

# Coherent Control of Trapped-Ion Spin-Boson Systems

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Trapped ions have proven to be a formidable platform for quantum computation, with record-high fidelities in state preparation and measurement, single- and two-qubit gates. However, scaling the number of qubits remains a key challenge, requiring either larger traps or distributed architectures. An alternative paradigm is to exploit the inherently hybrid nature of trapped-ion systems, leveraging the coupling between the ions' quantised motion and their internal electronic states. This approach provides access to the large Hilbert space of bosonic modes while alleviating some experimental challenges of continuous-variable approaches. Nonetheless, control schemes for trapped-ion hybrid systems remain limited and relatively unexplored.

In previous work, we have shown how the application of simultaneous, non-commuting spin-dependent forces in hybrid spin-boson systems allows for the generation of a wide range of effective nonlinear bosonic interactions [1], including squeezing, trisqueezing, and quadsqueezing [2]. Combined with single-qubit rotations and mid-circuit measurements, these interactions enable the generation of arbitrary superpositions of exotic bosonic states [3]. These states exhibit strong non-classical features, such as Wigner negativity and non-Gaussianity.

Building on these tools, we show how such resources can be used to generate squeezing-mediated many-body interactions in multi-qubit chains [4]. These versatile interactions pave the way for enhanced control of discrete, continuous-variable, and hybrid quantum systems, with potential applications in quantum computing, simulation, and sensing.

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[1] R. T. Sutherland *et al.*, *Phys. Rev. A* **104** 032609 (2021).

[2] O. Băzăvan *et al.*, arXiv.2403.05471 (2024).

[3] S. Saner *et al.*, arXiv.2409.03482 (2024).

[4] K. Shinbrough *et al.*, In preparation.