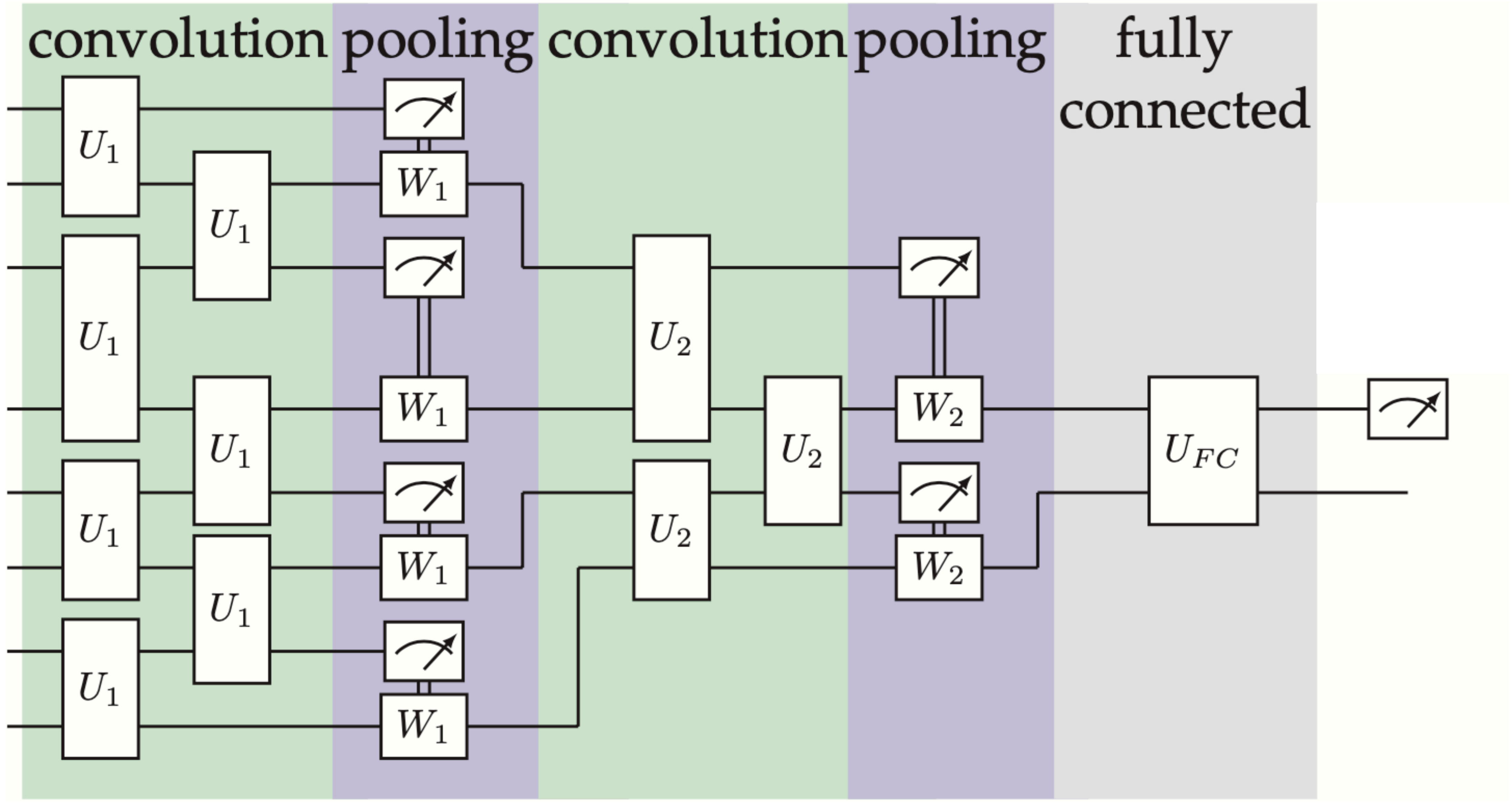
Quantum convolutional neural networks for the recognition of many-body topological phases of matter

Petr Zapletal



Munich Quantum Valley
University of Erlangen-Nuremberg
FAU
Universität Basel

MARIE CURIE ACTIONS
Funded by the European Union

Quantum machine learning

Quantum computers to recognize patterns in large data

Promising application for near-term quantum computers

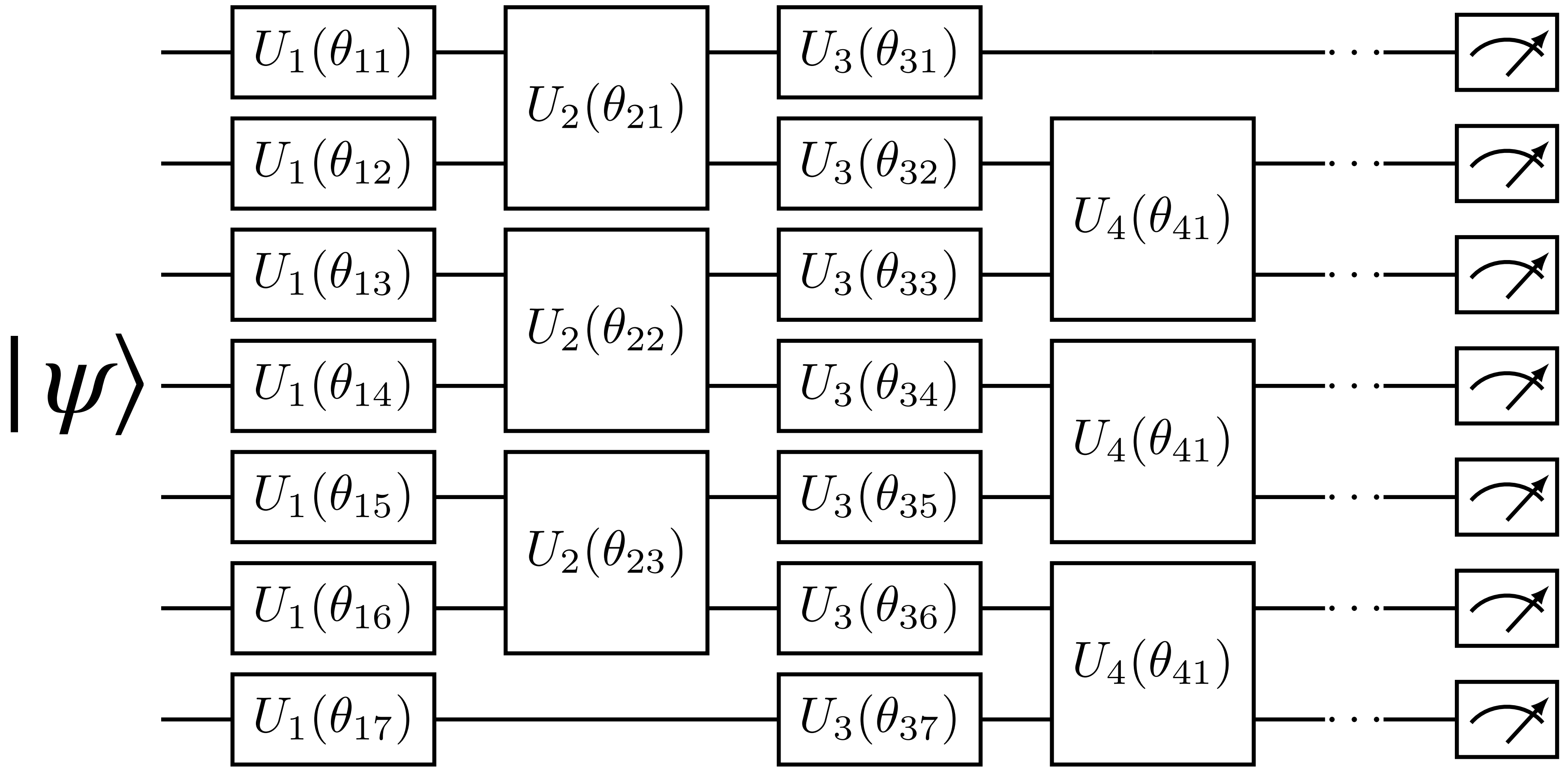
Biamonte et al., Nature **549**, 195 (2017)

Parametrized quantum circuits

Cost function - task specification

Measurement and classical optimization

Variational quantum algorithms



Cost function:

$$C = \langle H(\vec{\alpha}) \rangle$$

$$\vec{\theta} \rightarrow \vec{\theta} - \eta \nabla C$$

Cerezo et al., Nat Rev Phys **3**, 625 (2021)

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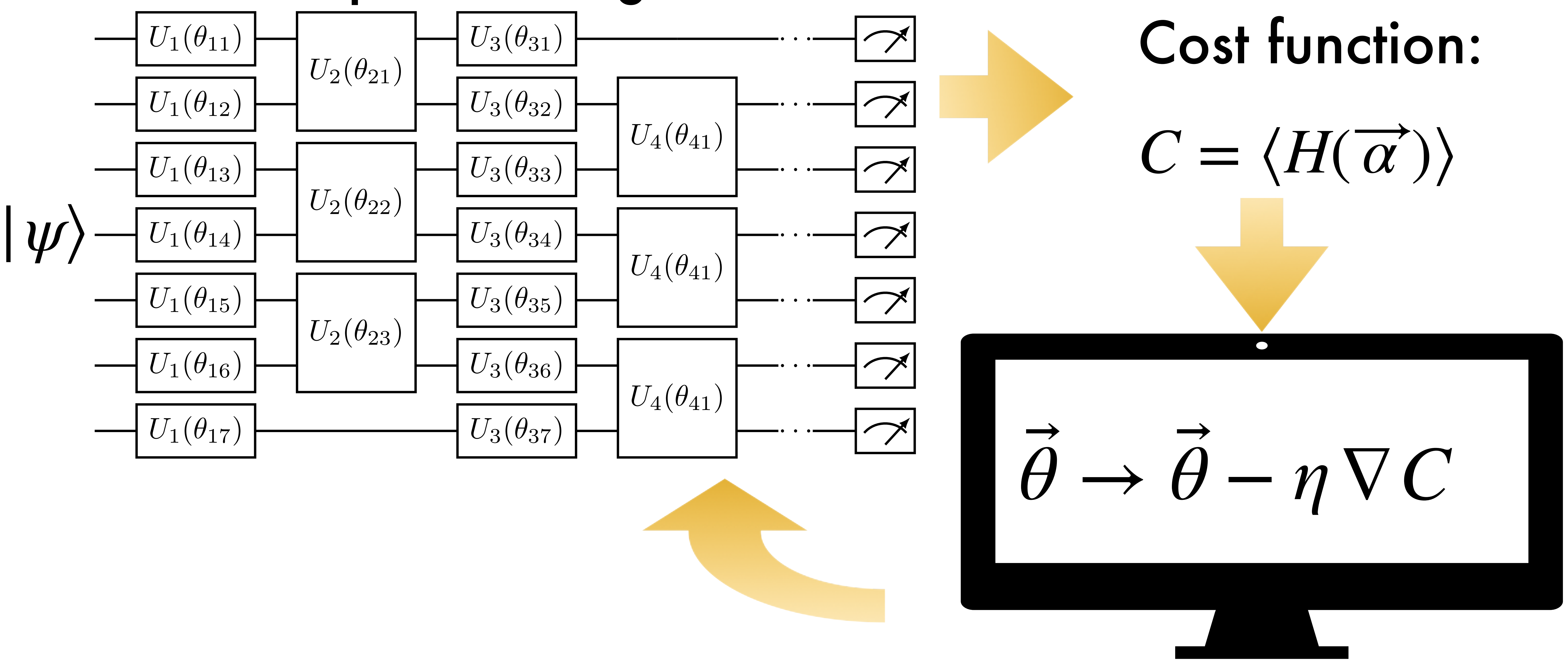


Quantum data:

States $|\psi\rangle$ produced by quantum algorithms

Native (no encoding)

Characterization tools for scalable quantum computers

Robust against errors on near-term quantum devices

Cerezo et al., Nat Rev Phys **3**, 625 (2021)

Characterization of quantum states

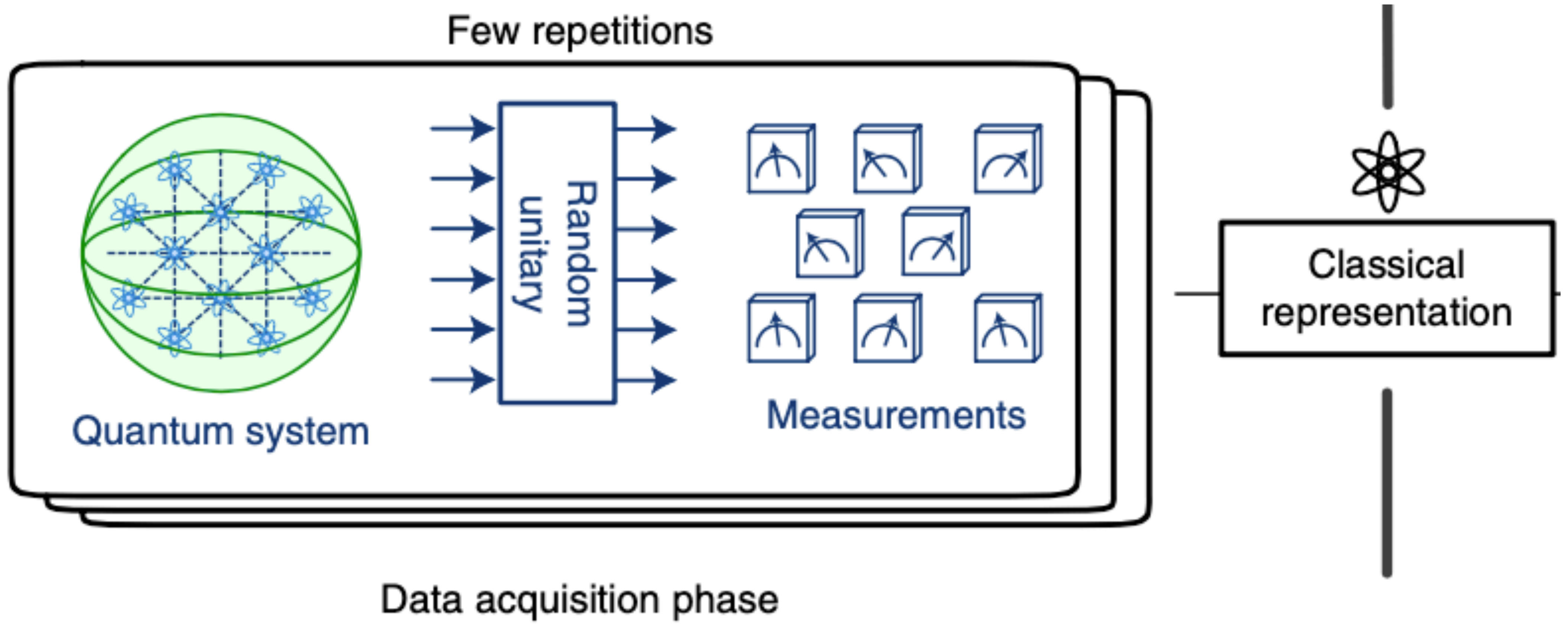
Sample complexity: number of state copies to determine an observable/characteristic

Quantum state tomography

- Sample complexity $\sim e^N$

Classical shadows: randomized measurements

- Efficient for k-local observables
- Sample complexity $\sim e^k$



Huang et al., *Nat Phys* **16**, 1050 (2020)

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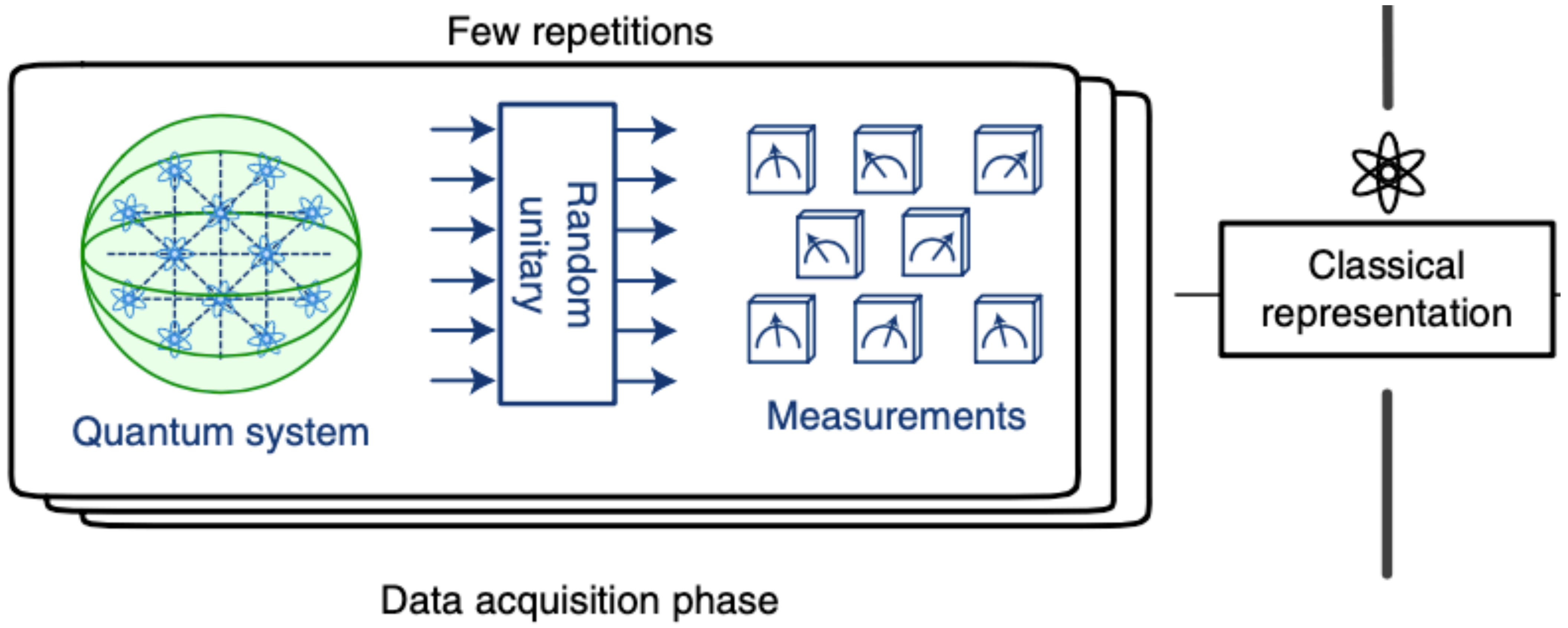
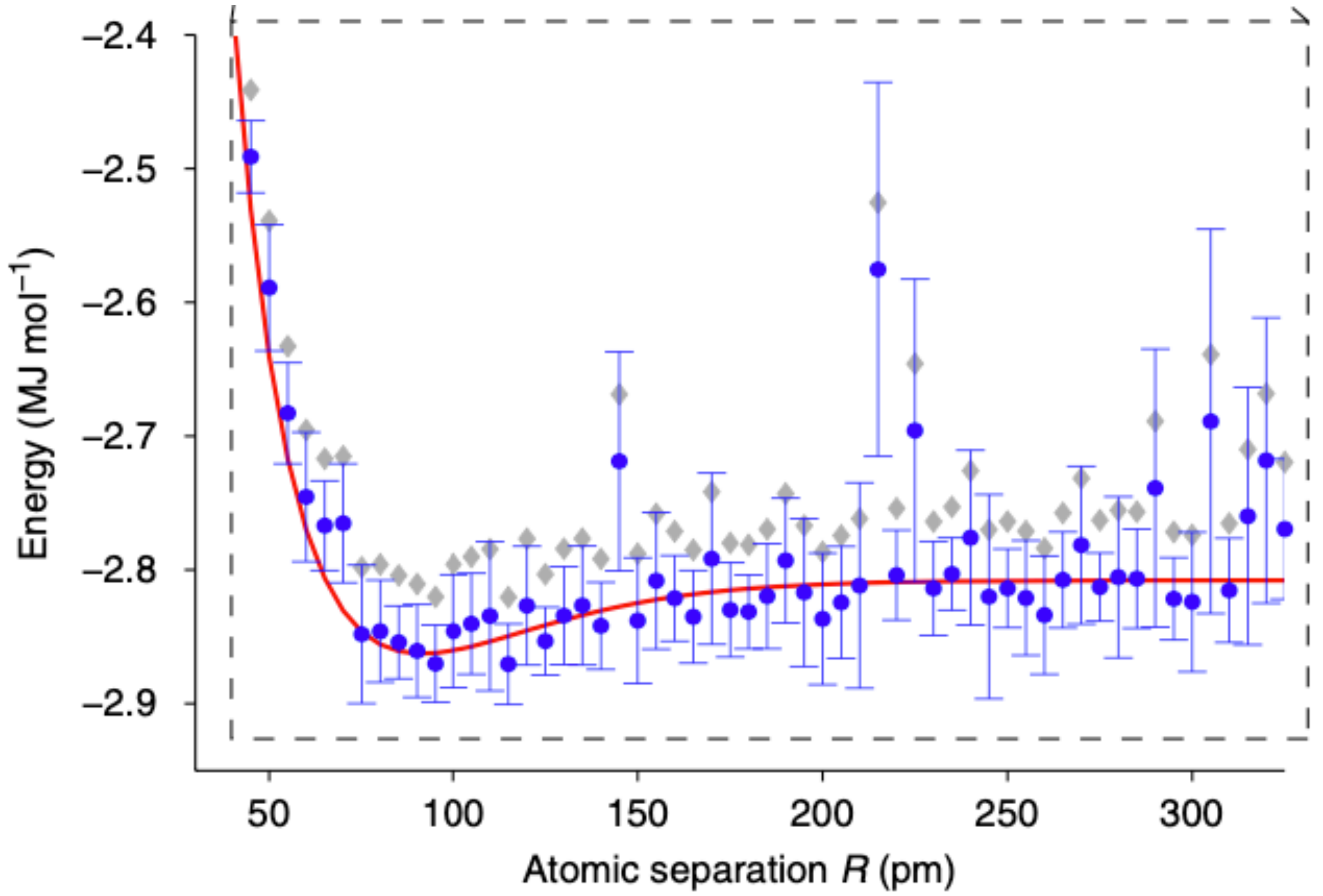
Variational quantum eigensolver

- VQA for GS of many-body Hamiltonians
- Quantum chemistry - fermion-to-qubit mapping
- Sample complexity $\sim N^4$



Huang et al., *Nat Phys* **16**, 1050 (2020)



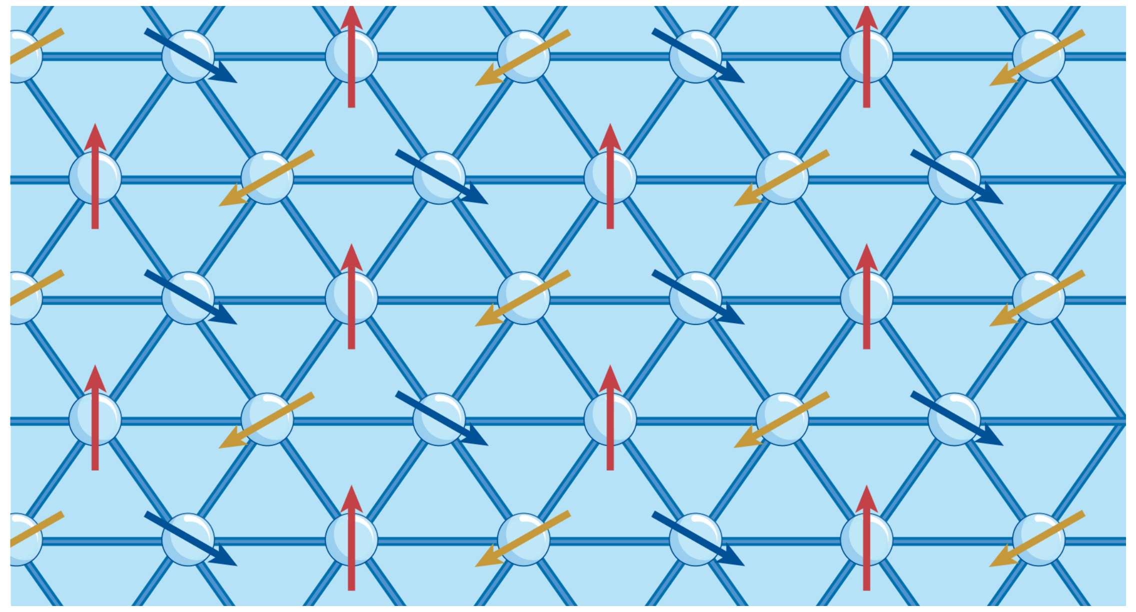
Peruzzo et al. *Nat Commun* **5**, 4213 (2014)

Quantum phases of matter

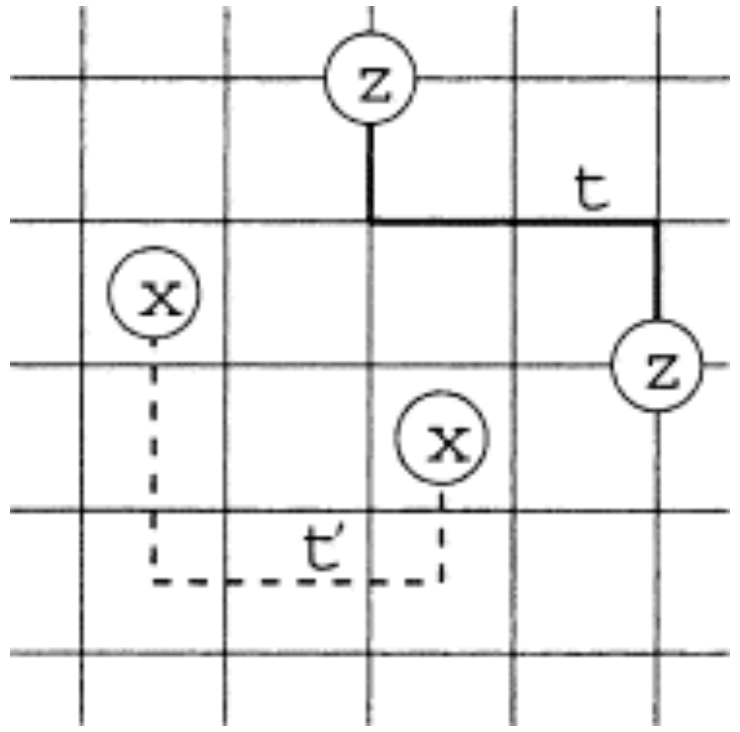
Topological ordered: at zero temperature

- Non-local quantum correlations
- Invariant under local transformations

Spin liquids
Kivelson et al. Nat Rev Phys **5** 368 (2023)



Toric code: Kitaev, Ann Phys **303** 2 (2003)



Symmetry-protected top. order: Chen et al., PRB 83 035107 (2011)

Hard to simulate:
Exponential growth of Hilbert space

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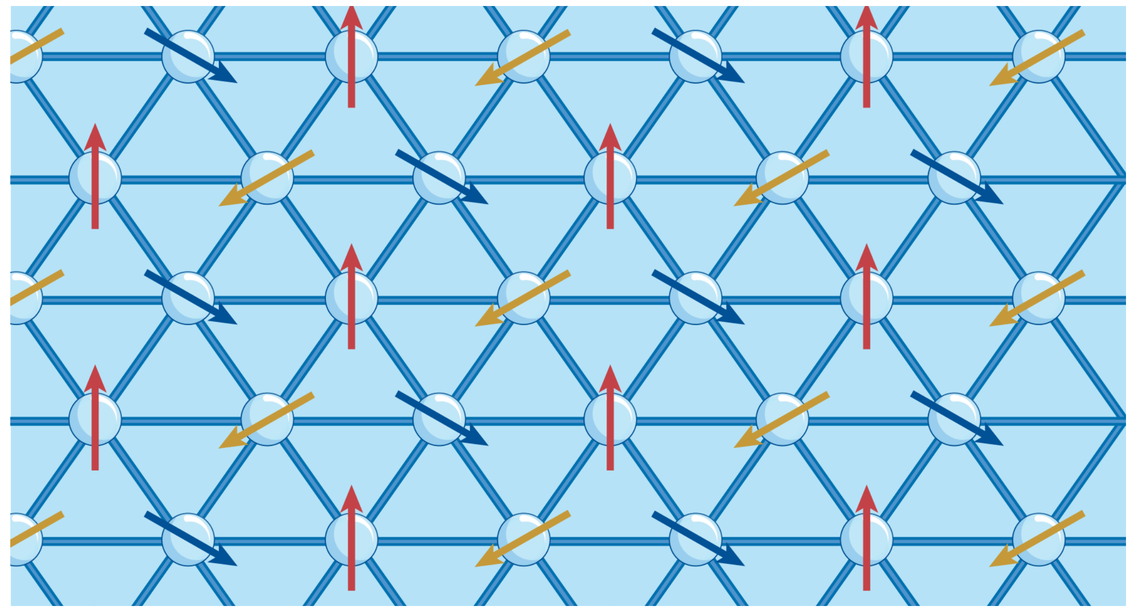

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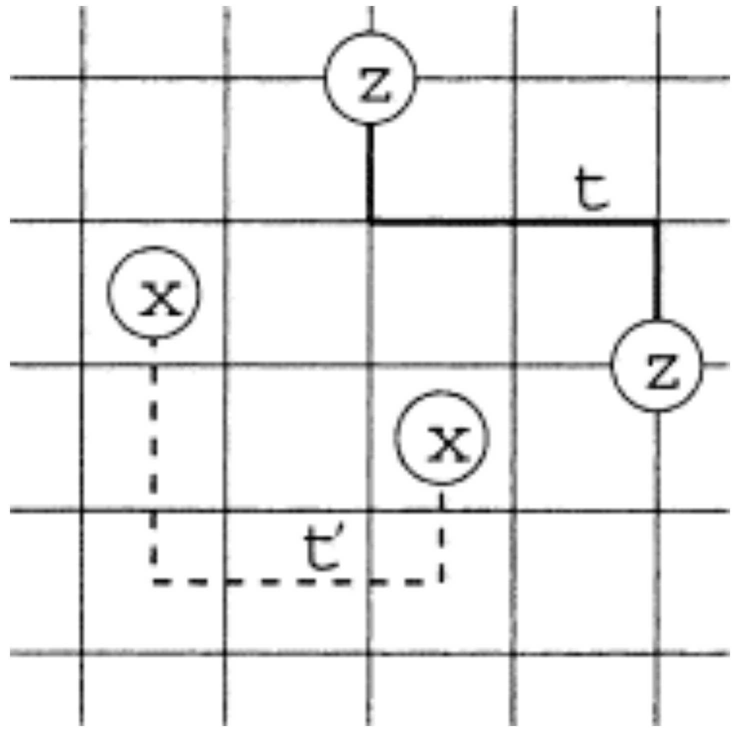

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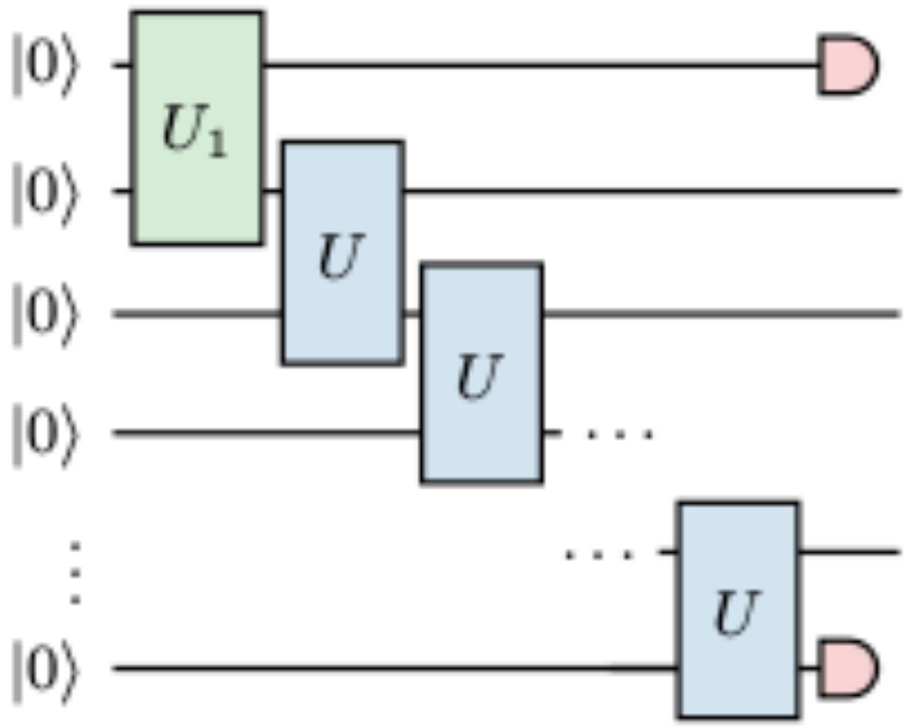
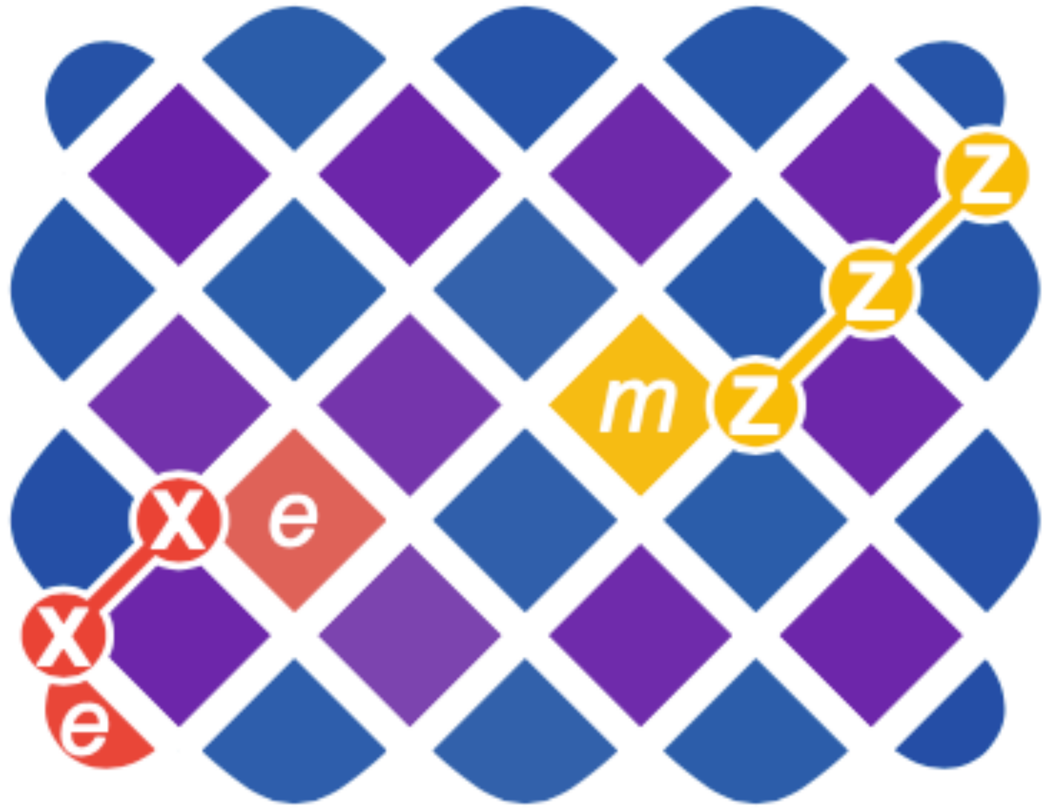
Quantum computers

Symmetry-protected and intrinsic topological order



Smith et al., PRR **4** L022020 (2022)



Satzinger et al., Science **374** 1237 (2021)

Quantum phases of matter

Topological ordered: at zero temperature
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Spin liquids
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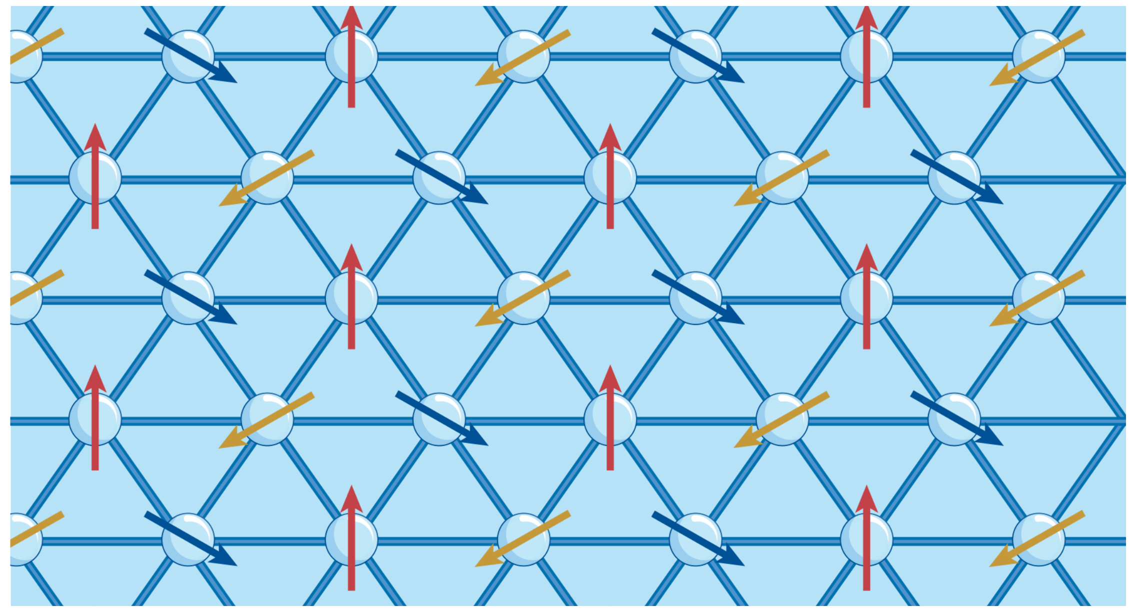

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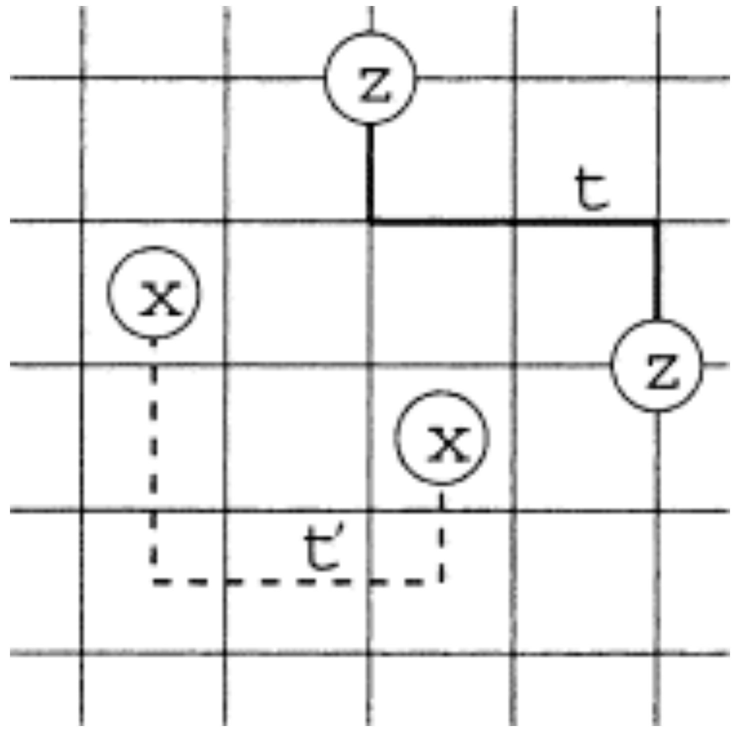

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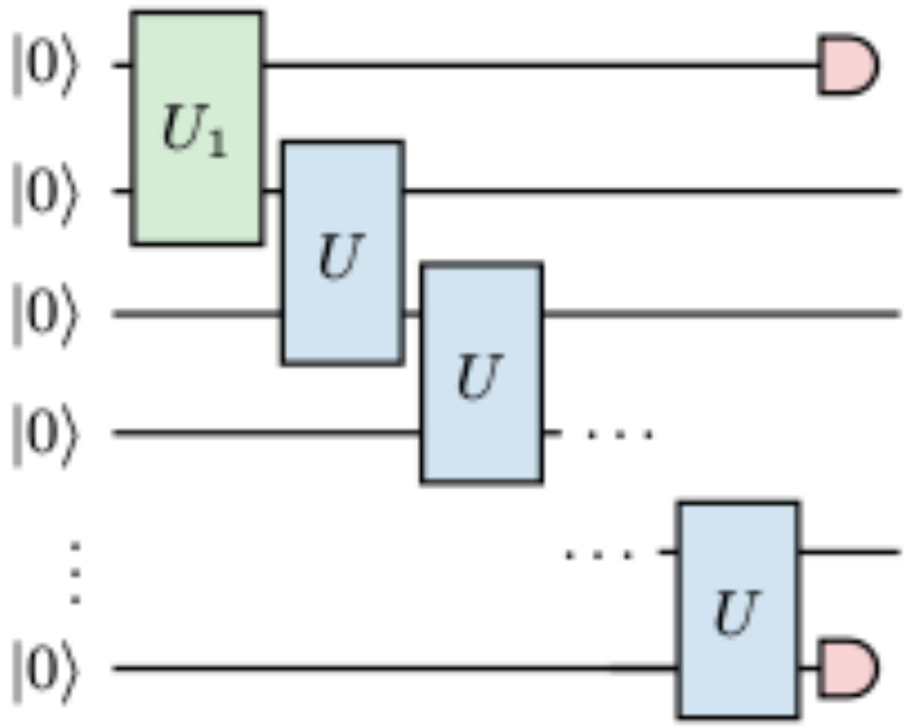
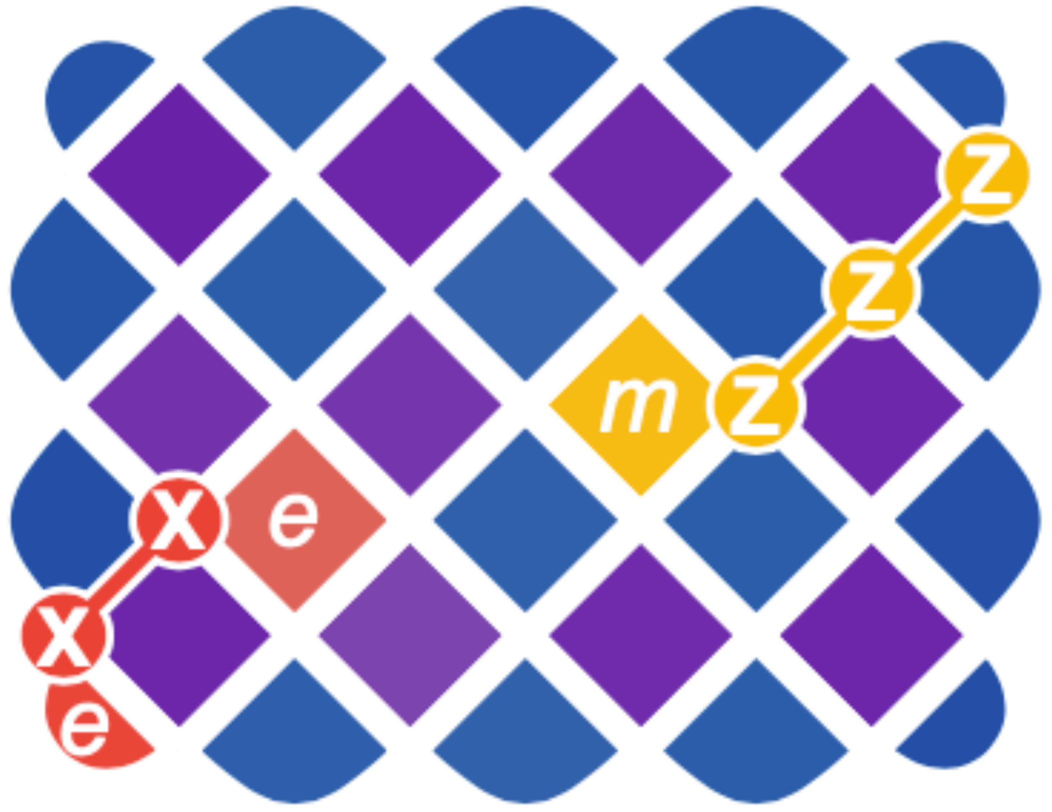


Smith et al., PRR **4** L022020 (2022)

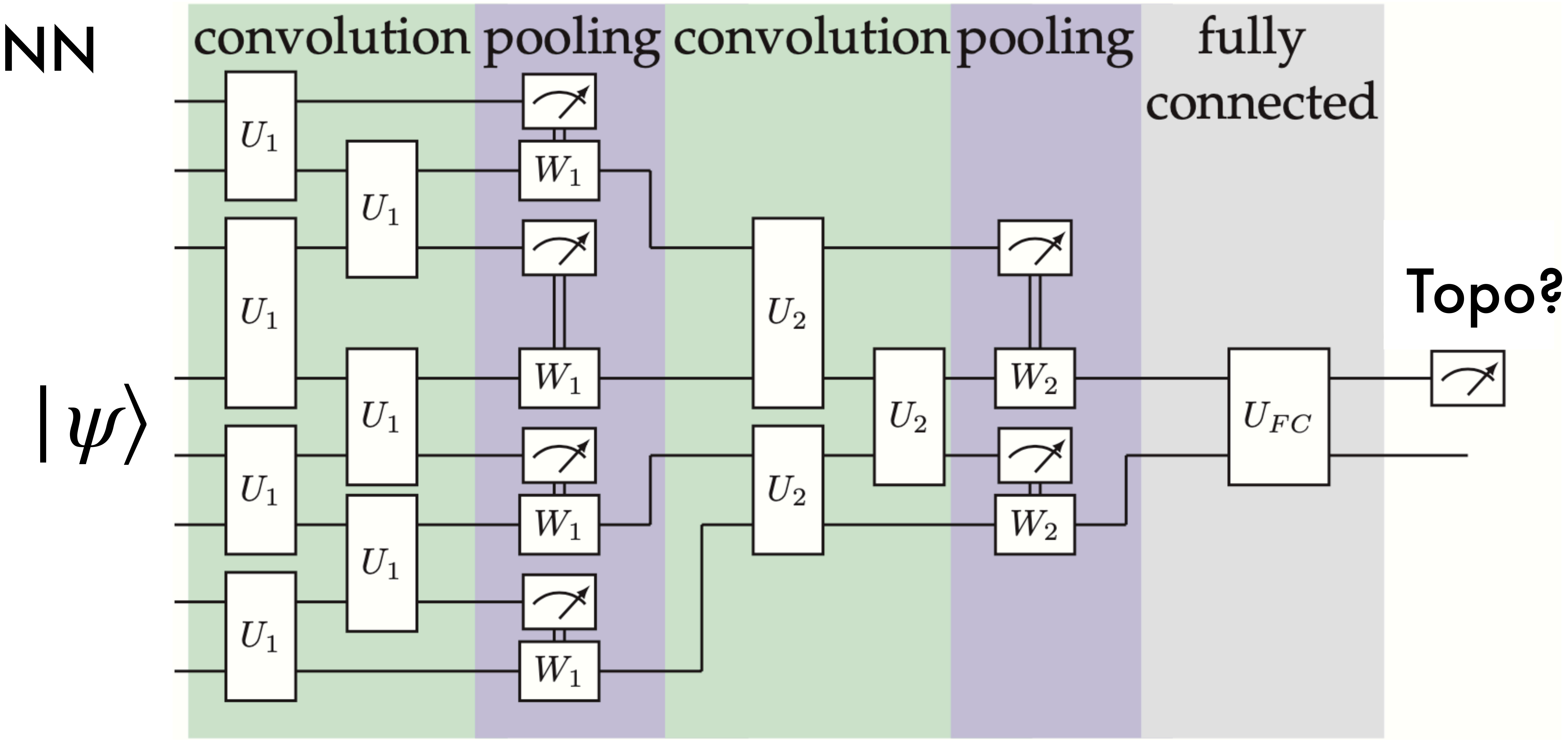


Satzinger et al., Science **374** 1237 (2021)

Quantum phase recognition:
- Quantum state $|\psi\rangle \longrightarrow$ quantum phase?
- No local order parameter
- Hard to measure fidelity, entanglement

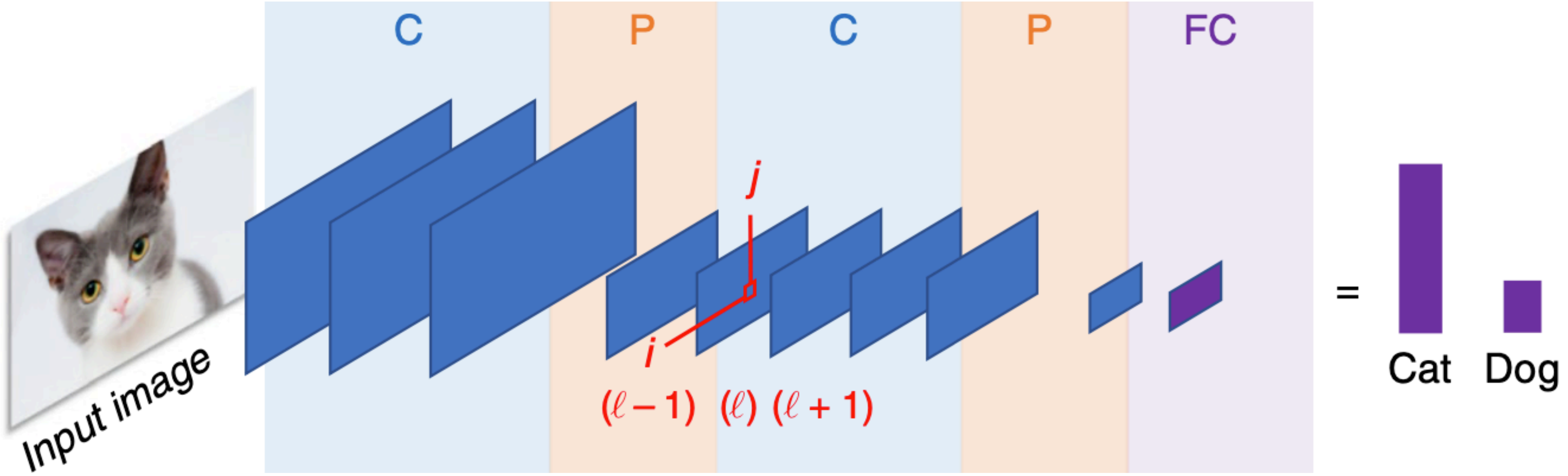
Quantum convolutional neural network

QCNN



- Parametrized quantum circuit
- Analogous to convolutional neural networks
- Qubits→neuron, Measurements→nonlinearity
- Recognizing phase of state $|\psi\rangle$

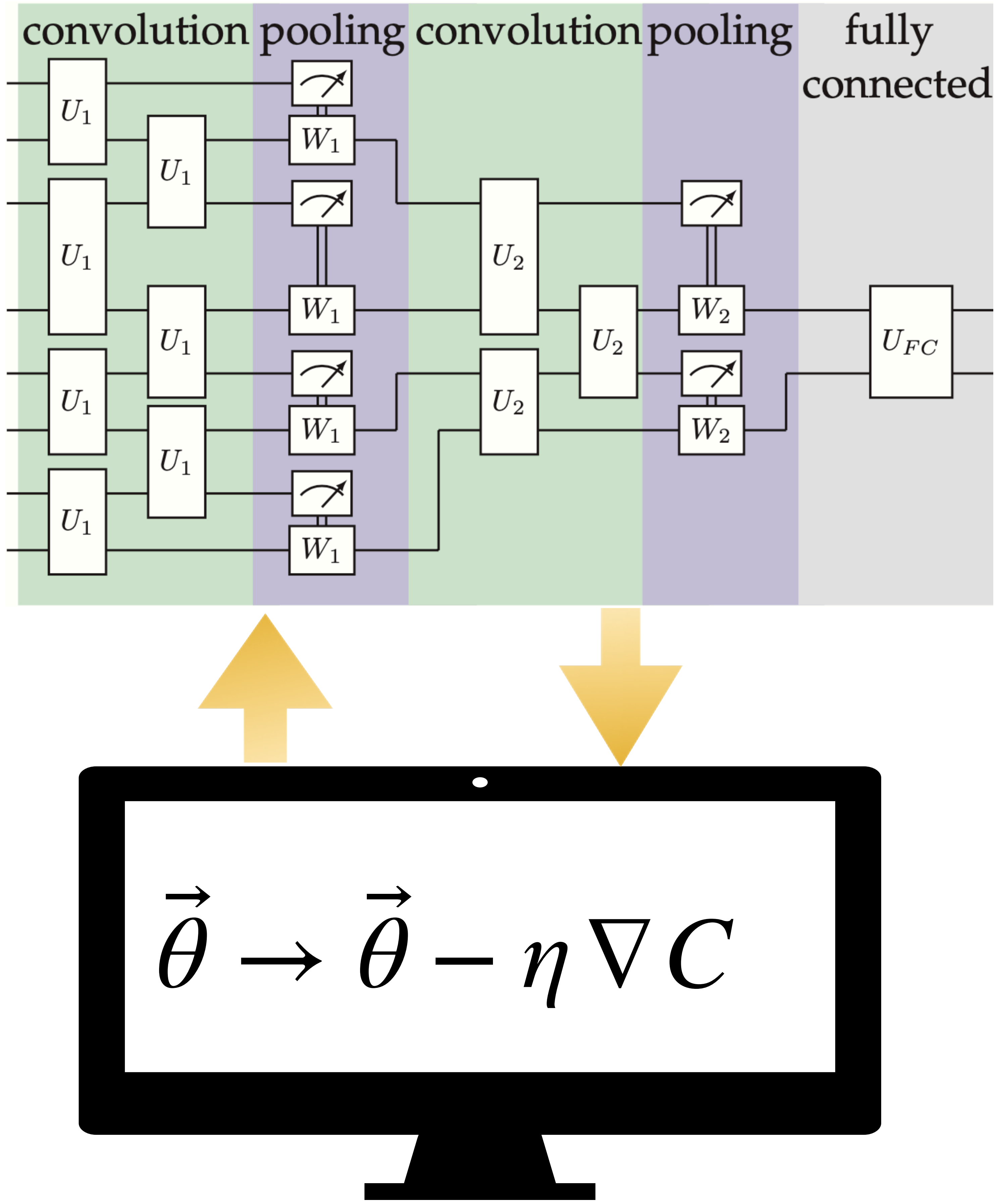
Convolutional neural networks



Cong et al., Nat Phys **15** 1273 (2019)

$\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry-protected topological phases

See my poster in SESSION A



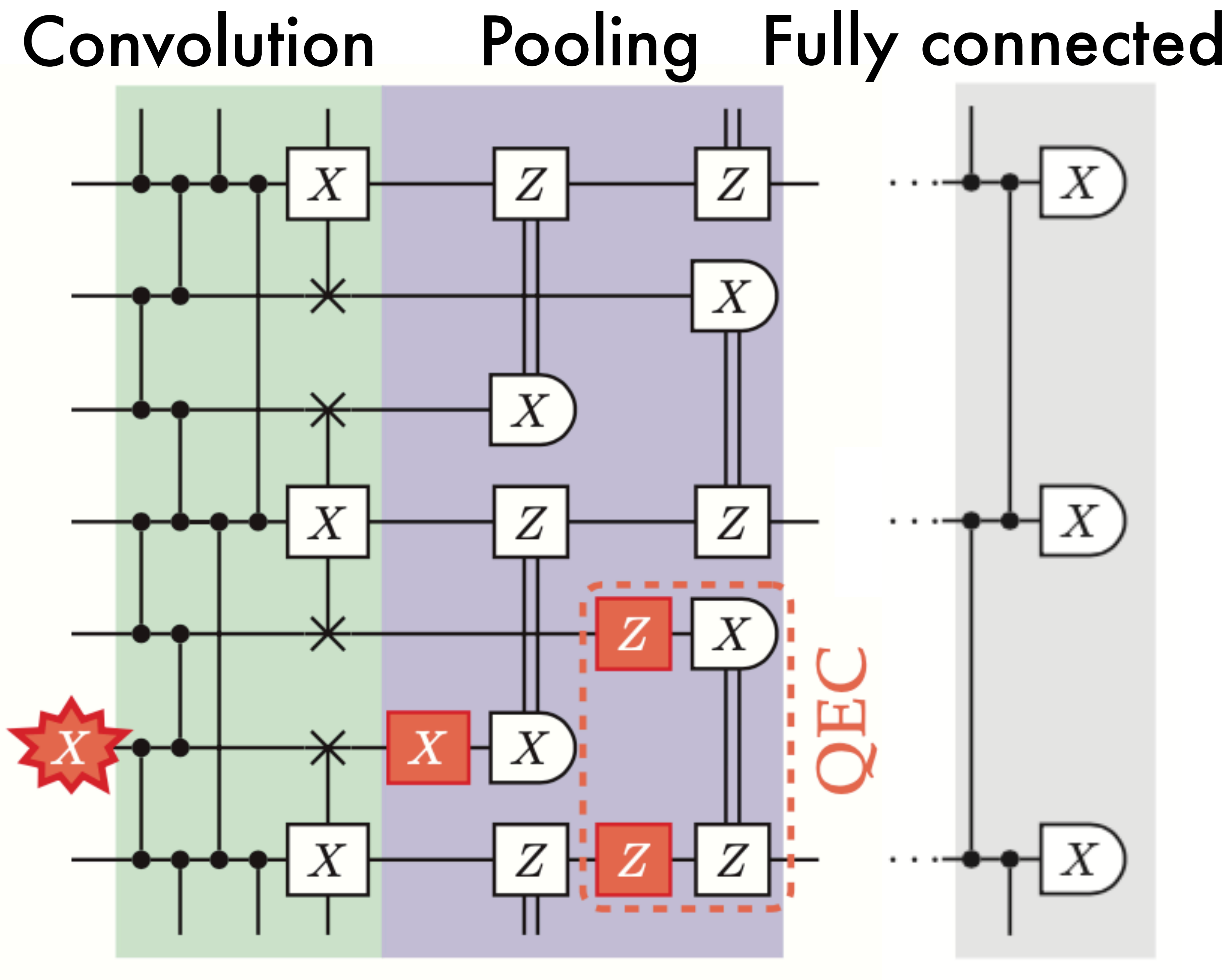
Variational optimization

e.g. supervised learning

Liu et al., PRL **130**, 220603 (2023)

$\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry-protected topological phases

See my poster in SESSION A



Explicit construction Cong et al.

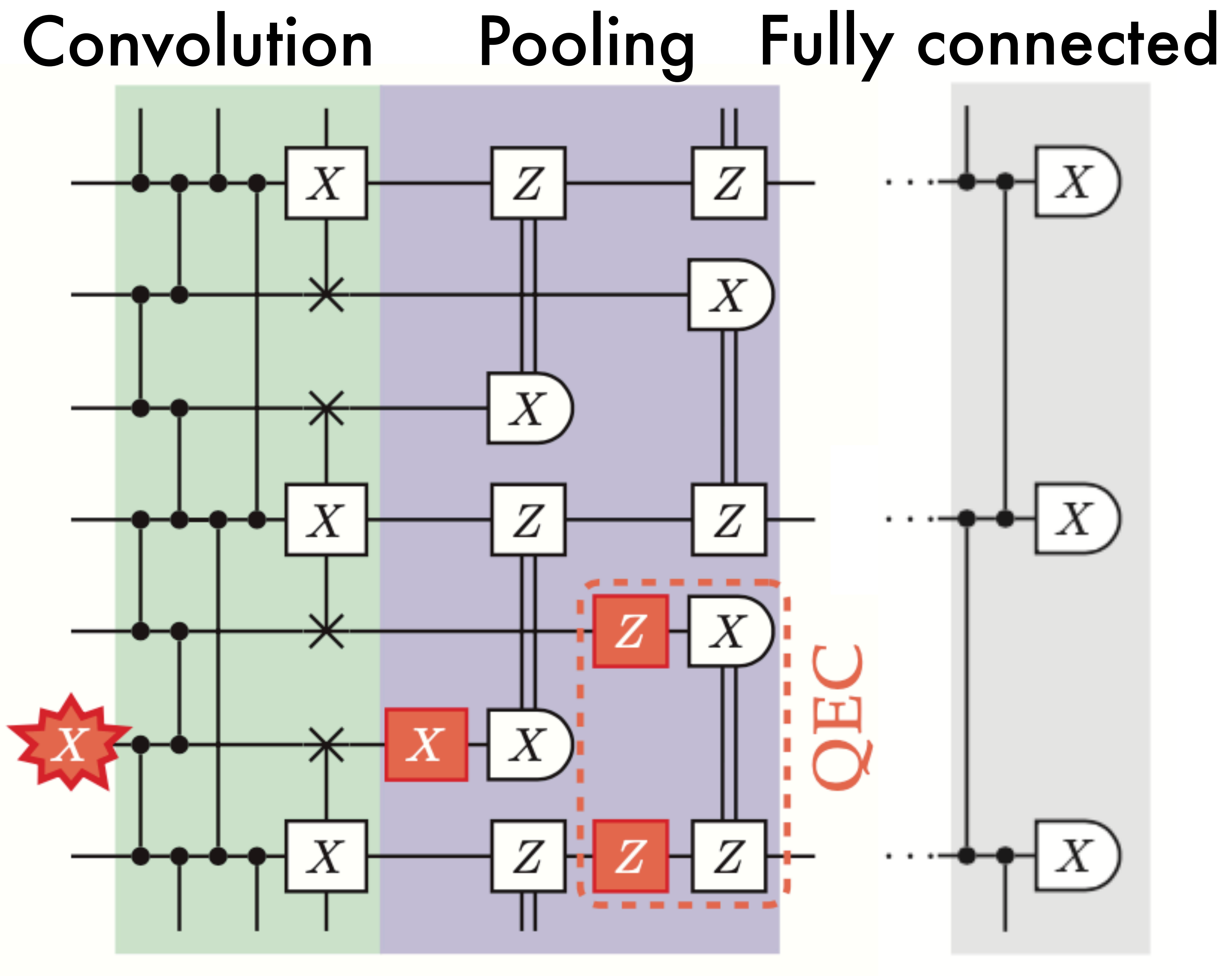
Renormalization group

Sachdev, *Quantum phase Transitions* (2011)

Quantum error correction

$\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry-protected topological phases

See my poster in SESSION A



Explicit construction Cong et al.

Renormalization group

Sachdev, *Quantum phase Transitions* (2011)

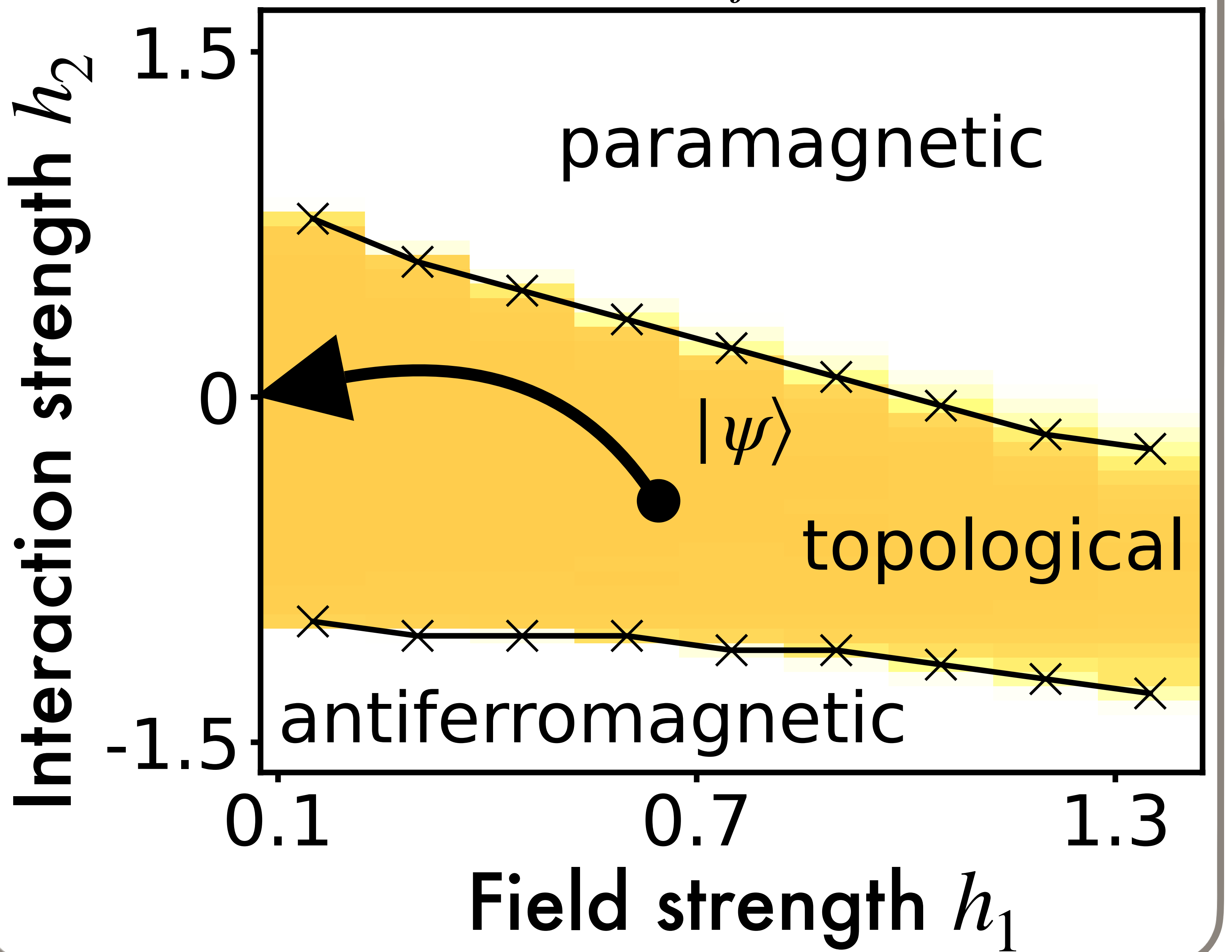
Quantum error correction

1D cluster-Ising model

$$H = -\sum_j Z_{j-1}X_jZ_{j+1}$$

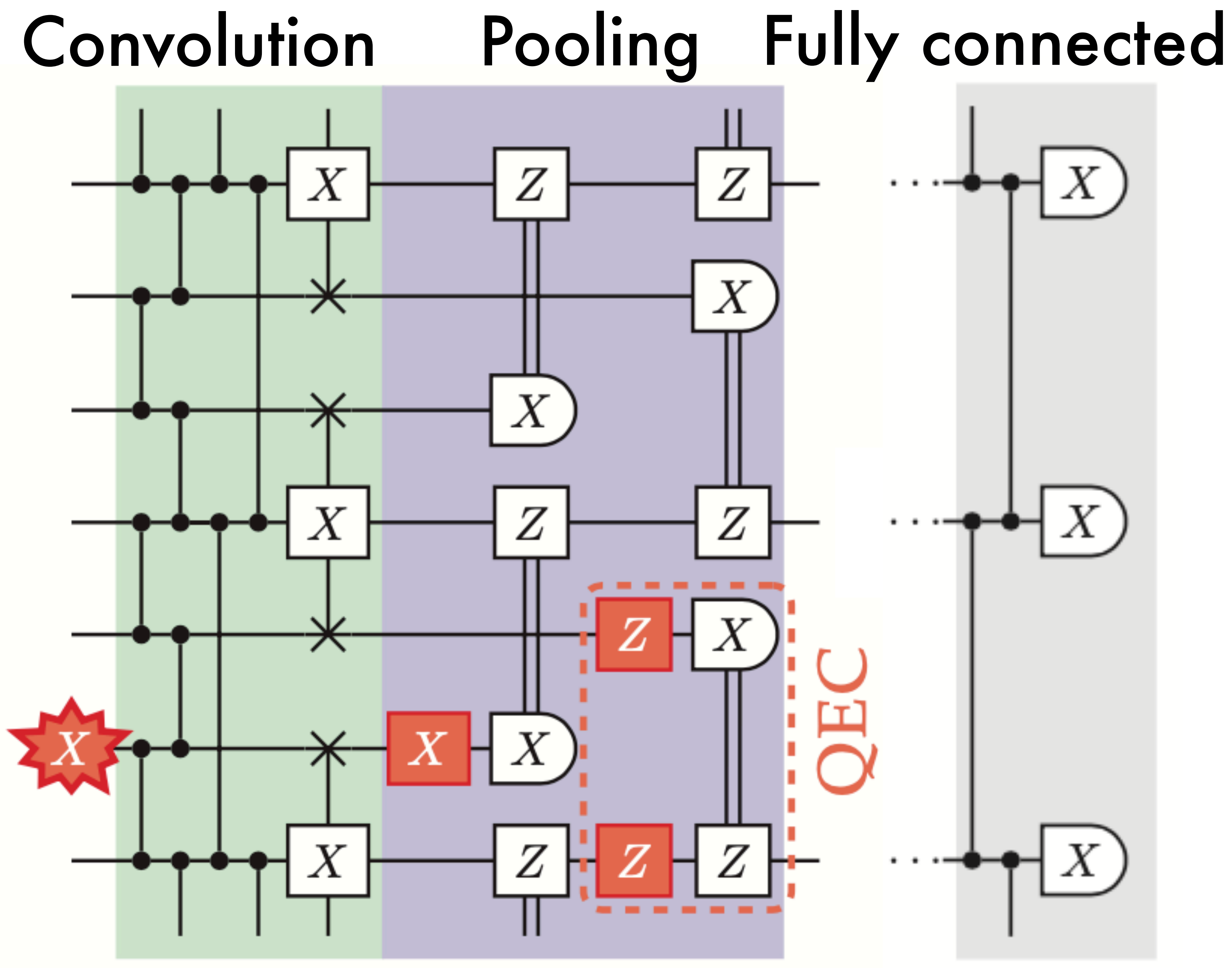
$$-h_1\sum_j X_j - h_2\sum_j X_jX_{j+1}$$

Symmetries $P_{e/o} = \prod_j X_{2j/2j+1}$



$\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry-protected topological phases

See my poster in SESSION A



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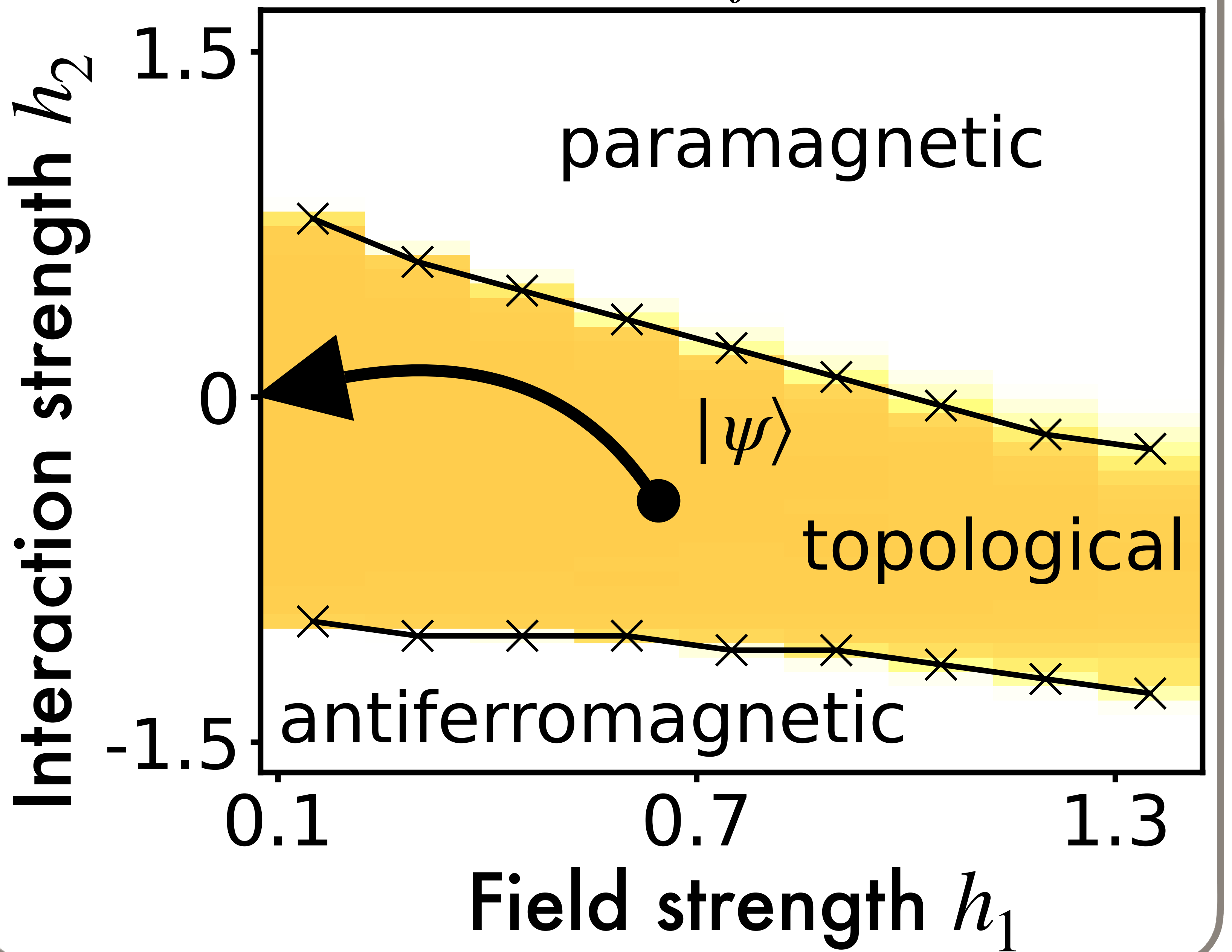

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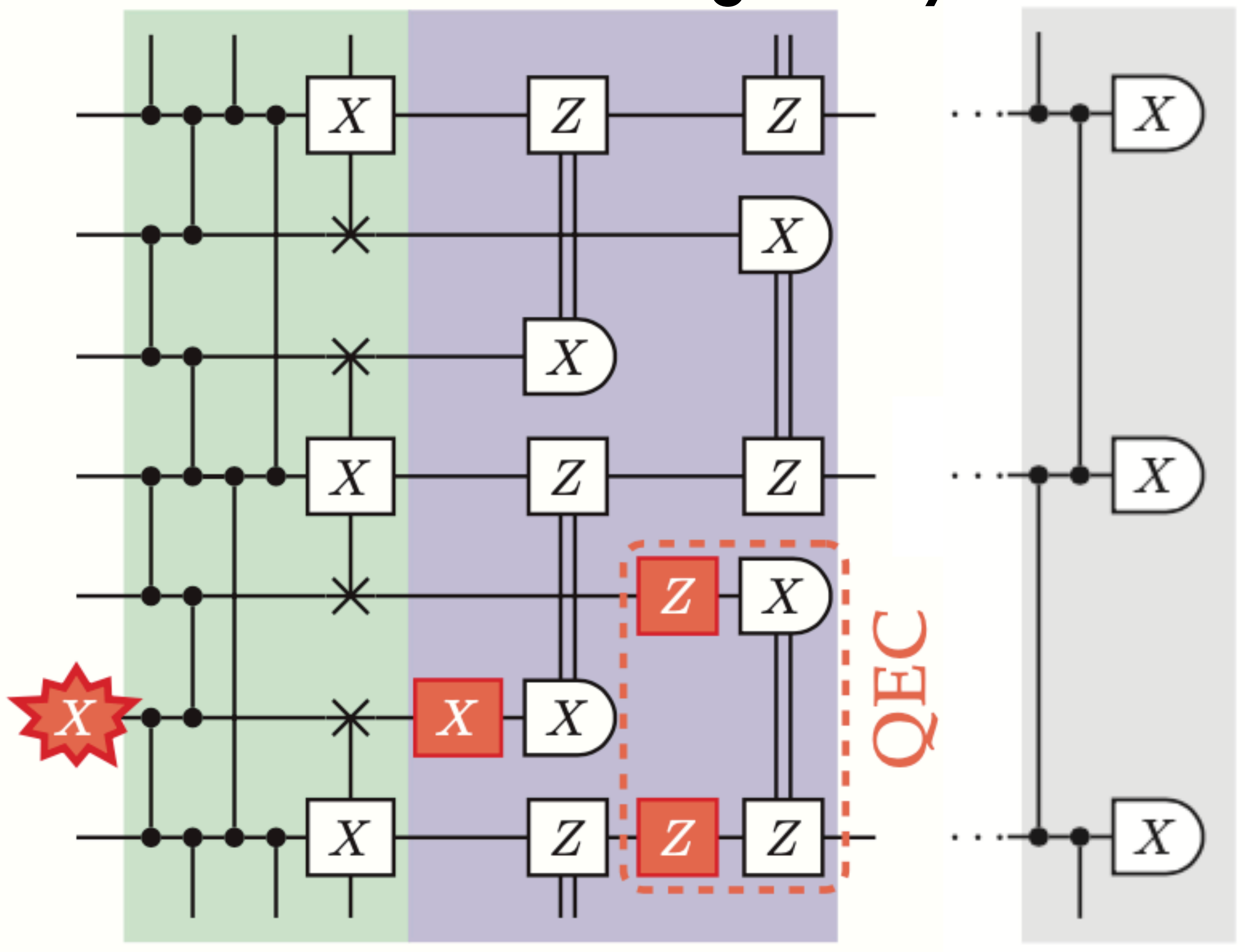

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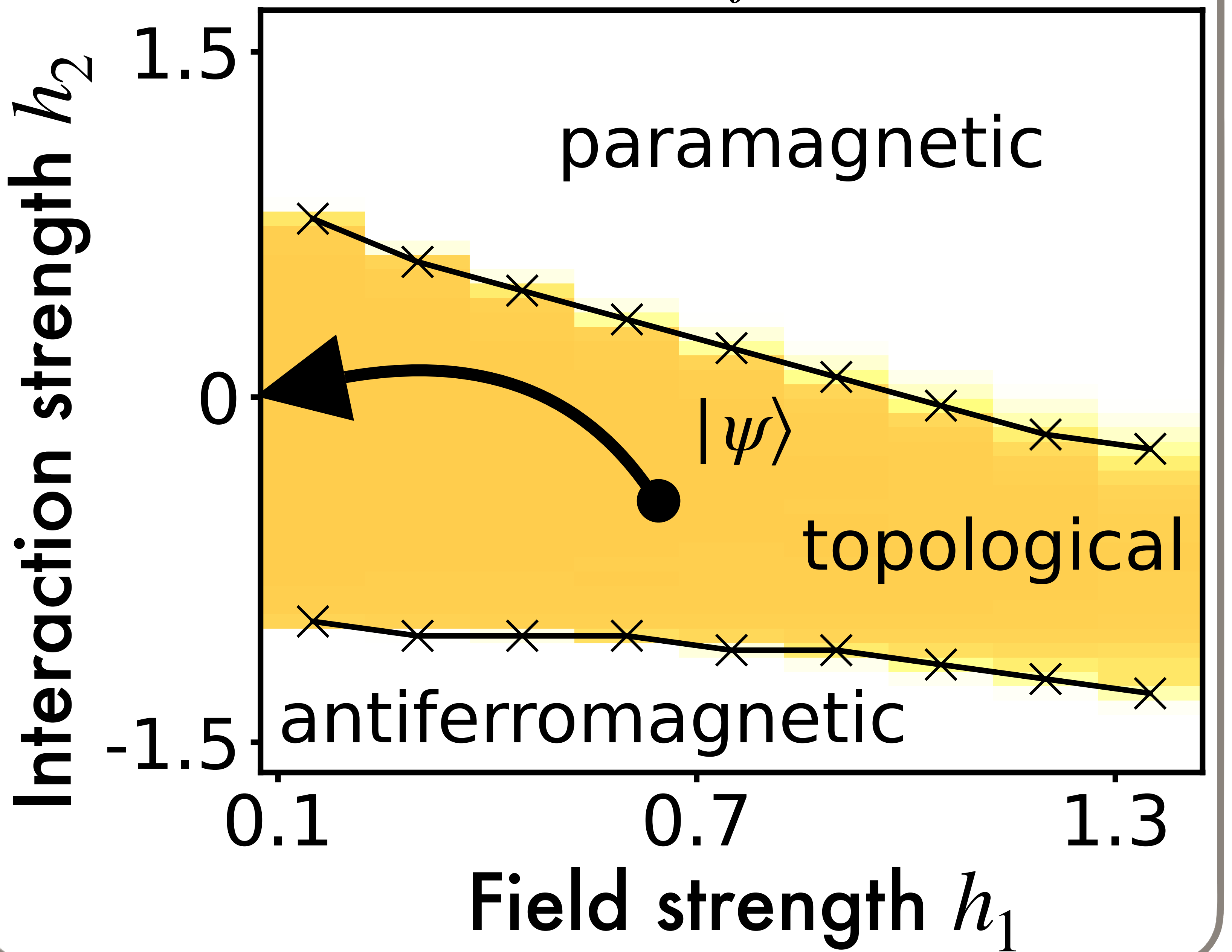
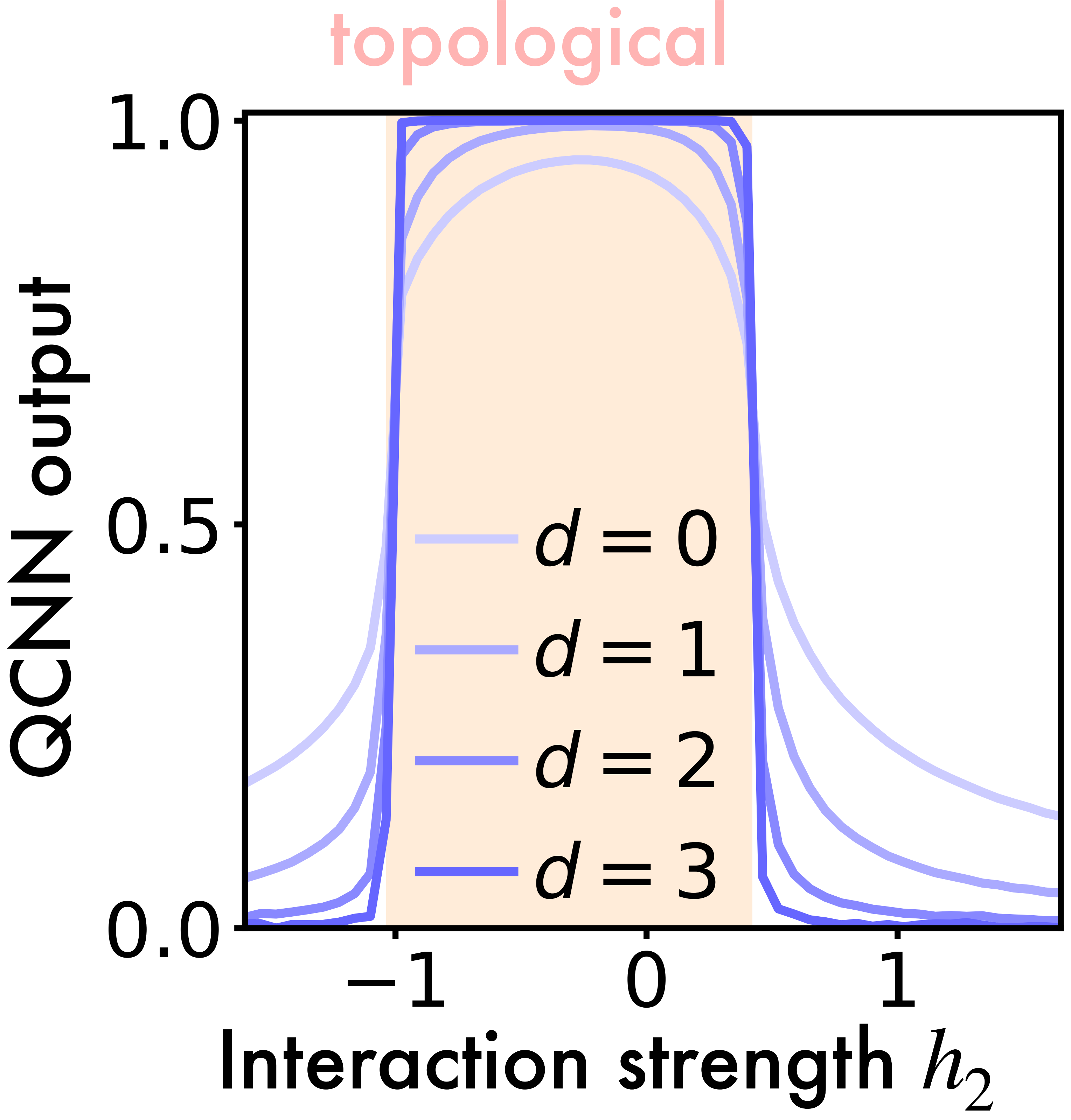




Matrix-product-state simulations

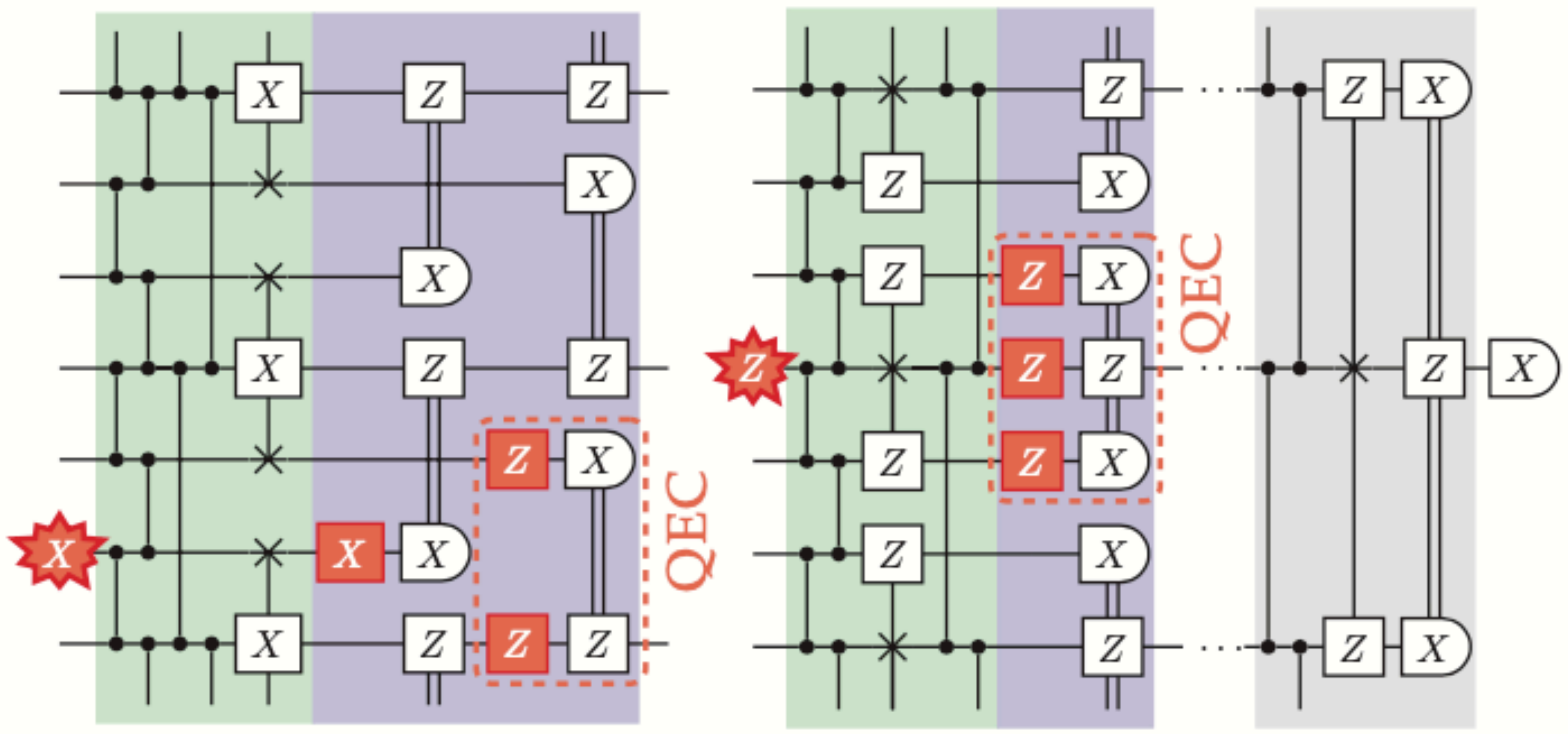
Error-tolerant QCNNs

See my poster in SESSION A

PZ, Nathan McMahon, Michael Hartmann

Integrate quantum error correction

Tolerance to noise on NISQ computers



PRResearch **6**, 033111 (2024)

Error-tolerant QCNNs

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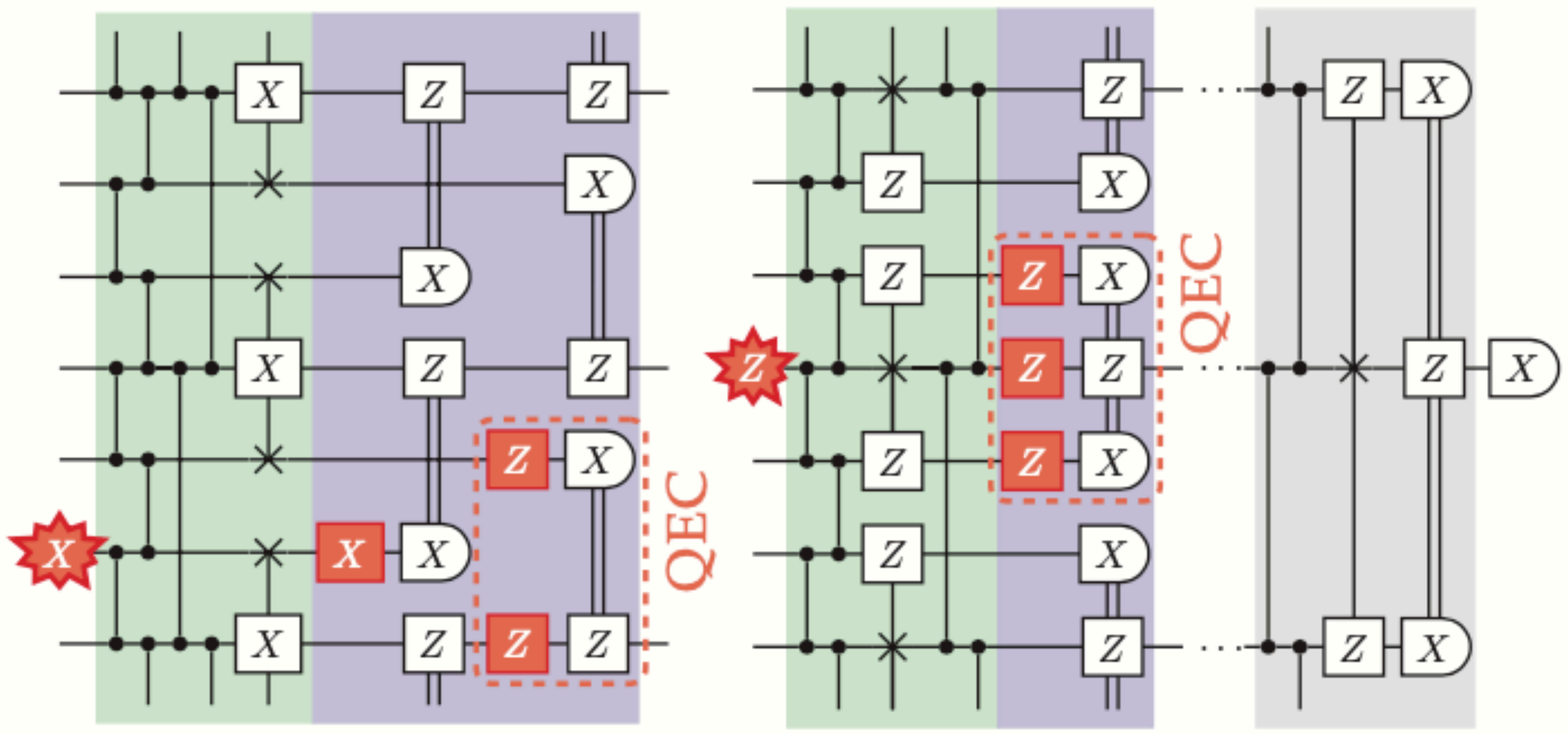
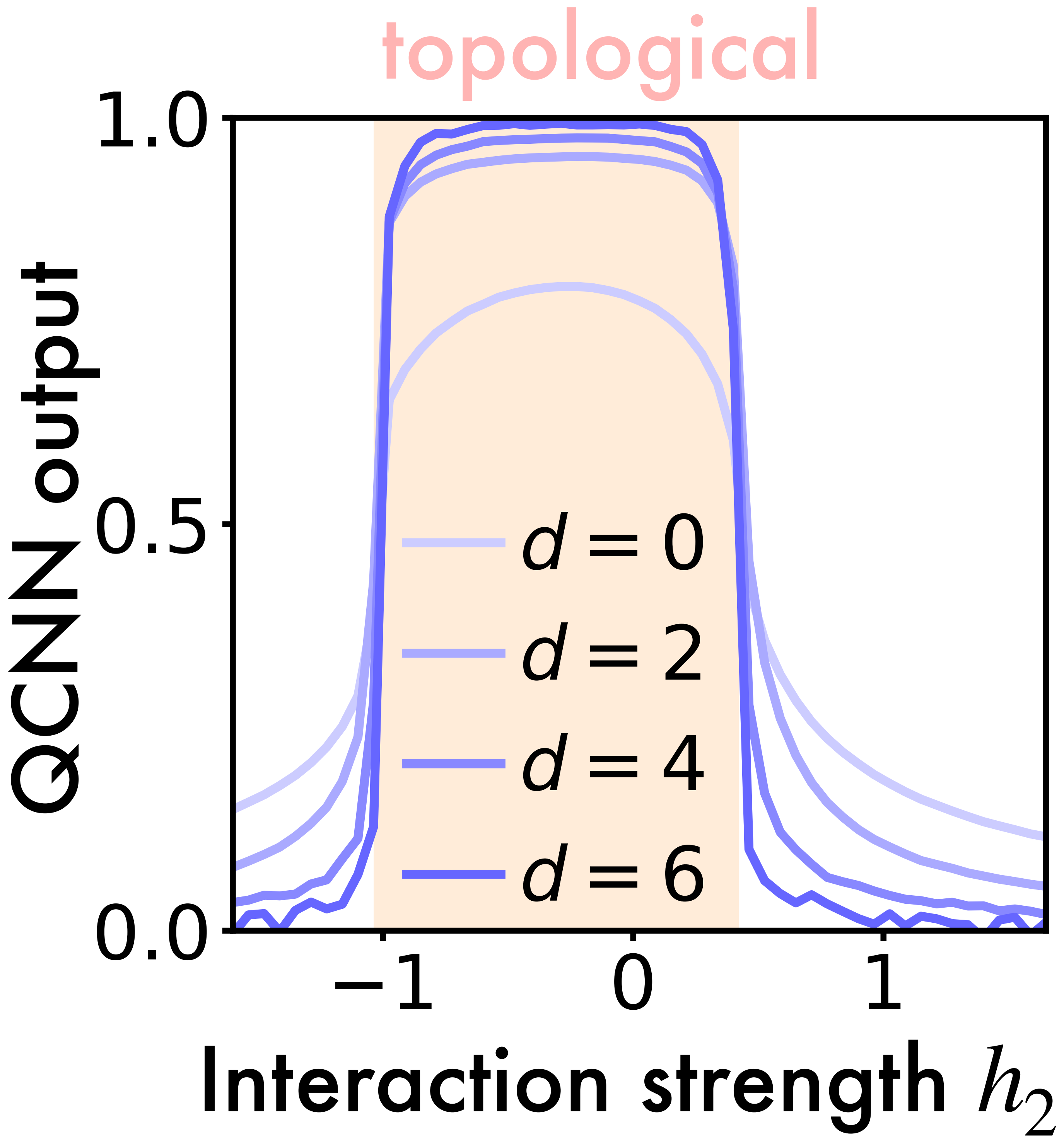
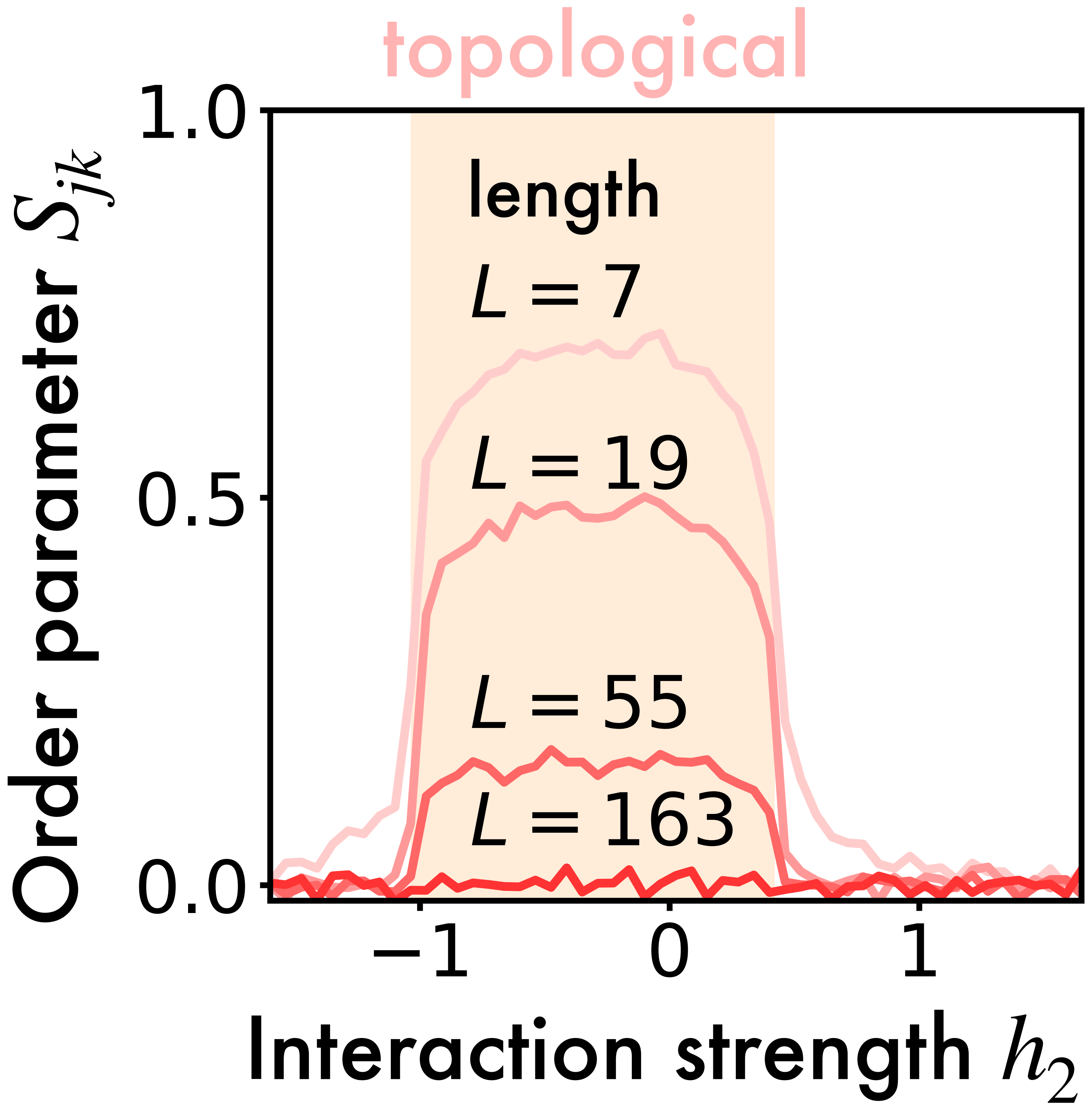




Depolarizing noise

$p_E = 4.5\,\%$

Sample complexity $\mathcal{O}(1)$



$S_{jk} = Z_j X_{j+1} X_{j+3} \dots X_{k-1} Z_k$

Sample complexity $\exp(\mathcal{O}(N))$

PRResearch **6**, 033111 (2024)

Realizing QCNNs on a superconducting quantum processor to recognize quantum phases

Johannes Herrmann[1✉], Sergi Masot Llima[1], Ants Remm[1], Petr Zapletal[2], Nathan A. McMahon[2], Colin Scarato[1], François Swiadek[1], Christian Kraglund Andersen[1], Christoph Hellings[1], Sebastian Krinner[1], Nathan Lacroix[1], Stefania Lazar[1], Michael Kerschbaum[1], Dante Colao Zanuz[1], Graham J. Norris[1], Michael J. Hartmann[2], Andreas Wallraff[1,3] & Christopher Eichler[1✉]

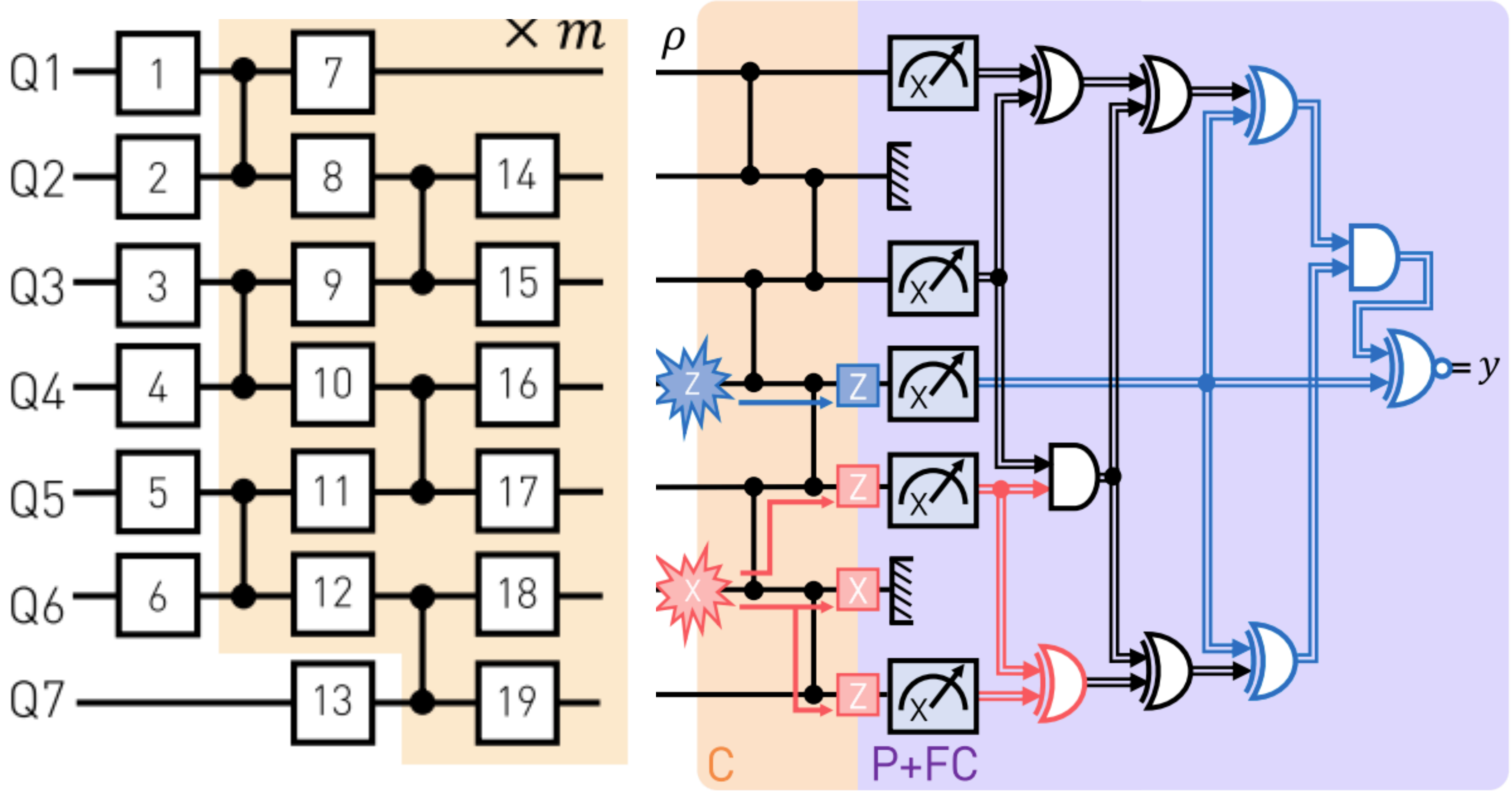
Nat Commun **13** 4144 (2022)

ETH Zürich

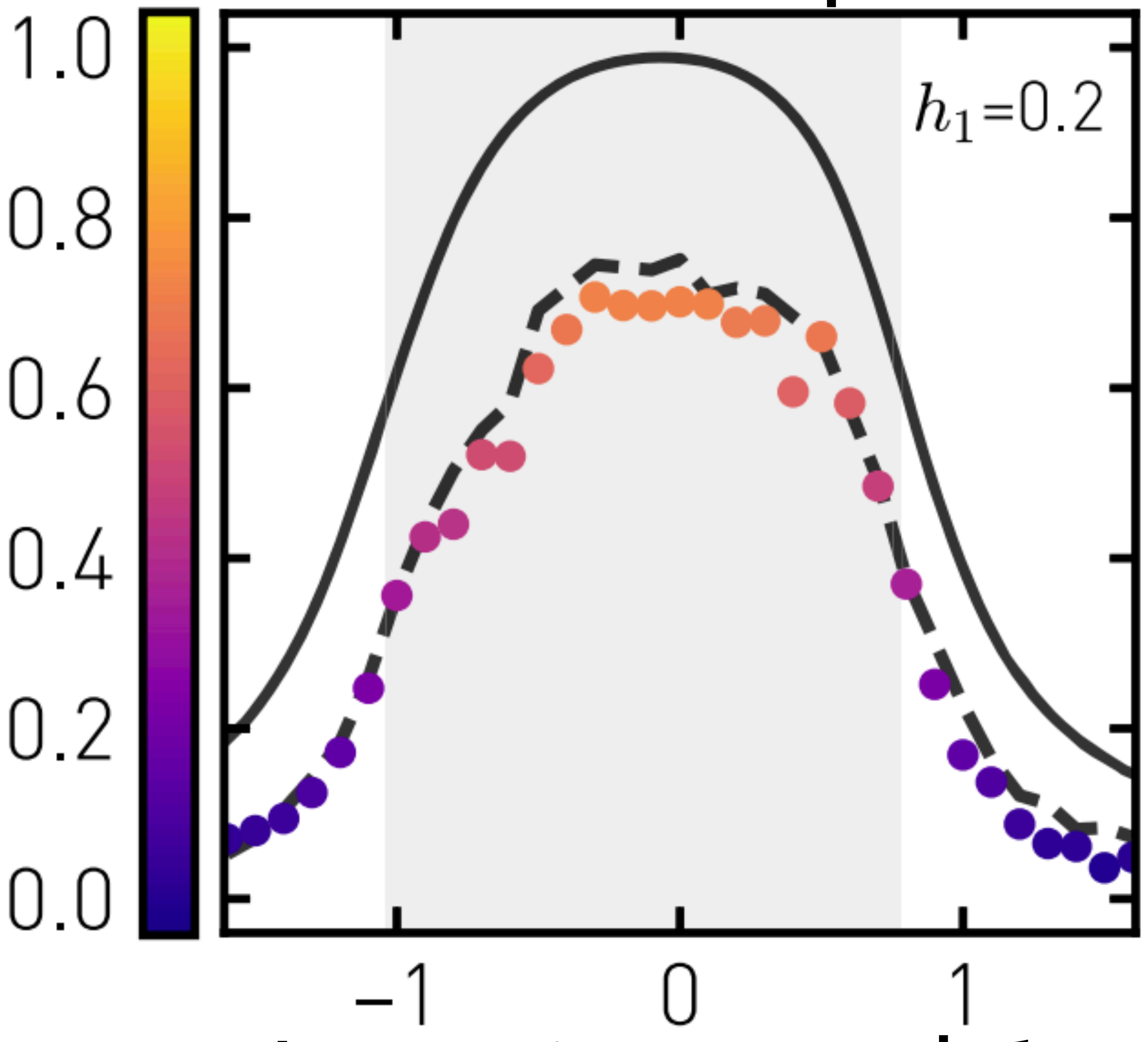
FAU

Variational quantum eigensolver

7-qubit processor
Depth-1 QCNN



QCNN output



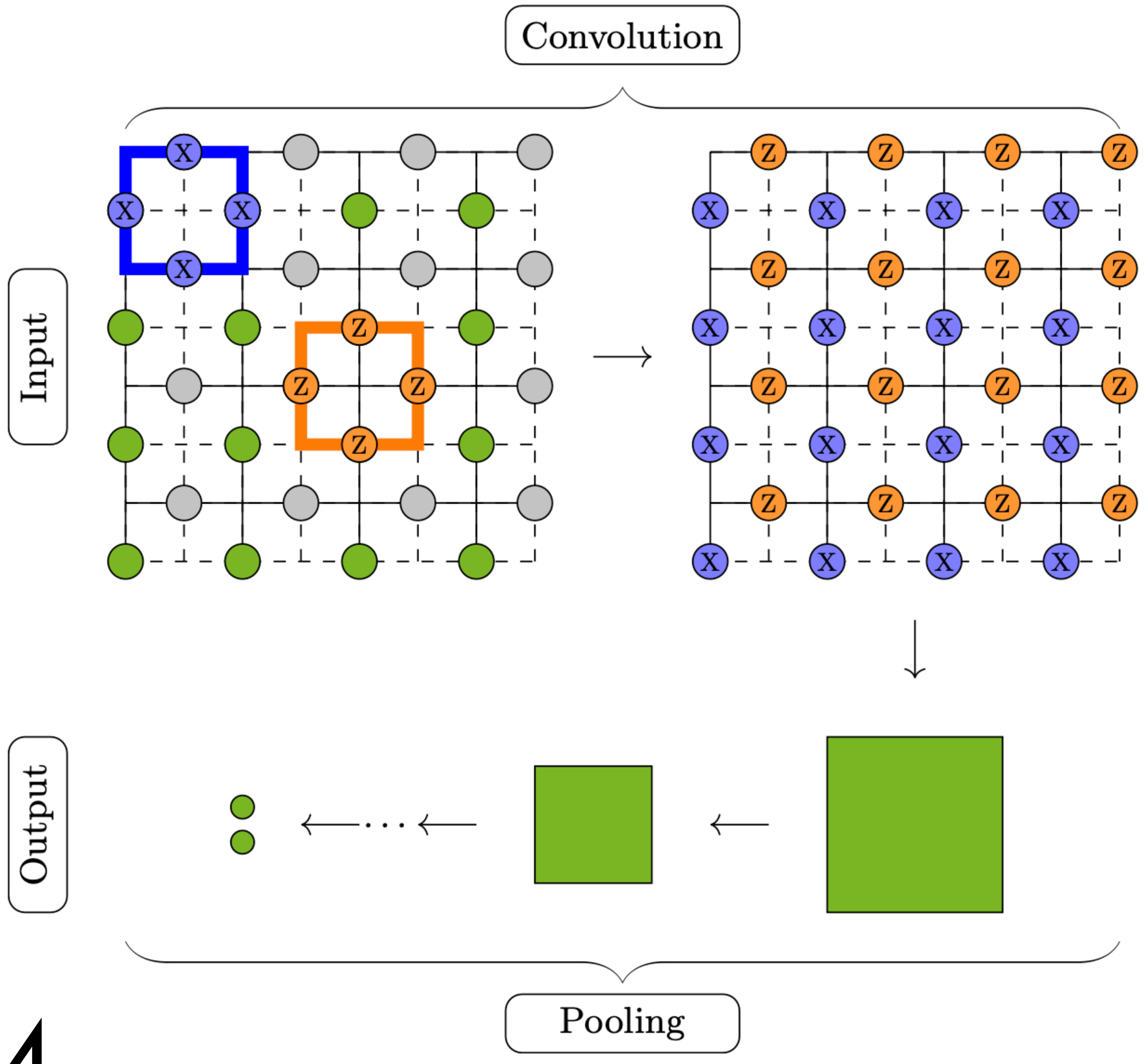
Related projects in Poster SESSION B

QCNN for Phase Recognition in 2D

Leon C. Sander

Toric code in magnetic field

$$H = -\sum_i A_i - \sum_i B_i - h_Z \sum_{j=1}^{N} Z_j$$

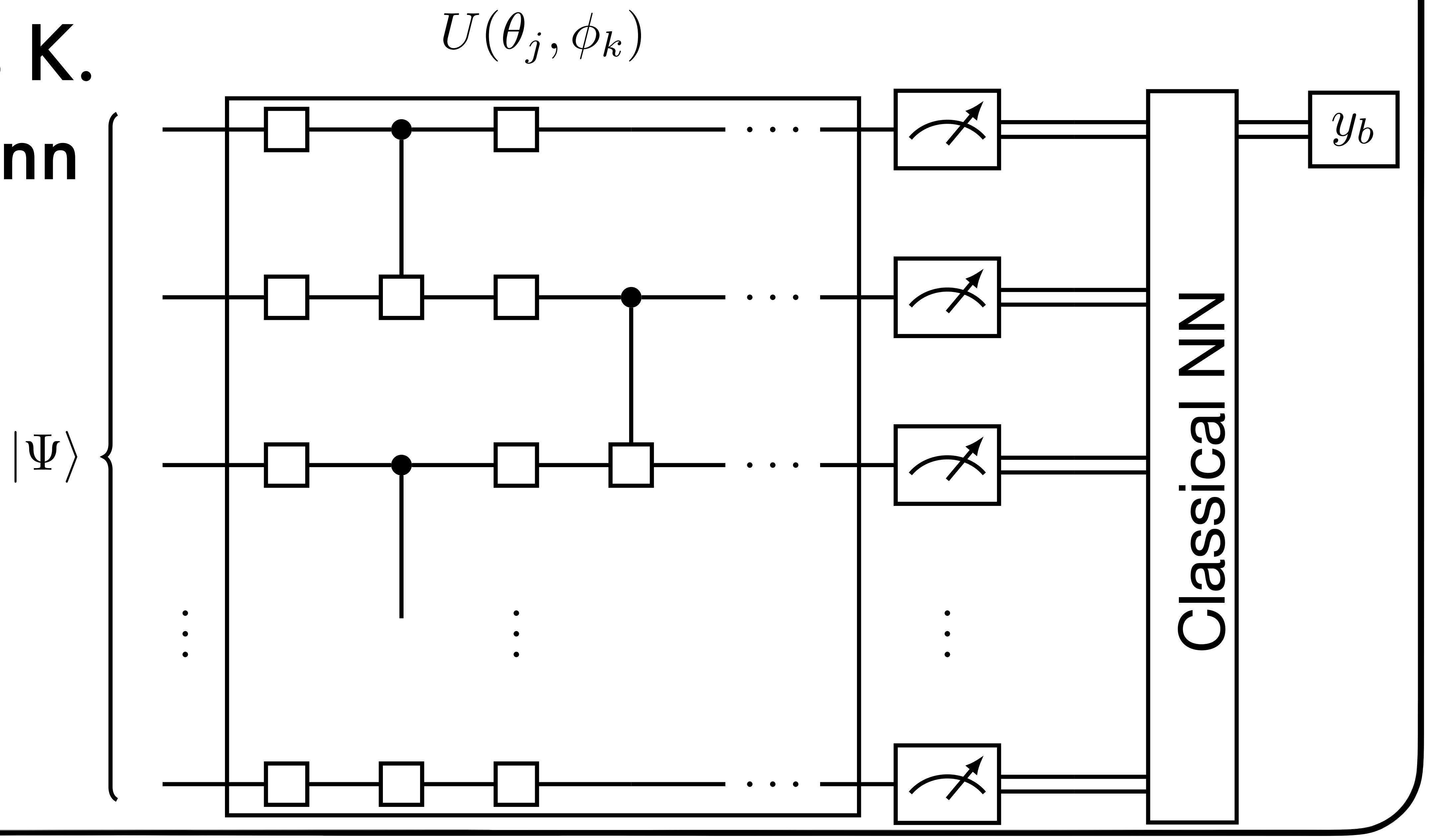


Sander, McMahon, PZ, Hartmann, arXiv:2407.04114

Training hybrid quantum-classical neural networks to recognize topological phases

Markus K. Hoffmann

(Un)supervised learning
- Short-depth quantum circuit
- Measurement
- Classical neural network



Conclusions

Quantum convolutional neural networks

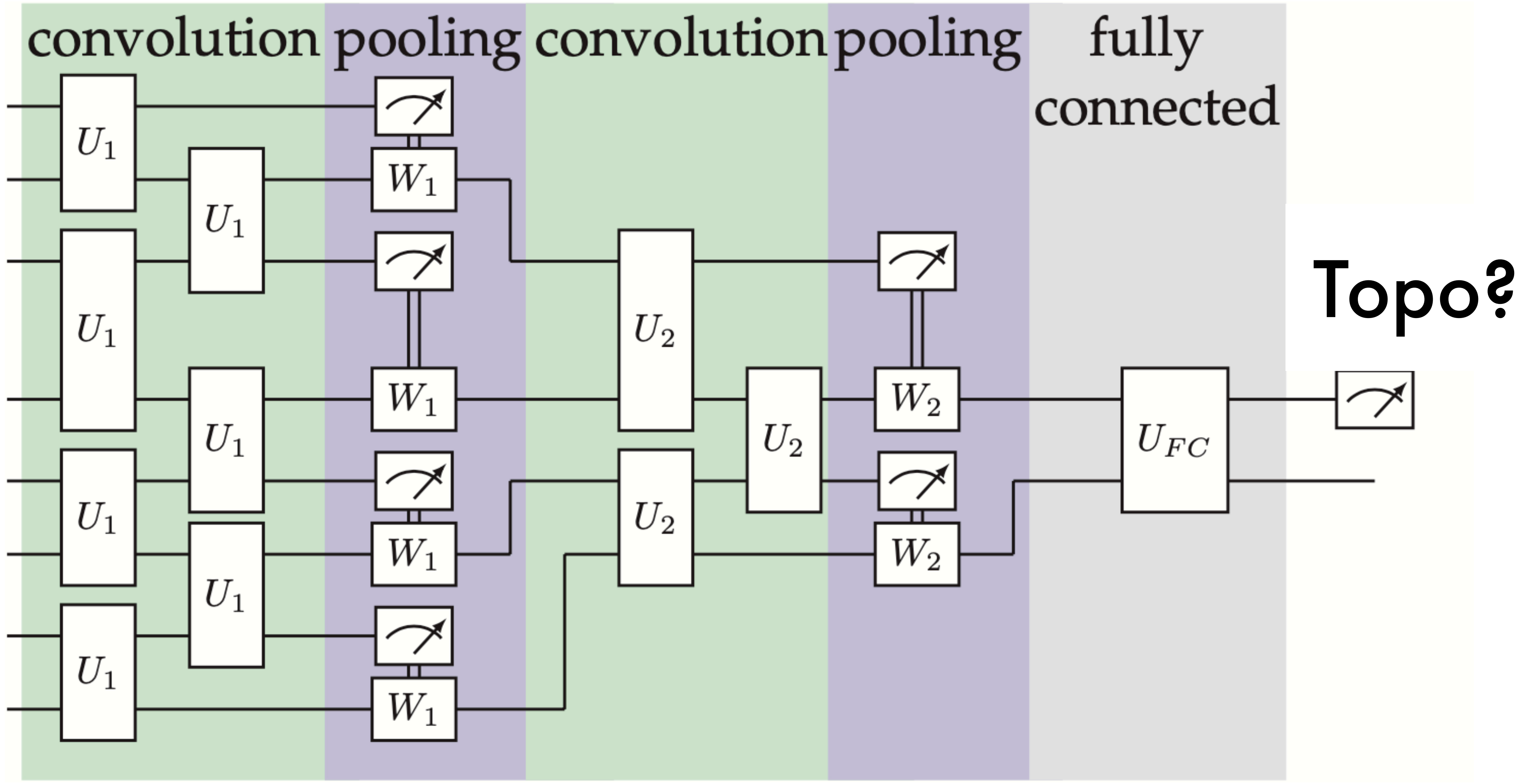
Integrated quantum error correction

Exponential reduction of sample complexity

Realized on 7-qubit superconducting processor

Intrinsic topological order in 2D

Autonomous recognition of quantum phases



petr.zapletal@unibas.ch

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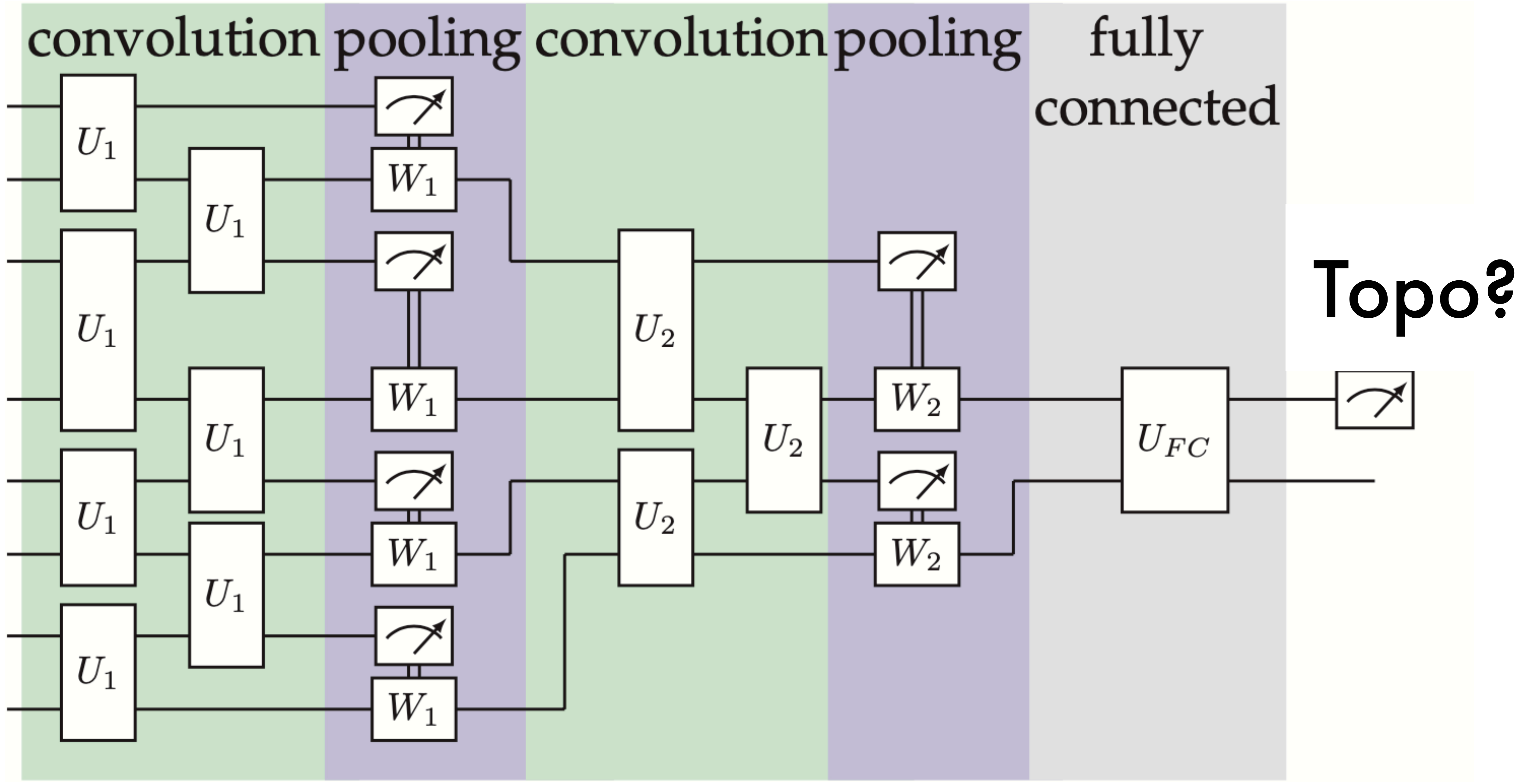
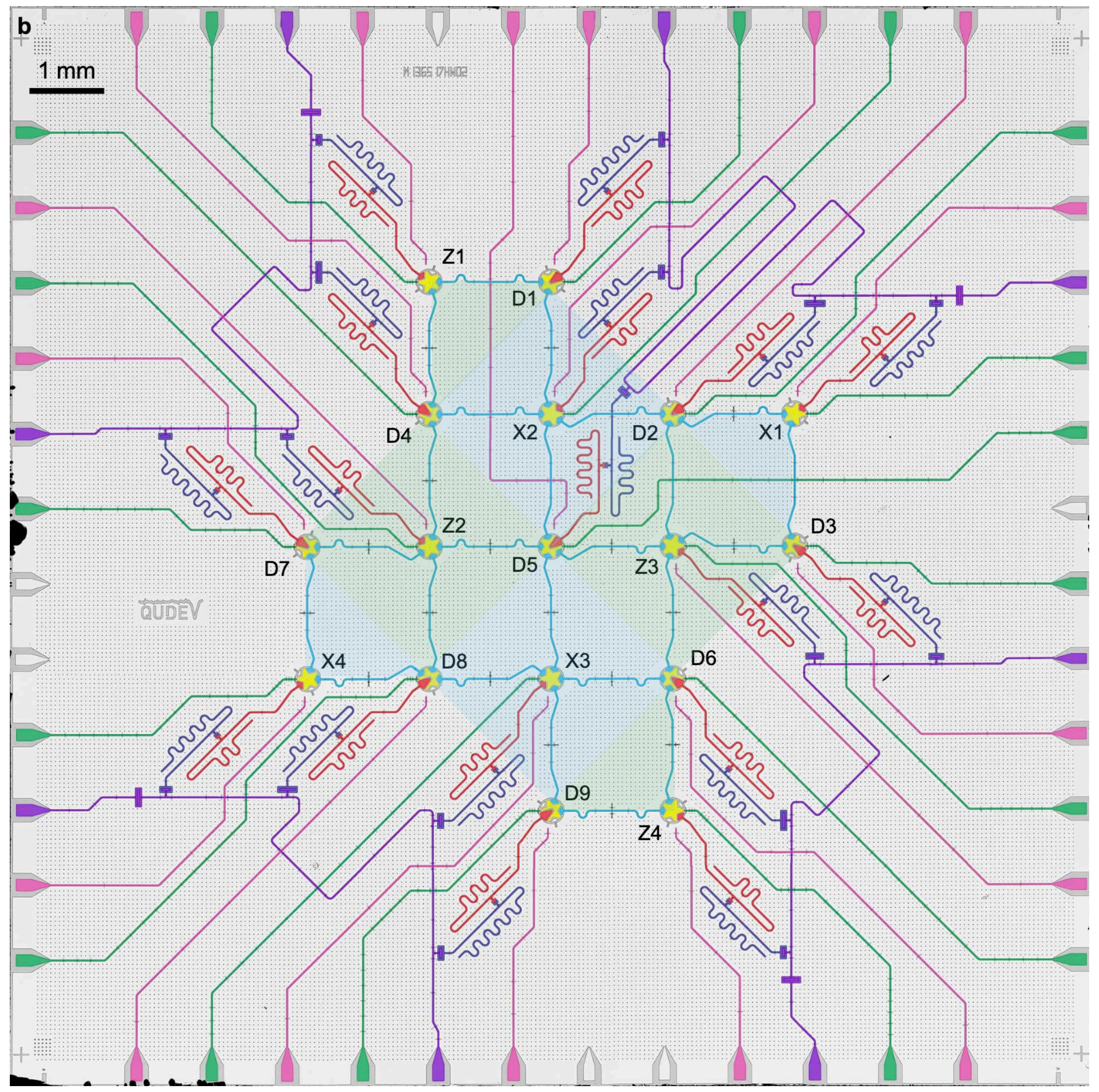


Outlook:

Training of QCNNs on superconducting quantum processors

Less-understood models:

quantum spin liquids, anyonic chains



Krinner et al.,

Nature **605** 669 (2022)

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