QAT: Heterogeneous Digital Analog Quantum Dynamics Simulations

Pavel Lougovski

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Introduction to the Team

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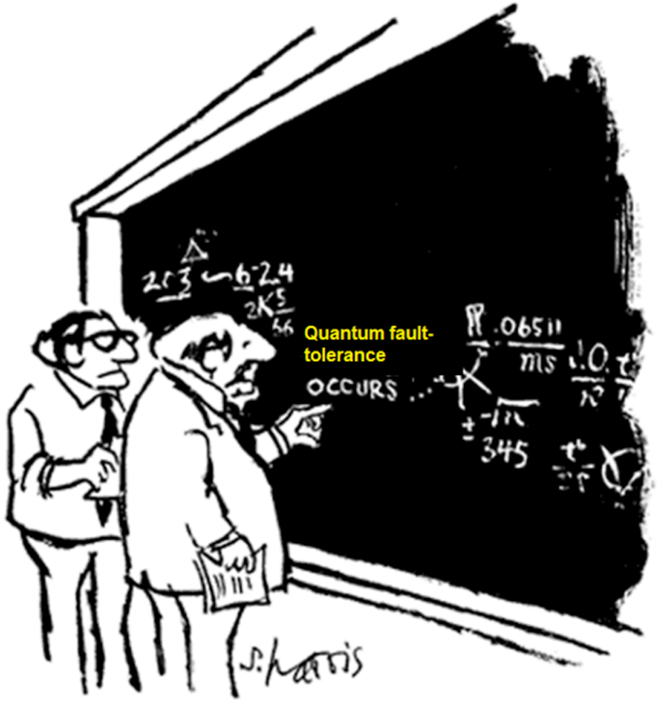
Our Scientific Goals

- *Design quantum algorithm for simulating the dynamics of quantum many-body systems on near-term quantum (NISQ) hardware.*
- *Catalyze and enrich the quantum computing field by engaging various research communities across DOE's Office of Science*
- *Identify missing elements in the basic algorithm design principles that would connect high-level science goals to quantum hardware and software.*



Quantum Fault-tolerance occurs

Research Approaches

- Heterogeneous:
  i. Synergize quantum and classical algorithms to enable solutions scalable beyond traditional techniques.
  ii. Synergize digital and analog quantum operations to achieve favorable scaling on NISQ hardware.
- Dynamics Simulations:
  i. Time dynamics of fermionic systems e.g., two-point correlation functions $\langle c_i^\dagger(0) c_j(\tau) \rangle$

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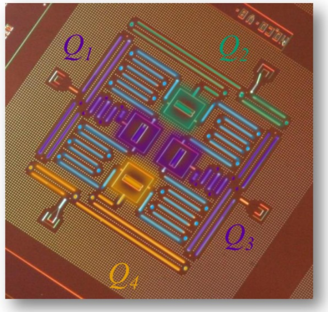
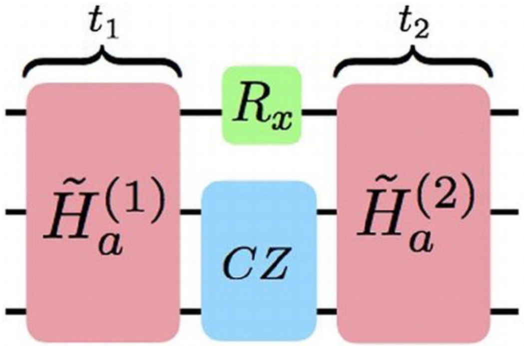
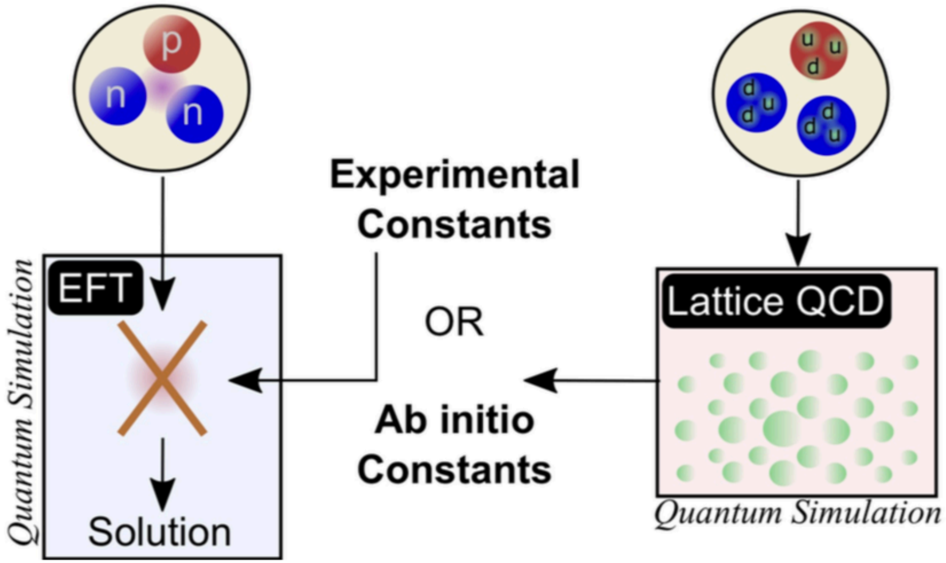




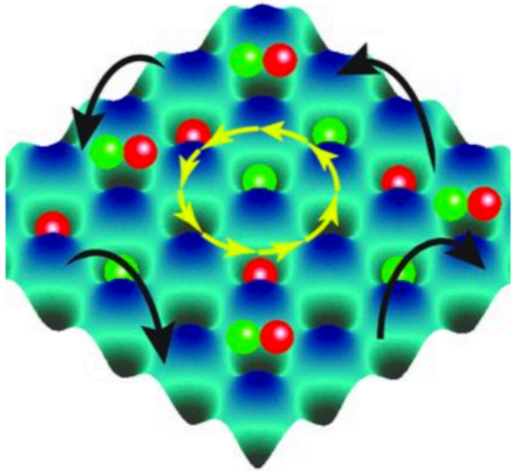
Scientific Applications

Nuclear Physics



$$\mathcal{H}_{EFT} = \sum \alpha_{ij} c_i^\dagger c_j + \beta_{ijkl} c_i^\dagger c_j^\dagger c_k c_l + \gamma_{ijklmn} c_i^\dagger c_j^\dagger c_k^\dagger c_l c_m c_n + \mathrm{h.c.}$$

Strongly Correlated Electrons



PRL**116** 125301

$$\mathcal{H} = -t \sum (\hat{c}_{i,\sigma}^\dagger \hat{c}_{j,\sigma} + \mathrm{h.c.}) + U \sum \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}$$

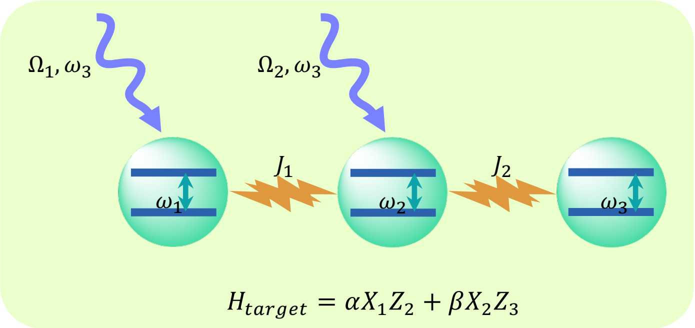
Scientific Output (Publications)

1. Alex Shaw, Natalie Klco, Pavel Lougovski, Jesse Stryker, Nathan Wiebe, “Resource-Adaptable Quantum Algorithms for Scalable Simulation of the Schwinger Mode”
2. Alessandro Roggero, Andy C. Y. Li, Joseph Carlson, Rajan Gupta, Gabriel N. Perdue, “Quantum Computing for Neutrino-nucleus Scattering”
3. Eugene F. Dumitrescu, Pavel Lougovski ”Hamiltonian Assignment for Open Quantum Systems”
4. T. Keen, T. Maier, S. Johnston, P. Lougovski “Quantum-classical simulation of two-site dynamical mean-field theory on noisy quantum hardware”
5. Hsuan-Hao Lu, Andrew M Weiner, Pavel Lougovski, Joseph M Lukens “Quantum Information Processing with Frequency-Comb Qudits”
6. Natalie Klco, Jesse R. Stryker, Martin J. Savage, “SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers”
7. Ana Martin, Lucas Lamata, Enrique Solano, Mikel Sanz, “Digital-analog quantum algorithm for the quantum Fourier transform”
8. Natalie Klco, Martin J. Savage, “Minimally-Entangled State Preparation of Localized Wavefunctions on Quantum Computers”
9. Alessandro Roggero, Alessandro Baroni, “Short-depth circuits for efficient expectation value estimation”
10. Hsuan-Hao Lu, Natalie Klco, Joseph M Lukens, Titus D Morris, Aaina Bansal, Andreas Ekström, Gaute Hagen, Thomas Papenbrock, Andrew M Weiner, Martin J Savage, Pavel Lougovski, “Simulations of subatomic many-body physics on a quantum frequency processor”

Highlights

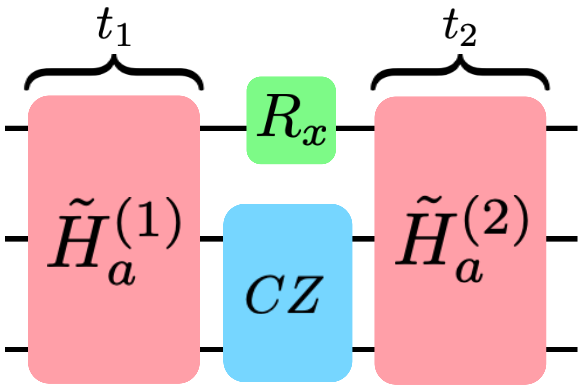
Digital-Analog Simulation of the Heisenberg model

- Effective Hamiltonian for Digital-Analog Simulation of the Heisenberg model



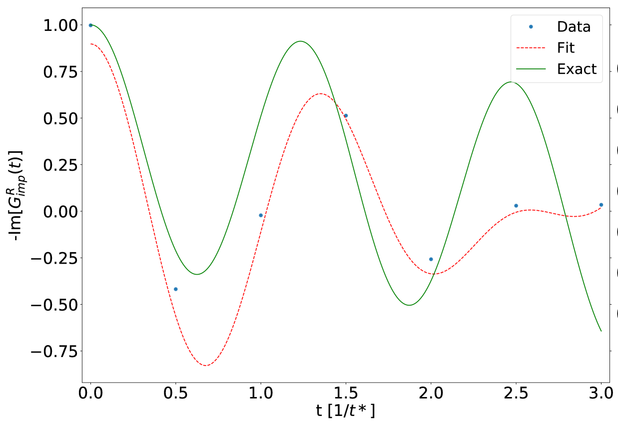
- Thermalization of closed quantum systems

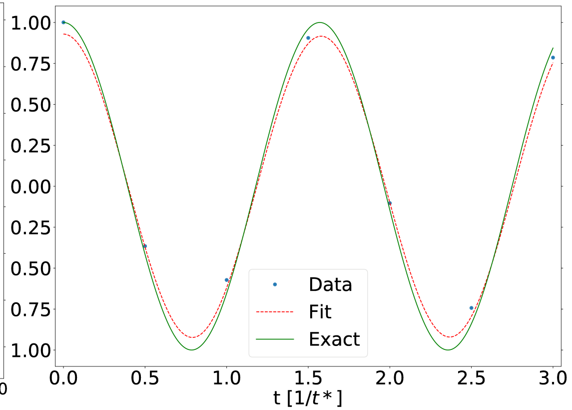
- Digital-analog quantum computation



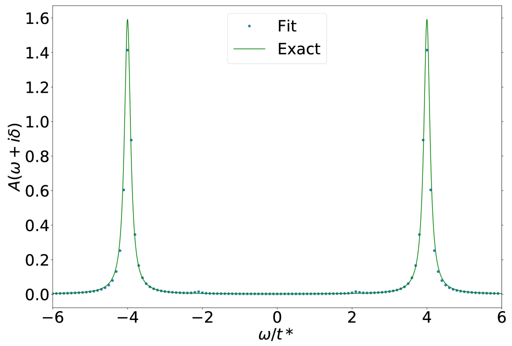
- Digital-analog quantum algorithm for the quantum Fourier transform

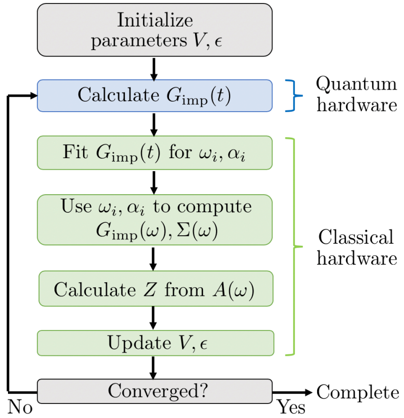
Quantum-classical simulation of two-site DMFT on noisy quantum hardware





Data and fit for impurity Green's function at the first step (left) and in the last step (right) self-consistency loop with U=8t and V=t compared against the exact result.





T. Keen, T. Maier, S. Johnston, P. Lougovski arXiv:1910.09512

Scientific Achievement

Implemented quantum-classical simulation of the single-band Hubbard model using two-site dynamical mean-field theory on IBM's quantum hardware.

Significance and Impact

First demonstration of self consistent solution to a DMFT problem on digital quantum hardware, guiding future quantum simulations of Hubbard physics.

Research Details

- Computed the zero-temperature impurity Green's function in the time domain using quantum hardware
- Used classical computer to fit the measured Green's functions and extract their frequency domain parameters
- Demonstrated convergence to self-consistency for a half-filled Mott insulating system after applying quantum error mitigation techniques to the quantum simulation data

First Digital Quantum Simulation of SU(2) non-Abelian Gauge Field Theory

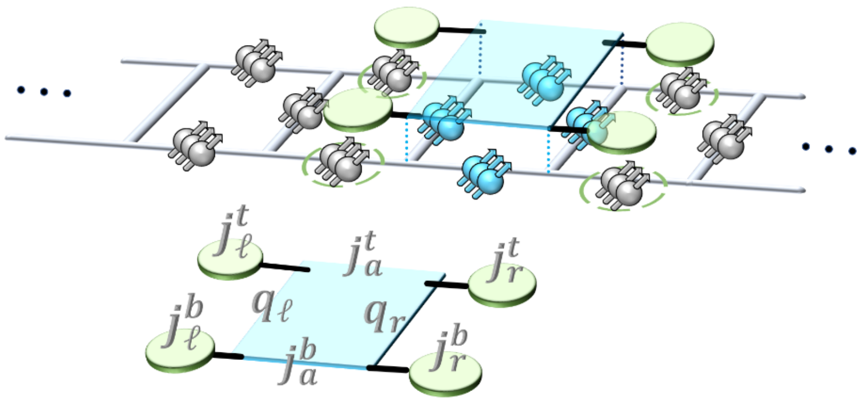
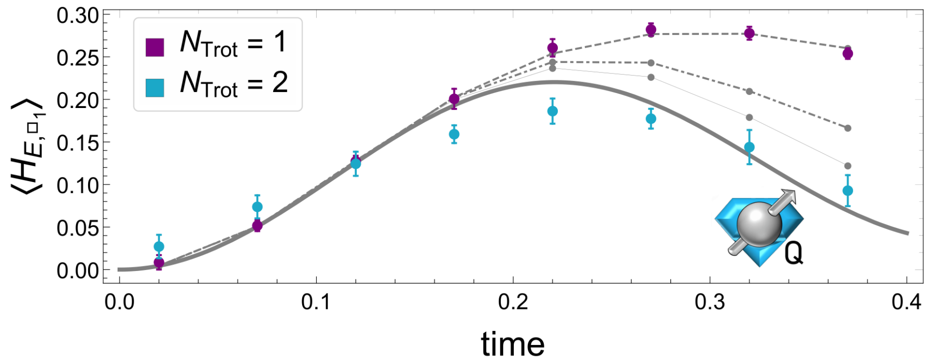


Diagram of the distribution of qubit registers and the structure of the plaquette operator in the one-dimensional SU(2) plaquette lattice.



Time Evolution of the electric plaquette energy contribution expectation value measured on IBM's quantum hardware after error mitigation.

Natalie Klco, Jesse R. Stryker, and Martin J. Savage [arXiv:1908.06935]

Scientific Achievement

Designed quantum operators and implemented truncated SU(2) dynamics complete with spatially-extended plaquette operators and a gauge invariant subspace on superconducting qubits.

Significance and Impact

First implementation of non-Abelian gauge theory on digital quantum hardware, guiding future quantum simulations of gauge field theories including QCD.

Research Details

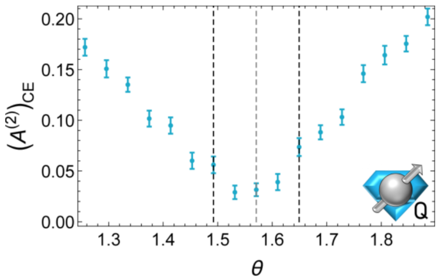
– Leveraged local gauge symmetry to analytically express Hilbert space with total electric flux per link

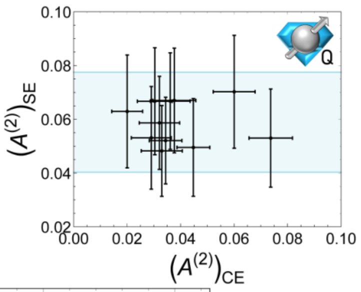
– Constructed plaquette operators for digital devices exploiting the unphysical Hilbert subspace

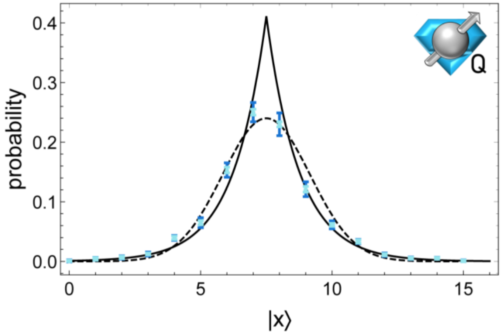
– Measured gauge-invariant survival probabilities for a two-plaquette lattice as a diagnostic for simulating gauge theories on near term quantum devices

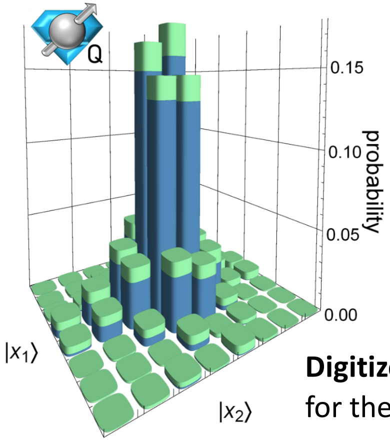
– Implemented error mitigation and data analysis specific to recapturing the gauge invariant Hilbert space.

Low-Noise Quantum State Preparation for Scalar Field Theory









Hardware Calibrations based on wavefunction asymmetry are used to prepare symmetric exponentials as approximations to the (non-interacting scalar field ground state using IBM's quantum devices

Digitized field-space wavefunction for the 2-dimensional scalar field

Natalie Klco and Martin J. Savage [arXiv:1904.10440]

Scientific Achievement

Designed low-entanglement wavefunctions relevant for the scalar field and assessed viability for near-term quantum devices through implementation on superconducting qubits.

Significance and Impact

Demonstrates the ability to leverage field digitization and entanglement reduction to prepare wavefunctions isolating the relevant physics in quantum field theory simulation

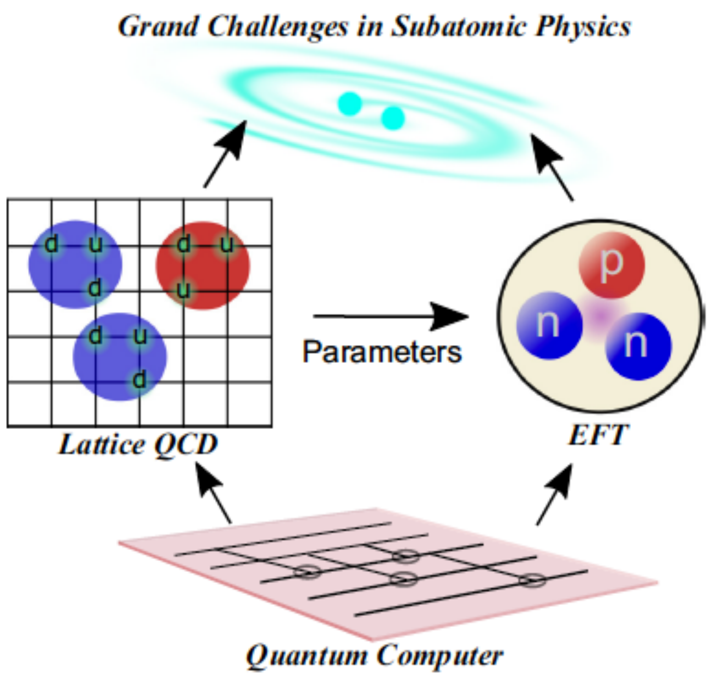
Research Details

– Developed and employed a workflow that interleaves calibrations to mitigate hardware systematic errors

– Defined and implemented an effective gate application function of the Hadamard gate, correcting the operation both in vacuum and in medium

– Entangling gates identified as significant source of wavefunction asymmetry

Simulations of subatomic physics on a quantum frequency processor



Diagrammatic role of quantum devices in subatomic physics. Ideally, quantum simulation applied to both QCD (left side) and EFT (right side) will enable high-precision predictions of static and dynamic properties of nuclei and nuclear matter. EFT parameters may be determined from experiment or by a complementary program of classical and quantum simulation.

Hsuan-Hao Lu, Natalie Klco *et al.*, Phys. Rev. A (2019)
https://doi.org/10.1103/PhysRevA.100.012320

Scientific Achievement

Calculated the two- and three-body forces between heavy mesons in the Schwinger model as well as binding energies of light nuclei via quantum simulations.

Significance and Impact

Explored conceptual tools at the advent of quantum computing for future use in nuclear theory---solving relatively large-dimensional models (for quantum computing) via quantum simulation on a quantum frequency processor

Research Details

– Captured shielding effects of the (1+1)-dimensional QED vacuum, calculating the potential between static charges with a quantum frequency processor

– Realized the bridge from prototypical field theory to atomic nuclei utilizing quantum devices

– Determined the precision of the quantum frequency processor conducive to reliably determining binding energies up to ^4He in pionless effective field theory

Thank you! Questions?