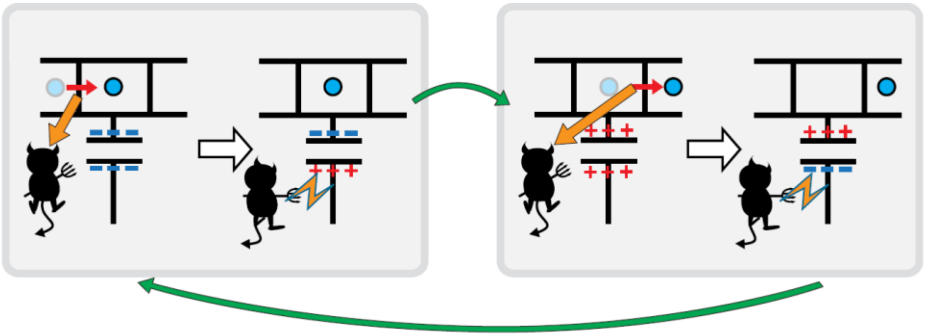
Electronic Realizations of a Maxwell's Demon



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QTC2017 8.8.2017

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V. F. Maisi, A. Kutvonen, I. M. Khaymovich, T. Sagawa,
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Entropy & Maxwell’s demon

Electronic Szilard’s engine

Autonomous Maxwell’s demon

Entropy

State $\boldsymbol{s}$ probability $P_{\boldsymbol{s}}$

Entropy $S_s = -k_B \sum_s P_s \ln P_s$ quantifies disorder

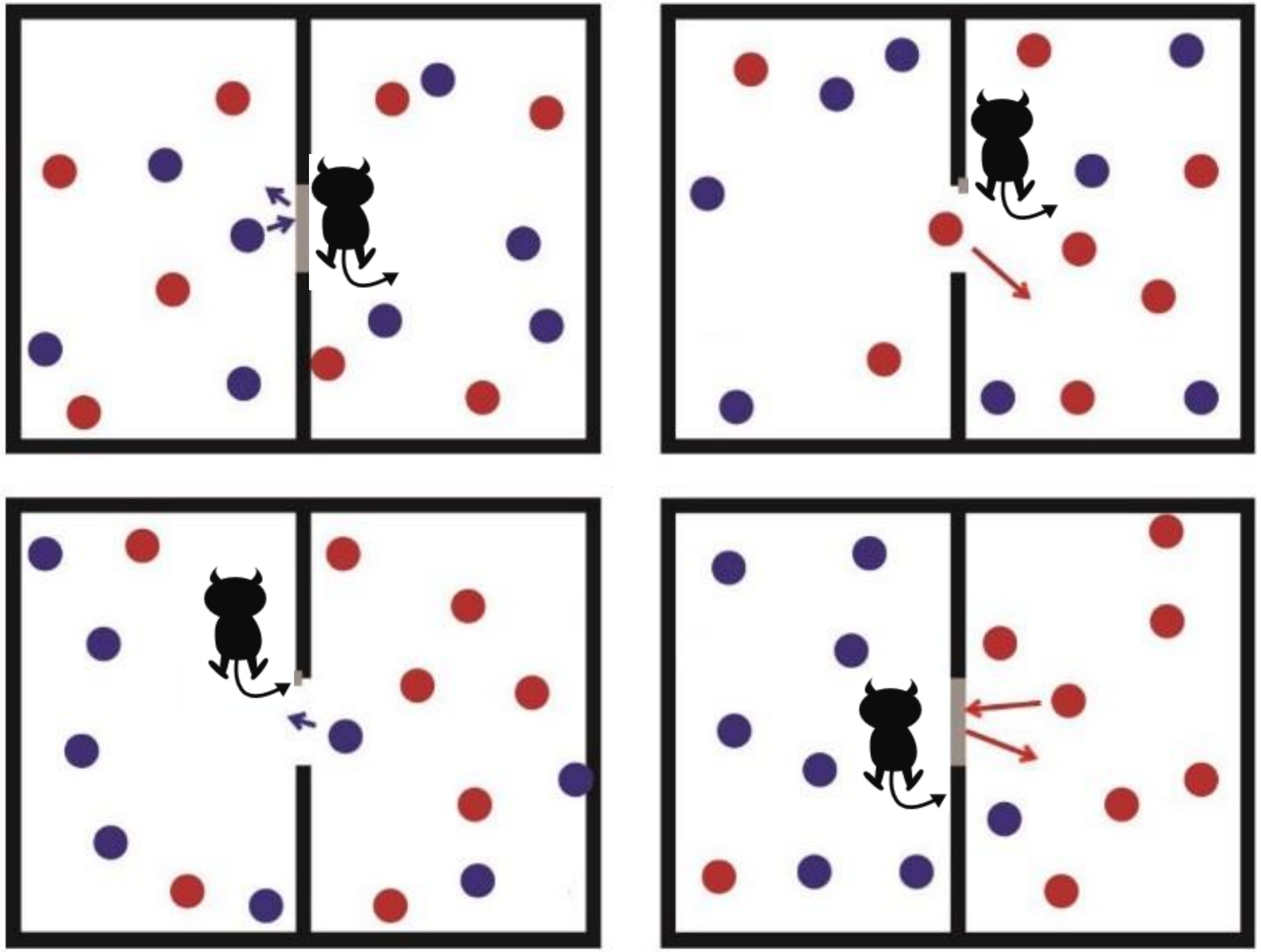
Heat bath macroscopic & at equilibrium

- Characterize with temperature T : $\frac{dS_b}{dQ} = \frac{1}{T}$
- $\Delta S_b = Q/T$

Second law: $\Delta S = \Delta S_s + \Delta S_b \geq 0$

Every process is dissipative

Maxwell’s demon



Heat flow: **cold → hot?**

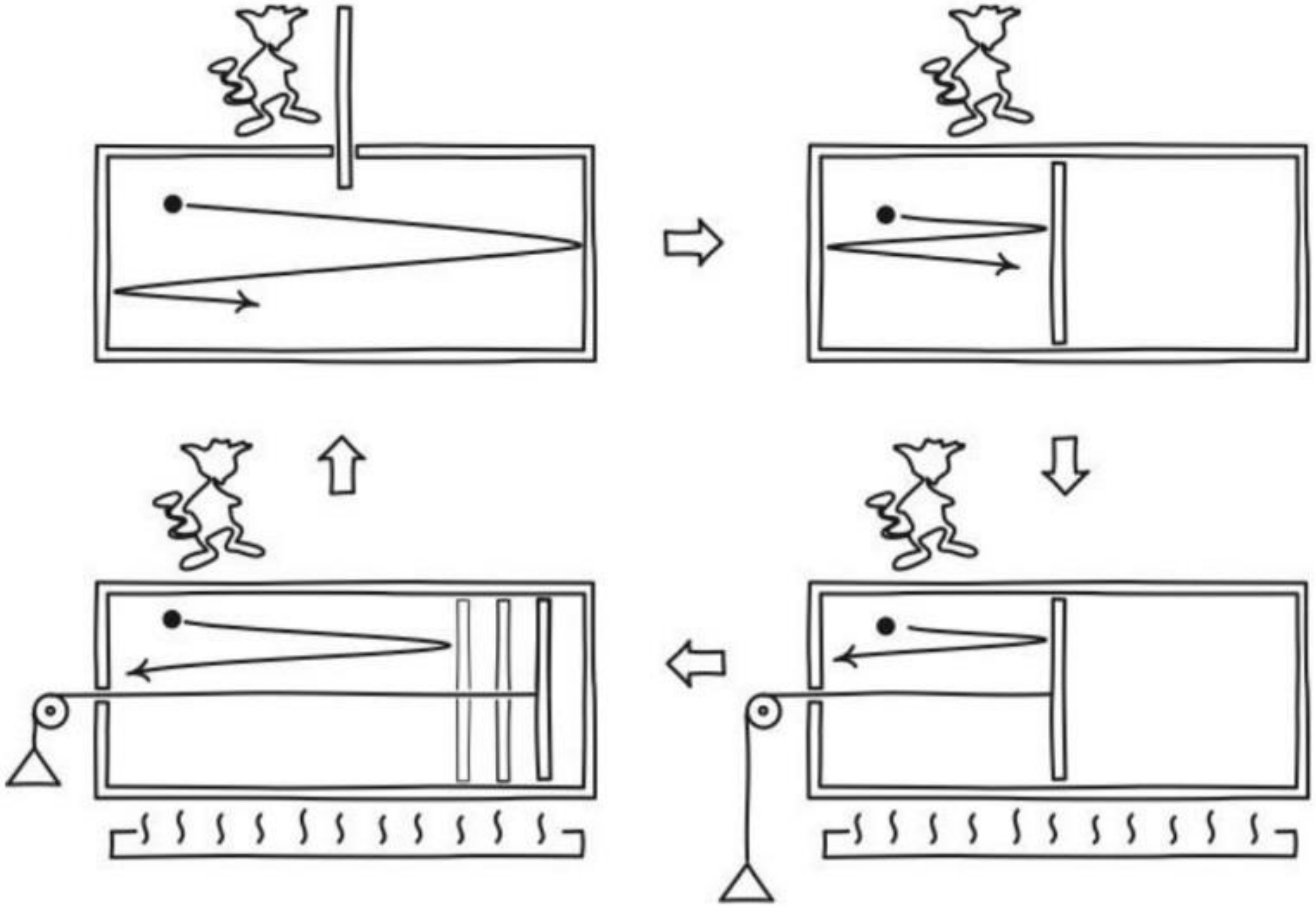
System more **ordered**?

Second law violated?

Szilard's engine

Setup:

Single particle in box



Measure:

Particle in left or right half?

Feedback:

Expand 'gas' to full volume

Work:

$$pV = k_B T$$

$$W = -\int dV p(V)$$

$$= -k_B T \log(2)$$

Energy for free?

Landauer’s principle

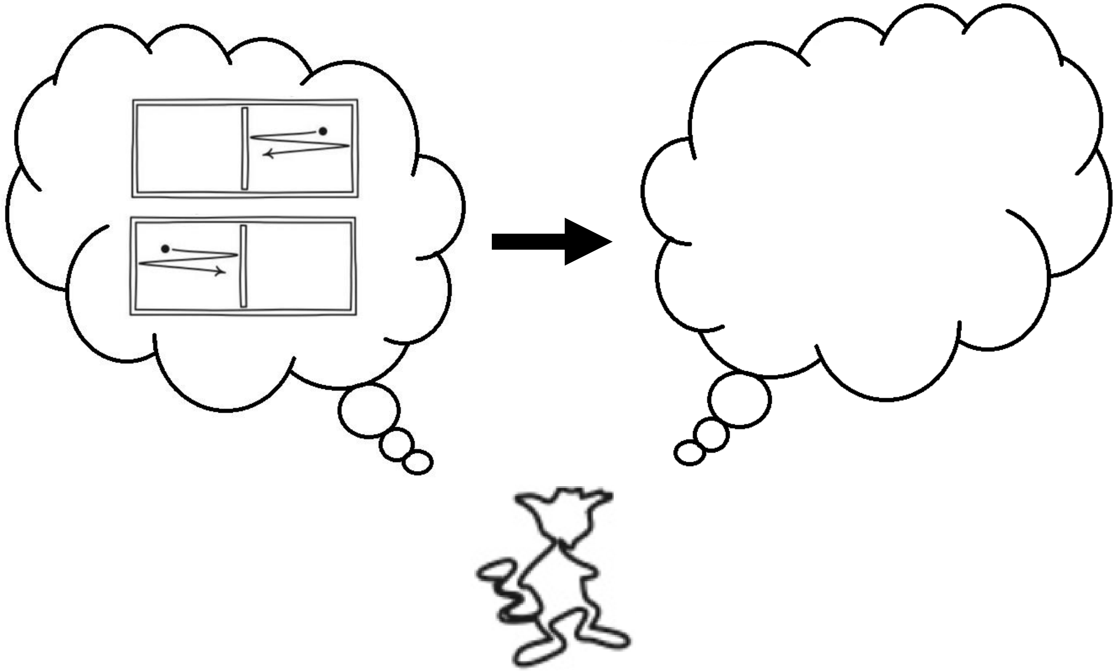
Erasure of information changes entropy:

$$\Delta S_s = 0 - k_B \left(\frac{1}{2}\log(2) + \frac{1}{2}\log(2)\right) = -k_B \log(2)$$

Second law:

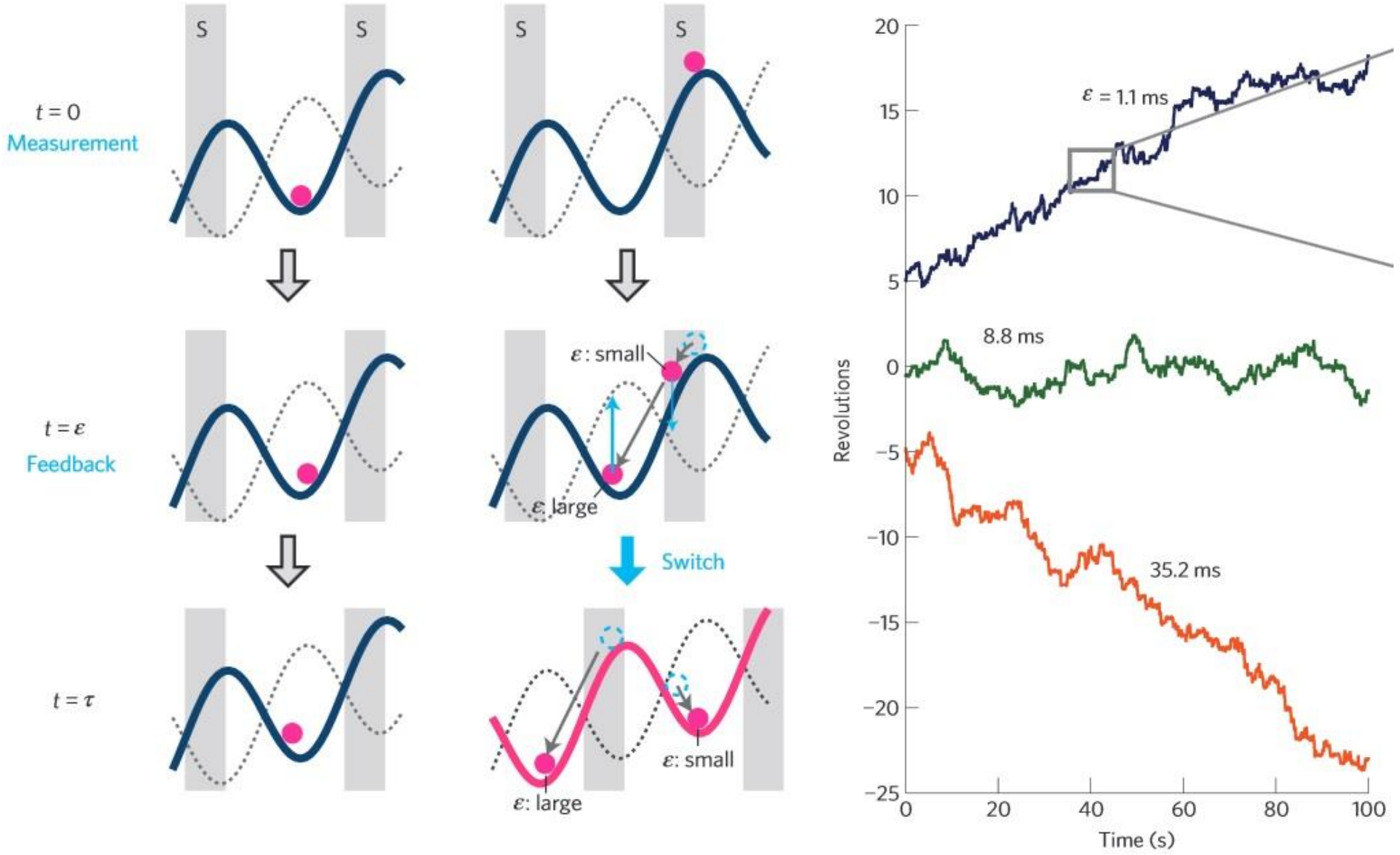
$$\Delta S_b \geq -\Delta S_s$$

$$\mathrm{W} = \mathrm{Q} \geq k_B T \log(2)$$



‘Forgetting‘ spends energy

Experiments on Maxwell’s demon



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

Also

É. Roldán *et al.*, *Nature Phys*. **10**, 457 (2014)

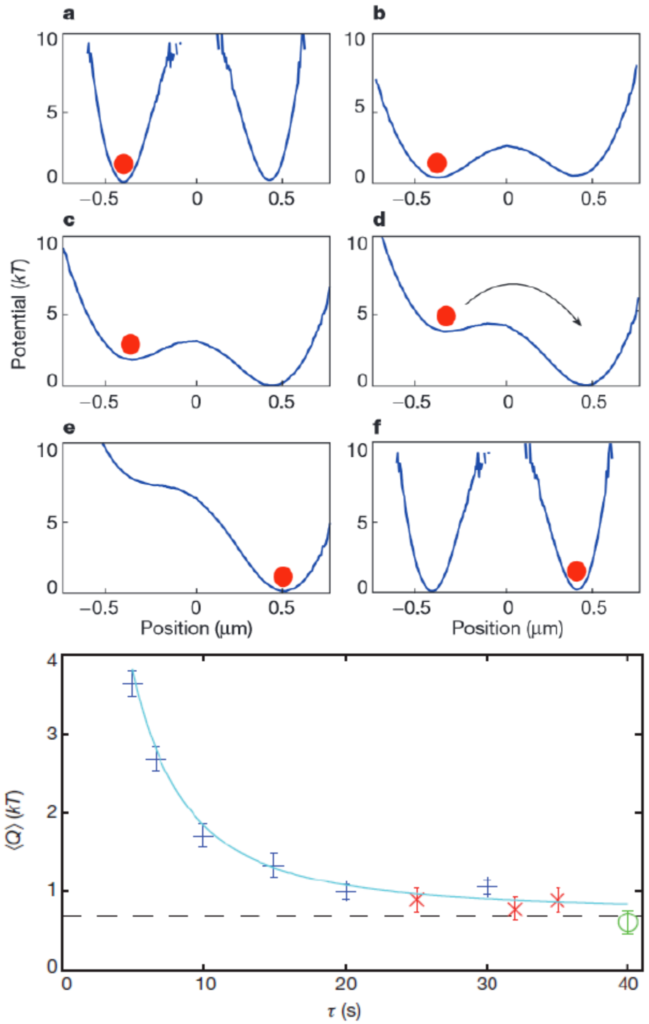
Photonic MD

Mihai D. Vidrighin *et al.*, Phys. Rev. Lett. **116,** 050401 (2016)

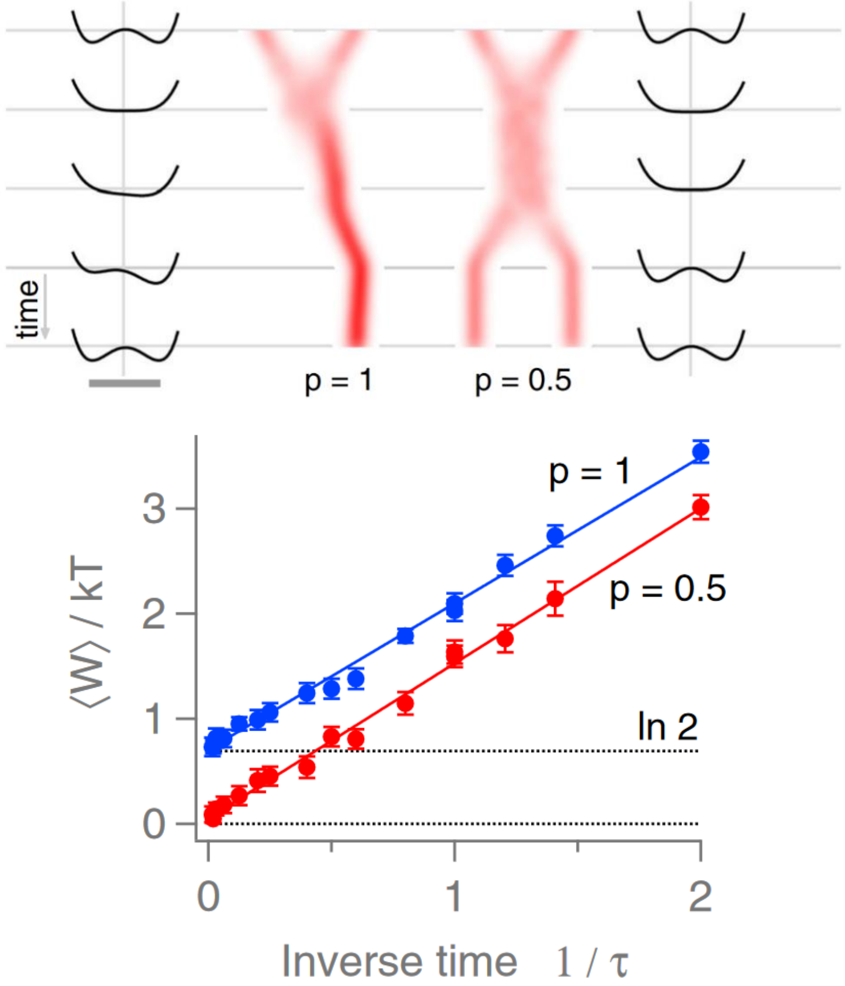
Quantum MD

N. Cottet *et al.*, PNAS **114**, 7561 (2017)

Tests on Landauer’s principle



A. Bérut *et al.*, Nature **483**, 187 (2012)



Y. Jun *et al.*, PRL **113**, 190601 (2014)

Entropy & Maxwell’s demon

Electronic Szilard’s engine

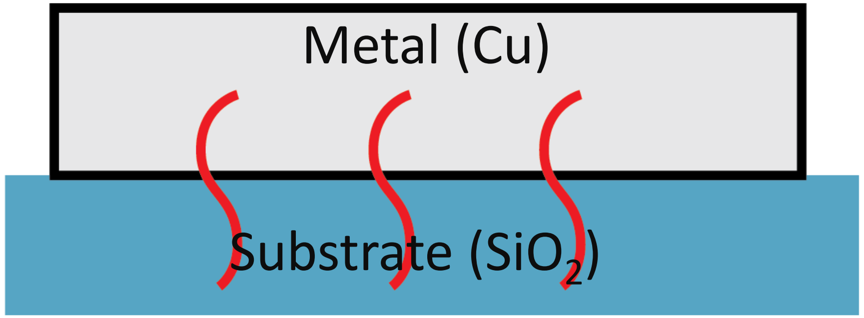
Autonomous Maxwell’s demon

Heat in electronics

Metal block of $(100\ \mathrm{nm})^3$:

$\sim 10^{10}$ Conduction electrons

Electron-electron interaction: T_{el}



Electron-phonon interaction:

$$T_{el} \rightarrow T_{ph}$$

Heat in electronics

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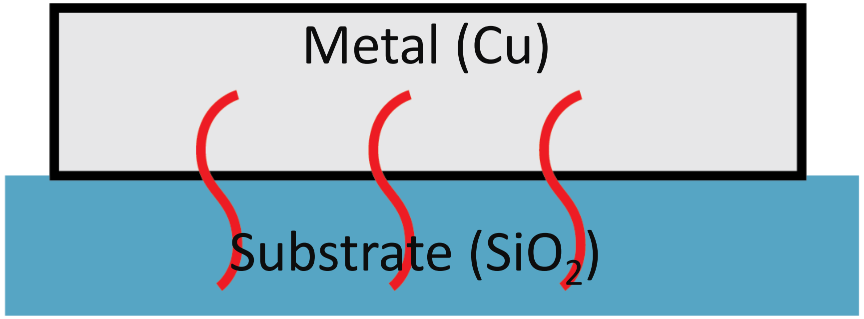
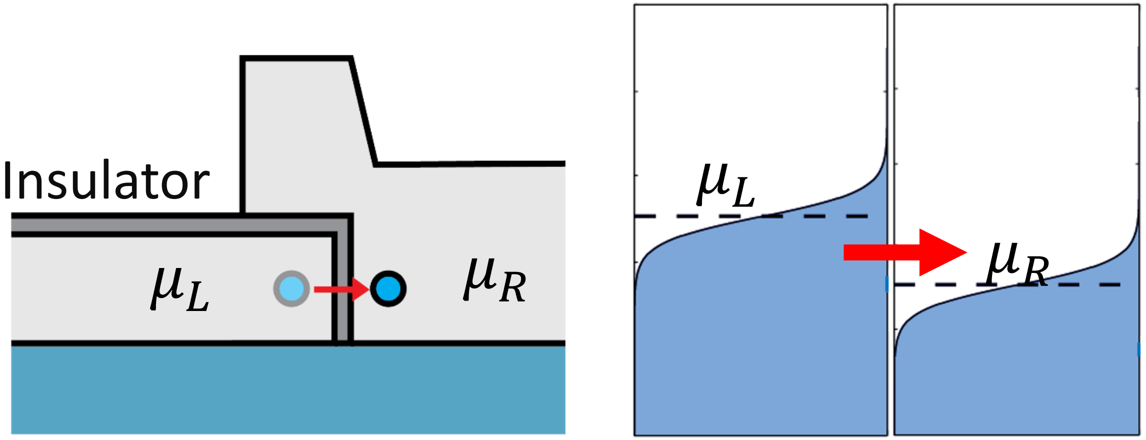


Electron-phonon interaction:

$$T_{el} \rightarrow T_{ph}$$

Electron tunneling

Tunneling through tunnel barrier



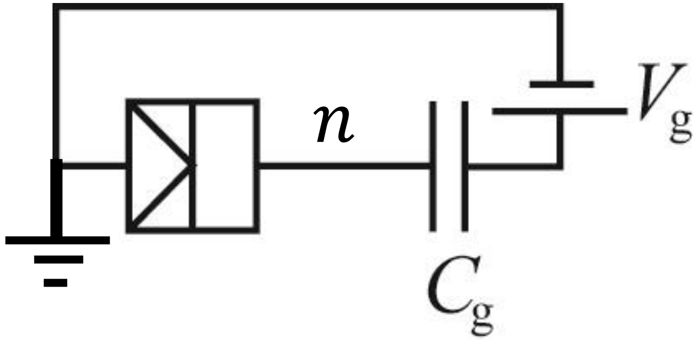
$$Q = \mu_L - \mu_R$$

Tunneling rate (for metallic junction):

$$\Gamma = \frac{1}{e^2 R} \int dE\, f(E - \mu_L)\,(1 - f(E - \mu_R))$$

Tunneling resistance R

Single electron box



n electrons on a metallic island

$H = E_C(n - n_g)^2 \quad E_C = \frac{e^2}{2C_\Sigma} \sim 1$ K

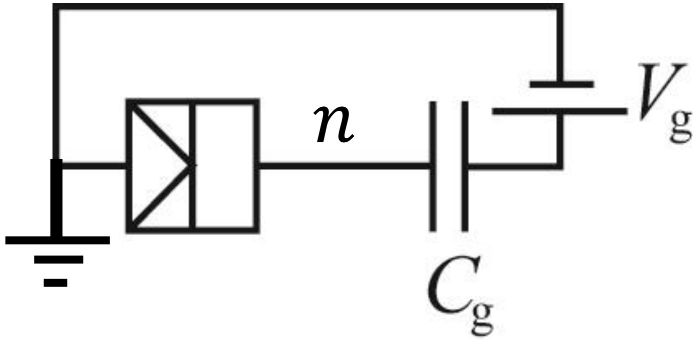
$n_g = V_g(C_g / e)$

When $E_C \gg k_B T$:

Two-level system $(n = 1, n = 0)$:

- Changes by tunneling
- $H(1) - H(0) = 2E_C(n_g - \frac{1}{2})$

Single electron box / Transistor



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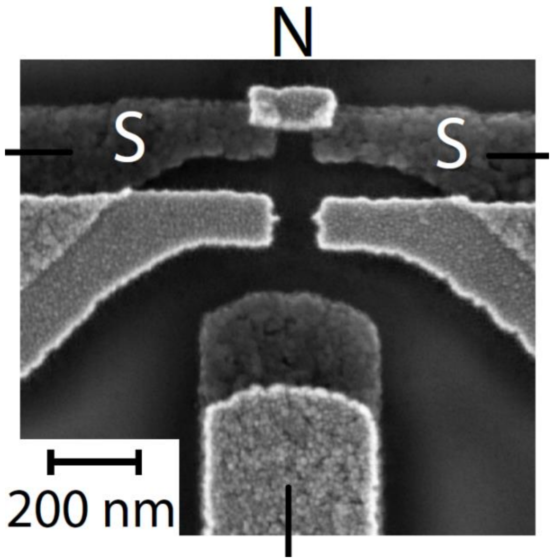
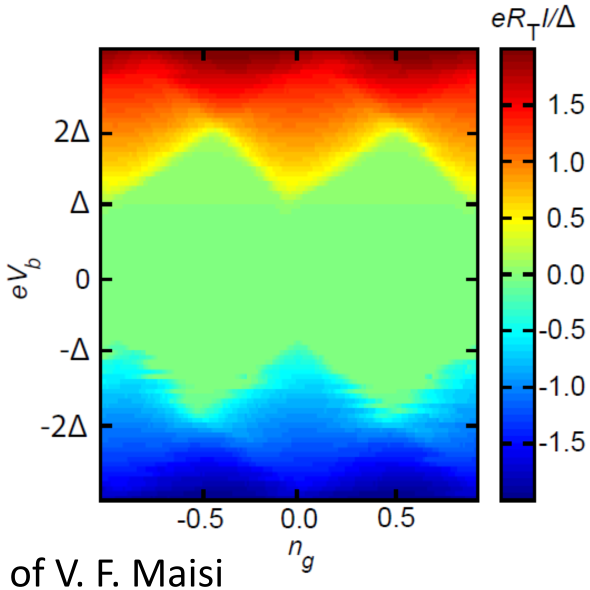




Figures from Ph. D. Thesis of V. F. Maisi

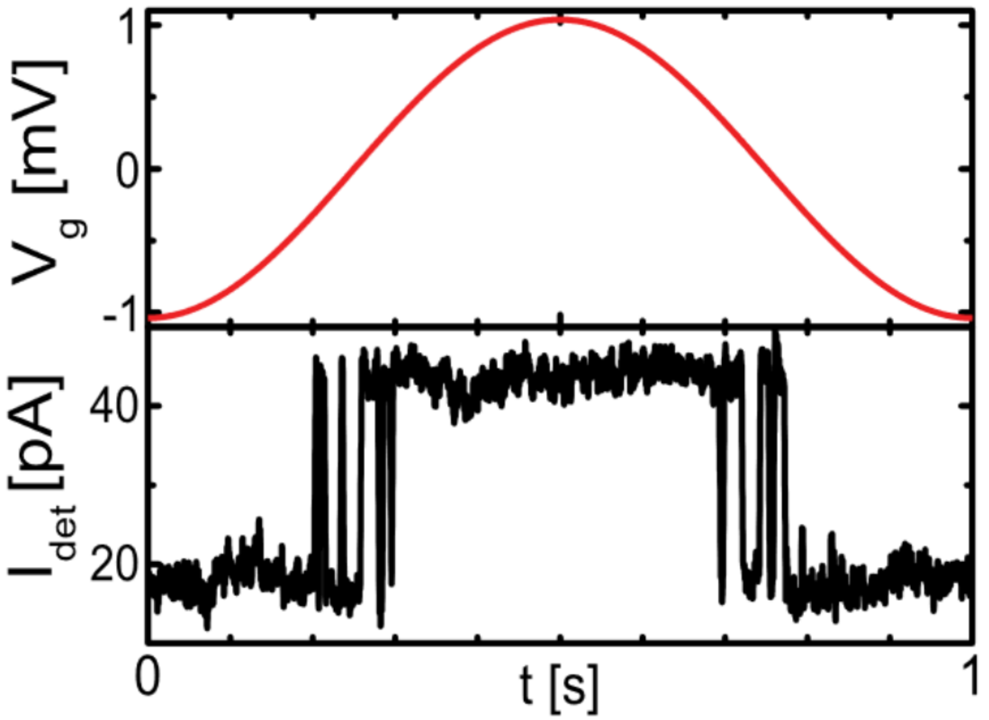
Electric current gateable

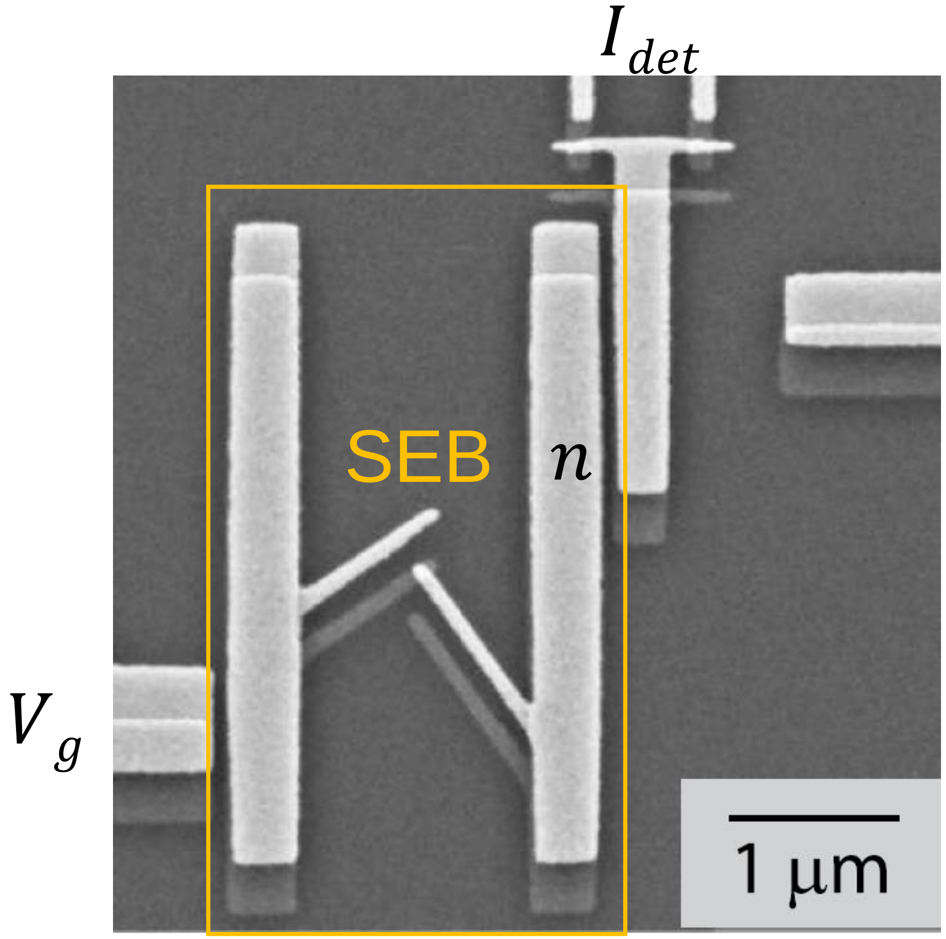
Sensitive to nearby charge

→ Charge detection

Driving a single electron

Driving the SEB

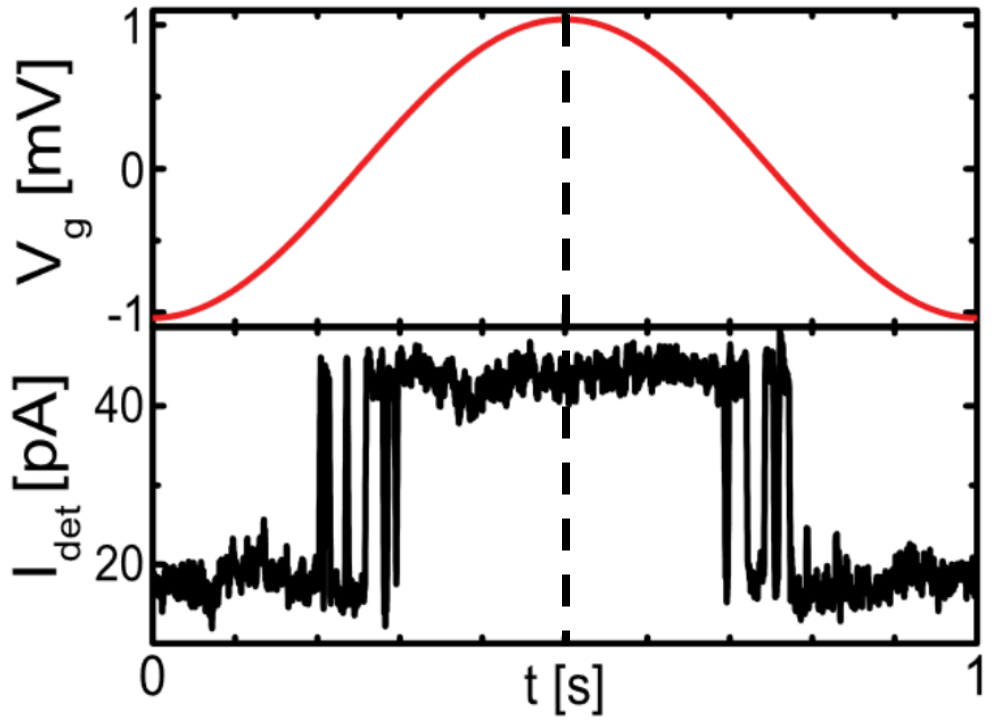




O.-P. Saira, Y. Yoon, T. Tanttu, M. Möttönen, D. V. Averin, and J. P. Pekola, PRL **109**, 180601 (2012)

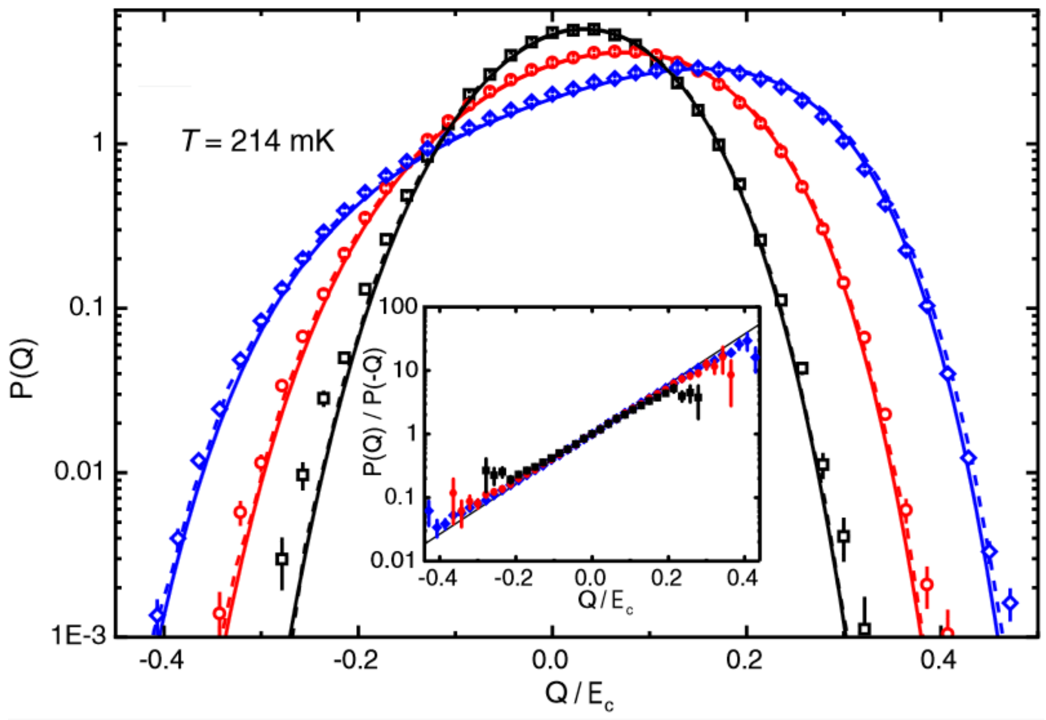
Driving a single electron

Driving the SEB



$Q_1 = \sum_j Q_{j,1}$ $Q_2 = \sum_j Q_{j,2}$

><u>100000</u> runs



O.-P. Saira, Y. Yoon, T. Tanttu, M. Möttönen, D. V. Averin, and J. P. Pekola, PRL **109**, 180601 (2012)

Driving a single electron

Fluctuation relations

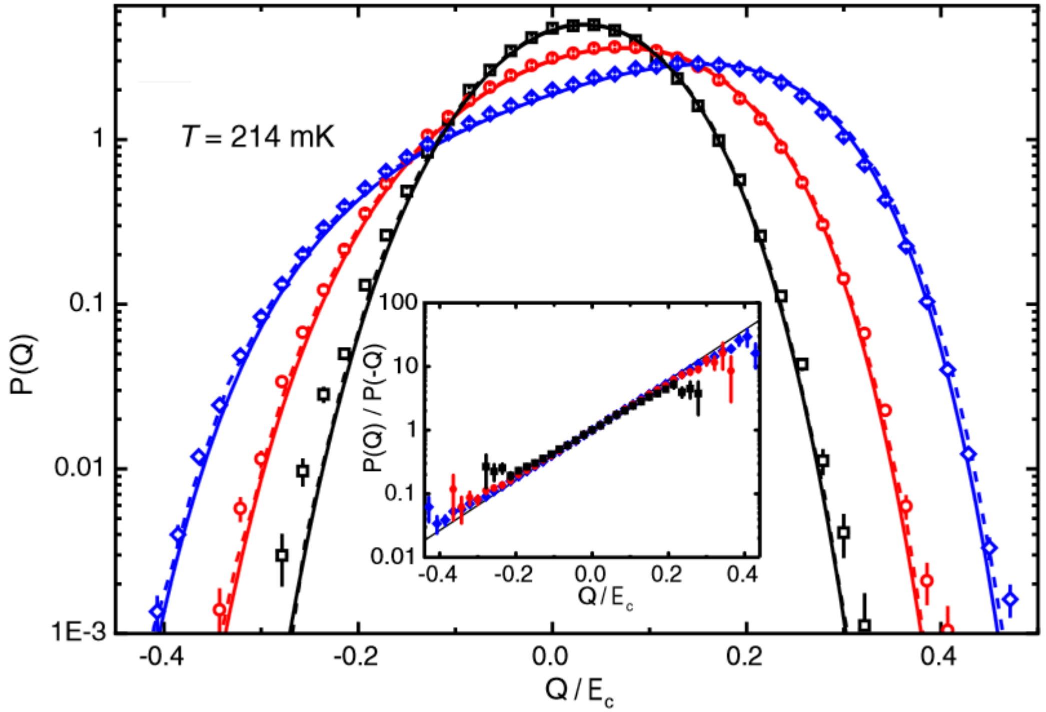
$$\left\langle e^{-W/k_BT} \right\rangle = e^{-\Delta F/k_BT}$$

C. Jarzynski, PRL **78**, 2690 (1997)

$$\frac{P(W)}{P(-W)} = e^{(W - \Delta F)/k_BT}$$

G. E. Crooks, PRE **60**, 2721 (1999)

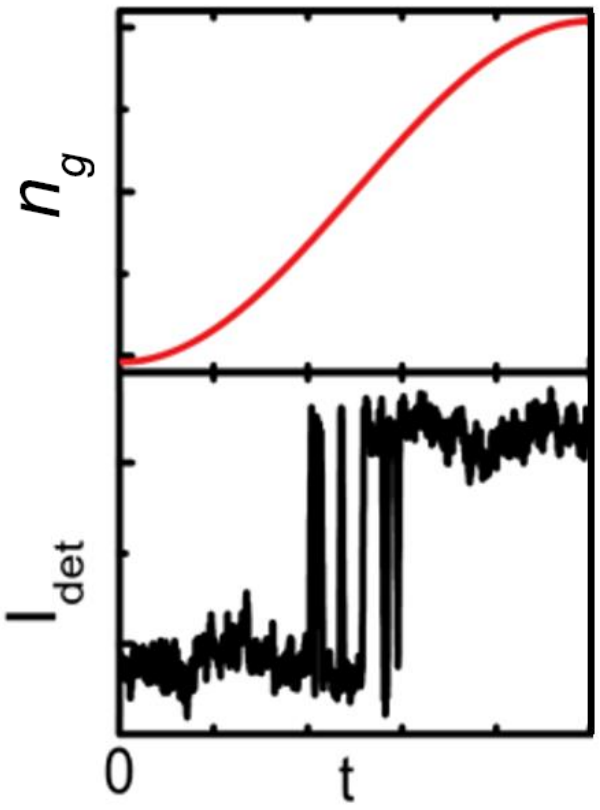
><u>100000</u> runs

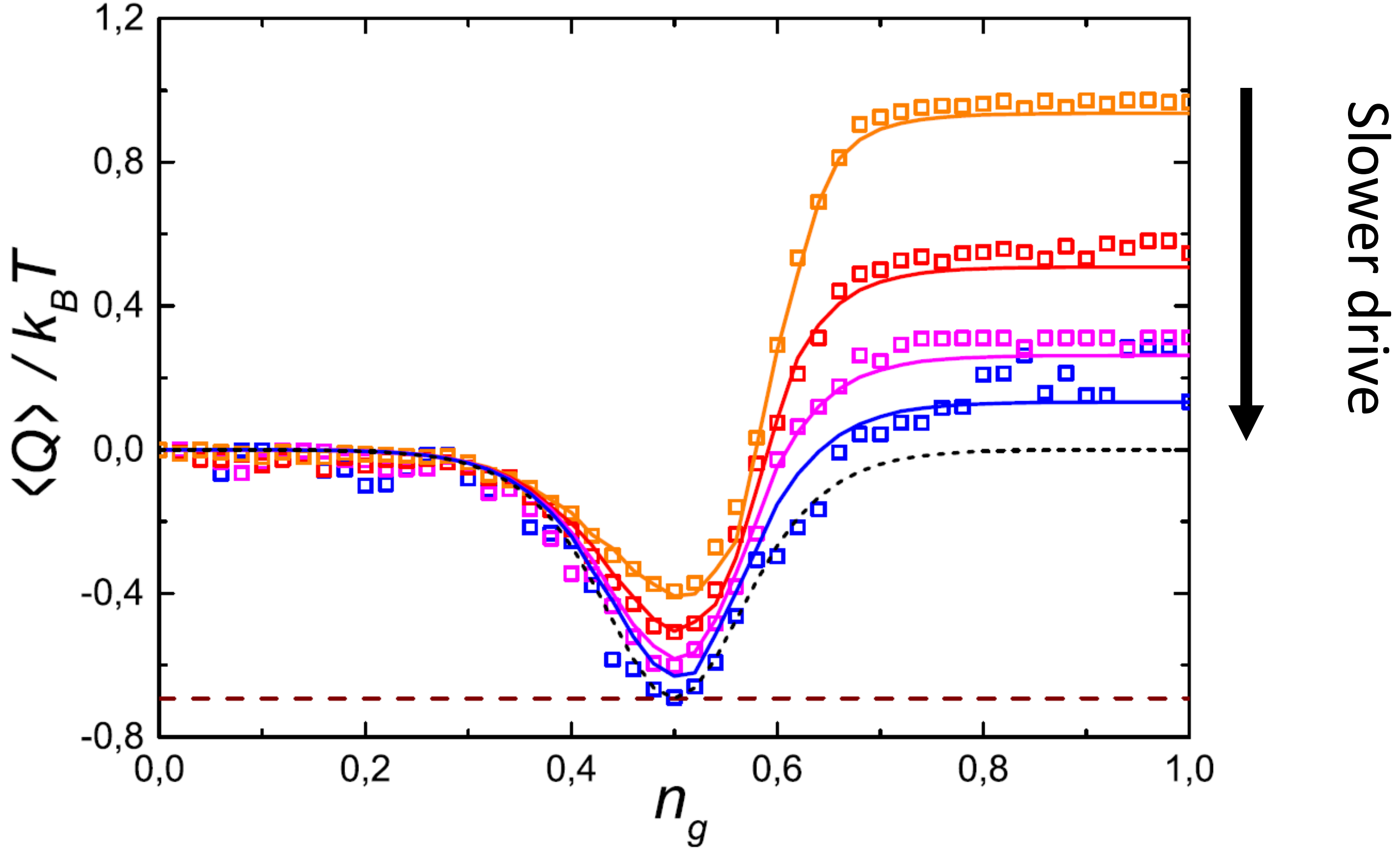


$$\left\langle e^{-W/k_BT} \right\rangle \approx 1.03$$

O.-P. Saira, Y. Yoon, T. Tanttu, M. Möttönen, D. V. Averin, and J. P. Pekola, PRL **109**, 180601 (2012)

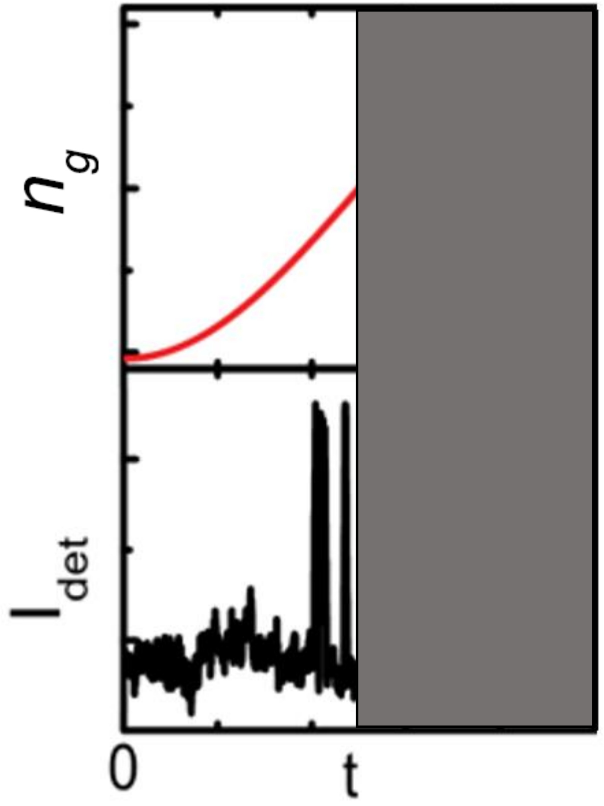
Szilard engine with a single electron

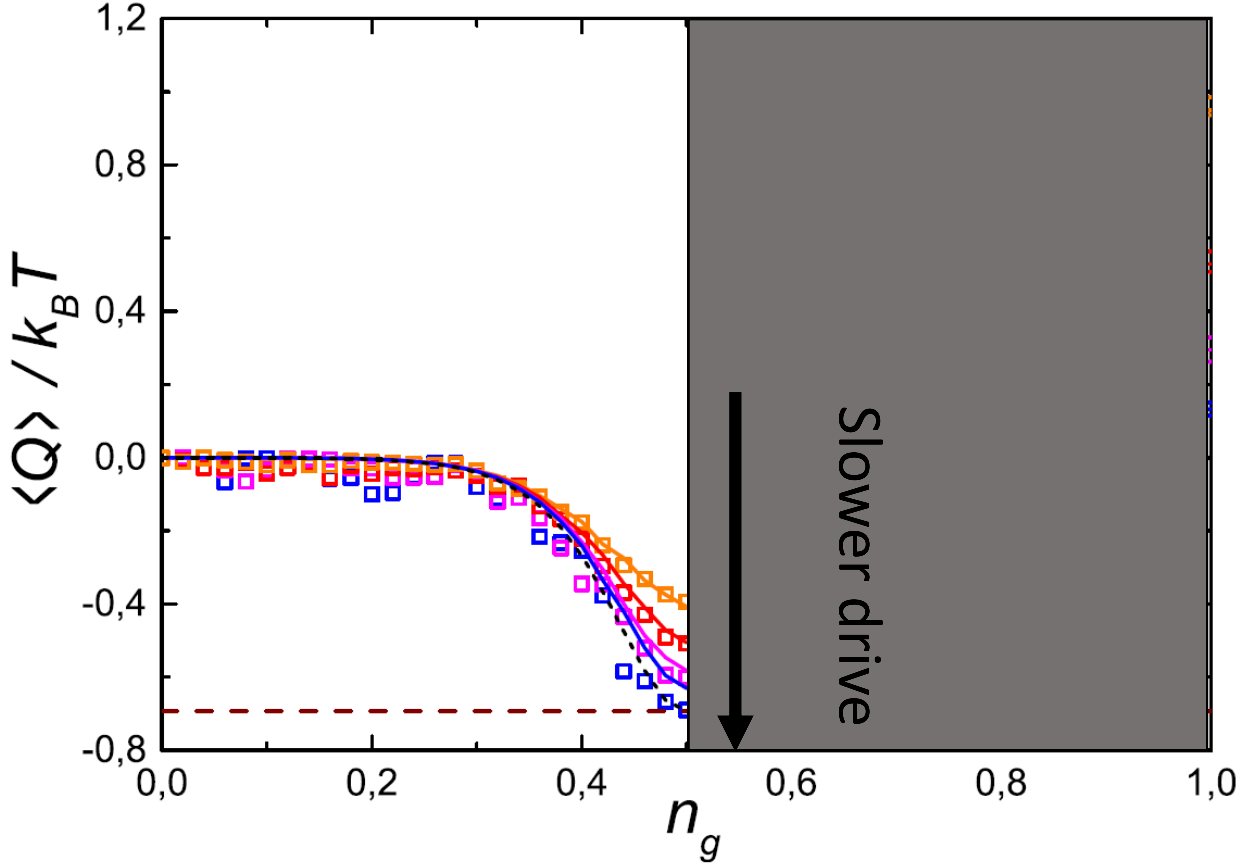




JVK, V. F. Maisi, J. P. Pekola & D. V. Averin, *PNAS* (2014)

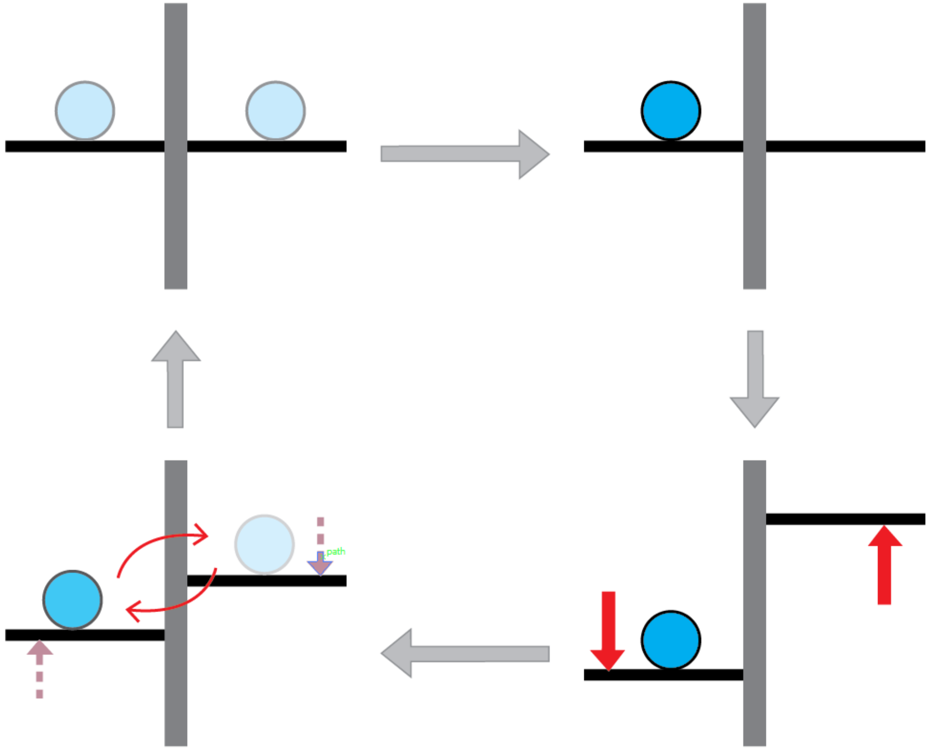
Szilard engine with a single electron





JVK, V. F. Maisi, J. P. Pekola & D. V. Averin, *PNAS* (2014)

Szilard engine with a single electron



Setup:

Single electron in box

Measurement:

Determine n

Feedback part 1:

Trap the electron

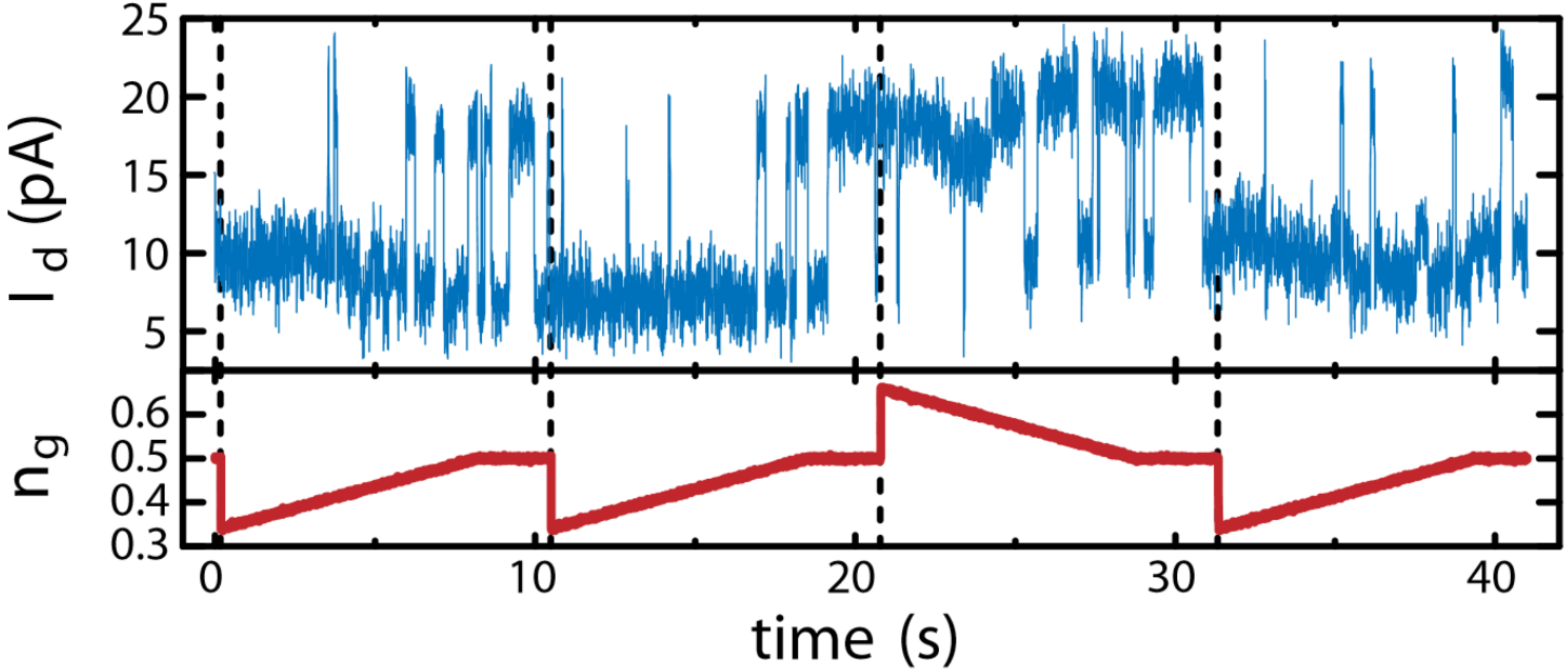
Feedback part 2:

Adiabatic expansion

Experimental realization

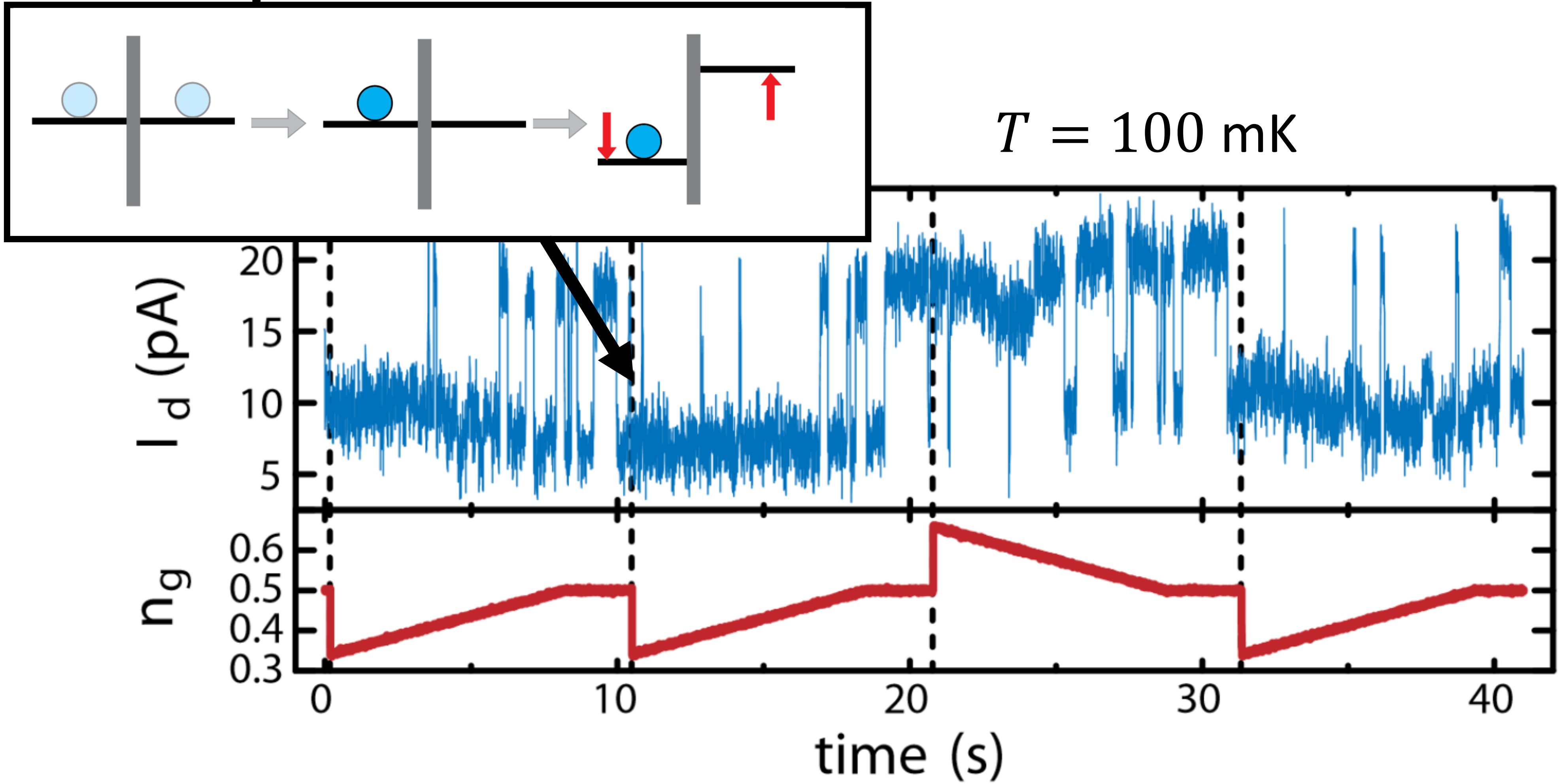
Four example traces

$T = 100$ mK



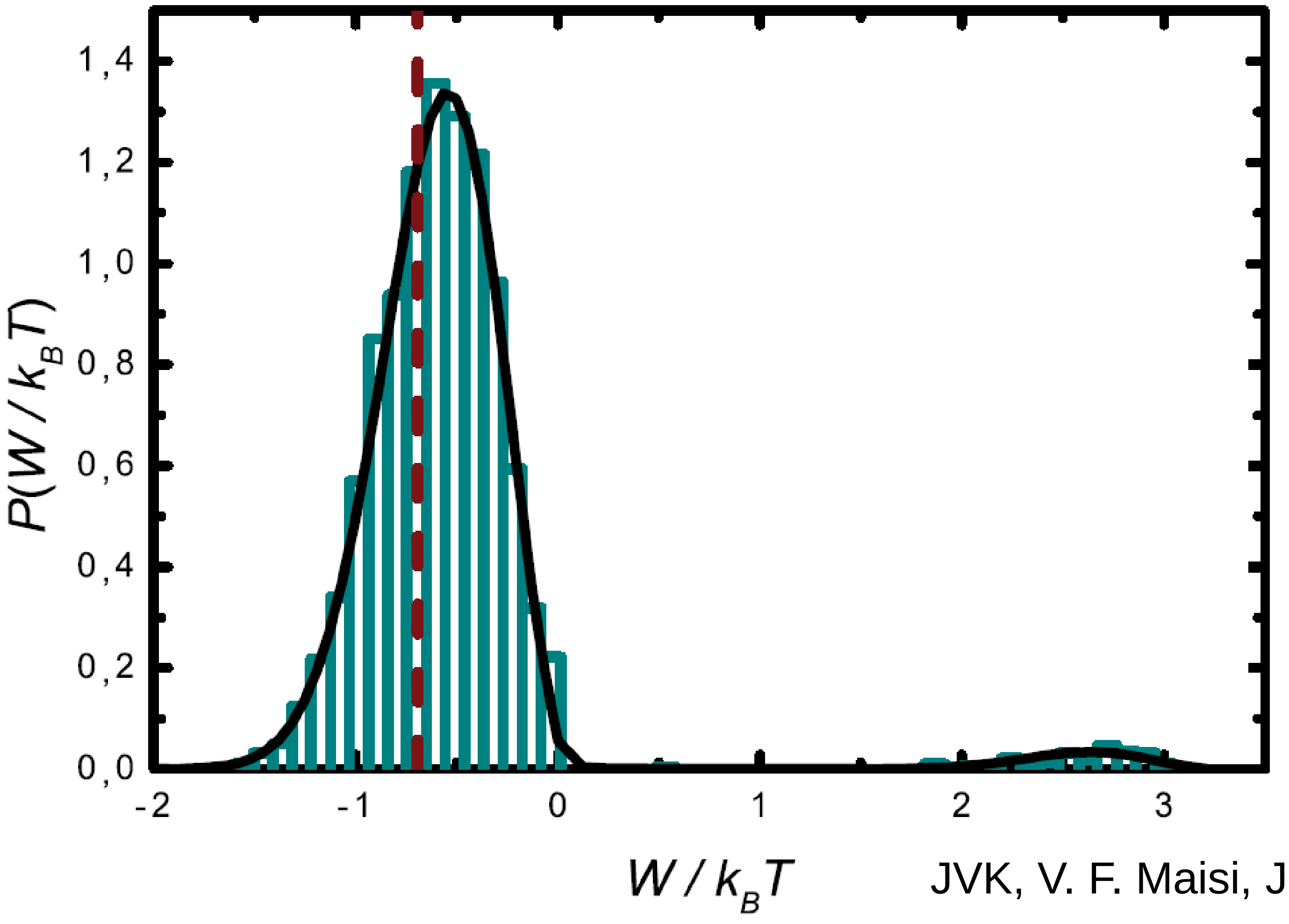
JVK, V. F. Maisi, J. P. Pekola & D. V. Averin, *PNAS* (2014)

Experimental realization



JVK, V. F. Maisi, J. P. Pekola & D. V. Averin, *PNAS* (2014)

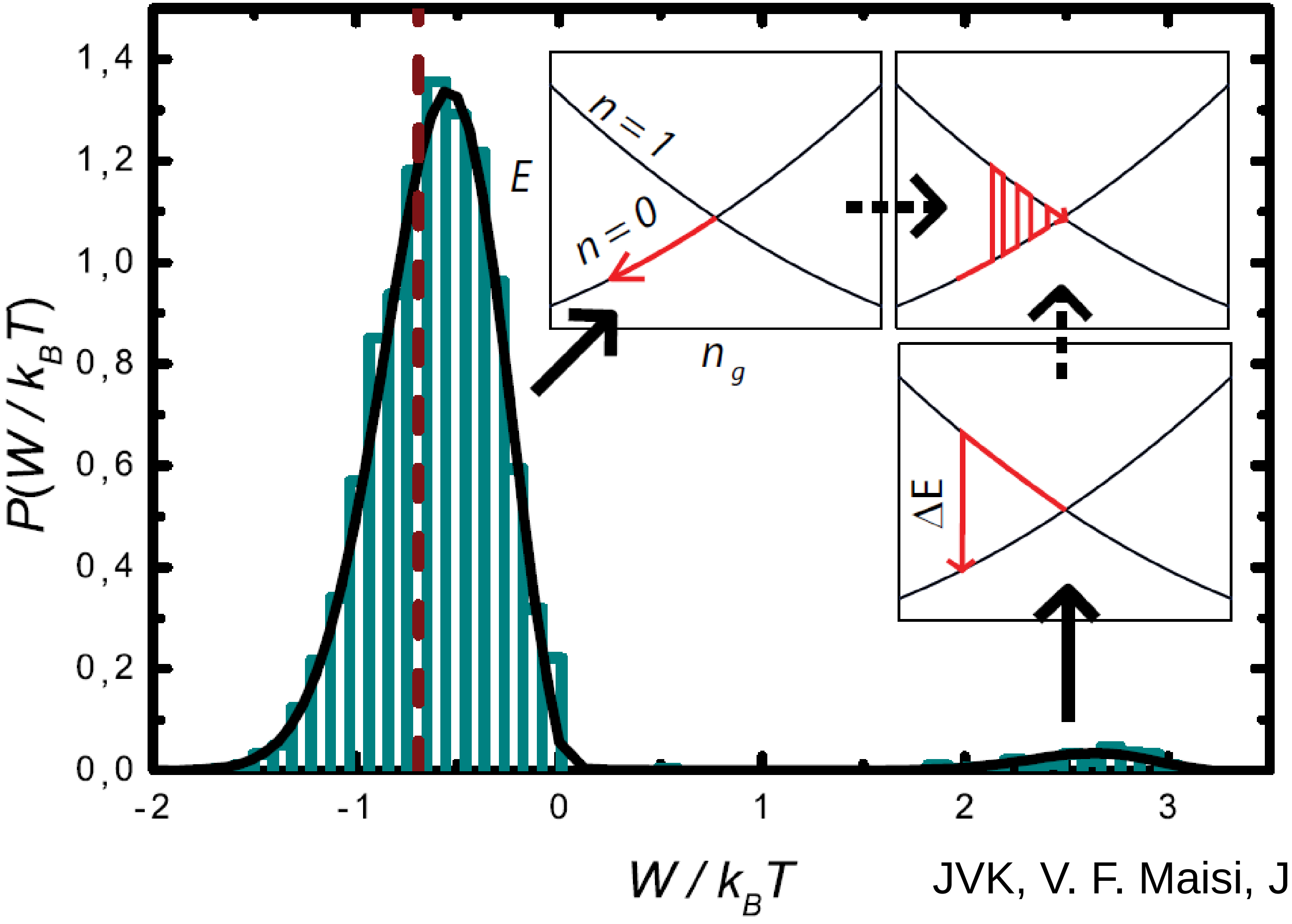
Distribution of work



$\sim$ 3000 realizations:
$\langle W \rangle \approx -0.75\, k_B T \log(2)$

JVK, V. F. Maisi, J. P. Pekola & D. V. Averin, *PNAS* (2014)

Distribution of work



~ 3000 realizations:
$\langle W \rangle \approx -0.75\, k_B T \log(2)$

Main peak:
$\langle W \rangle \approx -0.90\, k_B T \log(2)$

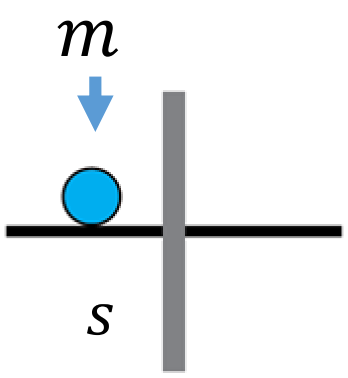
Errors dissipate energy

JVK, V. F. Maisi, J. P. Pekola & D. V. Averin, *PNAS* (2014)

Mutual information

State: s Measurement outcome: m

Usually $m = s$, but sometimes: $m \neq s$ → error!



Mutual information: $I = \log\left(P_{s|m}\right) - \log(P_s)$

$$P_{s|m=s} = 1: \quad I = -\log(P_s)$$
$$P_{s|m=s} = P_s: \quad I = 0$$

Fluctuation relation:

$$\left\langle e^{-(W - \Delta F)/k_B T - I} \right\rangle = 1$$

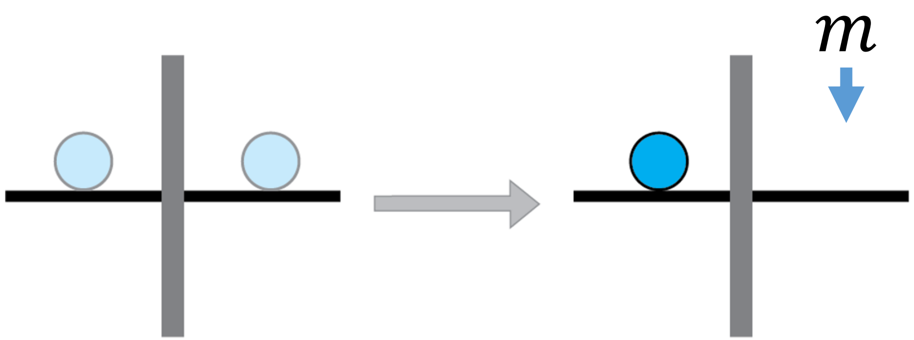
$$\langle W \rangle \geq \Delta F - k_B T \langle I \rangle$$

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

Errors in Szilard engine

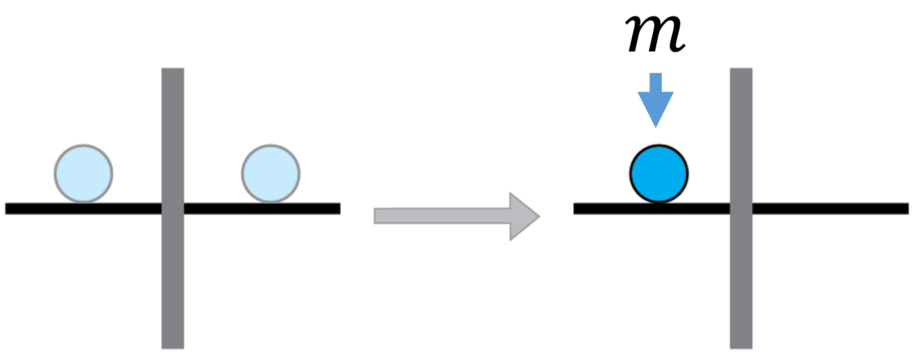
Two alternatives for I :

Error: $P_{n \neq m} = \varepsilon$



$$I = \log(\varepsilon) + \log(2)$$

$P_{n = m} = 1 - \varepsilon$

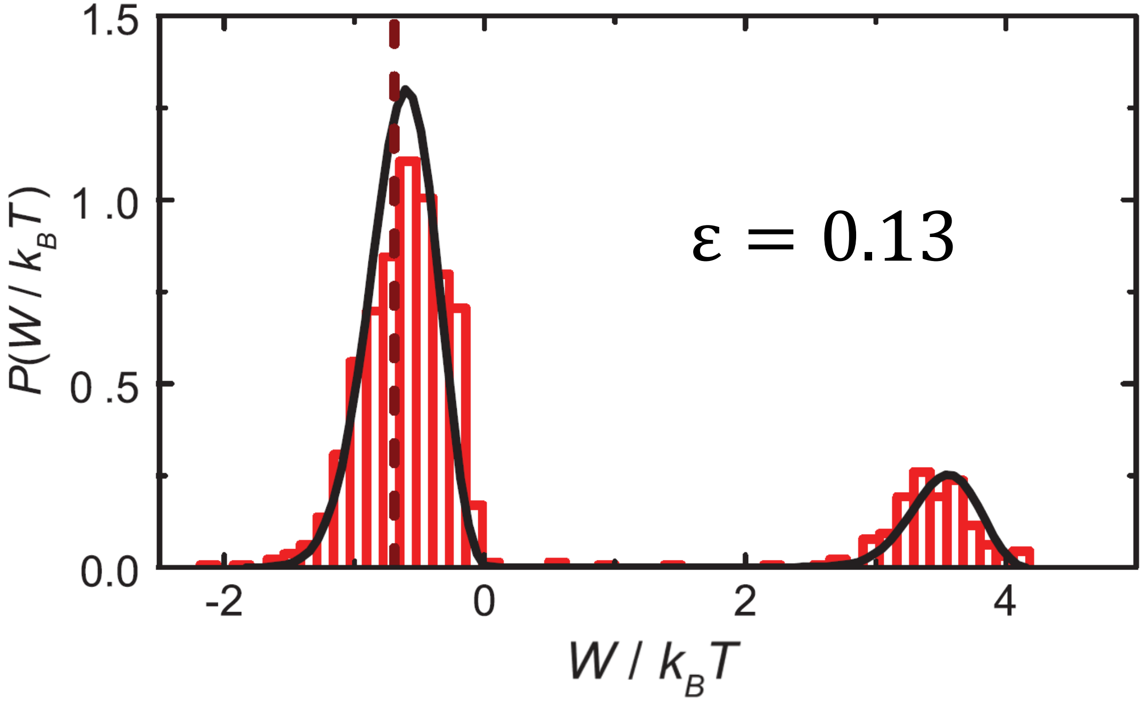


$$I = \log(1 - \varepsilon) + \log(2)$$

Experimental control of ε: average detector signal

Mutual information in a Szilard's engine

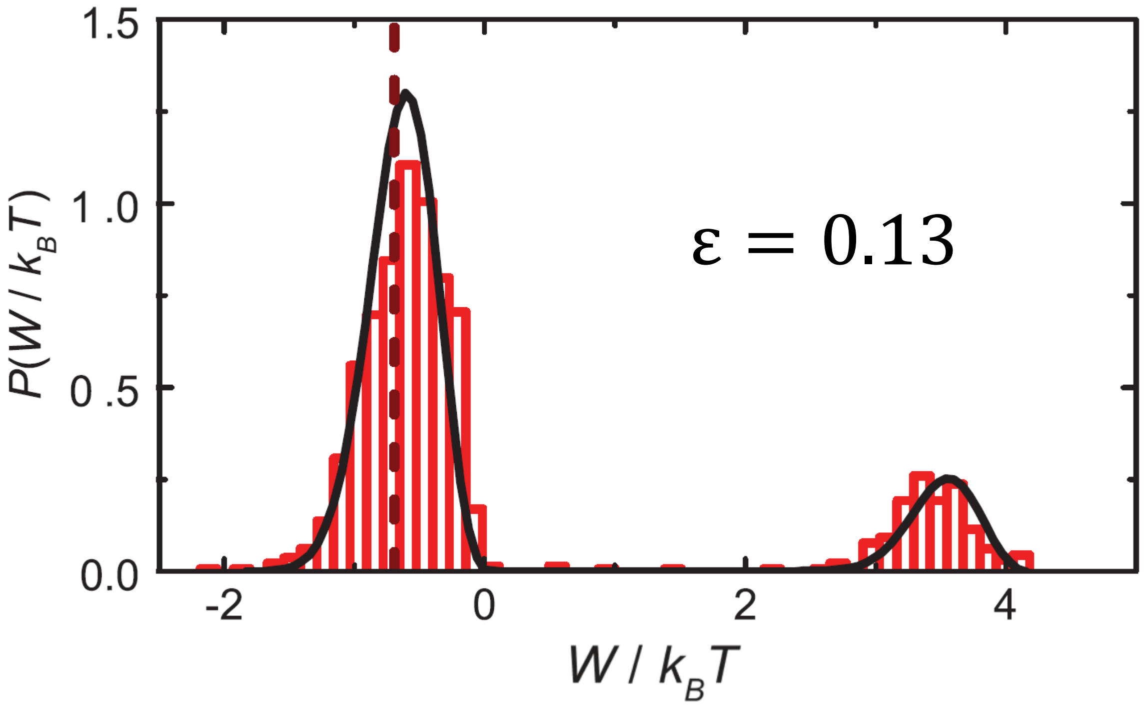
Work distribution



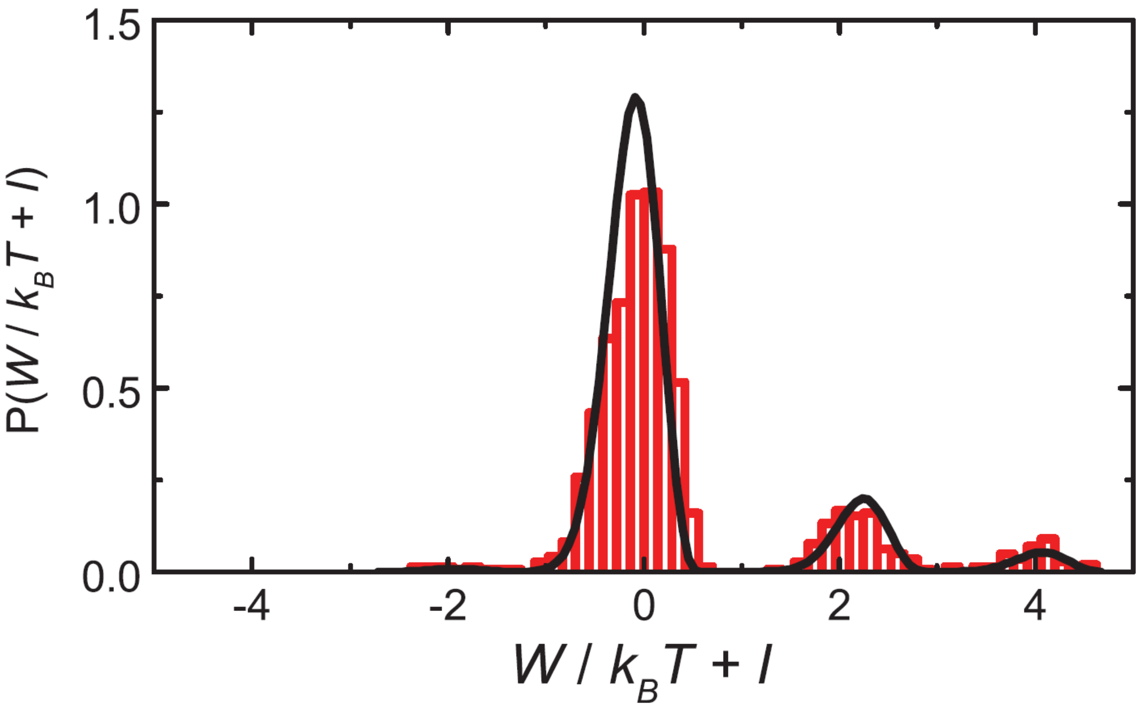
JVK, V. F. Maisi, T. Sagawa & J. P. Pekola, *PRL* (2014)

Mutual information in a Szilard's engine

Work distribution



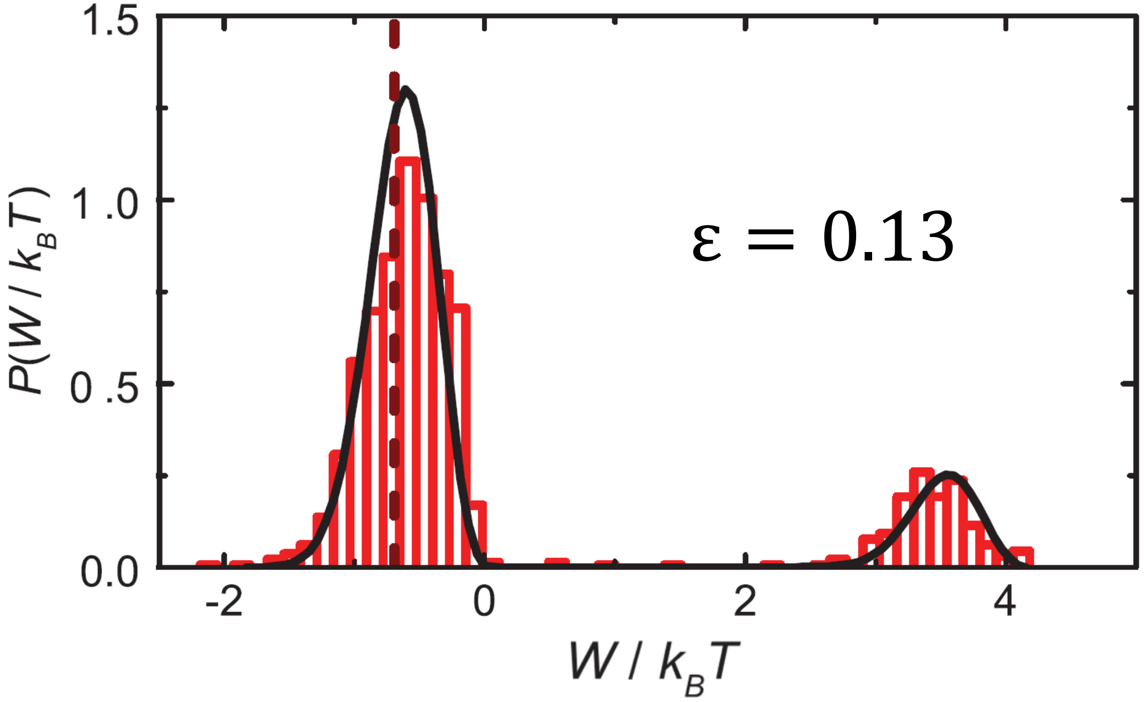
Work + information



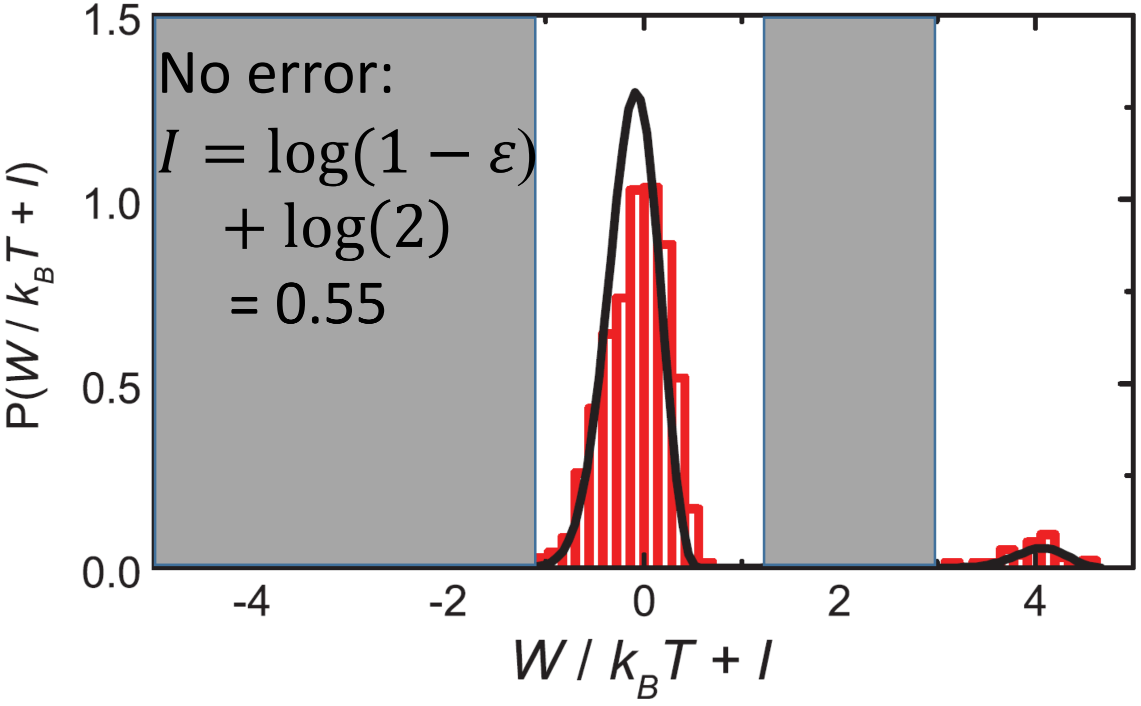
JVK, V. F. Maisi, T. Sagawa & J. P. Pekola, *PRL* (2014)

Mutual information in a Szilard’s engine

Work distribution



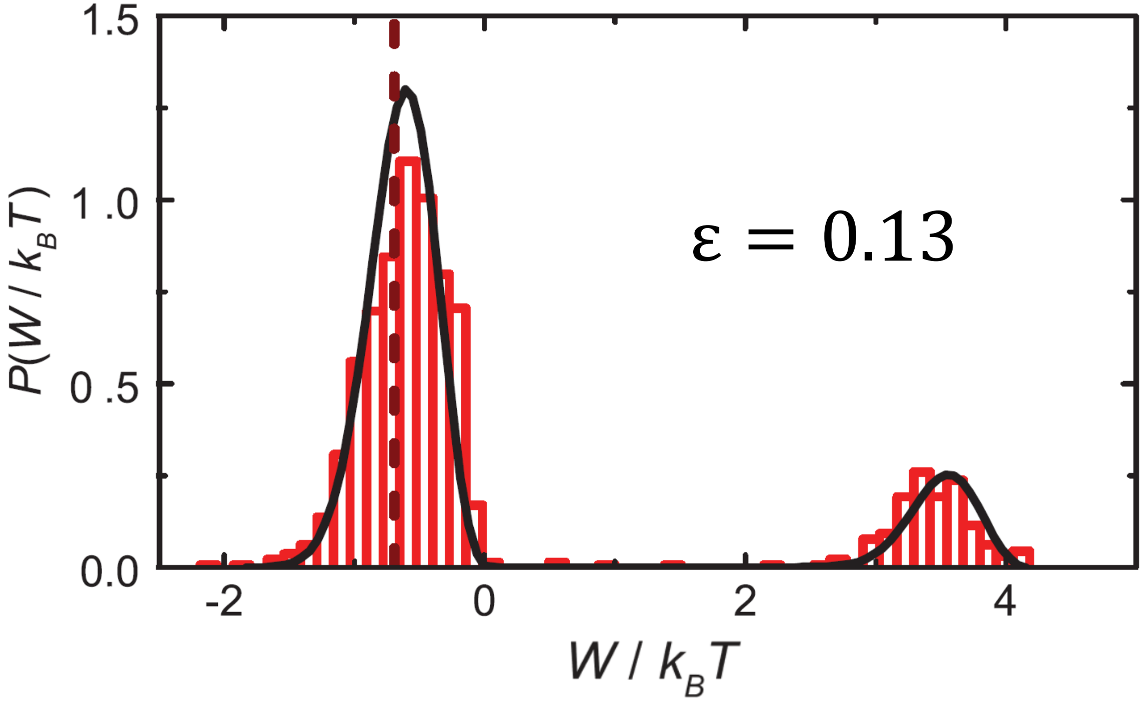
Work + information



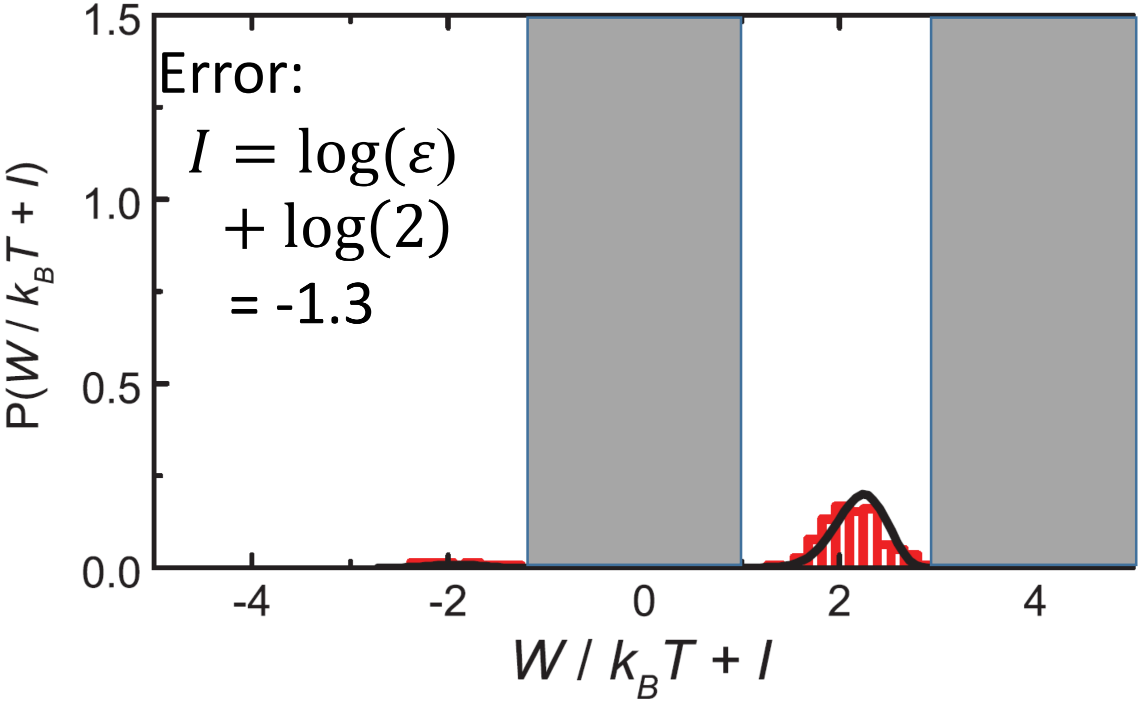
JVK, V. F. Maisi, T. Sagawa & J. P. Pekola, *PRL* (2014)

Mutual information in a Szilard's engine

Work distribution



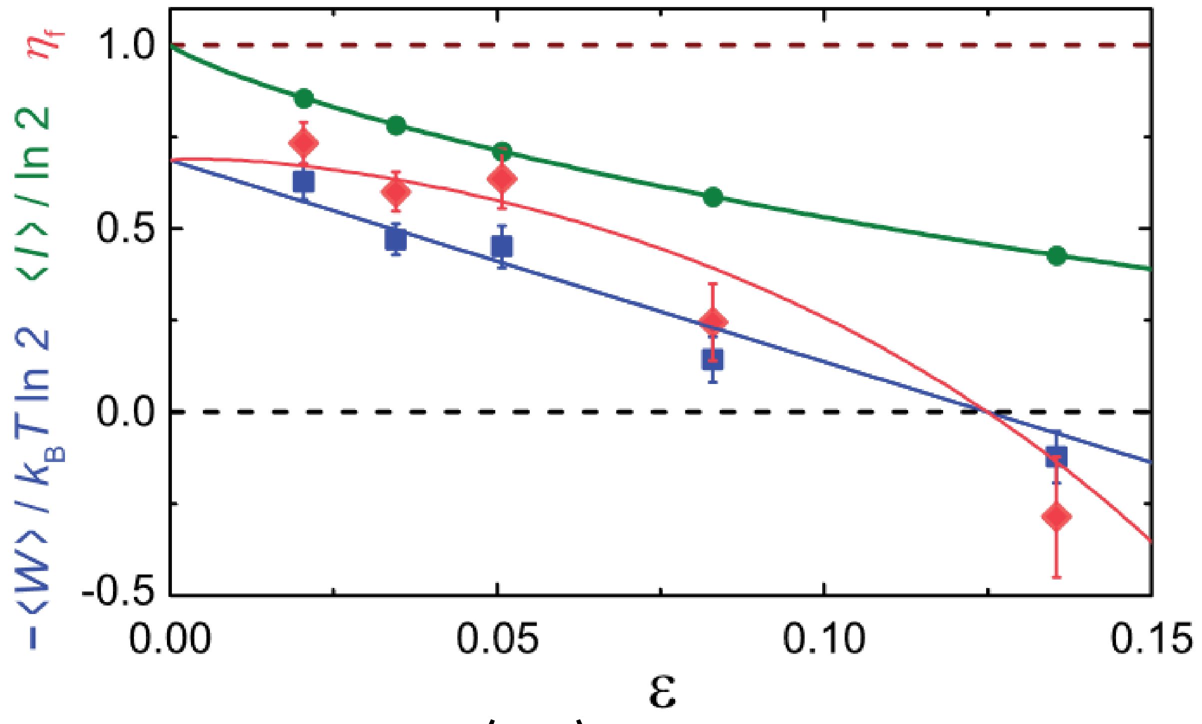
Work + information



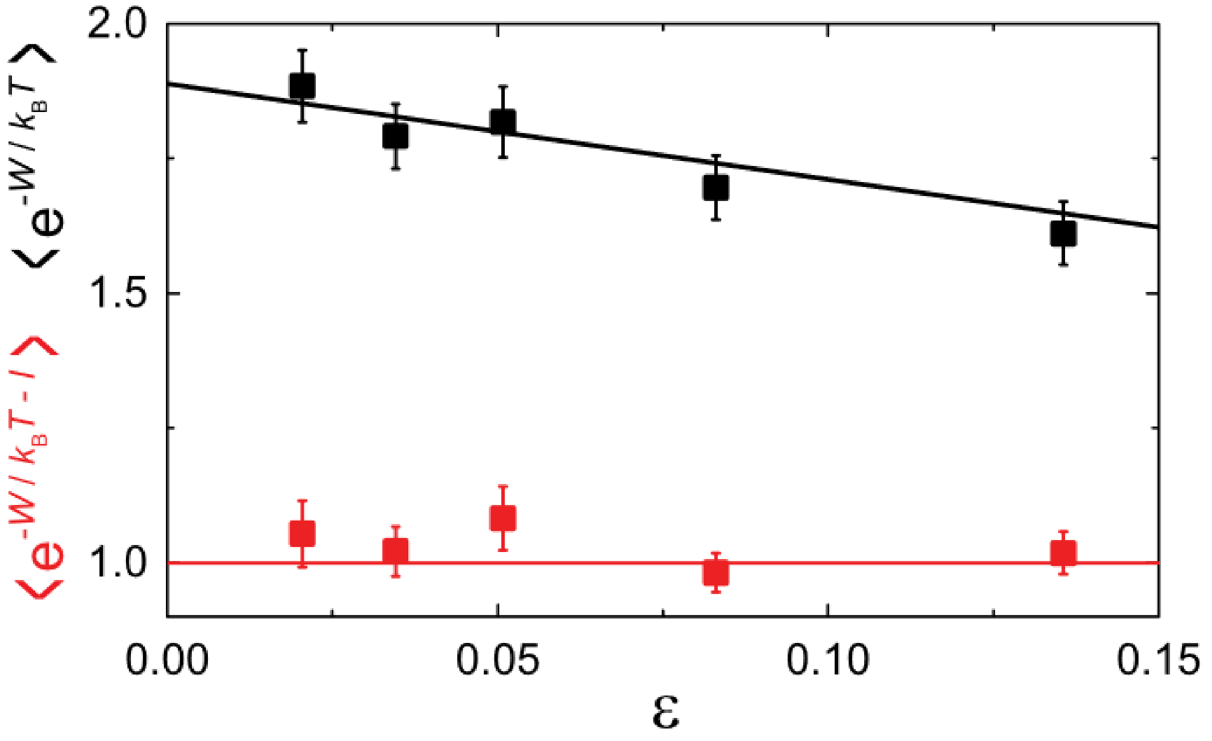
JVK, V. F. Maisi, T. Sagawa & J. P. Pekola, *PRL* (2014)

Mutual information in a Szilard's engine

Work, information, efficiency



Fluctuation relations



$$\eta_f = -\frac{\langle W \rangle}{k_B T \langle I \rangle}$$

JVK, V. F. Maisi, T. Sagawa & J. P. Pekola, *PRL* (2014)

Entropy & Maxwell’s demon

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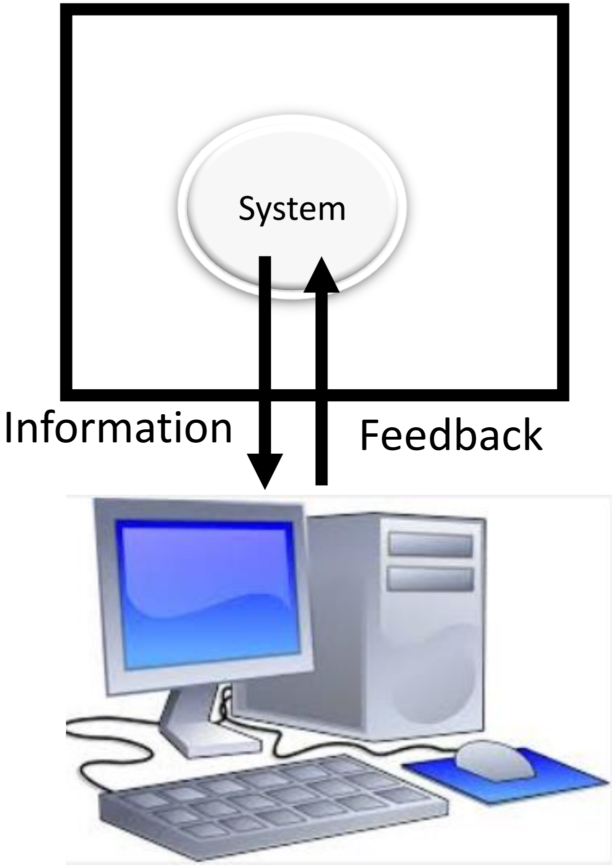
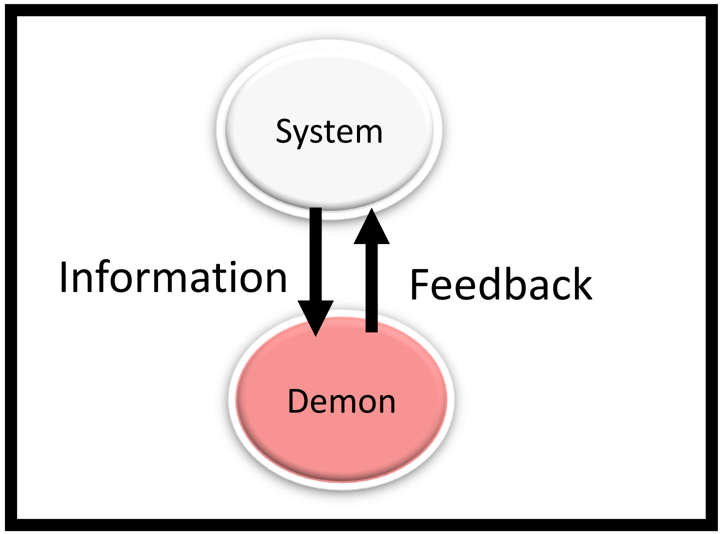
Autonomous Maxwell's demon



Non-autonomous



Autonomous

D. Mandal and C. Jarzynski, PNAS **109**, 11641 (2012)
P. Strasberg *et al.*, PRL **110**, 040601 (2013)

How to realize?
How to measure? Cooling?

Two coupled single electron transistors

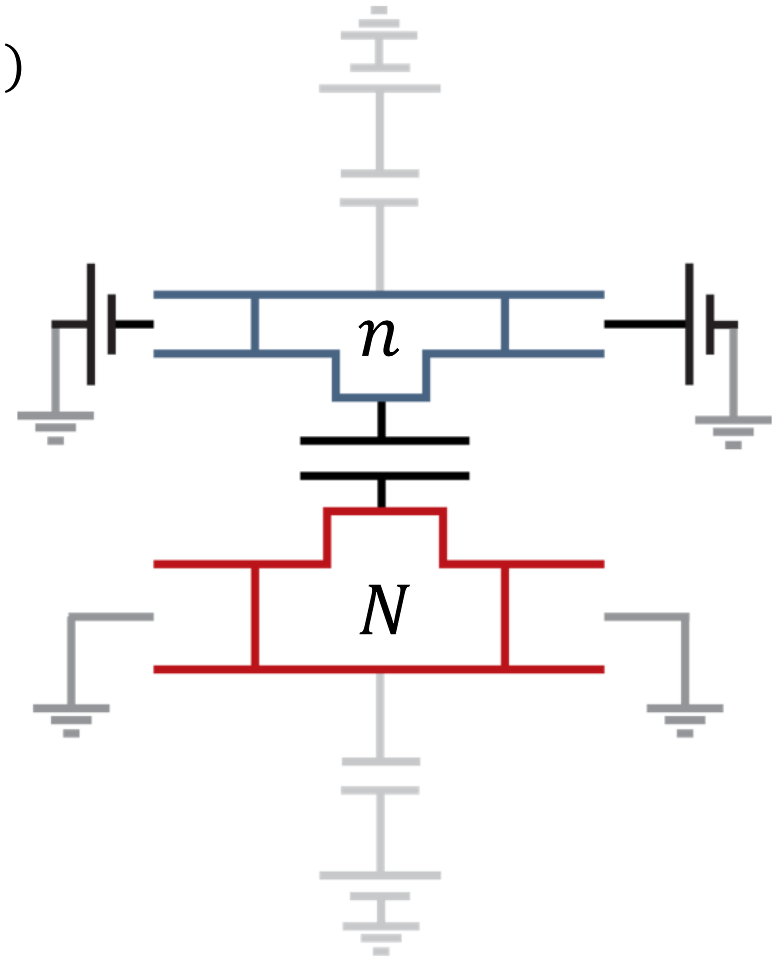
$$H = E_{C1}(n - n_g)^2 + E_{C2}(N - N_g)^2 + 2J(n - n_g)(N - N_g)$$

Operate at $n_g = N_g = \frac{1}{2}$:

$$H(0,1) = H(1,0) = -\frac{J}{2}$$

$$H(0,0) = H(1,1) = +\frac{J}{2}$$

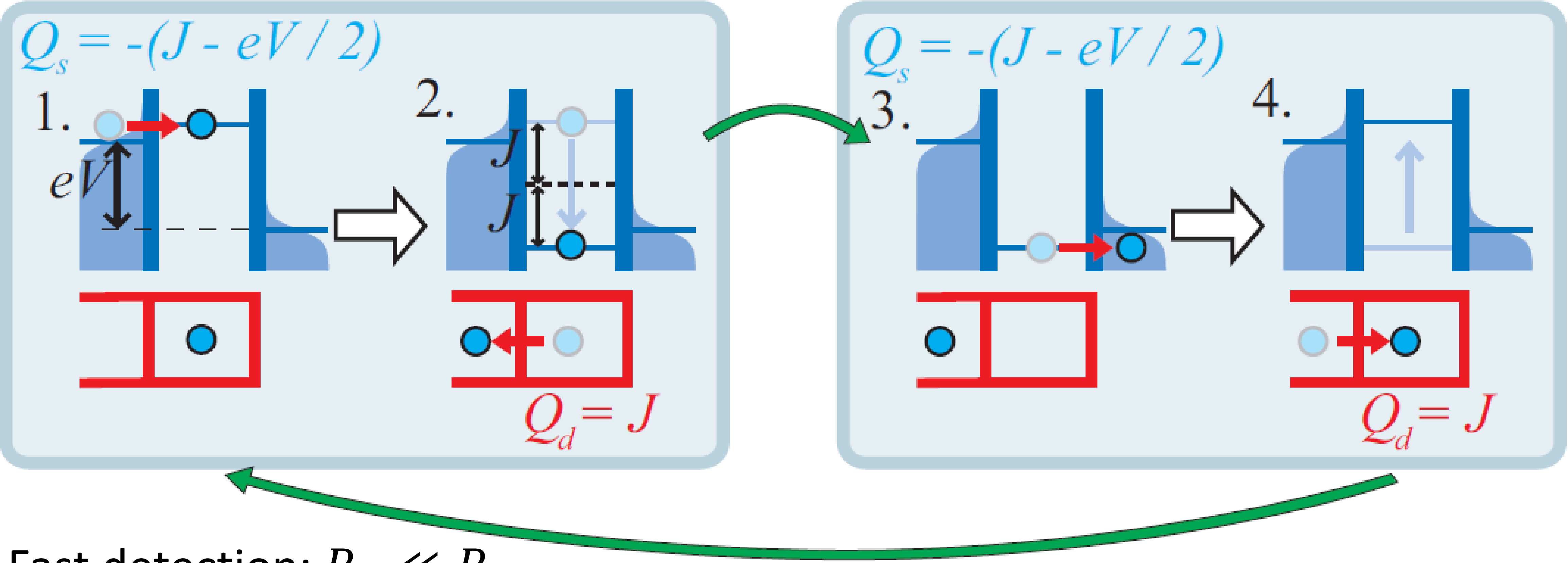
Chemical potential $\mu = \pm J$



Operation Cycle

Allow transitions: $eV > 0$

Error-free detection: $k_B T \ll J$



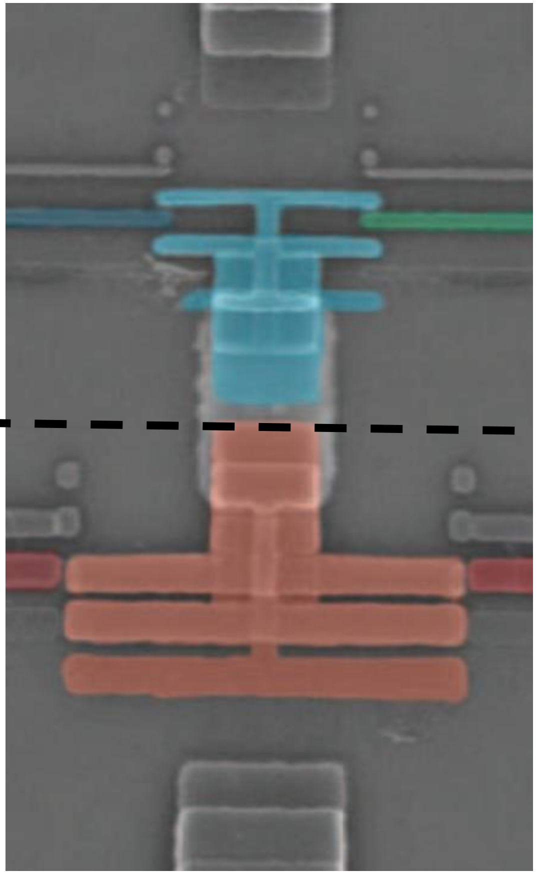
Fast detection: $R_d \ll R_s$

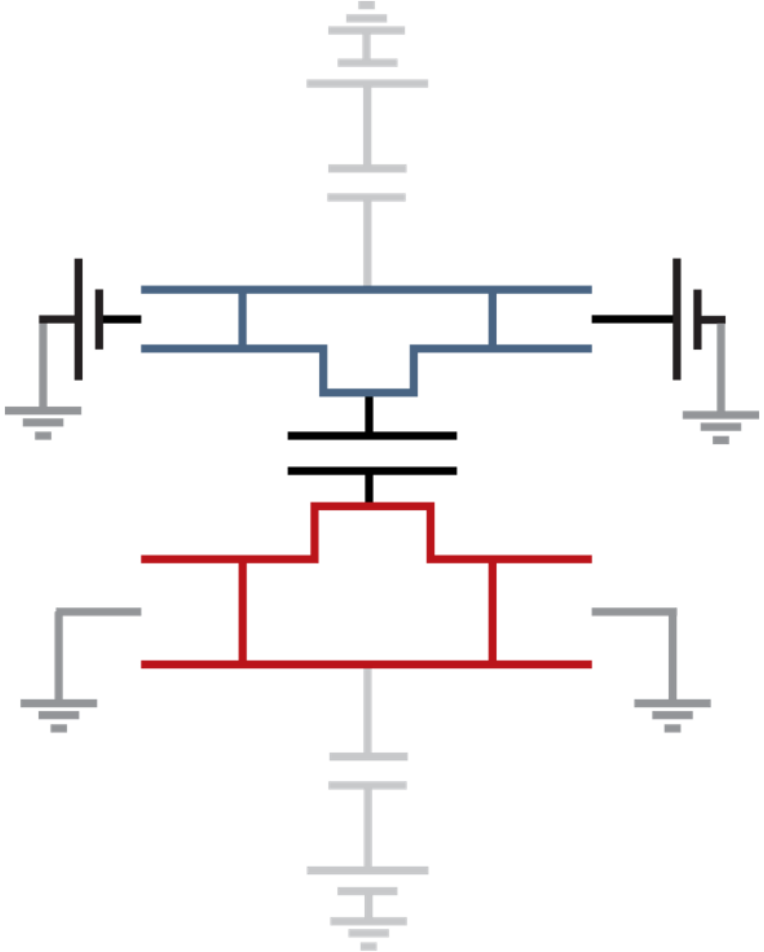
Small cotunneling: $R_d, R_s > h/e^2$

Implementation

System

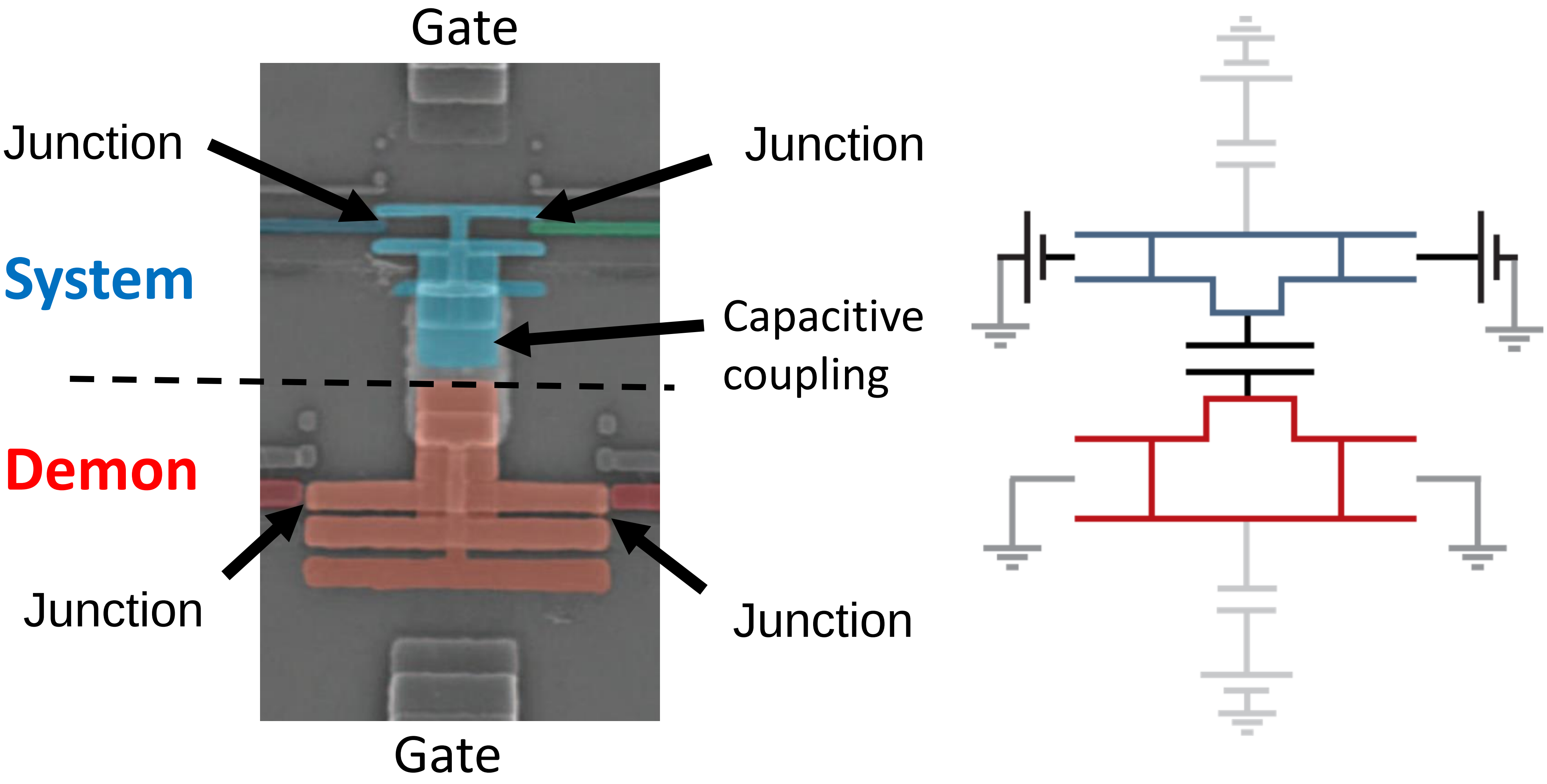
Demon





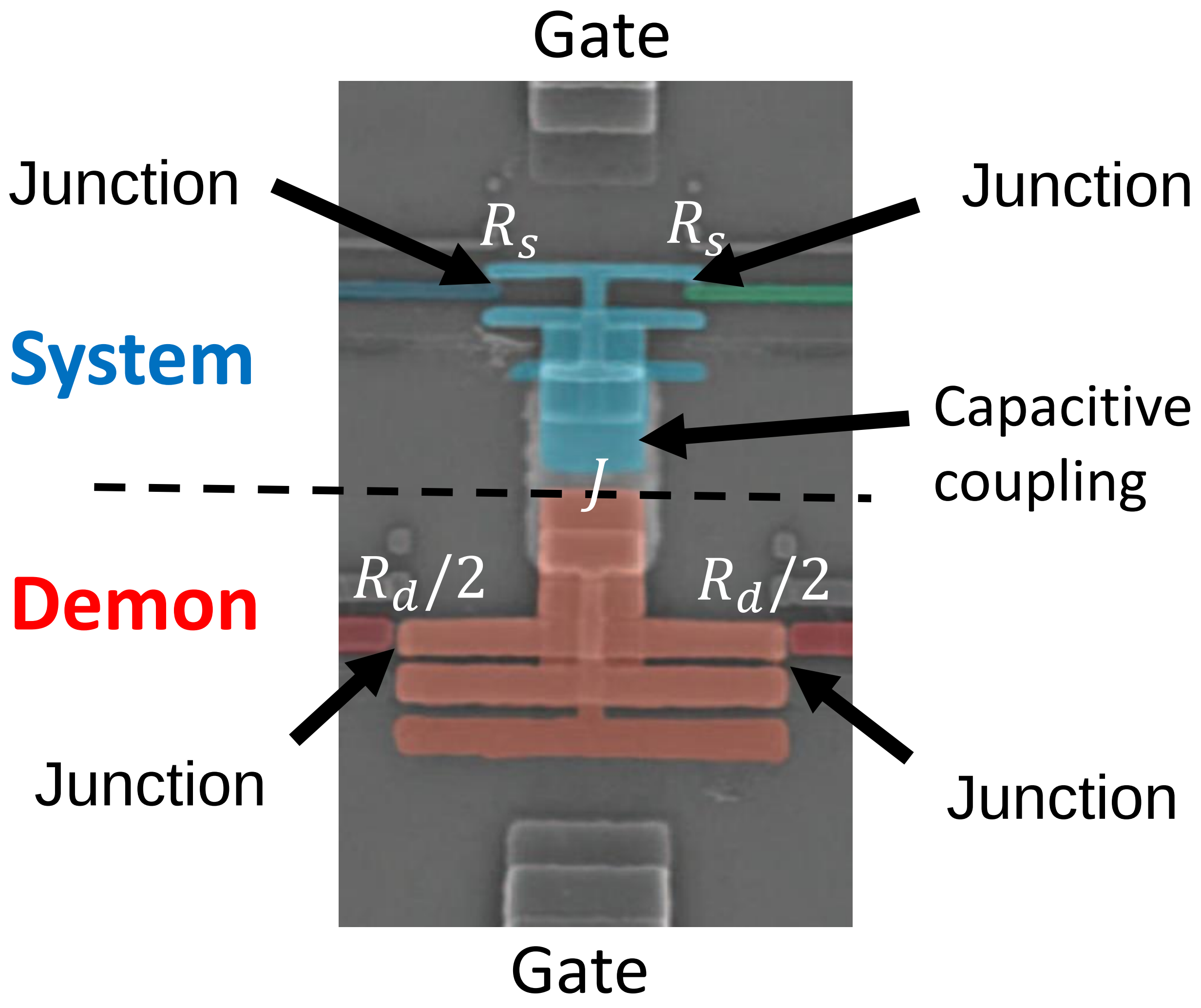
JVK, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and J. P. Pekola, PRL **115,** 260602 (2015)

Implementation



JVK, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and J. P. Pekola, PRL **115,** 260602 (2015)

Implementation



I / V characterization

$R_s \cong 580\ k\Omega$

$R_d \cong 43\ k\Omega$

$J \cong 350$ mK / k_B

$T \cong 50$ mK

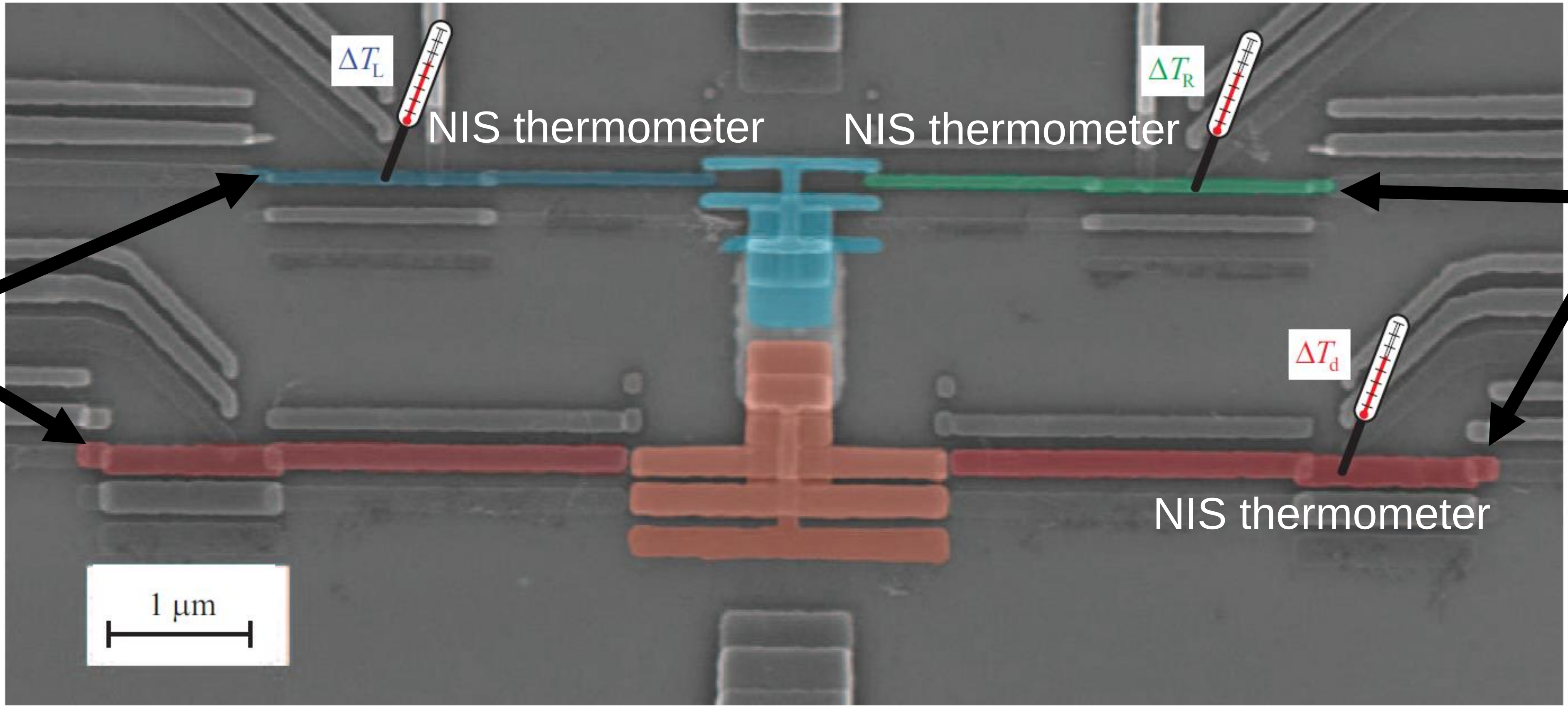
JVK, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and J. P. Pekola, PRL **115,** 260602 (2015)

Implementation

Thermometry:

M. Nahum and John M. Martinis
Appl. Phys. Lett. **63**, 3075 (1993)

Measure changes in T: $\frac{dQ}{dt} \propto \Delta T$

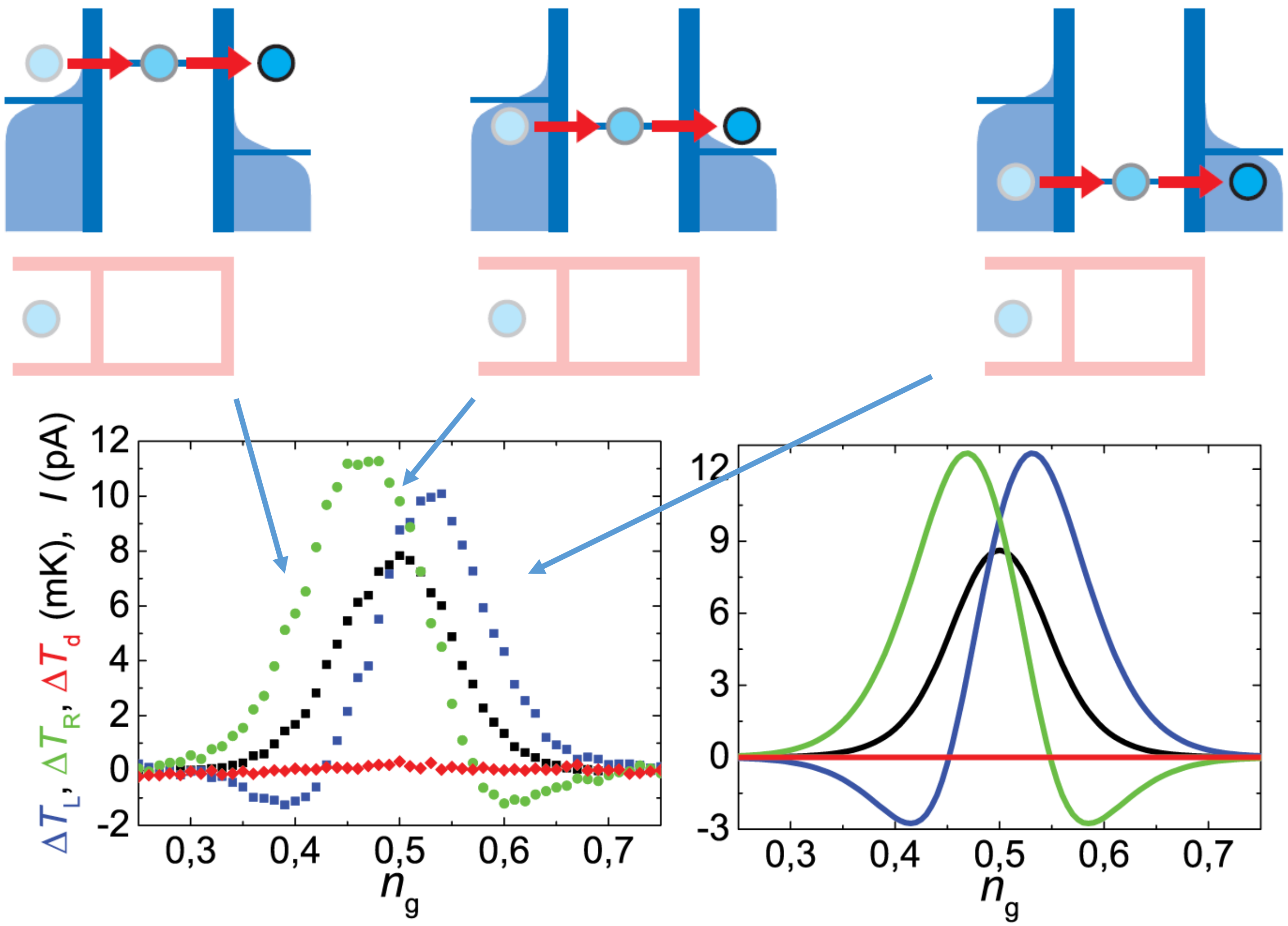


SN contacts:
Heat insulation

Heat
insulation

JVK, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and J. P. Pekola, PRL **115,** 260602 (2015)

Performance: demon inactive ($N_g = 0$)



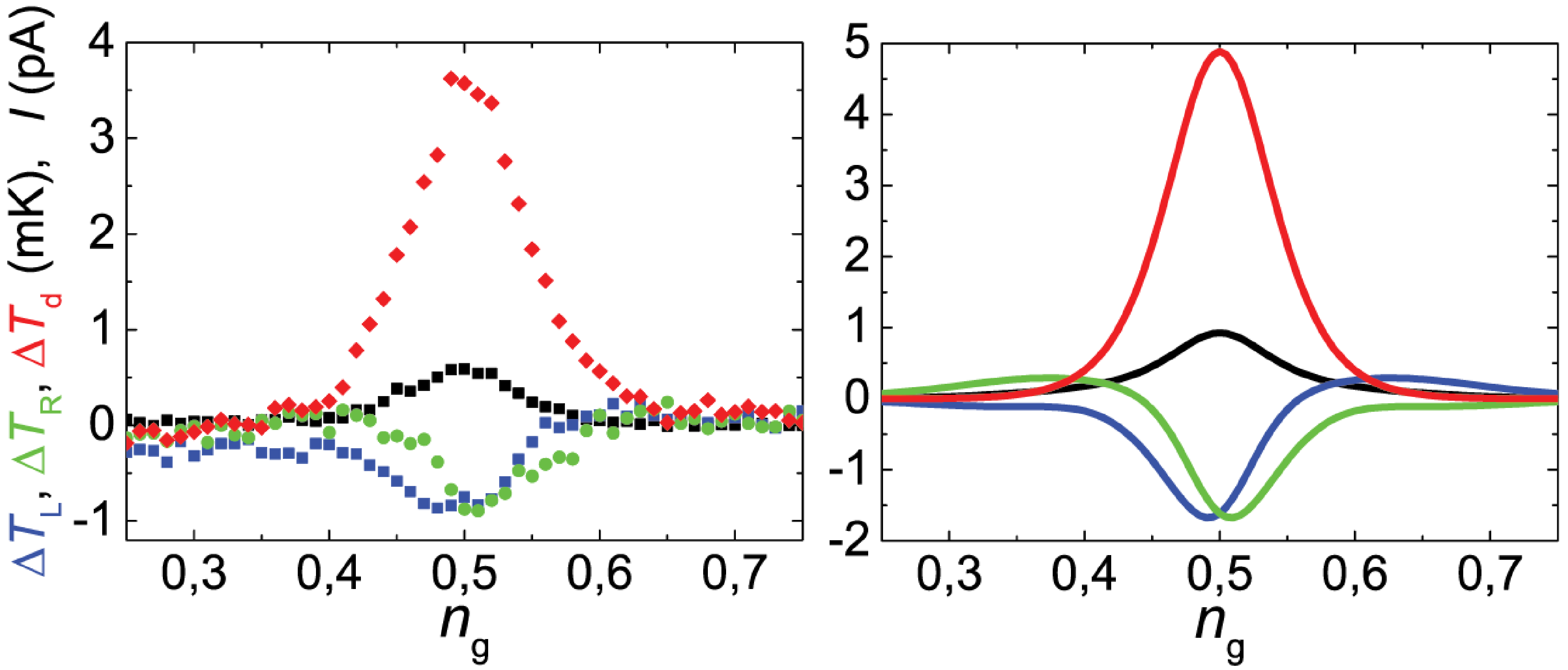
Single-sided cooling of L / R at the expense of heating the other end

J. P. Pekola, JVK, D. V. Averin, PRB **89**, 081309 (2014)
A. V. Feshchenko, JVK, J. P. Pekola, PRB **90**, 201407(R) (2014)

No effect on the demon

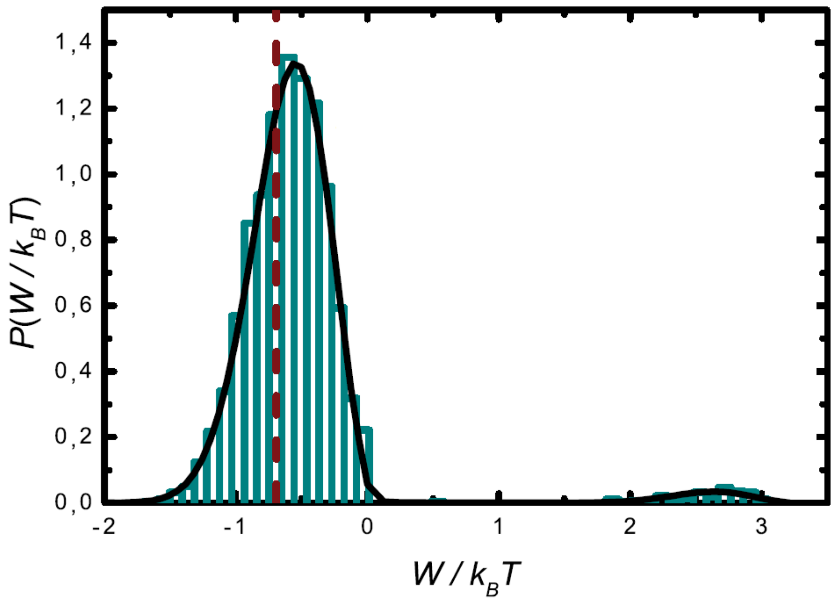
Performance: demon active ($N_g = 1/2$)

System cooling down, heat in the demon

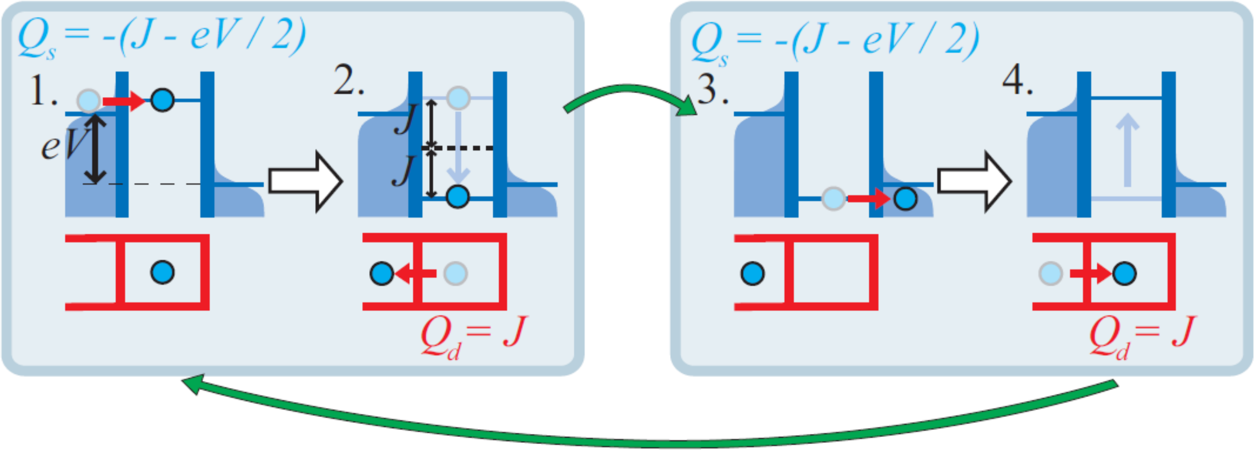


JVK, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and J. P. Pekola, PRL **115,** 260602 (2015)

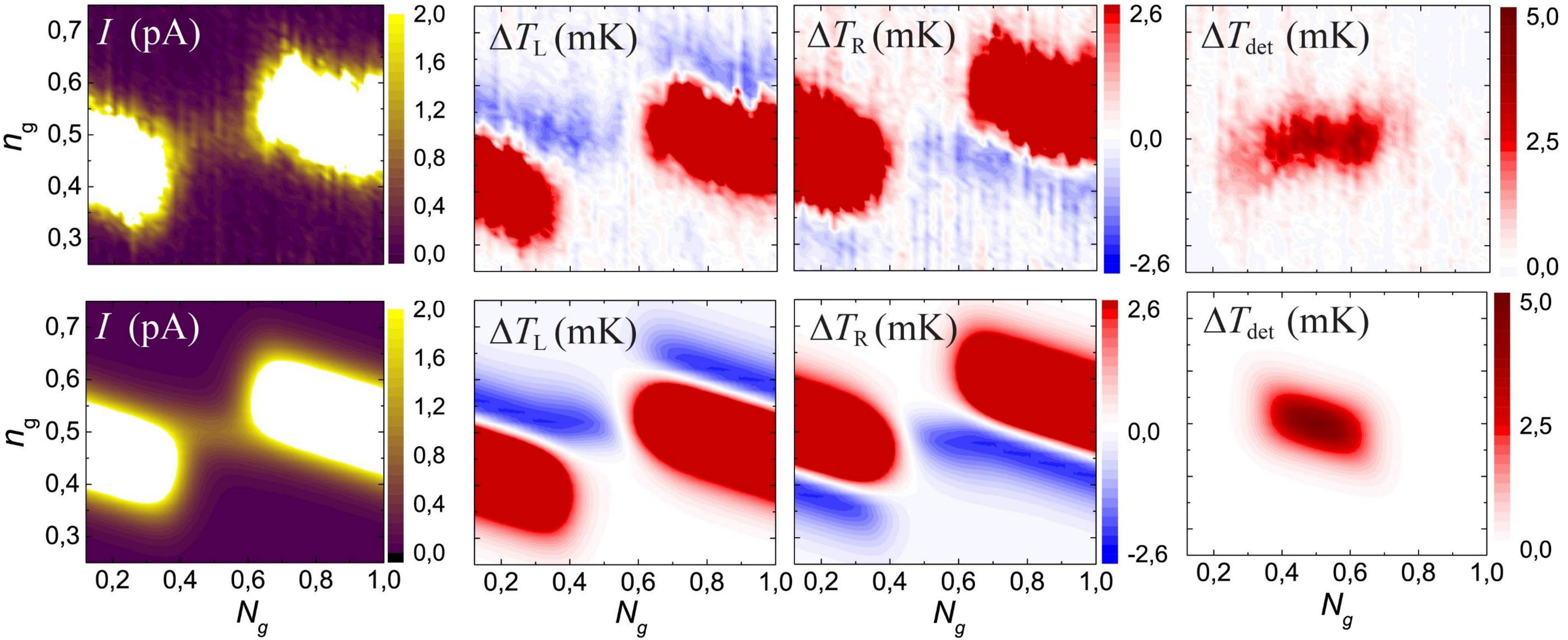
Conclusions & outlook



- One bit of information converted to energy
- Role of mutual information demonstrated
- Autonomous Maxwell's demon: information engine with fast operation



Gate modulation



Second law for Maxwell's demon

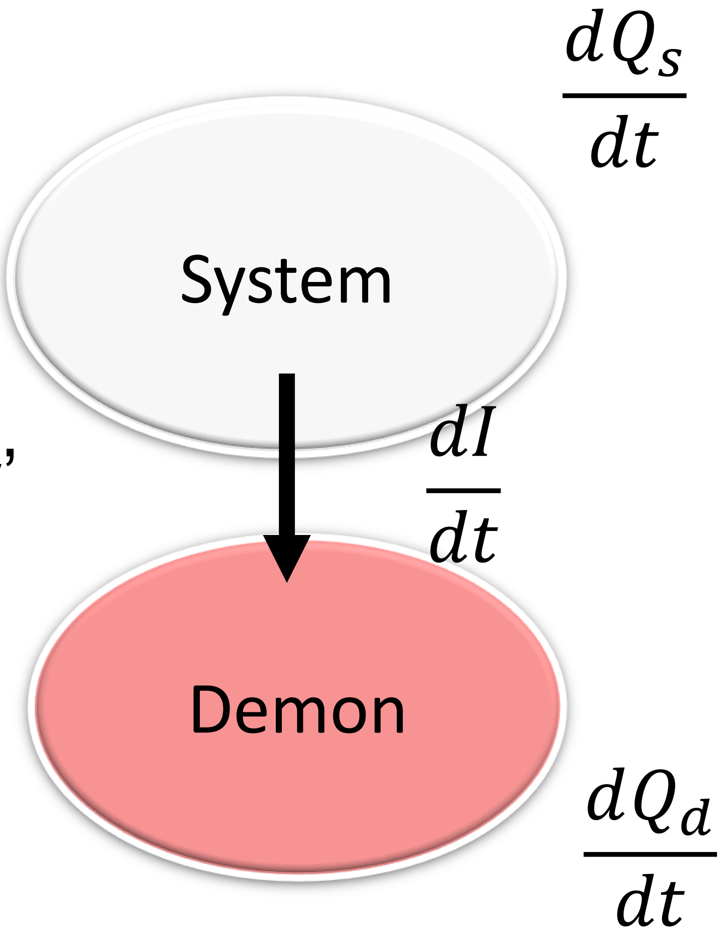
J. M. Horowitz, M. Esposito, PRX **4**, 031015 (2014)

$$\frac{dS_s}{dt} + \frac{dQ_s}{dt}/T \geq 0 \qquad \frac{dS_d}{dt} + \frac{dQ_d}{dt}/T \geq 0$$

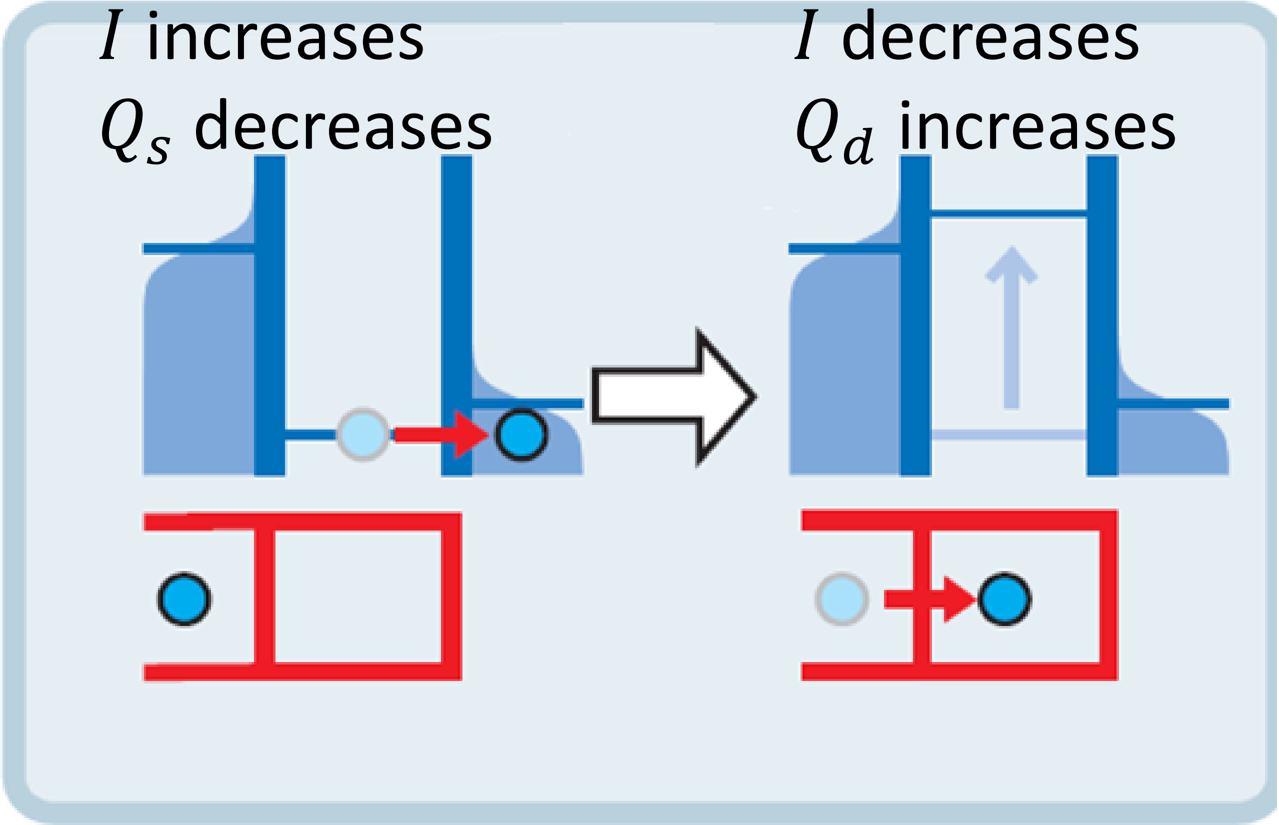
Closed loop: $\frac{dS_d}{dt} = -\frac{dS_s}{dt} \equiv \frac{dI}{dt}$, 'information flow'

Cooling and heating bound by $\frac{dI}{dt}$:

$$-\frac{dQ_s}{dt} \leq \frac{dI}{dt}T \qquad \frac{dQ_d}{dt} \geq \frac{dI}{dt}T$$



Information Flow



Fast demon:

$$P(n,N) = \frac{1}{Z} e^{-\frac{E(n,N)}{k_B T_d}}$$

Detailed balance:

$$\frac{dI}{dt} = \frac{dQ_d}{dt} \frac{1}{T_d}$$

Information flow can be measured