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Quantum Computing
@ INFN workshop
November 15th 2022

Speaker: Alice Pagano

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# Ab-initio two-dimensional digital twin for quantum computer benchmarking

# Collaboration of…

Ab-initio two-dimensional digital twin for quantum computer benchmarking

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QRyd Demo

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TOPTICA PHOTONICS

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# Classical simulation of QPU

QPU = Quantum Processing Unit

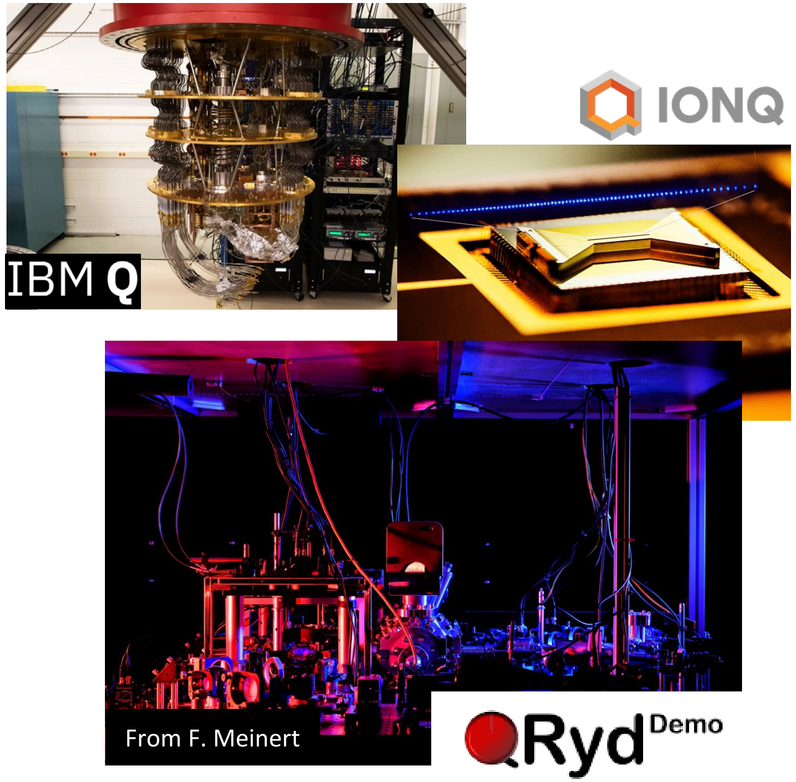
## Goal

- Gain insights on quantum hardware for QPU development
- Large scale simulation to support the next decades of hardware developments

## Our approach

| | We don't do | We do |
|---|---|---|
| **Gate:** | Matrix | Pulse |
| **Qubits:** | >100 | >100 |
| **Speed:** | Faster | Slower |

Entanglement entropy production in Quantum Neural Networks,
Marco Ballarin at **4:30pm**



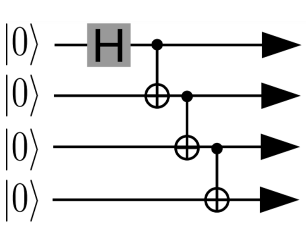

QRyd Demo

- Our **digital twin** can simulate different platform, e.g. Rydberg quantum computer

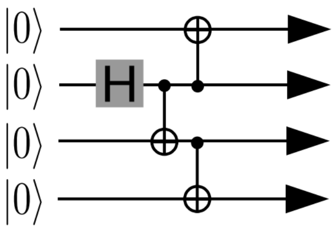
# A lot of ingredients…

**Question**

➢ Prepare global GHZ state



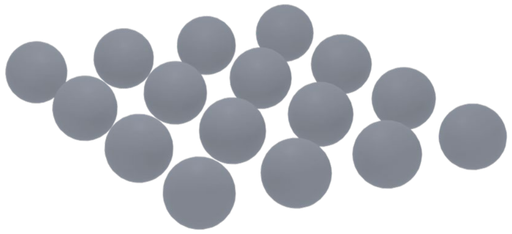

$$|GHZ\rangle = \frac{|0\rangle^{\otimes n} + |1\rangle^{\otimes n}}{\sqrt{2}}$$

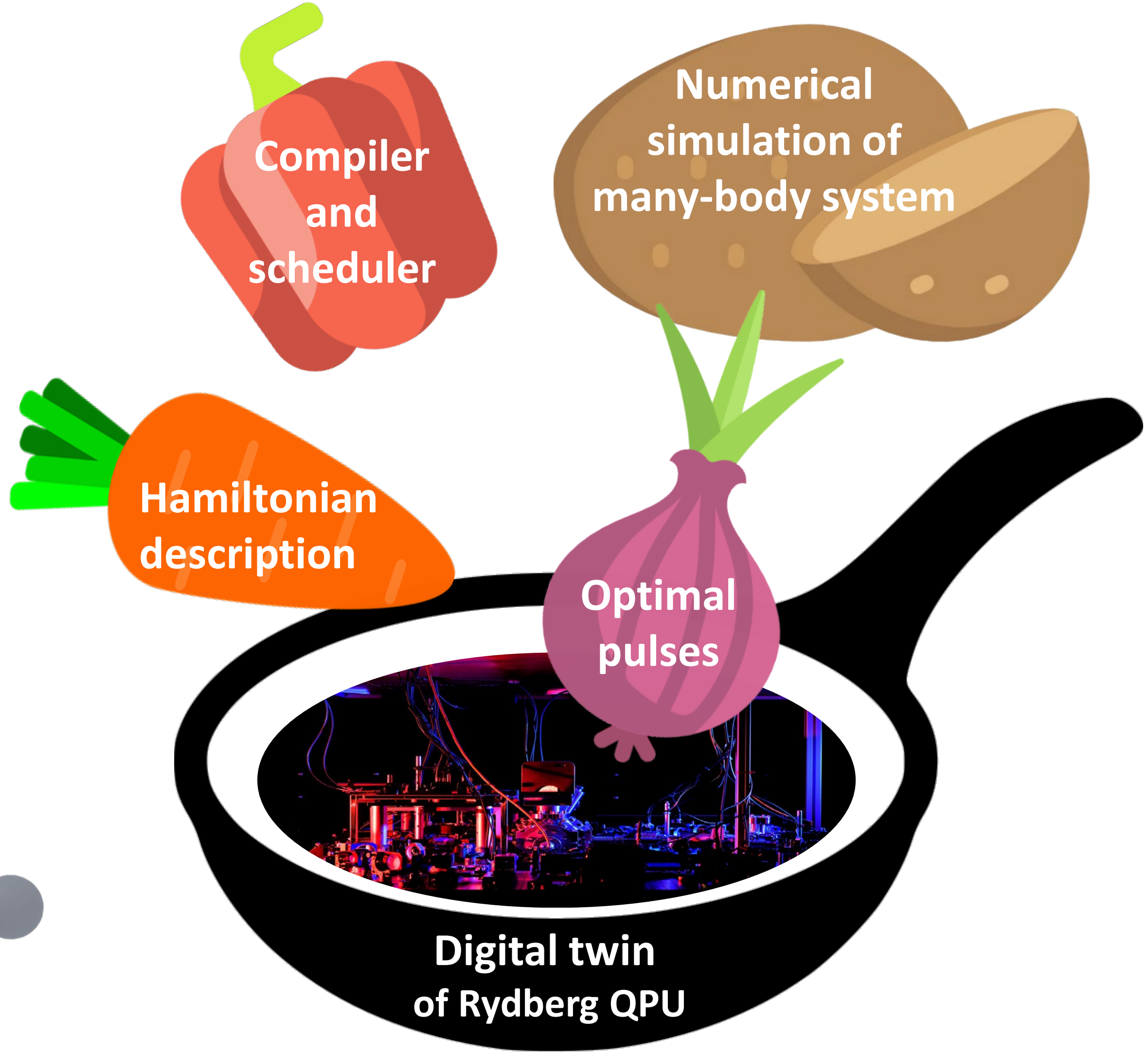



Serial 1D case
Circuit depth D=N

Parallel 1D case
Circuit depth D=N/2+1

To which extent can we profit in 2d Rydberg systems from parallelization?





# Hamiltonian of Rydberg QPU

- 2d array of Rydberg atoms trapped in optical tweezers
- Three-level system description: 0, 1, r

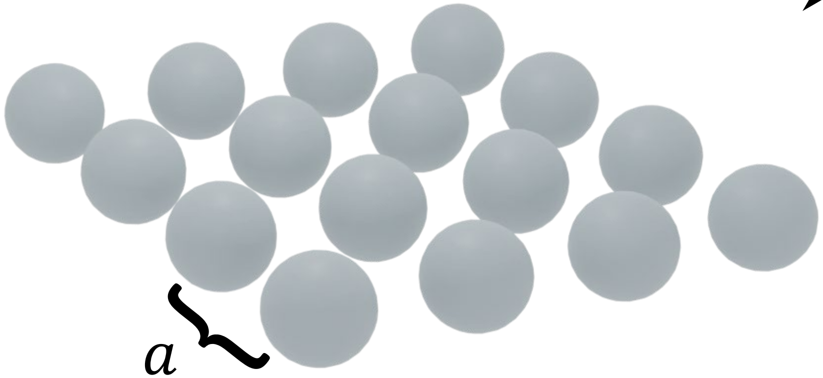
$$H_{\mathrm{Ryd}} = \sum_{j,k} \Omega^x_{j,k}(t)\sigma^x_{j,k} + \Omega^z_{j,k}(t)\sigma^z_{j,k} + \sum_{j,k}\left(\Omega^R_{j,k}(t)\sigma^+_{j,k} + h.c.\right) + \sum_{j,k}\sum_{j',k'} V(j,k,j'k')n_{j,k}n_{j',k'}$$

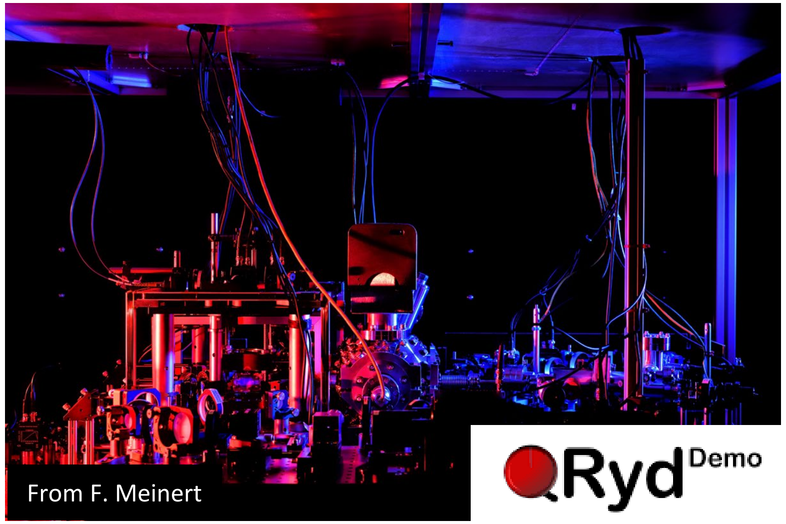
**Sr88**

$$|r\rangle = |60^3S_1, m_J = 1\rangle$$

$$|1\rangle = |5^3P_2\rangle$$

$$|0\rangle = |5^3P_0\rangle$$



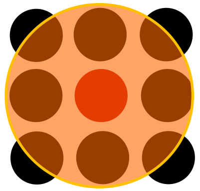




QRyd Demo

- Strong long-range Rydberg interaction

$$V(j,k,j',k') = \frac{-C_6}{d^6} \propto n^{11}$$

**Rydberg blockade mechanism**

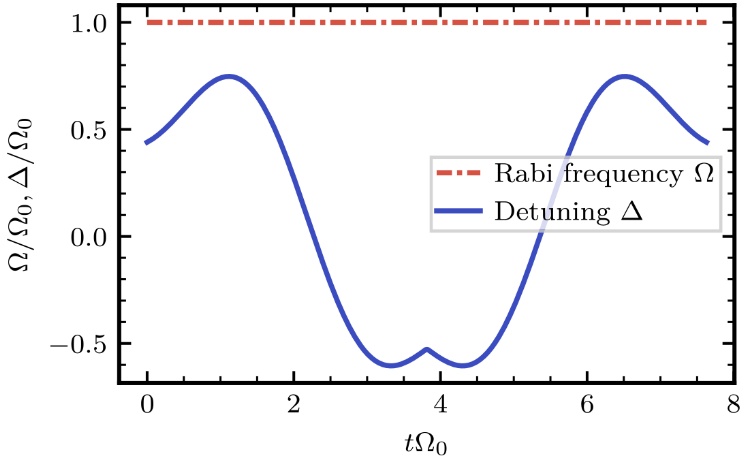


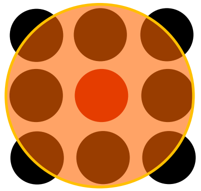
# Optimal pulses and gates

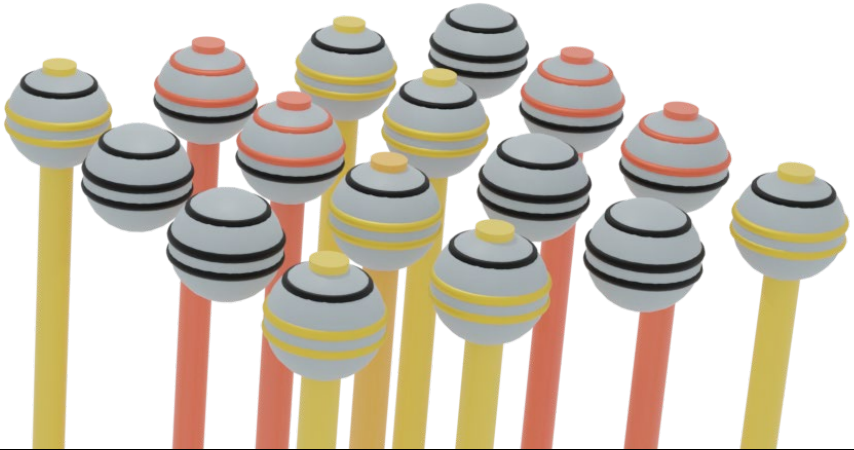
- Single-qubit gates: are implemented via Raman lasers
- Two-qubit gates: use the Rydberg interaction in the r-state to implement a CZ gate
- Protocol from Pagano et al, PRR… 10% time speedup

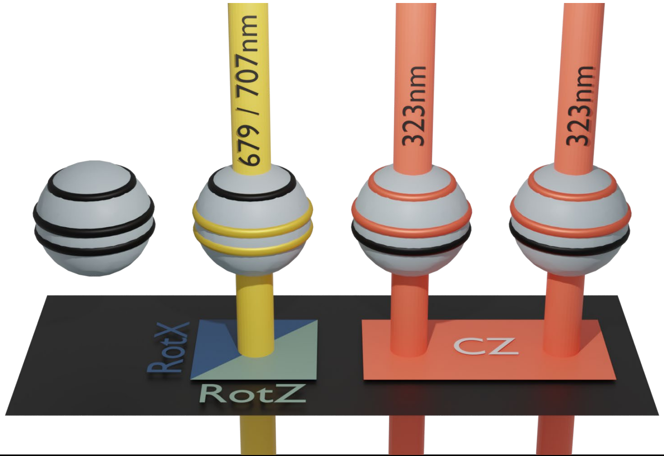
$$H_{\mathrm{Ryd}} = \sum_{j,k} \boxed{\Omega^x_{j,k}(t)\sigma^x_{j,k} + \Omega^z_{j,k}(t)\sigma^z_{j,k}} + \sum_{j,k} \boxed{\left(\Omega^R_{j,k}(t)\sigma^+_{j,k} + h.c.\right)} + \sum_{j,k}\sum_{j',k'} V(j,k,j'k') n_{j,k} n_{j',k'}$$

Pagano et al.
Phys. Rev. Research **4**, 033019

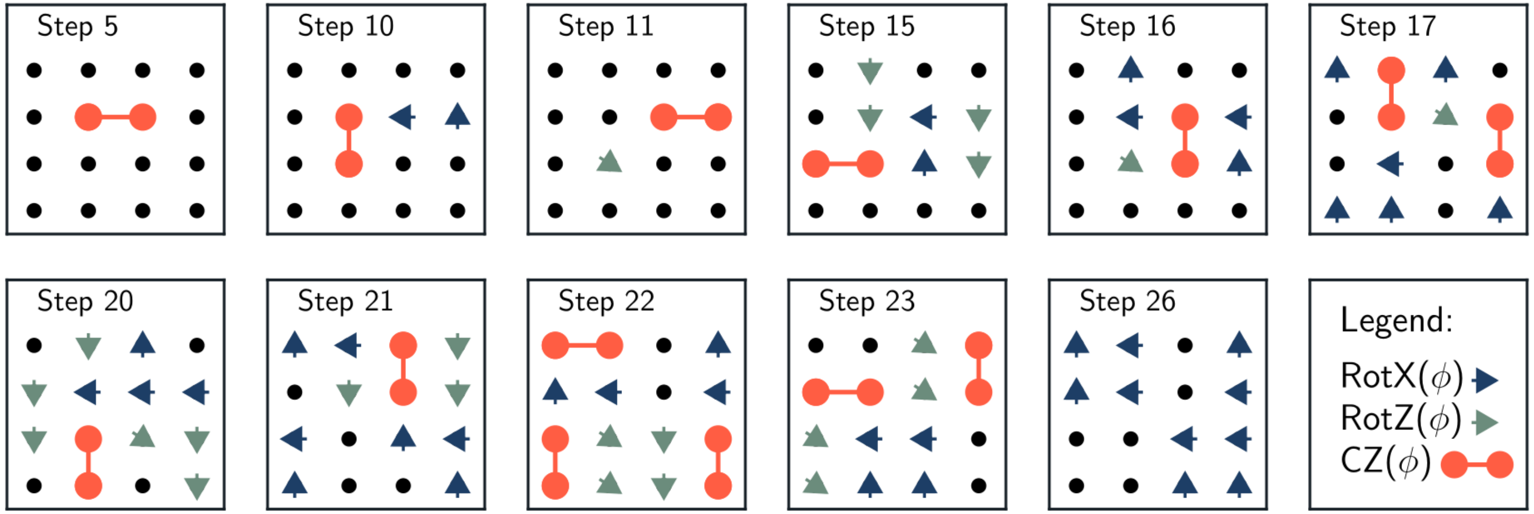






# Algorithm: compiler




## 2. Dedicated GHZ compiler

- Set minimal distance $r_g$ between CZ gates in parallel
- Track possibilities, consider rotations and reflections, …

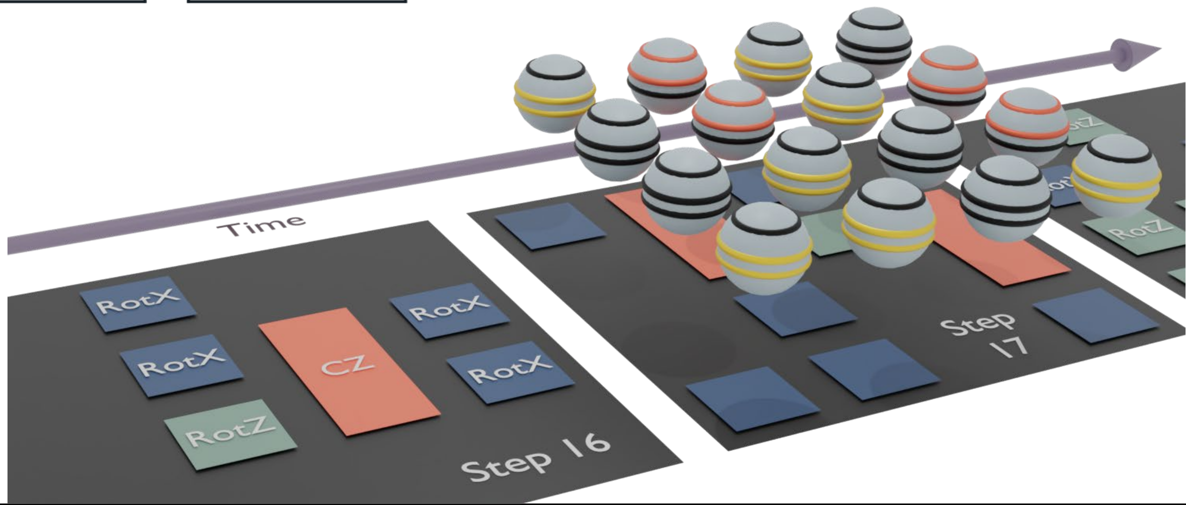
## 1. Qoqo compiler

HQS QUANTUM SIMULATIONS

- Translate Hadamard into native gate set

$$H = \mathrm{Rot}_Z\left(\frac{\pi}{2}\right)\mathrm{Rot}_X\left(\frac{\pi}{2}\right)\mathrm{Rot}_Z\left(\frac{\pi}{2}\right)$$

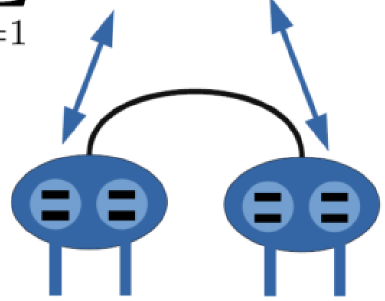
- Translate CNOT into >10 native gates, CZ …



# Numerical simulation with TTN

- We solve the Schrödinger equation
- Tree Tensor Networks (TTN) run Hamiltonian evolution
- Truncation in entanglement via Schmidt decomposition
- Time evolution via time-dependent variational principle
- Van der Waals interaction included up to $r_g + d_{offset}$

$$|\psi_{1,2,3,4}\rangle = \sum_{i=1}^{n} \lambda_i |\psi_{1,2,i}\rangle |\psi_{3,4,i}\rangle$$




Maximal bond dimension $3^8 = 6561$

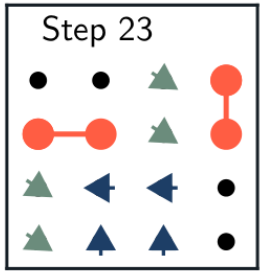
# GHZ state preparation

**Question**

- Prepare global GHZ state

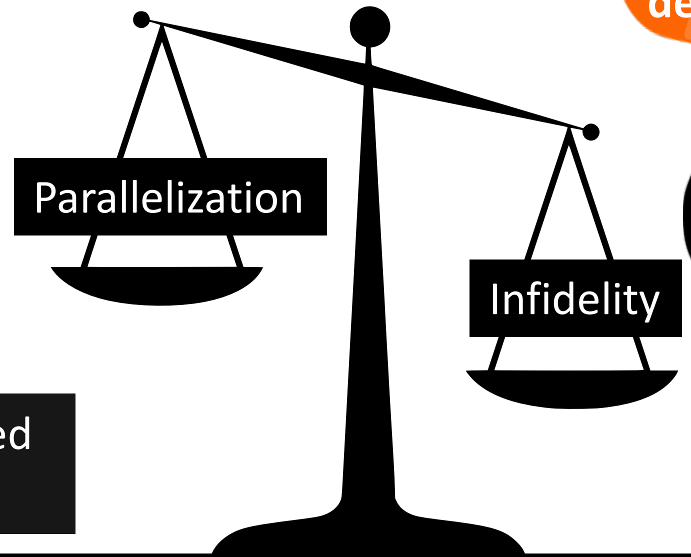
To which extent can we profit in 2d Rydberg systems from parallelization?

$r_g = 2a$

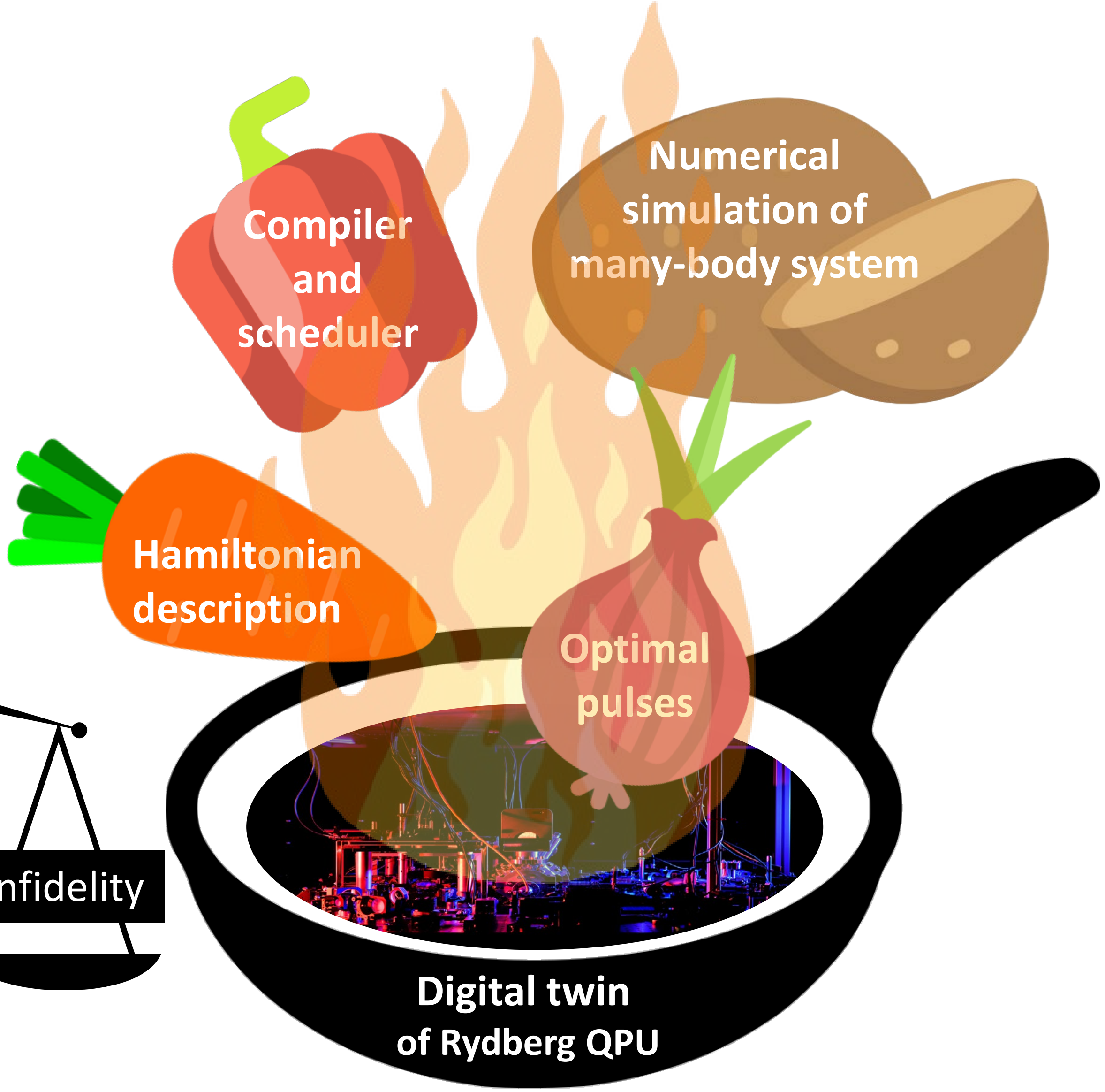



**Issue**

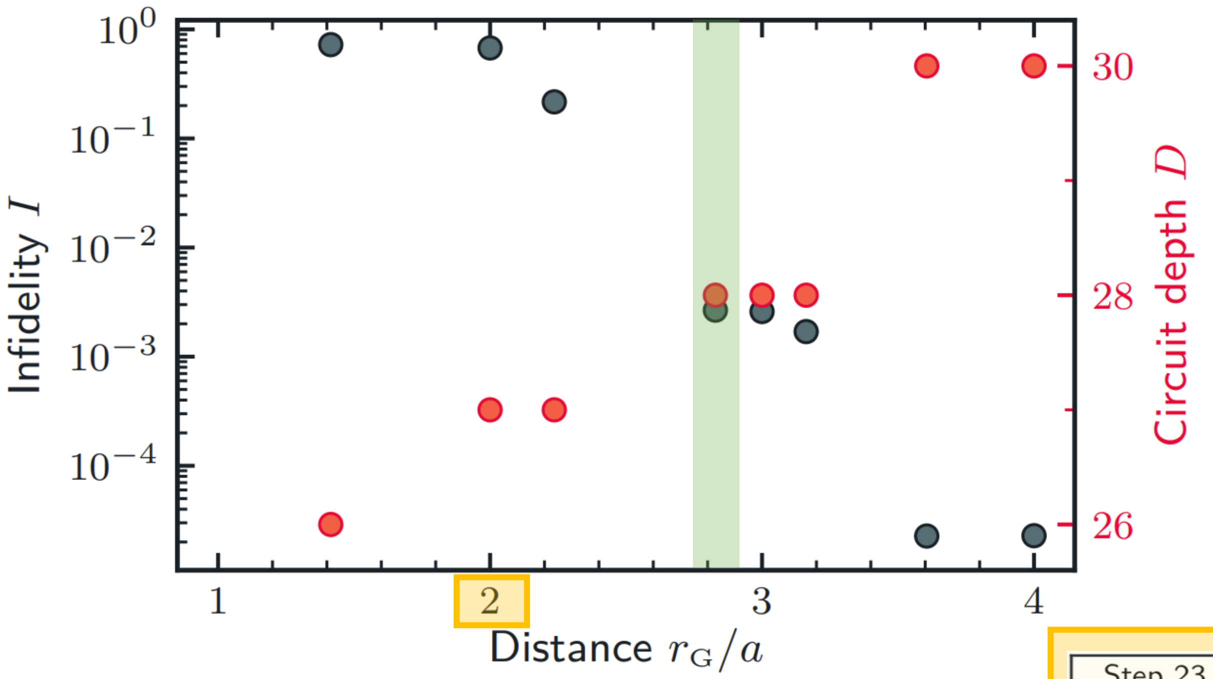
- Rydberg interaction is long-range and introduces crosstalk



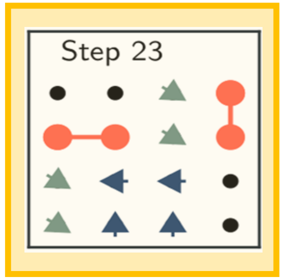

Find minimal distance $r_g$ required between CZ gates in parallel



# Quantify crosstalk 4x4




$$\mathcal{F}_{CZ}^{15} = 0.999998355^{15} = 0.999976$$

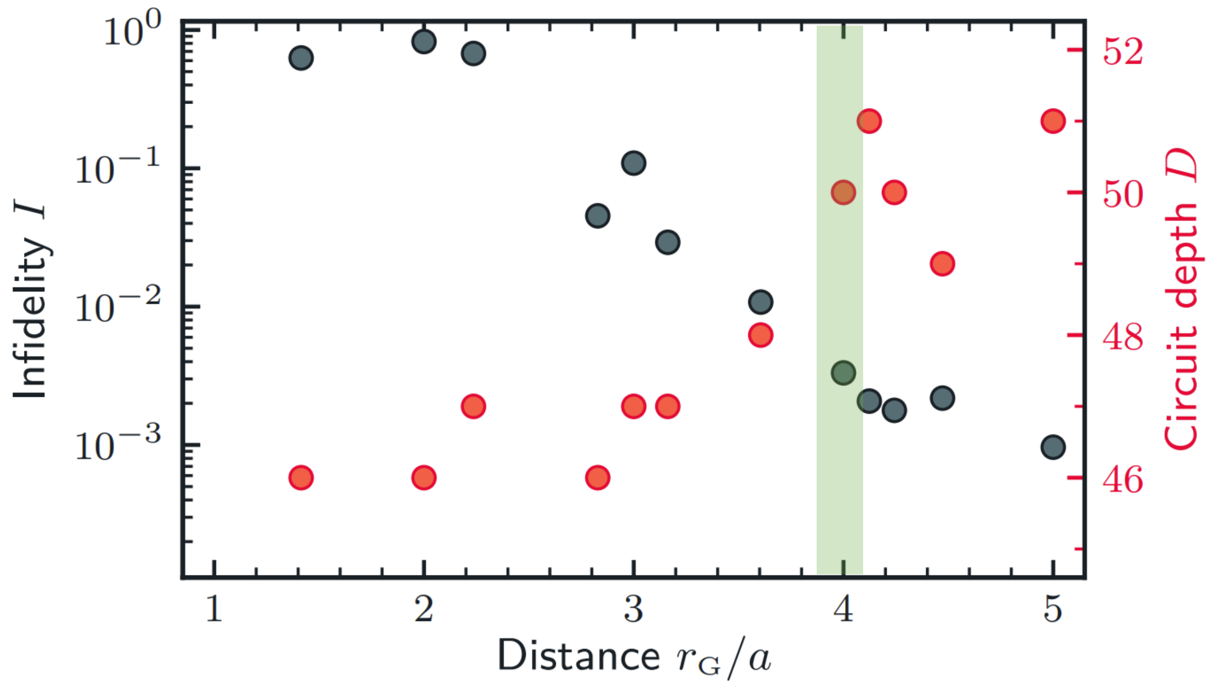



- The fidelity F of the algorithm is the state fidelity at the end

$$F = |\langle\psi(\tau)|\psi_{\text{GHZ}}\rangle|^2$$
$$I = 1 - F$$

- 16 qubit GHZ state can reach fidelities above 0.9999 in a closed system
- We define the safety distance for parallel execution of CZ gate at $\sqrt{8}a$

# Quantify crosstalk 8x8




| Circuit property | 4 × 4 (16) | 6 × 6 (36) | 8 × 8 (64) |
|---|---|---|---|
| $r_S$ | $\sqrt{8}a$ | $4a$ | $4a$ |
| $D_{\min}$ | 23 | 33 | 43 |
| $D(r_S)$ | 28 | 39 | 50 |
| $D_{\mathrm{CZ-serial}}$ | 30 | 50 | 78 |
| $D_{\mathrm{serial}}$ | 168 | 388 | 696 |

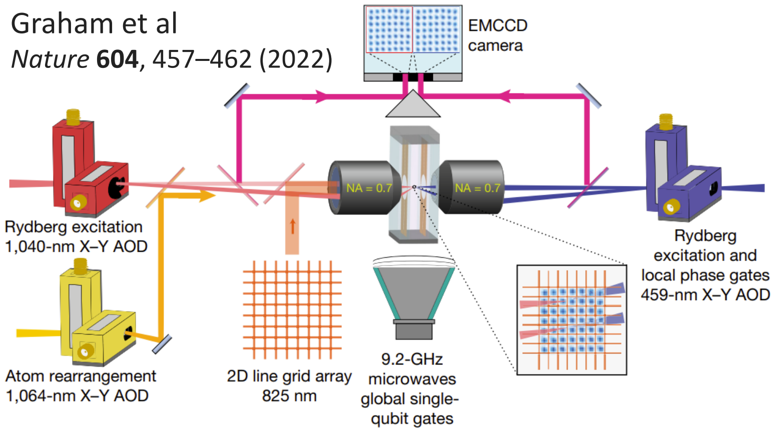
- 64 qubit GHZ state can reach fidelities above 0.99 in a closed system
- We define the safety distance for parallel execution of CZ gate at $4a$
- Larger system sizes profit more from parallelization

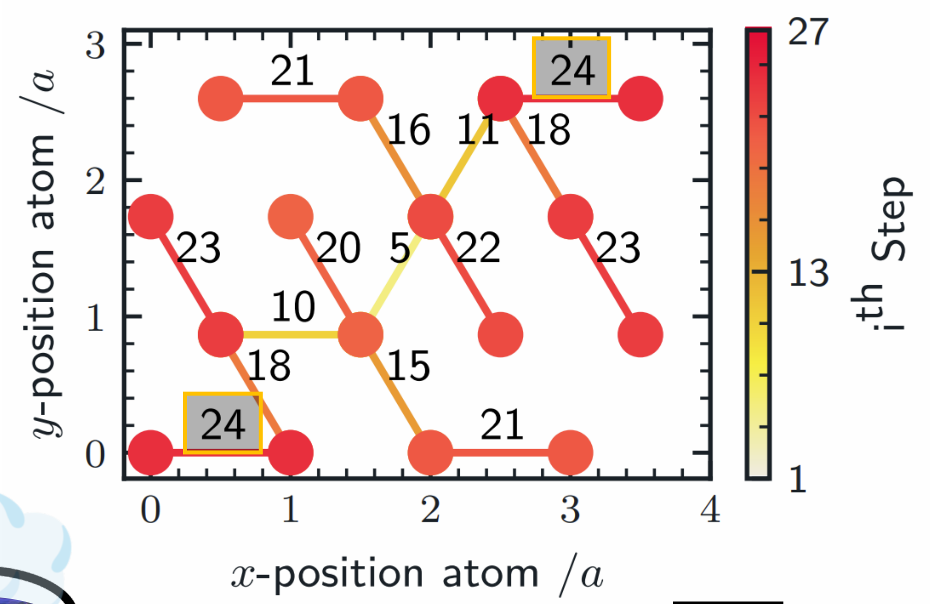
**64**
- **< 15%** overhead compared to min $r_g$ circuit
- **> 35%** speedup compared to CZ-serial circuit
- **> 92%** speedup compared to all-serial circuit

# Triangular lattice layout

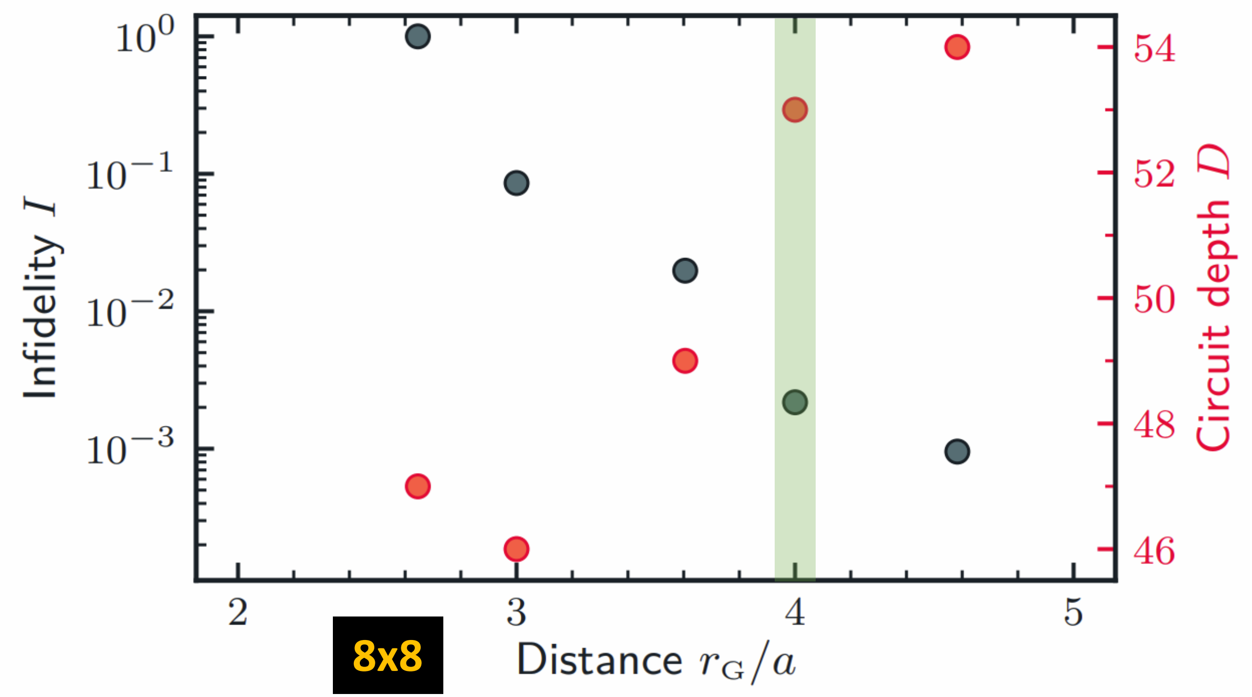
- ➢ Different qubit layout can be implemented
- ➢ An atom can have 6 nearest neighbors

Graham et al
*Nature* **604**, 457–462 (2022)




4x4



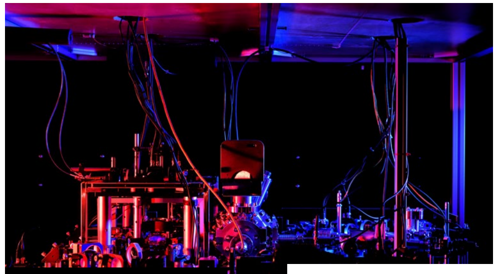

8x8

# Conclusions

**Figures and Supplemental Material**
available here

**figshare.com**

- Develop digital twin of a quantum computer, e.g. Rydberg QPU
- Prepare global GHZ state and study gate crosstalk
  - For 8x8 array, parallel CZ must be four lattice spacings apart
  - Then, crosstalk is negligible in comparison to other sources of error

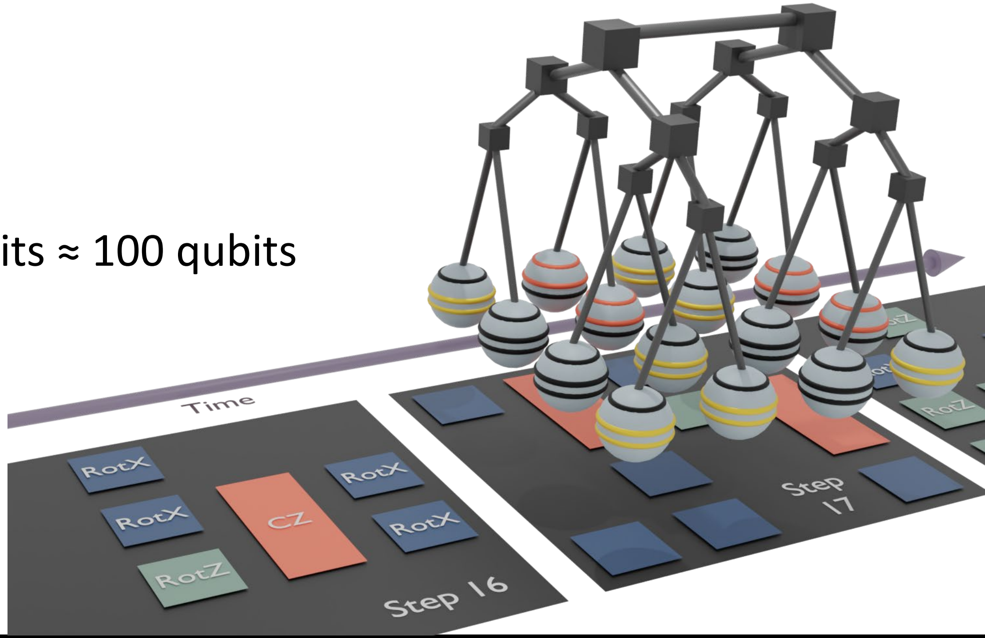

From F. Meinert

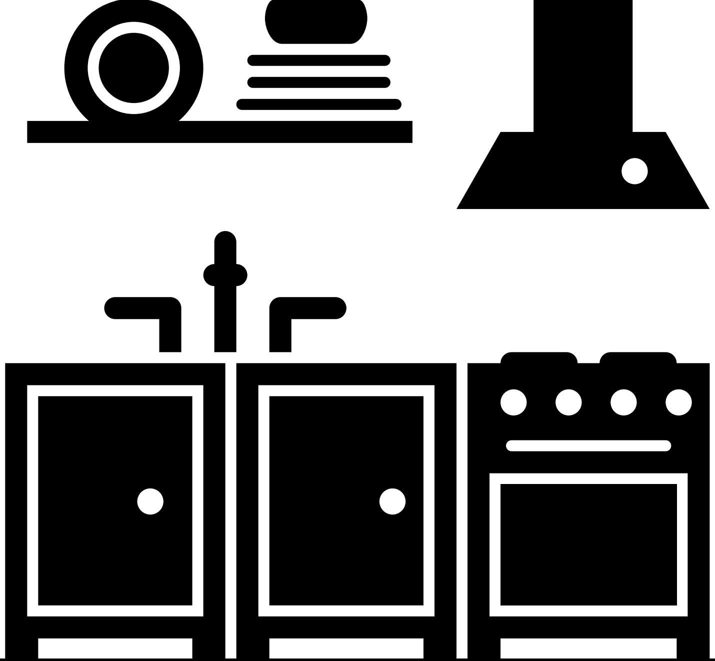
QRyd Demo

| | We don't do | We do |
|---|---|---|
| **Gate:** | Matrix | Pulse |
| **Qubits:** | >100 | >100 |
| **Speed:** | Faster | Slower |

64 qutrits ≈ 100 qubits

**THANK YOU !**





# Backup slides

# Rydberg measurement 8x8

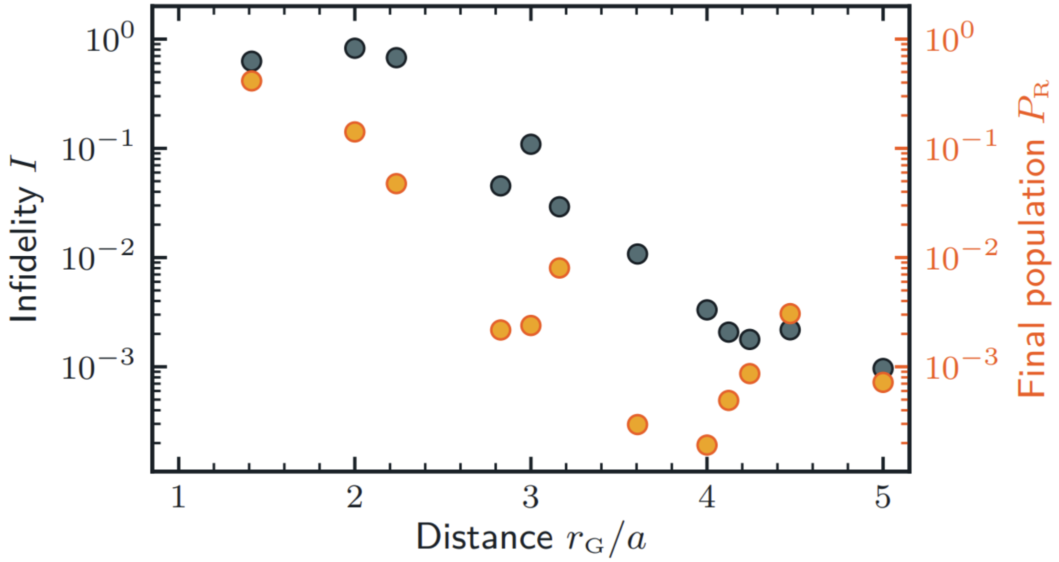
- Decay from the Rydberg state is the most important source of error for a single CZ gate

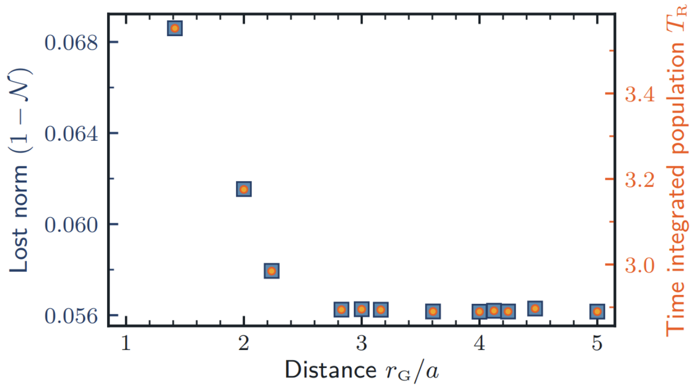
$$H_{\mathrm{OQS}} = H_{\mathrm{Ryd}} - \mathrm{i}\gamma \sum_{j,k} |r\rangle\langle r|_{j,k}$$

$$L_{\mathrm{decay}} = |d\rangle\langle r|$$

- Parallel execution of CZ gates leads to a remaining population in the Rydberg state as the gate is designed for serial use

- Remaining population quantifies the crosstalk: indicator of the fidelity of the state preparation.




**8x8**

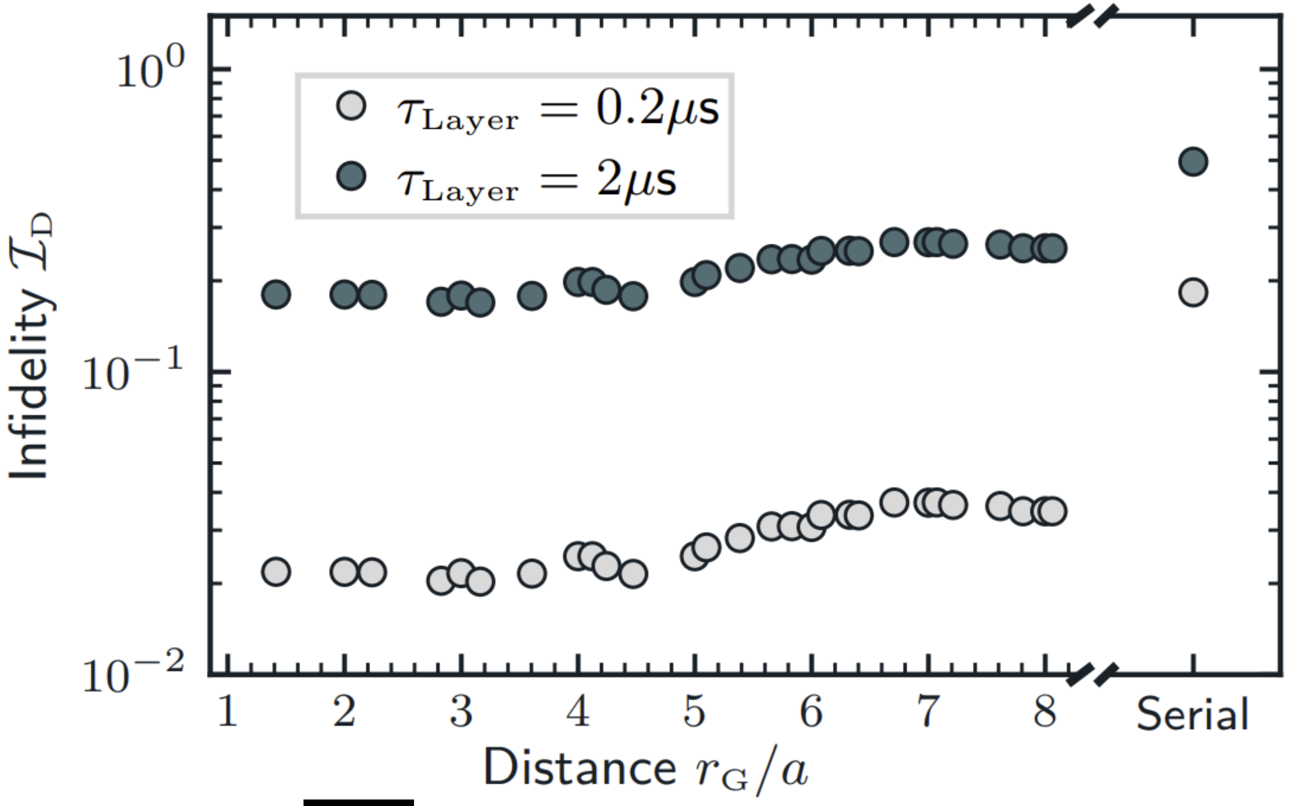
# Dephasing 8x8

- Fluctuations around the magic trapping condition lead to decoherence

- Fidelity between GHZ of n qubits and perfect GHZ state

$$\mathcal{F}_{\mathrm{D}}(t) = \frac{1}{2} + \frac{1}{2}\exp\left(-\frac{n \cdot t}{T_2}\right)$$

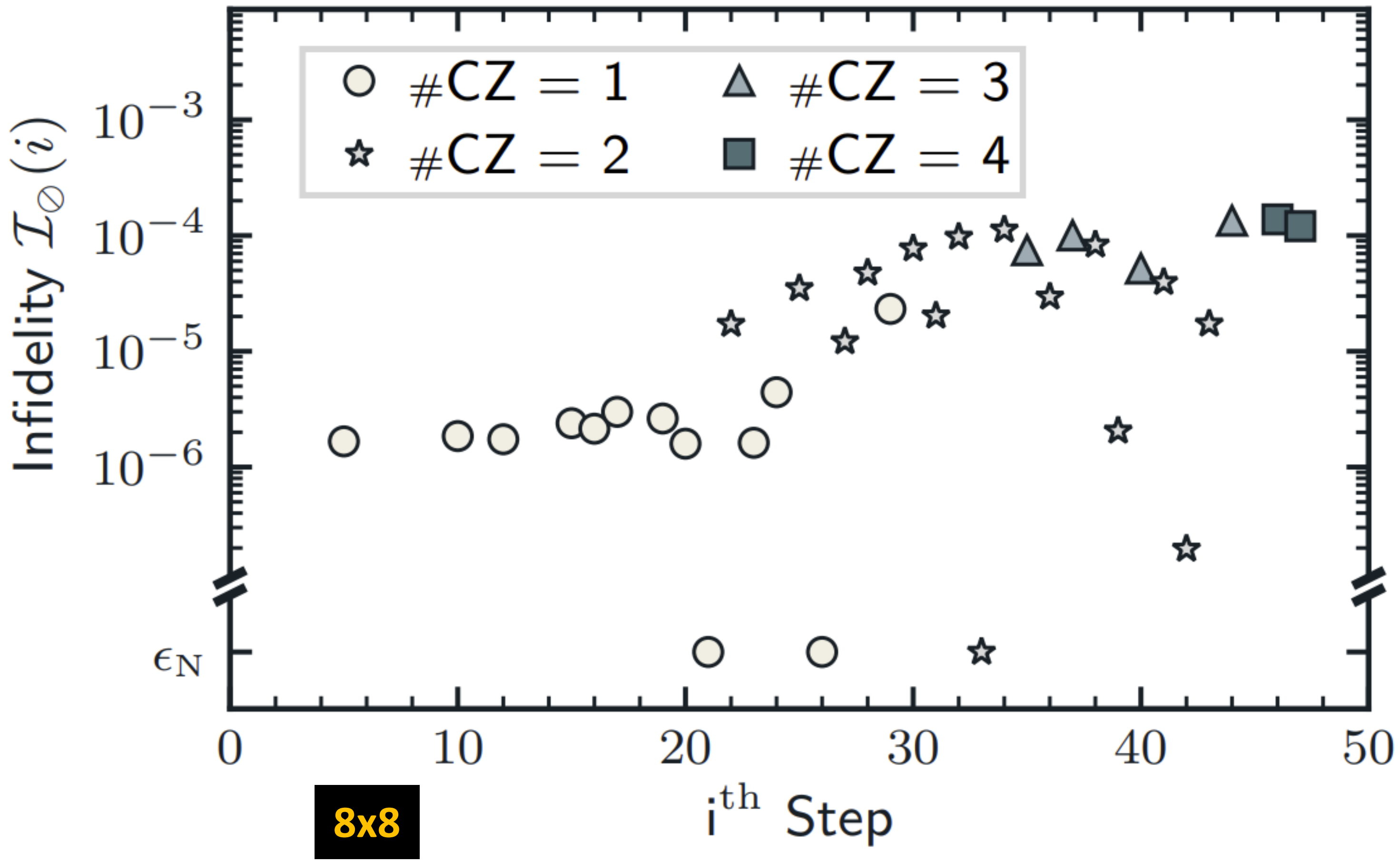
- Proves the need to parallelize the circuit




8x8

# Average error per layer

- Evaluate which layers contribute the most to the final infidelity




8x8