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Book of Abstracts

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Speeding up early fault-tolerant quantum simulations of chemistry with modern signal processing tools

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Quantum phase estimation (QPE) is a flagship algorithm for quantum simulation on fault-tolerant quantum computers. However, recent resource stimates[1] suggest that surpassing classical simulation techniques requires millions of gates and hundreds of logical qubits. Consequently, significant effort is being devoted to developing QPE-like algorithms that could demonstrate practical quantum advantage on early fault-tolerant quantum computers—i.e., devices with error correction but a limited number of qubits[2].

A promising approach to reducing QPE's computational cost lies in recognizing that it estimates molecular energies by sampling the autocorrelation function in the time domain and performing a Fourier transform. This connection to signal recovery has recently inspired several methods for computing eigenvalues of quantum Hamiltonians using shallower QPE-like circuits[3,4,5]. Speeding up computation requires minimizing three key factors: (i) the total number of sampled points, (ii) the number of measurements per sampled point of the autocorrelation function, and (iii) the total length of the acquired signal.

We adapt recent results from the field of compressed sensing[6,7] to design a quantum algorithm that simultaneously estimates ground and excited state energies while drastically reducing the total number of circuit executions[8]. At the same time, it demonstrates robustness to shot noise. We perform a numerical analysis in both weak and strong correlation regimes, providing evidence that the algorithm achieves optimal (Heisenberg) scaling. Finally, we explore how the quality of the initial input state affects the accuracy of the estimates, suggesting that these improvements could lead to a practical quantum advantage.

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Design of an analog quantum simulators with superconducting transmon qubit

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Analog quantum computing is emerging as a powerful approach for addressing computationally intractable problems in quantum many-body physics. Classical computers struggle to simulate these systems due to the exponential growth in computational resources required as system size increases. Unlike digital quantum computers, which rely on discrete qubits and gate-based operations, analog quantum computers use continuous variables to directly model quantum dynamics. This allows for a more natural representation of quantum systems, minimizing the need for error-prone digital decompositions. However, this advantage comes at a cost: analog quantum computing requires specialized hardware architectures tailored to specific problems, sacrificing the flexibility of digital approaches.

In this direction, the Quantum Architecture for Theory & Technology (QUART&T) project aims to develop a quantum device composed of multiple coupled superconducting qubits and resonators, designed for efficient quantum simulations of many-body interactions, including (p, d), (p, ^{3}H), and (p, ^{3}He) scattering processes and possibly real time-evolution of models mimicking lattice models with gauge degrees of freedom. The project focuses on key technological advancements, such as implementing all-to-all coupling through tunable couplers, integrating high-coherence superconducting qubits, and exploring higher-dimensional quantum systems (qudits) to enhance computational capabilities.

As an initial step for this project, we are conducting an in-depth study on tunable couplers due to their significant advantages in building analog quantum simulators. Notably, these couplers allow for parametrically controlled communication between qubits, which enables real-time regulation of how each quantum element contributes to the system's time evolution by simply adjusting an external parameter. Moreover, tunable couplers can enhance communication between quantum elements, effectively creating a fully configurable network up to all-to-all connectivity configuration. These couplers leverage on tunable elements, such as a Direct Current Superconducting QUantum Interference Device (DC-SQUID) that can be tuned with an external magnetic flux.

In this presentation, we will outline the general aim of the project, the preliminary simulation results for the Hamiltonian that governs the desired evolution, and the first simulated design that will implement it.

Acknowledgements
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Estimating molecular ground-state energies with Rydberg arrays

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Janas is a startup that uses quantum computing technologies and techniques to solve today's industrial problems. In the NISQ settings, we think that only a hybrid approach with the right mix of conventional high performance computing (the specialty of our parent company eXact lab), machine learning and quantum processing can provide an edge in the near term. We further claim that quantum simulation provides a more reliable platform until error corrected digital quantum computing will become available.
We show the computation of the ground state energy of small molecules on neutral-atom quantum computing platforms, comparing the digital and analog paradigms. The smart arrangement of the register makes the analog drive competitive with digital quantum computing.

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A quantum photonic integrated SWAP test circuit for entanglement witness

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The detection and quantification of quantum entanglement poses significant challenges, especially as the size of quantum systems increases. Conventional methods such as quantum state tomography become impractical for large systems due to their exponential complexity. In this context, the SWAP test circuit, known for calculating the overlap between two quantum states, can be adapted as a tool for entanglement witnessing. The talk will present an integrated photonic circuit designed to implement the SWAP test algorithm and show how it can be used for entanglement detection. The circuit relies solely on linear optical components and operates at room temperature.

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Unraveling the emergence of quantum state designs in systems with symmetry

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Quantum state designs enable efficient sampling of random quantum states, with applications ranging from circuit design to black hole physics. While symmetries are known to reduce randomness, their role in generating state designs remains unclear. The projected ensemble framework [2, 3], which uses local projective measurements and many-body quantum chaos, has recently been introduced to generate efficient approximate state t-designs. In this framework, projective measurements are applied to the larger subsystem (bath) of a single bipartite state undergoing quantum chaotic evolution. This process generates a set of pure states on the smaller subsystem. These states, along with the Born probabilities, form the projected ensembles. Remarkably, when the measured subsystem is sufficiently large, the projected ensembles converge to state designs. This phenomenon, known as emergent state designs, is closely related to a stringent generalization of the well-studied eigenstate thermalization hypothesis.

In our work 1, we probe how symmetries influence the emergence of state designs from random generator states. Our main findings involve identifying a sufficient condition on the measurement bases when the generator states are eigenstates of an arbitrary symmetry operator. Failing to satisfy this condition can lead to the localization of projected states in the Hilbert space, as illustrated in Fig. 1. By considering the translation symmetric generator states, we derive this condition and identify bases that fail to generate the designs when the condition is violated. To solidify our results, we

study the emergence of designs from a generator state evolving under the dynamics of a chaotic tilted field Ising chain with translation symmetry with the Hamiltonian:

\begin{equation}
H=\sum_{j}\sigma^{x}{j}\sigma^x{j+1}+h_x\sum_{j}\sigma^{x}{j}+h_y\sum{j}\sigma^{y}_{j}
\end{equation}

We find faster convergence towards designs compared to when translation symmetry is broken. We extend these findings to other symmetries, offering insights into deep thermalization and equilibration in quantum many-body systems.

Due to the generality of our formalism, we extend the results to other symmetry classes,s including Z2 and reflection symmetries. We further obtain the moments of the projected ensembles under the symmetry constraints.

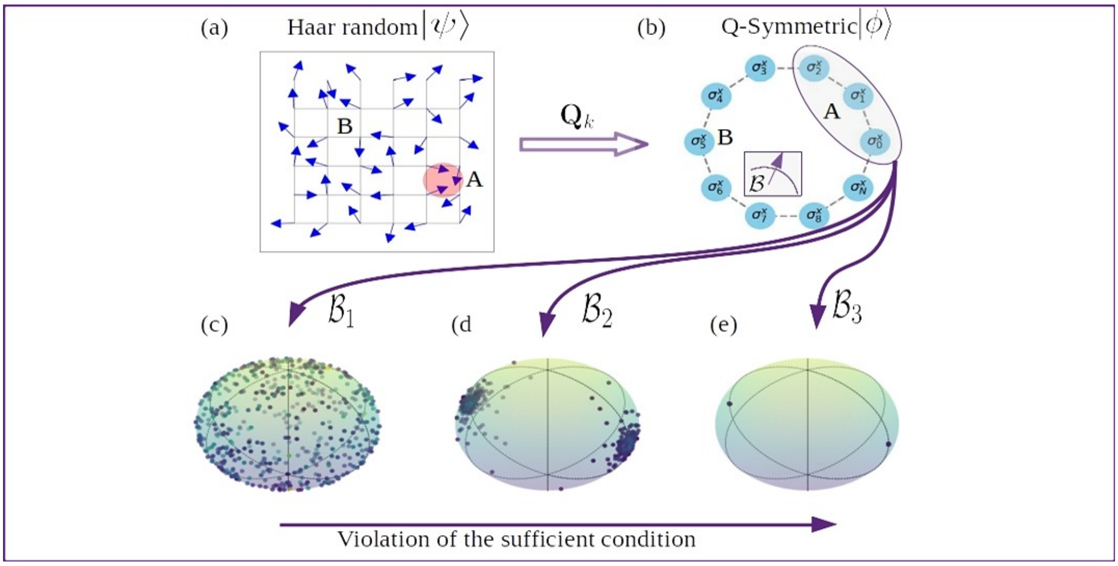

Figure 1: Schematic representation of the projected ensemble framework for a Q-symmetric state (an eigenstate of a symmetry generator Q), showcasing the interplay between measurement bases and symmetry.

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Dynamical Mean-Field Theory for Open Many-Body Quantum Systems

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Understanding and simulating the complexities of quantum many-body systems out of equilibrium is still a major challenge in quantum physics. In this talk, I will introduce Dynamical Mean-Field Theory (DMFT) as a powerful approach to tackle this problem, with a focus on bosonic, driven-dissipative lattices.

Starting from the basic intuition behind DMFT, I will discuss its extension to open, bosonic quantum systems (OpenBDMFT) and highlight recent insights —such as the emergence of the steady-state quantum Zeno effect —that showcase the method's reach and versatility. I will also discuss numerical strategies —including Krylov subspaces and polynomial expansions —that allow OpenBDMFT to scale beyond the limits of full exact diagonalization.

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Directional emission of a giant atom super-strongly coupled to a Coupled Cavity Array

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The introduction of high kinetic platforms in circuit QED allow for realization of coupled cavity array with low disorder, small footprint and large inter-site couplings 1. This enables the study of challenging regimes of light-matter interaction within the paradigm of waveguide QED [2] e.g., giant qubits coupled non-locally to the waveguide. In this work, we conduct an experiment using a giant atom super-strongly coupled to a 1D bath reproducing the photonic analogue of the Su-Schrieffer-Heeger model [3]. Remarkably, on top of standard atom-photon bound states, the qubit induces mode localization in the waveguide, somehow similar to the formation of a Bound-In-Continuum state [4], when the qubit is tuned in the bandgap of the system. This localization phenomenon can be harnessed to induce directional spontaneous emission of the qubit. We explain the emergence of this qubit-induced localization with a Green-function-based argument [5] and propose a setup in which the qubit is manipulated by exploiting the atom-photon bound state in the bandgap and then the information stored in it is sent out directionally through these localized bath modes. These findings open new direction to manipulate nonclassical excitation in waveguide QED e.g., for routing or state transfer applications.

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Classification of qubit cellular automata on hypercubic lattices

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In this talk, I will provide an introduction to Quantum Cellular Automata (QCAs) and to the problem of their classification. Then I will present a thorough classification in the case of translation-invariant

qubit systems on hypercubic lattices with nearest neighbor scheme — a foundational framework for both many-body quantum physics and quantum computation.
Our classification encompasses all admissible local rules for these qubit QCAs, along with their implementation as finite-depth quantum circuits.
Furthermore, we define a multidimensional-index that measures the information flow generated by these QCAs, generalizing those one-dimensional indices as GNVW index, Kitaev flow or winding number, and the associated classification. Our results offer valuable insights into the ongoing challenge of classifying QCAs and topological phases in $D \geq 2$ spatial dimensions, potentially advancing both theoretical understanding and practical applications in quantum simulation. We simulate various families of these QCAs to relate their entanglement generation capabilities to the parameters of the quantum gates implementing them, showcasing the potential wealth of applications of our classification.
This talk is based on joint work with Paolo Perinotti and Alessandro Bisio arXiv:2408.04493.

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Calculation of Green's Functions using quantum computers for small superfluid systems

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Quantum many-body problems, such as the study of nuclear structure, are difficult to treat with classical computers due to exponential complexity. One way to overcome this limitation would be to use quantum computers, which allow to reduce computational cost. In this context, it is important to test quantum algorithms on simple, yet nontrivial models, with the goal of assessing their efficiency and benchmarking them. Focusing on the pairing Hamiltonian, this work addresses the computation of odd systems and Green's functions. Hybrid quantum-classical computations are compared to exact results and standard BCS techniques.