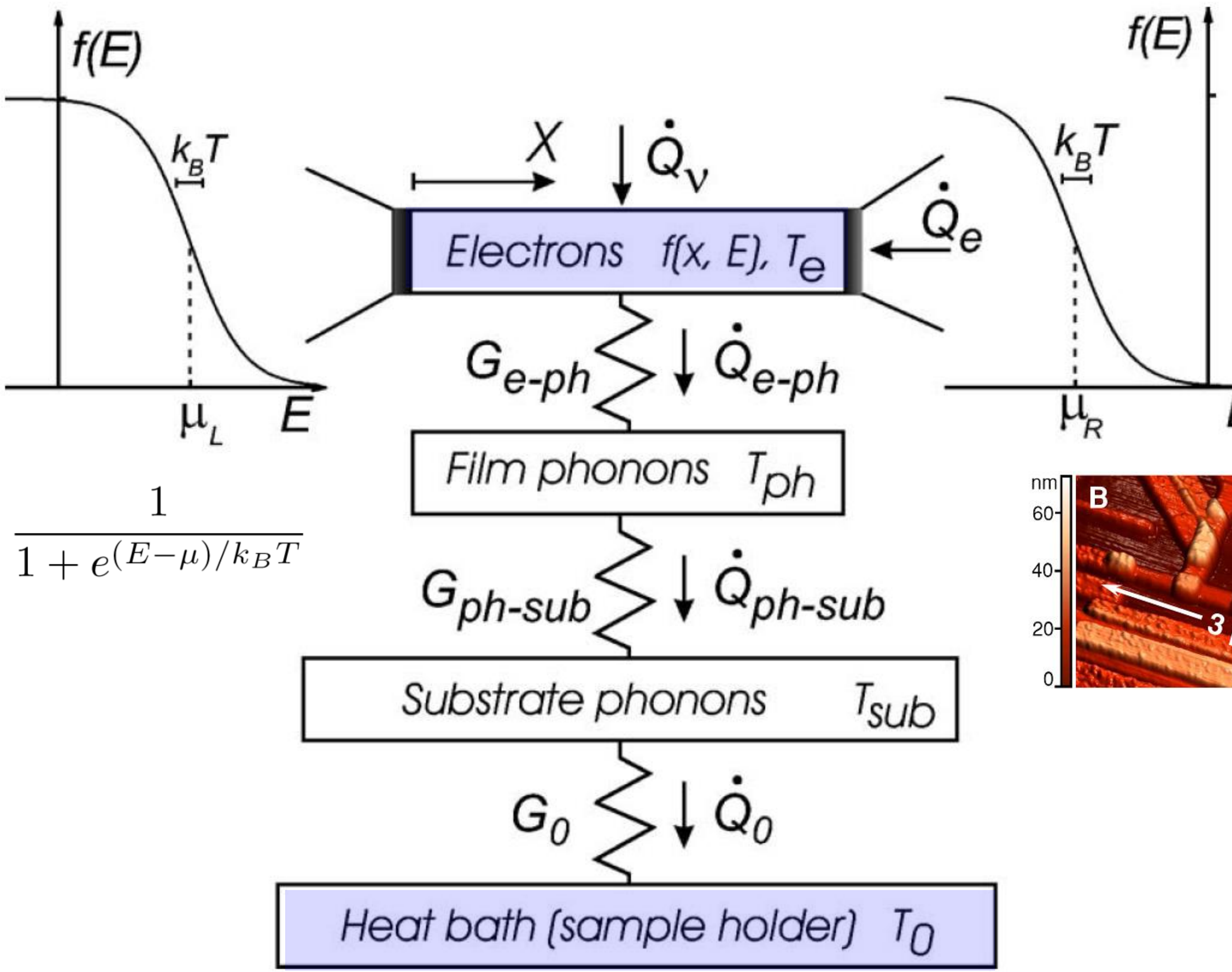
Towards quantum thermodynamics in electric circuits

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

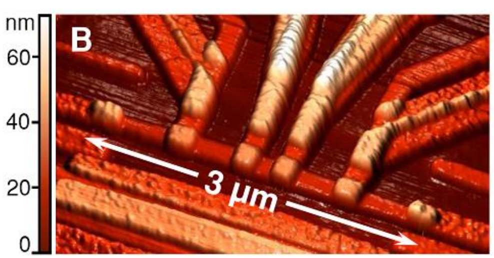
1. **Dissipation and thermodynamics in electric circuits**
2. **Experiments on fluctuations and Maxwell's Demon**
3. **Quantum thermodynamics**

Low temperature laboratory

Generic thermal model for electrons



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



The energy distribution of electrons in a small metal conductor

The distribution is determined by energy relaxation:

Equilibrium with the temperature of the ”bath”

Quasi-equilibrium within the electron system with temperature different from that of the ”bath”

Non-equilibrium – no well defined temperature

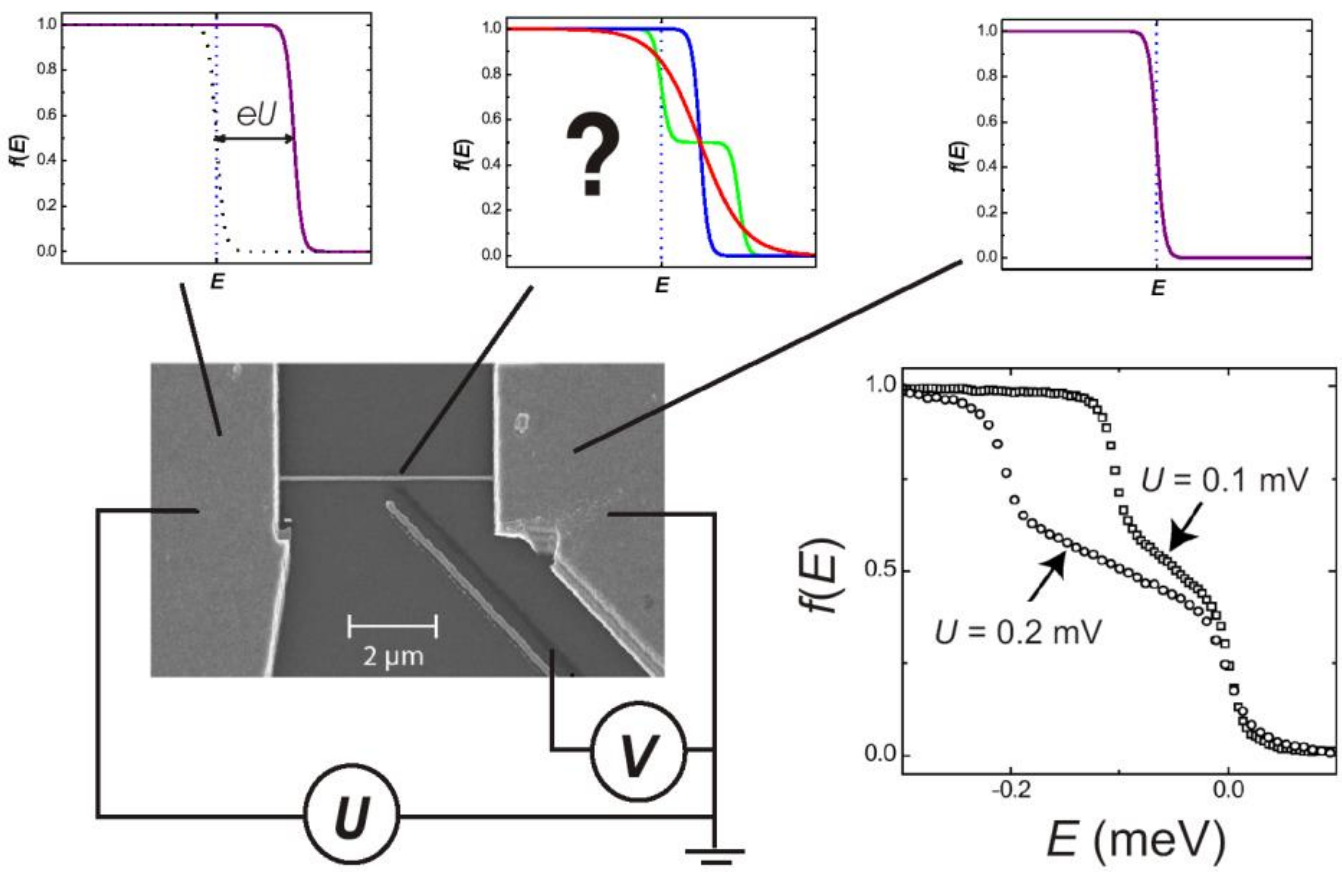
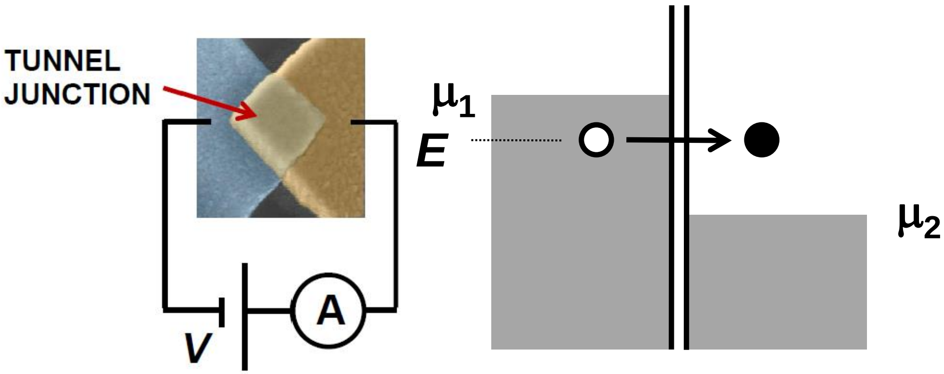


Illustration: diffusive normal metal wire

H. Pothier et al. 1997

Dissipation in transport through a barrier - tunneling



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

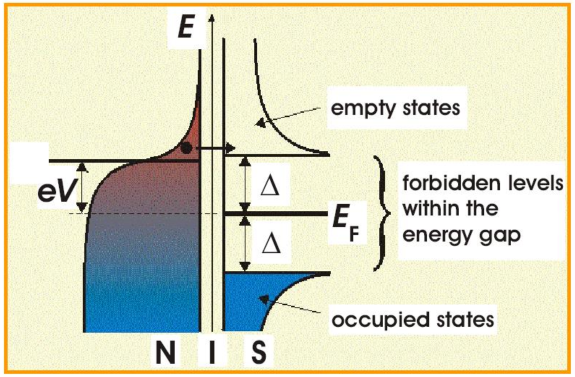
$$\Delta Q = (\mu_1 - E) + (E - \mu_2) = \mu_1 - \mu_2 = eV$$

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

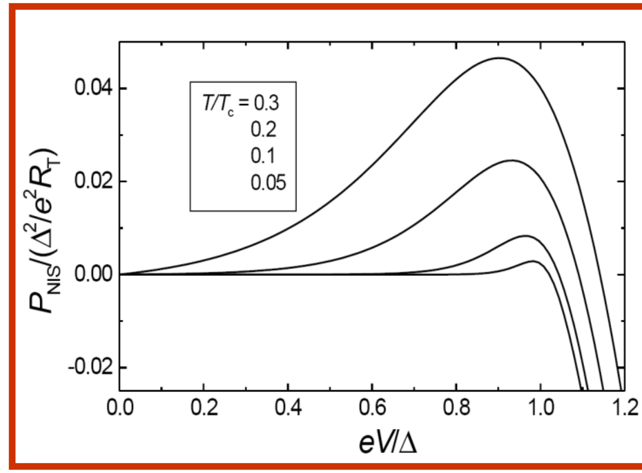
For average current *I* through the junction, the total average power dissipated is naturally

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

Electronic coolers



Cooling power of a NIS junction:



$$P_{\rm NIS} = \frac{1}{e^2 R_T}\int dE(E - eV)n_S(E)[f_N(E - eV) - f_S(E)]$$

Optimum cooling power is reached at $V \cong \Delta/e$:

$$P_{\rm NIS} \approx 0.6\frac{\Delta^2}{e^2 R_T}(\frac{k_B T_N}{\Delta})^{3/2}$$

Efficiency (coefficient of performance) of a NIS junction cooler:

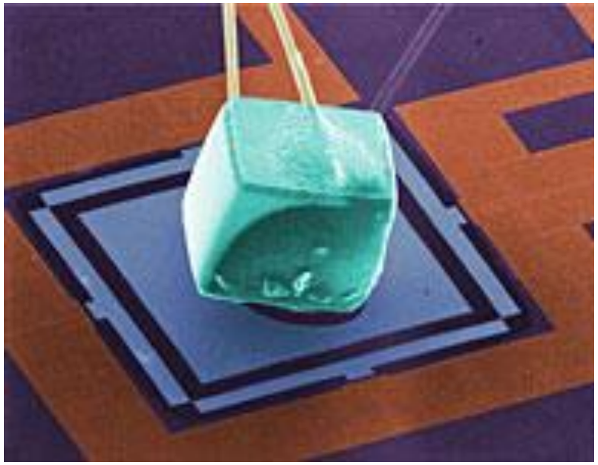
$$\eta \simeq k_B T/\Delta$$

Experimental status of electronic refrigeration

Nahum et al. 1994 *Demonstration of NIS cooling*
Leivo et al. 1996 *Cooling electrons 300 mK -> 100 mK by SINIS*
Manninen et al. 1999 *Cooling by SIS'IS*
Manninen et al. 1997, Luukanen et al. 2000 *Lattice refrigeration by SINIS*
S*avin et al. 2001 *S – Schottky – Semiconductor – Schottky – S cooling
Clark et al. 2005, Miller et al. 2008 *x-ray detector refrigerated by SINIS*
Prance et al. 2009 *Electronic refrigeration of a 2DEG*
Kafanov et al. 2009 *RF-refrigeration*
Quaranta et al 2011 *Cooling from 1 K to 0.4 K*
Nguyen et al 2013 *Cooling power up to 1 nW*
Nguyen et al 2014 *Cooling down to 30 mK*

For reviews, see Rev. Mod. Phys. 78, 217 (2006); Reports on Progress in Physics 75, 046501 (2012).

Refrigeration of a "bulk" object



A. Clark et al., Appl. Phys. Lett. **86**, 173508 (2005).

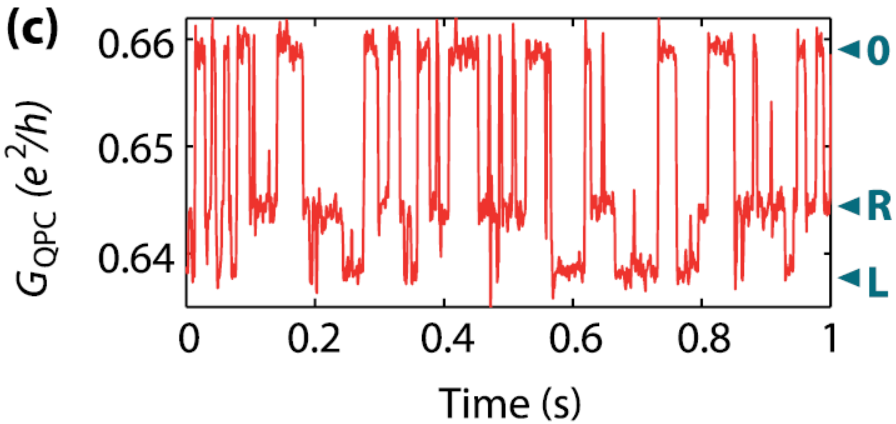
Fluctuation theorem

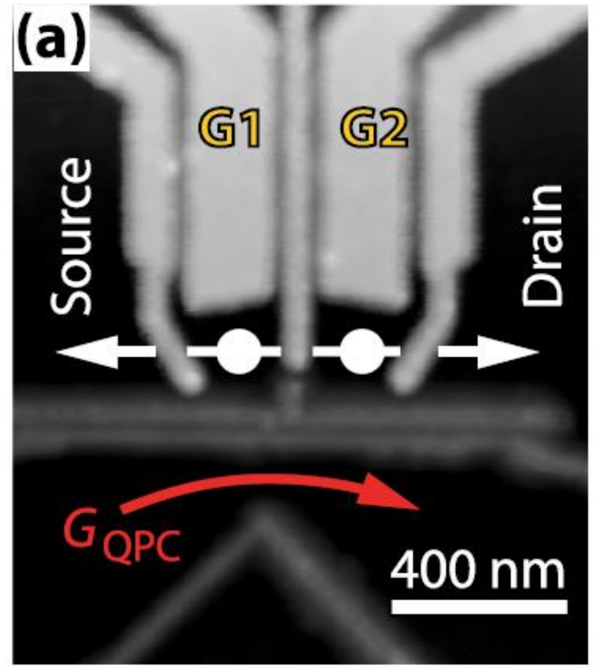
$$\frac{P_\tau(\Delta S)}{P_\tau(-\Delta S)} = e^{\Delta S/k_\mathrm{B}}$$

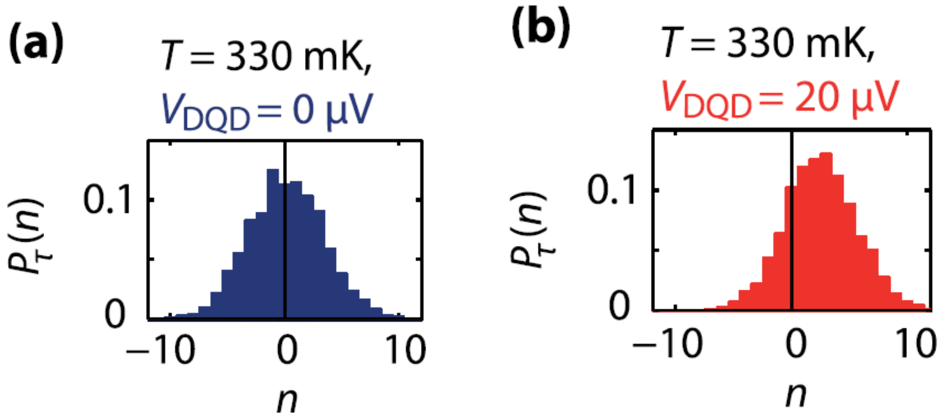
U. Seifert, Rep. Prog. Phys. **75**, 126001 (2012)

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

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



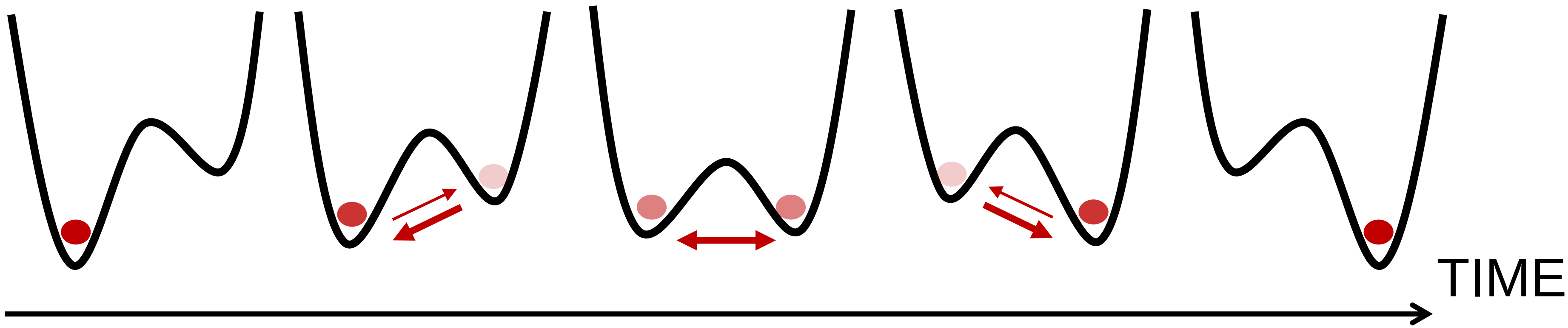




$$\frac{P_\tau(n)}{P_\tau(-n)} = e^{neV_\mathrm{DQD}/k_\mathrm{B}T}$$

Driven systems

Work and dissipation in a driven process?



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

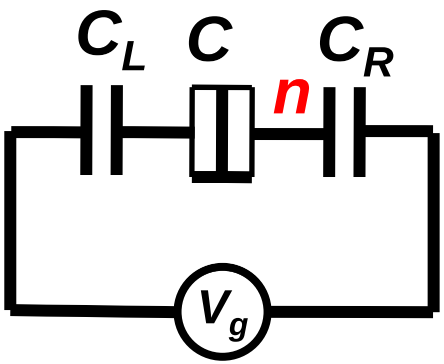
C. Jarzynski 1997 $\langle e^{-\beta W_d} \rangle = 1 \quad \Rightarrow \quad \langle W \rangle \geq \Delta F$

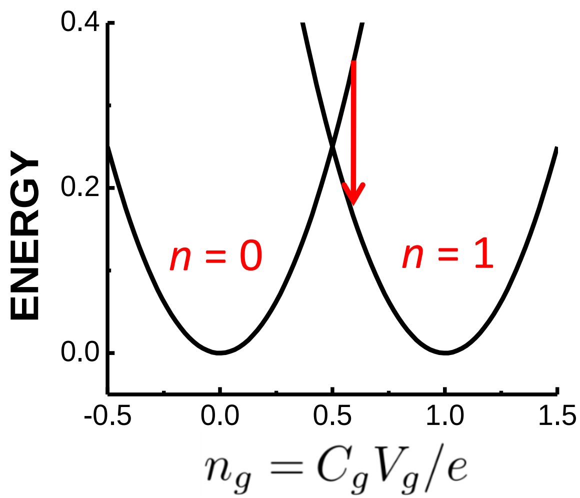
2nd law of thermodynamics

G. Crooks 1999 $p_F(W_d)/p_R(-W_d) = e^{\beta W_d}$

These relations are valid for systems with one bath at inverse temperature β, also far from equilibrium

Dissipation in single-electron transitions





$$H = E_C (n - n_g)^2$$

Heat generated in a tunneling event *i*:

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

Total heat generated in a process:

$$Q = \sum_i Q_i$$

Work in a process:

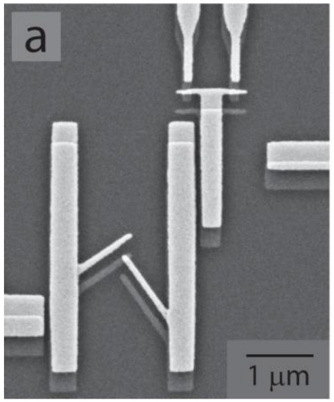
$$W = Q + \Delta U$$

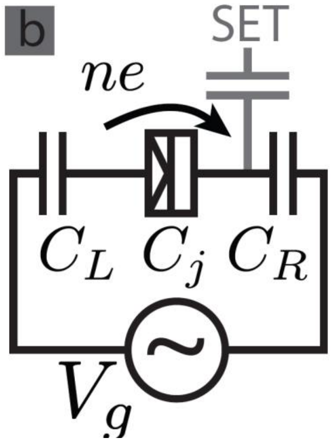
Change in internal (charging) energy

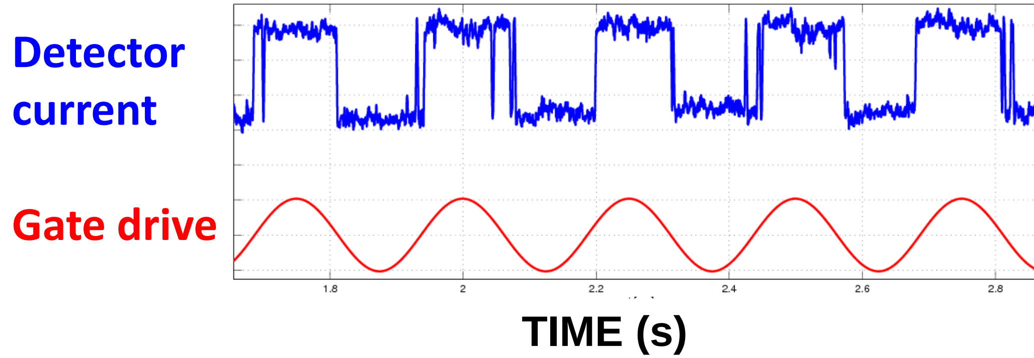
D. Averin and JP, EPL 96, 67004 (2011)

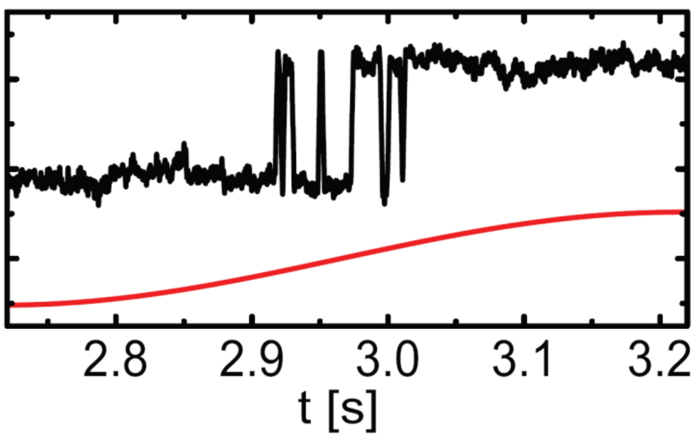
Experiment on a single-electron box

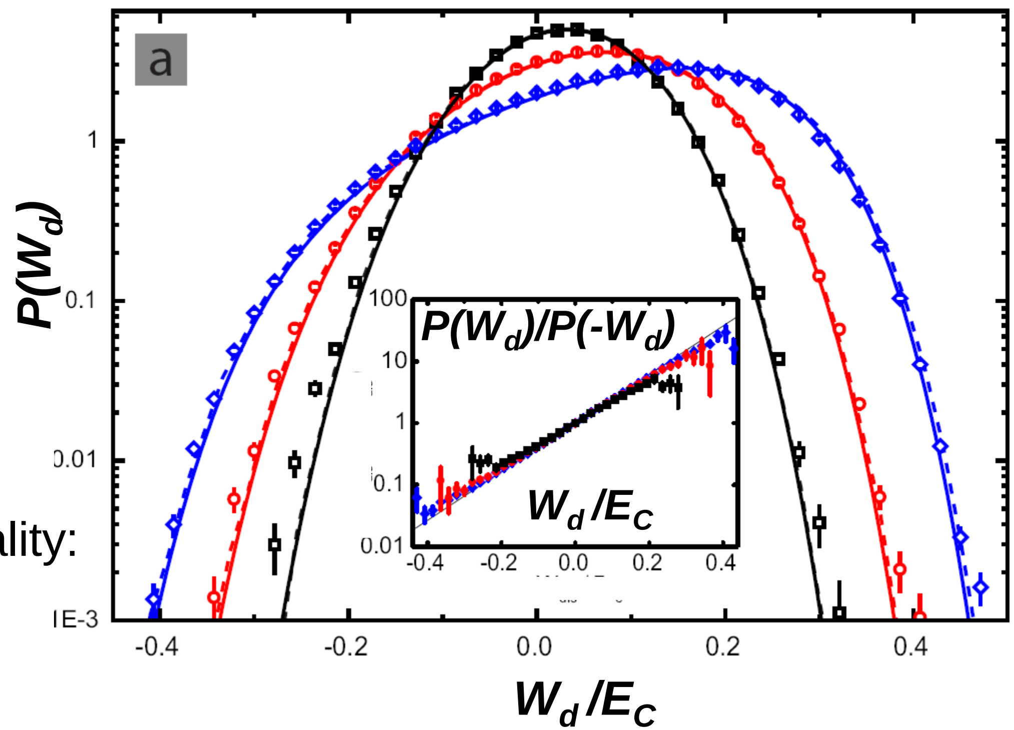
O.-P. Saira et al., PRL 109, 180601 (2012); J.V. Koski et al., Nature Physics 9, 644 (2013).







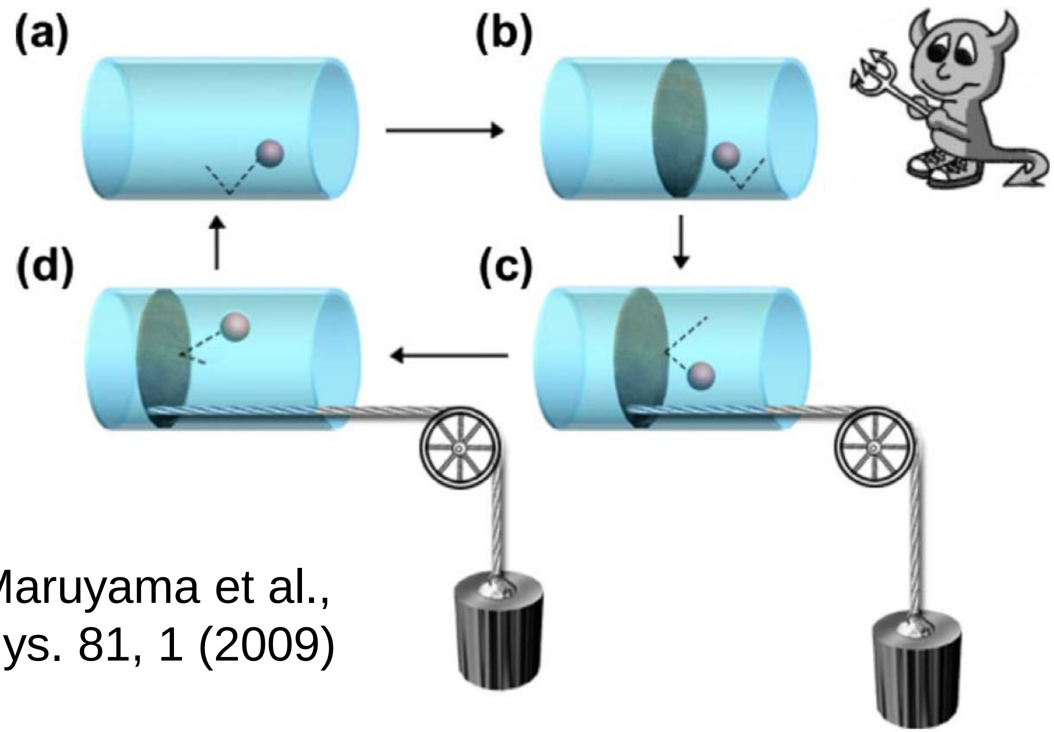




The distributions satisfy Jarzynski equality:

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

Maxwell's demon



Szilard's engine
(L. Szilard 1929)

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

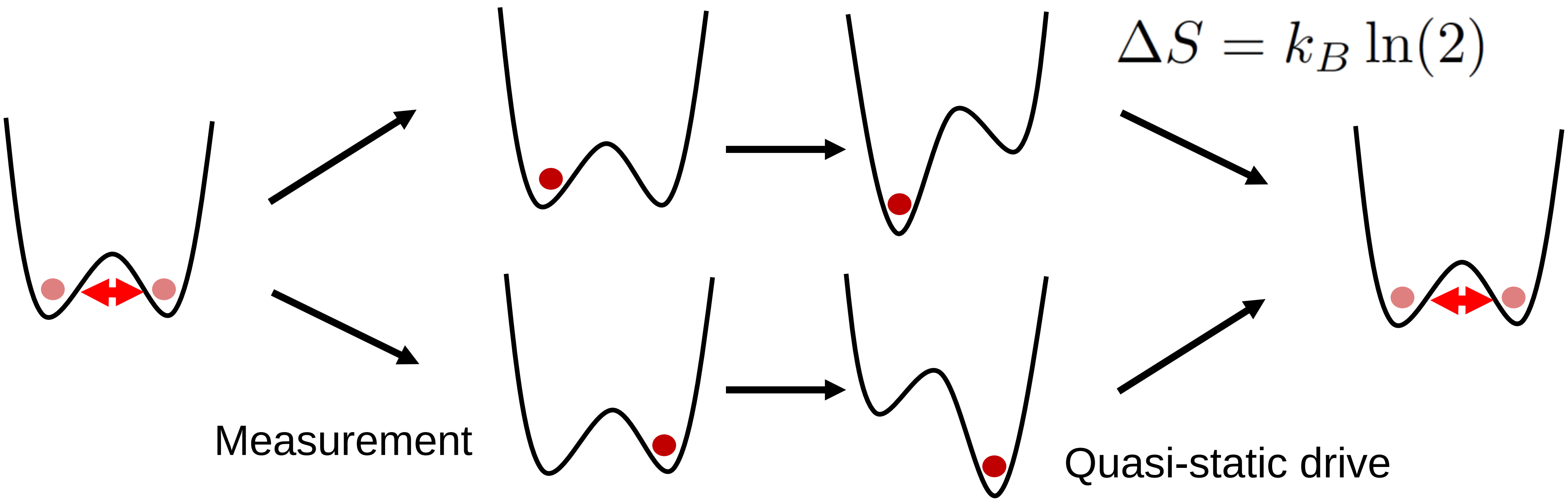
Isothermal expansion of the "single-molecule gas" does work against the load

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

Maxwell's demon for single electrons

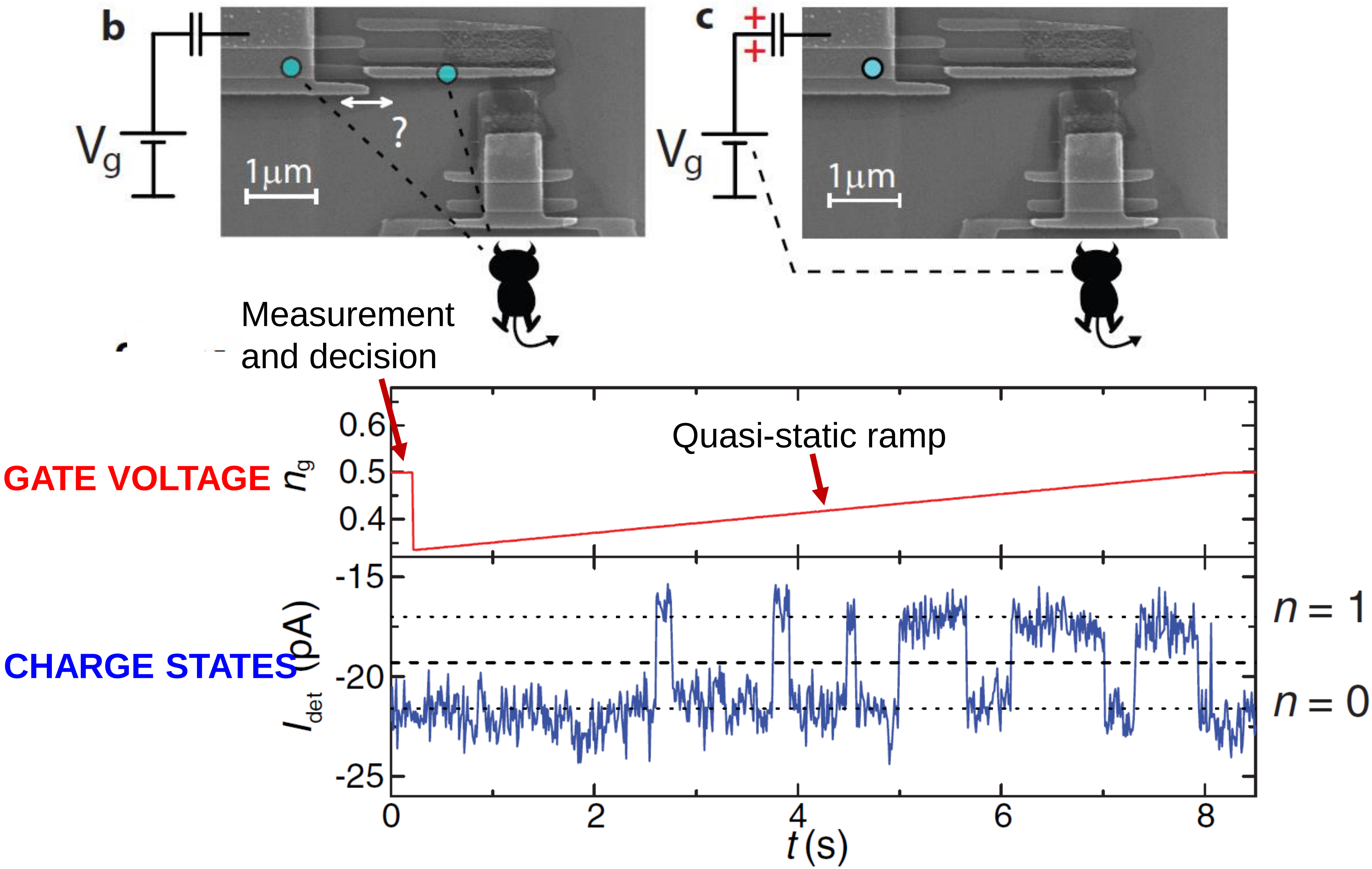
J. V. Koski et al., PNAS 111, 13786 (2014); PRL 113, 030601 (2014).

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

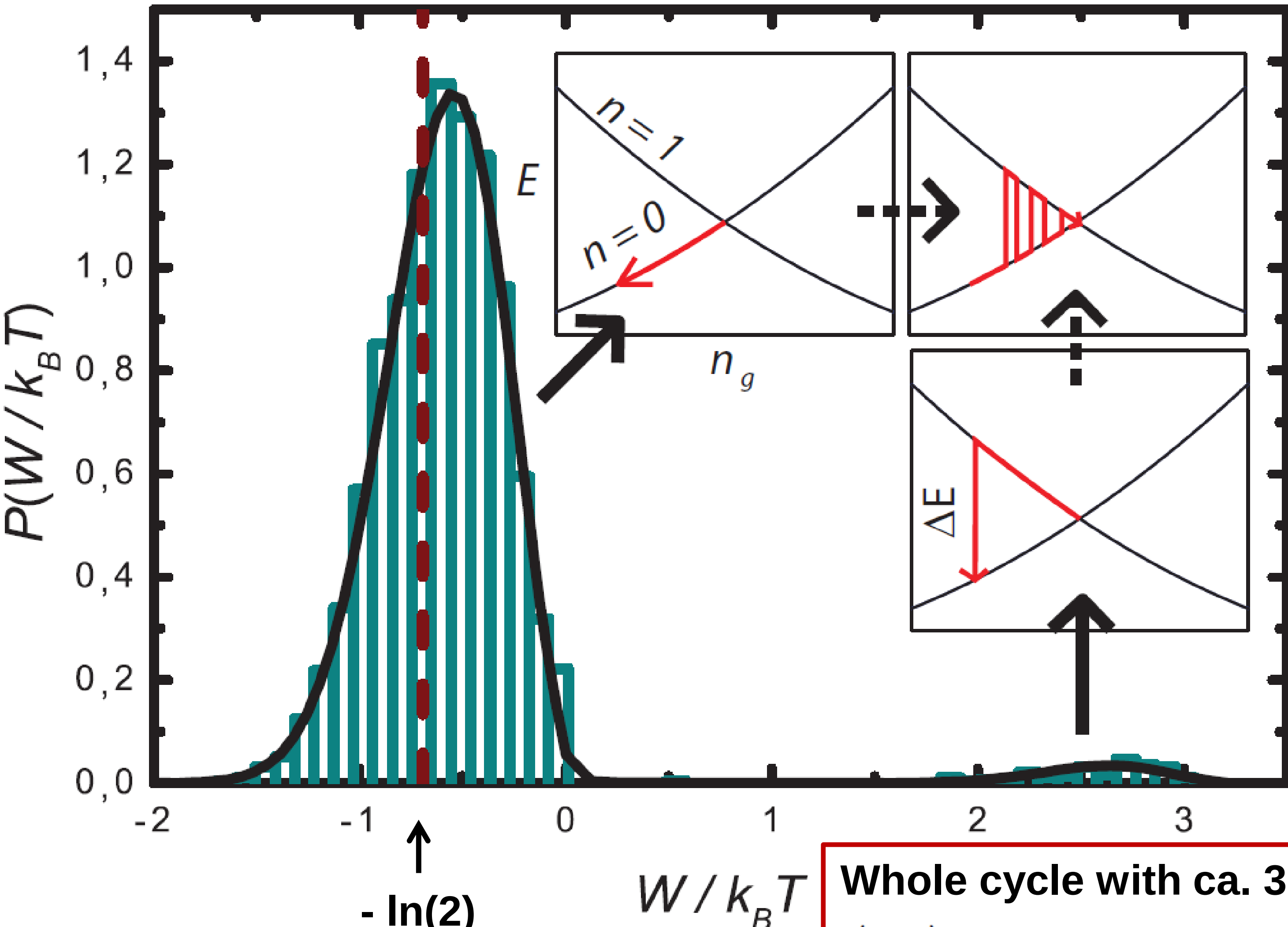


In the full cycle (ideally): $Q = W = -k_B T \ln(2)$

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)

Sagawa-Ueda relation

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

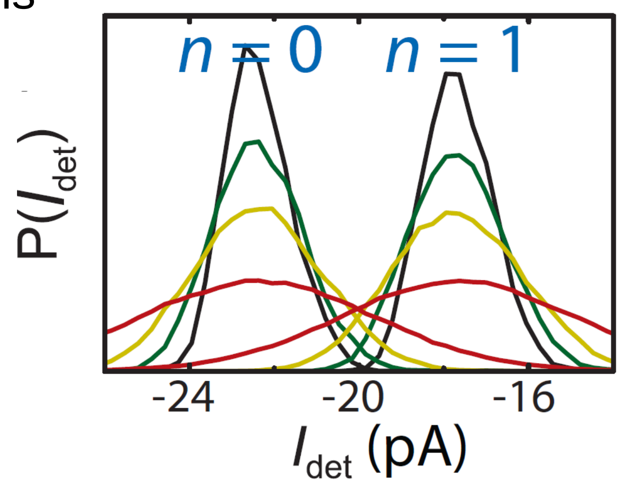
T. Sagawa and M. Ueda, PRL 104, 090602 (2010)

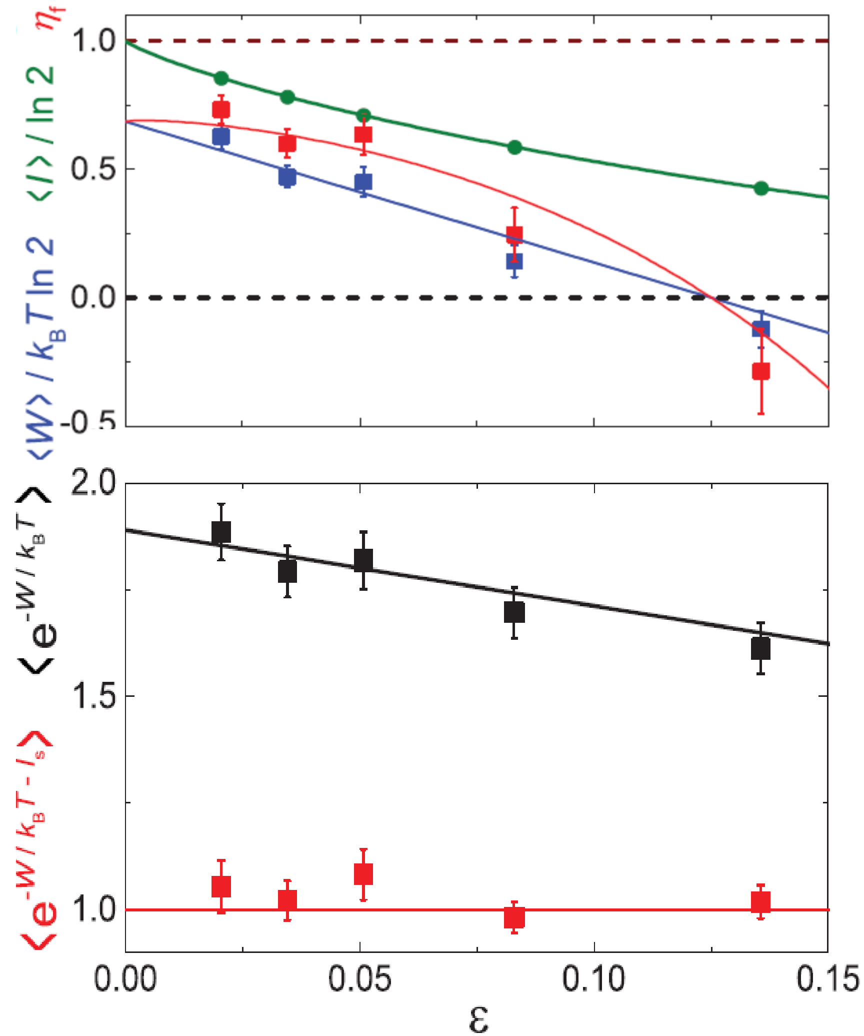
For a symmetric two-state system:

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

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

Measurements of *n* at different detector bandwidths



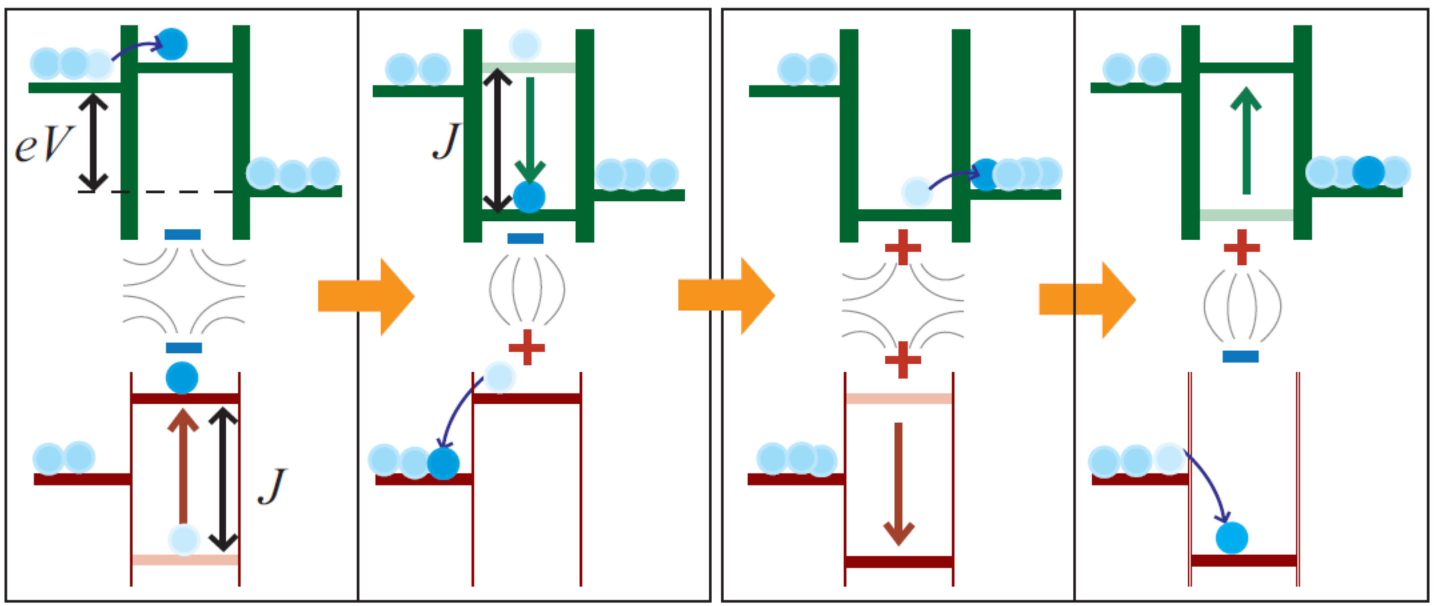


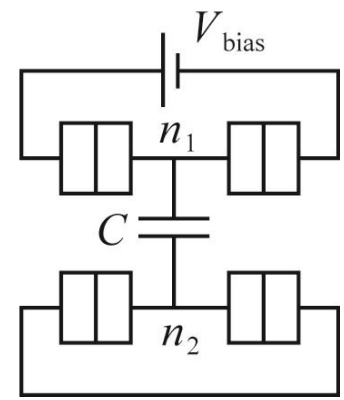
Koski et al., PRL 113, 030601 (2014)

Autonomous Maxwell's demon

System and Demon: all in one

Realization in a circuit:



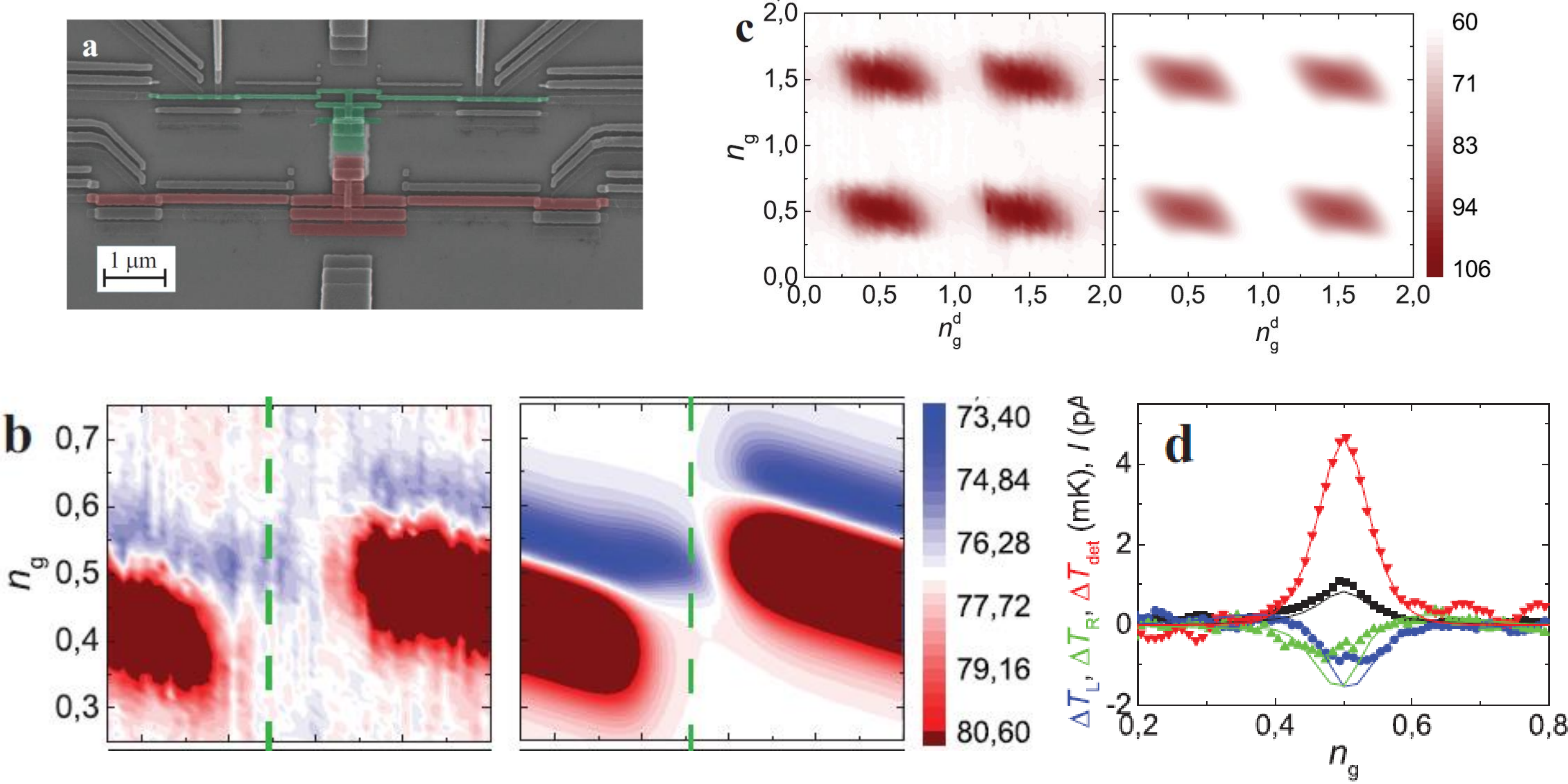


J. Koski et al., in preparation (2015).

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

Autonomous Maxwell's demon – information-powered refrigerator

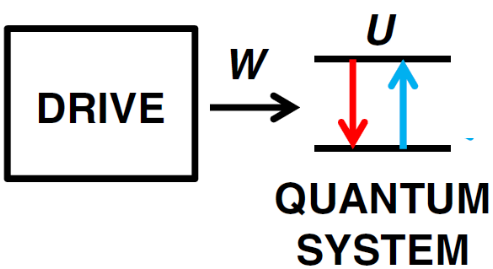
Actual device and experimental results

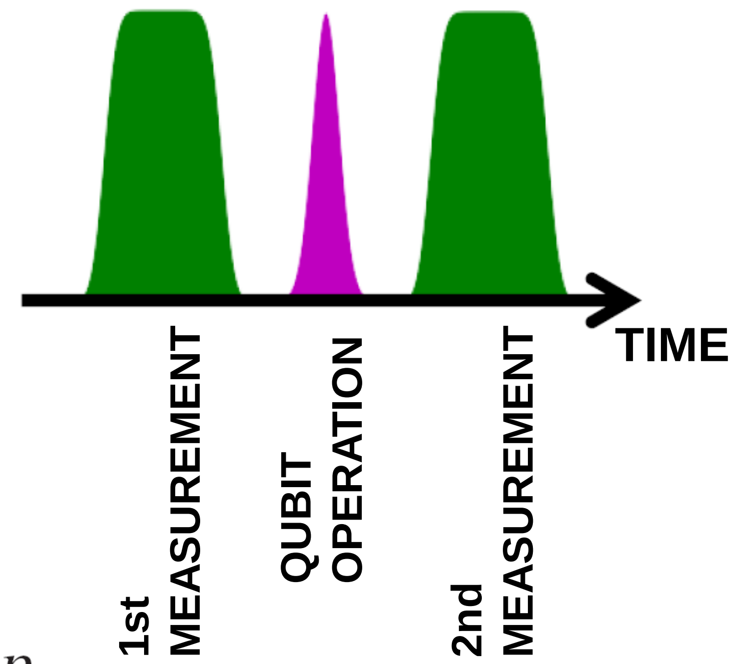


Work measurement in a quantum system

Two-measurement protocol (TMP):

W = E*_*f* – *E*_*i



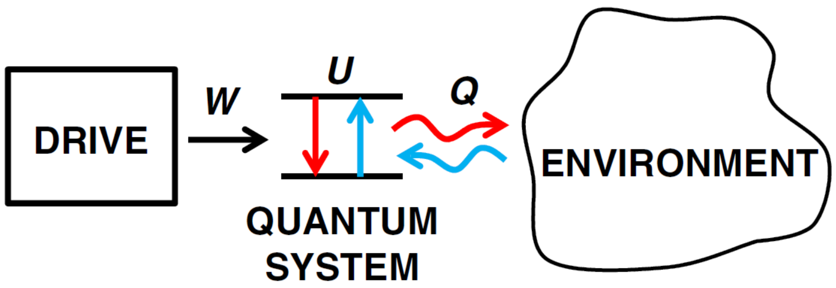


$$p(w) = \sum_{n,m} \delta(w - [e_m(t_f) - e_n(0)])p(m, t_f|n)p_n$$

Kurchan 2000, Talkner et al. 2007, Campisi et al. 2011

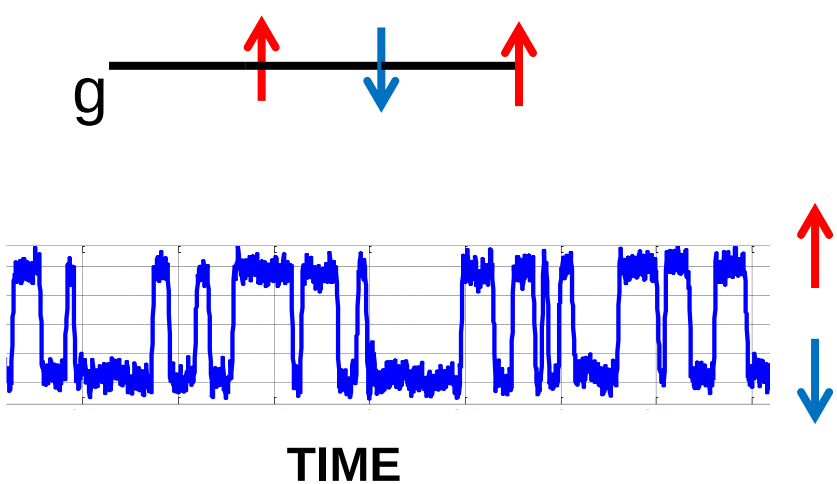
Since $W = \Delta U + Q$, and $\Delta U = E_f - E_i$, this measurement works only for a closed system

Evolution of a classical vs quantum dissipative two-level system

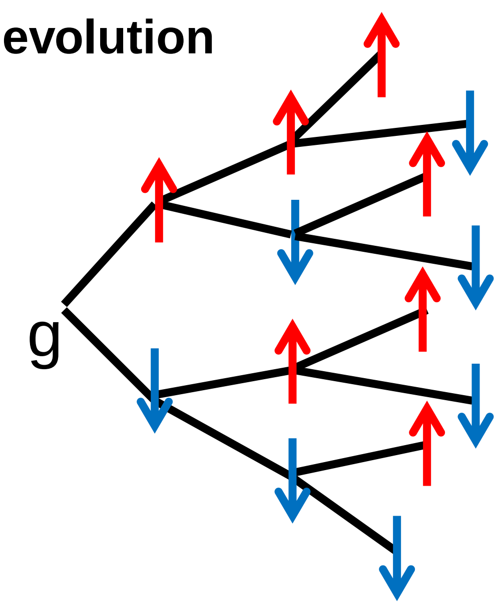


F. Hekking and JP, PRL 111, 093602 (2013)
JP et al., NJP 15, 115006 (2013)
M. Campisi et al., RMP 83, 711 (2011)
S. Suomela et al., PRB 90, 094304 (2014)

Classical evolution

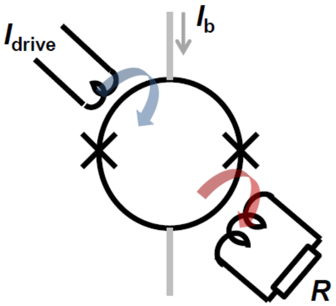


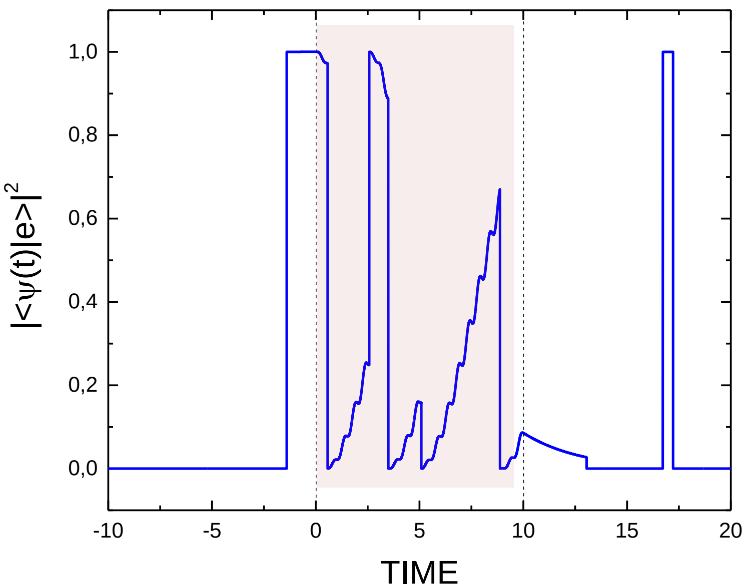
Quantum evolution



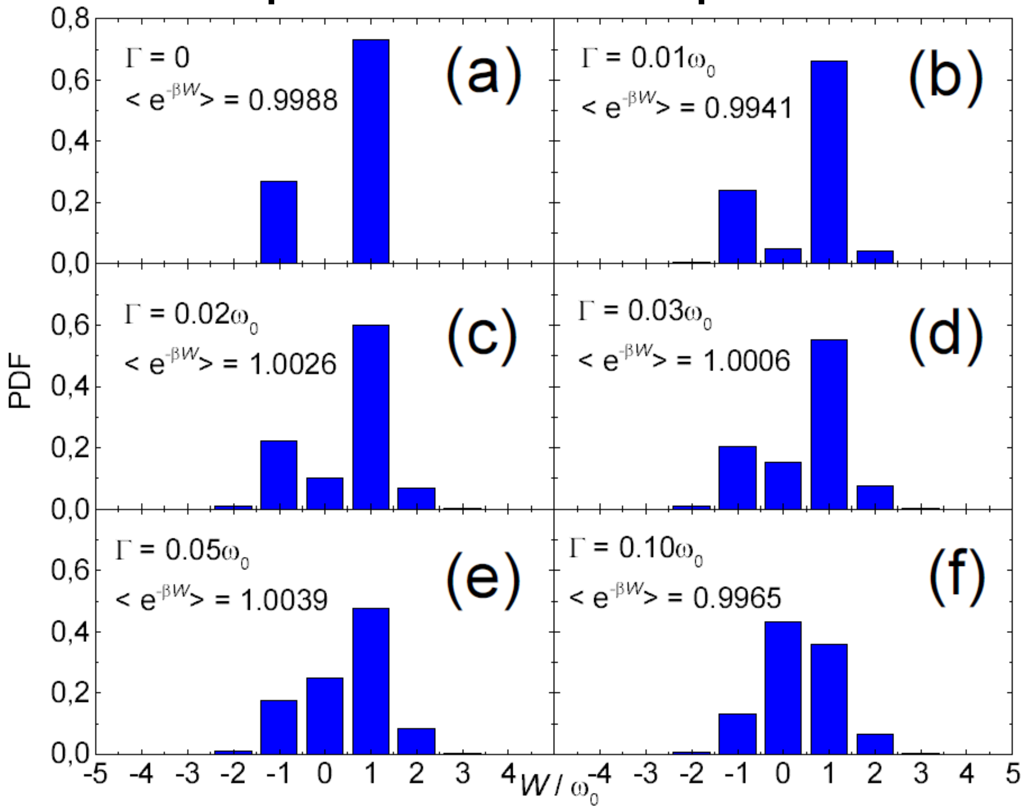
Quantum jump approach

In a two-level system the measurement of the environment (calorimetry) is in principle perfect since it yields *Q* and ALSO Δ*U* via the measurement of the "guardian photons".



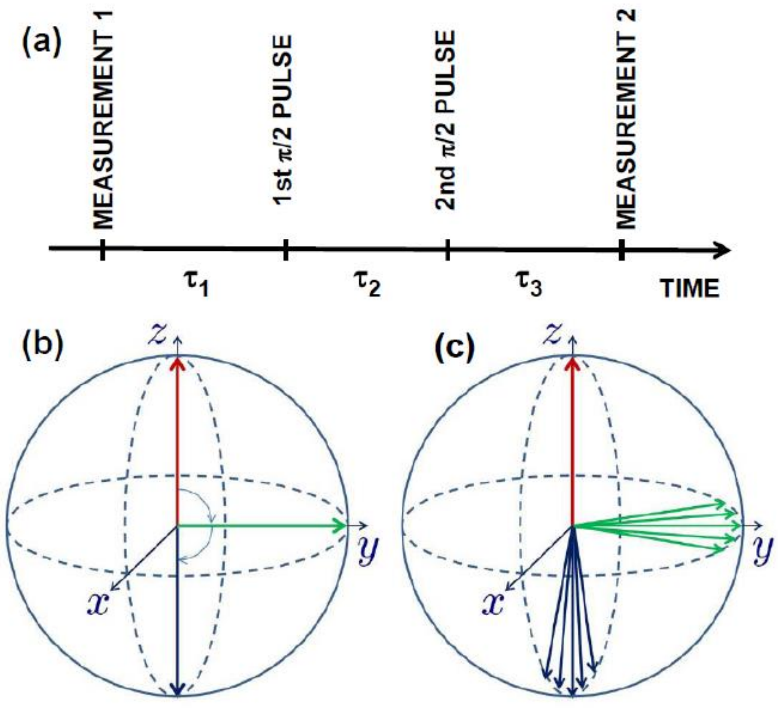


π pulse with dissipation



F. Hekking and JP, PRL 111, 093602 (2013).

TMP in a qubit coupled to environment



With long interval between the two measurements for any driving protocol

$$\langle e^{-\beta U}\rangle = 2 - \cosh^{-2}(\beta\hbar\omega_0/2)$$

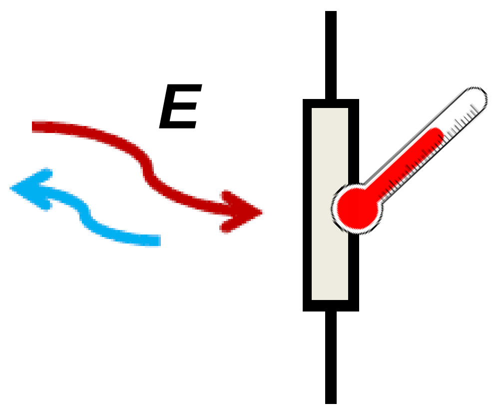
In weak dissipation regime

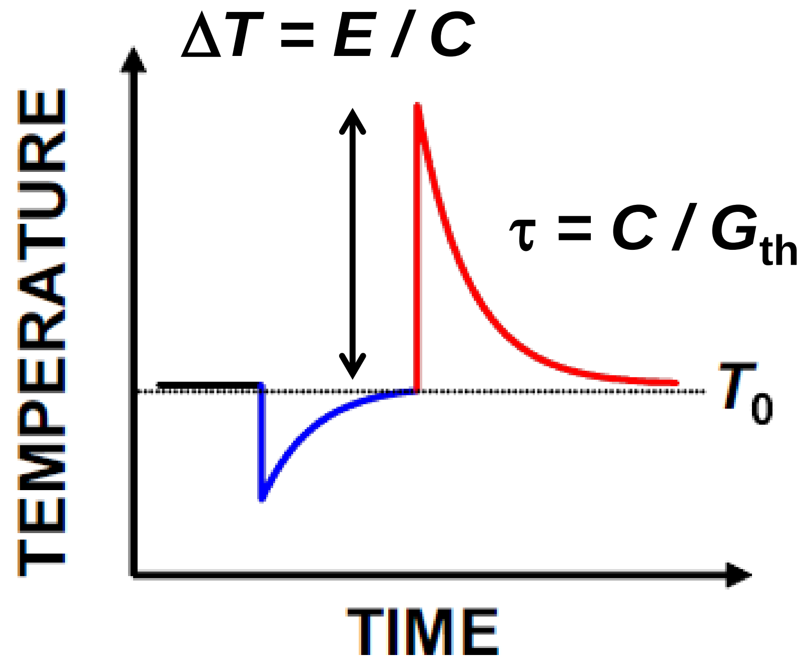
$$\langle e^{-\beta U}\rangle = 1+[(\tau_3 - e^{-(\Gamma_\phi \tau_2)^2}\tau_1]\,\Gamma_\Sigma \coth^2(\beta\hbar\omega_0/2)$$

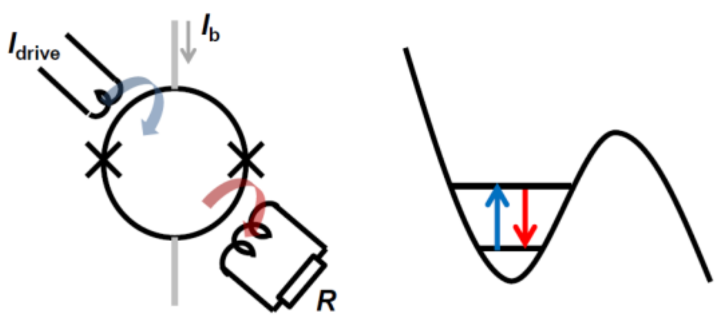
JP, Y. Masuyama, Y. Nakamura, J. Bergli, and Y. Galperin, arxiv:1503.05940.

Calorimetry

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



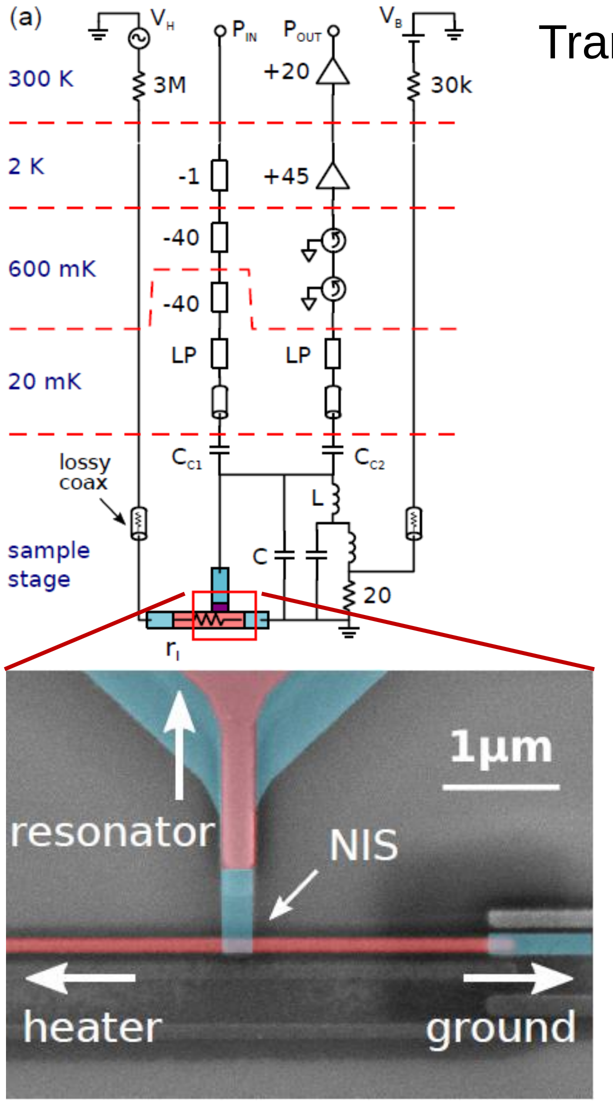




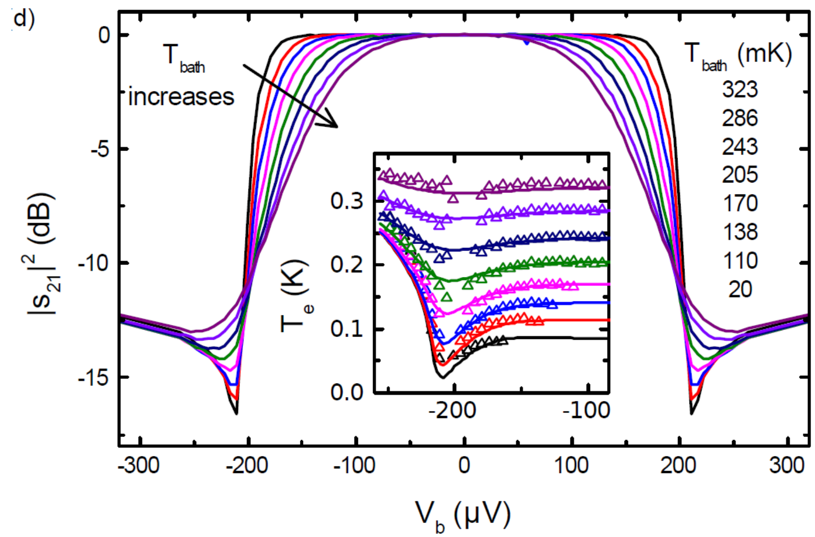
Typical parameters for sc qubits:
ΔT ~ 1 - 3 mK, τ ~ 0.01 - 1 ms

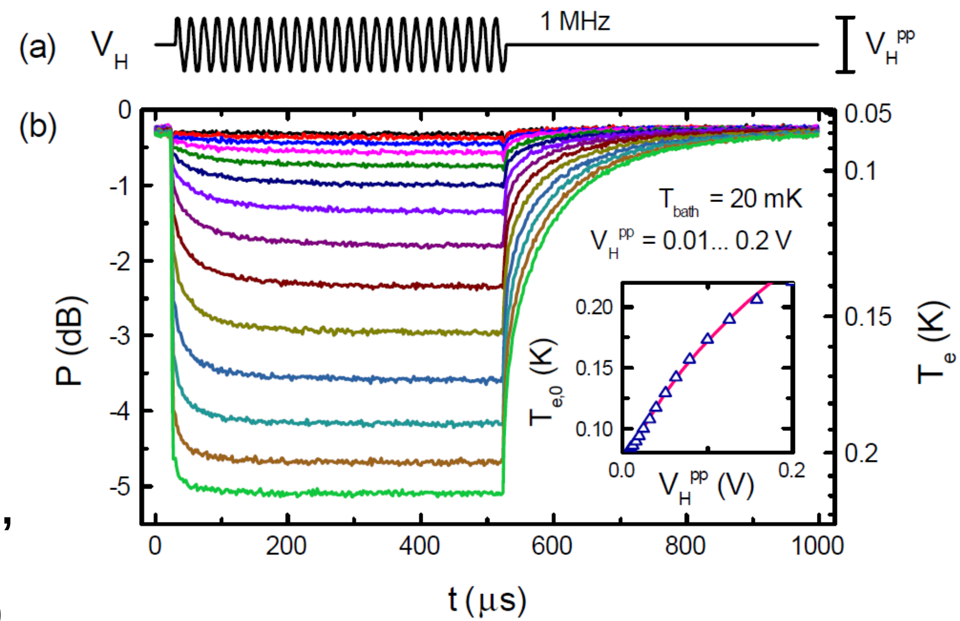
10 μK/(Hz)$^{1/2}$ is sufficient for single photon detection

Fast thermometry



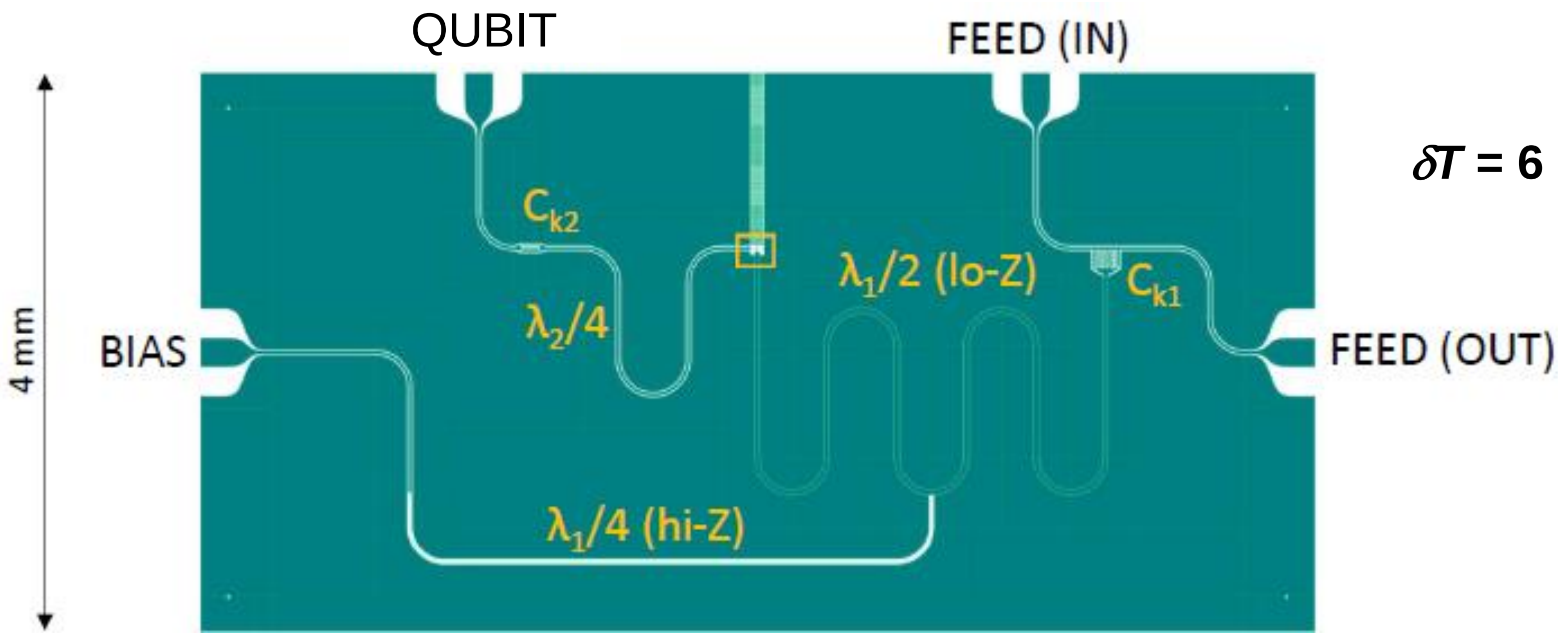
Transmission read-out at 600 MHz of a NIS junction



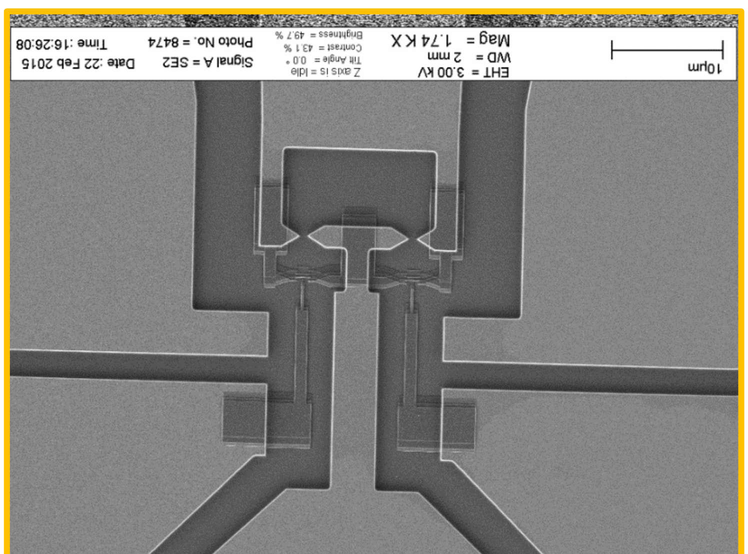


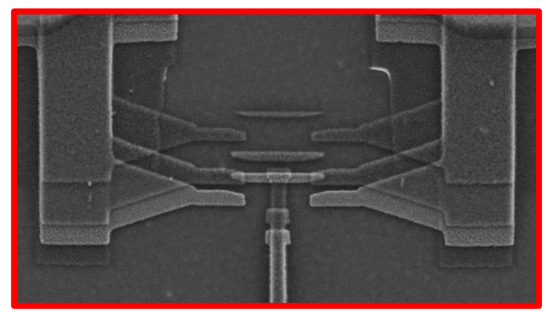
S. Gasparinetti et al., Phys. Rev. Applied 3, 014007 (2015).
(proof of the concept by Schmidt et al., 2003)

Actual micro-wave device



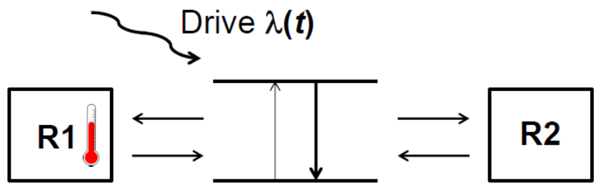
δT = 6 μK/(Hz)$^{1/2}$





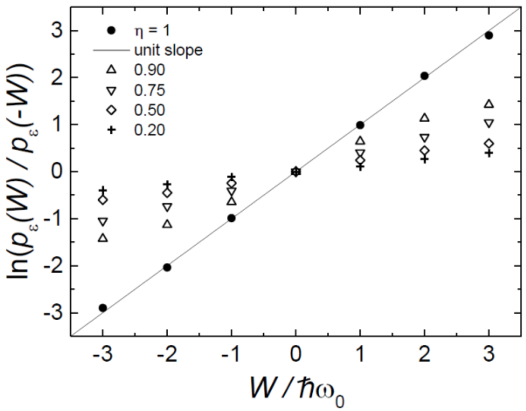
Measurements of
- temperature fluctuations
- work distribution of a driven qubit

Calorimetry on quantum two-level systems: ”errors”

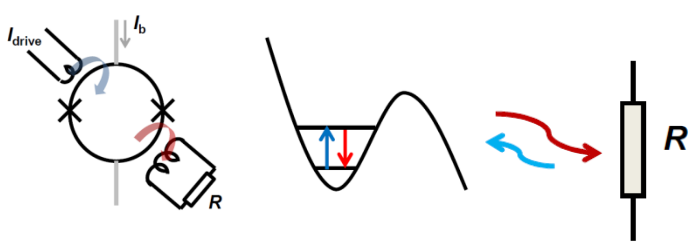


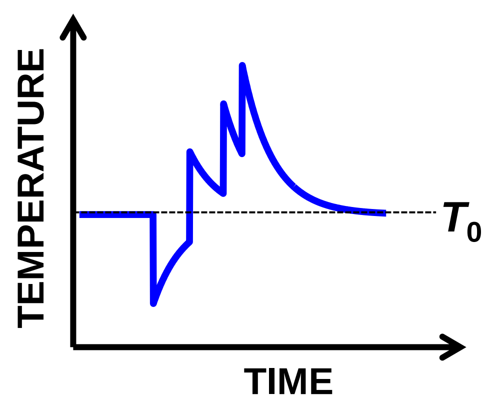
1. Hidden environments/noise sources

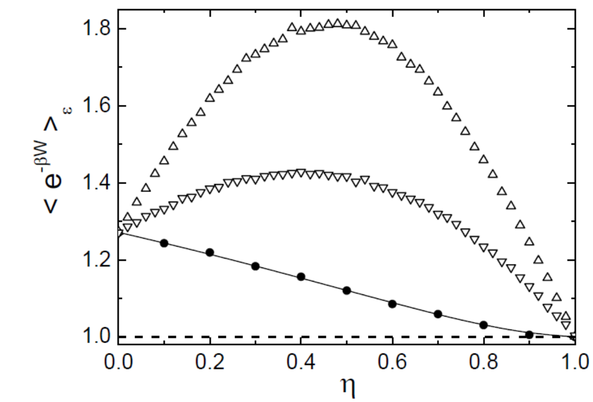
K. Viisanen et al., arXiv:1412.7322, NJP (2015)



2. Finite heat capacity of the absorber (non-Markovian)







Summary

Refrigeration, quantum heat transport, non-equilibrium fluctuation relations and Maxwell's demon investigated in electronic circuits

On-going and future experiments:

"Autonomous" Maxwell's demon

Brownian refrigeration

Temperature fluctuations

Direct calorimetric measurement of dissipation - towards single-photon detection

Quantum fluctuation relations

Recent progress article: JP, Nature Physics 11, 118 (2015).

Collaborators

Experiments:

Olli-Pentti Saira

Jonne Koski

Ville Maisi

now at ETHZ

Simone Gasparinetti

now at ETHZ

Klaara Viisanen

Other collaborators: Ivan Khaymovich, Dmitri Golubev, Dmitri Averin (SUNY), Takahiro Sagawa (Univ. Tokyo), Frank Hekking (CNRS Grenoble), Joachim Ankerhold (Ulm), Tapio Ala-Nissila, Samu Suomela, Aki Kutvonen, Massimo Borrelli, Sabrina Maniscalco (Turku), Michele Campisi (Pisa), Yuri Galperin (Oslo), Yasu Nakamura (Tokyo), Yuta Masuyama (Tokyo)