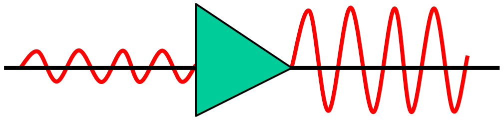
Measuring high frequency signals

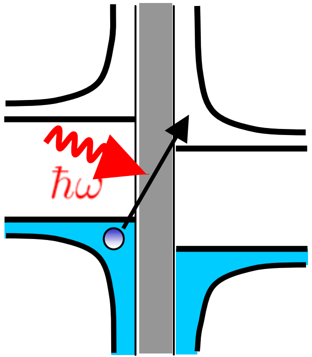
⇨ Direct probe of characteristics time scales & energies

i) Cryogenic amplifiers



Versatile *but* very difficult above 20GHz in dilution units

ii) On-chip detectors



- Very large bandwidth (~100GHz) & flat coupling
- Ideal in cryogenic environments
- *Quantum detectors*

On-chip Detection of Non-Symmetrized Quantum Noise with a SIS Junction

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What quantity is measured?

Non-symmetrized current noise spectrum density:

$$\boxed{S_I(\nu)=\int_{-\infty}^{\infty} d\tau \exp(i2\pi\nu\tau)\left\langle \Delta\hat{I}(t)\Delta\hat{I}(t+\tau)\right\rangle}$$

($\nu<0$: emission, $\nu>0$: absorption)

BUT ***classical* detector** ⇒ meas. *symmetrized* current correlator

(Limitation might be avoided with a circulator)

Quantum detectors?

-*Passive* detector ⇒ $\nu<0$ only

-*Active* detector: depends on detection scheme

Gavish *et al.* PRB (2000)

Q detectors have pot. for measuring non-symmetrized noise

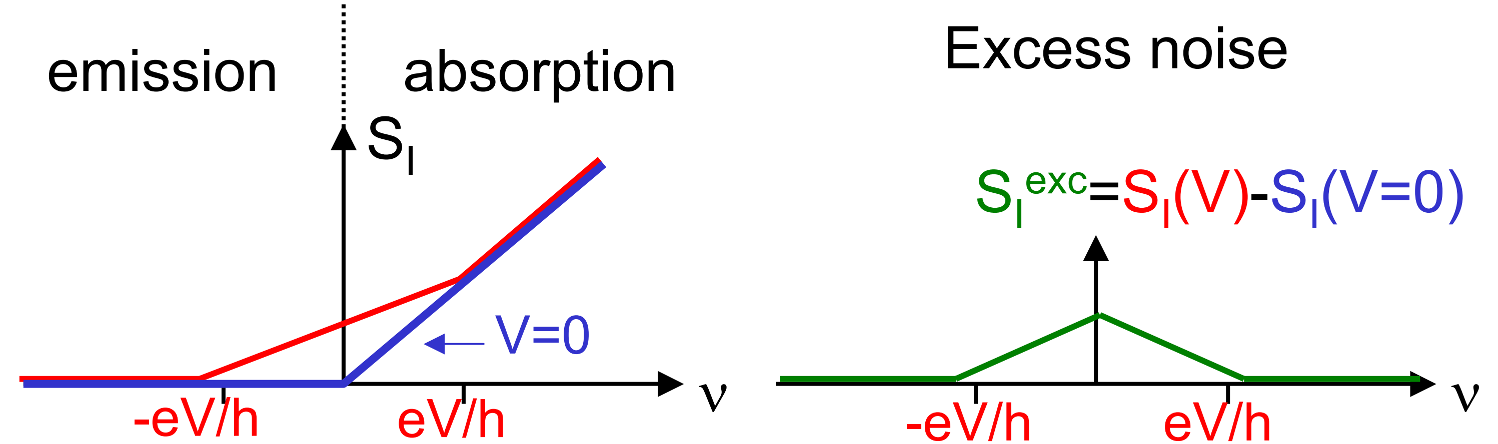
Classical & quantum noise (T=0K)

Classical regime ($\nu \ll k_B T/h$): S_I symmetric ($S_I(\nu)=S_I(-\nu)$)

(V=0: Johnson-Nyquist, $V \gg k_B T/e$: Shot noise)

Quantum regime ($\nu > k_B T/h$): S_I **NOT** symmetric

Ex: Tunnel junction (T=0K)



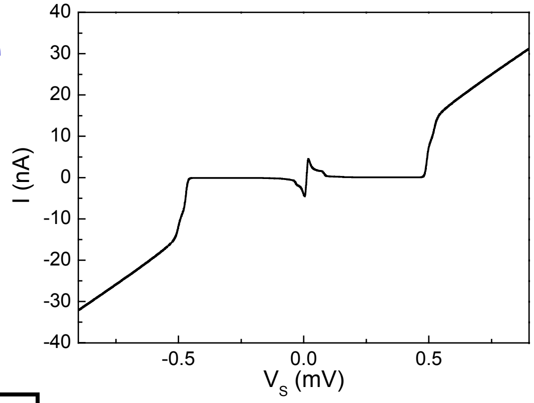
Practical difficulty: meas. often *excess noise*

⇒ *symmetric* for Tunnel Junctions, QPCs, diffusive wires, ..

Known source with asymmetric excess noise needed

SIS as signal source

2 operating modes



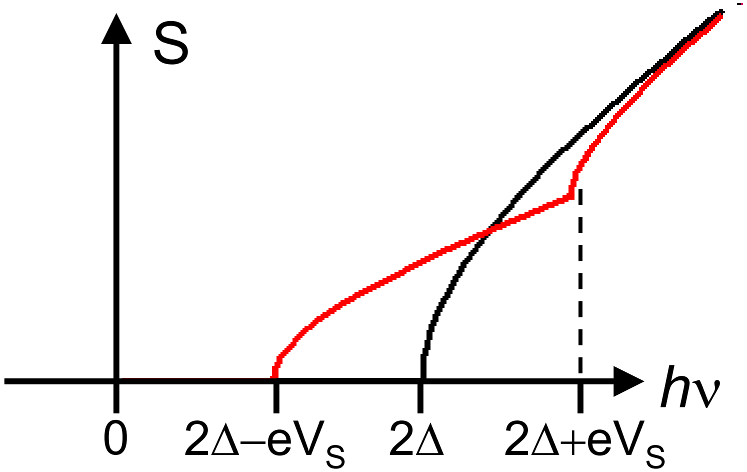
Cooper pair tunneling: AC Josephson effect

$$I = I_0 \sin(\phi) \quad \text{with} \quad \frac{d\phi}{dt} = \frac{2eV_S}{\hbar}$$

⇒ symmetric peaks at $\nu = \pm 2eV_S/h$

Quasiparticles tunneling: shot noise (k$_B$T<<2Δ)

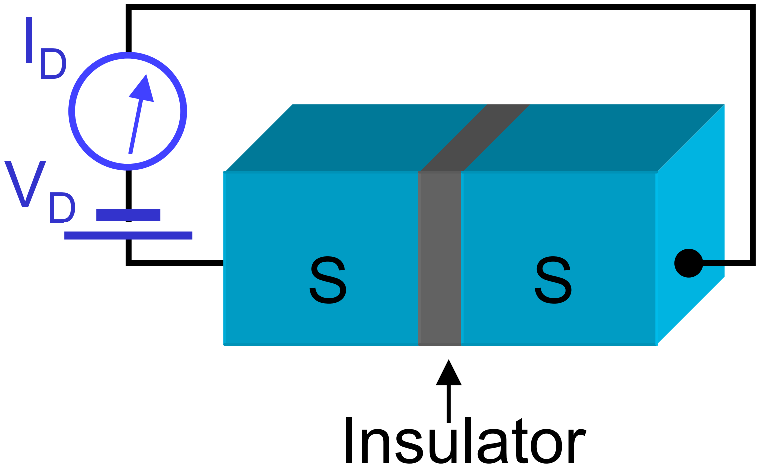
$$S(\nu, V_S) = e\left[I_{QP}(V_S + h\nu/e)\,\theta(V_S + h\nu/e) + I_{QP}(V_S - h\nu/e)\,\theta(V_S - h\nu/e)\right]$$



⇒ non-symmetric excess noise:

- Absorption only at $e|V_S| < 2\Delta$
- Emission & absorption at $e|V_S| > 2\Delta$
- Singularity at $2\Delta \pm eV_S$

SIS direct detection

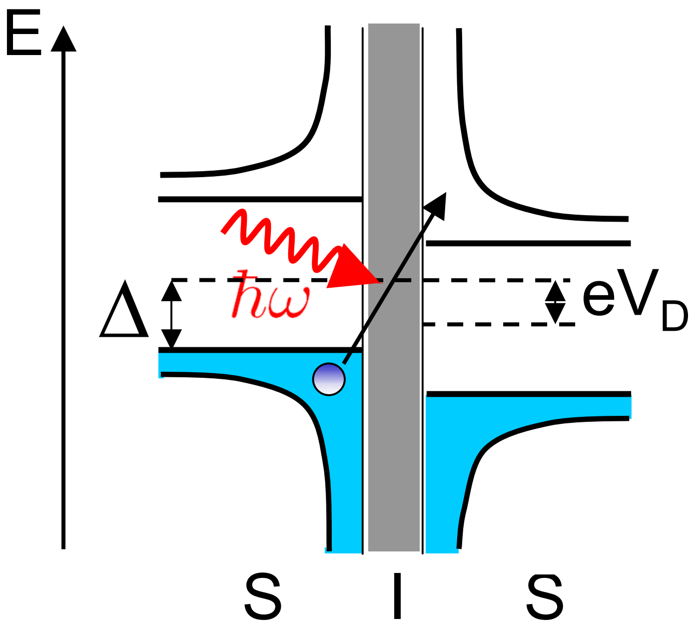


Astronomy (80s)

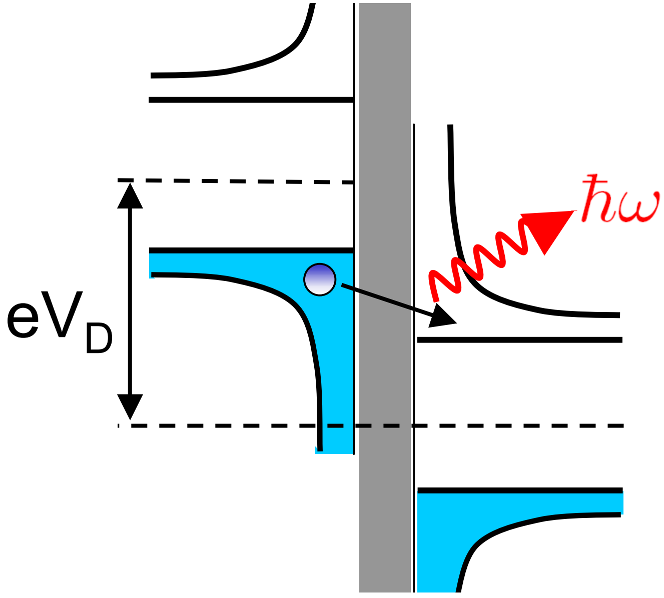
Tucker & Feldman, Rev Mod Phys (1985)

Mesoscopic physics (2003)

Deblock *et al.*, Delft, Science (2003)

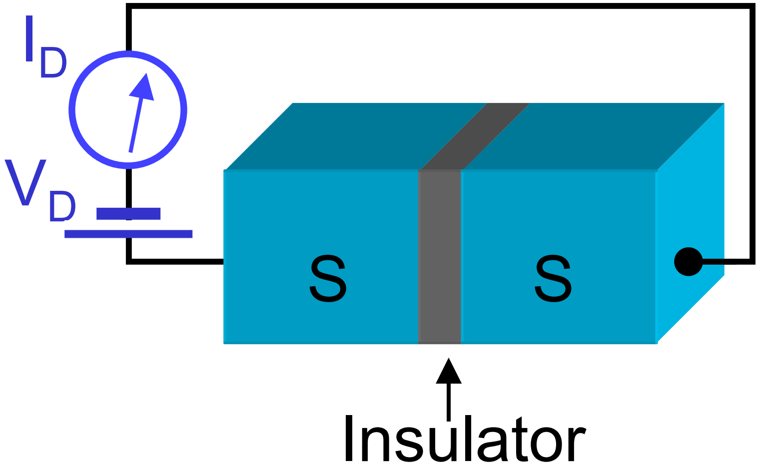


$eV_D<2\Delta$: emission noise



$eV_D>2\Delta$: absorption

SIS direct detection



Photon-Assisted Tunneling (PAT) of quasiparticles:

Bandwidth = $2\Delta/h$

- Al ~ 100 GHz
- Nb ~ 1 THz

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

Aguado & Kouvenhowen PRL (2000)

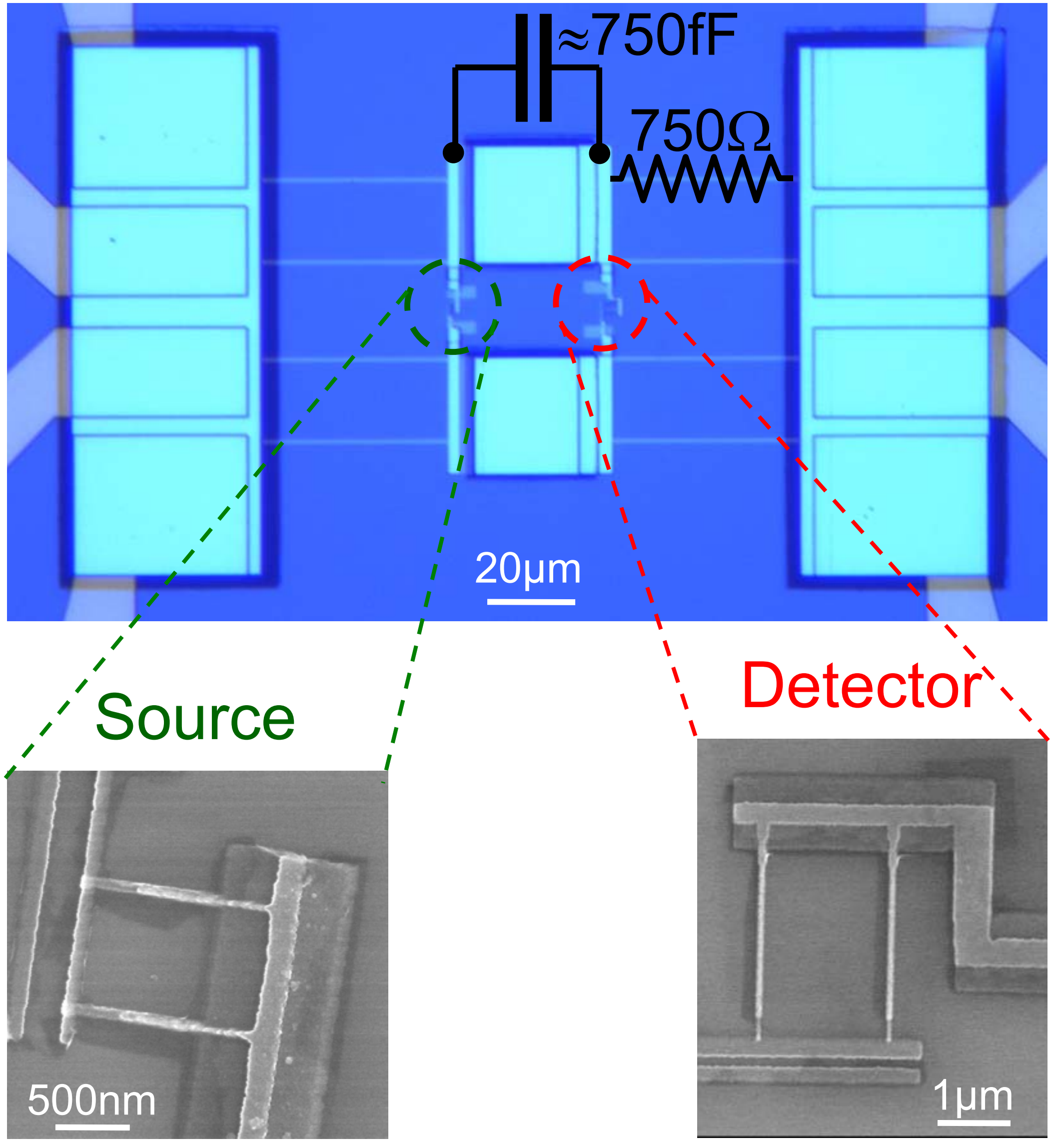
$Z(\omega)\equiv$transimpedance, T=0K

Measured sample

$T=20\,\text{mK}$

Al

$\Delta=240\,\mu\text{eV}$

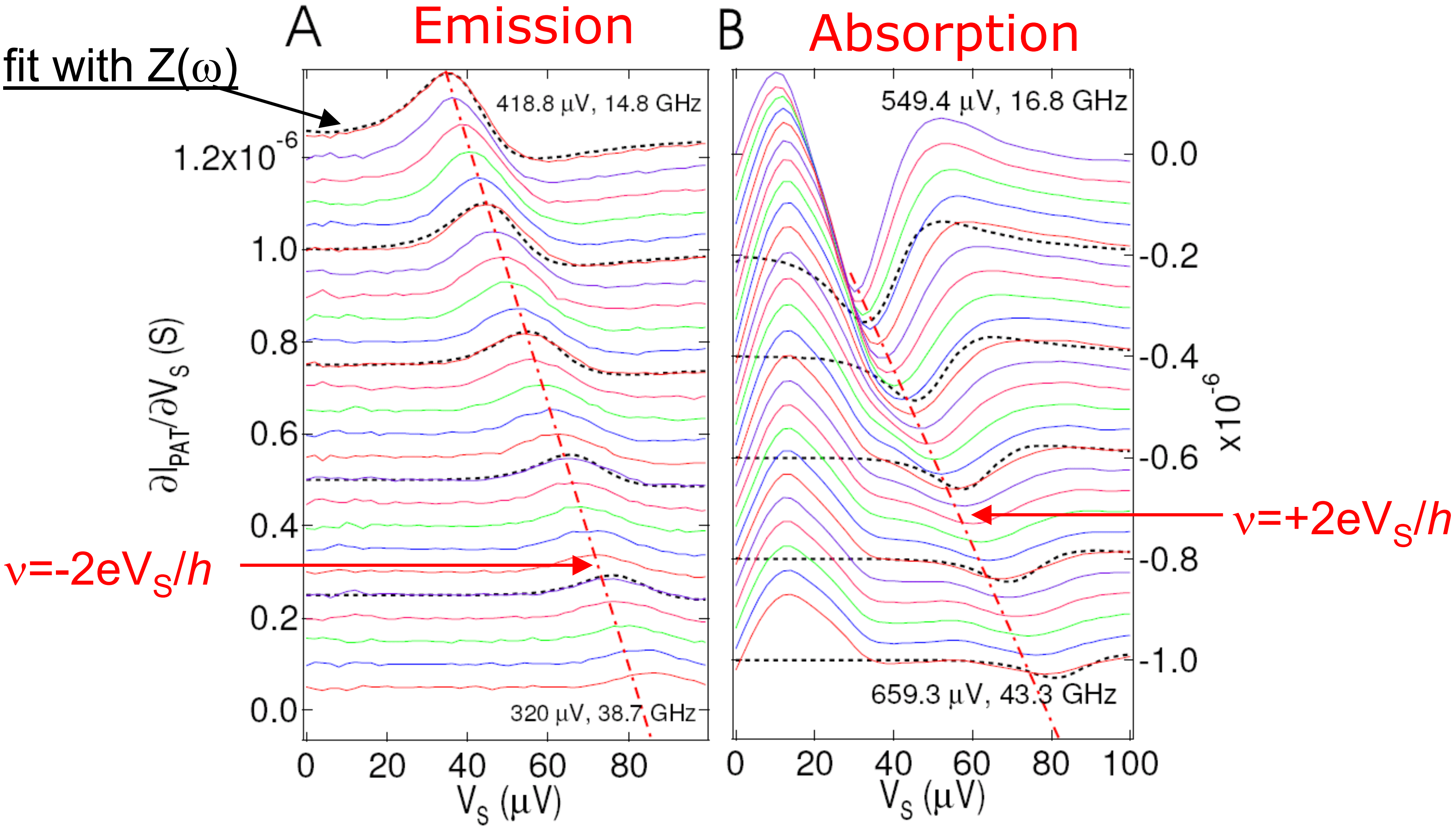


(A-B) $R_T=28\,\text{k}\Omega$

$I_0=13\,\text{nA}$

$R_T=47\,\text{k}\Omega$

PAT detection of AC Josephson signal



fit with Z(ω)

Emission

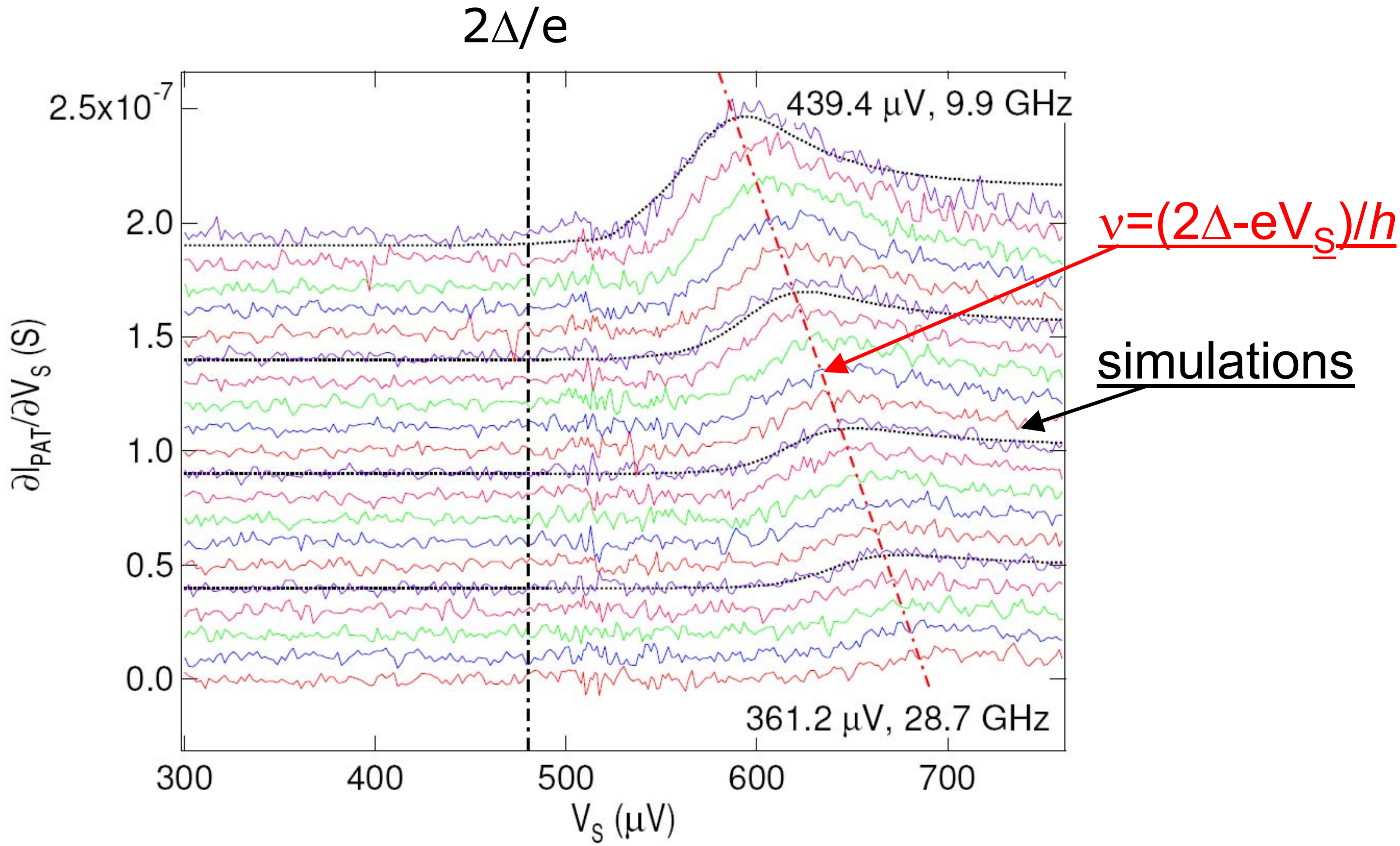
Absorption

$\nu=-2eV_S/h$

$\nu=+2eV_S/h$

Detector fully operational and calibrated but are we really measuring non-symmetrized noise?

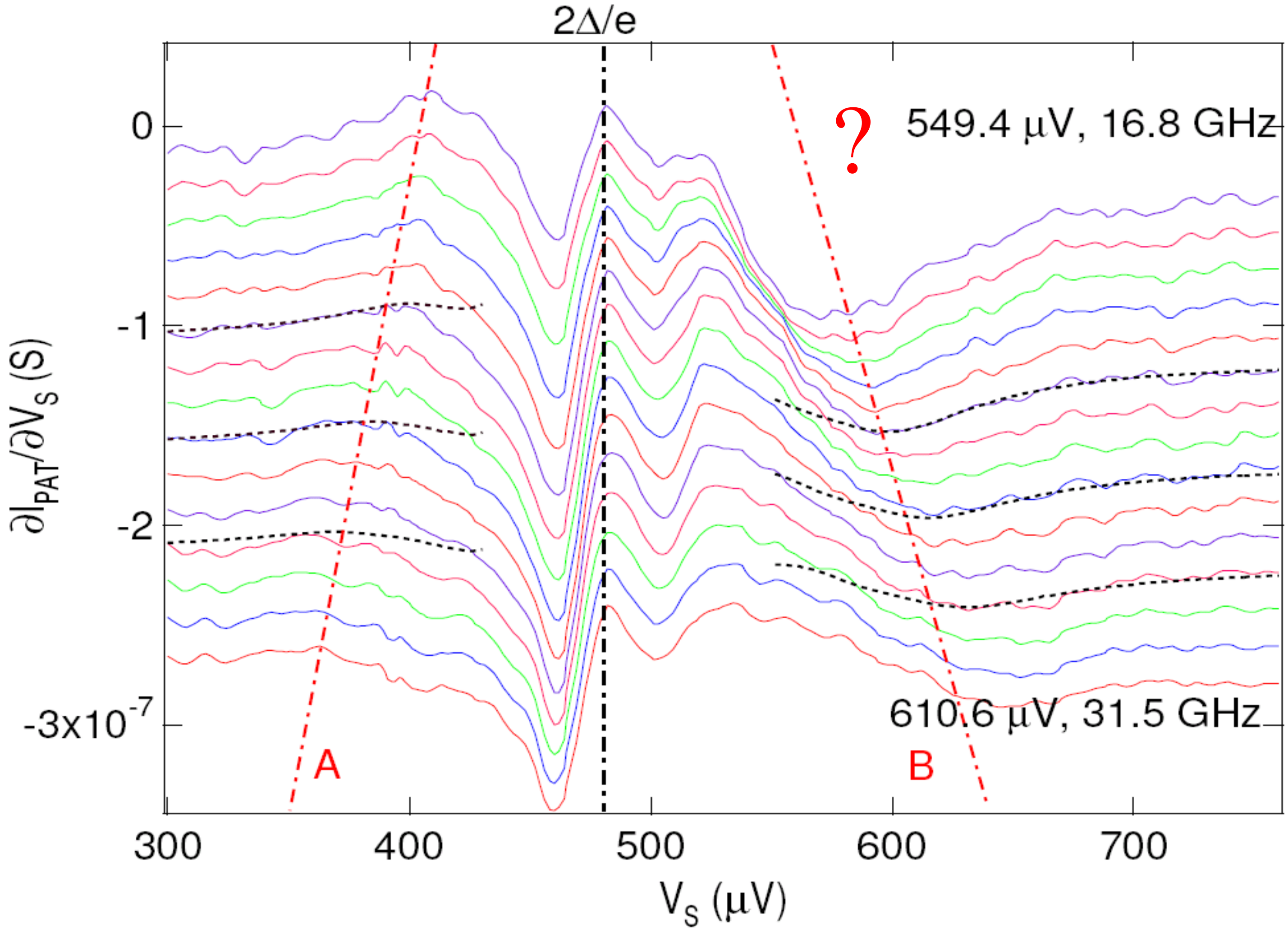
PAT due to emission noise ($eV_D<2\Delta$)



- No emission noise for $V_S<2\Delta/e$
- Singularity at $\nu=(2\Delta-eV_S)/h$ for $V_S>2\Delta/e$

$\Rightarrow$ For $V_D<2\Delta/e$ the detector probes only emission!

PAT due to absorption noise ($V_D>2\Delta/e$)



- Singularity at $\nu=(2\Delta-eV_S)/h$ for $V_S<2\Delta/e$ (A)
- Unexpected signal at $\nu=(eV_S-2\Delta)/h$ (B)

Contributions to measured absorption noise

I) source junction: $S_I^{SIS}(\nu, V_S)$

II) resistive part of the on-chip circuit: $S_I^R(\nu) = 2h\nu\theta(\nu)/R$

$$S_V(\nu, V_S) = \overbrace{\left|Z(\nu, \underset{\uparrow}{V_S})\right|^2 S_I^{SIS}(\nu, V_S)}^{\text{I}} + \overbrace{\left|Z'(\nu, \underset{\uparrow}{V_S})\right|^2 S_I^R(\nu)}^{\text{II}}$$

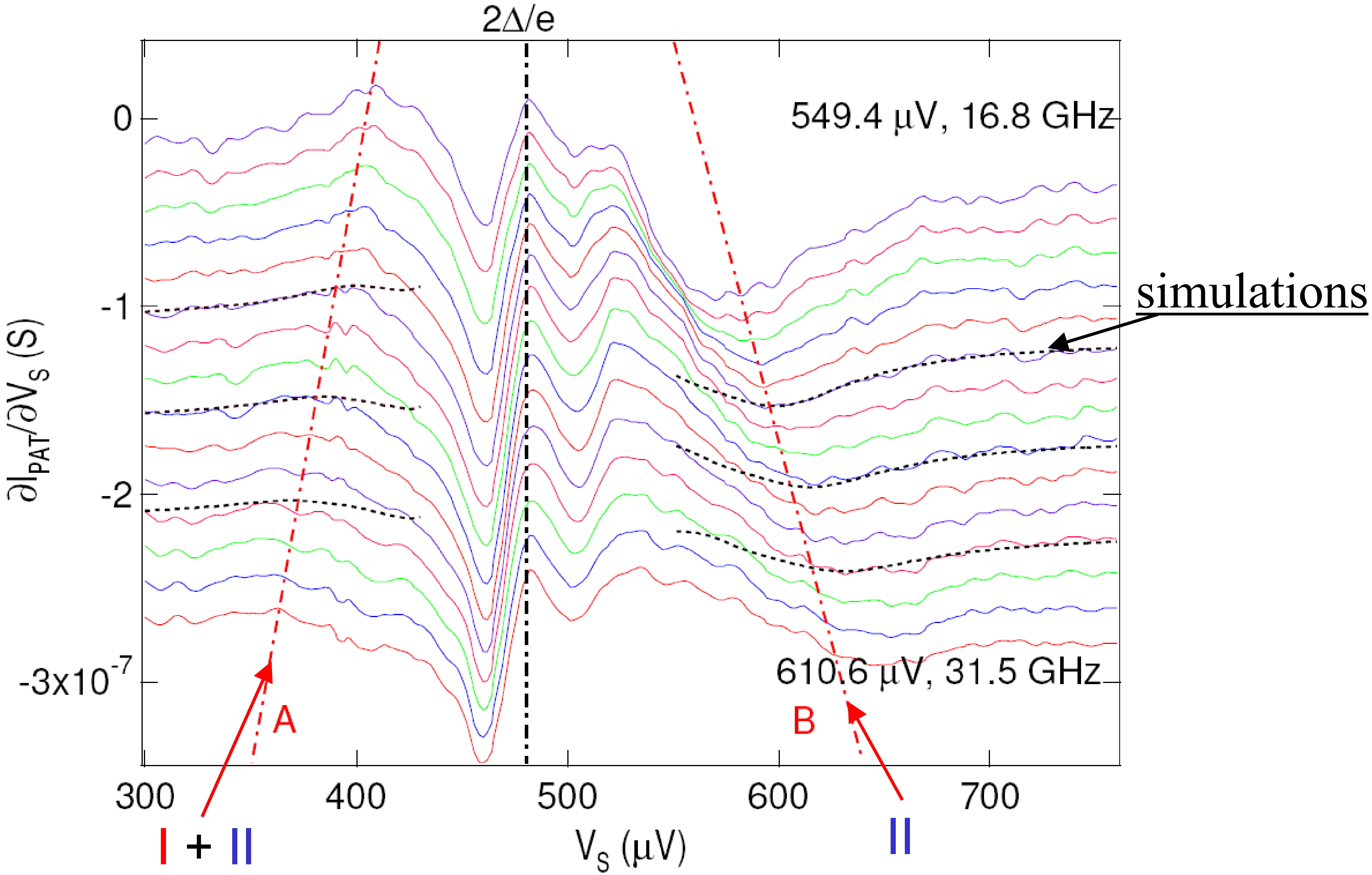
Functions of V_S *via* source impedance:

$$\mathrm{Re}(Z_{source}(\nu, V_S)) = e\frac{I_{QP}(V_S + h\nu/e) - I_{QP}(V_S - h\nu/e)}{2h\nu}$$

Worsham *et al.* PRL (1991)

Adds singularity at $\nu=(eV_S-2\Delta)/h$ for $V_S>2\Delta/e$

PAT due to absorption noise ($V_D>2\Delta/e$)



add with opposite sign
(reduced amplitude)

Conclusion

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

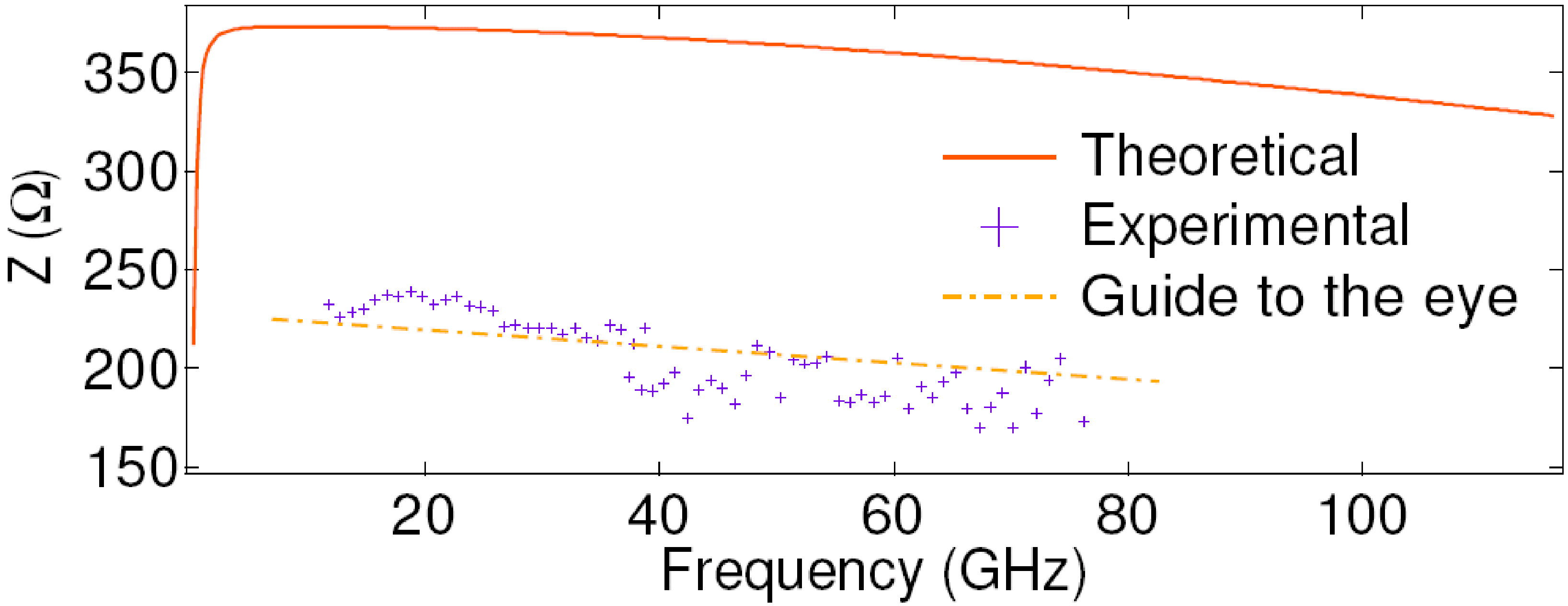
Detection with a SIS junction :

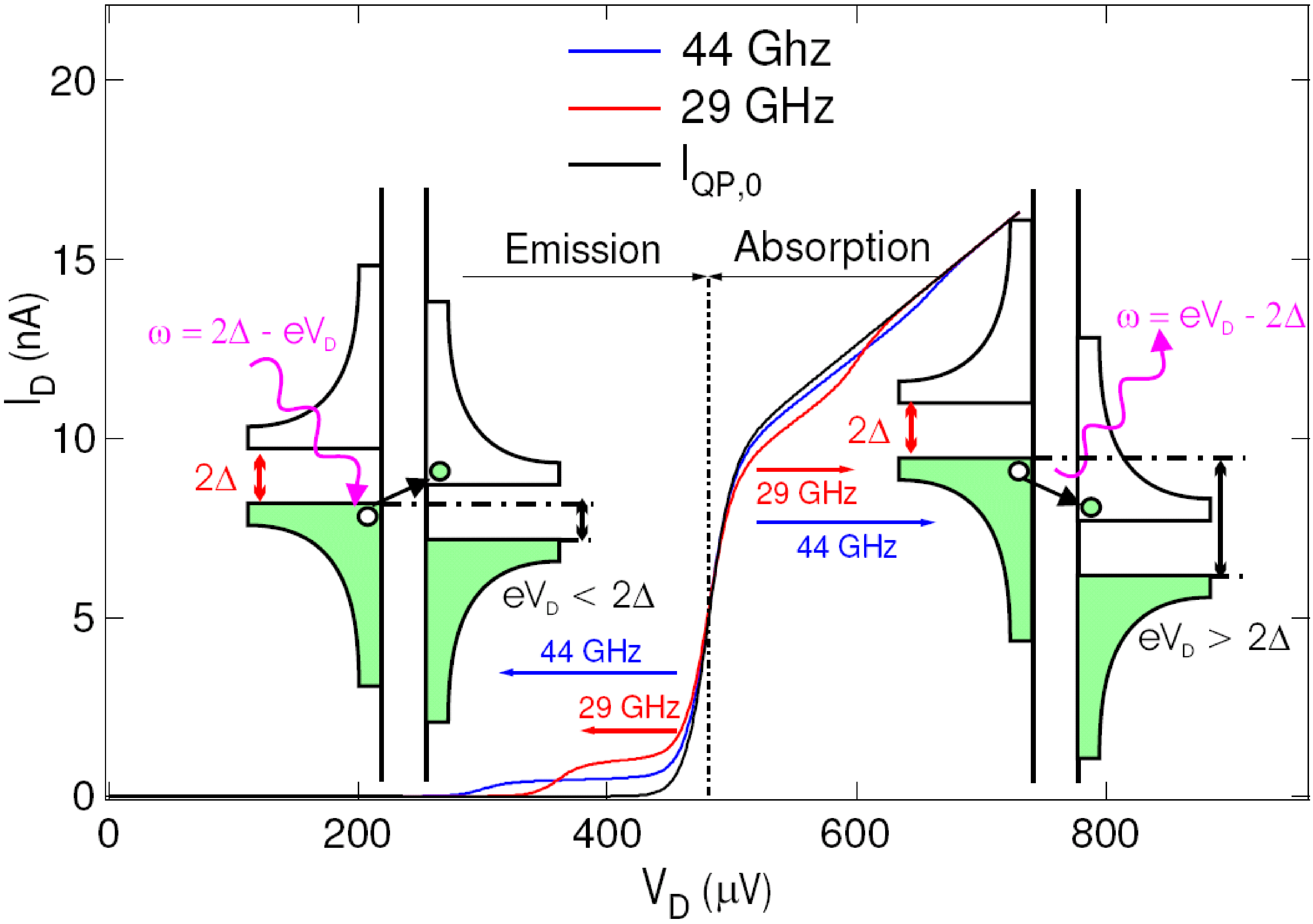
- separate detection of emission and absorption
- emission : source noise
- absorption : source + resistive part of the on-chip circuit

⇒ Detection of non-symmetrized noise

Billangeon, Pierre, Bouchiat, Deblock, Phys. Rev. Lett. **96**, 136804 (2006).

Transimpedance




44 Ghz
29 GHz
$I_{QP,0}$
Emission
Absorption
$\omega = 2\Delta - eV_D$
$\omega = eV_D - 2\Delta$
2Δ
2Δ
$eV_D < 2\Delta$
$eV_D > 2\Delta$
29 GHz
44 GHz
44 GHz
29 GHz
I_D (nA)
V_D (μV)
0
5
10
15
20
0
200
400
600
800