Scalar QED with Rydberg atoms

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QuLAT collaboration
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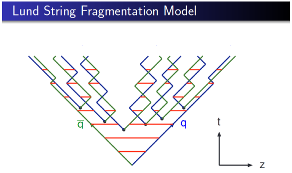
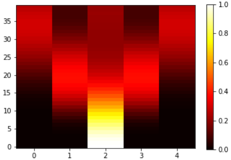
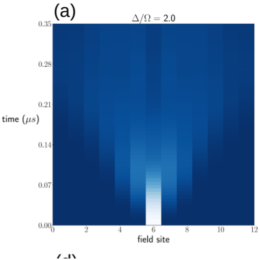
Contents

- Hybrid hadronization in event generators?
- Toy model: the compact Abelian Higgs Model (Scalar QED)
- Model building (literally!) with Arrays of Rydberg atoms
- Matching the target model with the simulator (or vice-versa!)
- Effective theory for the simulator
- Practical examples and work with QuERa
- Phase diagram of the simulator
- Towards an hybrid event generator (QuPYTH), with K. Heitritter and S. Mrenna, arxiv:2212.02476

Hybrid hadronization in event generators?







Hadronization of a particle-antiparticle pair with the Lund model/Pythia (left), the Abelian Higgs model in 1+1 dimensions (middle), and a Rydberg atom simulator for this model (right).

Compact Abelian Higgs Model (CAHM)

The lattice compact Abelian Higgs model is a non-perturbative regularized formulation of scalar quantum electrodynamics (scalar electrons-positrons + photons with compact fields).

$$Z_{CAHM} = \prod_{x} \int_{-\pi}^{\pi} \frac{d\varphi_x}{2\pi} \prod_{x,\mu} \int_{-\pi}^{\pi} \frac{dA_{x,\mu}}{2\pi} e^{-S_{gauge}-S_{matter}},$$

$$S_{gauge} = \beta_{plaquette} \sum_{x,\mu<\nu} (1 - \cos(A_{x,\mu} + A_{x+\hat{\mu},\nu} - A_{x+\hat{\nu},\mu} - A_{x,\nu})),$$

$$S_{matter} = \beta_{link} \sum_{x,\mu} (1 - \cos(\varphi_{x+\hat{\mu}} - \varphi_x + A_{x,\mu})).$$

- local invariance: $\varphi'_x = \varphi_x + \alpha_x$ and $A'_{x,\mu} = A_{x,\mu} - (\alpha_{x+\hat{\mu}} - \alpha_x)$.
- φ is the Nambu-Goldstone mode of the original model. The Brout-Englert-Higgs mode is decoupled (heavy).

Transfer matrix and Gauss's law with NISQ machines

PHYSICAL REVIEW D **102,** 014506 (2020)

Discrete aspects of continuous symmetries in the tensorial formulation of Abelian gauge theories

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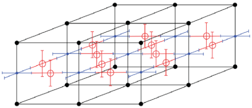
We show that standard identities and theorems for lattice models with $U(1)$ symmetry get reexpressed discretely in the tensorial formulation of these models. We also explain the geometrical analogy between the continuous lattice equations of motion and the discrete selection rules of the tensors. We further construct a gauge-invariant transfer matrix in arbitrary dimensions, show the equivalence with its gauge-fixed version in a maximal temporal gauge, and explain how a discrete Gauss's law is always enforced. Moreover, we propose a noise-robust way to implement Gauss's law in arbitrary dimensions, and we reformulate Noether's theorem for global, local, continuous, or discrete Abelian symmetries: for each given symmetry, there is one corresponding tensor redundancy. We discuss semiclassical approximations for classical solutions with periodic boundary conditions in two solvable cases, and we show the correspondence of their weak coupling limit with the tensor formulation after Poisson summation. Finally, we briefly discuss connections with other approaches and implications for quantum computing.



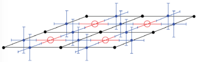


FIG. 3. Magnetic layer of the transfer matrix for $D = 3$ on a time slice. Small circles (blue) are used for the A tensors and large circles (red) for the B tensors.

For introduction to Tensor Lattice Field Theory (TLFT) see Y. M., R. Sakai, and J. Unmuth-Yockey, Rev. Mod. Phys. 94, 025005; Y. M., QFT: a quantum computation approach, IoP book.

AHM: Hamiltonian and Hilbert space in 1+1 dim.

The continuous-time limit yields the Hamiltonian

$$H = \frac{U}{2}\sum_{i=1}^{N_s}(L_i^z)^2 + \frac{Y}{2}\sum_i (L_{i+1}^z - L_i^z)^2 - X\sum_{i=1}^{N_s} U_i^x$$

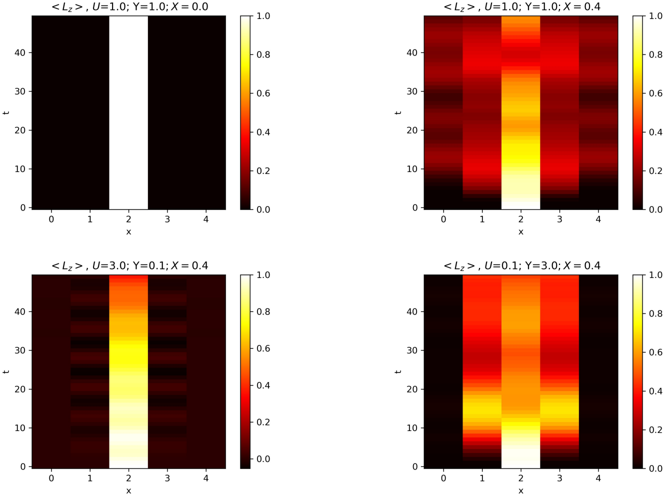
with $U^x \equiv \frac{1}{2}(U^+ + U^-)$ and $L^z|m\rangle = m|m\rangle$ and $U^{\pm}|m\rangle = |m \pm 1\rangle$.

- m is a discrete electric field quantum number ($-\infty < m < +\infty$)
- In practice, we need to apply truncations: $U^{\pm}|\pm m_{max}\rangle = 0$.
- We focus on the spin-1 truncation ($m = \pm 1, 0$ and $U^x = L^x/\sqrt{2}$.)
- U-term: electric field energy.
- Y-term: matter charges (determined by Gauss's law)
- X-term: currents inducing temporal changes in the electric field.

Target simulations (E-field, spin-1, 5 sites)

$$H = \frac{U}{2}\sum_{i=1}^{N_s}\left(L_i^z\right)^2 + \frac{Y}{2}\sum_i (L_{i+1}^z - L_i^z)^2 - X\sum_{i=1}^{N_s} U_i^x$$

Initial state: particle-antiparticle (connected by an electric field +1)



Configurable Arrays of Rydberg Atoms (CARA)

- One can adapt (Y.M., PRD 104) the optical lattice construction (J. Zhang et al. PRL 121) using ^{87}Rb atoms separated by controllable (but not too small) distances, coupled to the excited Rydberg state $|r\rangle$ with a detuning Δ.
- The ground state is denoted $|g\rangle$ and the two possible states $|g\rangle$ and $|r\rangle$ can be seen as a qubit. $n|g\rangle = 0,\ n|r\rangle = |r\rangle$.
- The (effective) Hamiltonian reads

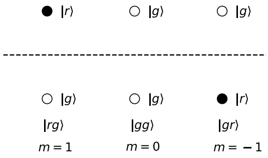
$$H = \frac{\Omega}{2}\sum_i (|g_i\rangle\langle r_i| + |r_i\rangle\langle g_i|) - \Delta \sum_i n_i + \sum_{i<j} V_{ij} n_i n_j,$$

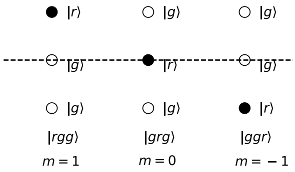
  with

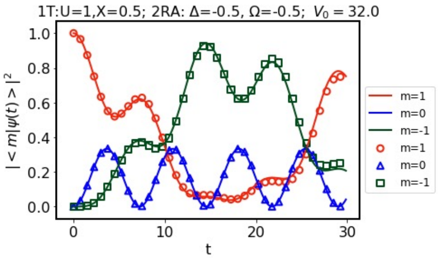
$$V_{ij} = \Omega R_b^6 / r_{ij}^6,$$

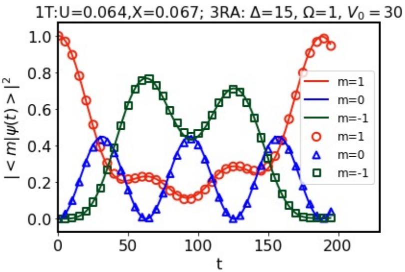
  for a distance r_{ij} between the atoms labelled as i and j. Note: when $r = R_b$, $V = \Omega$.
- This repulsive interaction prevents two atoms close enough to each other to be both in the $|r\rangle$ state. This is the so-called blockade mechanism.

One site spin-1 with 2 and 3 atoms (Y.M. PRD 104)





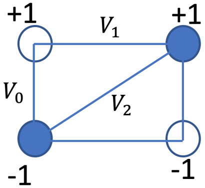




Solid line: target, Symbols: simulator

Exact matching vs. study of continuum limit

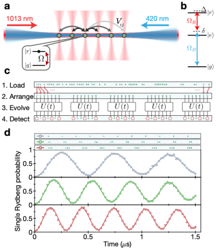
- 1 site, 2 atoms: exact up to $|rr\rangle$ transitions (when $\Omega = 0$, can be implemented by setting $\Delta = -U/2$ and $\Omega = -X$
- 2 sites, 4 atoms: when $X = \Omega = 0$ reads $\Delta = -U/2 - \frac{Y}{2},\ V_1 = Y,\ V_2 = -Y$. No solution with current technology (homogeneous setup).

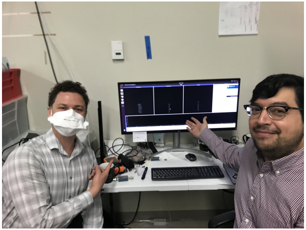


- 1 site, 3 atoms: it's complicated! (ideally: inhomogeneous Δ to split $m = 0$ and $m = \pm 1$, otherwise use degenerate perturbation theory as a guide, James Corona's work in progress).

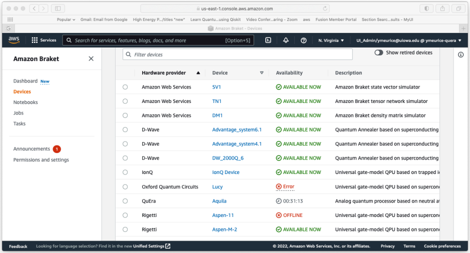
A better approach may be to study all the continuum limits (where correlation lengths become large) that can be obtained with the simulator.

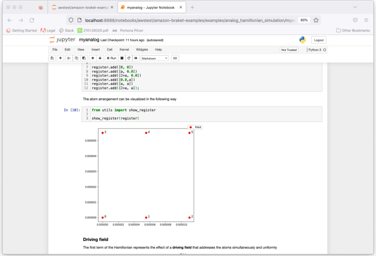
QuEra


a
1013 nm
420 nm
b
c
1. Load
2. Arrange
3. Evolve
4. Detect
d
Single Rydberg probability
Time (μs)

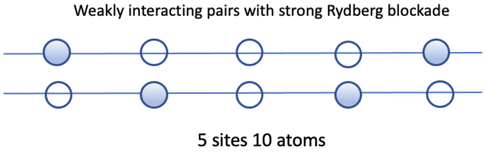



QuEra


Amazon Braket
Dashboard New
Devices
Notebooks
Jobs
Tasks
Announcements
Permissions and settings
Filter devices
Show retired devices
Hardware provider | Device | Availability | Description
Amazon Web Services | SV1 | AVAILABLE NOW | Amazon Braket state vector simulator
Amazon Web Services | TN1 | AVAILABLE NOW | Amazon Braket tensor network simulator
Amazon Web Services | DM1 | AVAILABLE NOW | Amazon Braket density matrix simulator
D-Wave | Advantage_system6.1 | AVAILABLE NOW | Quantum Annealer based on superconducting
D-Wave | Advantage_system4.1 | AVAILABLE NOW | Quantum Annealer based on superconducting
D-Wave | DW_2000Q_6 | AVAILABLE NOW | Quantum Annealer based on superconducting
IonQ | IonQ Device | AVAILABLE NOW | Universal gate-model QPU based on trapped i
Oxford Quantum Circuits | Lucy | Error | Universal gate-model QPU based on supercon
QuEra | Aquila | 00:31:13 | Analog quantum processor based on neutral a
Rigetti | Aspen-11 | OFFLINE | Universal gate-model QPU based on supercon
Rigetti | Aspen-M-2 | AVAILABLE NOW | Universal gate-model QPU based on supercon

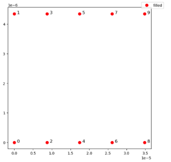

jupyter myanalog
The atom arrangement can be visualized in the following way
from utils import show_register
show_register(register)
Driving field
The first term of the Hamiltonian represents the effect of a driving field that addresses the atoms simultaneously and uniformly

10 atoms (5 sites) with QuEra and H_{eff}.

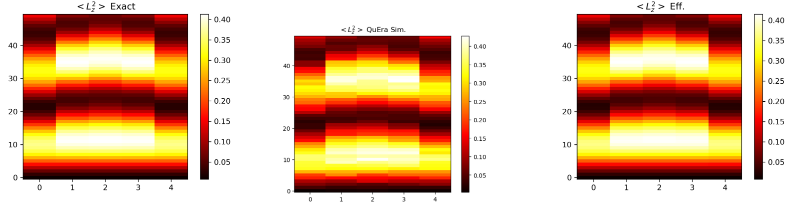


In [11]:
```python
register = AtomArrangement()
H = Hamiltonian()

ahs_program = AnalogHamiltonianSimulation(
        hamiltonian=H,
        register=register
    )
for nn in range(nsites):
        register.add([nn*aax, 0])
        register.add([nn*aax, aay])
show_register(register)
```



Values of $< L_z^2 >$ for five sites (10 atoms) starting in the $|gggggggggg\rangle$ state, $\Omega = 4\pi MHz$, $\Delta = 2\Omega$, for 50 steps of 10^{-8}s, $a_x = 1R_b \simeq 8.7\mu m$; $a_y = 0.5R_b$ so $|rr\rangle$ at that site are unlikely. Left: exact diagonalization. Middle: QuEra (local simulator). Right: Effective Hamiltonian.



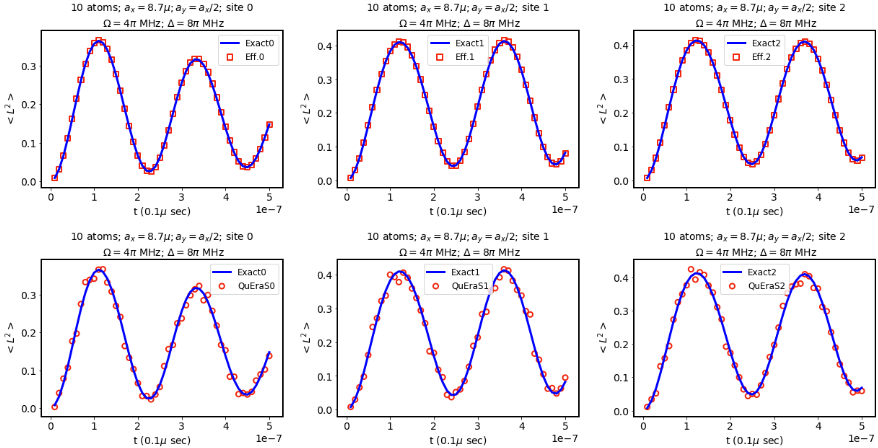
Effective Hamiltonian (with J. Zhang and S.-W. Tsai)

The basic spin relation is $L^z_i = n_{i,2} - n_{i,1}$ for atoms 1 and 2 at a site.
$\left(L^z_i\right)^2 \simeq n_{i,2} + n_{i,1}$ if we ignore $|rr\rangle$.
This implies $n_{i,2(1)} \simeq \left[\left(L^z_i\right)^2 \pm L^z_i\right]/2$.
Plugging into the simulator Hamiltonian we get the effective Hamiltonian

$$\begin{aligned}\hat{H}^{\mathrm{eff}}_{\mathrm{2LR}} \quad = \quad & -\Delta \sum_{i=1}^{N_s} (L^z_i)^2 + \sum_k \left(\frac{V^{(k)}_1 - V^{(k)}_2}{2} \sum_{i=1}^{N_s-1} L^z_i L^z_{i+k} \right. \\ & \left. + \frac{V^{(k)}_1 + V^{(k)}_2}{2} \sum_{i=1}^{N_s-1} (L^z_i)^2 \left(L^z_{i+k}\right)^2 \right) \\ & + \frac{\Omega}{2} \sum_{i=1}^{N_s} \left(\hat{U}^+_i + \hat{U}^-_i \right).\end{aligned}$$

If the distance between the sites is of order of 1.0 R_b or more we can neglect the NNN intereactions (which is done in the following).

Exact diagonalization, QuEra and H_{eff}.



Comparison between $H_{eff.}$ and H_{CAHM}

$$H_{CAHM} = \frac{U}{2}\sum_{i=1}^{N_s}\left(L_i^z\right)^2 - Y\sum_{i=1}^{N_s-1} L_{i+1}^z L_i^z - X\sum_{i=1}^{N_s} U_i^x$$

$$H_{eff.} = -\Delta\sum_{i=1}^{N_s}(L_i^z)^2 + \frac{V_1 - V_2}{2}\sum_{i=1}^{N_s-1} L_i^z L_{i+1}^z + \Omega\sum_{i=1}^{N_s} U_i^x + H_{quartic}$$

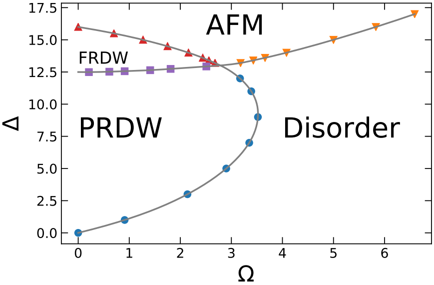
$$H_{quartic} = \frac{V_1 + V_2}{2}\sum_{i=1}^{N_s-1}\left(L_i^z\right)^2\left(L_{i+1}^z\right)^2.$$

Matching

- $\Delta = -U/2$ (sign matters!)
- The coefficient for $L_i^z L_{i+1}^z$ is positive ($V_1 > V_2$) for the simulator (repulsive/antiferromagnetic) but the CAHM has ferromagnetic interactions. This can be remedied by redefining the observable $L_{2i+1}^z \rightarrow -L_{2i+1}^z$ (staggered)
- After redefinition $V_1 = -V_2 = Y > 0$ but $V_2 > 0$
- $\Omega = -X$ (sign does not matter)

Everything agrees with two-rung results (YM, PRD104)

Effect of new quartic term (Jin Zhang)



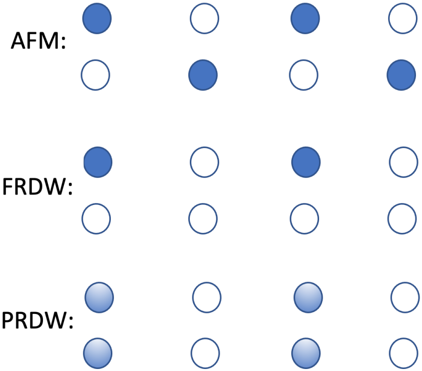
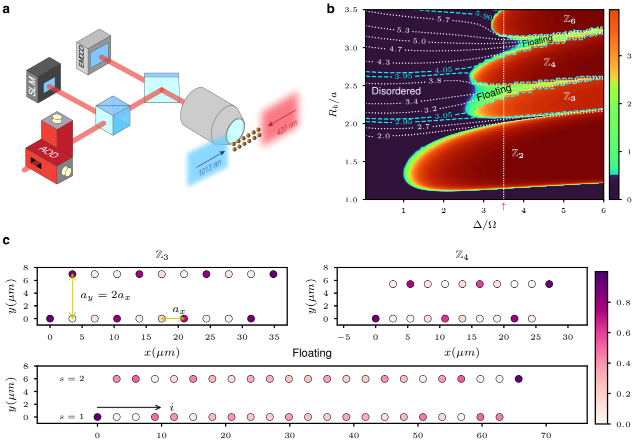
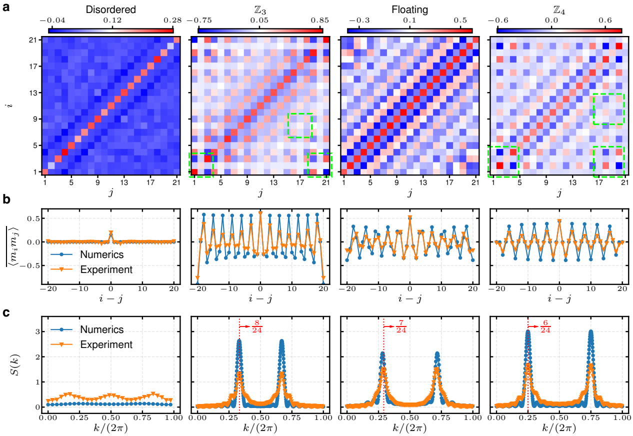


Figure: Ground-state phase diagram for the effective Hamiltonian of the two-leg Rydberg ladder. Here $L = 512$, $V_0 = 1000$, $\rho = dy/dx = 0.5$. The PRDW phase is disordered in even or odd sites, and the FRDW phase is FM in even or odd sites.

Phase diagram for a two-leg ladder with Sergio Cantu (QuEra), Fangli Liu (QuERA), Shan-Wen Tsai (UCR), Shengtao Wang (QuERA), Jin Zhang (ChongQing U.)



First row: for i and j; second row: versus $i - j$; third row: Fourier Tr.



Hadron Multiplicity (graph by K. Heitritter, 2212.02476)

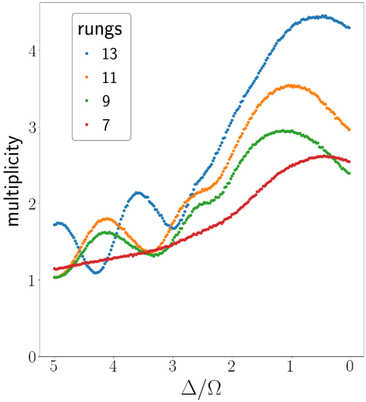


Figure: Hadron multiplicity output of the Rydberg hadronization model for $R_b/a = 2.173$. Δ/Ω plotted in decreasing order. We see by looking at multiplicity output of smaller ladders, that number of rungs is the main limiting factor on the measured hadron multiplicity. The recently public Rydberg simulator, Aquila, has the ability to investigate ladders with 128 atoms.

Conclusions

- QC/QIS in HEP and NP: big goals with many intermediate steps
- Tensor Lattice Field Theory (TLFT): generic tool to discretize path integral formulations of lattice model with compact variables (truncations preserve symmetries).
- Ladder-shaped Rydberg arrays with two (or three) atoms per site: simulators for the compact Abelian Higgs model.
- Matching between simulator and target model should be understood in the continuum limit (universal behavior).
- Effective Hamiltonians for the simulator: same three types of terms as the target model plus an extra quartic term.
- The two-leg ladder has a very rich phase diagram.
- Implementations with AWS/QuEra (ongoing).
- Progress with hybrid hadronization
- Thanks for listening!
- For questions, email: yannick-meurice@uiowa.edu .

Thanks for listening!

Figure: Isingized version of Emmy Noether

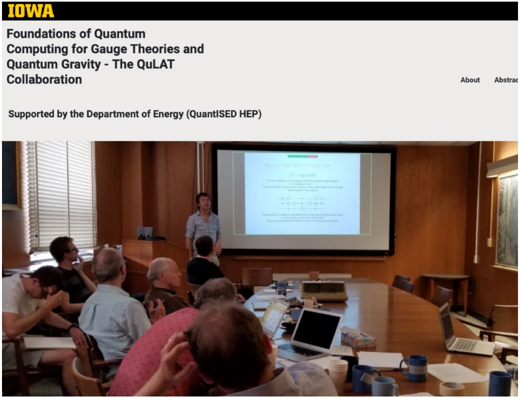
Other work with Rydberg atoms

- F. M. Surace, P. P. Mazza, G. Giudici, A. Lerose, A. Gambassi, and M. Dalmonte, Phys. Rev. X 10, 021041 (2020).
- A. Celi, B. Vermersch, O. Viyuela, H. Pichler, M. D. Lukin, and P. Zoller, Phys. Rev. X 10, 021057 (2020).
- S. Notarnicola, M. Collura, and S. Montangero, Phys. Rev. Research 2, 013288 (2020).
- Pierre Fromholz, Mikheil Tsitsishvili, Matteo Votto, Marcello Dalmonte, Alexander Nersesyan, Titas Chanda, Phys. Rev. B 106, 155411 (2022)
- Daniel Gonzalez-Cuadra, Torsten V. Zache, Jose Carrasco, Barbara Kraus, Peter Zoller, Phys. Rev. Lett. 129, 160501 (2022)
- For more refs. see: C. Bauer, Z. Davoudi et al., arXiv:2204.03381, PRX Quantum 4 (2023) 2, 027001

QuLAT Collaboration

QuLAT Collaboration

https://qulat.sites.uiowa.edu/



Goals of the collaboration

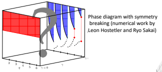
Quantum computers are expected to exceed the capacity of classical computers and to revolutionize several aspects of computation especially for the simulation of quantum systems. We develop new methods for using quantum computers to study aspects of the evolution of strongly interacting particles in collisions, the quantum behavior of gravitational systems and the emergence of space-time which are beyond the reach of classical computing. Our goal is to design the building blocks of universal quantum computers relevant for these problems and develop algorithms which scale reasonably with the size of the system.

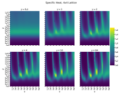
Principal Investigators

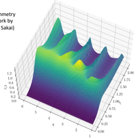
Alexei Bazavov, Michigan State University
David Berenstein, University of Cal. Santa Barbara
Richard Brower, Boston University
Simon Catterall, Syracuse University
Xi Dong, UCSB (consultant)
Stephen Jordan, University of Maryland/Microsoft
Seth Lloyd, MIT (consultant)
Yannick Meurice, University of Iowa (Spokesperson)

Related upcoming talks

Symmetry Breaking and Clock Model Interpolation in 2D Classical O(2) Spin Systems Leon Hostetler (Michigan State University) 8/4/23, 9:00 AM







Simulations of the Hyperbolic Ising Model Goksu Toga (Syracuse University) 8/4/23, 10:00 AM

Simulating Field Theories with Quantum Computers Muhammad Asaduzzaman (University of Iowa) 8/4/23, 10:20 AM

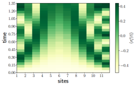


FIG. 5: Trotter evolution with exact diagonalization

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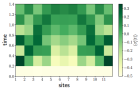

FIG. 6: Trotter evolution of local magnetization $\langle\sigma_i^z(t)\rangle$ computed using guadalupe Quantum Processing Unit (QPU).

Faculty Job at U. Iowa

`https://jobs.uiowa.edu/faculty/view/74834`

Areas of either neutrino/very weakly interacting particle phenomenology in laboratory and astroparticle physics, or in the areas of applications of quantum information/computation in quantum field theory and particle physics.

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Department:	Physics & Astronomy

SALARY

Salary:	Commensurate

POSITION DETAILS

Full/Part Time Status:	Full Time
Position Description:	The Department of Physics and Astronomy at the University of Iowa invites applications for a full-time, tenure-track Assistant Professor position in theoretical particle physics to begin in Fall 2024. Candidates in areas of either neutrino/very weakly interacting particle phenomenology in laboratory and astroparticle physics, or in the areas of applications of quantum information/computation in quantum field theory and particle physics are encouraged to apply. Candidates are expected to have an established publication record in at least one of the research areas listed above.