Quantum Noise of a Carbon Nanotube Quantum Dot in the Kondo Regime

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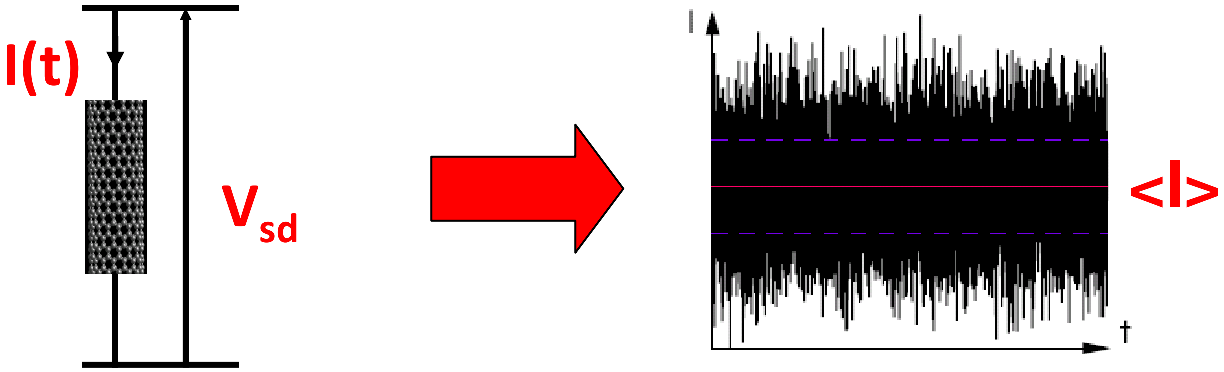
Workshop: « Charge and heat dynamics in nano-systems »
Orsay 2011

Introduction to electronic noise

- What is electronic noise?

Conducting system

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



$$\boxed{S_I(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} d\tau e^{i\omega\tau} \langle \delta I(t+\tau)\delta I(t) \rangle}$$

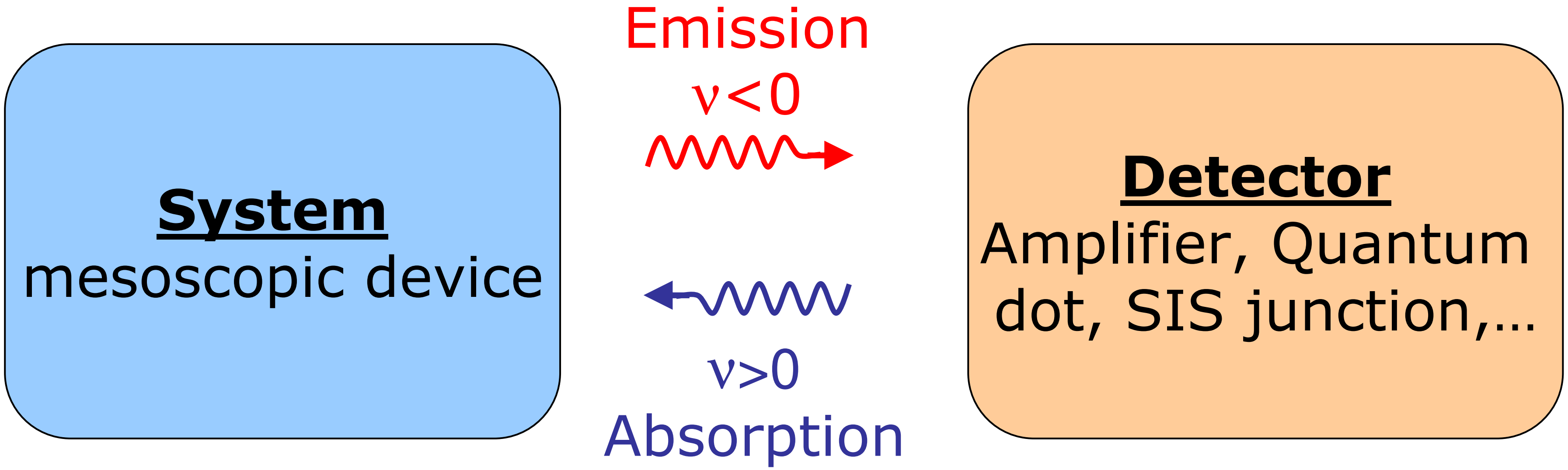
- Why measure noise?

Electronic correlations, effective charge, characteristic energy scale, …

Noise in the quantum regime

$h\nu \gg k_B T,\ h\nu > eV$

- energy scales (eV, Δ, …) and characteristic times
- quantum noise : zero point fluctuations



Emission

$\nu<0$

System

mesoscopic device

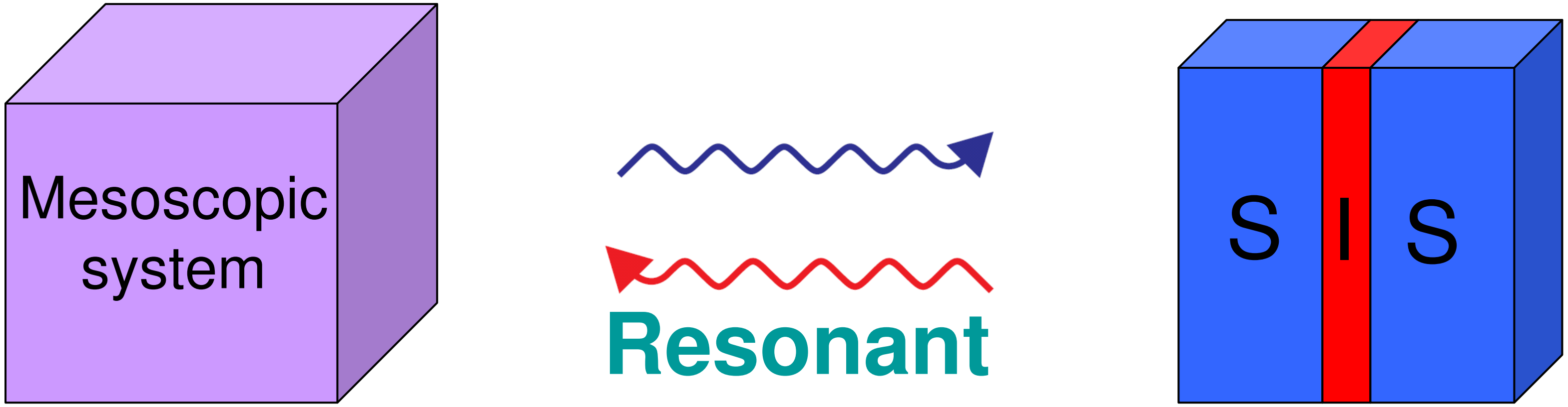
Detector

Amplifier, Quantum dot, SIS junction,…

$\nu>0$

Absorption

Noise measurement in the quantum regime



Source

Detector

Resonant Circuit

Carbon nanotube in the Kondo regime

SIS junction

Noise detection with SIS junction :
Kouwenhoven's group, Science (2003)
P.M. Billangeon *et al.*,PRL (2006)

T=20 mK

Quantum Noise Detection with a SIS Junction

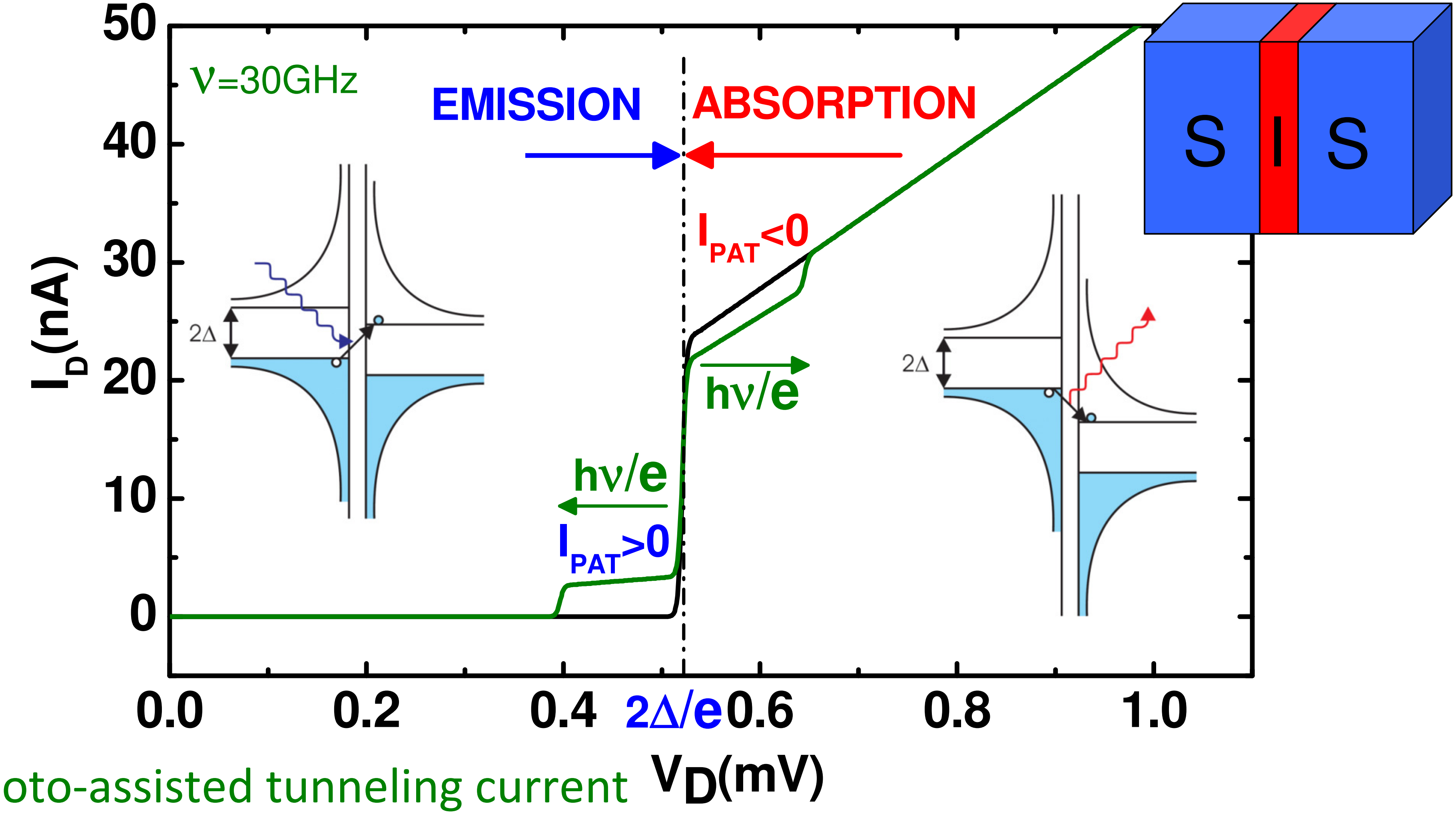


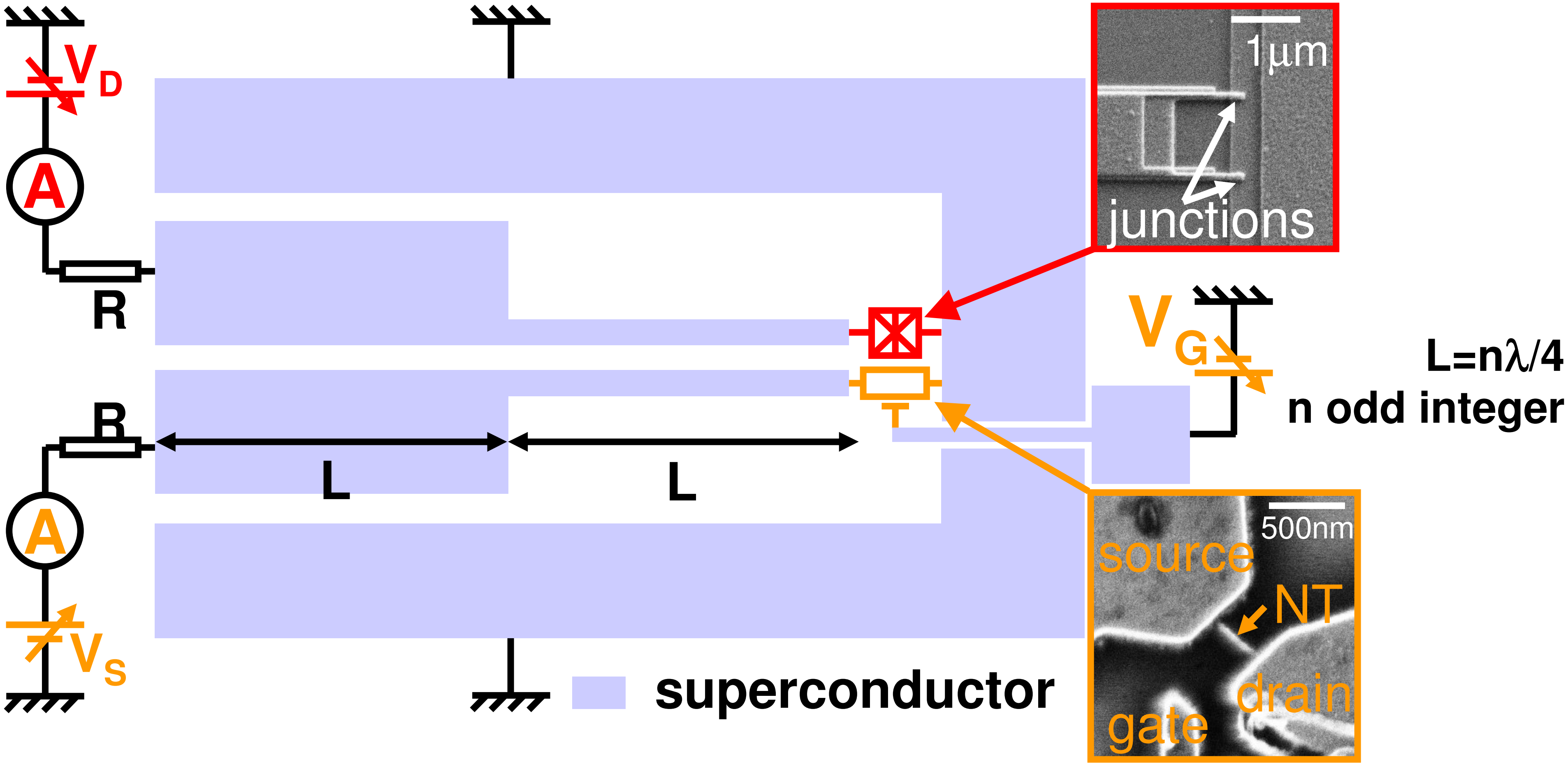
Photo-assisted tunneling current (PAT)

$$I_{PAT}(V_D) = \overbrace{\int_0^{\infty} d\nu \left(\frac{e}{h\nu}\right)^2 S_V(-\nu) I_{QP,0}\left(V_D + \frac{h\nu}{e}\right)}^{\text{EMISSION}} + \overbrace{\int_0^{eV_D/h} d\nu \left(\frac{e}{h\nu}\right)^2 S_V(\nu) I_{QP,0}\left(V_D - \frac{h\nu}{e}\right)}^{\text{ABSORPTION}}$$

$$- \int_{-\infty}^{+\infty} d\nu \left(\frac{e}{h\nu}\right)^2 S_V(\nu) I_{QP,0}(V_D)$$

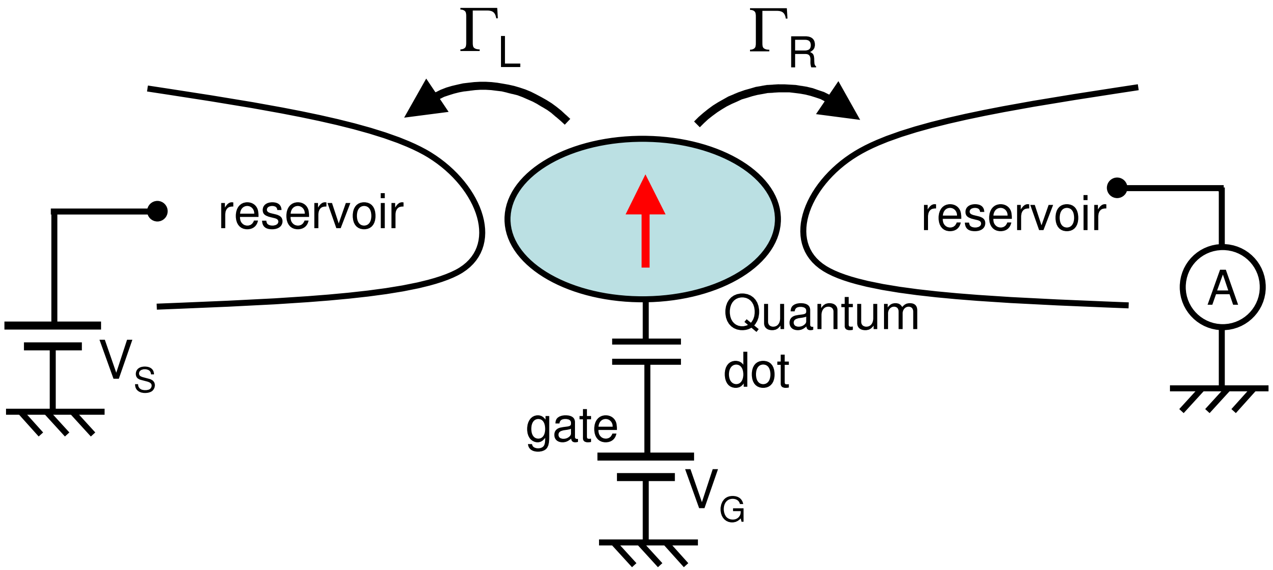
Ingold & Nazarov (1992)

Resonant coupling betwen a Carbon nanotube and a SIS detector



- ➔ ¼ wavelength resonant circuit
- ➔ Independent DC polarisations of the source and the detector
- ➔ Coupling at eigen frequencies of the resonator (30 GHz and harmonics)
- ➔ Coupling proportional to the quality factor (J. Basset *et al.* PRL 2010)

Kondo effect in quantum dots



U : charging energy; ε_0: energy level; $\Gamma=\Gamma_L+\Gamma_R$: coupling to the reservoirs

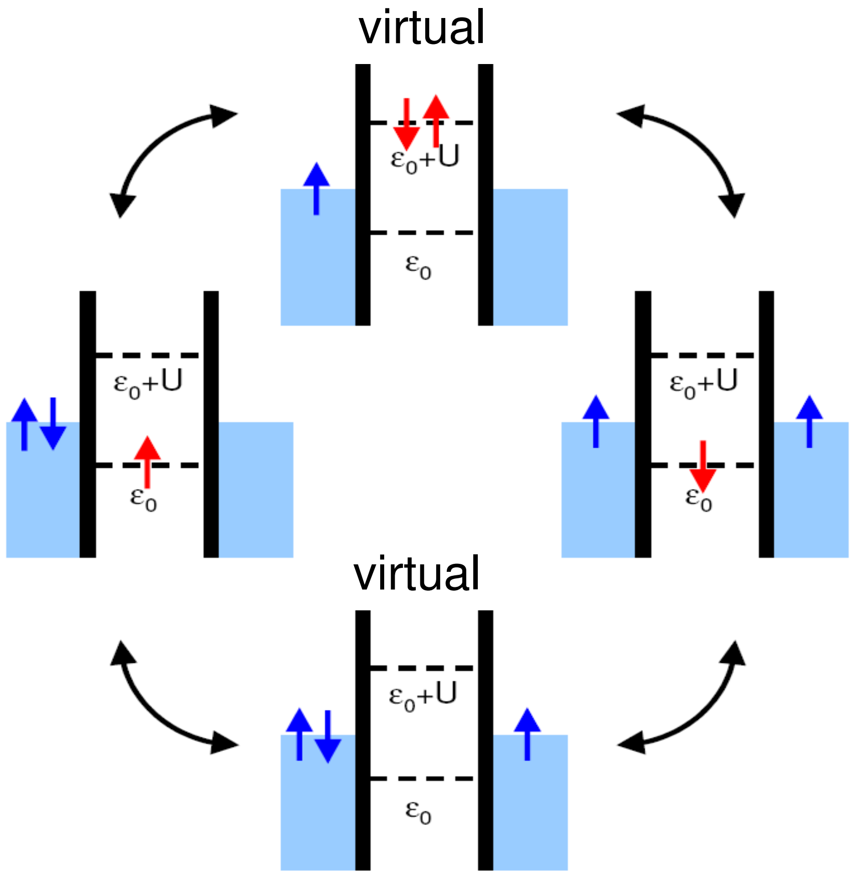
Kondo effect : dynamical screening of the dot's spin

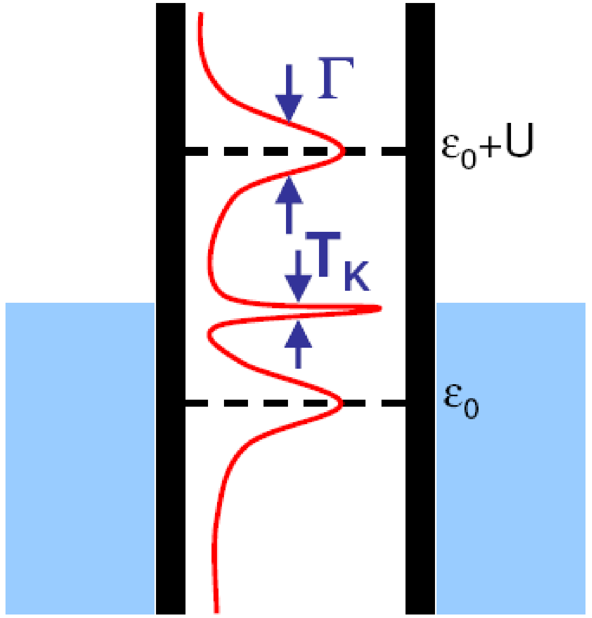
Under specific conditions:

- Odd number of electrons in the dot
- Intermediate transparency of the contacts
- Temperature below Kondo temperature T_K

Kondo resonance in quantum dots

$H_{eff} = J_{eff}\, \sigma . S$ with $J_{eff} = \Gamma/\nu\, U$ ν: DOS

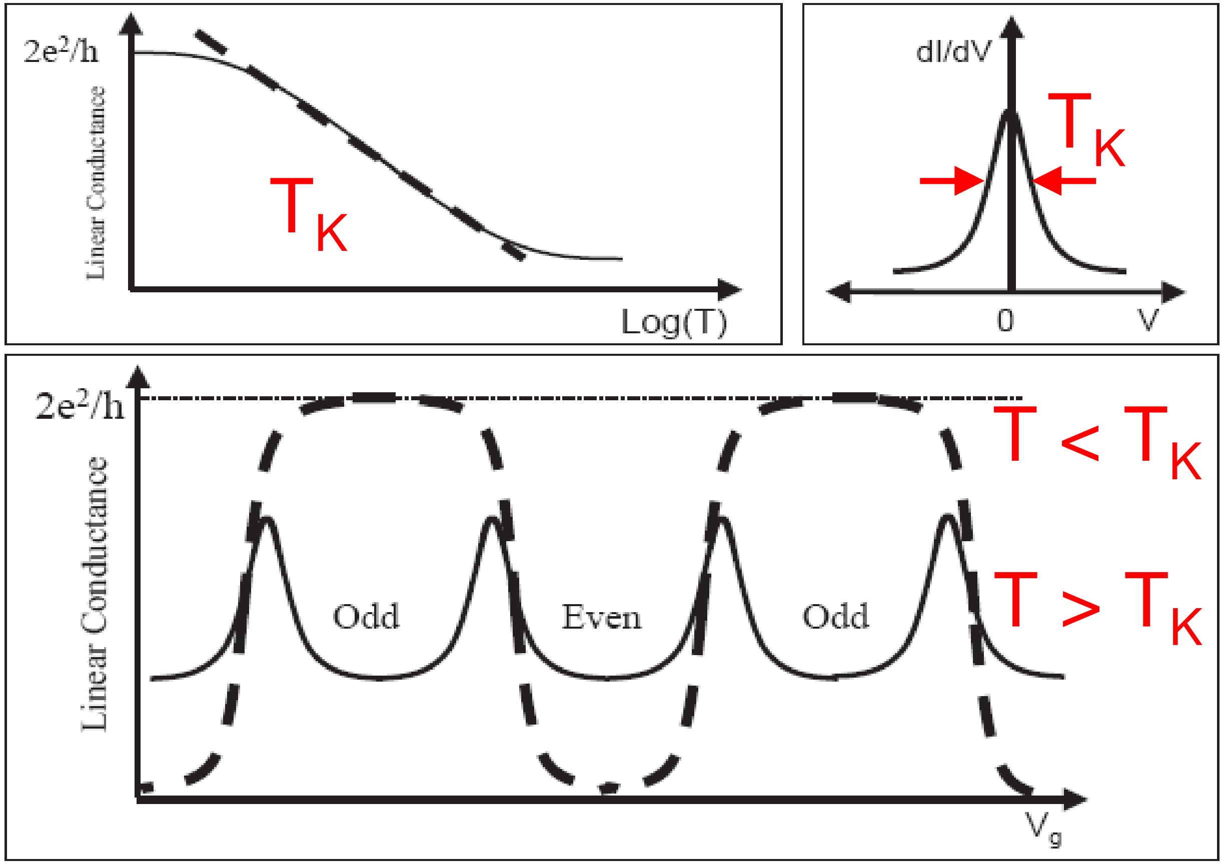




$$T_K = (U\,\Gamma)^{1/2} \exp(-1/ J_{eff}\, \nu)$$

- Transport through second order spin flip events
- Formation of a many body spin singlet (spin of the dot + conduction electrons)
- Peak in the DOS of the dot at the Fermi energy of the leads ➔ Kondo resonance

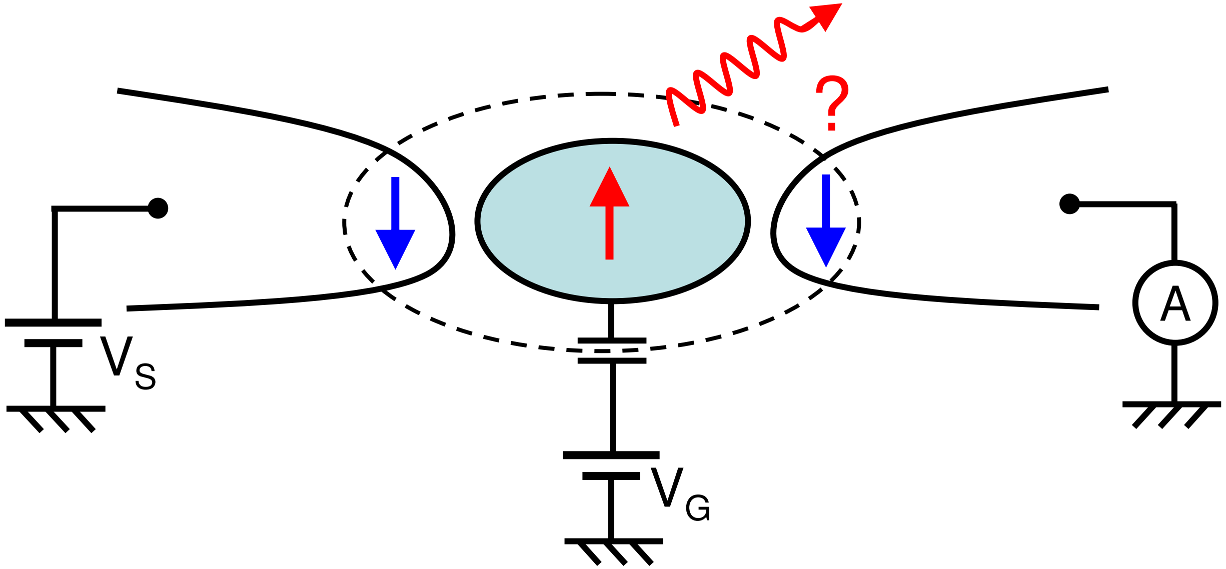
Signature of the Kondo effect on conductance



Increase of conductance at low temperature

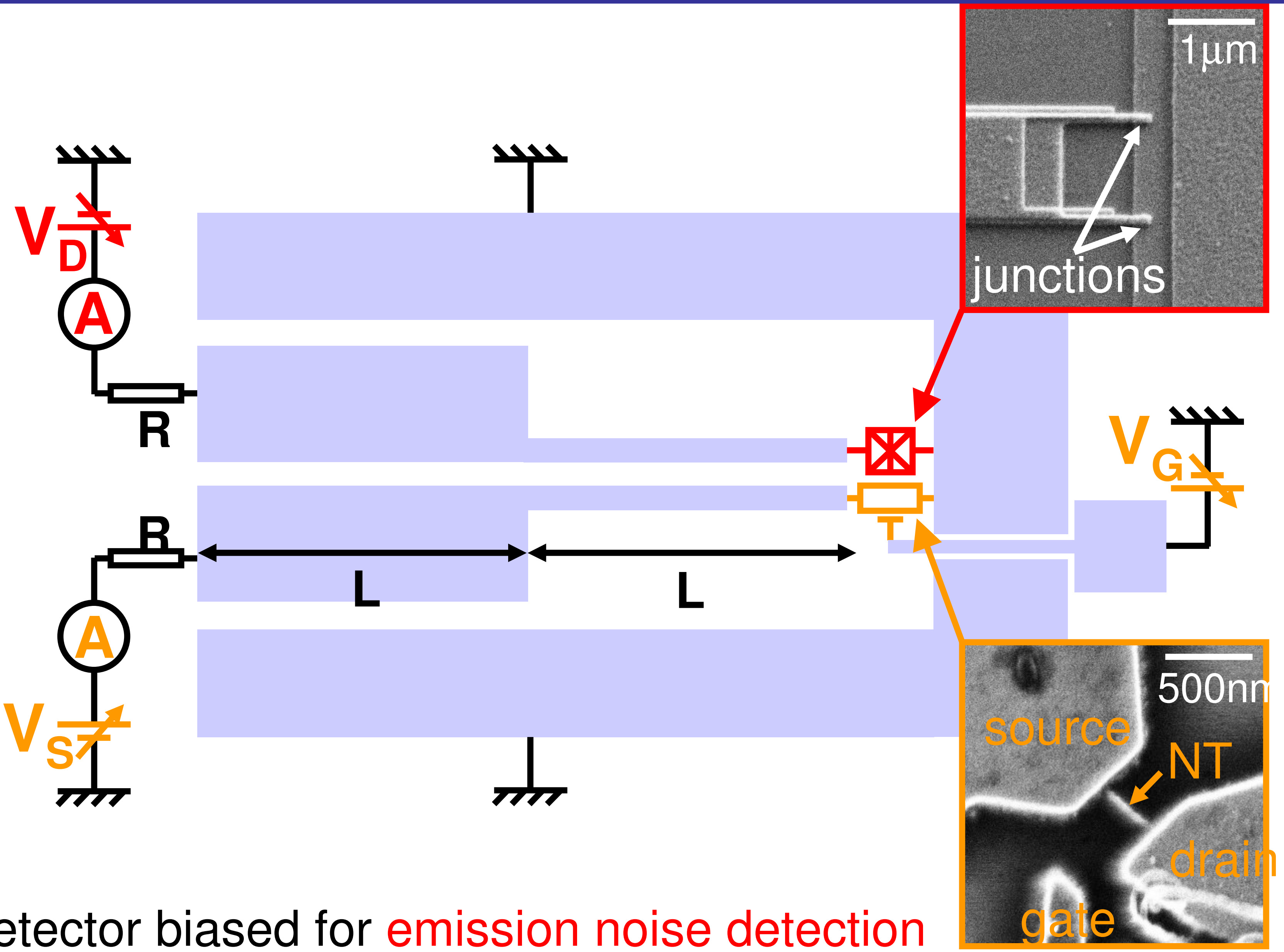
What about Kondo dynamics?

What about emission noise?



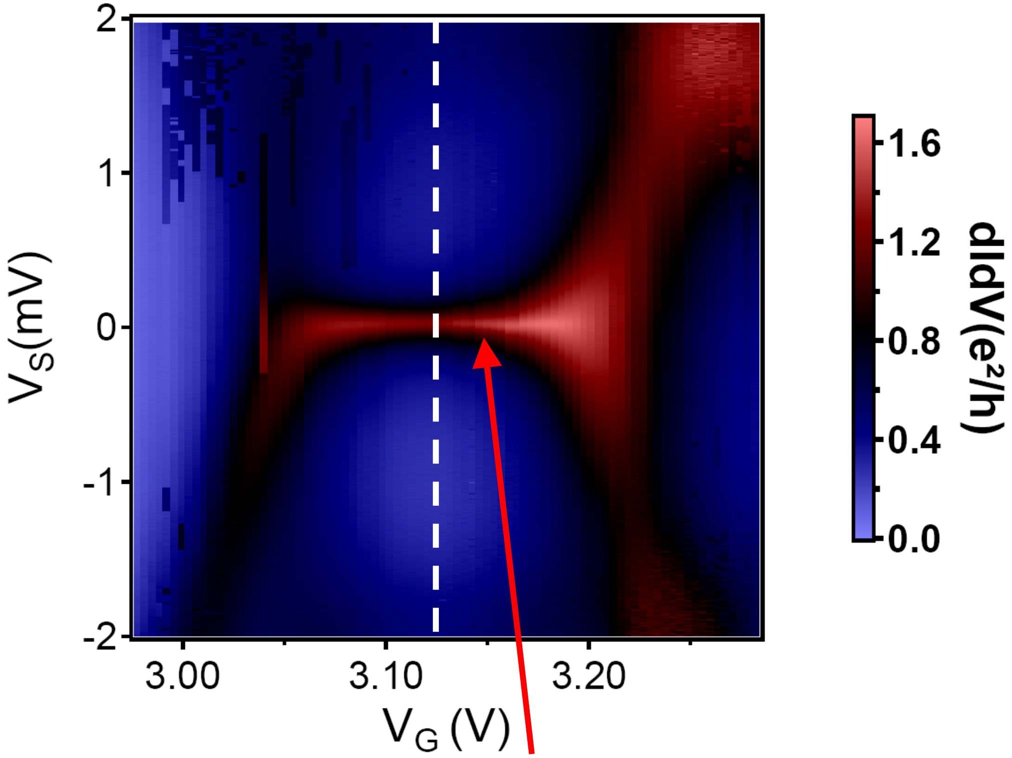
Out-of-equilibrium Kondo dynamics at frequencies $h\nu \sim k_B T_K$?

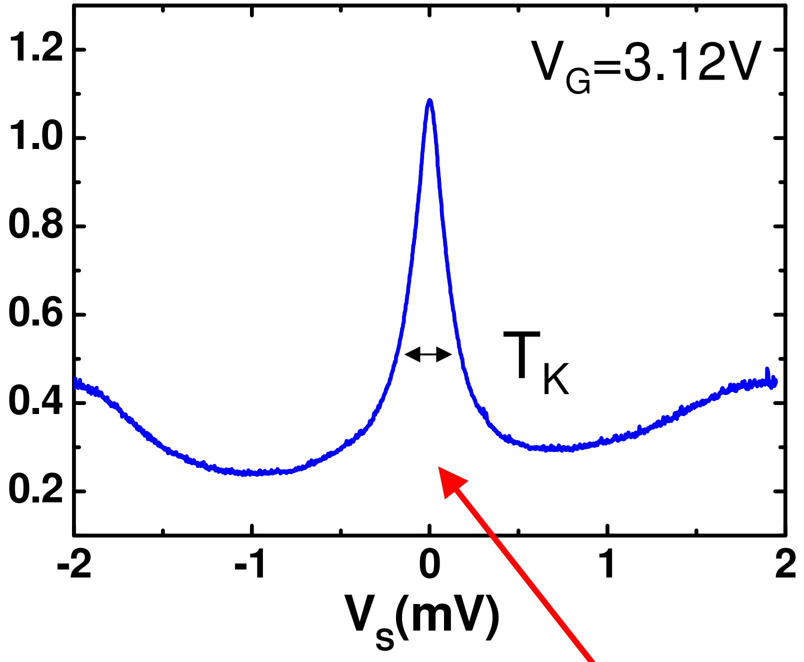
Carbon nanotube coupled to the SIS detector



Detector biased for emission noise detection

Kondo effect in the measured carbon nanotube





Kondo ridge

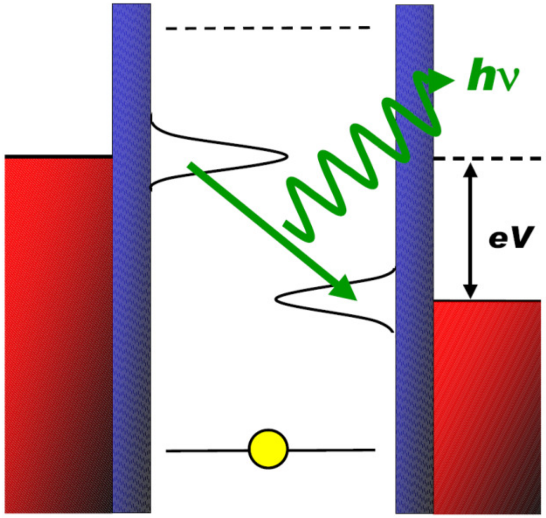
Zero bias peak

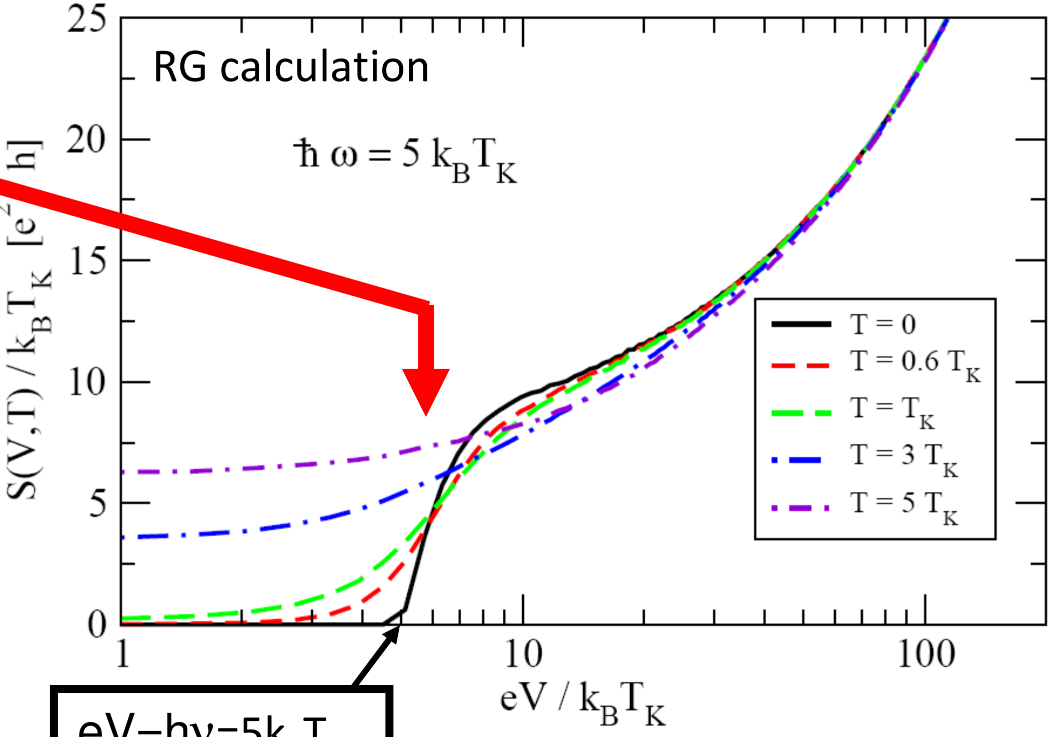
Center of the ridge ➔ T_K=1.4K ⇔ ν=30GHz

What about noise?

Recent theoretical predictions

Signature of the Kondo effect on noise :
Logarithmic singularity at V=hν/e



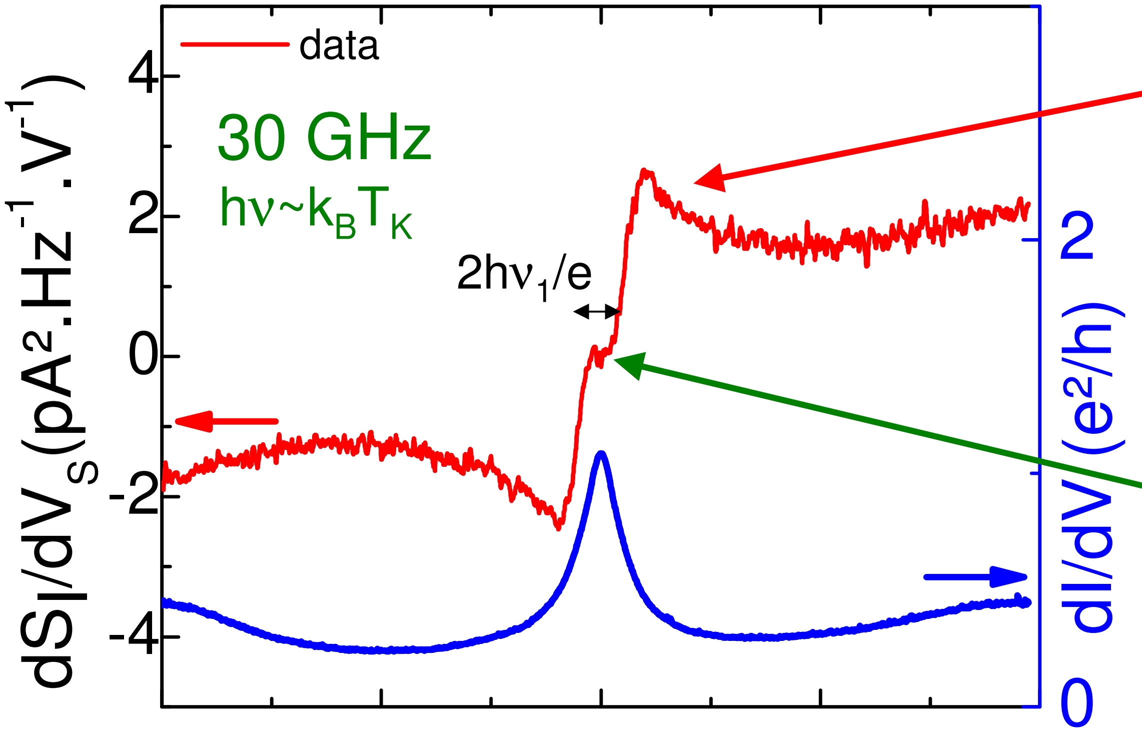


eV=hν=5k_BT_K

C.P. Moca *et al.*, PRB (2011)

- RG calculations at high frequency hν>k_BT_K and out-of-equilibrium
- Prediction of a logarithmic singularity at eV=hν even when hν>>k_BT_K

High frequency noise in the Kondo regime



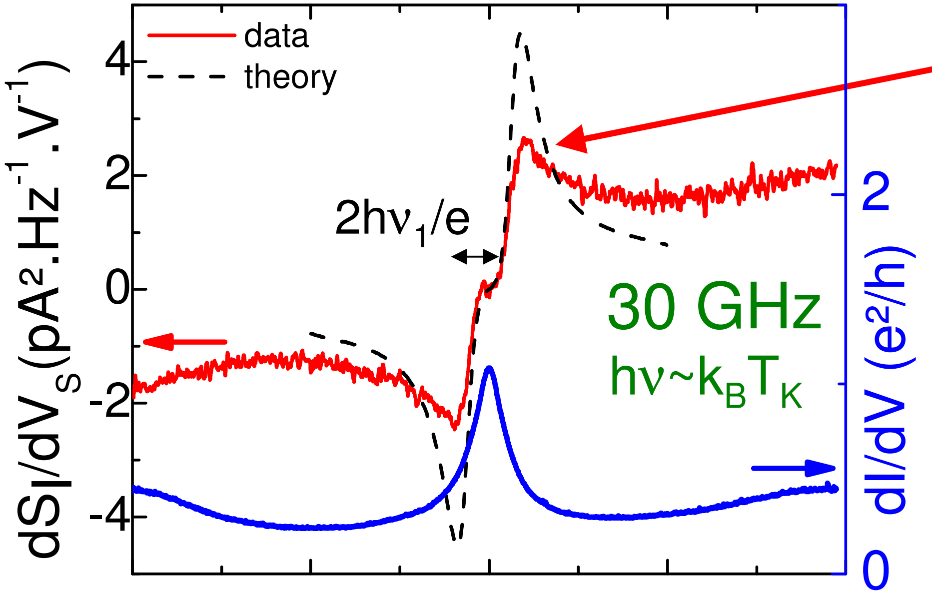
Small singularity related to the Kondo resonance at $h\nu \sim k_B T_K$

No emission noise if $|eV_S| < h\nu$

$h\nu \sim k_B T_K$:

- Absence of emission noise if $|eV_S| < h\nu$
- Singularity at $|eV_S| = h\nu$ qualitatively consistent with predictions

High frequency noise in the Kondo regime

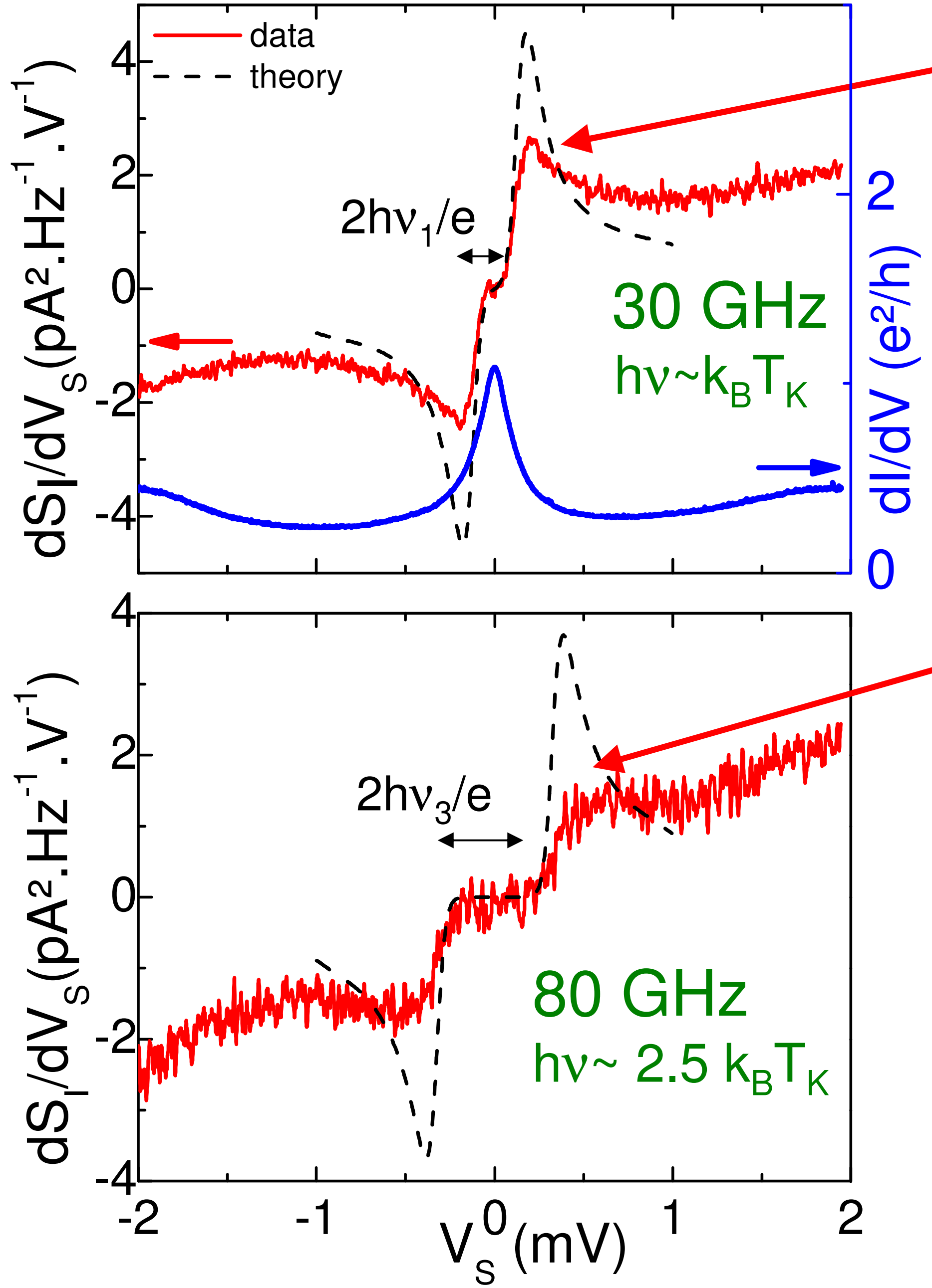


Singularity related to the Kondo resonance at $h\nu \sim k_BT_K$
➔ Qualitatively consistent but not quantitatively

Coll. with C.P.Moca, G.Zarand and P.Simon

- Theoretical comparison takes into account experimental data with no fitting parameter!
    - Kondo temperature T_K=1.4K ⇔ T_K^{RG}=0.38K
    - asymmetry a=0.67
    - U=2.5meV, Γ=0.51meV
- Theoretical predictions approximately 2 times higher than experimental result

High frequency noise in the Kondo regime



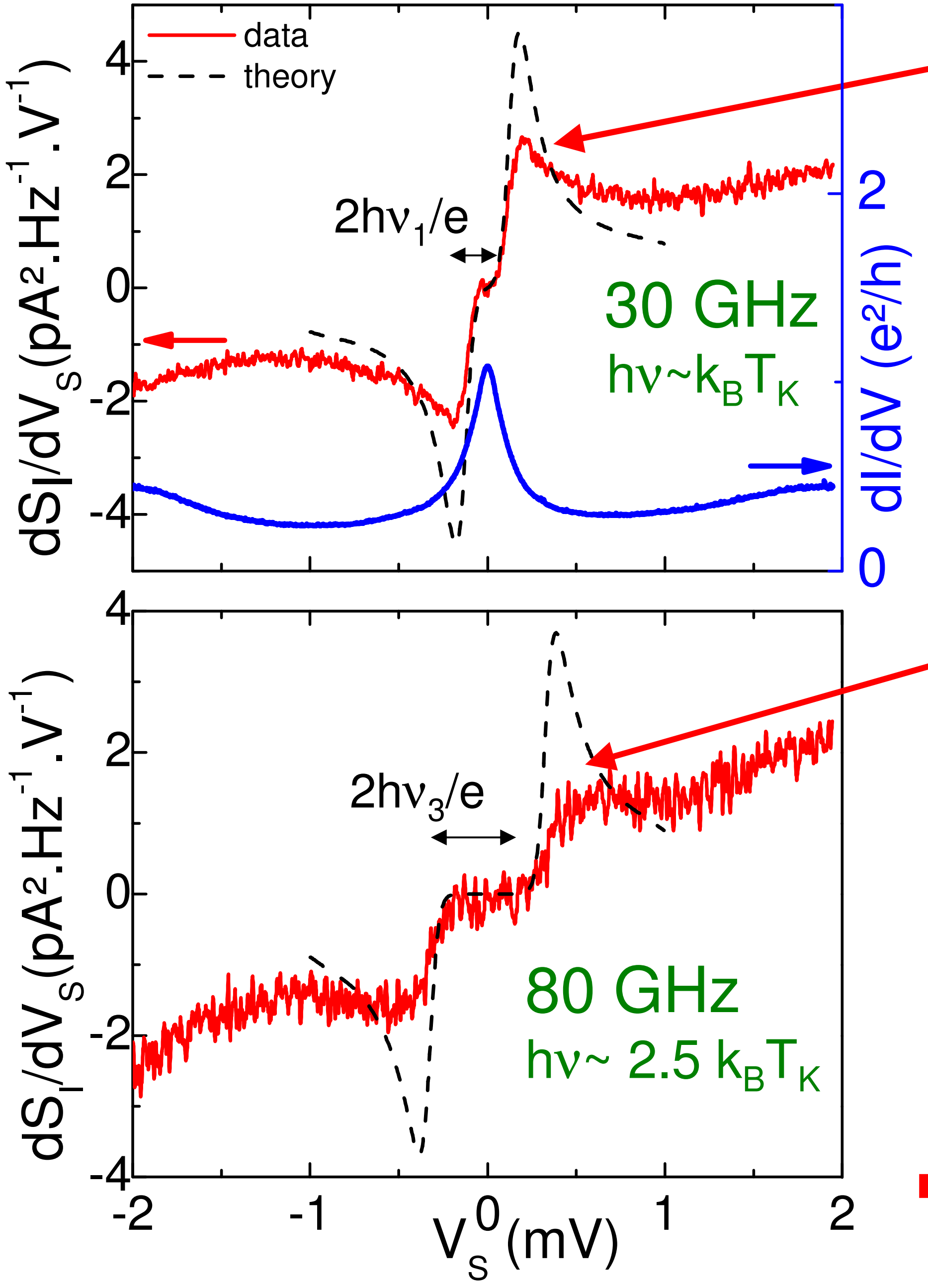
Singularity related to the Kondo resonance at $h\nu \sim k_B T_K$

➔ Qualitatively consistent but not quantitatively

No singularity at $h\nu \sim 2.5\ k_B T_K$!

➔ Not consistent with theory

High frequency noise in the Kondo regime



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ANY EXPLANATIONS??

➔ Decoherence at high V_S ?

Monreal *et al.* PRB 05
Van Roermund *et al.* PRB 10
De Franceschi *et al.* PRL 02

➔ Fit with additional spin decoherence rate

Decoherence due to voltage bias

- External decoherence rate

➔ Form similar to the intrinsic rate (C.P. Moca *et al.* PRB 11)
➔ Consistent with the differential conductance
➔ Consistent with the noise power for both frequencies

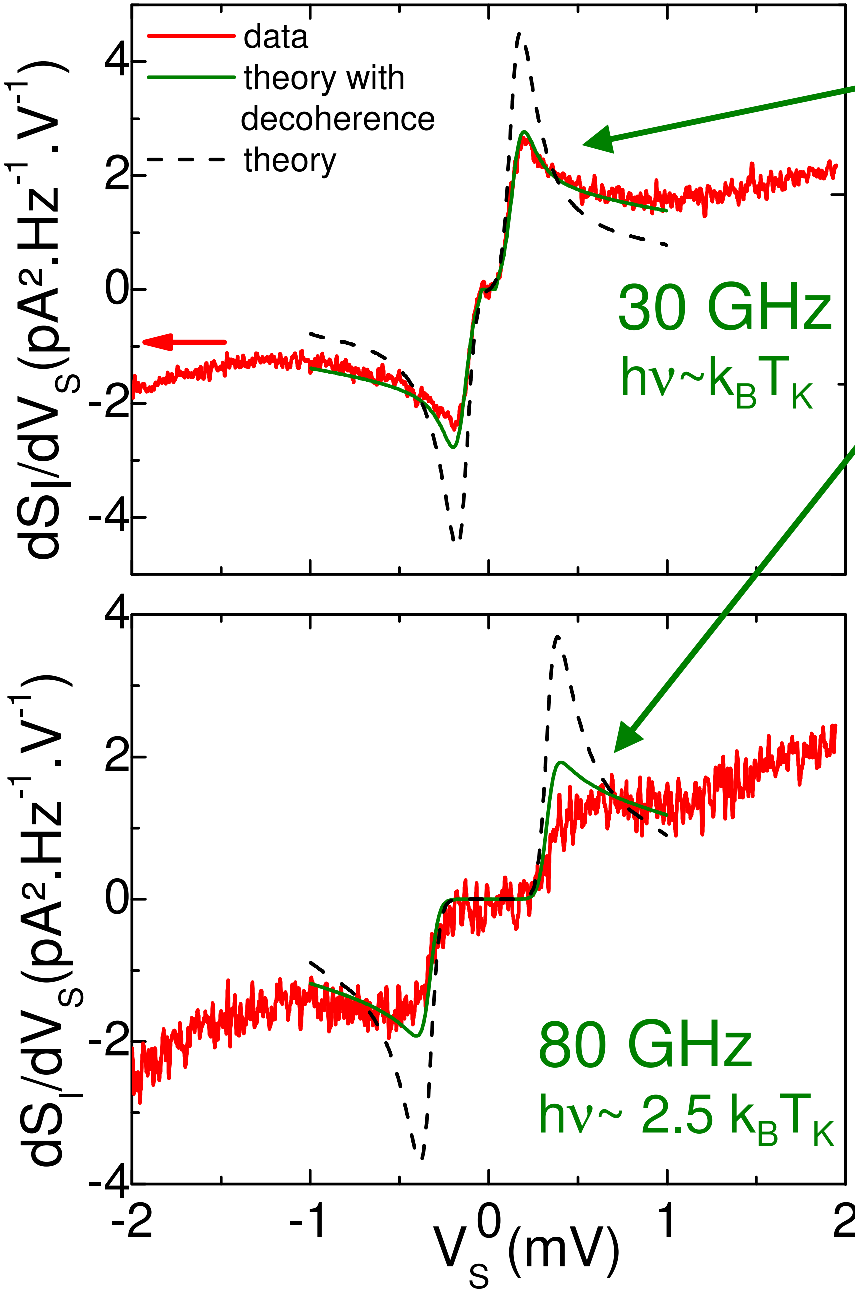
$$\boxed{h/\tau_S \approx \alpha\, k_B T_K^{\mathrm{RG}} \mathrm{atan}(\frac{\beta e V_S}{k_B T_K^{\mathrm{RG}}})}$$

α, β : fitting parameters

Spin lifetime in the dot reduces with applied voltage bias V_S

Coll. with C.P.Moca, G.Zarand and P.Simon

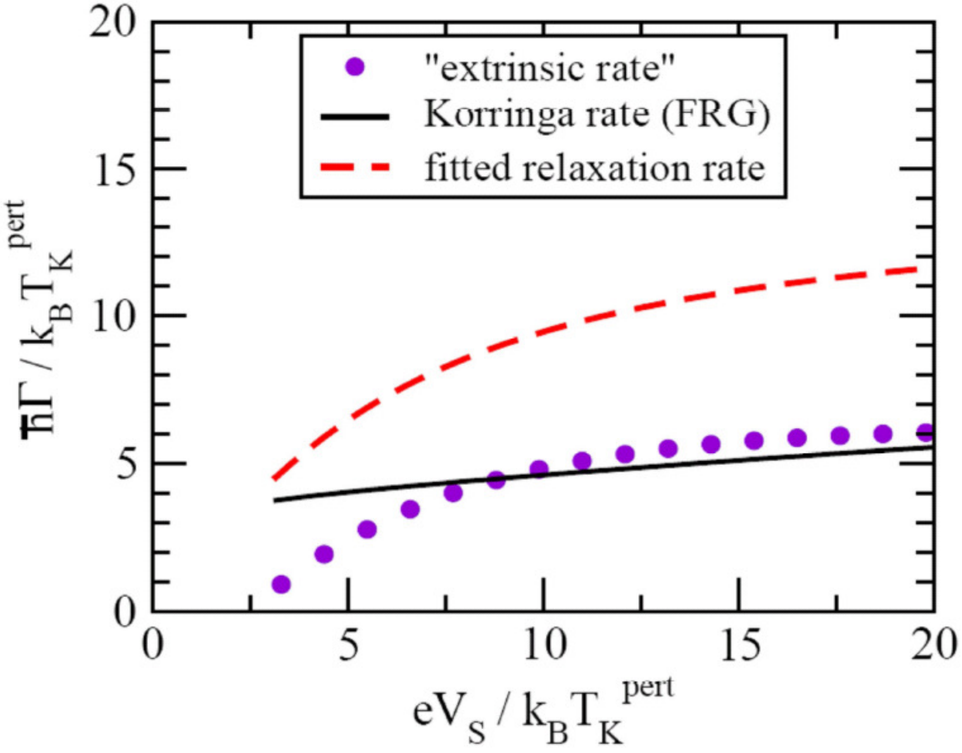
Single decoherence rate function reproduce the data



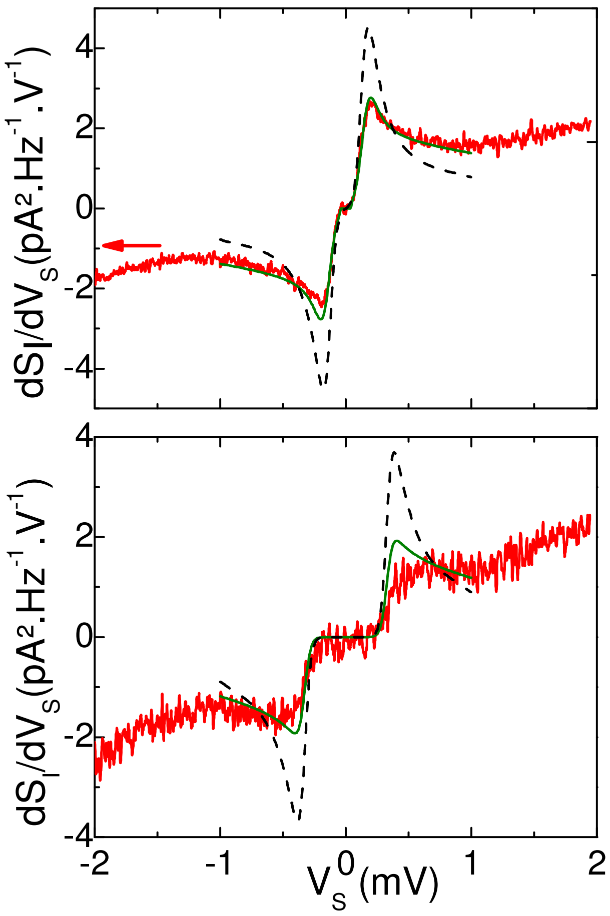
Fits OK using a single bias dependent spin decoherence rate function

$$h/\tau_S \approx \alpha\ k_B T_K^{\mathrm{RG}} \mathrm{atan}\left(\frac{\beta e V_S}{k_B T_K^{\mathrm{RG}}}\right)$$

with α=14, β=0.15

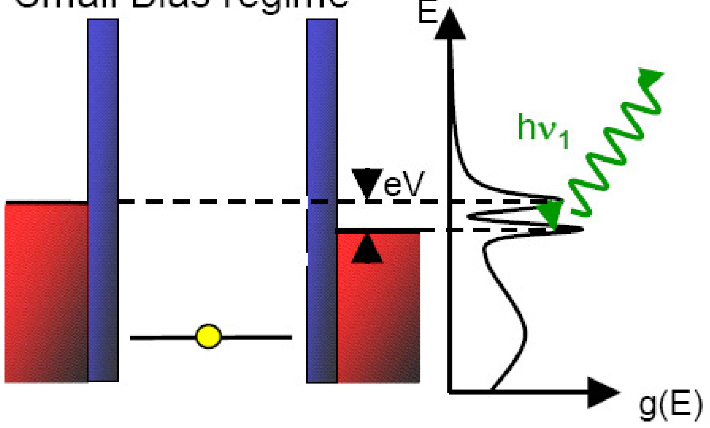


Logarithmic singularity and decoherence effects



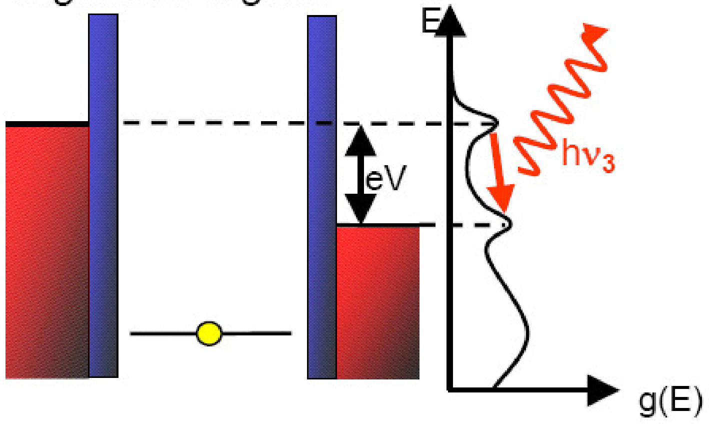
Many photons emitted at $eV=h\nu_1$

Small Bias regime



Few photons emitted at $eV=h\nu_3$

High Bias regime



- eV increases ➔ Kondo peaks in the density of states (attached to the leads) split and vanish due to decoherence
- Decoherence already pointed out

Exp. : De Franceschi *et al.* PRL 02, Leturcq *et al.* PRL 05

Th. : Monreal *et al.* PRB 05, Van Roermund *et al.* PRB 10

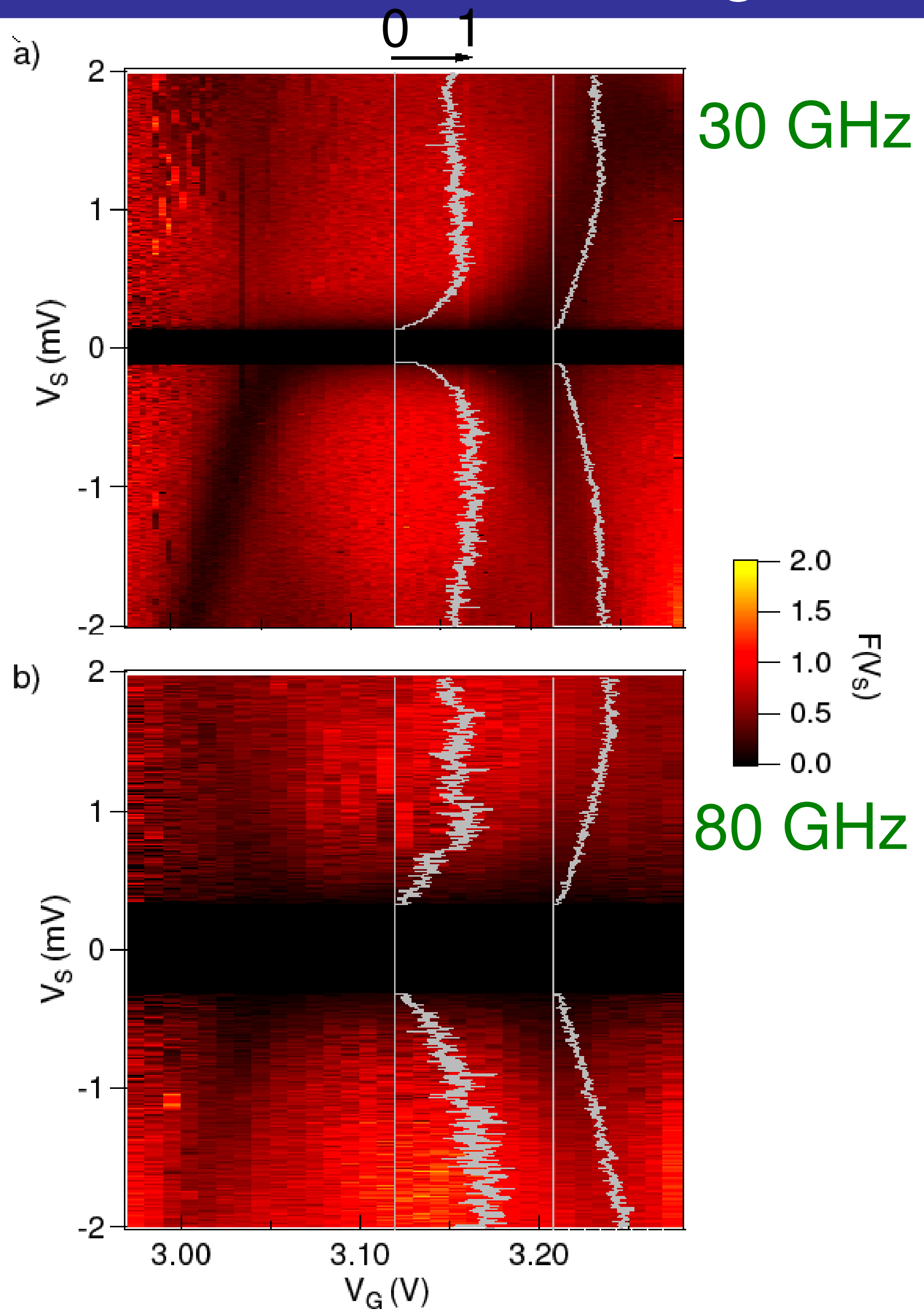
High frequency Fano like factor in the Kondo regime

$$\boxed{F(V) = \frac{dS_I/dV_S}{e\,dI/dV_S(V_S - h\nu/e)}}$$

N.B. : Energy independent transmission
➔ Fano factor

- Subpoissonian Noise $F \leq 1$
- F decreases when conductance increases

➔ Consistent with a highly transmitted channel



Conclusions

High frequency noise in the Kondo regime

- Singularity due to Kondo effect for $h\nu \sim k_B T_K$
- No singularity for $h\nu \sim 2.5\, k_B T_K$
- Consistent with theory with decoherence due to the bias voltage

arXiv:1110.1570