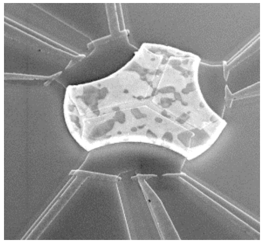
Dynamical Coulomb Blockade under a temperature bias



H. Duprez, E. Sivré, A. Anthore, A. Aassime, F.D. Parmentier,
U. Gennser, A. Cavanna, A. Ouerghi, Y. Jin, F. Pierre

I. Safi , C. Mora, E. Boulat

université PARIS-SACLAY

LPS ORSAY

C2N

cnrs

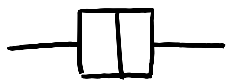
Université Paris Cité

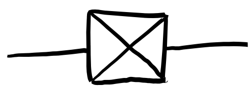
MPQ

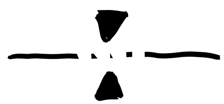
QPC team / PHYNANO group / C2N/ Palaiseau

Quantum transport in composite circuits

- Quantum conductors:

Tunnel junction 

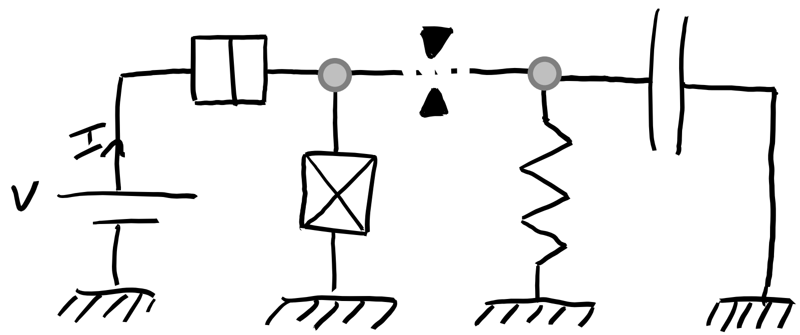
Josephson junction 

Quantum point contact 

Coherent diffusive metal

⋮

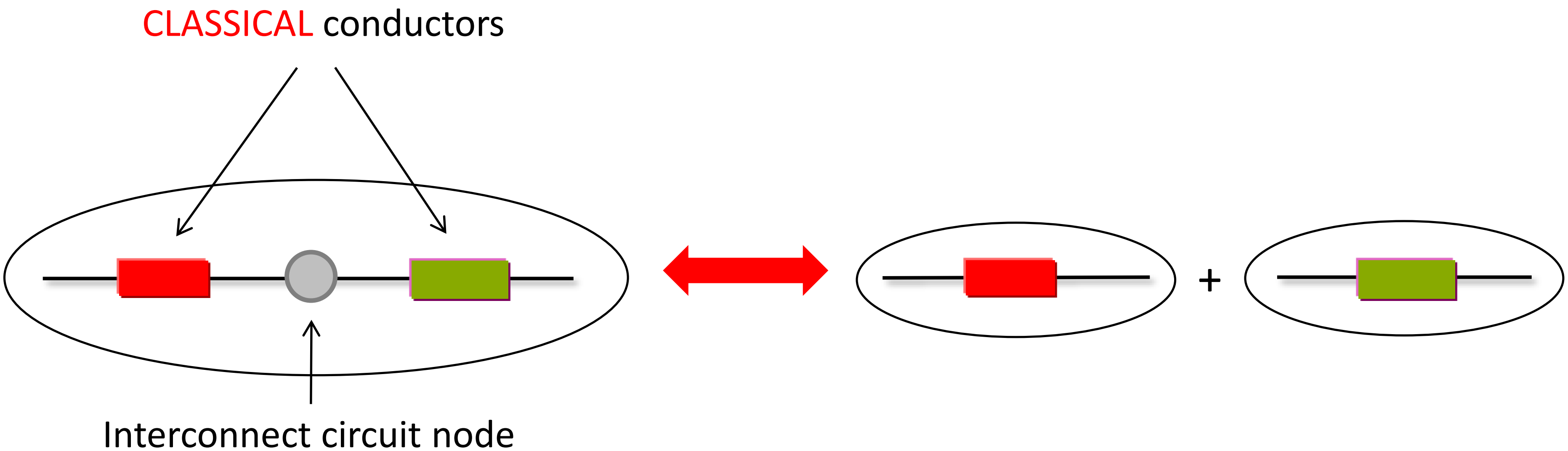
- Composite circuits:



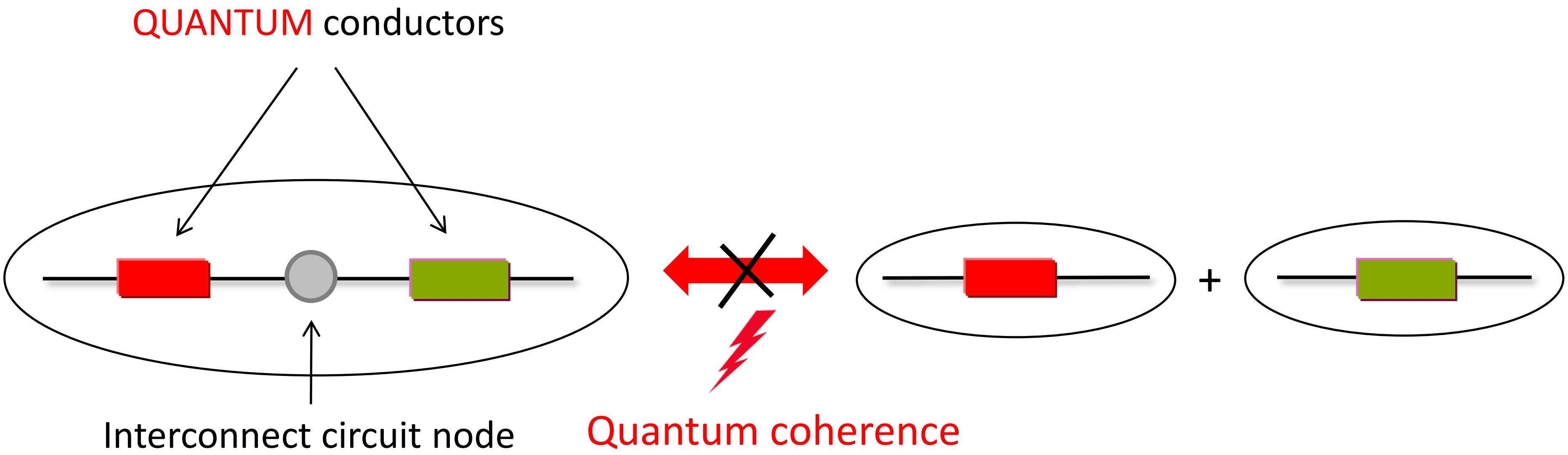
G^al problematic:

Individually well-understood $\xrightarrow{?}$ Assembled mesoscopic circuit

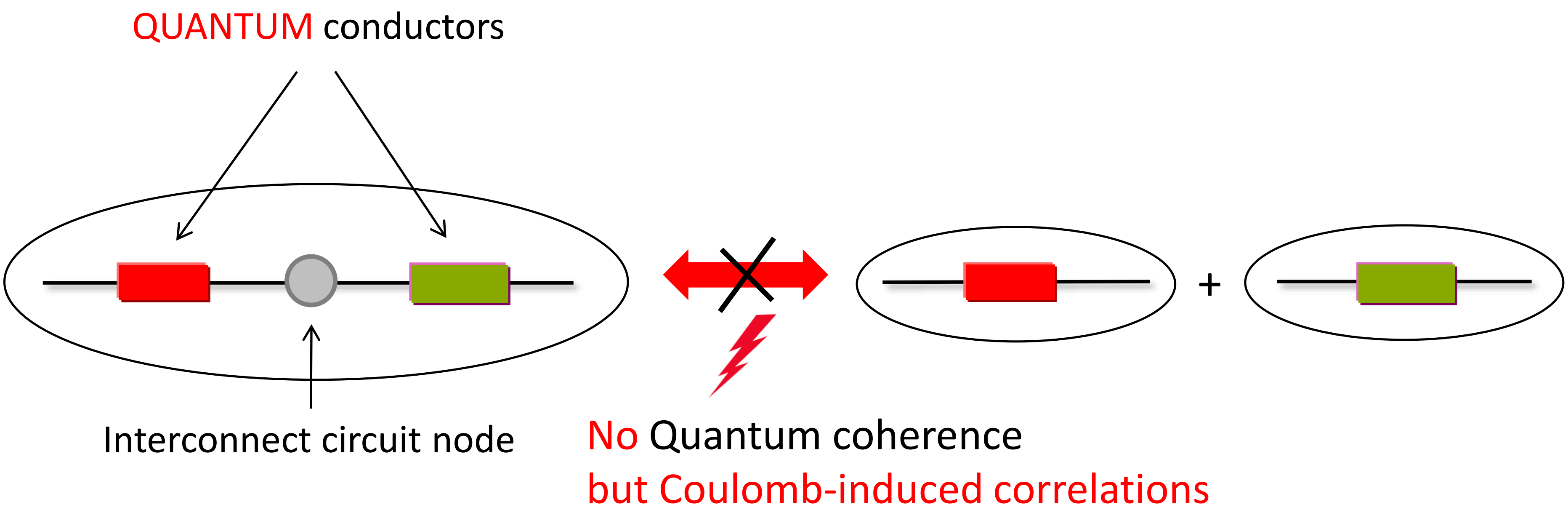
~~Quantum~~ Transport in composite circuits



Quantum transport in composite circuits

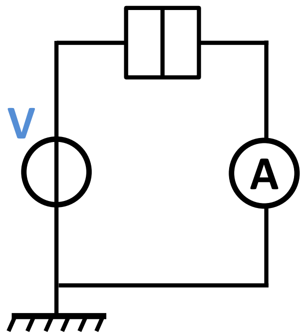


Quantum transport in composite circuits

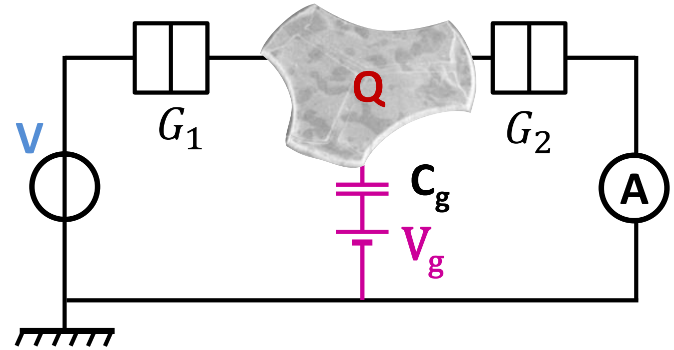


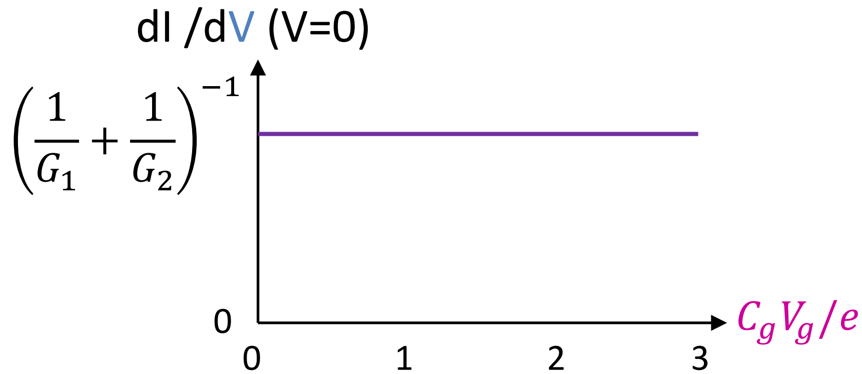
- Charge quantization in the node ⇒ Single-electron transistor (Coulomb blockade)

Single electron transistor, Coulomb blockade



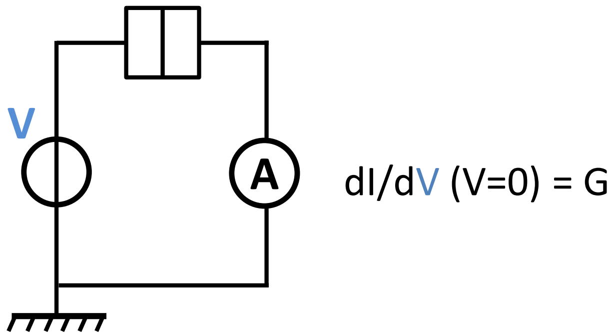
dI/dV (V=0) = G

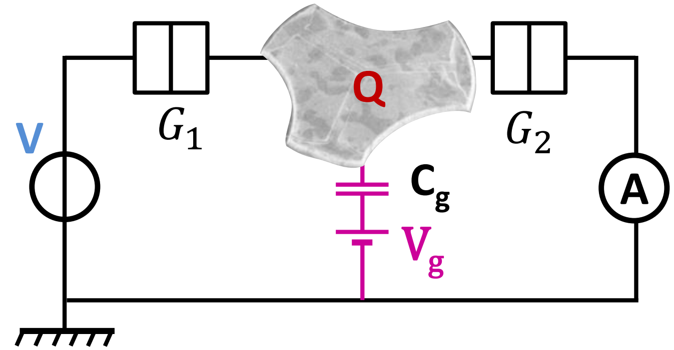


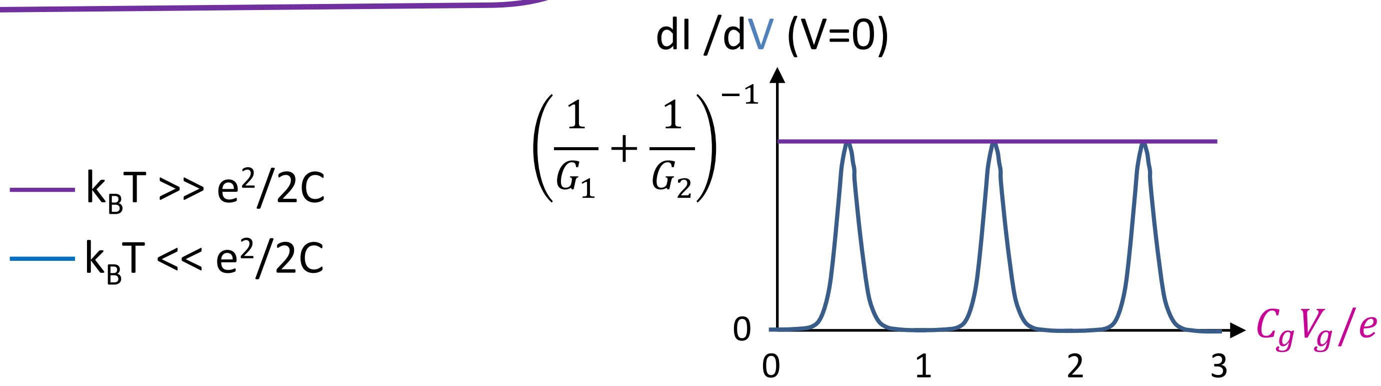


— $k_BT >> e^2/2C$

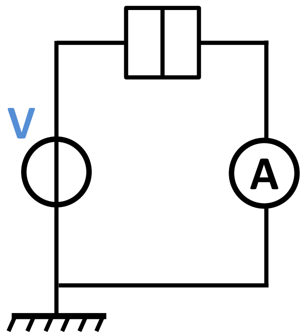
Single electron transistor, Coulomb blockade



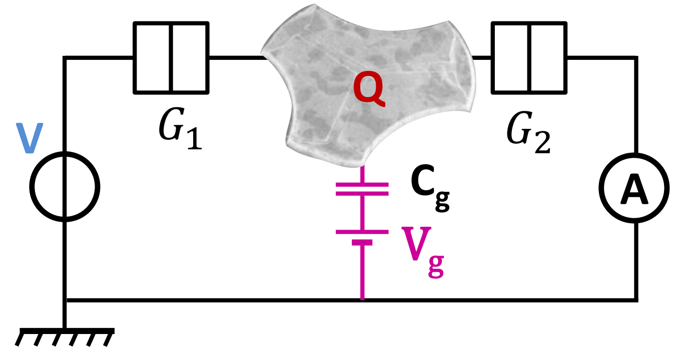


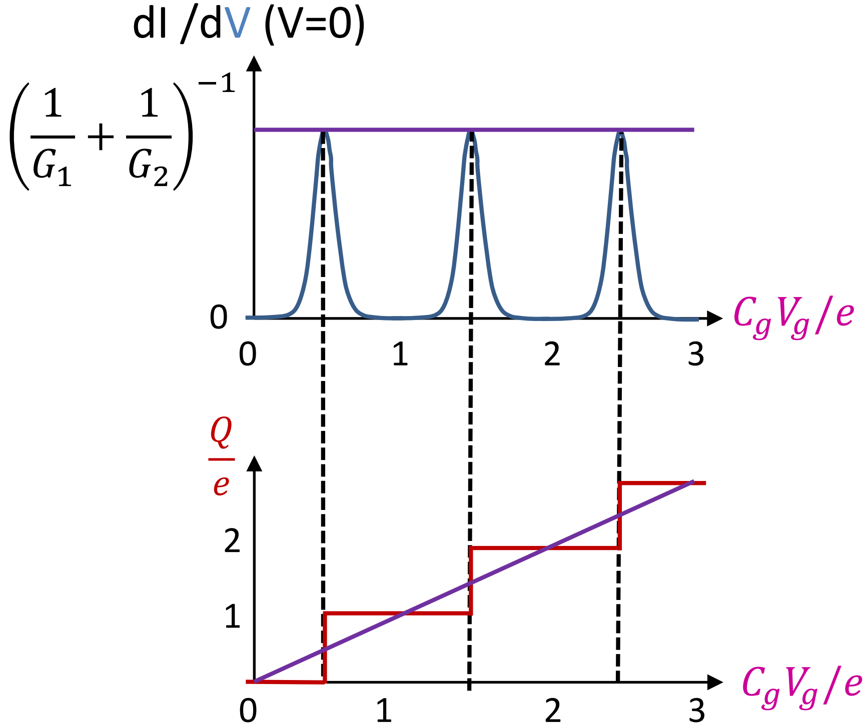


Single electron transistor, Coulomb blockade



dI/dV (V=0) = G

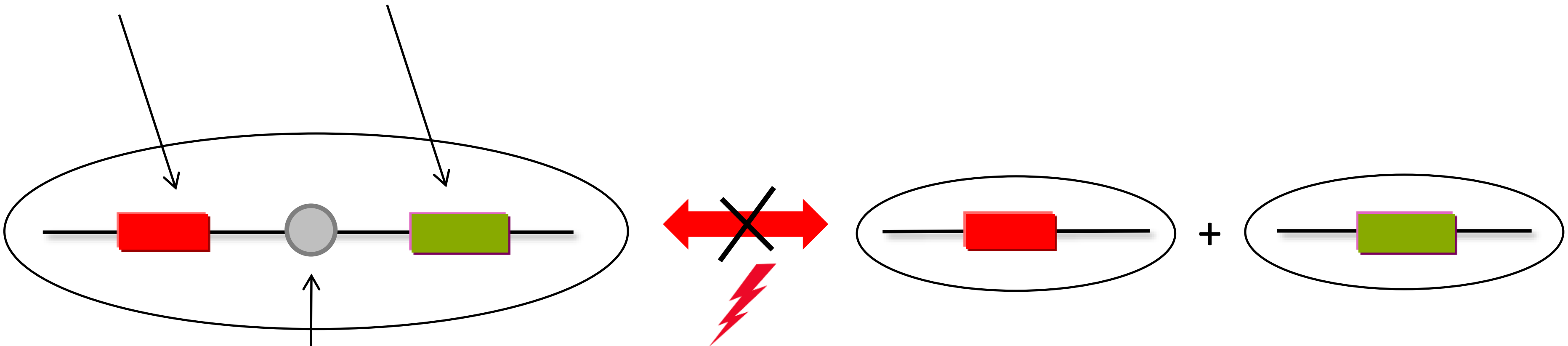




- $k_B T >> e^2/2C$
- $k_B T << e^2/2C$
- T=0

Quantized charge on a weakly coupled node

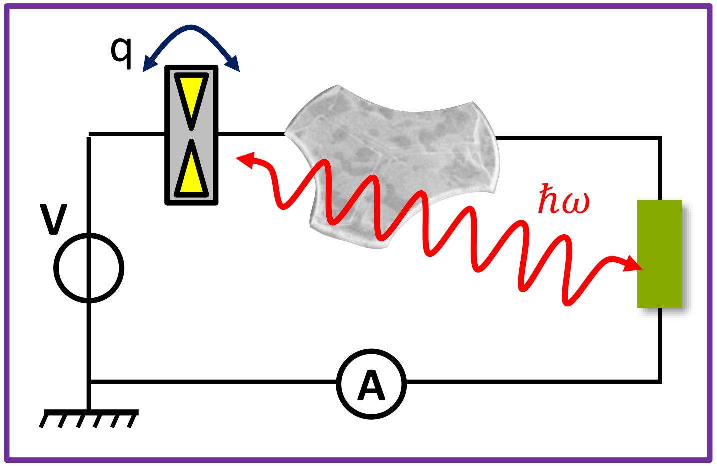
Quantum transport in composite circuits



- Charge quantization in node → Single-electron transistor (Coulomb blockade)

Today :
- No charge quantization in node
  But granularity of charge transfers in one conductor → Dynamical Coulomb blockade

Dynamical Coulomb Blockade (DCB)

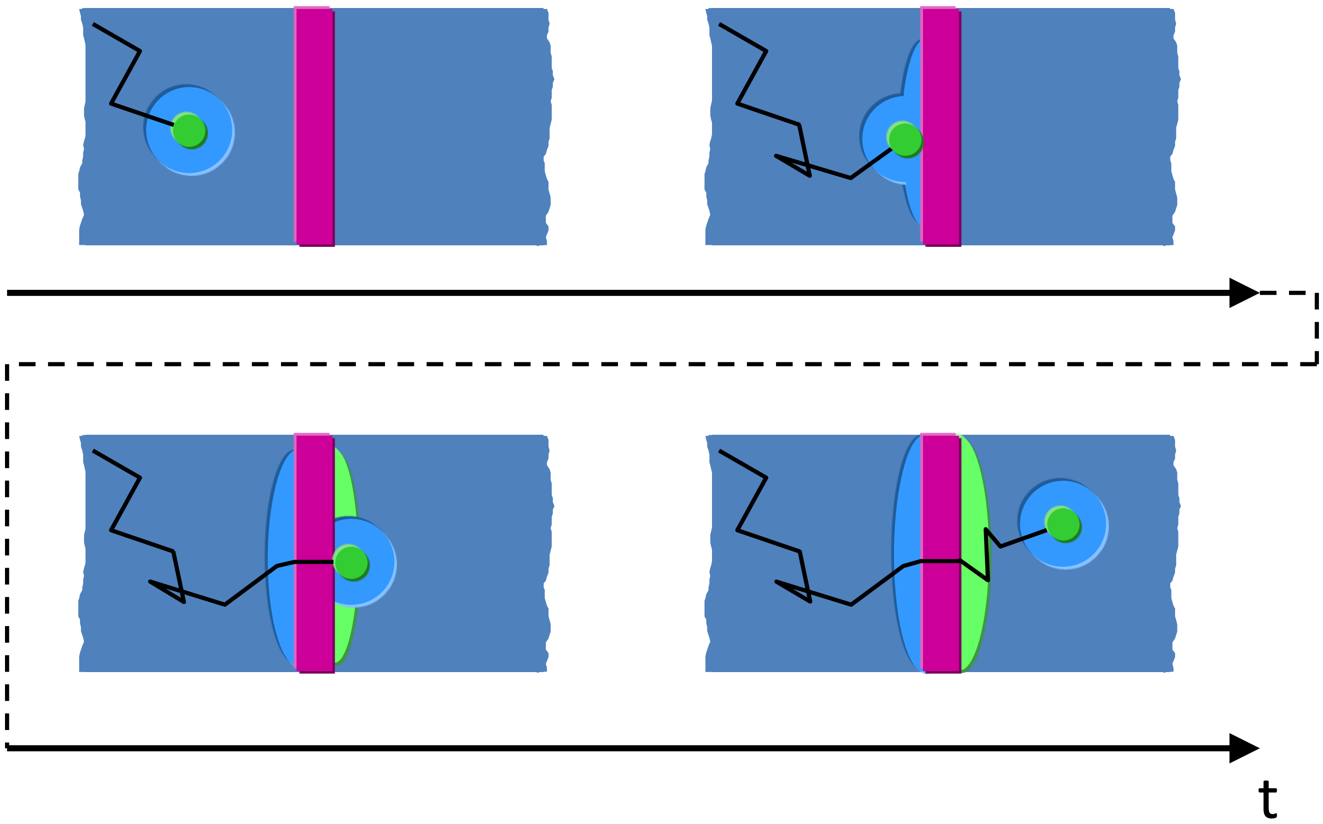


granularity of charge transfers q

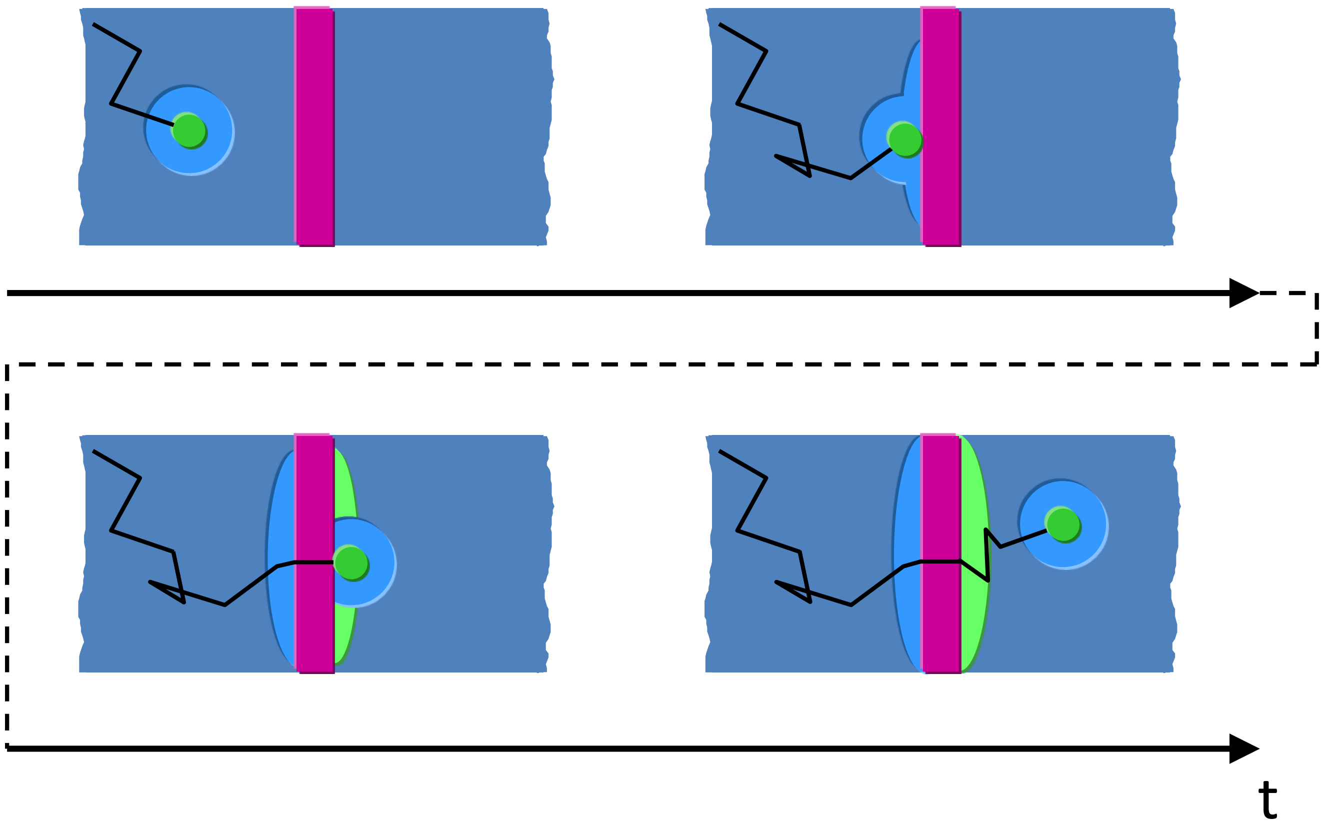
Shot-noise → Excitation of the environment's mode $\hbar\omega$

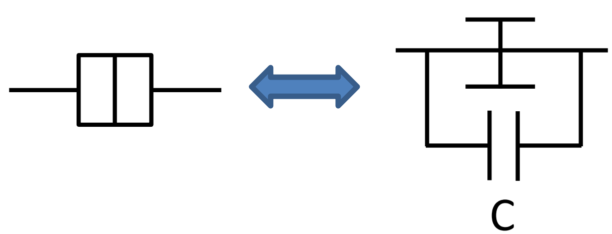
→ Suppression of the electrical conductance at low energy

Microscopic picture of tunneling in presence of Coulomb interactions



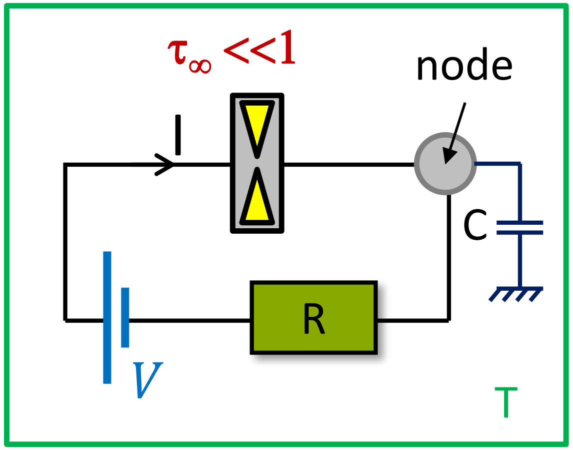
Microscopic picture of tunneling in presence of Coulomb interactions



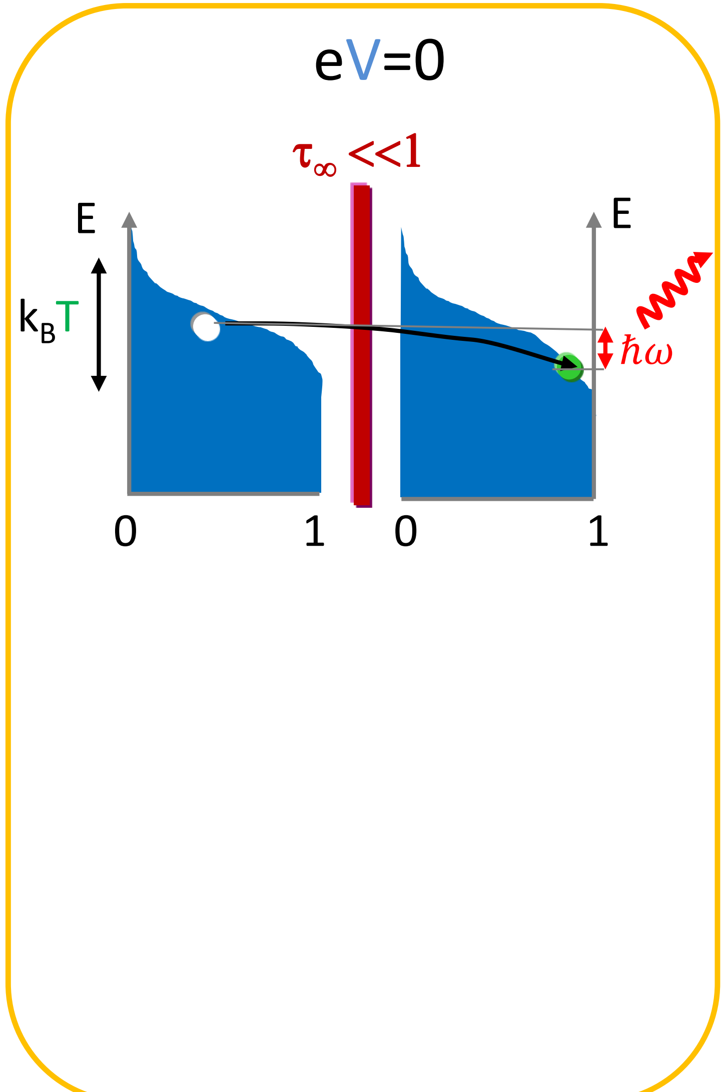


Tunnel event : charge e on C
=
energy to relax

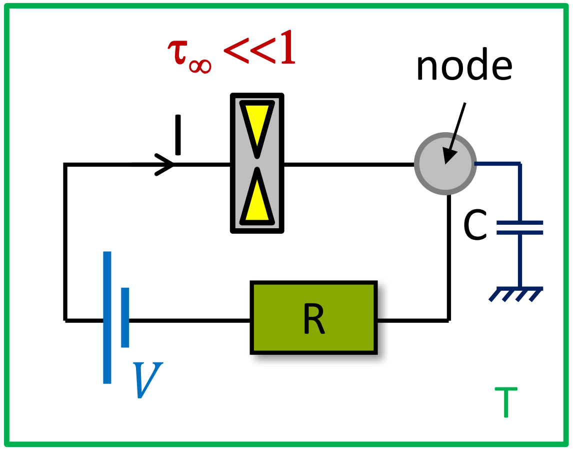
Dynamical Coulomb Blockade : tunnel regime



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



Dynamical Coulomb Blockade : tunnel regime



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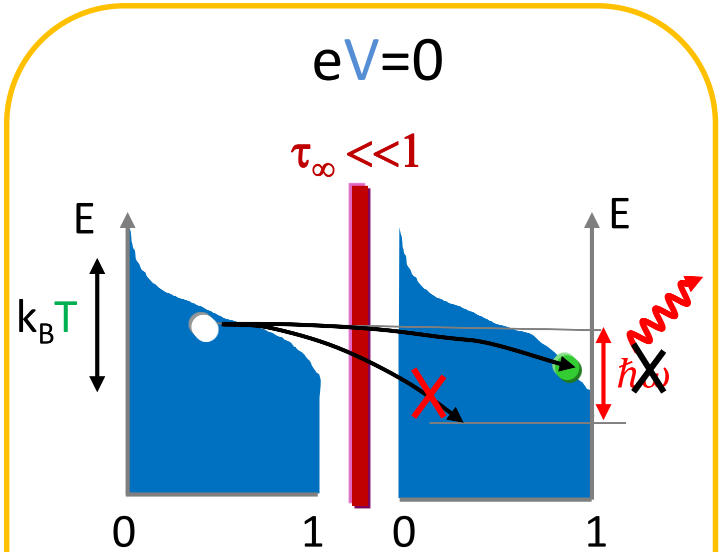
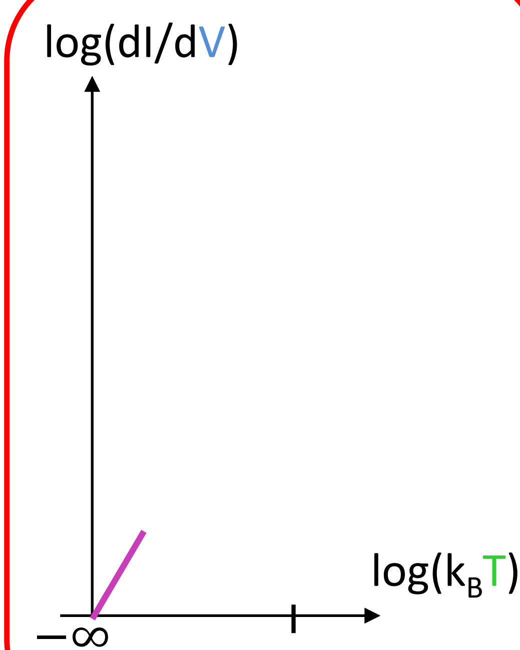
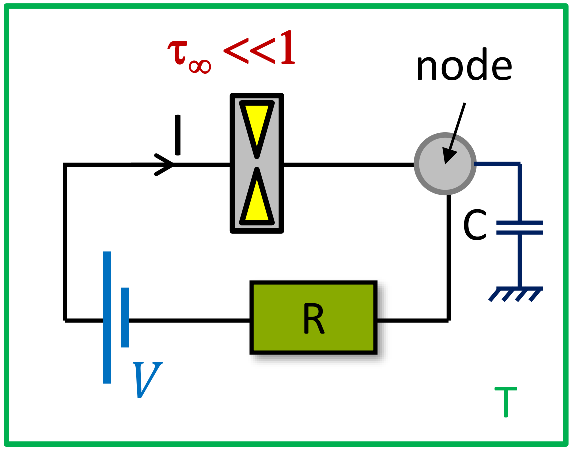




Dynamical Coulomb Blockade : tunnel regime



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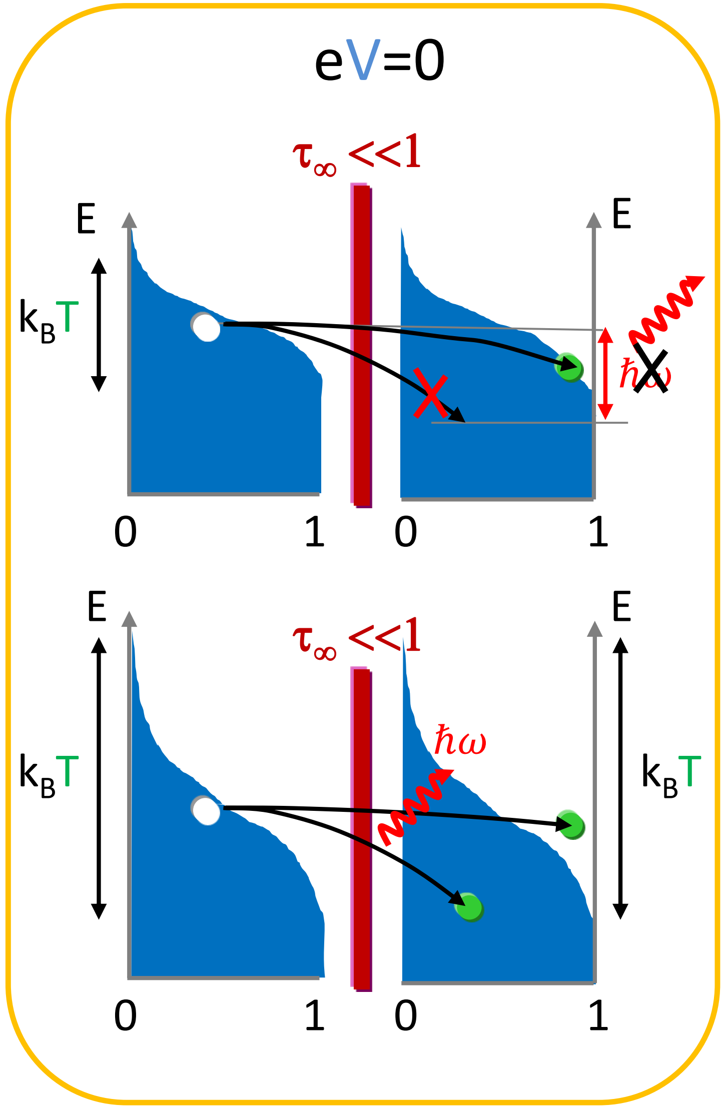
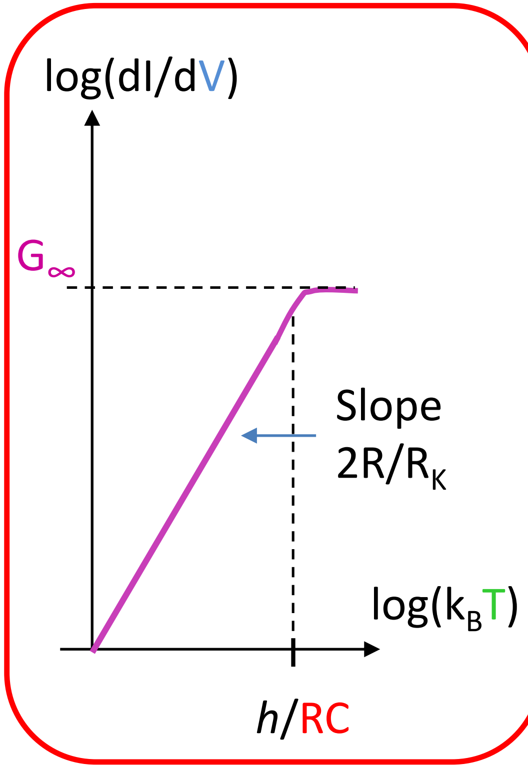
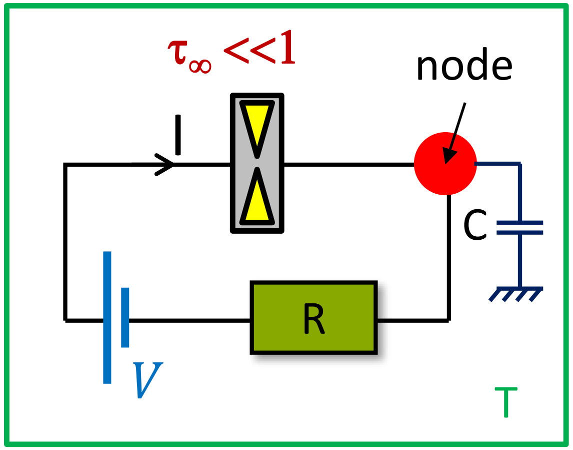
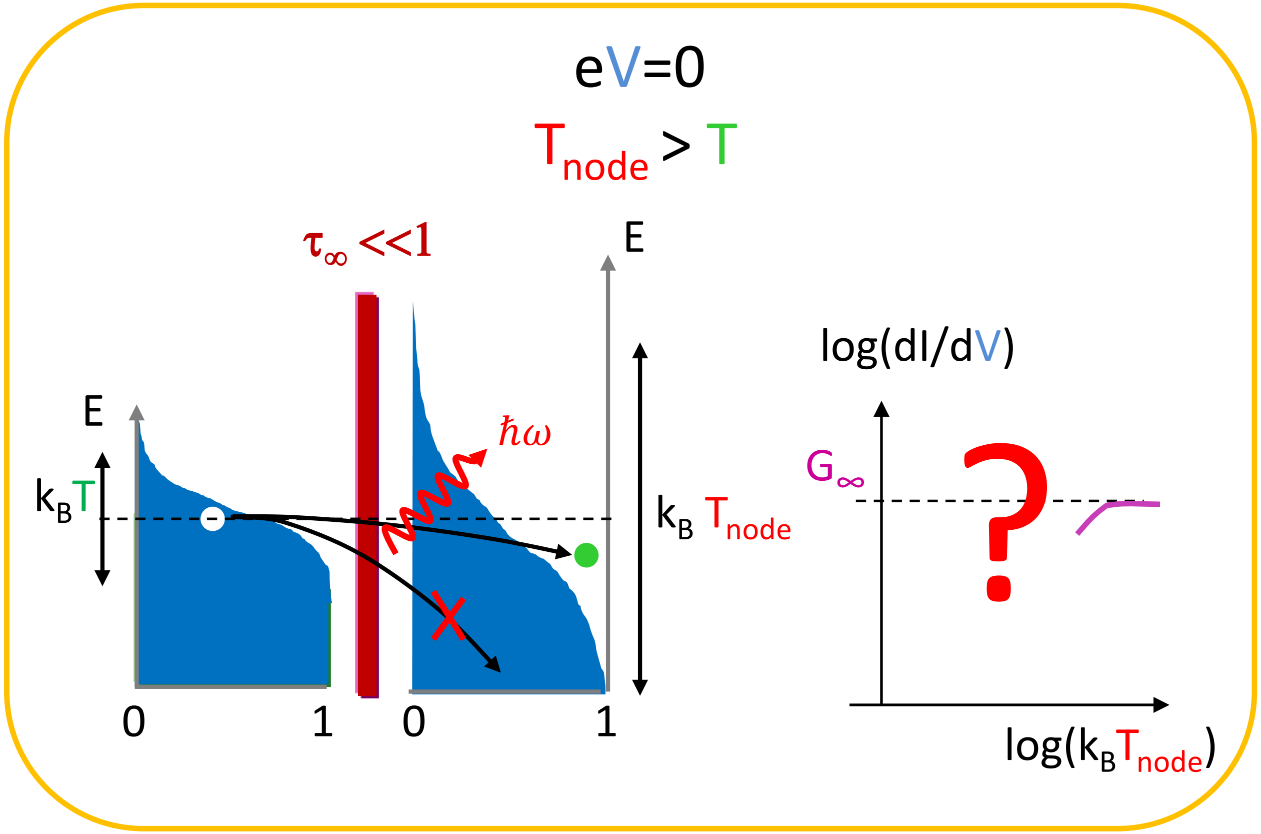


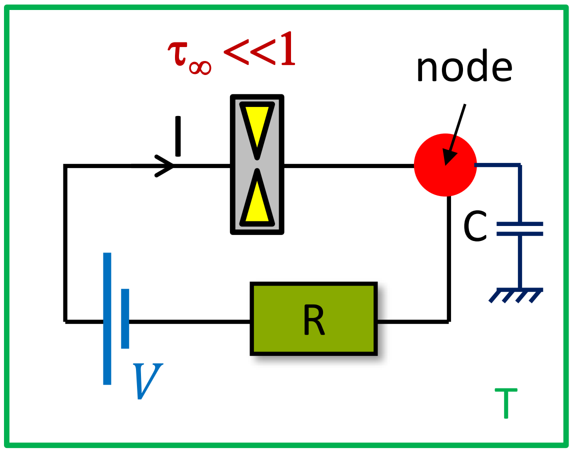


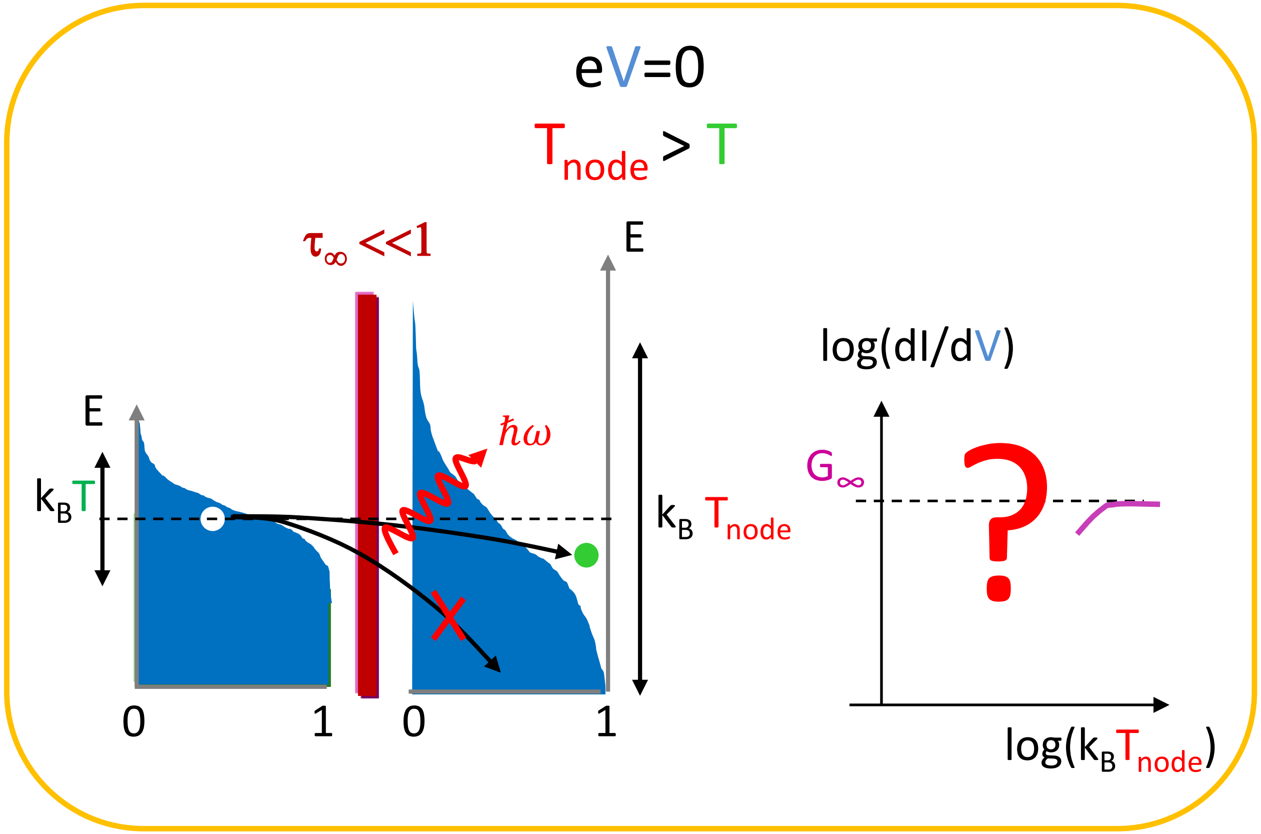
Dynamical Coulomb Blockade : temperature bias





Dynamical Coulomb Blockade : temperature bias

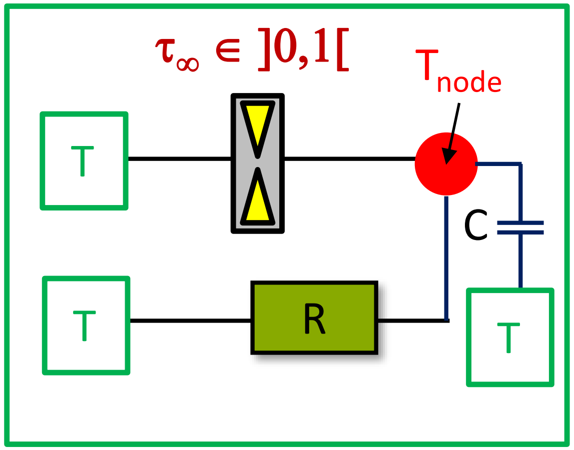


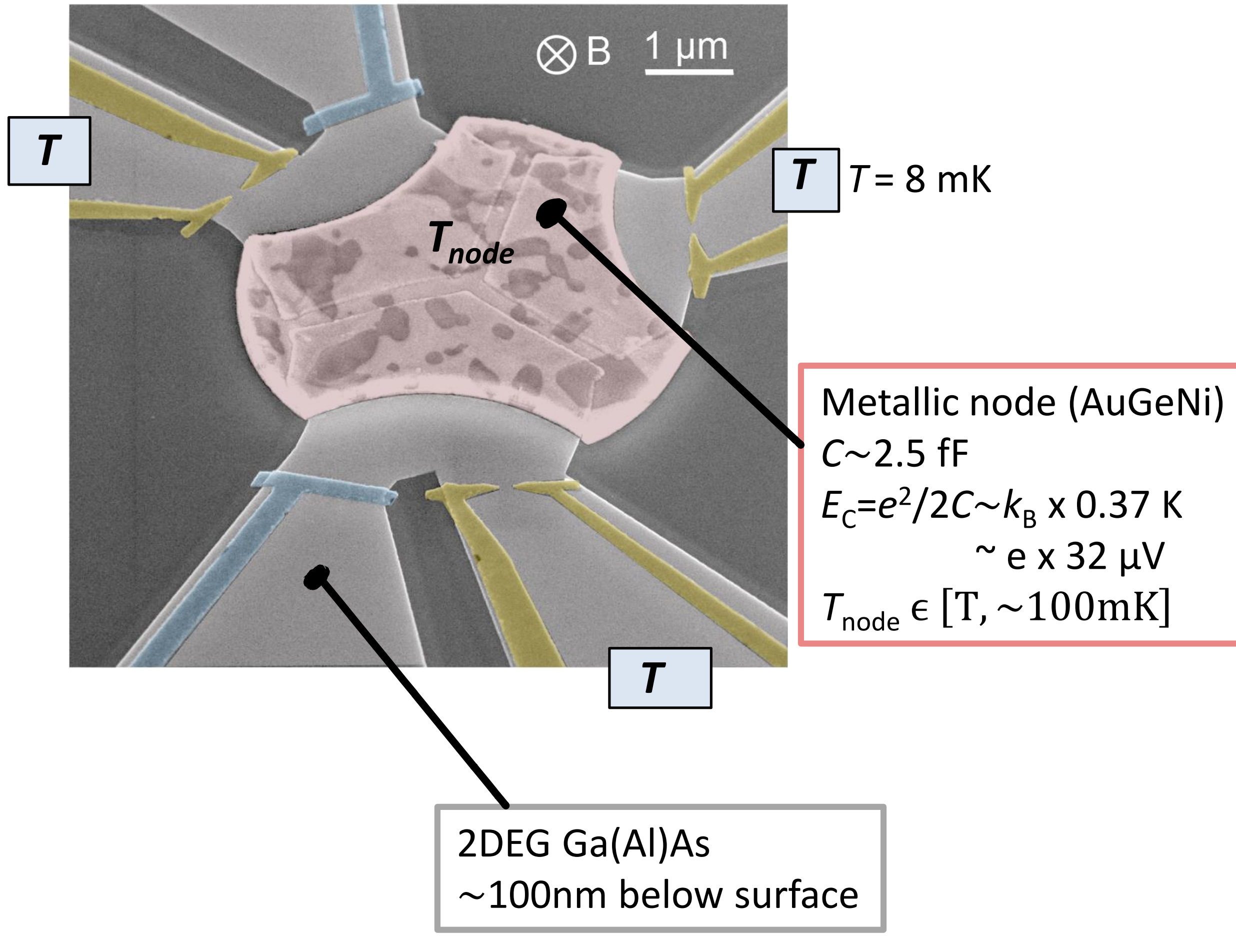


Electron-hole symmetry ➡ No thermoelectricity : $\Delta V=0$ even if $T_{node}-T \neq 0$

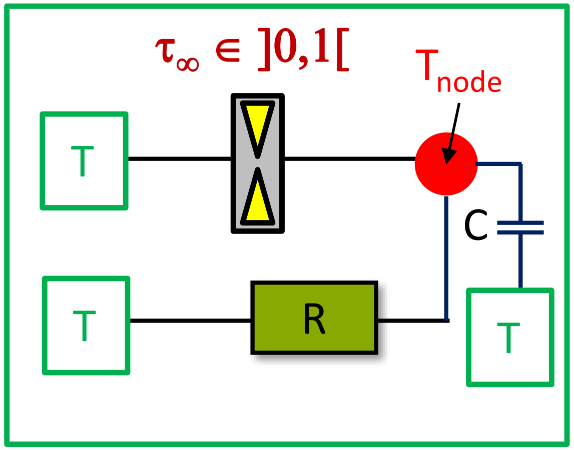
Beyond tunnel regime when $\tau_\infty \in]0,1[$? (V=0)

Test-bed circuit



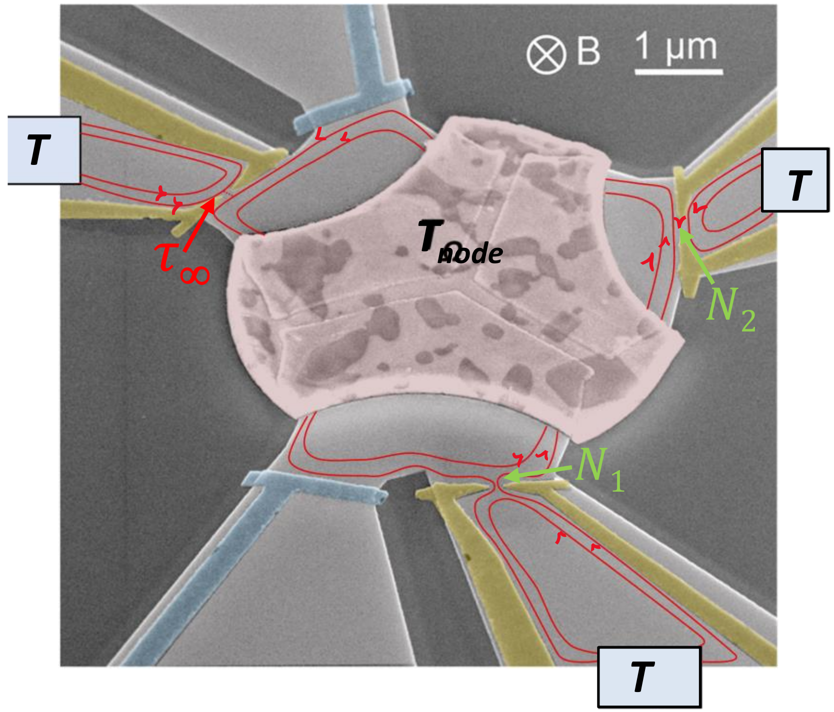


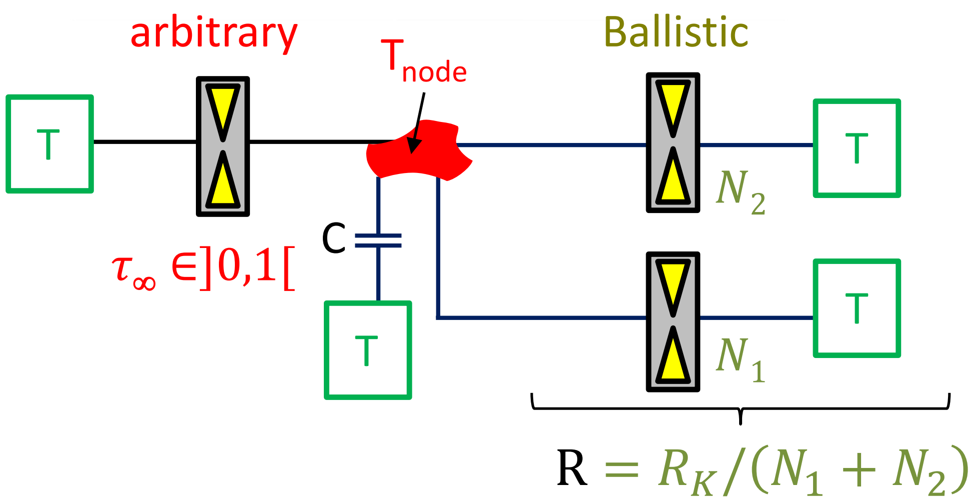
Test-bed circuit



T = electronic temperature

= fridge temperature



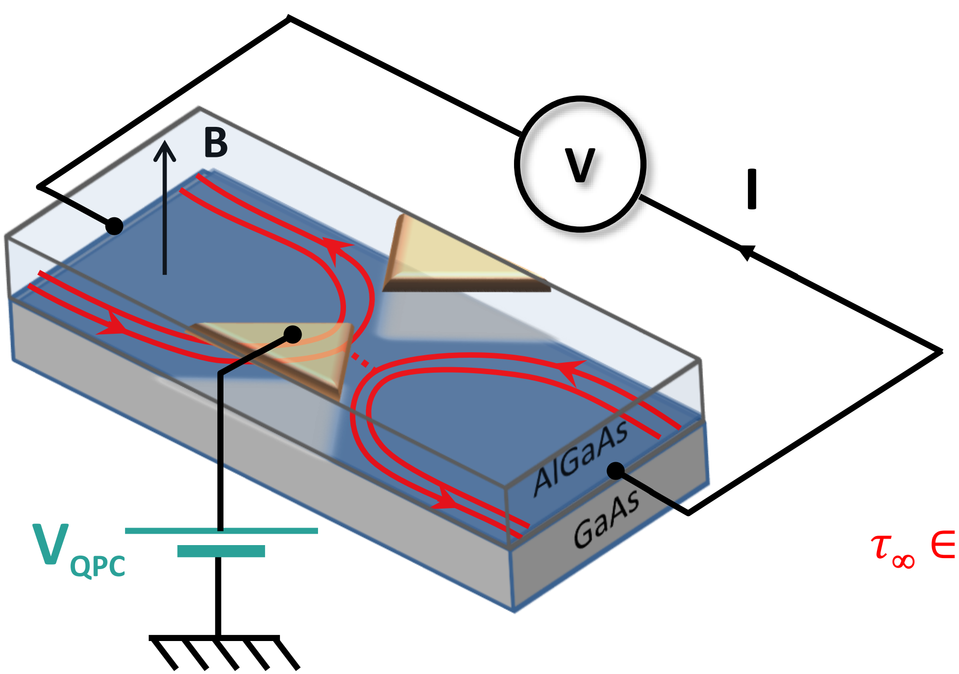


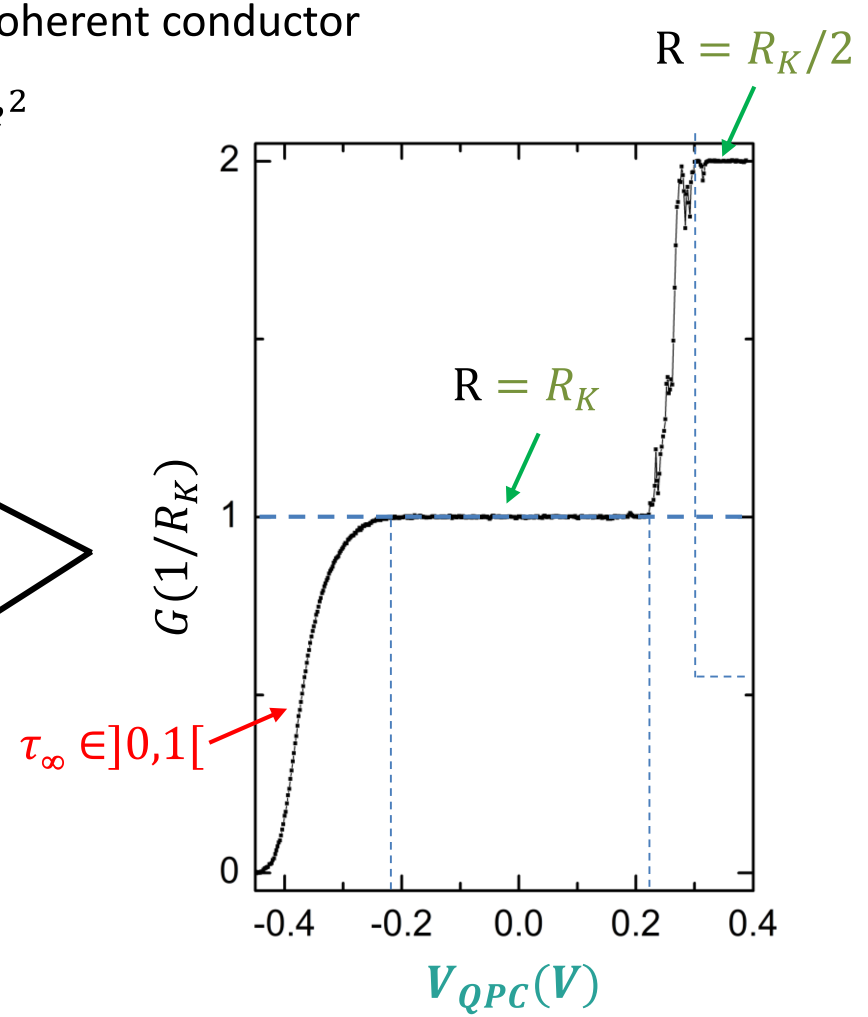
Quantum point contacts

A model of quantum conductor + a calibrated resistor

Scattering approach description of a coherent conductor
(Landauer, Büttiker, Martin)

$R_K = h/e^2$

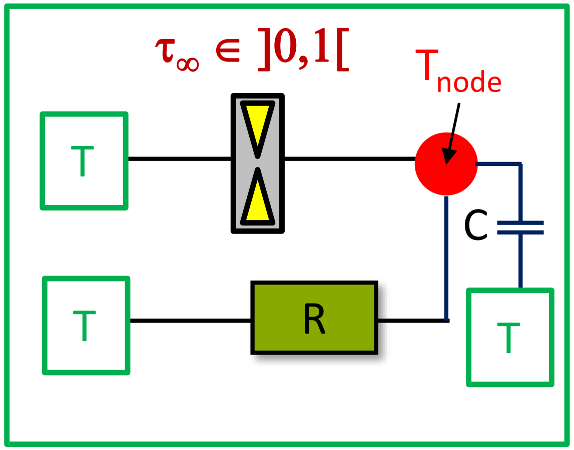




$n_S = 2.5\ 10^{15}\ m^{-2}$, $\mu = 10^2\ m^2V^{-1}s^{-1}$
grown @ C2N by A. Cavanna and U. Gennser

Test-bed circuit

Heat knob



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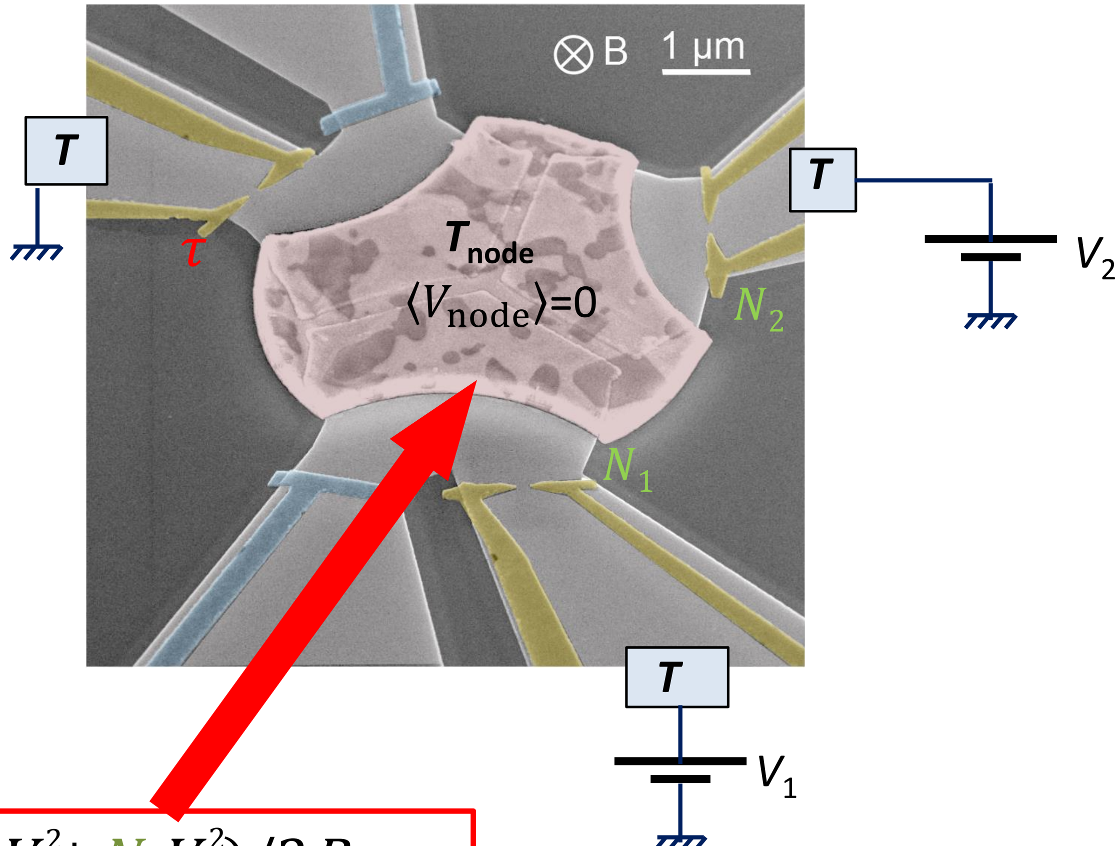


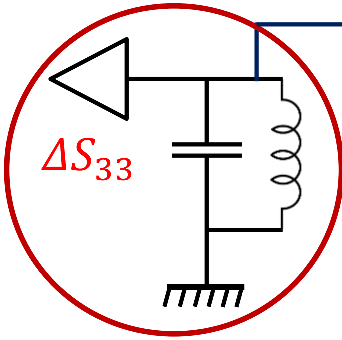
$$P_{inj} = (N_1 V_1^2 + N_2 V_2^2)/2R_K$$

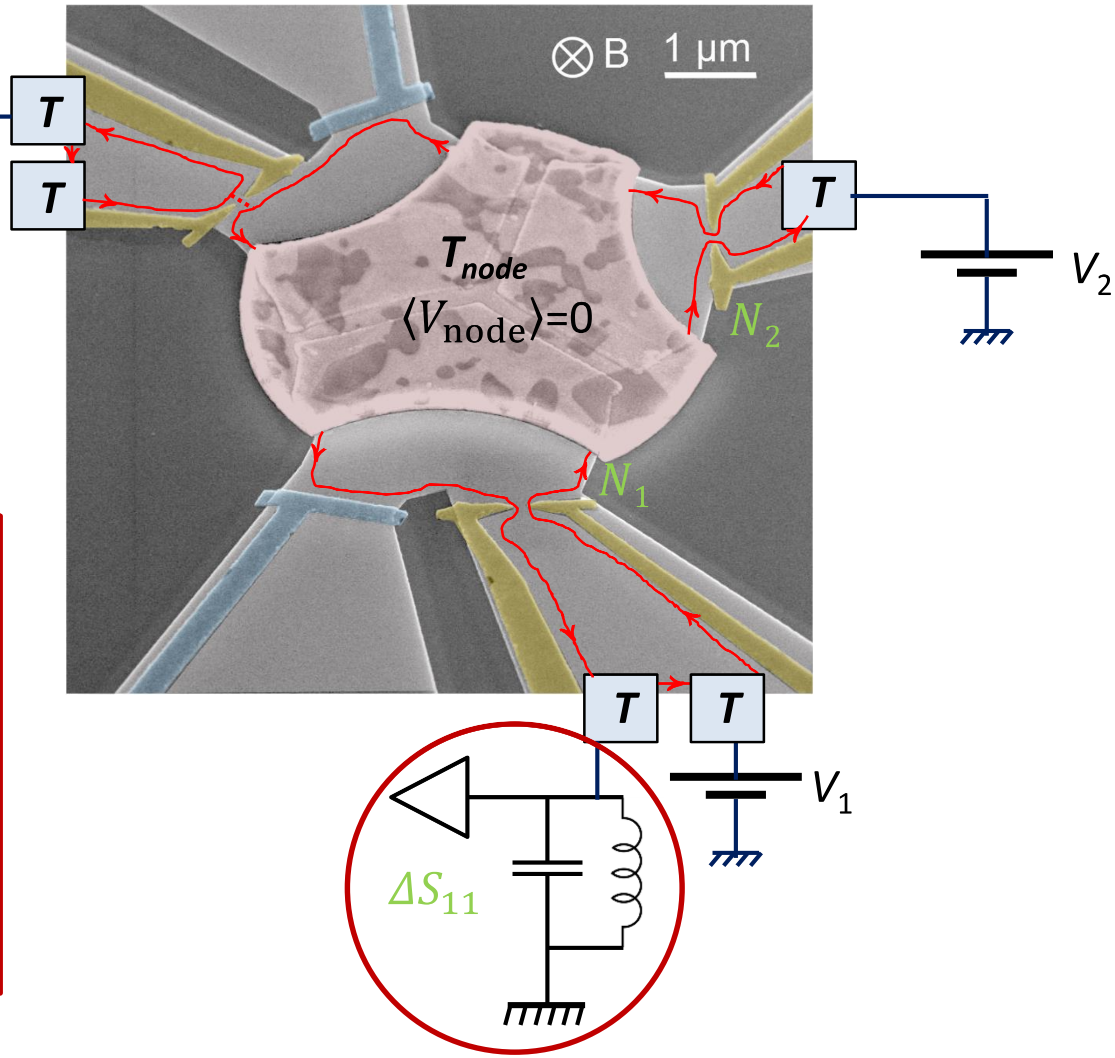
$$= J_{total} = J^{el} + J^{phonons}$$

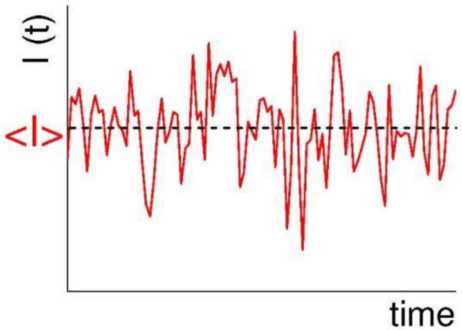
T bias:

$N_1V_1+N_2V_2=0$ → $\langle V_{node}\rangle=0$

Test-bed circuit





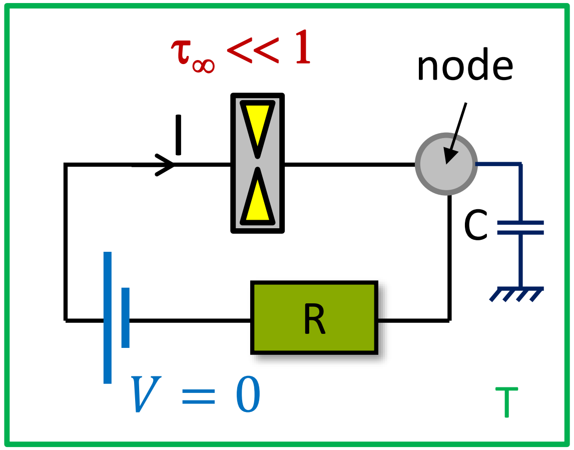


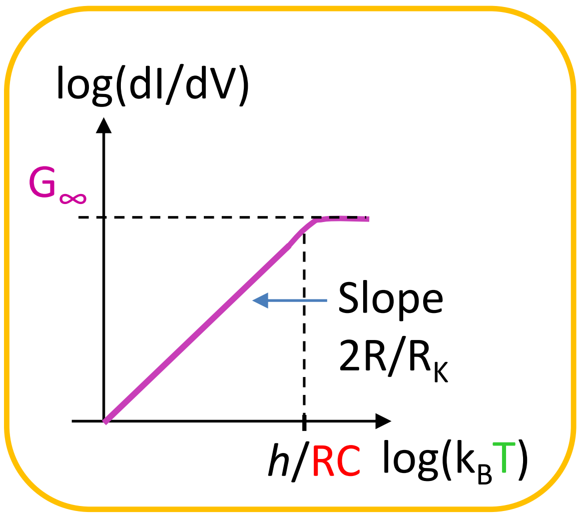
Noise thermometry

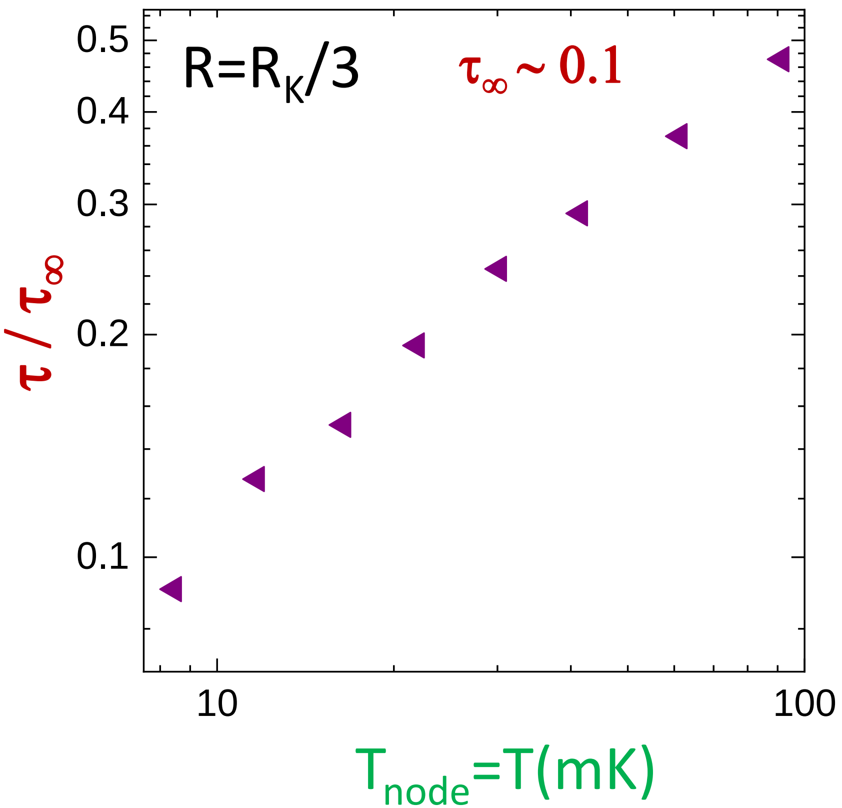
$$\frac{2\,k_B(T_{\text{node}} - T)}{R_K} = \Delta S_{11}\left(\frac{1}{N_1} + \frac{1}{N_2}\right) - \Delta S_{33}\,\frac{N_1}{N_2(N_1 + N_2)}$$

DCB in tunnel regime

Test-bed sample versus T ?

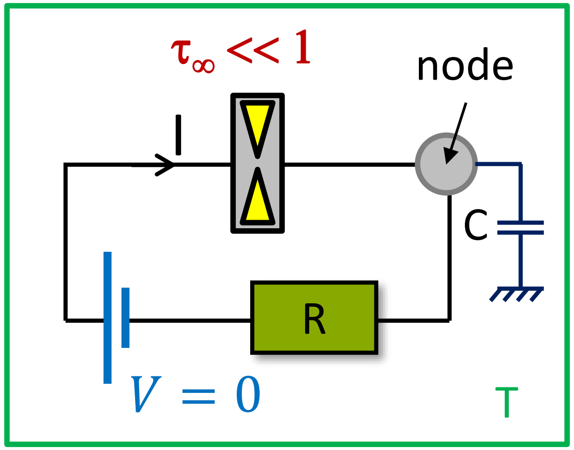


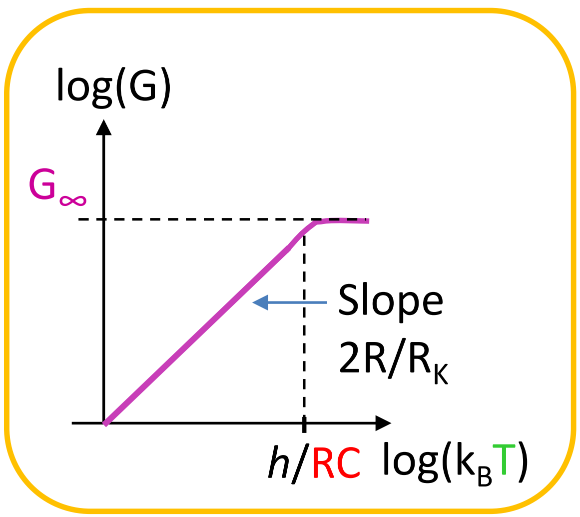


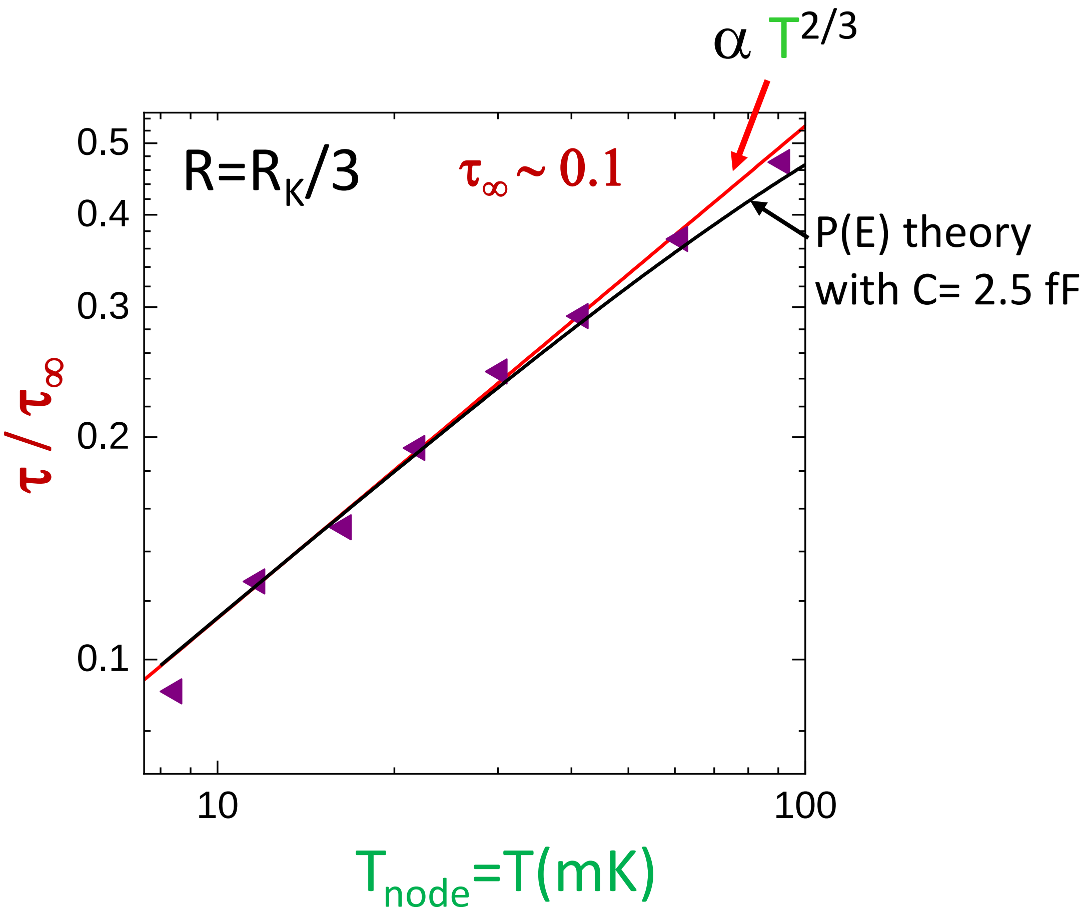


DCB in tunnel regime

Test-bed sample versus T ?

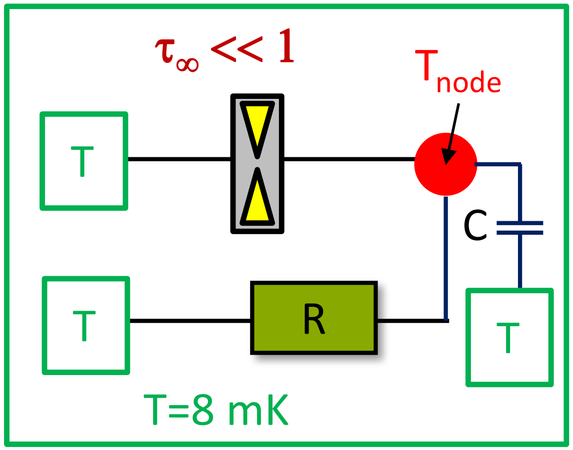


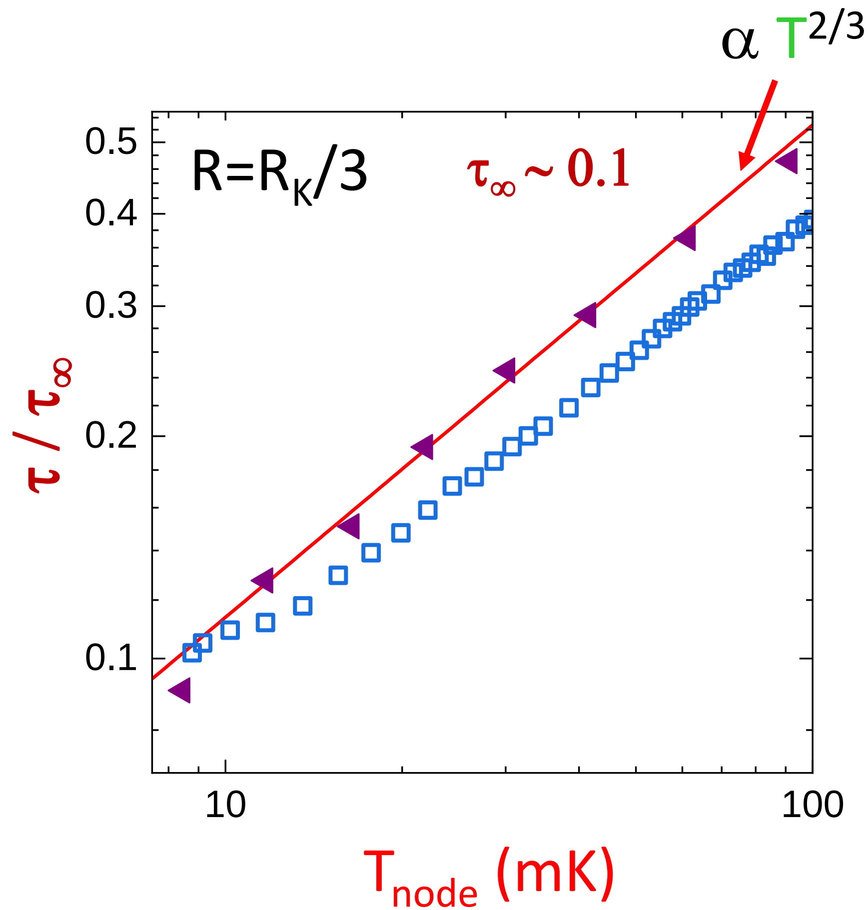




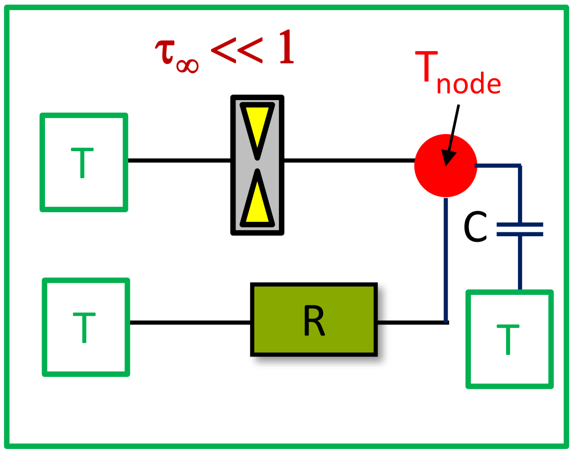
See Ingold & Nazarov in "Single Charge Tunneling" (Ed. Grabert & Devoret, 1992)

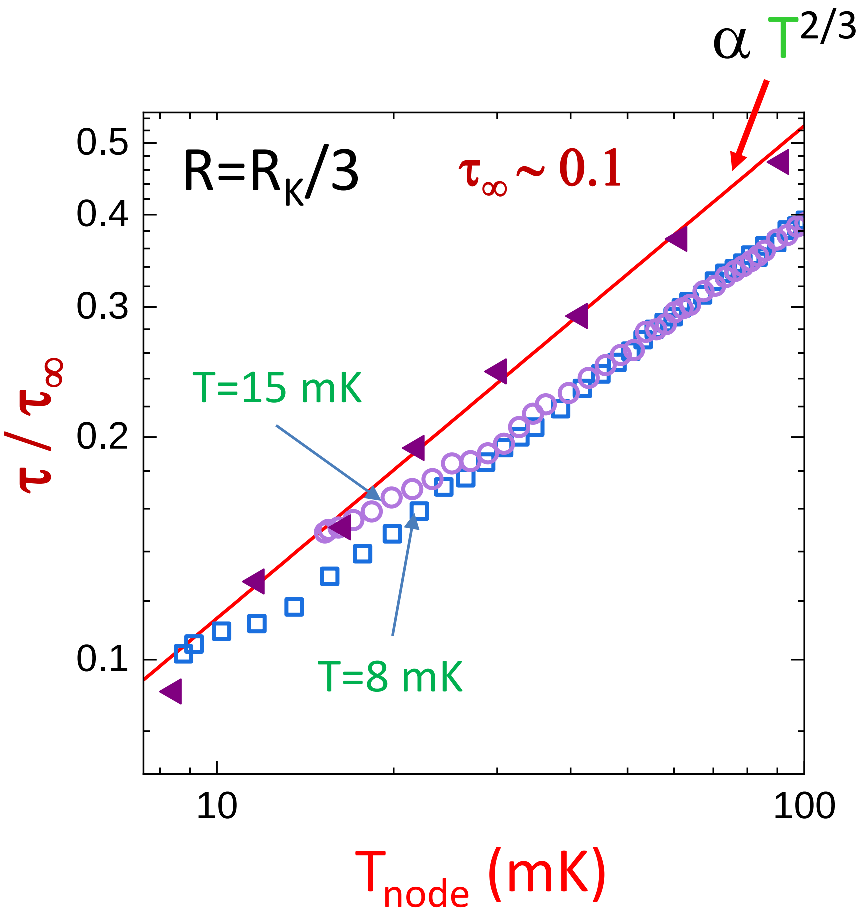
DCB in tunnel regime under a temperature bias



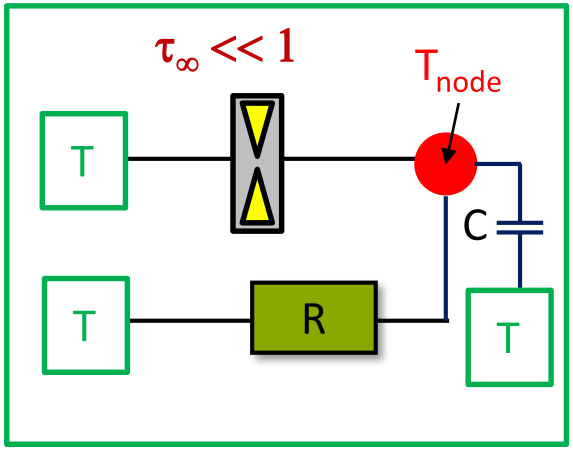


DCB in tunnel regime under a temperature bias





DCB in tunnel regime under a temperature bias



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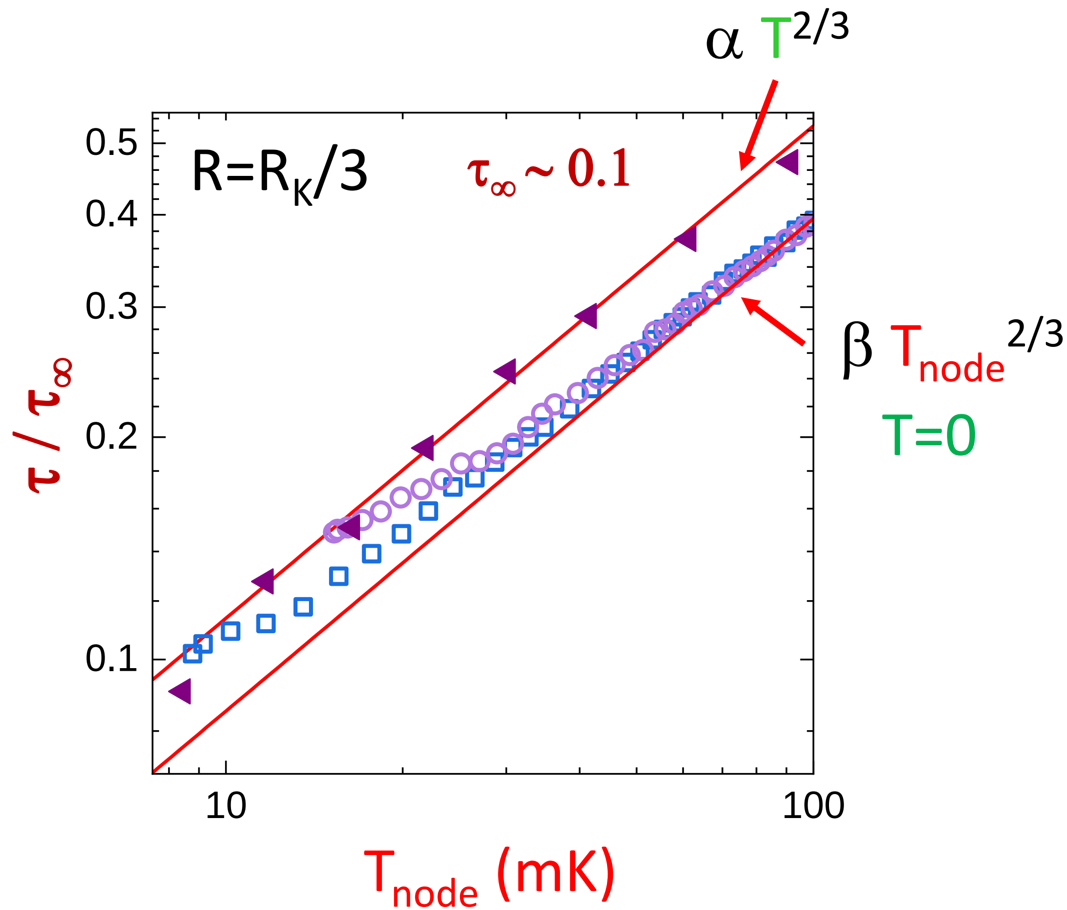
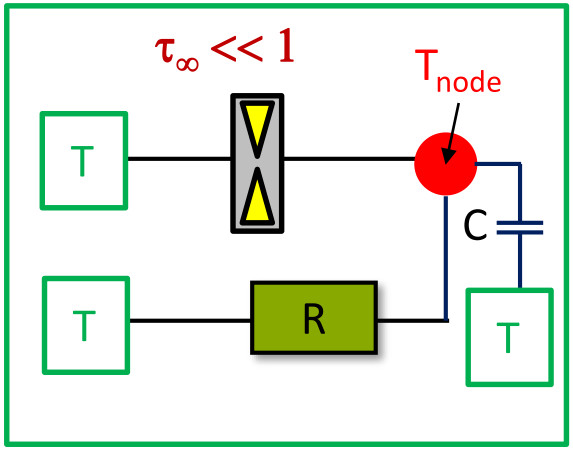


β prefactor from P(E) theory with $T_{env} = T_{node}/2$, T=0

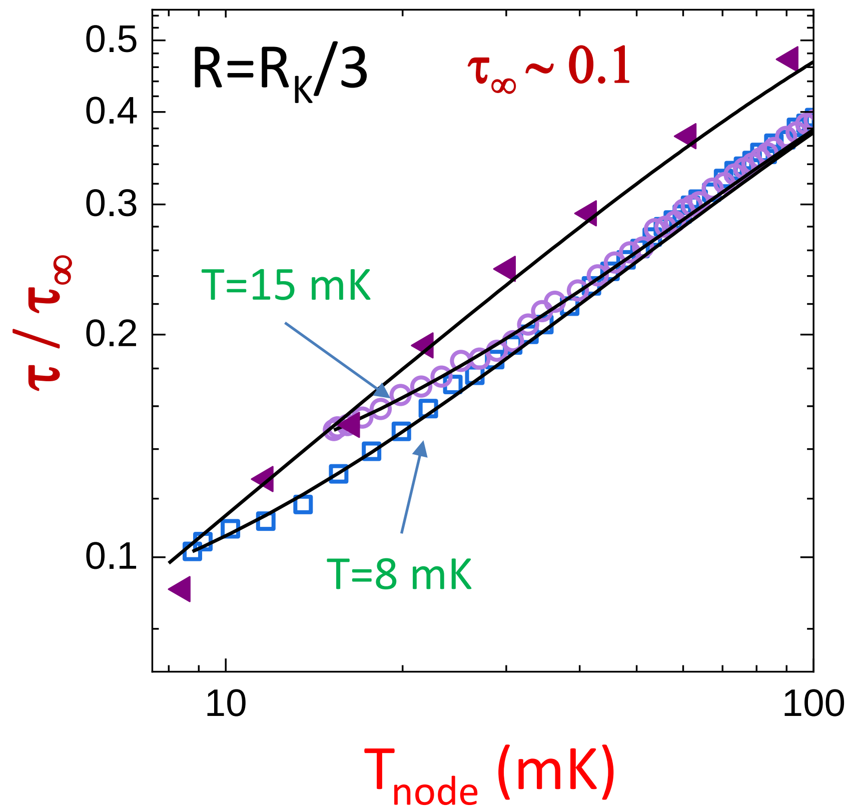
$$\frac{\beta}{\alpha} = \frac{2}{\sqrt{\pi}} \frac{\Gamma\left(1.5 + R/R_K\right)}{\Gamma(1 + R/R_K)} 2^{-2R/R_K}$$

DCB in tunnel regime under a temperature bias



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

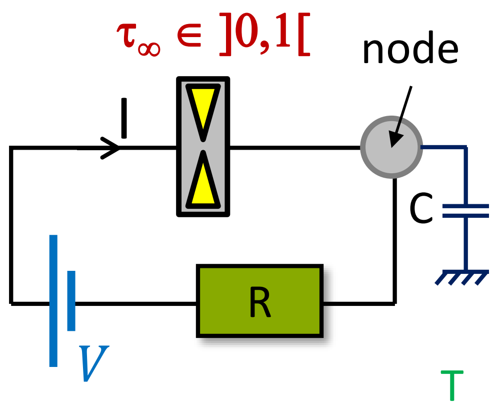
Full P(E) theory with $T_{env} = (T_{node} + T)/2$



Beyond tunnel regime when $\tau_\infty \in]0,1[$? (V=0)

Mapping between DCB and the impurity problem in a Luttinger liquid

One-channel conductor in series with a resistance

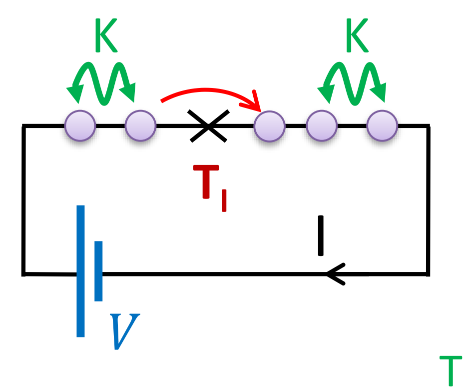


at low energy

$$K = \frac{1}{1 + R/R_K}$$

$T_I = f(\tau_\infty)$
non universal

1-D conductor of interacting electrons with an impurity



Universal conductor-insulator crossover : G = dI/dV → 0 when T ↘

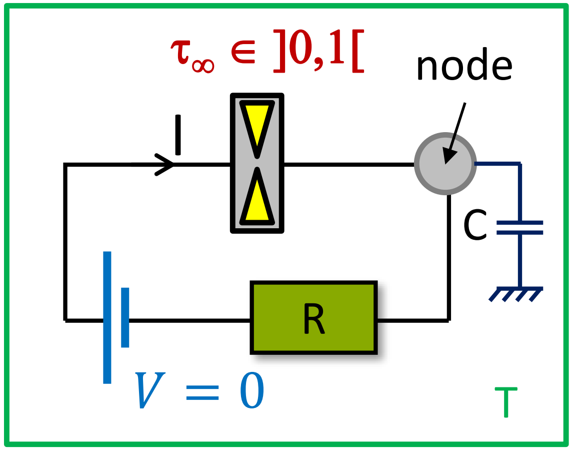
V ↘

Th. : PRL **93**, 126602 (2004)
PRB **85,** 125421 (2012)

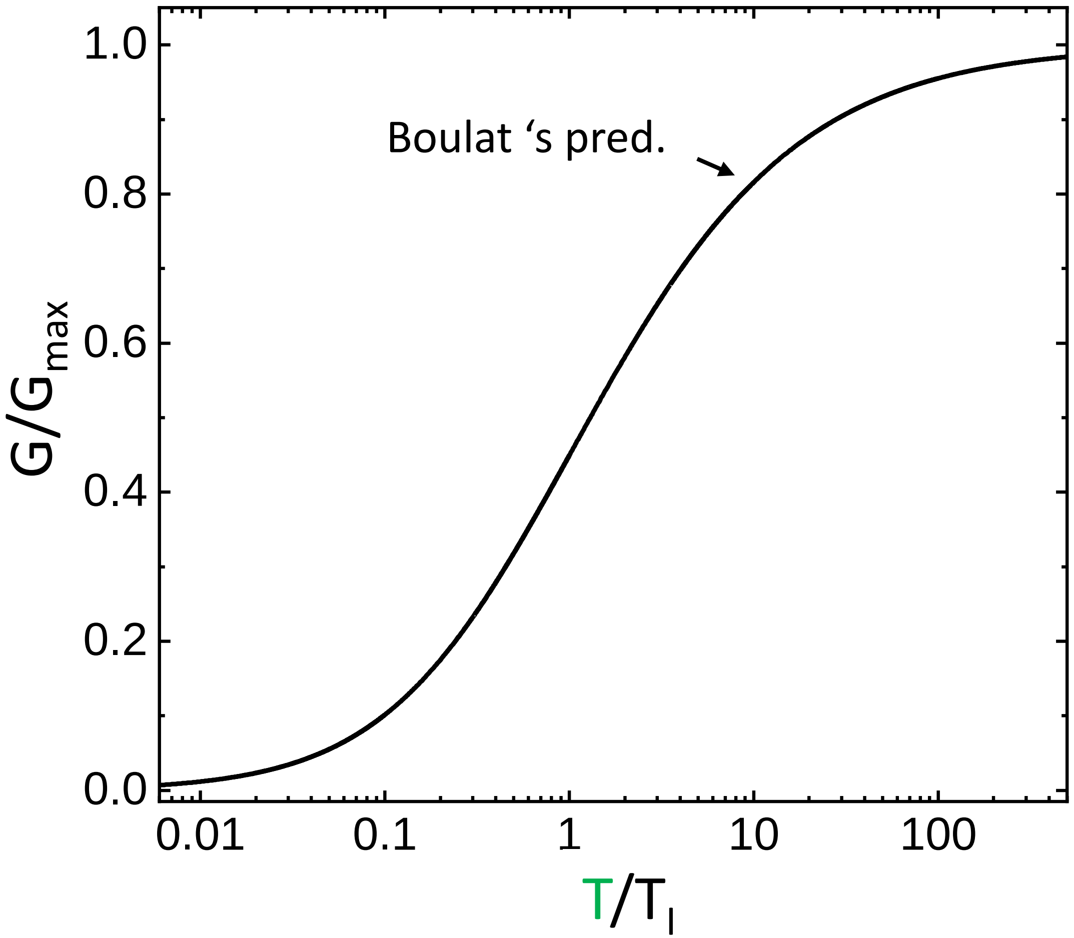
Exp. : Nat. Comm. **4**, 1802 (2013)
PRX **8**, 031075 (2018)

Conductor-insulator crossover

with T : $G = dI/dV \in [0, G_{max} = (R_K + R)^{-1}]$

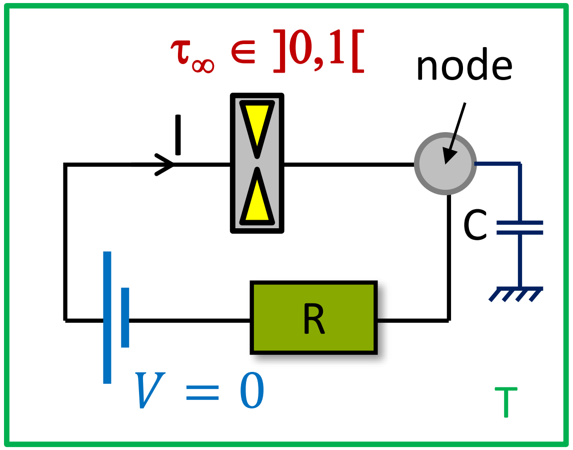


PRX **8**, 031075 (2018)



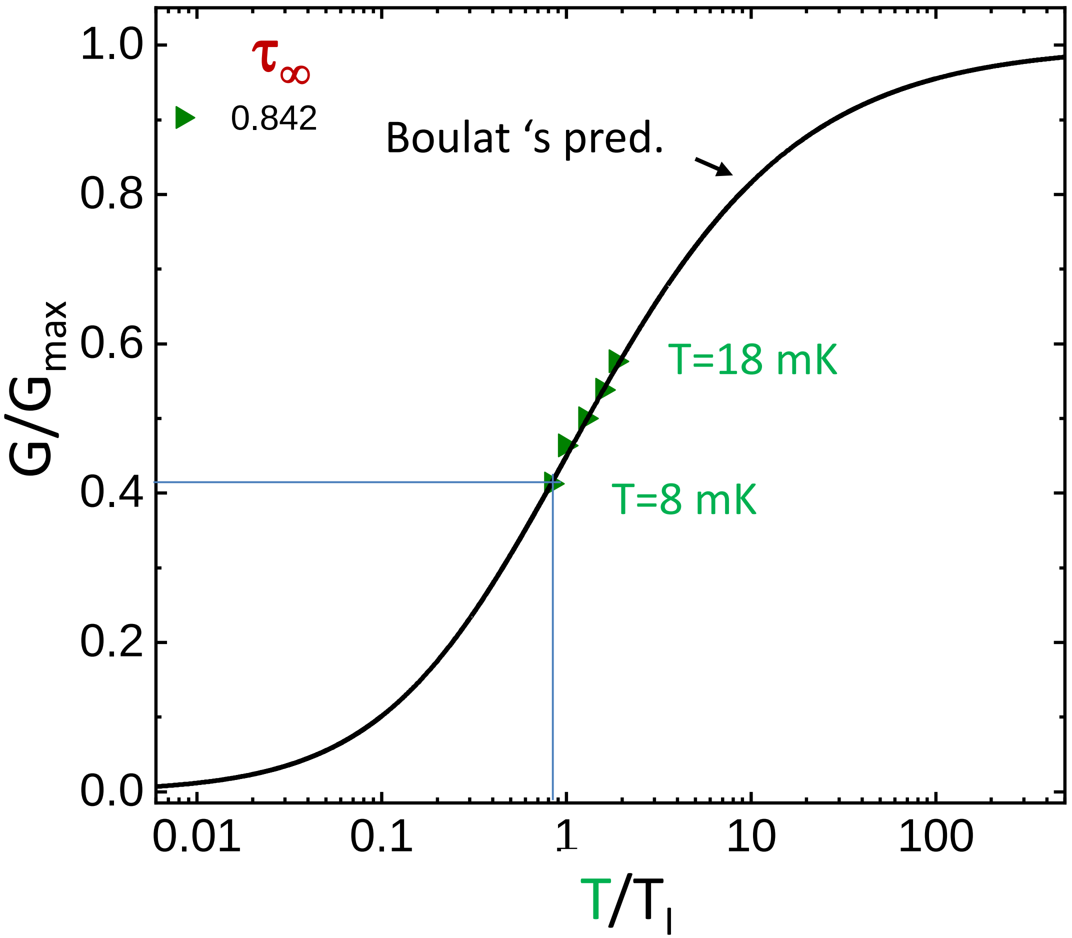
Conductor-insulator crossover

with T : $G = dI/dV \in [0, G_{max} = (R_K + R)^{-1}]$



Exp : 8 mK ≤ T ≤ 18 mK

PRX **8**, 031075 (2018)

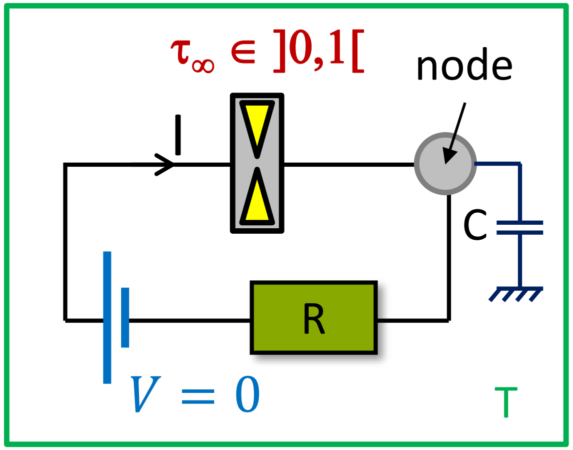


$G(\tau_\infty = 0.842, T = 8\ \text{mK}) / G_{max} = 0.41$

$T_I(\tau_\infty = 0.842) = 8\ \text{mK} / 0.83$

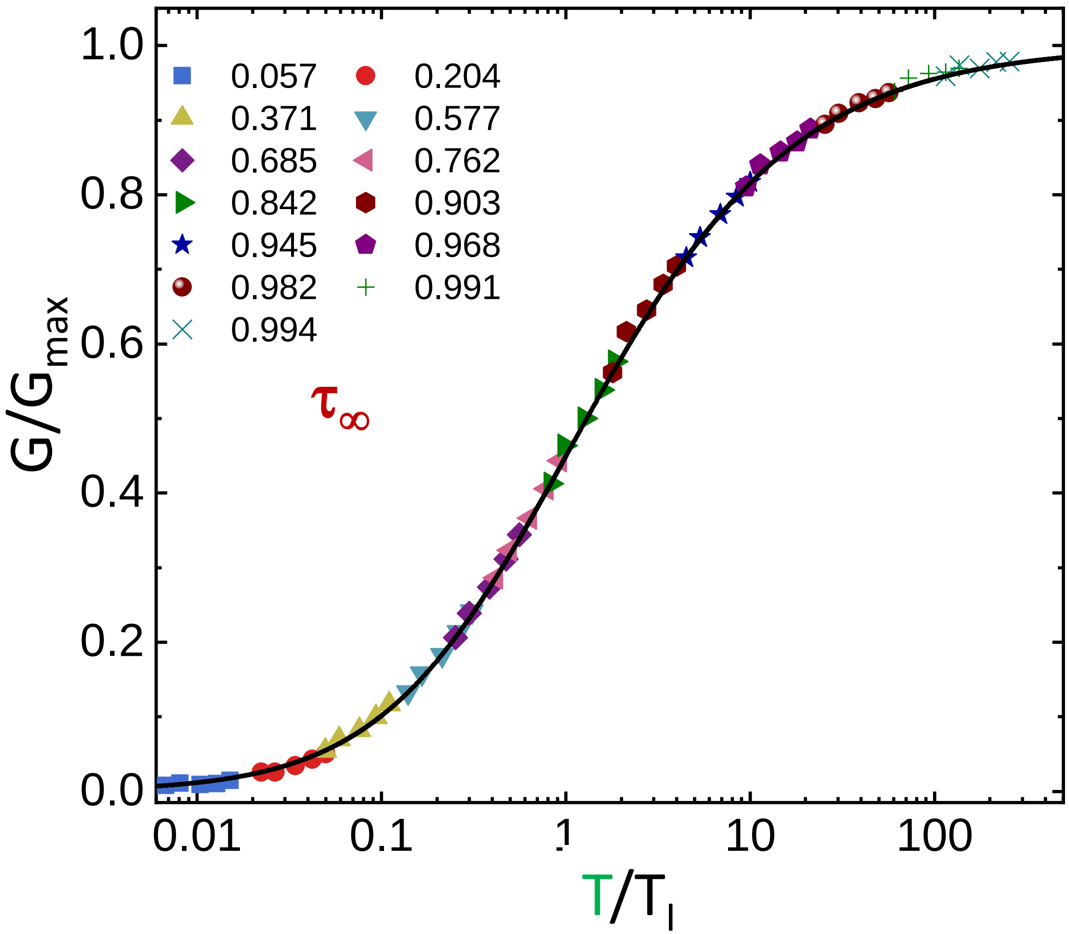
Conductor-insulator crossover

with T : $G = dI/dV \in [0, G_{max} = (R_K + R)^{-1}]$



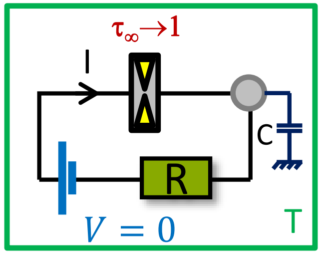
Exp : 8 mK ≤ T ≤ 18 mK

PRX **8**, 031075 (2018)



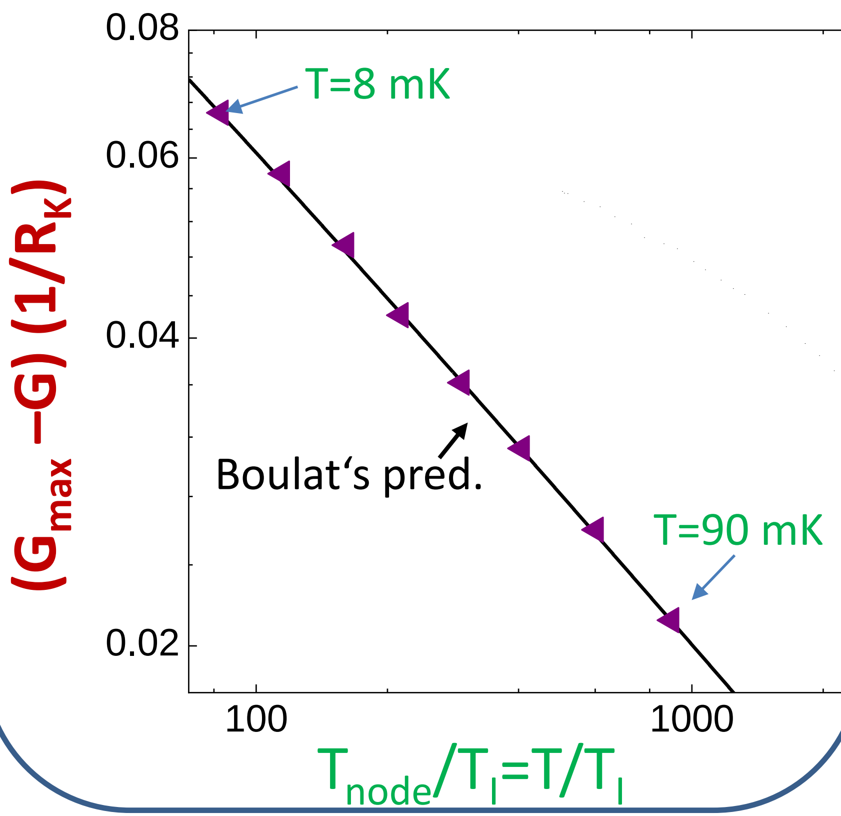
$T_I = f(\tau_\infty)$
universal crossover

DCB in weak-backscattering regime : mapping

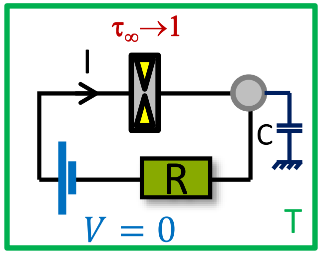


Luttinger parameter $K = \frac{1}{1+R/R_K}$, $G_{max} = (R_K+R)^{-1} = K/R_K$

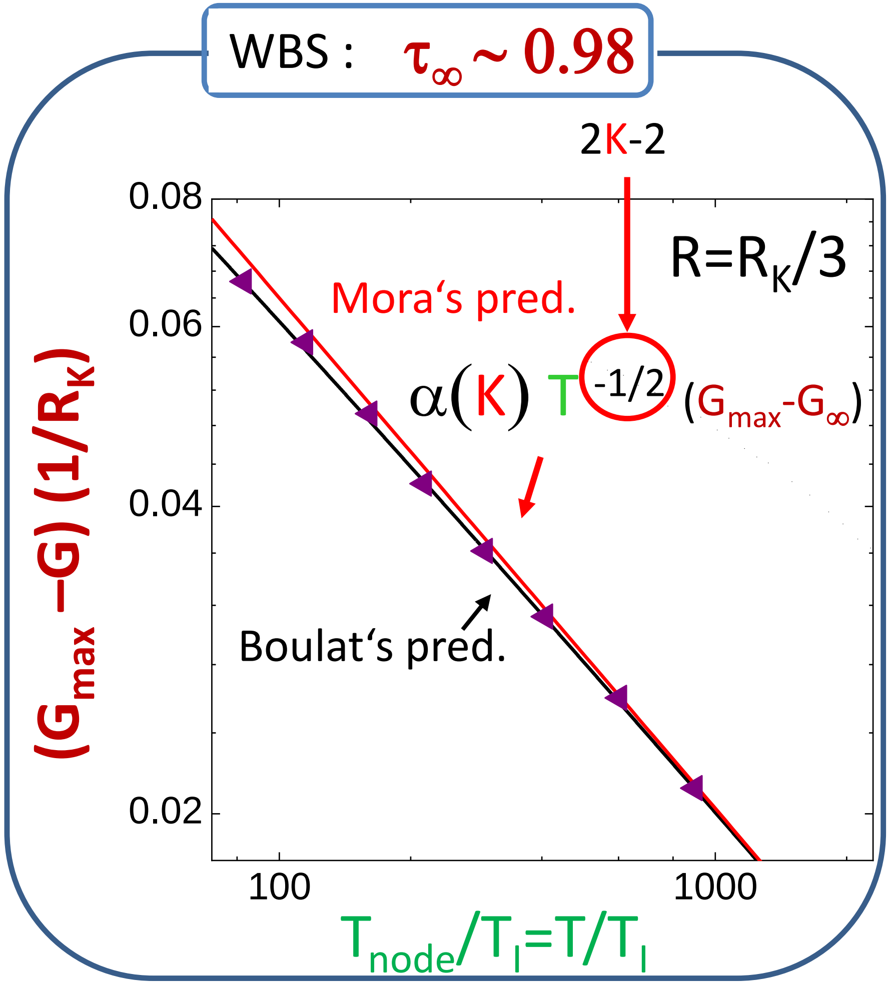
WBS : $\tau_\infty \sim 0.98$



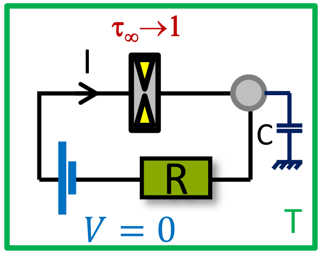
DCB in weak-backscattering regime : mapping



Luttinger parameter $K = \frac{1}{1+R/R_K}$, $G_{max} = (R_K+R)^{-1} = K/R_K$

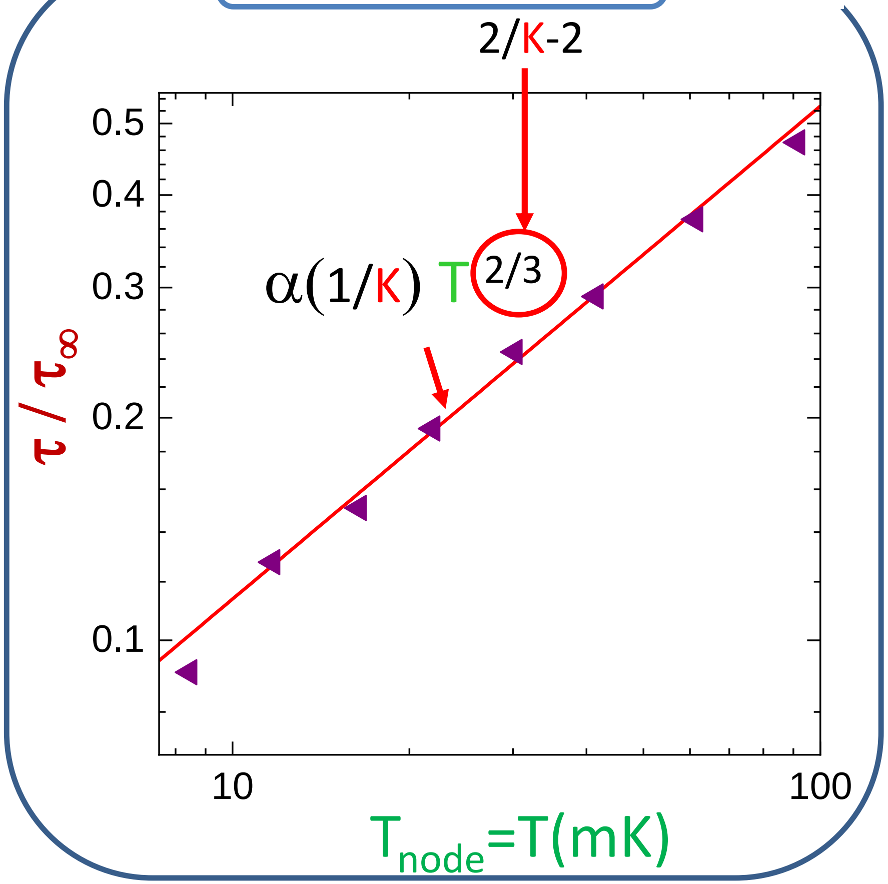


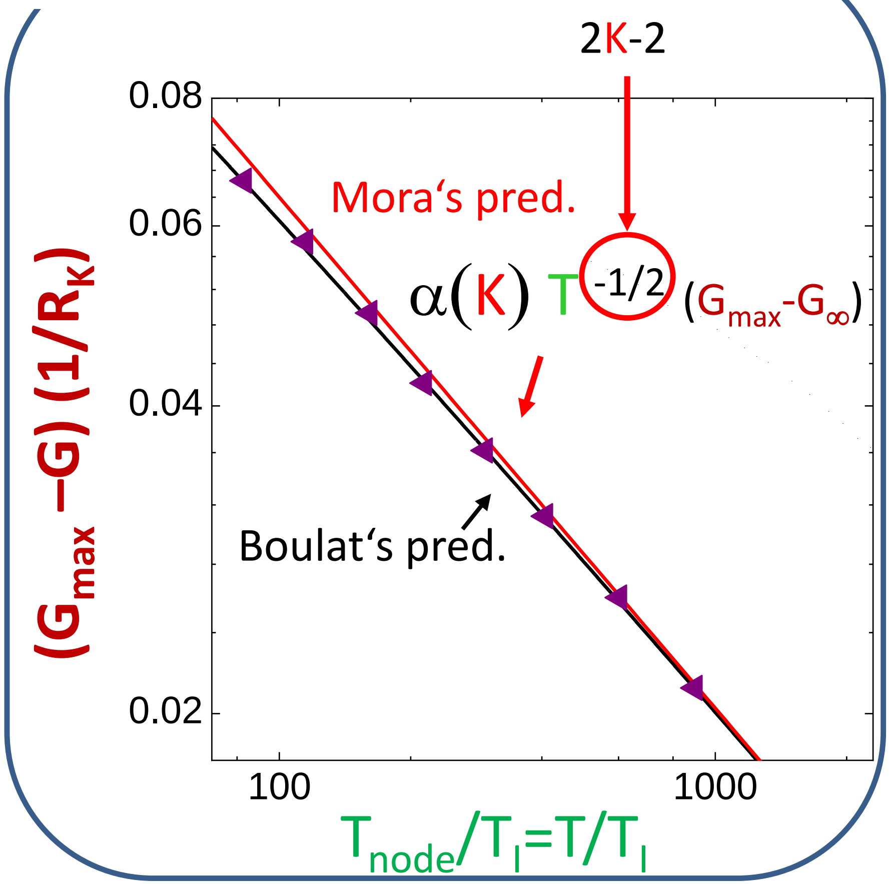
DCB in weak-backscattering regime : duality with tunnel regime



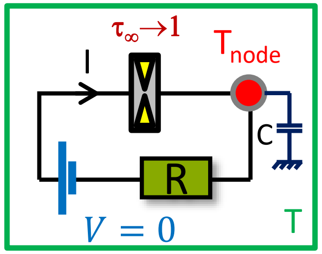
Luttinger parameter $K = \frac{1}{1+R/R_K}$, $G_{max} = (R_K+R)^{-1} = K/R_K$

Tunnel : $\tau_\infty \sim 0.1$ K ➡ 1 / K WBS : $\tau_\infty \sim 0.98$



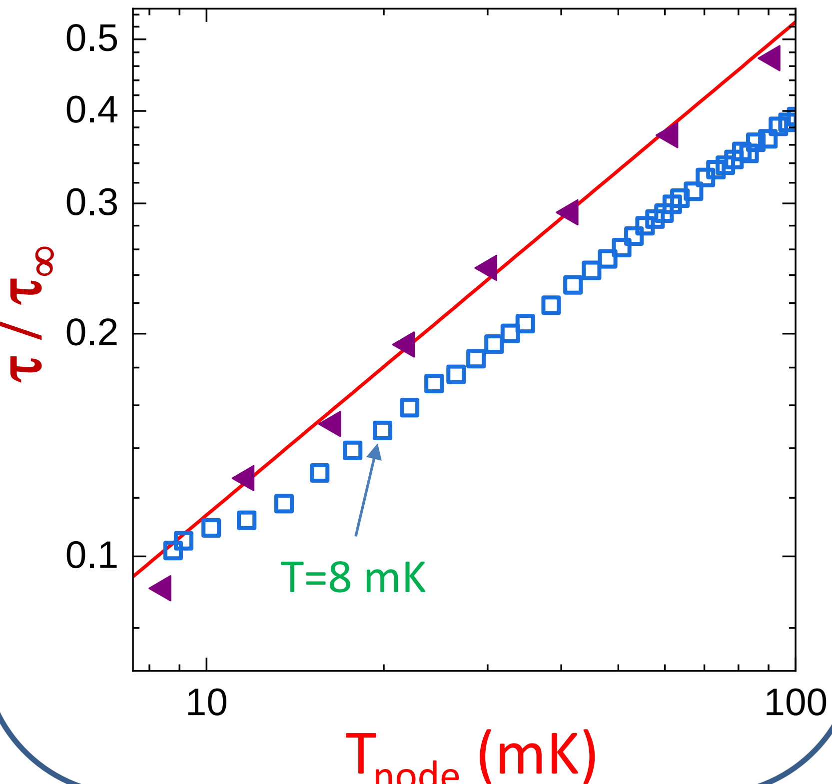


DCB in weak-backscattering regime : temperature bias

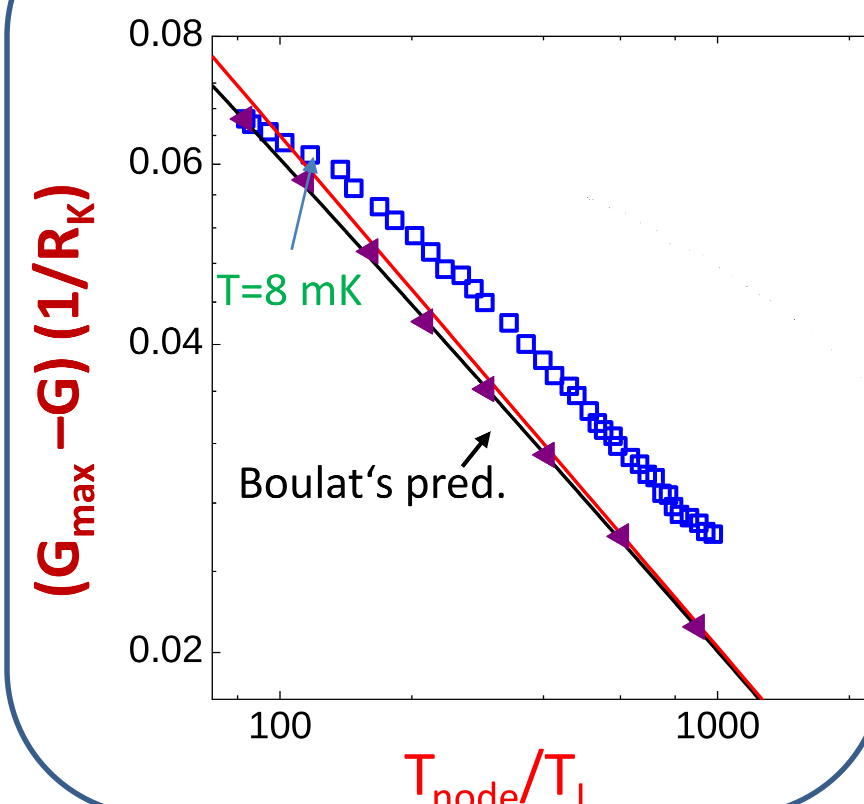


Luttinger parameter $K = \frac{1}{1+R/R_K}$, $G_{max} = (R_K+R)^{-1} = K/R_K$

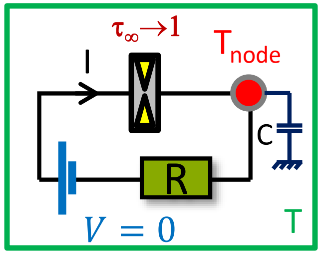
Tunnel : $\tau_\infty \sim 0.1$



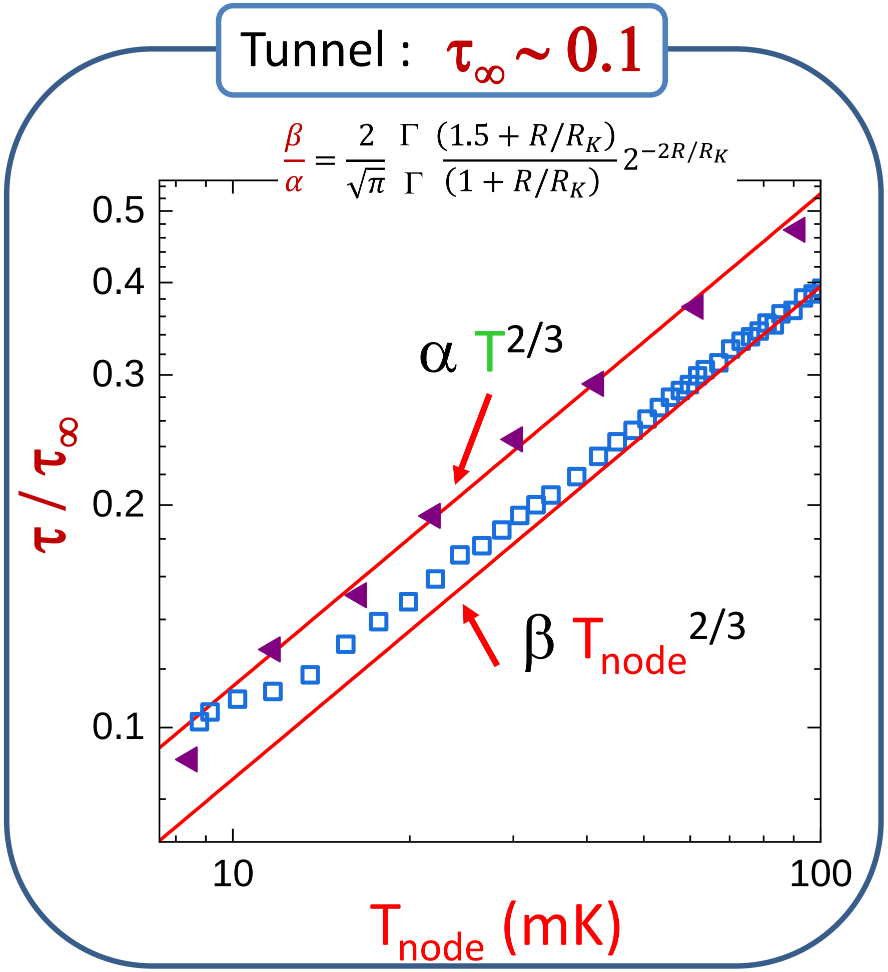
WBS : $\tau_\infty \sim 0.98$

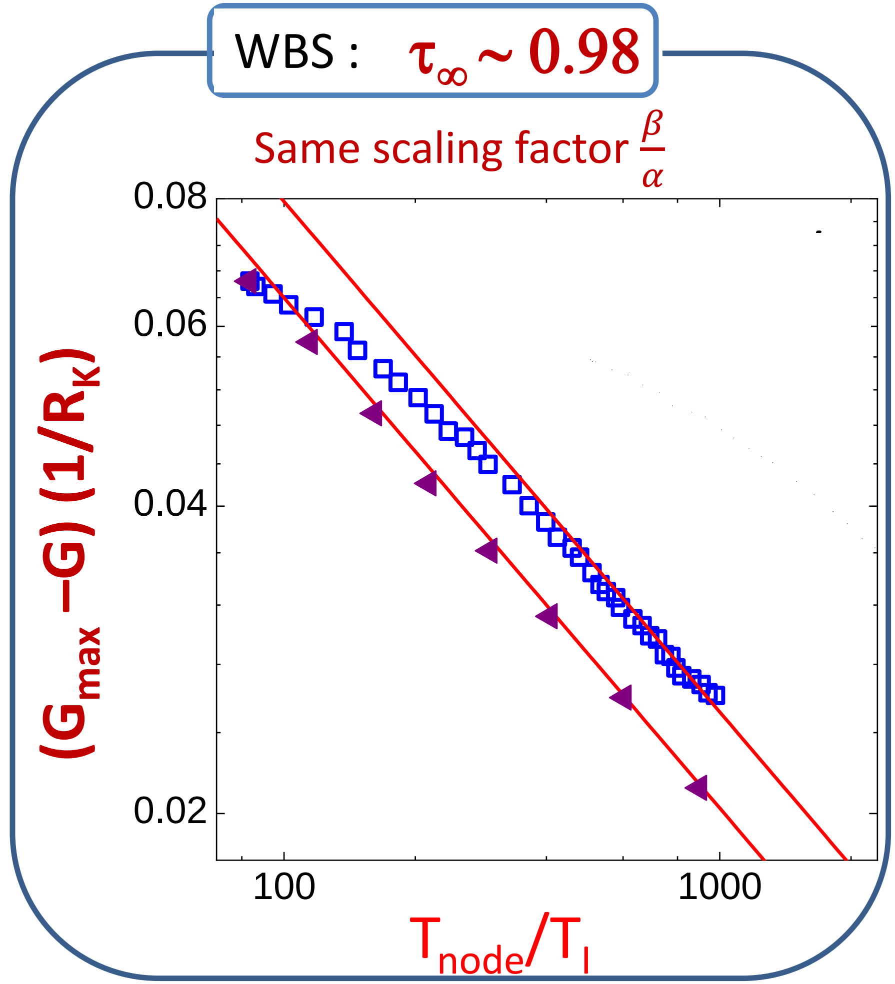


DCB in weak-backscattering regime : temperature bias

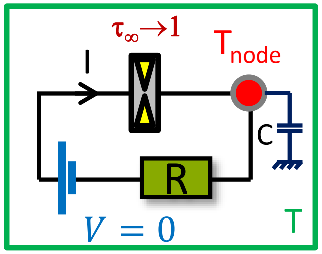


Luttinger parameter $K = \frac{1}{1+R/R_K}$, $G_{max} = (R_K+R)^{-1} = K/R_K$



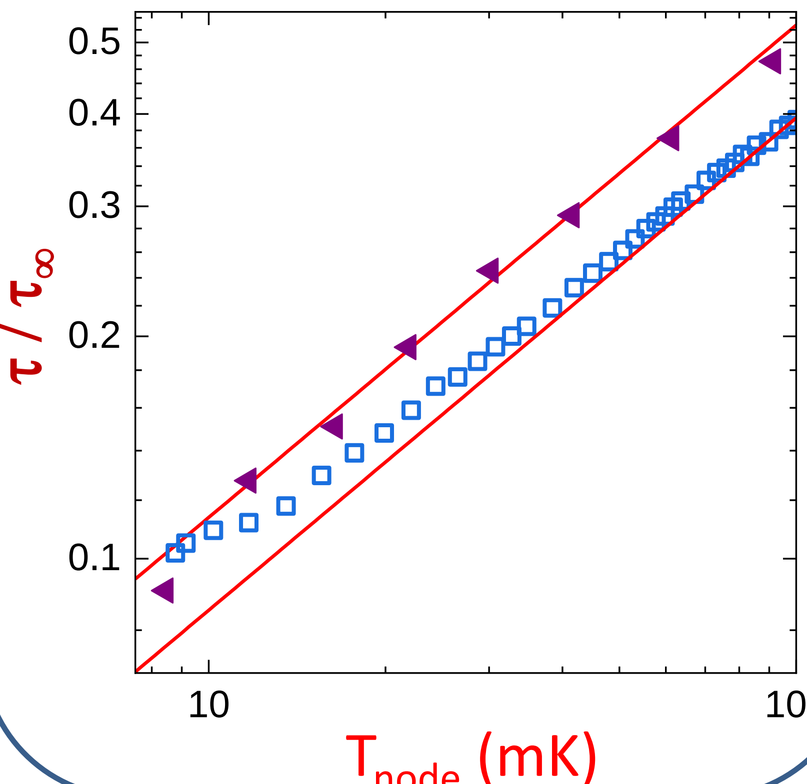


DCB in weak-backscattering regime : temperature bias

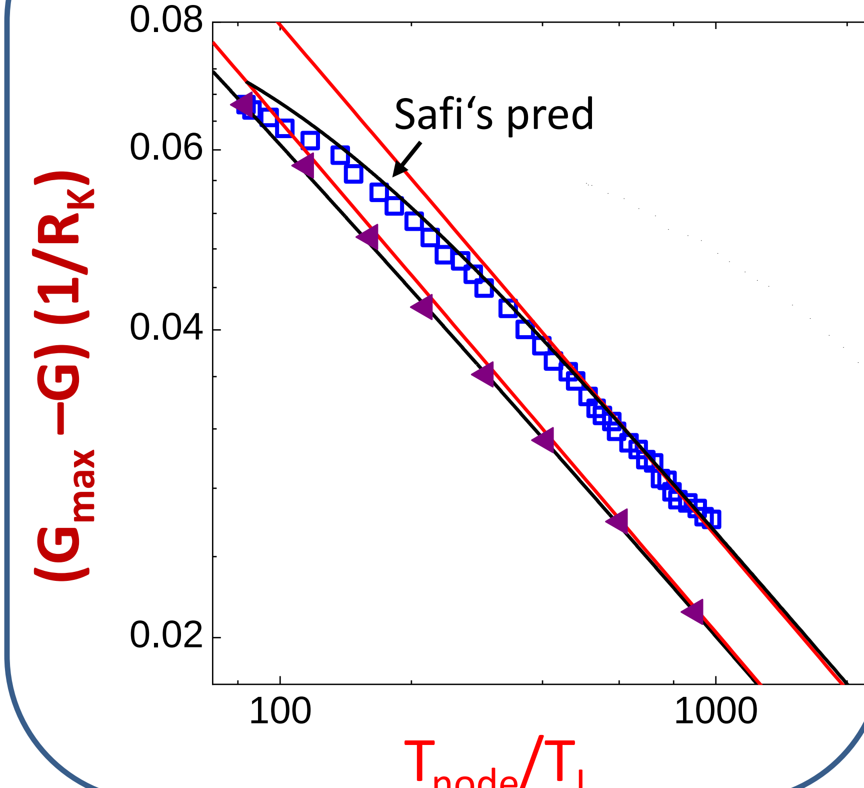


Luttinger parameter $K = \frac{1}{1+R/R_K}$, $G_{max} = (R_K+R)^{-1} = K/R_K$

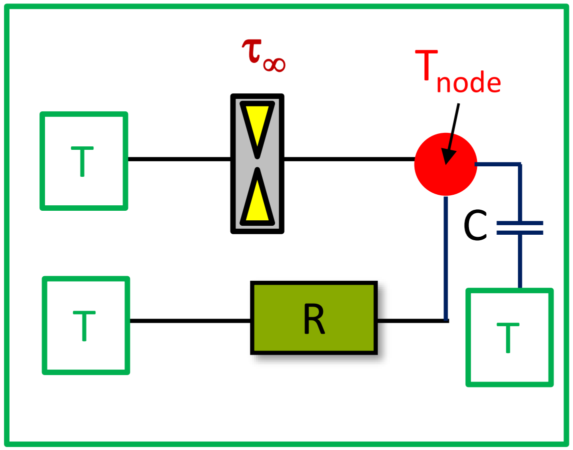
Tunnel : $\tau_\infty \sim 0.1$



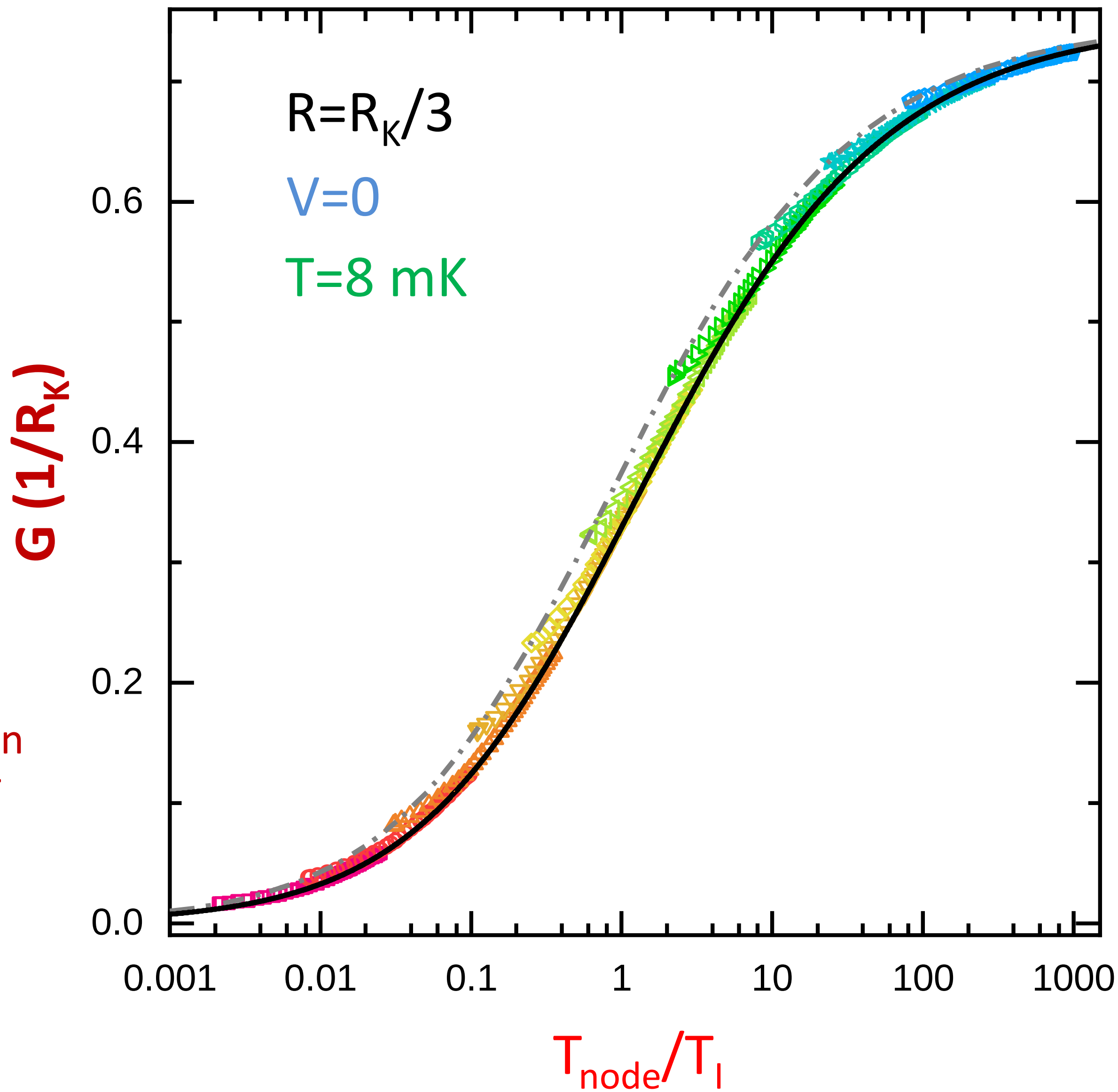
WBS : $\tau_\infty \sim 0.98$



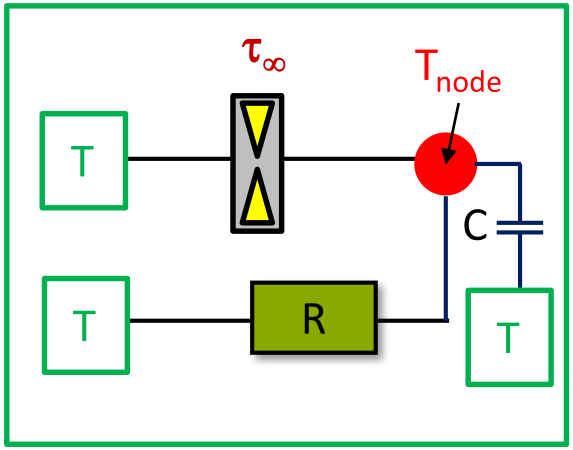
DCB under a T bias



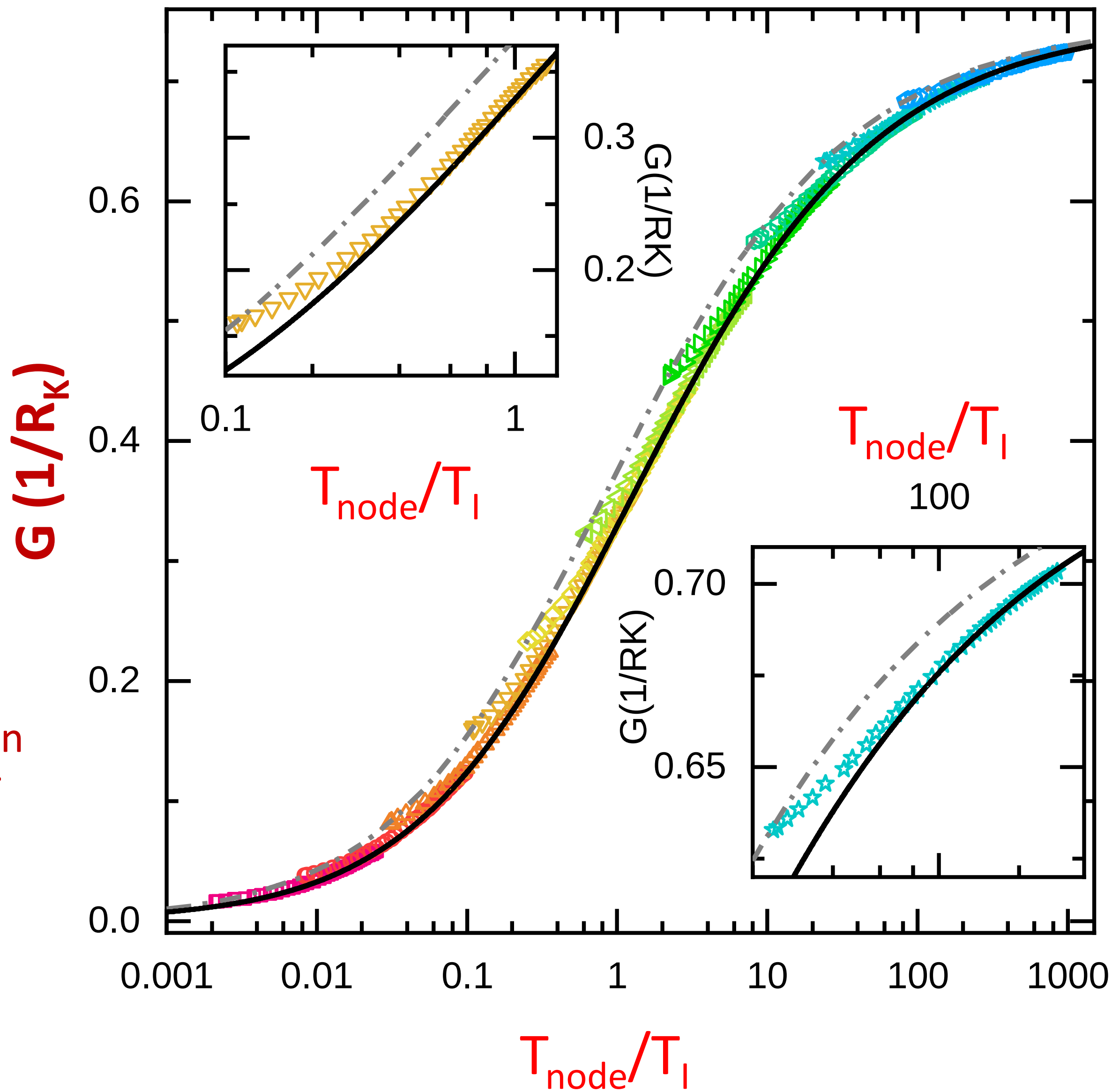
Same scaling factor between equilibrium T and T_{node} >> T on full τ_∞ range



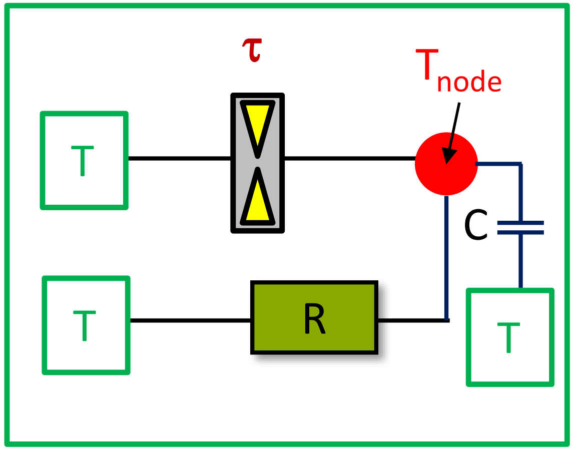
DCB under a T bias



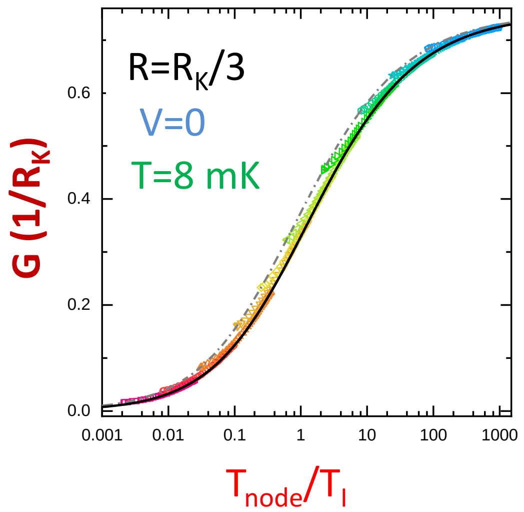
Same scaling factor between equilibrium T and T_{node} >> T on full τ_∞ range



DCB under a T bias : conclusions



PRR **3**, 023122 (2021)



- Exp. : T_{node} >> T = equilibrium prediction at a rescaled $T_r = \gamma T_{node}$

- Thy : γ values predictions only in tunnel and WBS regimes

	$R_K/2$	$R_K/3$	$R_K/4$
Tunnel thy	0.637	0.648	0.655
WBS thy	0.61	0.62	0.64

Slight difference ↗ with R

- Duality between tunnel and WBS regimes in a RC environment in power law and amplitude

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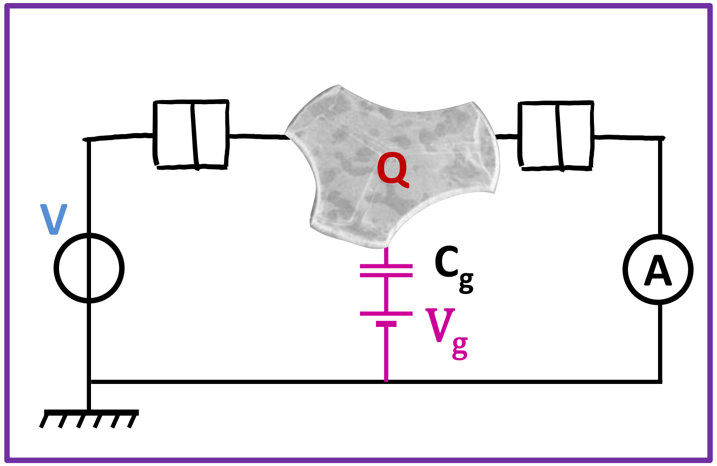
Theory

Edouard Boulat
UP Cité

Christophe Mora
UP Cité

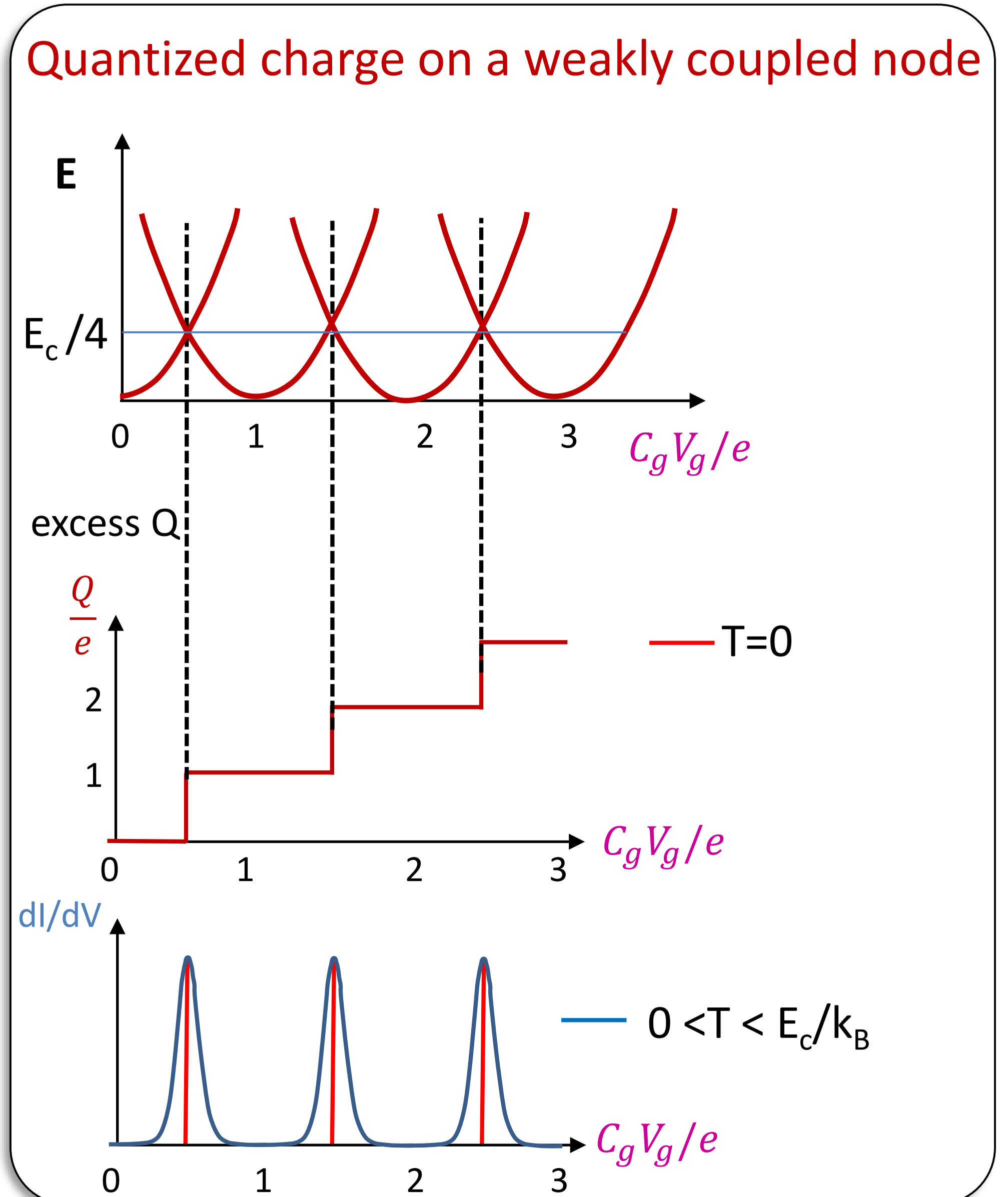
Ines Safi
CNRS

Single electron transistor Coulomb blockade

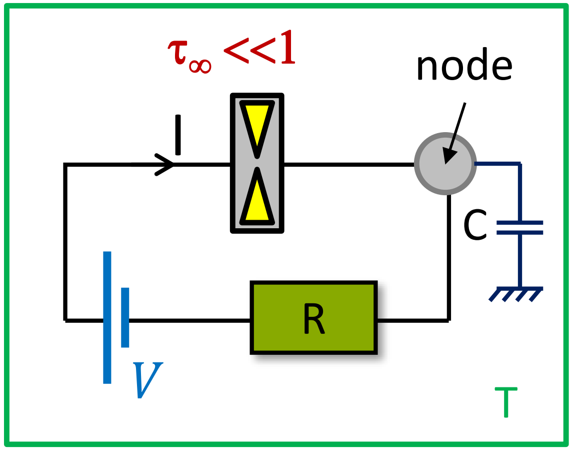


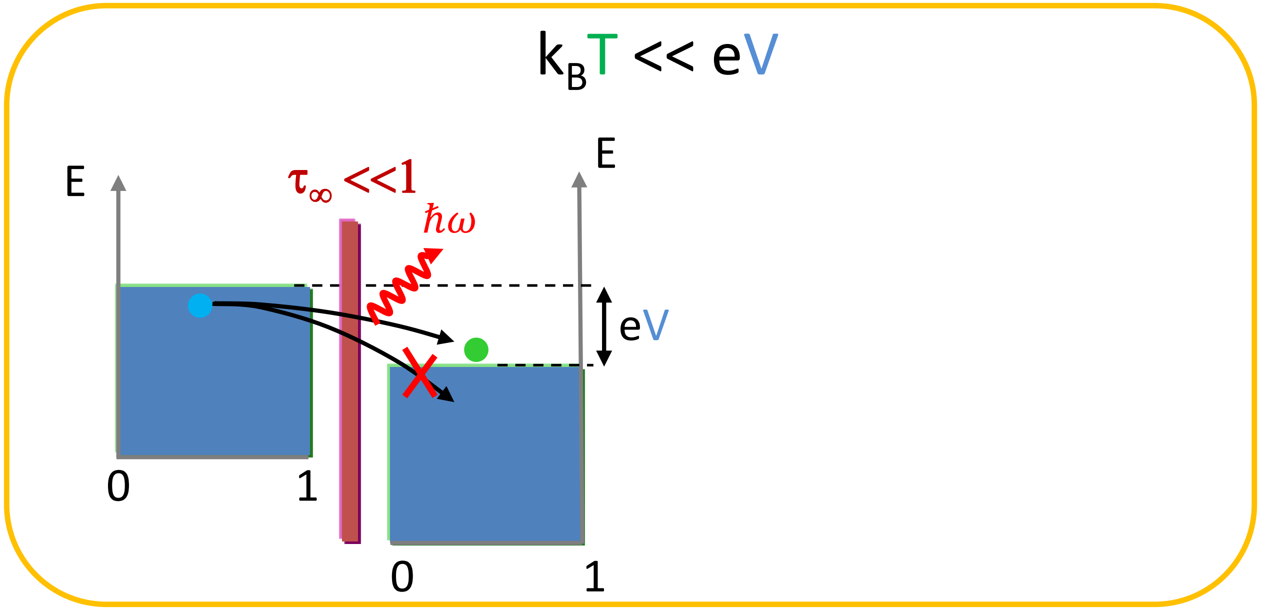
Weakly coupled node

Charging energy $E_c = e^2/2C$



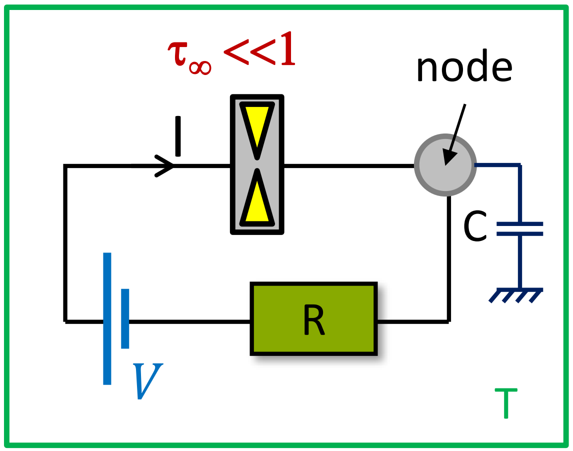
Dynamical Coulomb Blockade : tunnel regime

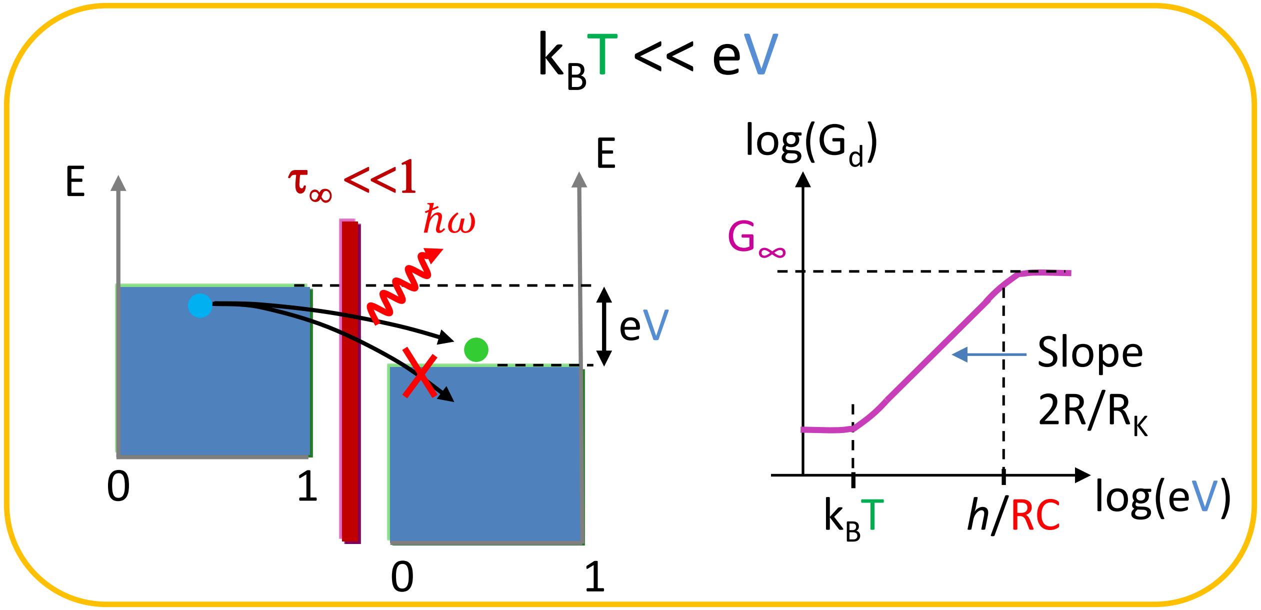




See Ingold & Nazarov in "Single Charge Tunneling" (Ed. Grabert & Devoret, 1992)

Dynamical Coulomb Blockade : tunnel regime





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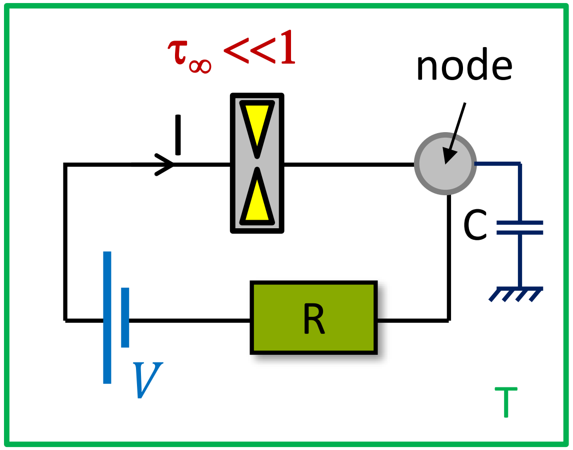
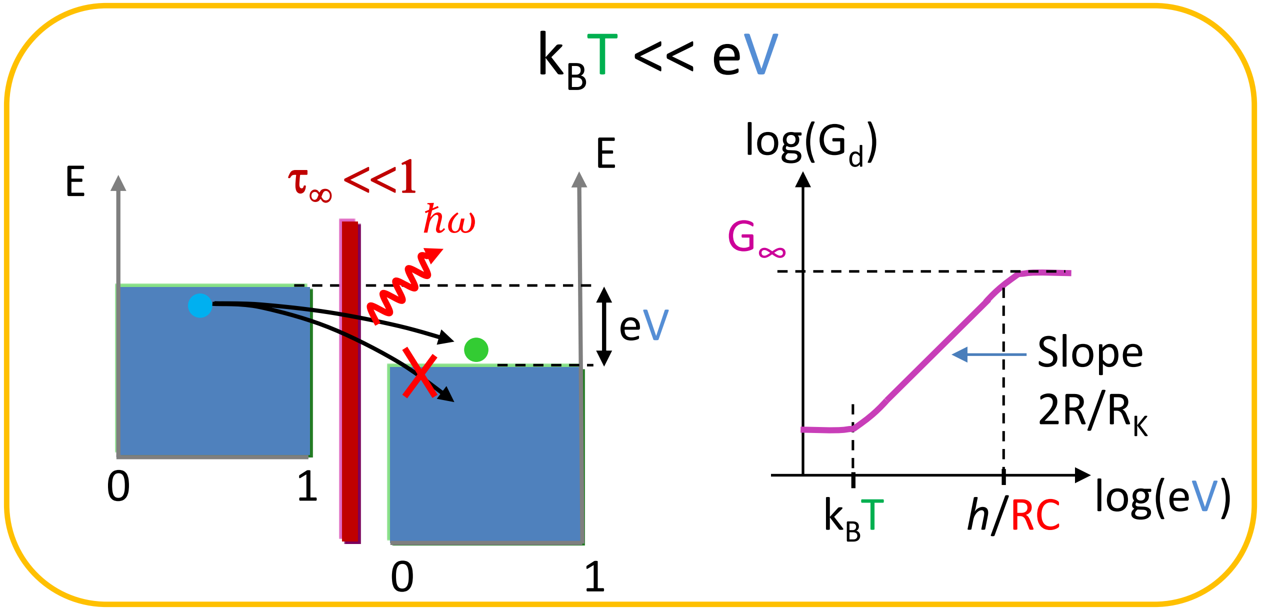
Dynamical Coulomb Blockade : tunnel regime





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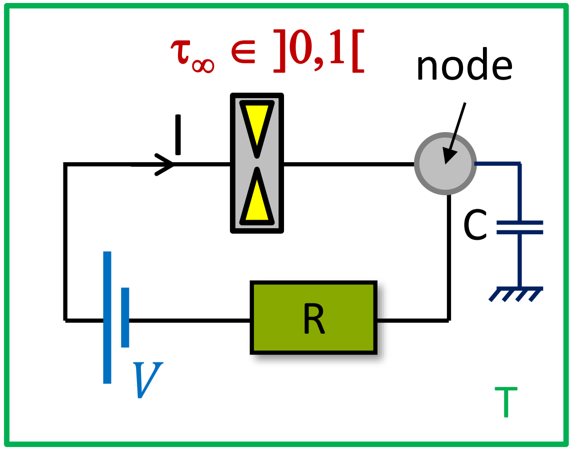
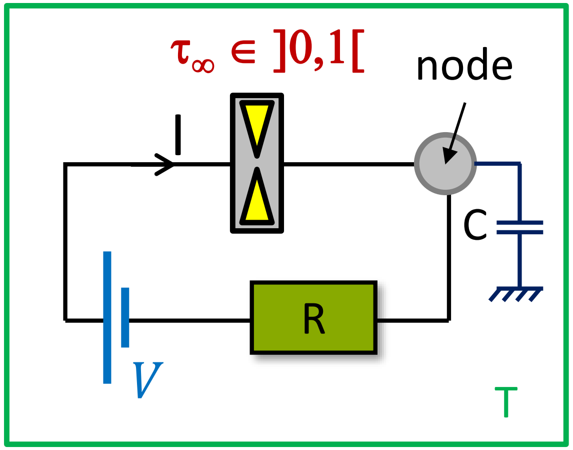
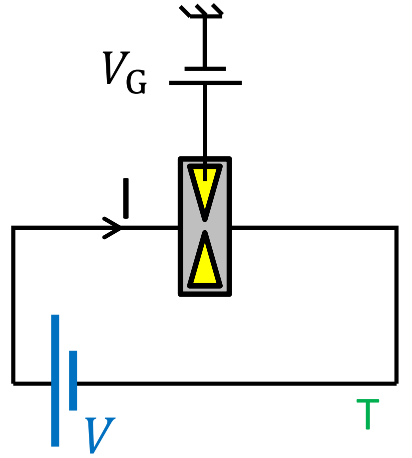
DCB : One-channel quantum conductor in series with a resistance

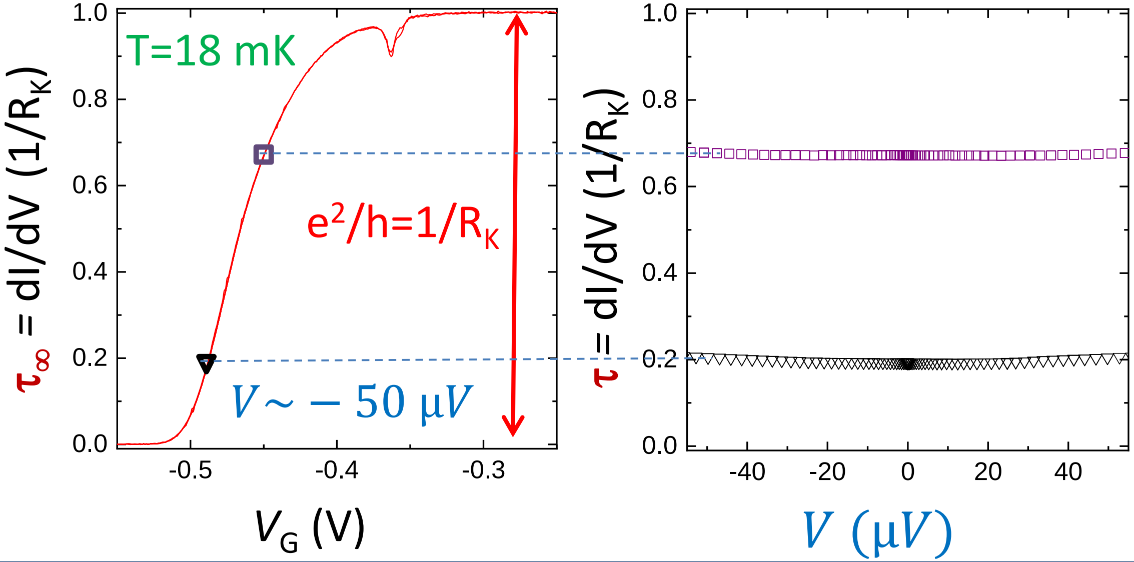


DCB : One-channel quantum conductor in series with a resistance



One-channel quantum conductor : quantum point contact





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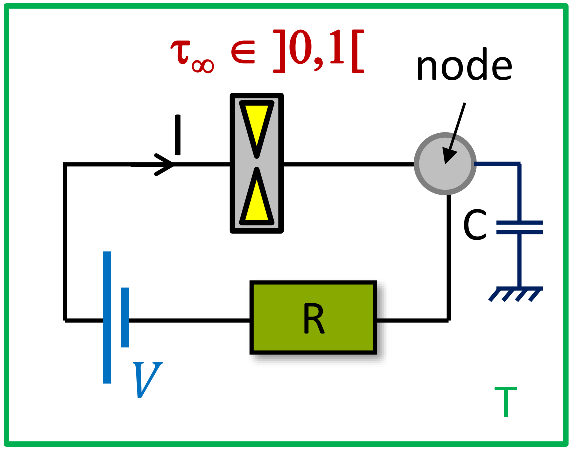
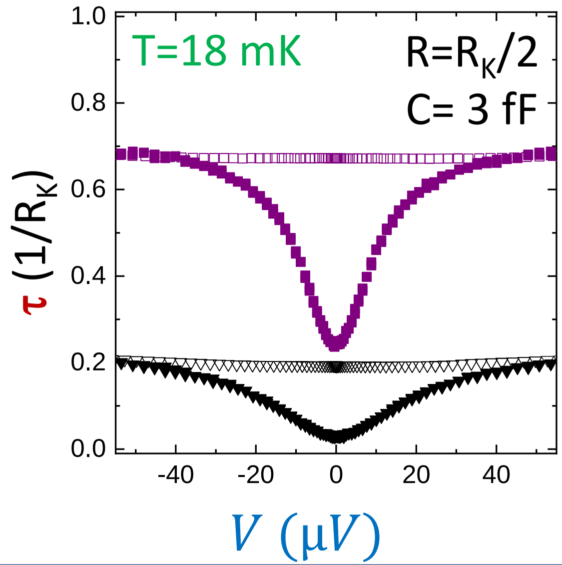


Effect of RC environment

granularity of charge transfers, $\tau_\infty \in]0,1[$

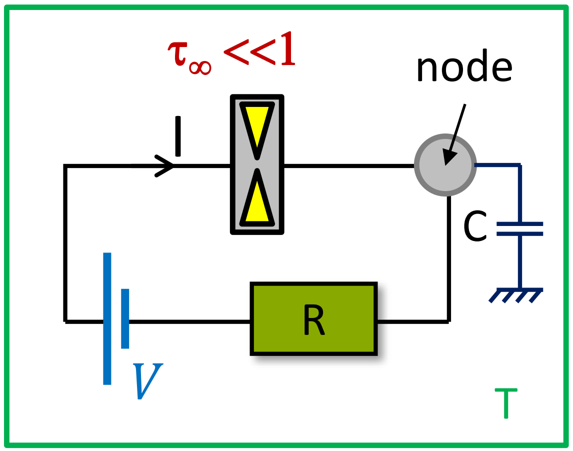
Shot-noise → Environment excitation (δQ_{node} + RC dynamics)

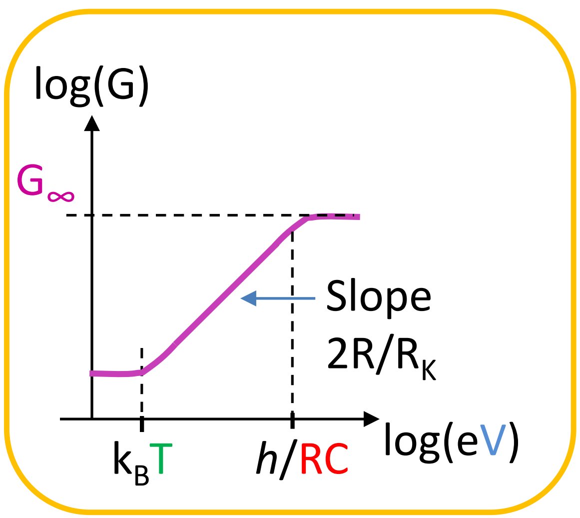
→ Suppression of the electrical conductance at low energy

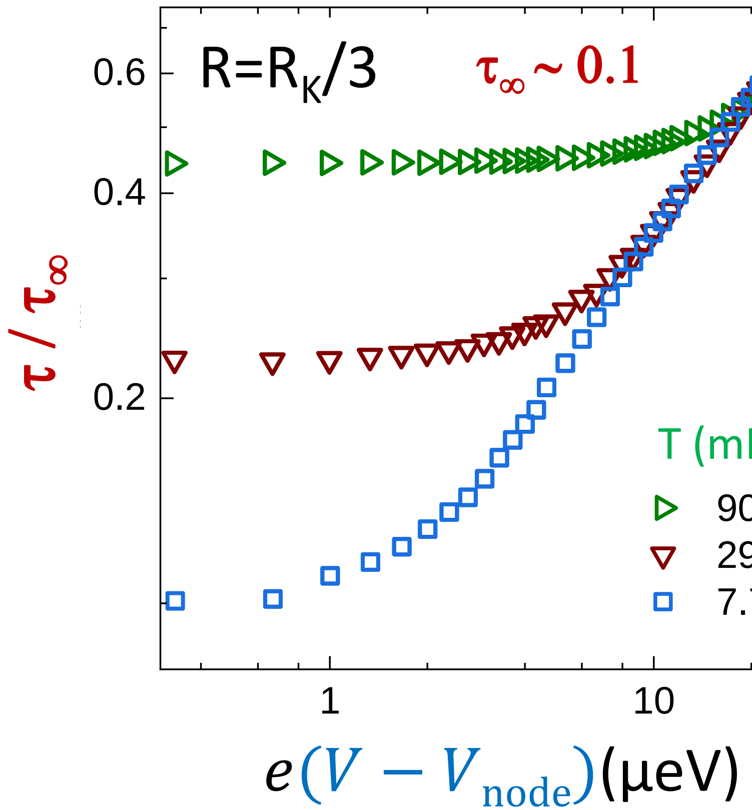


DCB in tunnel regime

Test-bed sample versus V ?







DCB in tunnel regime

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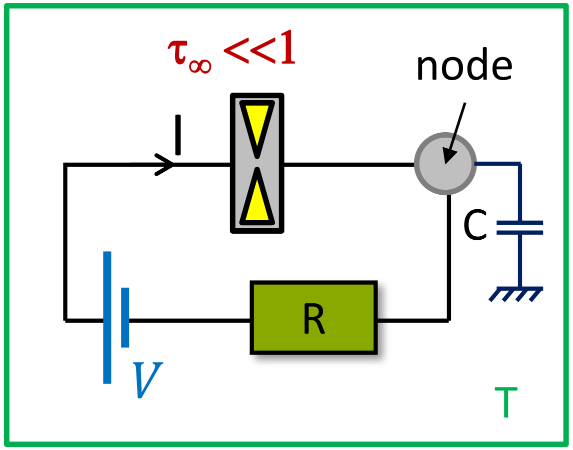

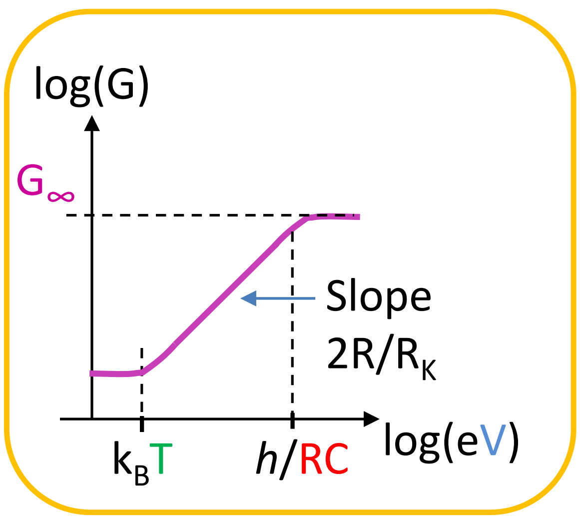

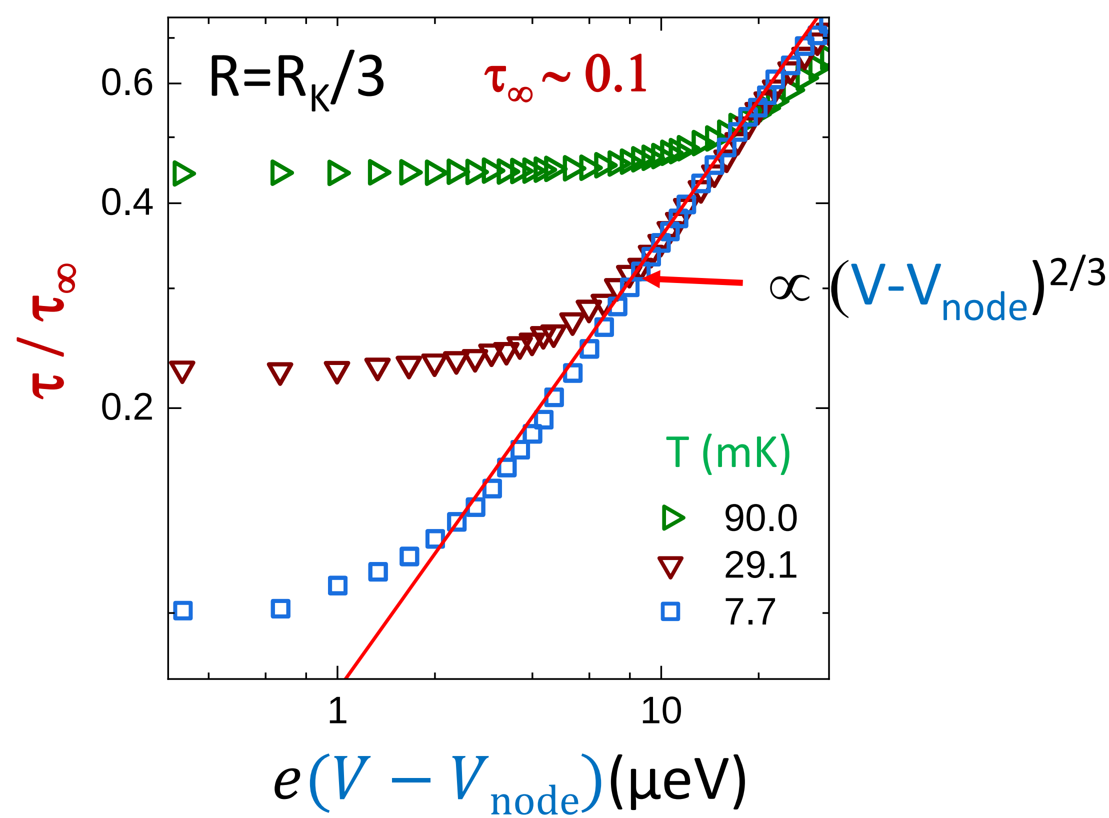

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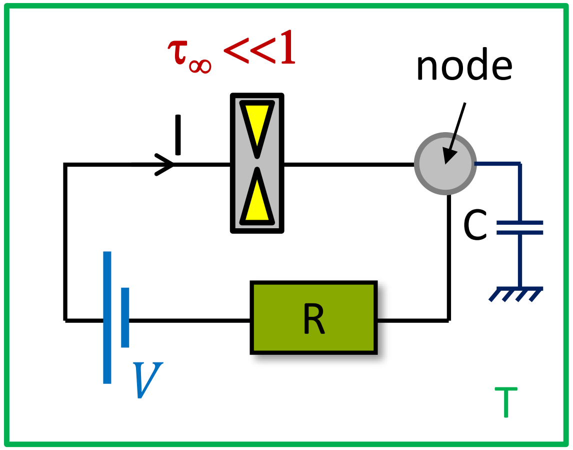

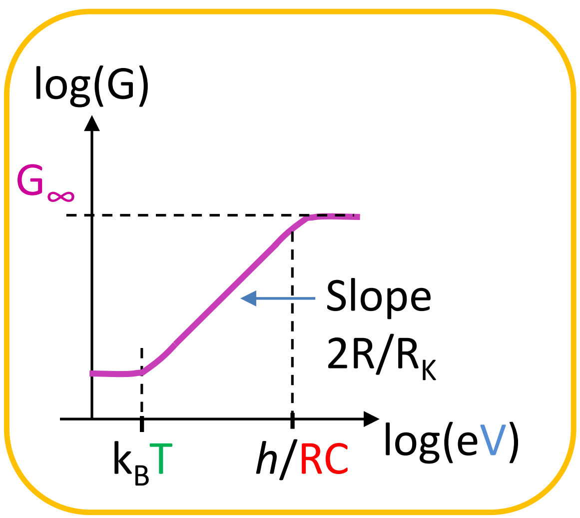

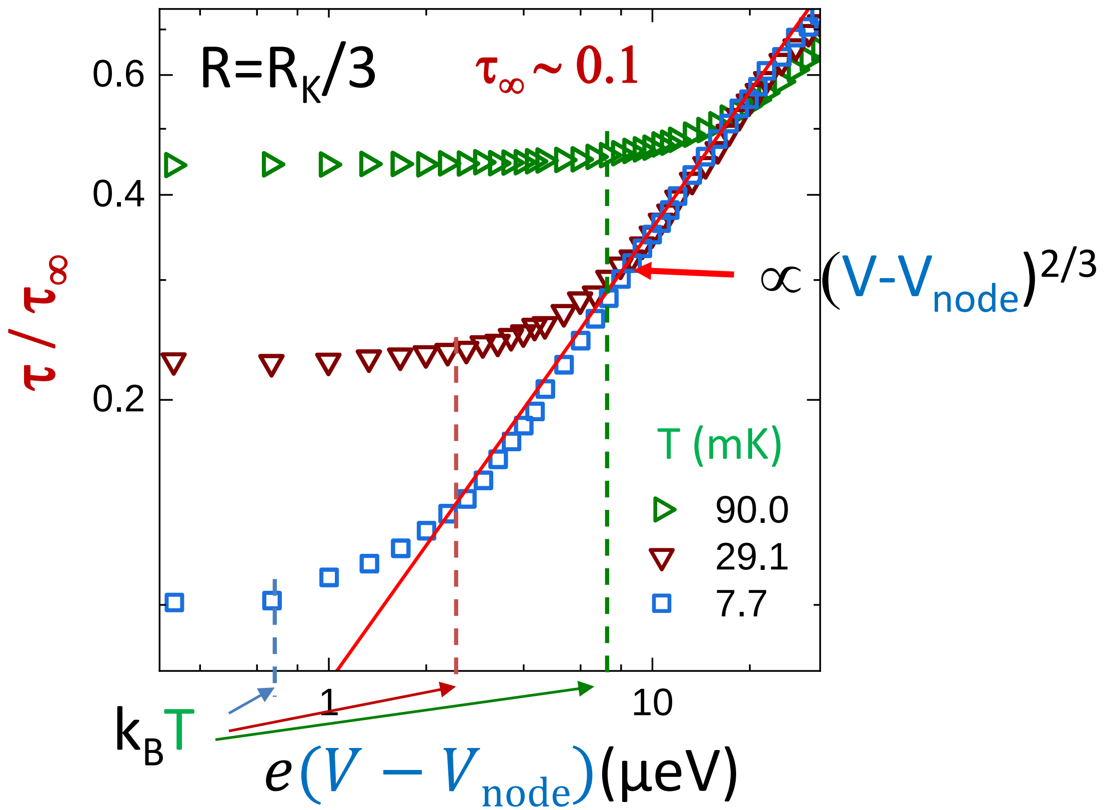

DCB in tunnel regime

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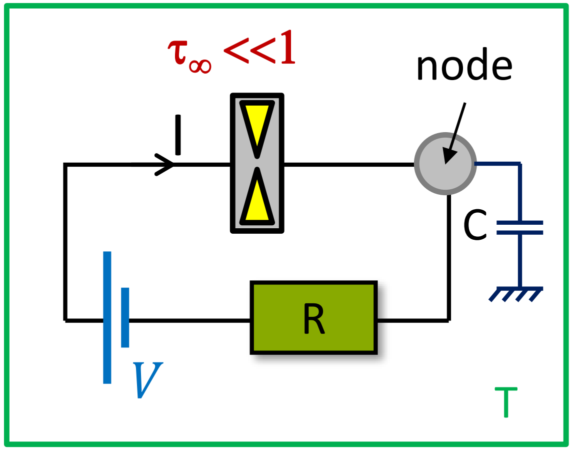

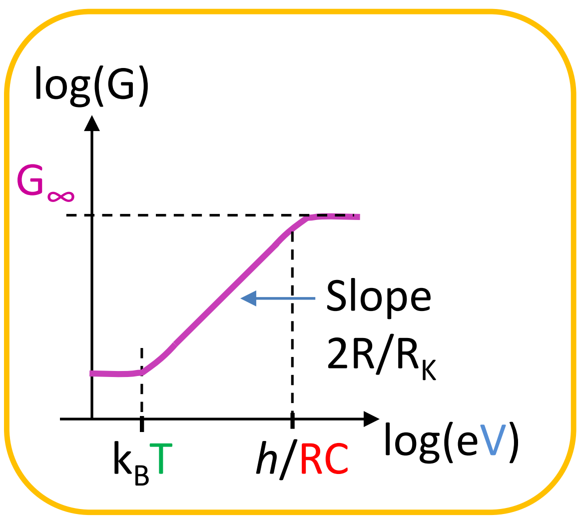

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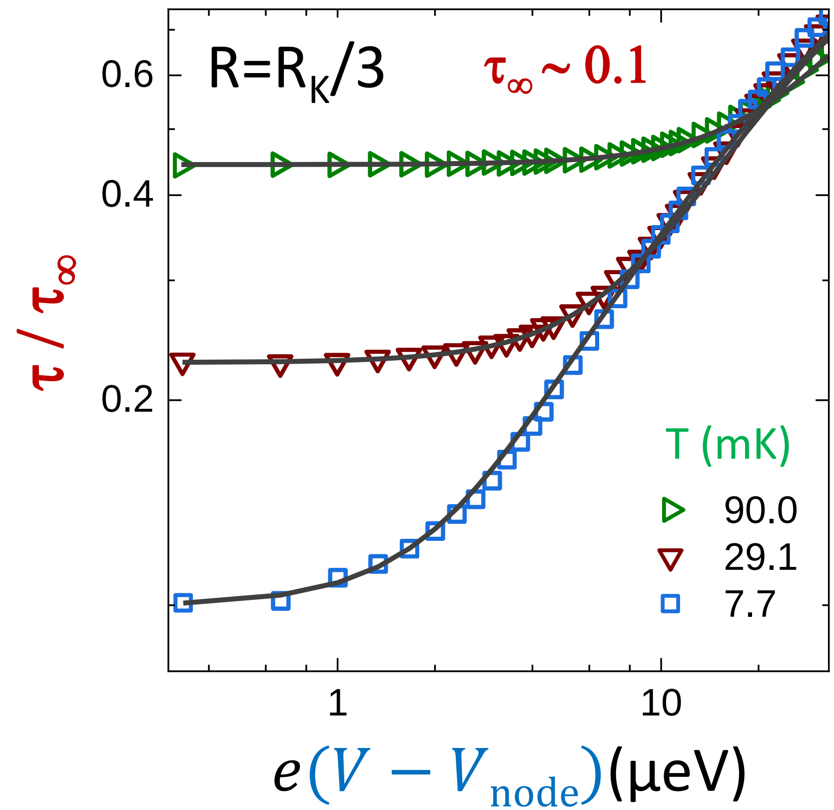
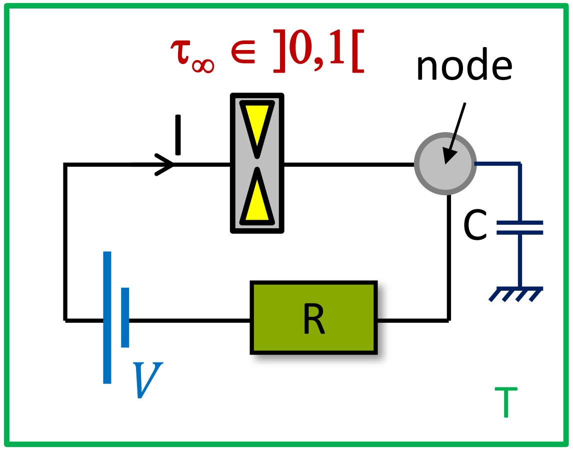
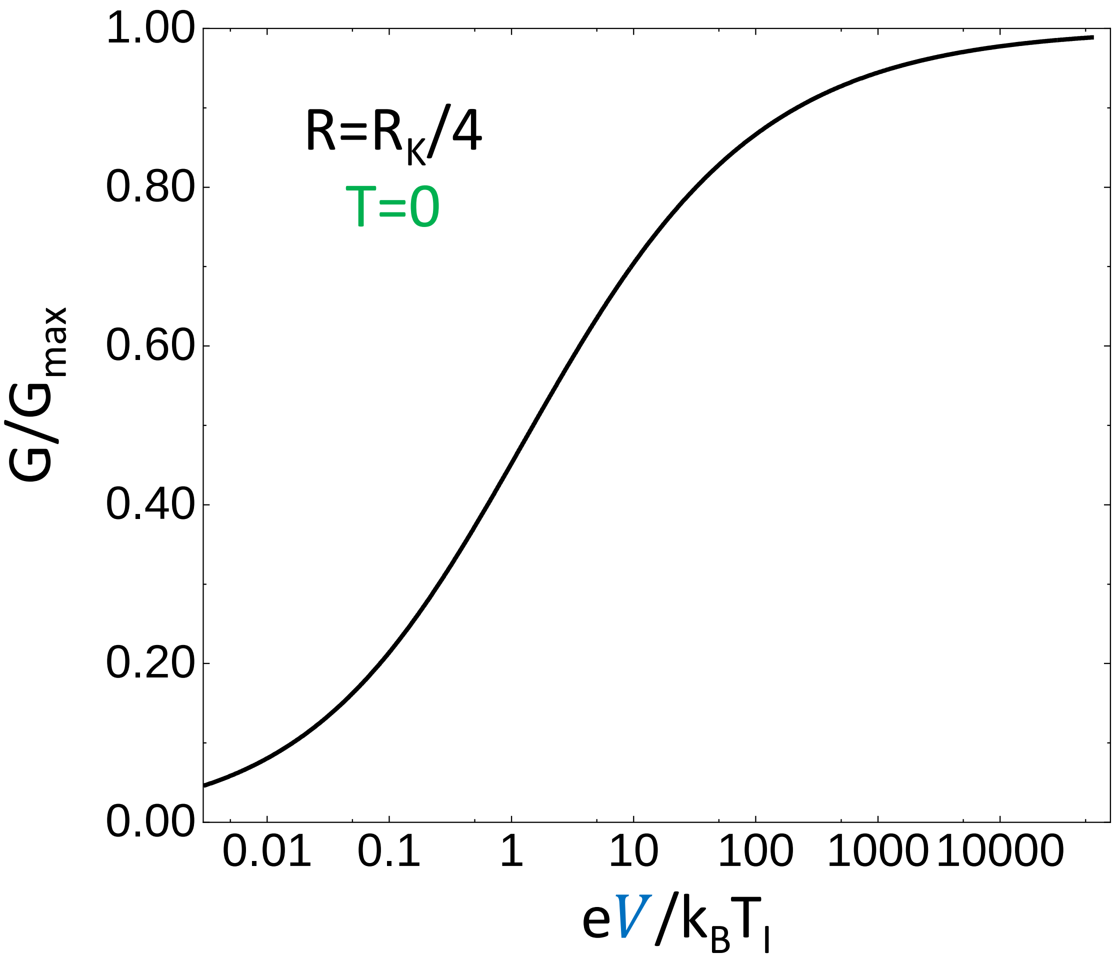


P(E) theory ➡ C= 2.5 fF

Conductor-insulator crossover

with V : $G = dI/dV \in [0, G_{max} = (R_K + R)^{-1}]$

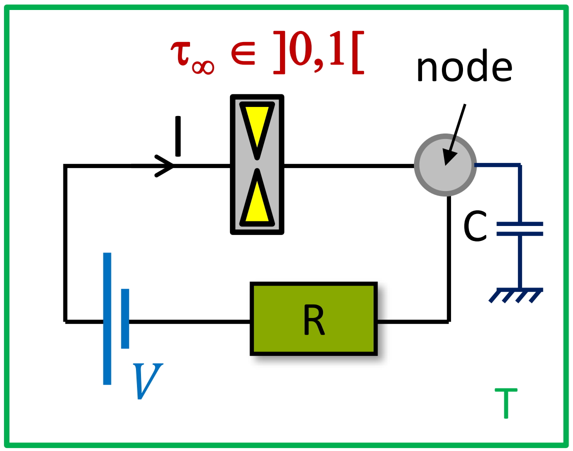




PRB **52,** 8934 (1995), PRL **93**, 126602 (2004)

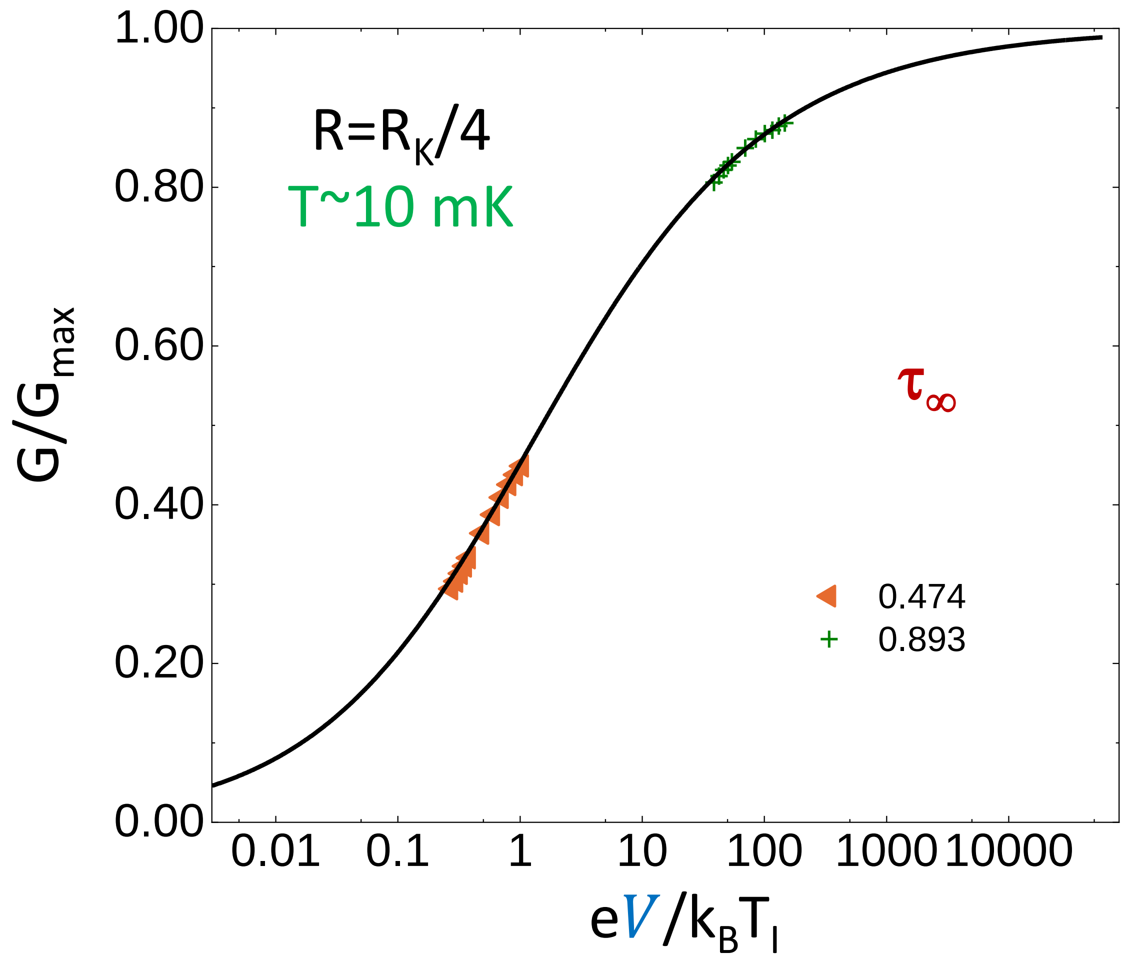
Conductor-insulator crossover

with V : $G = dI/dV \in [0, G_{max} = (R_K + R)^{-1}]$



$h/RC \gg eV > 12\, k_B T$

Exp : 30 µV > V > 8 µV



PRB **52,** 8934 (1995), PRL **93**, 126602 (2004)
Nat. Comm. **4**, 1802 (2013) and PRX **8**, 031075 (2018)

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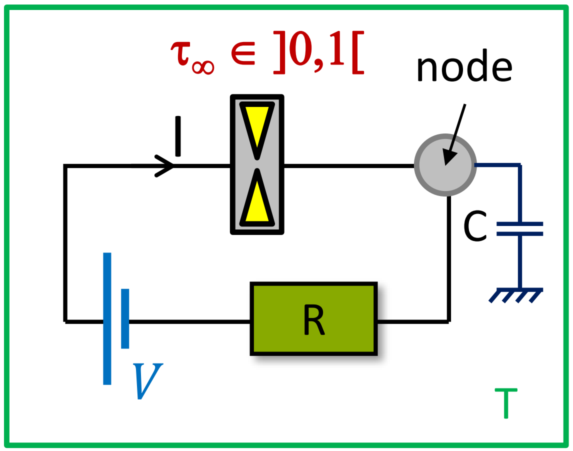

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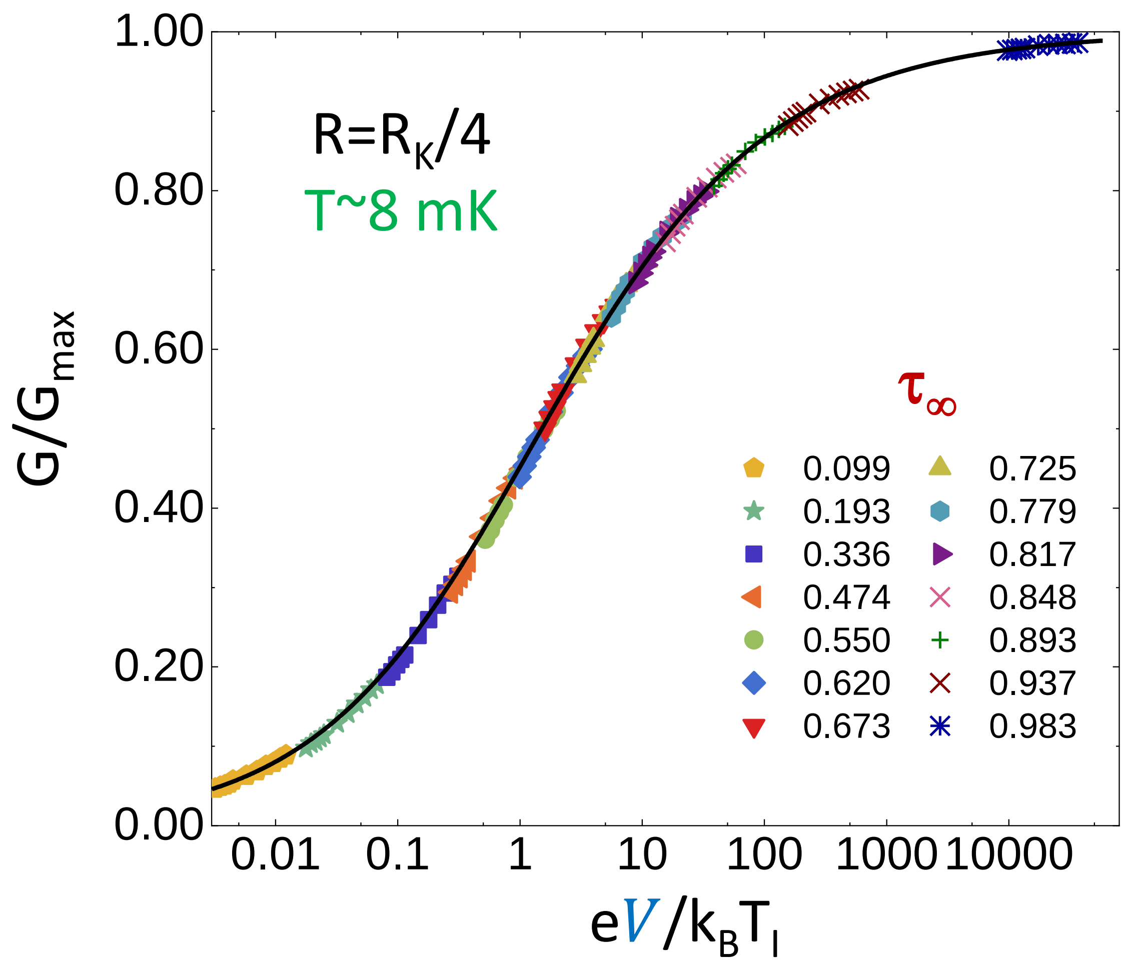

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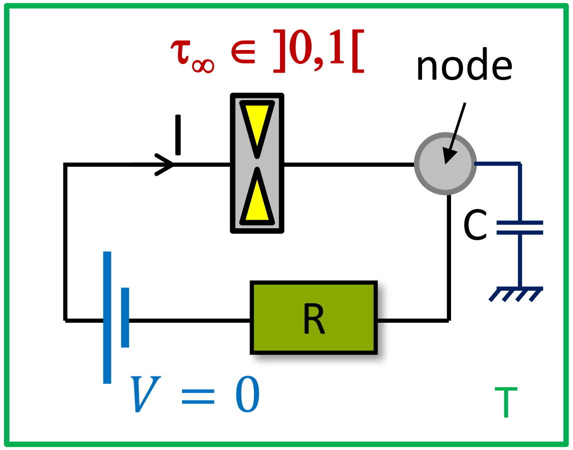
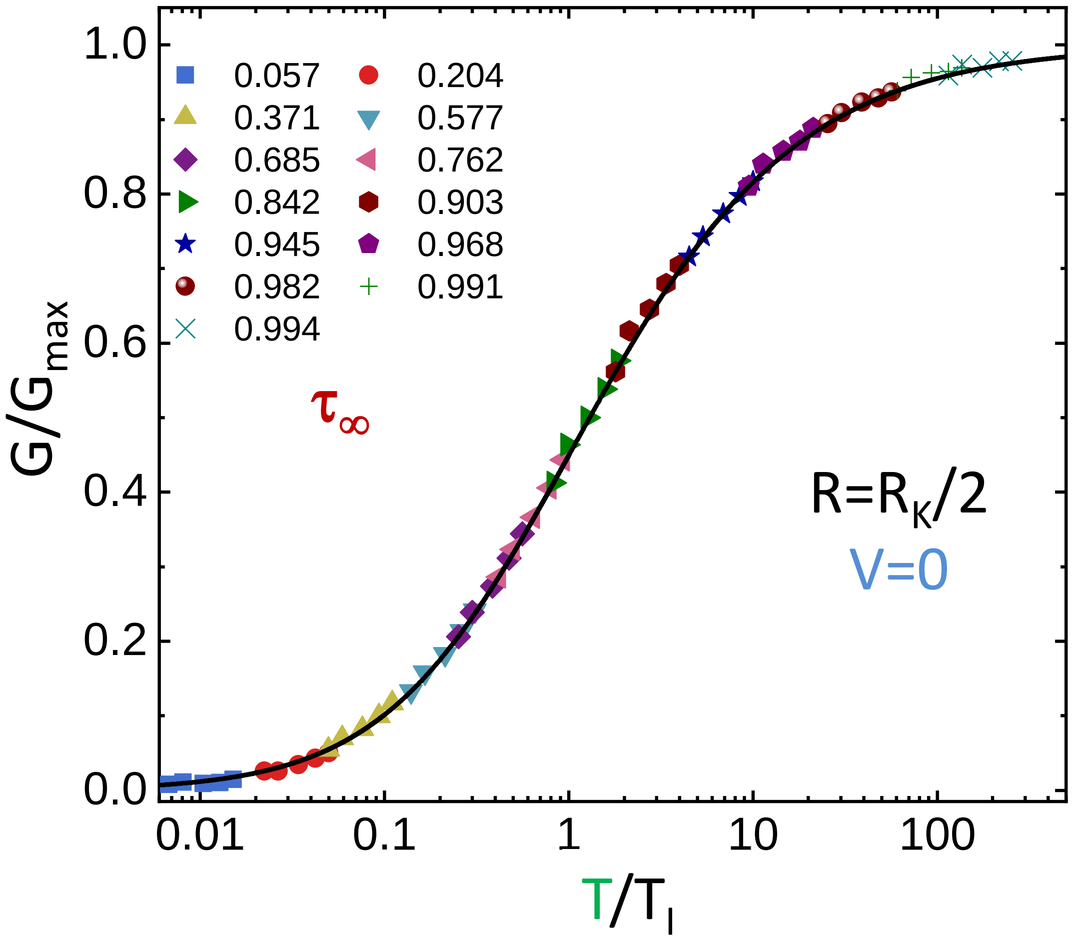


Exp : 8 mK ≤ T ≤ 18 mK

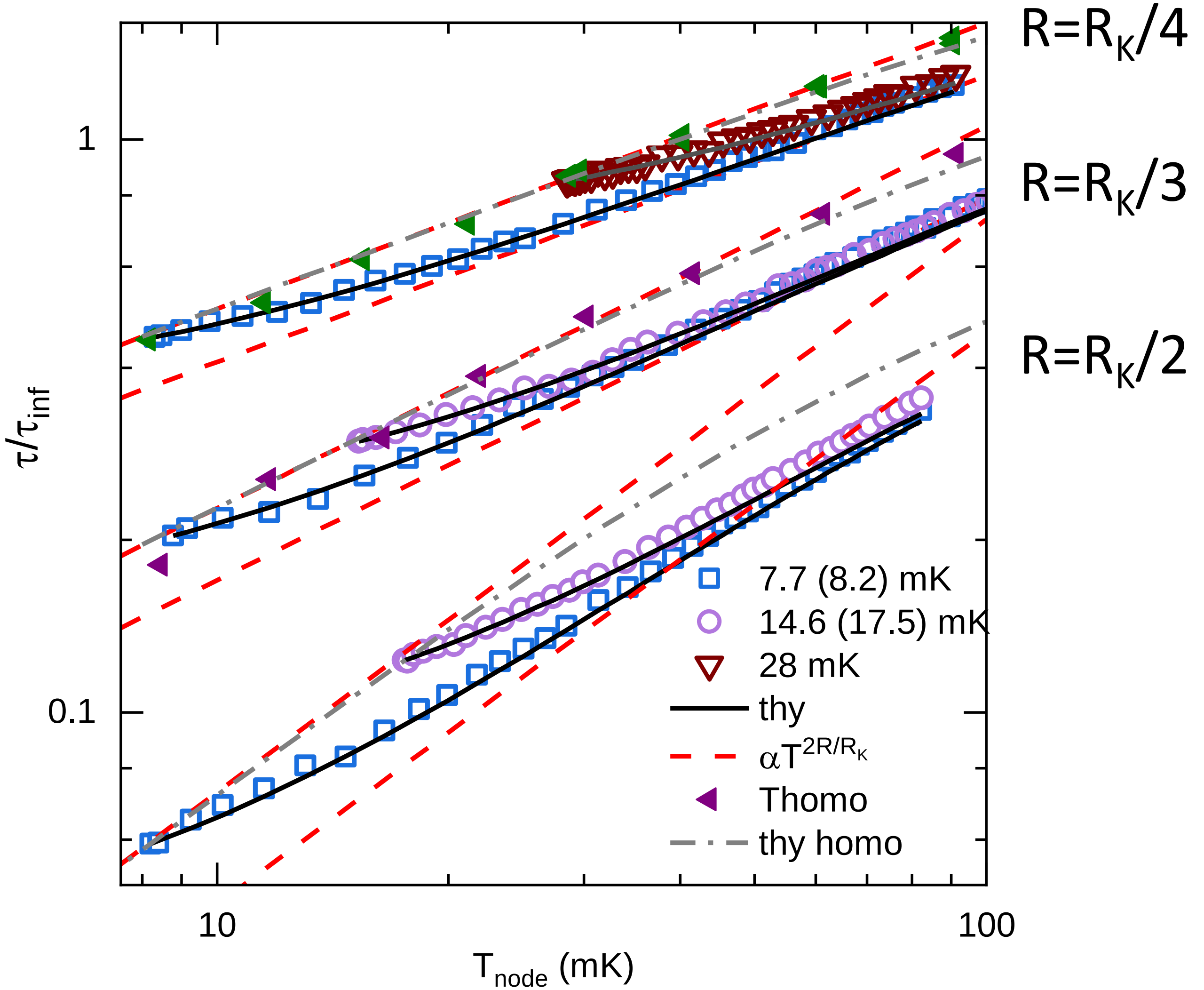
PRX **8**, 031075 (2018)



Temperature bias effect ? $T_{node} \neq T$ (V=0)

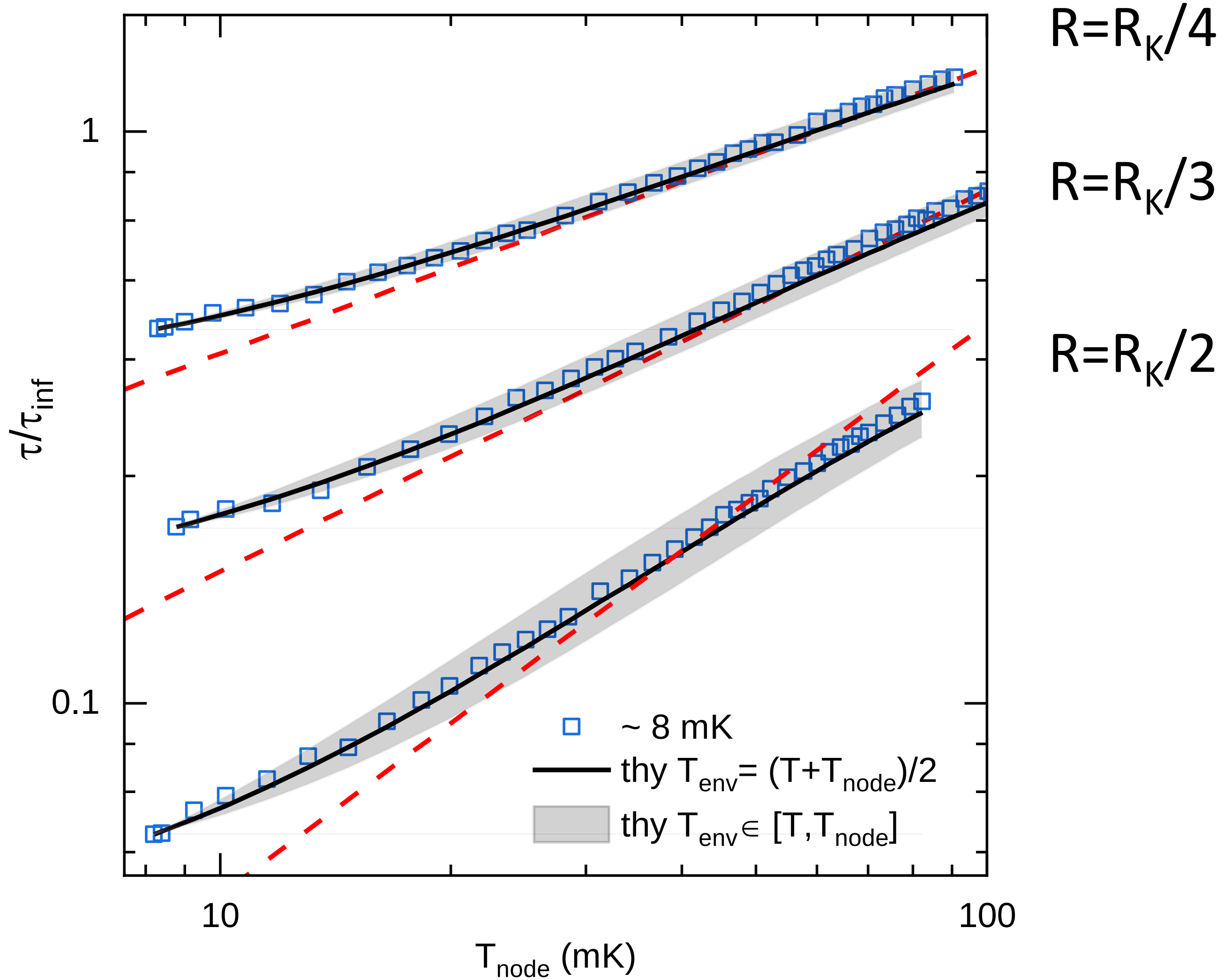
DCB in tunnel regime under a temperature bias

Different environment

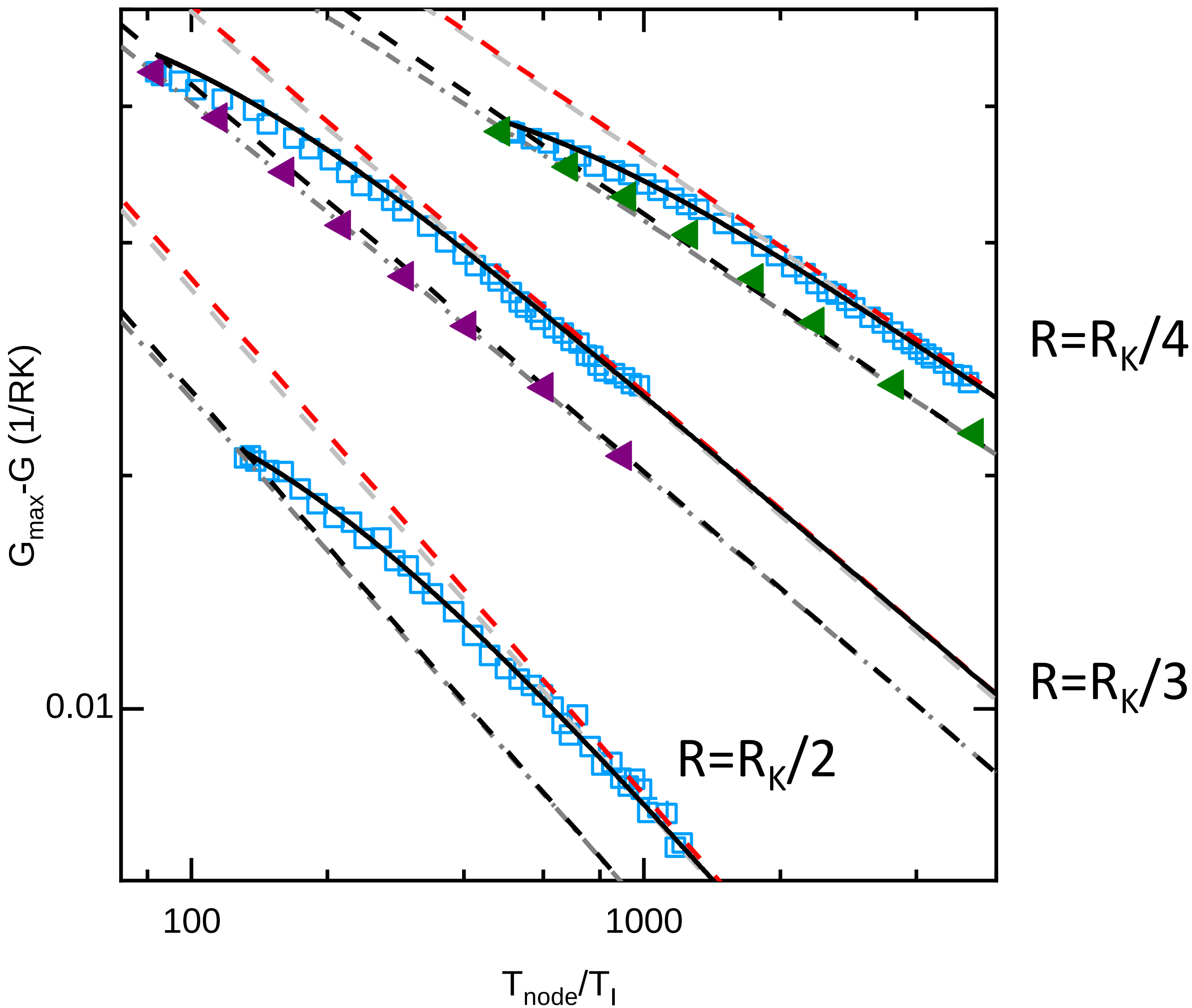


DCB in tunnel regime under a temperature bias

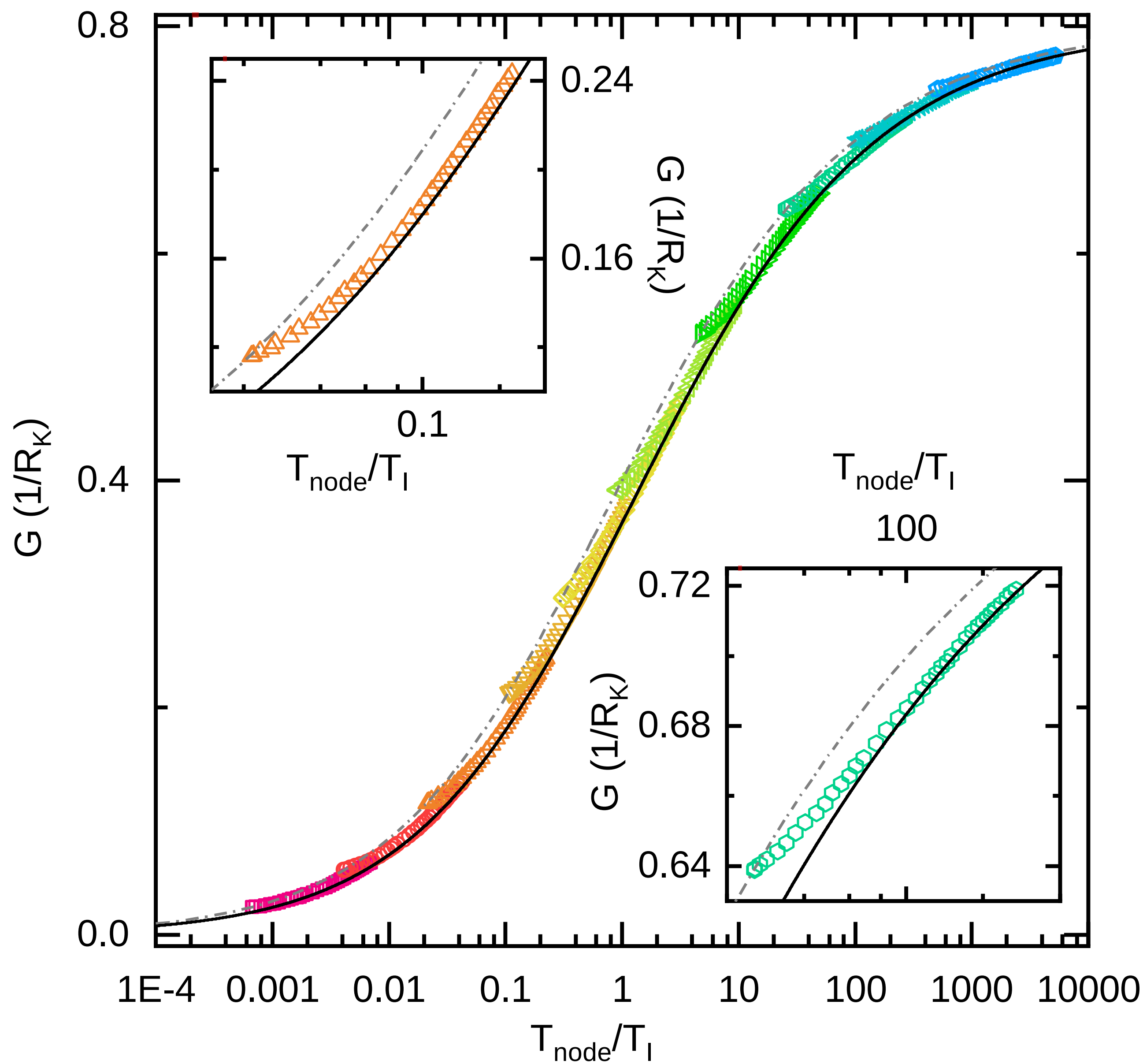
Environment temperature ?



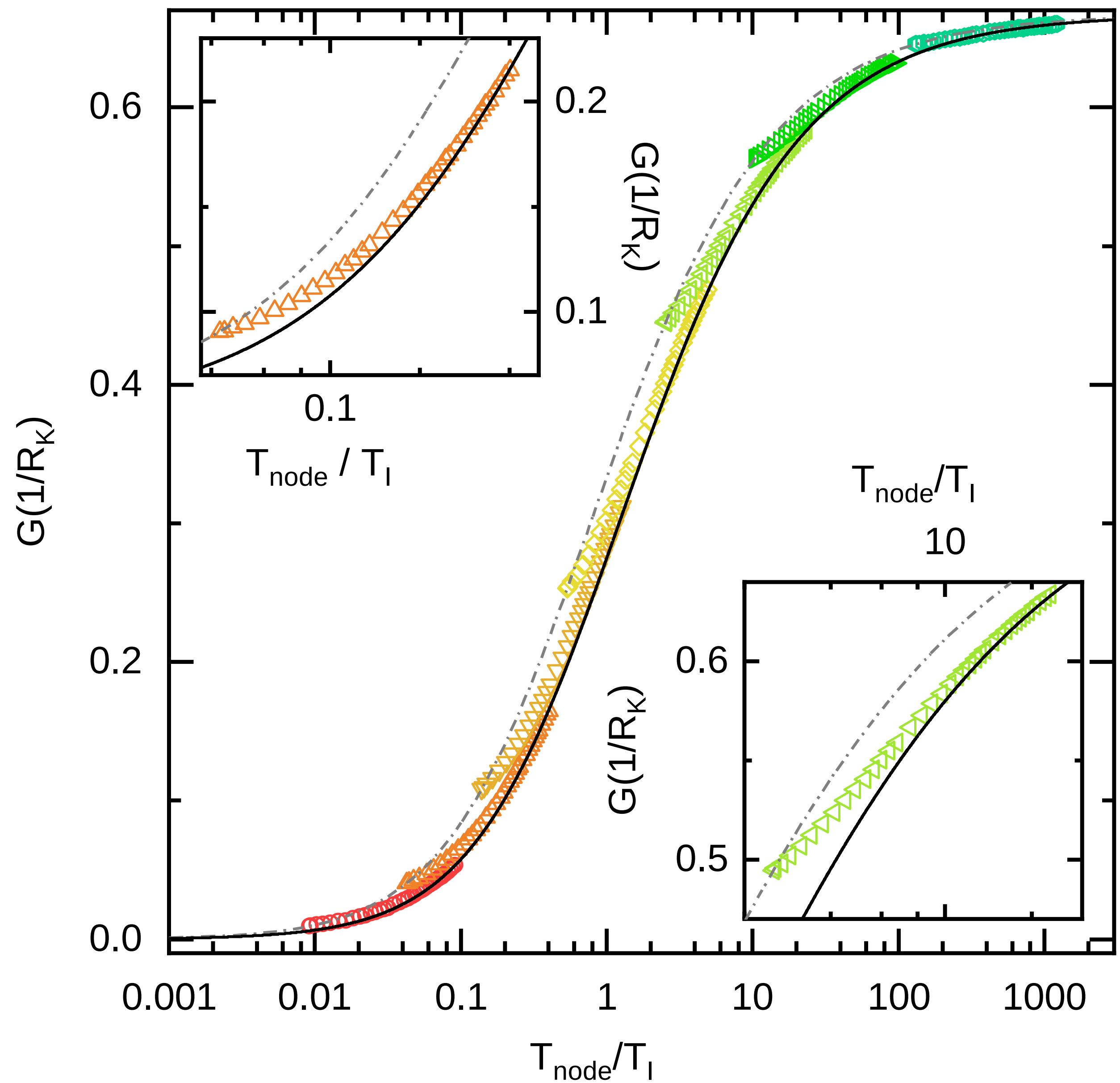
DCB under a temperature bias : Weak-backscattering regime



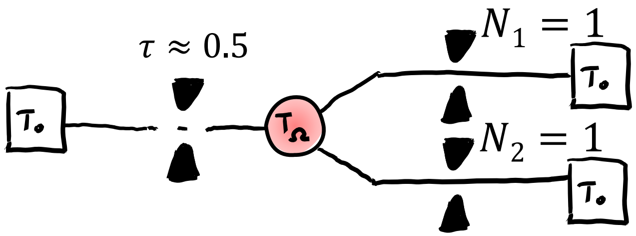
DCB under a temperature bias : $R_K/4$

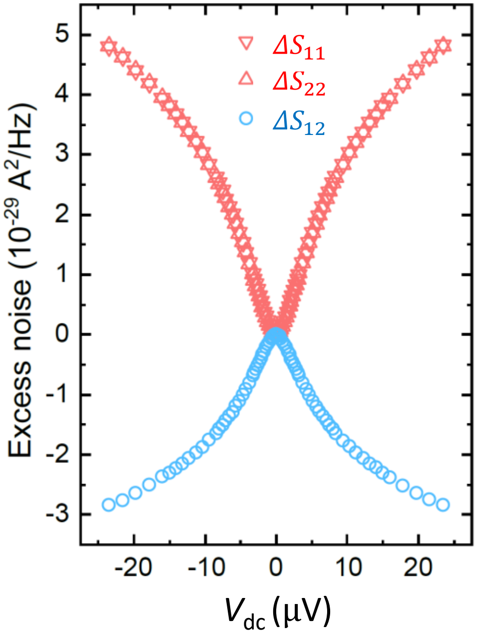


DCB under a temperature bias : $R_K/2$

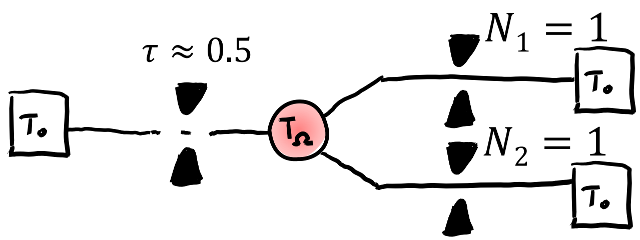


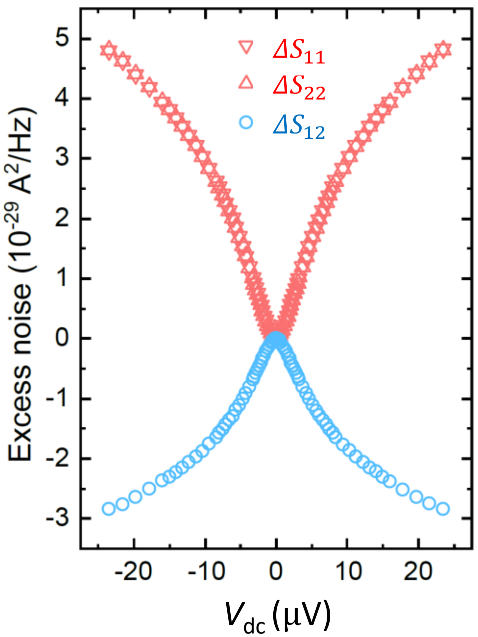
Noise sources extraction





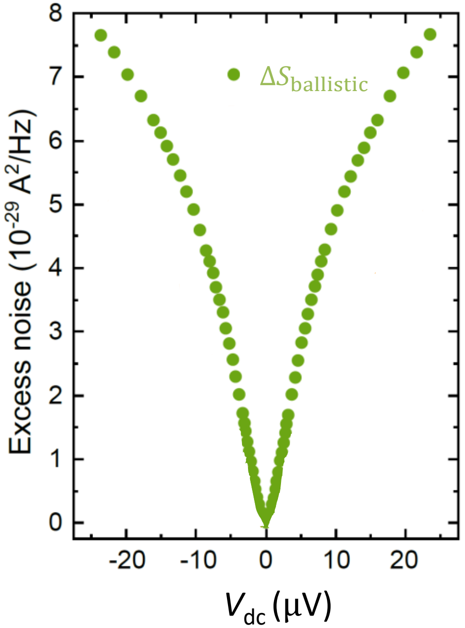
Noise sources extraction



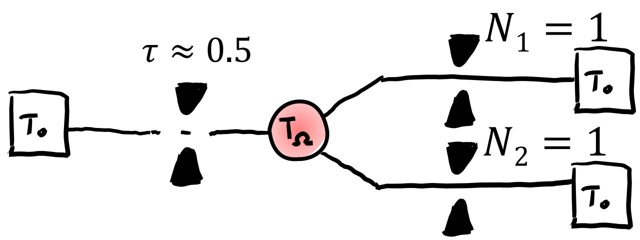


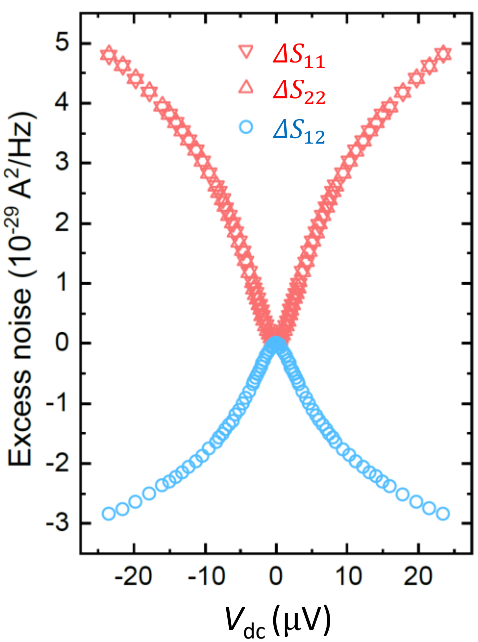
$$\Delta S_{\text{ballistic}} = \frac{\Delta S_{11}}{2N_1} + \frac{\Delta S_{22}}{2N_2} - \frac{\Delta S_{12}}{2N_1 N_2}(N_1 + N_2)$$

$$= \frac{2\,k_B(T_\Omega - T_0)}{R_K}$$



Noise sources extraction

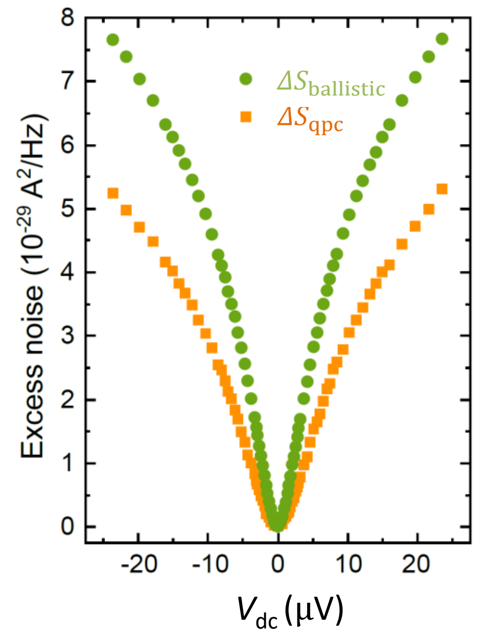




$$\Delta S_{\text{ballistic}} = \frac{\Delta S_{11}}{2N_1} + \frac{\Delta S_{22}}{2N_2} - \frac{\Delta S_{12}}{2N_1 N_2}(N_1 + N_2)$$

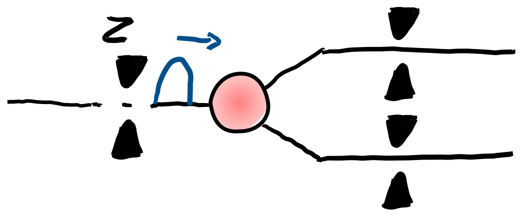
$$= \frac{2\, k_B (T_\Omega - T_0)}{R_K}$$

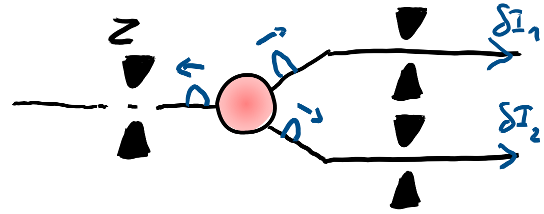
$$\Delta S_{\text{qpc}} = (N_1 + N_2 + 2\tau)\left[\frac{\Delta S_{11}}{2N_1} + \frac{\Delta S_{22}}{2N_2}\right] + \Delta S_{12}\frac{(N_1 + N_2 + \tau)^2 + \tau^2}{2N_1 N_2}$$



Noise sources extraction

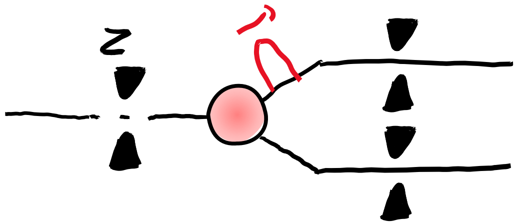
- Shot noise from the non-ballistic channel

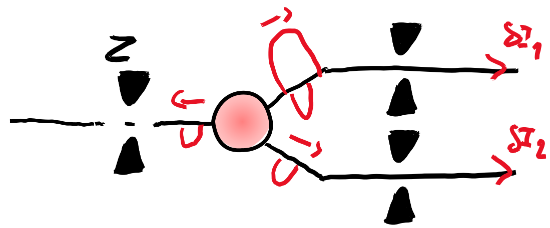




$< \delta I_1 \delta I_1 >$: $+$
$< \delta I_1 \delta I_2 >$: $+$

- Thermal noise emitted in one ballistic channel





$< \delta I_1 \delta I_1 >$:$+$
$< \delta I_1 \delta I_2 >$: $-$

➡ Different impact of thermal and shot noise on auto- and cross-correlations

Rq: ≥3 electrical paths