# Stochastic thermodynamics in single electron circuits

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arXiv:1712.01693

Quantum thermodynamics, KITP, June 26, 2018

# Outline

- **General introduction:**
  - ✓ Definition of entropy. Fluctuation relations
  - ✓ Coulomb blockade and thermodynamics
  - ✓ Jarzynski and Crooks relations in single-electron circuits
  - ✓ Realization of Maxwell's Demons
  - ✓ Quantum calorimetry and heat transport
- **Nonequilibrium steady state**
  - ✓ Negative entropy events
  - ✓ Statistics of finite-time minima of entropy production
- **Experimental verification of theoretical results**
  - ✓ Double-dot structure as a minimal physical model
  - ✓ Boundaries for entropy production records
  - ✓ Relation with the heat absorbtion
- **Summary and outlook**

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# Stochastic thermodynamics

**Gibbs-Shanon system entropy**

$$S_{sys} = -\ln P(n(t);t)$$

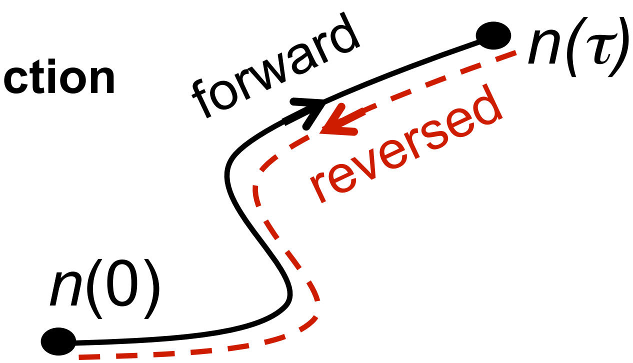
$$\langle S_{sys} \rangle = -\langle \ln P(n(t);t) \rangle = S_{Gibbs}(t) = \frac{U(t) - F(t)}{T}$$

$$\Delta S_{Gibbs} = \frac{\Delta U - \Delta F}{T}$$

**Heat and microscopic reversibility (local detailed balance)**

$$Q(\tau) = \int_0^\tau \frac{\partial H}{\partial t} dt \qquad \frac{p_{i \to j}}{p_{j \to i}} = e^{-(U_j - U_i)/T}$$

$$\frac{P(\{n(t)\} \,|\, n(0))}{P_R(\{n(\tau - t)\} \,|\, n(\tau))} = e^{-Q(\tau)/T}$$




**Stochastic total entropy production**

$$\Delta S = \Delta S_{sys} + Q(\tau)/T$$

$$\Delta S = \ln \frac{P(\{n(t)\})}{P_R(\{n(\tau - t)\})}$$

**Measure of irreversibility**

**Crooks relation**

$$\frac{P(\Delta S)}{P_R(-\Delta S)} = e^{\Delta S}$$

**Jarzynski equality**

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

**2nd law of thermodynamics**

$$\langle \Delta S \rangle \geq 0$$

G. Crooks PRE **60**, 2721(1999); C. Jarzynski J.Stat.Phys. **96**, 415 (1999); U. Seifert, PRL **95,** 040602 (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)

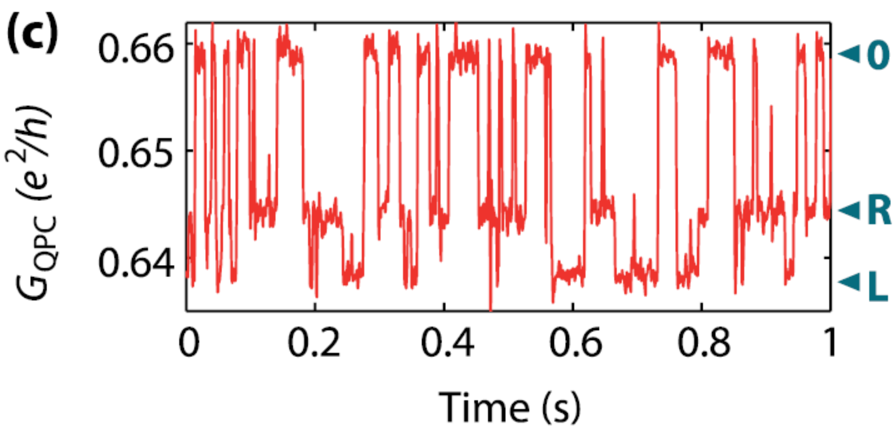
$$\langle e^{-\Delta S/k_B} \rangle = 1$$

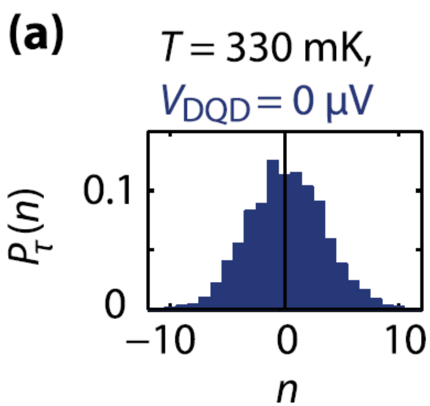
G. Bochkov, Yu. Kuzovlev, JETP 1977, Physica A 1981

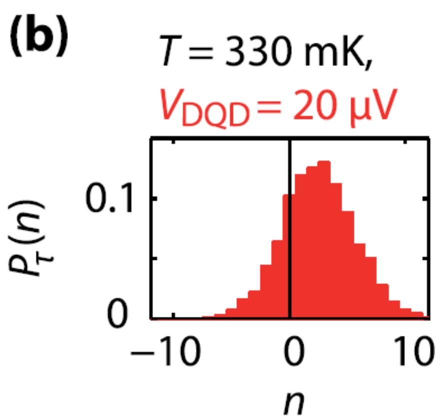
*Electric circuits: Experiment on a double quantum dot*

Y. Utsumi et al. PRB **81**, 125331 (2010),

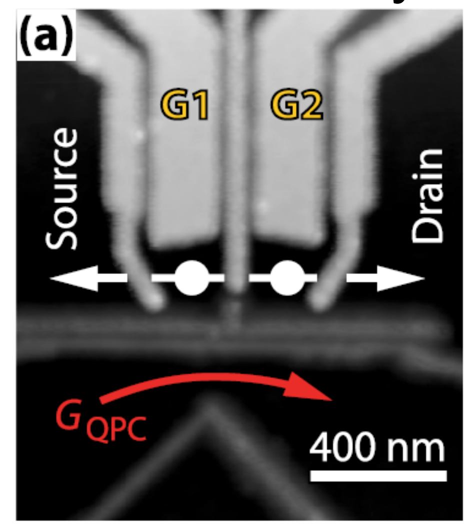
B. Kung et al. PRX **2**, 011001 (2012)




## Nonequilibrium steady state




## Crooks as detailed balance

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

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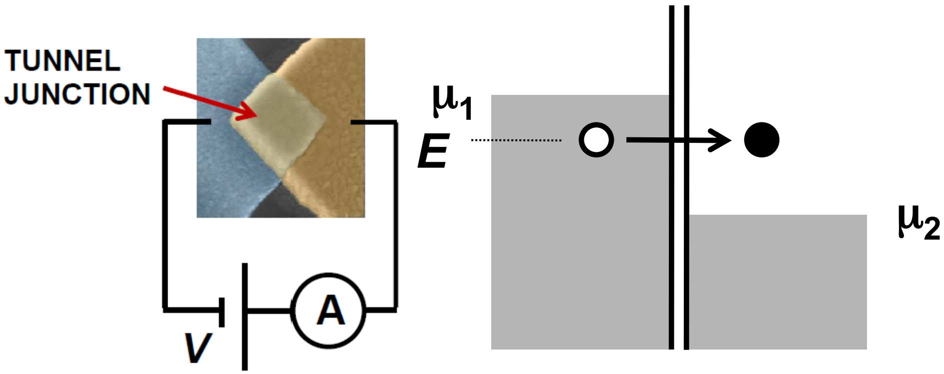
# Dissipation in circuit transport through a barrier - tunneling



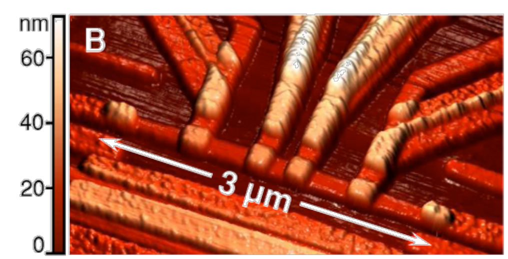

Dissipation generated by a tunneling event in a junction biased at voltage $V$

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

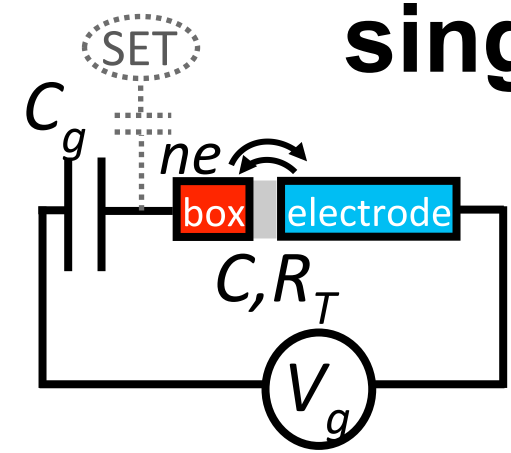
$\Delta Q = T\Delta S$ is first quickly distributed among the electron system, then - to the lattice by electron-phonon scattering

For average current $I$ through the junction, total average power dissipated is naturally Joule heating power

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

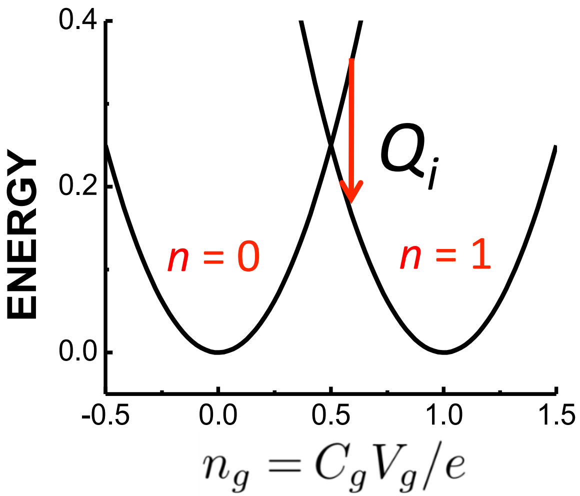


# Thermodynamics and dissipation in single-electron transitions




Heat generated in a tunneling event *i*:

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



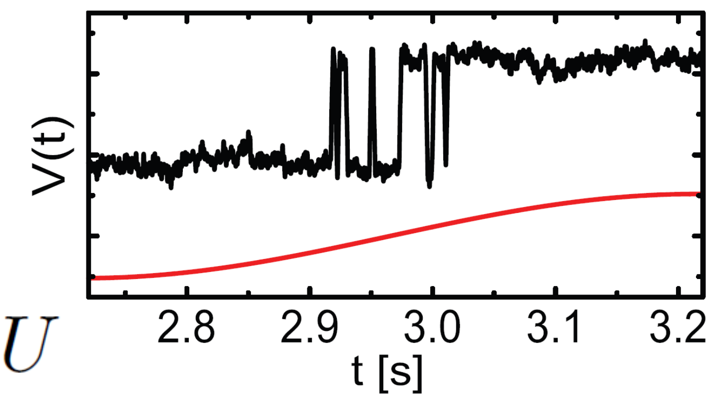

Total heat generated in a process:

$$Q = \sum_i Q_i$$

Work in a process:

$$W = Q + \Delta U$$

Change in internal (charging) energy




| - charge state n

| - gate voltage $n_g$

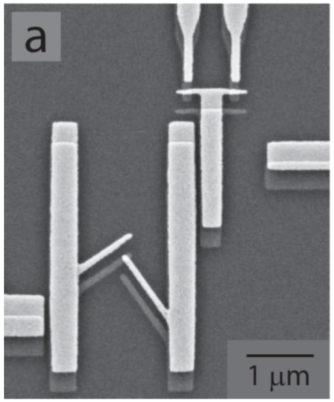
$$H = E_C(n - n_g)^2$$

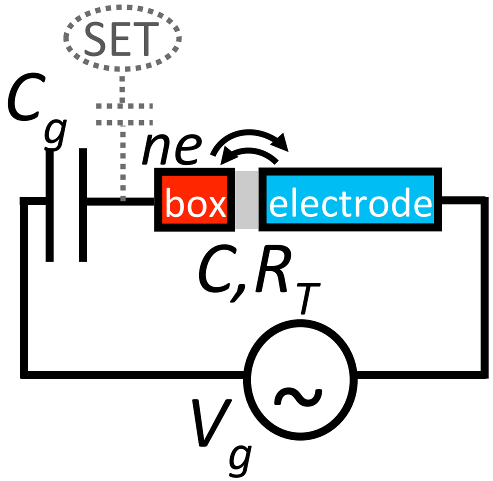
$$U = H(n(t), n_g(t)) - H(n(0), n_g(0))$$

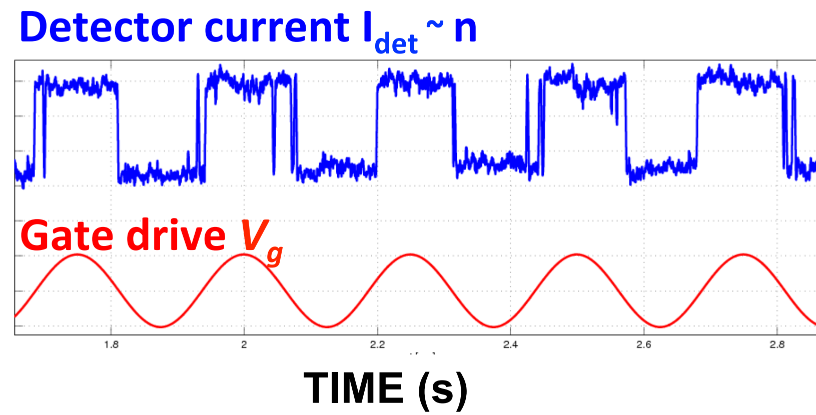
D. Averin and J.Pekola EPL **96**, 67004 (2011);
J. Pekola and O.-P. Saira JLTP **169**, 70 (2012).

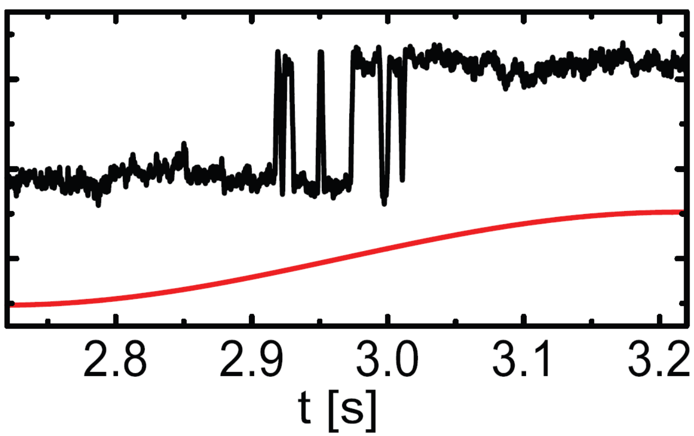
# Experiment on a single-electron box

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

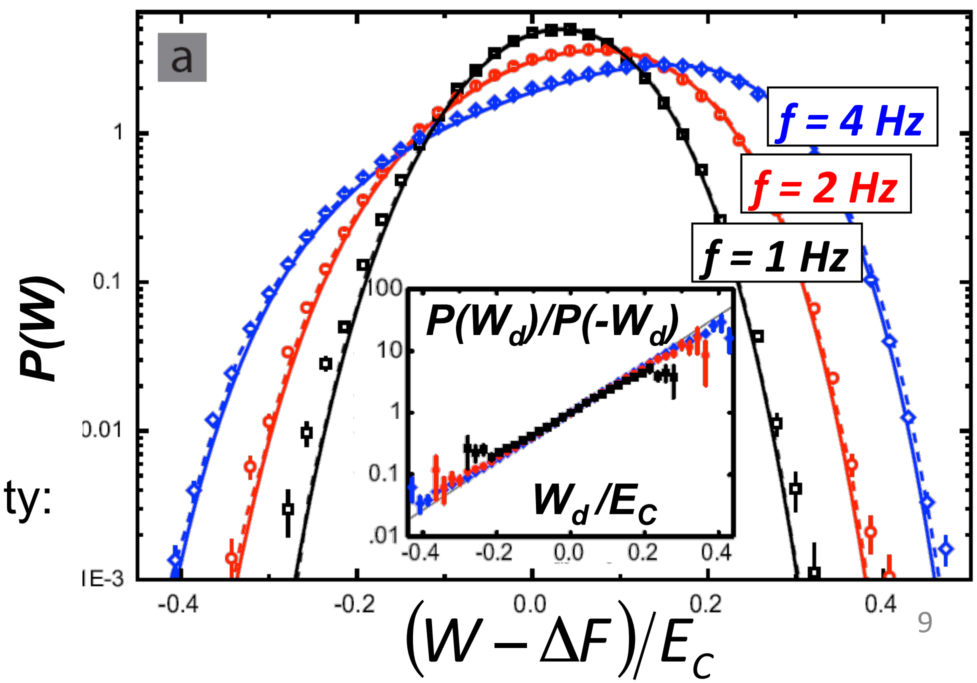



$$T\Delta S = W - \Delta F$$




The distributions satisfy Jarzynski equality:

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

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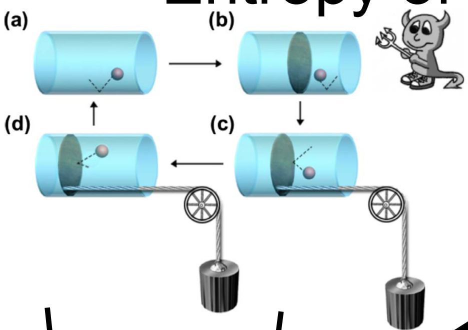
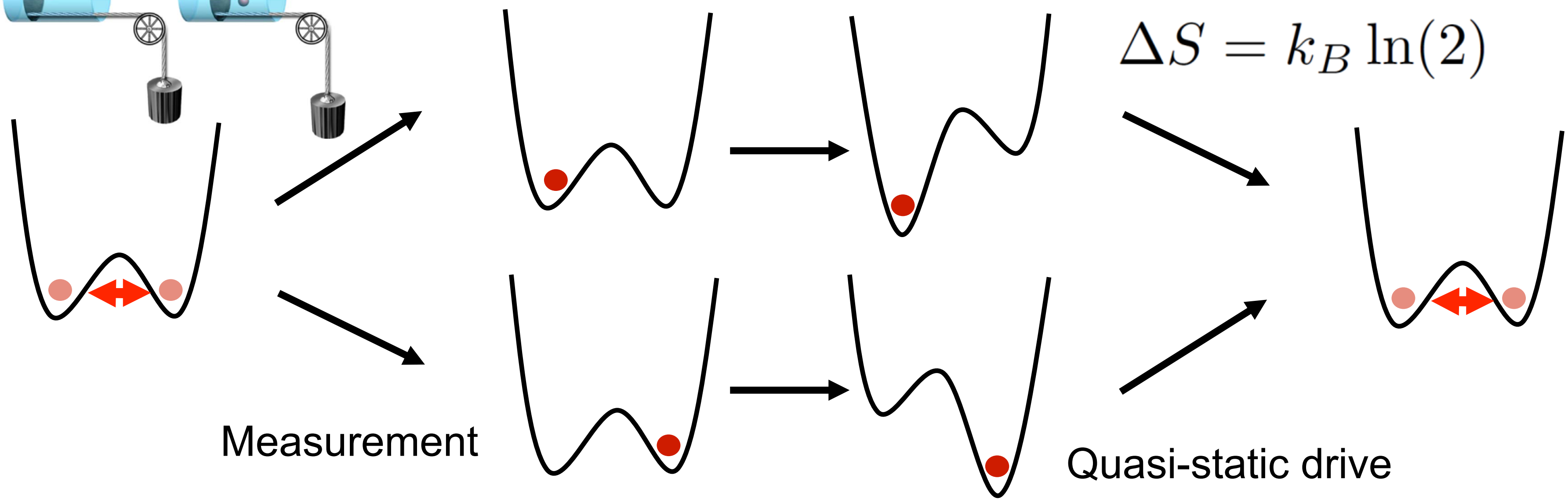
# Maxwell's demon for single electrons

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): $Q_{sys} = W_{sys} = -k_B T \ln 2 < 0$

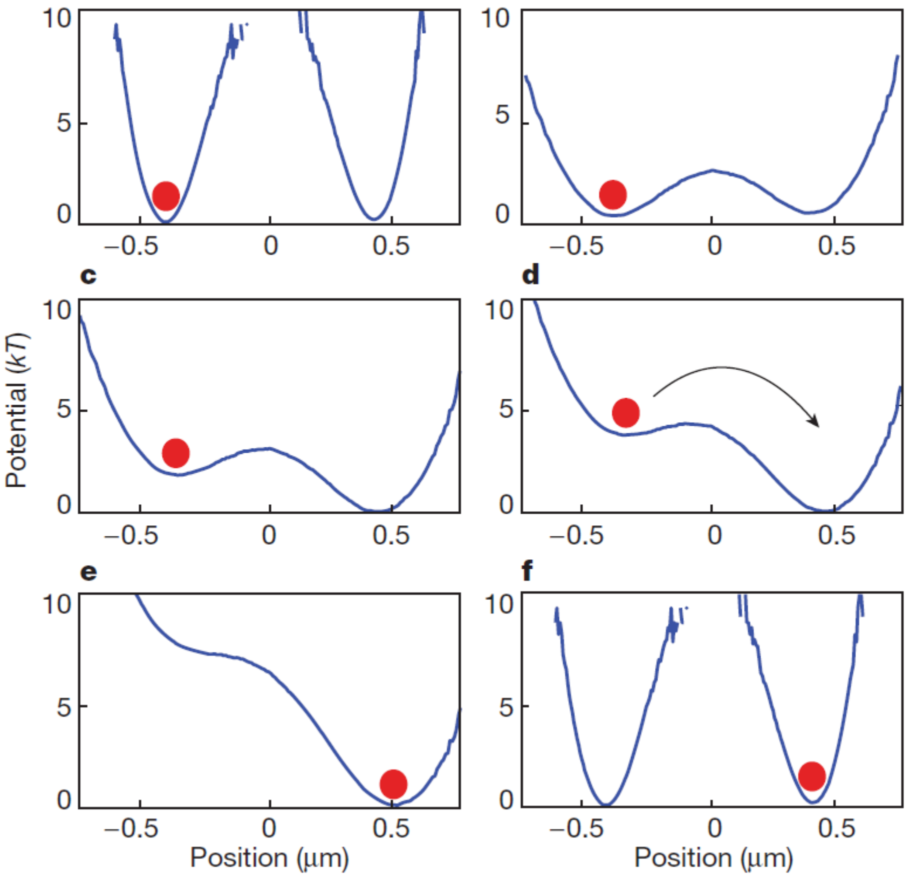
J. V. Koski et al., PNAS **111**, 13786 (2014); PRL **113**, 030601 (2014).

# Erasure of information

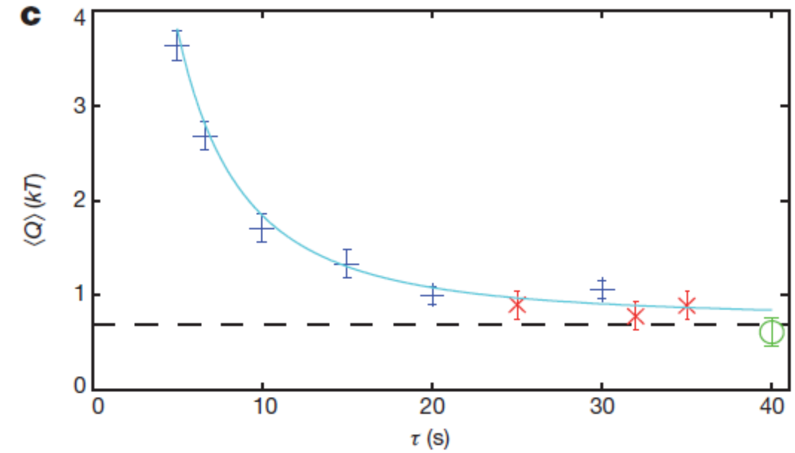
R. Landauer, IBM J. Res. Dev. 1961

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

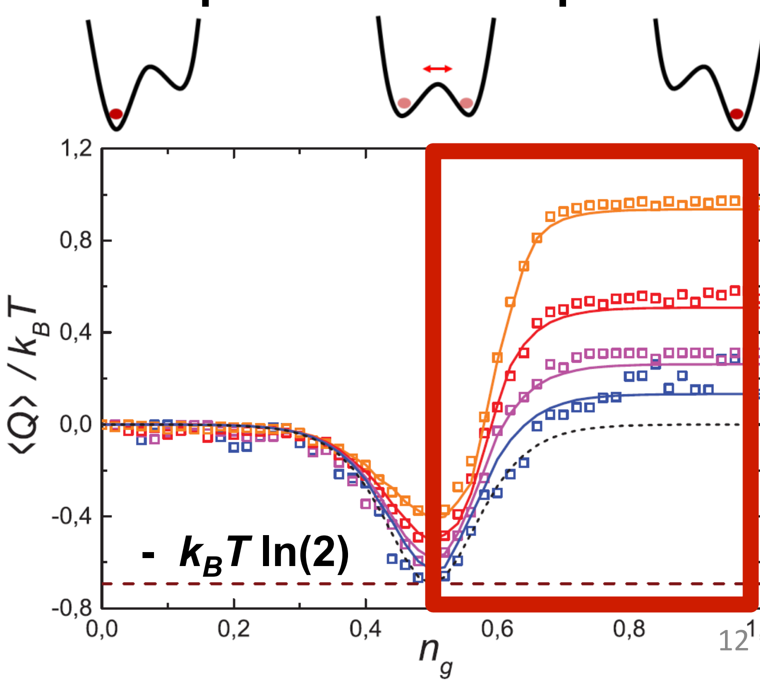
Experiment on a colloidal particle:




A. Berut et al., Nature 2012

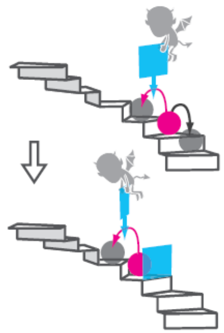


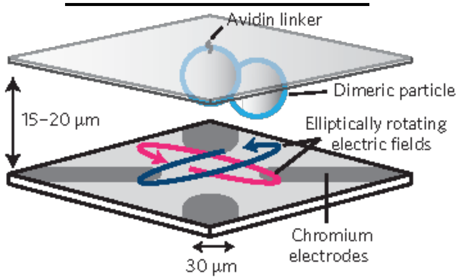

**Corresponds to MD experiment:**

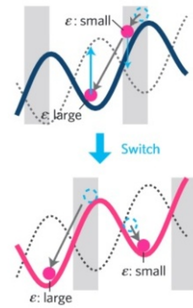


# Examples of Maxwell's demon

## A colloidal particle in electric field

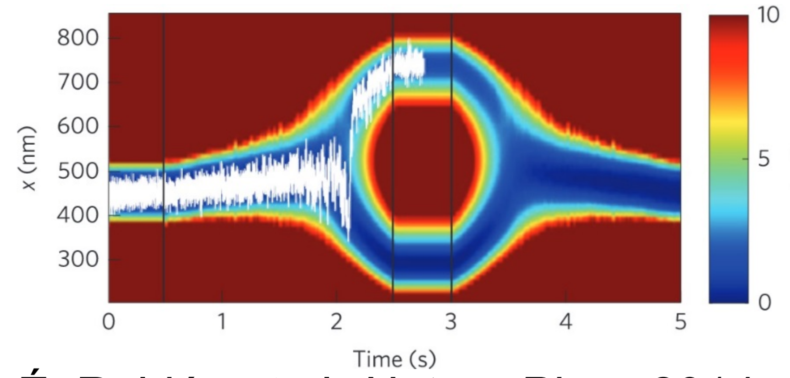




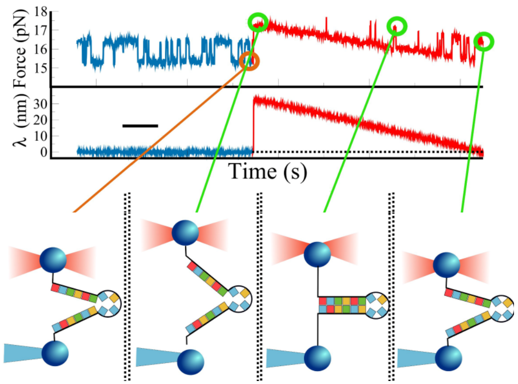

S. Toyabe et al., Nature Physics 2010

## A colloidal particle in laser tweezers




É. Roldán et al., *Nature Phys.* 2014

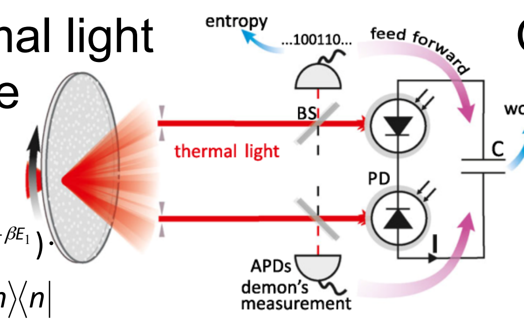
## DNA molecule




M. Ribezzi-Crivellari et al., in preparation

## Photonic MD

Thermal light source



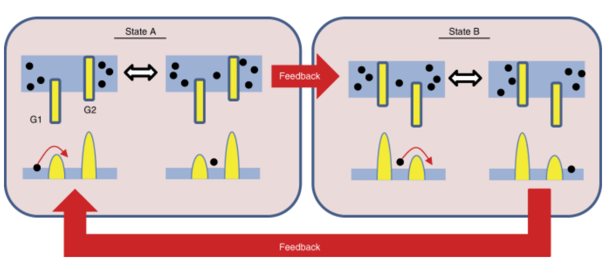

$$\rho = (1 - e^{-\beta E_1}) \cdot \sum_n e^{-n\beta E_1} |n\rangle\langle n|$$

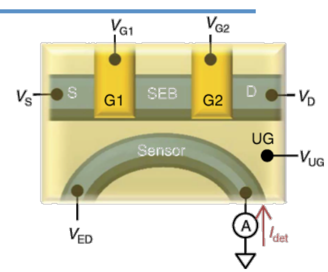
Change C polarity

Charging a battery

M. D. Vidrighin et al PRL 2016

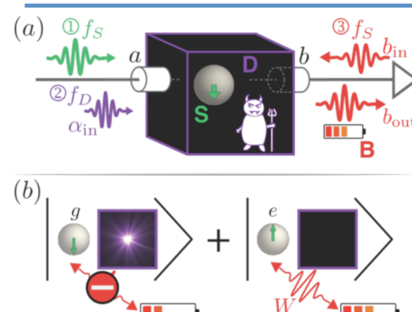
## MD electronic pump




K. Chida et al, Nat. Comm. 2017

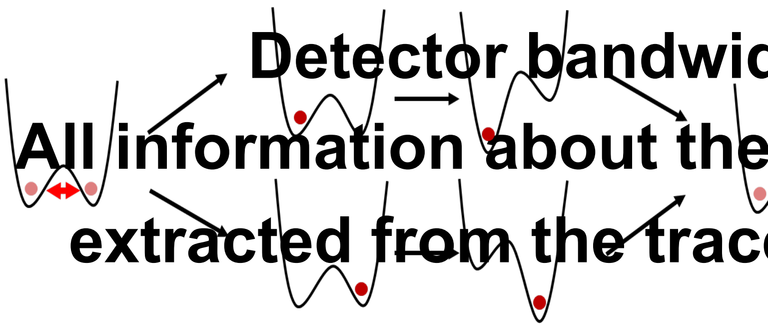
## Quantum MD

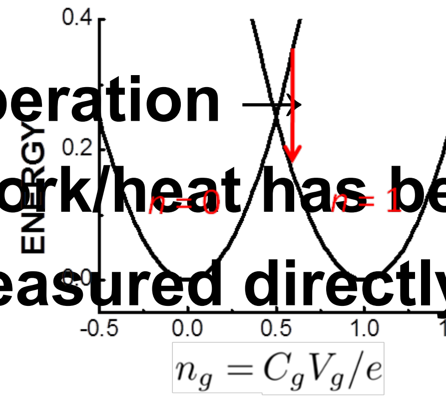


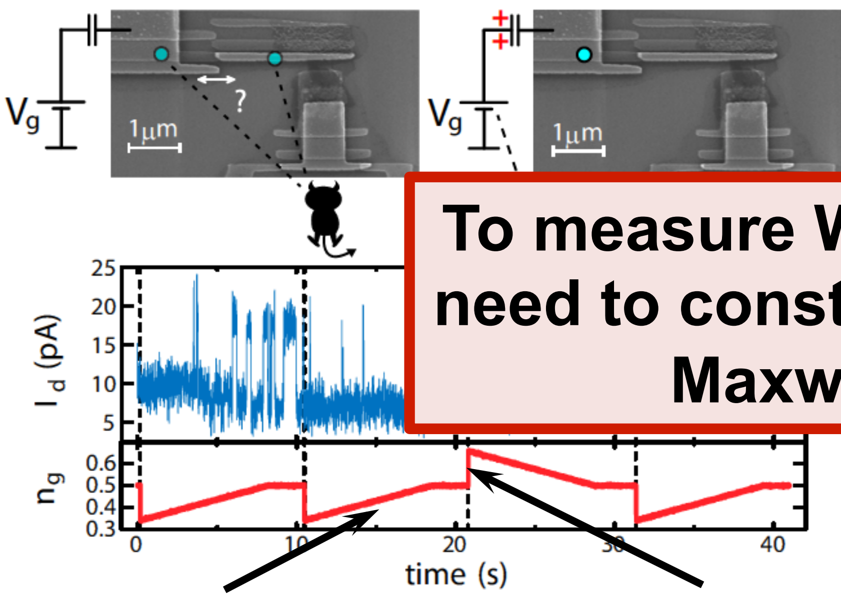

N. Cottet et al, PNAS 2017

# Maxwell's demon with SEB

**Detector bandwidth → Slow operation → All information about the dissipated work/heat has been extracted from the traces, but not measured directly.**





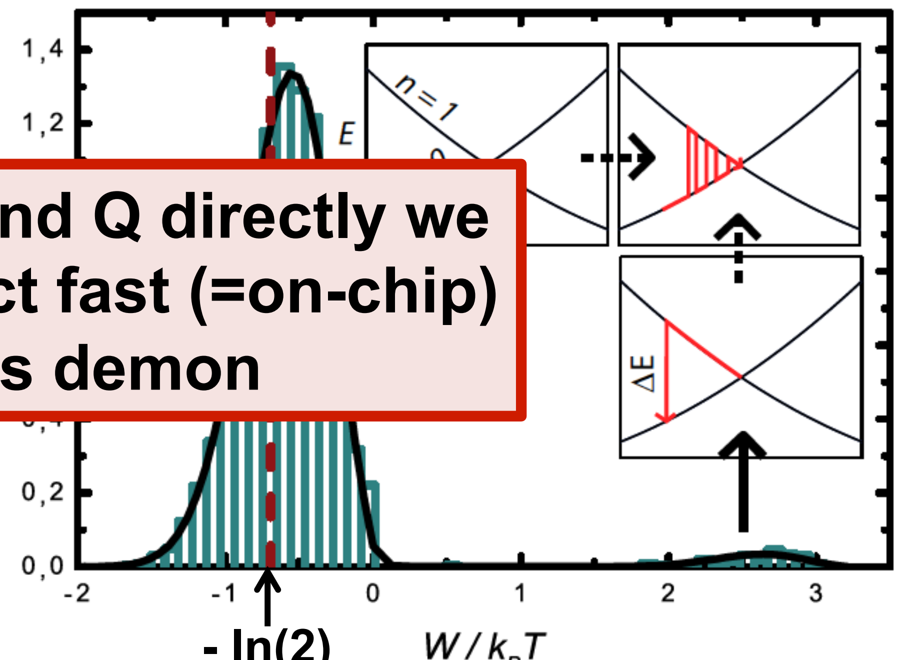




**Quasi-static ramp**

**Measurement and decision**

| - charge state

| - gate voltage




**To measure W and Q directly we need to construct fast (=on-chip) Maxwell's demon**

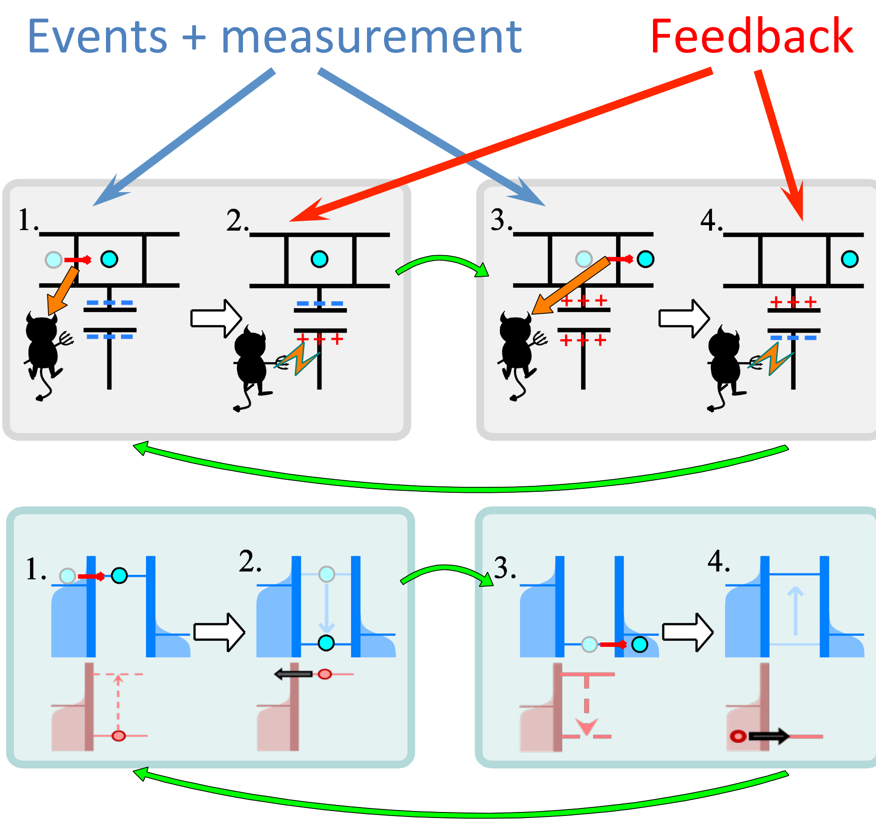
**- ln(2)** $W / k_B T$

Efficiency *(~3000 repetitions)*:

$\langle W \rangle \approx -0.75\ k_B T \ln 2$

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

# Autonomous Maxwell's demon. Operation principle




1. or 3. Demon detects that electron enters or leaves SET island (Event + measurement)

2. or 4. Feedback:

-Enter: trap with + charge

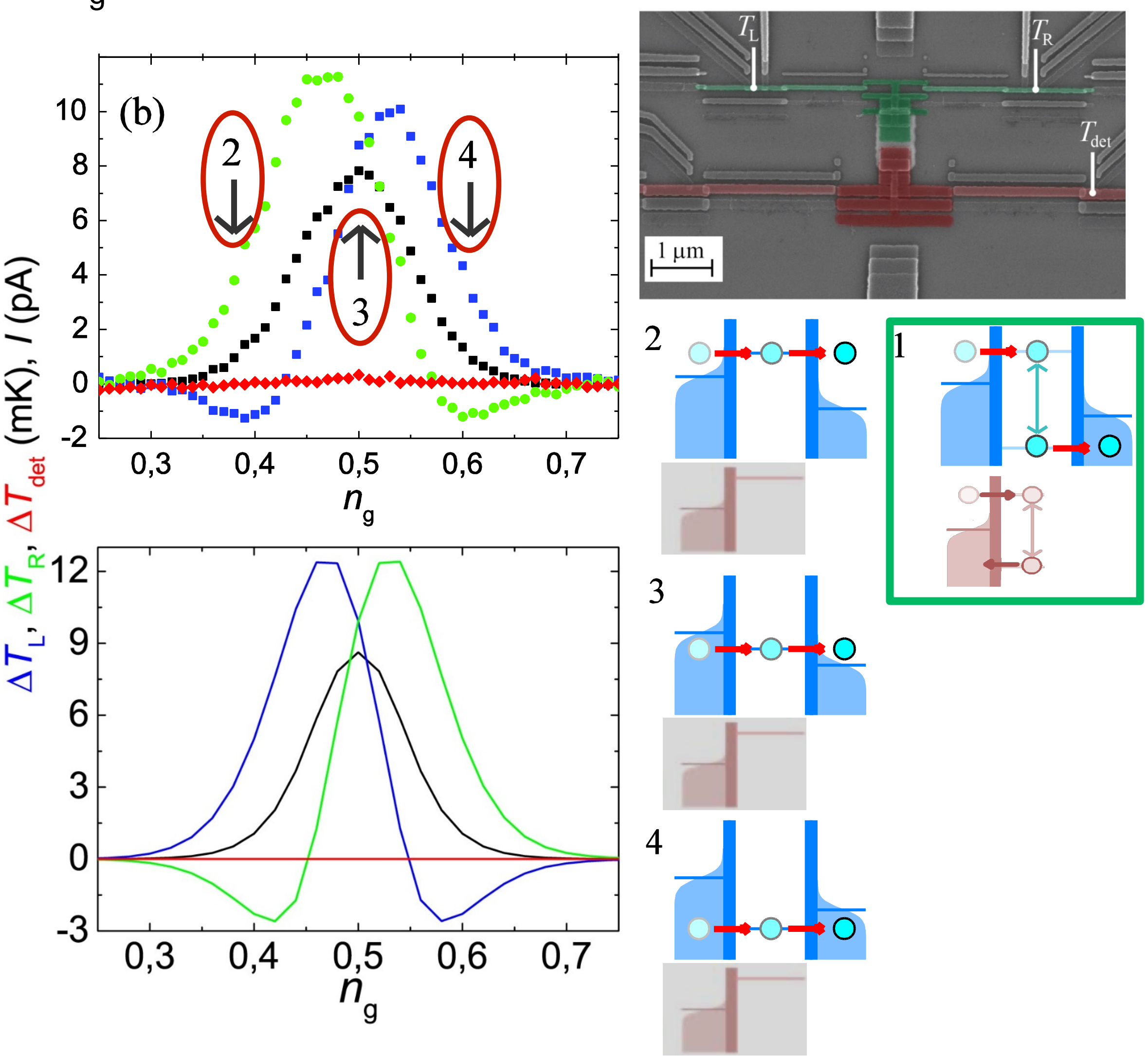
-Leave: block with - charge

Electrons tunnel through the system more slowly and 'cool' down

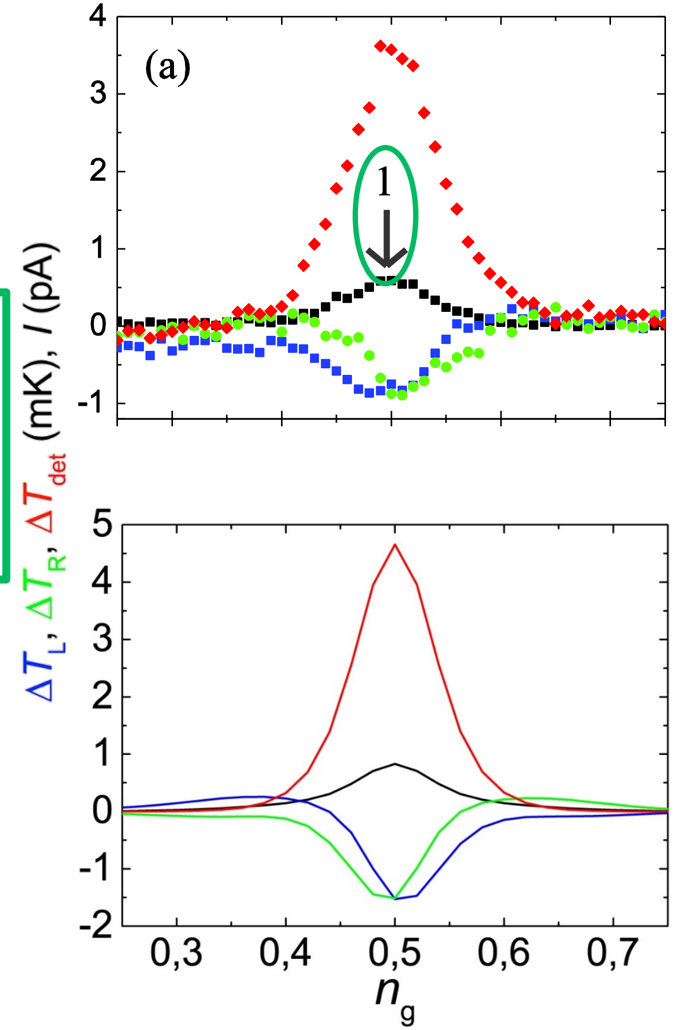
J.V. Koski et al PRL 115, 260602 (2015)

# Results. $N_g$ = 1/2: feedback control

$N_g$ = 1: no feedback control




$N_g$ = 1/2: feedback control




J.V. Koski et al PRL <u>115</u>, 260602 (2015)

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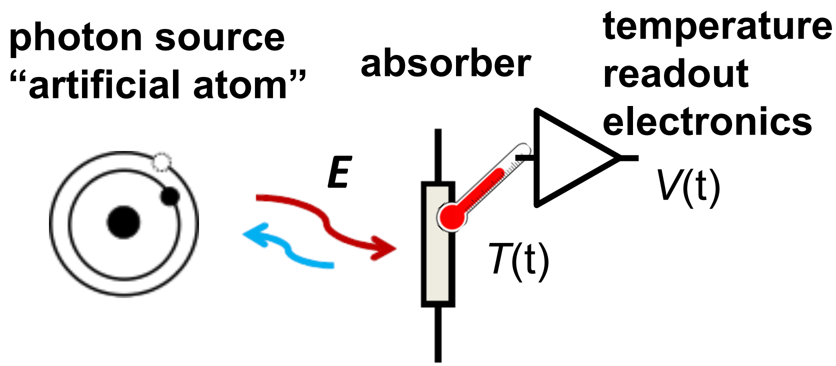
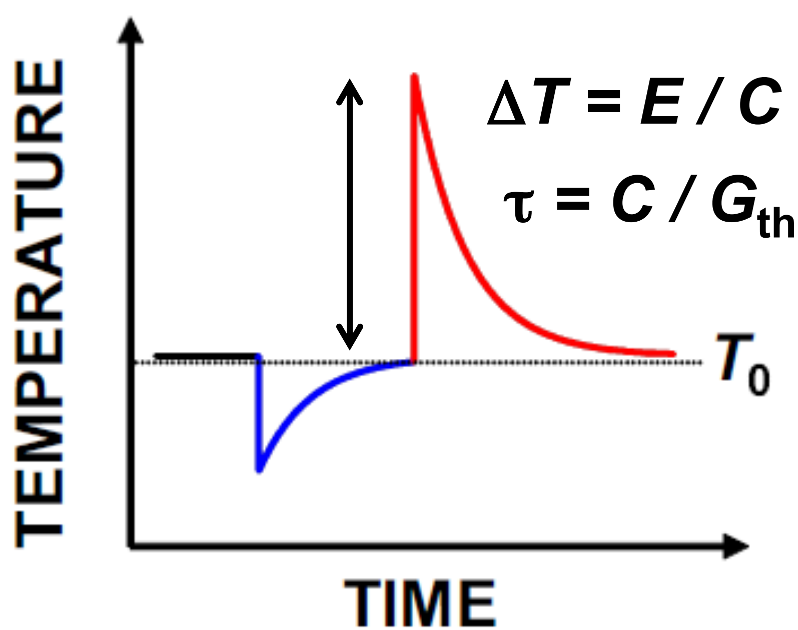
# Calorimetry for measuring MW photons

Requirements for calorimetry on single microwave quantum level. Photons from relaxation of a superconducting qubit.




Typical parameters:

Operating temperature
$T_0$ = 0.1 K

$E/k_B$ = 1 K, $C$ = 300...1000$k_B$

$\Delta T$ ~ 1 - 3 mK, $\tau$ ~ 0.01 - 1 ms

$T_{NET}$ = 10 $\mu$K/(Hz)$^{1/2}$ is sufficient for single photon detection

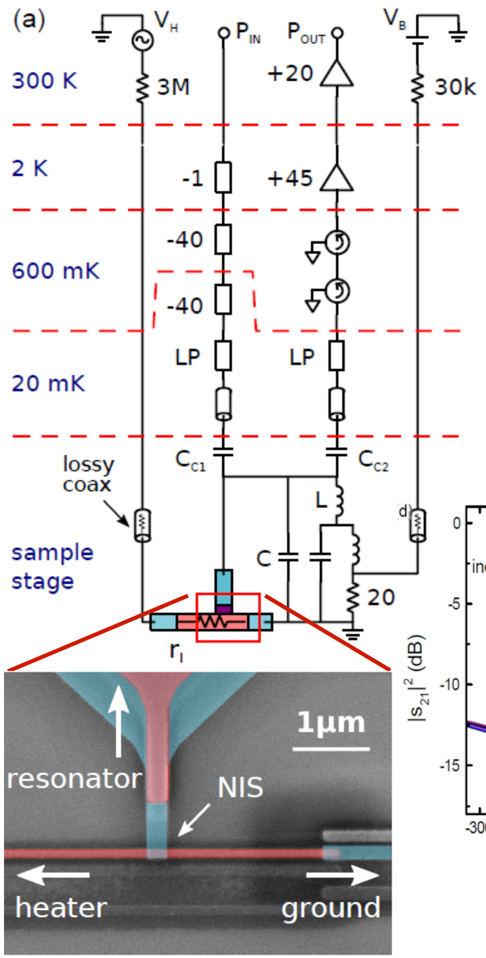
$\delta E = T_{NET} \, (C \, G_{th})^{1/2}$

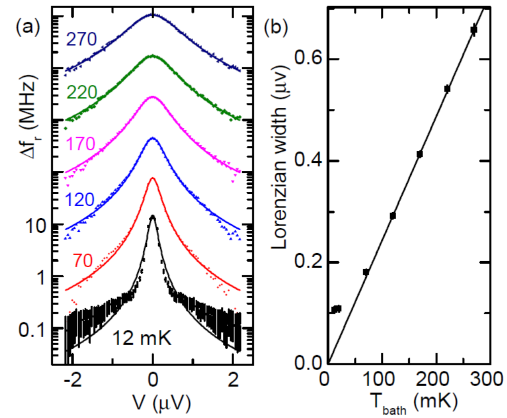
J. Pekola, P. Solinas, A. Shnirman, D. V. Averin., NJP **15**, 115006 (2013).

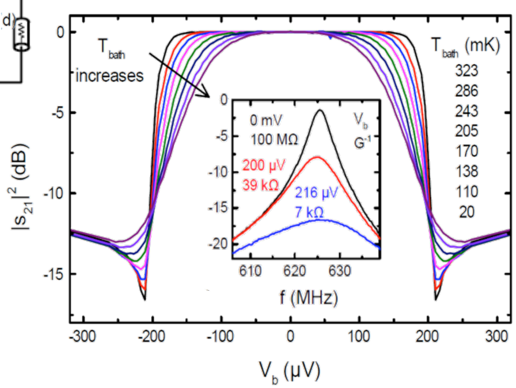
# Fast NIS thermometry on electrons

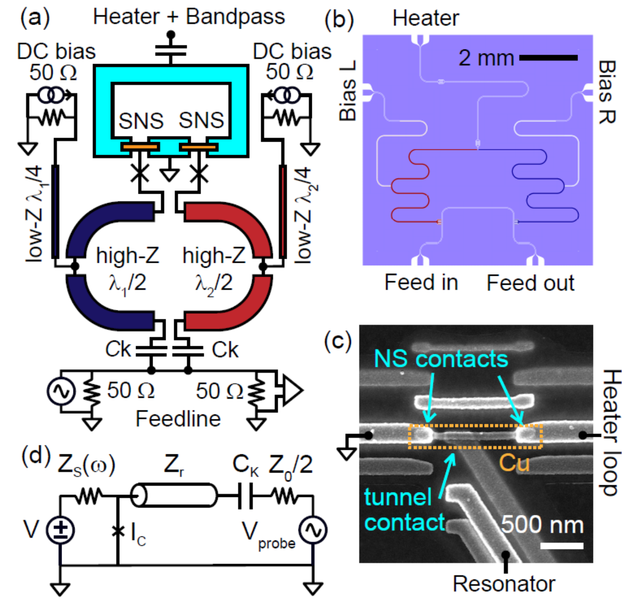
Read-out at 600 MHz of a NIS junction,
10 MHz bandwidth

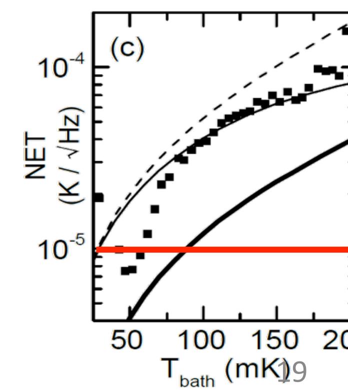
**O.-P. Saira et al. PRAppl. 6, 024005 (2016)**
**M. Zgirski et al. arXiv:1704.04762,**
**L. Wang et al., arXiv: 1710.10082**



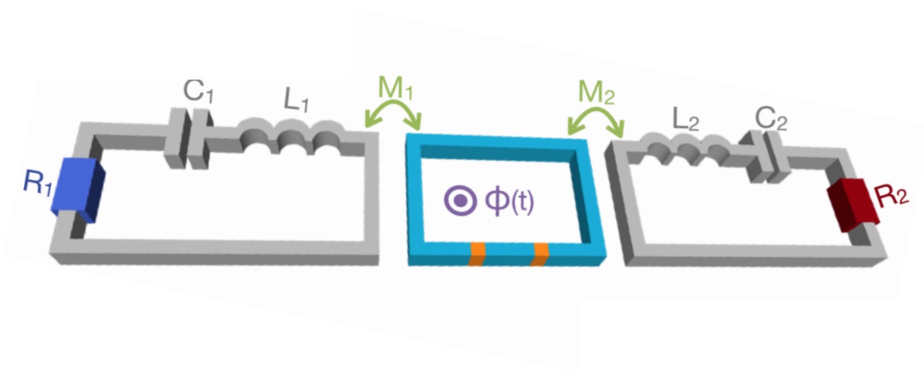



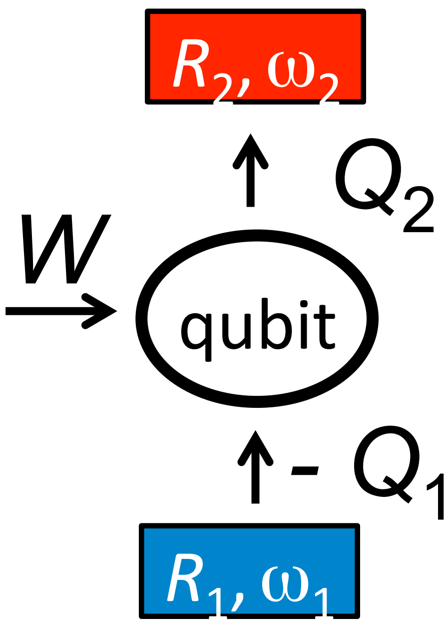



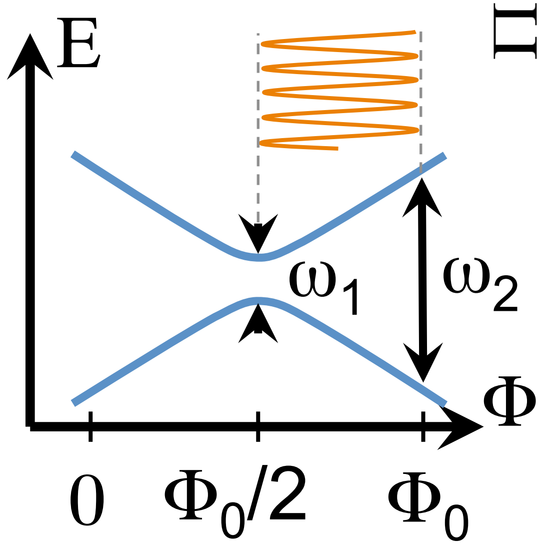



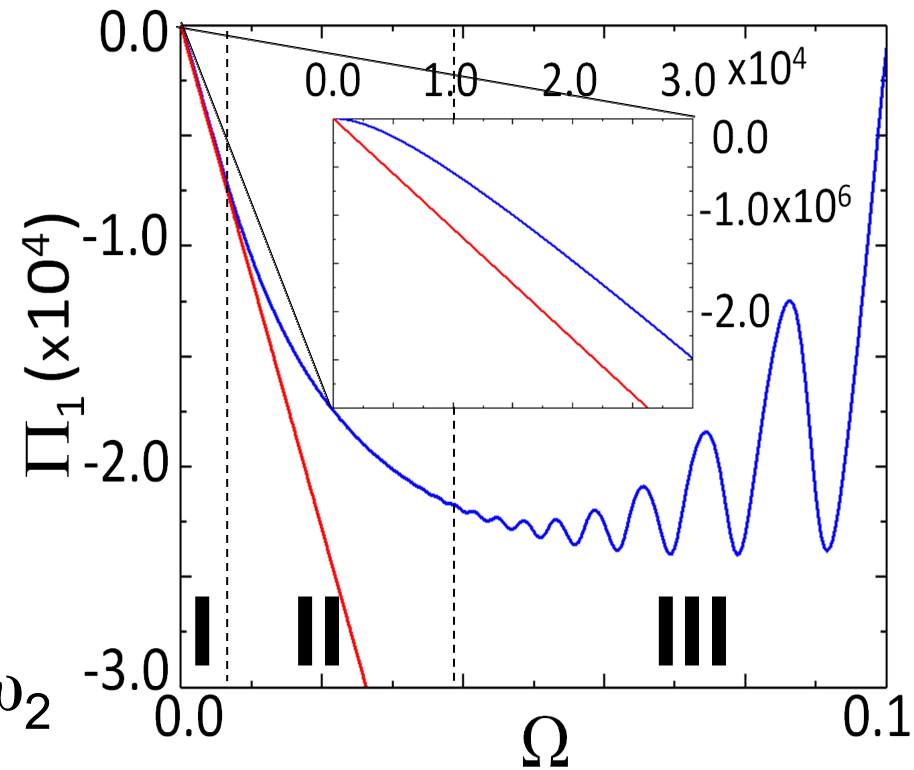

**S. Gasparinetti et al., Phys. Rev. Applied 3, 014007 (2015);**
**K. L. Viisanen et al., New J. Phys. 17, 055014 (2015).**
**Proof of the concept: Schmidt et al., 2003;**

# Quantum Otto refrigerator




I. Nearly adiabatic regime

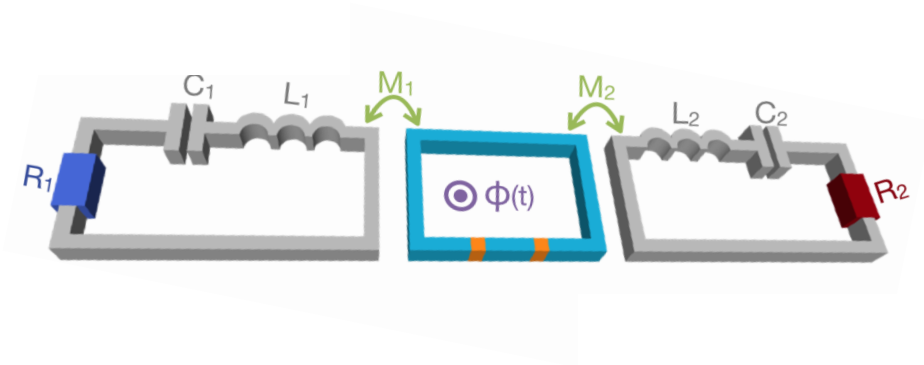
II. Ideal Otto cycle

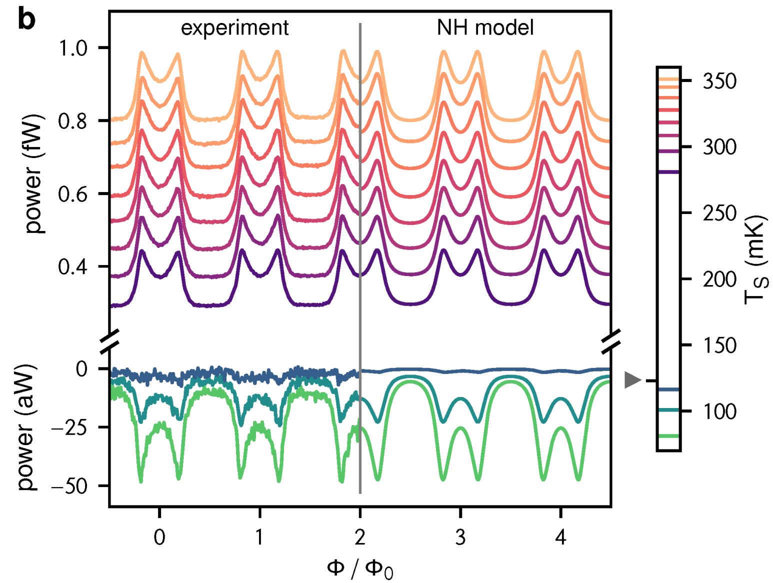
III. Coherent oscillations at high frequencies

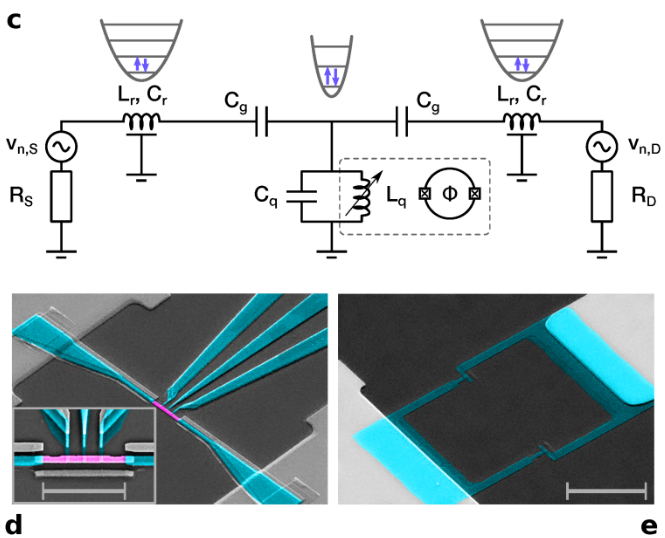
Niskanen, Nakamura, Pekola, PRB 76, 174523 (2007)

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

# Quantum Heat Valve



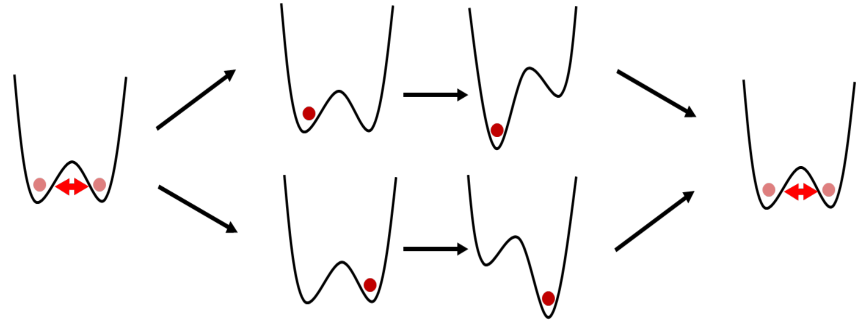

Tunable photonic heat transport (both cooling and heating) between QED resonators via a qubit

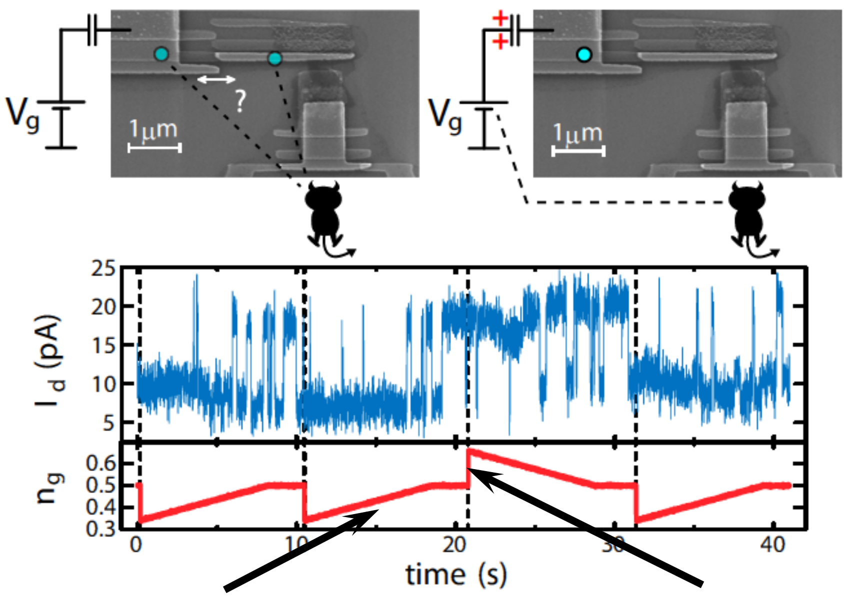
A. Ronzani, B. Karimi, J. Senior, Y.-C. Chang, J. T. Peltonen, C. D. Chen, J. P. Pekola arXiv:1801.09312 accepted to Nat. Phys. (2018)

# Outline

- General introduction:
  - ✓ Definition of entropy. Fluctuation relations
  - ✓ Coulomb blockade and thermodynamics
  - ✓ Jarzynski and Crooks relations in single-electron circuits
  - ✓ Realization of Maxwell's Demons
  - ✓ Quantum calorimetry and heat transport
- **Nonequilibrium steady state**
  - ✓ **Negative entropy events**
  - ✓ **Statistics of finite-time minima of entropy production**
- Experimental verification of theoretical results
  - ✓ Double-dot structure as a minimal physical model
  - ✓ Boundaries for entropy production records
  - ✓ Relation with the heat absorbtion
- Summary and outlook

# Negative entropy production events in feedback controlled systems

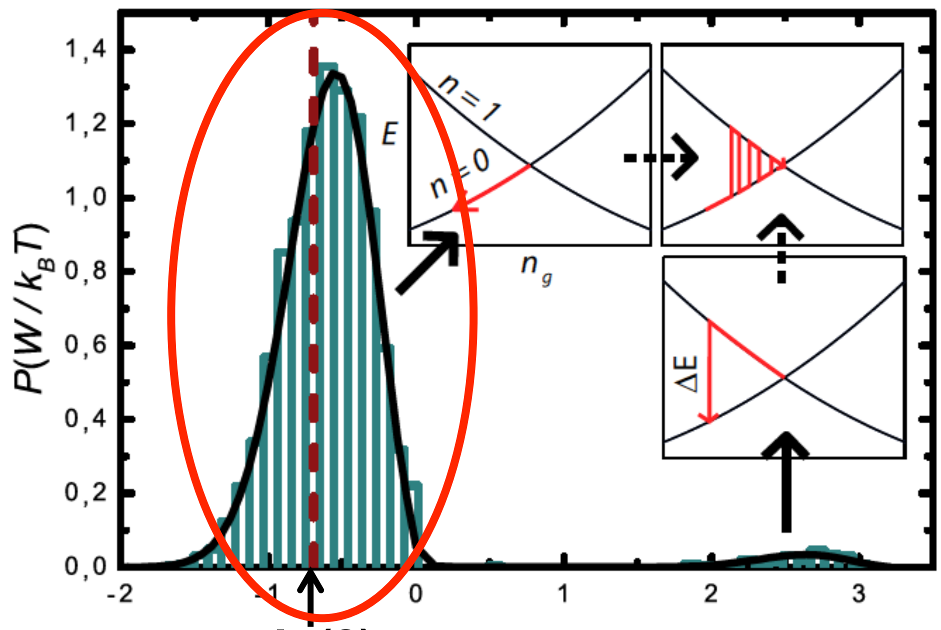





**Quasi-static ramp**

**Measurement and decision**

| - charge state  | - gate voltage




**- ln(2)**

Efficiency *(~3000 repetitions)*:

$\langle W \rangle \approx -0.75\ k_B T \ln 2$

J. V. Koski et al., PNAS (2014); PRL (2014); PRL (2015)

# Negative entropy production events in NESS

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

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

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

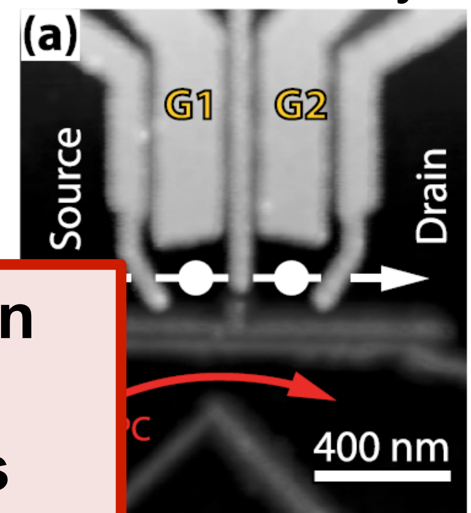
G. Bochkov, Yu. Kuzovlev, JETP 1977, Physica A 1981

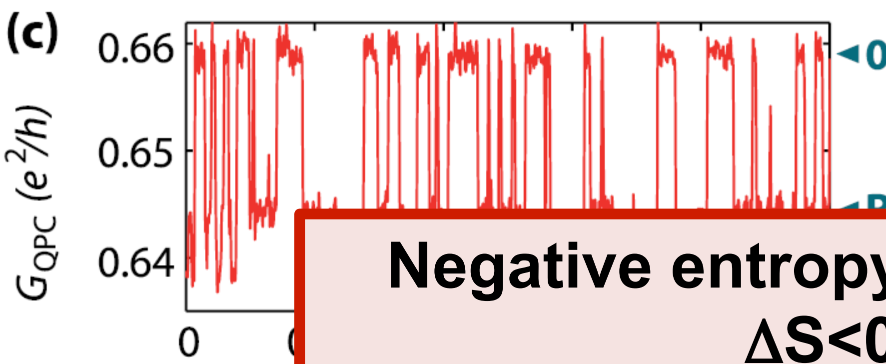
*Electric circuits: Experiment on a double quantum dot*

Y. Utsumi et al. PRB **81**, 125331 (2010),

B. Kung et al. PRX **2**, 011001 (2012)

Nonequilibrium steady state



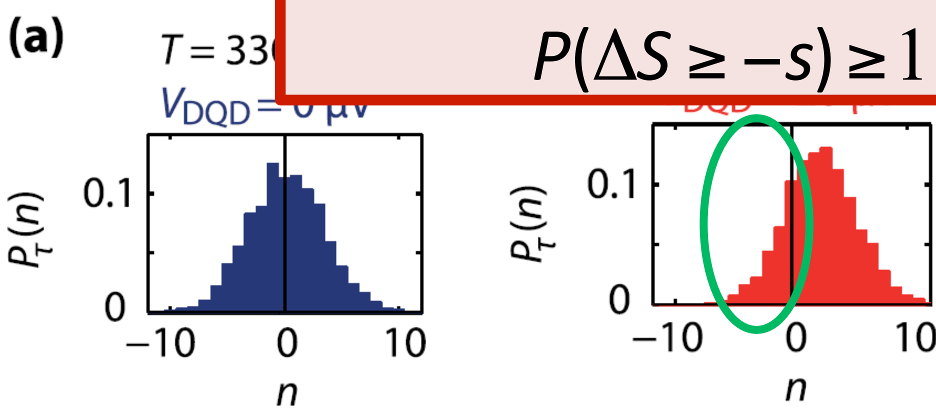

**Negative entropy production**

**ΔS<0**

**due to thermal fluctuations**

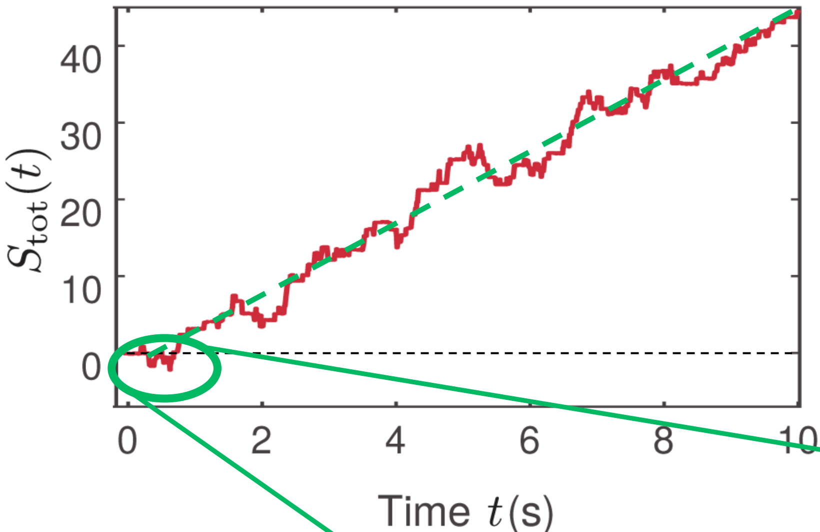
$$P(\Delta S \geq -s) \geq 1 - e^{-s}$$

Crooks as detailed balance




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

# NESS. Negative events of entropy




$$\frac{P(\Delta S)}{P_R(-\Delta S)} = e^{\Delta S} \qquad \left\langle e^{-\Delta S} \right\rangle = 1$$

$$\Delta S = \ln \frac{P(\{n(t)\})}{P_R(\{n(\tau - t)\})}$$

**Single bath**

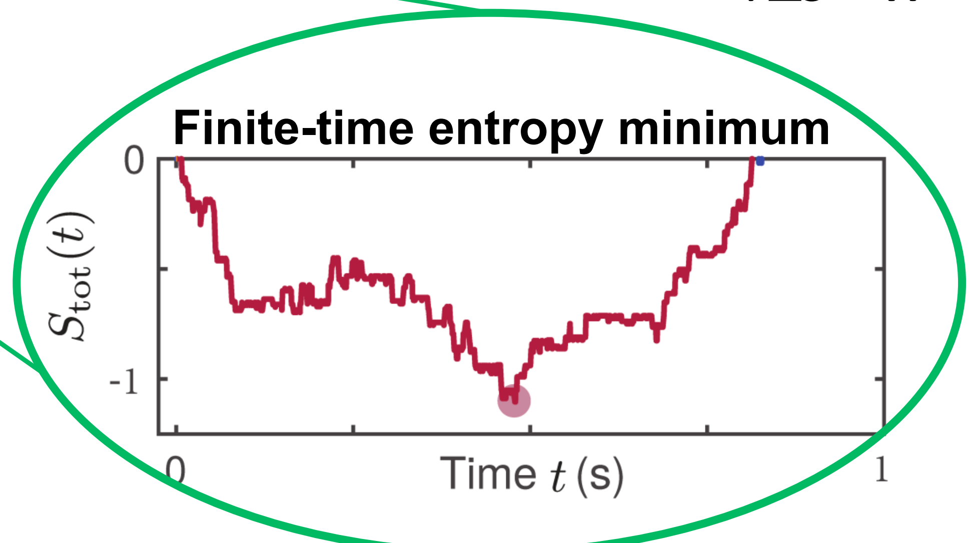
$$T\Delta S = W - \Delta F$$

**2nd law of thermodynamics**

$$\langle \Delta S \rangle \geq 0$$

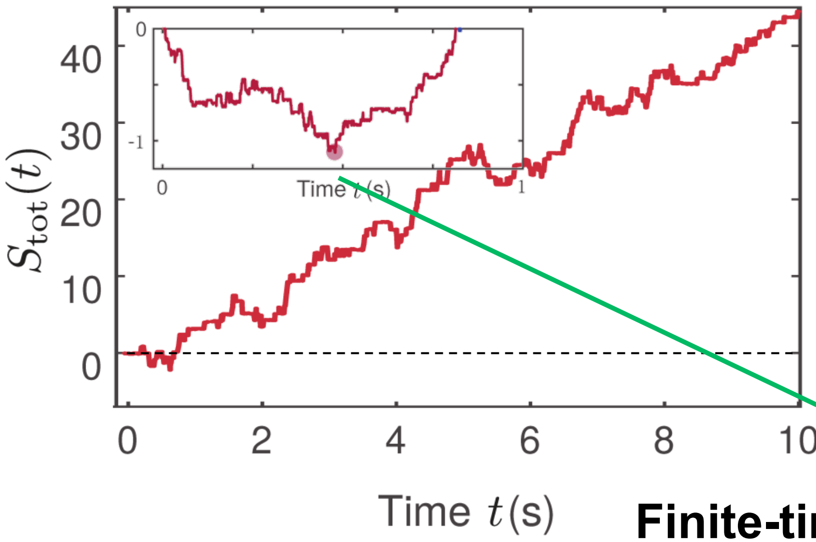
**Nonequilibrium steady state**

$$\left\langle \frac{d\Delta S}{dt} \right\rangle (t) \equiv \sigma = const > 0$$




K. Sekimoto, Prog.Theor.Phys.Suppl.**130**, 17 (1998);
U. Seifert, Phys. Rev. Lett. **95,** 040602 (2005).

# NESS. Negative records of entropy




$$\Delta S = \ln \frac{P(\{n(t)\})}{P_R(\{n(\tau - t)\})}$$

$e^{-\Delta S}$ is a ***martingale*** variable

(J. L. Doob, *Stochastic Processes*, 1953)

$$\left\langle e^{-\Delta S(t)} \,|\, e^{-\Delta S(t_1)}, \ldots, e^{-\Delta S(t_N)} \right\rangle = e^{-\Delta S(t_N)}$$

**Finite-time entropy minimum**

$$P(\Delta S \geq -s) \geq 1 - e^{-s}$$

$$\Delta S_{\min} = \min_{0<t<\tau} \Delta S(t) \leq 0$$

**Doob's Maximal inequality**

(cumulative distribution function)

$$P(\Delta S_{\min} \geq -s) \geq 1 - e^{-s}$$

**Infimum law**

Average minimum entropy production is above -1

$$\langle \Delta S_{\min} \rangle \geq -1$$



I. Neri, E. Roldan, F. Jülicher, PRX **7**, 011019 (2017)

# Outline

- General introduction:
  - ✓ Definition of entropy. Fluctuation relations
  - ✓ Coulomb blockade and thermodynamics
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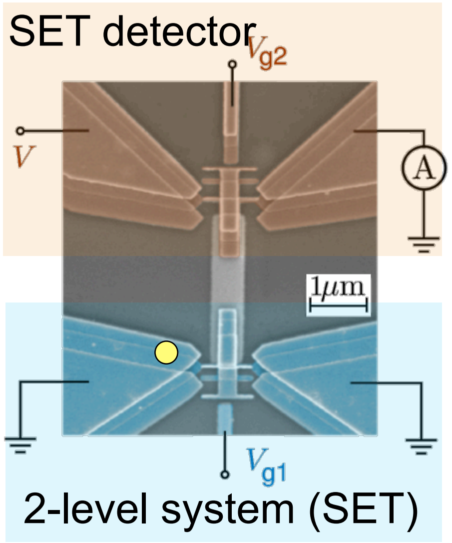
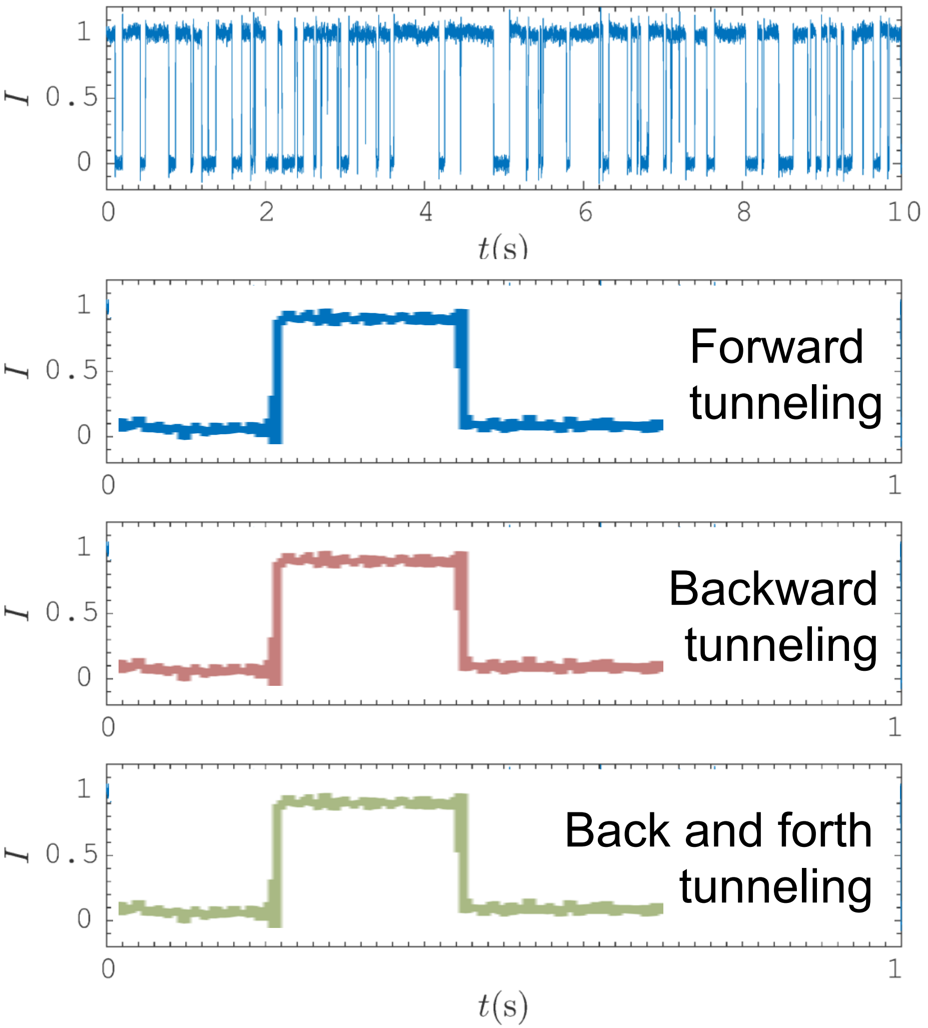
# Single-electron transistor




**Insensitive to a direction of current**

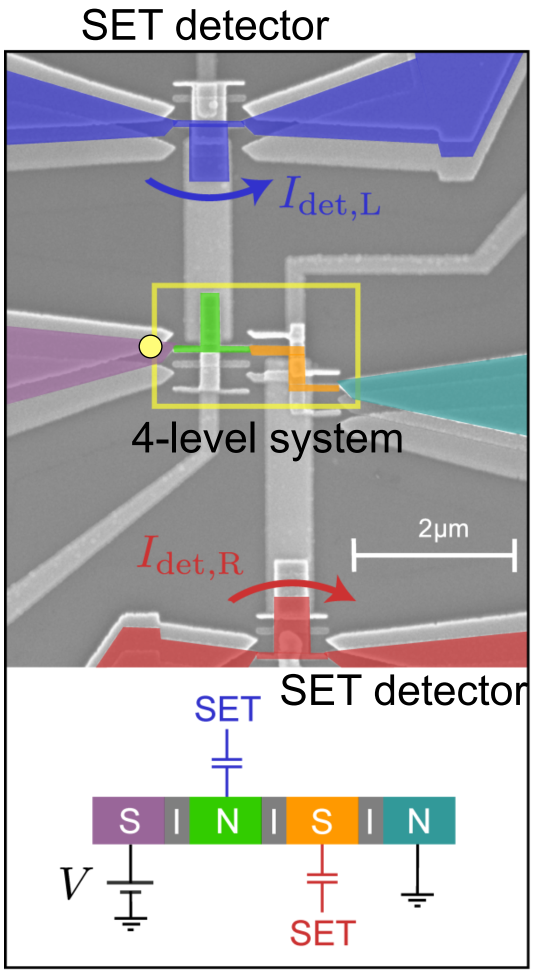
$R_s$ ~ 54 MΩ
$E_s$ ~ 138 meV

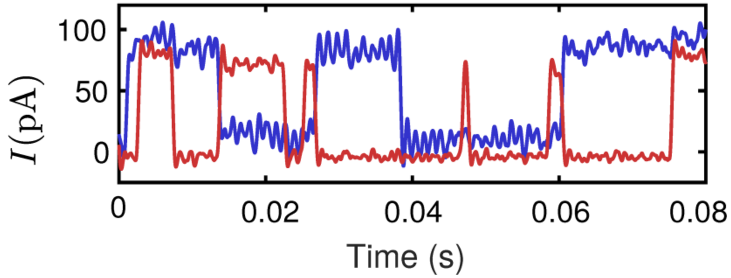
$R_D$ ~ 12.5 MΩ
$E_D$ ~ 137 meV

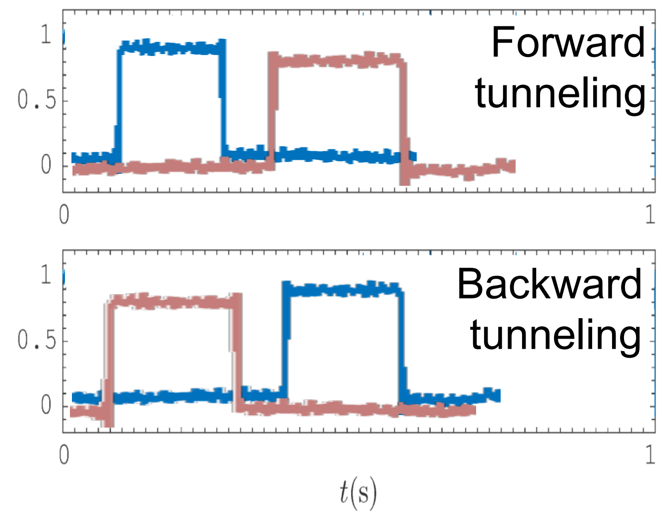



Singh, Peltonen, IMK, Koski, Flindt, Pekola, PRB, **94**, 241407 (2016)

# Multi-island structure



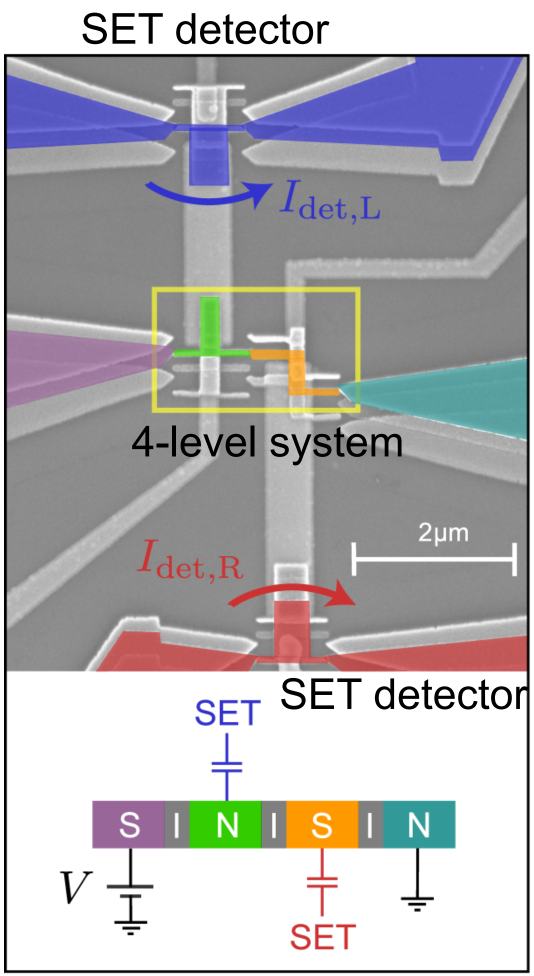



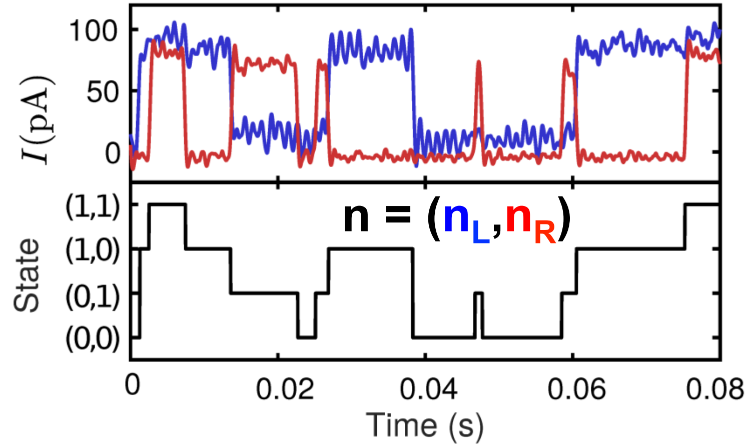

Direction of mesoscopic currents characterizes entropy production

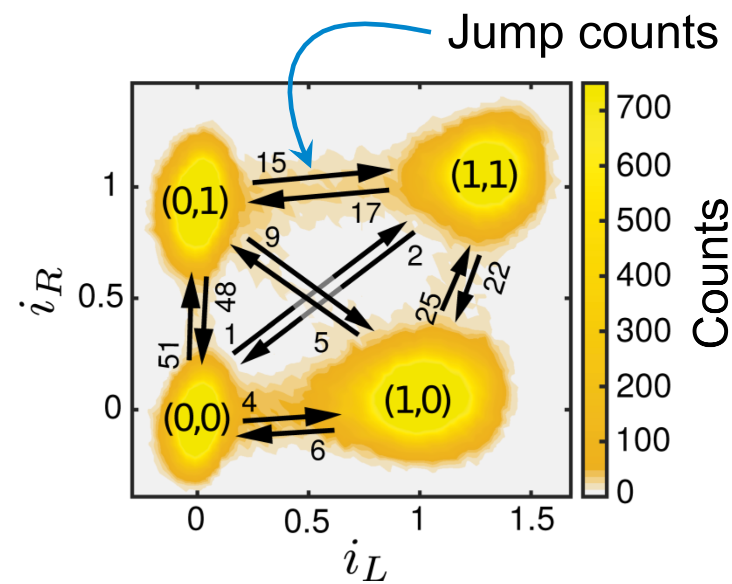
$$\Delta S(\tau) = \ln \frac{P(\{n(t)\})}{P_R(\{n(\tau - t)\})}$$

S. Singh, É. Roldán, I. Neri, I. M. Khaymovich, D. S. Golubev, V. F. Maisi, J. T. Peltonen, F. Jülicher, J. P. Pekola, arXiv:1712.01693 (2017)

# Classical 4-level system



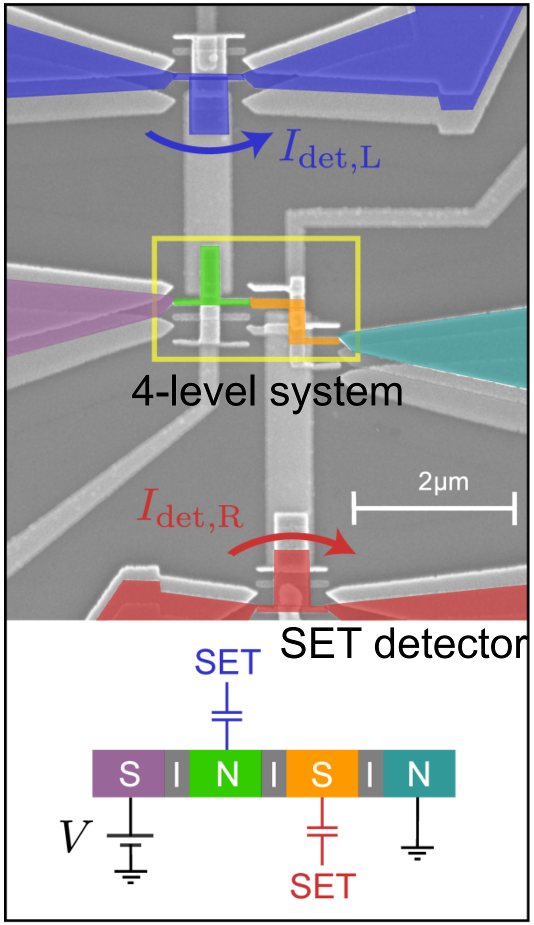



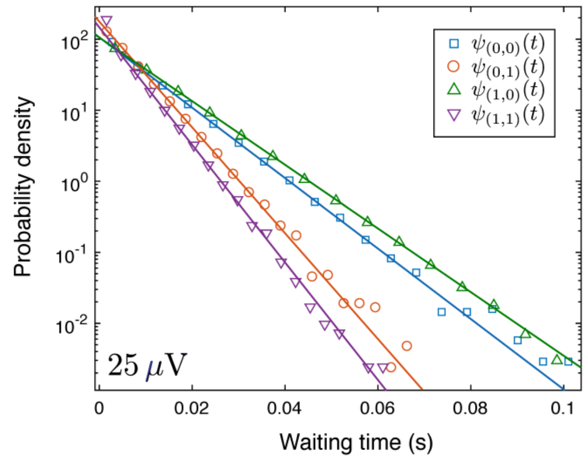

S. Singh, É. Roldán, I. Neri, I. M. Khaymovich, D. S. Golubev, V. F. Maisi, J. T. Peltonen, F. Jülicher, J. P. Pekola, arXiv:1712.01693 (2017)

# Markovian 4-level system

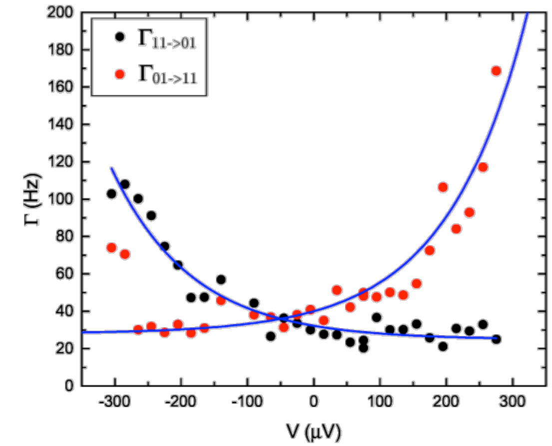
SET detector

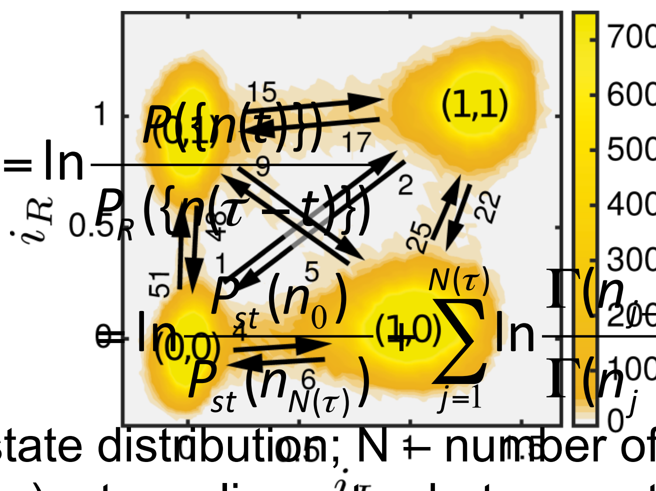



Exponential waiting time distributions = Markovian dynamics




Thermal tunneling rates = Quasiequilibrium regime



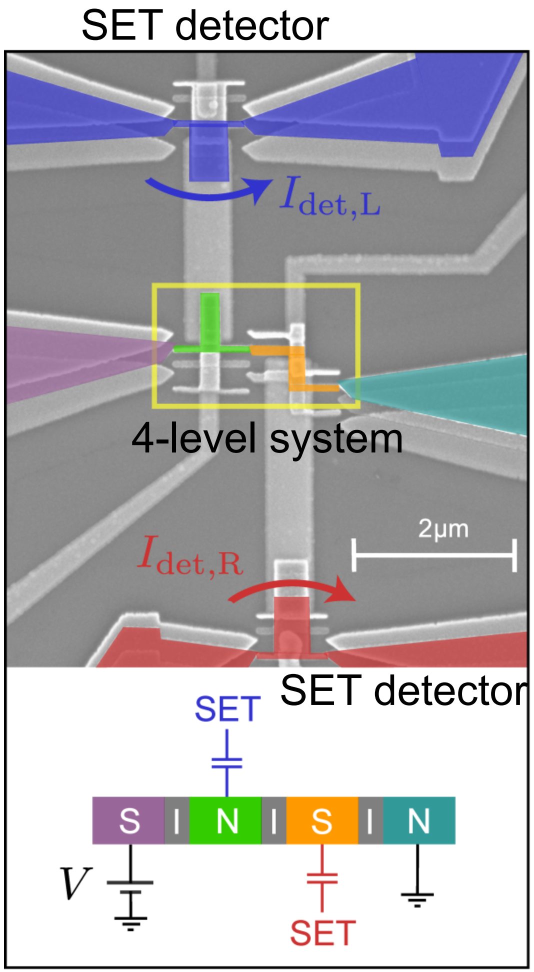




$$\Delta S(\tau) = \ln \frac{P(\{n(t)\})}{P_R(\{n(\tau - t)\})} = \ln \frac{P_{st}(n_0)}{P_{st}(n_{N(\tau)})} + \sum_{j=1}^{N(\tau)} \ln \frac{\Gamma(n_{j-1} \to n_j)}{\Gamma(n_j \to n_{j-1})}$$

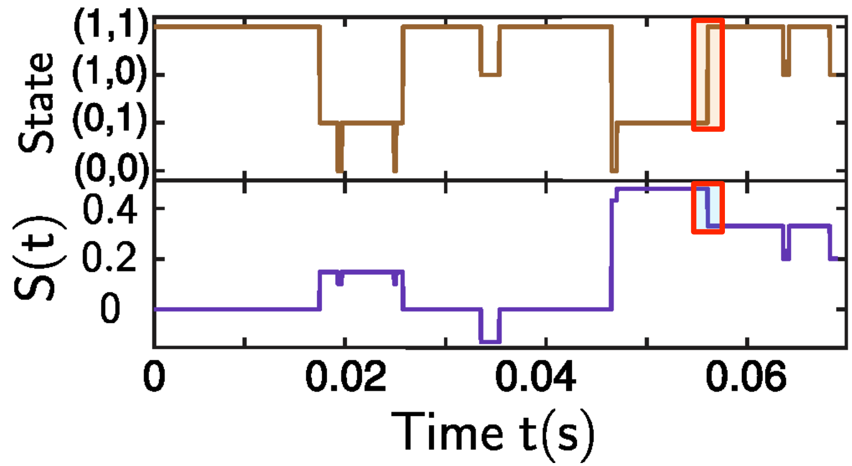
$P_{st}(n)$ – steady state distribution; N – number of jumps on the trajectory; Γ(n->m) – tunneling rates between states n and m.

S. Singh, É. Roldán, I. Neri, I. M. Khaymovich, D. S. Golubev, V. F. Maisi, J. T. Peltonen, F. Jülicher, J. P. Pekola, arXiv:1712.01693 (2017)

# Stochastic entropy on trajectory




State trajectory unambiguously determines finite-time stochastic entropy production



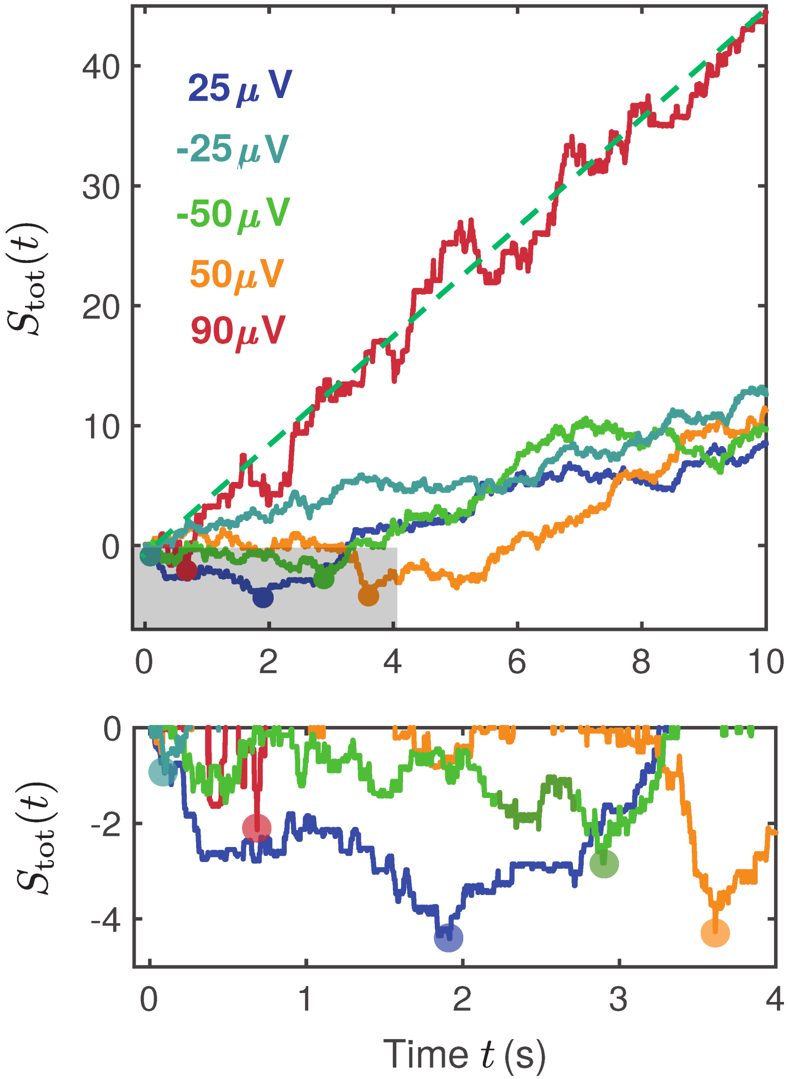

$$\Delta S(\tau) = \ln \frac{P(\{n(t)\})}{P_R(\{n(\tau - t)\})}$$

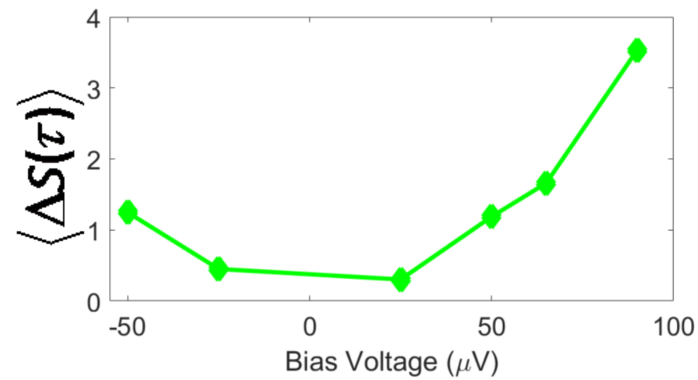
$$= \ln \frac{P_{st}(n_0)}{P_{st}(n_{N(\tau)})} + \sum_{j=1}^{N(\tau)} \ln \frac{\Gamma(n_{j-1} \to n_j)}{\Gamma(n_j \to n_{j-1})}$$

$P_{st}(n)$ – steady state distribution; N – number of jumps on the trajectory; Γ(n->m) – tunneling rates between states n and m.


S. Singh, É. Roldán, I. Neri, I. M. Khaymovich, D. S. Golubev, V. F. Maisi, J. T. Peltonen, F. Jülicher, J. P. Pekola, arXiv:1712.01693 (2017)

# Stochastic entropy on trajectory. Mean



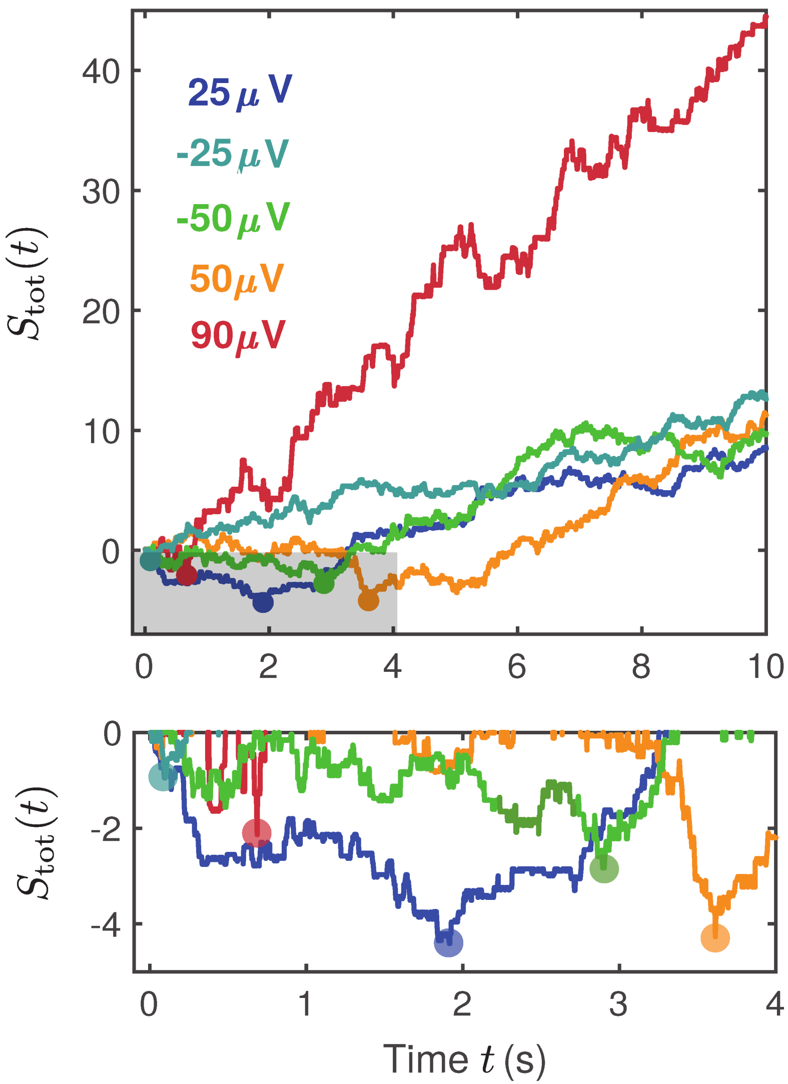

$$\langle \Delta S(\tau) \rangle = IV / T \propto V^2$$

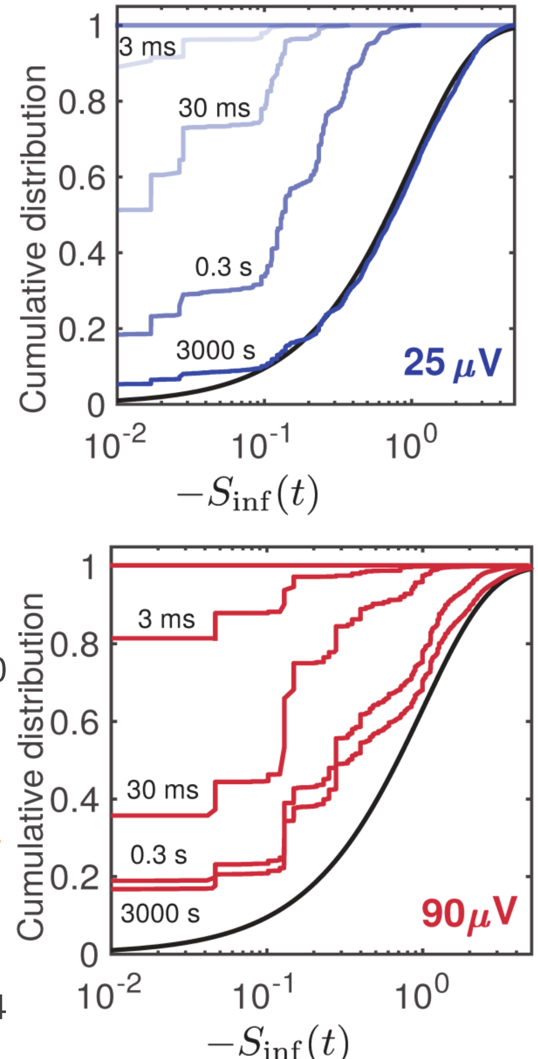
Average entropy production is mostly due to Joule heating

$$\Delta S(\tau) = \ln \frac{P_{st}(n_0)}{P_{st}(n_{N(\tau)})} + \sum_{j=1}^{N(\tau)} \ln \frac{\Gamma(n_{j-1} \to n_j)}{\Gamma(n_j \to n_{j-1})}$$

S. Singh, É. Roldán, I. Neri, I. M. Khaymovich, D. S. Golubev, V. F. Maisi, J. T. Peltonen, F. Jülicher, J. P. Pekola, arXiv:1712.01693 (2017)

# Stochastic entropy on trajectory. CDF




$$\Delta S_{\min} = \min_{0<t<\tau} \Delta S(t)$$

**Doob's Maximal inequality**

(cumulative distribution function)

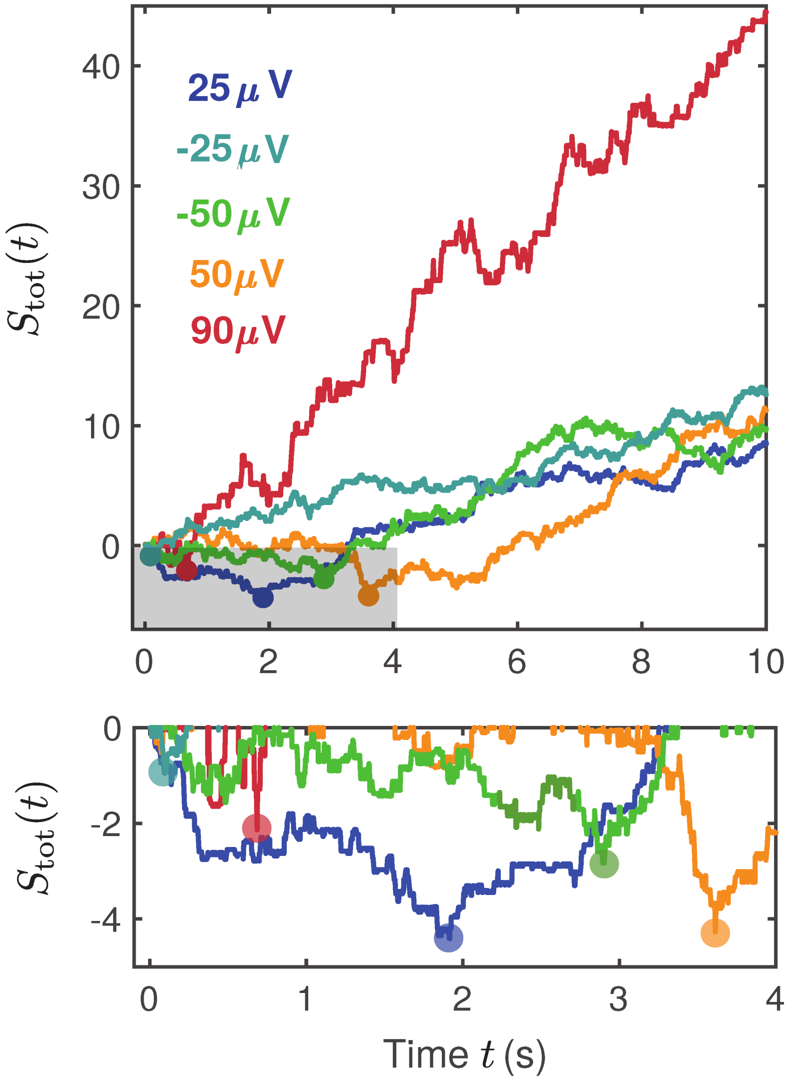
$$P(\Delta S_{\min} \geq -s) \geq 1 - e^{-s}$$

Cumulative distribution function for the finite-time minimal entropy production is limited by exponent'l distribution.

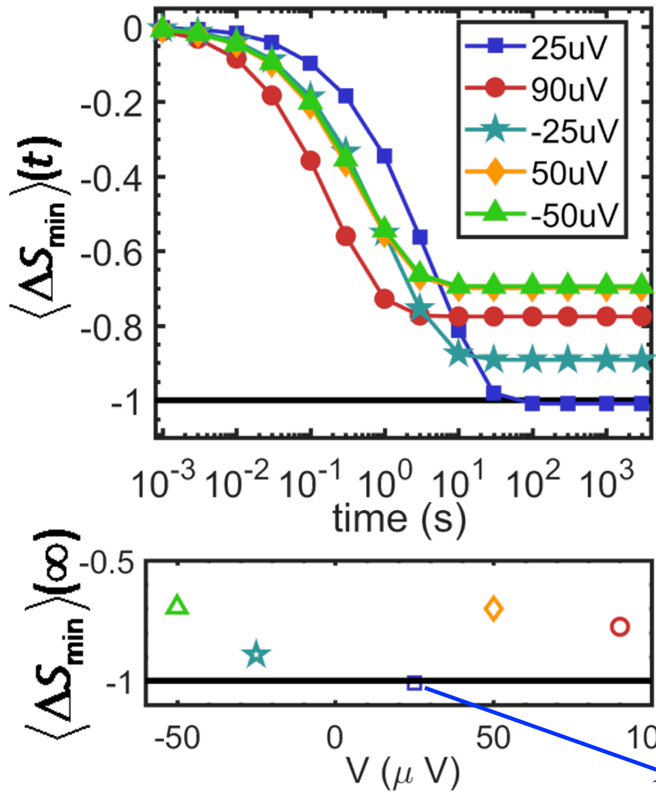
$$\Delta S(\tau) = \ln \frac{P_{st}(n_0)}{P_{st}(n_{N(\tau)})} + \sum_{j=1}^{N(\tau)} \ln \frac{\Gamma(n_{j-1} \to n_j)}{\Gamma(n_j \to n_{j-1})}$$

S. Singh, É. Roldán, I. Neri, I. M. Khaymovich, D. S. Golubev, V. F. Maisi, J. T. Peltonen, F. Jülicher, J. P. Pekola, arXiv:1712.01693 (2017)

# Stochastic entropy on trajectory. <$\Delta S_{min}$>




$$\Delta S_{min} = \min_{0<t<\tau} \Delta S(t)$$




**Infimum law**

Average min.entropy production is above -1

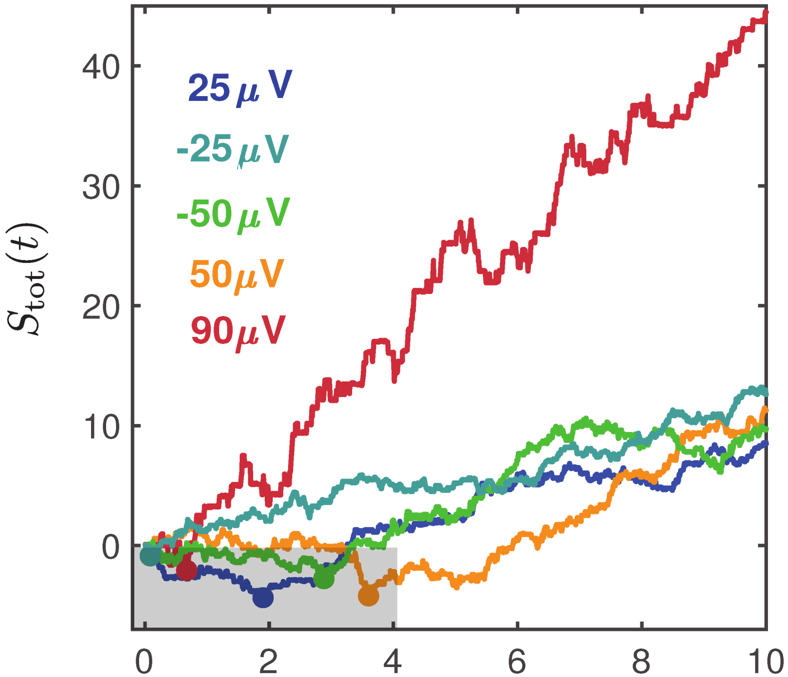
$$\langle \Delta S_{min} \rangle \geq -1$$

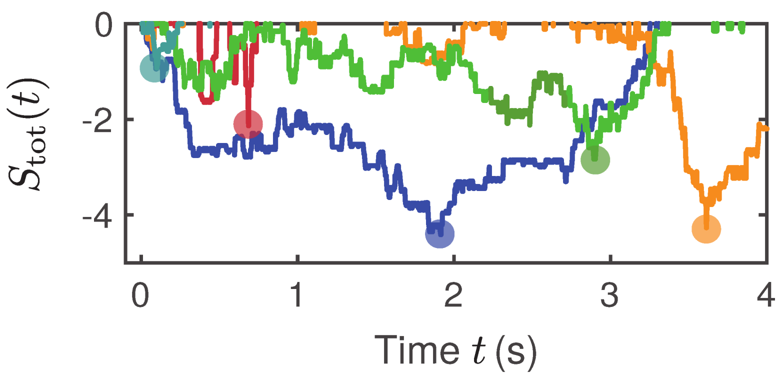
Close to equilibrium $\langle \Delta S_{min} \rangle(\infty) = -1.01 \pm 0.02$

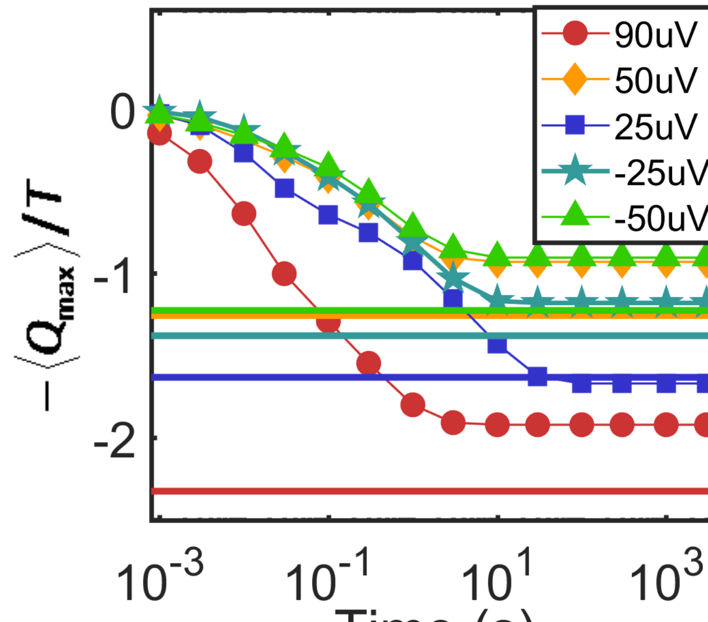
$$\Delta S(\tau) = \ln \frac{P_{st}(n_0)}{P_{st}(n_{N(\tau)})} + \sum_{j=1}^{N(\tau)} \ln \frac{\Gamma(n_{j-1} \rightarrow n_j)}{\Gamma(n_j \rightarrow n_{j-1})}$$

S. Singh, É. Roldán, I. Neri, I. M. Khaymovich, D. S. Golubev, V. F. Maisi, J. T. Peltonen, F. Jülicher, J. P. Pekola, arXiv:1712.01693 (2017)

# Stochastic entropy on trajectory. $<Q_{max}>$




**Heat supremum law**

Average max.absorbed heat is below

$$\frac{\langle Q_{max} \rangle}{T} \leq 1 + \sum_n P_{st}(n) \ln \frac{P_{st}(n)}{P_{st}^{min}}$$

$P_{st}(n)$ – steady state distribution;

$$\Delta S(\tau) = \ln \frac{P_{st}(n_0)}{P_{st}(n_{N(\tau)})} + \sum_{j=1}^{N(\tau)} \ln \frac{\Gamma(n_{j-1} \to n_j)}{\Gamma(n_j \to n_{j-1})}$$

S. Singh, É. Roldán, I. Neri, I. M. Khaymovich, D. S. Golubev, V. F. Maisi, J. T. Peltonen, F. Jülicher, J. P. Pekola, arXiv:1712.01693 (2017)

# Summary

Realization of a Coulomb blockaded device with single-electron counting sensitive to the direction of the current.

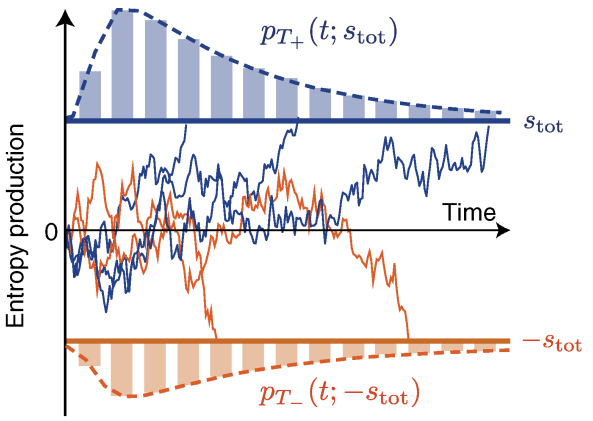
First experimental study of extreme-value statistics of stochastic entropy production in nonequilibrium steady states.

Statistics of ~$10^6$ records of negative entropy production in an electronic double dot is in agreement with the universal bounds.

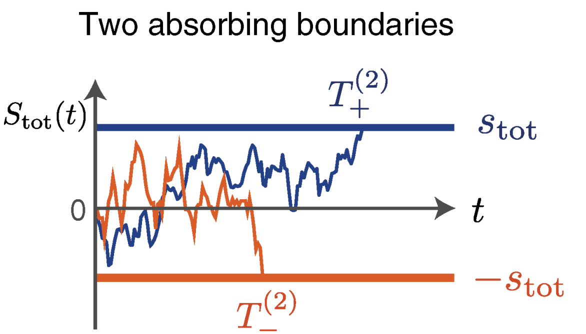
The bound for the average maximal amount of absorbed heat is derived theoretically and verified experimentally.

# Outlook

Relations between first passage time distributions




Stopping time distributions




Moments and cumulants of minimal entropy production. Relation with full-counting statistics

$$\left\langle \Delta S_{\min}^{n} \right\rangle \geq ???$$

$$\left\langle\left\langle \Delta S_{\min}^{n} \right\rangle\right\rangle \geq ???$$

# Contributions

## Experiment (PICO)

Department of Applied Physics,
Aalto University, Finland

- ***Prof. Jukka Pekola***
- ***Doc. Matthias Meschke (now @Hoch Schule Munich)***
- ***Olli-Pentti Saira (now @Caltech)***
- ***Ville Maisi (now @Lund)***
- ***Jonne Koski (now @ETH Zurich)***
- ***Shilpi Singh***
- ***Joonas Peltonen***
- ***Simone Gasparinetti (now @ETH Zurich)***
- ***Klaara Viisanen***
- ***Bayan Karimi***
- ***Alberto Ronzani (@ VTT, Finland)***
- ***Jorden Senior***

## Theory

Max Planck Institute for Physics of
Complex Systems, Dresden, Germany

- ***Prof. Frank Julicher***
- ***Edgar Roldan (now@ICTP)***
- ***Izaak Neri (moving to King's college)***

Department of Applied Physics,
Aalto University, Finland

- ***Dmitry Golubev***

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MAX-PLANCK-GESELLSCHAFT