THU 1: Fault-Tolerant Quantum Computing: Contributed Session (Quantum Error Correction)

Time: Thursday 14:15–16:00 Location: ZHG001

THU 1.1 Thu 14:15 ZHG001

Myths around quantum computation before full fault tolerance: What no-go theorems rule out and what they don't — •Zoltán Zimborás — University of Helsinki, Finland — Algorithmiq Ltd, Helsinki, Finland

In this talk, following the reasoning of our Perspective article (arXiv:2501.05694), we critically evaluate prevailing viewpoints on the capabilities of near-term quantum computing and the transition toward fully fault-tolerant quantum computing. We examine theoretical no-go results on the practicality of quantum error mitigation techniques and scalability of variational quantum algorithms. By emphasizing the nuances of error scaling, circuit depth, and algorithmic feasibility, we assess the realistic prospects of near-term quantum devices. Our discussion explores strategies for addressing current challenges, such as barren plateaus in variational circuits and the integration of quantum error mitigation and quantum error correction techniques. We conclude with a cautiously optimistic outlook on the possibility for a meaningful quantum advantage in the era of late noisy intermediate scale and early fault-tolerant quantum devices.

THU 1.2 Thu 14:30 ZHG001

Universal fault-tolerant logic with holographic codes — •Alexander Jahn[1], Matthew Steinberg[2,3], Junyu Fan[2], Jens Eisert[1], Sebastian Feld[2], and ChunJun Cao[4] — [1]Department of Physics, Freie Universität Berlin, Germany — [2]QuTech, Delft University of Technology, The Netherlands — [3]Global Technology Applied Research, JPMorganChase, New York, USA — [4]Department of Physics, Virginia Tech, Blacksburg, USA

A core challenge for practical quantum computing lies in the construction of quantum codes with logical gates that are both universal and fault-tolerant. In our work, we introduce a new approach for achieving both features by constructing a class of quantum error-correcting codes - heterogeneous holographic codes - that are derived from models of holographic bulk-boundary dualities, which were previously thought to be unsuitable for applied quantum computing. Overturning earlier work, we show that a universal set of non-Clifford gates can be applied fault-tolerantly on the physical boundary of these codes, while also demonstrating that they allow for high erasure thresholds, another desired feature of quantum codes. Compared to previous concatenated code constructions that our work generalizes, we achieve large overhead savings in physical qubits, e.g. a 21.8% reduction for a two-layer Steane/quantum Reed-Muller combination. Unlike standard concatenated codes, we establish that the new codes can encode more than a single logical qubit per code block by applying "black hole" deformations with tunable rate and distance, while possessing fully addressable, universal fault-tolerant gate sets. [arXiv:2504.10386]

THU 1.3 Thu 14:45 ZHG001

Lattice surgery in near term experimental planar architectures — •Lukas Bödeker[1,2], Áron Márton[1,2], Luis Colmenárez[1,2], Ilya Besedin[3,4,5], Michael Kerschbaum[3,4,5], Jonathan Knoll[3], Ian Hesner[3,4,5], Nathan Lacroix[3,5], Luca Hofele[3,5], Christoph Hellings[3,5], François Swiadek[3,5], Alexander Flasby[3,4,5], Mohsen Bahrami Panah[3,4,5], Dante Colao Zanuz[3,4,5], Andreas Wallraff[3,4,5], and Markus Müller[1,2] — [1]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Jülich — [2]Institute for Quantum Information, RWTH Aachen University — [3]Department of Physics, ETH Zürich — [4]ETH Zürich - PSI Quantum Computing Hub, Paul Scherrer Institute, Villigen — [5]Quantum Center, ETH Zürich

On the pathway to construct a scalable and fault-tolerantly error-corrected quantum computer, the question of implementing a fault-tolerant gate set must be addressed. For experimental platforms with planar design and limited qubit connectivity, the surface code – complemented with lattice surgery – has emerged as a leading candidate for delivering first proof-of-principle implementations of foundational building blocks. We demonstrate one early building block by creating entanglement between two repetition codes in a superconducting qubit architecture [1]. This is achieved by splitting a distance-three surface code using lattice surgery. Building on this result, we further investigate, through detailed simulations, the realistic performance of teleporting a logical surface-code state [2]. In doing so, we explore optimized lattice surgery protocols that preserve fault tolerance and are compatible with near-term superconducting qubit architectures.

[1] I. Besedin, M. Kerschbaum, J. Knoll, I. Hesner, L. Bödeker et al., "Realizing lattice surgery on two distance-three repetition codes with superconducting qubits", arXiv:2501.04612 (2025).
[2] L.Bödeker et al., "Lattice surgery for near term experimental entanglement creation in planar architectures", In preparation (2025).

THU 1.4 Thu 15:00 ZHG001

Measurement-free quantum error correction optimized for biased noise — •Katharina Brechtelsbauer[1], Friederike Butt[2,3], David F. Locher[2,3], Santiago Higuera Quintero[1], Sebastian Weber[1], Markus Müller[2,3], and Hans Peter Büchler[1] — [1]Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — [2]Institute for Quantum Information, RWTH Aachen University, Aachen, Germany — [3]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Jülich, Jülich, Germany

In this work, we derive optimized measurement-free protocols for quantum error correction and the implemen- tation of a universal gate set optimized for an error model that is noise biased . The noise bias is adapted for neutral atom platforms, where two- and multi-qubit gates are realized with Rydberg interactions and are thus expected to be the dominating source of noise. Careful design of the gates allows to further reduce the noise model to Pauli-Z errors. In addition, the presented circuits are robust to arbitrary single-qubit gate errors, and we demonstrate that the break-even point can be significantly improved compared to fully fault-tolerant measurement-free schemes. The obtained logical qubits with their suppressed error rates on logical gate operations can then be used as building blocks in a first step of error correction in order to push the effective error rates below the threshold of a fully fault-tolerant and scalable quantum error correction scheme.

THU 1.5 Thu 15:15 ZHG001

Benchmarking decoding accuracy — •Kiara Hansenne[1], Pierre Cussenot[1,2], Anthony Benois[1], Grégoire Misguich[1], and Nicolas Sangouard[1] — [1]Université Paris Saclay, CNRS, CEA, Institut de Physique Théorique, 91191 Gif-sur-Yvette, France — [2]Direction Générale de l'Armement, 75015 Paris, France

The development of practical quantum computers is currently a major research topic, with quantum error correction playing a crucial role in achieving fault-tolerant quantum computing. Researchers are working towards qubits with physical noise rate below the error correction code threshold, a critical metric for evaluating an error correction code. This threshold is highly influenced by the noise model and by the decoding techniques used.

In this work, we propose to compare the performances of different decoding strategies (such as belief-propagation or minimum-weight perfect matching) against optimal decoding. Whereas such analysis is usually done by error sampling, our approach follows the quantum state through the circuit, allowing us to reach arbitrarily small error rates. Although this limits the exploration to small code distances, our results will provide essential benchmarks for current decoders and potentially estimate code thresholds with higher accuracy.

THU 1.6 Thu 15:30 ZHG001

Bosonic quantum error correction with neutral atoms in optical dipole traps — •David F. Locher[1,2], Leon H. Bohnmann[1,2], Johannes Zeiher[3,4], and Markus Müller[1,2] — [1]Institut für Quanteninformation, RWTH Aachen University, Germany — [2]Peter Grünberg Institut (PGI-2), Forschungszentrum Jülich, Germany — [3]Ludwig-Maximilians-Universität München, Germany — [4]Max-Planck-Institut für Quantenoptik, Garching, Germany

An atom trapped in an optical tweezer or optical lattice exhibits vibrational modes. In the present work [1] we analyse an experimentally motivated approach to encode quantum information in the vibrational motion of trapped neutral atoms. Specifically, we investigate the realisation of Gottesman-Kitaev-Preskill (GKP) code states [2]. We discuss the feasibility of our idea in realistic setups and we devise protocols for encoding and error correction of GKP states that are compatible with state-of-the-art experimental setups. The key element of our protocols is the controlled coupling of atomic motion to the atom's internal electronic states, which has recently been achieved in arrays of trapped atoms. We lay out that an optical lattice augmented with dynamical optical tweezers is a favourable setup whose experimental feasibility we confirm in numerical simulations. Our work therefore constitutes a significant step towards the first experimental realisation of GKP states in the motion of trapped neutral atoms.

[1] Bohnmann, Locher, Zeiher, Müller, *Phys. Rev. A* **111** 022432 (2025)
[2] Gottesman, Kitaev, Preskill, *Phys. Rev. A* **64** 012310 (2001)

THU 1.7 Thu 15:45 ZHG001

Graph Representations and Circuit-Based Codes from GHZ States — •Zahra Raissi[1], Hrachya Zakaryan[1], Konstantinos-Rafail Revis[1], Yinzi Xiao[1], Stanislaw Soltan[1], Mario Flory[2], and Johannes Blömer[1] — [1]Department of Computer Science and Institute for Photonic Quantum Systems (PhoQS), Paderborn University, Paderborn, Germany — [2]Jagiellonian University, Cracow, Poland

GHZ states are key resources for quantum communication and error correction. While symmetric GHZ states (defined as equal superpositions of basis states) are known to be locally unitary (LU) equivalent to both star-shaped and fully connected graph states, their non-symmetric counterparts lack a comparable framework. Non-symmetric GHZ states, defined as unequal superpositions of basis states, naturally arise in experiments due to decoherence and imperfections in state preparation.

We establish that these non-symmetric GHZ states are LU-equivalent to two graphical formalisms: (i) fully connected weighted hypergraph states, and (ii) controlled-unitary star-shaped graphs. Although weighted hypergraph states typically lack a stabilizer description, we construct a complete stabilizer set using only a single ancilla qubit, independent of system size.

Building on this, we consider a qutrit quantum error-correcting code with parameters $[[n = 3, k = 1, d = 2]]_3$, whose codewords take the form of GHZ states. We inject these codewords into quantum circuits arranged in brickwall architectures and construct new quantum codes. Using this method, we obtain both optimal and good codes.