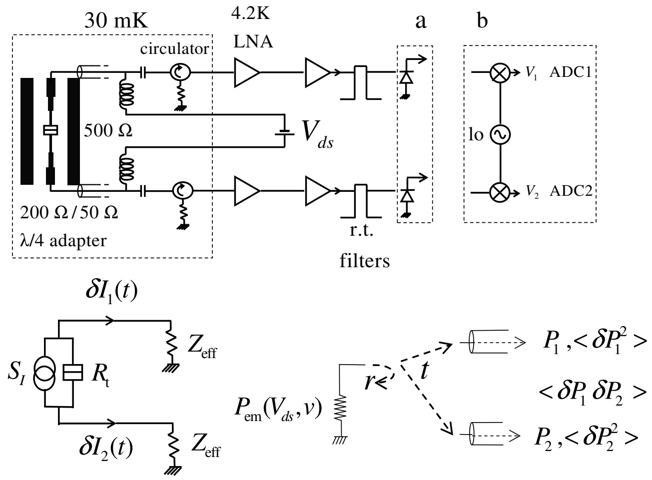

FIG. 1: Schematic diagram of the measurement set-up corresponding to a) detection of the amplified microwave power by quadratic detectors b) fast digitization of the down-converted current fluctuations. c) Equivalent microwave circuit.

presses the Al superconductivity. The two sides of the tunnel junction are separately connected to 50 Ω coaxial transmission lines via two quarter wave length impedance adapters, raising the effective input impedance of the detection lines to $Z_{\rm eff} = 200\Omega$ over a one octave bandwidth centered at 6 GHz. Two rf-circulators, thermalized at mixing chamber temperature ensure a circuit environment at base temperature.

We note $\delta I_{1,2}$ the fluctuating currents in either detection branches resulting from the fluctuations of the current through the tunnel junction. $S_{I_1}, S_{I_2}, S_{I_1,I_2}$ stand for the autocorrelated and cross-correlated spectral densities. From the equivalent circuit represented in figure 1, one easily sees that:

$$\begin{aligned} S_{I_1}(\nu,T,V_{ds}) &= S_{I_2}(\nu,T,V_{ds}) = -S_{I_1 I_2}(\nu,T,V_{ds}) \\ &= \left(\frac{R_{\rm t}}{2Z_{\rm eff}+R_{\rm t}}\right)^2 S_I(\nu,T,V_{ds}), \end{aligned} \qquad (1)$$

where the two first equalities result from current conservation. The noise power detected in each detection line in a frequency range $\Delta\nu$ reads

$$P_{1,2} = Z_{\rm eff}\overline{\delta I_{1,2}^2} = \frac{4Z_{\rm eff}R_{\rm t}}{(2Z_{\rm eff}+R_{\rm t})^2}P_{\rm em}, \qquad (2)$$

where $P_{\rm em} = R_{\rm t}S_I(\nu,T,V_{ds})\Delta\nu/4$ is the emitted power. This can be expressed as an excess noise temperature $\Delta T_{n1,2} = P_{1,2}/[k_{\rm B}\Delta\nu_{1,2}]$.

The two emitted signals are then amplified by two cryogenic Low Noise Amplifiers. Up to a calculable gain factor, the detected noise power contains the weak excess noise $\Delta T_{n1,2}$ on top of a large additional noise generated by the cryogenic amplifiers $T_{n1,2} \simeq 5$K. After further room temperature amplification and eventually narrow bandpass filtering, current fluctuations are detected using three alternative techniques. First (fig. 1.a), we implemented the measurement scheme described in [7], using two calibrated quadratic detectors whose output voltage is proportional to noise power. Secondly (fig. 1.b), current fluctuations are digitized, after down conversion achieved by mixing with a suited local microwave signal, using an AP240 Acqiris Acquisition Card able to sample at 1Gsample/s. A quantitative comparison with the well established first method has qualified this new method. The third method, dedicated to the study of photon noise, is a hybridization of the two previous ones: the outputs of the two quadratic detectors are digitized to perform the photon HBT cross and auto correlations fluctuations of $P_{1,2}$.

First experiment: mean photon occupation number. We measure the increase in noise temperature due do the photon emission by shot noise, as a function of V_{ds} and the measuring frequency ν, using the quadratic detectors. In order to remove the background noise of the amplifiers, we measure the excess noise, $\Delta S_{I_{1,2}}(\nu,T,V_{ds}) = S_{I_{1,2}}(\nu,T,V_{ds}) - S_{I_{1,2}}(\nu,T,0)$. Practically, this is done by applying a 93Hz 0-V_{ds} square-wave bias voltage on the sample through the DC input of a bias-Tee, and detecting the first harmonic of the square-wave noise response of the detectors using lock-in techniques. The results are quite similar to the one reported in ref.[7], and lead to an electron temperature $T_e \sim 70$ MA. Although T_e is significantly higher than the mixing chamber temperature, it is low enough to make the thermal population of photons negligible in the 4-8 GHz frequency range, where all our measurements are done. In the high bias limit ($eV_{ds} \gg k_{\rm B}T, h\nu$), $\Delta S_I \sim 2eI$. Equation 2 then yields an excess noise temperature $\Delta T_{n1,2} = eV_{ds}/4k_{\rm B}$ in both detection branches in the case of ideal coupling $R_{\rm t} = 2Z_{\rm eff}$. In practice, we get excess noise temperatures ~ 2dB lower than expected from the independently measured attenuation of the various microwave components connecting the sample to both amplifiers. A ~ 100fF capacitance for the junction, shunting part of the microwave signal, accounts for this discrepancy. This value is quite reasonable given the area of our tunnel junction (1.4 μm^2).

Second experiment: auto and cross-correlated electronic noise. We record the current fluctuations with the acquisition card using a 5 ns sampling time, chosen large enough to avoid any correlation between successive points, thus maximizing the effective bandwidth. Here again, we eliminate background noise and parasitic correlation between the two inputs of the acquisition card by measuring excess fluctuations . $\Delta\overline{\delta V_1^2}$ and $\Delta\overline{\delta V_2^2}$ are proportional to the excess noise power:

$$\Delta\overline{\delta V_{1,2}^2} = G_{1,2}Z_0P_{1,2} = G_{1,2}Z_0Z_{\rm eff}\Delta S_{I_{1,2}}\Delta\nu,$$