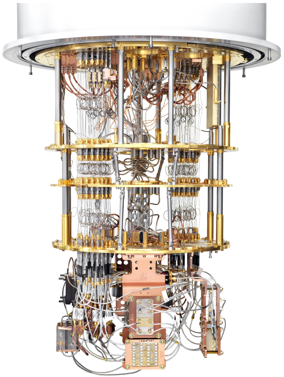
Toward Scalable Quantum Simulation of Lattice Gauge Theories: The Orbifold Lattice.[†]

Emanuele Mendicelli
Department of Mathematical Sciences, Theoretical Physics Wing, University of Liverpool

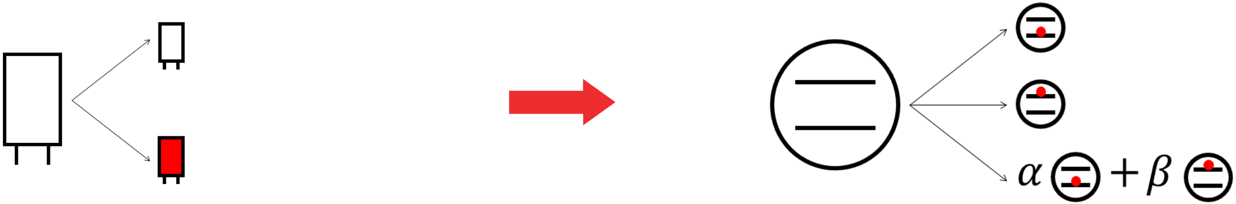
TP-Wing Lattice Meeting, March 17th, University of Liverpool

[†]In collaboration with: Georg Bergner and Masanori Hanada

Quantum Hardware and Qubits

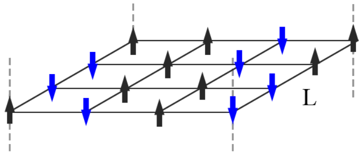


- Quantum superposition
- Entanglement



Classical Vs Quantum resources

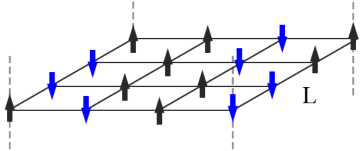
Let's consider a simple 3D spin model system with N spin-1/2



$\longrightarrow$ Hamiltonian $2^N \times 2^N$
(Hamiltonian approach is not feasible)

Classical Vs Quantum resources

Let's consider a simple 3D spin model system with N spin-1/2



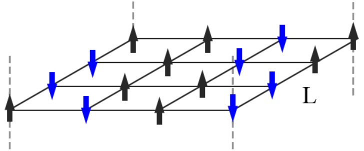
$\longrightarrow$ Hamiltonian $2^N \times 2^N$
(Hamiltonian approach is not feasible)

Let's estimate the computational resources needed to study a system with N spins:

$Z = \int dx\, dy\, dz\, e^{-S} \longrightarrow \approx 2^N$

Classical Vs Quantum resources

Let's consider a simple 3D spin model system with N spin-1/2



$\longrightarrow$ Hamiltonian $2^N \times 2^N$
(Hamiltonian approach is not feasible)

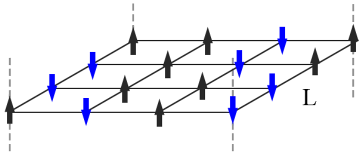
Let's estimate the computational resources needed to study a system with N spins:

$Z = \int dx\, dy\, dz\, e^{-S} \longrightarrow \approx 2^N$

Classical computer: 2^N memory slots $\Longrightarrow$ Quantum computer: N qubits

Classical Vs Quantum resources

Let's consider a simple 3D spin model system with N spin-1/2



$\longrightarrow$ Hamiltonian $2^N \times 2^N$
(Hamiltonian approach is not feasible)

Let's estimate the computational resources needed to study a system with N spins:

$Z = \int dx\, dy\, dz\, e^{-S} \longrightarrow \approx 2^N$

Classical computer: 2^N memory slots $\Longrightarrow$ Quantum computer: N qubits

---

Let's double the system: N spins $\longrightarrow 2N$ spins

Classically

- $2^N \longrightarrow \left(2^{2N}\right) = \left(2^N\right)^2$

(escape importance sampling Monte Carlo)

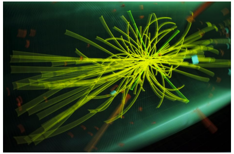
Quantum

- N qubits $\longrightarrow 2N$ qubits

Hamiltonian formalism is feasible on quantum computer!

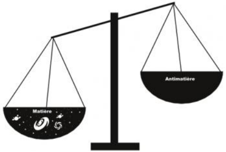
Hamiltonian formulation $\Longrightarrow$ No Sign problem

Real-time evolution

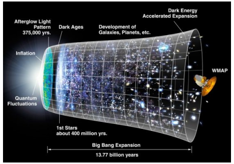


propagations/collisions

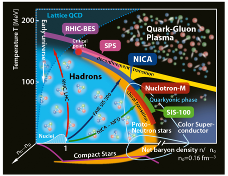
Non-zero chemical potential



Imbalance matter-antimatter

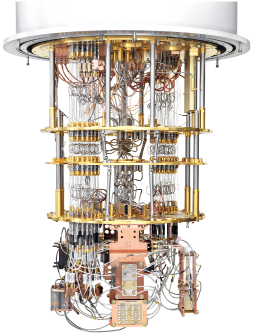


Early Universe



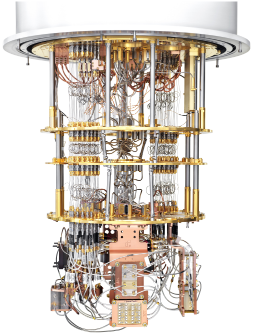
QCD phase diagram

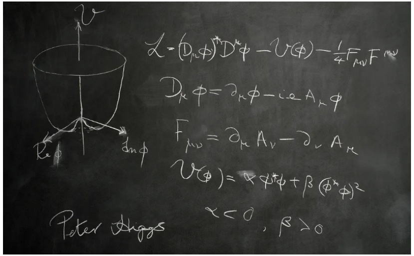
Challenges in using quantum computers: Hardware & Formalism



- Few qubits
- Low qubit connectivity
- Noisy gates
- No error correction $\Rightarrow$ **Error mitigation**!

Challenges in using quantum computers: Hardware & Formalism





- Few qubits
- Low qubit connectivity
- Noisy gates
- No error correction $\Rightarrow$ **Error mitigation**!

- Hamiltonian formulation
- Representation of the Hamiltonian
- Scalability of the continuum limit
- Scalability of the thermodynamic limit

Encoding challenges

The seminal work of Byrnes and Yamamoto

PHYSICAL REVIEW A **73**, 022328 (2006)

Simulating lattice gauge theories on a quantum computer

Tim Byrnes*
National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan

Yoshihisa Yamamoto
E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA and National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan
(Received 4 October 2005; published 17 February 2006)

We examine the problem of simulating lattice gauge theories on a universal quantum computer. The basic strategy of our approach is to transcribe lattice gauge theories in the Hamiltonian formulation into a Hamiltonian involving only Pauli spin operators such that the simulation can be performed on a quantum computer using only one- and two-qubit manipulations. We examine three models, the U(1), SU(2), and SU(3) lattice gauge theories, which are transcribed into a spin Hamiltonian up to a cutoff in the Hilbert space of the gauge fields on the lattice. The number of qubits required for storing a particular state is found to have a linear dependence on the total number of lattice sites. The number of qubit operations required for performing the time evolution corresponding to the Hamiltonian is found to be between a linear to quadratic function of the number of lattice sites, depending on the arrangement of qubits in the quantum computer. We remark that our results may also be easily generalized to higher SU(N) gauge theories.

[arXiv:0510027]

- "Hamiltonian formulation of Wilson's lattice gauge theories" by Kogut and Susskind [PhysRevD.11.395]
- Building blocks for Hamiltonian construction in U(1), SU(2) and SU(3)
- Guidelines for future quantum simulations on qubits

The nightmare... of using compact variables

$$\Box_1 |\psi_{\text{initial}}\rangle = \sum_{M_E}\sum_{M'_E}\sum_{M_J}\sum_{M'_J}\sum_{M_F}\sum_{M'_F}\sum_{M_I}\sum_{M'_I}\sum_{m_A}\sum_{m'_A}\sum_{m_B}\sum_{m'_B}\sum_{m_C}\sum_{m'_C}\cdots\sum_{m_L}\sum_{m'_L}\sum_{J_F}\sum_{J_E}\sum_{J_I}\sum_{J_J}\sum_{s_1}\sum_{s_2}\sum_{s_6}\sum_{s_5}$$
$$(-1)^{s_1+s_2+s_6+s_5}(-1)^{-2j_E-2j_J-2j_F-2j_I+M_E+M'_E+M_J+M'_J+M_F+M'_F+M_I+M'_I}$$
$$\sqrt{2j_E+1}\sqrt{2J_E+1}\sqrt{2j_J+1}\sqrt{2J_J+1}\sqrt{2j_F+1}\sqrt{2J_F+1}\sqrt{2j_I+1}\sqrt{2J_I+1}$$
$$\begin{pmatrix} j_A & j_E & j_I \\ m'_A & m_E & m_I \end{pmatrix}\begin{pmatrix} j_C & j_E & j_J \\ m_C & m'_E & m_J \end{pmatrix}\begin{pmatrix} j_C & j_G & j_K \\ m'_C & m_G & m'_K \end{pmatrix}\begin{pmatrix} j_A & j_G & j_L \\ m_A & m'_G & m_L \end{pmatrix}$$
$$\begin{pmatrix} j_B & j_F & j_I \\ m'_B & m_F & m'_I \end{pmatrix}\begin{pmatrix} j_D & j_F & j_J \\ m_D & m'_F & m'_J \end{pmatrix}\begin{pmatrix} j_D & j_H & j_K \\ m'_D & m_H & m'_K \end{pmatrix}\begin{pmatrix} j_B & j_H & j_L \\ m_B & m'_H & m'_L \end{pmatrix}$$
$$\begin{pmatrix} j_E & \frac{1}{2} & J_E \\ m_E & -s_1 & -M_E \end{pmatrix}\begin{pmatrix} j_E & \frac{1}{2} & J_E \\ m'_E & s_2 & -M'_E \end{pmatrix}\begin{pmatrix} j_J & \frac{1}{2} & J_J \\ m_J & -s_2 & -M_J \end{pmatrix}\begin{pmatrix} j_J & \frac{1}{2} & J_J \\ m'_J & s_6 & -M'_J \end{pmatrix}$$
$$\begin{pmatrix} j_F & \frac{1}{2} & J_F \\ m_F & s_5 & -M_F \end{pmatrix}\begin{pmatrix} j_F & \frac{1}{2} & J_F \\ m'_F & -s_6 & -M'_F \end{pmatrix}\begin{pmatrix} j_I & \frac{1}{2} & J_I \\ m_I & s_1 & -M_I \end{pmatrix}\begin{pmatrix} j_I & \frac{1}{2} & J_I \\ m'_I & -s_5 & -M'_I \end{pmatrix}$$
$$|j_A, m_A, m'_A\rangle\,|j_B, m_B, m'_B\rangle\,|j_C, m_C, m'_C\rangle\,|j_D, m_D, m'_D\rangle\,|J_E, M_E, M'_E\rangle\,|J_F, M_F, M'_F\rangle$$
$$|j_G, m_G, m'_G\rangle\,|j_H, m_H, m'_H\rangle\,|J_I, M_I, M'_I\rangle\,|J_J, M_J, M'_J\rangle\,|j_K, m_K, m'_K\rangle\,|j_L, m_L, m'_L\rangle\ . \tag{A15}$$

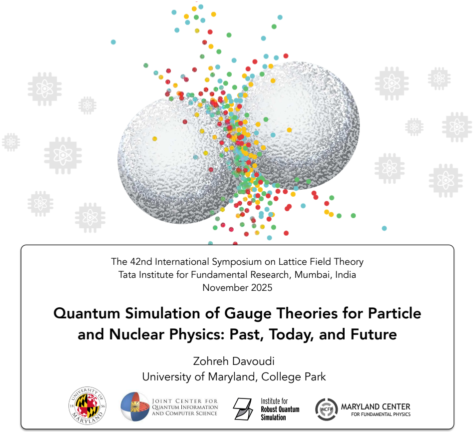
Applying a final state to that result allows all sums to be performed and the answer simplifies to

$$\langle\psi_{\text{final}}|\,\Box_1\,|\psi_{\text{initial}}\rangle = (-1)^{j_A+j_B+j_C+j_D+2J_E+2J_F+2j_I+2j_J}$$
$$\sqrt{2j_E+1}\sqrt{2J_E+1}\sqrt{2j_J+1}\sqrt{2J_J+1}\sqrt{2j_F+1}\sqrt{2J_F+1}\sqrt{2j_I+1}\sqrt{2J_I+1}$$
$$\begin{Bmatrix} j_A & j_E & j_I \\ \frac{1}{2} & J_I & J_E \end{Bmatrix}\begin{Bmatrix} j_B & j_F & j_I \\ \frac{1}{2} & J_I & J_F \end{Bmatrix}\begin{Bmatrix} j_C & j_E & j_J \\ \frac{1}{2} & J_J & J_E \end{Bmatrix}\begin{Bmatrix} j_D & j_F & j_J \\ \frac{1}{2} & J_J & J_F \end{Bmatrix} \tag{A16}$$

[arXiv:2205.09247]

Progress of Quantum Computing for LGT

- For a review of the progress in **Quantum Simulation** and **Hamiltonian Formulations** of LGT:



Lattice 2025 plenary by Zohreh Davoudi

Lattice 2025 plenary by Indrakshi Raychowdhury

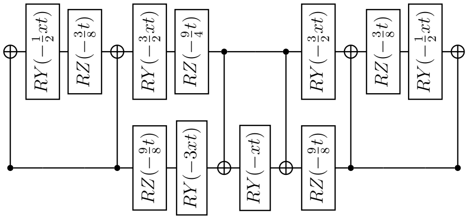
The encoding challenge

$$\hat{H} = \frac{g^2}{2}\left(\sum_{i=\text{links}} \hat{E}_i^2 - 2x \sum_{i=\text{plaquettes}} \hat{\square}_i\right)$$

Gate decomposition

$$H = \frac{3}{8}(7 - 3Z_0 - Z_0Z_1 - 3Z_1) - \frac{x}{2}(3 + Z_1)X_0 - \frac{x}{2}(3 + Z_0)X_1$$

$\Downarrow$



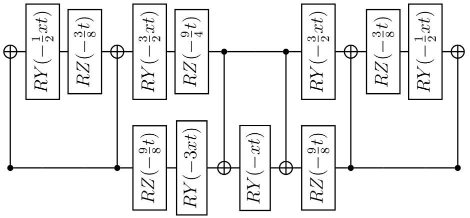
The encoding challenge

$$\hat{H} = \frac{g^2}{2}\left(\sum_{i=\text{links}} \hat{E}_i^2 - 2x \sum_{i=\text{plaquettes}} \hat{\square}_i\right)$$

Gate decomposition

$$H = \frac{3}{8}(7 - 3Z_0 - Z_0Z_1 - 3Z_1) - \frac{x}{2}(3 + Z_1)X_0 - \frac{x}{2}(3 + Z_0)X_1$$

$$\Downarrow$$



- Spin-like systems $H \longrightarrow$ quantum circuit (Ok)
- No spin-like systems:
  - Matrix representation (**scales exponentially**)
  - Convert matrix to quantum gates, Pauli decomposition (worst-case $\mathcal{O}(4^Q)$ [arXiv:2310.13421])

The encoding of Kogut-Susskind Hamiltonian

arXiv > quant-ph > arXiv:2505.02553

Quantum Physics

[Submitted on 5 May 2025 (v1), last revised 9 Oct 2025 (this version, v3)]

Exponential improvement in quantum simulations of bosons

Masanori Hanada, Shunji Matsuura, Emanuele Mendicelli, Enrico Rinaldi

Hamiltonian quantum simulation of bosons on digital quantum computers requires truncating the Hilbert space to finite dimensions. The method of truncation and the choice of basis states can significantly impact the complexity of the quantum circuit required to simulate the system. For example, a truncation in the Fock basis where each boson is encoded with a register of Q qubits, can result in an exponentially large number of Pauli strings required to decompose the truncated Hamiltonian. This, in turn, can lead to an exponential increase in Q in the complexity of the quantum circuit. For lattice quantum field theories such as Yang-Mills theory and QCD, several Hamiltonian formulations and corresponding truncations have been put forward in recent years. There is no exponential increase in Q when resorting to the orbifold lattice Hamiltonian, while we do not know how to remove the exponential complexity in Q in the commonly used Kogut-Susskind Hamiltonian. Specifically, when using the orbifold lattice Hamiltonian, the continuum limit, or, in other words, the removal of the ultraviolet energy cutoff, is obtained with circuits whose resources scale like Q, while they scale like $\mathcal{O}(\exp(Q))$ for the Kogut-Susskind Hamiltonian: this can be seen as an exponential speed up in approaching the physical continuum limit for the orbifold lattice Hamiltonian formulation. We show that the universal framework, advocated by three of the authors (M.~H., S.~M., and E.~R.) and collaborators, provides a natural avenue to solve the exponential scaling of circuit complexity with Q, and it is the reason why using the orbifold lattice Hamiltonian is advantageous.

- The Kogut-Susskind Hamiltonian remains challenging to efficiently encode on a quantum hardware
- It is difficult to write quantum circuits explicitly
- Exponential classical preprocessing is often required
- No systematic analysis of resource scaling for quantum simulations

Whether an efficient encoding is achievable remains an open question

A scalable formalism? maybe the Orbifold lattice

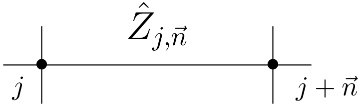
Why do I like the Orbifold Lattice for QCD and Yang-Mills ?

- The Hamiltonian is given explicitly for any gauge group, lattice size and truncation level
- Quantum circuit can be written explicitly
- Gate count grows polynomially with qubits
- The Kogut-Susskind Hamiltonian is obtained as Orbifold large-mass limit
- **It requires a substantial number of bosons!**

Orbifold lattice approach for SU(N)

Compact Variables ⟶ Cartesian Coordinate:

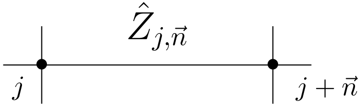
- $\mathrm{SU}(N) \subset \mathbb{C}^{N^2} \cong \mathbb{R}^{2N^2}$



Orbifold lattice approach for SU(N)

Compact Variables $\longrightarrow$ Cartesian Coordinate:

- $\mathrm{SU}(N) \subset \mathbb{C}^{N^2} \cong \mathbb{R}^{2N^2}$



$$Z_{j,\vec{n}} = \sqrt{\frac{a^{d-2}}{2g_d^2}}\, W_{j,\vec{n}}\, U_{j,\vec{n}}$$

- $W_{j,\vec{n}} = \exp\left(ag_d\phi_{j,\vec{n}}\right)$ positive-definite Hermitian $\longrightarrow$ ϕ_j adjoint scalar field
- $U_{j,\vec{n}} = \exp(\mathrm{i}ag_dA_{j,\vec{n}})$, unitary link variable $\longrightarrow$ A_j gauge field
  (Note: $\det(U)$ is not fixed to 1)

Toward a Yang-Mills theory coupled to scalars

The $SU(N)$ Orbifold Hamiltonian

$$\hat{H} = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{g_{\mathrm{d}}^2}{2a^d} \left| \sum_{j=1}^{d} \left(\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} - \hat{\bar{Z}}_{j,\vec{n}-\hat{j}} \hat{Z}_{j,\vec{n}-\hat{j}} \right) \right|^2 + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta \hat{H}$$

where

$$\Delta \hat{H} = \frac{m^2 g_d^2}{2a^{d-2}} \sum_{\vec{n}} \sum_{j=1}^{d} \mathrm{Tr} \left| \hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} - \frac{a^{d-2}}{2g_d^2} \right|^2 + \frac{m_{\mathrm{U}(1)}^2 a^{d-2}}{2g_d^2} \sum_{\vec{n}} \sum_{j=1}^{d} \left| \left(\frac{a^{d-2}}{2g_d^2} \right)^{-N/2} \det(\hat{Z}_{j,\vec{n}}) - 1 \right|^2$$

- first term forces $W \to \mathbf{1}_N$
- second term forces $\det(U) \to 1$

The $SU(N)$ Orbifold Hamiltonian

$$\hat{H} = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{g_{\mathrm{d}}^2}{2a^d} \left| \sum_{j=1}^{d} \left(\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} - \hat{\bar{Z}}_{j,\vec{n}-\hat{j}} \hat{Z}_{j,\vec{n}-\hat{j}} \right) \right|^2 + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta\hat{H}$$

where

$$\Delta\hat{H} = \frac{m^2 g_d^2}{2a^{d-2}} \sum_{\vec{n}} \sum_{j=1}^{d} \mathrm{Tr} \left| \hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} - \frac{a^{d-2}}{2g_d^2} \right|^2 + \frac{m_{\mathrm{U}(1)}^2 a^{d-2}}{2g_d^2} \sum_{\vec{n}} \sum_{j=1}^{d} \left| \left(\frac{a^{d-2}}{2g_d^2} \right)^{-N/2} \det(\hat{Z}_{j,\vec{n}}) - 1 \right|^2$$

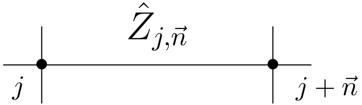
- first term forces $W \to \mathbf{1}_N$
- second term forces $\det(U) \to 1$

The Kogut-Susskind limit: m^2 and $m_{\mathrm{U}(1)}^2 \to \infty$:

- $(W = \mathbf{1}_N)$, scalar fields ϕ_j with large mass decouple
- $\det(U) = 1 \longrightarrow Z \equiv U \longrightarrow \in SU(N)$

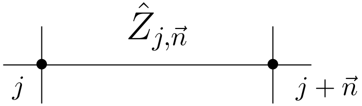
Pure Yang-Mills is recovered!

Quantum computing for $SU(N)$ Orbifold lattice



- Z and P $\in \mathbb{R}^{2N^2} \longrightarrow 2N^2$ components $(x_1, \ldots x_{2N^2}), (p_1, \ldots p_{2N^2}) \longrightarrow 2N^2$ bosons
- Q qubits per each boson, truncation level $\Lambda = 2^Q$

Quantum computing for $SU(N)$ Orbifold lattice



- Z and P $\in \mathbb{R}^{2N^2} \longrightarrow 2N^2$ components $(x_1, \dots x_{2N^2}), (p_1, \dots p_{2N^2}) \longrightarrow 2N^2$ bosons
- Q qubits per each boson, truncation level $\Lambda = 2^Q$

Λ point on 2R circle $\delta_x = 2R/\Lambda$

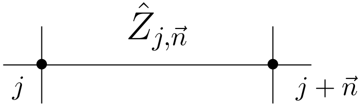
Λ point on 2R circle $\delta_p = \pi/R$

$$\hat{x}_a = -\frac{\delta_x}{2} \cdot \left(\hat{\sigma}_{z;a,1} + 2 \cdot \hat{\sigma}_{z;a,2} + \cdots + 2^{Q-1} \cdot \hat{\sigma}_{z;a,Q}\right)$$

$$\hat{p}_a = -\frac{\delta_p}{2} \cdot \left(\hat{\sigma}_{z;a,1} + 2 \cdot \hat{\sigma}_{z;a,2} + \cdots + 2^{Q-1} \cdot \hat{\sigma}_{z;a,Q}\right)$$

- Quantum Fourier Transform for connecting the coordinate and momentum bases

Quantum computing for $SU(N)$ Orbifold lattice



- Z and P $\in \mathbb{R}^{2N^2} \longrightarrow 2N^2$ components $(x_1, \ldots x_{2N^2}), (p_1, \ldots p_{2N^2}) \longrightarrow 2N^2$ bosons
- Q qubits per each boson, truncation level $\Lambda = 2^Q$

Λ point on 2R circle $\delta_x = 2R/\Lambda$

Λ point on 2R circle $\delta_p = \pi/R$

$$\hat{x}_a = -\frac{\delta_x}{2} \cdot \left(\hat{\sigma}_{z;a,1} + 2 \cdot \hat{\sigma}_{z;a,2} + \cdots + 2^{Q-1} \cdot \hat{\sigma}_{z;a,Q}\right) \qquad \hat{p}_a = -\frac{\delta_p}{2} \cdot \left(\hat{\sigma}_{z;a,1} + 2 \cdot \hat{\sigma}_{z;a,2} + \cdots + 2^{Q-1} \cdot \hat{\sigma}_{z;a,Q}\right)$$

- Quantum Fourier Transform for connecting the coordinate and momentum bases

- $\# Q_{\text{tot}} = d\, N_{\text{site}}\ 2N^2\ Q_{\text{boson}}$
- $\# Gates \propto N_{\text{site}}\ Q^4_{\text{boson}} N^4$

Computationally cheaper SU(N) Hamiltonians

Two cheaper SU(N) Orbifoldish Hamiltonians

$$\hat{H} = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{g_{\mathrm{d}}^2}{2a^d} \left| \sum_{j=1}^{d} \left(\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} - \hat{\bar{Z}}_{j,\vec{n}-\hat{j}} \hat{Z}_{j,\vec{n}-\hat{j}} \right) \right|^2 + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta \hat{H}$$

- In the K-S limit $(m^2 \to \infty) \implies (\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} \to \mathbf{1}_N)$, the second term $\to 0$, so it can be omitted:

Two cheaper SU(N) Orbifoldish Hamiltonians

$$\hat{H} = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{g_{\mathrm{d}}^2}{2a^d} \left| \sum_{j=1}^{d} \left(\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} - \hat{\bar{Z}}_{j,\vec{n}-\hat{j}} \hat{Z}_{j,\vec{n}-\hat{j}} \right) \right|^2 + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta \hat{H}$$

- In the K-S limit $(m^2 \to \infty) \Longrightarrow (\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} \to \mathbf{1}_N)$, the second term $\to 0$, so it can be omitted:

$$\boxed{\hat{H}_1 = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta \hat{H}}$$

Two cheaper SU(N) Orbifoldish Hamiltonians

$$\hat{H} = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{g_{\mathrm{d}}^2}{2a^d} \left| \sum_{j=1}^{d} \left(\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} - \hat{\bar{Z}}_{j,\vec{n}-\hat{j}} \hat{Z}_{j,\vec{n}-\hat{j}} \right) \right|^2 + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta \hat{H}$$

- In the K-S limit $(m^2 \to \infty) \implies (\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} \to \mathbf{1}_N)$, the second term $\to 0$, so it can be omitted:

$$\boxed{\hat{H}_1 = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta \hat{H}}$$

- Additionally, other terms $(\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} \to \mathbf{1}_N)$ inside the modulus can be omitted:

$$\boxed{\hat{H}_2 = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} - \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left(\hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} \hat{\bar{Z}}_{j,\vec{n}+\hat{k}} \hat{\bar{Z}}_{k,\vec{n}} + \mathrm{h.c.} \right) \right) + \Delta \hat{H}}$$

Two cheaper SU(N) Orbifoldish Hamiltonians

$$\hat{H} = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{g_{\mathrm{d}}^2}{2a^d} \left| \sum_{j=1}^{d} \left(\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} - \hat{\bar{Z}}_{j,\vec{n}-\hat{j}} \hat{Z}_{j,\vec{n}-\hat{j}} \right) \right|^2 + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta \hat{H}$$

- In the K-S limit $(m^2 \to \infty) \implies (\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} \to \mathbf{1}_N)$, the second term $\to 0$, so it can be omitted:

$$\boxed{\hat{H}_1 = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} + \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left| \hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} - \hat{Z}_{k,\vec{n}} \hat{Z}_{j,\vec{n}+\hat{k}} \right|^2 \right) + \Delta \hat{H}}$$

- Additionally, other terms $(\hat{Z}_{j,\vec{n}} \hat{\bar{Z}}_{j,\vec{n}} \to \mathbf{1}_N)$ inside the modulus can be omitted:

$$\boxed{\hat{H}_2 = \sum_{\vec{n}} \mathrm{Tr}\left(\sum_{j=1}^{d} \hat{P}_{j,\vec{n}} \hat{\bar{P}}_{j,\vec{n}} - \frac{2g_{\mathrm{d}}^2}{a^d} \sum_{j<k} \left(\hat{Z}_{j,\vec{n}} \hat{Z}_{k,\vec{n}+\hat{j}} \hat{\bar{Z}}_{j,\vec{n}+\hat{k}} \hat{\bar{Z}}_{k,\vec{n}} + \mathrm{h.c.} \right) \right) + \Delta \hat{H}}$$

- **Is the K-S limit well under control for H_1 and H_2? $\longrightarrow$ Monte Carlo Lattice Simulations**

Orbifold for $SU(2)$

$SU(2)$ Orbifold-ish Lattice on $\mathbb{R}^4$

- Let's halve the number of boson per link:

$SU(2)$ Orbifold-ish Lattice on $\mathbb{R}^4$

- Let's halve the number of boson per link:

$$\text{Orbifold} \longrightarrow \text{Orbifold-ish}$$

$$\mathrm{SU}(2) \subset \mathbb{C}^4 \cong \mathbb{R}^8 \longrightarrow \mathrm{SU}(2) \cong \mathbb{S}^3 \subset \mathbb{R}^4$$

$$\text{8 bosons per link} \longrightarrow \text{4 bosons per link}$$

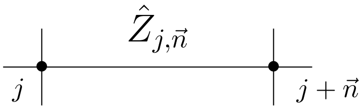
$SU(2)$ Orbifold-ish Lattice on $\mathbb{R}^4$

- Let's halve the number of boson per link:

$$\text{Orbifold} \quad \longrightarrow \quad \text{Orbifold-ish}$$

$$\mathrm{SU}(2) \subset \mathbb{C}^4 \cong \mathbb{R}^8 \quad \longrightarrow \quad \mathrm{SU}(2) \cong \mathbb{S}^3 \subset \mathbb{R}^4$$

$$\text{8 bosons per link} \quad \longrightarrow \quad \text{4 bosons per link}$$

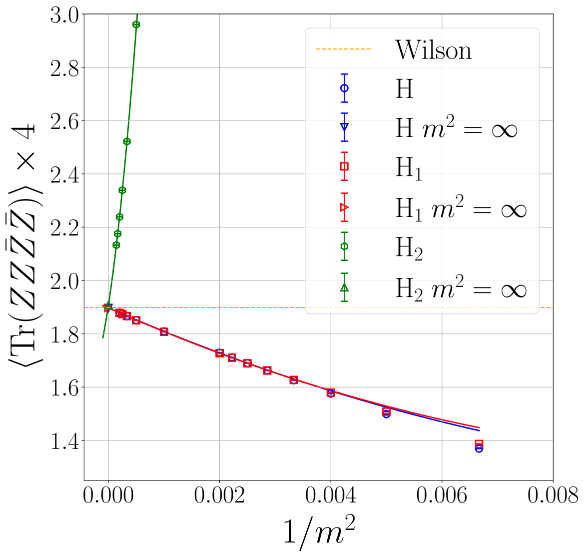


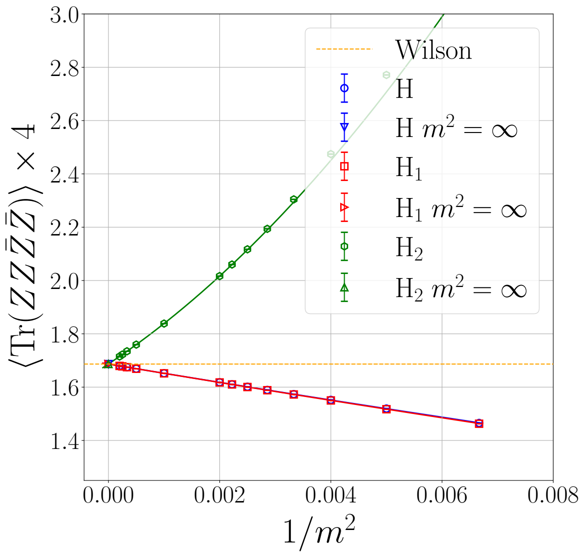
$$Z_{j,\vec{n}} = \sqrt{\frac{a^{d-2}}{2g_d^2}}\, W_{j,\vec{n}}\, U_{j,\vec{n}}$$

$$m^2 \to \infty \quad \longrightarrow \quad Z \to \in SU(2)$$

The Kogut-Susskind limit for $SU(2)$ Orbifoldish Lattice on $\mathbb{R}^4$ $\left(m^2 \to \infty\right)$

Spatial plaquette $\langle \mathrm{Tr}(ZZ\bar{Z}\bar{Z}) \rangle$

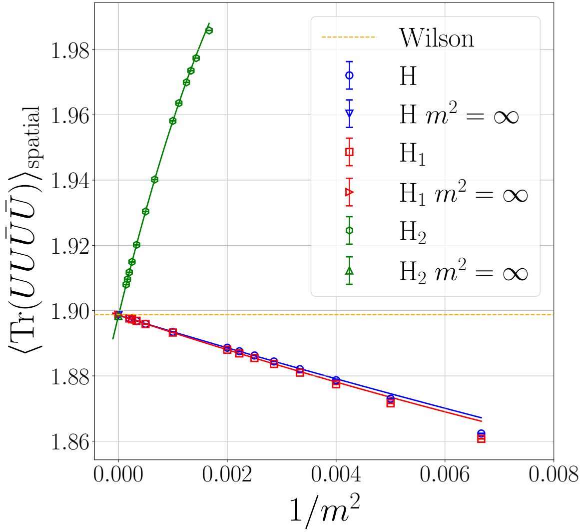


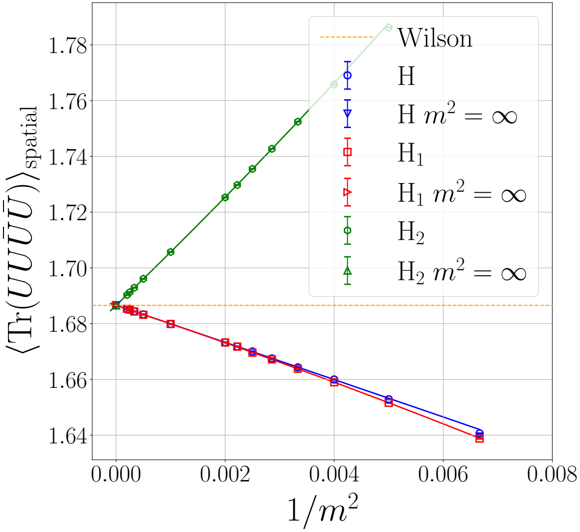


- $16^2 \times 16 \quad a_s = a_t = 0.1$
- $16^2 \times 16 \quad a_s = a_t = 0.3$

- Orbifold lattice agrees with Wilson action

Spatial plaquette $\langle \mathrm{Tr}(UUU^\dagger U^\dagger)\rangle_{\mathrm{spatial}}$

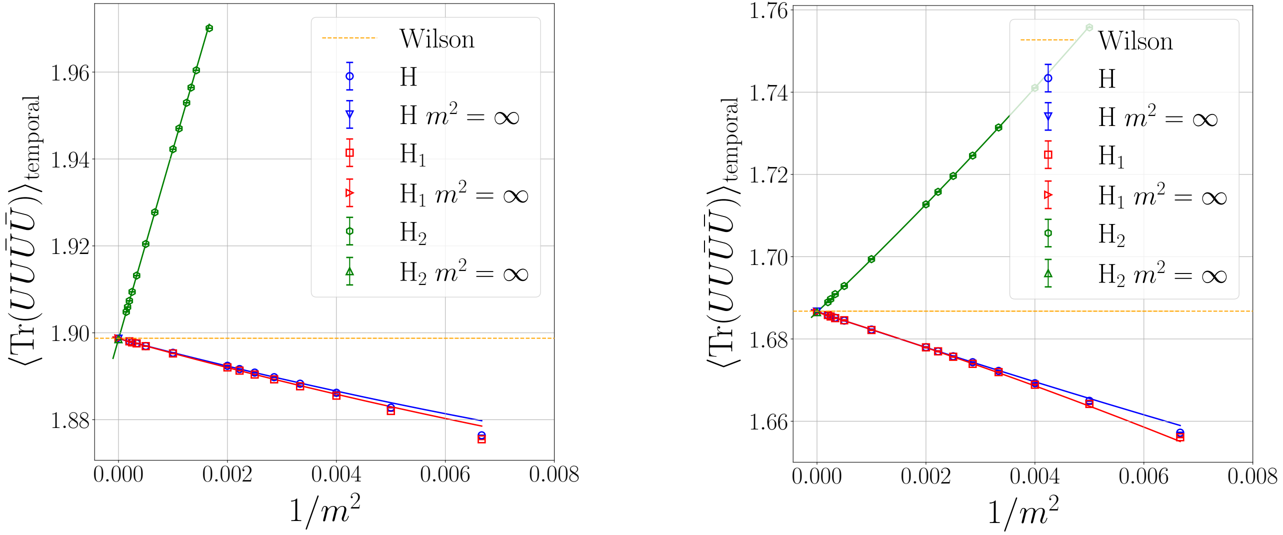




- $16^2 \times 16 \quad a_s = a_t = 0.1$
- $16^2 \times 16 \quad a_s = a_t = 0.3$

- Orbifold lattice agrees with Wilson action

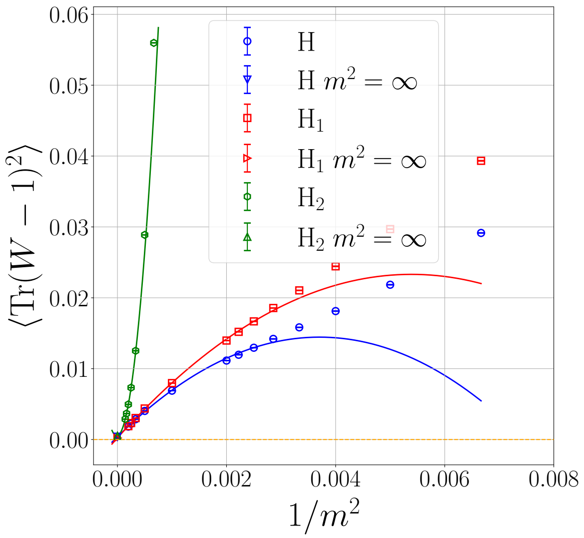
Spatial plaquette $\langle \mathrm{Tr}(UUU^\dagger U^\dagger) \rangle_{\mathrm{temporal}}$

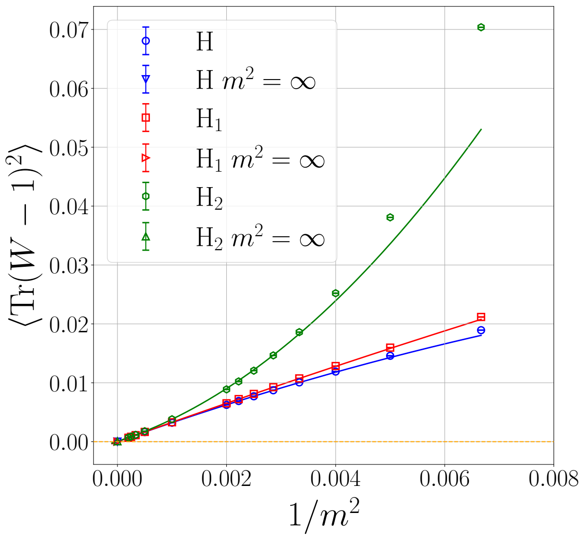


- $16^2 \times 16 \quad a_s = a_t = 0.1$
- $16^2 \times 16 \quad a_s = a_t = 0.3$

- Orbifold lattice agrees with Wilson action

$\langle \mathrm{Tr}(W - \mathbf{1}_N)^2 \rangle$





- $16^2 \times 16 \quad a_s = a_t = 0.1$
- $16^2 \times 16 \quad a_s = a_t = 0.3$

- Numerical confirmation that the large mass scalar ϕ_j decouples $(W = \mathbf{1}_N)$

Conclusions

Take-home message

- Quantum hardware has revived interest in the Hamiltonian formulation of LGT
- The challenges in encoding Kogut–Susskind should be addressed by the community
- There is the need of a formalism that can make quantum advantage tangible
- Orbifold lattice seems to go in the right direction but there is much more to explore
- Orbifold lattice reproduce Kogut-Susskind in a controlled limit ($m^2 \to \infty$)
- Lattice simulations confirm no issues in extracting the K-S limit for SU(2) in (2+1)d

Take-home message

- Quantum hardware has revived interest in the Hamiltonian formulation of LGT
- The challenges in encoding Kogut–Susskind should be addressed by the community
- There is the need of a formalism that can make quantum advantage tangible
- Orbifold lattice seems to go in the right direction but there is much more to explore
- Orbifold lattice reproduce Kogut-Susskind in a controlled limit ($m^2 \to \infty$)
- Lattice simulations confirm no issues in extracting the K-S limit for SU(2) in (2+1)d

Ongoing work:

- Explore Orbifold lattice properties, like phase diagram etc.
- Quantify the bosons truncation effects for quantum simulations
- Quantum simulation of Orbifold lattice for SU(2) and SU(3) systems


4th QuantHEP @ Queen Mary
University of London
LONDON, JULY 13-16, 2026
FRIEDRICH-SCHILLER-
UNIVERSITÄT
JENA
UNIVERSITY OF
LIVERPOOL
University of
Southampton

Thank you all for your time!

Time for Questions!

Backup Slides

Orbifold Lattice for Quantum Computing: A Timeline

- 2002 D. B. Kaplan, E. Katz and M. Unsal [arXiv:hep-lat/0206019]
  (Original formulation, Orbifold projection)
- 2020 A. J. Buser, H. Gharibyan, M. Hanada, M. Honda and J. Liu [arXiv:2011.06576]
  (Orbifold for quantum simulations of U(k))
- 2024 G. Bergner, M. Hanada, E. Rinaldi, A. Schafer [arXiv:2401.12045]
  (Orbifold lattice for quantum simulations of QCD)
- 2024 J. C. Halimeh, M. Hanada, S. Matsuura, F. Nori, E. Rinaldi and A. Schäfer [arXiv:2411.13161]
  (Universal framework for quantum simulations of SU(N) Yang-Mills)
- 2025 G. Bergner and M. Hanada [arXiv:2506.00755]
  (Lattice simulations (2+1)d: Kogut-Susskind as Orbifold limit)
- 2025 J. C. Halimeh, M. Hanada and S. Matsuura [arXiv:2506.18966]
  (Universal framework with fermions)