Title: Quantum simulation of 2D and 3D spin models in a linear chain of ions

Speakers: Kazi-Rajibul Islam

Collection: Many-Body States and Dynamics Workshop II

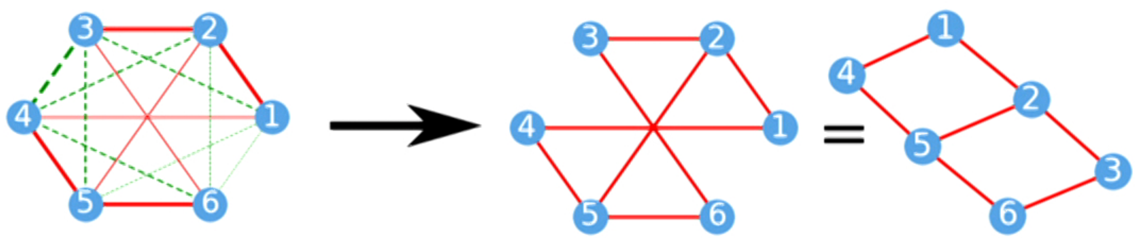
Date: June 13, 2019 - 11:00 AM

URL: http://pirsa.org/19060031

Abstract: Trapped ions are among the most advanced technology platforms for quantum information processing, in particular quantum simulation. However, ions are most readily trapped as a linear chain in radio-frequency traps, limiting their use to simulate higher dimensional quantum systems. In this talk, I'll describe an analog and an analog-digital hybrid [1] quantum simulation protocols to simulate programmable 2D and 3D spin models in a linear ion chain, by manipulating phonon-mediated long-ranged interactions between ion spins. The ability to dynamically engineer lattice geometries enables the investigation of a rich variety of physical phenomena such as spin frustration, topological states, and quantum quenches.

[1] Rajabi et al., npj Quantum Information 5:32 (2019)

Quantum simulation of 2D and 3D spin models in a linear chain of ions



Rajibul Islam

Institute for Quantum Computing (IQC) and Department of Physics and Astronomy

University of Waterloo

research.iqc.uwaterloo.ca/qiti/

Many-body states and Dynamics workshop, Perimeter Institute

Jun 6, 2019

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

Quantum Information with Trapped Ions (QITI)

research.iqc.uwaterloo.ca/qiti/

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

POSTDOCS

Fereshteh Rajabi
Roland Habluetzel

GRAD STUDENTS

Chung-You (Gilbert) Shih
Nikhil Kotibhaskar
Sainath Motlakunta
Manas Sajjan

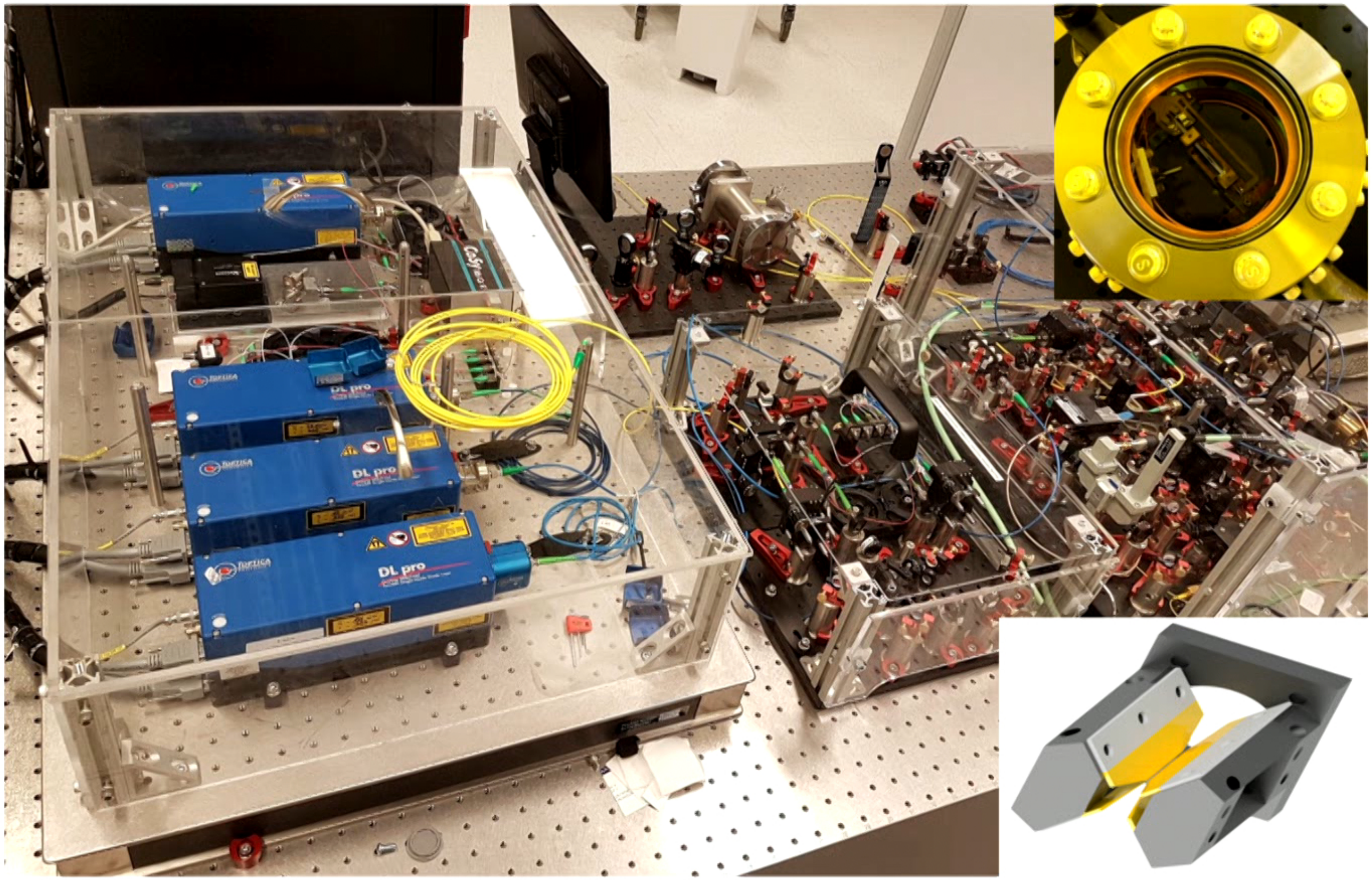
UNDERGRADS

Yi Hong Teoh
Duale Omar
Joshua Da Costa

$$

University of Waterloo
US ARO
NSERC Canada
TQT (CFREF)

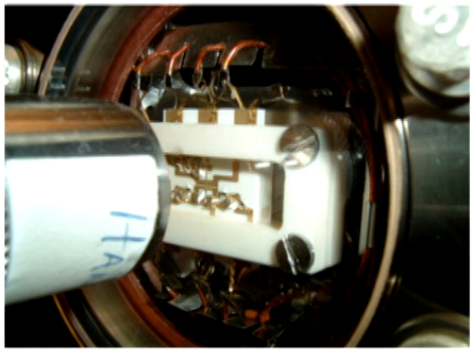
Building a trapped ion quantum simulator



Quantum Simulation

- Simulating quantum many-body system is hard, especially quantum dynamics where the quantum state has `a lot of' entanglement!
- Exponential growth of Hilbert space, 2^N for N qubits/spin-1/2 objects
- "Can Physics be simulated by a universal computer?" (Feynman, 1982)
  - "Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."

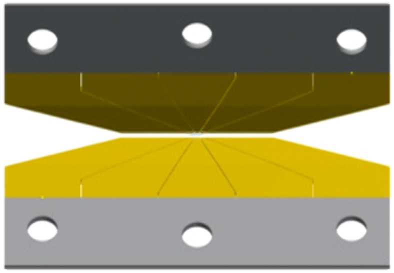
  ➡ Quantum computer
- Quantum simulator – restricted quantum computer, may not be universal.



well-controlled quantum system
(Quantum simulator)

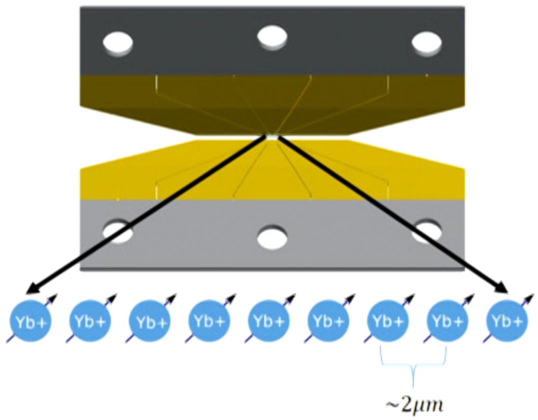
>> Qsolve *H=J XX + B Y*

$^{171}Yb^{+}$ ion based quantum simulator



Ultra-high vacuum ~ 10^{-11} mbar

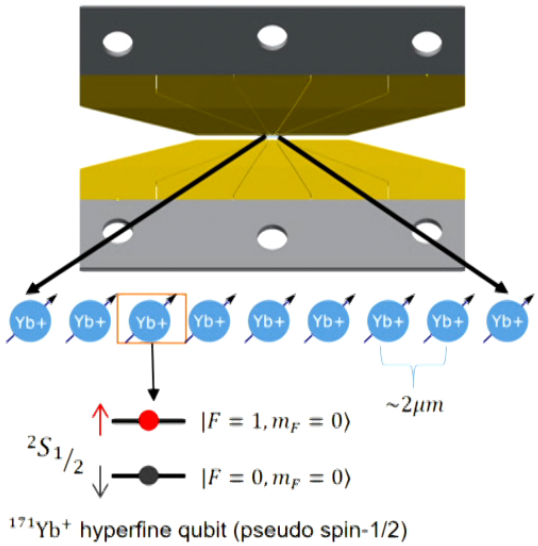
$^{171}Yb^+$ ion based quantum simulator



Ultra-high vacuum ~ 10^{-11} mbar

5

$^{171}Yb^{+}$ ion based quantum simulator



Ultra-high vacuum ~ 10^{-11} mbar

Ions as a platform for quantum computation/simulation

- All qubits/spins are identical
- Long coherence time
- Near perfect state initialization
  and detection of quantum states
- High fidelity control of individual spins/qubits and interaction between spins (entangling gates)
- Spin-spin interaction graph can in principle be made arbitrary → simulation of higher dimensional spin systems.

Spin-spin interactions using collective vibration (phonon) of ions

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. **82**, 1835 (1999)

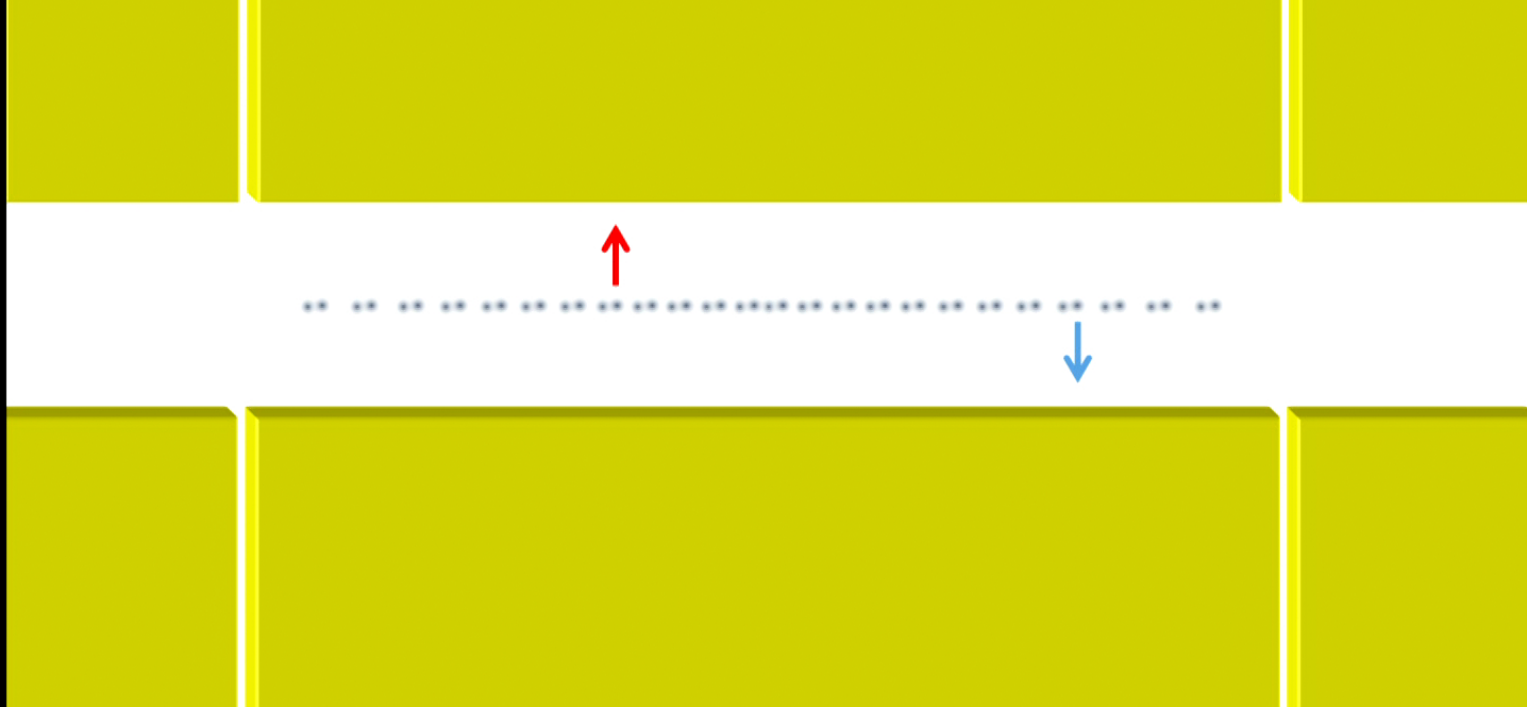
Spin-spin interactions using collective vibration (phonon) of ions

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. **82**, 1835 (1999)

Spin-spin interactions using collective vibration (phonon) of ions

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. **82**, 1835 (1999)

Spin-spin interactions using collective vibration (phonon) of ions

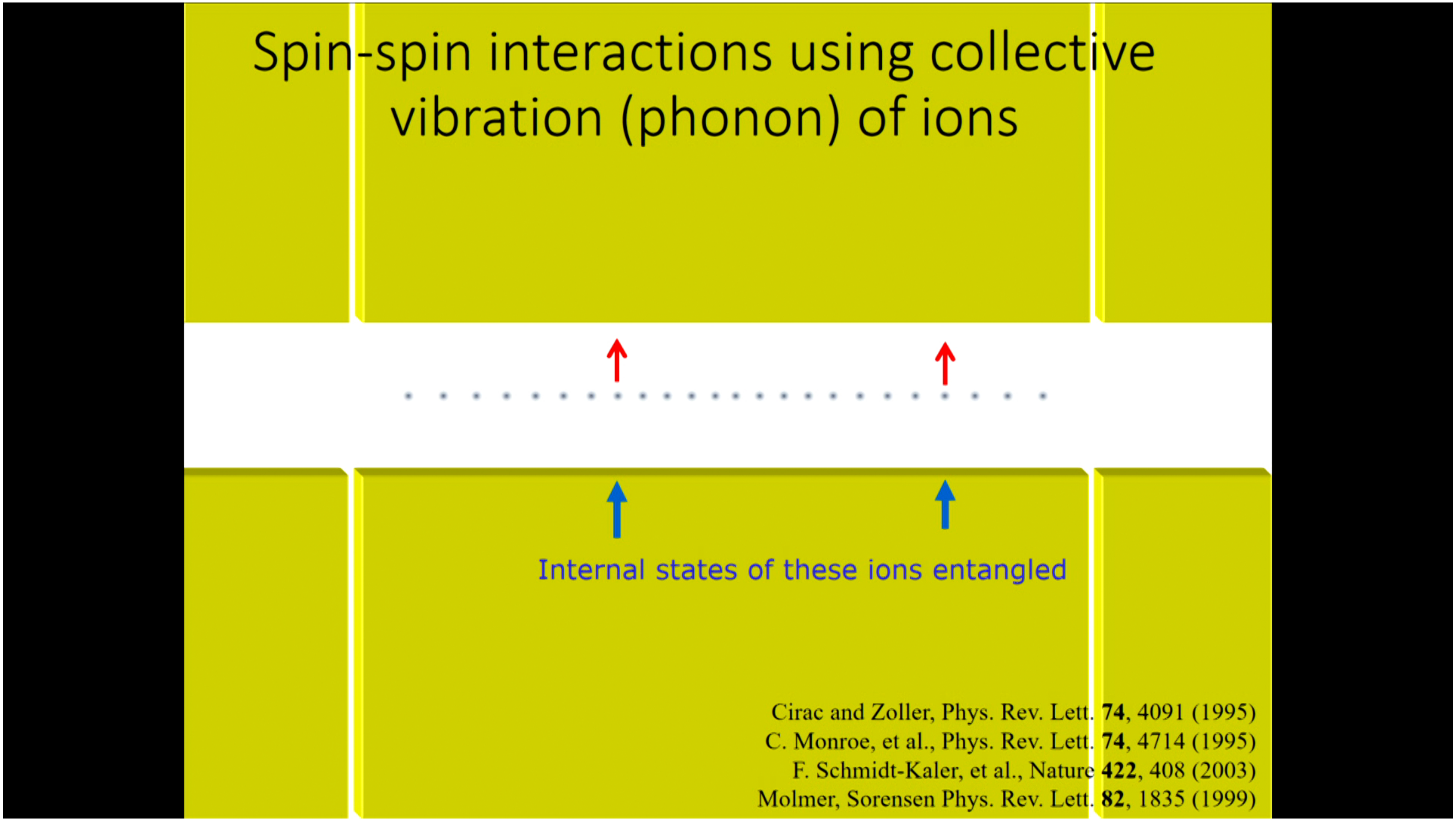


Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. **82**, 1835 (1999)

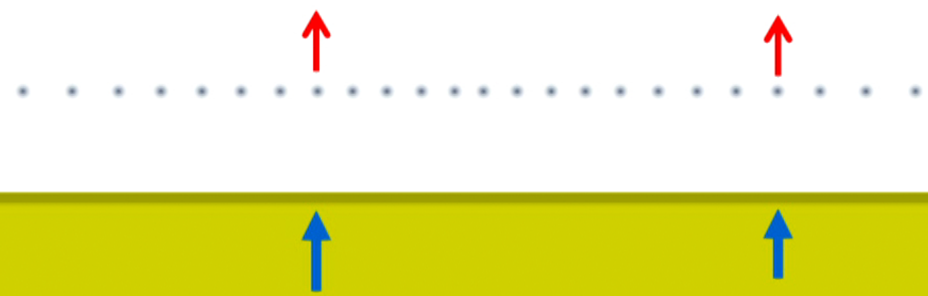
Spin-spin interactions using collective vibration (phonon) of ions

$$\omega_{field} = \omega_{qubit} - \omega_{vibration}$$

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. **82**, 1835 (1999)


Spin-spin interactions using collective vibration (phonon) of ions
Internal states of these ions entangled
Cirac and Zoller, Phys. Rev. Lett. 74, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. 74, 4714 (1995)
F. Schmidt-Kaler, et al., Nature 422, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. 82, 1835 (1999)

Spin-spin interactions using collective vibration (phonon) of ions



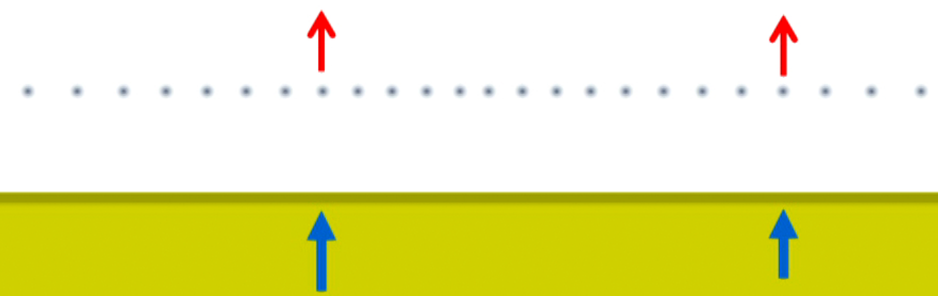
Internal states of these ions entangled

$H = \sum J_{i,j}\, \sigma_x^i \sigma_x^j$ (Ising)

$$H_{XY} = \sum J_{i,j} \left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j \right) \; Flip - flop$$

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. **82**, 1835 (1999)

Spin-spin interactions using collective vibration (phonon) of ions



Internal states of these ions entangled

$H = \sum J_{i,j}\, \sigma_x^i \sigma_x^j$ (Ising)

$H_{XY} = \sum J_{i,j} \left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j\right)$ *Flip – flop*

Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
C. Monroe, et al., Phys. Rev. Lett. **74**, 4714 (1995)
F. Schmidt-Kaler, et al., Nature **422**, 408 (2003)
Molmer, Sorensen Phys. Rev. Lett. **82**, 1835 (1999)

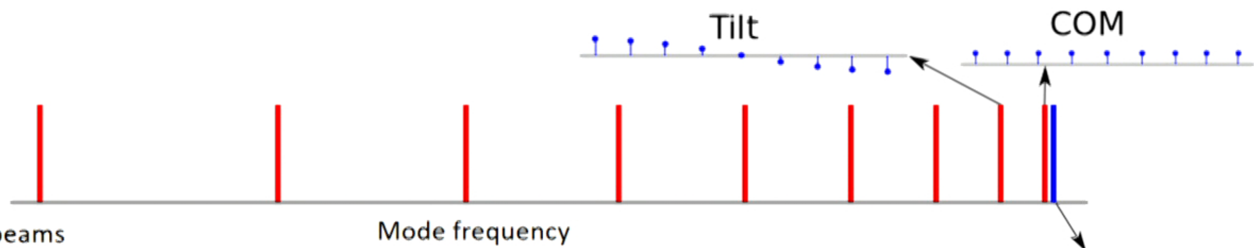
Spin-Spin Interactions

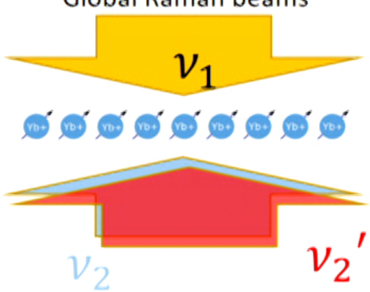
$$J_{i,j} = \Omega_i \Omega_j \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

Normal mode eigenvector components

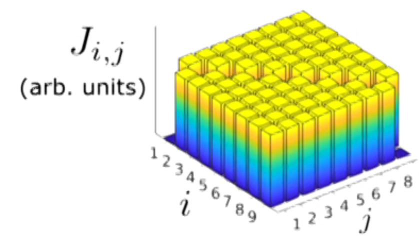
Laser intensity over each ion

Mølmer-Sørensen detuning





$\nu_1 - \nu_2 = \nu_{hyperfine} + \mu$



Various interaction profiles accessible by changing the detuning μ

8

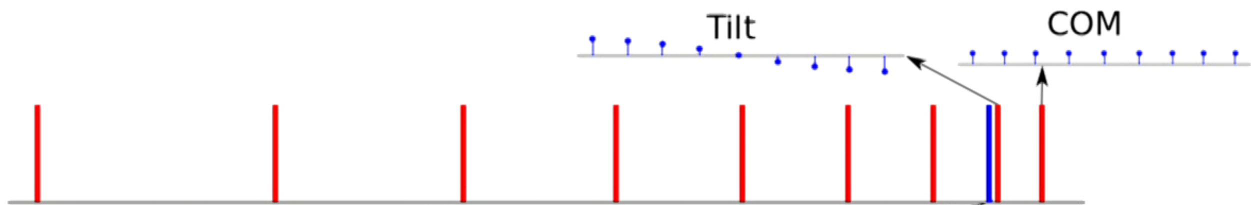
Spin-Spin Interactions

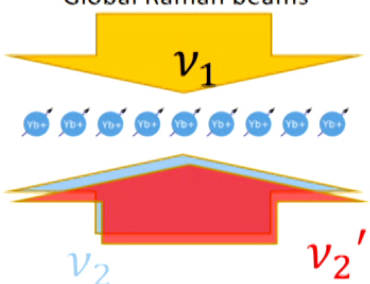
Normal mode eigenvector components

$$J_{i,j} = \Omega_i \Omega_j \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

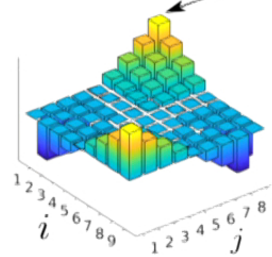
Laser intensity over each ion

Mølmer-Sørensen detuning





$\nu_1 - \nu_2 = \nu_{hyperfine} + \mu$



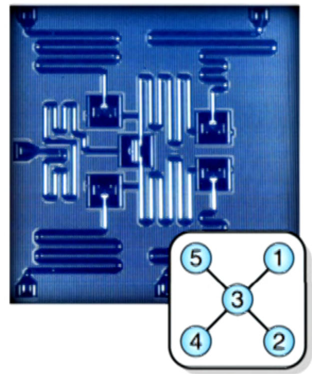
Various interaction profiles accessible by changing the detuning μ

8

Full connectivity

IBM superconducting system

A

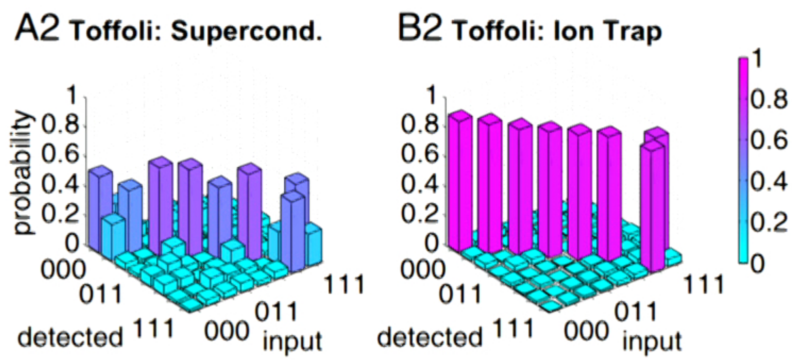


B

Maryland/JQI ion system

PNAS 114, 13 (2017)
Monroe group

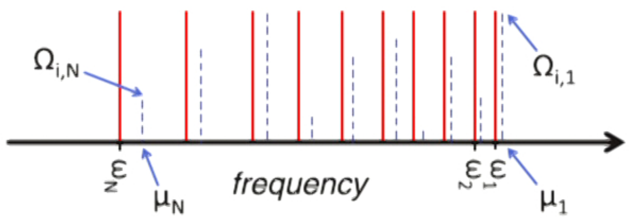
"… quantum algorithms and circuits that use more connectivity clearly benefit from a better-connected system of qubits."

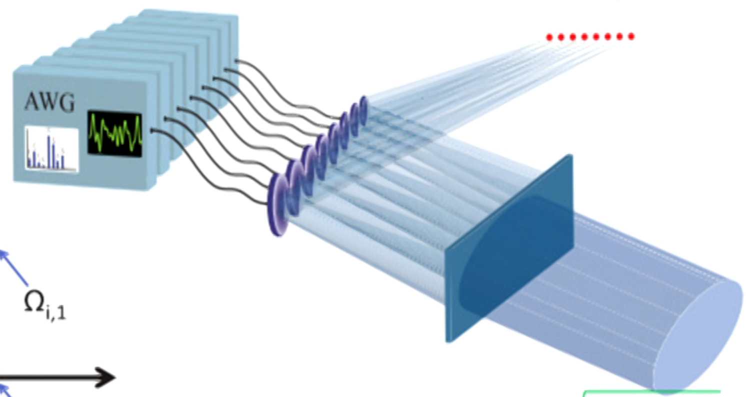


Success probability 52.6(8)% 85.0(2)%

S Korenblit et al 2012 New J. Phys. 14 095024.

Arbitrary interaction graph between spins





$$\eta_{i,m} = b_{i,m}\delta k\sqrt{\frac{\hbar}{2M\omega_m^{(x)}}}$$

$$J_{i,j} = \sum_n \Omega_{i,n}\Omega_{j,n}\sum_m^N \frac{\eta_{i,m}\eta_{j,m}\omega_m^{(x)}}{\mu_n^2 - \left(\omega_m^{(x)}\right)^2}$$

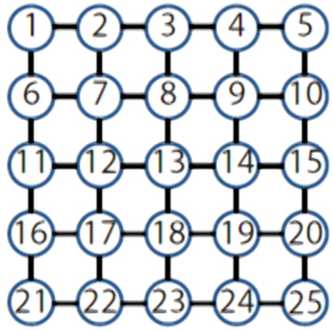
Laser power
(Rabi frequency)

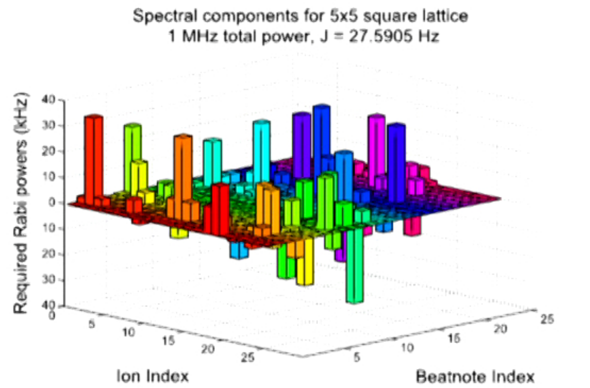
Individual addressing

~ laser detuning

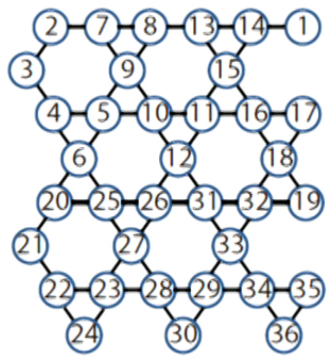
Excite multiple modes selectively

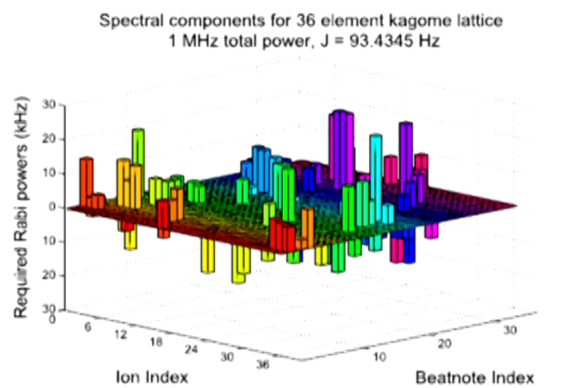
Reconfigurable interaction graph





Also see efforts to build 2D traps (Phil Richerme, Kihwan Kim, NIST …)





Korenblit et al, NJP 14, 095024 (2012)

$\boldsymbol{O}(\boldsymbol{N}^2)$ controls required.

Finding the N^2 Rabi frequencies is a hard problem involving non-linear optimization

$$\eta_{i,m} = b_{i,m}\delta k \sqrt{\frac{\hbar}{2M\omega_m^{(x)}}}$$

Lamb-Dicke parameter

EASY ←

$$J_{i,j} = \sum_n \Omega_{i,n}\Omega_{j,n} \sum_m^N \frac{\eta_{i,m}\eta_{j,m}\omega_m^{(x)}}{\mu_n^2 - \left(\omega_m^{(x)}\right)^2}$$

→ HARD

Rabi Frequencies (laser powers), N^2 parameters

Raman Beatnote Detunings (laser frequencies), N parameters

S Korenblit et al 2012 New J. Phys. 14 095024

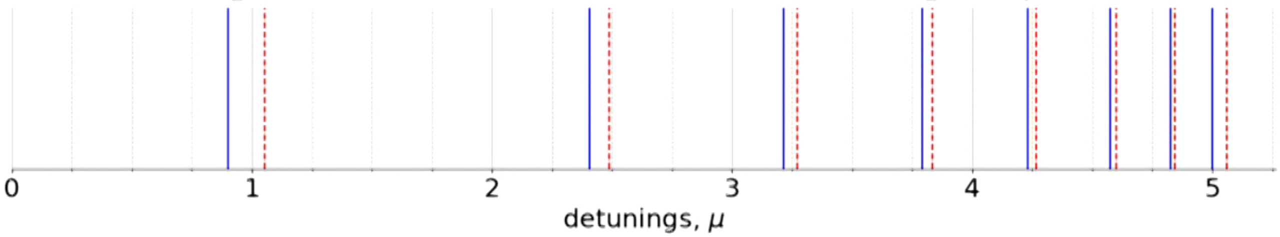
APPROACH: Use machine learning to find the Rabi frequencies, $\Omega_{i,n}$, given an arbitrary $J_{i,j}$.

12

Generating Data

$$J_{i,j} = \sum_n \Omega_{i,n}\Omega_{j,n} \sum_m^N \frac{\eta_{i,m}\eta_{j,m}\omega_m^{(x)}}{\mu_n^2 - \left(\omega_m^{(x)}\right)^2}$$

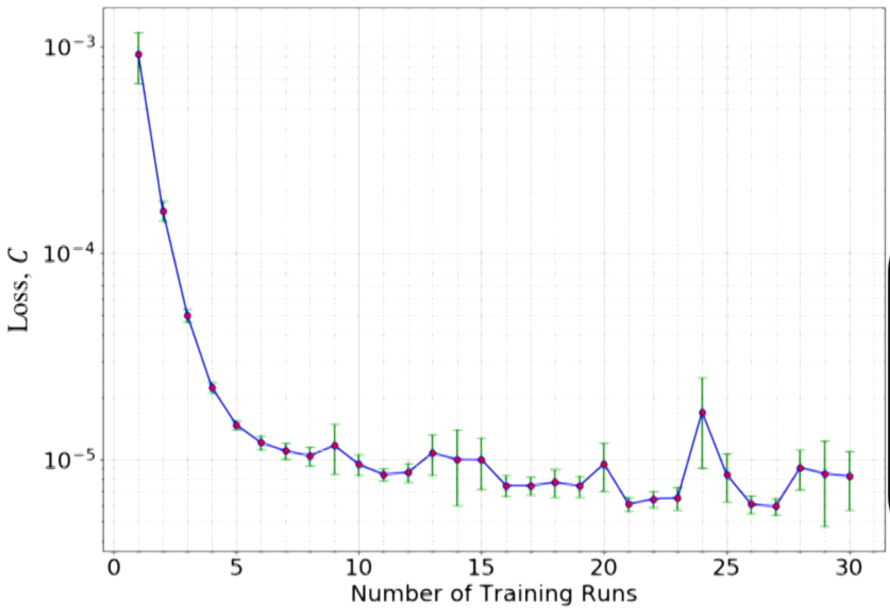
We set the detunings, μ_n, such that each detuning is close to a particular vibrational normal mode frequency.



$\Omega_{i,n}$ drawn from a continuous uniform distribution on $[-1,1]\ \forall\ i, n$

Using $\mu_n, \Omega_{i,n} \rightarrow J_{i,j}$

Training Network

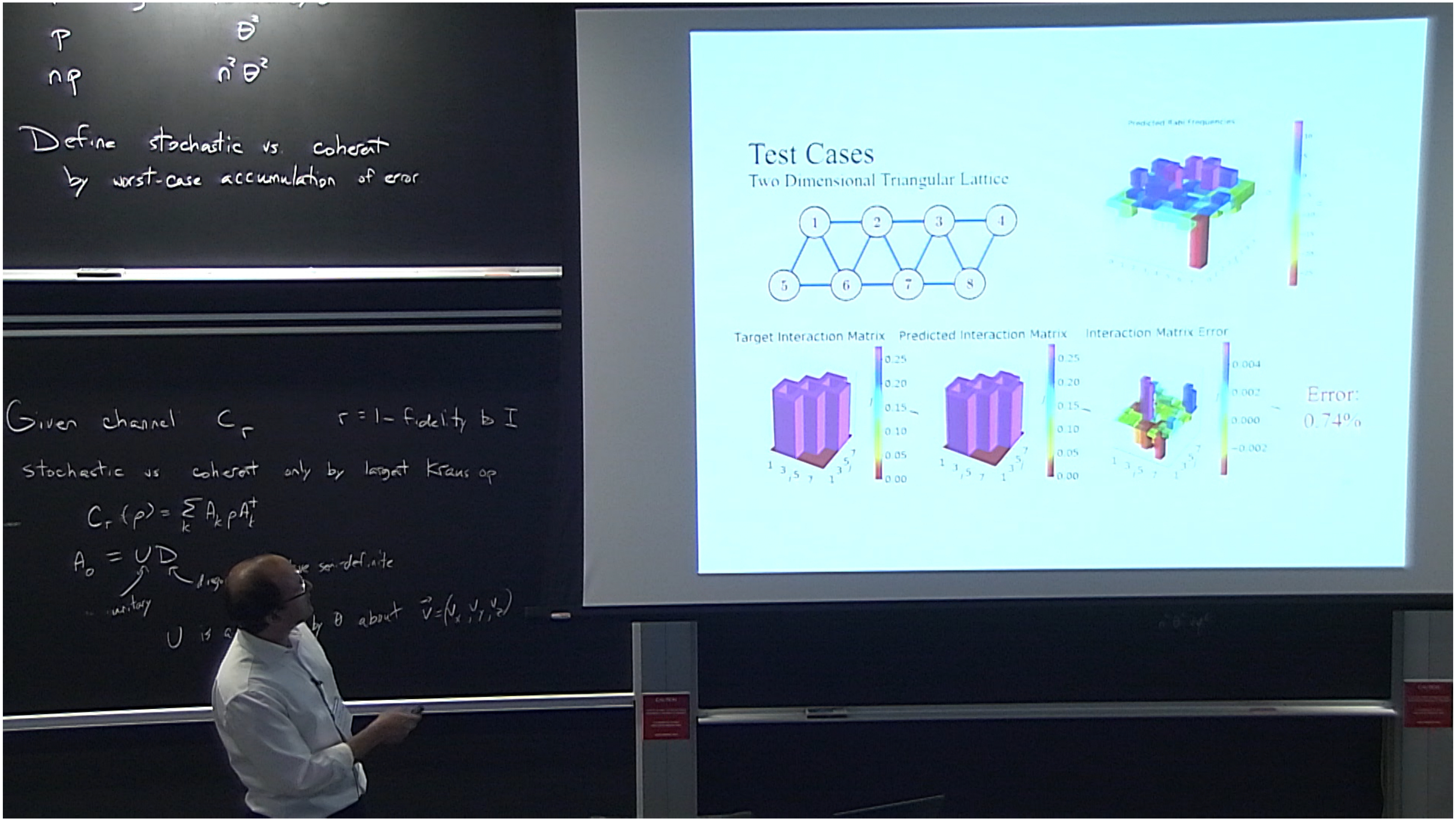


Loss of 10^{-5} implies the error between target and simulated interaction matrices are of order 1%.

$$E = \frac{\|J_{i,j} - J_{i,j}^{\text{pred}}\|}{\|J_{i,j}\|}$$

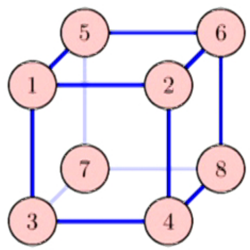
Technical details:

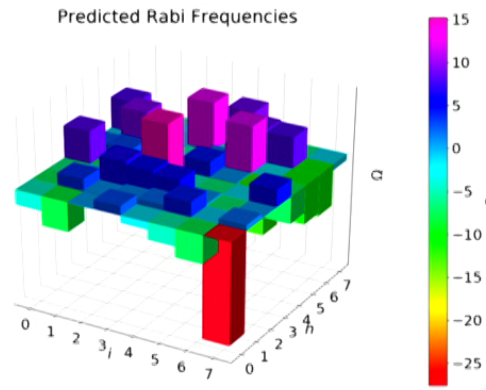
- Mean square error cost function
- ADAM algorithm for optimization
- Learning rate = 10^{-3}
  - Learning rate decay per 5 epochs = 0.9
- Training dataset 45000 data points
  - Batch size 450
- Test dataset 5000 data points
- 30 epochs

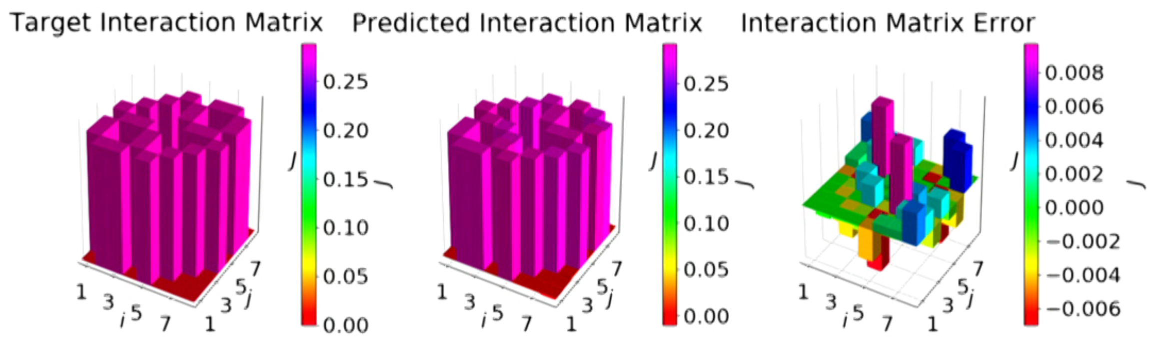

Define stochastic vs. coherent
by worst-case accumulation of error
Given channel C_r r = 1 - fidelity to I
stochastic vs coherent only by largest Kraus op
Test Cases
Two Dimensional Triangular Lattice
Target Interaction Matrix
Predicted Interaction Matrix
Interaction Matrix Error
Error:
0.74%

Test Cases

Three Dimensional Cubic Lattice

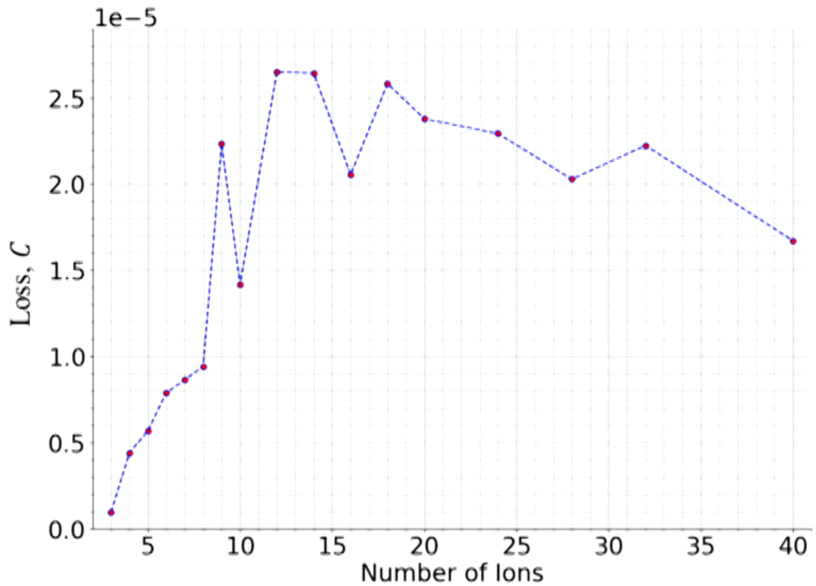






Error:
1.2%

Scaling with Number of Ions



- Notice the loss remains low even when you increase the number of ions.

Hybrid simulation – Analog + Digital

- Start with a fully connected interaction profile generated using global Raman beams with single detuning.

$$H_{XY} = \sum_{i<j} J_{ij} S_i^+ S_j^- + h.c. \qquad J_{i,j} = \frac{J_0}{|i-j|^\alpha} \qquad 0 < \alpha < 3$$

19

Hybrid simulation – Analog + Digital

- Start with a fully connected interaction profile generated using global Raman beams with single detuning.

$$H_{XY} = \sum_{i<j} J_{ij} S_i^+ S_j^- + h.c. \qquad J_{i,j} = \frac{J_0}{|i-j|^\alpha} \qquad 0 < \alpha < 3$$

- Suppress unwanted interactions by modifying spin evolution by imparting single spin phases

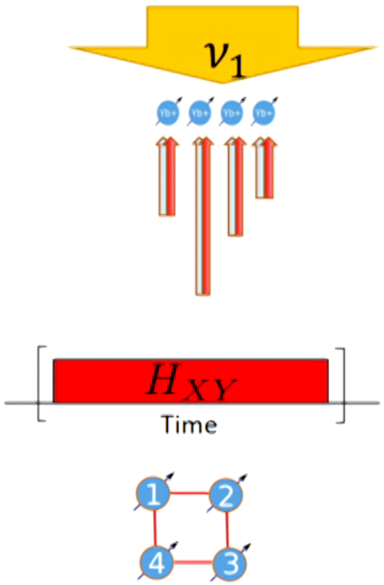
$$H_Z = \sum_{i=1}^{N} \omega_i S_i^z$$

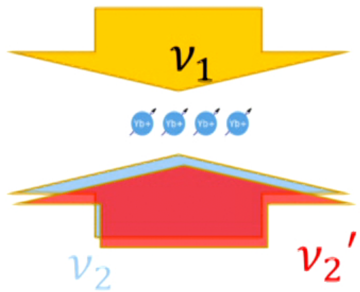
Site dependant AC-stark shift ω_i

19

Analog vs Hybrid

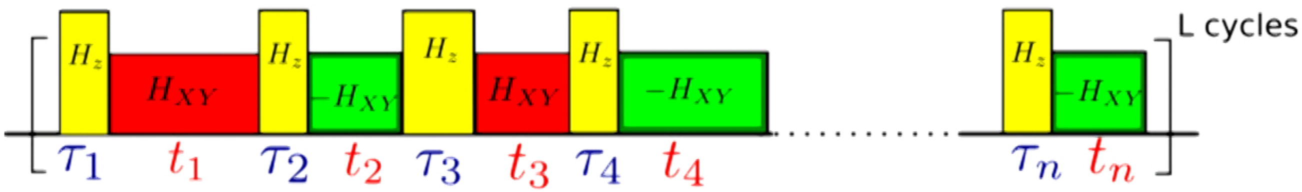
frequency and intensity control at the level of **individual** ions





Global frequency and intensity control

Average Hamiltonian of the pulse sequence



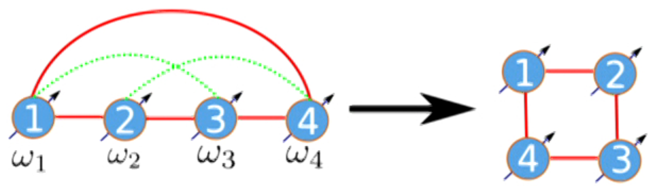
$$H_{avg} = \sum_{i>j} J''_{i,j} S_i^+ S_j^- + h.c$$

$$J'_{i,j} = \frac{J_{ij}}{L} * (e^{i\omega_{ij}\tau_{tot}} - e^{2i\omega_{ij}\tau_{tot}} + ...e^{Li\omega_{ij}\tau_{tot}})$$

$$J''_{i,j} = \frac{J'_{i,j}}{T_{cycle}} * (t_1 e^{i\omega_{ij}\tau_1} - t_2 e^{i\omega_{ij}(\tau_1+\tau_2)}...)$$

21

Example for 4 ions

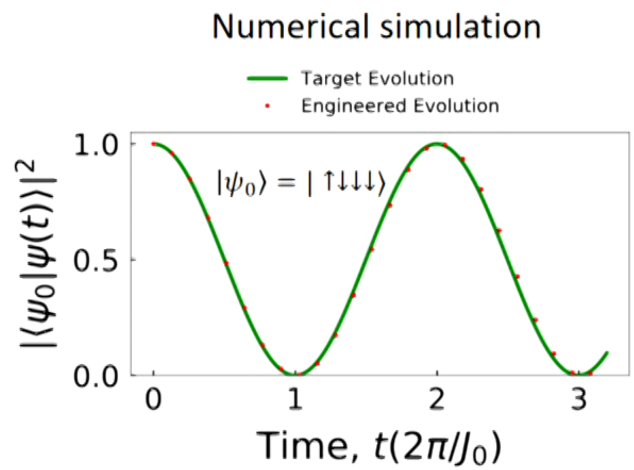


Rescale

(1,2),(2,3),
(3,4),(1,4)

Cancel

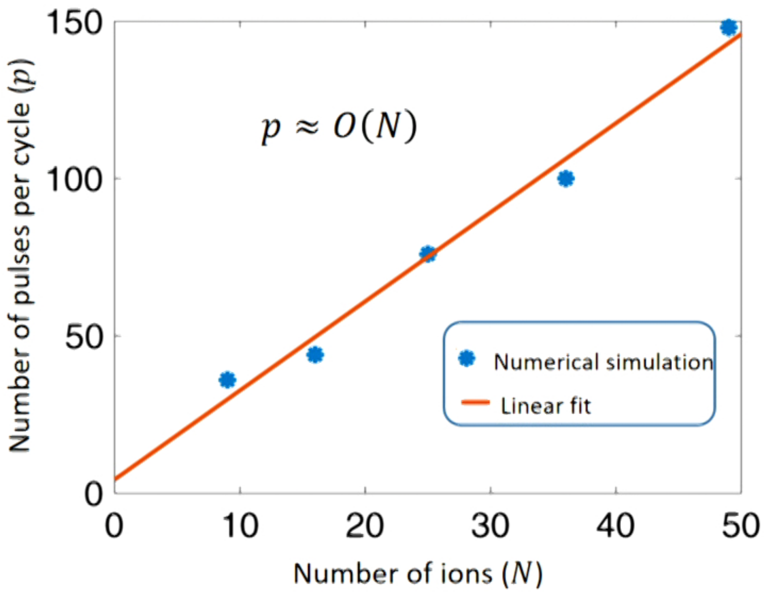
(1,3),(2,4)



RMS error in J_{ij} < 0.1 % (assuming perfect initial interaction profile)

F. Rajabi, S. Motlakunta, C. Shih, N. Kotibhaskar, Q. Quraishi, A. Ajoy, R. Islam –
npj Quantum Information **5:32** (2019)

Scaling with the number of ions

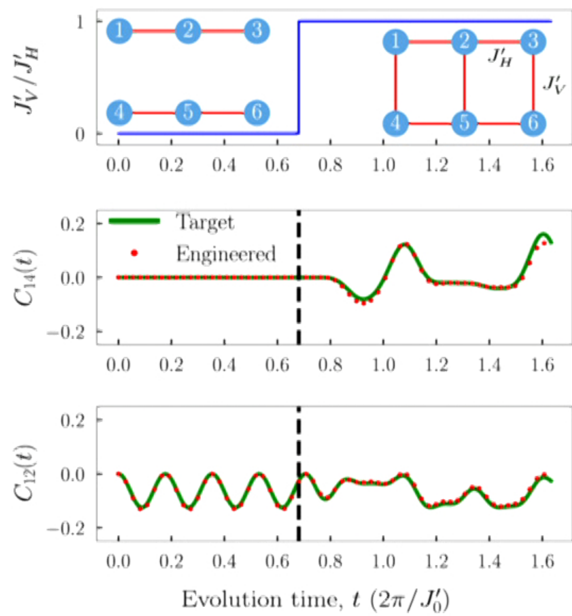


Number of pulses per cycle scales linearly with number of ions for a target 2D square lattice

F. Rajabi, S. Motlakunta, C. Shih, N. Kotibhaskar, Q. Quraishi, A. Ajoy, R. Islam – *npj Quantum Information* **5:32** (2019)

Dynamically change the interaction profile

Numerical simulation



$|\psi_{init}\rangle = |\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\rangle$

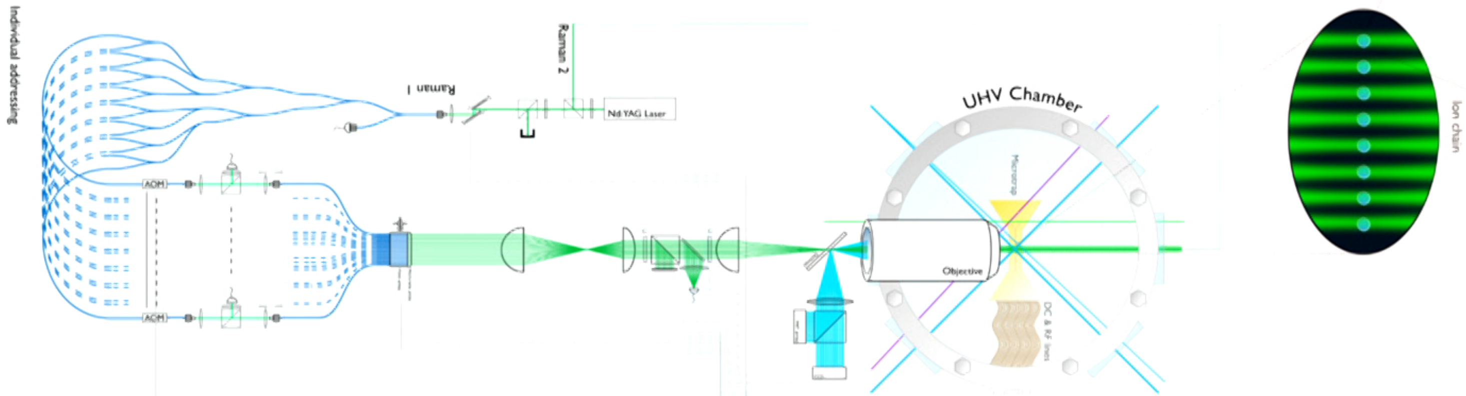
$$C_{14}(t) = \langle S_z^1 S_z^4 \rangle - \langle S_z^1 \rangle \langle S_z^4 \rangle$$

$$C_{12}(t) = \langle S_z^1 S_z^2 \rangle - \langle S_z^1 \rangle \langle S_z^2 \rangle$$

F. Rajabi, S. Motlakunta, C. Shih, N. Kotibhaskar, Q. Quraishi, A. Ajoy, R. Islam –
npj Quantum Information **5:32** (2019)

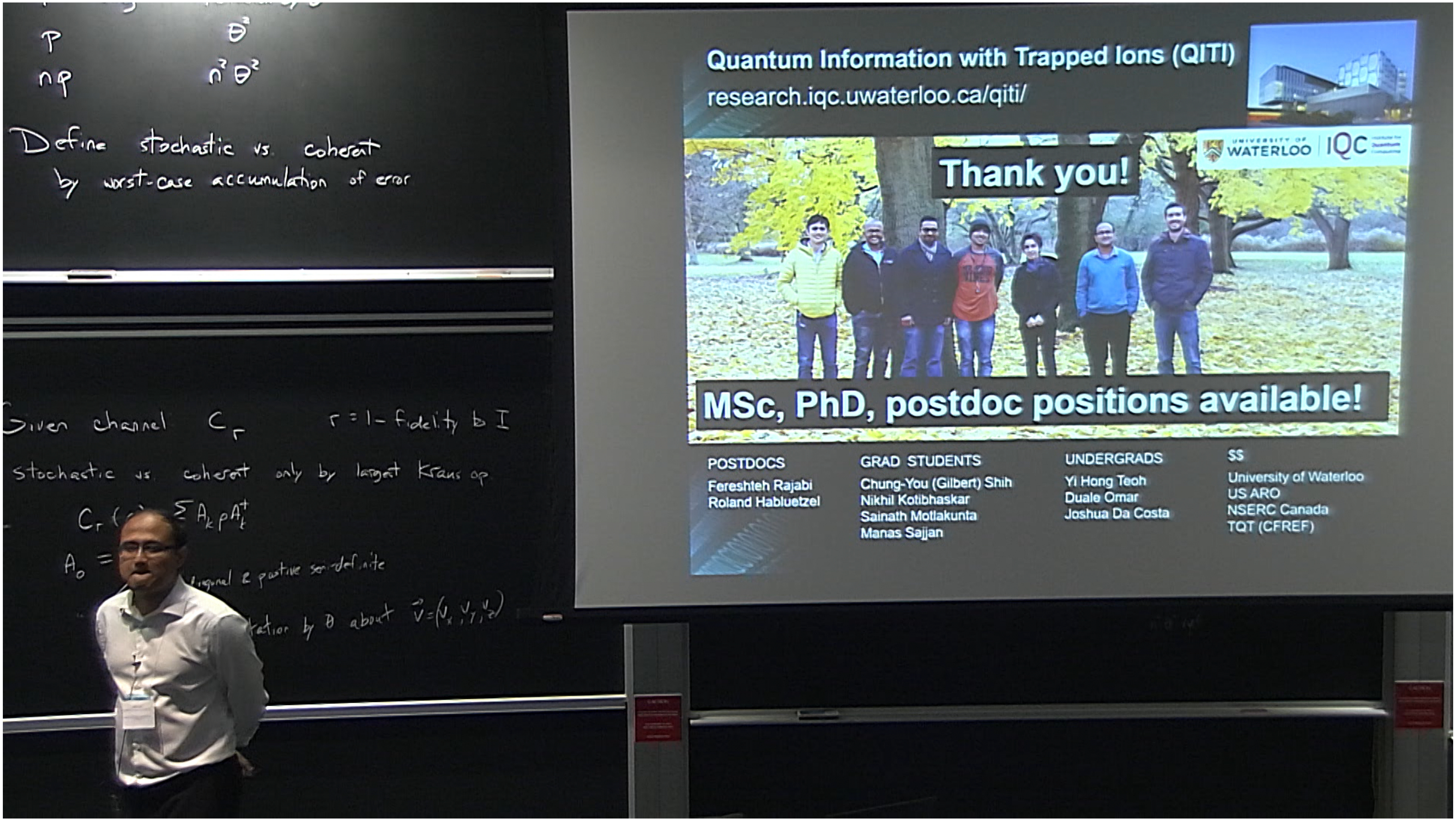
QuantumION: A shared trapped ion computer

In collaboration with Dr. Senko's group at IQC



- Remotely accessible by academic researchers (from their laptops)
- Users have fine-grained control of the system (e.g. optimizing the pulse shape for single qubit gates)
- Access to qu**d**it operations
- Capability to implement error correction protocols
- Capability to implement hybrid classical-quantum algorithms

27


Quantum Information with Trapped Ions (QITI)
research.iqc.uwaterloo.ca/qiti/
UNIVERSITY OF WATERLOO
IQC
Thank you!
MSc, PhD, postdoc positions available!
POSTDOCS
Fereshteh Rajabi
Roland Habluetzel
GRAD STUDENTS
Chung-You (Gilbert) Shih
Nikhil Kotibhaskar
Sainath Motlakunta
Manas Sajjan
UNDERGRADS
Yi Hong Teoh
Duale Omar
Joshua Da Costa
$$
University of Waterloo
US ARO
NSERC Canada
TQT (CFREF)
Define stochastic vs coherent
by worst-case accumulation of error
Given channel
r = 1 - fidelity to I
stochastic vs coherent only by largest Kraus op

Quantum Information with Trapped Ions (QITI)

research.iqc.uwaterloo.ca/qiti/

POSTDOCS
- Fereshteh Rajabi
- Roland Habluetzel

GRAD STUDENTS
- Chung-You (Gilbert) Shih
- Nikhil Kotibhaskar
- Sainath Motlakunta
- Manas Sajjan

UNDERGRADS
- Yi Hong Teoh
- Duale Omar
- Joshua Da Costa

$$
- University of Waterloo
- US ARO
- NSERC Canada
- TQT (CFREF)