Quasiparticle dynamics in a superconducting island and lead

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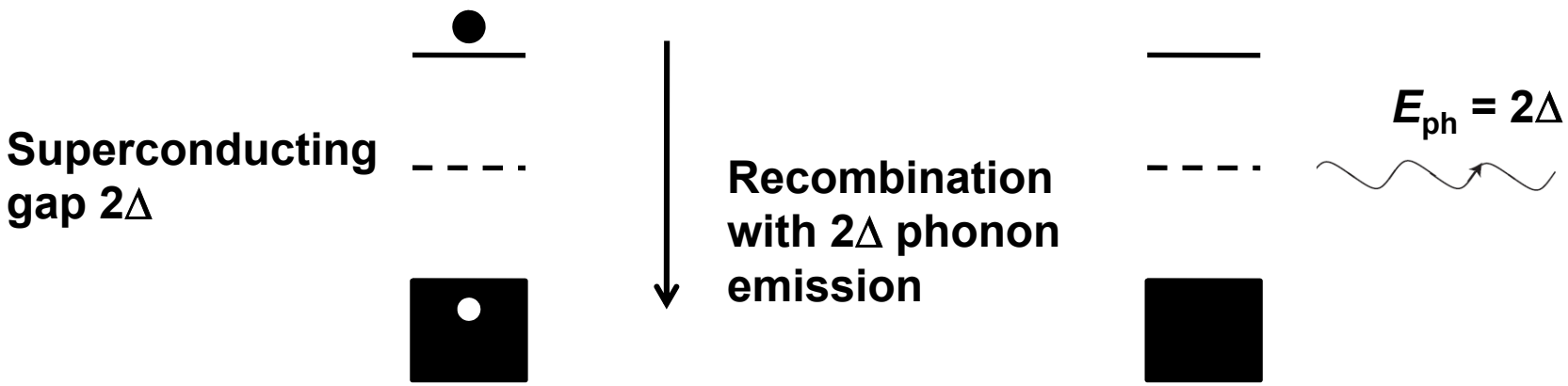
Quasiparticle recombination

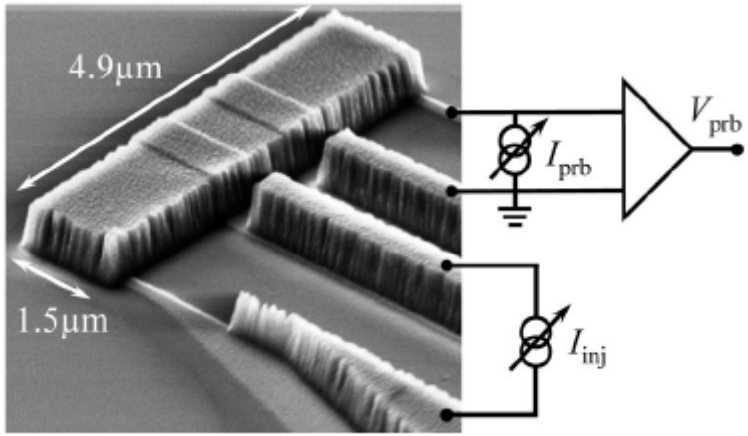


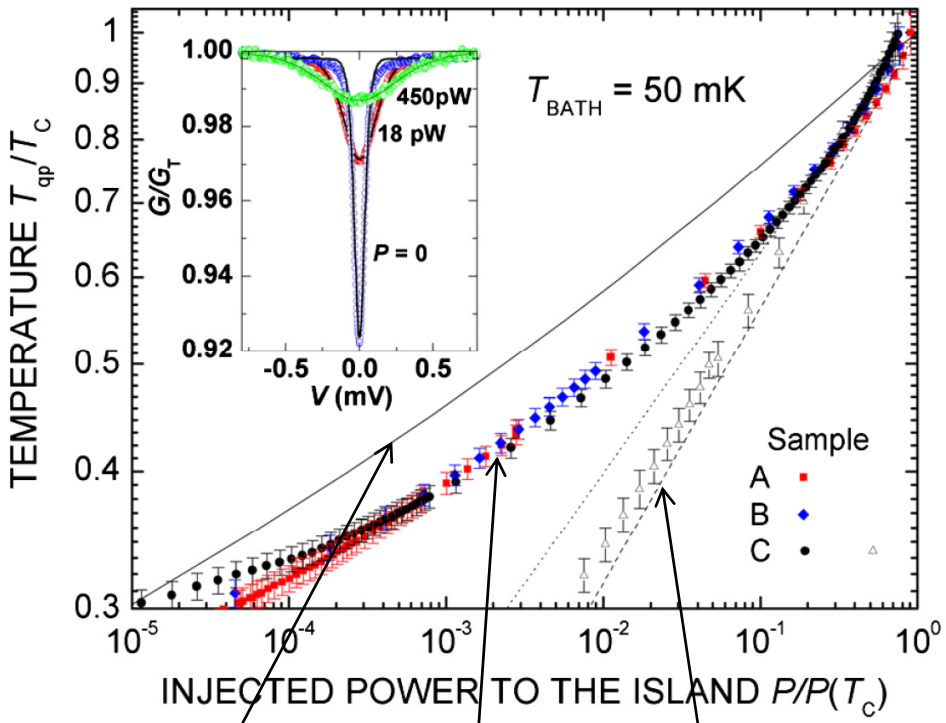
Rothwarf and Taylor, 1967

$$\frac{1}{\tau_{rec}} = \frac{1}{\tau_0}\sqrt{\pi}\left(\frac{2\Delta}{kT_c}\right)^{5/2}\sqrt{\frac{T}{T_c}}e^{-\frac{\Delta}{kT}}$$

Kaplan et al, 1976
Barends et al., 2008

Measurement of energy relaxation in a superconductor





Measurement of energy relaxation in an aluminium bar, A. Timofeev et al, 2009

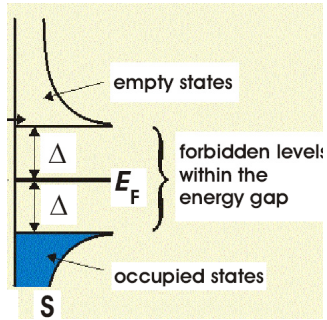
$$P_{\text{qp-ph}} \simeq \frac{64}{63\zeta(5)} \Sigma \mathcal{V} T^5 \; e^{-\Delta/k_B T}$$

Superconducting (theory)

Superconducting (exp)

Normal state

Quasiparticle heat conduction in a superconductor

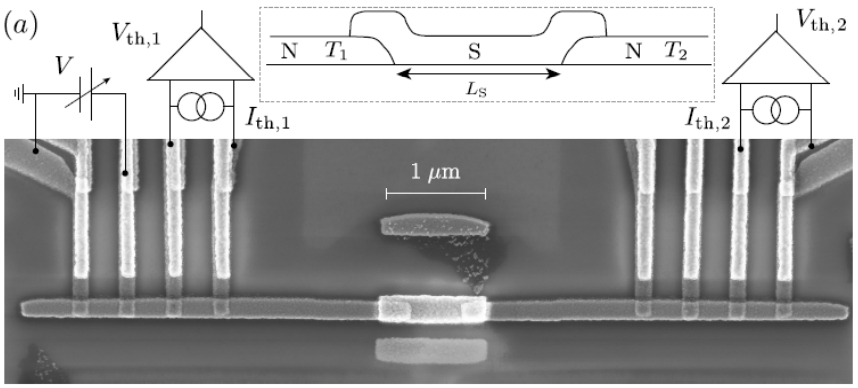


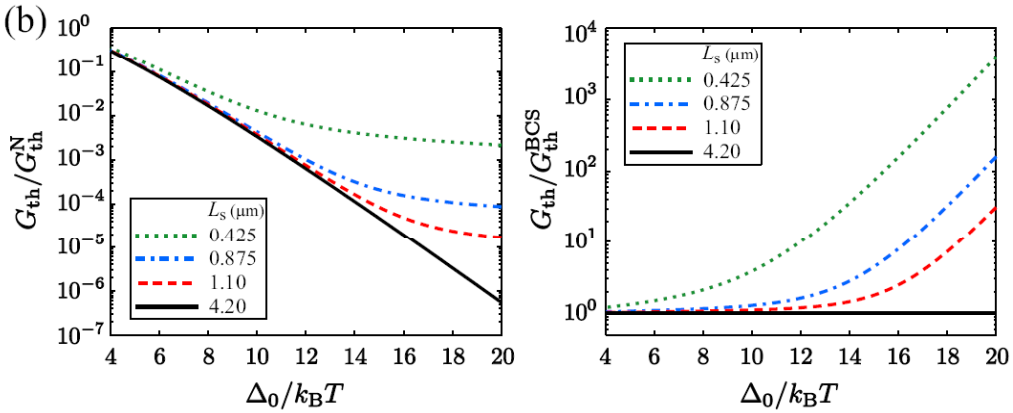
Bardeen et al. 1958

$$\gamma(T) = \frac{G_{\rm th}}{G_{\rm th}^{\rm N}} = \frac{3}{2\pi^2}\int_{\Delta/k_{\rm B}T}^{\infty} dx \frac{x^2}{\mathrm{sech}^2(x/2)} \simeq \frac{3}{2\pi^2}\left(8+8a+4a^2\right)e^{-a} \qquad a = \Delta/k_{\rm B}T$$

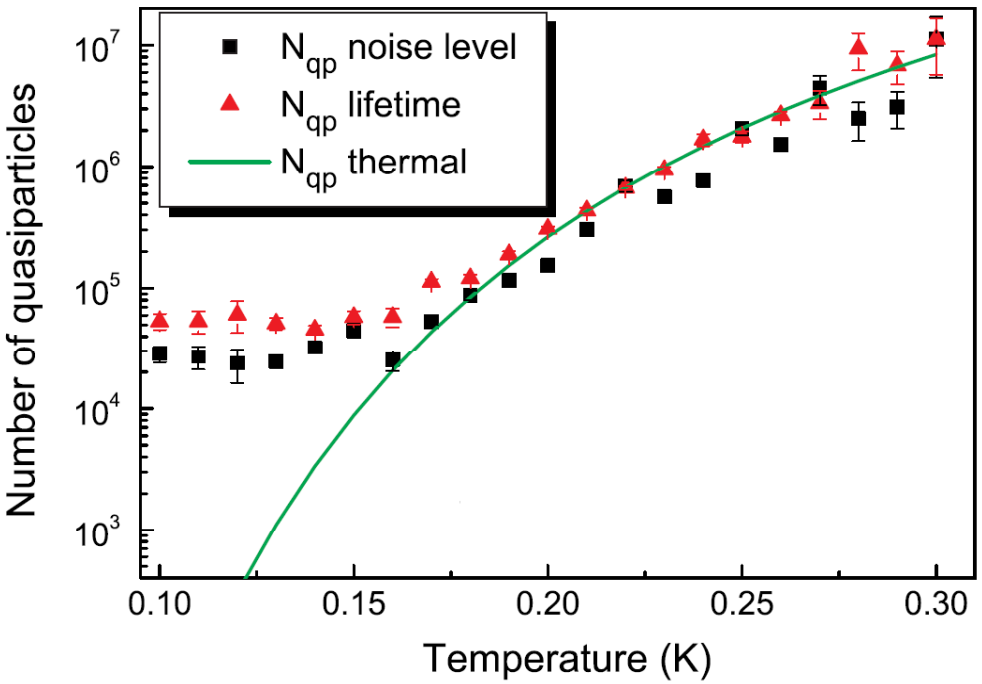
Quasiparticle (heat) transport is exponentially suppressed at low temperatures in a superconductor

Measurement inc. inverse proximity effect, Peltonen et al., PRL 2010.





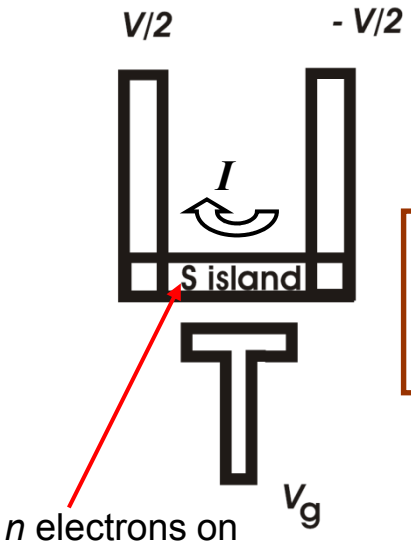
Typical quasiparticle numbers



de Visser et al., PRL 2011.

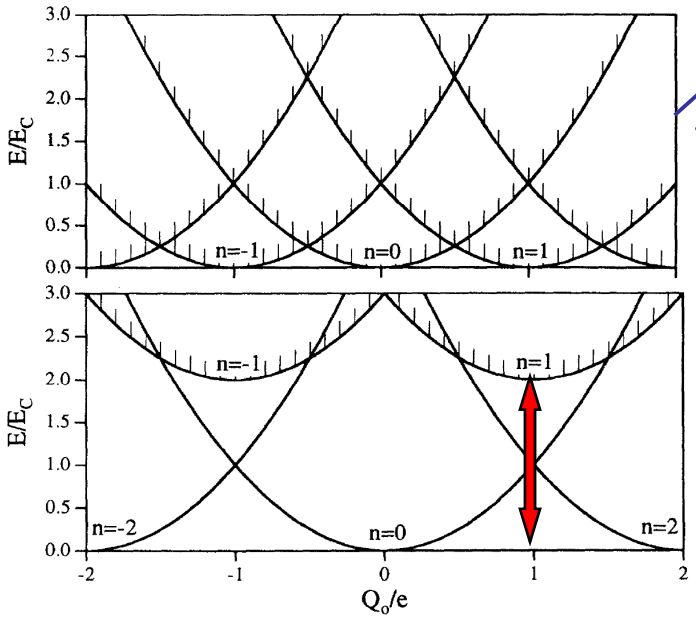
$$n_{\mathrm{qp}} = 2N_F \int_{\Delta}^{\infty} \mathrm{d}E \frac{E}{\sqrt{E^2 - \Delta^2}} f(E) \approx N_F \sqrt{2\pi k_B T \Delta}\, e^{-\Delta/k_B T}$$

Parity effect in superconducting SETs



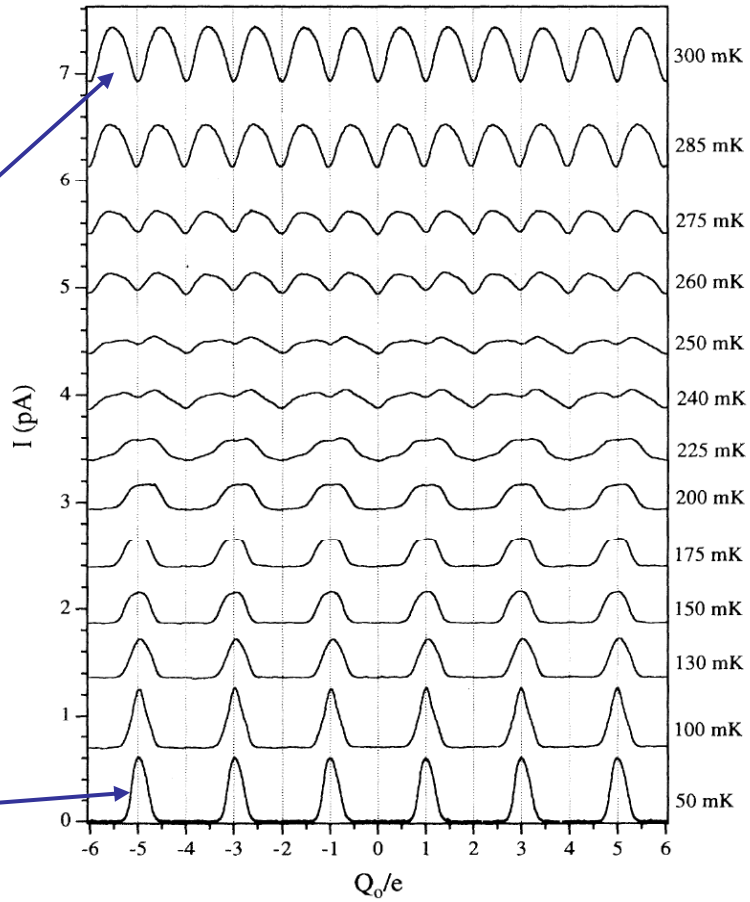
n electrons on the island

$$F = E_C(n+n_g)^2, \quad n \text{ even}$$
$$F = E_C(n+n_g)^2 + \Delta, \quad n \text{ odd}$$



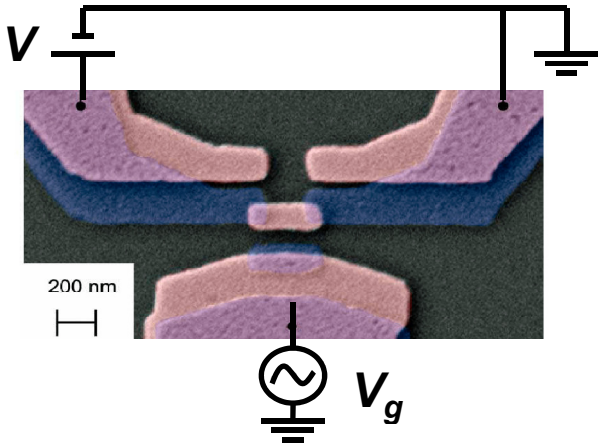
Normal state, $\Delta = 0$

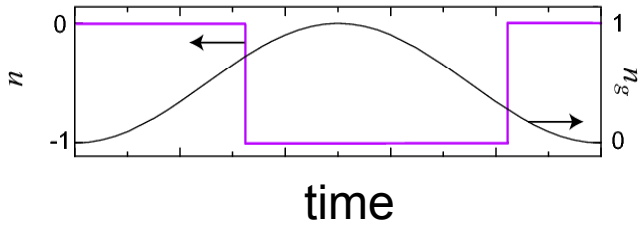
Superconducting state, $\Delta > E_C$



M. Tuominen et al. (1992)

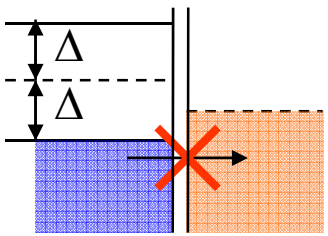
Single-electron turnstile with NIS-junctions



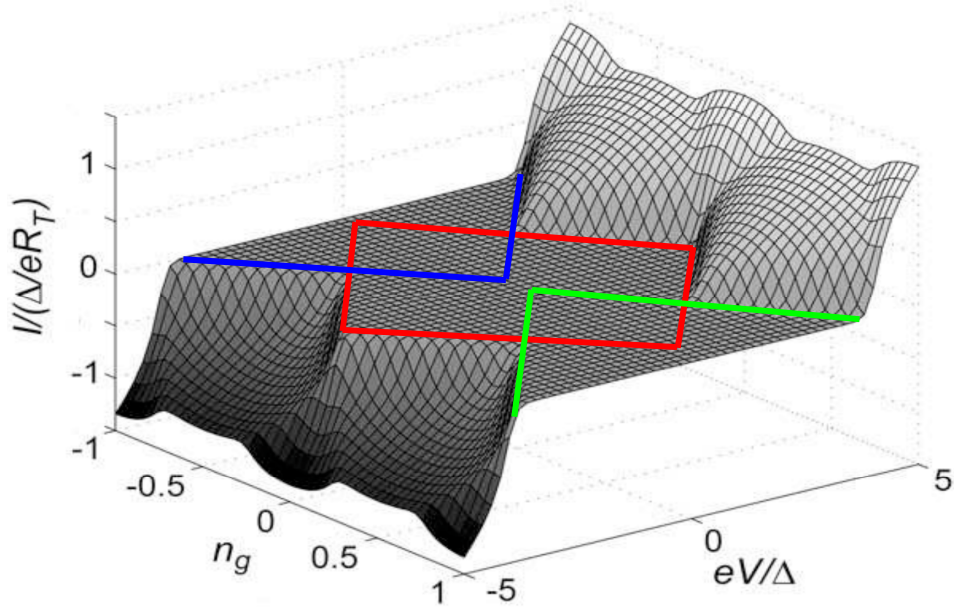


Nature Physics 4, 120 (2008)

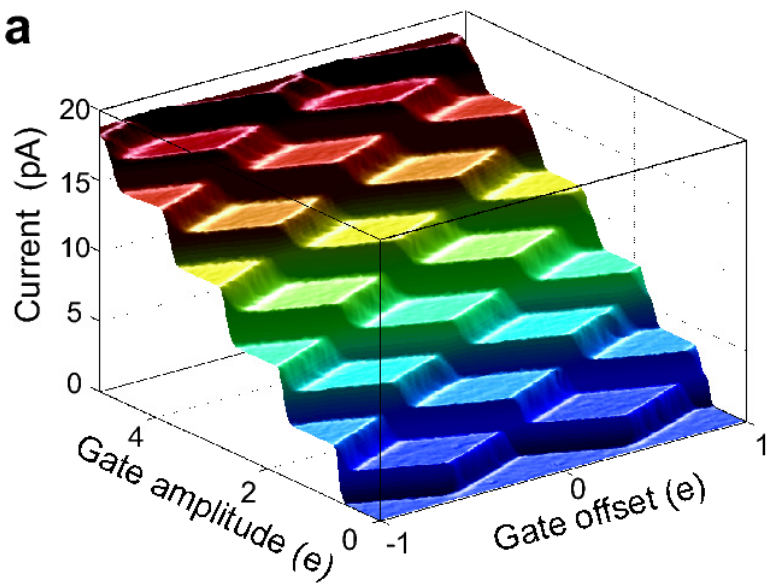
One electron is transferred through the turnstile in each gate cycle: *I* = *ef*.

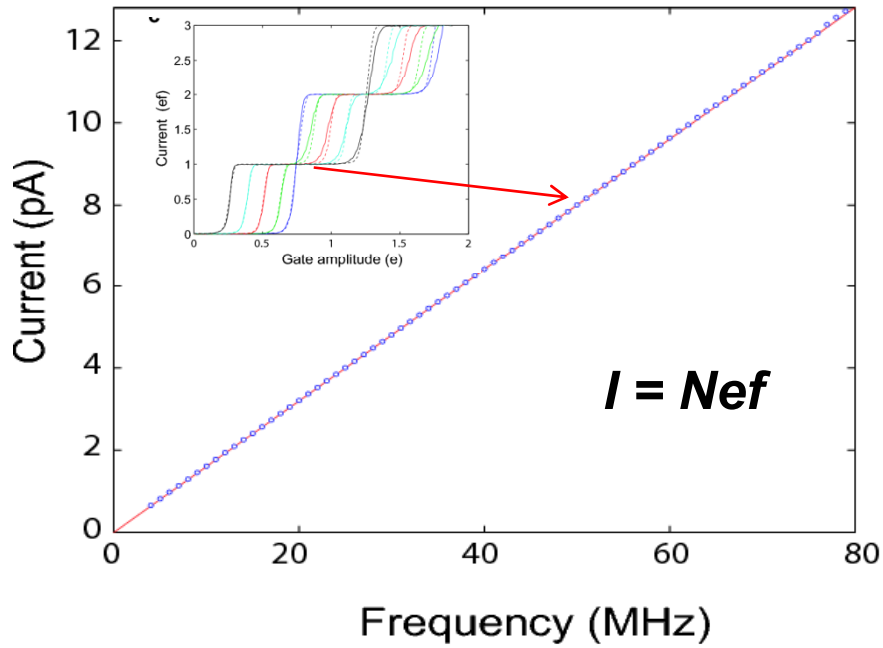


Superconducting gap blocks single-electron tunneling at low energies



Hybrid single-electron turnstile





Errors in pumping

Thermal errors

Photon-assisted tunneling (coupling to environment)

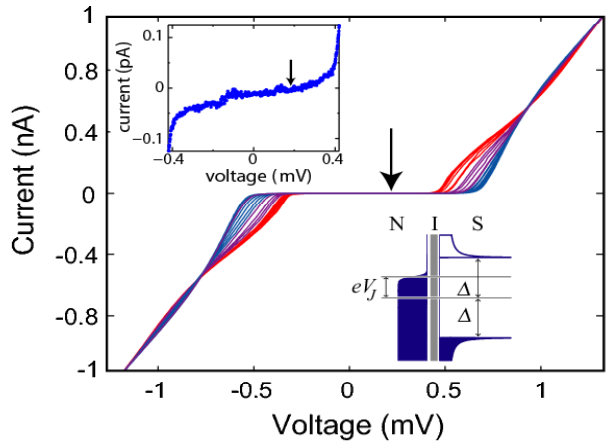
Multi-electron processes (co-tunneling, Andreev tunneling etc.)

Residual and generated quasiparticles in a superconductor

Thermal error rates

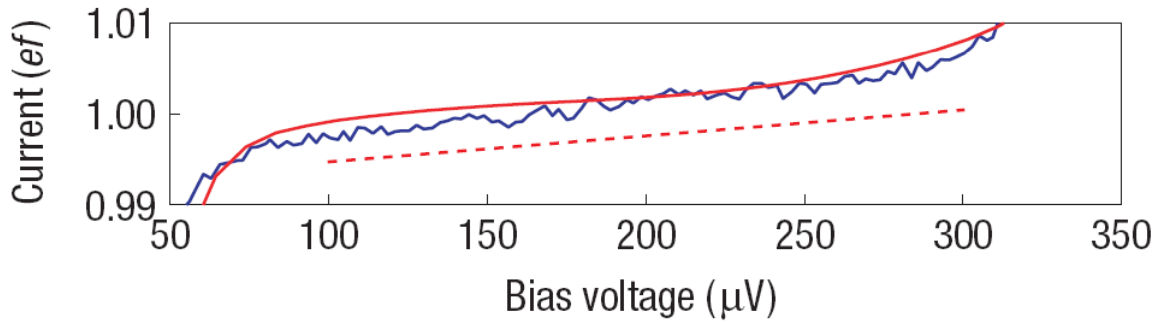
Optimum operation point of the turnstile is at $eV = \Delta$, where the error rate is

$$\sim \exp(-\frac{\Delta}{k_B T_N})$$

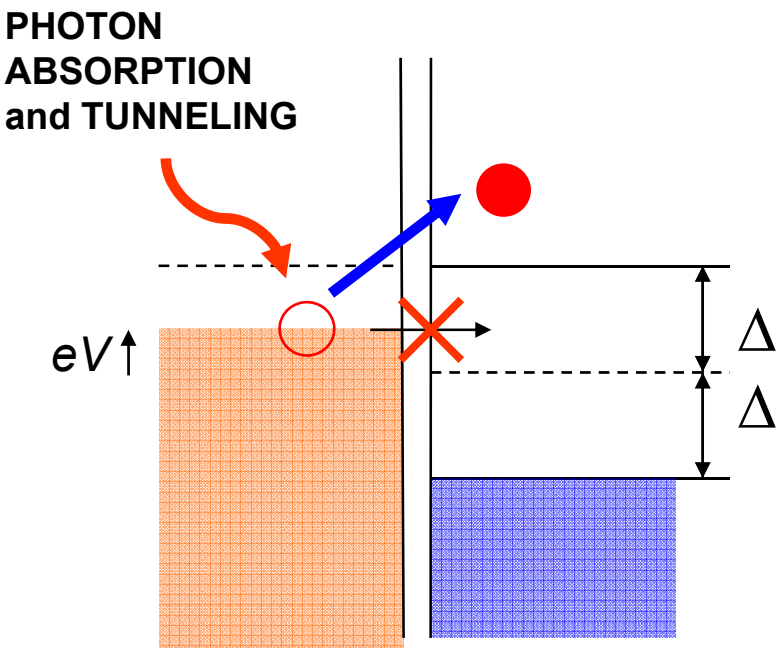


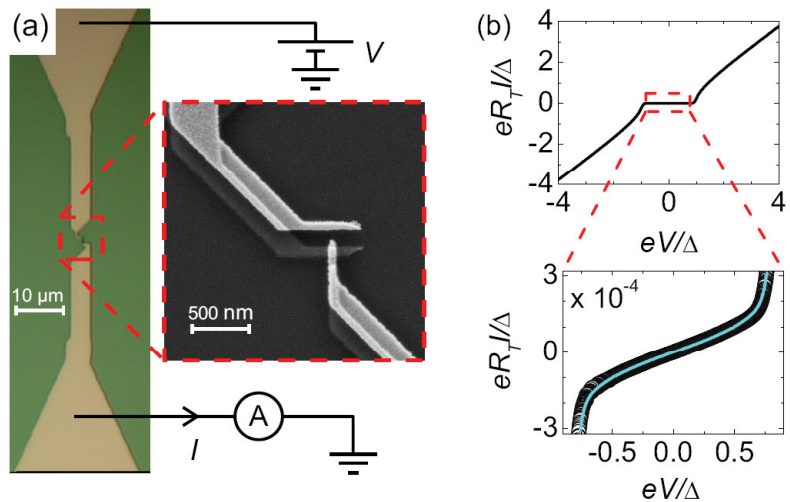
At 100 mK for aluminium ($k_B T_N / \Delta = 0.04$), this error is $<< 10^{-8}$.

Yet the errors in the first experiments were much higher.



Influence of em-environment on single-electron current in a NIS-junction





$$I(V) = \frac{1}{eR_T} \int_{-\infty}^{\infty} dE\, n_S^{\gamma}(E)\, [f_N(E - eV) - f_S(E)]$$

with

$$n_S^{\gamma}(E) = |\mathrm{Re} \frac{E/\Delta + i\gamma}{\sqrt{(E/\Delta + i\gamma)^2 - 1}}|$$

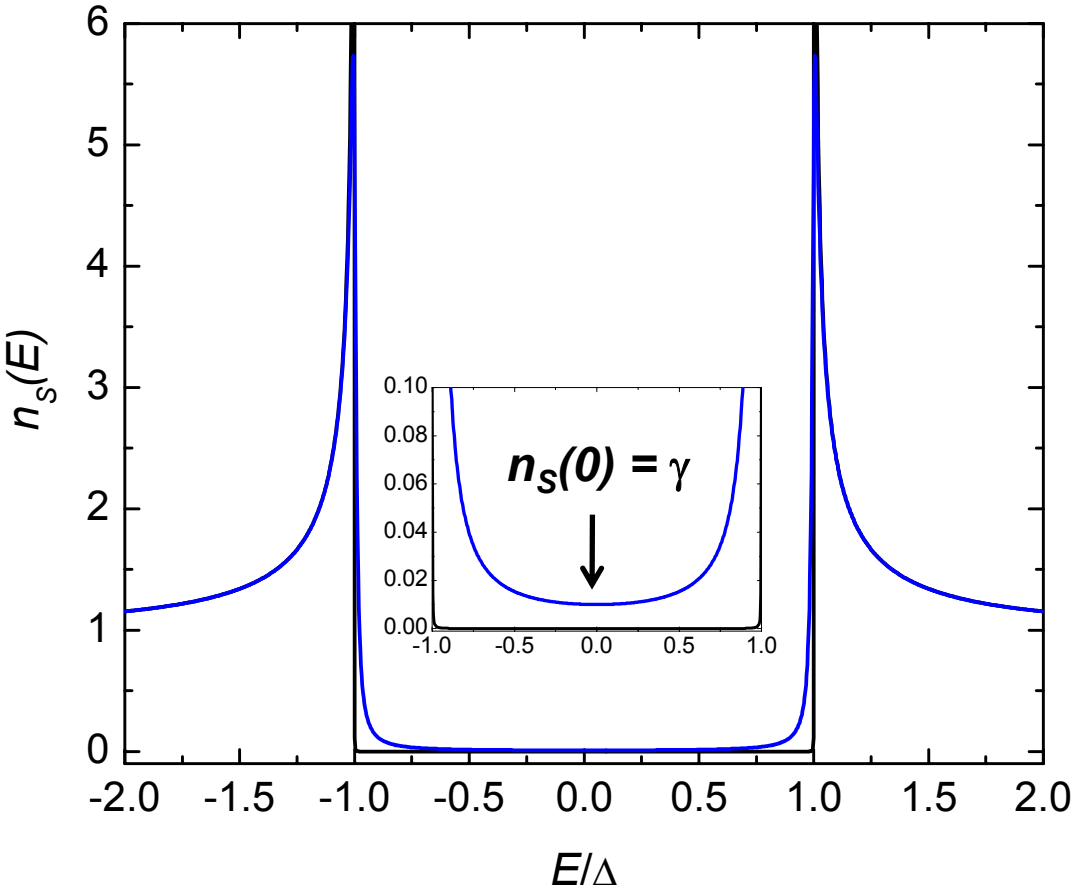
$$\gamma = 2\pi \frac{R}{R_K} \frac{k_B T_{\mathrm{env}}}{\Delta}$$

PRL **105**, 026803 (2010)

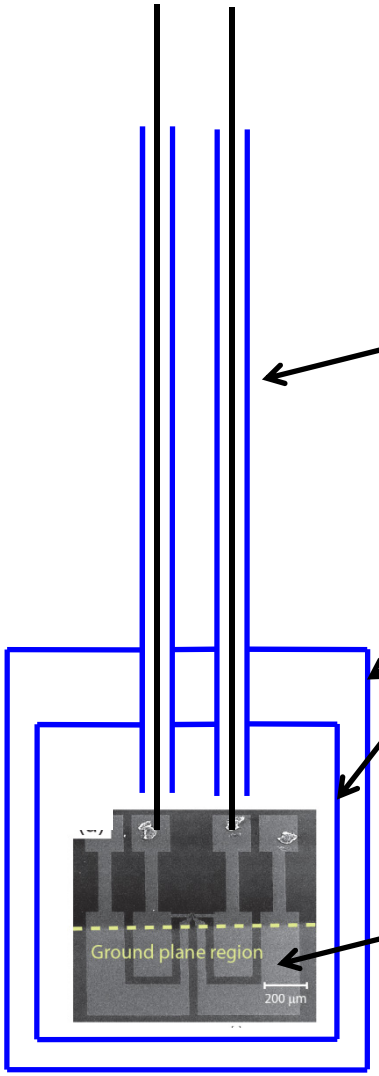
Dynes Density of States

$$n_S(E) = |\mathrm{Re}\frac{E/\Delta + i\gamma}{\sqrt{(E/\Delta + i\gamma)^2 - 1}}|$$

Dynes 1978, 1984



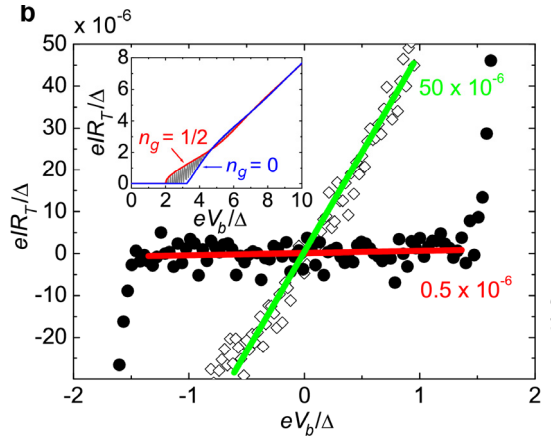
Careful filtering and shielding

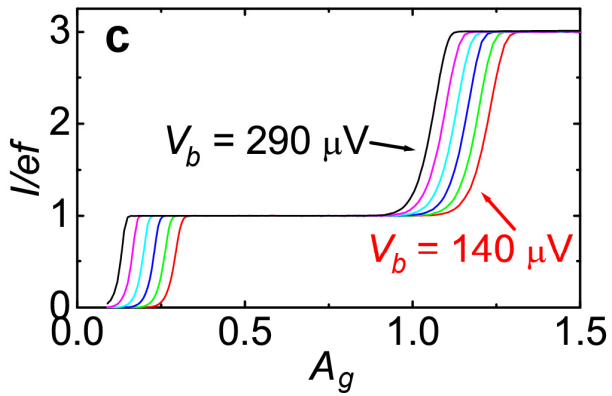


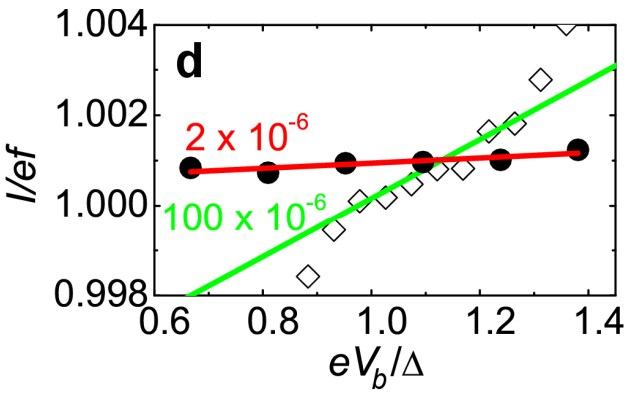
Lossy coaxes with a feed-through

Double-walled hermetic metallic sample stage

On-chip capacitance to shunt the junctions

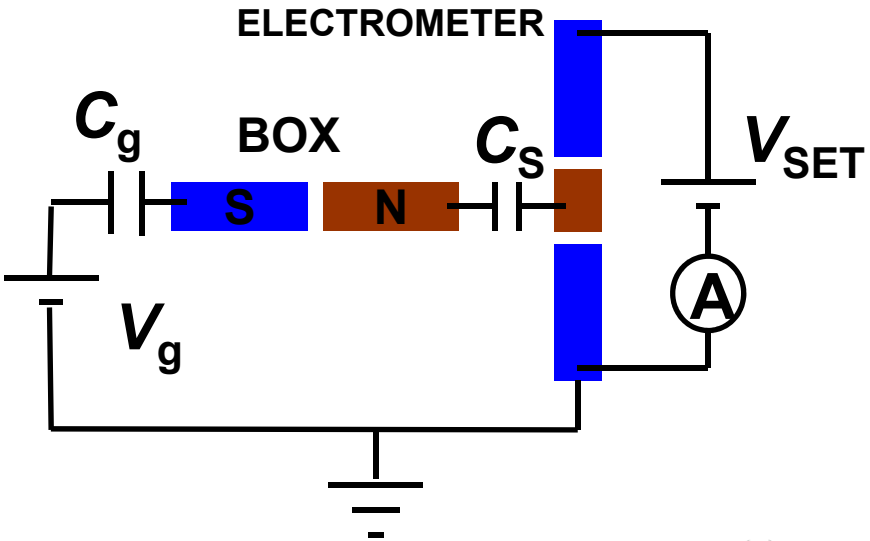


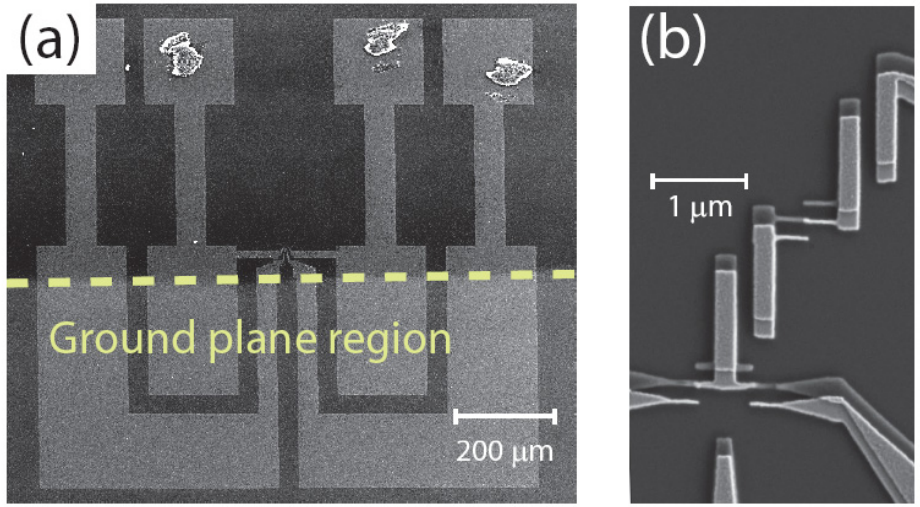




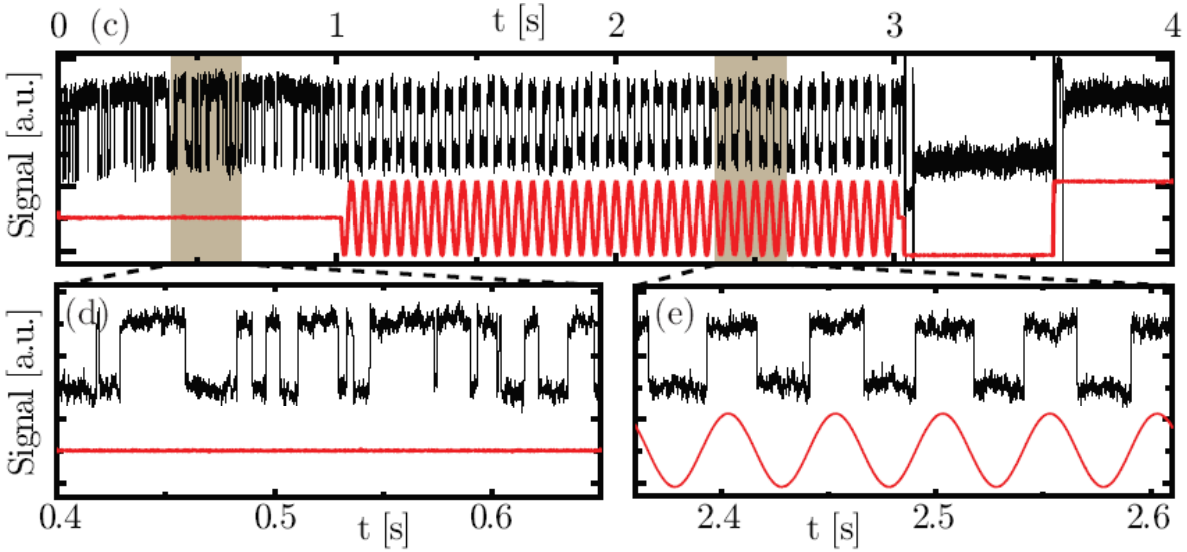
Counting single-electrons

O.-P. Saira et al., PRB 82, 155443 (2010)

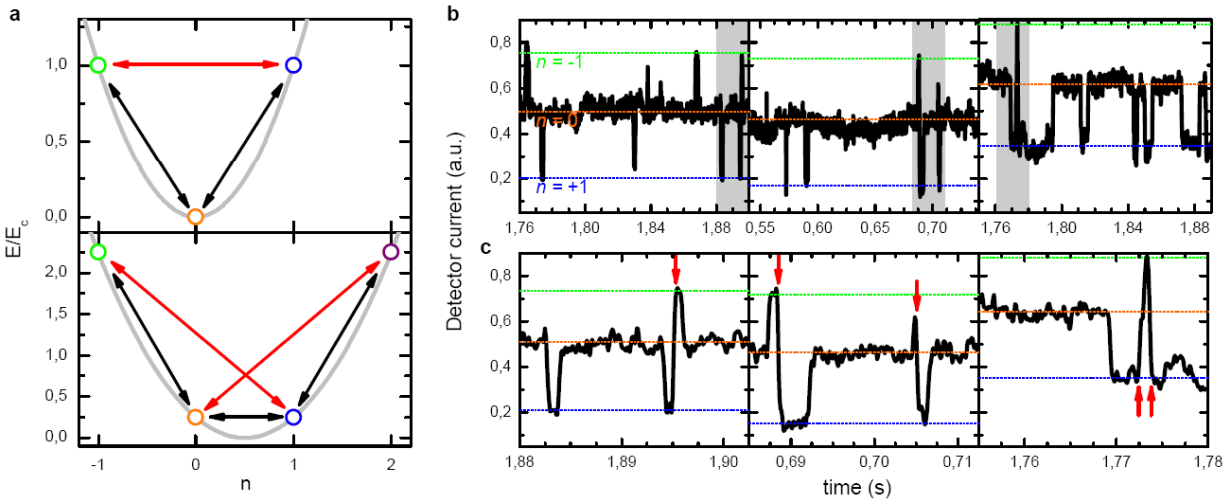




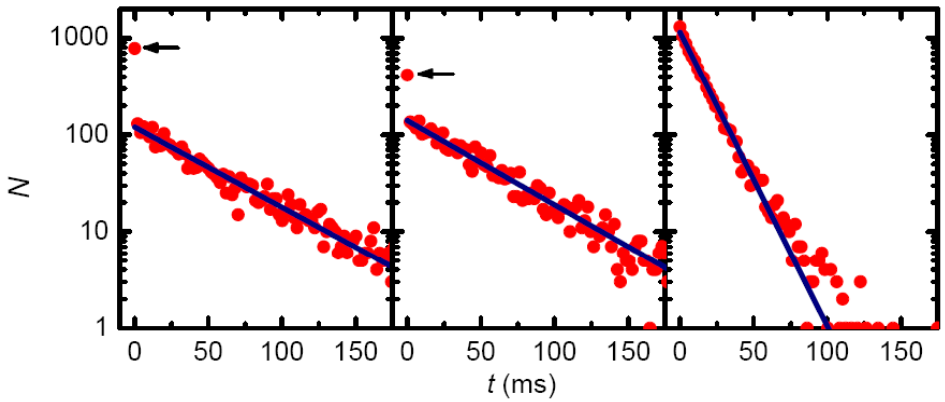
0 – 1 s counting random errors at charge degeneracy
1 – 3 s pumping electrons at 20 Hz frequency
3 – 4 s quiet in the two hold modes

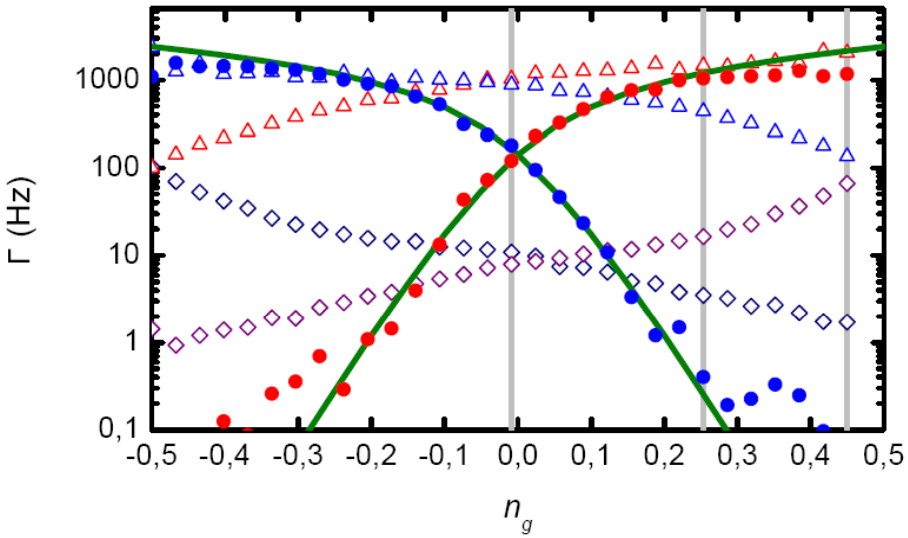


Andreev 2e transitions also observed

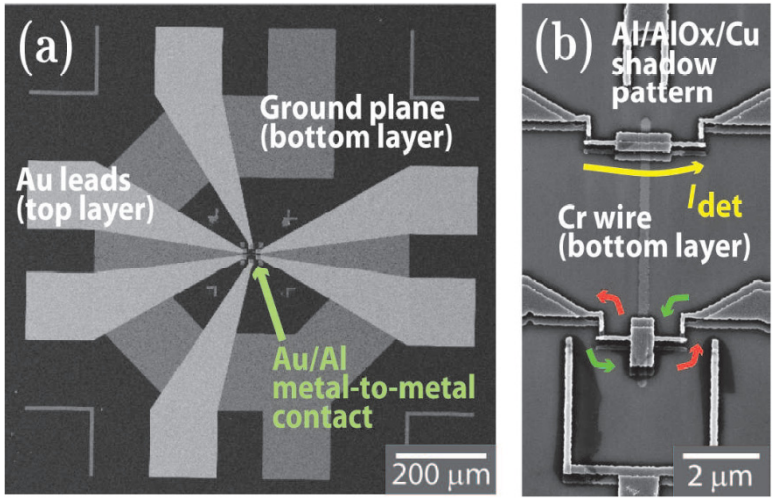


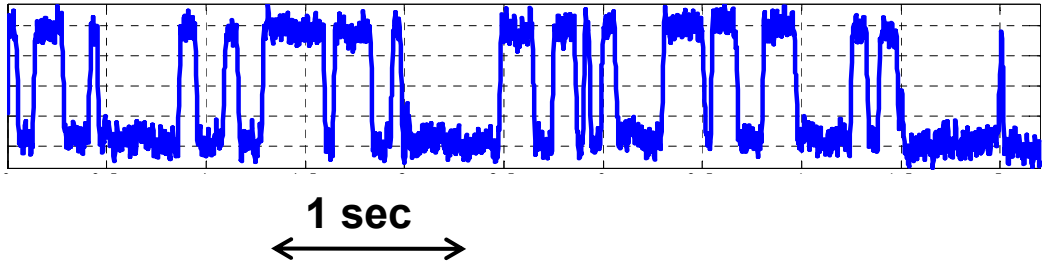
V. Maisi et al., PRL 106, 217003 (2011)





Counting single-electrons on a turnstile





The observed transition rate equals

$$\Gamma^{1e}(eV_{ds}/2) + \Gamma^{1e}(-eV_{ds}/2)$$

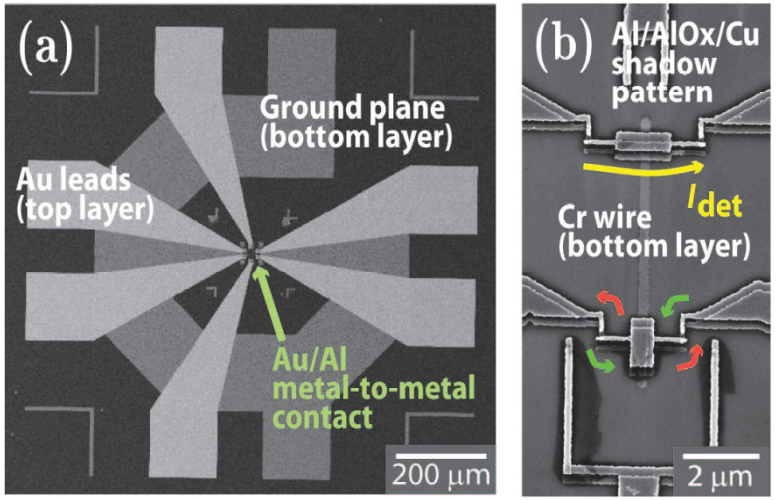
The rates can be attributed to:

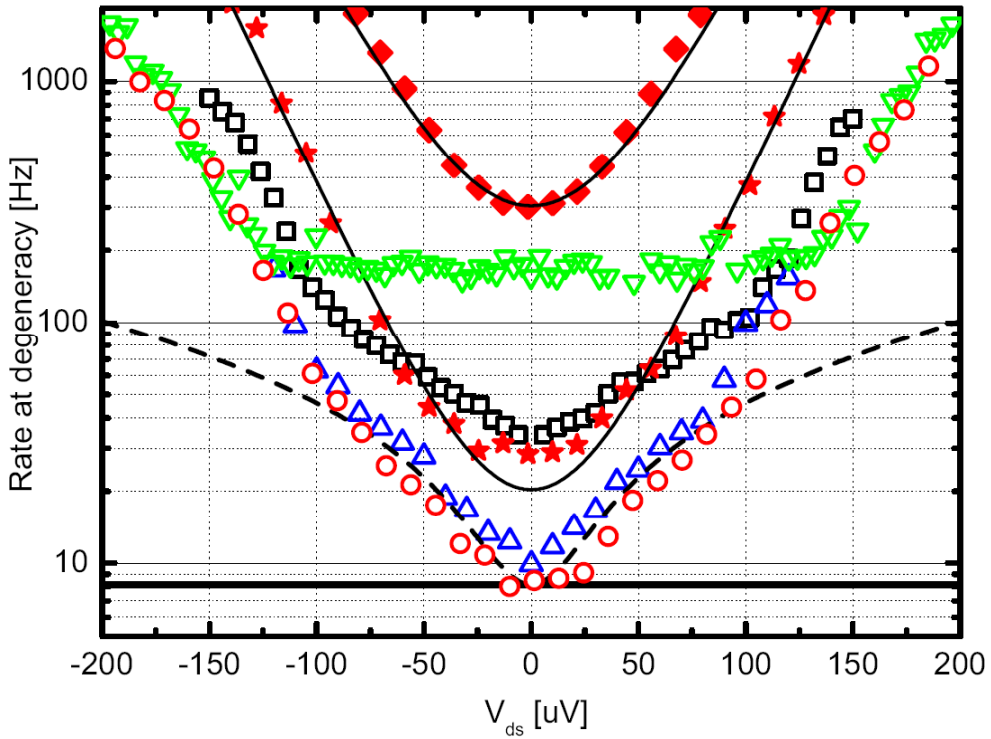
1. **Residual density of quasiparticles in the superconductor** n_{qp}:

$$\Gamma^{1e}_{nqp} = \frac{n_{qp}}{2e^2 R_T D(E_F)}$$

2. **Dynes parameter (DOS in the gap)** γ: $\Gamma^{1e}(0) = \gamma \frac{k_B T}{e^2 R_T}$

How ideal is Al superconductor?





Two major conclusions:

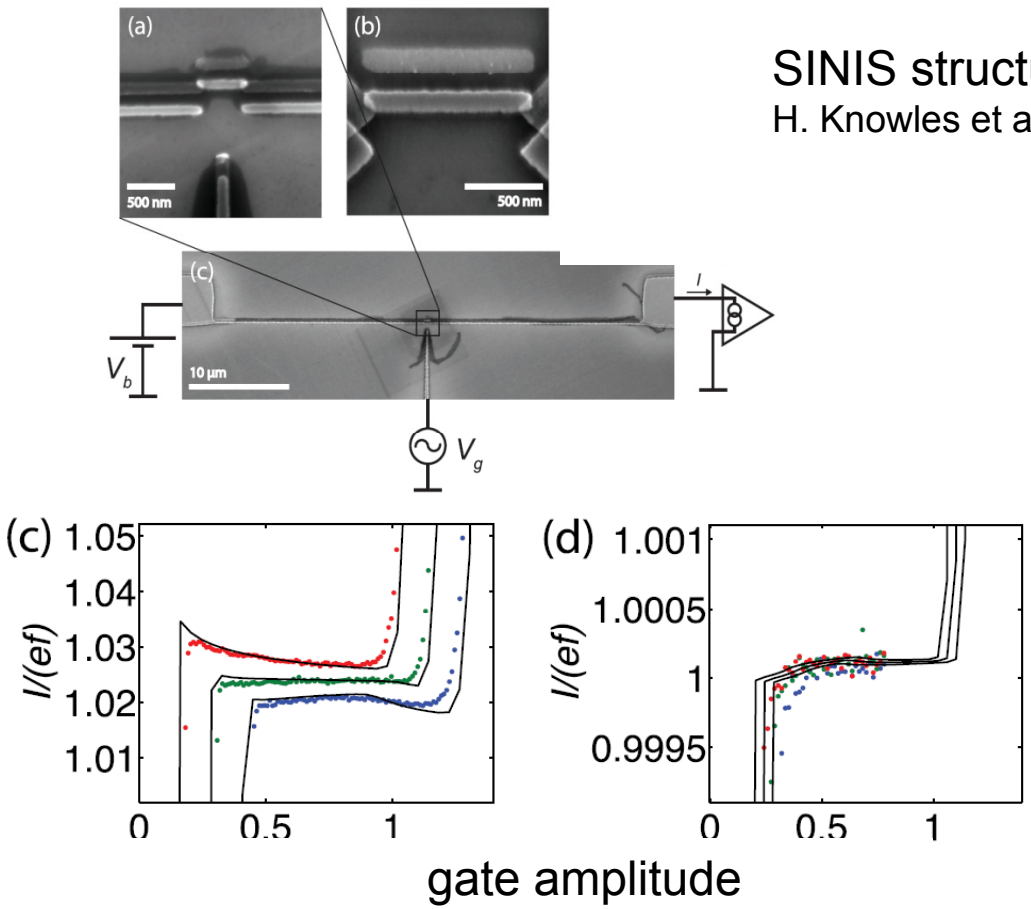
1. Residual quasiparticle density < 0.033 $(\mu m)^{-3}$:

<u>Typical qp number in the leads = 0</u>

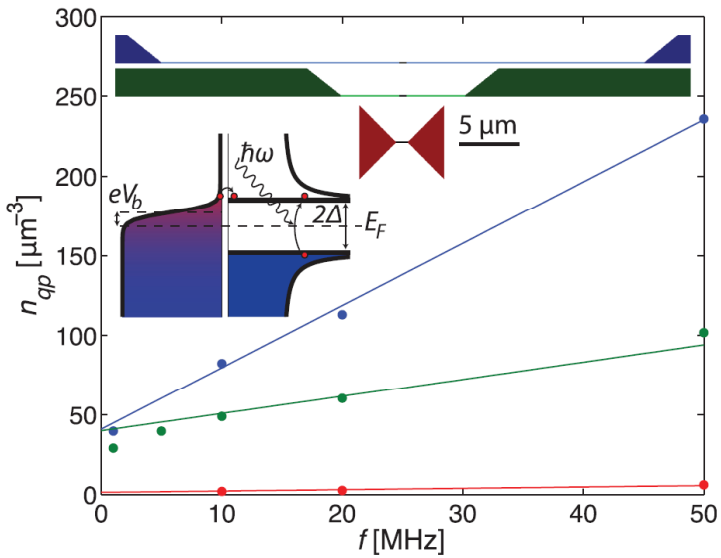
2. Sub-gap density of states < 2 X 10^{-7} $D(E_F)$

O.-P. Saira et al., PRB 85, 012504 (2012).

Relaxation of generated quasiparticles (I)



SINIS structures with different S-lead geometries
H. Knowles et al., APL **100**, 262601 (2012).

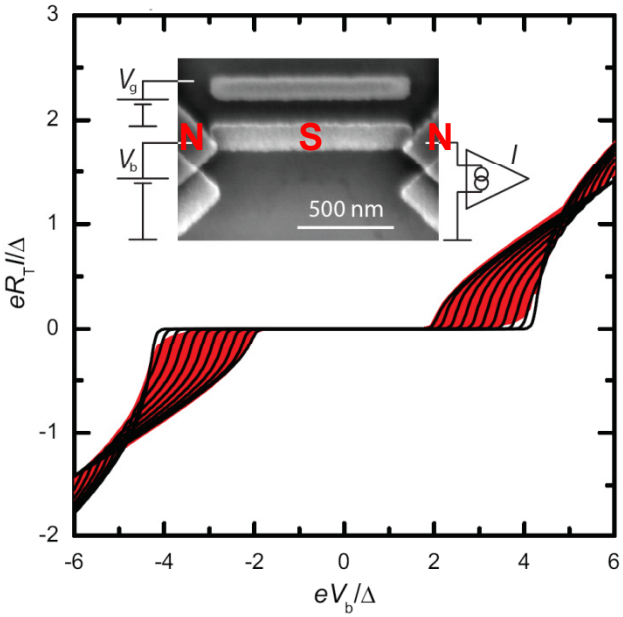


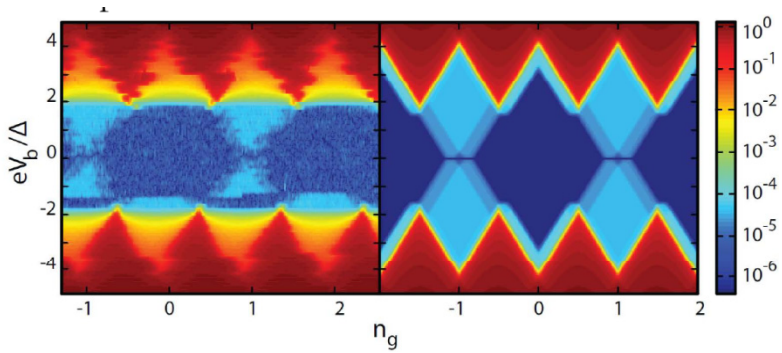
Note: injection and relaxation of qp's has been traditionally studied close to T_c, see e.g. A. Schmid and G. Schön, JLTP 20, 207 (1975).

Relaxation of generated quasiparticles (II)

NISIN structure

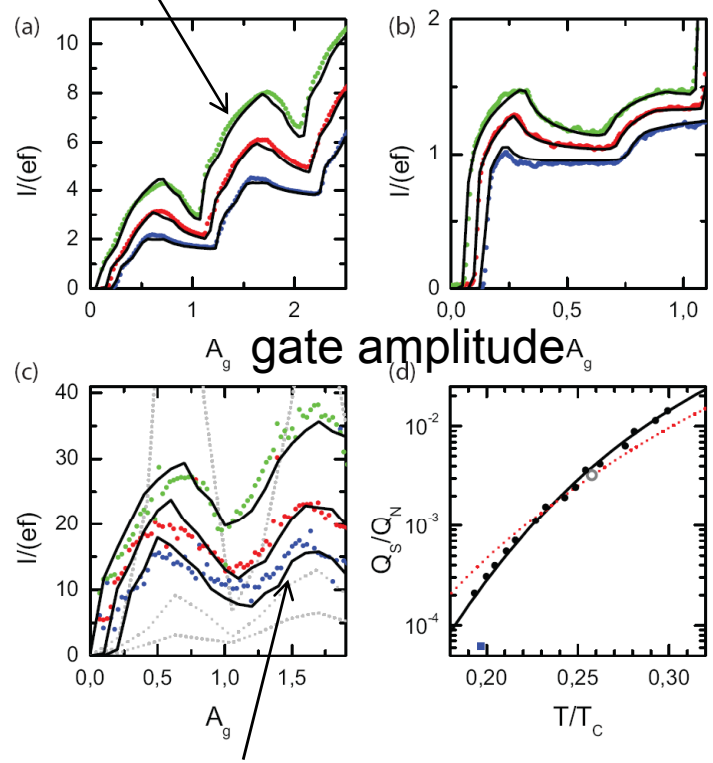
V. Maisi et al., in preparation.





Black lines:

$$\dot{Q}_{ep} = \frac{\Sigma V}{24\zeta(5)k_B^5}\int_0^\infty d\epsilon\, \epsilon^3 \left(n(\epsilon,T_S)-n(\epsilon,T_P)\right)\int_{-\infty}^{\infty} dE \times$$
$$n_S(E)n_S(E+\epsilon)\left(1-\frac{\Delta^2}{E(E+\epsilon)}\right)\left(f(E)-f(E+\epsilon)\right).$$



Black lines: qp pair relaxation τ^{-1} = 8 kHz

Summary

Quasiparticles can be controlled and modelled

- **record-low quasiparticle densities [0.03 (μm)$^{-3}$] achieved by filtering and qp trapping**
- **residual qp number can be suppressed to <<1 in "practical" conductors**
- **injected quasiparticles pose a difficult problem and need care**

With proper qp control SINIS turnstile may eventually qualify for quantum metrology