EN ESSAYANT CONTINUELLEMENT
ON FINIT PAR RÉUSSIR. DONC:
PLUS ÇA RATE, PLUS ON A
DE CHANCES QUE ÇA MARCHE.

Probabilistic work extraction with single-electron devices

O. Maillet
Service de Physique de l'Etat Condensé (SPEC), CEA Saclay

Outline

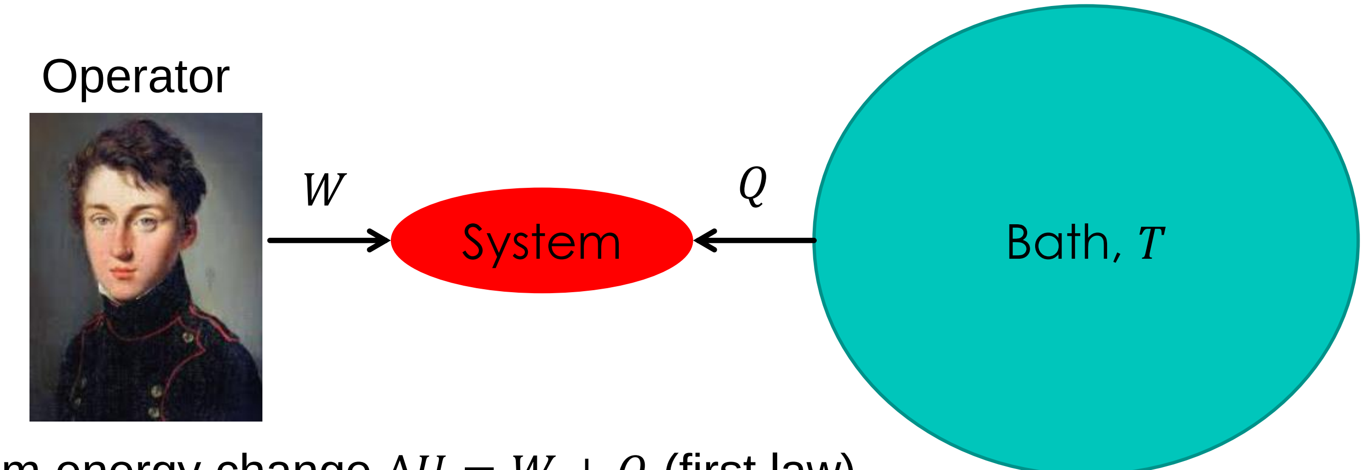
I. Context

II. Single-electron device energetics

III. Work extraction bounds with quenches

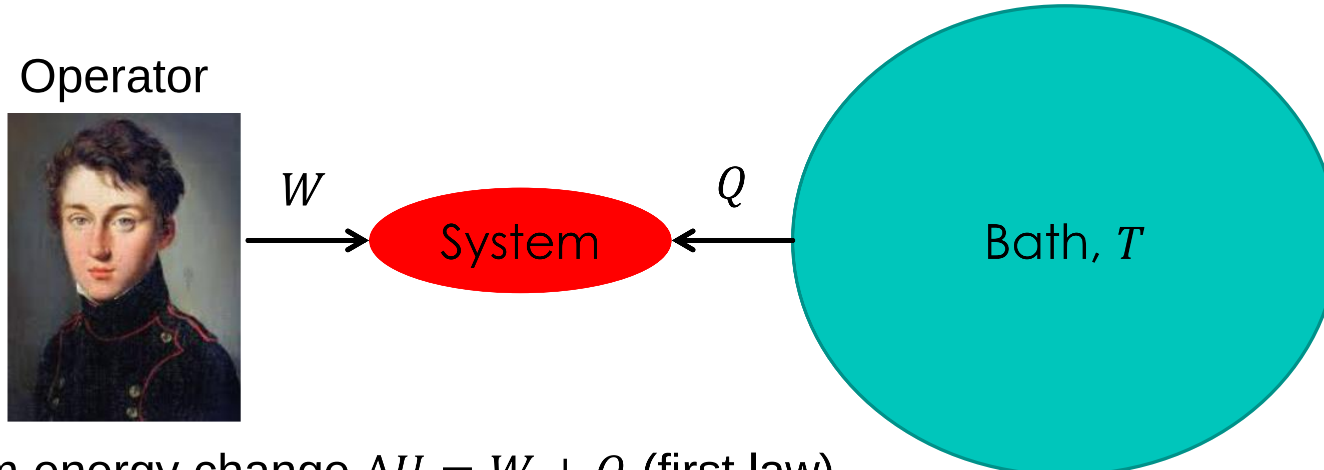
IV. Work extraction with « gambling » strategy

Context

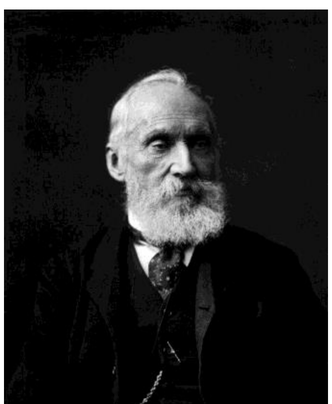


- System energy change $\Delta U = W + Q$ (first law)

Context



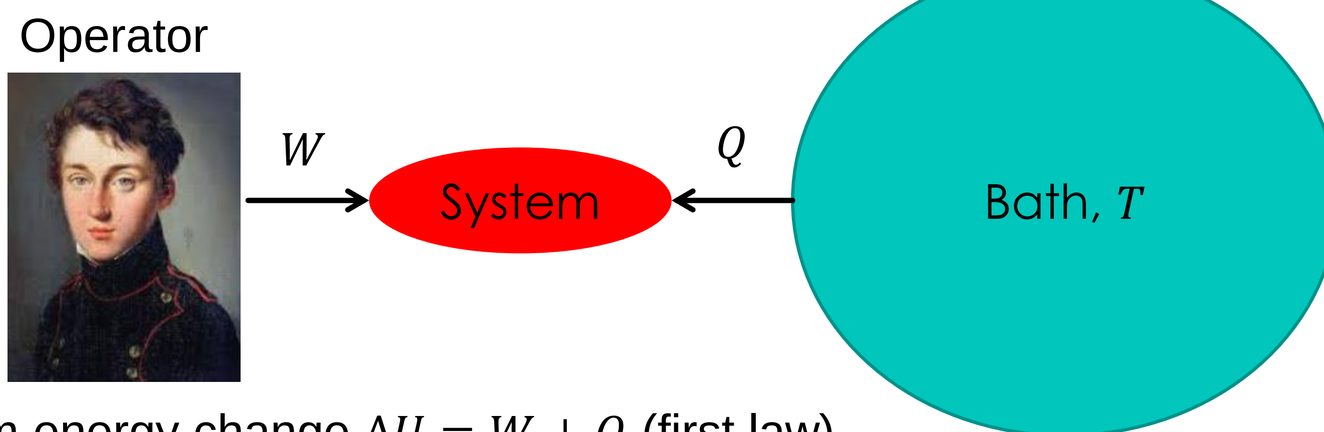
- System energy change $\Delta U = W + Q$ (first law)



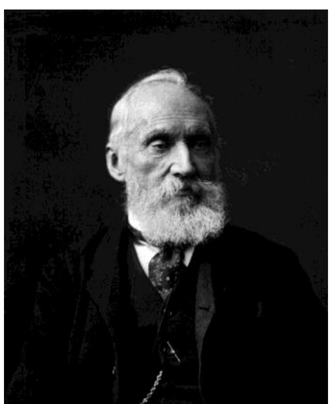
2nd law by Kelvin:

"It is impossible to convert heat completely in a cyclic process."

Context



- System energy change $\Delta U = W + Q$ (first law)



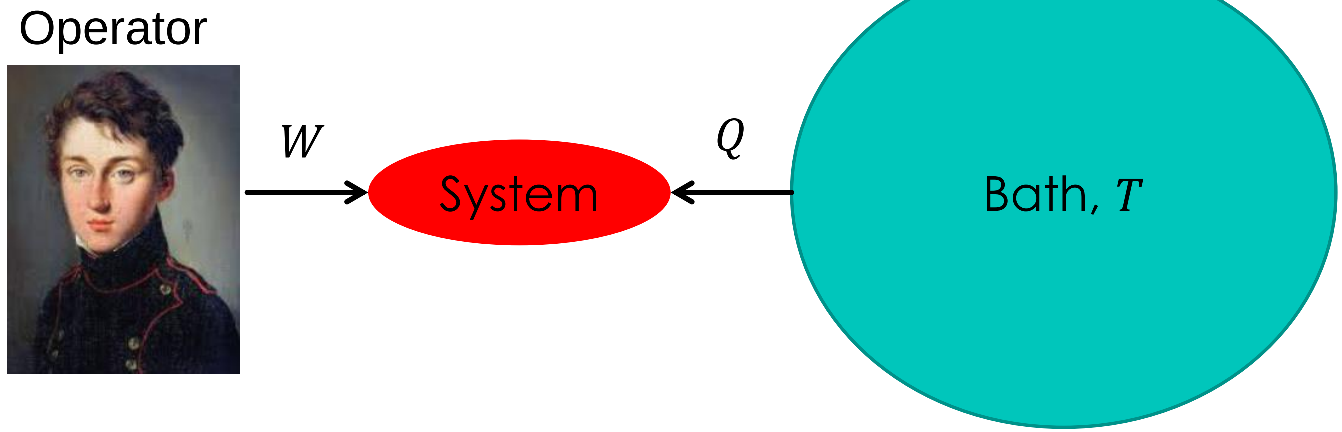
2nd law by Kelvin:

"It is impossible to convert heat completely in a cyclic process."

- For a system connected to a single heat bath, under an isothermal transformation:

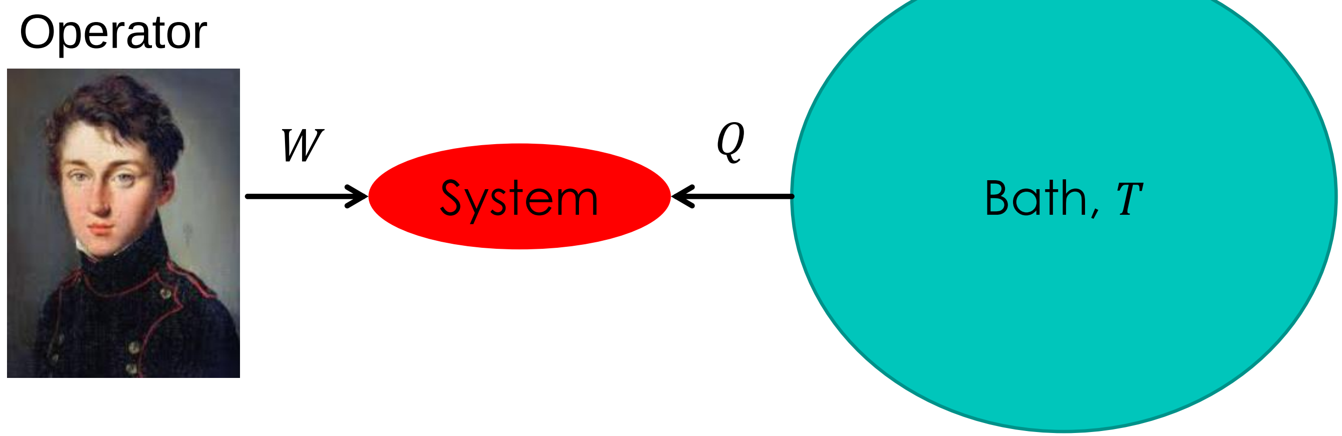
$$W \geq \Delta F = \Delta U - T\Delta S_{sys}$$

Context



- System Hamiltonian $H_\lambda\ [\{q_k(t)\}]$, λ: control parameter, $\{q_k\}$: system degrees of freedom

Context

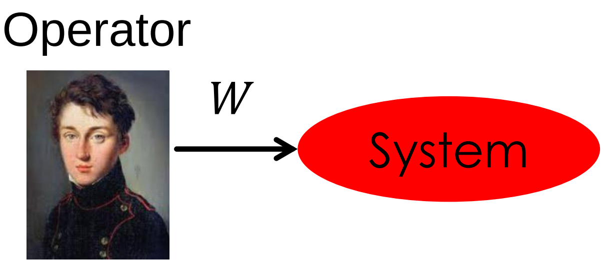


- System Hamiltonian H_λ $[\{q_k(t)\}]$, λ: control parameter, $\{q_k\}$: system degrees of freedom

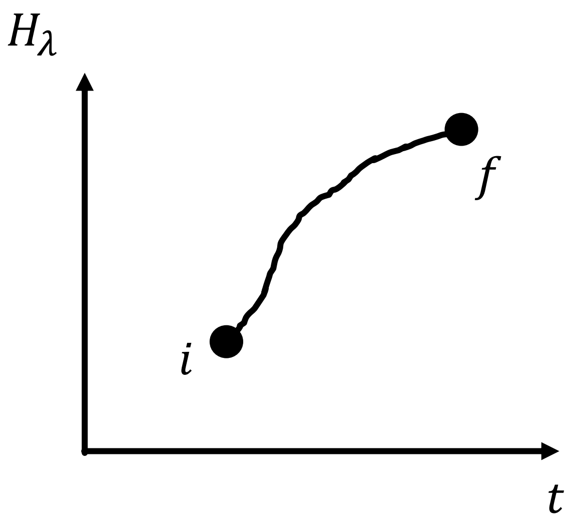
- Nonequilibrium work done by the operator through λ variation in time (« protocol »)

$$W[\{q_k(t)\}, \lambda(t)] = \int_{t_i}^{t_f} dt\, \dot{\lambda}(t) \frac{\partial H_\lambda[\{q_k(t)\}]}{\partial \lambda}$$

Context

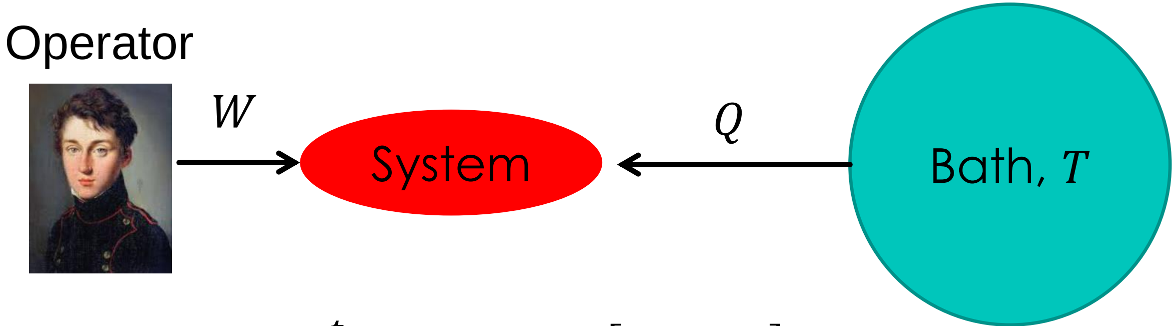


$$W[\{q_k(t)\}, \lambda(t)] = \int_{t_i}^{t_f} dt\, \dot{\lambda}(t) \frac{\partial H_\lambda[\{q_k(t)\}]}{\partial \lambda}$$

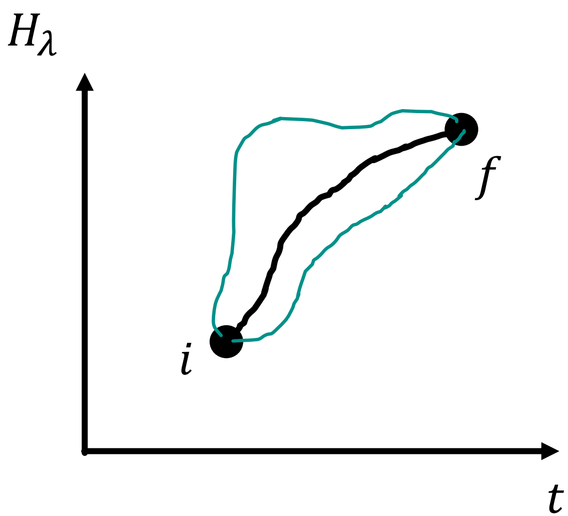


- Isolated system: deterministic trajectory, invariant upon time-reversal

Context



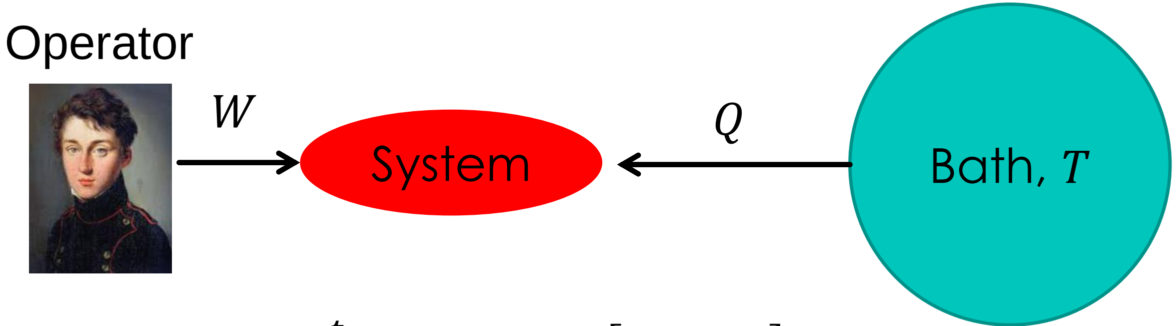
$$W[\{q_k(t)\}, \lambda(t)] = \int_{t_i}^{t_f} dt\, \dot{\lambda}(t) \frac{\partial H_\lambda[\{q_k(t)\}]}{\partial \lambda}$$



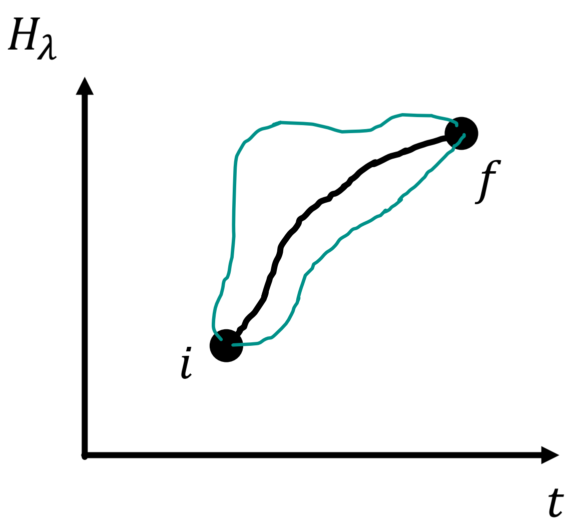
- Isolated system: deterministic trajectory, invariant upon time-reversal
- Heat bath: fluctuating degrees of freedom

  → **fluctuating nonequilibrium work**
- Relevant for small ($\sim k_B\, T$) energy scales, few DOF

Context



$$W[\{q_k(t)\},\lambda(t)] = \int_{t_i}^{t_f} dt\, \dot{\lambda}(t)\, \frac{\partial H_\lambda[\{q_k(t)\}]}{\partial \lambda}$$

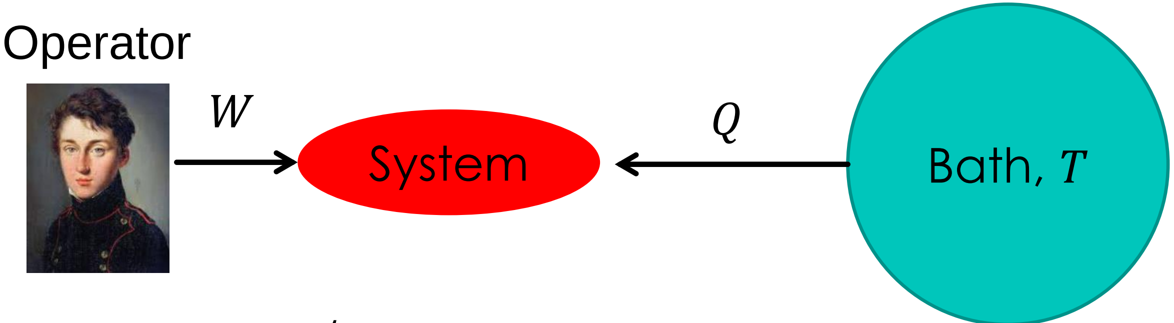


- C. Jarzynski, PRL **78** 2690 (1997):

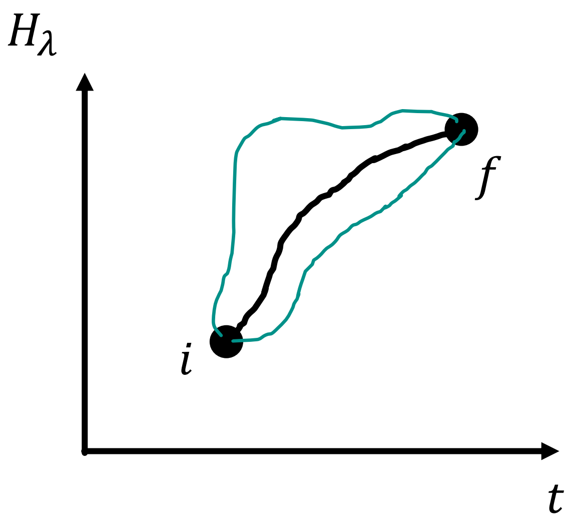
$$\left\langle e^{-W/k_B T} \right\rangle = e^{-\Delta F_{i\to f}/k_B T}$$

Links nonequilibrium, stochastic work to equilibrium, deterministic free energy difference over the transformation

Context



$$W[\{q_k(t)\}, \lambda(t)] = \int_{t_i}^{t_f} dt\, \dot{\lambda}(t) \frac{\partial H_\lambda[\{q_k(t)\}]}{\partial \lambda}$$



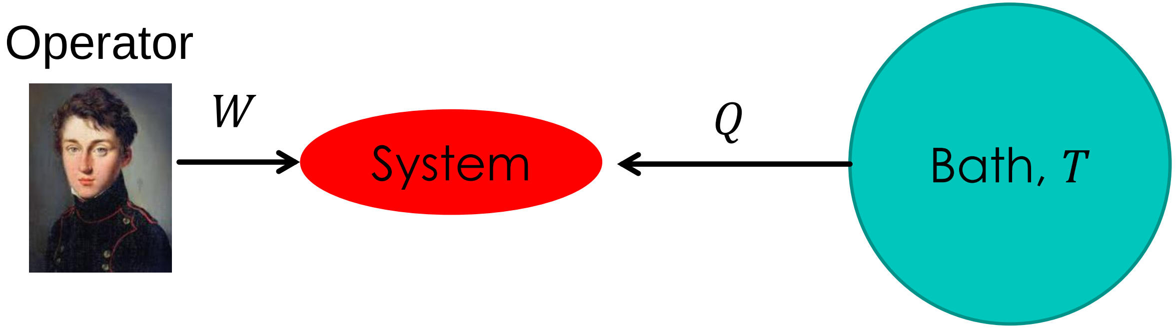
- C. Jarzynski, PRL **78** 2690 (1997):

$$\left\langle e^{-W/k_B T} \right\rangle = e^{-\Delta F_{i\to f}/k_B T}$$

Links nonequilibrium, stochastic work to equilibrium, deterministic free energy difference over the transformation

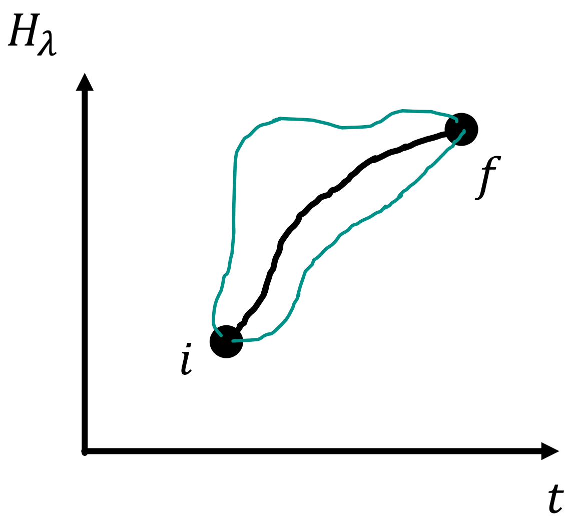
- 2nd law recovered **on average** $\langle W \rangle \geq \Delta F_{i\to f}$

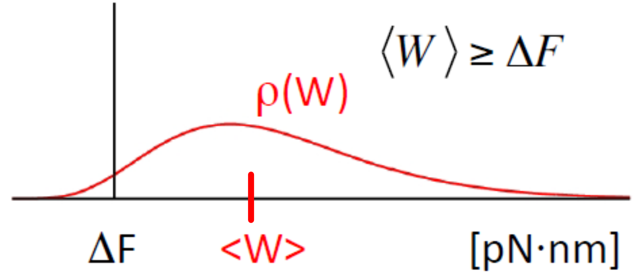
Context



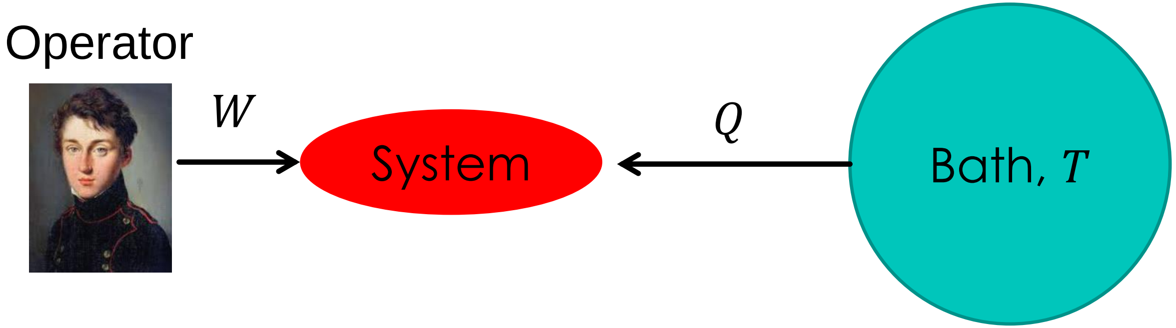
2nd law **on average** $\langle W \rangle \geq \Delta F_{i \to f}$

$\langle e^{-W/k_B T} \rangle = e^{-\Delta F_{i \to f}/k_B T}$:
« generalized 2nd law »



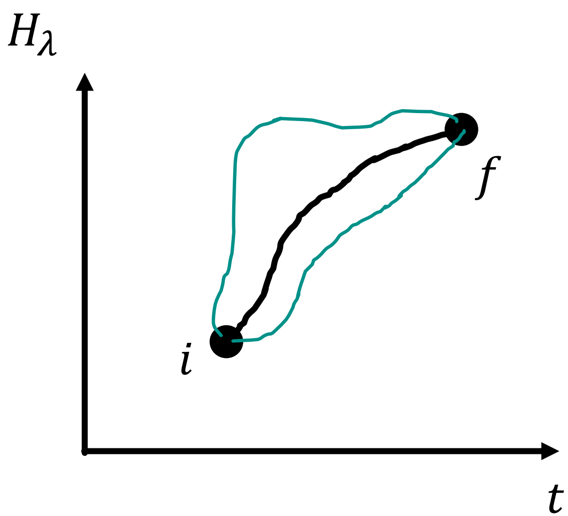


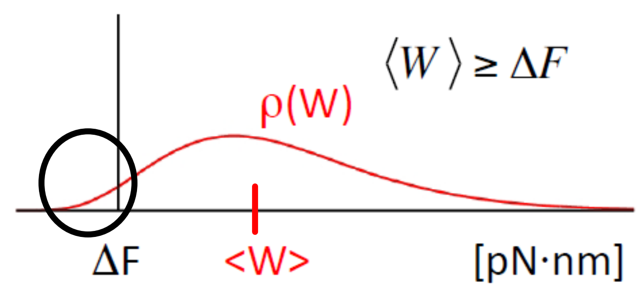
Context



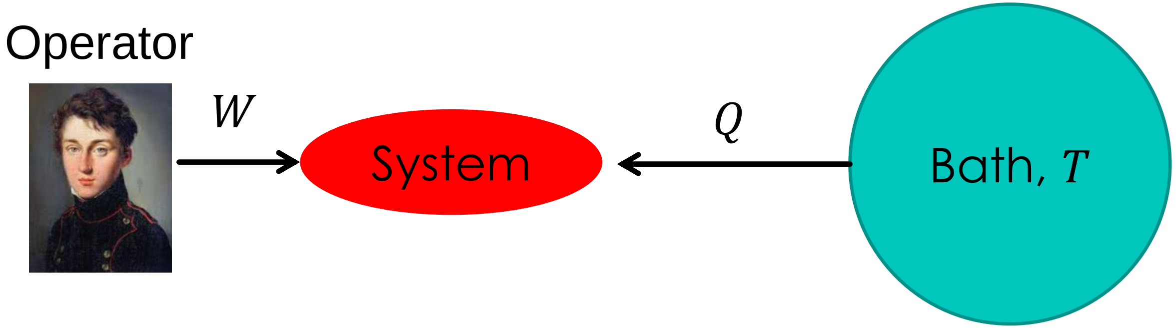
2$^{\text{nd}}$ law **on average** $\langle W \rangle \geq \Delta F_{i \to f}$

$\langle e^{-W/k_B T} \rangle = e^{-\Delta F_{i \to f}/k_B T}$:
« generalized 2$^{\text{nd}}$ law »



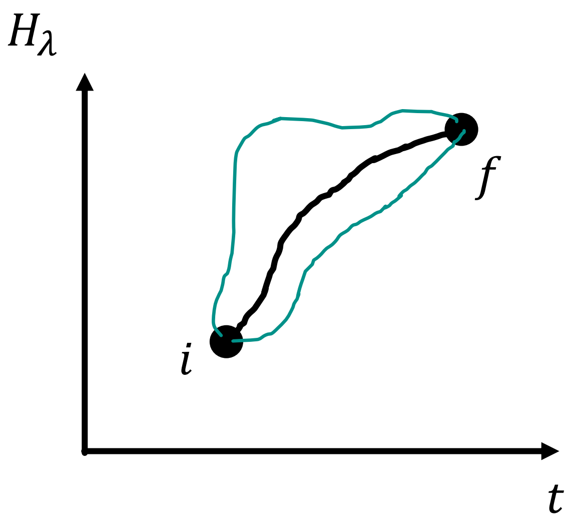


Context

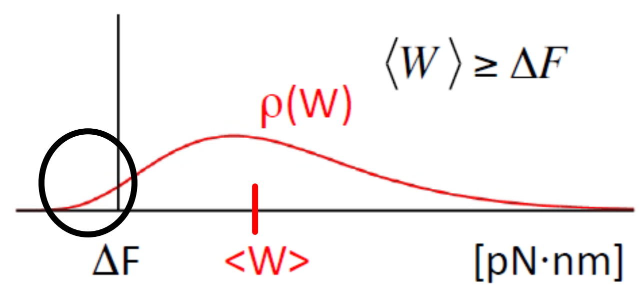


2nd law **on average** $\langle W \rangle \geq \Delta F_{i\to f}$

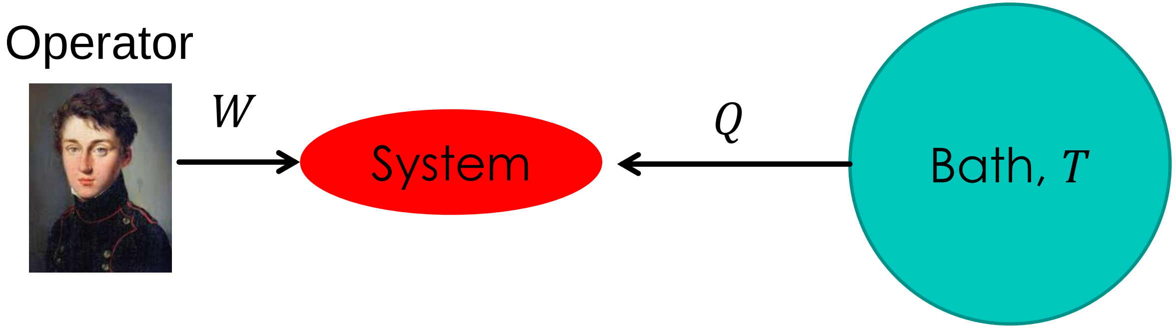
$\langle e^{-W/k_BT} \rangle = e^{-\Delta F_{i\to f}/k_BT}$:
« generalized 2nd law »



→ For some trajectories, one can have work extraction, $W < \Delta F_{i\to f}$!

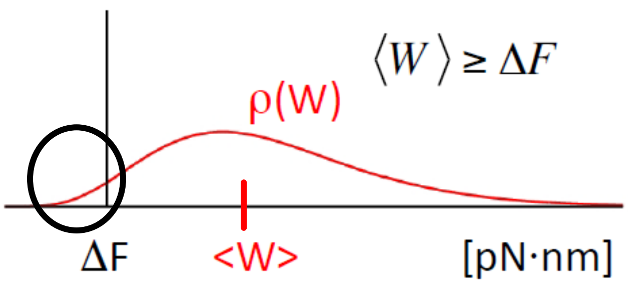


How far can we “violate” the 2nd law ?

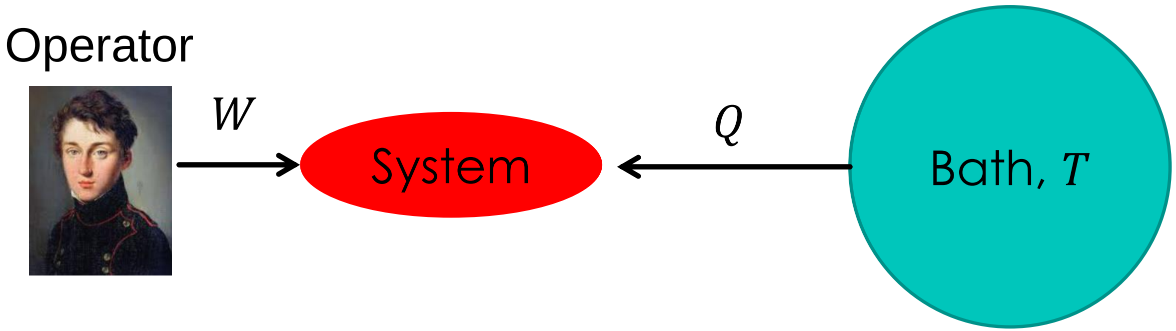


$\langle e^{-W/k_BT} \rangle = e^{-\Delta F/k_BT}$: « generalized 2nd law »

→ **For some trajectories, one can have work extraction, $\boldsymbol{W < \Delta F}$**

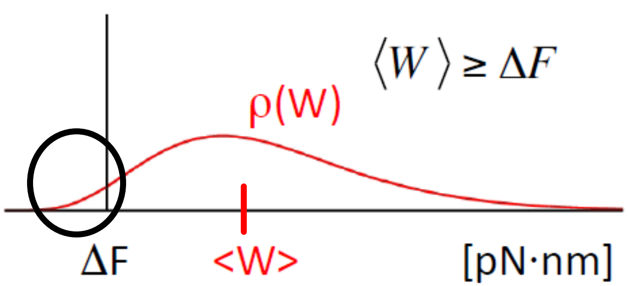


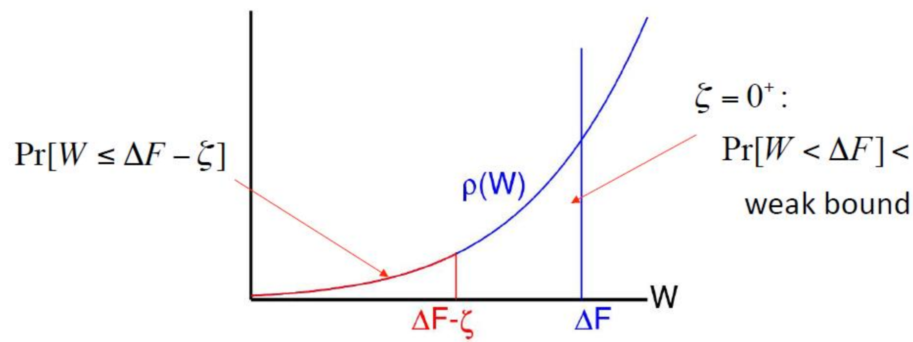
How far can we “violate” the 2nd law ?



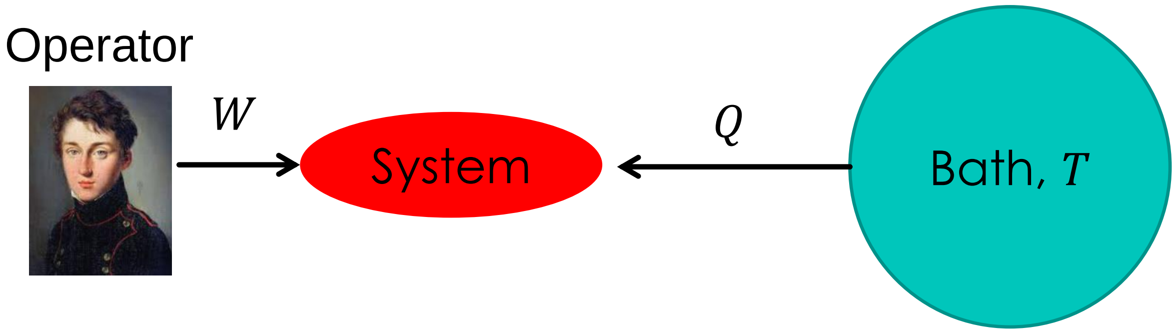
$\left\langle e^{-W/k_B T}\right\rangle = e^{-\Delta F/k_B T}$: « generalized 2nd law »

→ **For some trajectories, one can have work extraction, $W < \Delta F$**



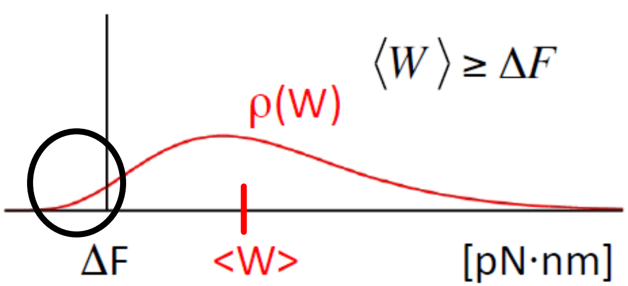


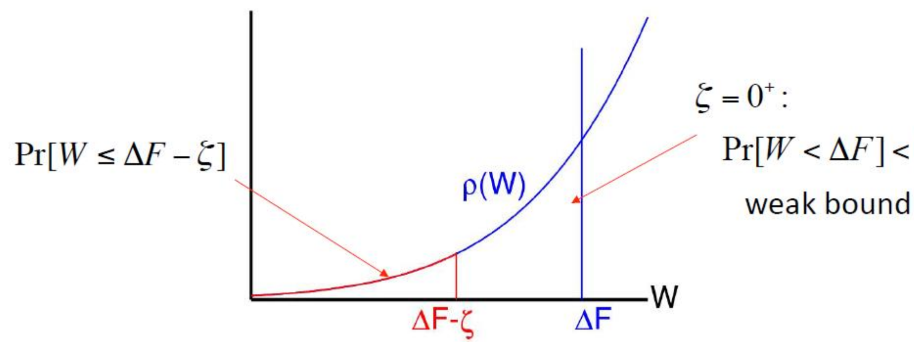
How far can we "violate" the 2nd law ?



$\langle e^{-W/k_BT} \rangle = e^{-\Delta F/k_BT}$: « generalized 2nd law »

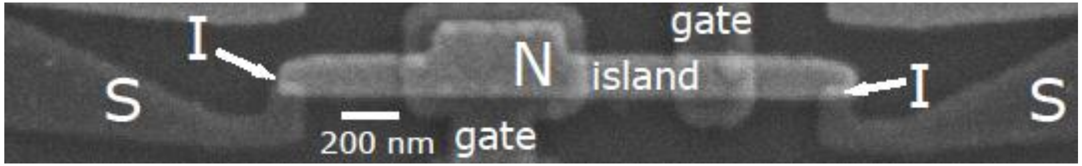
→ **For some trajectories, one can have work extraction, $W < \Delta F$**





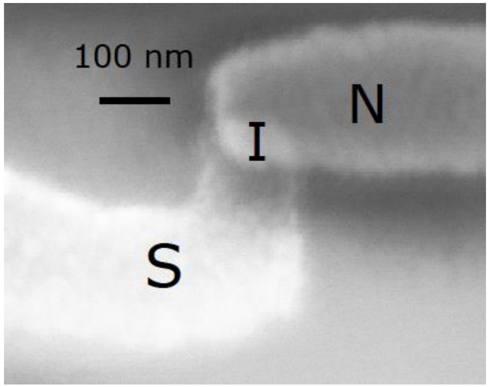
→ **We use a highly fluctuating tunable system, e.g. a single-electron box**

Single electron box



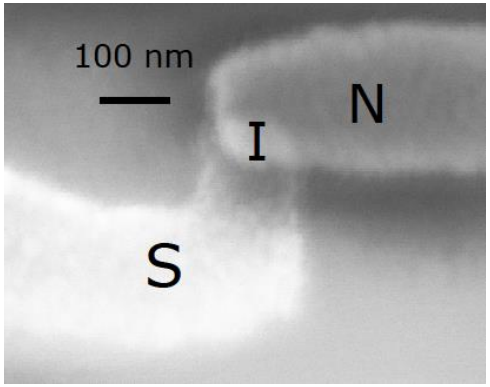
- Small metallic island, with small capacitance C_Σ dominated by tunnel junctions

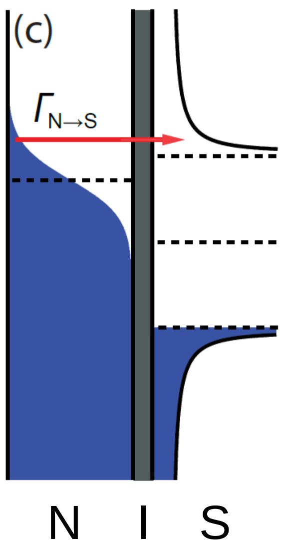
NIS tunnel junction



- Fabrication: EBL+ angle evaporation + low pressure oxidation of Aluminum

NIS tunnel junction

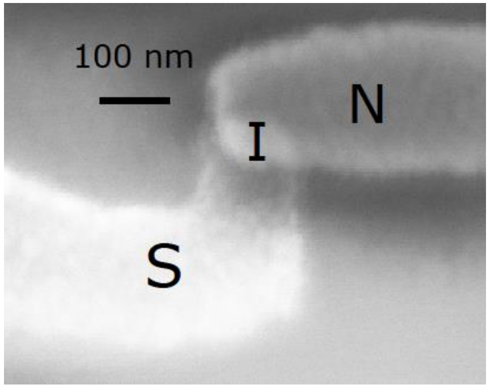


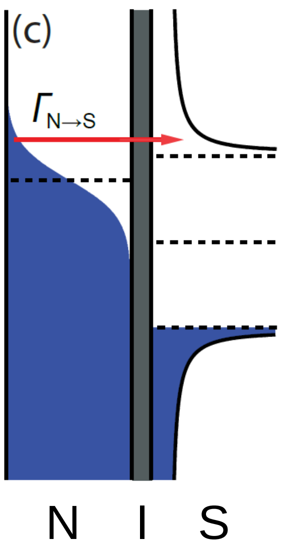


- Fabrication: EBL+ angle evaporation + low pressure oxidation of Aluminum
- Tunneling rate:

$$\Gamma_{S\to N}(\mu_N) = \frac{1}{e^2 R_T} \int dE [1 - f(E - \mu_N, T_N)] f(E, T_s) n_s(E)$$

NIS tunnel junction





- Fabrication: EBL+ angle evaporation + low pressure oxidation of Aluminum

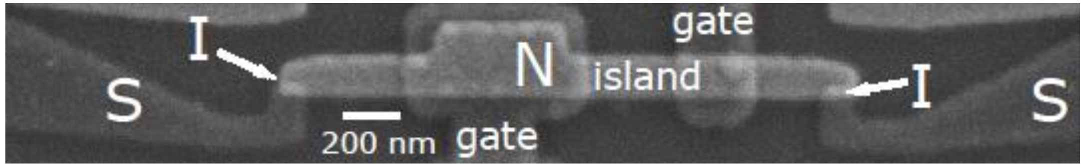
- Tunneling rate:

$$\Gamma_{S\to N}(\mu_N) = \frac{1}{e^2 R_T}\int dE[1 - f(E-\mu_N, T_N)]f(E, T_s)n_s(E)$$

- Use of superconductor: energy gap = low rates

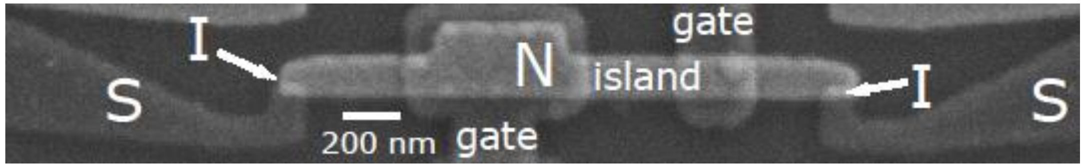
- **Thermally activated** tunneling at $T_{S,N} \neq 0$, **even with** $\boldsymbol{\mu_N = 0}$**: role of thermal fluctuations**

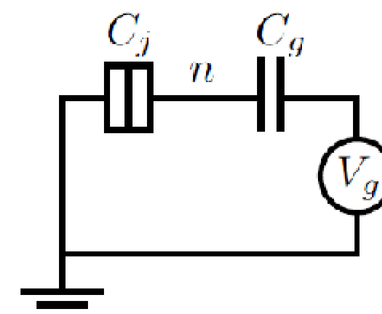
Single electron box



- Small metallic island, with small capacitance C_Σ dominated by tunnel junctions
- Ultrasmall junctions (area < 100 nm x 100 nm): $C_\Sigma \leq 1$ fF
- Energy cost of tunneling: **charging energy** $E_c = \frac{e^2}{2C_\Sigma}$
- Two junctions: SINIS transistor for transport measurements → E_c, R_T can be measured

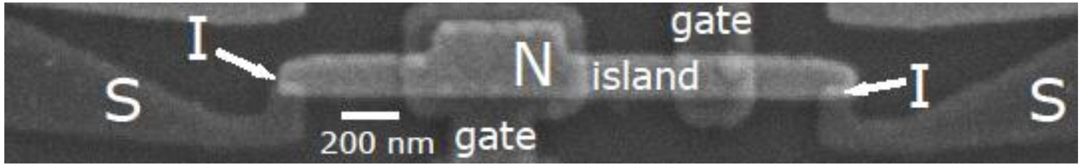
Single electron box

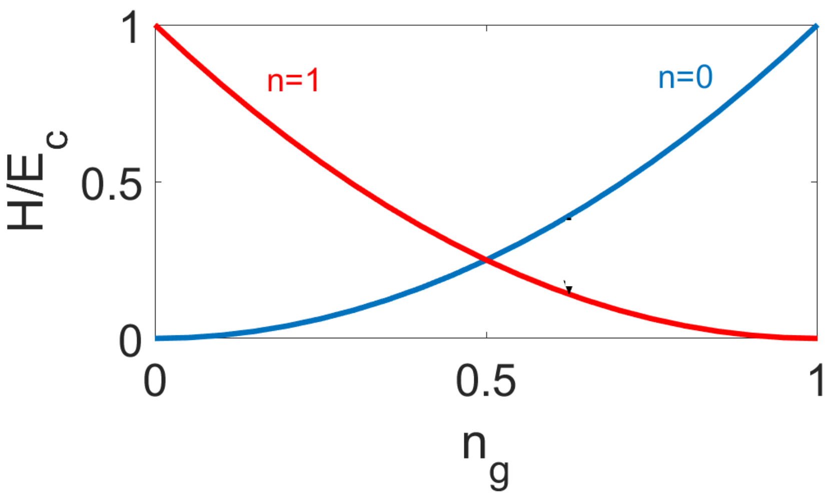




- Hamiltonian for equivalent circuit: $H(n, n_g) = E_C(n - n_g)^2$
- Tunable electrostatic energy with gate voltage $n_g = \frac{C_g V_g}{e}$
- E_C~1 K: occupation of two charge states $N_0 + n, n = 0{,}1$ for $n_g \in [0; 1]$ below 1K

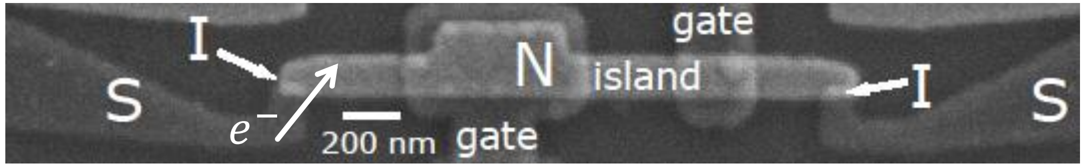
Single electron box

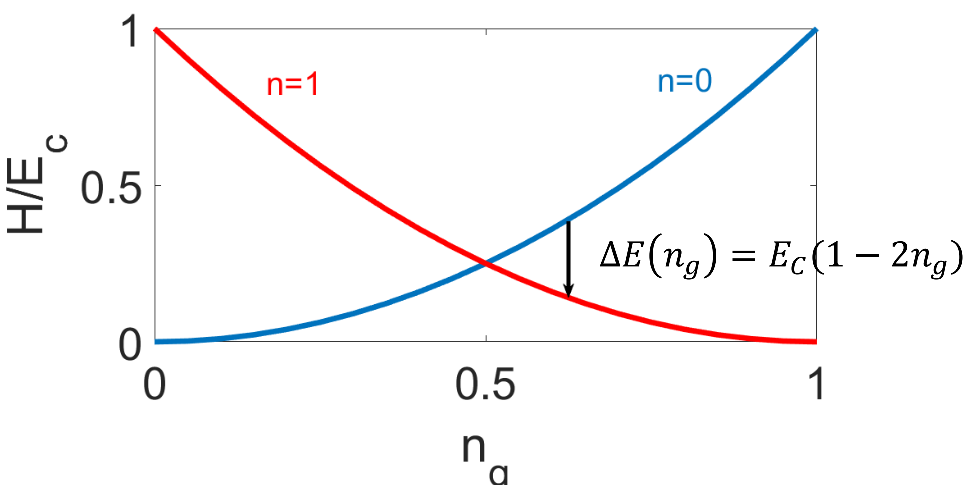




$$H(n, n_g) = E_C(n - n_g)^2$$

Single electron box

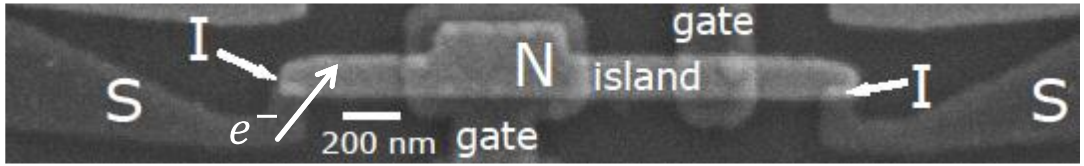


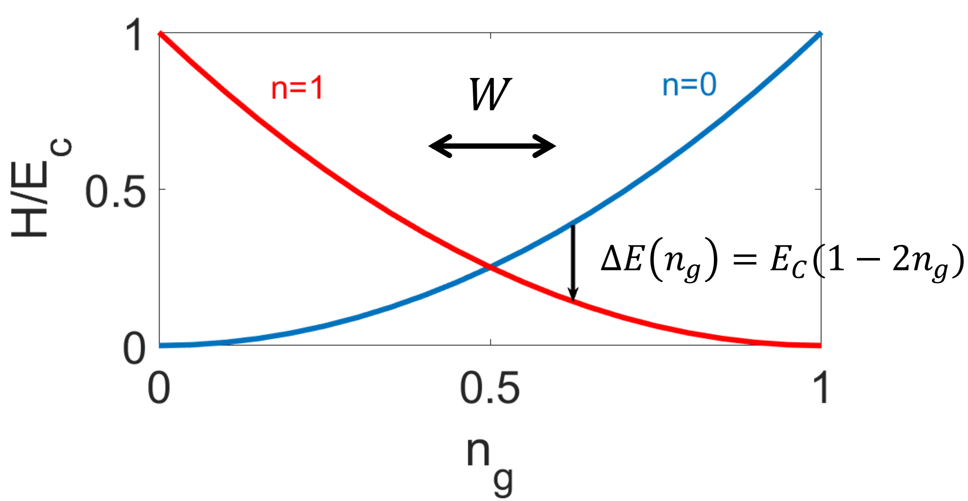


$$H(n, n_g) = E_C(n - n_g)^2$$

- Electron tunneling = heat exchange **(stochastic)**

Single electron box

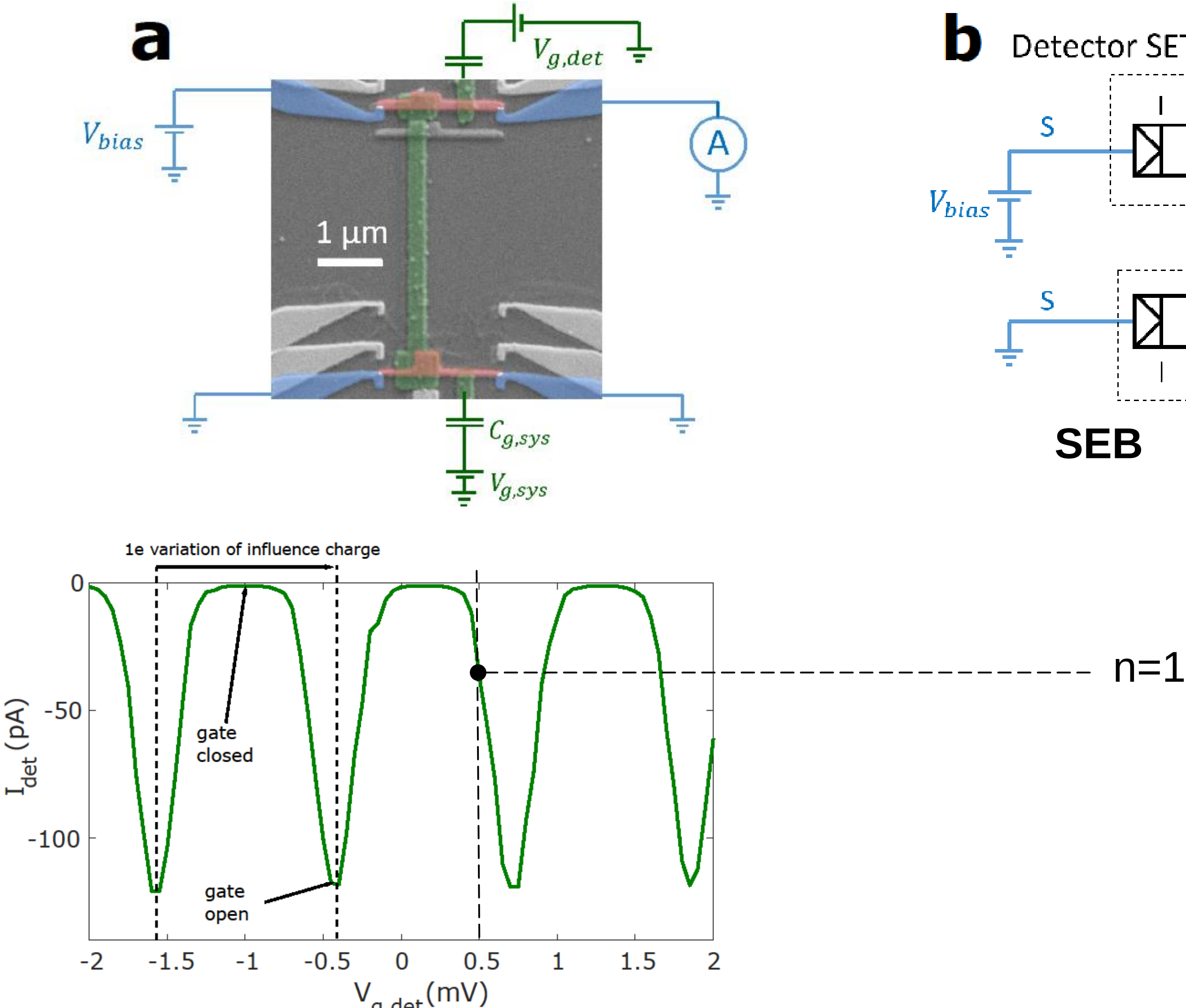


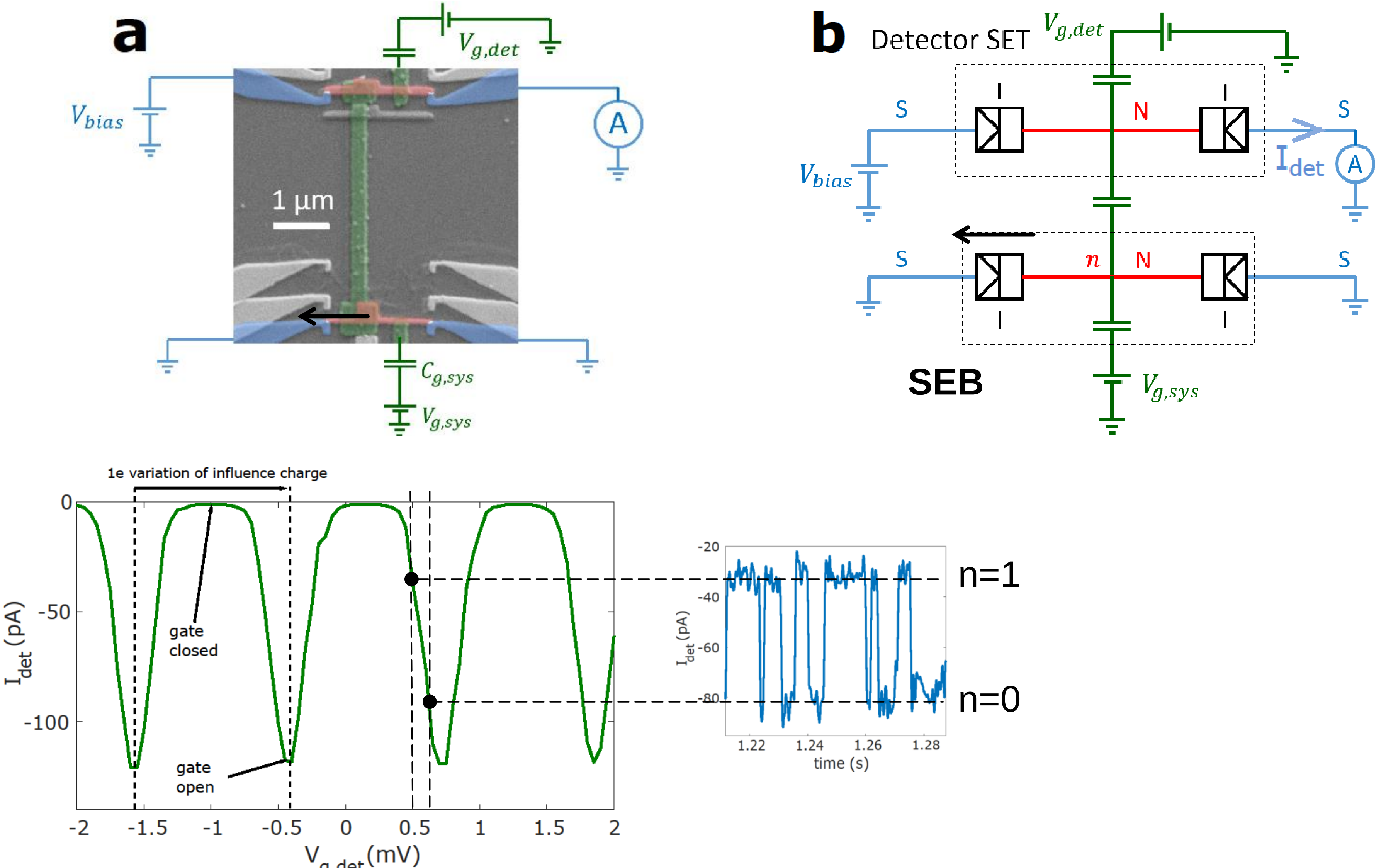


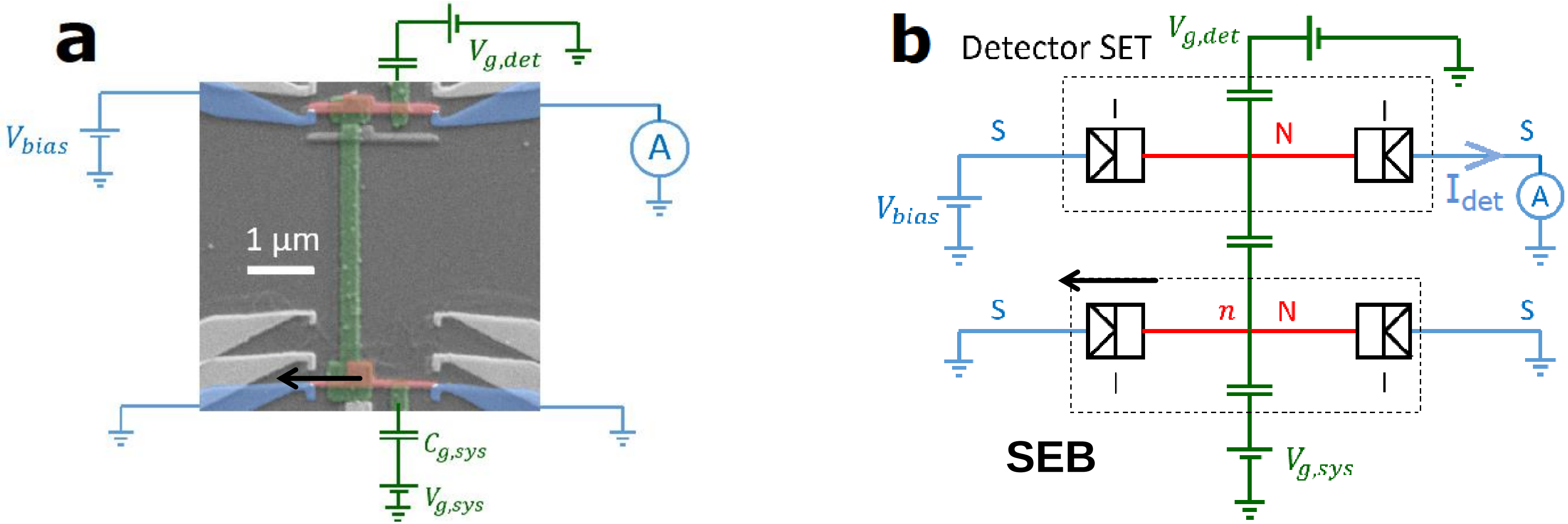
$$H(n, n_g) = E_C(n - n_g)^2$$

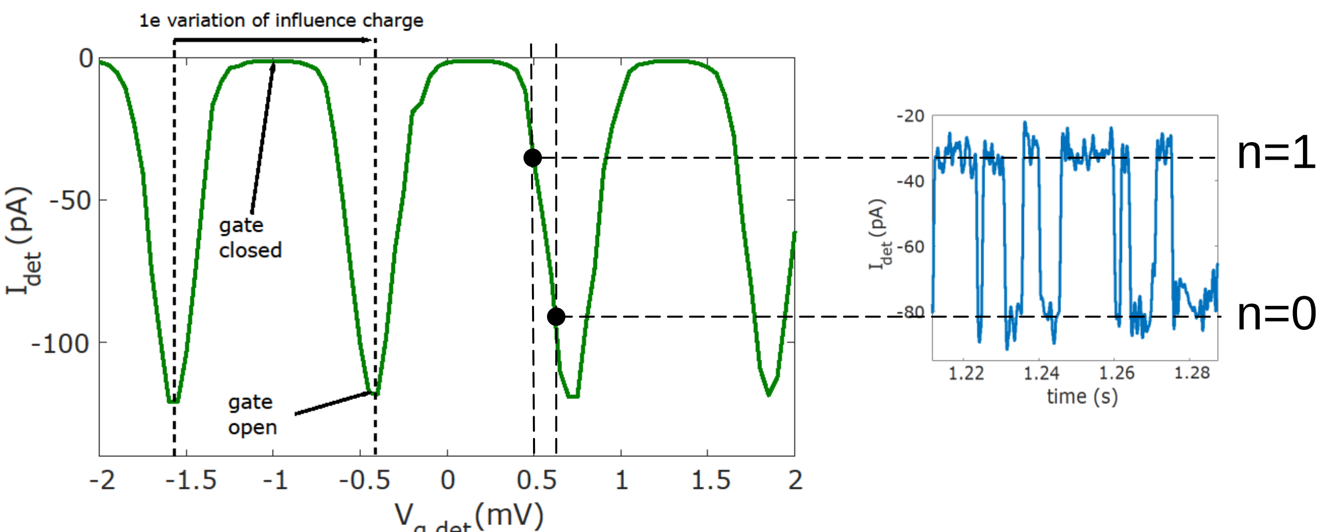
- Electron tunneling = heat exchange **(stochastic)**
- Gate driving $n_g(t)$ = work applied

$$W[n(t), n_g(t)] = \int dt \dot{n}_g(t) \frac{\partial H}{\partial n_g}$$


a
$V_{g,det}$
V_{bias}
1 µm
A
$C_{g,sys}$
$V_{g,sys}$
b
Detector SET
$V_{g,det}$
S
N
S
V_{bias}
I_{det}
A
S
n
N
S
SEB
$V_{g,sys}$
1e variation of influence charge
gate closed
gate open
n=1
I_{det} (pA)
0
-50
-100
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
$V_{g,det}$(mV)

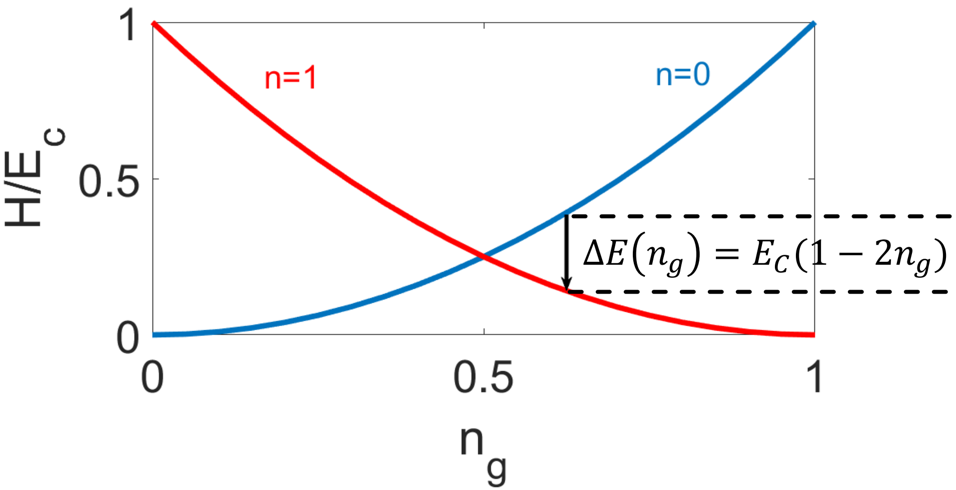

a
Vg,det
Vbias
A
1 µm
Cg,sys
Vg,sys
b
Detector SET
Vg,det
S
N
S
Vbias
Idet
A
S
n
N
S
SEB
Vg,sys
1e variation of influence charge
gate closed
gate open
Idet (pA)
Vg,det (mV)
0
-50
-100
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Idet (pA)
-20
-40
-60
-80
1.22
1.24
1.26
1.28
time (s)
n=1
n=0

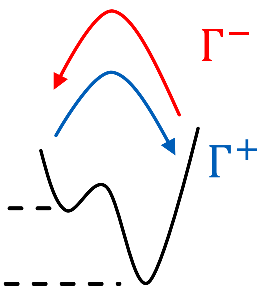


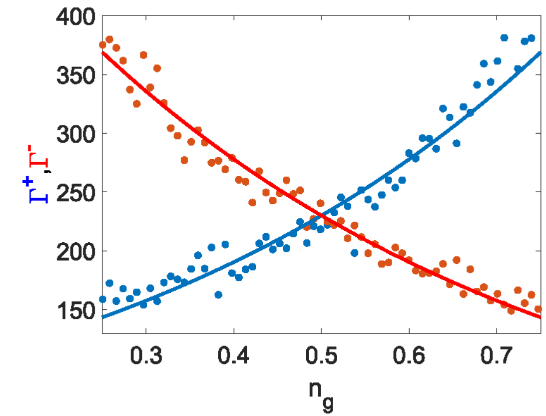


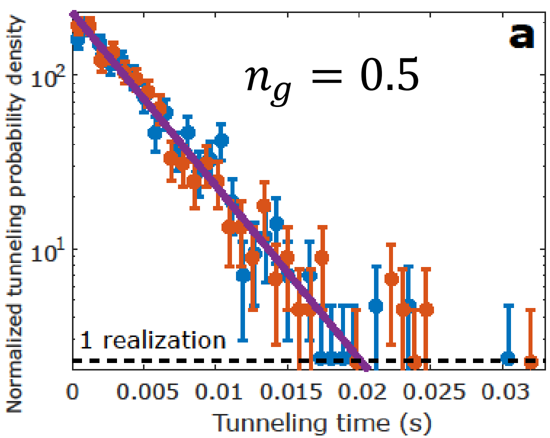
- SET detection: sensitive electrometry
- Real-time monitoring of electron jumps in the SEB (« system »): heat exchanges recorded

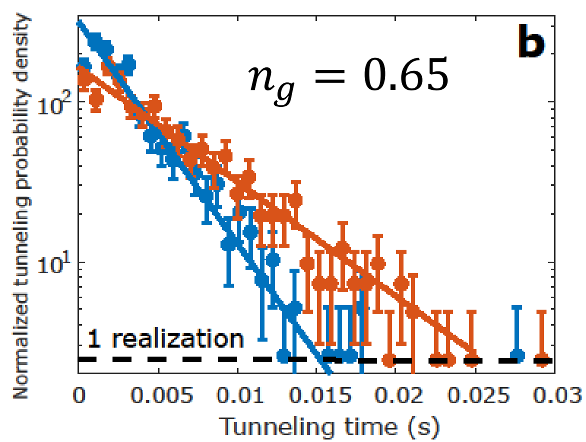
Single electron box





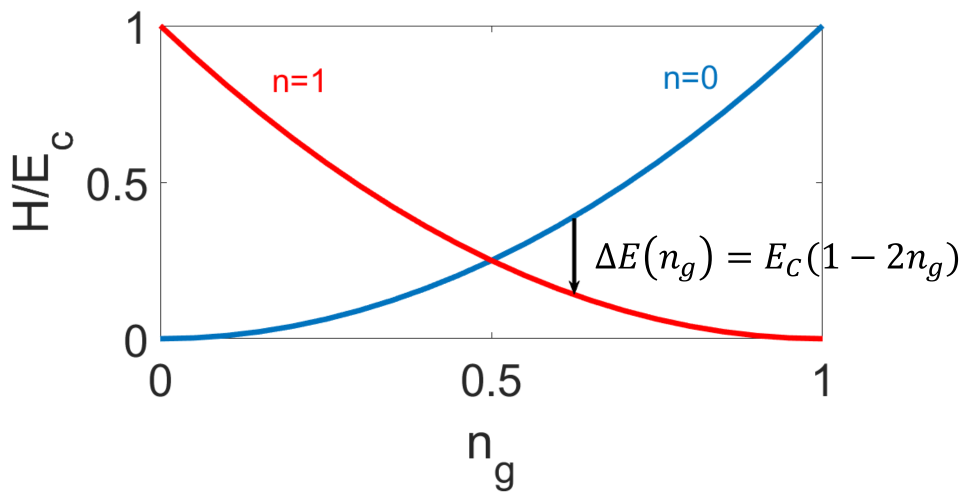


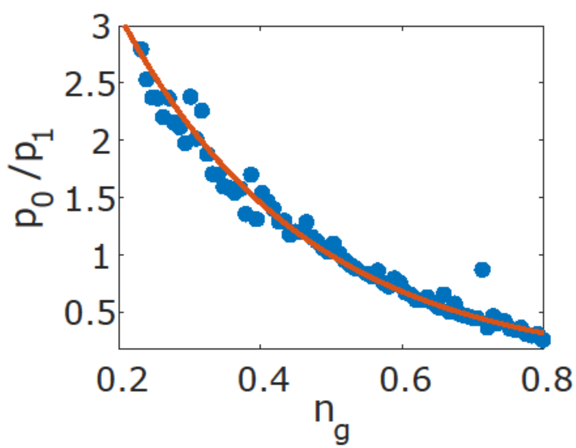




- Typical tunneling rates ~ 100-300 Hz
- Waiting time distribution for a Poisson process

Single electron box





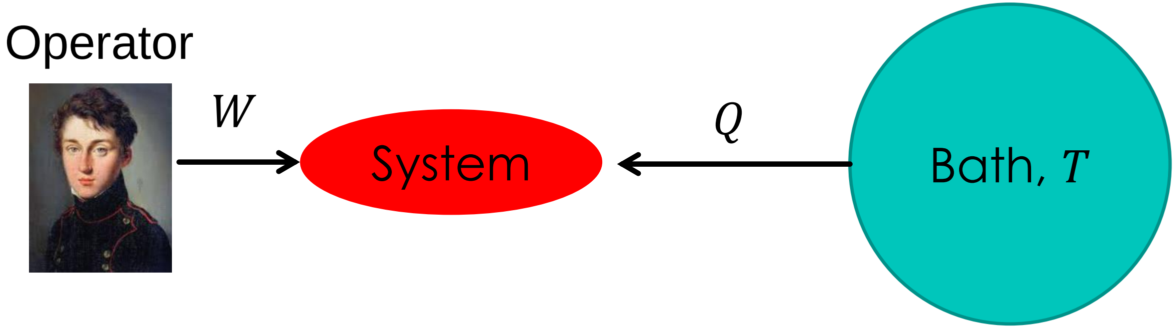
- Master equation:

$$\begin{cases} \partial_t p_0 = -\Gamma^+ p_0 + \Gamma^- p_1 \\ \partial_t p_1 = -\Gamma^- p_1 + \Gamma^+ p_0 \end{cases}$$

- Detailed balance at equilibrium:

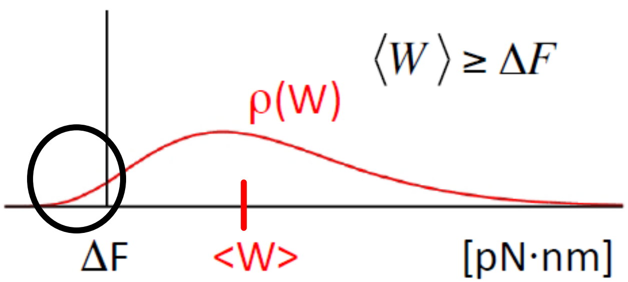
$$\frac{p_0}{p_1} = \frac{\Gamma^-}{\Gamma^+} = e^{\Delta E(n_g)/k_B T}$$

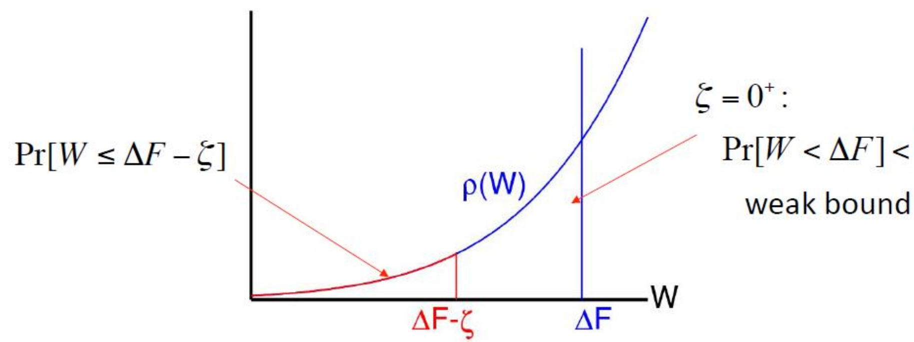
How far can we “violate” the 2nd law ?



$\left\langle e^{-W/k_BT} \right\rangle = e^{-\Delta F/k_BT}$: « generalized 2nd law »

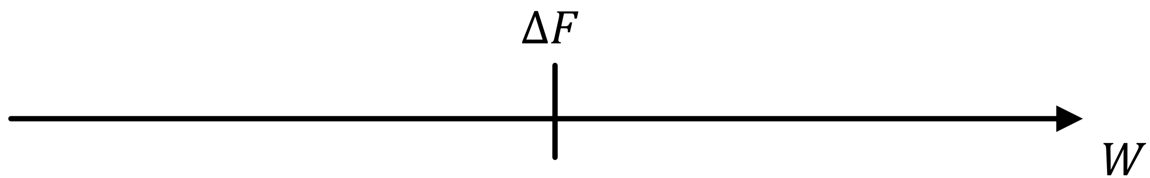
→ **For some trajectories, one can have work extraction, $W < \Delta F$**





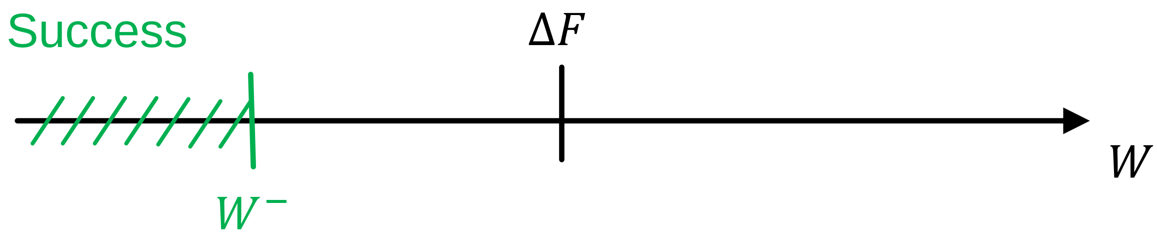
Probabilistic work extraction

Work applied $W[n(t), n_g(t)] = \int_0^T dt \dot{n}_g(t) \frac{\partial H}{\partial n_g}$



Probabilistic work extraction

Work applied $W[n(t), n_g(t)] = \int_0^T dt \dot{n}_g(t) \frac{\partial H}{\partial n_g}$

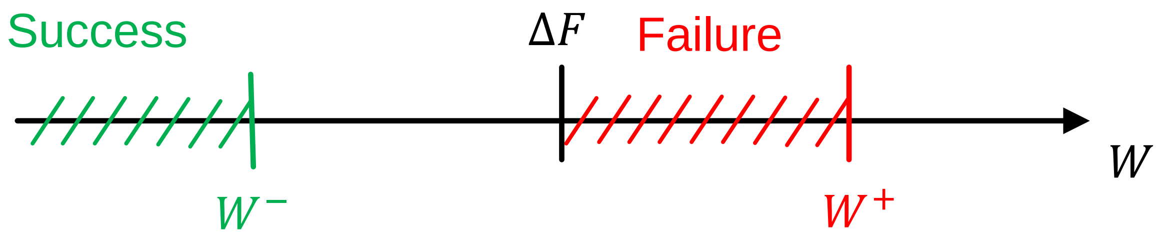


Requirements for the driving protocol over a cycle:

- Bound on minimum work extracted $W^- - \Delta F$ if successful attempt

Probabilistic work extraction

Work applied $W[n(t), n_g(t)] = \int_0^T dt\dot{n}_g(t)\frac{\partial H}{\partial n_g}$

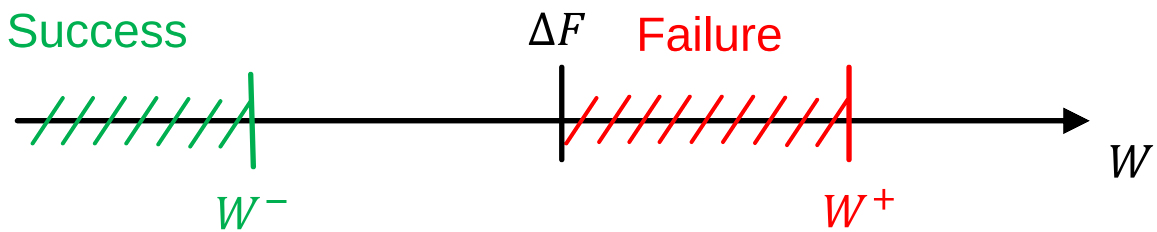


<u>Requirements for the driving protocol over a cycle</u>:

- Bound on minimum work extracted $W^- - \Delta F$ if successful attempt
- Bound on maximum work paid $W^+ - \Delta F$ if failed attempt

Probabilistic work extraction

Work applied $W[n(t), n_g(t)] = \int_0^T dt \dot{n}_g(t) \frac{\partial H}{\partial n_g}$

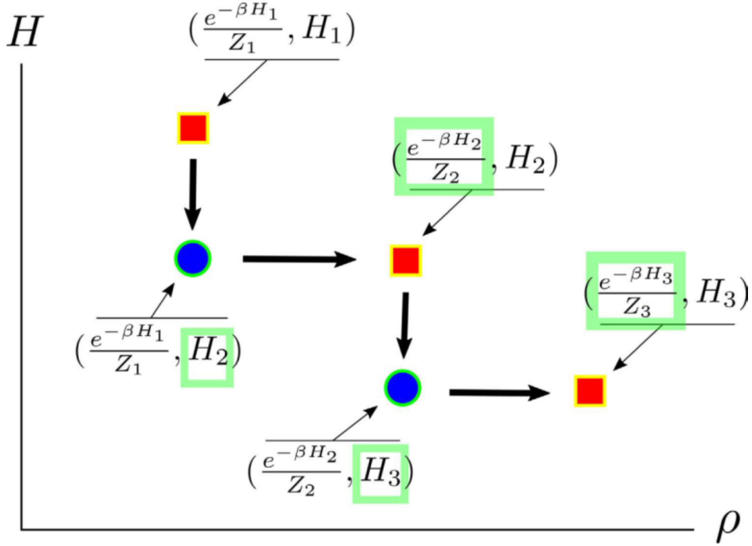


<u>Requirements for the driving protocol over a cycle</u>:

- Bound on minimum work extracted $W^- - \Delta F$ if successful attempt
- Bound on maximum work paid $W^+ - \Delta F$ if failed attempt
- Maximum probability $p_{W^+}(W \leq W^-)$ allowed by Jarzynski's equality

$$p_{W^+}(W \leq W^-) \leq \frac{e^{\Delta F/k_B T} - e^{-W^+/k_B T}}{e^{-W^-/k_B T} - e^{-W^+/k_B T}}$$

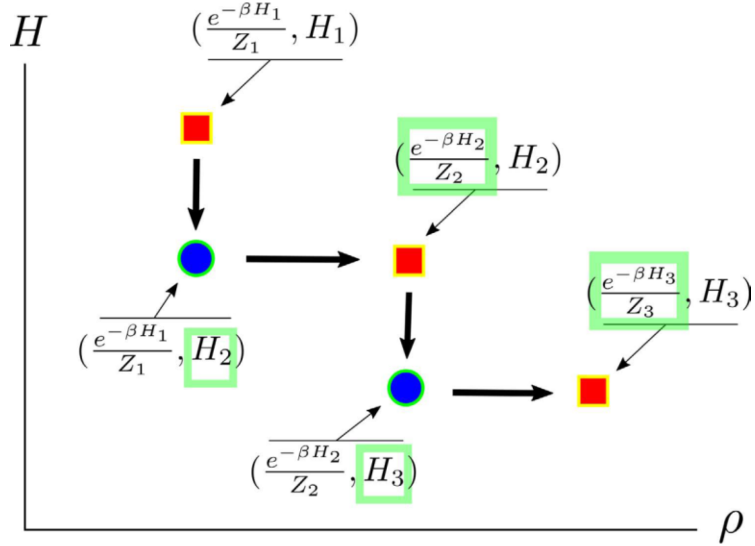
V. Cavina et al., Sci. Rep. (2016)

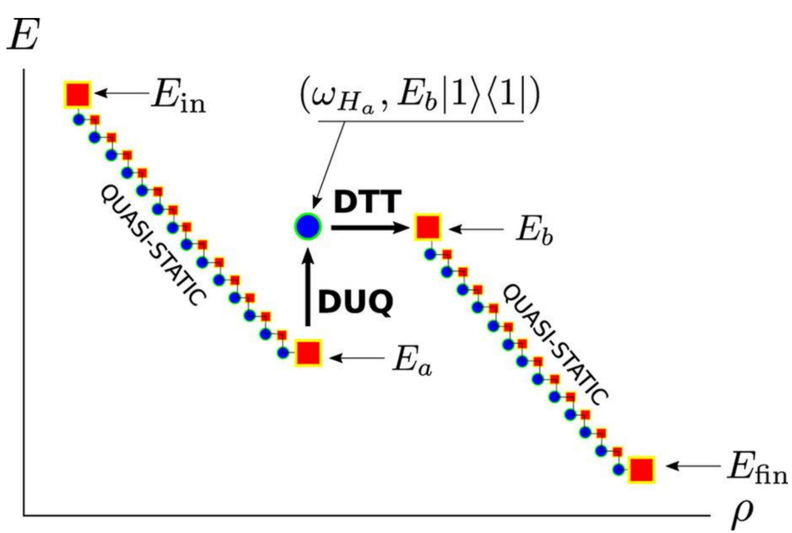


V. Cavina et al., Sci. Rep. (2016): sequence of « discrete » steps describing a transformation:

- **Quench**: fast = no heat exchanged, only work

- **Thermalization**: no work done, heat removed from/released to the bath



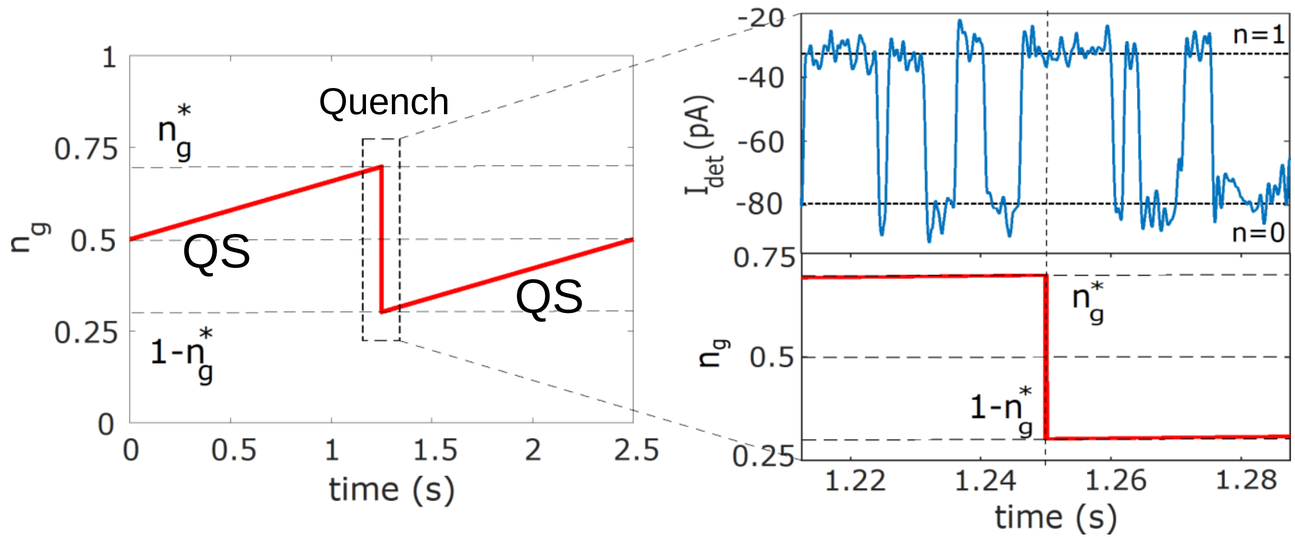


V. Cavina et al., Sci. Rep. (2016): sequence of « discrete » steps describing a transformation:

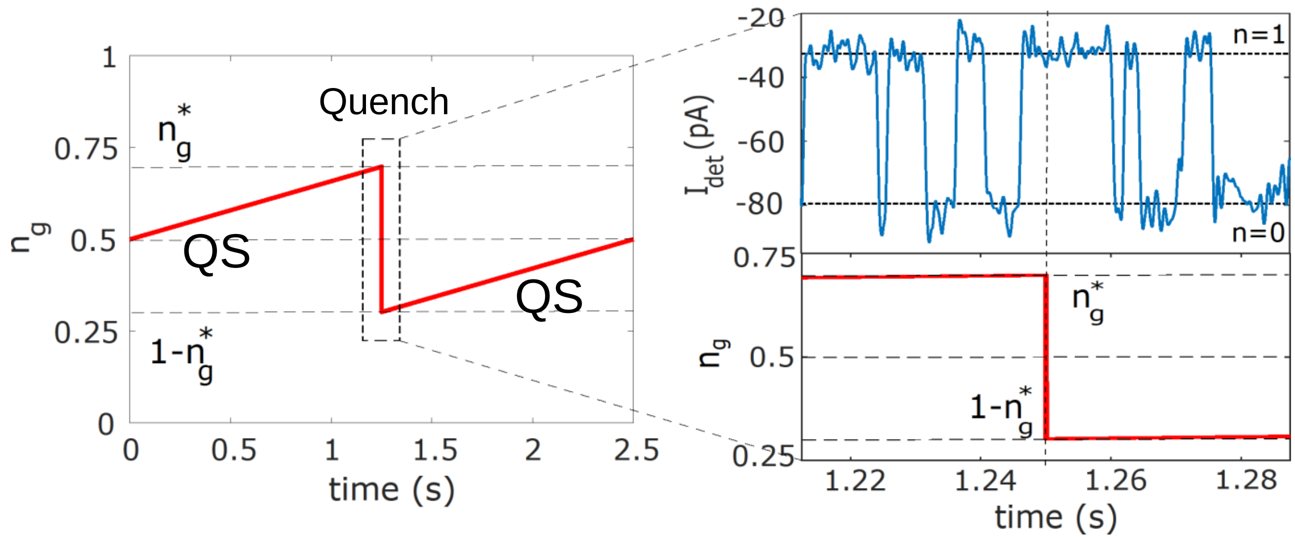
- **Quench**: fast = no heat exchanged, only work
- **Thermalization**: no work done, heat removed from/released to the bath
- Large quench = splits in two the work distribution

$$p(W) = p_0\delta(W - W^+) + (\mathbf{1} - \boldsymbol{p_0})\boldsymbol{\delta}(\boldsymbol{W} - \boldsymbol{W^-})$$

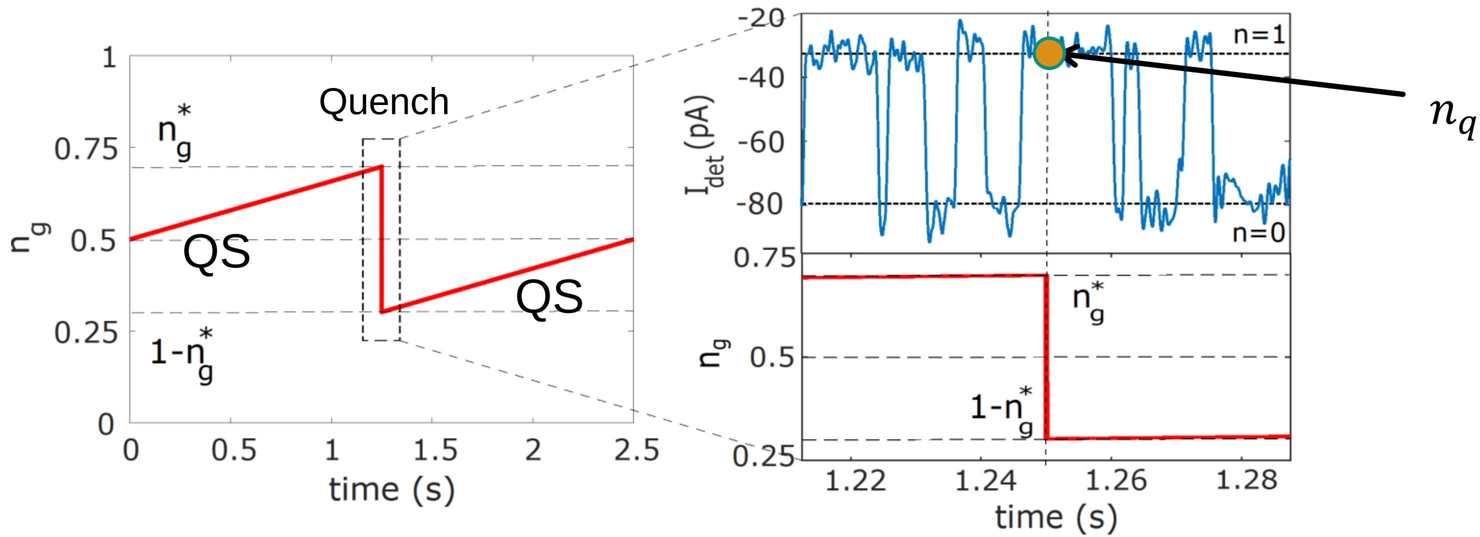
- $p_0 = \frac{1}{e^{-(E_b - E_a)/k_B T} + 1}$ (Gibbs)



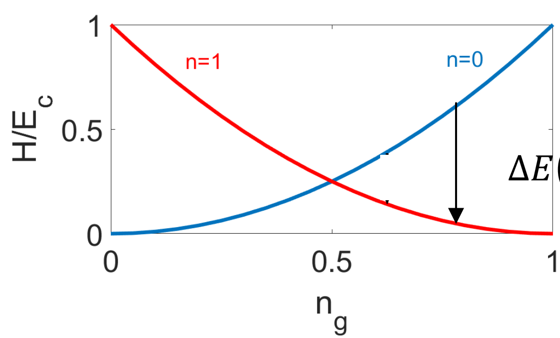
- ➢ Two « reversible » ramps, time interval ≫ tunneling time
- ➢ Quench time ≪ tunneling time: **no heat exchange**



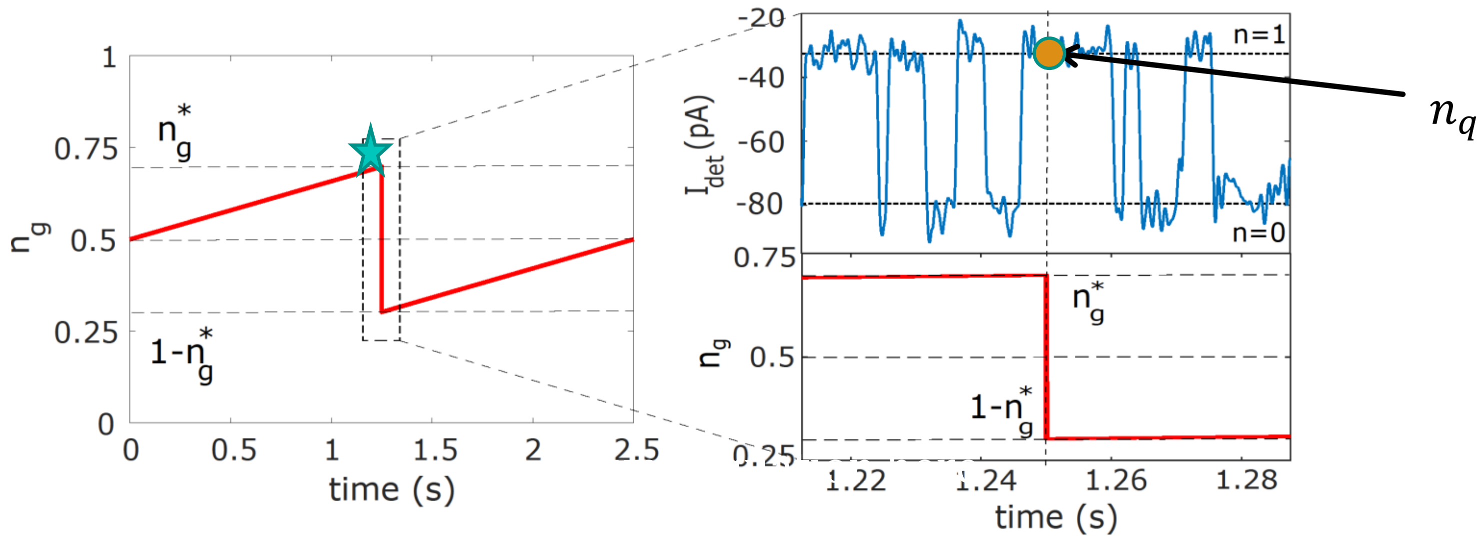
- Two « reversible » ramps, time interval ≫ tunneling time
- Quench time ≪ tunneling time: **no heat exchange**
- Closed driving cycle: $W = -Q = -\sum_i \Delta E\left[n_g(t_i)\right]\Delta n(t_i)$, with Q obtained from the jump record → work done over one trajectory can be inferred
- ca. 1000 repetitions = distribution of work fluctuations



Theory for truly QS ramps: $W(n_q) = (1 - 2n_q)\Delta E\left(n_g^*\right)$

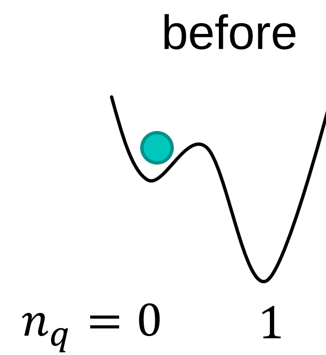


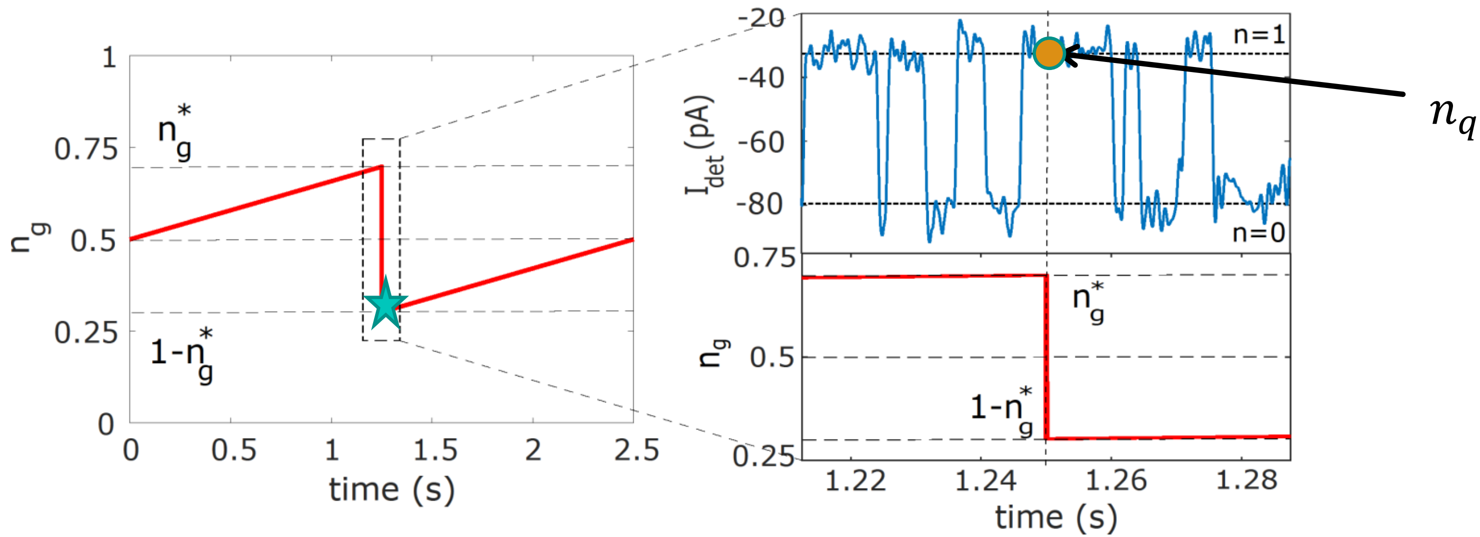
$\Delta E\left(n_g^*\right) = E_C\left(1 - 2n_g^*\right) < 0$



$$W^{\pm} = \mp \Delta E\left(n_g^*\right)$$

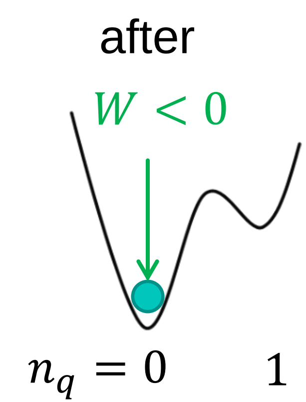
- Depends only on state n_q at quench onset:

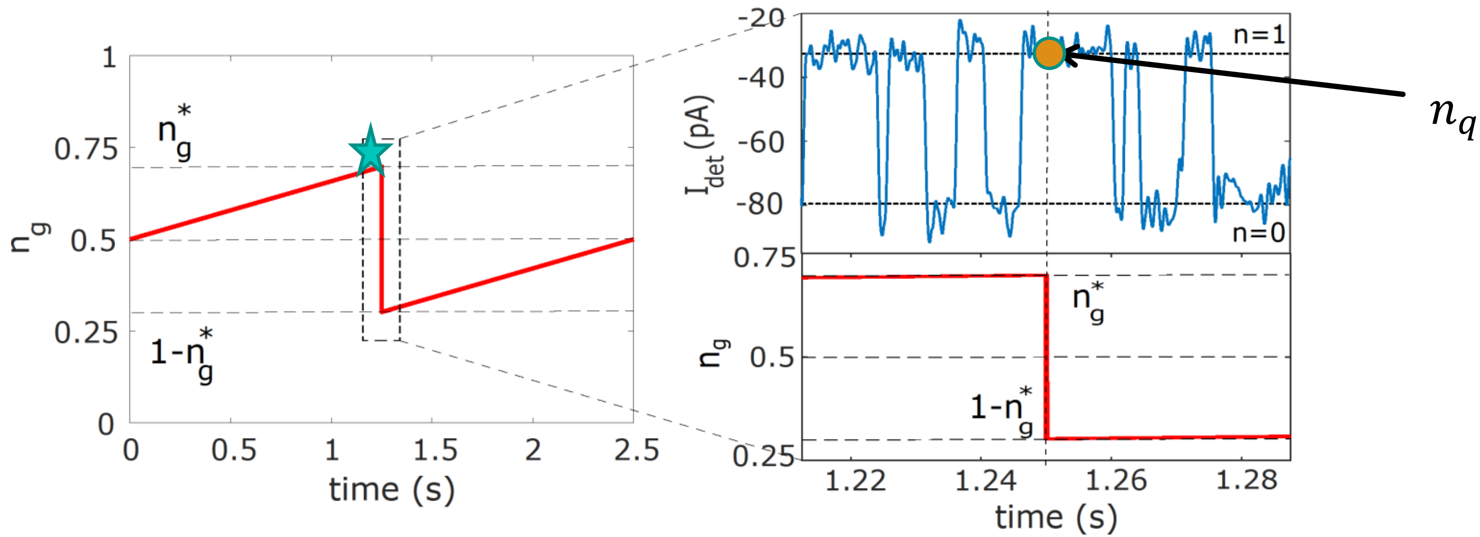




$$W^{\pm} = \mp \Delta E\left(n_g^*\right)$$

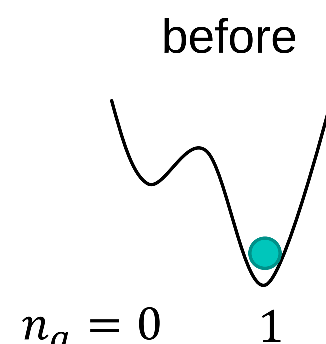
- Depends only on state n_q at quench onset: win if excited state

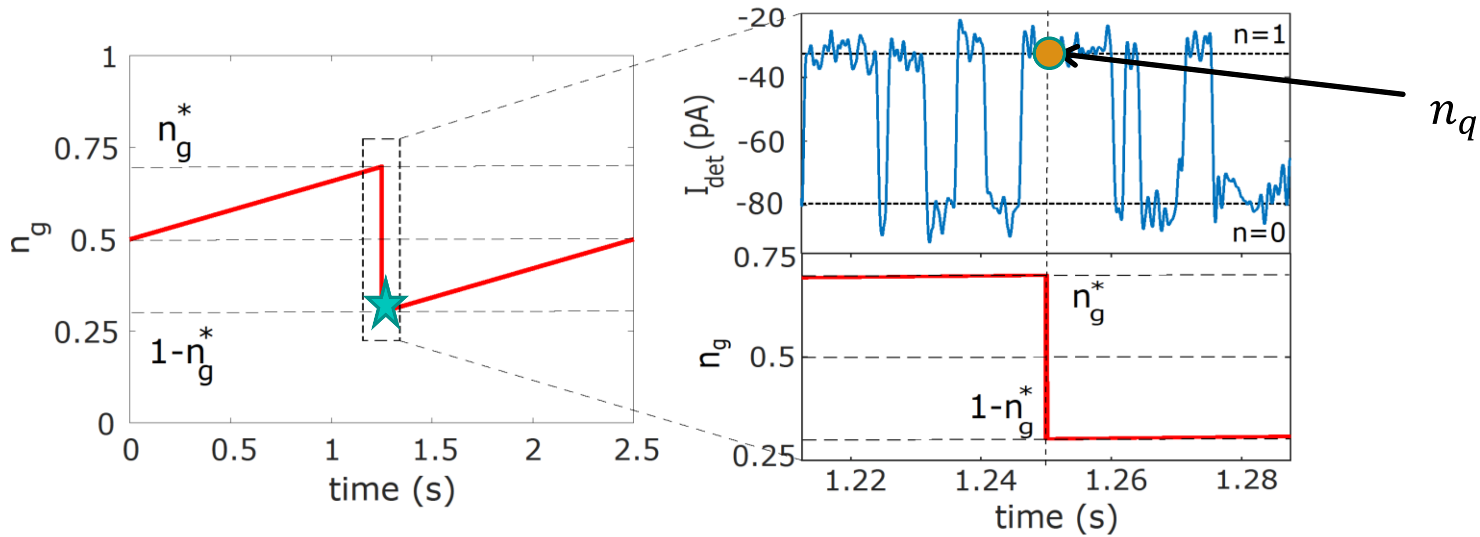




$$W^{\pm} = \mp \Delta E\left(n_g^*\right)$$

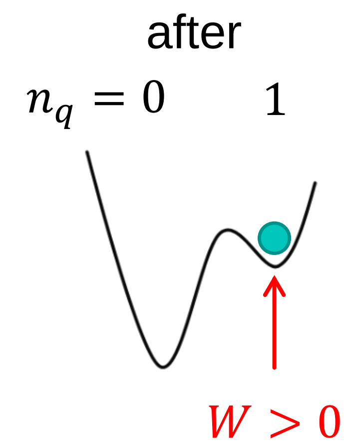
➢ Depends only on state n_q at quench onset:

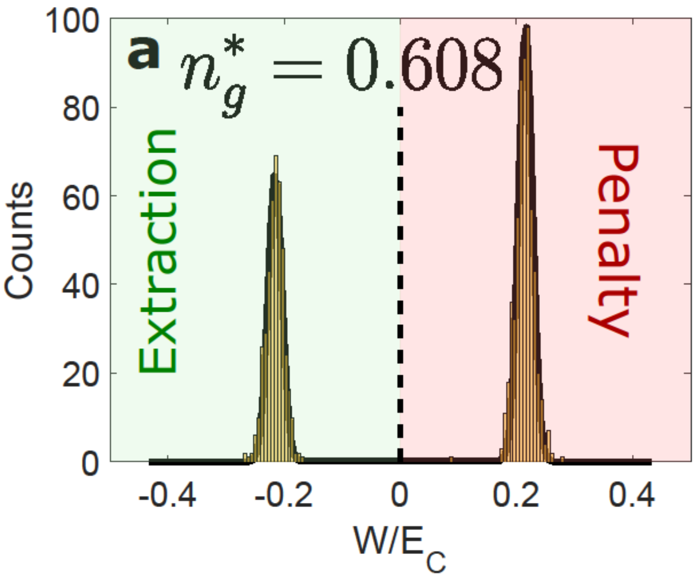




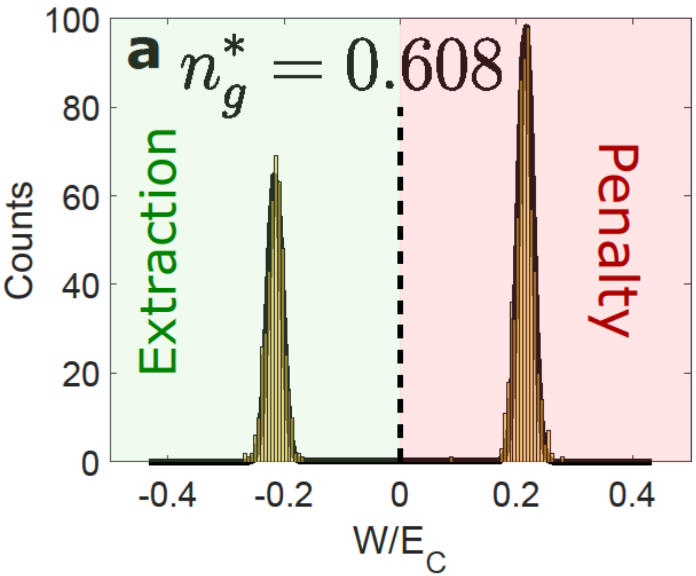
$$W^{\pm} = \mp \Delta E\left(n_g^*\right)$$

➢ Depends only on state n_q at quench onset: lose if ground state

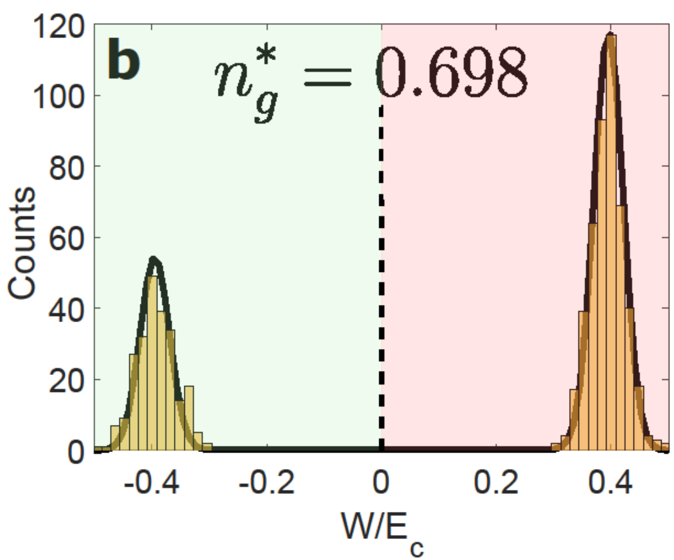




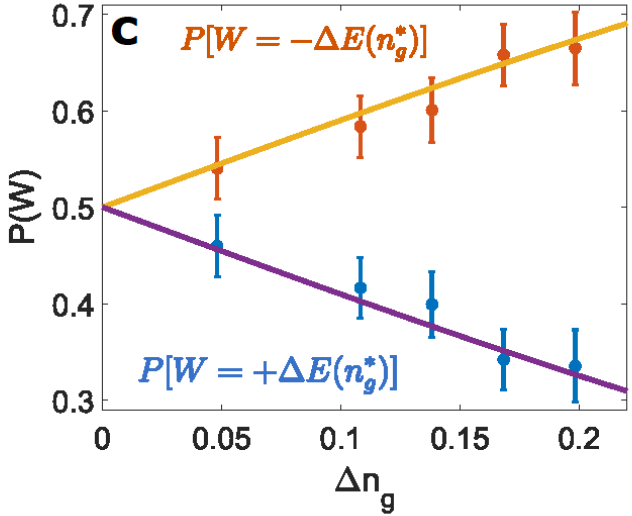
- $\Delta n_g = n_g^* - 1/2 = 0.11 \rightarrow$ small quench amplitude
- Finite peak width: imperfect quasistatic ramp



- $\Delta n_g = n_g^* - 1/2 = 0.11 \rightarrow$ small quench amplitude
- Finite peak width: imperfect quasistatic ramp

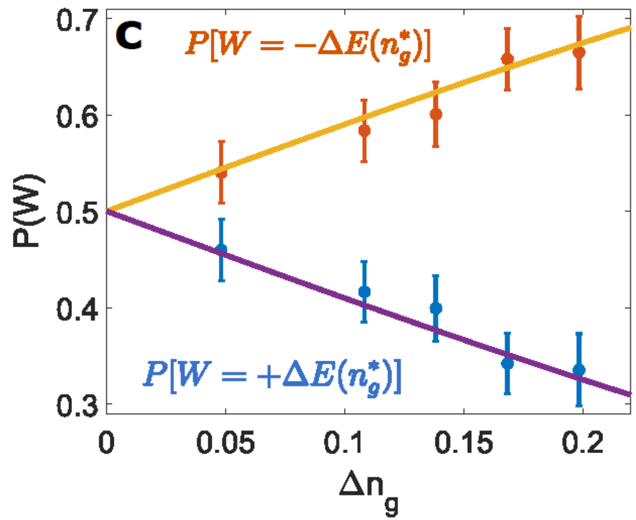


- $\Delta n_g = 0.17 \rightarrow$ large quench amplitude
- Larger « violations », but smaller probability

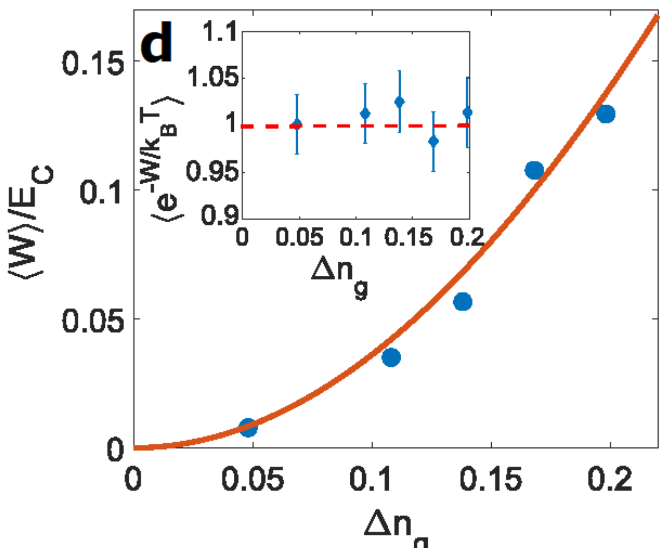


- Probability of violation decreases with quench amplitude $\Delta n_g = n_g^* - 1/2$

- Weights: Gibbs functions $p_0, 1 - p_0$ for favorable/unfavorable state just before the quench

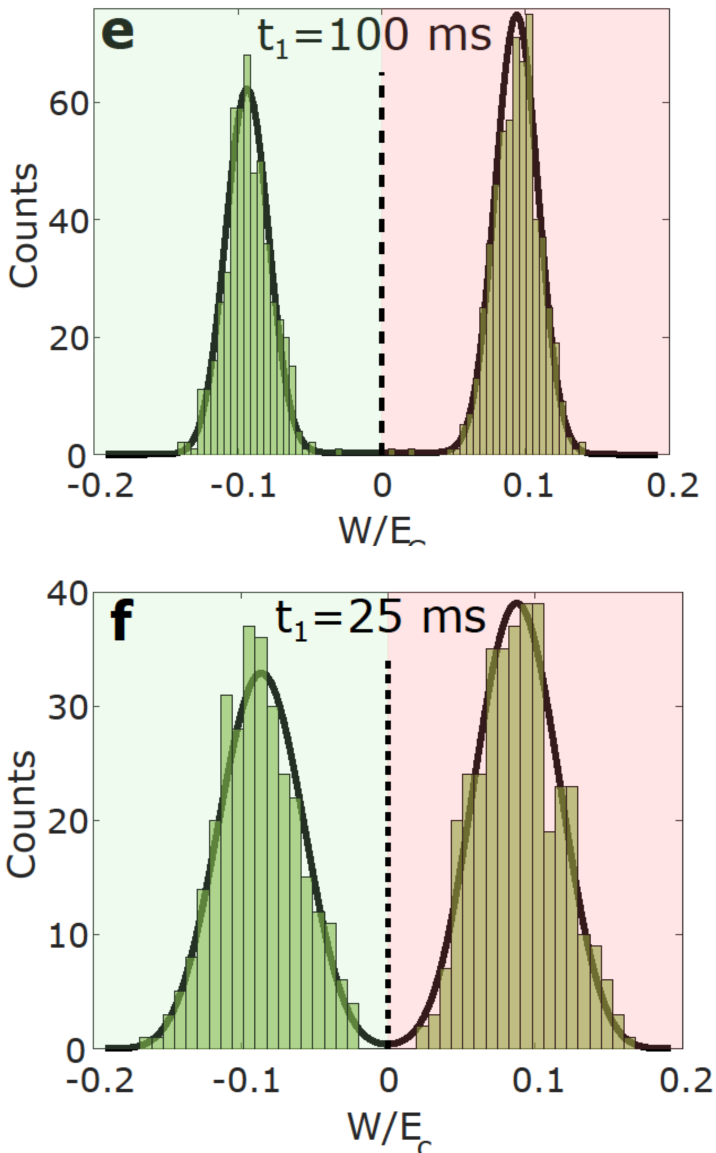


- Probability of violation decreases with quench amplitude $\Delta n_g = n_g^* - 1/2$
- Weights: Gibbs functions $p_0, 1 - p_0$ for favorable/unfavorable state just before the quench

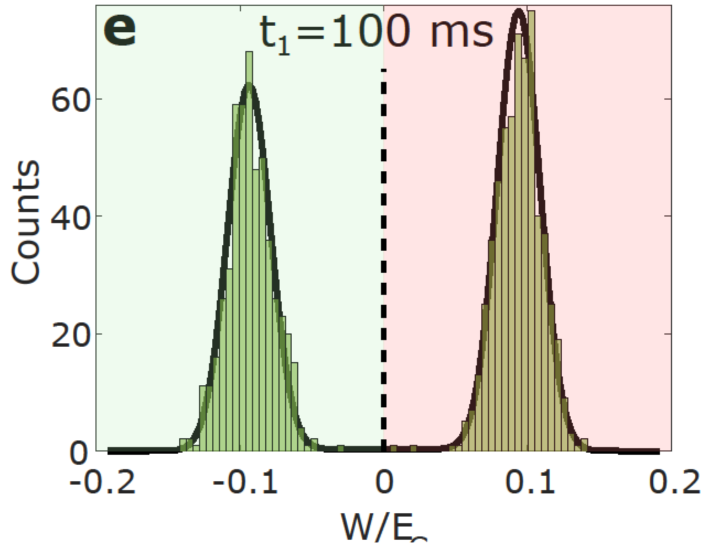


- Average work performed on system positive: in agreement with second law ($\Delta F = 0$ for our closed cycle)
- Increases with quench amplitude: more irreversibility introduced

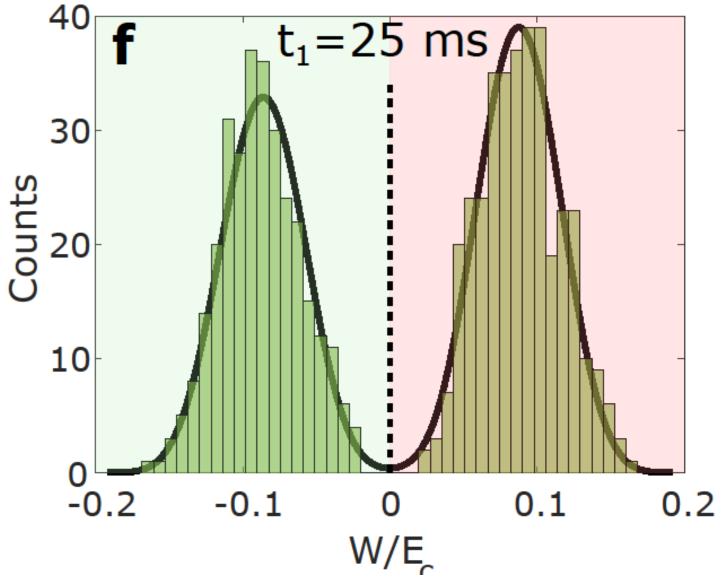
O. Maillet *et al.*, Phys. Rev. Lett. **122,** 150604 (2019)



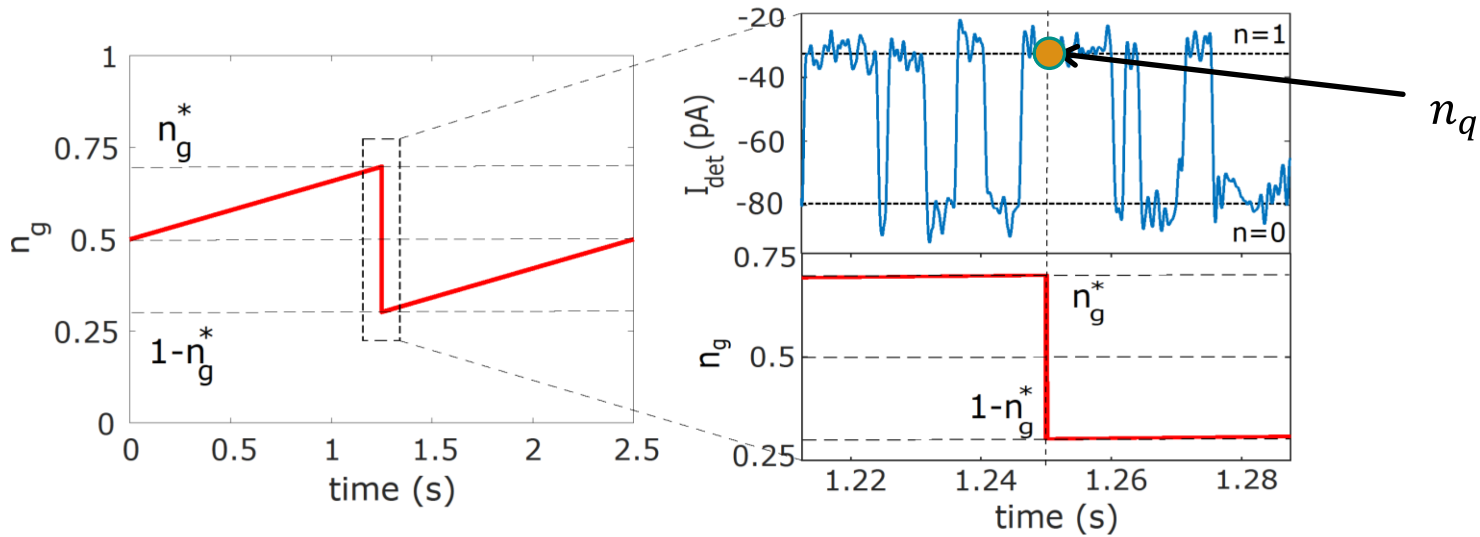
- Heat dissipated by imperfect quasi-static driving: broadening
- Additional irreversibility increases with a steeper ramp slope



- Heat dissipated by imperfect quasi-static driving: broadening
- Additional irreversibility increases with a steeper ramp slope

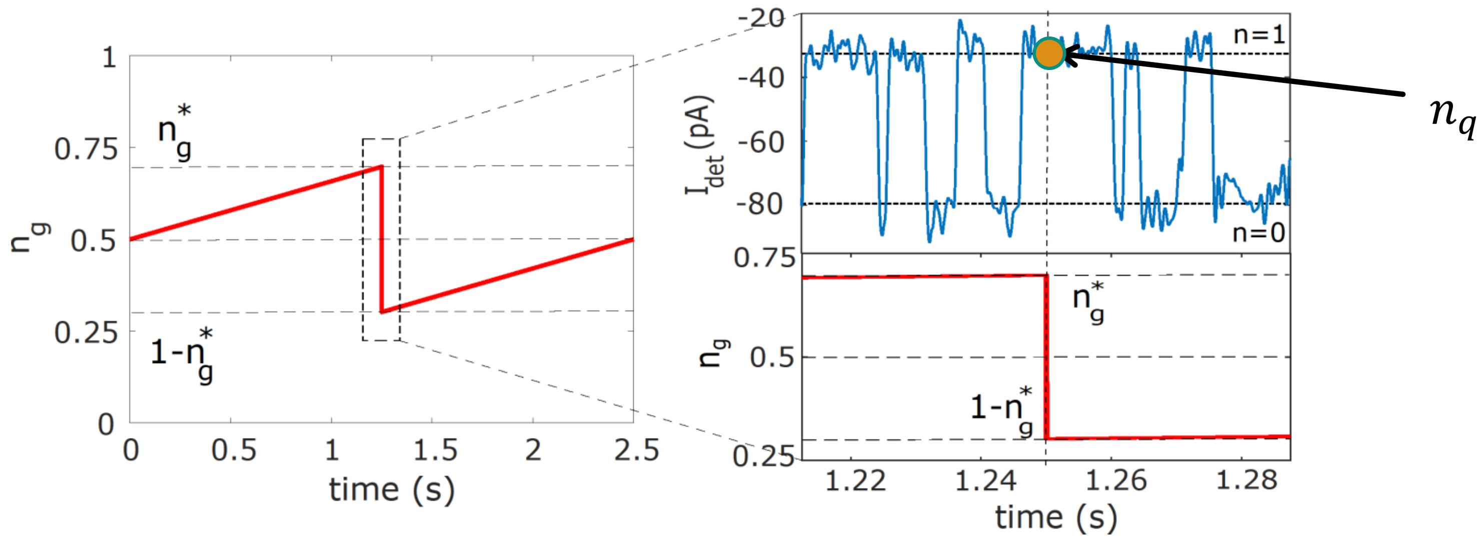


- Master equation approach: time evolution of work probability distribution $\rho(W,t)$
- Good agreement with data, **no free parameter**



$$W(n_q) = (1 - 2n_q)\Delta E(n_g^*)$$

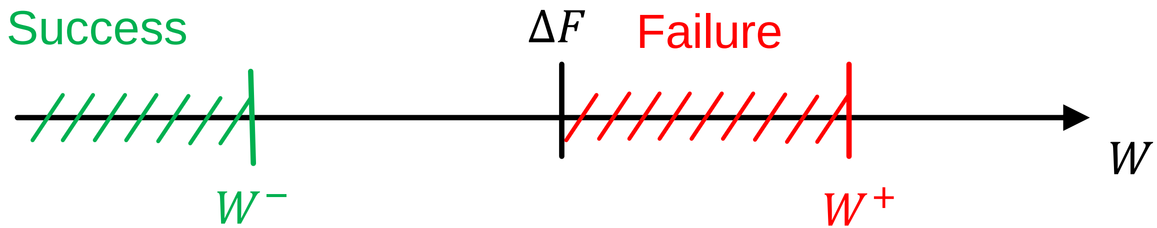
- Depends only on state at quench onset: win if excited state = less likely
- Work extracted can be arbitrarily close to E_C if successful
- The larger, the less probable



$$W(n_q) = (1 - 2n_q)\Delta E(n_g^*)$$

- ➢ Depends only on state at quench onset: win if excited state = less likely
- ➢ Work extracted can be arbitrarily close to E_C if successful
- ➢ **The larger, the less probable = how to make extraction more probable ?**

A neat limit



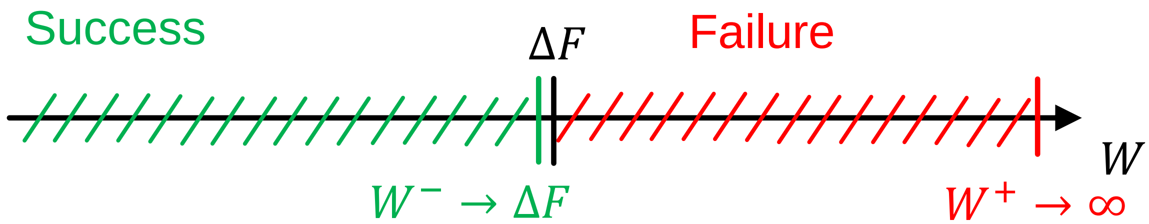
Requirements:

- Bound on minimum work extracted $W^- - \Delta F$ if successful attempt
- Bound on maximum work paid $W^+ - \Delta F$ if failed attempt
- Maximum probability $p_{W^+}(W \leq W^-)$ allowed by Jarzynski's equality

$$p_{W^+}(W \leq W^-) \leq \frac{e^{\Delta F/k_B T} - e^{-W^+/k_B T}}{e^{-W^-/k_B T} - e^{-W^+/k_B T}}$$

V. Cavina et al., Sci. Rep. (2016)

A neat limit

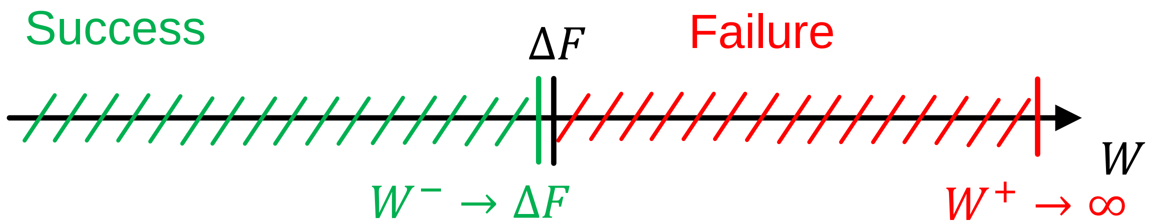


If we loosen requirements: $W^- \to \Delta F$, $W^+ \to \infty$

- Maximum probability $p_\infty(W \leq W^-)$ allowed by Jarzynski's equality

$$p_\infty(W \leq W^-) \leq e^{-\frac{W^- - \Delta F}{k_B T}} \xrightarrow[W^- \to \Delta F]{} 1$$

A neat limit

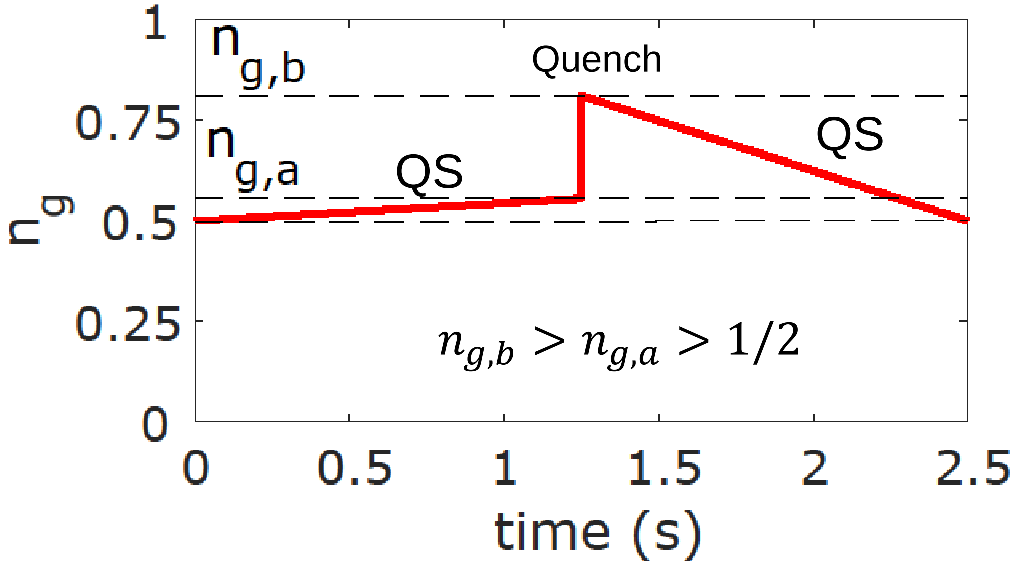


If we loosen requirements: $W^- \to \Delta F$, $W^+ \to \infty$

- Maximum probability $p_\infty(W \leq W^-)$ allowed by Jarzynski's equality

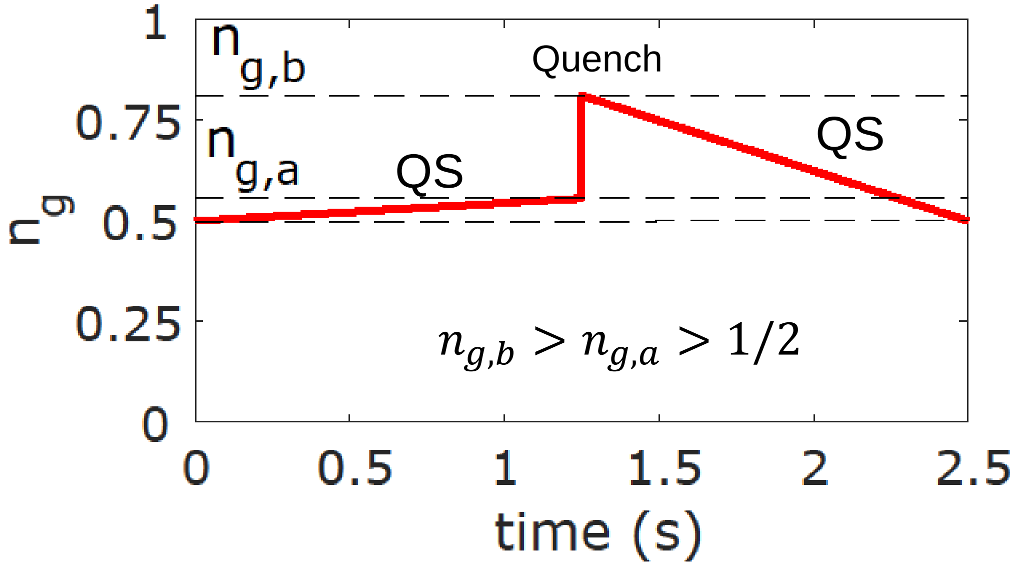
$$p_\infty(W \leq W^-) \leq e^{-\frac{W^- - \Delta F}{k_B T}} \xrightarrow[W^- \to \Delta F]{} 1$$

→ **« Violation » probability can be made arbitrarily close to 1!**



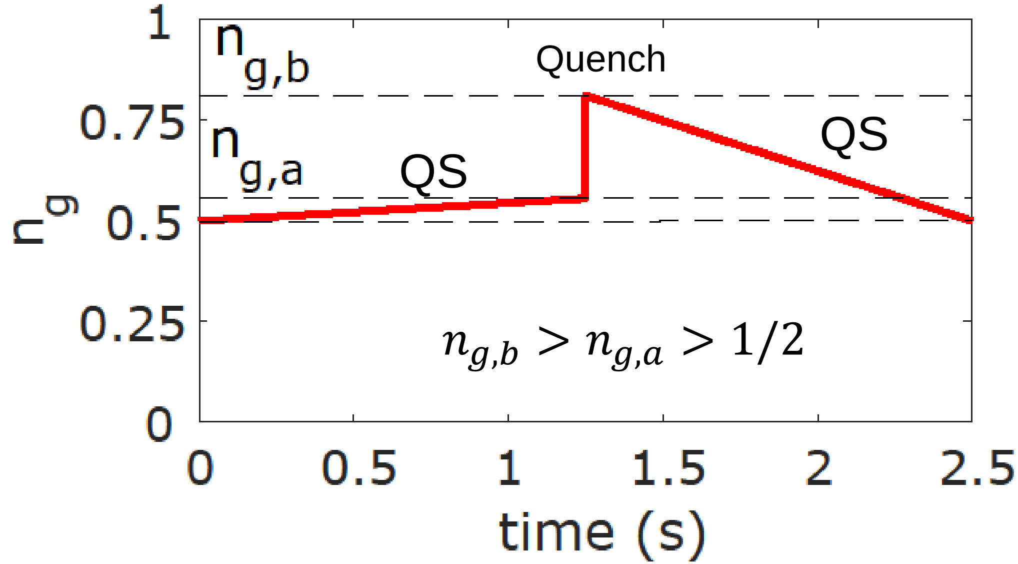
$$W(n_q) = k_B T (\Delta S)_{quench} + \Sigma(n_q)$$

n_q: charge state at quench onset



$$W(n_q) = k_B T(\Delta S)_{quench} + \Sigma(n_q)$$

$$(\Delta S)_{quench} = S(n_{g,b}) - S(n_{g,a})$$

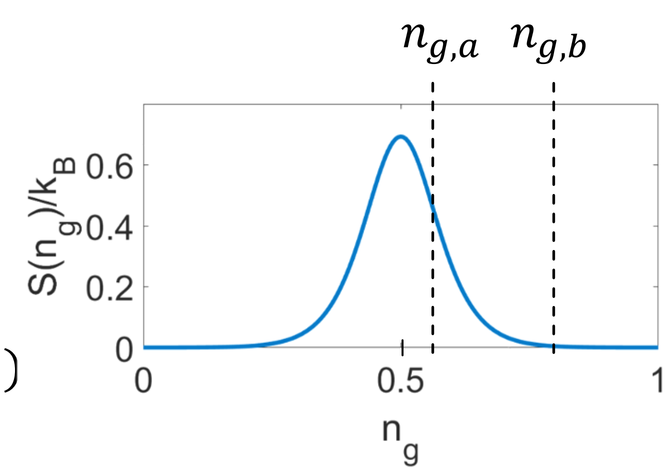


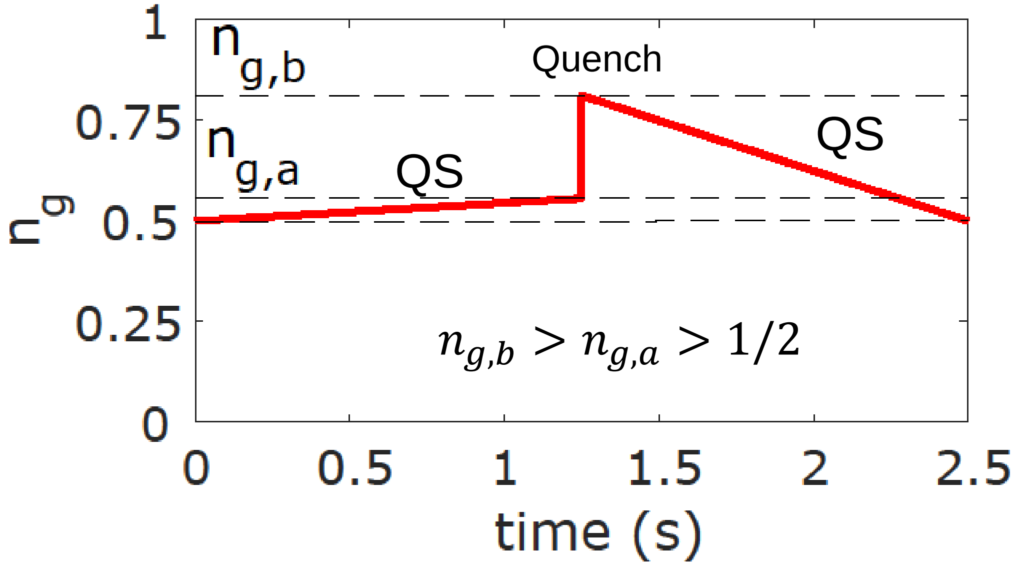
$$W(n_q) = k_B T(\Delta S)_{quench} + \Sigma(n_q)$$

$$(\Delta S)_{quench} = S(n_{g,b}) - S(n_{g,a})$$

S: Shannon entropy for a TLS:

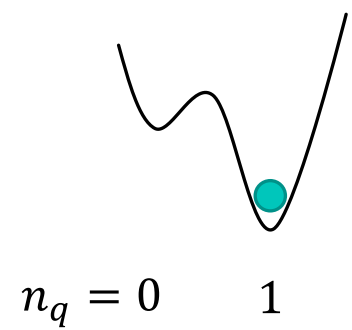
$$S(n_g) = -(1 - p_0(n_g)) \ln(1 - p_0(n_g)) - p_0(n_g) \ln p_0(n_g)$$

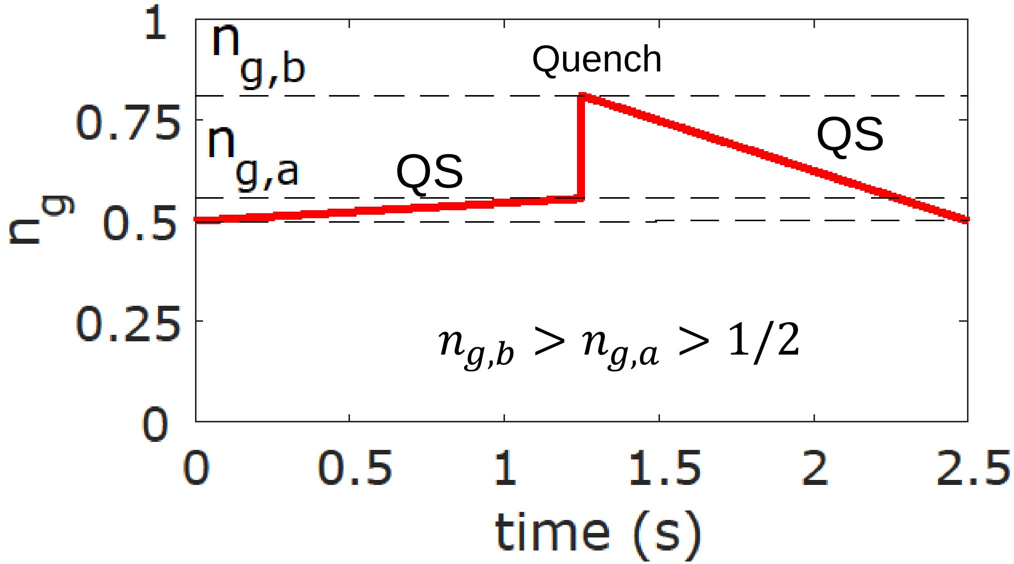




$$W(n_q) = \underbrace{k_B T(\Delta S)_{quench}}_{<0!} + \Sigma(n_q)$$

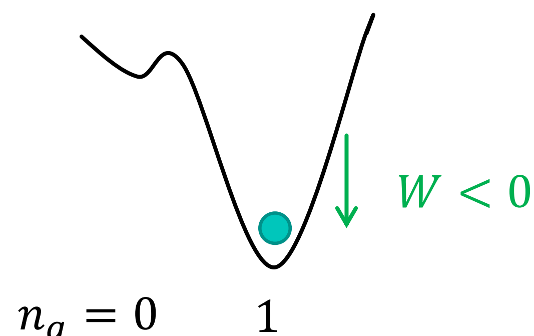
- $\Sigma(n_q) > 0$ if $n_{g,b} > n_{g,a} > 1/2$
- $\Sigma(n_q = 1) < -k_B T(\Delta S)_{quench}$

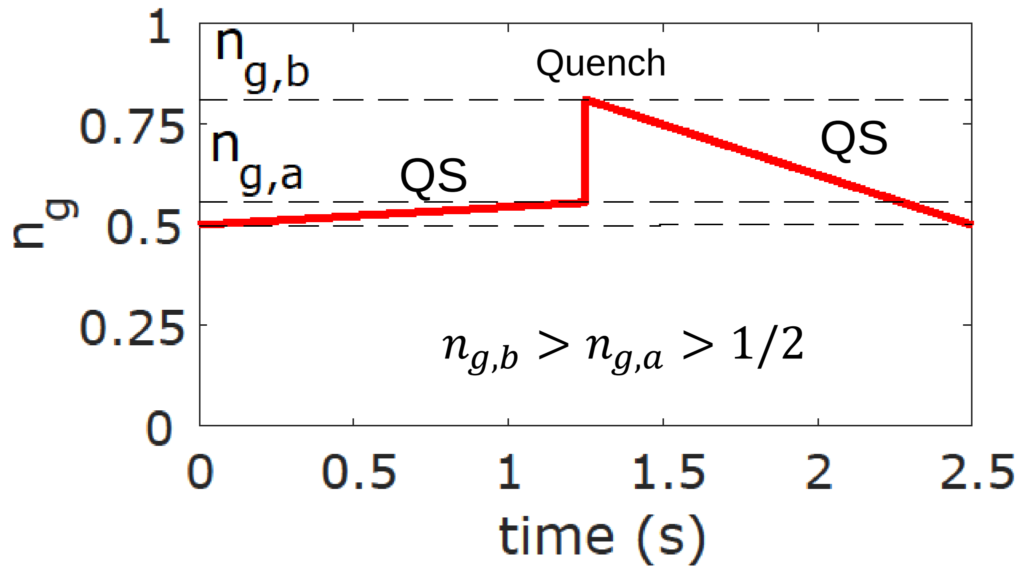




$$W(n_q) = \underbrace{k_B T(\Delta S)_{quench}}_{<0!} + \Sigma(n_q)$$

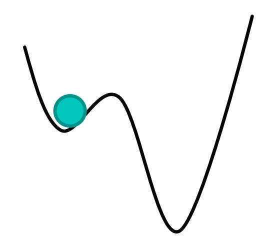
- $\Sigma(n_q) > 0$ if $n_{g,b} > n_{g,a} > 1/2$
- $\Sigma(n_q = 1) < -k_B T(\Delta S)_{quench}$ → win



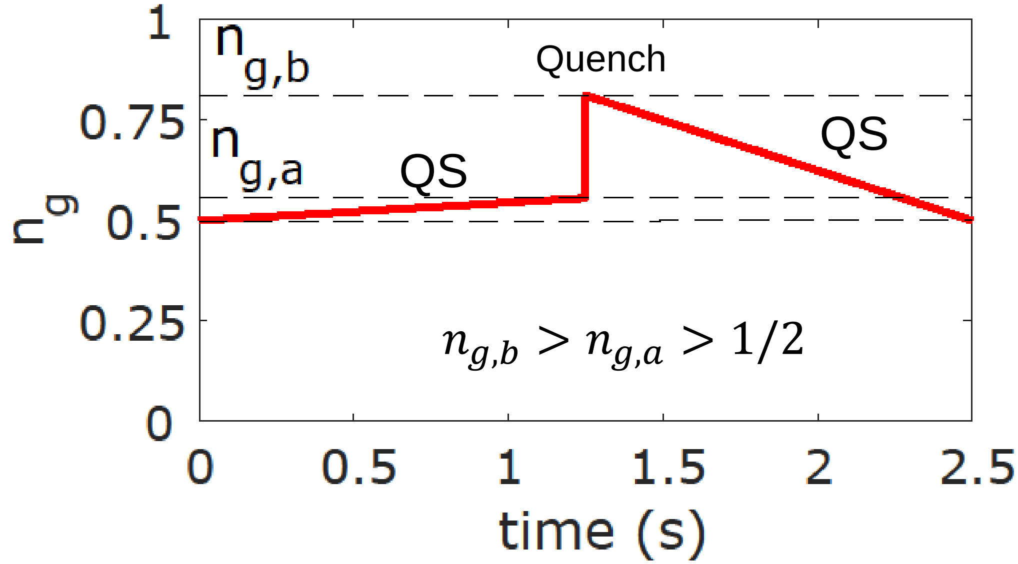


$$W(n_q) = \underbrace{k_B T(\Delta S)_{quench}}_{<0!} + \Sigma(n_q)$$

- $\Sigma(n_q) > 0$ if $n_{g,b} > n_{g,a} > 1/2$
- $\Sigma(n_q = 1) < -k_B T(\Delta S)_{quench} \rightarrow$ win
- $\Sigma(n_q = 0) > -k_B T(\Delta S)_{quench}$

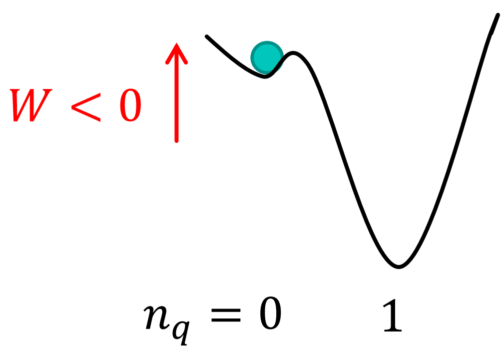


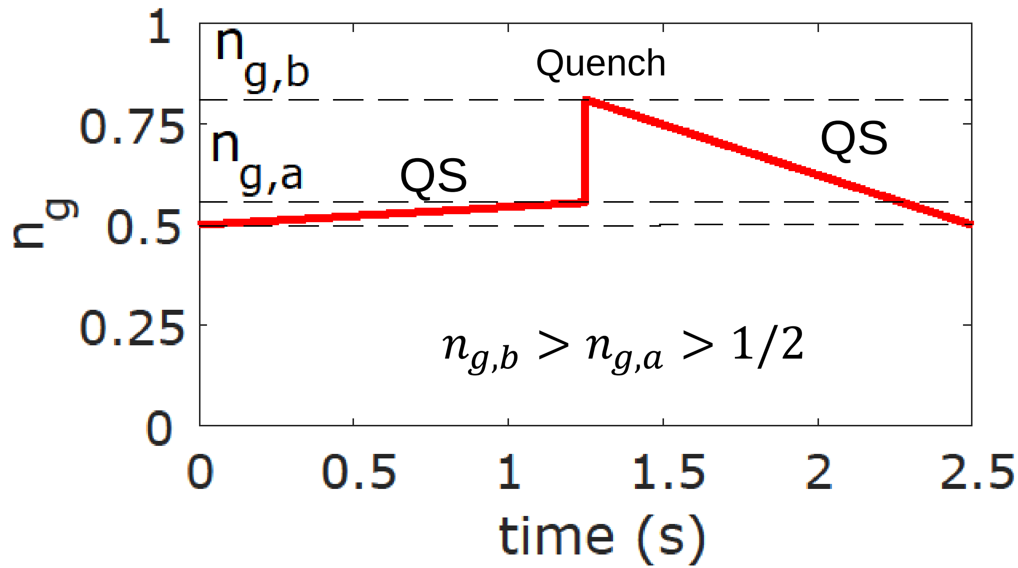
$n_q = 0 \quad 1$



$$W(n_q) = \underbrace{k_B T(\Delta S)_{quench}}_{<0!} + \Sigma(n_q)$$

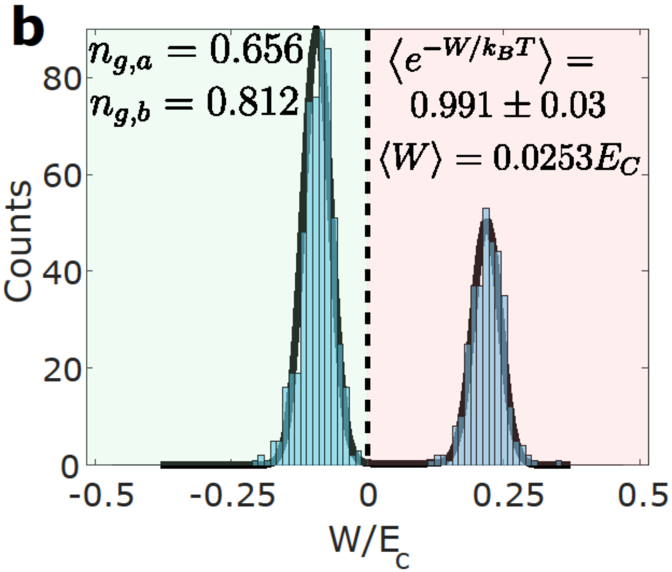
- $\Sigma(n_q) > 0$ if $n_{g,b} > n_{g,a} > 1/2$
- $\Sigma(n_q = 1) < -k_B T(\Delta S)_{quench} \rightarrow$ win
- $\Sigma(n_q = 0) > -k_B T(\Delta S)_{quench} \rightarrow$ lose





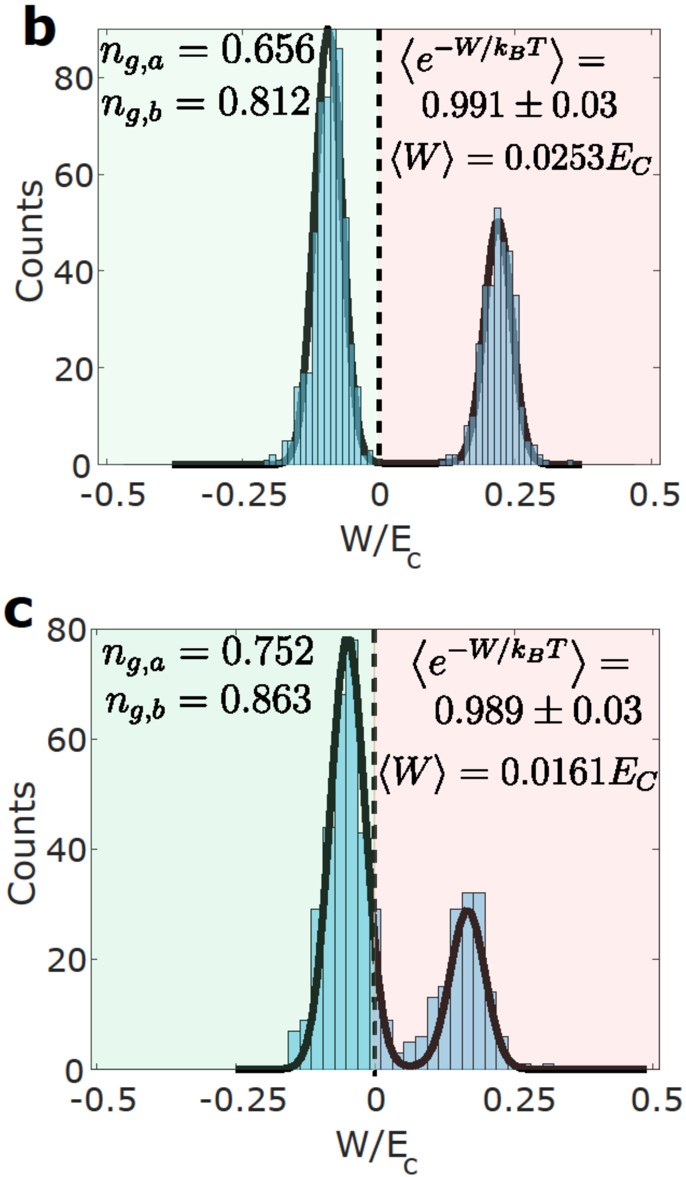
$$W(n_q) = \underbrace{k_B T (\Delta S)_{quench}}_{<0!} + \Sigma(n_q)$$

- 1st term: Shannon entropy decreases away from degeneracy
- $W(n_q = 1) < 0$: probability of work extraction = **ground state probability at the quench onset = favorable!**



O. Maillet *et al.*, Phys. Rev. Lett. **122,** 150604 (2019)

- 65 % of successful, « violation » events ($W < \Delta F$)



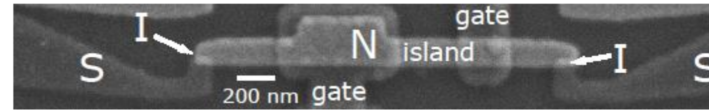
O. Maillet *et al.*, Phys. Rev. Lett. **122,** 150604 (2019)

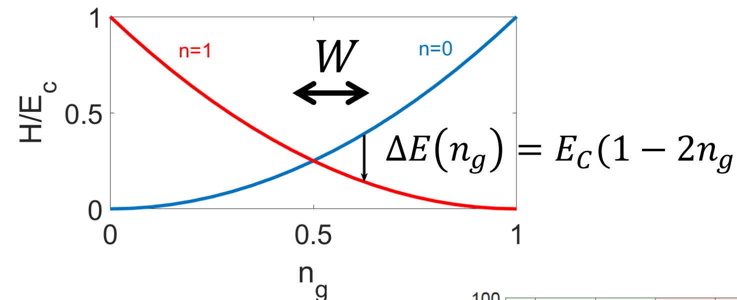
- 65 % of successful, « violation » events ($W < \Delta F$)

- Efficiency limited by irreversible driving
- No theoretical bound to 99,999… % probable work extraction: optimization required (RF SET, longer ramps…)!
- **Statistics matters!**

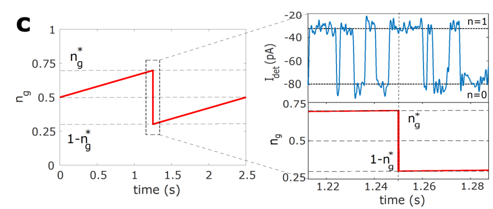
Partial summary

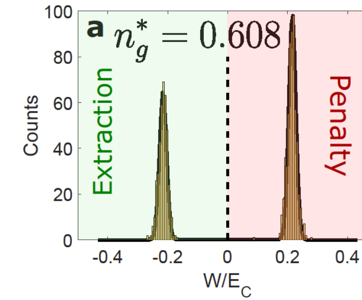
- Hybrid normal-superconducting single-electron box with simple energetics as a model system for stochastic thermodynamics





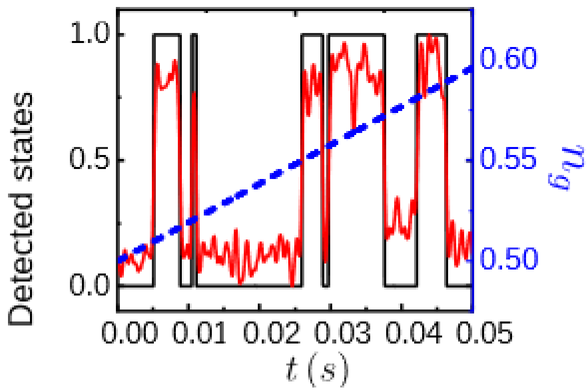
O. Maillet *et al.*, Phys. Rev. Lett. **122,** 150604 (2019)





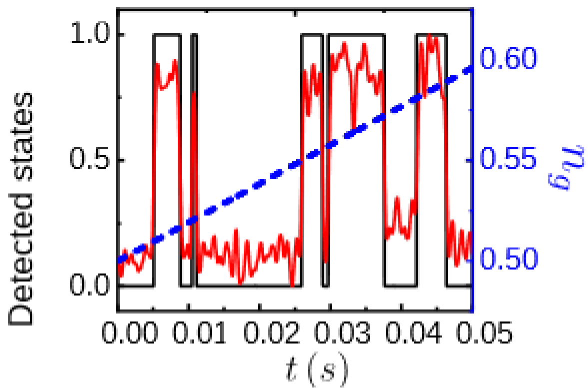
- Optimal protocol to extract work from thermal fluctuations far beyond the 2nd law prescription

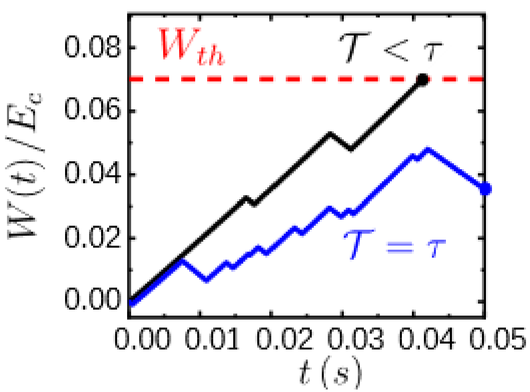
Average work ?



- $\langle W \rangle \geq \langle \Delta F \rangle$ ***if all protocols have the same duration…***

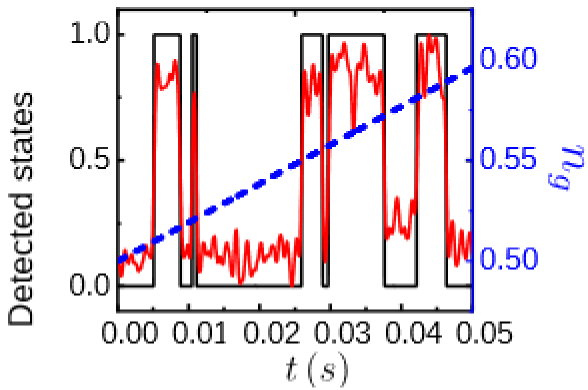
Average work ?

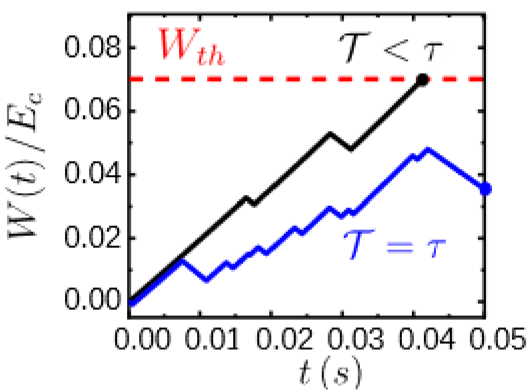




- $\langle W \rangle \geq \langle \Delta F \rangle$ ***if all protocols have the same duration…***
- What if we stop driving when we are happy about the work output ? (*« A gambler who knows when to walk away »*)

Average work ?



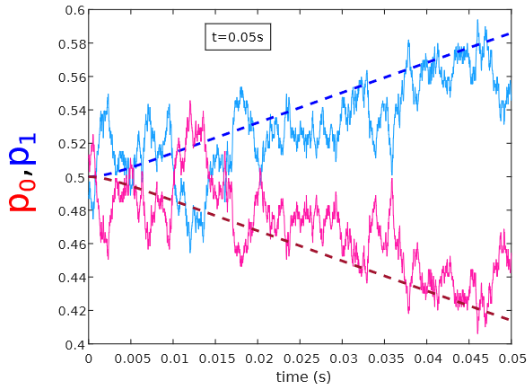


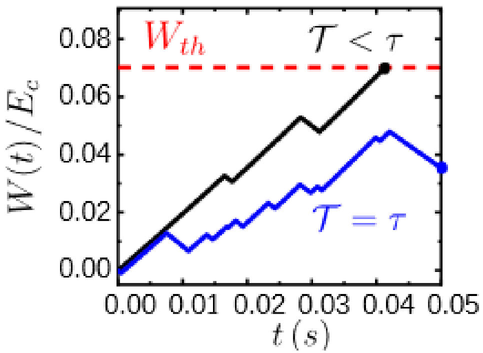
- $\langle W \rangle \geq \langle \Delta F \rangle$ ***if all protocols have the same duration…***

- What if we stop driving when we are happy about the work output ? (« *A gambler who knows when to walk away* »)

→ for all trajectories, $W \leq W_{th}$. What about $\langle W \rangle_{\mathrm{T}}$?

Gambling demon

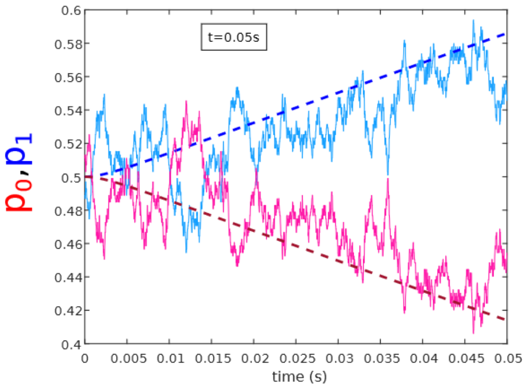


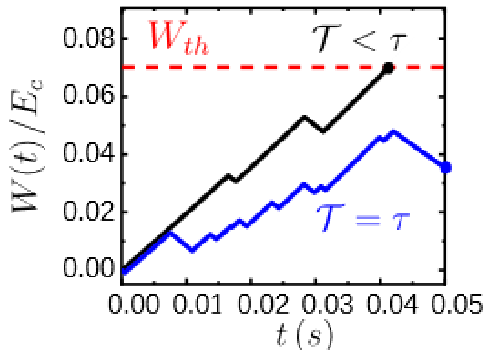


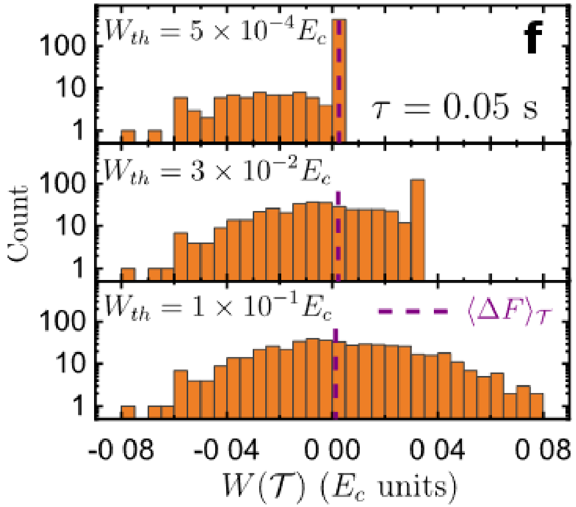
- Stochastic free energy incl. $p_{n(\mathrm{t})}(t)$ (measured + ME)

$$\Delta F(\mathrm{T}) = \Delta U(\mathrm{T}) + k_B T \log p_{n(\mathrm{T})}(\mathrm{T})/p_{n(0)}(0)$$

Gambling demon





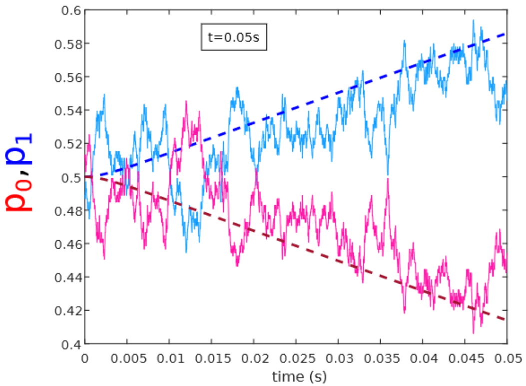


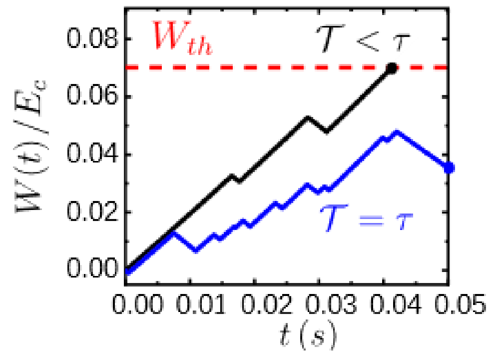
- Stochastic free energy incl. $p_{n(\mathrm{t})}(t)$ (measured + ME)

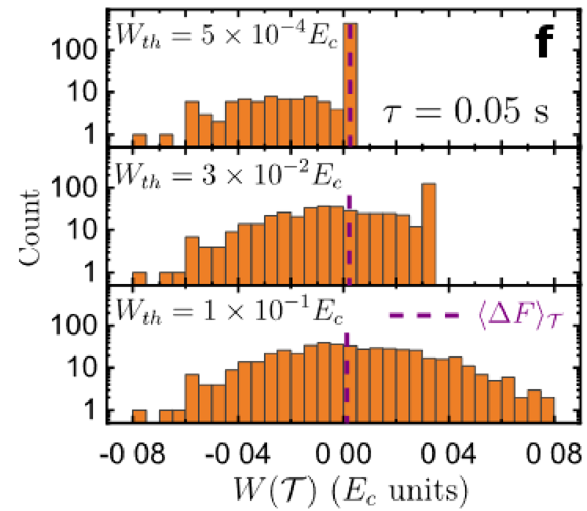
$$\Delta F(\mathrm{T}) = \Delta U(\mathrm{T}) + k_B T \log p_{n(\mathrm{T})}(\mathrm{T})/p_{n(0)}(0)$$

- Small work threshold:
  - Many full trajectories with negative work

Gambling demon

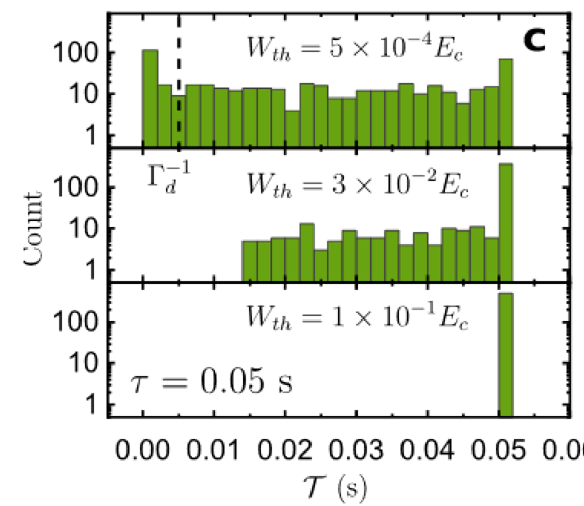






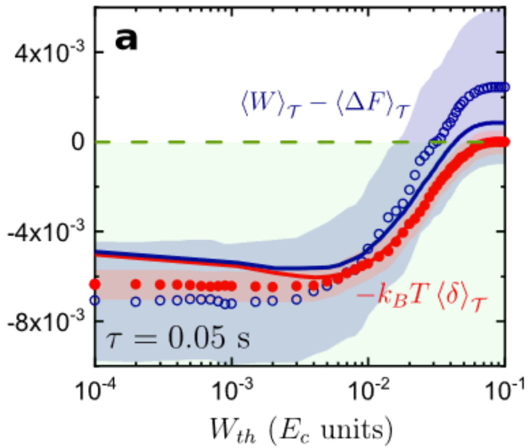
- Stochastic free energy incl. $p_{n(\mathrm{t})}(t)$ (measured + ME)

$$\Delta F(\mathrm{T}) = \Delta U(\mathrm{T}) + k_B T \log p_{n(\mathrm{T})}(\mathrm{T}) / p_{n(0)}(0)$$



- Small work threshold:
  - ➢ Many full trajectories with negative work
  - ➢ Many trajectories stopped before ramp completed, at times $\mathrm{T} \sim \Gamma_d^{-1}$

Gambling demon



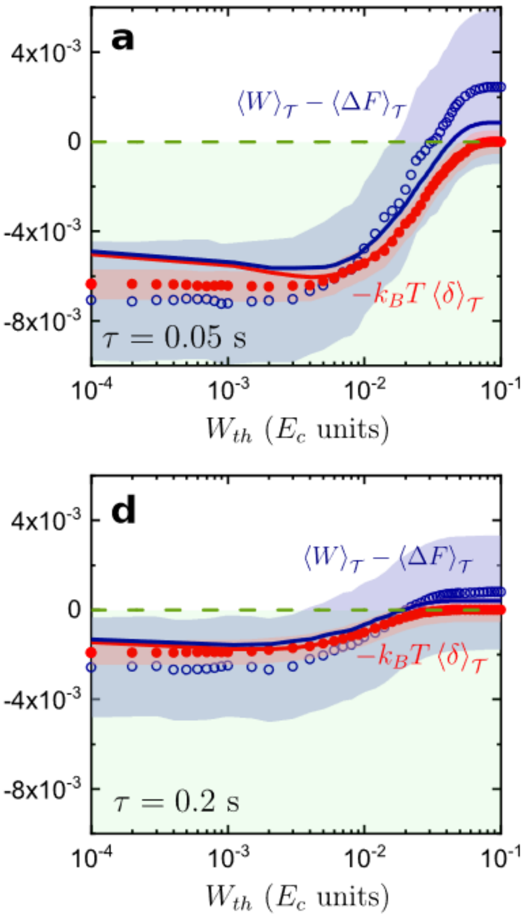
- For low thresholds, $\langle W \rangle_{\mathrm{T}} < \langle \Delta F \rangle_{\mathrm{T}}$

→ redefinition of 2nd law for stopping-time trajectories: $\langle W \rangle_{\mathrm{T}} \geq \langle \Delta F \rangle_{\mathrm{T}} - k_B T \langle \delta \rangle_{\mathrm{T}}$

$$\langle \delta \rangle_{\mathrm{T}} = \frac{p_{n(\mathrm{T}-\tau)}(\mathrm{T}-\tau)_{n_g(\mathrm{T}-\tau)}}{n(\mathrm{T})_{n_{g(\mathrm{T})}}}$$

Stochastic distinguishability between forward and backward-under-time-reversed-protocol trajectory

Gambling demon



- For low thresholds, $\langle W\rangle_{\mathrm{T}} < \langle \Delta F\rangle_{\mathrm{T}}$

→ redefinition of 2nd law for stopping-time trajectories: $\langle W\rangle_{\mathrm{T}} \geq \langle \Delta F\rangle_{\mathrm{T}} - k_B T\langle\delta\rangle_{\mathrm{T}}$

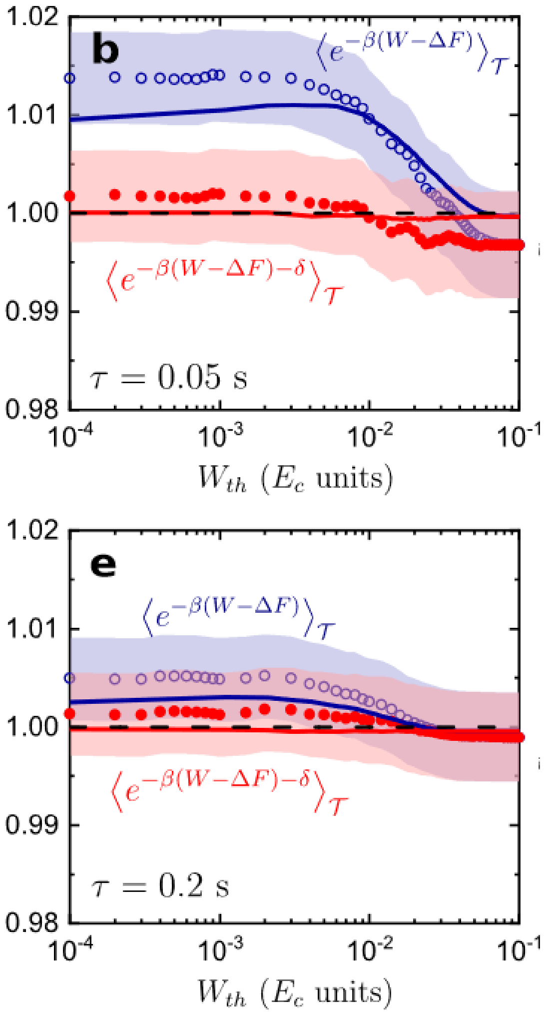
$$\langle\delta\rangle_{\mathrm{T}} = \frac{p_{n(\mathrm{T}-\tau)}(\mathrm{T}-\tau)_{n_g(\mathrm{T}-\tau)}}{n(\mathrm{T})_{n_{g(\mathrm{T})}}}$$

Stochastic distinguishability between forward and backward-under-time-reversed-protocol trajectory

- Longer ramp time (= more quasi-static): smaller « violation »

G. Manzano *et al.*, Phys. Rev. Lett. **126**, 060803 (2021)

Generalized Jarzynski's Equality



- Violation of standard JE for stopping-time trajectories

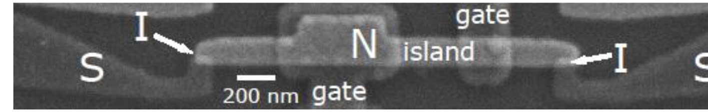
- JE restored when including stochastic distinguishability :

$$\langle e^{-\beta(W-\Delta F)-\delta} \rangle_\mathrm{T} = 1$$

G. Manzano *et al.*, Phys. Rev. Lett. **126**, 060803 (2021)

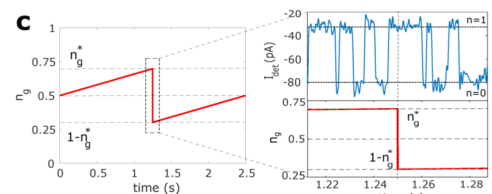
Summary

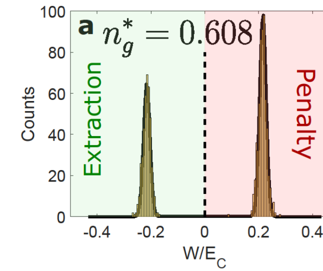
- Hybrid normal-superconducting single-electron box for stochastic thermodynamics



- Optimal protocol to extract work from thermal fluctuations far beyond the 2nd law prescription

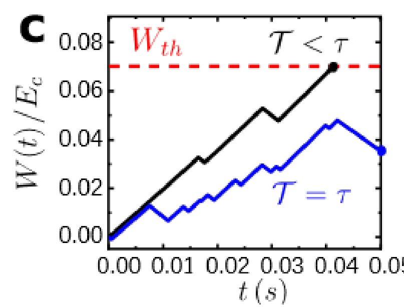
O. Maillet *et al.*, Phys. Rev. Lett. **122,** 150604 (2019)

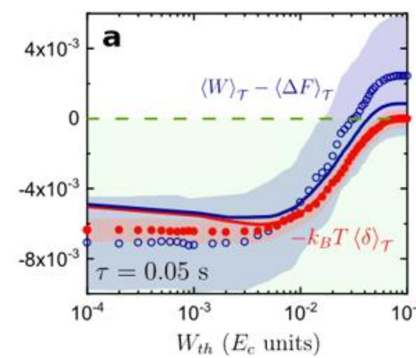




- Stopping-time « gambling » strategy in fast ramps to favor average work extraction
- Extended Jarzynski equality and 2nd law bound including stochastic stopping time

G. Manzano *et al.,* Phys. Rev. Lett. **126**, 060803 (2021)





Thank you !

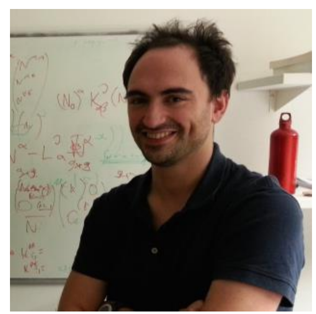
Jukka
Pekola

Diego
Subero

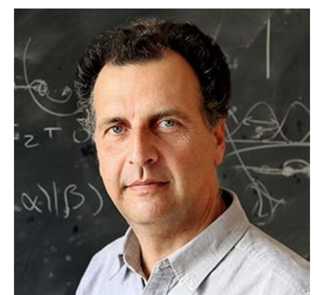
Paolo
Erdman

Christopher
Jarzynski

Gonzalo
Manzano



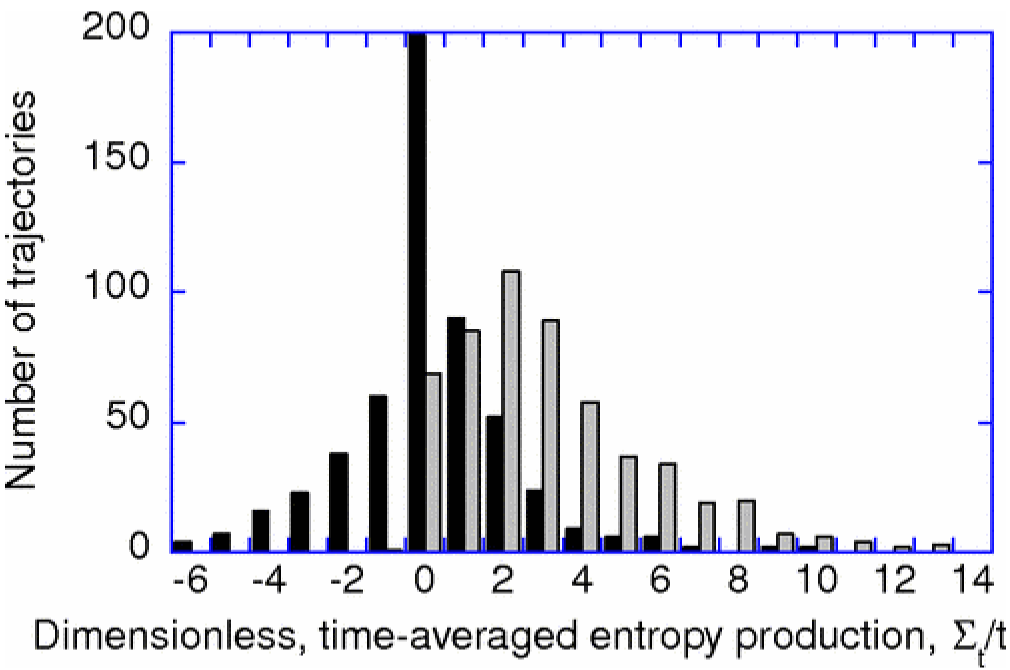
Edgar
Roldán



Rosario
Fazio

Experiments with mesoscopics

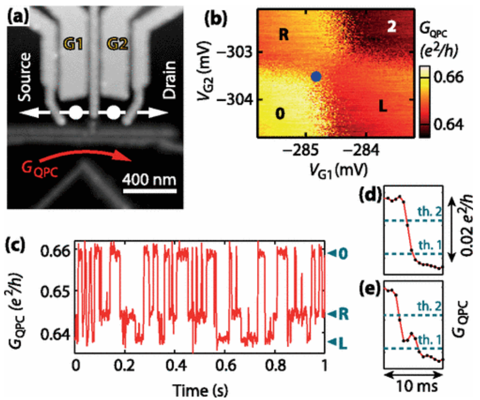
- Colloidal particle in an harmonic trap
- Experimental demonstration of second law « violations » at short timescales (black data)



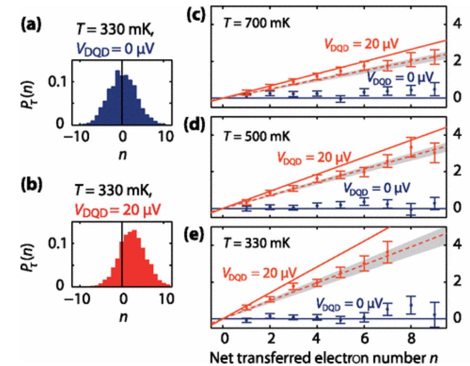
G. M. Wang *et al.*, Phys. Rev. Lett. (2002)

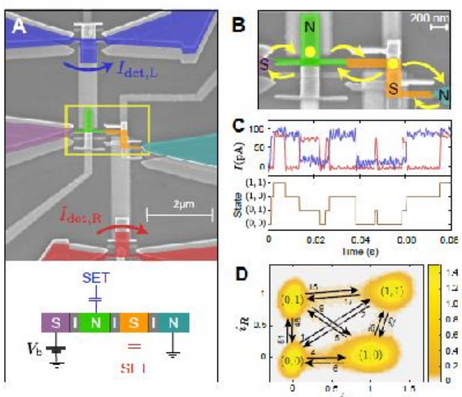
Experiments with mesoscopics

- Double (quantum) dot = direction of electron tunneling = entropy measurements

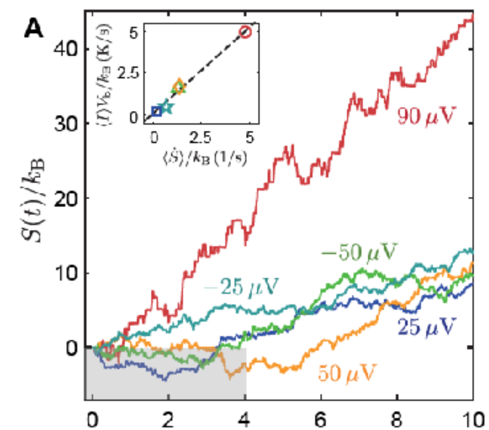


B. Küng *et al.*, Phys. Rev. X (2012)



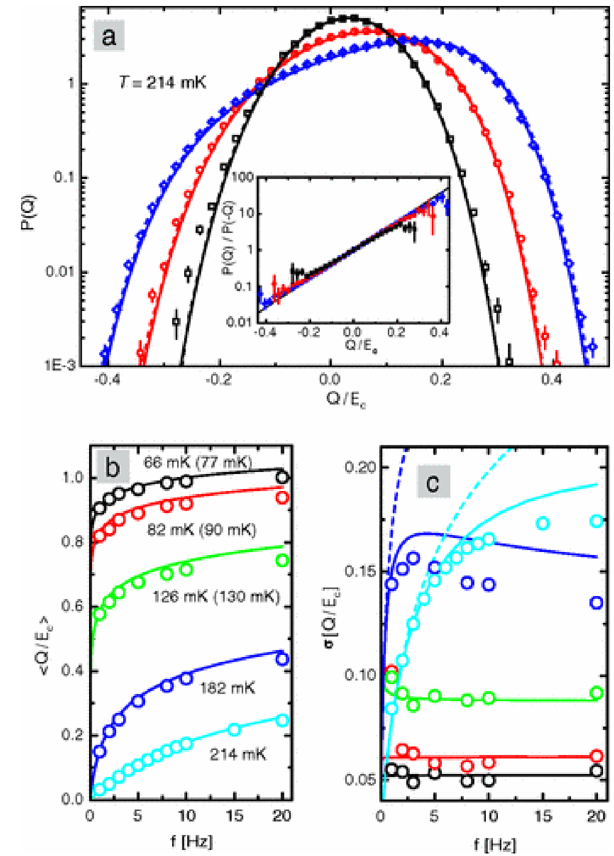


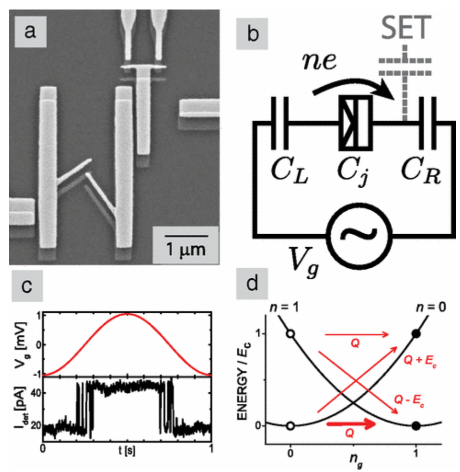
S. Singh *et al.*, Phys Rev. B (2019)



Experiments with mesoscopics

- Test of Jarzynski equality with a single electron box
- Gate driving cycle, measurement of heat exchange (tunneling events) during the cycle





O.-P. Saira *et al.*,
Phys. Rev. Lett. (2012)

Experiments with mesoscopics

- Szilard engine: feedback on system driving applied using the information gained by a detector (= Maxwell Demon operation)
- Work extracted from the system on average, close to Landauer limit (-kTlog2)
- Not a true violation of 2nd law: entropy created in the Demon («cost of information»)

J. V. Koski *et al.*, PNAS (2014)

J. V. Koski *et al.*, Phys. Rev. Lett. (2015)