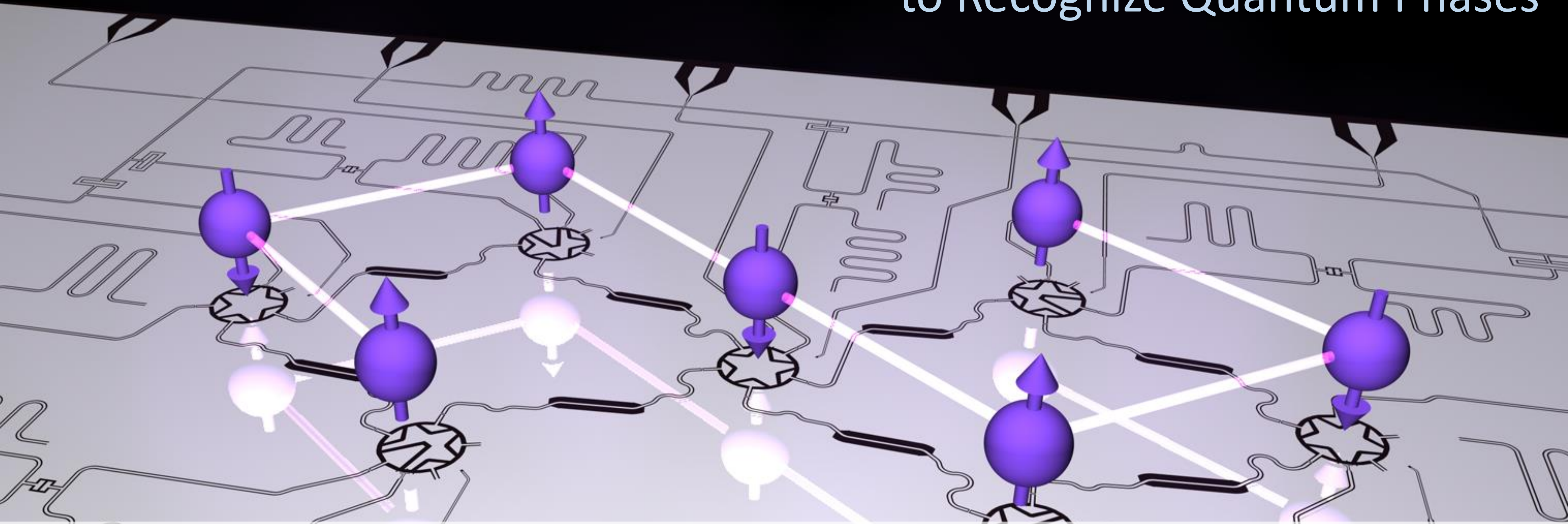
Sergi Masot Llima,
BSC-Quantic,
Benasque, 23/02/2022

Realizing Quantum Convolutional Neural Networks on a Superconducting Quantum Processor to Recognize Quantum Phases



J. Herrmann,[1] S. M. Llima,[1,4] A. Remm,[1] P. Zapletal,[2] N. A. McMahon,[2] C. Scarato,[1] F. Swiadek,[1] C. K. Andersen,[1] C. Hellings,[1] S. Krinner,[1] N. Lacroix,[1] S. Lazar,[1] M. Kerschbaum,[1] D. Zanuz,[1] G. J. Norris,[1] M. J. Hartmann,[2] A. Wallraff,[1,3] and C. Eichler [1]

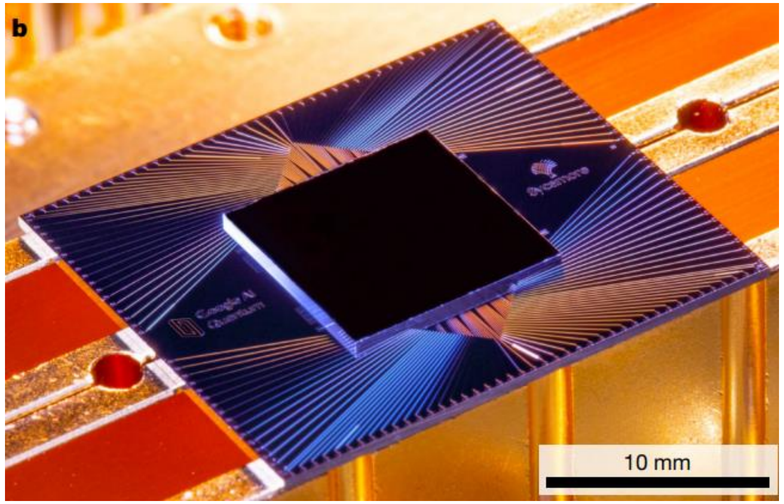
[1] Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland
[2] Friedrich-Alexander University Erlangen-Nürnberg (FAU), Institute for Theoretical Physics, Germany
[3] Quantum Center, ETH Zurich, CH-8093 Zurich, Switzerland
[4] Quantic-CASE, Barcelona Supercomputing Center, Barcelona, Spain

IARPA BE THE FUTURE
BSC Barcelona Supercomputing Center Centro Nacional de Supercomputación
erc
Quromorphic
QSIT Quantum Science and Technology
National Centre of Competence in Research
QUANTUMCAT
QuSurf
FNSNF SWISS NATIONAL SCIENCE FOUNDATION

Motivation: Quantum Phase Recognition

- Experimentally study applications and performance of quantum neural network.
- *In particular:* Scenarios in which processed data is intrinsically quantum (no classical analogue, circumvents data loading bottleneck)

	Classical Algorithm	Quantum Algorithm
Classical Data	**CC** Image or Speech Recognition	**CQ** Quantum speedup for classifying classical data [1]
Quantum Data	**QC** Using NN for qubit readout [2]	**QQ** This experiment



States output by quantum hardware are becoming too complex to be analyzed by classical means [3]

- *Possible use in:*
  - Quantum auto-encoding [5]
  - Certification of Hamiltonian dynamics [6]
  - Quantum error correction [4]
  - Quantum phase recognition [4]

[1] Havlicek et al., *Nature* **567** (2019), [2] Lienhard et al. *APS Phys.* (2020)
[3] Arute *et al., Nature* 574 (2019), [4] Cong et al., *Nat. Phys* (2019),
[5] Romero et al., *QST* (2017) [6] Wiebe et al., *PRL* (2017)

Overview

- Quantum Phase Recognition
  - Hamiltonian with a symmetry protected topological phase
  - Identifying quantum states: direct measurement vs QCNN
- Quantum Convolutional Neural Networks
  - Inspiration behind the algorithm: classical CNN
  - Advantages and physical interpretation
- Superconducting Quantum Processor
- Experimental results
  - Characterization of the prepared ground state
  - Performance of the QCNN
- Conclusions and outlook

The problem
Quantum Phase Recognition

Quantum Phase Recognition with a QCNN

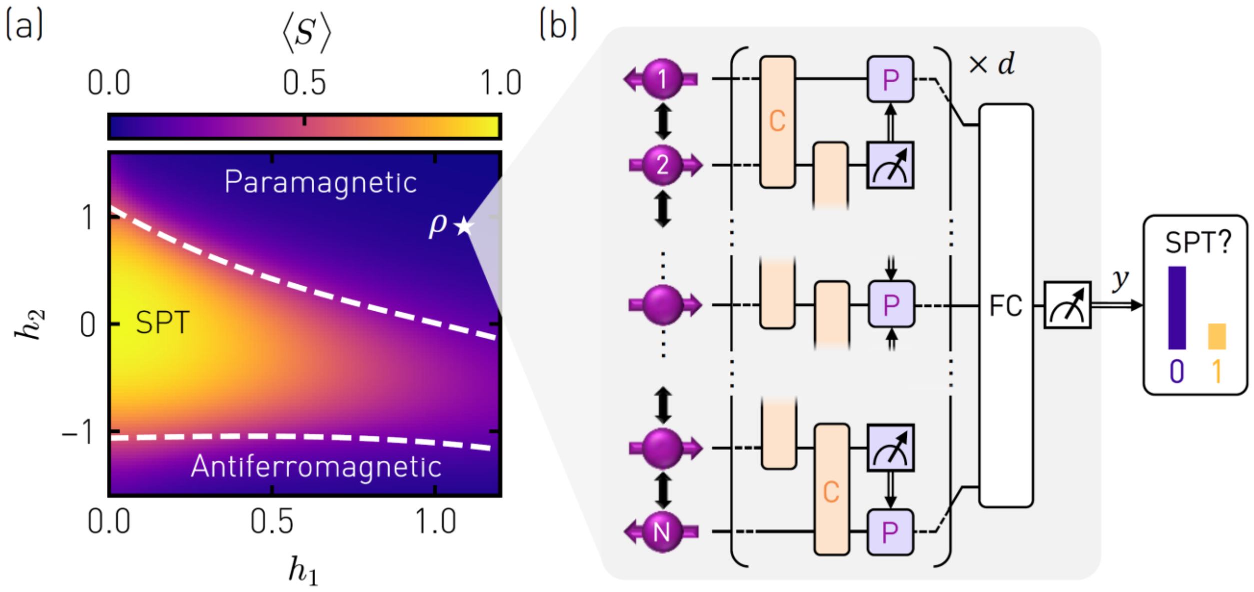
Quantum Face Recognition

- *Task:* Decide for a prepared quantum state ρ_0 if it exhibits symmetry-protected topological (SPT) order [1, 2].
- Model system: Ground states of the Cluster-Ising Hamiltonian

$$H = -\sum_{i=1}^{N-2} Z_i X_{i+1} Z_{i+2} - h_1 \sum_{i=1}^{N} X_i - h_2 \sum_{i=1}^{N-1} X_i X_{i+1}$$

- Signature of SPT phase: Finite string order parameter [3]

$$\langle S \rangle = \langle Z_1 X_2 X_4 \dots X_{N-3} X_{N-1} Z_N \rangle$$



[1] Smith et al., arxiv:1910.05351, [2] Azses et al., *PRL* (2020)
[3] Pollmann et al., *PRB* (2012), [4] Cong et al., *Nat. Phys* (2019)

Theoretical background – Hamiltonian

$$\mathcal{H} = -\sum_{i=1}^{N-2} Z_i X_{i+1} Z_{i+2} - h_1 \sum_{i=1}^{N} X_i - h_2 \sum_{i=1}^{N-1} X_i X_{i+1}$$

- Has an symmetry protected topological phase under $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry
  - $\prod_{i\ odd} X_i$
  - $\prod_{i\ even} X_i$

- Characterized by String Order Parameter [1]: $\langle S \rangle = \langle Z_1 X_2 X_4 \ldots X_{N-3} X_{N-1} Z_N \rangle$

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

[1] Pollmann et al., *PRB* (2012),

Theoretical background – Hamiltonian

$$\mathcal{H} = -X_1 Z_2 - Z_1 X_2 Z_3 - Z_2 X_3 - \frac{h_1}{J}(X_1 + X_2 + X_3) - \frac{h_2}{J}(X_1 X_2 + X_2 X_3)$$

- Has an SPT phase under $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry
  - $X_1 X_3$
  - X_2 - Not exact due to boundary terms!
- Characterized by String Order Parameter
  - $\langle S \rangle = Z_1 X_2 Z_3$

Limits:

- $h_1 \to \infty$: $\mathcal{H} = -h_1 \sum_{i=1}^{N} X_i$

  $|\psi_g\rangle = |+ + +\rangle$

- $h_1 = 0, h_2 = 0$: $\mathcal{H} = -\sum_{i=2}^{N-1} Z_{i-1} X_i Z_{i+1}$

  $|\psi_g\rangle = \frac{1}{\sqrt{2}}(|+ 0 +\rangle + |- 1 -\rangle)$

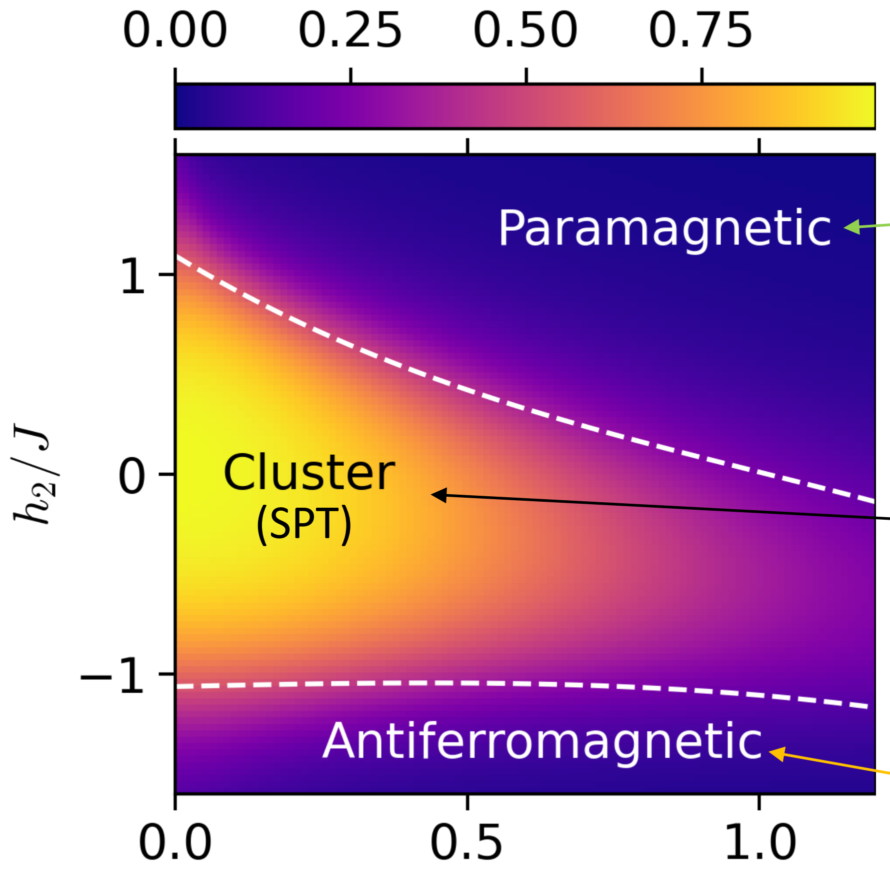
  (cluster state)

- $h_2 \to -\infty$: $\mathcal{H} = -h_2 \sum_{i=1}^{N-1} X_i X_{i+1}$

  $|\psi_g\rangle = |+ - +\rangle$

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Theoretical background – SPT phase



Limits:

- $h_1 \to \infty: \quad \mathcal{H} = -h_1 \sum_{i=1}^{N} X_i$

  $|\psi_g\rangle = |{+}{+}\,{+}\rangle$

- $h_1 = 0, h_2 = 0: \quad \mathcal{H} = -\sum_{i=2}^{N-1} Z_{i-1} X_i Z_{i+1}$

  $|\psi_g\rangle = \frac{1}{\sqrt{2}}(|+\,0\,+\rangle + |-\,1\,-\rangle)$

  (cluster state)

- $h_2 \to -\infty: \quad \mathcal{H} = -h_2 \sum_{i=1}^{N-1} X_i X_{i+1}$

  $|\psi_g\rangle = |{+}{-}\,{+}\rangle$

Quantum Phase Recognition with a QCNN

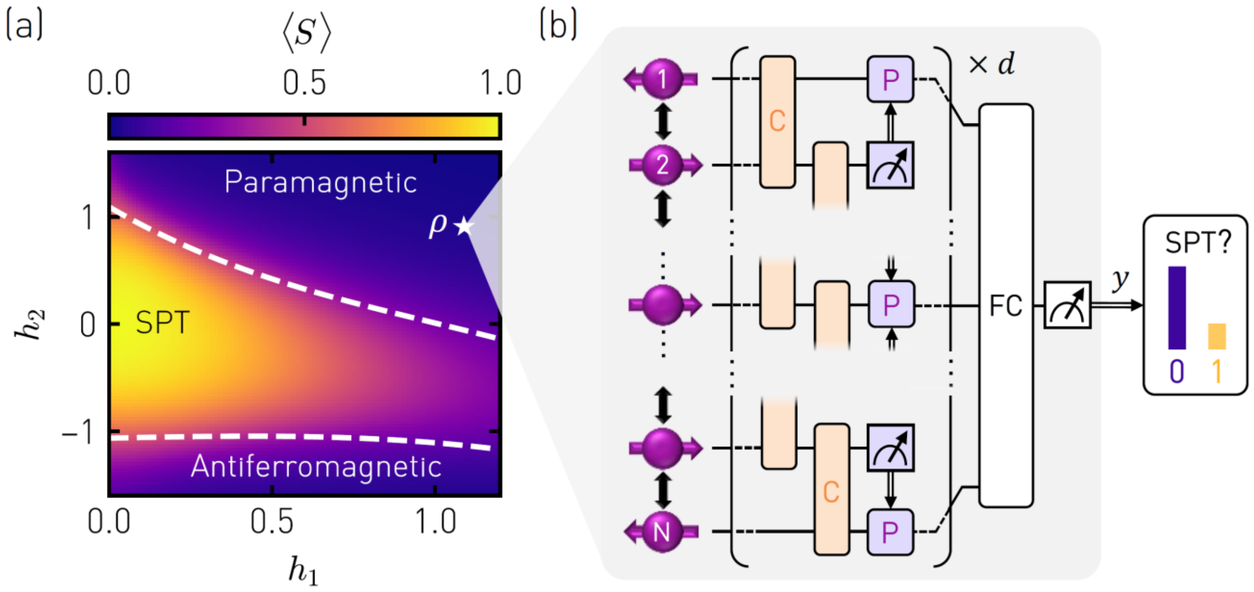
Quantum Face Recognition

- *Task:* Decide for a prepared quantum state ρ_0 if it exhibits symmetry-protected topological (SPT) order [1, 2].
- Model system: Ground states of the Cluster-Ising Hamiltonian

$$H = -\sum_{i=1}^{N-2} Z_i X_{i+1} Z_{i+2} - h_1 \sum_{i=1}^{N} X_i - h_2 \sum_{i=1}^{N-1} X_i X_{i+1}$$

- Signature of SPT phase: Finite string order parameter [3]

$$\langle S \rangle = \langle Z_1 X_2 X_4 \ldots X_{N-3} X_{N-1} Z_N \rangle$$



Questions

- Can we detect SPT phase by processing ρ_0 with a quantum algorithm rather than by averaging $\langle S \rangle$?
- *Possible advantages:* Improve sampling efficiency close to phase boundary and error tolerance capability [4]

[1] Smith et al., arxiv:1910.05351, [2] Azses et al., *PRL* (2020)
[3] Pollmann et al., *PRB* (2012), [4] Cong et al., *Nat. Phys* (2019)

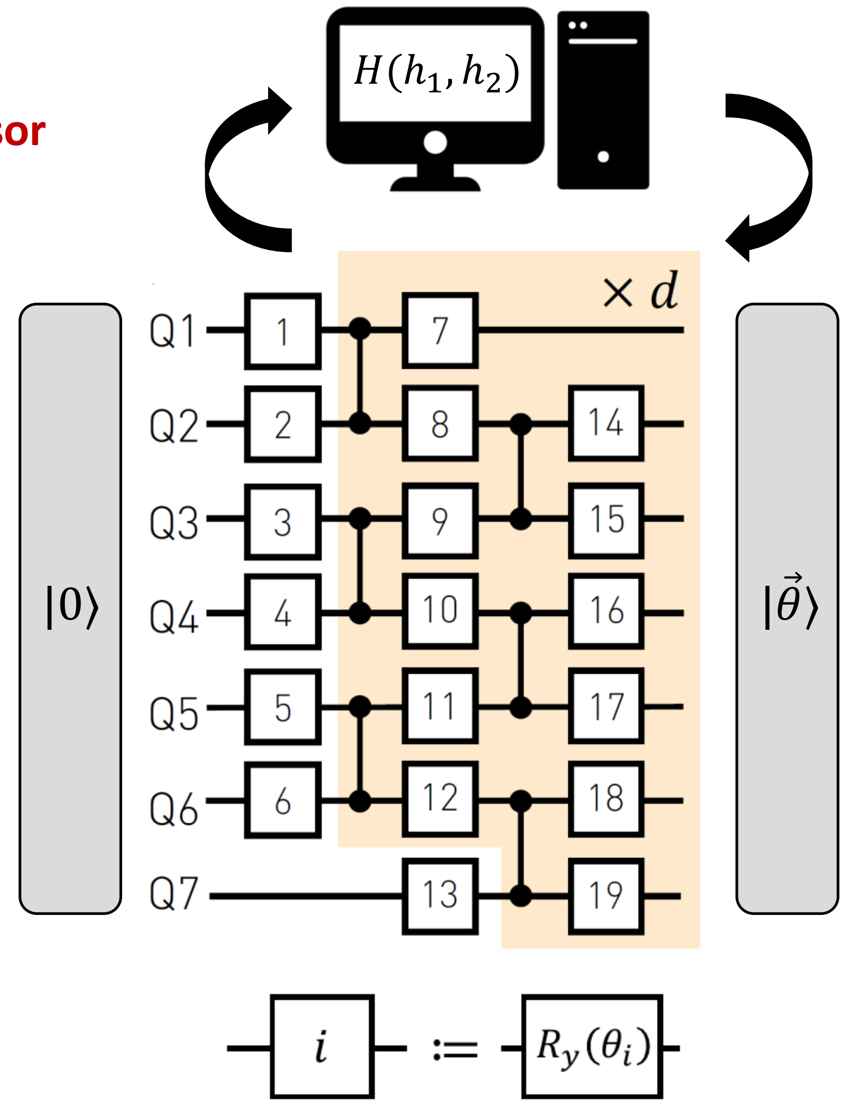
The algorithm

Quantum Convolutional Neural Networks

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Variational state preparation circuit

Step 1: Prepare (approximate) ground states of H on quantum processor



Ansatz

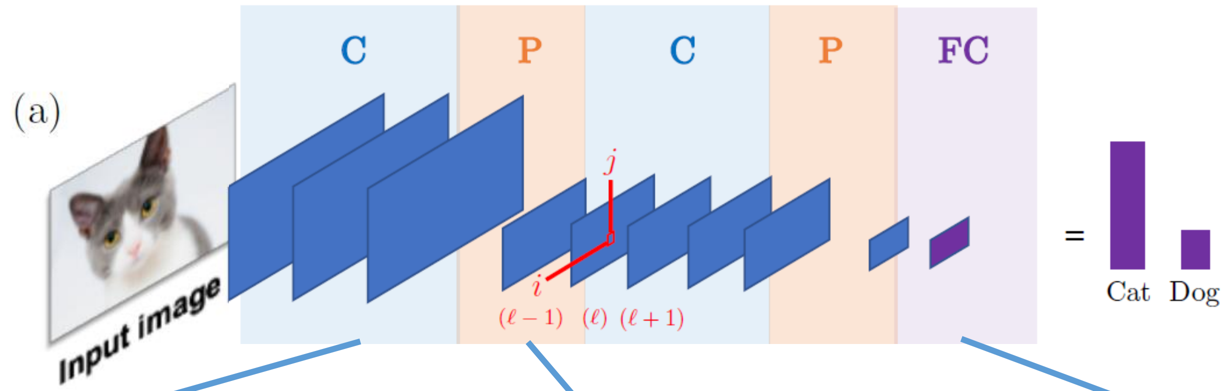
- Hardware-efficient ansatz alternating between layers of CZ gates and single qubit rotations
- Use single layer d=1 in experiment
- 19 variational parameters
- Optimize variational parameters offline on classical computer by minimizing energy $\langle\vec{\theta}|H|\vec{\theta}\rangle$ with L-BFGS B
- Fidelity w.r.t. exact GS exceeds 82% for all states

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

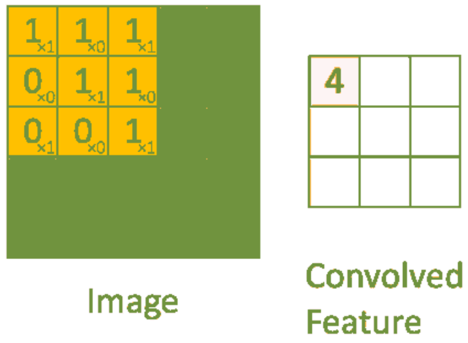
State preparation ansatz: C. Bravo-Prieto, et. al, arXiv:2002.06210 (2020)

Classical convolutional neural networks

Example: Image recognition



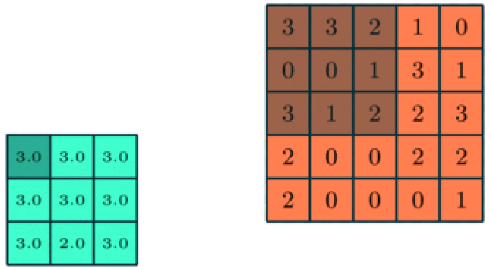
Convolutional layer



Data is processed using trainable weights w on the input data x

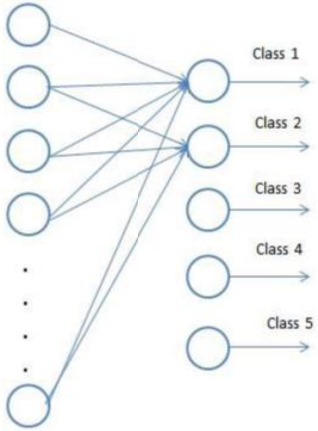
$$y_{i,j} = w_o x_{i,j} + w_1 x_{i+1,j} + \ \dots + w_8 x_{i+2,j+2}$$

Pooling layer



Reduce size of data to the most relevant features (maximum, averaging,...)

Fully connected

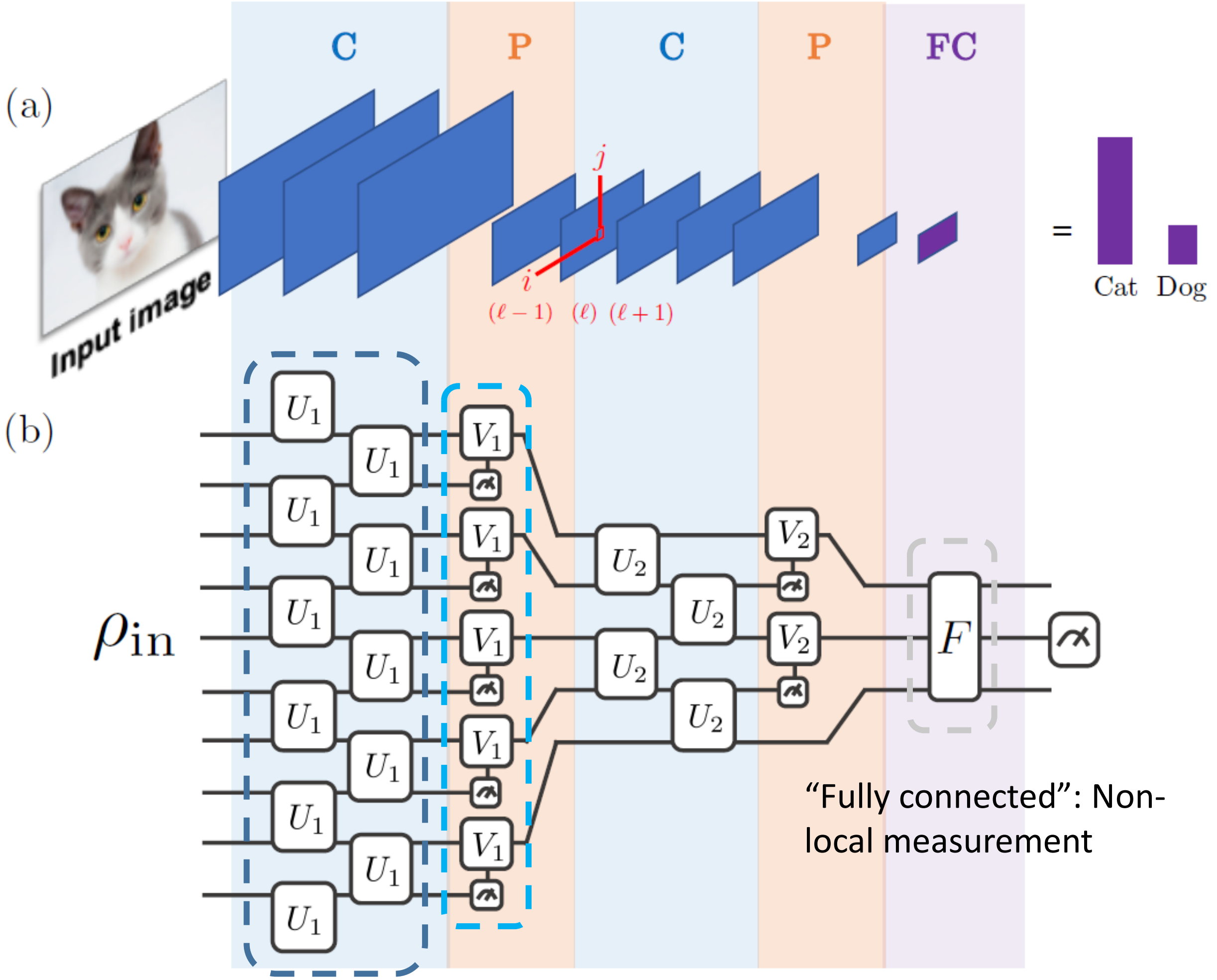


All remaining data points are processed simultaneously with trainable weights

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Images from A Comprehensive Guide to Convolutional Neural Networks, Sumit Saha

Quantum CNN structure



“Fully connected”: Non-local measurement

“Convolution” with quasilocal unitaries

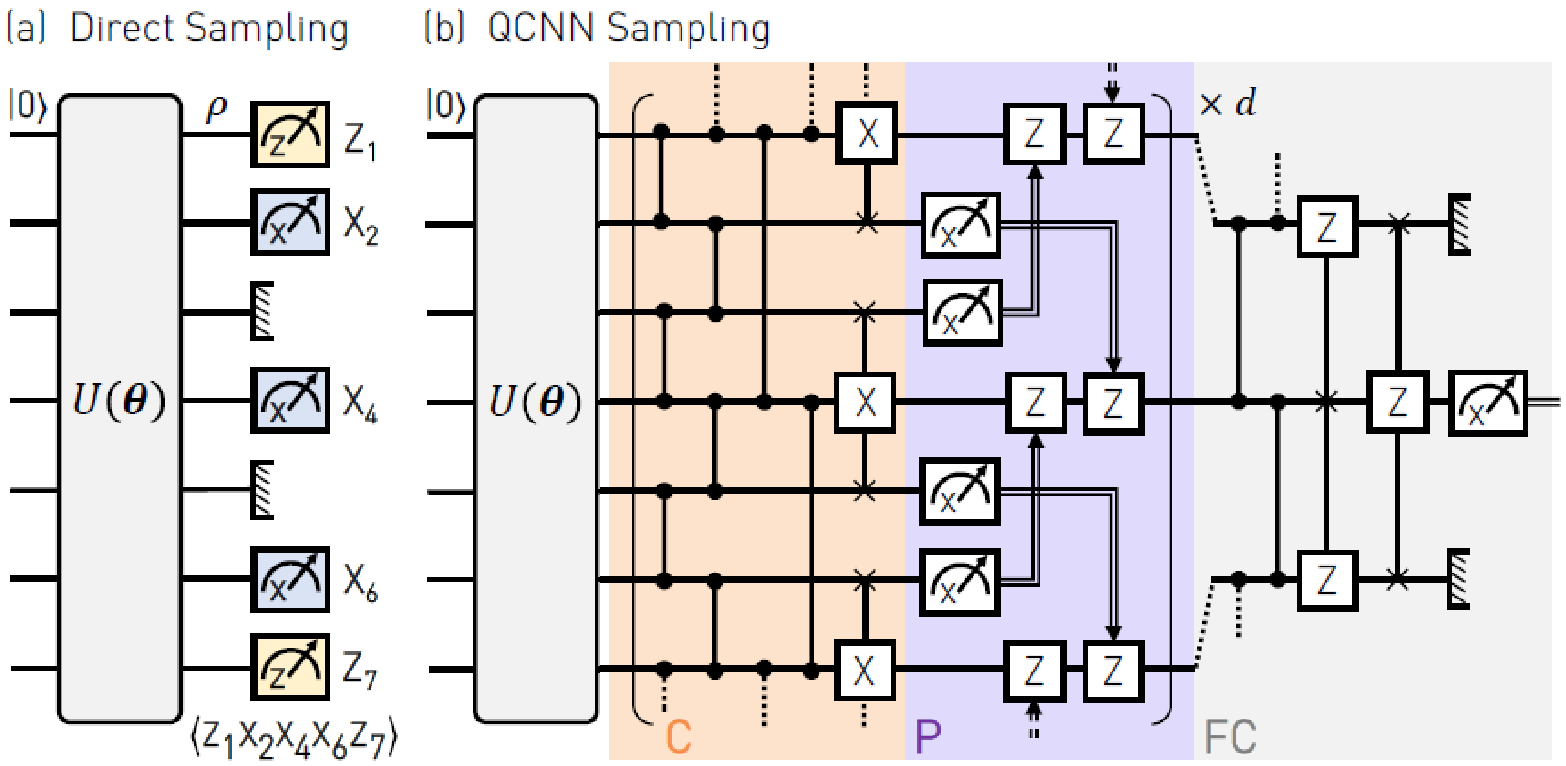
“Pooling”: Measure and apply controlled unitaries

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Quantum Convolutional Neural Networks, Cong et al., Nat. Phys. (2019)

Quantum Phase Recognition with a QCNN

Step 2: Measure $\langle S \rangle$ or QCNN output from state preparation circuit



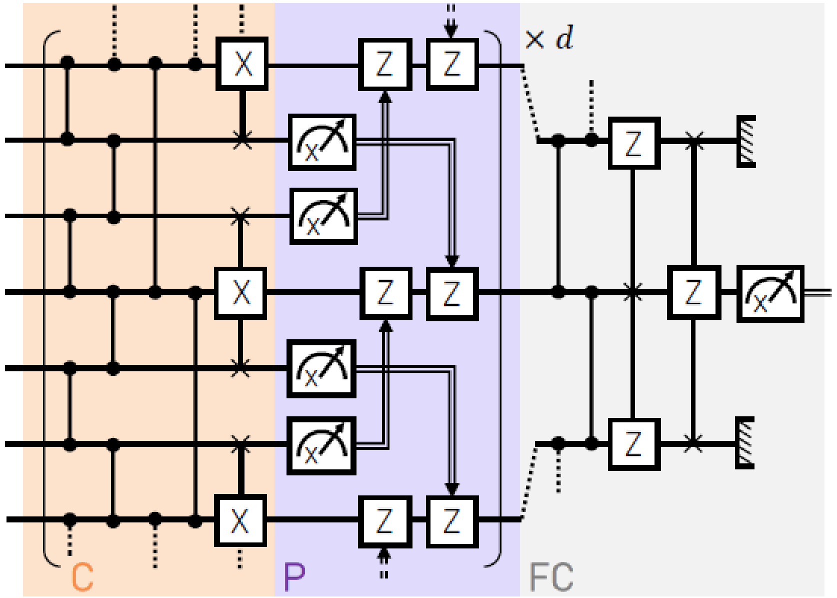
Quantum Convolutional Neural Network

- Convolutional layer ideally maps cluster state onto ground state $|00000\rangle$
- Inspired by the multiscale entanglement renormalization ansatz (MERA)

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

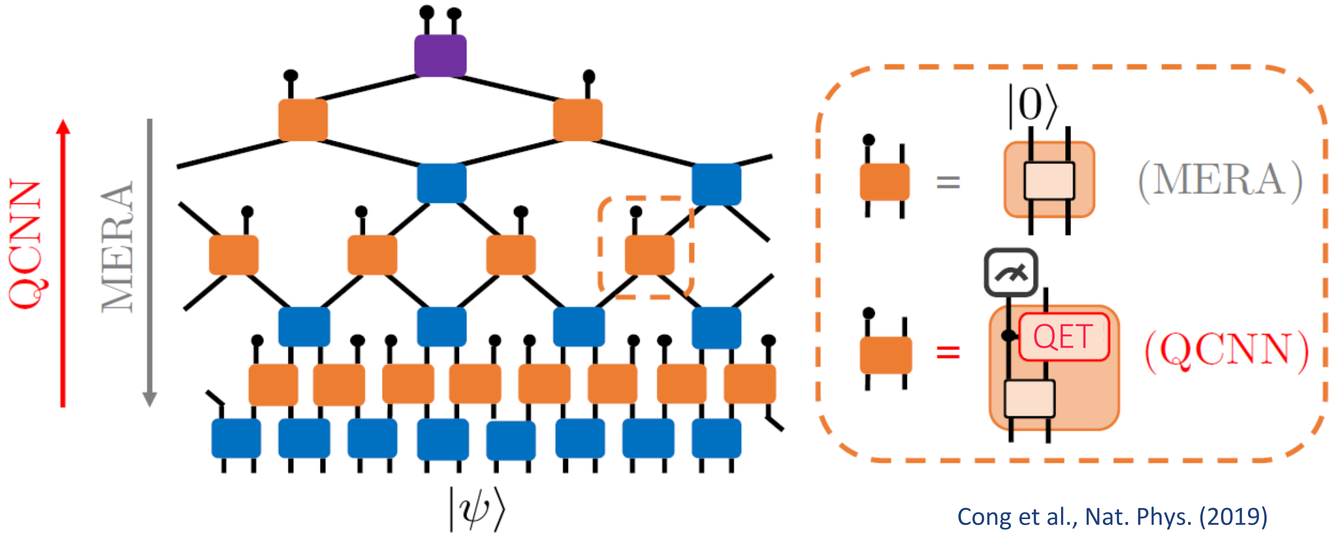
Compare Cong et al., Nat. Phys. (2019)

Theoretical understanding



Herrmann, Masot-Llima et al. (2021)

QCNN = Multiscale Entanglement Renormalization Ansatz (MERA)
+ Quantum Error Tolerance (QET)



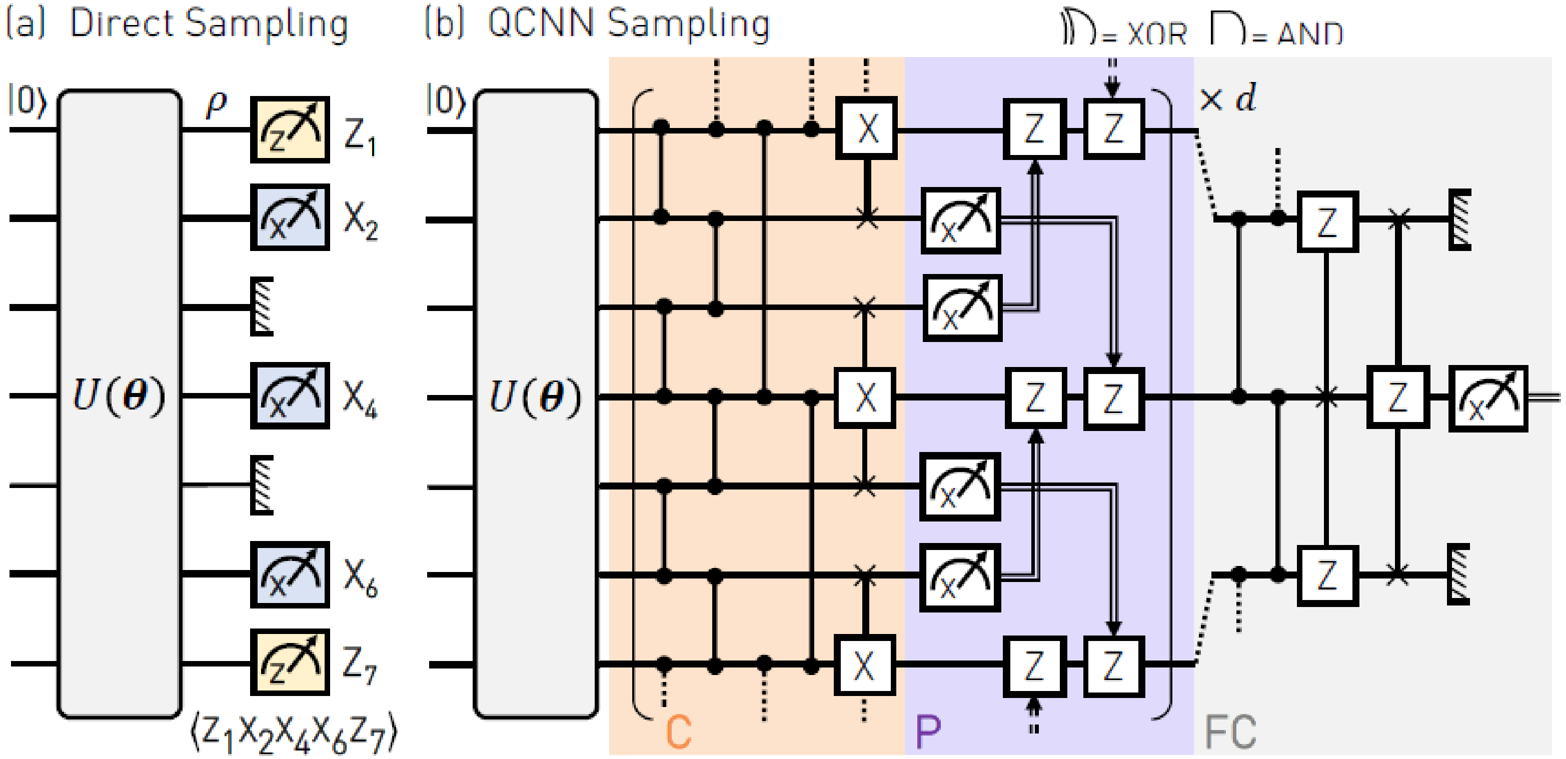
Cong et al., Nat. Phys. (2019)

The QCNN output corresponds to measuring a multi-scale string order parameter of the form

$$S_M = \sum_{jk} \eta_{jk}^{(1)} S_{jk} + \sum_{jklm} \eta_{jklm}^{(2)} S_{jk} S_{lm} + \cdots$$

- The number of terms grows double exponentially with the depth of the circuit
- For our experiment with $N = 7$ and $d = 1$ the QCNN measures a sum of 10 different string order parameters
- All terms are measured simultaneously and cannot be constructed from a direct measurement of all qubits in a single local basis (*X*, *Y* or *Z* basis)

Quantum Phase Recognition with a QCNN



um Convolutional Neural Network

ve Pooling and Fully Connected layers
classical sector (AND & XOR gates) to
sampled multibit string $\vec{x}$ onto single
put bit y described by Boolean
ction $f(x)$.

ability to tolerate errors (depicted for
nd Z errors)

Compare Cong et al., Nat. Phys. (2019)

Quantum Phase Recognition with a QCNN

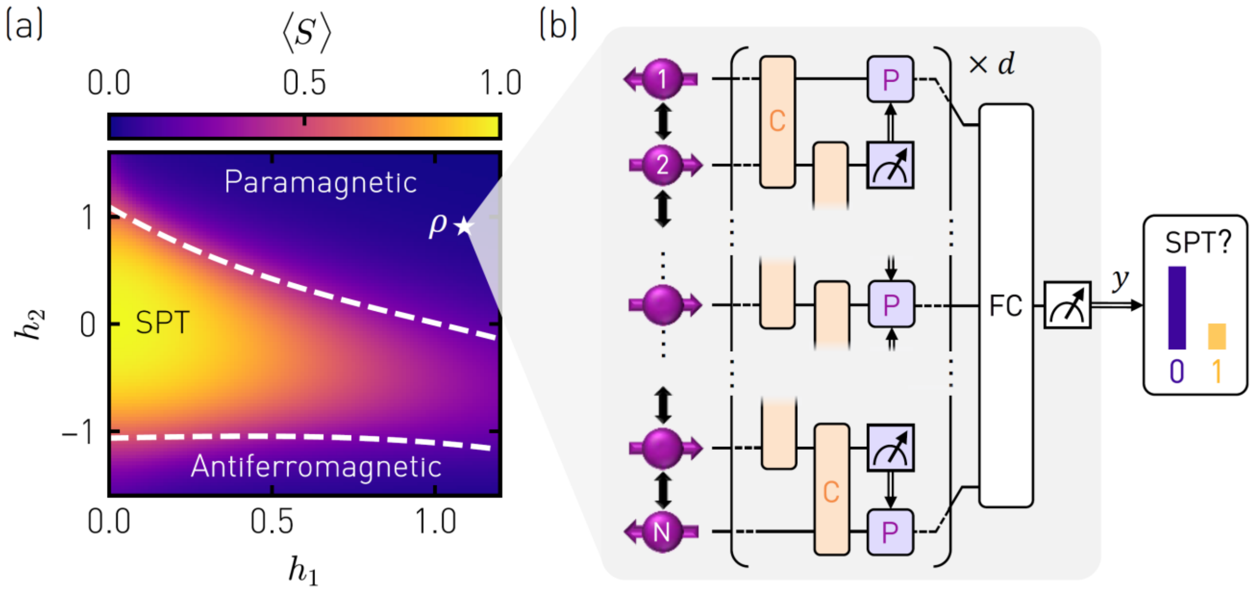
Quantum Face Recognition

- *Task:* Decide for a prepared quantum state ρ_0 if it exhibits symmetry-protected topological (SPT) order [1, 2].
- Model system: Ground states of the Cluster-Ising Hamiltonian

$$H = -\sum_{i=1}^{N-2} Z_i X_{i+1} Z_{i+2} - h_1 \sum_{i=1}^{N} X_i - h_2 \sum_{i=1}^{N-1} X_i X_{i+1}$$

- Signature of SPT phase: Finite string order parameter [3]

$$\langle S \rangle = \langle Z_1 X_2 X_4 \ldots X_{N-3} X_{N-1} Z_N \rangle$$



Questions

- Can we detect SPT phase by processing ρ_0 with a quantum algorithm rather than by averaging $\langle S \rangle$?
- *Possible advantages:* Improve sampling efficiency close to phase boundary and error tolerance capability [4]

The algorithm

- Variant of Quantum Convolutional Neural Network [4]
- Entangling gates in convolutional layer
- **Pooling** reduces the number of qubits while retaining characteristic features
- **Fully-connected** layer to map decision onto a single output qubit

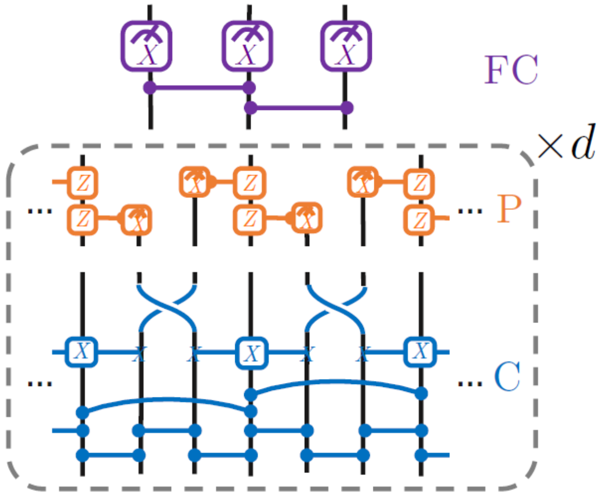
Barcelona Supercomputing Center
Centro Nacional de Supercomputación

[1] Smith et al., arxiv:1910.05351, [2] Azses et al., *PRL* (2020)
[3] Pollmann et al., *PRB* (2012), [4] Cong et al., *Nat. Phys* (2019)

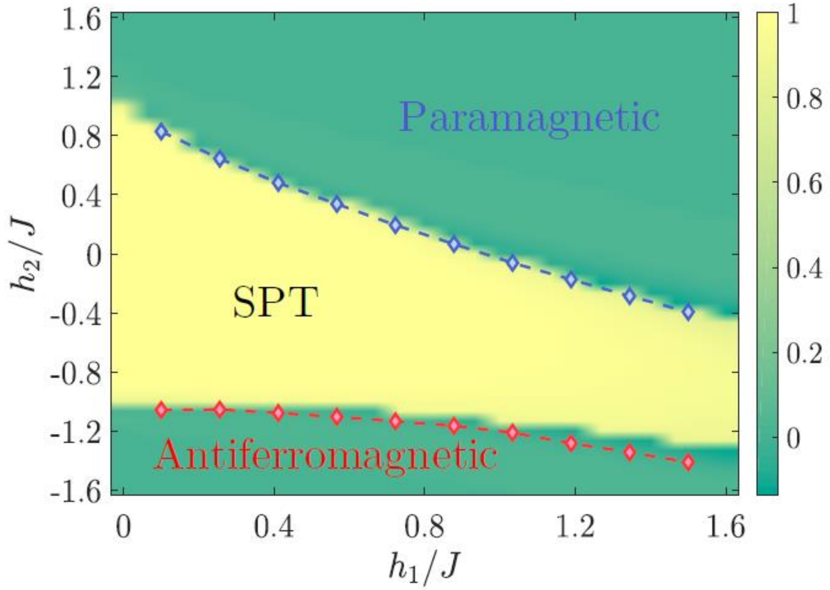
Advantage: Sample complexity

Theoretical proposal with a long chain:

$$H = -\sum_{i=1}^{N-2} Z_i X_{i+1} Z_{i+2} - h_1 \sum_{i=1}^{N} X_i - h_2 \sum_{i=1}^{N-1} X_i X_{i+1}$$



Analytical QCNN



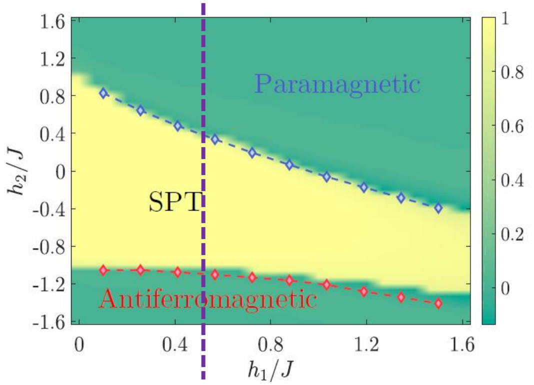
N=45 chain

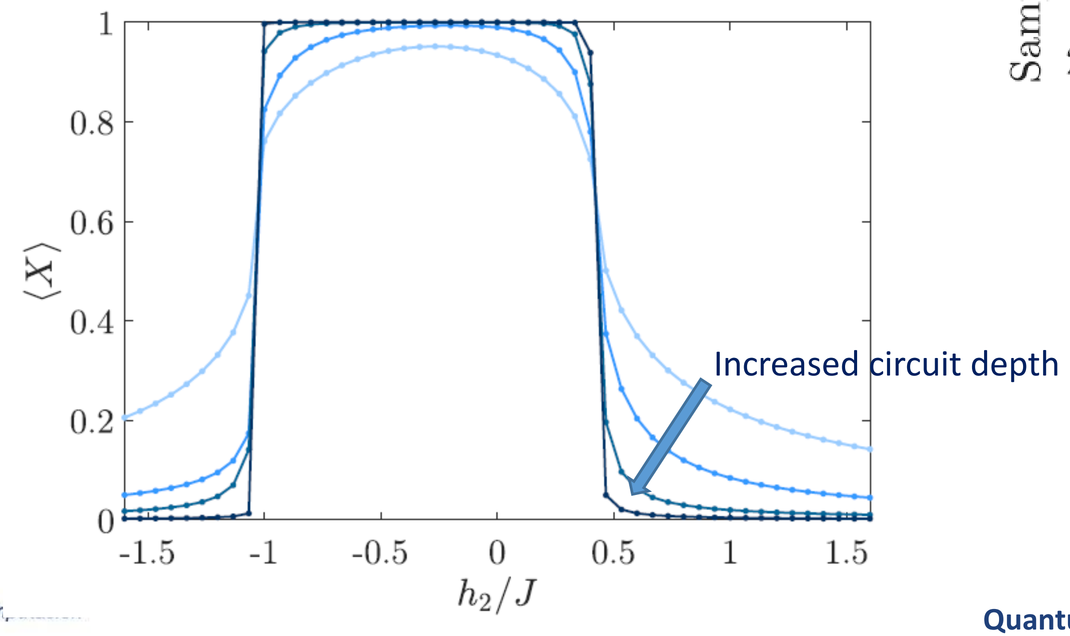
- Boundaries calculated with iDMRG simulation
- Color indicates phases according to analytical QCNN

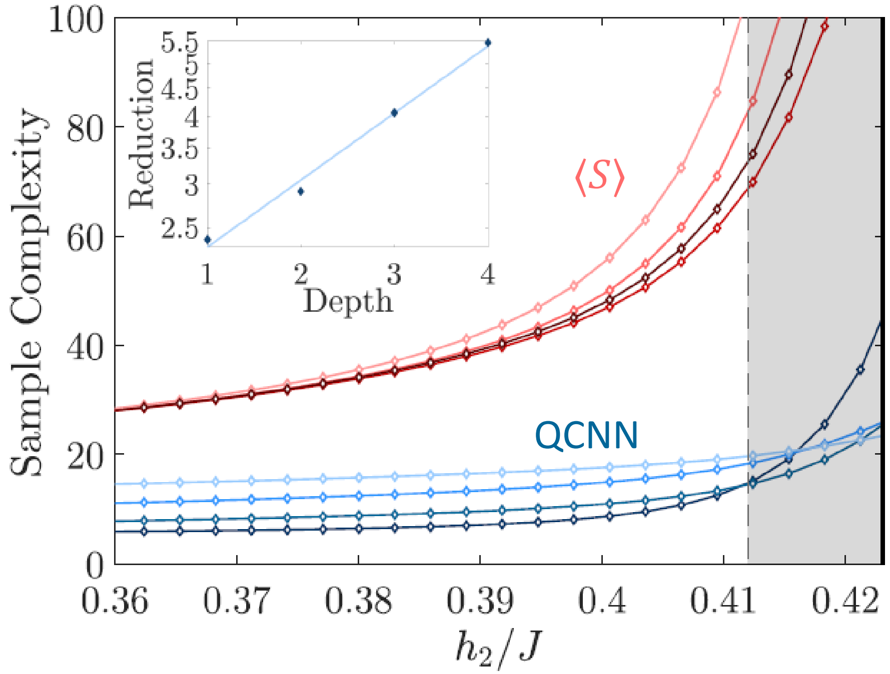
Quantum Convolutional Neural Networks, Cong et al., Nat. Phys. (2019)

Advantage: Sample complexity

$$H = -\sum_{i=1}^{N-2} Z_i X_{i+1} Z_{i+2} - h_1 \sum_{i=1}^{N} X_i - h_2 \sum_{i=1}^{N-1} X_i X_{i+1}$$







Barcelona Supercomputing Center
Centro Nacional de Supercomputación

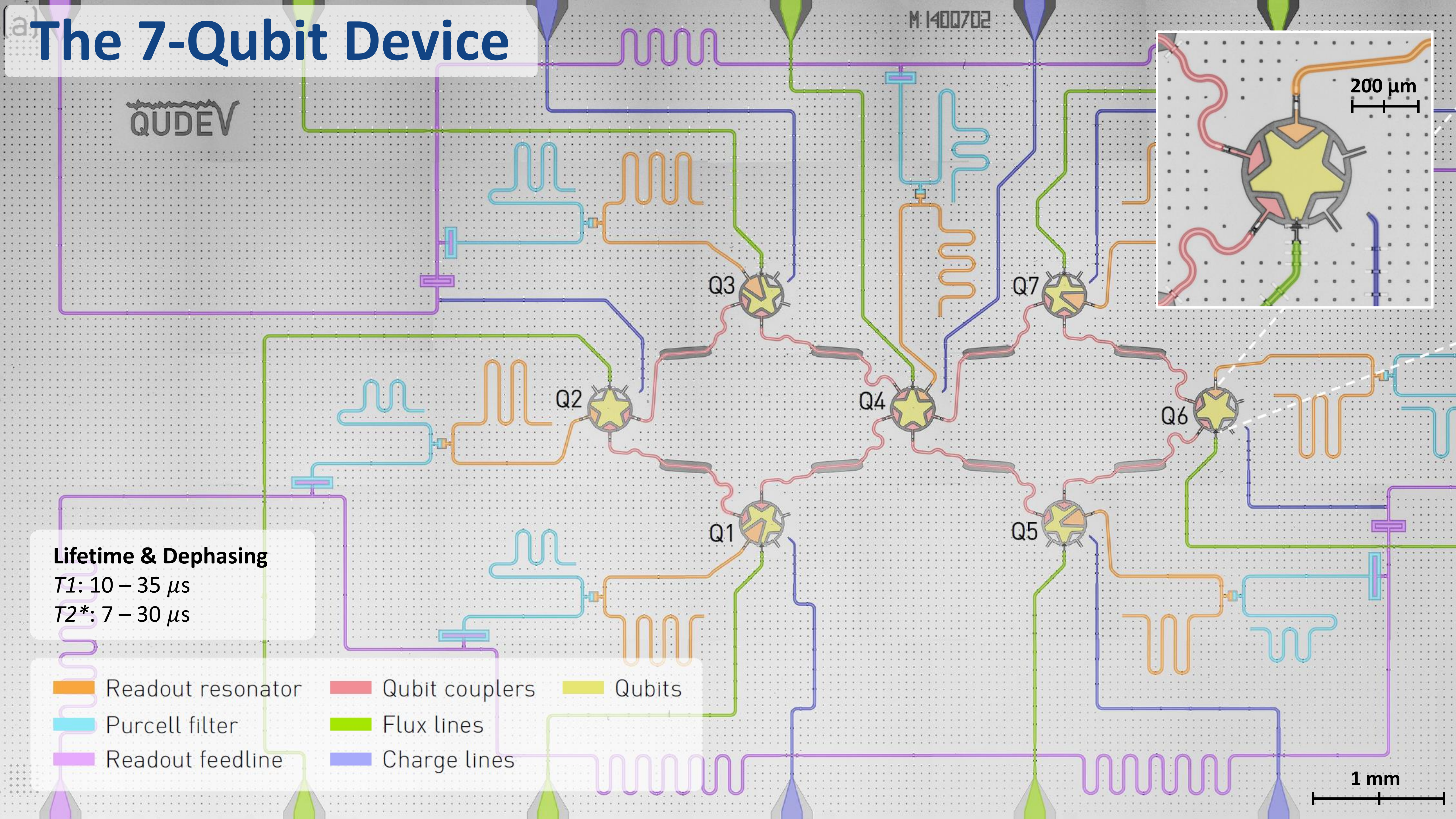
Quantum Convolutional Neural Networks, Cong et al., Nat. Phys. (2019)

The device

Superconducting Quantum Processor

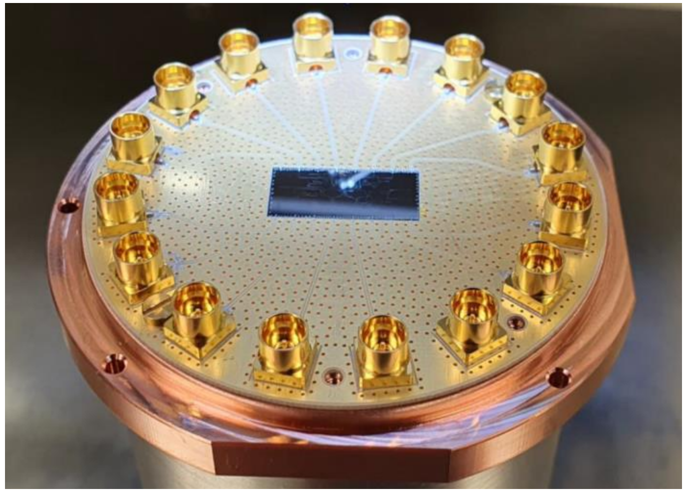
Barcelona Supercomputing Center
Centro Nacional de Supercomputación

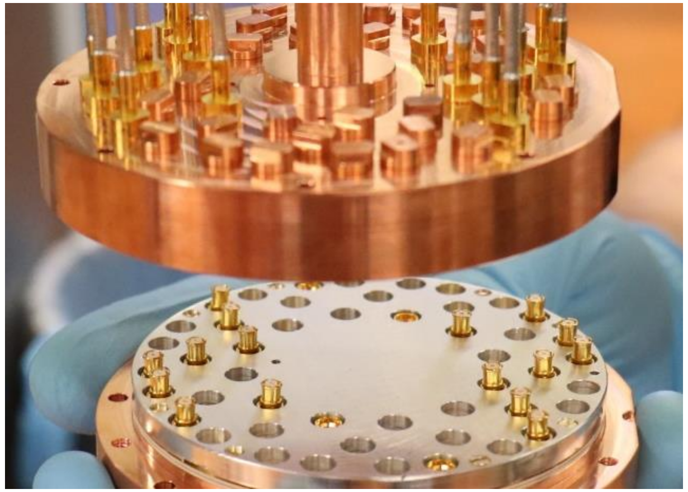
The 7-Qubit Device

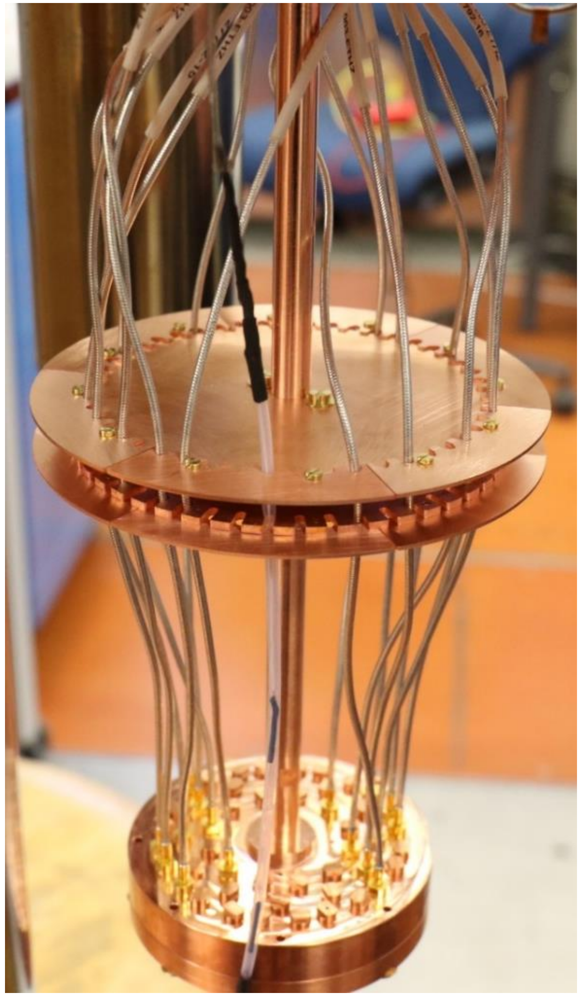


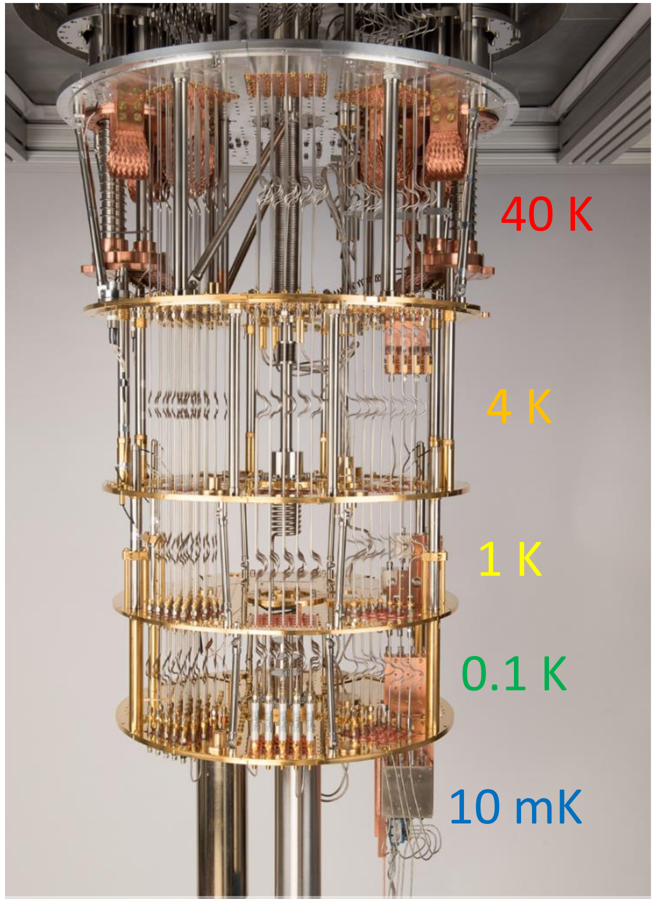
Lifetime & Dephasing
T1: 10 – 35 μs
*T2**: 7 – 30 μs

Cryogenic setup for superconducting qubits







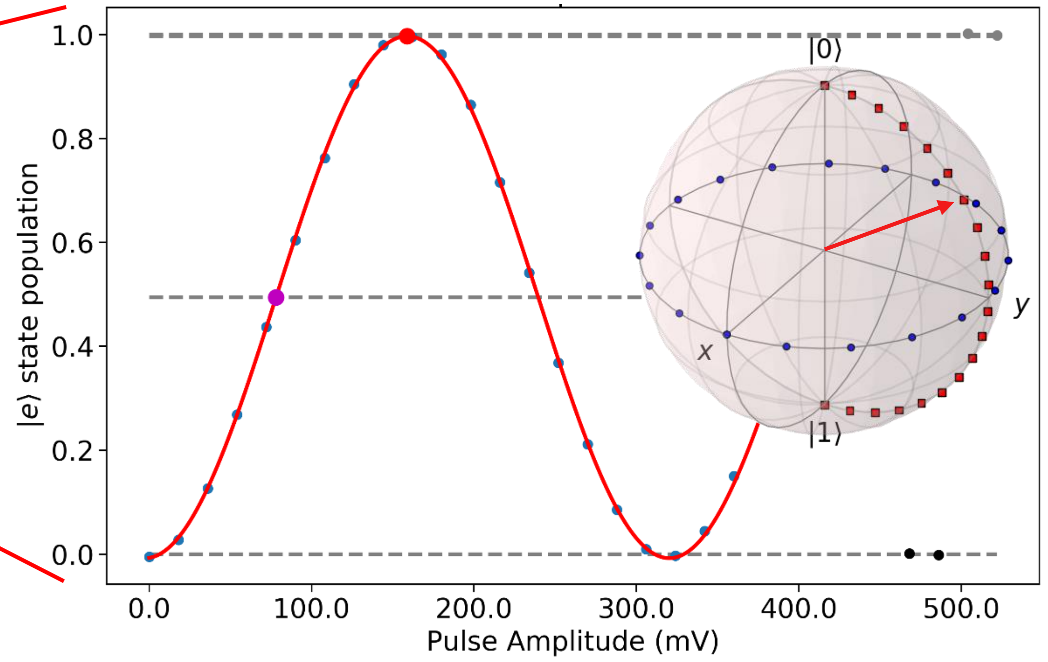


[1] Suppress thermal excitations:
$\hbar\omega_{ge} \ll k_B T$ (6 GHz $\leftrightarrow$ 300 mK)

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

[1] Krinner et al., EPJ Quantum Technology (2018)

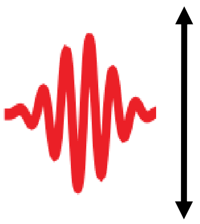
Single & Two Qubit Gate Control



- Required qubit connectivity is 1D linear chain
- **Single qubit** error from randomized benchmarking

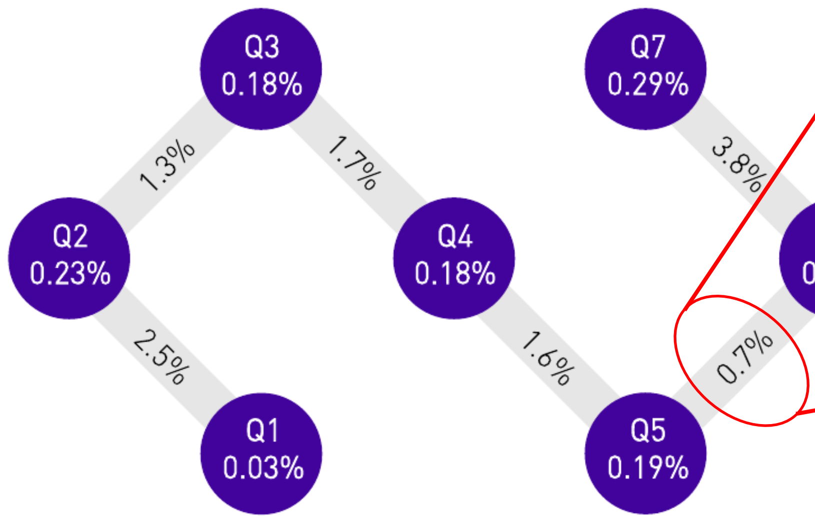
Single Qubit Control:

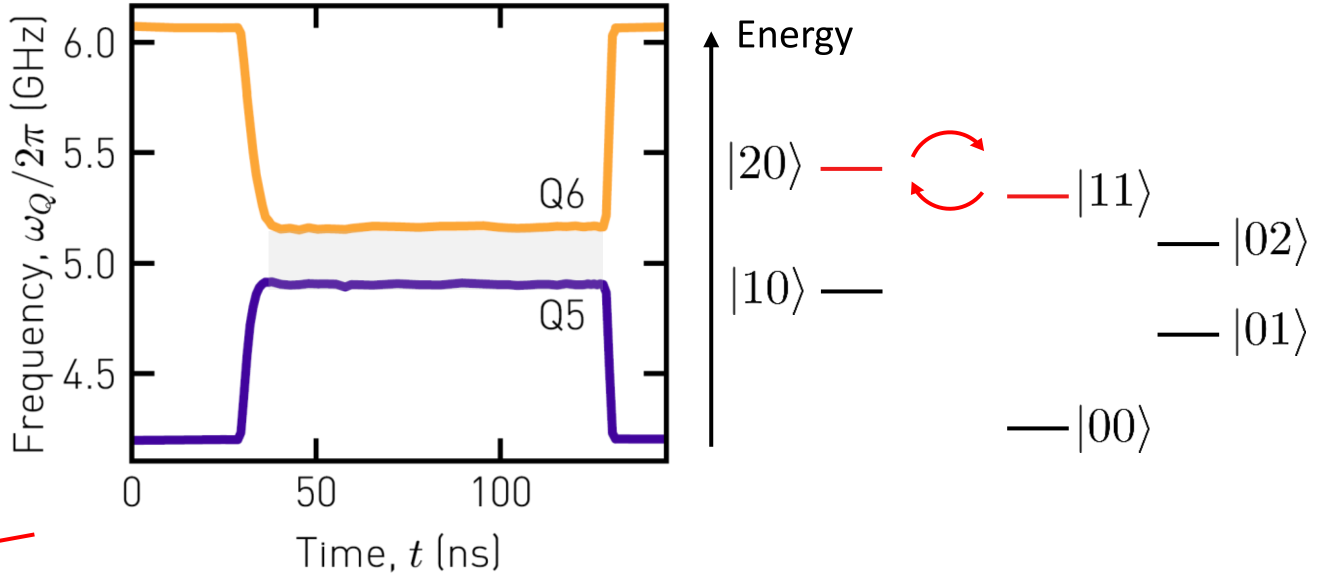
- Via microwave pulses (50 ns length) [1]
- Scale pulse amplitude linearly to implement arbitrary $R_y(\theta_i)$ rotation



[1] Motzoi *et al.* *PRL* 103, 110501 (2009)

Single & Two Qubit Gate Control





Two Qubit CZ Gate:

- Implemented via dc-flux pulses bringing $|11\rangle \leftrightarrow |20\rangle$ [1, 2]
- Both qubits are fluxed to reach interaction frequency
  - Flexible choice of interaction frequency

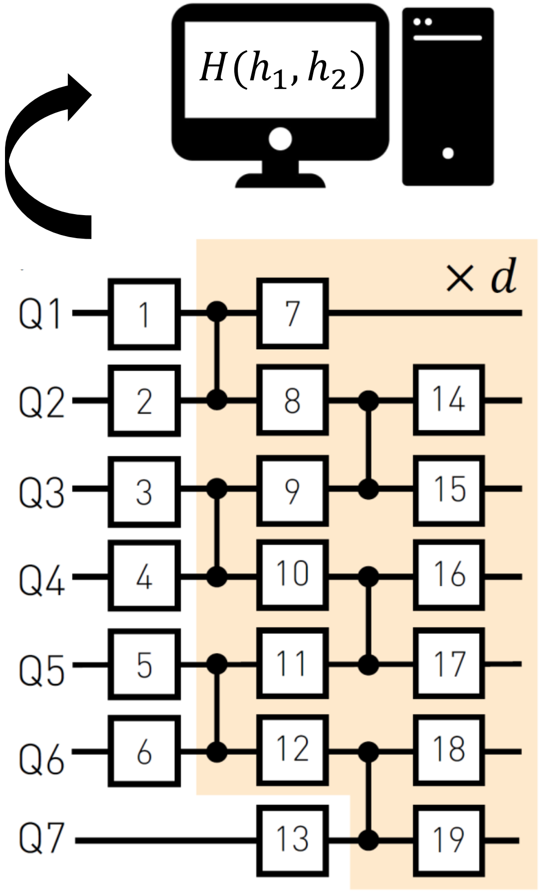
- Required qubit connectivity is 1D linear chain
- **Single qubit** error from randomized benchmarking
- **Two qubit CZ** error, from quantum process tomography
  - Measured Chi-Matrices reused for simulation

[1] Strauch *et al. PRL* 91, 167005 (2003), [2] DiCarlo *et al. Nature* 460, 240 (2009)

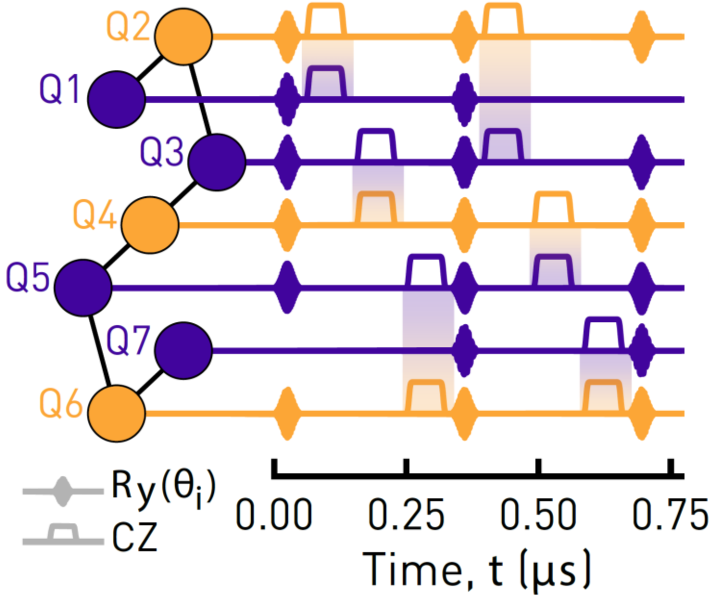
The outcome
Experimental results

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

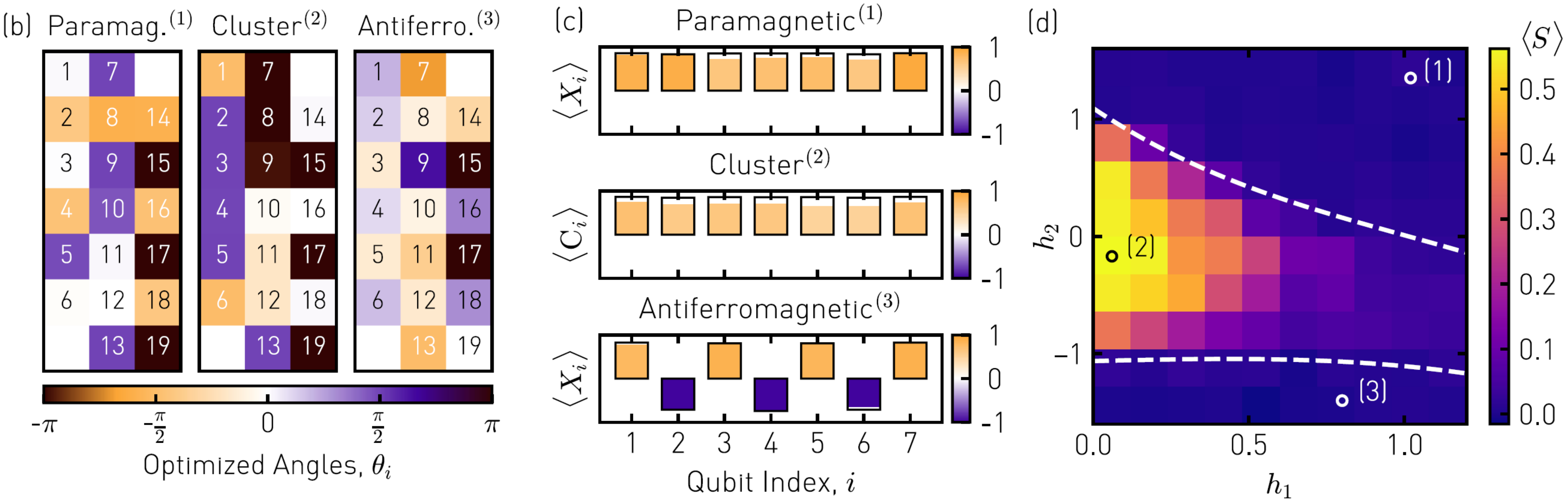
Variational ground state preparation



Compile pulse sequence and run on quantum device



Characterization of exp. prepared Variational Ground



- Examples for optimized set of rotation angles
- Exploit symmetries in state preparation circuit to mitigate effect of T1 decay [1]

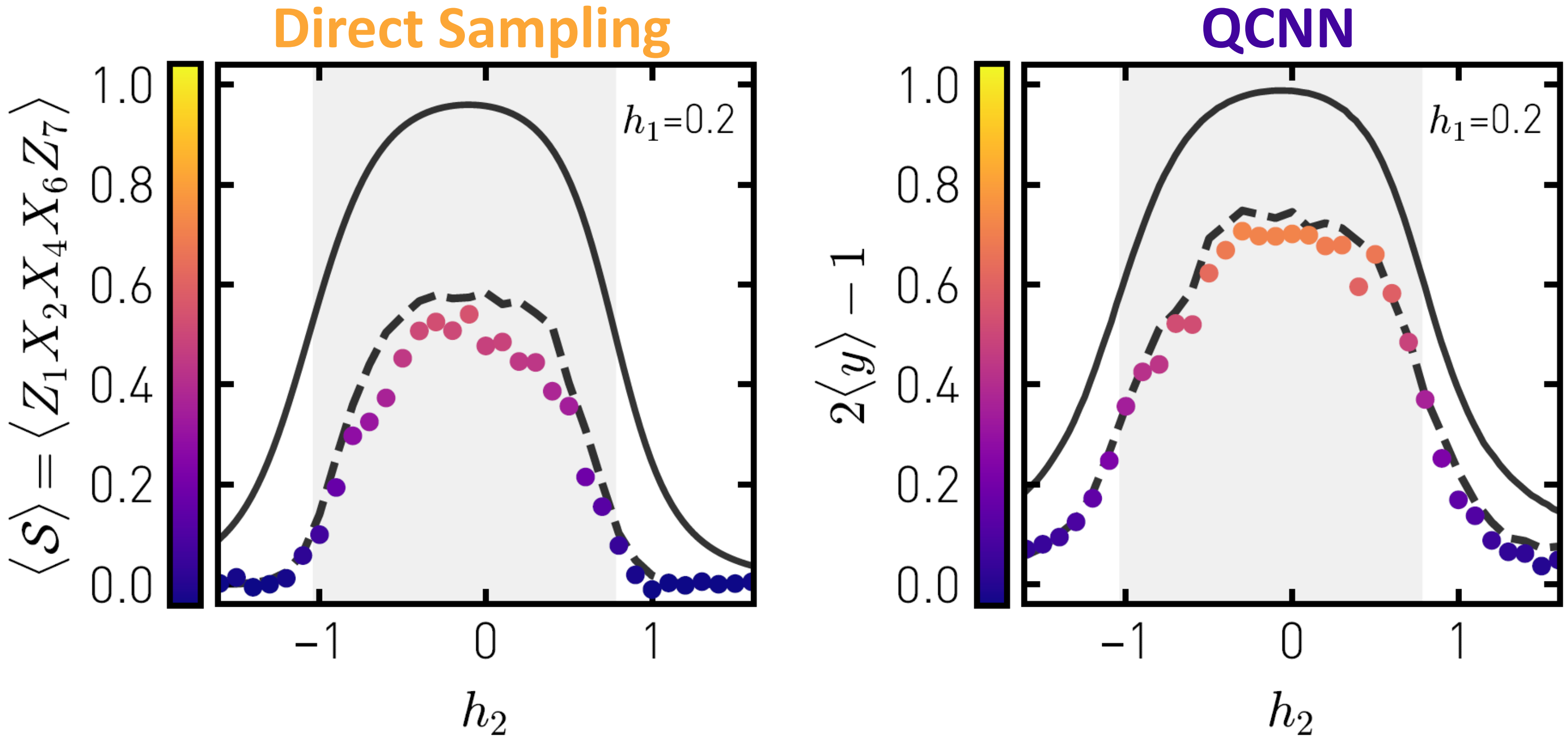
- Paramagnetic (antiferromagnetic) phases exhibit finite local $\langle X_i \rangle$ with identical (toggling) sign
- Cluster phase characterized by finite $\langle C_i \rangle = \langle Z_{i-1} X_i Z_{i+1} \rangle$ correlations

- Measured phase diagram showing the measured $\langle S \rangle$ in good agreement with theoretically expected one
- Reduced contrast due to finite state preparation fidelity

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

[1] Fontana et al., arXiv:2011.08763 (2020)

Comparison between Direct Sampling and QCNN



Measure S across phase boundaries

- Output of QCNN and directly sampled SOP both follow the simulation (dashed line).
- Reduced contrast compared to ideal value (solid line) due to finite error probability
- QCNN achieves higher contrast due to error correcting capability

BSC Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Realizing Quantum Convolutional Neural Networks on a Superconducting Quantum Processor to Recognize Quantum Phases, Herrmann, Masot-Llima et al. (2021)

Conclusions and outlook

Barcelona
Supercomputing
Center
Centro Nacional de Supercomputación

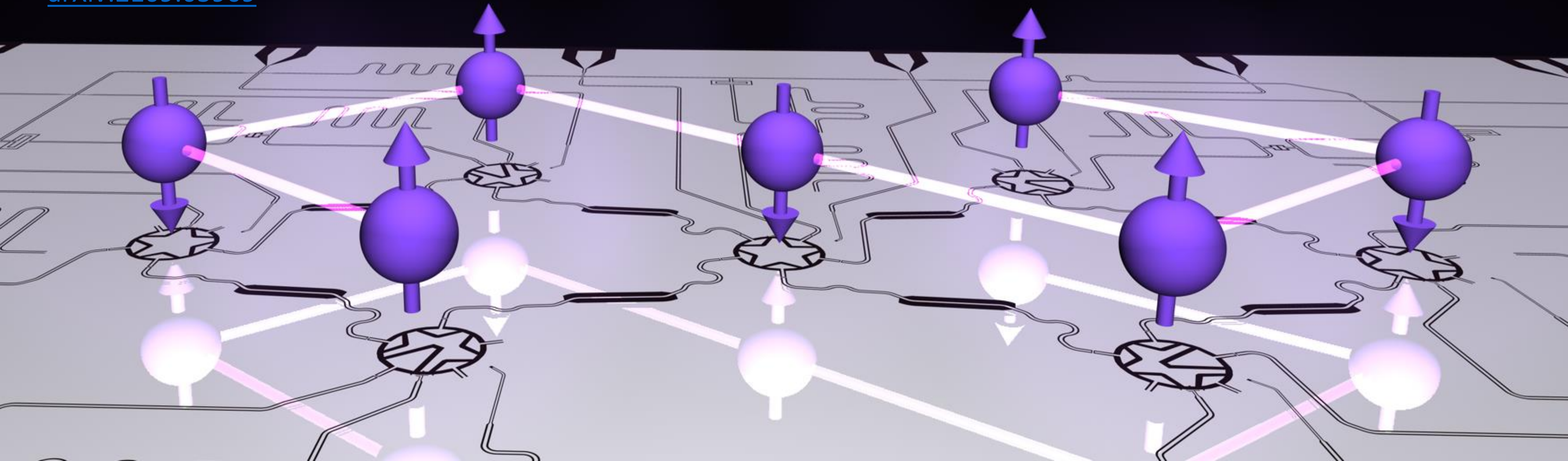
Achieved

- Built and operated a programmable 7Q quantum processor to demonstrate …
  - … the preparation of a topological quantum phase
  - … a Quantum Convolutional Neural Network to recognize topological order

arXiv:2109.05909

Next steps Quantum Neural Networks

- Use larger system size to study sampling efficiency near phase boundary in dependence on depth of QCNN
- Explore trainability of parametrized QCNN
- Applications beyond quantum phase recognition (eg. in Quantum Error Correction)



Thank you for your attention!

arXiv:2109.05909