Maxwell's Demon in a single-electron circuit

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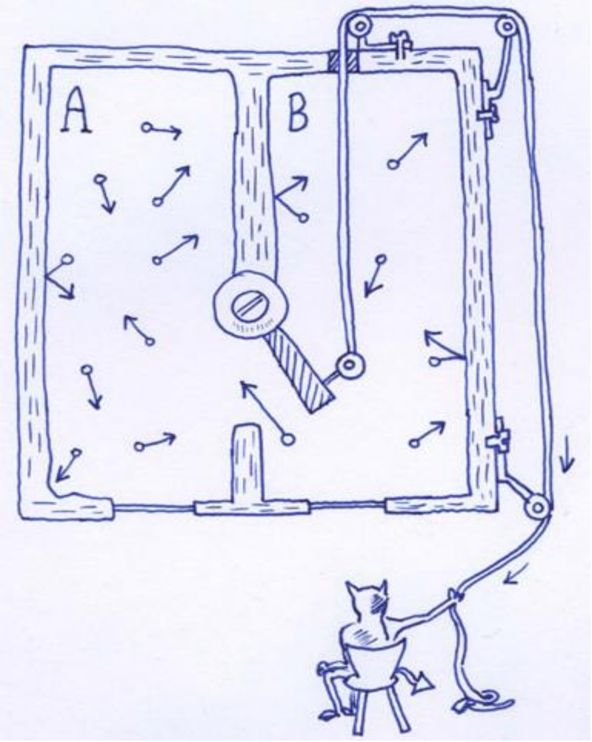
Low temperature laboratory

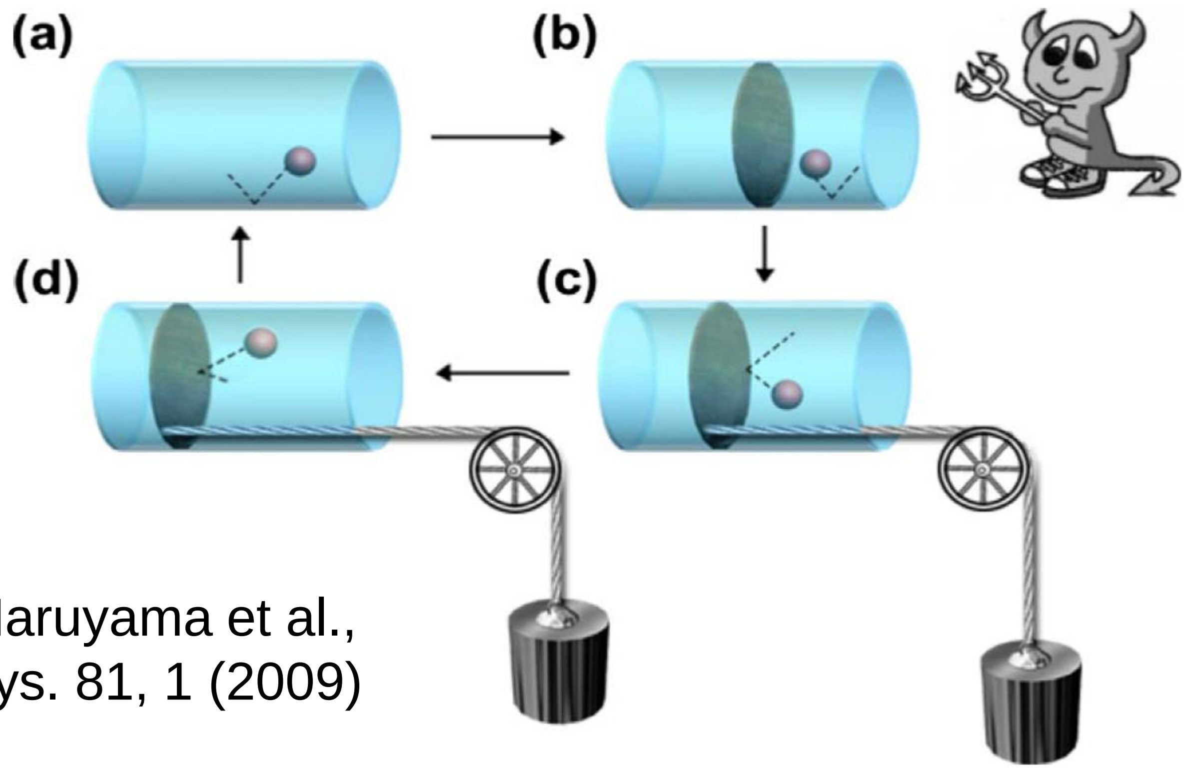
Outline

1. Maxwell's demon
2. Experiment on a single-electron Szilard's engine
3. Experiment on an autonomous Maxwell's demon
4. MD based on a single qubit



Role of information in thermodynamics

Szilard’s engine



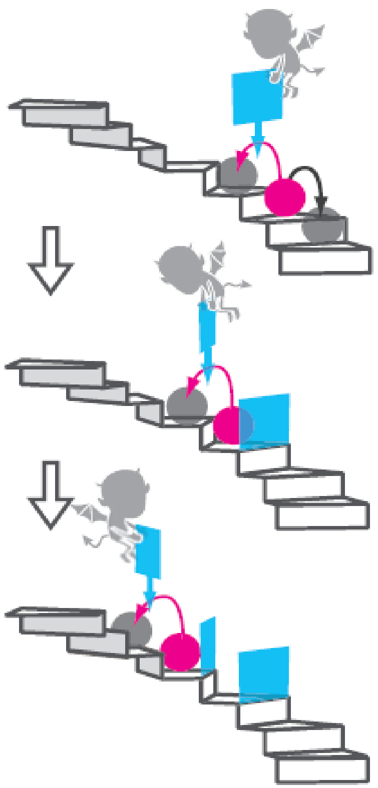
(L. Szilard 1929)

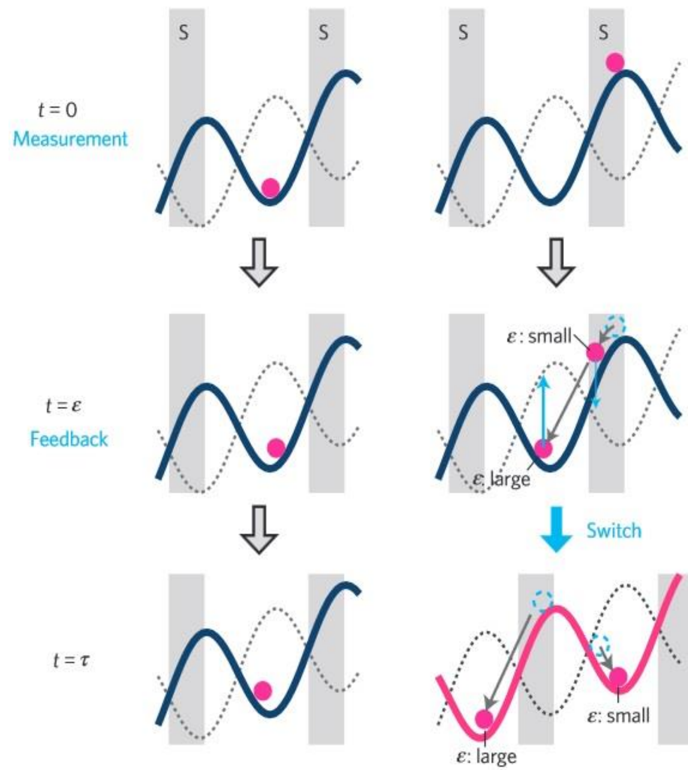
Figure from Maruyama et al.,
Rev. Mod. Phys. 81, 1 (2009)

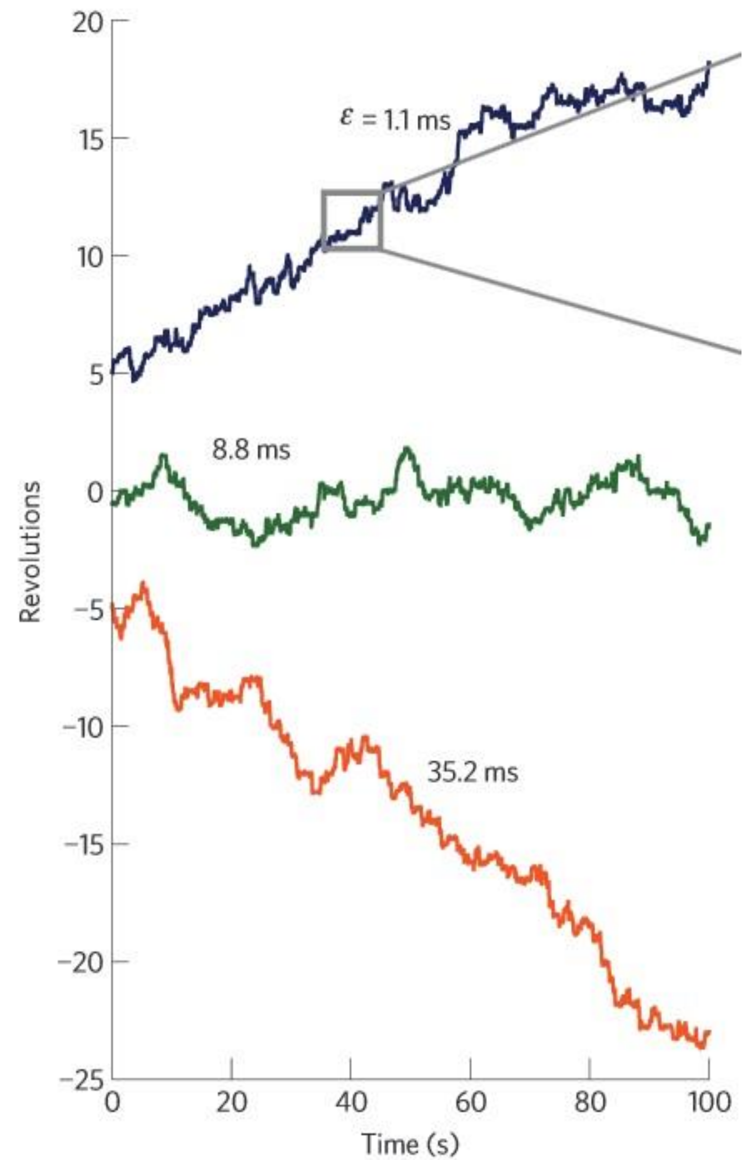
Isothermal expansion of the ”single-molecule gas” does work against the load

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

Experiments on Maxwell's demon



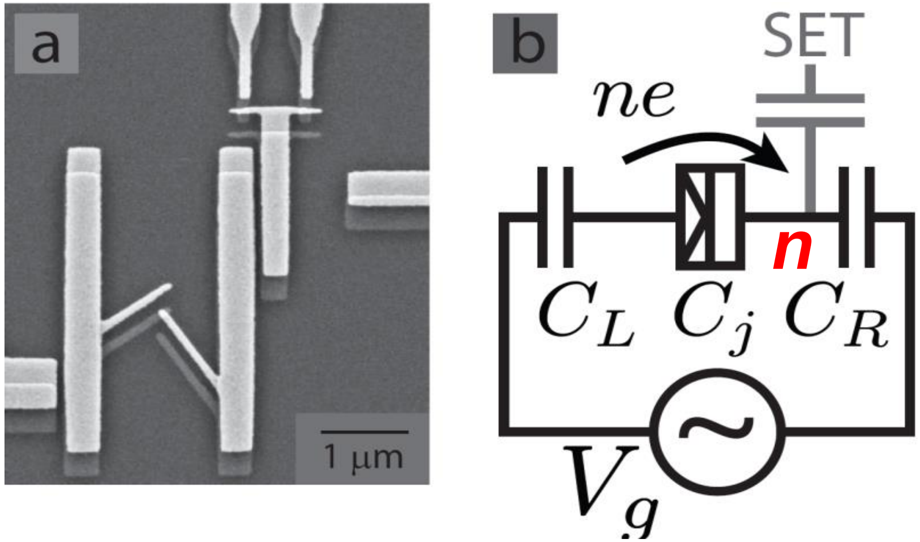




S. Toyabe, T. Sagawa, M. Ueda, E. Muneyuki, M. Sano, Nature Phys. **6**, 988 (2010)

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*:

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

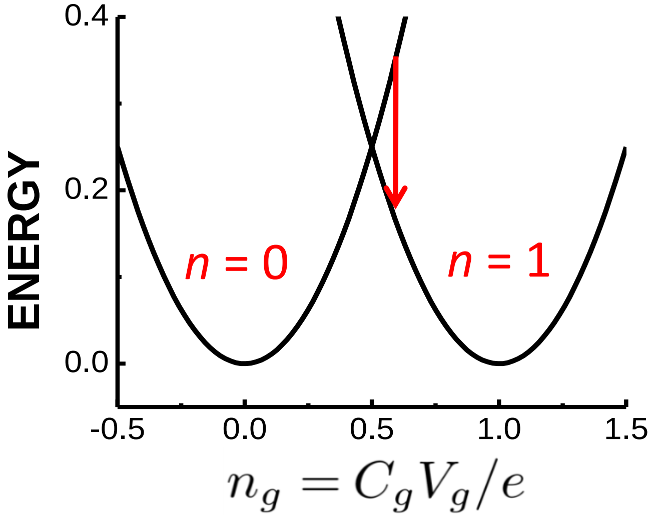
Total heat generated in a process:

$$Q = \sum_i Q_i$$

Work in a process:

$$W = Q + \Delta U$$

Change in internal (charging) energy



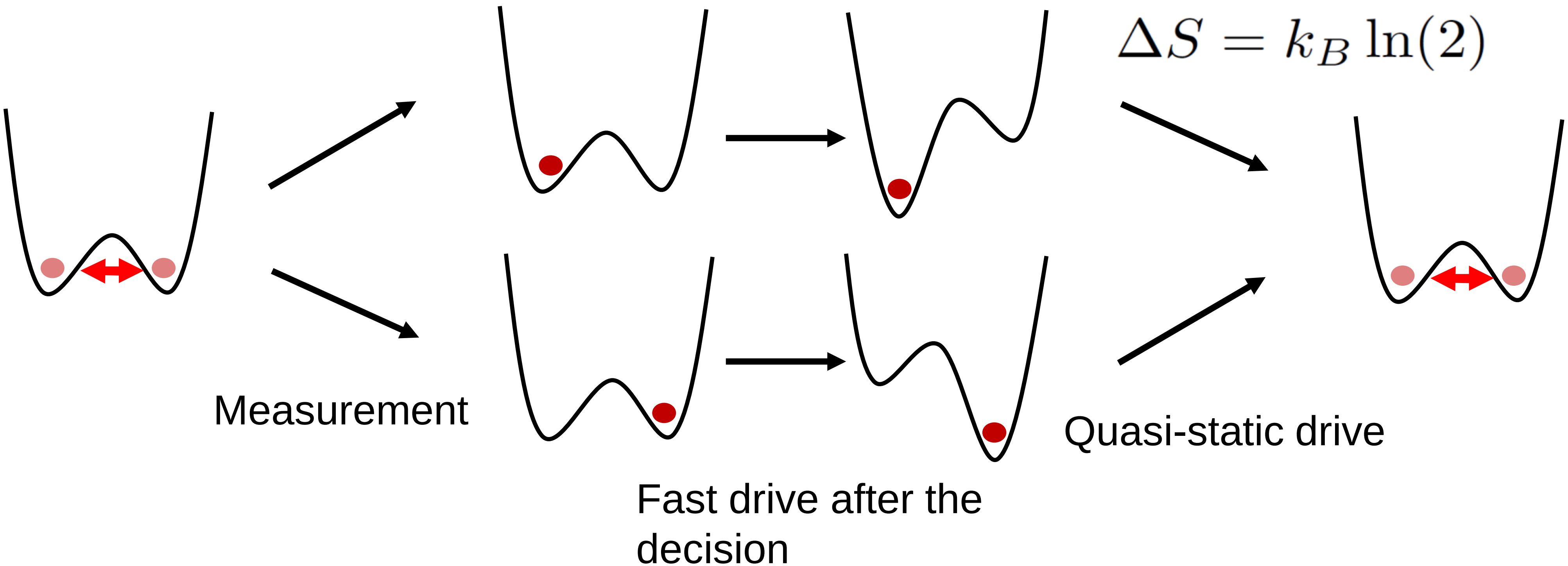
D. Averin and JP, EPL 96, 67004 (2011)

Szilard’s engine for single electrons

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

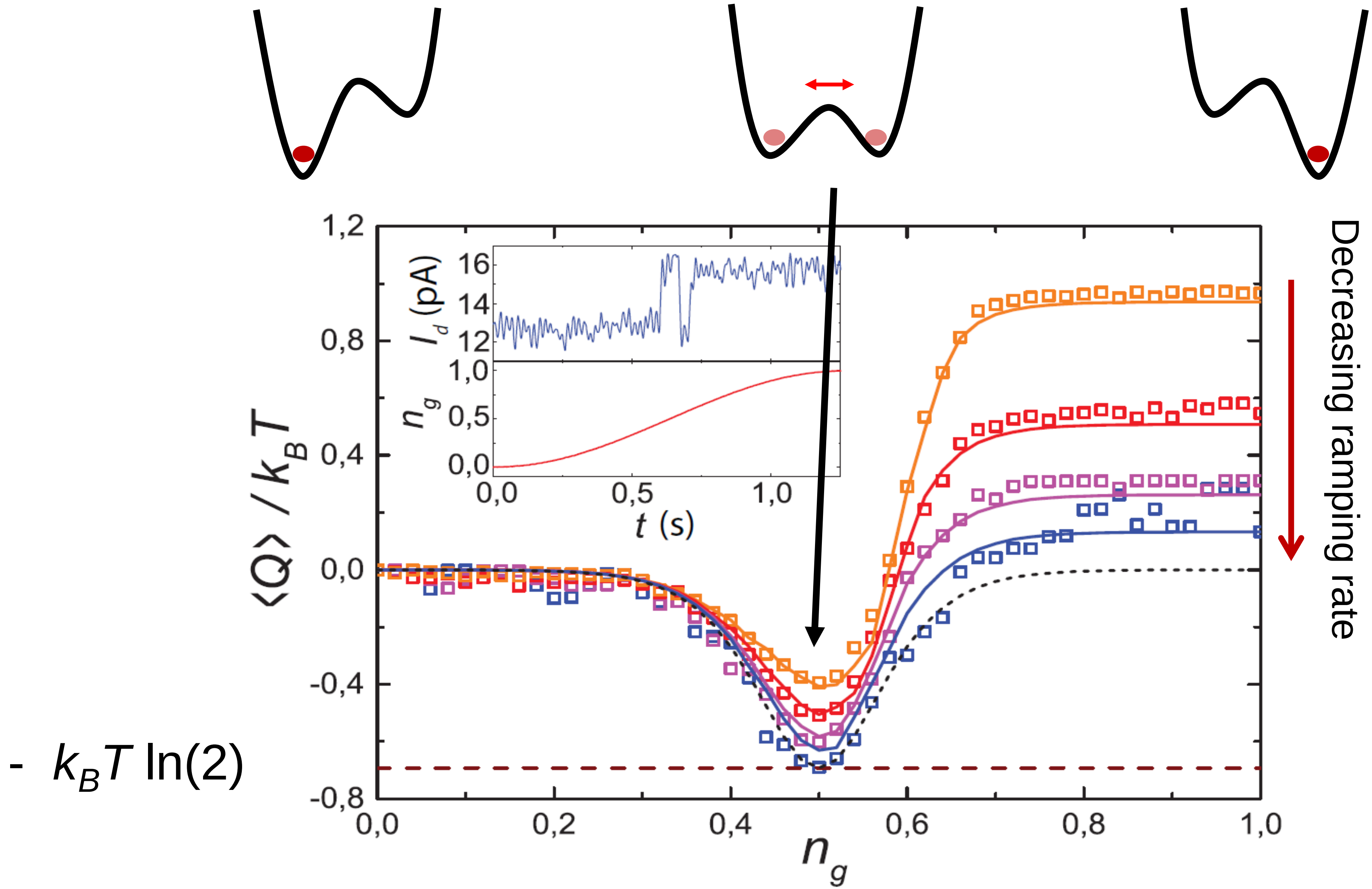
Entropy of the charge states: $$S = -k_B \sum_{i=0,1} p(i) \ln[p(i)]$$

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



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

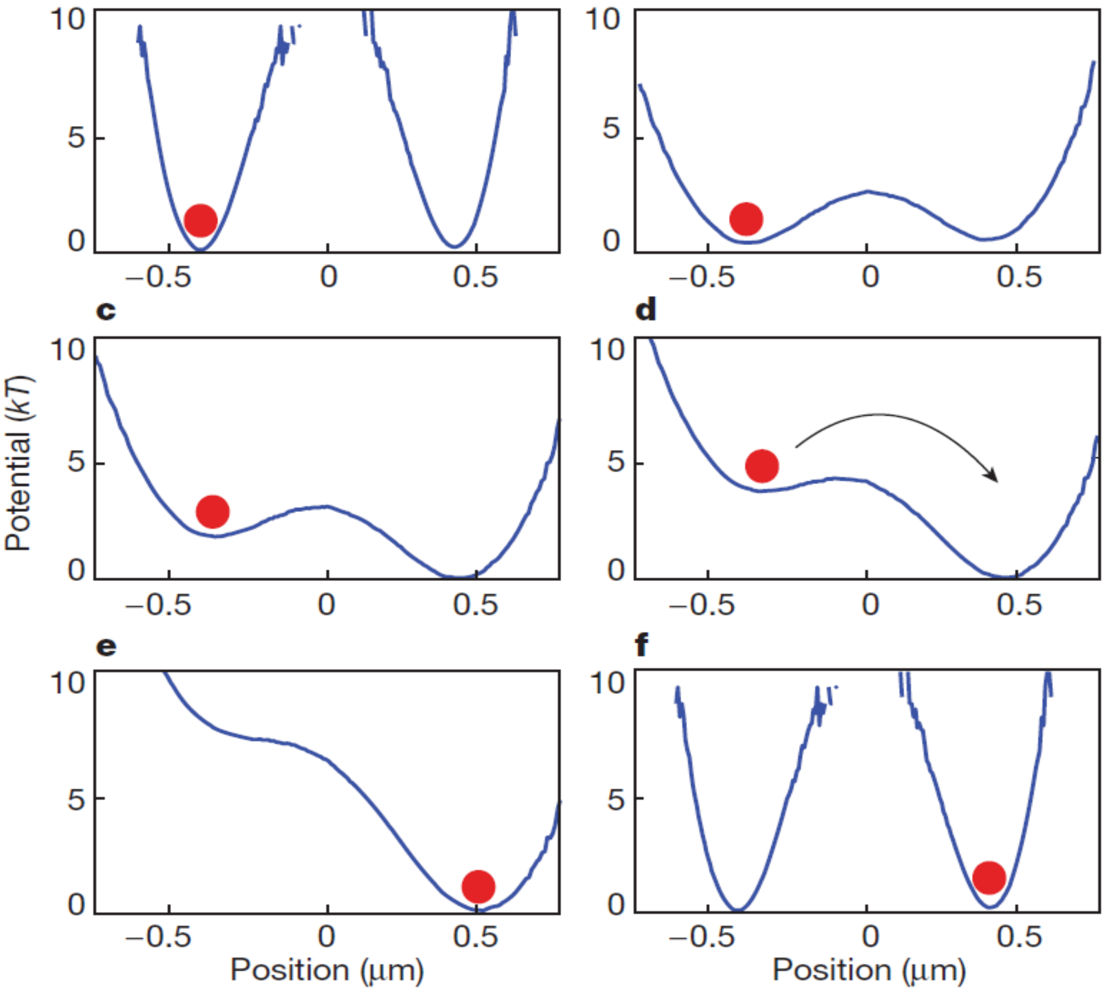
Extracting heat from the bath



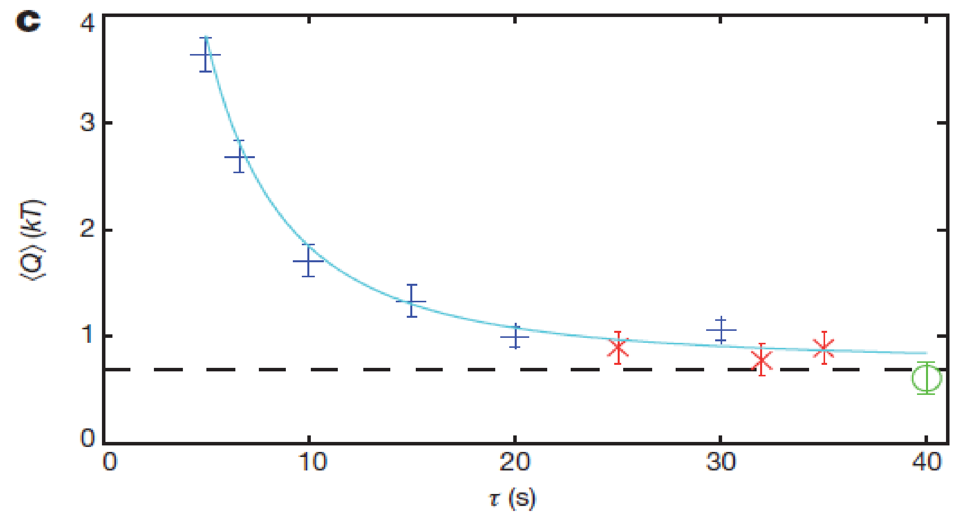
Erasure of information

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

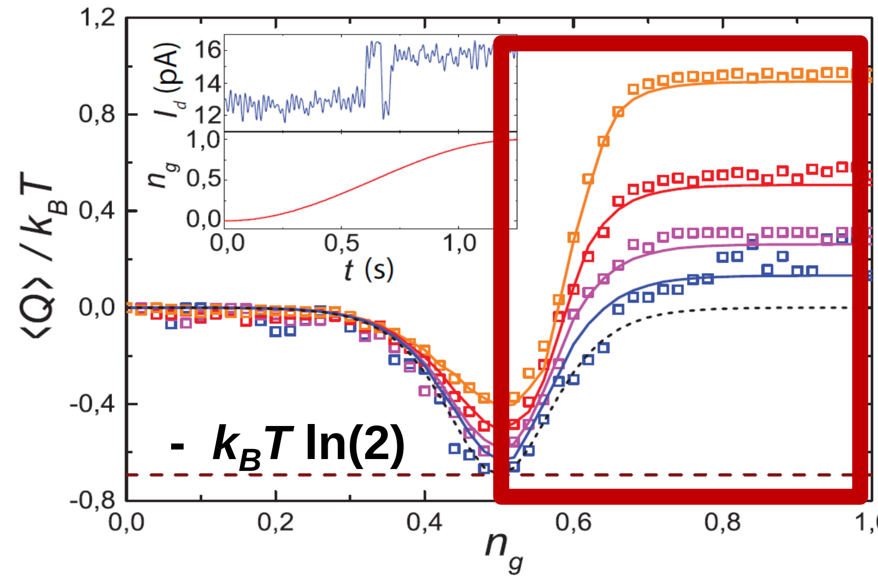
Experiment on a colloidal particle:



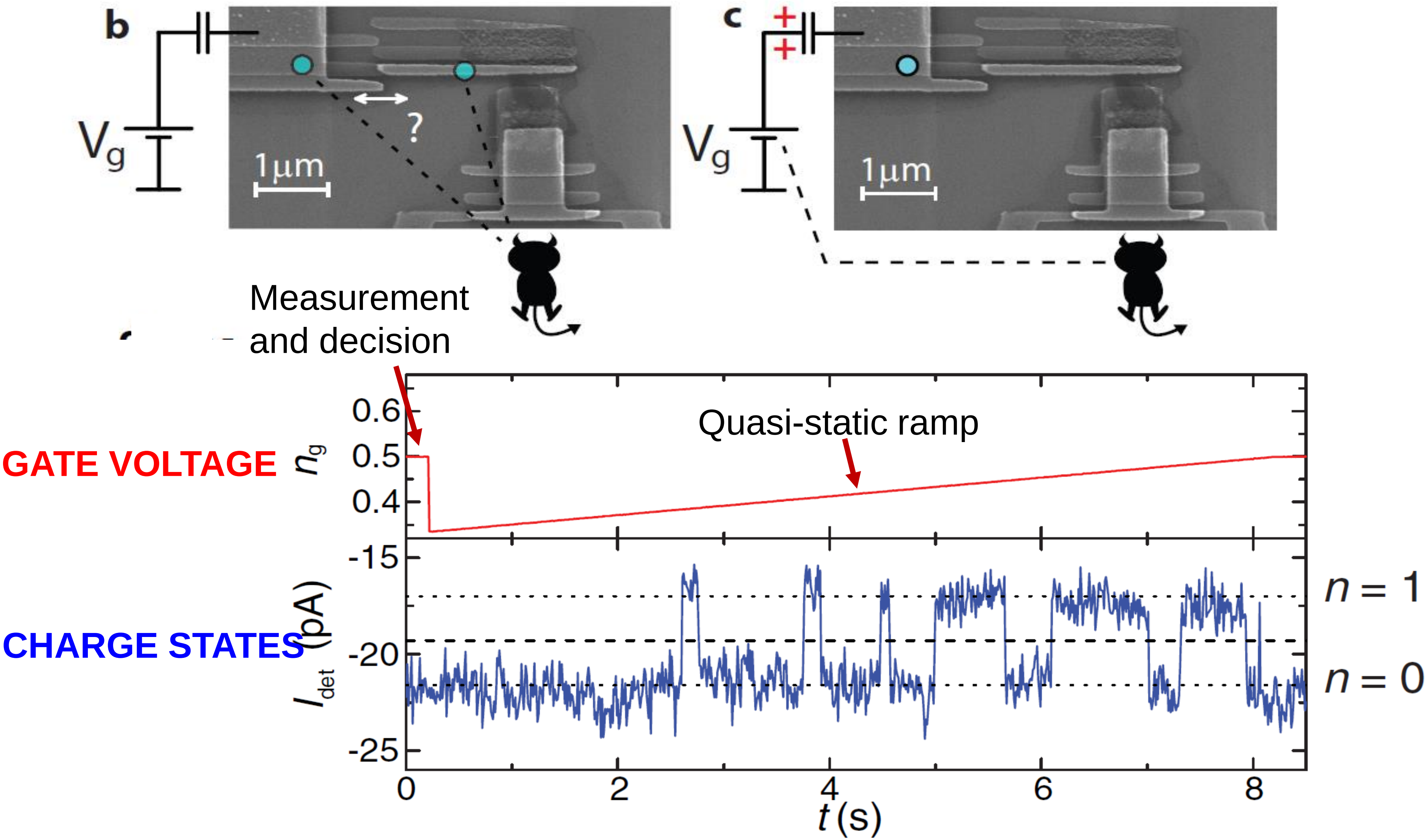
A. Berut et al., Nature 2012



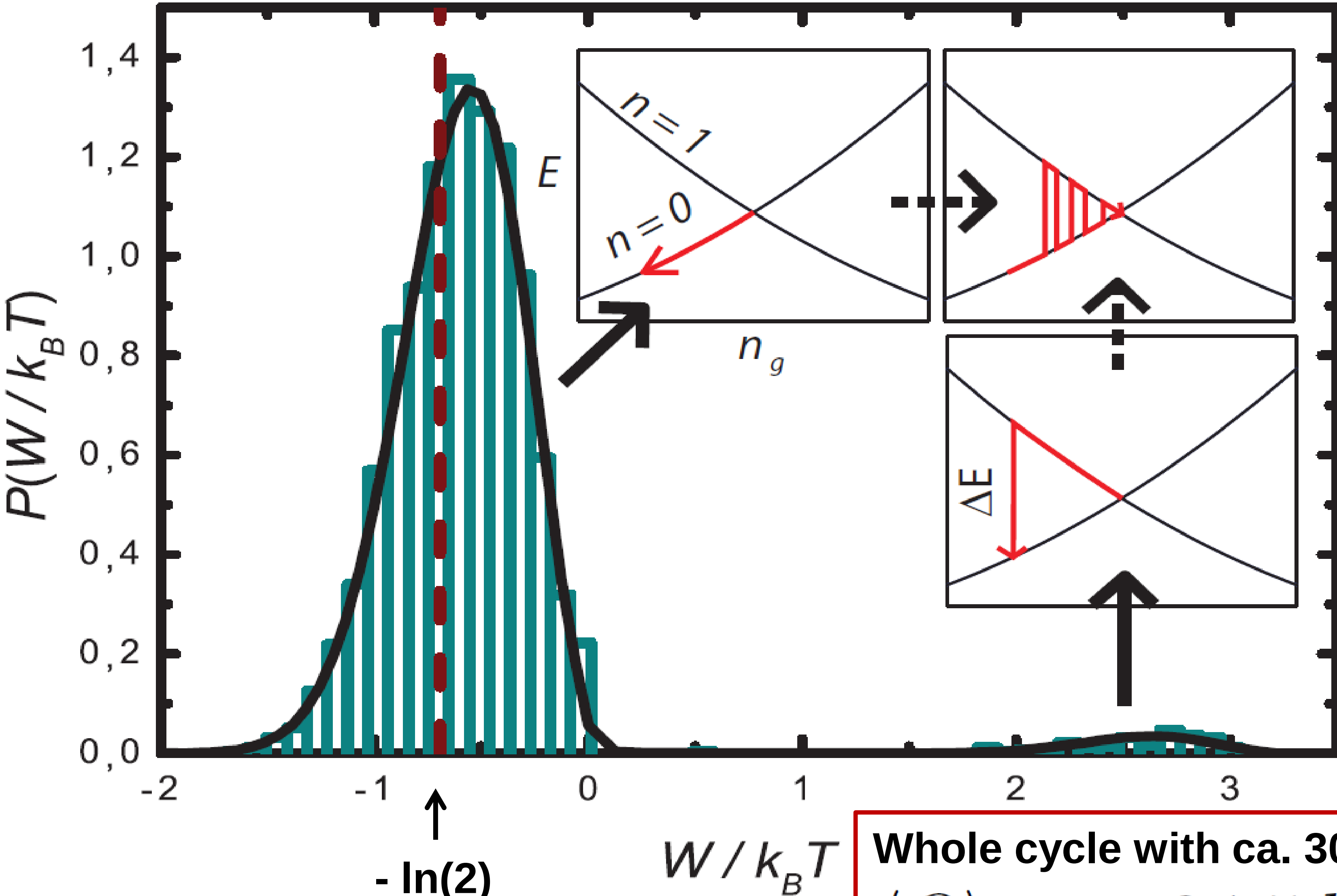
Corresponds to our experiment:



Realization of the MD with an electron



Measured distributions in the MD experiment



↑ **- ln(2)**

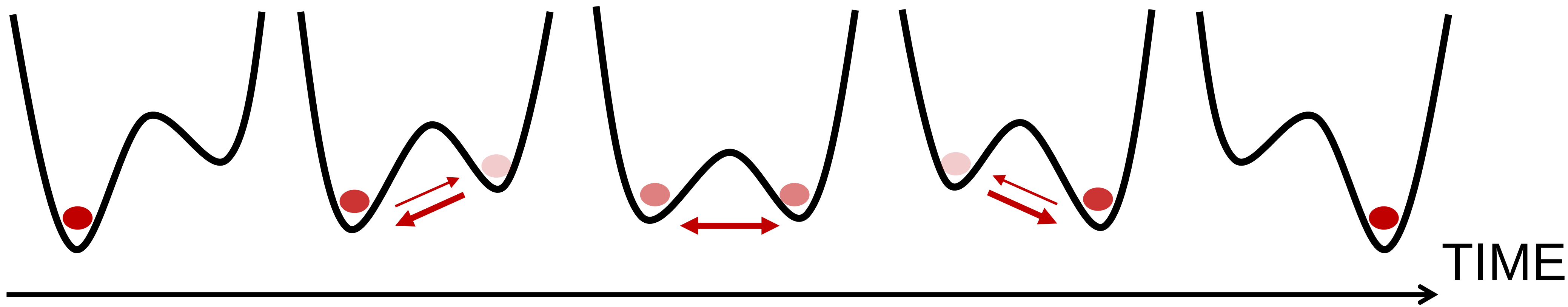
Whole cycle with ca. 3000 repetitions:

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

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

Fluctuation relations

Work and dissipation in a driven process?



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

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

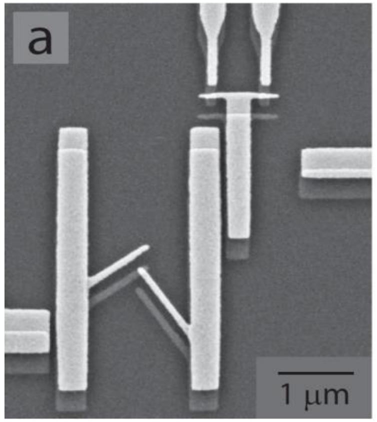
2nd law of thermodynamics

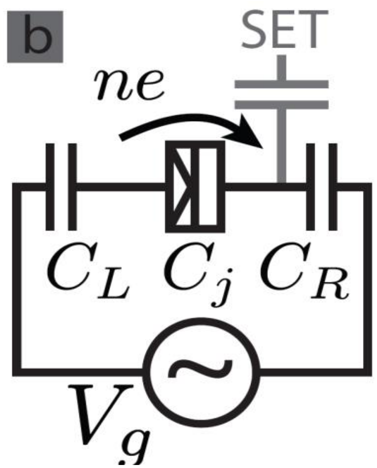
This relation is valid for a system with one bath at inverse temperature β, also far from equilibrium

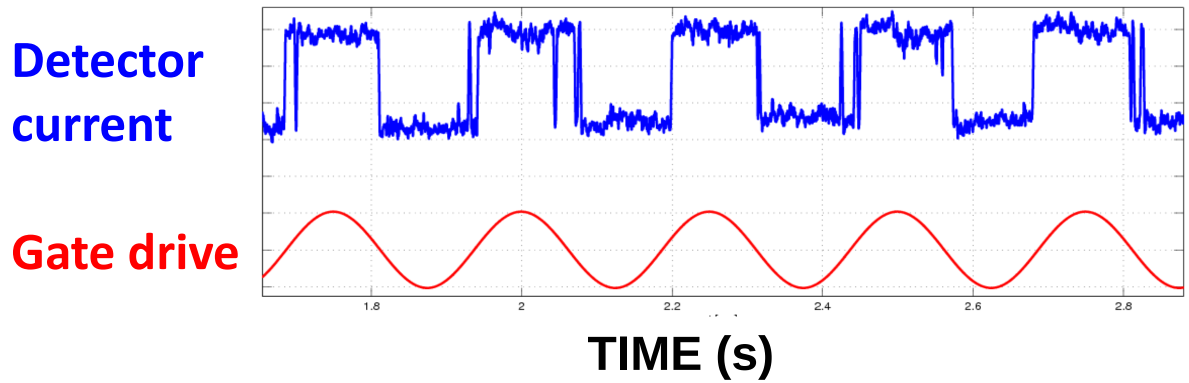
review: U. Seifert, Rep. Prog. Phys. **75**, 126001 (2012)

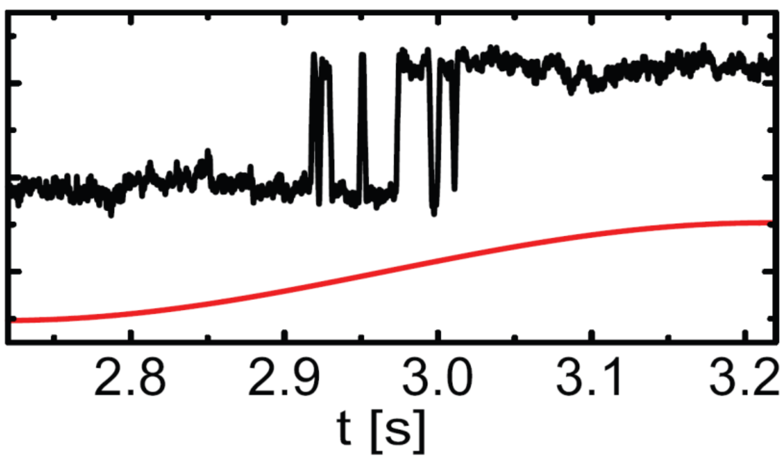
Experiment on a single-electron box

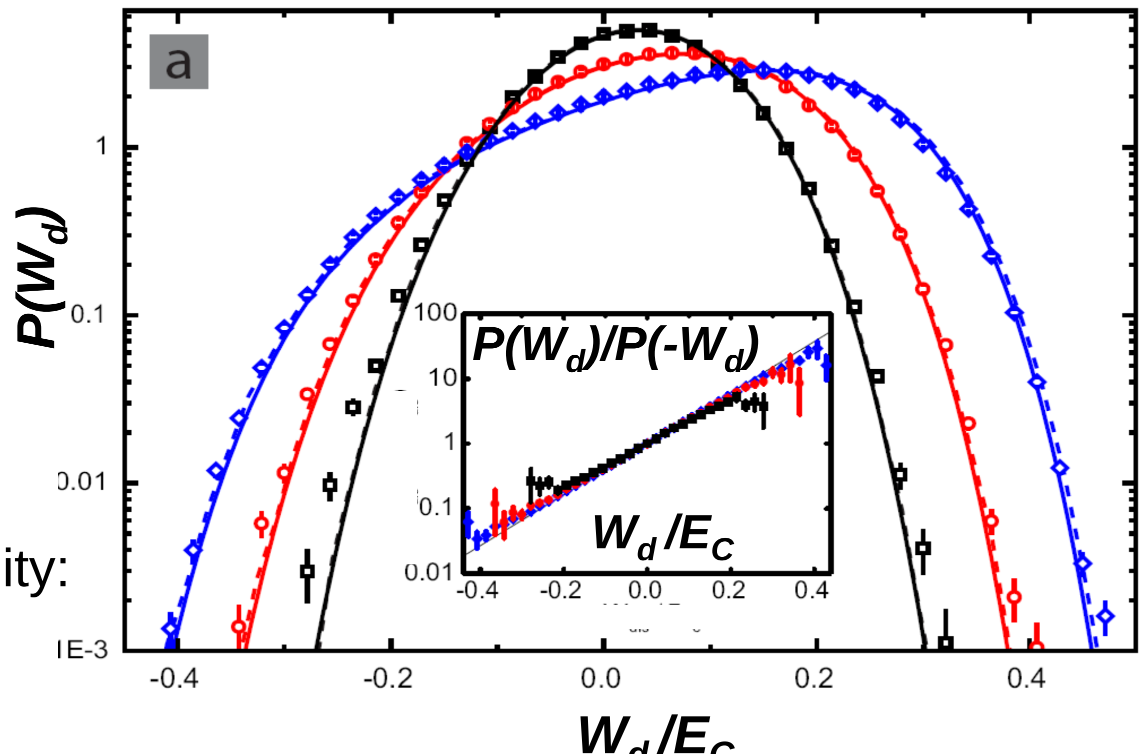
O.-P. Saira et al., PRL 109, 180601 (2012); J.V. Koski et al., Nature Physics 9, 644 (2013).











The distributions satisfy Jarzynski equality:

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

Sagawa-Ueda relation

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

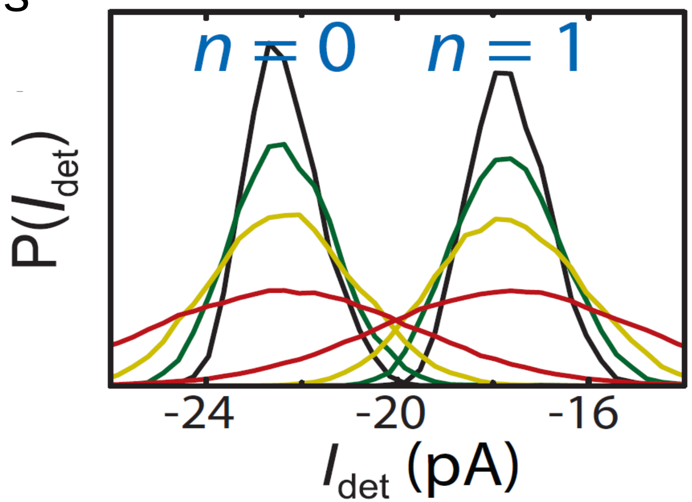
T. Sagawa and M. Ueda, PRL 104, 090602 (2010)

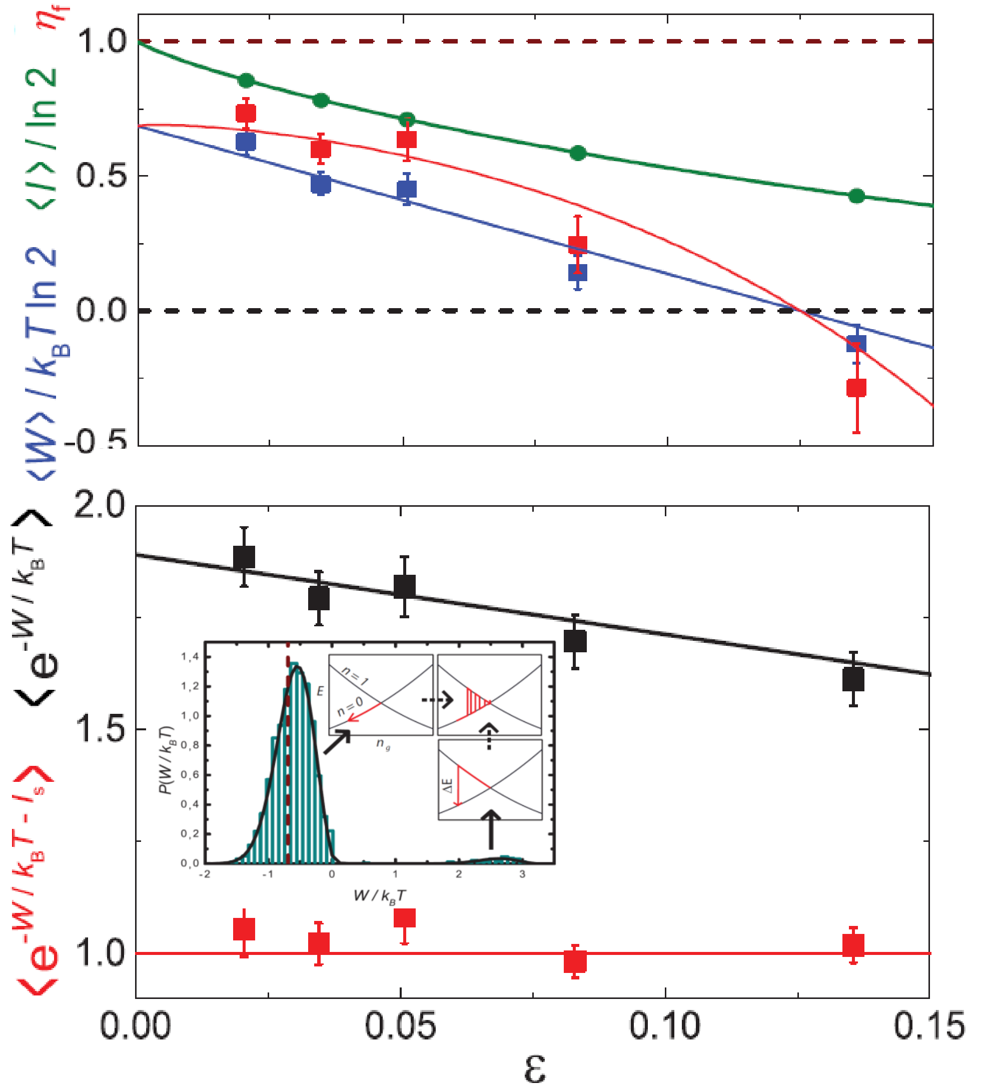
For a symmetric two-state system:

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

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

Measurements of *n* at different detector bandwidths



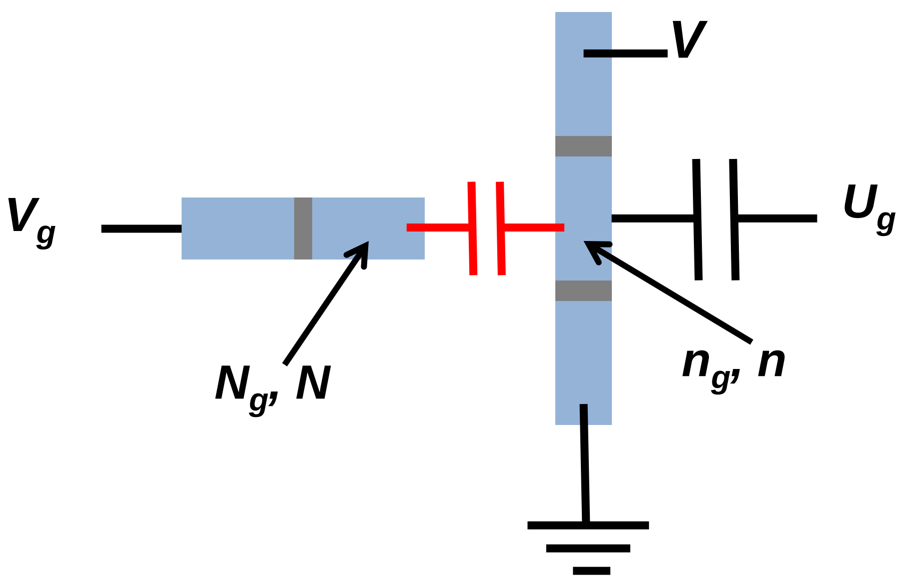


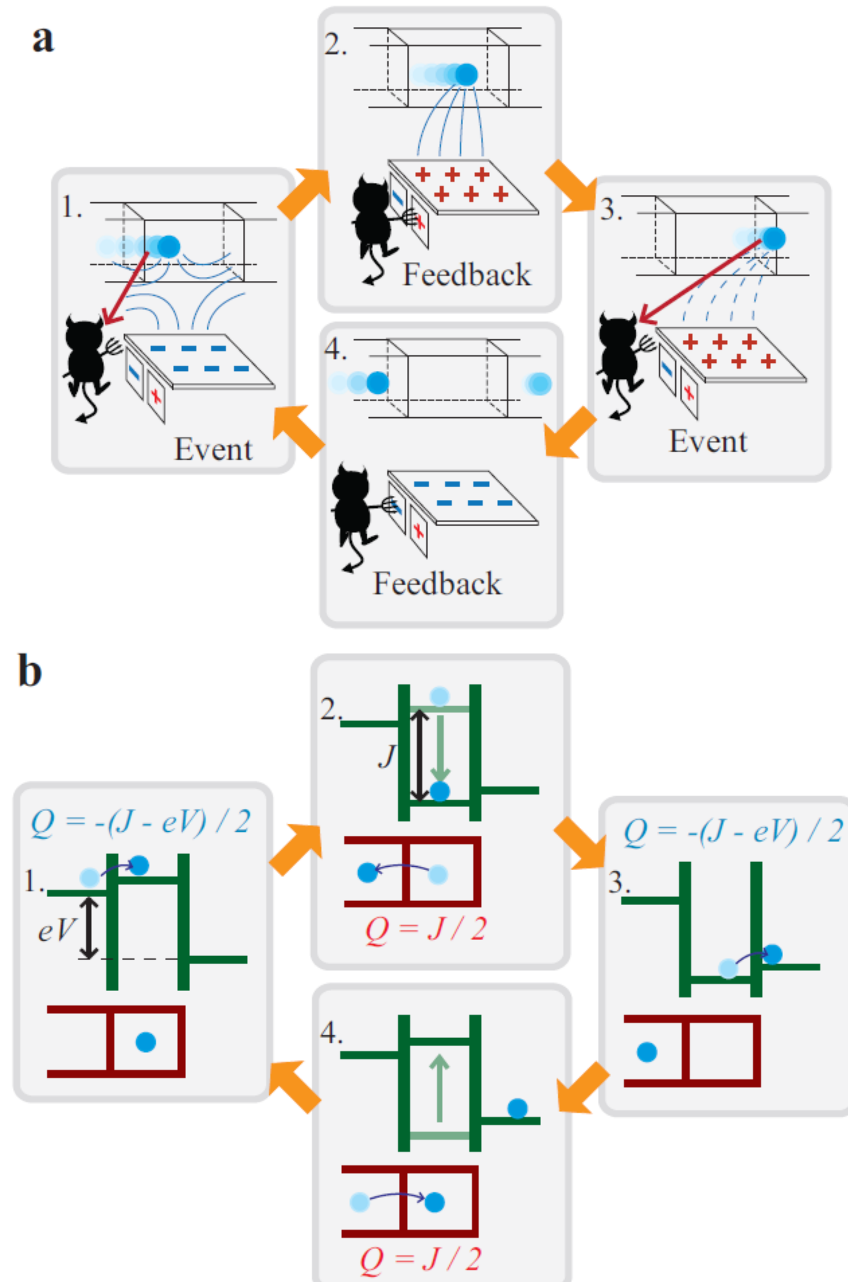
J. V. Koski et al., PRL 113, 030601 (2014)

Autonomous Maxwell's demon

System and Demon: all in one

Realization in a circuit:



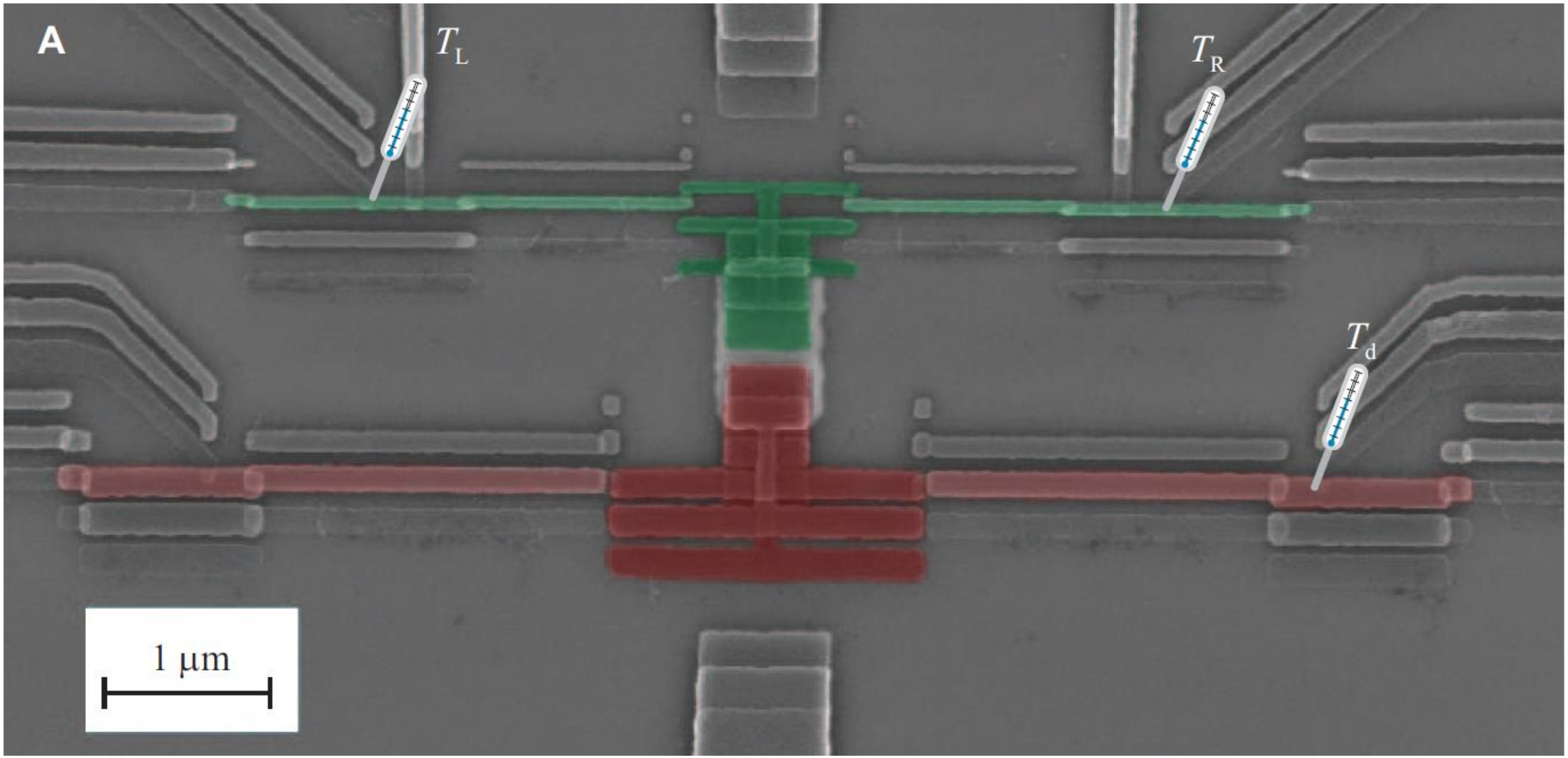


J. Koski et al., arXiv:1507.00530 (2015).

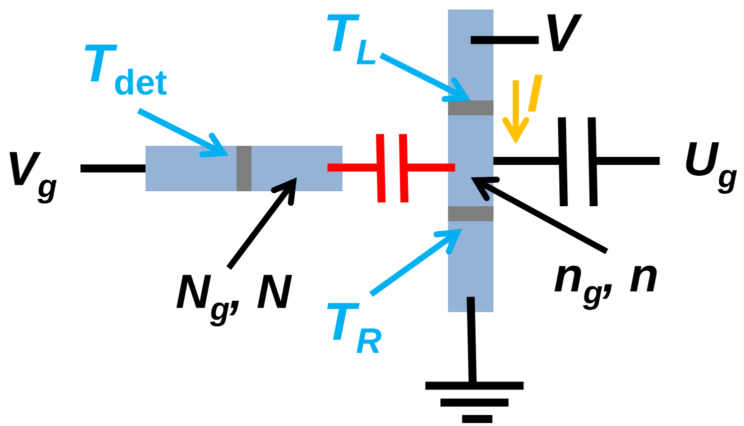
P. Strasberg et al., Phys. Rev. Lett. 110, 040601 (2013).

Autonomous Maxwell's demon – information-powered refrigerator

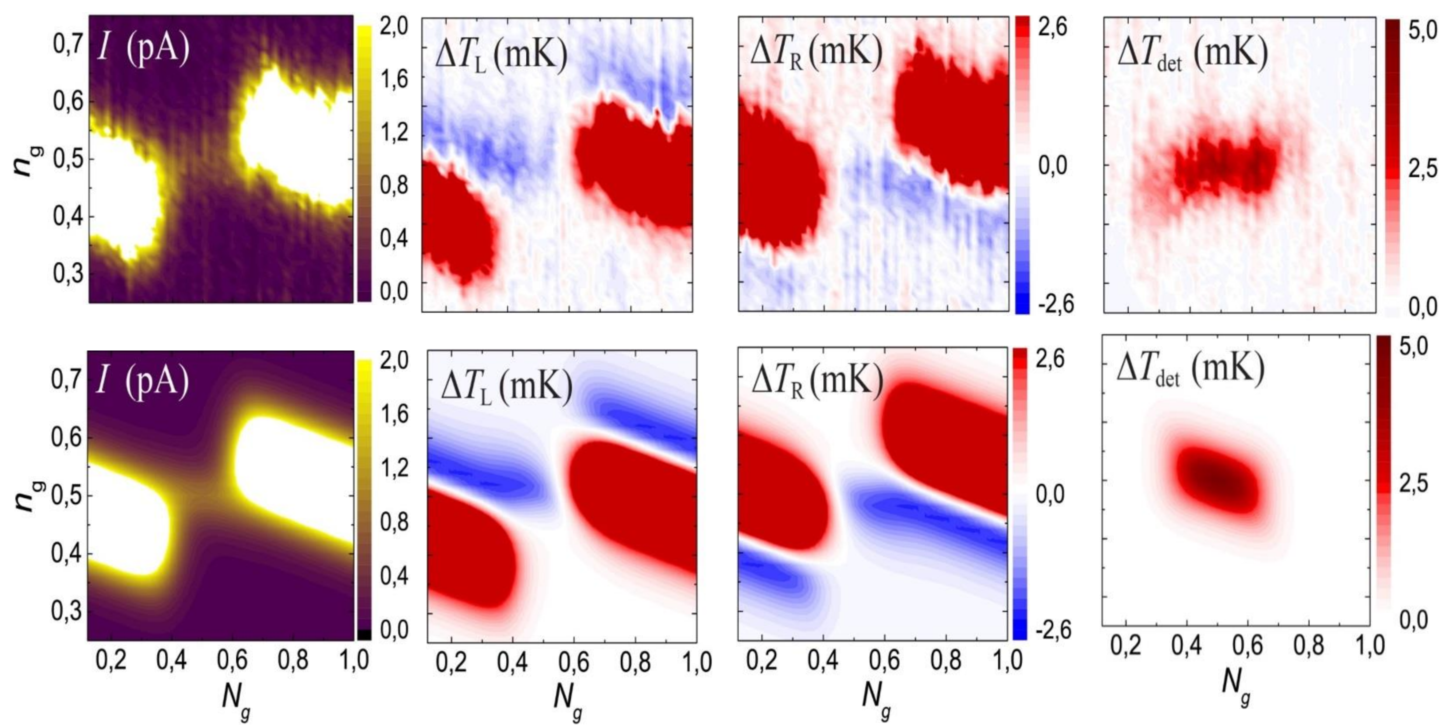
Image of the actual device



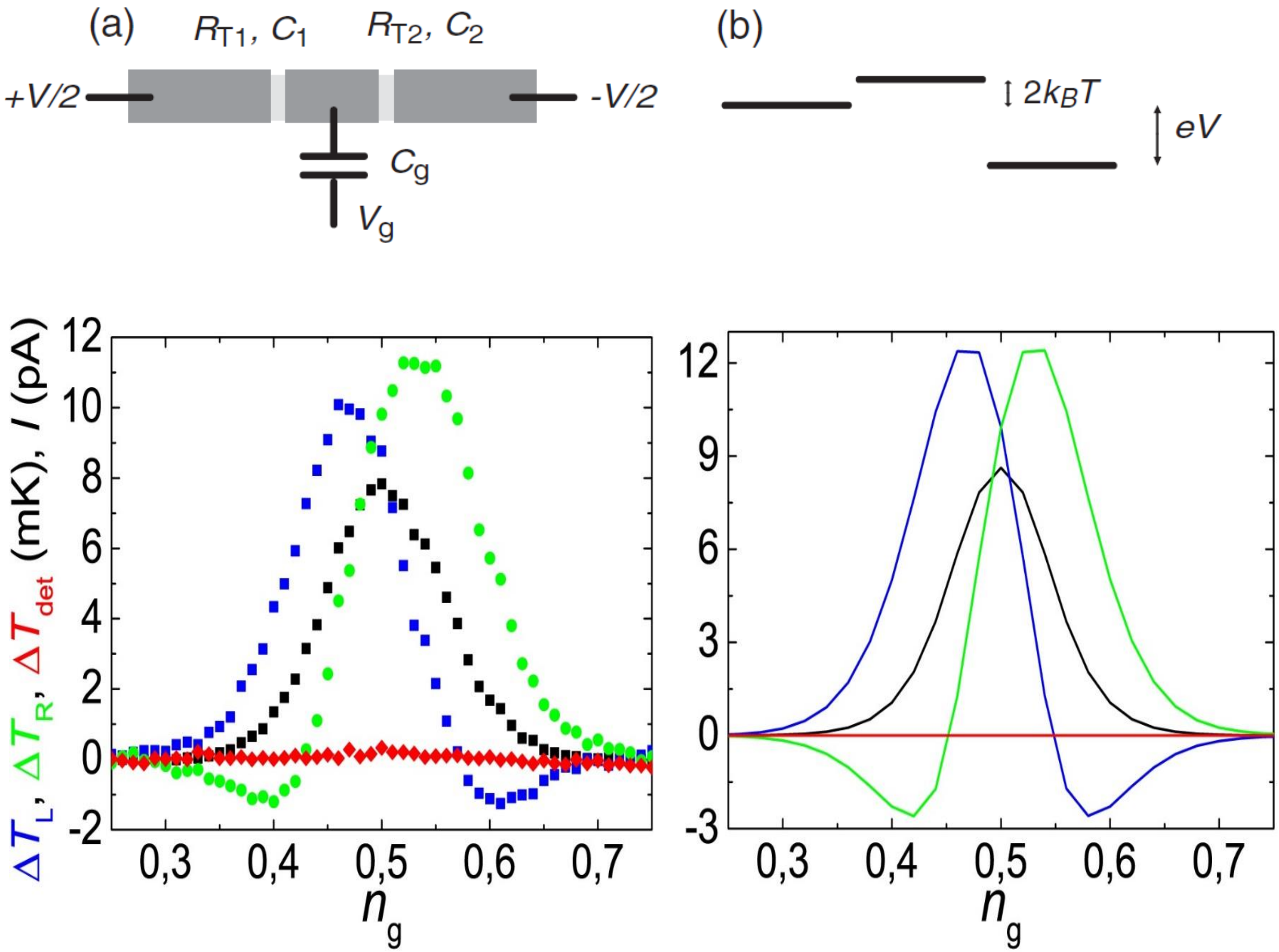
Current and temperatures at different gate positions

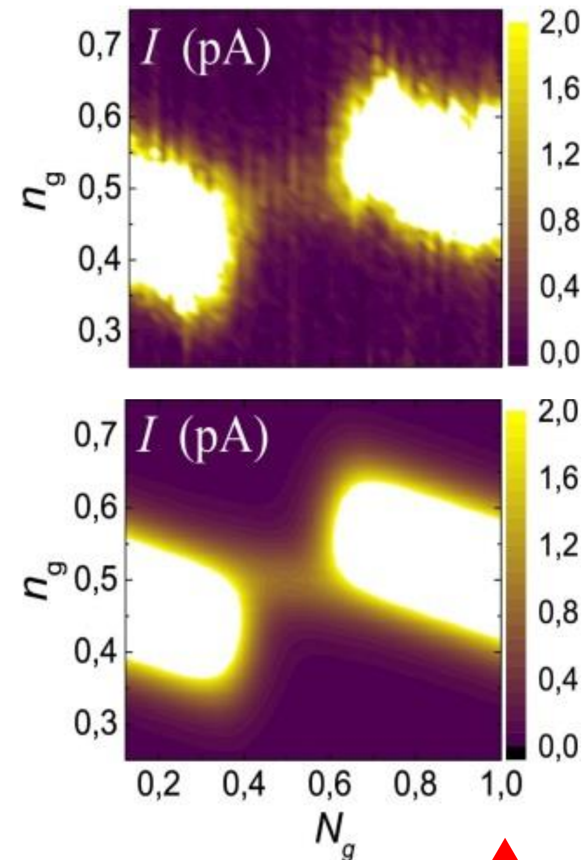


V = 20 μV, T = 50 mK



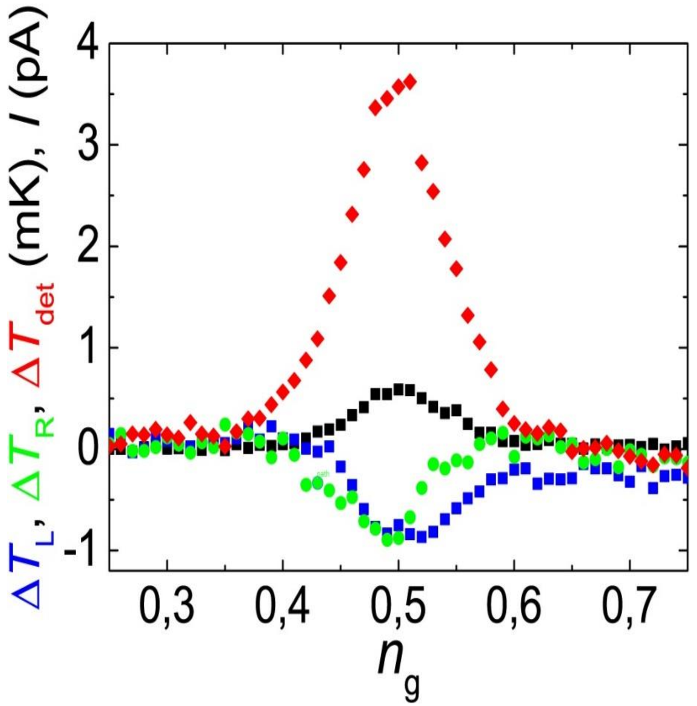
N_g = 1: No feedback control ("SET-cooler")

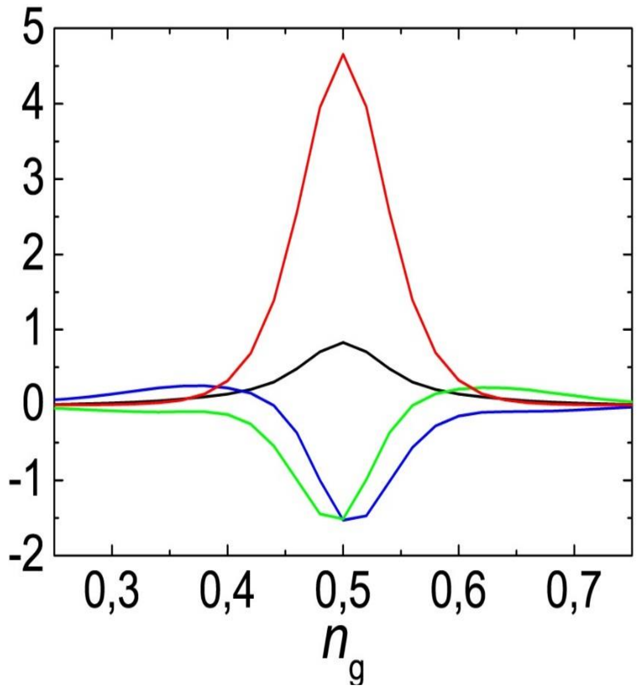


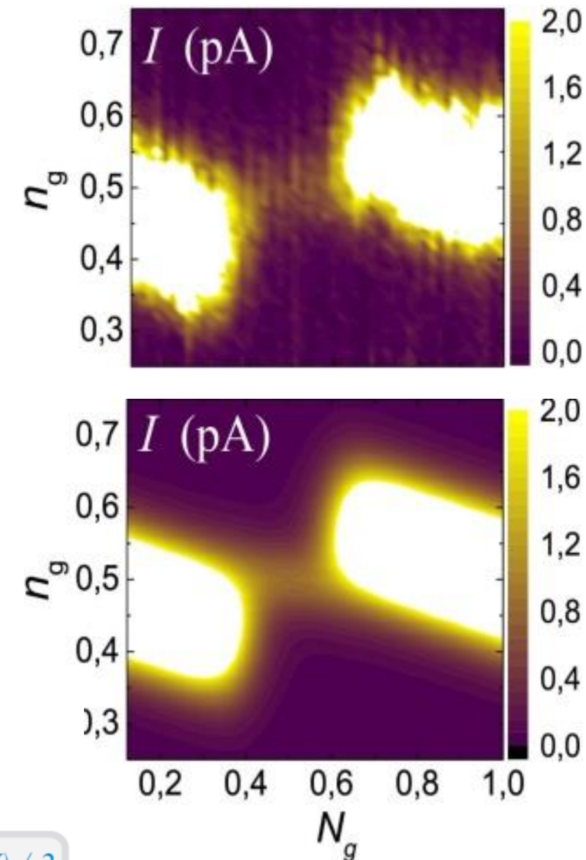


JP, J. V. Koski, and D. V. Averin, PRB **89**, 081309 (2014)
A. V. Feshchenko, J. V. Koski, and JP, PRB **90**, 201407(R) (2014)

N_g = 0.5: feedback control (Demon)

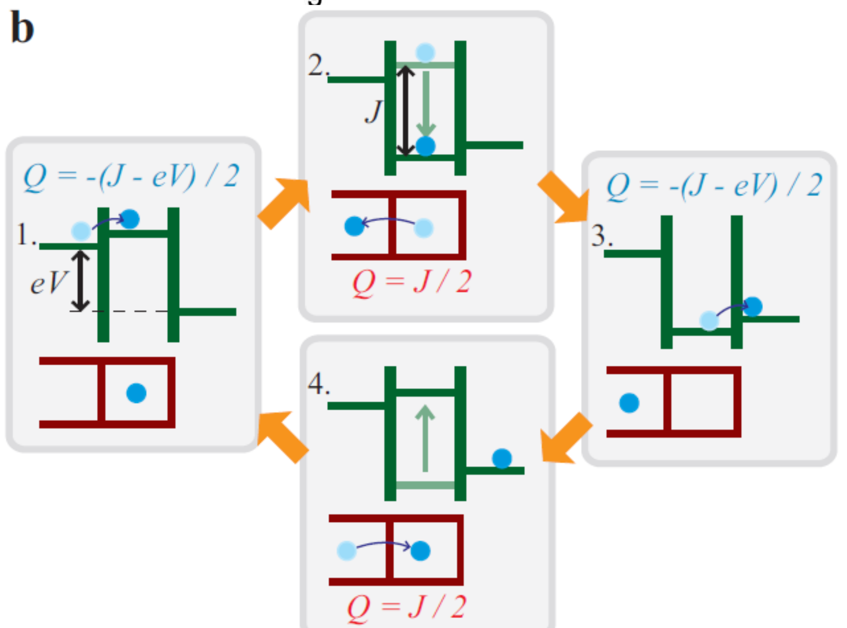






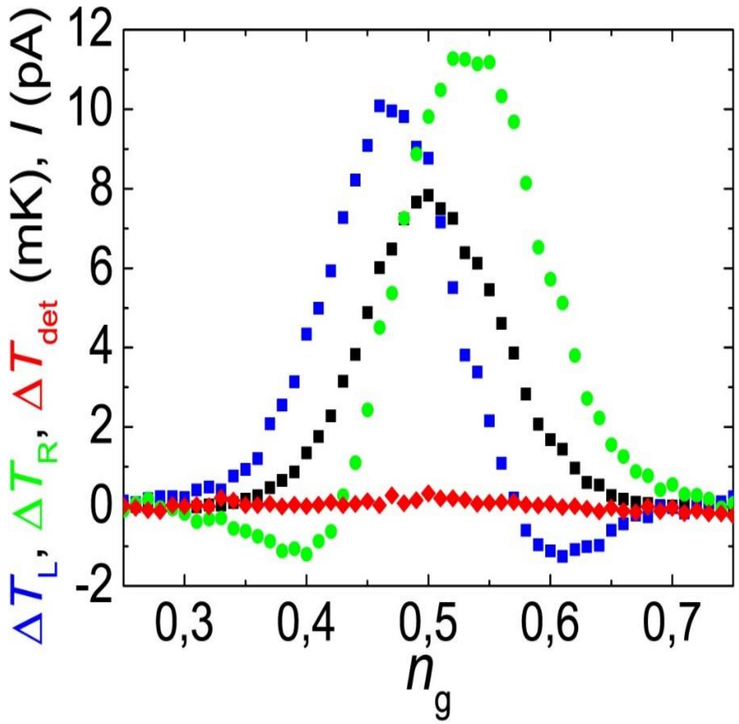
Both T_L and T_R drop: SET entropy decreases

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

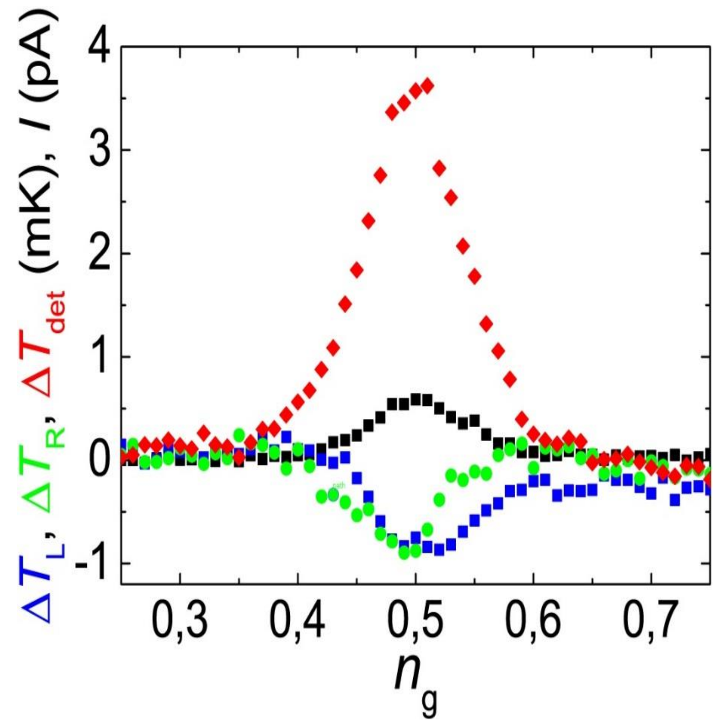


Summary of the autonomous demon experiment

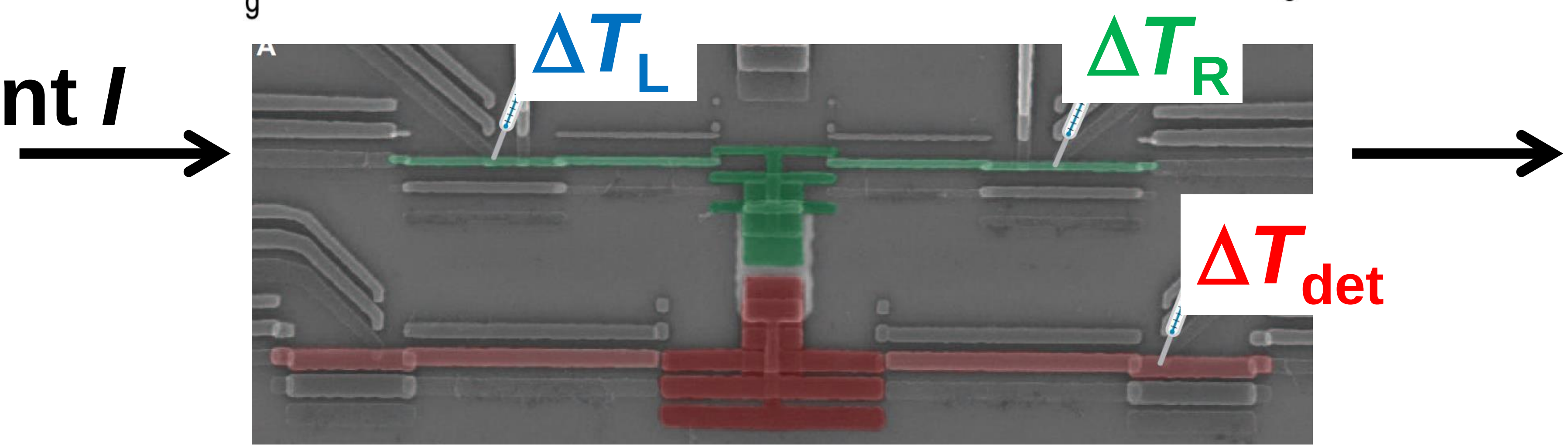
SET cooler



Demon

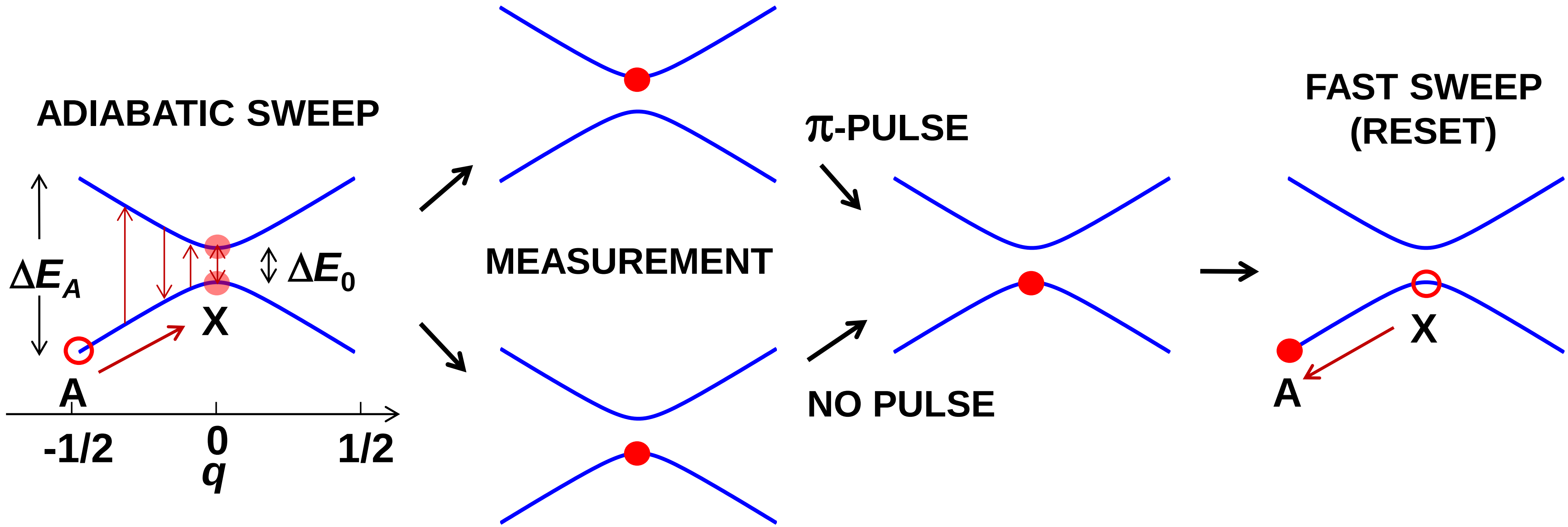


current I



Maxwell's Demon based on a Single Qubit

J. P. Pekola, D. S. Golubev, and D. V. Averin, arXiv:1508.03803



Ideally $$\langle Q \rangle = -\beta^{-1} \ln(1 + e^{\beta \Delta E_0}) + \frac{\Delta E_0}{1 + e^{-\beta \Delta E_0}}$$

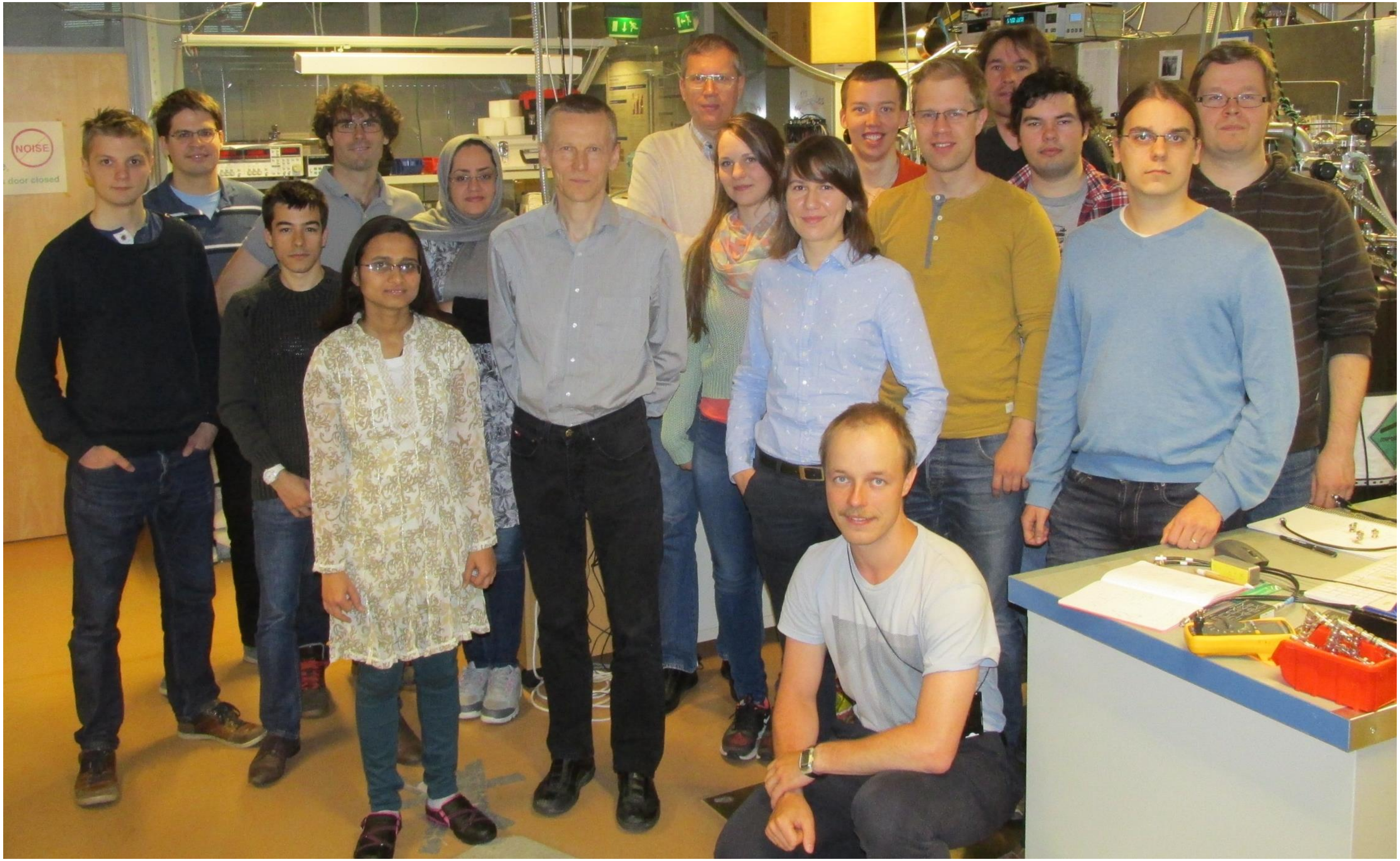
Conclusions

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

Proposal of a **Maxwell's demon based on a single qubit**


NOISE
door closed