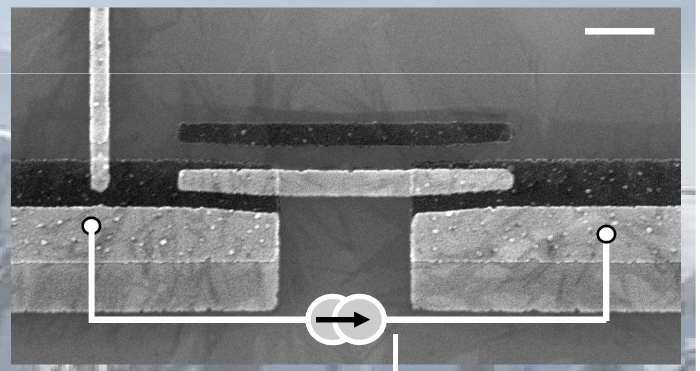
Electronic refrigeration using superconducting tunnel junctions



Sukumar Rajauria

H. Courtois, F. W. J. Hekking and B. Pannetier

Motivation

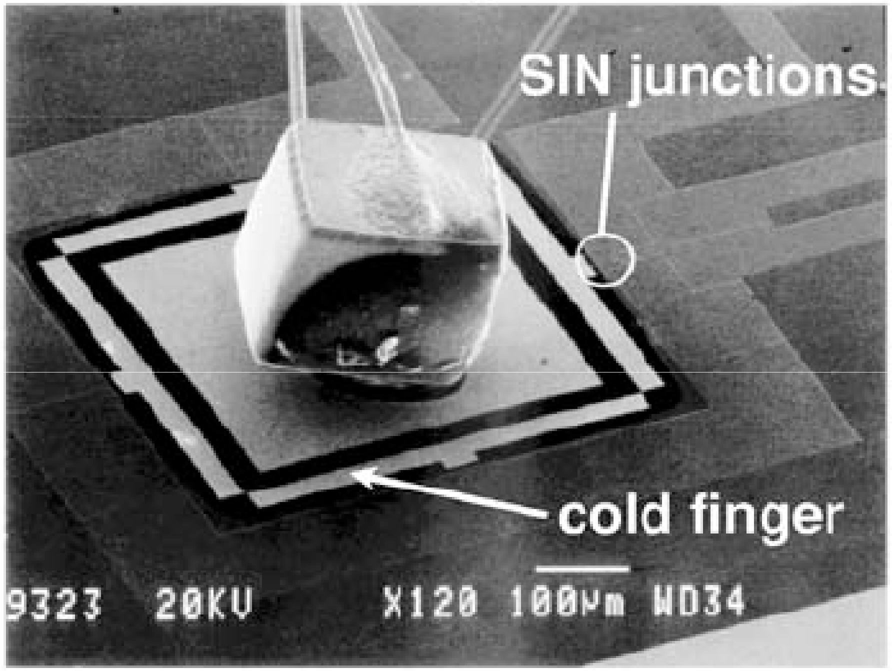
Quantum nano-electronics:
- New devices with new functionality (SET, qubits, …)
- High performance at (very) low temperature.

On-chip cooling of a nano-device:
- Improved efficiency, more compact,
- N-I-S micro-coolers promising.

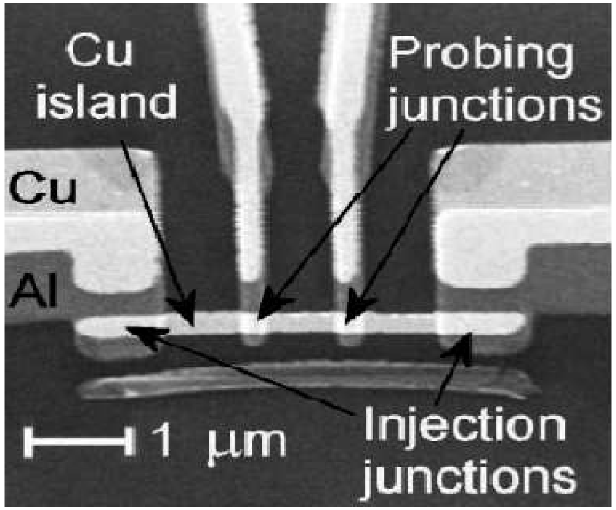
Basic knowledge on:
- N-I-S junction with a heat perspective,
- Heat transport at micro- or nano-scale.

Motivation

Prototype cooler – N. I.S.T.

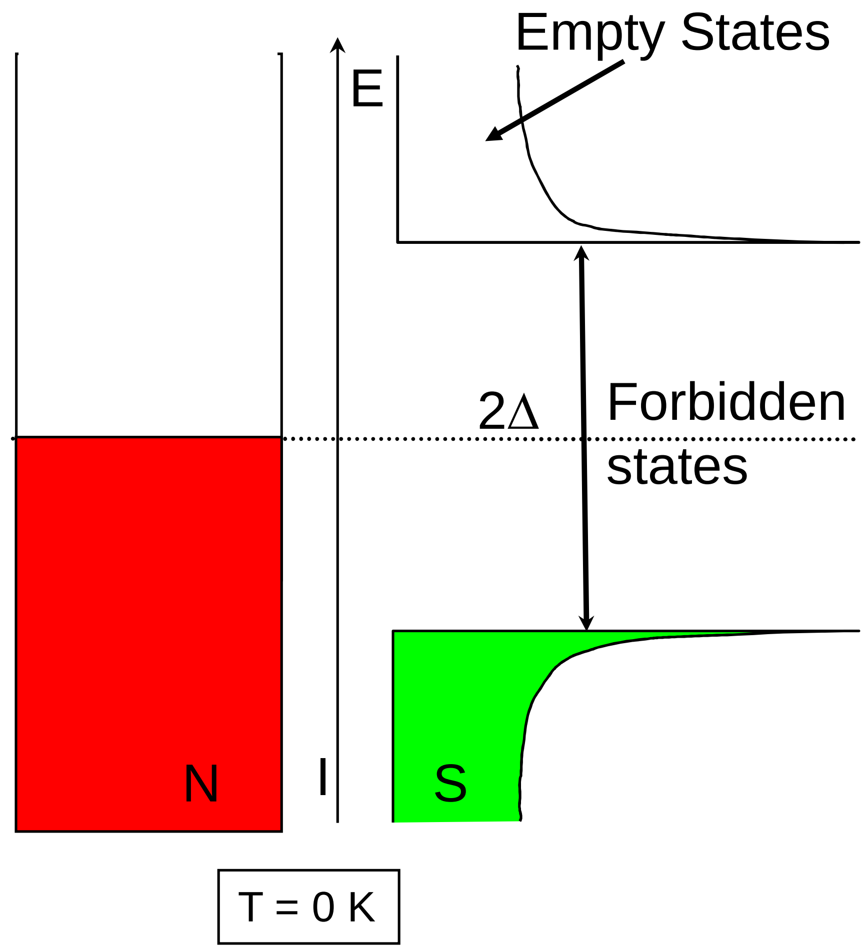


First S-I-N-I-S cooler – Helsinki



Quasiparticle tunneling in N-I-S junction

Principle of N-I-S cooler
The superconductor energy gap induces an energy-selective tunneling.



Quasiparticle tunneling in N-I-S junction

Principle of N-I-S cooler

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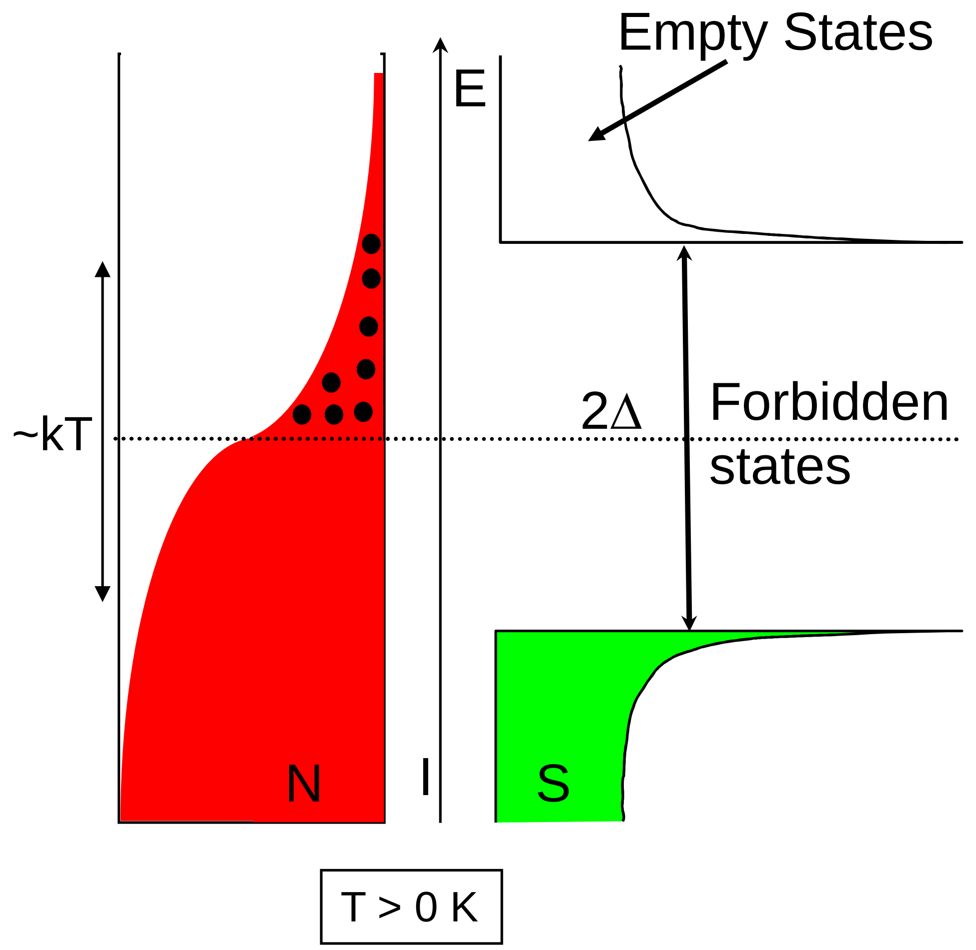
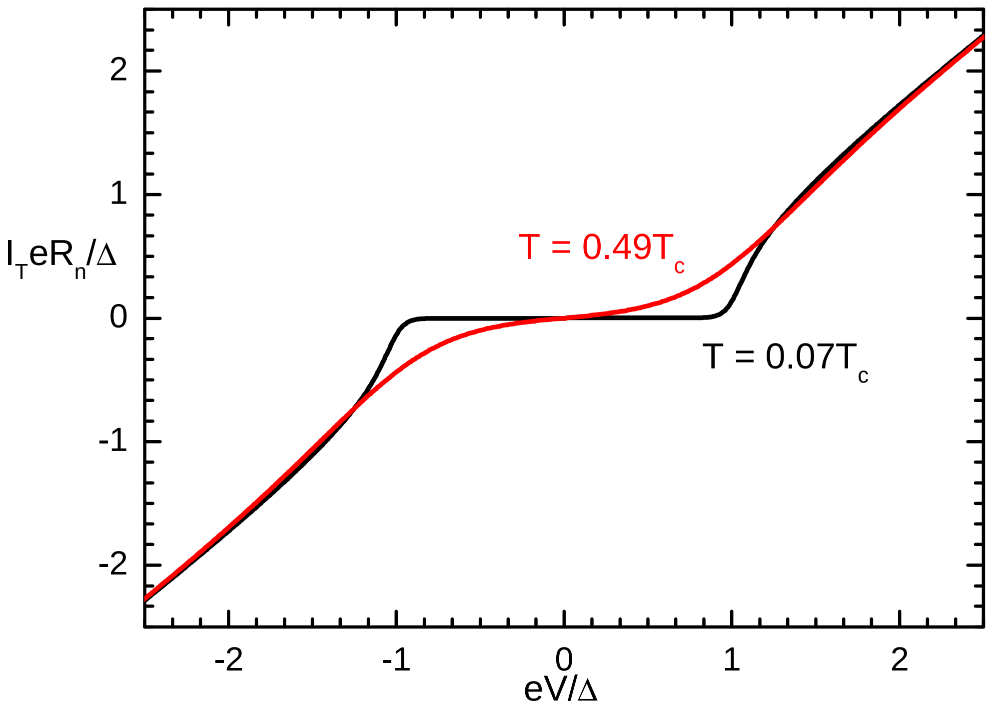
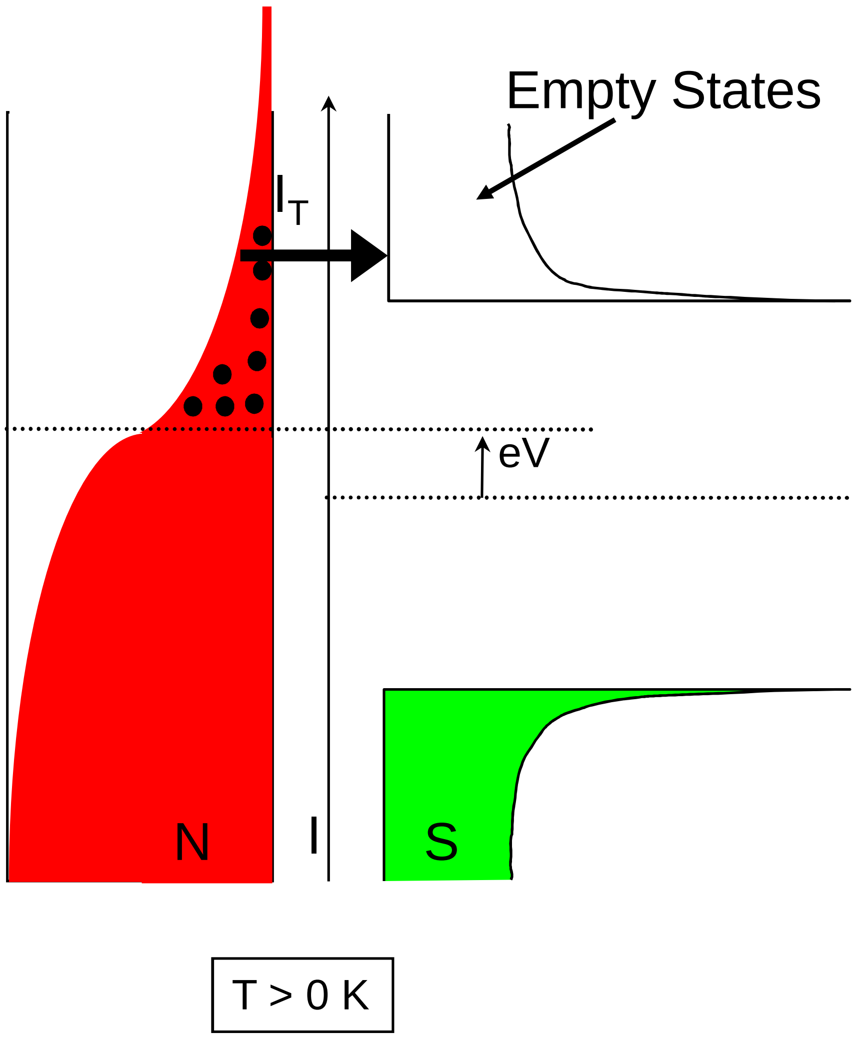


Quasiparticle tunneling in N-I-S junction

Quasiparticle tunnel current:

$$I_T = \frac{1}{eR_N}\int_{-\infty}^{\infty} n_S(E)\left[f_N(E-eV) - f_S(E)\right] dE$$





Quasiparticle tunneling in N-I-S junction

Quasiparticle tunnel current:

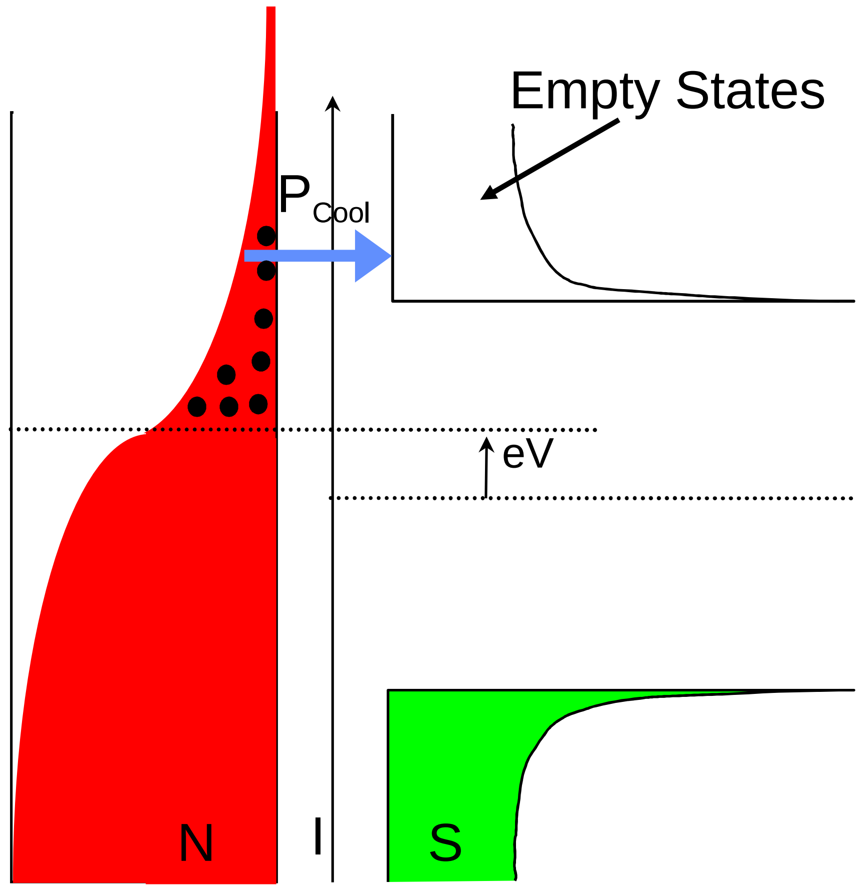
$$I_T = \frac{1}{eR_N} \int_{-\infty}^{\infty} n_S(E)\left[f_N(E-eV) - f_S(E)\right] dE$$

Net Cooling Power:

$$P_{Cool} = \frac{1}{e^2 R_N} \int_{-\infty}^{\infty} (E-eV) n_S(E)\left[f_N(E-eV) - f_S(E)\right] dE$$

Cooling   Joule heat

$P_{Cool} \approx (\bar{E}/e).\ I_T - V.I_T$



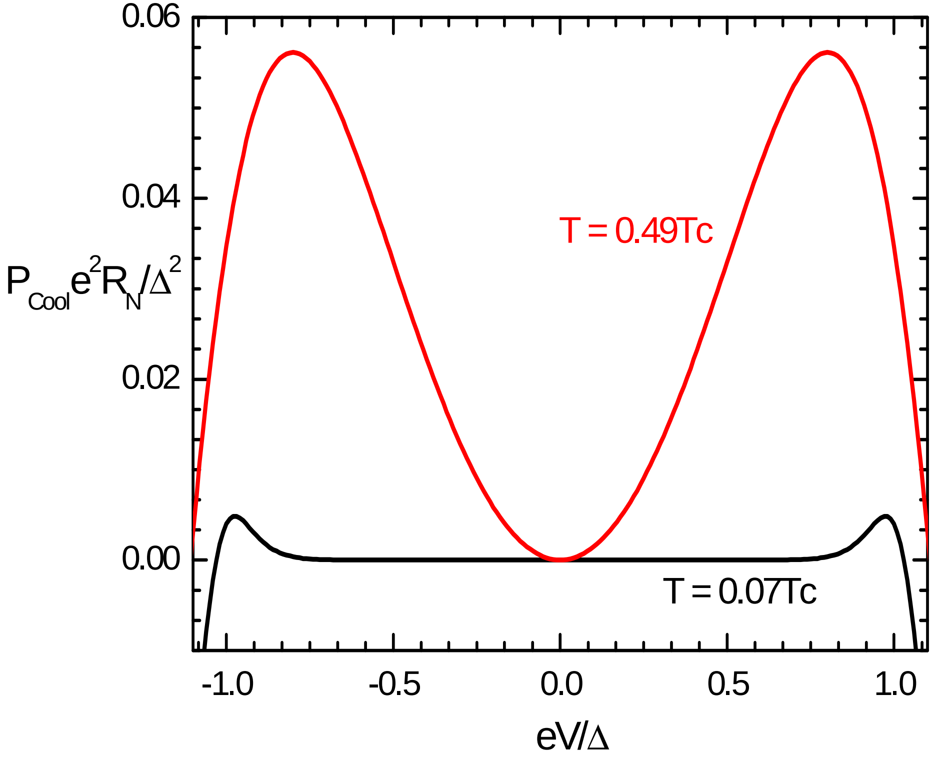
T > 0 K

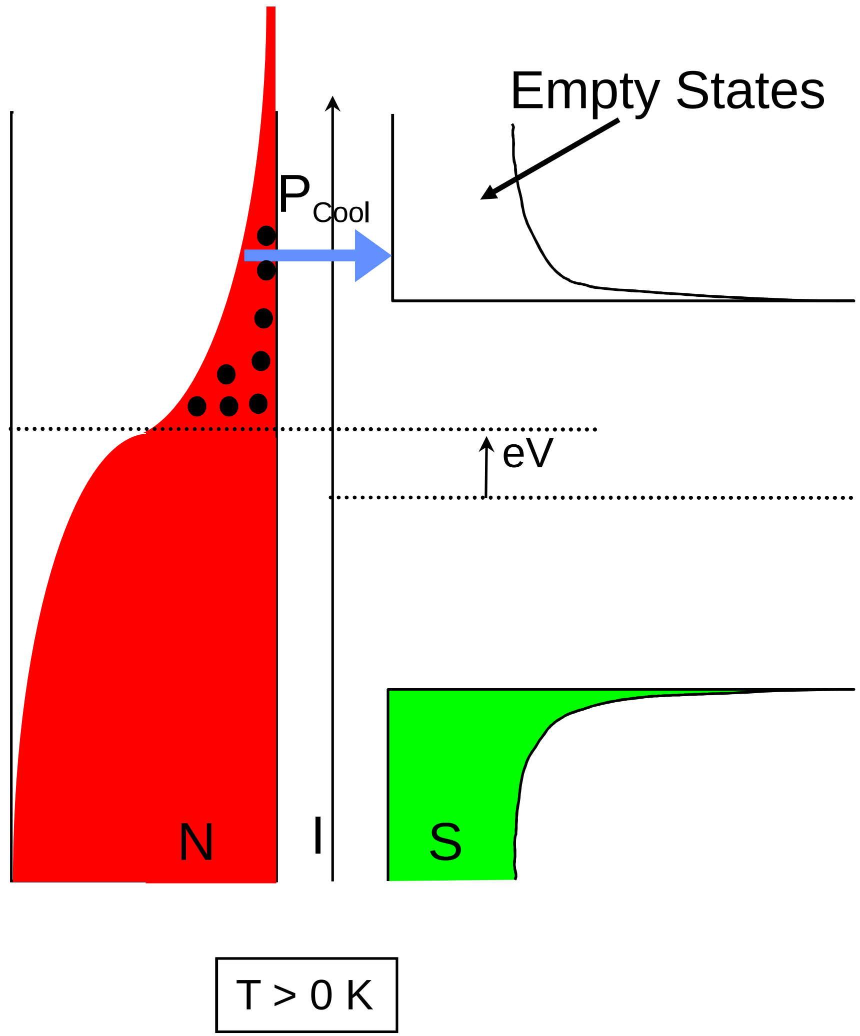
Quasiparticle tunneling in N-I-S junction

Net Cooling Power:

$$P_{Cool} = \frac{1}{e^2 R_N} \int_{-\infty}^{\infty} (E - eV) n_S(E) [f_N(E - eV) - f_S(E)] \, dE$$

$$P_{Cool} \approx (\bar{E}/e).\, I_T - V.I_T > 0$$





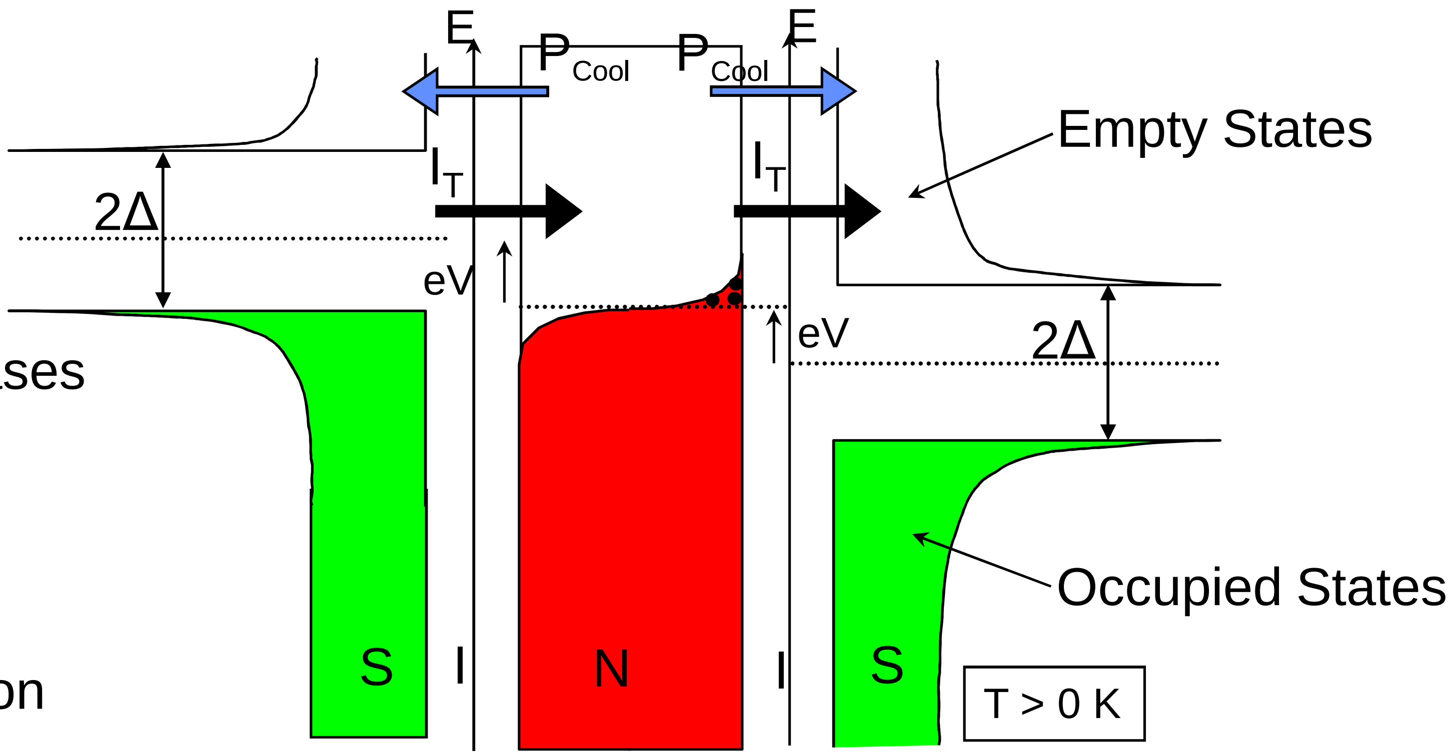
P_{Cool} is symmetric to bias.

S-I-N-I-S junction

S-I-N-I-S = 2 N-I-S junction in series

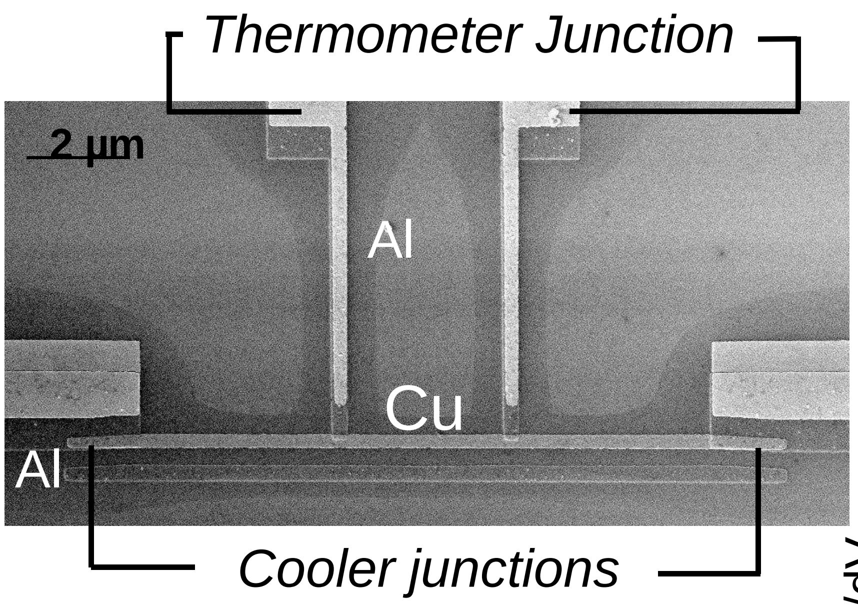
Cooling power increases by a factor of 2

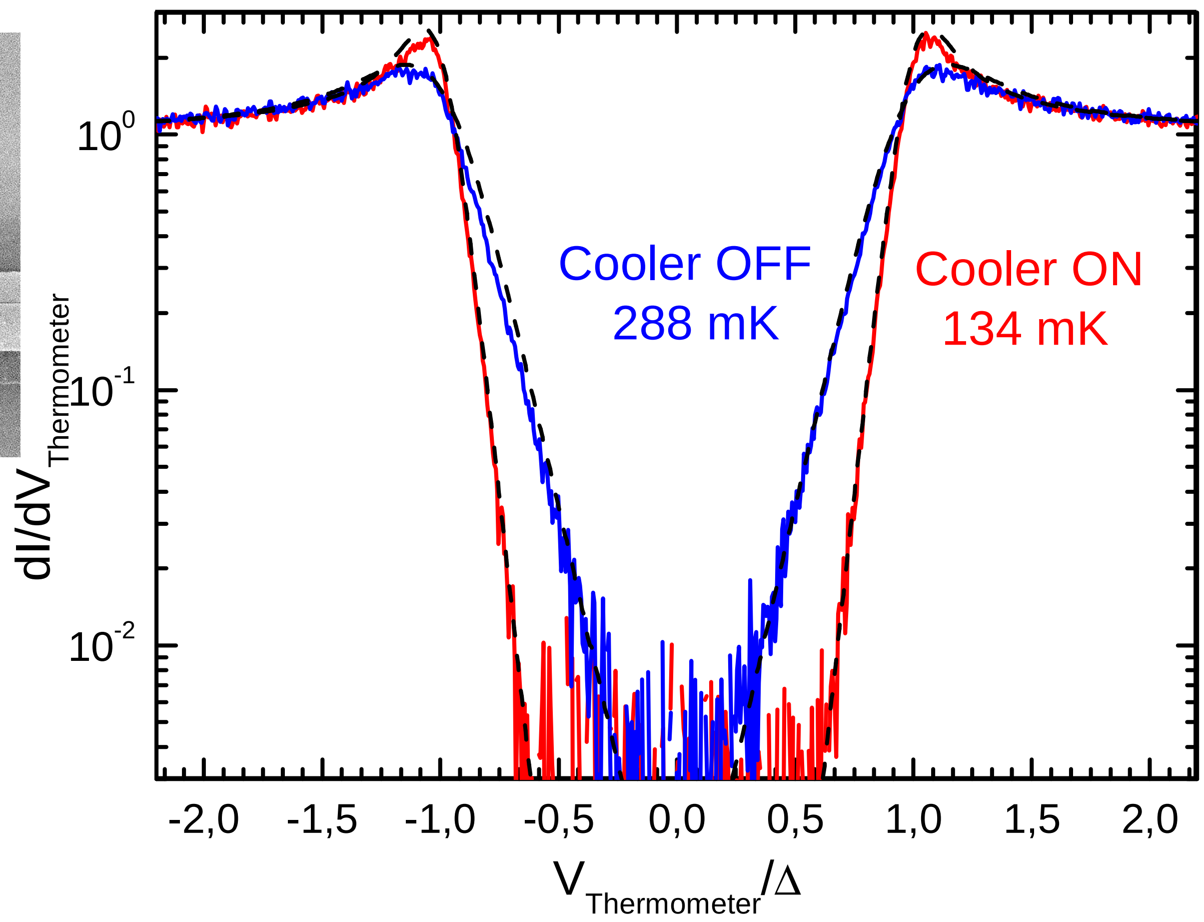
Better thermal isolation of N-island



F. Giazotto, T. T. Heikkila, A. Luukanen, A. M. Savin and J. P. Pekola, Rev. Mod. Phys. 78, 217 (2006).

Cooler with External thermometer





$$I \approx I_0 \exp\left(\frac{eV - \Delta}{k_B T_N}\right)$$

E. Favre-Nicollin et. al.

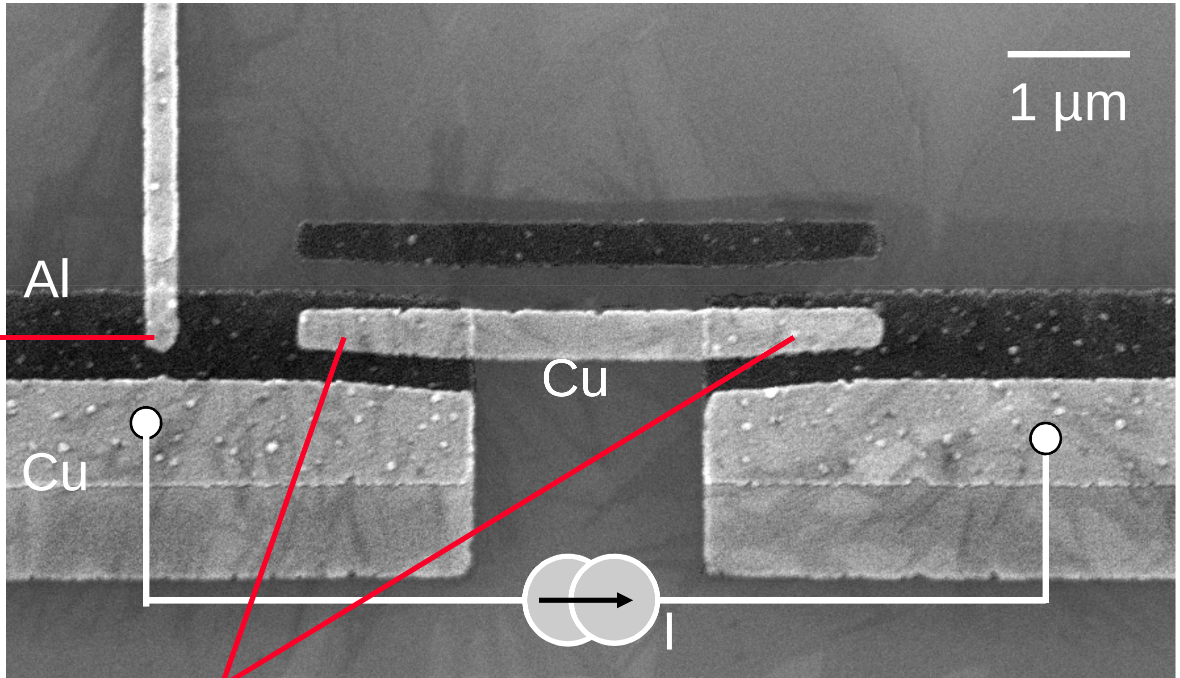
Outline

- Electronic temperature without thermometer
- Thermal model
- Andreev current contributions
- Conclusions

Quasiparticle diffusion based heating in S-I-N-I-S cooler

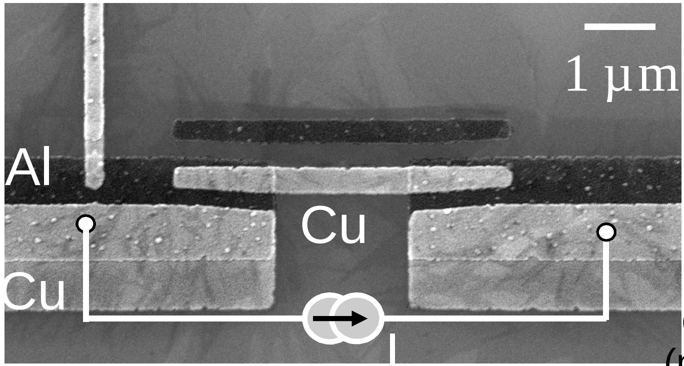
Cooler with **NO** external thermometer

Probe Junction:
N electrode is strongly thermalized, litlle cooling effect expected.

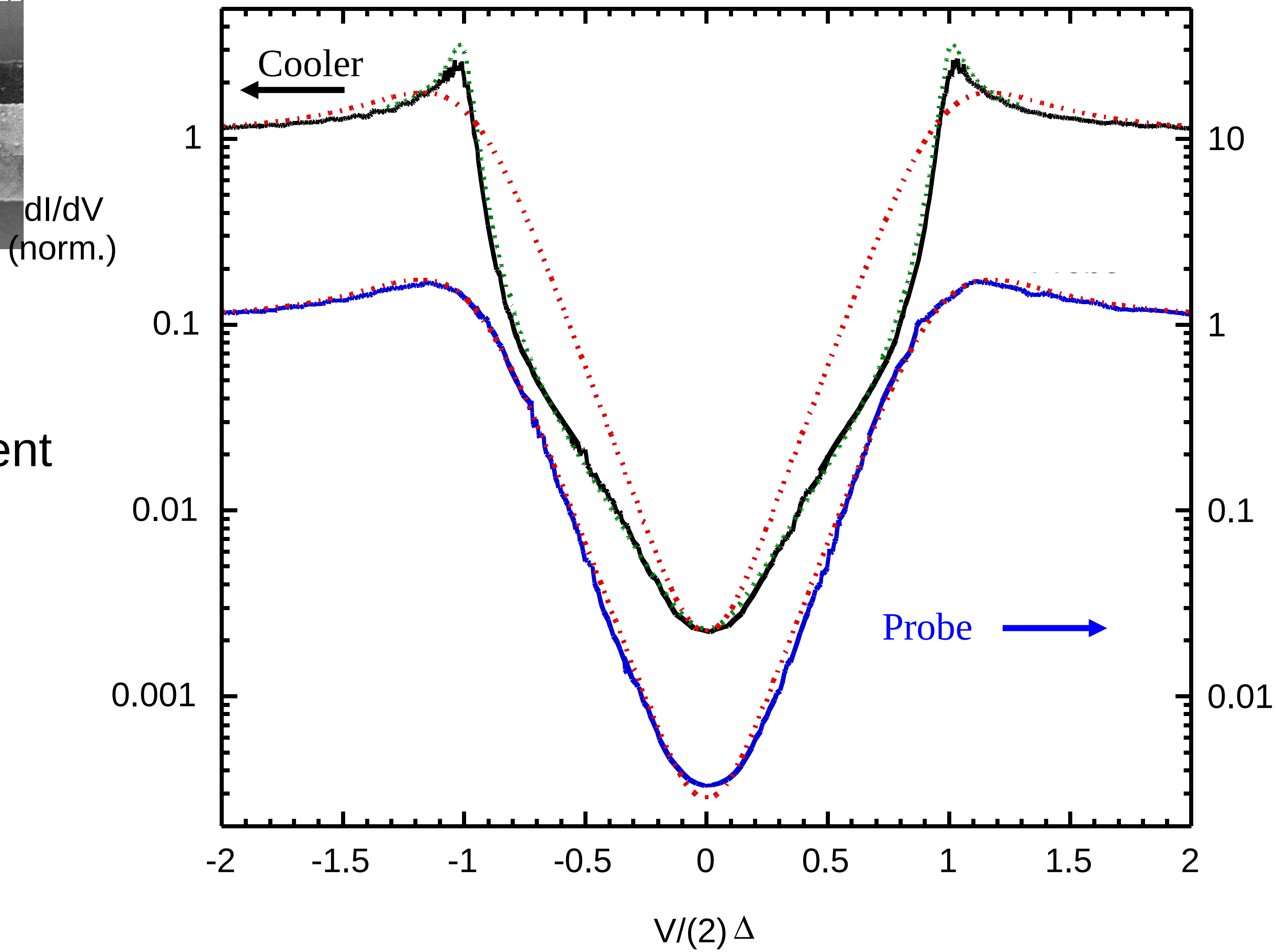


Cooler junctions: N electrode is weakly coupled to external world, strong cooling effect expected.

Cooling in S-I-N-I-S junction



T_{bath} = 304 mK



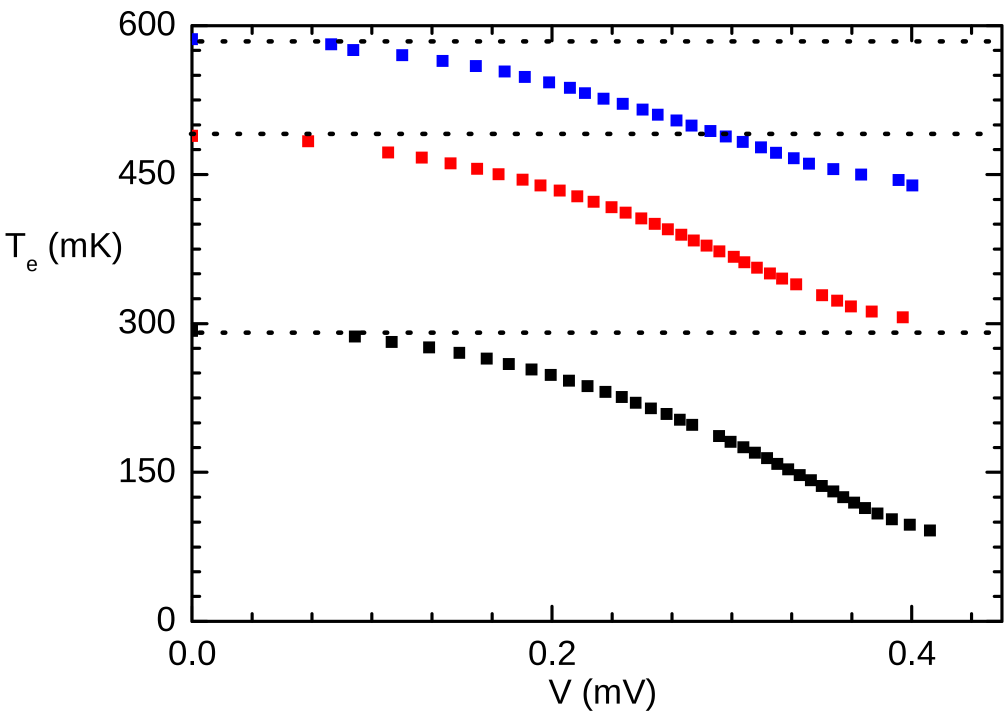
High resolution measurement (log scale)

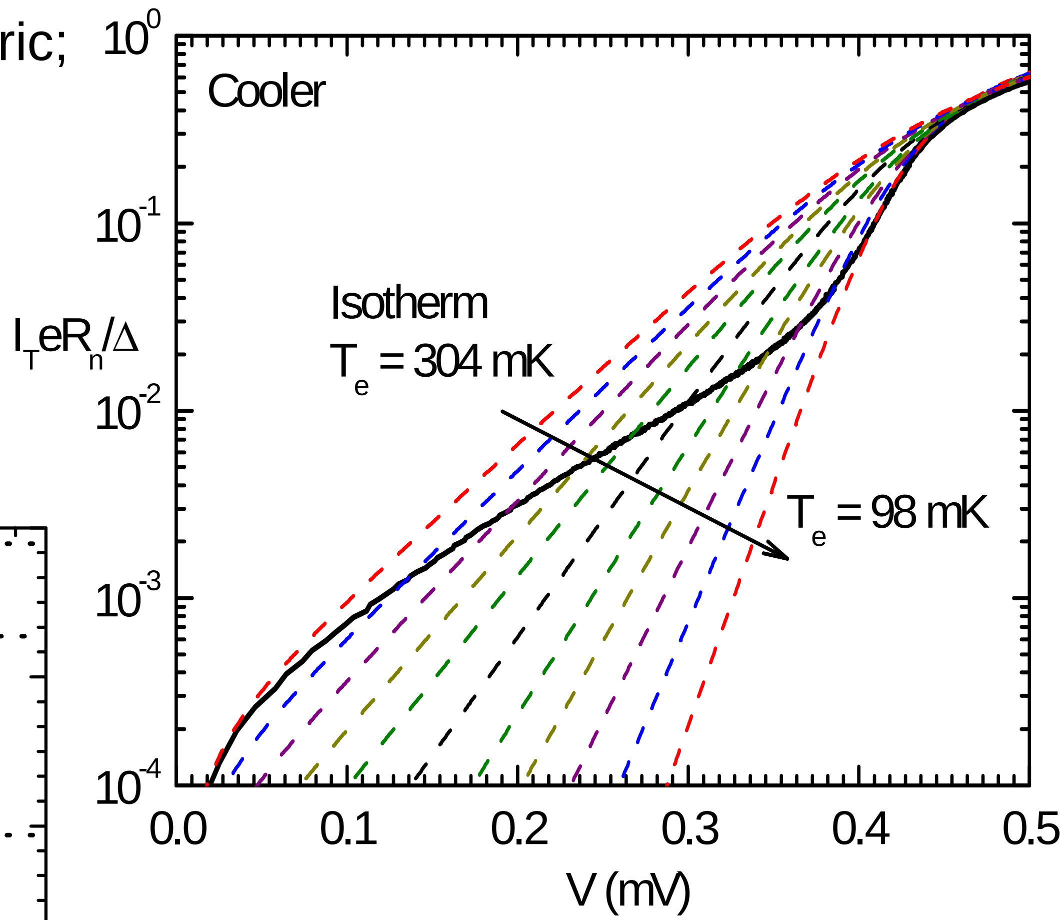
$$I \approx I_0 \exp\left(\frac{eV - \Delta}{k_B T_e}\right)$$

Probe follows isothermal prediction at T_{bath}.

Temperature determination

- two refrigerating junction are symmetric;
- N-metal is at quasi-equilibrium;
- Ideal superconductor;



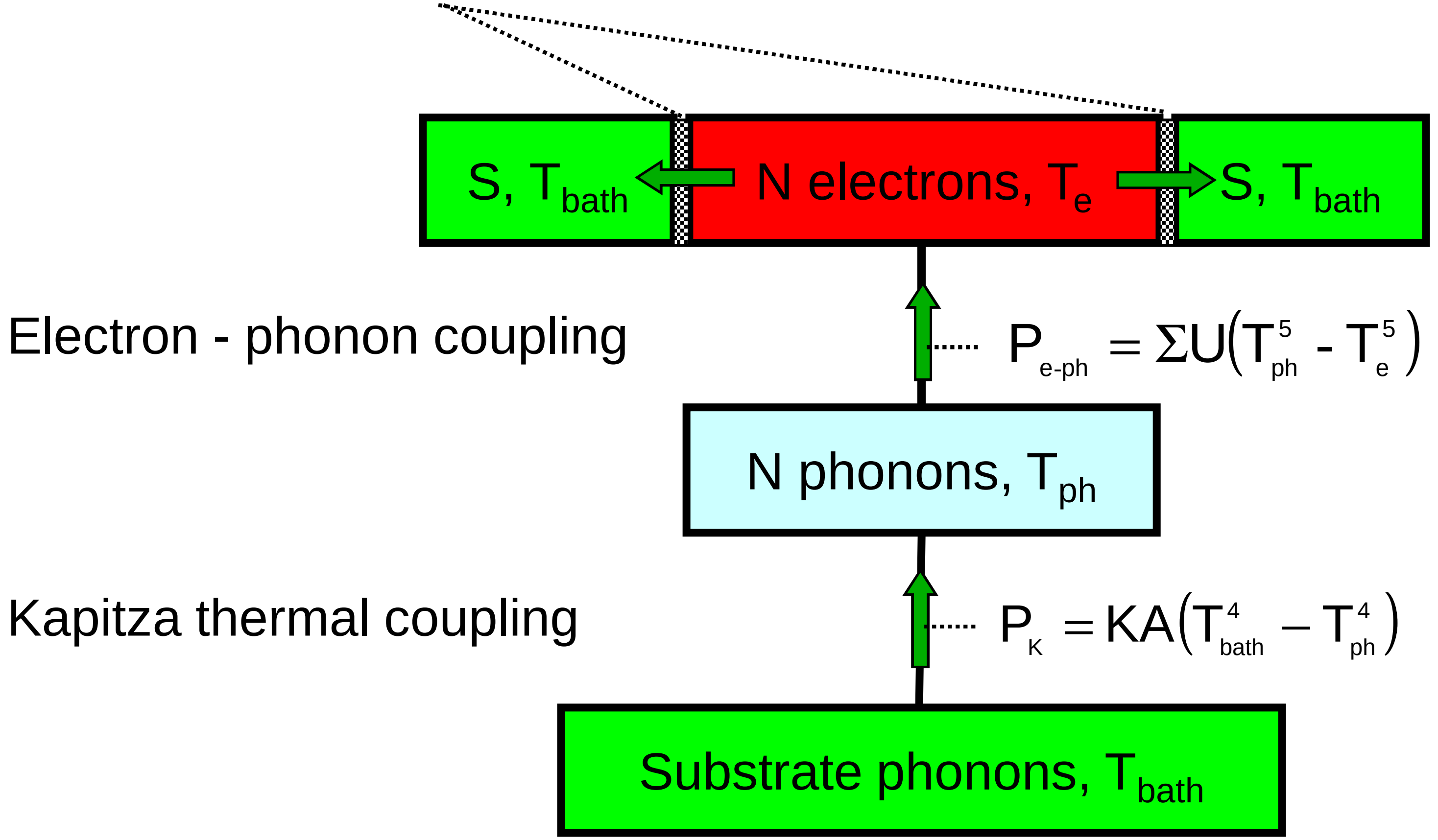


Thermal model

The thermal model

Power flow from N electrons to the S electrodes remaining at base temperature

$$P_{Cool}(V) = \frac{1}{eR_N}\int_{-\infty}^{+\infty}(E - eV)n_S(E)[f_S(E) - f_N(E + eV)]dE$$



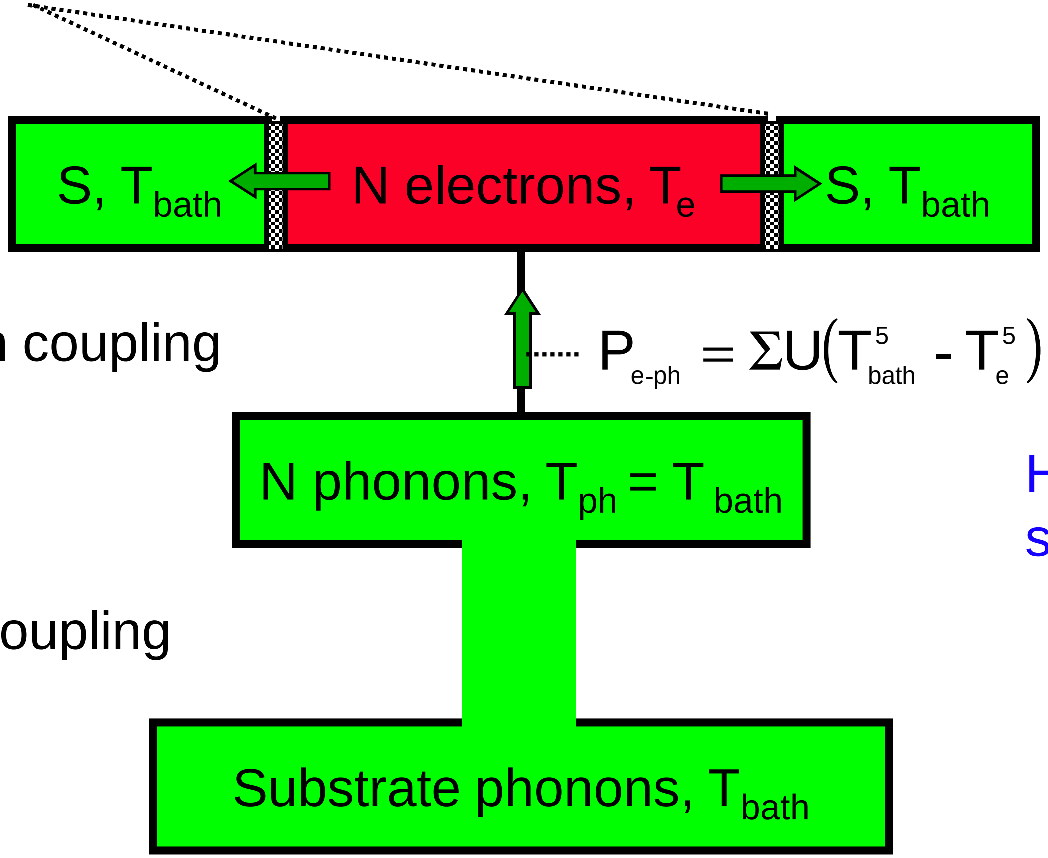
The thermal model - Hypothesis

Power flow from N electrons to the S electrodes remaining at base temperature

$$P_{Cool}(V) = \frac{1}{eR_N}\int_{-\infty}^{+\infty}(E - eV)\,n_S(E)\left[f_S(E) - f_N(E + eV)\right]dE$$

Electron - phonon coupling

Kapitza thermal coupling



Hyp.: N phonons are strongly thermalized

Hypothesis of phonon thermalized to the bath

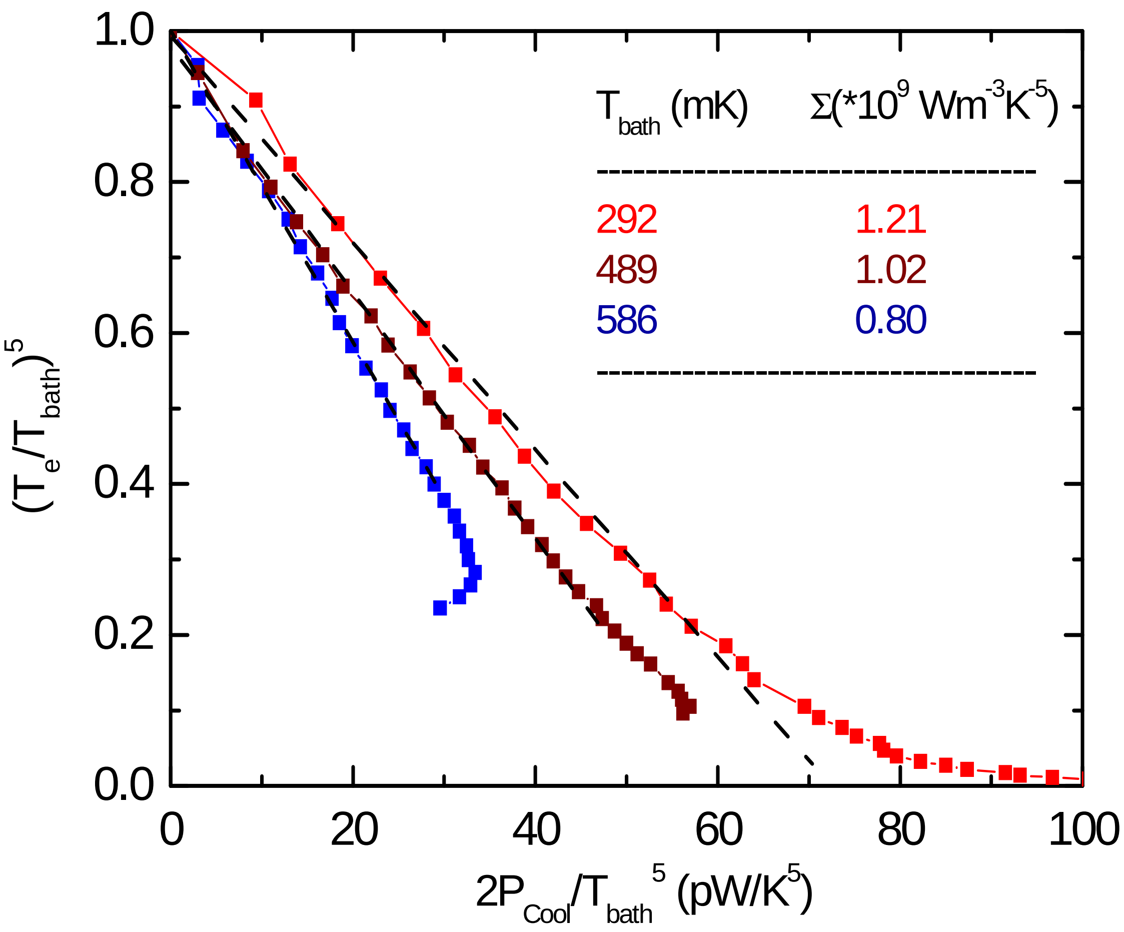
For $T_{ph} = T_{bath}$

$$2P_{Cool} = \Sigma U\left(T_e^5 - T_{bath}^5\right)$$

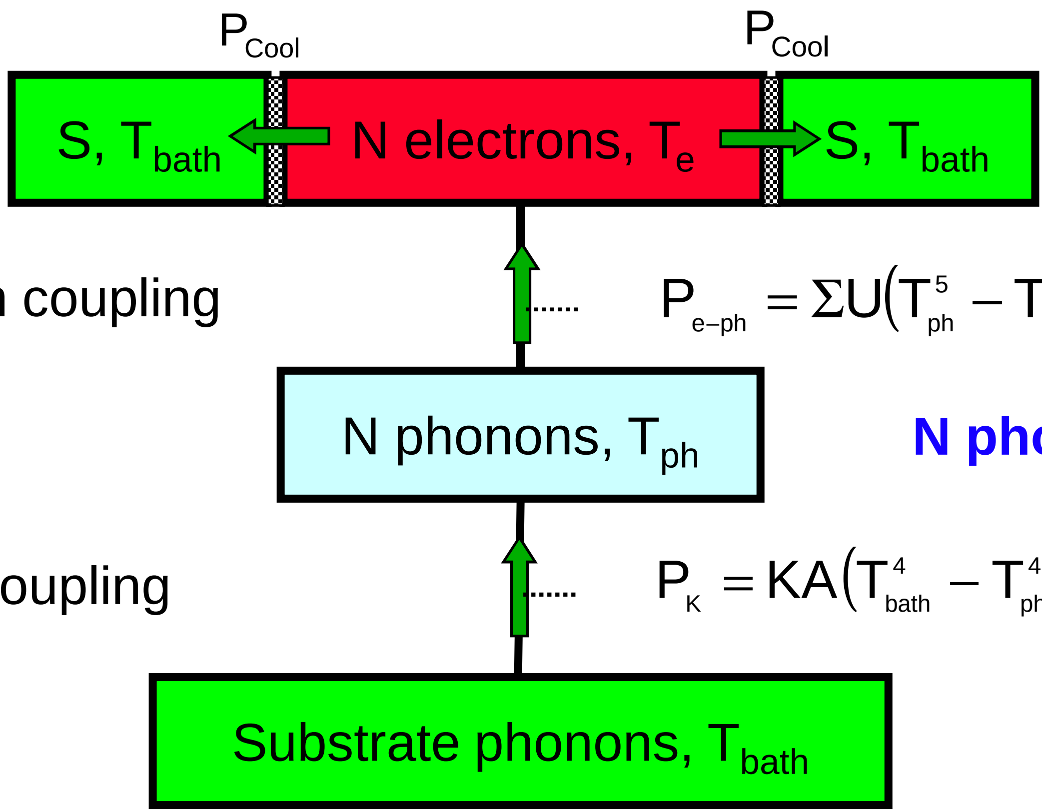
$$\left(\frac{T_e}{T_{bath}}\right)^5 = 1 - \frac{1}{\Sigma U}\frac{2P_{Cool}}{T_{bath}^5}$$

Impossible to fit data with a given Σ

Fitted Σ much smaller than expected (2 nW.µm^{-3}.K^{-5})



The thermal model



Electron - phonon coupling

$$P_{e-ph} = \Sigma U\left(T_{ph}^{5} - T_{e}^{5}\right)$$

N phonons can be cooled

Kapitza thermal coupling

$$P_{K} = KA\left(T_{bath}^{4} - T_{ph}^{4}\right)$$

Phonon cooling

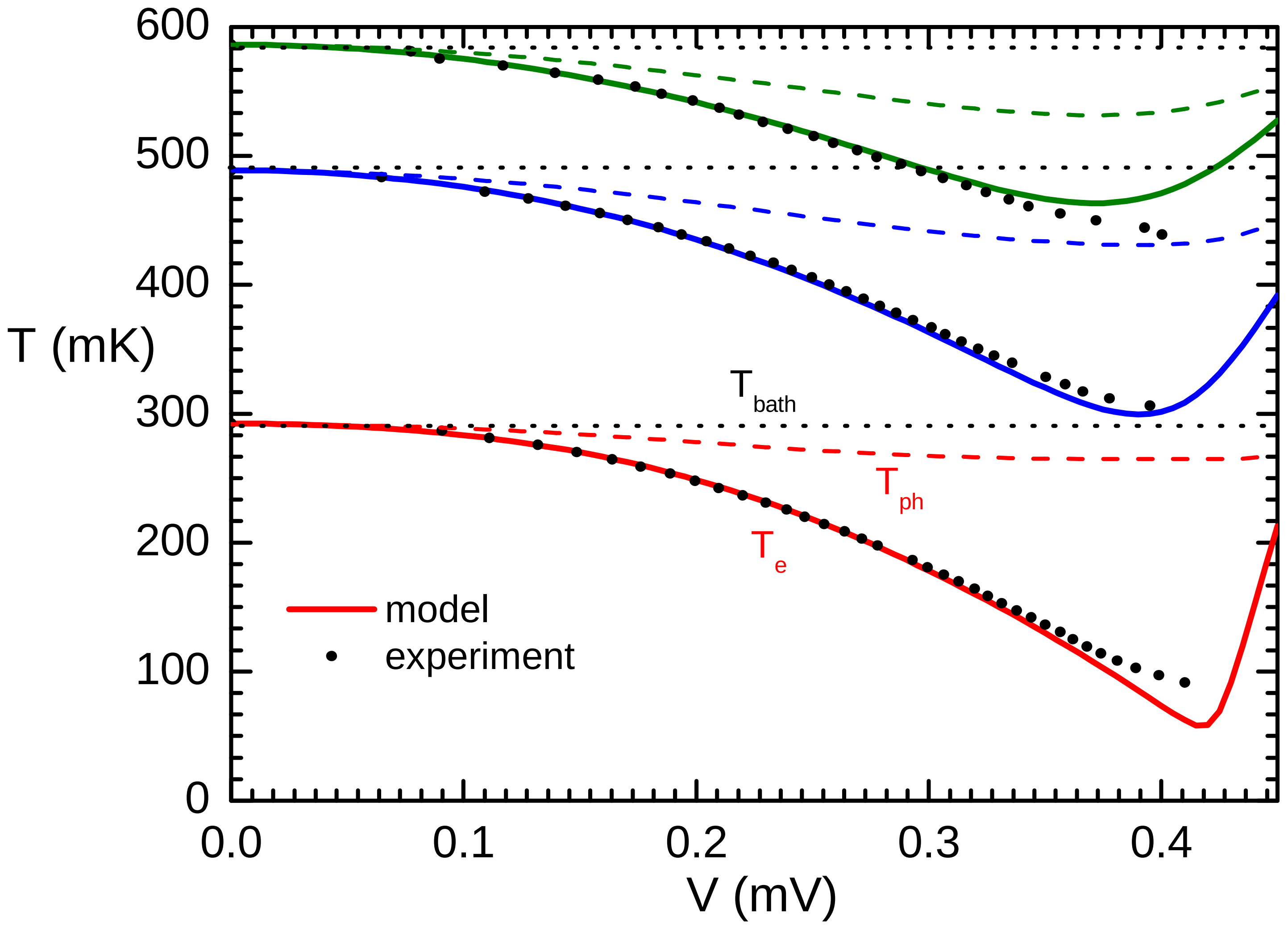
Two free fit parameters:

$\Sigma = 2\ nW.\mu m^{-3}.K^{-5}$

$K = 55\ W.m^{-2}.K^{-4}$

Kapitza coupling smaller by a factor of 3 than bulk.

Phonon cooling dominant at high temperature.



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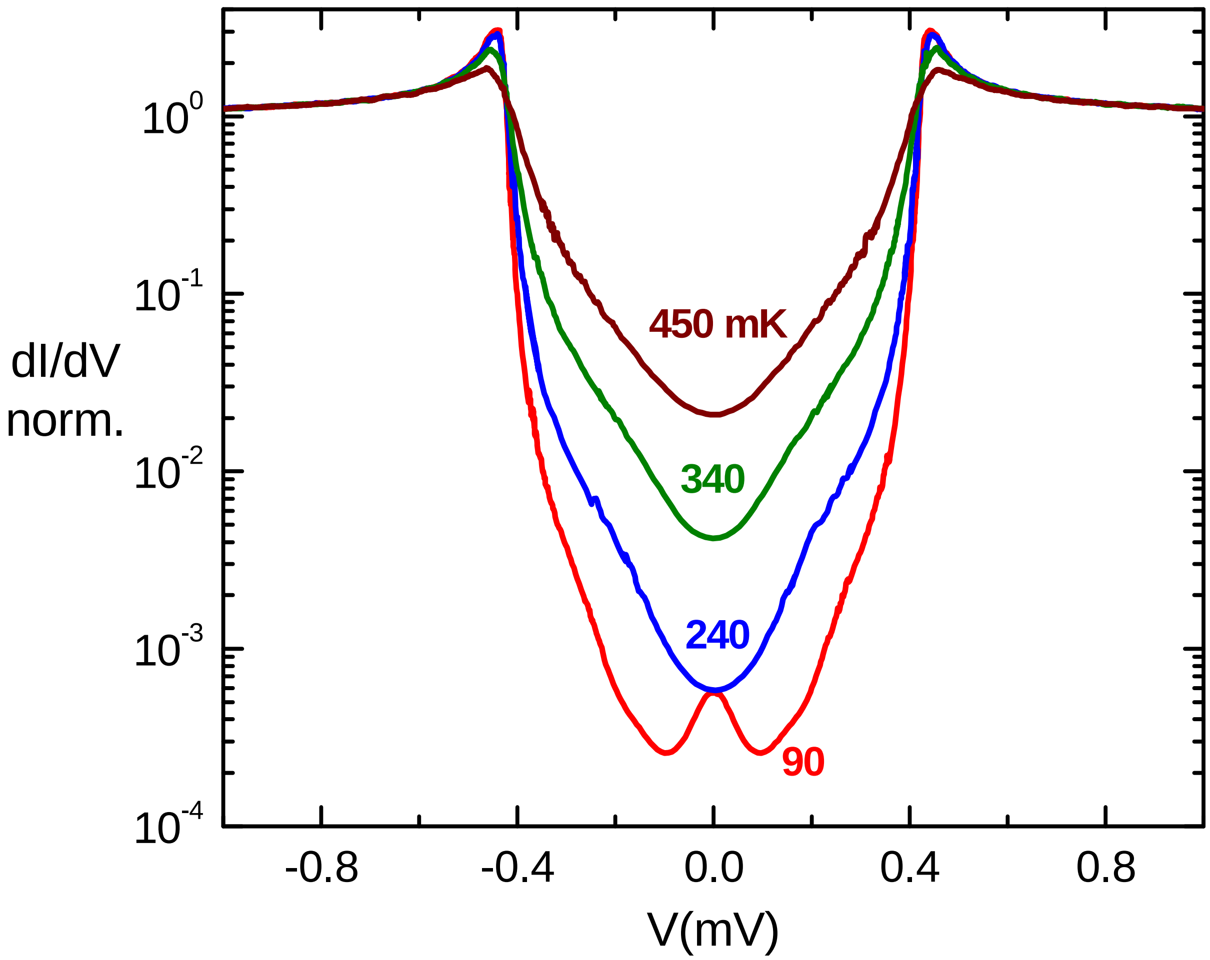
What now?

- How much can we lower the electronic temperature ?
- Can we reach below 10mK starting with a dilution temperature ?
- What about the other contribution like Andreev Current etc. ?
- Is a quantitative analysis possible ?

Andreev current-induced dissipation

Experiment at a very low temperature



Zero-bias anomaly.

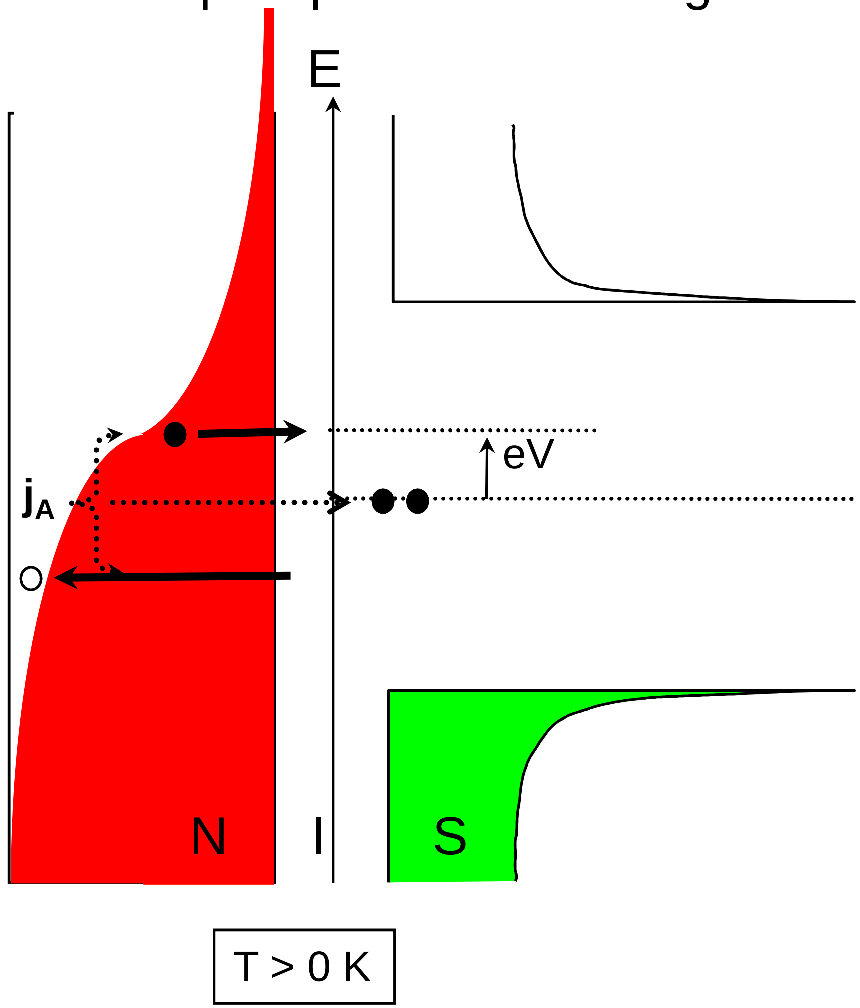
Not a linear leakage.

Cannot be fitted with a smeared D.O.S or a non-equilibrium distribution in N.

Likely two electron tunneling process.

Andreev reflection

E < Δ : No quasiparticle tunneling



Transmission probability
proportional: t^2

For tunnel barrier:
t is very small

Andreev reflection probability
vanishes for a tunnel barrier

A. F. Andreev, Zh. Eksp. Teor. Fiz. ’64 , D. Saint-James, J. Phys. (Paris) ‘64

Confinement-enhanced of the Andreev current

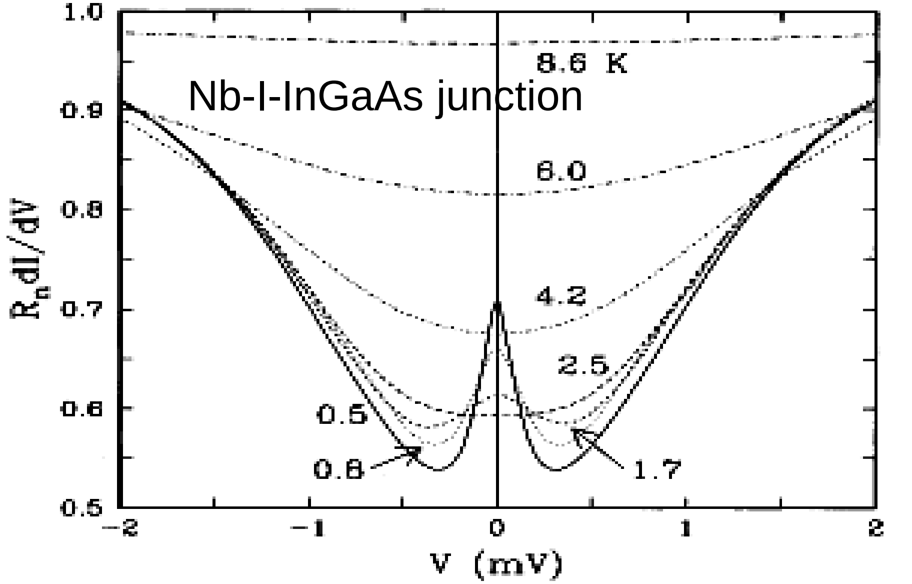


FIG. 2. Normalized conductance-voltage characteristics at temperatures of 8.6, 6.0, 4.2, 2.5, 1.7, 0.8, and 0.5 K and zero magnetic field for a 2.5×10^{19}-cm^{-3} device (R_n =0.27 Ω).

Kastalsky et al PRL 91

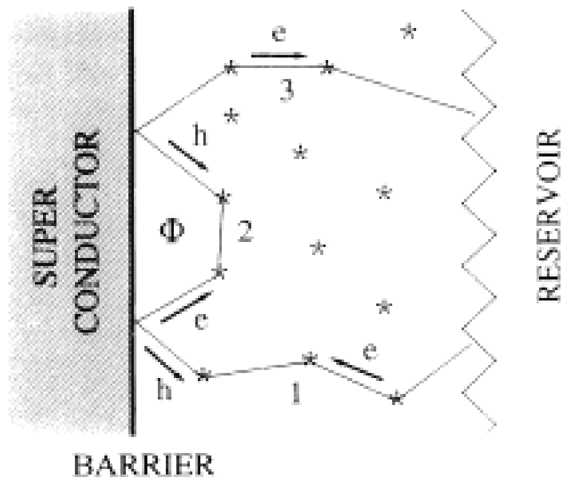


FIG. 1. Geometry of the model, consisting of three sections (see text).

van Wees-Klapwijk et al PRL 92

Confinement of electron by disorder + Quantum coherence

Enables coherent addition of 2e tunneling amplitudes

= Enhances sub gap conductivity

$$G_A = G_N^2 . R_{diff}$$

Andreev current in disordered N-I-S junction

Hekking and Nazarov model : Tunnel barrier in between N and S.
Sub-gap conductivity is more sensitive to disorder.

$$I_A(V) = \int_{-\infty}^{\infty} I(E)\,\{f_N(E/2 - eV) - f_N(E/2 + eV)\}\,dE$$

where I(E) is the spectral current

$$I(E) = \frac{hG_n^2}{16\pi S e^3 \nu_0} \int_{\text{barrier}} \{P_E(r) + P_{-E}(r)\}\,d^2r$$

where $P_E(r)$ is the cooperon.

Length scale: Phase coherence length, bias or temperature cut off.

Hekking et al PRL 93 and PRB 94, Pothier et al PRL 94

Isotherm of Andreev and Quasiparticle current

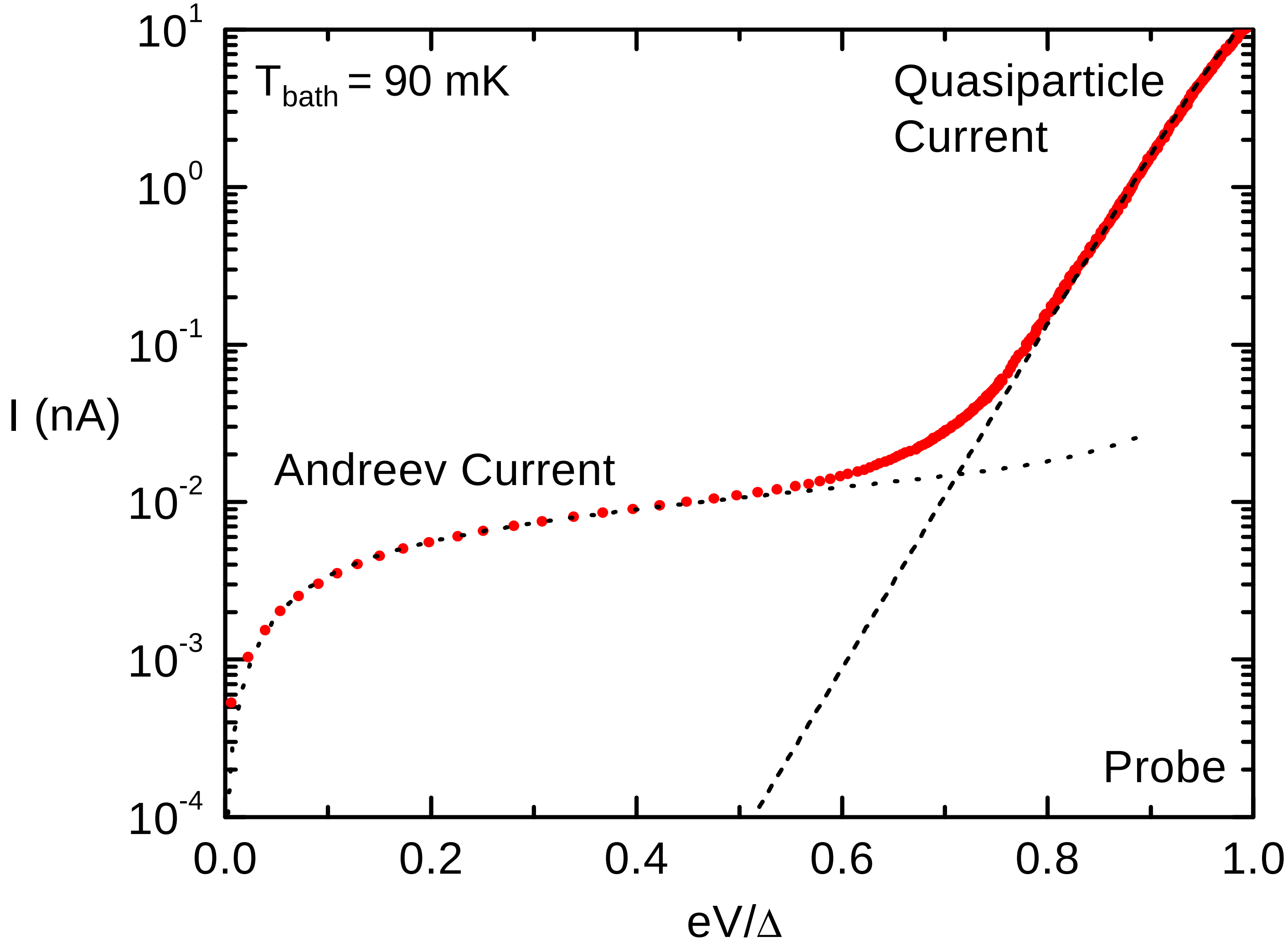
Total current =
Andreev current +
Quasiparticle current

$I_{Probe} = I_A + I_T$

Fit parameters :

$L_\varphi = 1.5\ \mu m$
Scaling factor 1.4

Good fit for the probe.



Quasiparticle cooling fit

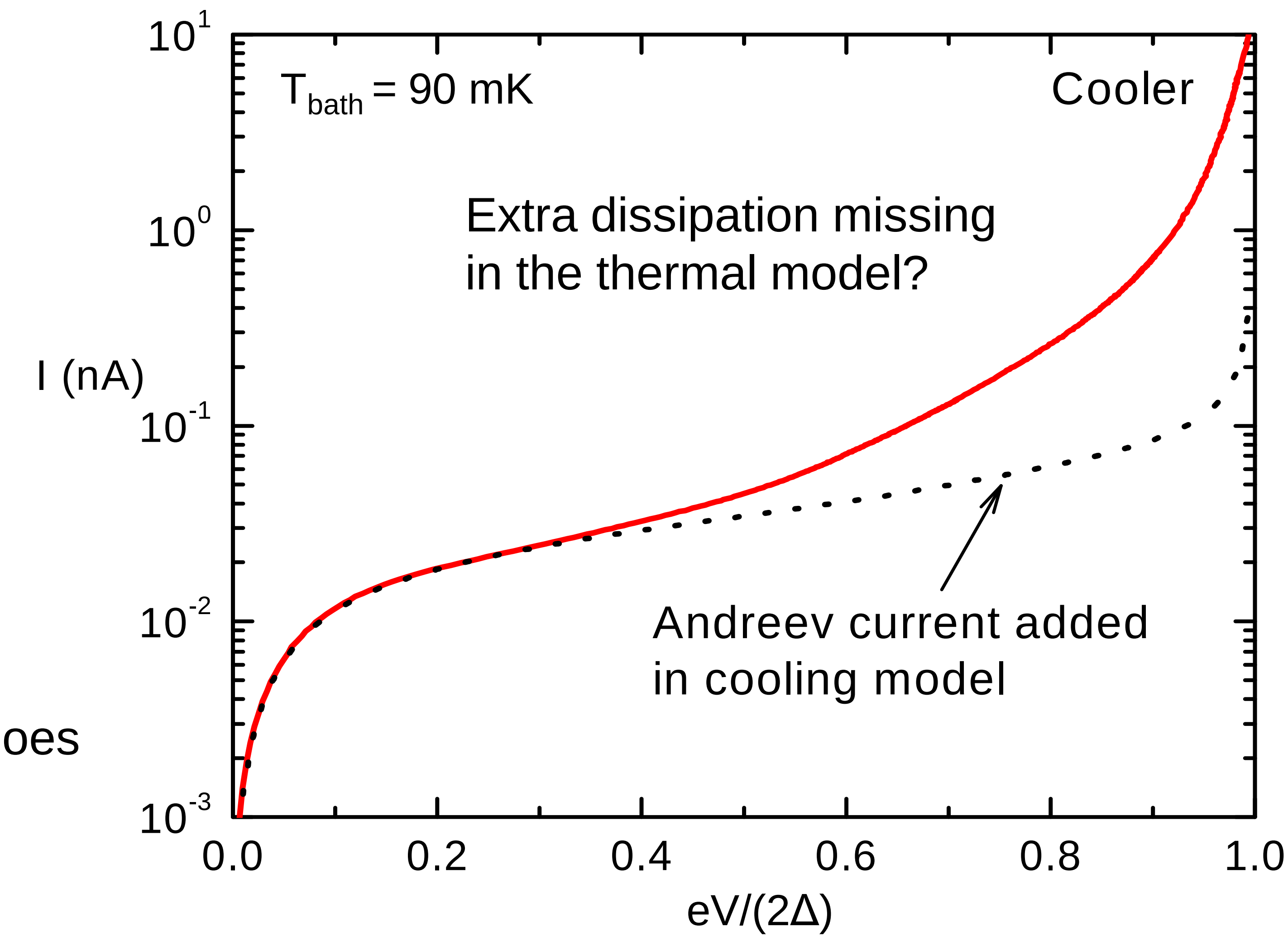
Total current =
Andreev current +
Quasiparticle current

$I_{Cooler} = I_A + I_T$

Fit parameters :

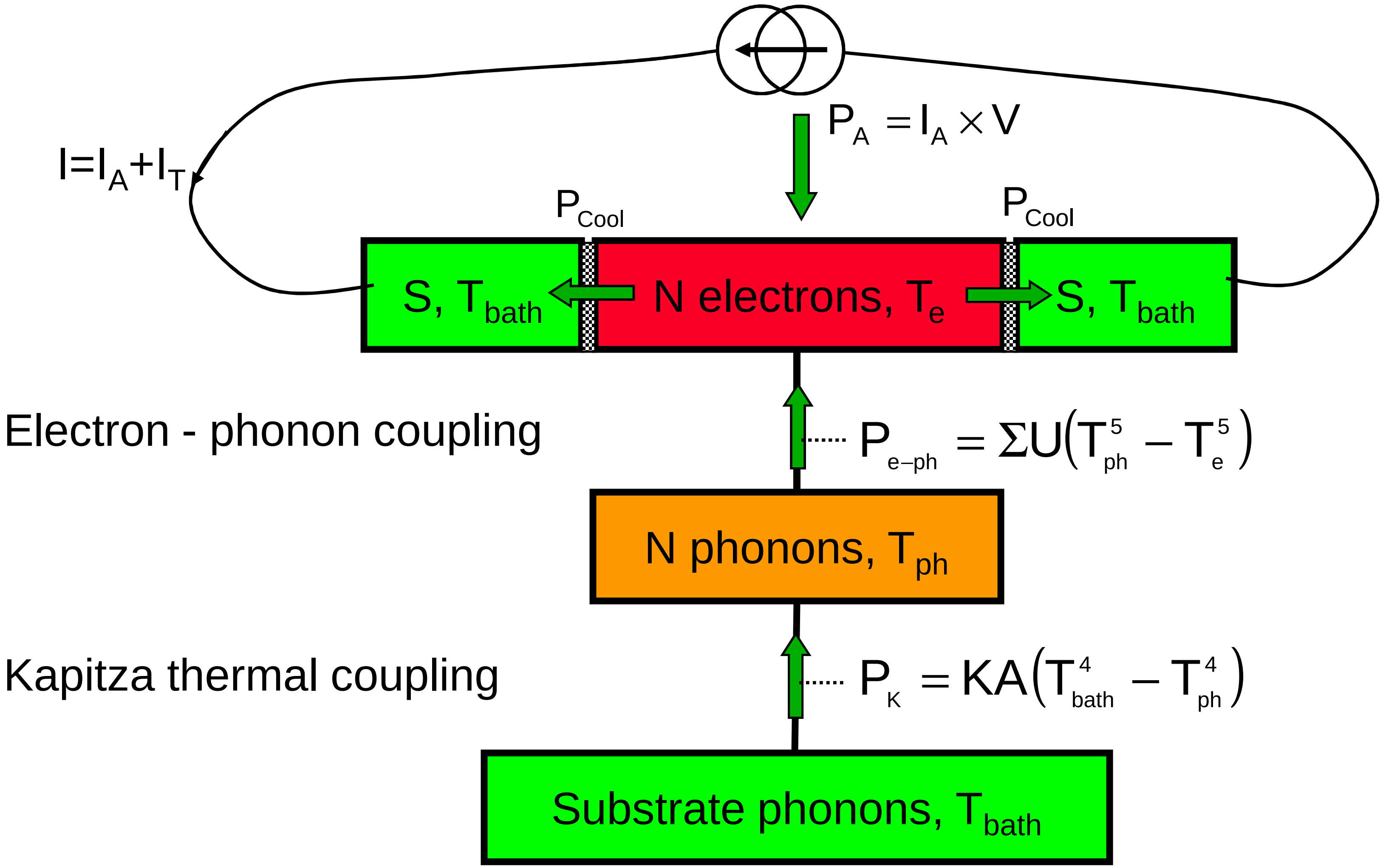
$L_\varphi = 1.5\ \mu m$
Scaling factor 0.5
$K = 120\ W.m^{-2}.K^{-4}$

Quasiparticle cooling does not fit experiment.

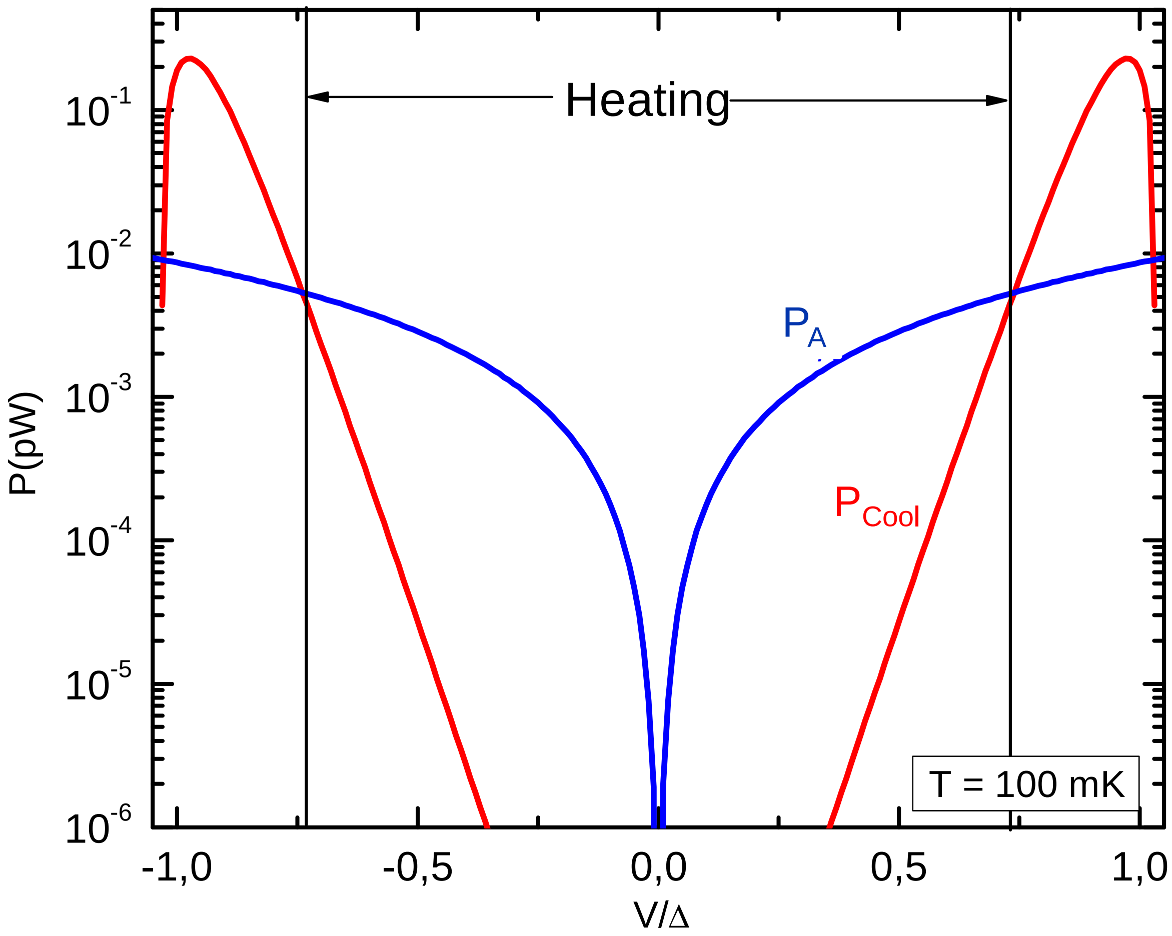


Thermal model with Andreev heat

The current source work results in a Joule power in the normal metal



Andreev heat subjugate Quasiparticle cooling



Low bias:

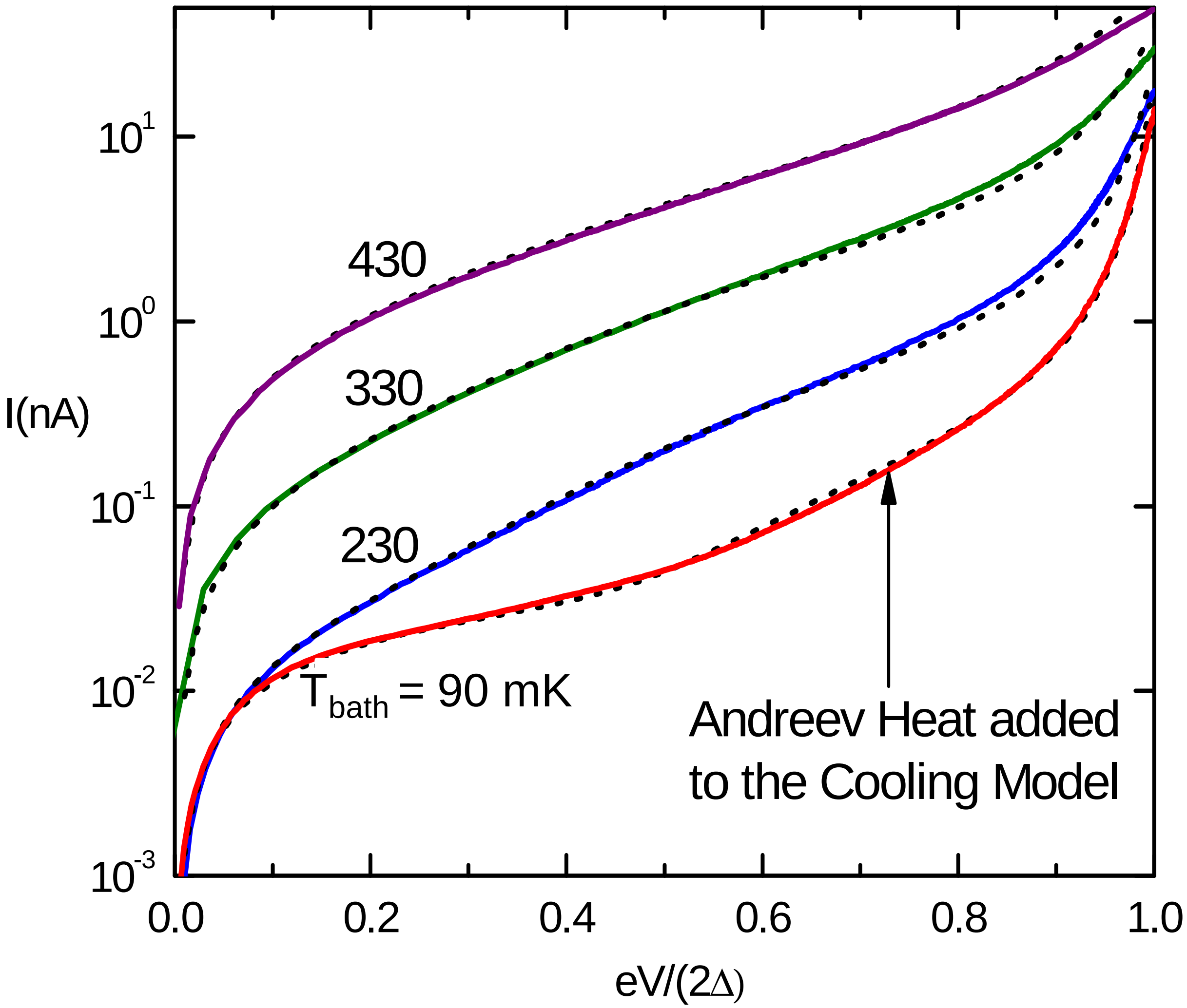
Andreev heating dominates

Near gap bias:

Quasiparticle cooling again prevails.

Net cooling power = $P_{Cool} - P_A$

Experiment Vs Model



Fit parameters :

L_φ = 1.5 µm

Scaling factor 0.5

K = 120 $W.m^{-2}.K^{-4}$

Fits experiment from 430 mK to 90 mK.

Andreev reflection contributes both to charge and heat current.

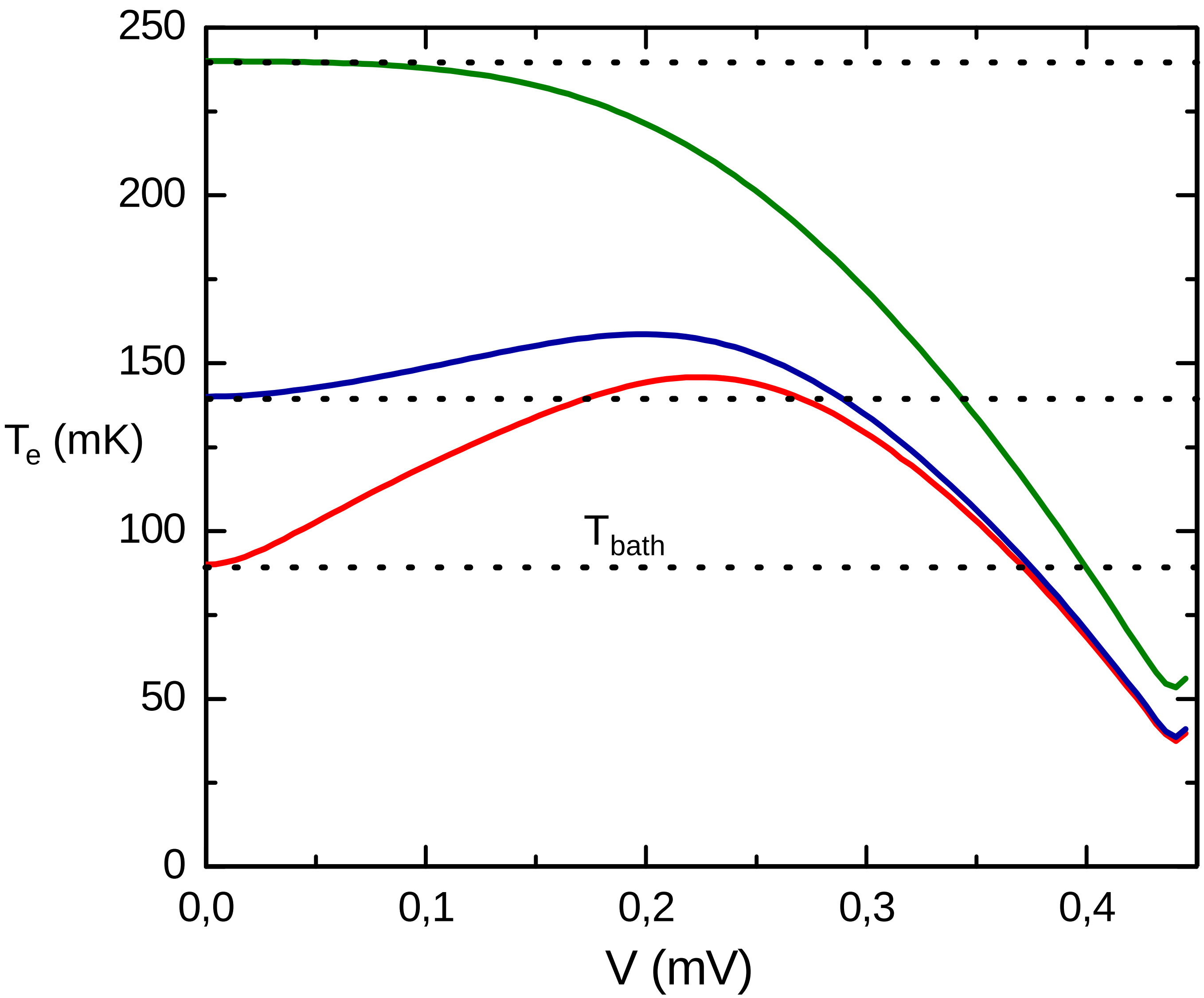
Heating at low temperature

Andreev reflection gives:

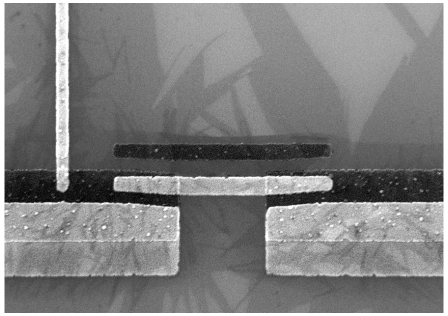
- a small charge current

- a significant heat current

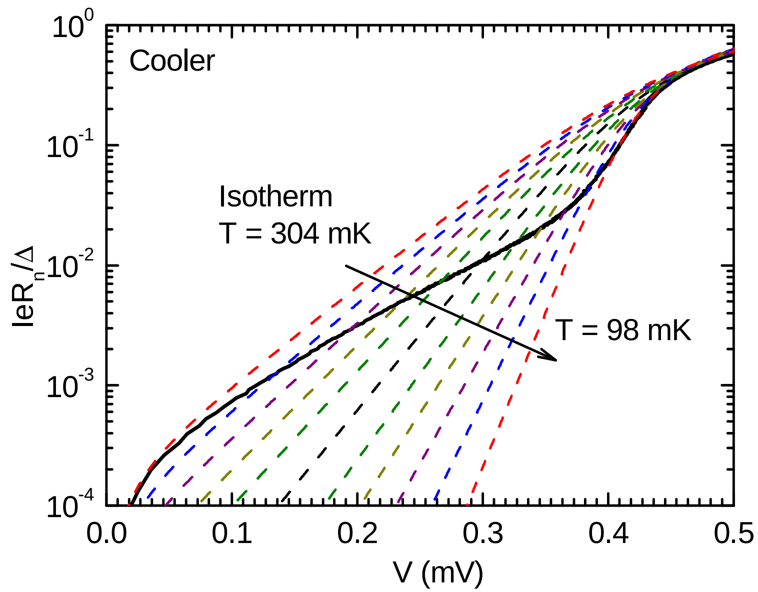
Andreev reflection-induced heating is fully efficient.



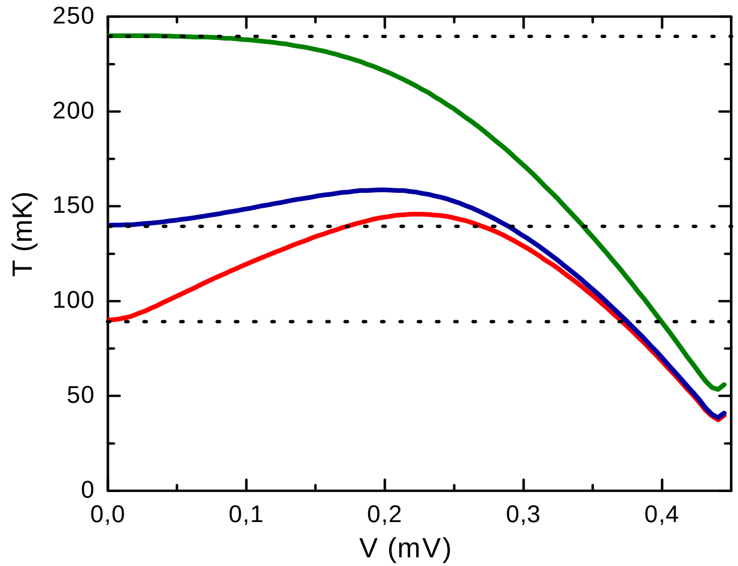
Sukumar Rajauria, P. Gandit, T. Fournier, F. W. J. Hekking, B. Pannetier and H. Courtois, PRL (2008)

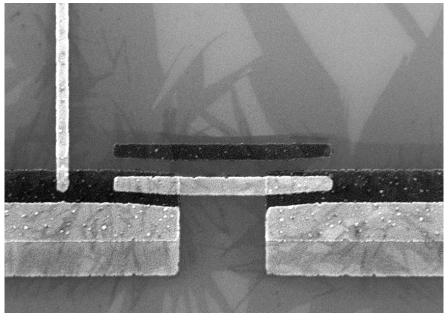


Conclusions

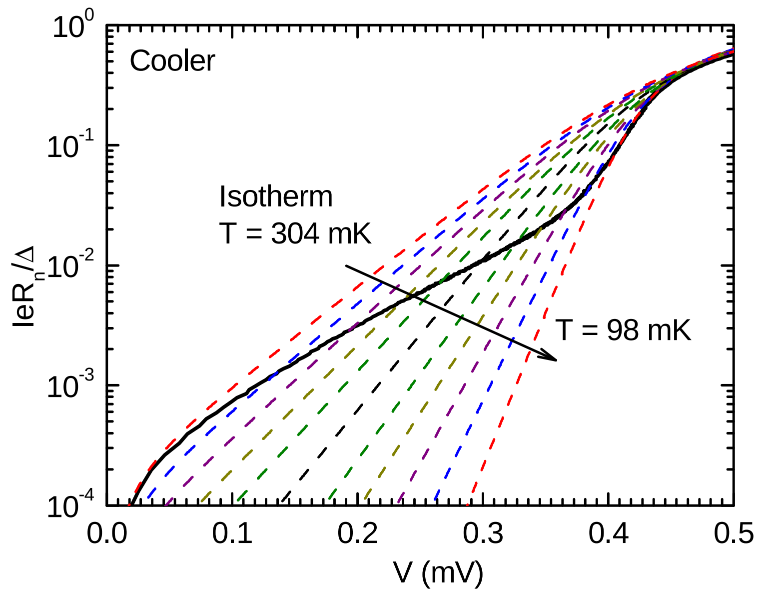


- Direct determination of the electronic temperature in the N-metal
- Electron and Phonon cooling in N-I-S nano-junctions
- Andreev current heating at very low temperature





Thanks to

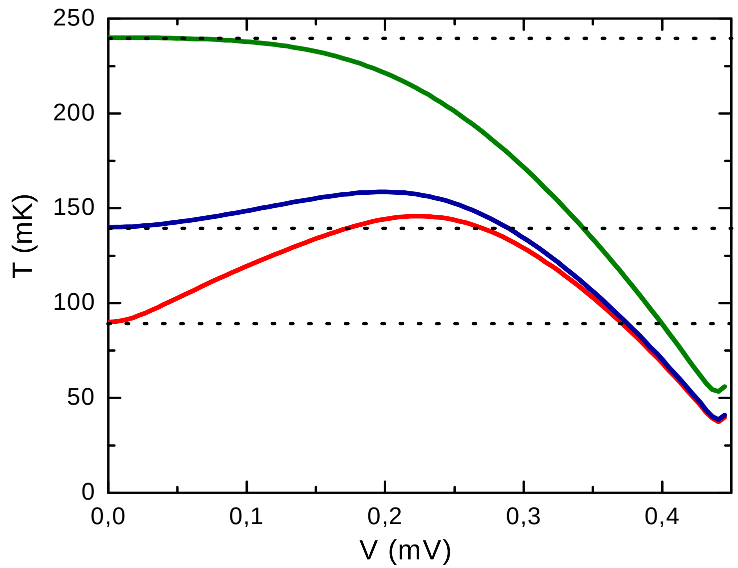


Thesis advisor :

B. Pannetier and H. Courtois.

Experiment

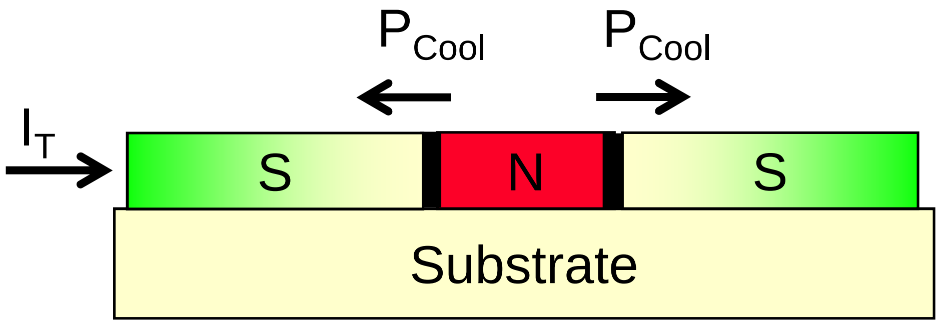
- T. Fournier, T. Crozes, B. Fernandez and C. Lemonias.
- P. Brosse for Cryogenics.
- Electronics team.
- Ph. Gandit for measurement in dilution refrigerator.

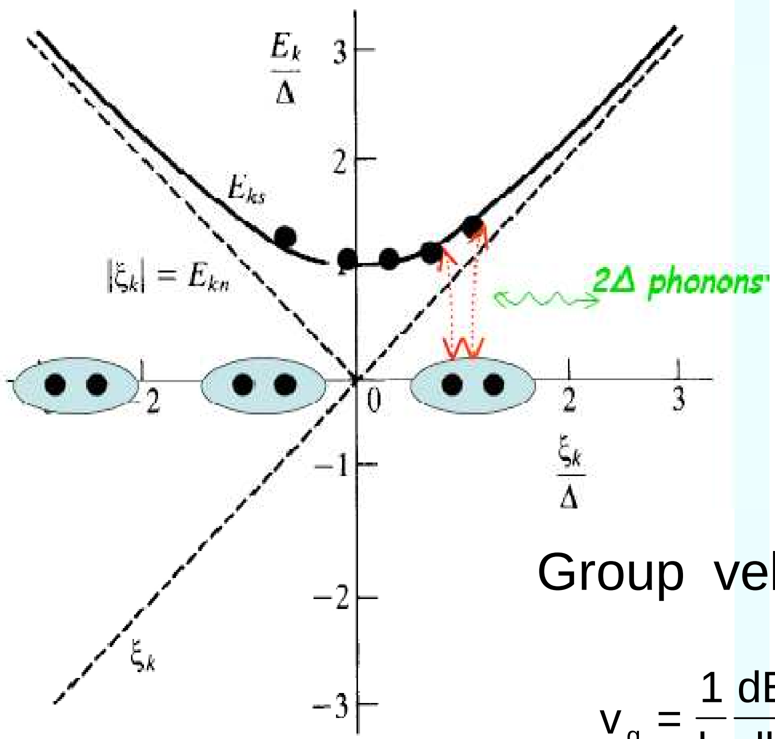


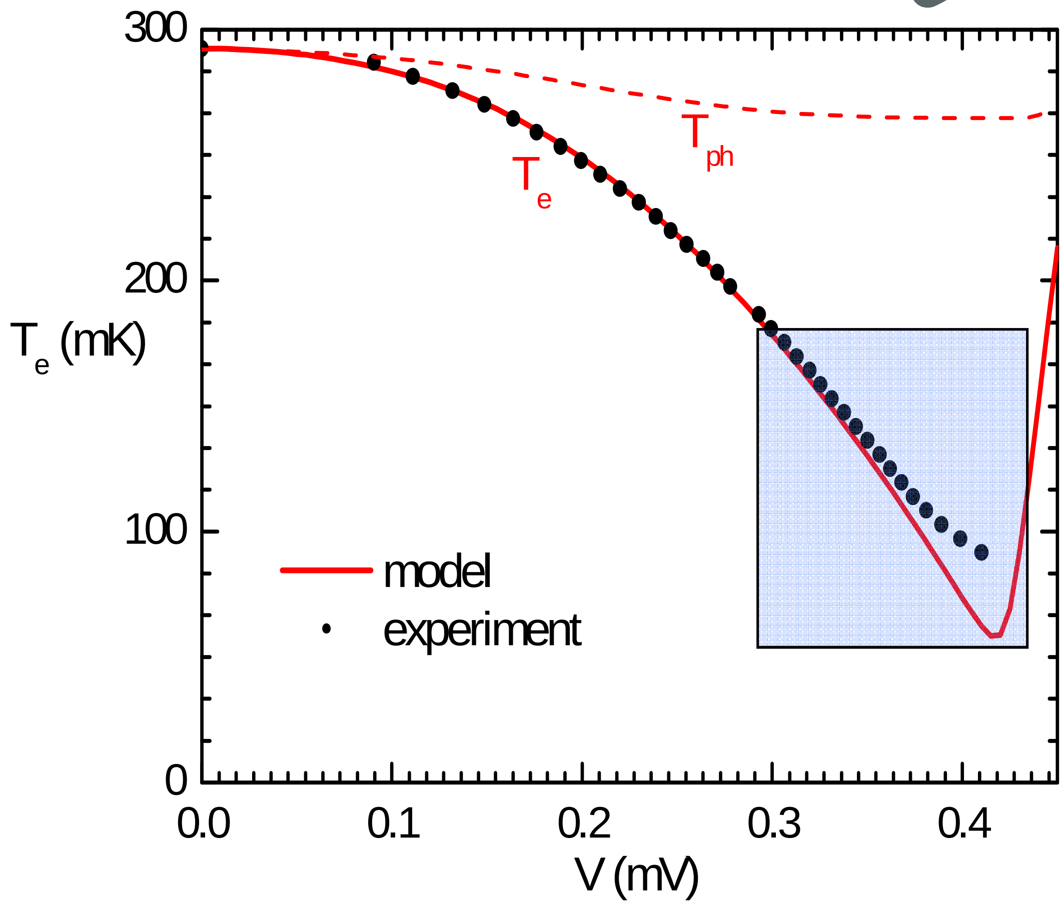
Theory

F. Hekking, A. Vasenko and M. Houzet.

Perspective (2) – Efficient Traps



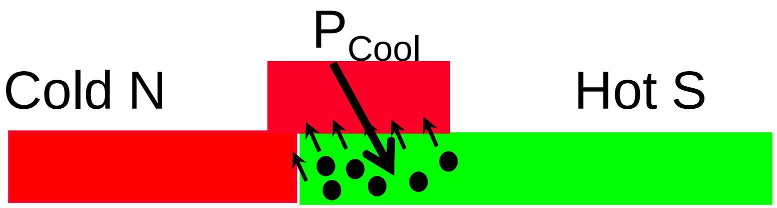




Group velocity of qp (at Δ)

$$v_g = \frac{1}{\hbar}\frac{dE}{dk} \longrightarrow 0$$

Perspective (2) – Efficient Traps



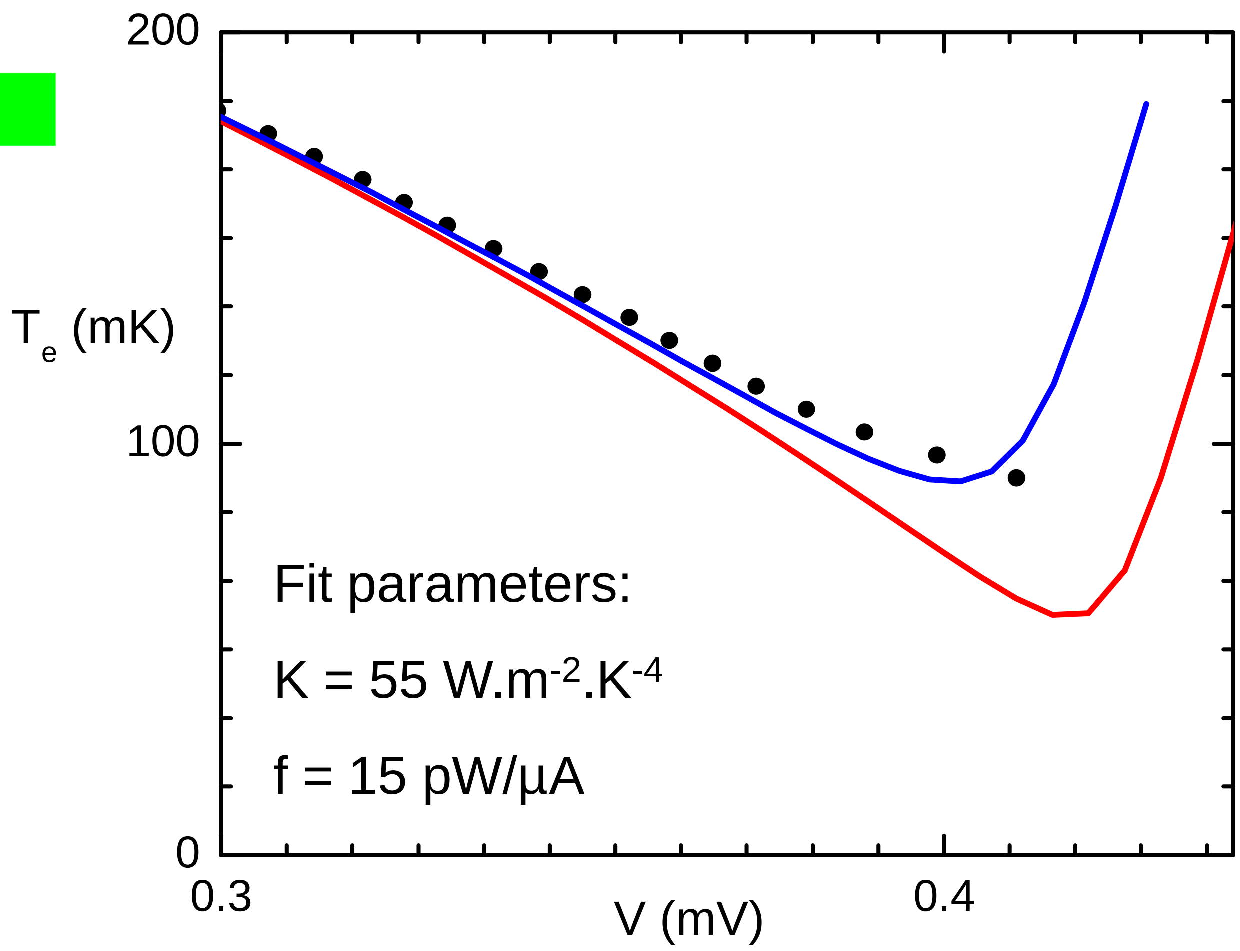
Heat returns in N due to backtunneling of quasiparticles

$\sim N_{qp} - N_{qp0}$

Net Cooling power:

$P_{Cool} - f.I_T$

Quasiparticles accumulation contribute to return power.



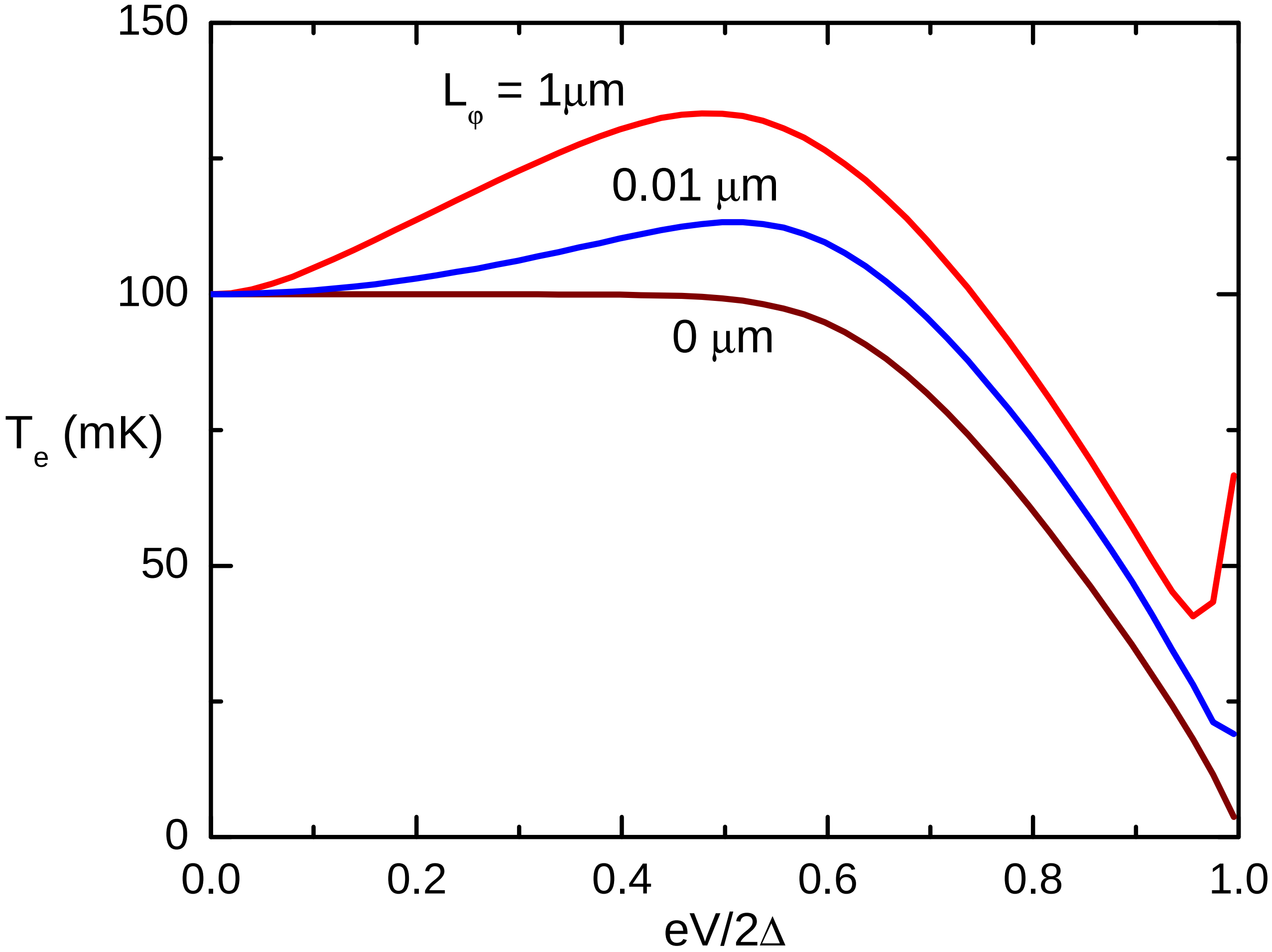
Sukumar Rajauria, H. Courtois and B. Pannetier, submitted (2009)

Perspective (3) – Reduce Andreev heat

- N-metal with small L_φ: AuPd

- Ferromagnetic material

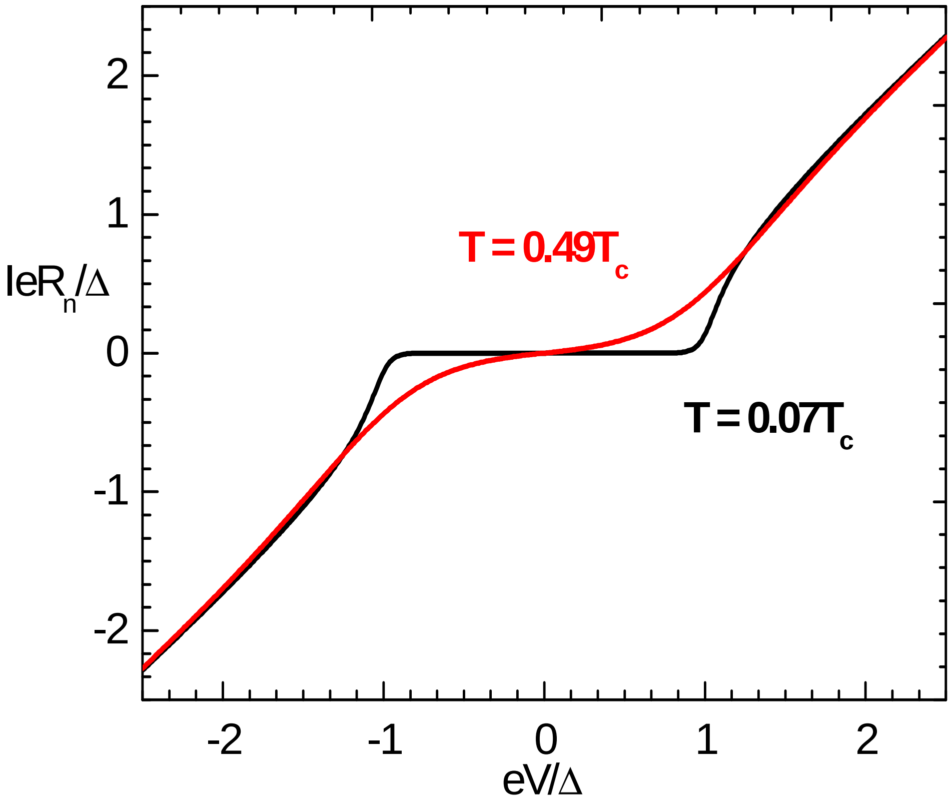
- NSQUIDS

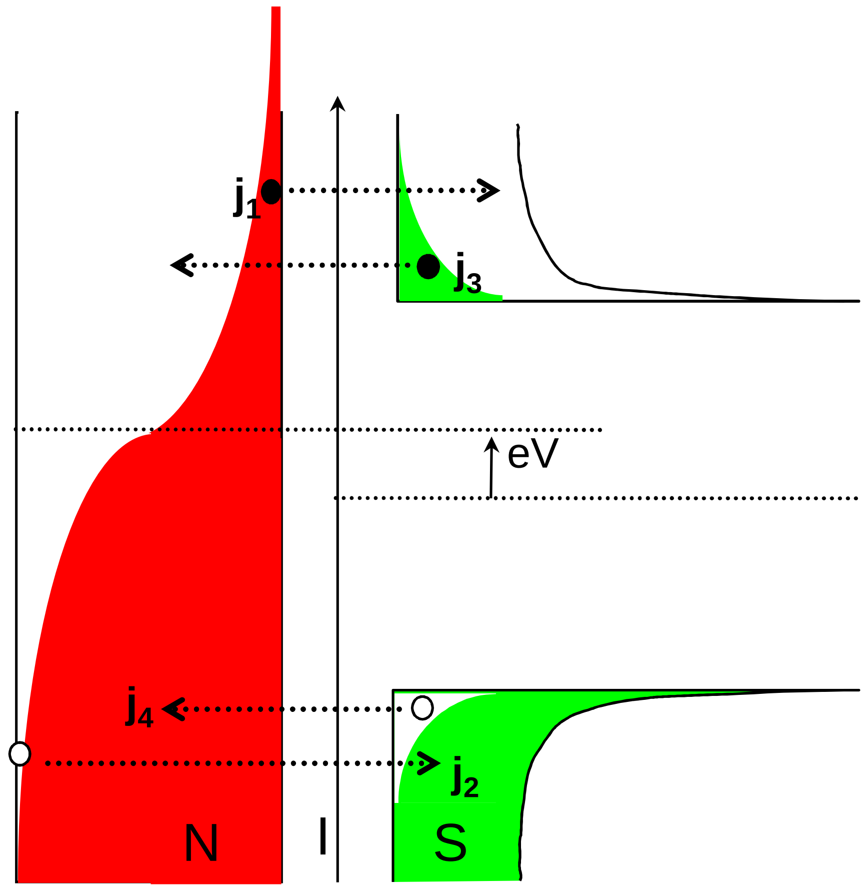


Quasiparticle tunneling in N-I-S junction

Charge current : $j_1 - j_2 - j_3 + j_4$

$$I_T = \frac{1}{eR_N}\int_{\Delta}^{\infty} n_S(E)\left[f_N(E-eV) - f_N(E+eV)\right] dE$$





T > 0 K

Quasiparticle tunneling in N-I-S junction

Charge current : $j_1 - j_2 - j_3 + j_4$

Joule heat

$$I_T = \frac{1}{eR_N}\int_{\Delta}^{\infty} n_S(E)\left[f_N(E - eV) - f_N(E + eV)\right] dE$$

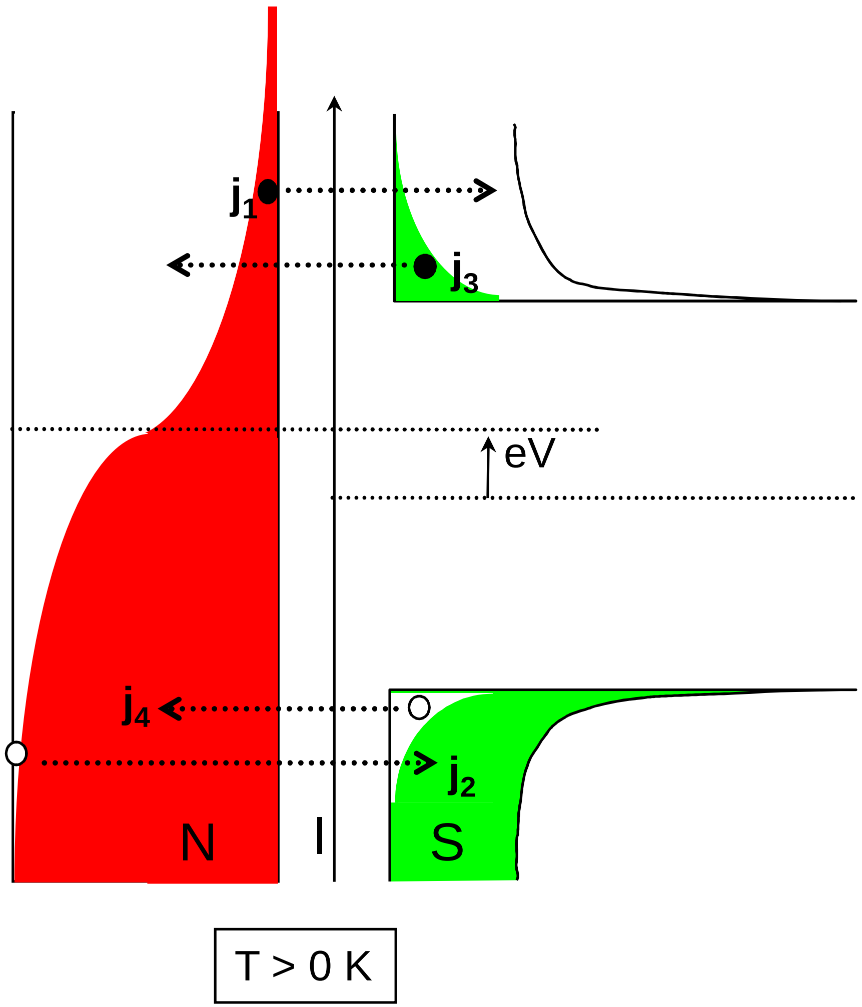
Cooling

Quasiparticle current : $j_1 + j_2 - j_3 - j_4$

$$J_q = \frac{1}{e^2R_N}\int_{\Delta}^{\infty} n_S(E)\left[f_N(E - eV) + f_N(E - eV) - f_S(E)\right] dE$$

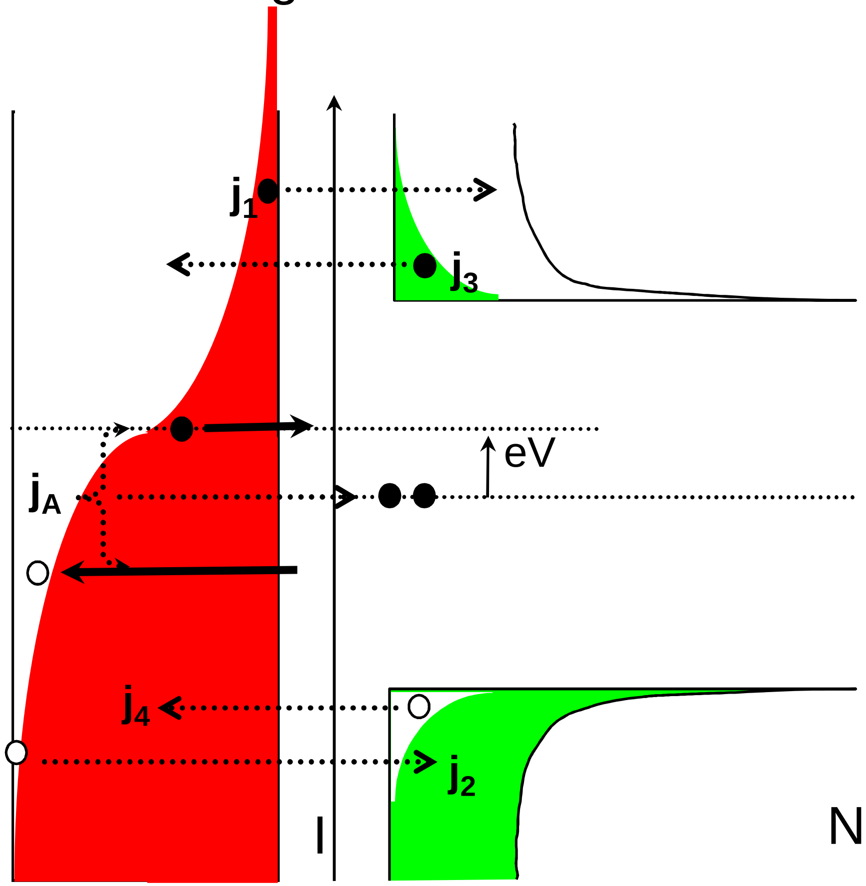
Net Cooling Power : $- I_T.V + E.J_q$

$$P_{Cool} = \frac{1}{e^2R_N}\int_{-\infty}^{\infty} (E - eV)n_S(E)\left[f_N(E - eV) - f_S(E)\right] dE$$



Andreev and Quasiparticle current

Net charge transfer



T > 0 K

Joule heat

Charge current: $j_1 - j_2 - j_3 + j_4$ $\mathbf{+ j_A}$

Quasiparticle current: $j_1 + j_2 - j_3 - j_4$

Cool

Net Current : $I = I_T$ $\mathbf{+ I_A}$

Net cooling power : $P = P_{Cool}$ $\mathbf{- I_A.V}$