Fighting qubit loss in topological QEC codes: theory and experiments

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Theory and Phenomenology of Fundamental Interactions

UNIVERSITY AND INFN · BOLOGNA

HPC and Quantum Computing - 3rd Edition

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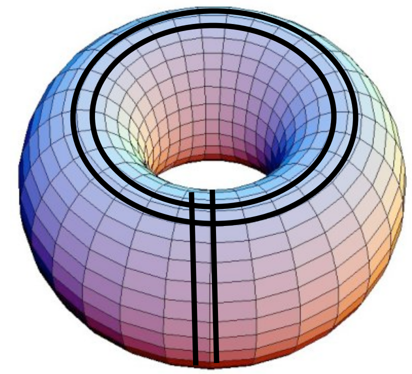
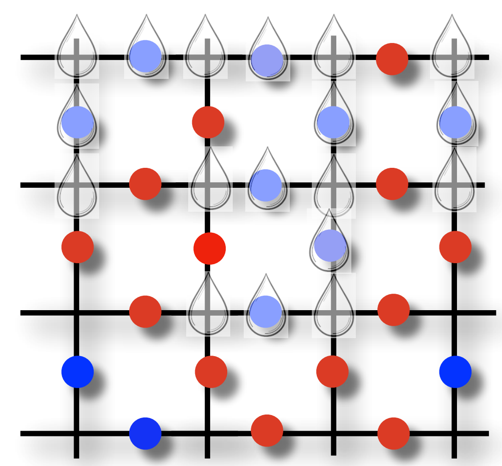
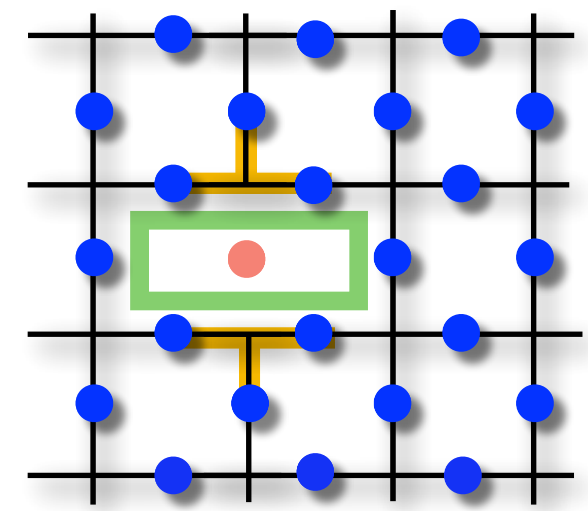
Talk outline

1 - Brief introduction to Kitaev's Toric Code



2 - Qubit Loss Error Correction: Theory...





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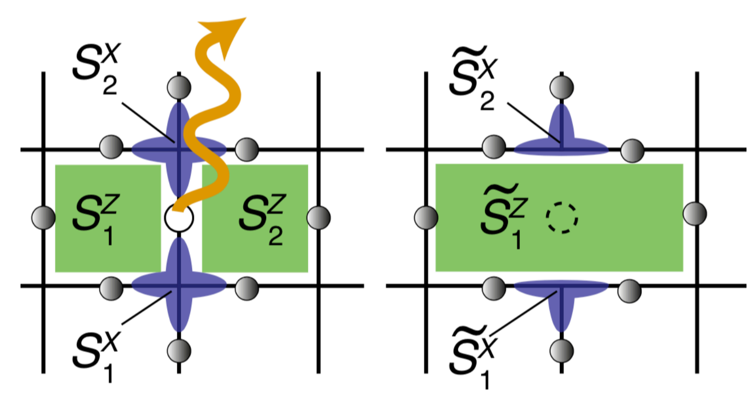

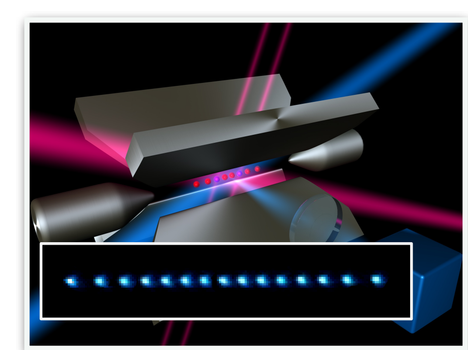

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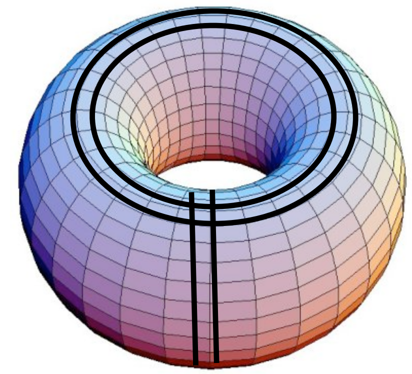

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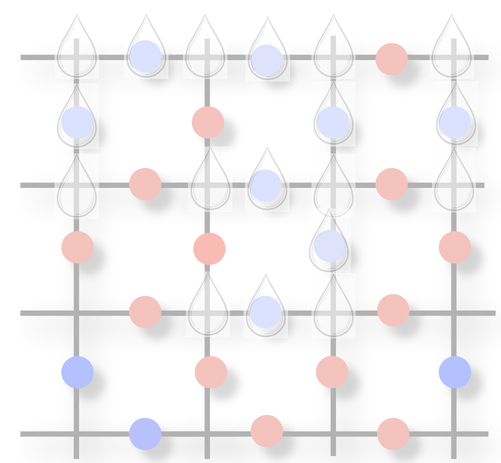

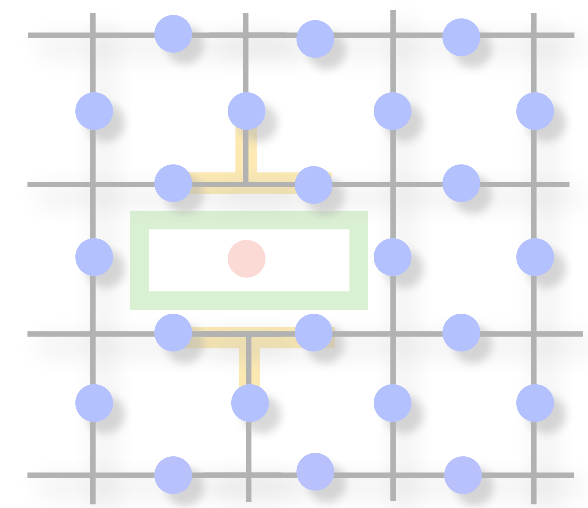

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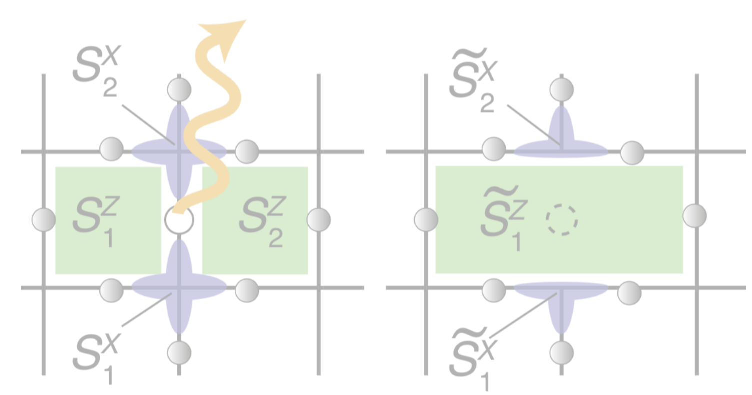
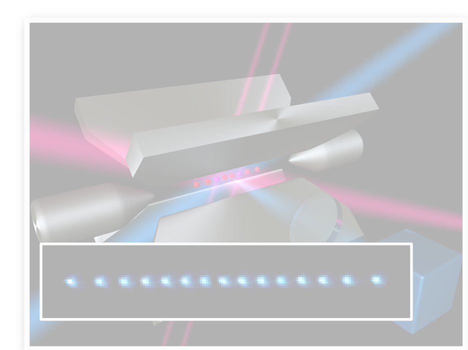
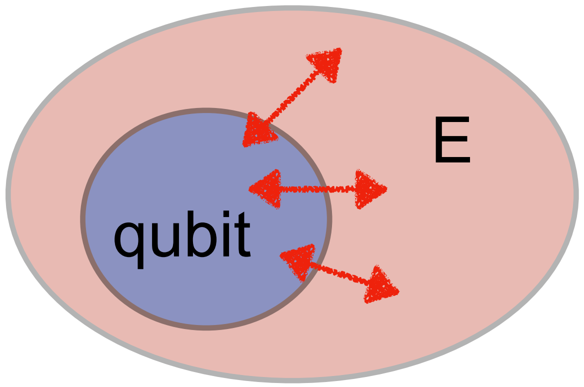




Main obstacle towards quantum computers: errors & losses

Coupling to the environment causes decoherence



Examples

1. Magnetic field fluctuations

$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$ quantum state

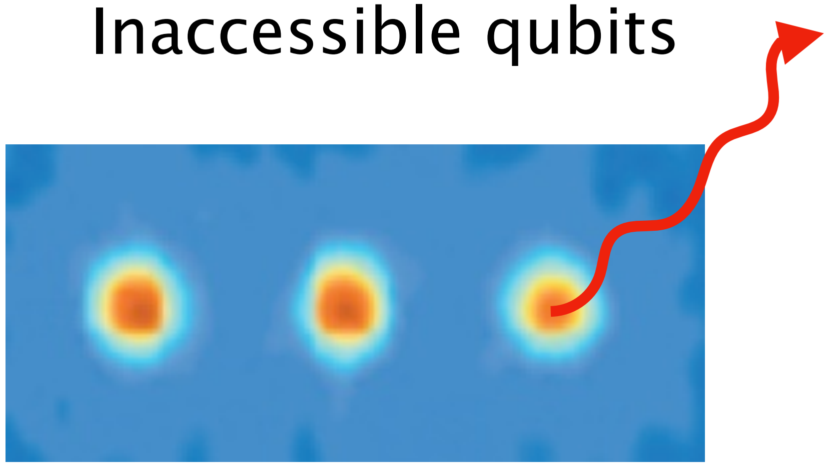
dephasing

$\rho = |\alpha_0|^2|0\rangle\langle 0| + |\alpha_1|^2|1\rangle\langle 1|$ classical state

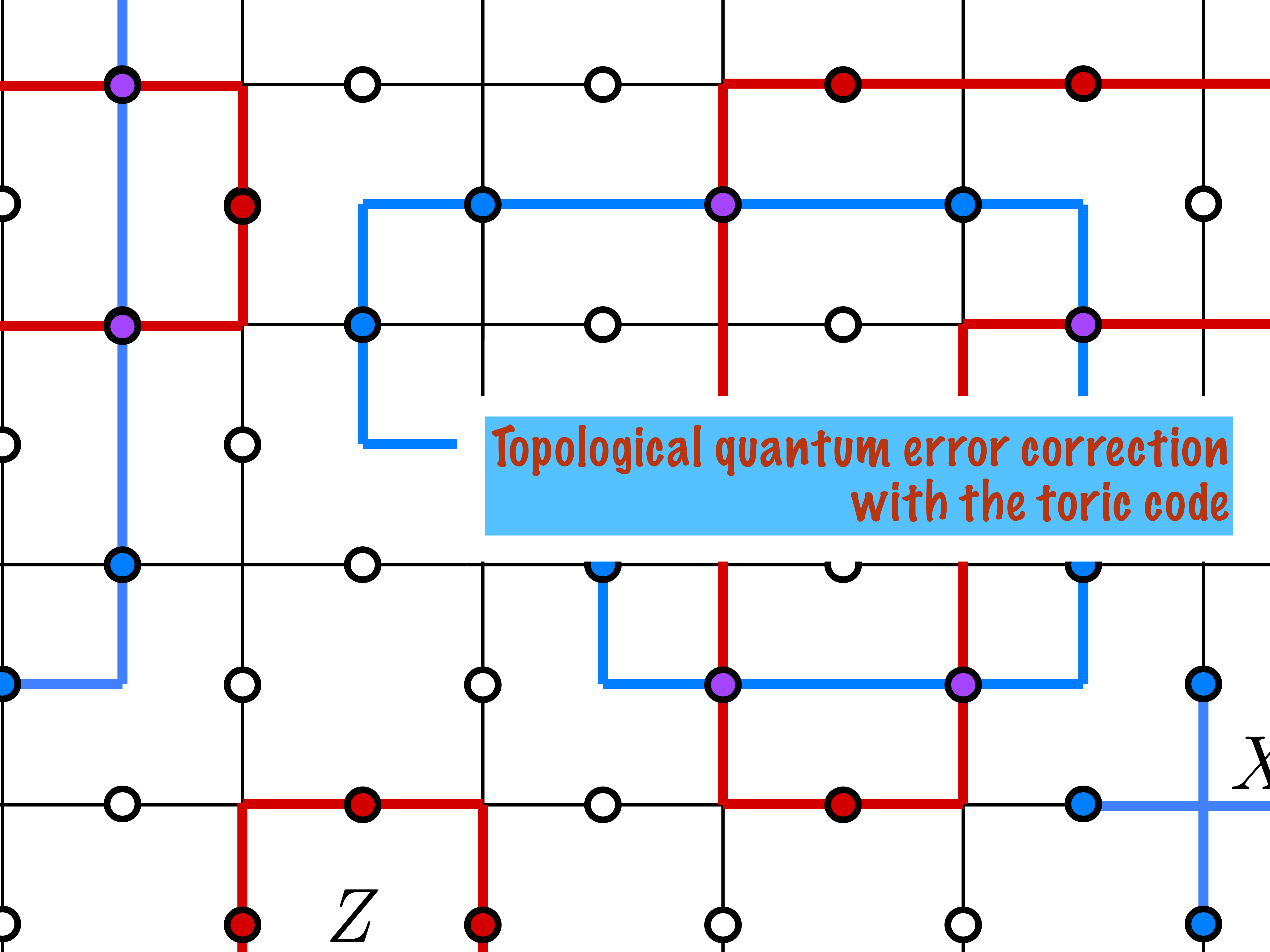
2. Losses

This talk

Inaccessible qubits

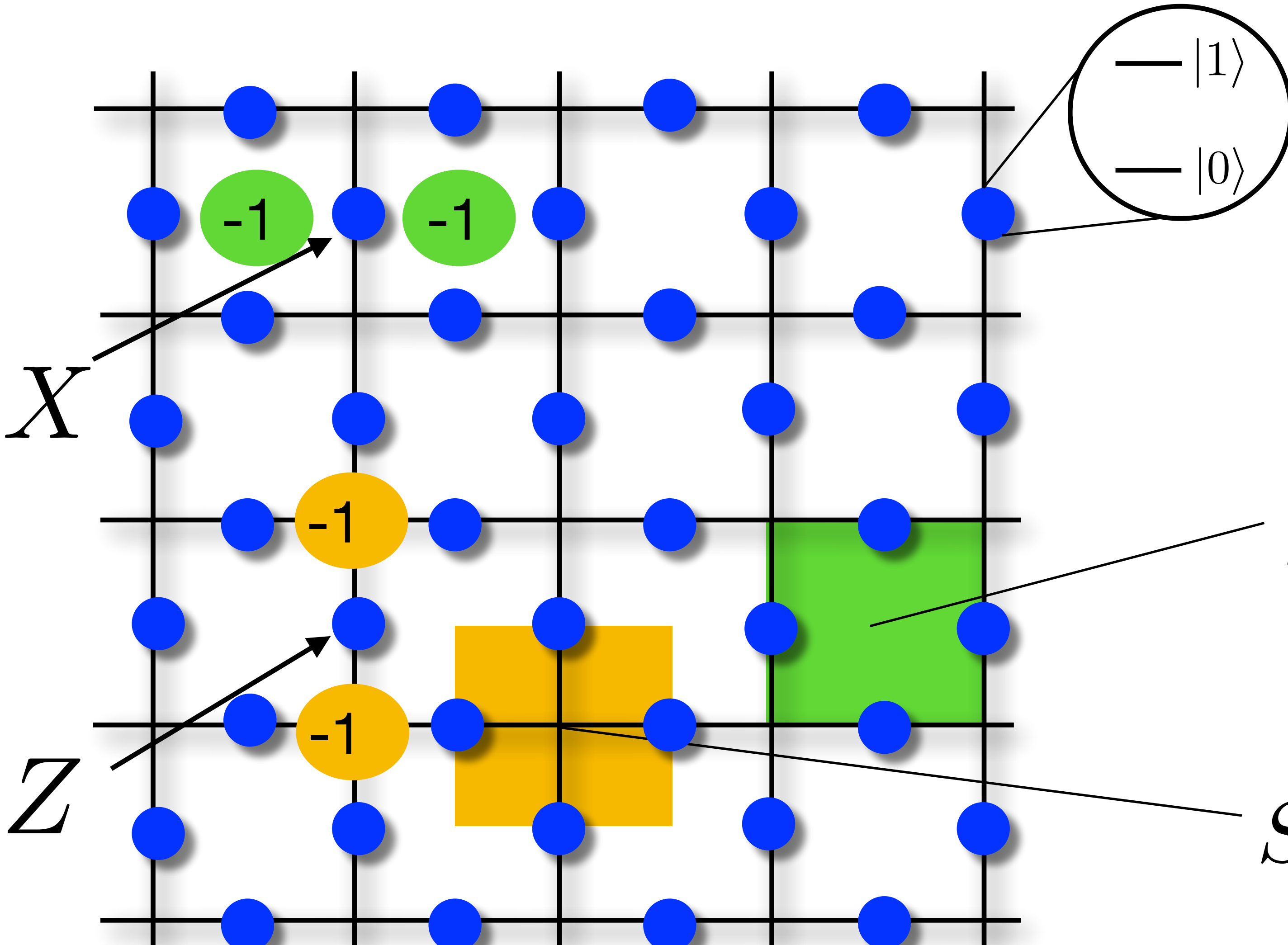


Topological quantum error correction with the toric code

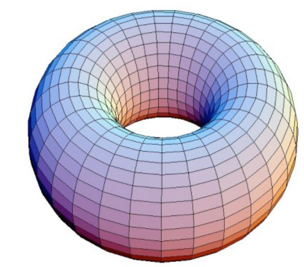


Kitaev's toric code

A. Yu. Kitaev, *Annals of Physics*, **303** (2003)



- Qubits on the links / bonds of a 2D square lattice
- 2 types of stabilisers



$$S_z = ZZZZ$$

$$S_x = XXXX$$

they all commute and form a group

Errors

- X type error will anticommute with the Z-type stabilizers
- Z type error will anticommute with the X-type stabilizers

Logical info

code space

$$S_z|\psi_L\rangle = +|\psi_L\rangle \qquad S_x|\psi_L\rangle = +|\psi_L\rangle$$

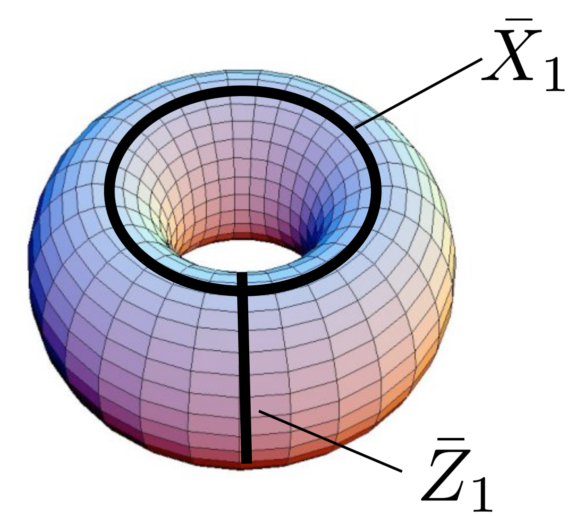
$|\bar{0}\rangle|\bar{0}\rangle$ $|\bar{0}\rangle|\bar{1}\rangle$ $|\bar{1}\rangle|\bar{0}\rangle$ $|\bar{1}\rangle|\bar{1}\rangle$

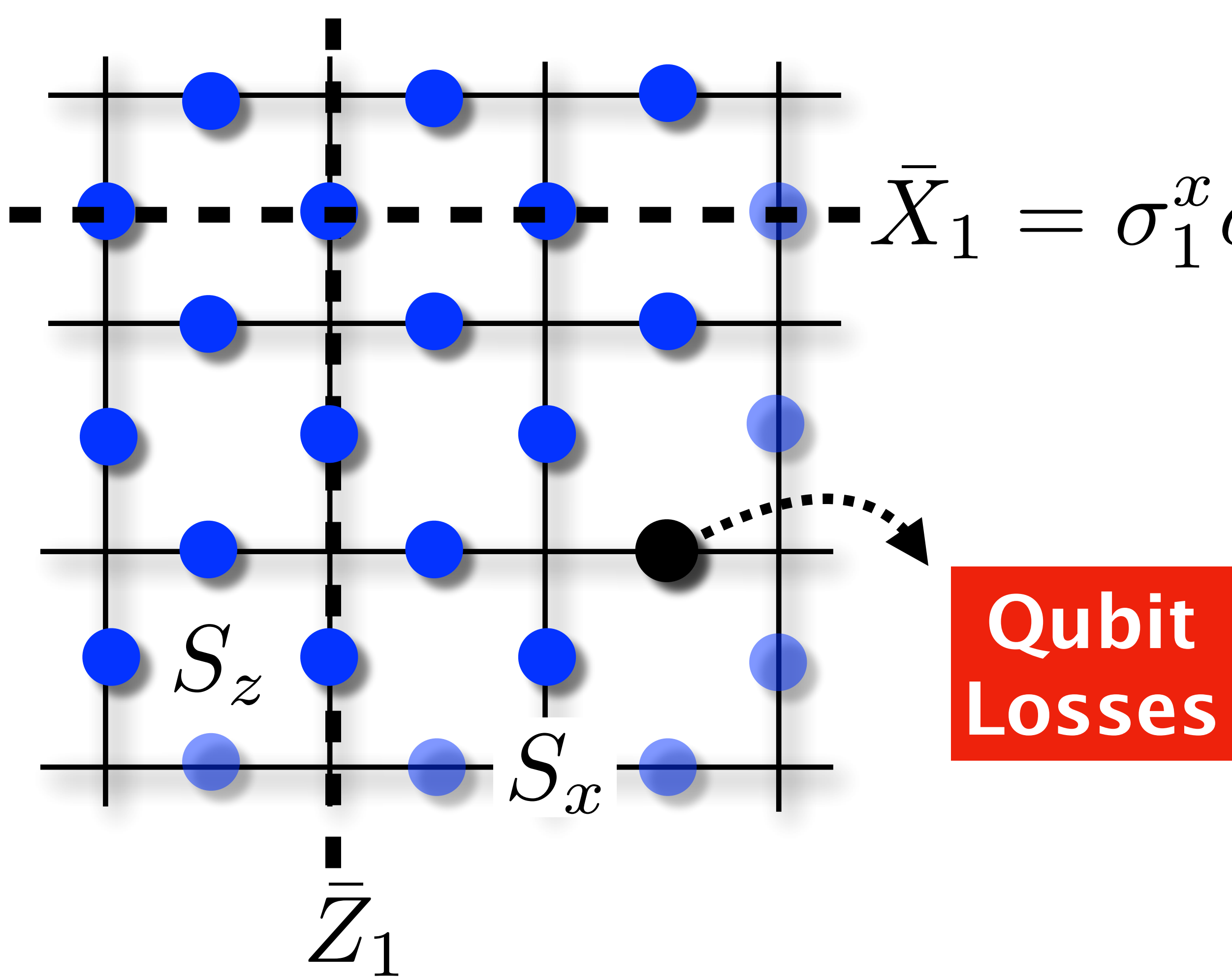
logical states

Logical qubits

Logical operators

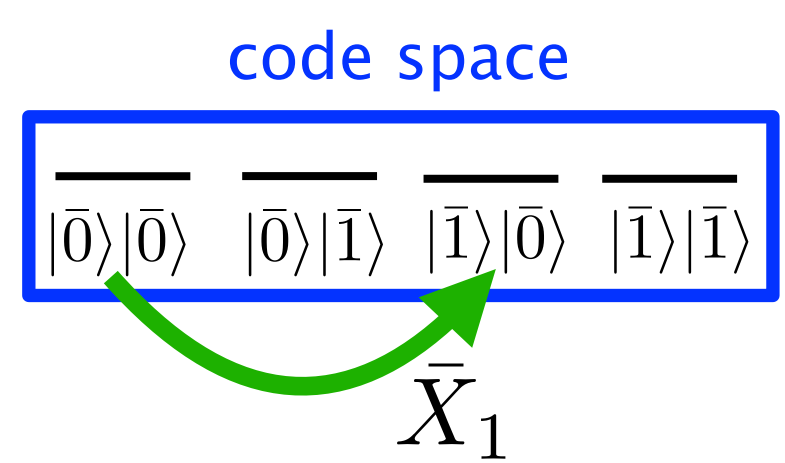
- must act non trivially within the code space





$$\bar{X}_1 = \sigma_1^x \sigma_2^x \ldots \sigma_n^x$$

Logical operators = strings that percolate through the lattice and change the logical state in the code space



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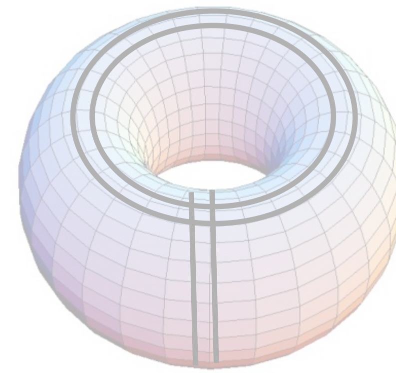

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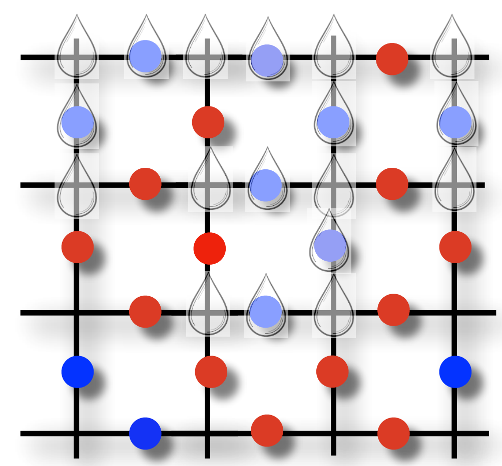

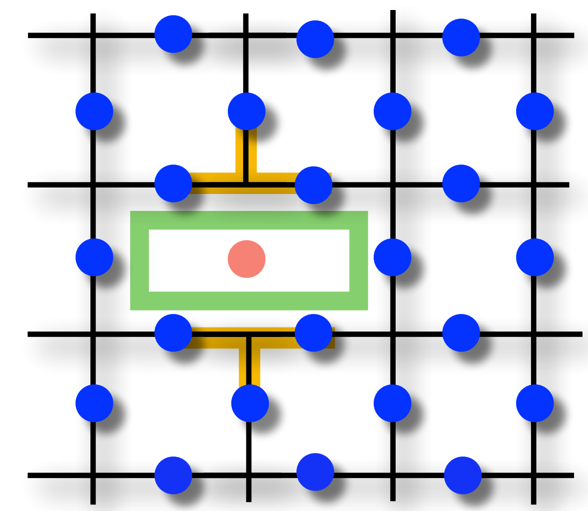

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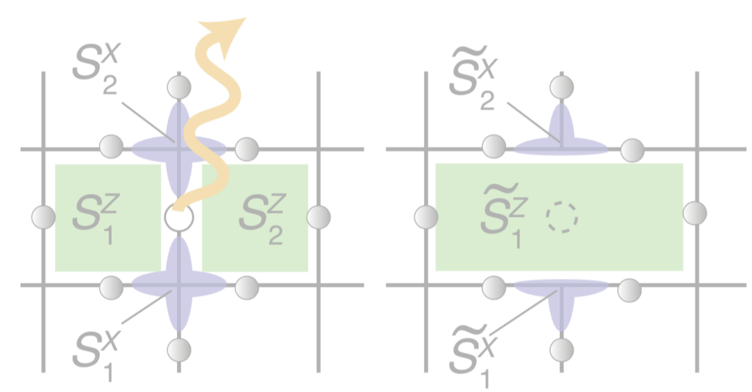
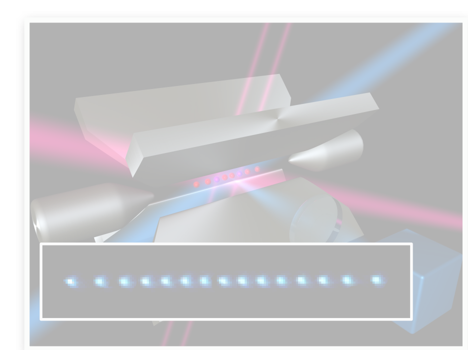




Qubit losses

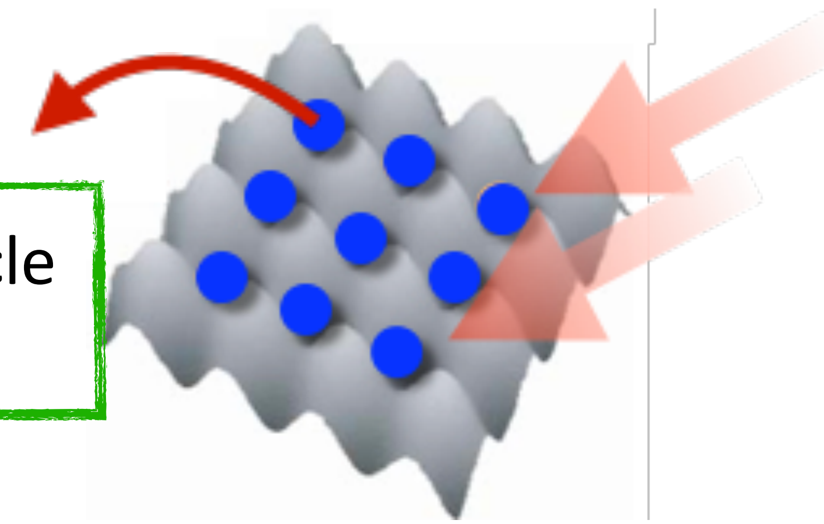
Motivation:

Losses and leakage can damage the performance of (topological) QEC codes

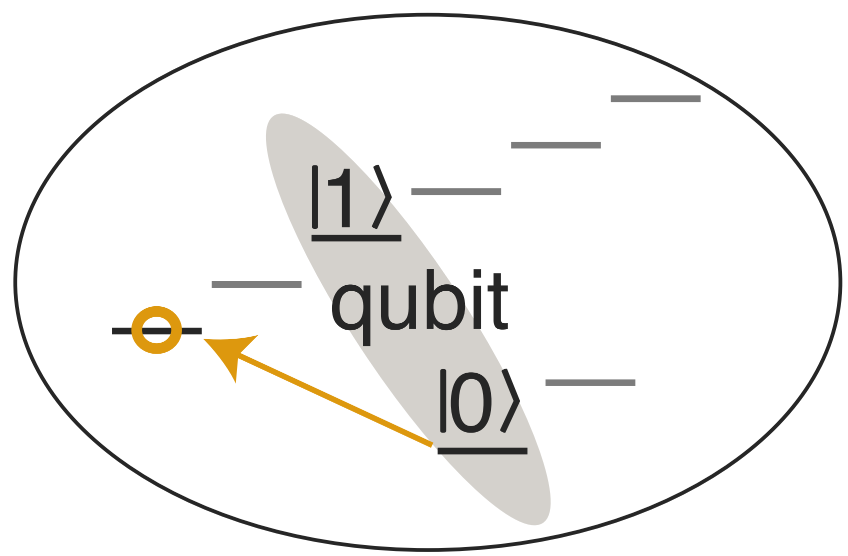
Challenges:

- Find protocols to deal with qubit loss
- Understand **robustness** of codes used
- Develop and experimentally test **in-situ leakage loss detection** and **correction** protocols

Particle loss



Electronic population leakage



Theory

Grassl M, Beth T, Pellizari T PRA 56 (1997)

T. Stace, S. Barrett, A. Doherty PRL **102**, (2009); PRA **81**, (2010)

DV, D. Amaro, M.A. Martin-Delgado, M. Müller PRL **121**, (2018)

Photons

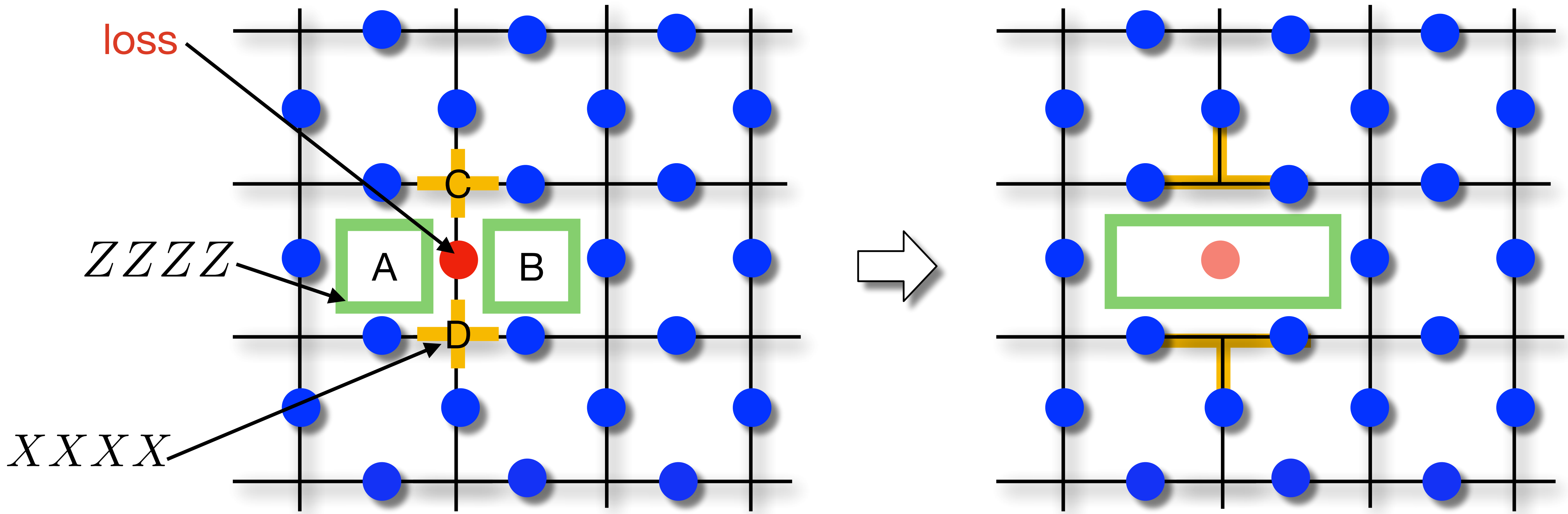
C.-Y. Lu, W.-B. Gao, J. Zhang, X.-Q. Zhou, T. Yang, and J.-W. Pan, PNAS **105**, (2008).

Qubit losses in the toric code

T. Stace, S. Barrett, A. Doherty, PRL **102** (2009)
T. Stace, S. Barrett, PRA **81** (2010)

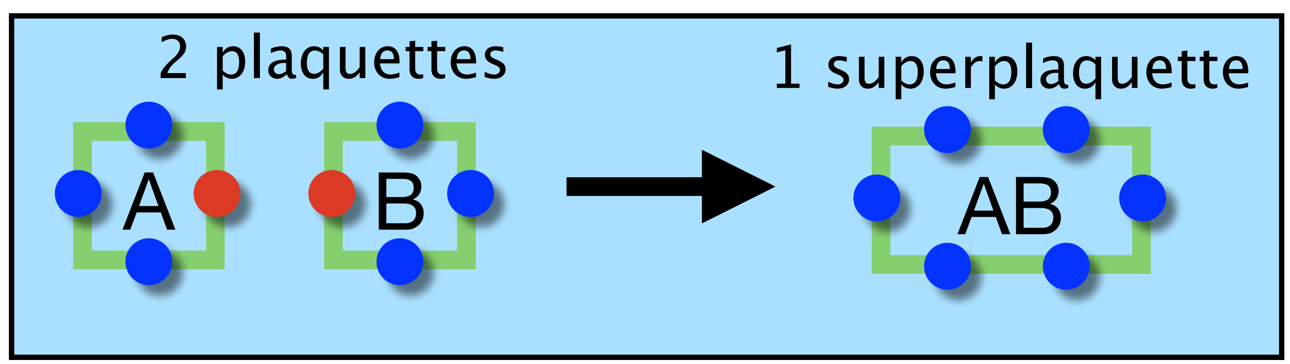
Goal

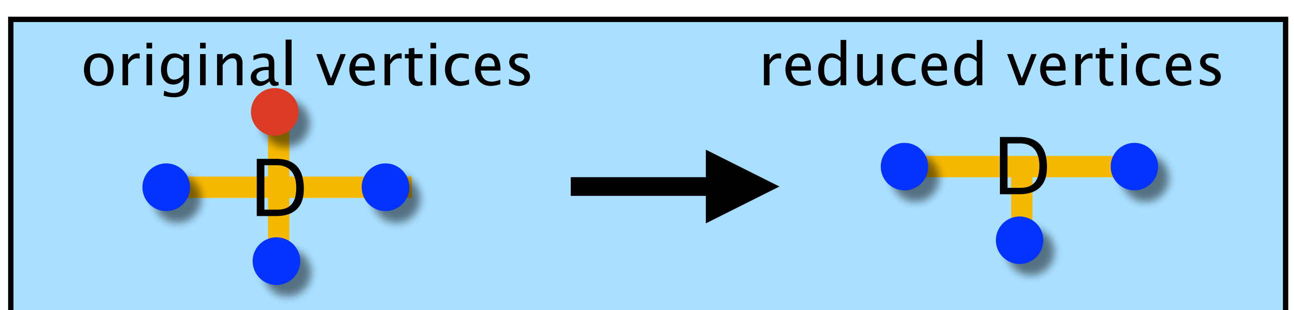
Redefine the plaquette/vertex and the logical operators



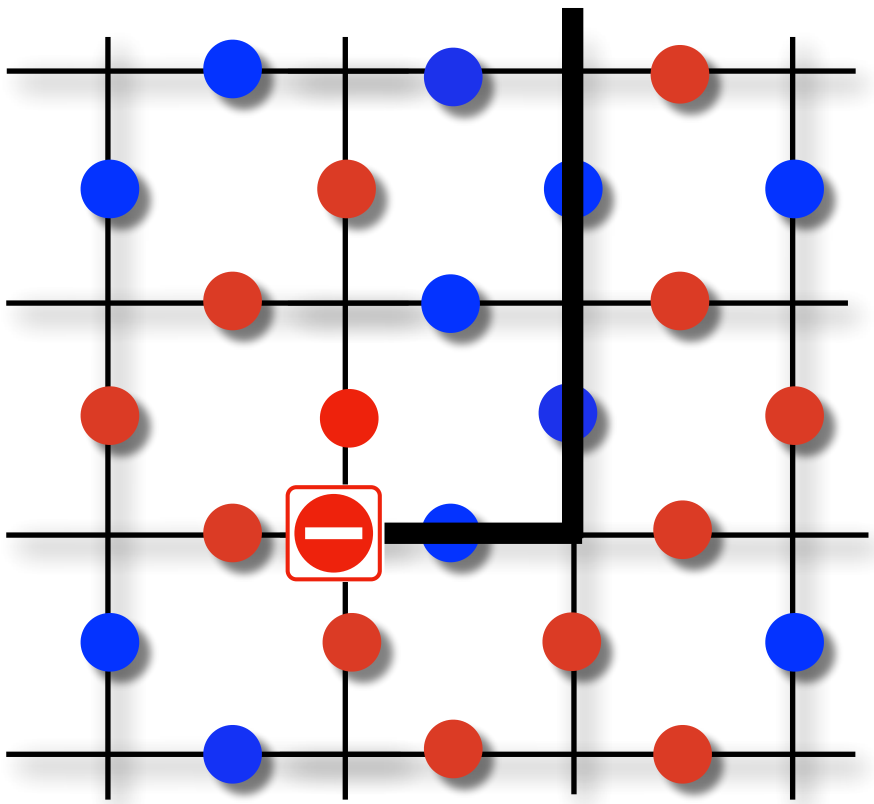
The loss affects

- two Z-stabilisers
- two X-stabilisers



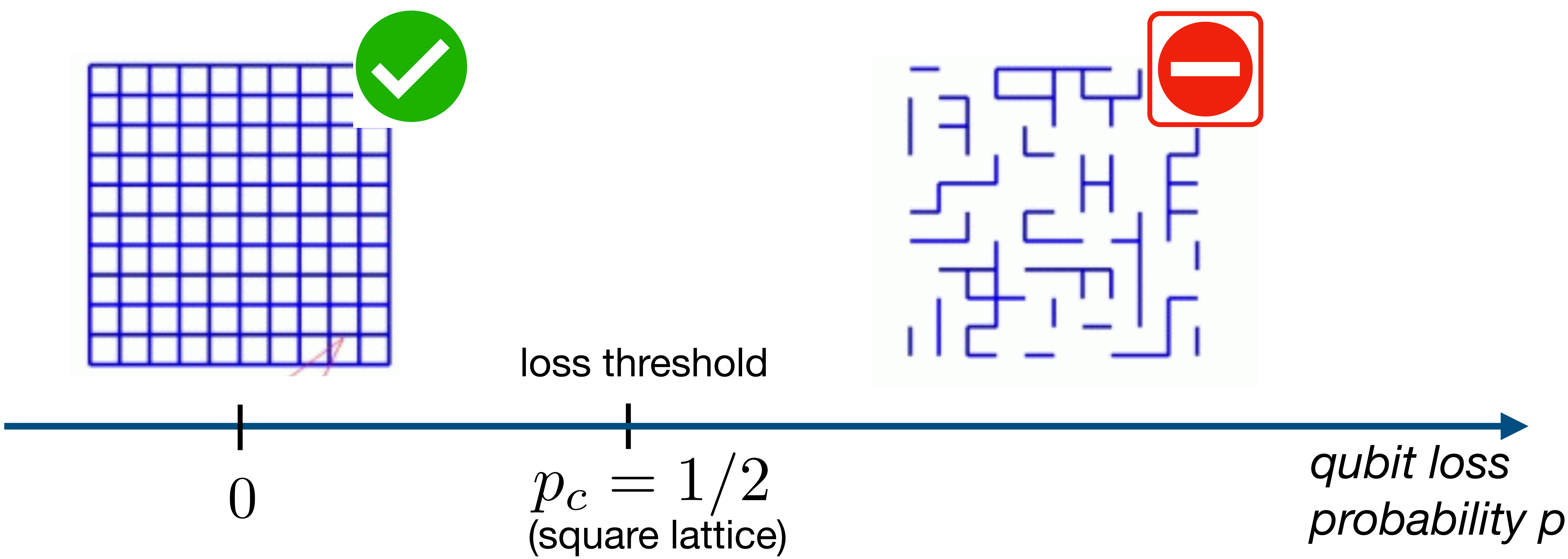


Qubit losses in the toric code



no **percolating** path ⟷ no logical operator

The threshold for losses is given by the **bond percolation threshold**



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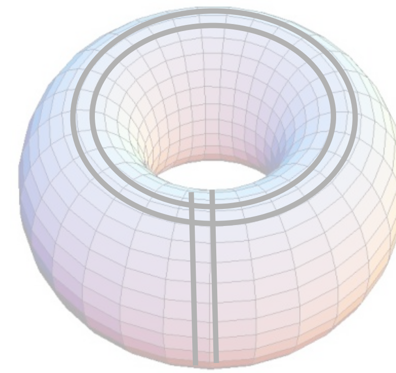

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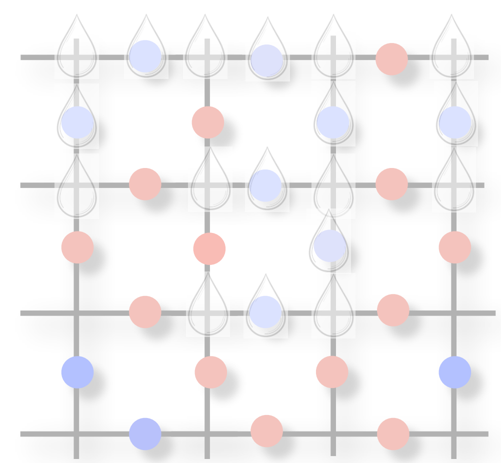

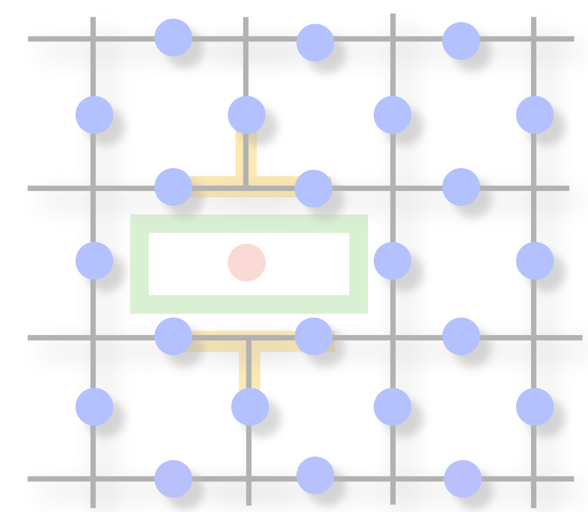

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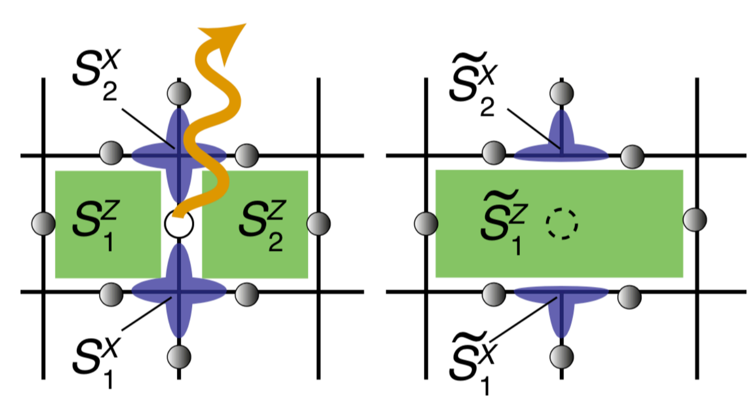
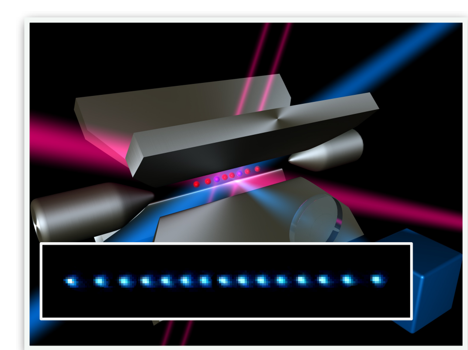




Qubit Loss Error Correction: Experiment

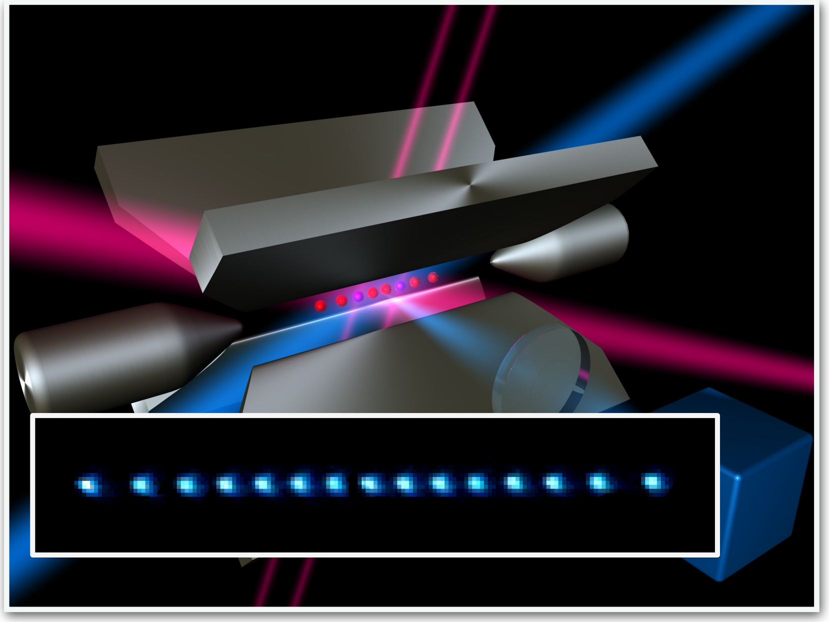
Goals

- Provide a toolbox for correcting losses in generic quantum codes

  Detect if the loss has happened

  Decide if correcting or not the code

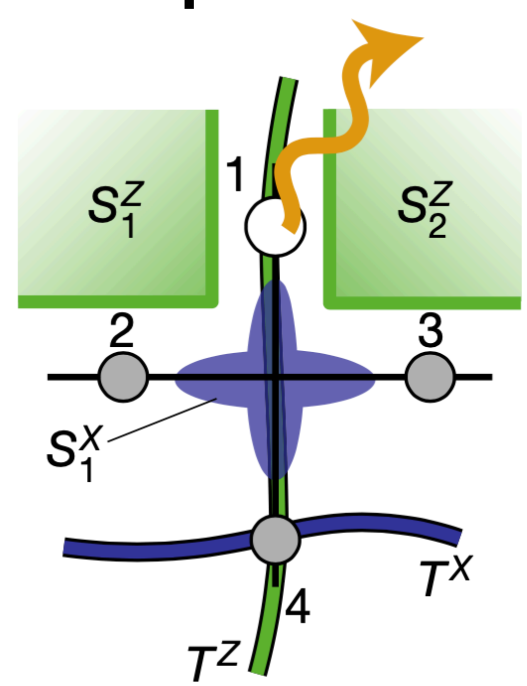
- Devise the smallest example in a trapped ion setup



R Stricker, DV, A Erhard, L Postler, M Meth,
M Ringbauer, P Schindler, T Monz, M Müller, R Blatt
Experimental deterministic correction of qubit loss, Nature 585, 207 (2020)

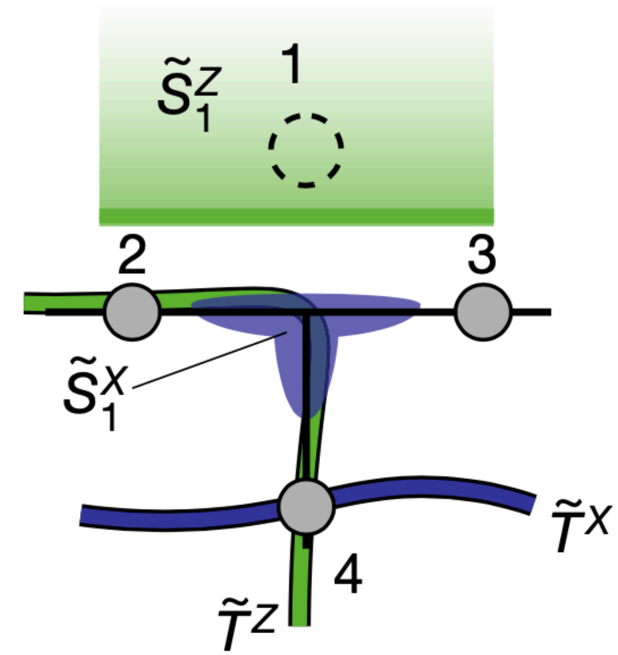
Qubit loss correction with four qubits

4 qubits



Loss

3 qubits



code-switching

3 stabilisers ~ toric code

$$S_1^Z = Z_1 Z_2 \qquad S_2^Z = Z_1 Z_3$$

$$S_1^X = X_1 X_2 X_3 X_4$$

Logical operators

$$T^Z = Z_1 Z_4 \qquad T^X = X_4$$

Code space

$$S_1^Z \left|\psi_L\right\rangle = +\left|\psi_L\right\rangle \quad S_2^Z \left|\psi_L\right\rangle = +\left|\psi_L\right\rangle$$

$$S_1^X \left|\psi_L\right\rangle = +\left|\psi_L\right\rangle$$

2 stabilisers

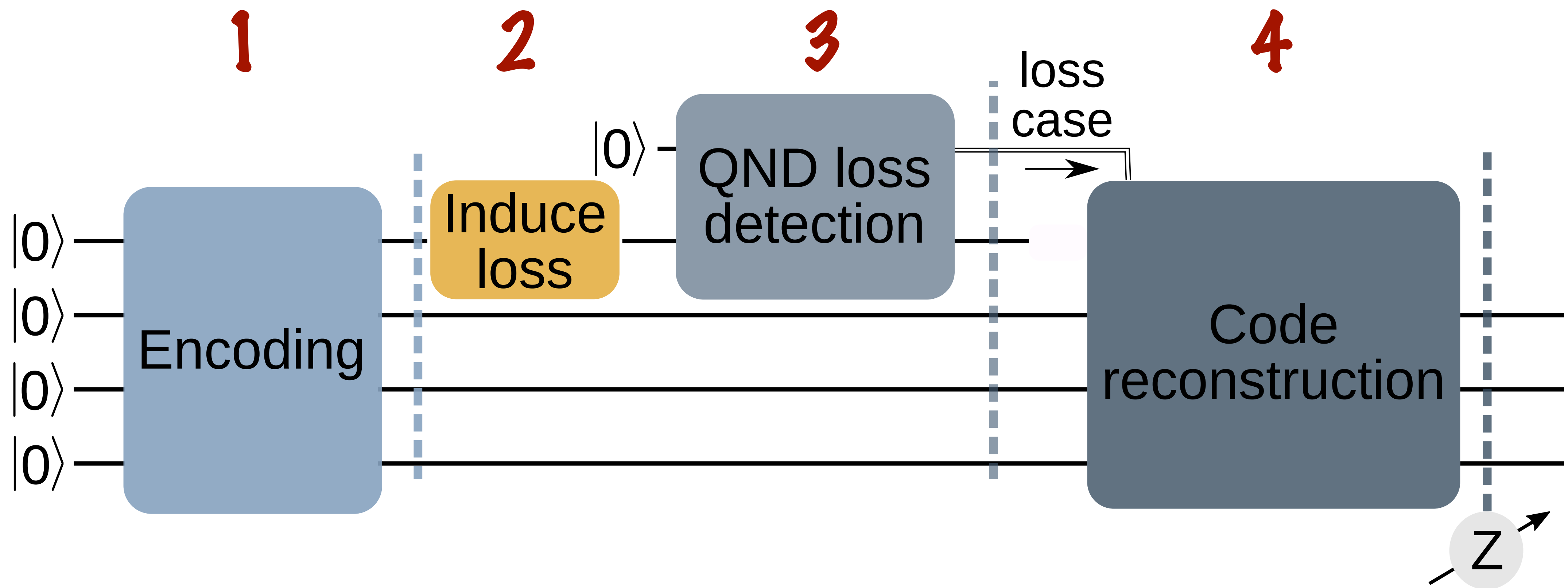
$$\tilde{S}_1^Z = S_1^Z S_2^Z = Z_2 Z_3$$ ✔

$$\tilde{S}_1^X = X_2 X_3 X_4$$ undetermined

$$\tilde{T}^Z = T^Z S_1^Z = Z_2 Z_4$$

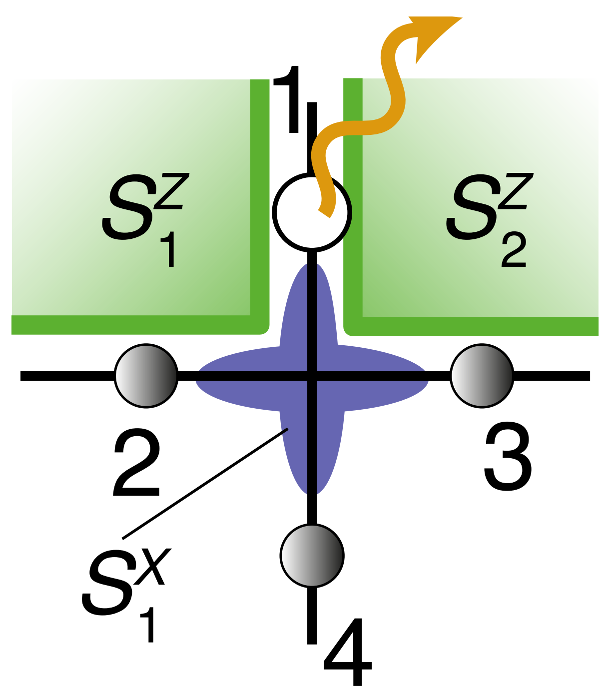
$$\tilde{T}^X = T^X = X_4$$

Experimental qubit loss detection and correction: The whole picture

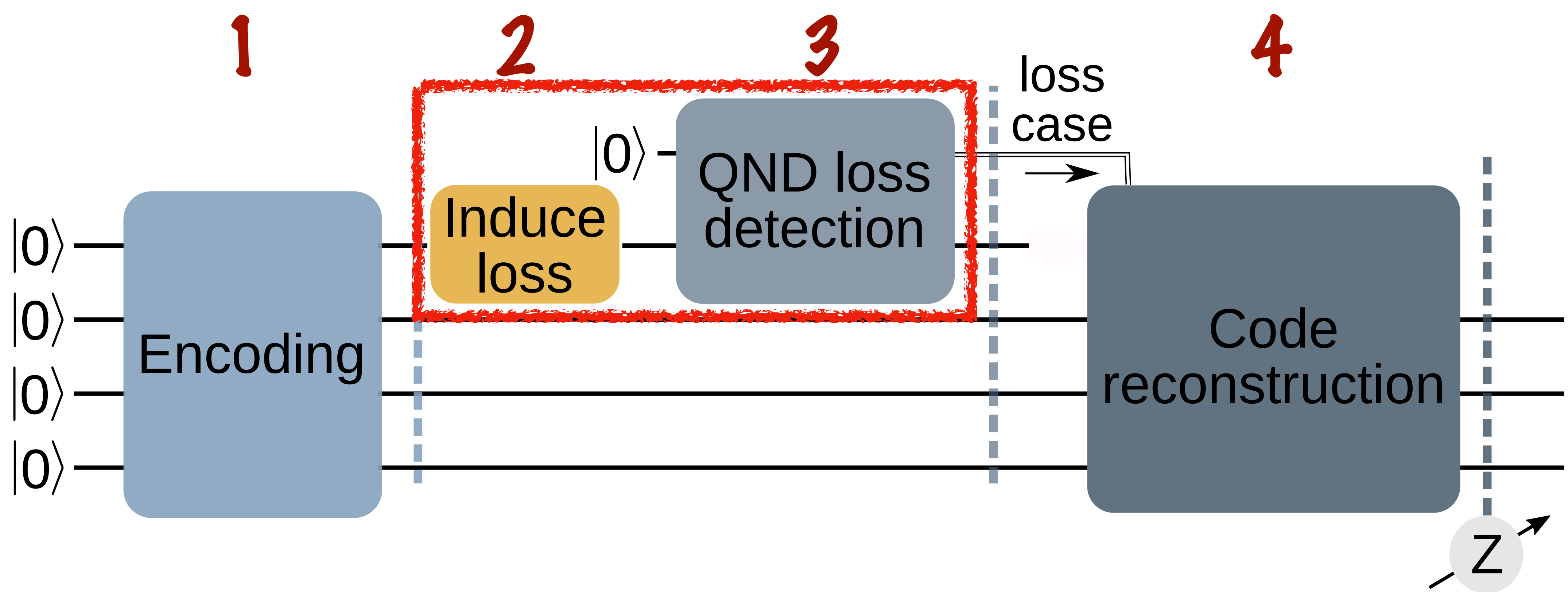


Minimal example

4 physical qubits



Experimental qubit loss detection and correction: The whole picture



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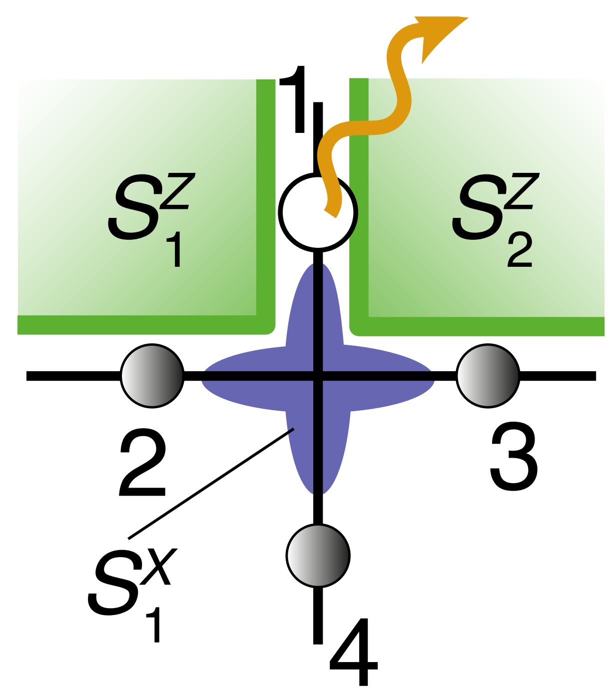
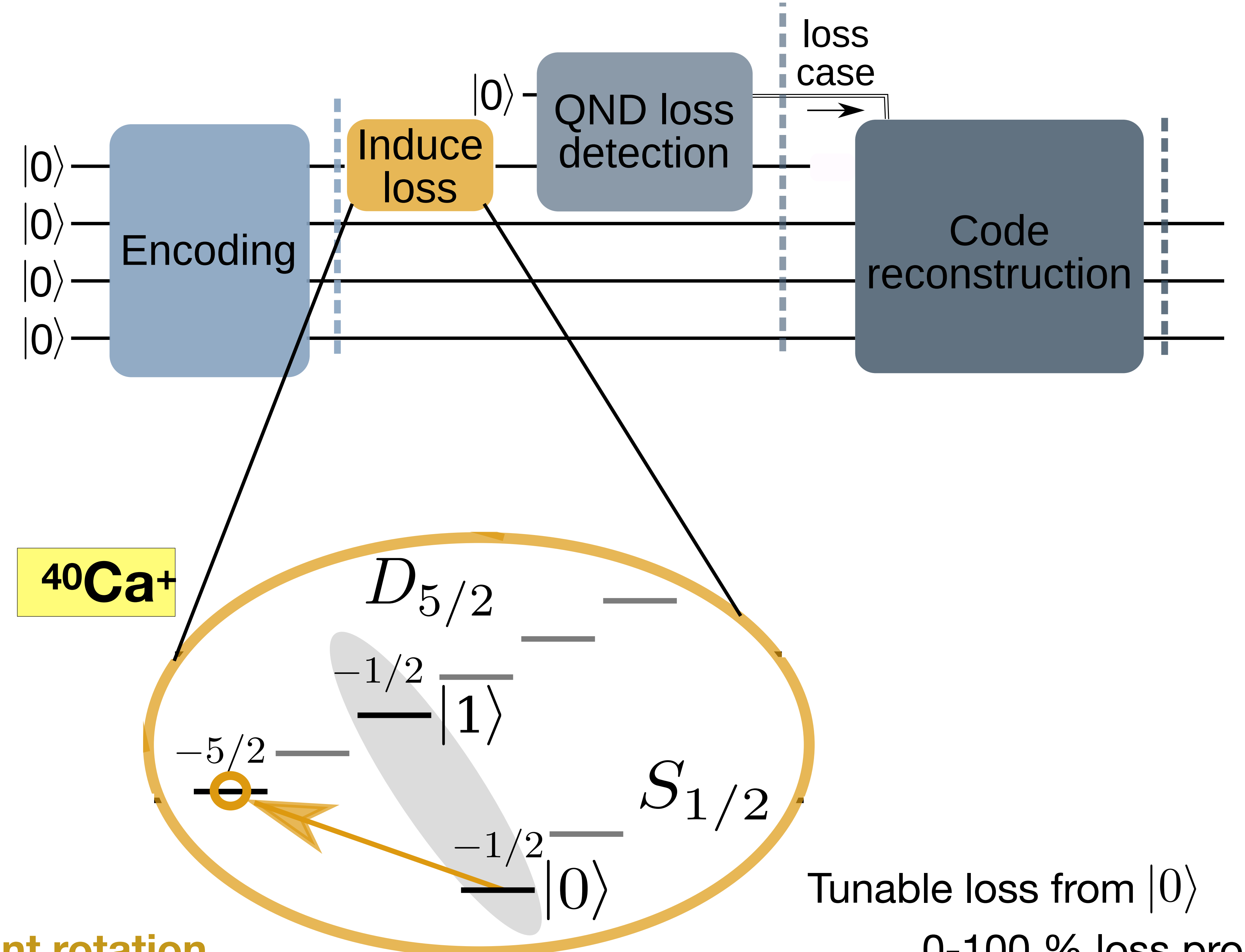
4 physical qubits



2 - Qubit loss event



Coherent rotation

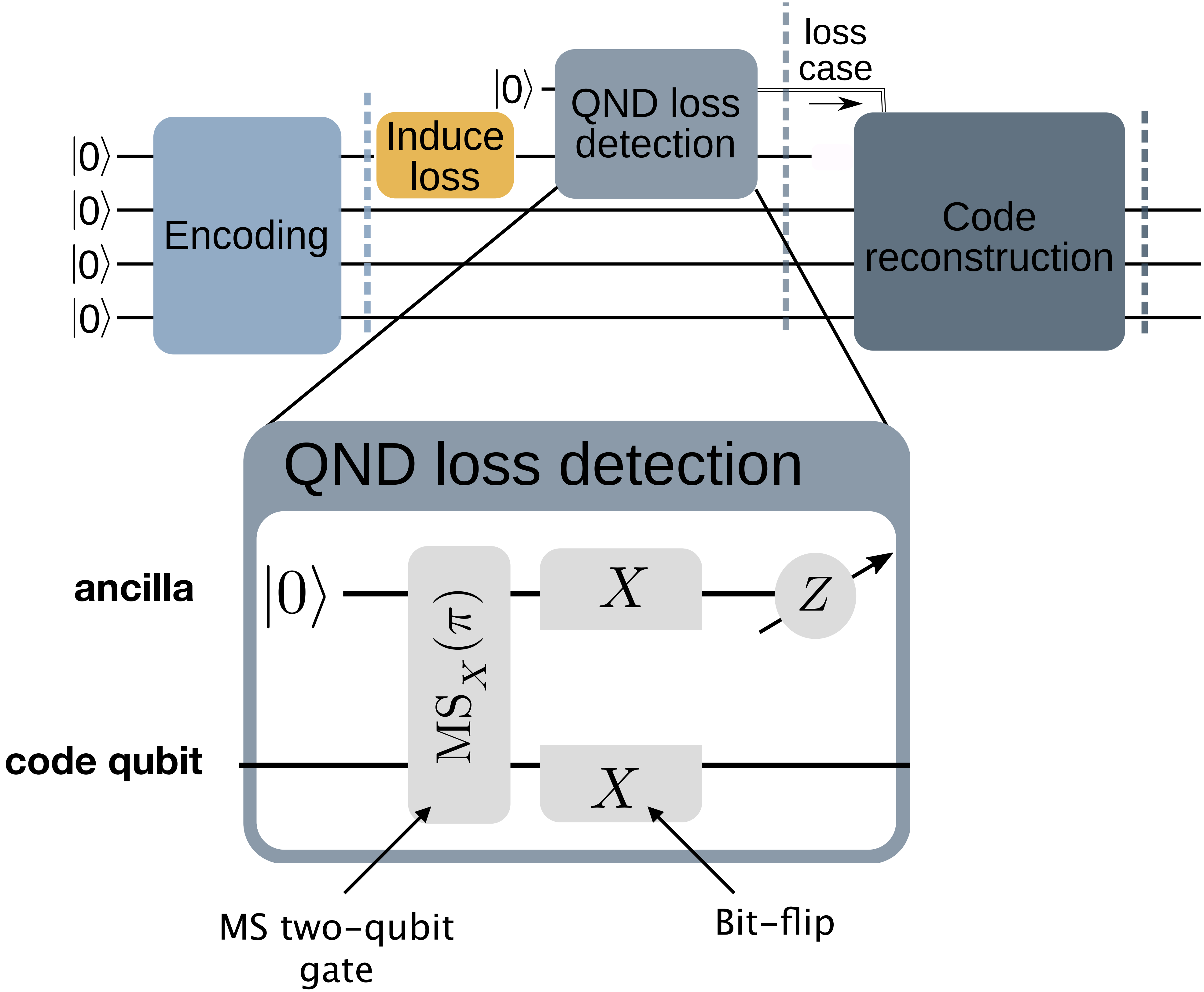
$\boxed{R(\phi)}$

Tunable loss from $|0\rangle$

0-100 % loss probability

$$p_L \sim \sin^2(\phi/2)$$

3 - QND qubit loss detection

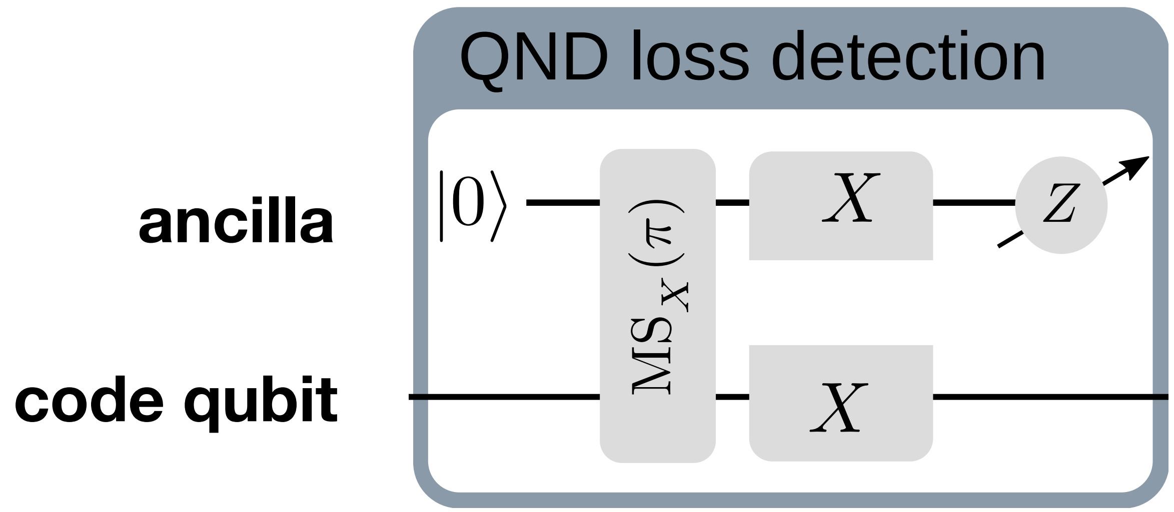


3 - Qubit loss detection

$\mathrm{MS}_X(\pi)$

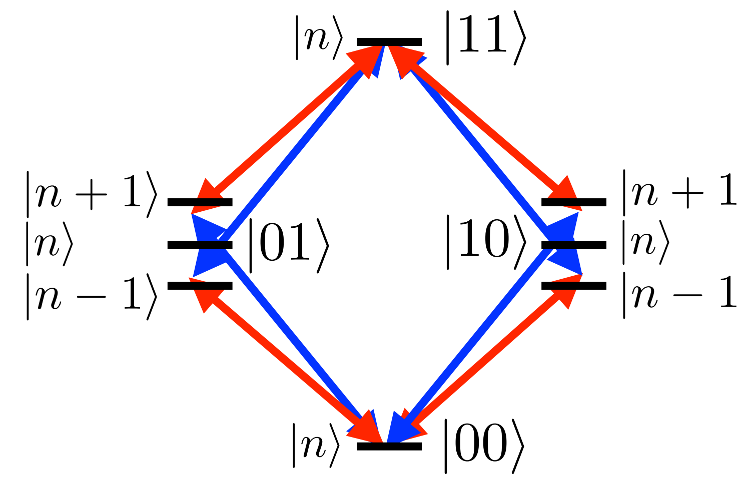
$|00\rangle \longrightarrow |11\rangle$

$|11\rangle \longrightarrow |00\rangle$

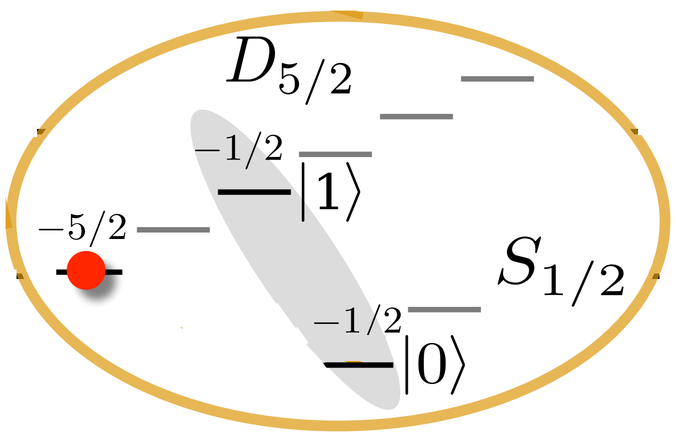


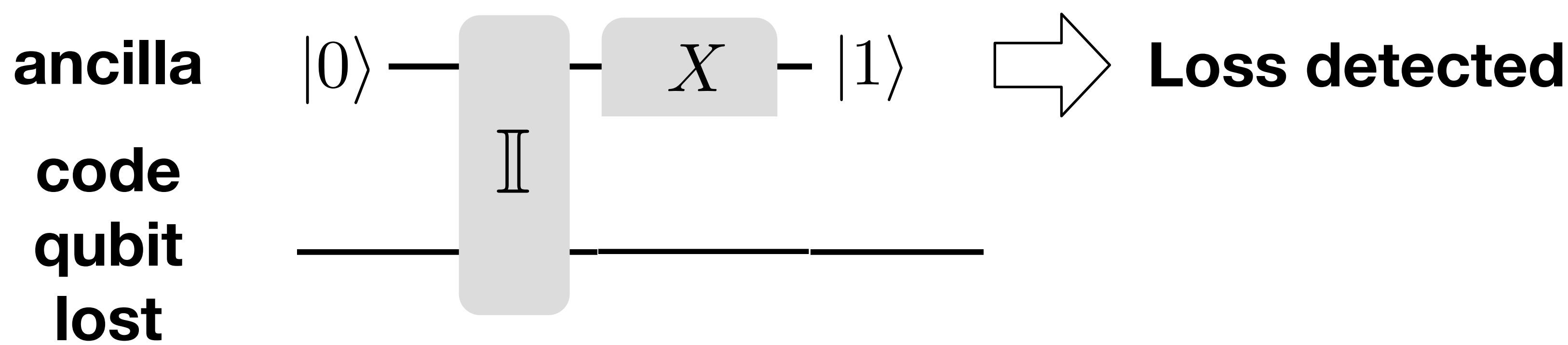
Mølmer-Sørensen gate:

- Bichromatic laser field
- Two-photon resonant process

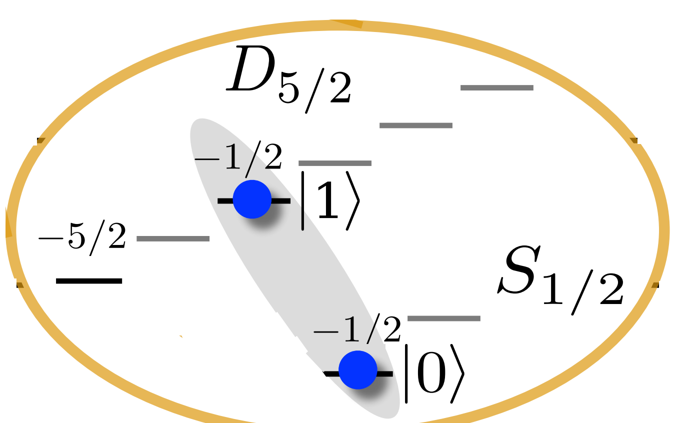


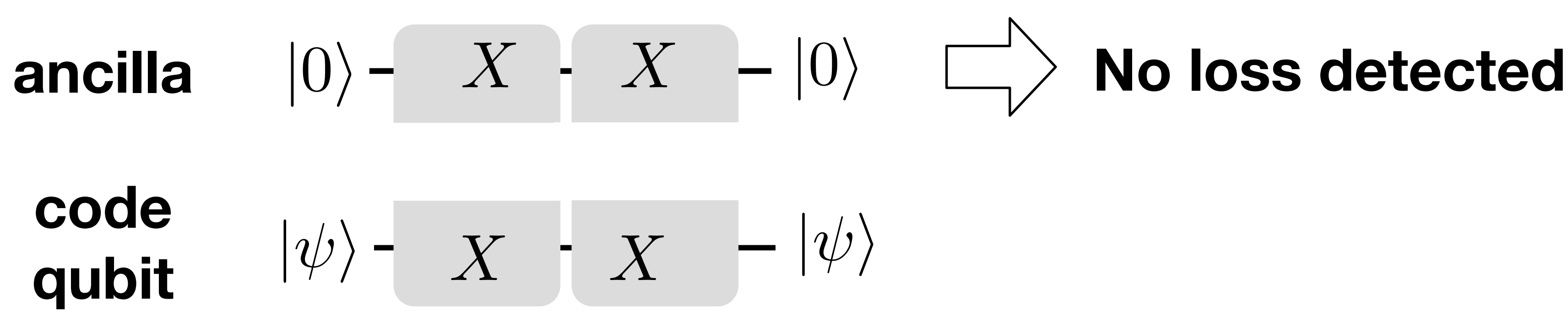
If code qubit is lost





If code qubit is not lost

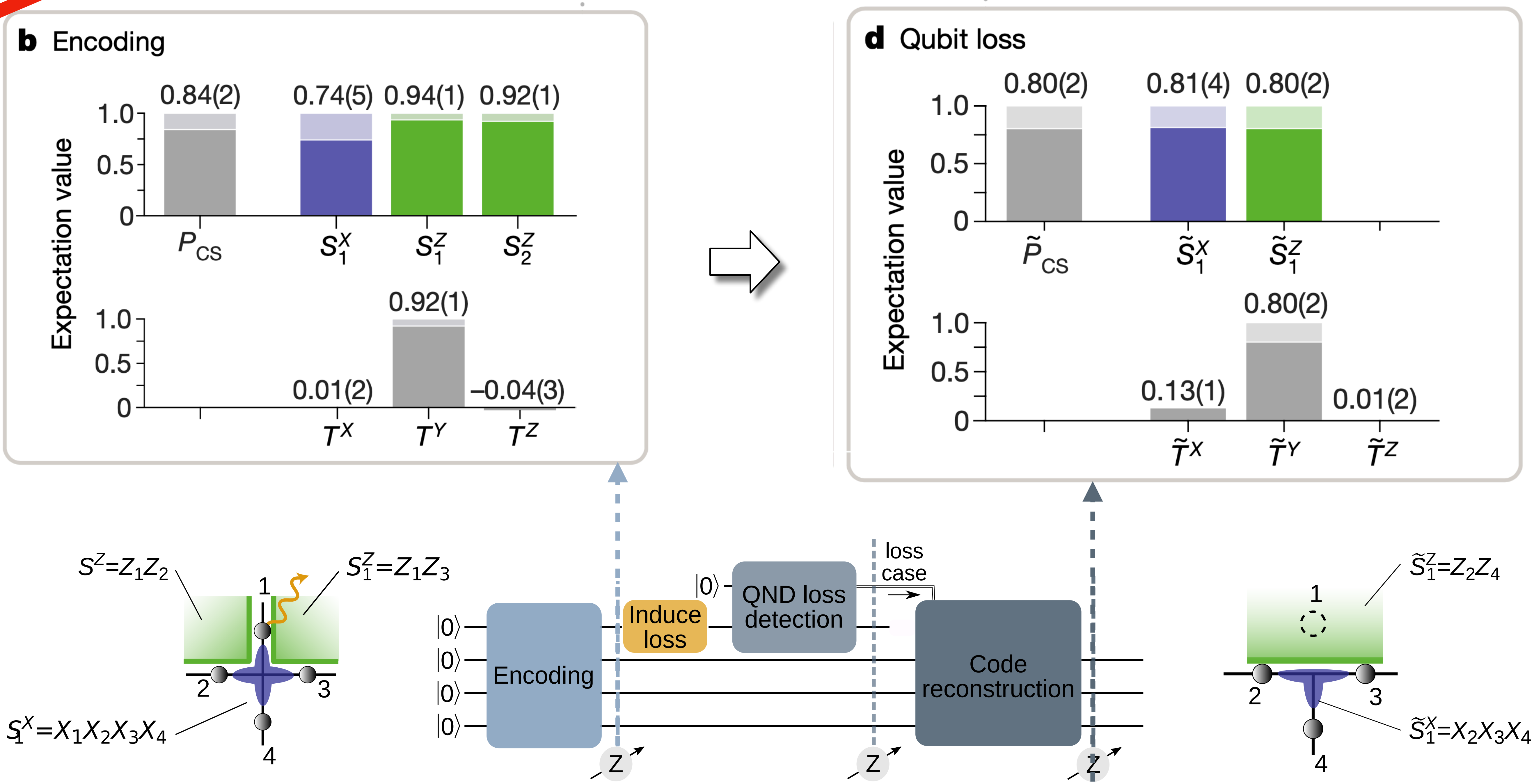




Qubit loss and correction - the entire cycle

Experimental data

$$|\psi_L\rangle = \frac{1}{\sqrt{2}}(|0_L\rangle + i|1_L\rangle)$$

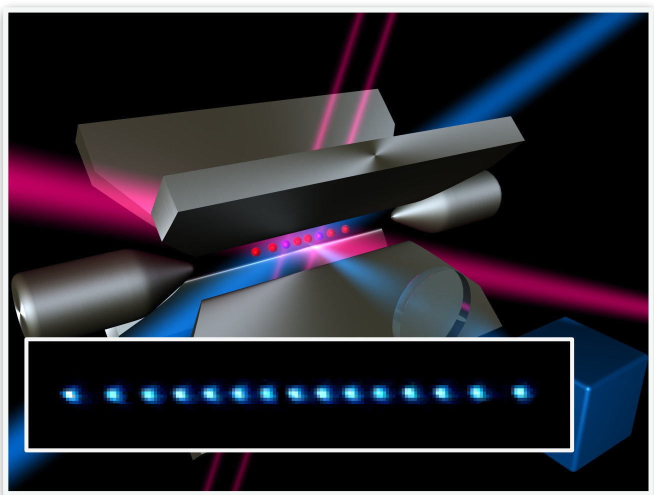


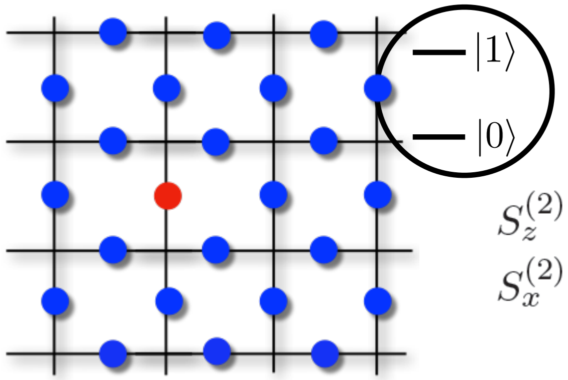
For the other logical states

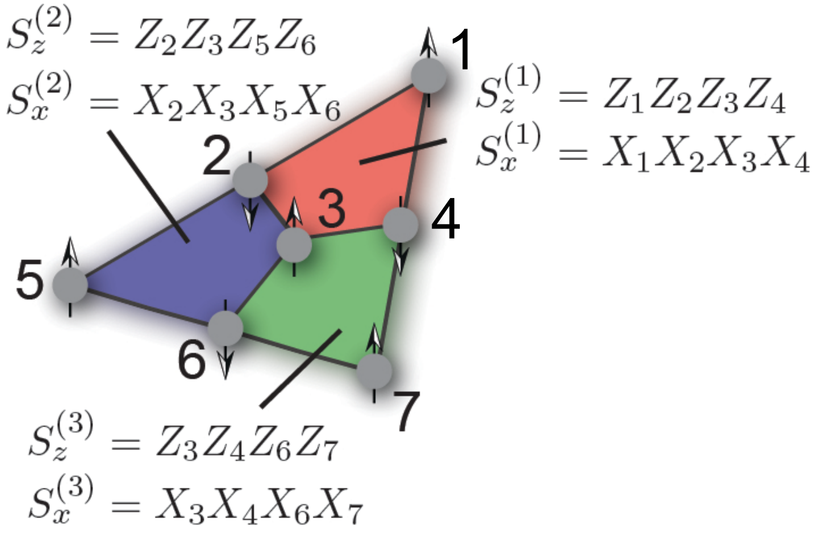
R Stricker et al, Nature 585 207 (2020)

Conclusions

- Quantum error correcting codes can be realised in topological systems
- Losses can affect quantum computers but can be cured with success
- Experimental schemes for detecting and correcting losses can be developed







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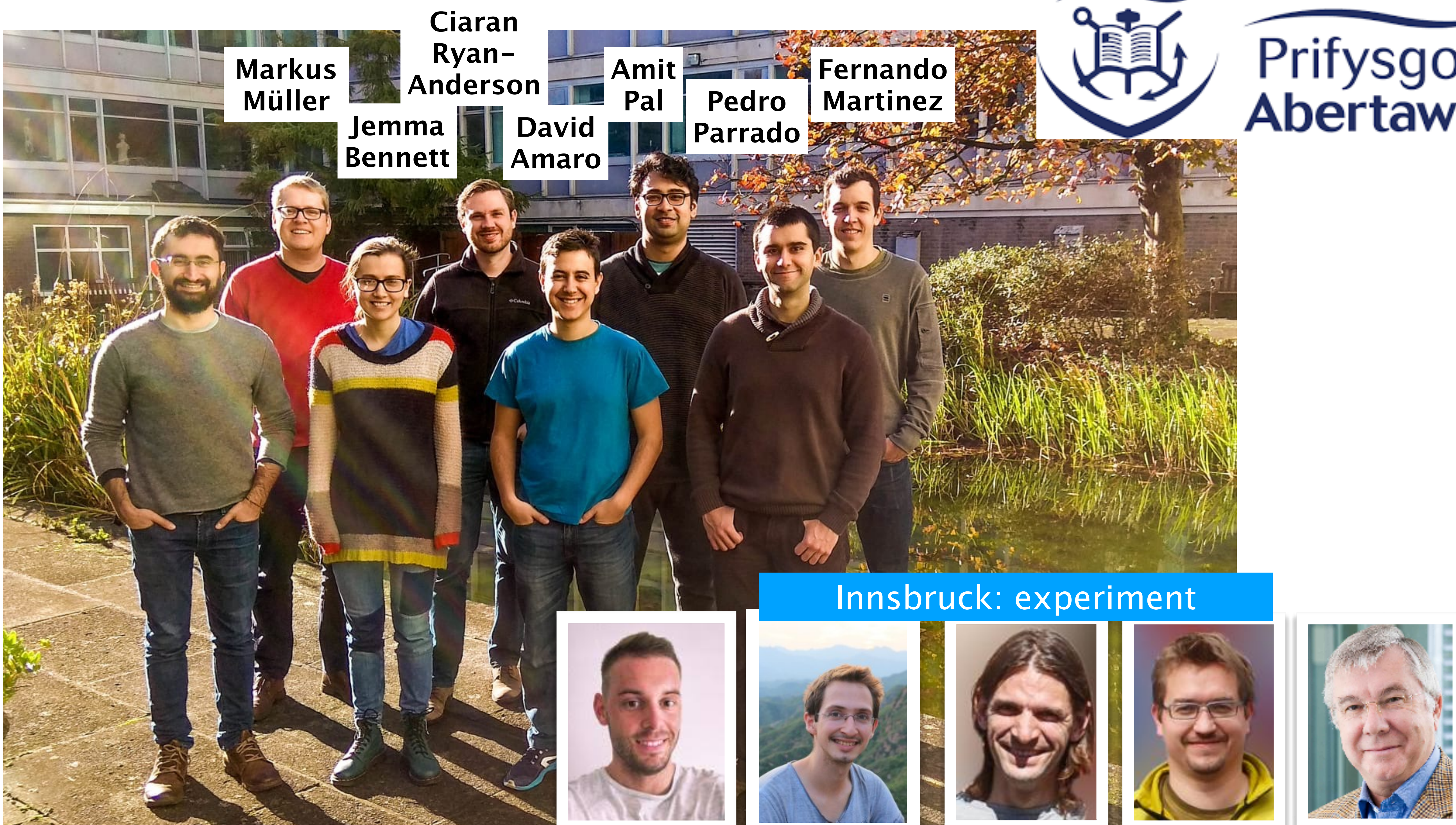
Where this work has started…



Swansea University
Prifysgol Abertawe

First slide image: Harald Ritsch
http://quantum-physics-illustration.com/