Quantum Partition Noise of photon excited electron-hole pairs

Is it possible to observe quantum partition noise
without net electron transport ?

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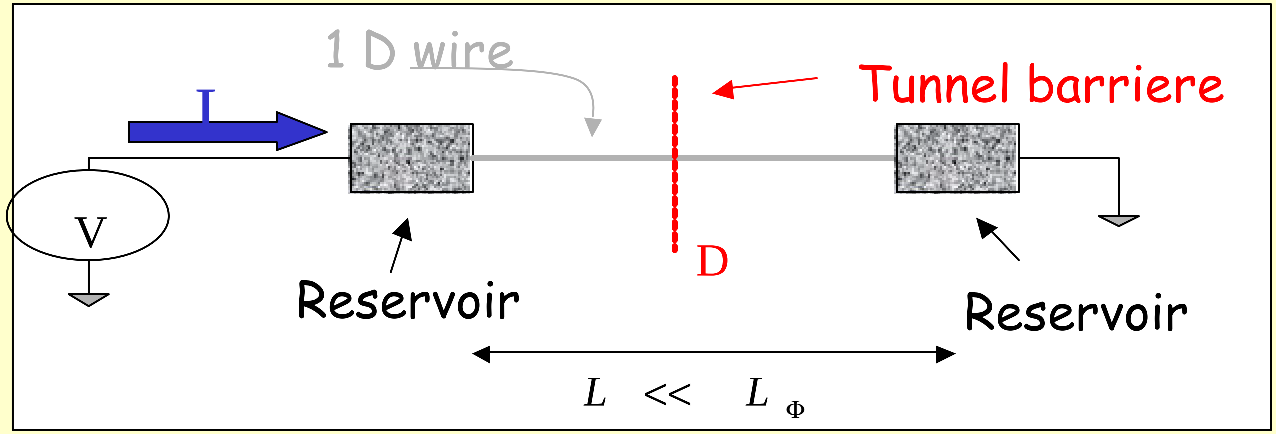
(ordinary) Transport Shot Noise

In general, shot noise requires non-equilibrium conditions.
In nearly all present works, non-equilibrium is provided by a voltage bias

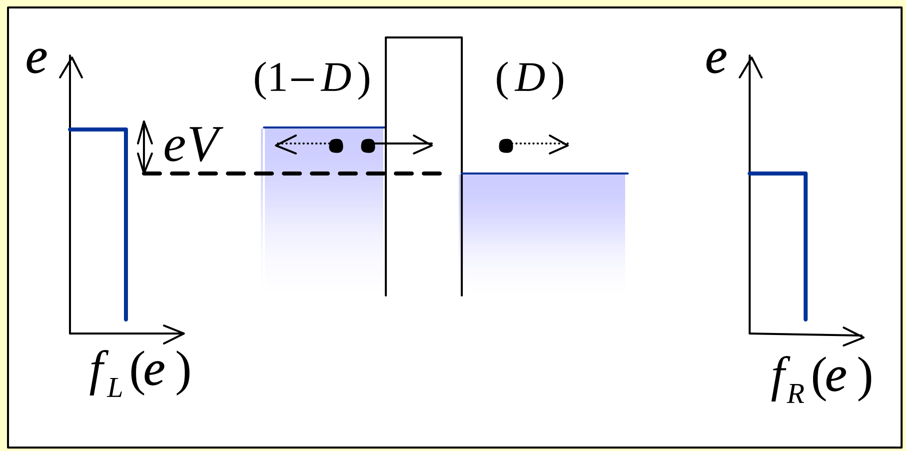


Incoming current :

$$I_0 = e\,(eV/h)$$

Transmitted current :

$$I = D\,I_0 = D\frac{e^2}{h}V$$

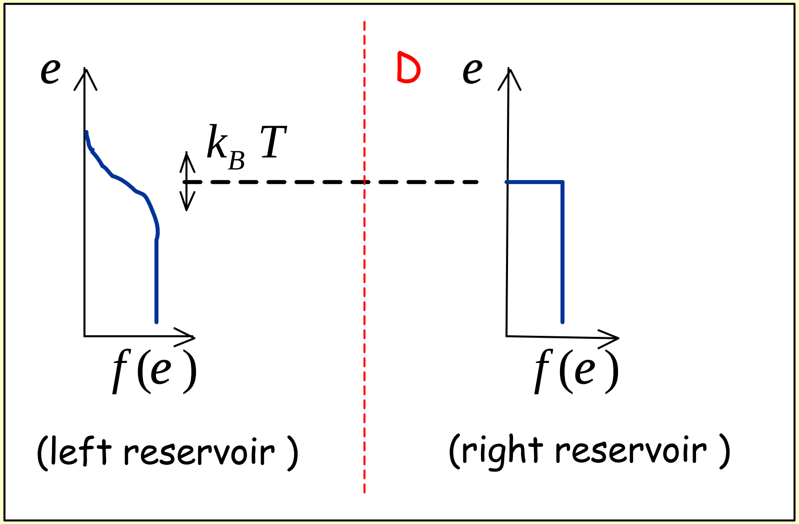


current shot noise power :

$$S_I = 2eI_0\,D(1-D) \quad = 2eI\,(1-D)$$

$$S_I(w) = \int \overline{I(t)I(t+t)}\cos(wt)\,dt$$

Other non-equilibrium cases are however possible while no electrons flow through the conductor (non-transport shot noise):

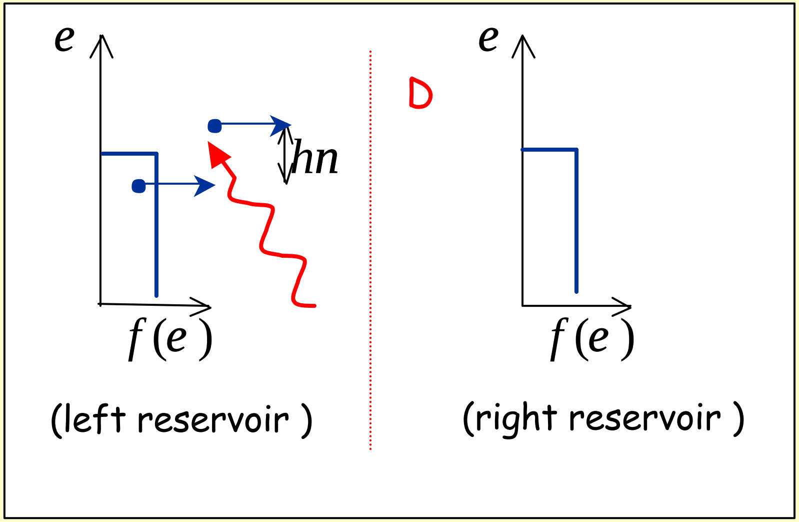


- heating one of the reservoirs.

Sukhorukov and Loss PRB (1999)

$$S_I = 2k_B T \frac{e^2}{h}\left[D^2 + 2Ln(2)D(1-D)\right]$$

(no measurements yet available)



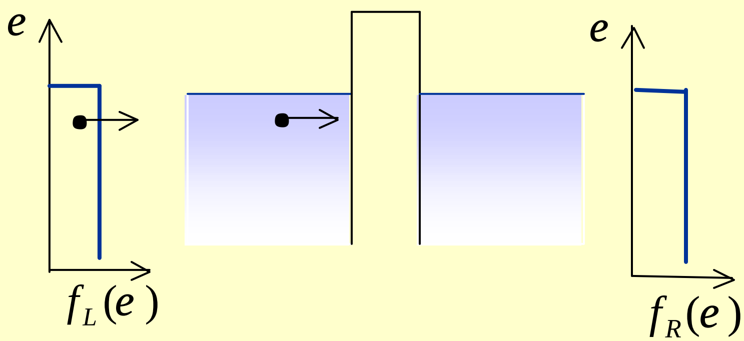
- coherent rf pumping of electron emitted from one side of the conductor.

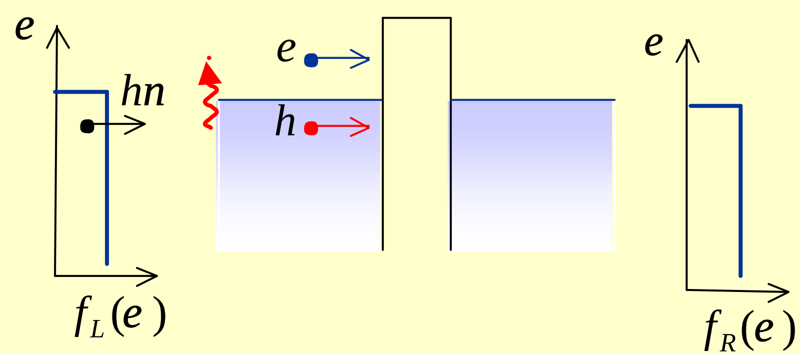
(this presentation)

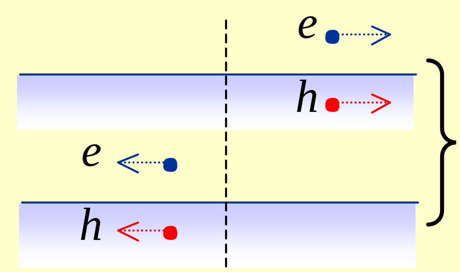
Partition noise of photon-created Electron-hole pairs
(non-transport Shot Noise)

an incoming electron can be either

unpumped (prob. P_0) or pumped (prob. P_1)

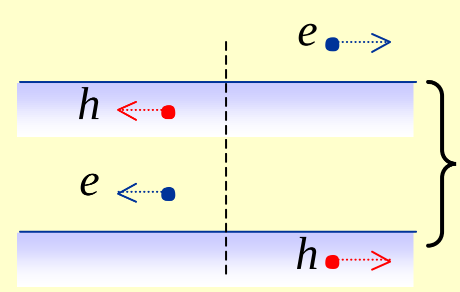






no current
no noise

unpumped electrons do not generate noise (ground state)



no current
e-h partition noise

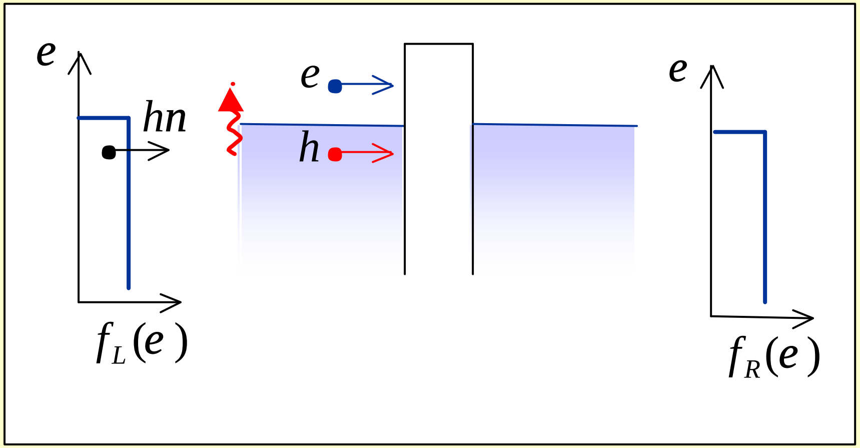
pumped electrons do generate noise as e - h pairs are dissociated by the elastic scatter.

current of pumped incoming electrons :

$$I_0^{(e)} = P_1 \frac{e}{h} (hn)$$

current of pumped incoming holes :

$$I_0^{(h)} = - I_0^{(e)}$$



the associated electron and hole shot noise powers are respectively:

$$S_I^{(e)} = 2 e I_0^{(e)} D(1-D) \quad \text{and} \quad S_I^{(h)} = 2 e I_0^{(h)} D(1-D) = S_I^{(e)}$$

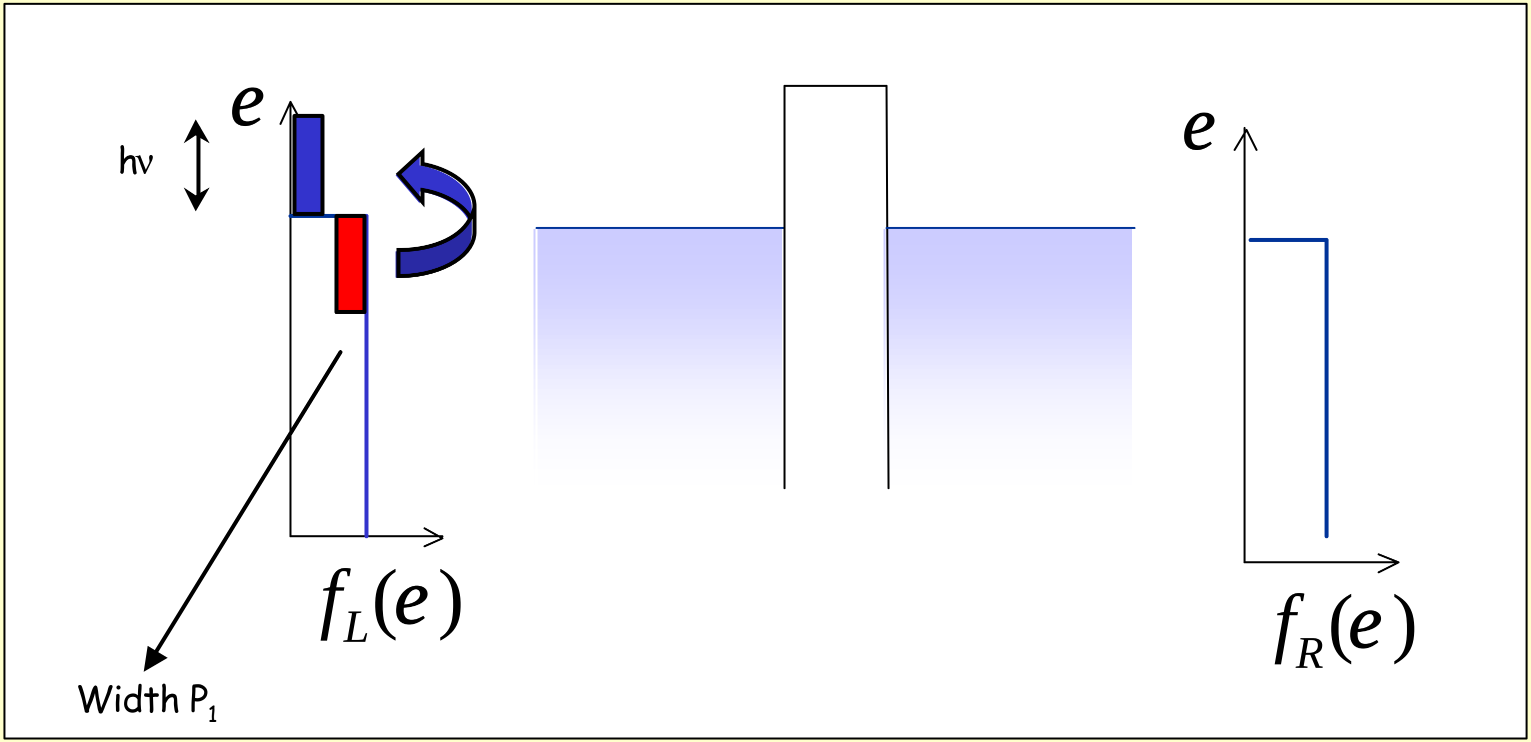
they add independently to give the electron-hole partition shot noise :

$$S_I = 4 hn \frac{e^2}{h} P_1 D(1-D)$$

while the mean current : $I = 0$

Not a simple thermal effect !

For an energy relaxation length shorter than the conductor :



$$S_I = 4h\nu \frac{e^2}{h}\left\{P_1 D(1-D) + P_1(1-P_1)D^2\right\}$$

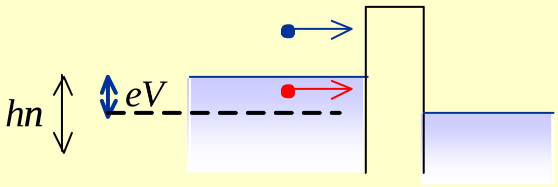
Electron hole partitioning

Occupation uncertainty

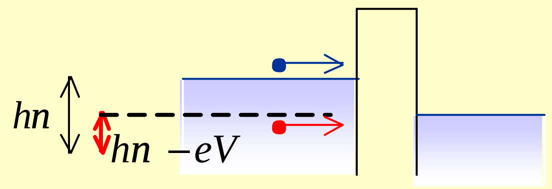
While Photon assisted process gives : $S_I = 4h\nu \frac{e^2}{h} P_1 D(1-D)$

Applying DC bias and RF

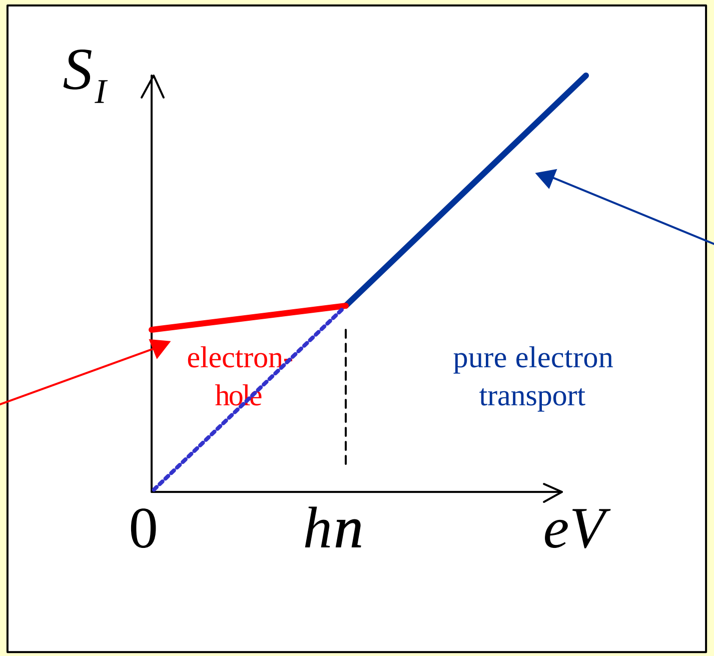
for a doubly non-equilibrium, when both a d-c voltage V and RF are applied, the slope of the transport shot noise variation with V was predicted to show a singularity at $eV = hn$



electron transport shot noise



electron-hole non-transport shot noise



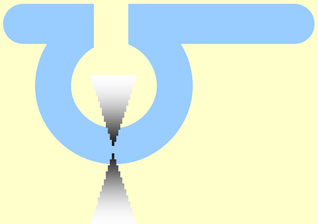
Slope

$$2\frac{e^2}{h}D(1-D)$$

Slope

$$2\frac{e^2}{h}D(1-D)(1-2P_1)$$

a complete formula have been derived by Levitov and Lesovik (PRL 94) :



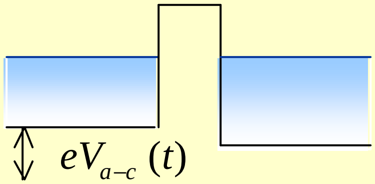
$$S_I = 4\,hn \left(\sum_l l\, P_l \right) \frac{e^2}{h} \sum_n D_n\,(1 - D_n) \qquad \text{where} \qquad P_l = J_l^{\,2}\,(f_w / f_0)$$

$$f\,(t) = f_w \cos w\,t \qquad \text{and} \qquad f_0 = h/e$$

"a-c Aharanov-Bohm effect"

later Pedersen et al. (98) have considered the equivalent case of an a-c potential applied to one contact :

$$V_{a-c}\,(t) = V_{a-c} \cos w\,t \quad \text{with} \quad P_l = J_l^{\,2}\,(eV_{a-c} / \hbar w)$$



$$V_{a-c}(t) = \frac{d f\,(t)}{dt}$$

At Finite Temperature :

$$T_N = \frac{S_I}{4G\,k_B} = T\left(\frac{\sum D_n^2}{\sum D_n} \right) + \frac{\sum_n D_n\,(1 - D_n)}{\sum_n D_n} \cdot \sum_{\pm} \sum_{l=0}^{\infty} \frac{(eV \pm lhn)}{2k_B} J_l^{\,2}(a) \coth\left(\frac{eV \pm lhn}{2k_B T} \right)$$

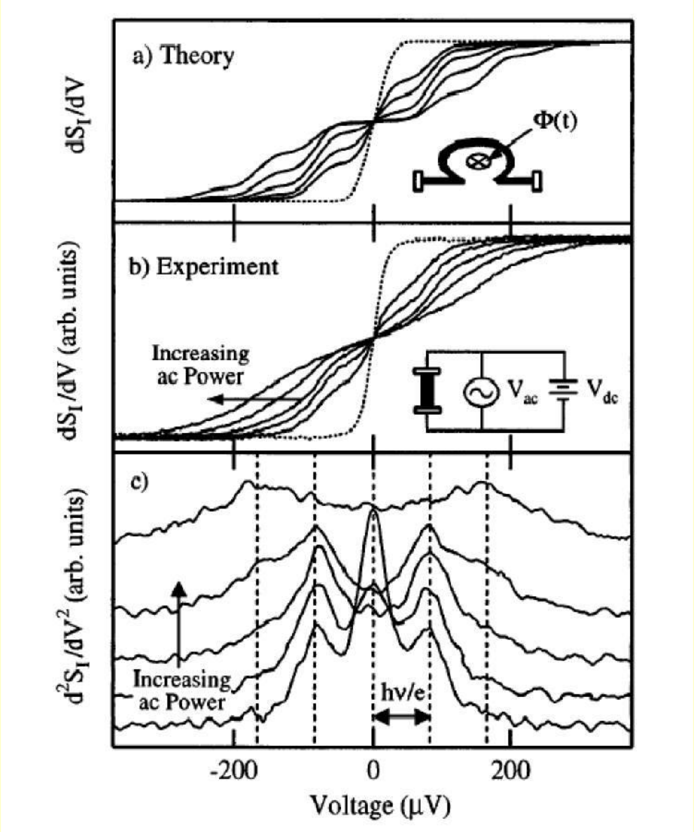
One needs $k_B T \ll h\nu$

$$17\,GHz \cong 850\,mK$$

Singularity at eV= hν

The singularity was observed by Schoelkopf et al. (PRL 98) in the doubly non-equilibrium regime (RF and V bias) using

- a diffusive system (and later a S-diffusive junction)
- measuring the derivative of the transport noise versus d-c bias voltage V
- they provide the first evidence of photon-assisted processes in shot noise, supporting Lesovik's model.



→ the Fano factor was fixed by the bimodal statistics of the transmission probabilities of a diffusive conductor:

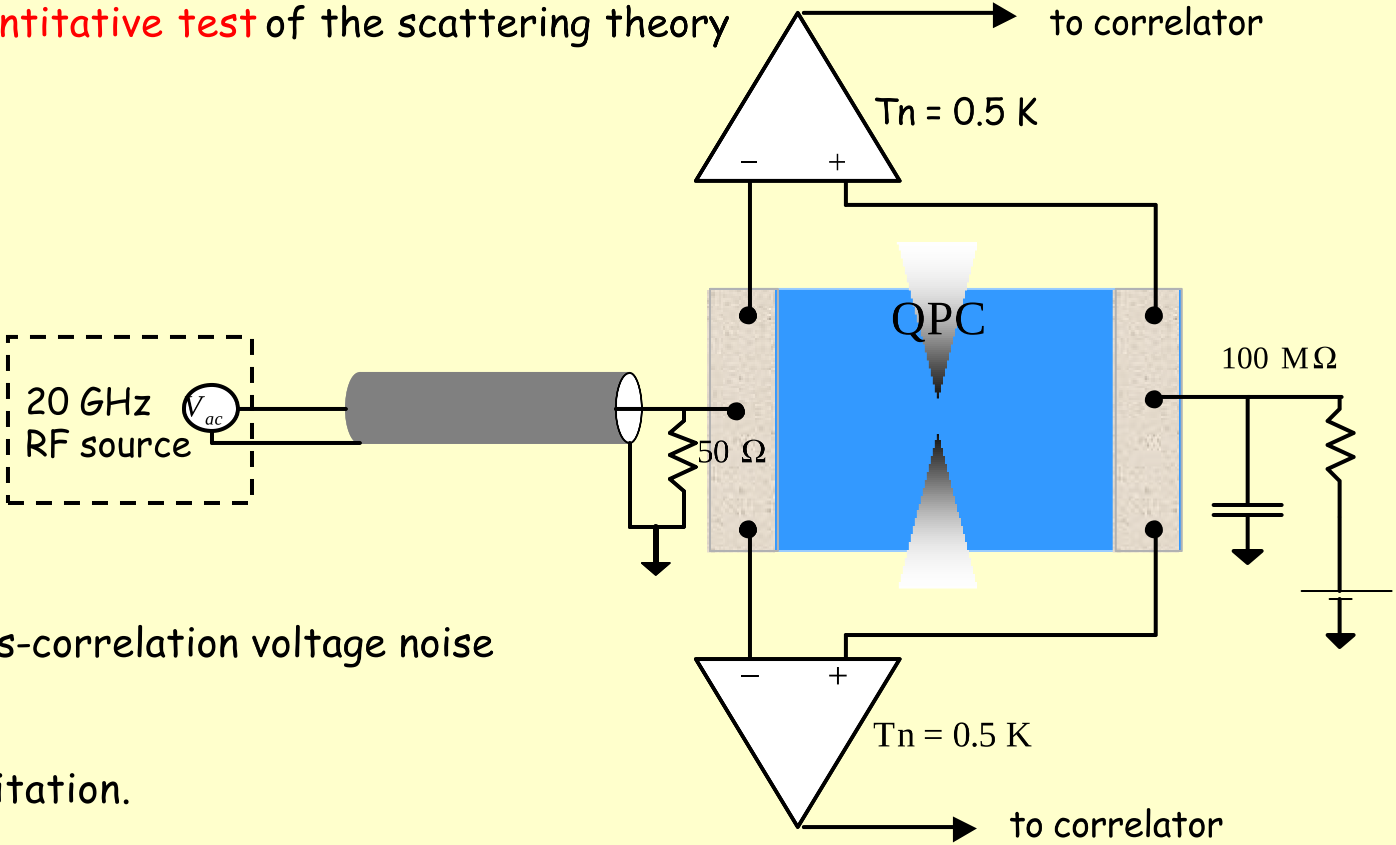
$$F = \frac{\left\langle \sum_n D_n (1 - D_n) \right\rangle}{\left\langle \sum_n D_n \right\rangle} = 1/3$$

→ no possibility to measure the total shot noise at zero bias (non-transport electron-hole pair shot noise)

- ballistic QPC to control the transmission and vary the Fano factor

- total shot noise measurements to probe the V=0 non transport electron-hole pairs shot noise

- allows for quantitative test of the scattering theory



- 2 to 4 kHz cross-correlation voltage noise measurements.

- ~17 GHz rf excitation.

Quantum Point Contact

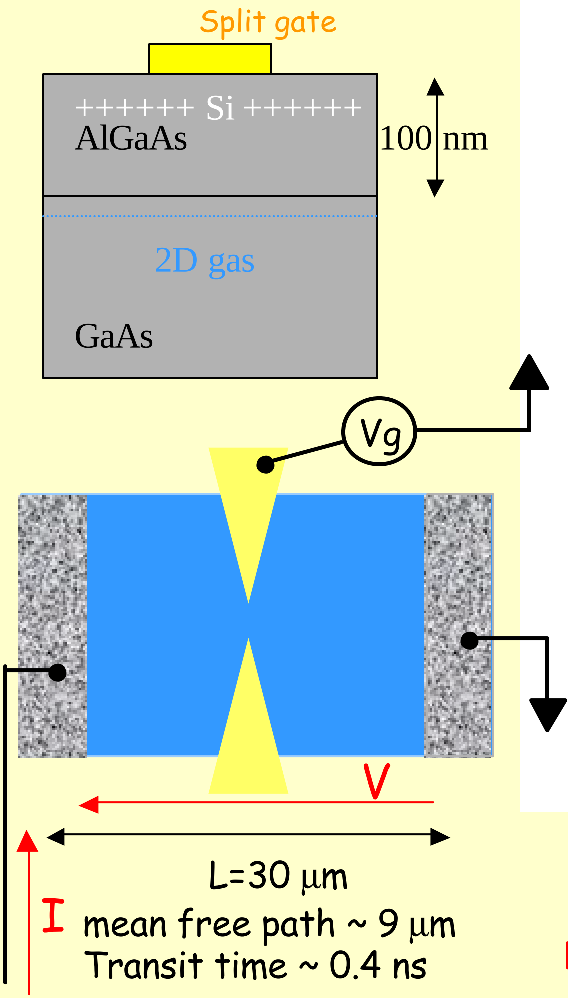
(tuning the transmission probability of the first two modes)

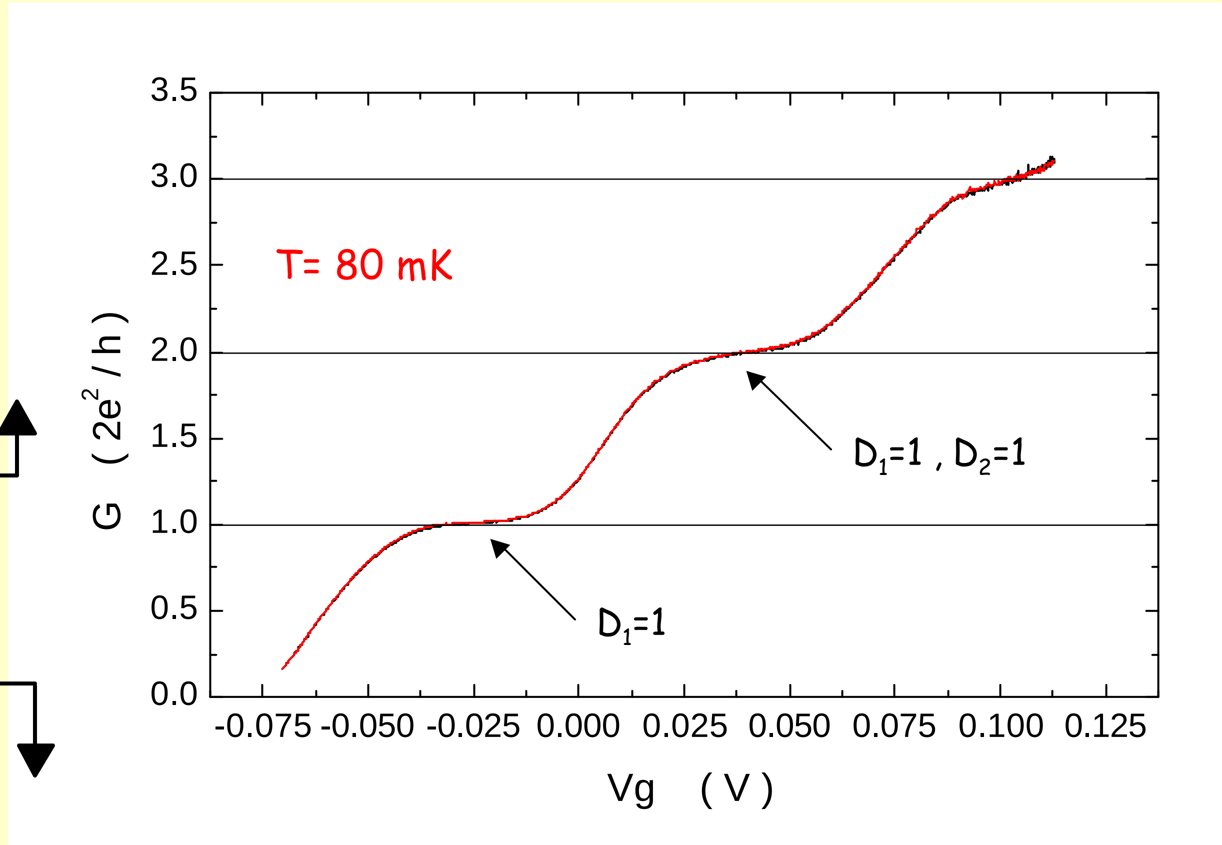
2D electron gas in GaAs/GaAlAs

$\mu = 8.10^5 cm^2/Vs$

$n_s = 4.8\ 10^{11}\ cm^{-2}$

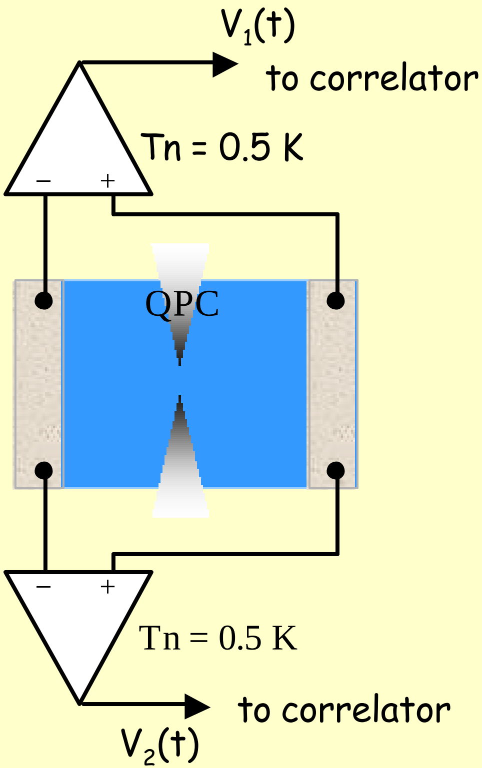
$$G = dI/dV = \frac{2e^2}{h}\sum_n D_n \qquad h/e^2 = 25812\,\Omega$$

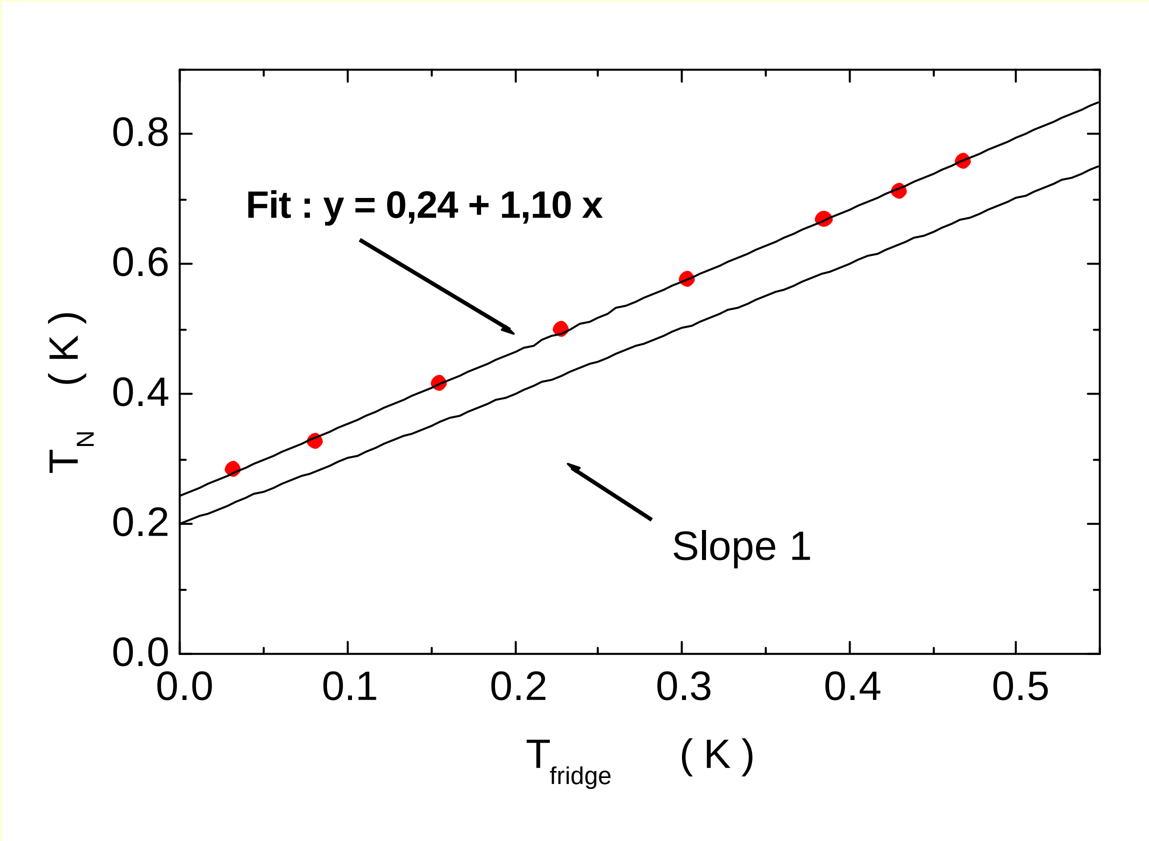




Tuning of the mode transmissions

Calibration using Johnson-Nyquist Noise at D = 1





Cross correlated power spectrum

$$S_{V_1V_2}(w) = \int \overline{V_1(t)V_2(t+t)} \cos(wt)dt$$

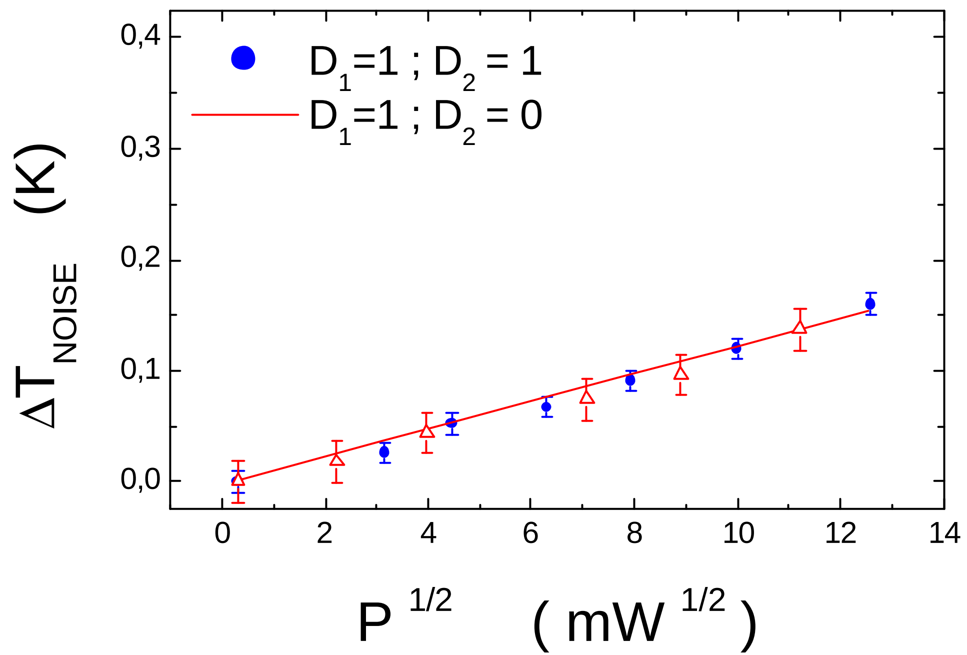
$$S_I = S_{V_1V_2}(w)G^2$$ 2 to 4 kHz frequency range

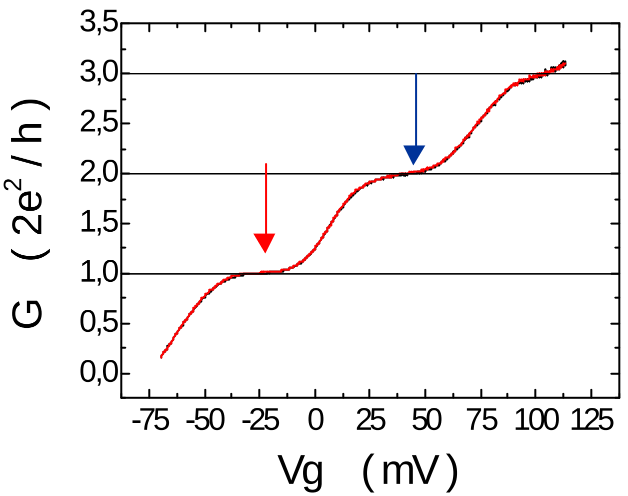
$$T_N = S_I / (4k_B G)$$

Sensitivity : 10 min. acq. time leads to 5 mK noise temperature accuracy at D = 1 $(12906\,\Omega)$

1 - check for possible heating by RF power (no bias voltage, i.e. no current)

At transmission 1 or 2 no electron-hole partition noise is expected !





$T_0 = 98\,\mathrm{mK}$

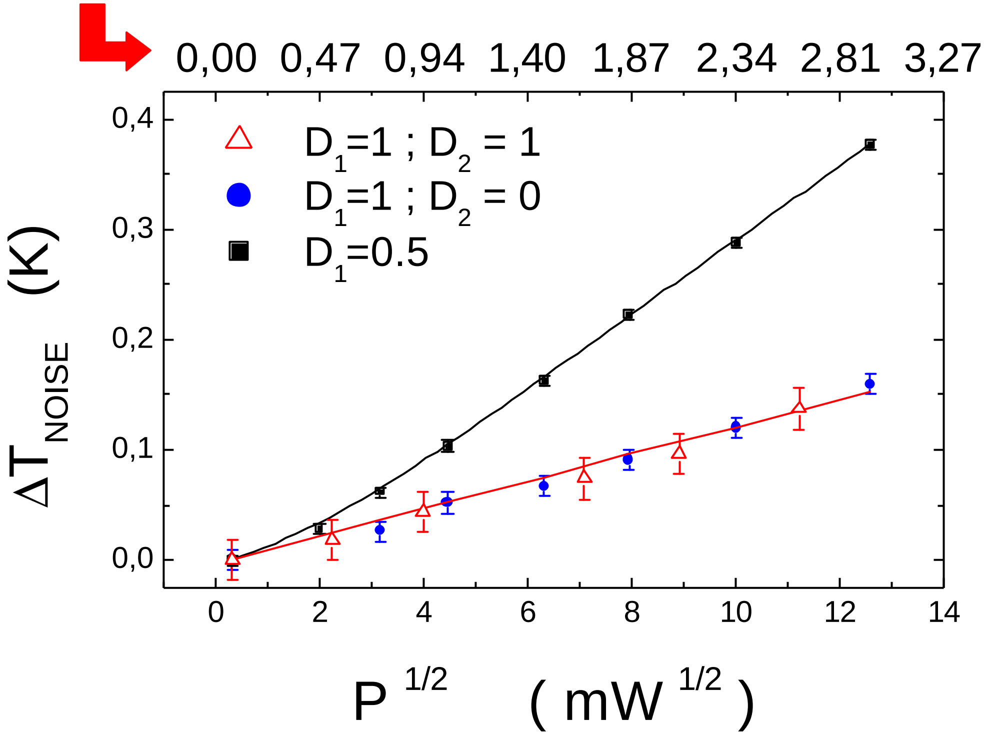
$n = 17.32\ \mathrm{GHz}$

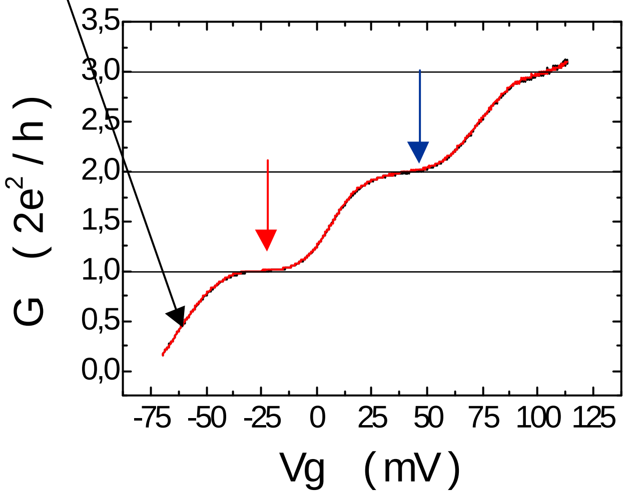
Determination of $T = T_0 + \Delta T_N$

2 - check for possible e-h partition noise at 1/2 transmission:

$$D_1 = 0.5 \quad \text{and} \quad D_{n>1} = 0$$

$$a \propto \sqrt{P}$$





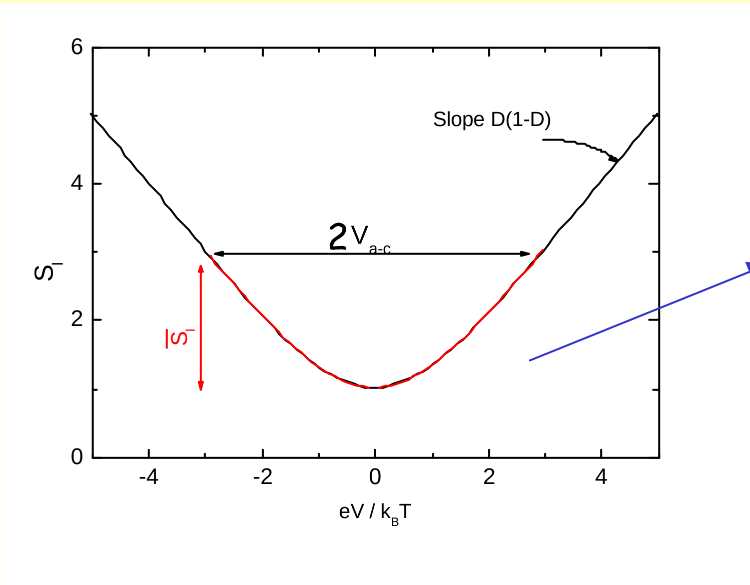
$T_0 = 98\,\text{mK}$

17.32 GHz

- good fit with theory gives a calibration of $a = eV_{ac} / h\nu$ with RF power

Determination of the coupling parameter α

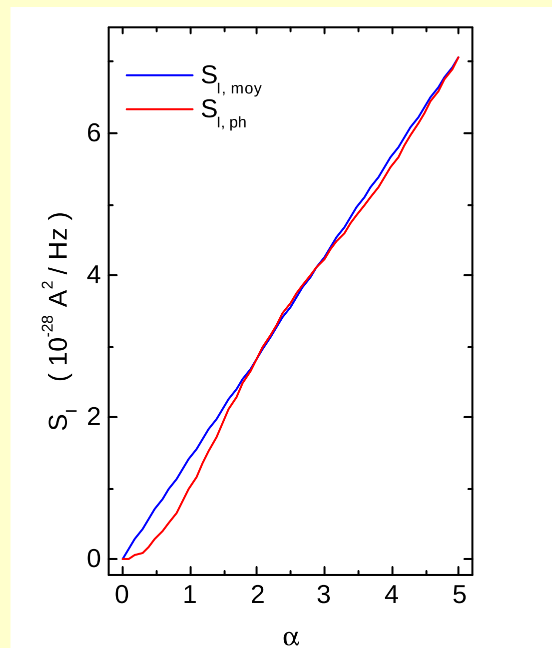
Quantum or Classical ?



$$V(t) = V_{a-c}\sin(2pnt) \quad ; \quad a = eV_{a-c}/hn$$

Low frequency approximation :

$$S_{I,moy} = 2e\frac{e^2}{h}\overline{V(t)}D(1-D) = 4hn\,\frac{e^2}{h}D(1-D)\frac{a}{p}$$

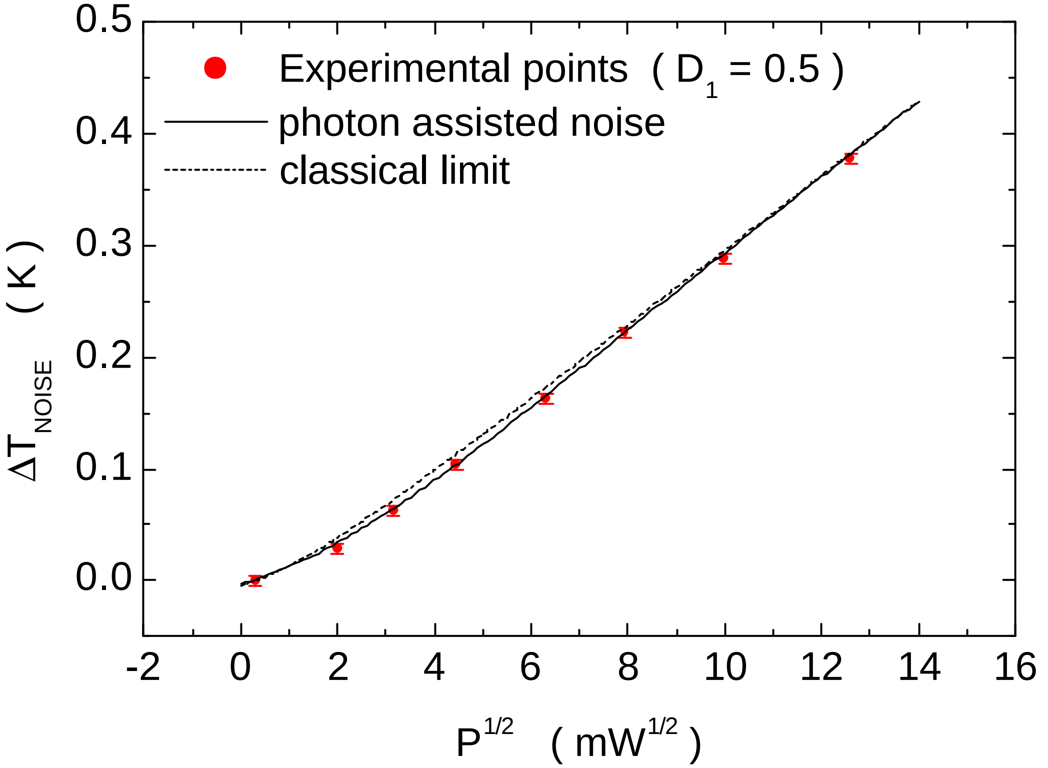


Photon assisted processes :

$$S_I = 4\,hn\,\frac{e^2}{h}D(1-D)\left(\sum_l l\;J_l^{\,2}(a)\right)$$

Same result if α >> 1

Quantum !



Experimental points (D1 = 0.5)
photon assisted noise
classical limit
ΔT NOISE (K)
P1/2 (mW1/2)
0.5
0.4
0.3
0.2
0.1
0.0
-2
0
2
4
6
8
10
12
14
16

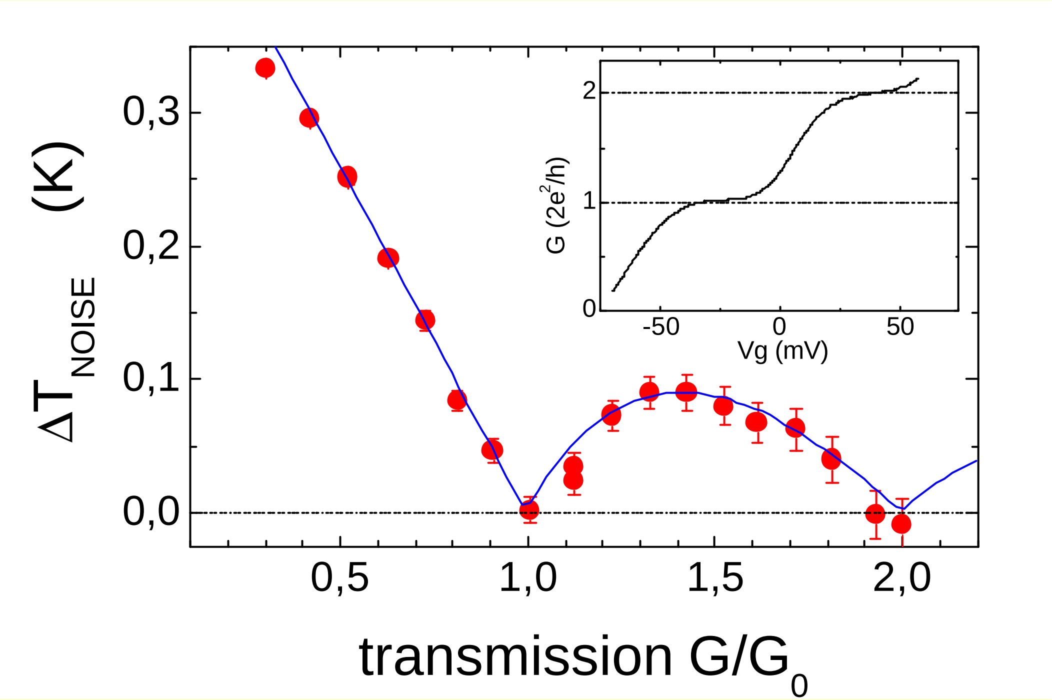
3 - Is this really the partition noise of photon-created electron-hole pairs ?

(no dc V bias, no current !)

QPC allows to measure

the Fano factor of the

e-h partition noise

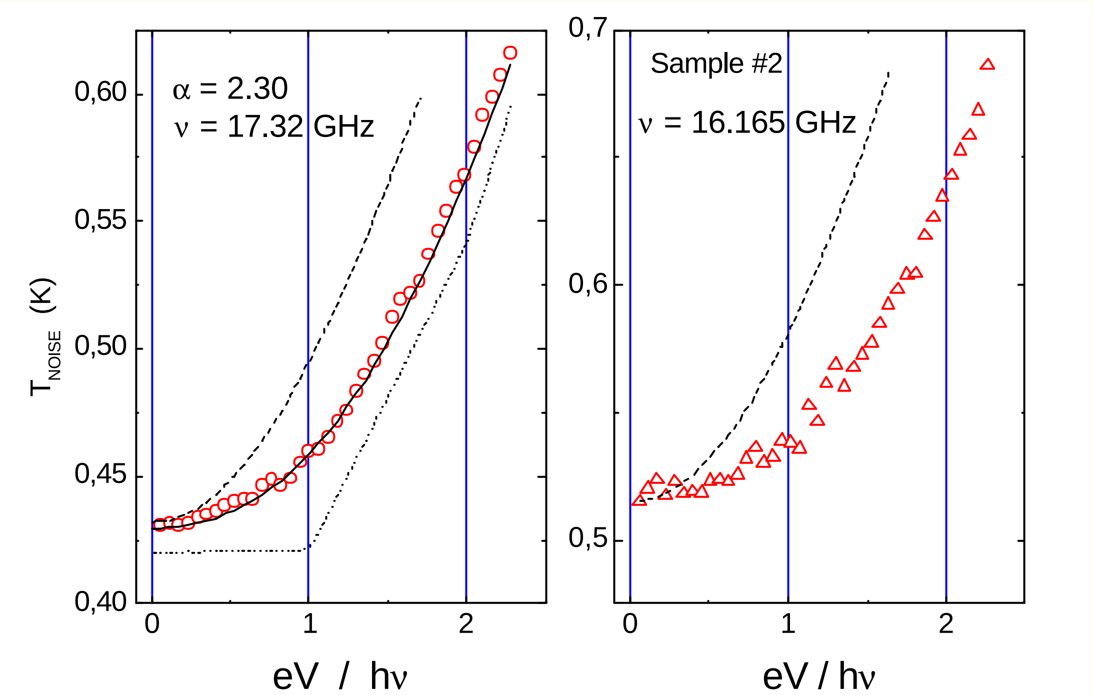


$$\frac{S_I}{4G\,k_B} = T\left(J_0^2(\alpha) + \frac{\sum D_n^2}{\sum D_n}(1 - J_0^2(\alpha)) \right) + \frac{h\nu}{k_B}\left(\sum_l l J_l^2(\alpha) \right) \frac{\sum_n D_n(1-D_n)}{\sum_n D_n}$$

α, D_n , T are known : perfect agreement without adjustable parameter

4 - additional confirmation of photon-created e-h pairs : RF and dc voltage V

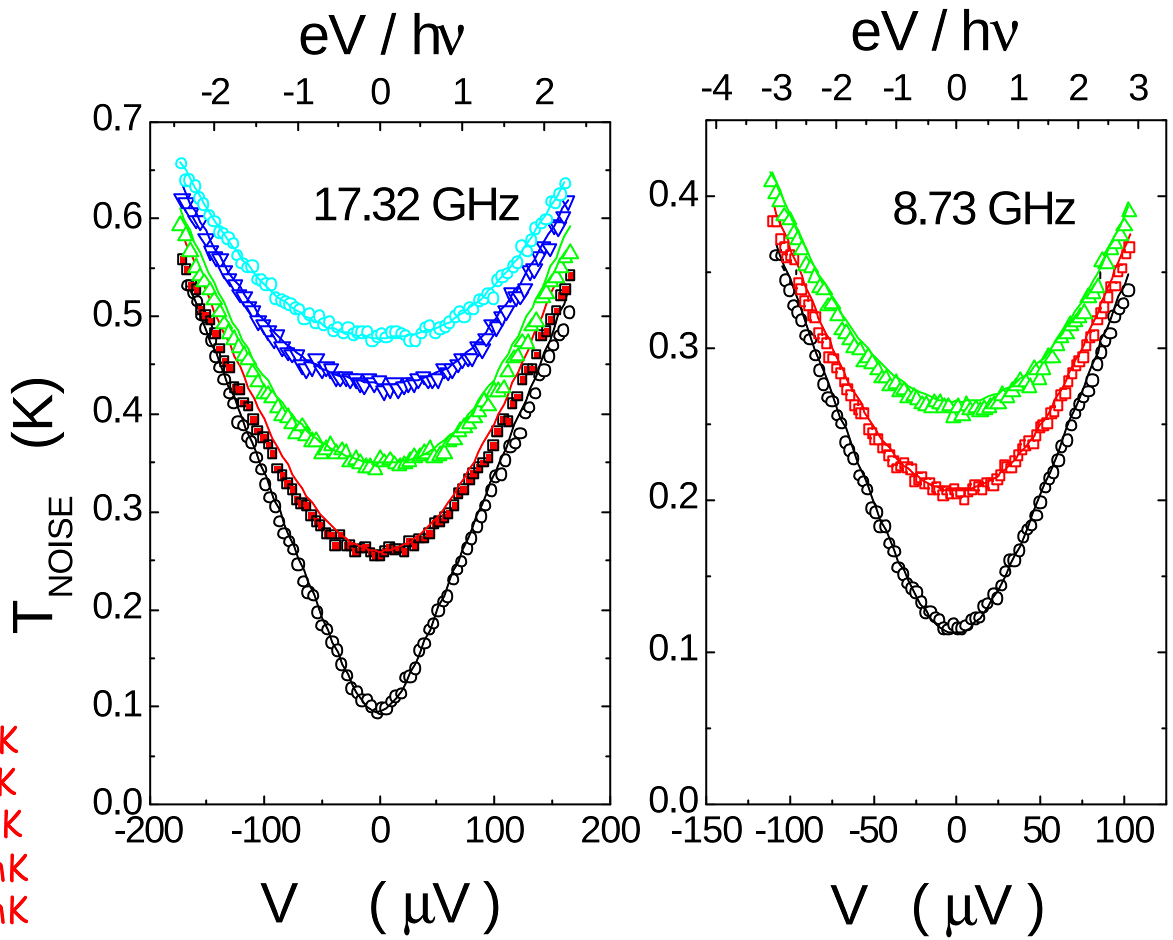
Transmission 1/2



$$T_N = \frac{S_I}{4G\,k_B} = T\left(\frac{\sum D_n^2}{\sum D_n}\right) + \frac{\sum_n D_n\,(1-D_n\,)}{\sum_n D_n} \cdot \sum_{\pm} \sum_{l=0}^{\infty} \frac{(eV \pm lhn\,)}{2k_B} J_l^{\,2}(a\,)\coth\left(\frac{eV \pm lhn}{2k_B T}\right)$$

α, D_n , T are known : perfect agreement without adjustable parameter

5 - transmission 1/2 , various rf power (or α), two different frequencies



α	T
0.065	94 mK
1.29	168 mK
1.83	200 mK
2.30	229 mK
2.58	246 mK

α	T
0.51	105.5 mK
1.81	145 mK
2.56	168 mK

(no fits, just comparison data / theory)

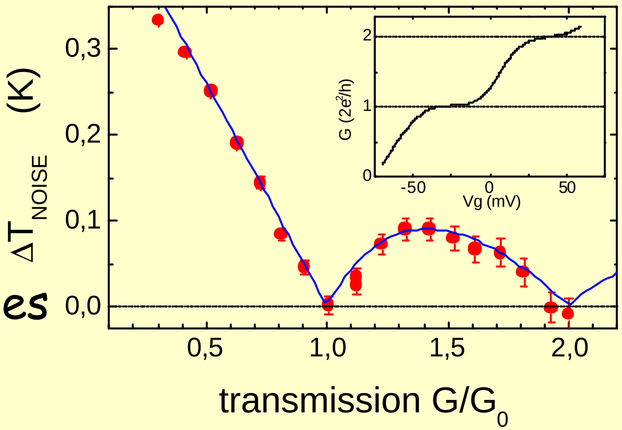
→ quantitative test of quantum scattering model of photo-assisted shot noise

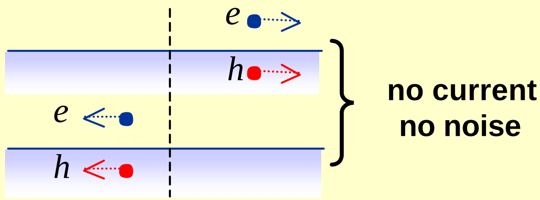
CONCLUSION

partition noise of photo-created Electron-hole pairs
(non-transport Shot Noise)

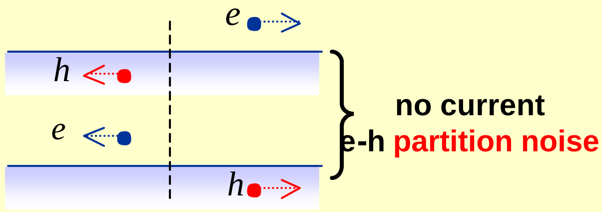
the Fano factor has been accurately measured

radiofrequency provide a new way to probe q-particles without necessary transport





at finite dc voltage and under various transmissions and r-f powers we have made an accurate test of the photon-assisted shot noise scattering theory



Reydellet et al. Phys. Rev. Lett. 90, 176803 (2003)