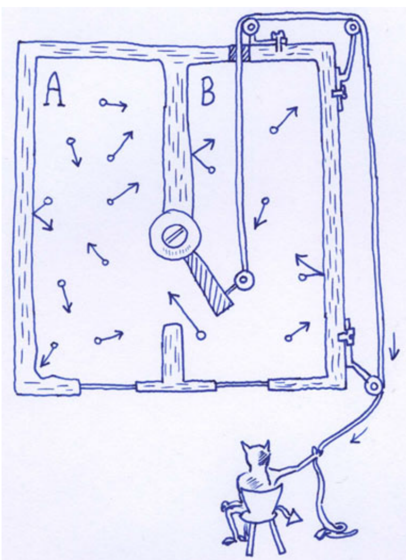
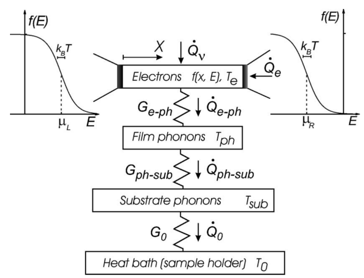
LECTURE 2, Jukka Pekola

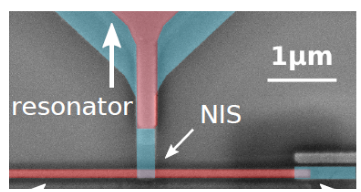
Outline

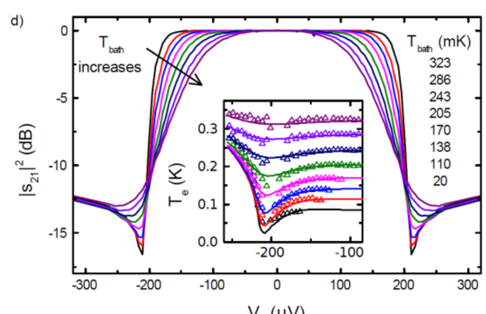
Maxwell's demon



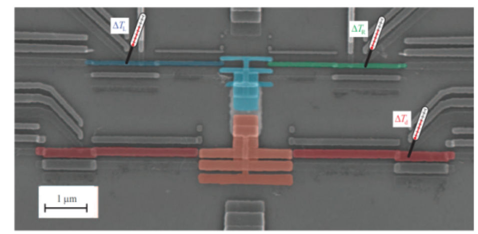
Energy relaxation and thermometry







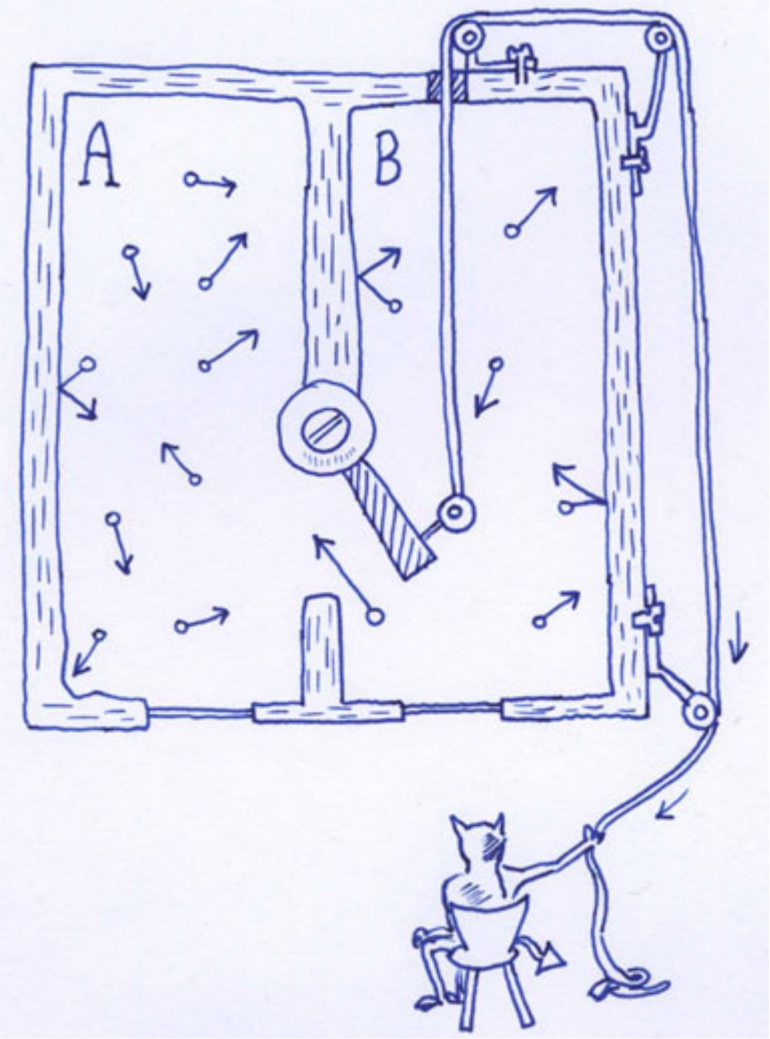
Autonomous Maxwell's Demon



... role of information

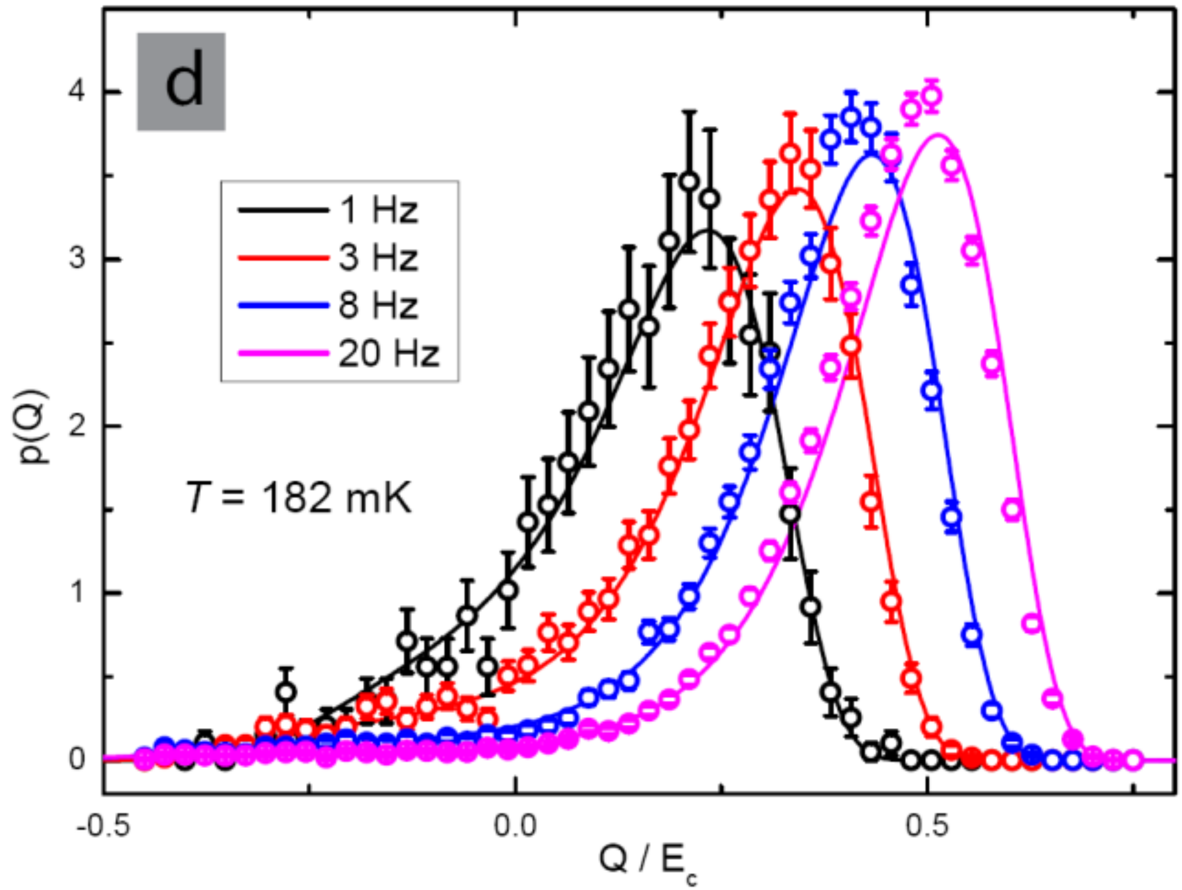
Maxwell's Demon

J. C. Maxwell 1867



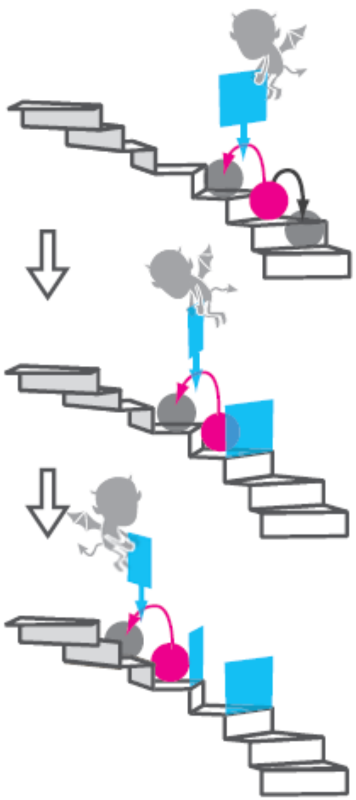
Negative heat

Possible to extract heat from the environment

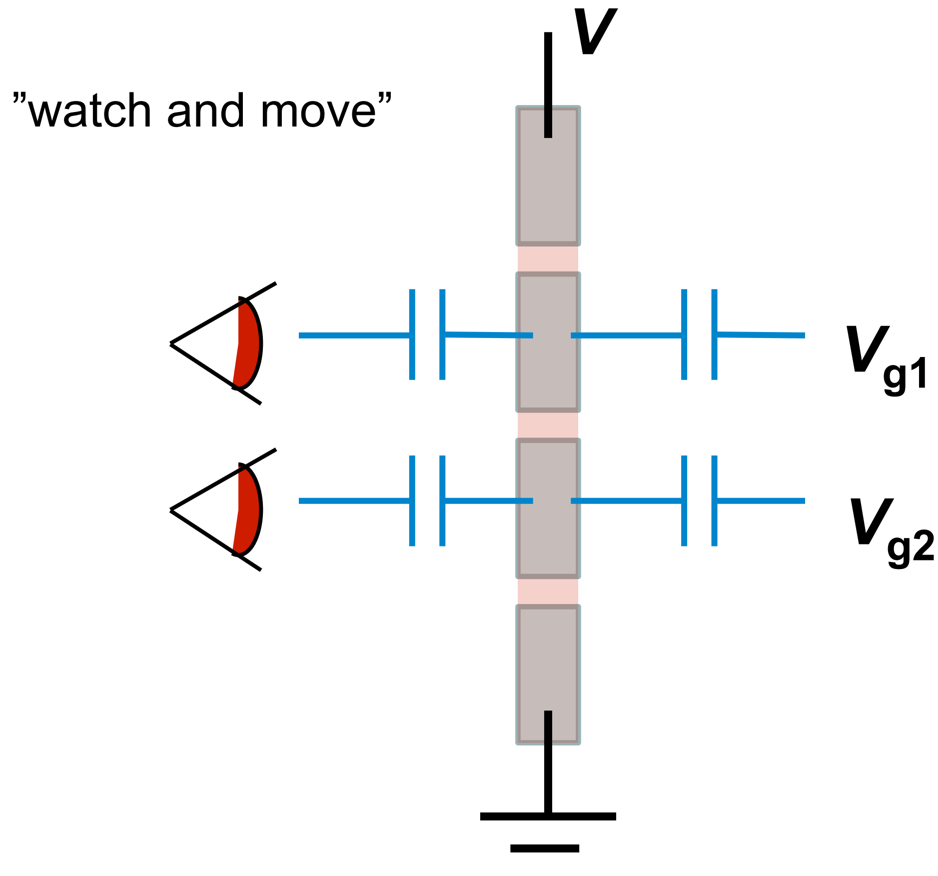


Provides means to realize Maxwell's demon using SETs

Electronic Maxwell's demon



S. Toyabe et al., Nature Physics 2010



D. Averin et al., PRB 84, 245448 (2011).
G. Schaller et al., PRB 84, 085418 (2011).
P. Strassberg et al., PRL 110, 040601 (2013).
J. Bergli et al., Phys. Rev. E 88, 062139 (2013).

Szilard's engine (L. Szilard 1929)

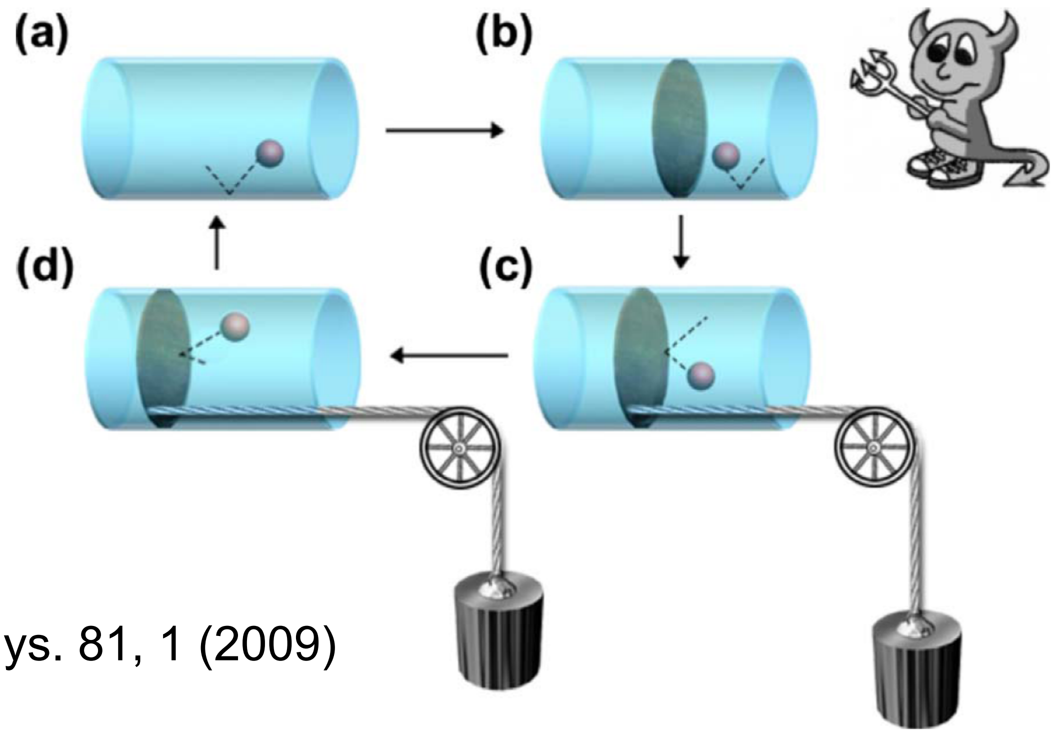


Figure from
Rev. Mod. Phys. 81, 1 (2009)

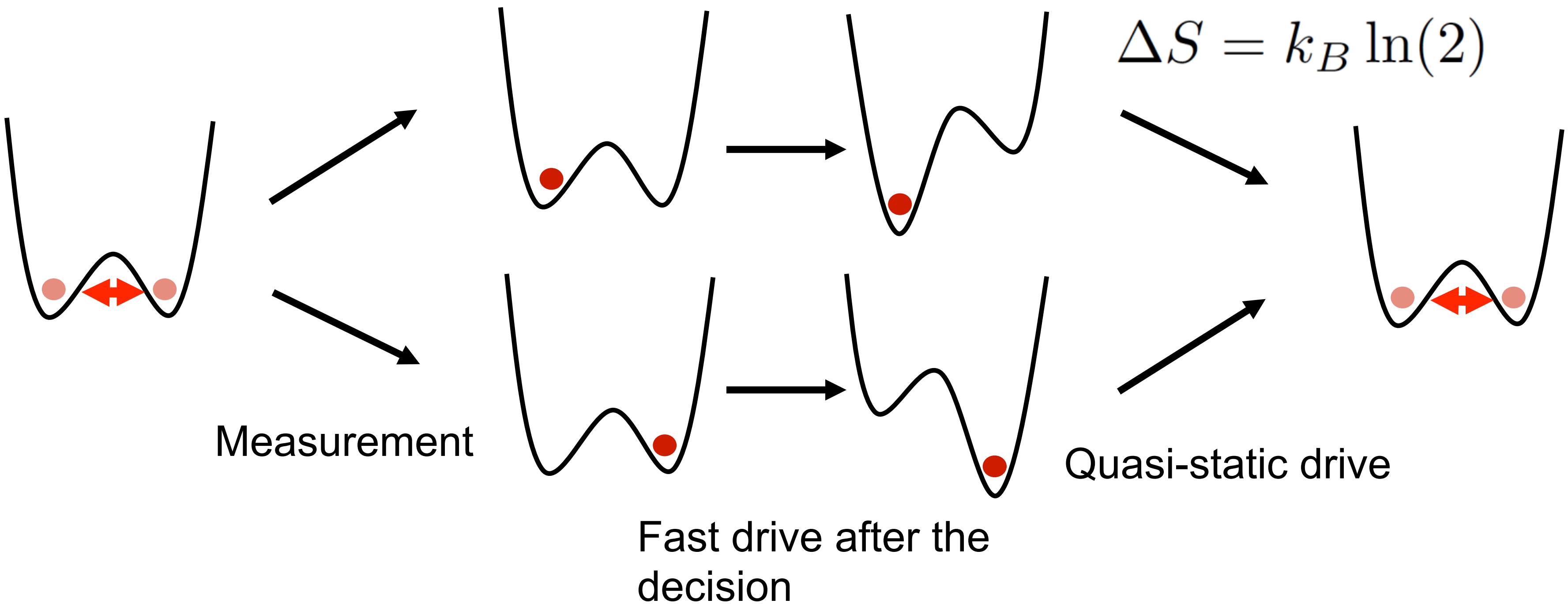
Isothermal expansion of the "single-molecule gas" does work against the load

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

Szilard’s engine for single electrons

J. V. Koski et al., PNAS 111, 13786 (2014); PRL 113, 030601 (2014).

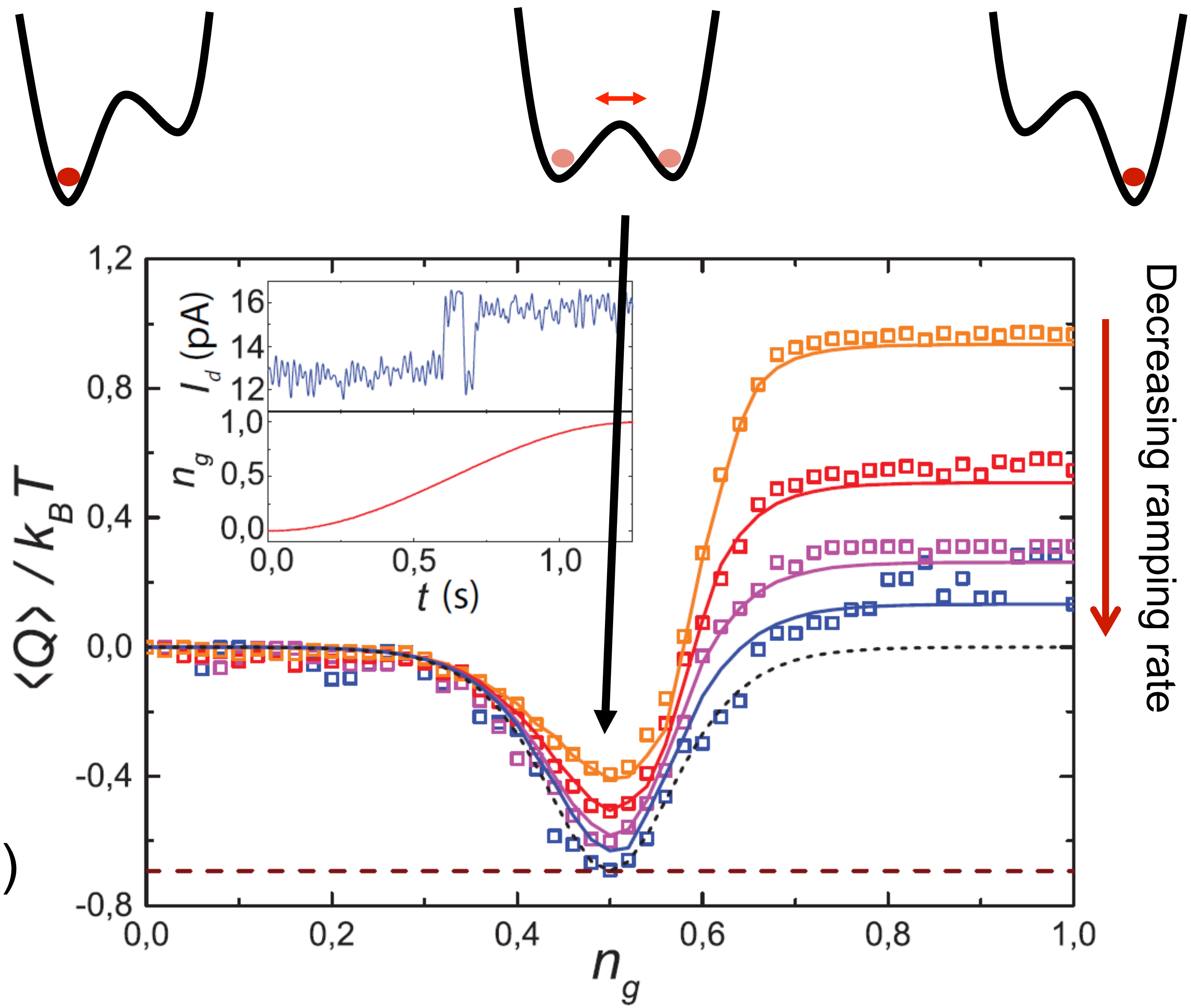
Entropy of the charge states: $$S = -k_B \sum_{i=0,1} p(i) \ln[p(i)]$$



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

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

Extracting heat from the bath



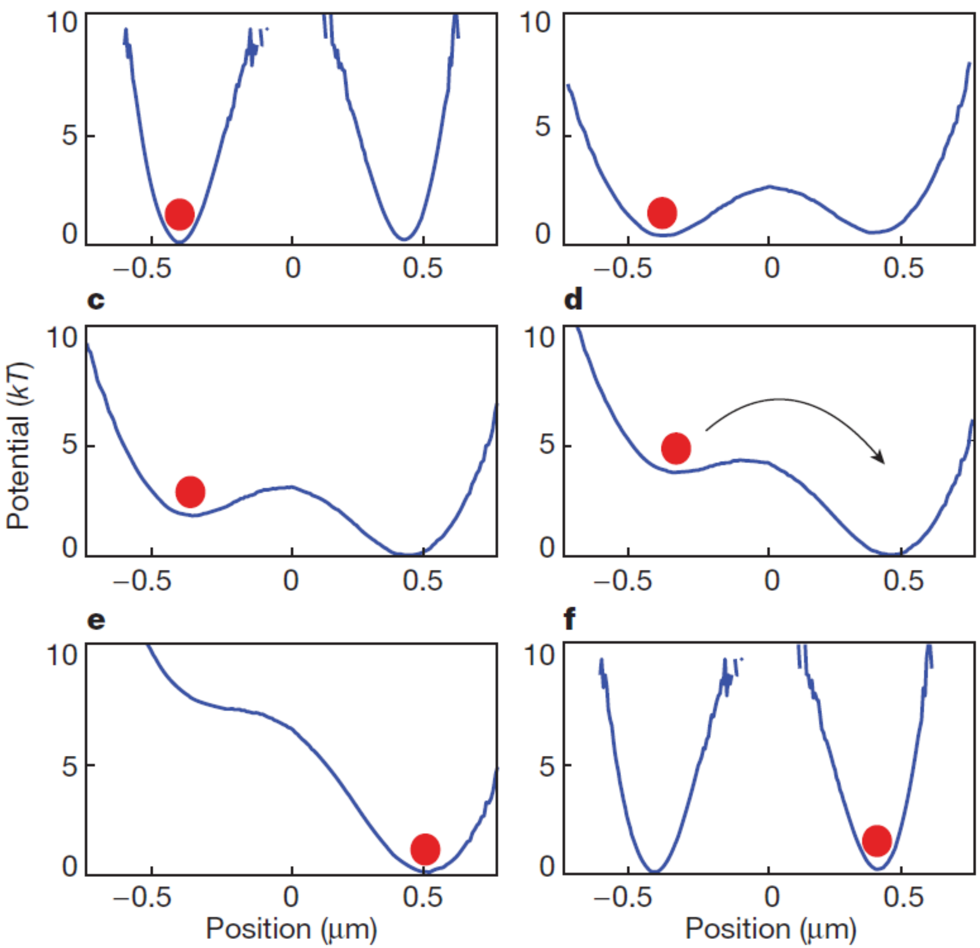
- $k_B T \ln(2)$

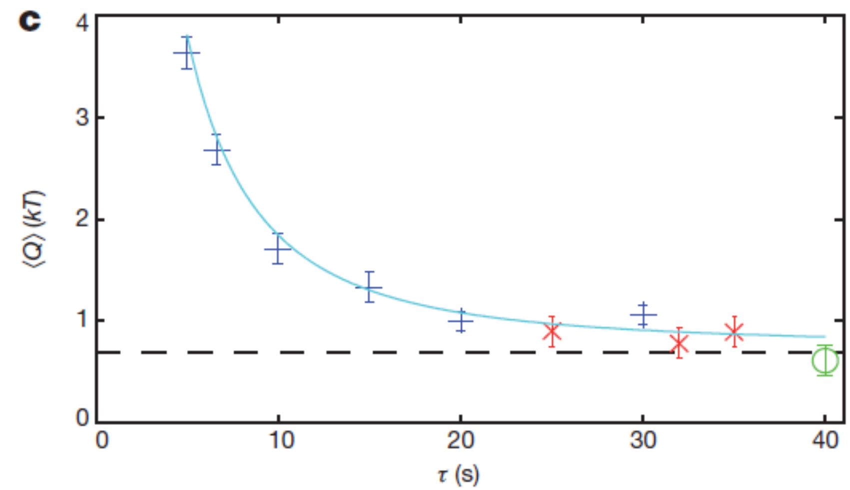
Erasure of information

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

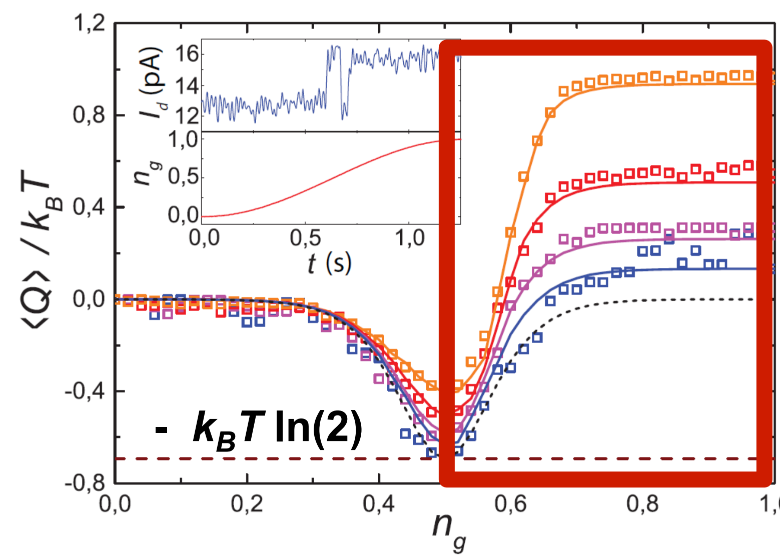
A. Berut, … , S. Ciliberto et al., Nature 2012

Experiment on a colloidal particle:

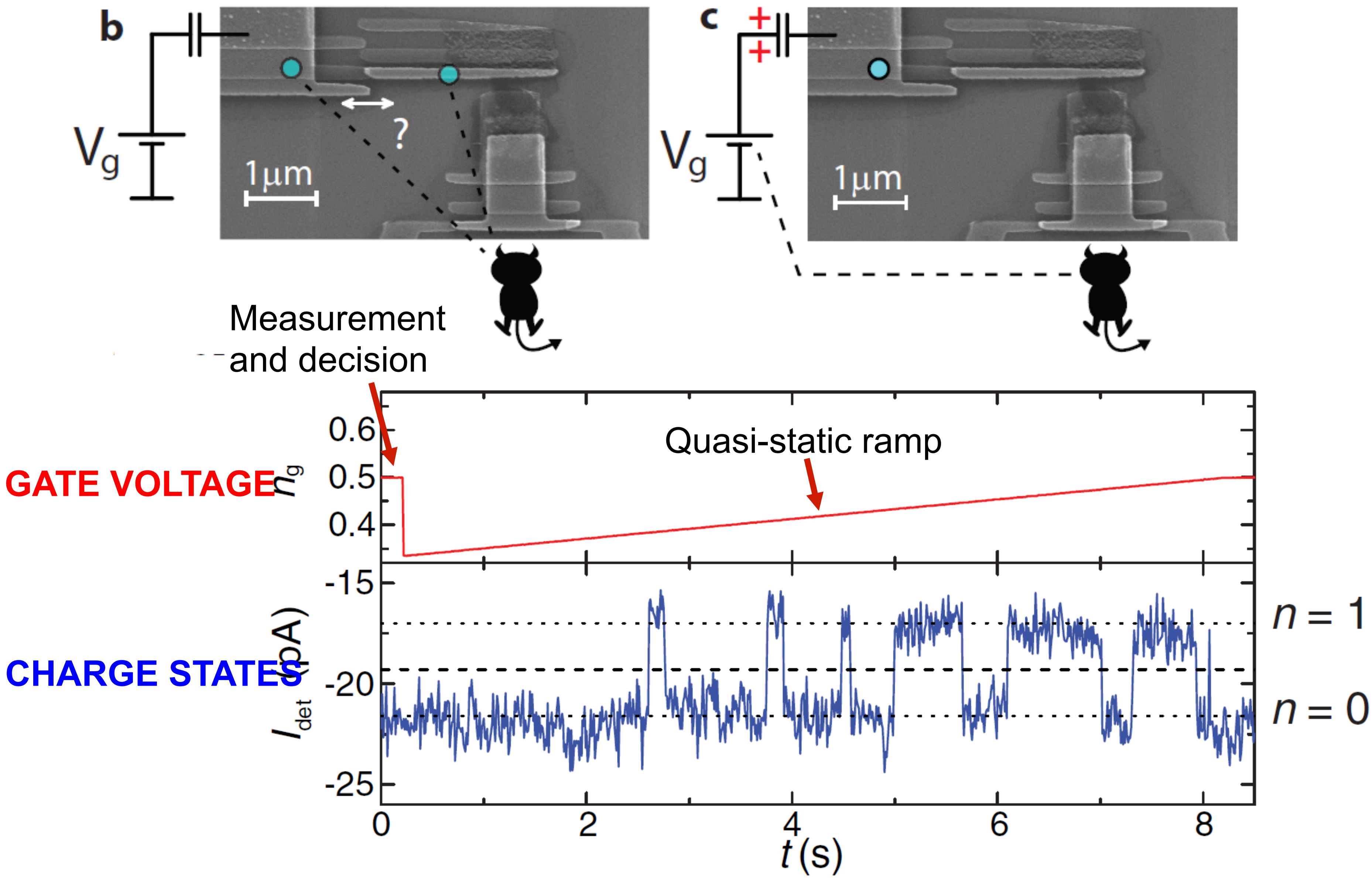




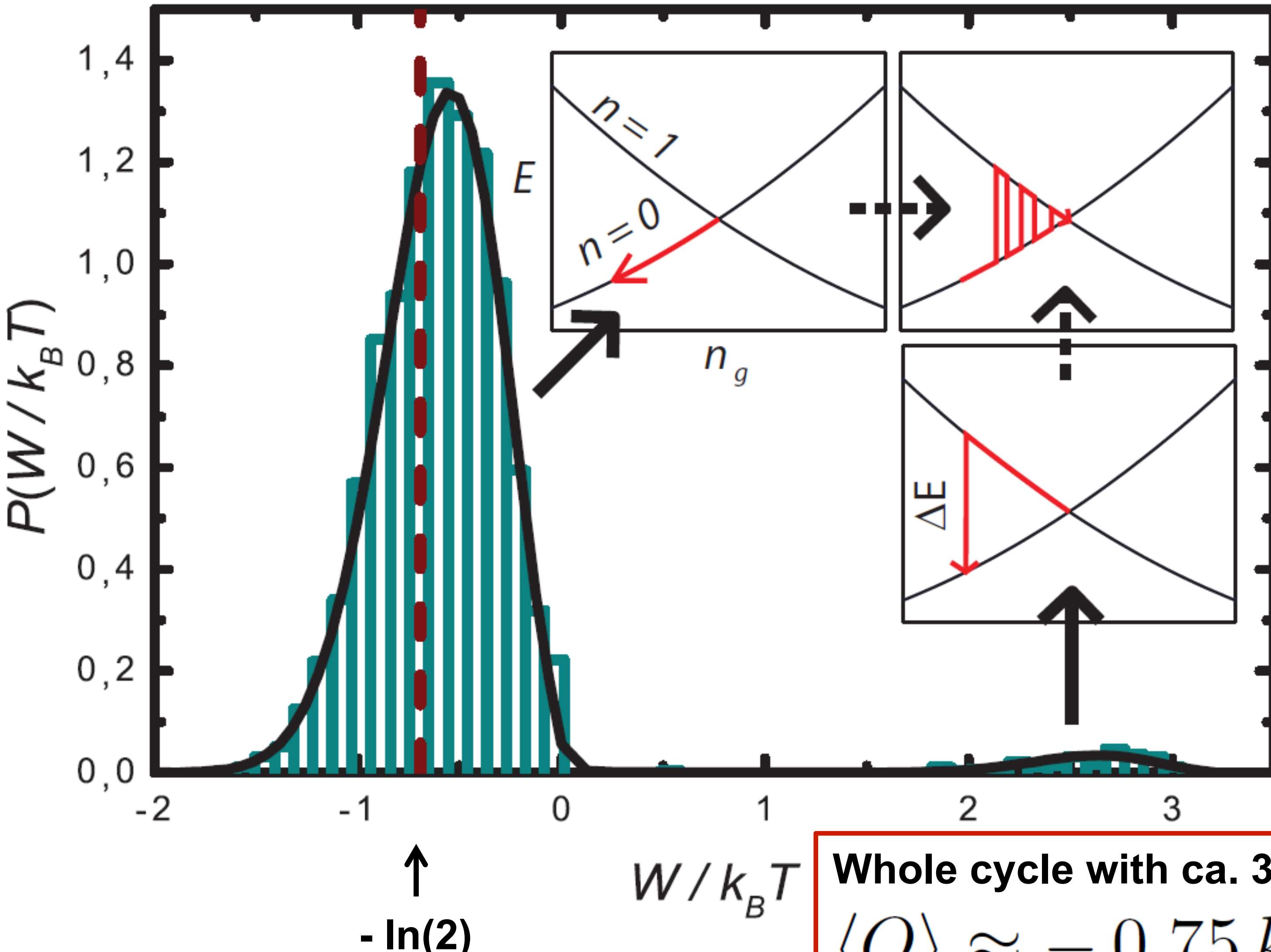
Corresponds to our experiment:



Realization of the Maxwell's demon with an electron



Measured distributions in the Szilard's engine



Whole cycle with ca. 3000 repetitions:

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

Sagawa-Ueda relation

$$\langle e^{-(W-\Delta F)/k_B T - I} \rangle = 1 \qquad I(m,n) = \ln\left(\frac{P(n|m)}{P(n)}\right)$$

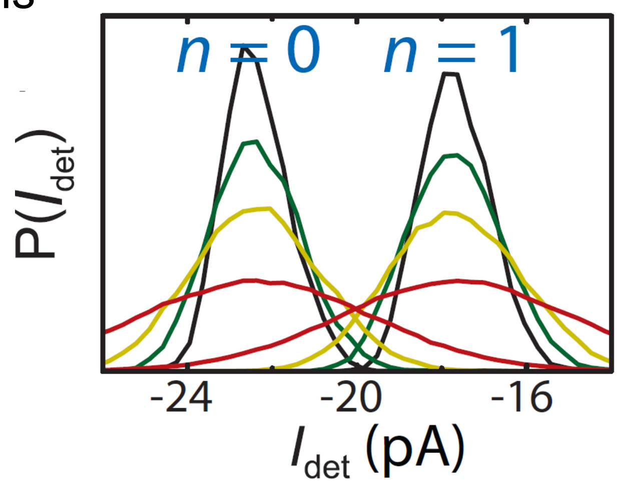
T. Sagawa and M. Ueda, PRL 104, 090602 (2010)

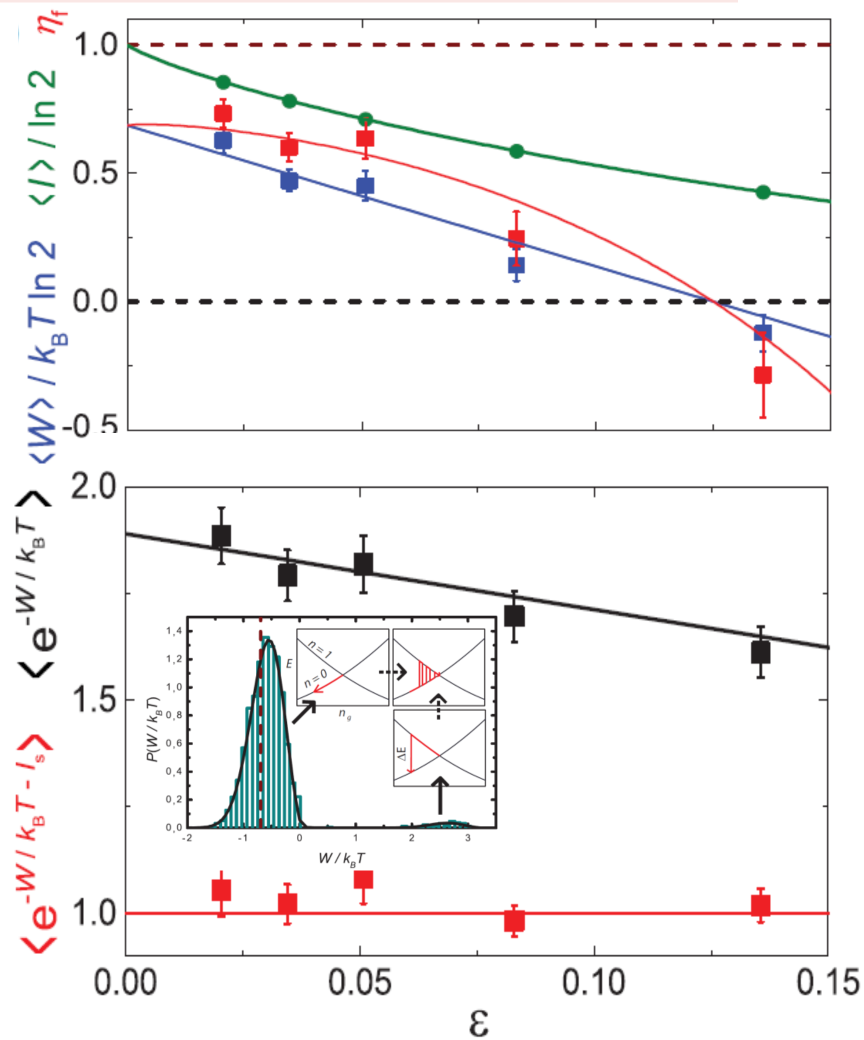
For a symmetric two-state system:

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

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

Measurements of *n* at different detector bandwidths

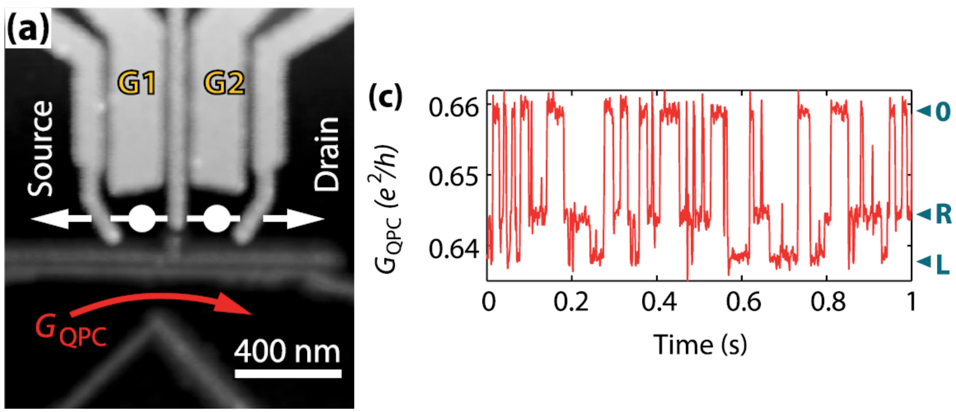


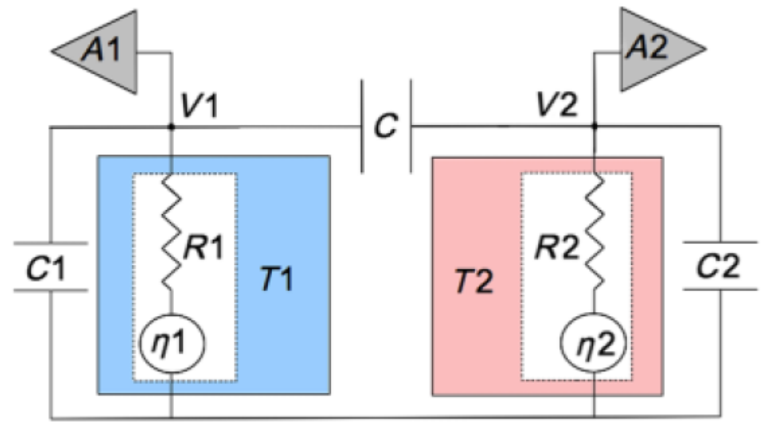


J. V. Koski et al., PRL 113, 030601 (2014)

Work and heat in small systems: experimental situation

Typically an indirect measurement, hinging on understanding the system sufficiently well





$$Q = neV_{DS}$$

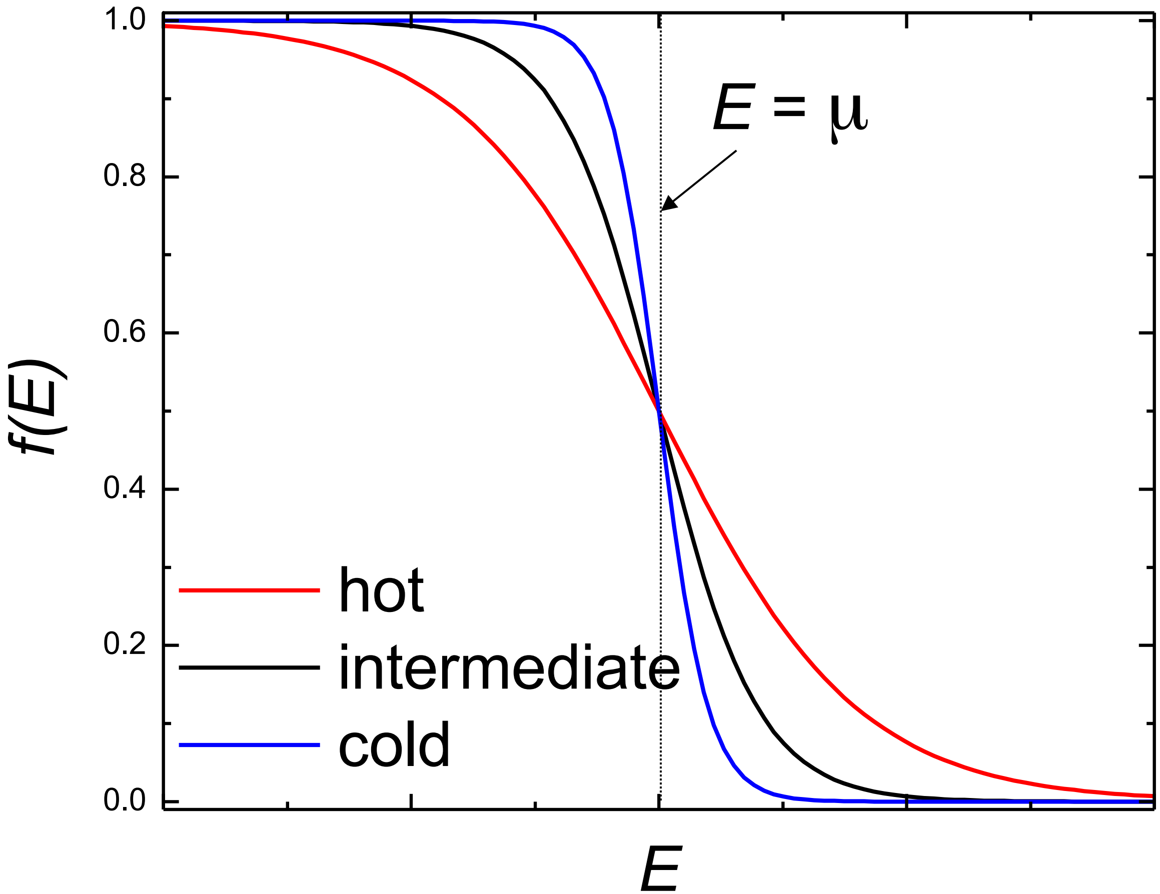
$$Q_{m,\tau} = \int_t^{t+\tau} i_m V_m dt$$

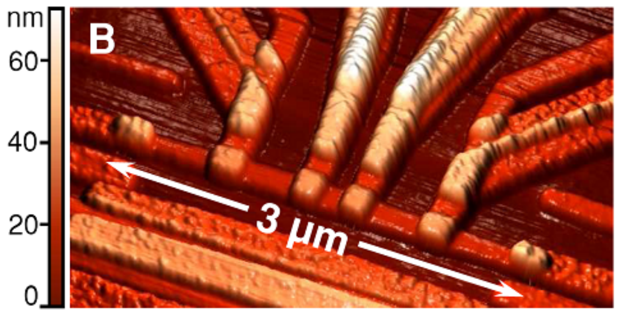
Y. Utsumi et al. PRB 81, 125331 (2010),
B. Kung et al. PRX 2, 011001 (2012)

S. Ciliberto et al., PRL 110, 180601 (2013)

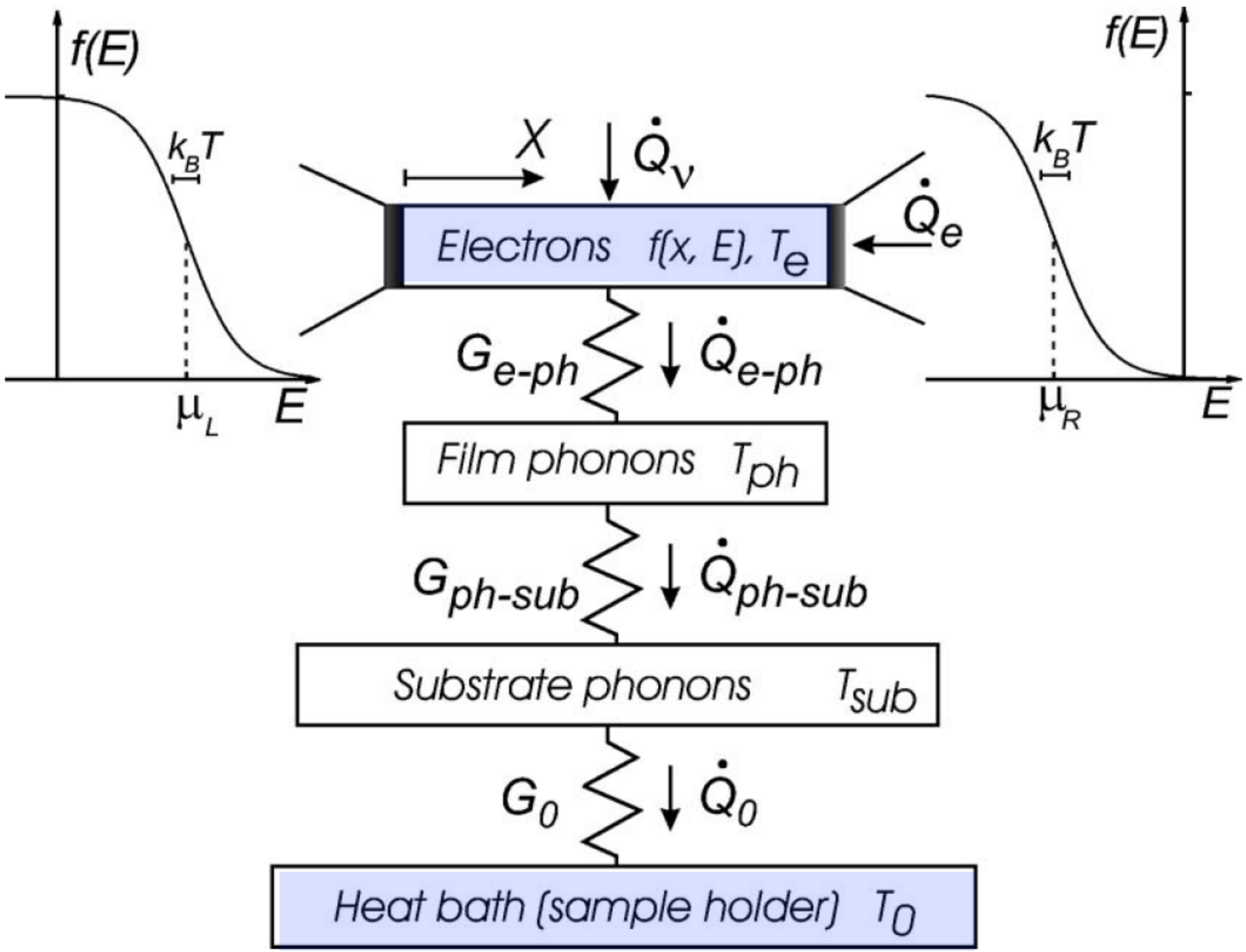
Temperature in an electronic device

$$f(E) = \frac{1}{1 + e^{(E-\mu)/k_B T}}$$

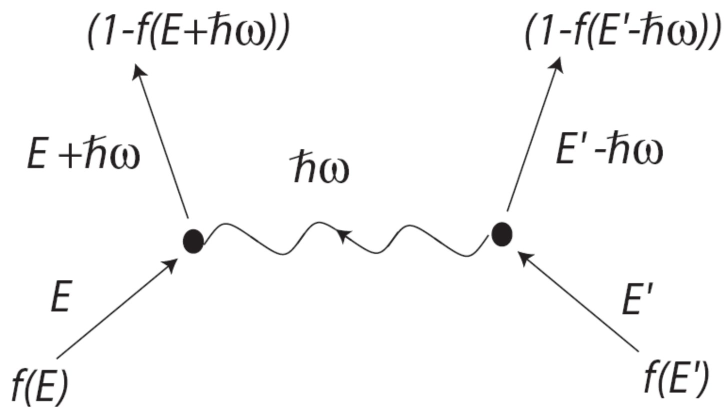




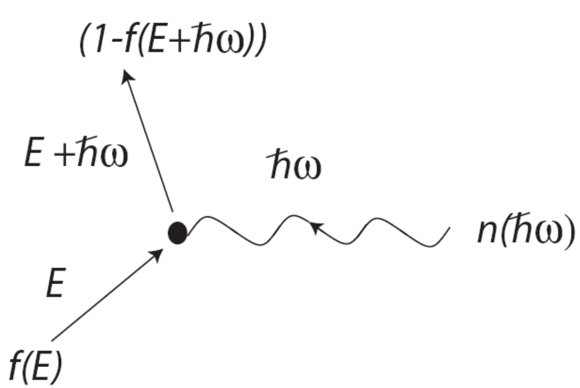
Generic thermal model for an electronic conductor

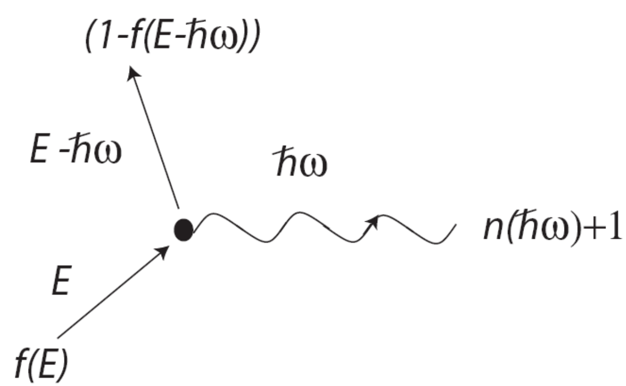


Electron-electron and electron-phonon relaxation



e-e relaxation drives the system towards *quasi-equilibrium*





e-p relaxation drives the system towards *equilibrium*

The energy distribution of electrons in a small metal conductor

The distribution is determined by energy relaxation:

Equilibrium –**Thermometer measures the temperature of the ”bath”**
Quasi-equilibrium –**Thermometer measures the temperature of the electron system which can be different from that of the ”bath”**
Non-equilibrium –**There is no well defined temperature measured by the ”thermometer”**

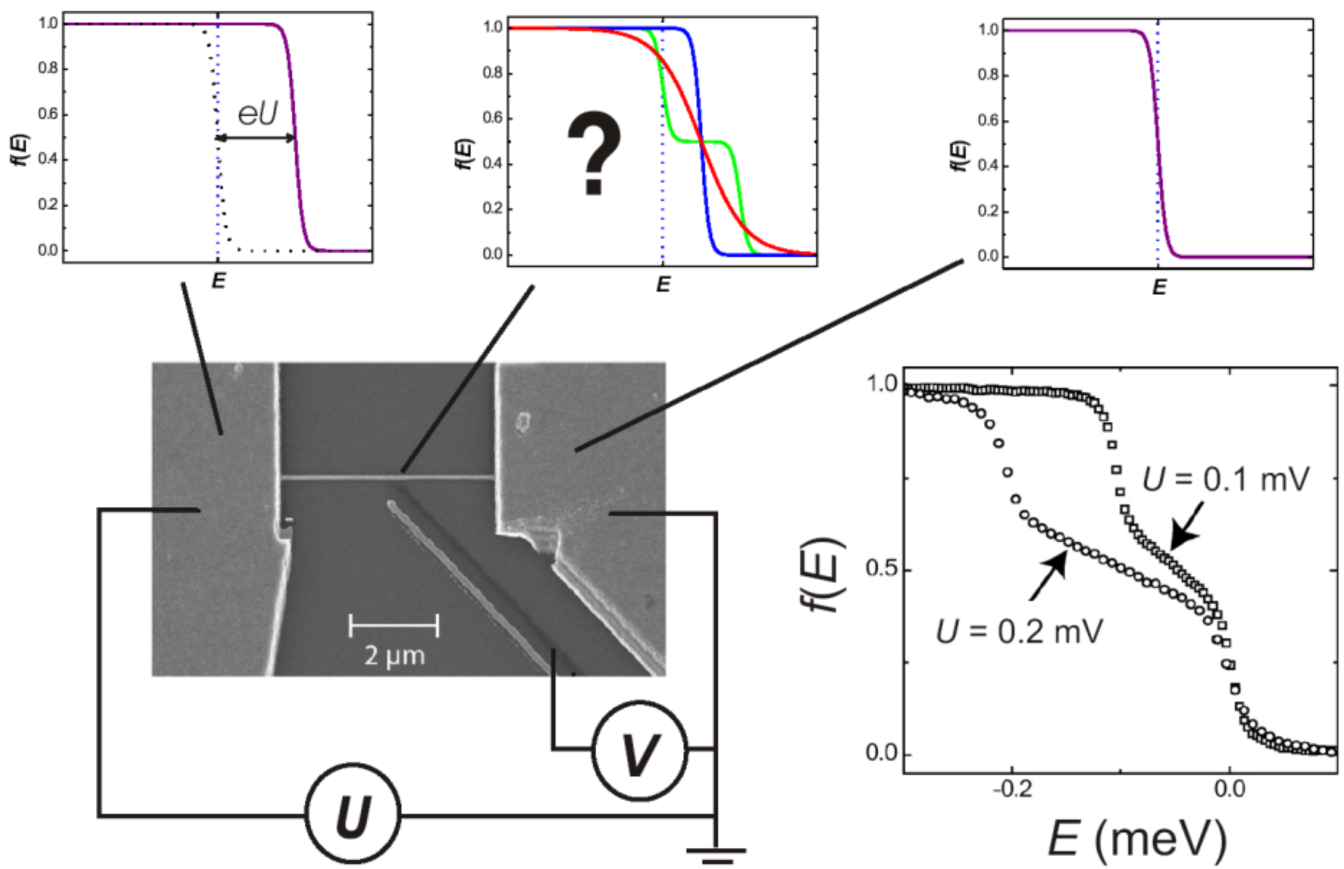


Illustration: diffusive normal metal wire
H. Pothier et al. 1997

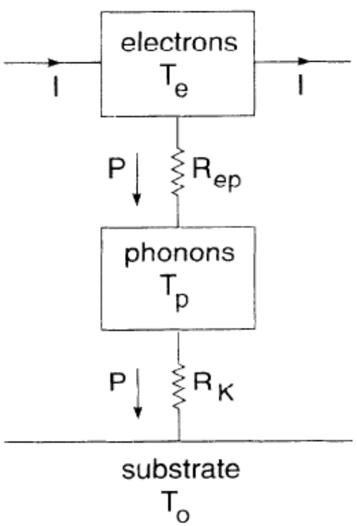
τ_{ee} = 1 ns
τ_{ep} = 10 μs

Electron-phonon relaxation in metals at low *T*

PHYSICAL REVIEW B VOLUME 49, NUMBER 9 1 MARCH 1994-I

Hot-electron effects in metals

F. C. Wellstood,* C. Urbina,† and John Clarke
Department of Physics, University of California, Berkeley, California 94720
and Materials Sciences Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 21 July 1993)



$$\dot{Q}_{ep} = \Sigma\Omega(T_e^5 - T_p^5)$$

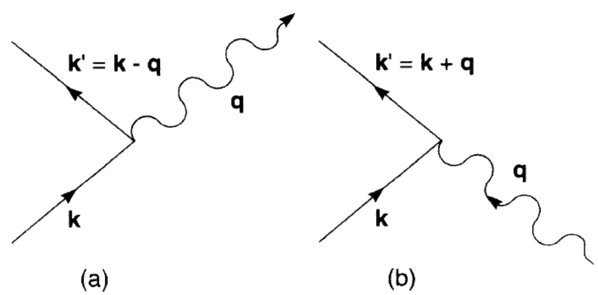
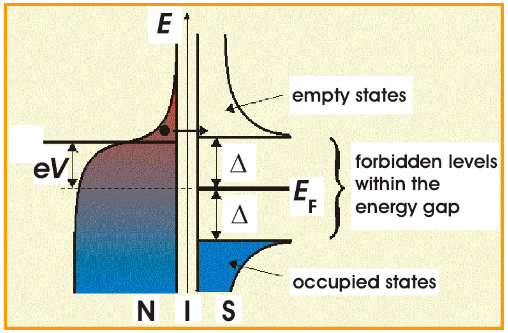


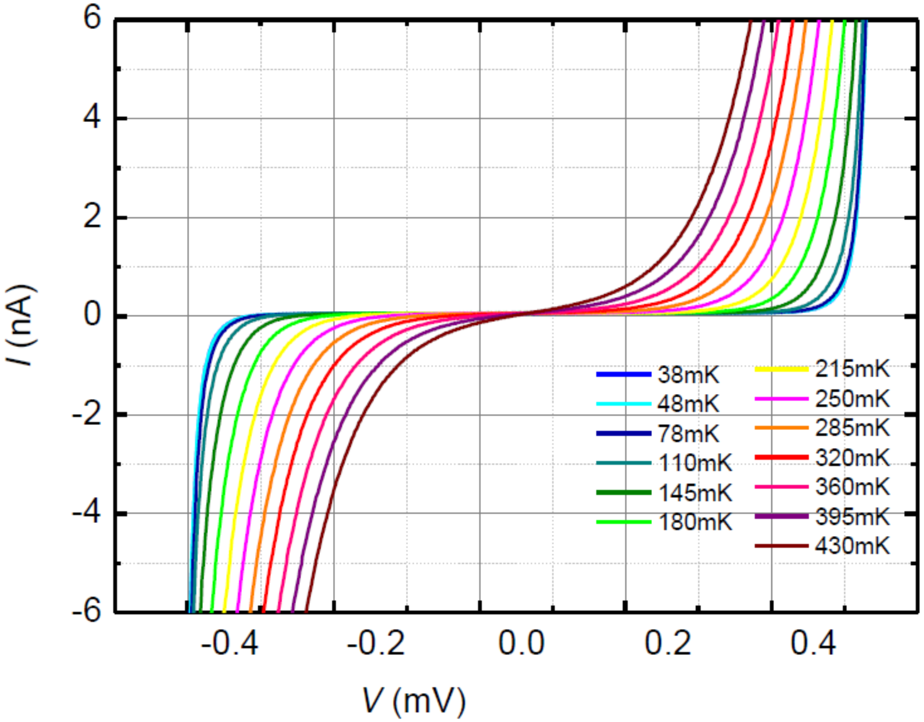
FIG. 2. Emission and absorption of phonons of wave vector **q** by an electron of wave vector **k**.

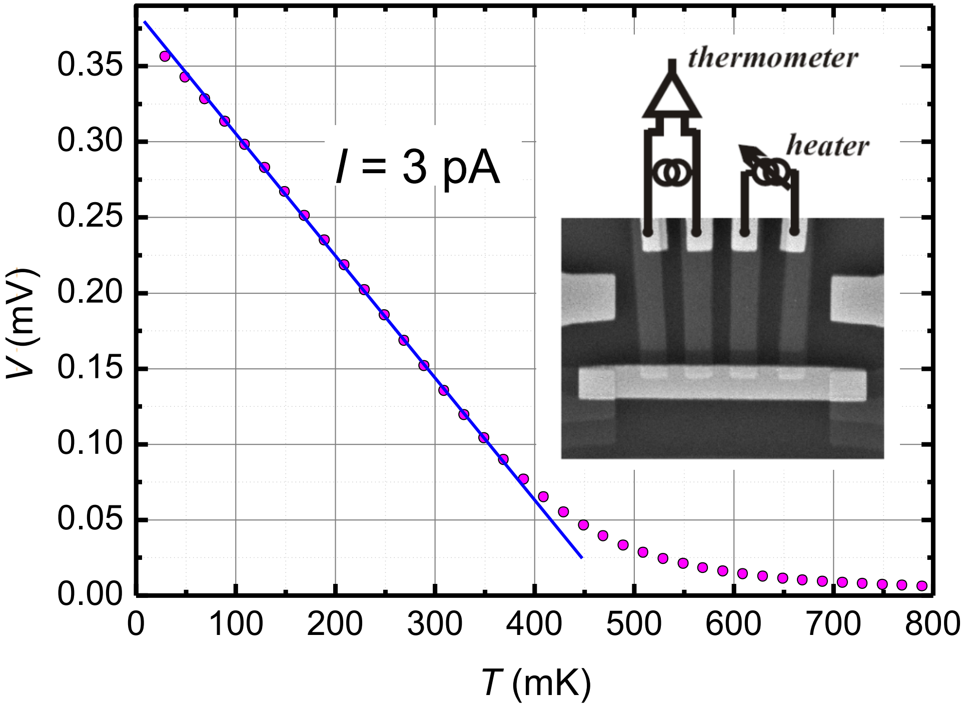
NIS-thermometry

$$I = \frac{1}{2eR_T} \int n_S(E)[f_N(E-eV) - f_N(E+eV)]dE$$

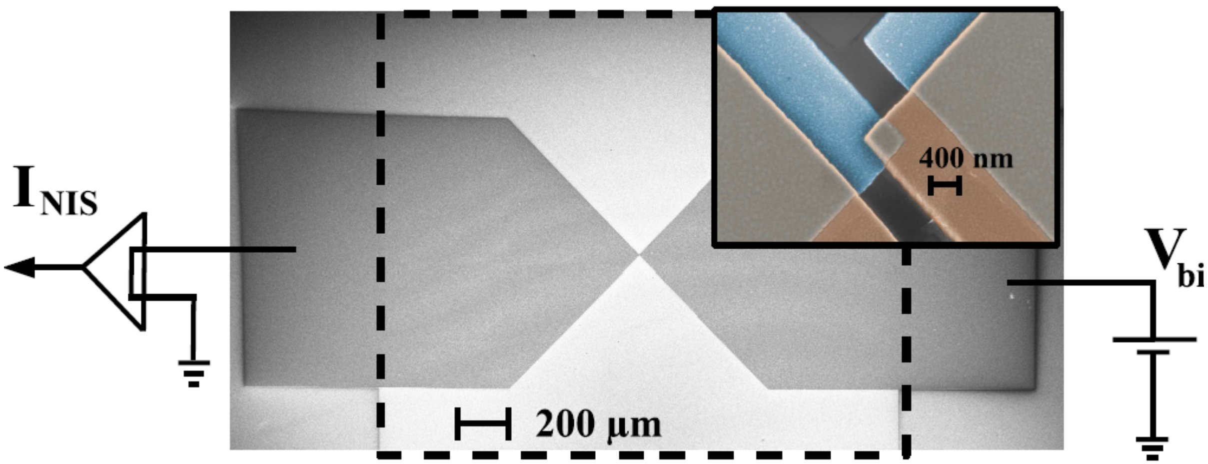


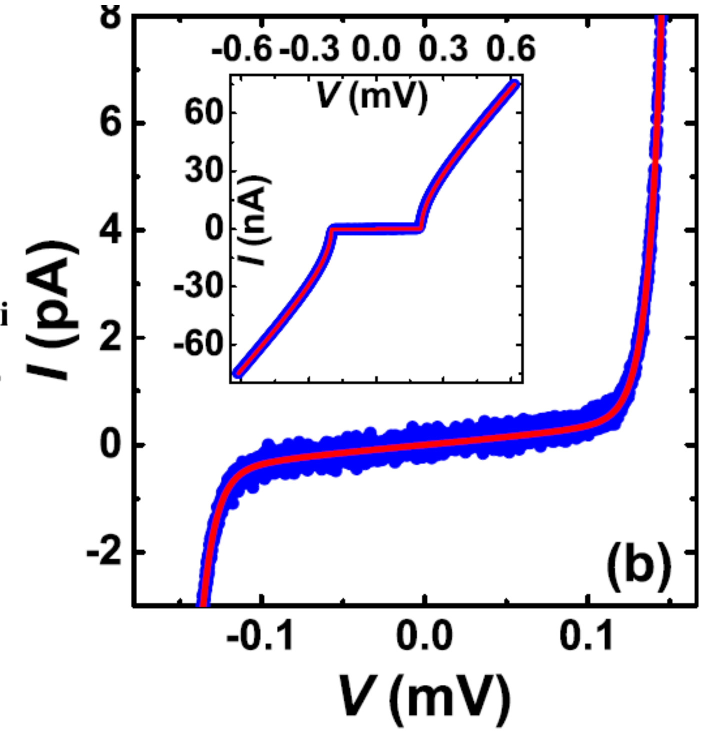
Probes electron temperature of N island (and not of S!)

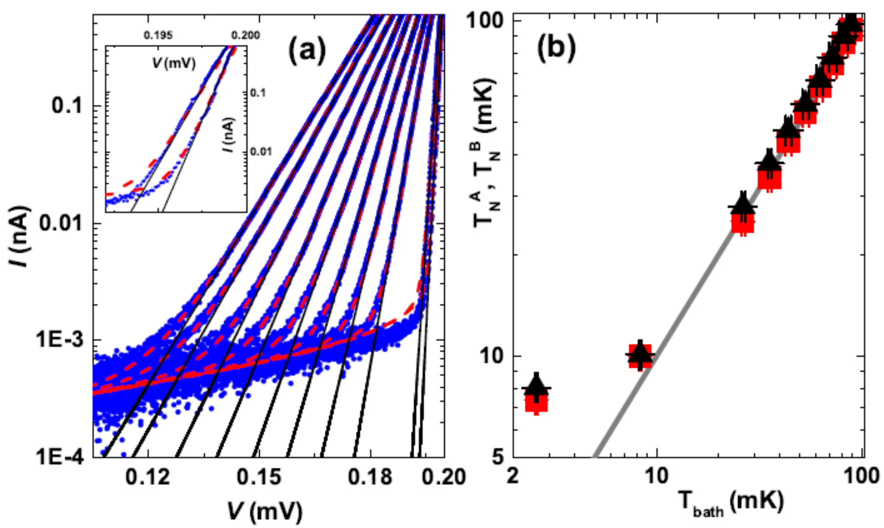




NIS-thermometry at mK temperatures





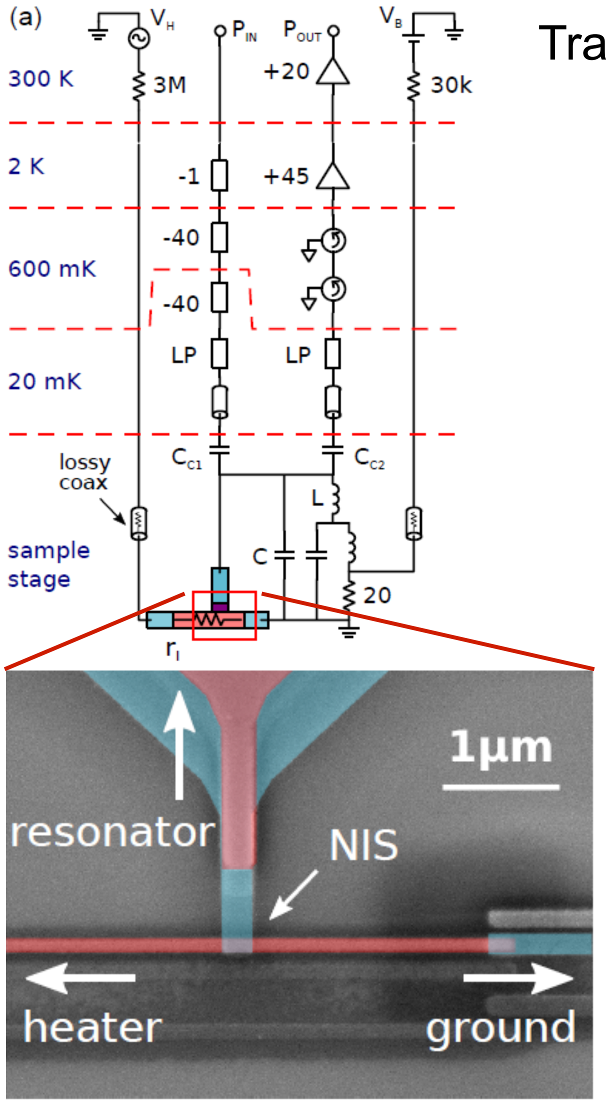


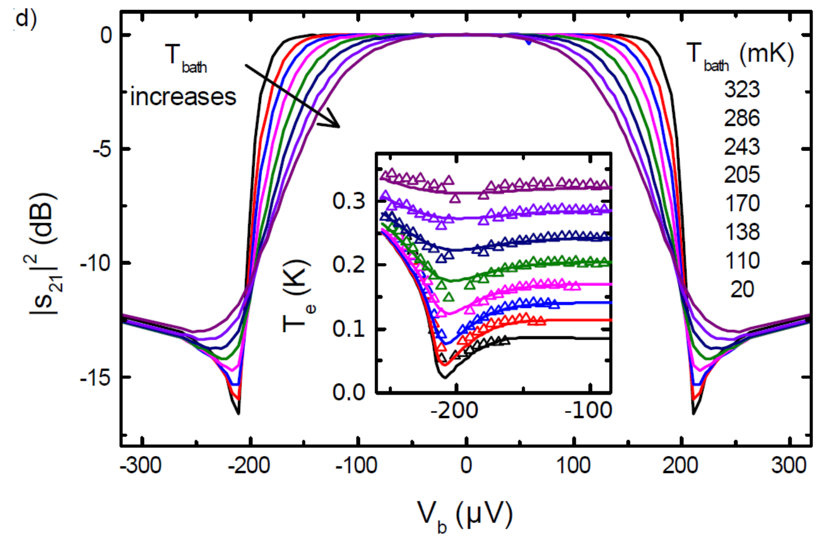
A. V. Feshchenko et al. (Aalto - Basel Univ. collaboration), Phys. Rev. Appl. 4, 034001 (2015).

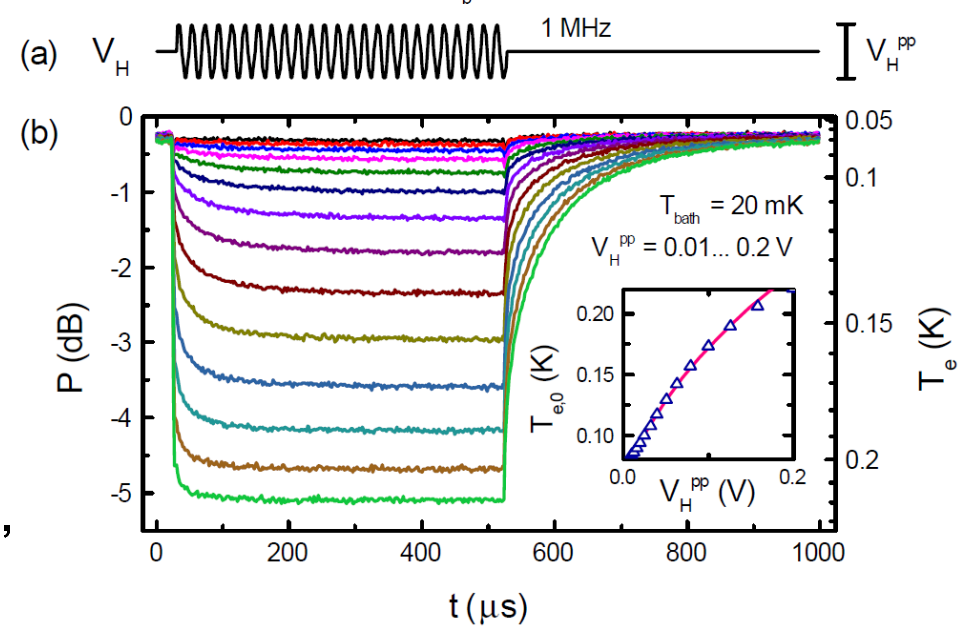
Potential to operate down to 1 mK

Fast thermometry

Transmission read-out at 600 MHz of a NIS junction

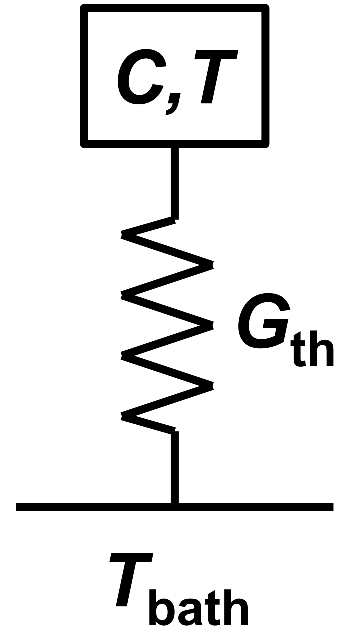




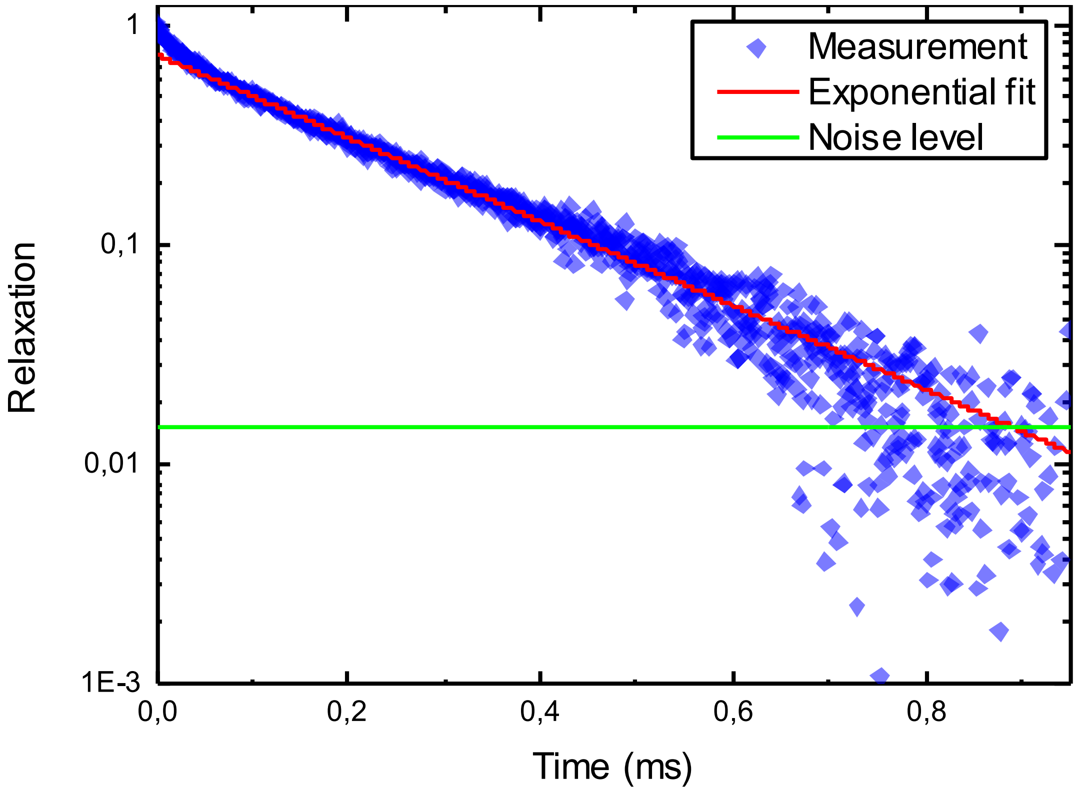


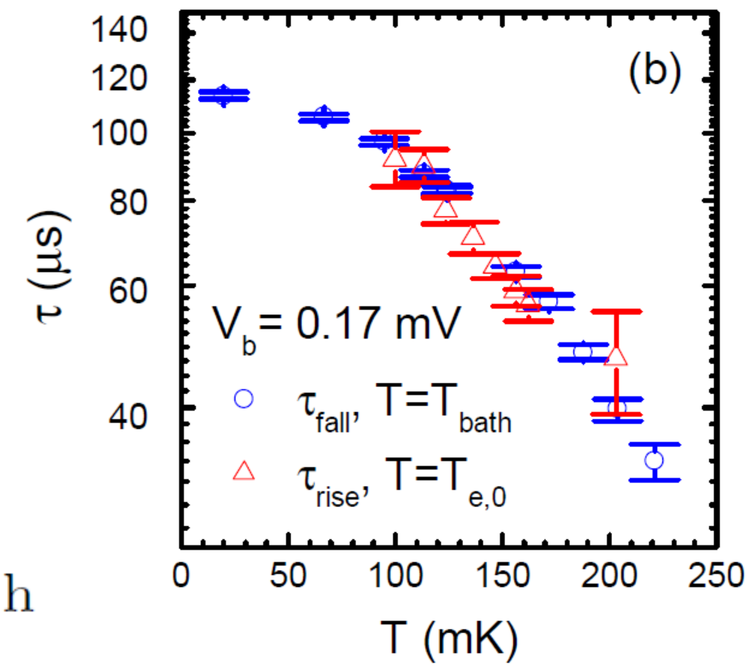
S. Gasparinetti et al., Phys. Rev. Applied 3, 014007 (2015); K. L. Viisanen et al., New J. Phys. 17, 055014 (2015).

Fast thermometry



Time-resolved measurements



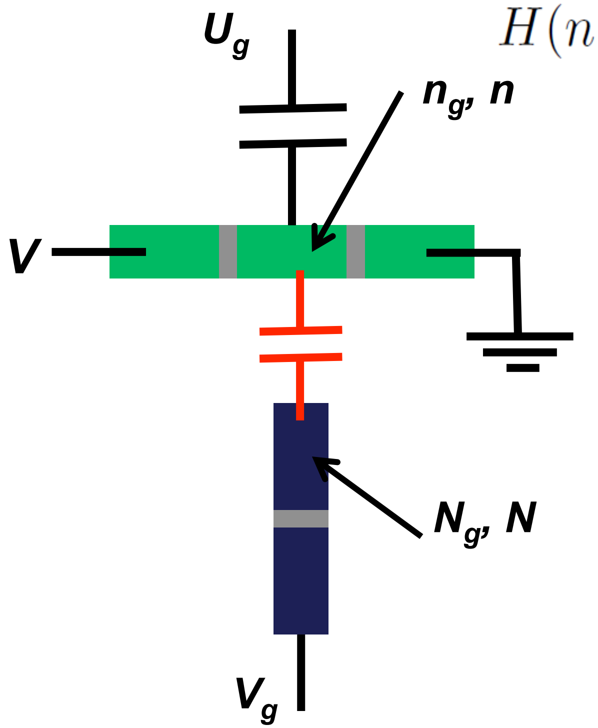


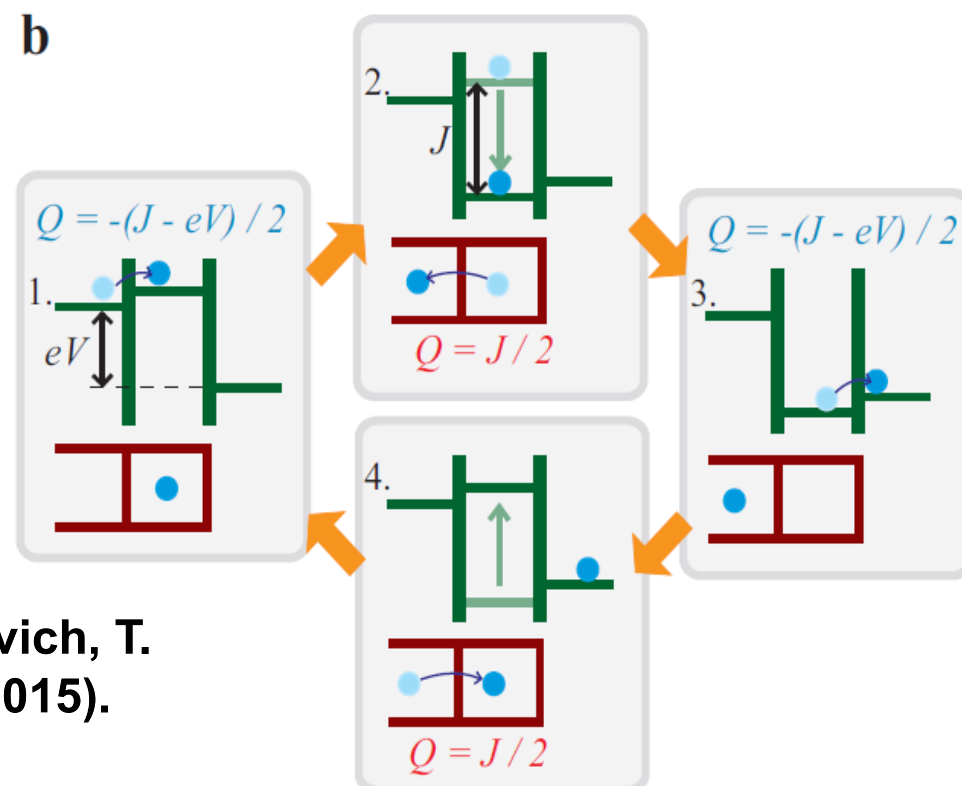
$$\mathcal{C}\frac{d\delta T}{dt} = -G_{\rm th}\delta T \qquad \tau = \mathcal{C}/G_{\rm th}$$

Autonomous Maxwell's demon

System and Demon: all in one
Realization in a circuit:

$$H(n,N) = E_{\mathrm{s}}(n-n_g)^2 + E_{\mathrm{d}}(N-N_g)^2 + 2J(n-n_g)(N-N_g)$$



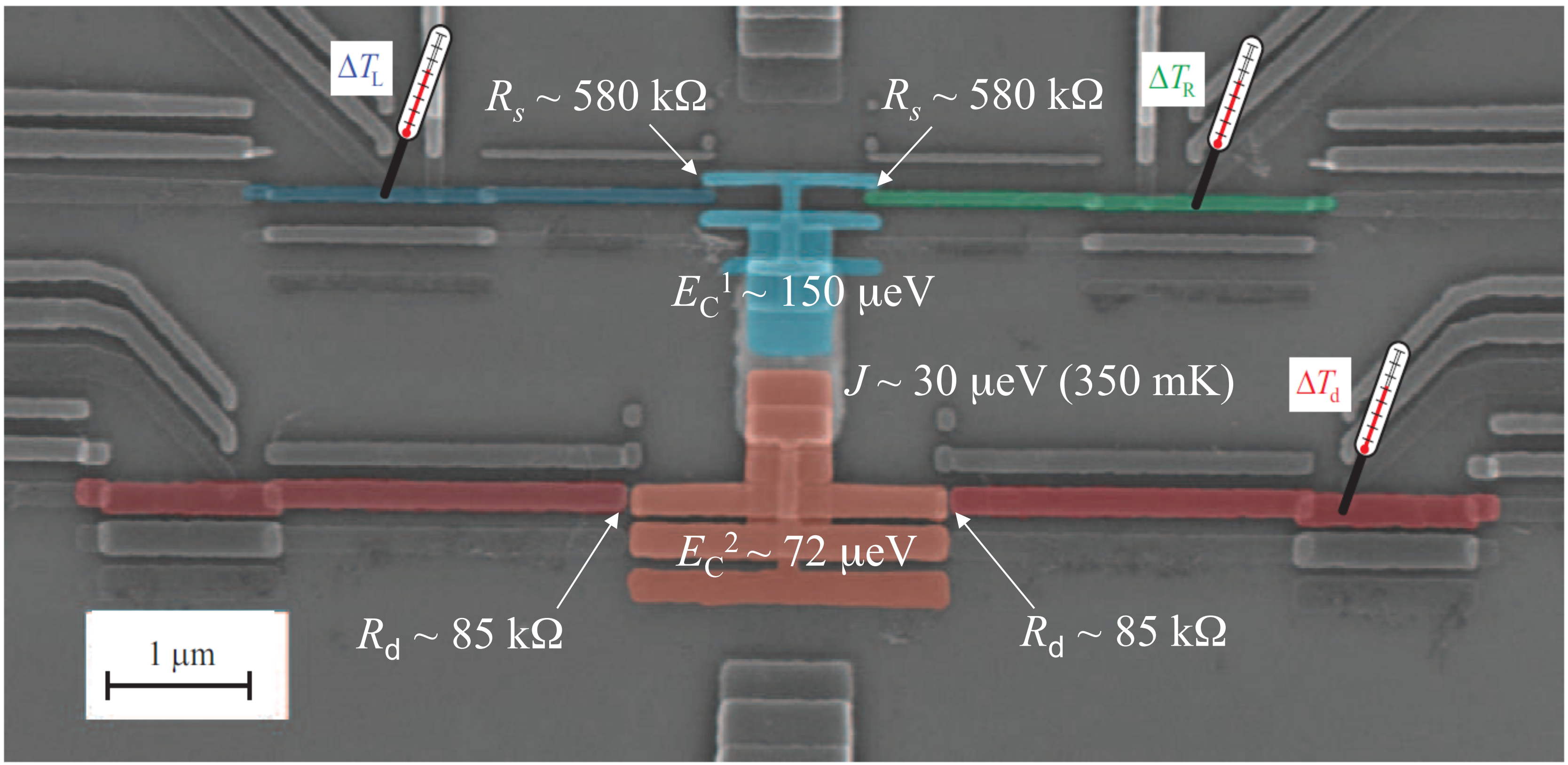


J. V. Koski, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and JP, PRL 115, 260602 (2015).

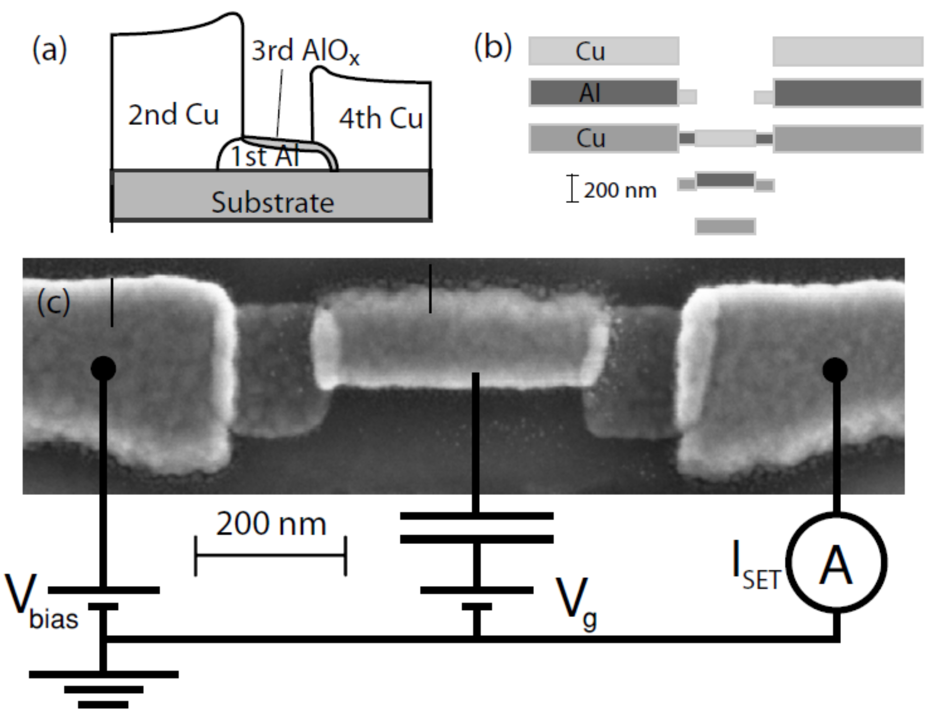
P. Strasberg et al., PRL 110, 040601 (2013).

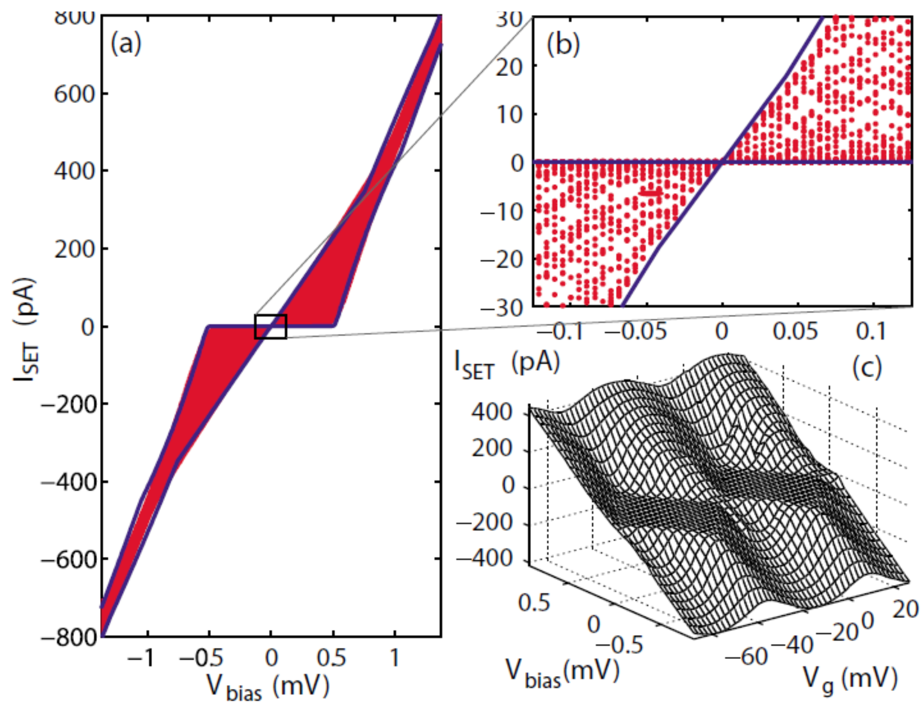
Autonomous Maxwell's demon – information-powered refrigerator

Image of the actual device



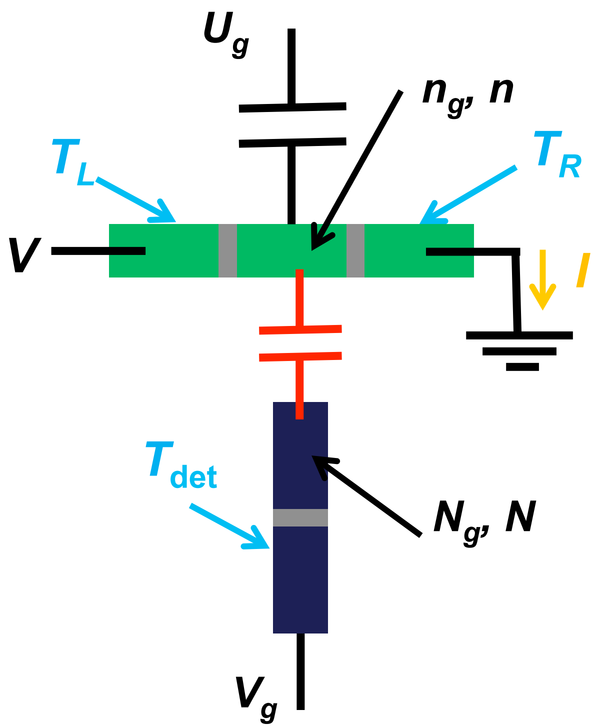
Technique to produce fully normal tunnel junctions and SETs

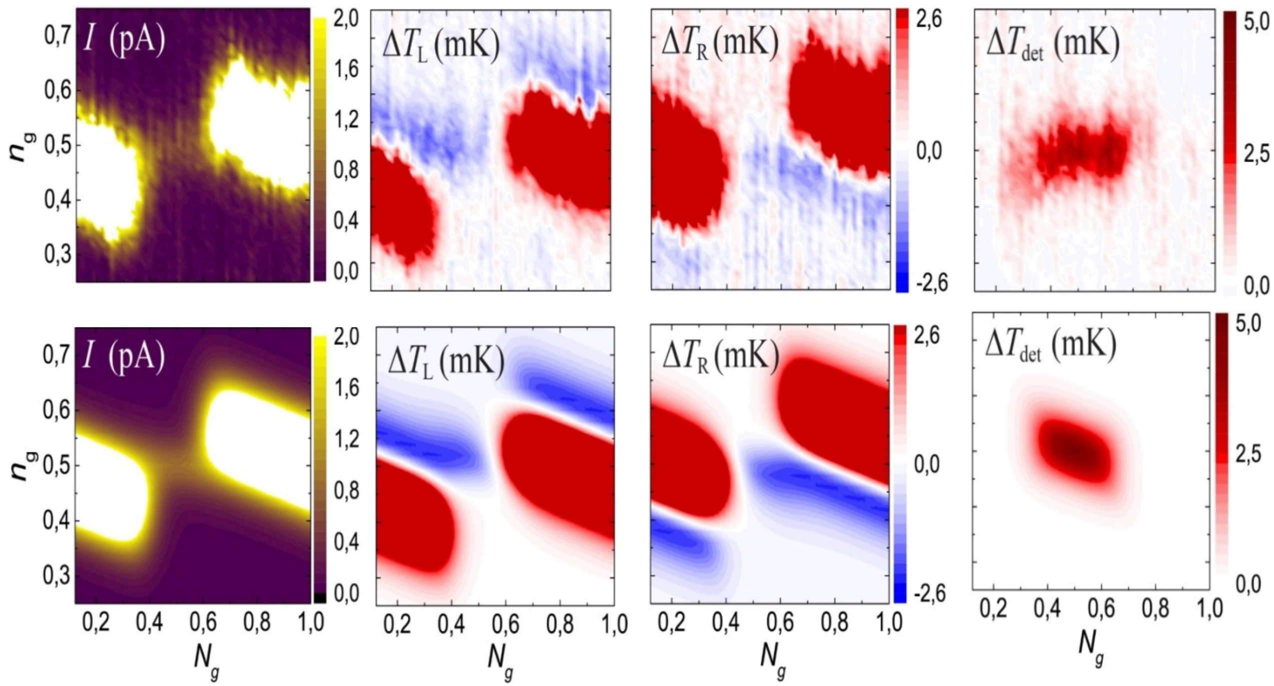




Laterally proximized tunnel junctions:
J. Koski et al., Appl. Phys. Lett. **98**, 203501 (2011).

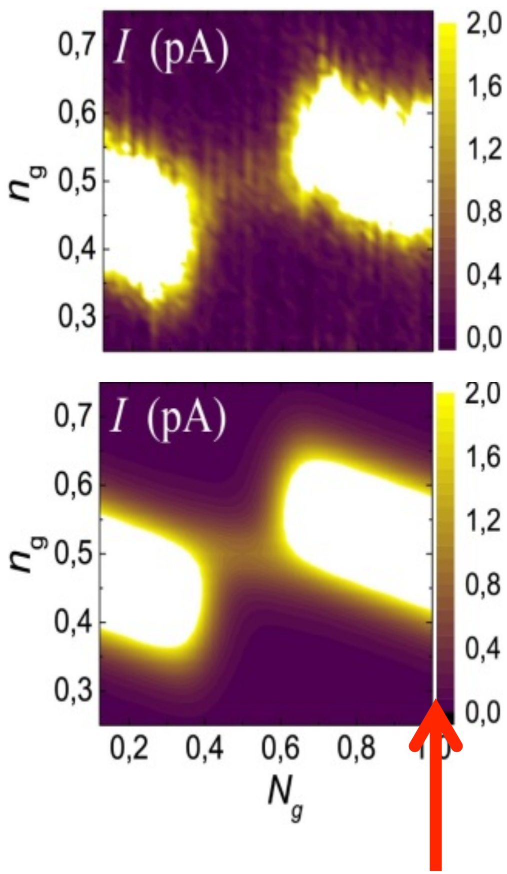
Current and temperatures at different gate positions

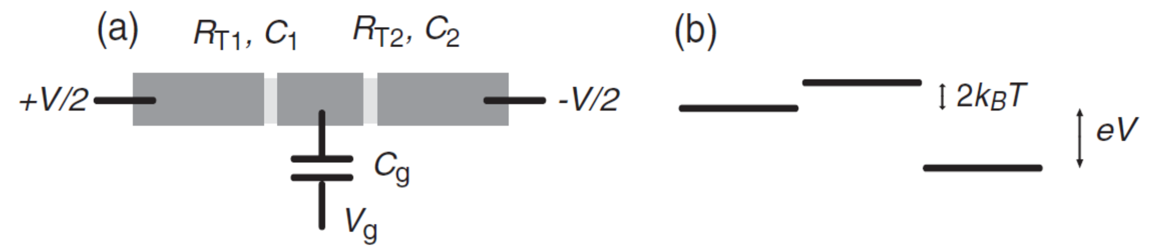


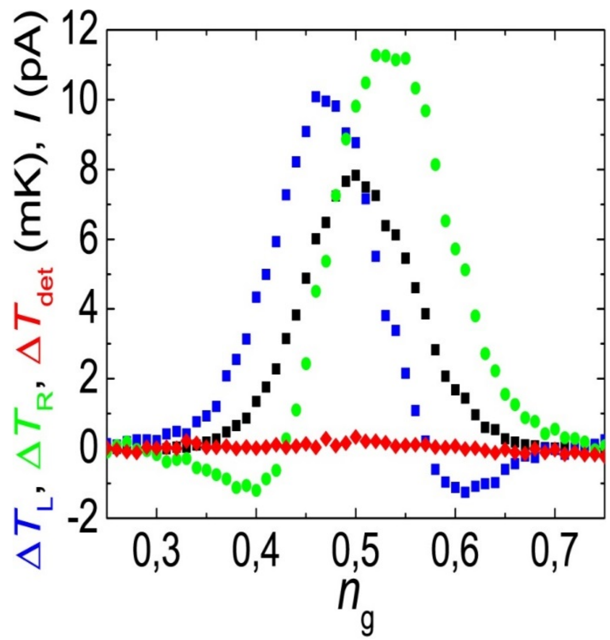


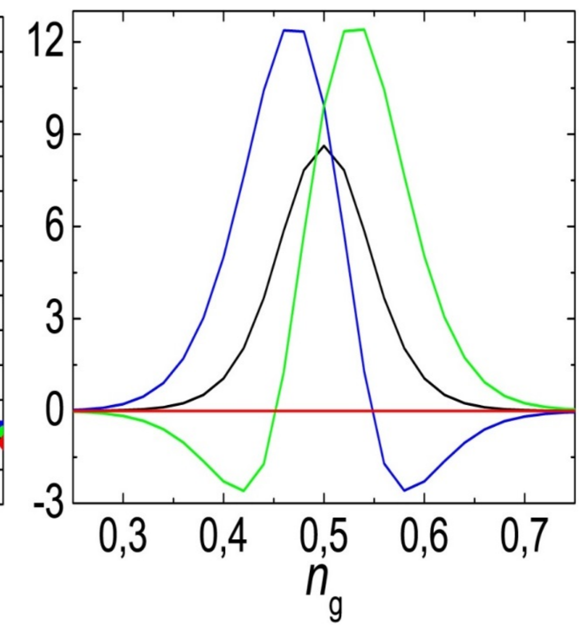
V = 20 μV, T = 50 mK

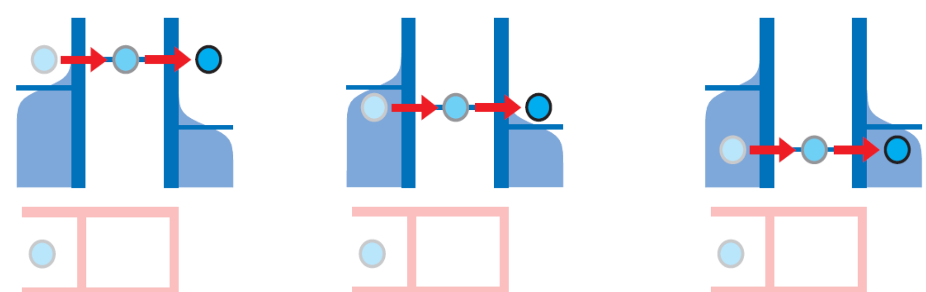
N_g = 1: No feedback control ("SET-cooler")





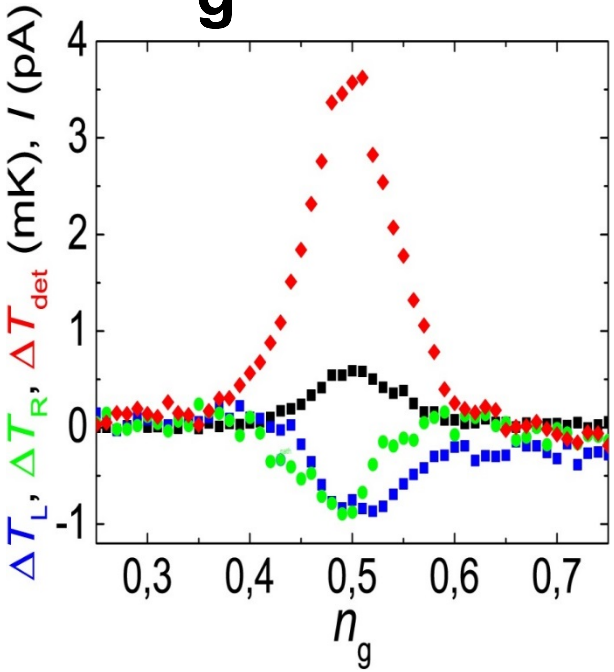


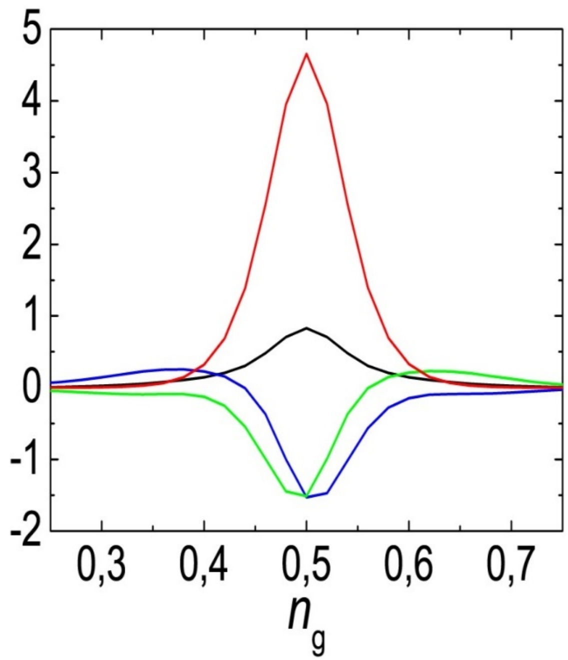


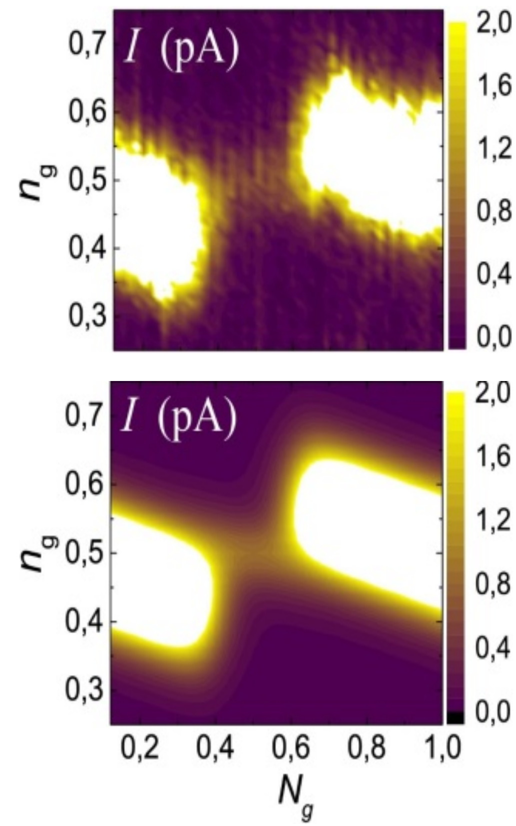


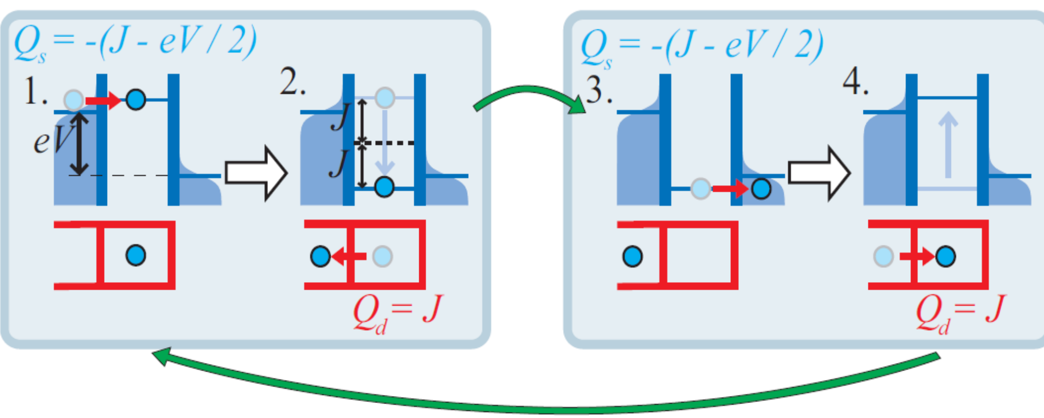
JP, J. V. Koski, and D. V. Averin, PRB **89**, 081309 (2014)
A. V. Feshchenko, J. V. Koski, and JP, PRB **90**, 201407(R) (2014)

N_g = 0.5: feedback control (Demon)





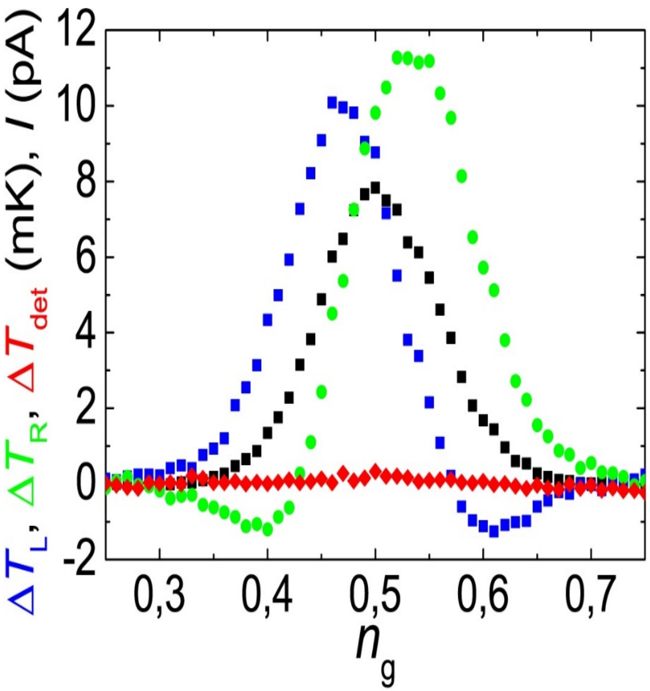




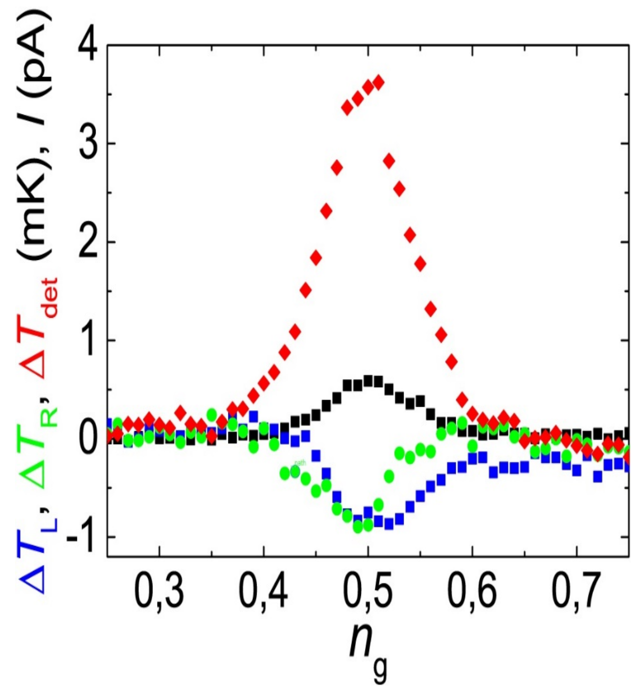
Both T_L and T_R drop: entropy of the System decreases;
T_{det} increases: entropy of the Demon increases

Summary of the autonomous demon experiment

SET cooler



Demon



current *I*