Information powered cooling in a single-electron circuit

Jukka Pekola, Low Temperature Laboratory
Aalto University, Helsinki, Finland

Jonne Koski

Olli-Pentti Saira

Ville Maisi

Dmitri Averin, SUNY

Takahiro Sagawa, U. Tokyo

Tapio Ala-Nissila, Aki Kutvonen

Low temperature laboratory

Outline

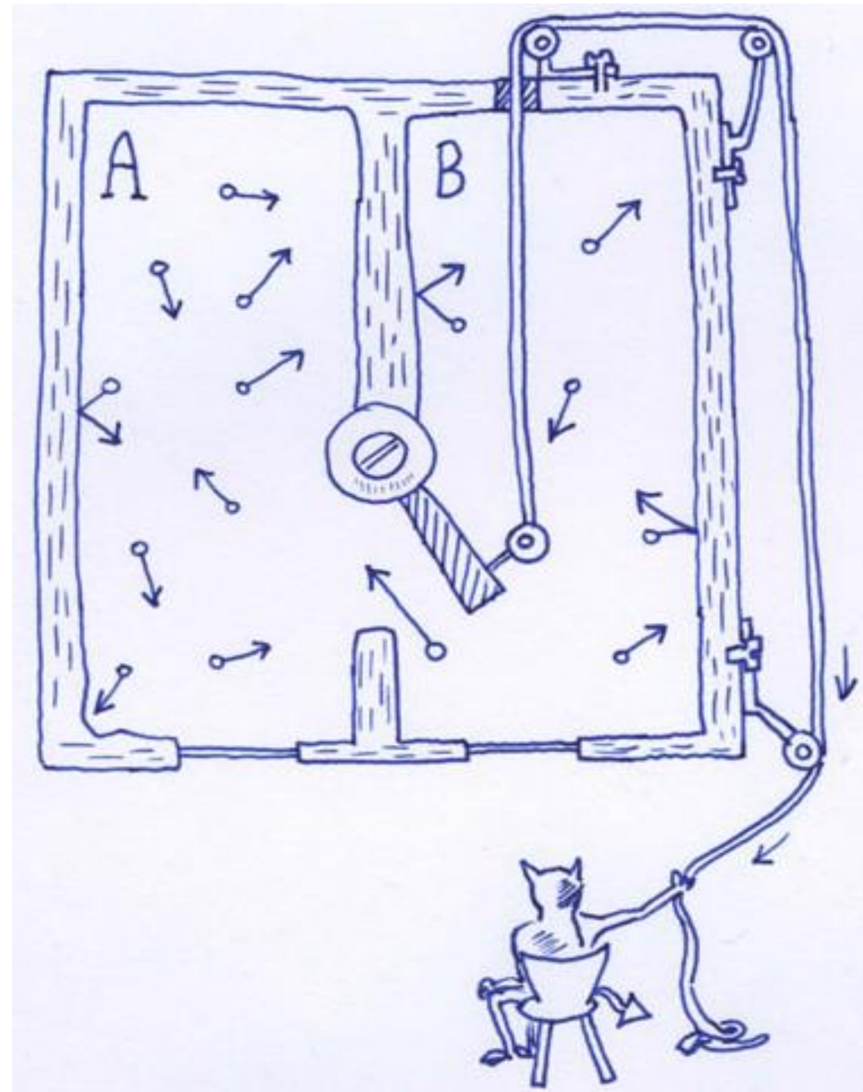
1. **Maxwell’s demon**
2. **Experiment on a single-electron Szilard’s engine**
3. **Experiment on an autonomous Maxwell’s demon**
4. **Calorimetry for quantum measurements (if time permits)**

Maxwell's demon: information in thermodynamics

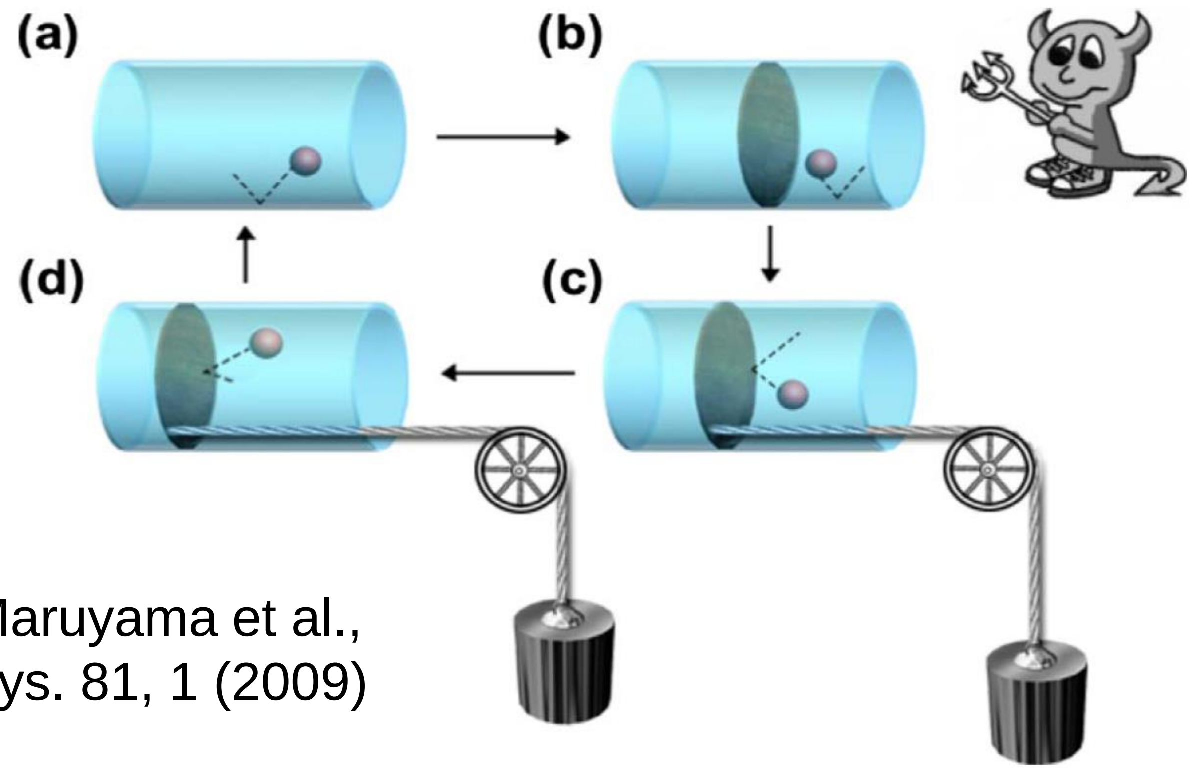
Second law of thermodynamics:
$\Delta S \geq 0$

Maxwell's demon observes the system, and lowers its entropy by feedback

Original though experiment (19th century) separates 'hot' and 'cold' particles



Szilard's engine



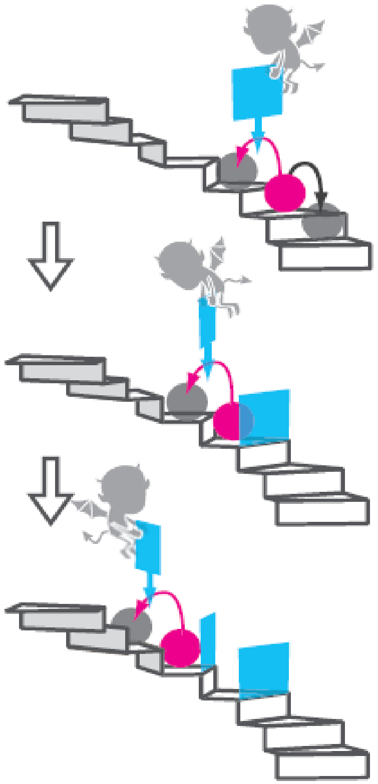
(L. Szilard 1929)

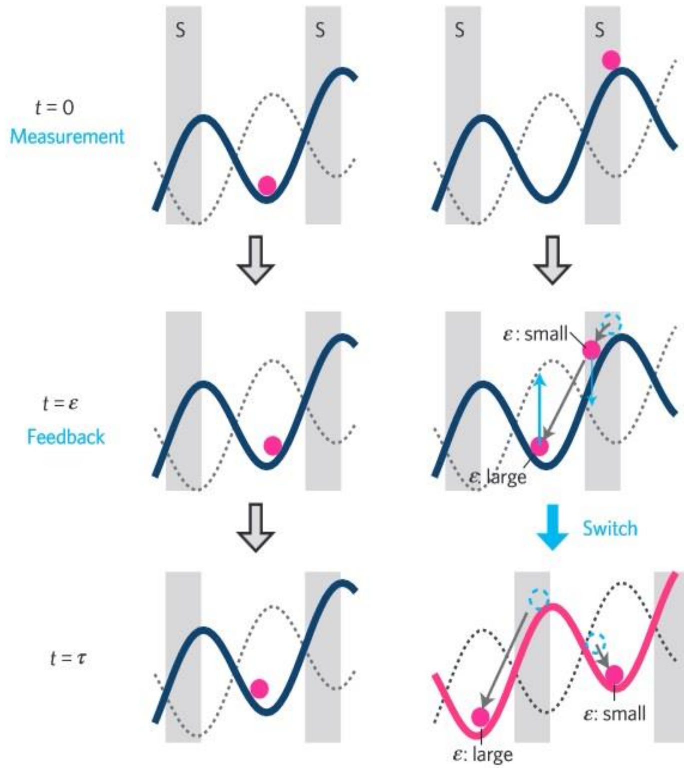
Figure from Maruyama et al.,
Rev. Mod. Phys. 81, 1 (2009)

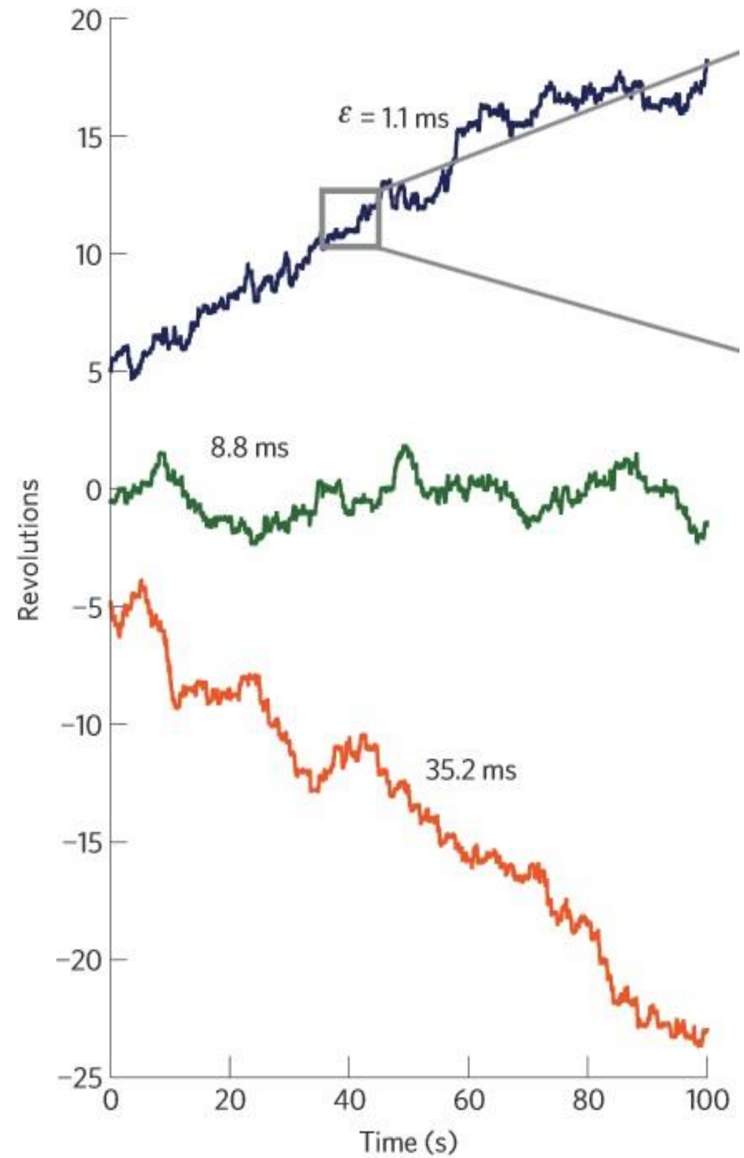
Isothermal expansion of the "single-molecule gas" does work against the load

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

Experiments on Maxwell's demon



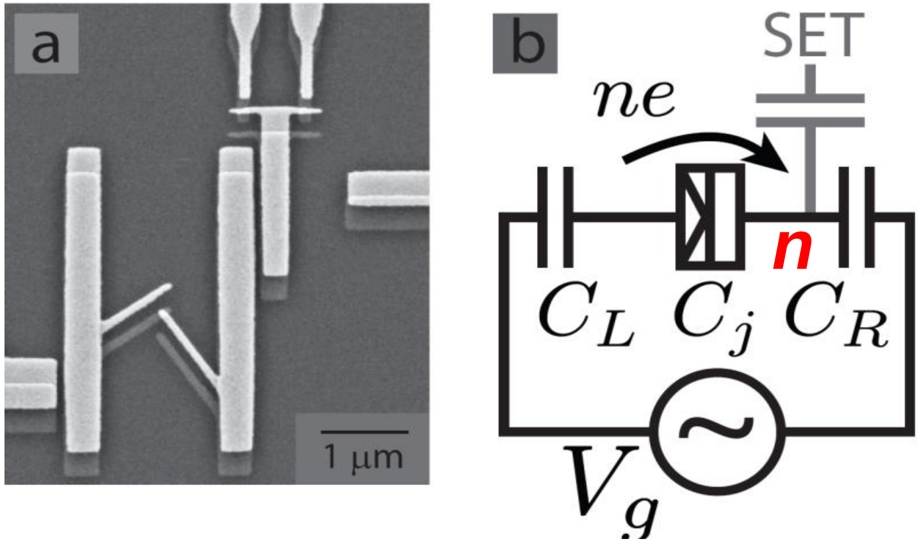


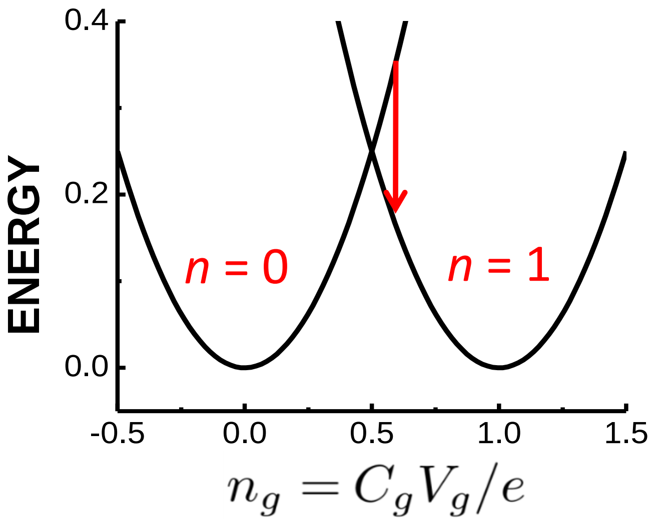


S. Toyabe, T. Sagawa, M. Ueda, E. Muneyuki, M. Sano, Nature Phys. **6**, 988 (2010)

É. Roldán, I. A. Martínez, J. M. R. Parrondo, D. Petrov, Nature Phys. **10**, 457 (2014)

Dissipation and work in single-electron transitions





Heat generated in a tunneling event *i*:

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

Total heat generated in a process:

$$Q = \sum_i Q_i$$

Work in a process:

$$W = Q + \Delta U$$

Change in internal (charging) energy

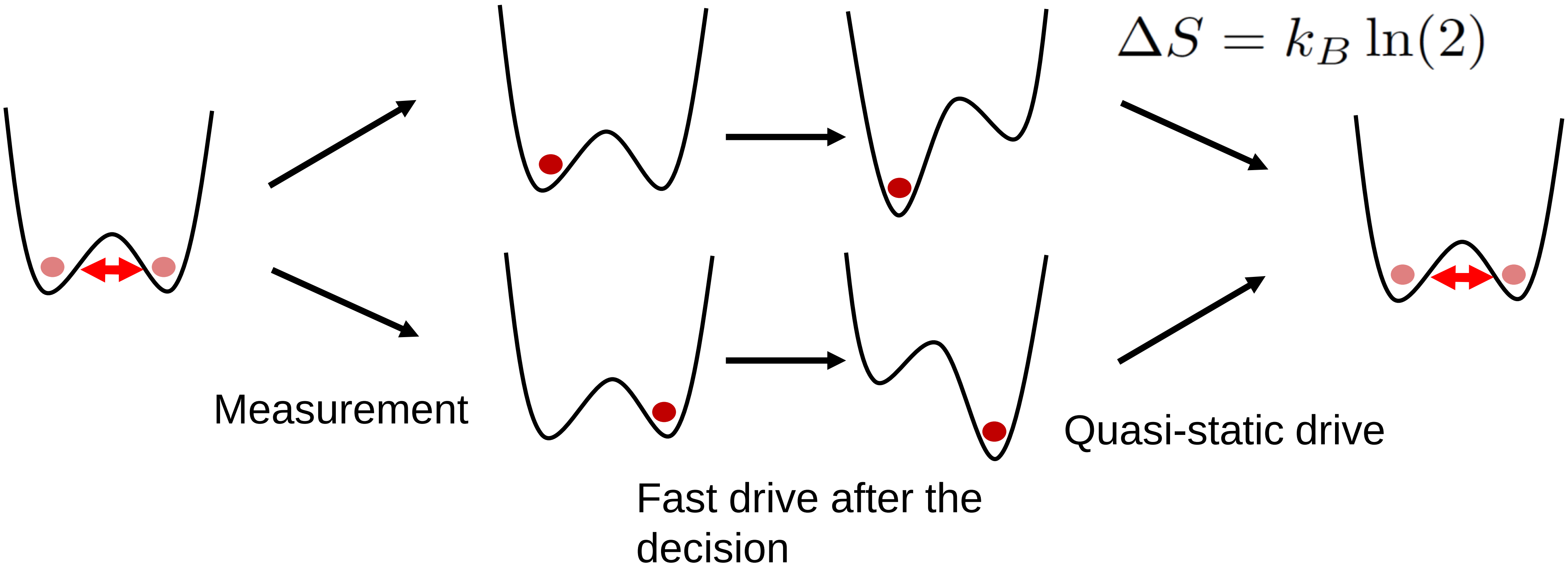
D. Averin and JP, EPL 96, 67004 (2011)

Szilard's engine for single electrons

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

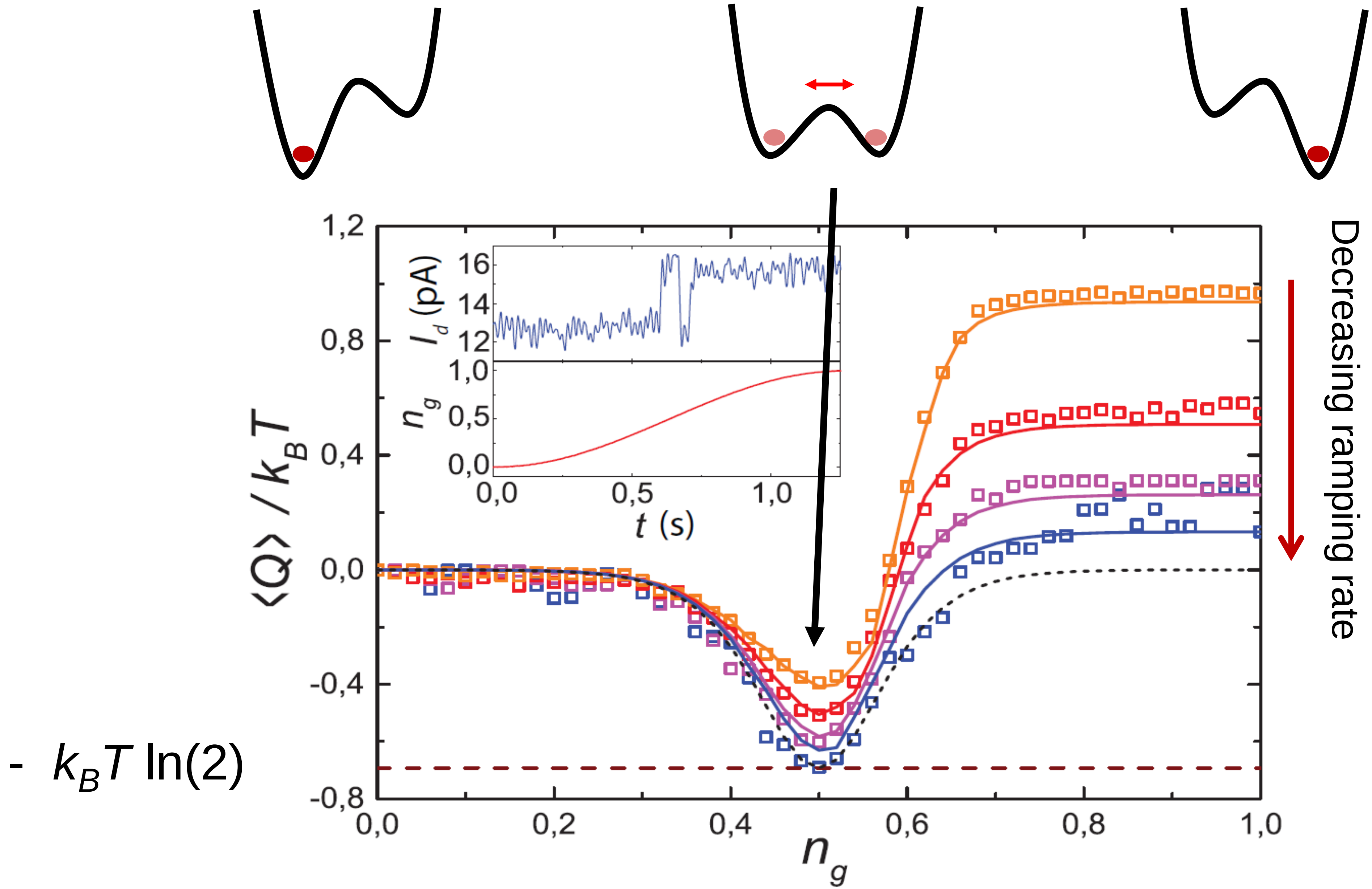
Entropy of the charge states: $$S = -k_B \sum_{i=0,1} p(i)\ln[p(i)]$$

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



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

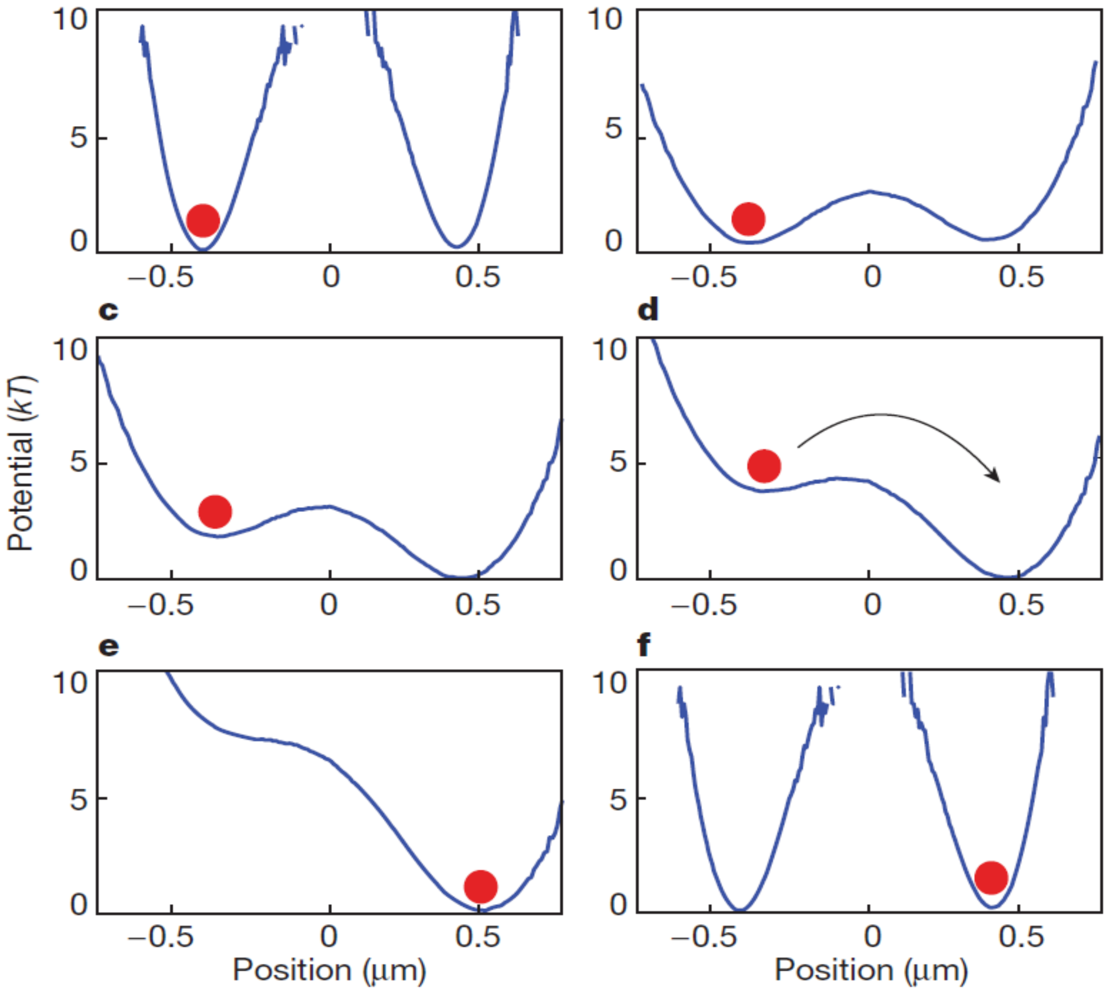
Extracting heat from the bath



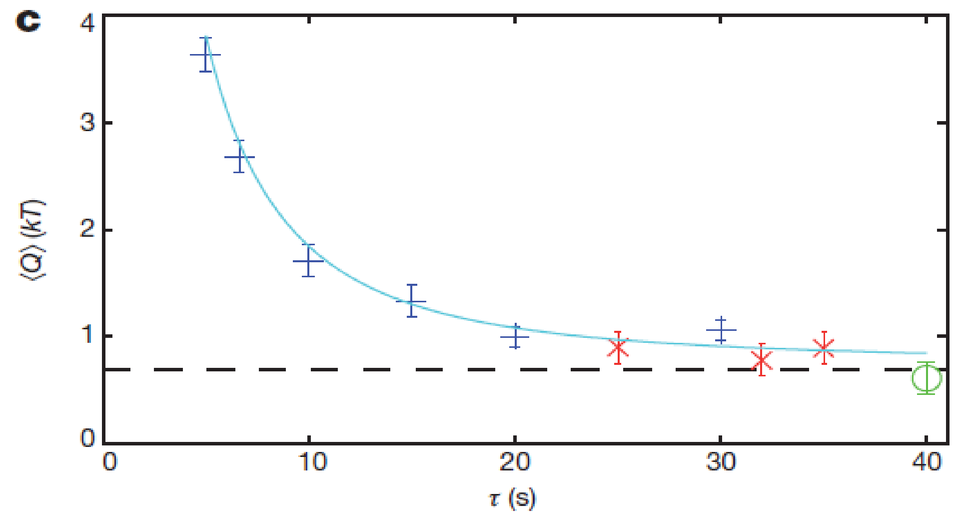
Erasure of information

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

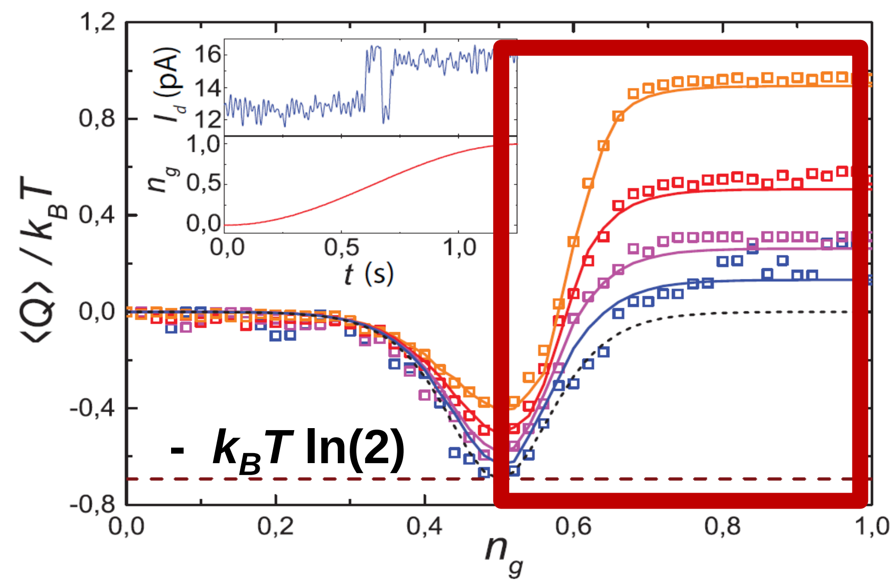
Experiment on a colloidal particle:



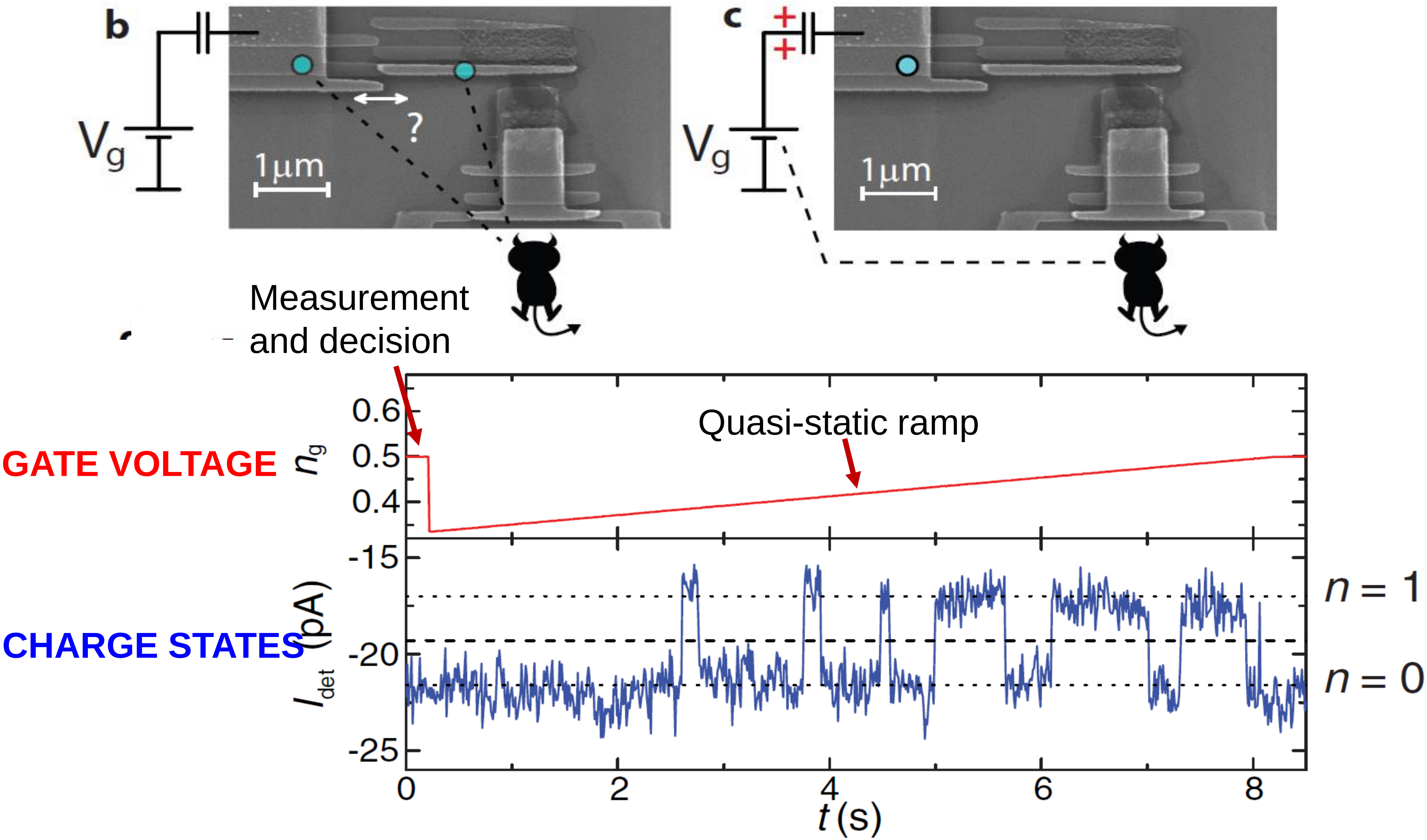
A. Berut et al., Nature 2012



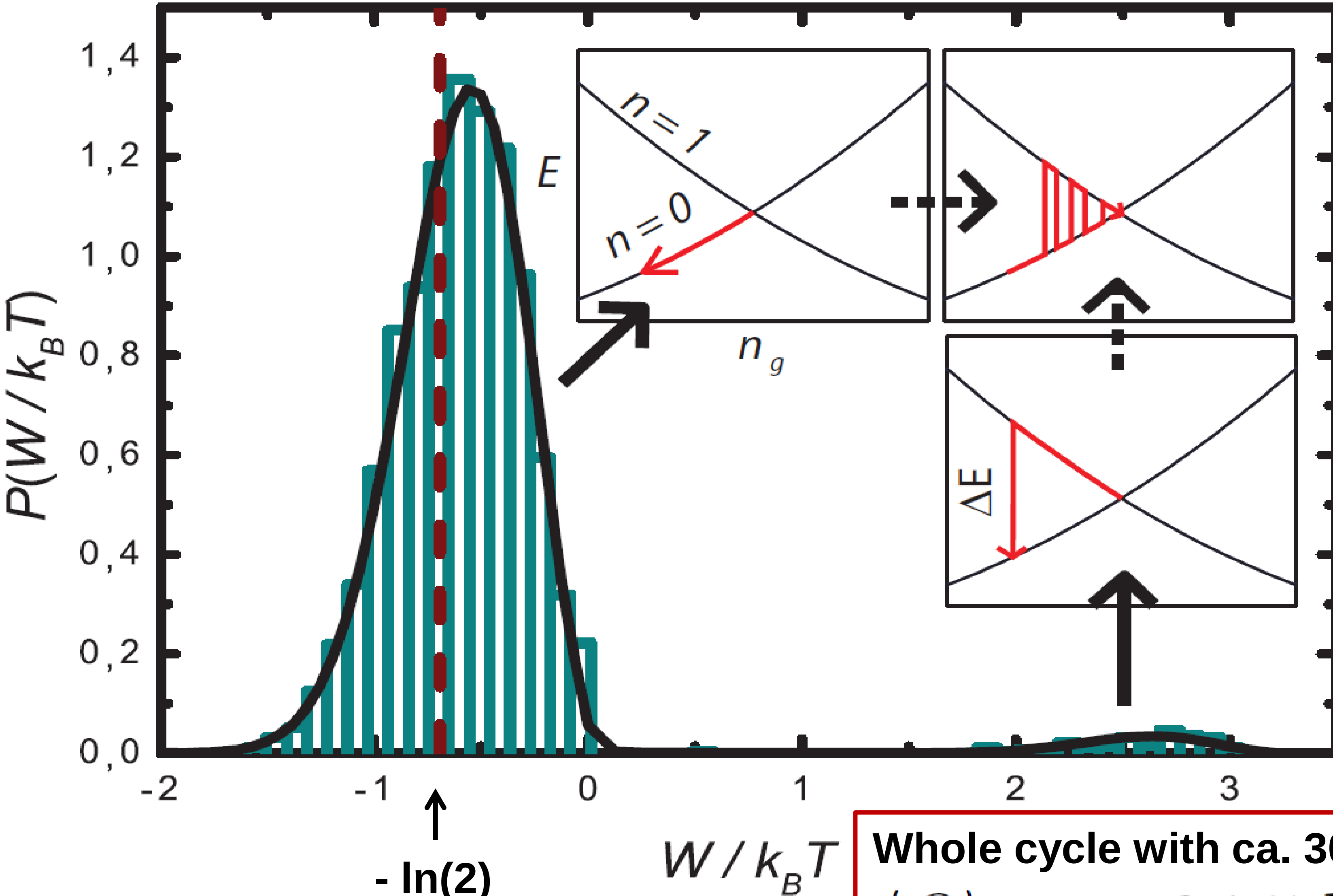
Corresponds to our experiment:



Realization of the MD with an electron



Measured distributions in the MD experiment



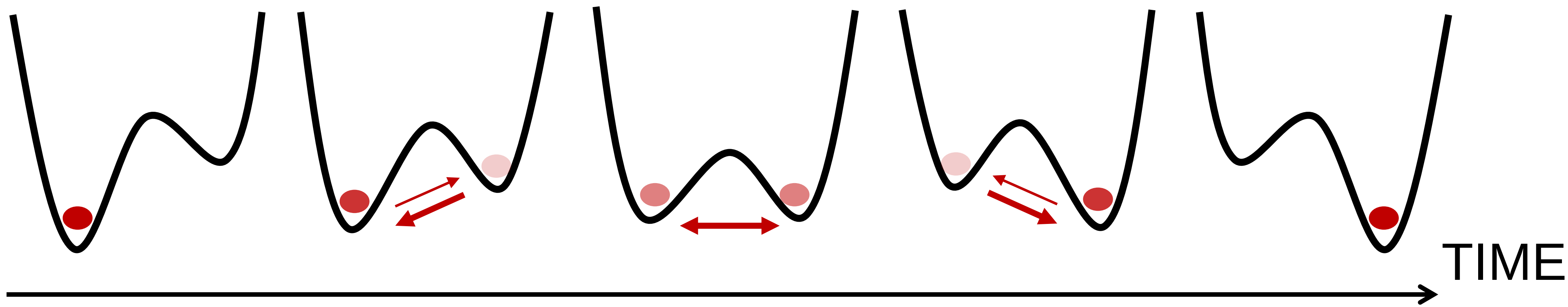
J. V. Koski et al., PNAS 111, 13786 (2014)

Whole cycle with ca. 3000 repetitions:

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

Fluctuation relations

Work and dissipation in a driven process?



$$W_d = W - \Delta F$$ "dissipated work"

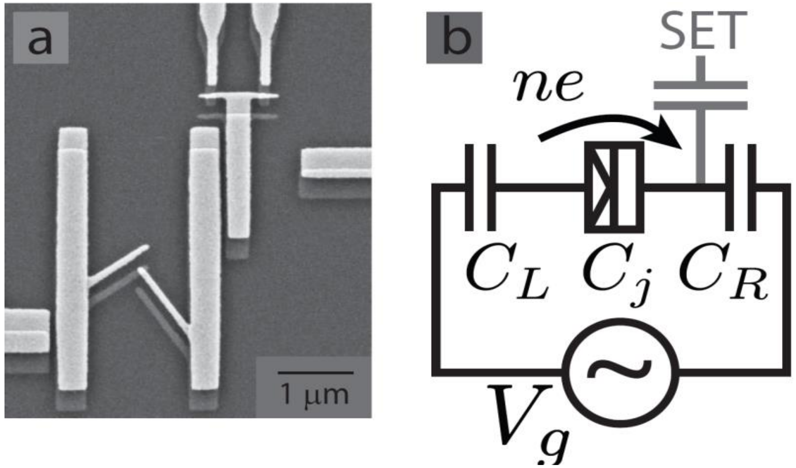
C. Jarzynski 1997 $$\langle e^{-\beta W_d} \rangle = 1 \Rightarrow \langle W \rangle \geq \Delta F$$

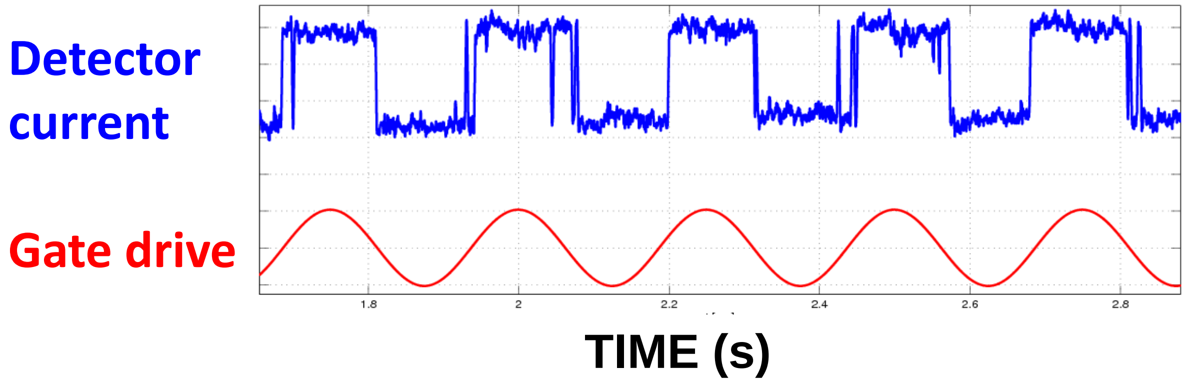
2nd law of thermodynamics

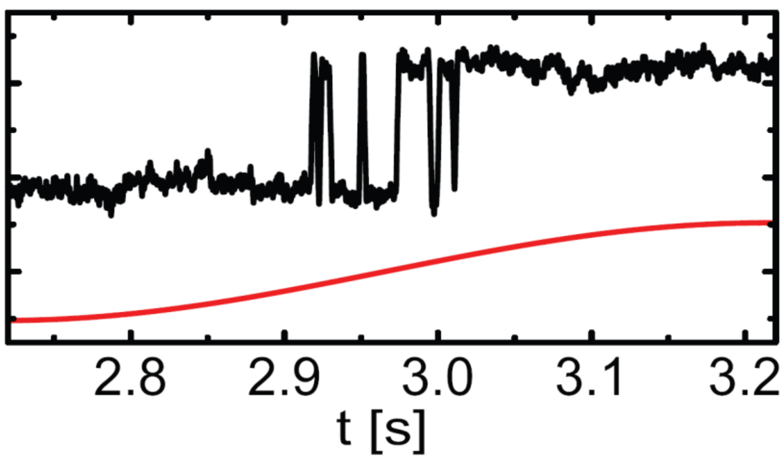
This relation is valid for a system with one bath at inverse temperature β, also far from equilibrium

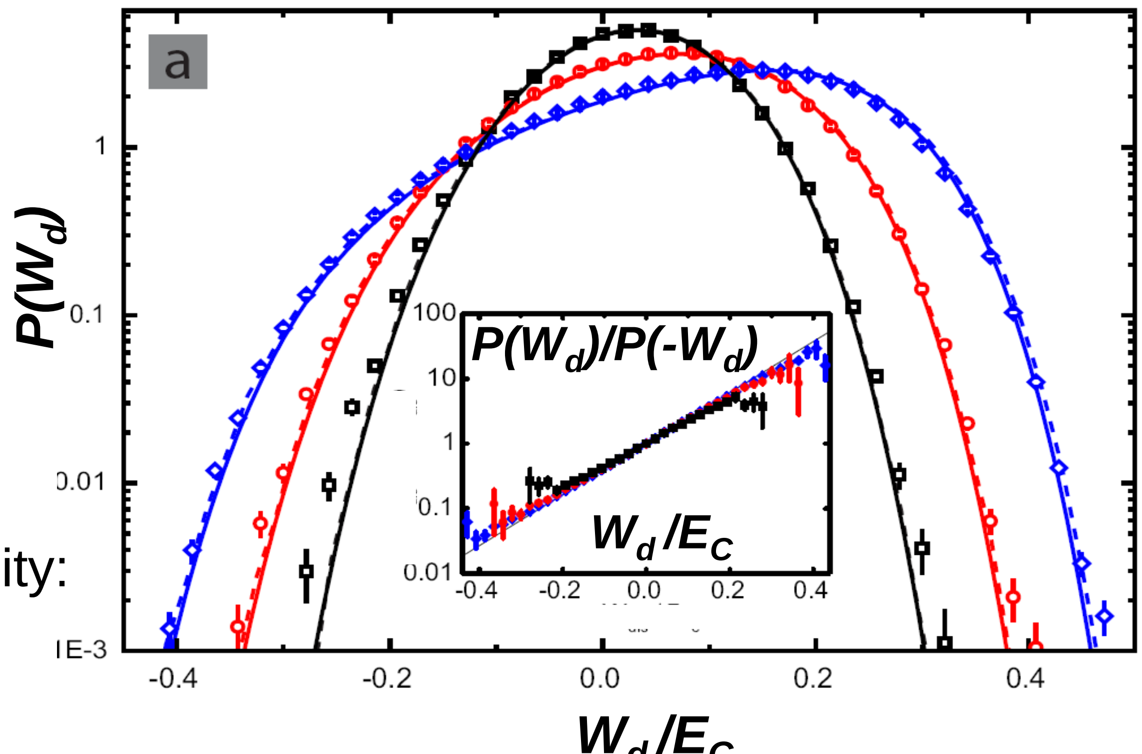
Experiment on a single-electron box

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









The distributions satisfy Jarzynski equality:

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

Sagawa-Ueda relation

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

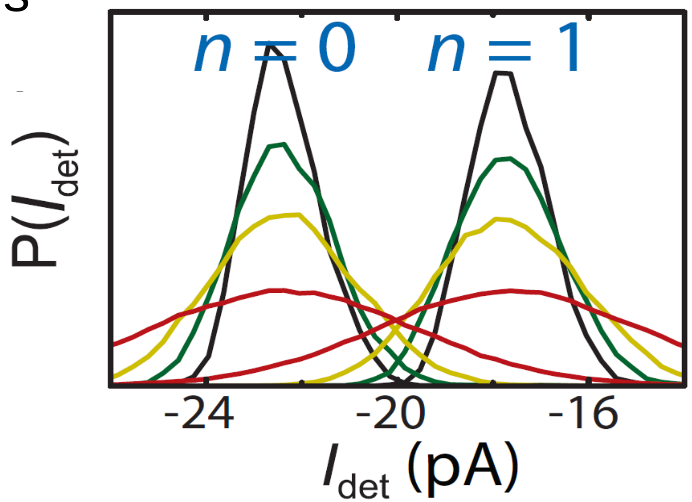
T. Sagawa and M. Ueda, PRL 104, 090602 (2010)

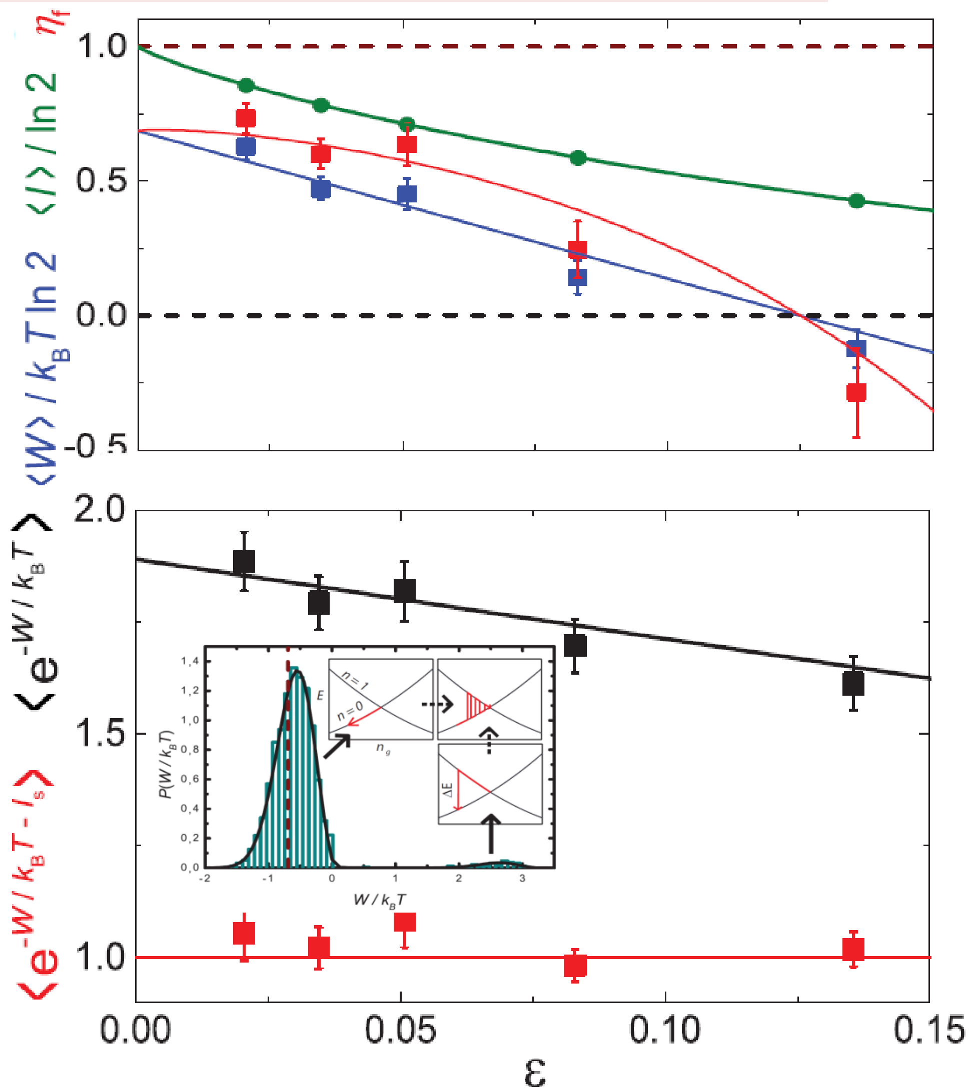
For a symmetric two-state system:

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

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

Measurements of *n* at different detector bandwidths



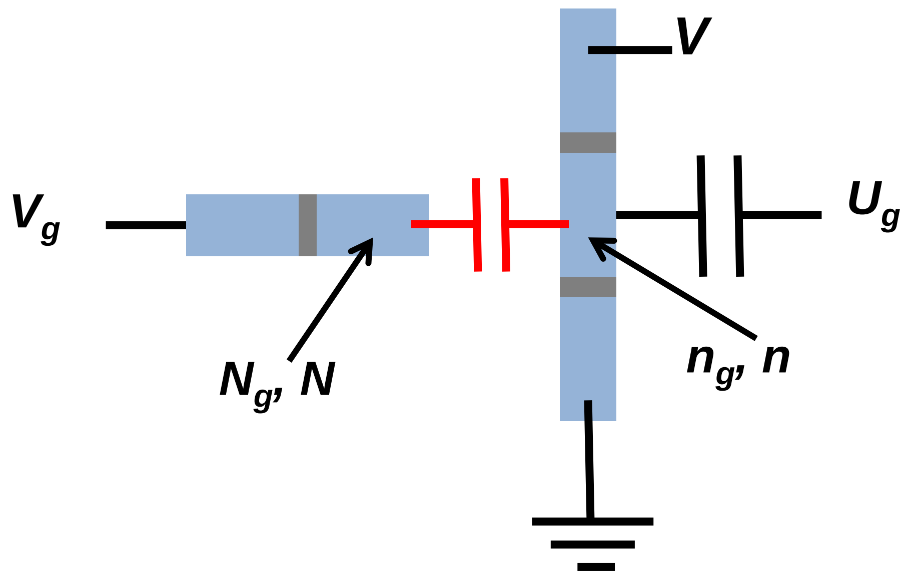


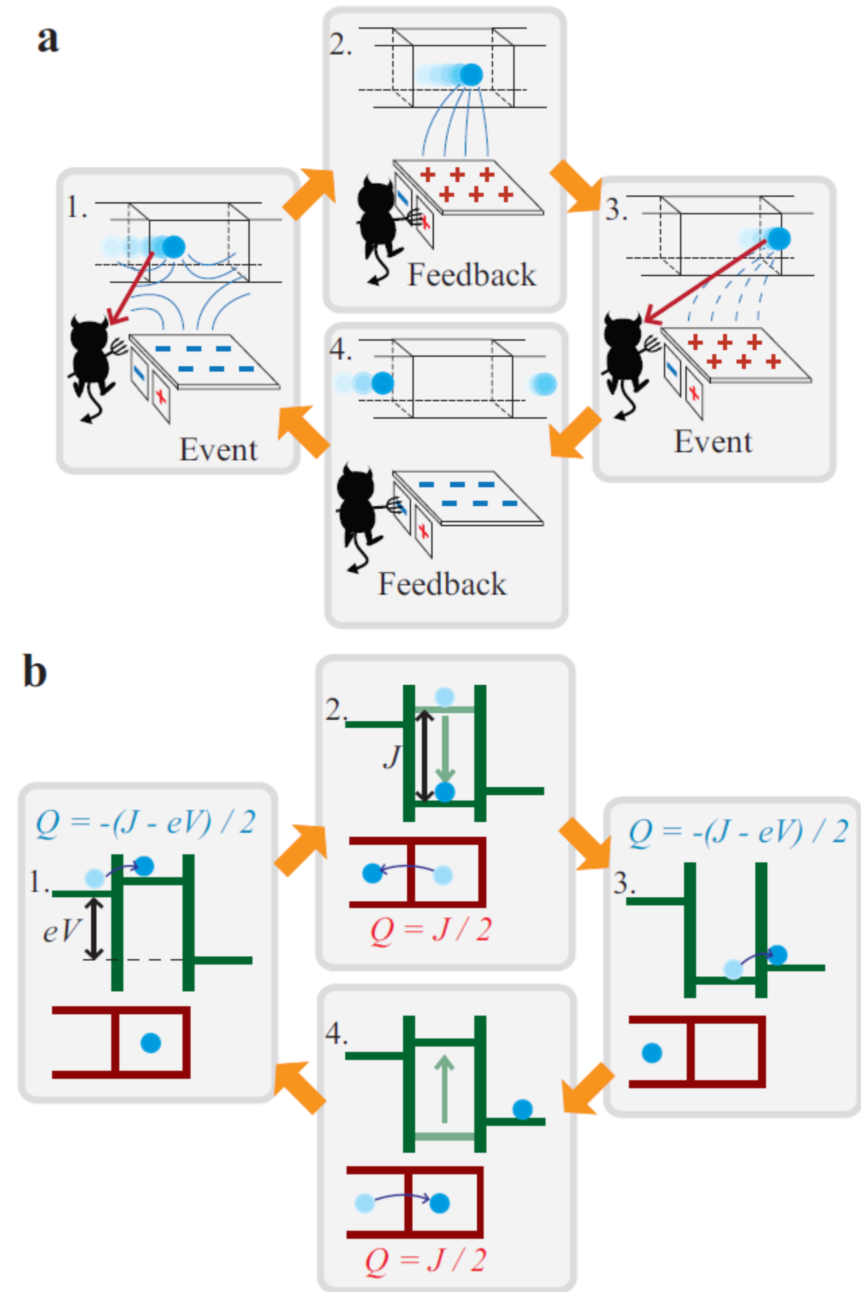
J. V. Koski et al., PRL 113, 030601 (2014)

Autonomous Maxwell's demon

System and Demon: all in one

Realization in a circuit:



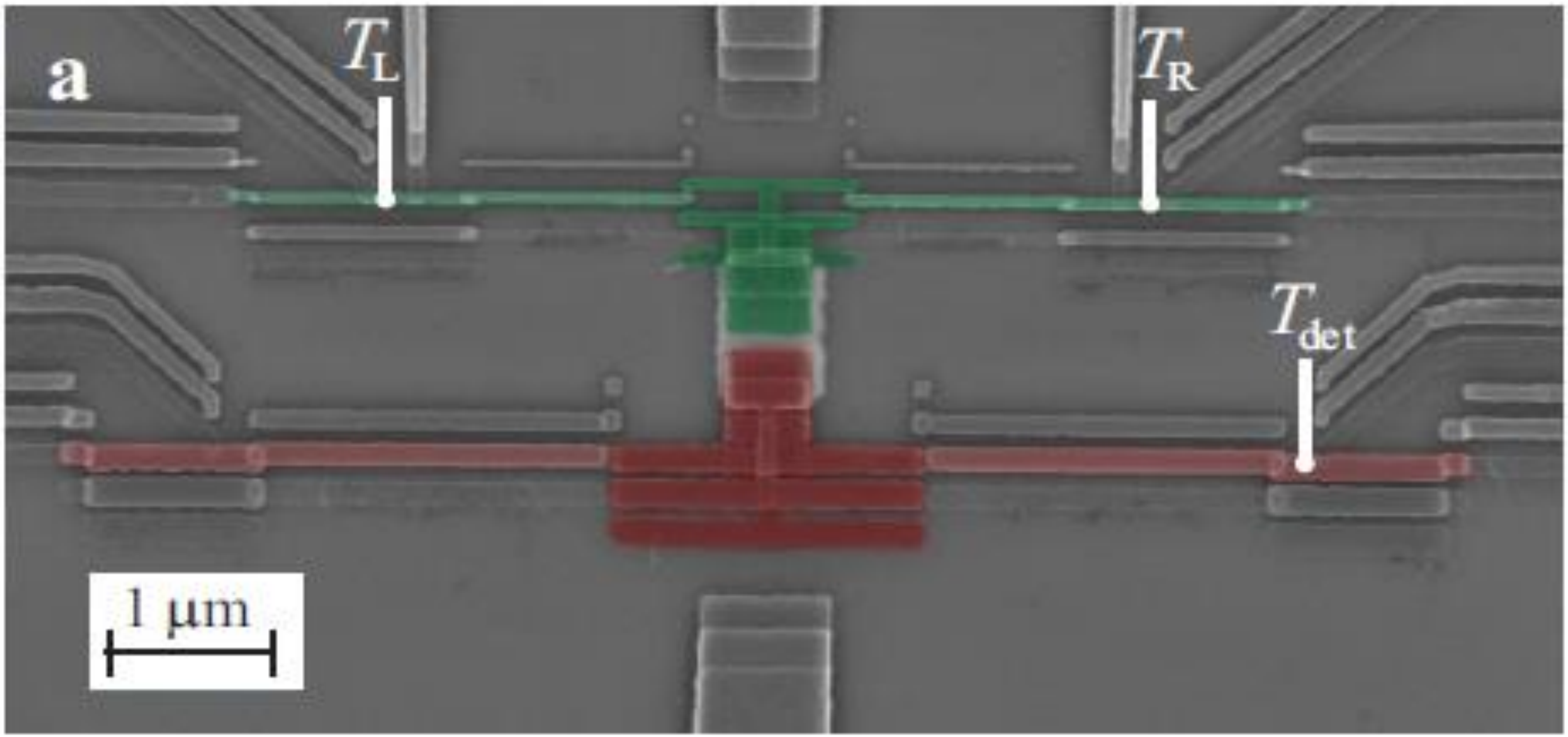


J. Koski et al., submitted (2015).

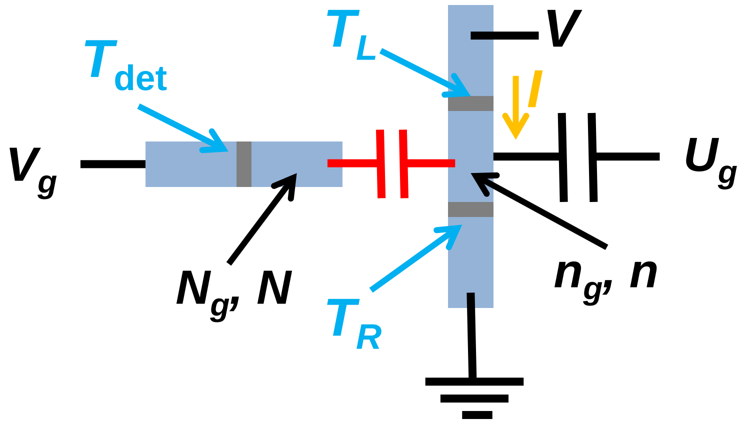
S. Deffner and C. Jarzynski, Phys. Rev. X 3, 041003 (2013).

Autonomous Maxwell's demon – information-powered refrigerator

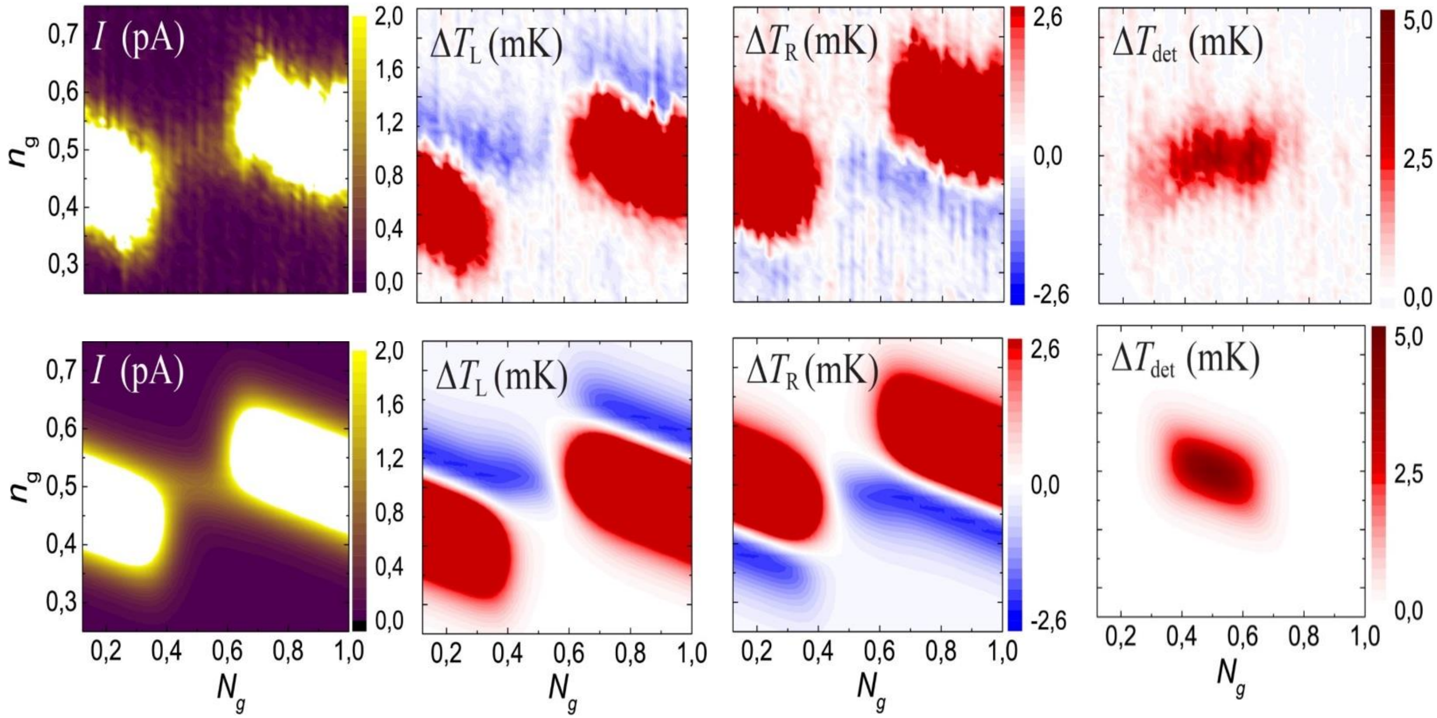
Image of the actual device



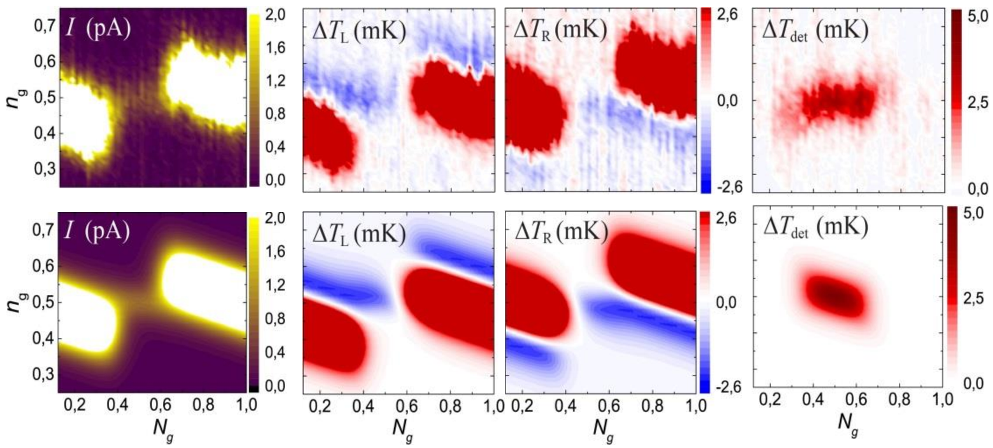
Current and temperatures at different gate positions

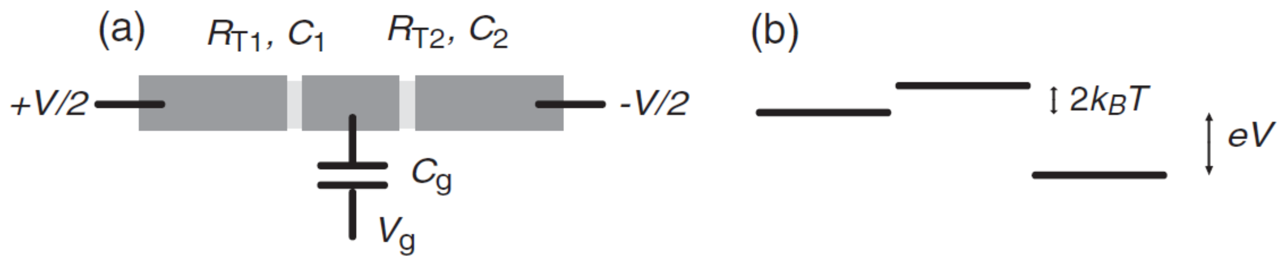


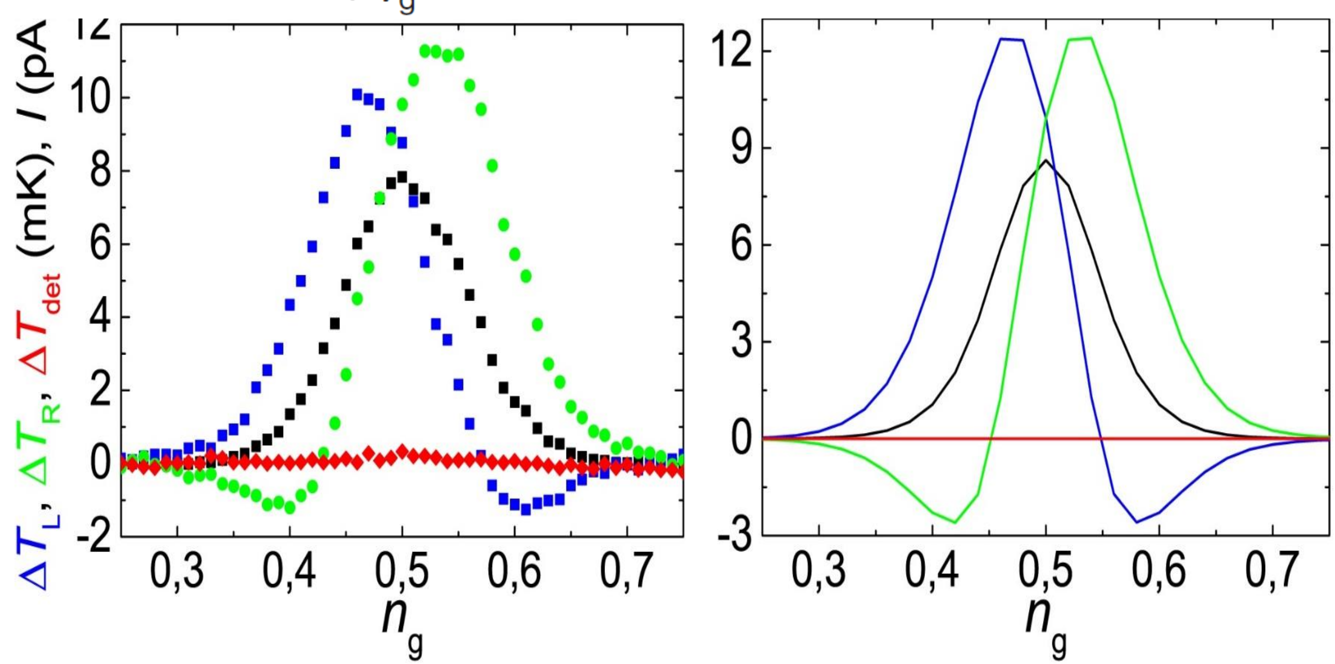
V = 20 μV, T = 50 mK

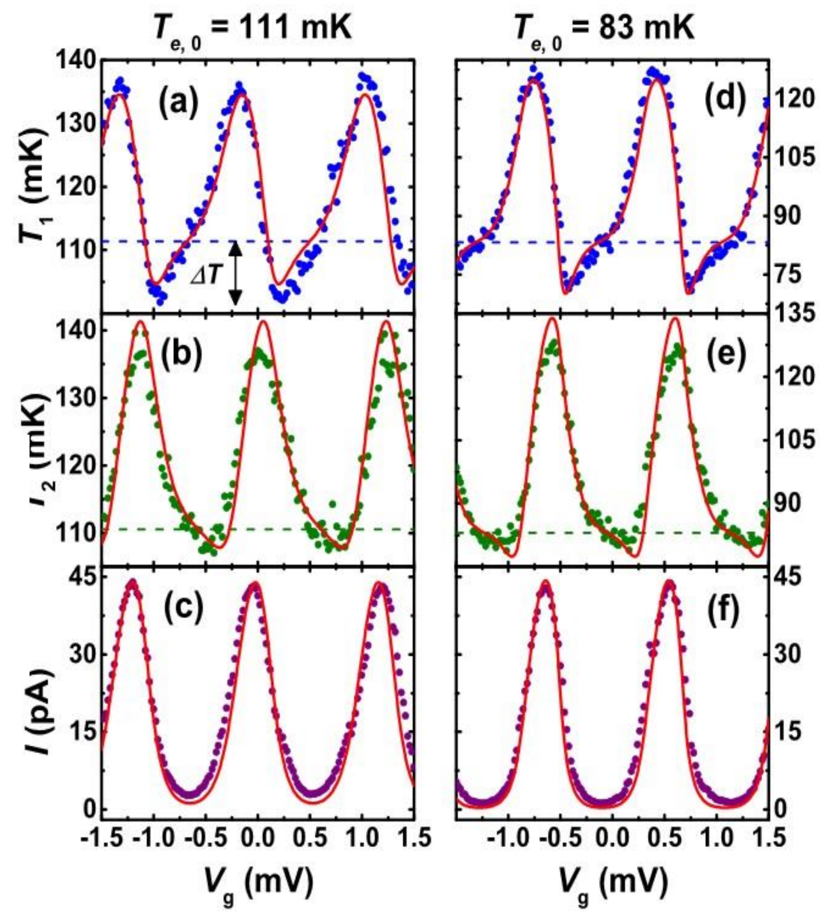


N_g = 1: No feedback control ("SET-cooler")



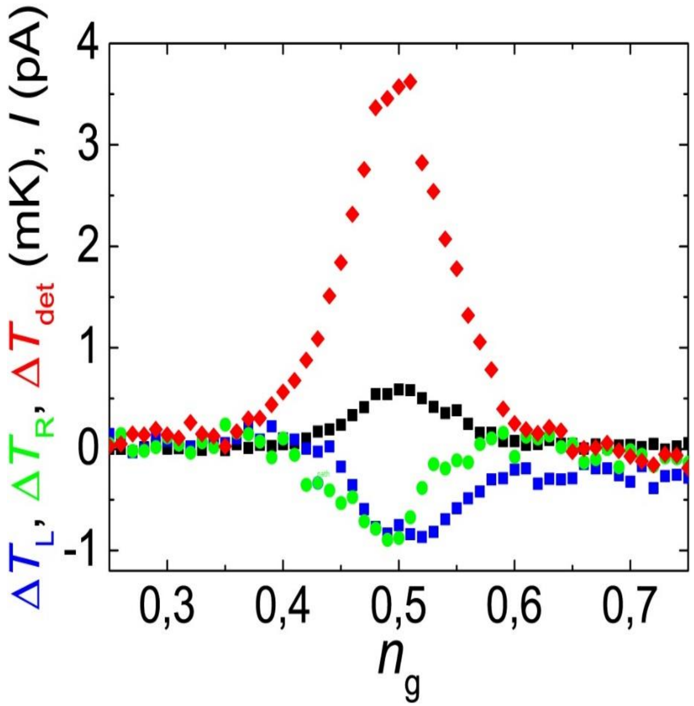


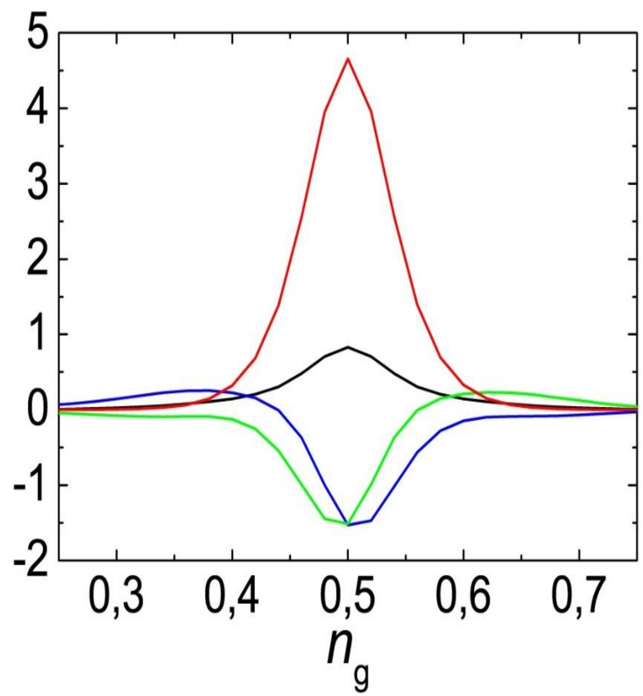


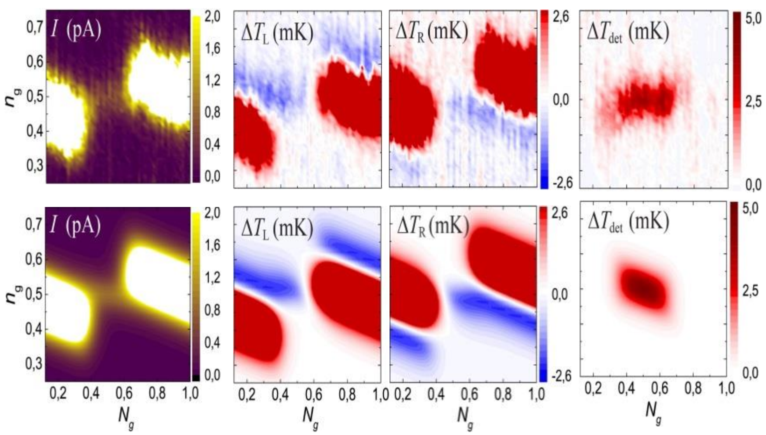


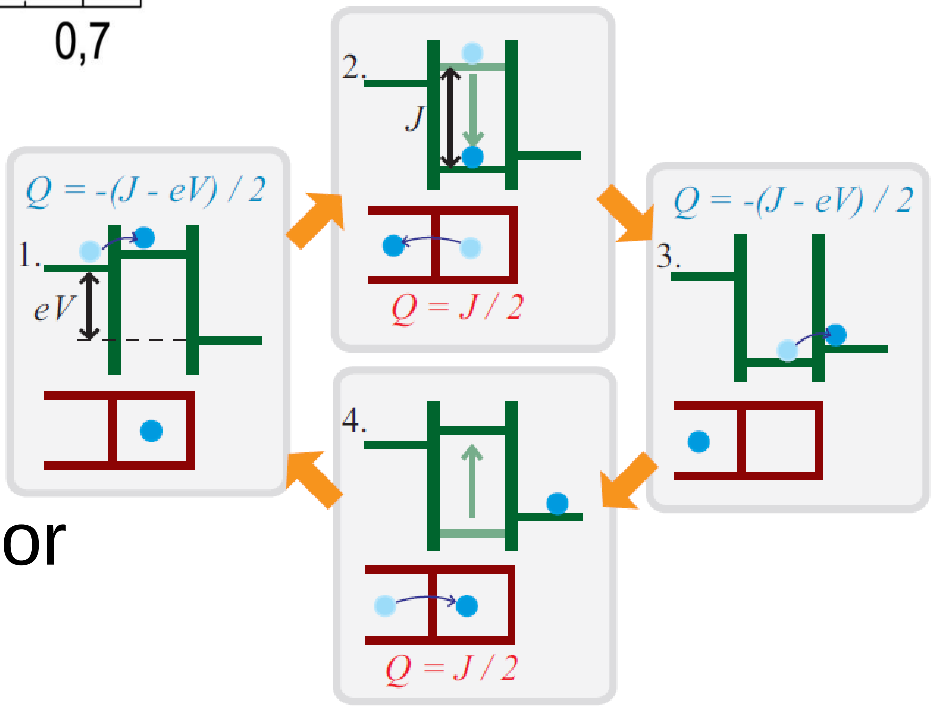
JP, J. V. Koski, and D. V. Averin, PRB **89**, 081309 (2014)
A. V. Feshchenko, J. V. Koski, and JP, PRB **90**, 201407(R) (2014)

N_g = 0.5: feedback control (Demon)







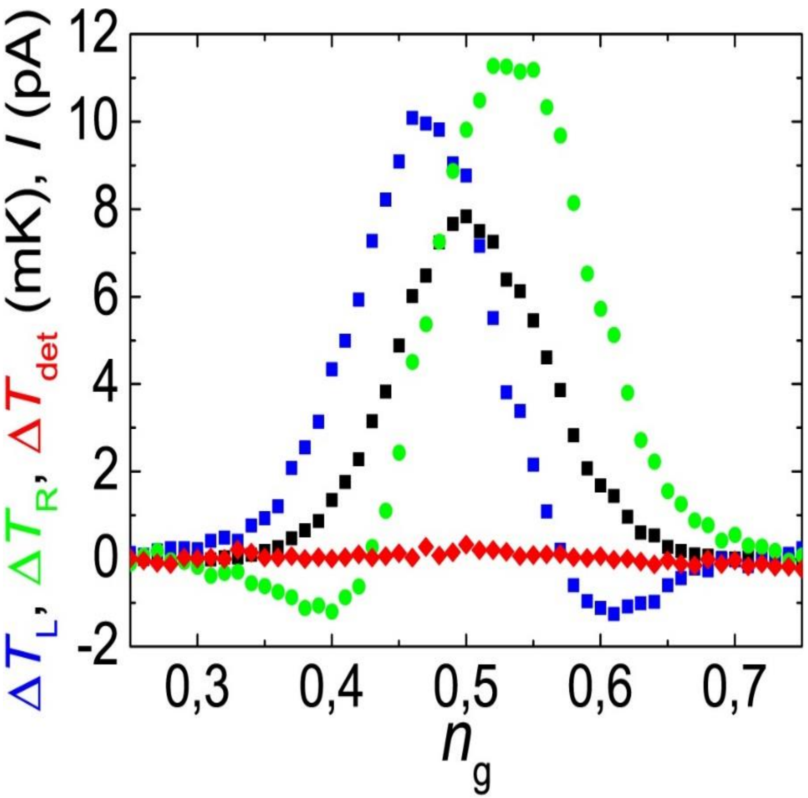


Both T_L and T_R drop: SET entropy decreases

Joule's law and 2nd law violated if not for the heat dissipation in detector

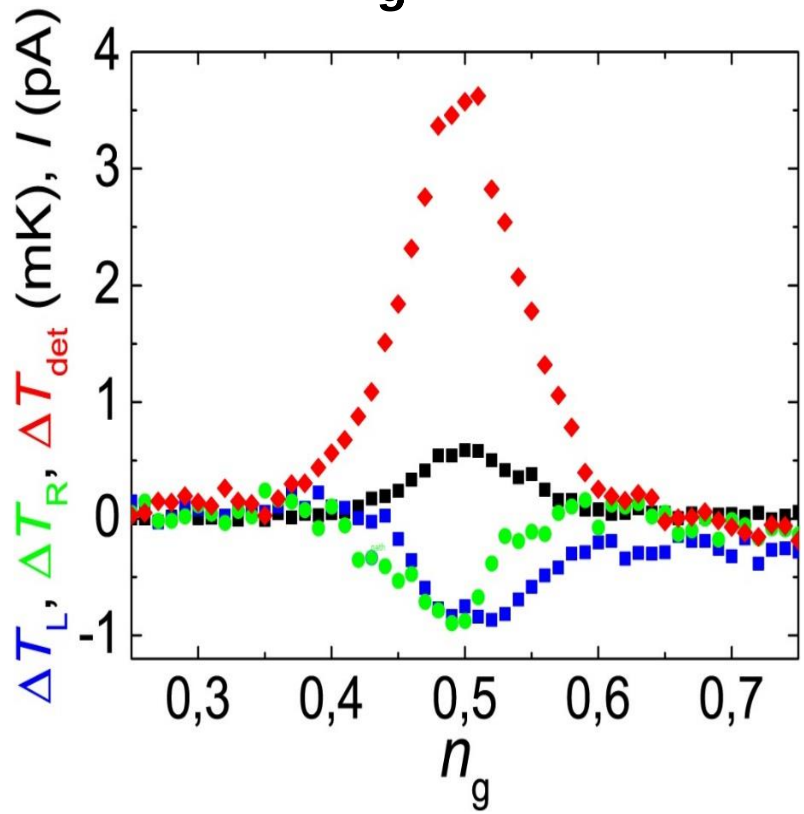
Summary of the autonomous demon characteristics

N_g = 1



SET cooler

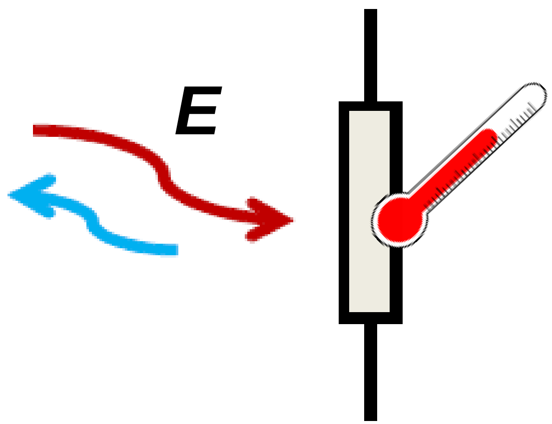
N_g = 0.5

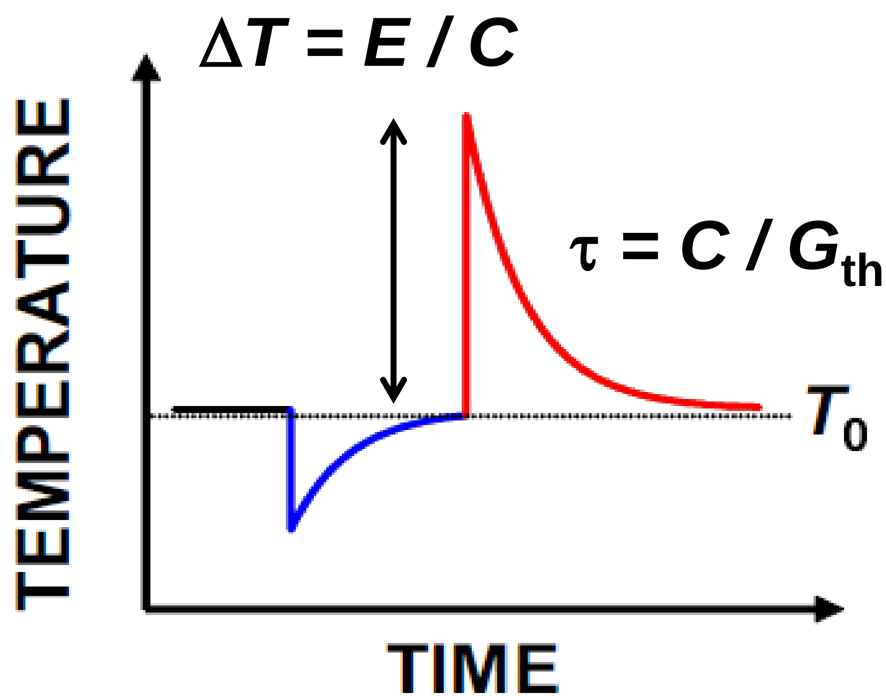


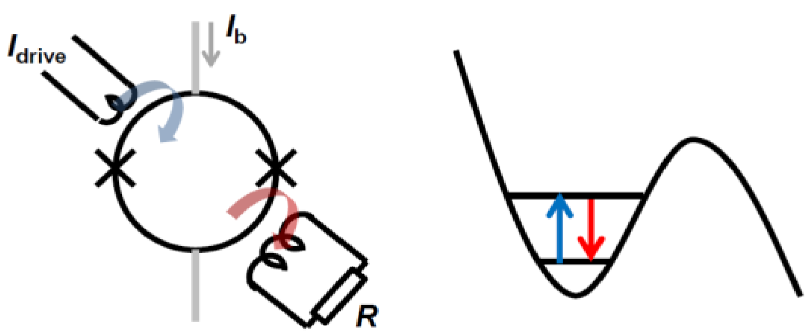
Demon

Calorimetry for quantum thermodynamics

Aims at measuring single quanta (energy *E*) of radiation by an absorber with finite heat capacity *C*.



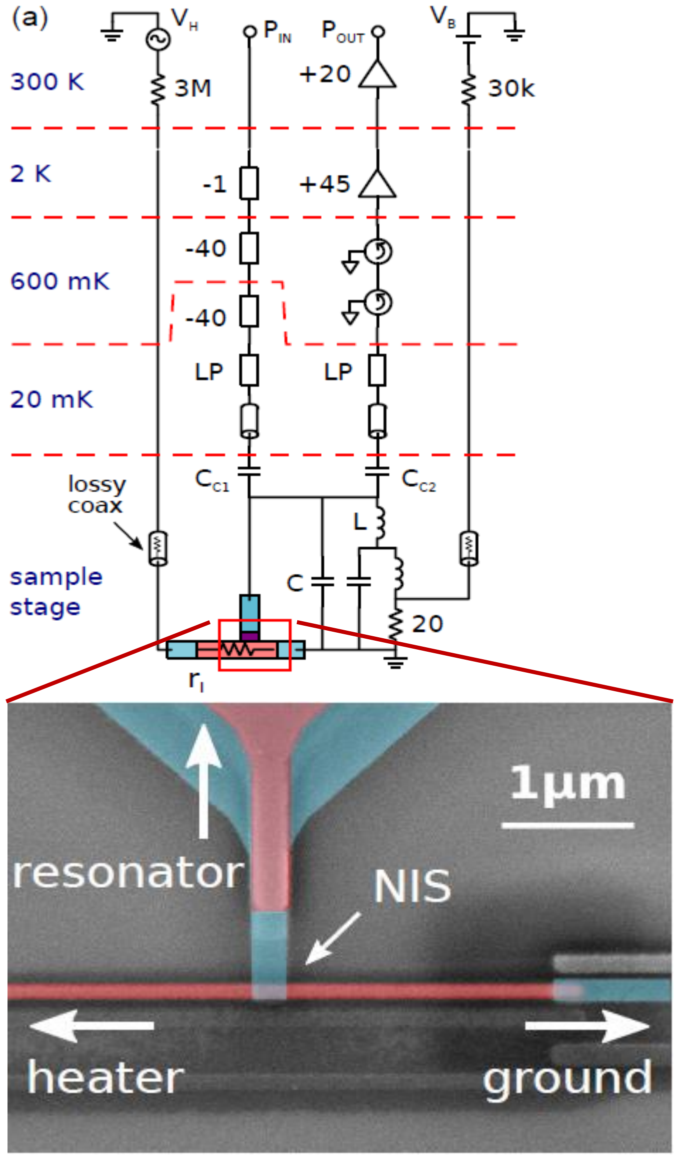




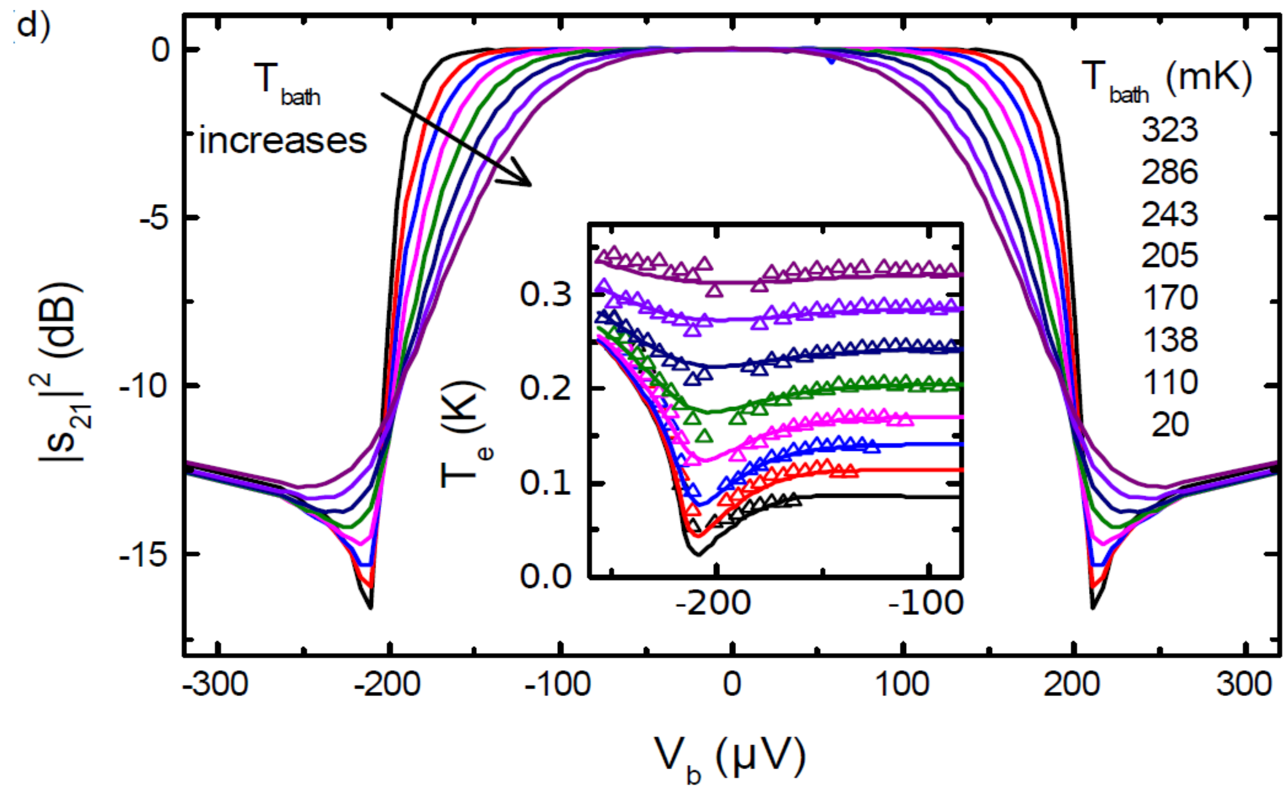
Typical parameters for sc qubits:
$\Delta T \sim 1 - 3$ mK, $\tau \sim 0.01 - 1$ ms

10 μK/(Hz)$^{1/2}$ is sufficient for single photon detection

Fast thermometry



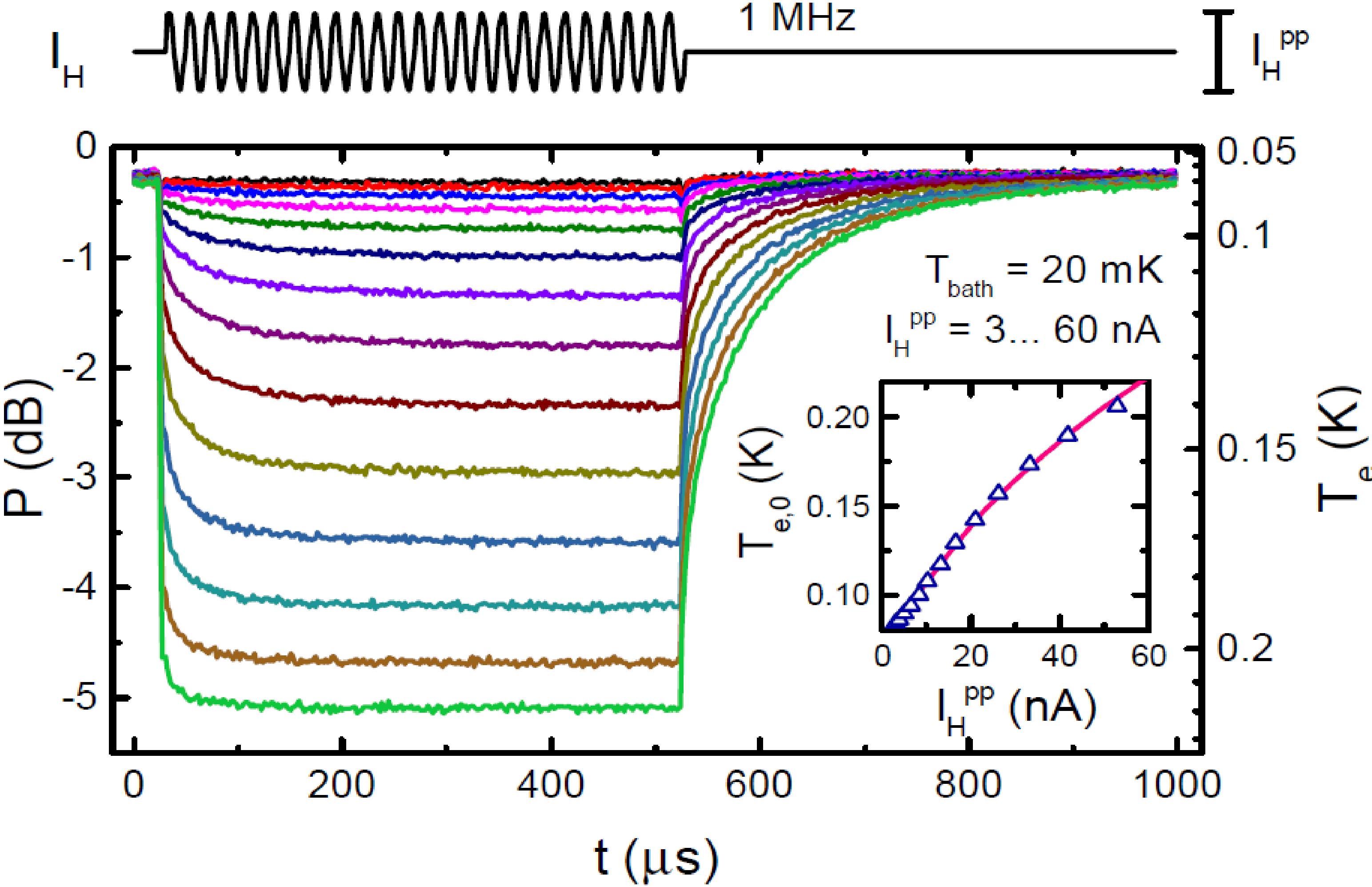
Transmission read-out at 600 MHz of a NIS junction

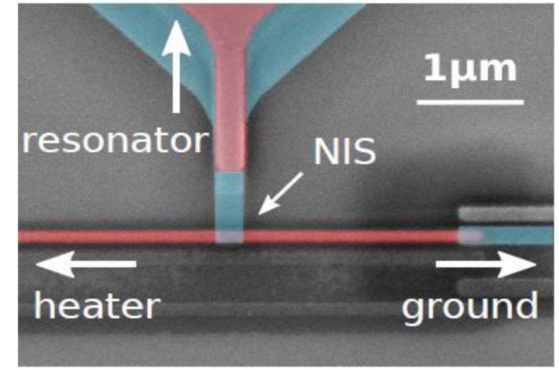


S. Gasparinetti et al., Phys. Rev. Applied 3, 014007 (2015);
K. L. Viisanen et al., New J. Phys. 17, 055014 (2015).
See also D. R. Schmidt, C. S. Yung, and A. N. Cleland, Appl. Phys. Lett. 83, 1002 (2003).

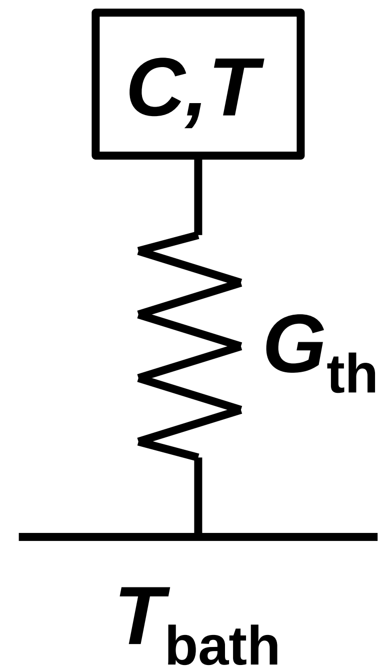
Fast thermometry

Time resolved measurements



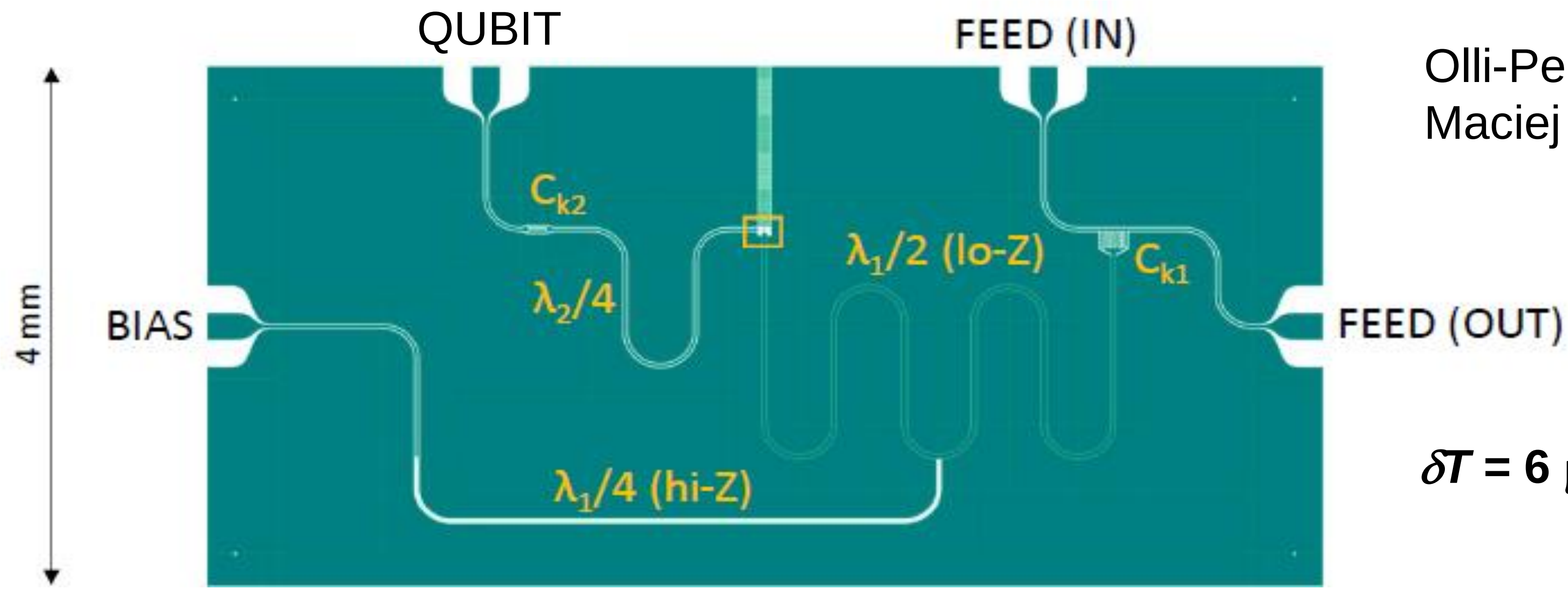


$$\mathcal{C}\frac{d\delta T}{dt} = -G_{\rm th}\delta T$$



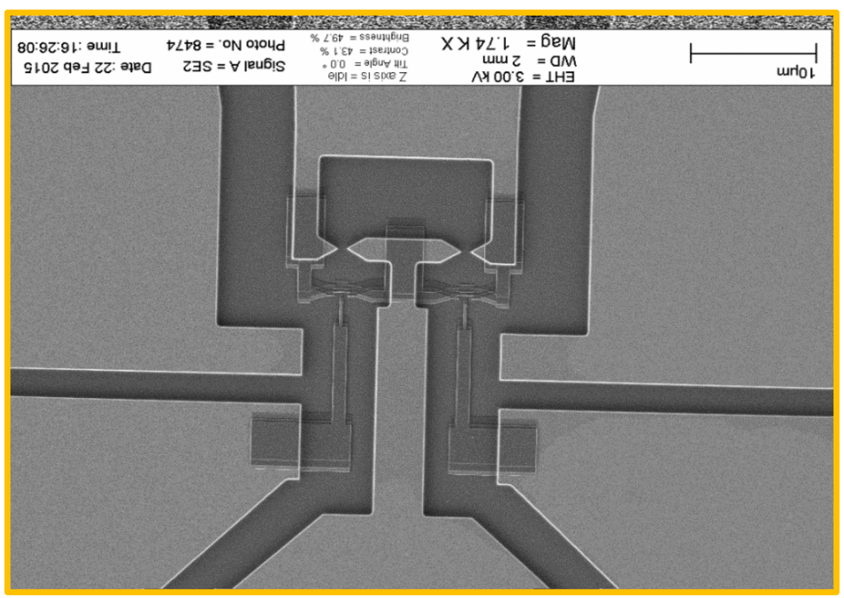
Currently we have 10 µK/Hz$^{1/2}$ which should be is sufficient for single photon detection

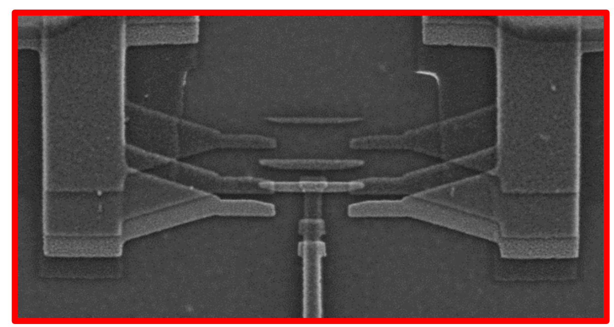
Micro-wave calorimeter (5 GHz)



Olli-Pentti Saira
Maciej Zgirski

δT **= 6 μK/(Hz)$^{1/2}$**





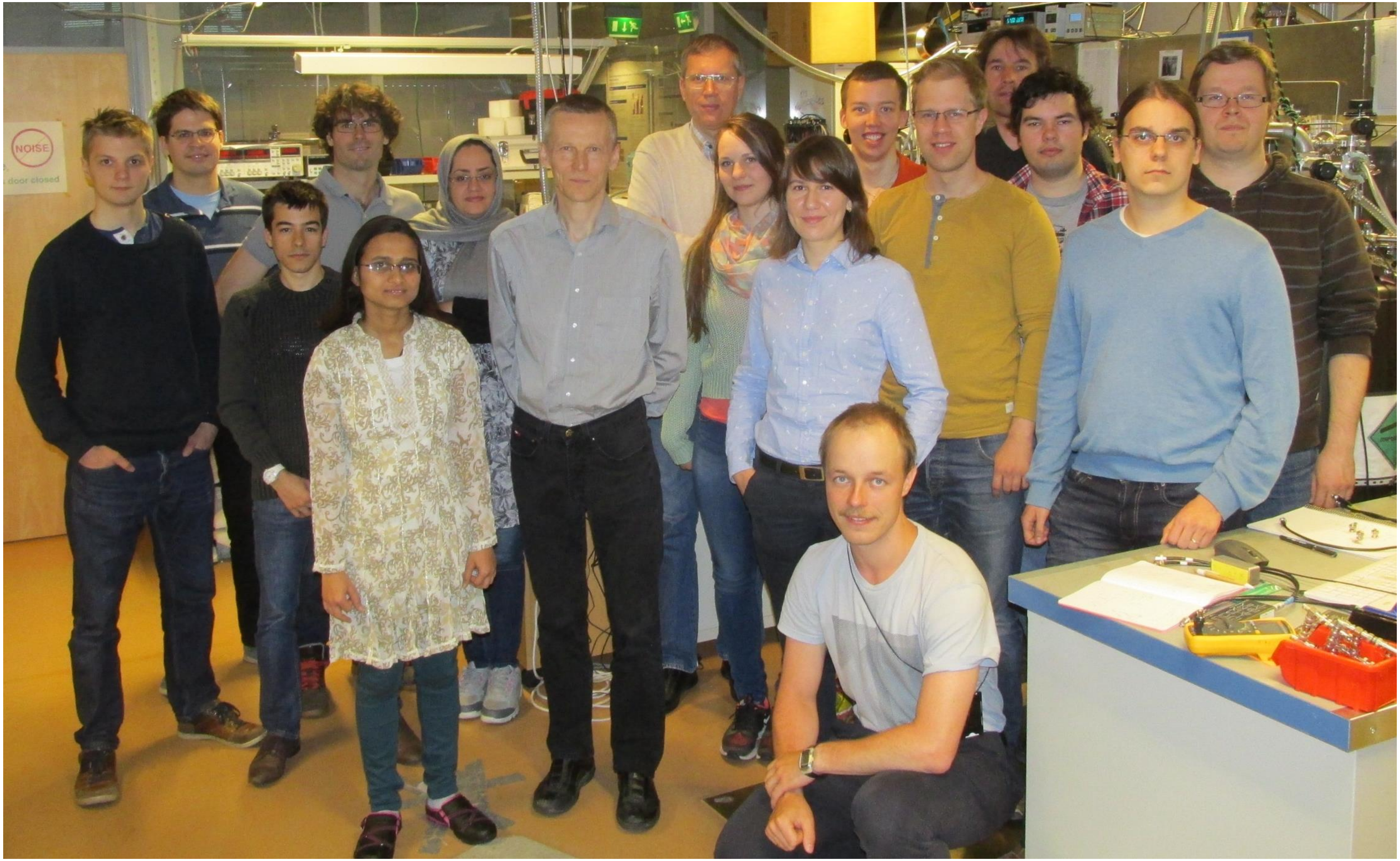
Measurements of
- **temperature fluctuations**
- **work distribution of a driven qubit**

Conclusions

Two different types of Maxwell’s demons demonstrated experimentally

Nearly $k_B T$ ln(2) heat extracted per cycle in the **Szilard’s engine**

Autonomous Maxwell’s demon – an ”all-in-one” device: effect of internal information processing observed as heat dissipation in the detector and as cooling of the system


NOISE
door closed