Emission/Absorption asymmetry in the quantum noise of a Josephson junction

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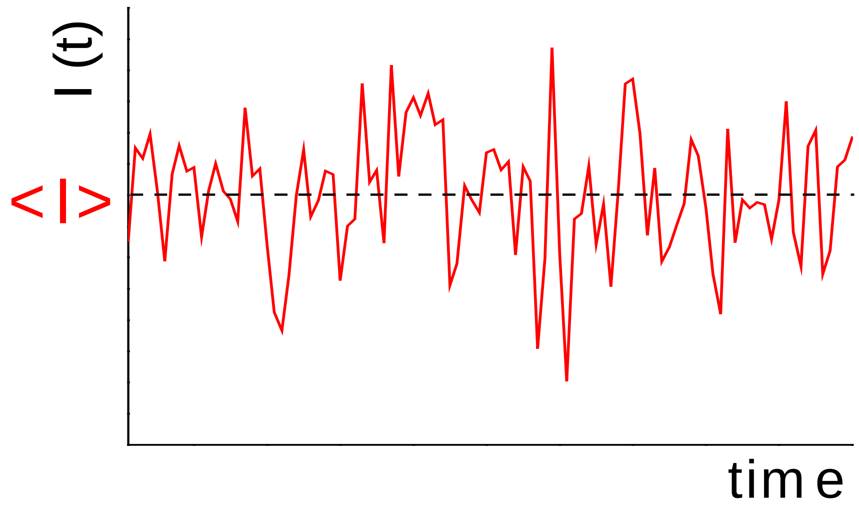
« The noise is the signal »



Current fluctuations :

$$\Delta I(t) = I(t) - < I >$$

Spectral density of noise :

$$S(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\tau \exp(i\omega\tau) < \Delta I(t)\Delta I(t+\tau) >$$

• equilibrium fluctuations : Nyquist noise

$$2S(\omega = 0) = 4k_B T G$$

• non-equilibrium fluctuations : shot noise (discrete transfer of charge quanta)

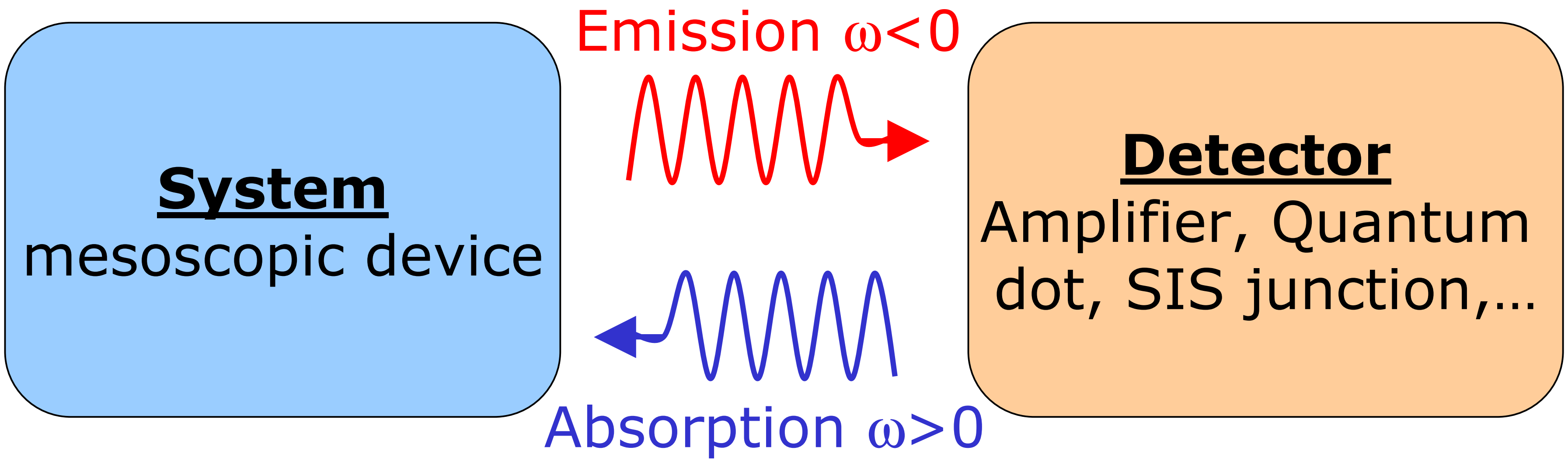
-charge of the current carriers (Cooper pairs, FQHE, …) : $2e^* < I >$

-correlation effects (statistics, interactions)

Noise measurement in the quantum regime

$$\hbar\omega \gg k_B T, \hbar\omega \geq eV$$

- quantum noise : zero point fluctuations
- internal energy scales and inverse of characteristic times
- back-action of a device, decoherence



Precisely what quantity is measured ?

What quantity is measured in a quantum noise experiment ?

Non symmetrized noise :

- current correlator : $C(\tau) =< \Delta I(t)\Delta I(t+\tau) >$
- spectral density of noise : real and $\omega \in]-\infty, +\infty[$

$$S(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\tau \exp{(i\omega\tau)} C(\tau)$$

Symmetrized noise :

- current correlator $C_{sym}(\tau) = \frac{1}{2}(< \Delta I(t)\Delta I(t+\tau) + \Delta I(t+\tau)\Delta I(t) >)$
- spectral density of noise : real and $\omega \in]-\infty, +\infty[$

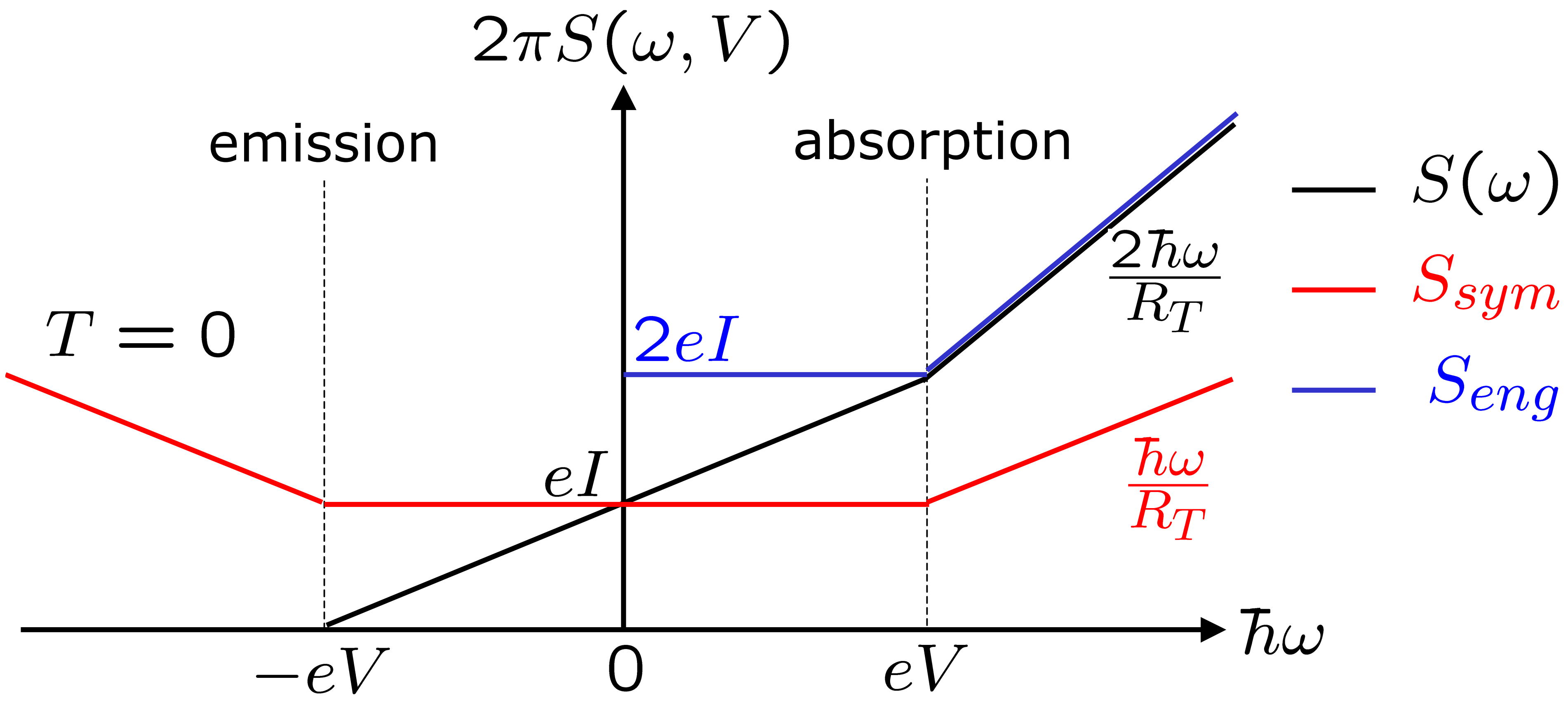
$$S_{sym}(\omega) = \frac{1}{2}(S(\omega) + S(-\omega))$$

Remark : « engineering » notation, defined with $\omega \in [0, +\infty[$

$$S_{eng}(\omega) = 2S_{sym}(\omega)$$

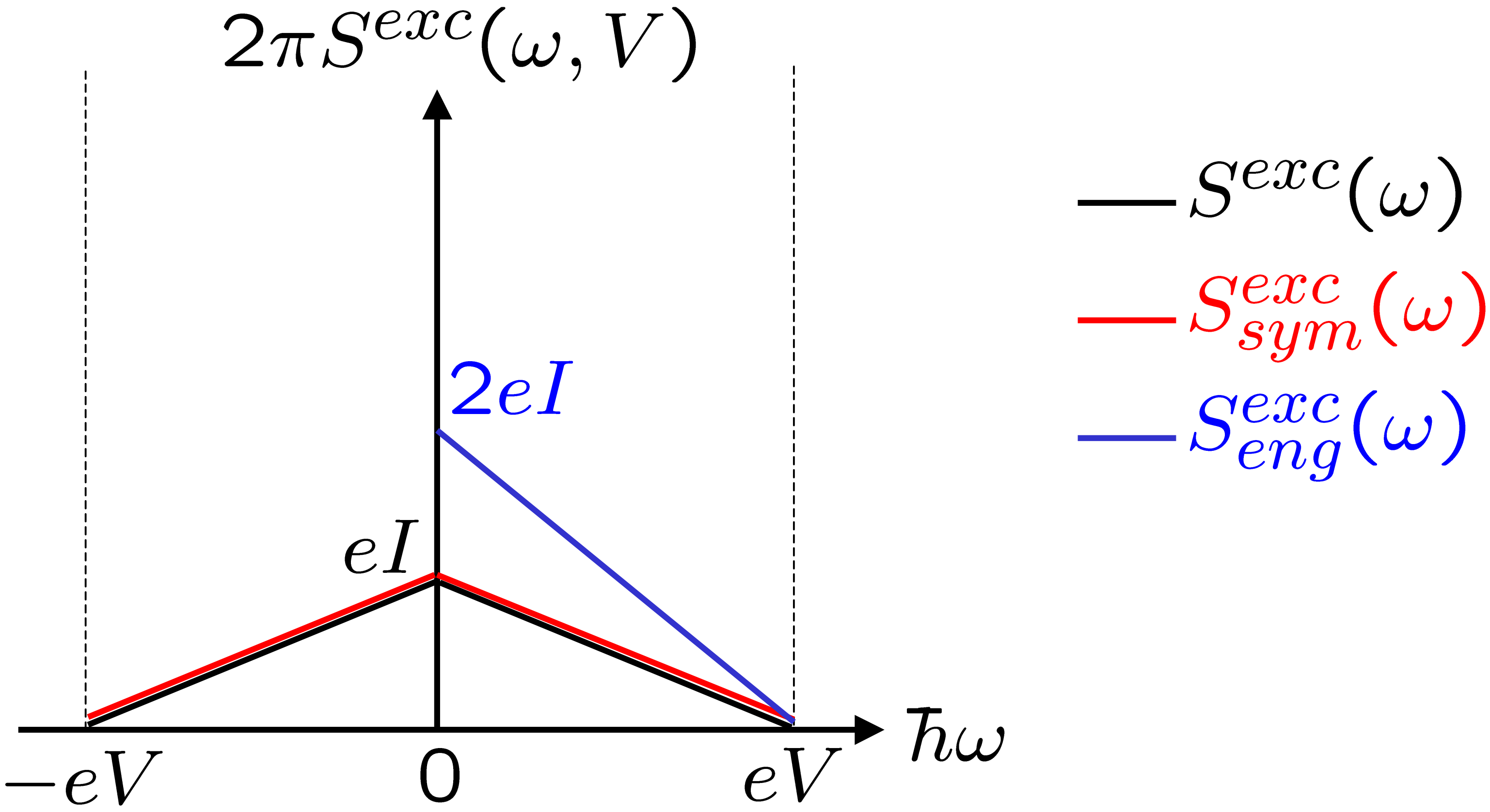
Noise of a tunnel junction

$$S(\omega,V)=\frac{1}{2\pi R_T}\left[\frac{\hbar\omega+eV}{1-\exp\left(-\frac{\hbar\omega+eV}{k_BT}\right)}+\frac{\hbar\omega-eV}{1-\exp\left(-\frac{\hbar\omega-eV}{k_BT}\right)}\right]$$



Excess noise of a tunnel junction

<u>Excess noise</u> : $S^{exc}(\omega,V) = S(\omega,V) - S(\omega,V=0)$



$$\Rightarrow \quad S^{exc}(\omega) = S^{exc}_{sym}(\omega)$$

Excess noise measurement in the quantum regime

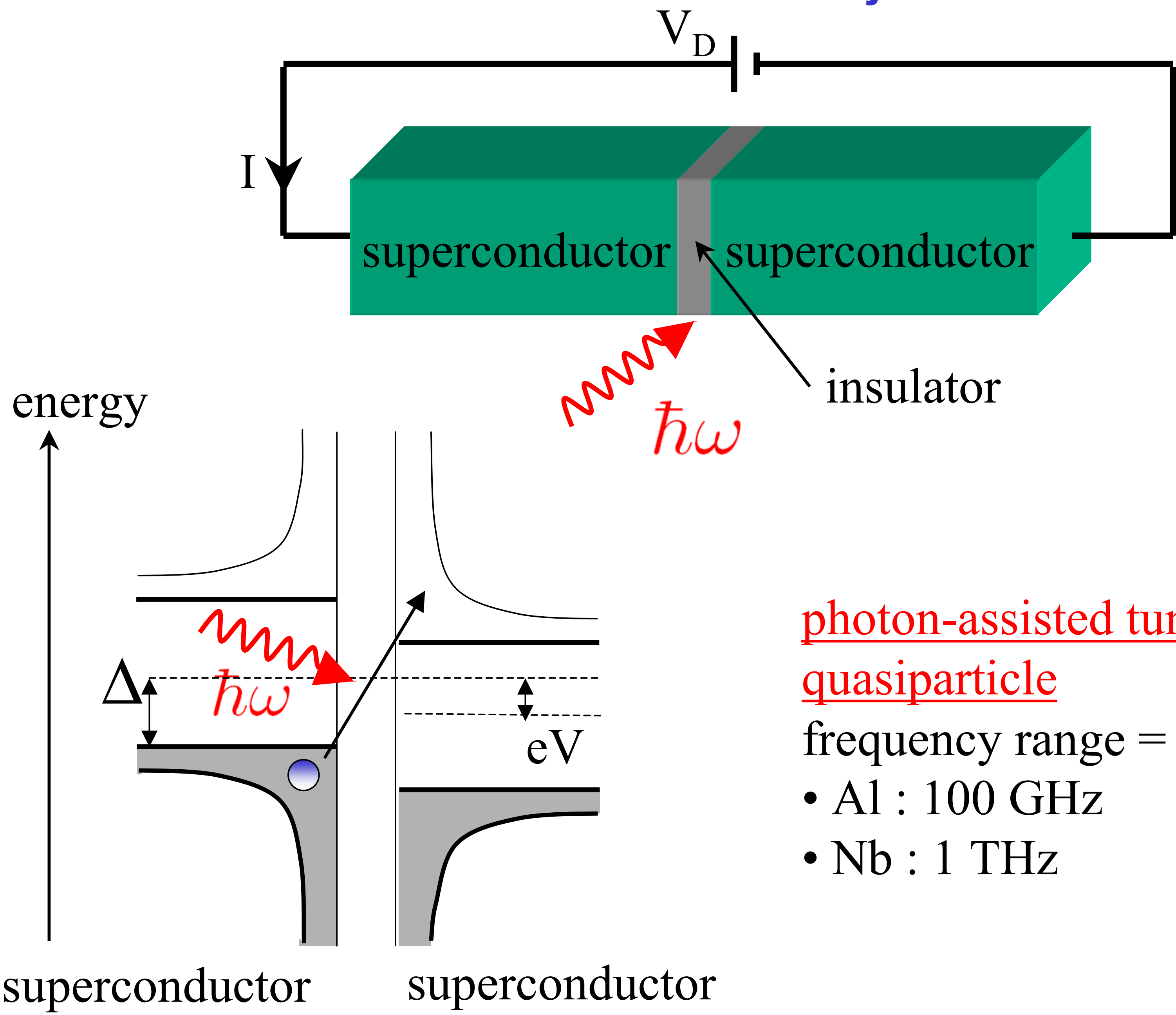
Excess noise measurement on tunnel junction, QPCs, diffusive wires : no difference between symmetrized and non-symmetrized noise

How to determine what quantity is measured in an excess noise experiment ?

Theory : depends on the detection scheme (Lesovik & Loosen JETP (1997), Gavish *et al.* PRB (2000))
Practically : not so relevant for QPCs, normal tunnel junctions, diffusive wires …

⇒ -noise source with excess current fluctuations with an asymmetry between absorption and emission
- detector able to distinguish emission and absorption

Detector : a SIS junction

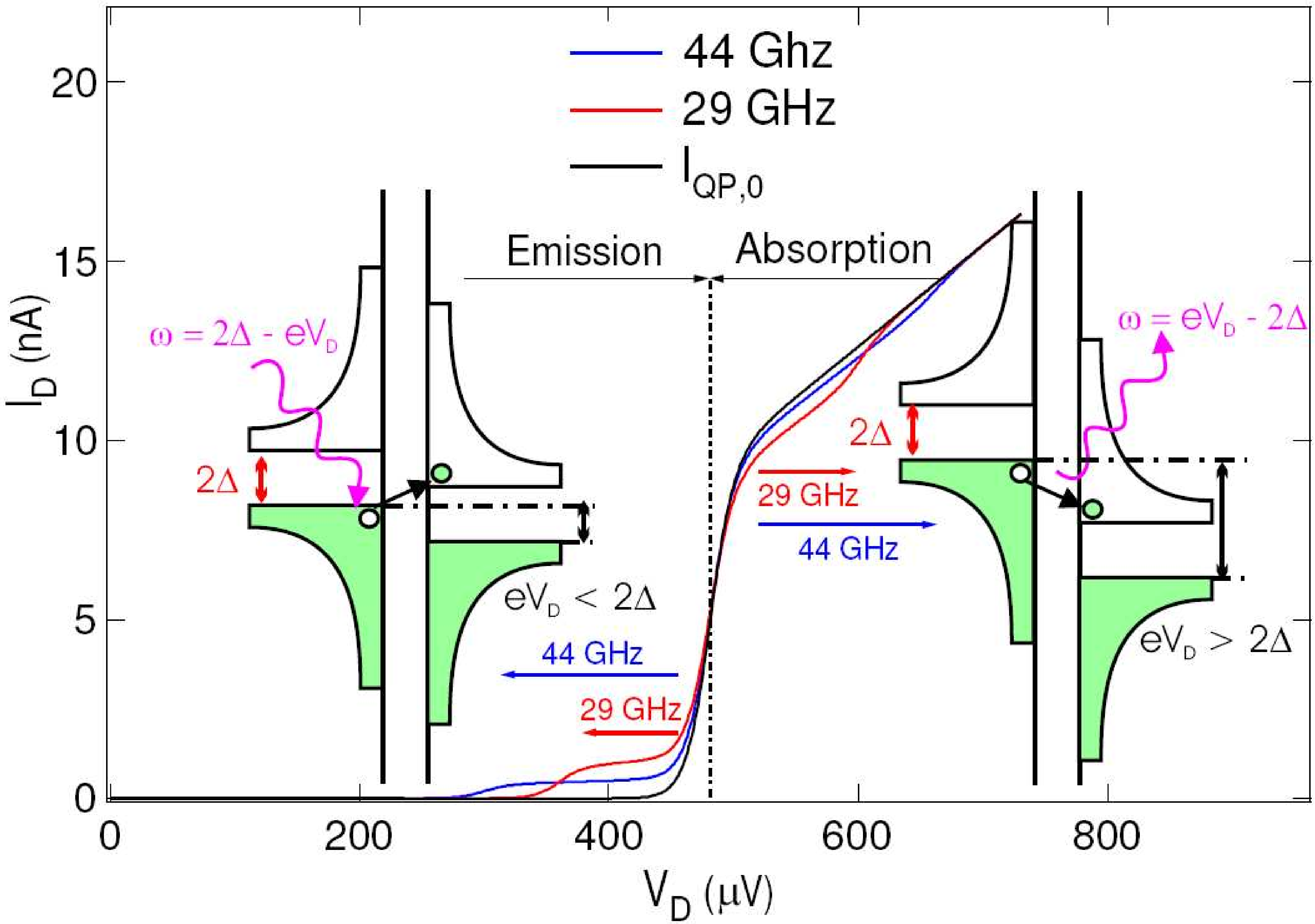


photon-assisted tunneling of quasiparticle

frequency range = 2Δ :

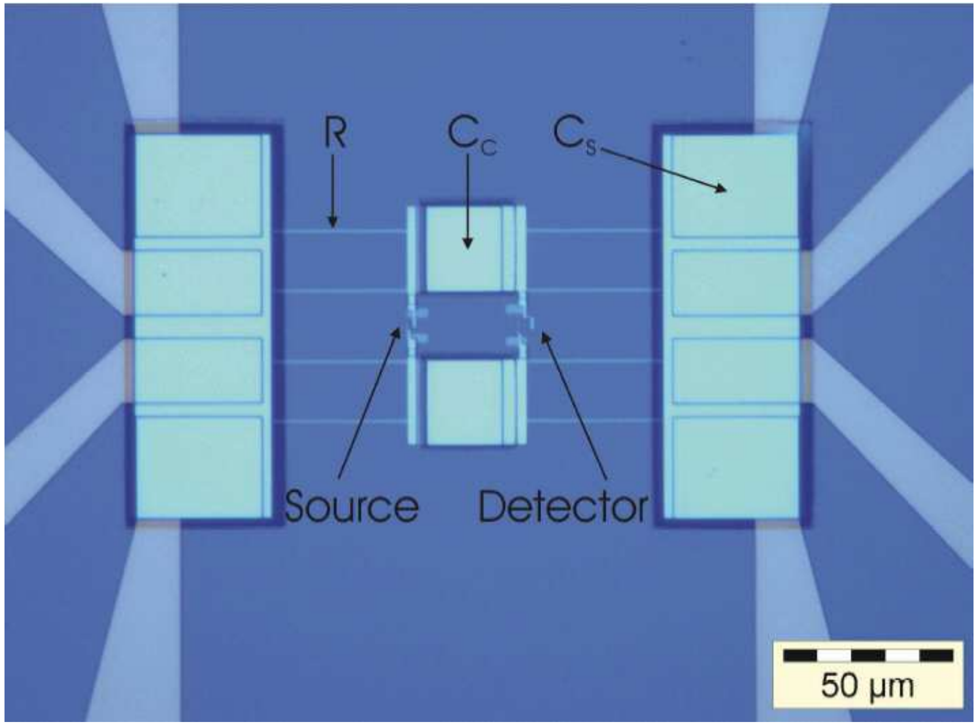
- Al : 100 GHz
- Nb : 1 THz

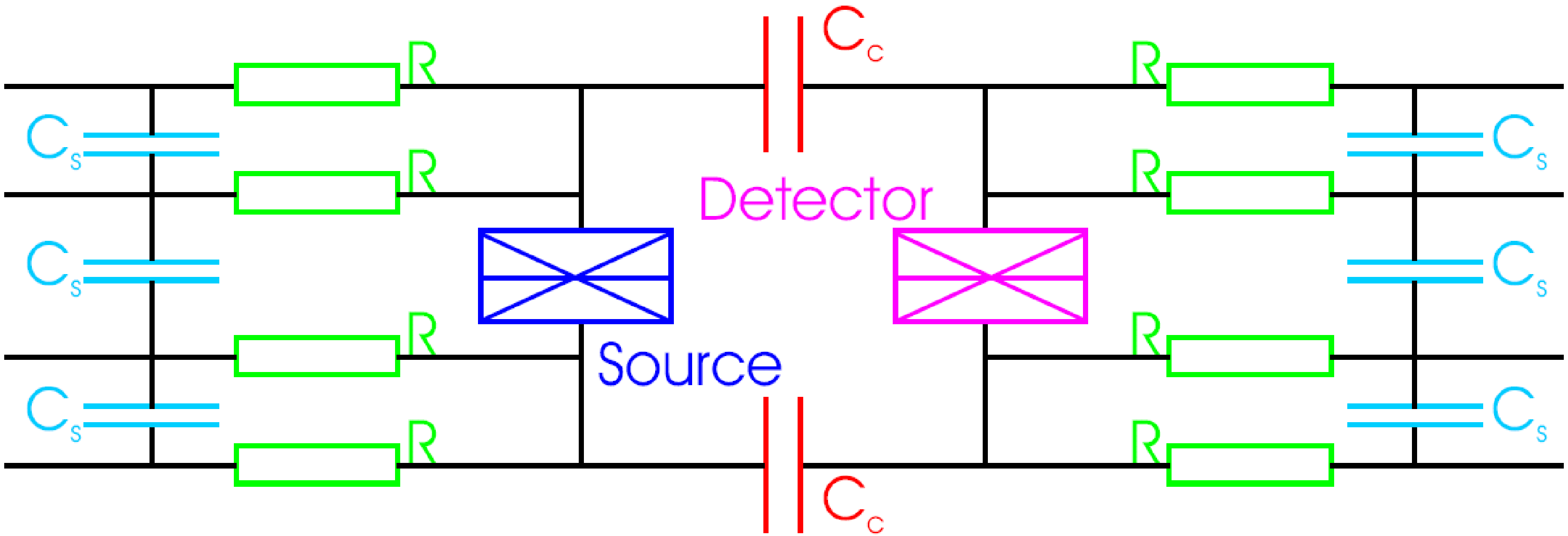
SIS detector for high frequency fluctuations



The sample

R = 750 Ω
Cc = 750 fF
Capacitance of source and detector : 1fF





Electromagnetic environment of the SIS detector

Quasi-particle current with an electromagnetic environment :

$$I_{QP}(V) = \int_0^{+\infty} d\epsilon \, P(eV - \epsilon) I_{QP,0}\left(\frac{\epsilon}{e}\right)$$

Ingold and Nazarov (1992)

Probability to exchange energy with the environment

Quasi-particle current without environment

with : $P(E) = \frac{1}{2\pi\hbar} \int_{-\infty}^{+\infty} dt \exp\left[J(t) + \frac{i}{\hbar} Et\right]$

and : $J(t) = < \delta\widetilde{\varphi}(t)\delta\widetilde{\varphi}(0) - (\delta\widetilde{\varphi}(0))^2 >$ the phase-phase correlator

where : $\delta\widetilde{\varphi}(t) = \frac{e}{\hbar} \int^t dt' \, \delta V(t')$

PAT current of the SIS detector

Aguado *et al.*, PRL (2000)

$$J(t) = \frac{2\pi}{\hbar R_K} \int_{-\infty}^{+\infty} d\omega \, \frac{|Z(\omega)|^2}{\omega^2} S_I(\omega) \left[\exp(-i\omega t) - 1\right]$$

$R_K = h/e^2$

$Z(\omega)$: transimpedance

$S_I(\omega)$: *non-symmetrized* current noise correlator of the noise source

noise source = electromagnetic environment of the SIS detector

Photon-assisted tunneling current (T=0) :

$$\begin{aligned} I_{PAT}(V) &= I_{QP}(V) - I_{QP,0}(V) \\ &= \int_0^{+\infty} d\omega \left(\frac{e}{\hbar\omega}\right)^2 |Z(\omega)|^2 S_I(-\omega) I_{QP,0}\left(V + \frac{\hbar\omega}{e}\right) \\ &+ \int_0^{eV} d\omega \left(\frac{e}{\hbar\omega}\right)^2 |Z(\omega)|^2 S_I(\omega) I_{QP,0}\left(V - \frac{\hbar\omega}{e}\right) \\ &- \int_{-\infty}^{+\infty} d\omega \left(\frac{e}{\hbar\omega}\right)^2 |Z(\omega)|^2 S_I(\omega) I_{QP,0}(V) \end{aligned}$$

emission (ω<0)

absorption (ω<0)

The SIS detector

- measure emission noise $(eV_D < 2\Delta)$
- measure absorption noise $(eV_D > 2\Delta)$
- frequency resolved detection

Used as **photo-detector** and **HF mixer**

(R. Tucker and M.J. Feldman, Rev.Mod.Phys. (1985))

In mesoscopic physics : detection of emission noise of :

- a **Cooper pair box**

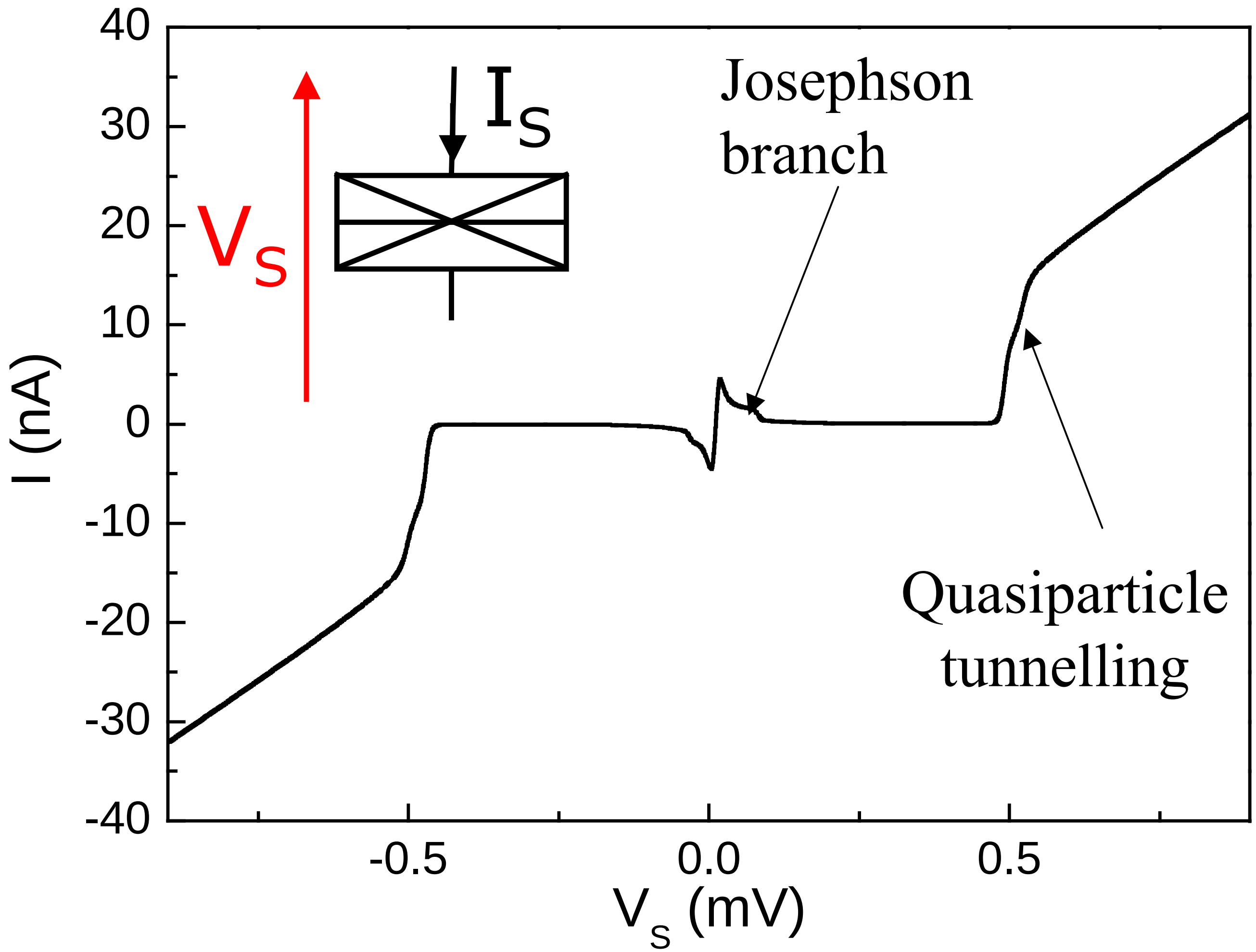
- a Josephson **junction (AC Josephson effect, « white » shot noise for** $V \gg 2\Delta/e$ **)**

(R.Deblock, E.Onac, L. Gurevich, L.P. Kouwenhoven, Science (2003))

- a **carbon nanotube**

(E. Onac, F. Balestro, B. Trauzettel, C. Lodewijk and L.P. Kouwenhoven, PRL (2006))

Source : a Josephson junction



Two type of current carriers :

- Cooper pairs
- Quasiparticles

Josephson junction : two « noise » regimes

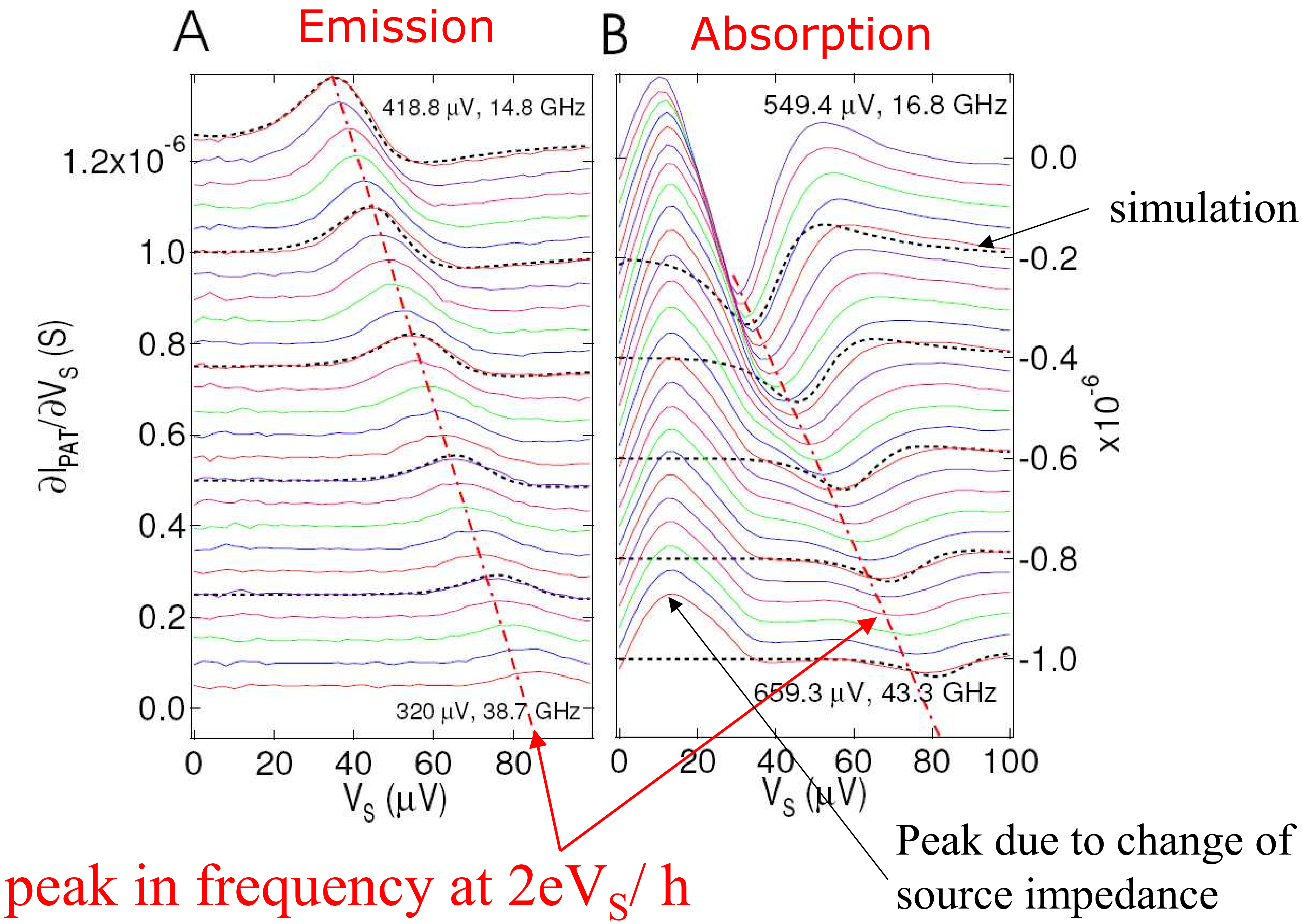
Cooper pairs : AC Josepshon effect

$$\frac{d\varphi}{dt} = 2\pi \frac{2eV_S}{h} \quad \text{and} \quad I = I_C \sin(\varphi)$$

For V_S>0 HF current generator with frequency $2eV_S/h$ and amplitude I_C
Spectrum with peaks at frequencies $\pm 2eV_S/h$

Quasiparticle (QP) noise : shot noise due to QP tunneling

PAT due to AC Josephson effect

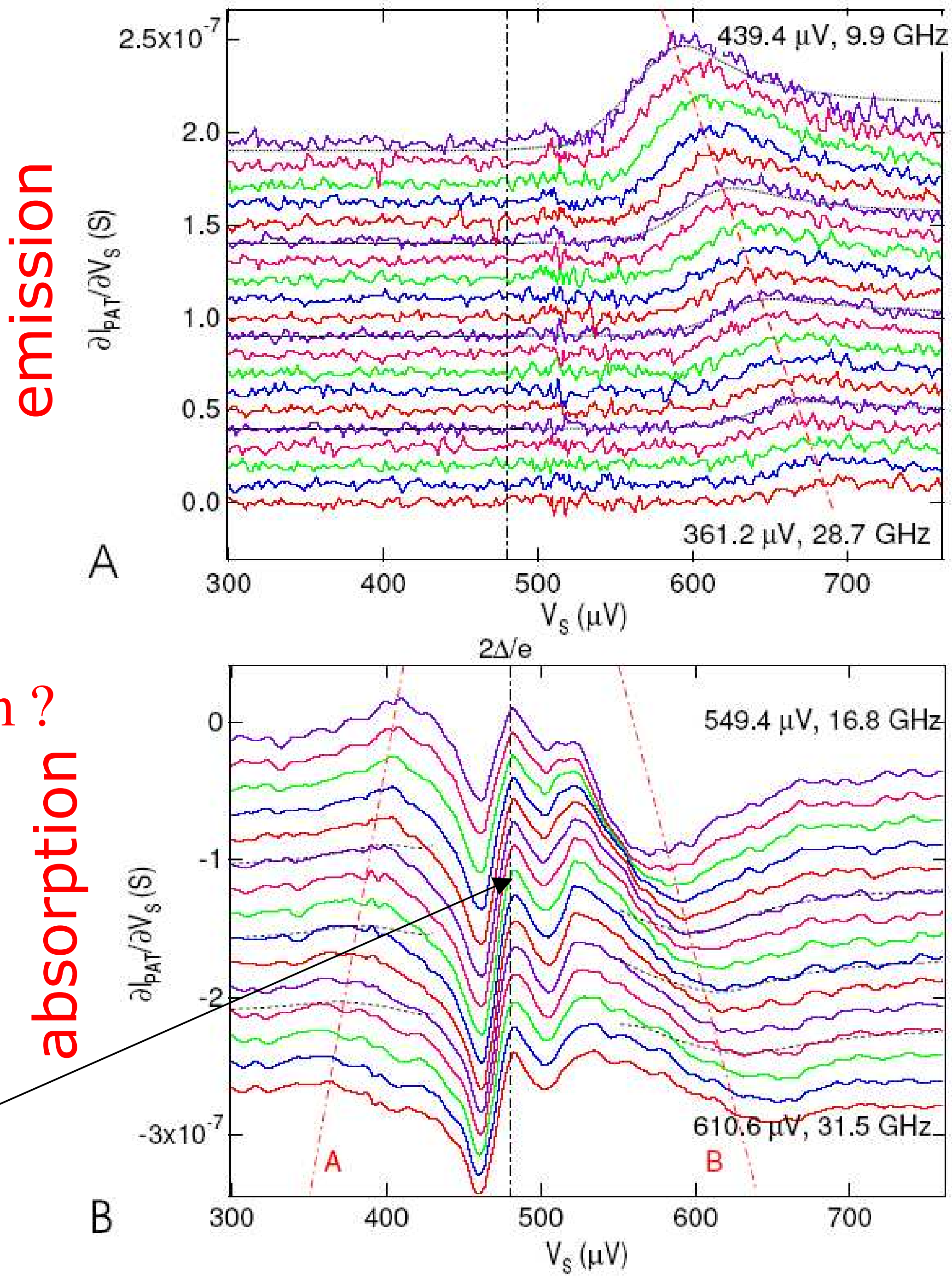


PAT due to QP noise

V_S around 2Δ

Difference between PAT in emission and absorption

→ Asymmetry in current fluctuations between emission and absorption ?



Peak due to change of source impedance

Non symmetrized QP noise of a Josephson junction

General formula for current noise :

$$S(\omega) = 2\pi\hbar \sum_{i,f} P_i | < i|J|f > |^2 \delta(\epsilon_i - \epsilon_f - \hbar\omega)$$

Result for quasiparticle noise :

$$S(\omega, V) = \frac{e}{2\pi}\left[\frac{I_{QP}(\hbar\omega + eV)}{1 - \exp\left(-\frac{\hbar\omega+eV}{k_B T}\right)} + \frac{I_{QP}(\hbar\omega - eV)}{1 - \exp\left(-\frac{\hbar\omega-eV}{k_B T}\right)}\right]$$

(Symmetrized version in Dahm *et al.* PRL (1969))

Non symmetrized QP noise of a Josephson junction

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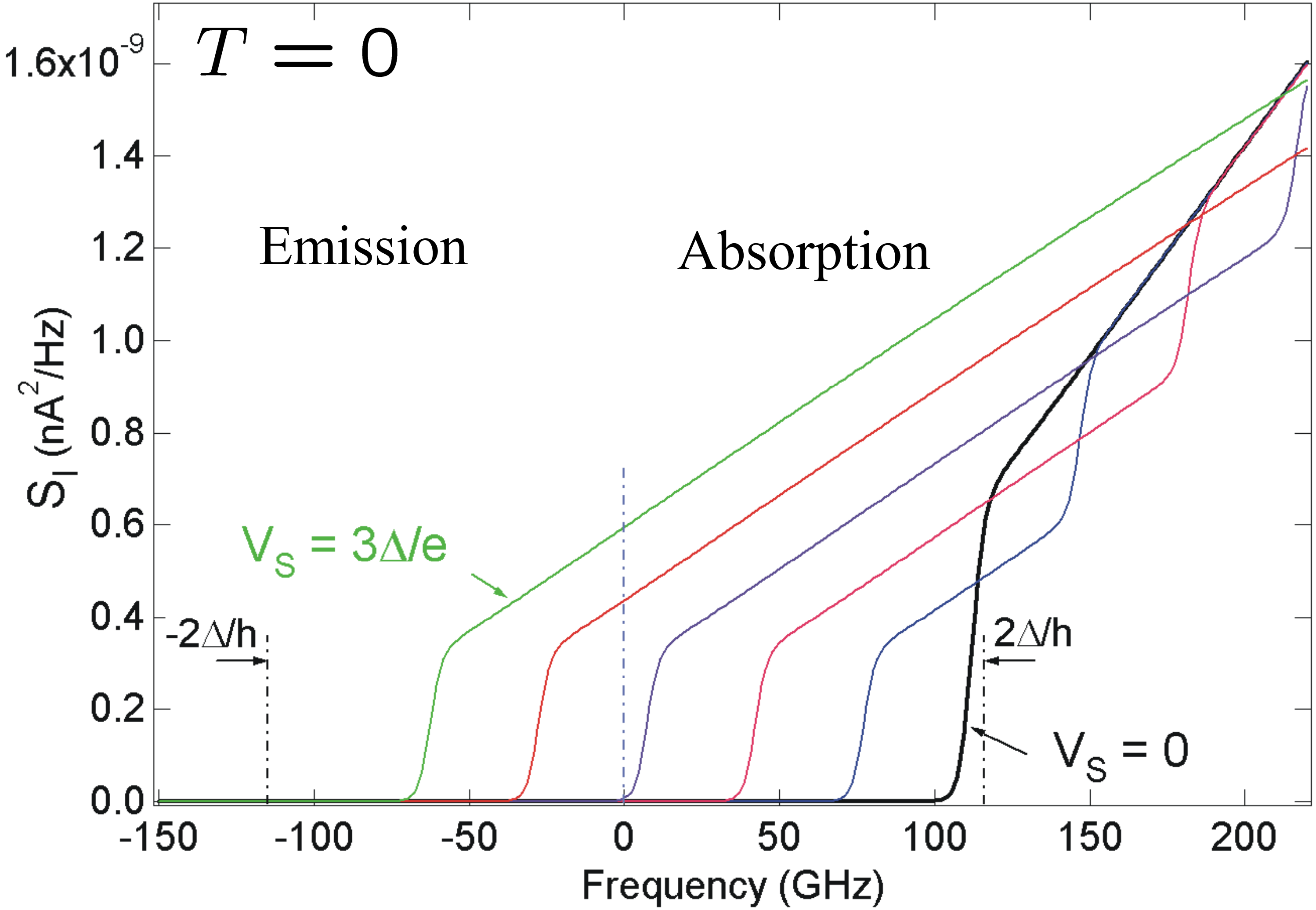

Non symmetrized QP noise of a Josephson junction

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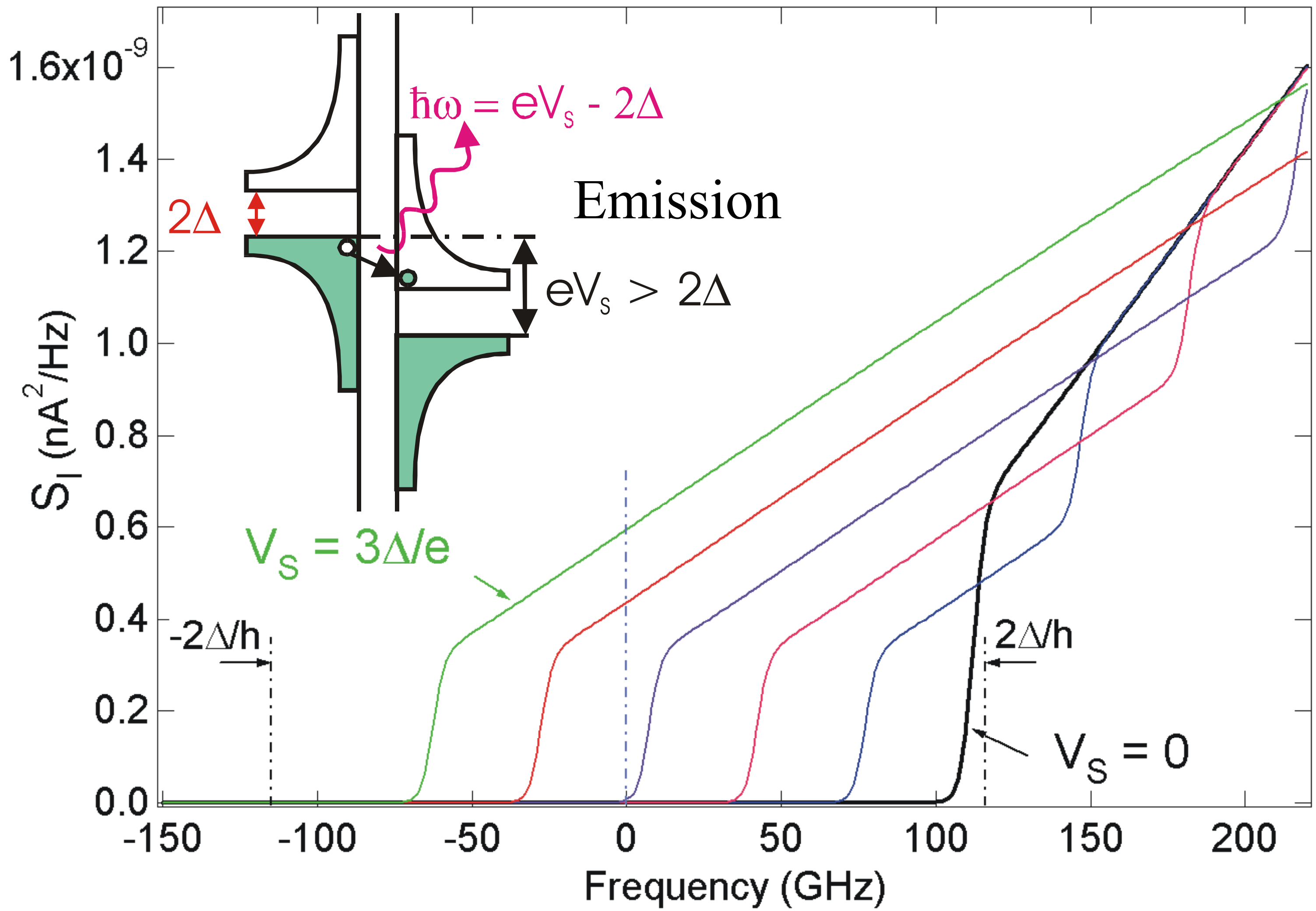

Non symmetrized QP noise of a Josephson junction

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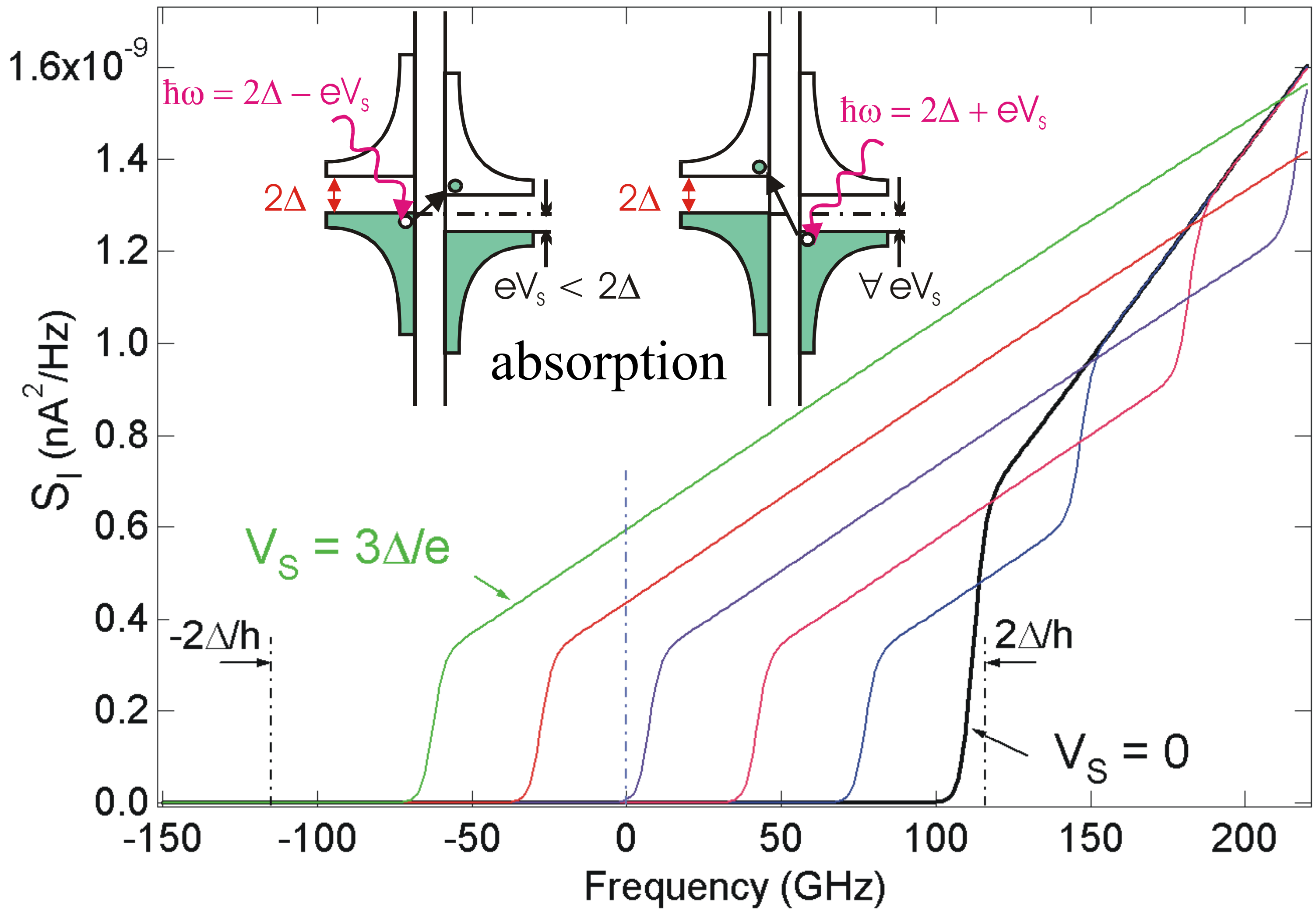


Non symmetrized QP noise of a Josephson junction

$$V_S < 2\Delta/e$$

- Only absorption noise
- Singularities at $\hbar\omega = 2\Delta \pm eV_S$

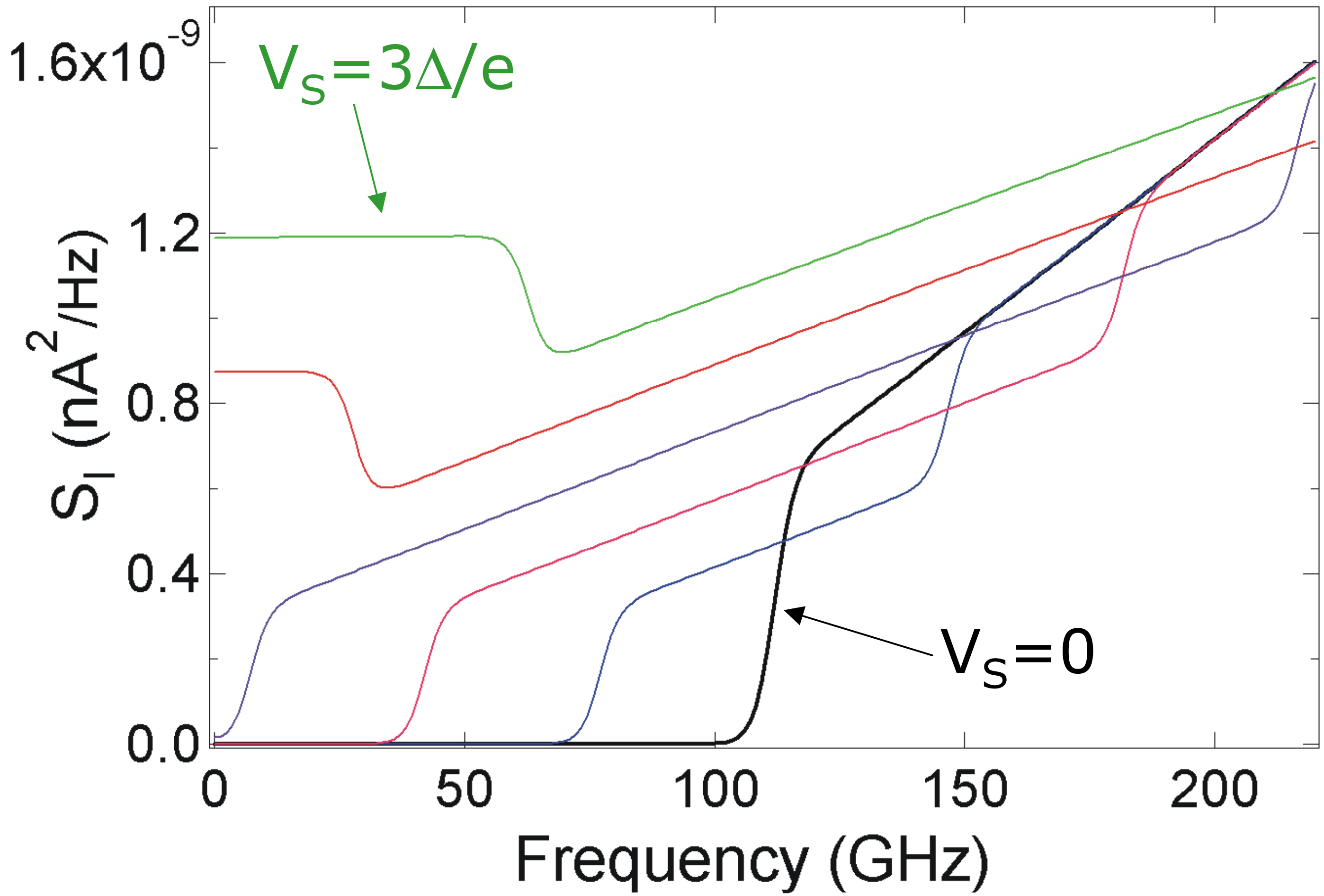
$$V_S > 2\Delta/e$$

- Emission and absorption noise
- Singularity in emission at $\hbar\omega = eV_S - 2\Delta$
- Singularity in absorption at $\hbar\omega = 2\Delta + eV_S$

⇒ Assymetry between emission and absorption in (excess) noise

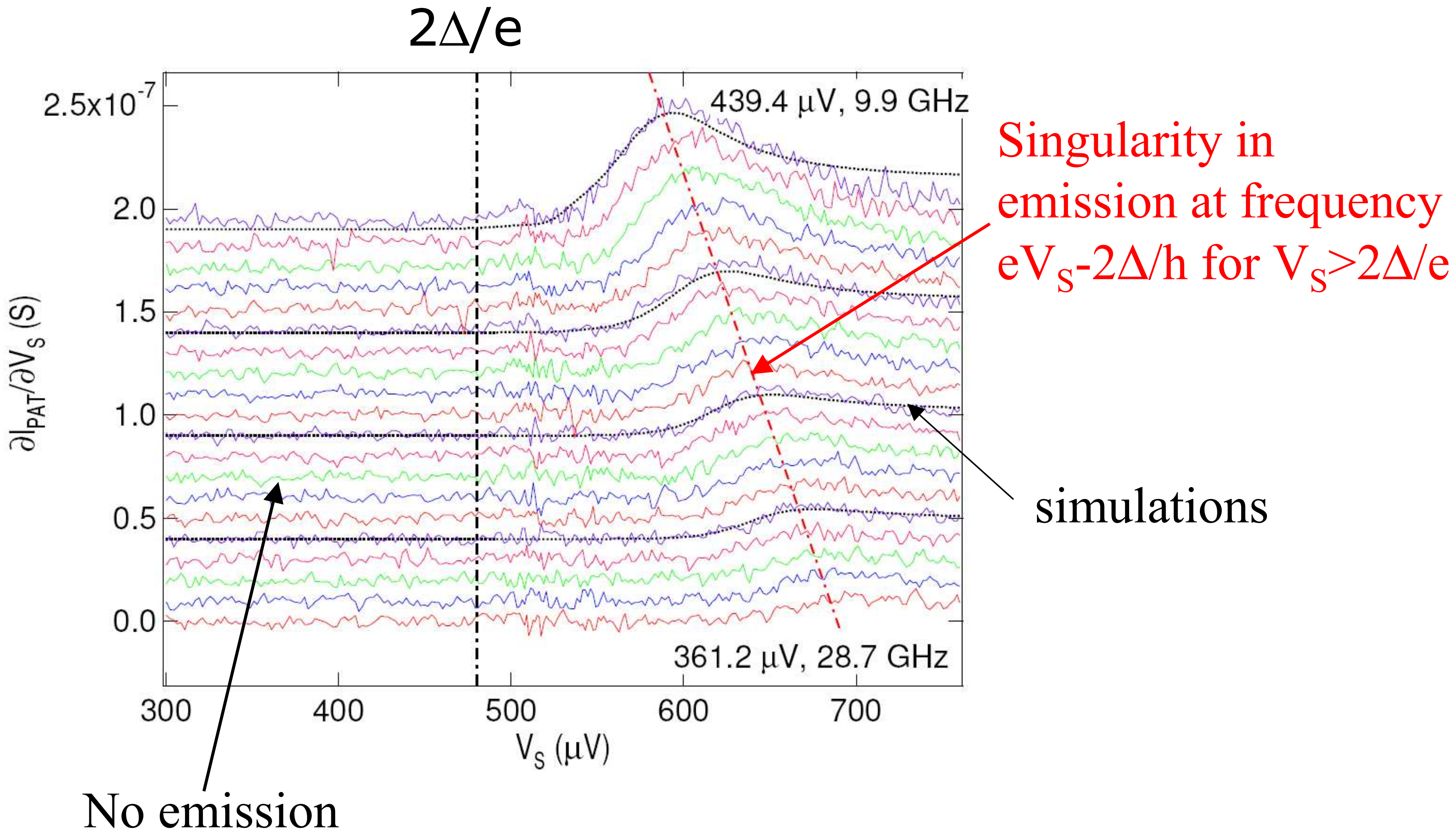
<u>Remark</u> : $S(\omega) = S^{exc}(\omega)$ for $\hbar\omega < 2\Delta$

Symmetrized QP noise of a Josephson junction



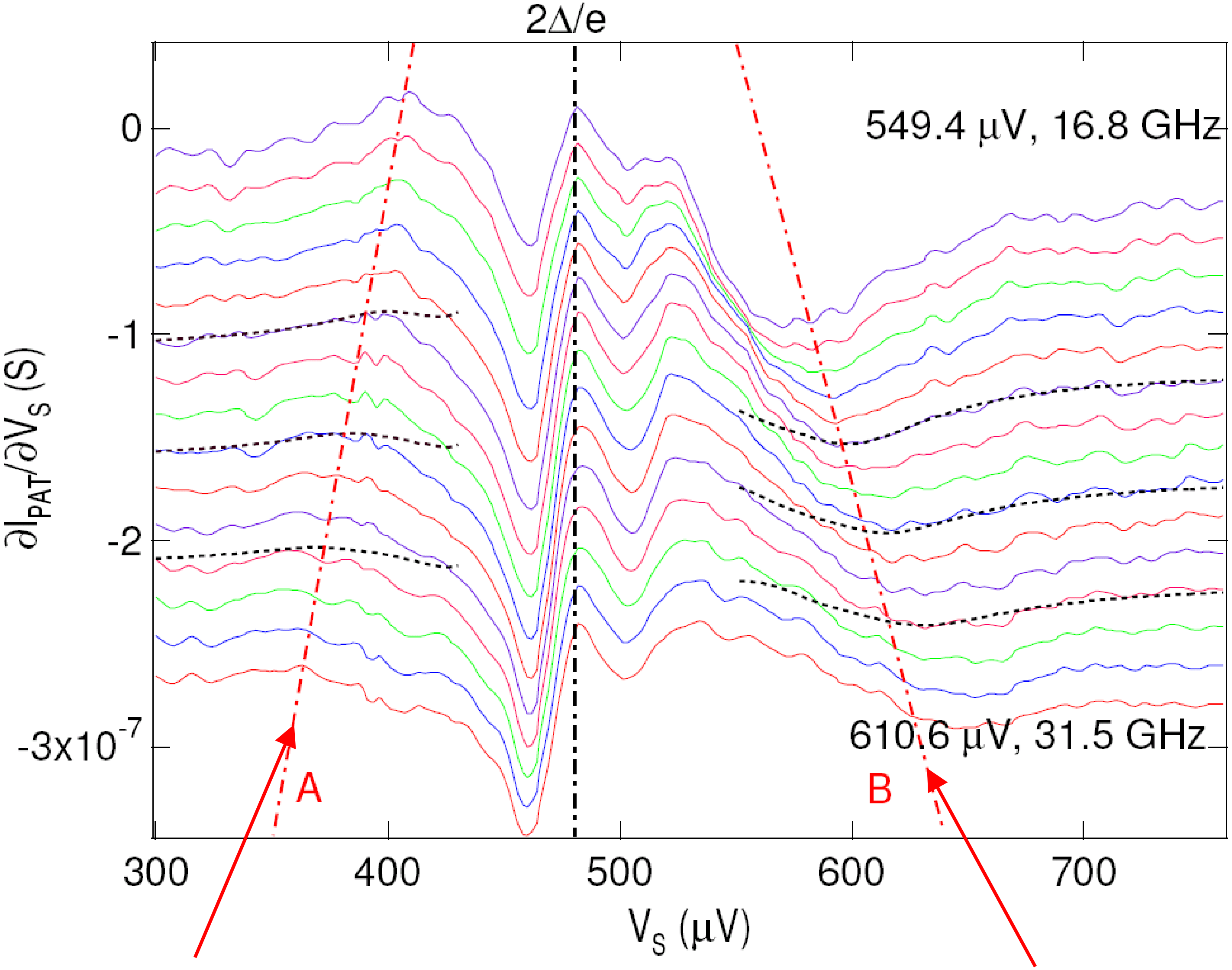
$$S^{exc}(\omega, V) \neq S^{exc}_{sym}(\omega, V)$$

PAT due to emission noise ($eV_D < 2\Delta$)



➡ Measure only emission part of non-symmetrized source noise

PAT due to absorption noise ($eV_D > 2\Delta$)



Singularity in absorption noise at $(2\Delta\text{-}eV_S)/h$?

?

Contributions to absorption noise

- source junction : $S_I(\omega, V_S)$
- resistive part of the on-chip circuit : $S_I^R(\omega) = 2\hbar\omega/(2\pi R)$

Voltage fluctuation across the detector :

contribution I — contribution II

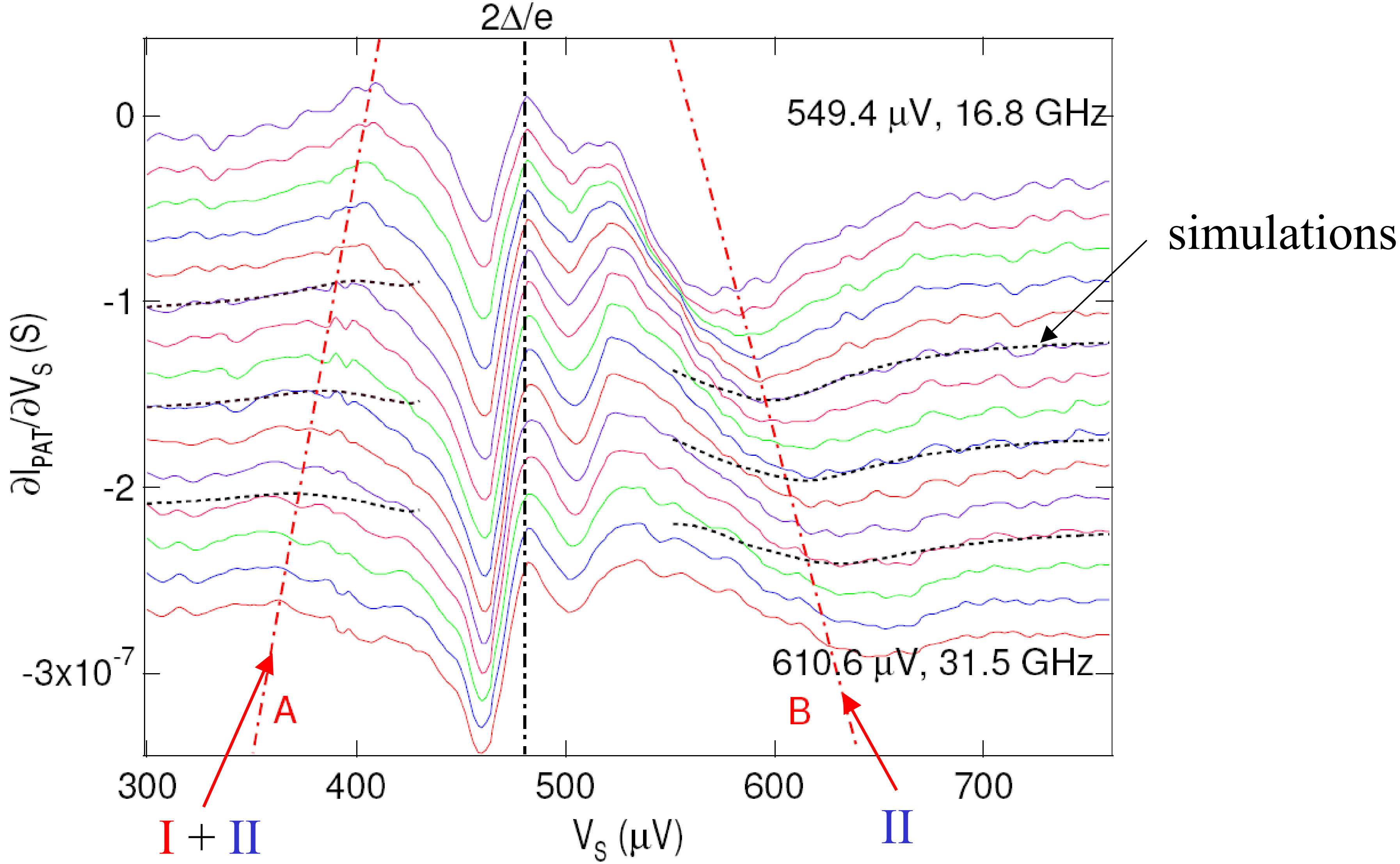
$$S_V(\omega, V_S) = \underbrace{|Z(\omega, V_S)|^2 S_I(\omega, V_S)}_{\text{contribution I}} + \underbrace{|Z'(\omega, V_S)|^2 S_I^R(\omega)}_{\text{contribution II}}$$

depend on V_S *via* the source impedance :

$$\sigma(\omega, V_S) = e\frac{I_{QP}(V_S + \hbar\omega/e) - I_{QP}(V_S - \hbar\omega/e)}{2\hbar\omega}$$

(real part, Worsham *et al.* PRL (1991))

PAT due to absorption noise ($eV_D > 2\Delta$)



add with opposite sign
(reduced amplitude)

Conclusions

QP excess current fluctuations of a Josephson junction :

- asymmetry between emission and absorption
- singularity in absorption and/or emission depending on bias condition

⇒ Test system for quantum noise measurement

Detection with a SIS junction :

- separate detection of emission and absorption
- emission : source noise
- absorption : source + resistive part of the on-chip circuit

⇒ Detection of non-symmetrized noise

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