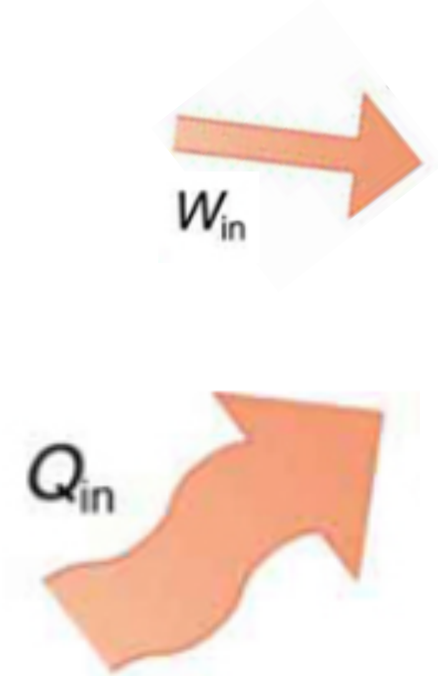
CHALMERS UNIVERSITY OF TECHNOLOGY | Department of MICROTECHNOLOGY AND NANOSCIENCE

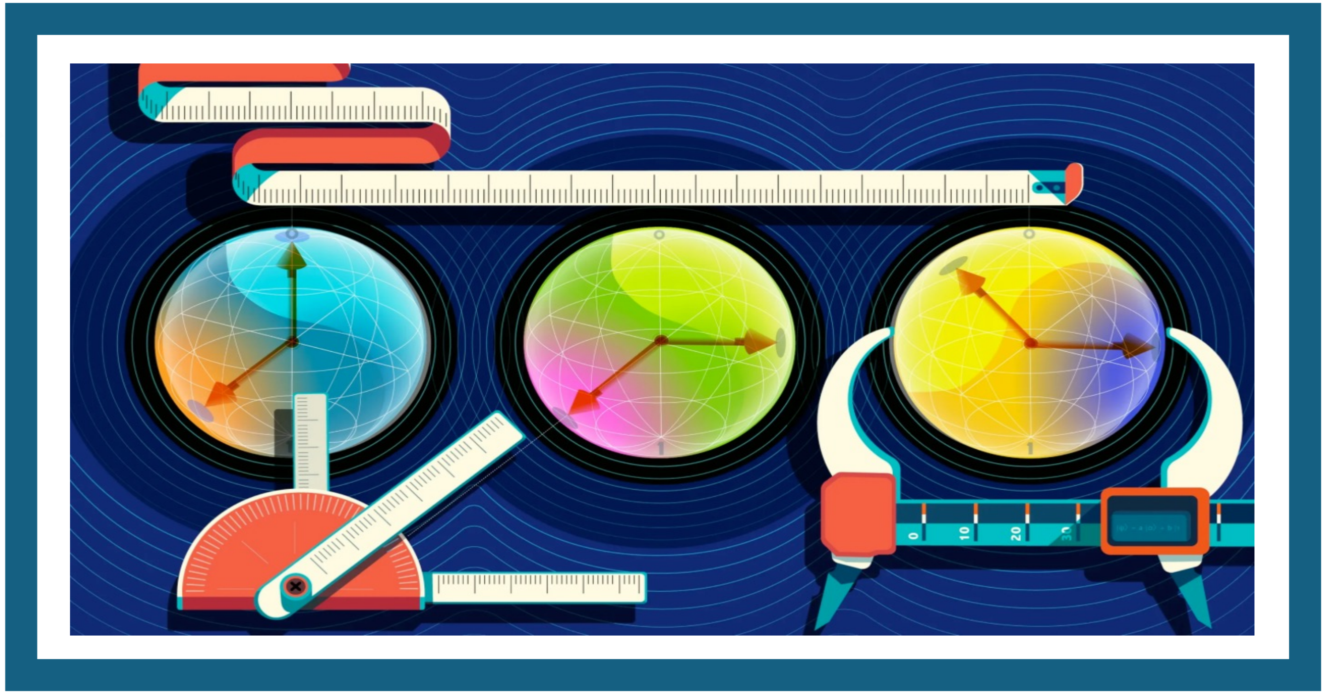
Penn Chemistry

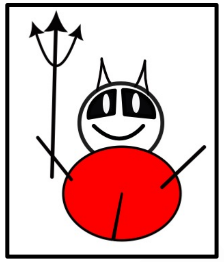
Quantum Information Engines

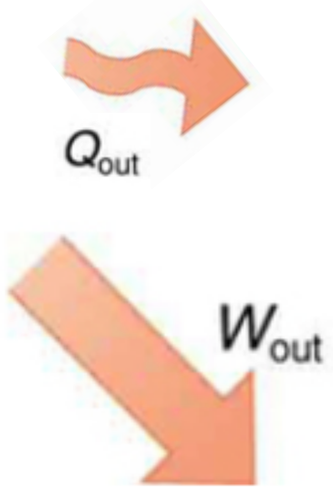
- *& Maxwell Demon revisited*

Assessing **Time**, **Cost** and **Performance Criteria**









Henning Kirchberg

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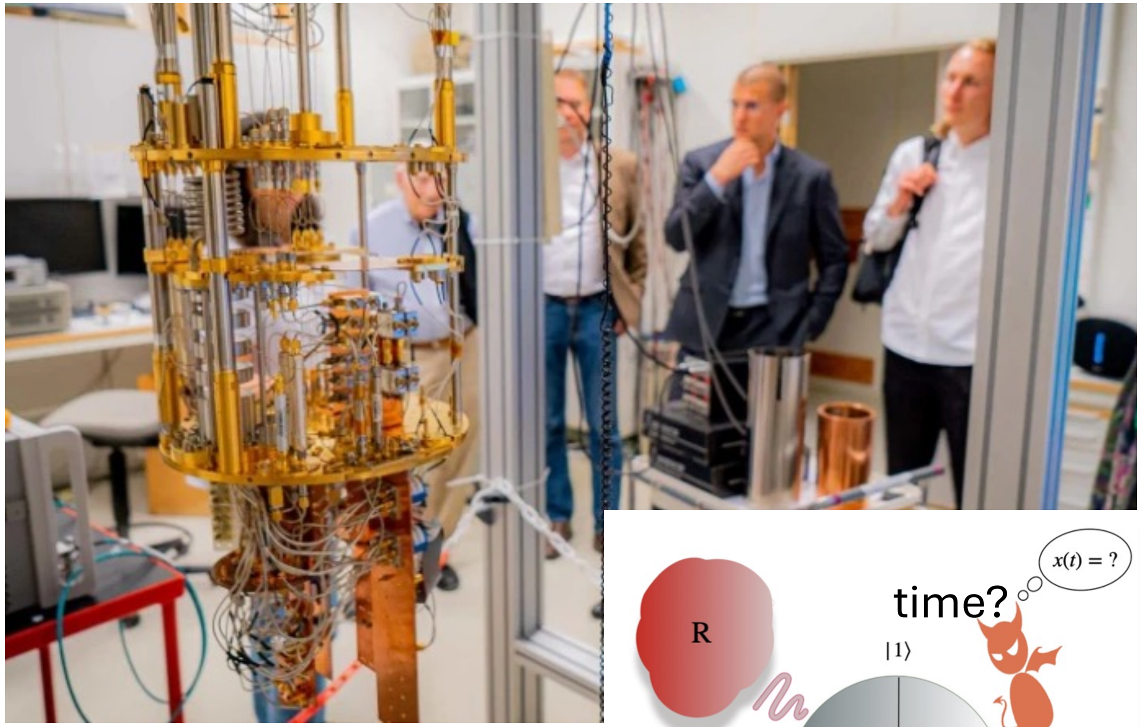
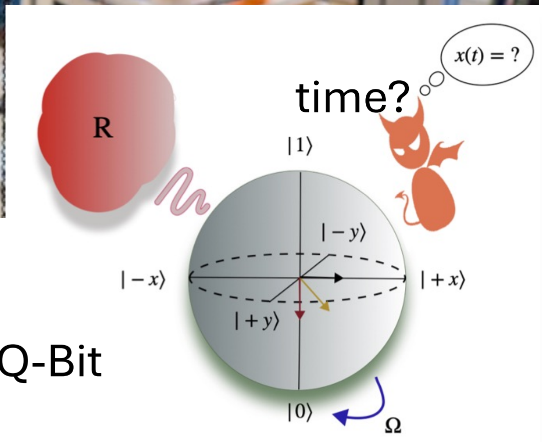
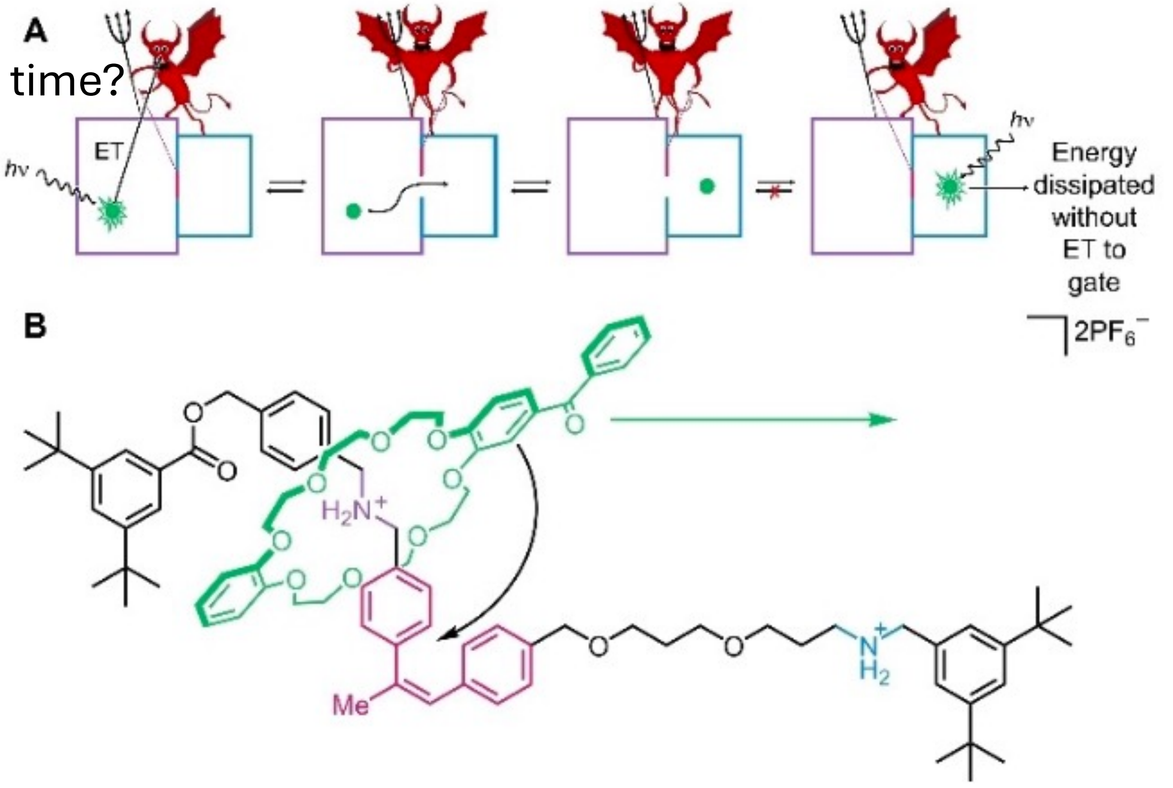
EOC24, Trinity College Dublin, July, 16th

Motivation: Measurement Time-
*How **fast** can one **get** information and **use** it ?*





Q-Bit



Molecular **information ratchet**: Macrocycle

©*Photo 1: Chalmers Quantum Computer*
©*Photo 2: K.* Yanik et al . *Phys. Rev. A* **106**, 04222 (2022)

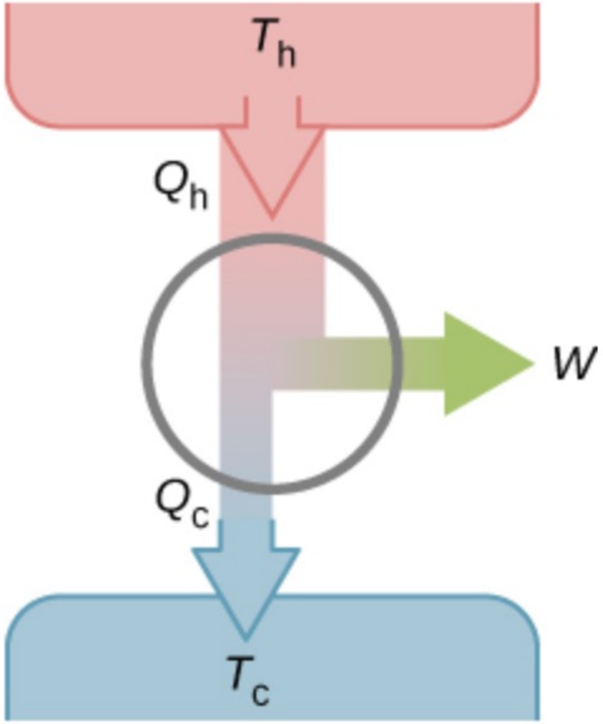
V. Serreli et *al.*, *Nature* ***445***, 523-527 (2024)
S. Borsley, D. A. Leigh, and B. M. W. Roberts, *Angew. Chem. Int. Ed.* **2024**, e202400495 (2024)

Overview

- Recap: Information Engine
- Quantum Measurement & Measurement Time
- Measurement Performance: Information Gain & Cost
- Information Engine Cycle
- Engine Performance: Efficiency and Power

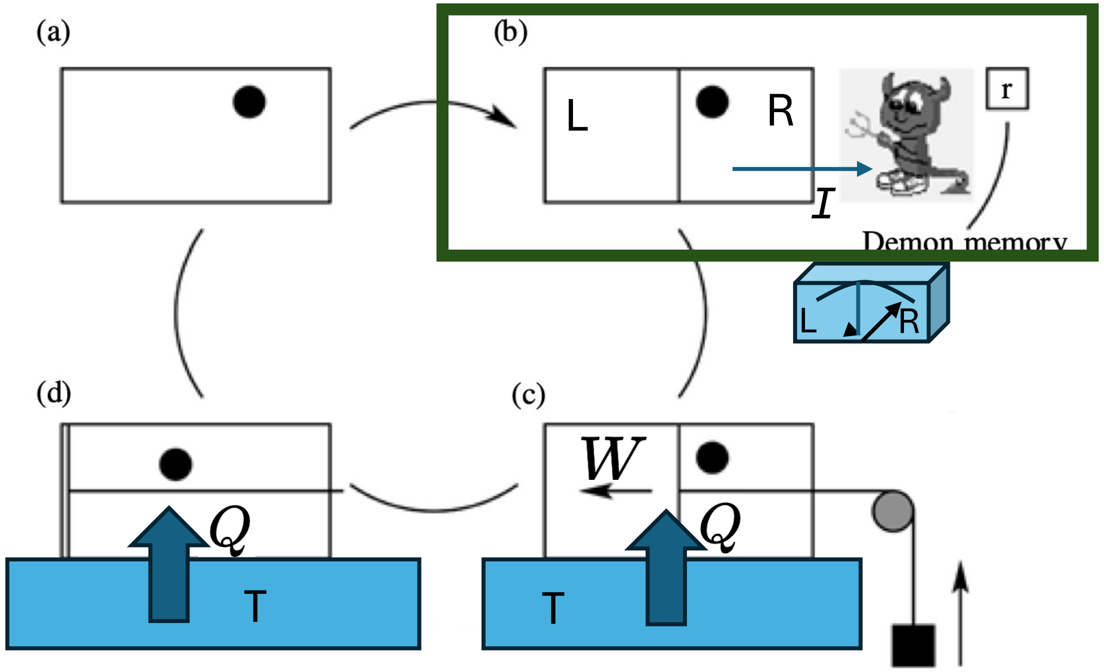
Recap: Information Engine

Heat engine



$$W \leq Q_h - Q_c$$

Szilard engine



1st law $\quad W \leq Q$

2nd law $\quad I = S = Q/T = k_B \ln 2$

© Carnot cycle: https://pressbooks.online.ucf.edu/phy2048tjb/chapter/4-5-the-carnot-cycle/

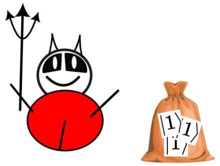
L. Szilard, *Zeitschrift fuer Physik*, ***53***, *11-12 (1921)*
M. B. Plenio and V. Vitelli, *Contemporary Physics*, ***42***, *25-60 (2001)*

Quantum Measurement

Strong Measurement

- **Projective measurement** on state

$|1\rangle$



- **Increase** of the systems **free energy**

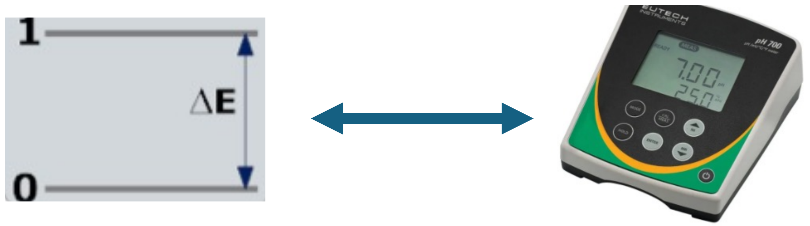
$$F = U - \boxed{TS}$$

- **2nd law** is **satisfied** by memory (Maxwell demon)
- **Landauer erasure:**

$$W_{eras} \geq k_B T S$$

Weak Measurement

- **System – ancilla/meter** entanglement



$|M\rangle$

- **Projection** on **ancilla** state => information on the system
- **POVM-operations**: e.g., "effective" Kraus operators

$$\langle M| U(\hat{\rho}_S \otimes \hat{\rho}_M) U^\dagger |M\rangle$$

time?

- **Energy cost (bound)**

$$W_{\text{meas}}^M + W_{\text{eras}}^M \geq k_B T I.$$

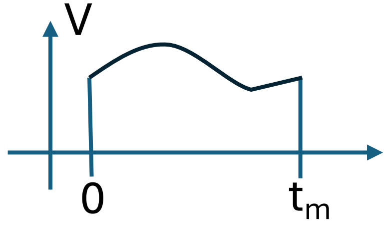
Time-dependence?

T. Sagawa and M. Ueda, PRL **102** (2009)

- **NOW: <u>Assessing measurement time</u>**

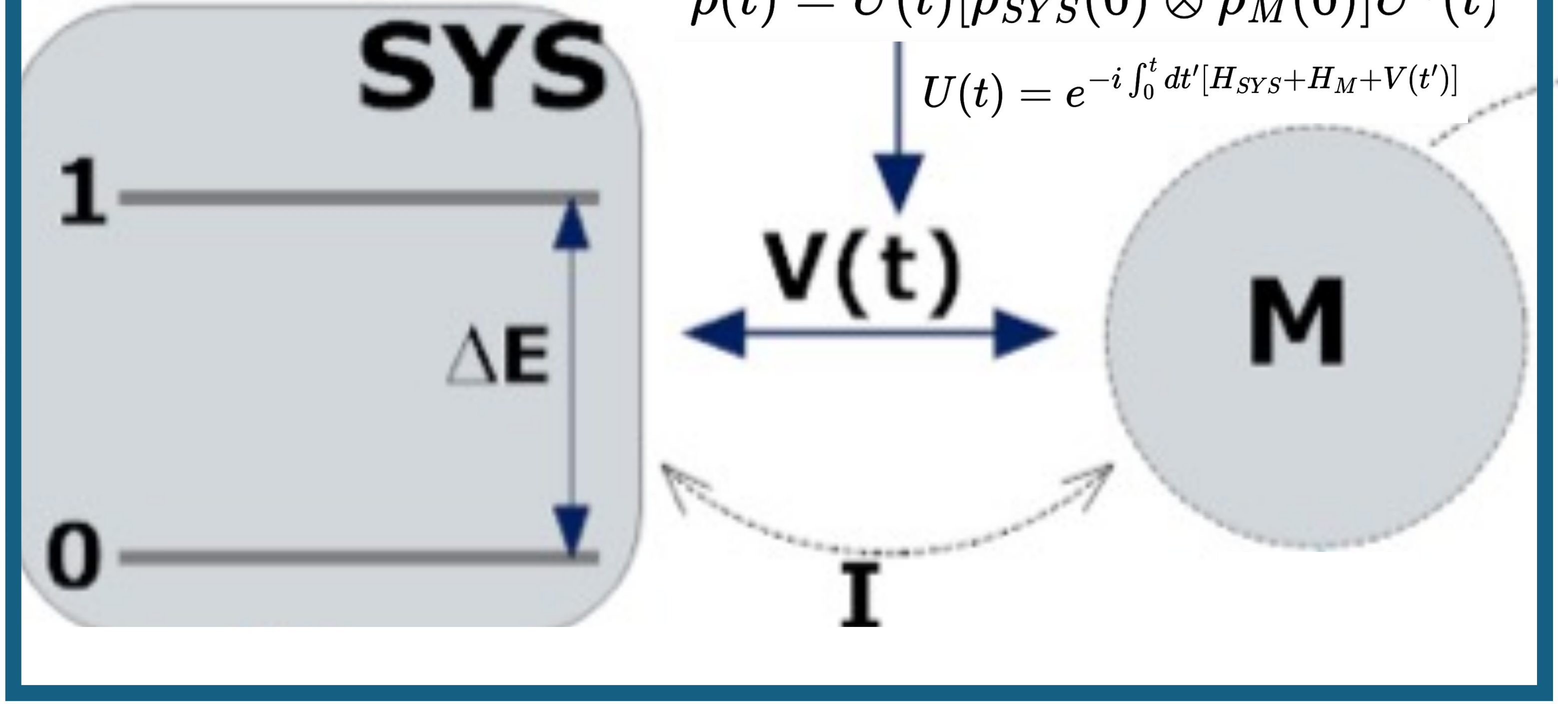
Core of Information Engine:
Measurement Process & Time

$$W_{meas} = \mathrm{tr}\Big(\hat{\rho}(0)\hat{V}(0)\Big) - \mathrm{tr}\Big(\hat{\rho}(t_m)\hat{V}(t_m)\Big)$$



$$\hat{\rho}(t) = U(t)[\hat{\rho}_{SYS}(0) \otimes \hat{\rho}_M(0)]U^{\dagger}(t)$$

$$U(t) = e^{-i\int_0^t dt'[H_{SYS}+H_M+V(t')]}$$



Measurement on meter:

$$\hat{P}(t_m|m) = |m\rangle\langle m|\hat{\rho}(t_m)|m\rangle\langle m|/p_m$$

$$p_m = \mathrm{tr}\big(\langle m|\hat{\rho}(t_m)|m\rangle\big)$$

Information gain:

$$I_m(t_m) \equiv S(0) - S(t_m)$$

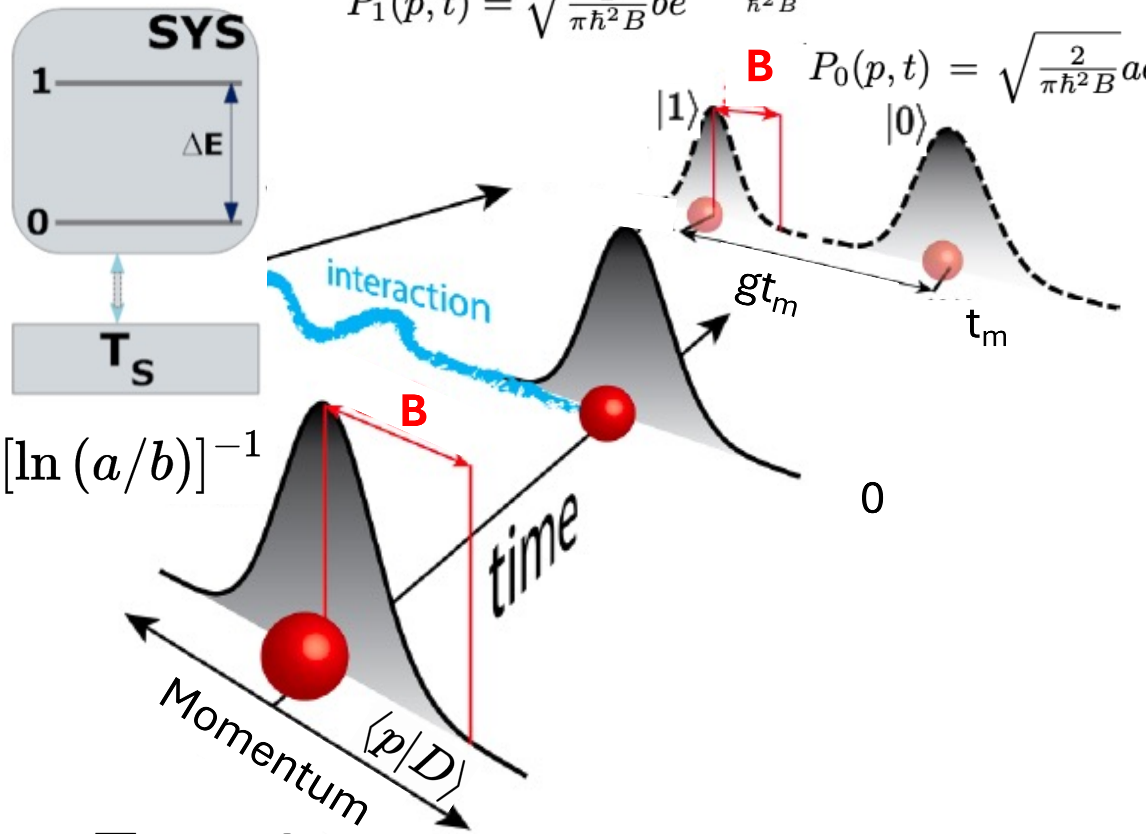
$$S(t_m) \equiv -k_B \sum_m p_m\, \mathrm{tr}\Big(\hat{P}(t_m|m)\ln \hat{P}(t_m|m)\Big)$$

H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Prototype: 2-Level-System & Free Particle Meter

$$P_1(p,t) = \sqrt{\frac{2}{\pi\hbar^2 B}}\, b e^{-\frac{2(p+gt)^2}{\hbar^2 B}}$$

$$P_0(p,t) = \sqrt{\frac{2}{\pi\hbar^2 B}}\, a e^{-\frac{2p^2}{\hbar^2 B}}$$



$$T_S = \Delta E / k_B [\ln(a/b)]^{-1}$$

$$T_M = 0$$

Entangling evolution:

$$\hat{\rho}(t_m) = e^{-i\hat{H}t_m/\hbar}\hat{\rho}(0)e^{i\hat{H}t_m/\hbar}.$$

$$\hat{\rho}(t=0) = \boxed{\hat{\rho}_S(t=0)} \otimes \boxed{\hat{\rho}_M(t=0)}$$

$$\hat{H} = \boxed{\Delta E \left|1\right\rangle\left\langle 1\right|} + \boxed{\frac{\hat{p}^2}{2}} + \boxed{\hat{V}(t)}$$

$$\boxed{\hat{V}(t)} \equiv \hat{V} = g \cdot \boxed{\hat{x}} \otimes \boxed{\left|1\right\rangle\left\langle 1\right|}$$

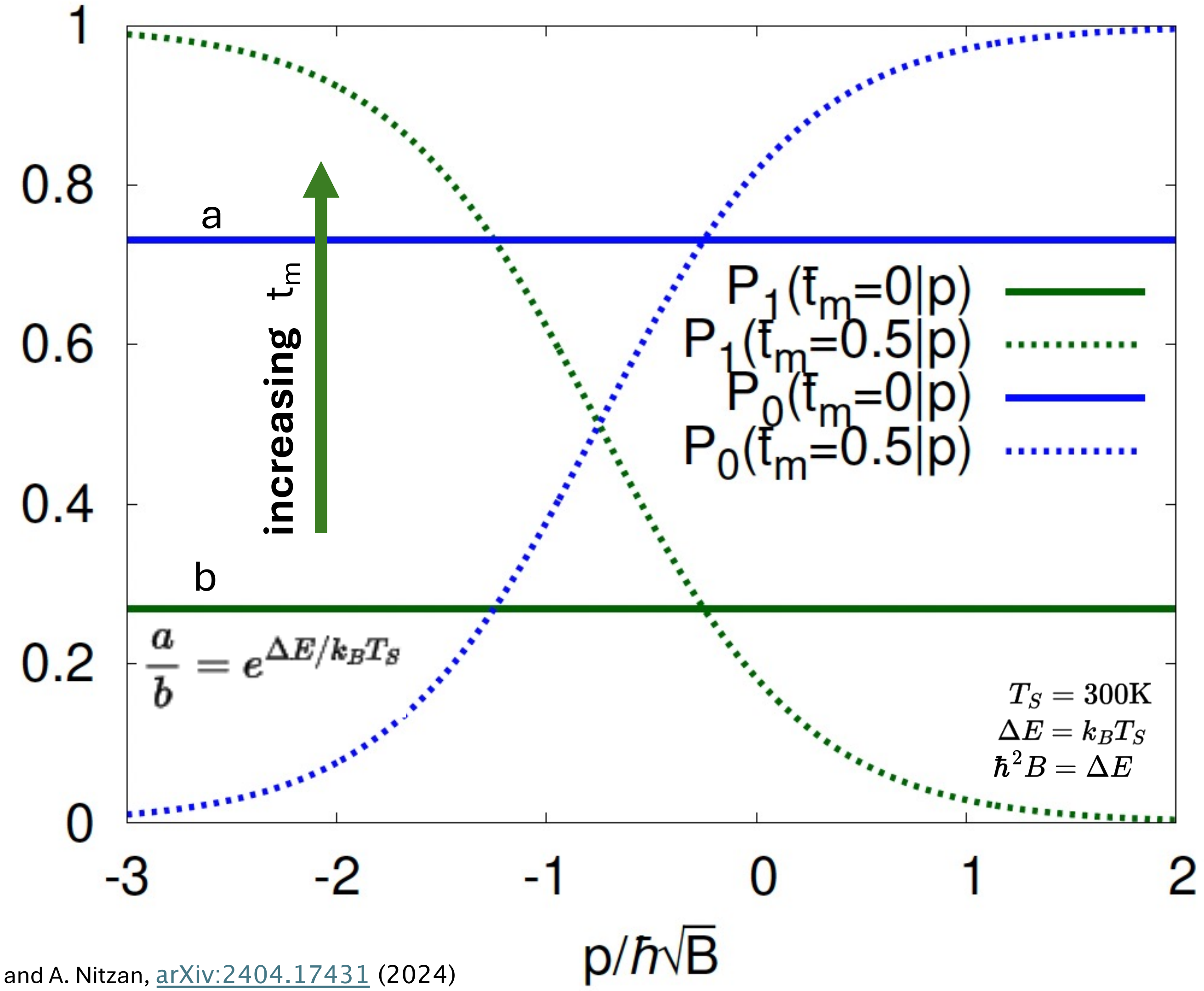
for $0 \leq t \leq t_m$

Projection on meter:

$$\left\langle p\right|\hat{\rho}(t_m)\left|p\right\rangle = \boxed{P_0(p,t_m)}\boxed{\left|0\right\rangle\left\langle 0\right|} + \boxed{P_1(p,t_m)}\boxed{\left|1\right\rangle\left\langle 1\right|}$$

H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Measurement Performance: Conditional Probability



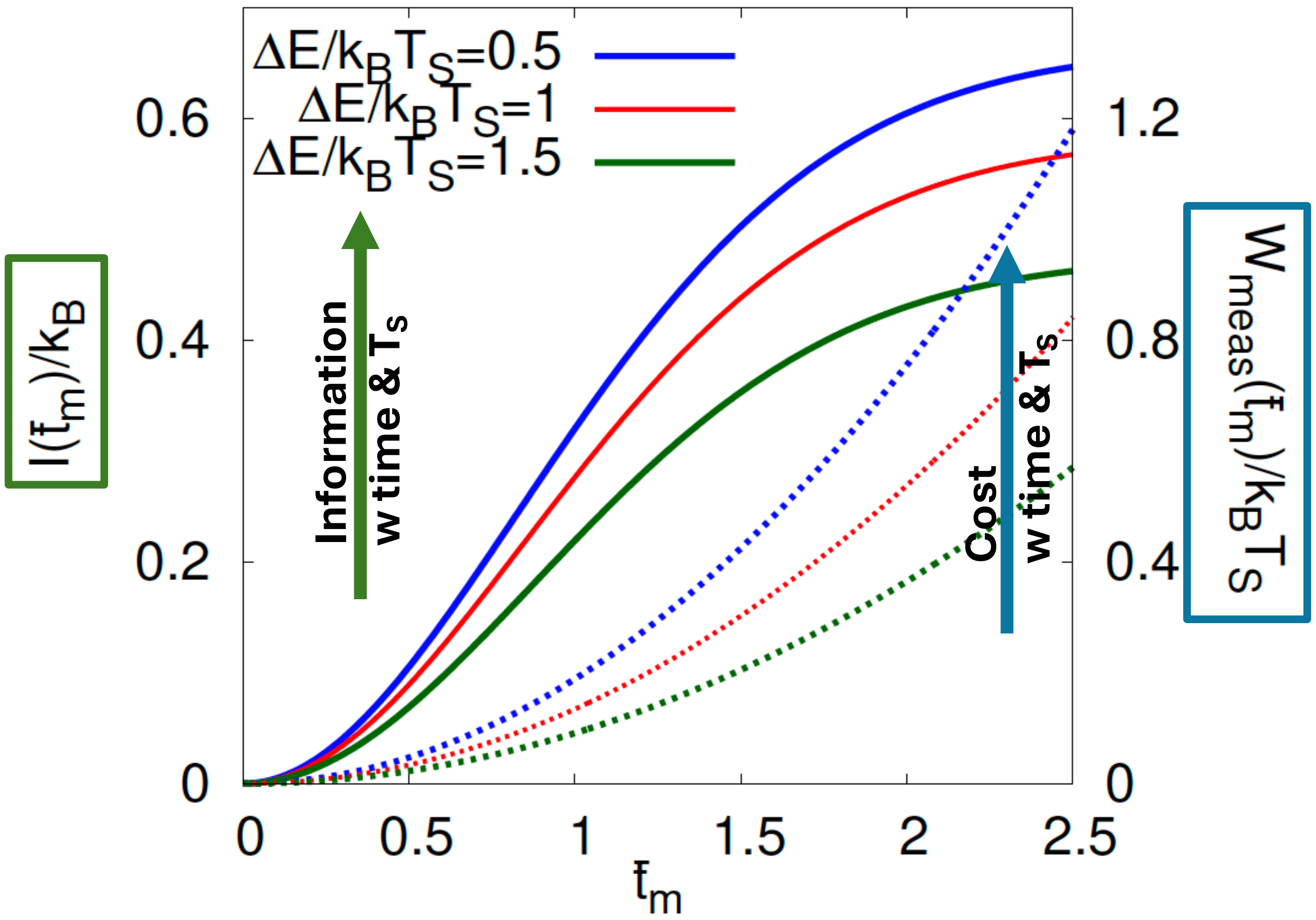
Increasing conditional probabilities to be in excited state for given meter outcomes with measurement time

Rescaled measurement time:

$$\bar{t}_m \equiv \boxed{g} t_m/\hbar \boxed{\sqrt{B}}$$

H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Measurement Performance: Information Gain & Cost



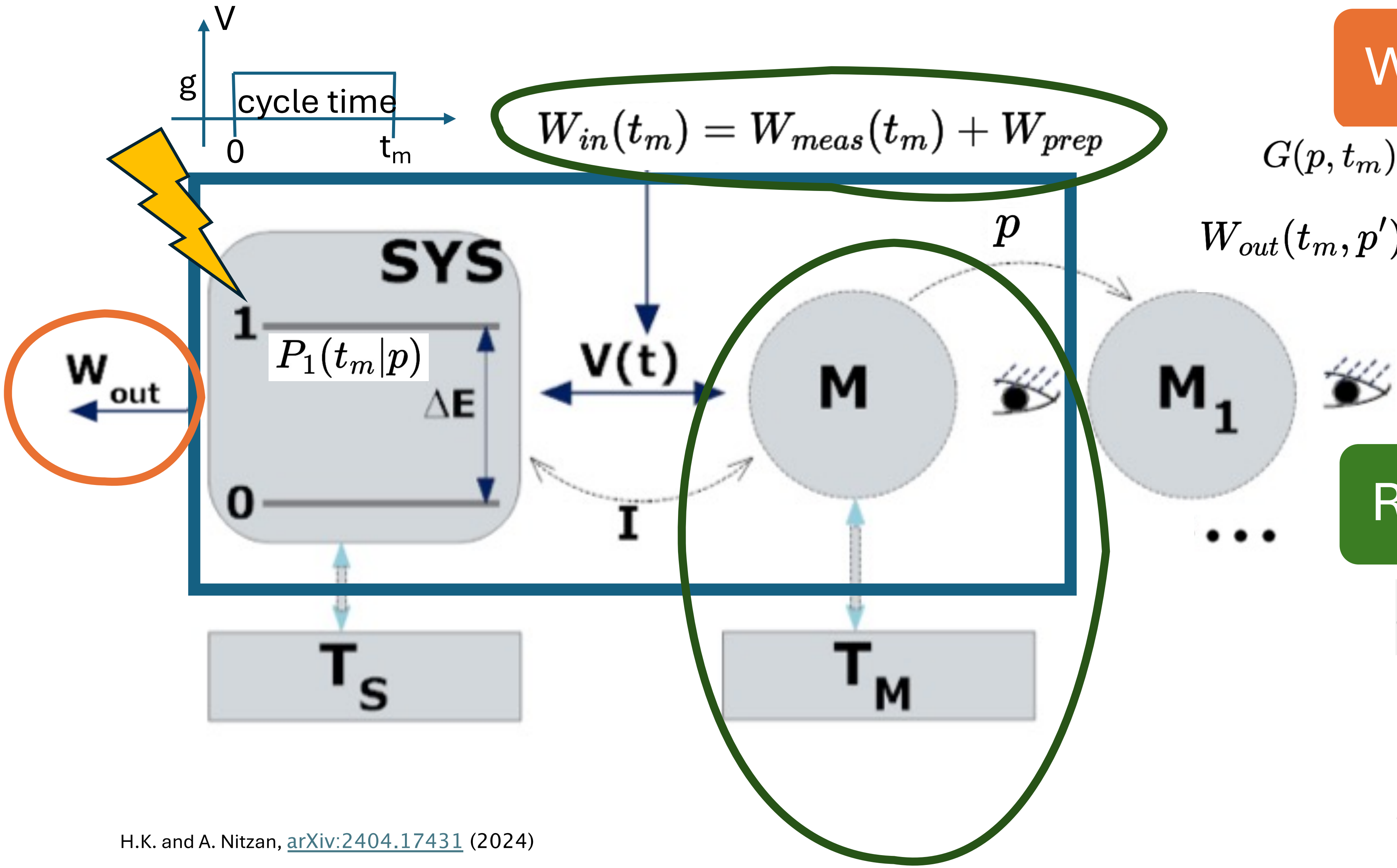
$$\boxed{I_m(t_m) \equiv S(0) - S(t_m)}$$

$$\boxed{W_{meas} = \mathrm{tr}\left(\hat{\rho}(0)\hat{V}(0)\right) - \mathrm{tr}\left(\hat{\rho}(t_m)\hat{V}(t_m)\right)}$$

More information gain with measurement time before saturating $-a\ln a - b\ln b$ but increasing measurement cost over time

H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Information Engine Cycle

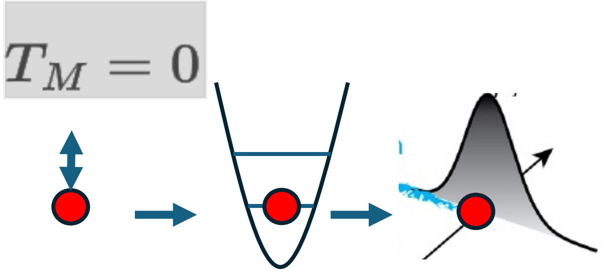


Work extraction

$$G(p, t_m) = \Delta E[P_1(t_m|p) - P_1(0|p)]$$

$$W_{out}(t_m, p') = \int_{-\infty}^{p'} dp P(p, t_m) G(p, t_m)$$

Restoration work



$$W_{prep} = \hbar\Omega/2 = \hbar^2 B/4$$

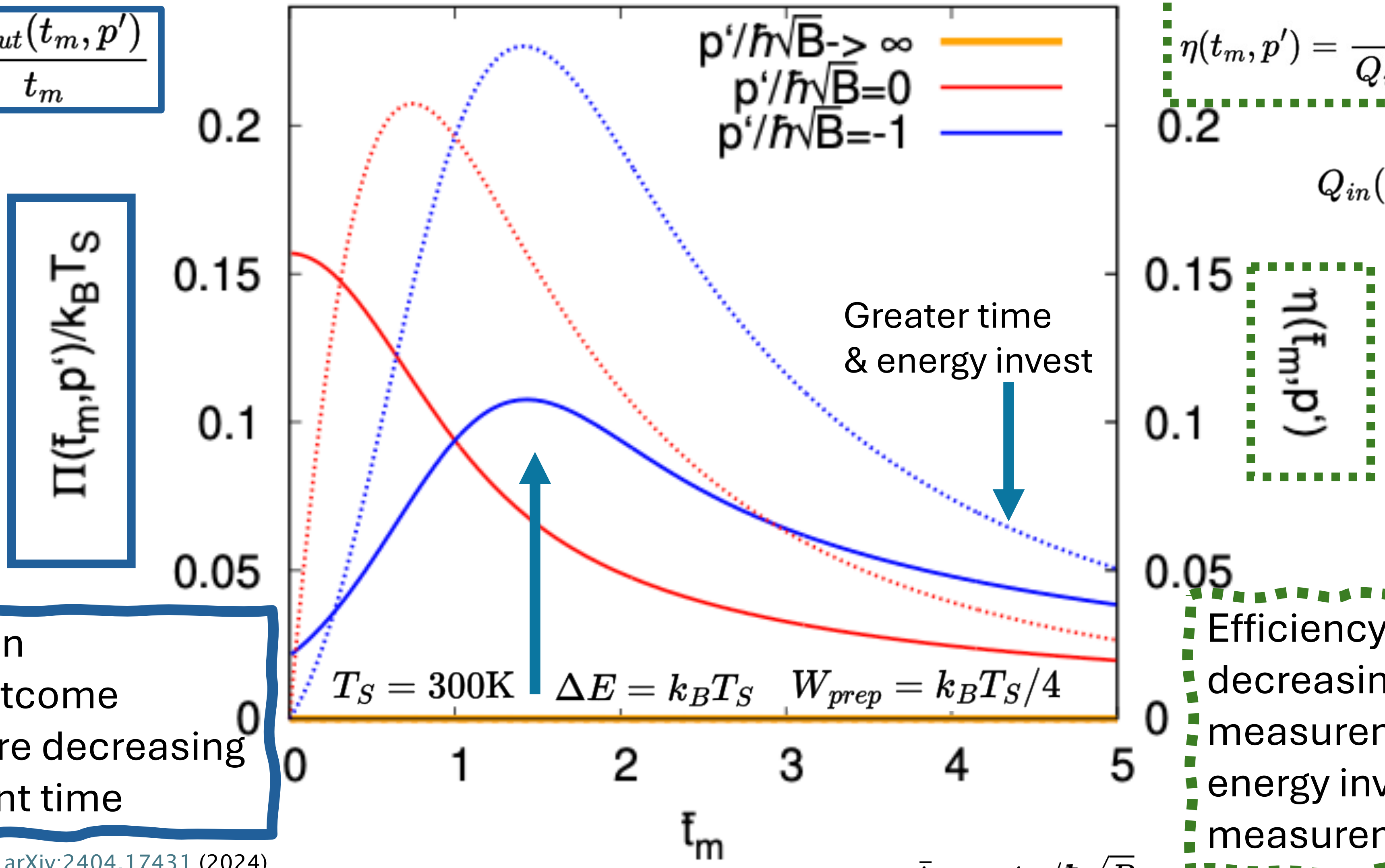
H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Engine Performance: Power and Efficiency

$$\Pi(t_m, p') = \frac{W_{out}(t_m, p')}{t_m}$$

$$\eta(t_m, p') = \frac{W_{out}(t_m, p')}{Q_{in}(t_m, p') + W_{in}(t_m)}$$

$$Q_{in}(t_m, p') \equiv W_{out}(t_m, p')$$



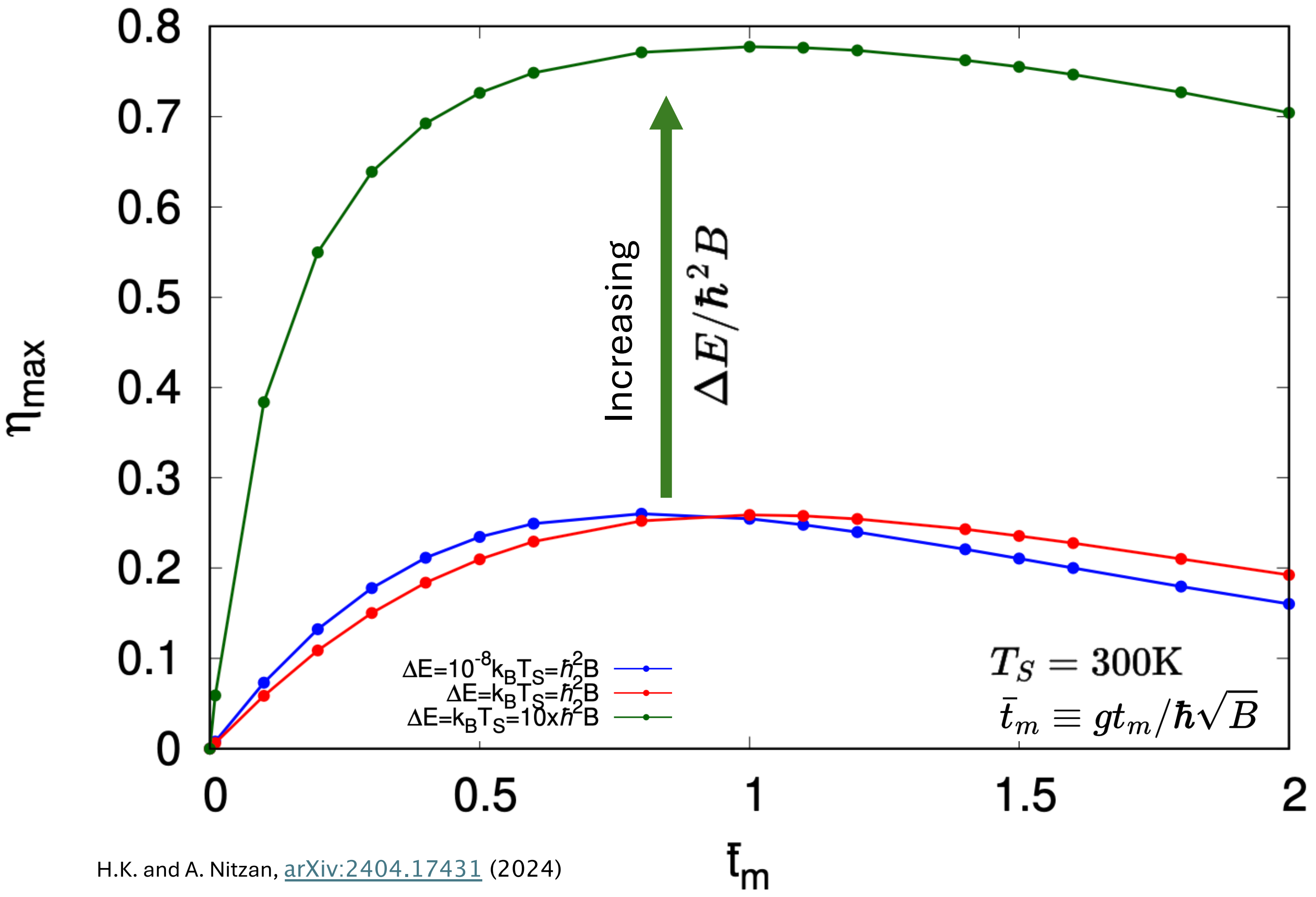
$\bar{t}_m \equiv g t_m/\hbar\sqrt{B}$

Power depends on measurement outcome threshold p' before decreasing with measurement time

Efficiency peaks before decreasing with measurement time as energy investment in measurement increases

H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Engine Performance: Maximum Efficiency



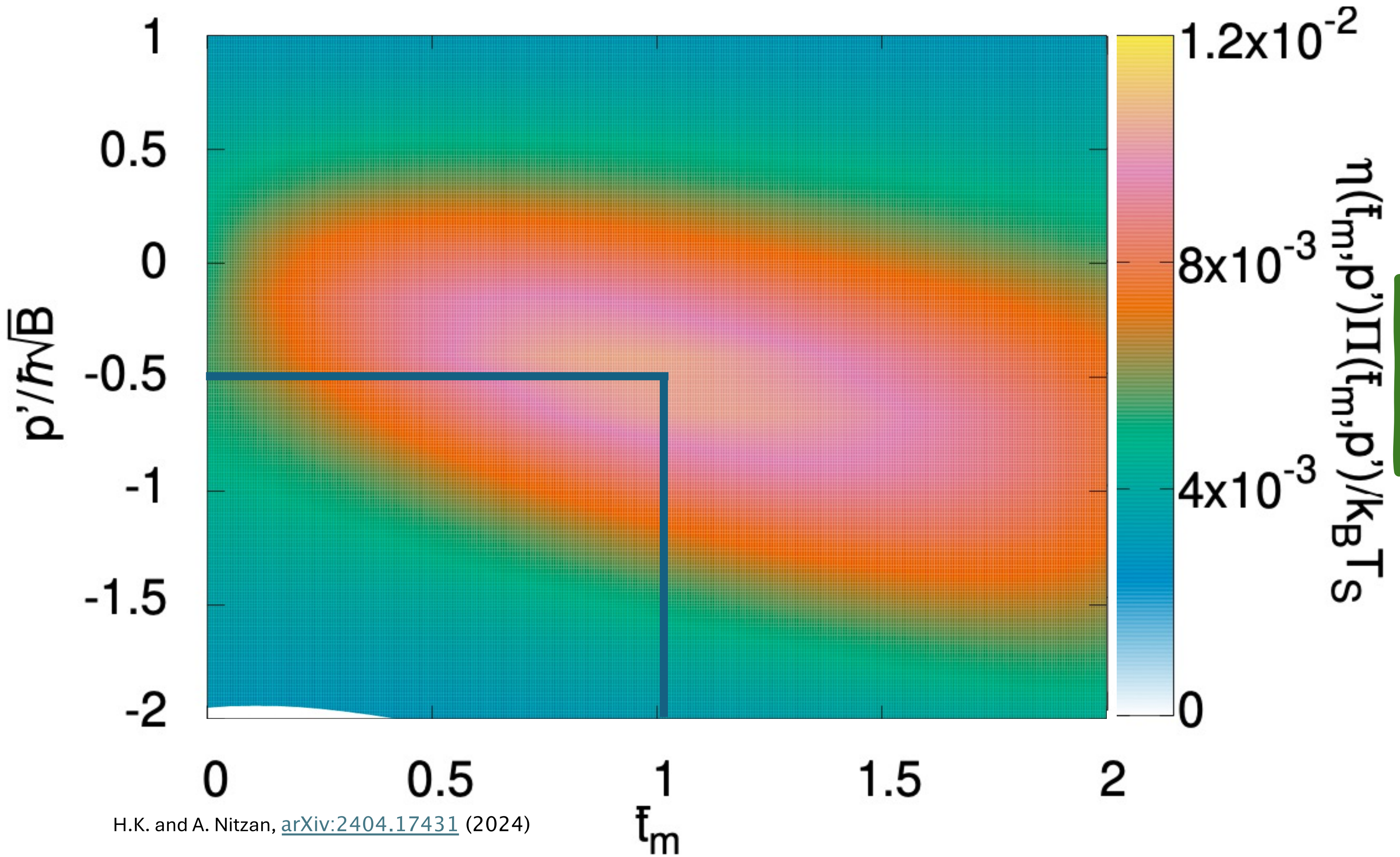
$$\eta(t_m,p') = \frac{1}{1+W_{in}(t_m)/W_{out}(t_m,p')}$$

$$W_{in}(t_m)/W_{out}(t_m,p') \propto \hbar^2 B/\Delta E$$

Higher efficiency if the system energy difference is larger than meter "fluctuations"!

H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Engine Performance: Efficiency x Power



Product of efficiency and power defines best engine operation

H.K. and A. Nitzan, arXiv:2404.17431 (2024)

$T_S = 300\text{K}$

$\Delta E = k_B T_S \;\; \hbar^2 B = \Delta E$

$\bar{t}_m \equiv g t_m / \hbar\sqrt{B}$

Comparison to heat engine

Carnot engine

- Efficiency: $\eta_c = 1 - T_c/T_h$

$$T_c = T_h => \eta_c = 0$$

$$T_c = 0 => \eta_c = 1$$

- Performance: Zero power at highest (Carnot) efficiency

Information engine

- Efficiency:

$$T_M = T_S => \eta \geq 0$$

$$T_M = 0 => \eta \leq 1$$

- Performance: Power **AND** efficiency can peak together

Part of the energy investment is ”work”

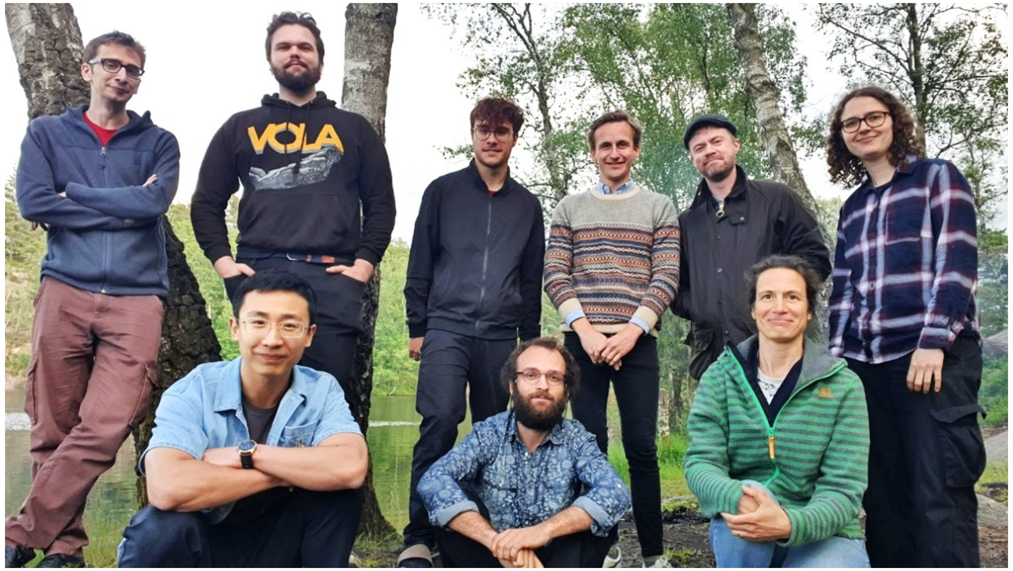
H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Conclusion & Outlook

- **Assessing measurement time** is important to address **measurement efficiency** => Information gain / time
- **Measurement time** is related to **the system-meter correlation time**
- **Cyclic time** of information engine is bounded by this time
- **Information gain & Measurement cost** are correlated to **measurement time**
- *Prototype Information Engine*:
  - **Efficiency:** Increases with time before going (diminishing returns)
  - **Power:** Decreasing over time
- **Next: Finite meter temperature & Implementation into molecular transfer** processes

H.K. and A. Nitzan, arXiv:2404.17431 (2024)

Thank you for your attention!



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UNIVERSITY OF TECHNOLOGY

Department of
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AND NANOSCIENCE

Open Positions

A. PhD position:
"Nanoelectronic devices coupled to light"

B. Master /Research Project:
"Quantum Information Engine: Converting Information to Useful Work"

School

"Quantum thermodynamics meets quantum transport", Chalmers, November, 11-15

Deadline: September, 15

https://sites.google.com/site/splettchalmers/research-group