Speed-ups to isothermality

Enhanced heat engines by strong couplings

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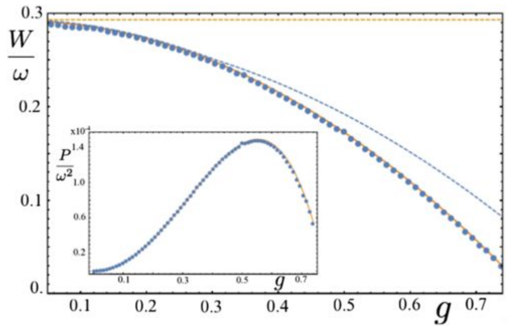
Motivations



- Quasi-static processes play a central role in thermodynamics
- They are normally very slow (one has to wait for long thermalization times)
    - How do we speed them up?
- Interactions speed up thermalization, but they induce dissipation

Can we increase the strength of the interactions while keeping the dissipated work constant?

Ingredients

1. Markovian regime
2. Control over the interaction strength
3. Numerics: quadratic Hamiltonians

Results

Less dissipated work/faster protocols

$$W_{\text{diss}} = \frac{\Sigma_\gamma}{T_{\text{tot}}^\gamma}$$

Efficiency at maximum power interpolates Carnot and Curzon-Ahlborn

$$\eta_C = 1 - \theta$$

$$\Updownarrow$$

$$\eta_{CA} = 1 - \sqrt{\theta}$$

Quasi Static Processes

Generic Thermodynamic protocol. We control:

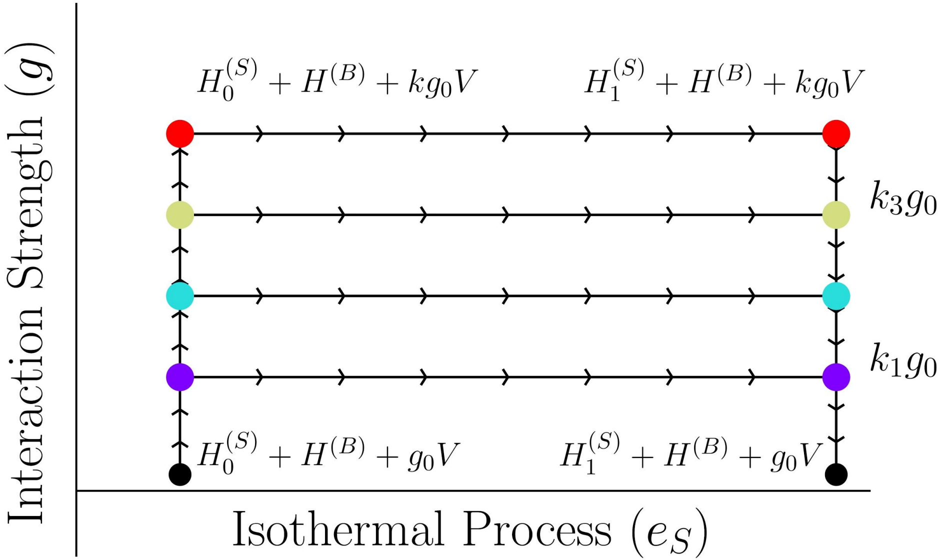
- The interaction strength (g)
- The Hamiltonian of the system

The time dependent Hamiltonian:

$$H(t) = H^{(S)}(t) + g(t)V + H^{(B)}$$

$$W = \Delta F + W_{\text{diss}}$$

$$W_{\text{diss}} = \frac{1}{T_{\text{tot}}} \int_0^1 dt\, G_{\omega_t}\left(\dot{H}_t, \dot{H}_t\right) + \mathcal{O}\left(\frac{1}{T_{\text{tot}}^2}\right)$$



$H_0^{(S)} + H^{(B)} + kg_0V$
$H_1^{(S)} + H^{(B)} + kg_0V$
k_3g_0
k_1g_0
$H_0^{(S)} + H^{(B)} + g_0V$
$H_1^{(S)} + H^{(B)} + g_0V$
Interaction Strength (g)
Isothermal Process (e_S)

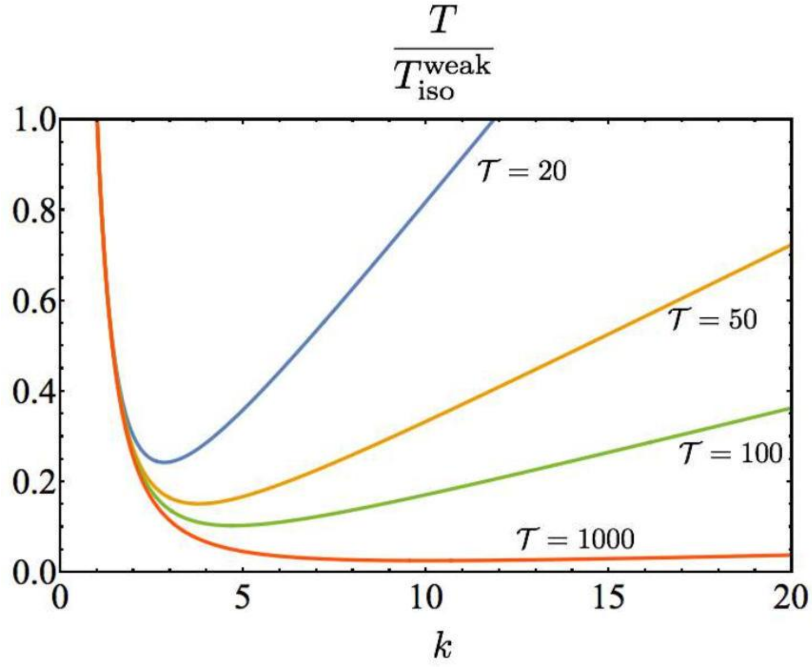
Enhanced Protocols

How to increase the interaction strength:

$$\boxed{g \propto t^{\alpha}}$$

$$\boxed{T_{\text{tot}} = 2F(\alpha,k)T^{\text{on}}_{\text{weak}} + \frac{T^{\text{iso}}_{\text{weak}}}{k^2}}$$

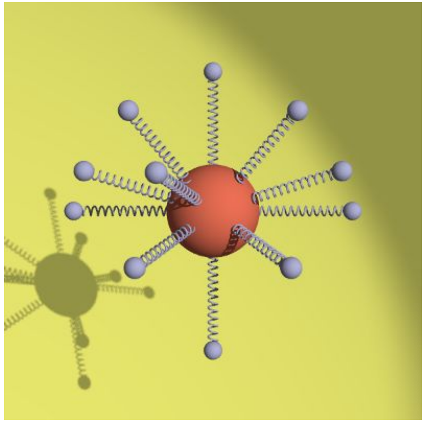
$$W^{\text{weak}}_{\text{diss}} = \frac{\Sigma}{T^{\text{weak}}_{\text{iso}}} \quad \Longrightarrow \quad W_{\text{diss}} = \Sigma C(\alpha)\frac{(T^{\text{weak}}_{\text{on}})^{2\alpha}}{T^{2\alpha+1}_{\text{tot}}}$$


$\frac{T}{T_{\rm iso}^{\rm weak}}$
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
k
$\mathcal{T} = 20$
$\mathcal{T} = 50$
$\mathcal{T} = 100$
$\mathcal{T} = 1000$

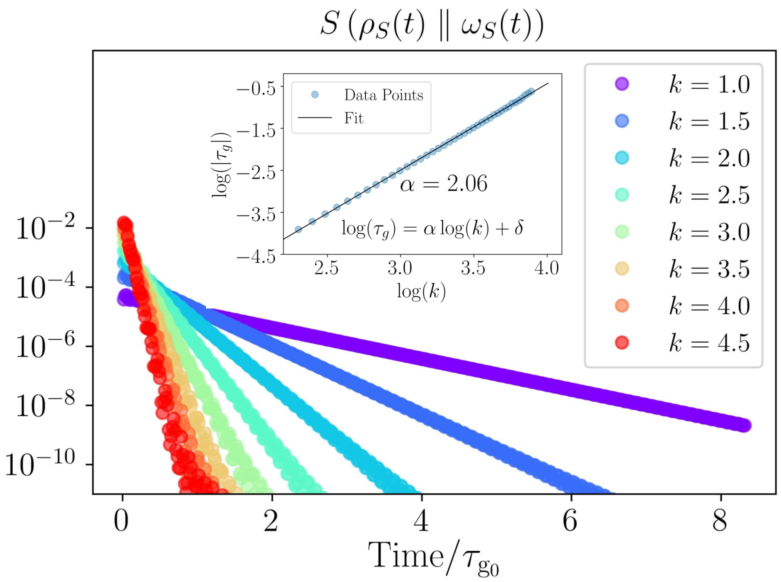
Caldeira-Leggett model

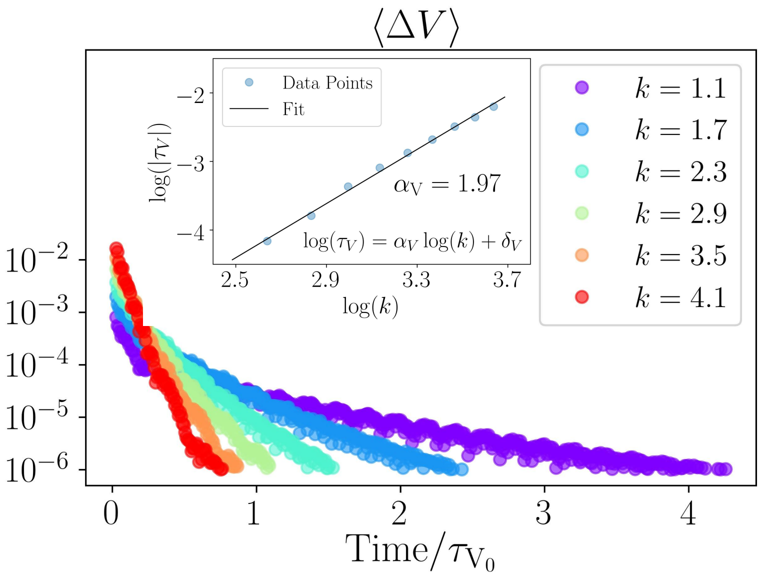
$$H_{CL} = H^{(S)} + gV + H^{(B)} + H^{(R)}$$

$$\begin{cases} H^{(S)} = \frac{1}{2}\left(m\omega_S^2 x^2 + \frac{p^2}{m}\right) \\ H^{(B)} = \frac{1}{2}\sum_{k=0}^{N}\left(\frac{p_k^2}{m_k} + m_k\omega_k^2 x_k^2\right) \\ V = x\sum_k \gamma_k x_k \end{cases}$$

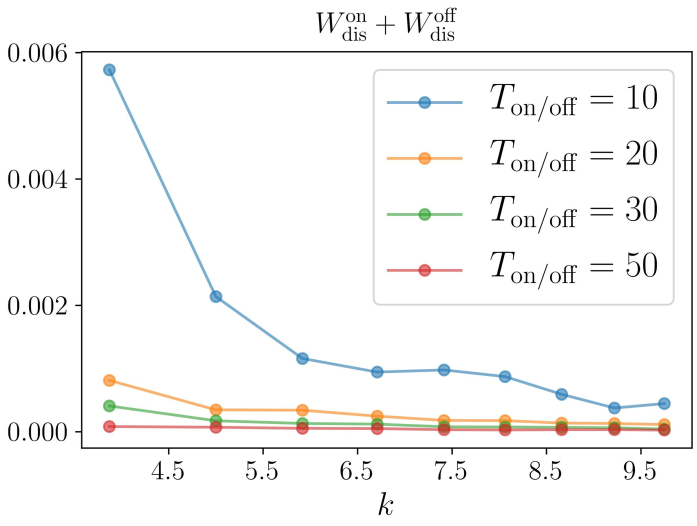


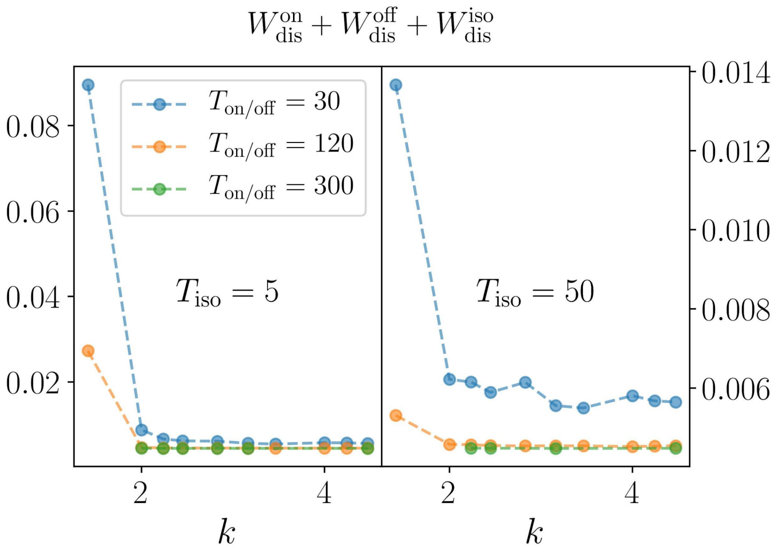
Caldeira-Leggett model: thermalization





Numerical Results





Efficiency at Maximum Power

$$
\left.\begin{aligned}
W_{\text{diss}} &= \frac{\Sigma_\gamma}{T_{\text{tot}}^\gamma} \\
P &= \frac{Q_c + Q_h}{T_c + T_h} \\
\eta &= 1 + \frac{Q_c}{Q_h}
\end{aligned}\right\} \quad \eta^*_\gamma = 1 - \frac{(\gamma\theta + 1)\theta^{\frac{1}{\gamma+1}} + (\gamma+1)\theta}{(\gamma+1)\theta^{\frac{1}{\gamma+1}} + \gamma + \theta} \qquad \theta = \frac{\beta_h}{\beta_c}
$$

$\gamma = \infty$

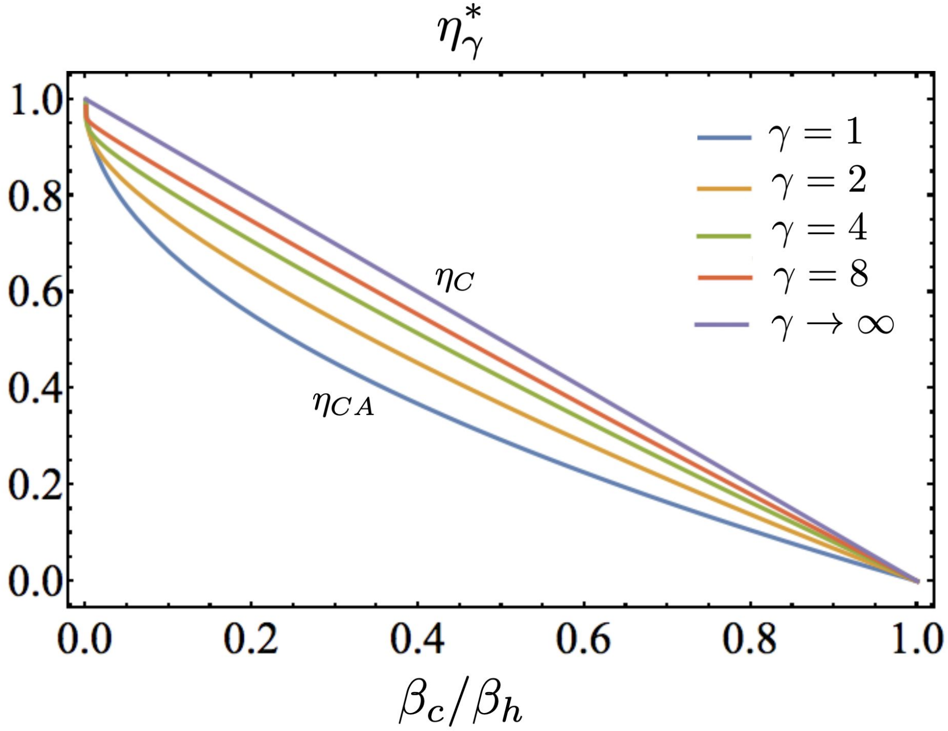
$\gamma = 1$

Carnot

$$\eta_C = 1 - \theta$$

Curzon-Ahlborn

$$\eta_{CA} = 1 - \sqrt{\theta}$$


η^*_γ
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
β_c/β_h
$\gamma = 1$
$\gamma = 2$
$\gamma = 4$
$\gamma = 8$
$\gamma \to \infty$
η_C
η_{CA}

Conclusions

- We design speed-ups of isothermal processes by controlling the interaction strength.
- We carefully account for the work cost of turning on/off the interaction, so that the overall dissipation stays constant.
- For the enhanced protocols, the efficiency at maximum power can interpolate between Carnot and Curzon-Ahlborn

Thanks for Your Attention