Spring College on the Physics of Complex Systems

Experimental demonstration of information-to-energy conversion and validation of the generalized Jarzynski equality

Authors: Shoichi Toyabe, Takahiro Sagawa, Masahito Ueda, Eiro Muneyuki and Masaki Sano.

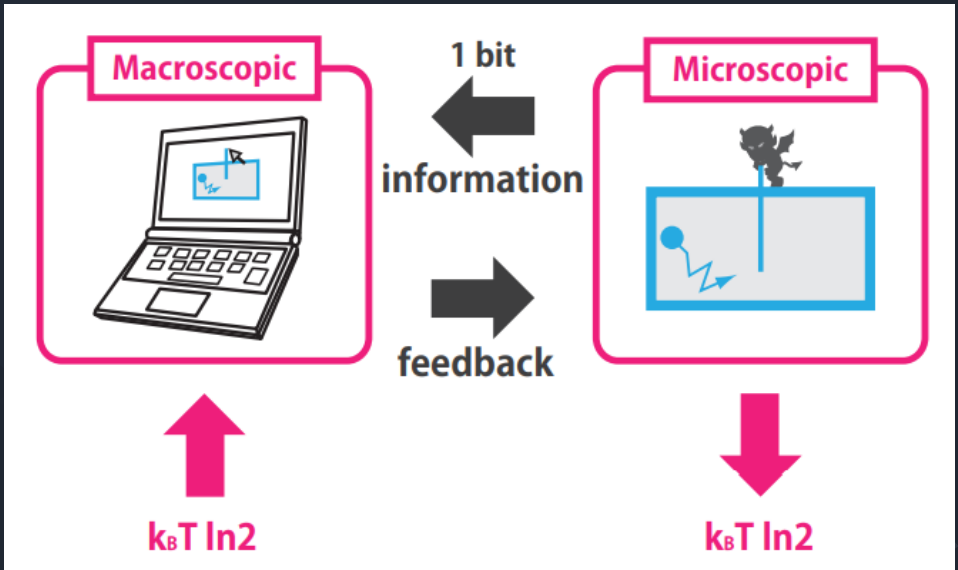
Presented by **Ana Forero**

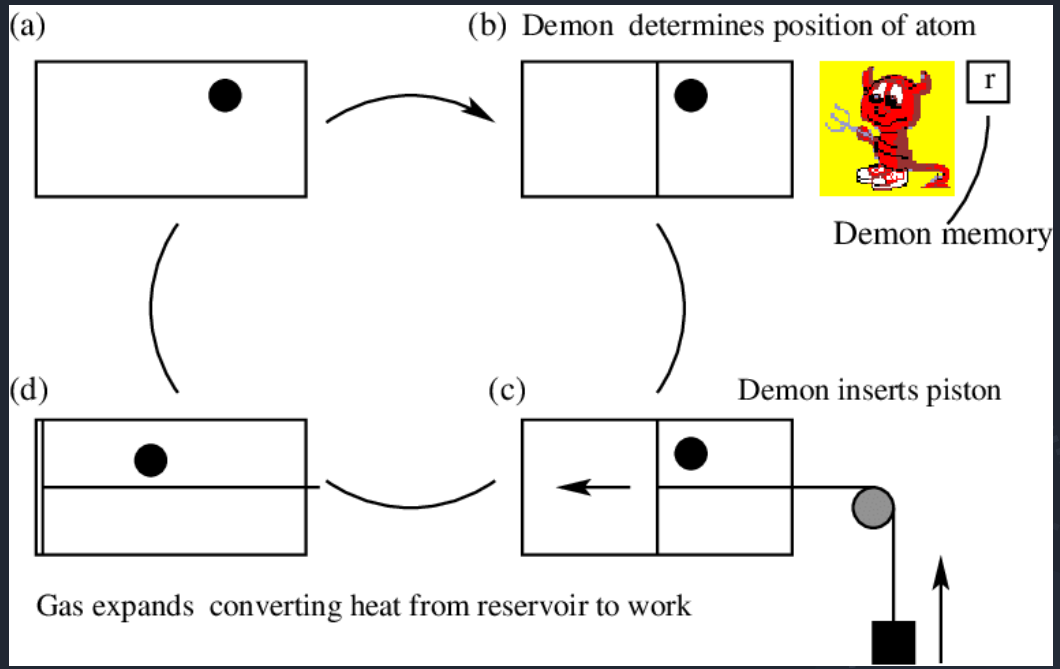
Stochastic Thermodynamics Exam

Szilárd's engine

No violation of the second law:

Energy cost is needed for the demon itself.





Plenio, M. and Vitelli, Vincenzo. Contemporary Physics **42**, (2001)

$$\Delta F = 0$$

$$\langle W \rangle = -k_B T \ln(2) \leq 0$$

Gedanken Experiment

$$\Delta F - \langle W \rangle \leq 0$$

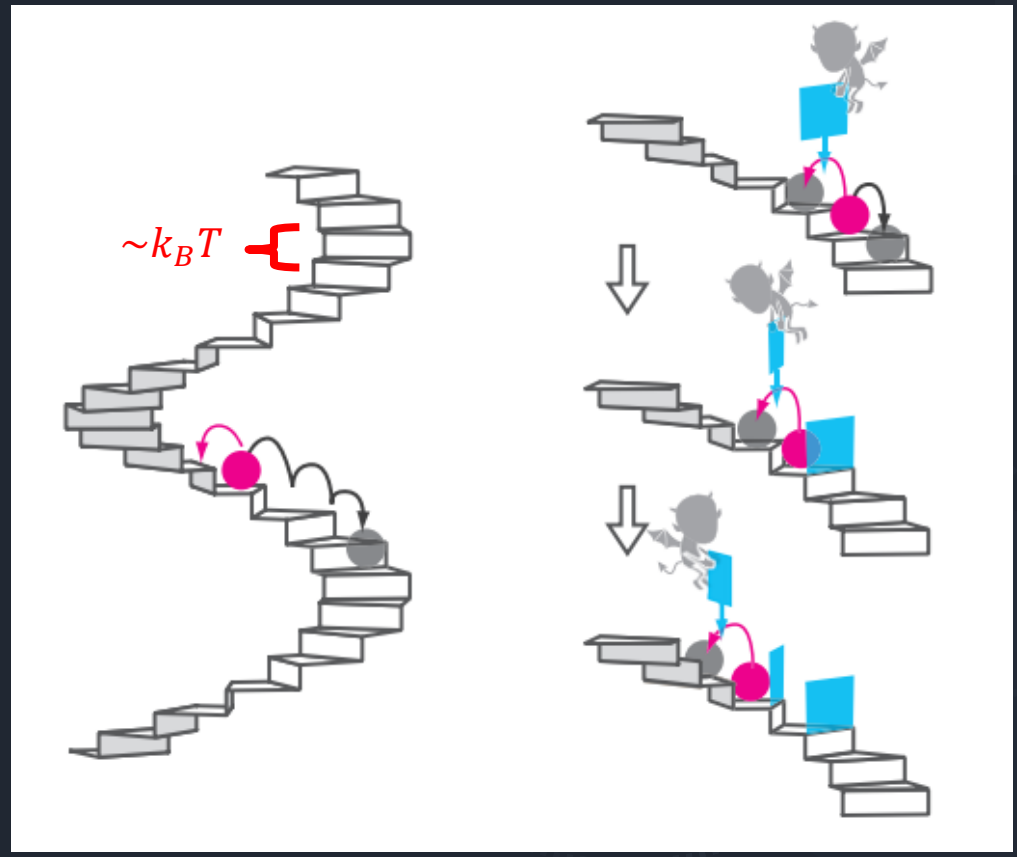
$$\Delta F - W > 0$$

2nd law of thermodynamics with **feedback control**:

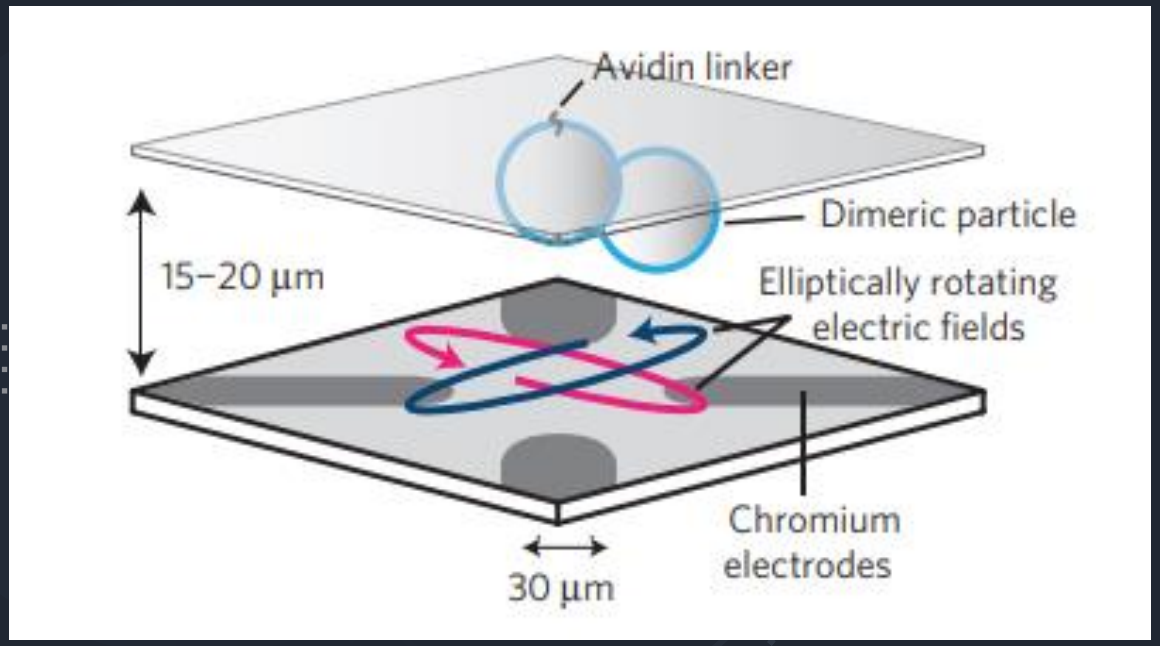
$$\Delta F - \langle W \rangle \leq k_B T \, I$$

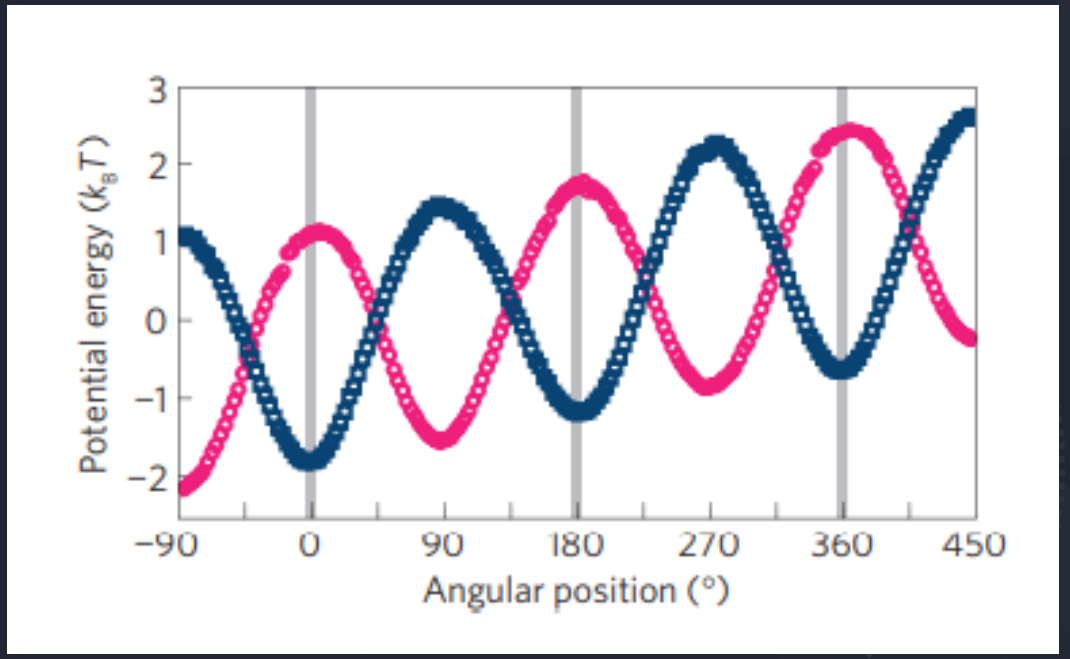
I is the mutual information content
obtained by measurements

$$I = \sum_{m,k} p(m|k)\, p(k) \ln\left(\frac{p(m|k)}{p(m)}\right)$$

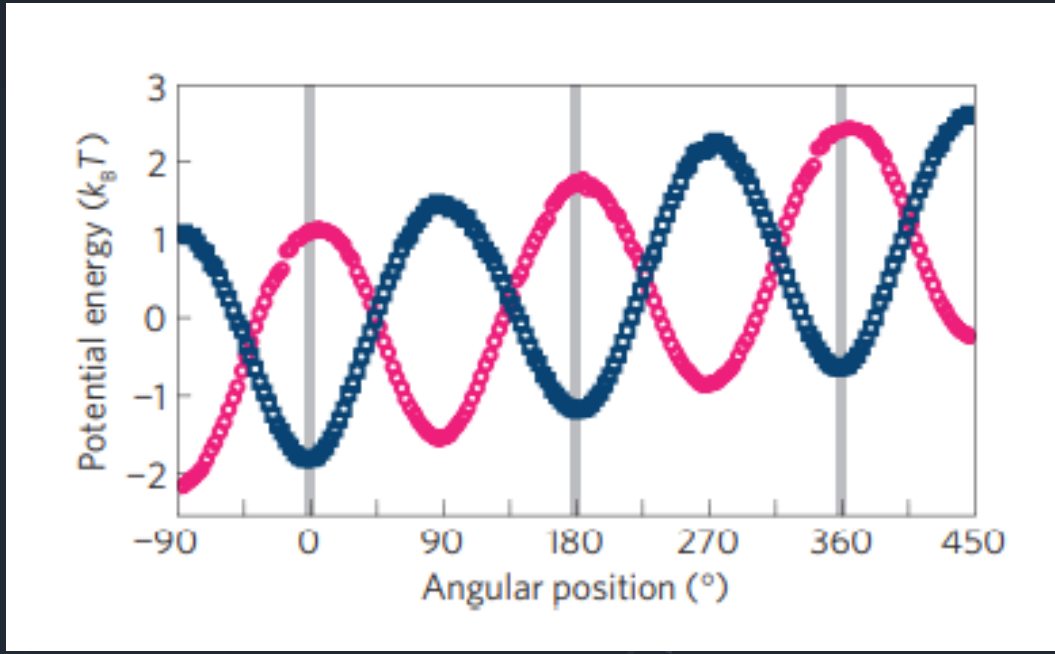


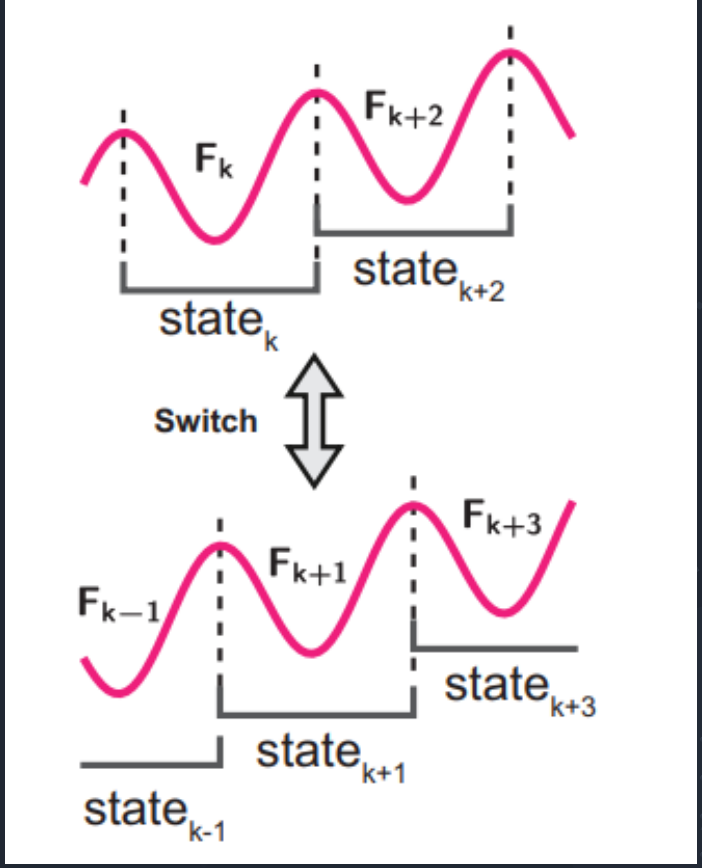
Experiment


Avidin linker
Dimeric particle
15–20 µm
Elliptically rotating
electric fields
Chromium
electrodes
30 µm


Potential energy (k_BT)
3
2
1
0
−1
−2
−90
0
90
180
270
360
450
Angular position (°)

Experiment

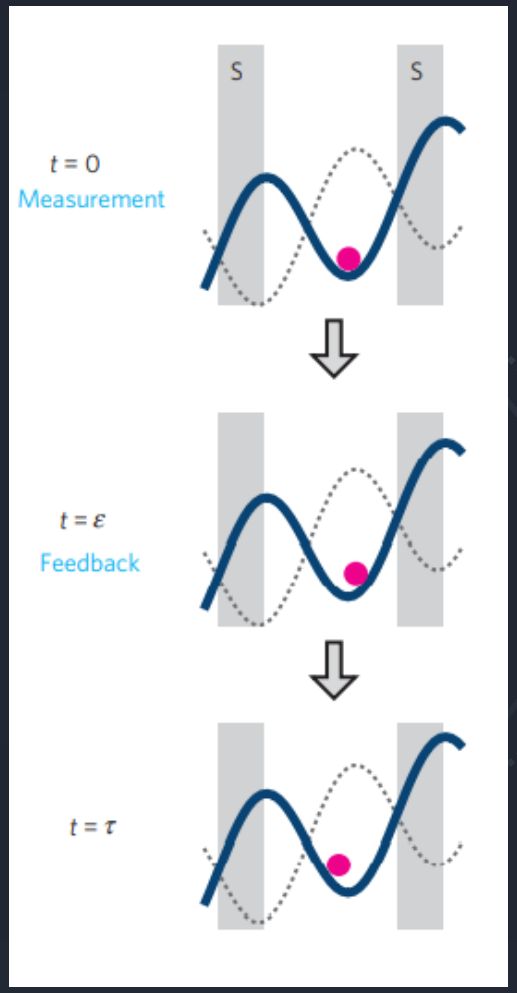


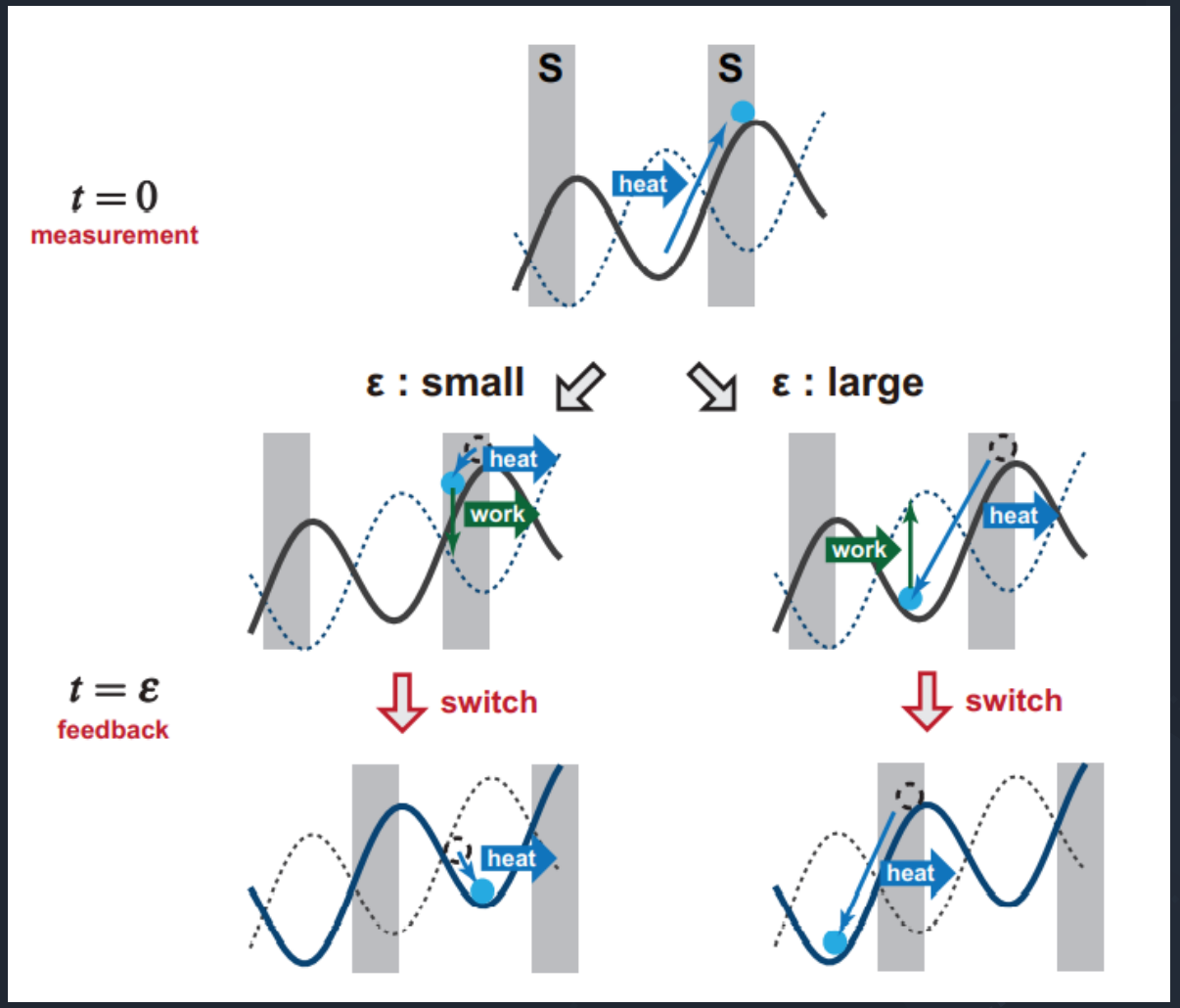


- **Free Energy and states:** the free energy of state k was calculated as:

$$F_k = -k_B T \ln\left(\int dx \; e^{-\frac{U(x)}{k_B T}}\right)$$

Experiment

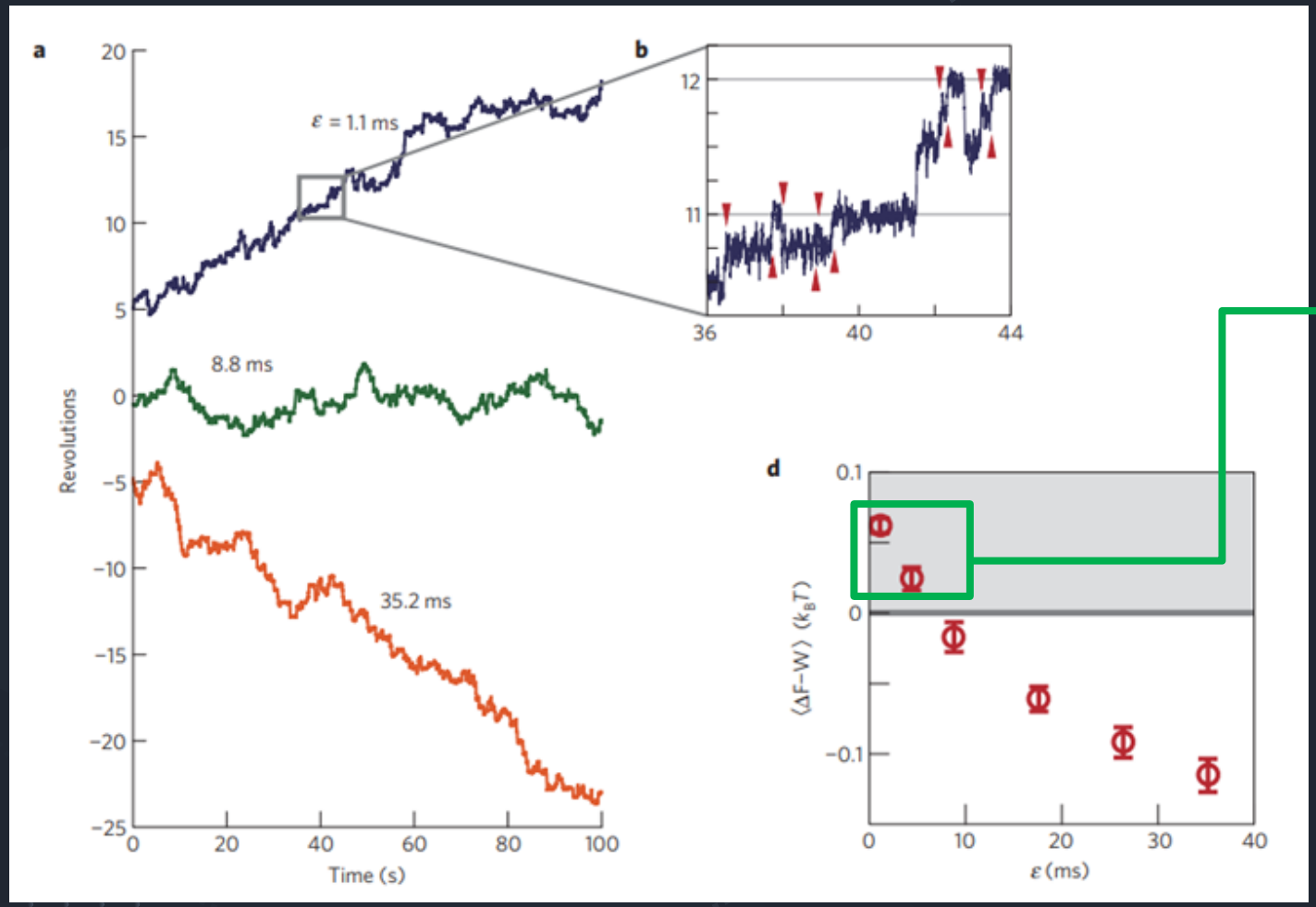




- **Feedback cycle:** period of $\tau = 44$ ms and minimum feedback delay $\varepsilon = 1.1$ ms.

Results

(information -to-energy conversion)



Typical trajectories and excess free energy under feedback control

$$\Delta F - \langle W \rangle \leq 0 \quad (*)$$

More work extracted than in bound (*)

For $\varepsilon = 1.1$ ms :

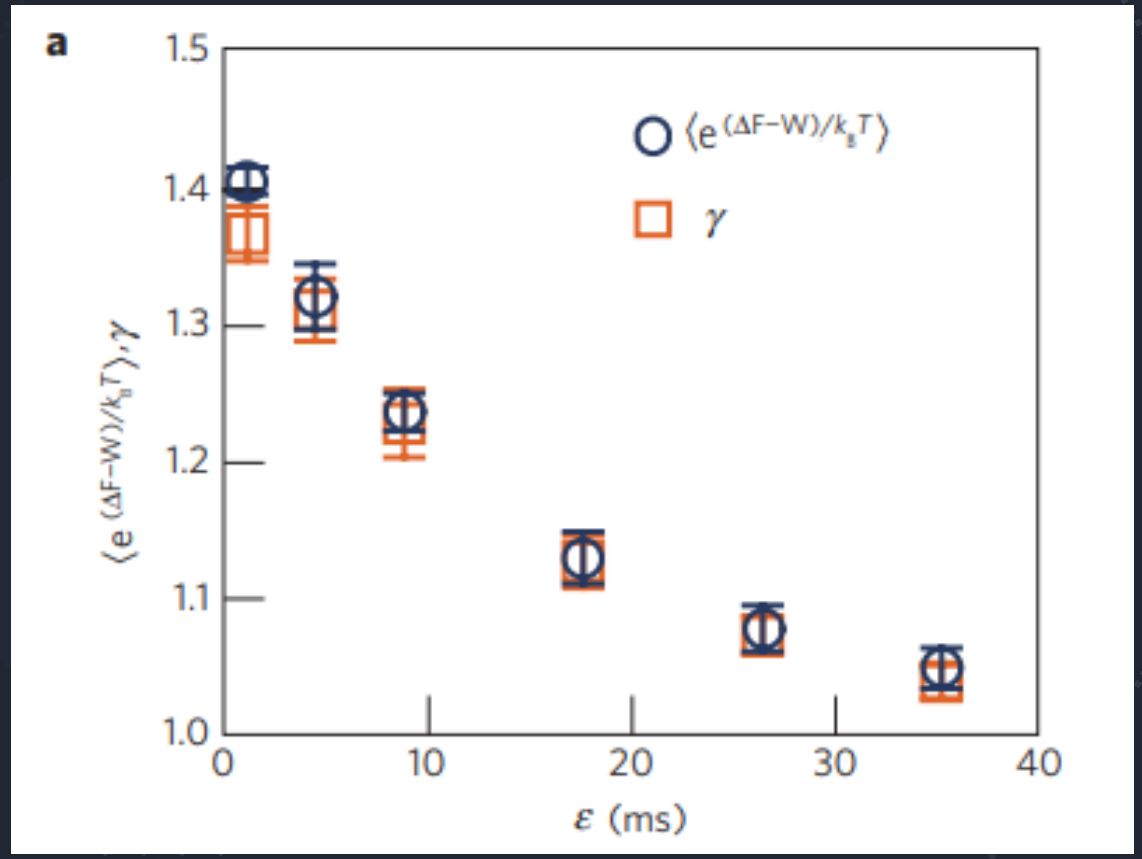
$$\langle \Delta F - W \rangle = 0.062\, k_B T$$

$$I = 0.22$$

$$\langle \Delta F - W \rangle \leq k_B T\, I$$

Results

(verification of generalized Jarzynski equality)



Jarzynski equality $e^{-\beta \Delta F} = \langle e^{-\beta W} \rangle$

$$\langle e^{-\beta (W - \Delta F)} \rangle = 1$$

Generalized Jarzynski equality (Feedback Control):

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

$$\gamma = \sum_{A} P^{\dagger}(A)$$

$P^{\dagger}(A)$ probability that the particle is observed in region A under the time reversed control protocol.

Summary

The authors proposed an experiment based on Szilárd engine to:

- Demonstrate that it is possible to achieve a Szilárd-type information-to-energy conversion.

$$\Delta F - \langle W \rangle \leq k_B T \, I$$

- Verify the generalized Jarzynski equality.

$$\left\langle e^{-\beta(W-\Delta F)} \right\rangle = \gamma$$