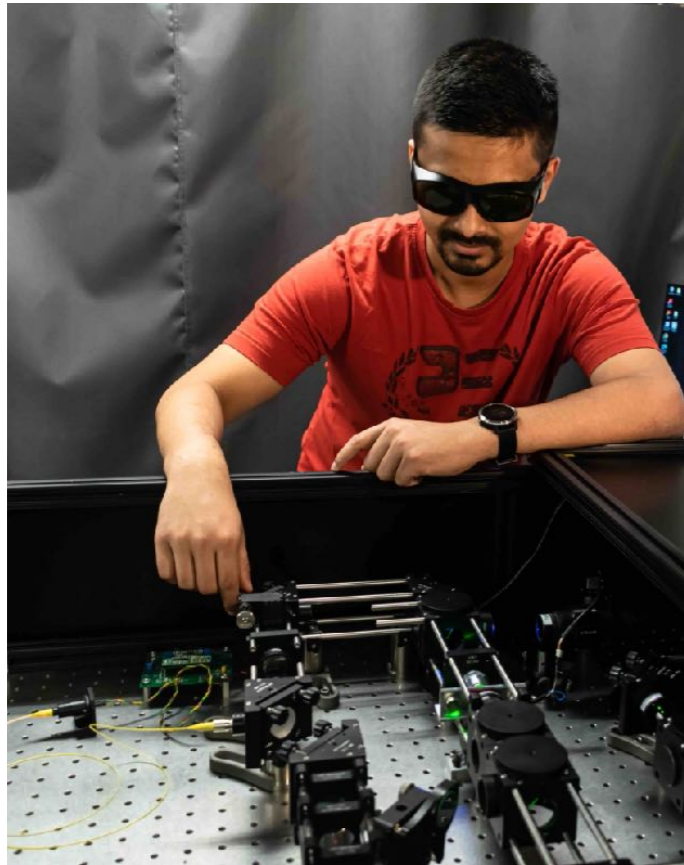


# What can Maxwell's demon do?

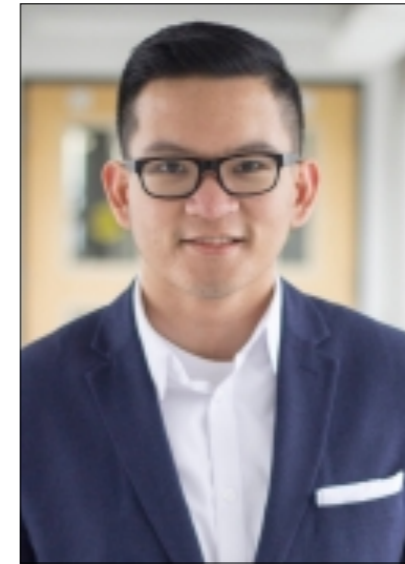
John Bechhoefer  
Simon Fraser Univ.



Tushar Saha



Jannik Ehrich



Joseph Lucero



David Sivak

British Columbia



Canada



4th Workshop on Statistical Physics  
Univ. Nacional de Colombia, Bogotá, October 6, 2023



# Outline

## I. A “modern” Maxwell demon

## II. Performance limits

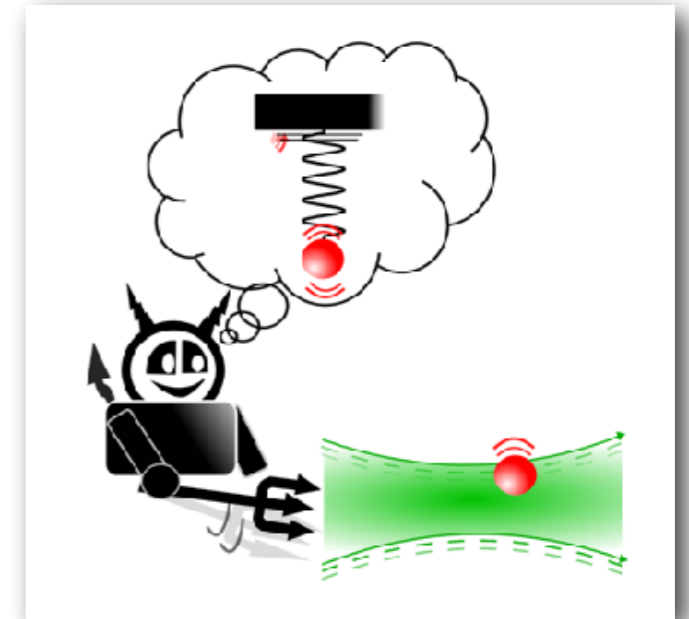
- power extracted
- speed of directed motion

## II. Measurement noise

- an unexpected phase transition, a sophisticated “cure”

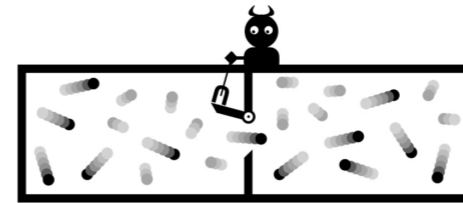
## III. Nonequilibrium environment

- more power & speed!
- applications?

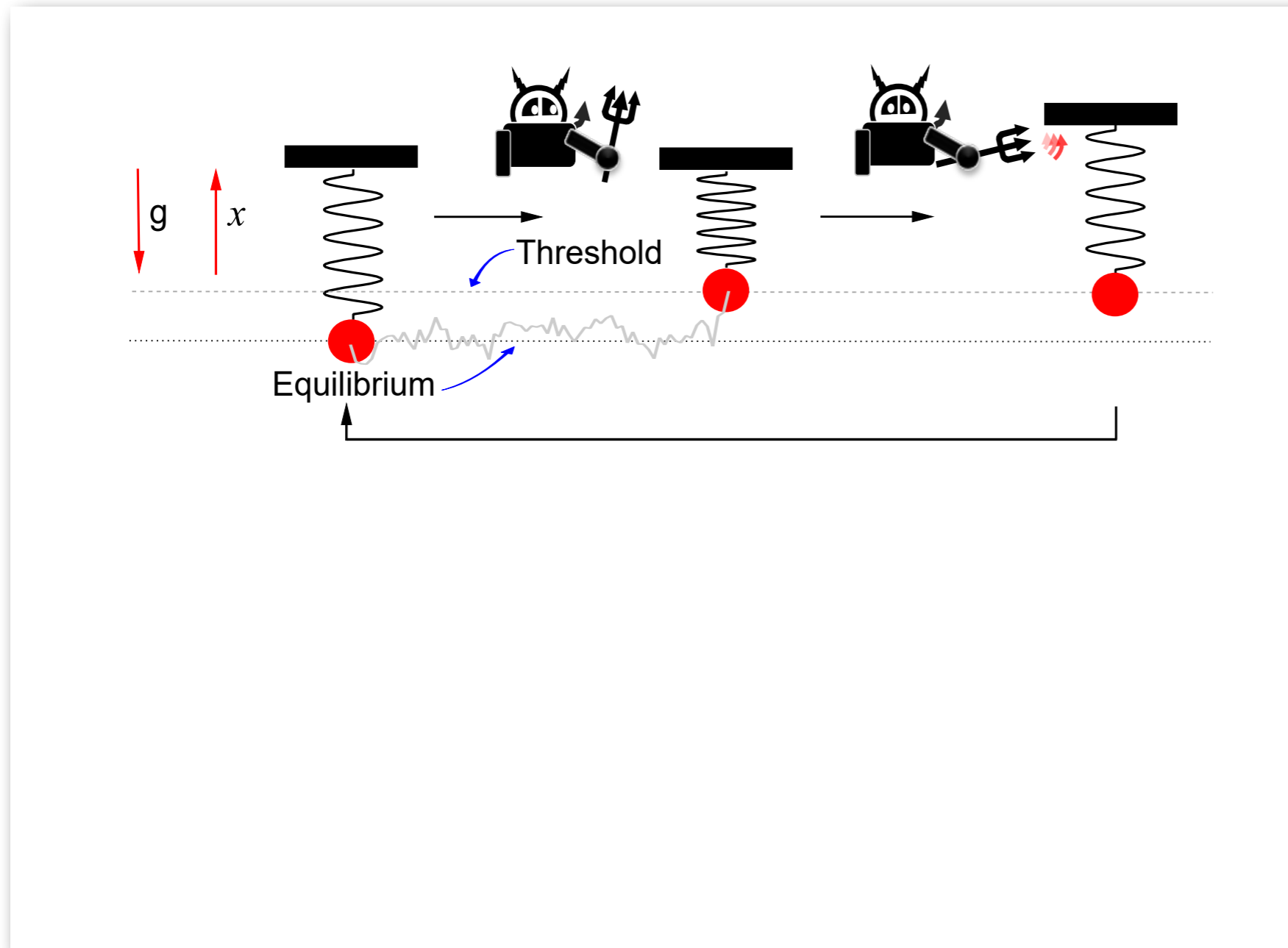


# Information ratchet

A modern Maxwell demon



Basic concept



Fluctuating particle, in bath

Wait for an “up” fluctuation

Raise platform w/o work

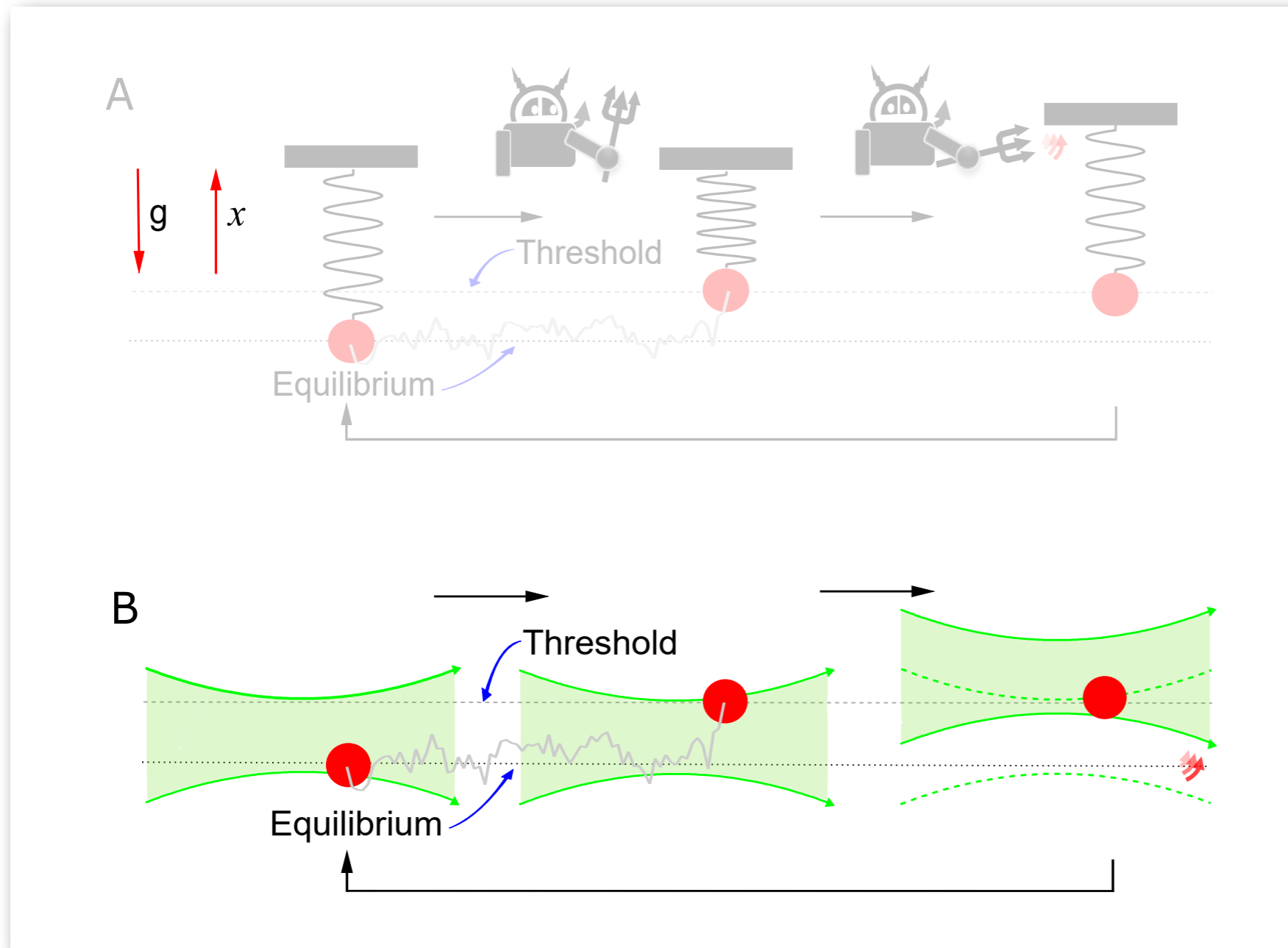
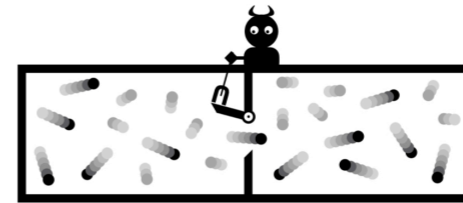
Repeat cycle

Energy stored in  
gravitational potential

# Information ratchet

Basic concept

A modern Maxwell demon



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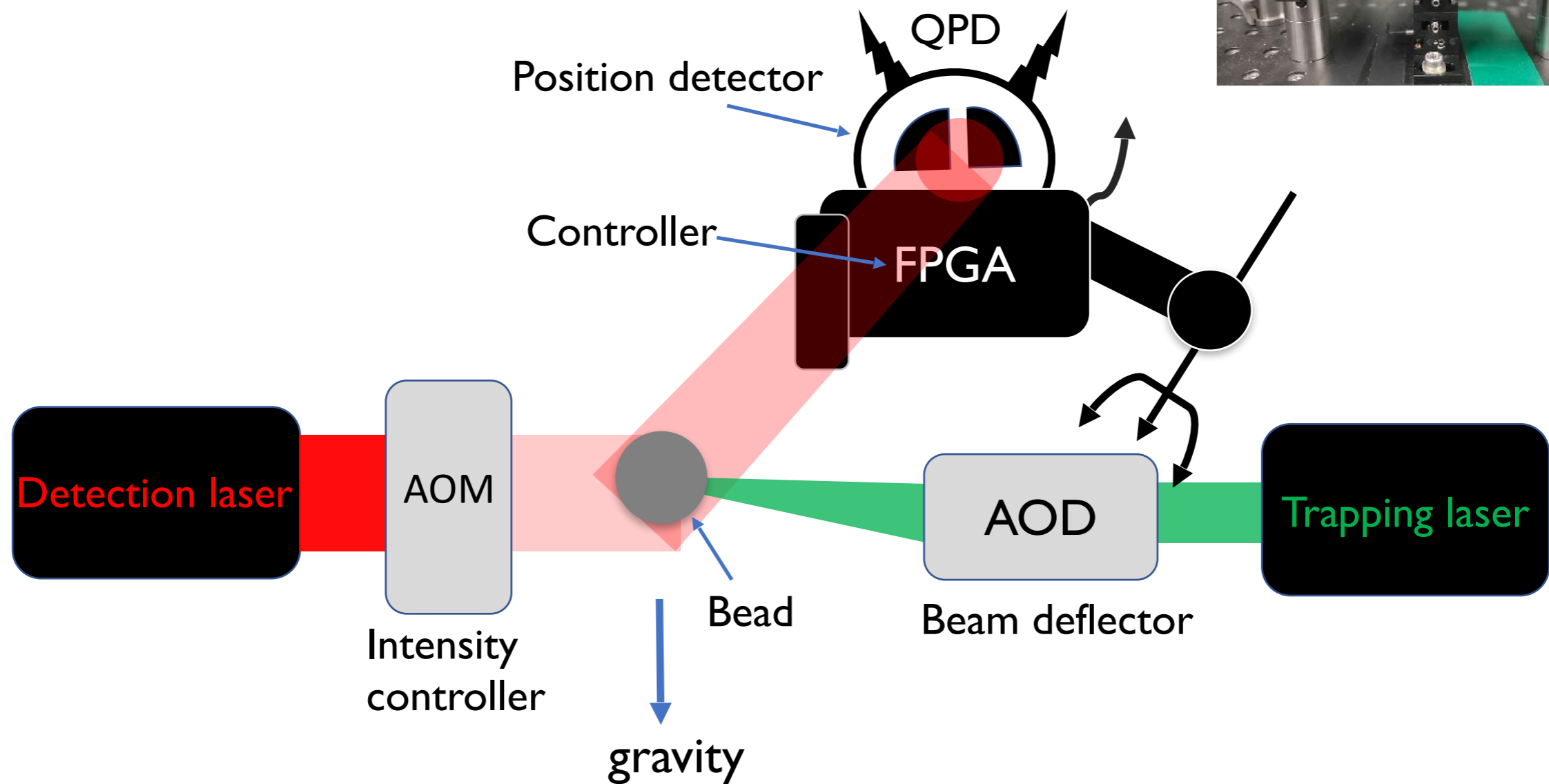
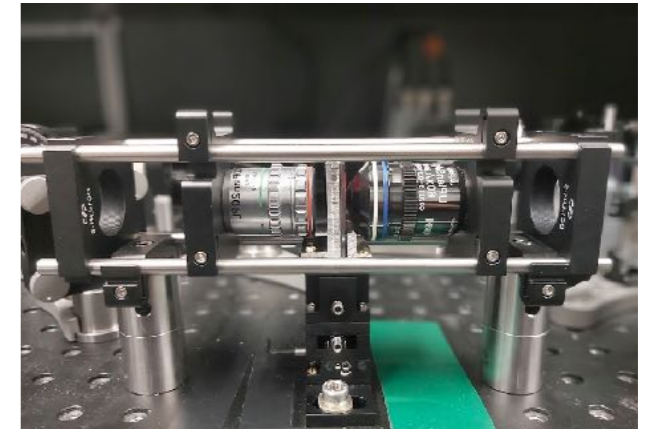
Energy stored in  
gravitational potential

Experimental realization  
using optical tweezers

# Optical tweezers & feedback

## Experimental set up

- loop rate = 50 kHz
- trap dyn.  $\sim$  0.1–5 kHz



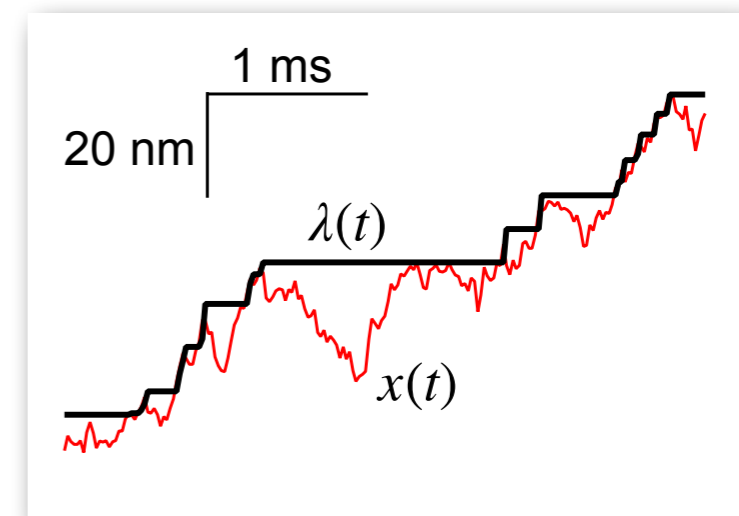
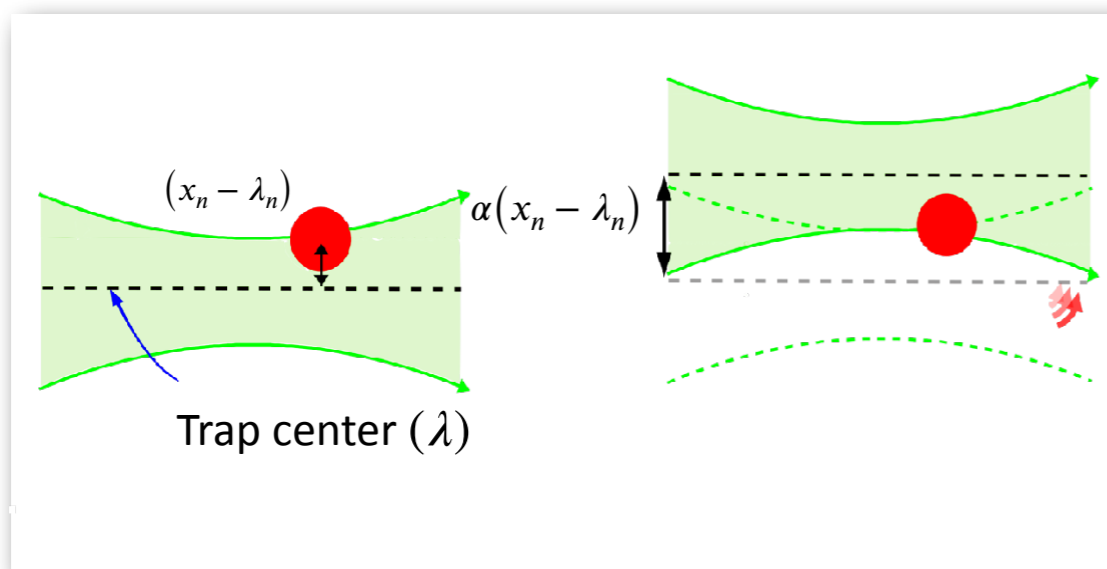
# Information ratchet

## Feedback algorithm

Ratchet on **up** fluctuation that exceeds threshold  $X_T$

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

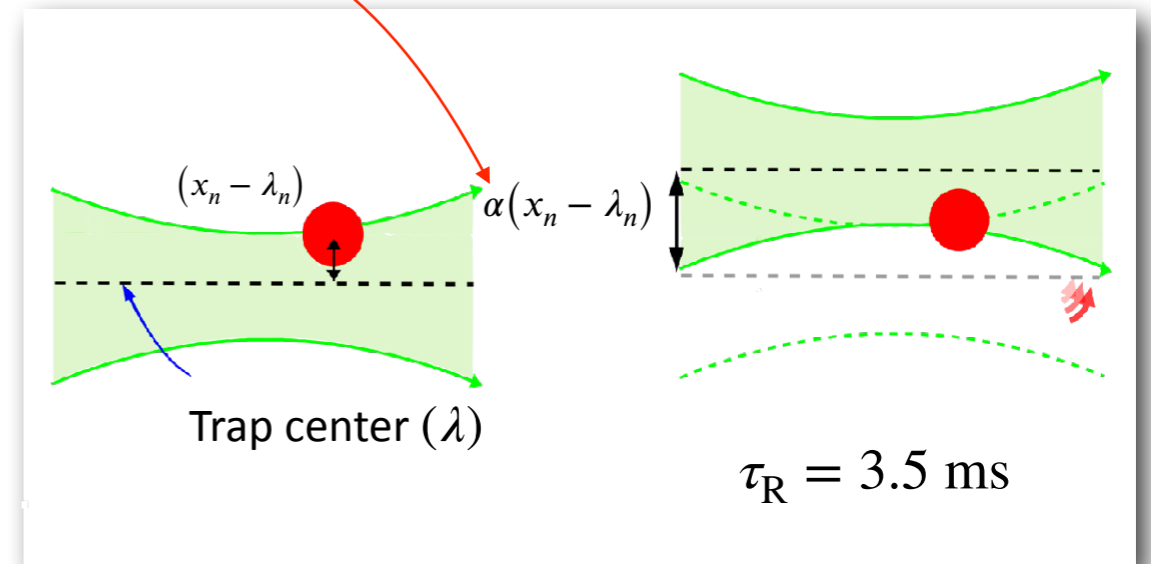
trap position      bead position      threshold



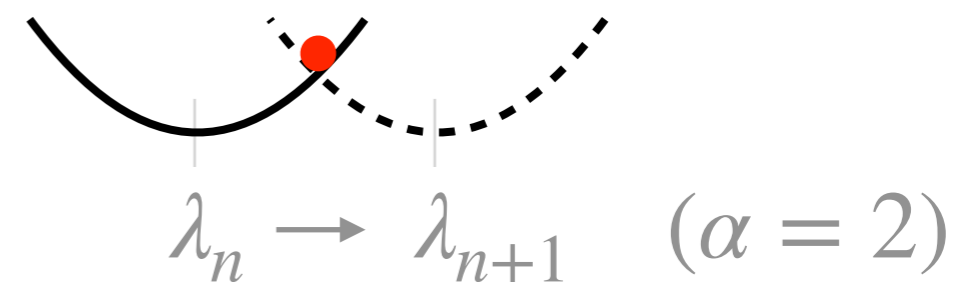
# Information ratchet

Pure information engine

Adjust feedback gain  $\alpha$  so that no work is done by ratcheting



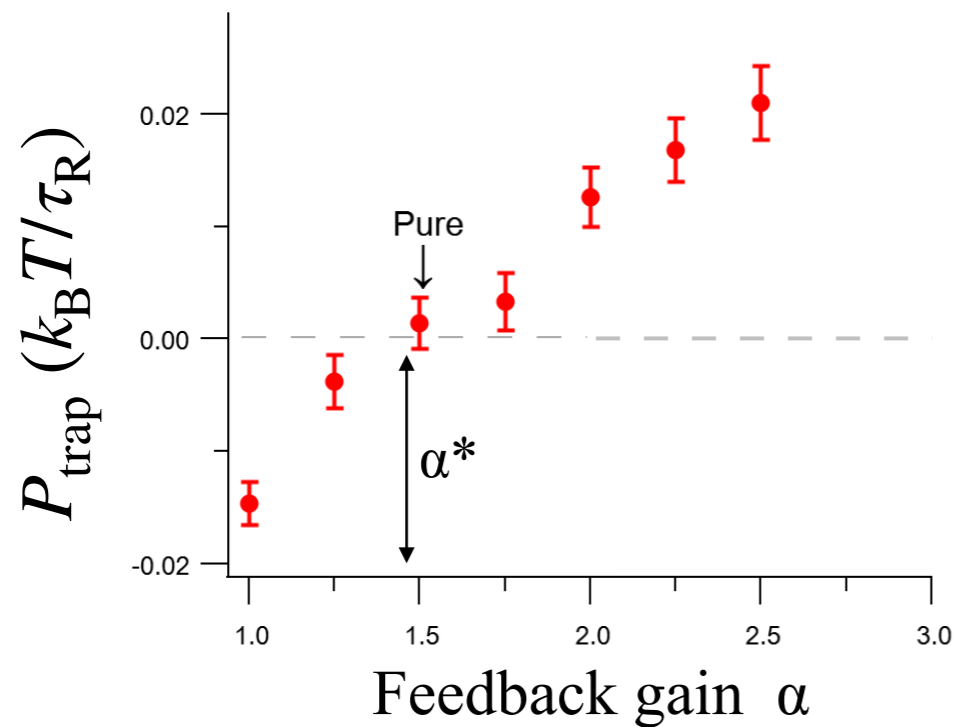
naive picture



# Information ratchet

# Pure information engine

Adjust feedback gain  $\alpha$  so that no work is done by ratcheting

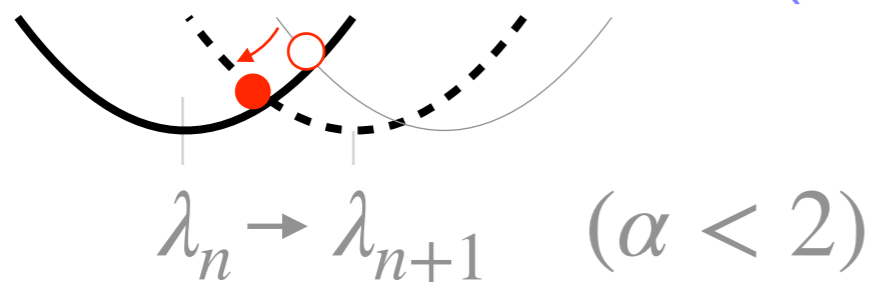


$$W_{n+1}^{\text{trap}} = \frac{\kappa}{2} \left[ (x_{n+1} - \lambda_{n+1})^2 - (x_{n+1} - \lambda_n)^2 \right]$$

work done on particle by the changing trap center

naive picture

- + delay
- + (bias)



naive picture





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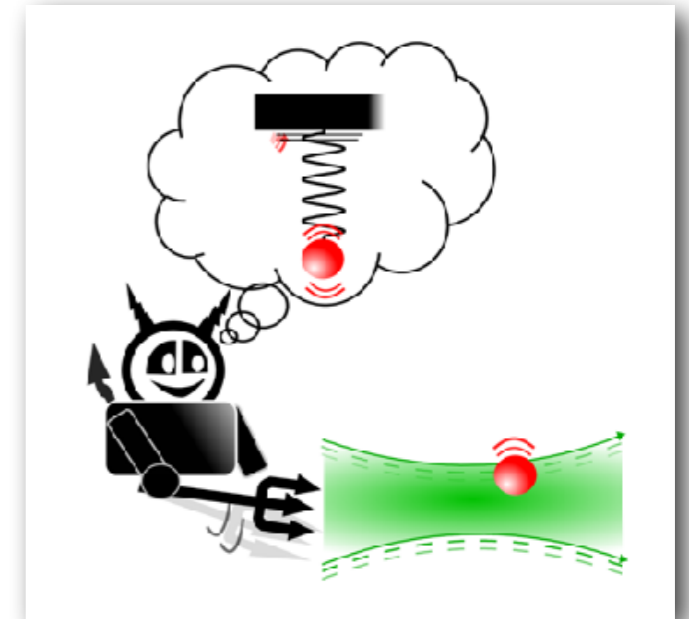
- power extracted
- speed of directed motion

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- an unexpected phase transition, a sophisticated “cure”

## III. Nonequilibrium environment

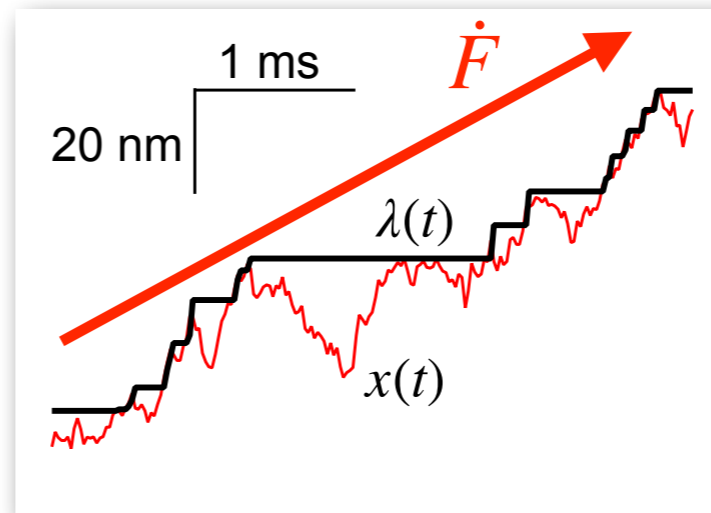
- more power & speed!
- applications?



# Information ratchet

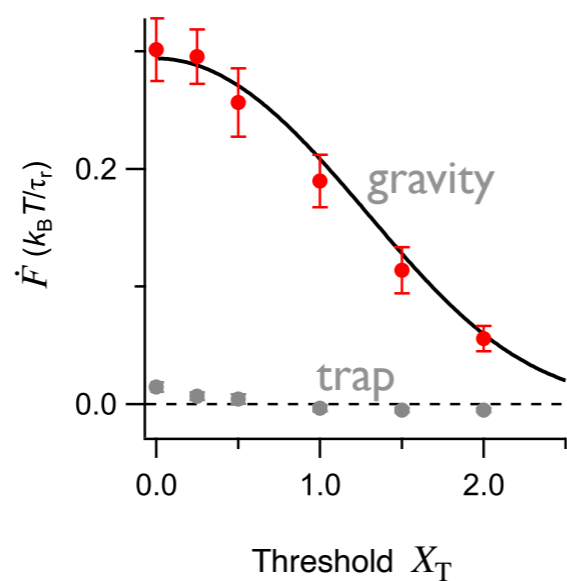
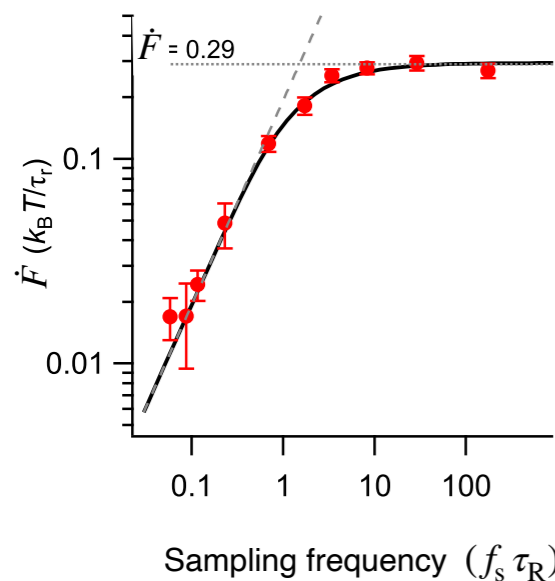
# Parameter optimization

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

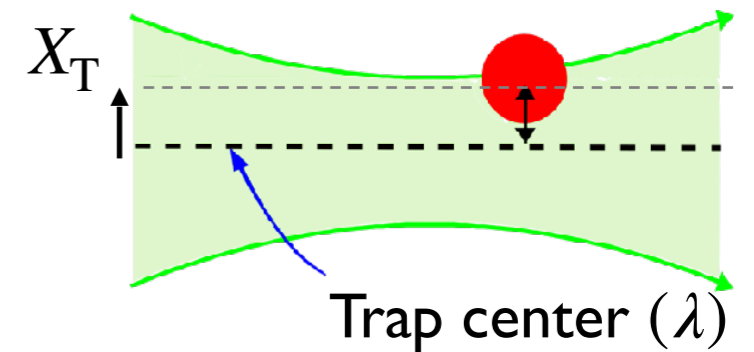


Max. sampling frequency

$X_T \rightarrow 0$



“Catch all up fluctuations”  
(continuous ratcheting)



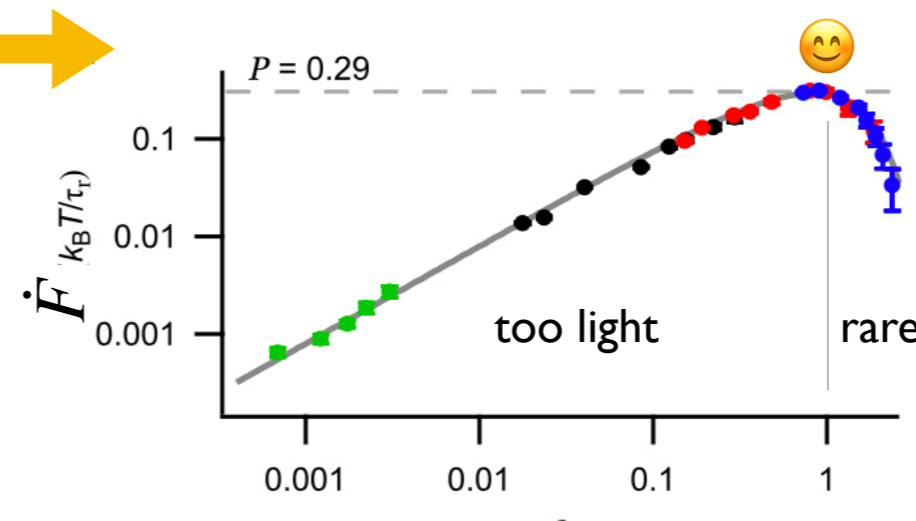
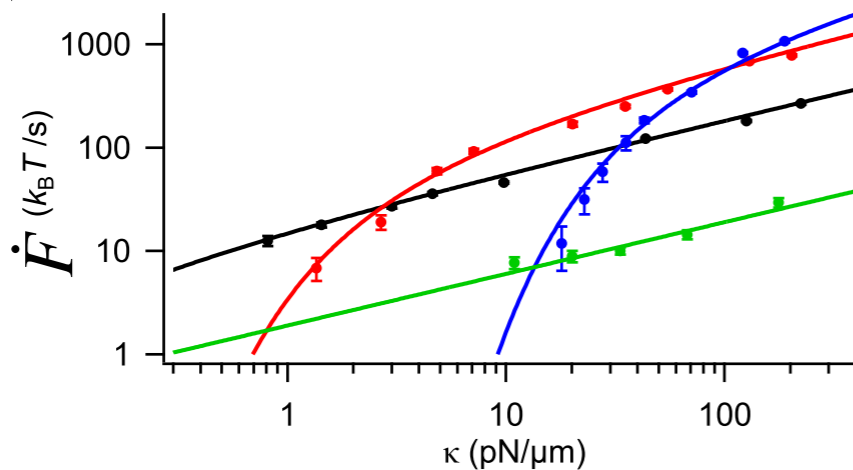
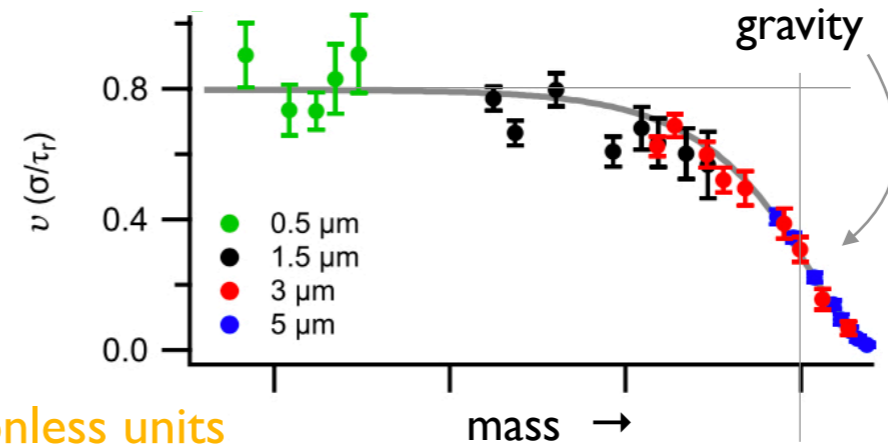
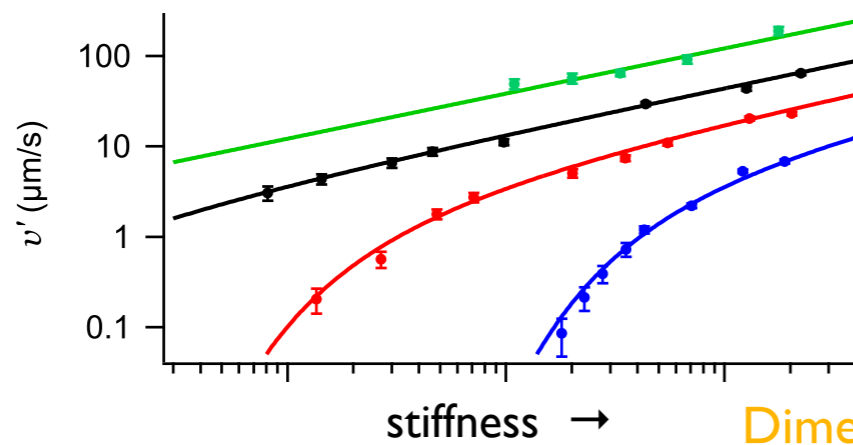
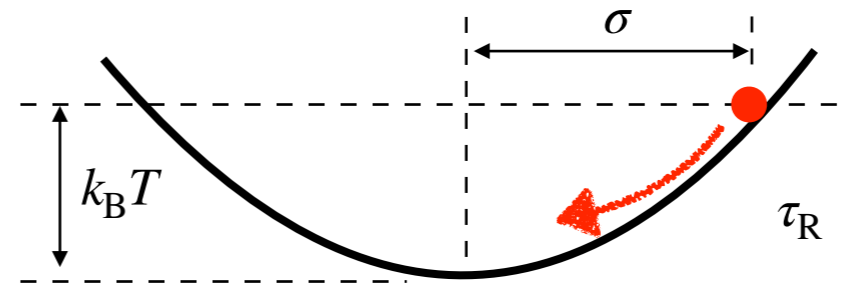
Trap relax: 3.5 ms      size: 24 nm  
stiffness: 7 pN/μm

# Information ratchet

## Theory for engine

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

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



trap stiffness, size:  $\kappa, \sigma$

relaxation time:  $\tau_r = \gamma/\kappa$

reduced mass:  $\delta_g = \frac{m g}{\kappa \sigma}$

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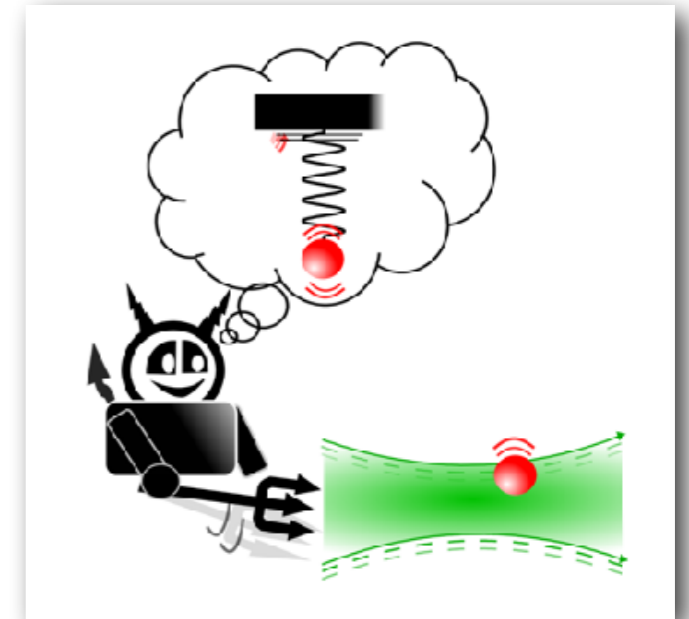
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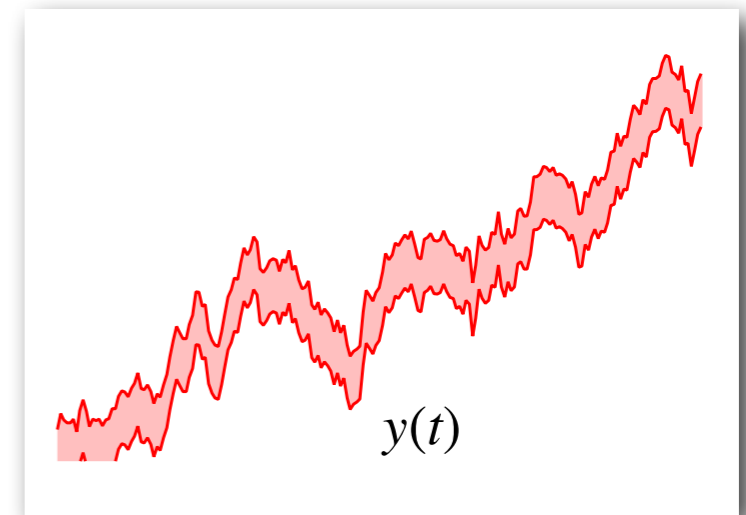
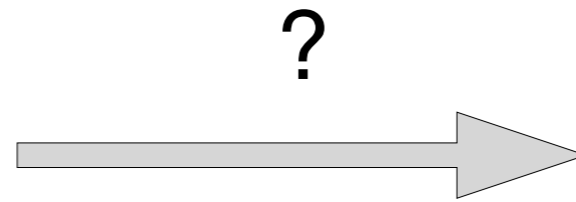
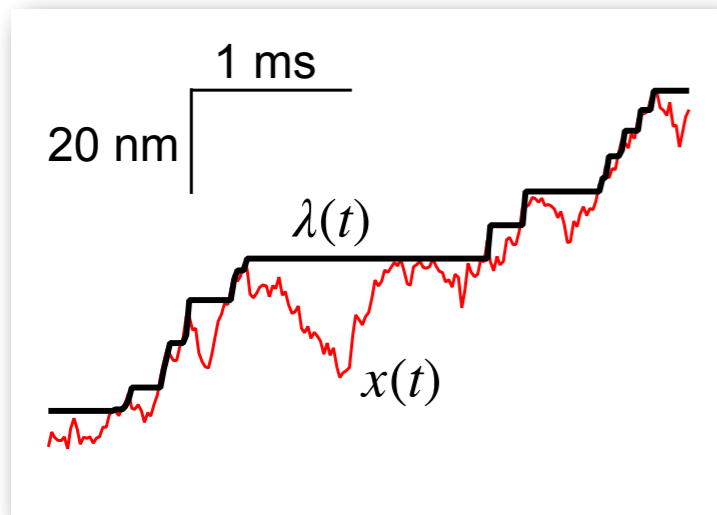
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- more power & speed!
- applications?



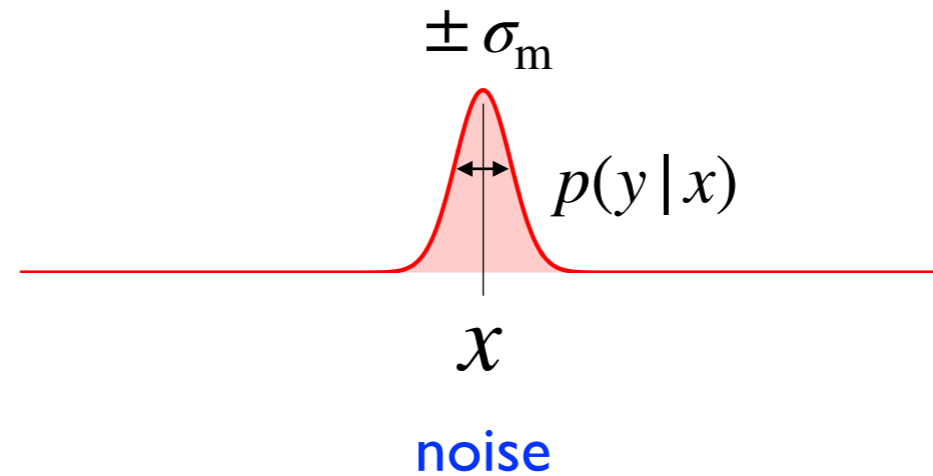
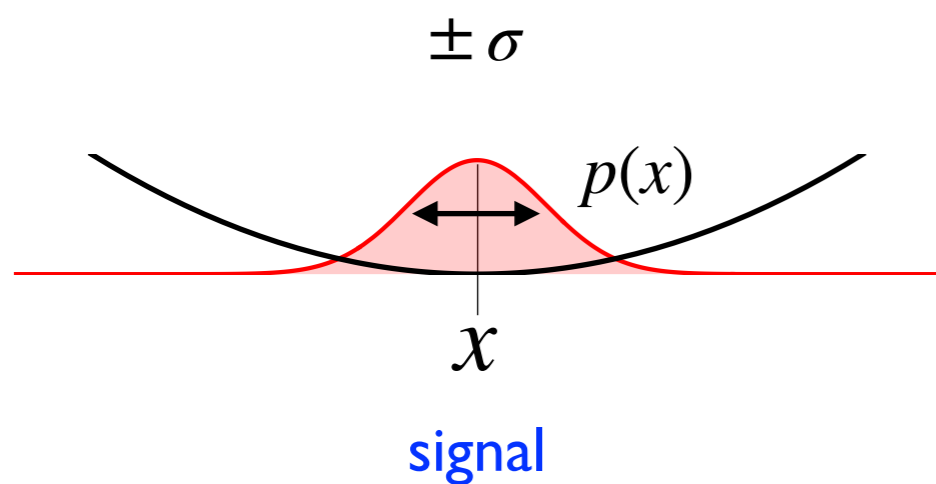
# Information ratchet

## Noisy measurements



$$y = x + \xi$$

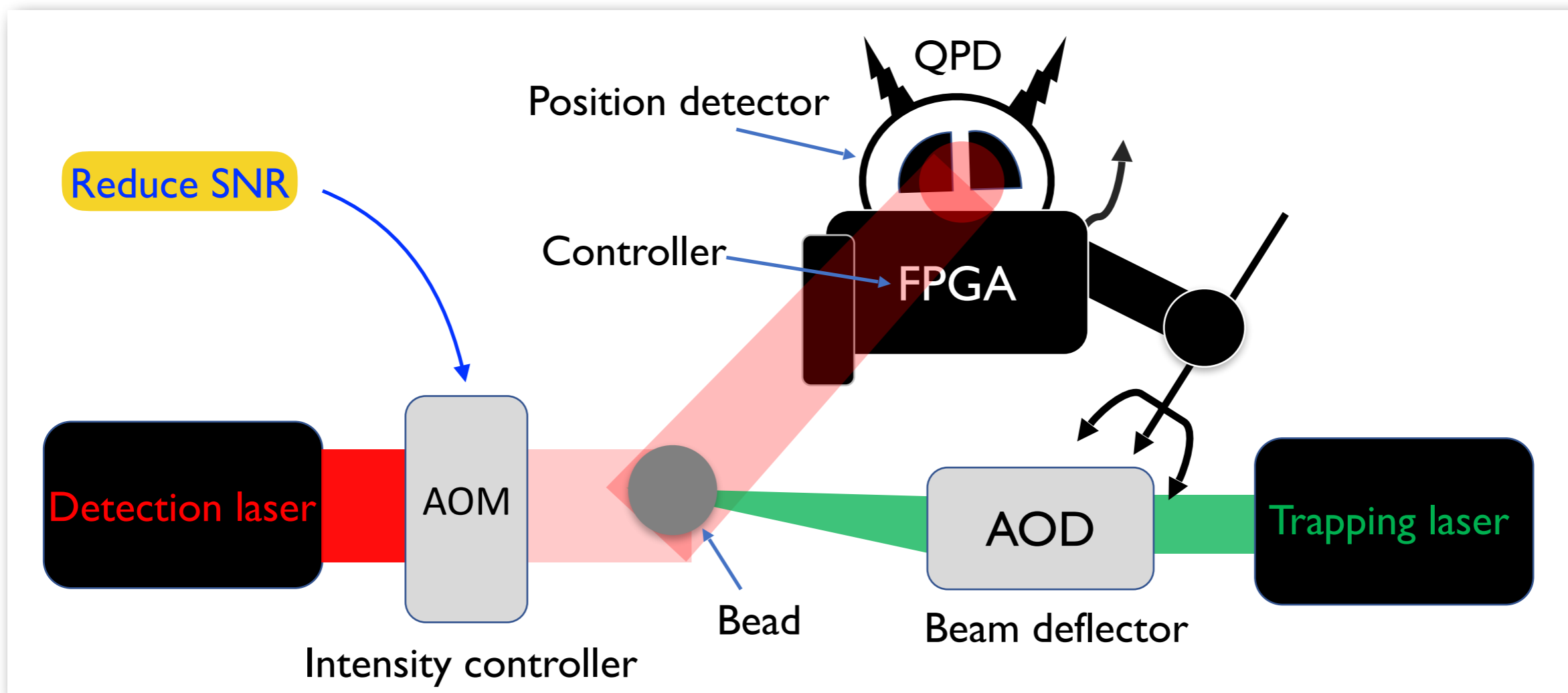
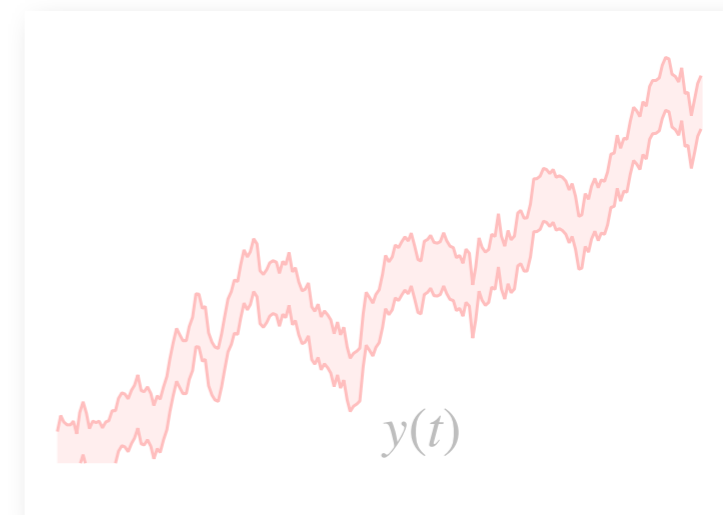
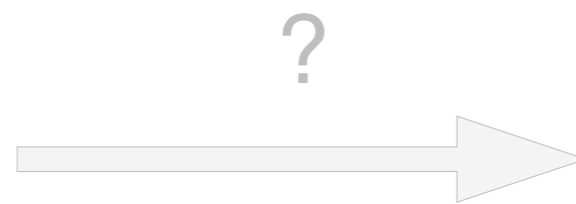
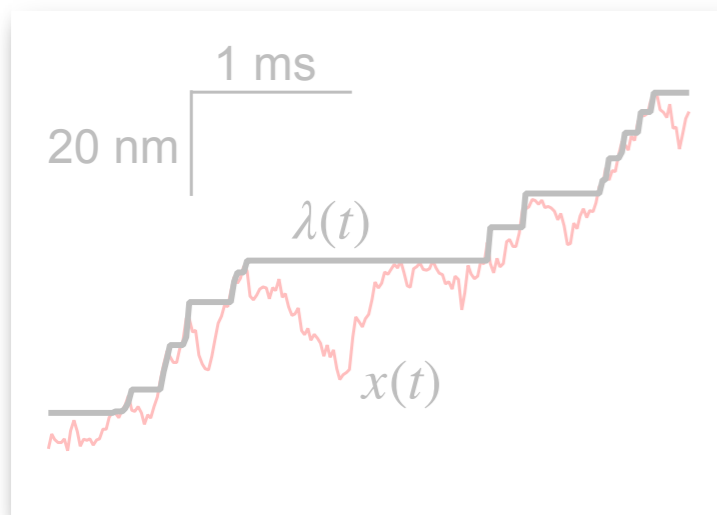
Define the signal-to-noise ratio, **SNR**



$$\text{SNR} \equiv \frac{\sigma}{\sigma_m}$$

# Information ratchet

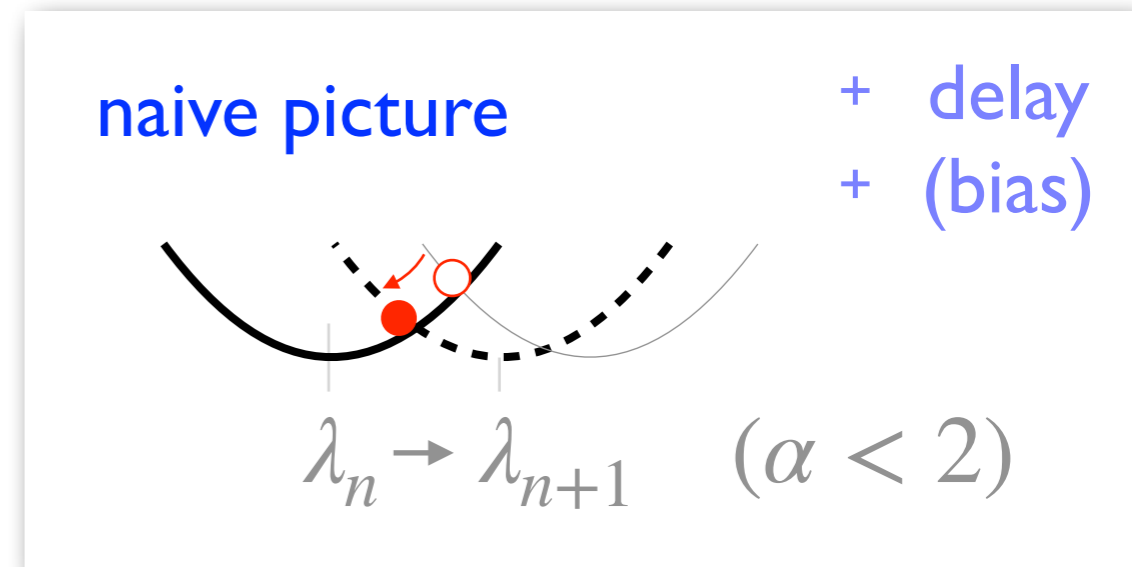
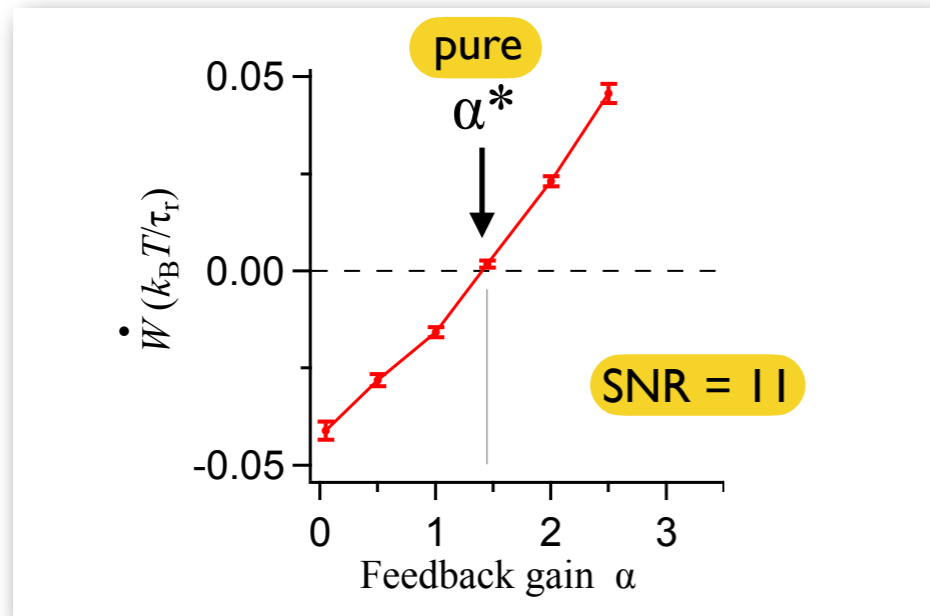
Noisy measurements



# Information ratchet

Noisy measurements

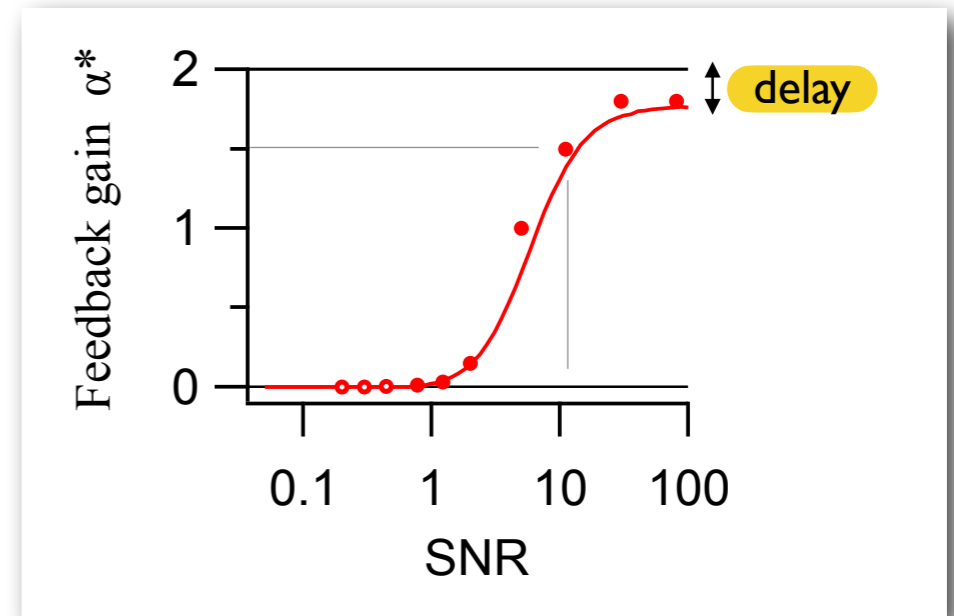
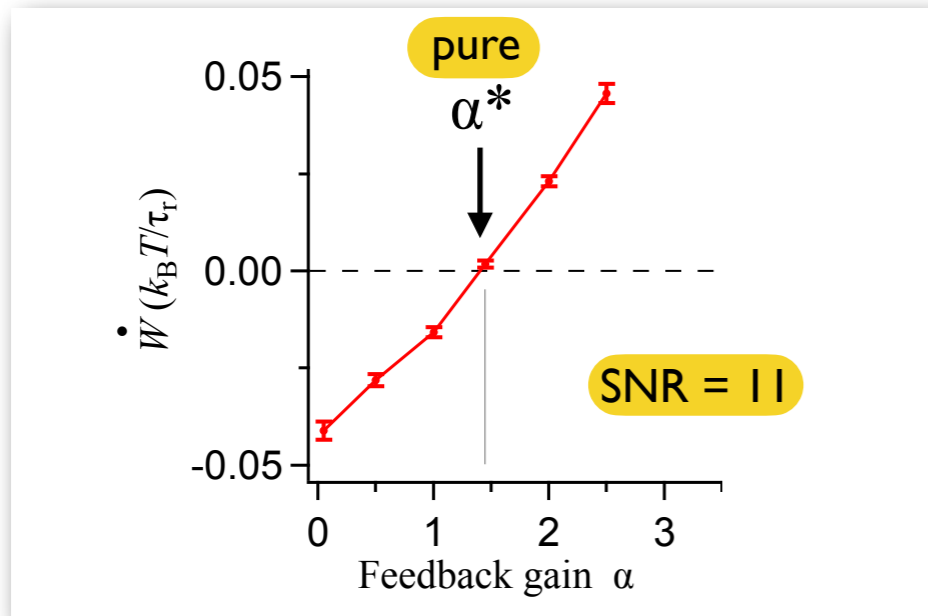
Recall need to reduce  $\alpha$  to have zero trap work



# Information ratchet

Noisy measurements

Naive info engine stops working for  $\text{SNR} < \text{SNR}_c$



Is  $\alpha^*$  small or zero?

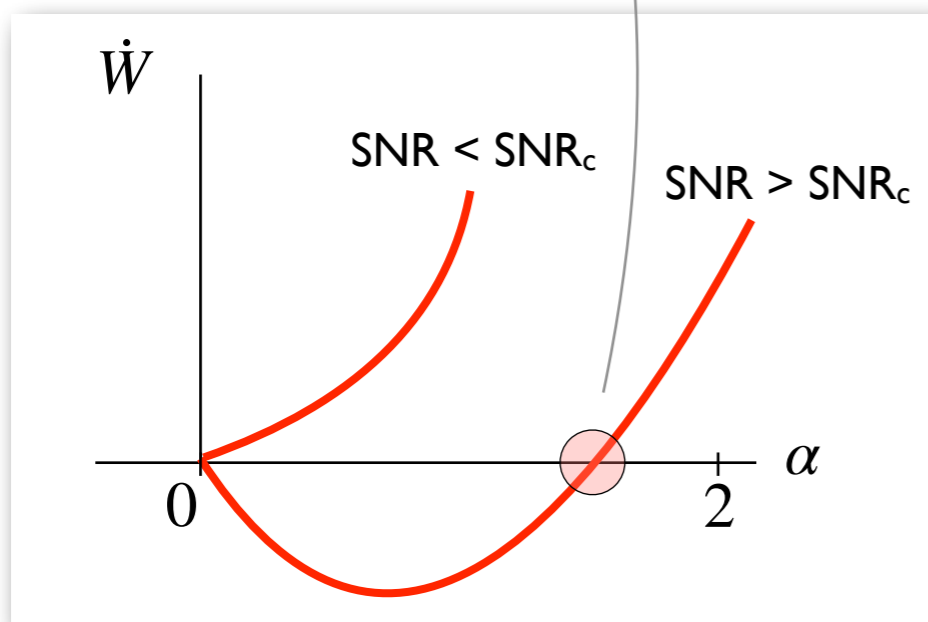
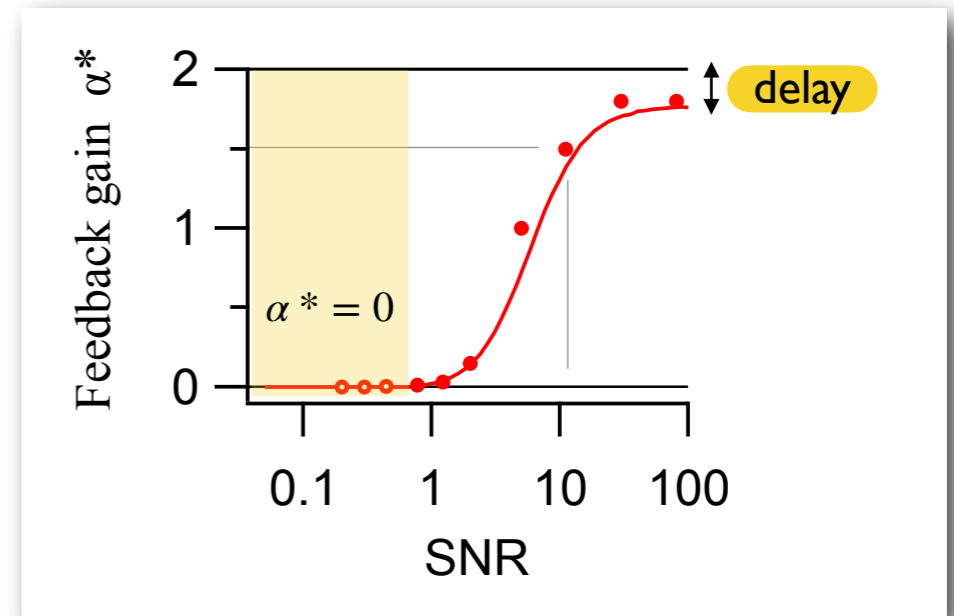
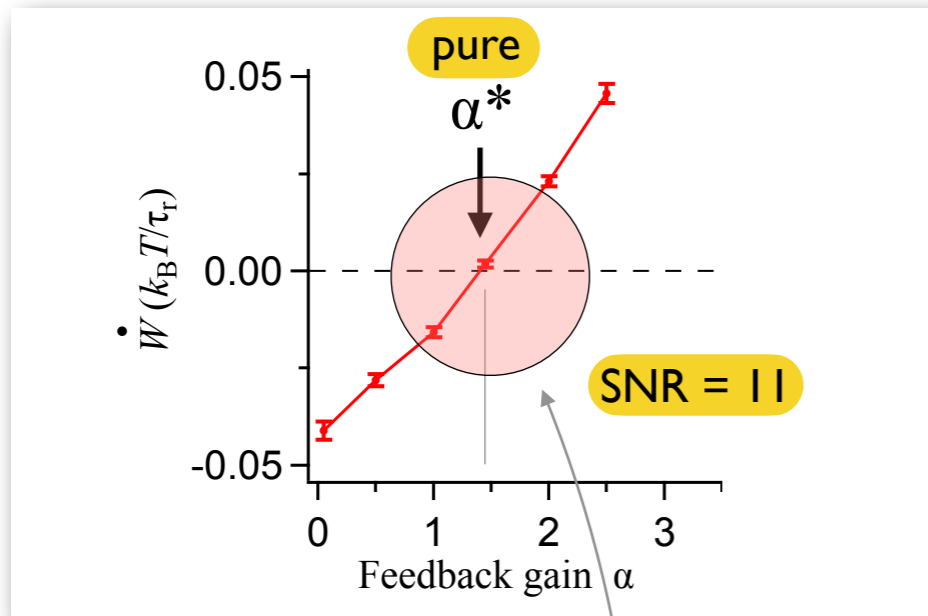
↔ is there a crossover or a phase transition?



# Information ratchet

Noisy measurements

Naive info engine stops working for  $\text{SNR} < \text{SNR}_c$



$\alpha^* = 0$  is always a solution

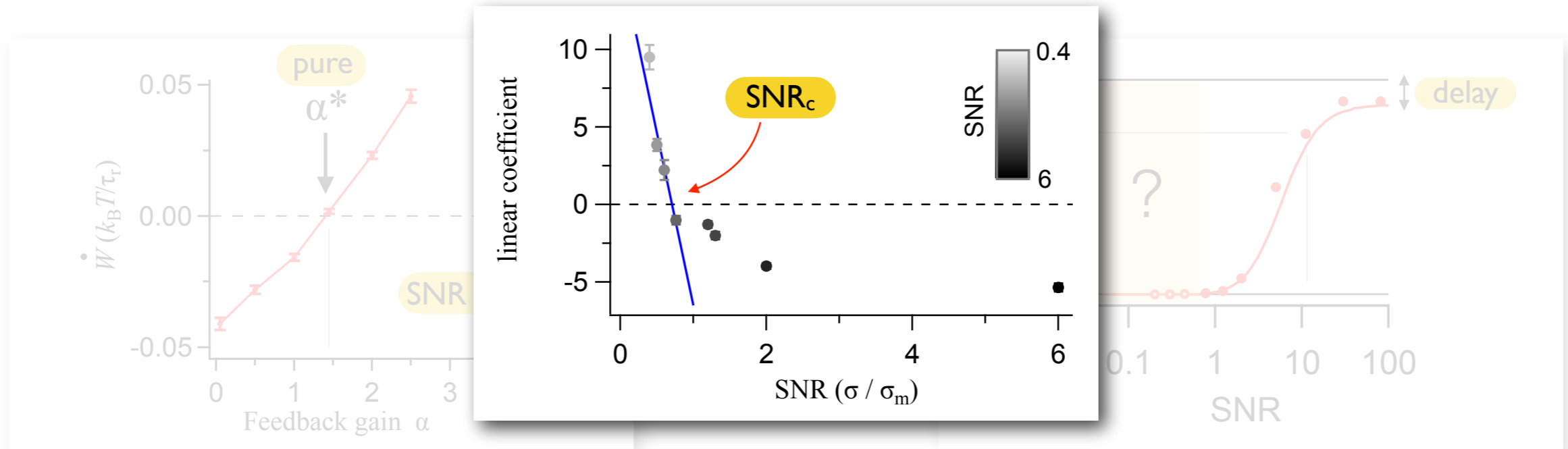
cannot find  $\dot{W} < 0$  for  $\alpha < \alpha_c$

→ Phase transition at  $\text{SNR}_c \approx 0.7$

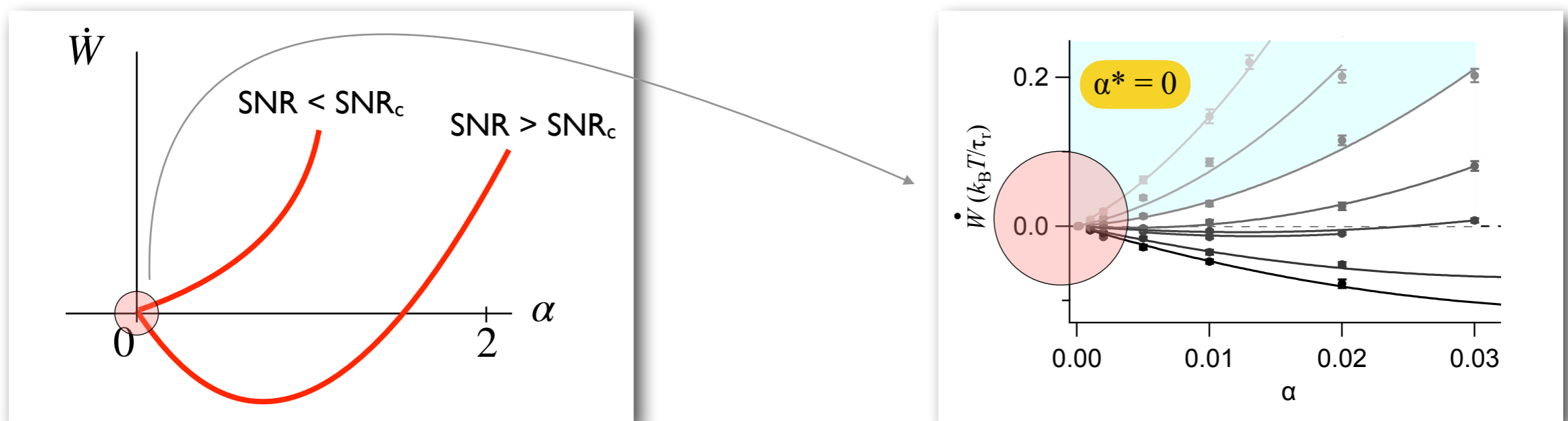
# Information ratchet

Noisy measurements

Naive info engine stops working for  $\text{SNR} < \text{SNR}_c$



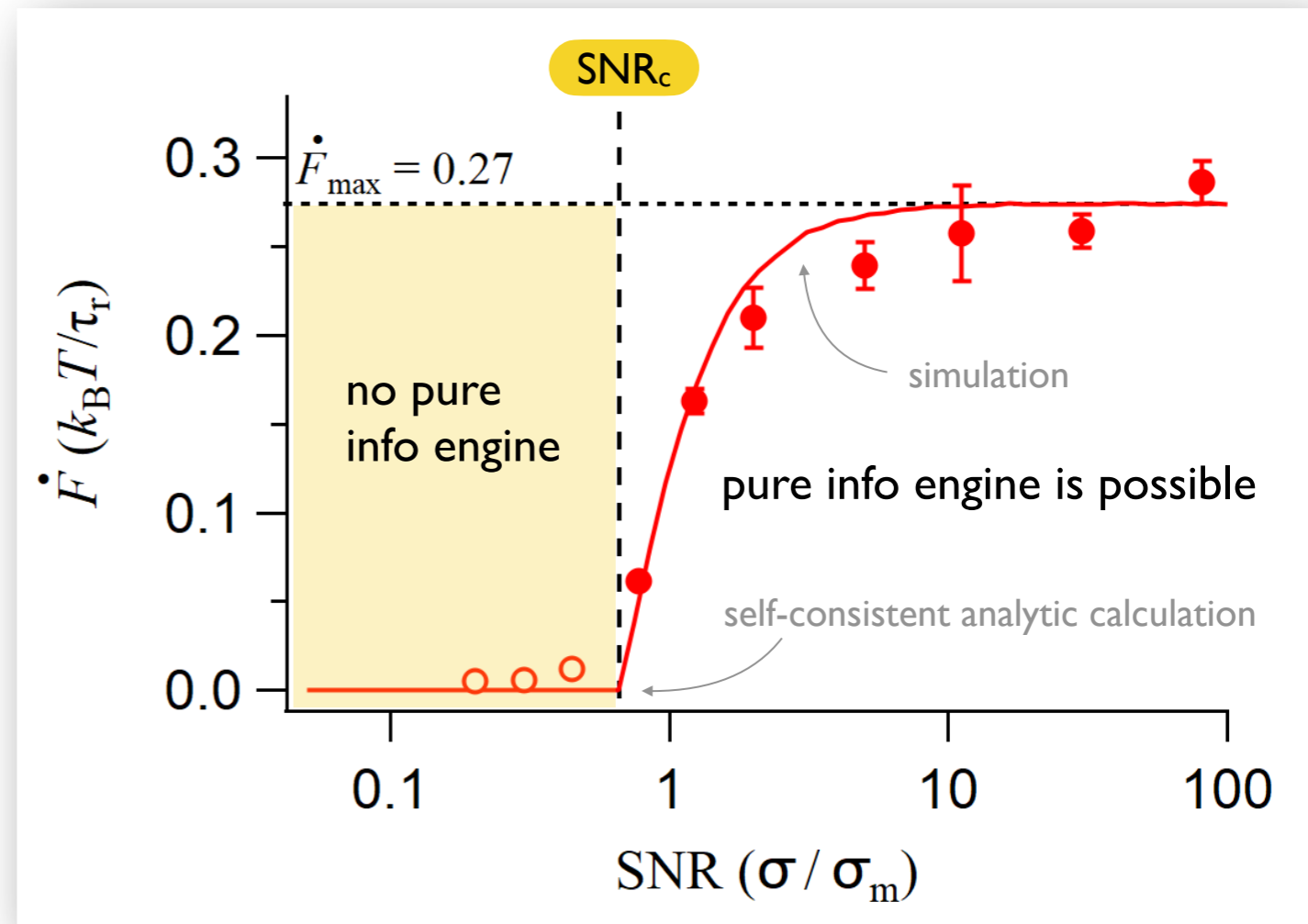
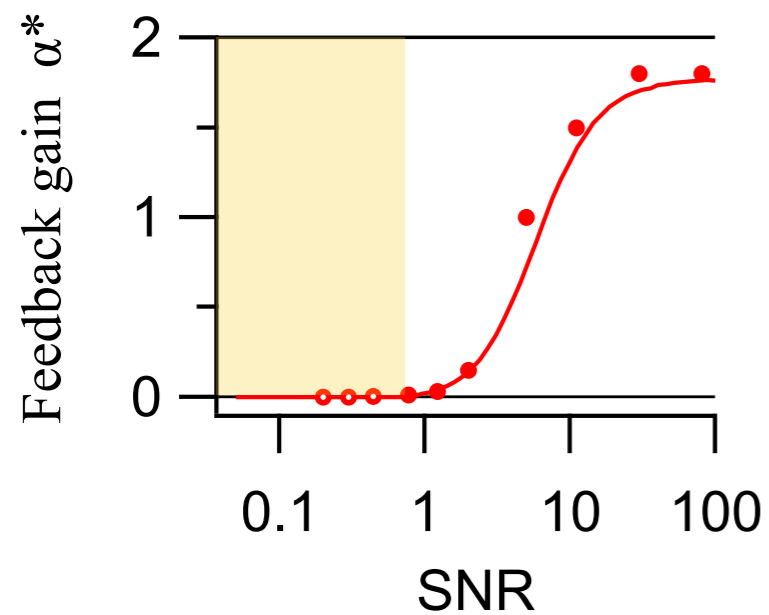
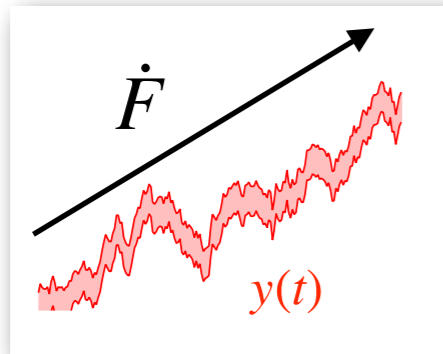
Phase transition at  $\text{SNR}_c \approx 0.7$



# Information ratchet

Noisy measurements

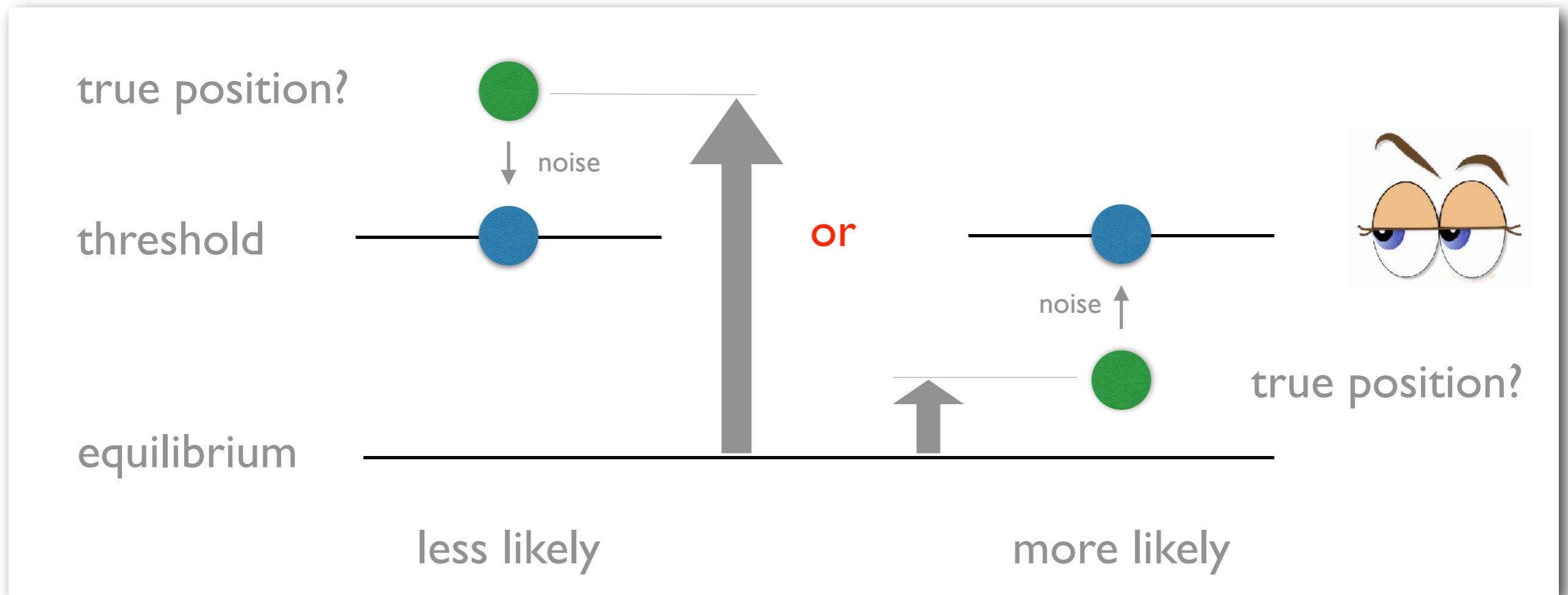
Phase transition at  $\text{SNR}_c \approx 0.7$



# Information ratchet

Noisy measurements

**Bias:** If you see a particle “at” threshold, it’s probably below it.



**Bias** → reduce  $\alpha$  to keep  $\dot{W} = 0$  but need  $\alpha \geq 0$ .

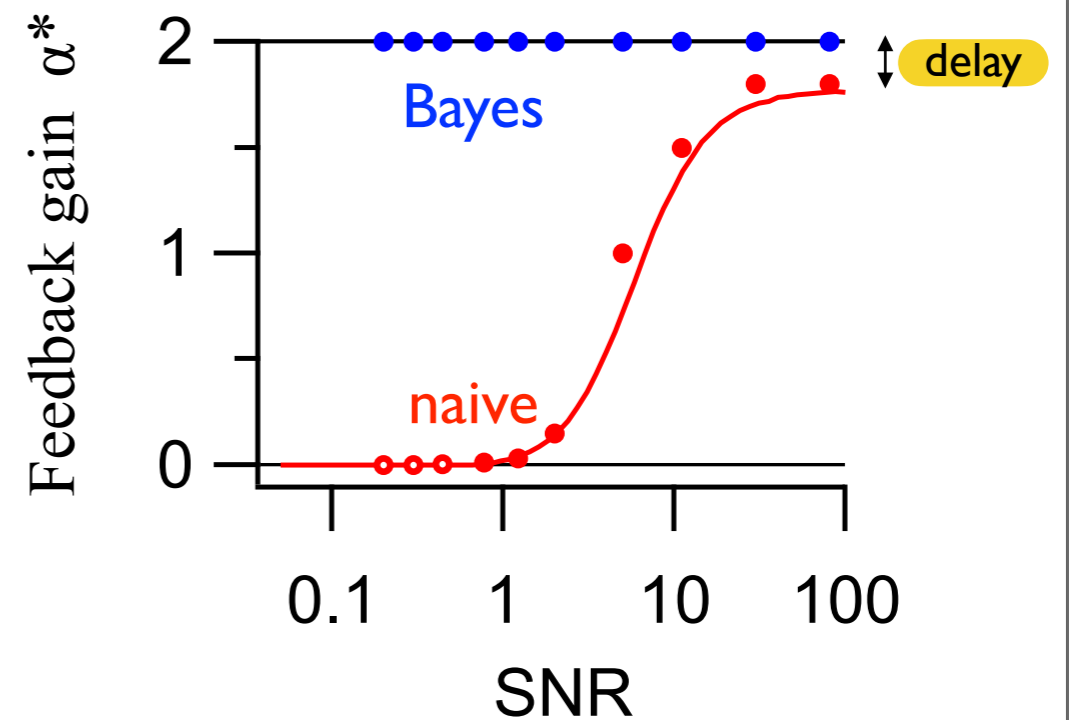
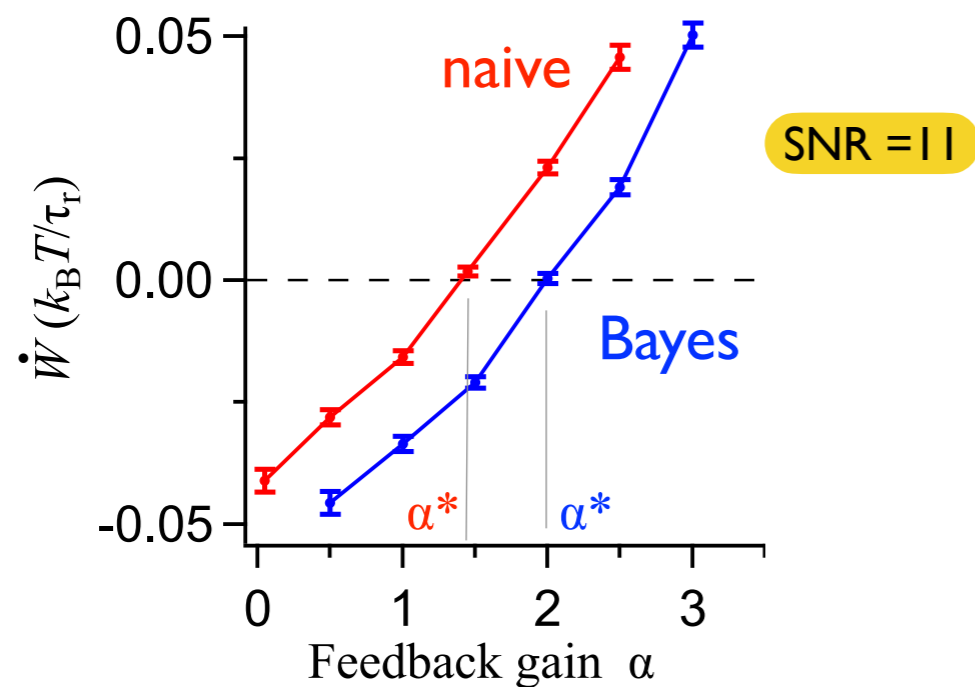
# Information ratchet

Noisy measurements

The problem: Phase transition due to **bias**.

The solution: Bayesian filter info engine works for all SNR.

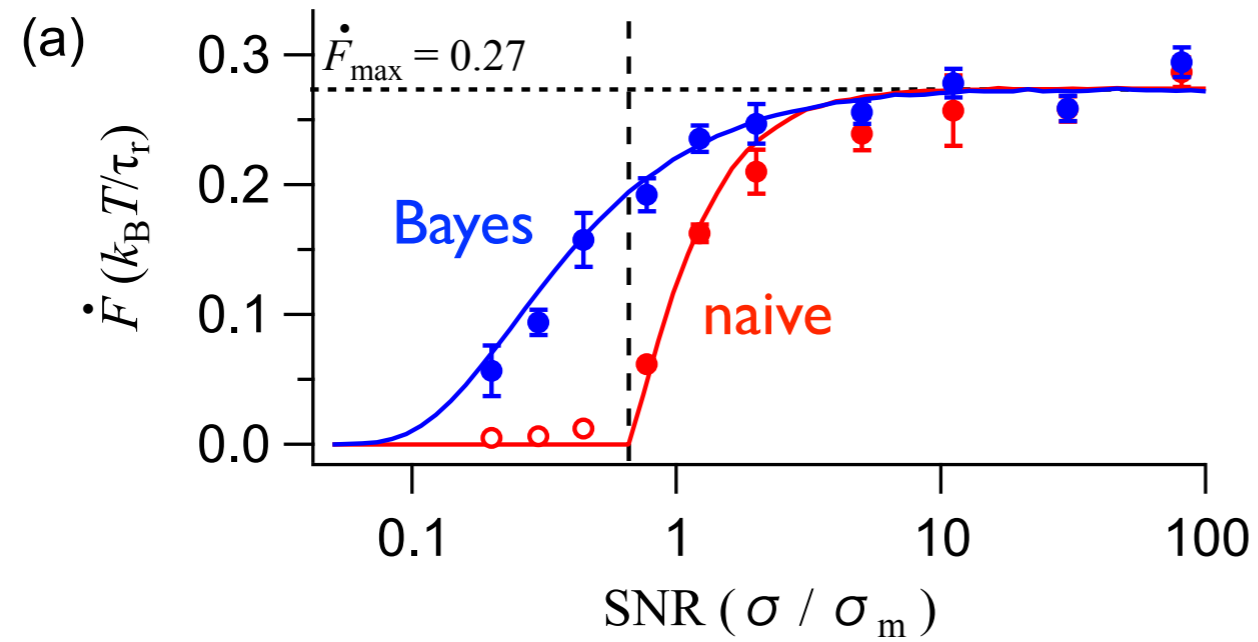
- Don't be naive: We know the dynamics!
- Use Bayes rule with dynamics prior to estimate  $x$  from past history  $\{y\}$ , without bias
- Technical implementation: Kalman filter, with prediction to remove time delay



# Information ratchet

Noisy measurements

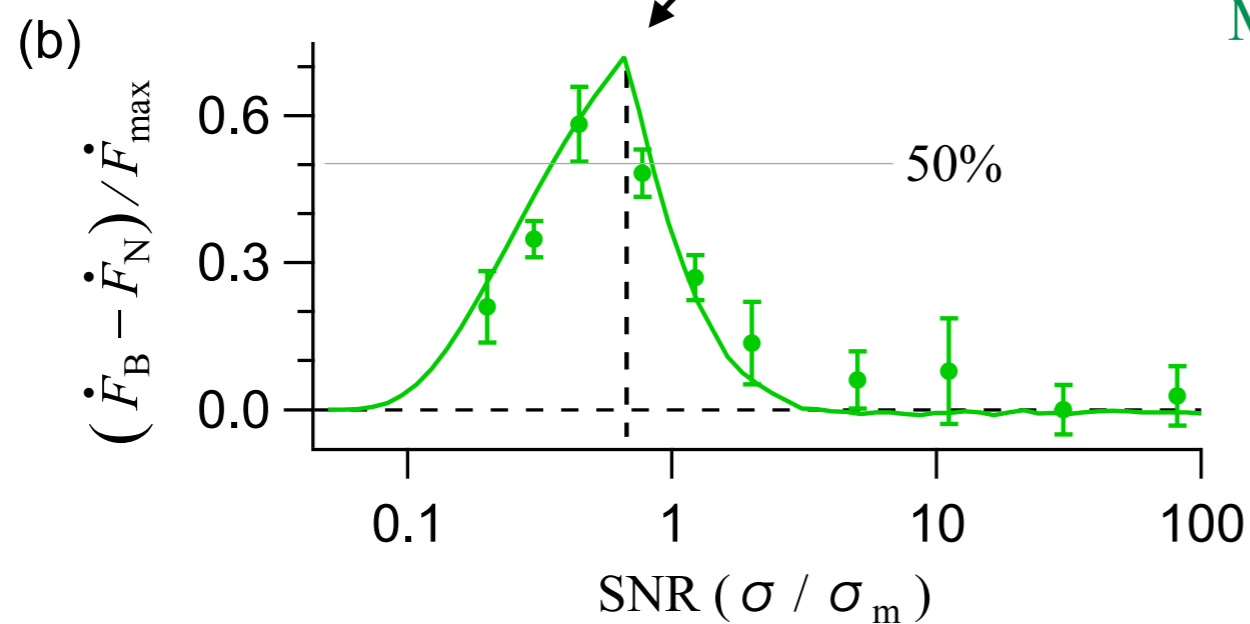
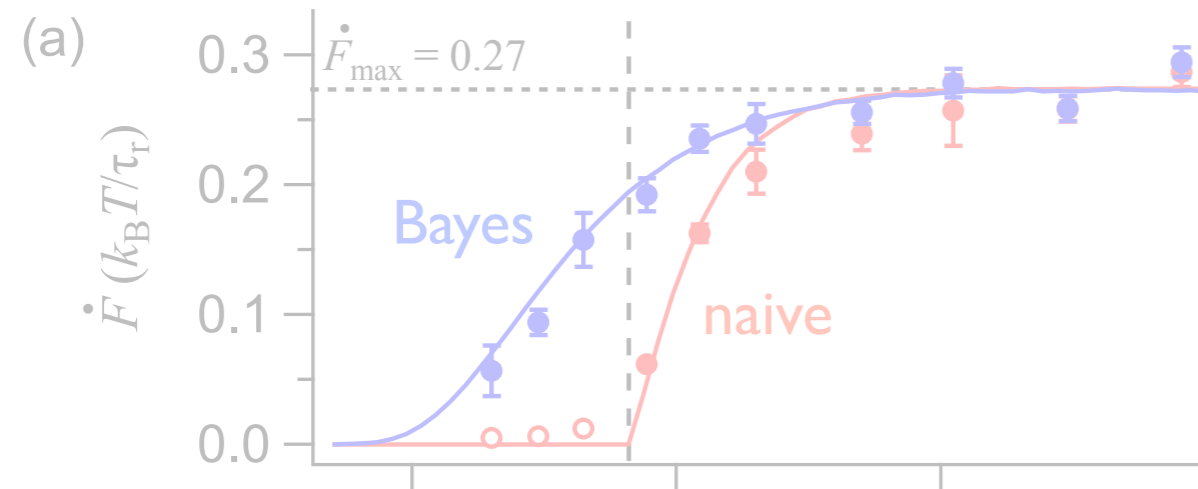
Bayesian filter info engine works for all SNR



# Information ratchet

Noisy measurements

Bayesian filter info engine works for all SNR



Maximum benefit for Bayesian filter at

intermediate SNR

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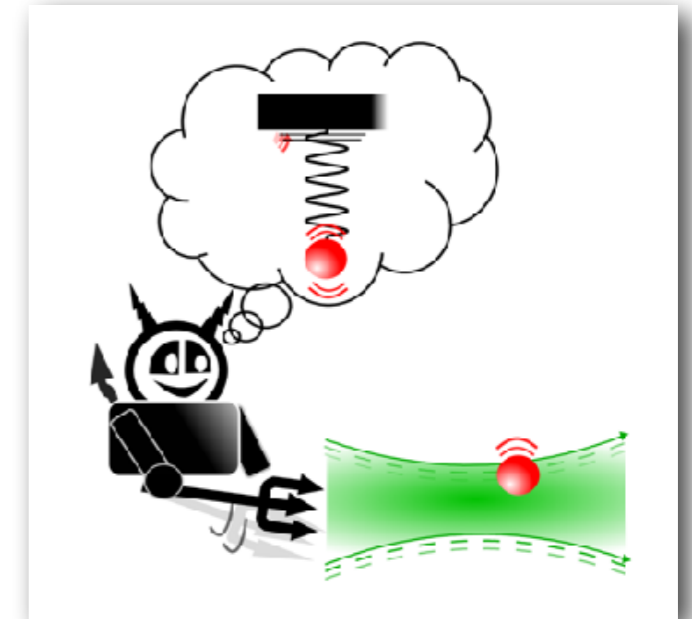
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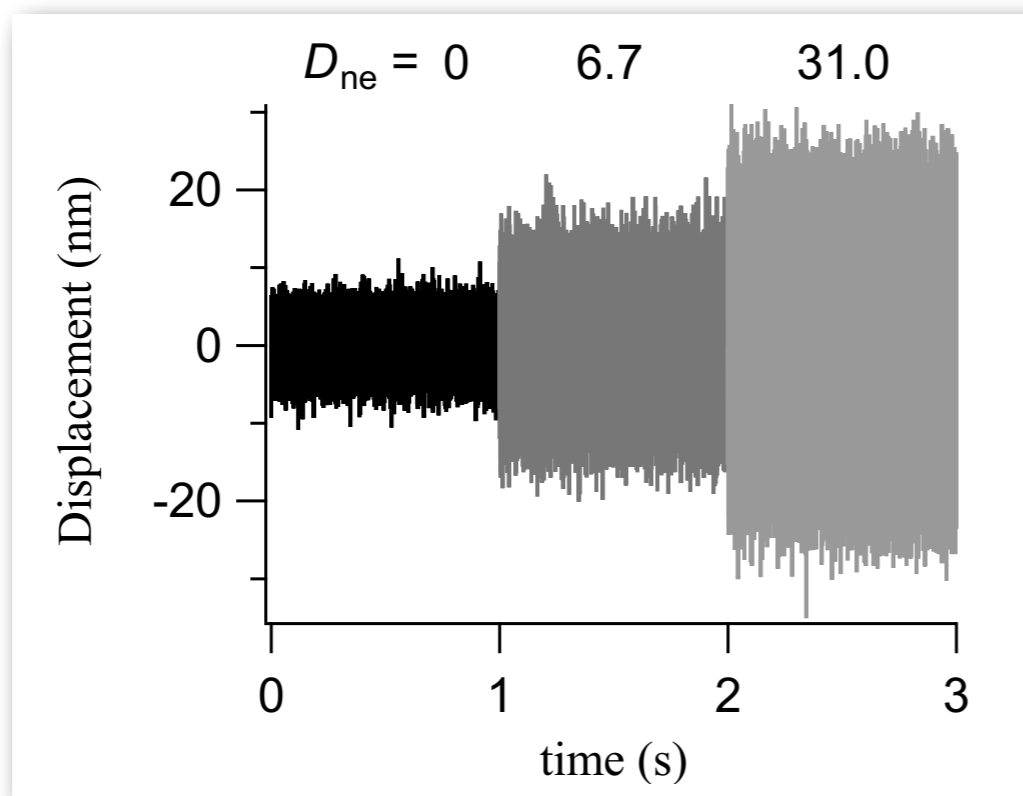
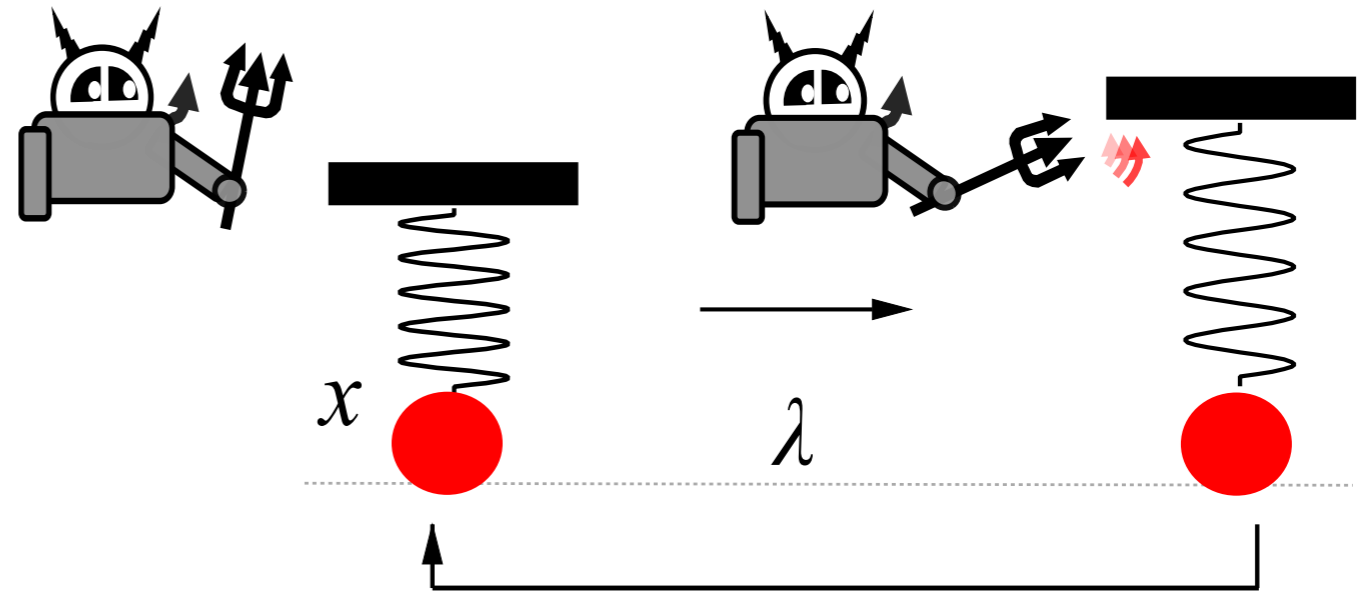
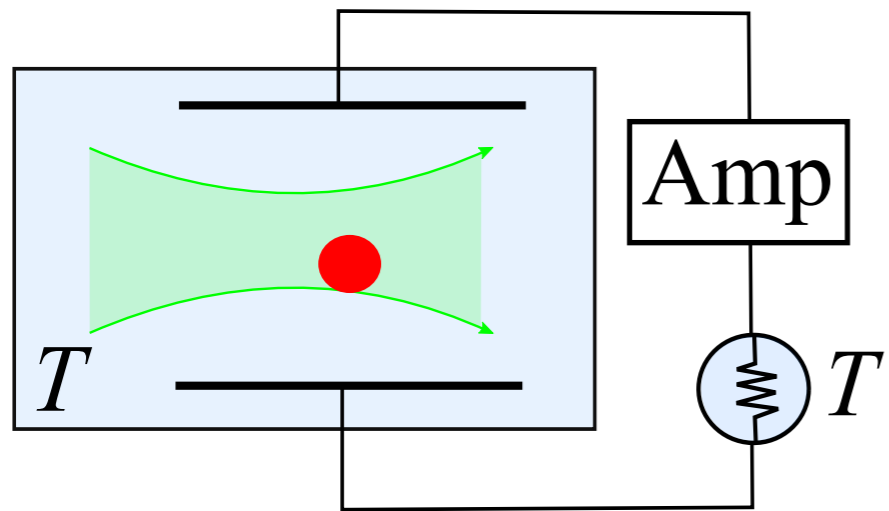
## III. Nonequilibrium environment

- more power & speed!
- applications?





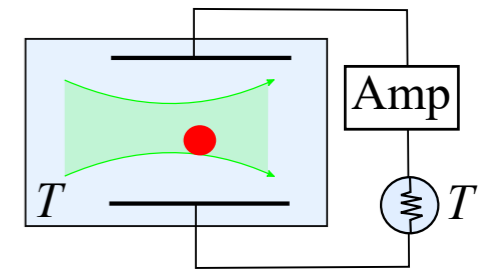
# Nonequilibrium environment



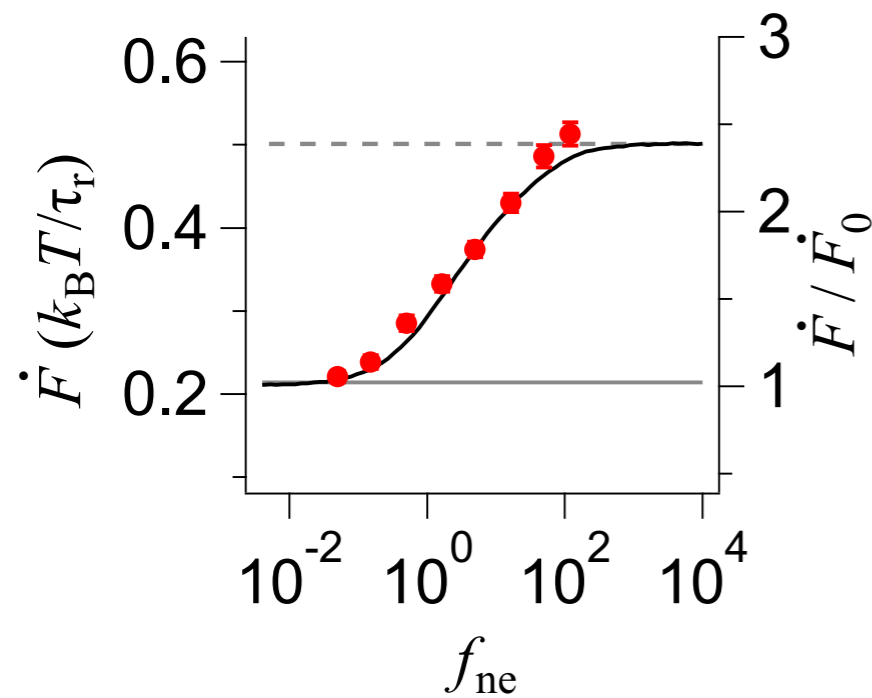
$$D_{ne} = \frac{\text{Noneq. D}}{\text{Eq. D}}$$

neglect measurement noise...

# Nonequilibrium environment

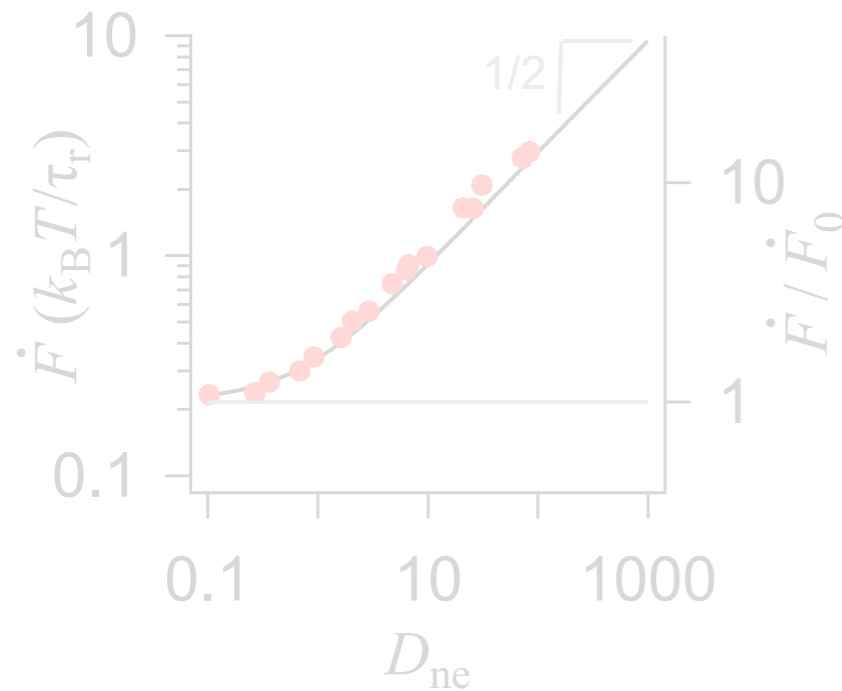
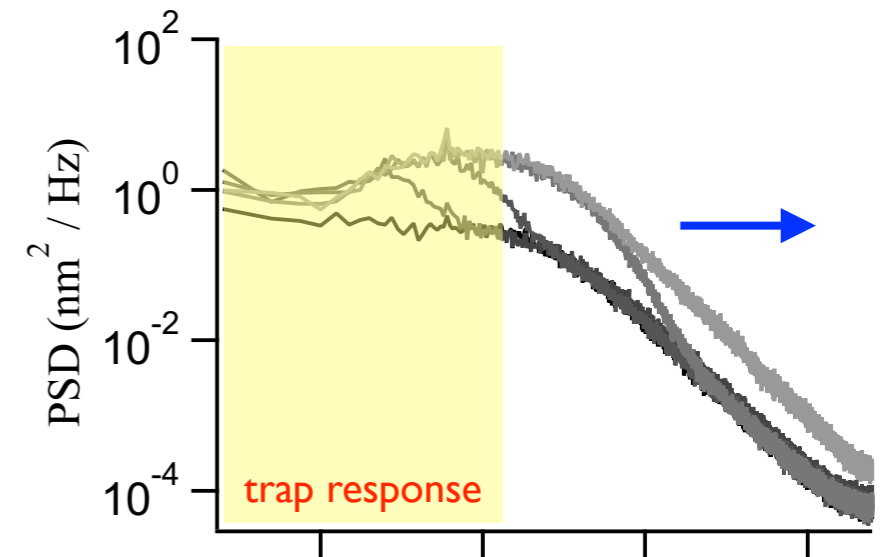


higher *bandwidth* of noneq. fluctuations  $\rightarrow$  more power



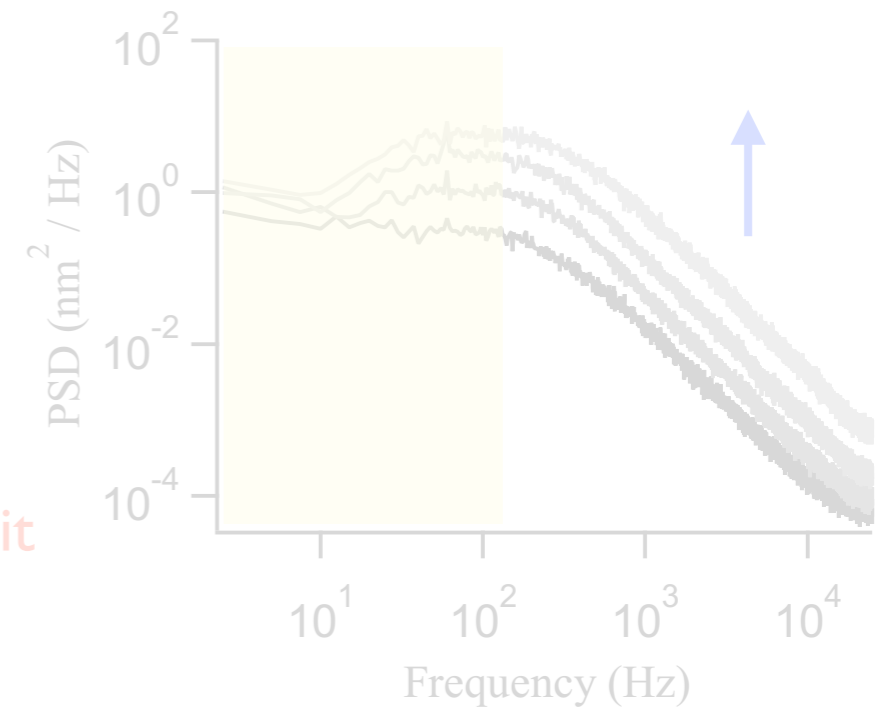
noise  
bandwidth

coloured-noise limit

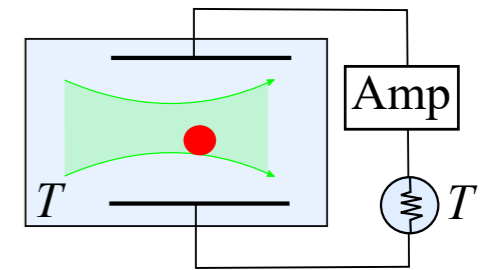


forcing  
amplitude

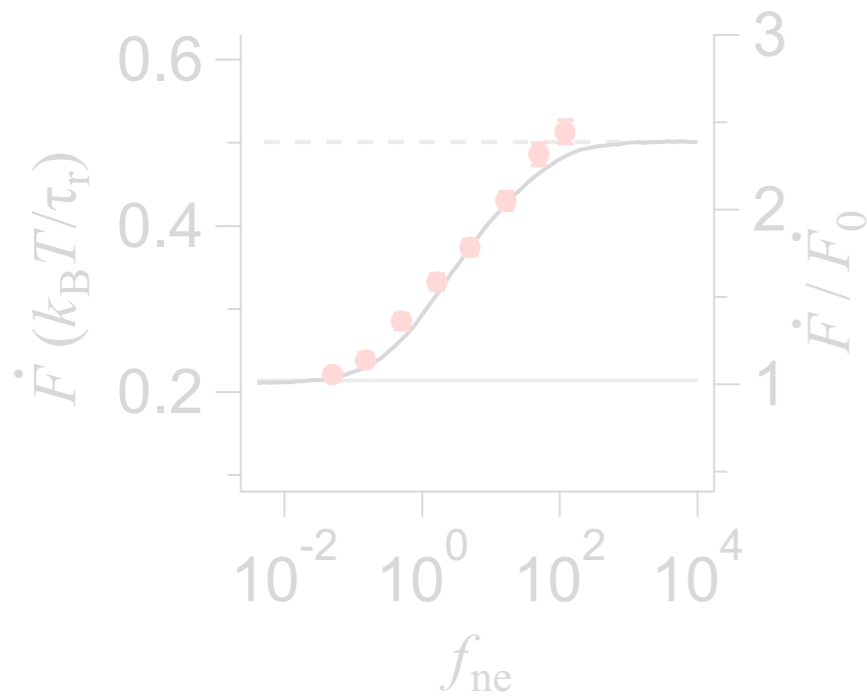
effective-temperature limit



# Nonequilibrium environment

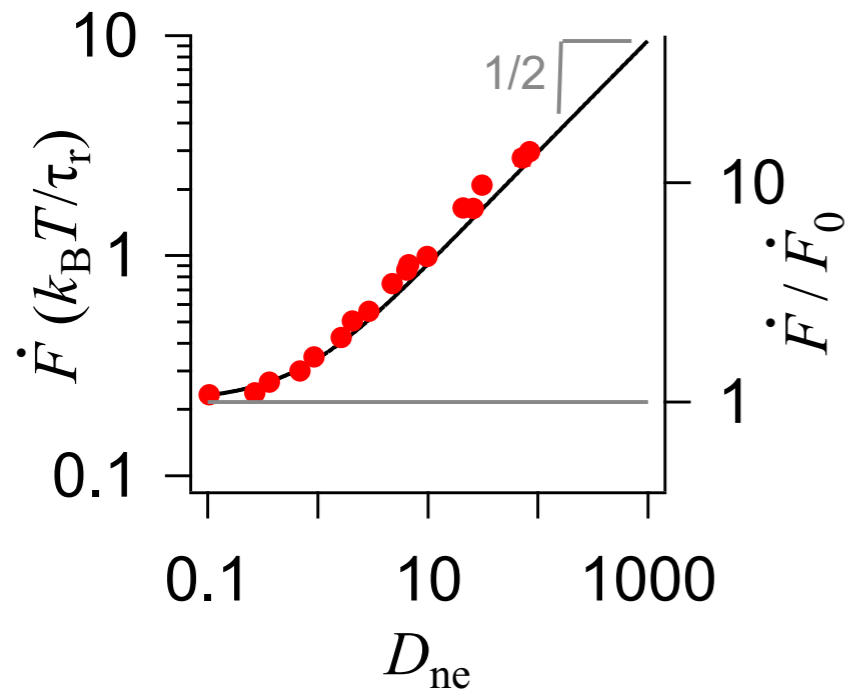
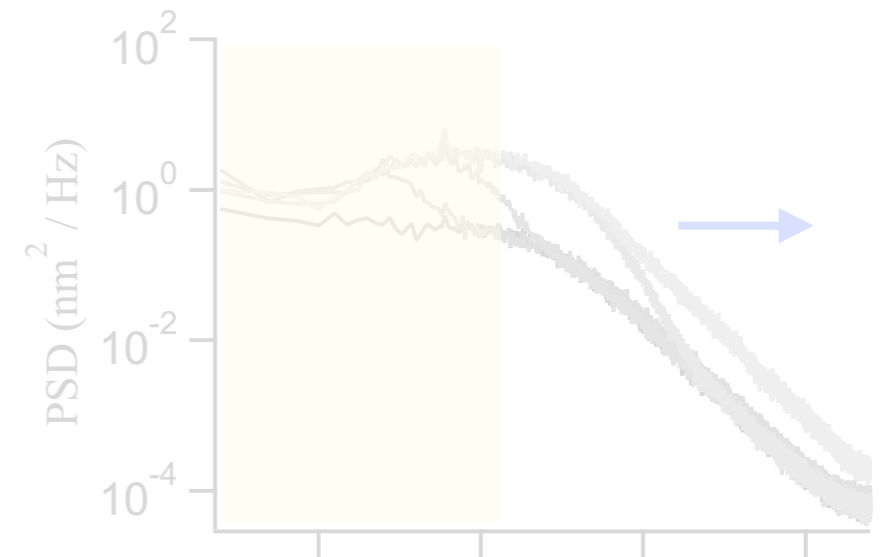


higher *amplitude* of noneq. fluctuations  $\rightarrow$  more power



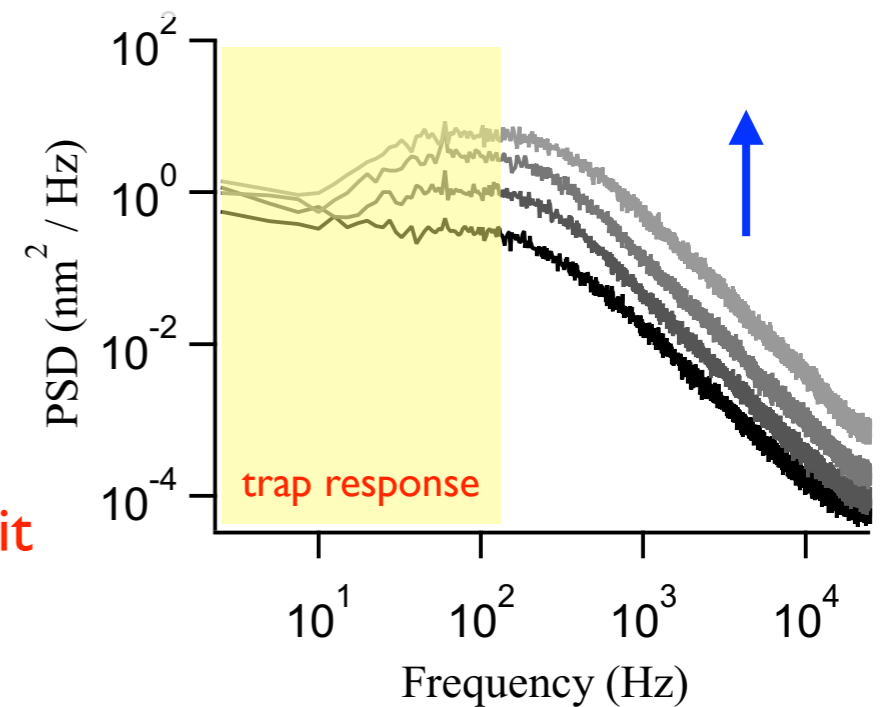
noise  
bandwidth

coloured-noise limit

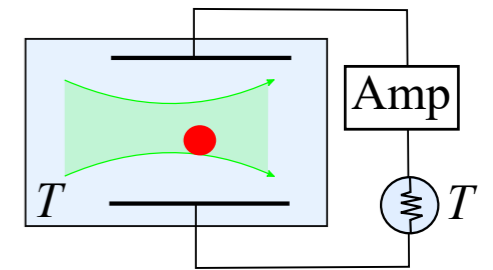


forcing  
amplitude

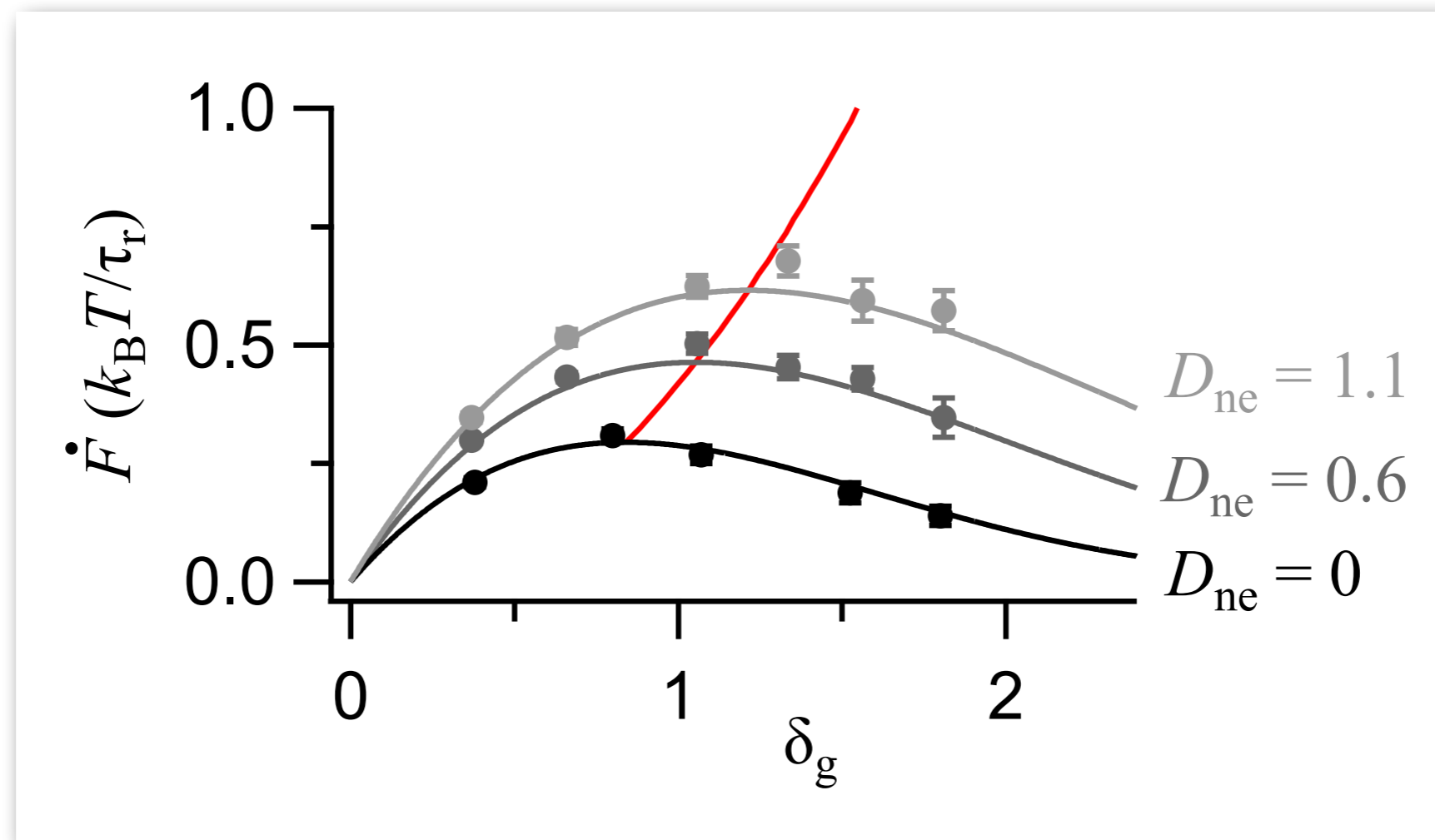
effective-temperature limit



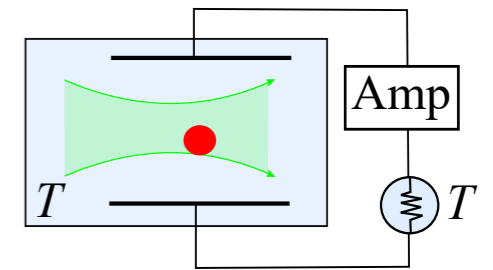
# Nonequilibrium environment



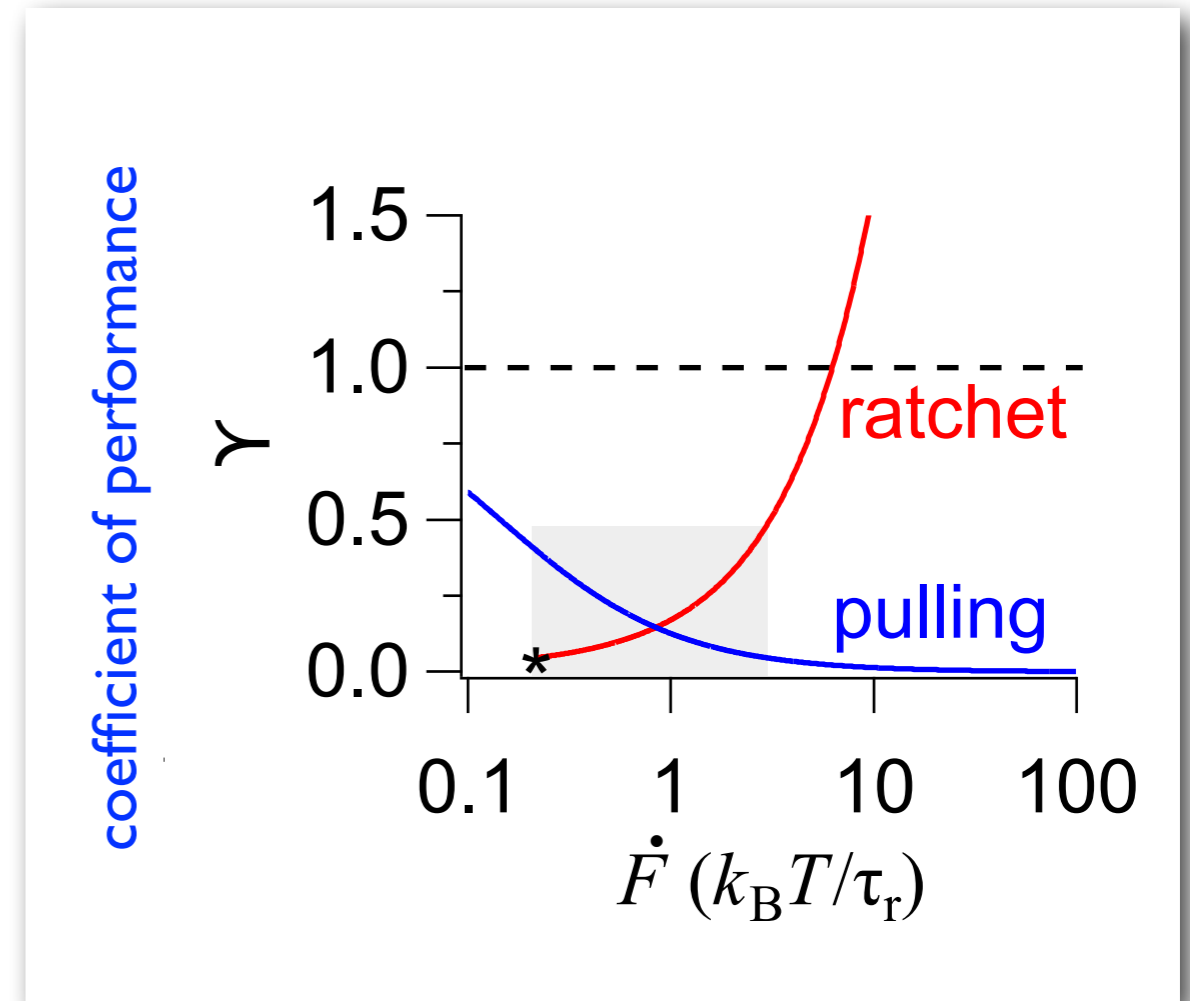
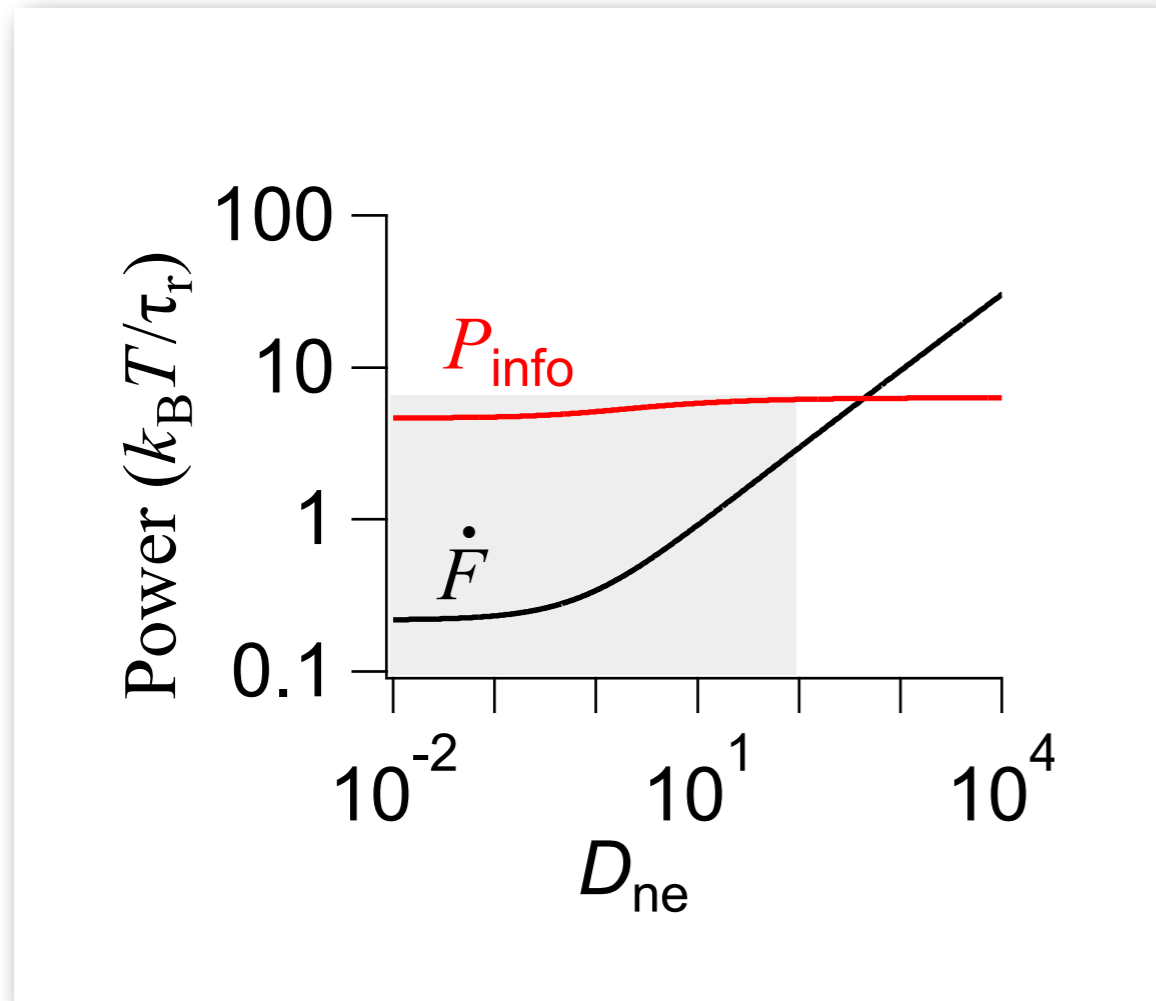
higher amplitude of noneq. fluctuations  $\rightarrow$  larger optimal mass



# Nonequilibrium environment



When is a ratchet better than dragging (match speeds)?



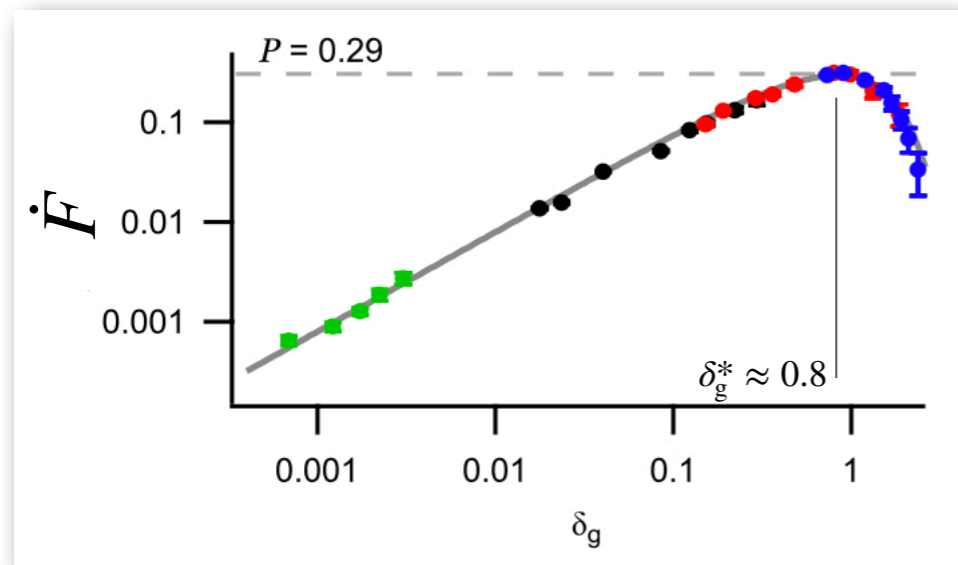
$$P_{\text{info}} \equiv \frac{H[\Lambda_{k-1} | X_k] - H[\Lambda_k | X_k]}{t_s} = \Delta \text{ joint entropy due to action of the controller}$$

cf. Ehrich, Still, and Sivak, *Phys. Rev. Research* 2023

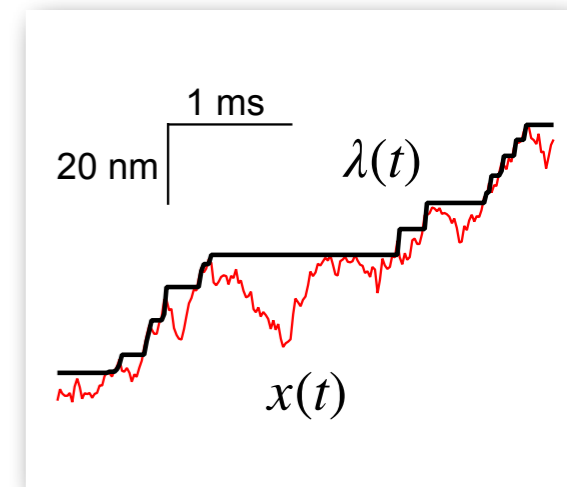
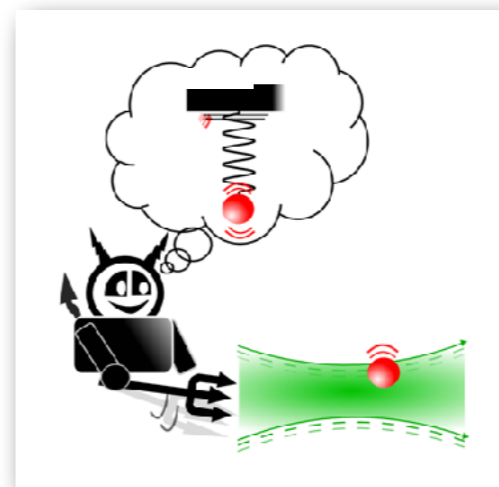
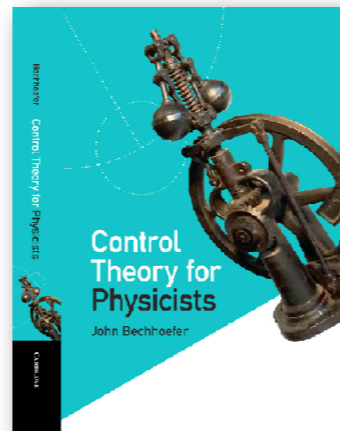
# Conclusions

“Textbook” information ratchet that can store energy

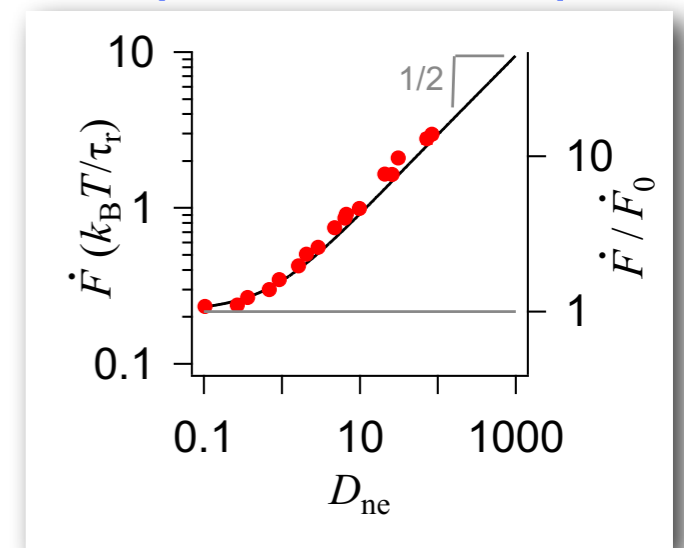
Part I optimize power for eq. bath



Saha, Lucero, Ehrich, Sivak, and JB, *PNAS* 2021

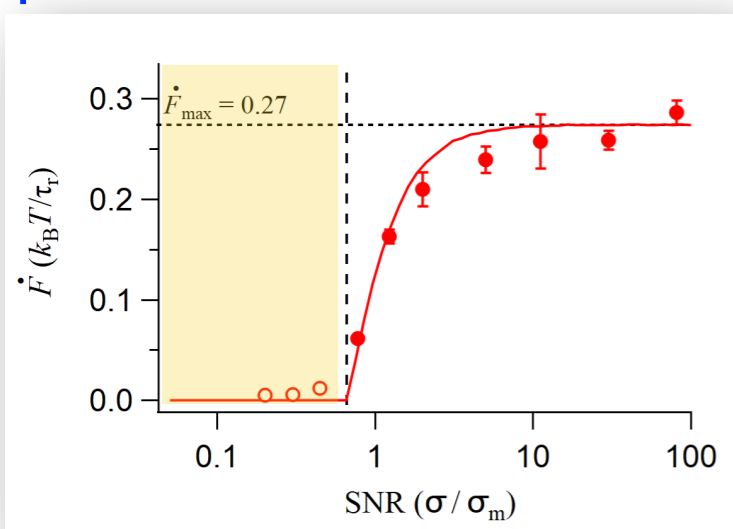


Part III more power in noneq bath

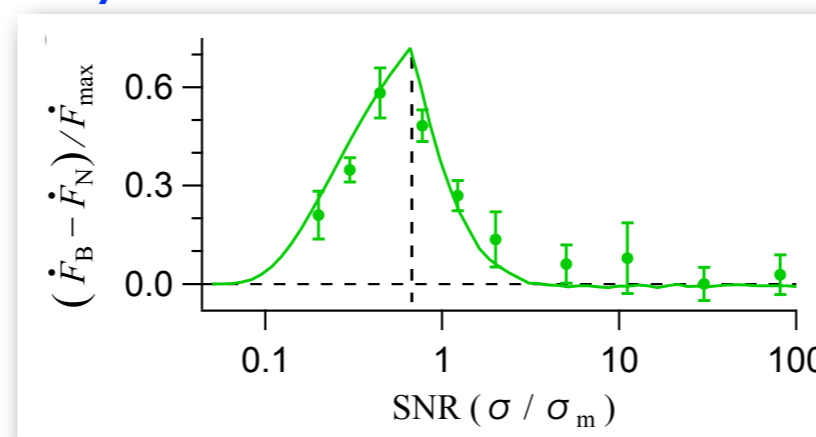


Part II

phase transition at low SNR

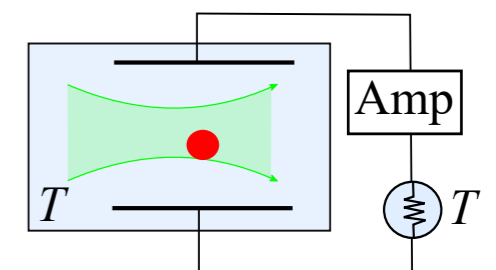


Bayes filter better at SNR ~ 1



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

apply to biomotors, energy harvesting



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