Exploring unknown regimes in quantum simulators with interpertable machine learning

G. Muñoz-Gil[1], **P. de Schoulepnikoff**[1], **H. Poulsen Nautrup**[1], **F. Møller**[2,3], **T. Schweigler**[3], **J. Schmiedmayer**[3], **H. J. Briegel**[1],

1. University of Innsbruck, Department for Theoretical Physics, Innsbruck, Austria
2. Institute of Science and Technology Austria, Am Campus 1, 3400 Klosterneuburg, Austria
3. Vienna Center for Quantum Science and Technology (VCQ), Atominstitut, TU Wien, Vienna, Austria

Quantum simulators offer a uniquely powerful route to exploring complex many-body physics beyond classical computation. Yet their utility is constrained by the limited and noisy set of observables accessible in experiment. Consequently, extracting robust and unbiased physical insight requires analysis tools that are both agnostic to microscopic details and capable of revealing hidden structures in the data.

In this talk, I will present our recent efforts within the field of interpretable machine learning to address these challenges. In particular, we develop a pipeline based on variational autoencoders that allows us to extract the hidden physical features of input data, without supervision or prior knowledge of the system under study.

First, we trained the VAE with snapshots from a Rydberg atom arrays [1], showing that the method autonomously uncovers the phase structure without access to prior labels or knowledge of relevant order parameters. Interestingly, the method is able to uncover a new regime, namely a ”corner”-ordered phase, that previous methods were unable to uncover. We further leverage symbolic regression techniques to devise a potential order parameter for such phase.

Second, we leveraged the same pipeline to analyze interference measurements from a tunnel-coupled one-dimensional Bose gases [2], which realizes the sine–Gordon quantum field theory. The method autonomously identifies a minimal latent variable that correlates strongly with the system's equilibrium control parameter, even under experimental noise and finite resolution. We then use this trained model to explore other interesting regimes realized under non-equilibrium conditions, from the detection of frozen-in solitons (topological defects) to fast quench regimes.

Through this talk, my aim is to convince the audience that these methods will help unlock the full potential of modern quantum simulators, enabling the fast and efficient exploration of regimes that have so far remained unexplored due to the lack of theoretical understanding.

References

[1] F. Møller *et al.*, Learning Minimal Representations of Many-Body Physics from Snapshots of a Quantum Simulator, arXiv:2509.13821 (2025)

[2] P. de Schoulepnikoff *et al.*, Interpretable representation learning of quantum data enabled by probabilistic variational autoencoders, arXiv:2506.11982 (2025)