Strong back-action of a linear circuit on a single electronic quantum channel

F. PIERRE

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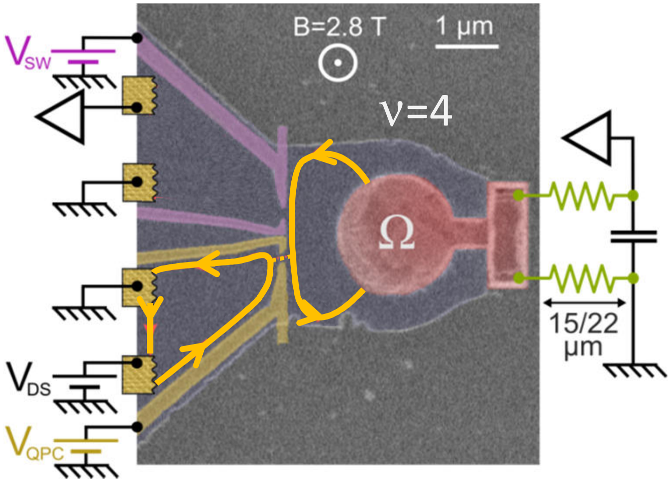

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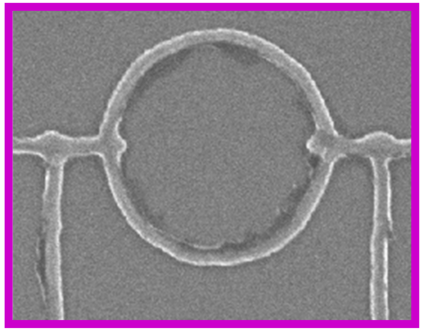
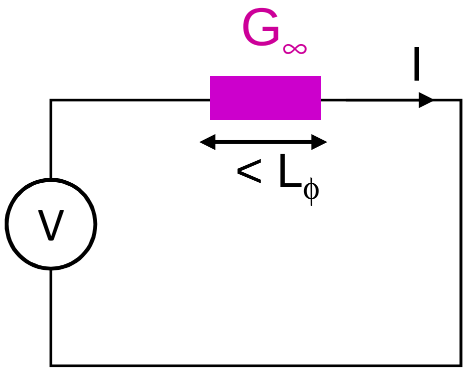
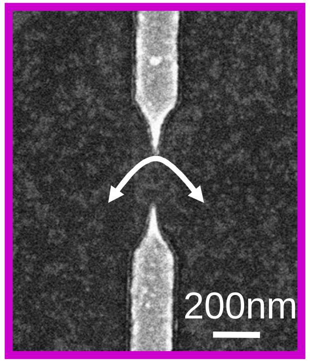
Problematic : quantum laws of electricity?

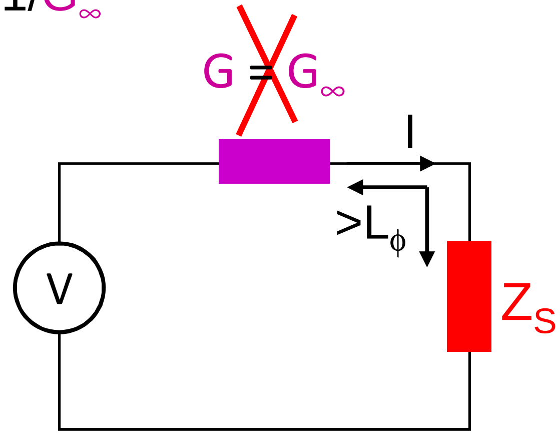
e.g. impedance composition with distinct coherent conductors





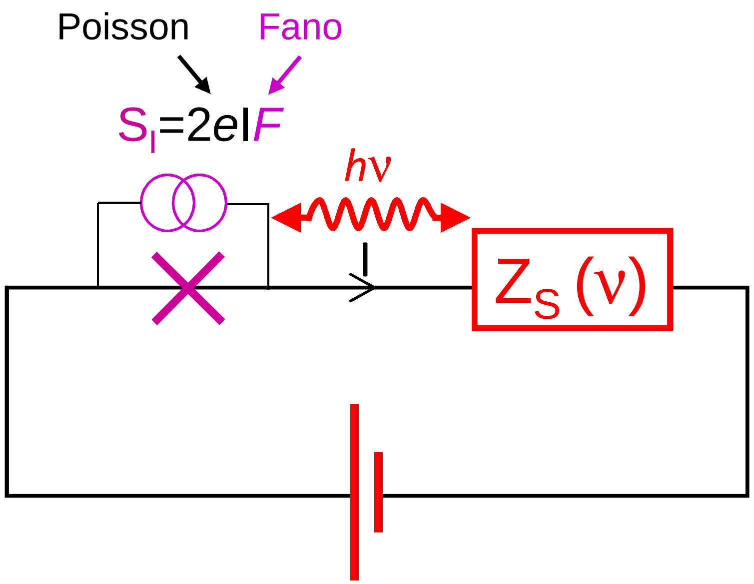
$V / I = 1/G_\infty$





$V / I = 1/G + Z_S$

Circuit back-action

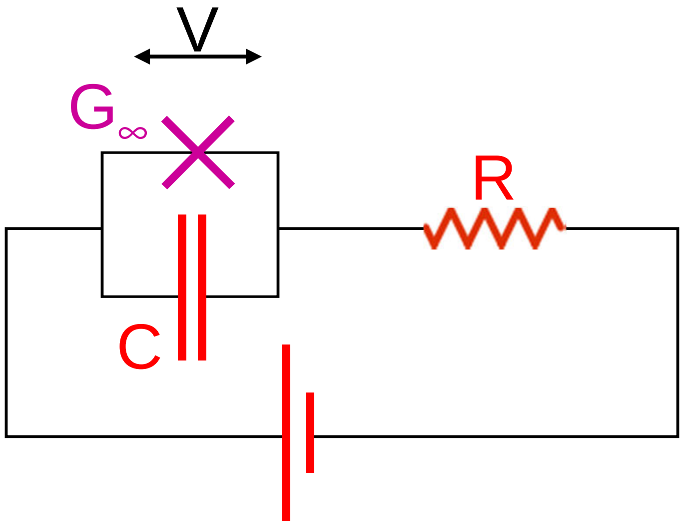


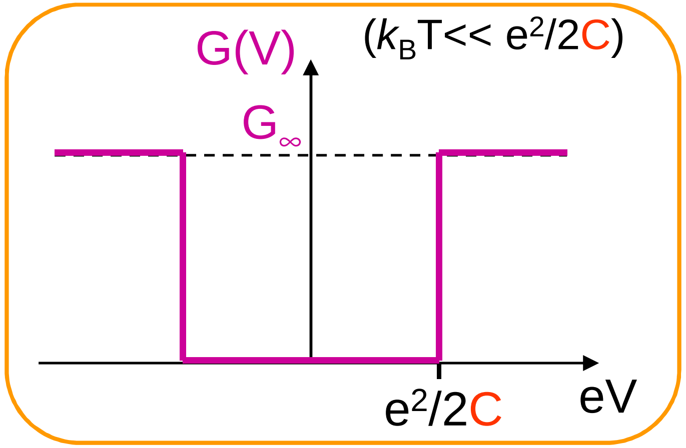
Granularity of charge transfers S_I ➡ Excitation of the circuit's EM modes

➡ Reduction of the conductance G
(dynamical Coulomb blockade)

Tunnel junction in a very resistive circuit

The ‘static’ Coulomb blockade limit





Charge dynamics ignored if:

$$E_C = e^2/2C >> \Delta E \approx h/RC$$

$$\Longleftrightarrow$$

$$R, 1/G_\infty >> R_K = h/e^2 \approx 25.8\mathrm{k}\Omega$$

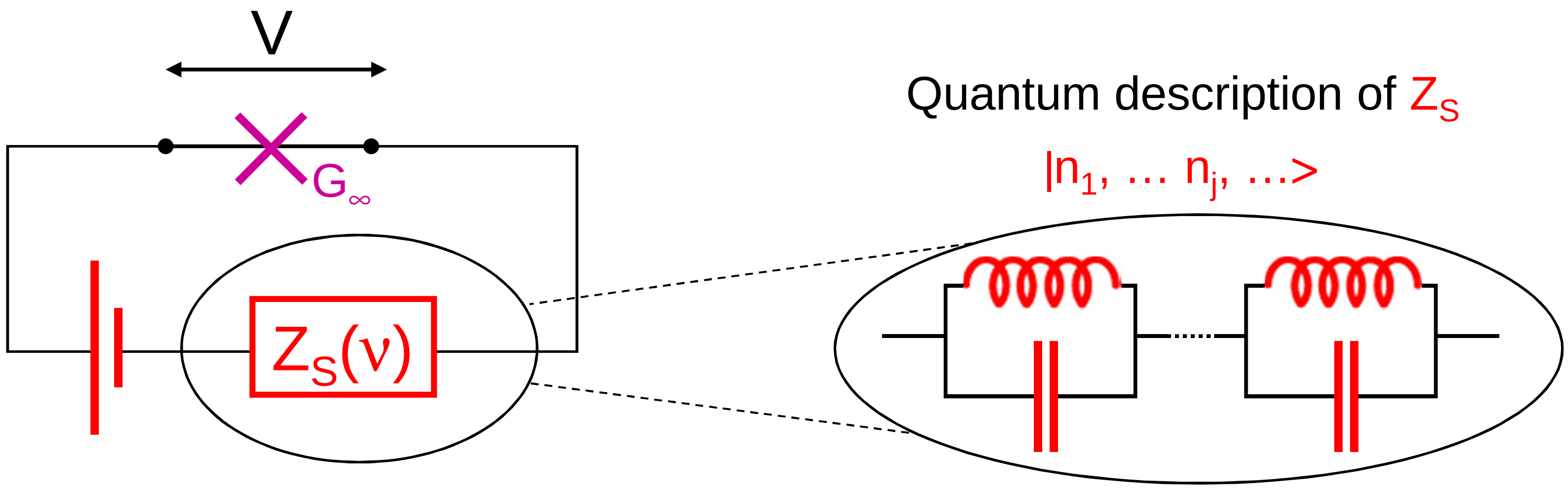
➡

$E_C = e^2/2C$ has to be paid for each tunnel event

➡

$$\boxed{G(V < e/2C) = 0}$$

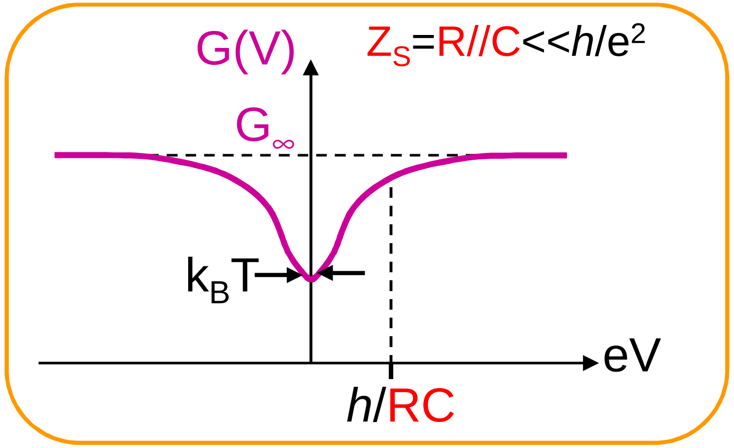
Tunnel junction in an arbitrary linear circuit



Quantum description of Z_S

$|n_1, \dots n_j, \dots>$

Caldeira & Leggett



(T=0K)

$$P(\varepsilon)=\sum_{\varepsilon=\sum n_i h\nu_i}\left|<n_1, \dots n_j, \dots|T_e|0,\dots,0>\right|^2$$

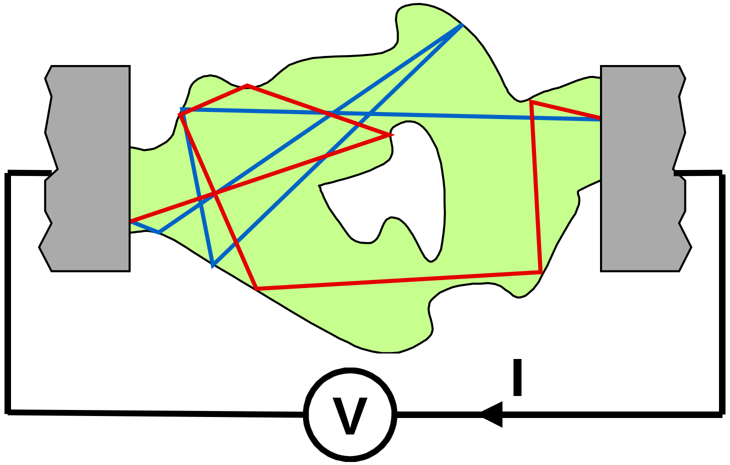
$\Downarrow$ $Z_S<<h/e^2$

$$P(\varepsilon) \approx 2\,\theta(\varepsilon)\,\frac{\mathrm{Re}\,Z_S(\varepsilon/h)}{\varepsilon R_K}$$

See Ingold & Nazarov in "Single Charge Tunneling" (Ed. Grabert & Devoret, 1992)

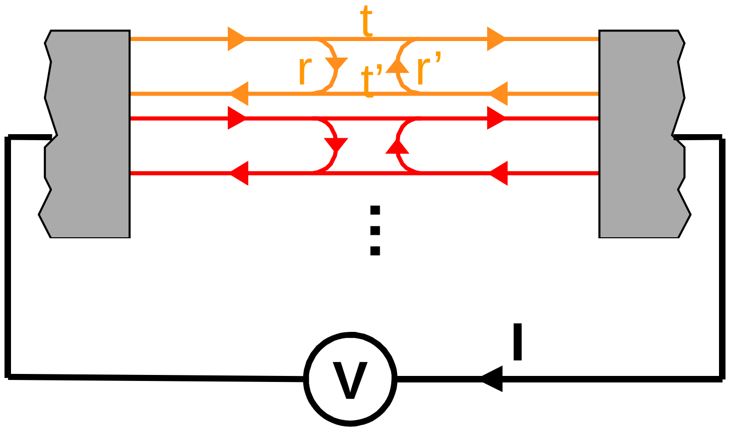
Scattering matrix description of a coherent conductor

coherent conductor



Landauer,
Büttiker,
Martin

set of independent conduction channels



MESOSCOPIC CODE: $\{\tau_i\}$

$$G_\infty = \frac{2e^2}{h}\sum_{i=1}^{N}\tau_i$$

Landauer formulae

$$S_I = 2eI\boxed{\sum_{i=1}^{N}\tau_i(1-\tau_i)\Big/\sum_{i=1}^{N}\tau_i}$$

Fano factor

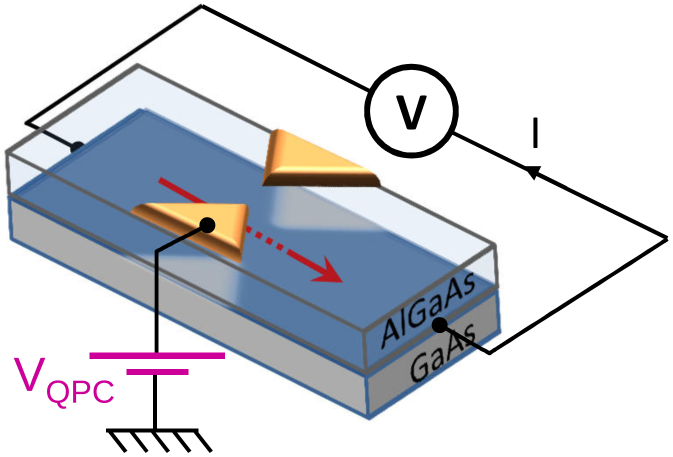
FCS

<u>tunnel junction</u> (τ_i<<1): $S_I \cong 2eI$

<u>single channel</u>: $G_\infty = \frac{2e^2}{h}\tau,\quad S_I = 2eI(1-\tau)$

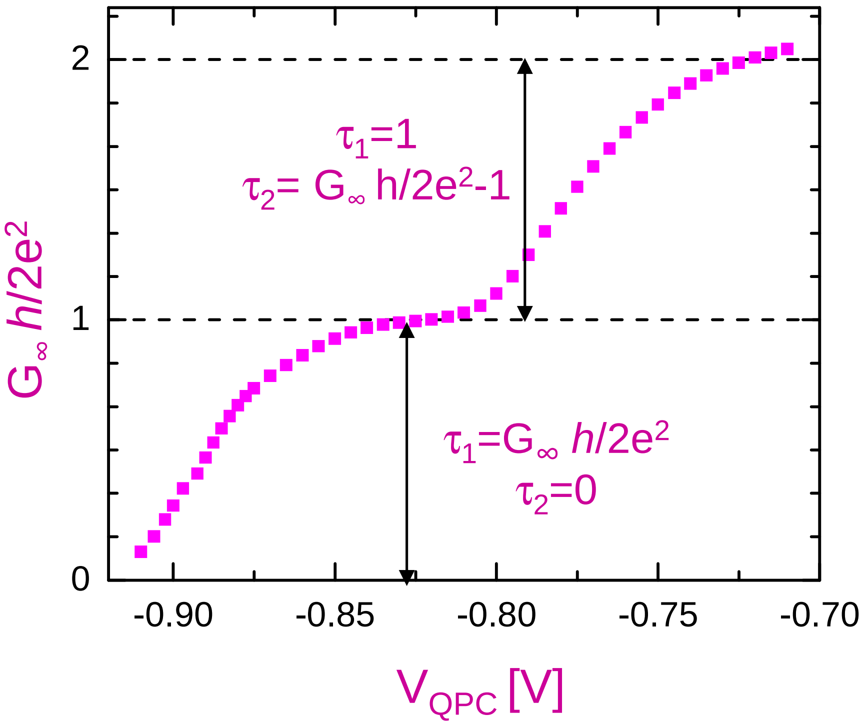
Quantum Point Contact in a 2DEG

A test-bed for coherent conductors

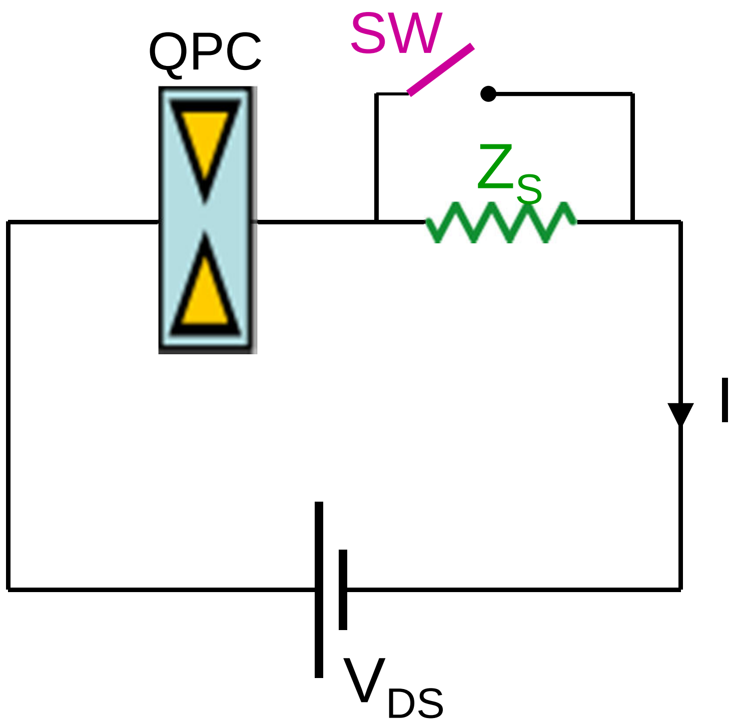


$$G=\frac{2e^2}{h}\sum\tau_i=\frac{2e^2}{h}(N\text{-}1+\tau_N)$$

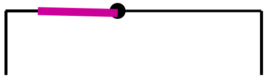
$\tau_i=1$ except $0<\tau_N<1$ for the last channel



Principle of the experiment



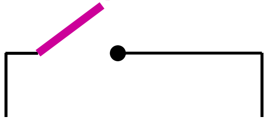
1) SW closed



: no back-action ⟶ G_∞

➡ Tune & measure ‘intrinsic’ $\{\tau_i\}$

2) SW open



: back-action ⟶ G_{QPC}

➡ Measure back-action signal
at V≈0 for the same ‘intrinsic’ $\{\tau_i\}$

back-action signal ≡
relative conductance reduction:

$$\frac{\delta G}{G_\infty} = \frac{G_{QPC} - G_\infty}{G_\infty}$$

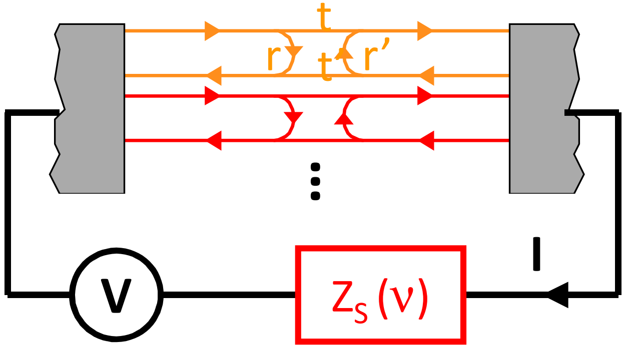
Coherent conductor in a linear circuit

Theoretical challenge: coherent conductor ≠ small perturbation

Milestone: weak back-action in a low impedance circuit

A. Levy Yeyati, A. Martin-Rodero, D. Esteve & C. Urbina, PRL **87**, 46802 (2001)

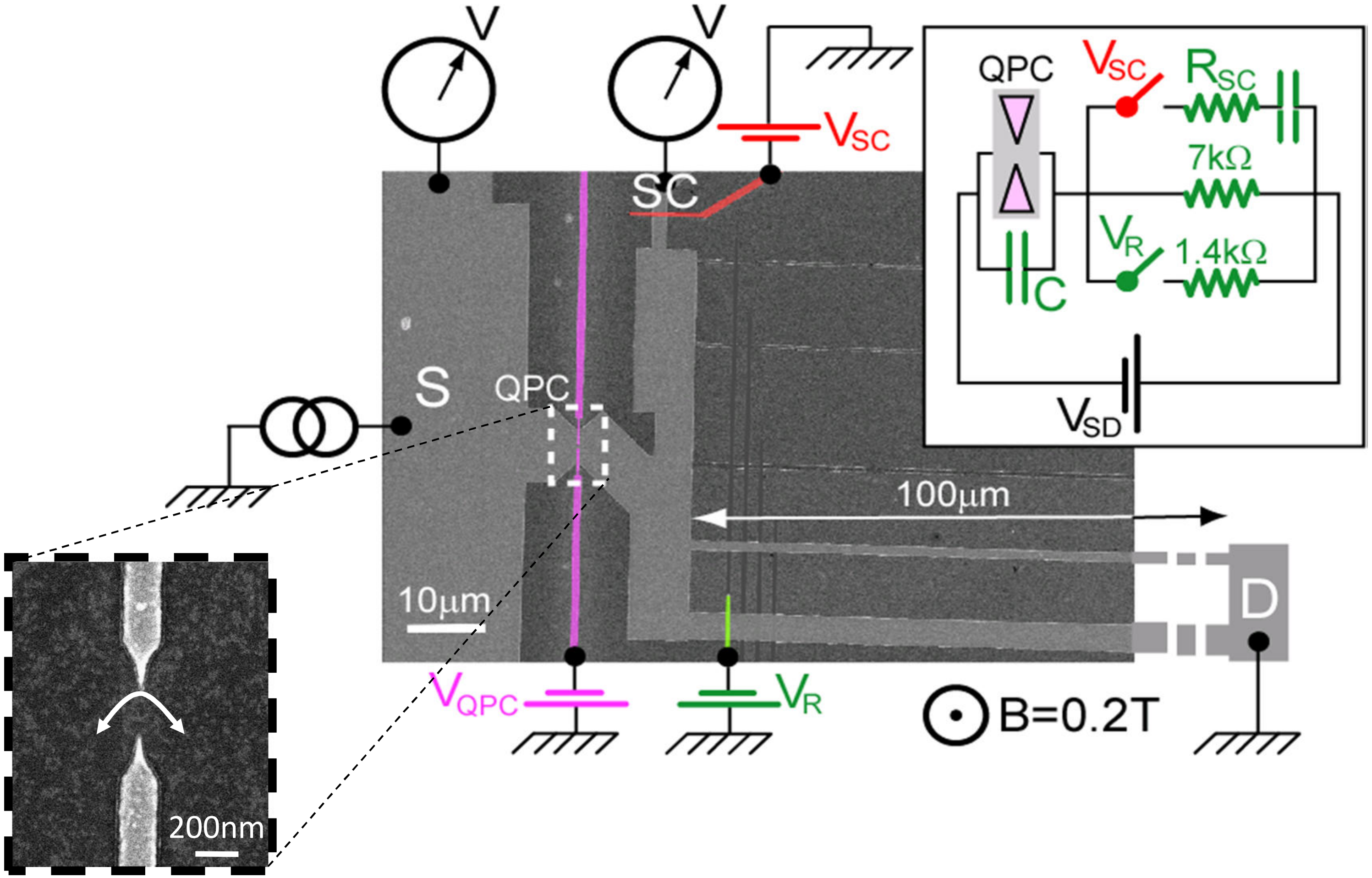
D.S. Golubev & A.D. Zaikin, PRL **86**, 4887 (2001)



- $Z_S << R_K = h/e^2 \approx 25.8$ kΩ
- weak back-action (small corrections)
- short coherent conductor

Same energy dependence as for tunnel junctions
BUT
Renormalized in amplitude by the same Fano factor as shot noise

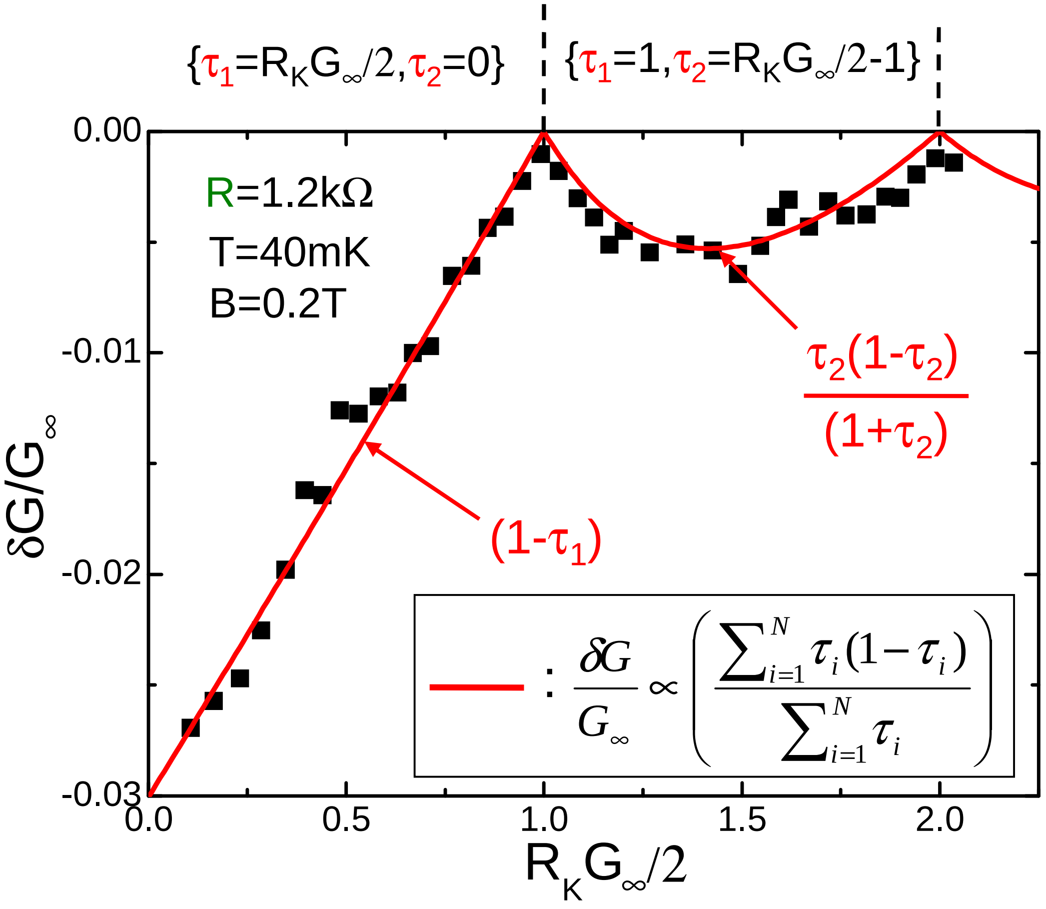
Experimental implementation



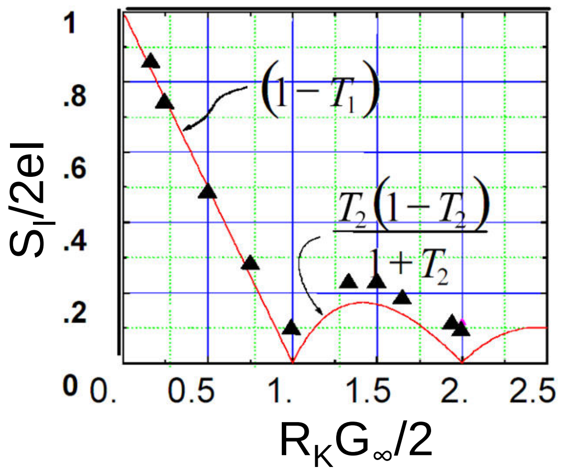
2DEG in GaAs/Ga(Al)As, n_S=2.5 $10^{15}$$m^{-2}$, µ=55$m^2V^{-1}s^{-1}$

Altimiras, Gennser, Cavanna, Mailly & Pierre, PRL **99**, 256805 (2007)

Exp^{tal} test of the weak-back action predictions



shot noise across a coherent conductor



Kumar, Saminadayar, Glattli, Jin & Etienne, PRL **76**, 2778 (1996)

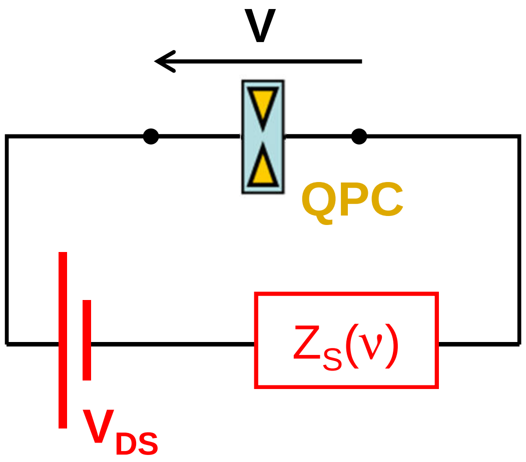
Quantitative agreement data/thy:

back-action signal ∝ ‘intrinsic’ Fano factor

Altimiras, Gennser, Cavanna, Mailly & Pierre, PRL **99**, 256805 (2007)

For the reduction of the back-action signal at τ~1, see also: Cron *et al.*, XXXVIth Moriond proceedings (2001)

Strong back-action of a linear circuit: theory



Problem unsolved in g^{al} BUT
important advances for $Z_S(\nu)=R$

$\delta G/G_\infty \cancel{\ll} 1$

DCB corrections linked to
noise in presence of back-action

$Z_S(\nu)=R$, 1 channel, T=0 [1] →

$$\frac{\partial G_{QPC}}{\partial \ln V_{DS}} = \frac{2R}{eR_K}\frac{\partial S_I}{\partial V_{DS}}$$

$Z_S(\nu)=R \ll R_K$, T=0 [1-3]

$Z_S(\nu)=R_K$, 1 channel, T=0 [1] →

$$\frac{\partial G_{QPC}}{\partial \ln V} = \frac{2R}{R_K} G_{QPC}(1 - R_K G_{QPC})$$

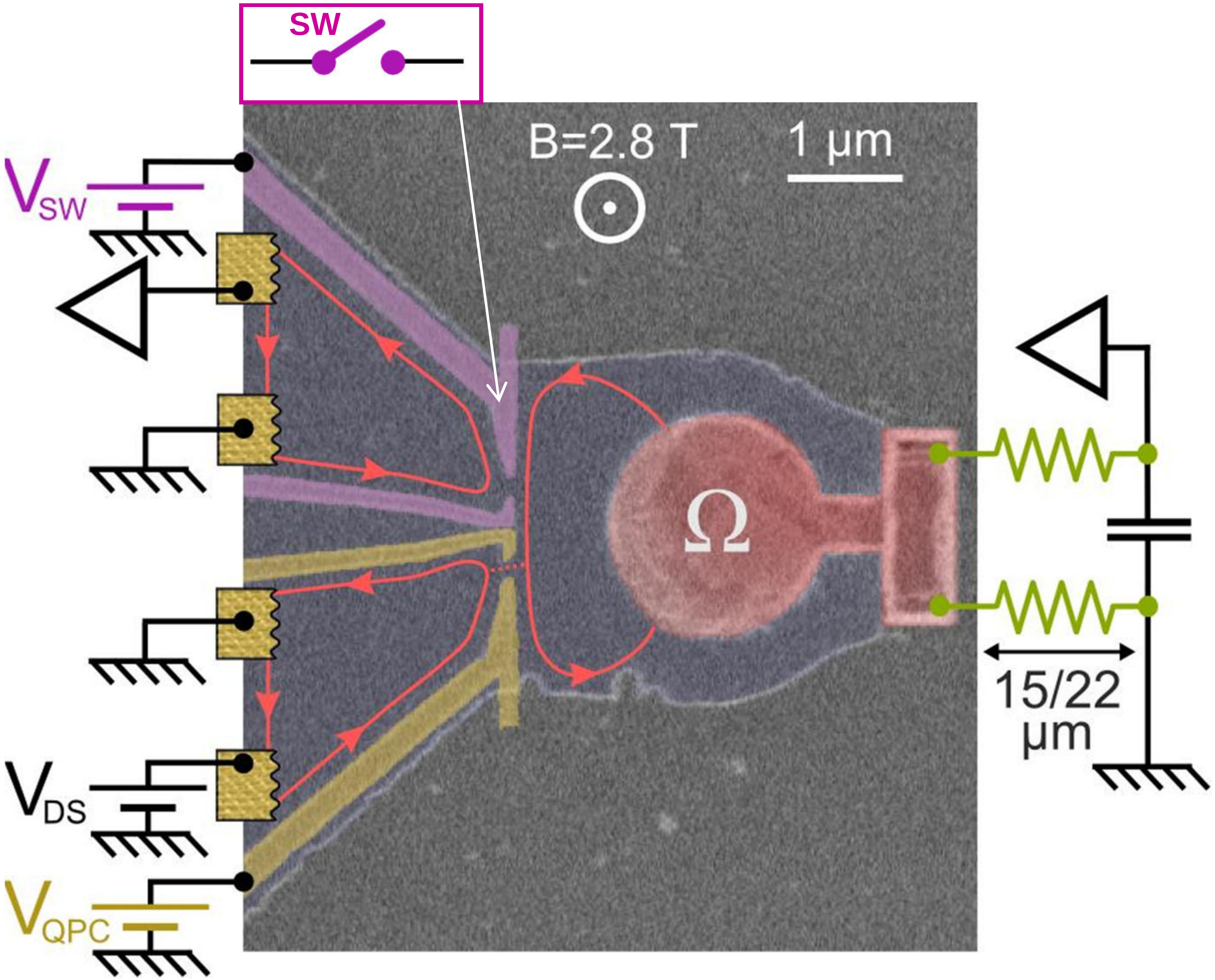
[1] Safi & Saleur, PRL **93**, 126602 (2004)

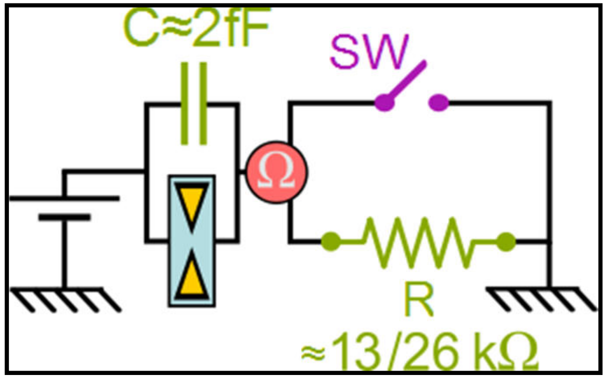
[2] Kindermann & Nazarov, PRL **91**, 136802 (2003)

[3] Golubev, Galaktionov & Zaikin, PRB **72**, 205417 (2005)

Experimental implementation

strong back-action regime

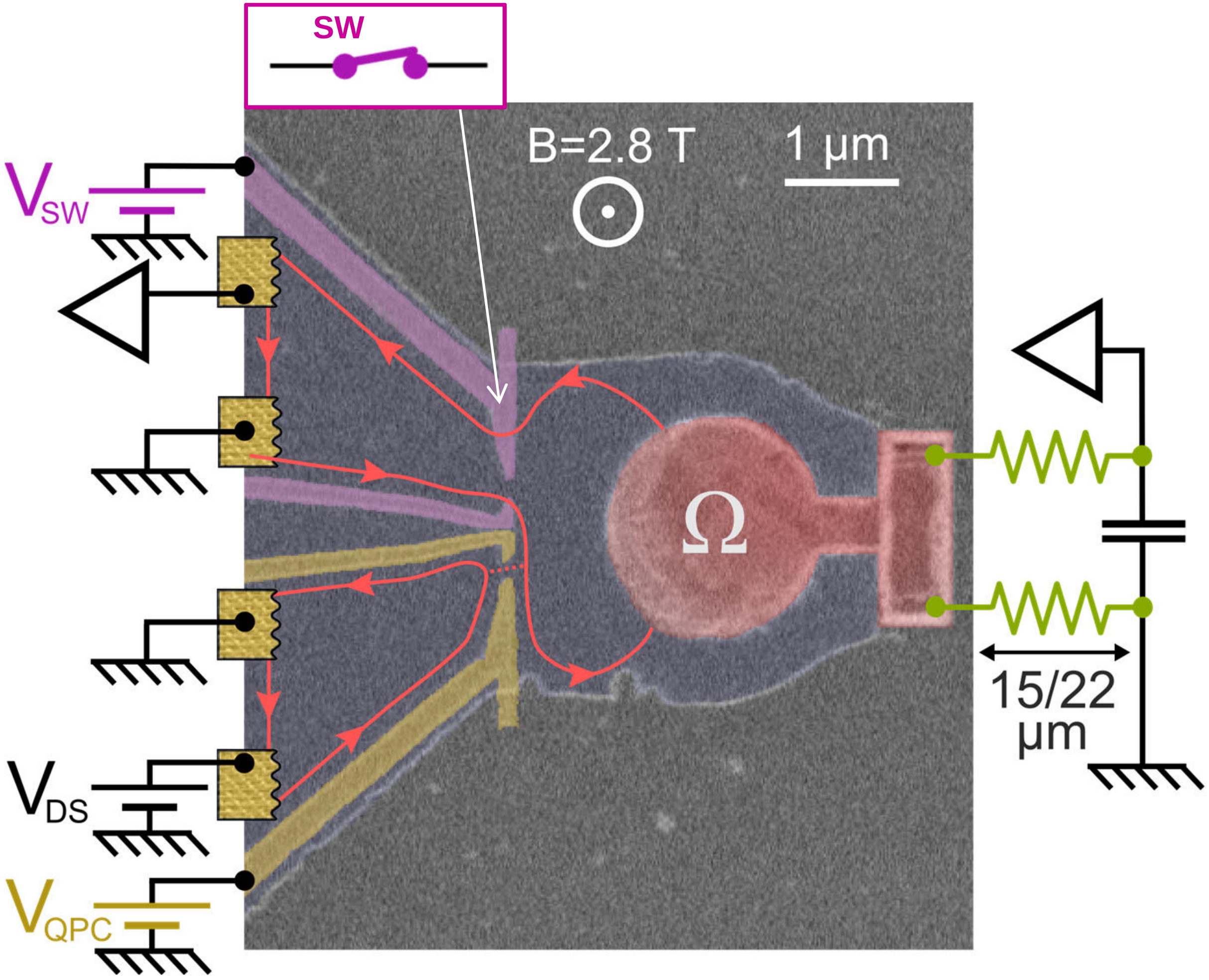


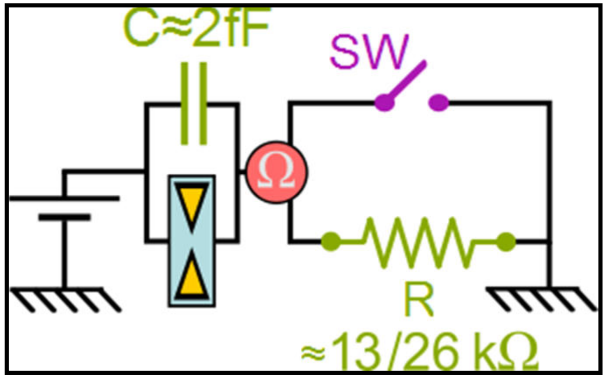


2DEG dans GaAs/Ga(Al)As, n_S=2.5 $10^{15}m^{-2}$, µ=55$m^2V^{-1}s^{-1}$

Experimental implementation

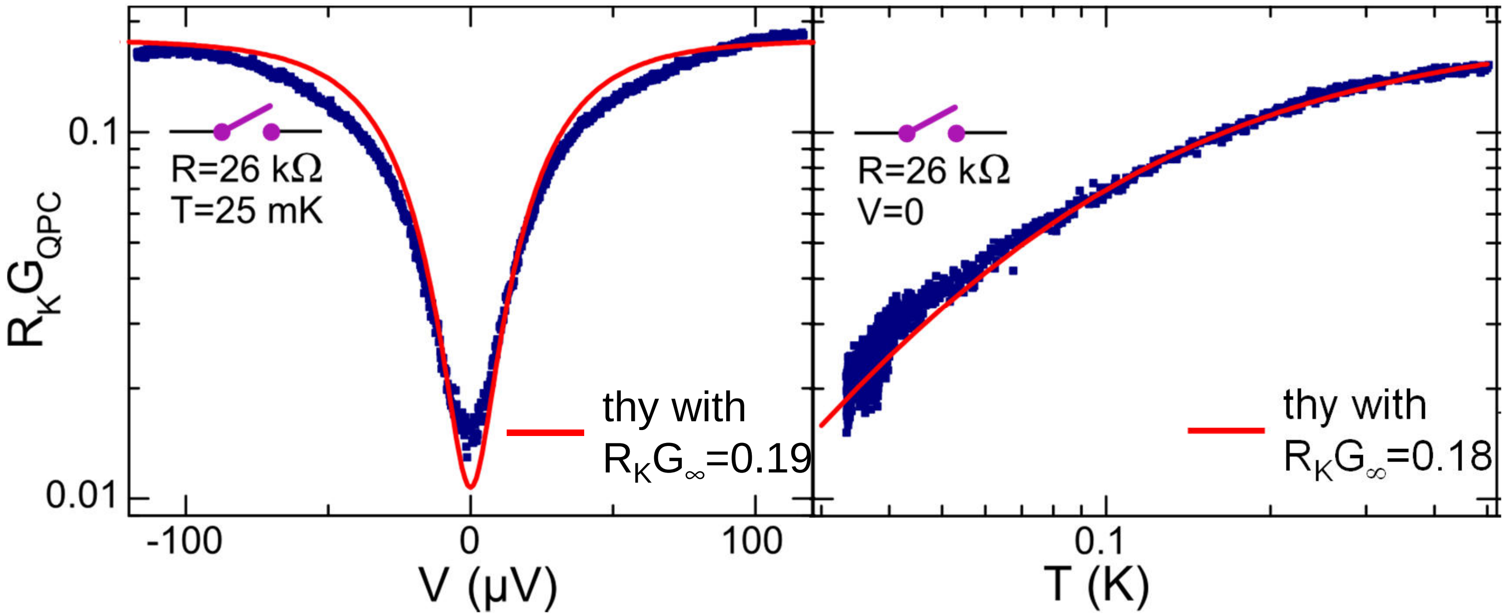
strong back-action regime

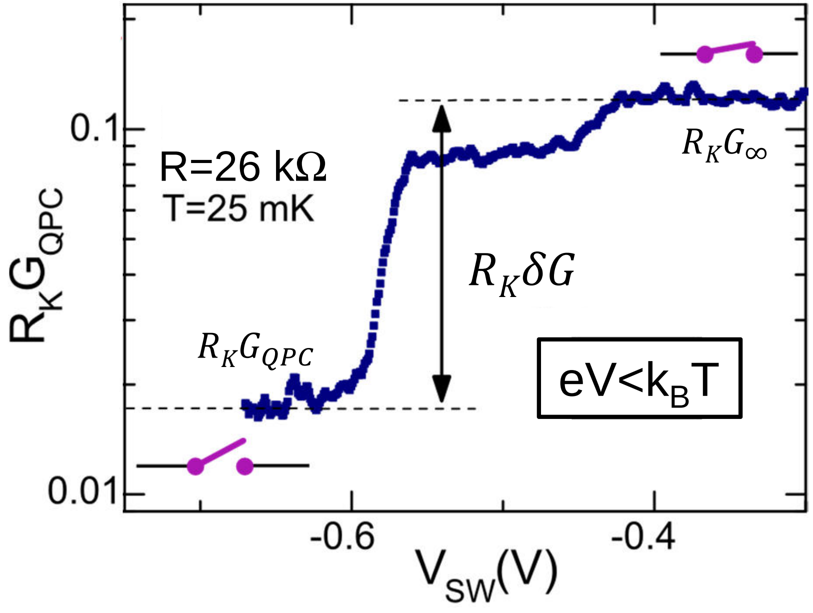




2DEG dans GaAs/Ga(Al)As, $n_S=2.5\ 10^{15}m^{-2}$, $\mu=55m^2V^{-1}s^{-1}$

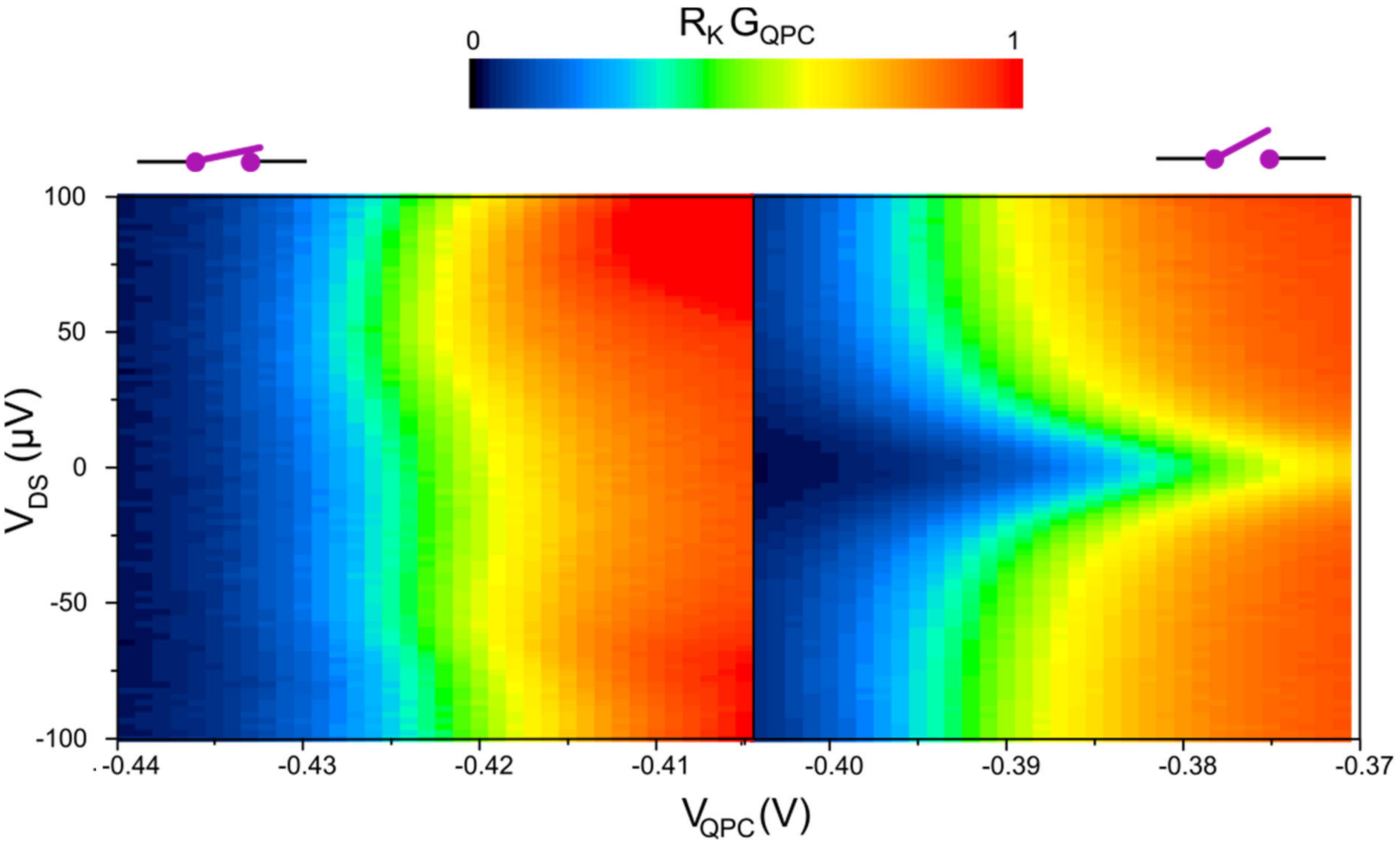
Back-action signal in the known tunnel regime



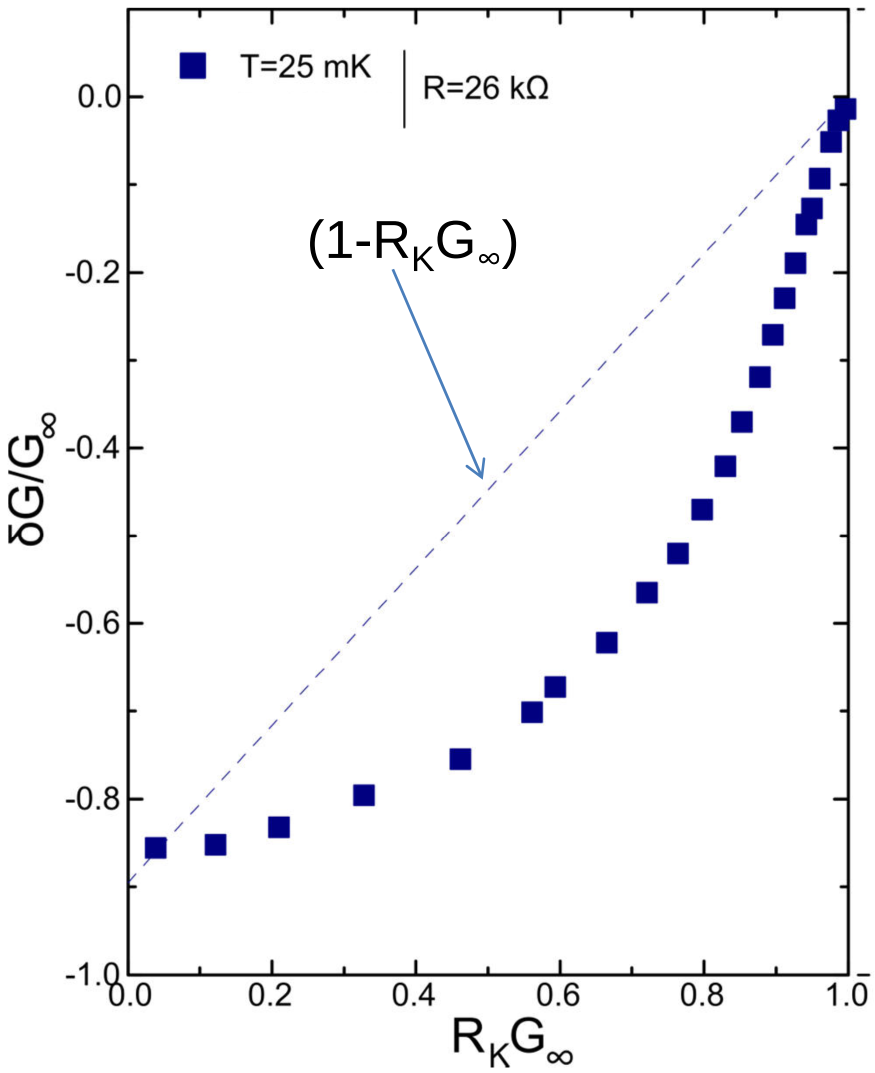


- Strong back-action (~ 90% red.)
- Expected EM environment
- Agreement between methods

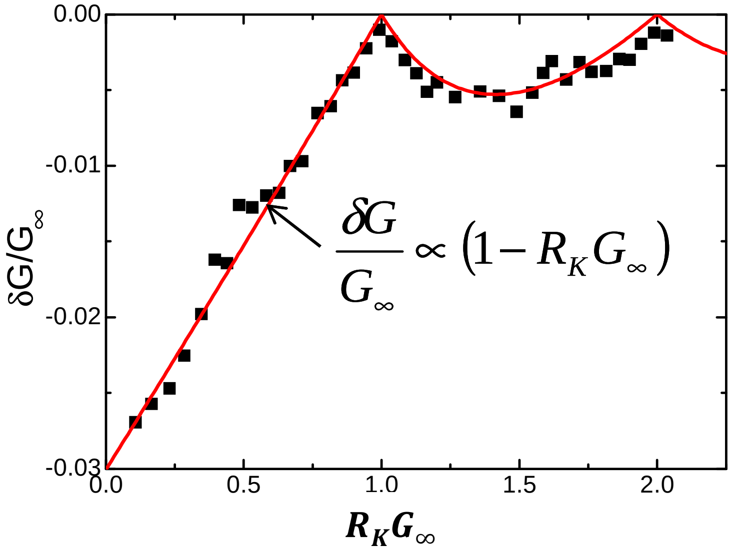
Further check of the environment switch



Back-action signal vs ‘intrinsic’ transmission

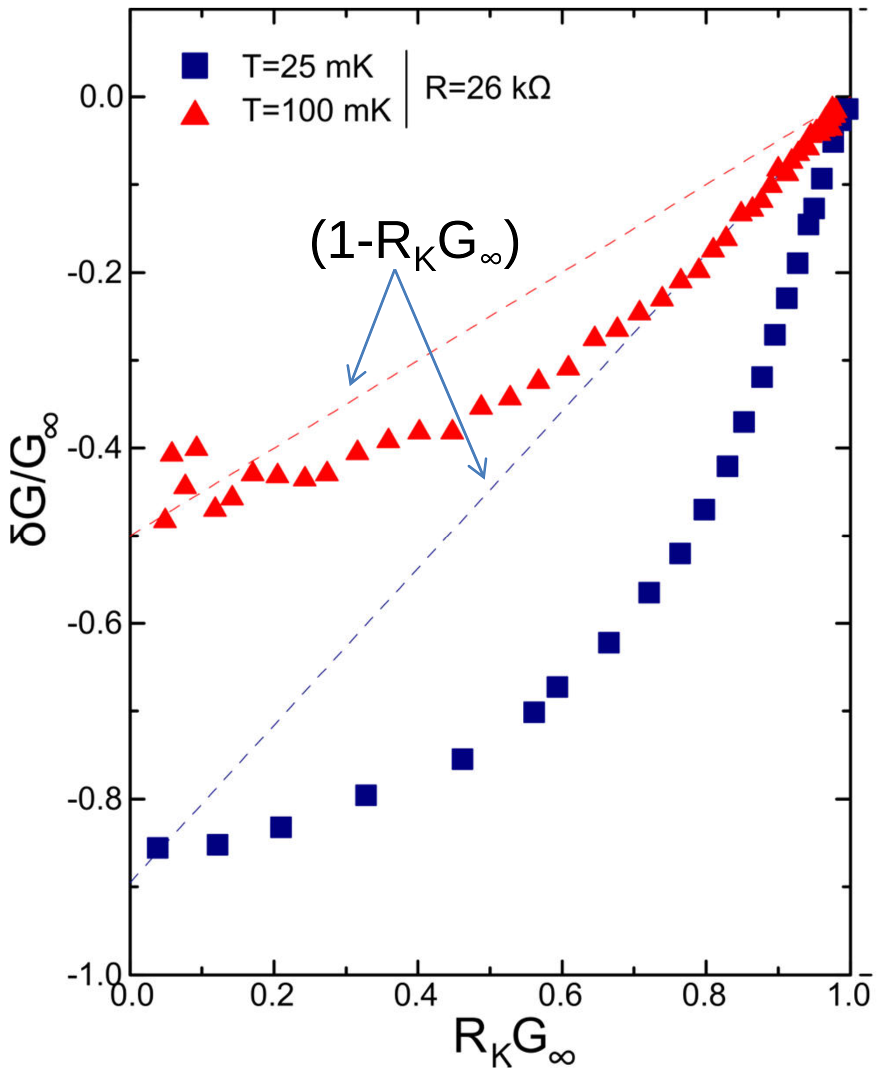


Altimiras *et al.,* 2007

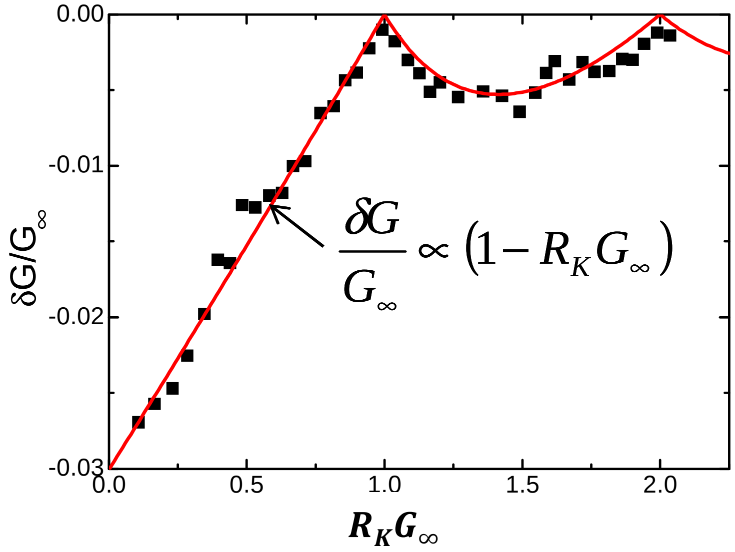


$$\frac{\delta G}{G_\infty} \propto \left(1 - R_K G_\infty\right)$$

Back-action signal vs ‘intrinsic’ transmission

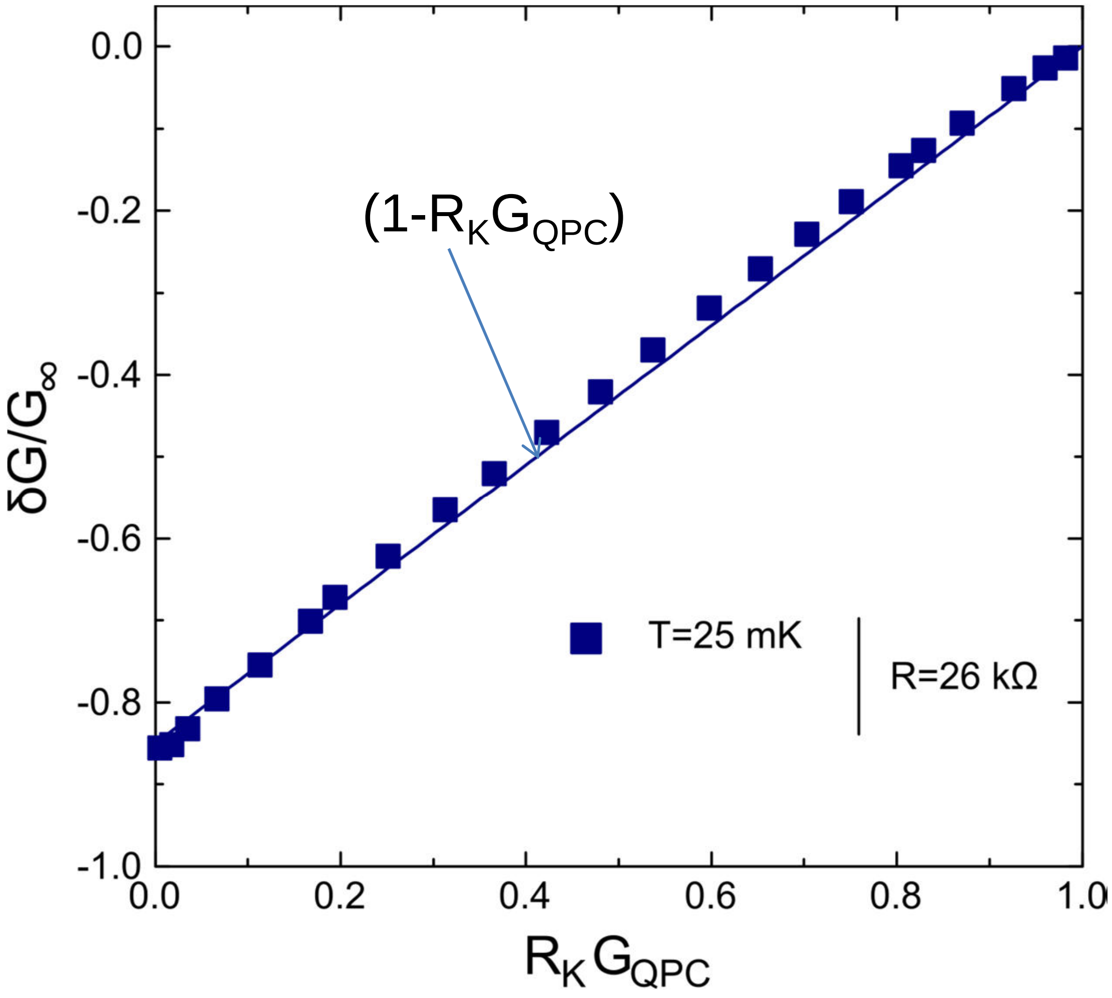


Altimiras *et al.*, 2007

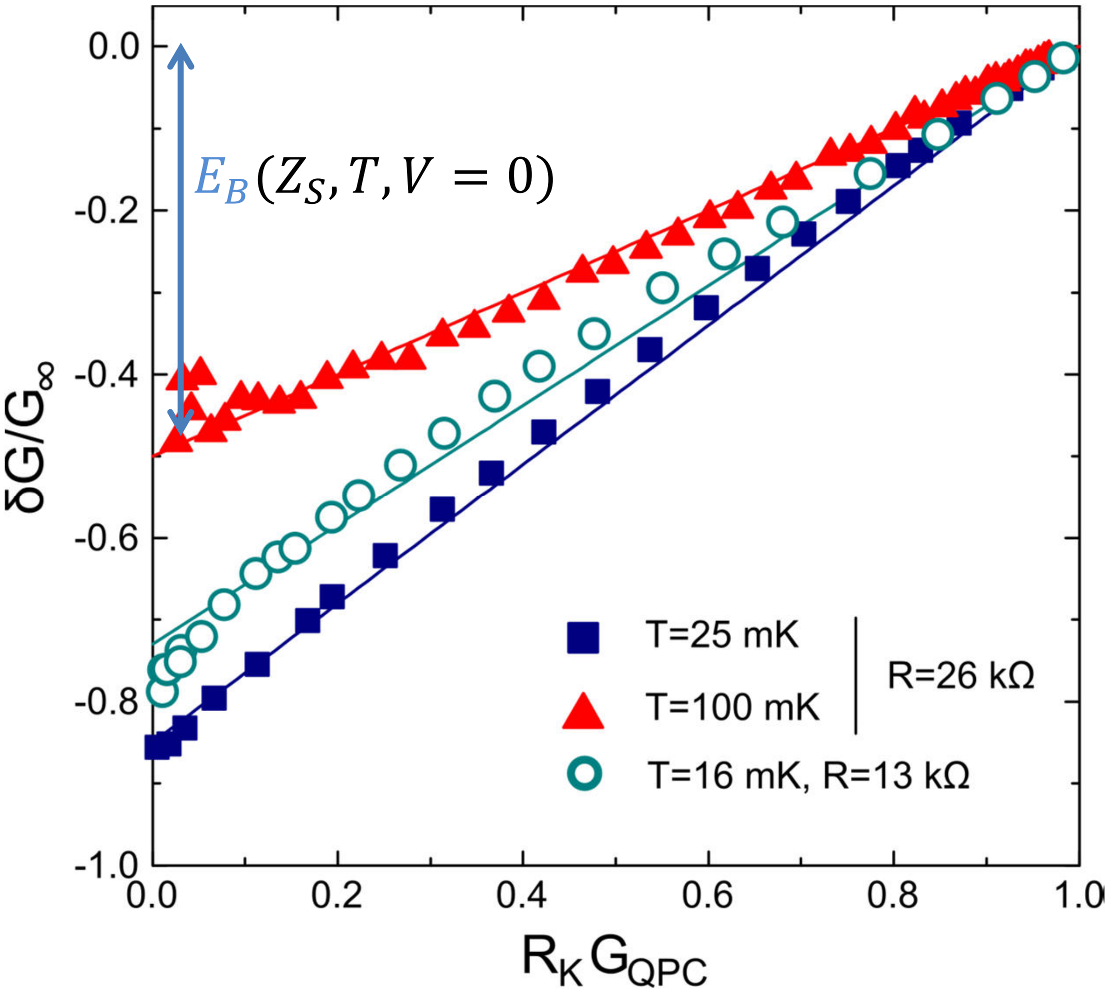


$$\frac{\delta G}{G_\infty} \propto (1 - R_K G_\infty)$$

Back-action signal vs ‘reduced’ transmission



Back-action signal vs ‘reduced’ transmission



Exp^{tal} finding:

$$\frac{\delta G}{G_\infty} \equiv \frac{G_{QPC} - G_\infty}{G_\infty}$$
$$\cong E_B(Z_S, T, V = 0) \times \left(1 - R_K G_{QPC}\right)$$

Proposed generalized expression

For a single electronic channel in an arbitrary linear environment

Hyp: Exp^tal finding valid for all Z_S, T & V

$$\frac{G_{QPC} - G_\infty}{G_\infty} = E_B(Z_S, T, V) \times \left(1 - R_K G_{QPC}\right)$$

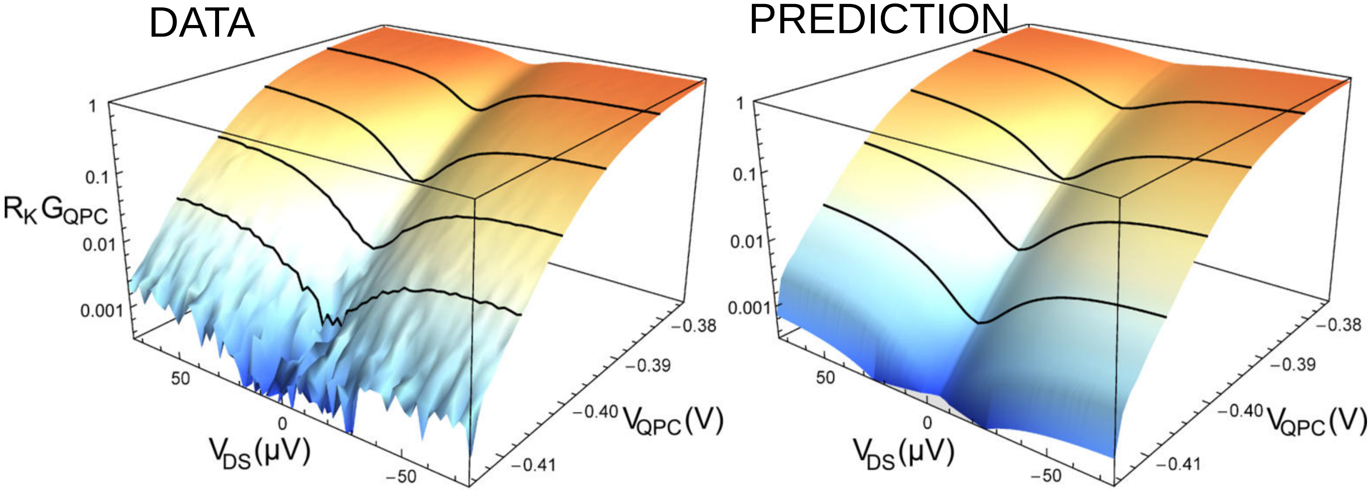
↖ Back-action signal for a tunnel junction
(can be calculated from *Ingold & Nazarov, 1992*)

$$\boxed{G_{QPC}(Z_S, T, V) = G_\infty \frac{1 + E_B(Z_S, T, V)}{1 + R_K G_\infty E_B(Z_S, T, V)}}$$

Finite bias test:

R=26 kΩ

T=25 mK



Proposed expression vs recent predictions

$Z_S(\nu)=R \ll R_K$, T=0 [1-3]

$Z_S(\nu)=R_K$, 1 channel, T=0 [1]

$$\frac{\partial G_{QPC}}{\partial \ln V} = \frac{2R}{R_K} G_{QPC}\left(1 - R_K G_{QPC}\right)$$

$$G_{QPC}\left(V = \frac{E_C}{e}\right) = G_\infty$$

[1] Safi & Saleur, PRL **93**, 126602 (2004)
[2] Kindermann & Nazarov, PRL **91**, 136802 (2003)
[3] Golubev, Galaktionov & Zaikin, PRB **72**, 205417 (2005)

$$G_{QPC} = G_\infty \frac{1 + \left({}^{eV}\!/_{E_C}\right)^{2R/R_K}}{1 + R_K G_\infty\left(\left({}^{eV}\!/_{E_C}\right)^{2R/R_K} - 1\right)}$$

$\leftrightarrow$

<u>Proposed expr.:</u>

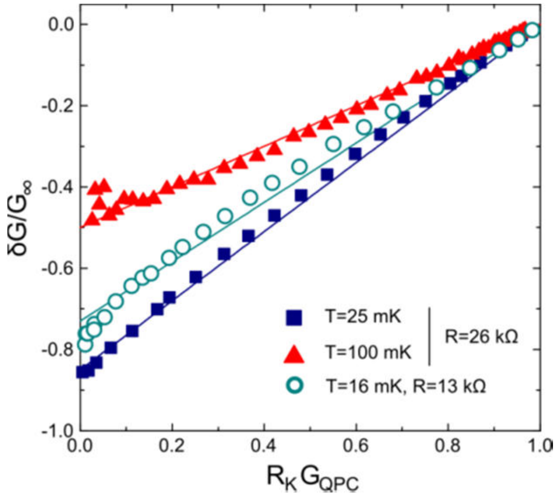
$$G_{QPC} = G_\infty \frac{1 + E_B}{1 + R_K G_\infty E_B}$$

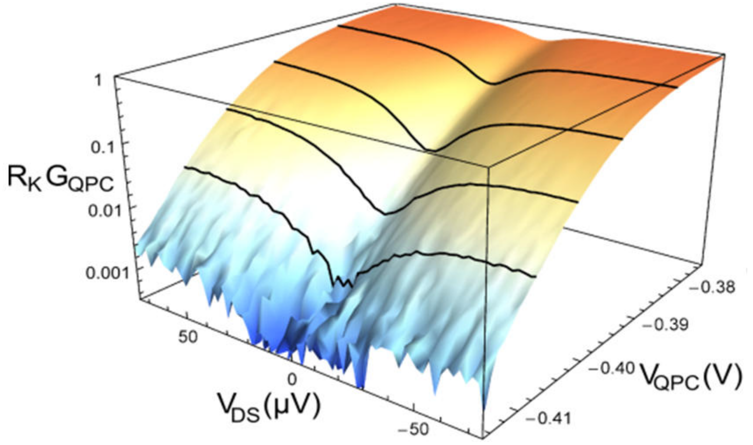
For a R//C environment at T=0:

$$E_B \cong \left({}^{eV}\!/_{E_C}\right)^{2R/R_K} - 1$$

SUMMARY

Experimental data…





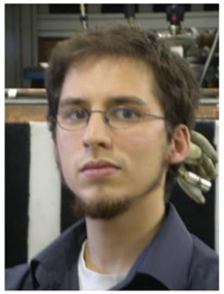
…suggest a generalized expression…

single channel in an arbitrary linear circuit

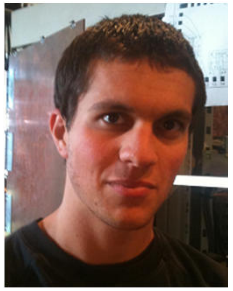
$$\boxed{G_{QPC}(Z_S,T,V) = G_\infty \frac{1+E_B(Z_S,T,V)}{1+R_K G_\infty E_B(Z_S,T,V)}}$$

…in good agreement with theoretical predictions in simplified frameworks !

Parmentier, Anthore, Jezouin, le Sueur, Gennser, Mailly & Pierre, Nature Phys. (advanced online publication)


François
Parmentier


Anne
Anthore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F. Lafont φ Nano Team

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