HEAT COULOMB BLOCKADE OF ONE BALLISTIC CHANNEL

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

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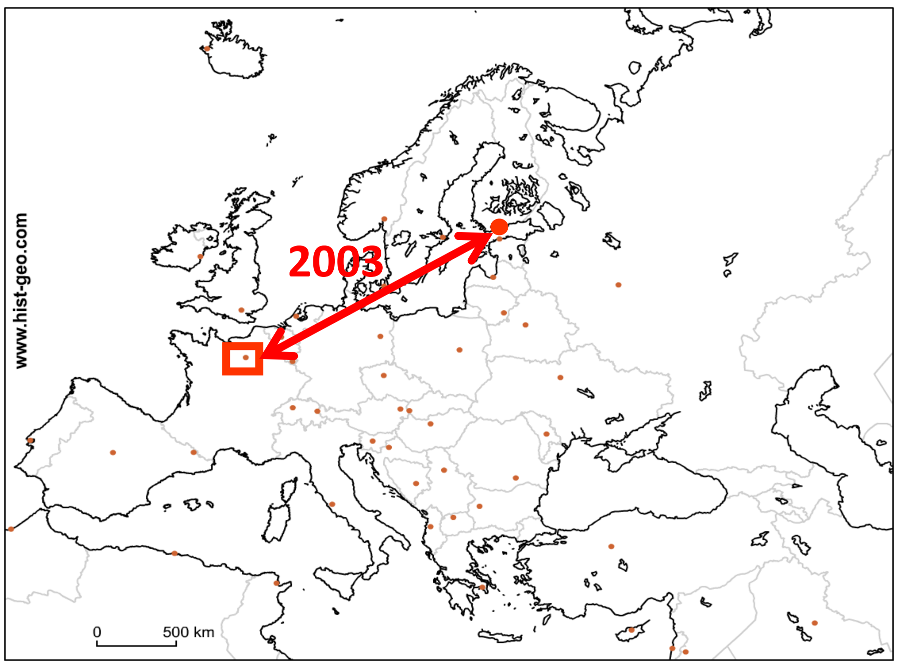
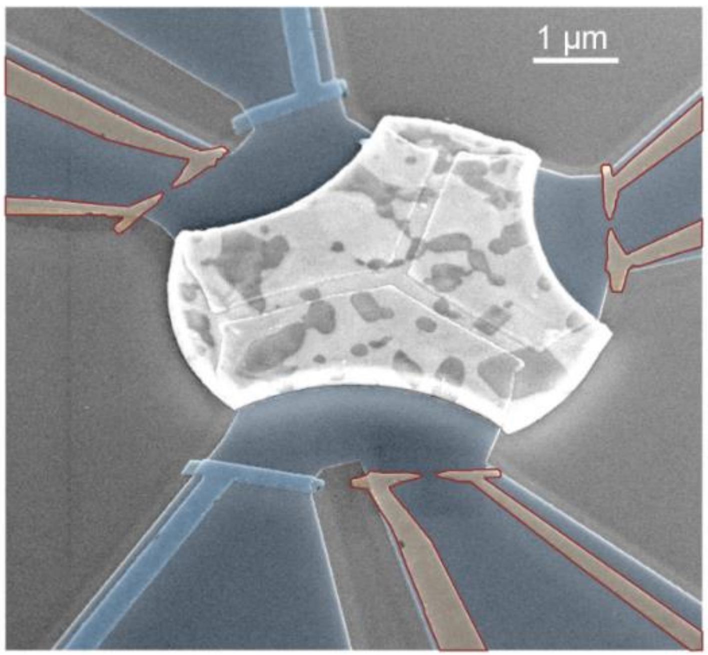
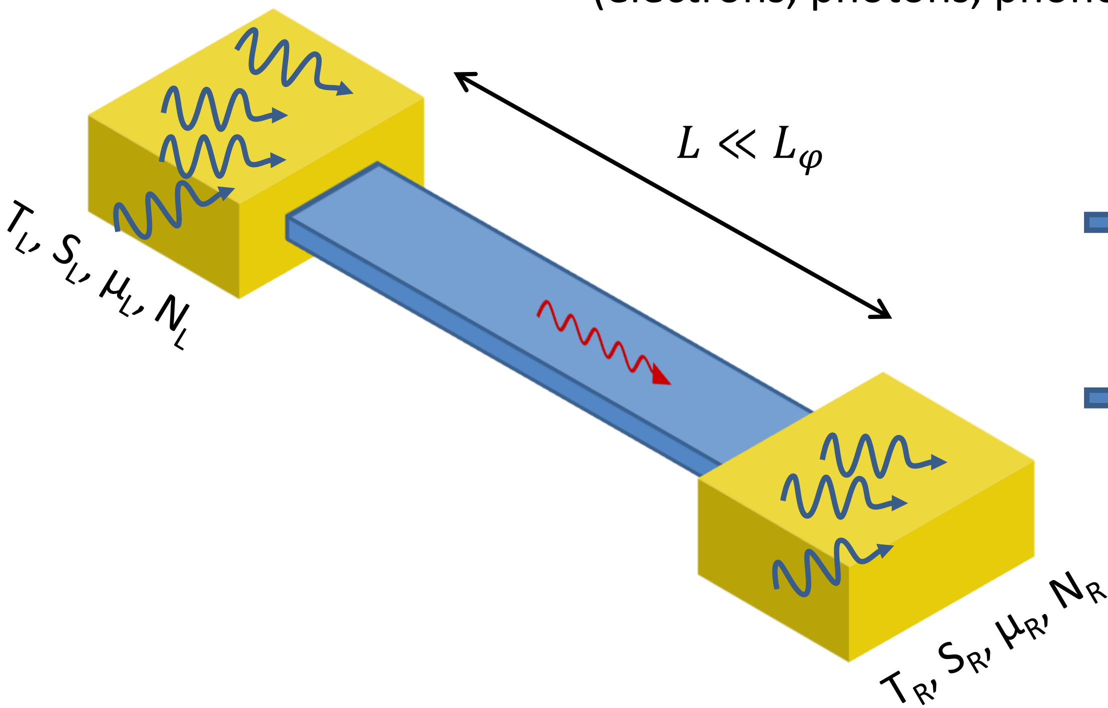
CNRS/ Univ Paris Sud/ Univ Paris Diderot, Palaiseau (France)





A quantum conductor

Quantum particles in reservoirs
(electrons, photons, phonons, anyons…)



➡ Coherent :
wave-like propagation

➡ Quantized transverse modes :
conduction channels

A quantum conductor

Quantum particles in reservoirs
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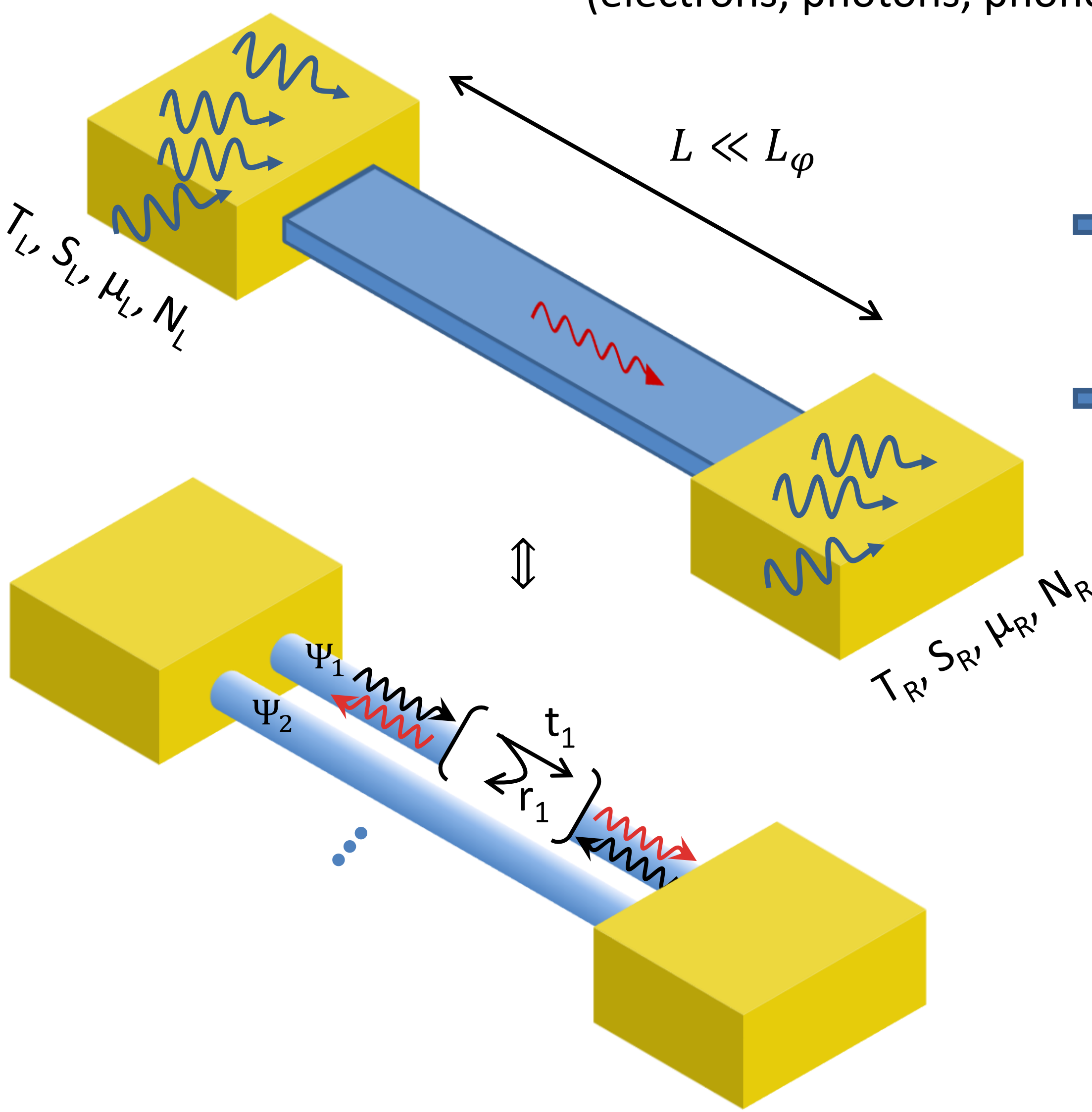


➡ Coherent :
wave-like propagation

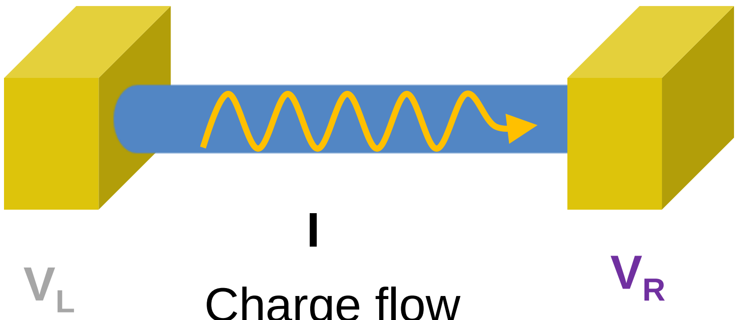
➡ Quantized transverse modes :
conduction channels

Quantum conductor
⇔
Parallel 1D waveguides

Landauer, Büttiker, Martin

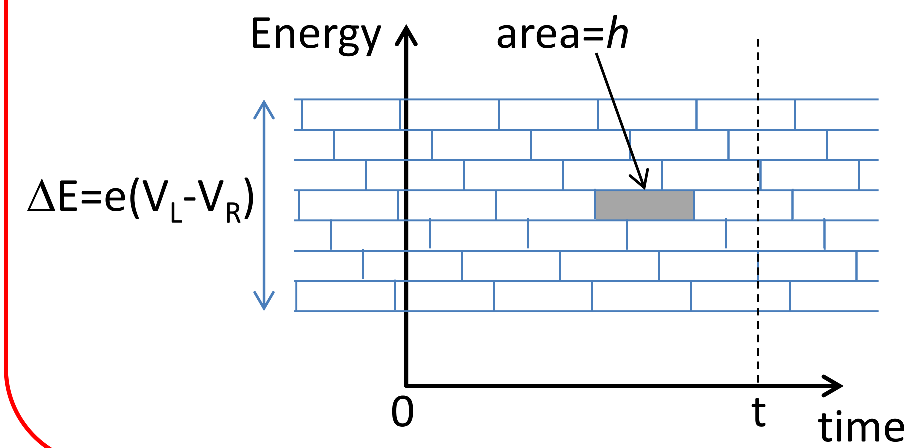
Quantum limits of conductance

Electrons transport across an elementary channel



$$G_e = \lim_{(V_L - V_R)\to 0} \frac{I}{V_L - V_R}$$

Heisenberg uncertainty principle:



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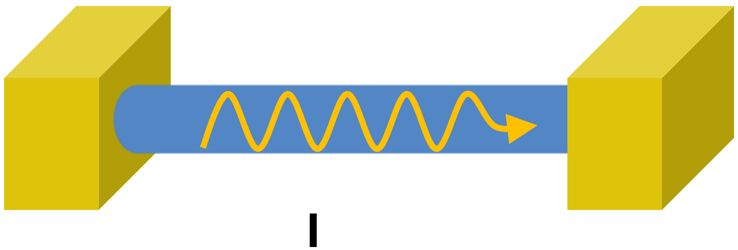

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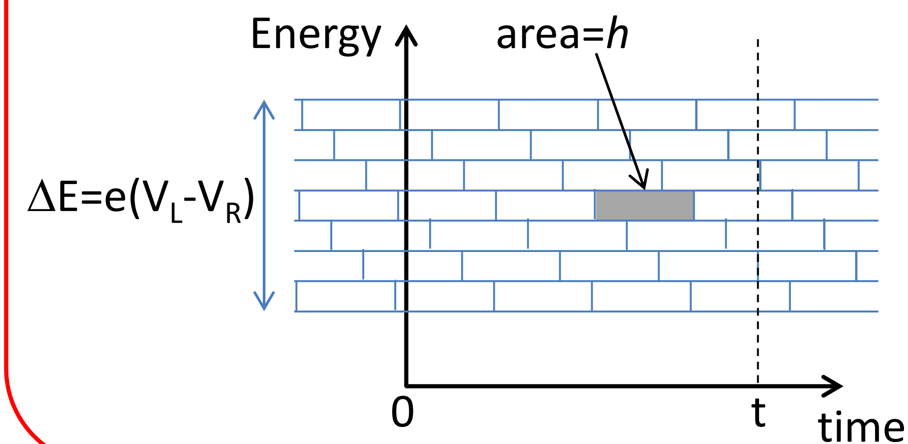


Transmited packets/electrons: $N^{max} = \frac{e(V_L - V_R) * t}{h}$

electrical current: $I^{max} = \frac{eN^{max}}{t} = \frac{e^2(V_L - V_R)}{h}$

$$G_e \leq \frac{e^2}{h}$$

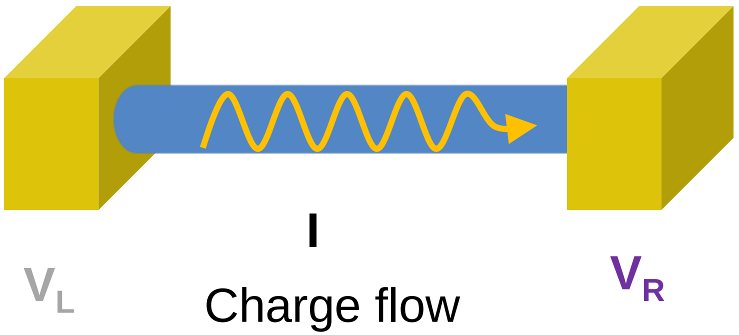
$\cong 1/(26\ \mathrm{k\Omega})$

Late 80's (thy & exp[t])

Universal to any material or geometry of the conductor !

Quantum limits of conductance

Electrons transport across an elementary channel : charge



$$G_e = \lim_{(V_L - V_R)\to 0} \frac{I}{V_L - V_R}$$

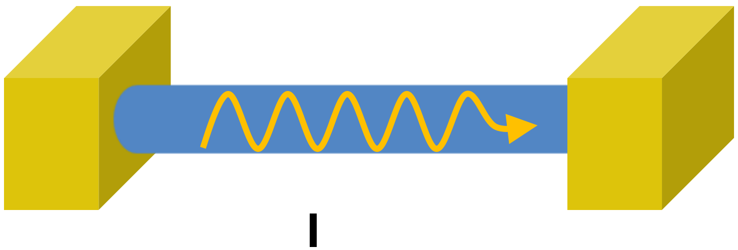
In a single mode :

$$G_e \leq G_K = \frac{e^2}{h} \cong 1/(26\ \mathrm{k\Omega})$$

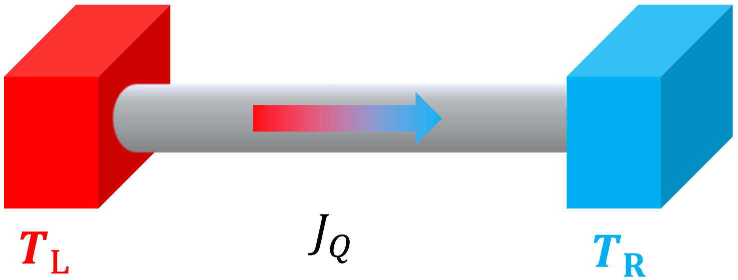
The same G_K per mode for electrons whatever the material !

Quantum limits of conductance

Electrons transport across an elementary channel : charge and heat



Charge flow



Heat flow

$$G_e = \lim_{(V_L - V_R)\to 0} \frac{I}{V_L - V_R}$$

$$G_{th} = \lim_{(T_L - T_R)\to 0} \frac{J_Q}{T_L - T_R}$$

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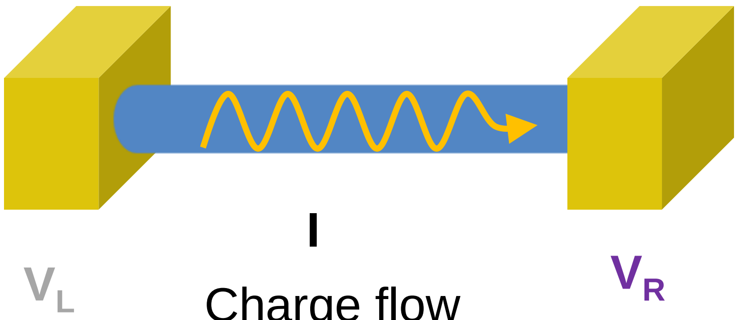

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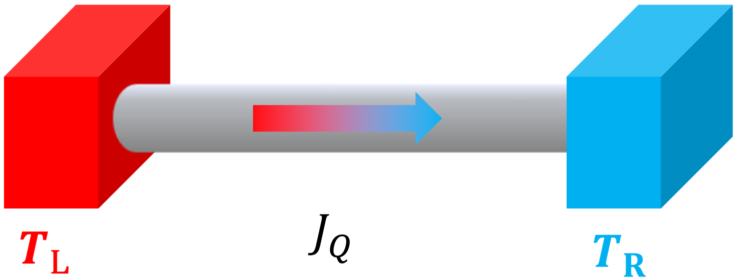


Heat flow

$$G_{th} = \lim_{(T_L - T_R) \to 0} \frac{J_Q}{T_L - T_R}$$

In a single mode :

$$G_{th} \leq G_Q = \frac{\pi^2 k_B{}^2}{3h} T = (1\ \mathrm{pW/K^2})\mathrm{T}$$

The same G_Q per mode whatever the heat carrier particles : fermions, bosons, anyons...

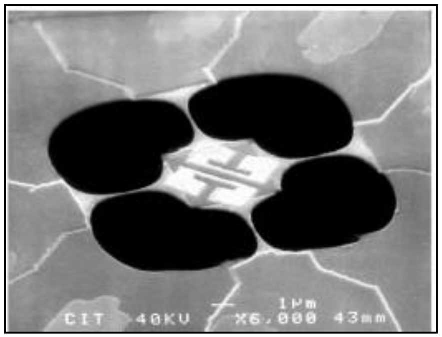
Pendry, J Phys A (1983), Rego & Kirczenow, PRB (1999), Blencowe & Vitelli, PRA (2000)

Thermal quantum of conductance

Experimental evidences G_Q=(1 pW/K^2)T

Phonons (2000)

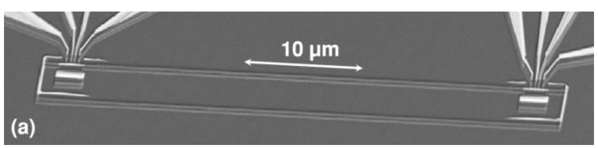
K. Schwab *et al.*, Nature (2000)



4x4 channels $G_{th} = 16 \times G_Q$

Photons (2006-2016)

M. Meschke *et al.*, Nature (2006)
A. Timofeev *et al.*, PRL (2009)
M. Partanen *et al. Nat. Phys.* **12**, 460–464 (2016)



$G_{th} \sim G_Q$
Macroscopic L (1 m)

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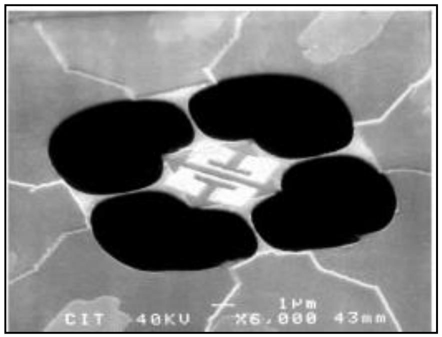

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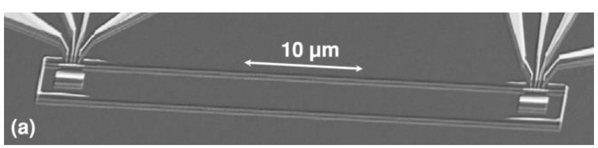

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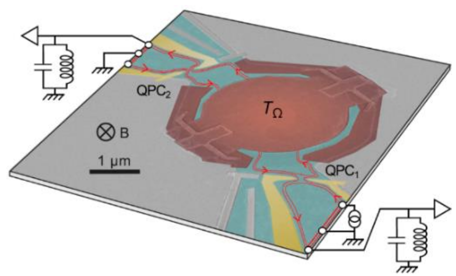
$G_{th} \propto number\ of\ modes\ n$

Molenkamp *et al.*, PRL (1992)
Chiatti, Nicholls *et al.*, PRL (2006)

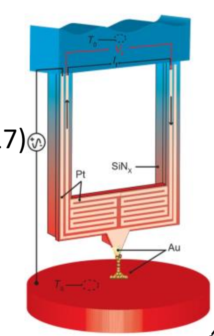
$G_{th}(n+1) - G_{th}(n) = G_Q$

Jezouin et al., Science **342**, 601 (2013)



$G_{th}(n) = nG_Q$
Room T

Mosso *et al*, Nat Nanotech (2017)
Cui *et al*, Science (2017)



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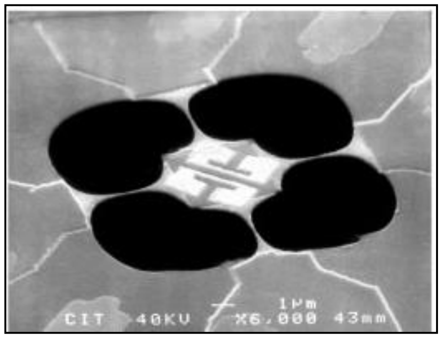

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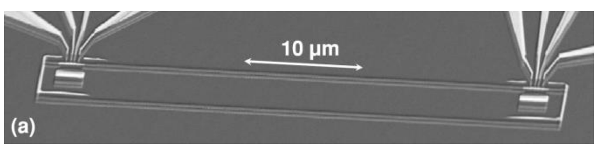

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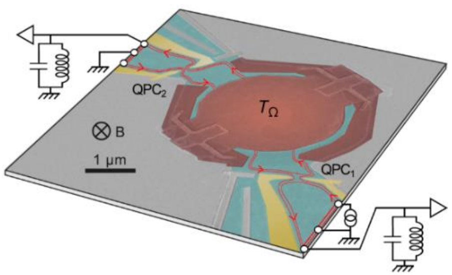

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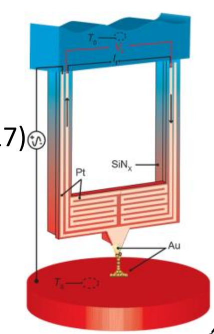
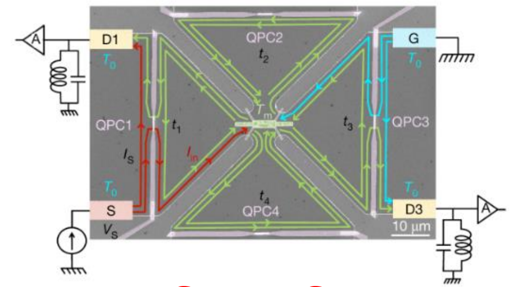


Anyons (2017)

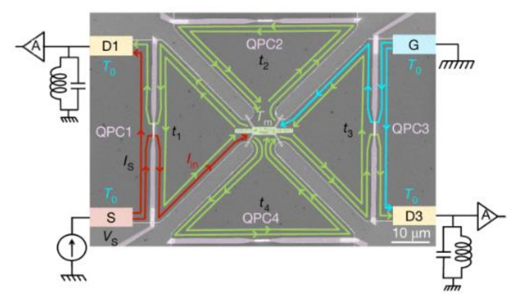
Banerjee *et al.*, Nature **545**, 75 (2017)



ν=1/3 $G_{th} = G_Q$

Non-abelian states (2018)

Banerjee *et al.*, Nature (2018)

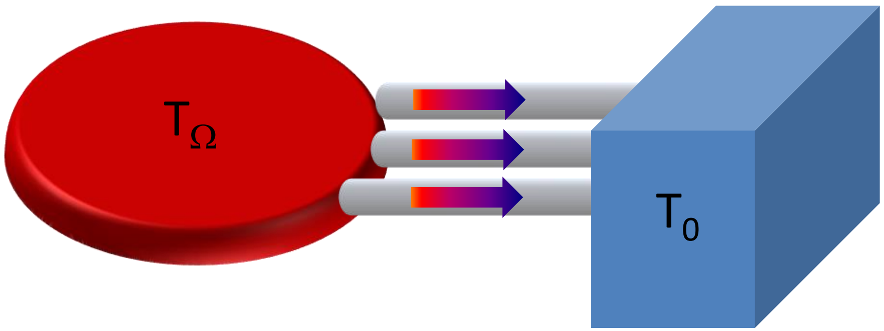


ν=5/2 $G_{th} = 2.5\ G_Q$

Heat Coulomb Blockade

What are the rules of thermal conductance composition in quantum circuits ?

n parallel ballistic modes :

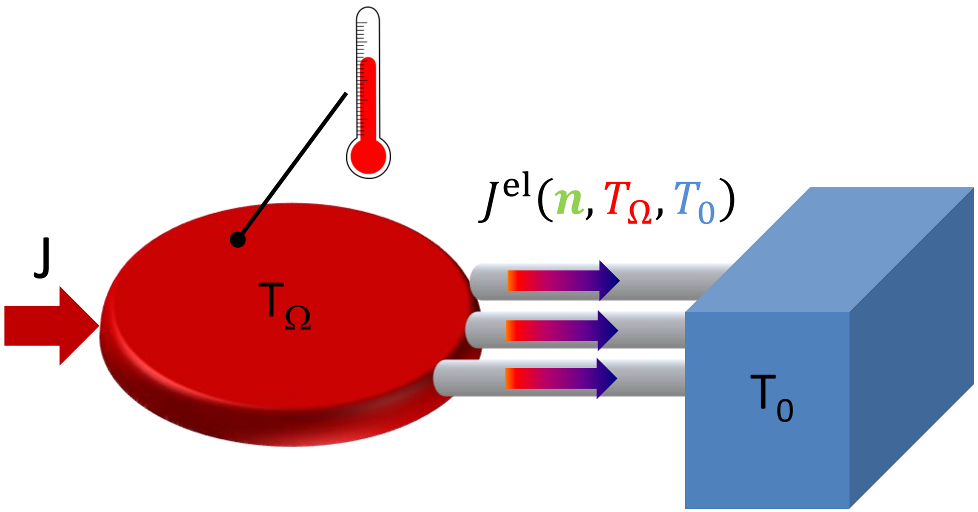


Electrical conduction: $G_e(n) = n\, G_K$

Thermal conduction: $G_{th}(n, T_\Omega, T_0)$?

Coulomb interactions ⇒ $G_{th}(n, T_\Omega, T_0) \neq n\, G_Q(T_\Omega, T_0)$

Infering electronic thermal conductance



Electronic thermal conductance: $G_{th} = \lim_{(T_\Omega - T_0)\to 0} \frac{J}{T_\Omega - T_0}$

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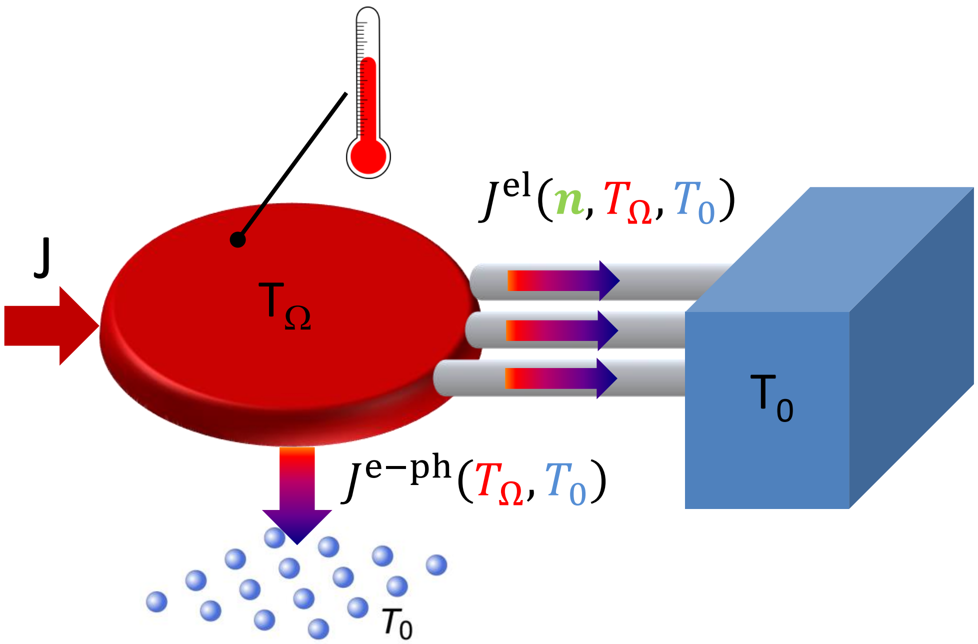
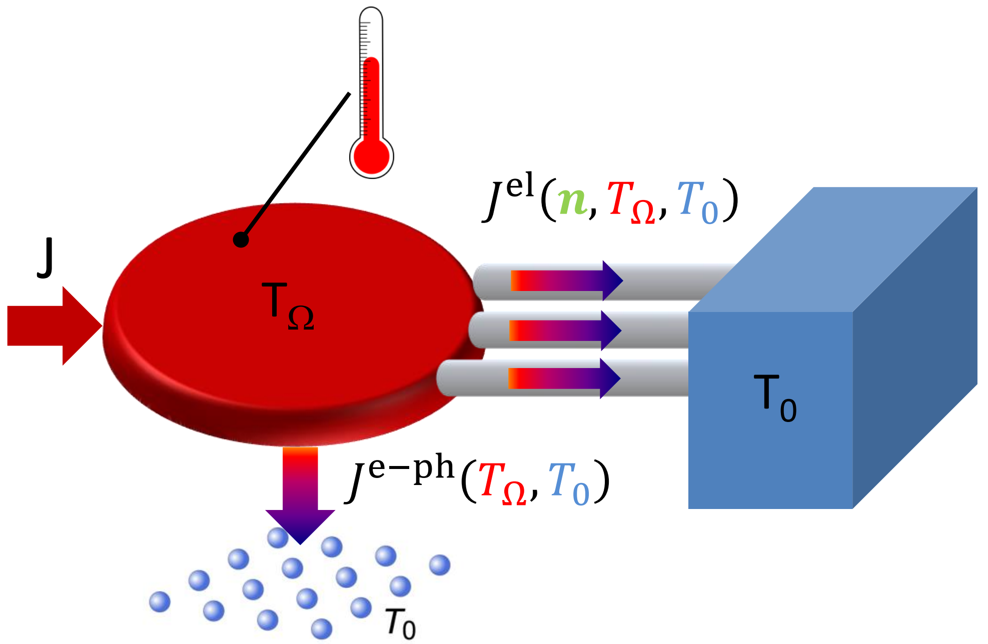


Electronic thermal conductance: $G_{th} = \lim_{(T_\Omega - T_0) \to 0} \frac{J^{\mathrm{el}}}{T_\Omega - T_0}$

Infering electronic thermal conductance

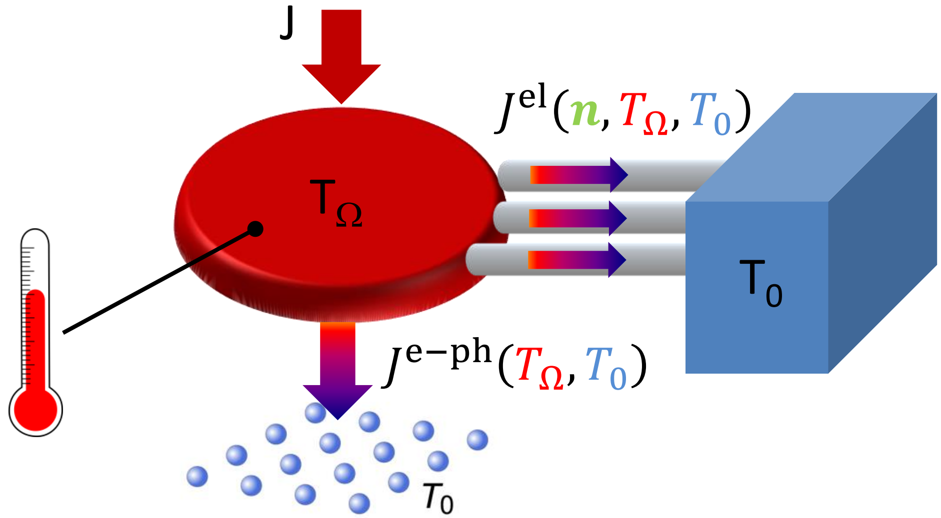


Electronic thermal conductance: $G_{th} = \lim_{(T_\Omega - T_0)\to 0} \dfrac{J^{el}}{T_\Omega - T_0}$

Heat balance : $J = J^{el}(n, T_\Omega, T_0) + J^{e-ph}(T_\Omega, T_0)$

How to focus on the electronic heat flow ?

Extracting the electronic heat flow



Heat balance :

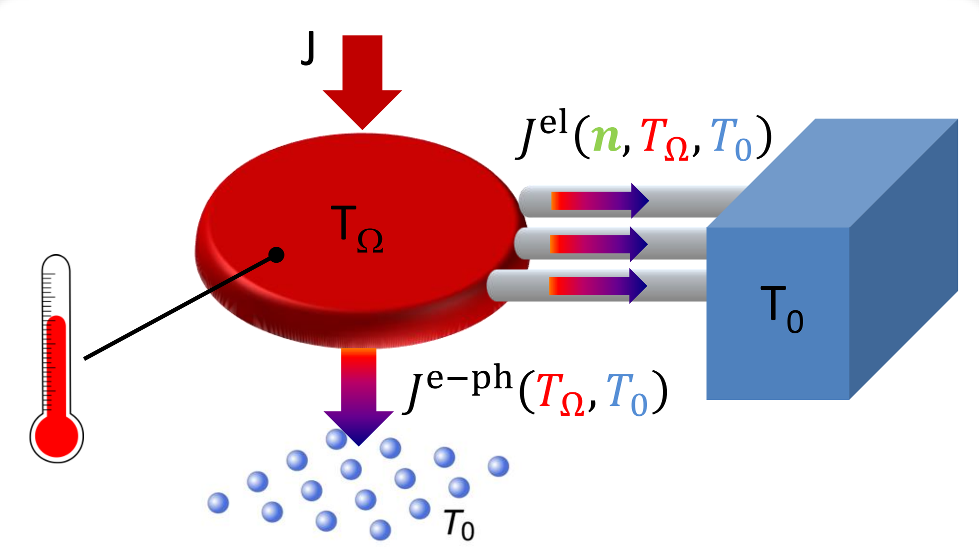
$$J = J^{\mathrm{el}}(n, T_\Omega, T_0) + J^{\mathrm{e-ph}}(T_\Omega, T_0)$$

Theory

$$\begin{cases} J^{e-ph}(T_\Omega, T_0) = \Sigma\Omega\left({T_\Omega}^{\beta} - {T_0}^{\beta}\right) \\ J^{\mathrm{el}}(1, T_\Omega, T_0) = \dfrac{\pi^2 {k_B}^2}{6h}\left({T_\Omega}^2 - {T_0}^2\right) \end{cases}$$

$\beta \sim 4$ to 6, $\Sigma\Omega \sim 5 \times 10^{-8}$ W.K$^{-\beta}$

Extracting the electronic heat flow



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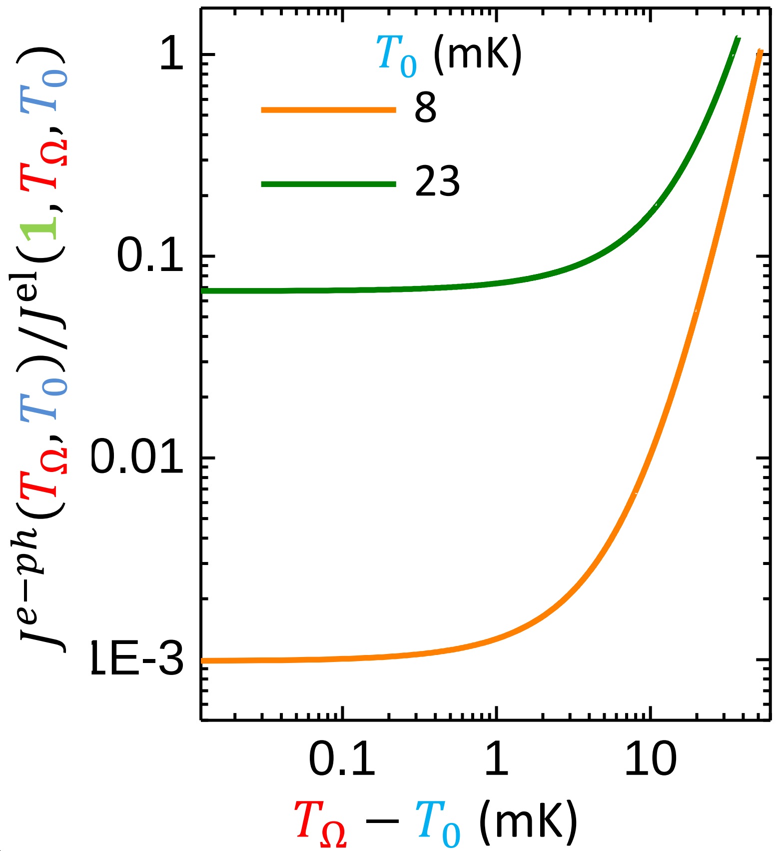
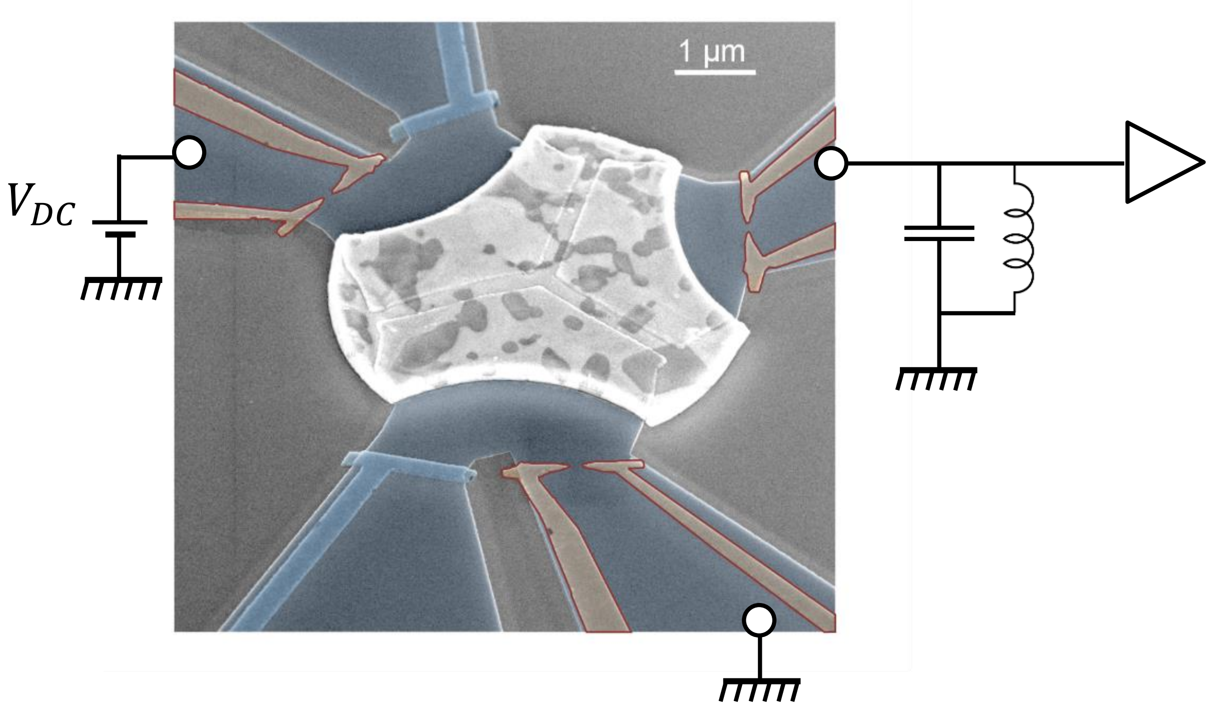
Reduce T_0



Experimental implementation



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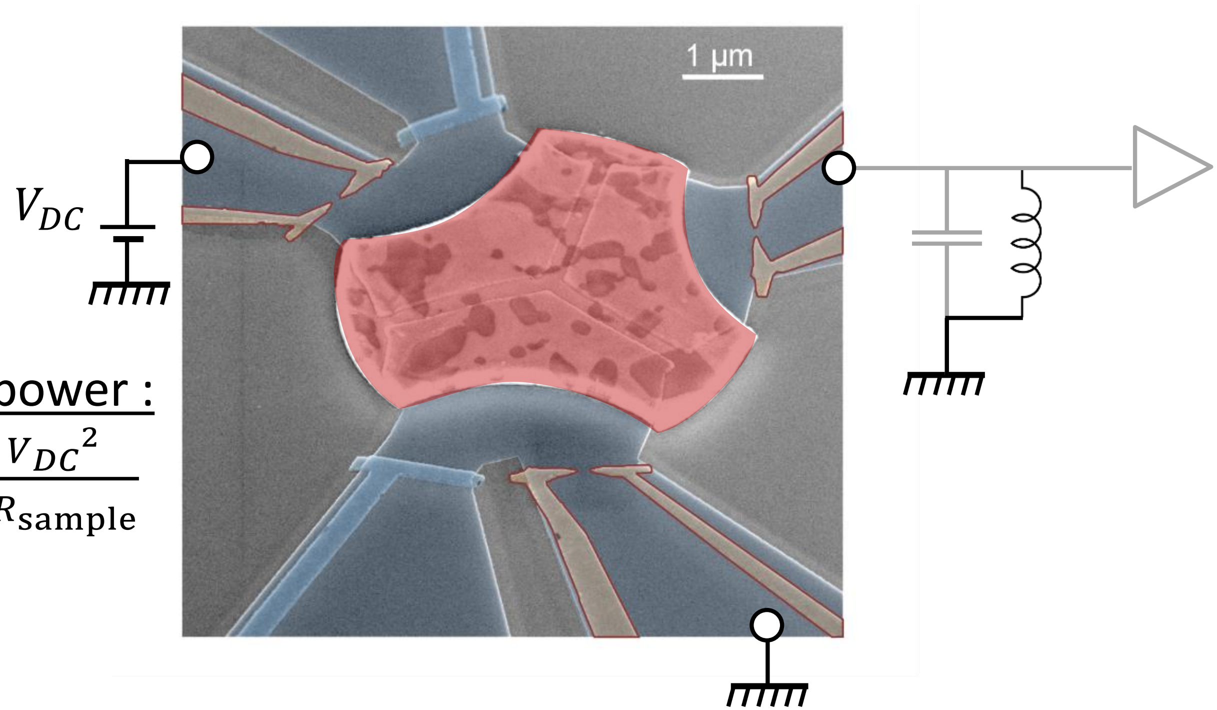
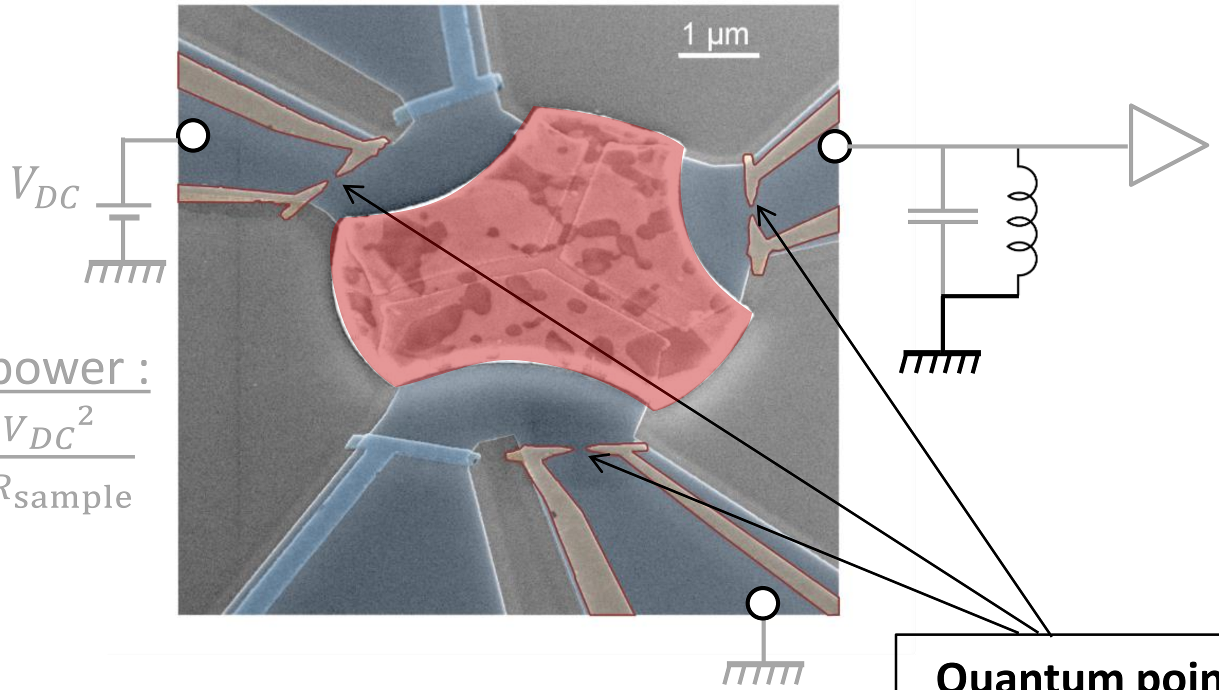


Joule power :

$$J = \frac{{V_{DC}}^2}{2R_{\text{sample}}}$$

Experimental implementation



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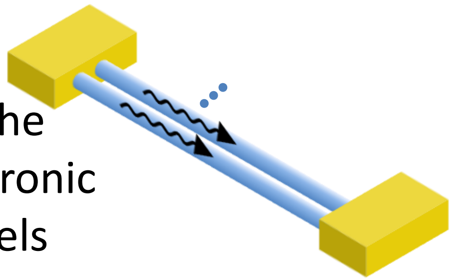
Quantum point contacts

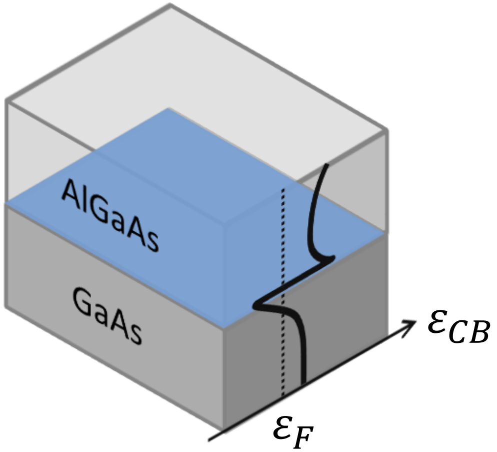
Fine control of the number of electronic quantum channels



Electronic channels revealed by QPC

Van Wees *et al.*, PRL (1988)
Warrham *et al.*, Solid State Phys. (1988)

2D electron gas (Ulf Gennser, Antonella Cavanna , Abdelkarim Ouerghi = C2N growers)



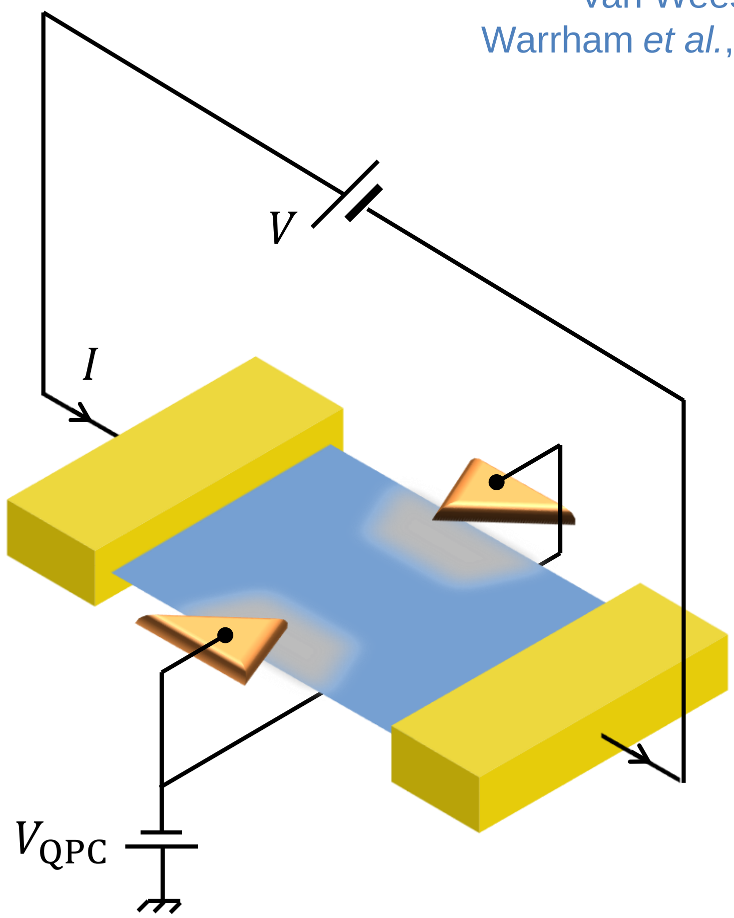
2DEG :

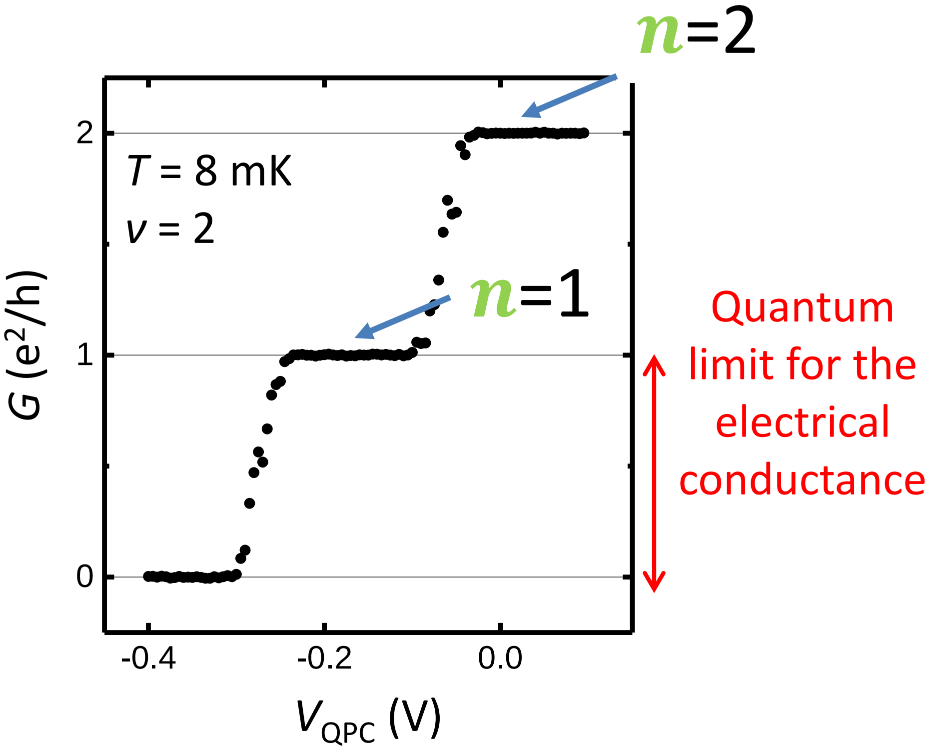
$n = 2.5 \times 10^{15}/\mathrm{m}^2$

$\mu = 55\ \mathrm{m}^2/V.s$

Electronic channels revealed by QPC

Van Wees *et al.*, PRL (1988)
Warrham *et al.*, Solid State Phys. (1988)





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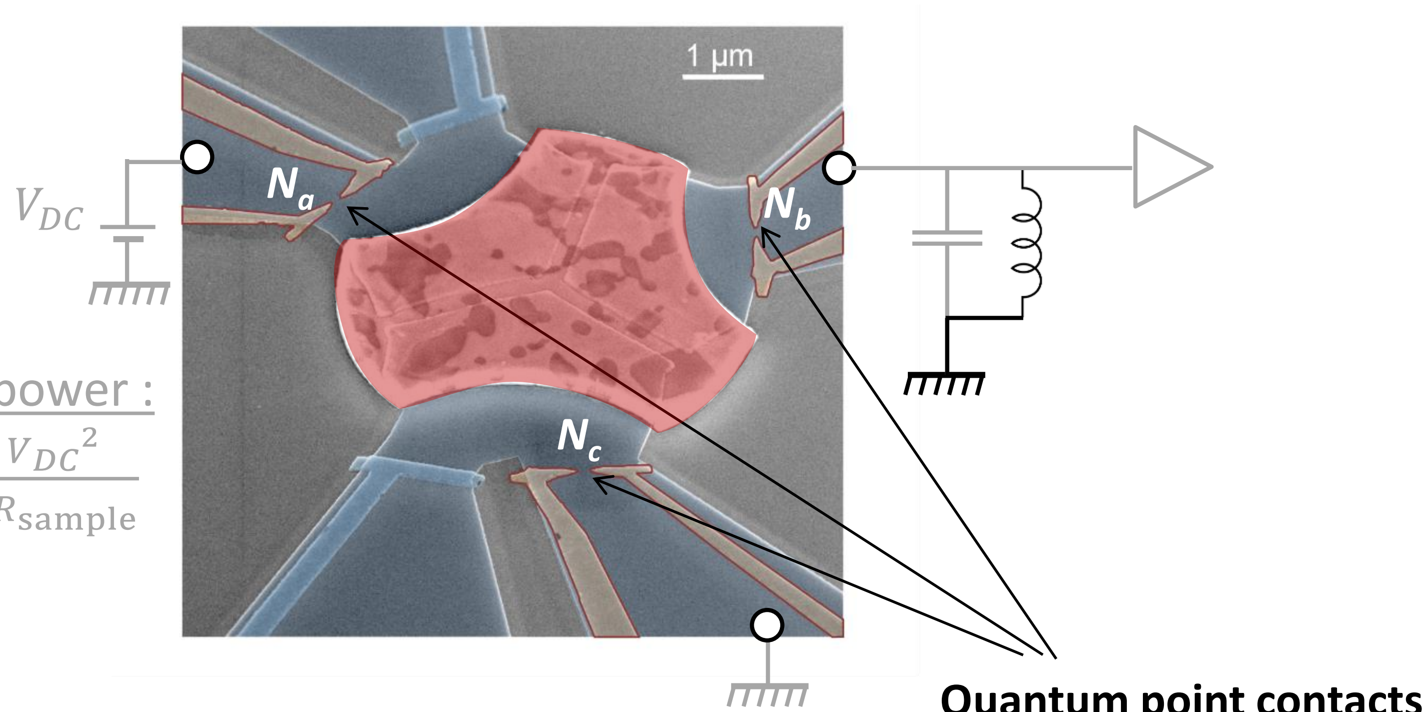

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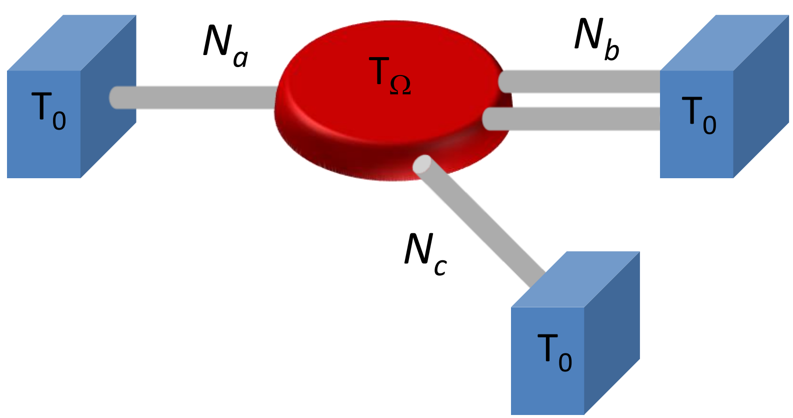
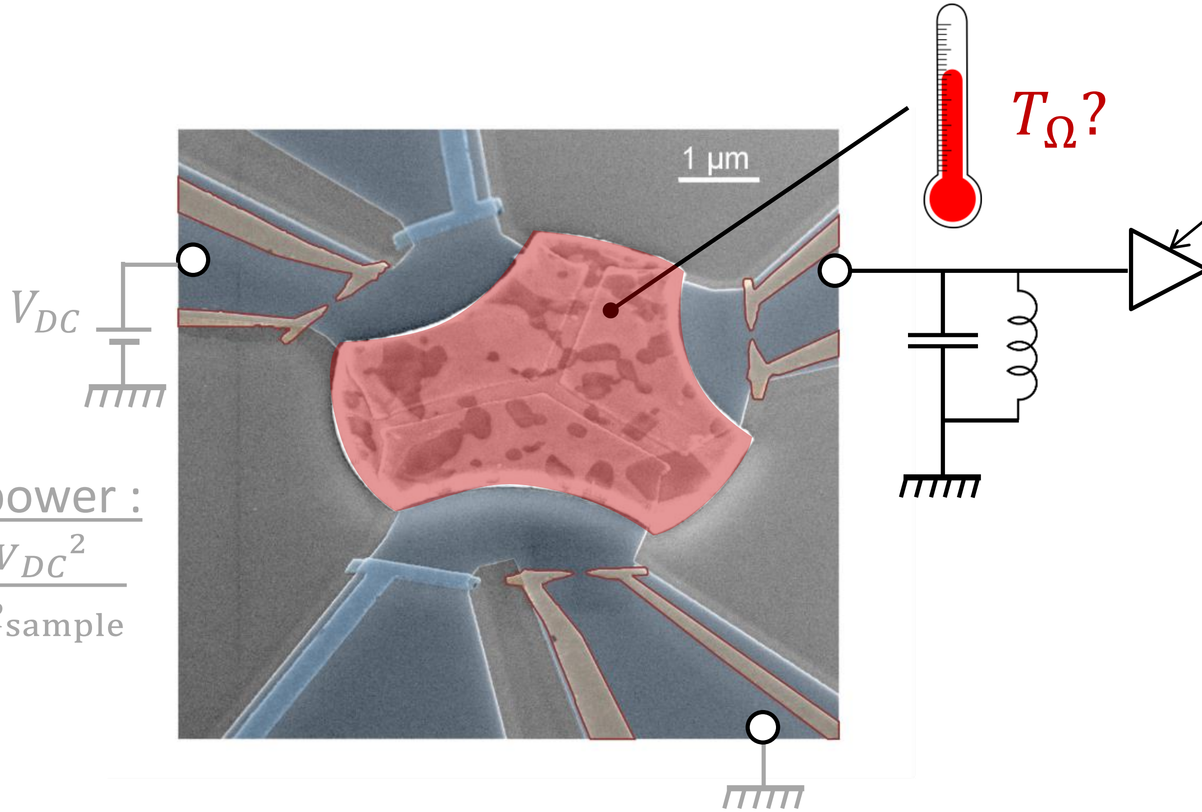


$n = N_a + N_b + N_c$

Temperature extraction

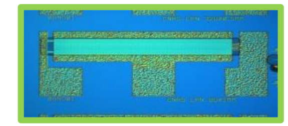


Joule power :

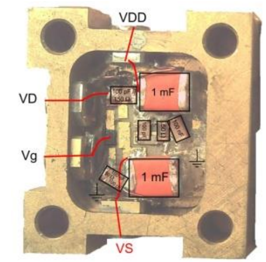
$$J = \frac{{V_{DC}}^2}{2R_{\text{sample}}}$$

HEMT

(Yong Jin, C2N)



Cryogenic amplifiers

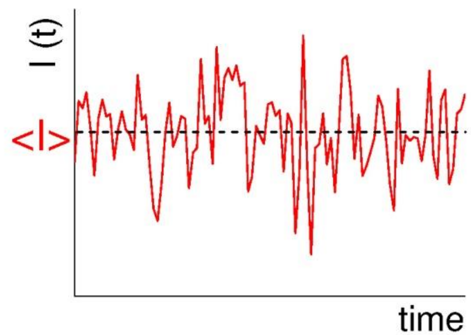


$0.2\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$

with low current noise

Ask for datasheet if interested

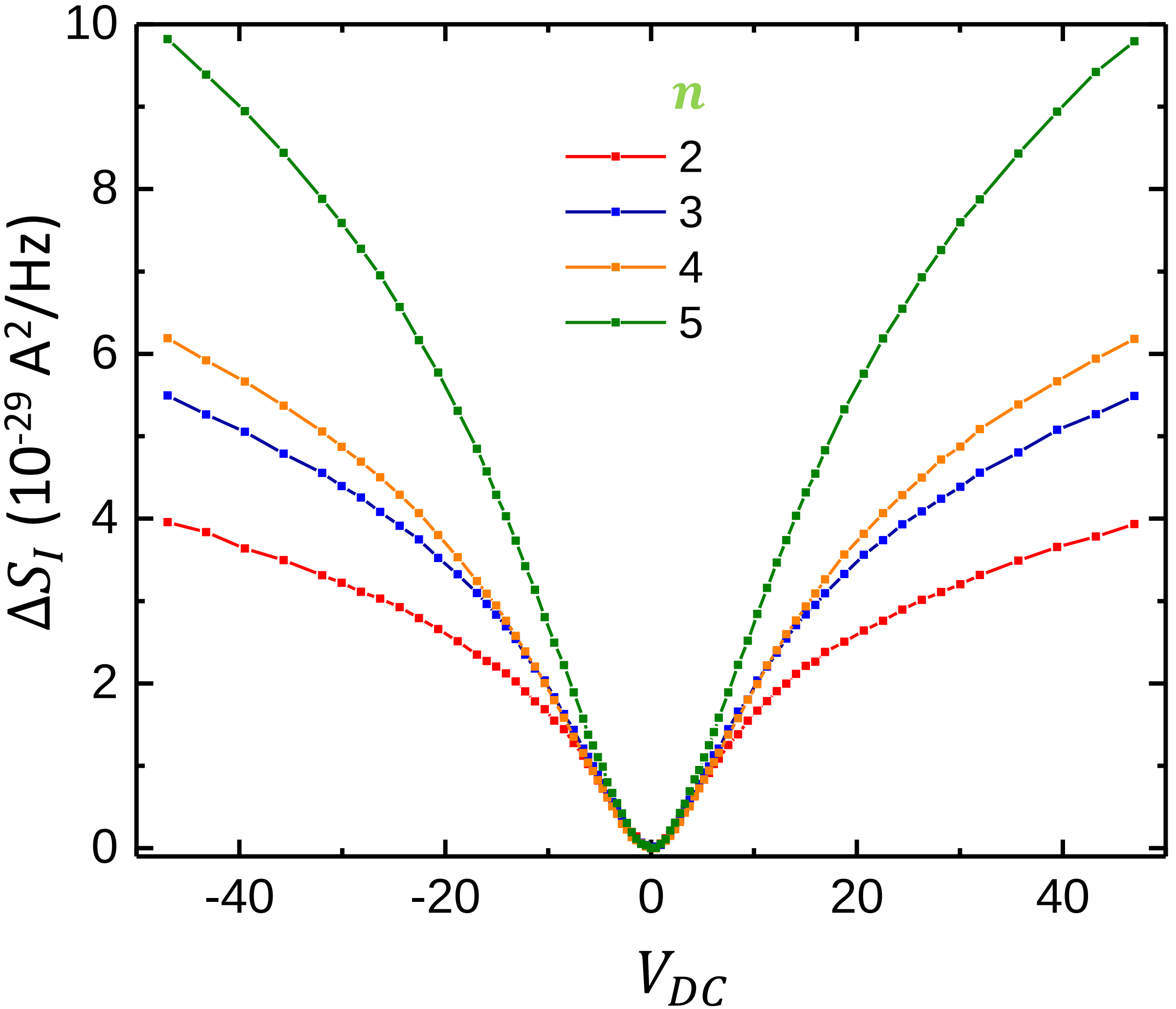
Noise thermometry:



Excess current noise:

$$\Delta S_I = \frac{2k_B(T_\Omega - T_0)}{R_{\text{sample}}}$$

Noise measurement



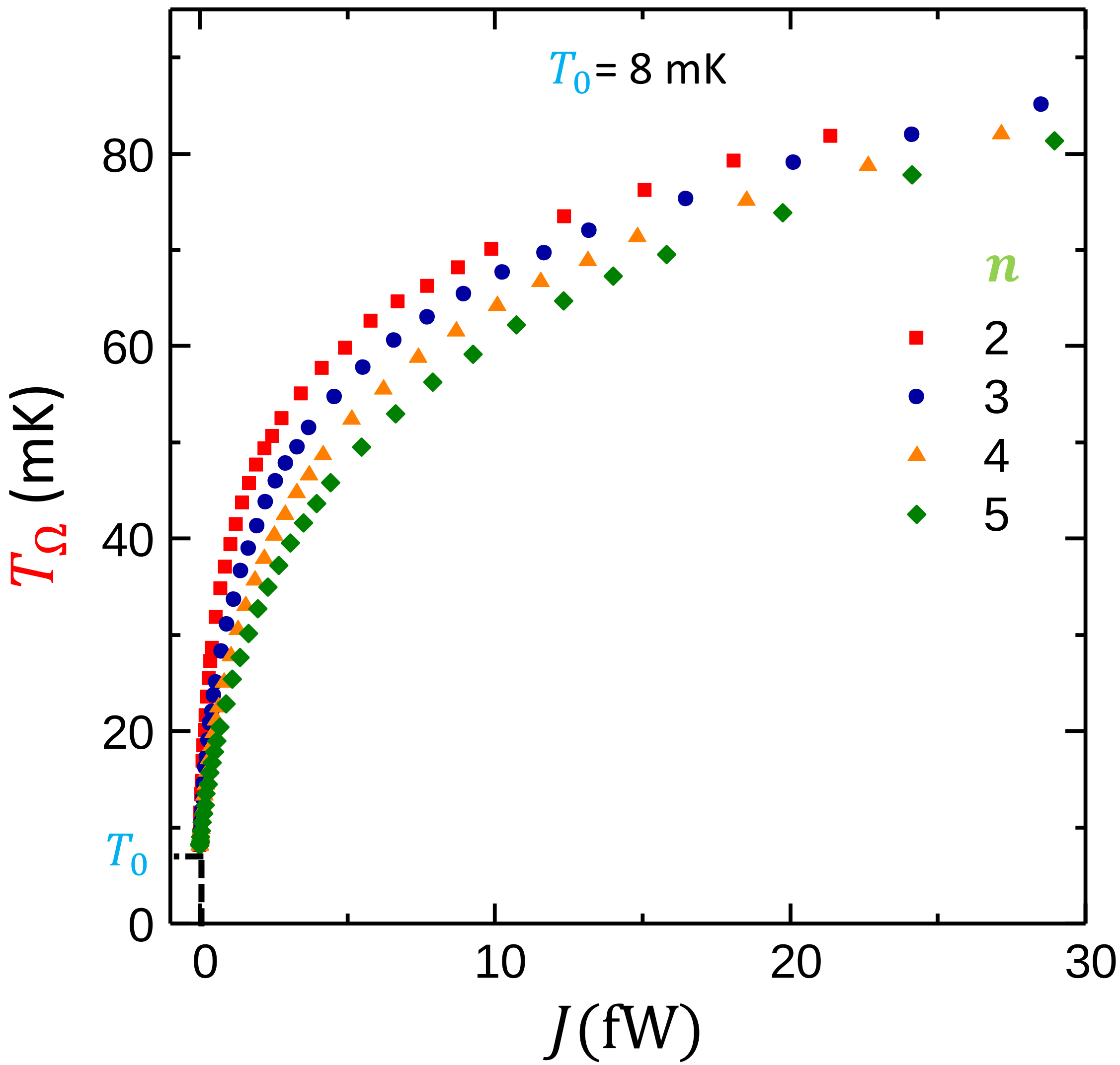
$n = N_a + N_b + N_c$

Convert to :

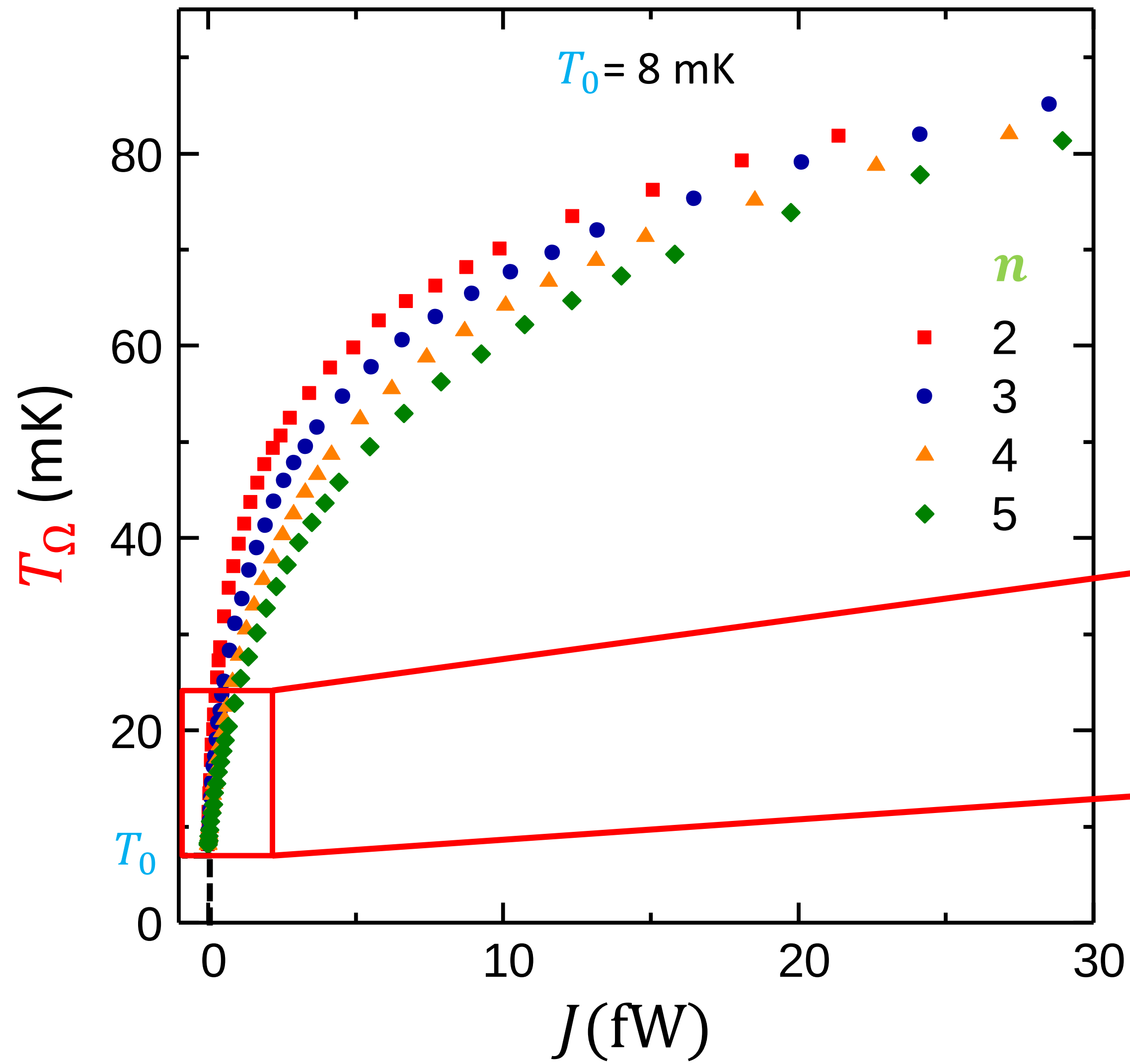
$$T_\Omega = T_0 + \frac{R_{\text{sample}}}{2k_B}\Delta S_I$$

$$J = \frac{{V_{\text{dc}}}^2}{2R_{\text{sample}}}$$

T_Ω–J characteristic

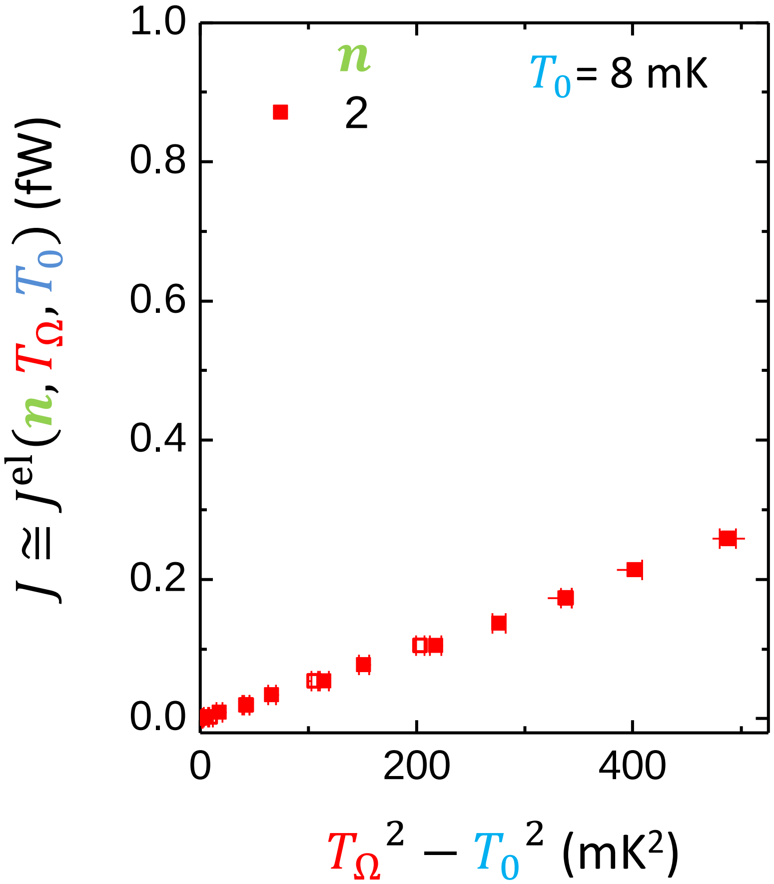


T_Ω–J characteristic



$$J \cong J^{\mathrm{el}}(n, T_\Omega, T_0)$$

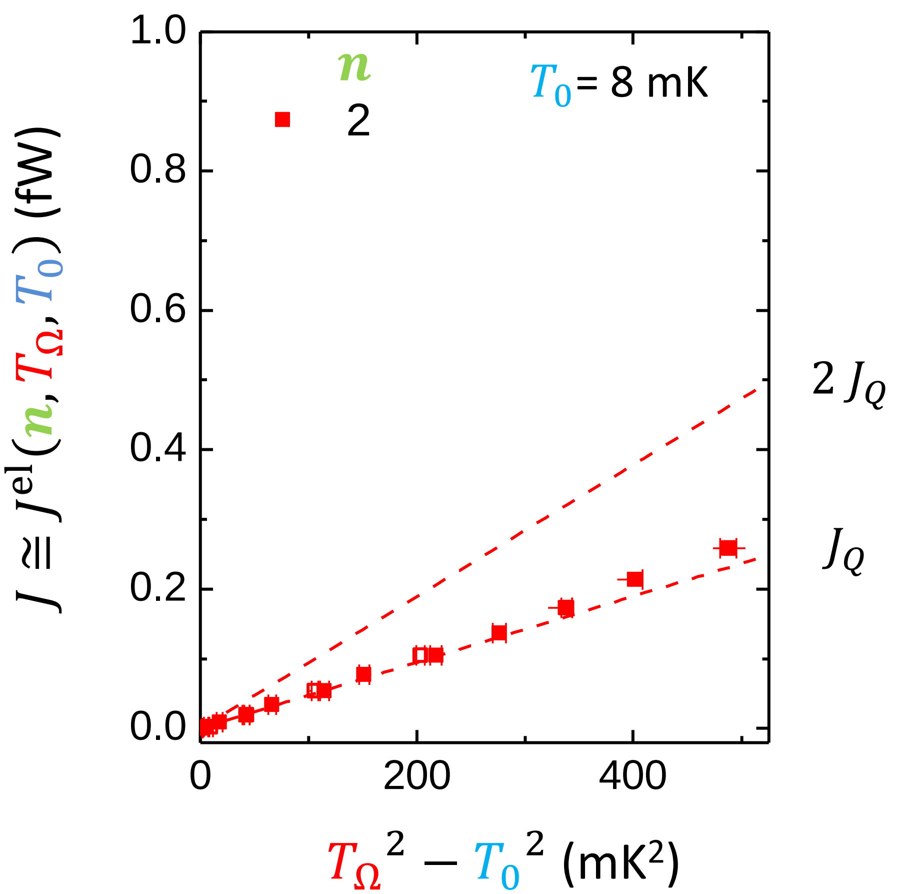
Electronic heat flow at $T_\Omega < 25$ mK



<u>Predictions for n independent channels</u>

$$J = n\,J_Q = n\frac{\pi^2 k_B{}^2}{6h}\left(T_\Omega{}^2 - T_0{}^2\right)$$

Electronic heat flow at $T_\Omega < 25$ mK



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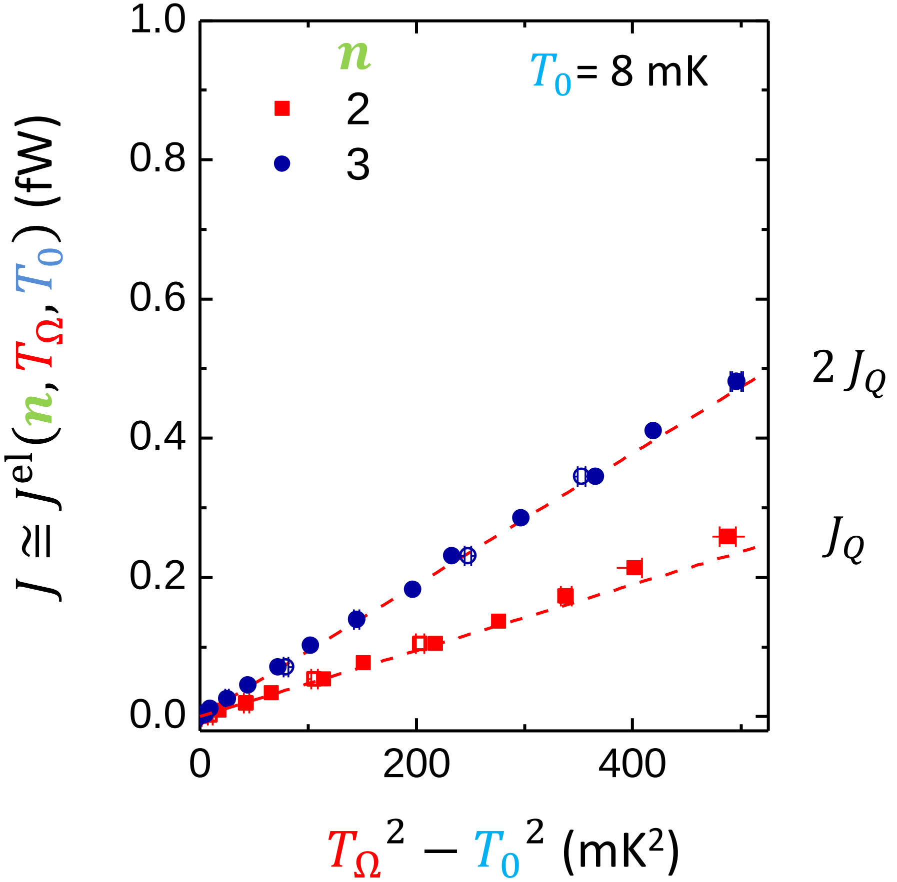
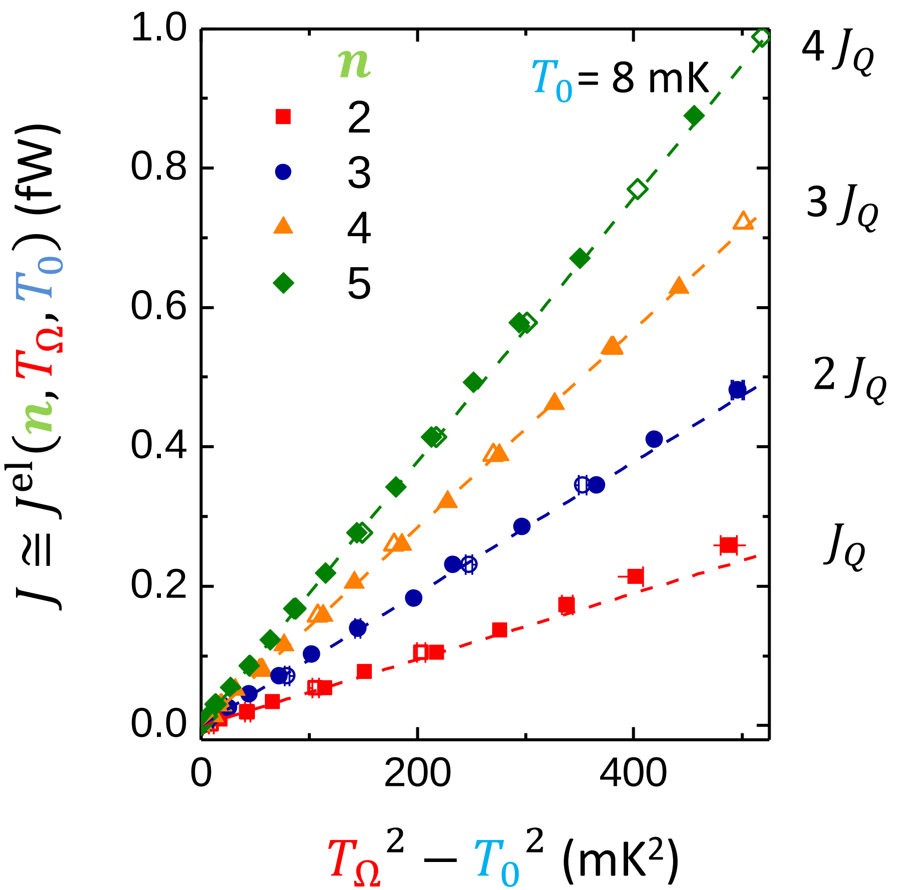


Predictions for n independent channels $J = n\,J_Q = n\dfrac{\pi^2 k_B{}^2}{6h}(T_\Omega{}^2 - T_0{}^2)$

Electronic heat flow at T_Ω< 25 mK



$$J^{el} = (n-1)\frac{\pi^2 k_B{}^2}{6h}\left(T_\Omega{}^2 - T_0{}^2\right)$$

The n channels are not independent !

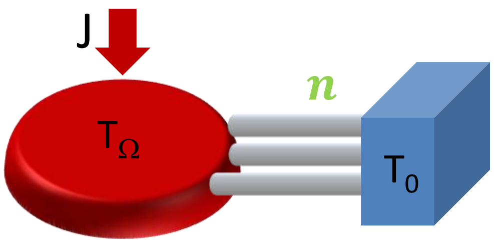
Predictions for n independent channels

$$J = n\,J_Q = n\frac{\pi^2 k_B{}^2}{6h}\left(T_\Omega{}^2 - T_0{}^2\right)$$

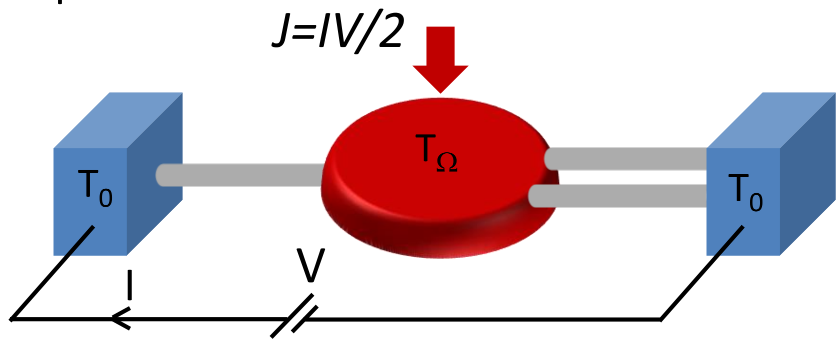
Heat Blockade

$$G_{th} = \frac{\mathrm{d}J^{el}}{\mathrm{d}(T_{\Omega} - T_0)} = (n-1)G_Q \neq n\,G_Q$$

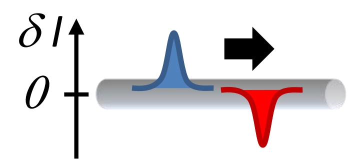
Principle



Implementation



Electronic heat transfer = Propagation of current fluctuations



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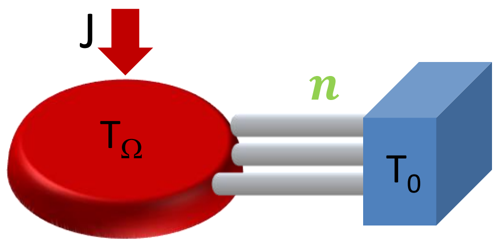
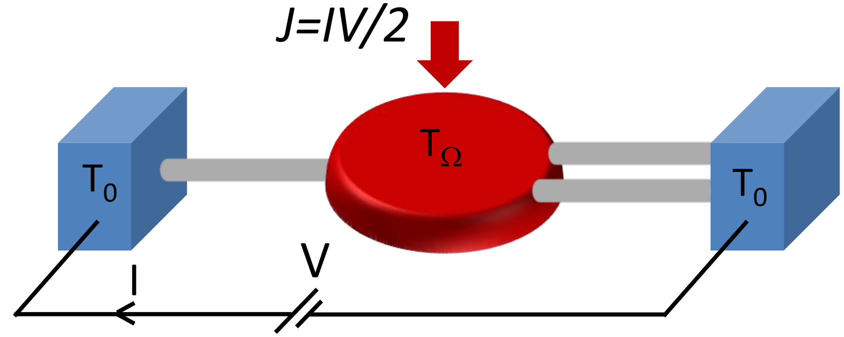


Implementation



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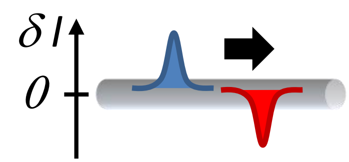
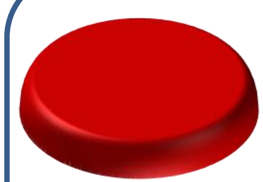
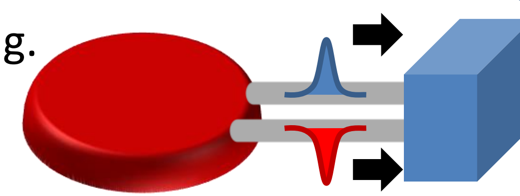




= Floating node
no charge
accumulation (if C=0)

Only neutral
excitations are
allowed

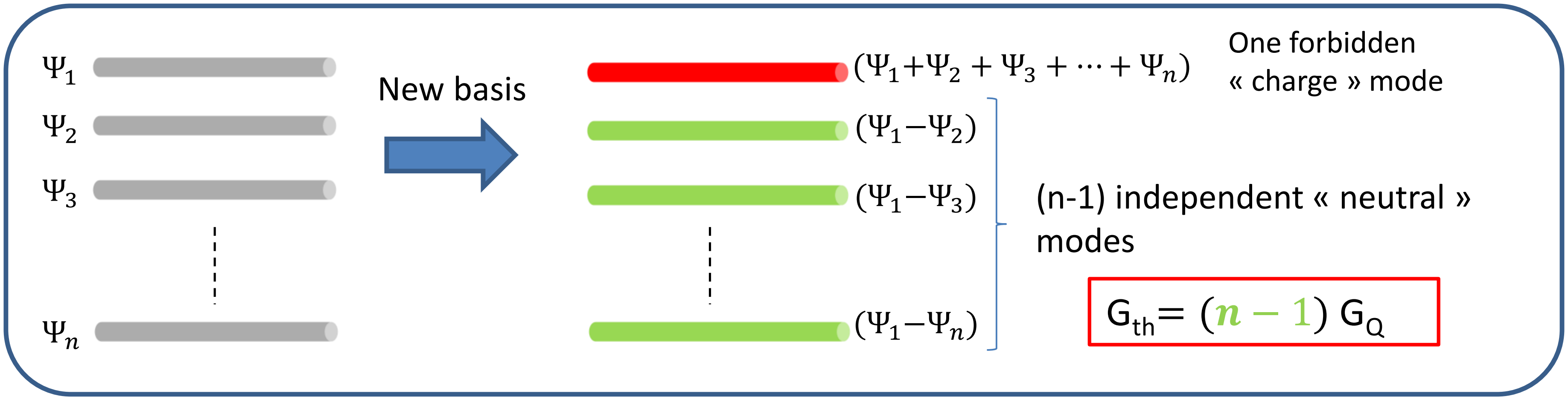
e.g.



⇒ Correlations between the n channels for heat transfer

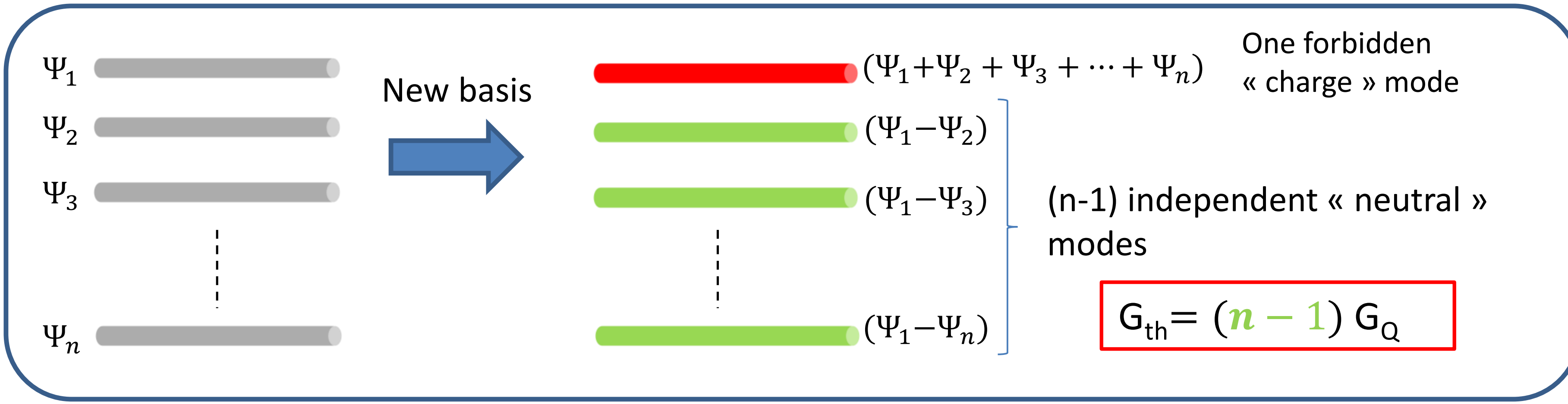
Heat Blockade

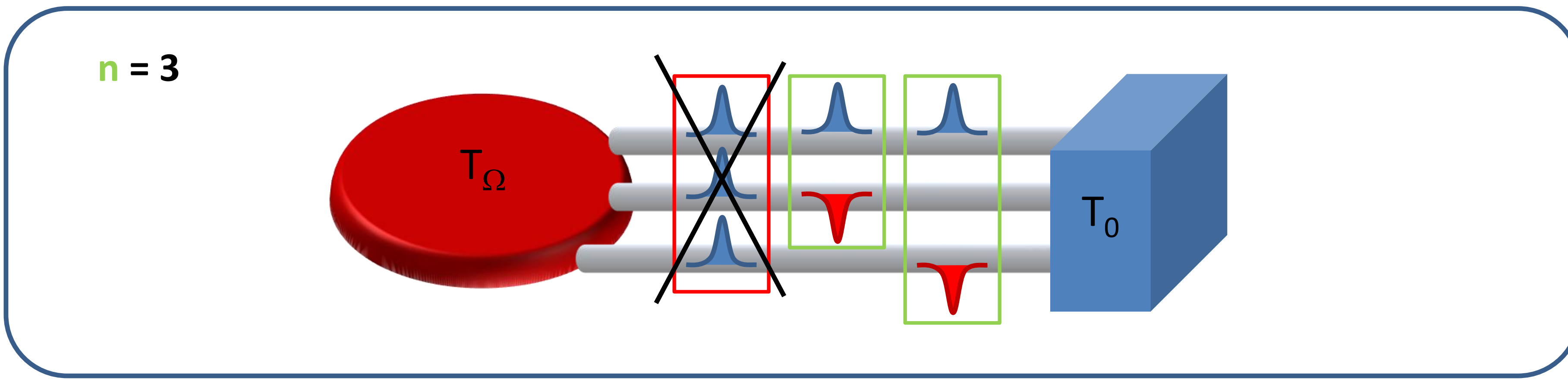
Floating node => Correlations between the **n** modes



Heat Blockade

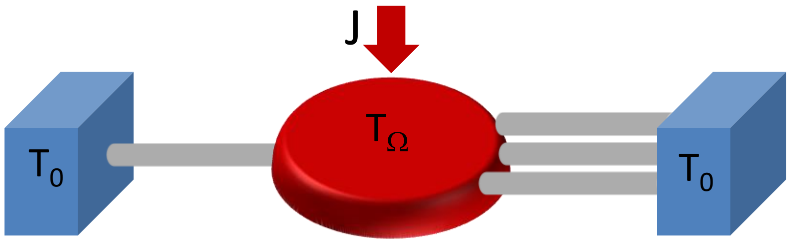
Floating node => Correlations between the n modes





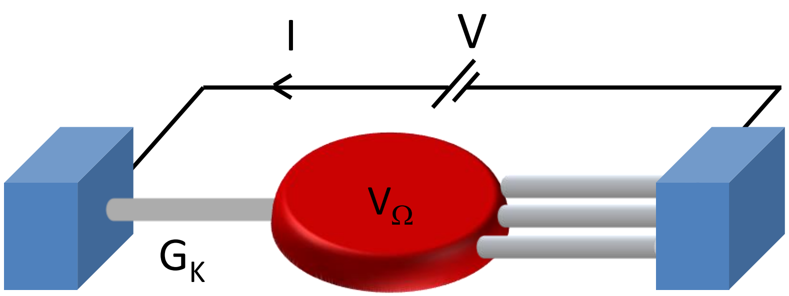
Violation of Wiedemann Franz law

n channels of heat conductances $G_Q \neq$ n independent modes for heat transfer



$$G_{th} = \frac{dJ^{el}}{d(T_\Omega - T_0)} = (n-1)G_Q$$

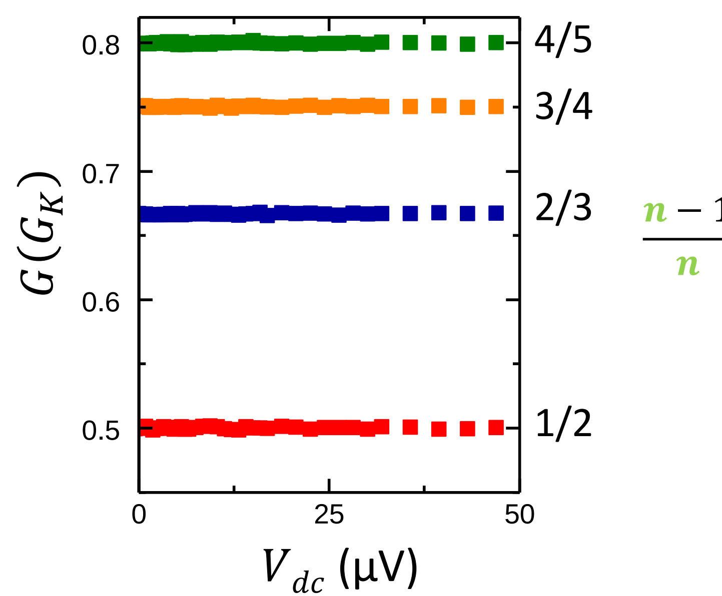
n channels of charge conductances G_K = n independent modes for charge transfer



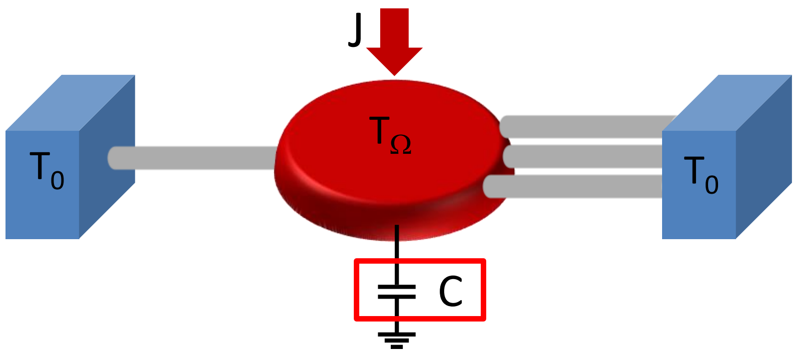
$$G_e = \frac{dI}{dV} = \frac{n-1}{n} G_K$$

Ballistic channels → Fano = 0

no charge Dyanmical Coulomb Blockade



Heat « Coulomb » Blockade



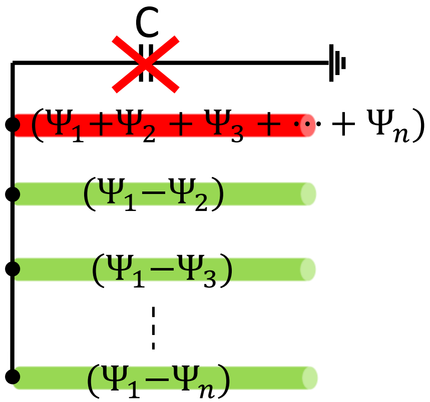
Capacitive cut-off frequency

$1/2\pi RC = nG_K/2\pi C$

T fluctuations upper frequency

$k_B T_\Omega / h$

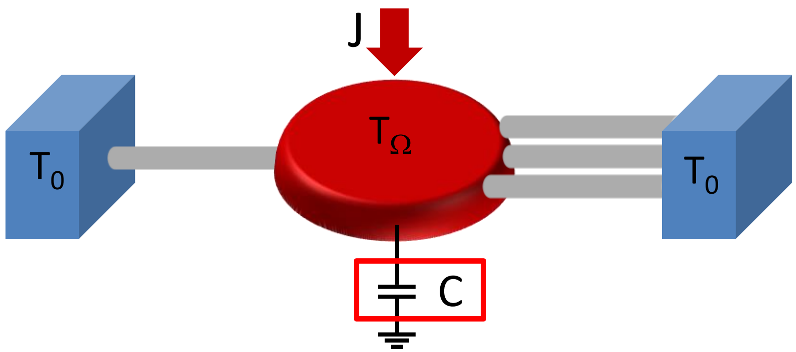
$k_B T_\Omega / h \ll n G_K / 2\pi C$



$n - 1$ modes

$G_{th} = (n-1) G_Q$

Heat « Coulomb » Blockade



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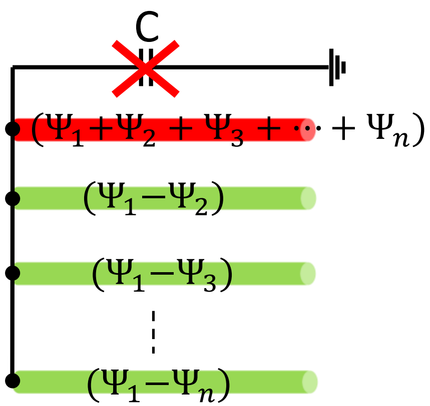
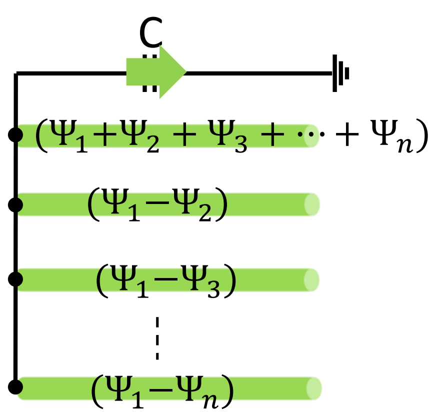


$n-1$ modes

$G_{th} = (n-1)G_Q$

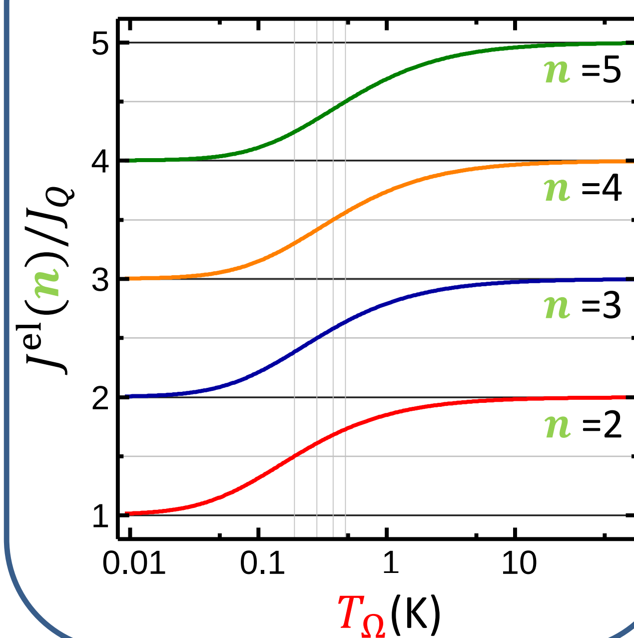
$k_B T_\Omega / h \gg nG_K / 2\pi C$



n modes

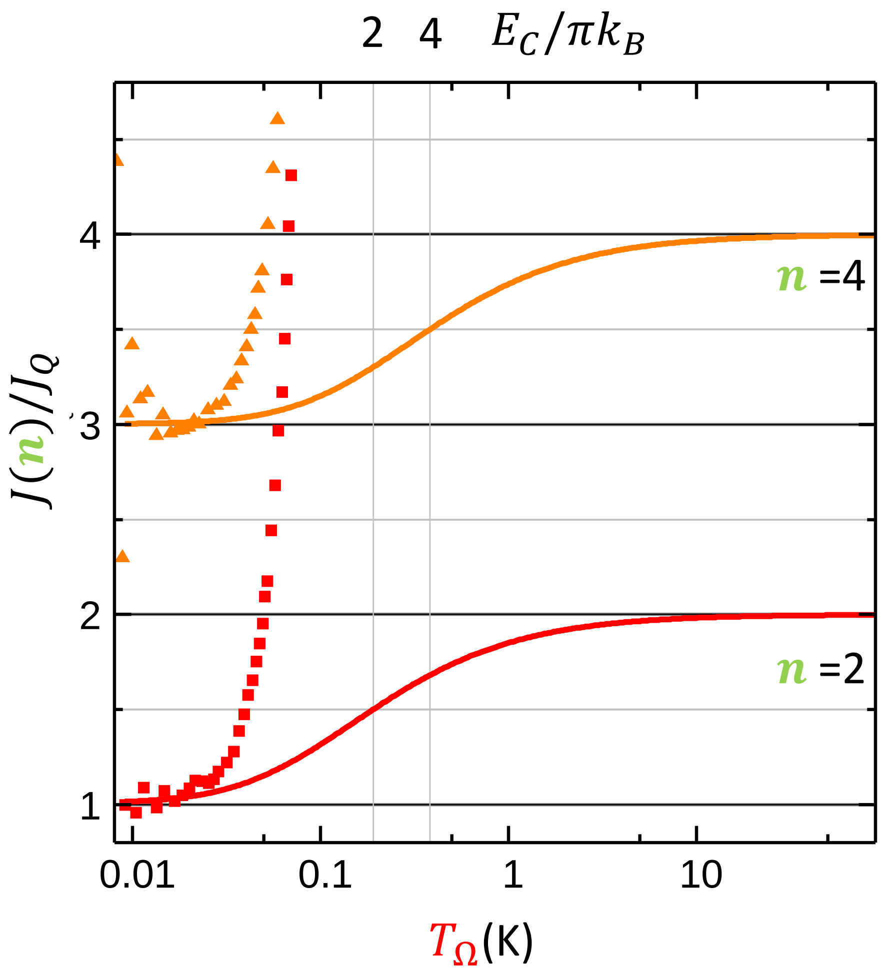
$G_{th} = n\, G_Q$

A. Slobodeniuk, I. Levkivskyi & E. Sukhorukov, Phys. Rev. B **88**, 165307 (2013)



Heat Coulomb Blockade: data vs theory

A. Slobodeniuk, I. Levkivskyi & E. Sukhorukov, Phys. Rev. B **88**, 165307 (2013)



Theory: $J^{\mathrm{el}}(n, T_\Omega, T_0)$

Experiment:

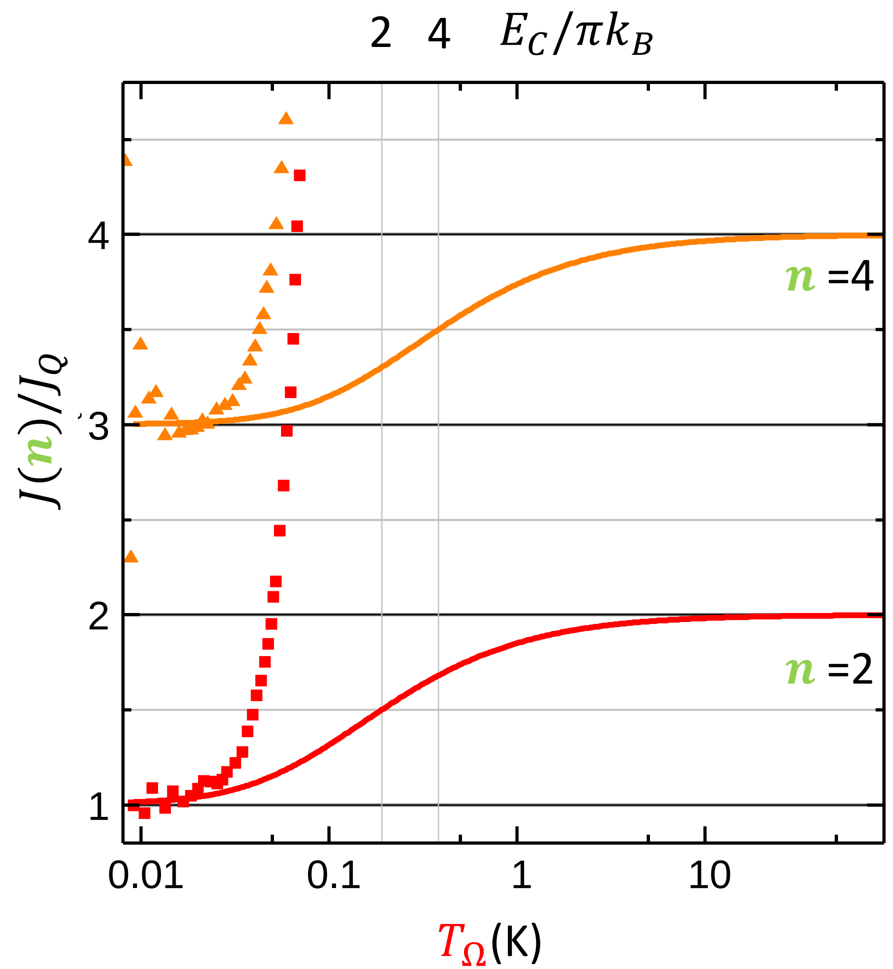
$$J(n) = J^{\mathrm{el}}(n, T_\Omega, T_0) + J^{\mathrm{e-ph}}(T_\Omega, T_0)$$

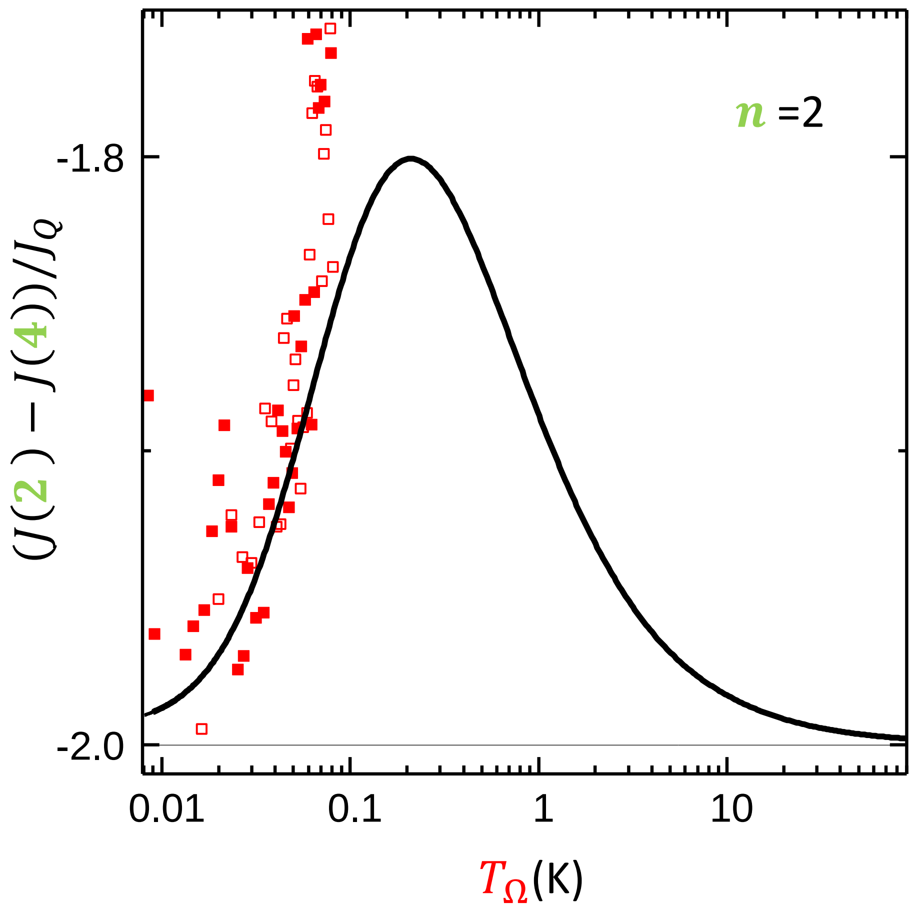
Non negligeable when T_Ω > 25 mK

E_C=300 mK

Heat Coulomb Blockade: data vs theory

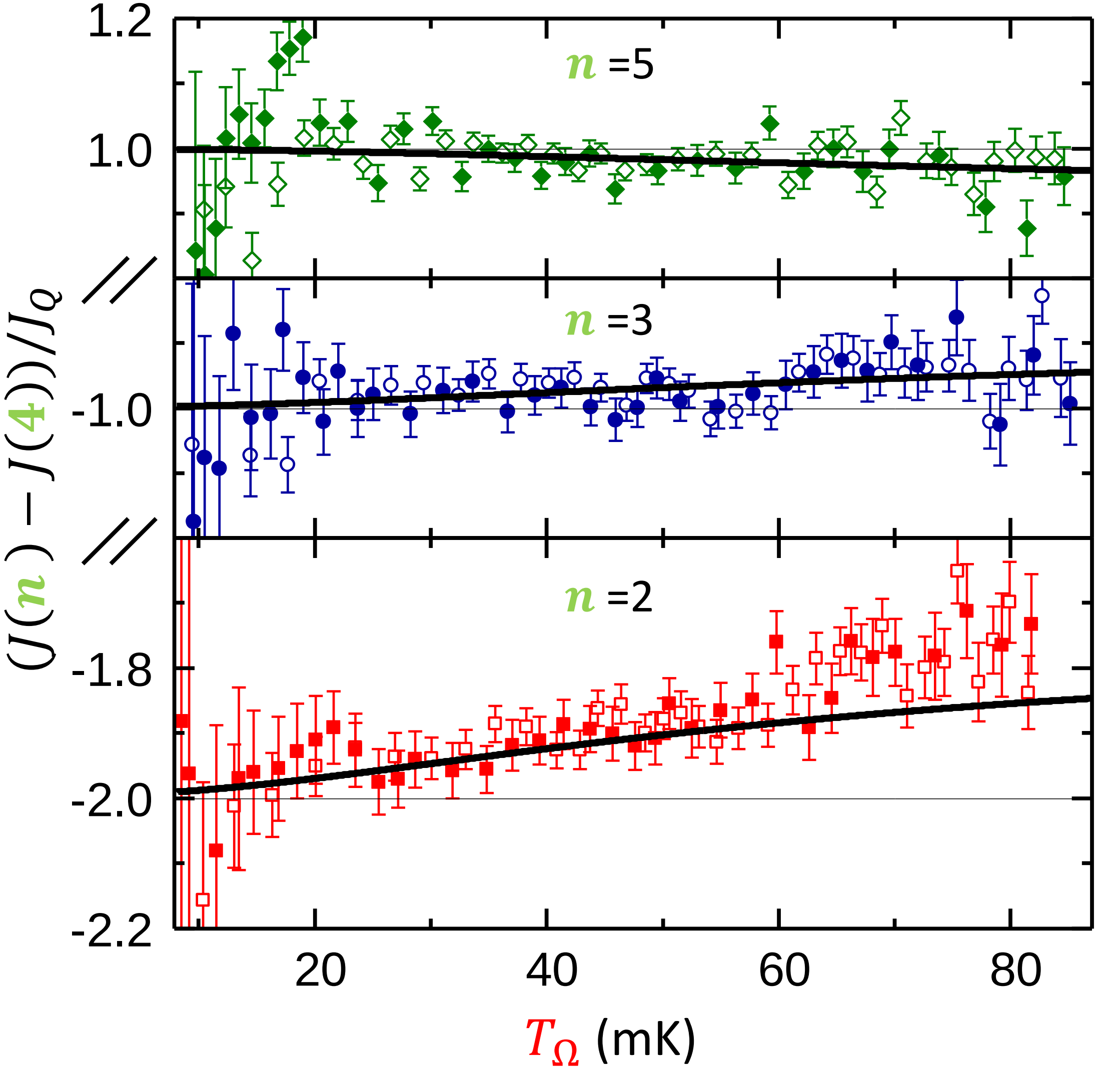
Focus on the electronic heat flow : J(2)-J(n_{ref}=4)





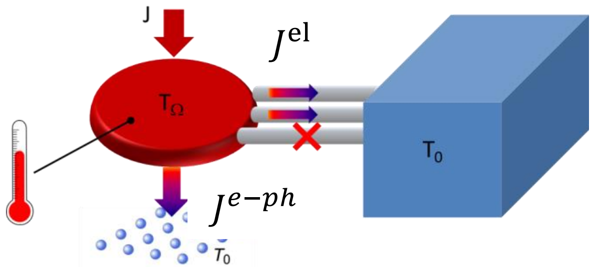
Focus on the electronic heat flow
J(n)-J(n_{ref}=4)

A. Slobodeniuk, I. Levkivskyi & E. Sukhorukov, Phys. Rev. B **88**, 165307 (2013)



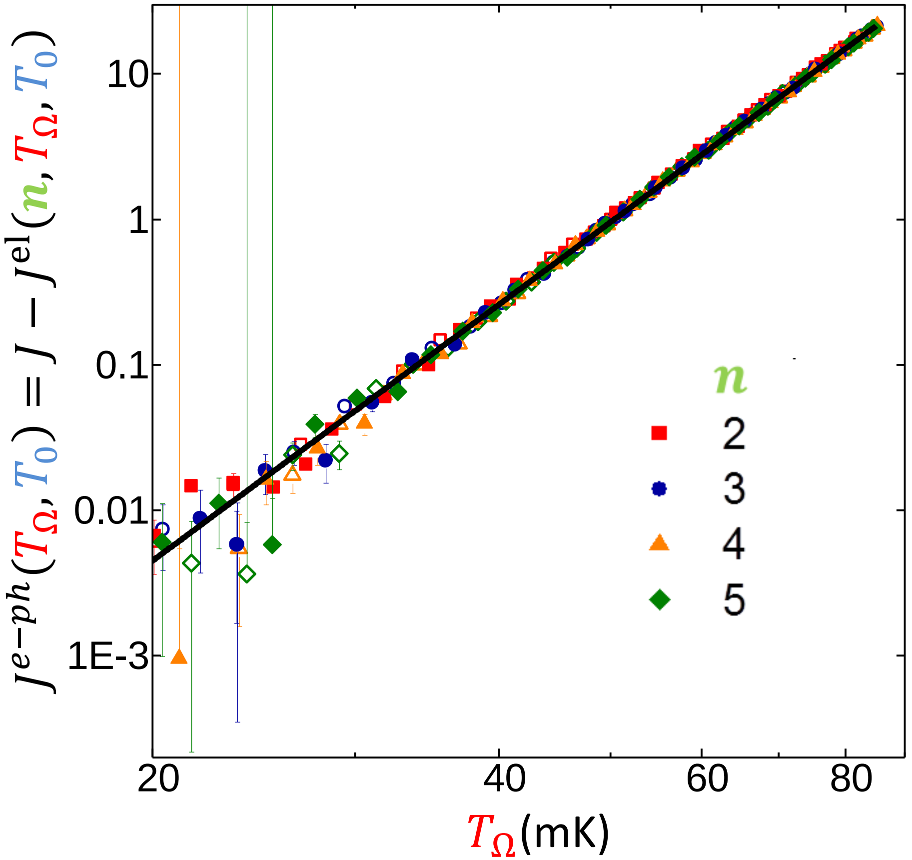
Heat Coulomb blockade predictions

Phononic heat flow modeling



$$\begin{cases} J^{e-ph}(T_\Omega, T_0) = \Sigma\Omega\left(T_\Omega{}^{\beta} - T_0{}^{\beta}\right) \\ J^{\mathrm{el}}(n, T_\Omega, T_0) = \text{HCB predictions} \end{cases}$$

A. Slobodeniuk, I. Levkivskyi & E. Sukhorukov, Phys. Rev. B **88**, 165307 (2013)



Fit :

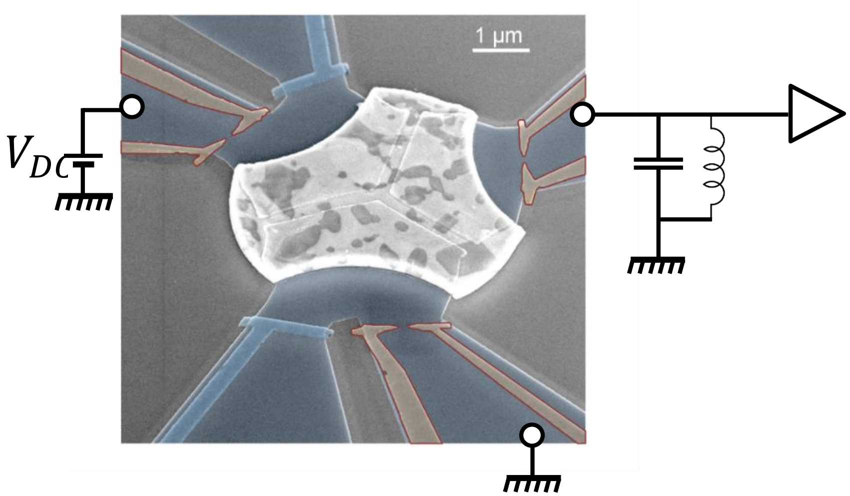
$\Sigma\Omega = 3.9 \times 10^{-8}$ W.K$^{-\beta}$

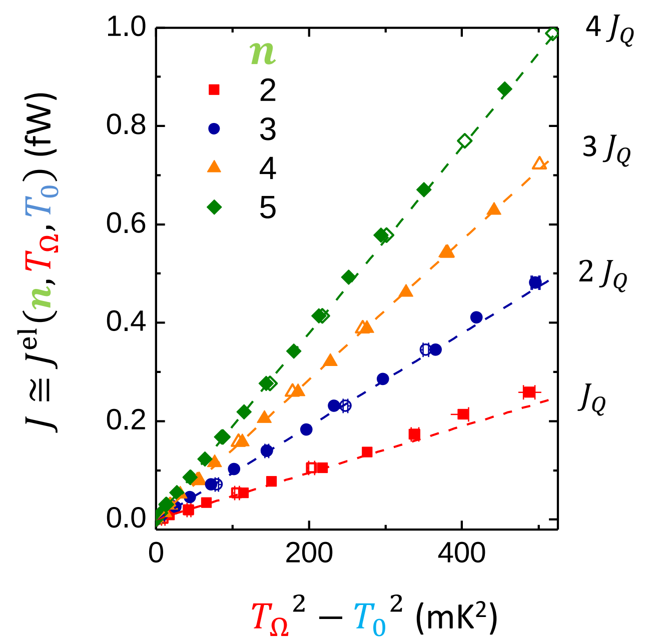
β=5.85

Conclusion and perspectives

✓ Heat Coulomb blockade without charge Coulomb blockade : New quantum rules checked

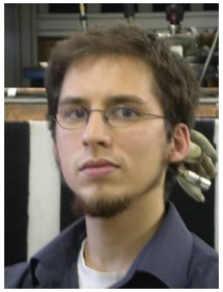
E. Sivre *et al.*, Nat. Phys. (**10.1038/nphys4280**)





- Heat Coulomb blockade for non ballistic channels ?
- Quantum coherence and correlations ?

Emile
Sivré



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