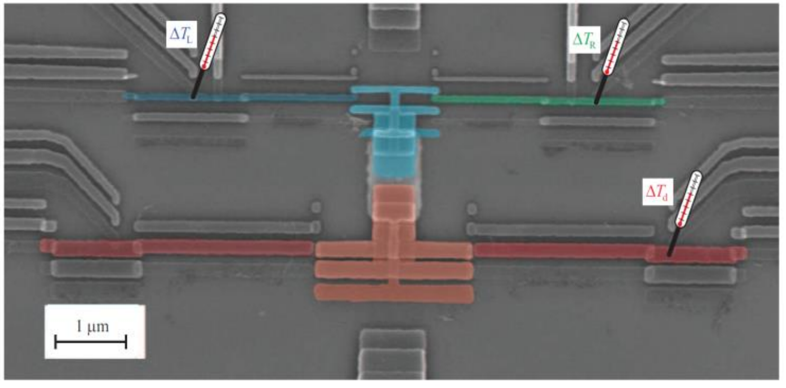
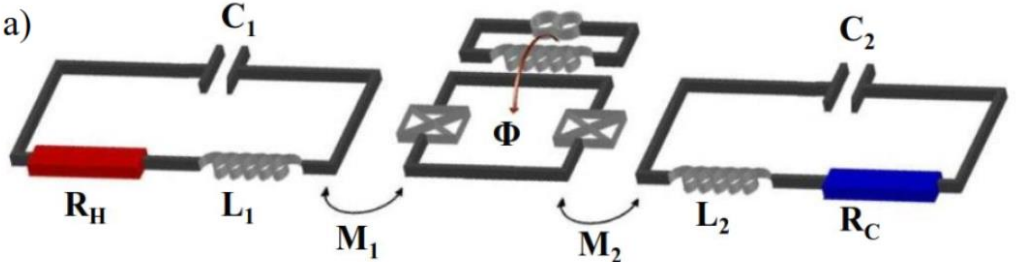
LECTURE 4: Information-powered refrigerators; quantum engines and refrigerators





Fluctuation relations

$$\frac{P_\tau(\Delta S)}{P_\tau(-\Delta S)} = e^{\Delta S/k_{\mathrm{B}}}$$

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

$$\langle e^{-\Delta S/k_B} \rangle = 1$$

General theory of thermal fluctuations in nonlinear systems

G. N. Bochkov and Yu. E. Kuzovlev

Gor'kiĭ State University

(Submitted June 17, 1976)
Zh. Eksp. Teor. Fiz. **72**, 238–247 (January 1977)

VOLUME 71, NUMBER 15 PHYSICAL REVIEW LETTERS 11 OCTOBER 1993

Probability of Second Law Violations in Shearing Steady States

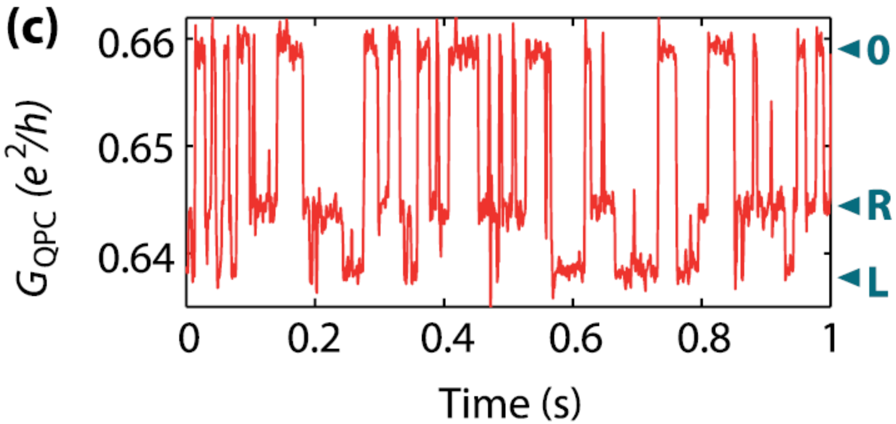
Denis J. Evans
Research School of Chemistry, Australian National University, Canberra, Australian Capital Territory 2600, Australia

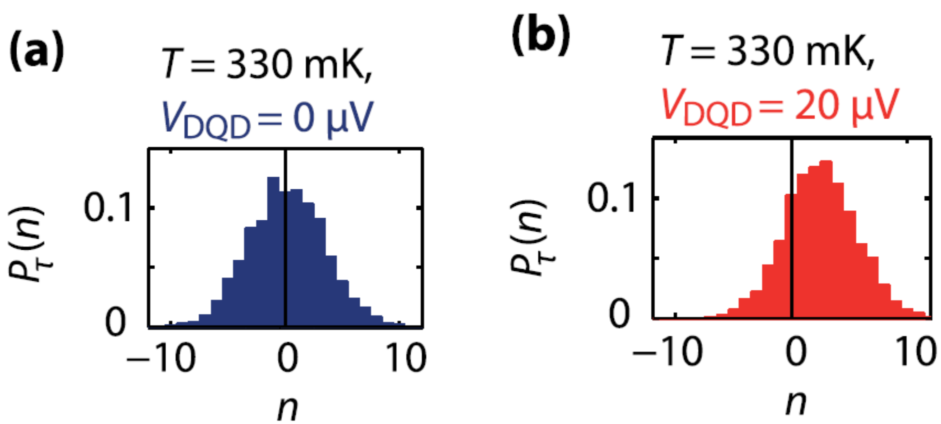
E. G. D. Cohen
The Rockefeller University, 1230 York Avenue, New York, New York 10021

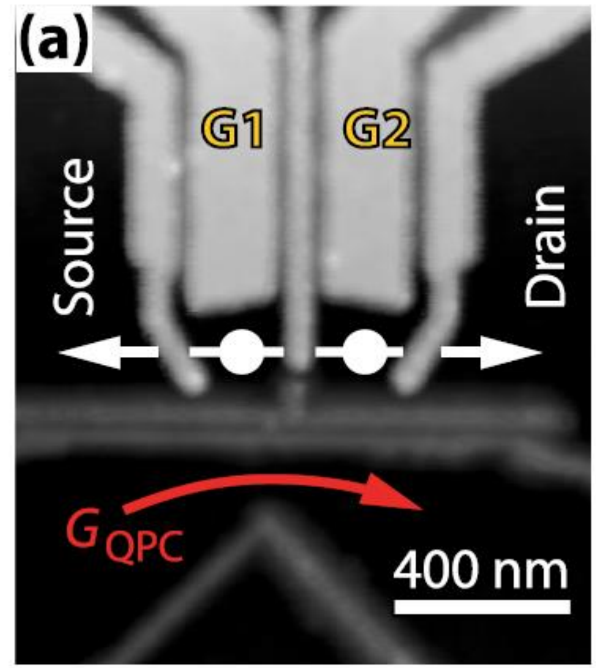
G. P. Morriss
School of Physics, University of South Wales, Kensington, New South Wales, Australia
(Received 26 March 1993)

Fluctuation relations in a circuit

Experiment on a double quantum dot
Y. Utsumi et al. PRB 81, 125331 (2010), B. Kung et al. PRX 2, 011001 (2012)



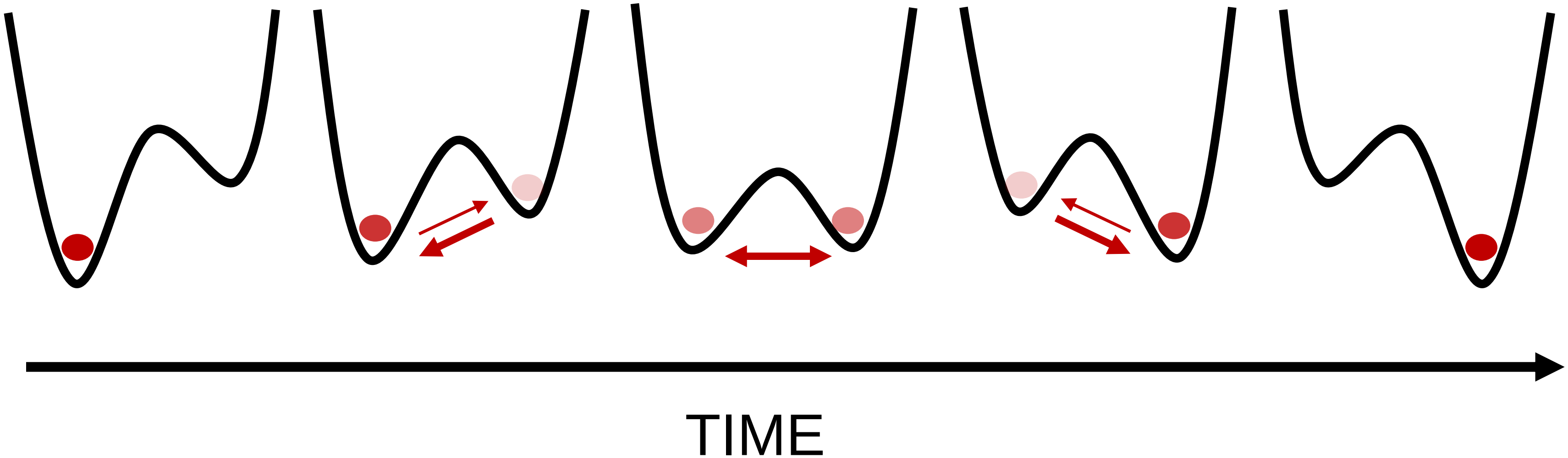




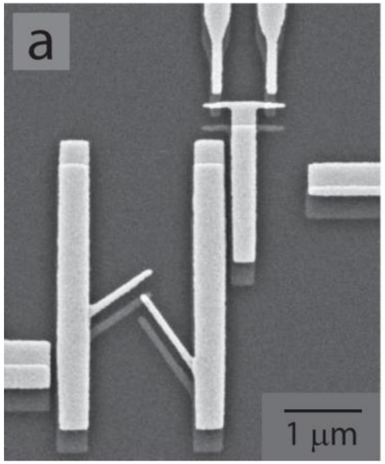
$$\frac{P_\tau(n)}{P_\tau(-n)} = e^{neV_{\mathrm{DQD}}/k_{\mathrm{B}}T}$$

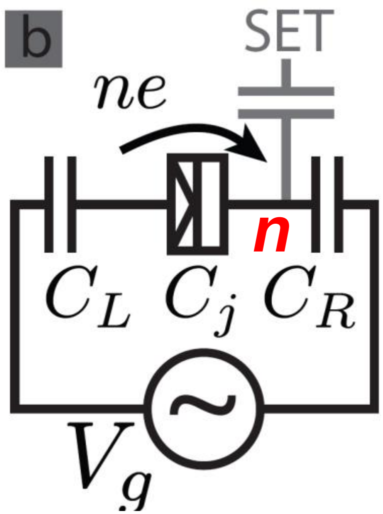
Driven systems

Work and dissipation in a driven process?

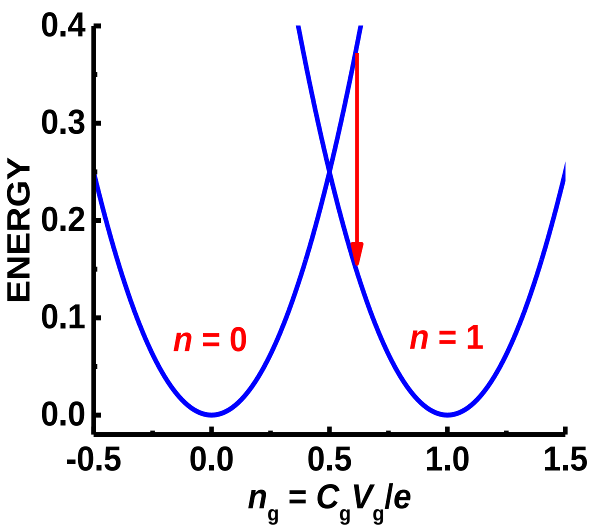


Dissipation and work in single-electron transitions





$E = E_C\,(n - CgVg/e)^2$



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:

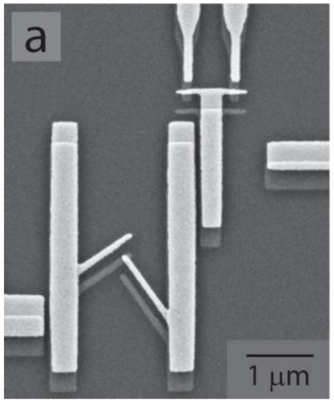
$$W = Q + \Delta U$$

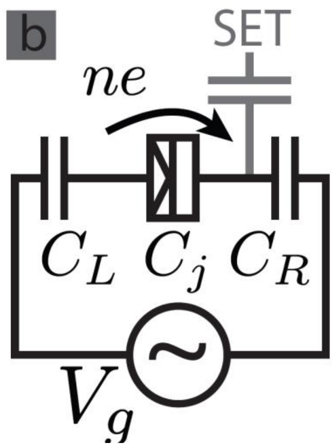
Change in internal (charging) energy

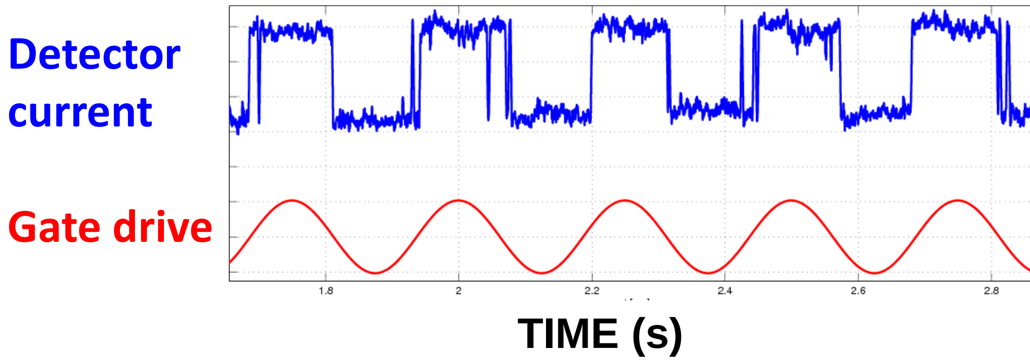
D. Averin and JP, EPL 96, 67004 (2011)

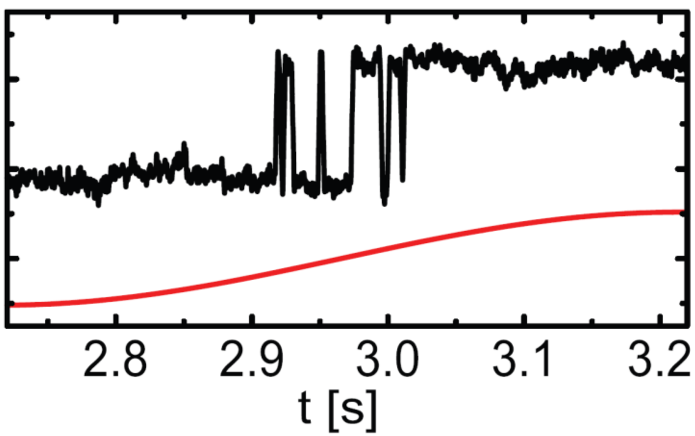
Experiment on a single-electron box

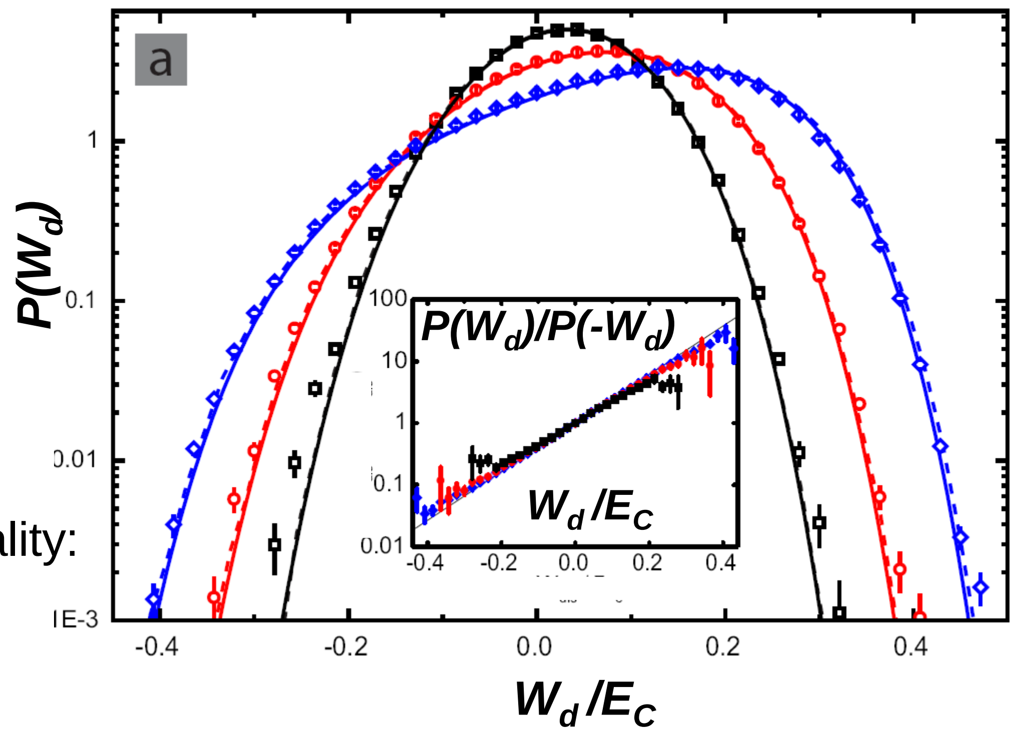
O.-P. Saira et al., PRL 109, 180601 (2012); J.V. Koski et al., Nature Physics 9, 644 (2013).











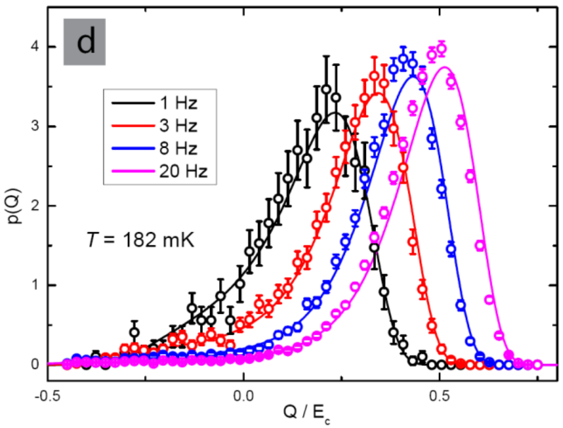
The distributions satisfy Jarzynski equality:

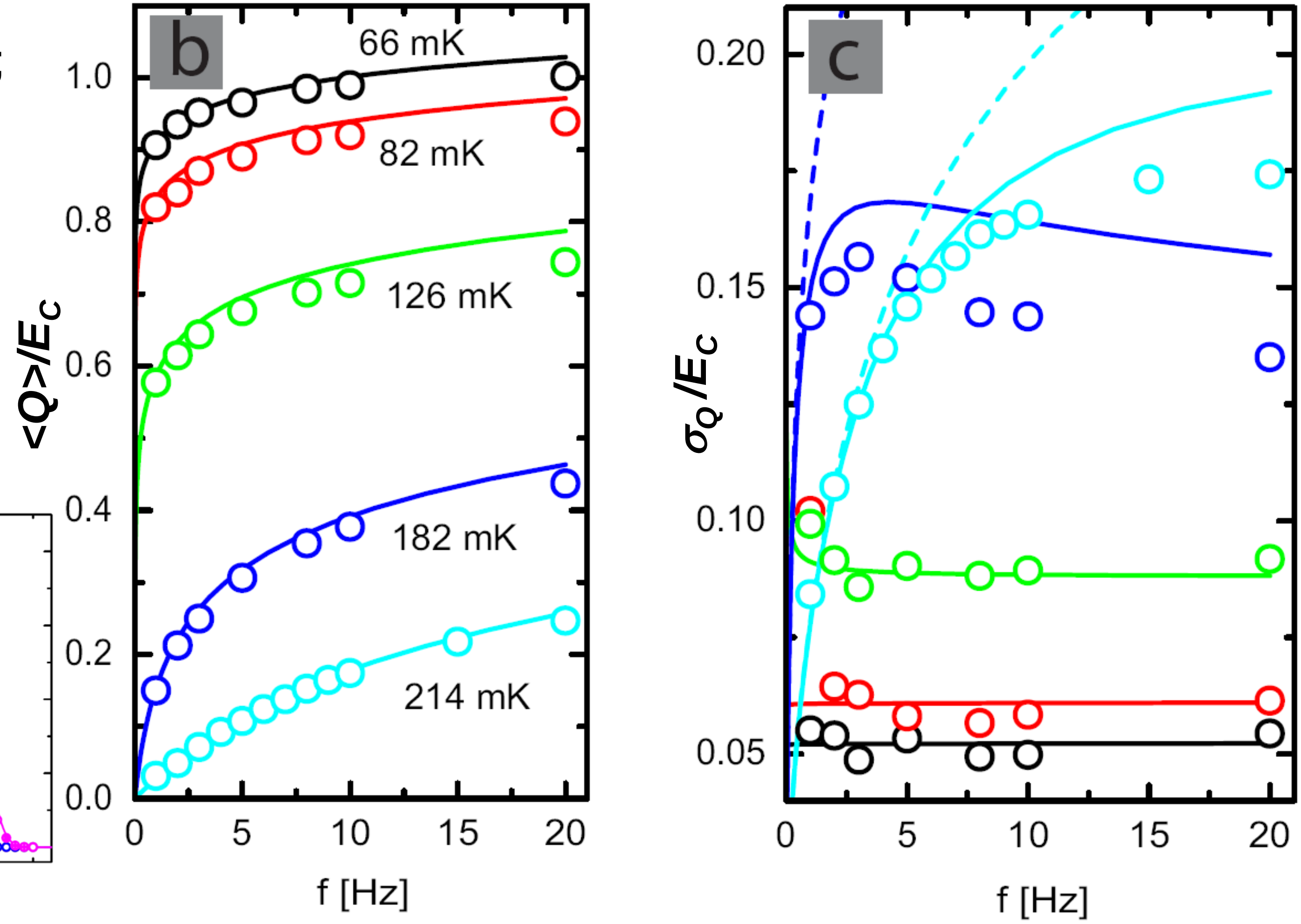
$$\langle e^{-\beta(W-\Delta F)} \rangle = 1.03 \pm 0.03$$

Measurements of the heat distributions at various frequencies and temperatures

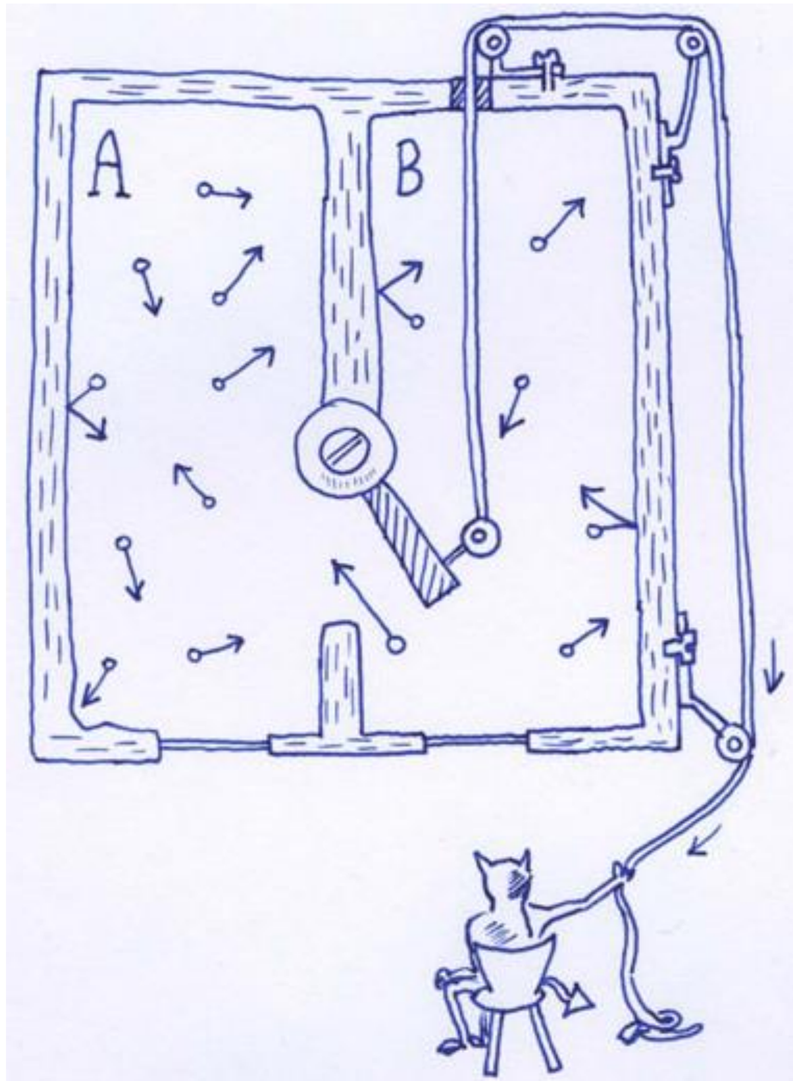
symbols: experiment;
full lines: theory;
dashed lines:

$$\sigma_Q^2 = 2k_B T\langle Q\rangle$$



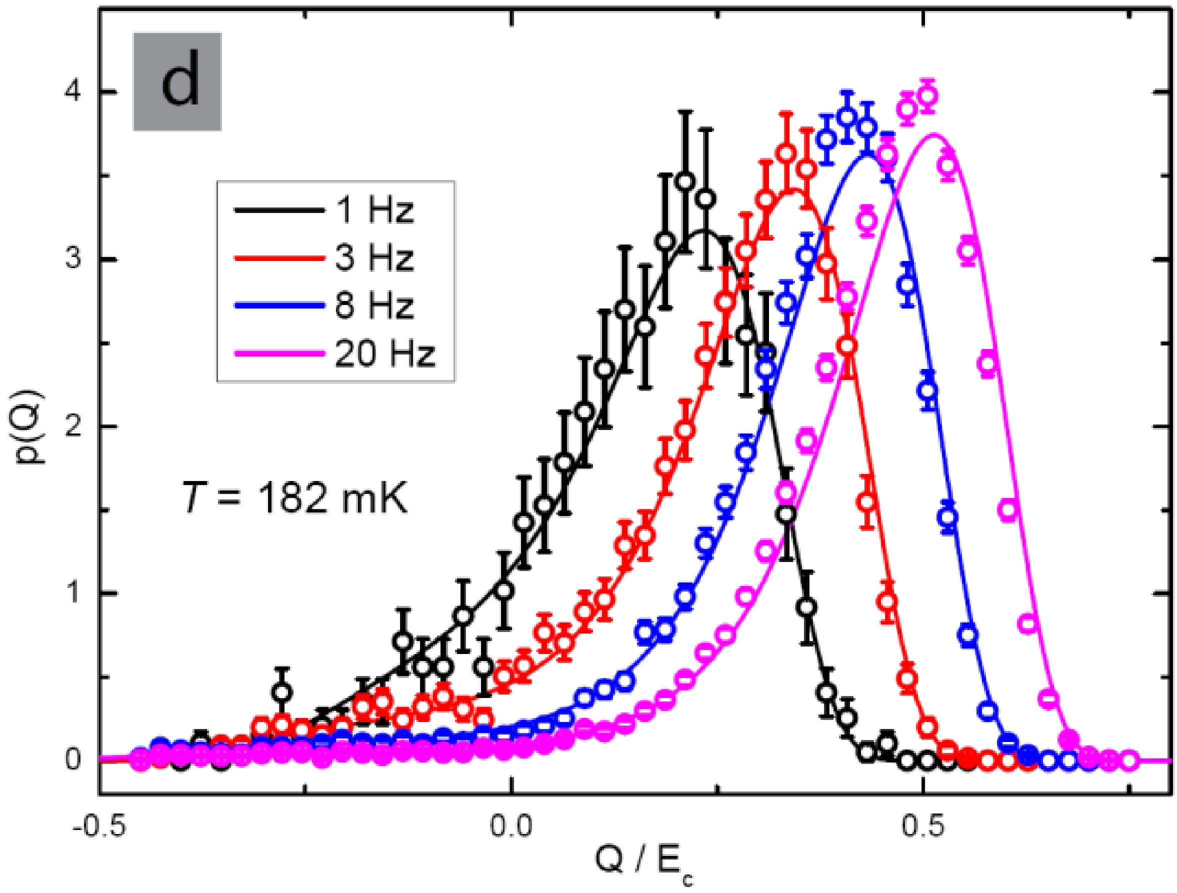


Maxwell's Demon



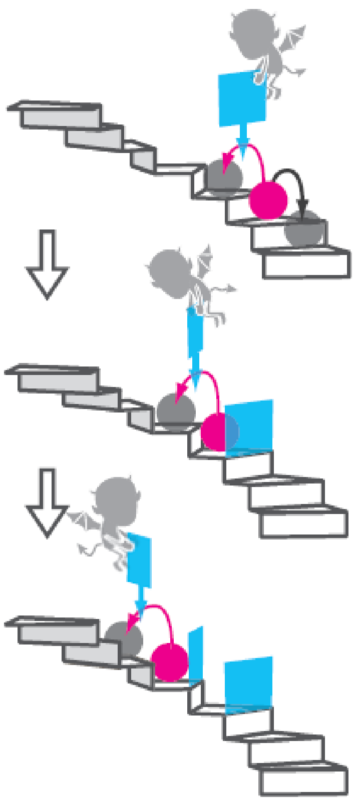
Negative heat

Possible to extract heat from the environment



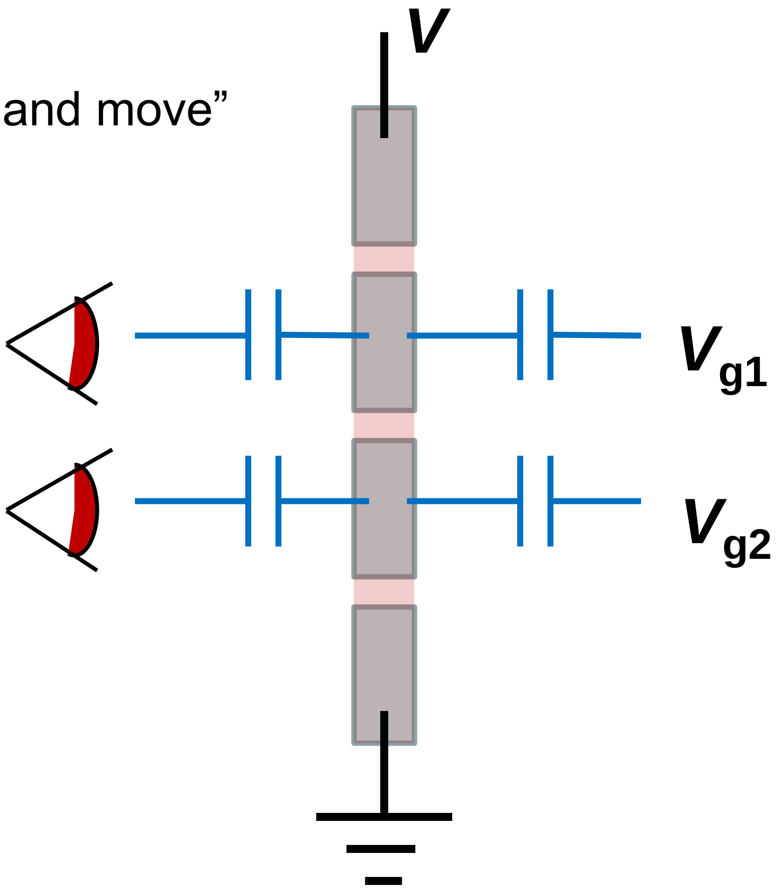
Provides means to realize Maxwell's demon using SETs

Electronic Maxwell’s demon



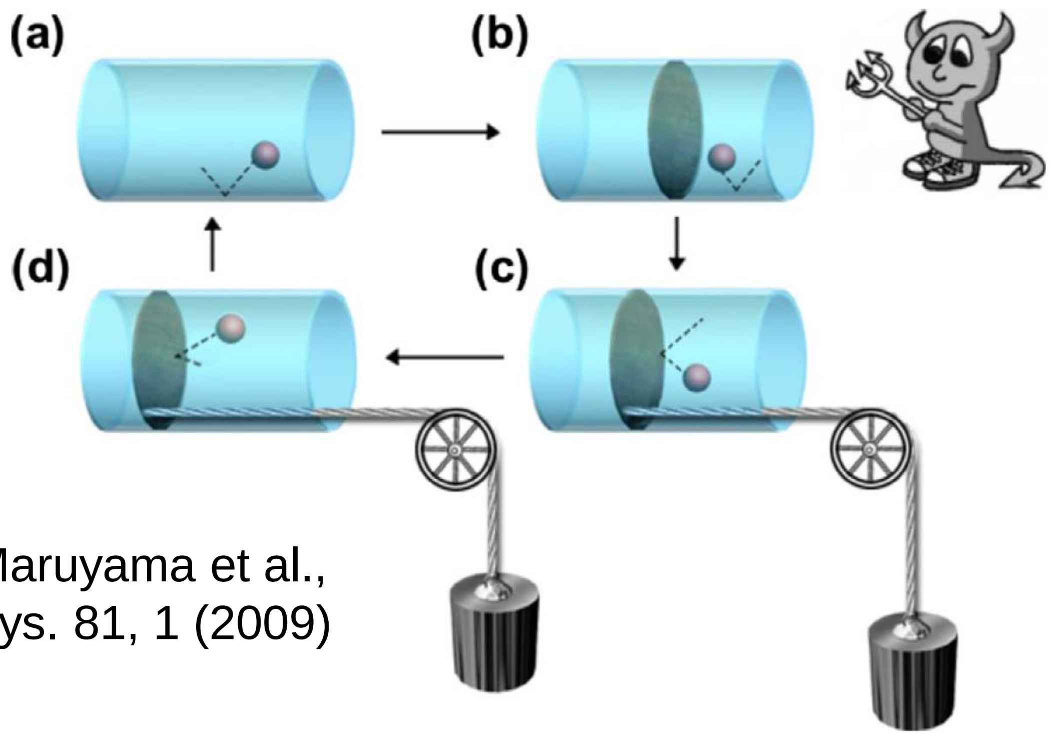
S. Toyabe et al., Nature Physics 2010

”watch and move”



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).

Information-powered cooling: Szilard's engine



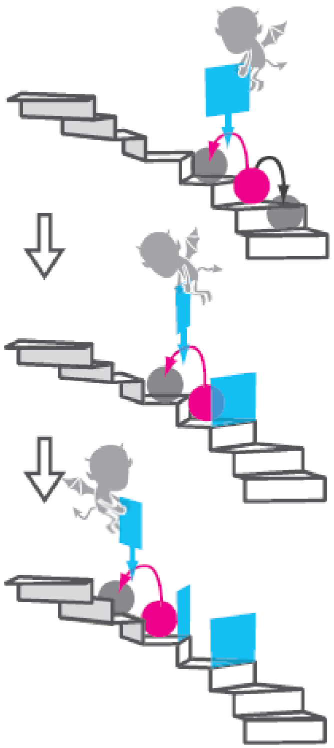
(L. Szilard 1929)

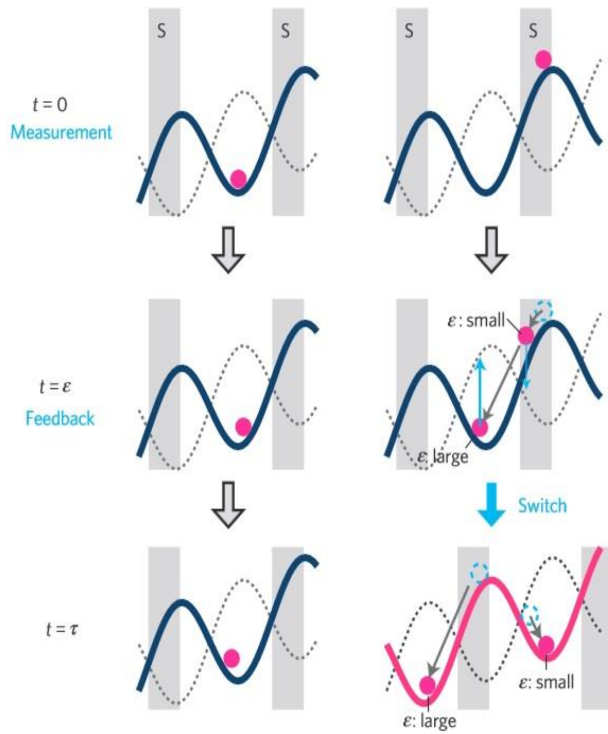
Figure from Maruyama et al., Rev. Mod. Phys. 81, 1 (2009)

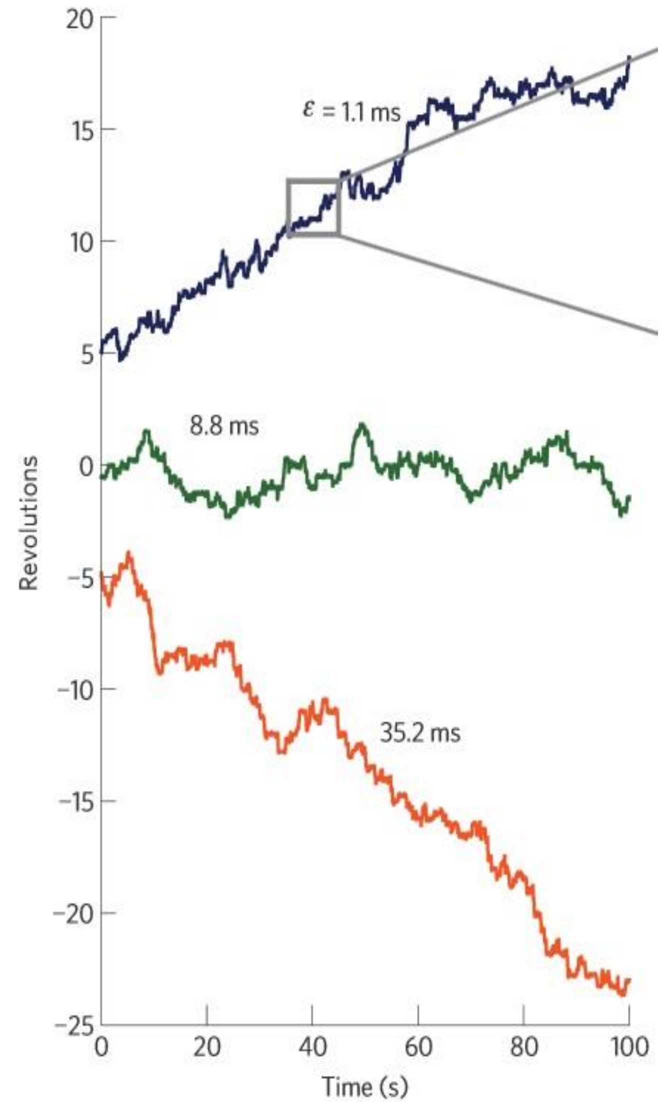
Isothermal expansion of the "single-molecule gas" does work against the load

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

Experiments on Maxwell's demon







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

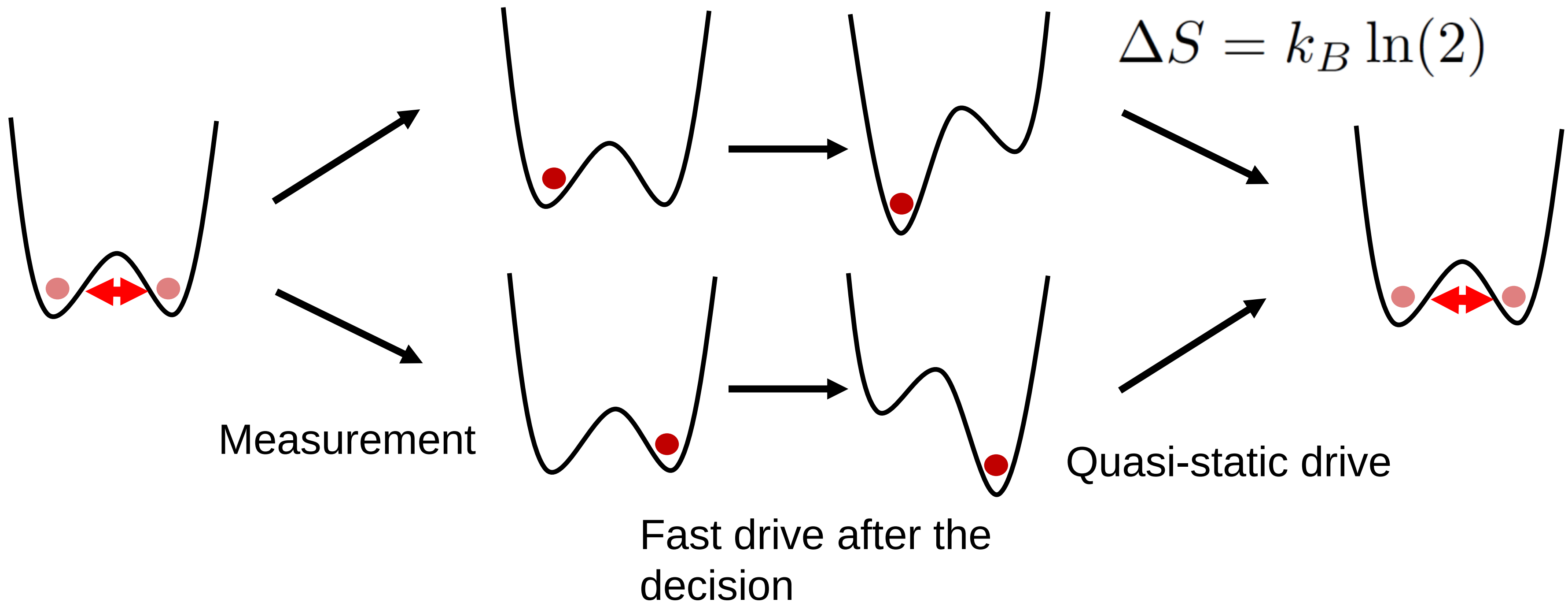
É. Roldán, I. A. Martínez, J. M. R. Parrondo, D. Petrov,
Nature Phys. **10**, 457 (2014)

Szilard’s engine for single electrons

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

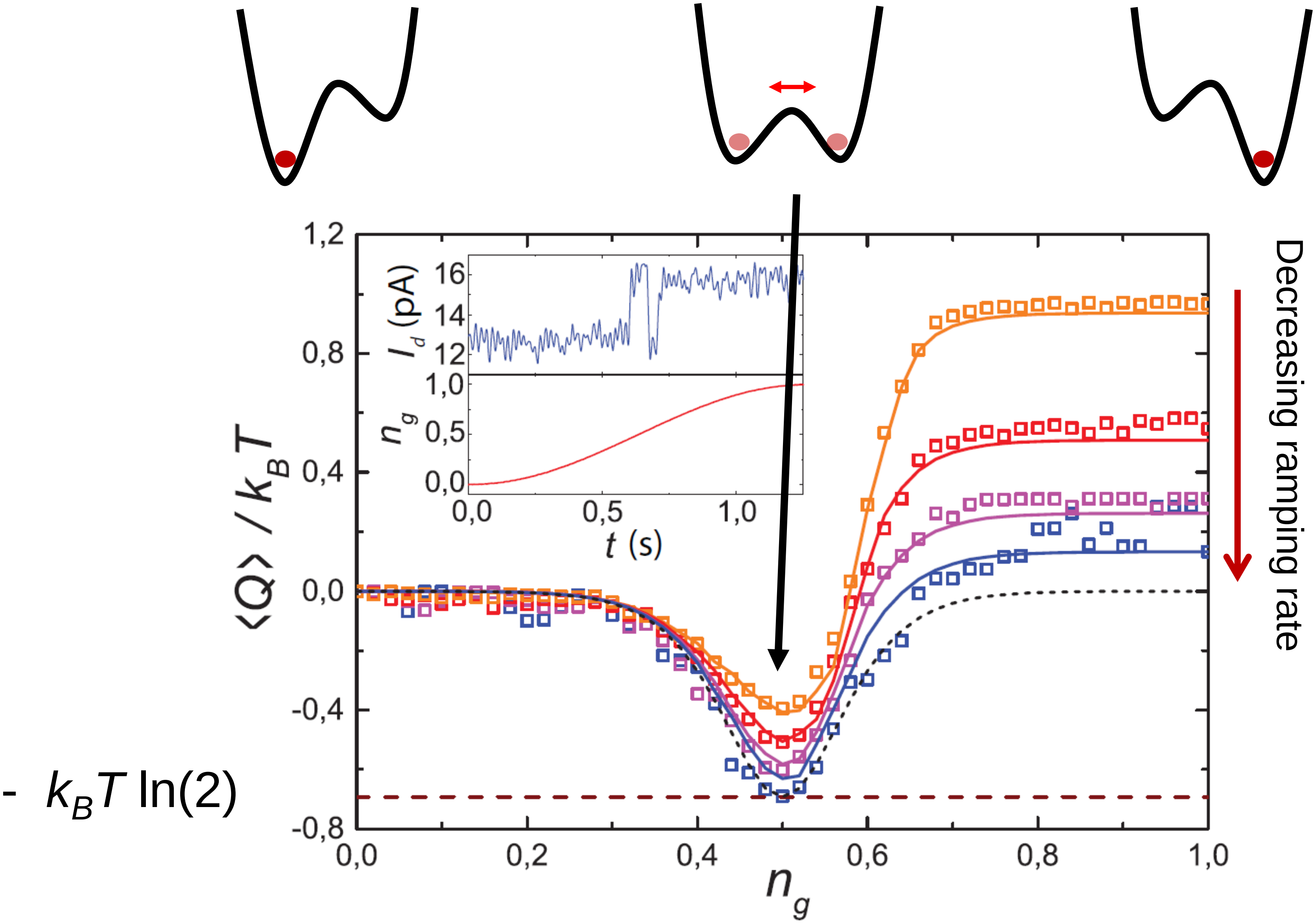
Entropy of the charge states: $S = -k_B \sum_{i=0,1} p(i) \ln[p(i)]$

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



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

Extracting heat from the bath

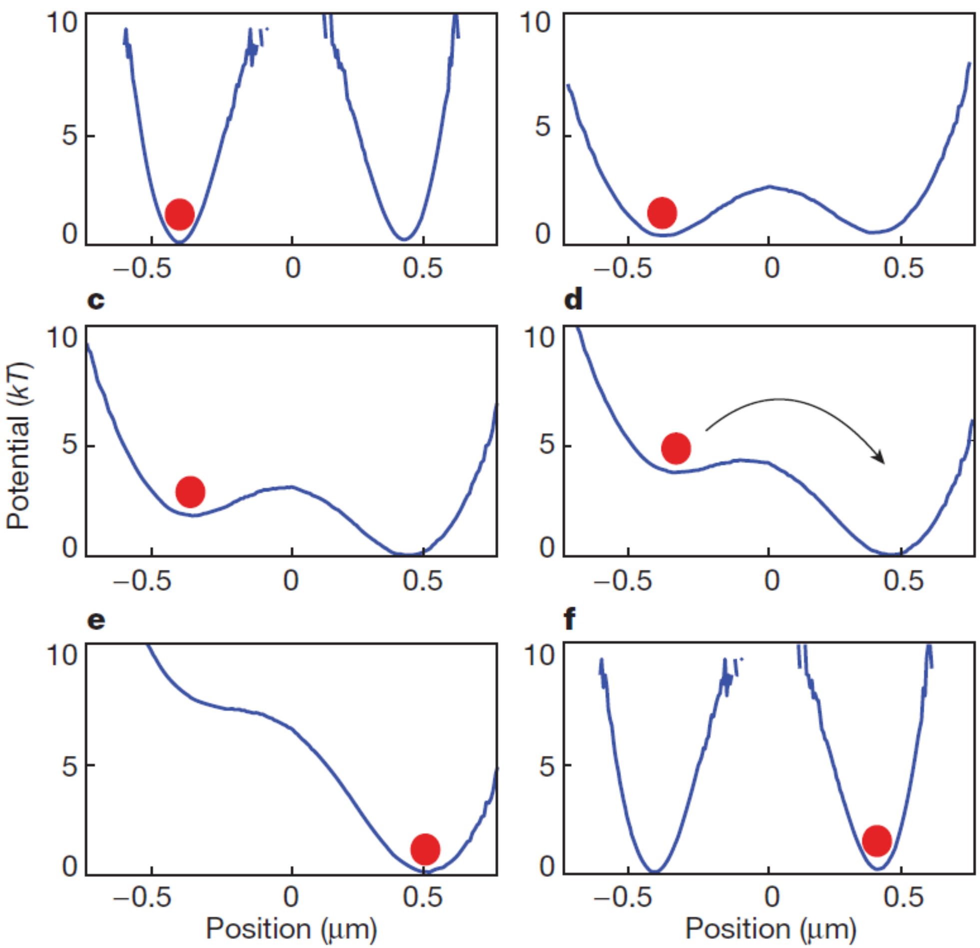


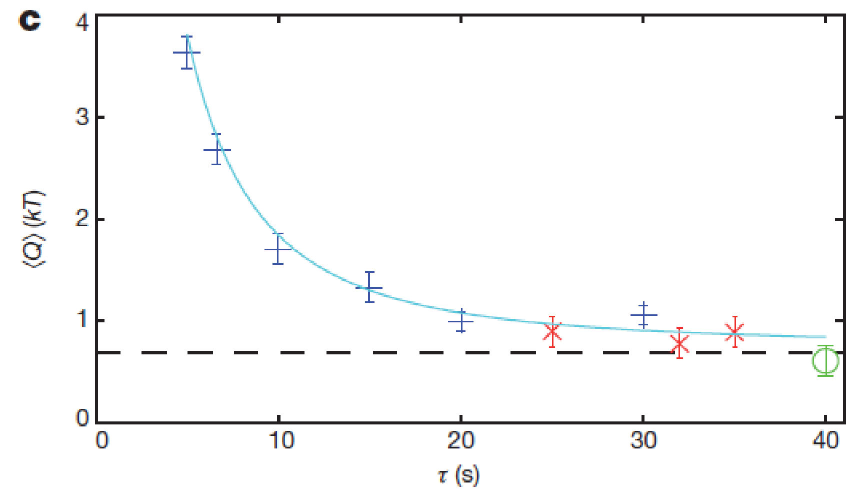
Erasure of information

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

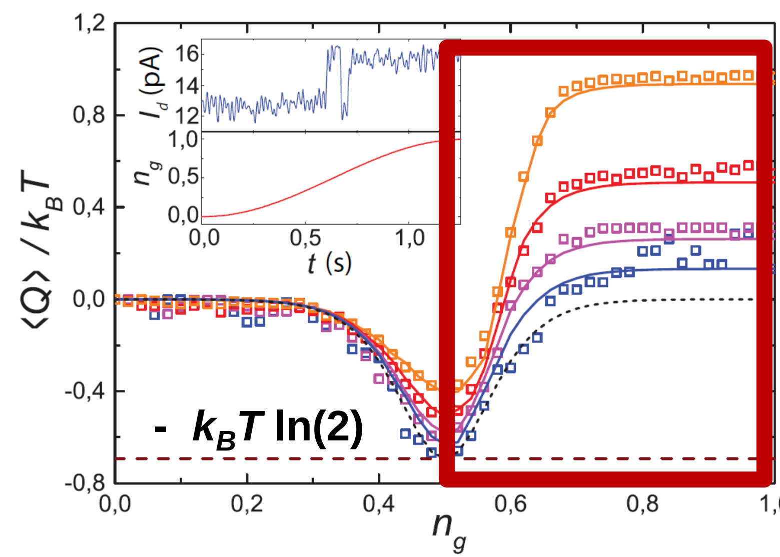
Experiment on a colloidal particle:

A. Berut et al., Nature 2012

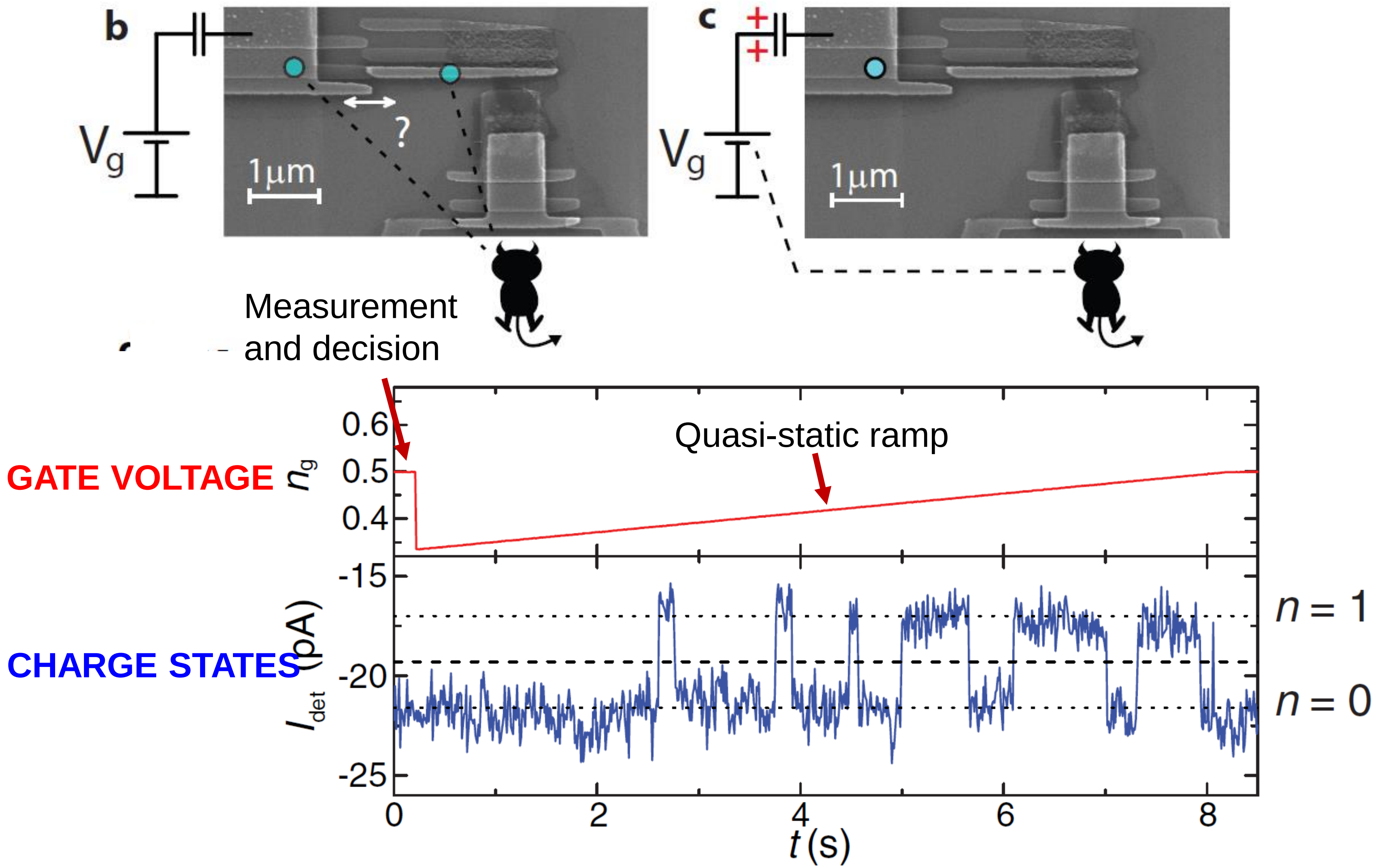




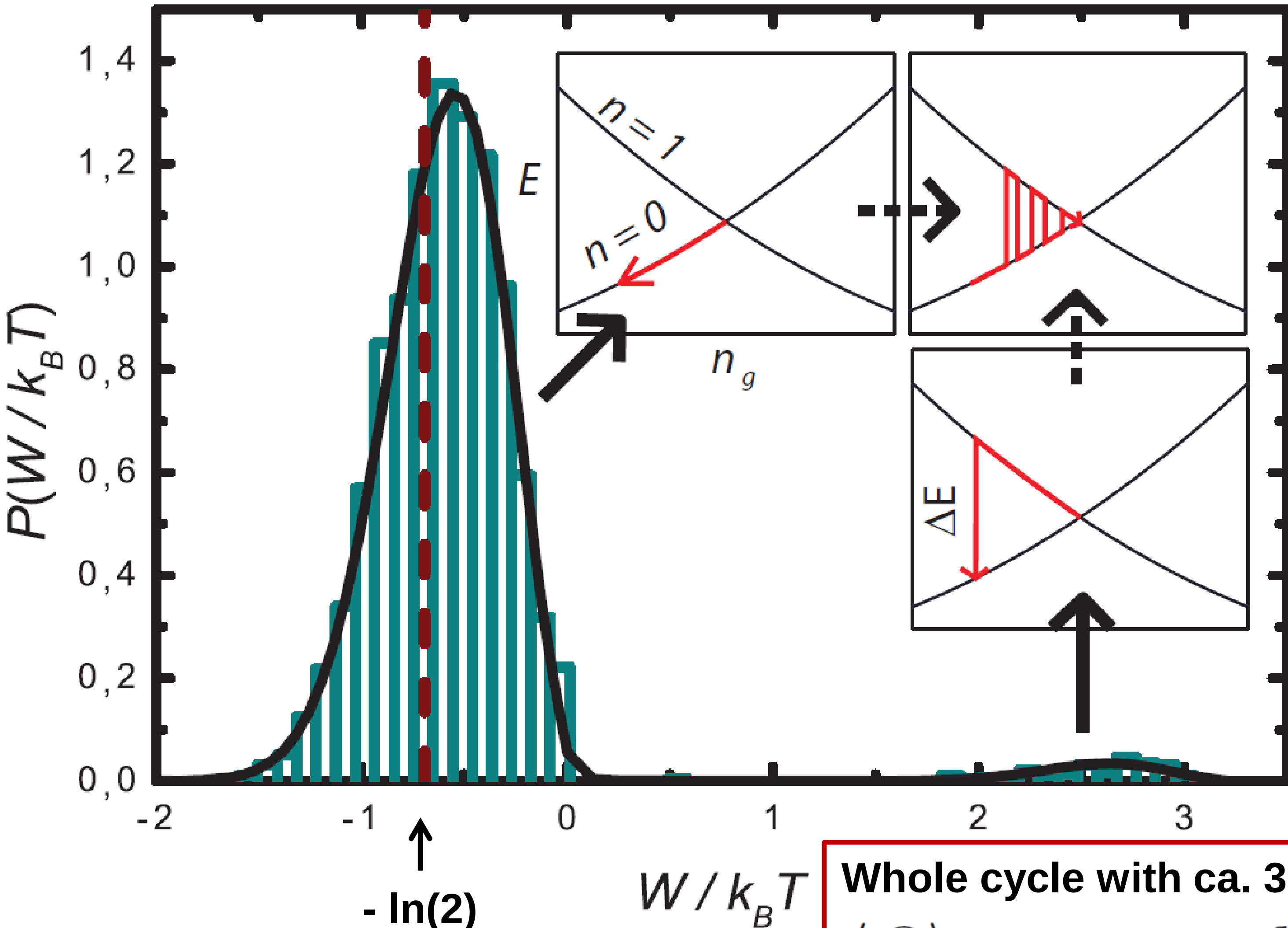
Corresponds to our experiment:



Realization of the MD with an electron



Measured distributions in the MD experiment



Whole cycle with ca. 3000 repetitions:

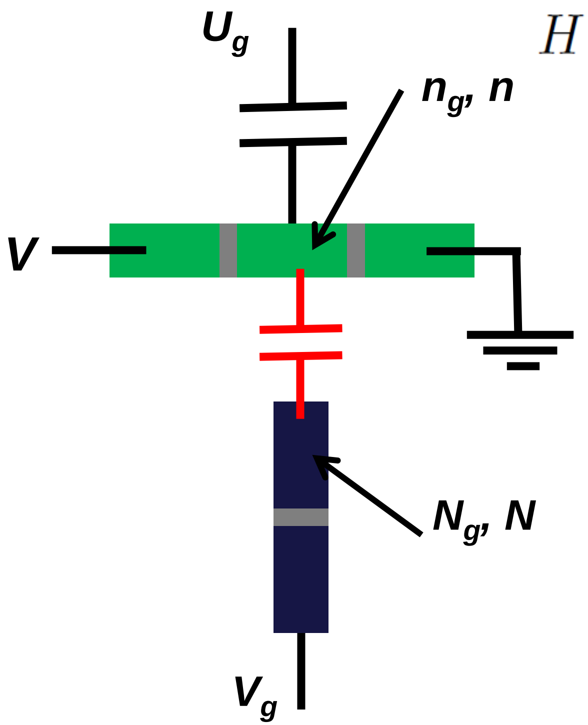
$$\langle Q \rangle \approx -0.75\, k_B T \ln(2)$$

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

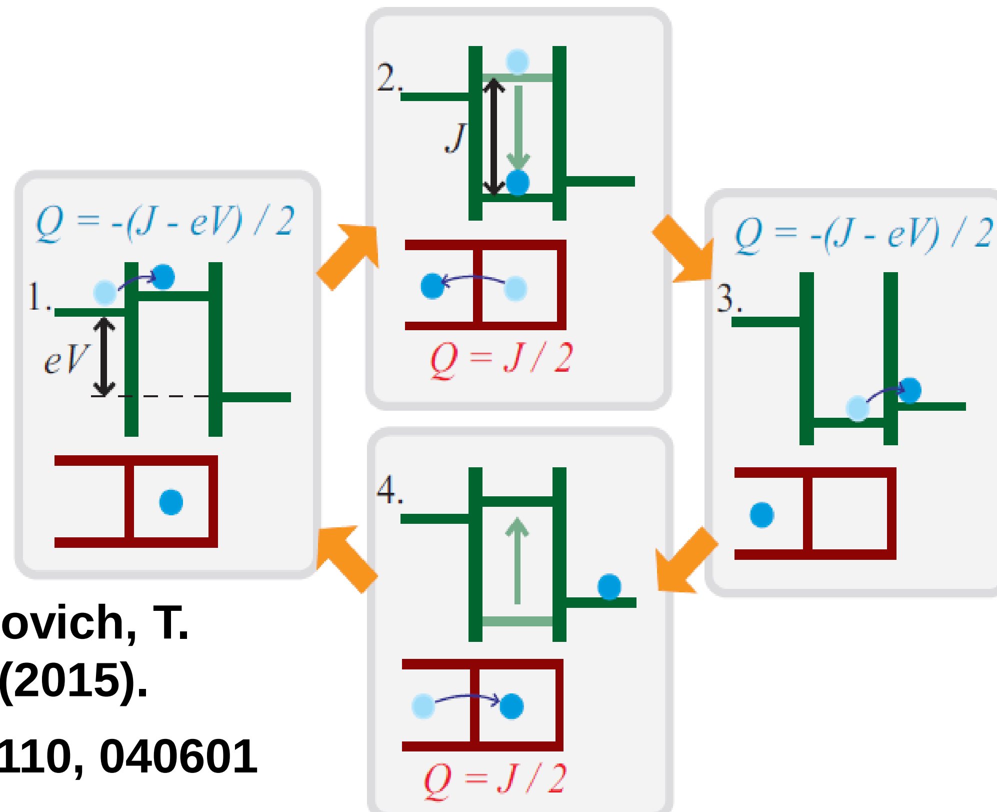
Autonomous Maxwell's demon

System and Demon: all in one

Realization in a circuit:



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

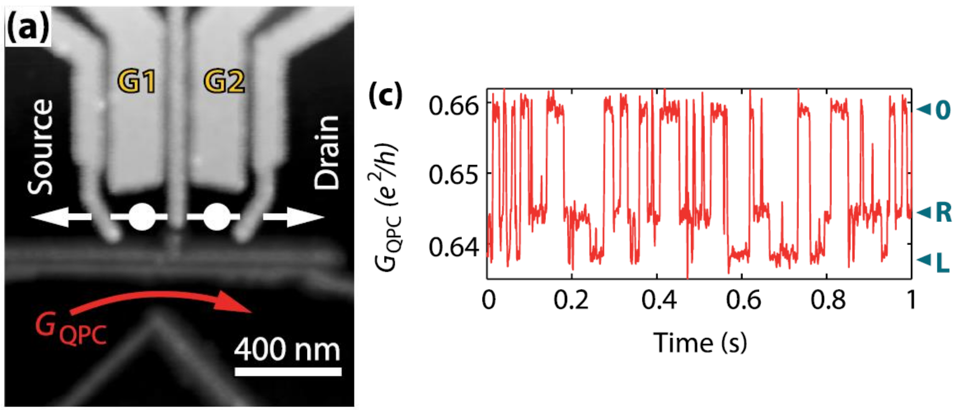


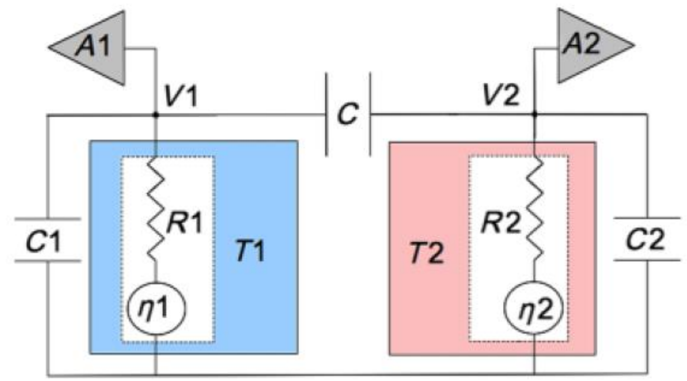
J. V. Koski, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and JP, PRL 115, 260602 (2015).

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

Work and heat in small systems: experimental situation

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





$$Q = neV_{\mathrm{DS}}$$

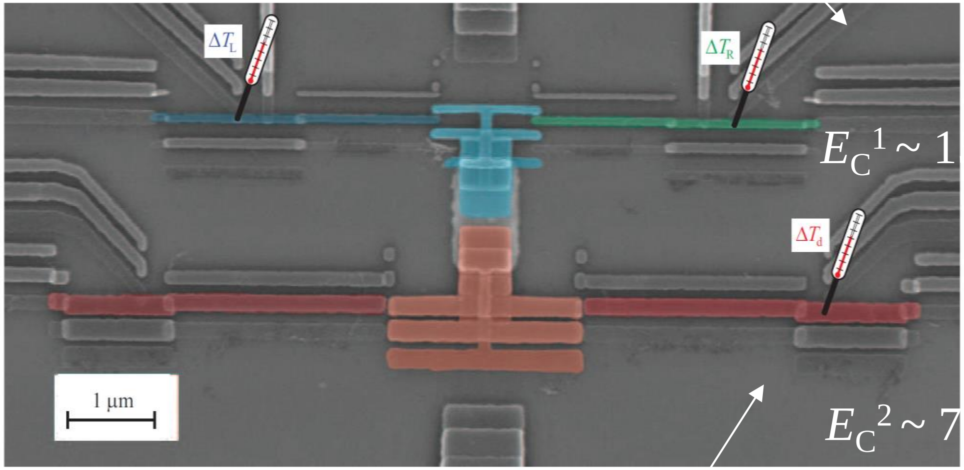
$$Q_{m,\tau} = \int_t^{t+\tau} i_m V_m dt$$

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

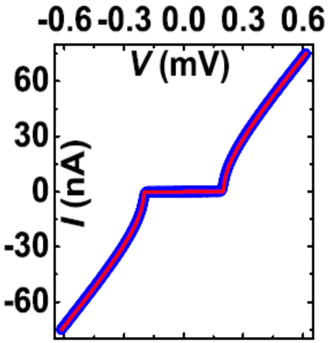
S. Ciliberto et al., PRL 110, 180601 (2013)

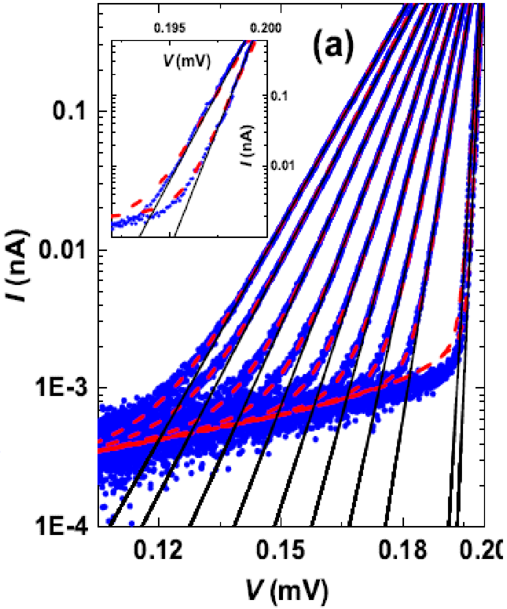
Autonomous Maxwell's demon – information-powered refrigerator

Image of the actual device



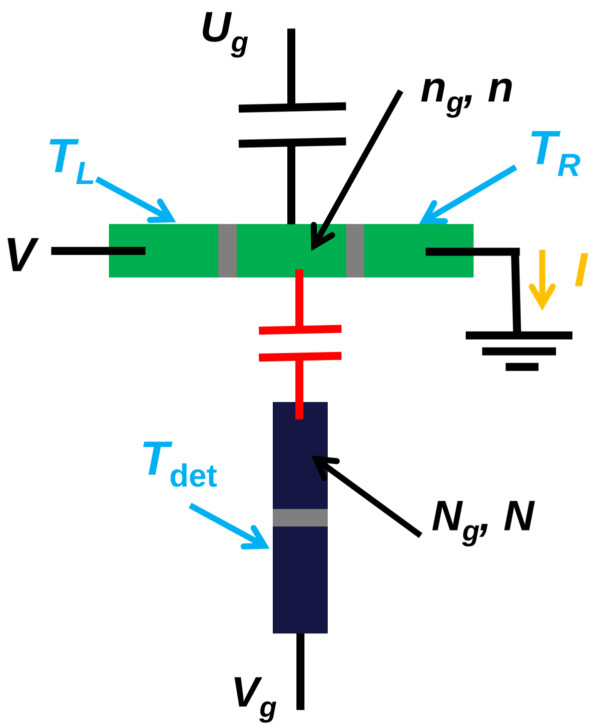
Thermometers based on standard NIS tunnel junctions

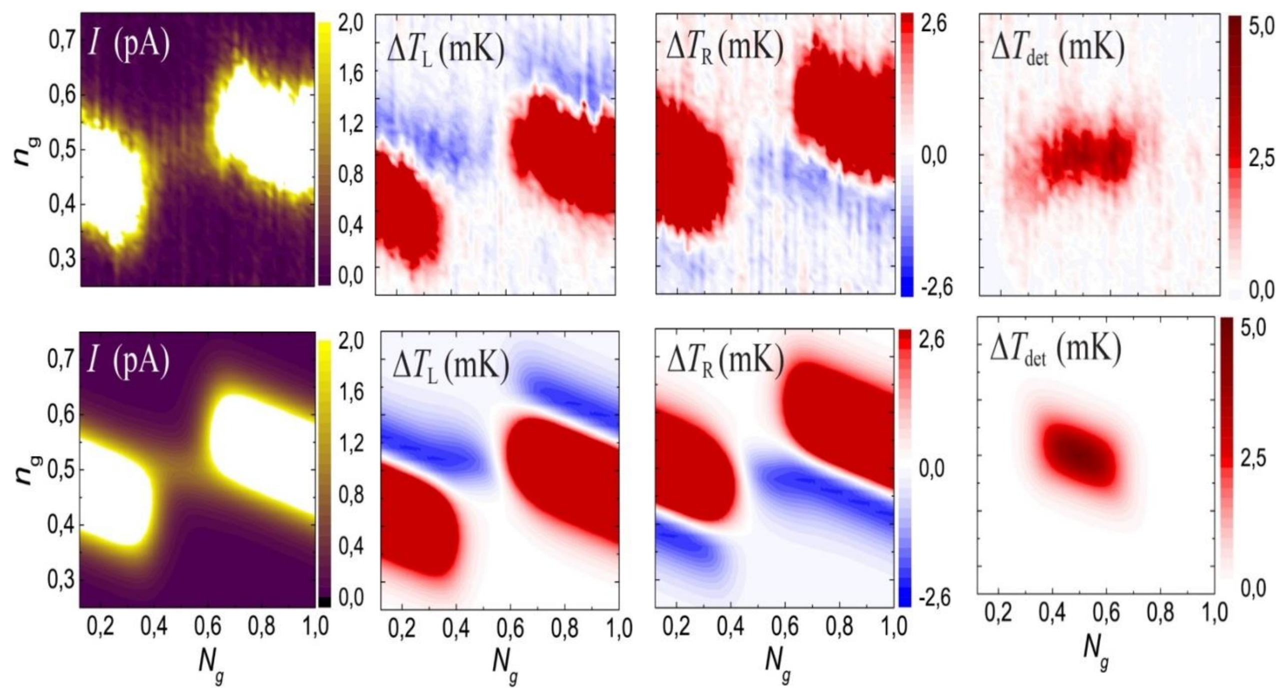




A. V. Feshchenko et al., Phys. Rev. Appl. 4, 034001 (2015).

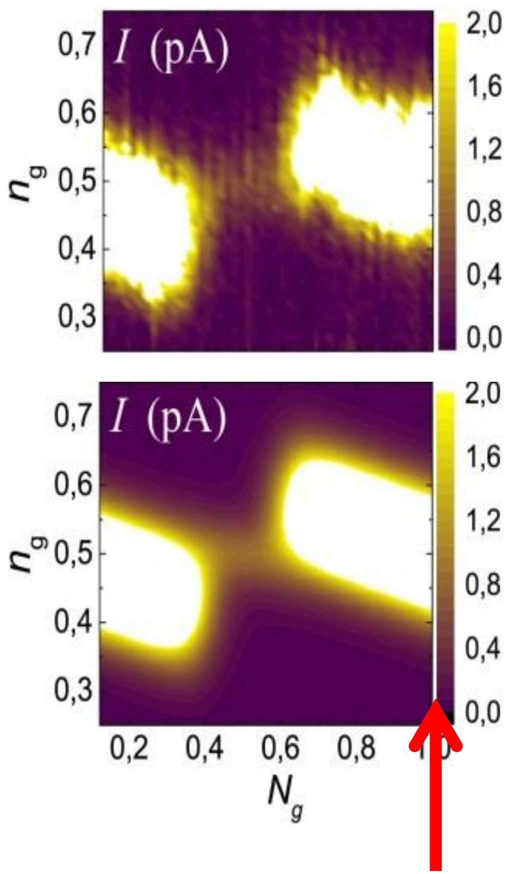
Current and temperatures at different gate positions

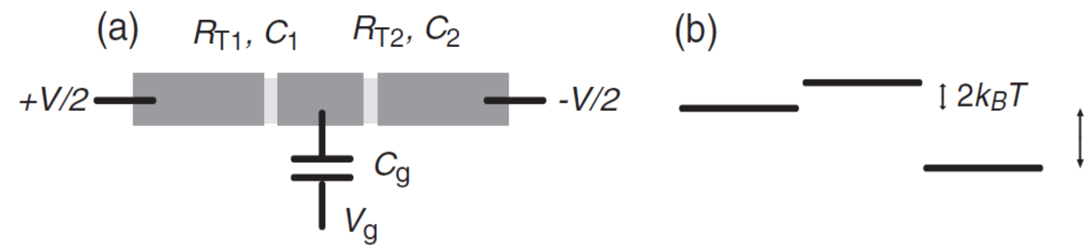


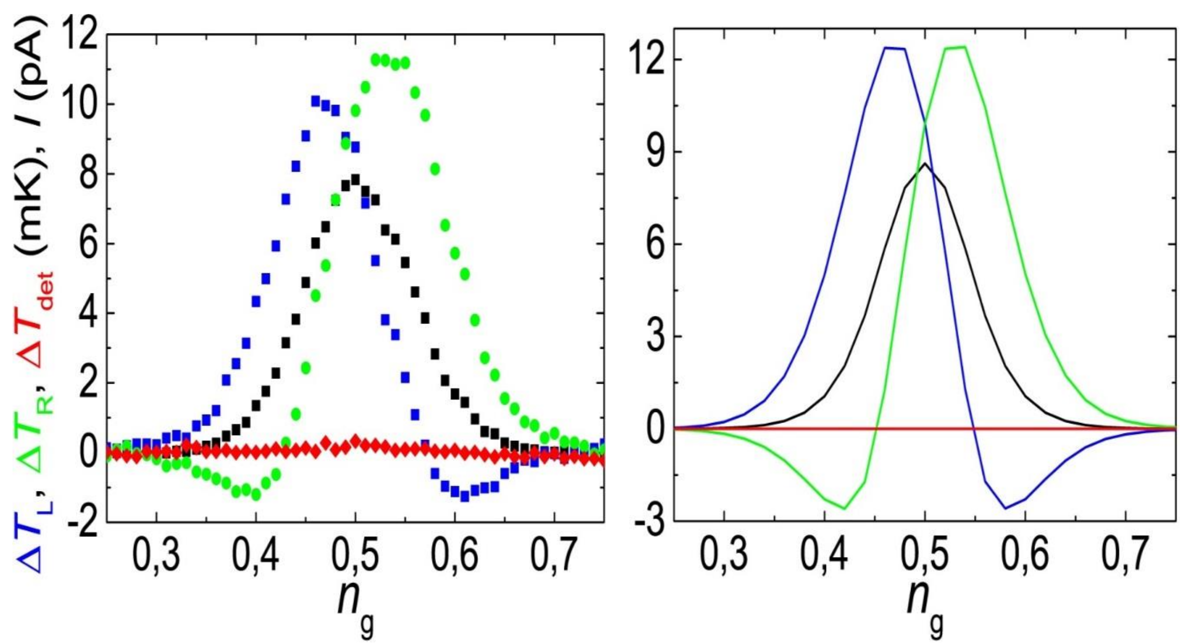


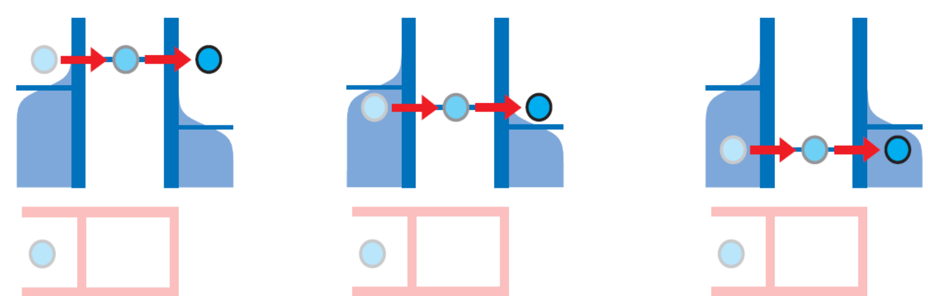
V = 20 μV, T = 50 mK

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



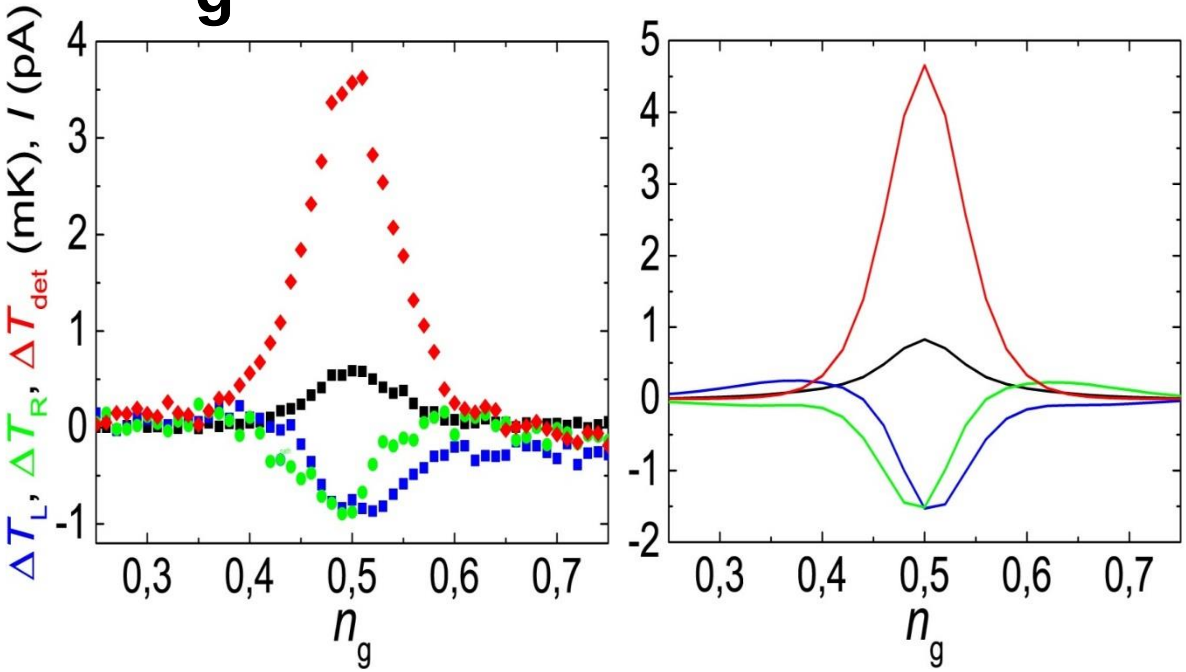


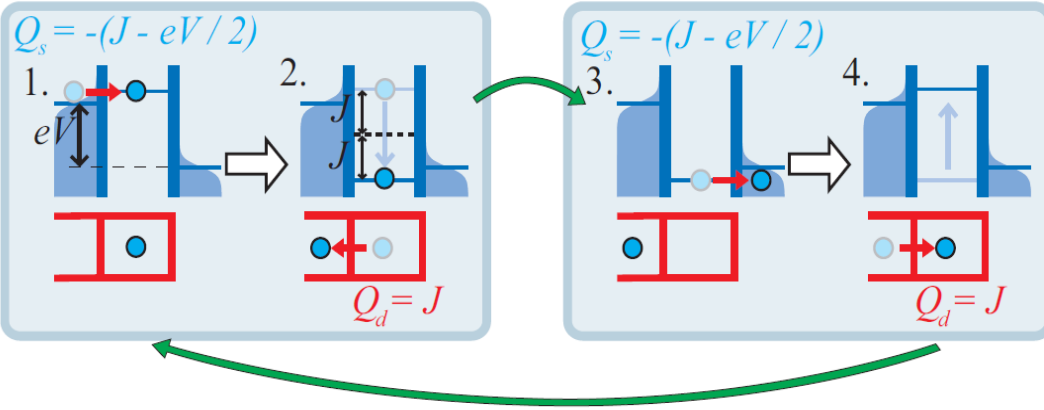


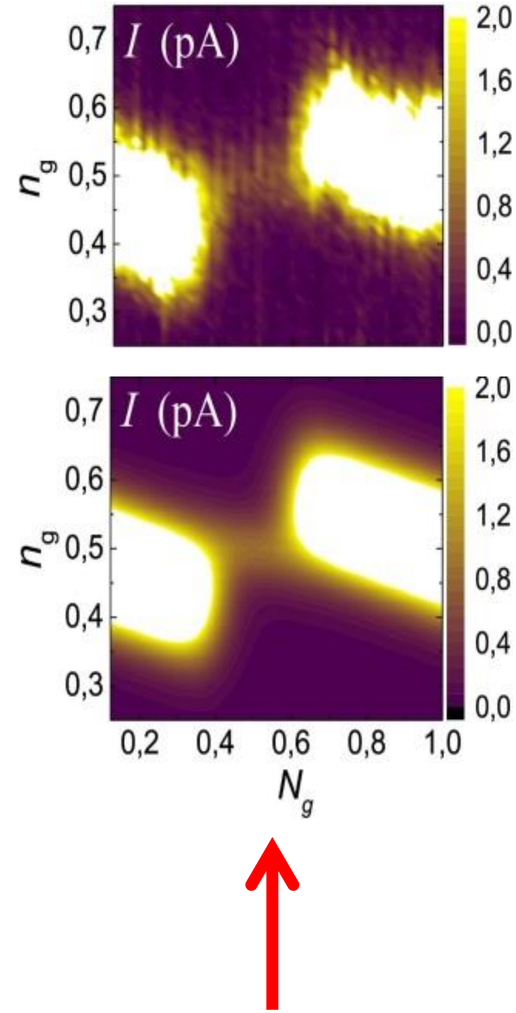


JP, J. V. Koski, and D. V. Averin, PRB **89**, 081309 (2014)
A. V. Feshchenko, J. V. Koski, and JP, PRB **90**, 201407(R) (2014)

N_g = 0.5: feedback control (Demon)



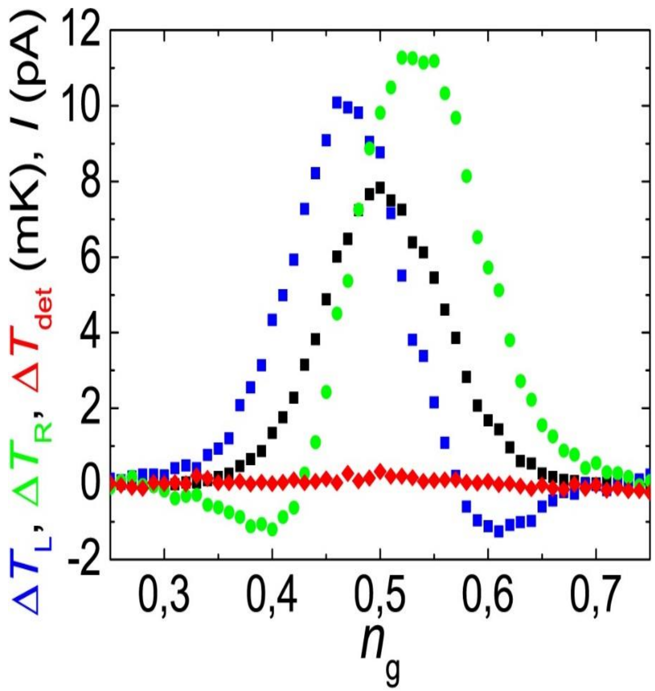




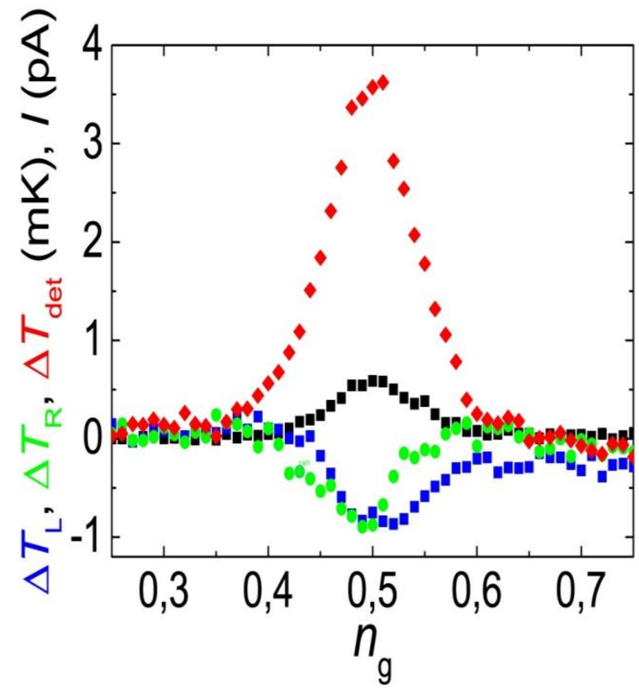
Both T_L and T_R drop: entropy of the System decreases;
T_{det} increases: entropy of the Demon increases

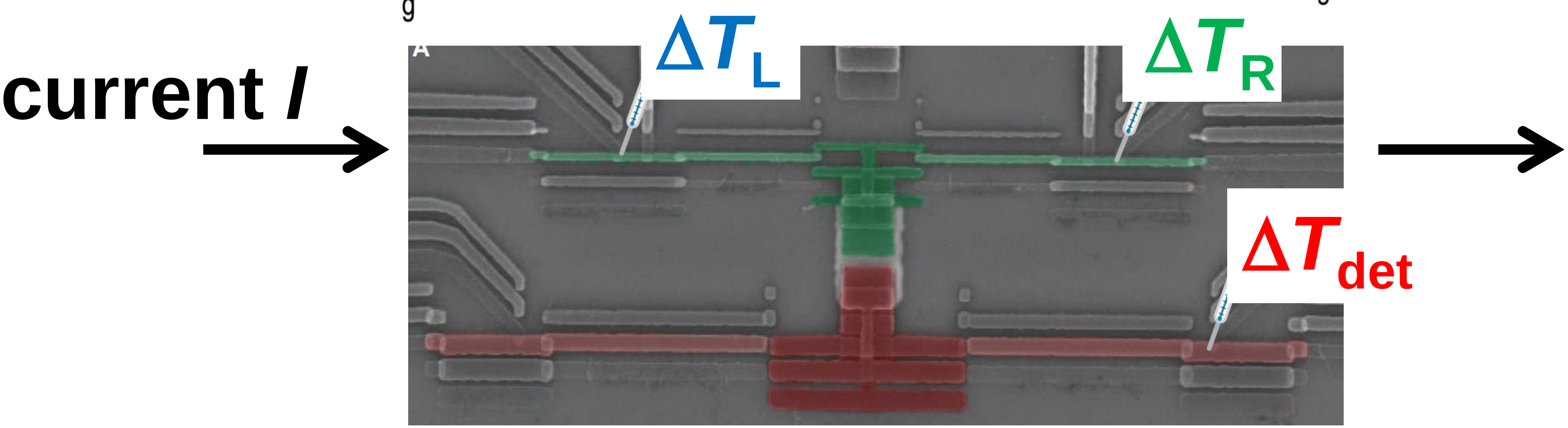
Summary of the autonomous demon experiment

SET cooler

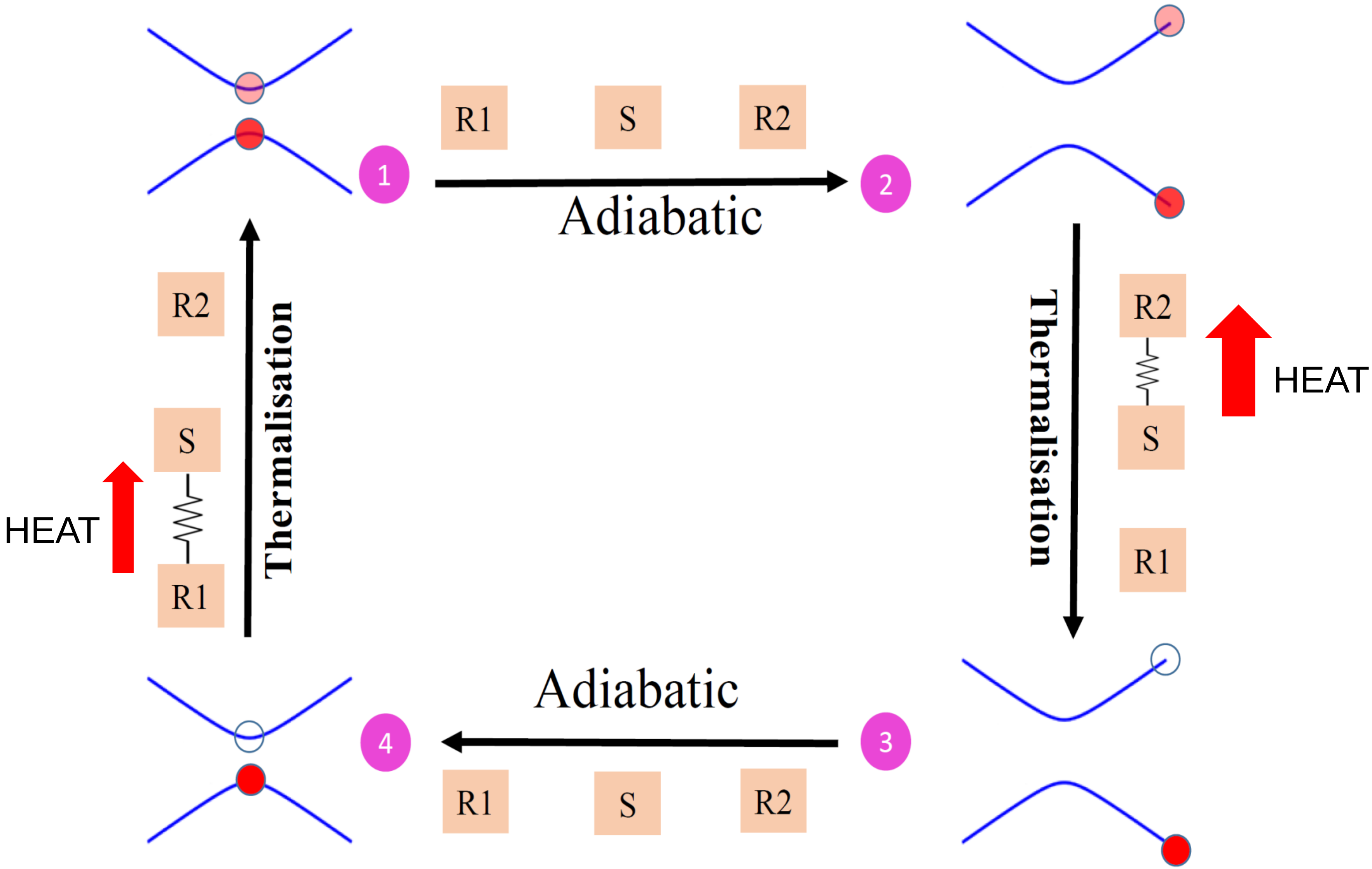


Demon

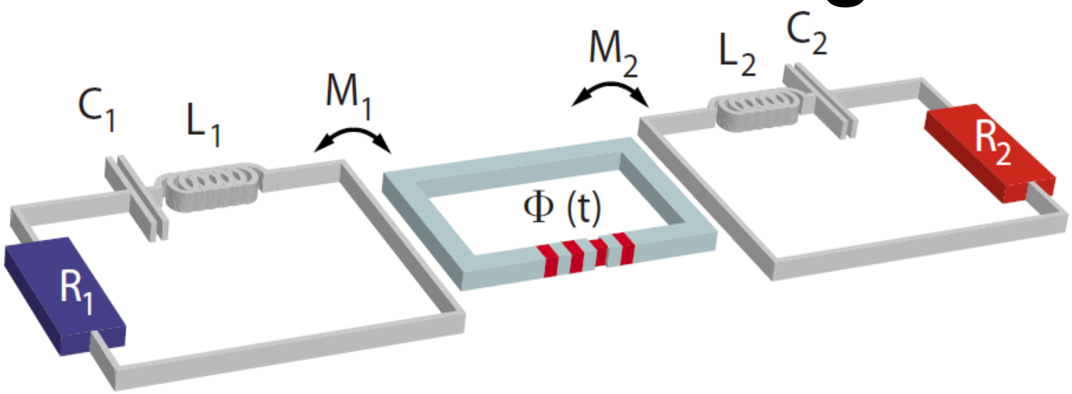




Quantum heat engines and refrigerators - the Otto cycle



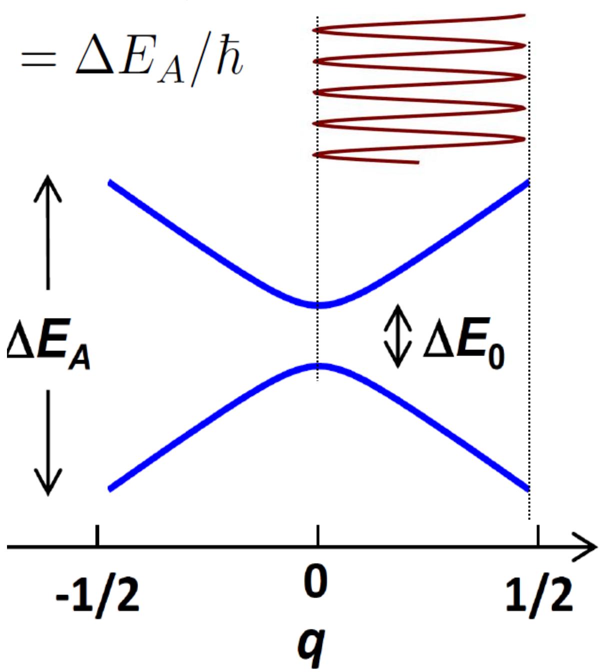
Quantum heat engines (quantum Otto refrigerator)

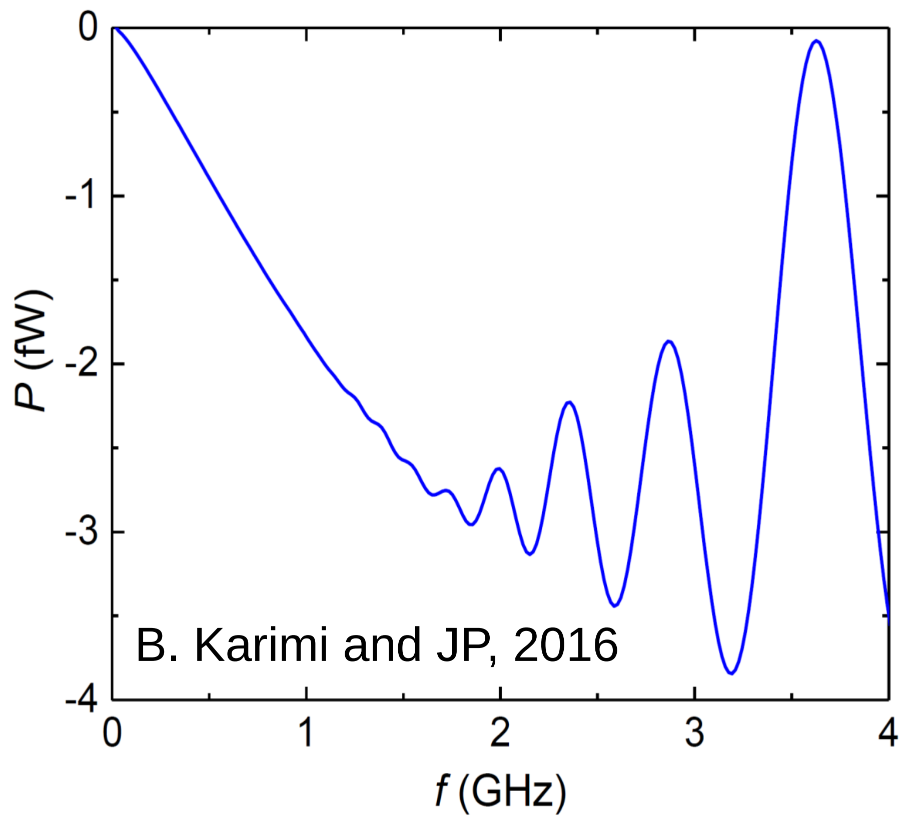


Niskanen, Nakamura, Pekola, PRB 76, 174523 (2007)

$$\omega_{LC,1} = \Delta E_0/\hbar$$

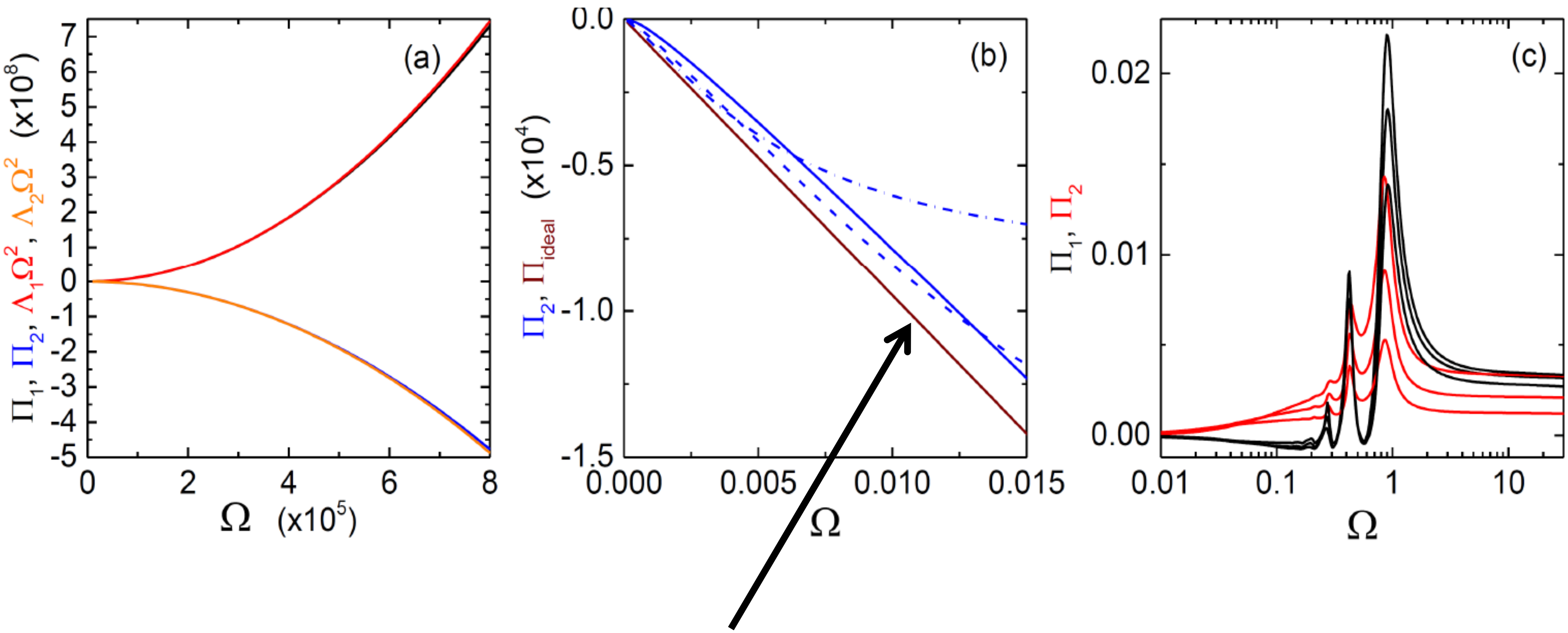
$$\omega_{LC,2} = \Delta E_A/\hbar$$





Properties of the qubit refrigerator

...in different frequency regimes

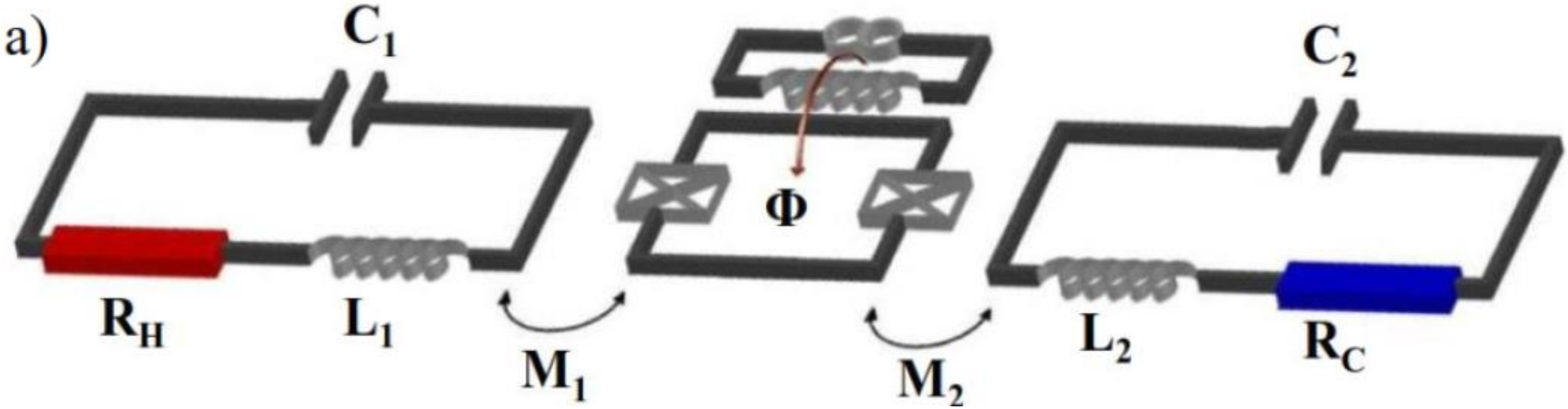


Ideal Otto cycle

$$P_2 = \frac{\hbar\omega_2}{2}[\tanh(\frac{\beta_2\hbar\omega_2}{2}) - \tanh(\frac{\beta_1\hbar\omega_1}{2})]f$$

B. Karimi and JP, in preparation

Quantum heat switch



Heat current between the two resistors under static conditions

$$P_{12} = 2\Delta^2 g_1 g_2 (\frac{E_0^2}{\hbar}) \frac{(1-e^{-\beta_1\hbar\omega})^{-1}(e^{\beta_2\hbar\omega}-1)^{-1} - (1-e^{-\beta_2\hbar\omega})^{-1}(e^{\beta_1\hbar\omega}-1)^{-1}}{g_1[1+Q_2^2(\frac{\omega}{\omega_{LC,2}}-\frac{\omega_{LC,2}}{\omega})^2]^2\coth(\frac{\beta_1\hbar\omega}{2}) + g_2[1+Q_1^2(\frac{\omega}{\omega_{LC,1}}-\frac{\omega_{LC,1}}{\omega})^2]^2\coth(\frac{\beta_2\hbar\omega}{2})}$$

PICO group from the left: Minna Günes, Robab Najafi Jabdaraghi, Klaara Viisanen, Shilpi Singh, Jesse Muhojoki, Anna Feshchenko, Elsa Mannila, Mattijs Mientki, Jukka Pekola, Ville Maisi, Joonas Peltonen, Bivas Dutta, Matthias Meschke, Libin Wang, Antti Jokiluoma, Alberto Ronzani, Dmitri Golubev, Jorden Senior. Separate photos: Olli-Pentti Saira, Jonne Koski, Bayan Karimi

Thank you