Quantum Computation and Quantum Simulation of the Lattice Schwinger Model
Quantum Computation and Quantum Simulation of the Lattice Schwinger Model

- Trapped Ca\(^+\) for quantum information processing
- Quantum computation: toolbox operations
- Quantum simulations with spin chains
- Digital quantum simulation of the Schwinger model
- Hybrid quantum simulation of the Schwinger model
- Towards scalable quantum information processing
The Quantum Information Processor with Trapped Ca⁺ Ions

Experiments with trapped Ca\(^{+}\) ions

\[\tau \approx 7\, \text{ns}\]

\[\tau \approx 1.1\, \text{s}\]

Quantum state detection

Quantum state manipulation

\[\sigma_z\] - measurement

Fluorescence

Quantum jump detection by electron shelving
Quantum state manipulation: carrier and sidebands

2-level-atom harmonic trap

$|e\rangle$  \(\Omega\)  \(\Gamma\)  \(\nu\)  \(|g\rangle\)

Coupled system

$|n - 1, e\rangle$  $|n, e\rangle$  $|n + 1, e\rangle$

$|n - 1, g\rangle$  $|n, g\rangle$  $|n + 1, g\rangle$

Excitation: various resonances

$D_{S/2}$  $\nu$

$S_{S/2}$

$n = 0$  $1$  $2$

Carrier:
manipulate qubit
\(\rightarrow\) internal superpositions

Sidebands:
manipulate motion and qubit
\(\rightarrow\) create entanglement

References:

J. I. Cirac, P. Zoller; PRL 74, 4091 (1995)

D. Leibfried, R. Blatt, C. Monroe, D. Wineland
RMP 75, 281 (2003)

S. Stenholm,
RMP 58, 699 (1986)
Quantum information processing with trapped ions

**algorithms:**
sequence of single qubit and two-qubit gate operations

**gate operations:**
sequences of laser pulses (carrier and/or sideband pulses)

\[ R(\vartheta, \varphi), \quad R^+(\vartheta, \varphi) \]

- carrier
- sideband

**analysis:**
measure density matrix of state or process (tomography)

\[ |\Psi^+\rangle = \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle) \]

measure entanglement via parity oscillations
Toolbox: Quantum computing with global and local operations

Global Mølmer-Sørensen entangling gate

\[ S_{x,y}^{2}(\theta) \]

\[ \tau = 50\mu s \]

\[ F_2 > 99\% \]

Collective Local Operations

\[ S_{x,y}(\theta) \]

\[ \tau = 20\mu s \]

\[ F > 99.5\% \]

Global

\[ ^{40}\text{Ca}^+ \]

\[ D_{5/2} \]

\[ S_{1/2} \quad |1\rangle \]

resonant manipulation

Local

\[ ^{40}\text{Ca}^+ \]

\[ D_{5/2} \]

\[ S_{1/2} \quad |1\rangle \]

off-resonant manipulation

Individual local operations

All three blocks combined realize a **universal gate set** for arbitrary quantum computation

Toolbox: Quantum computing with global and local operations

**Global Mølmer-Sørensen entangling gate**

- \( \tau = 50 \mu s \)
- \( F_2 > 99\% \)

**Collective Local Operations**

- \( S_{x,y}(\theta) \)
- \( \tau = 20 \mu s \)
- \( F > 99.5\% \)

**Local Mølmer-Sørensen entangling gate**

- \( \tau = 100 \mu s \)
- \( F \sim 98\% \)

**Individual (and parallel) local operations**

- \( S_z(\theta) \)
- \( S_{x,y}(\theta) \)
- \( \tau = 20 \mu s \)
- \( F > 99\% \)

**Local**

- Simultaneous addressing of multiple ions

---

Laser-ion interactions – geometry

Mølmer-Sørensen entangling operations

single-ion addressing by acousto-optical deflector

\[ \sigma_z^{(i)}(\theta) \]

\[ S_{x,y}^2(\theta) \]

Mølmer-Sørensen entangling operations

\[ S_{x,y}(\theta) \]

collective local operations

local beams
Toolbox: Quantum gate operations – unitaries

Quantum circuits:

- $U_1(\theta, j) = e^{-i\theta \sigma_j^z}$: local Stark shifts
- $U_2(\theta) = e^{-i\theta \sum_i \sigma_z^i}$: collective Stark shifts
- $U_3(\theta, \phi) = e^{-i\theta \sum_i \sigma_\phi^i}$: collective local ops.
- $U_4(\theta, \phi) = e^{-i\theta \sum_{i<j} \sigma_\phi^i \sigma_\phi^j}$: entangling MS ops.

$\sigma_\phi = \cos \phi \sigma_x + \sin \phi \sigma_y$

$\sigma_k^j$ $k$-th Pauli matrix acting on $j$-th qubit

**additional operations:**
- hiding operations (reduce/enlarge computat. subspace)
- dephasing operations (open systems)
- initialization/reset operation
- quantum (cache) memory
Quantum computation with global and local operations

- Global entangling gate
- Collective local ops.
- Global entangling gate
- Local op.

Input computation: sequence of quantum gates

|ψ₁⟩ → Global entangling gate → Collective local ops. → Global entangling gate → output |
|ψ₂⟩ → Global entangling gate → Collective local ops. → Global entangling gate → output |
|ψ₃⟩ → Global entangling gate → Collective local ops. → Global entangling gate → output |

Measurement

|000⟩ |001⟩ |010⟩ |011⟩ |100⟩ |101⟩ |110⟩ |100⟩
|---|---|---|---|---|---|---|---|

0 1 1

measured
Set of operations:

\[ \{Z_n, Z_C, C_x, C_y, C(\theta, \phi), MS_x, MS_y, MS(\theta, \phi)\} \]

procedure:

1. Propose sequence with n=0 entangling gates
2. Search numerically for sequence parameters that maximize the fidelity with the target unitary
3. If converging -> STOP ELSE n -> n+1

Write arbitrary unitaries as:

\[ U = L_n MS_{\phi_n}(\alpha_n) \ldots L_2 MS_{\phi_2}(\alpha_2) Z_1 MS_{\phi_1}(\alpha_1) L_0 \]

With local operations \( L_i, Z_i \)

---

Estebanizer: Toffoli - gate

Toffoli-gate: CCNOT (controlled-CNOT operation), usually requires 6 CNOT ops, plus several local ops

Estebanizer: 3 MS gates, 5 global ops, 3 local ops

With additional constraints -> further simplifications possible

Four-controlled NOT operation

<table>
<thead>
<tr>
<th>Pulse Nr.</th>
<th>Pulse</th>
<th>Pulse Nr.</th>
<th>Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$R(1/2, 1)$</td>
<td>6</td>
<td>$MS(1/4)$</td>
</tr>
<tr>
<td>2</td>
<td>$S_z(3/2, 1)$</td>
<td>7</td>
<td>$R(3/4, 0)$</td>
</tr>
<tr>
<td>3</td>
<td>$MS(3/4)$</td>
<td>8</td>
<td>$S_z(3/2, 1)$</td>
</tr>
<tr>
<td>4</td>
<td>$R(5/4, 1)$</td>
<td>9</td>
<td>$R(1/2, 0)$</td>
</tr>
<tr>
<td>5</td>
<td>$S_z(1, 1)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

algorithm works for arbitrary number of qubits (spectators allowed)

Thomas Monz et al., Science 351, 1068 (2016)
Fredkin gate – a controlled SWAP operation

**Constraint:**
algorithm works for three qubits only
(i.e. needs cache memory)

<table>
<thead>
<tr>
<th>Pulse Nr.</th>
<th>Pulse</th>
<th>Pulse Nr.</th>
<th>Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$R(1/2,1/2)$</td>
<td>10</td>
<td>$R(1/2,1)$</td>
</tr>
<tr>
<td>2</td>
<td>$S_x(3/2,3)$</td>
<td>11</td>
<td>$S_x(1/4,2)$</td>
</tr>
<tr>
<td>3</td>
<td>$MS(4/8)$</td>
<td>12</td>
<td>$S_x(3/2,3)$</td>
</tr>
<tr>
<td>4</td>
<td>$S_x(3/2,2)$</td>
<td>13</td>
<td>$MS(4/8)$</td>
</tr>
<tr>
<td>5</td>
<td>$S_x(1/2,3)$</td>
<td>14</td>
<td>$S_x(3/2,2)$</td>
</tr>
<tr>
<td>6</td>
<td>$R(3/4,0)$</td>
<td>15</td>
<td>$S_x(3/2,1)$</td>
</tr>
<tr>
<td>7</td>
<td>$MS(6/8)$</td>
<td>16</td>
<td>$R(1/2,1)$</td>
</tr>
<tr>
<td>8</td>
<td>$S_x(3/2,2)$</td>
<td>17</td>
<td>$S_x(3/2,1)$</td>
</tr>
<tr>
<td>9</td>
<td>$MS(4/8)$</td>
<td>18</td>
<td>$S_x(3/2,2)$</td>
</tr>
</tbody>
</table>

Quantum Simulation Approaches

Analog simulation:

\[ |\psi(0)\rangle \xrightarrow{e^{-\frac{i}{\hbar} \hat{H} t}} |\psi(t)\rangle \]

requires match between engineerable interactions and model

Digital simulation:

\[ |\psi(0)\rangle \rightarrow \text{ simulate any model } \hat{H}, \text{ but requires many gate operations} \]

\[ U_N(\delta(t)) \ldots U_2(\delta(t))U_1(\delta(t)) \]

Hybrid simulation:

Classical computer

analog quantum simulator
Analog Quantum Simulations with Spin Chains

Quantum simulations with spin chains

N ions interacting with a transverse bichromatic beam simulating the Hamiltonian

\[ H_{\text{Ising}} = \hbar \sum_{i<j} J_{ij} \sigma_i^x \sigma_j^x + \hbar B \sum_i \sigma_i^z \]

Coupling matrix \( J_{ij} \) has an approximate power law dependence with a tunable exponent \( \alpha \)

\[ J_{ij} \sim \frac{1}{|i - j|^{\alpha}} \]

- \( \alpha = 0 \) infinite range
- \( \alpha = 1 \) Coulomb
- \( \alpha = 3 \) dipole-dipole

for \( B \gg \max(|J_{ij}|) \) we get the XY interaction (hopping hardcore bosons)

\[ H_{\text{XY}} = \hbar \sum_{i<j} J_{ij} (\sigma_i^+ \sigma_j^- + \sigma_i^- \sigma_j^+) \]
Laser-ion interactions: Geometry

$H \propto \sigma^z_j$

single-ion addressing by acousto-optical deflector

$H = \sum_{i<j} \hbar J_{ij} \sigma^x_i \sigma^x_j$

$J_{ij} \approx \frac{J_0}{|i-j|^{\alpha}}$
Quantum simulations with spin chains prepare ground state, flip one spin (local quench), simulate interaction, measure quasiparticle dynamics.

Interactions $J_{ij}$ can be adjusted

$$J_{ij} = \Omega_i \Omega_j \frac{\hbar k^2}{2m} \sum_n \frac{\eta_{i,n} \eta_{j,n}}{\Delta^2 - \omega_n^2}$$

K. Kim et al., PRL 103, 120502 (2009)

- $\Omega_i$: Rabi frequency
- $\Delta$: detuning
- $k = 2\pi/\lambda$: wavenumber
- $m$: ion mass
- $\omega_n$: transverse mode frequency
- $\eta_{i,n}$: Lamb-Dicke factor of $i^{th}$ ion in $n^{th}$ mode
Entanglement distribution following a local quench

Spin-waves: propagation of entanglement

P. Jurcevic et al., Nature 511, 202 (2014)
The Universal Quantum Simulator with Trapped Ions

B. Lanyon et al., Science 334, 6052 (2011)
Digital Quantum Simulator

Goal
Simulate the physics of a quantum system of interest by another system that is easier to control and to measure.

Approach
Use a quantum computer as a quantum simulator

Decompose dynamics induced by system Hamiltonian into sequence of quantum gates

\[ U_{\text{sim}} = \prod_{j=1}^{N} U_j = U_1 U_2 U_3 \cdots U_N \]

Example:

\[ H = H_1 + H_2 + \ldots + H_k \]

\[ e^{-\frac{i}{\hbar} H t} = \left( e^{-\frac{i}{\hbar} H_1 t/n} e^{-\frac{i}{\hbar} H_2 t/n} \ldots e^{-\frac{i}{\hbar} H_k t/n} \right)^n \]

Trotter-Suzuki approximation

Digital Simulation: Universal Quantum Simulator

\[ H = \sum_k h_k \]

model of some local system to be simulated for a time \( t \)

1. build each local evolution operator separately, for small time steps, using operation set

\[ u_k = e^{-ih_k t / n} \]

2. approximate global evolution operator using the Trotter approximation

\[ U = e^{-iHt} \approx \left( e^{-i\frac{h_1}{n}t} e^{-i\frac{h_2}{n}t} e^{-i\frac{h_3}{n}t} \ldots e^{-i\frac{h_k}{n}t} \right)^n \]

\[ Et/h = \theta \]

“Efficient for local quantum systems”

Proof-of-principle demonstration

B. Lanyon et al., Science 334, 6052 (2011)

2-spin Ising system

\[ H = J \sigma_x^1 \sigma_x^2 + B (\sigma_z^1 + \sigma_z^2) \]

\[ \tilde{H} = \sigma_x^1 \sigma_x^2 + R (\sigma_z^1 + \sigma_z^2) \quad R = B/J \]

\[ U(\theta) \approx \left( e^{-i \sigma_x^l \sigma_x^k \theta / n} e^{-i \sum_j \sigma_z^j R \theta / n} \right)^n \]

Mølmer-Sørensen gate

AC-Stark gate

dynamics to simulate: \( e^{-iH\theta} |\uparrow\uparrow\rangle, \; R = 0.5 \)
Quantum Phase Transitions Go Dynamical

Synopsis: Victor Gurarie, Physics 10, 95 (2017)

Variational Quantum Simulation

Quantum simulation of lattice gauge theories
Quantum simulation of lattice gauge theories

Simulating lattice gauge theories with trapped ions

- QED in one dimension on a lattice
- Particles (Fermions) are encoded spins (two-level systems of ions)
- Gauge fields are transformed to long-range interactions
- Interactions are simulated stroboscopically with laser pulses

Schwinger-model:

E. Martinez, C. Muschik et al., Nature 534, 516-519 (2016)
Encoding Fermions to two-level systems

- Fermions ($e^-$, $e^+$) and holes are encoded in two-level systems (of ions)
- **Odd** ($o$) sites: $e^-$, **even** ($e$) sites: $e^+$

Encoding Fermions to two-level systems

**Notation:**

- $|0\rangle = \text{vacuum}$
- $|e^-\rangle = \text{particle}$
- $|e^+\rangle = \text{antiparticle}$

**Hilbert space:**

- $|0000\rangle = |\uparrow\downarrow\uparrow\downarrow\rangle$
- $|e^-e^+00\rangle = |\downarrow\uparrow\uparrow\downarrow\rangle$
- $|0e^+e^-0\rangle = |\uparrow\uparrow\downarrow\downarrow\rangle$
- $|00e^-e^+\rangle = |\uparrow\downarrow\uparrow\uparrow\rangle$
- $|e^-00e^+\rangle = |\downarrow\downarrow\uparrow\uparrow\rangle$
- $|e^-e^+e^-e^+\rangle = |\downarrow\uparrow\downarrow\uparrow\rangle$

- Investigate pair creation: $|0000\rangle = |\uparrow\downarrow\uparrow\downarrow\rangle \rightarrow |0e^+e^-0\rangle = |\uparrow\uparrow\downarrow\downarrow\rangle$

- States outside Hilbert space are considered unphysical

Long-range couplings

Gauge fields are encoded in the interactions

\[ H = J \sum_{i<j} c_{ij} \sigma^z_i \sigma^z_j + w \sum_i (\sigma^+_i \sigma^-_{i+1} + \sigma^+_i \sigma^-_i) + m \sum_i c_i \sigma^z_i + J \sum_i \bar{c}_i \sigma^z_i \]

- \(H_{zz}\): long-range interaction
- \(H_{\pm}\): particle-antiparticle creation/annihilation
- \(H_E\): effective

- \(J = \frac{g^2 a}{2}\)
- \(w = \frac{1}{2a}\)
- \(g\): Fermion-light coupling constant
- \(a\): lattice spacing

E. Martinez, C. Muschik et al., Nature 534, 516-519 (2016)
Digital quantum simulation

Trotter time slices

Implementation of coefficients

\[ H_{MS_z} = J_0 \sum_{i,j} \sigma^z_i \sigma^z_j \Delta t_j \]

\[ C_{ij} \]

with Mølmer-Sørensen gate operations
Compiled pulse sequence

Initialization sequence (prepares vacuum state)

Trotter sequence, repeated 4 times for digital quantum simulation

total sequence, including calibration pulses (not shown)

222 gate operations

trailing recoupling sequence
Schwinger mechanism: Particle – Antiparticle creation

Pair Creation

\[ |0000\rangle = |\uparrow\downarrow\uparrow\downarrow\rangle \]

\[ |0e^+ e^- 0\rangle = |\uparrow\uparrow\downarrow\downarrow\rangle \]
Schwinger mechanism: Particle – Antiparticle creation

- Mass is a tunable parameter
- Interaction $w$ is taken to be constant (sets the timescale)
- Particle number density $\nu$ defined: $\nu=0.5$ corresponds to one pair
Entanglement creation

Vacuum persistence:

\[ G(t) = \langle \text{vac} | e^{iHt} | \text{vac} \rangle \]

\[ E_n : \text{log. negativity} \]

bipartition

E. Martinez, C. Muschik, et al.
Variational Quantum Simulation

Variational Quantum Simulation

analog quantum simulator as a quantum co-processor with a classical computer

Goal: prepare groundstate of $\hat{H}_T$ by minimizing $\langle \psi(\Theta) | \hat{H}_T | \psi(\Theta) \rangle$

- Target - Hamiltonian “lives” only in the classical computer
- Feedback loop between classical computer and quantum co-processor

A. Peruzzo et al., Nature Comm. 5, 4213 (2014)
E. Farhi et al., arXiv:1411.4028 (2014)
J. McClean et al., NJP 18, 023023 (2016)
Nature 569, 355 (2019)
Variational Quantum Simulation

\[ \hat{H}_T = \sum_{n=1}^{M} \hat{h}_n \]  
sum of Pauli products

Example:  
\[ \hat{H}_T = A \cdot \hat{\sigma}_1^z + B \cdot \hat{\sigma}_3^z \hat{\sigma}_4^z + \ldots \]
What is $\langle \hat{H}_T \rangle$ for a given parameter vector $\Theta$?

Variational Quantum Simulation

Classical Computer

Analog Quantum Simulator

$\hat{H}_T = \sum_{n=1}^{M} \hat{h}_n$

sum of Pauli products

Example: $\hat{H}_T = A \cdot \hat{\sigma}_1^z + B \cdot \hat{\sigma}_3^z \hat{\sigma}_4^z + \ldots$

What is $\langle \hat{H}_T \rangle$ for a given parameter vector $\theta$?

$\hat{H}_T = \sum_{n=1}^{n_n} \text{sum of Pauli products}$

Example: $\hat{H}_T = A \cdot \hat{\sigma}_1^x + B \cdot \hat{\sigma}_3^z \hat{\sigma}_4^z + \ldots$

$\langle \hat{H}_T \rangle = \langle \psi(\theta) | \hat{H}_T | \psi(\theta) \rangle = \langle \psi(\theta) | A \cdot \hat{\sigma}_1^x + B \cdot \hat{\sigma}_3^z \hat{\sigma}_4^z | \psi(\theta) \rangle$
Target Hamiltonian: Lattice Schwinger Model

A model of quantum electrodynamics in 1D

\[ \hat{H} = \omega \sum_{n=1}^{N} \left[ \sigma_n^+ \sigma_{n+1}^- + \text{h.c.} \right] + \frac{m}{2} \sum_{n=1}^{N} (-1)^n \sigma_n^z + \sum_{n,l=1}^{N-1} J_{nl} \sigma_n^z \sigma_l^z \]

Kogut-Susskind encoding

- \( \varnothing \) = \( \varnothing \)
- \( e^- \) = \( e^- \)
- \( e^+ \) = \( e^+ \)
- \( \varnothing \) = \( \varnothing \)

C. Muschik et al., NJP 19, 103020 (2017)

J. Kogut, L. Susskind
Quantum resources for variational search

Entangling operations

$$U_1(\theta) = \exp(i\theta \sum_{i<j} J_{ij}(\sigma_i^+ \sigma_j^- + \sigma_i^- \sigma_j^+))$$

Single-qubit rotations

$$U_{2,i}(\theta) = \exp(i\theta \sigma_i^z)$$

Collective qubit rotations

$$U_G(\theta) = \exp(i\theta \sum_i \sigma_i^x)$$

20 ions, 6 layers of operations, 15 variational parameters
Finding the ground state of a Hamiltonian

8 ions, 10 parameters, example: Lattice Schwinger Model Hamiltonian

- Iteratively determine energies $\langle \hat{H}_T(\Theta) \rangle$
- Iteratively determine error bars from variances $\langle (\hat{H}_T(\Theta) - E_0^\Theta)^2 \rangle$

Exploration (search algorithm)
Refinement (search algorithm)
1st excited state (theory)
Ground state (theory)
Experimental Results: Energy Minimization

\[ E(\theta_i) = \langle \Psi(\theta_i) | \hat{H}_T | \psi(\theta_i) \rangle \]

20 ions

\[ E(\theta_i) = \langle \Psi(\theta_i) | \hat{H}_T | \psi(\theta_i) \rangle \]

\[ E^{(0)} \]

\[ E^{(1)} \]

Fidelity

\[ 0 \]
\[ 0.2 \]
\[ 0.4 \]
\[ 0.6 \]
\[ 0.8 \]

Iteration number \( i \)

\[ 0 \]
\[ 500 \]
\[ 1,000 \]
\[ 1,500 \]
\[ 2,000 \]

Energy \( E(\theta_i) \)

\[ \Delta \]

\[ -14 \]
\[ -12 \]
\[ -10 \]
\[ -8 \]
\[ -6 \]
\[ -4 \]

Experiment (measured results)

\[ E_{\text{exp}} \]

Theory (simulated results)

\[ E_{\text{th}} \]

55% in 2\( \sigma \)

(E\( \text{th} \): 69%)
Color indicates distance of $\Theta_i$ from $\Theta_{opt}$

8 ions

How much can we trust the experimentally determined energy?

Variance of the (Schwinger) model:

\[ \text{var}(\hat{H}_S) = \langle (\hat{H}_S - \langle \hat{H}_S \rangle)^2 \rangle_\Theta \]

Variance measures "closeness" to an eigenstate

Measurement in $3N$ different bases

Experimental Results: Quantum Phase Transition

Order parameter $\langle \hat{O} \rangle$

$$\langle \hat{O} \rangle \sim \sum_{i,j>i} \langle (1 + (-1)^i \hat{\sigma}_i^z)(1 + (-1)^j \hat{\sigma}_j^z) \rangle = \sum_{i,j>i} \langle \hat{n}_i \hat{n}_j \rangle$$

Renyi entropy:

$$S^{(2)}_{AB} = -\log_2 \text{Tr}(\rho_A^2), \quad \rho_A = \text{Tr}_B(\rho)$$


Variational Quantum Simulations

- Quantum system does the hard part
- No need to generate Hamiltonian → flexible
- No specific quantum resources required
- Scalable for interesting problems
- But: needs many repetitions

\[ \langle \hat{H} \rangle = \sum_i \langle \hat{h}_i \rangle \]

Future:
- Faster experiments
- speeding up feedback loop
- larger number of ions, 2D models
The Dream (and vision):

- local logical qubits,
- protected by error correction,
- interconnected via dipole-dipole interaction (on chip)
- ion-cavity interfaces (network)
QIP with ions: Future goals and developments

- more qubits (~20 – 50)
- better fidelities
- faster gate operations
- faster detection
- development of 2-d trap arrays, onboard addressing, onboard electronics etc.
- entangling of large(r) systems: characterization?
- implementation of error correction
- applications

  - small scale QIP (e.g. *repeaters*)
  - quantum *metrology*, enhanced S/N, tailored atoms and states
  - quantum *simulations* (spin Hamiltonians, 2-dimensional systems)
  - quantum *computation* (period finding, quantum Fourier transform, factoring)

„*qubit alive*“

59 ions
The international Team 2020

in collaboration with theorists:
The international Team 2020

D. Bykov  P. Hrmo  M. Hussain  M. Joshi  Th. Feldker  Ch. Marciniak  P. Holz  Yunfei Pu  Yueyang Zou  T. Ollikainen  M. Bock  
D. Heinrich  C. Maier  M. van Mourik  A. Erhard  T. Brydges  M. Guevara-Bertsch  V. Krčmarský  L. Postler  M. Meraner  R. Stricker  H. Hainzer  
V. Krutianskii  G. Cerchiari  L. Dania  D. Kiesenhofer  I. Pogorelov  M. Valentini  V. Messerer  M. Dietl  
M. Bussjäger  B. Wilhelm  V. Podlesnic  J. Franke

Theory collaboration:  
M. Dalmonte, C. Muschik, M. Heyl, P. Hauke, P. Zoller, M. Müller, M.A. Martin-Delgado, J. Emerson
Home of the Innsbruck Quantum Computer

made in Tirol

Alpine Quantum Technologies GmbH
Quantum Computer Development

AQTION

AQT
Quantum Computer Development