Maxwell's Demons and Quantum Heat Engines in Superconducting Circuits

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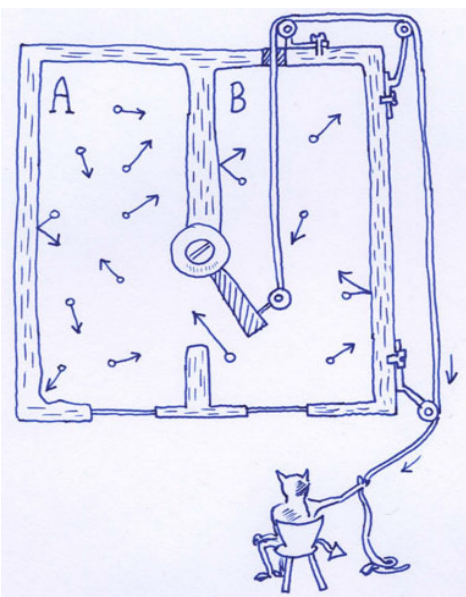
Outline and motivation

1. Heat management at nanoscale, fluctuation relations
2. Maxwell's demon
3. Experiment on a single-electron Szilard's engine
4. Experiment on an autonomous Maxwell's demon
5. Quantum heat engines and refrigerators



Basics of thermodynamics:

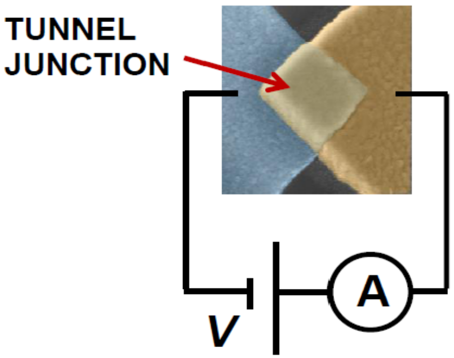
$$W = \Delta U + Q \qquad \langle \Delta S \rangle \geq 0$$

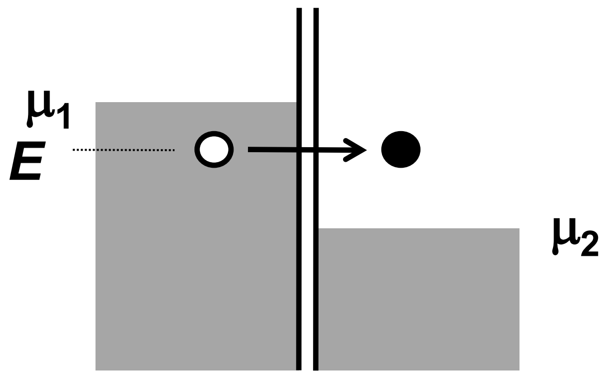
$$P(\Delta S)/P(-\Delta S) = e^{\Delta S/k_B}$$

The role of information in thermodynamics?

Reviews: Lutz, Ciliberto, Physics Today 68, 30 (2015); JP, Nature Physics 11, 118 (2015).

Dissipation in transport through a barrier





Dissipation generated by a tunneling event in a junction biased at voltage *V*

$$\Delta Q = (\mu_1 - E) + (E - \mu_2) = \mu_1 - \mu_2 = eV$$

$\Delta Q = T\Delta S$ is first distributed to the electron system, then typically to the lattice by electron-phonon scattering

For average current *I* through the junction, the total average power dissipated is naturally

$$P = (I/e)\Delta Q = IV$$

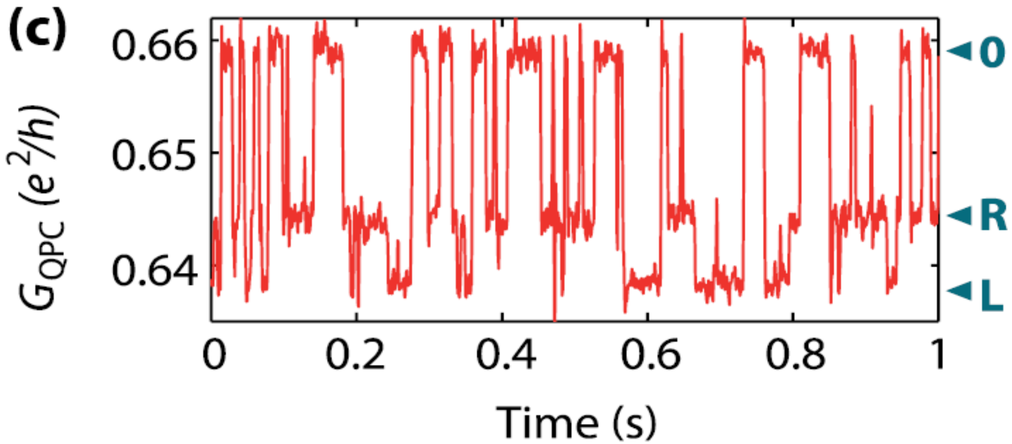
Fluctuation relations in a circuit

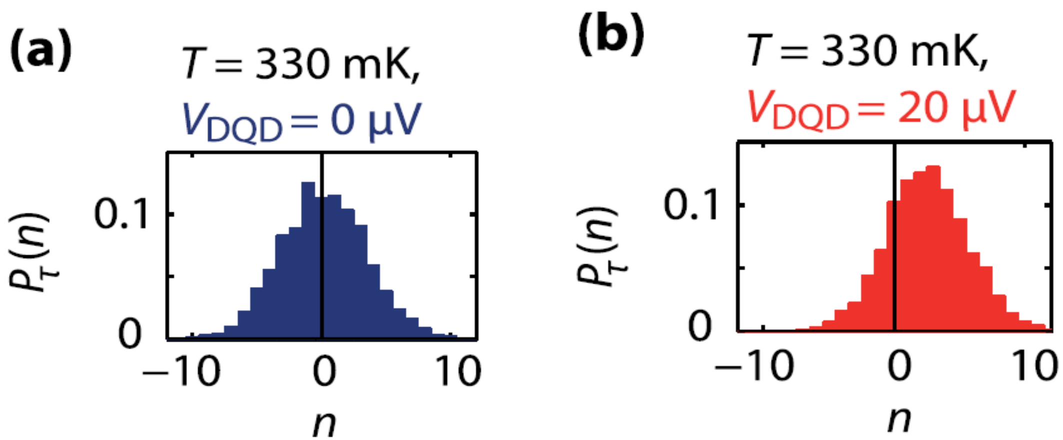
$$\frac{P_\tau(\Delta S)}{P_\tau(-\Delta S)} = e^{\Delta S/k_\mathrm{B}}$$

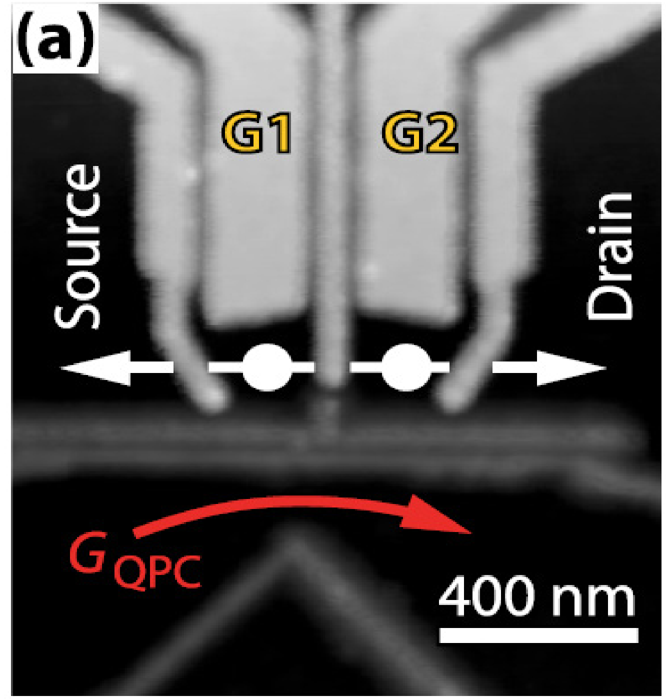
U. Seifert, Rep. Prog. Phys. **75**, 126001 (2012)

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

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



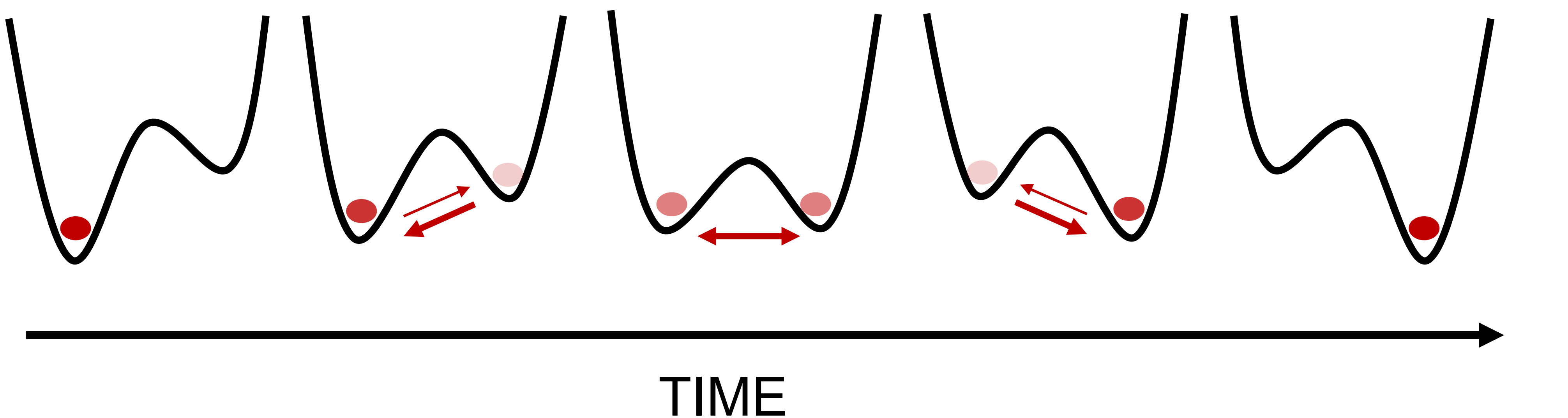




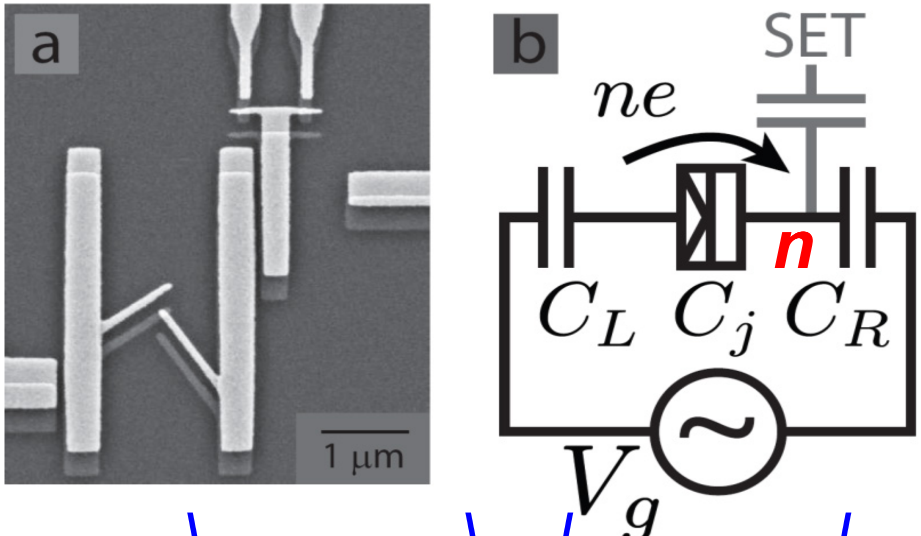
$$\frac{P_\tau(n)}{P_\tau(-n)} = e^{neV_\mathrm{DQD}/k_\mathrm{B}T}$$

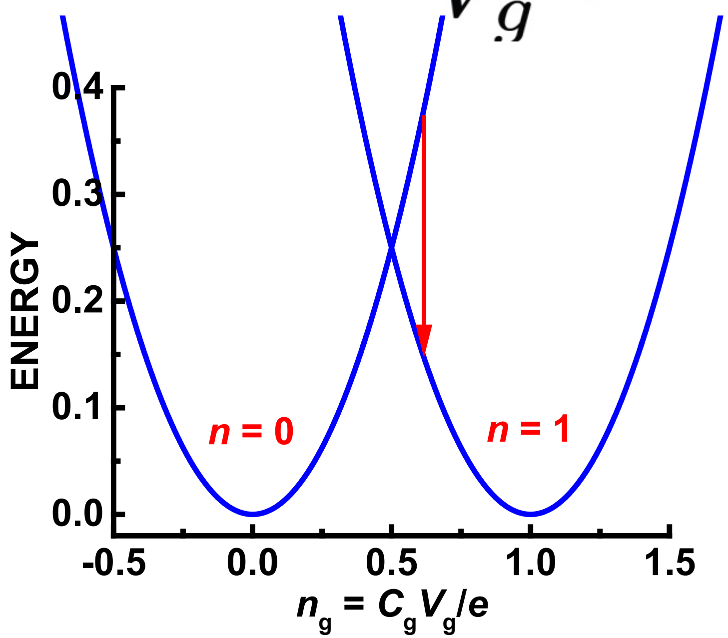
Driven classical systems

Work and dissipation in a driven process?



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:

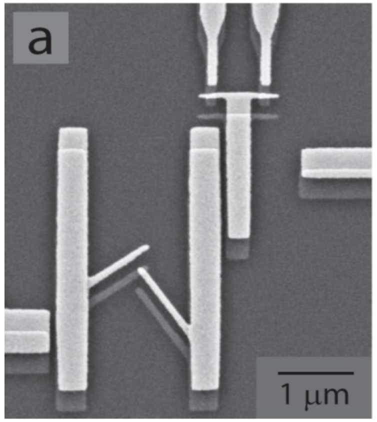
$$W = Q + \Delta U$$

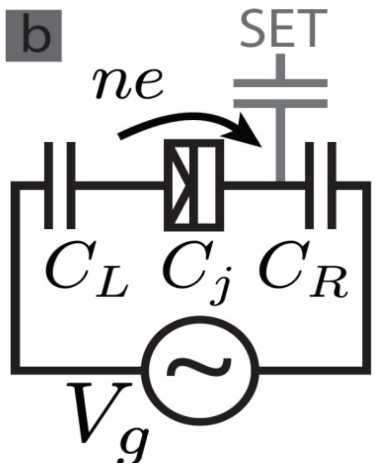
Change in internal (charging) energy

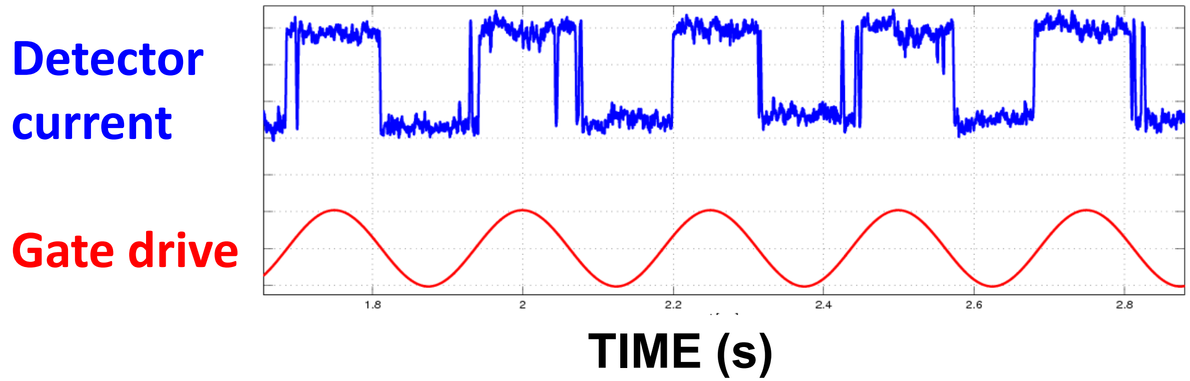
D. Averin and JP, EPL 96, 67004 (2011)

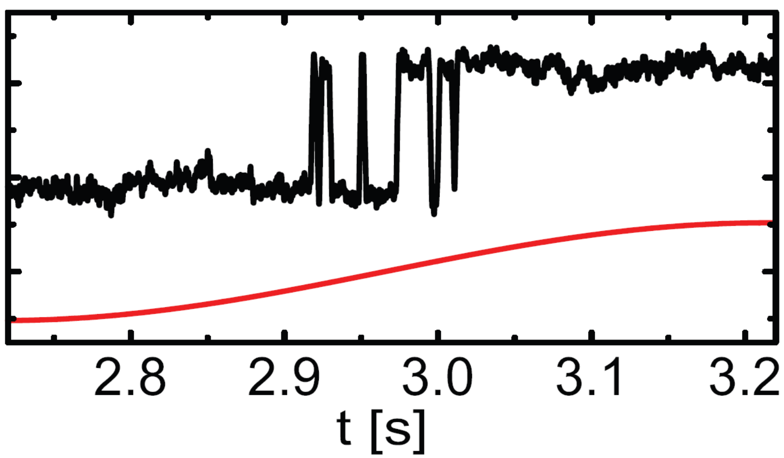
Experiment on a single-electron box

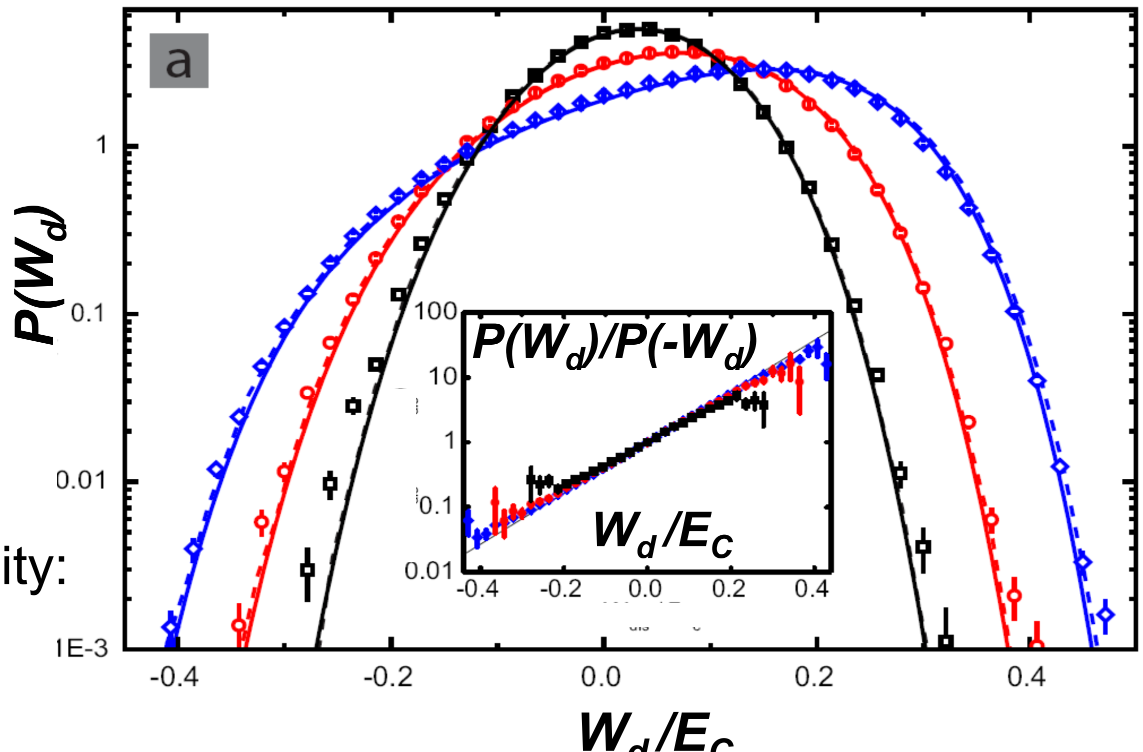
O.-P. Saira et al., PRL 109, 180601 (2012); J.V. Koski et al., Nature Physics 9, 644 (2013); I. M. Khaymovich et al., Nat. Comm. 6, 7010 (2015).







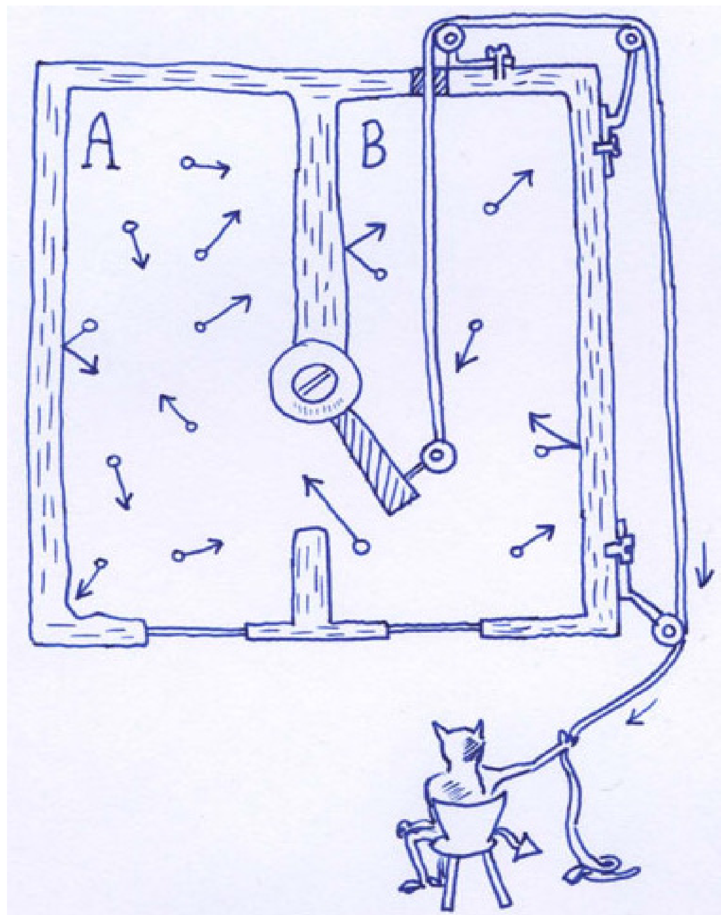




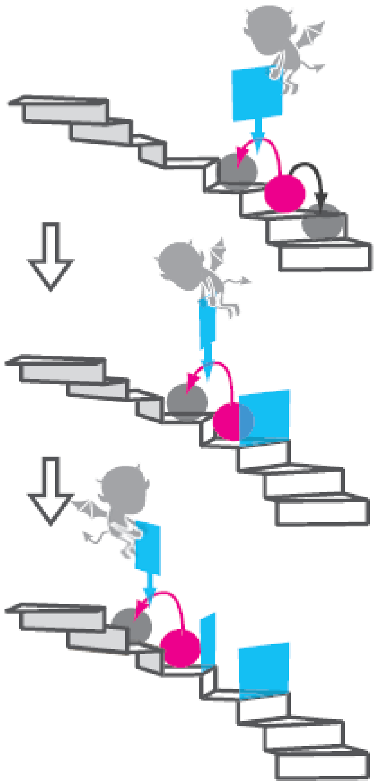
The distributions satisfy Jarzynski equality:

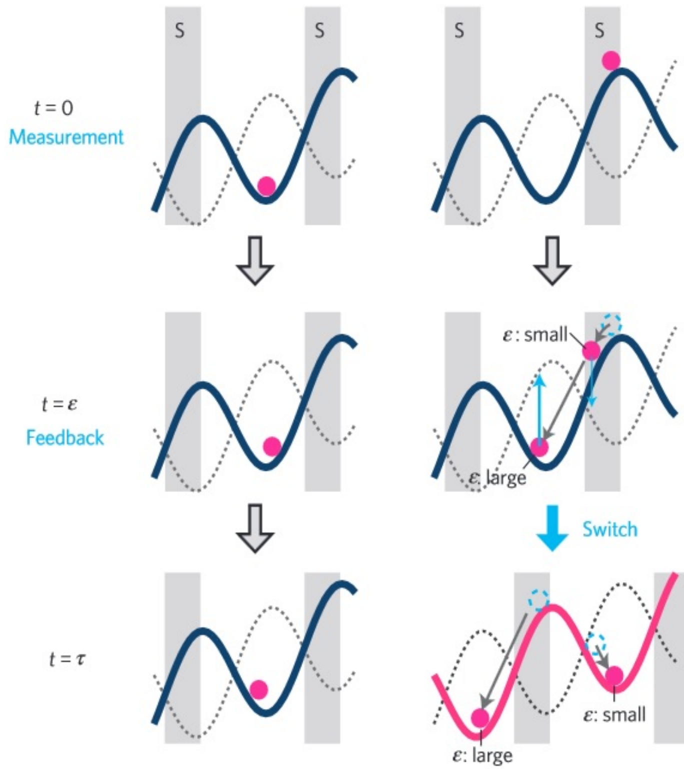
$$\langle e^{-\beta(W-\Delta F)}\rangle = 1.03 \pm 0.03$$

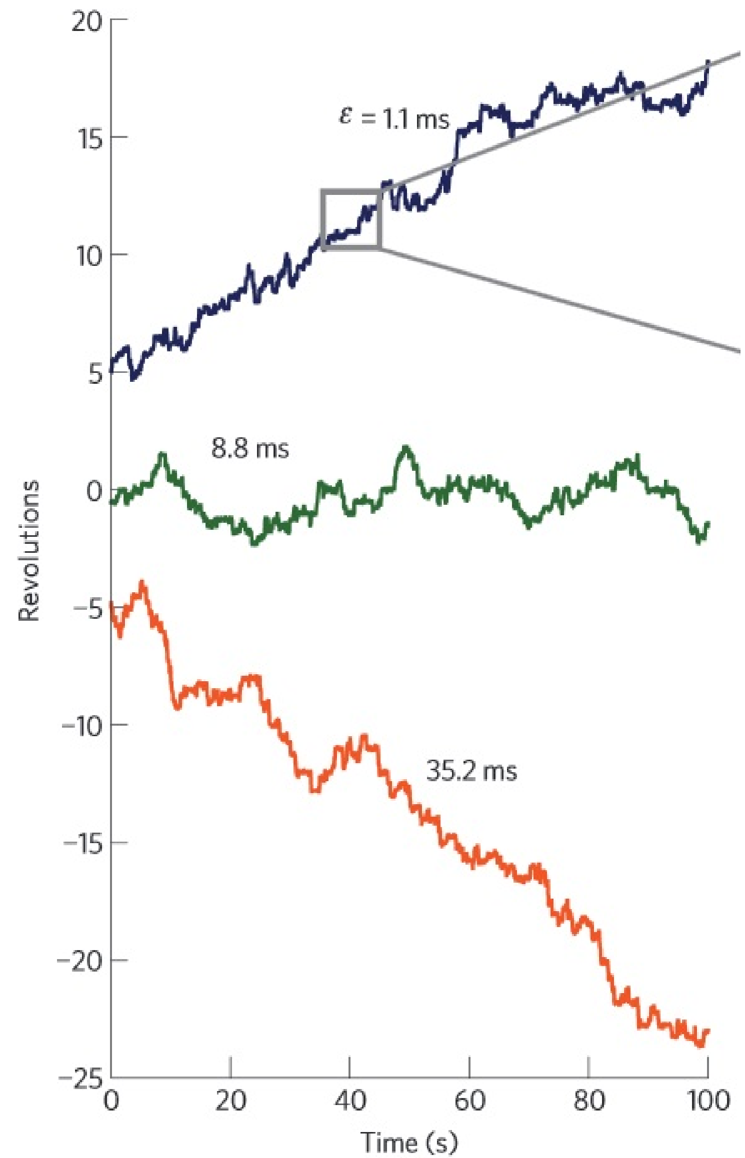
Maxwell’s Demon



Experiments on Maxwell’s demon



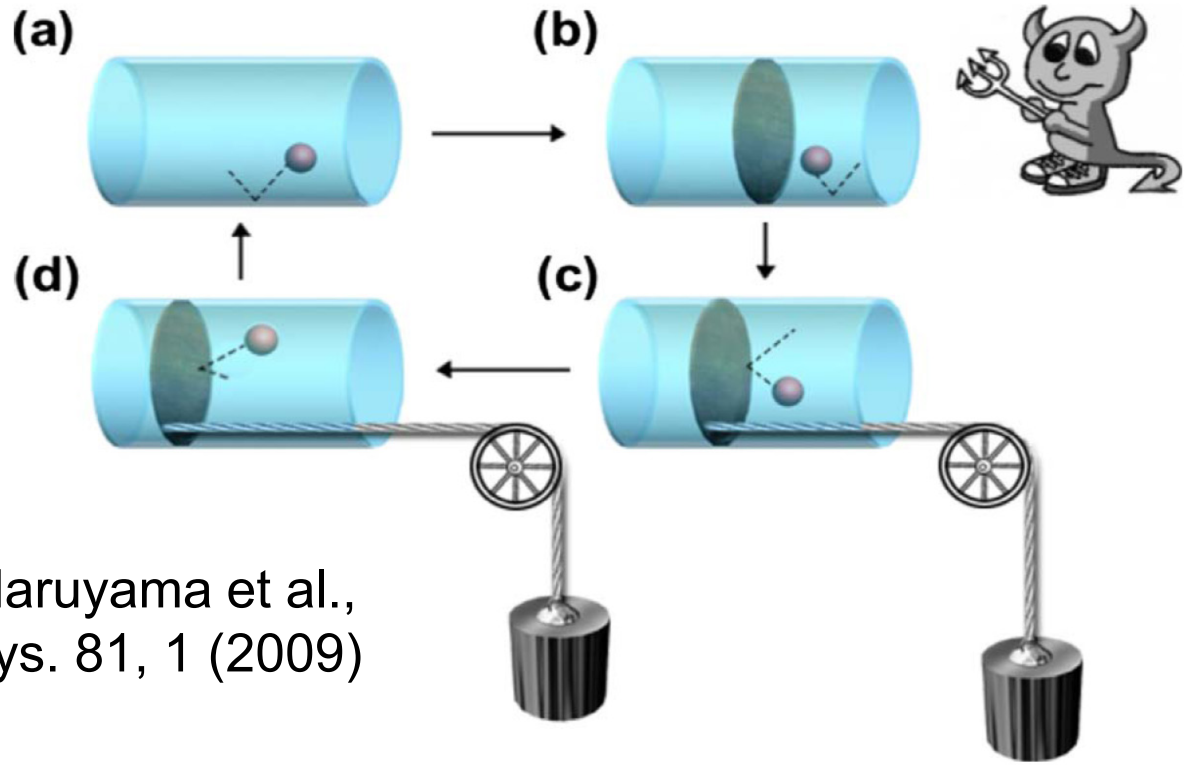




S. Toyabe, T. Sagawa, M. Ueda, E. Muneyuki, M. Sano, Nature Phys. **6**, 988 (2010)

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

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

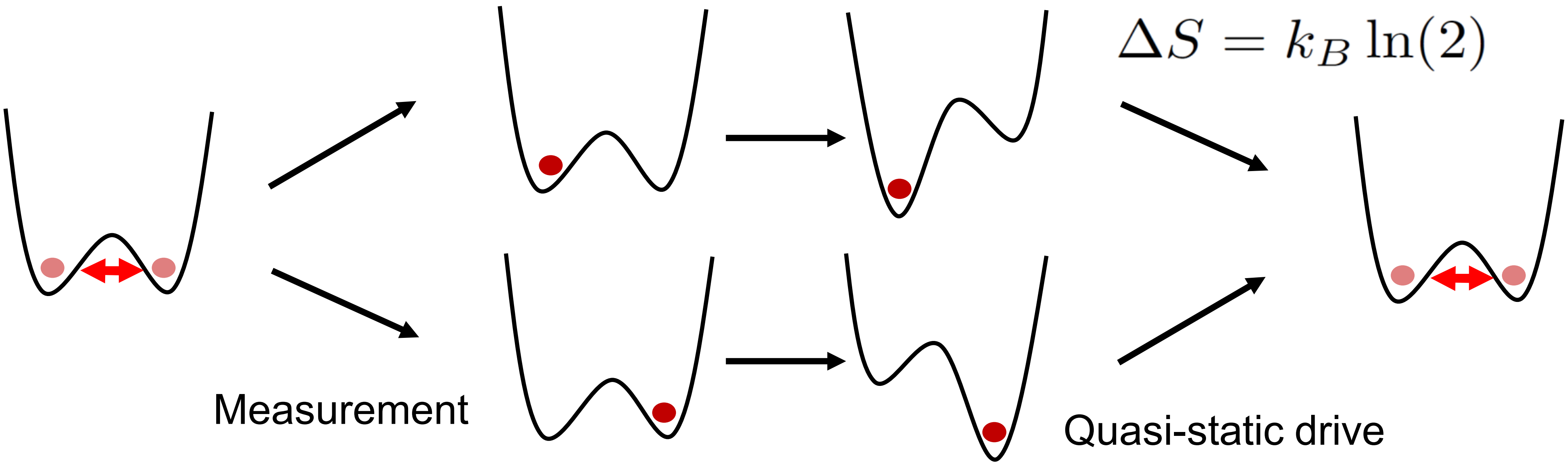
$$W = Q = \int_{V/2}^{V} p dV = \int_{V/2}^{V} \frac{k_B T}{V} dV = k_B T \ln 2$$

Szilard's engine for single electrons

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

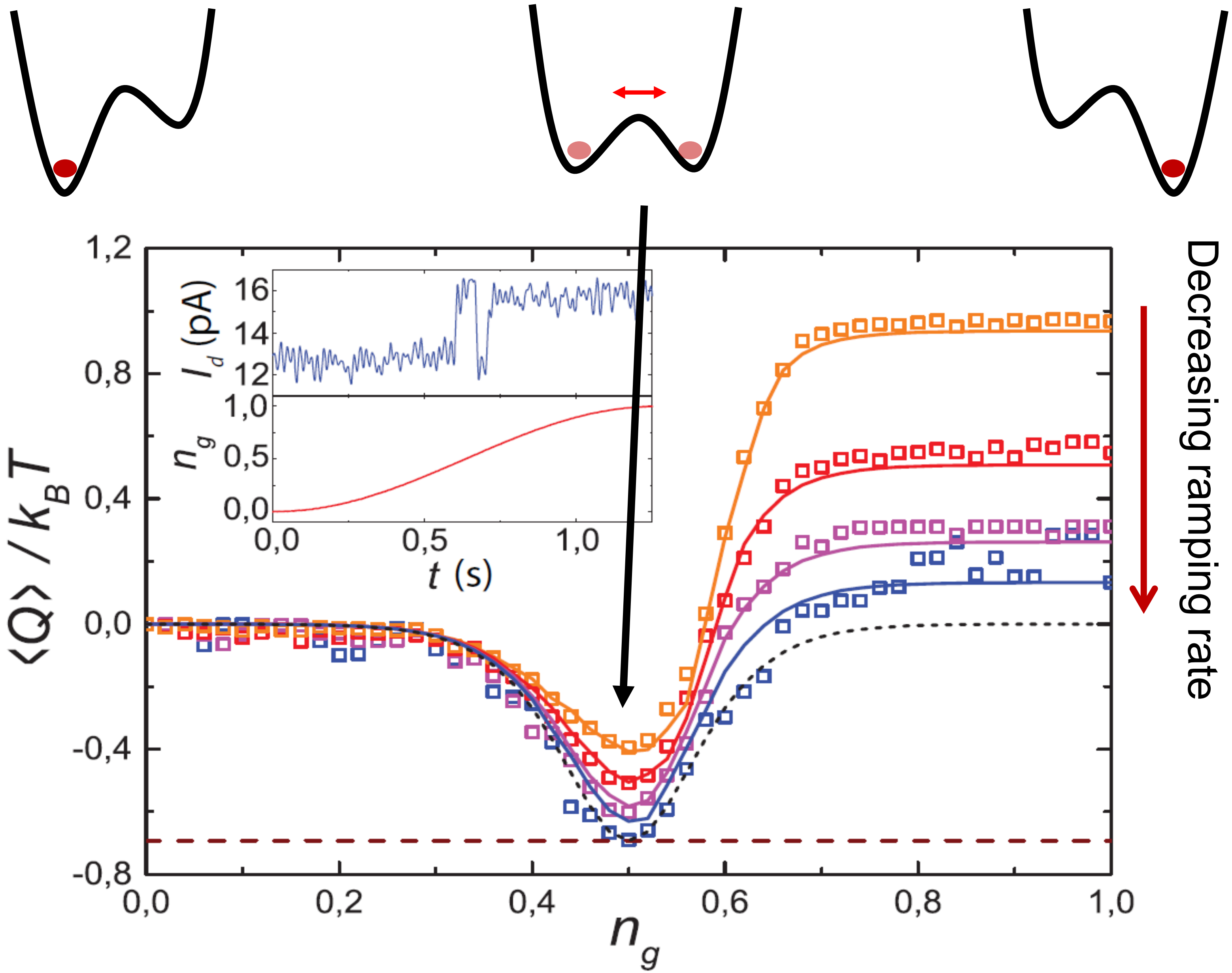
Entropy of the charge states: $S = -k_B \sum_{i=0,1} p(i) \ln[p(i)]$

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



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

Extracting heat from the bath

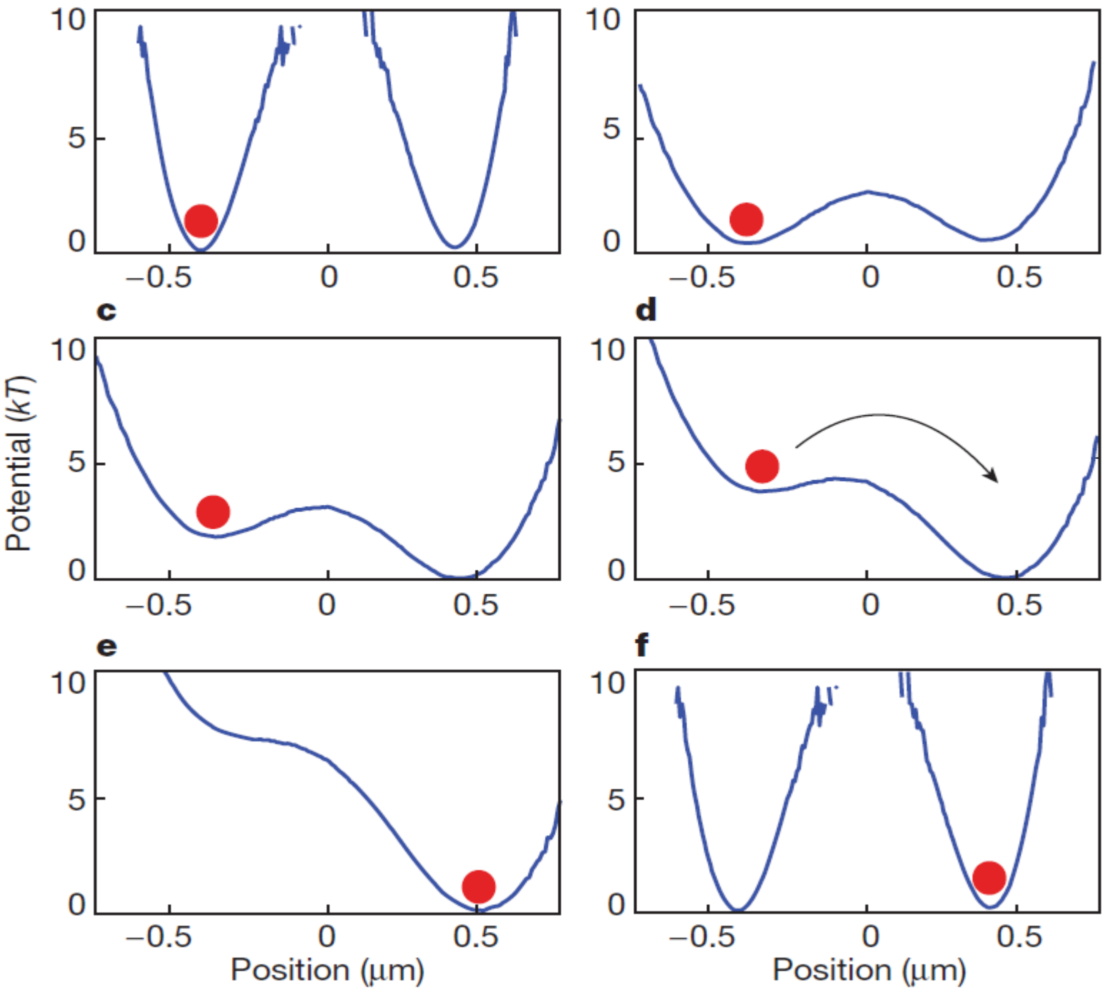


$- \; k_B T \ln(2)$

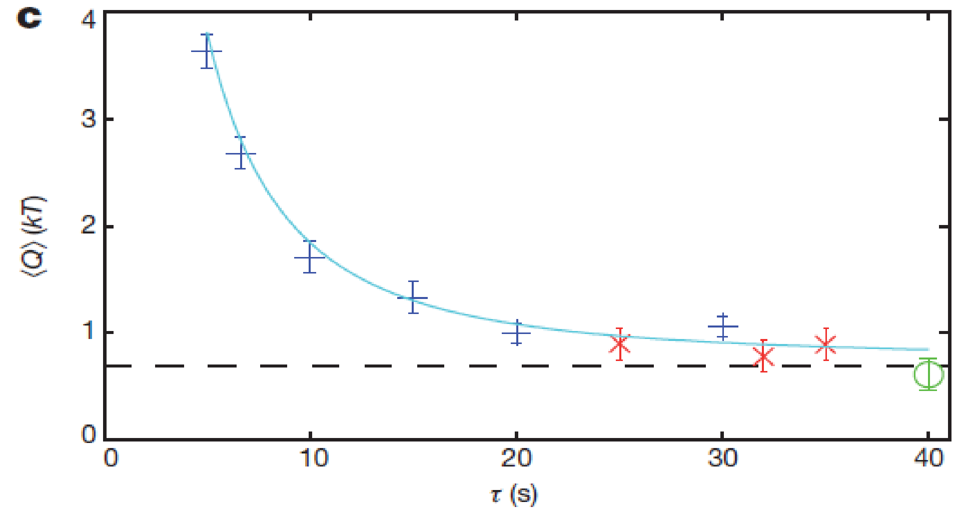
Erasure of information

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

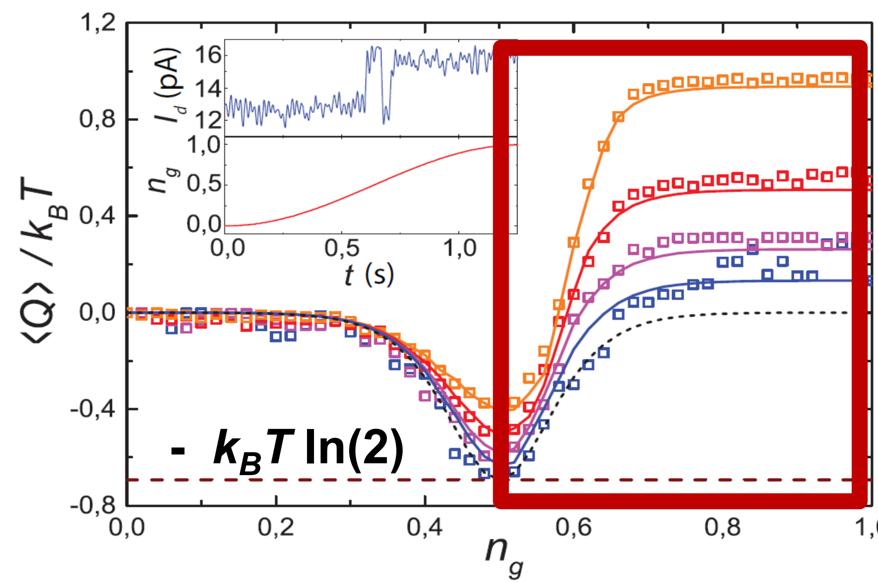
Experiment on a colloidal particle:



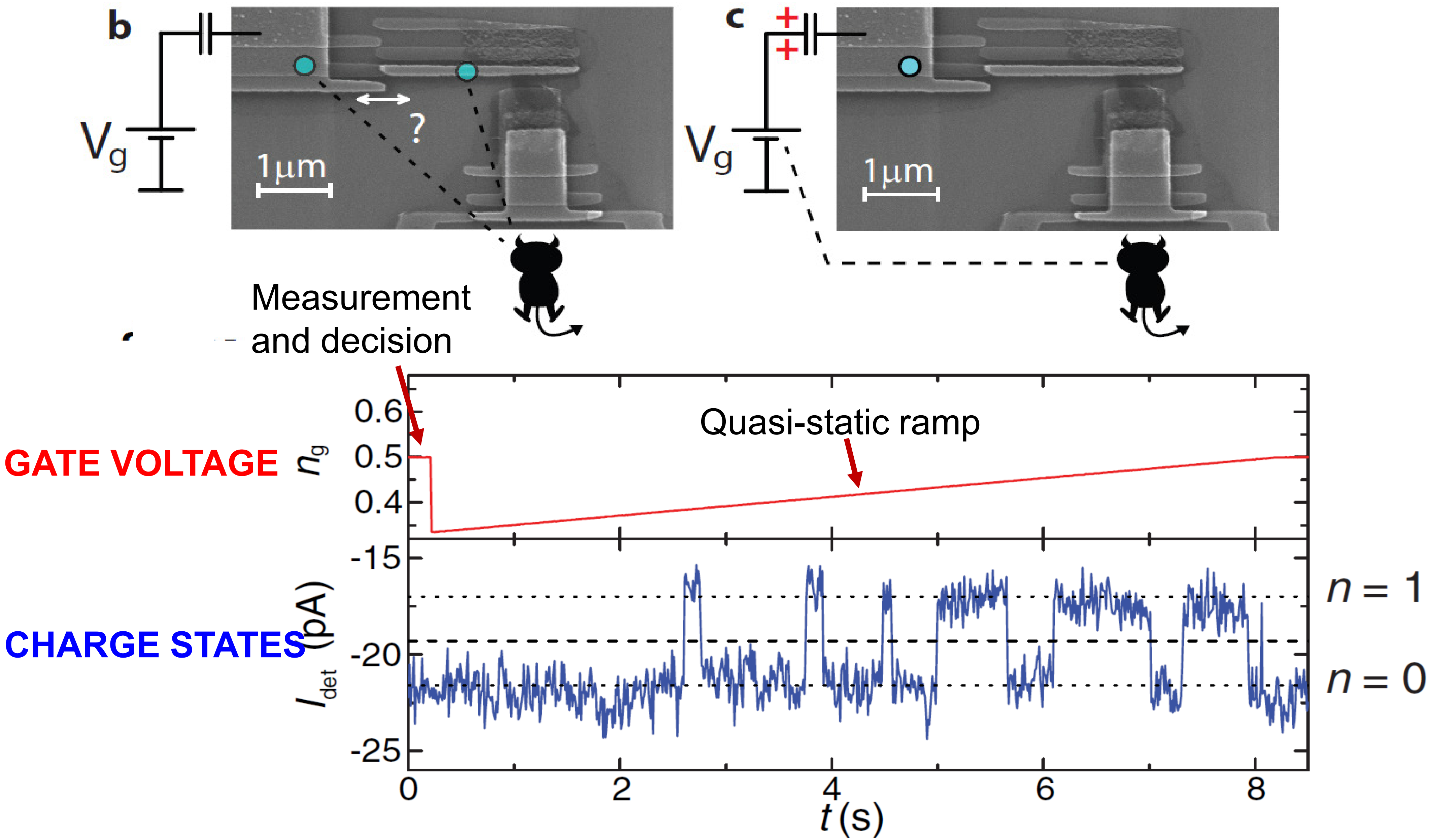
A. Berut et al., Nature 2012



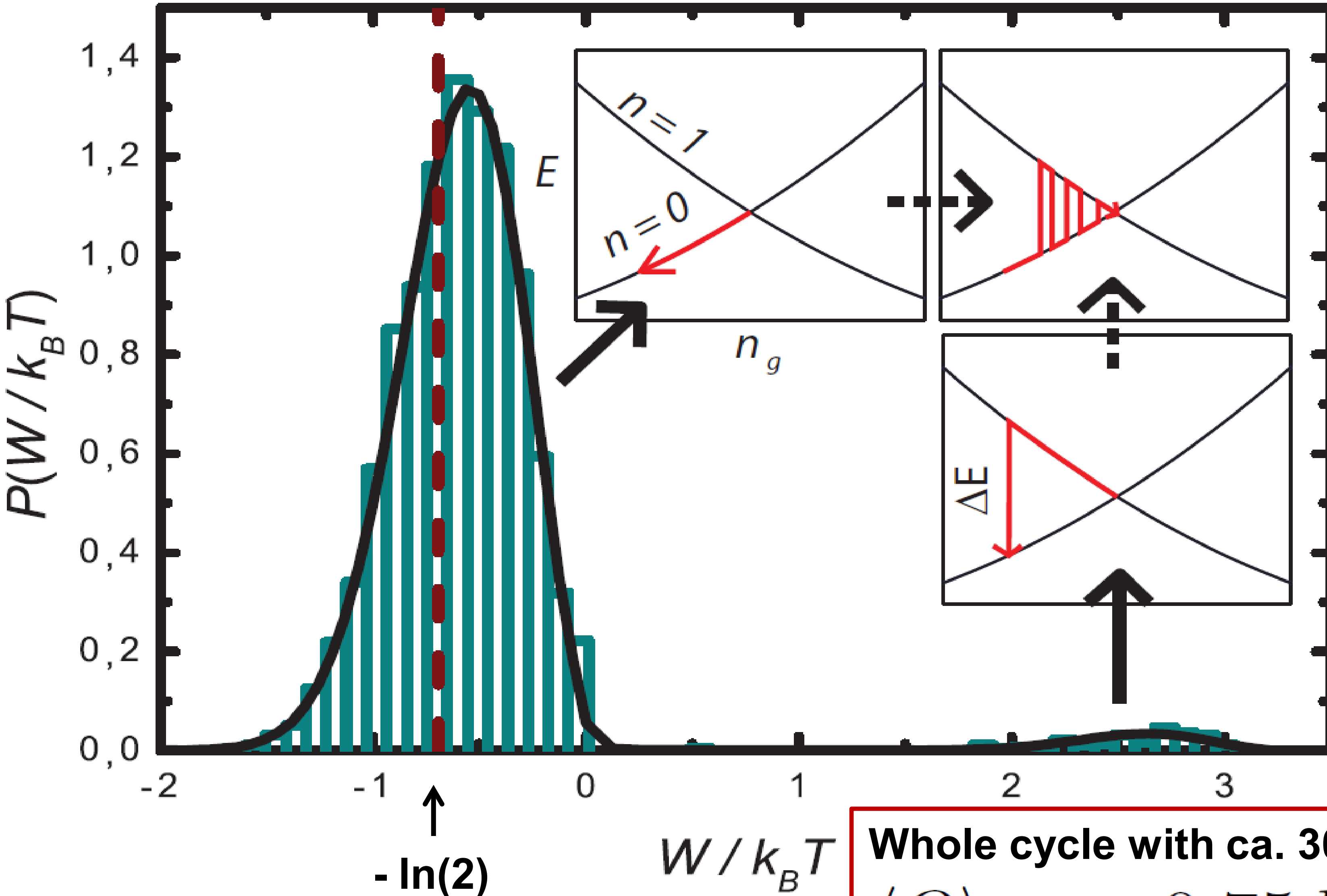
Corresponds to our experiment:



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:

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

Sagawa-Ueda relation

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

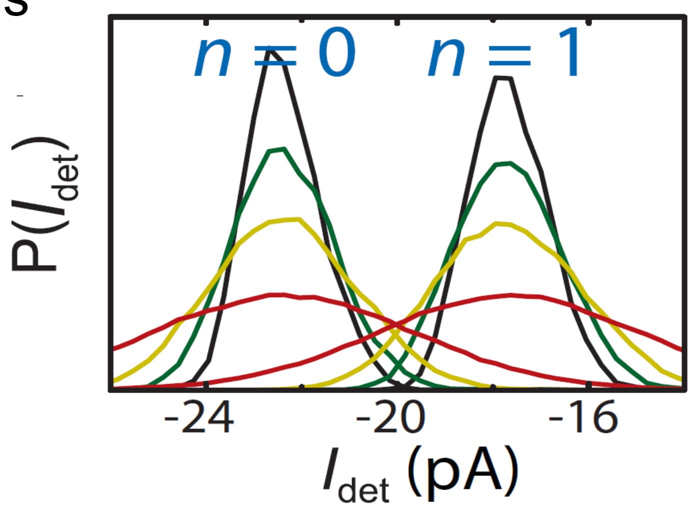
T. Sagawa and M. Ueda, PRL 104, 090602 (2010)

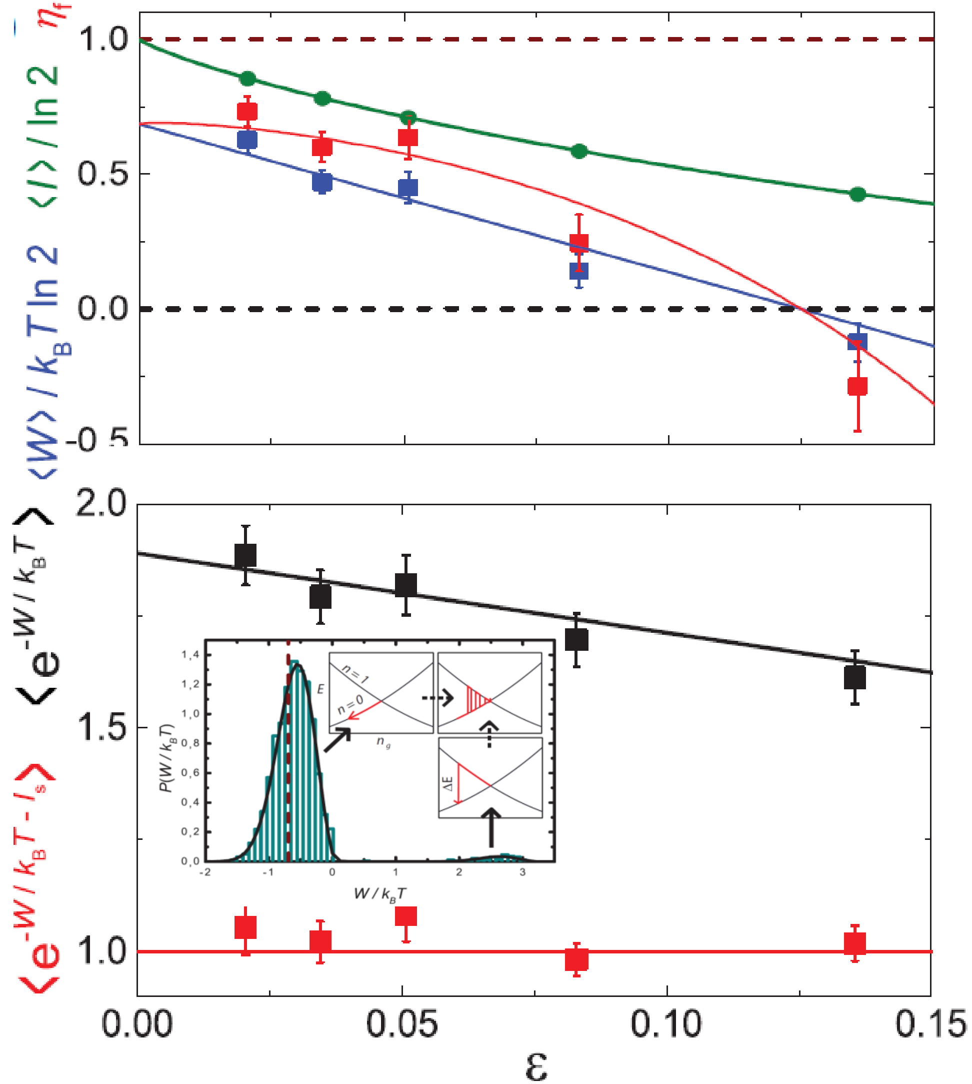
For a symmetric two-state system:

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

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

Measurements of *n* at different detector bandwidths



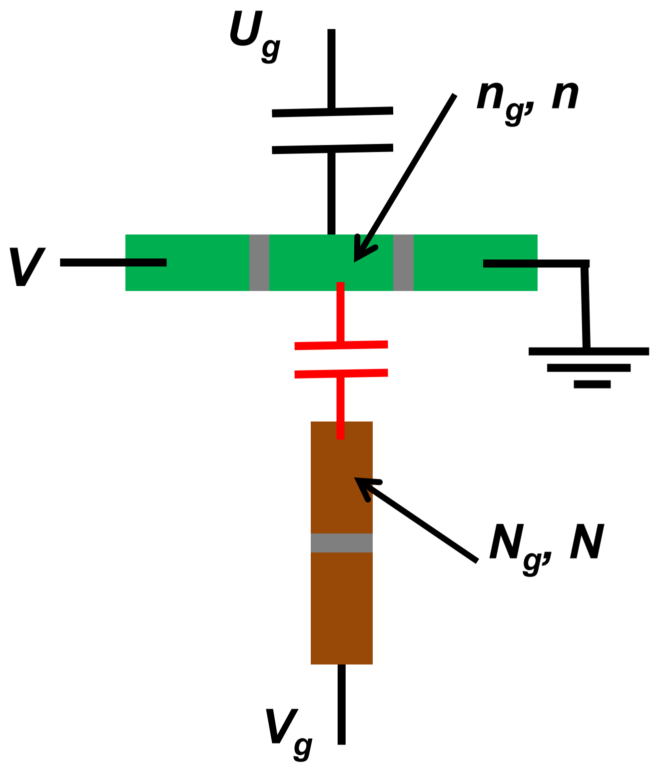


J. V. Koski et al., PRL 113, 030601 (2014)

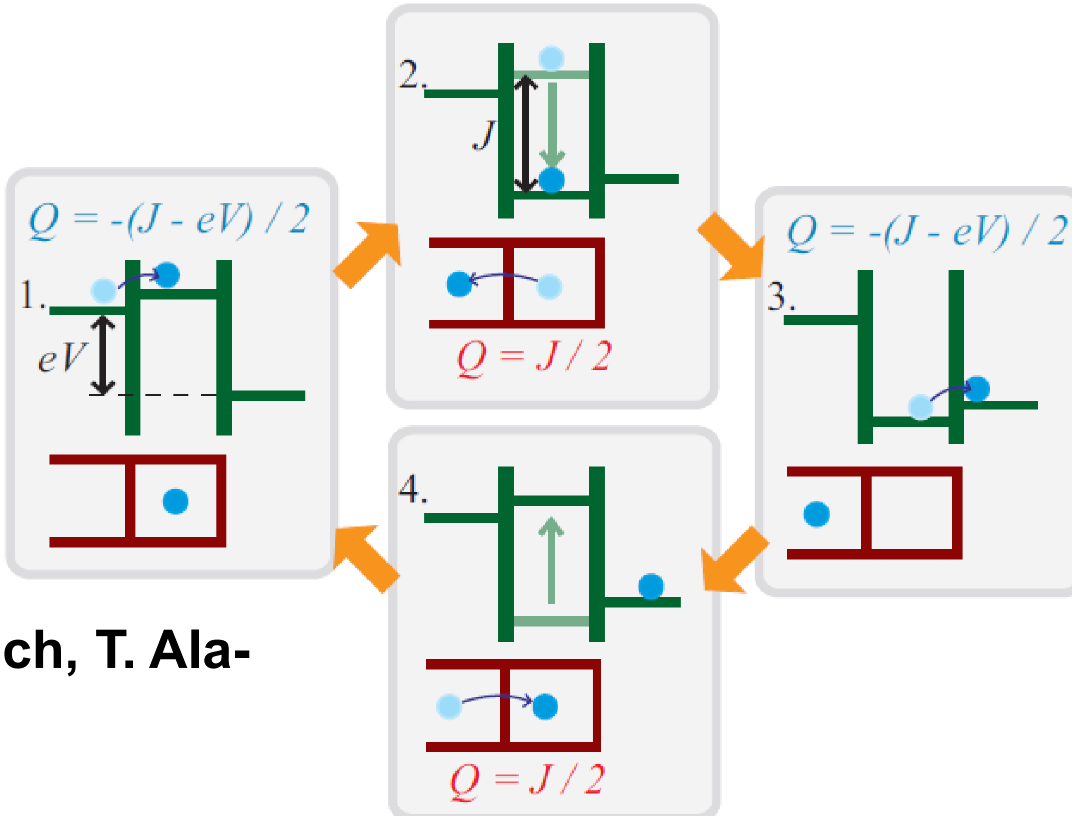
Autonomous Maxwell's demon

System and Demon: all in one

Realization in a circuit:



$$H(n,N) = E_s(n-n_g)^2 + E_d(N-N_g)^2 + 2J(n-n_g)(N-N_g)$$

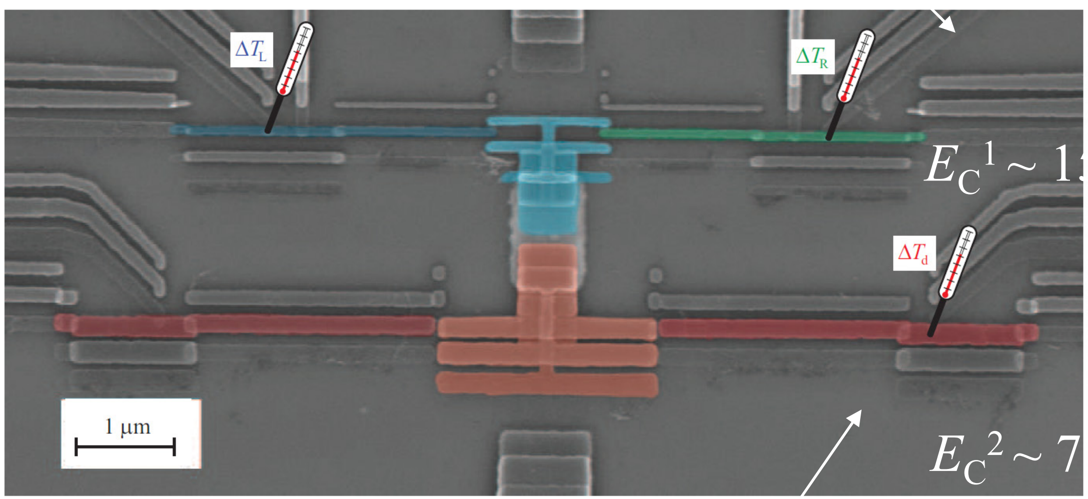


J. V. Koski, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and JP, PRL 115, 260602 (2015).

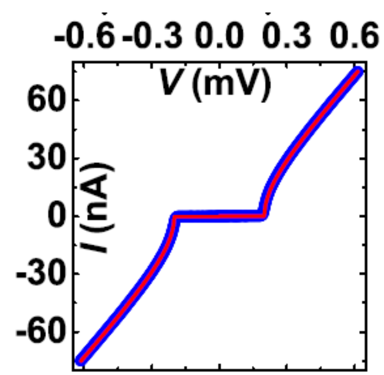
Similar idea: P. Strasberg et al., PRL 110, 040601 (2013).

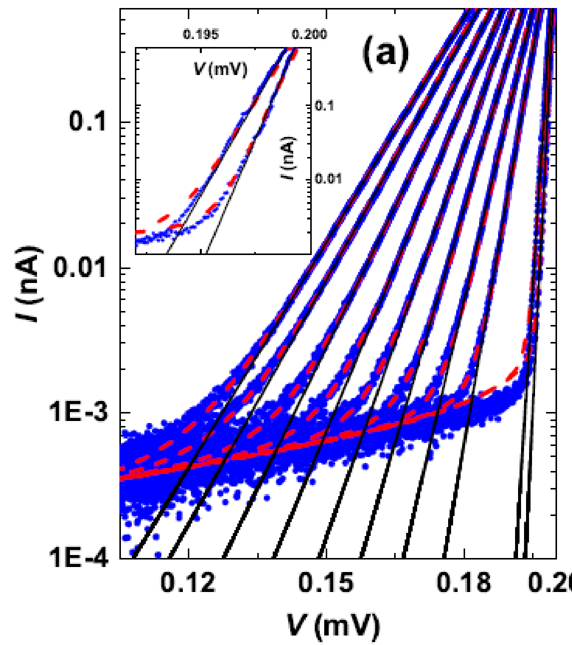
Autonomous Maxwell's demon – information-powered refrigerator

Image of the actual device



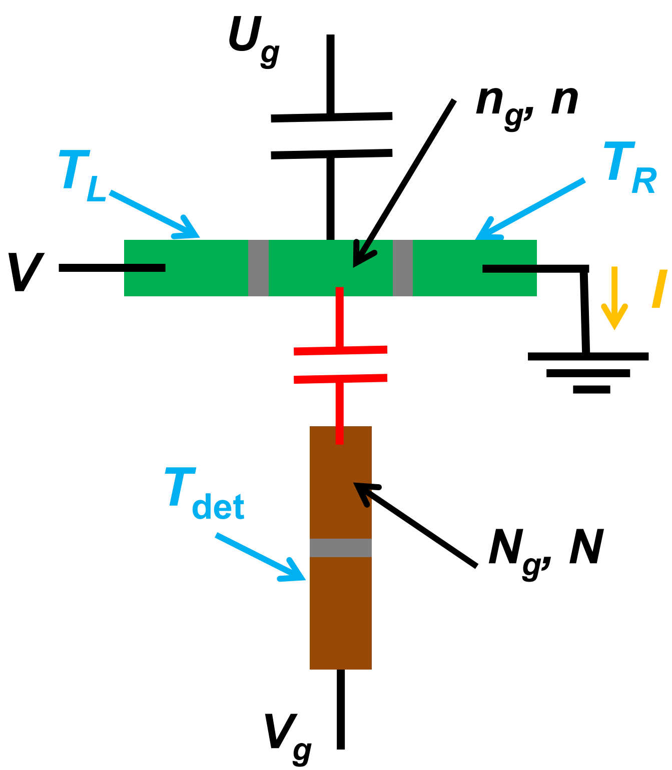
Thermometers based on standard NIS tunnel junctions

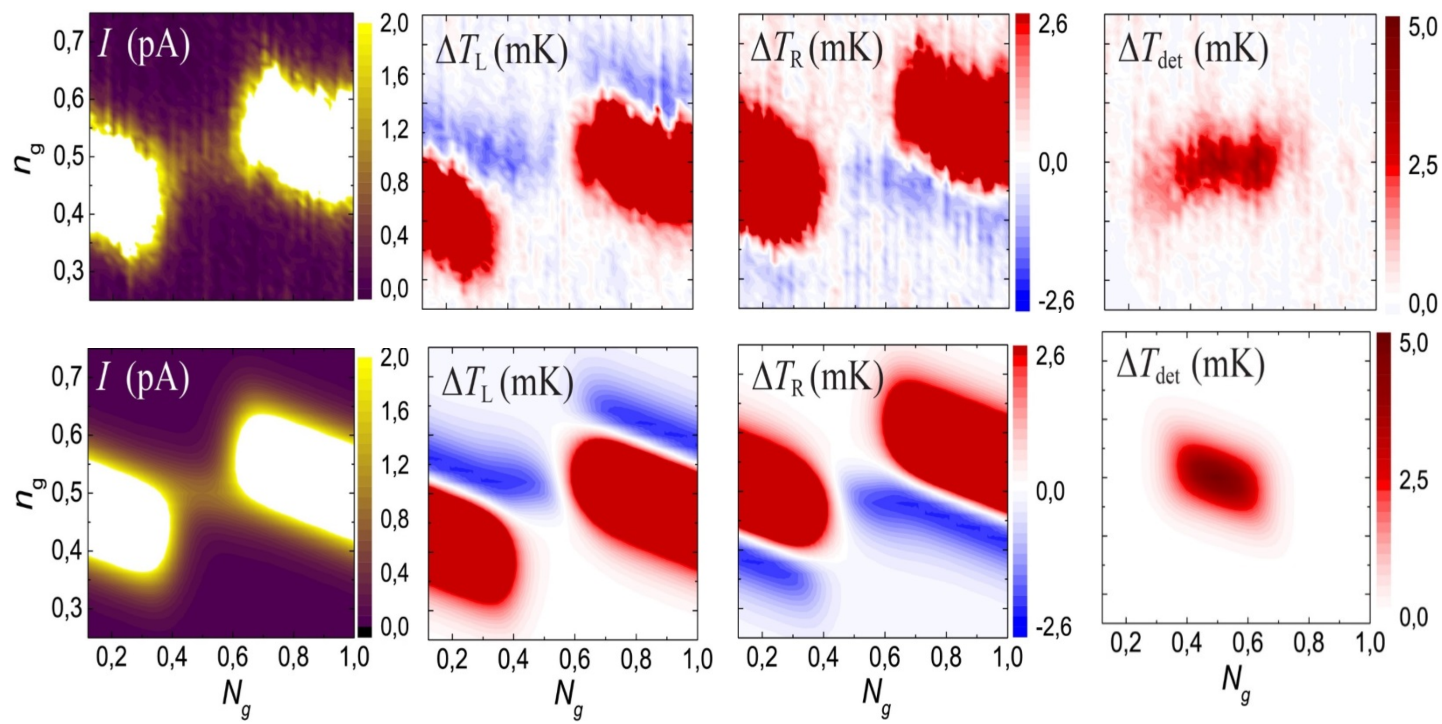




A. V. Feshchenko et al., Phys. Rev. Appl. 4, 034001 (2015).

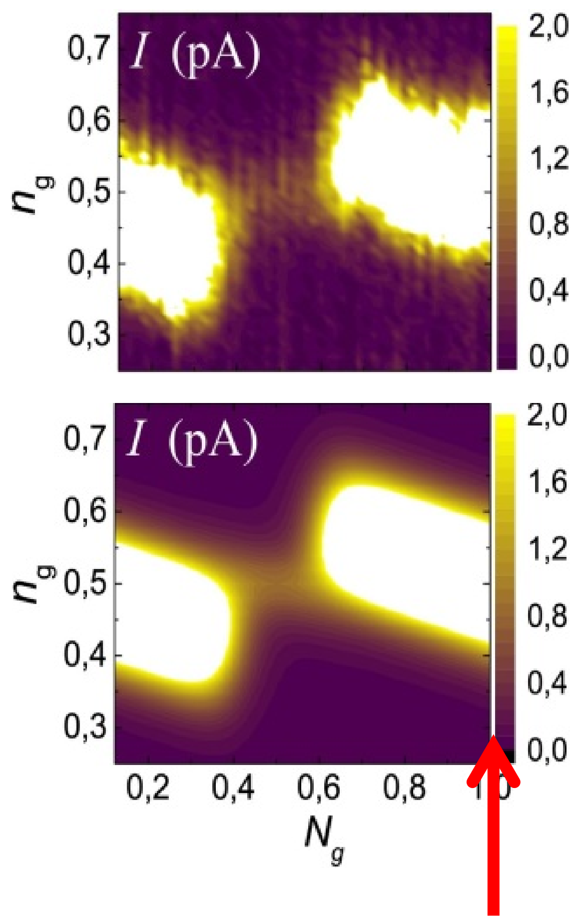
Current and temperatures at different gate positions

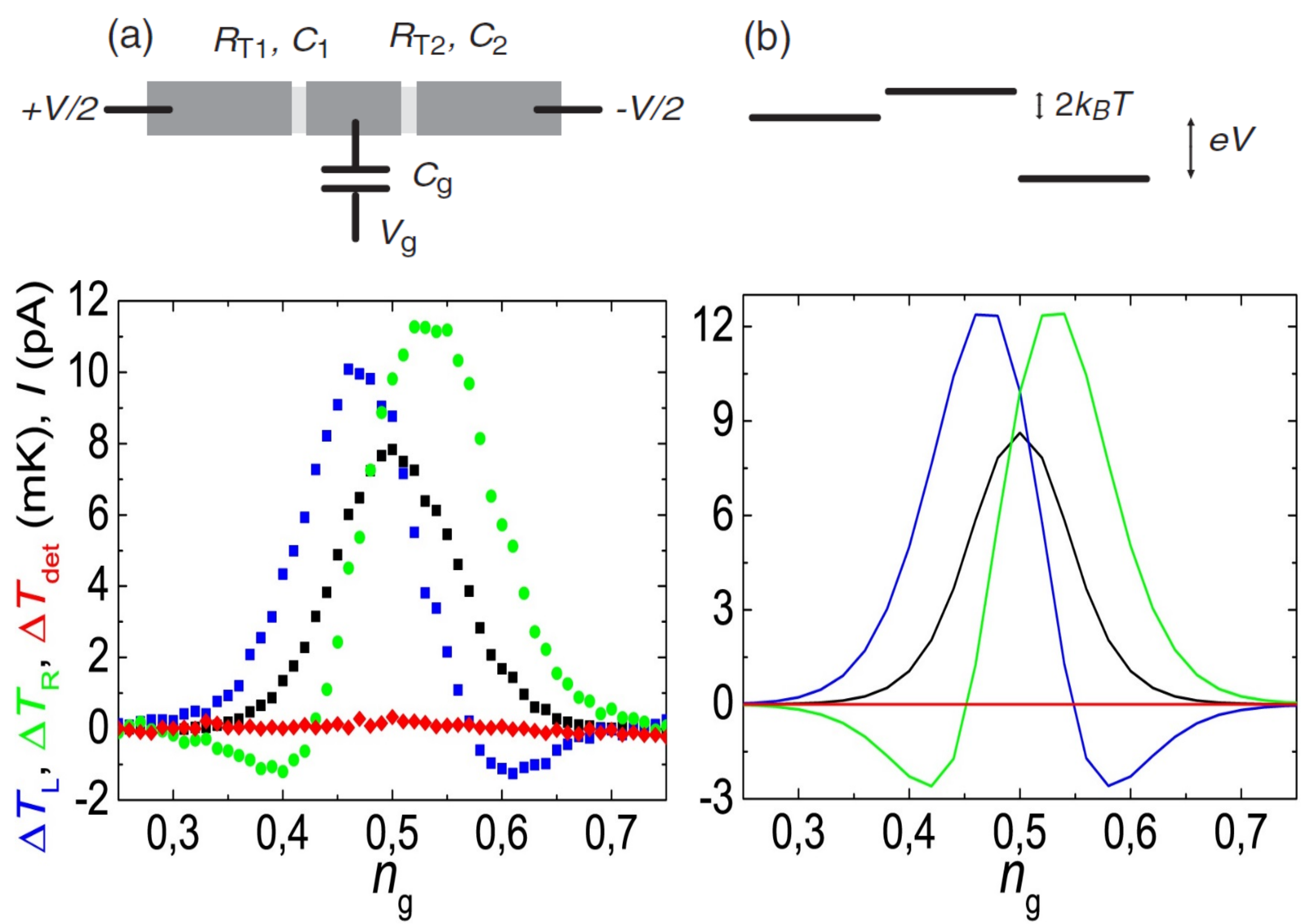




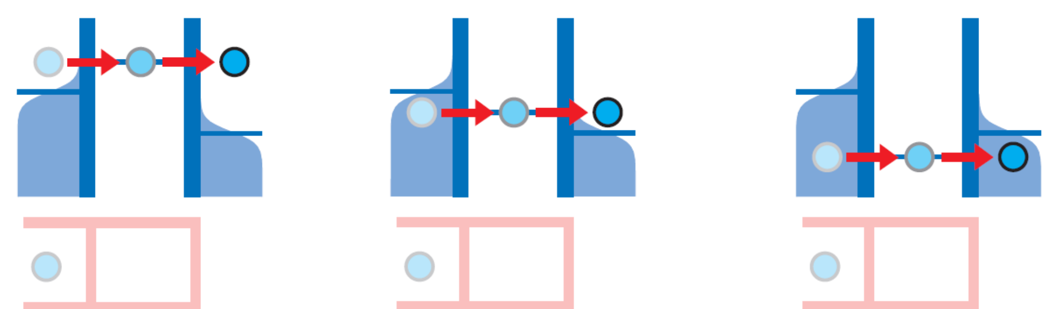
V = 20 μV, T = 50 mK

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

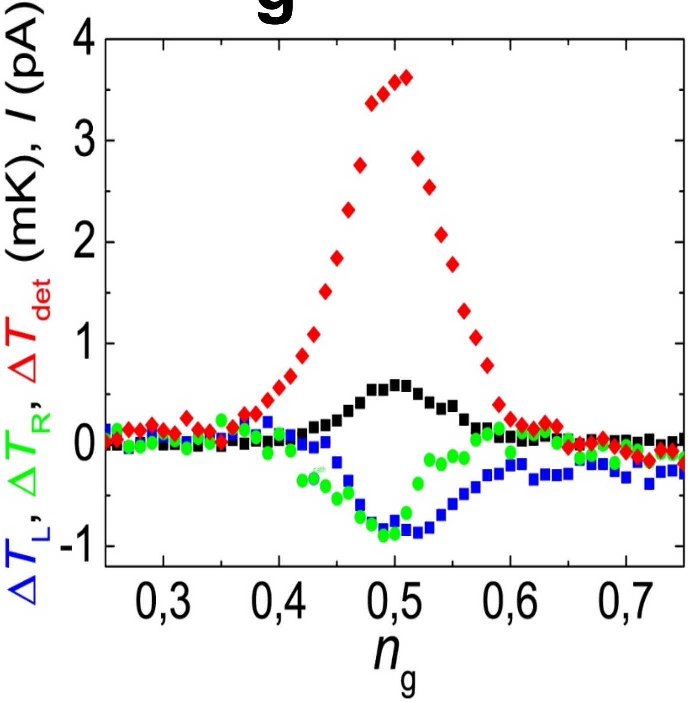


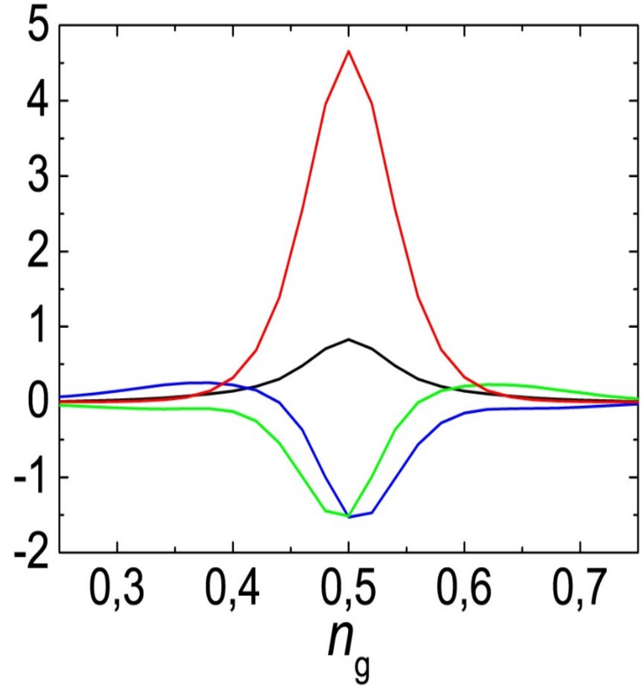


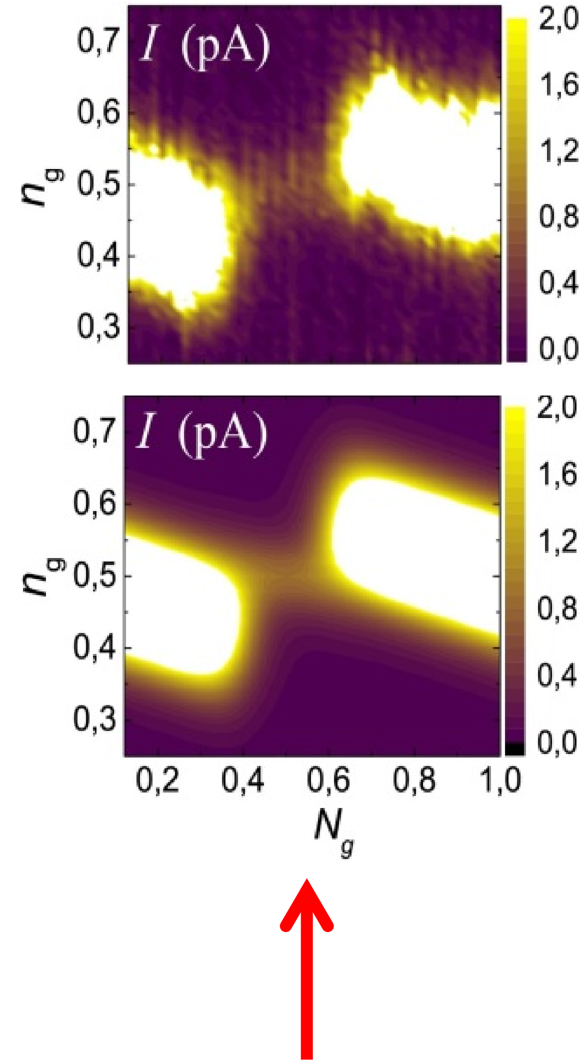
JP, J. V. Koski, and D. V. Averin, PRB **89**, 081309 (2014)
A. V. Feshchenko, J. V. Koski, and JP, PRB **90**, 201407(R) (2014)

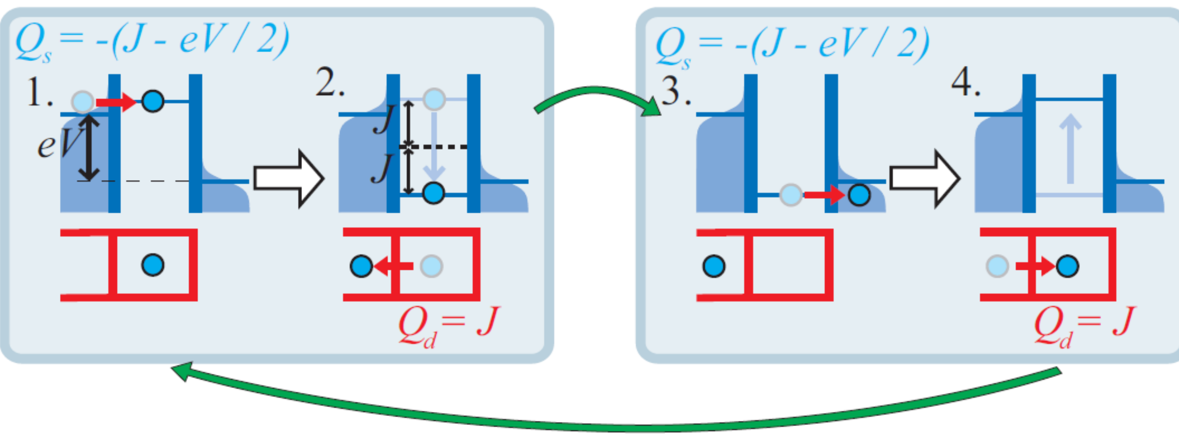


N_g = 0.5: feedback control (Demon)





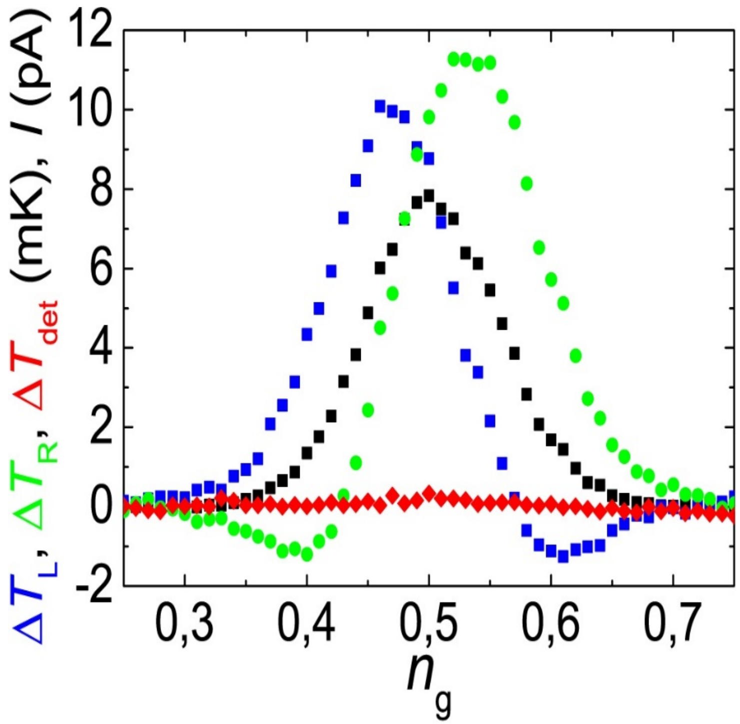




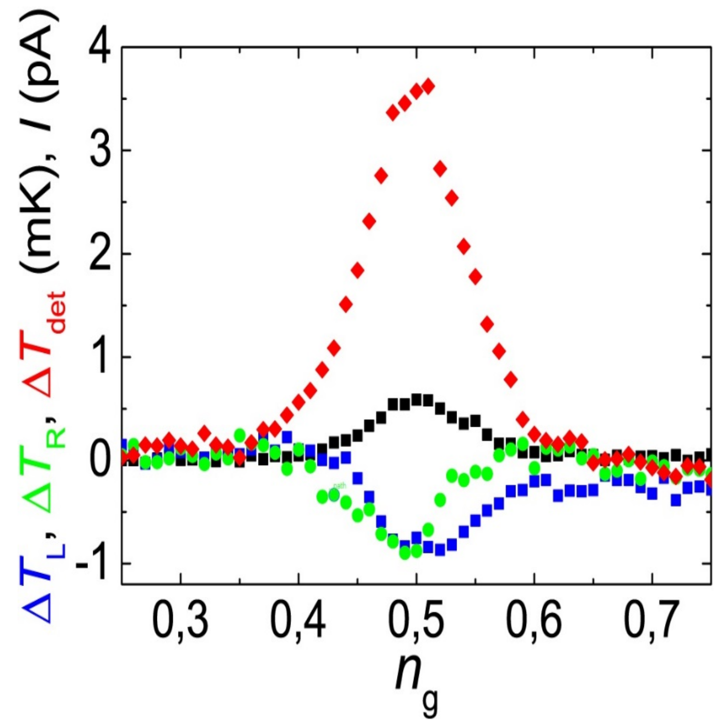
Both T_L and T_R drop: entropy of the System decreases;
T_{det} increases: entropy of the Demon increases

Summary of the autonomous demon experiment

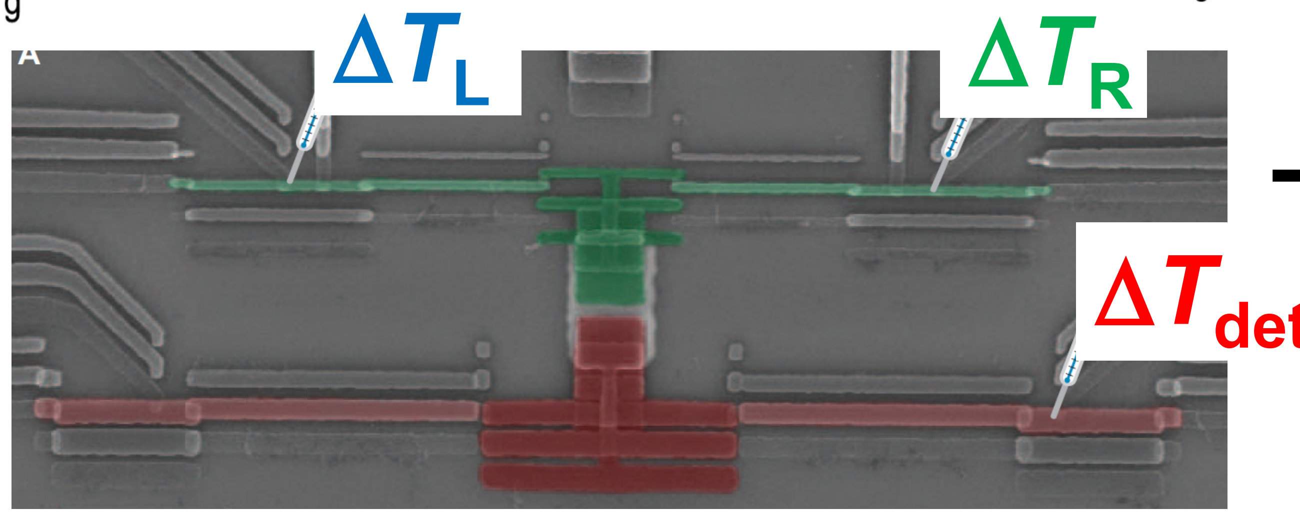
SET cooler



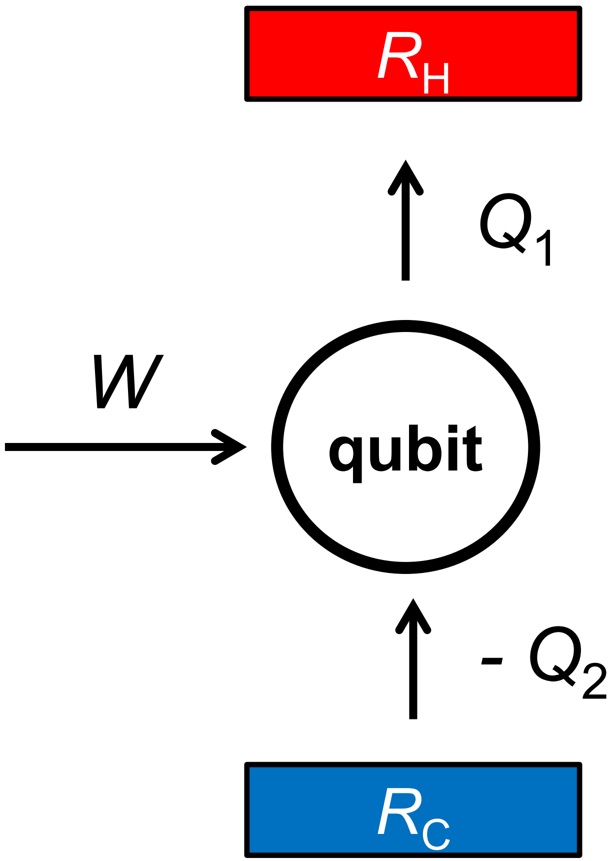
Demon

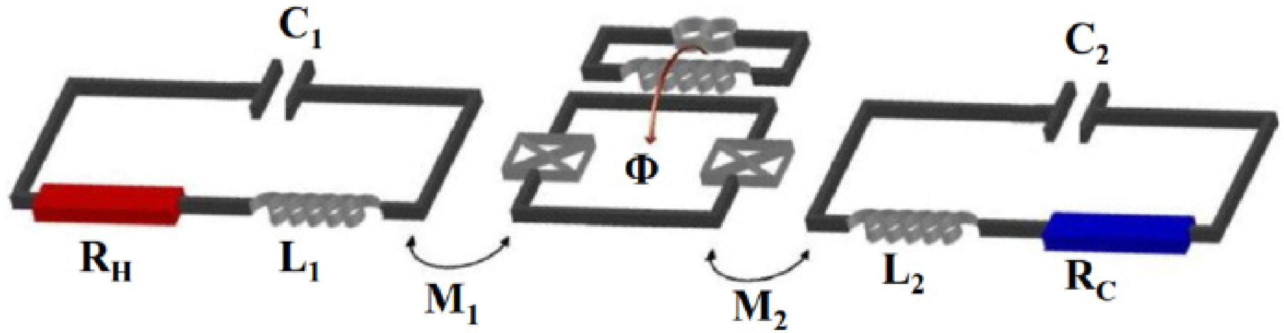


current I



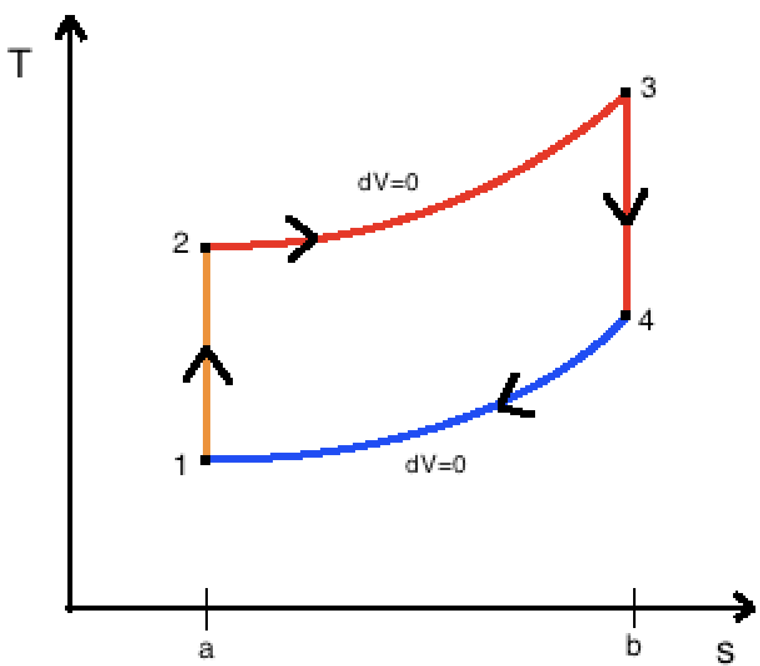
Heat engines and refrigerators in quantum circuits

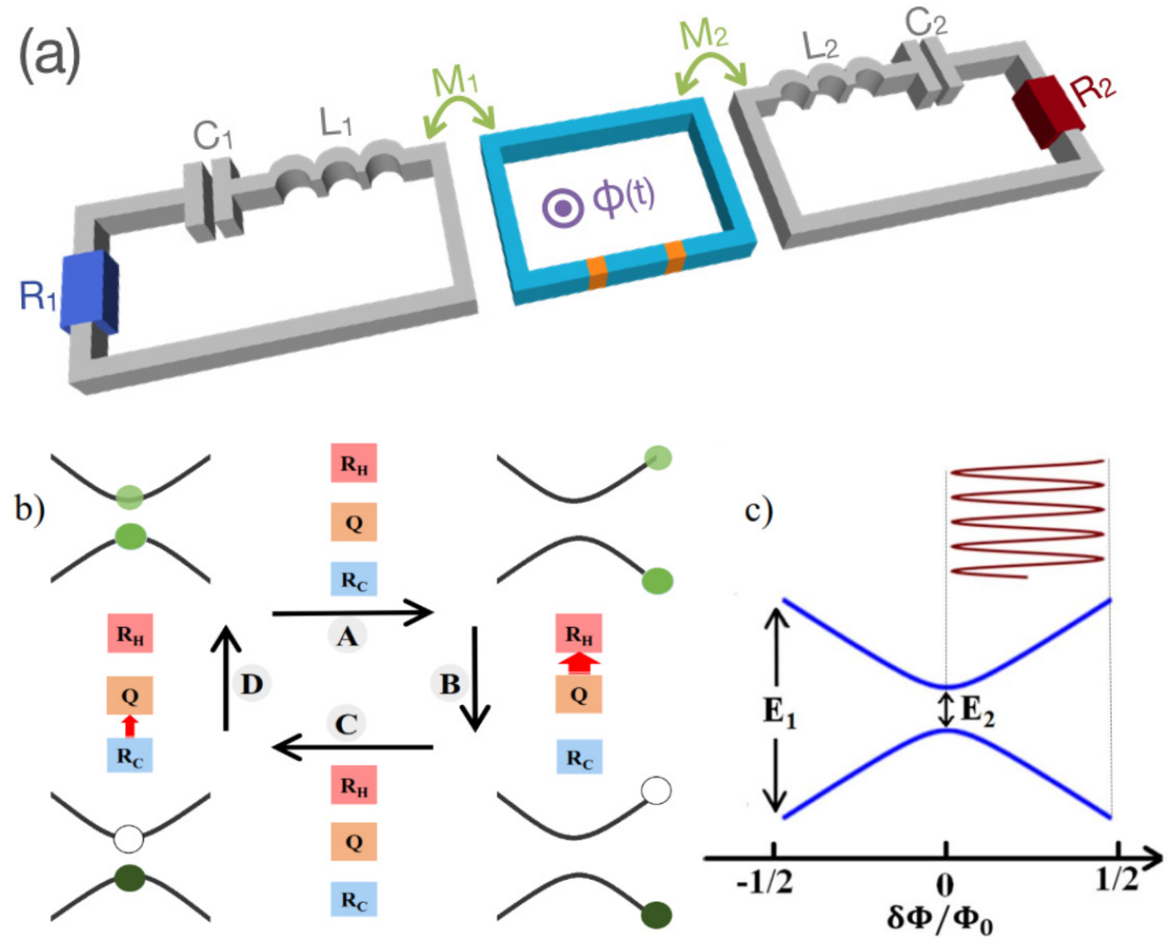




Quantum heat engine (quantum Otto refrigerator)

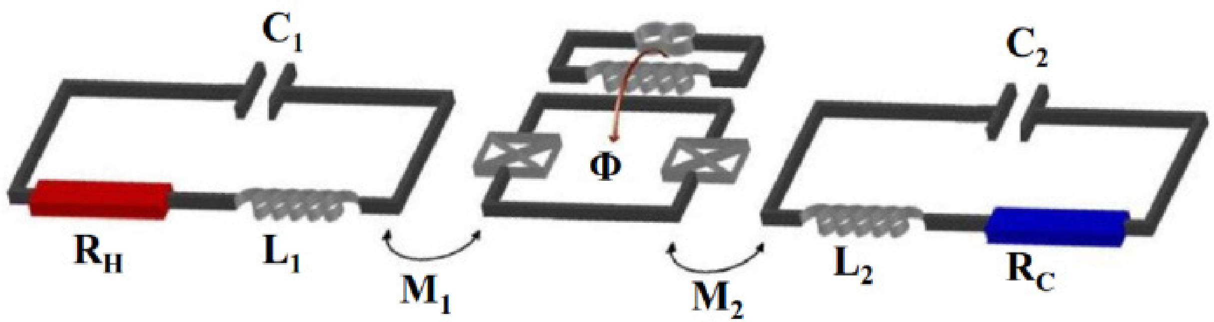
Otto cycle





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

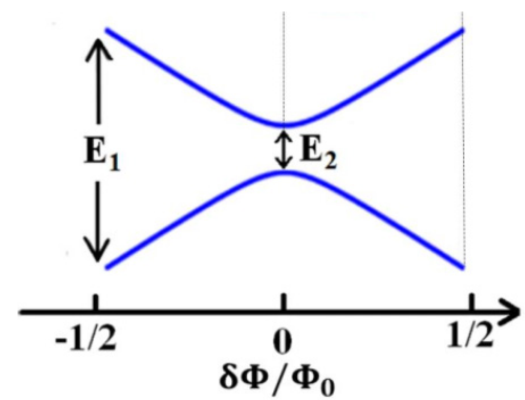
System and Hamiltonian



$$H = H_{R_{\rm H}} + H_{R_{\rm C}} + H_{\rm cH} + H_{\rm cC} + H_{\rm Q}$$

$$H_{\rm Q} = -E_0(\Delta\sigma_x + q\sigma_z)$$

$$\Delta = E_2/(2E_0)$$
$$q \equiv \delta\Phi/\Phi_0$$



$$\dot{\rho}_{gg} = -\frac{\Delta}{q^2+\Delta^2}\dot{q}\,\mathrm{Re}[\rho_{ge}e^{i\phi(t)}] - \Gamma_\Sigma\rho_{gg} + \Gamma_\downarrow$$

$$\dot{\rho}_{ge} = \frac{\Delta}{q^2+\Delta^2}\dot{q}(\rho_{gg} - 1/2)e^{-i\phi(t)} - \frac{1}{2}\Gamma_\Sigma\rho_{ge}$$

$$\Gamma_{\downarrow,\uparrow,j} = \frac{E_0^2 M_j^2}{\hbar^2\Phi_0^2}\frac{\Delta^2}{q^2+\Delta^2}S_{I,j}(\pm E/\hbar)$$

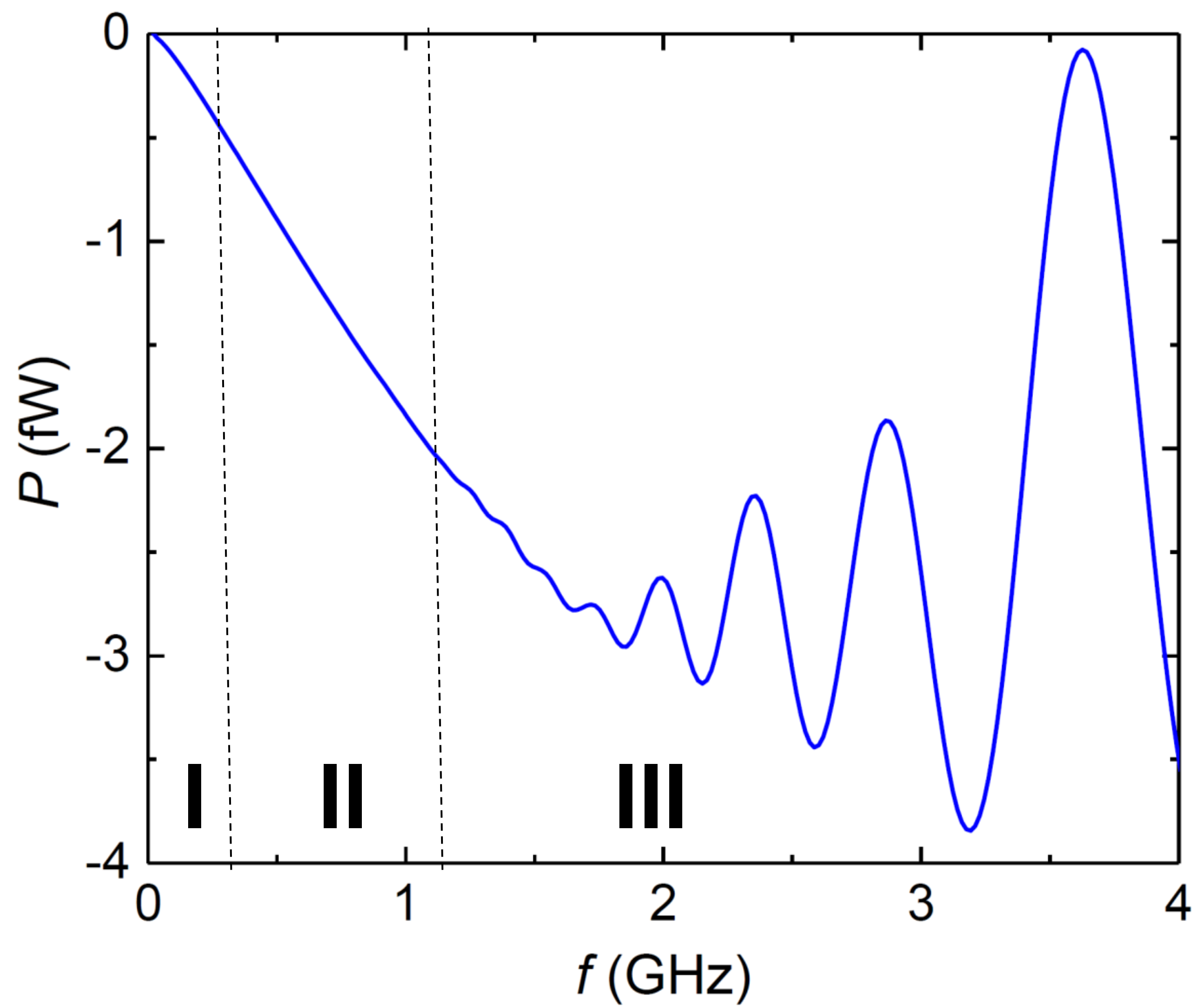
$$P_j = E(t)(\rho_{ee}\Gamma_{\downarrow,j} - \rho_{gg}\Gamma_{\uparrow,j})$$

Quantum heat engine (quantum Otto refrigerator)

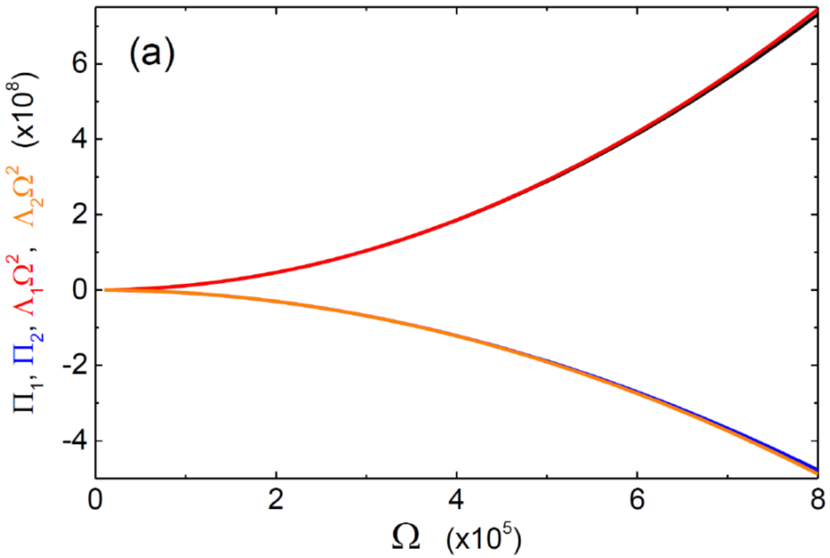
Different operation regimes:

I. Nearly adiabatic regime
II. Ideal Otto cycle
III. Coherent oscillations at high frequencies

B. Karimi and JP, Phys. Rev. B **94**, 184503 (2016).



I. Nearly adiabatic regime



Dimensionless power to reservoir j, $\Pi_j \equiv P_j/(E_0^2/\hbar)$ as a function of dimensionless frequency $\Omega = 2\pi\hbar f/E_0$

$$\Pi_j^{(2)} = \Lambda_j \Omega^2$$

1. Classical rate equation: $\dot{\rho}_{gg} = -\Gamma_\Sigma \rho_{gg} + \Gamma_\downarrow$

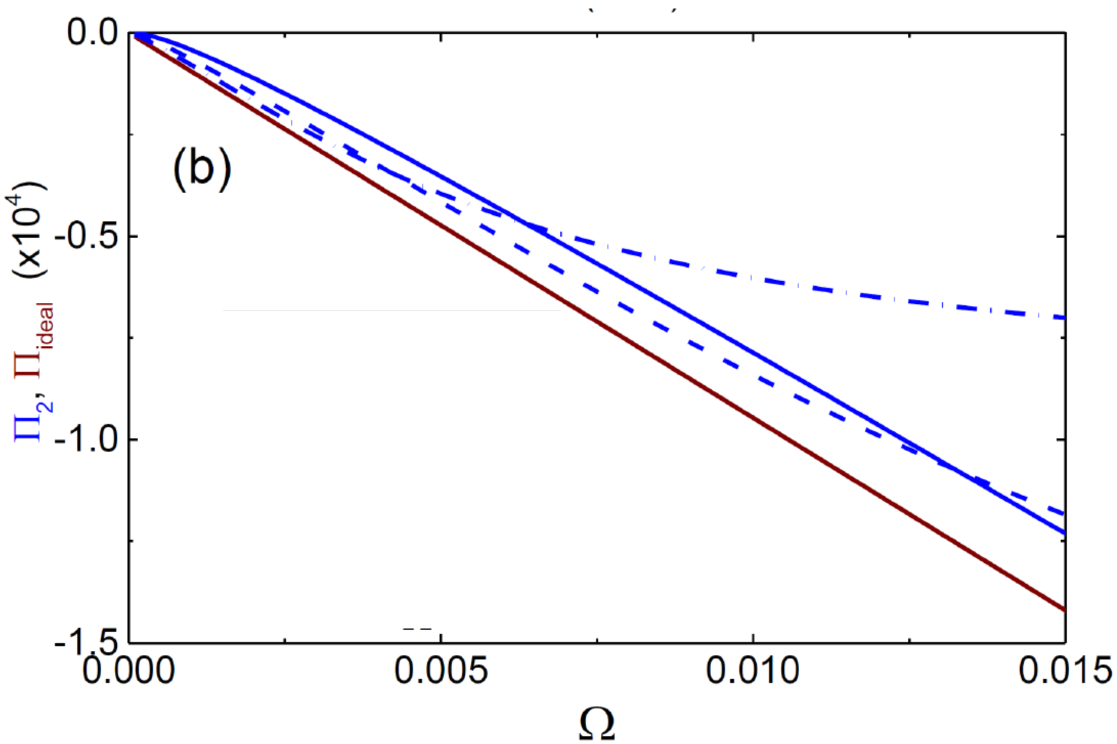
$$\Lambda_{j,\mathrm{CL}} = -\frac{1}{\pi}\int_0^{2\pi} du \sqrt{q^2+\Delta^2}\left(\frac{\frac{d^2\rho_{\mathrm{eq},gg}}{du^2}}{\xi_\Sigma^2} - \frac{\left(\frac{d\rho_{\mathrm{eq},gg}}{du}\right)\left(\frac{d\xi_\Sigma}{du}\right)}{\xi_\Sigma^3}\right)\xi_{\Sigma,j}$$

2. Full (quantum) master equation: $\Lambda_j = \Lambda_{j,\mathrm{CL}} + \delta\Lambda_{j,\mathrm{Q}}$

$$\delta\Lambda_{j,\mathrm{Q}} = \frac{1}{\pi}\int_0^{2\pi} du \frac{\Delta^2}{(q^2+\Delta^2)^{3/2}}\left(\frac{dq}{du}\right)^2 \frac{(\xi_\downarrow - \xi_\uparrow)\xi_{\Sigma,j}}{\xi_\Sigma[\xi_\Sigma^2 + 16(q^2+\Delta^2)]} \quad > 0$$

Quantum coherence degrades the performance of the refrigerator

II. Ideal Otto cycle



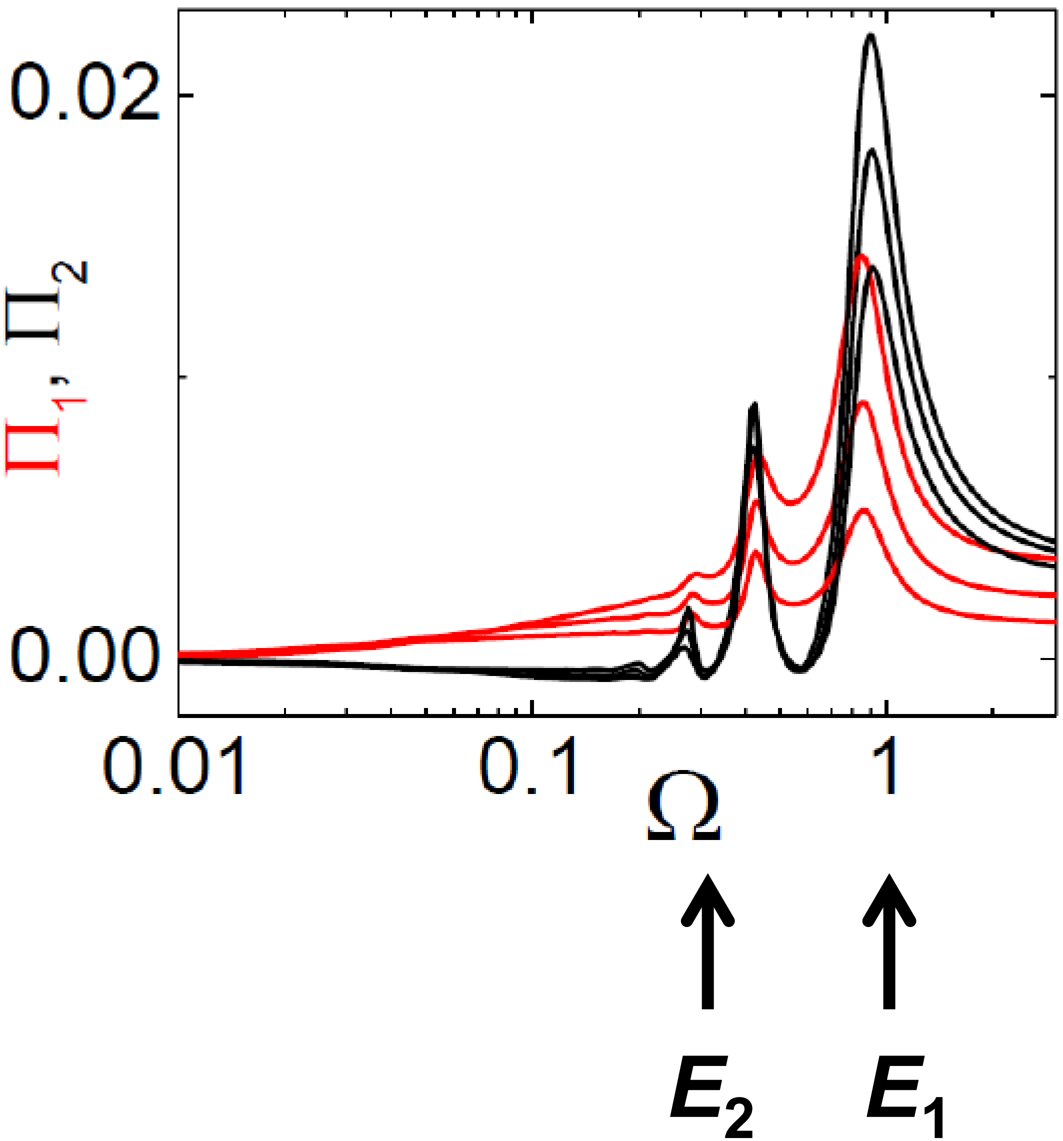
Ideal Otto cycle: brown line

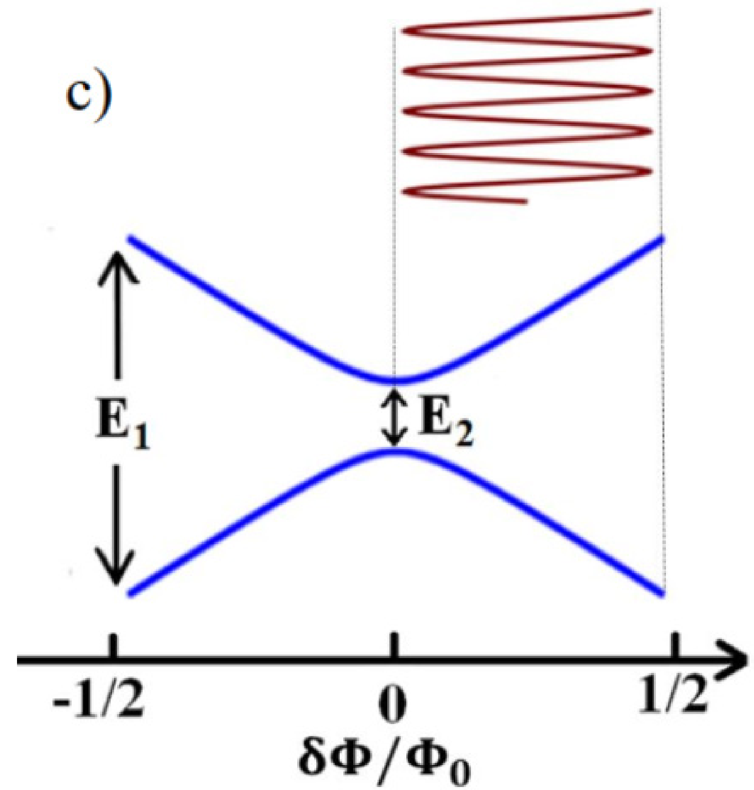
Different coupling to the baths: blue lines

$$P_1 = +\frac{\hbar\omega_1}{2}[\tanh(\frac{\beta_1\hbar\omega_1}{2}) - \tanh(\frac{\beta_2\hbar\omega_2}{2})]f,$$

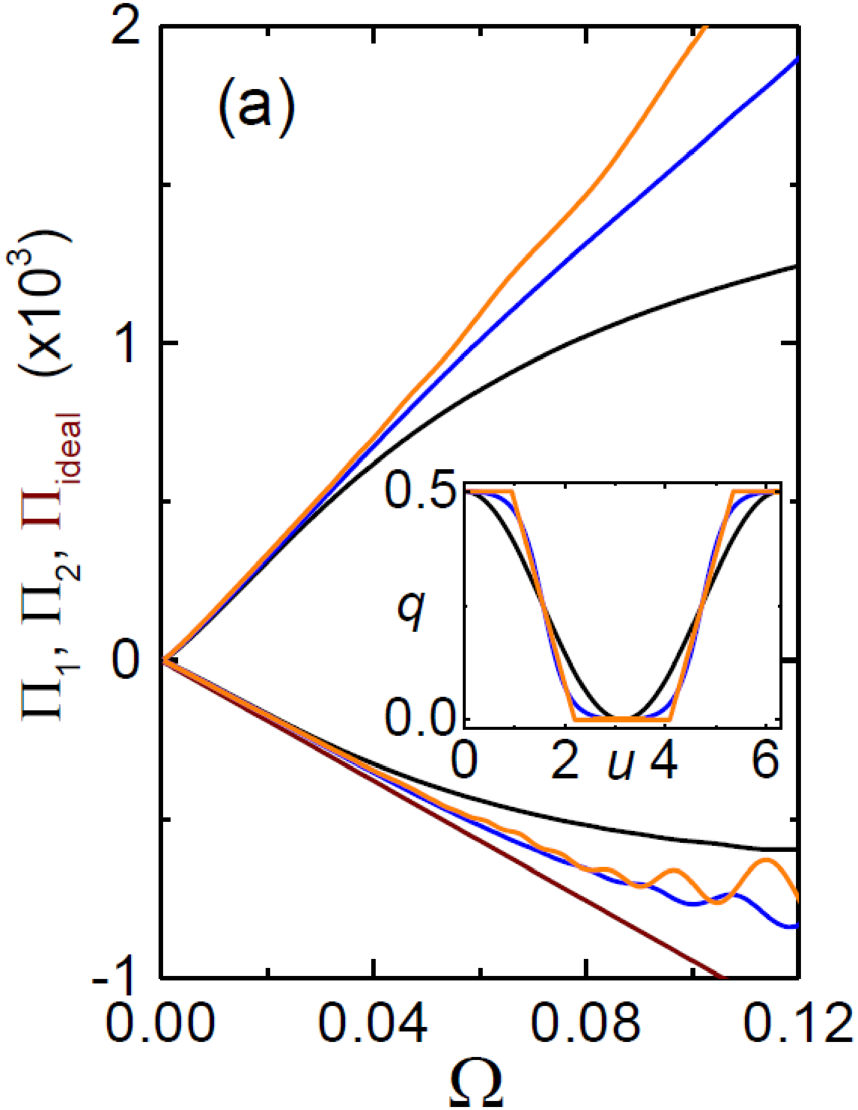
$$P_2 = -\frac{\hbar\omega_2}{2}[\tanh(\frac{\beta_1\hbar\omega_1}{2}) - \tanh(\frac{\beta_2\hbar\omega_2}{2})]f.$$

III. Coherent oscillations at high frequencies





Different waveforms



Sinusoidal (black)

Trapezoidal (orange)

and

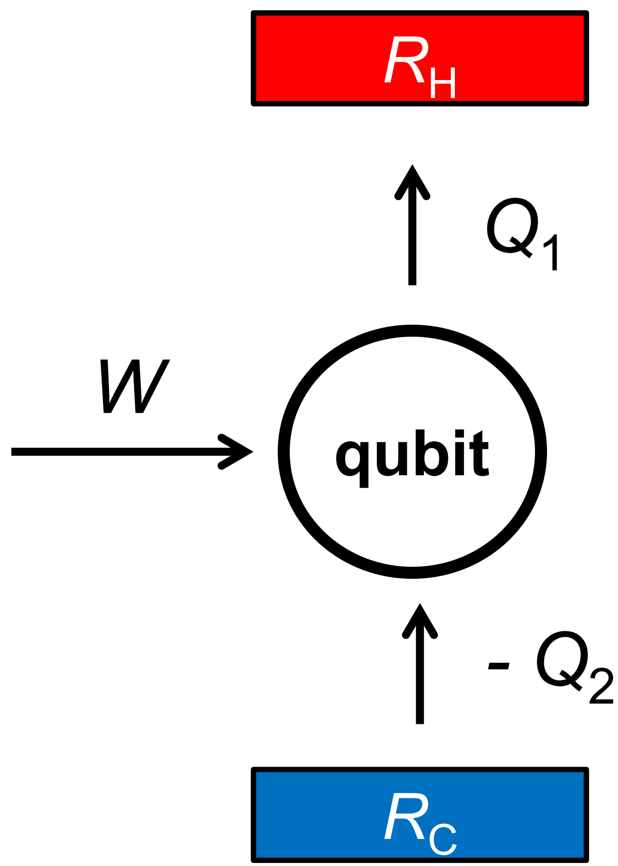
”Truncated trapezoidal” waveforms (blue)

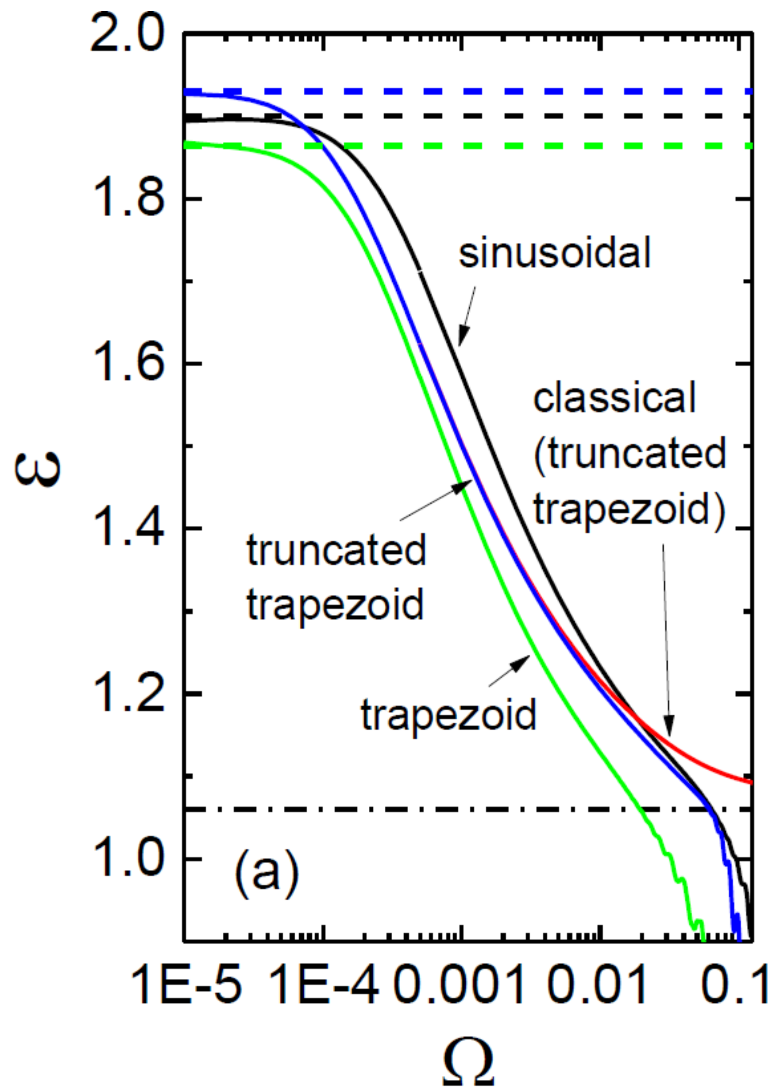
$$q(u) = \frac{1}{4}[1 + \tanh(a \cos u)/\tanh a]$$

Efficiency

$$\epsilon = -Q_2/W = -Q_2/(Q_1 + Q_2)$$

$$\epsilon_C = 1/(T_H/T_C - 1)$$



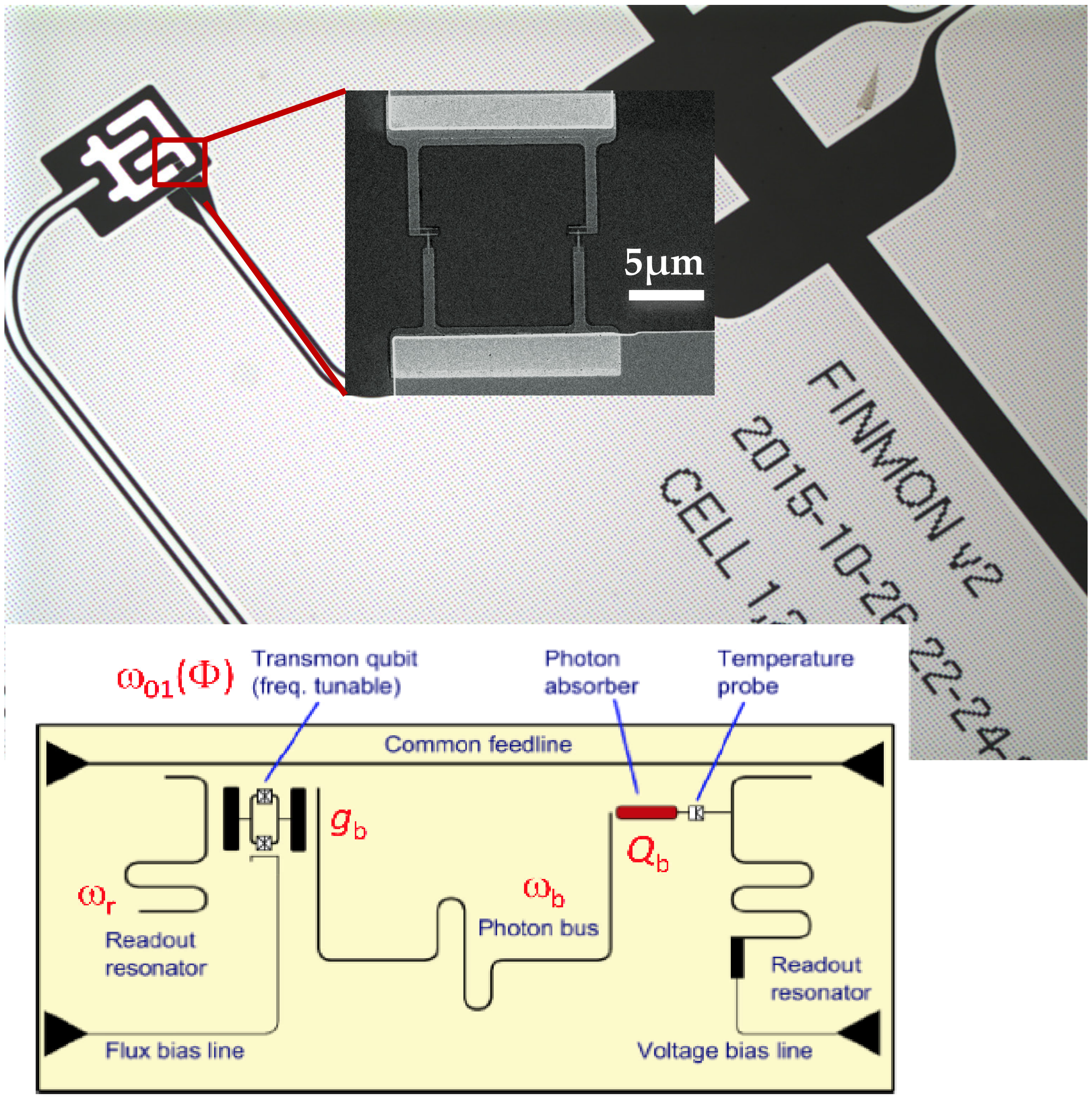


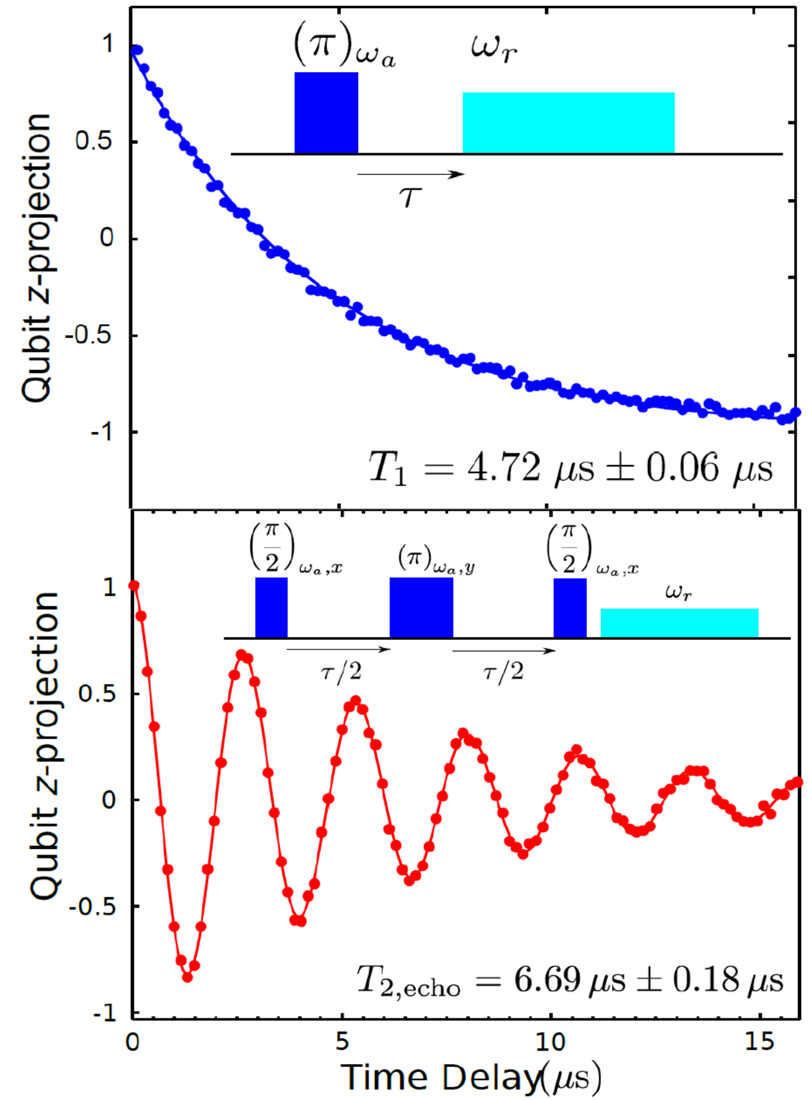
$$\epsilon_p = \frac{1}{\Lambda_1/|\Lambda_2| - 1}$$

$$\epsilon_{\text{ideal}} = \frac{1}{\omega_1/\omega_2 - 1}$$

Superconducting qubits

J. Senior, R. George, O.-P- Saira et al., 2016





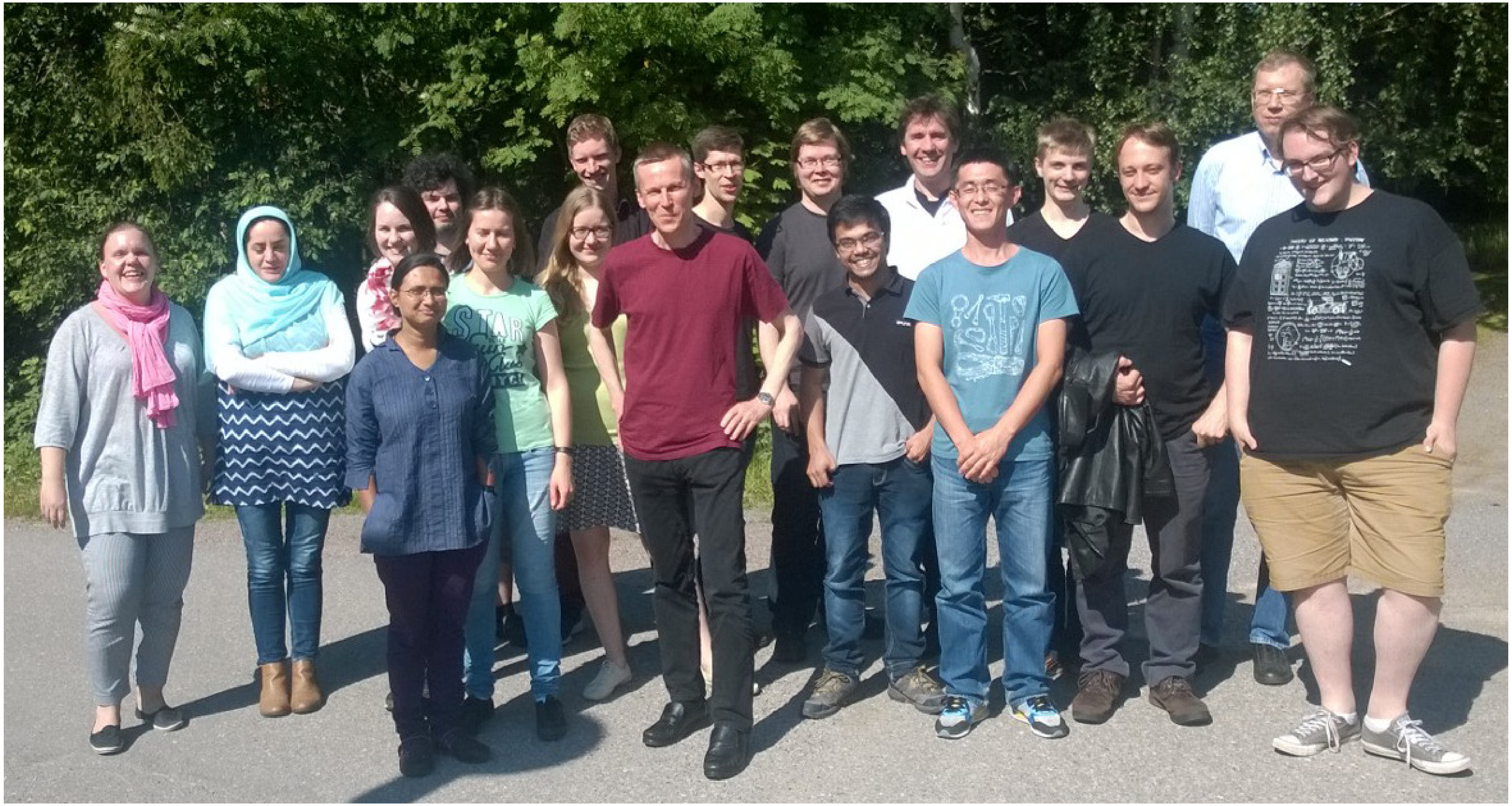
Summary

Two different types of Maxwell’s demons demonstrated experimentally

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

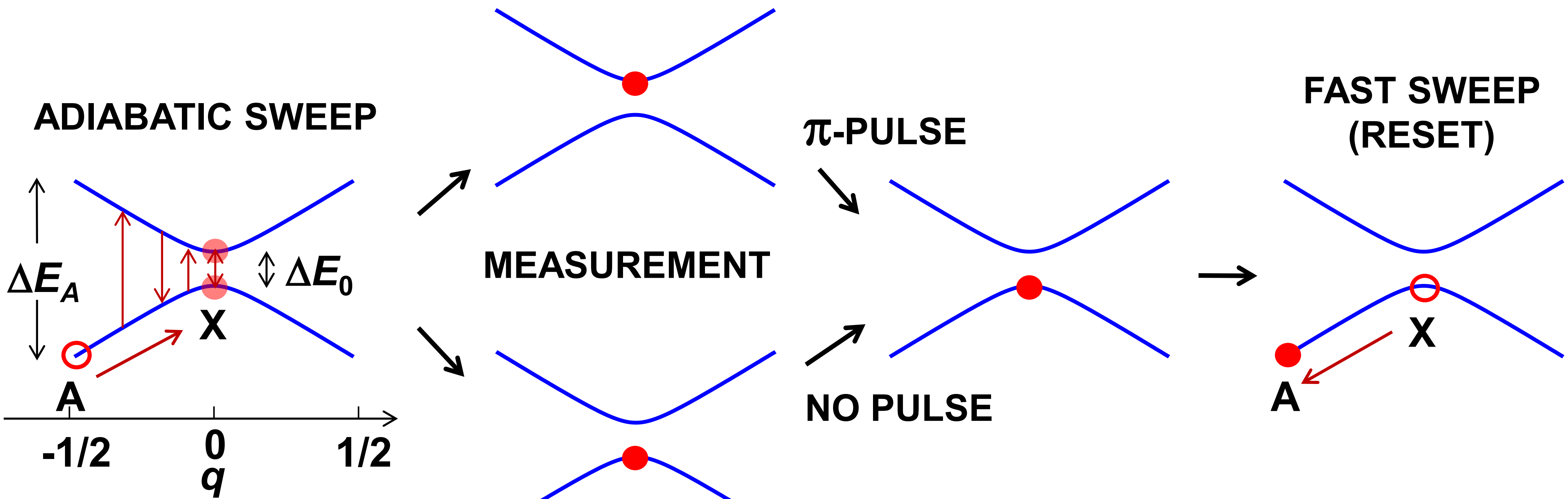
Autonomous Maxwell’s demon – an ”all-in-one” device: effect of internal information processing observed as heat dissipation in the detector and as cooling of the system

Quantum heat engines and refrigerators



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

Maxwell's Demon based on a Single Qubit



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

J. P. Pekola, D. S. Golubev, and D. V. Averin, PRB 93, 024501 (2016)