An optically pumped two-stroke thermal machine

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1. Introduction

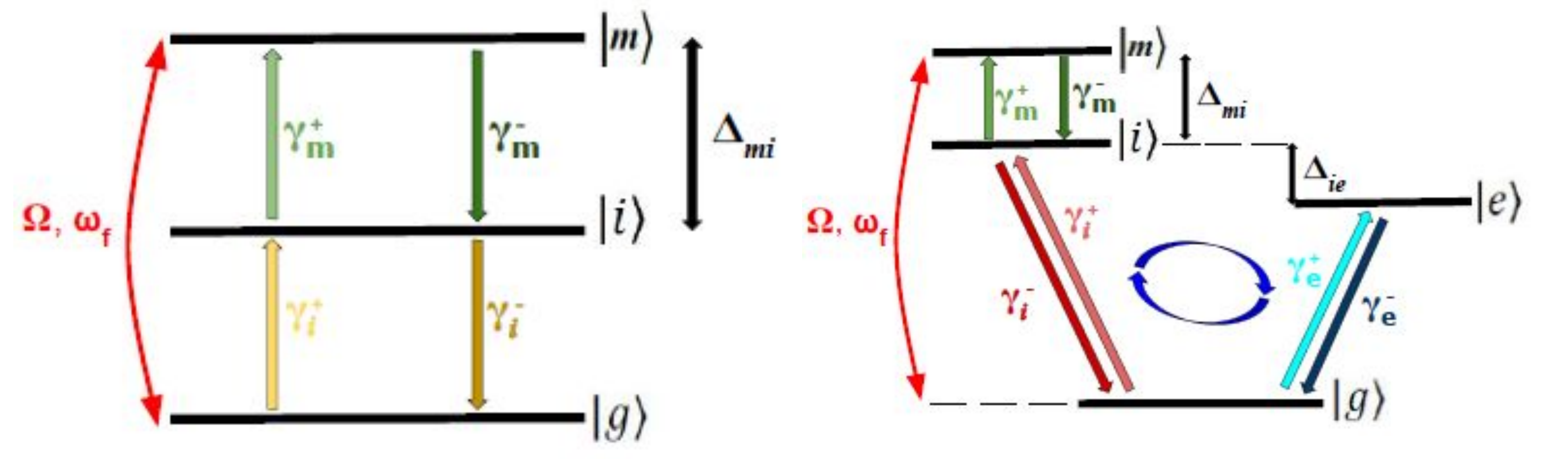


Fig. 1: (a) Quantum battery model. (b) Quantum thermal machine model.

In this work we analyse the efficiency and the stored power in a quantum battery due to an optical pumping process, and the performance of this quantum battery operating as the working fluid of a two-stroke quantum thermal machine.

Our quantum battery consists of a qutrit that is connected to a thermal reservoir and to an external work drive (Fig. 1 (a)). The machine includes a fourth level (Fig. 1 (b)) and operates a cycle where energy is stored through the optical pumping and extracted by means of an unitary transformation.

We focus on the limit in which we can adiabatically eliminate the higher energy level, i.e., level **|m⟩** (Fig. 1).

2. Quantum battery

We assume that initially **(t = 0)** the system (qutrit) is in a Gibbs state. Then an external work drive is turned on, and the system evolves to a nonequilibrium steady state, $\boldsymbol{\varrho}_{\mathbf{NESS}}$, with energy stored in it. In the following $\hbar$ = 1 and k_B = 1.

$$\rho(0) = e^{-\beta H_0}/Z \qquad H_0 = \omega_j\,|E_j\rangle\langle E_j| \qquad \beta = 1/T \qquad Z = \mathrm{Tr}(e^{-\beta H_0})$$

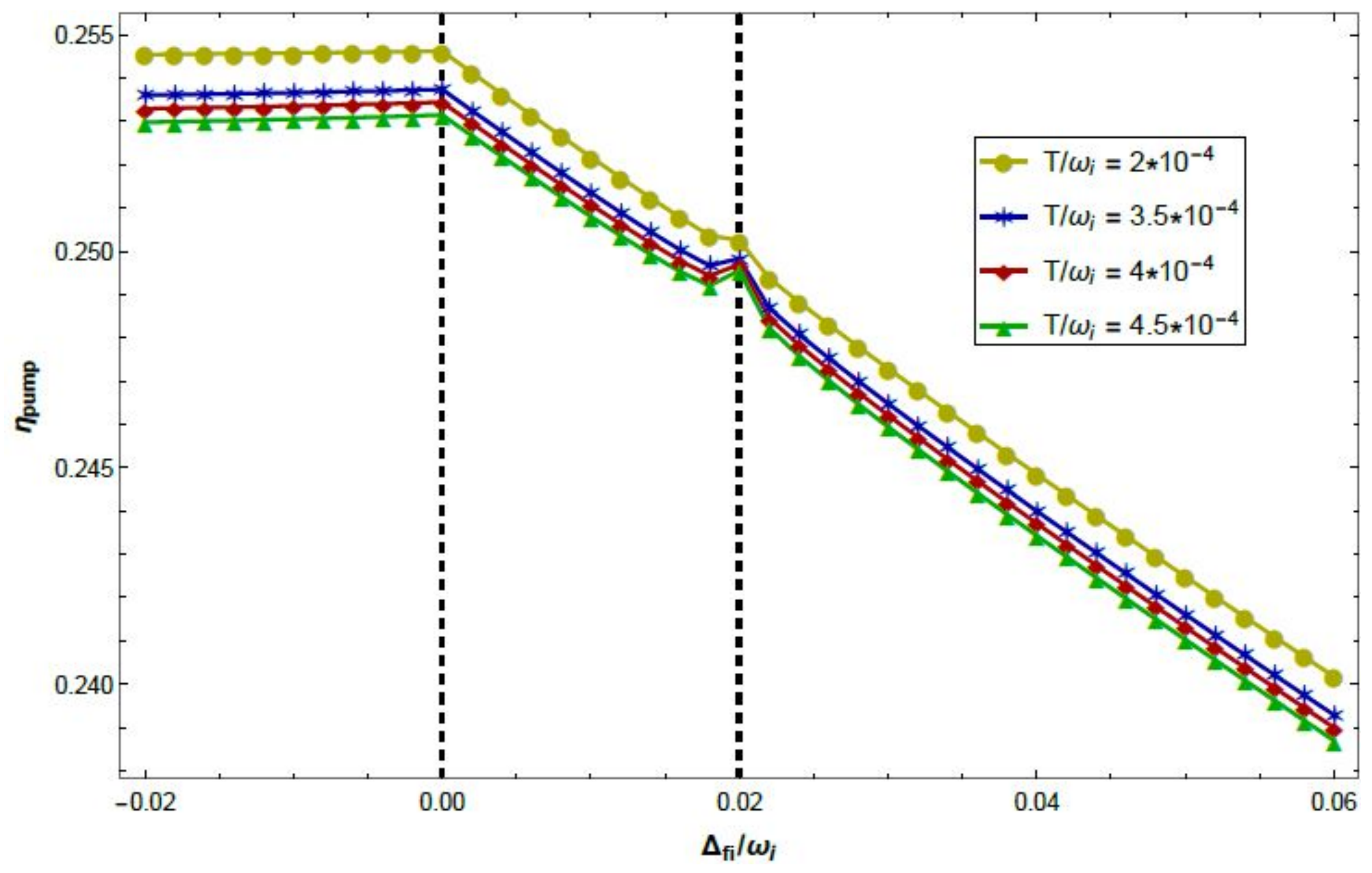


Fig. 2: We plot the pumping efficiency, $\eta_{\mathbf{pump}}$= **ΔF/E$_{\mathbf{in}}$**, as a function of **$\Delta_{\mathrm{fi}} = \omega_{\mathrm{f}} - \omega_{\mathrm{i}}$**, where **ΔF** is the variation of the Helmholtz free energy (**F = E(t) - TS(t)**) and **E$_{\mathbf{in}}$** is the energy injected into the system in the optical pumping process.

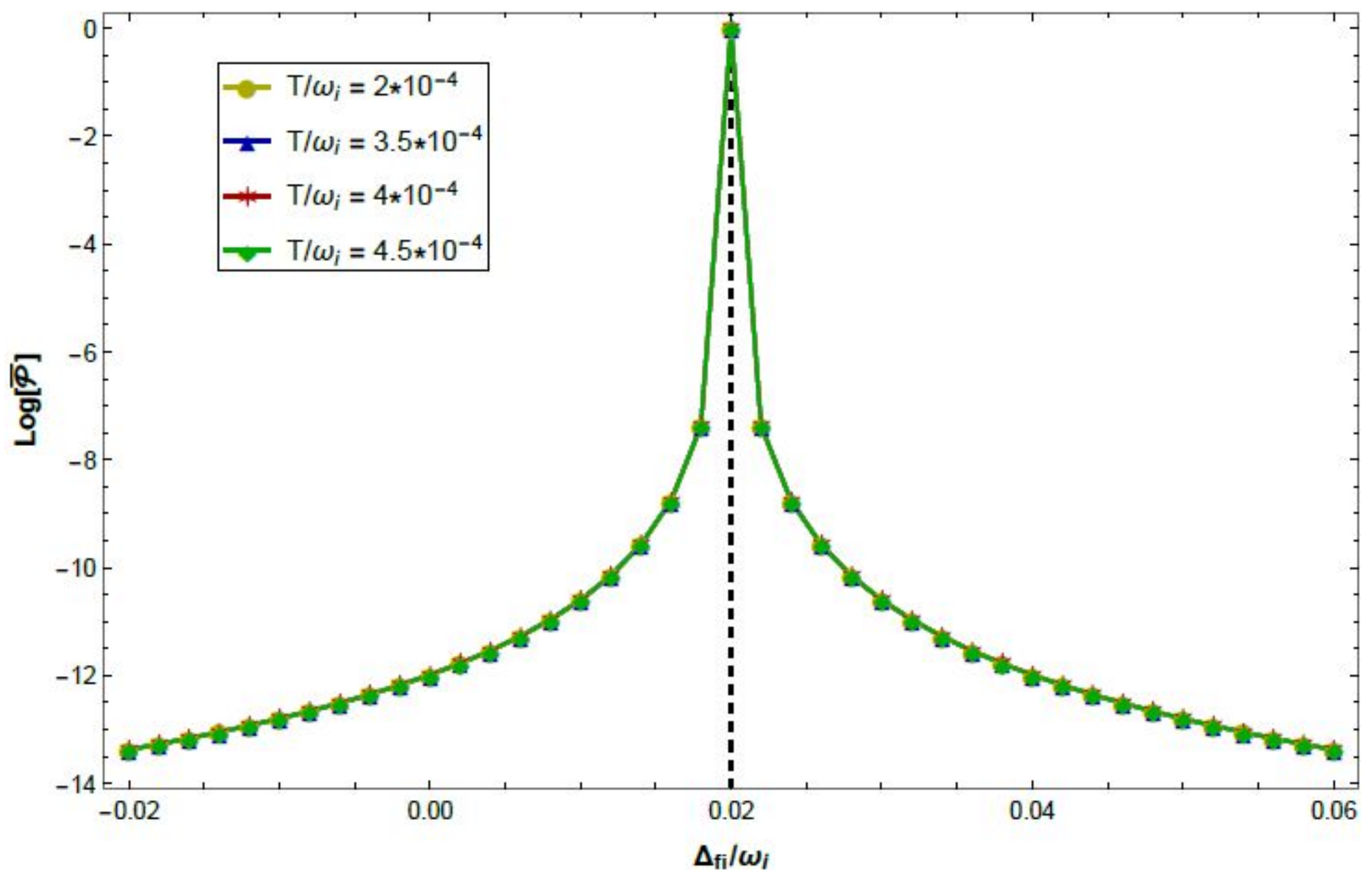
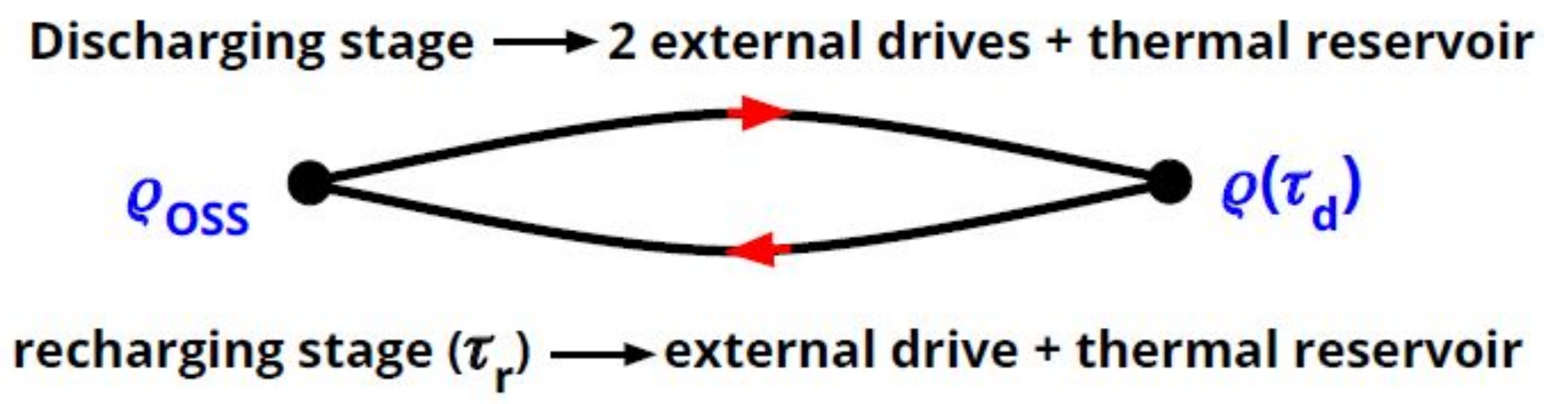


Fig. 3: We plot the log of the stored power, $\mathcal{P}_{\mathbf{pump}}$ **= ΔF/$\boldsymbol{\tau}$**, divided by its maximum, where $\boldsymbol{\tau}$ is the time it takes for the system to reach $\boldsymbol{\varrho}_{\mathbf{NESS}}$ from the initial Gibbs state, as function of **$\Delta_{\mathrm{fi}} = \omega_{\mathrm{f}} - \omega_{\mathrm{i}}$**.

3. Thermal Machine



Discharging stage → 2 external drives + thermal reservoir

recharging stage (τ_r) → external drive + thermal reservoir

Fig. 4: The machine operates in a two-stroke cycle: a discharging stage and a recharging stage **[1, 2]**. The total duration of the cycle is given by $\boldsymbol{\tau} = \boldsymbol{\tau}_{\mathbf{d}} + \boldsymbol{\tau}_{\mathbf{r}}$, where $\boldsymbol{\tau}_{\mathbf{d}}$ is the time duration of the discharging stage and $\boldsymbol{\tau}_{\mathbf{r}}$ is the time duration of the recharging stage. The starting point of our cycle is an active state that we shall refer to as an **operational steady state** $\boldsymbol{\varrho}_{\mathbf{OSS}}$.

As an example, we compute the efficiency and the output power in the ideal case and in the short cycle limit **($\Sigma_j \gamma_j \tau << 1$)**.

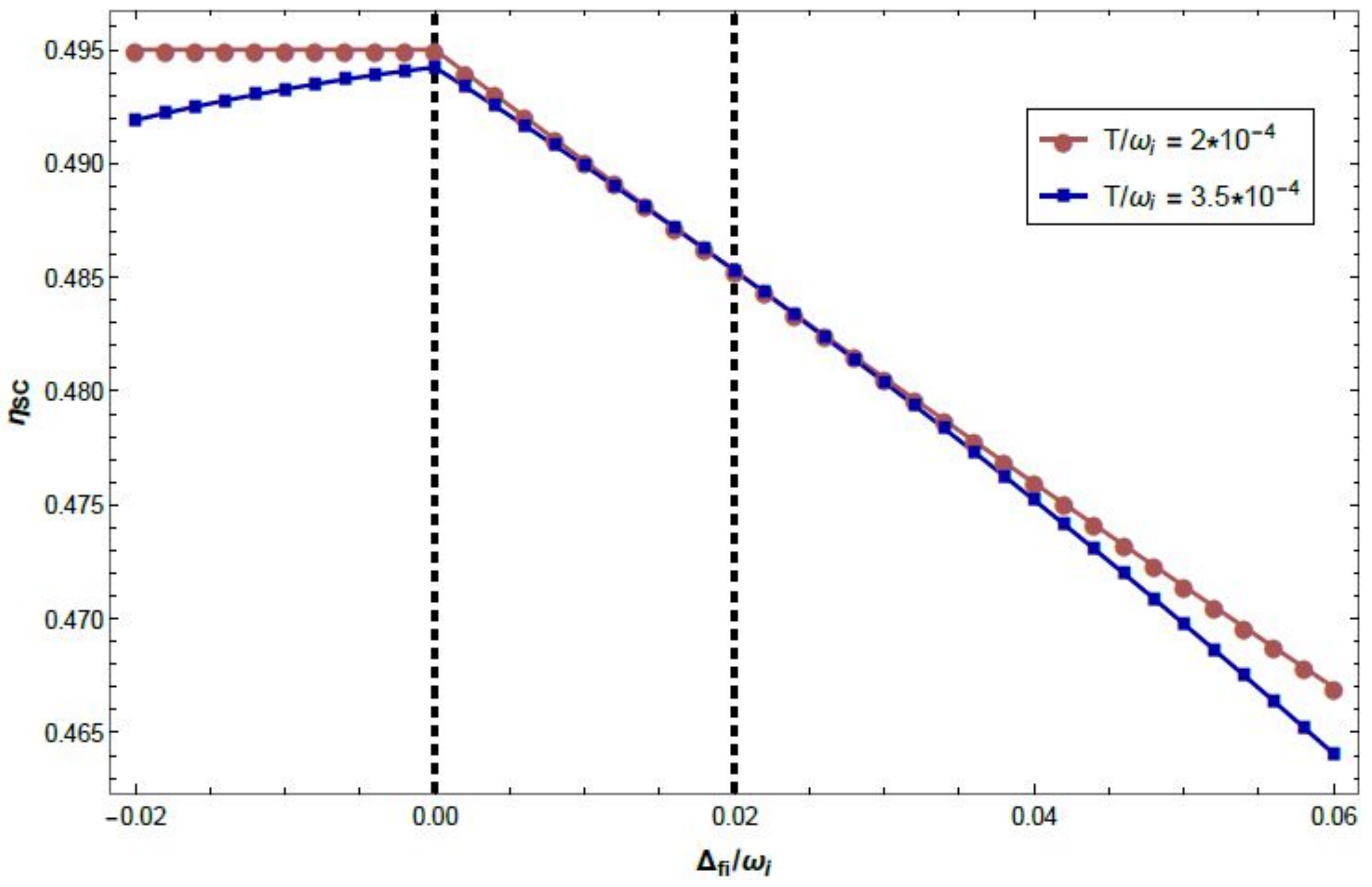


Fig.5: We plot the efficiency in the ideal short cycle limit, $\eta_{\mathbf{SC}}$ **= Ɛ/E$_{\mathbf{in}}$,** as a function of **$\Delta_{\mathrm{fi}} = \omega_{\mathrm{f}} - \omega_{\mathrm{i}}$**. In this scenario the work performed by the machine is equal to the ergotropy **[3]**, **Ɛ**, stored in the operational steady state $\boldsymbol{\varrho}_{\mathbf{OSS}}$. Here **E$_{\mathbf{in}}$** is the energy injected into the system in a cycle

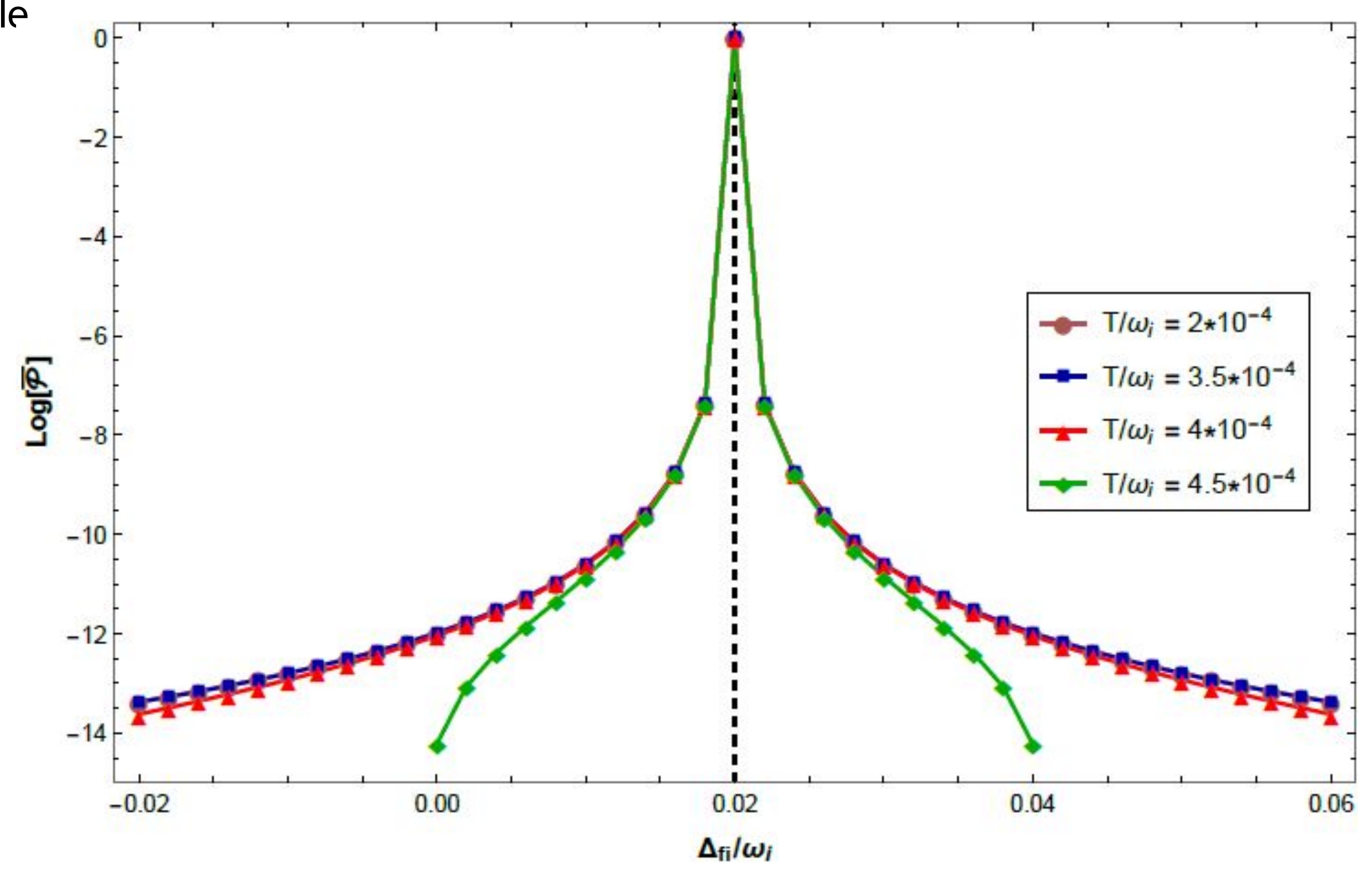


Fig.6: We plot the log of the delivered power, $\mathcal{P}_{\mathbf{SC}}$ **= Ɛ/$\boldsymbol{\tau}$**, divided by its maximum, where $\boldsymbol{\tau}$ is the total duration of the cycle, as a function of **$\Delta_{\mathrm{fi}} = \omega_{\mathrm{f}} - \omega_{\mathrm{i}}$**.

4. Conclusion

We present an analysis of the efficiency and input power of optical pumping in the adiabatic elimination limit as the charging mechanism of a quantum battery. We also study the efficiency and output power of this charged battery as the working fluid of a two-stroke thermal machine. We show that both the charging of the battery and the thermal machine are more efficient when the external drive is resonant to the level that stores energy in the battery, even though the regime that achieves the best input and output powers takes place when the external drive is resonant to the adiabatically eliminated level of the optical pumping scheme.

5.References

[1] F. Tacchino, T. F. F. Santos, D. Gerace, M. Campisi, and M. F. Santos, Charging a quantum battery via nonequilibrium heat current, Phys. Rev. E 102, 062133 (2020).
[2] T. F. F. Santos, F. Tacchino, D. Gerace, M. Campisi and M. F. Santos, Maximally efficient quantum thermal machines fueled by nonequilibrium steady states, Phys. Rev. A 103, 062225 (2021).
[3] A. E. Allahverdyan, R. Balian, and Th. M. Nieuwenhuizen, Maximal work extraction from finite quantum systems, Europhys. Lett. 67, 565 (2004).