

On-site interactions in quantum thermal machines: efficiency, rectification and entanglement beyond local and global master equations

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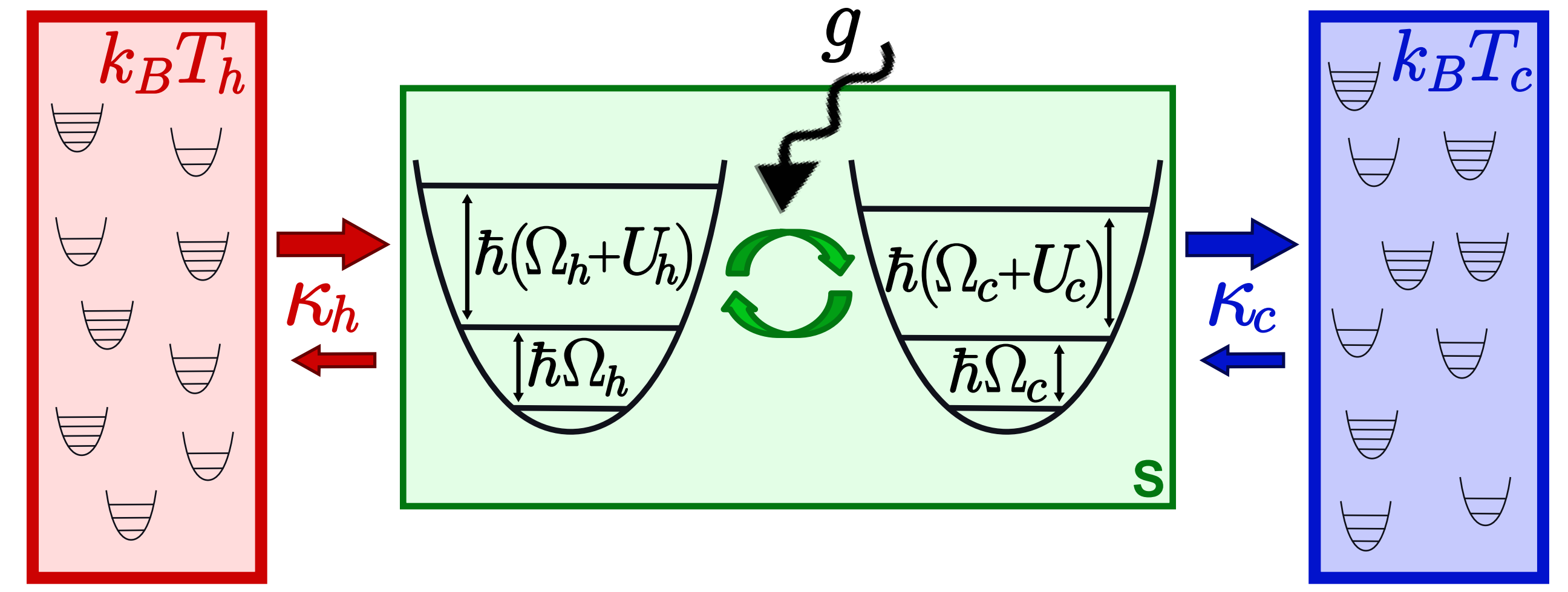
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1. Context

- Accurate descriptions of **quantum transport** in junction connecting reservoirs is key for new **quantum thermodynamic** and **directional** devices (e.g., heat engines, batteries or transistors) [1].
- There exists a debate on which **reduced approach** should be preferred to study the junction dissipative dynamics [2].
- It has been suggested that systems with many-body interactions (e.g., on-site interactions) may exhibit a quantum advantage regarding thermal machines [3].
- Our goals:**
 - Show that the Redfield Master Equation (RME) is the most suitable reduced approach
 - Derive expressions for system-bath correlators, such as heat and particle currents, consistently across different frameworks.
 - Understand how the on-site interactions affect the efficiency of the heat engine and how they induce non-reciprocal transport

2. Model

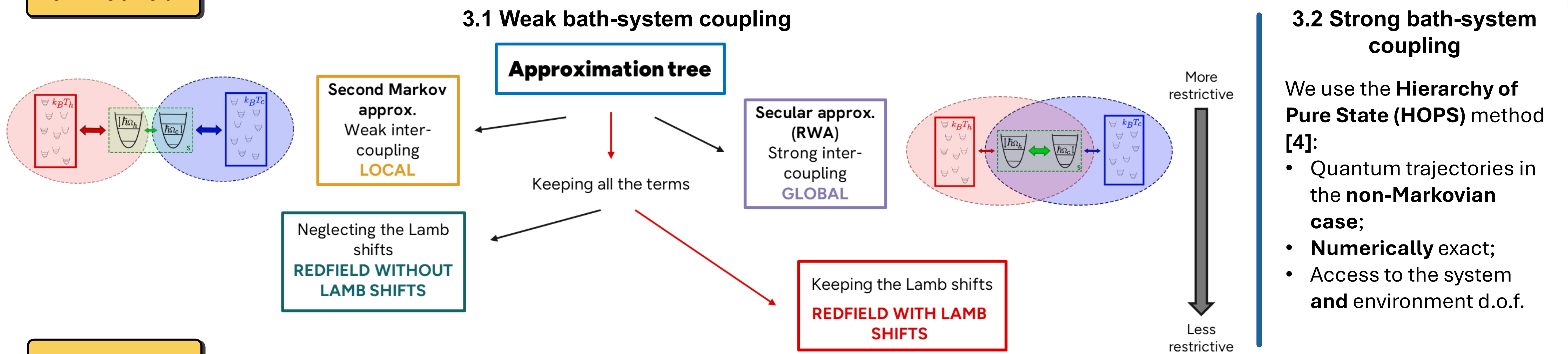


$$H^l(t) = H_S^l(t) + H_h^l + H_c^l + H_I^l,$$

$$H_S^l(t) = \sum_{\ell} \Omega_{\ell} a_{\ell}^{\dagger} a_{\ell} + g(a_c^{\dagger} a_h e^{i(\Omega_h - \Omega_c)t} + \text{h.c.}) + \frac{U_{\ell}}{2} n_{\ell}(n_{\ell} - 1),$$

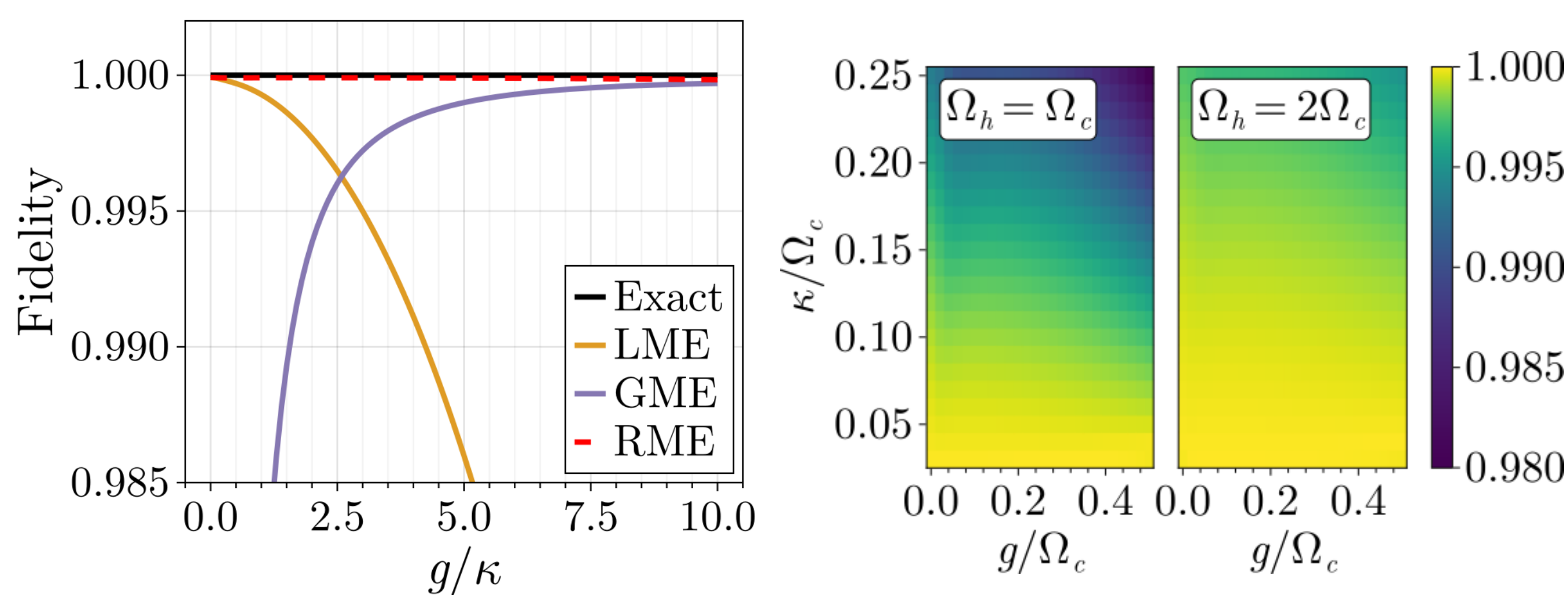
$$H_{\ell}^l = \sum_k \omega_{\ell k} a_{\ell k}^{\dagger} a_{\ell k} \quad (\ell = h, c), \quad H_I^l = \sum_{\ell=h,c} \sum_k (g_{\ell k} a_{\ell}^{\dagger} a_{\ell k} + \text{h.c.})$$

3. Method



4. Results

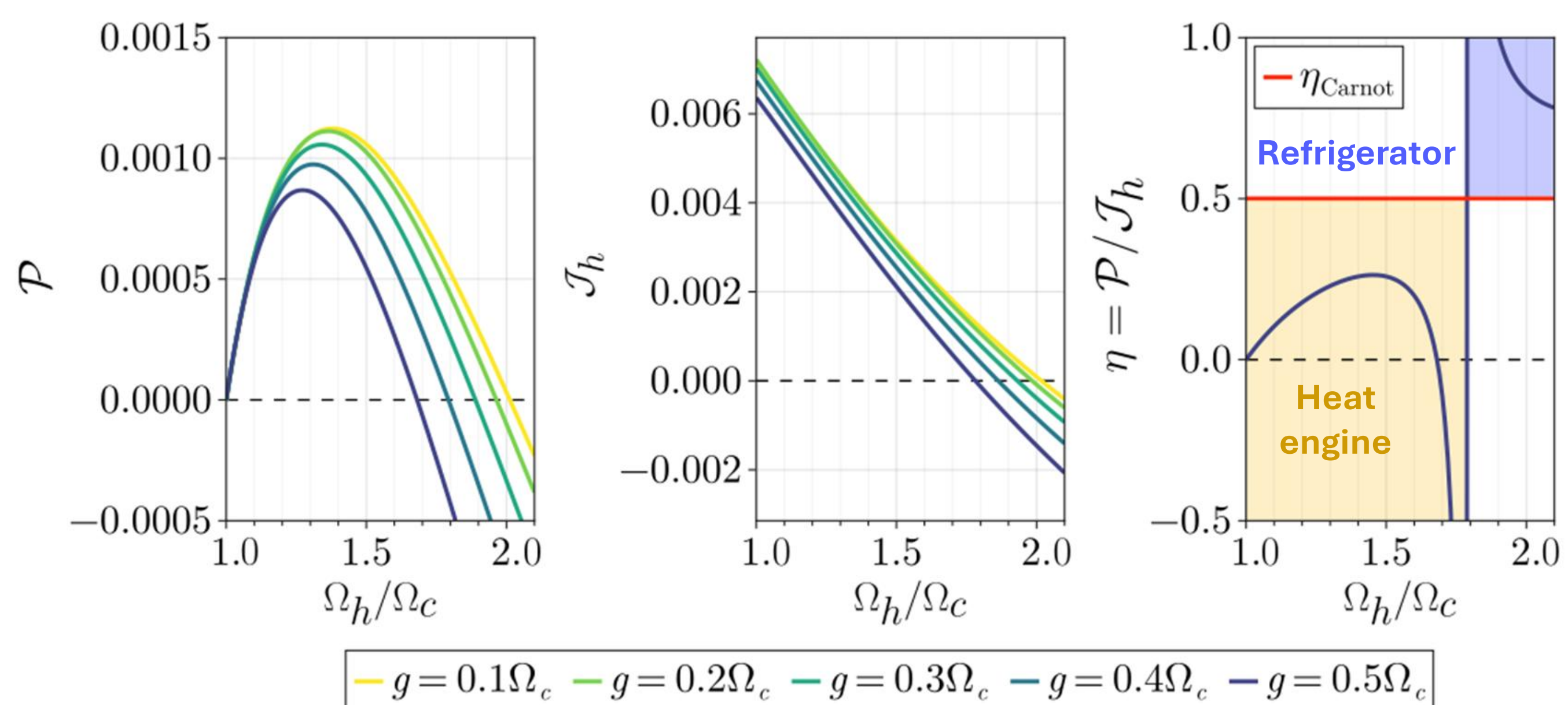
4.1 Non-interacting two-site junction $U = 0$



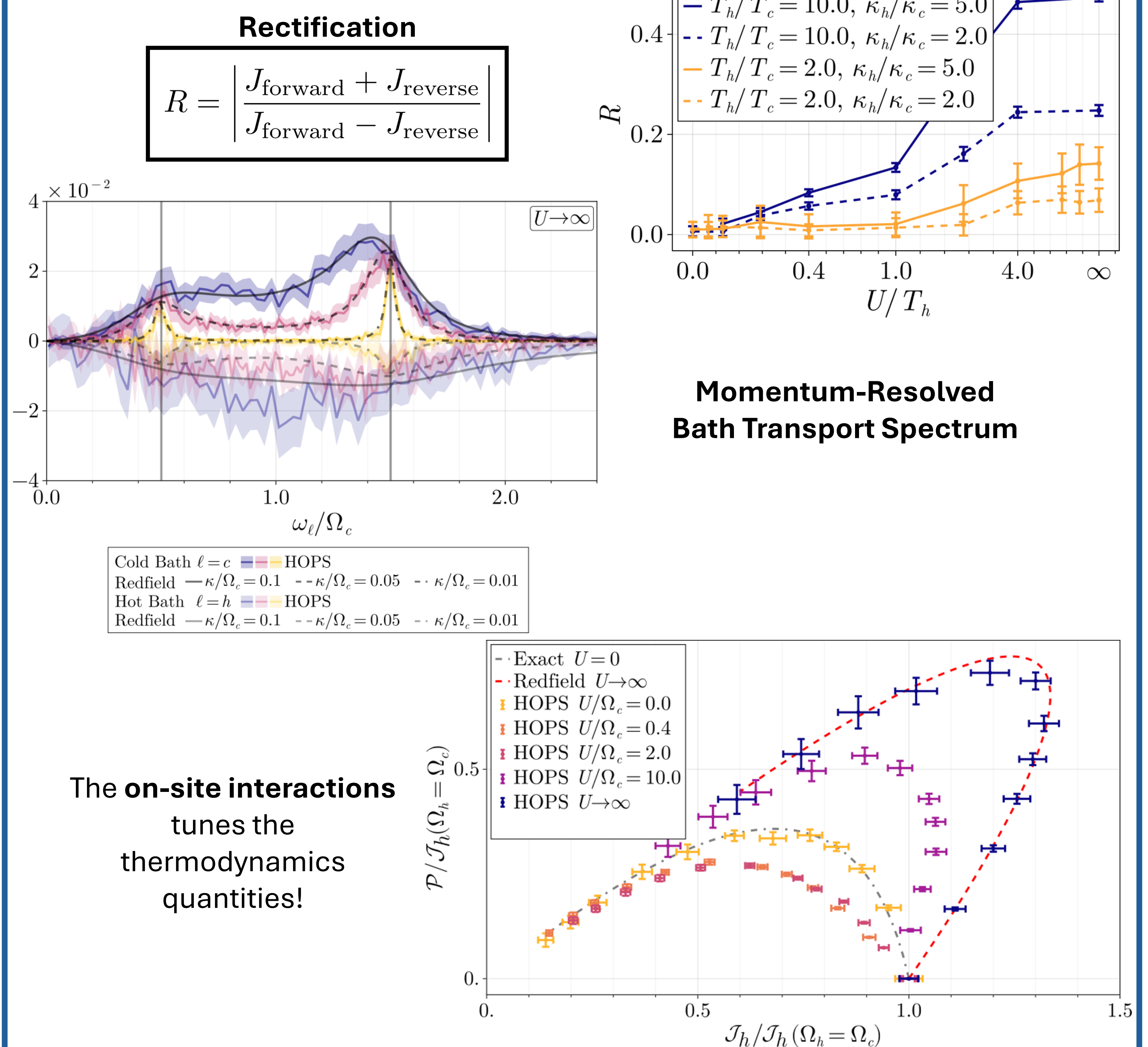
$$\frac{d\langle H_S^l \rangle}{dt} = \left\langle \frac{\partial H_S^l}{\partial t} \right\rangle + i\langle [H^l, H_S^l] \rangle$$

$$= -\mathcal{P} + \sum_{\ell} \mathcal{J}_{\ell}$$

The **fidelity** is great, even for moderate coupling with the baths!



4.2 On-site interacting two-site junction $U \neq 0$



The **on-site interactions** tunes the thermodynamics quantities!

5. Conclusion

- The RME interpolates between the local and global approaches and remains valid for moderate coupling with the baths.
- We identify different thermal machine behaviors such as heat engine and refrigerator by tuning the intercoupling parameter as well as the on-site.
- On-site interactions can be leveraged to tune the thermodynamic performance of the machine.
- Under asymmetric reservoir couplings, the on-site interactions enable non-reciprocal transport.

6. References

- [1] S. Campbell et al., "Roadmap on quantum thermodynamics", Quantum Sci. Techno **11**, 012501 (2026).
- [2] P. Hofer et al., "Markovian master equations for quantum thermal machines: local versus global approach", NJP **19**, 123037 (2017).
- [3] D. Rossini et al., "Quantum Advantage in the Charging Process of Sachdev-Ye-Kitaev Batteries", PRL **125**, 236402 (2020).
- [4] D. Suess et al., "Hierarchy of Stochastic Pure States for Open Quantum System Dynamics", PRL **113**, 150403 (2014).