Signatures of critical dynamics in quantum phase transitions observed through digital quantum simulations

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Digital quantum simulation (DQS) is useful for studying complex quantum phenomena, but faces challenges when studying systems involving vanishing energy gaps, because DQS typically models dynamics. Therefore, in contexts like quantum phase transitions, the Kibble-Zurek mechanism (KZM), which has been used to study phenomena such as galaxy formation in the early universe to the creation of vortices in superfluid Helium, provides a more natural measurement paradigm for DQS. Here we study novel KZM-based techniques for studying critical dynamics in quantum phase transitions, which are more compatible with DQS implementations. In particular, we introduce a *ramp-and-hold* protocol that provides access to spectral characteristics, and in turn provides new access to exploring system critical exponents.

The quantum Rabi model (QRM), which describes a simple field-dipole coupling mechanism of light-matter interactions, was recently shown [1] to exhibit a zero-temperature superradiant quantum phase transition (QPT) in extreme parameter regimes, at a critical coupling point where all system energy gaps close. The QRM can also be realised in a comparatively simple quantum processor based on DQS [2], providing us with an interesting QPT model in which to explore our new techniques for analysing criticality using realistic parameters from recent experiments [2]. By performing dynamical ramps in coupling strength and measuring the photon number expectation value, we can extract the critical exponents of the QPT. Furthermore, having identified oscillations in the expectation value of various observables as a key signature of the underlying QPT, we use our new ramp-and-hold protocol to study the spectrum of lowest energy transition in the system as a function of ramp rate. In this way, we can independently extract the critical exponent of the effective length-scale parameter, and the dynamic exponent. This new protocol allows reliable measurement of Kibble-Zurek excitations even at low excitation numbers and should have broad applicability across different critical quantum systems.

[1] M-J.Hwang, R. Puebla and M.B. Plenio, *Phys Rev Lett* **115**, 180404 (2015).

[2] N.K. Langford, R. Sagastizabal, M. Kounalakis, C. Dickel, A. Bruno, F. Luthi, D.J. Thoen, A. Endo and L. DiCarlo, *Nat Commun* **8**, 1715 (2017).