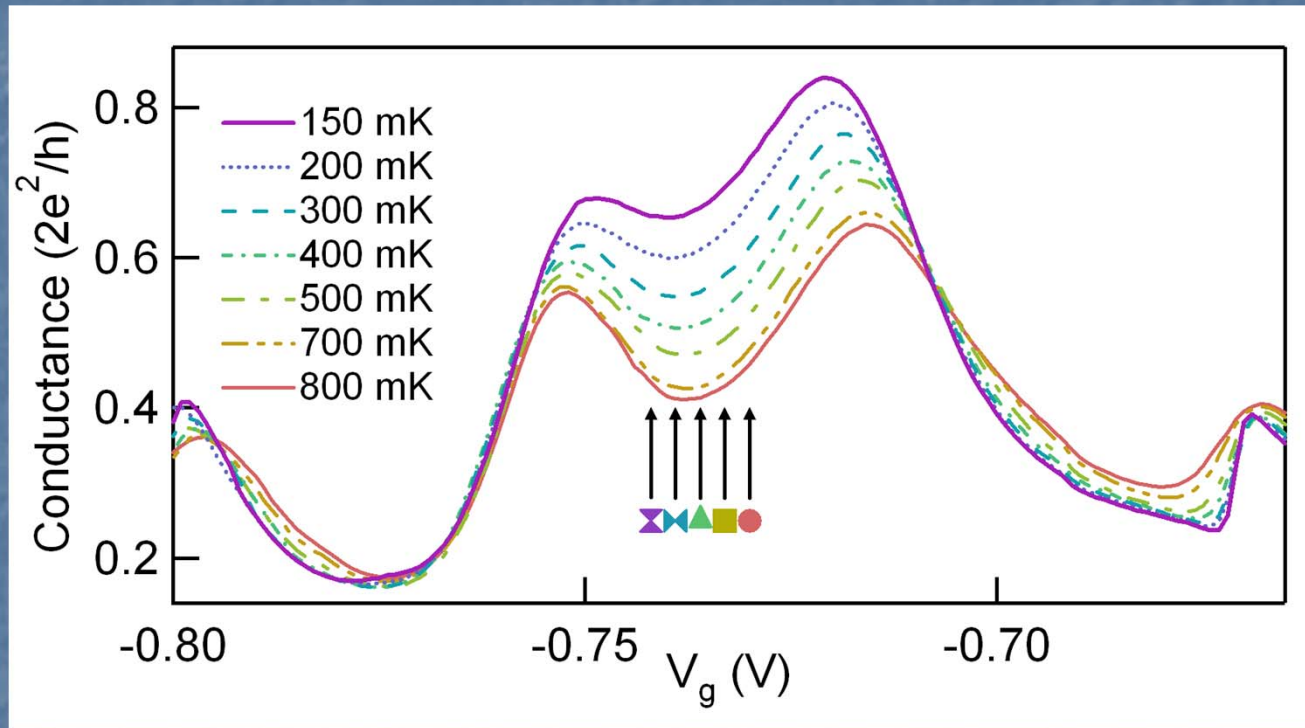


AlGaAs/GaAs 2DEG



- ✓ G increases at low T
- ✓ Parity effect
- ✓ Zero-bias anomaly.

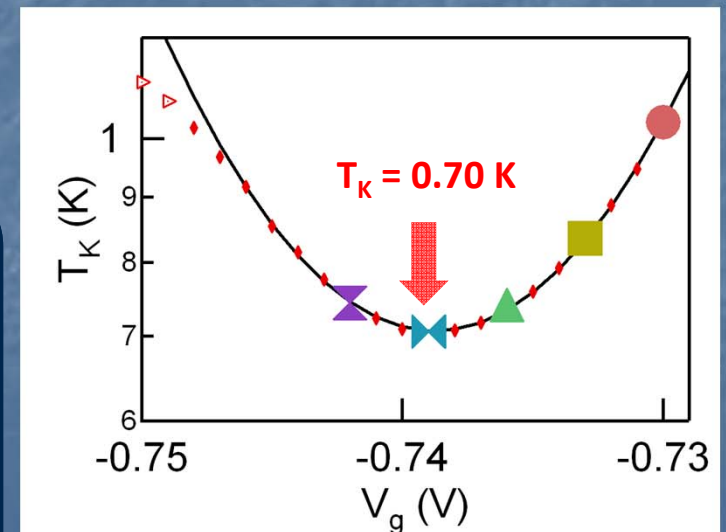
DC characteristic



$$G(T) = G_0 / (1 + (2^{1/s} - 1)(T/T_K)^2)^s$$

$$T_K = \frac{\sqrt{\Gamma U}}{2} \exp\left(\frac{\pi \epsilon_0 (\epsilon_0 - U)}{\Gamma U}\right)$$

$U = 0.56$ meV
 $\Gamma = 0.34$ meV
 $s = 0.18$
 $G_0 = 0.83 \frac{2e^2}{h}$
 Asymmetric QD



Nonequilibrium Conductance

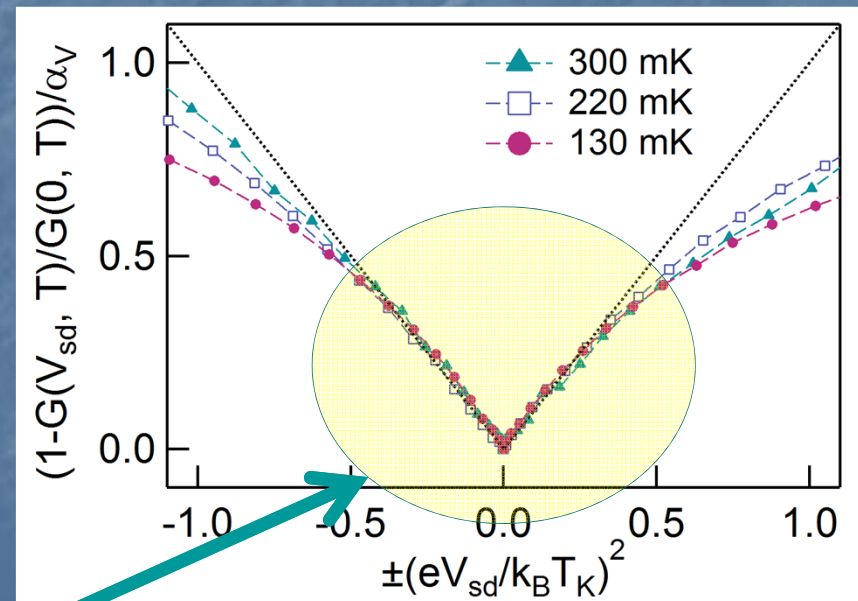
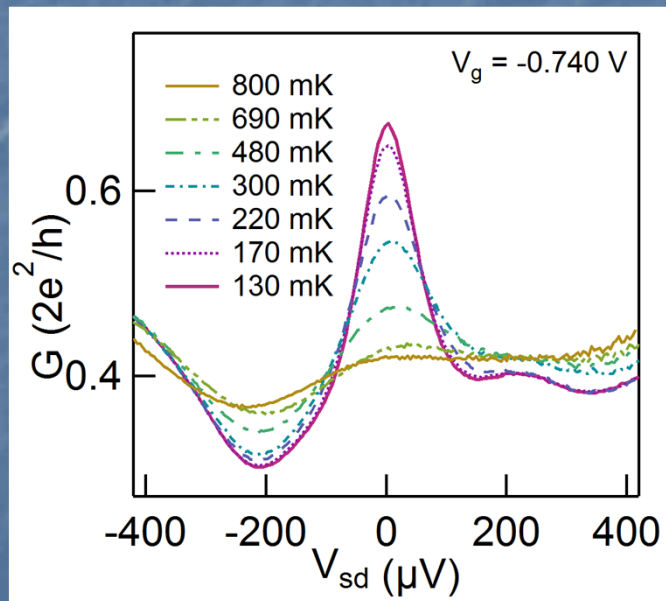
$$\frac{d\langle I \rangle}{dV} \simeq \frac{2e^2}{h} \left[1 - c_V \left(\frac{eV}{\tilde{\Gamma}} \right)^2 - c_T \left(\frac{\pi k_B T}{\tilde{\Gamma}} \right)^2 \right],$$

$$c_V = \frac{1 + 5(R - 1)^2}{4}, \quad c_T = \frac{1 + 2(R - 1)^2}{3}$$

Scaling with Wilson ratio R , T_K , and eV .

Theory: Schiller & Hershfield, PRB 51, 12896 (1995);
Oguri, J. Phys. Soc. Jpn. 74, 110 (2005).

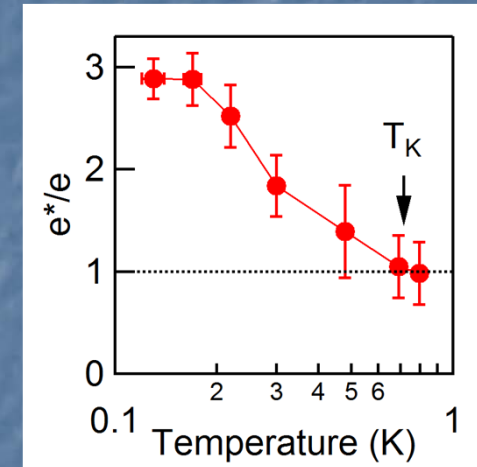
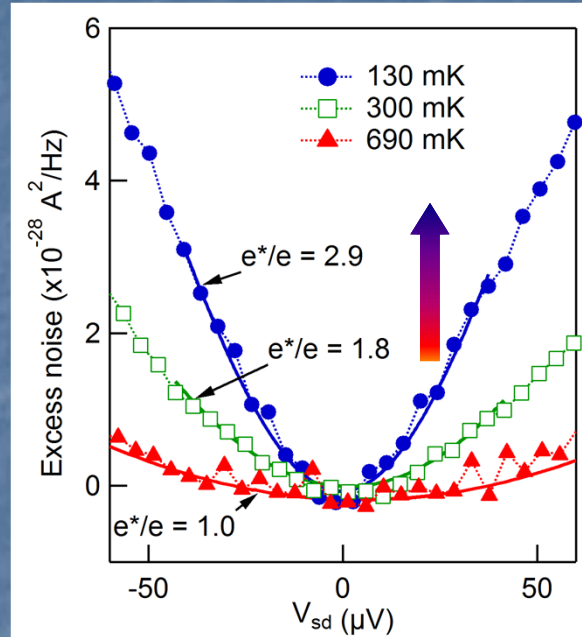
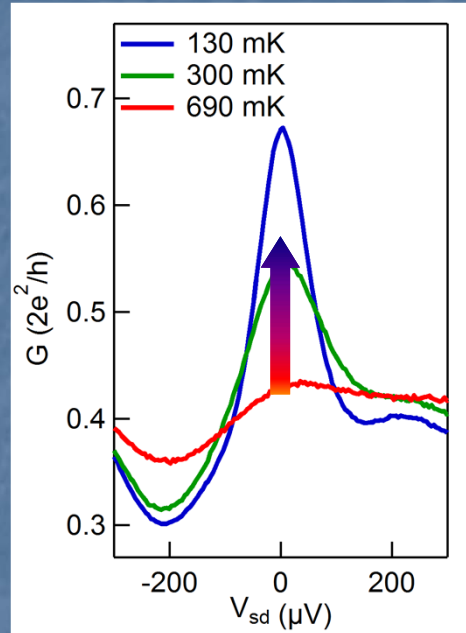
Exp: Grobis *et al.*, PRL 100, 246601 (2008);
Delattre *et al.*, Nat. Phys. 5, 208 (2009).
Kretinin *et al.* Phys. Rev. B **84**, 245316 (2011).



Good scaling at low temperature: T_K is reasonable.

Effective charge

$$S_I = 2e^*I$$



$$S_I = 4k_B T G + 2e^* V_{sd} \underbrace{G}_{\text{Transmission}} \left(1 - \underbrace{\frac{G}{2e^2/h}}_{\text{Reflection}} \right) \left(\coth \left(\frac{eV_{sd}}{2k_B T} \right) - \frac{2k_B T}{eV_{sd}} \right)$$

Effective charge e^*/e

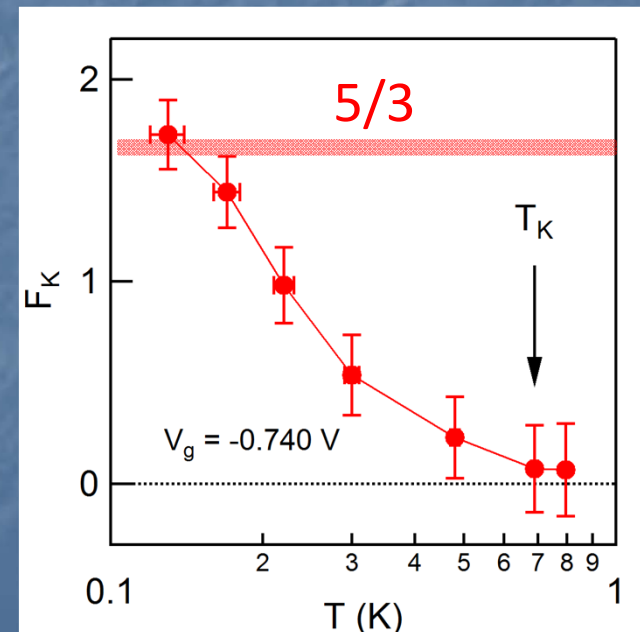
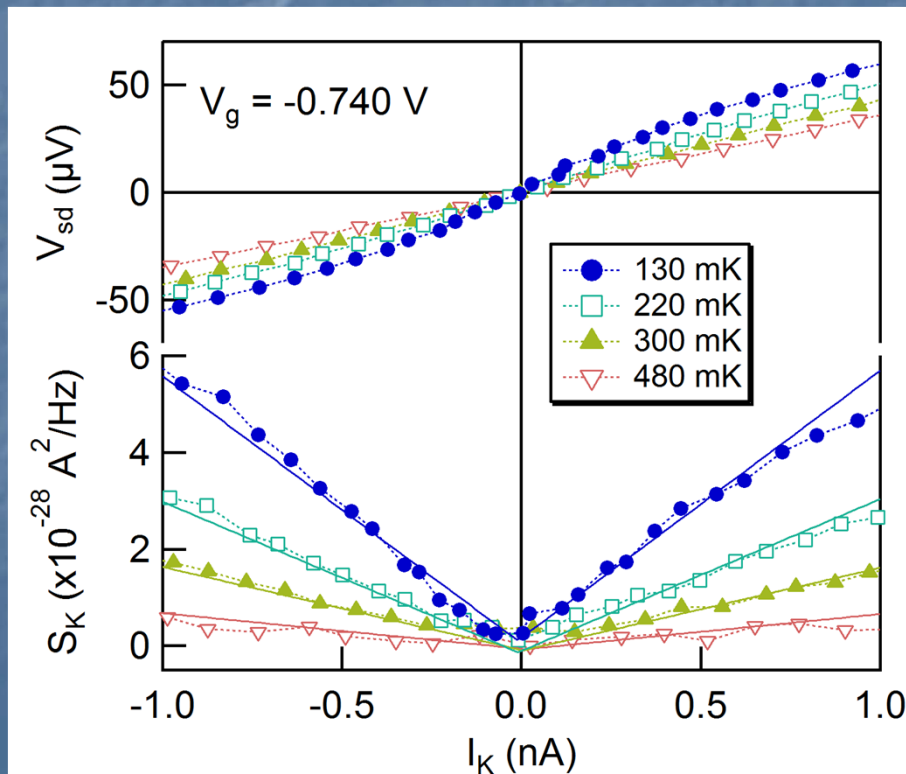
- Equals 1 above T_K . (like free electron)
- More enhanced than 5/3 at low T .
- Free electron picture validated?

$$F = \frac{S_I}{2eI}$$

Finite- T Fano factor

Mora, Leyronas, Regnault PRL **100**, 036604 (2008); Mora et al., PRB **80**, 155322 (2009); Fujii, JPSJ **79**, 044714 (2010); Sakano, Fujii, Oguri, PRB **83**, 075440 (2011). etc...

$$F_K \equiv \frac{S_K}{2eI_K} \left\{ \begin{array}{l} S_K \equiv S_I(V_{sd}, T) - 4k_B T G(V_{sd}, T) - S_0 \\ S_0 \equiv 2e \frac{2e^2}{h} \delta^2 (1 - \delta^2) V_{sd} \left(\coth \left(\frac{eV_{sd}}{2k_B T} \right) - \frac{2k_B T}{eV_{sd}} \right) \\ I_K \equiv \frac{2e^2}{h} (1 - \delta^2) V_{sd} - I(V_{sd}, T) \end{array} \right. \quad \text{Asymmetry of QD } (\delta^2) \text{ taken into account}$$



$F_K = 5/3$?

- $5/3$ is only realized in the unitary limit in a symmetric QD.
- Asymmetry, finite temperature, and finite U/Γ reduces F_K below $5/3$. (In the present case, $F_K \sim 1.2$.)

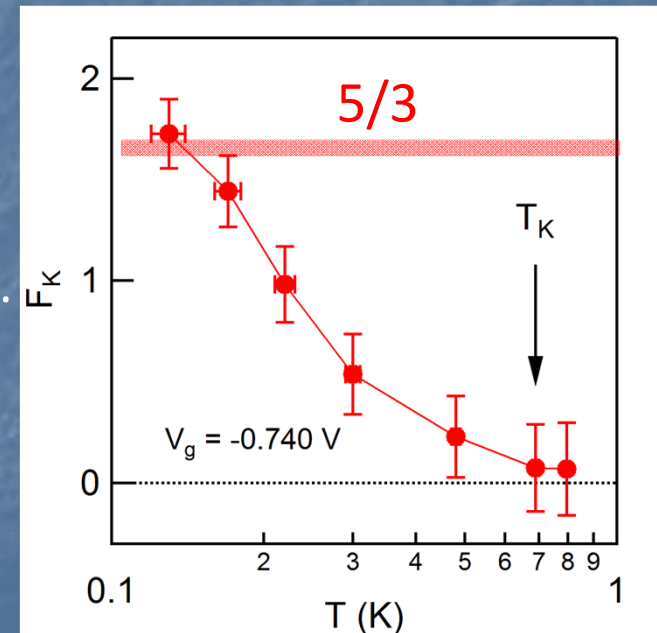
Sakano, Fujii, Oguri, PRB **83**, 075440 (2011).

- ⇒ Shot noise in Kondo regime is MORE enhanced than theoretical prediction.
- ⇒ The same for the case Zarchin *et al.* (2008).

Inelastic co-tunneling?

Effect of adjacent levels?

Long range Coulomb interaction?



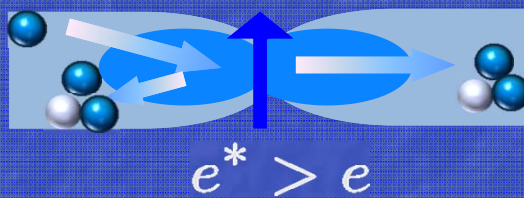
Electron bunching

Bunching

$$S_I > 2eI$$

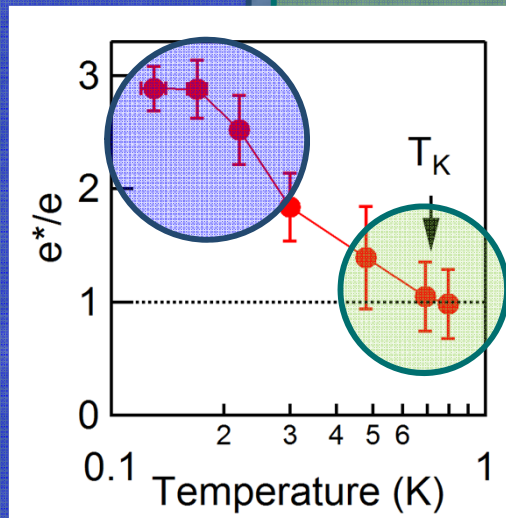


Kondo state



Two particle scattering at Kondo resonance.

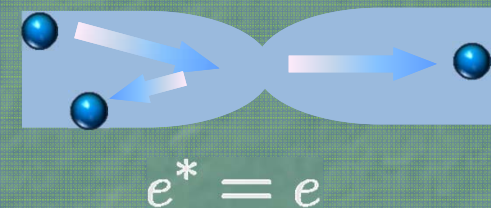
Theoretically, $F(e^*/e) = 5/3$



Poissonian Process $S_I = 2eI$



Free electron like



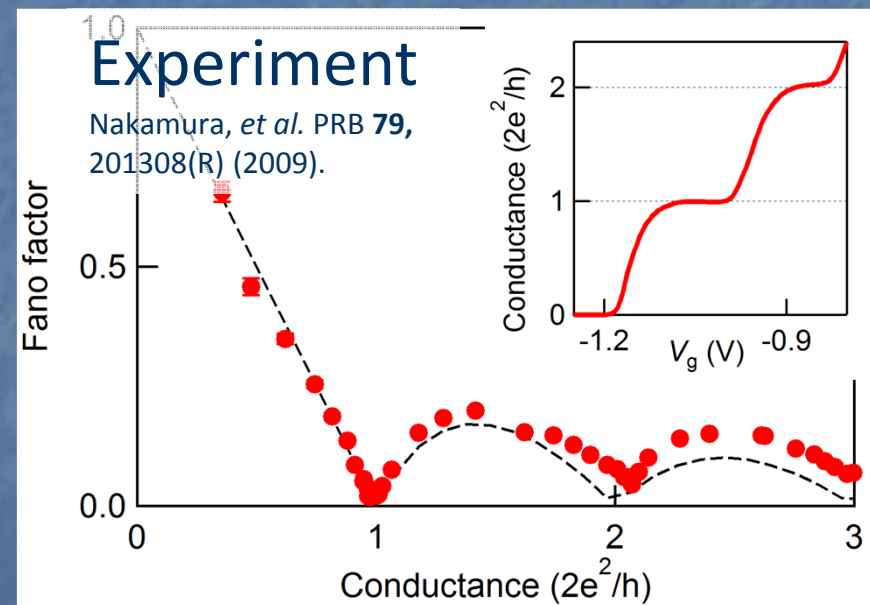
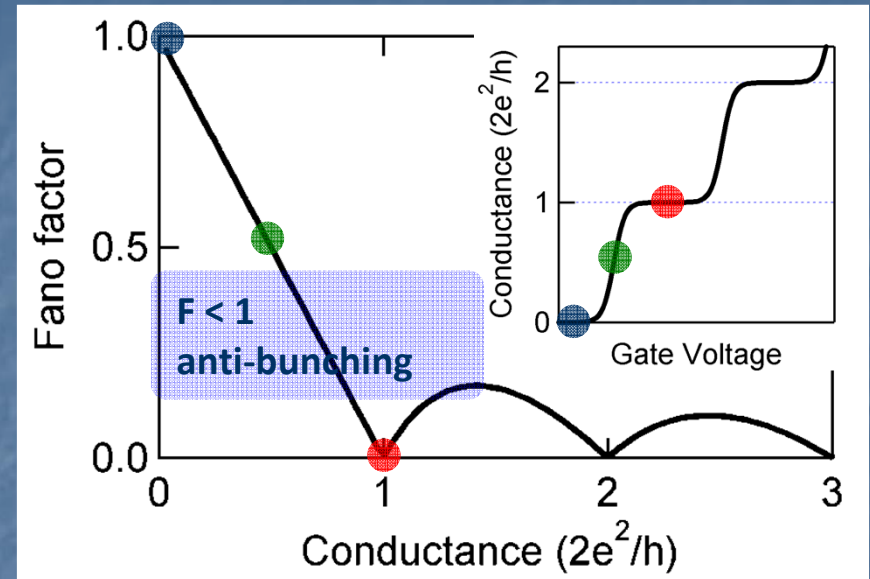
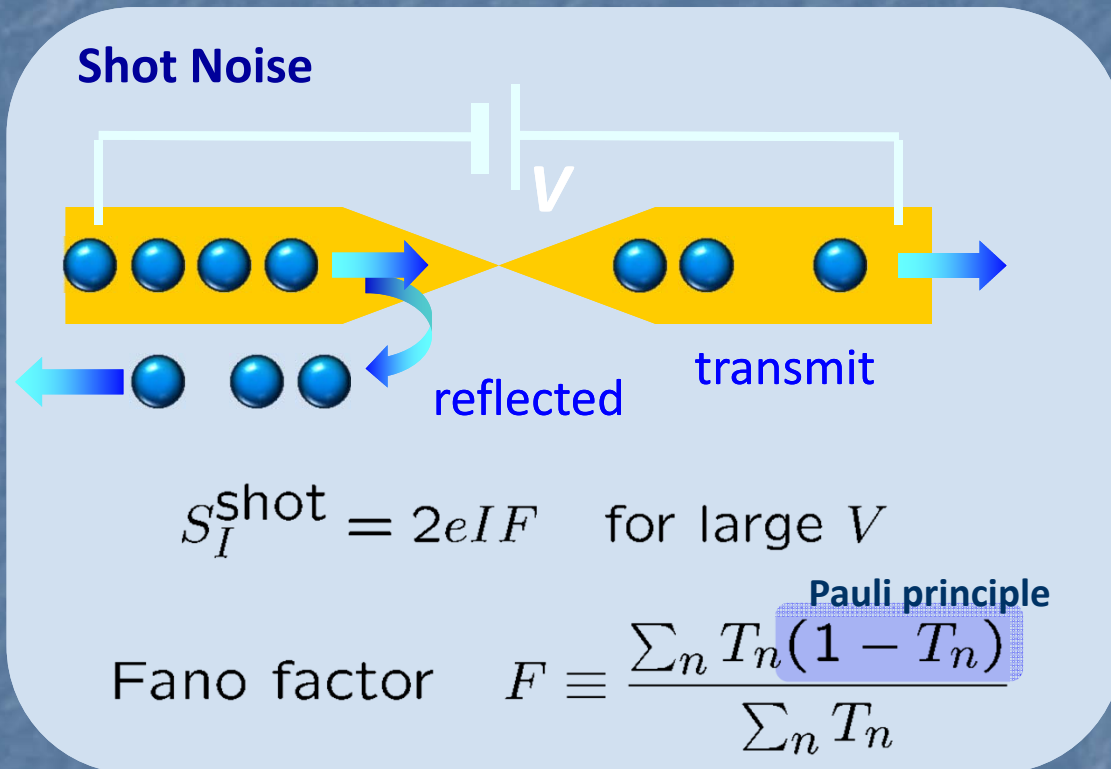
“Collision experiment” on a chip

Theory: Meir and Golub, PRL **88**, 116802 (2002); Sela, Oreg, von Oppen, and Koch, PRL **97**, 086601 (2006); Golub, PRB **73**, 233310 (2006); Gogolin and Komnik, PRL **97**, 016602 (2006); Mora, Leyronas, and Regnault PRL **100**, 036604 (2008); Vitushinsky, Clerk, and Le Hur, PRL **100**, 036603 (2008). Fujii, JPSJ **79**, 044714 (2010); Sela and Malecki, PRB **80**, 233103 (2010); Sakano, Fujii, and Oguri, PRB **83**, 075440 (2011).

Spin Polarization Deduced by Shot Noise

Shot Noise in QPC

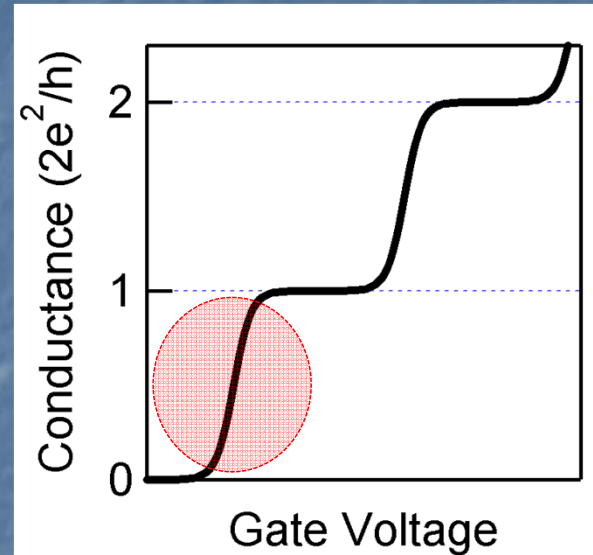
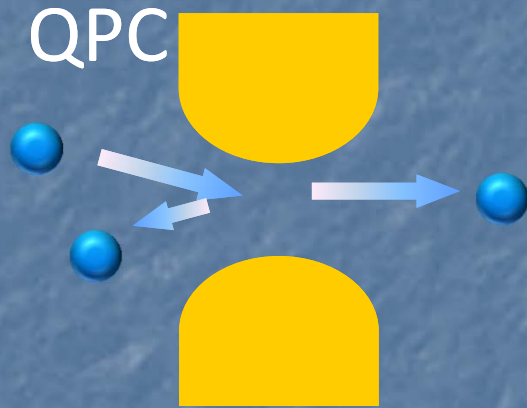
Büttiker, PRB **46** 12485 (1992).



Reznikov, et al. PRL **75**, 3340 (1995); Kumar, ibid. **76**, 2778 (1996). Liu, et al. Nature **391**, 263 (1998); Y. M. Blanter and M. Buttiker, Phys. Rep. **336**, 1 (2000).

When channels are spin-dependent

Blanter & Büttiker, *Phys. Rep.* **336**, 1 (2000).

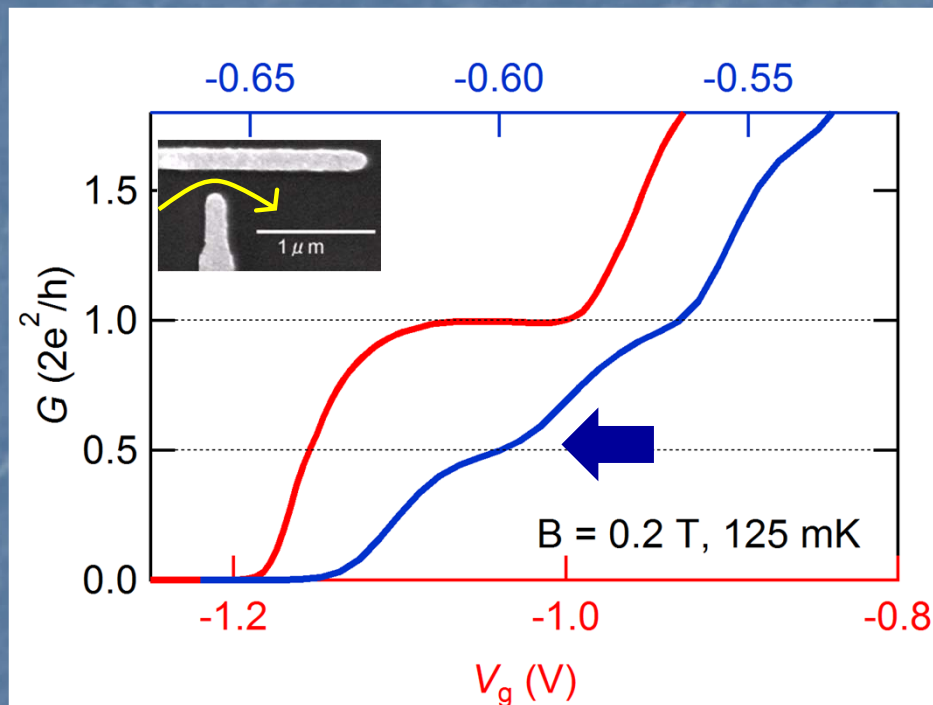


	Spin degenerate	Spin-dependent channels
Conductance	$G = \frac{2e^2}{h} T$	$G = \frac{e^2}{h} (T_{\uparrow} + T_{\downarrow})$
Fano factor	$F = 1 - T$	$F = \frac{T_{\uparrow}(1 - T_{\uparrow}) + T_{\downarrow}(1 - T_{\downarrow})}{T_{\uparrow} + T_{\downarrow}}$
Electron spin polarization	---	$P \equiv \frac{ T_{\uparrow} - T_{\downarrow} }{T_{\uparrow} + T_{\downarrow}} = \sqrt{\frac{2e^2}{h} \frac{1 - F}{G} - 1}$

Case I: “Conductance Anomaly”

Anomaly & Polarizaion

Conventional QPC in 2DEG at $B \sim 0$ T

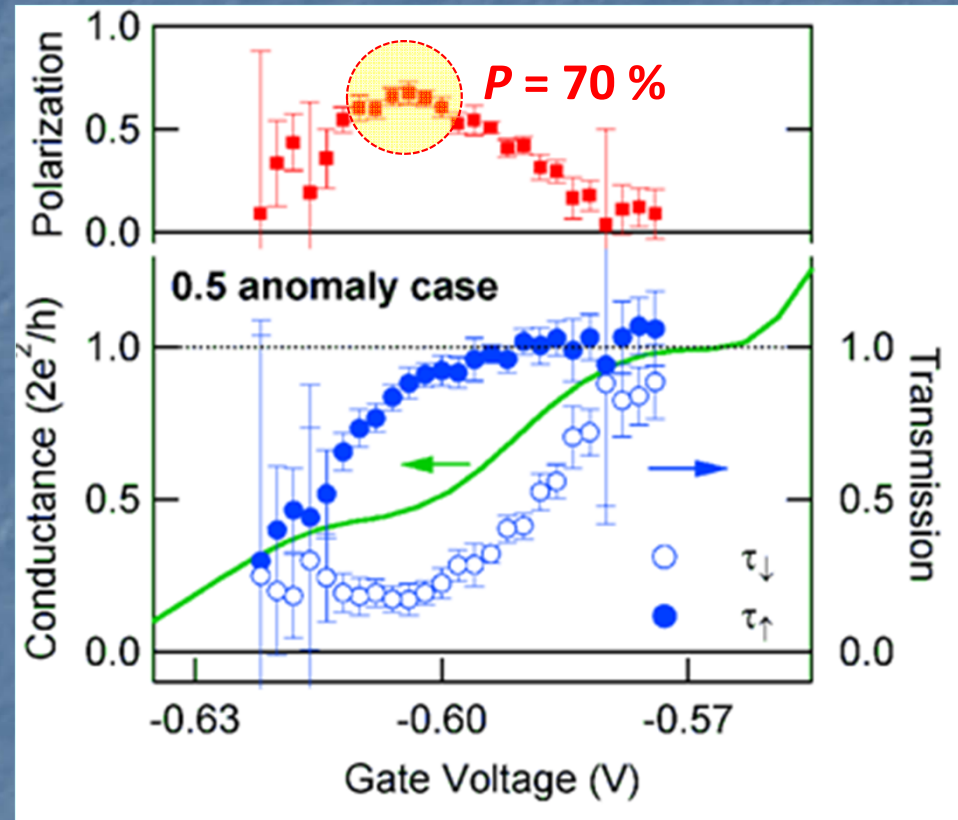


Conductance anomaly in QPC (EXP.)

Spin-related many body effect Thomas *et al.*, PRL **77**, 135 (1996); Kristensen *et al.*, PRB **62**, 10 950 (2000); Reilly *et al.*, PRB **63**, 121311(R) (2001); Cronenwett *et al.*, PRL **88**, 226805 (2002); Reilly *et al.*, PRL **89**, 246801 (2002).

Anomaly in shot noise Roche *et al.*, PRL **93**, 116602 (2004); DiCarlo *et al.*, PRL **97**, 036810 (2006).

Electric control of the anomaly Crook *et al.*, Science **312**, 1359 (2006); Chung *et al.* PRB **76**, 035316 (2007)



Nakamura, KK et al. PRB **79**, 201308 (R) (2009).

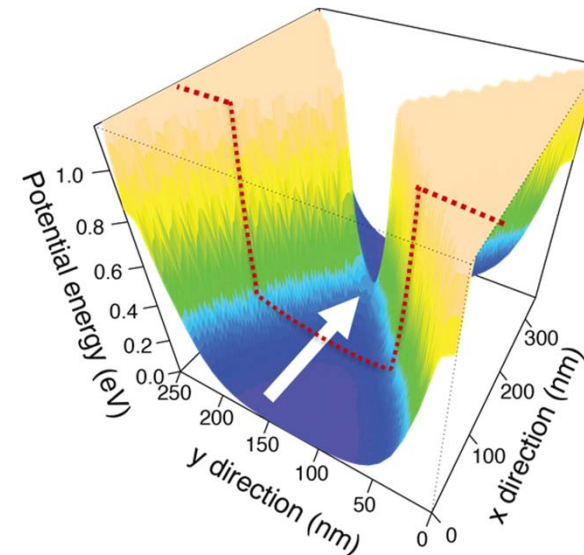
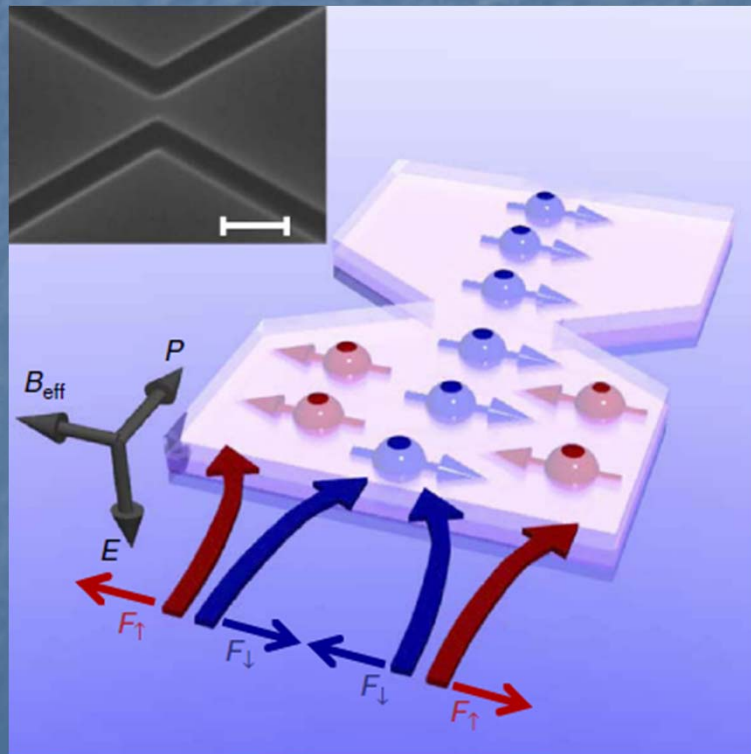
Mechanism?

Case II: Rashba Spin-orbit Interaction

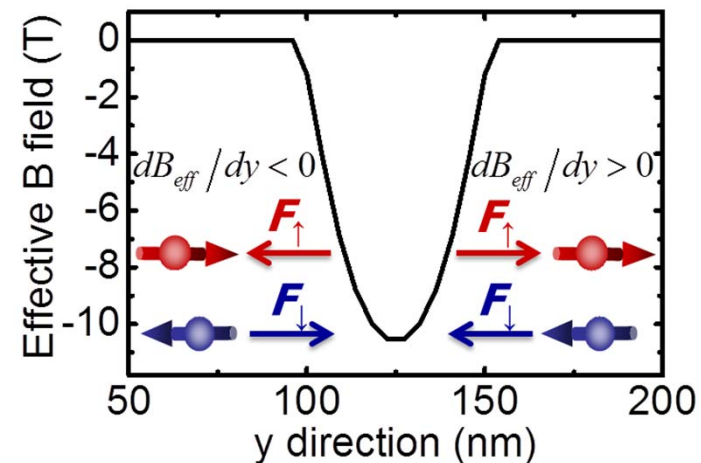
QPC on InGaAs/InGaAsP heterostructure

strong Rashba spin-orbit interaction

$$E_{SOI} = \pm \alpha k_F = \pm \frac{1}{2} g \mu_B B_{eff}$$

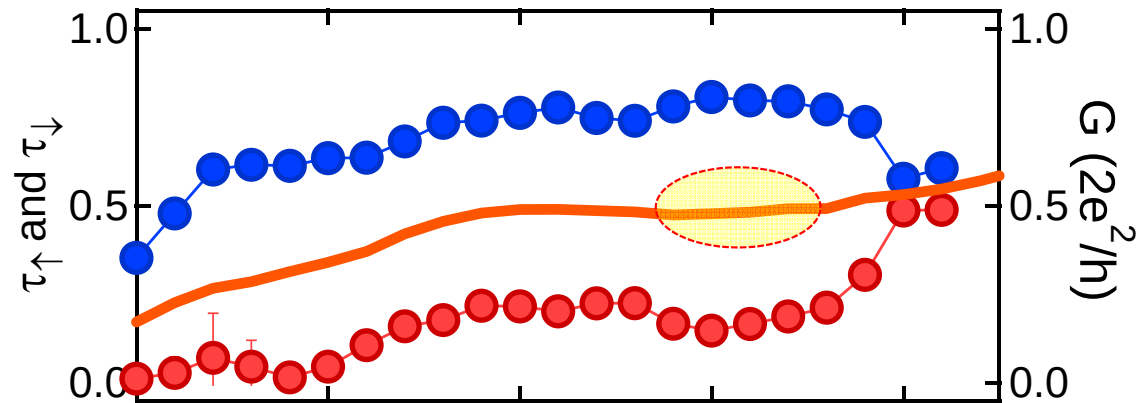
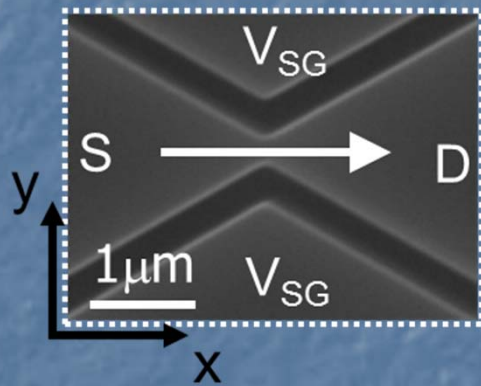


Effective B field along y-direction

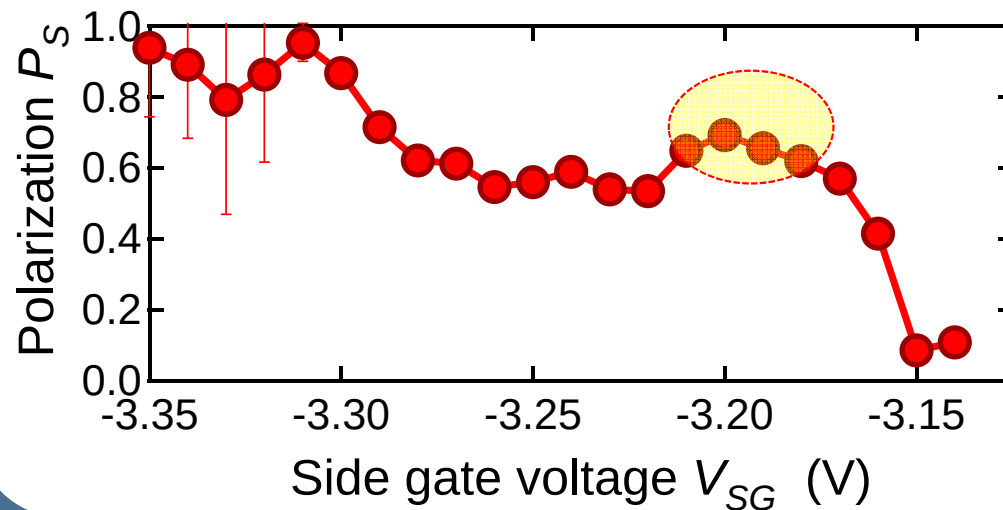


Spin polarization

QPC on InGaAs 2DEG



$P = 70\%$ at $0.5(2e^2/h)$



M. Kohda, S. Nakamura, Y. Nishihara, KK, T. Ono, J. Ohe, Y. Tokura, T. Mineno, and J. Nitta, Nature Comm. (to appear).

Conclusion

- Electron bunching in the Kondo regime

- Test the nonequilibrium Kondo physics.
- “Collision experiment” on a chip

Yamauchi et al., Phys. Rev. Lett. **106**, 176601 (2011).

- Electron spin polarization in QPC

- Anomaly case

Nakamura et al. Phys. Rev. B **79**, 201308 (R) (2009).

- Rashba SOI case

Kohda et al. Nature Communications (to appear).

Shot noise is a powerful tool to address
spin-dependent quantum transport.