Information engines with high performance & efficiency

football stadium



museum of "science"



Simon Fraser University

KIAS Workshop, Seoul, Korea
July 22, 2026

Information engines with high performance & efficiency

experiment



Tushar Saha



Prithviraj Basak



Avijit Kundu



Kensaku Chida (NTT)

theory



Antonio Patrón Castro



David Sivak



Dorian Daimer



Susanne Still

Simon Fraser University

KIAS Workshop, Seoul, Korea

July 22, 2026

NSERC CRSNG

FQXi FOUNDATIONAL QUESTIONS INSTITUTE

UNIVERSITY of HAWAI'I MĀNOA

SFU

Outline

I. A modern information engine

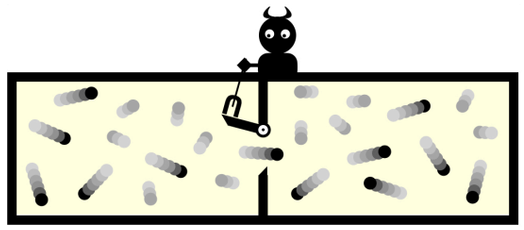
- experiments with feedback traps
- optimizing performance
- nonequilibrium environments
- 2d info engine: performance and efficiency with storage?

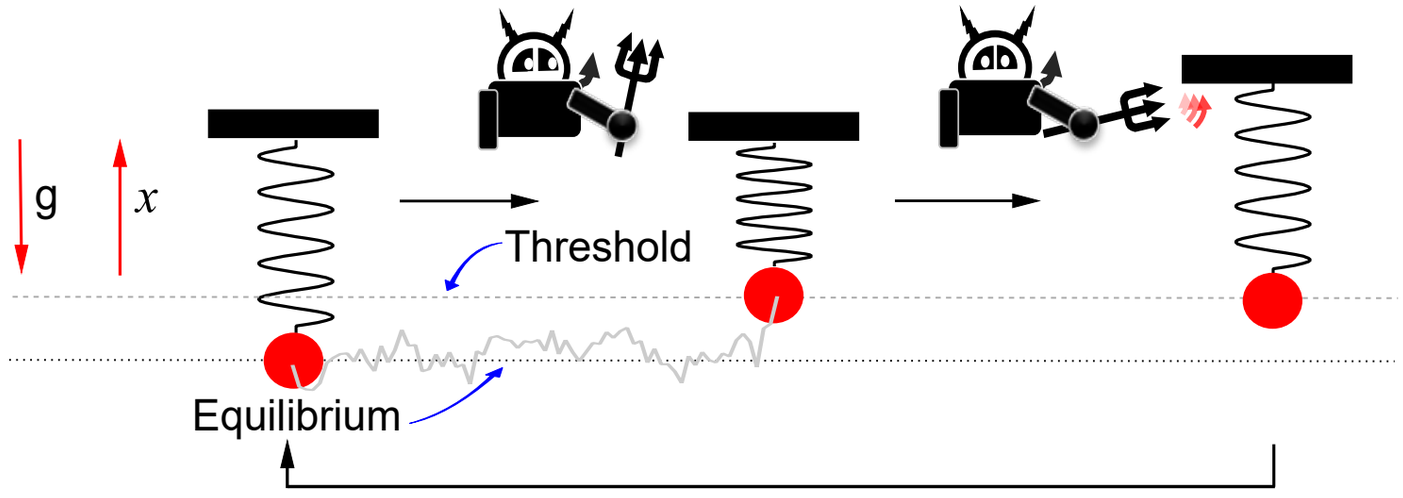
II. Random vs. deterministic protocols in a Szilard engine

- intro: info costs resolve the Maxwell-demon paradox (Szilard engine)
- Structural limitations: partially observable Szilard engine
- probabilistic information encoding (soft coarse graining)
- random can be better!

Information engine

A modern Maxwell demon





Fluctuating particle, in bath

Wait for an “up” fluctuation

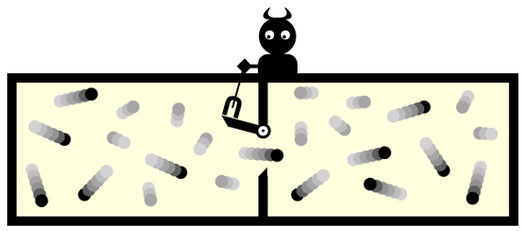
Raise platform w/o work

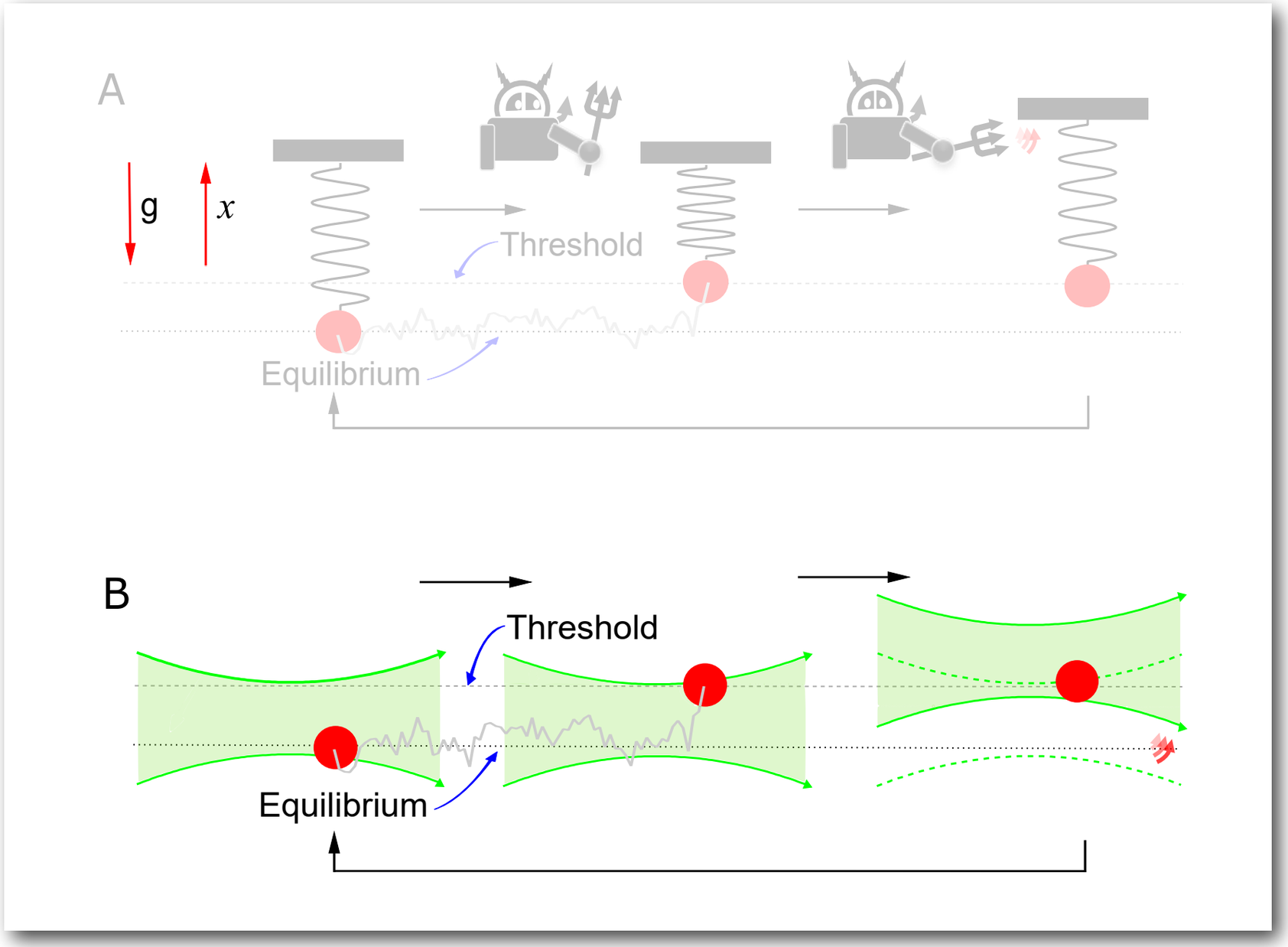
Repeat cycle

Energy stored in gravitational potential

Information engine

A modern Maxwell demon





Fluctuating particle, in bath

Wait for an "up" fluctuation

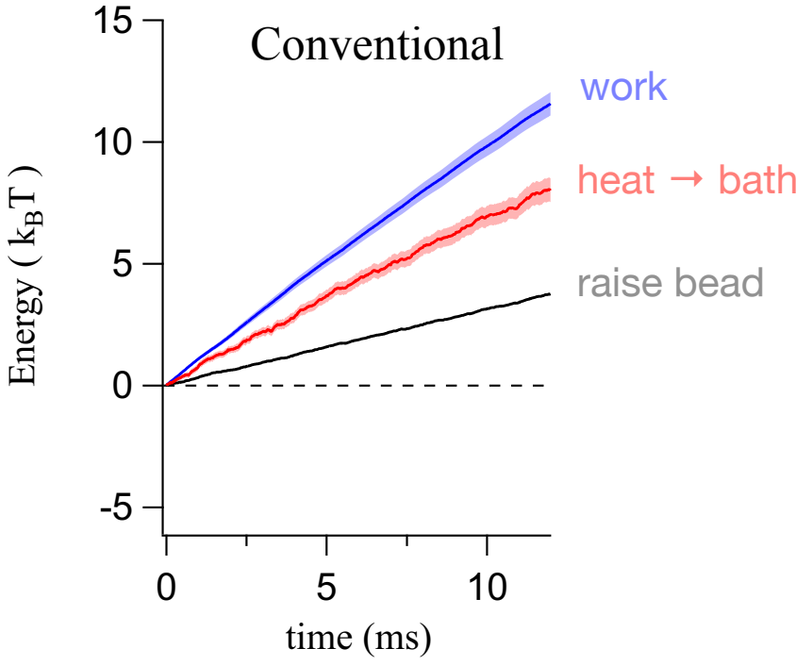
Raise platform w/o work

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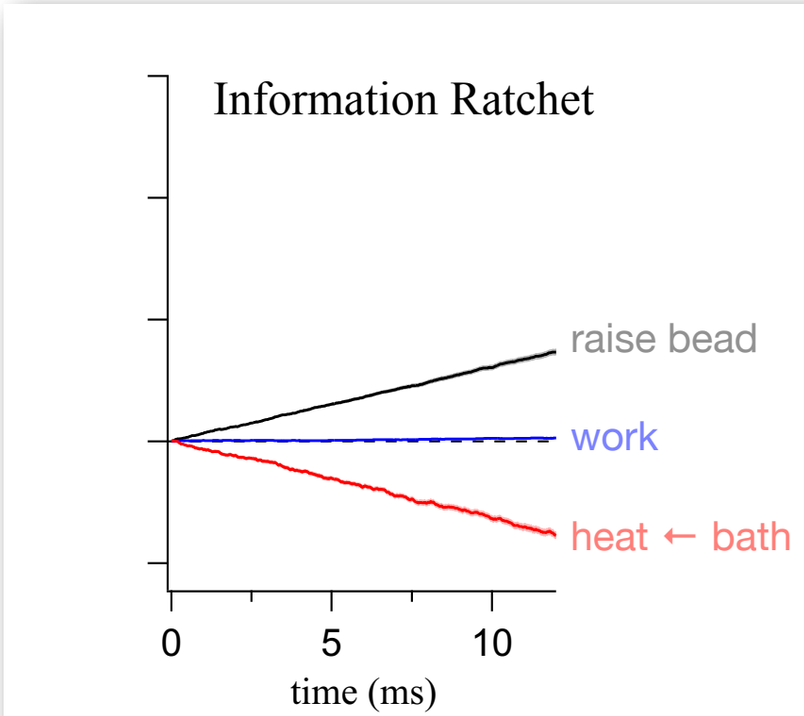
Energy stored in gravitational potential

Experimental realization using optical tweezers

Two archetypes of motors



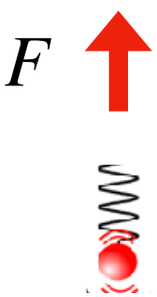
Chemical fuel

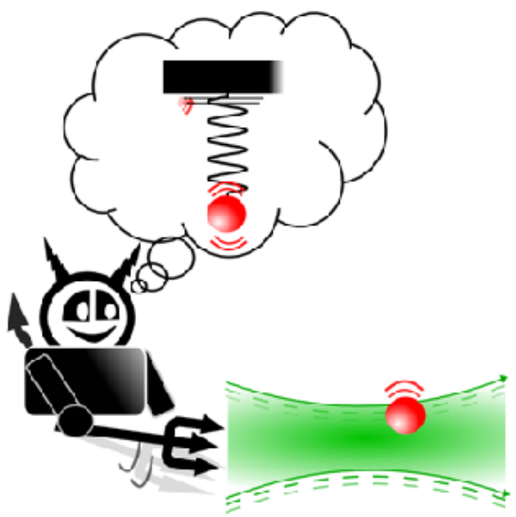


Information fuel

data from our experiment

both satisfy 1st law





work independent of fluctuations

work is zero because of fluctuations

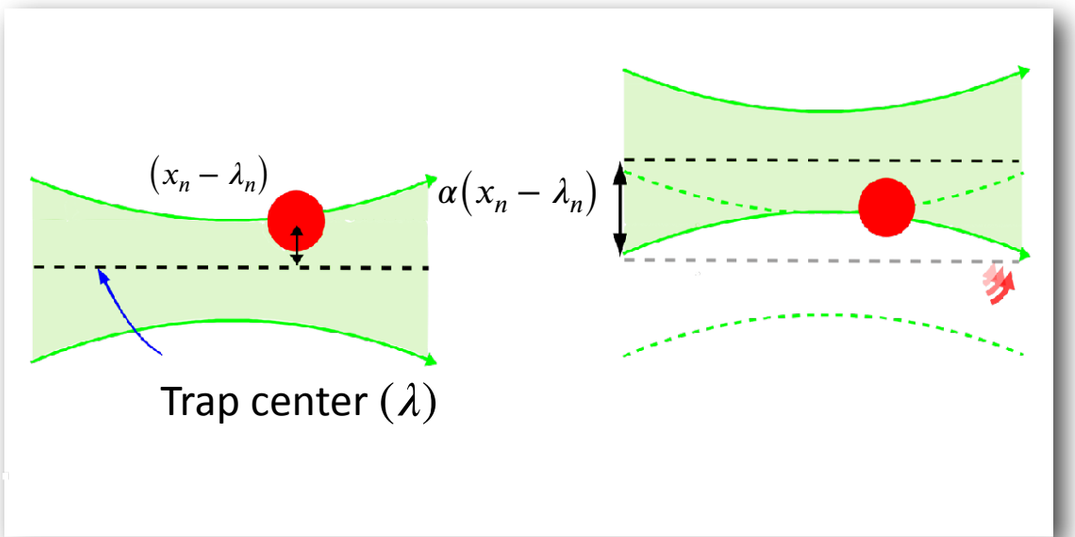
Information ratchet

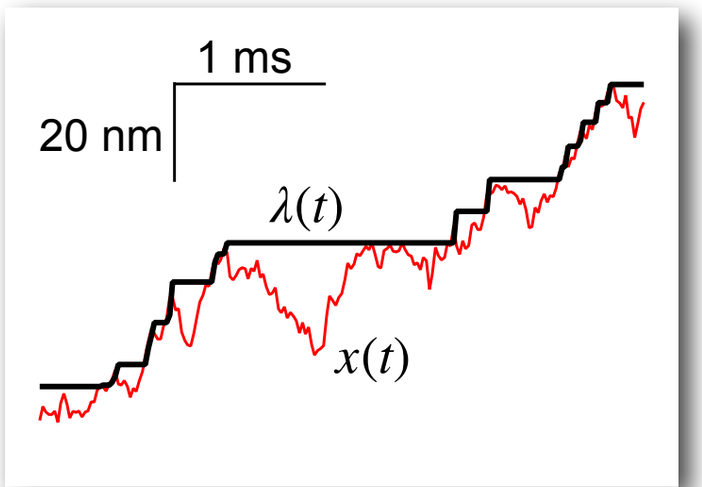
Feedback algorithm

Ratchet on up fluctuation that exceeds threshold X_T

$$\lambda_{n+1} = \begin{cases} \lambda_n + \alpha(x_n - \lambda_n), & (x_n - \lambda_n) \geq X_T \\ \lambda_n & \text{otherwise} \end{cases}$$

trap position — bead position — threshold

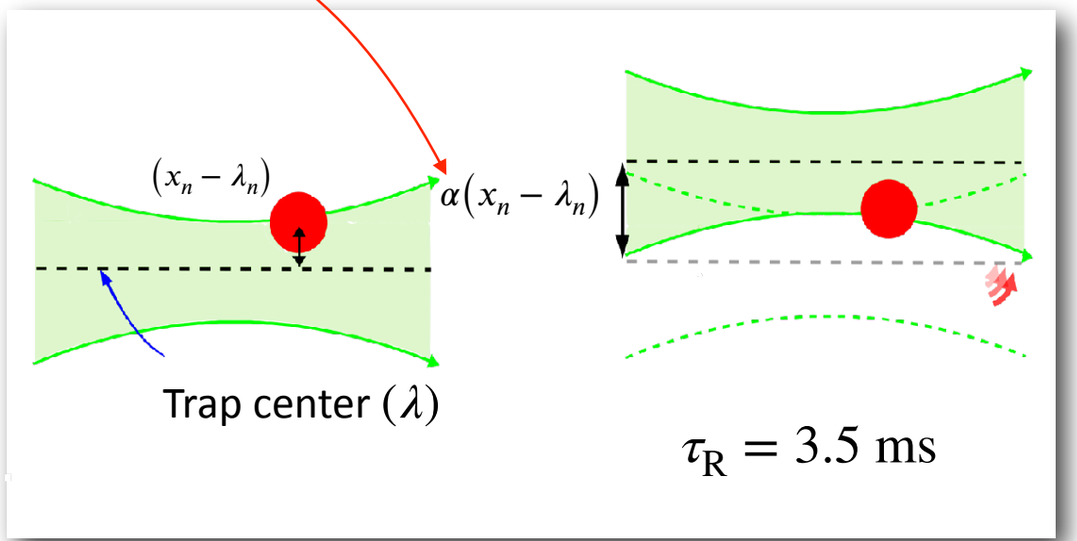




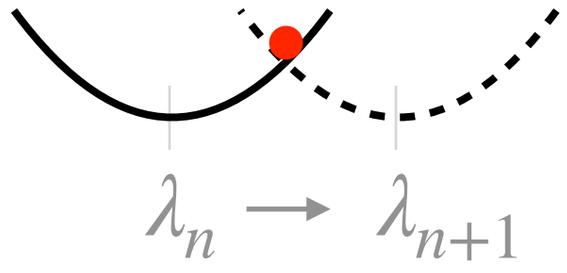
Information engine

Pure information engine

Adjust feedback gain α so that no work is done by ratcheting



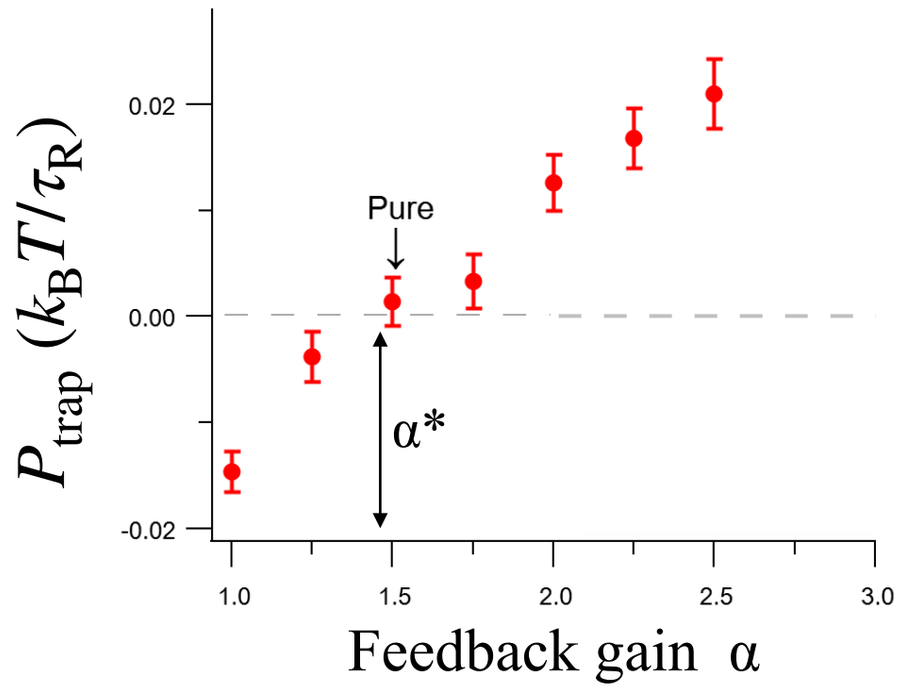
naive picture



Information engine

Pure information engine

Adjust feedback gain α so that no work is done by ratcheting



$$W_{n+1}^{\mathrm{trap}} = \frac{\kappa}{2}\left[(x_{n+1} - \lambda_{n+1})^2 - (x_{n+1} - \lambda_n)^2\right]$$

trap

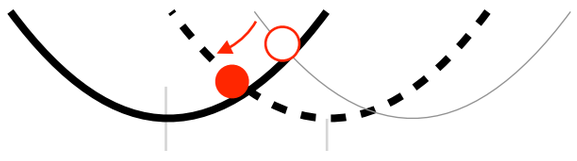
particle

work done on particle when quickly changing trap position

naive picture

\+ delay

\+ (bias)



$\lambda_n \to \lambda_{n+1} \quad (\alpha < 2)$

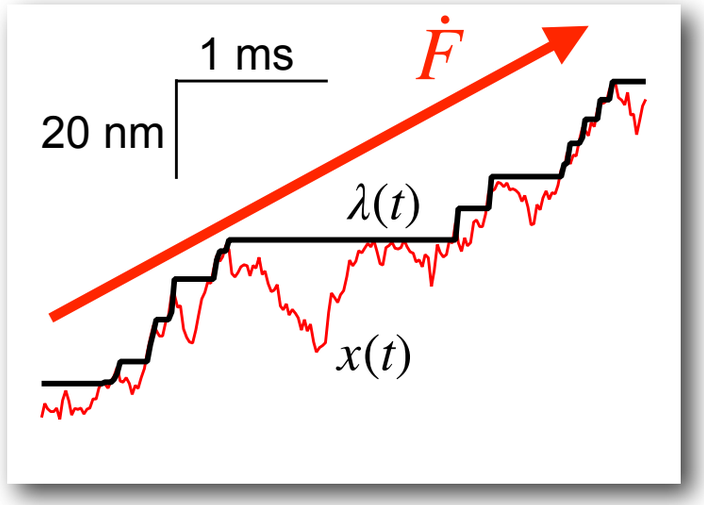
naive picture

$\lambda_n \to \lambda_{n+1} \quad (\alpha = 2)$

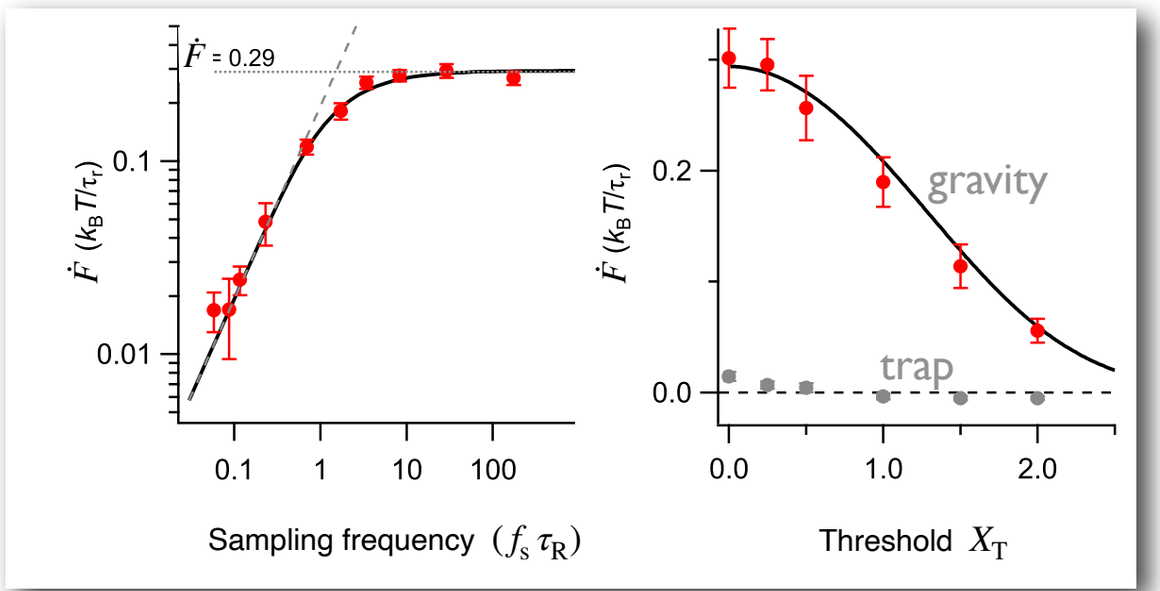
Information engine

Parameter optimization

$\dot{F}$ = rate work is extracted and stored as gravitational potential energy

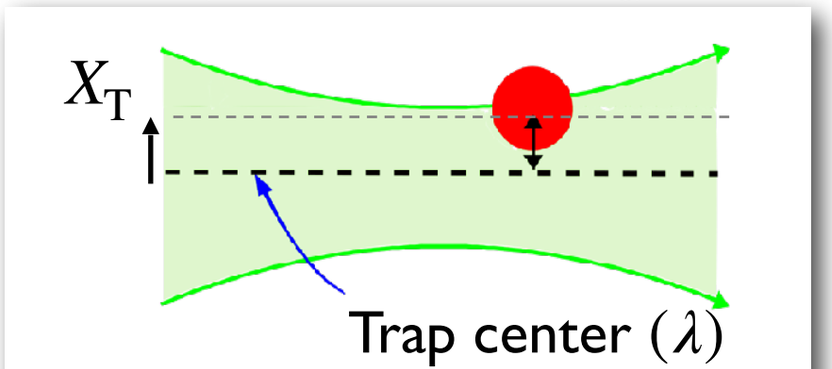


Max. sampling frequency $X_T \to 0$



"Catch all up fluctuations"

(~continuous ratcheting)



Trap relax: 3.5 ms **size:** 24 nm

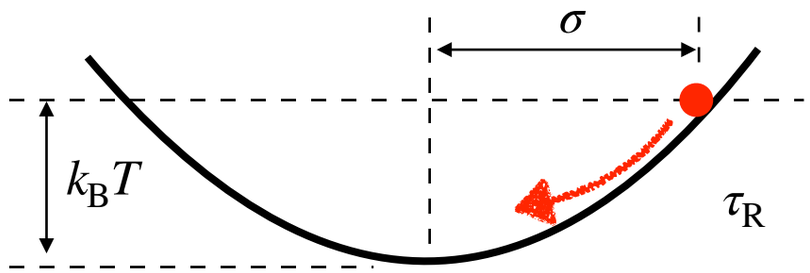
stiffness: 7 pN/μm

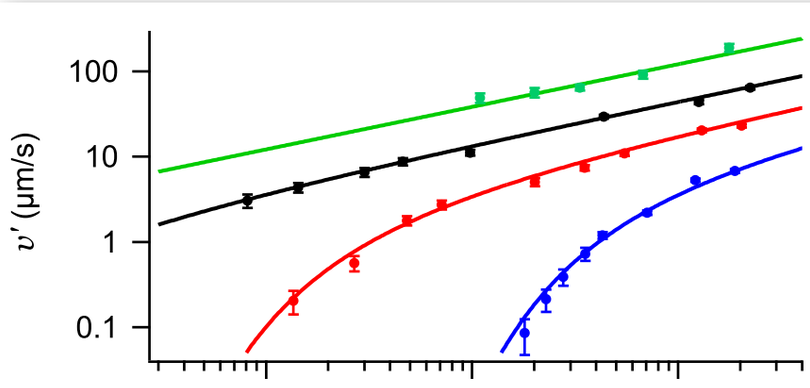
Information engine

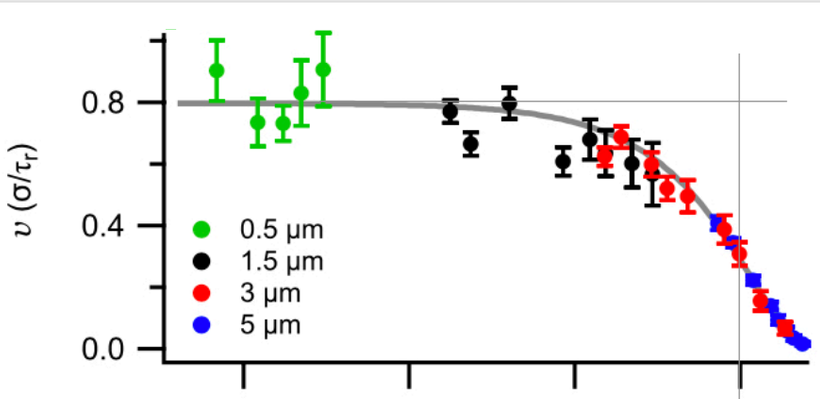
Theory for engine

$$\dot{F}_{\max} \approx 0.3 \left(\frac{k_B T}{\tau_R} \right)$$

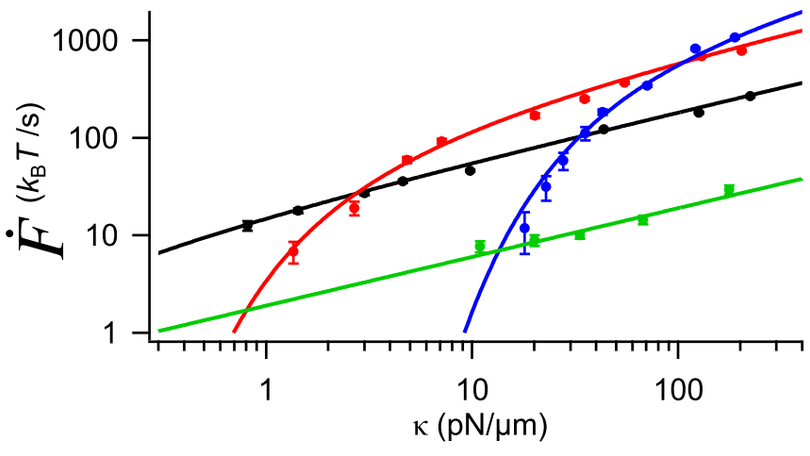
$$v_{\max} \approx 0.8 \left(\frac{\sigma}{\tau_R} \right)$$

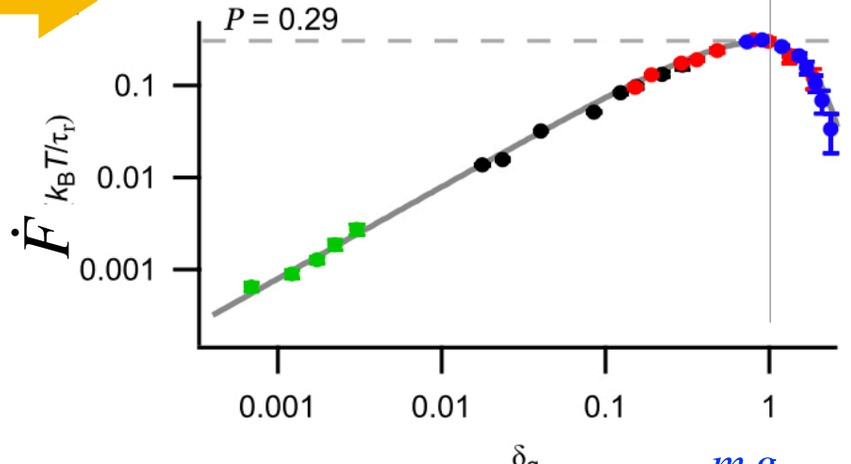






Dimensionless units





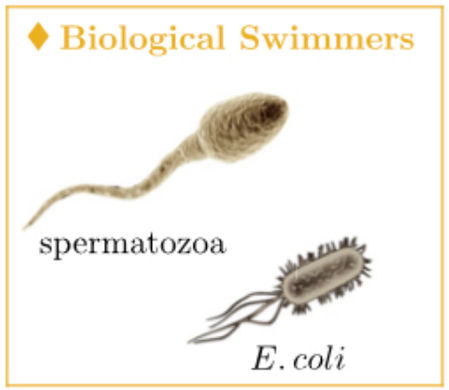
trap stiffness, size: κ, σ relaxation time: $\tau_r = \gamma/\kappa$ relative mass: $\delta_g = \frac{m\,g}{\kappa\,\sigma}$

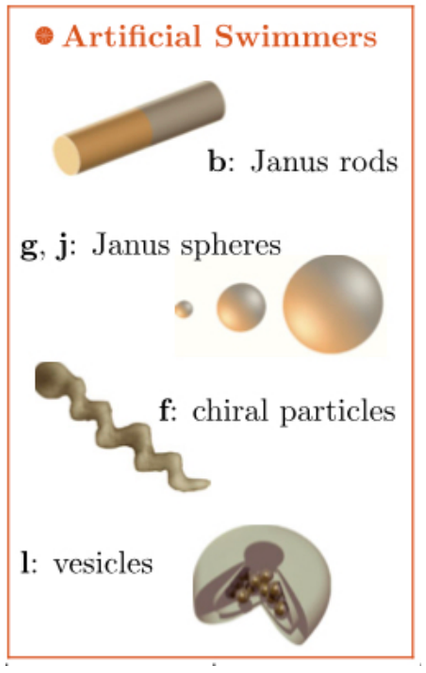
Park-Lee-Noh *PRE* 2016 [our version = Saha et al. *PNAS* 2021]

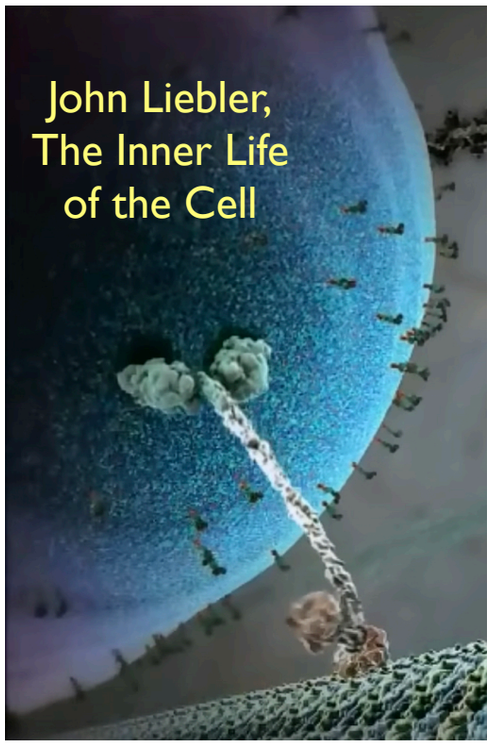
Nonequilibrium environment

The generic situation!

active matter







Bechinger et al., RMP 2016



hexbug (bristle-bot)

or

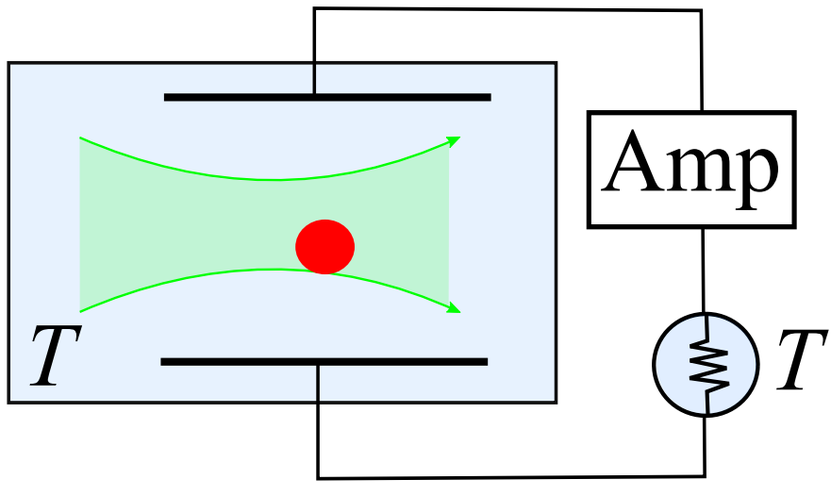
external forcing

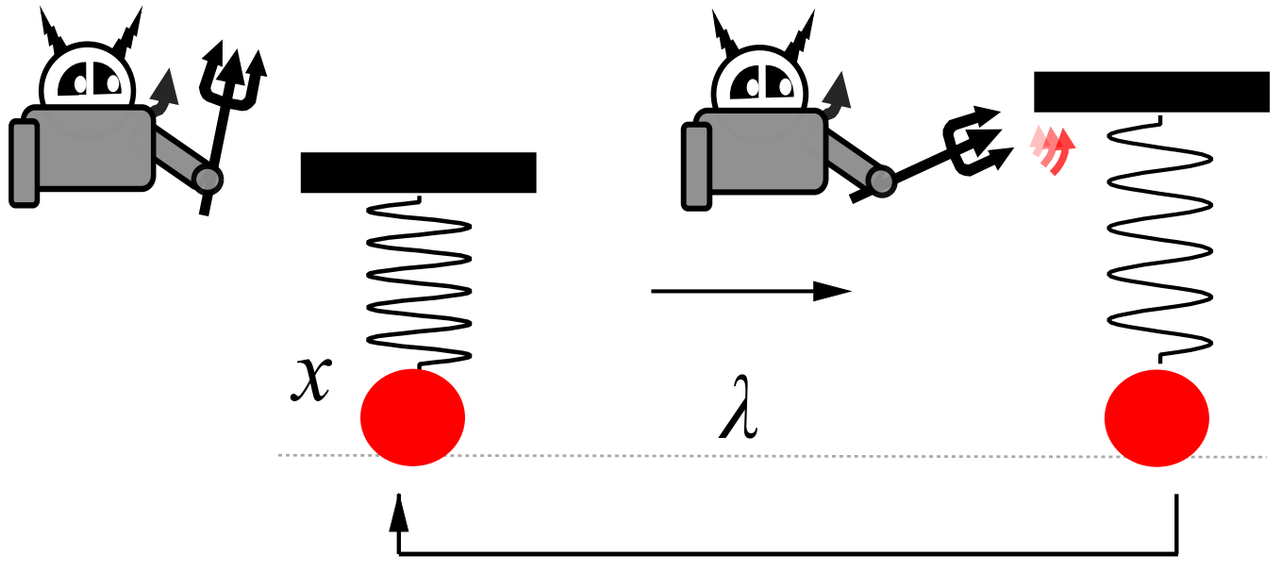
wind

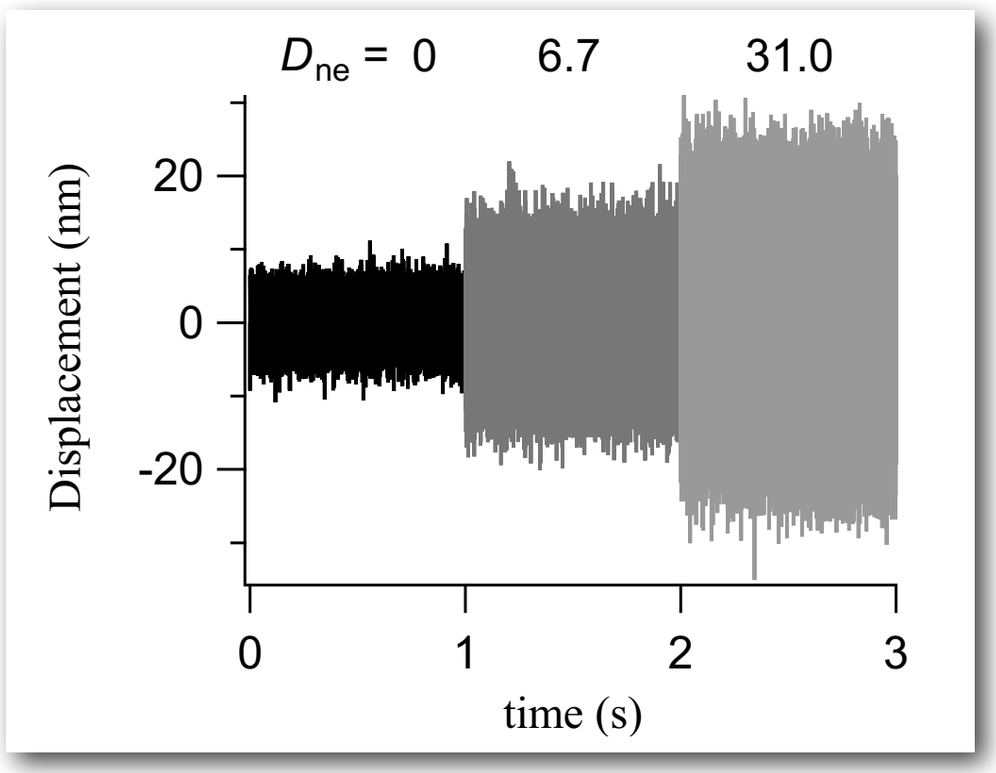


waves

Nonequilibrium environment



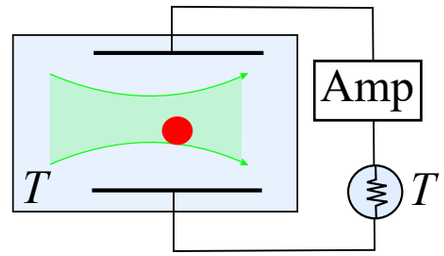




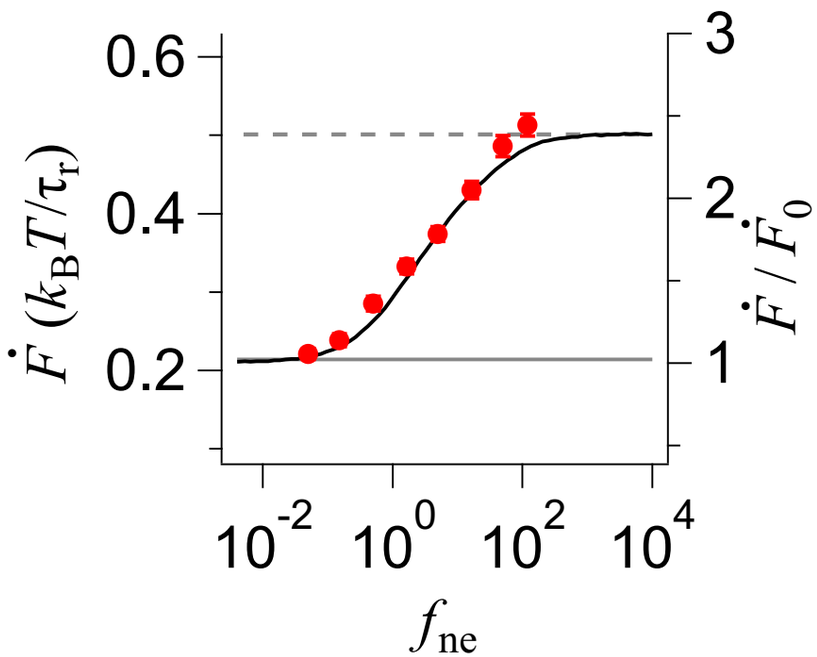
$$D_{ne} = \frac{\text{Noneq. D}}{\text{Eq. D}}$$

high SNR ↔ neglect measurement noise…

Nonequilibrium environment

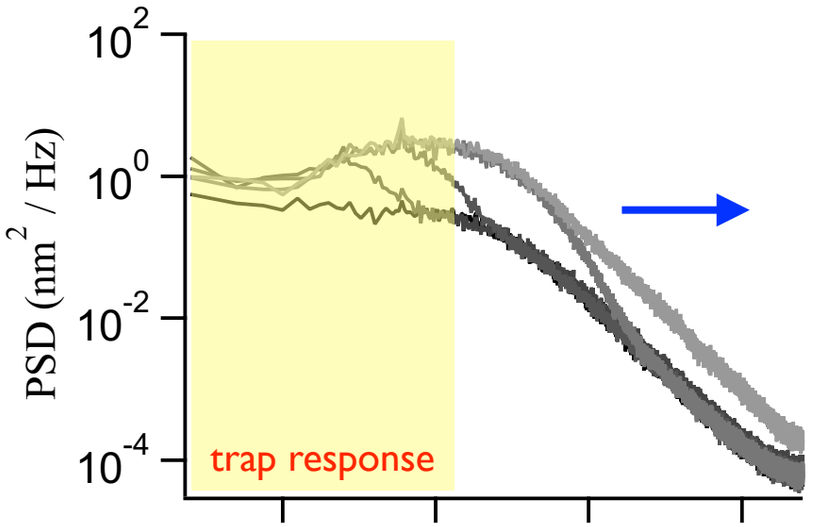


higher *bandwidth* of noneq. fluctuations → more power



noise bandwidth

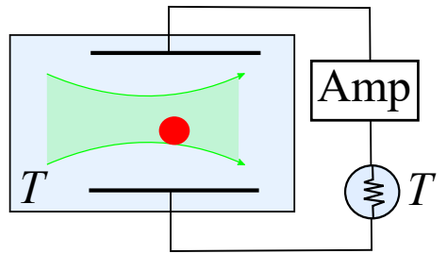
coloured-noise limit



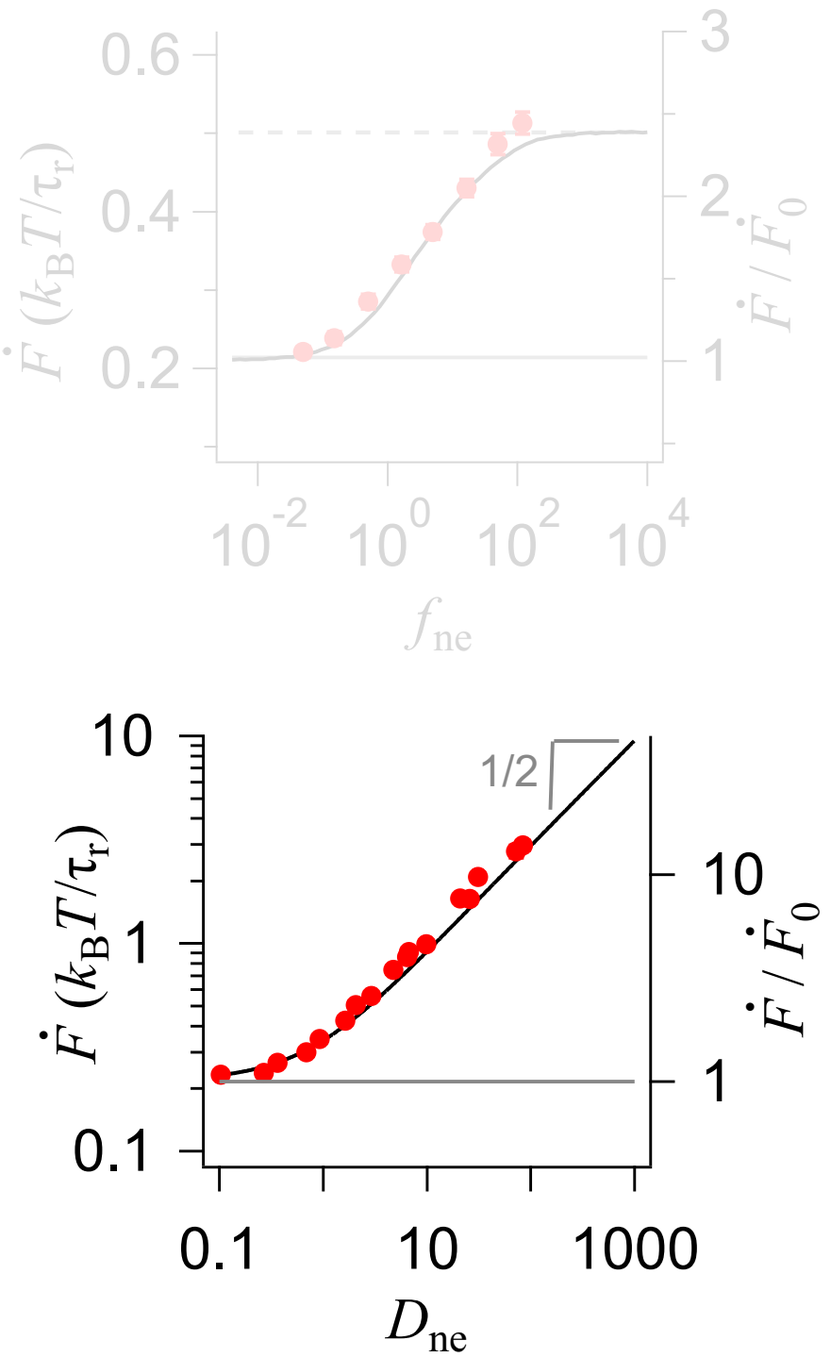
forcing amplitude

effective-temperature limit

Nonequilibrium environment



higher *amplitude* of noneq. fluctuations → more power

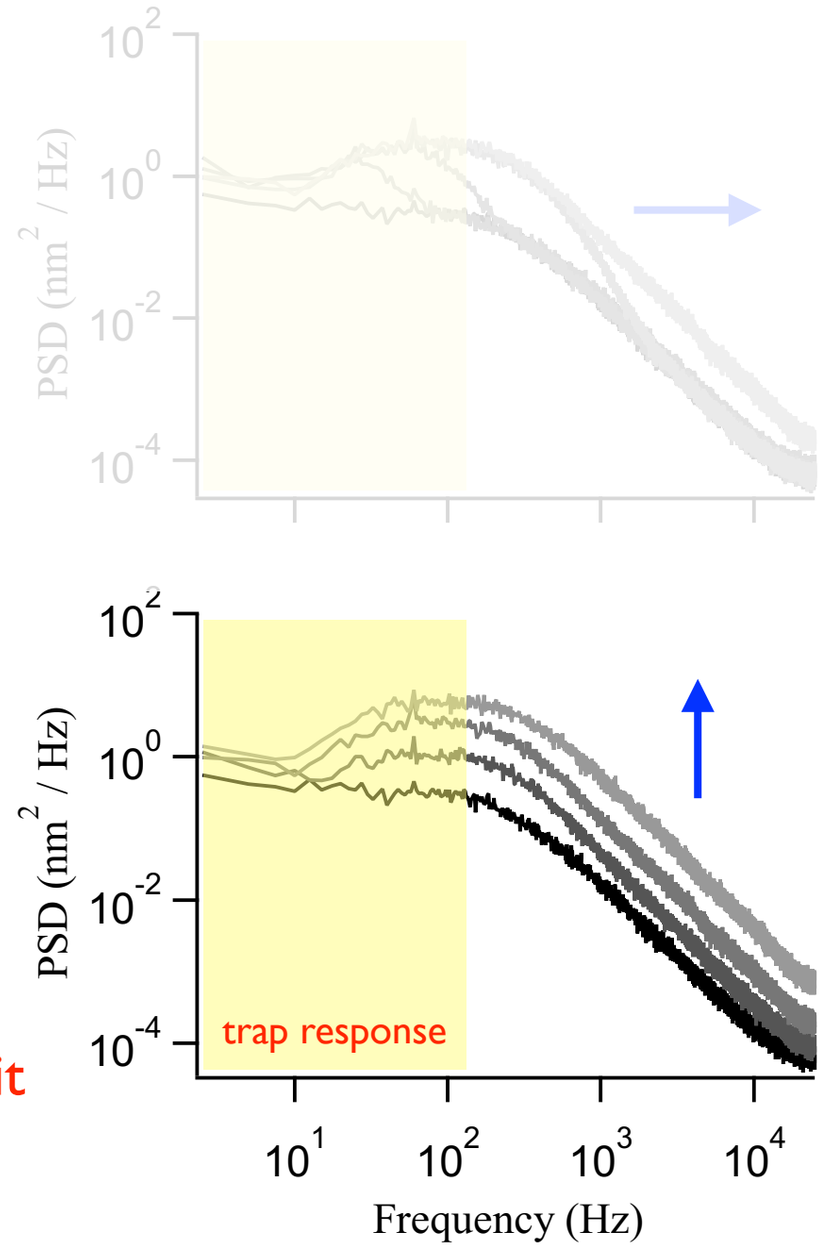


noise bandwidth

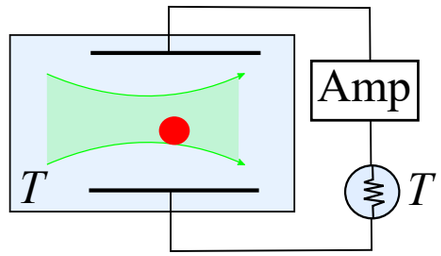
coloured-noise limit

forcing amplitude

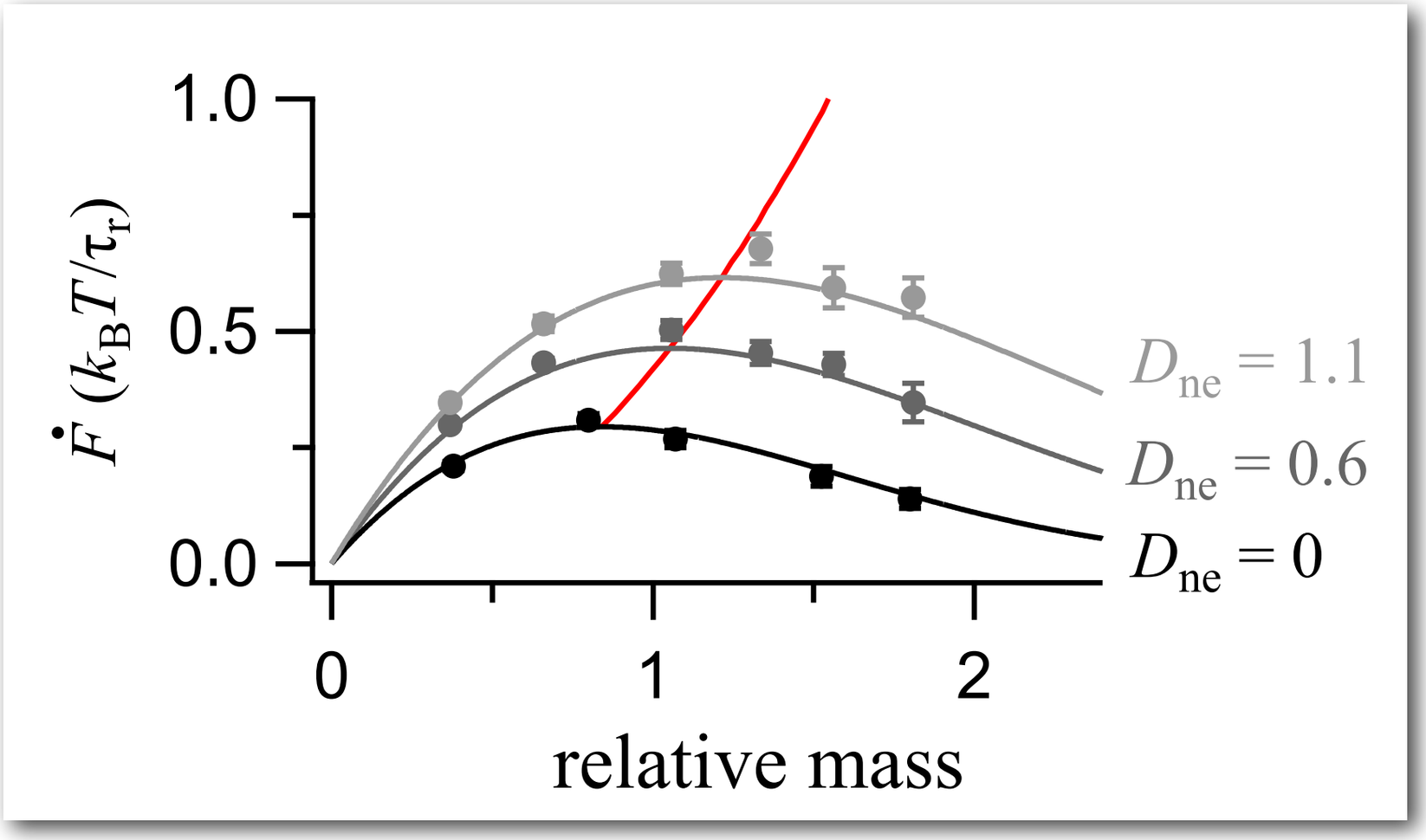
effective-temperature limit



Nonequilibrium environment



higher amplitude of noneq. fluctuations → larger optimal mass



Saha, Ehrich, Gavrilov, Still, Sivak, and JB, *PRL* 2023

Nonequilibrium environment

- info engines in noneq. environments can be useful machines

- huge values of effective temperature (here, ~10^4 K; granular media ~10^{17} K)

- only 10^{-11} modes noneq slow, long λ

  in even the stormiest sea,
  energy of waves is ≪ heat

- paradigm: big cargo, small sensor

  noneq fluct.

  eq. bath

external forcing

wind



waves

2d information engine

Antonio Patrón Castro, JB, Sivak, *PRL* 2026

Motivations:

- Szilard engine claims to extract & store all info

  (for single slow cycle)

$$\eta = \frac{\langle W \rangle}{\langle I \rangle} = 1$$

work extracted & stored

mutual info between sys & meas

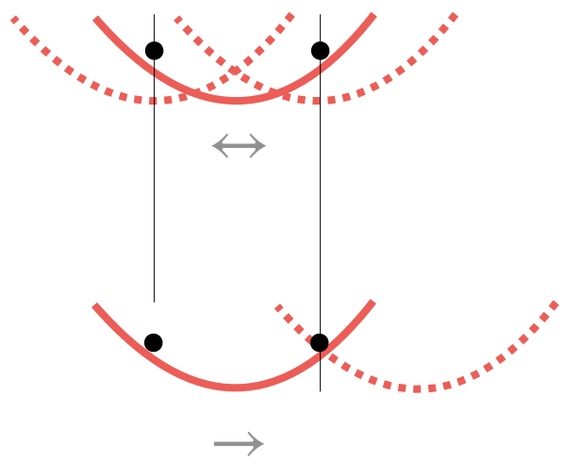
BUT

- Experiments to date have all had structural compromises:

  – Extract all* fluctuations but no storage (feedback cooling)

  – Extract & store only some of the fluctuations (e.g., our engine)

Hyuk Kyu Pak group, e.g.
DY Lee et al., *Sci Rep*. 2018



symmetric (capture)

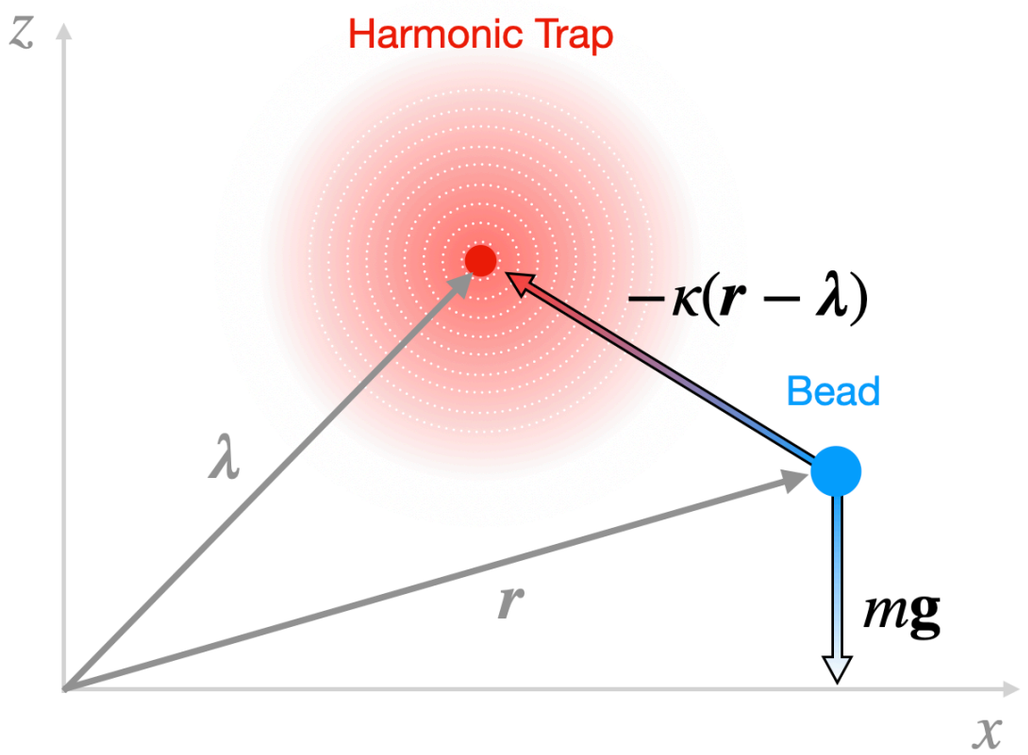
asymmetric (storage)

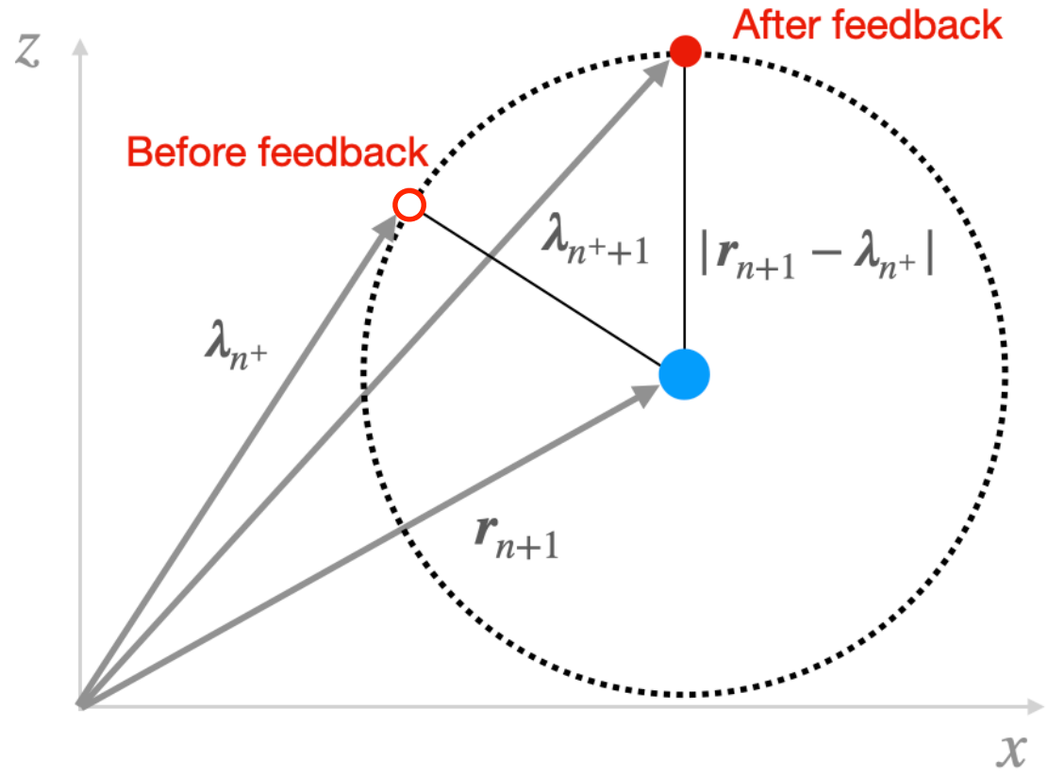
*most

2d information engine

"have your cake & eat it, too"

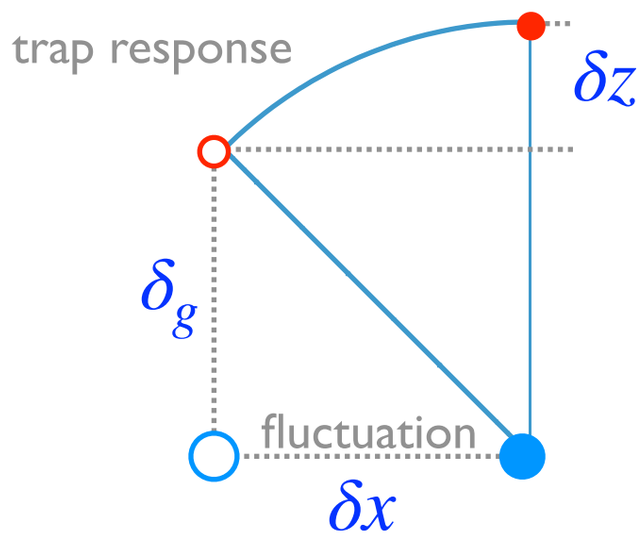




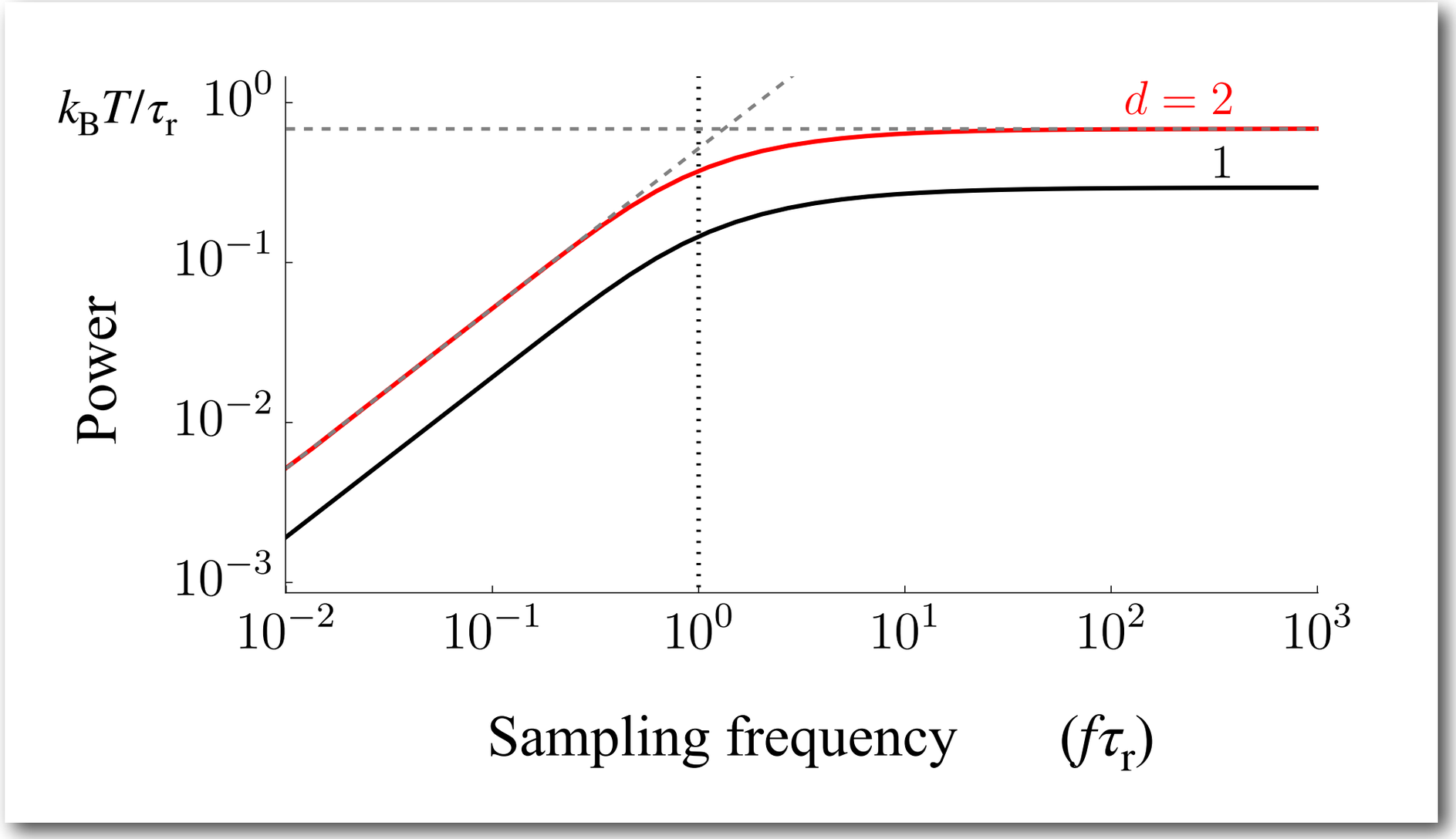


→ Look at lateral fluctuations:

$$\delta z \approx \frac{(\delta x)^2}{2\delta_g}$$

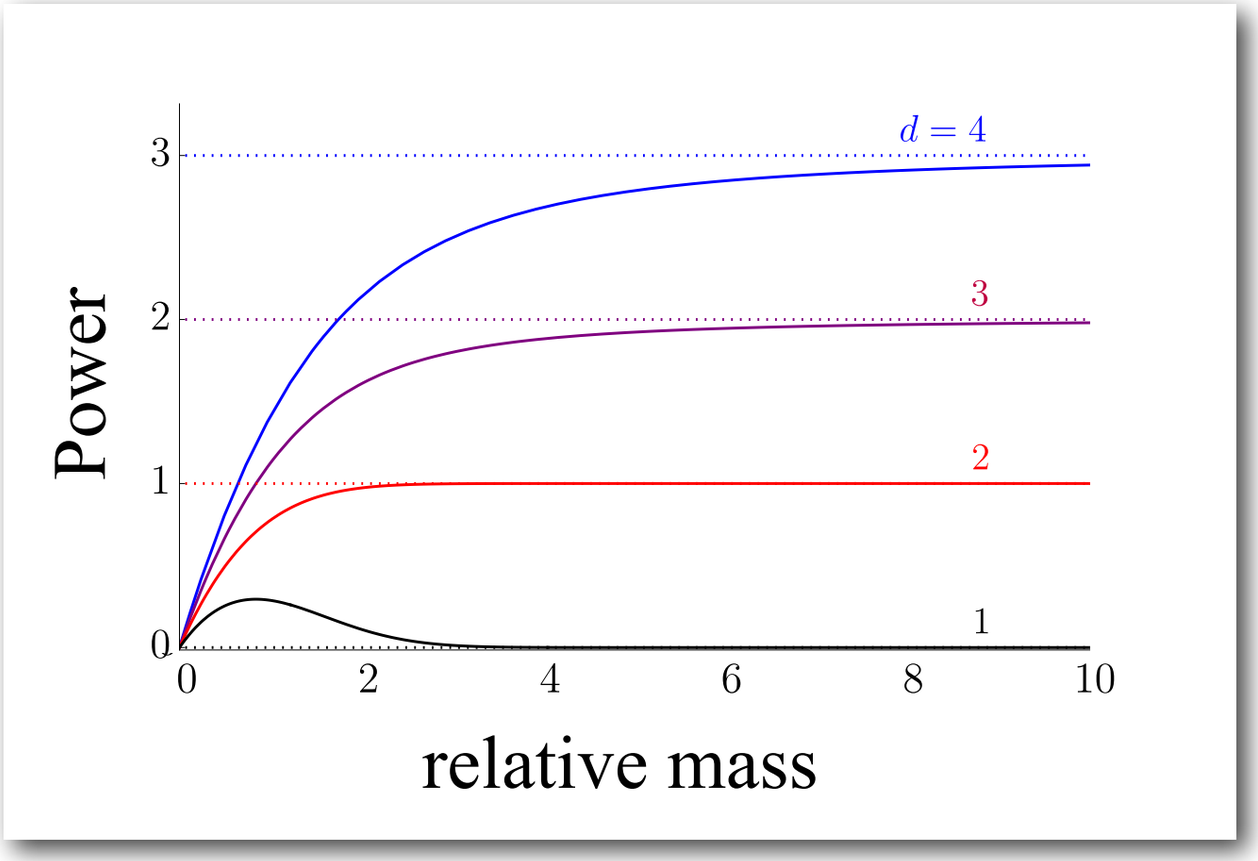


2d information engine



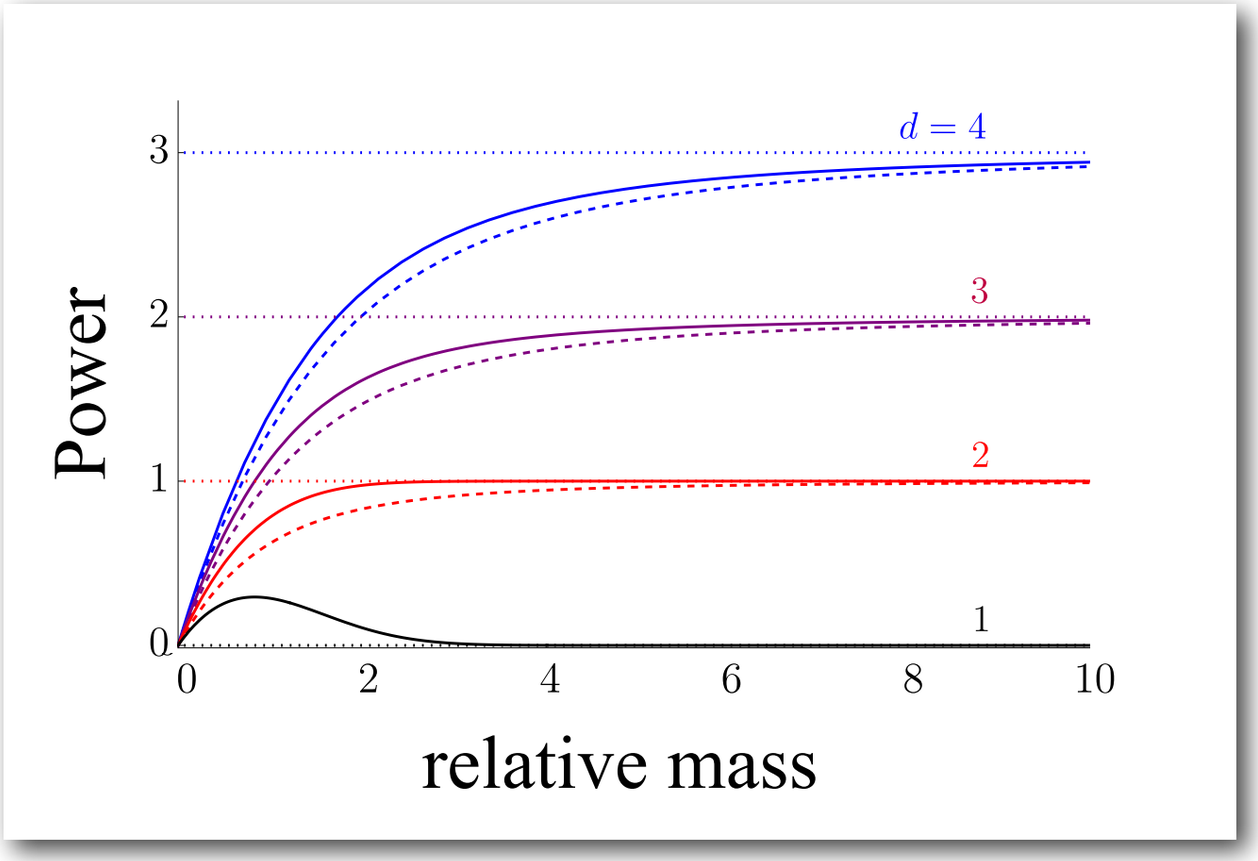
→ Adding a lateral dimension increases power

High-dimensional information engine



- Qualitative improvement:
  Lift any mass for $d > 1$!

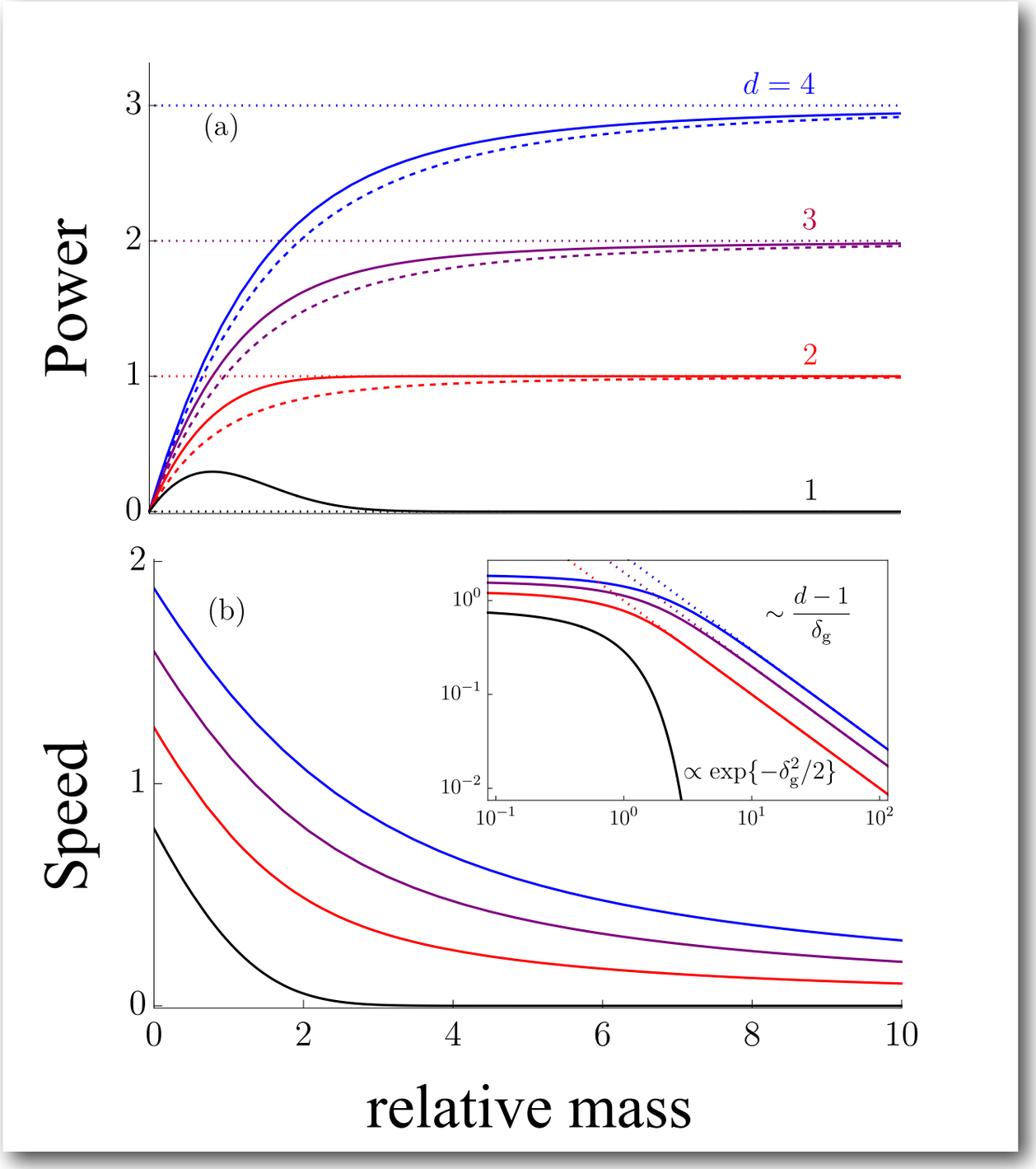
High-dimensional information engine



- Qualitative improvement:
  Lift any mass for $d > 1$!
- For $d > 1$ ~same without z!
  (set $\langle W \rangle = 0$ rather than $W = 0$;
  see dashed lines)

→ Measure only lateral dimension(s)

High-dimensional information engine



- Similar story for velocity
- In progress:
  - Increases efficiency 2x ?
  - experiments in progress….

Outline

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– experiments with feedback traps

– optimizing performance

– nonequilibrium environments

– 2d info engine: performance and efficiency with storage?

II. Random vs. deterministic protocols in a Szilard engine

– intro: info costs resolve the Maxwell-demon paradox (Szilard engine)

– Structural limitations: partially observable Szilard engine

– probabilistic information encoding (soft coarse graining)

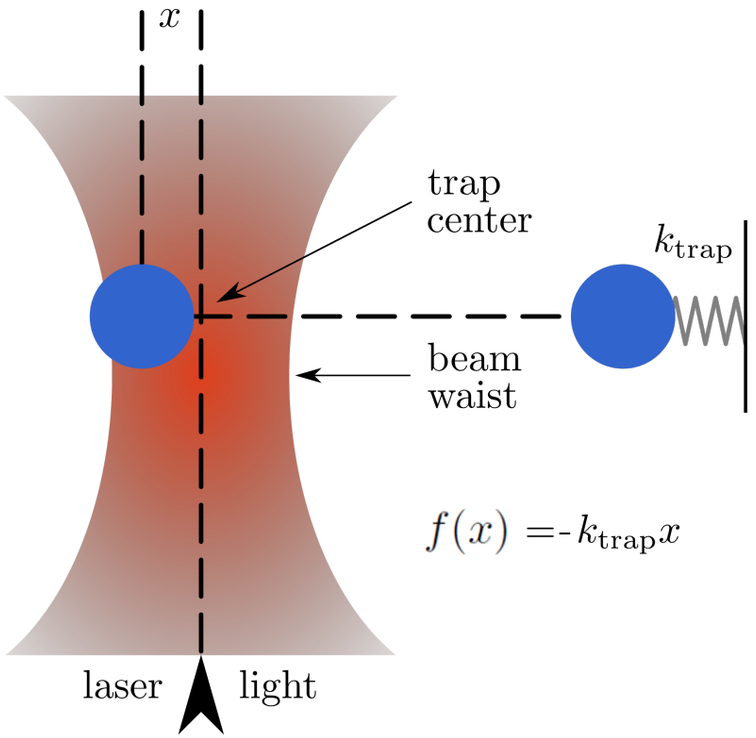
– random can be better! (P. Basak)

Feedback trap

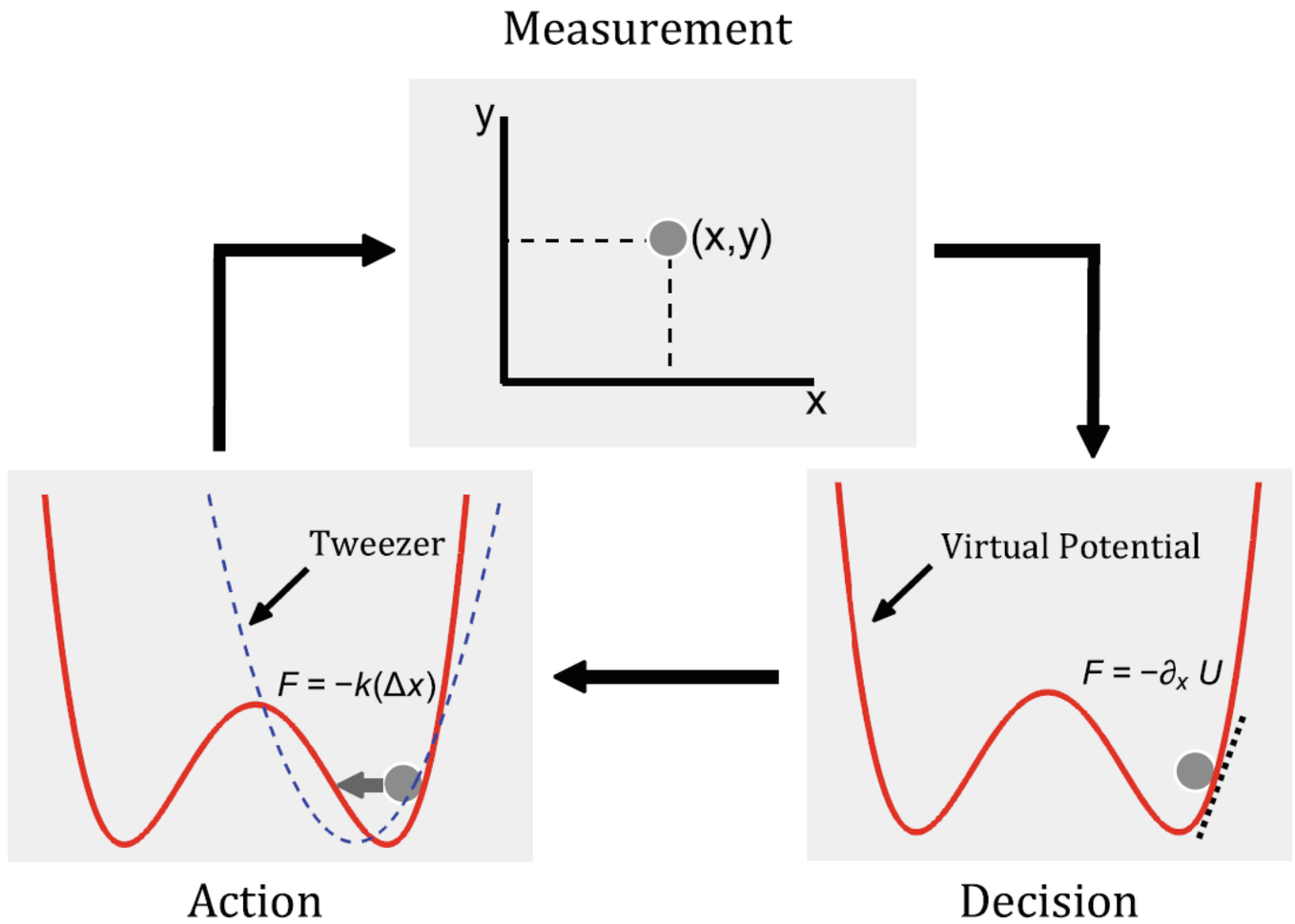
Avinash Kumar
and JB, *APL* 2018

JAC Albay, …, Yonggun Jun
Opt. Express 2018

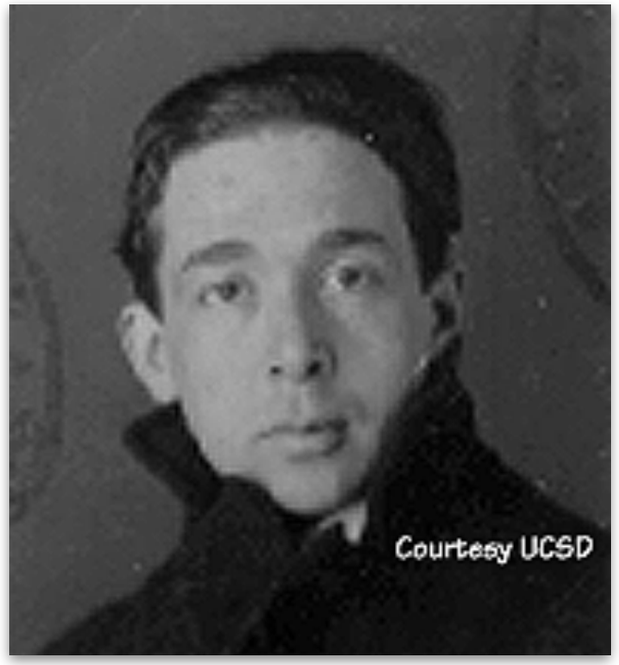
- ~ arbitrary potential shapes
- small length scales → fast dynamics



first version developed by
Yonggun Jun & Momcilo Gavrilov
2008–2014

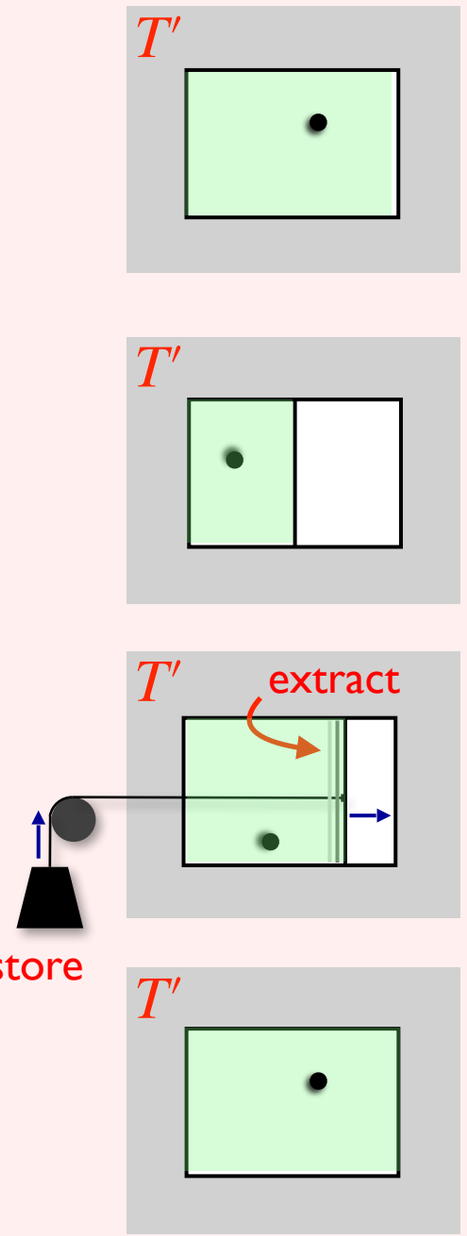


Szilard's info. engine, 1929



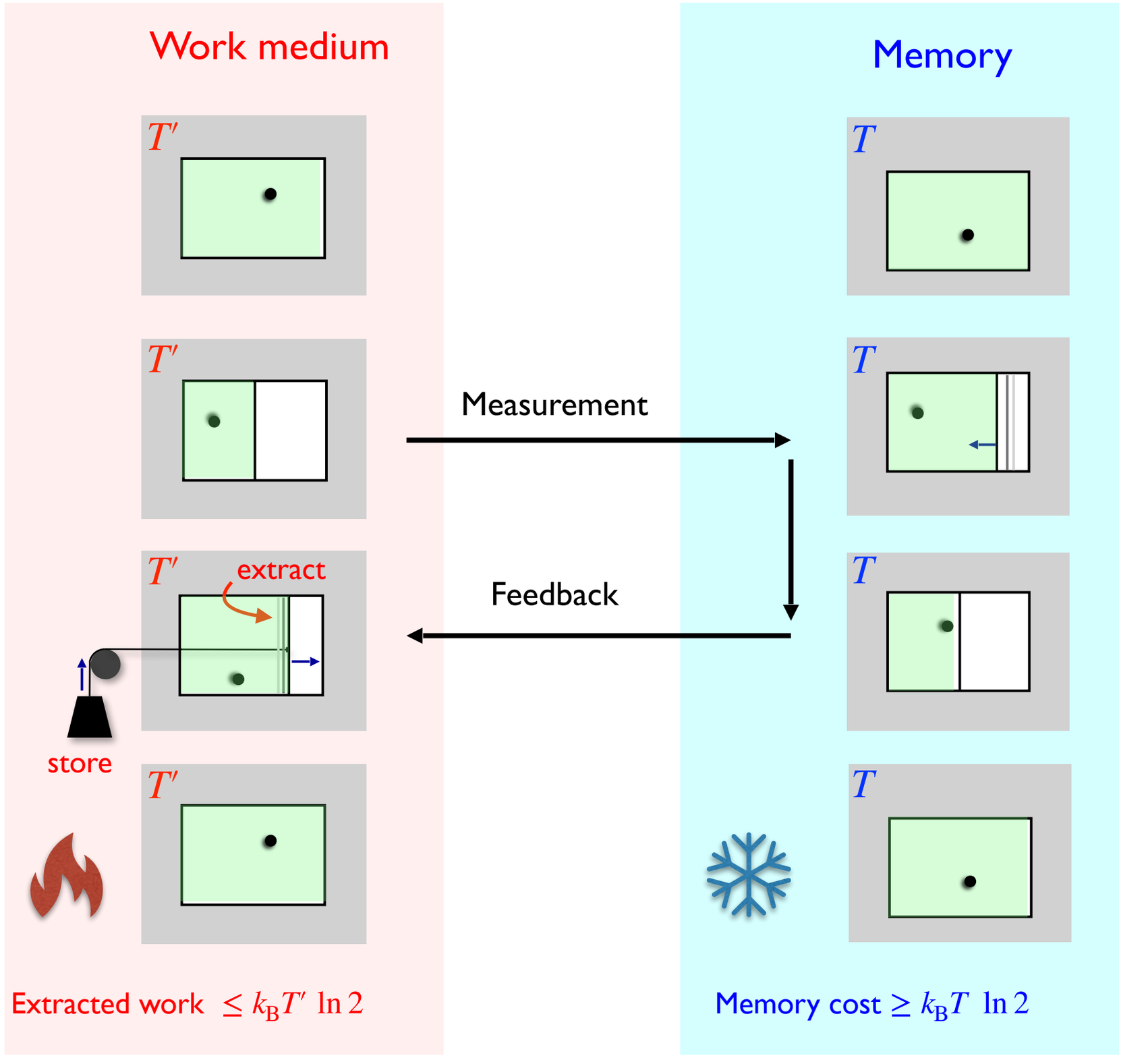
Leo Szilard in 1926

Work medium



Extracted work $\leq k_{\mathrm{B}} T' \ln 2$

Szilard's info. engine, + mem.





Leo Szilard in 1926

Information

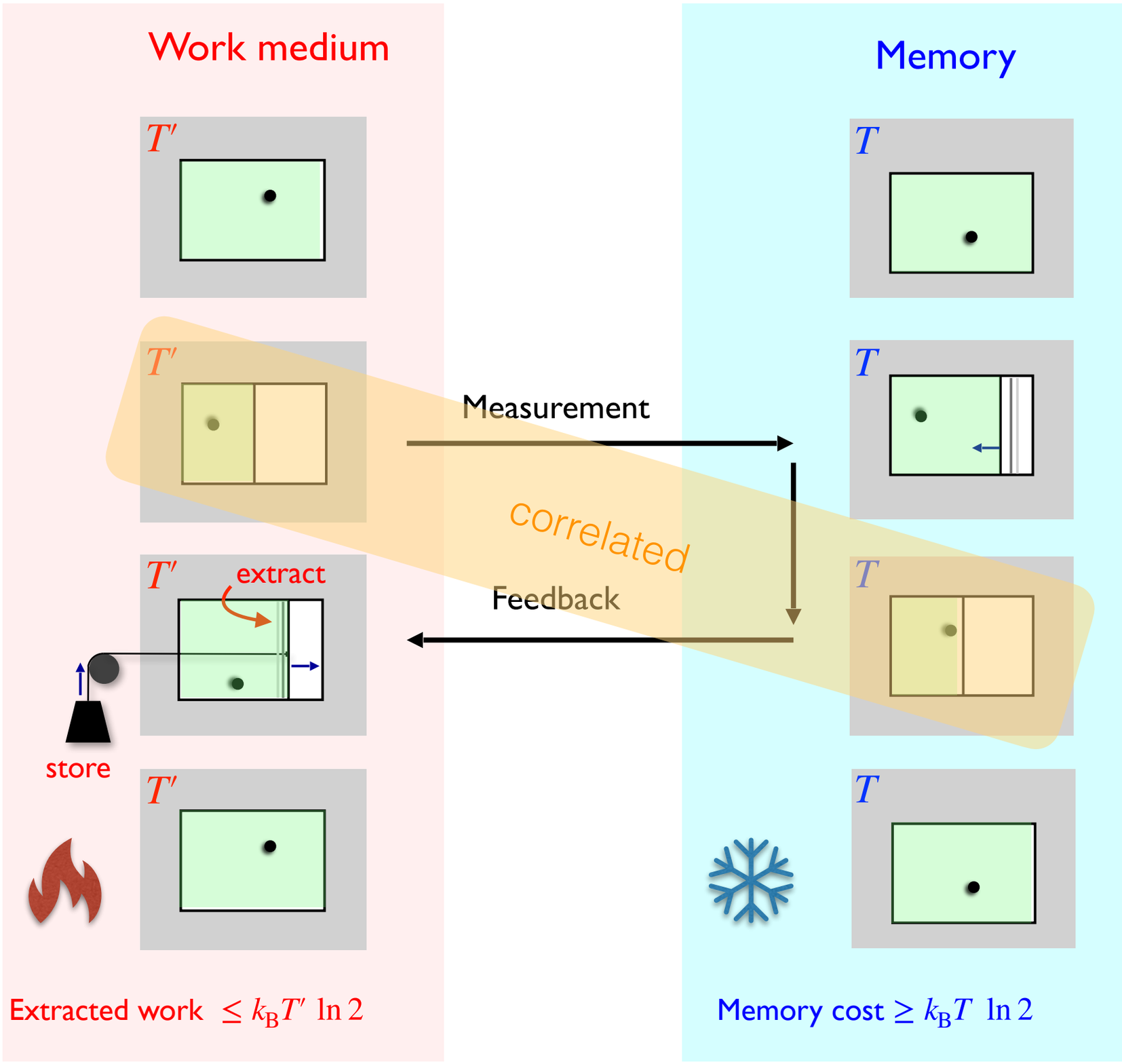
heat ⟶ work

$$W = -\int_{V/2}^{V} \mathrm{d}V\, P = -\,k_{\rm B}T'\,\ln 2$$

Can harvest energy if

$T' > T$

Szilard's info. engine, + mem.





Leo Szilard in 1926

Information

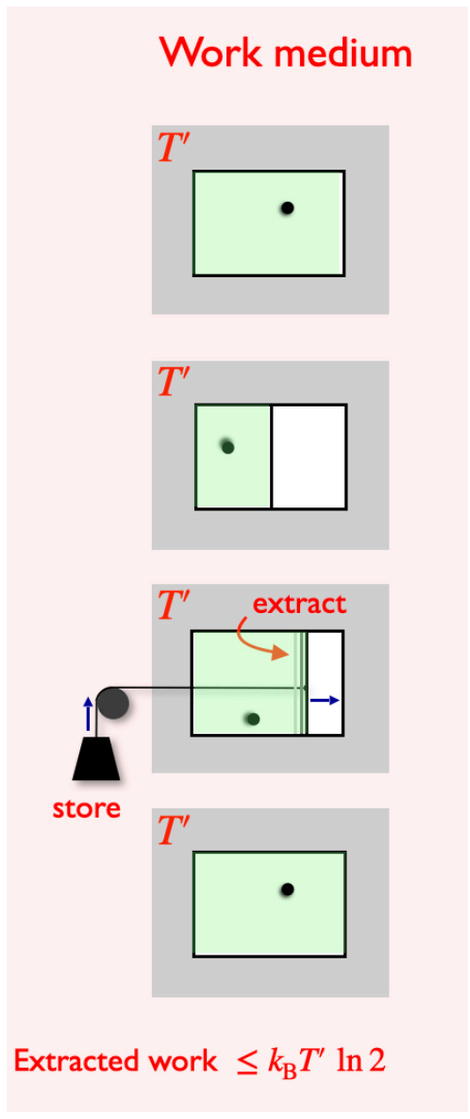
heat → work

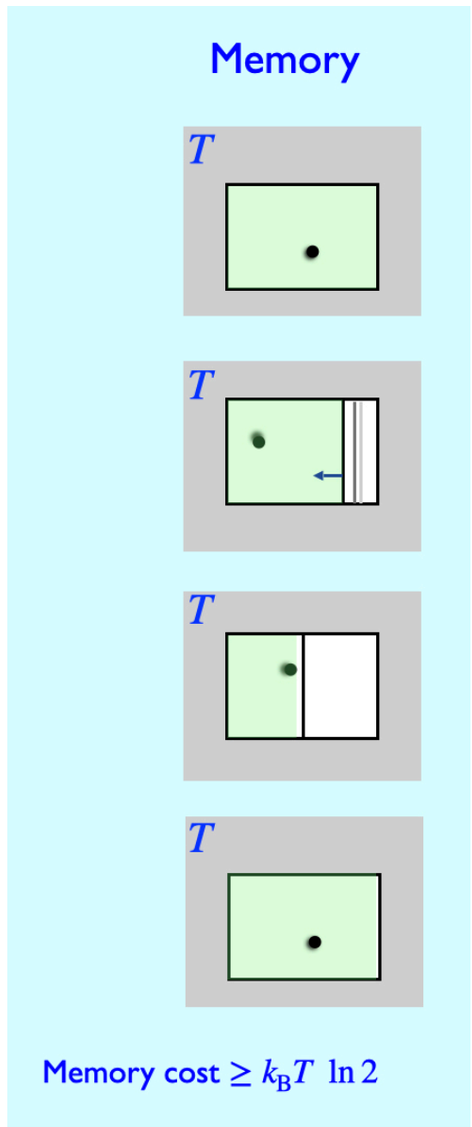
$$W = -\int_{V/2}^{V} \mathrm{d}V\, P = -k_B T' \ln 2$$

Can harvest energy if

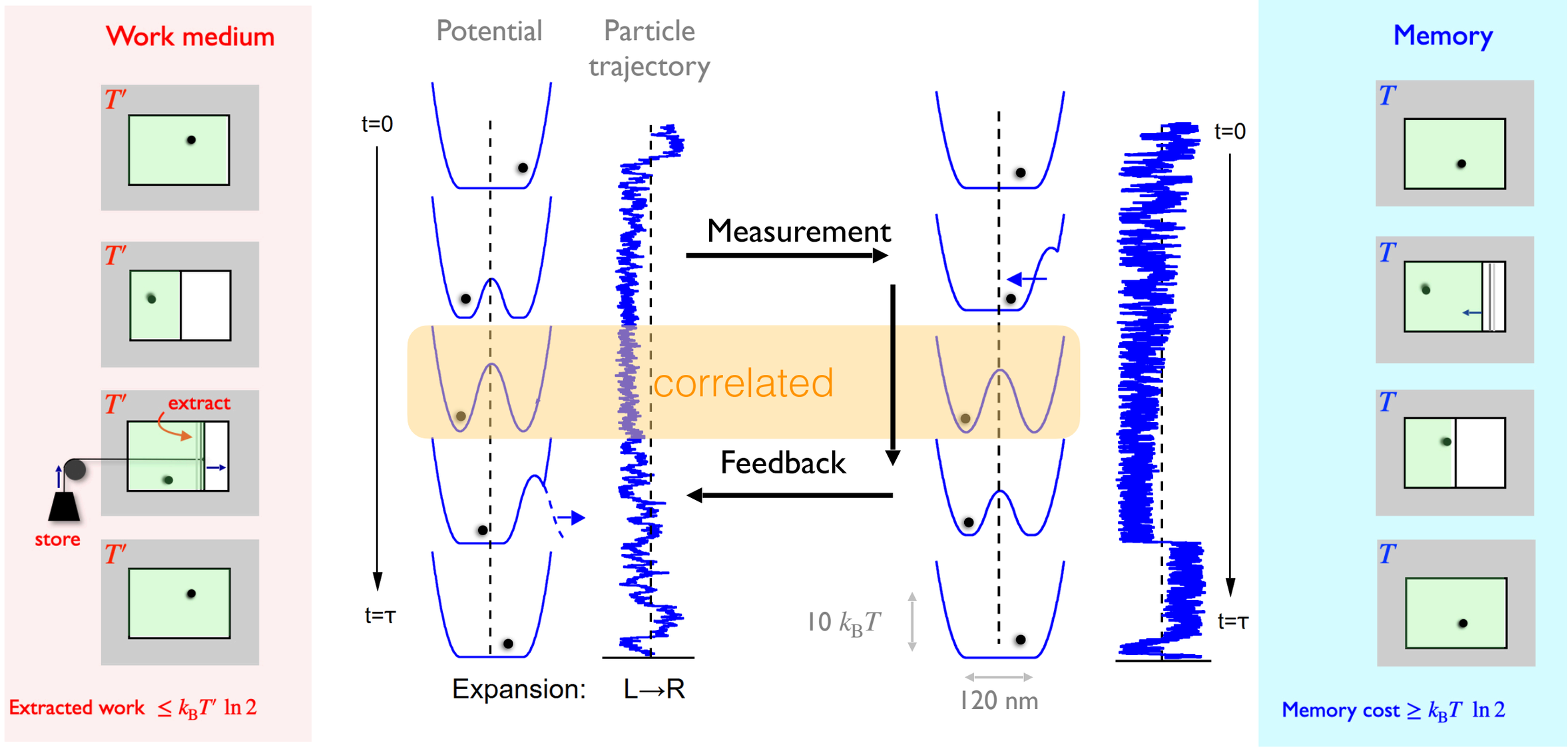
$T' > T$

Szilard's info. engine, experimental

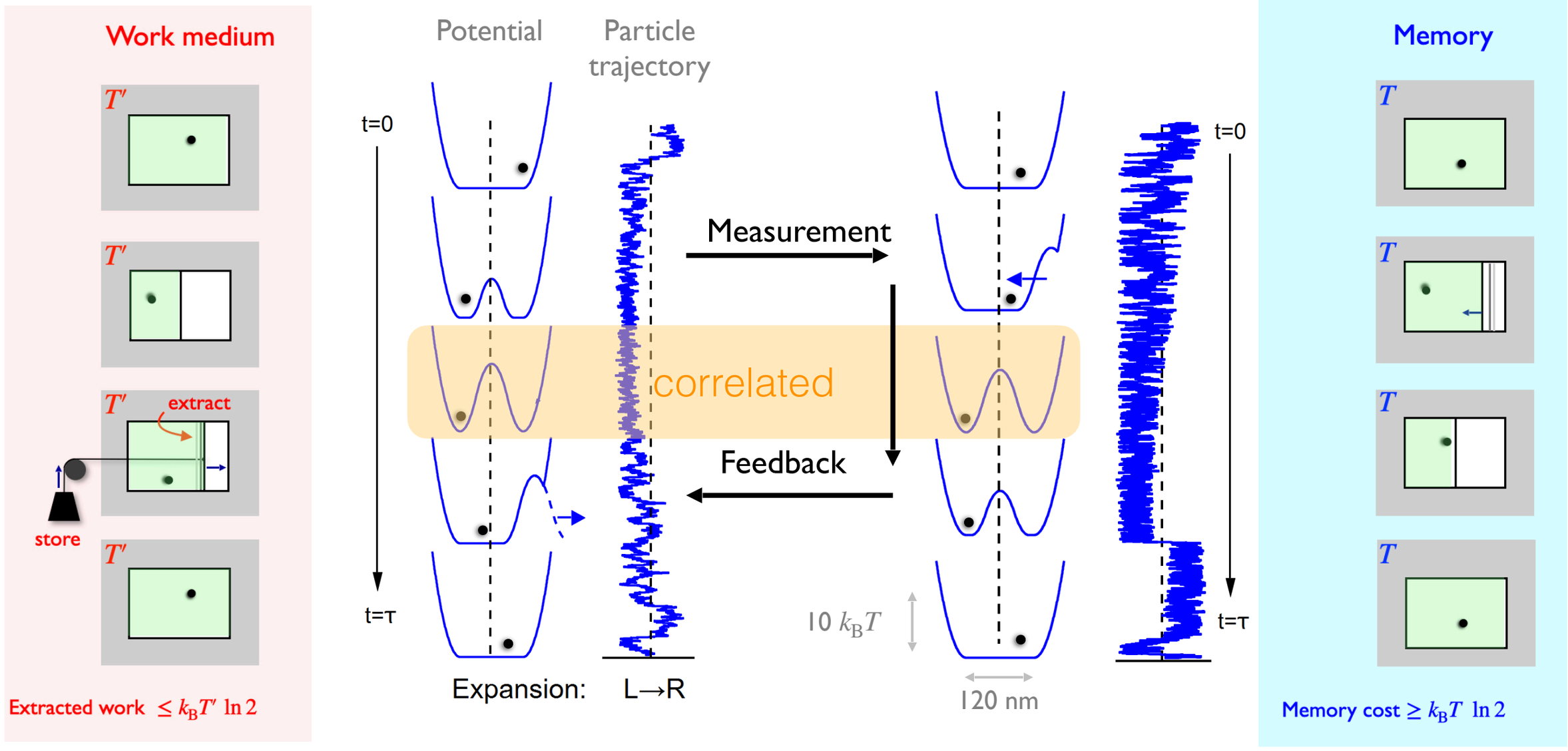




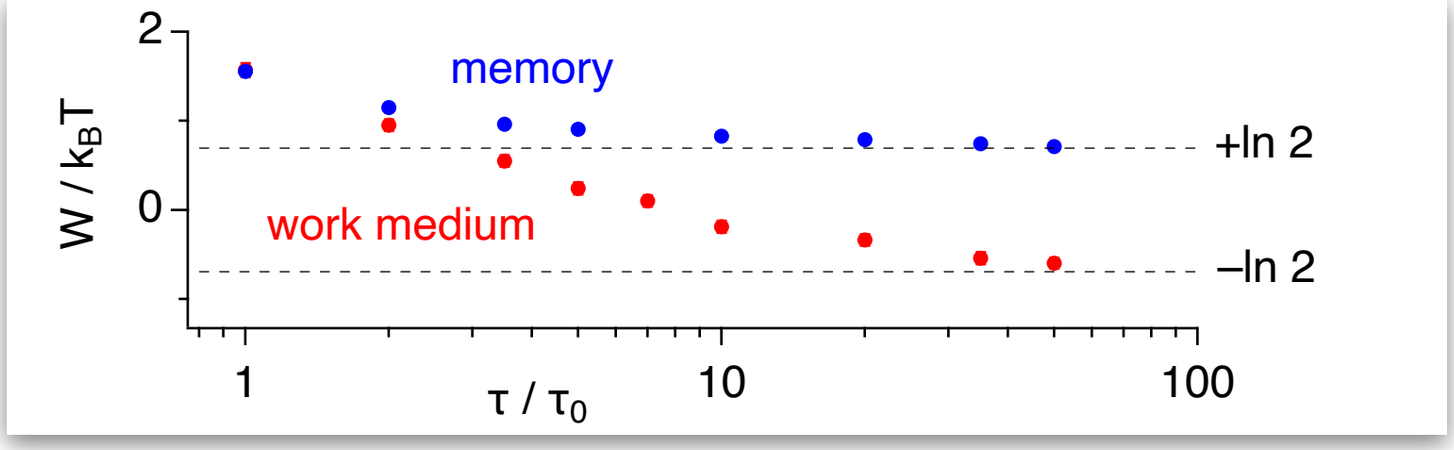
Szilard's info. engine, experimental



Szilard's info. engine, experimental



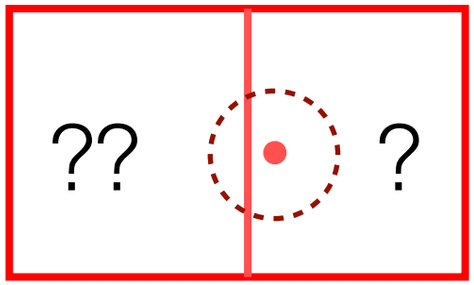
$$W = \left\langle \int_0^\tau \mathrm{d}t \left. \frac{\partial U(x,t)}{\partial t} \right|_{x(t)} \right\rangle$$



P. Basak and JB, unpublished

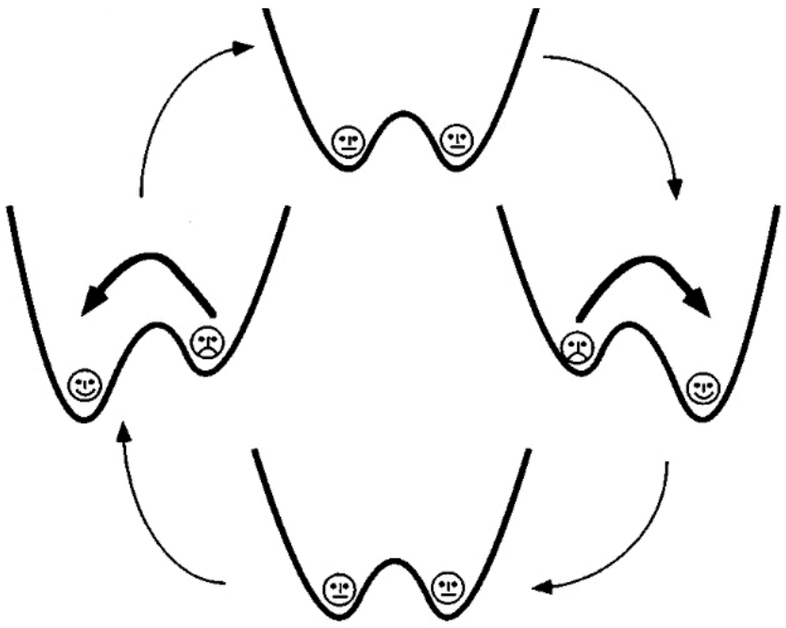
Real-world restrictions

Noisy observation



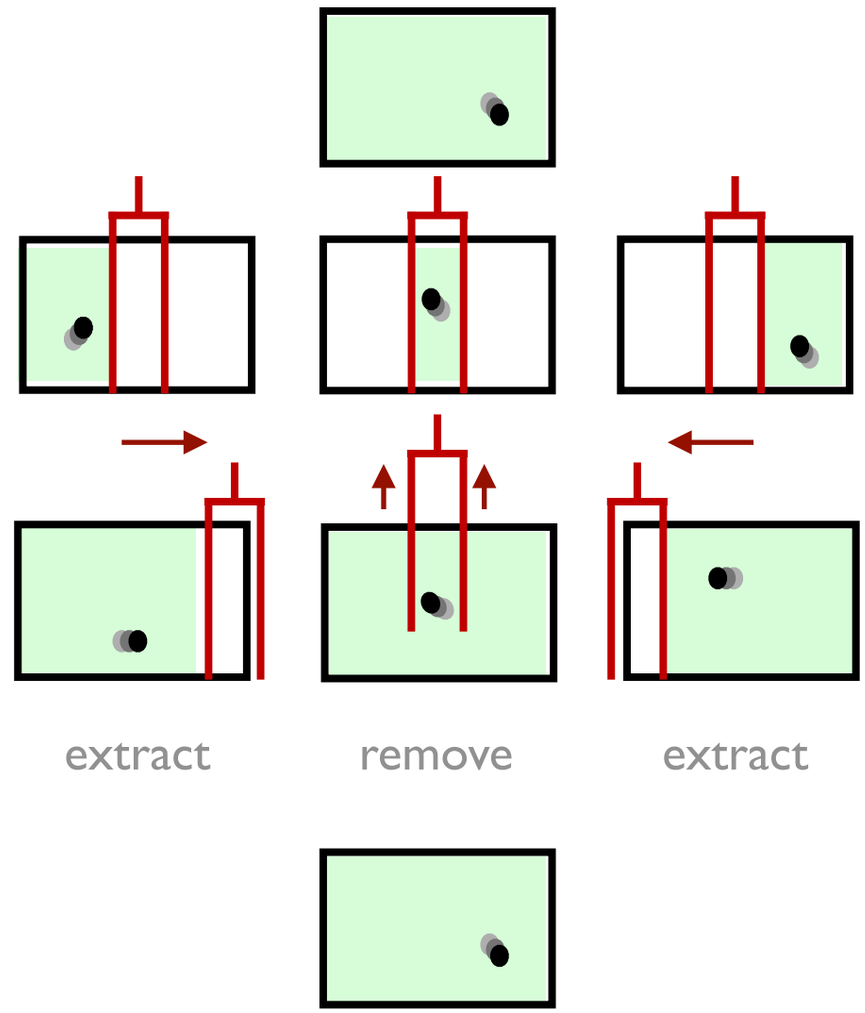
adding noise
<u>decreases</u>
work extracted

Saha, Lucero, Ehrich, Sivak, JB, *PRL* 2022

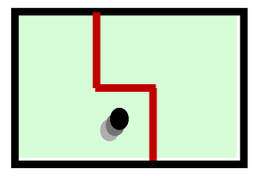


Stochastic Resonance: Benzi et al., *Tellus* 1982

Szilard engine with restricted region



- Structural limitations are generic
- tend to reduce work extracted
- other models: crooked barrier, …

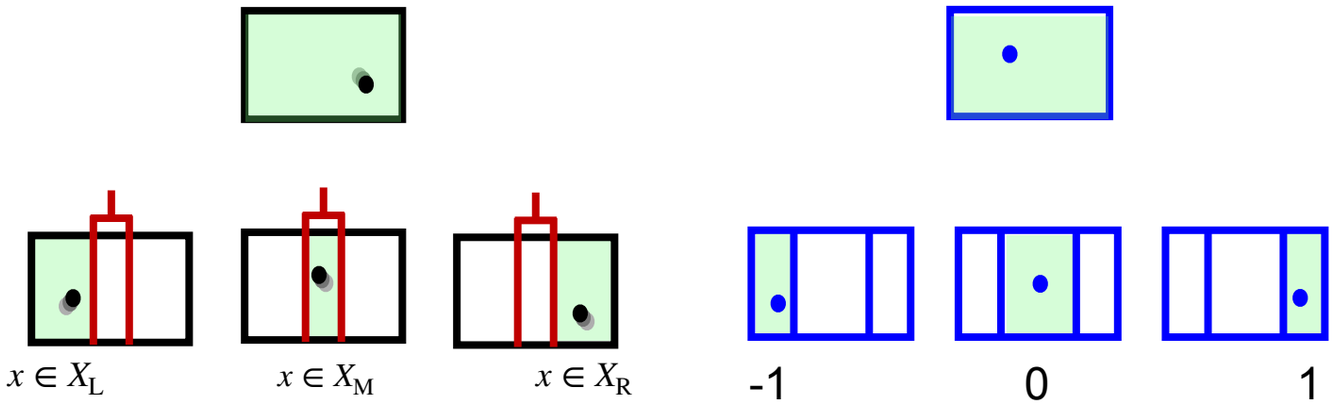


- Noisy encoding can <u>increase</u> work extracted!

D. Daimer and S. Still, *arXiv* 2023

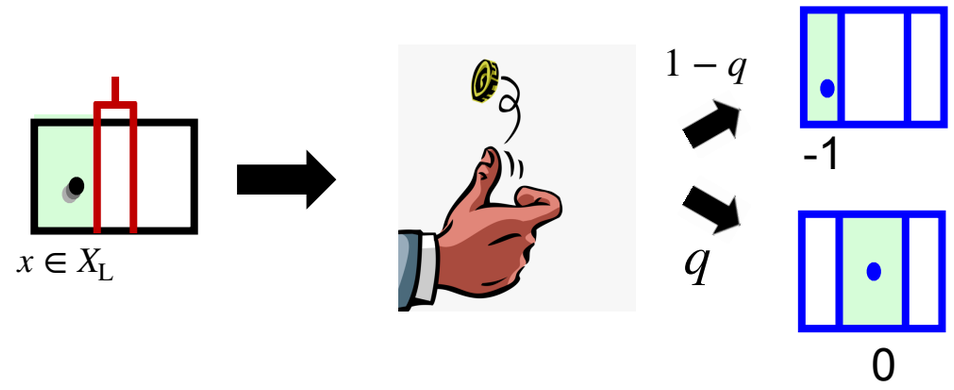
Deterministic vs. Probabilistic Encoding

Deterministic strategy



memory	$x \in X_L$	$x \in X_M$	$x \in X_R$
-1	1	0	0
0	0	1	0
$+1$	0	0	1

Probabilistic strategy



usual extraction

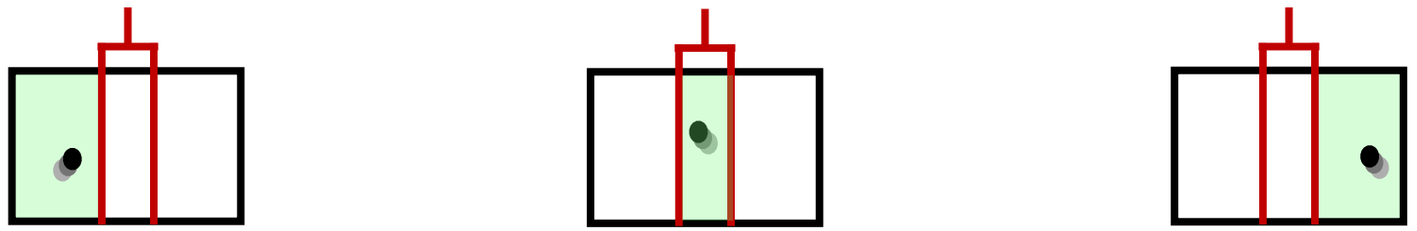
sometimes do nothing

memory	$x \in X_L$	$x \in X_M$	$x \in X_R$
-1	1-q	0	0
0	q	1	q
$+1$	0	0	1-q

$0 \le q \le 1$

(q depends on width of ambiguous region, relative temperature, ….)

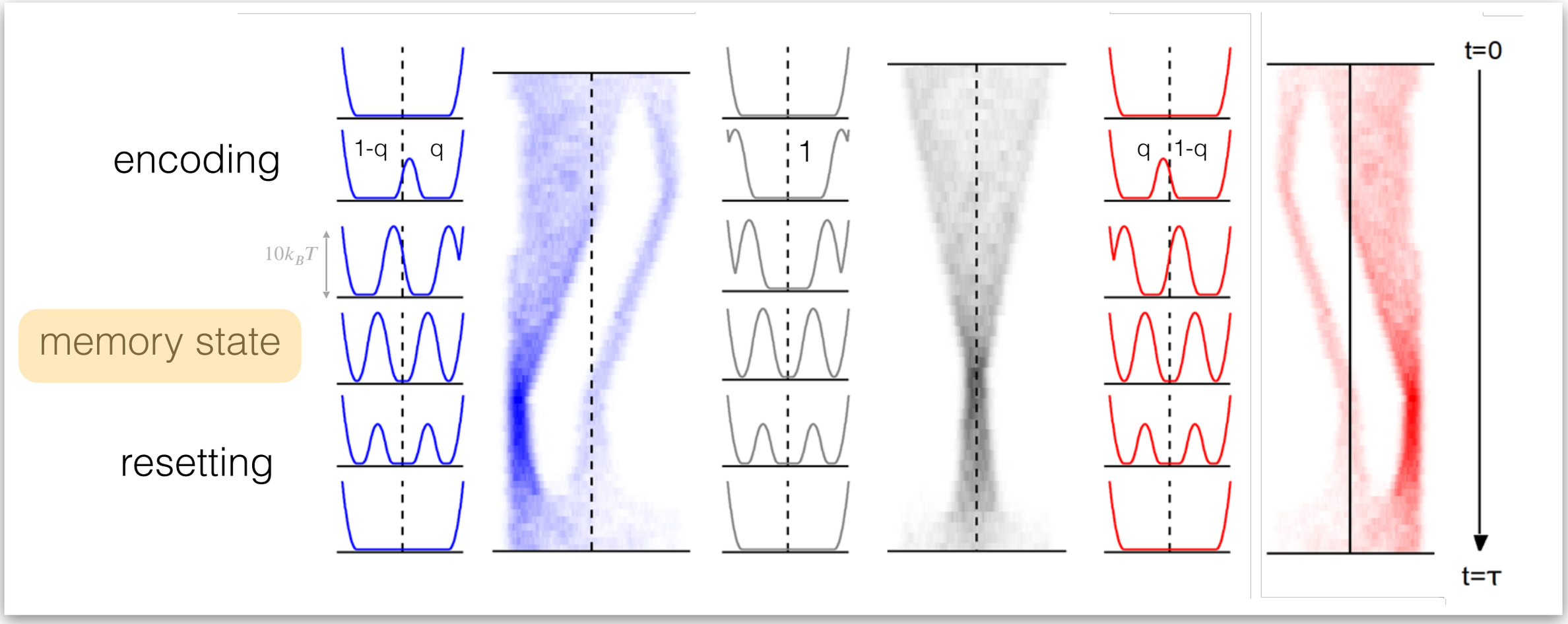
Making a Probabilistic Memory

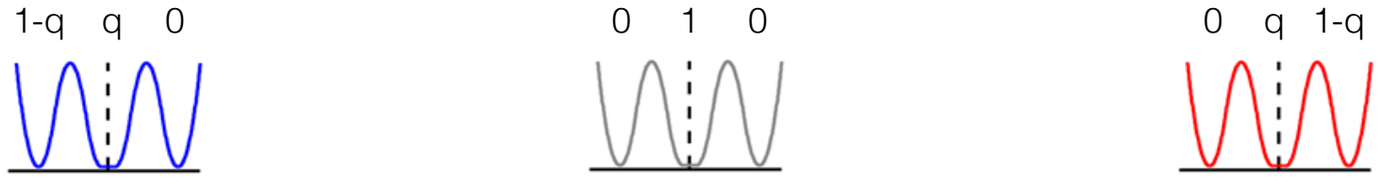


encoding

memory state

resetting





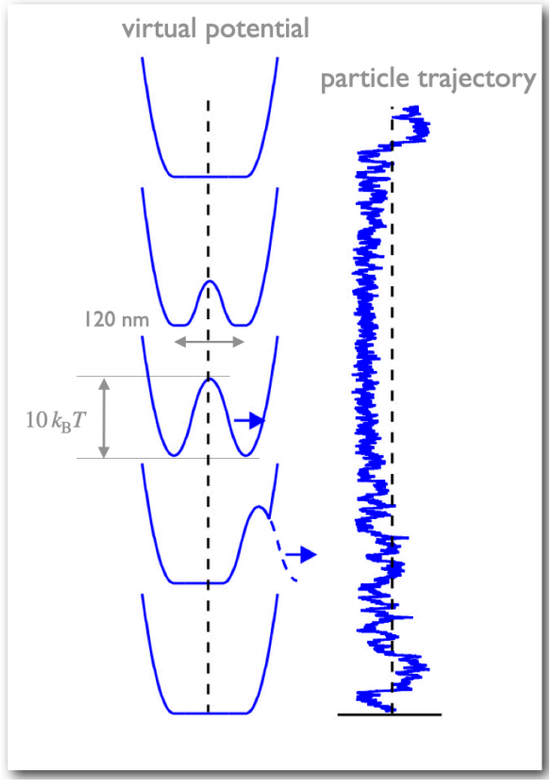
memory state

same potential, 3 different well probabilities (coarse-grained states)

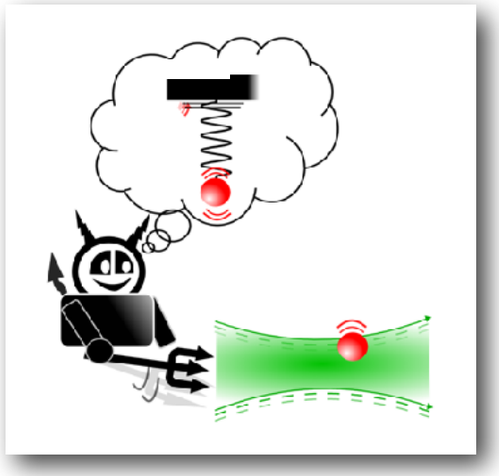
Conclusions

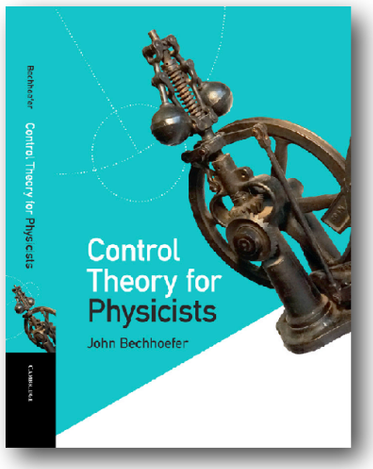
From Maxwell demons to real experiments

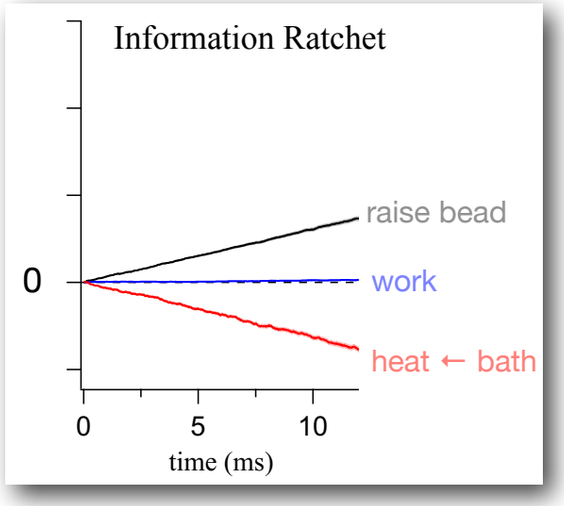
Szilard → information engines → nonequilibrium environment



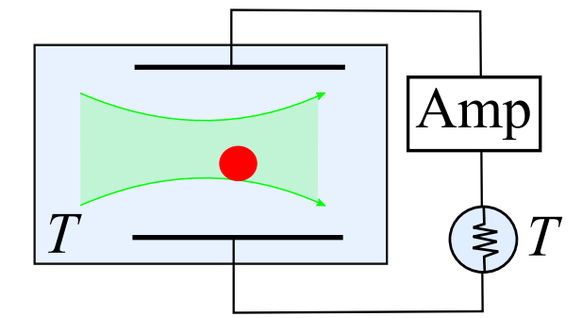
Basak, Daimer, Still, JB, unpublished

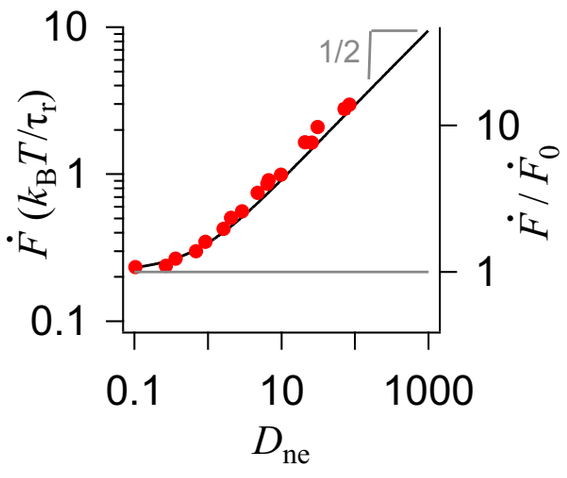






du Buisson et al. *Adv Phys X* 2024

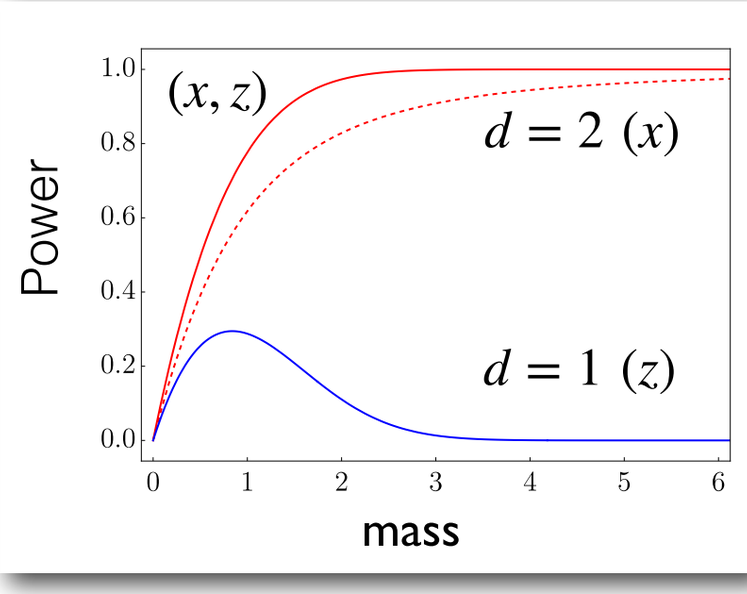




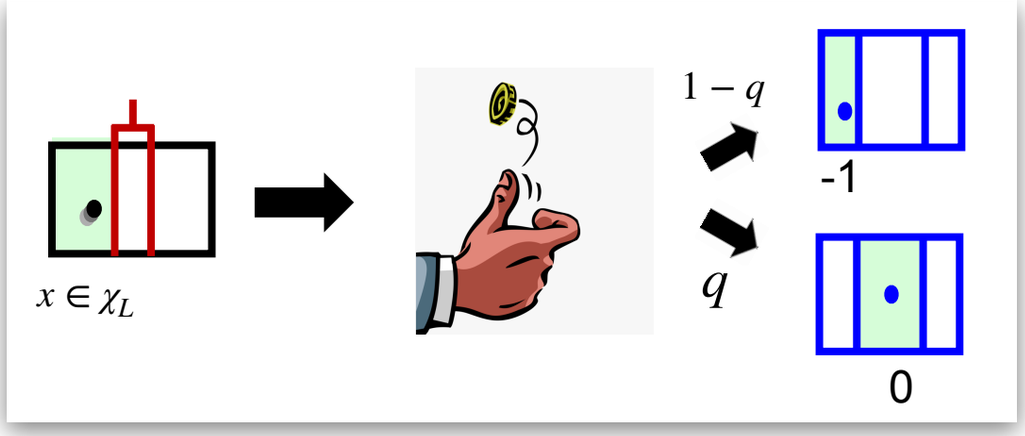
more power in noneq bath
biophysical implications?

Saha, Ehrich, Gavrilov, Still, Sivak, and JB, *PRL* 2023

separate harvest & storage – doubles efficiency?



Patrón Castro, JB, Sivak, *PRL* 2026



probabilistic encoding

du Buisson, Ehrich, Leighton, Kundu, Saha, JB, DAS arXiv 2025