A Maxwell's demon that can work at macroscopic scales

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with
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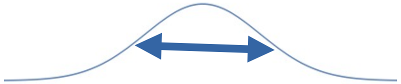
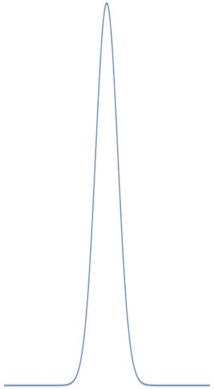
Introduction

$$\frac{1}{\sqrt{N}}$$



Stochastic

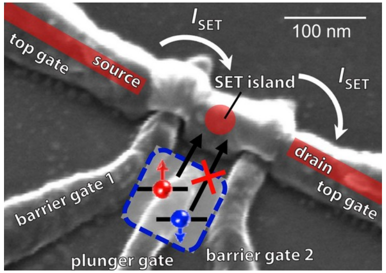
Macroscopic limit →

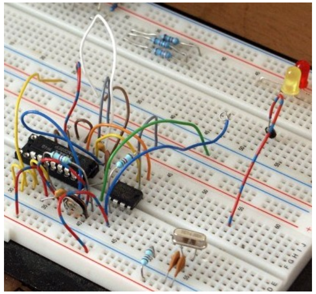


Deterministic

Macroscopic Stochastic Thermodynamics
Falasco & Esposito
arXiv: 2307.12406

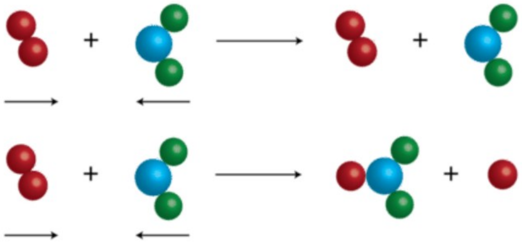
Electronic circuits





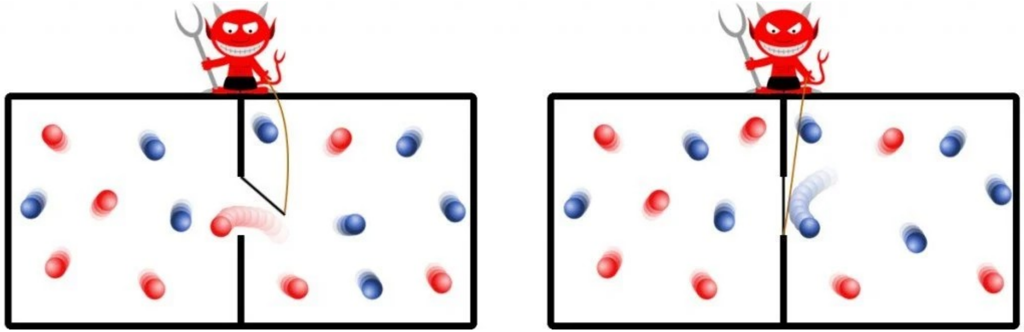
Freitas, Delvenne & Esposito PRX 11, 031064 (2021)

Chemical reaction networks



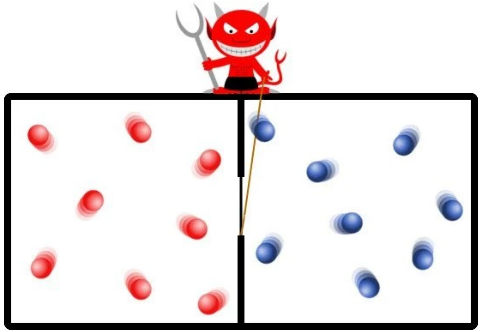
Rao & Esposito JCP 149, 245101 (2018)

Maxwell's demon



Thermal Equilibrium + Measurement and feedback control

Maxwell's demon exploits fluctuations



Thermal gradient ↔ Work extraction

Experimental implementations

A molecular information ratchet
Nature, 445, 523 (2007)
Viviana Serreli[1], Chin-Fa Lee[1], Euan R. Kay[1] & David A. Leigh[1]

Single-photon cooling at the limit of trap dynamics: Maxwell's demon near maximum efficiency
S Travis Bannerman[1], Gabriel N Price[1], Kirsten Viering[1] and Mark G Raizen
NJP 11, 063044 (2009)

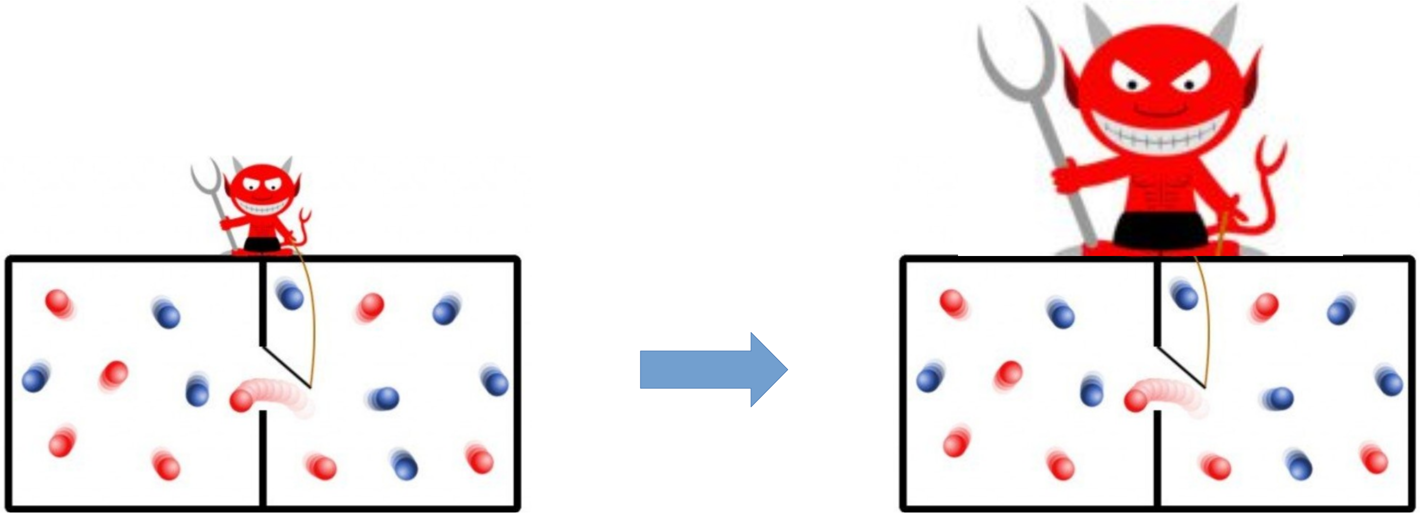
Experimental Observation of the Role of Mutual Information in the Nonequilibrium Dynamics of a Maxwell Demon
J. V. Koski, V. F. Maisi, T. Sagawa, and J. P. Pekola
Phys. Rev. Lett. **113**, 030601 – Published 14 July 2014

Observing a quantum Maxwell demon at work PNAS 114, 7561 (2017)
Nathanaël Cottet, Sébastien Jezouin, Landry Bretheau, Philippe Campagne-Ibarcq, Quentin Ficheux, Janet Anders, Alexia Auffèves, Rémi Azouit, Pierre Rouchon, and Benjamin Huard -6 Authors Info & Affiliations

Experimental demonstration of information-to-energy conversion and validation of the generalized Jarzynski equality Nat. Phys. 6, 988 (2010)
Shoichi Toyabe, Takahiro Sagawa, Masahito Ueda, Eiro Muneyuki & Masaki Sano

All work in microscopic regimes
(single molecules, single atoms, single electrons, single photons ...)

Can we build a macroscopic Maxwell's demon?



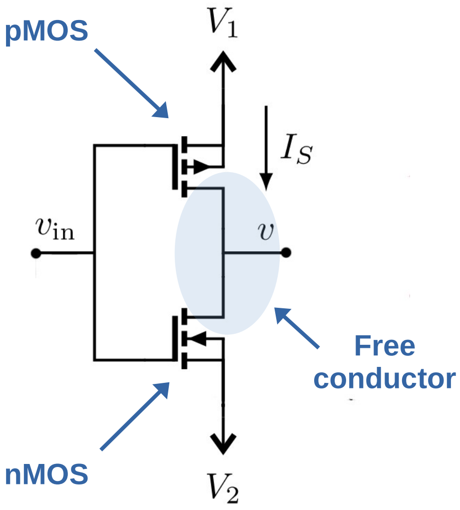
A priori **no** because fluctuations disappear in the macroscopic limit

Can we prevent that?

We will explore these questions in a CMOS based electronic Maxwell's demon

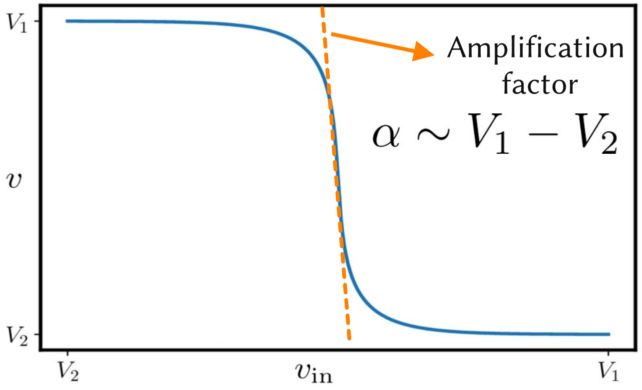
Esposito, Freitas, PRL 129,120602 (2022) & PRE 107, 014136 (2023)

The CMOS inverter



At steady state:

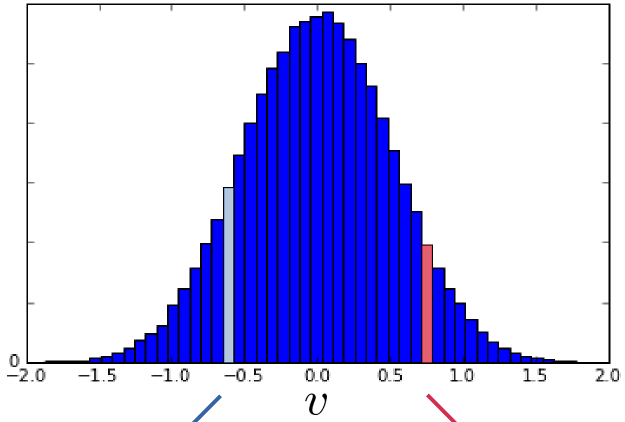
$$V_1 > V_2 \Rightarrow I_S > 0$$

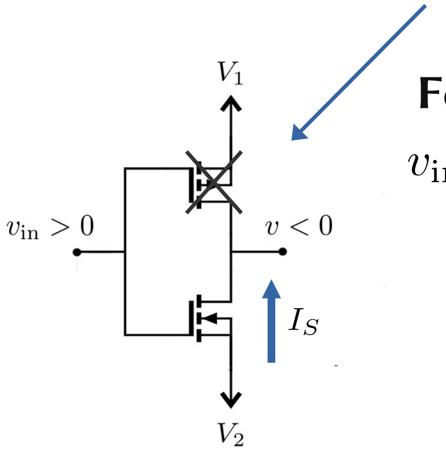


At equilibrium: $V_1 = V_2 = 0 \Rightarrow I_S = 0$

$$P_{\text{eq}}(v) \propto e^{-\frac{E(v)}{k_b T}}$$

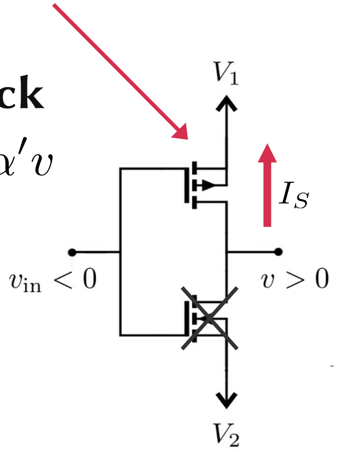
$$E(v) = \frac{v^2}{2C}$$





Feedback

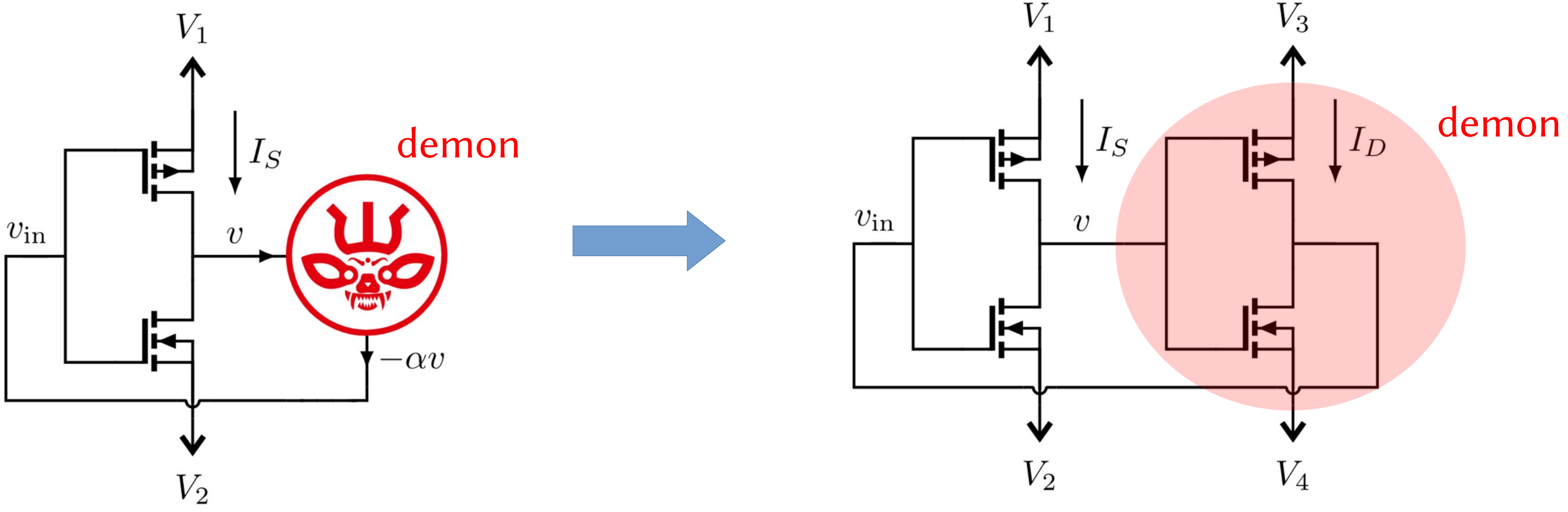
$$v_{\text{in}} = -\alpha' v$$



The feedback should invert the current even at small bias

$V_1 > V_2$

An autonomous demon



If the demon can achieve rectification of the current through the system ($I_S < 0$):

Entropy production rates:

System side: $\dot{\Sigma}_S = I_S \overbrace{(V_1 - V_2)}^{>0} = I_S \Delta V_S < 0$

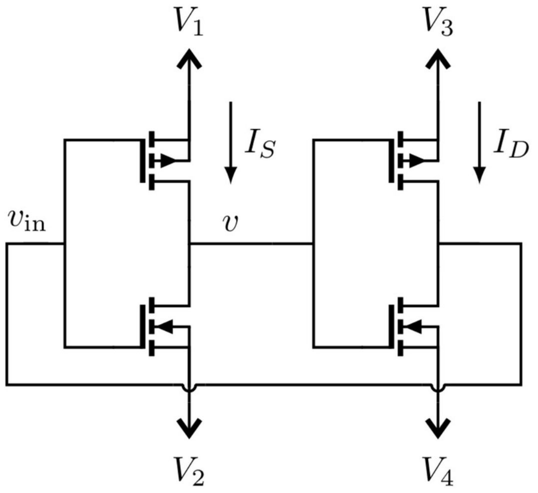
Total: $\dot{\Sigma} = \dot{\Sigma}_S + \dot{\Sigma}_D \geq 0$

Demon side: $\dot{\Sigma}_D = I_D \overbrace{(V_3 - V_4)}^{>0} = I_D \Delta V_D > 0$

Thermodynamic efficiency

$$\eta = -\frac{\dot{\Sigma}_S}{\dot{\Sigma}_D} < 1$$

Deterministic description



$$C\, d_t v = I_{\rm p}(v, v_{\rm in}; \Delta V_S) - I_{\rm n}(v, v_{\rm in}; \Delta V_S)$$

$$C\, d_t v_{\rm in} = I_{\rm p}(v_{\rm in}, v; \Delta V_D) - I_{\rm n}(v_{\rm in}, v; \Delta V_D)$$

$$\begin{aligned} I_{\rm p}(v, v_{\rm in}; \Delta V) &= I_0 e^{(\Delta V/2 - v_{\rm in} - V_{\rm th})/n} \left(1 - e^{-(\Delta V/2 - v)}\right) \\ &= I_{\rm n}(-v, -v_{\rm in}; \Delta V) \end{aligned}$$

At steady state:

$$V_2 < v < V_1$$
$$V_4 < v_{\rm in} < V_3$$

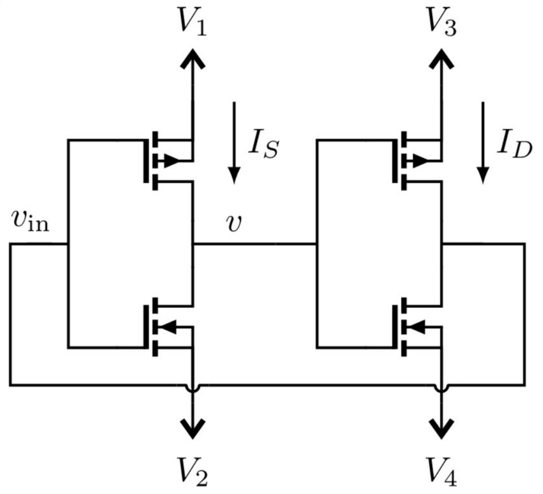
$\Rightarrow$

$$I_S > 0$$
$$I_D > 0$$

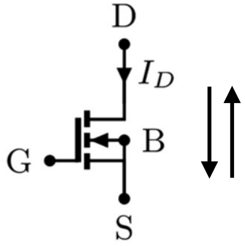
Rectification is impossible at the deterministic level

Also, the system becomes bistable for $\alpha^2 = \alpha_S \alpha_D > 1$ with $\alpha_{S/D} = e^{\Delta V_{S/D}/2} - 1$

Stochastic description



Conduction through each transistor is modeled as a bidirectional jump process



$\lambda_{\pm}(\Delta V_{DS}, \Delta V_{GS})$

The rates can be fully determined from the *I-V curve characterization* and the *local detailed balance conditions* (see *Phys. Rev. X 11, 031064*)

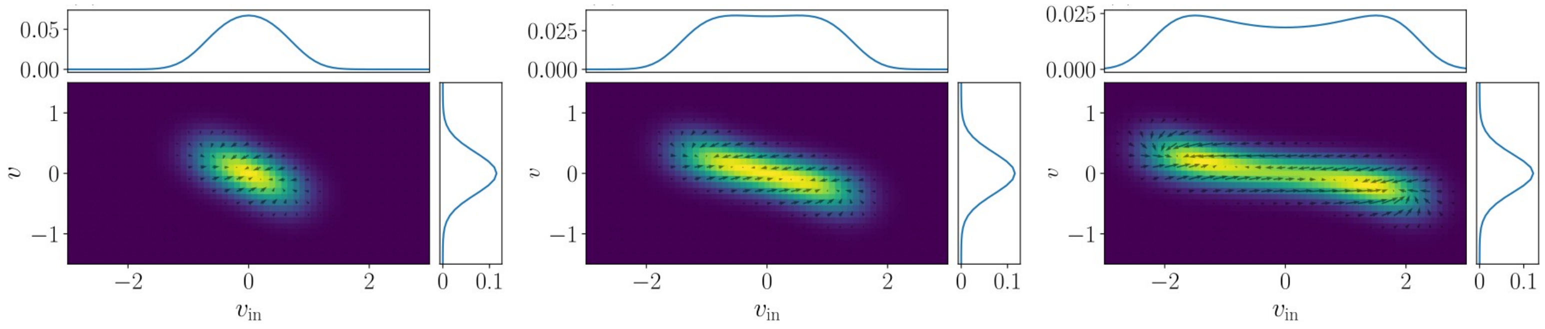
$$d_t P_t(\boldsymbol{v}) = \sum_{\rho=n,p} \lambda_\rho(\boldsymbol{v} - \boldsymbol{\Delta}_\rho v_e) P_t(\boldsymbol{v} - \boldsymbol{\Delta}_\rho v_e) - \lambda_\rho(\boldsymbol{v}) P_t(\boldsymbol{v})$$

Circuit state $\boldsymbol{v} = (v, v_{\mathrm{in}})$

$$v_e = \frac{q_e}{C}$$

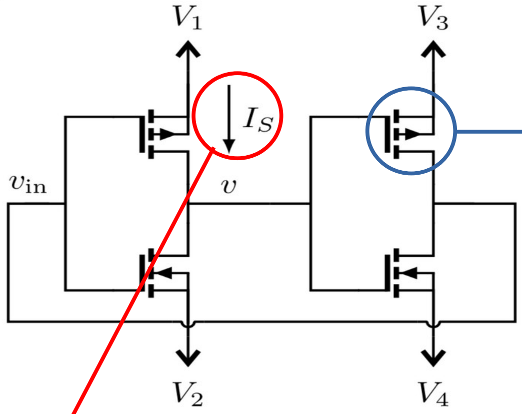
Steady states for

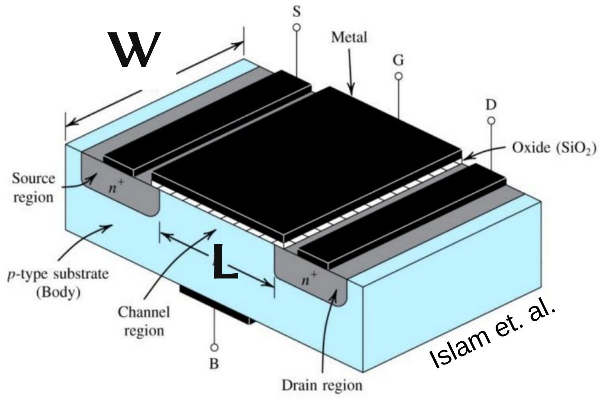
$\Delta V_S = 0.4$



$\Delta V_D = 2 \rightarrow \alpha^2 < 1$ $\Delta V_D = 3.4 \rightarrow \alpha^2 = 1$ $\Delta V_D = 5 \rightarrow \alpha^2 > 1$

Macroscopic limit





L fixed & increasing **W**

$C \uparrow \;\Rightarrow\; v_e = q_e/C \downarrow$

$\langle I \rangle \uparrow \;\Rightarrow\; \lambda_\pm \uparrow$

$$\langle I_S \rangle \simeq \frac{q_e}{2\tau_0}\Big[\Delta V_S - v_e \underbrace{\left(e^{\Delta V_D/2} - 1\right)}_{\alpha_D}\Big] + \mathcal{O}(\Delta V_S^2)$$

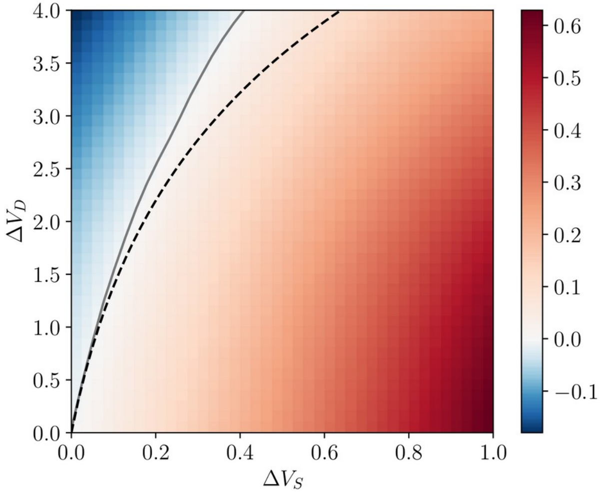
Rectification ($\langle I_S \rangle < 0$) is possible only if:

$$v_e^{-1} < \frac{\alpha_D}{\Delta V_S} \;\rightarrow\; \text{Maximum scale}$$

It disappears in the macro limit $v_e \to 0$

Equivalently, it is possible if:

$$\Delta V_D > 2\log(1 + \Delta V_S/v_e) \propto 2\log(v_e^{-1}) \;\rightarrow\; \text{Minimum powering voltage}$$



Rectification is possible if ΔV_D is high enough

Rectification can survive the macroscopic limit if one scales power with size !!!

For fixed $\alpha^2 = (e^{\Delta V_S/2} - 1)(e^{\Delta V_D/2} - 1)$ with $\Delta V_S = c v_e$ $\longrightarrow$ $\Delta V_D = 2\log(1 + 2\alpha^2/c v_e)$

$v_e \to 0$

$$\langle I_S \rangle \simeq \frac{q_e}{2\tau_0}\left[\Delta V_S - v_e \frac{\alpha^2}{(e^{\Delta V_S/2} - 1)}\right] + \mathcal{O}(\Delta V_S^2)$$

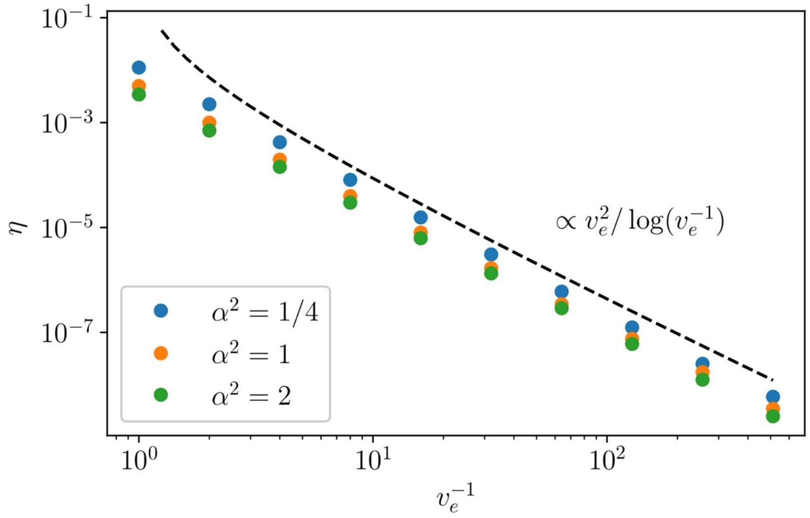
$\tau_0 \sim v_e$

$$T\dot{\Sigma}_S = \Delta V_S \langle I_S \rangle \sim -\alpha^2/c$$

$$T\dot{\Sigma}_D = \Delta V_D \langle I_D \rangle \sim \log(v_e^{-1})/v_e^2$$

$$\eta \sim v_e^2/\log(v_e^{-1})$$

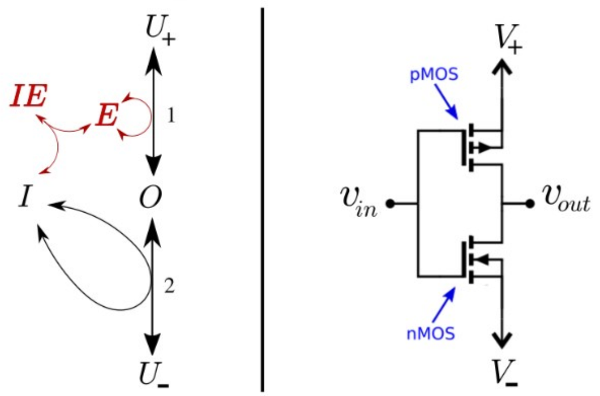
... but efficiency drops down

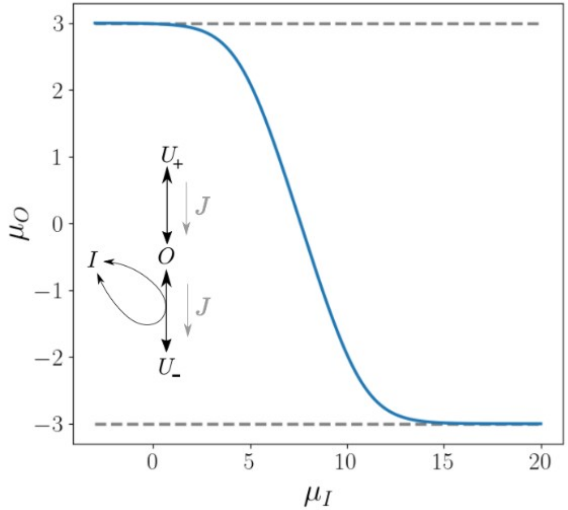


Esposito, Freitas,
PRL 129,120602 (2022)
& PRE 107, 014136 (2023)

Chemical Maxwell Demon

Inverter



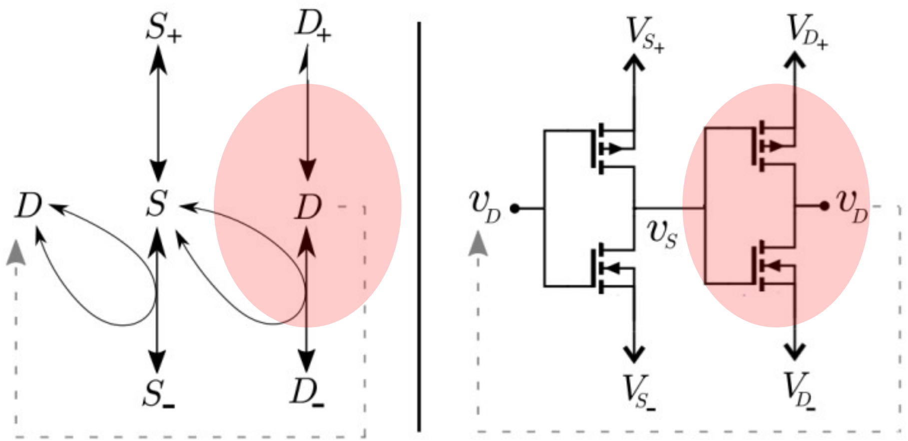


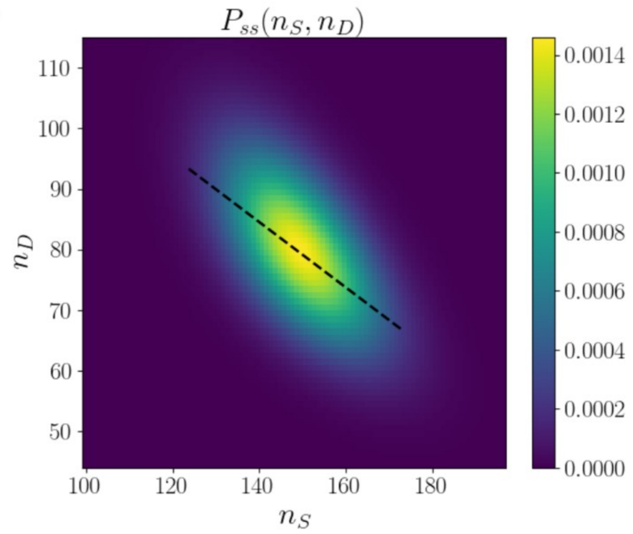
Bilancioni, Esposito, Freitas,
J Chem Phys **159**, 204103 (2023)

Key difference:
Response is bounded

$$\alpha = \left|\frac{d\mu_O}{d\mu_I}\right| \leq n \tanh\left(\Delta\mu/4\right) \leq n$$

The chemical demon does not survive the macroscopic limit





Perspectives

Strategies to transfer phenomena that are typical of the micro scale to the macro scale
(breaking the macro limit by other mechanisms than equilibrium phase transitions)

Electrons in circuits $\longleftrightarrow$ Molecules in chemical reactions networks

Interplays between nonequilibrium fluctuations and nonlinear dynamics
$\longrightarrow$ very rich phenomenology