Bayesian optimization for state engineering of quantum gases

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The recent realization of dual-species quantum gases in space opens up new opportunities for studying interspecies interactions as well as applications in fundamental physics tests. Deploying these gases to precision atom interferometry, for instance, requires accurate quantum state engineering beyond the current state-of-the-art.
For single species, optimal state preparation sequences have been theoretically proposed [1,2] and experimentally realized [3,4]. However, these optimization techniques are not applicable for the dual-species case as they are limited either by approximations or impractical computational costs. To address these limitations, we propose Bayesian optimization with multi-output Gaussian processes [5] as machine learning surrogates to significantly reduce computational costs. We evaluate its performance on an optimization study case of diabatically transporting a Bose-Einstein condensate (BEC) while keeping it in its ground state. Within few hundreds of executions, we reach a competitive performance to other protocols. This corresponds to only a fraction of the simulations required by state-of-the-art methods based on optimal control theory (OCT) [2]. From these few simulations, the Gaussian processes even learn the physical properties of the BEC, enabling the optimization to efficiently navigate also complex cost landscapes and to be reused for changing optimization goals.
We expect this approach to be directly applicable to optimize the dynamics of interacting two-component BECs under realistic experimental conditions based on 3D dual-species simulations.

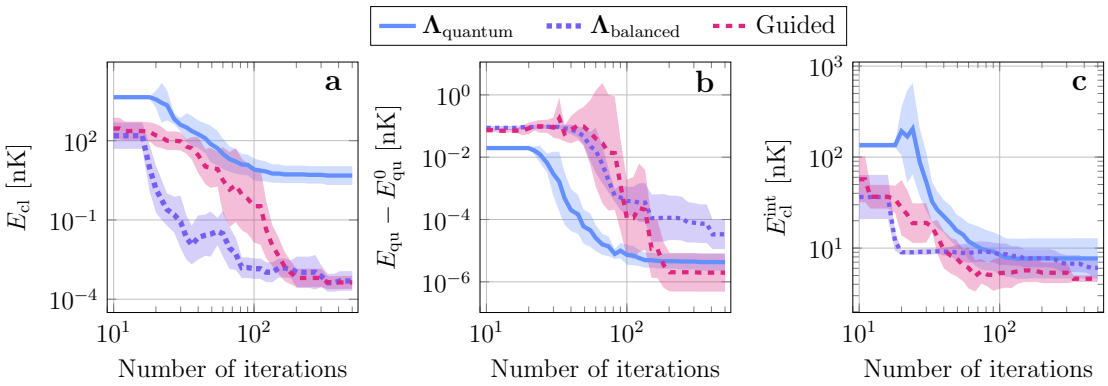

Figure 1: Convergence behaviour for different optimization goals. Multiple Gaussian processes learn the physical BEC properties at the end of a transport and thus, are able to efficiently minimize different energy contributions, simultaneously. The guided optimization case is a special feature of Bayesian optimizations and targets absolute values for the different energy contributions, thus, reaching the best overall transport performance.

[1] R. Corgier, et al. *New Journal of Physics* 20.5 (2018): 055002. [2] S. Amri, et al. Scientific Reports 9(1), 5346 (2019). [3] C. Deppner, et al. *Physical Review Letters* 127.10 (2021): 100401. [4] N. Gaaloul et al., Nature communications 13(1), 7889 (2022). [5] G. Müller, et al. *arXiv preprint arXiv:2404.18234* (2024).

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