Kopnin and nanophysics experiments

Jukka Pekola, LTL, Aalto University, Helsinki, Finland

Nikolai Kopnin *on 10.3.2011*

Informal celebration on the occasion of the Simon memorial prize at LTL

My scientific interaction with Nikolai over the years

Superfluid 3He (Phase slips in capillary flow), 1981 – 1988

Non-equilibrium superconductivity, 2002 – 2013

N. B. Kopnin, F. Taddei, J. P. Pekola, and F. Giazotto, Influence of photon-assisted tunneling on heat flow in a normal metal - superconductor tunnel junction, Phys. Rev. B **77**, 104517 (2008).

A. V. Timofeev, C. Pascual Garcia, N. B. Kopnin, A. M. Savin, M. Meschke, F. Giazotto, and J. P. Pekola, Recombination-Limited Energy Relaxation in a Bardeen-Cooper-Schrieffer Superconductor, Phys. Rev. Lett. **102**, 017003 (2009).

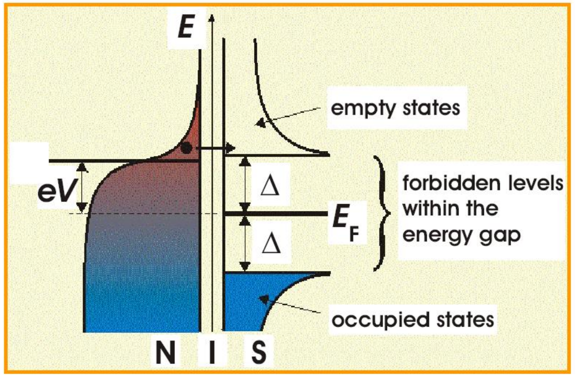
J. T. Peltonen, J. T. Muhonen, M. Meschke, N. B. Kopnin, and J. P. Pekola, Magnetic-field-induced stabilization of nonequilibrium superconductivity in a normal-metal/insulator/superconductor junction, Phys. Rev. B **84**, 220502 (2011).

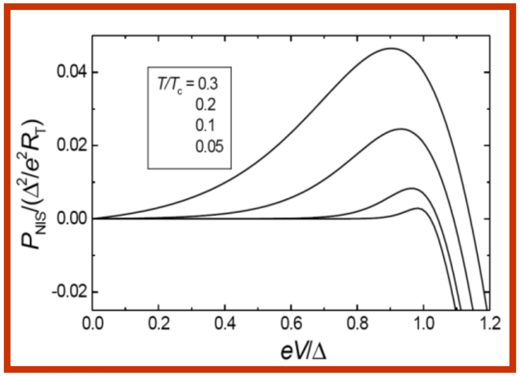
Maxwell’s demon (Thermodynamics of small systems), 2011 – 2013

NIS junction as a refrigerator

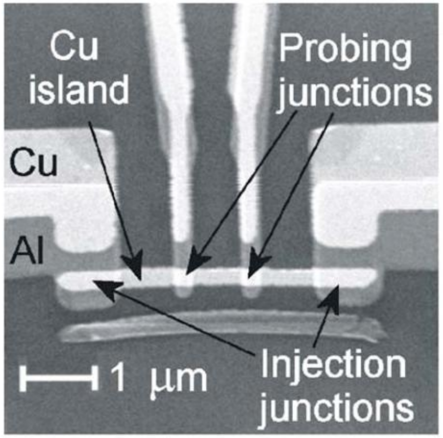
Cooling power of a NIS junction:

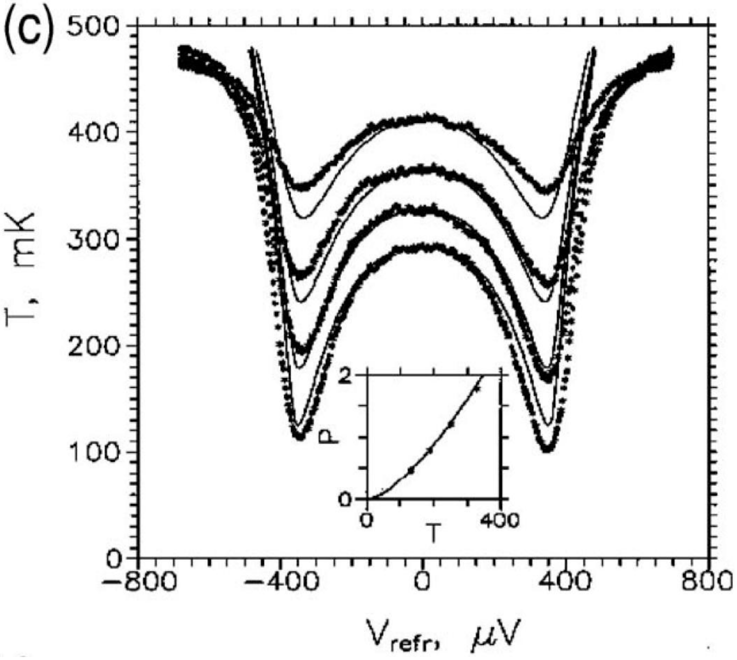
$$P(V) = \frac{1}{eR_T} \int (E - eV) N_S(E) [f_N(E - eV) - f_S(E)] dE$$





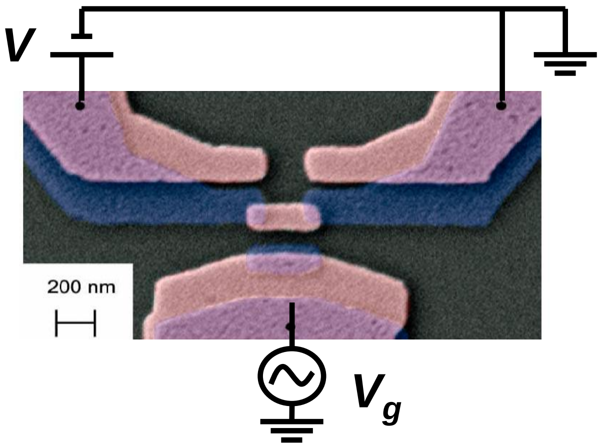
$$P_{\mathrm{NIS,max}} \simeq 0.59 \frac{\Delta^2}{e^2 R_T} \left(\frac{k_B T_N}{\Delta}\right)^{3/2}$$

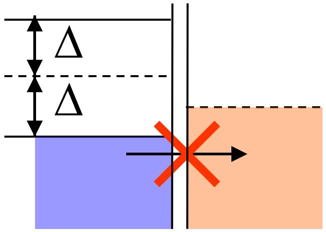


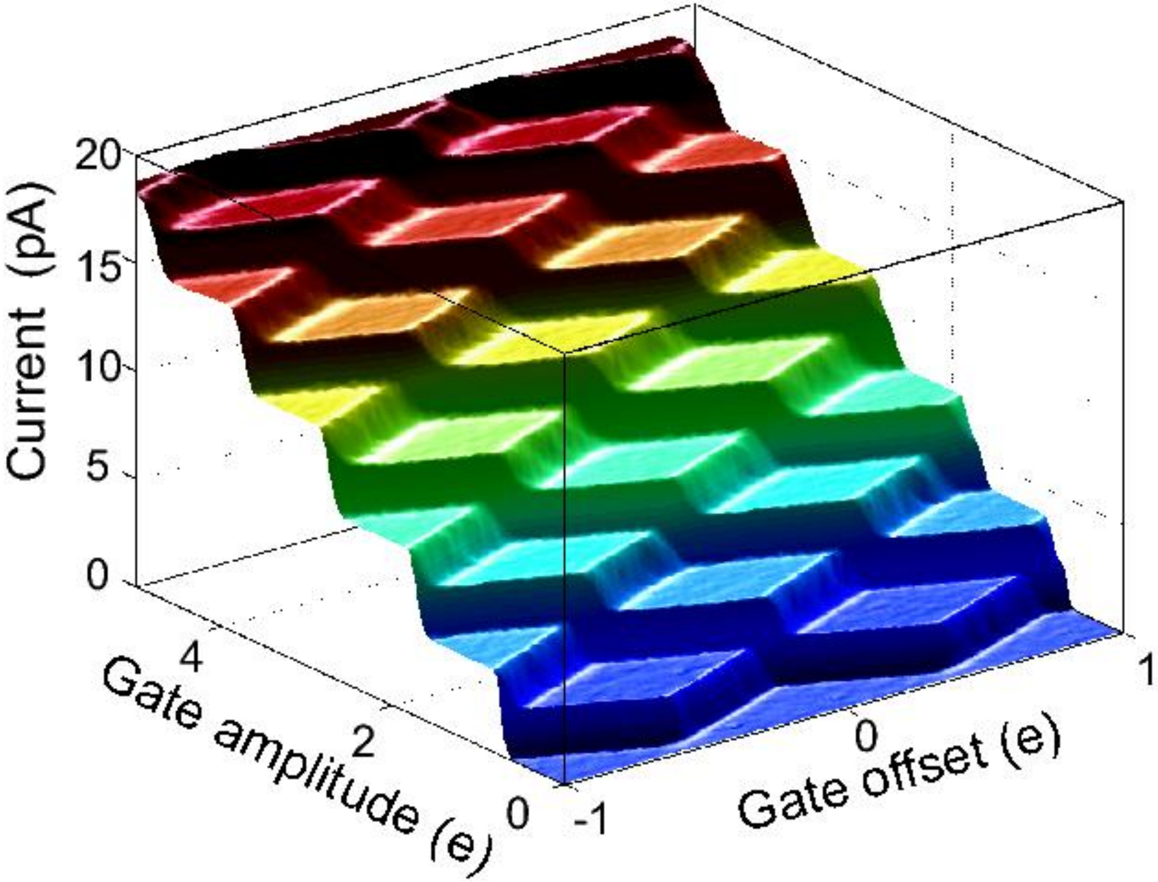


Leivo et al, 1996

Single-electron turnstile with NIS-junctions for metrology

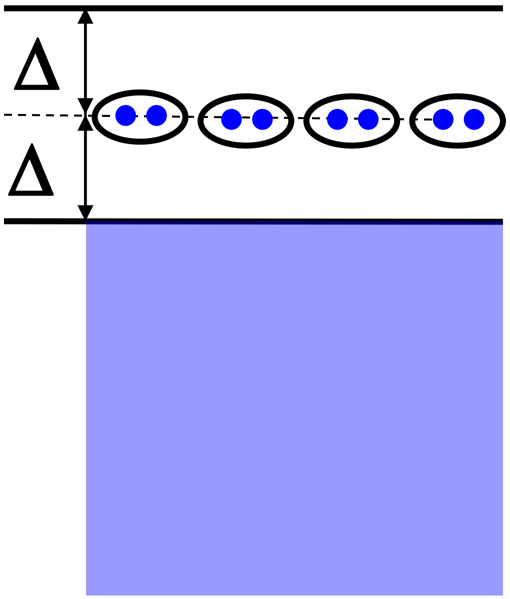




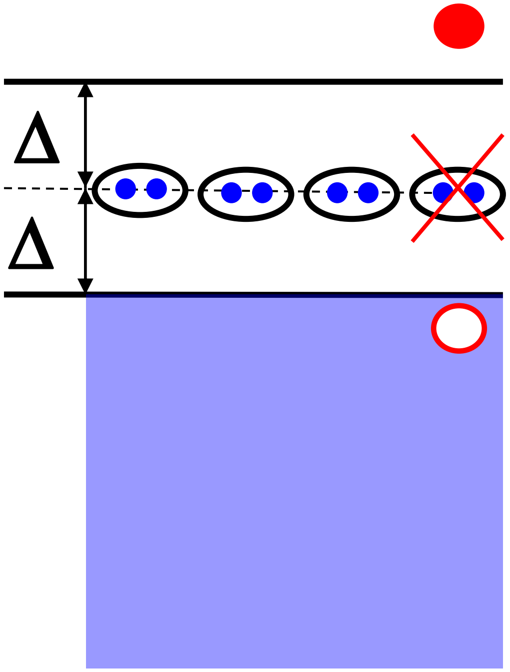


J. P. et al., Nature Physics **4**, 120 (2008)

Cooper-pairs and quasiparticles

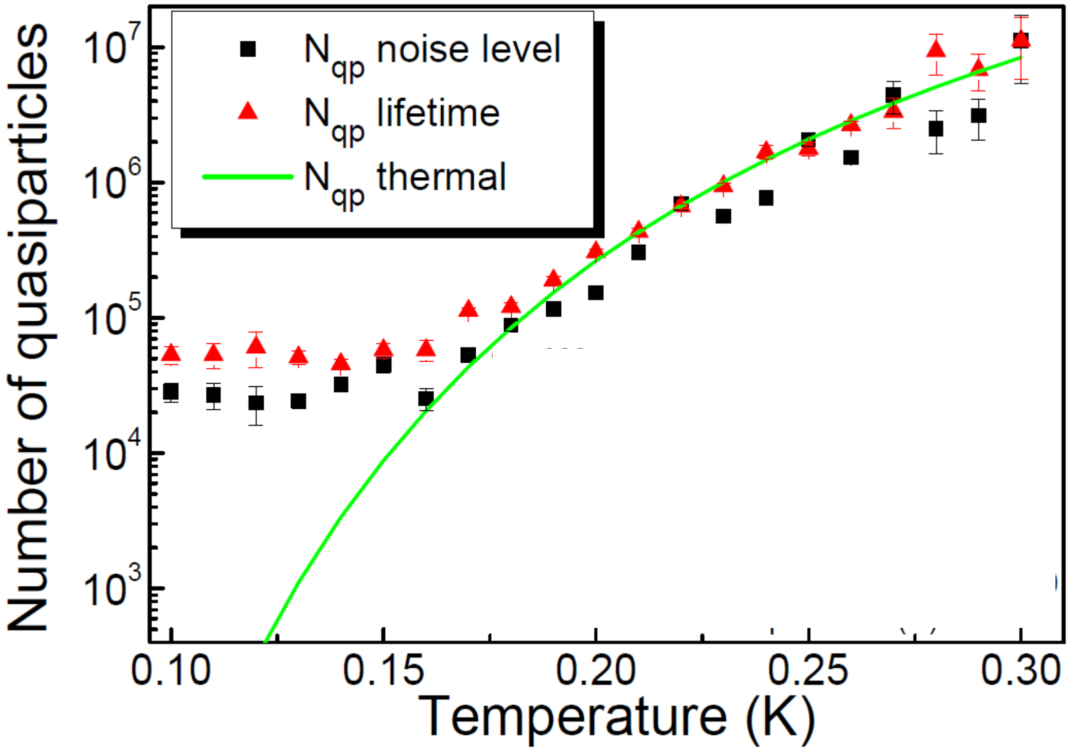


T = 0, ideally no quasiparticle excitations



T ≠ 0 or non-equilibrium: broken pairs / quasiparticle excitations

Typical experimental situation



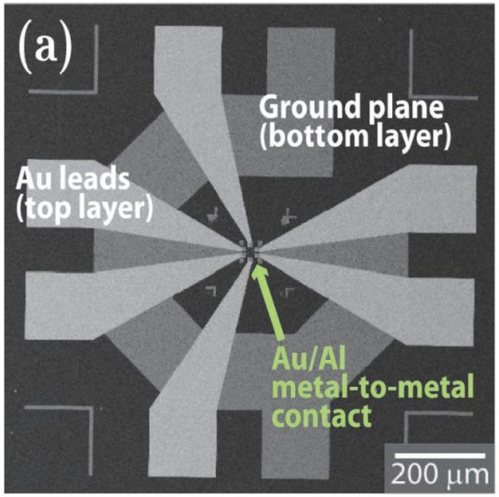
Aluminium (kinetic inductance detector)

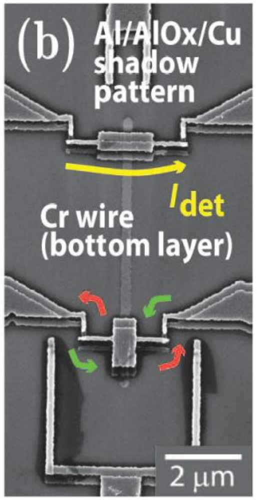
P. J. De Visser et al., PRL 106, 167004 (2011).

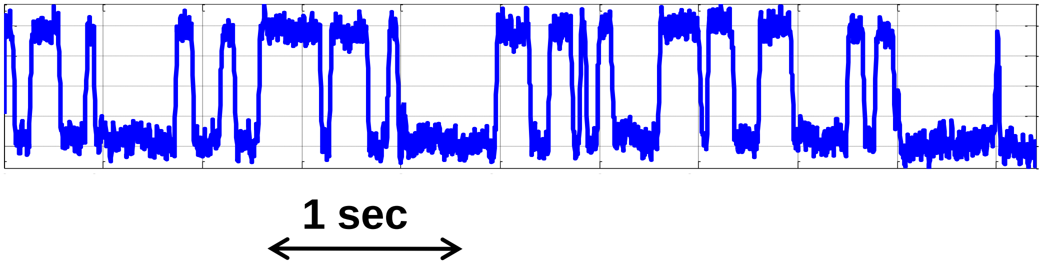
Thermal density of quasiparticles:

$$n_{qp} = 2N_0\sqrt{2\pi k_B T\Delta}\,\exp(-\Delta/k_B T)$$

Counting single-electrons on a turnstile





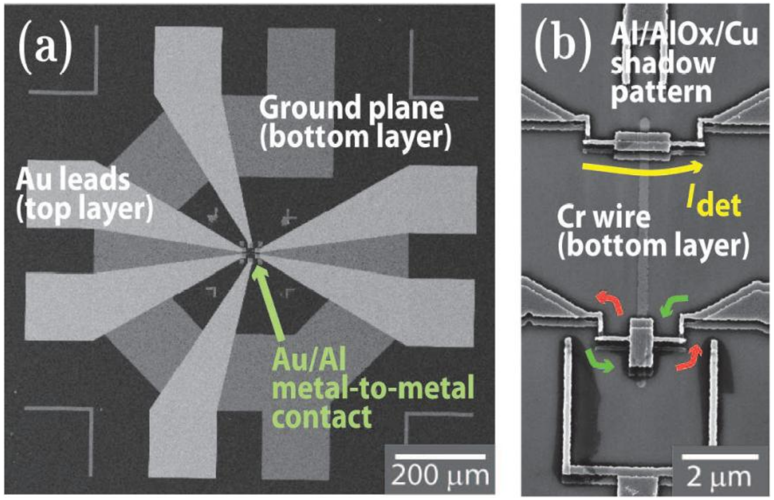


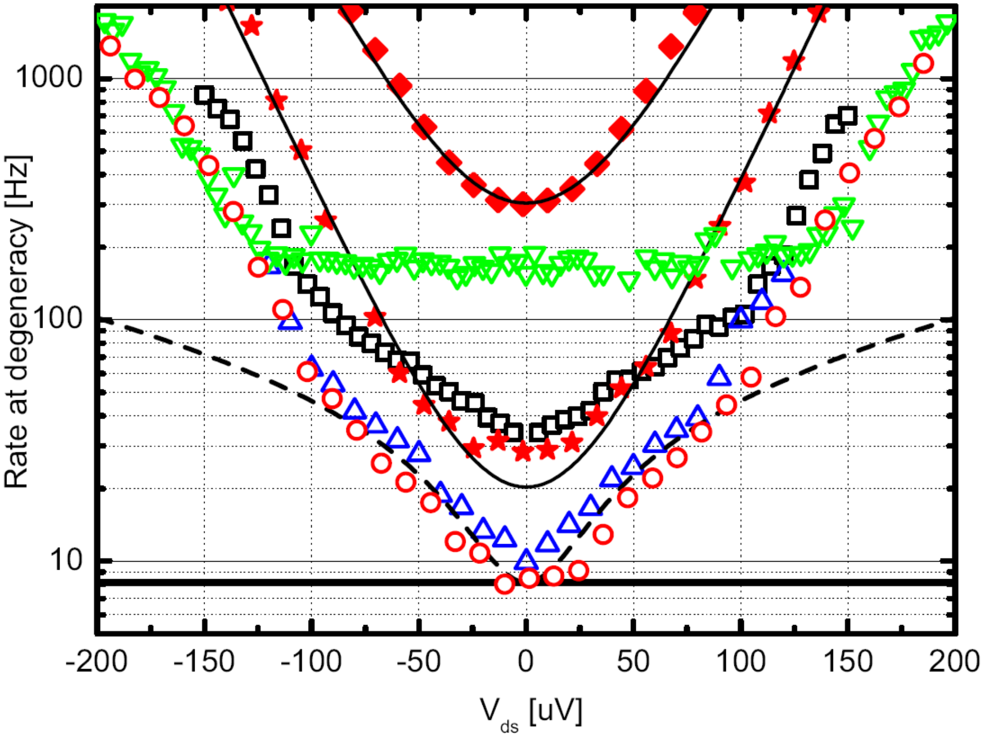
The observed transition rate equals $\Gamma^{1e}(eV_{ds}/2) + \Gamma^{1e}(-eV_{ds}/2)$

The rates can be attributed to the residual density of quasiparticles in the superconductor, n_{qp}:

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

Ultralow qp-density





Conclusion:

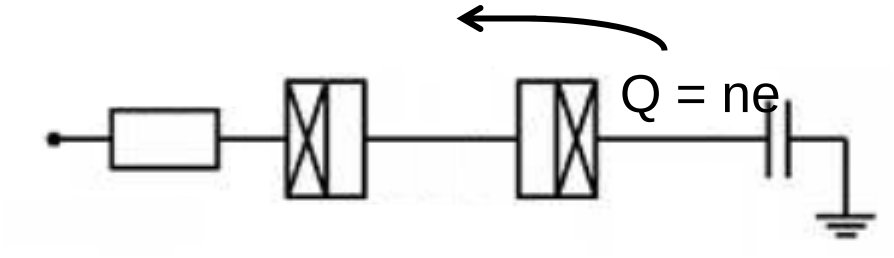
Residual quasiparticle density < 0.033 $(\mu m)^{-3}$

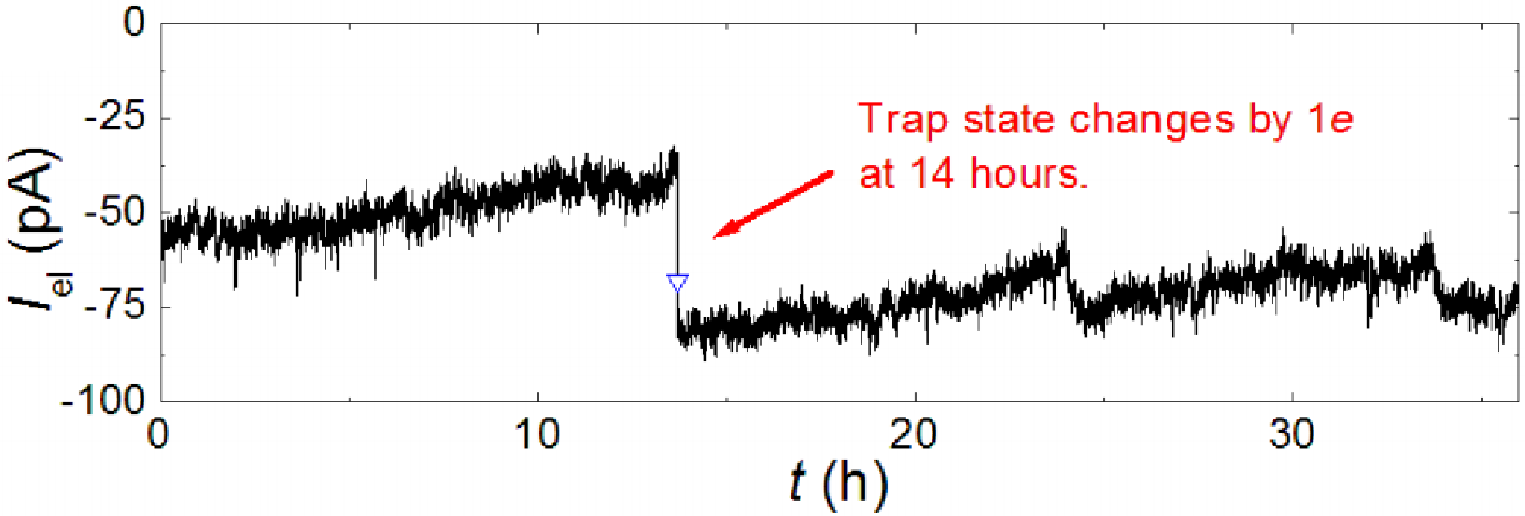
<u>Typical qp number in the leads = 0 !</u>

O.-P. Saira et al., PRB 85, 012504 (2012),
D. Riste, Nature Comm. 4, 1913 (2013).

Ultralow qp-density

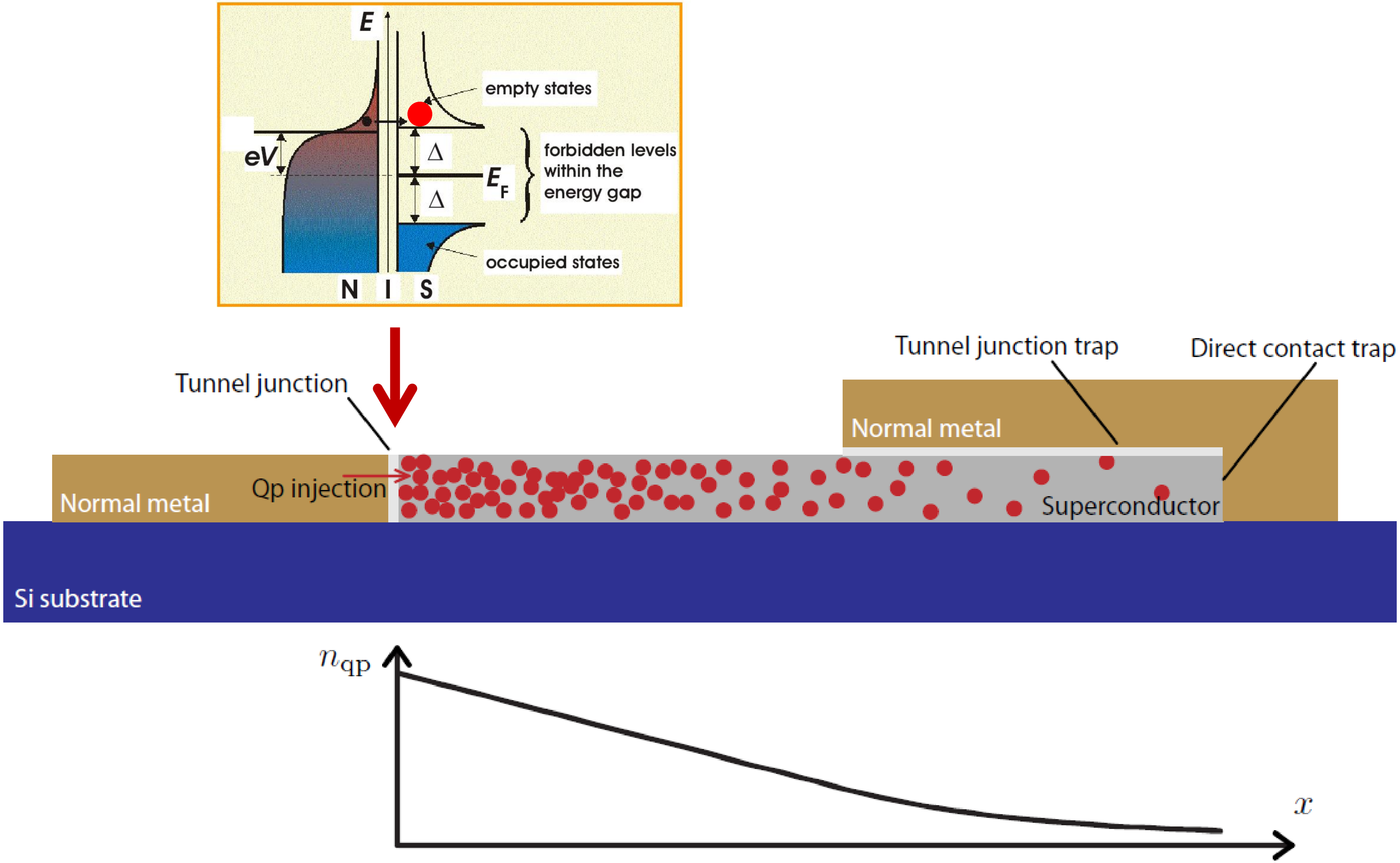
Only a single-escape event in 35 hours.




Trap state changes by 1*e* at 14 hours.

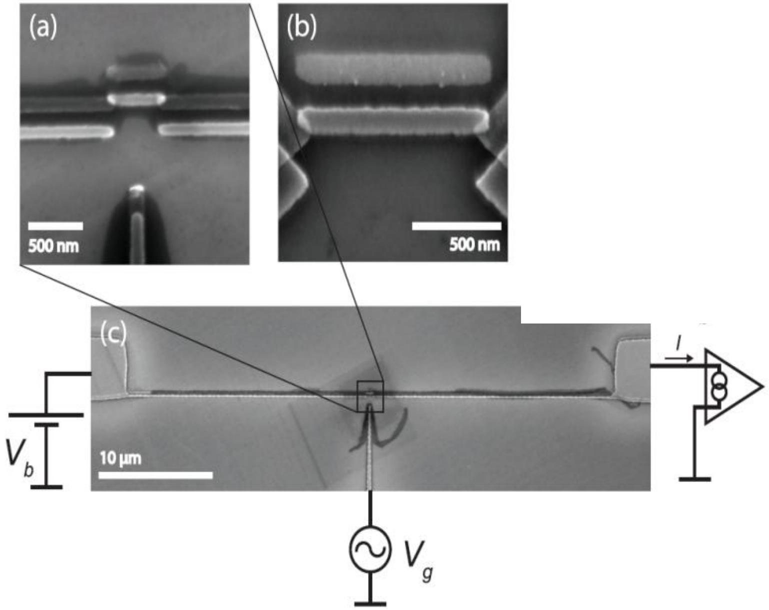
A. Kemppinen et al., APL **99,** 142106 (2011).

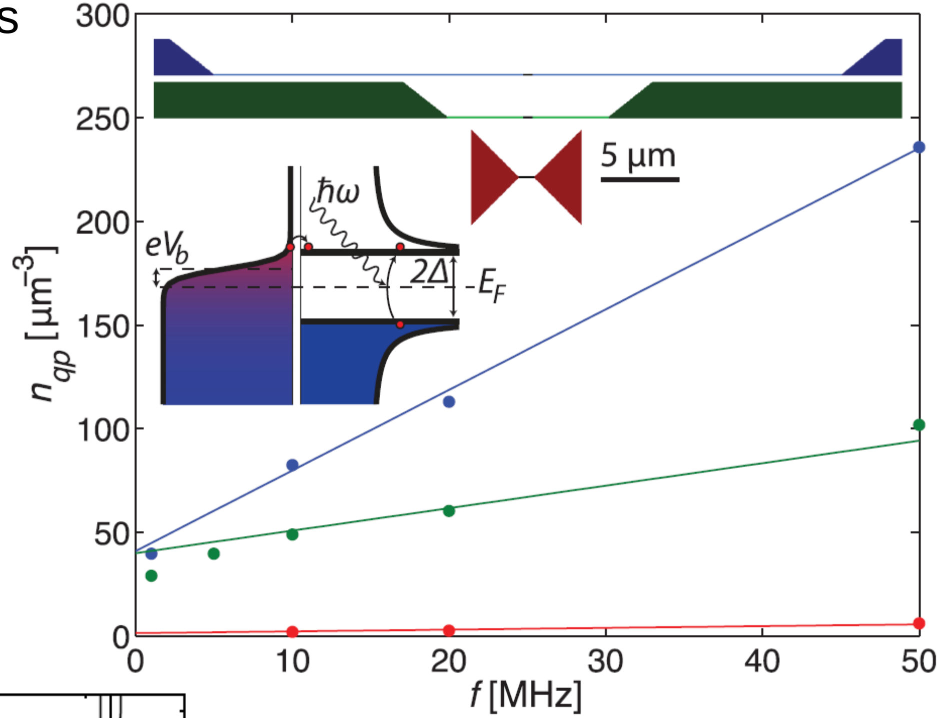
Generation of quasiparticles

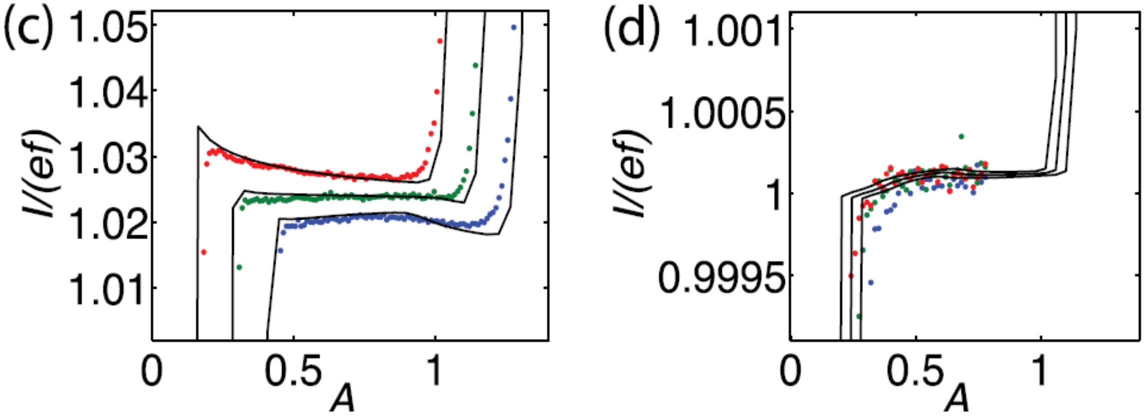


Relaxation of generated quasiparticles in a sc lead

SINIS structures, different S-lead geometries





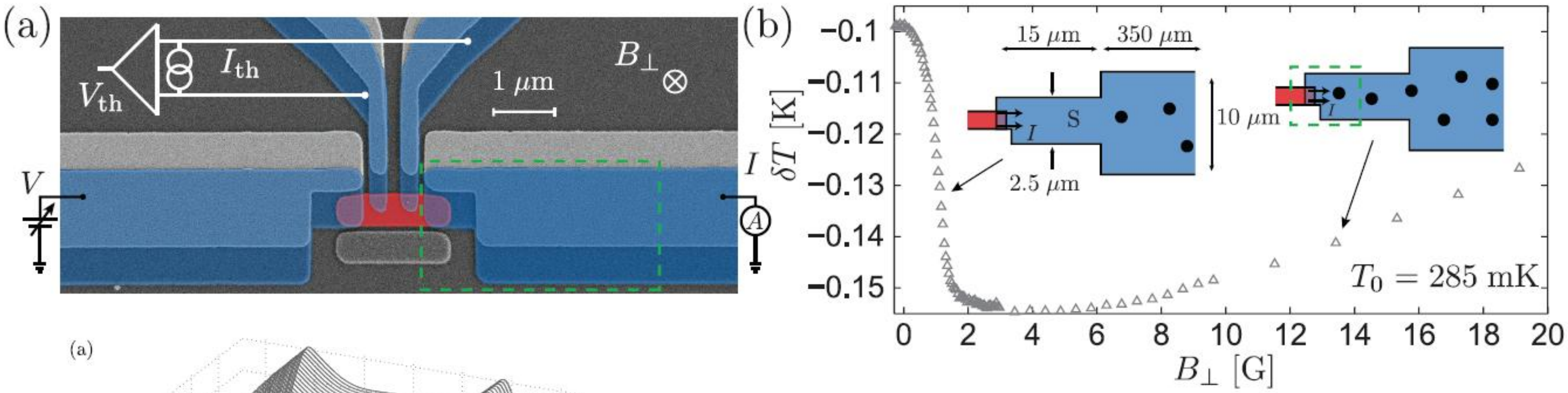


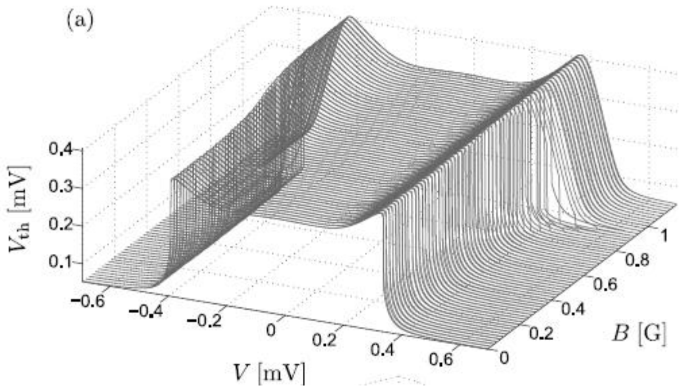
gate amplitude

H. Knowles et al., APL **100**, 262601 (2012).

Relaxation of generated quasiparticles in a sc lead

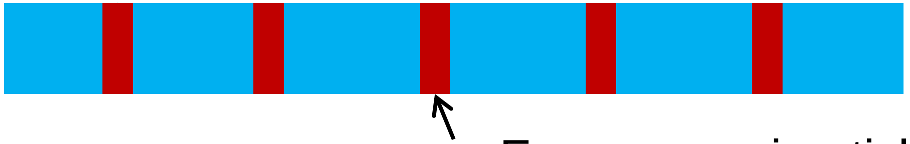
Magnetic field enhanced relaxation





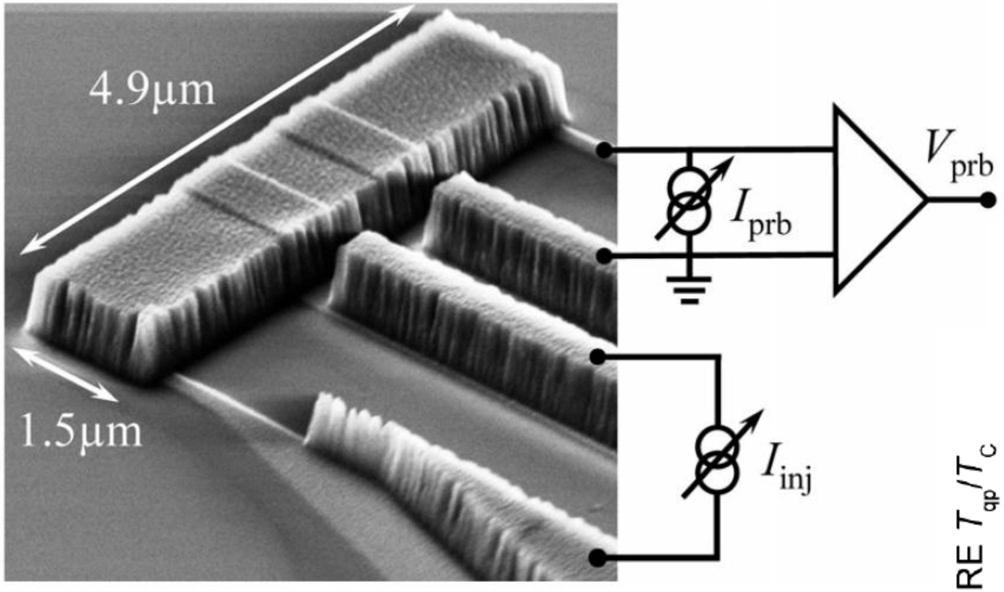
Quasiparticle relaxation is improved in the superconductor due to the presence of vortices

J. T. Peltonen, ... , N. B. Kopnin et al., PRB 84, 220502 (2011).

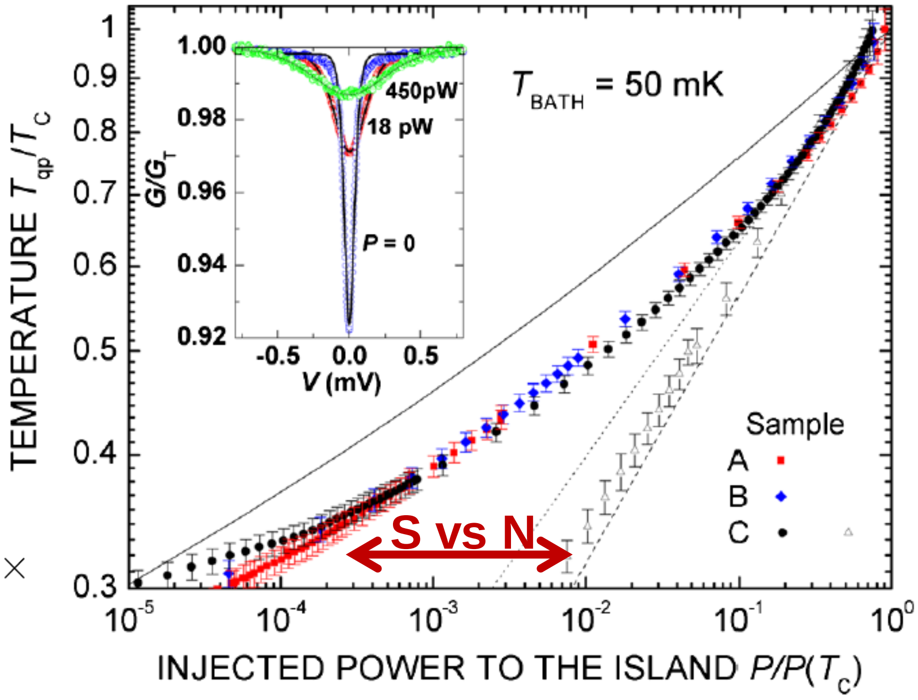


Excess quasiparticles decay in the normal regions (vortices)

Relaxation of generated quasiparticles on a sc island



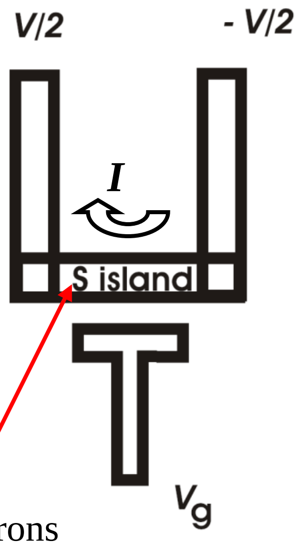
A. V. Timofeev, …, N. B. Kopnin et al., Phys. Rev. Lett. **102**, 017003 (2009).



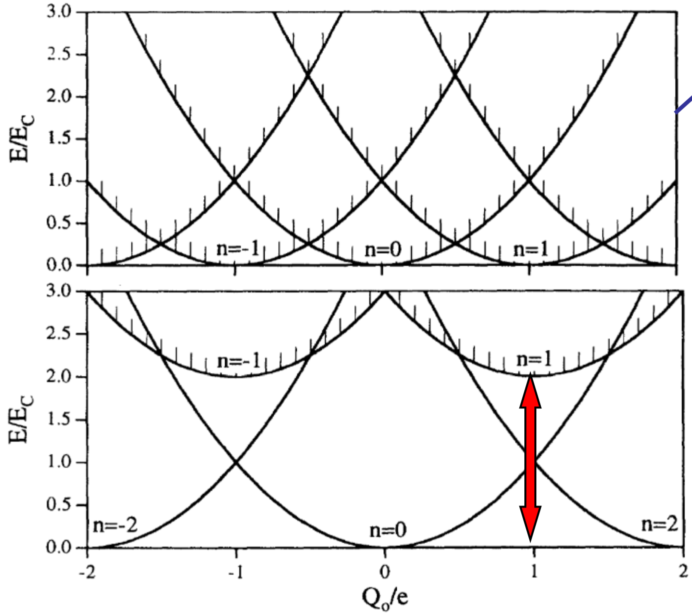
Relaxation by recombination, heat current strongly suppressed

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

Parity effect in a superconducting island

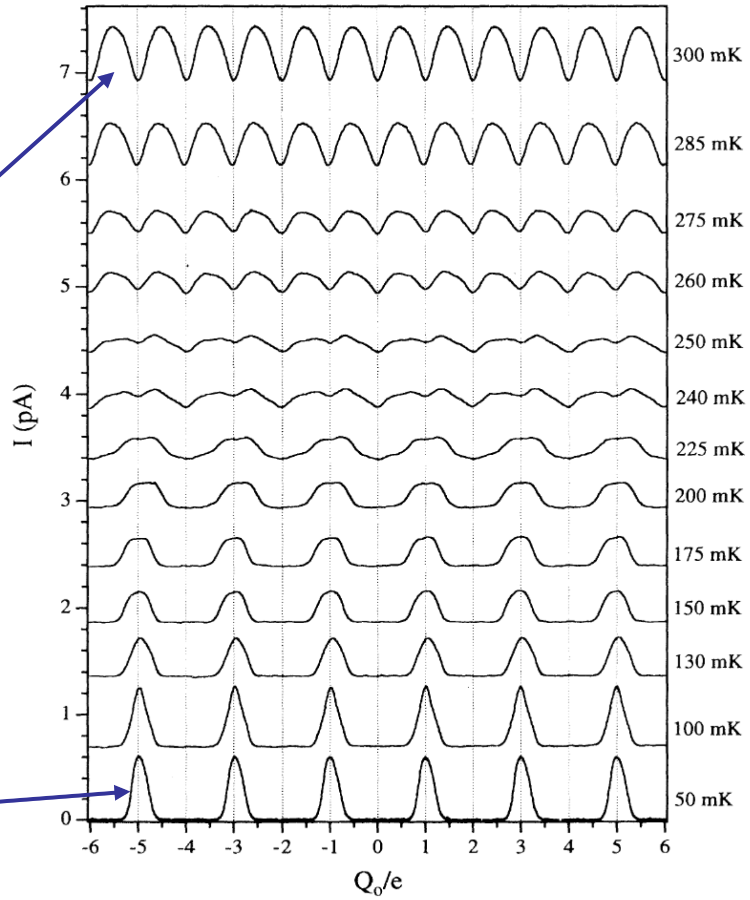


n electrons
on the island



Normal state,
$\Delta = 0$

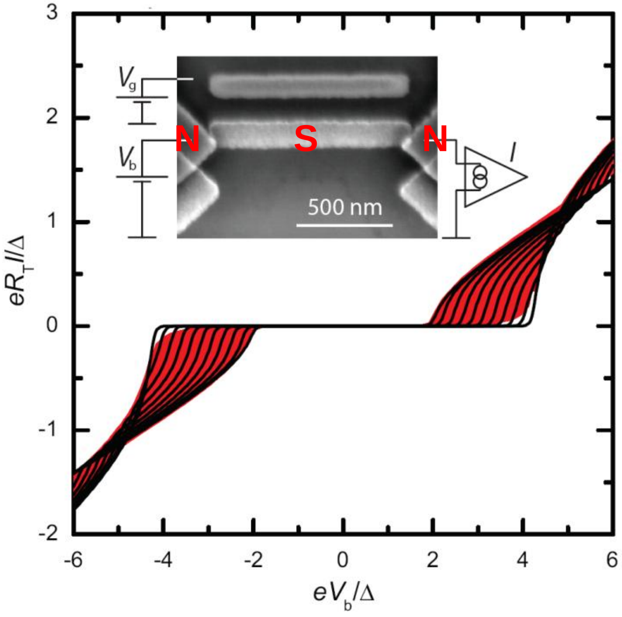
Superconducting
state, $\Delta > E_C$

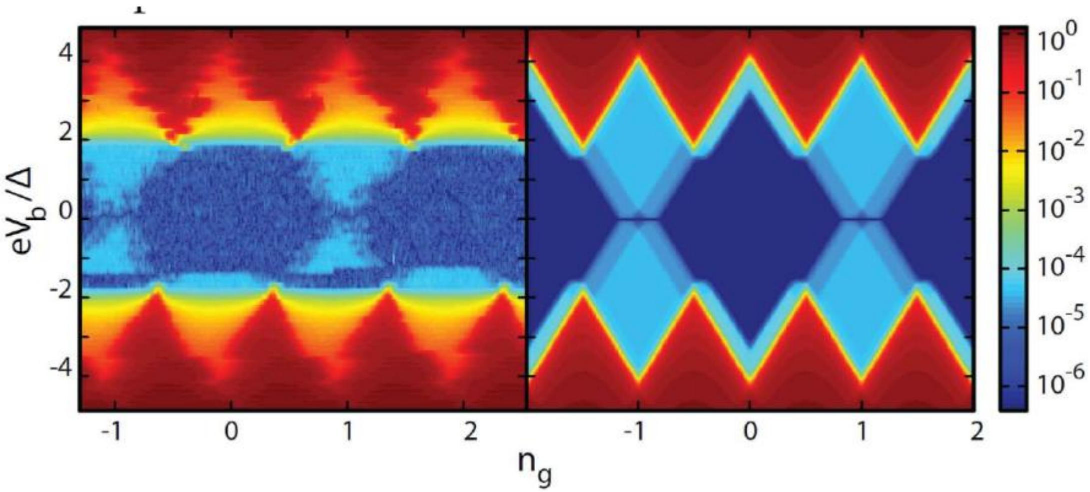


M. Tuominen et al. (1992)

Relaxation of generated quasiparticles on a sc island

NISIN structure
V. Maisi et al, PRL 111, 147001 (2013).

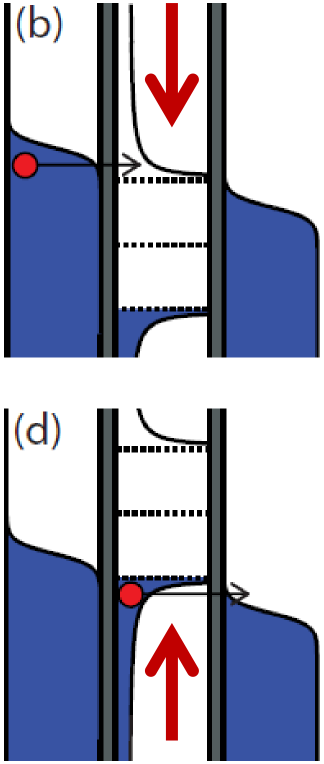




Parity effect seen in the DC characteristics

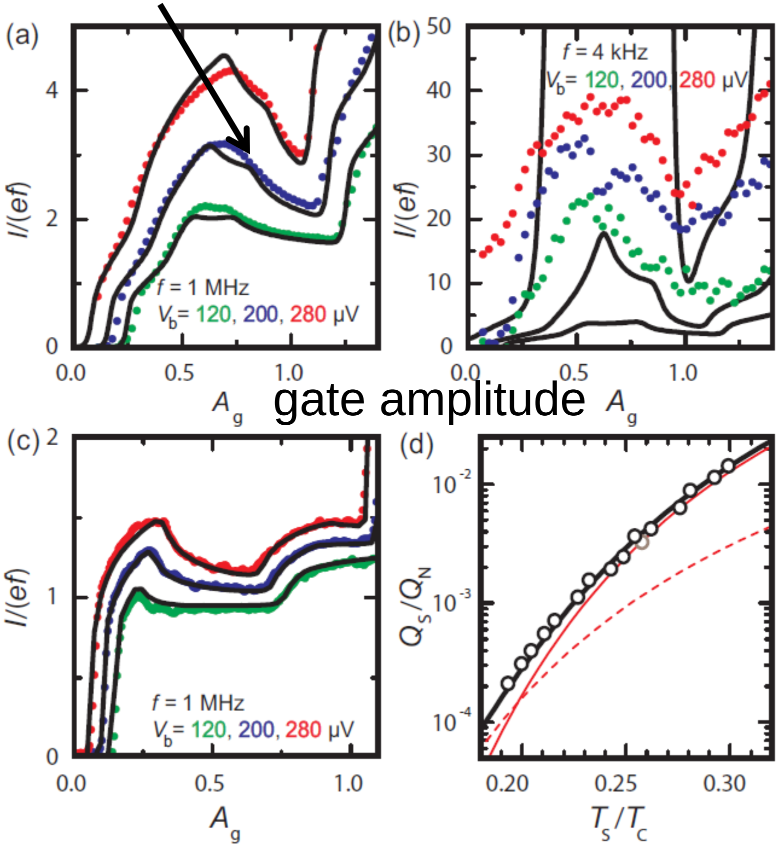
Pumping quasiparticles onto the island

Pump qp:s onto the island at frequency *f*



Black lines arise from the thermal model:

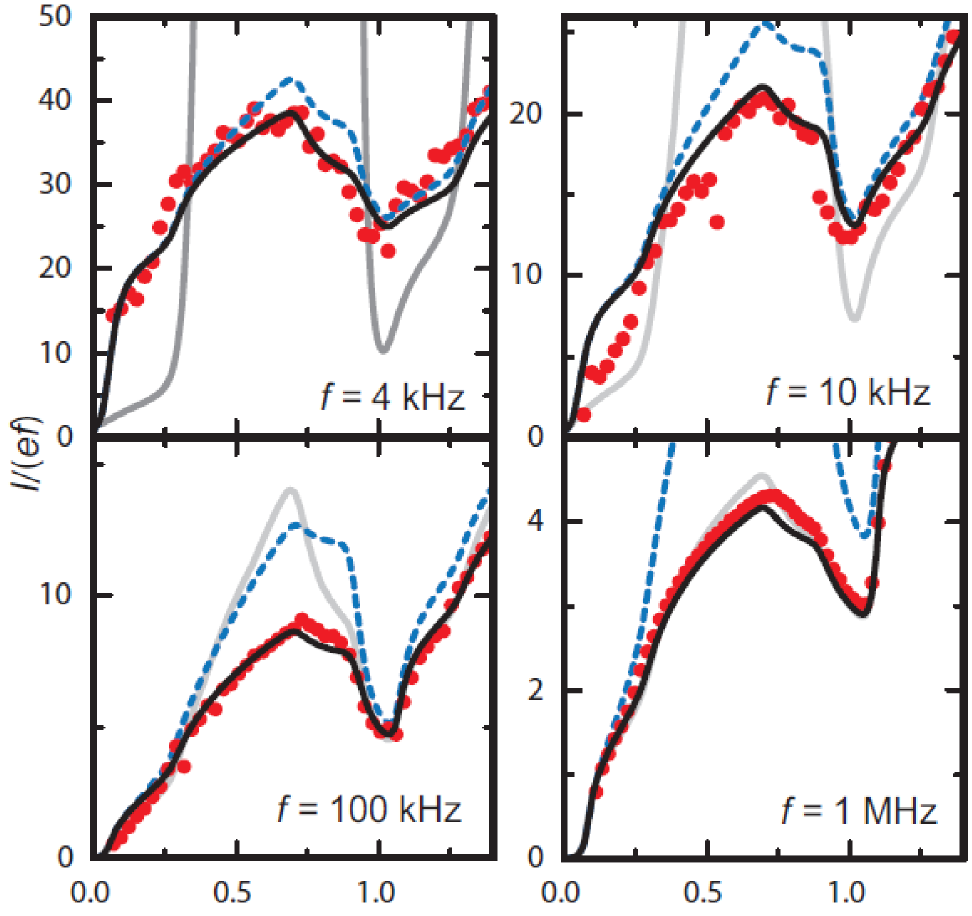
$$\dot{Q}_{ep} = \frac{\Sigma V}{24\zeta(5)k_B^5}\int_0^\infty d\epsilon\,\epsilon^3\left(n(\epsilon,T_S)-n(\epsilon,T_P)\right)\int_{-\infty}^{\infty}dE\times$$
$$n_S(E)n_S(E+\epsilon)\left(1-\frac{\Delta^2}{E(E+\epsilon)}\right)\left(f(E)-f(E+\epsilon)\right).$$



gate amplitude

Detailed analysis

$$\dot{P}(N, N_S) = \sum_{N', N'_S} \Gamma_{N' \to N, N'_S \to N_S} P(N', N'_S)$$



gate amplitude

Include in the master equation both the number of excess electrons and excess quasi-particle excitations on the island

qp (pair) relaxation rate in Al:

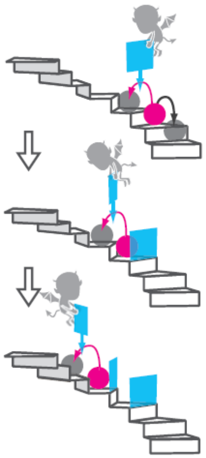
τ^{-1} = 16 kHz

INFERNOS

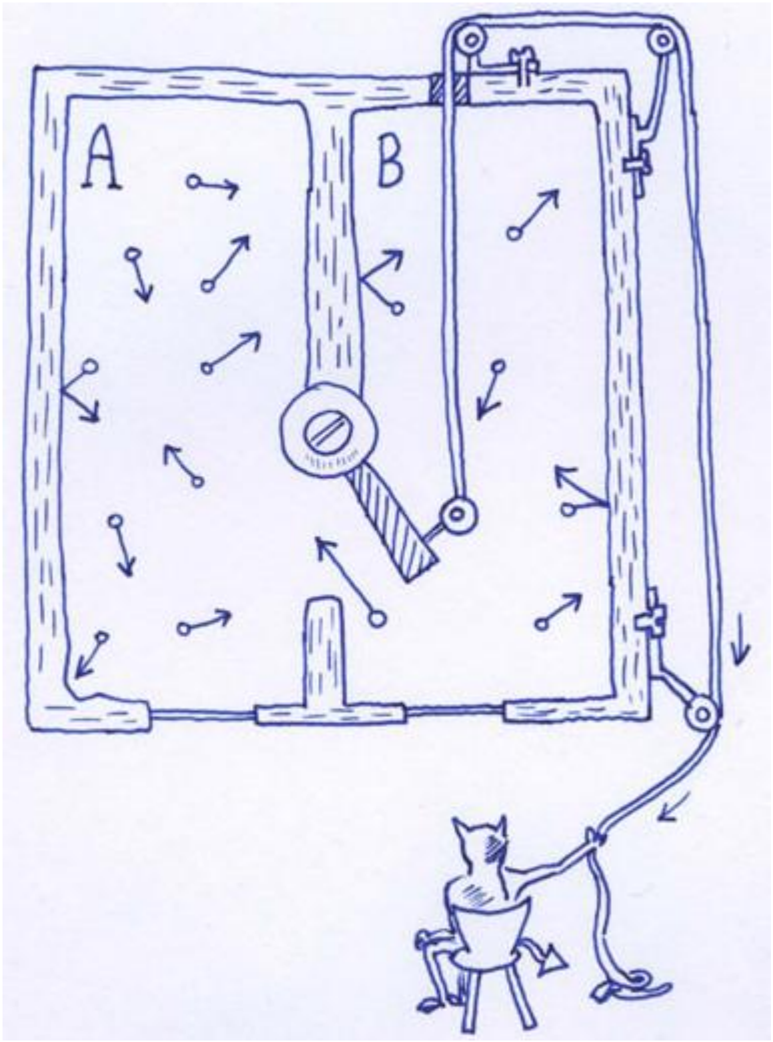
Information, Fluctuations, and Energy Control in Small Systems

EU project that Nikolai coordinated in its preparation stage in 2012 and during the project in 2013.

Maxwell’s demon



J. C. Maxwell 1867



Experiment with micro-particles:

S. Toyabe et al., Nature Physics 2010

Proposals in electric circuits:

D. Averin, M. Mottonen, and J. P., PRB 84, 245448 (2011)
G. Schaller et al., PRB 84, 085418 (2011)
P. Strassberg et al., PRL 110, 040601 (2013)
J. Bergli, Y. Galperin, and N. B. Kopnin, PRE 88, 062139 (2013)

Szilard’s engine (L. Szilard 1929)

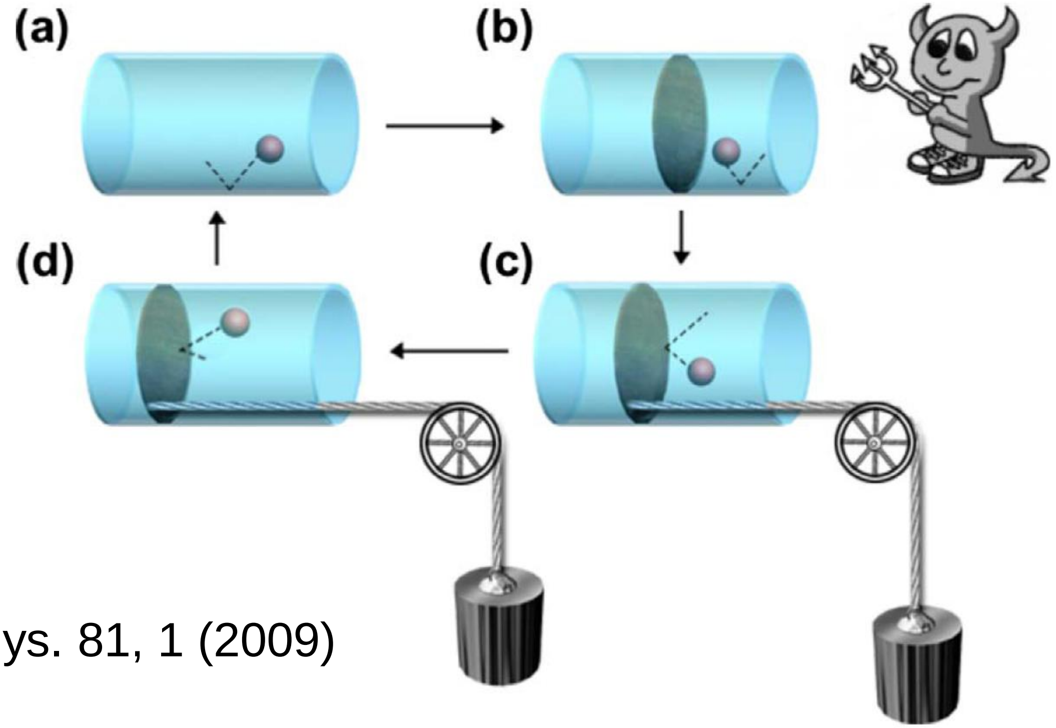
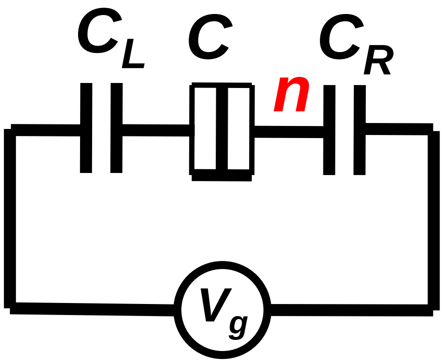


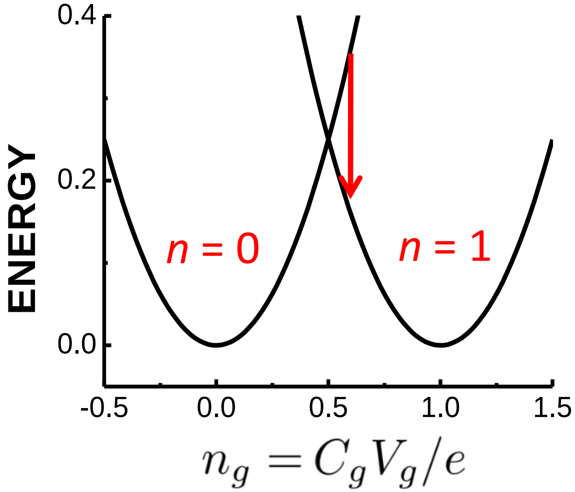
Figure from
Rev. Mod. Phys. 81, 1 (2009)

Isothermal expansion of the ”single-molecule gas” does work against the load

$$W = Q = \int_{V/2}^{V} p\,dV = \int_{V/2}^{V} \frac{k_B T}{V} dV = k_B T \ln 2$$

Dissipation in single-electron transitions





$$H = E_C (n - n_g)^2$$

Heat generated in a tunneling event *i*:

$$Q_i = \pm 2 E_C (n_{g,i} - 1/2)$$

Total heat generated in a process:

$$Q = \sum_i Q_i$$

Work in a process:

$$W = Q + \Delta U$$

Change in internal (charging) energy

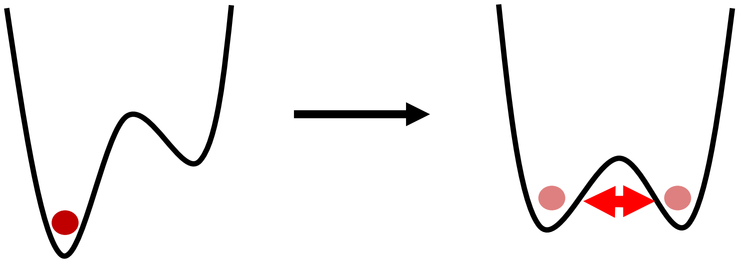
D. Averin and J. P., EPL **96**, 67004 (2011).

Szilard’s engine for single electrons

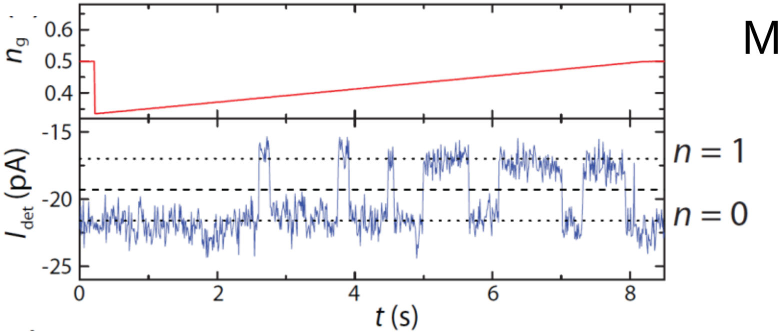
J. V. Koski et al., arXiv:1402.5907 and arXiv:1405.1272, PRL (2014).

Entropy of the charge states: $S = -k_B \sum_{i=0,1} p(i) \ln[p(i)]$

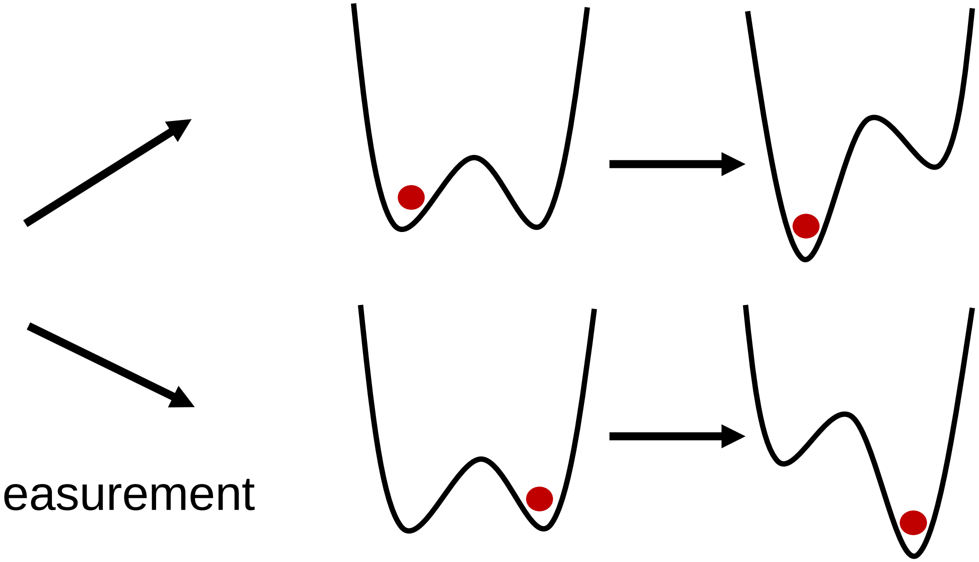
$$\Delta S = k_B \ln(2)$$



Quasi-static drive



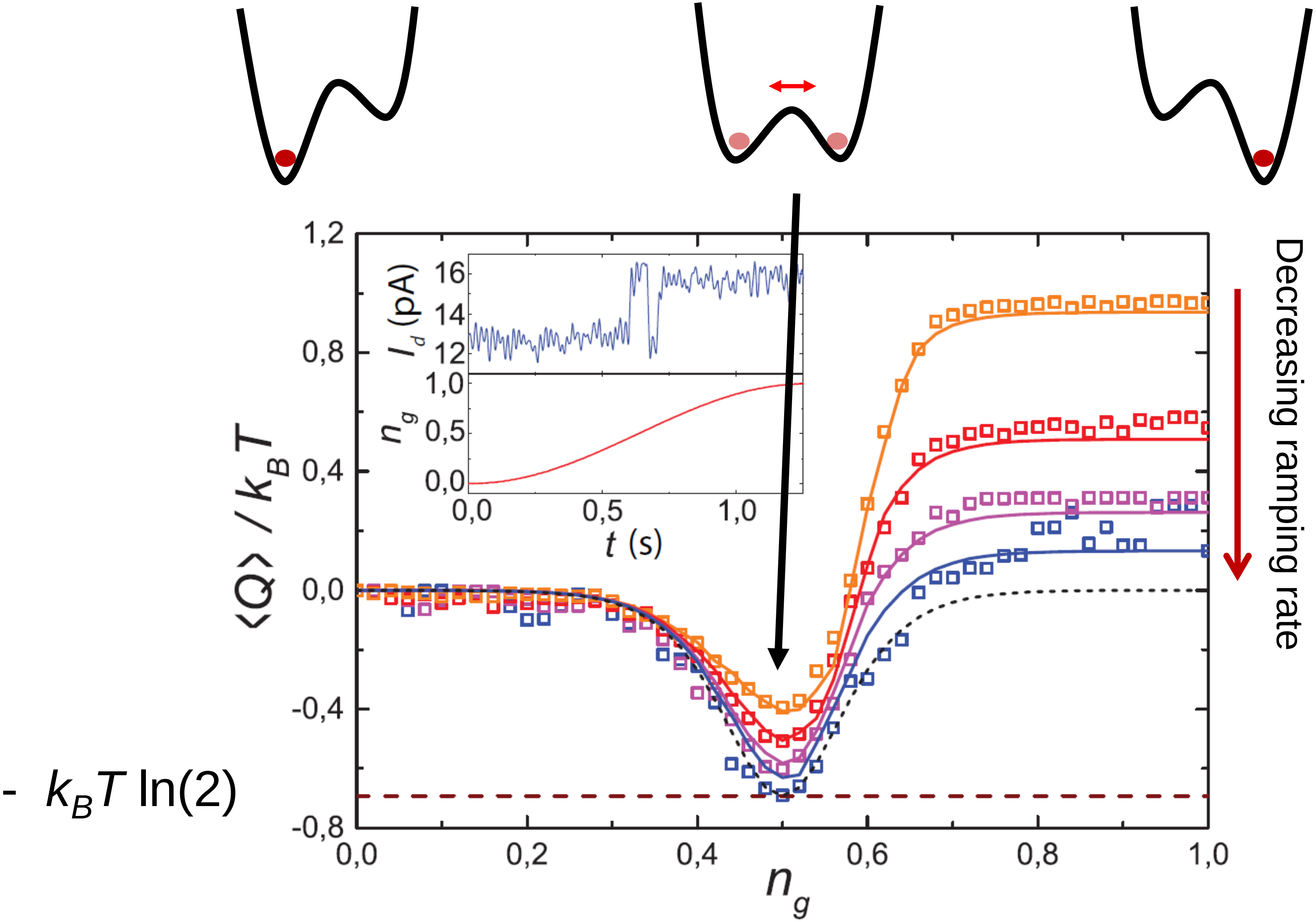
Measurement



Fast drive after the decision

In the full cycle (ideally): $Q = W = -k_B T \ln(2)$

Extracting heat from the bath

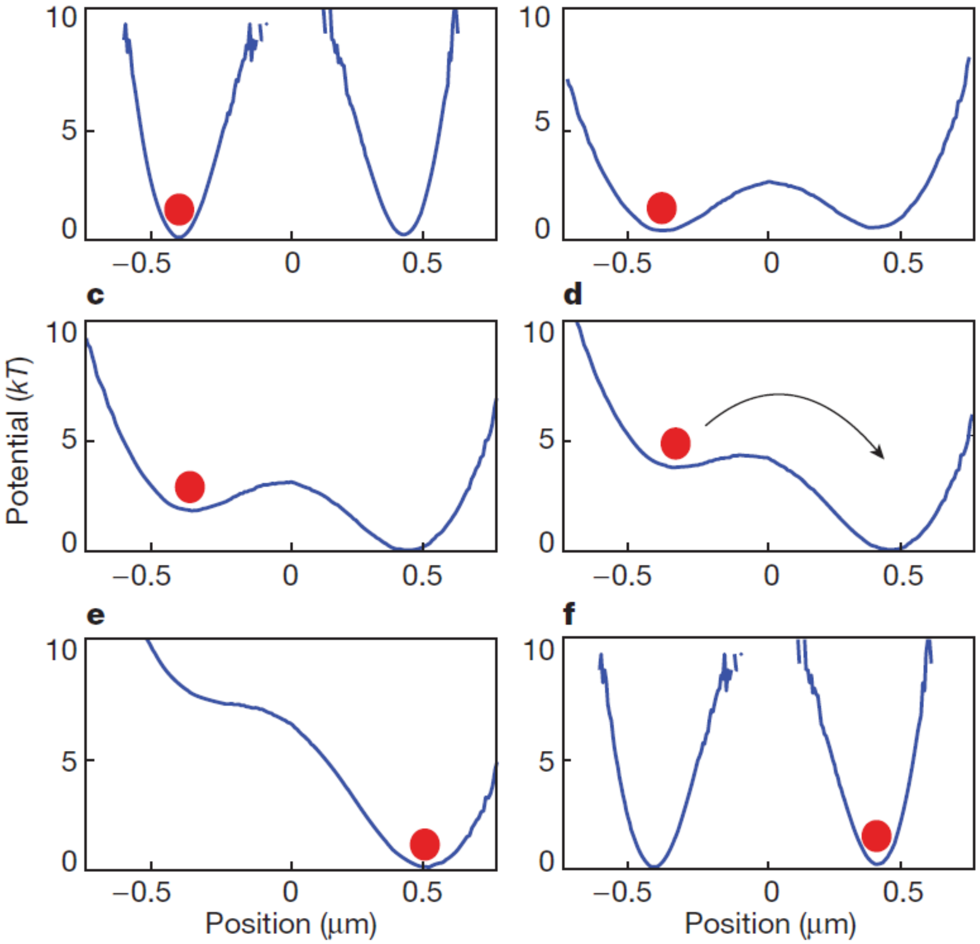


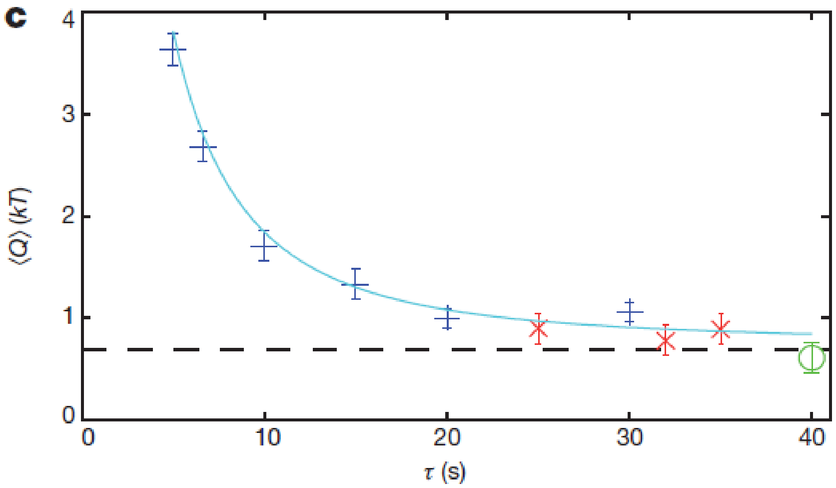
Erasure of information

Landauer principle: erasure of a single bit costs energy of at least $k_B T \ln(2)$

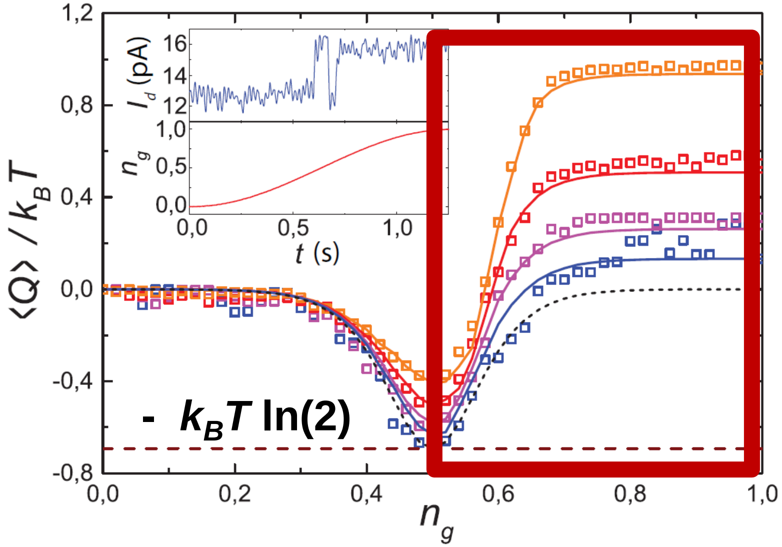
A. Berut, … , S. Ciliberto et al., Nature 2012

Experiment on a colloidal particle:

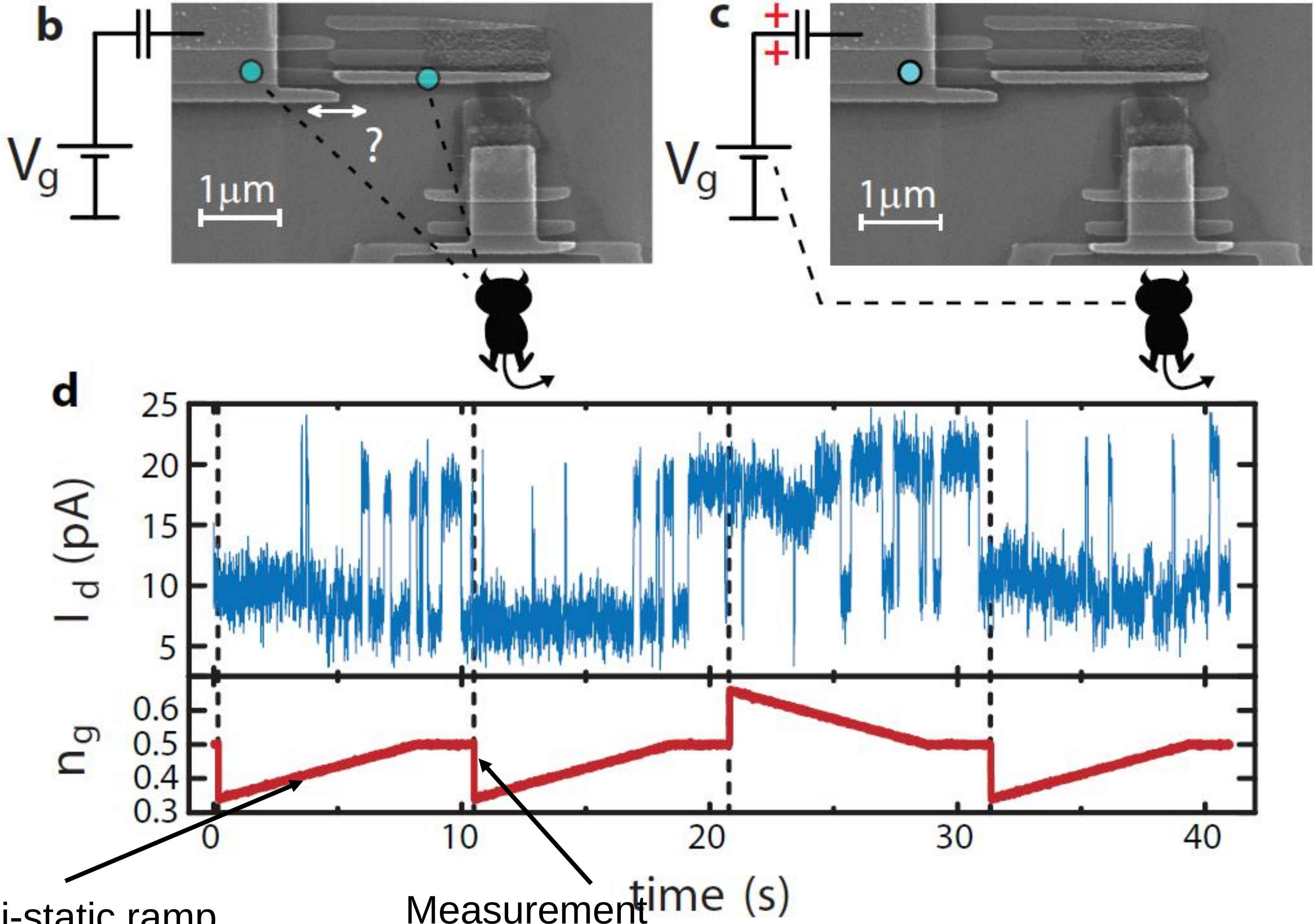




Corresponds to our experiment:



Realization of the Szilard’s engine with an electron



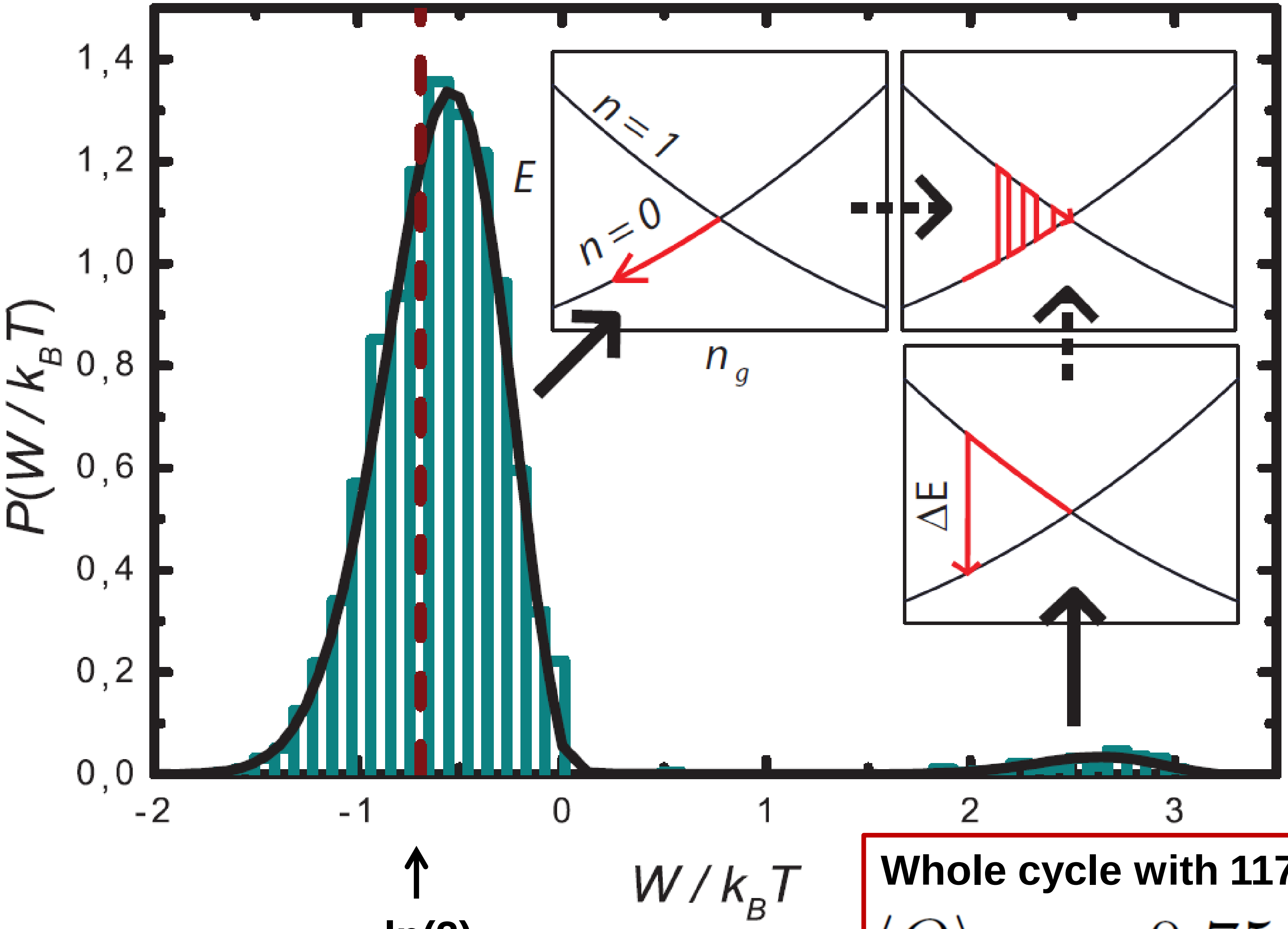
CHARGE STATES

GATE VOLTAGE

Quasi-static ramp

Measurement and decision

Measured distributions in the Szilard’s engine



↑

- ln(2)

Whole cycle with 1177 repetitions:

$$\langle Q\rangle \approx -0.75\, k_B T \ln(2)$$

Fluctuation relation with information exchange

T. Sagawa and M. Ueda, PRL 104, 090602 (2010)

Generalized Jarzynski equality and the second law in a system with feedback:

$$\boxed{\begin{aligned} &\langle e^{-(W-\Delta F)/k_B T - I} \rangle = 1 \\ &\langle W \rangle \ \geq \ -k_B T \langle I \rangle + \Delta F \end{aligned}}$$

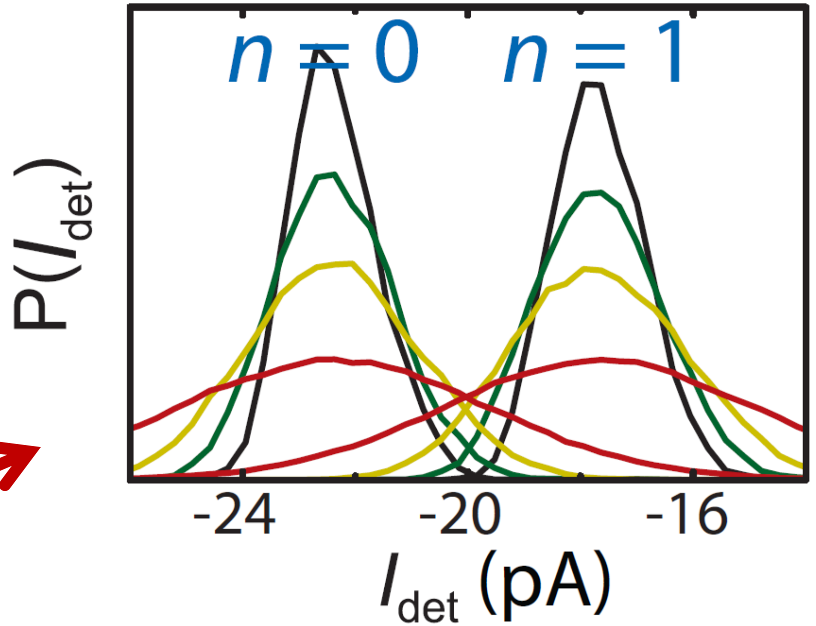
Mutual information *I*, given by the measurement error:

$$I(m,n) = \ln\left(\frac{P(n|m)}{P(n)}\right)$$

Mutual information in our system

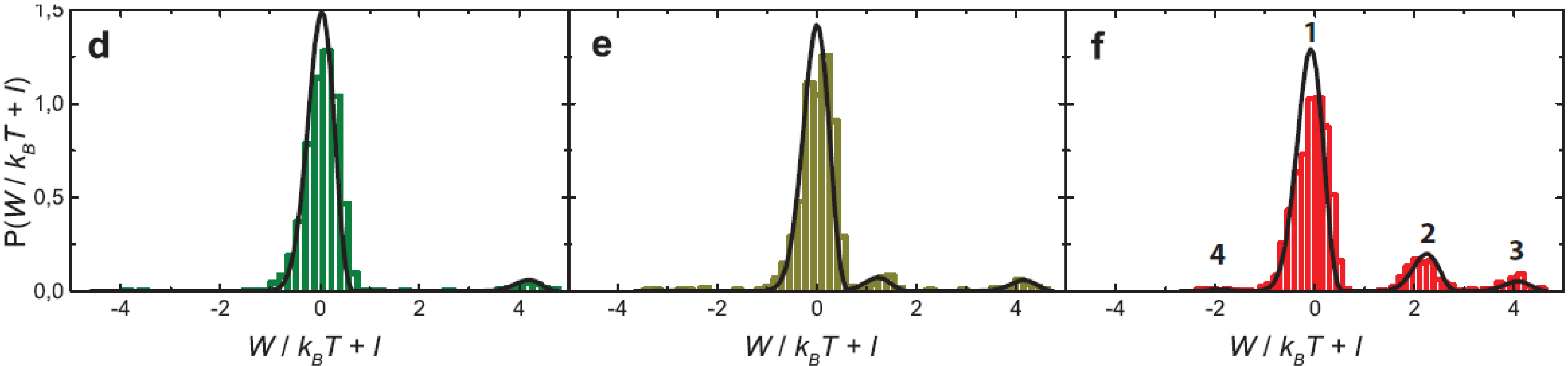
$$I(n = m) = \log(2(1 - \epsilon))$$

$$I(n \neq m) = \log(2\epsilon)$$

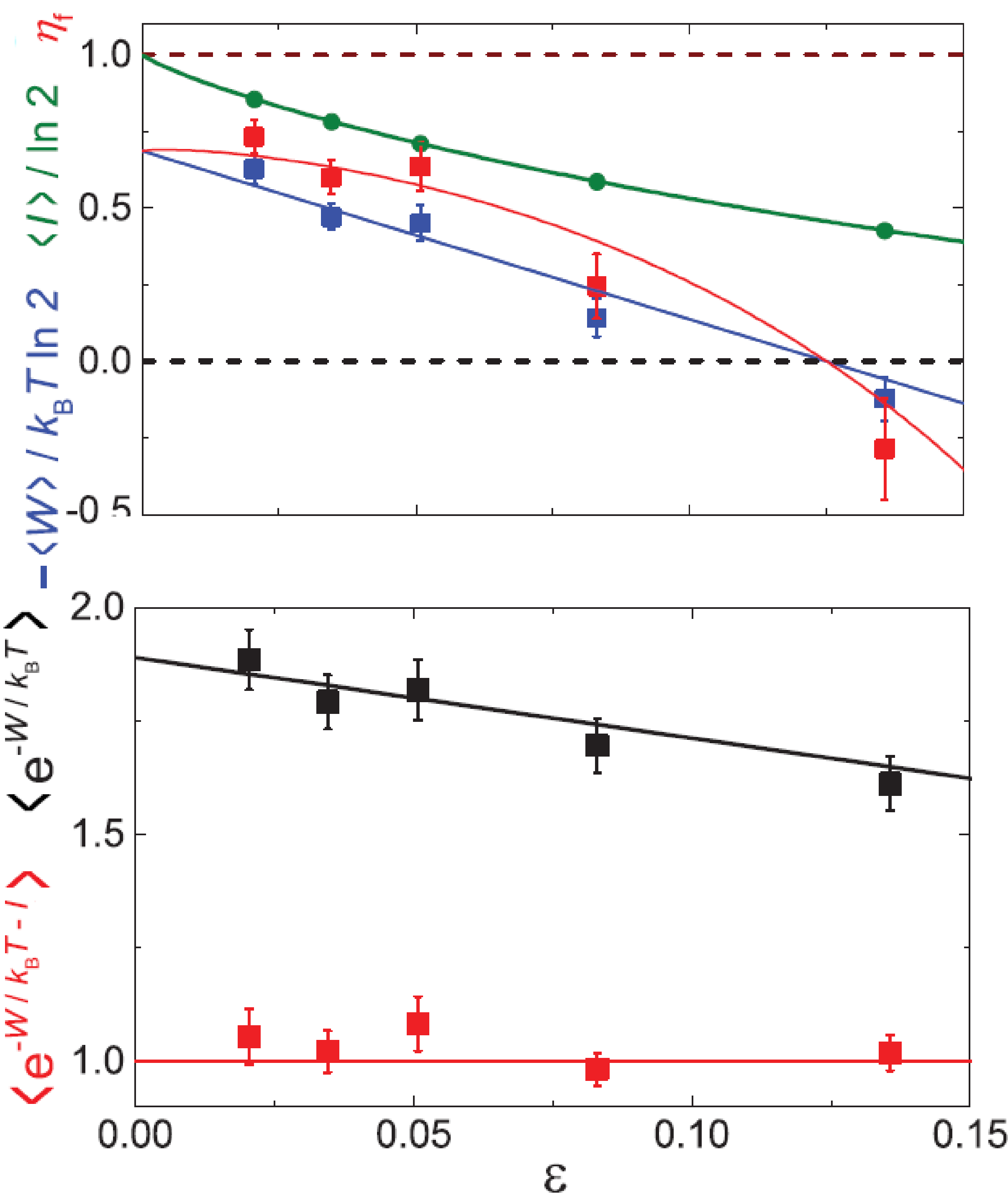


Measurements of *n* at different detector bandwidths

Convert the experimental distributions based on the measured values of ε:



Efficiency and fluctuation relations



Generalized Jarzynski equality

$$\langle e^{-(W-\Delta F)/k_B T - I} \rangle = 1$$

verified

J.V. Koski et al., arXiv:1405.1272, PRL (2014).

Tribute to Nikolai

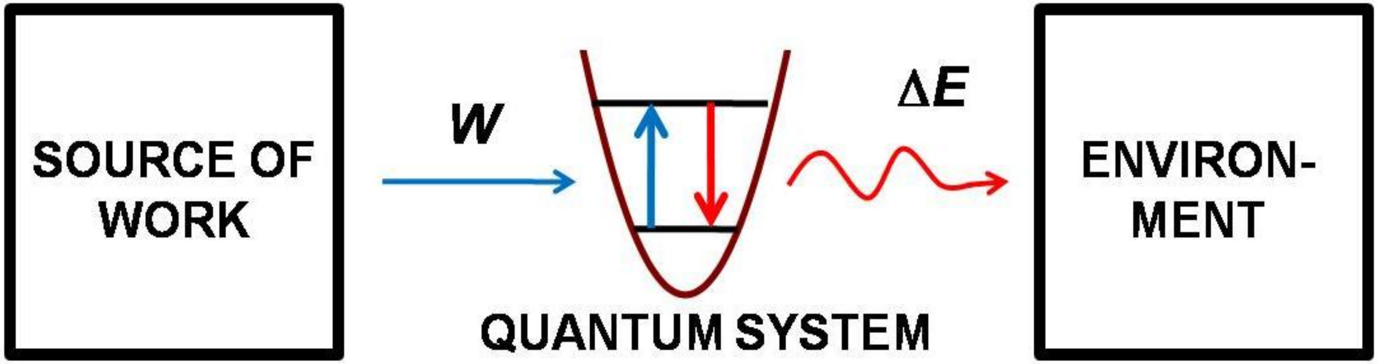
Collaboration in science on a person – to – person level can be most enjoyable and rewarding. I was very fortunate to have Kolya - a great scientist and human being - as my friend and colleague for more than 30 years.

The intensity of our interaction in physics varied a lot during those years. Most regrettably, it was suddenly over just at a moment when I thought it was only starting.

Work and dissipation in a quantum system: calorimetry

Work on a (closed) quantum system?
Kurchan 2000, Talkner et al. 2007, Campisi et al. 2011

Open system? We propose to measure the photons exchanged between the system and environment

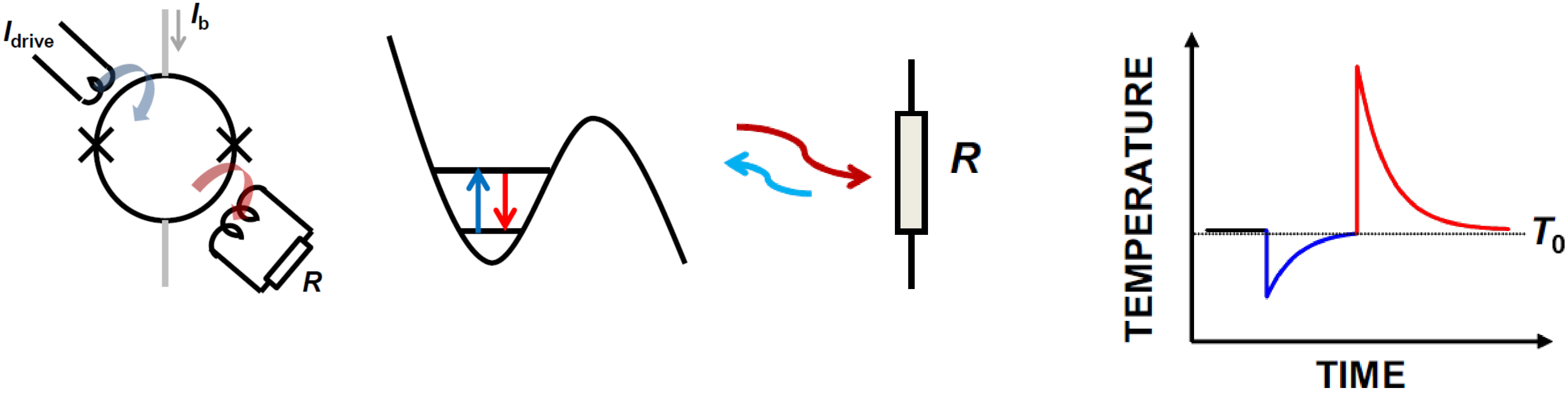


J. P., P. Solinas, A. Shnirman, D. Averin, NJP 15, 115006 (2013).

Measurement of work distribution of a two-level system

Calorimetric measurement:
Measure temperature of the resistor upon relaxation

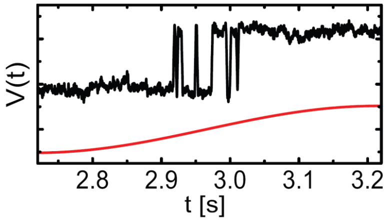
”Typical parameters”:
$\Delta T_R \sim 1 - 10$ mK over 0.01 - 1 ms time

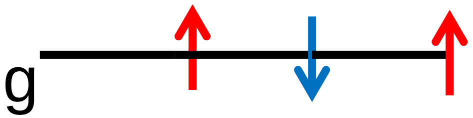


Quantum jump approach for dissipation

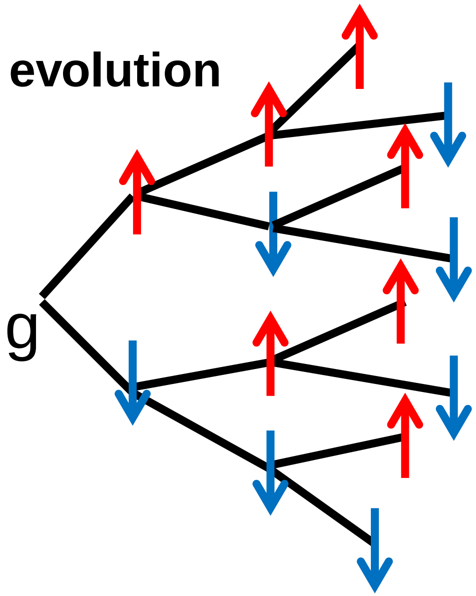
The jump method: Dalibard et al., PRL **68**, 580 (1992); Plenio and Knight, RMP **70**, 101 (1998). We apply the jump method to a driven qubit

Classical evolution

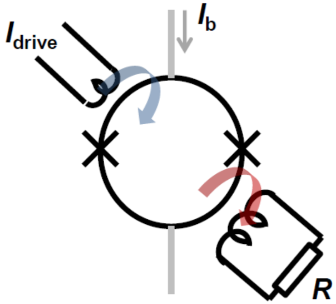


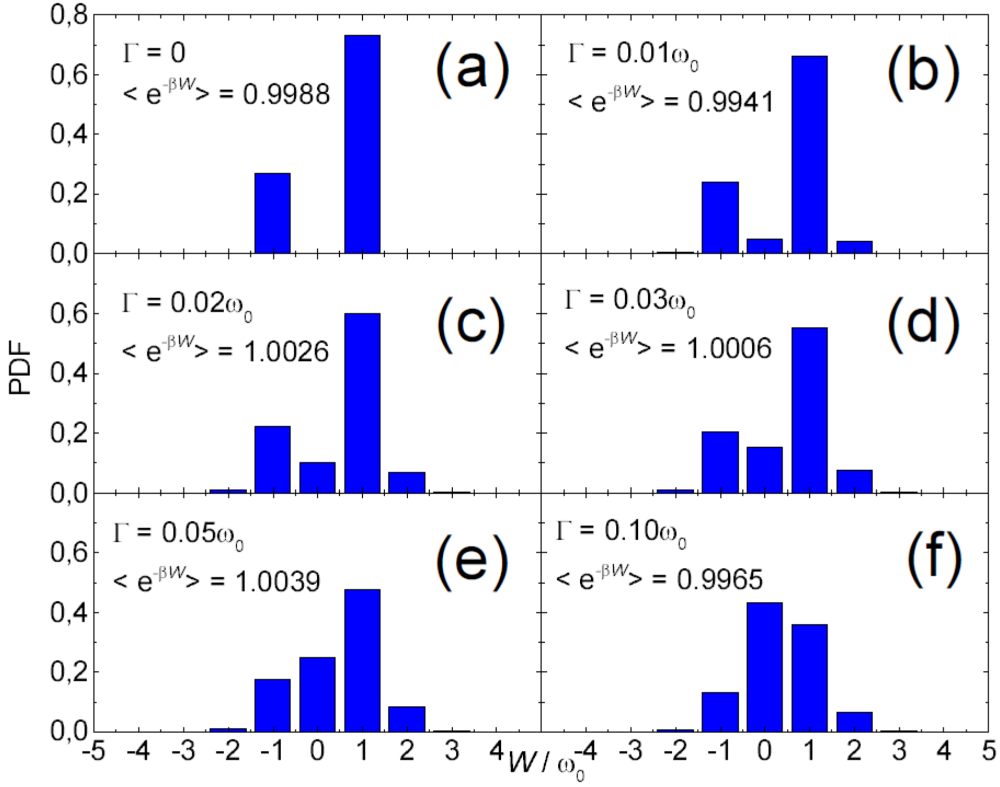


Quantum evolution



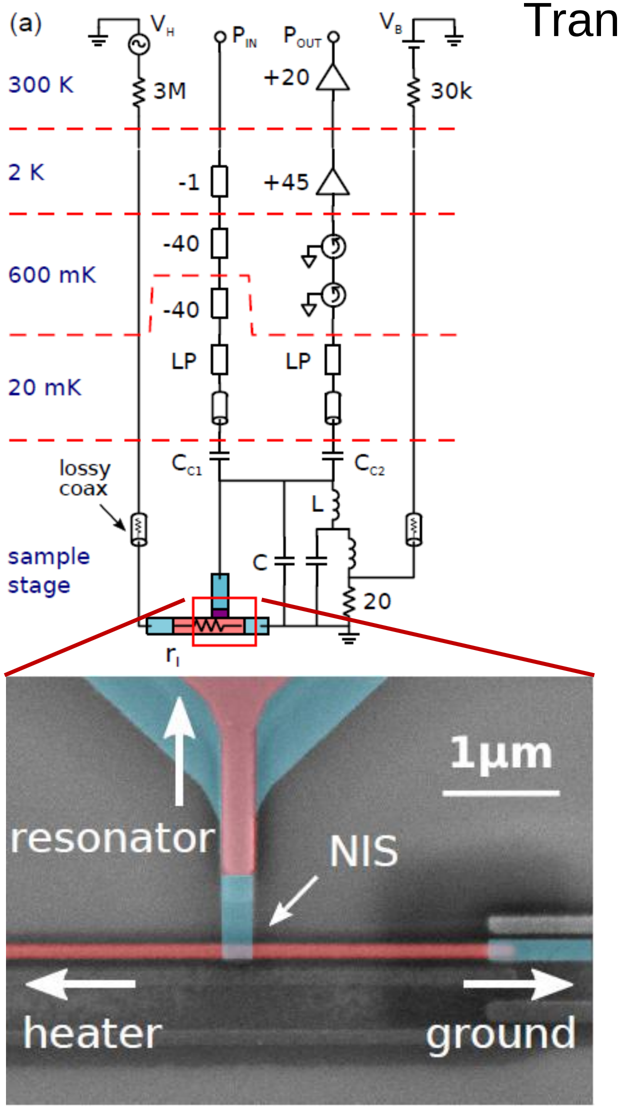
π pulse with dissipation



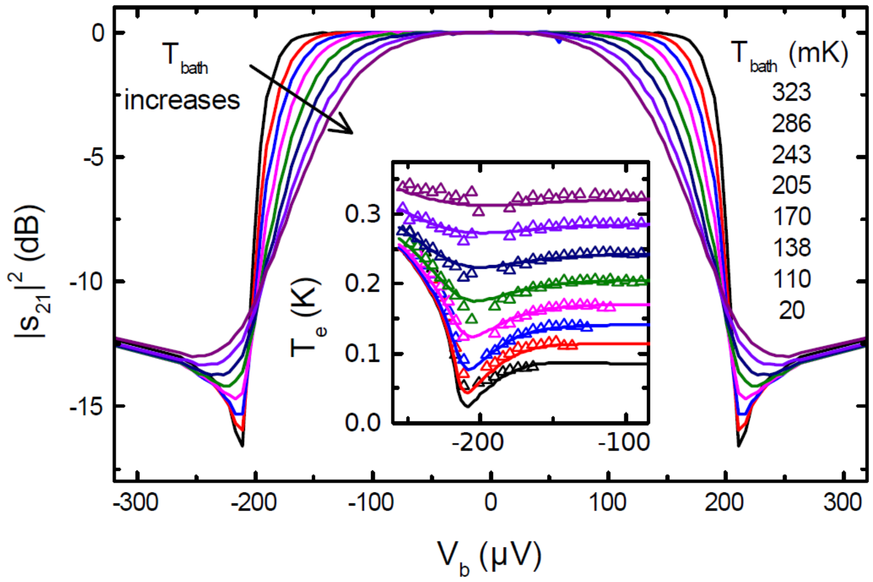


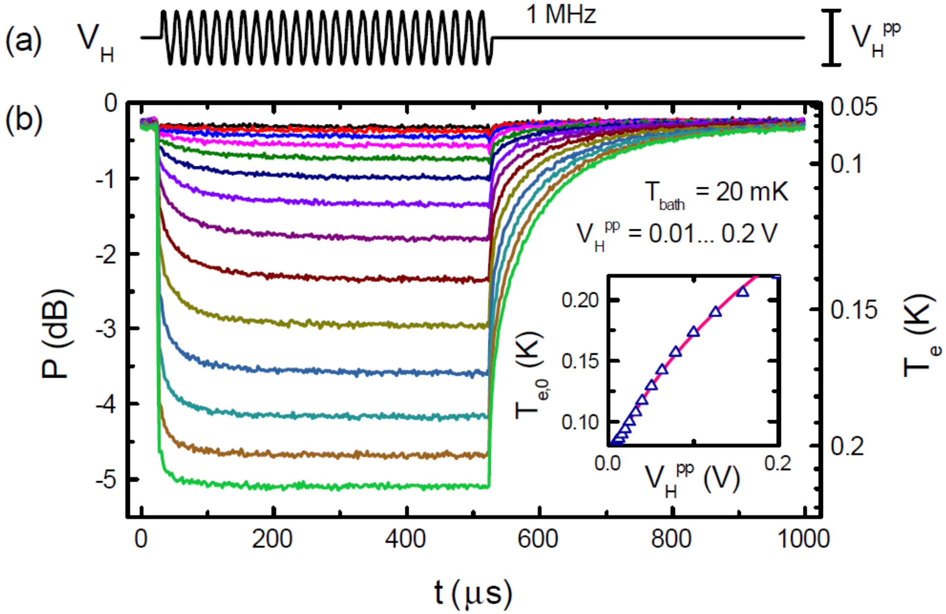
F. Hekking and J.P., PRL 111, 093602 (2013).

Fast NIS thermometry



Transmission read-out at 600 MHz of a NIS junction





S. Gasparinetti, K. Viisanen, O. Saira et al., arXiv:1405.7568 (2014)
(proof of the concept by Schmidt et al., 2003)

Summary

Beyond the 2nd law of thermodynamics: non-equilibrium fluctuation relations investigated

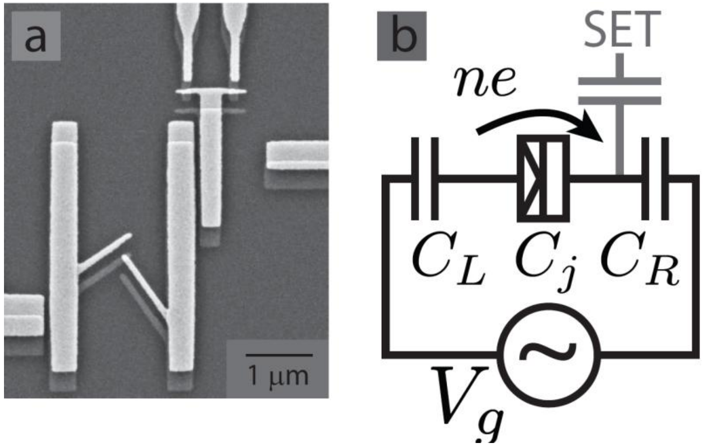
Maxwell's demon – Szilard's engine realized for single electrons

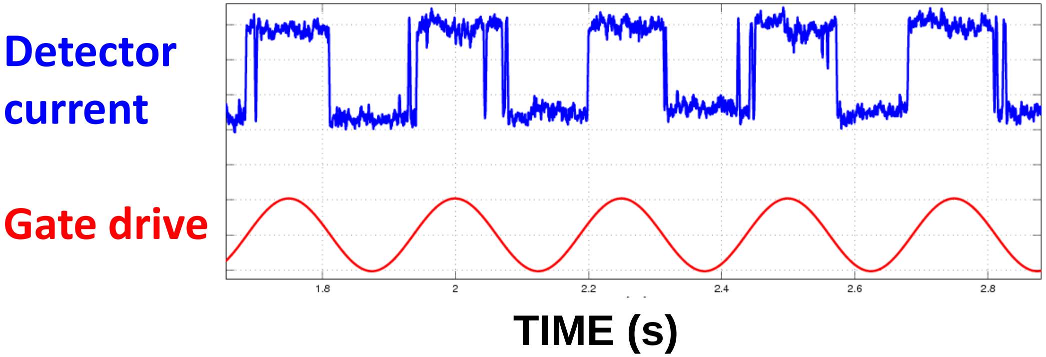
Generalized Jarzynski equality measured under feedback control

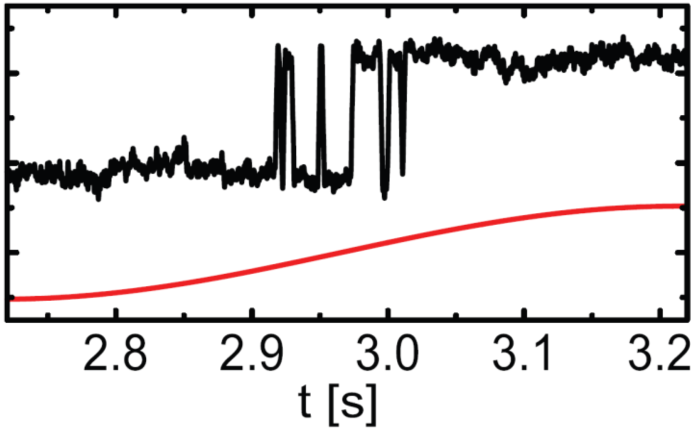
Future and on-going experiments:
Direct calorimetric measurement of heat
Quantum fluctuation relations

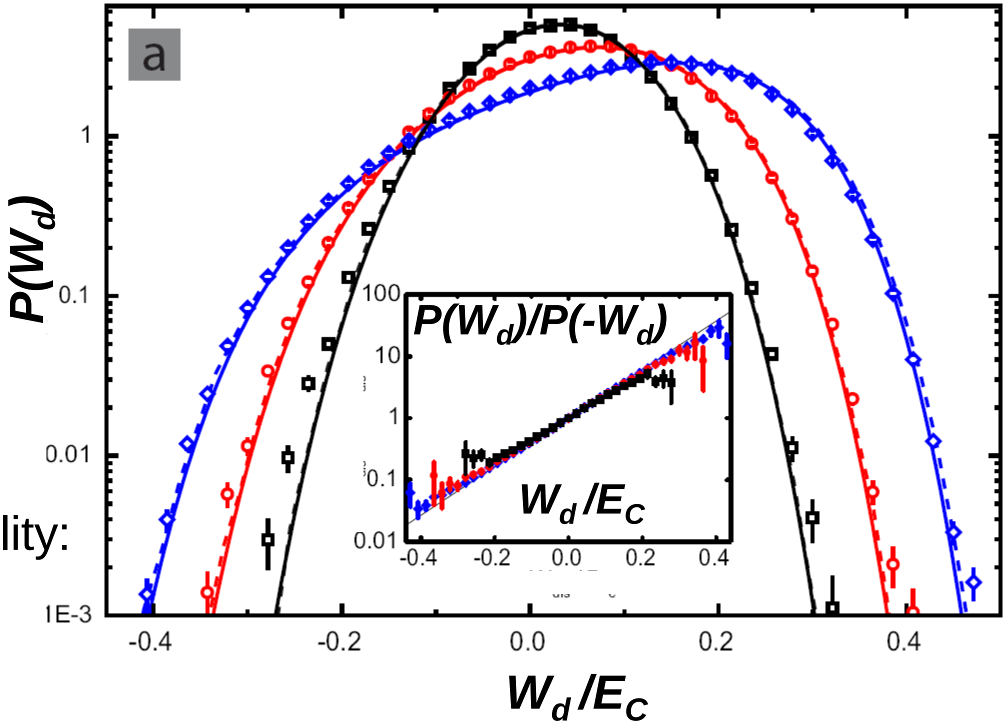
Experiment on a single-electron box

O.-P. Saira et al., PRL 109, 180601 (2012); J.V. Koski et al., Nature Physics 9, 644 (2013).









The distributions satisfy Jarzynski equality:

$$\langle e^{-\beta(W-\Delta F)}\rangle = 1.03 \pm 0.03$$