SU(2) & SU(4) Kondo Effects in a Carbon Nanotube Probed by Shot-Noise

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Theory

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Quick reminder

Shot noise

Kondo effect in CNT

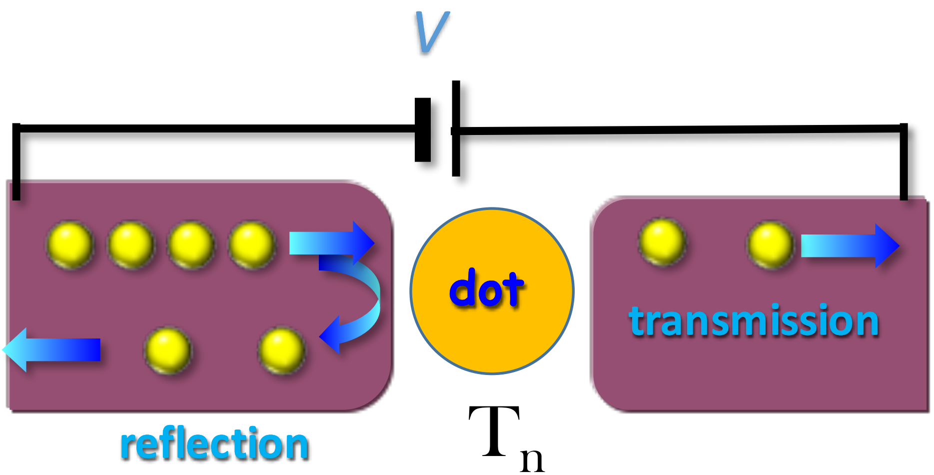
Linear shot noise of SU(2) and SU(4) Kondo effect

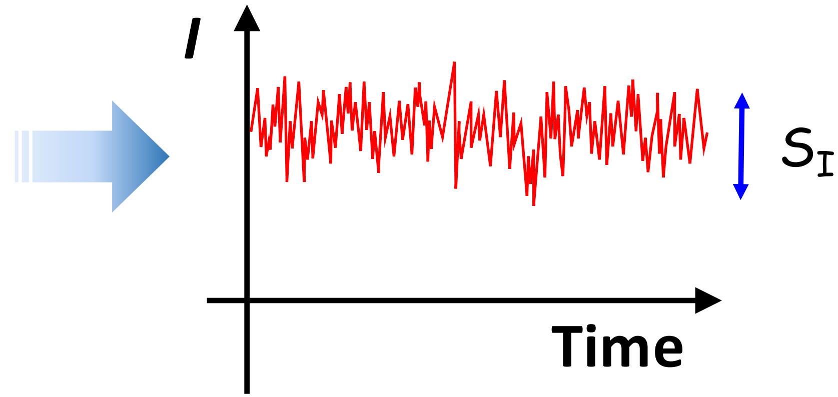
Direct signature of the symmetry class

Non-linear noise:

Observation of 2-particle scattering induced by interactions out of equilibrium

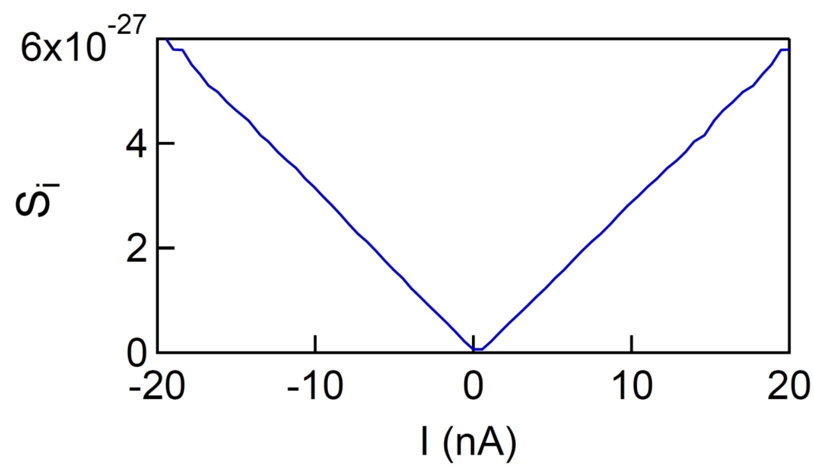
Origin of shot noise





Fluctuations due to the partition of scattered particles

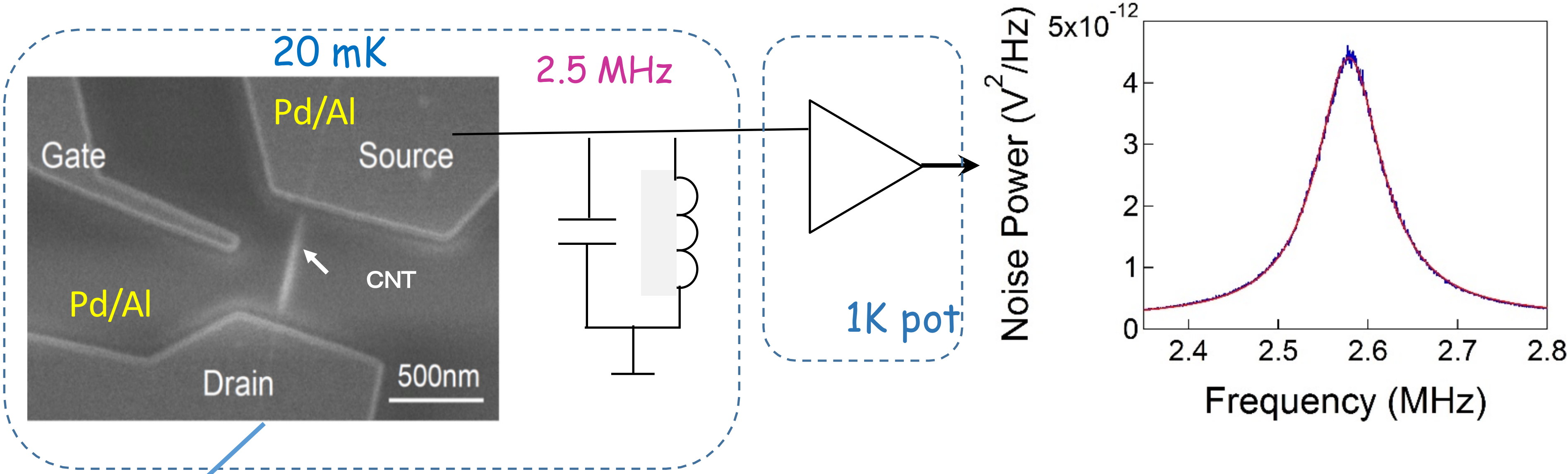
$$S_I = 2eF\,I \quad \text{with} \quad F = \frac{\sum T_n(1-T_n)}{\sum T_n}$$

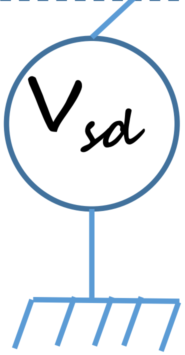


e = charge of the particle
F = Fano factor = statistics of the particles

Nature of the quasiparticle and the scattering mechanism

Experimental set-up for noise measurement





DC measurement +
resonant circuit for noise

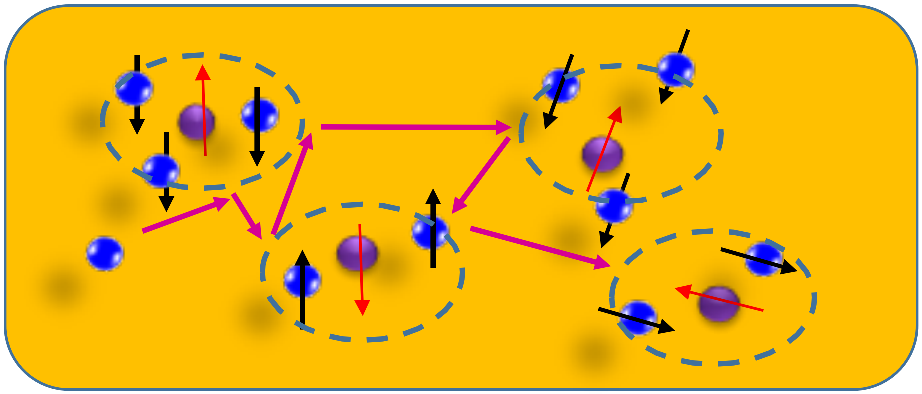
Sensitivity ~ 10^{-29} A^2/Hz

Hashisaka, KK *et al.* Rev. Sci. Inst. 80, 096105 (2009);
Arakawa, KK, et al. Appl. Phys. Lett. 103, 172104 (2013).

Signature of the Kondo effect

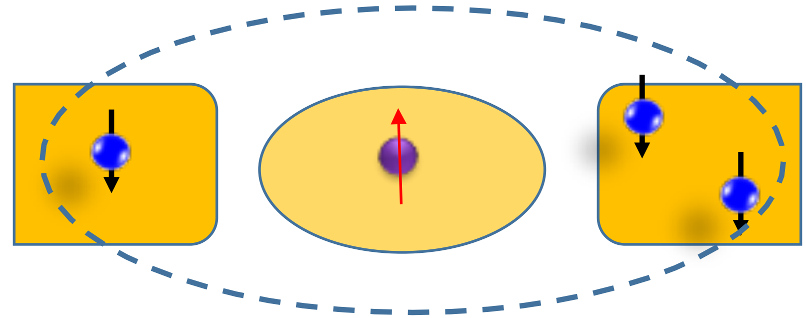
→ Spin screening induced by electron interaction

Macroscopic sample

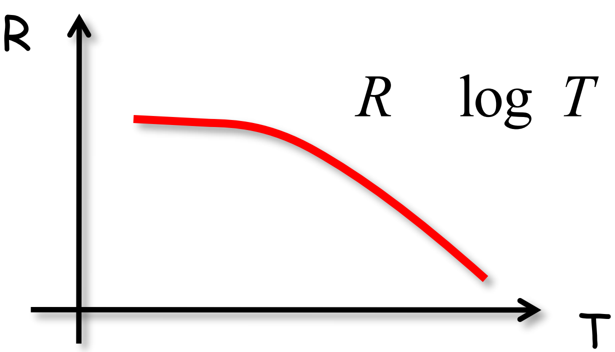


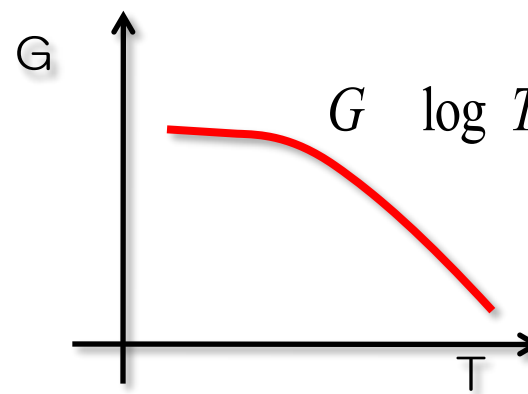
Scattering enhanced

Quantum dot (1 electron)



Delocalization enhanced





Probe locally a many body state

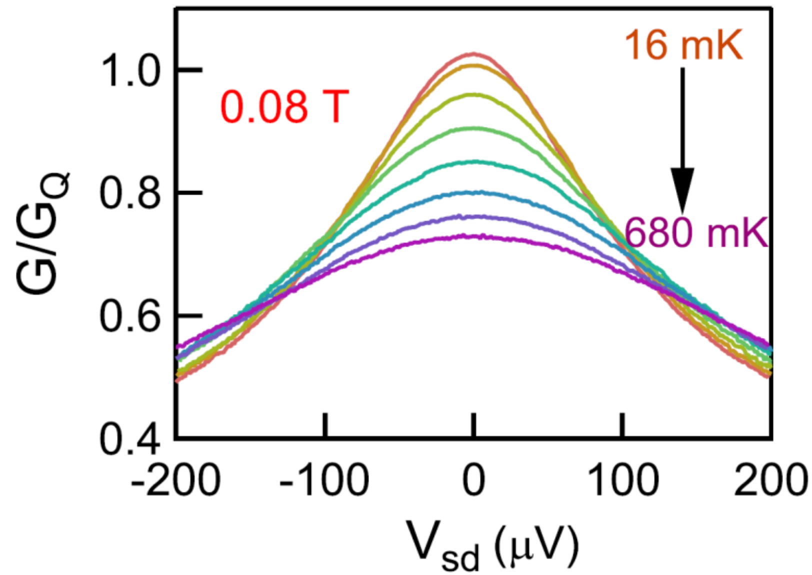
Interaction and Non-equilibrium Kondo physics

« First order » correction:

Non-linear conductance

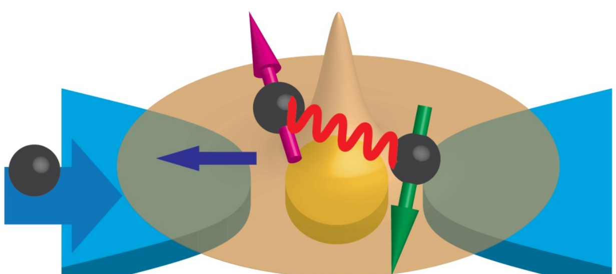
Scaling with T,B,V

Kretinin et al, Phys. Rev. B 84 (2011)



Higher order : 2-particle scattering induced by residual interaction

Non-linear noise   Enhanced current fluctuations



Zarchin et al, PRB (2008)

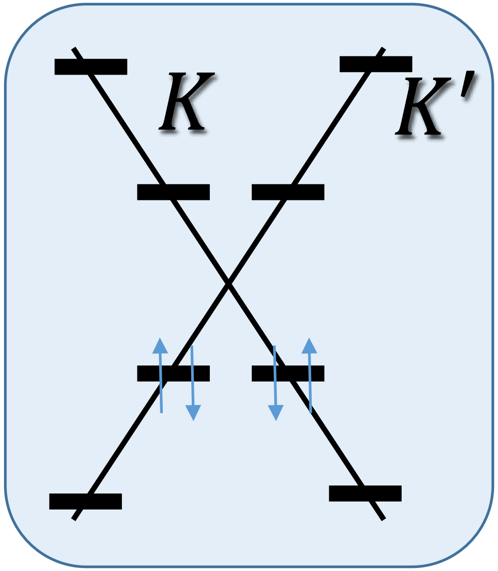
Delattre et al, Nature Physics (2009)

Yamauchi et al, PRL (2011)

not quantitative

Nanotube dot = 2 different Kondo states

nanotube band structure

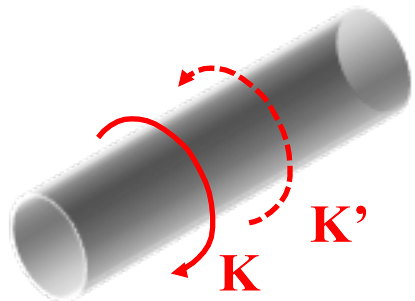


4 e⁻ per shell

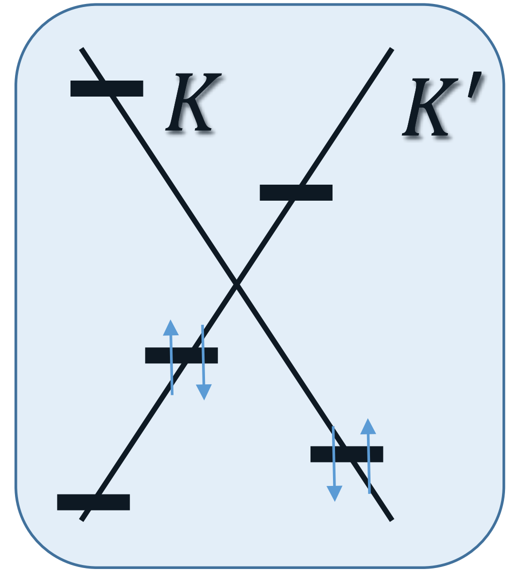
2 « spin » are screened

2 transport channels

SU(4) symmetry



Disorder, spin-orbit = splitting



2 e⁻ per shell

Only the usual spin is screened

1 transport channel

SU(2) symmetry

Signature of interaction depends on the symmetry class

Part 1

Noise in the linear regime

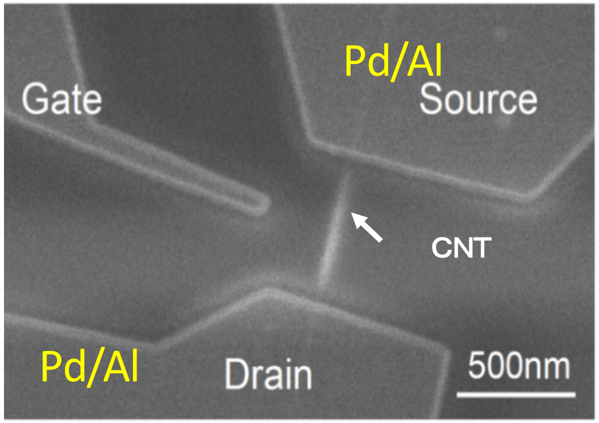
$$eV \ll k_B T_K$$

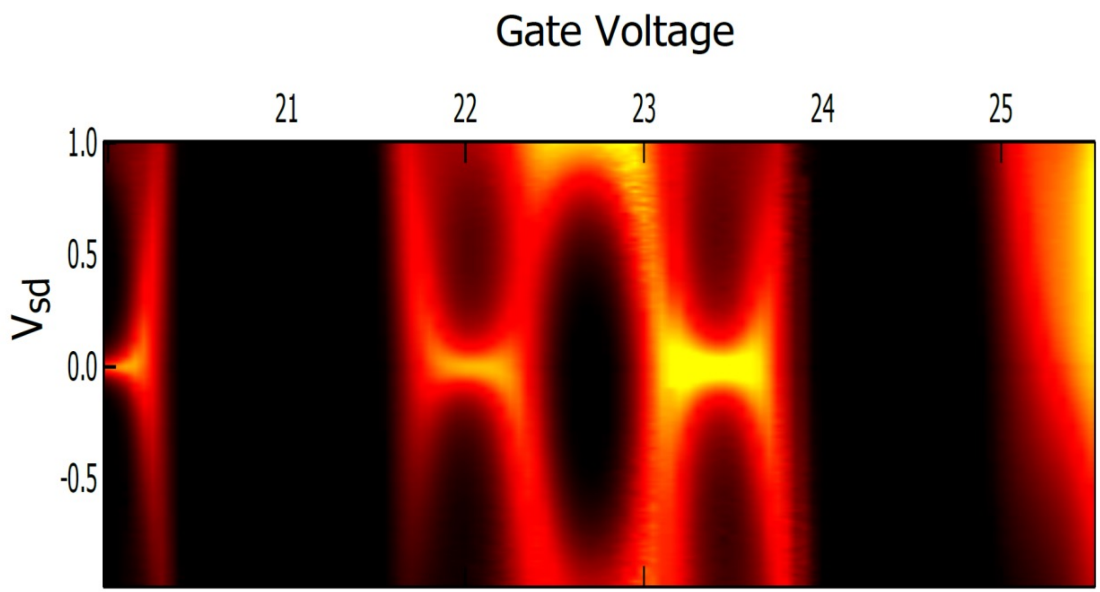
➡ Kondo state = Fermi-liquid constituted of non-interacting quasi-particles

➡ Signature of the symmetry class of the Fermi-liquid

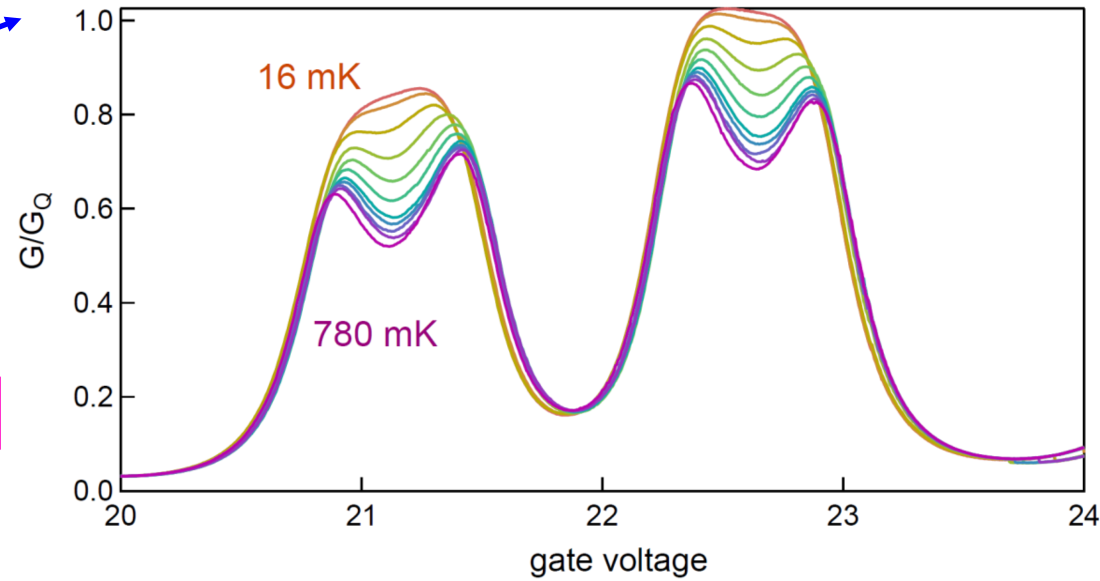
SU(2) or SU(4)

Carbon Nanotube in the SU(2) Kondo state





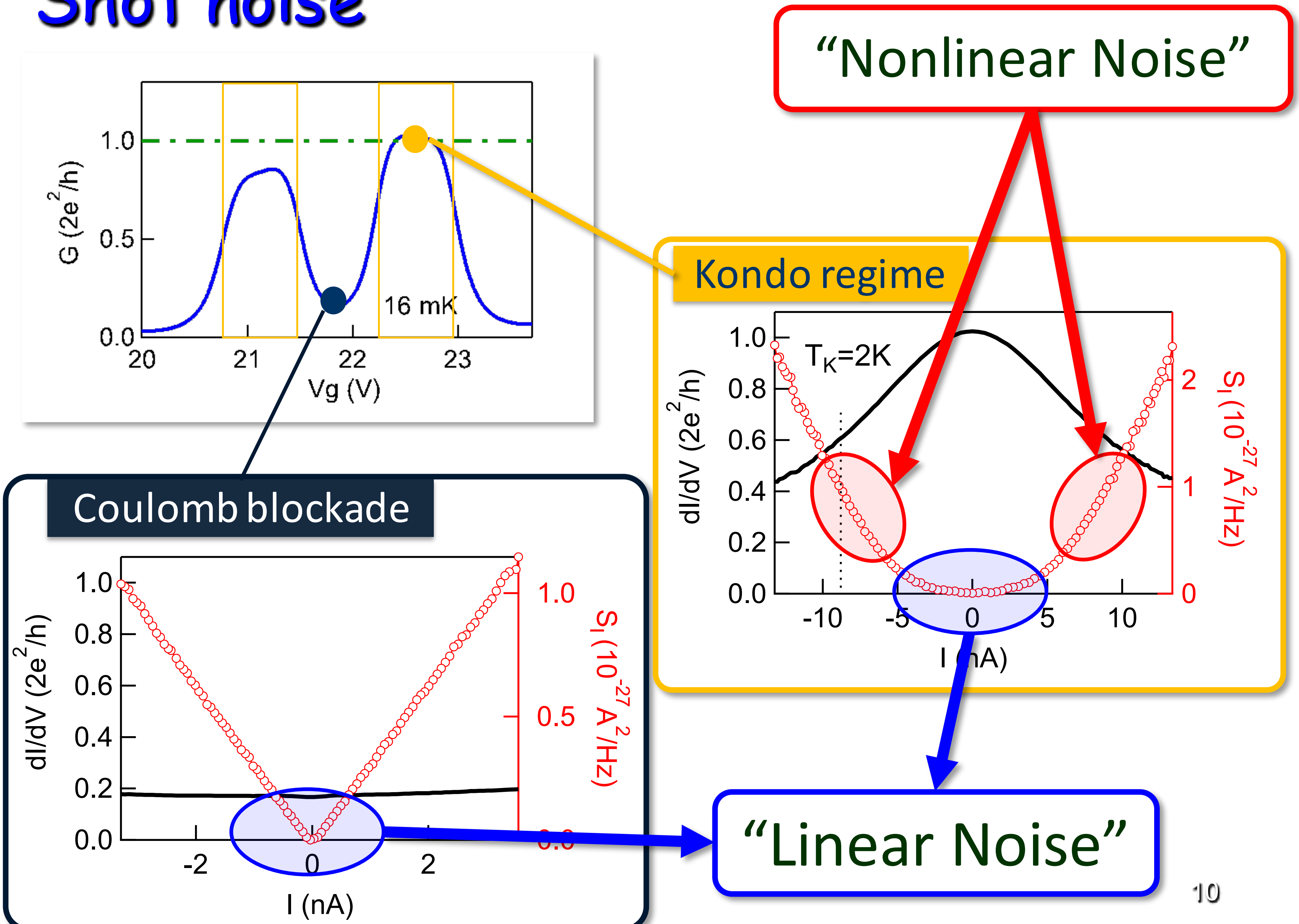
$$G = \frac{2e^2}{h}$$



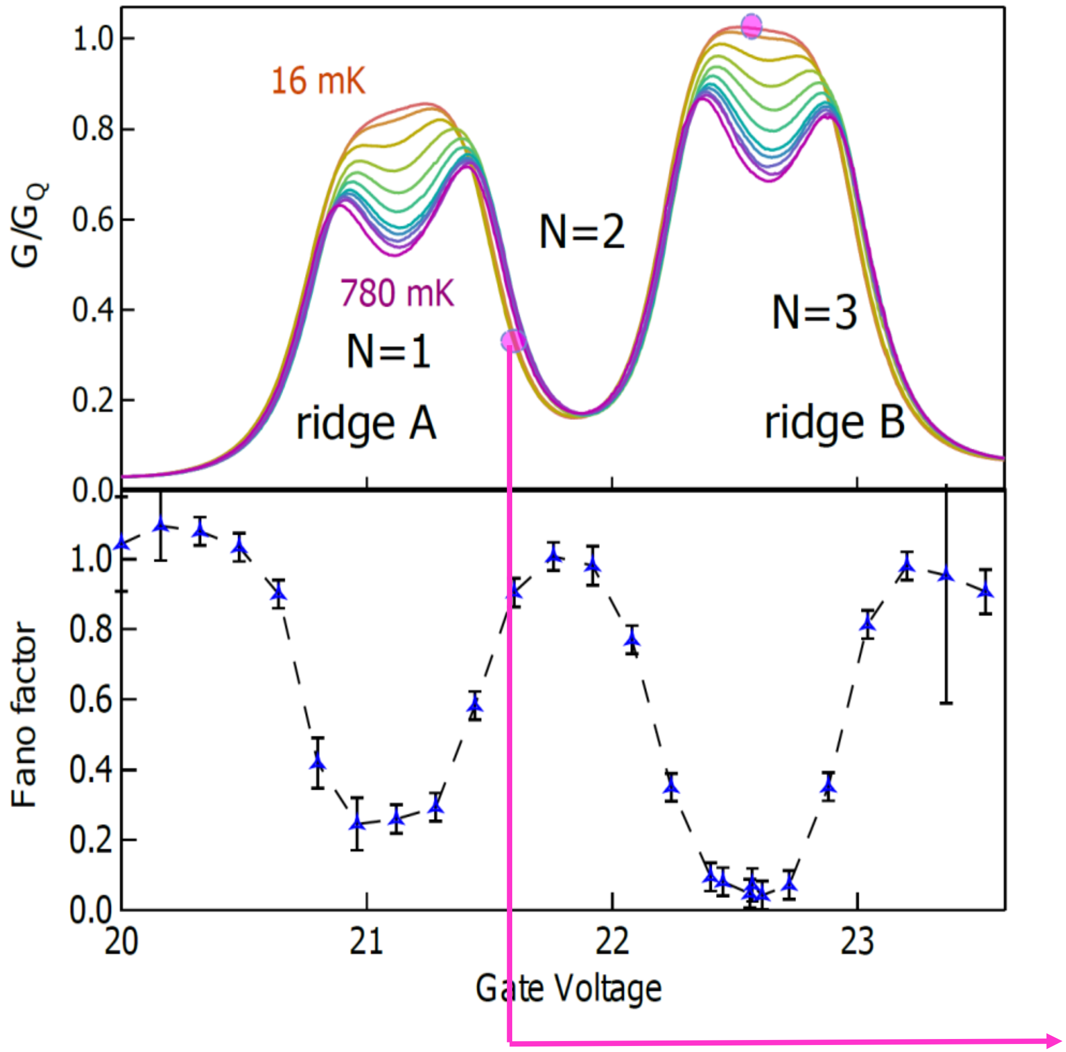
B=0.08T to destroy superconductivity

Unitary limit reached at low T

Shot noise


"Nonlinear Noise"
G (2e²/h)
1.0
0.5
0.0
20
21
22
23
Vg (V)
16 mK
Kondo regime
T_K=2K
dI/dV (2e²/h)
1.0
0.8
0.6
0.4
0.2
0.0
-10
-5
0
5
10
I (nA)
S_I (10⁻²⁷ A²/Hz)
2
1
0
Coulomb blockade
dI/dV (2e²/h)
1.0
0.8
0.6
0.4
0.2
0.0
-2
0
2
I (nA)
S_I (10⁻²⁷ A²/Hz)
1.0
0.5
0.0
"Linear Noise"

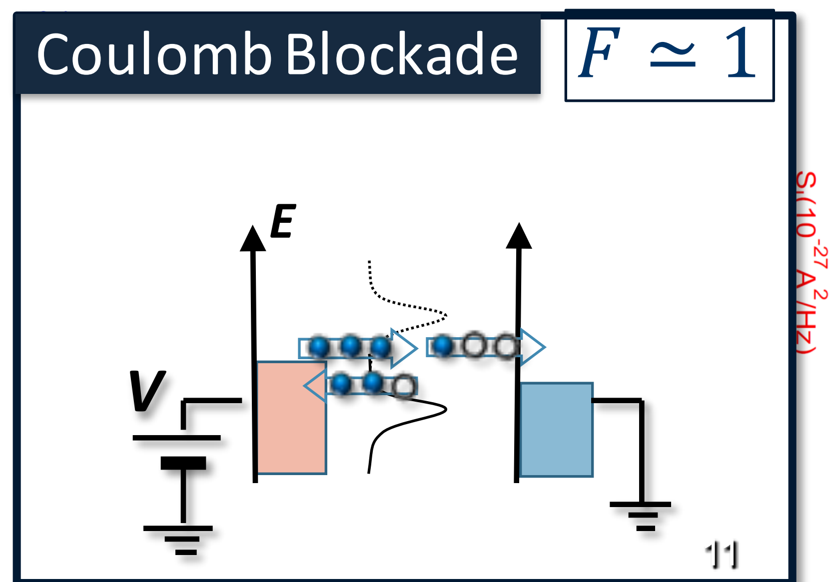
Linear Noise ($eV \ll T_K$) in the Coulomb Valley



No interaction:

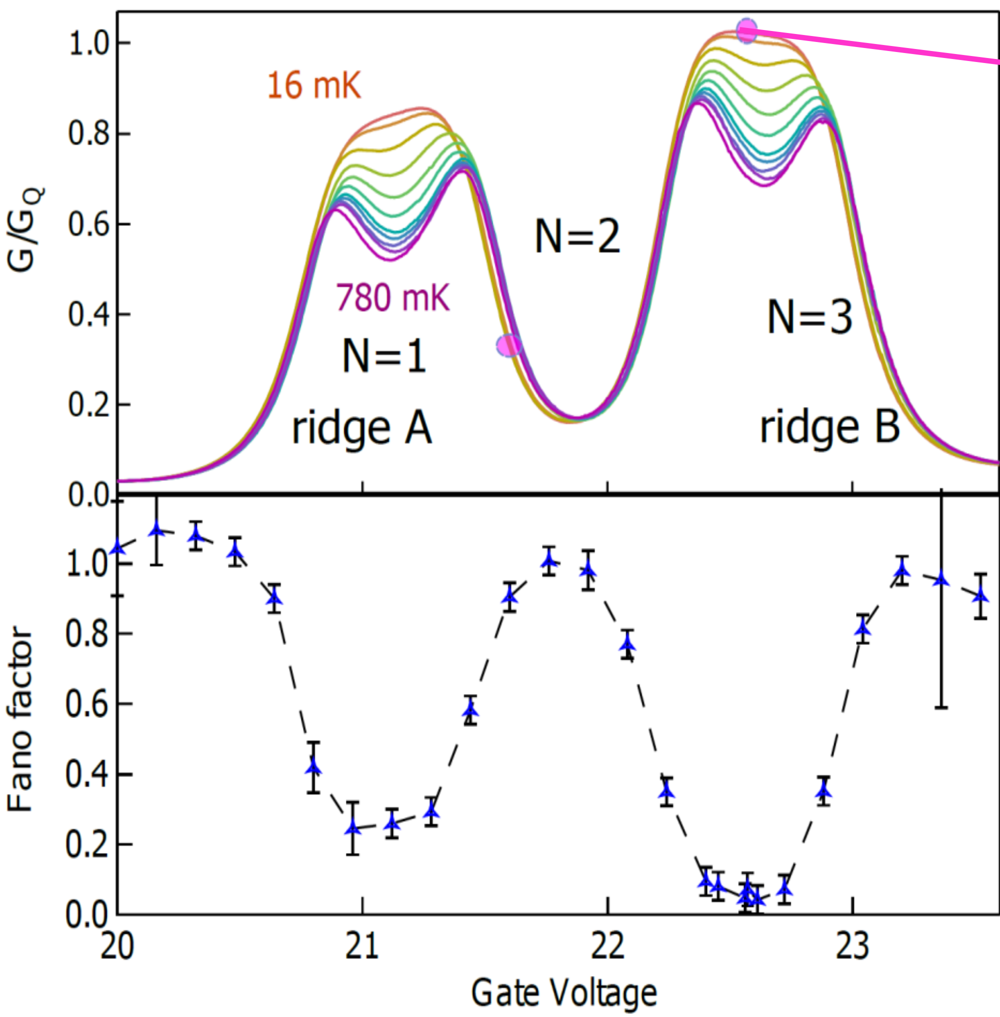
$$G = G_Q T$$

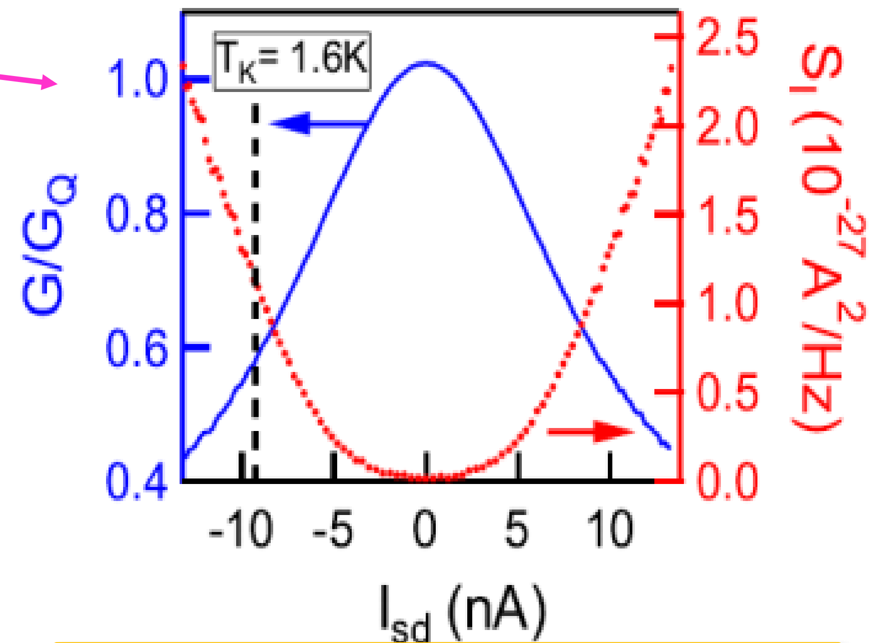
$$F=1-T$$



Conventional Poissonian tunneling

Linear Noise (eV « T_K) on the Kondo ridge

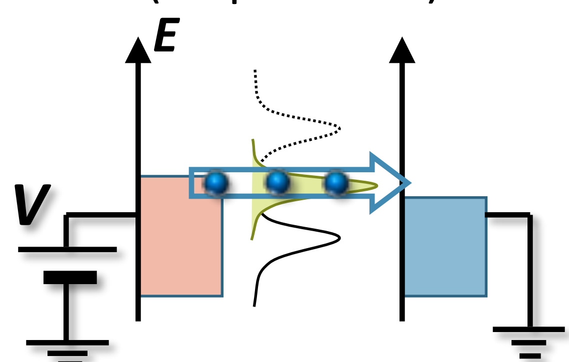




Kondo regime

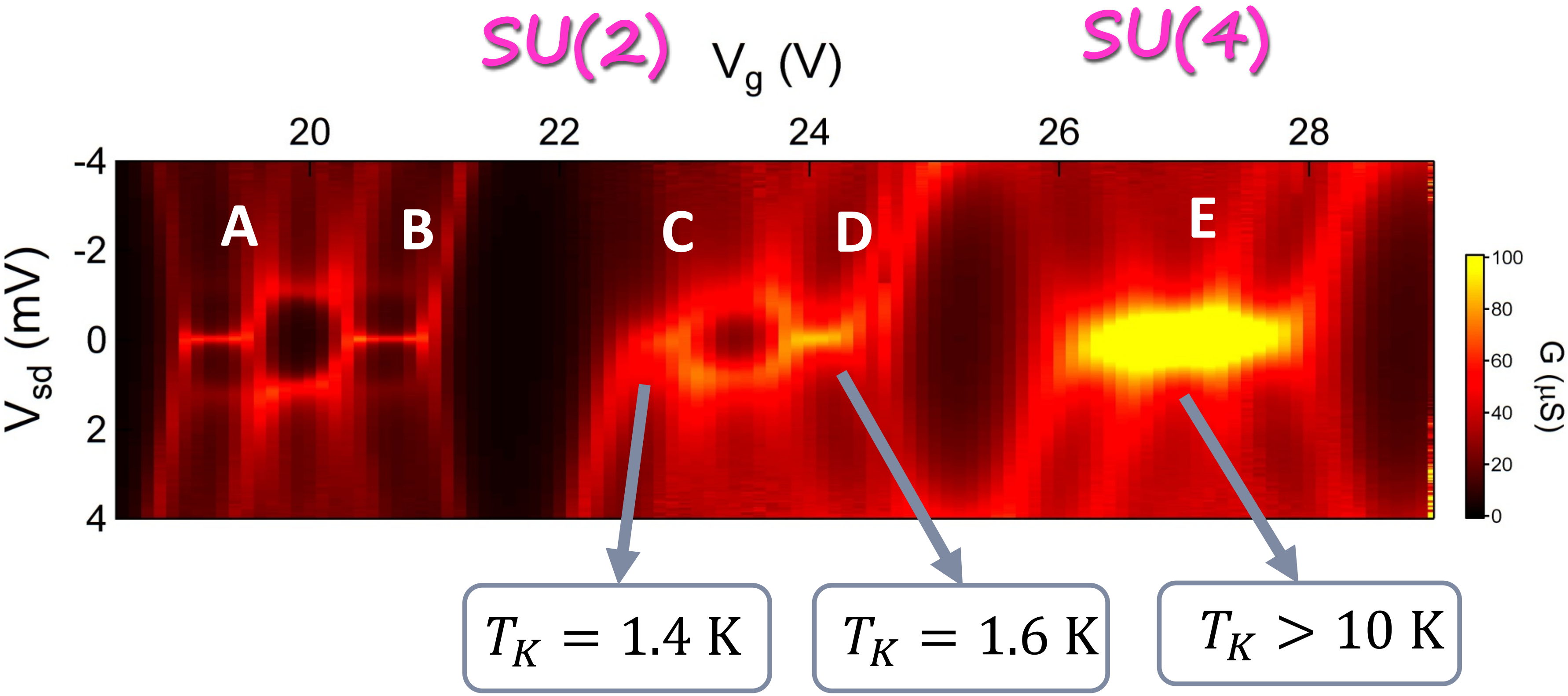
$F \ll 1$

Perfect transmission through resonance (no partition)



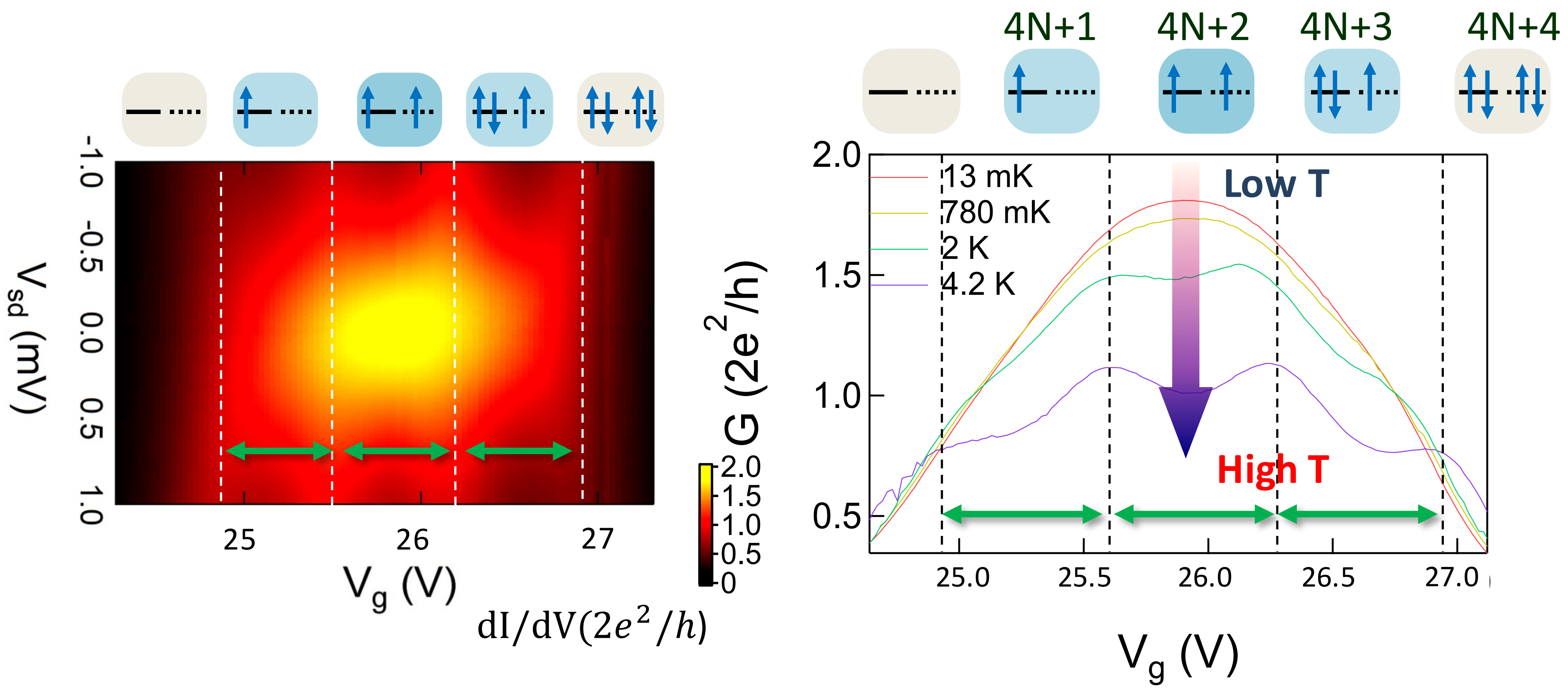
silent impurity around V=0

Different Kondo effect in the same Nanotube



The SU(4) Kondo state

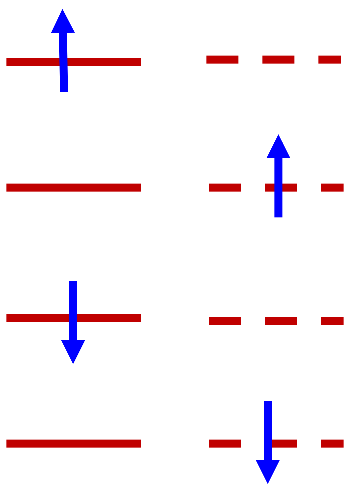
Coulomb diamond

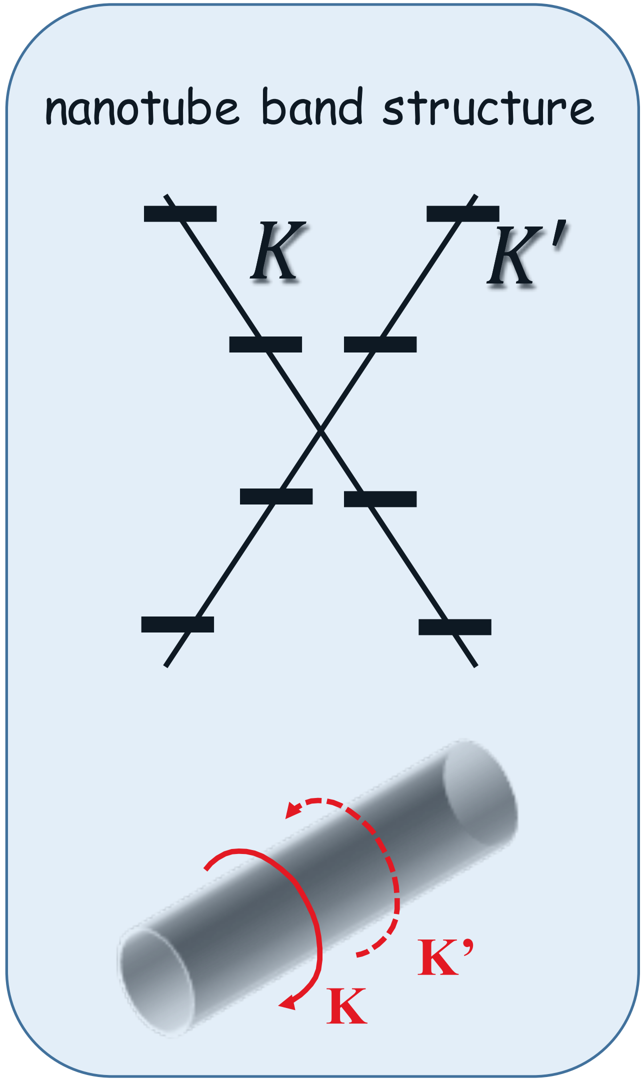


Kondo resonance for N=1,2 and 3 electrons

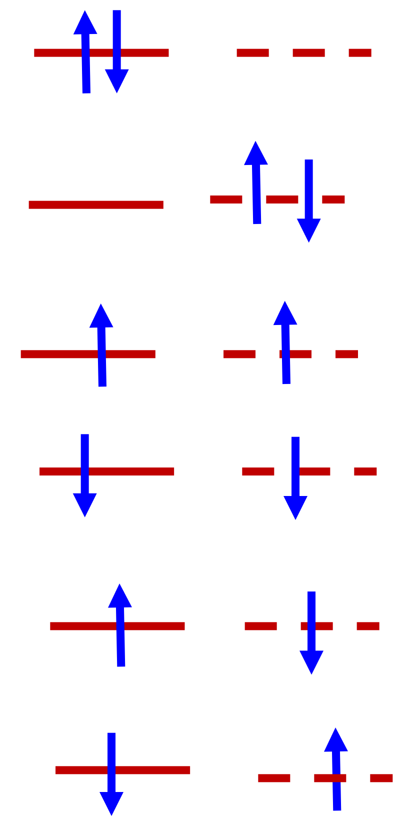
Screening of spin & orbit degrees of freedom

1 electron:
4 degenerate states





2 electrons:
6 degenerate states



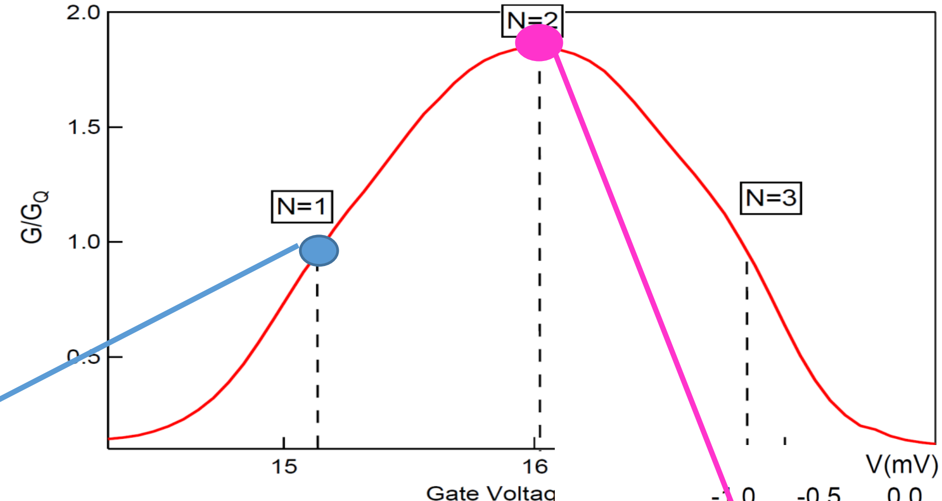
2 channels participates for transport

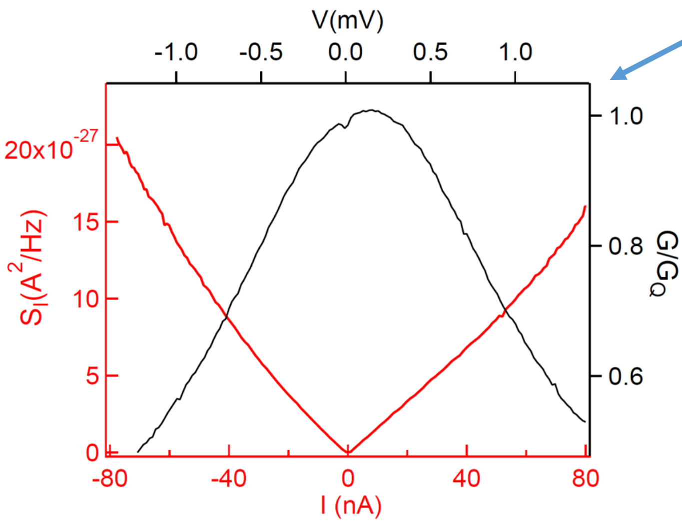
Kondo screening for odd and even number of electrons

Shot noise and SU(4) Kondo effect

$$G = G_Q(T_1 + T_2)$$

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

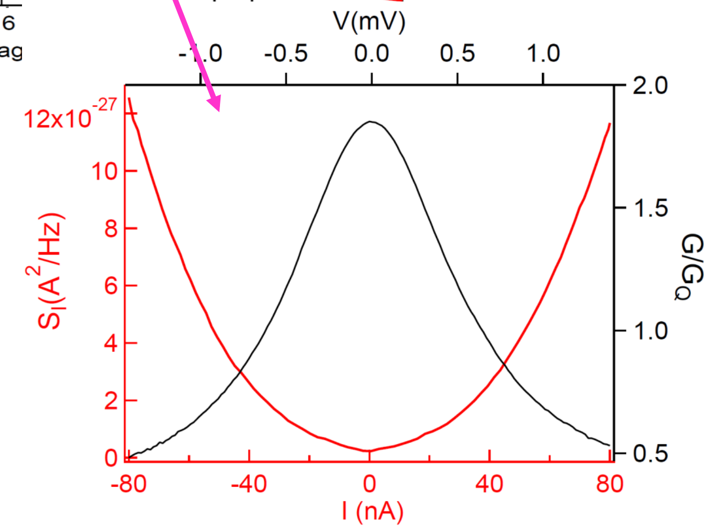




2 channels with T= 1/2

$G = G_Q \qquad F \approx 0.5$

Delattre et al, Nature Physics (2009)

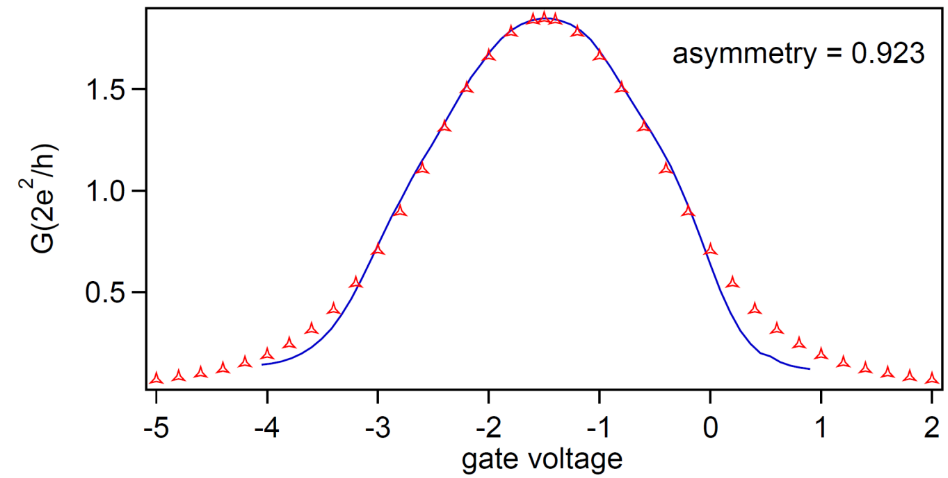


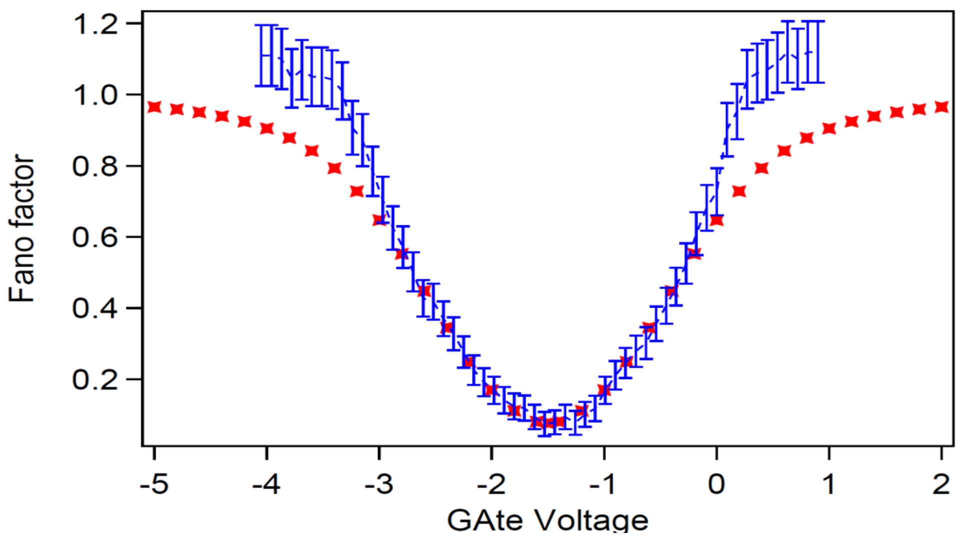
2 perfect channels : Noise 0

$G = 1.82\, G_Q \qquad F = 0.15$

Odd and Even SU(4) Kondo effect unambigously observed

Comparison with NRG calculation





Anderson model with 2 orbitals

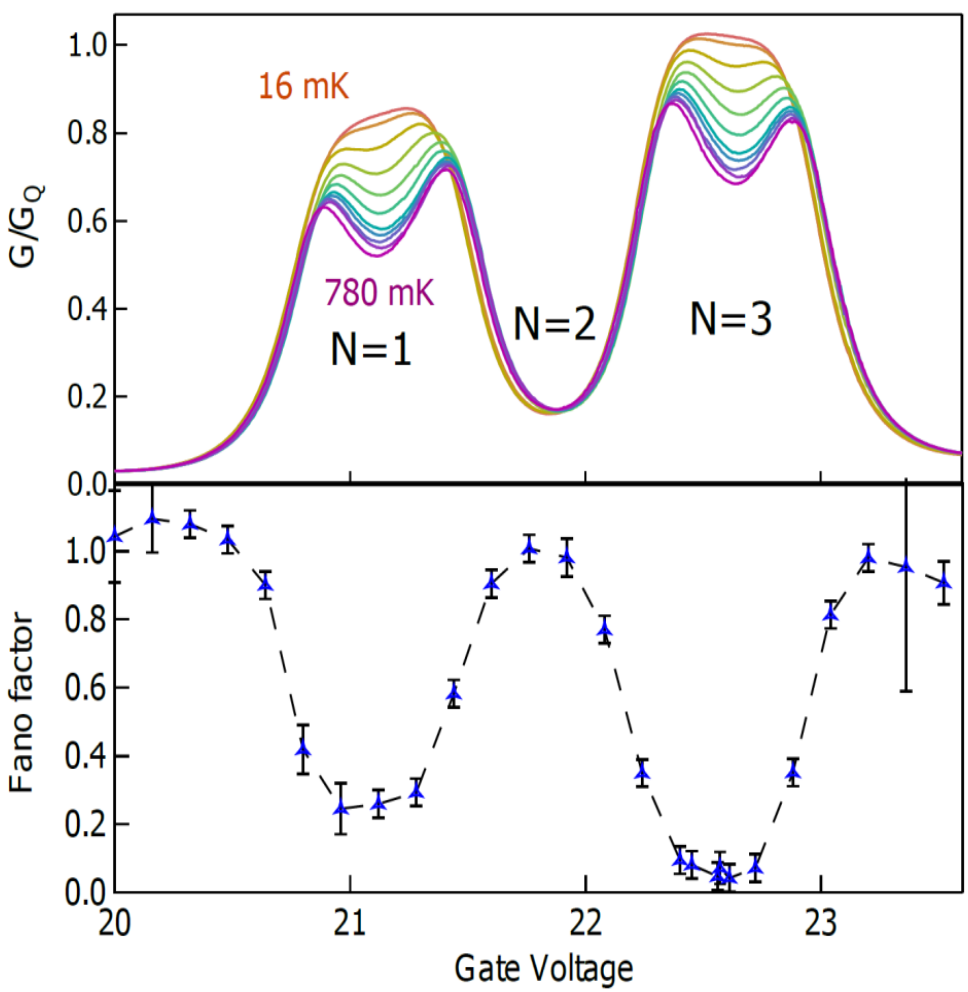
2 parameters:
U/G and L/R asymetry

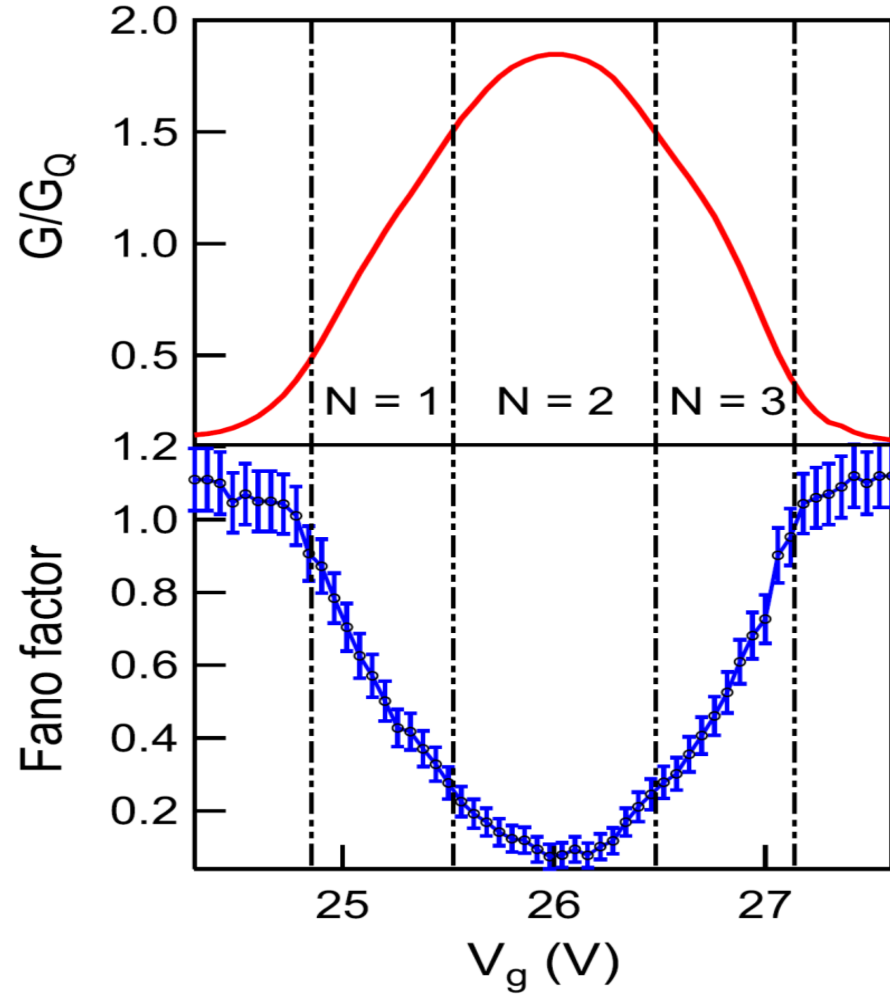
Fixed: same as SU(2)

A. Oguri calculation

Very good agreement in the linear regime

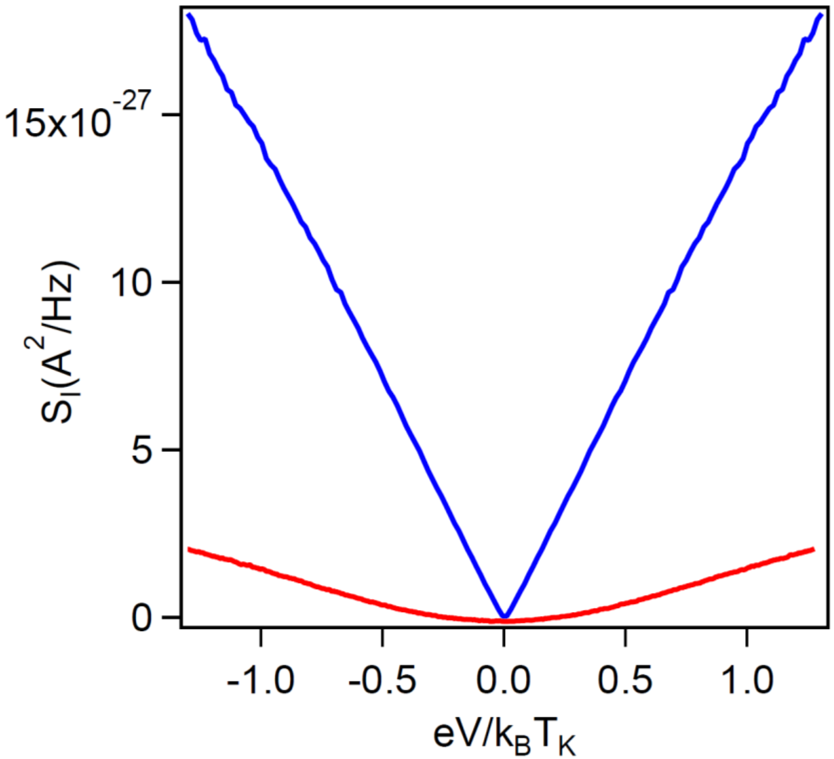
Summary for the linear shot noise





Symmetry distinguished by the linear shot noise

Noise contains more information than conductance !



SU(2) odd

$$G = G_Q \times 1$$

SU(4) odd

$$G = G_Q \times \left(\frac{1}{2} + \frac{1}{2}\right)$$

SU(2) = 1 perfect channel = NO NOISE

$F = 1 - 1$

SU(4) = 2 channels with T = 1/2 strong partition = strong shot noise

Very difficult to distinguish experimentally $F = 2 \times \left(1 - \frac{1}{2}\right)$

Scattering is fundamentally different

Linear noise completely described by non-interacting quasi-particles

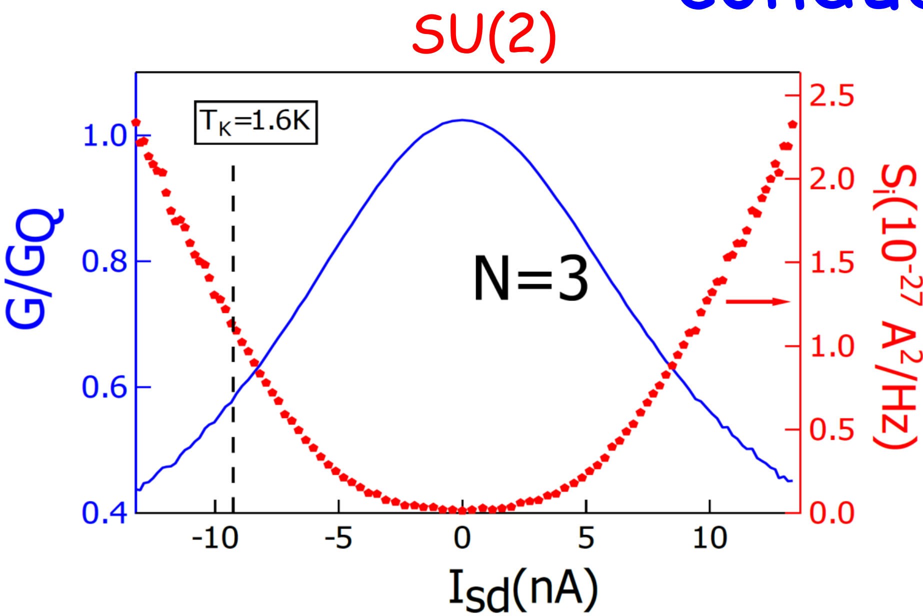
↓

Part 2

What about non-linear Noise?

Observation of 2-quasi-particle scattering induced by interaction

Is non-linear noise only due to non-linear conductance?



Kondo effect : Transmission depends strongly on energy

$$\frac{dI}{dV} = G_Q T(V)$$

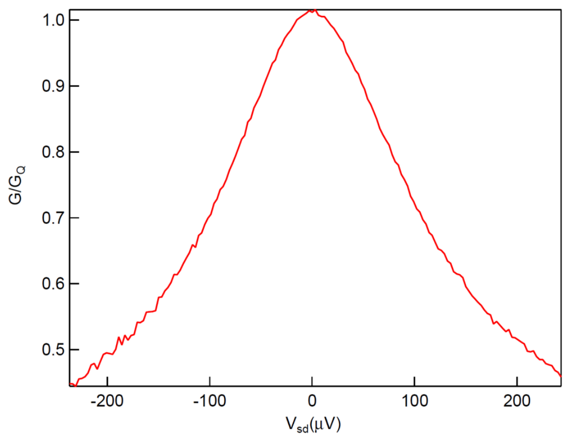
Without interaction non-linearities appear in noise:

$$S(V) = 2G_Q \int_0^{eV} T(\epsilon)\left(1 - T(\epsilon)\right) d\epsilon = 2 \int_0^{eV} G(\epsilon)\left(1 - \frac{G}{G_Q}(\epsilon)\right) d\epsilon$$

Non-linear Fano factor for non interacting particles

$$S(V^3) = 2eF_K I(V^3)$$

Non-linear conductance :



@ low voltage

$$\begin{cases} T(\varepsilon) = 1 - \alpha\varepsilon^2 \\ I(V) = G_Q V - \dfrac{\alpha}{3} G_Q V^3 \end{cases}$$

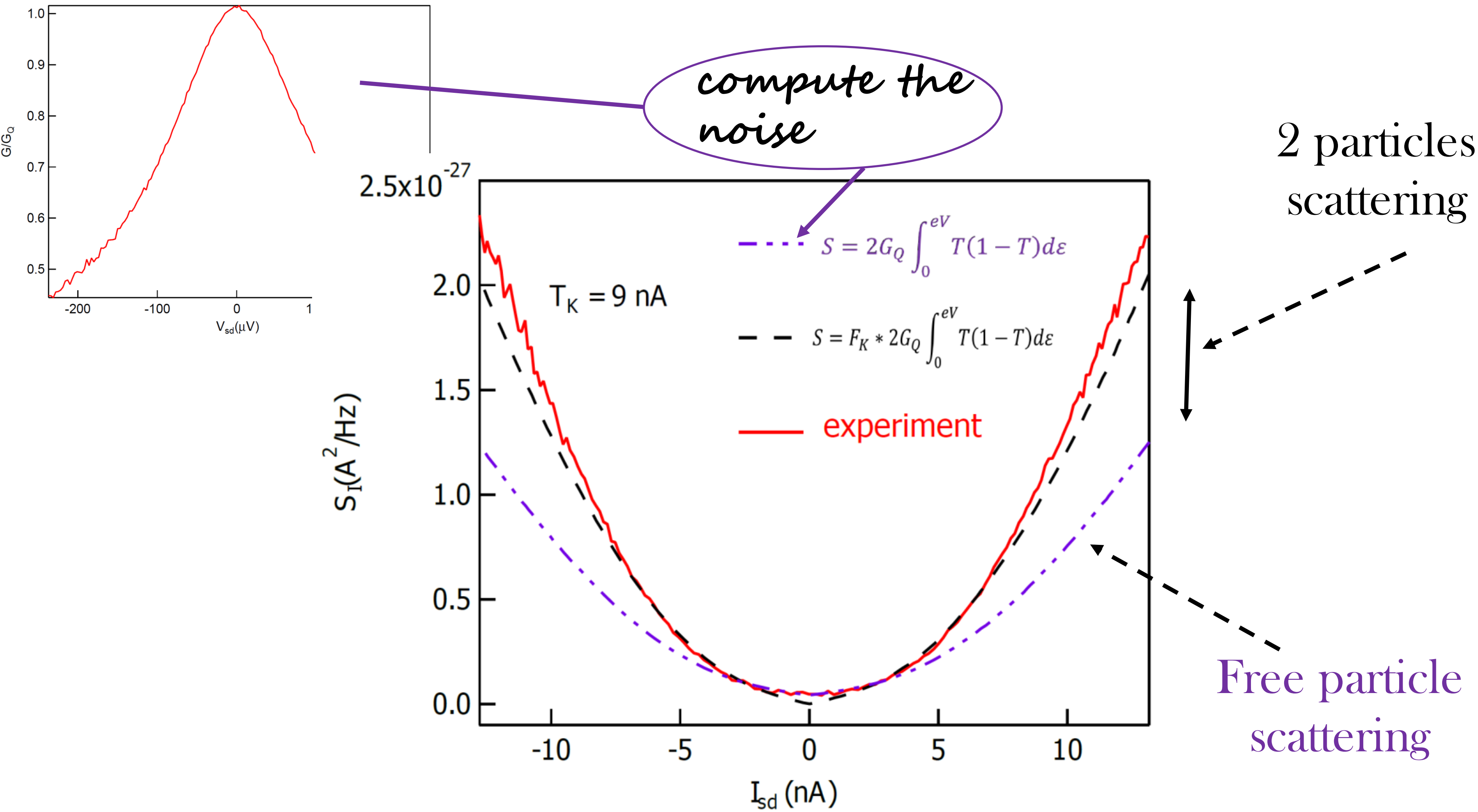
Non interacting quasi-particle picture :

$$S(V) = 2G_Q \int_0^{eV} T(\epsilon)\left(1 - T(\epsilon)\right) d\epsilon = 2e\frac{\alpha e^2 G_Q}{3} V^3$$

$$\boxed{F_K = 1}$$

F_K measures the probability for 2-particle scattering

Direct observation of the many-body effect

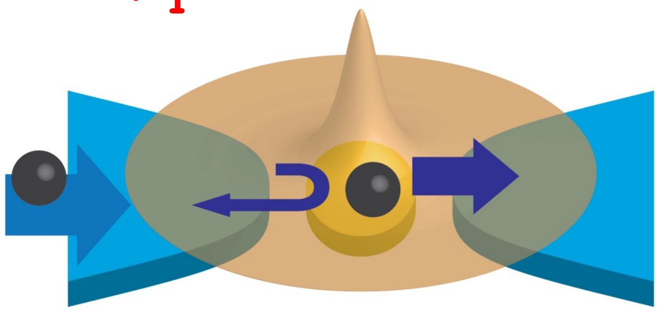


Shot noise contains signature of 2 e scattering which is not in the dI/dV

Non-linear Fano factor : « effective charge »

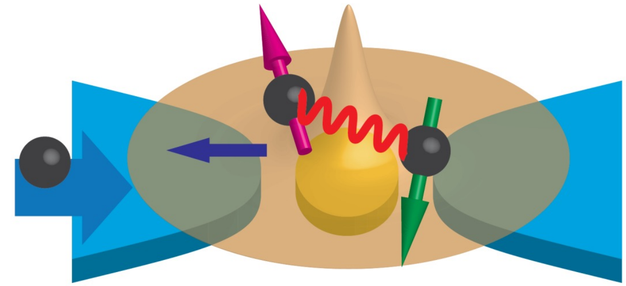
$$S(V^3) = 2eF_K I(V^3)$$

P_1



$$F_K = \frac{P_1 + 4P_2}{P_1 + 2P_2}$$

P_2



Not normalized ! $P_1 + P_2 \neq 1$

no interaction P_2=0

F_K=1

SU(2) P_1=P_2

F_K=5/3

Sela *et al*, PRL **97** 086601 (2006)

SU(4) P_1=2P_2

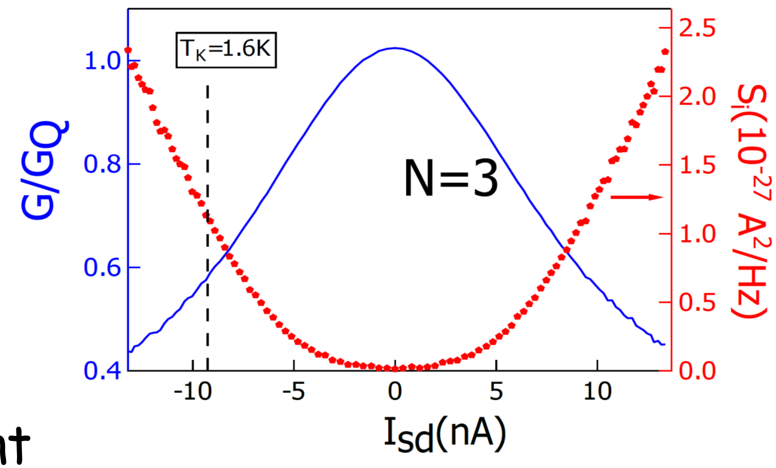
F_K=3/2

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

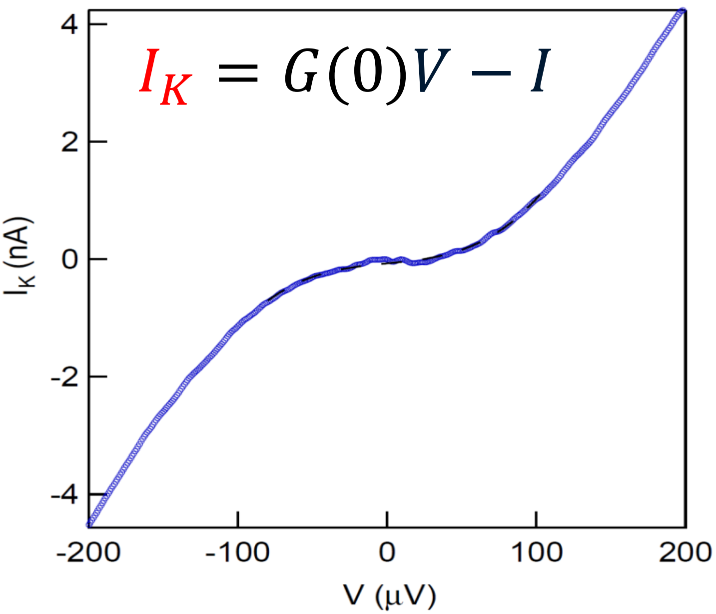
Sakano et al PRB **83** (2011)

F_K measures the probability for 2-particle scattering

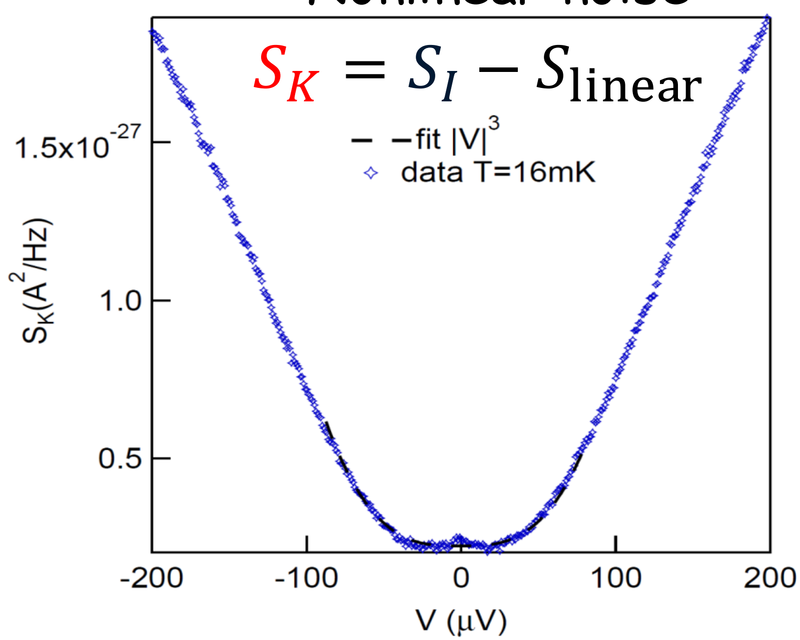
Extraction of non-linear Fano factor



Back scattered current



Nonlinear noise



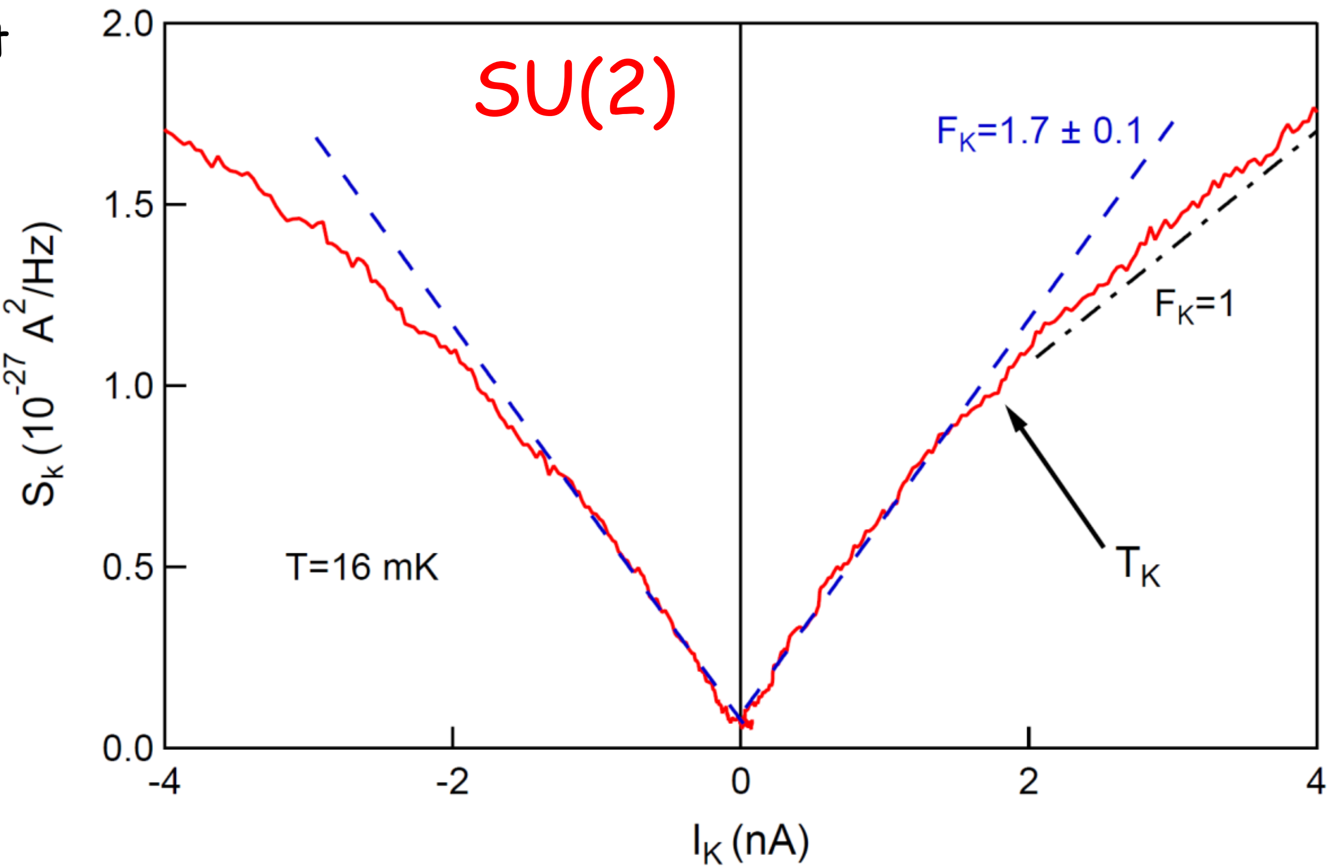
Non equilibrium Fano factor:

$$S_K = 2eF_K I_K$$

Measurement of Kondo Fano factor

Nonlinear component

$S_K = S_I - S_{\text{linear}}$



Other experiments

Zarchin et al, PRB (2008)

Yamauchi et al, PRL (2011)

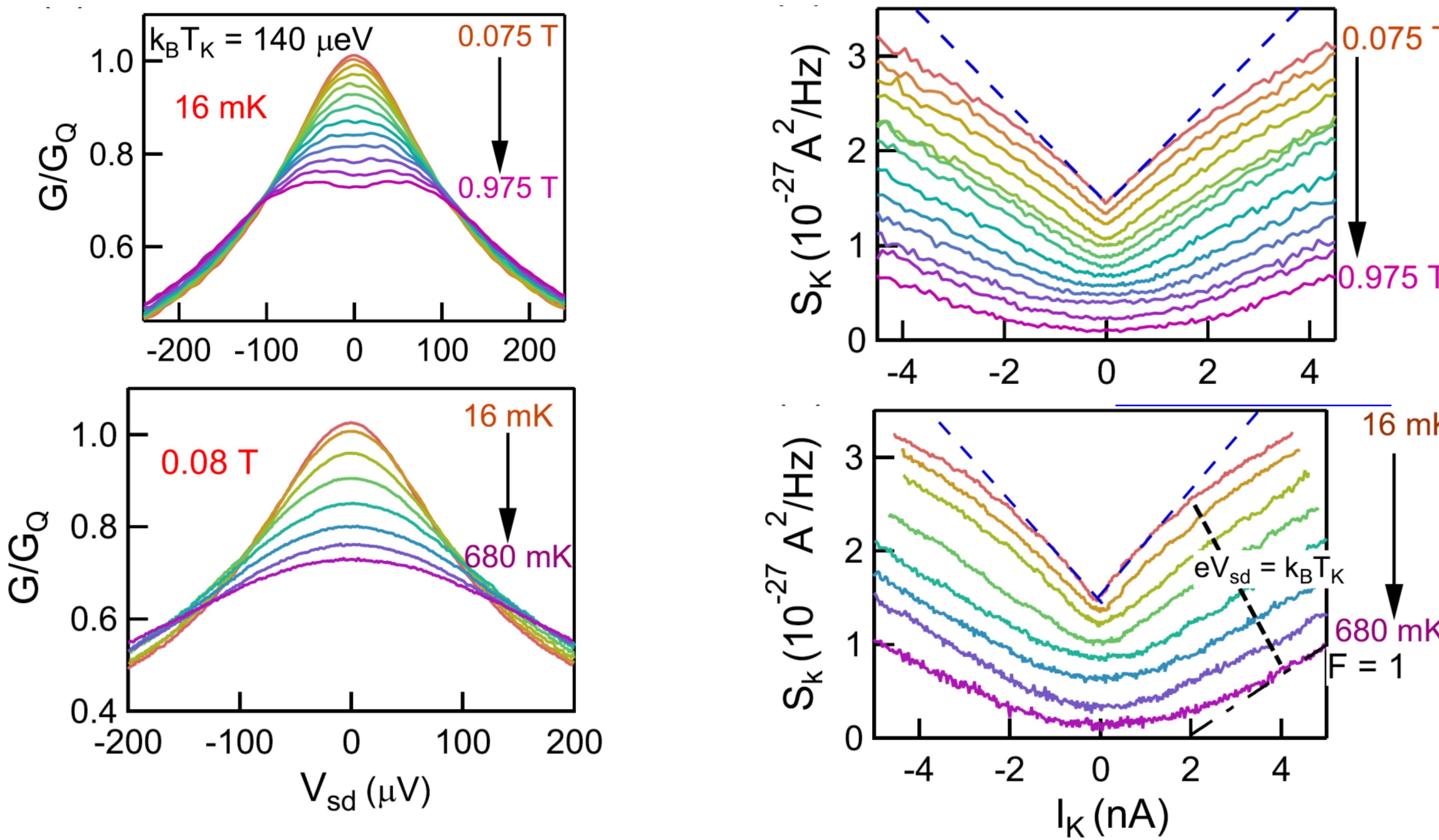
not quantitative

Asymetric dot, low T_K

Back scattered current $I_K = G(0)V - I$

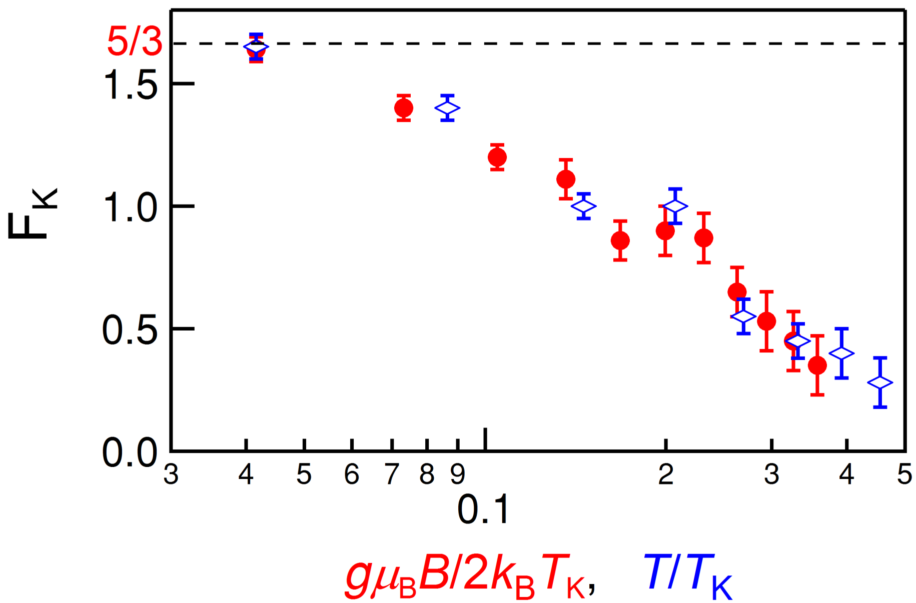
Quantitative agreement with theory

Evolution of Kondo shot noise



2 particles scattering destroyed by magnetic field and temperature

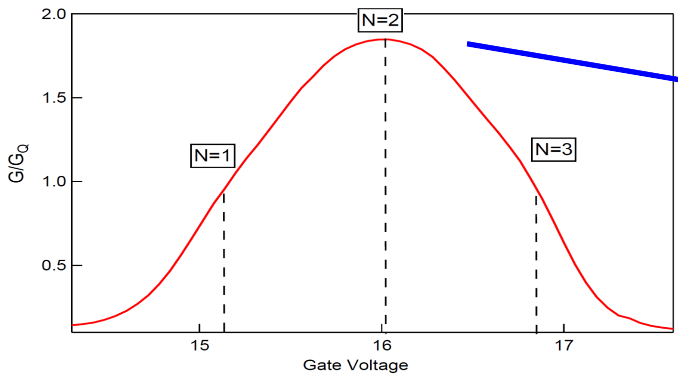
Scaling properties of F_K

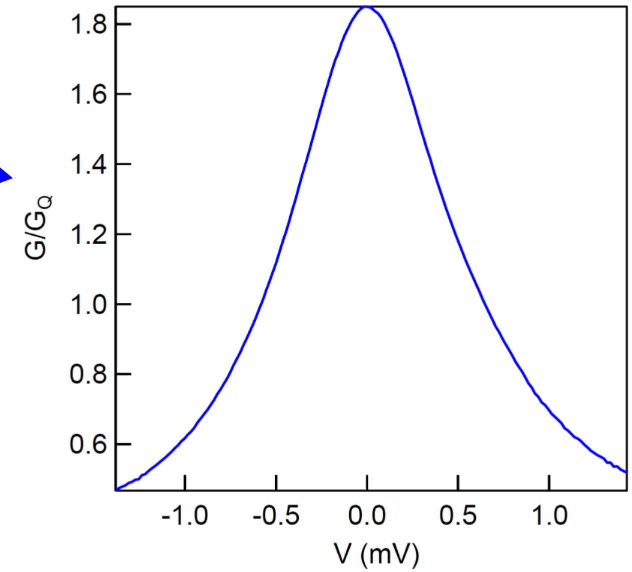


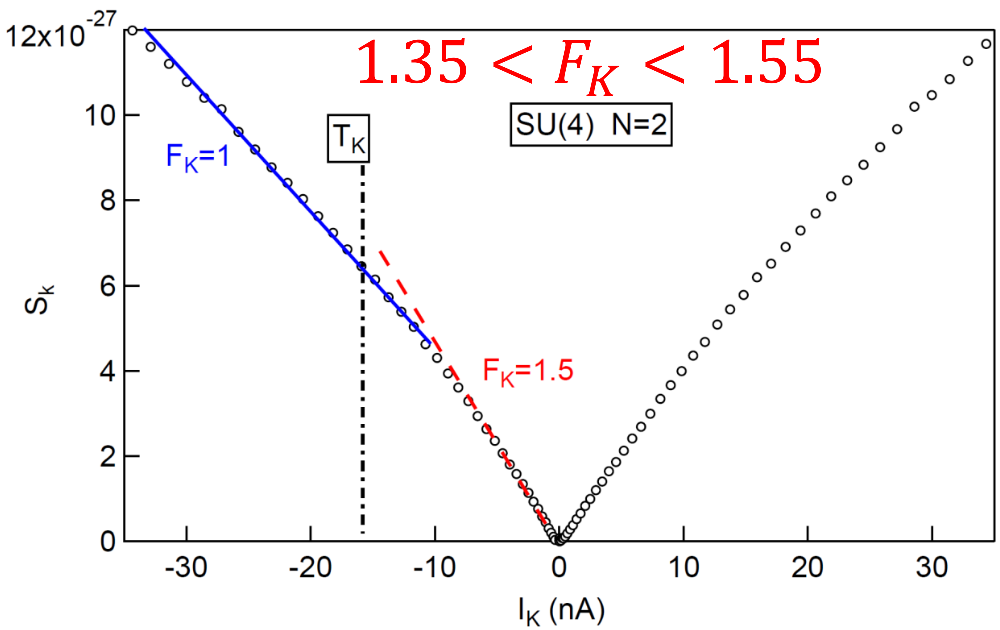
Seems to be logarithmic

Same scaling properties as the conductance

F_K for SU(4) N=2 electrons







3/2 predicted for SU(4):

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

Sakano *et al* PRB **83,** 075440 (2011).

Interaction decreases when degeneracy increases

Significance of these experiments

Around equilibrium

Kondo state = non interacting quasi-particles

Noise = Landauer-Buttiker theory

Out of equilibrium

Interaction between quasi-particles shows up

Noise is non-linear and strongly enhanced

→ $\boxed{F_K > 1 \text{ appears}}$

Very good quantitative agreement with theory

Extension of Fermi-liquid theory out of equilibrium demonstrated experimentally

CONCLUSION

On-chip collision experiment: Probe dynamical behaviors of a quantum many body system

Noise shows the symmetry class

Direct evidence of 2 quasi-particles scattering due to interaction

F_K~1.7 for two different kind of SU(2)

F_K~1.5 for SU(4) @ N=2

Cross-over in the symmetry class monitored by shot noise

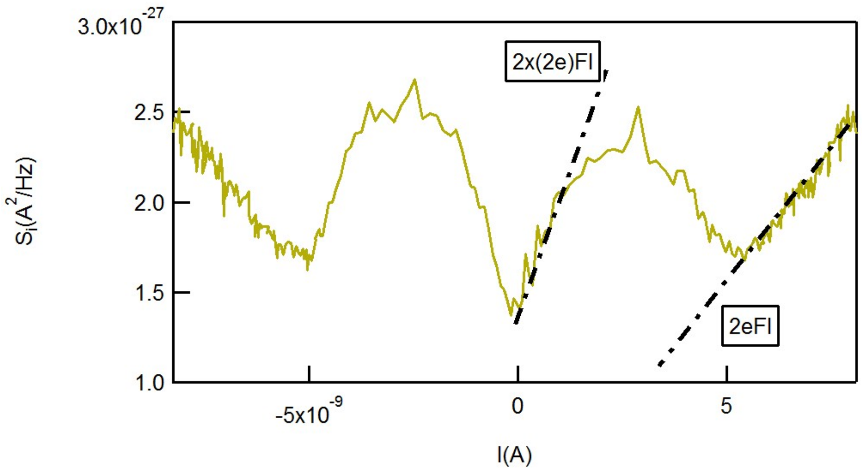
Also tuned by the magnetic field

Next…

Effect of Superconducting leads:

See Tokuro Hata's poster

Mixing Kondo and Andreev states



Noise in the Coulomb regime : bunching effect F=1.5