Pauli-Heisenberg Oscillations in Electron Quantum Transport

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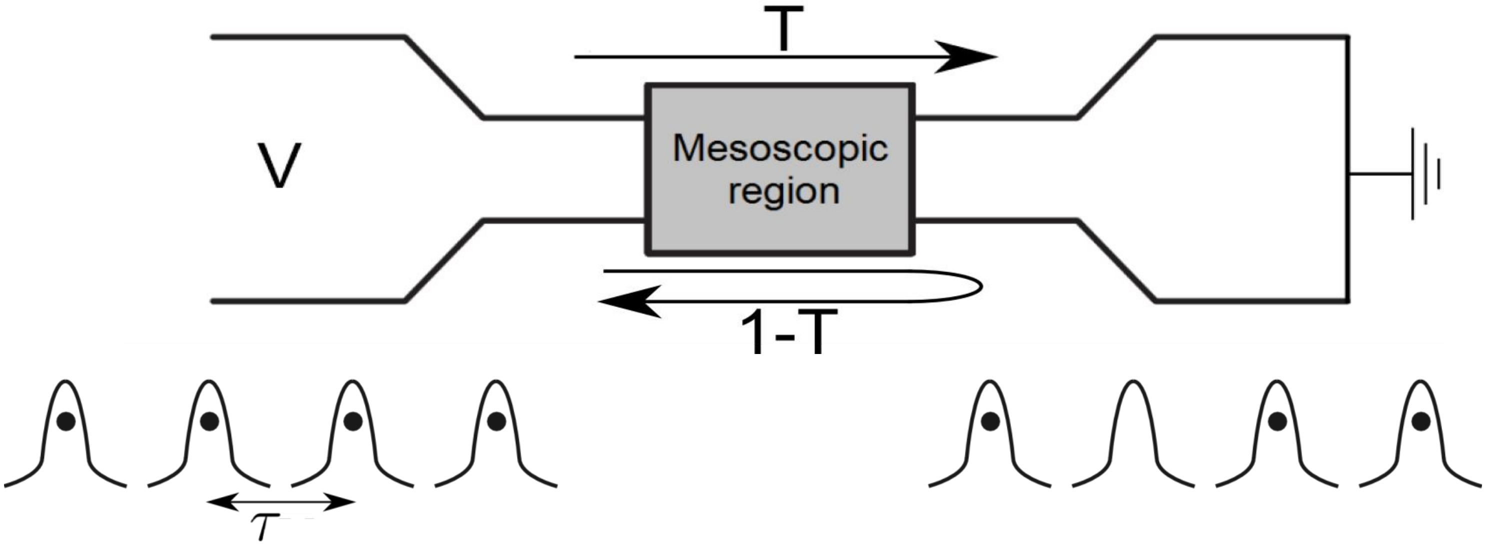
Outline

- Motivation
- Method
- Sample and Experimental set-up
- Results
- Interpretation
- Conclusion

Motivation

$$\langle i_n(t)\rangle = G_n V = \frac{e}{\tau}T_n \Rightarrow \tau = \frac{h}{eV} \qquad G_n = \frac{e^2}{h}T_n$$



Theory of quantum transport predicts that electrons are emitted regularly each h/eV [1].

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1. Lesovik, G. B. & Levitov, L. S. Noise in an ac biased junction : Nonstationary Aharonov-Bohm effect. *Phys. Rev. Lett.* **72,** 538–541 (1994).

Method

Goal :

Measure the current-current correlator in the time domain

$$C(\tau) = \langle i(t) i(t+\tau) \rangle$$

and show that $C(\tau) \propto \cos\left(\frac{eV\tau}{\hbar}\right)$.

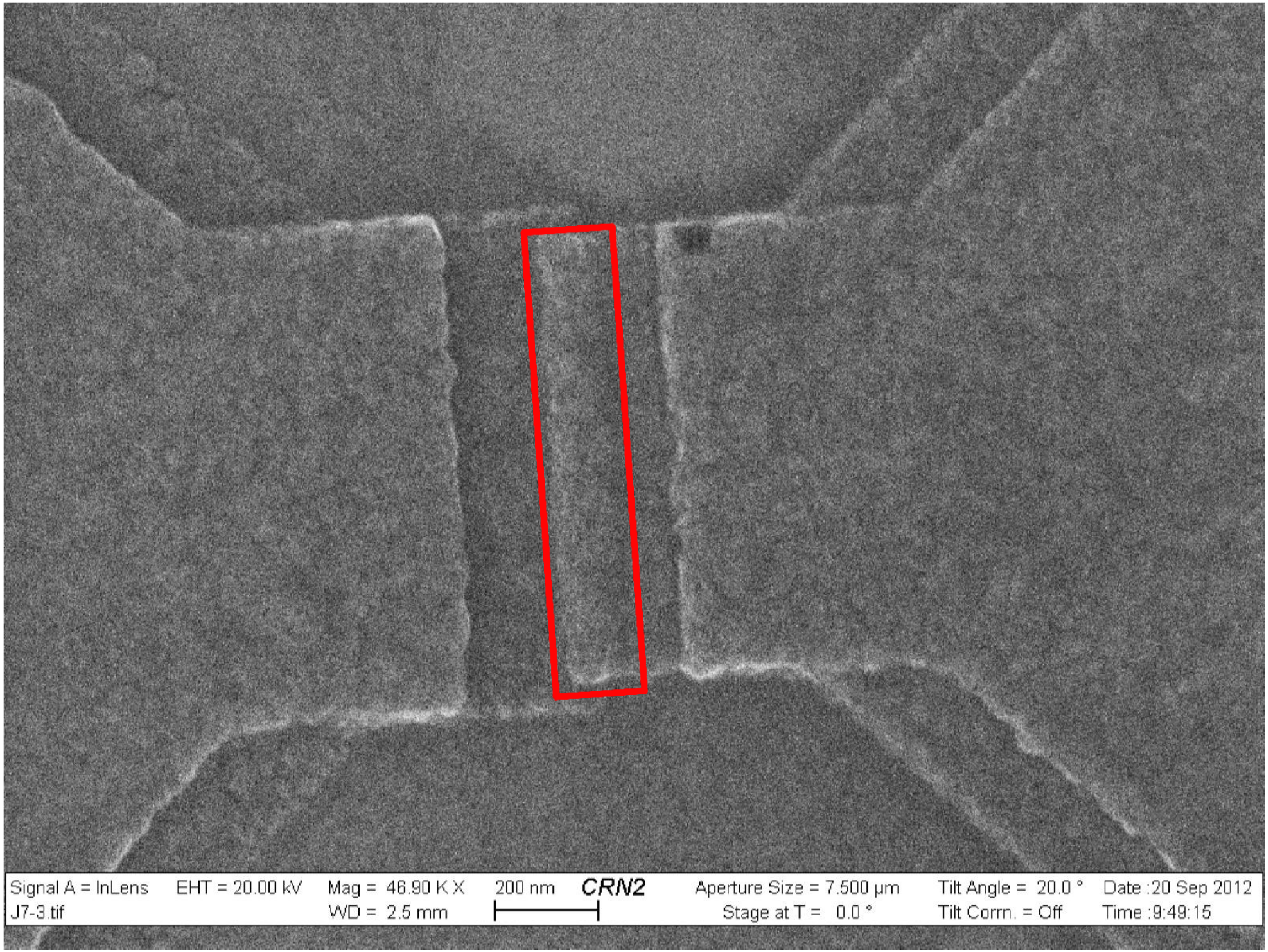
Method :

Measure the noise spectral density vs frequency

$$S(f) = \langle i(f) i(-f) \rangle = \mathrm{Fourier}[C(\tau)]$$

with a very large bandwidth.

Tunnel junction



Tunnel junction

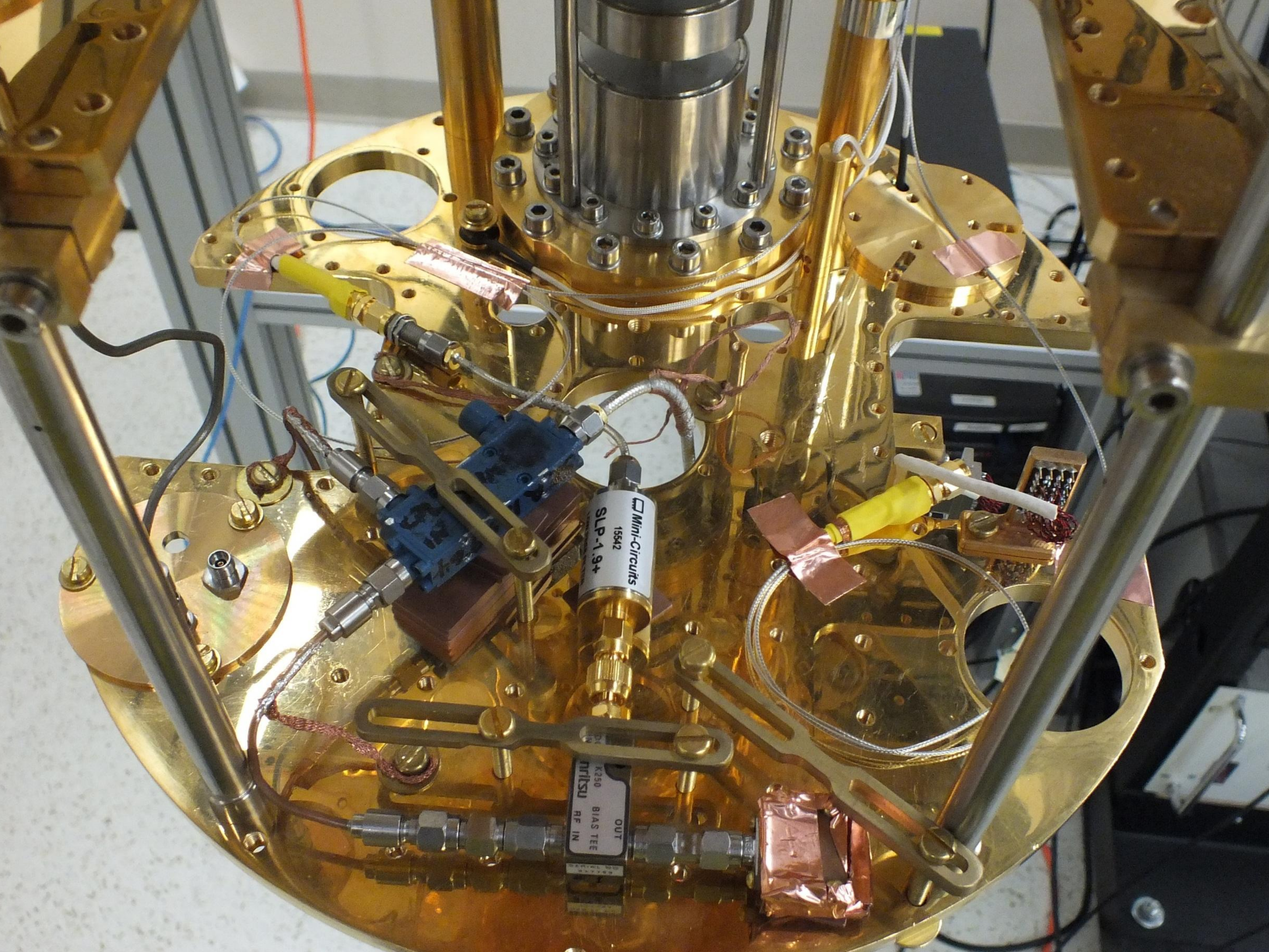
Normal-metal – Isolator – Normal-metal

- Classical regime : current is a succession of uncorrelated random impulses

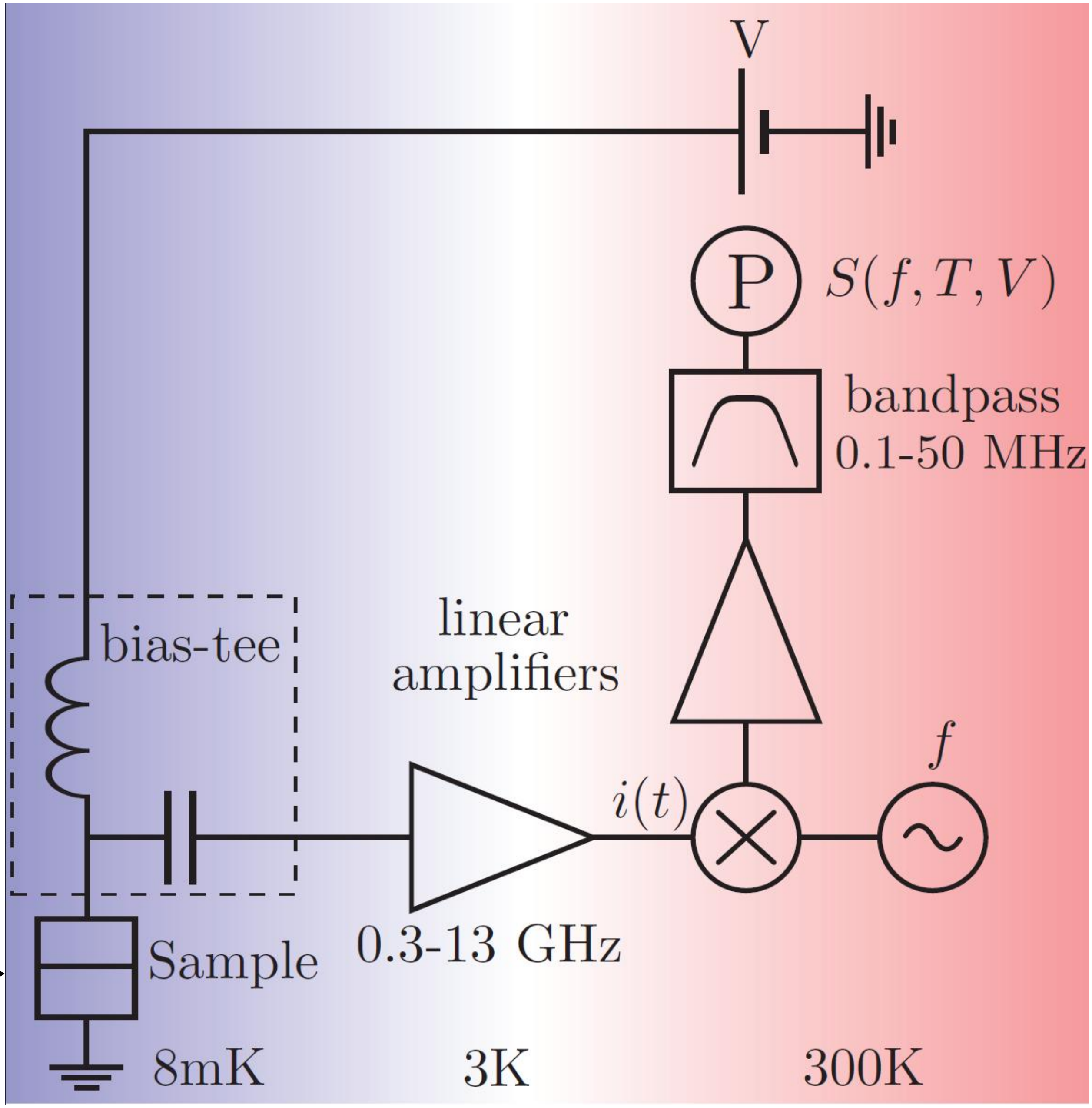
  ➔current follows a Poisson distribution

  ➔shot noise : $S = e|I|$

- Quantum regime : Correlations appear


Mini-Circuits
15542
SLP-1.9+
K250
nritsu
BIAS TEE
OUT
RF IN

Experimental set-up



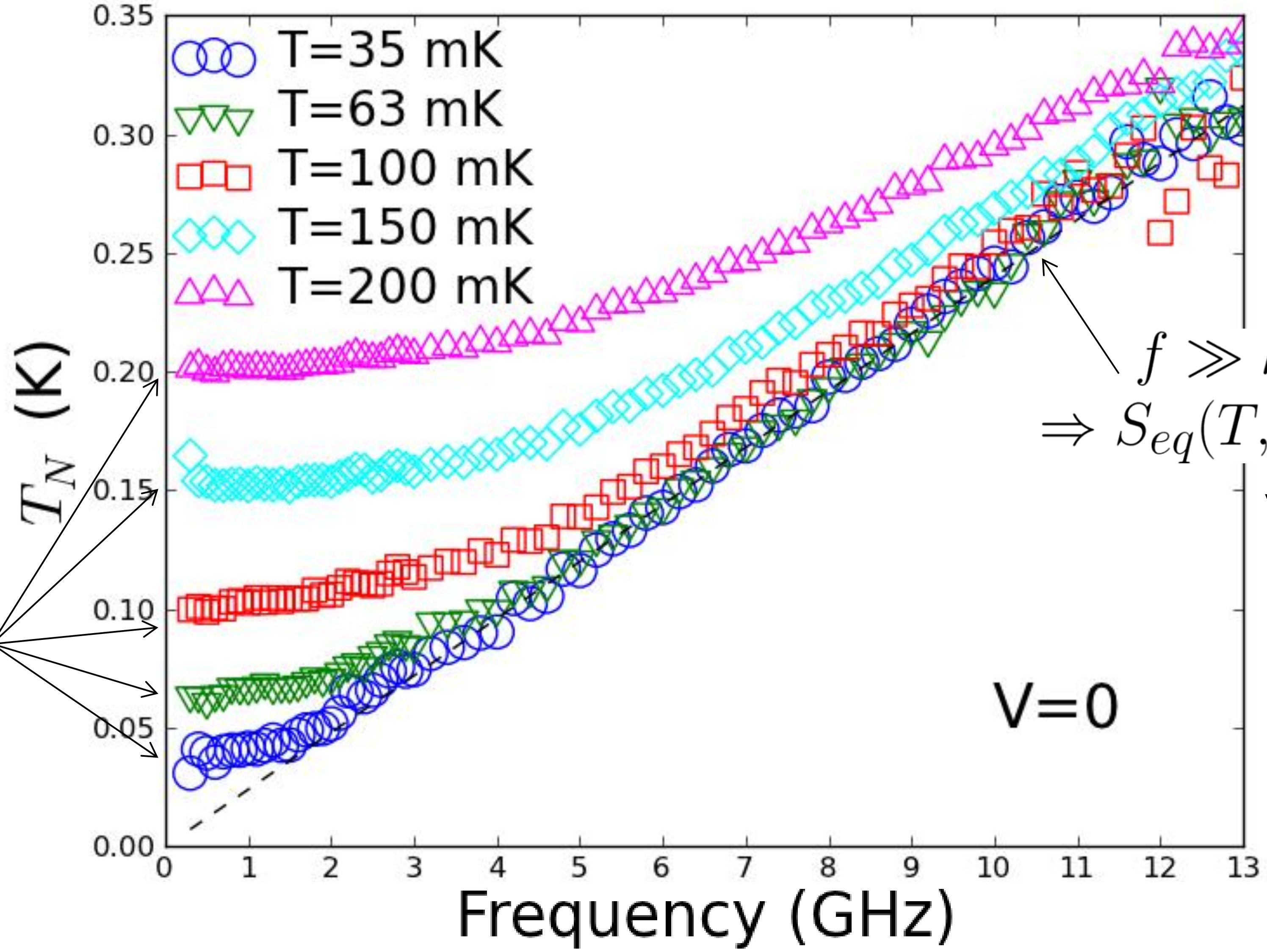
Tunnel junction

Noise temperature

In general, we express the spectral density of current-current fluctuations as a noise temperature :

$$T_N(f) = \frac{S(f)}{2k_B G}$$

Thermal noise : V=0



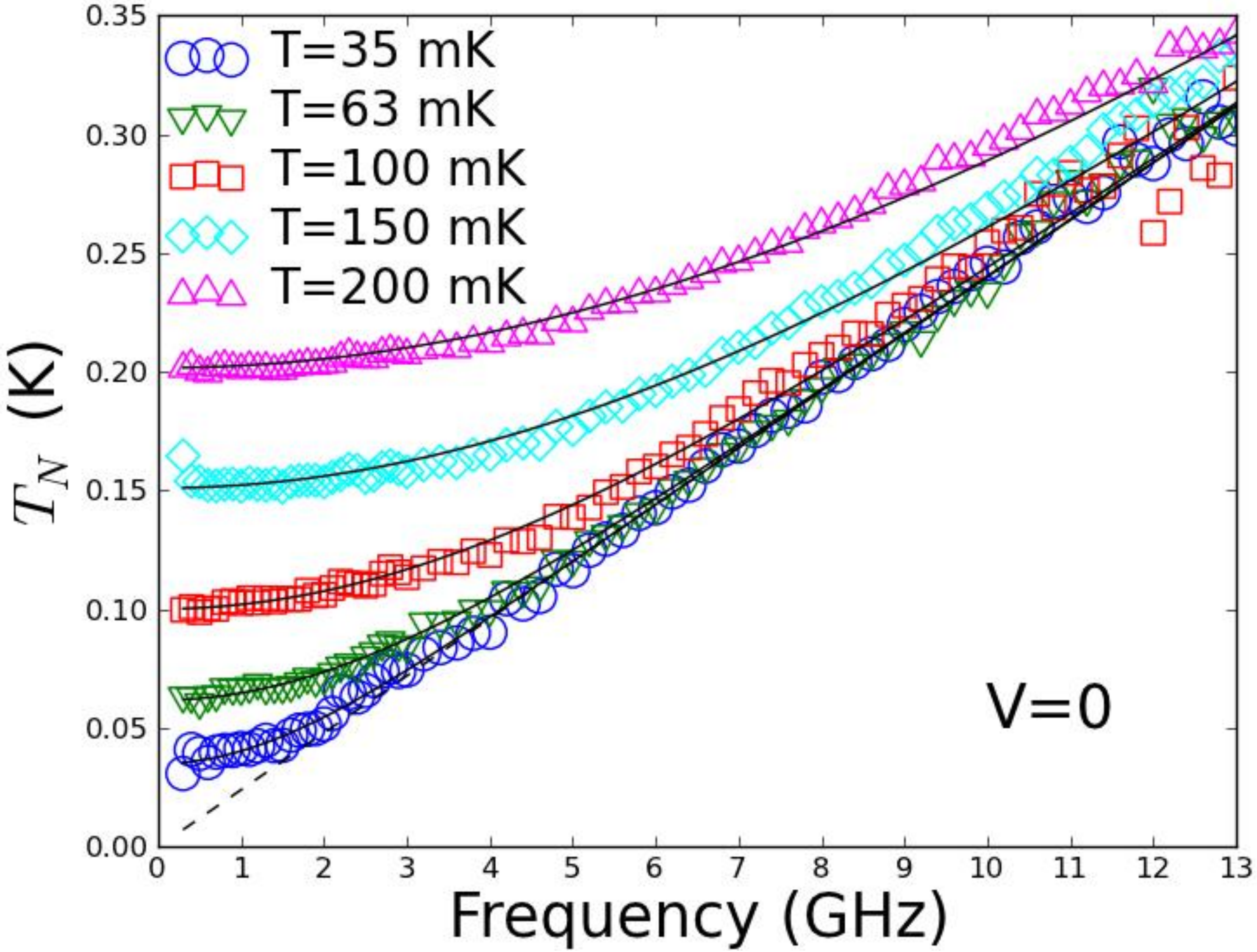
$T_N(0) = T$

$f \gg k_B T/h$

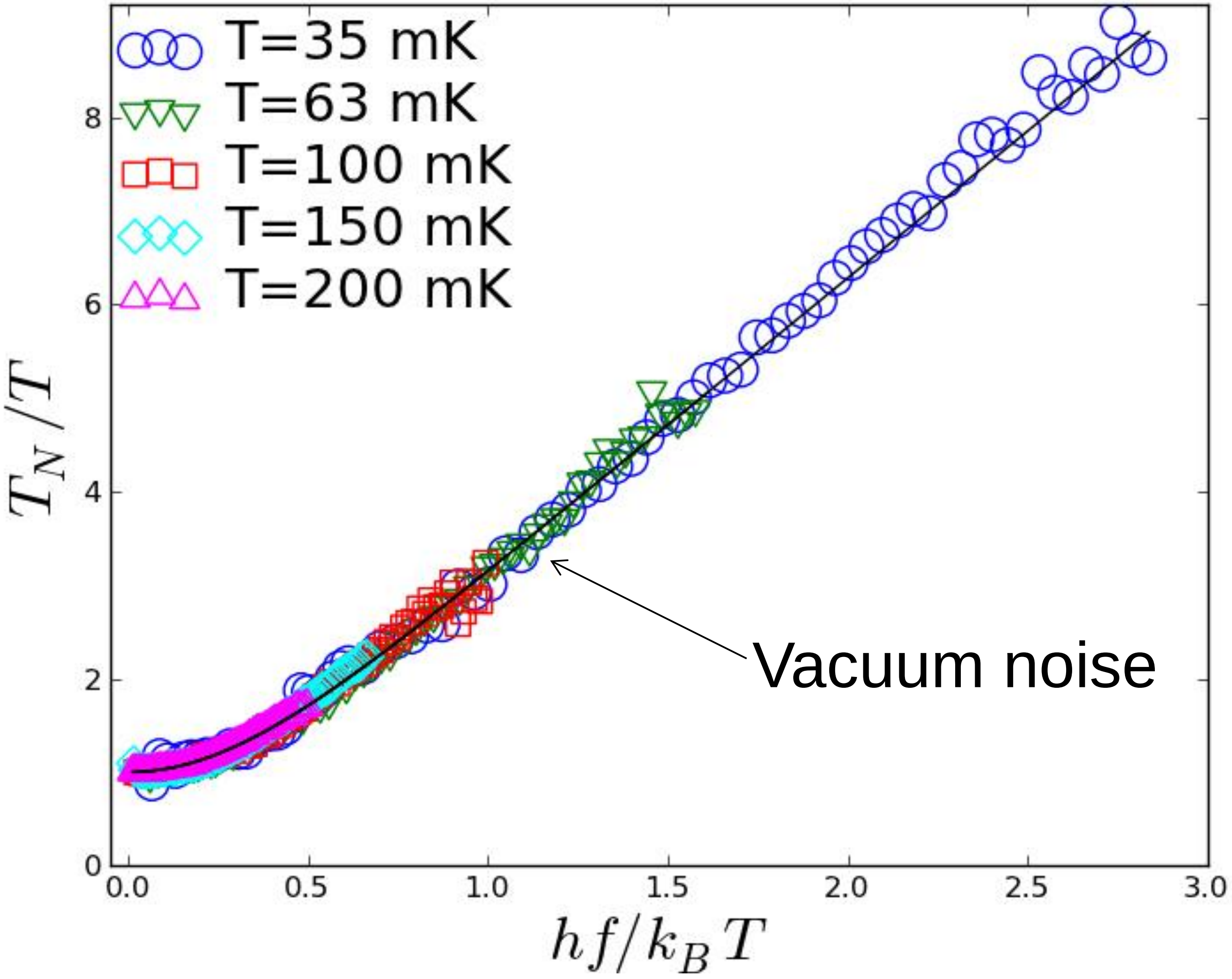
$\Rightarrow S_{eq}(T,f) = Ghf$

Vacuum noise

$$S_{eq}(f,T) = Ghf\coth\left(\frac{hf}{2k_BT}\right)$$

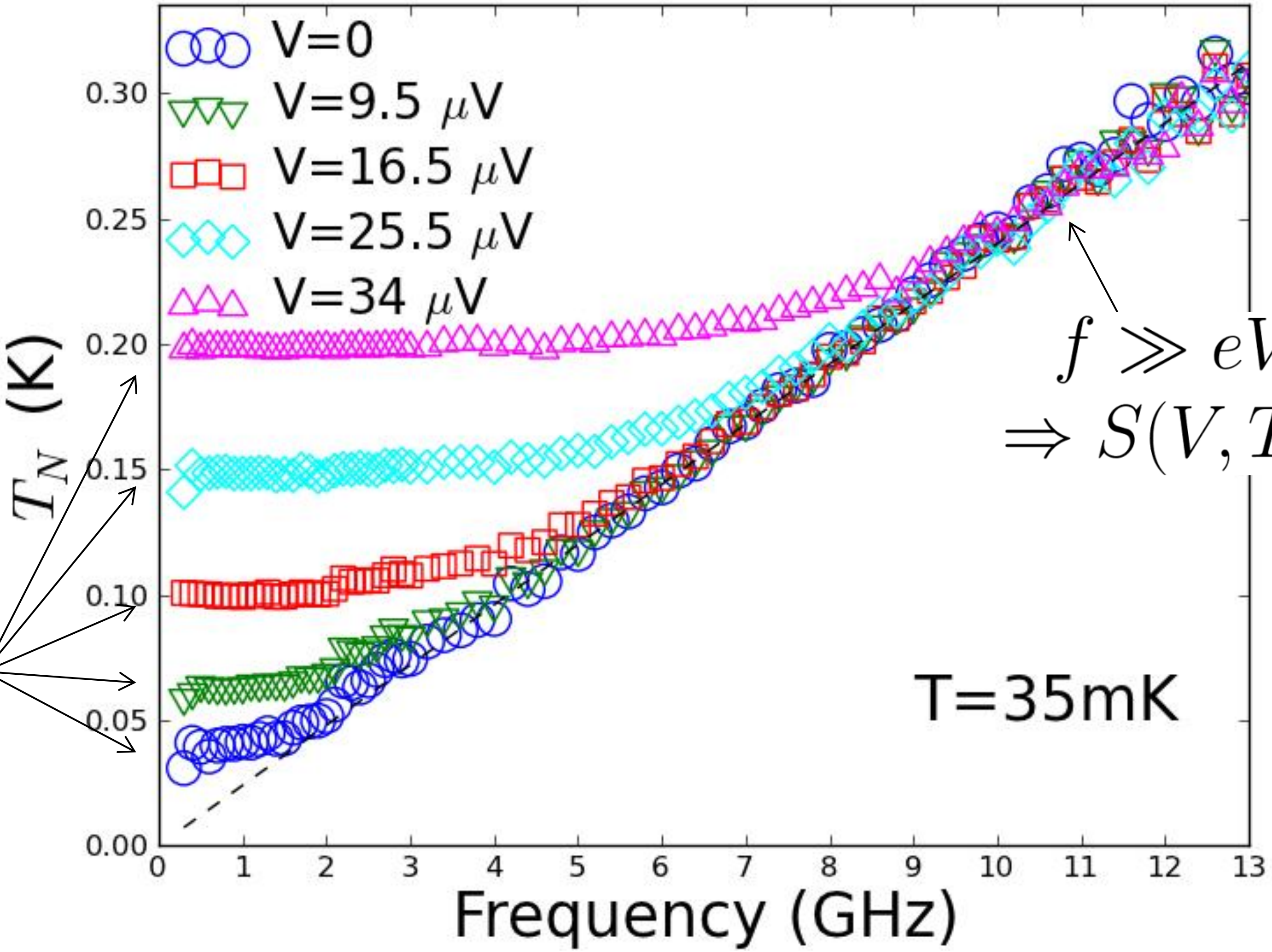


$$\frac{S_{eq}(f)}{2k_BTG} = \frac{T_N(f)}{T} = \frac{hf}{2k_BT}\coth\left(\frac{hf}{2k_BT}\right)$$



Vacuum noise

Shot Noise



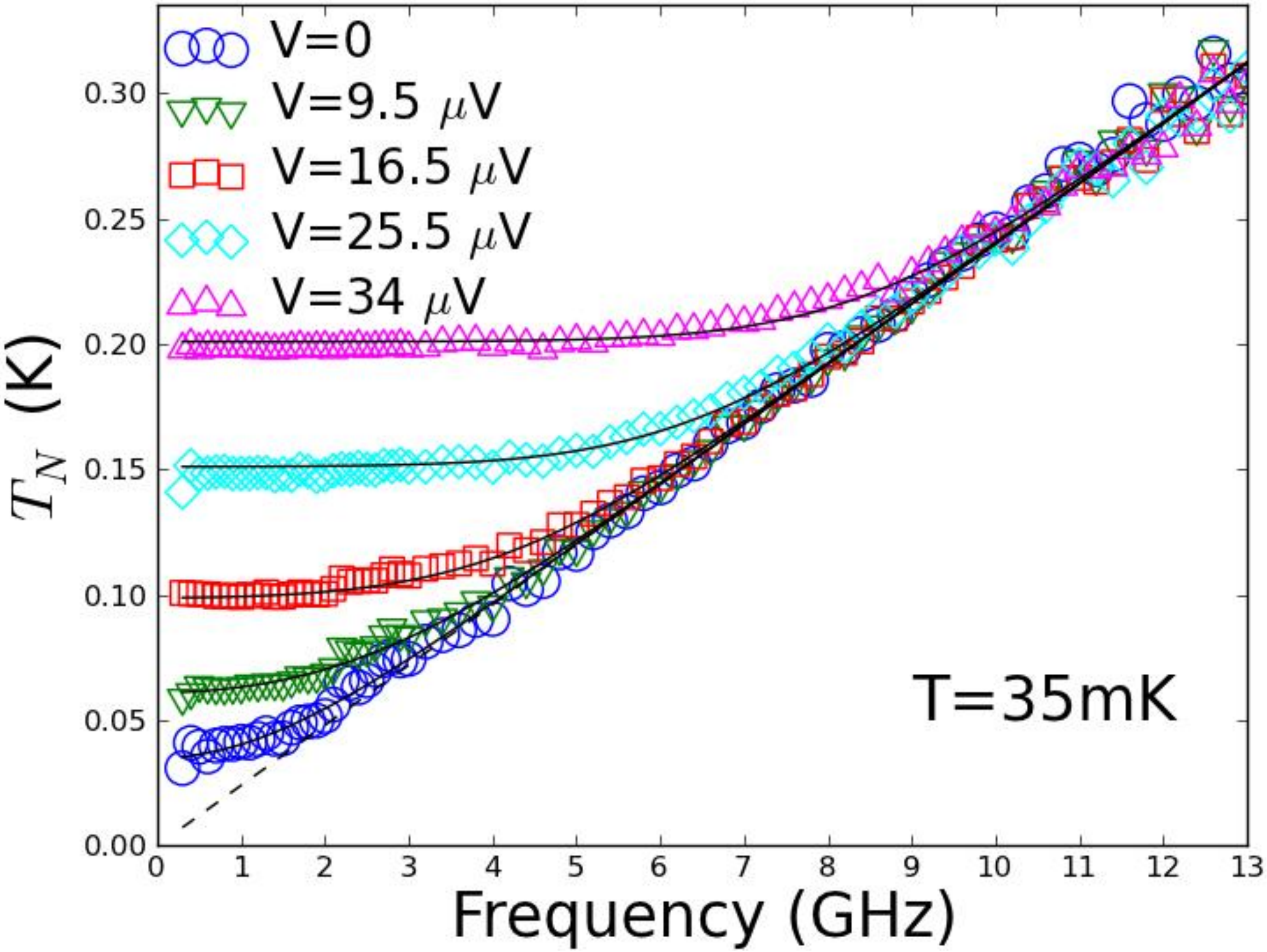
$$T_N(0) = \frac{eV}{2k_B}$$

$$f \gg eV/h$$

$$\Rightarrow S(V,T,f) = Ghf$$

Vacuum noise

$$S_V(T,f) = \frac{1}{2}\left[S_{eq}\left(T, f - \frac{eV}{h}\right) + S_{eq}\left(T, f + \frac{eV}{h}\right)\right]$$



Time-domain : Equilibrium (V=0)

$$S_{eq}(T,f) = Ghf\coth\left(\frac{hf}{2k_BT}\right)$$

$$S_{eq}(T,f) = Gh|f| + S_T(f)$$

↕ Fourier Transform

$$C_{eq}(t) = C_Q(t) + C_T(t)$$

↓

Diverges!

$$C_T(t) = C_{eq}(t) - C_Q(t)$$

Time-domain : Shot noise (V≠0)

$$S(f) = \frac{1}{2}\left[S_{eq}\left(f - \frac{eV}{h}\right) + S_{eq}\left(f + \frac{eV}{h}\right)\right]$$

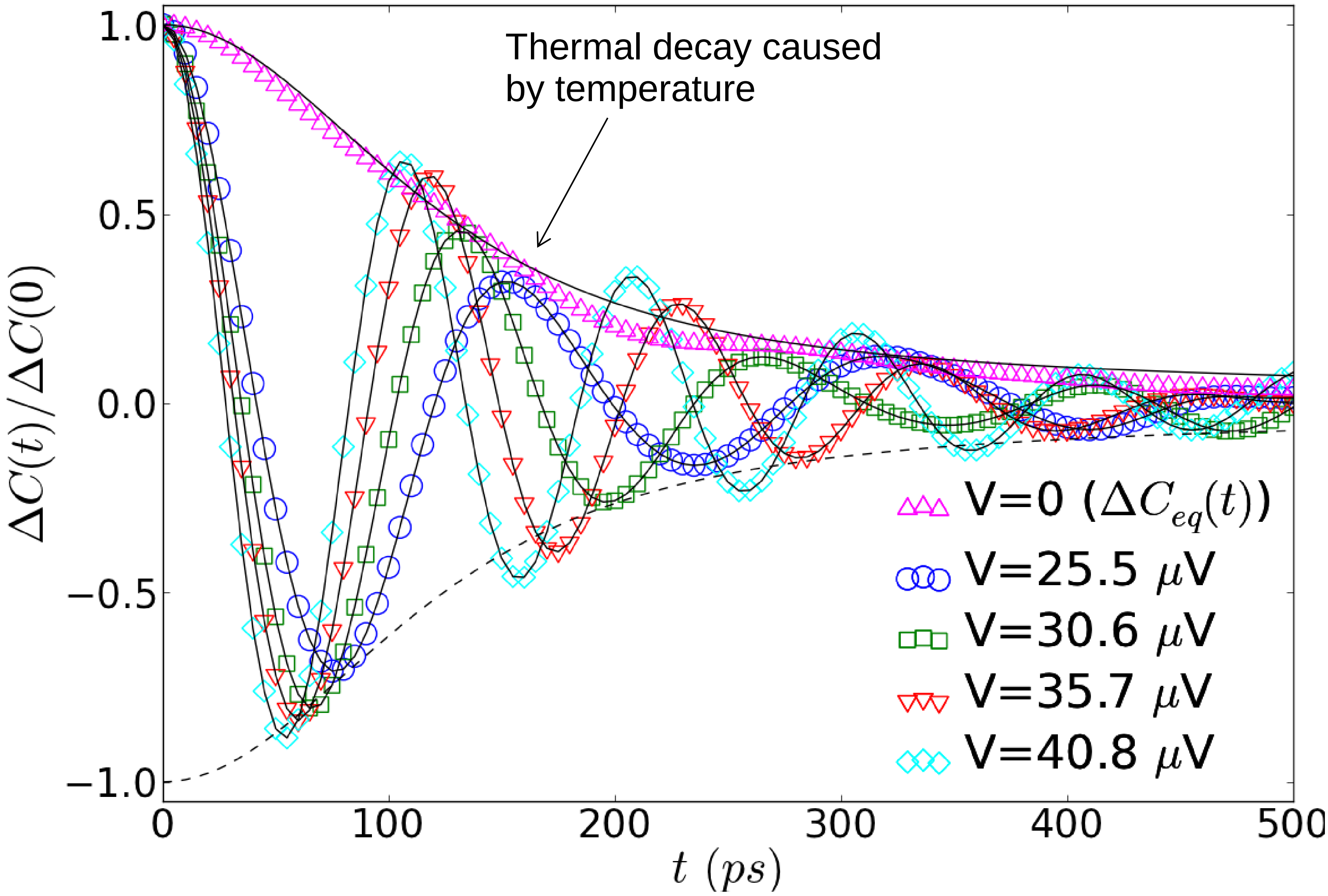
$\updownarrow$ Fourier Transform

$$C(t) = C_{eq}(t)\cos\left(\frac{eVt}{\hbar}\right)$$

Since the quantum part diverges, we need to substract it :

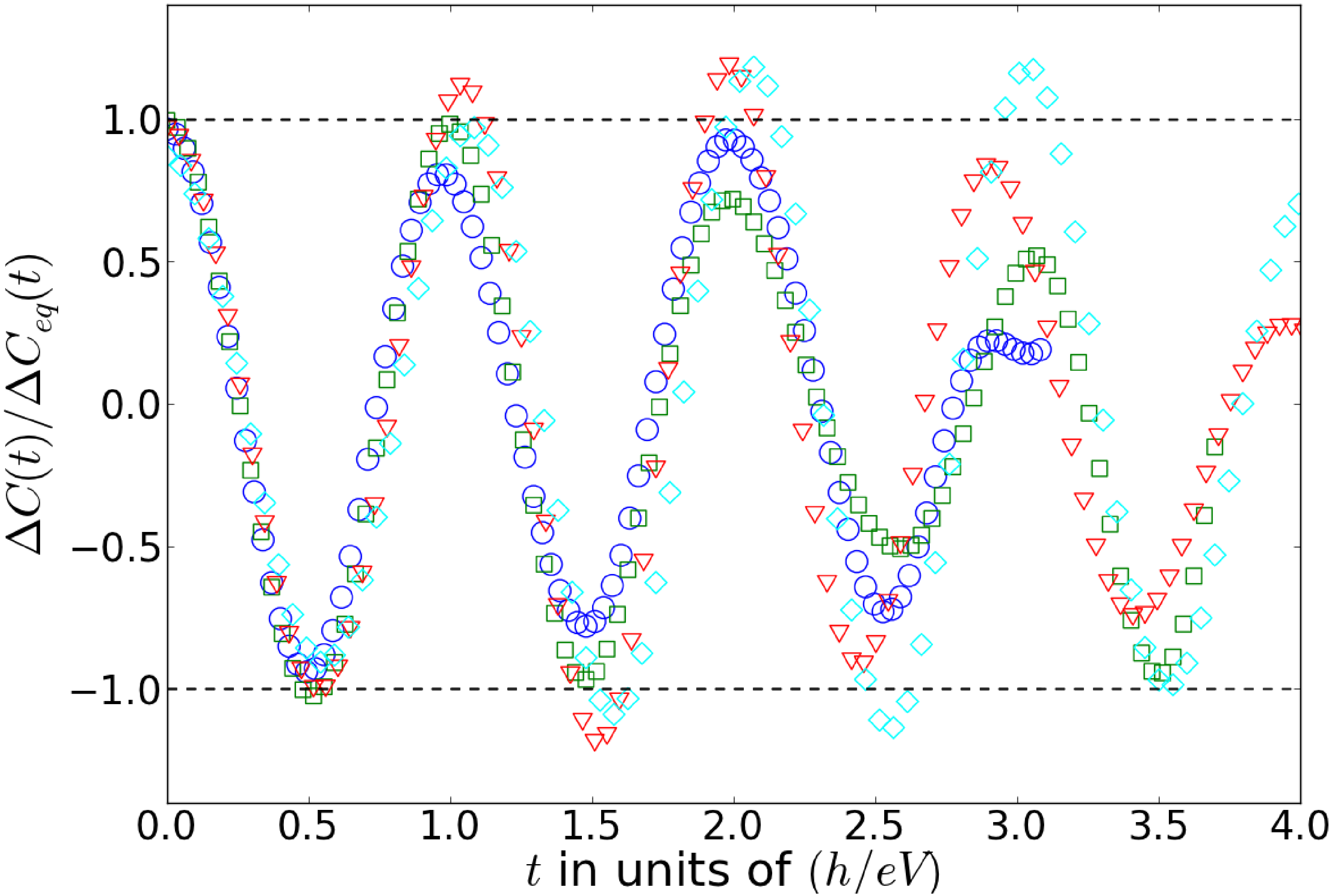
$$\Delta C(t) = C(t) - C_Q(t)\cos\left(\frac{eVt}{\hbar}\right) = C_T(t)\cos\left(\frac{eVt}{\hbar}\right)$$

Fourier Transform
Shot noise (V≠0)

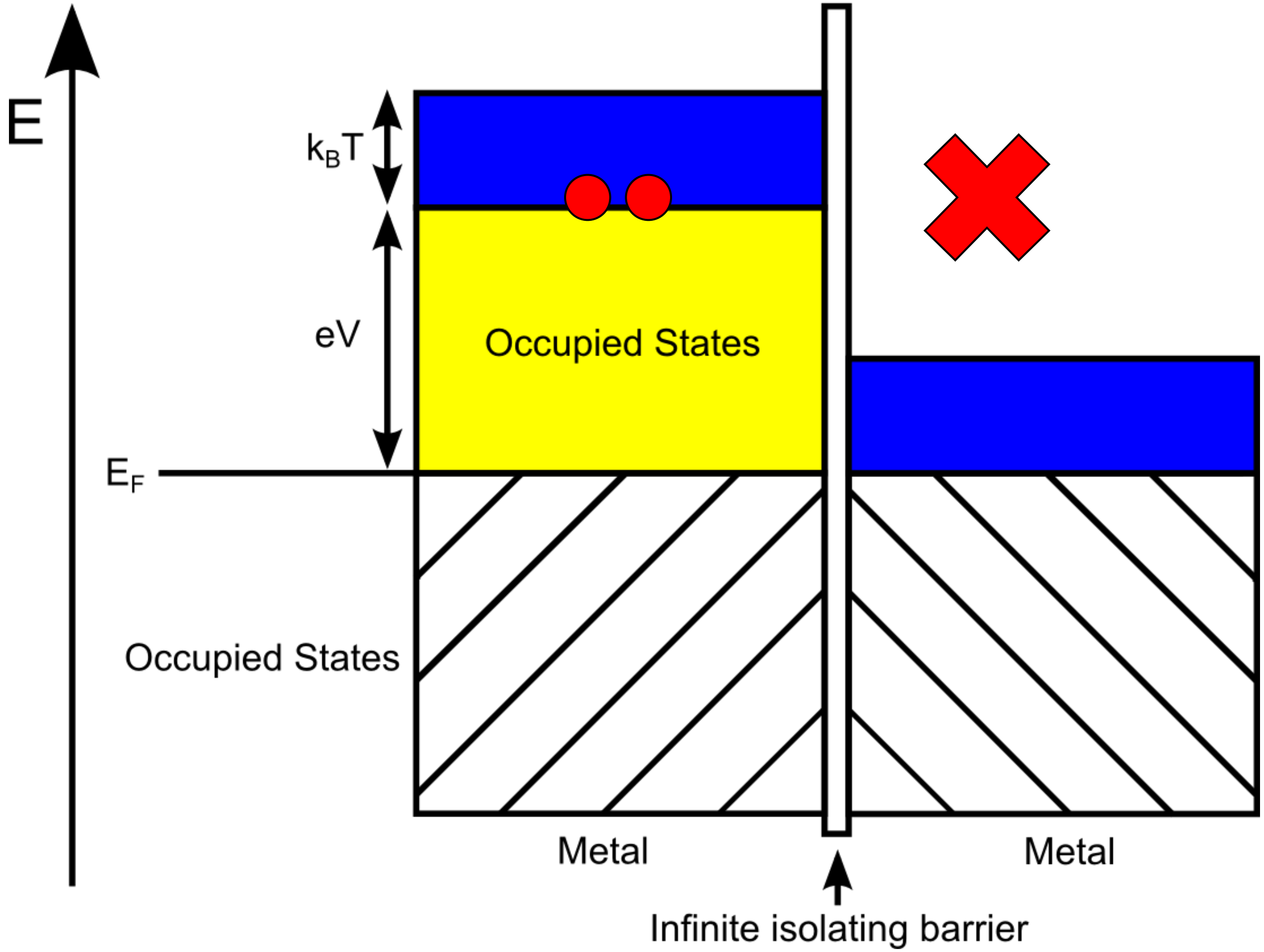


Thermal decay caused by temperature

Oscillations in h/eV.



Interpretation using Pauli and Heisenberg principles



$$\Delta E \Delta t \geq \hbar$$

$$\Downarrow$$

$$\Delta t \geq \frac{\hbar}{eV}$$

Conclusion

- We have measured the current-current correlator in time domain $\langle i(t)i(t+\tau)\rangle$ and shown that it oscillates with a period h/eV.

Future Work

- Measuring $\langle i(t)i(t+\tau)\rangle$ in a device where the are other intrinsic time scales (like a diffusive wire, where τ_D is important).
- Measure this correlator in the non-stationnary regime.

Thank you!

Questions?

Calibration

What we actually measure is :

$$P(f) = A(f)[S(f) + S_A(f)]$$

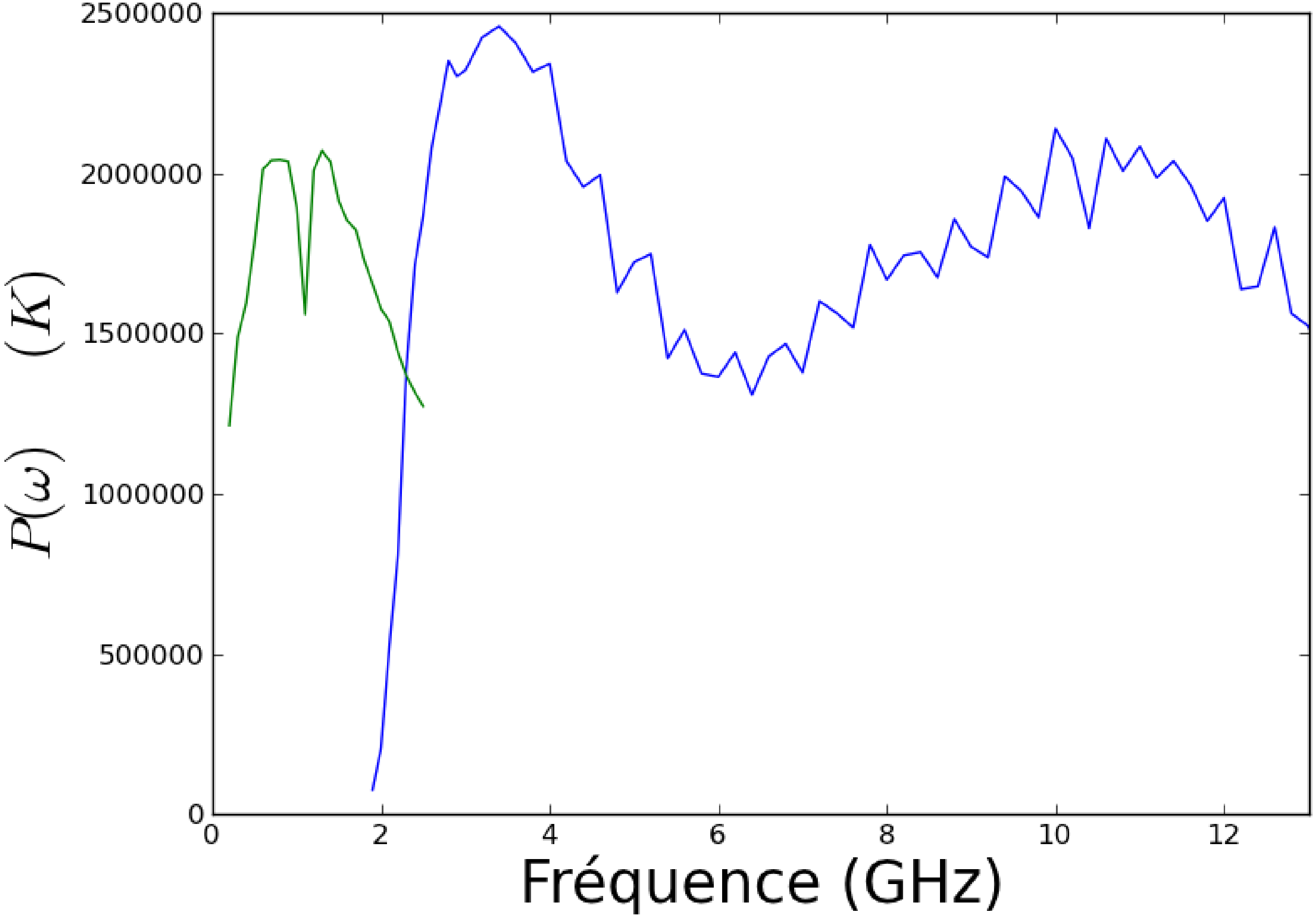
$A(f) =$ Gain of the system , $S_A(f) =$ Amplifier Noise

Problem : $A(f)? \quad , \quad S_A(f)?$

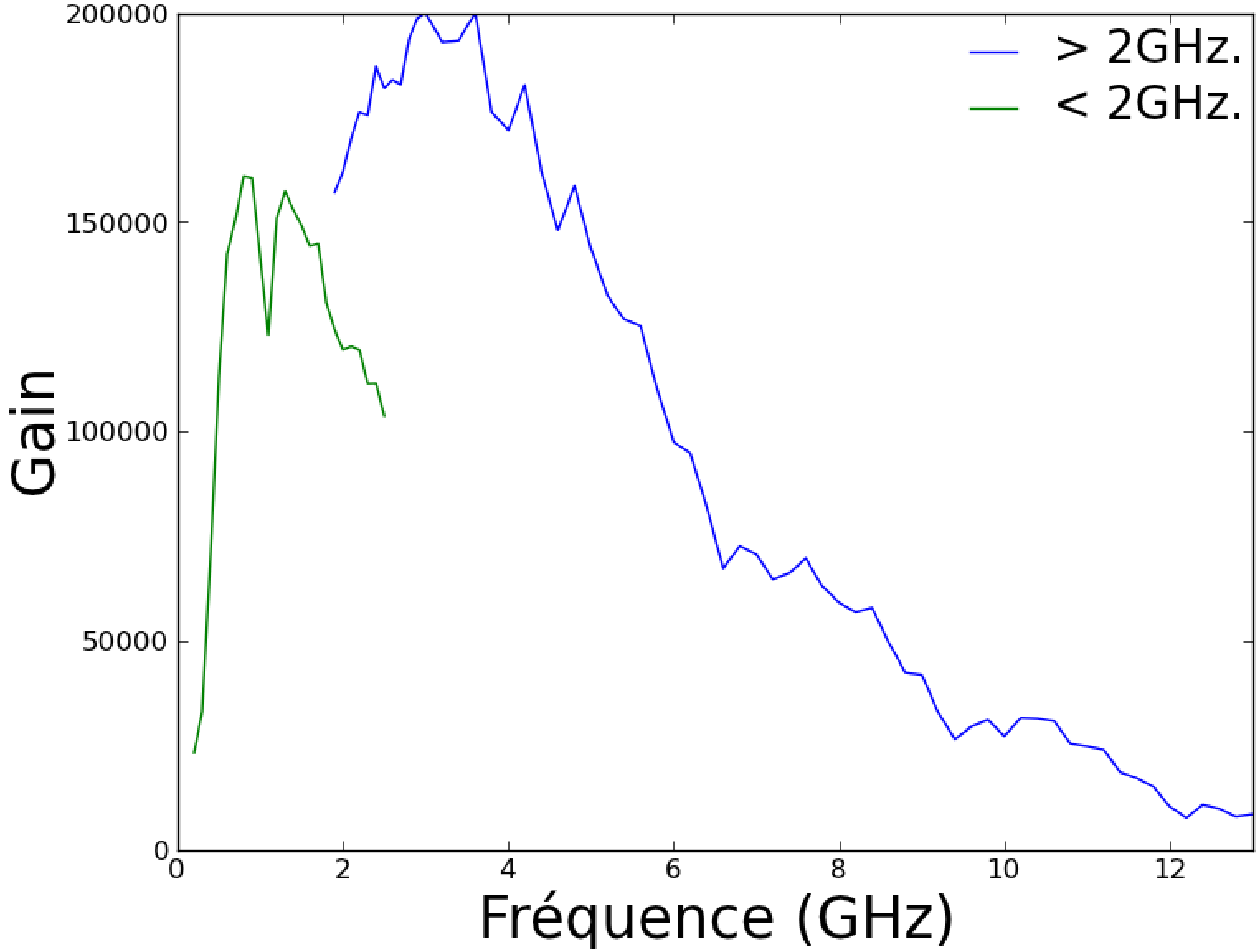
Method : classical limit/Schottky formula

$$S(V \gg hf/e, k_BT/e) = eI$$

Spectral density before calibration



Calibration – Gain of the measurement system



Calibration – Noise temperature of the measurement system