

*Alternative paths to fault-tolerance:
from measurement-free QEC
to cellular automata dynamics*

*FTQT, Benasque
August 2026*





*Professor at
Institute for
Quantum Information,
RWTH Aachen*



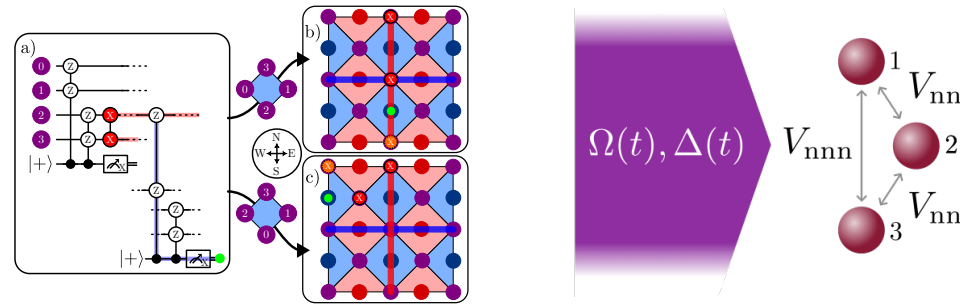
*Director Peter-
Grünberg
Institute (PGI-2),
Forschungs-
zentrum Jülich*

Key Theory and Experimental Areas

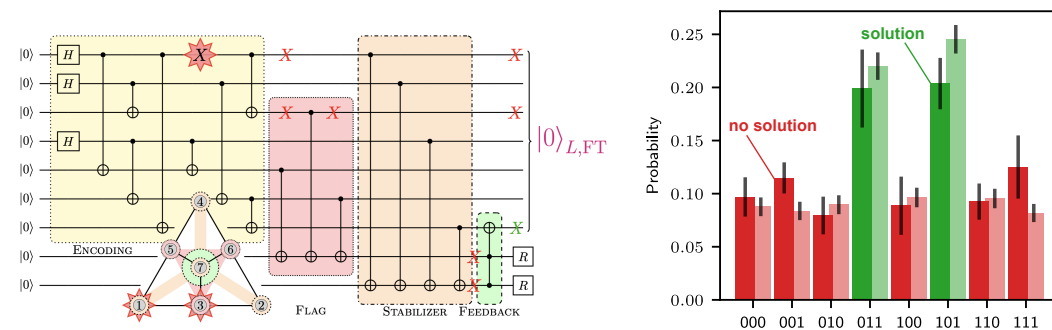
- Quantum error correction
- Fault-tolerant quantum computing
- Open quantum systems
- Semiconductor spin qubits
- Majorana qubits
- Superconducting qubits
- QIP with AMO systems



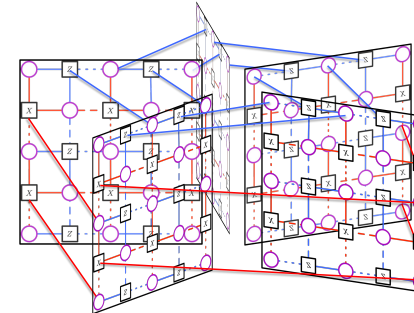
1 - FT QEC with optimized 3-qubit gates only



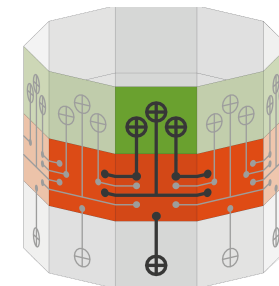
2 - FT Measurement-free QEC and universal computation



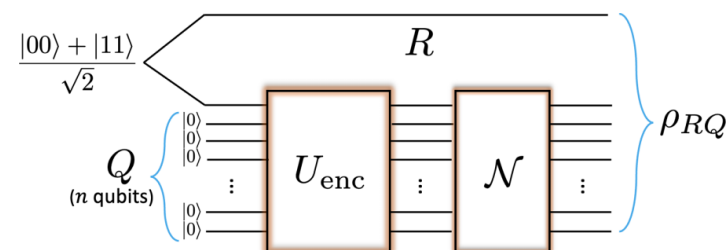
3 - Universal FT QC with lift-connected surface codes



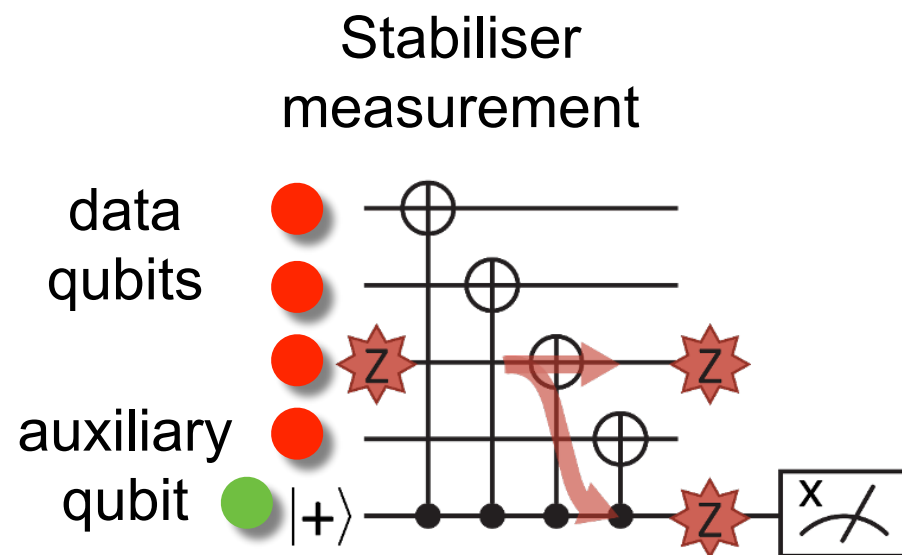
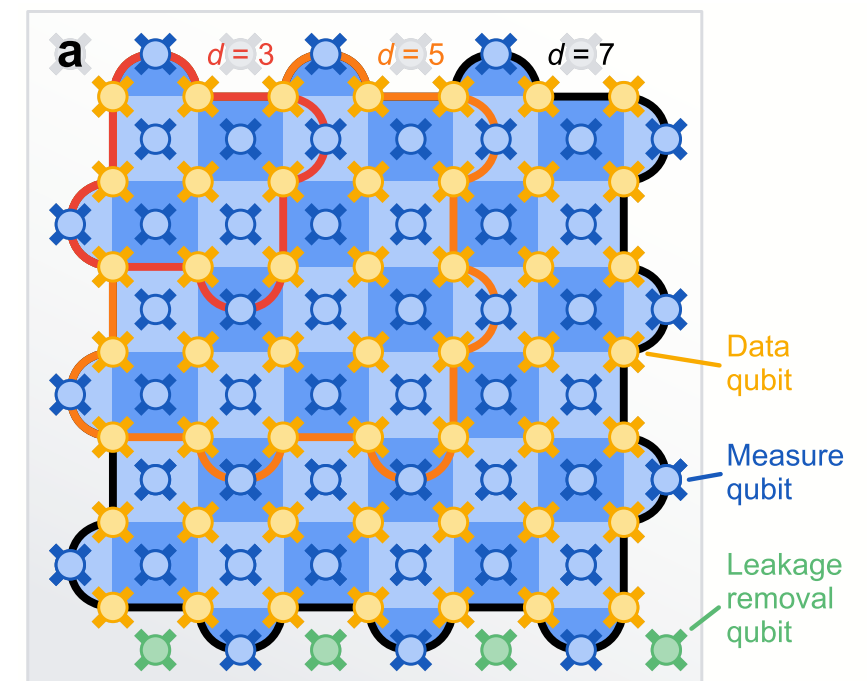
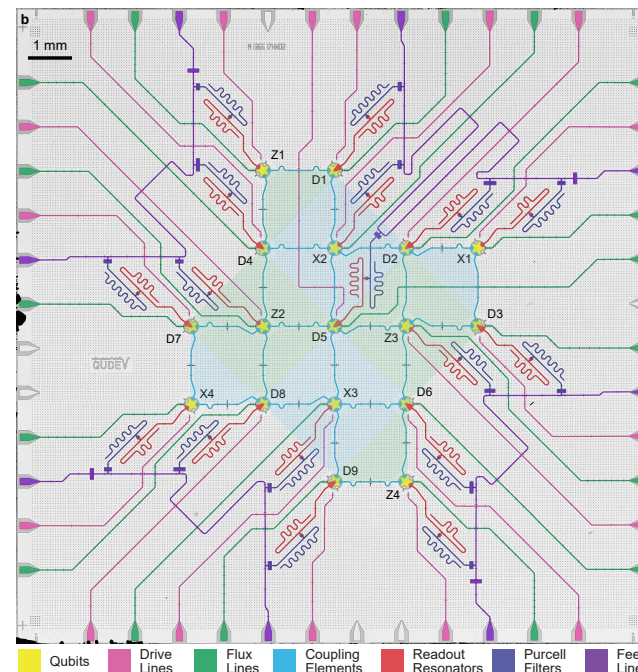
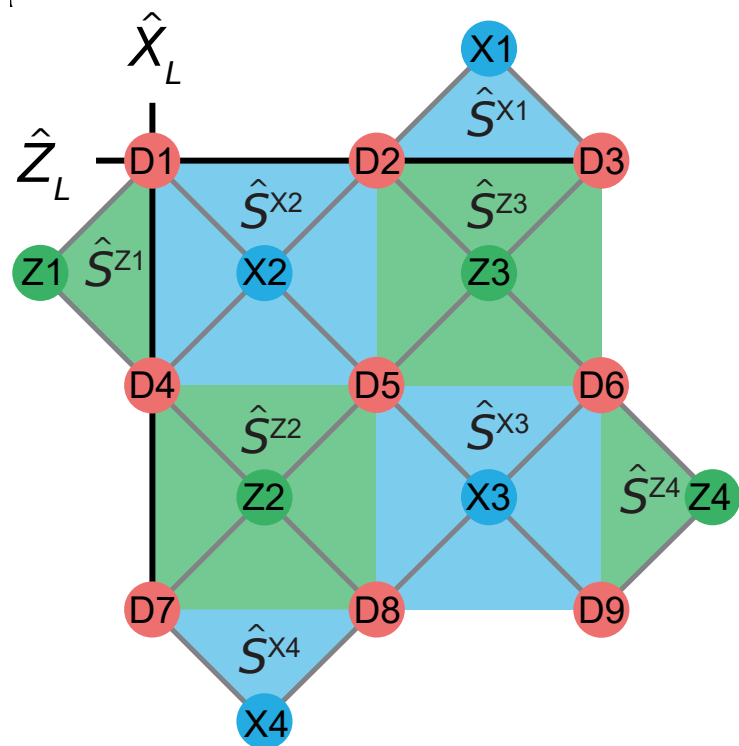
4 - Classical and quantum cellular automata for QEC



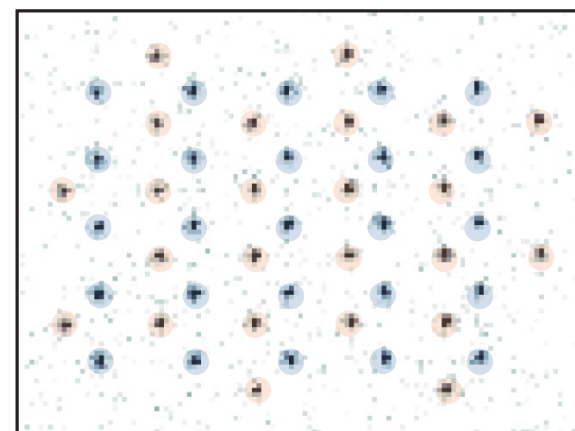
5 - Enhancing QEC thresholds by Syndrome Resampling



Surface code quantum error correction

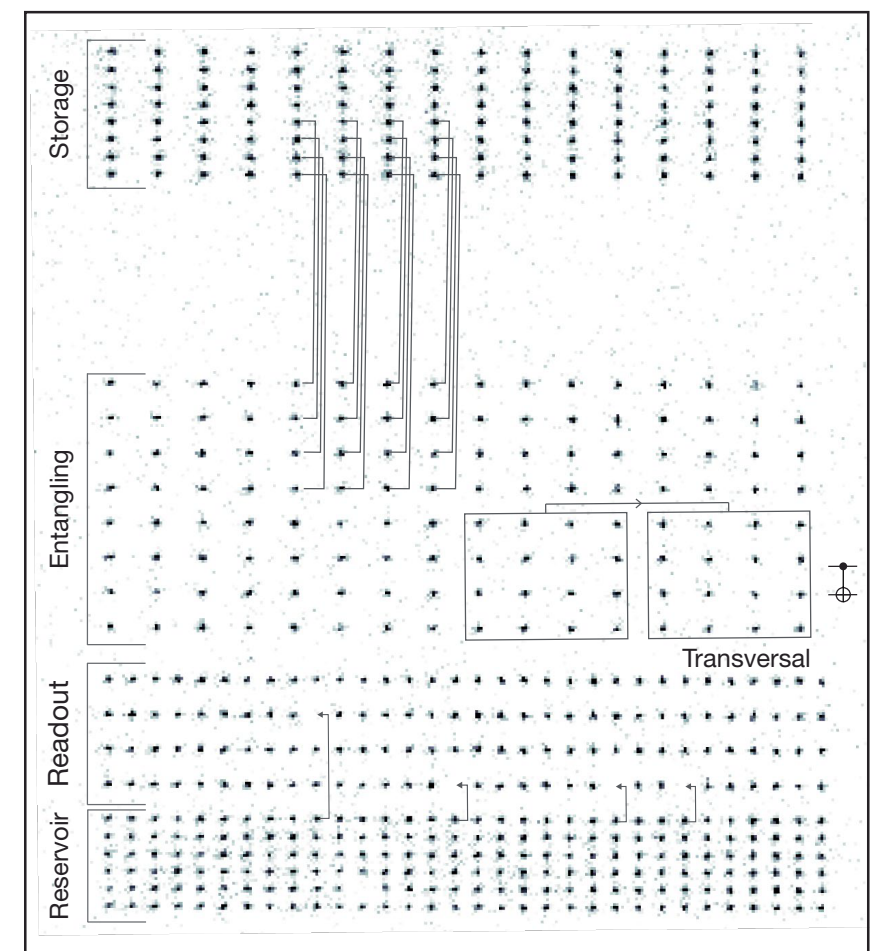


$$|\psi_L\rangle \rightarrow \left[\text{QEC} \right]^N \rightarrow \text{Measurement} \rightarrow X/Z$$



$d = 5$ surface code ● Data ● Ancilla

Architecture



Realizing Repeated Quantum Error Correction in a Distance-Three Surface Code

S. Krinner, ..., M. M., A. Blais, C. Eichler, A. Wallraff, **Nature 605, 669 (2022)**

Quantum error correction below the surface code threshold

Google Quantum AI and Collaborators, **Nature 638, 920 (2025)**

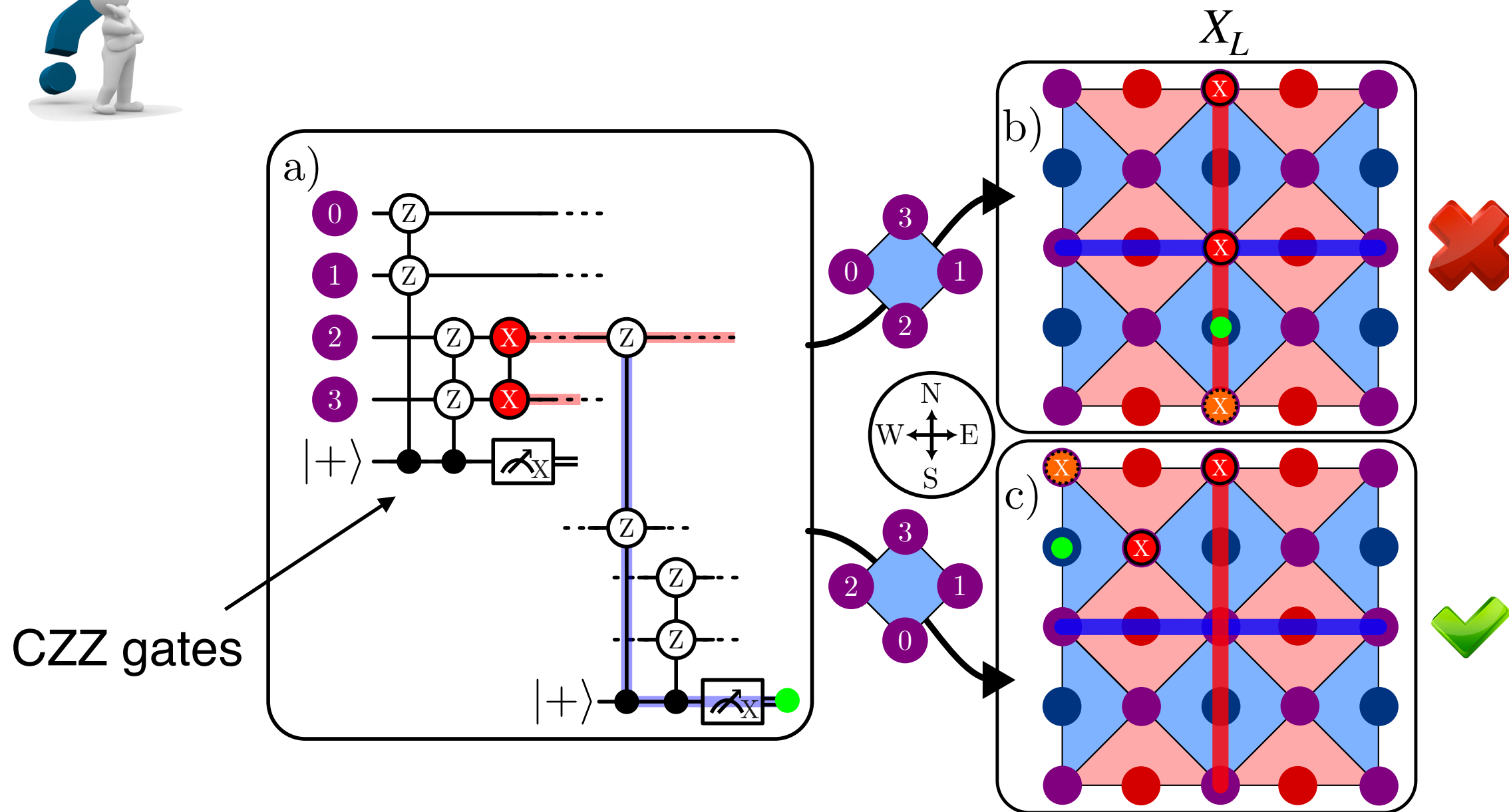
A fault-tolerant neutral-atom architecture for universal QC

D. Bluvstein et al. (Harvard & QuEra), **Nature 649, 39 (2026)**

Fault-tolerant quantum error correction with 3-qubit gates?



Can we use 3-qubit instead of 2-qubit entangling gates, without breaking fault-tolerance?



► Yes, stabiliser readout in the **unrotated surface code** can be fault-tolerant with 3-qubit gates only

Fault-Tolerant Stabilizer Measurements in Surface Codes with Three-Qubit Gates

J. Old, S. Tasler, M. J. Hartmann, M. M., **Phys. Rev. Lett.** 135, 240601 (2025)

See also back-to-back publication:

Low-Depth QEC via Three-Qubit Gates in Rydberg Atom Arrays

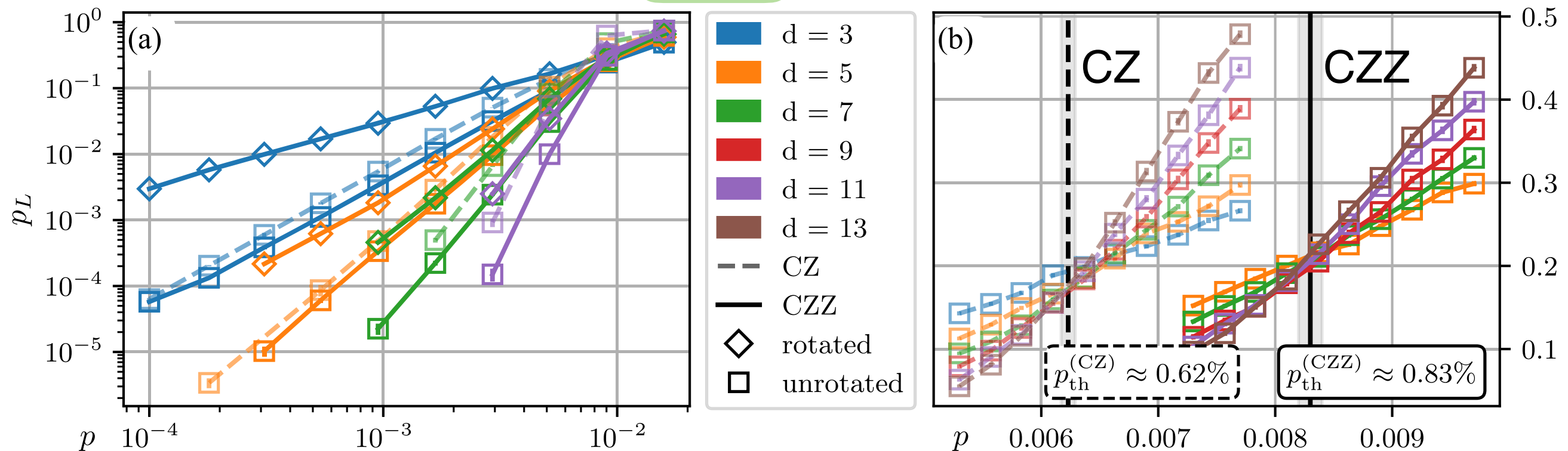
L. Pecorari, S. Jandura, G. Pupillo, **Phys. Rev. Lett.** 135, 240602 (2025)

Fault-tolerant quantum error correction with 3-qubit gates?



Can we use 3-qubit instead of 2-qubit entangling gates, without breaking fault-tolerance?

Circuit-level noise model with $p_3 = \frac{3}{2}p$ (and $p_{\text{idle}} = \frac{p}{2}$): decoherence-limited regime



- Yes, stabiliser readout in the **unrotated surface code** can be fault-tolerant with 3-qubit gates only
- Up to 50% lower logical error rate, and moderate increase of the threshold

Fault-Tolerant Stabilizer Measurements in Surface Codes with Three-Qubit Gates

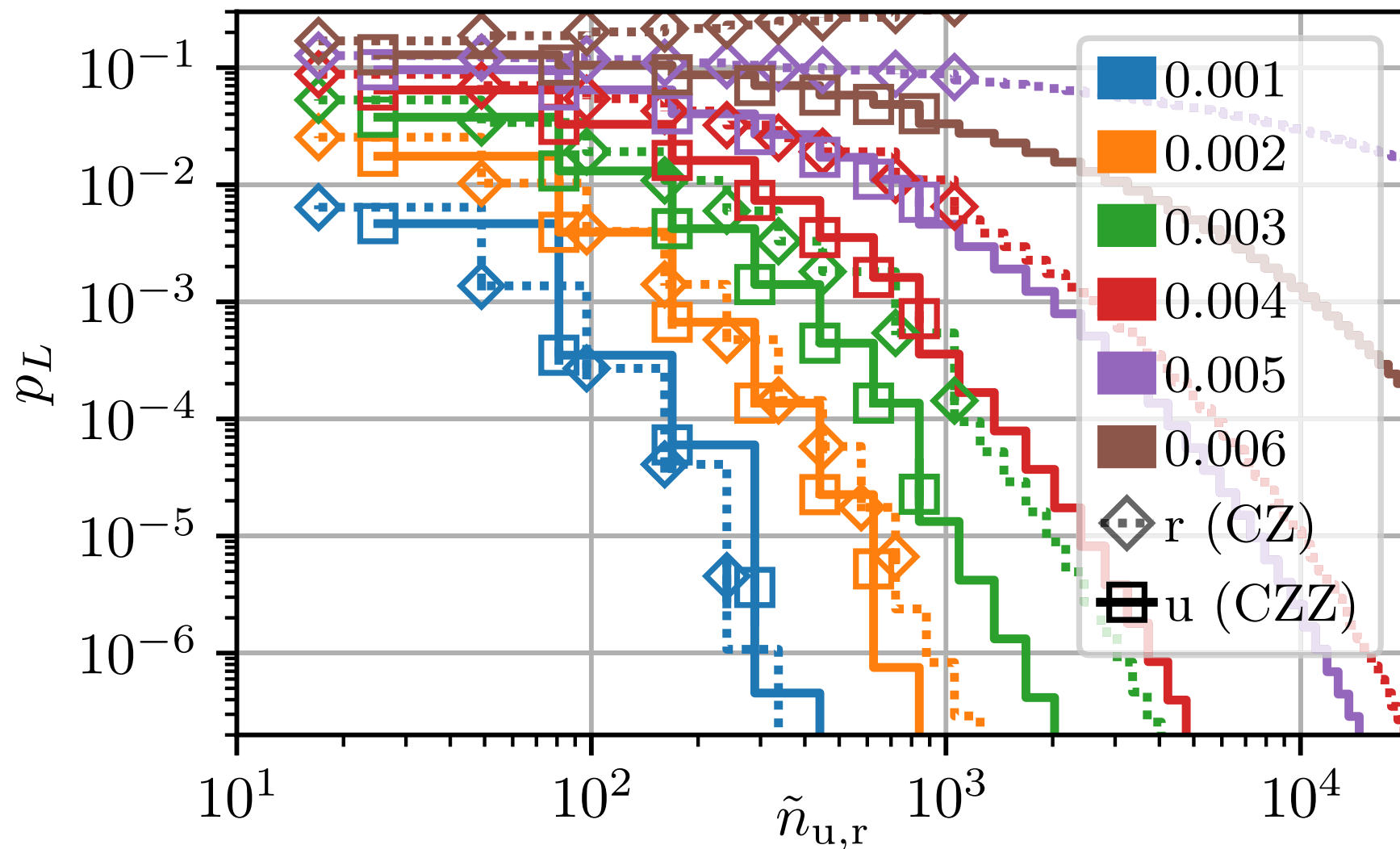
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Fault-tolerant quantum error correction with 3-qubit gates?



- ▶ **Lower physical qubit count** for equal target logical error rate in decoherence-limited regime:
- ▶ For $p > 0.2\%$ the **CZZ-based unrotated surface code** ($n = 4d^2 - 4d + 1$) outperforms the **CZ-based rotated surface code** ($n = 2d^2 - 1$)
- ▶ E.g. for $p_L = 10^{-6}$ one requires $d_u = 13$ ($n_u = 625$) vs $d_r = 21$ ($n_u = 881$): 40% qubit saving

Fault-Tolerant Stabilizer Measurements in Surface Codes with Three-Qubit Gates

J. Old, S. Tasler, M. J. Hartmann, M. M., **Phys. Rev. Lett.** **135**, 240601 (2025)

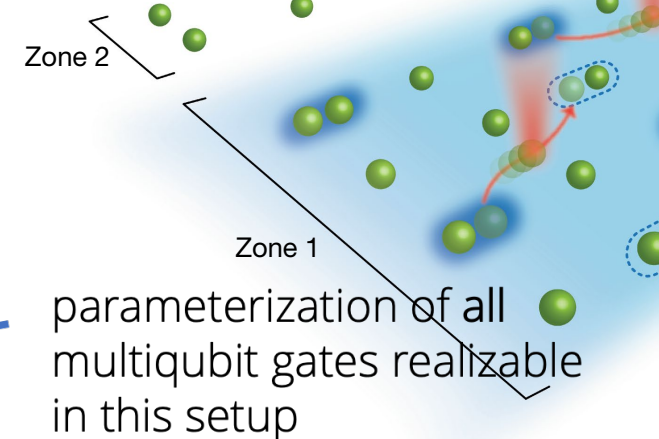
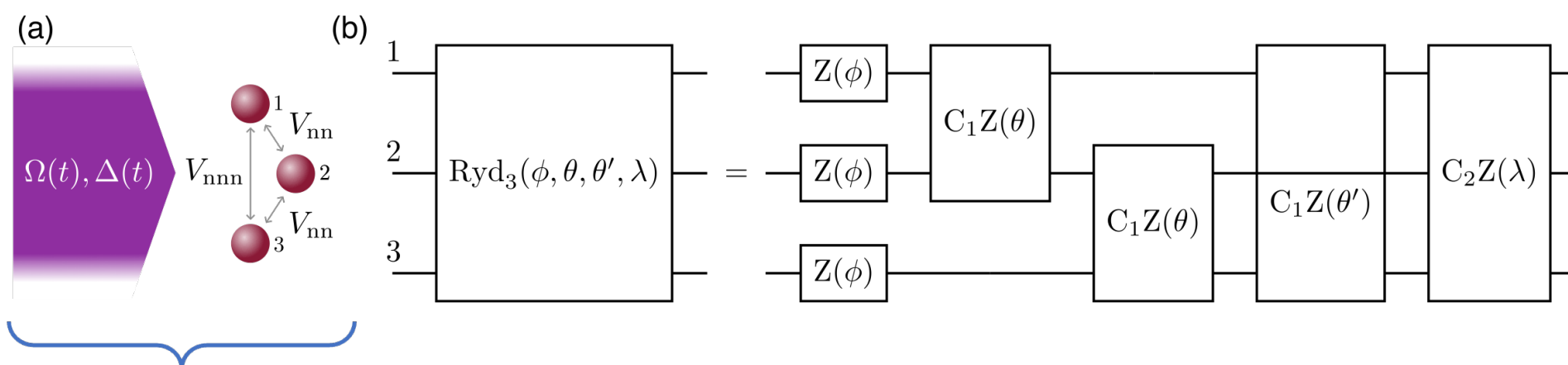
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Optimised multi-qubit Rydberg gates

- ▶ Joint work with H.P. Büchler's group at Stuttgart University
- ▶ Experimentally practicable approach: “global” Rydberg laser pulses, e.g.



$$H(t) = \hbar \sum_{i=1}^N \frac{1}{2} (\Omega(t) |r_i\rangle \langle 1_i| + \text{h.c.}) + \Delta(t) |r_i\rangle \langle r_i| + \sum_{i,j < i} V_{ij} |r_i r_j\rangle \langle r_i r_j|$$

- ▶ Open-source Python package **RydOpt**

🏠 / RydOpt - A Multiqubit Rydberg Gate Optimizer [View page source](#)

RydOpt - A Multiqubit Rydberg Gate Optimizer

docs passing tests passing pypi v0.1.0

RydOpt is a Python package for the optimization of laser pulses implementing two- and multiqubit Rydberg gates in neutral atom quantum computing platforms. The optimization methods support GPUs and multi-core CPUs, using an efficient implementation based on JAX.

- ▶ Key features:

- generate smooth, analytical pulse shapes, described by a small number of parameters

e.g.
$$\xi(t) = \sum_{n=1}^K \alpha_n \sin \left(\frac{2\pi}{T} n \left(1 + \frac{1}{2} \tanh(A_n) \right) \left(t - \frac{T}{2} \right) \right)$$

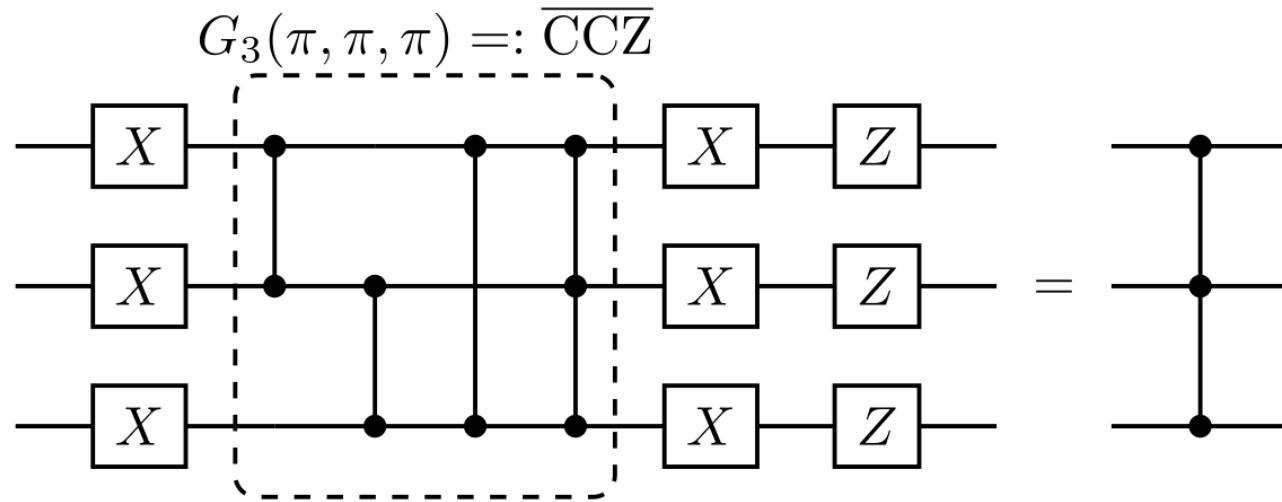
- pulse complexity can be increased systematically by increasing the parameter count
- find parameter-optimal, time-optimal, and Rydberg-time optimal gate pulses

Multiqubit Rydberg Gates for QEC

D. F. Locher, J. Old, K. Brechtelsbauer, J. Holschbach, H.-P. Büchler, S. Weber, and M. M., PRX Quantum 7, 020354 (2026)

Example: CCZ gate

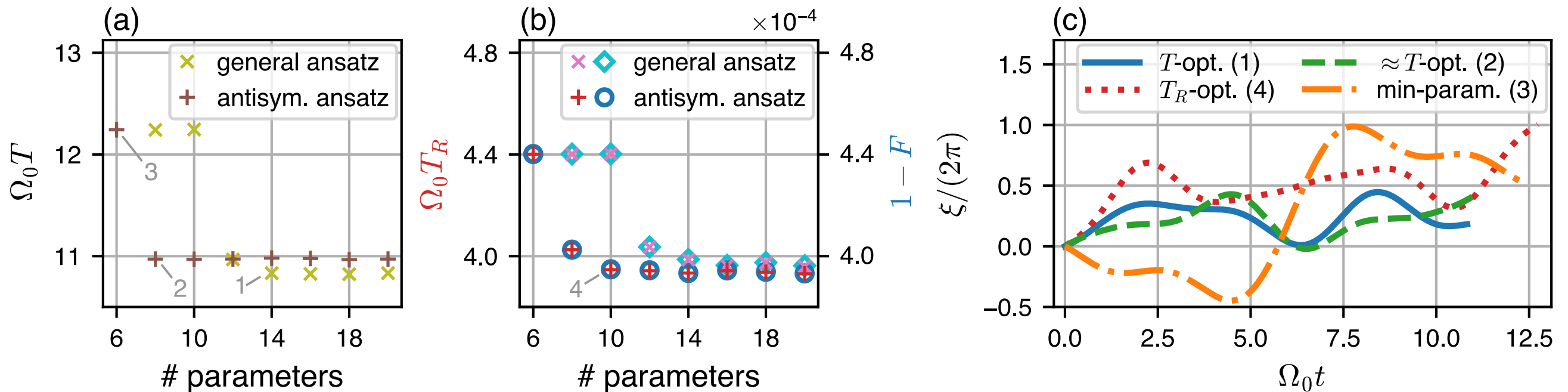
Optimised multi-qubit Rydberg gates



faster than “standard” CCZ [Evered et al. Nature (2023)]

- A good gate should
- have **small # parameters**
 - be **fast**
 - **minimise decay** from Rydberg states (included in optimisation)

$$T_R = \int_0^T \sum_{i=1}^N \langle + |^{\otimes N} U(t)^\dagger | r_i \rangle \langle r_i | U(t) | + \rangle^{\otimes N} dt$$



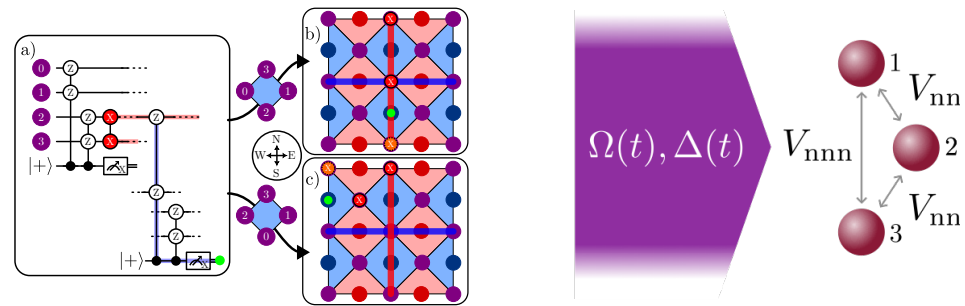
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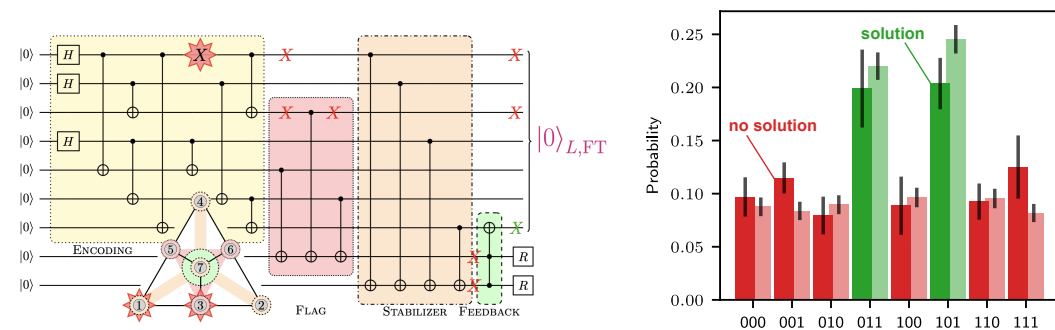
Optimizing Superconducting Three-Qubit Gates for Surface-Code Error Correction

S. Tasler, J. Old, L. Heunisch, V. Feulner, T. Eckstein, M. M., and M. J. Hartmann, arXiv:2506.09028 (2025)

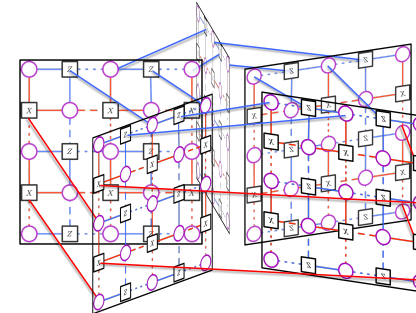
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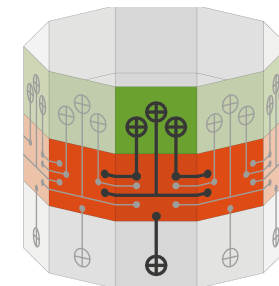
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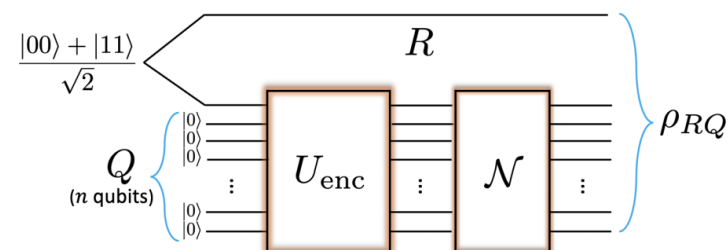
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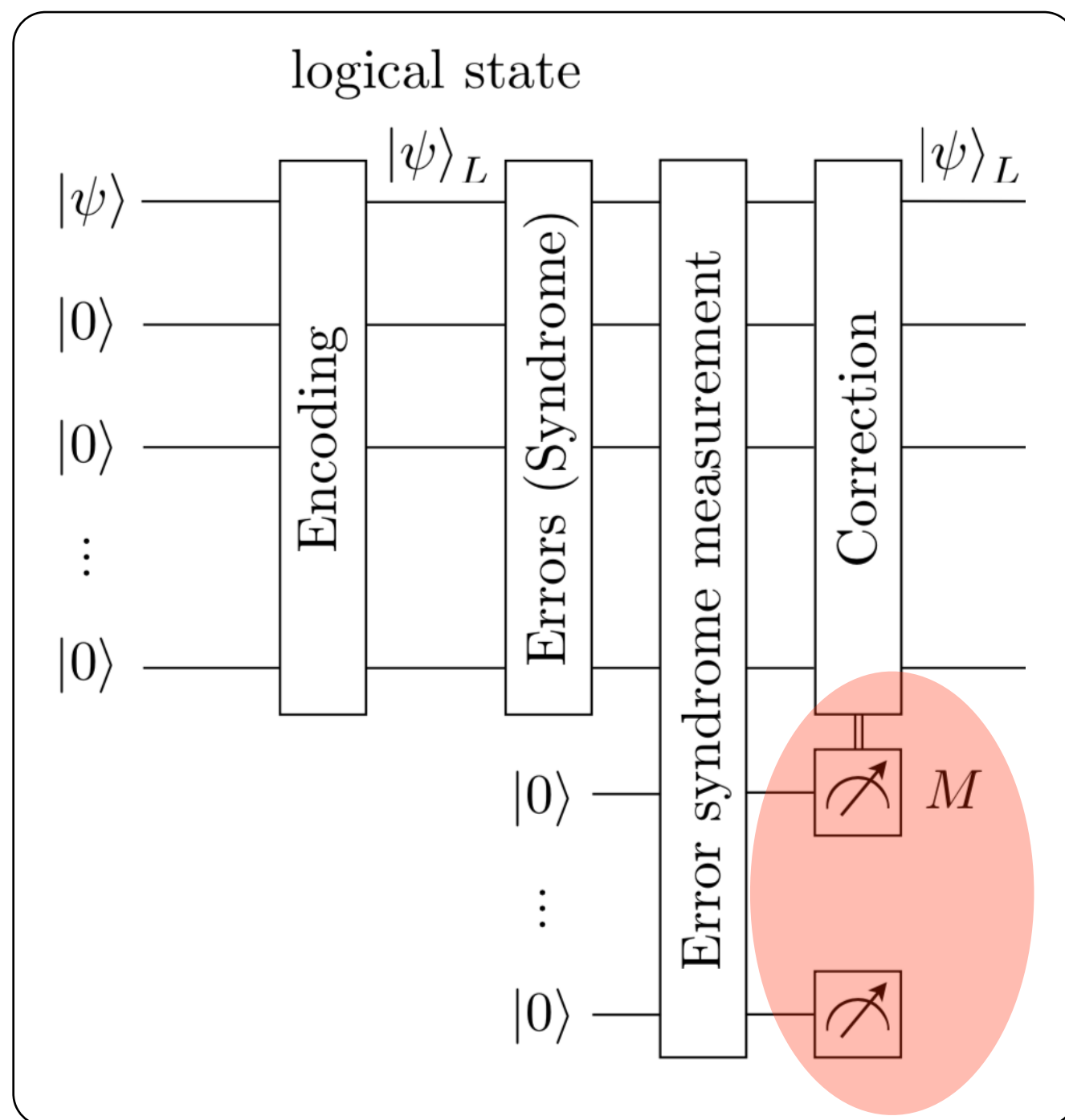


Measurement-free, yet fully fault-tolerant QEC

Can we realise fault-tolerant QEC without in-sequence measurements?

Motivation and challenges

- ▶ **Measuring qubits** often orders of magnitude **slower** than gates and/or **destructive** (e.g. neutral atoms)
- ▶ Can be **technologically challenging**
- ▶ Standard quantum error correction: needs **in-sequence measurements**, possibly in-sequence logic
- ▶ **Quantum fault-tolerance:** overhead, but prevents error propagation



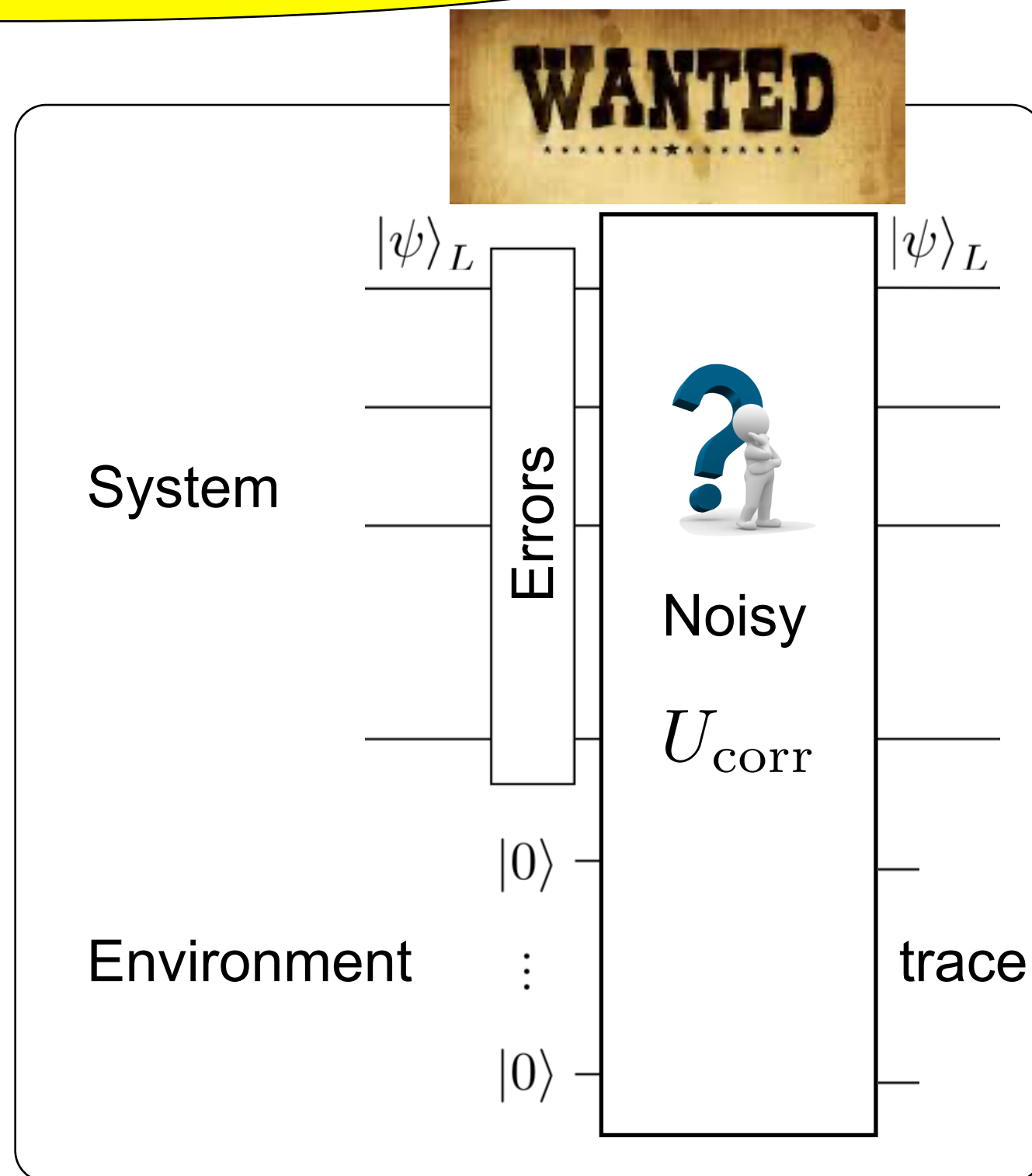
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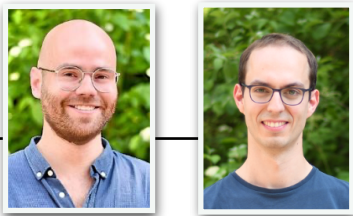


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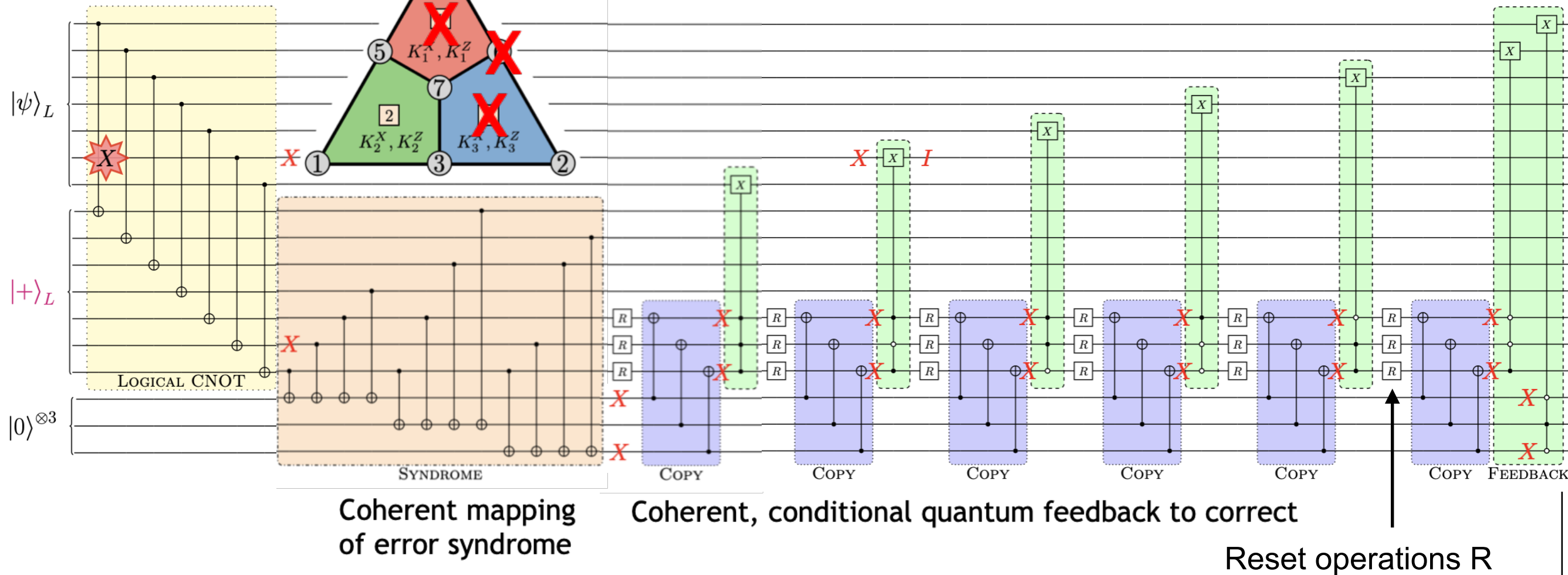
S. Heußen D. Locher

Measurement-free, yet fully fault-tolerant QEC

Measurement-free fault-tolerant quantum error correction in near-term devices

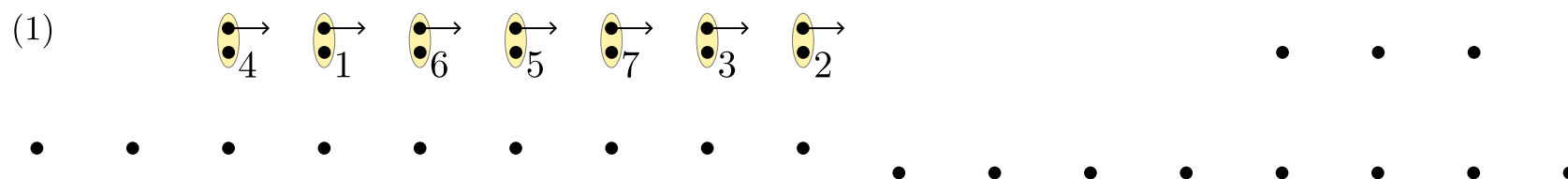
S. Heußen, D. F. Locher, M. Müller, PRX Quantum 5, 010333 (2024)

Featured in Physics



► Fully fault-tolerant, general protocol (CSS codes)

► Realistic implementation protocol in atom tweezer array



✓ Ideal e.g. for neutral Rydberg-atom quantum computers

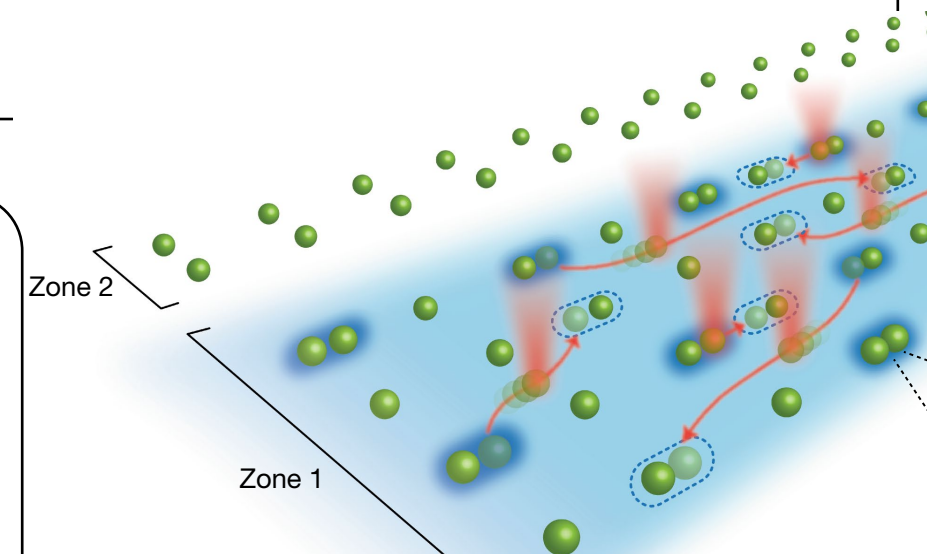
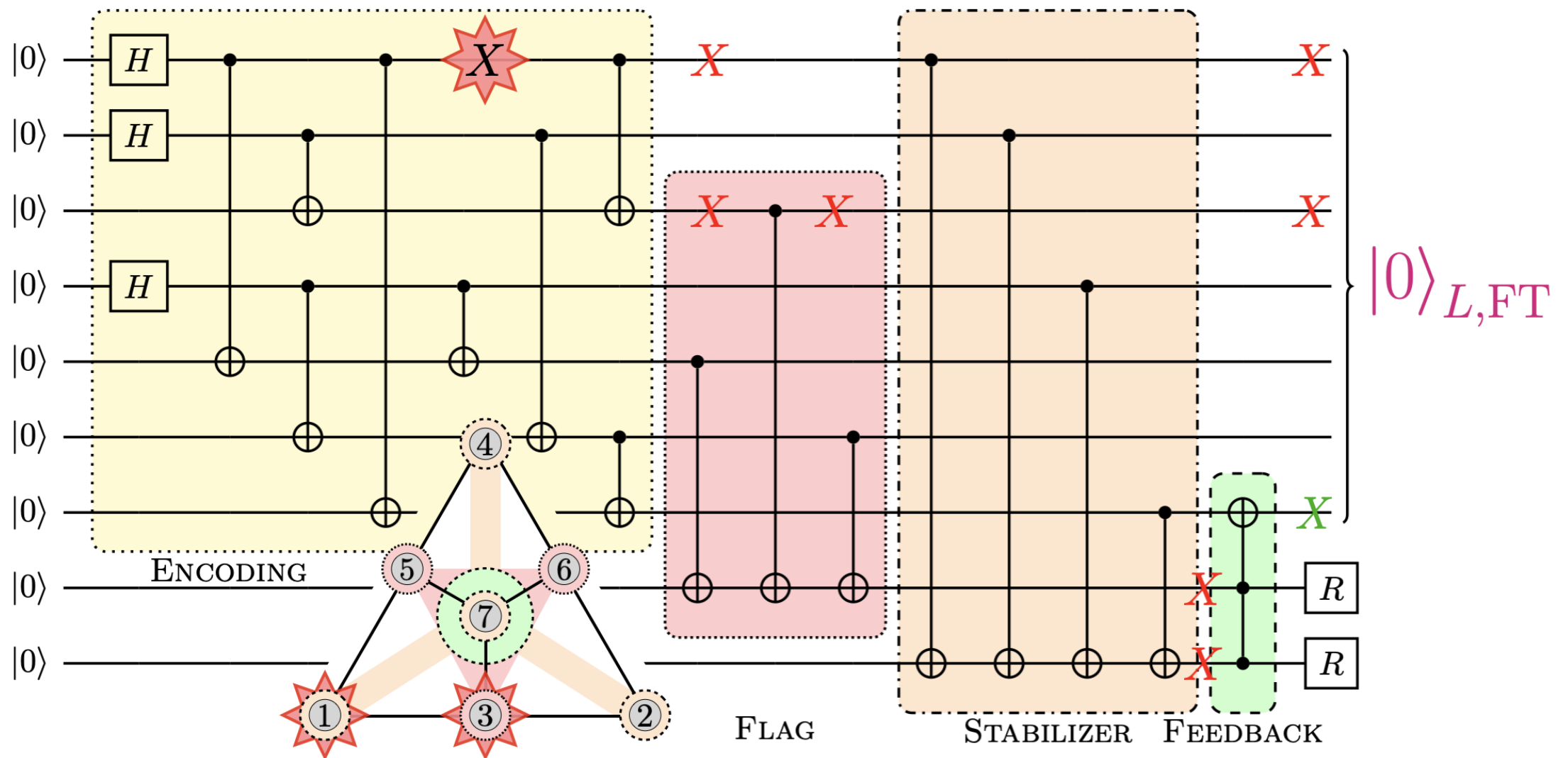


Figure adapted from Nature 604, 451 (2022)

Measurement-free, yet fully fault-tolerant QEC

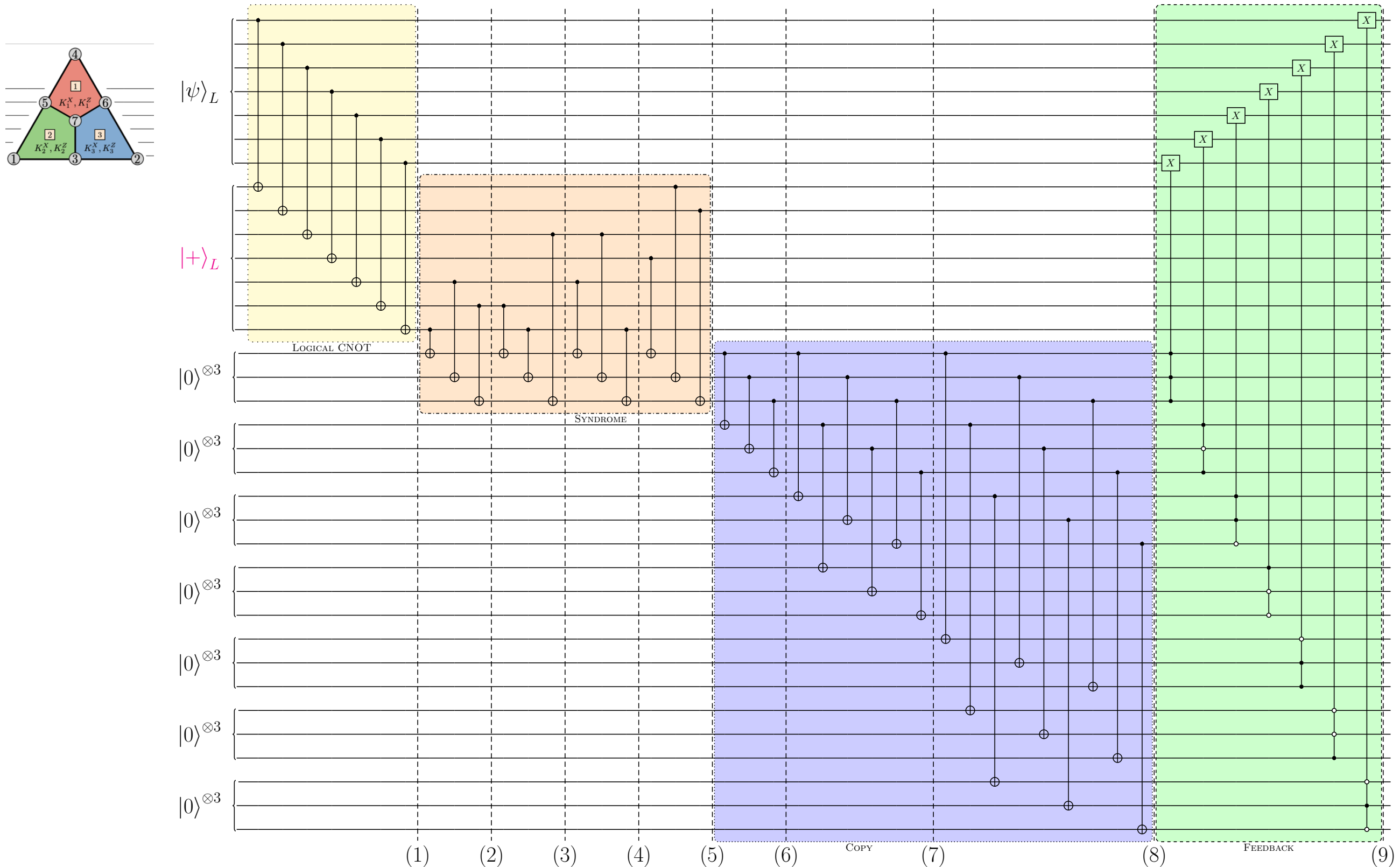
- Fault-tolerant measurement-free initialization of the logical Steane-code qubit



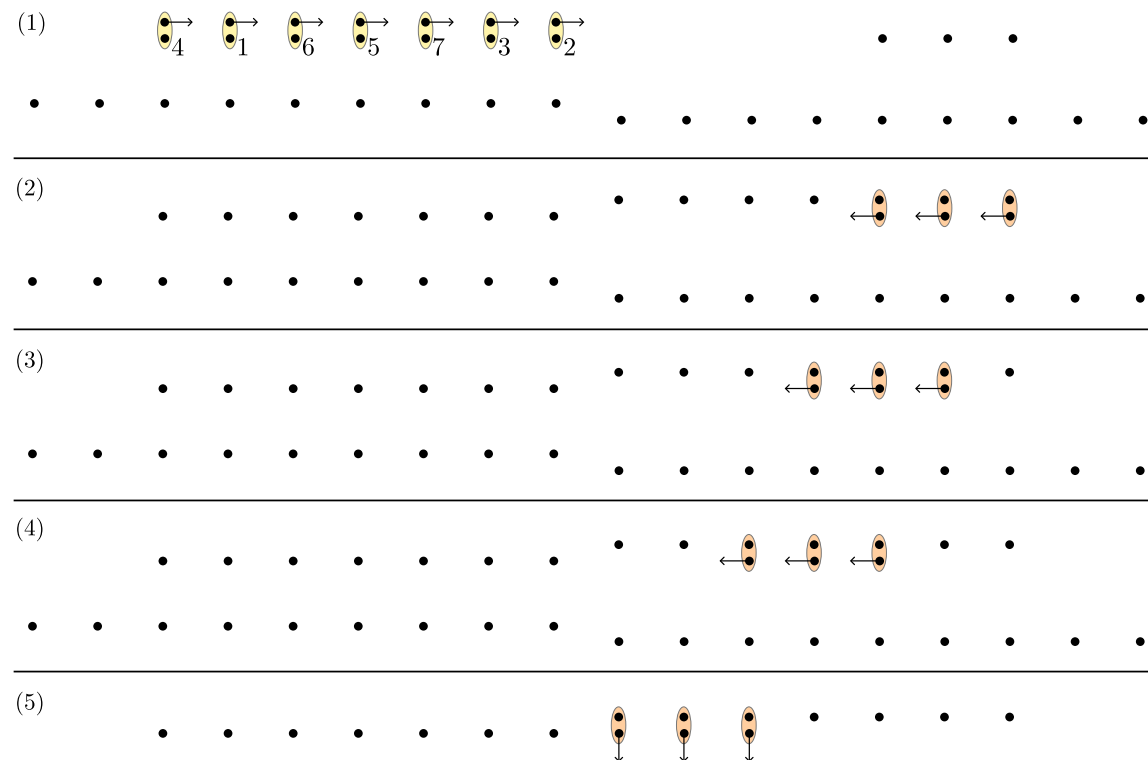
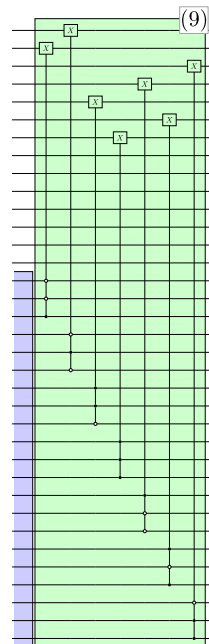
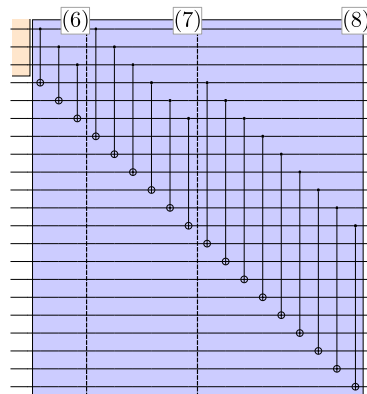
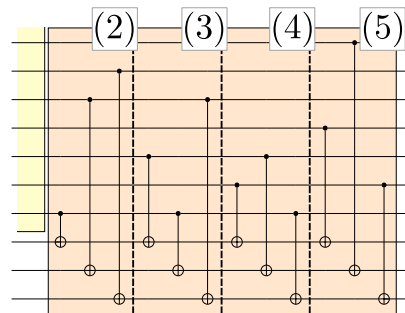
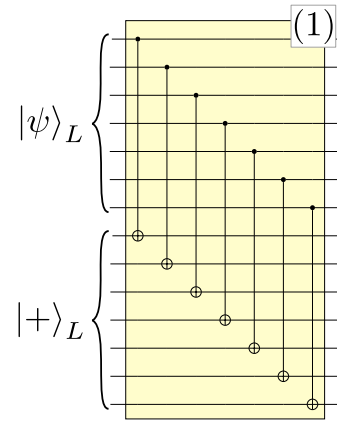
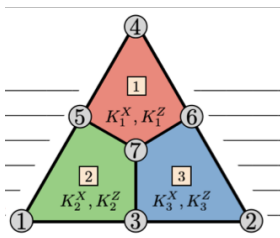
Measurement-free FT QEC: ideal for tweezer arrays

► No qubit reset needed if sufficient fresh ancilla qubits are available

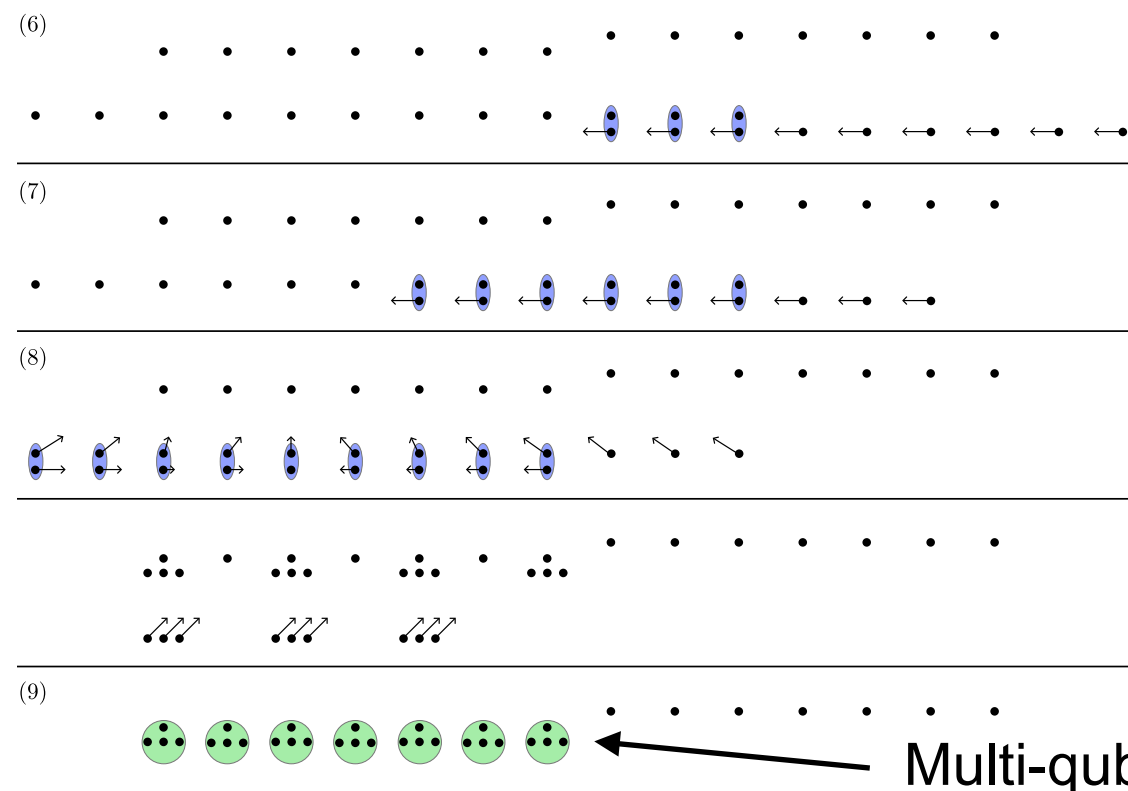
► Strong parallelisation possible: reduction of circuit depth



Measurement-free FT QEC: ideal for tweezer arrays



First realistic protocol for measurement-free fault-tolerant QEC

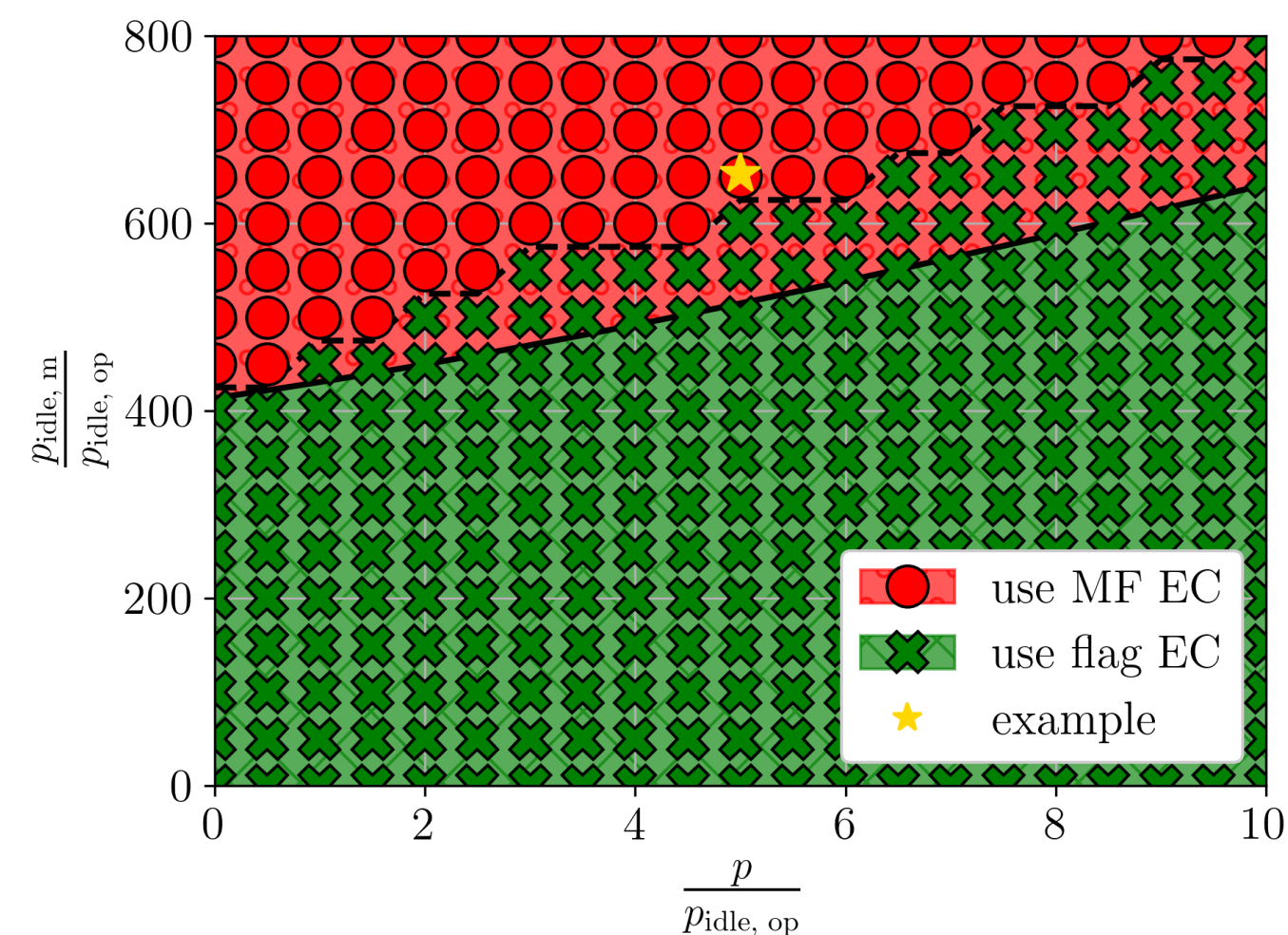


Multi-qubit Rydberg gates

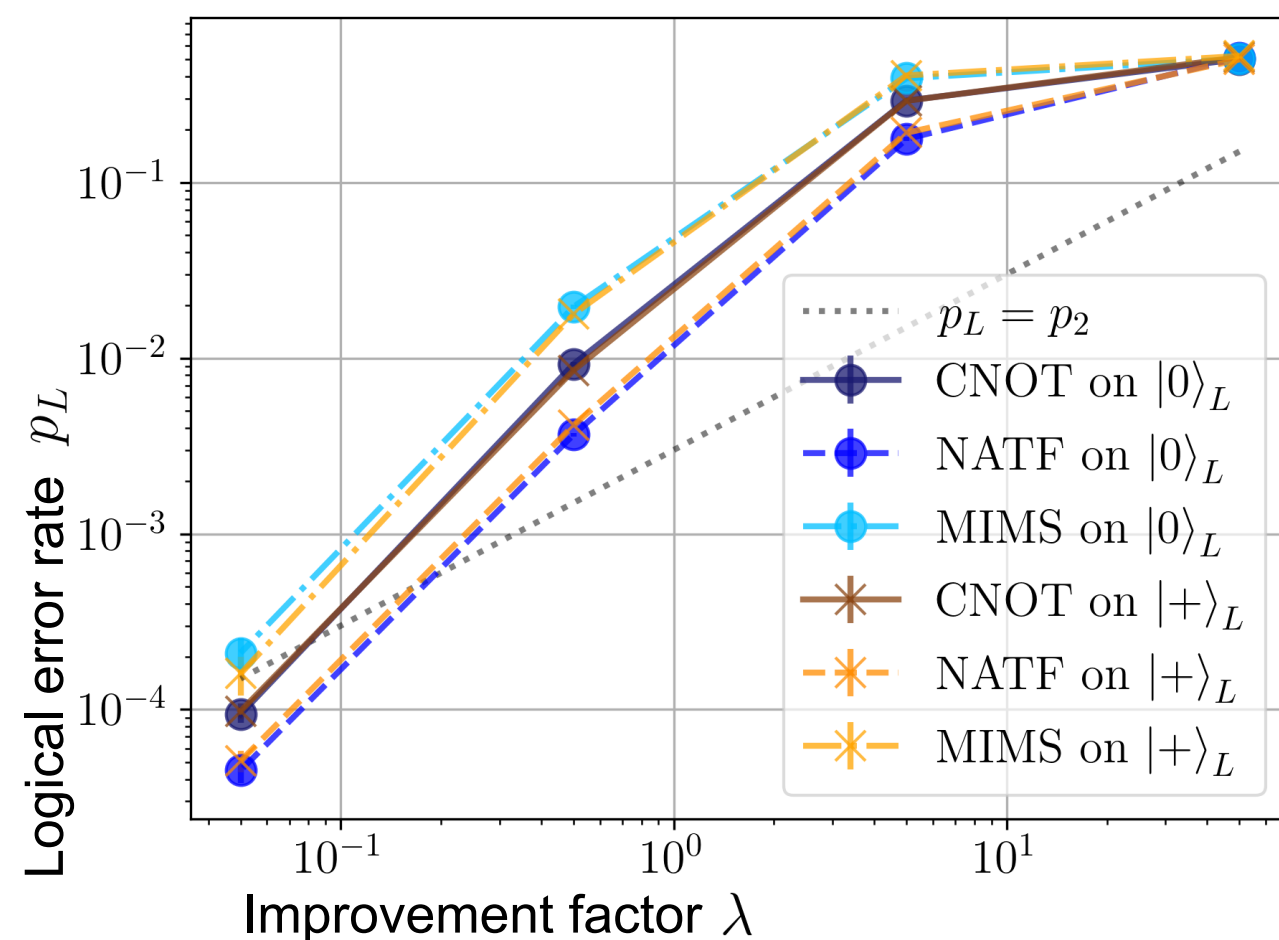
Measurement-free, yet fully fault-tolerant QEC

- When is it advantageous to use the measurement-free protocol?

For long measurement- and gate times, and high-fidelity gates ($p \simeq 5 \times 10^{-4}$)



- Break-even for various schemes with native multi-qubit gates

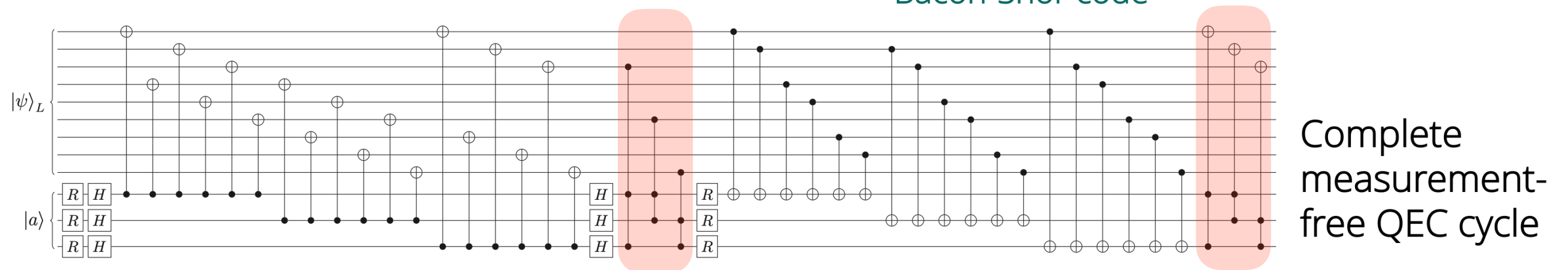
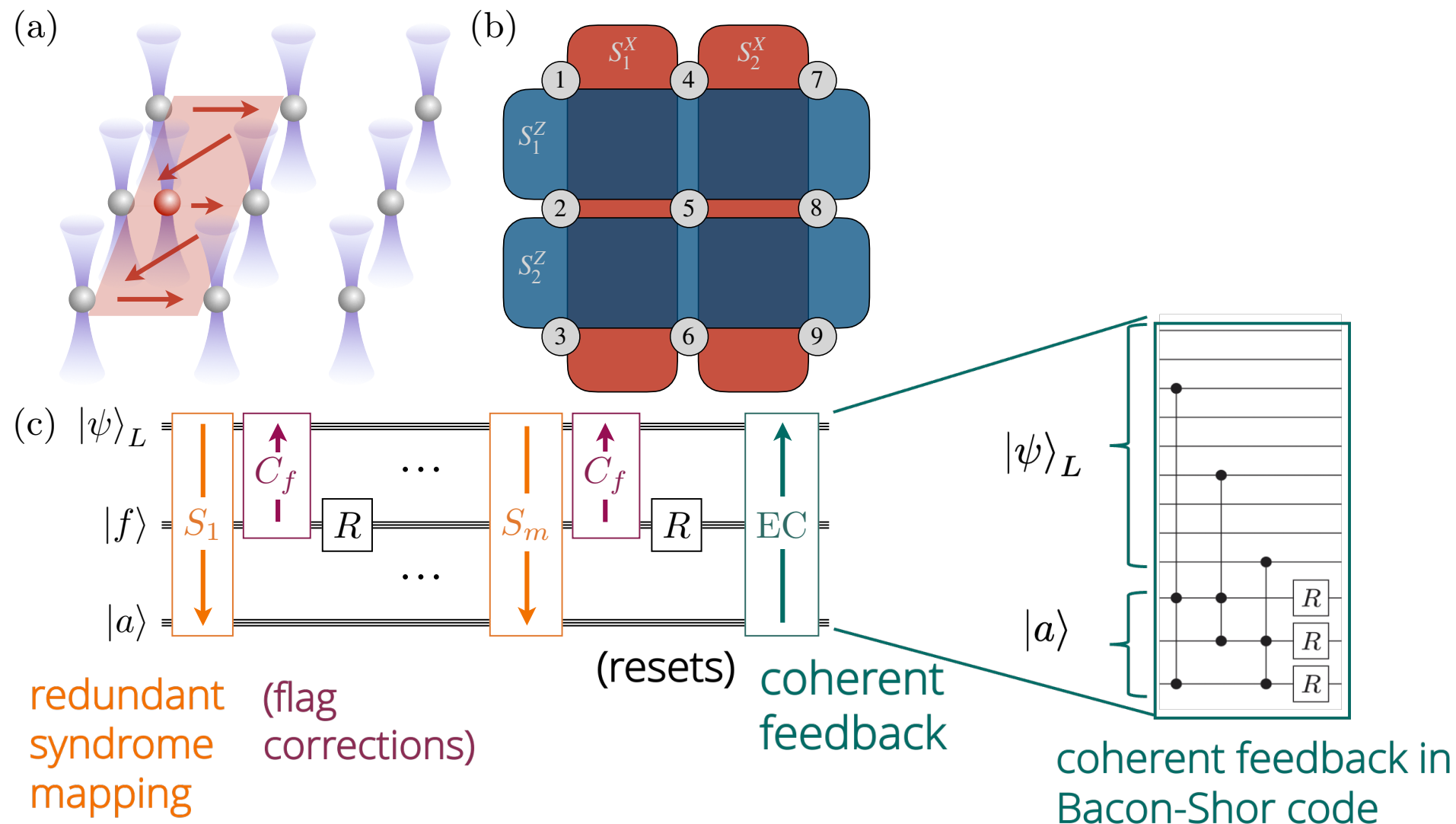


Impl.	p_1 [%]	p_2	p_3	p_4	p_5	p_i	p_m	p_{idle}
CNOT	0.007	0.3	-	-	-	0.0002	0.3	$p/100$
NATF	0.007	0.3	1	1	1	0.0002	0.3	$p/100$
MIMS	0.007	0.3	1	1	1	0.0002	0.3	$p/100$

Measurement-free fault-tolerant quantum error correction in near-term devices

S. Heußen, D. F. Locher, M. Müller, **PRX Quantum** 5, 010333 (2024)

3-qubit Rydberg gates for measurement-free FT QEC



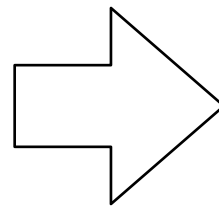
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Meas.-free QEC protocols from: *Optimized measurement-free and fault-tolerant QEC for neutral atoms*

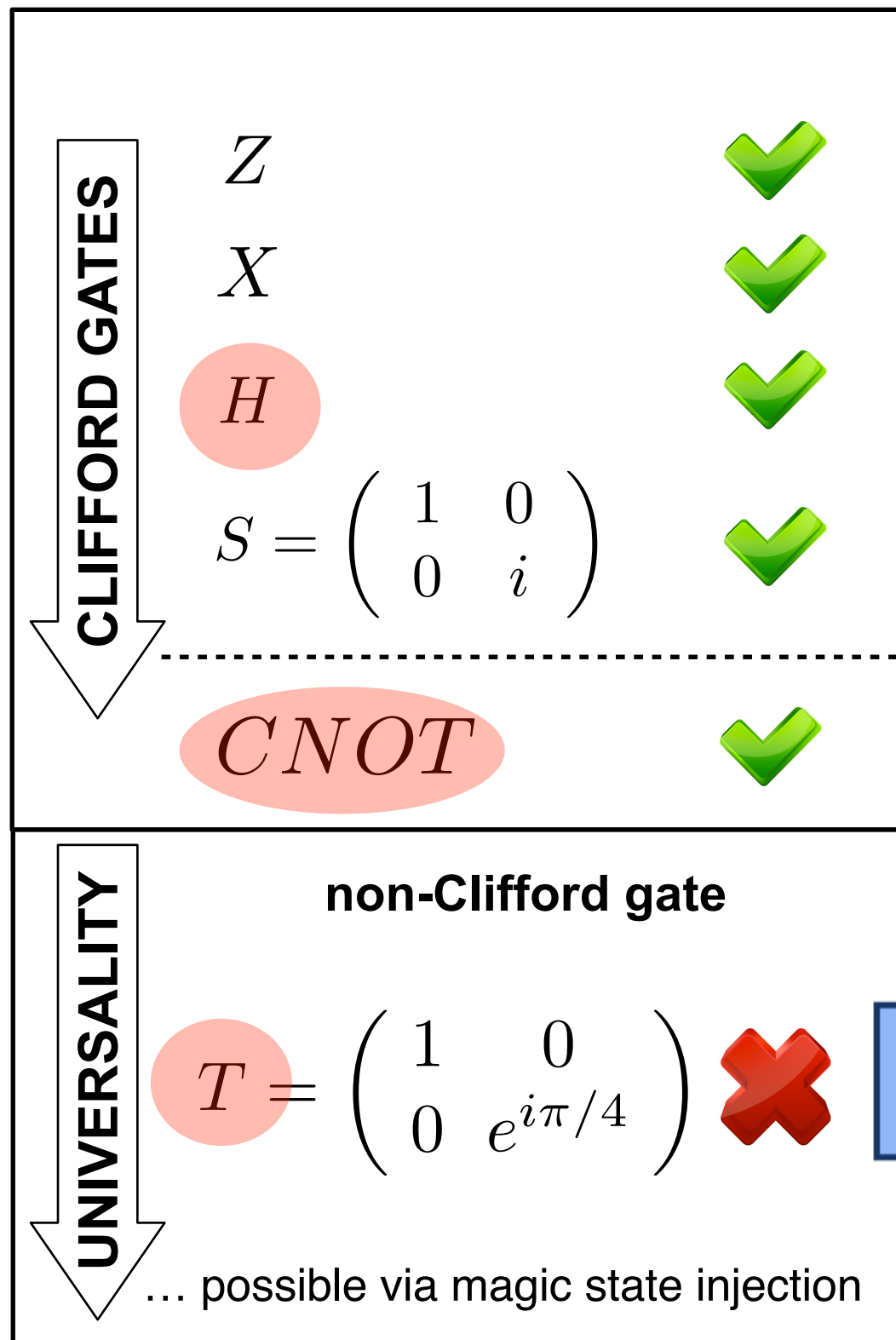
S. Veroni, M. Müller, G. Giudice, Phys. Rev. Research 6, 043253 (2024)

From quantum **memories** to... universal logical
quantum **processors**



Pathways to universal logical quantum computation?

2D Color Codes

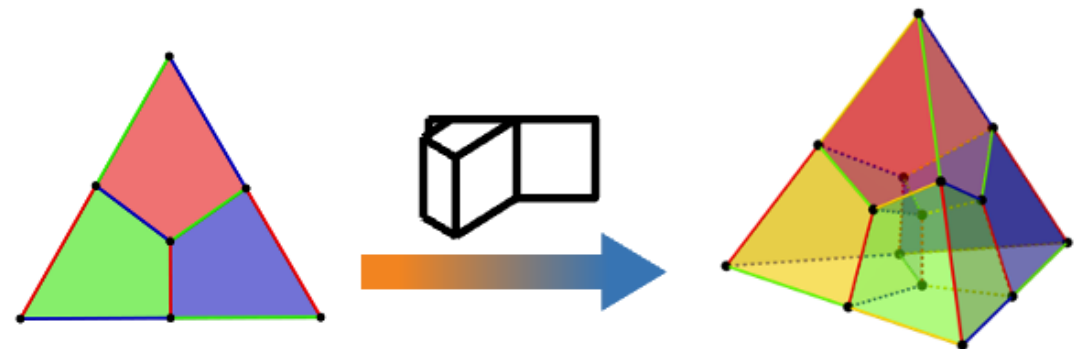


Eastin-Knill Theorem:

No quantum error correcting code can transversally implement a universal gate set.

Eastin, Knill (2009)

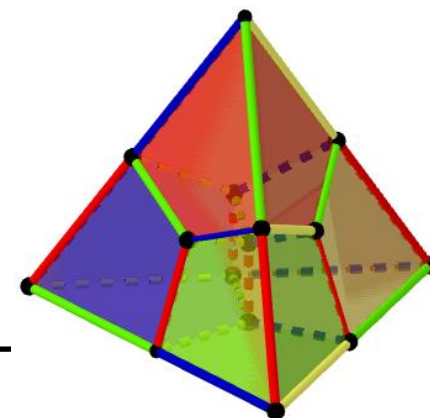
Fault-tolerant code switching





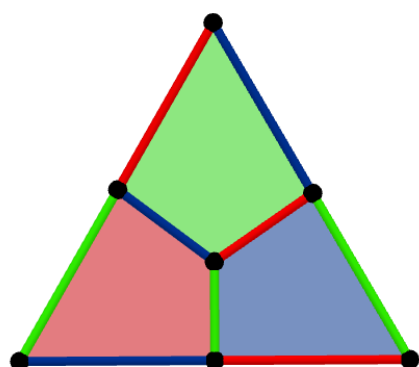
F. Butt S. Heußen

Universality via Code Switching



2D Color Codes

3D Color Codes



UNIVERSALITY

Clifford gates

Z



X



H



$$S = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$$



$CNOT$



non-Clifford gate

$$T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$



Clifford gates

Z



X



H



$$S = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$$



$CNOT$

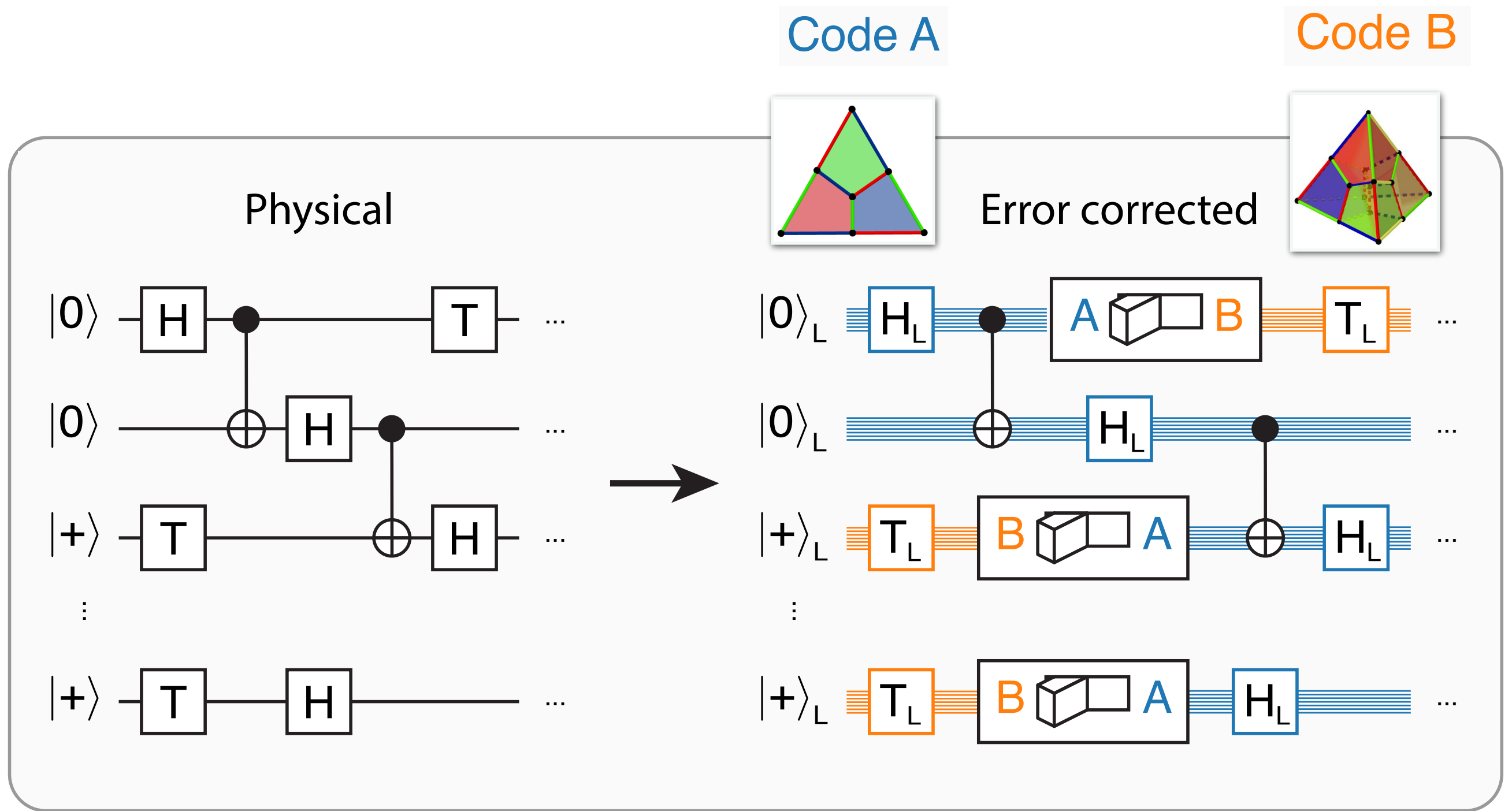


non-Clifford gate

$$T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$



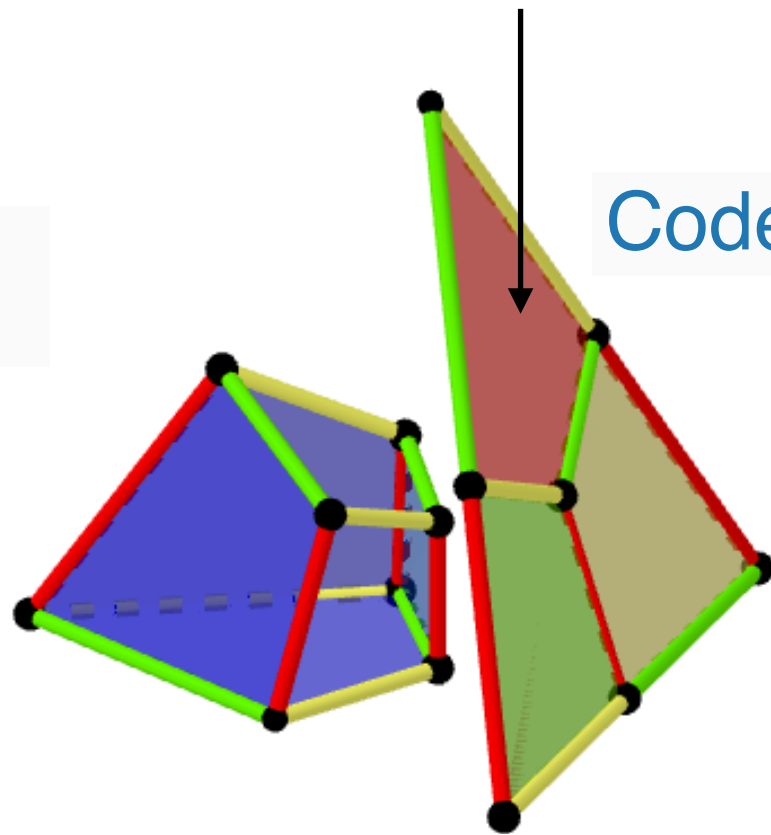
Universal quantum computation via code switching



Universal quantum computation via code switching

4-qubit face-type X- and Z-stabilisers

Code A



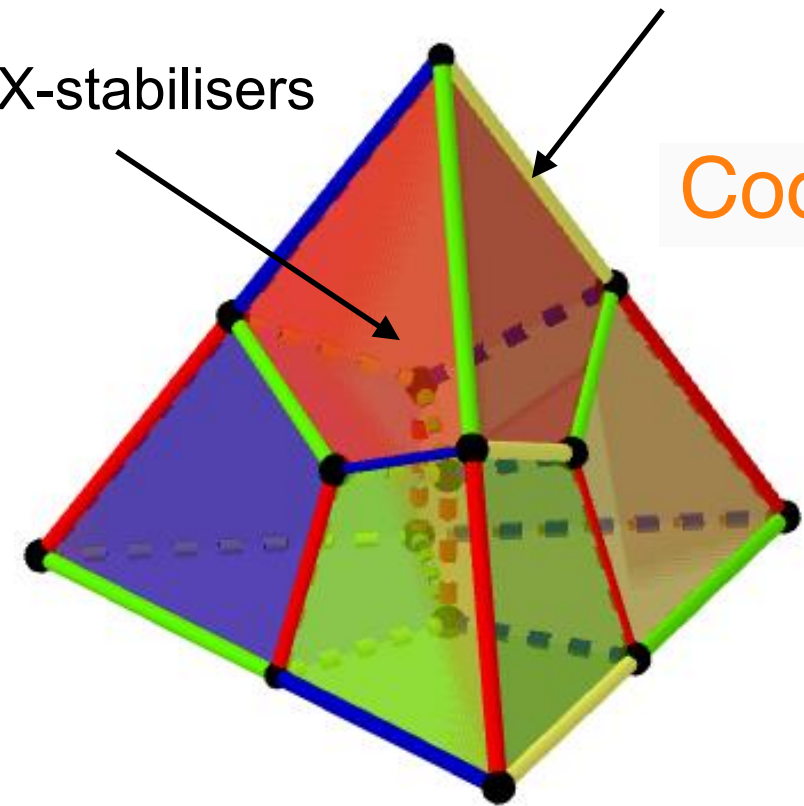
7-qubit 2D color code

8-qubit cell-type X-stabilisers

switch

4-qubit face-type Z-stabilisers

Code B

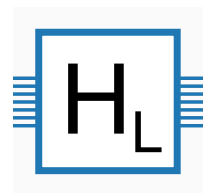


15-qubit 3D color code

$$|\psi\rangle_S = |\psi\rangle_B \otimes |\psi\rangle_{2D}$$

$$|\psi\rangle_{tetra}$$

► **2D** color code:
Transversal **Hadamard**



► **3D** color code:
Transversal **T-gate**

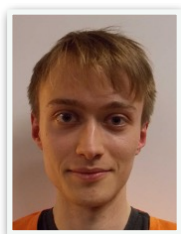
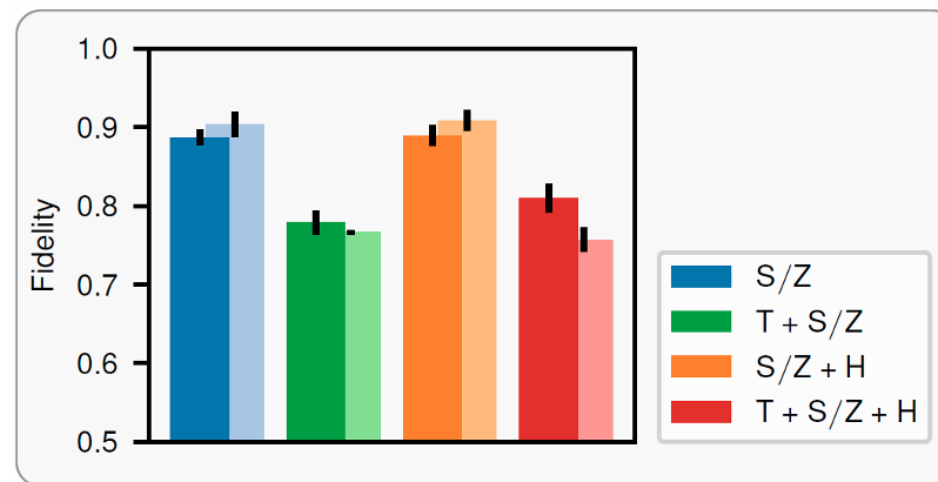
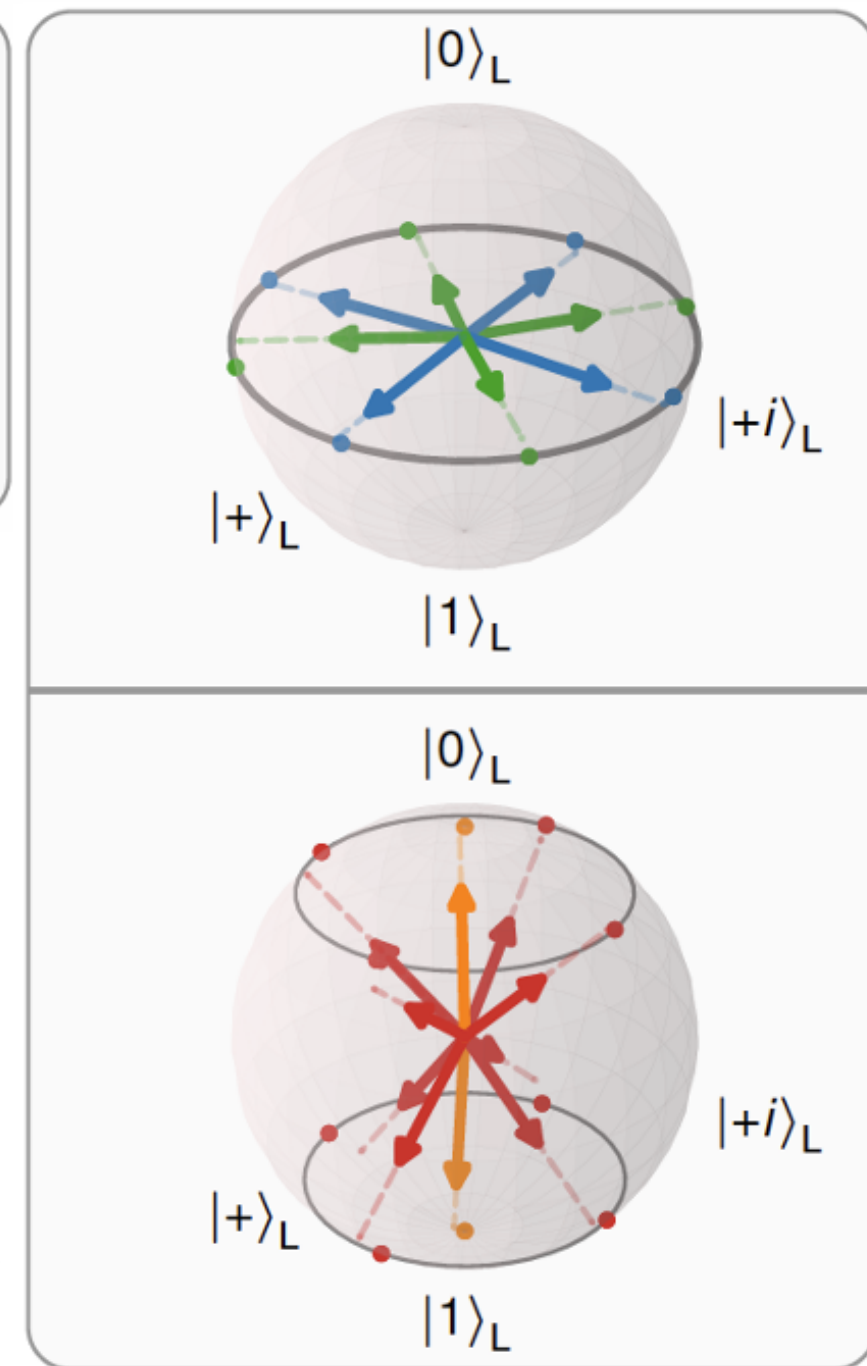
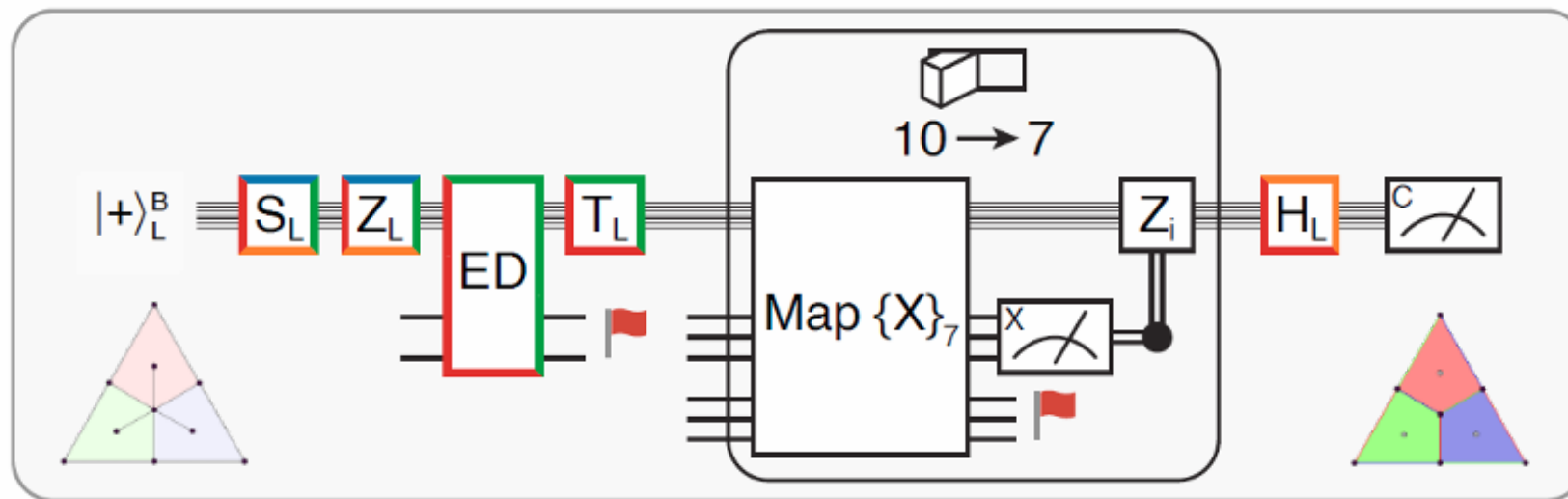
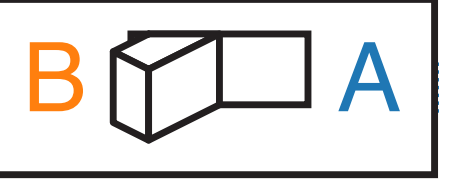


► **Switching:** must be realised fault-tolerantly, similar to FT rounds of QEC

Fault-tolerant Code Switching Protocols for Near-Term Quantum Processors,

F. Butt, S. Heussen, M. Rispler, M.M., PRX Quantum 5, 020345 (2024)

First experimental fault-tolerant code switching



V. Pogorelov F. Butt T. Monz

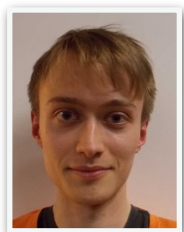
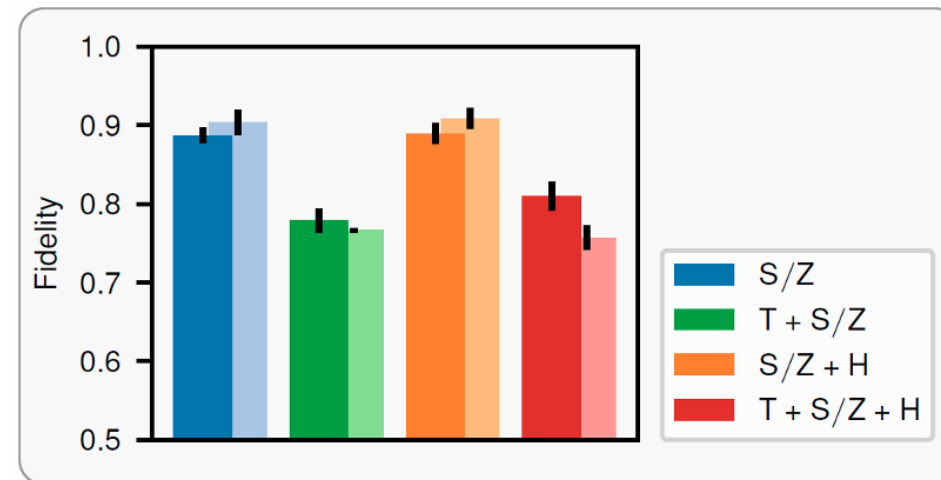
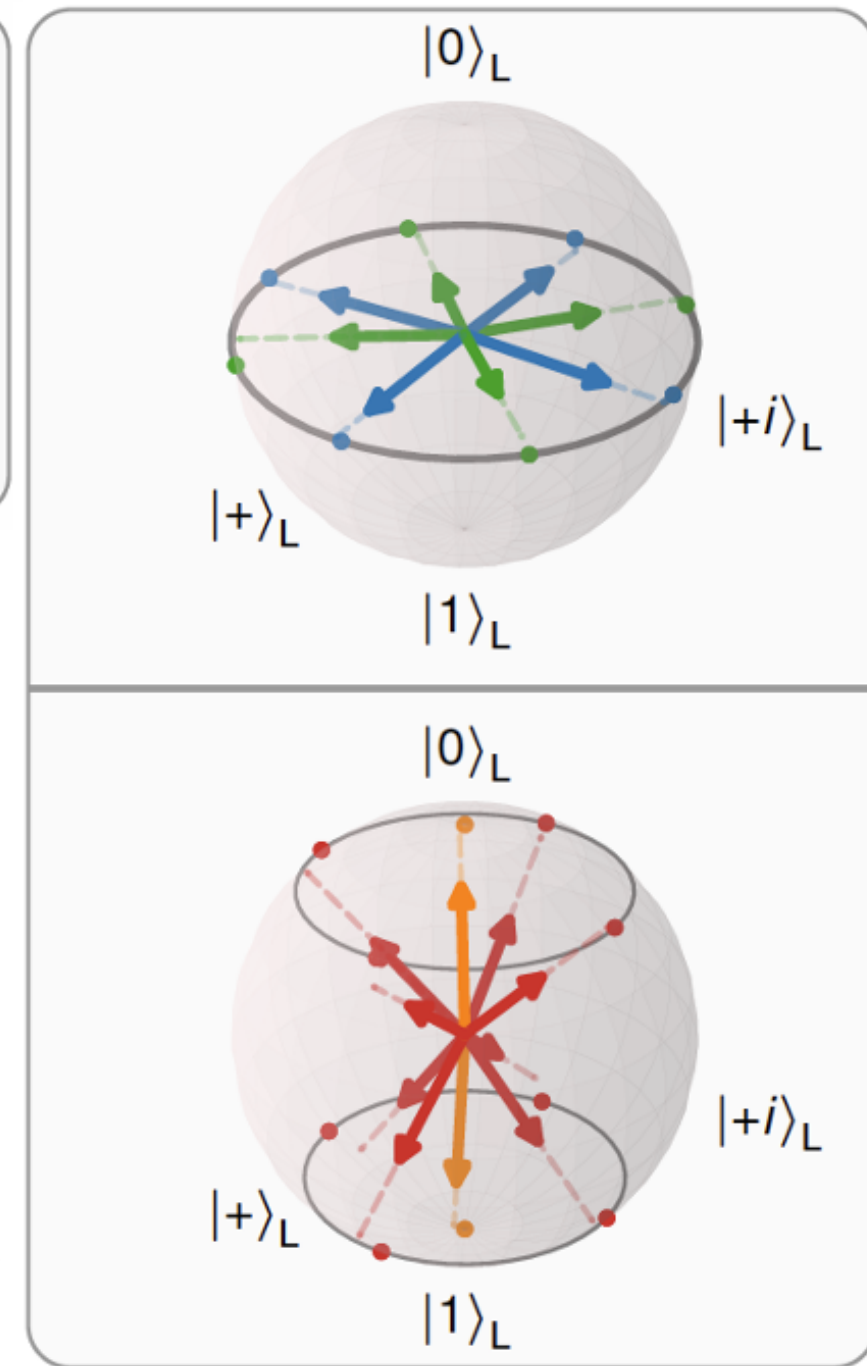
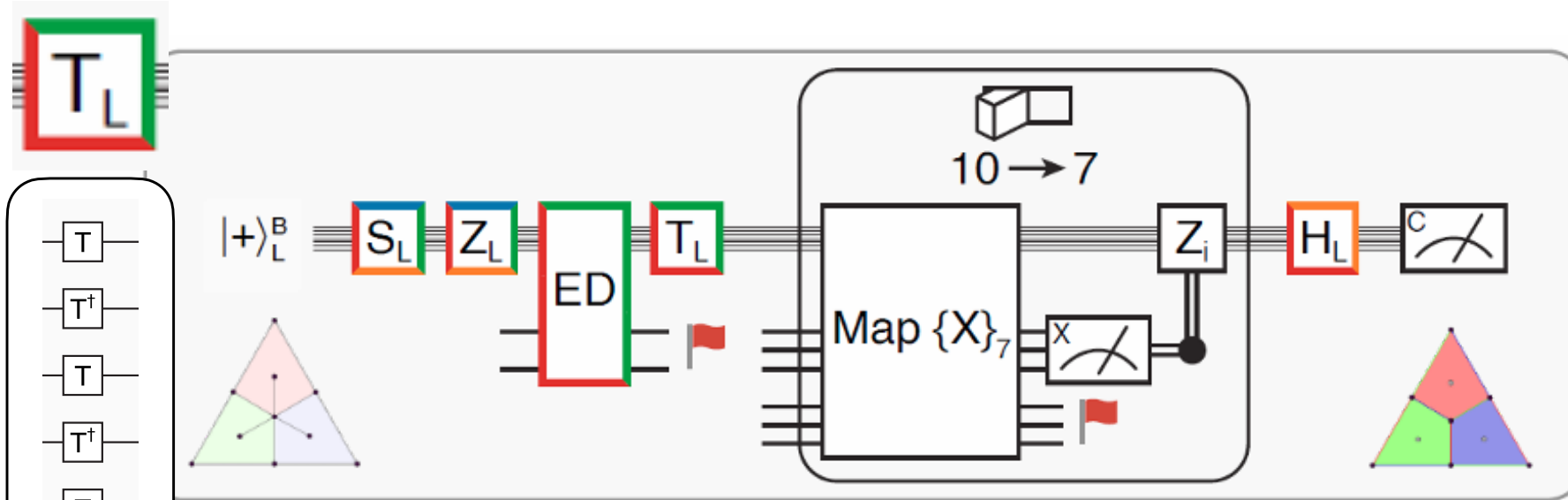
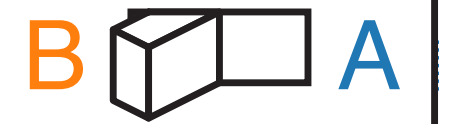
✔ Prepare logical states that are not reachable within a single code
... towards densely covering the logical Bloch sphere

Experimental fault-tolerant code switching

I. Pogorelov, F. Butt, L. Postler, C. D. Marciniak, P. Schindler, M. M., T. Monz, Nature Physics 21, 298 (2025)

[[10,1,2]] code proposed in *Morphing quantum codes*, M. Vasmer, A. Kubica, PRX Quantum 3, 030319 (2022)

First experimental fault-tolerant code switching



V. Pogorelov F. Butt T. Monz

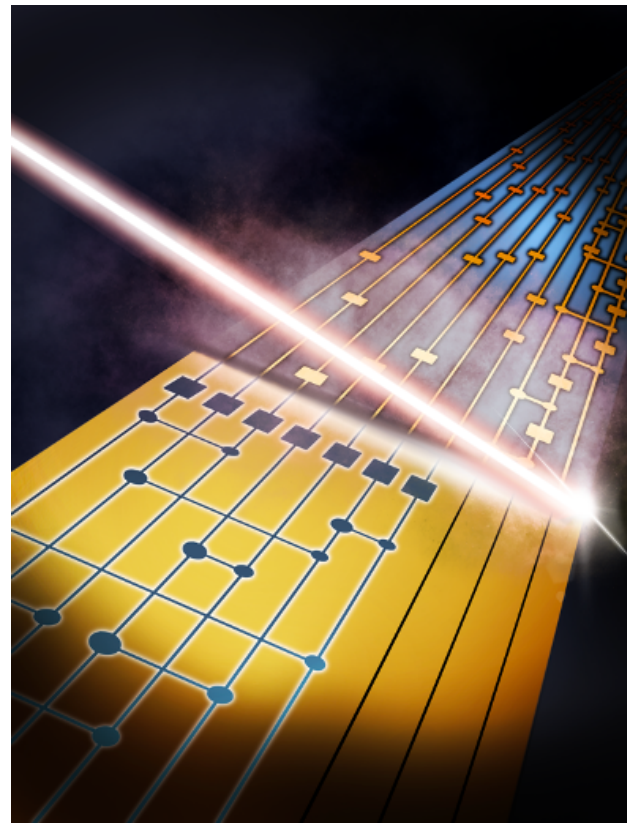
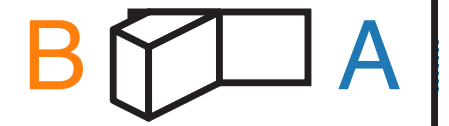
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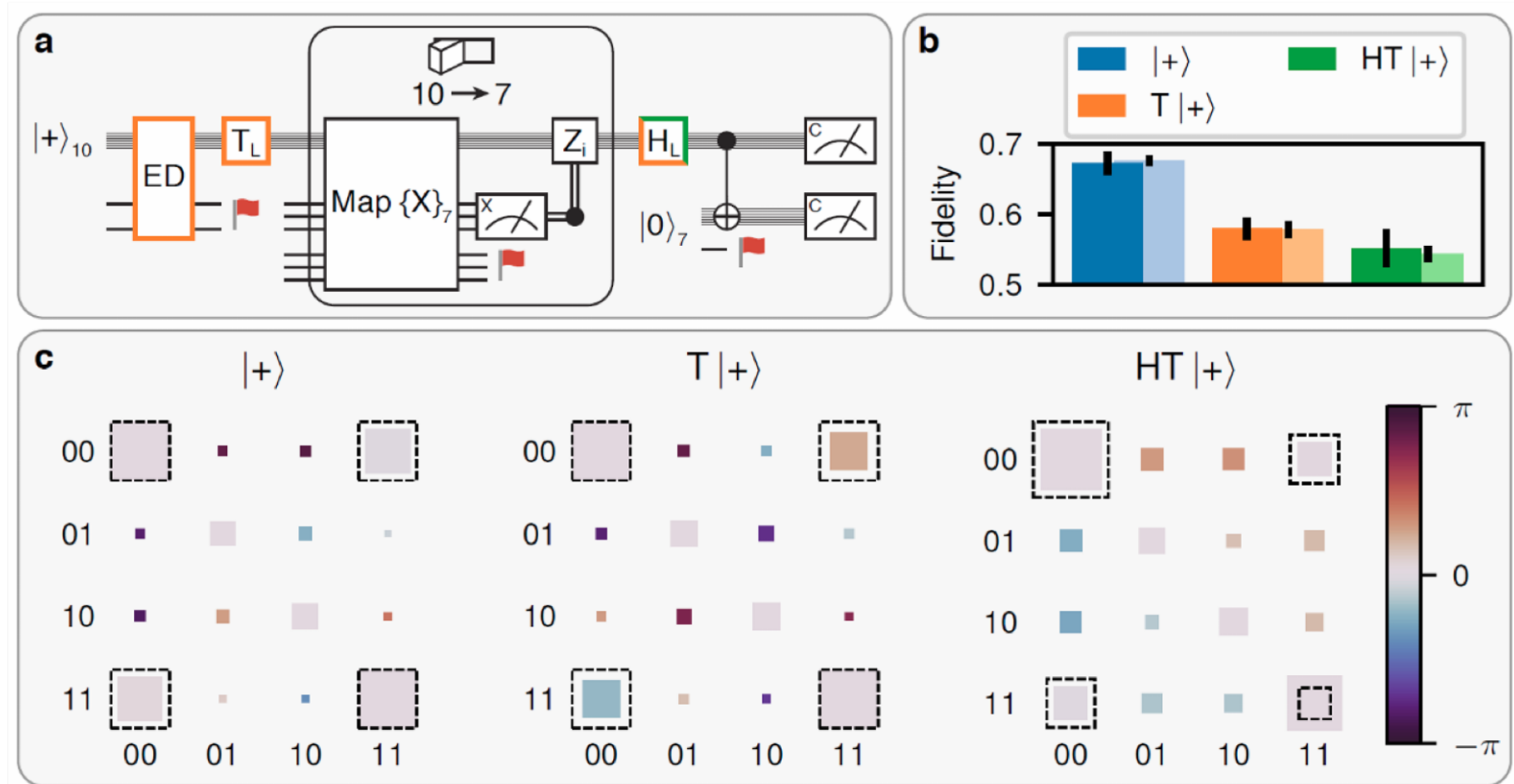
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First experimental fault-tolerant code switching



Helene Hainzer



In: $|+\rangle$
 Out: $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

$T|+\rangle$
 $\frac{1}{\sqrt{2}}(|00\rangle + e^{i\frac{\pi}{4}}|11\rangle)$

$HT|+\rangle$
 $\propto (\cos(\frac{\pi}{8})|00\rangle + i \sin(\frac{\pi}{8})|11\rangle)$



Fault-tolerant preparation of non-stabiliser entangled two-qubit states



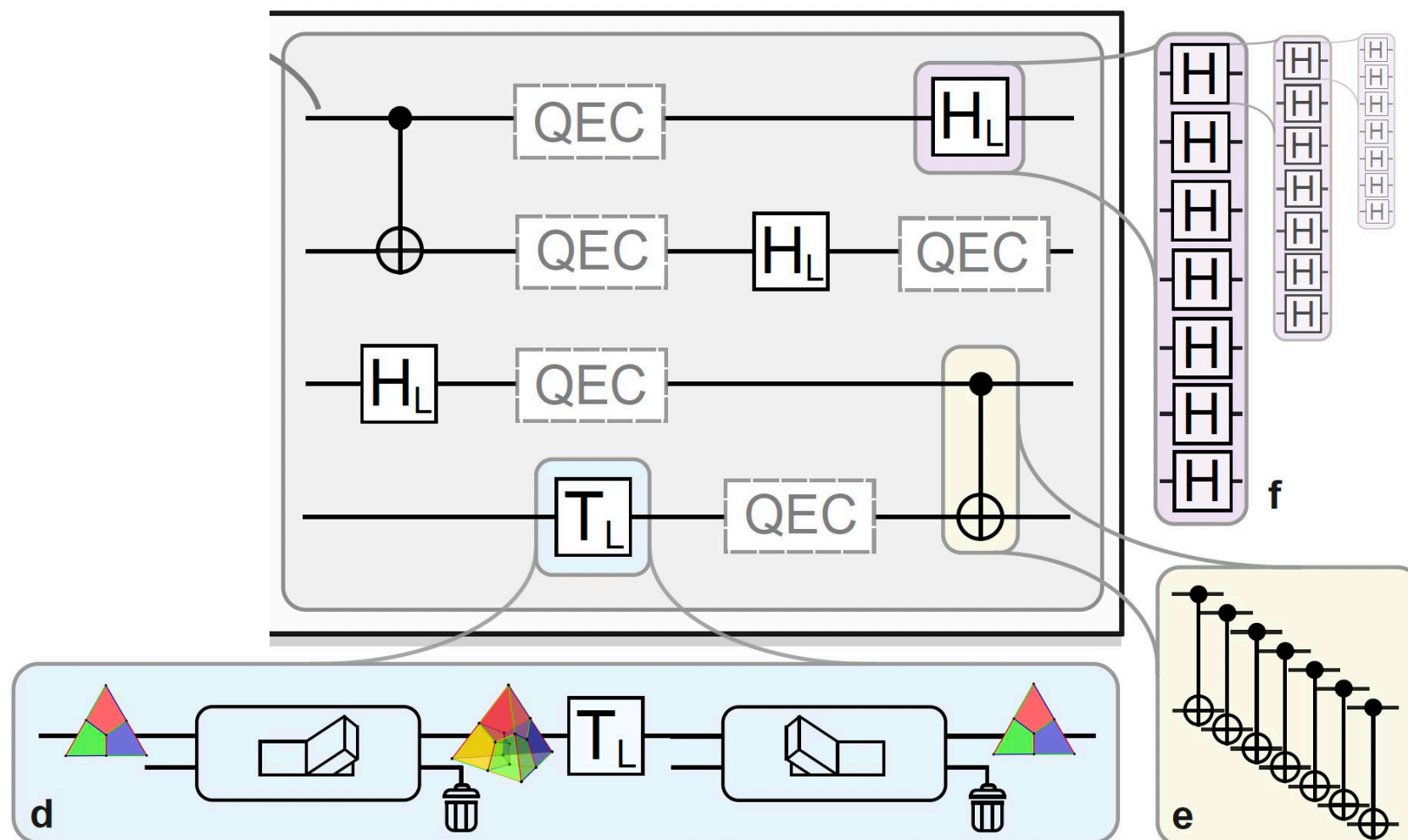
First minimal **universal** logical quantum algorithms using H, T, CNOT

Experimental fault-tolerant code switching, I. Pogorelov, F. Butt, L. Postler, C. D. Marciniak, P. Schindler, M. M., T. Monz, Nature Physics 21, 298 (2025)



F. Butt

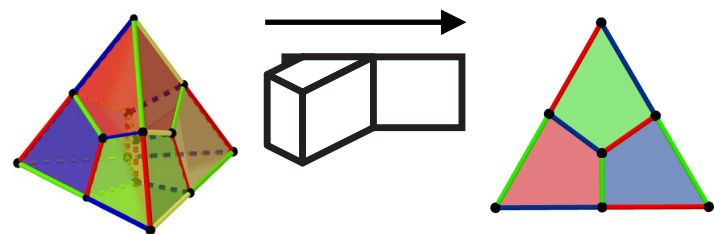
Universal measurement-free FT QC?



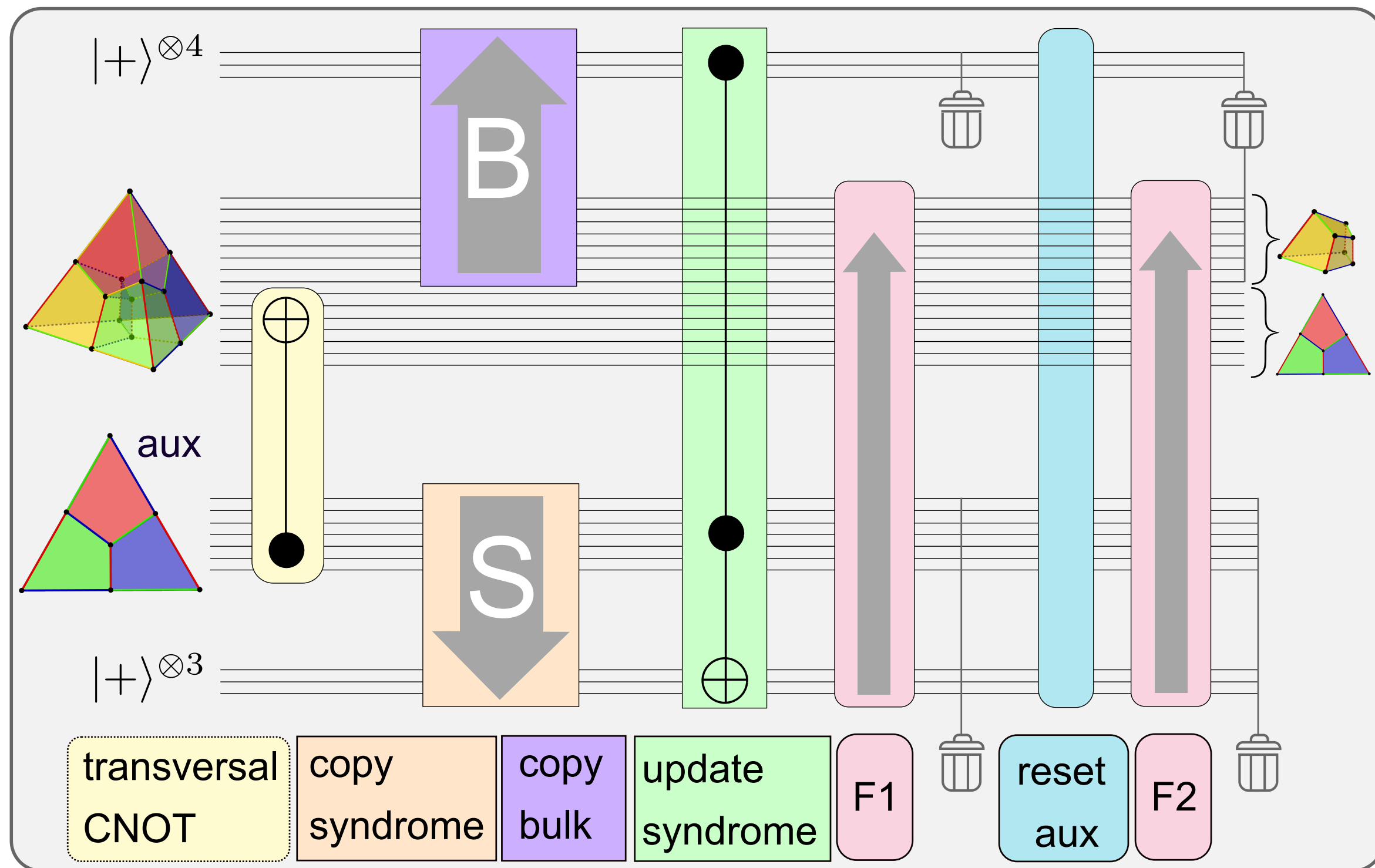
- **FT Measurement-free code switching**
to achieve universal logical gates

Measurement-free, scalable and fault-tolerant universal quantum computing

F. Butt, D. F. Locher, K. Brechtelsbauer, H. P. Büchler, and M. Müller, Science Advances 11, eadv2590 (2025)



Universal measurement-free FT QC?

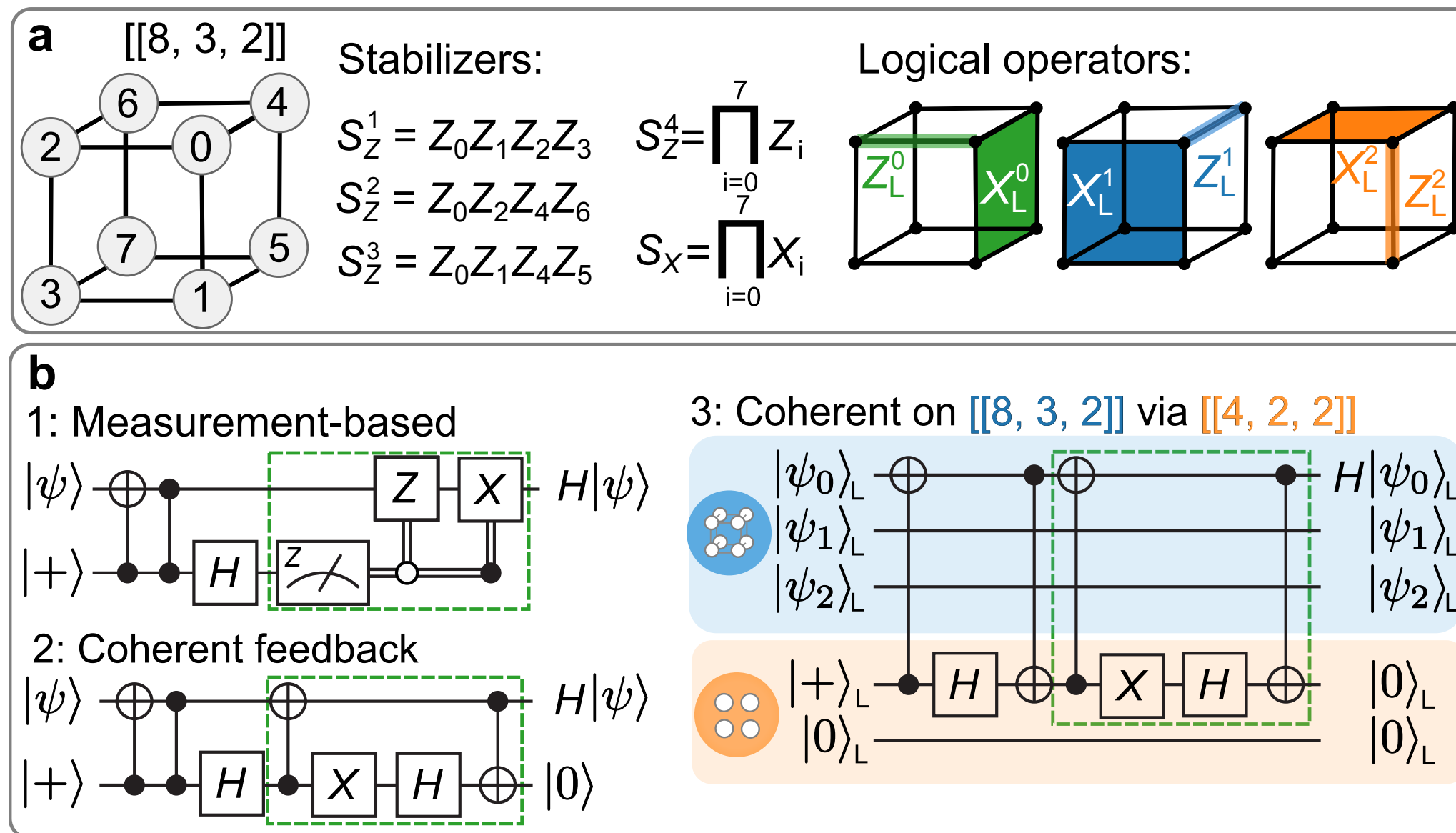
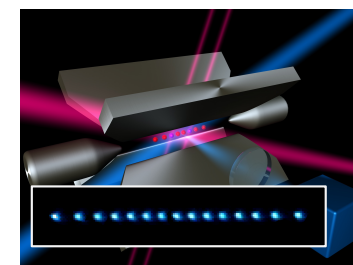


Measurement-free, scalable and fault-tolerant universal quantum computing

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First experimental measurement-free fault-tolerant QC

- ▶ First experimental demonstration of measurement-free universal fault-tolerant quantum computation on any physical platform
- ▶ Work with a small cubic 3D color code: 3 logical qubits, $d=2$ (error detection only)



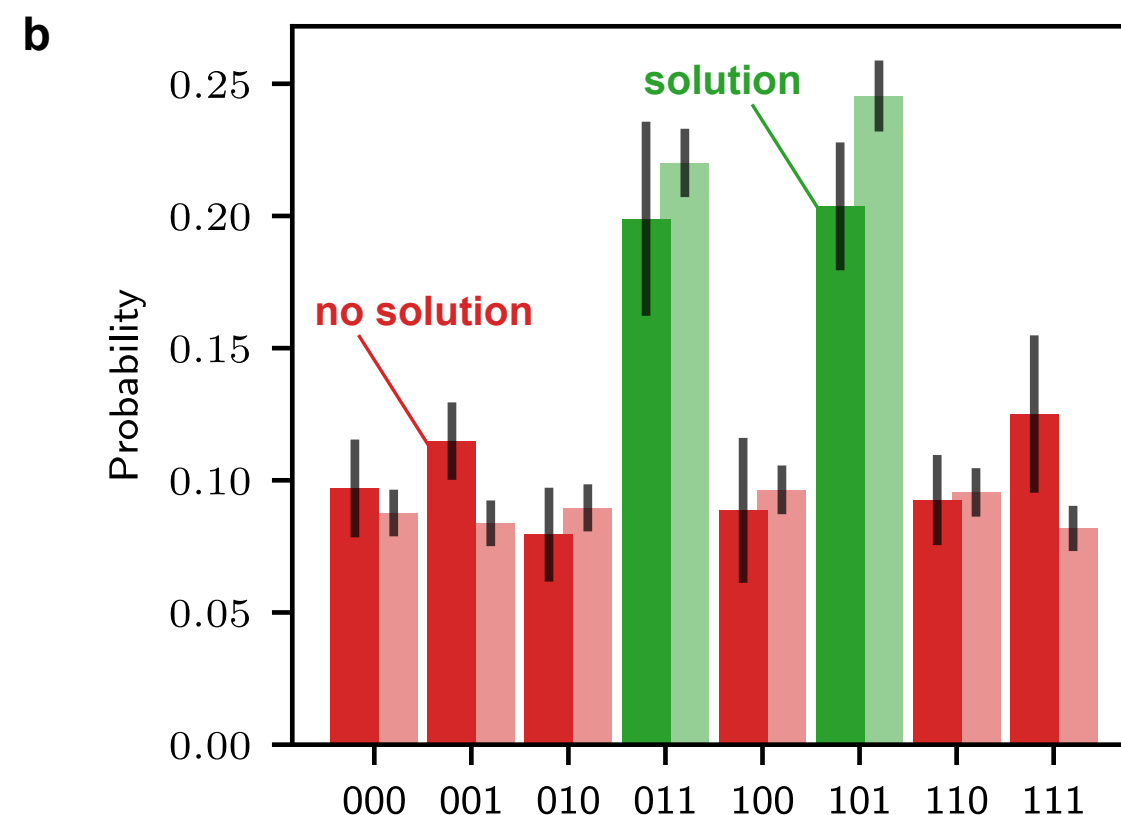
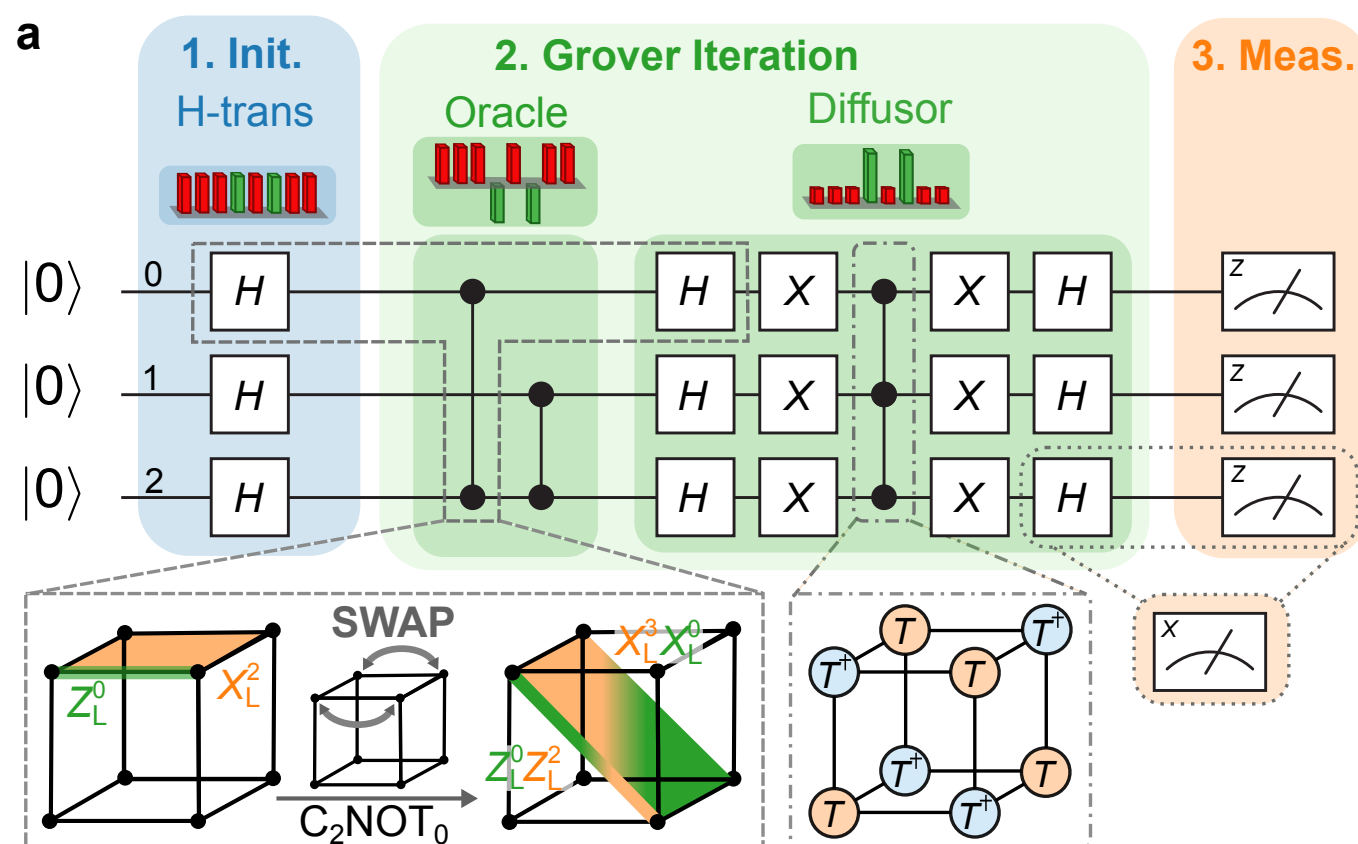
- ▶ Coherent FT injection of a logical Hadamard gate

Demonstration of measurement-free universal fault-tolerant quantum computation

F. Butt, I. Pogorelov, R. Freund, A. Steiner, M. Meyer, T. Monz, M. M., Nature Communications 17, 995 (2026)

First experimental measurement-free fault-tolerant QC

- Demonstration of a measurement-free logical algorithm requiring a universal logical gate set
- **Grover search algorithm** in a database of $N=8$ elements with 2 solutions, using 3 logical qubits

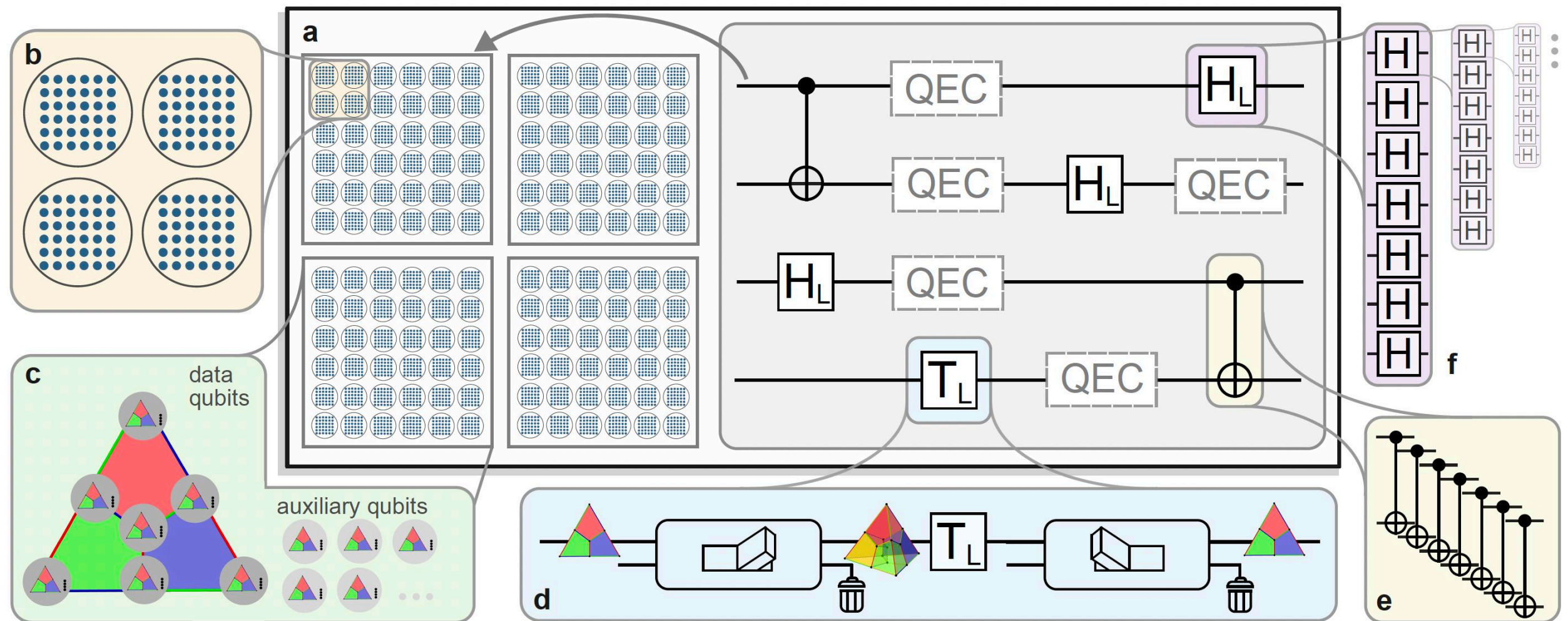


- Solutions clearly identified
- Further improvements and larger systems needed for break-even with physical qubits

Demonstration of measurement-free universal fault-tolerant quantum computation

F. Butt, I. Pogorelov, R. Freund, A. Steiner, M. Meyer, T. Monz, M. M., Nature Communications 17, 995 (2026)

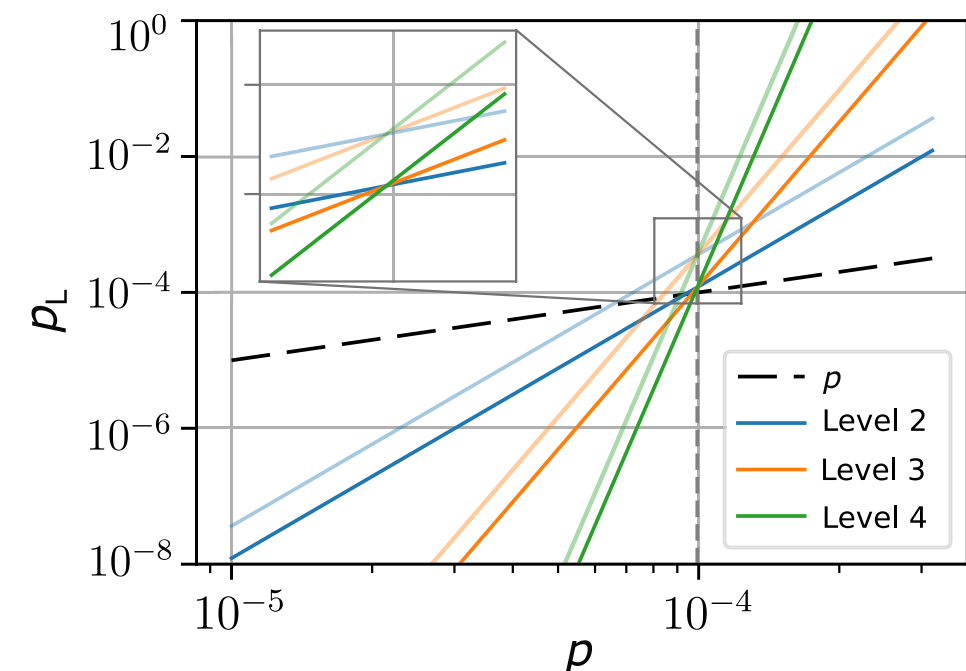
Scalable universal measurement-free FTQC



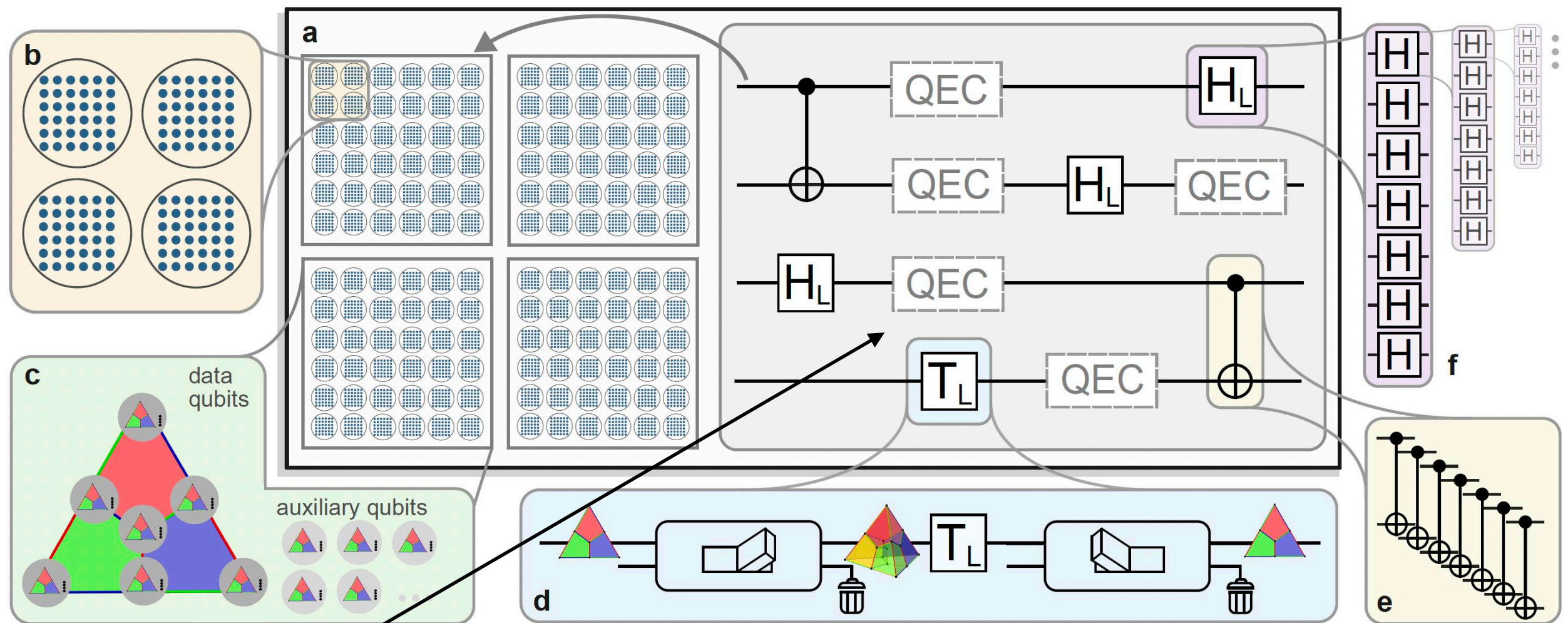
- **FT Measurement-free code switching** to achieve universal logical gates
- **Code concatenation** to exponentially suppress logical error rates

Measurement-free, scalable and fault-tolerant universal quantum computing

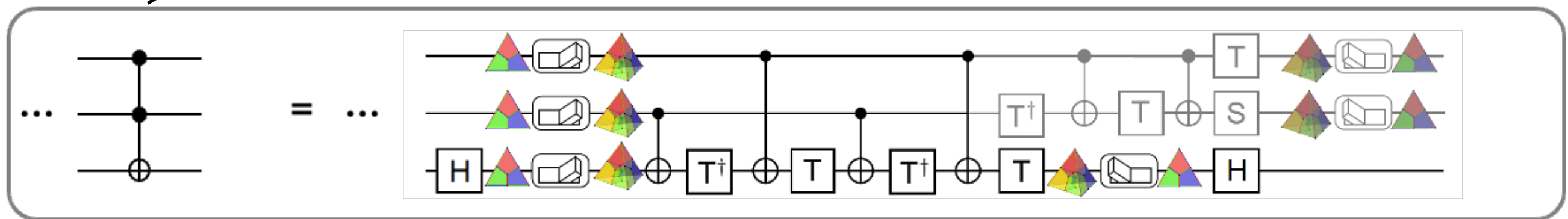
F. Butt, D. F. Locher, K. Brechtelsbauer, H. P. Büchler, and M. Müller,
Science Advances 11, eadv2590 (2025)



Scalable universal measurement-free FTQC



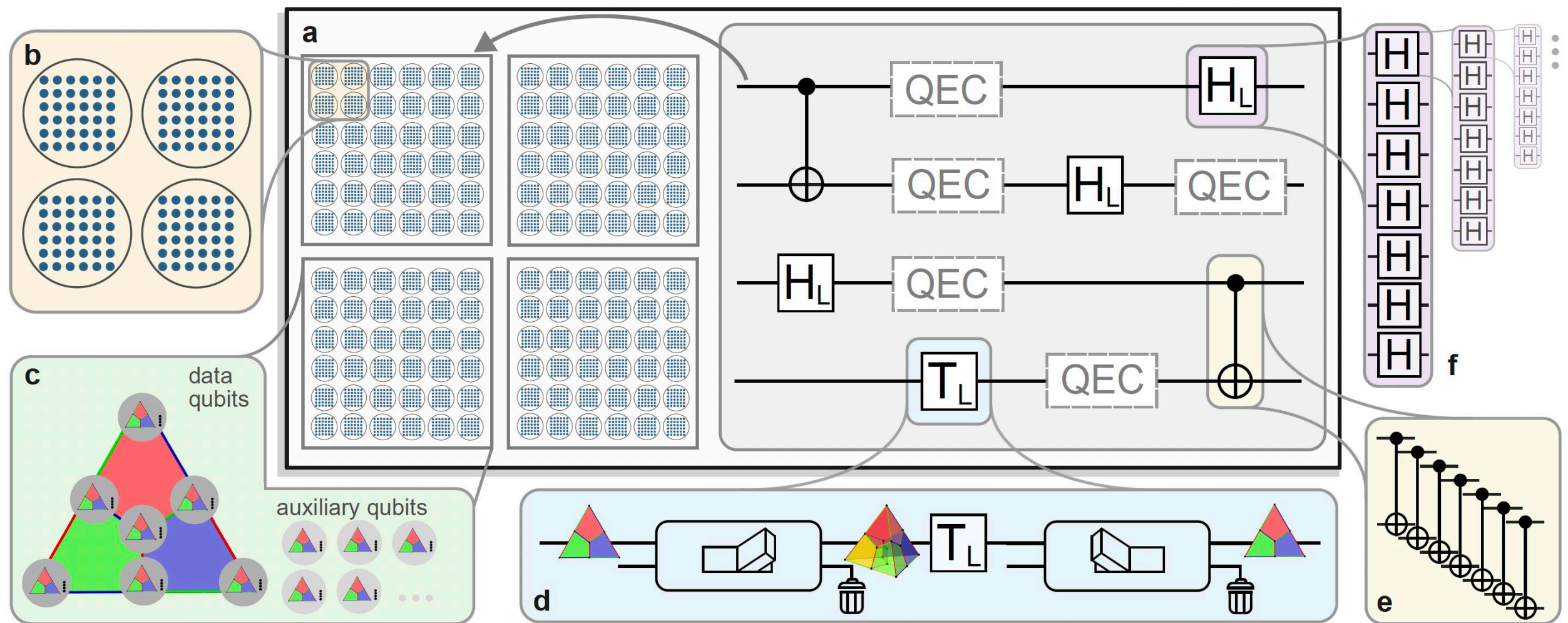
Concatenation: Code switching and QEC on logical level contains logical Toffoli-gate: needs H , T , $CNOT$ $\rightarrow$ Switching on lower level



Measurement-free, scalable and fault-tolerant universal quantum computing

F. Butt, D. F. Locher, K. Brechtelsbauer, H. P. Büchler, and M. Müller, Science Advances 11, eadv2590 (2025)

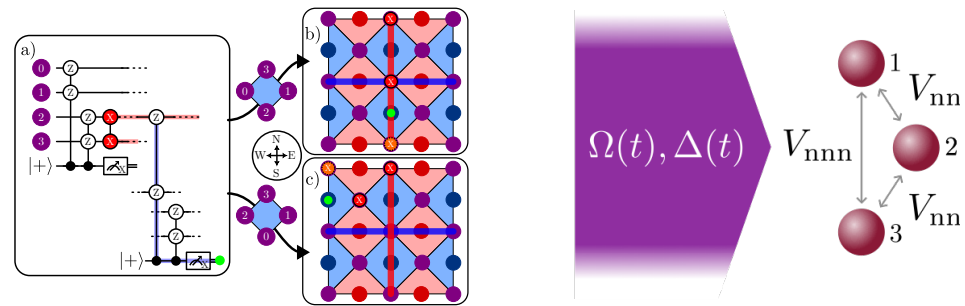
Scalable universal measurement-free FTQC



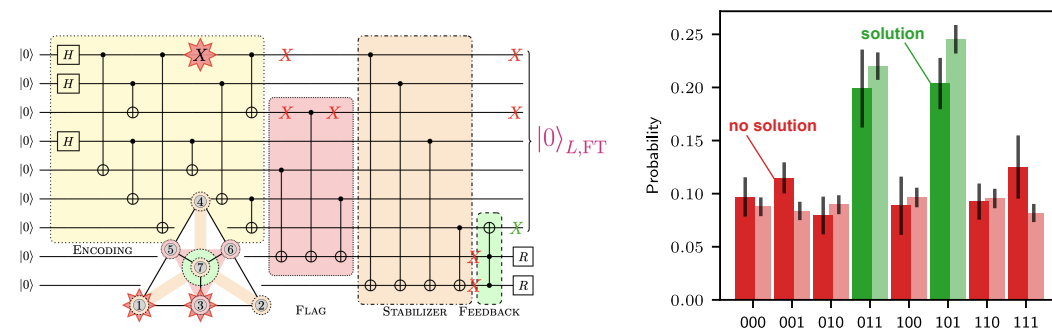
- ▶ **FT Measurement-free code switching** to achieve universal logical gate set
- ▶ **Code concatenation** to exponentially suppress logical error rates

- ▶ **Waiting for a scalable neutral atom realisation!**
... starting with only 35 physical qubits

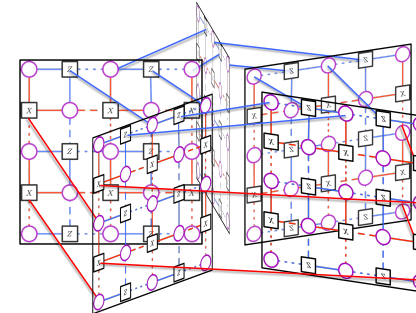
1 - FT QEC with optimized **3-qubit gates** only



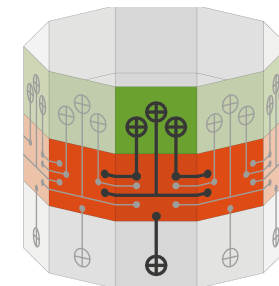
2 - FT **Measurement-free** QEC and universal computation



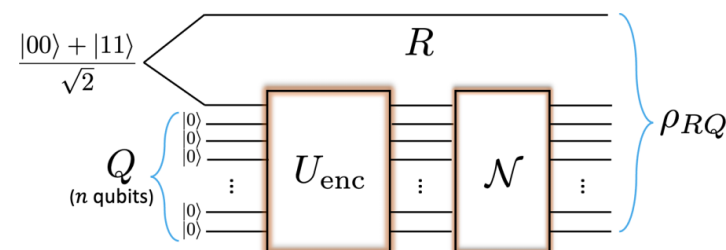
3 - Universal FT QC with **lift-connected surface codes**



4 - Classical and quantum **cellular automata** for QEC



5 - Enhancing QEC thresholds by **Syndrome Resampling**



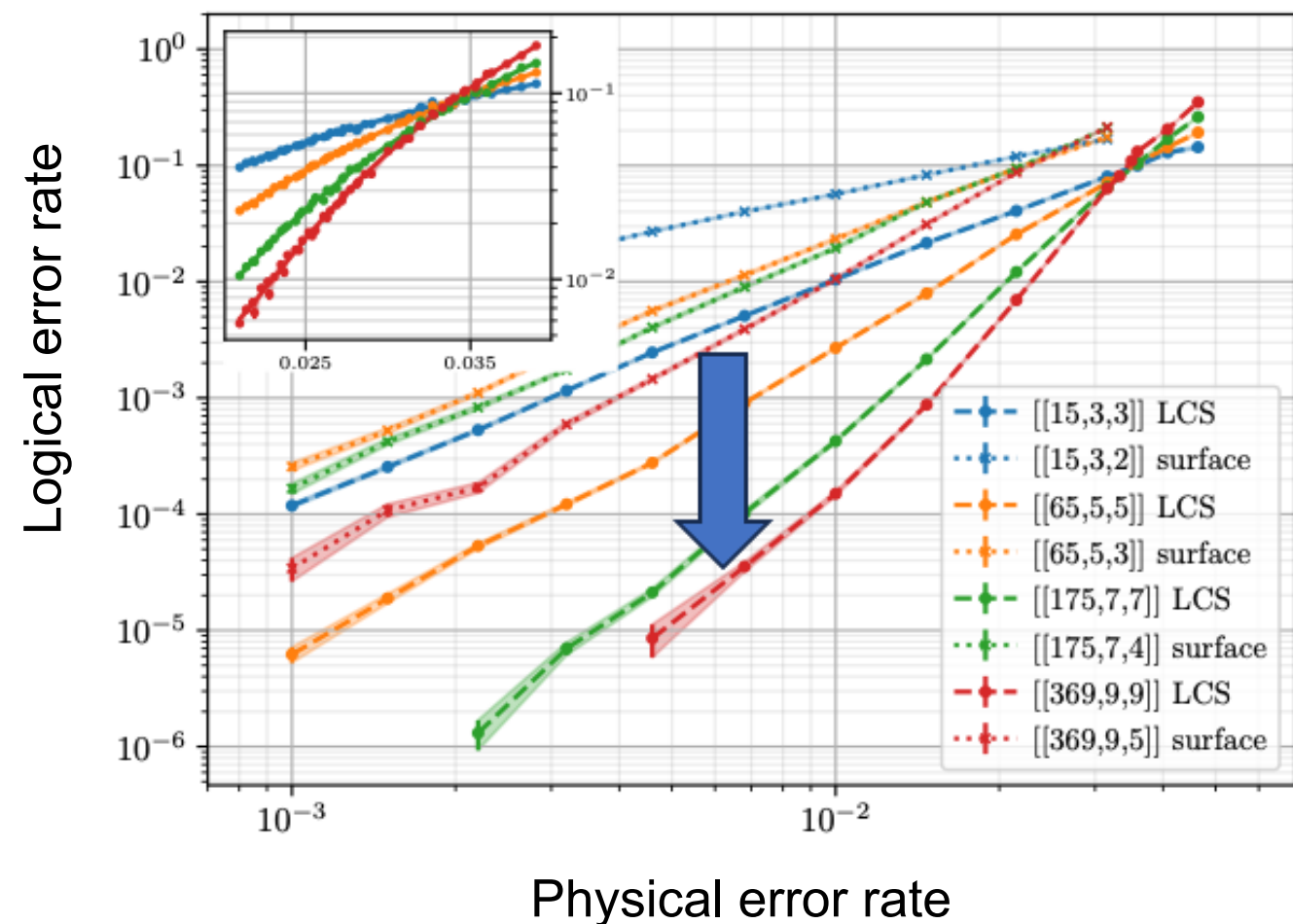
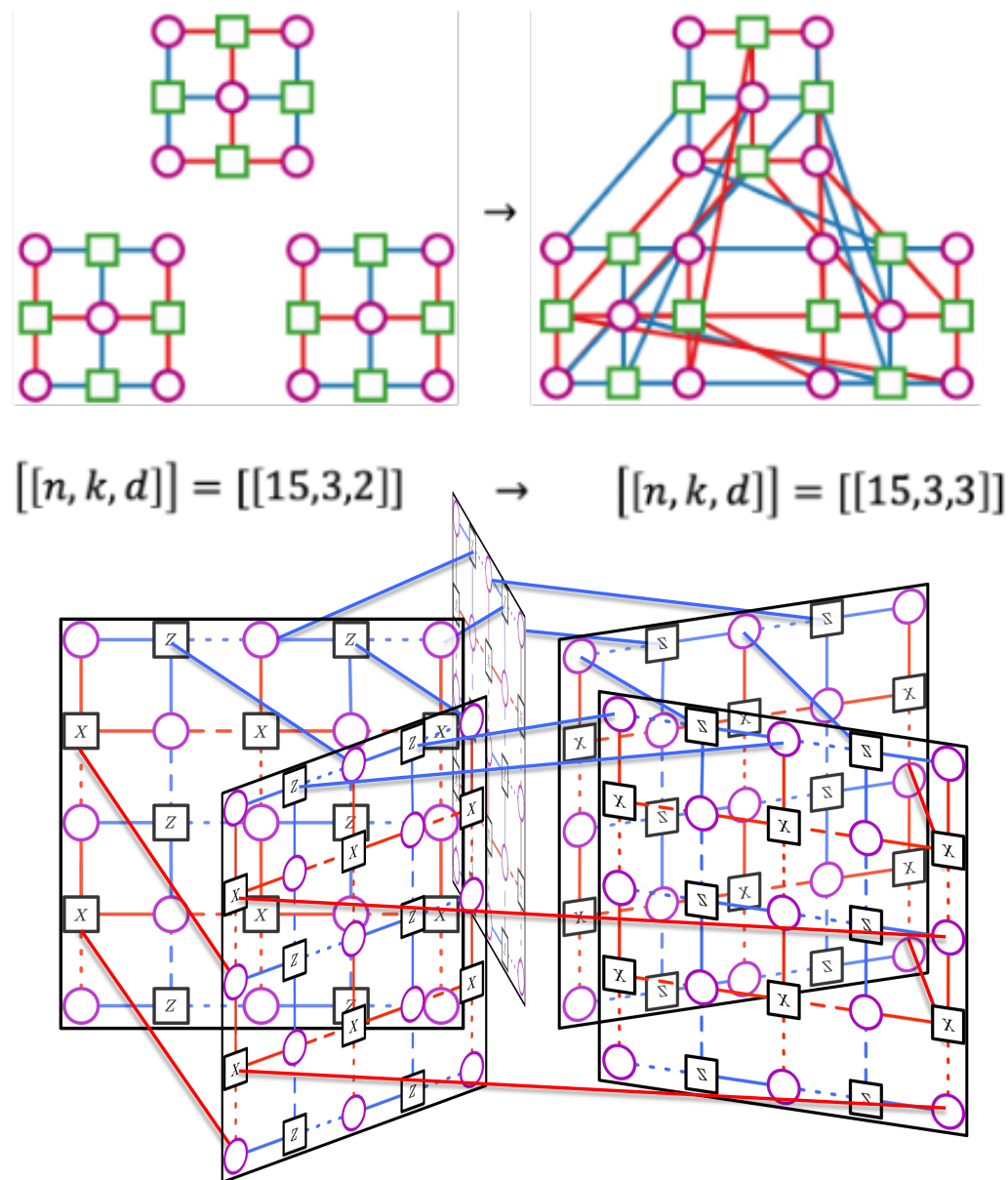
qLDPC Codes: Lift-connected surface code family



J. Old

► Key features of new lift-connected surface code family

- Attractive parameters in low-qubit number regime
- Efficient decoders
- Strong suppression of logical error rates



3D local – interesting for e.g. (static) neutral atom tweezer arrays



Strong suppression of logical error rate as compared to surface codes

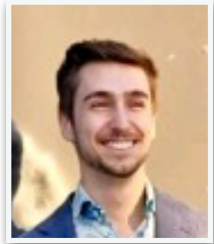
Lift-Connected Surface Codes

J. Old, M. Rispler and M. M.,
Quantum Science and Technology 9, 045012 (2024)

Universal FT logical gates in lift-connected surface codes



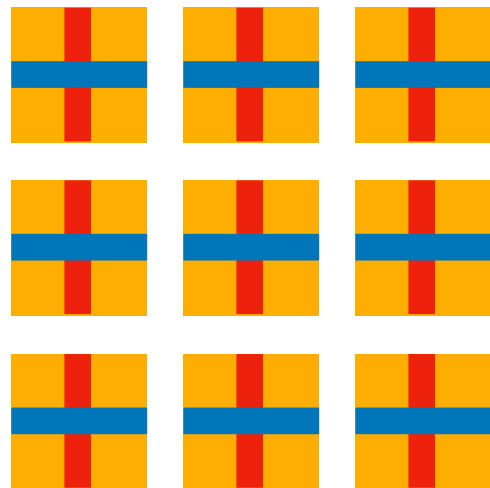
J. Old



J. Bechar



S. Heußen



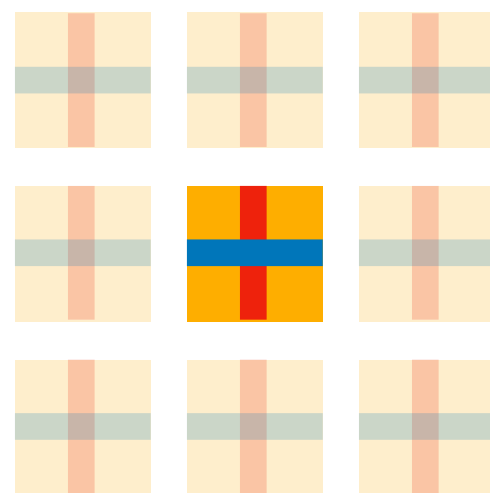
$$k \cdot [[n, 1, d]]$$

VS



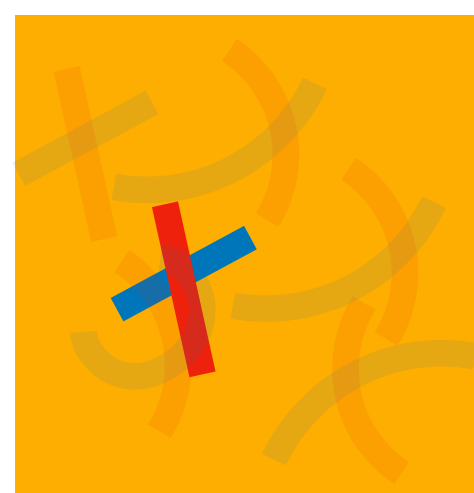
$$[[n, k, d]]$$

- Interwoven logical qubit encodings in qLDPC codes



$$k \cdot [[n, 1, d]]$$

VS



$$[[n, k, d]]$$

- Challenge: realize **addressable** logical gates

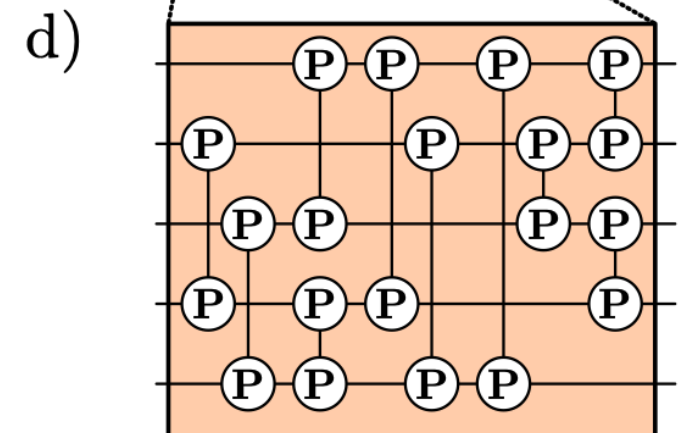
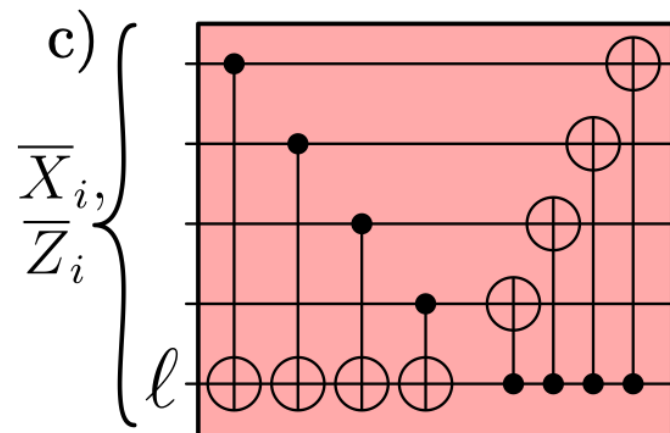
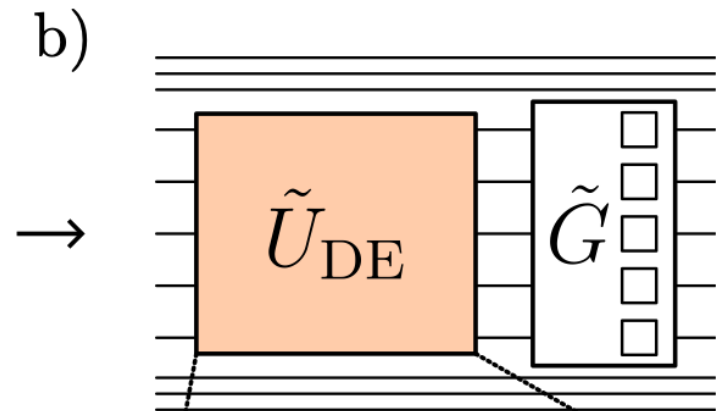
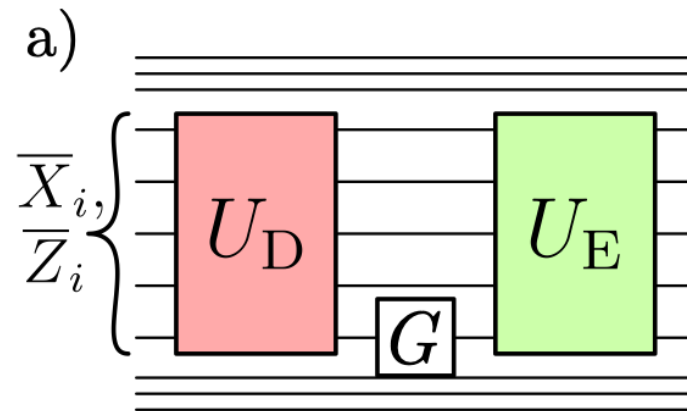
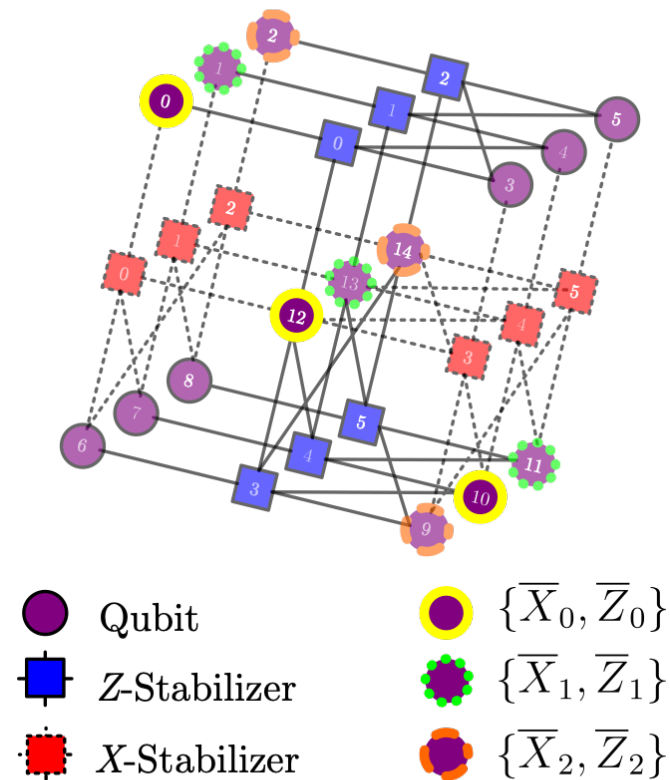
Addressable fault-tolerant universal quantum gate operations for high-rate lift-connected surface codes

J. Old, J. Bechar, M. M., S. Heußen, arXiv:2511.10191 (2025)

FT logical Clifford gates in lift-connected surface codes

- FT constructions for full Clifford group (S, H, CNOT), targeting arbitrary logical qubits in d=3 LCS codes

e.g. $[[15,3,3]]$:

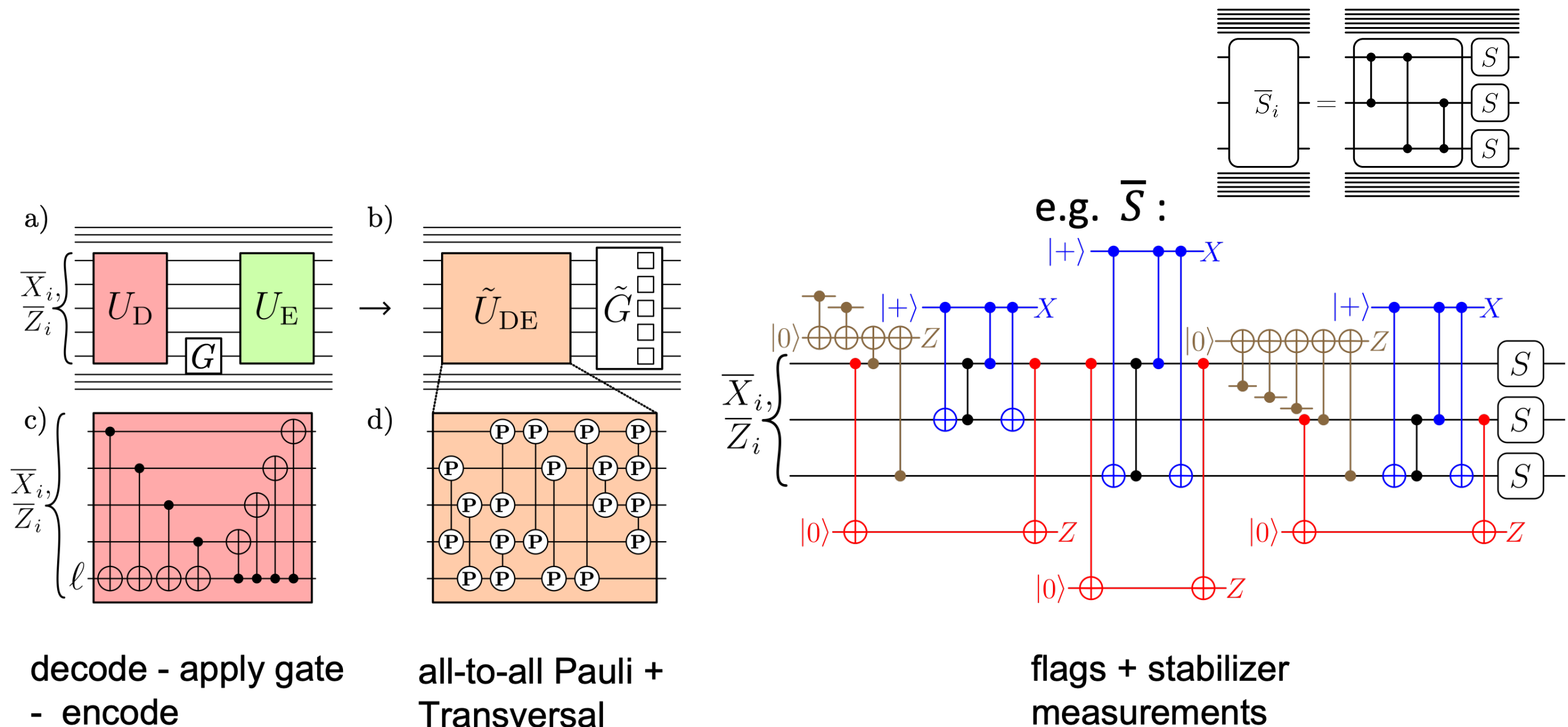


decode - apply gate
- encode

all-to-all Pauli +
Transversal

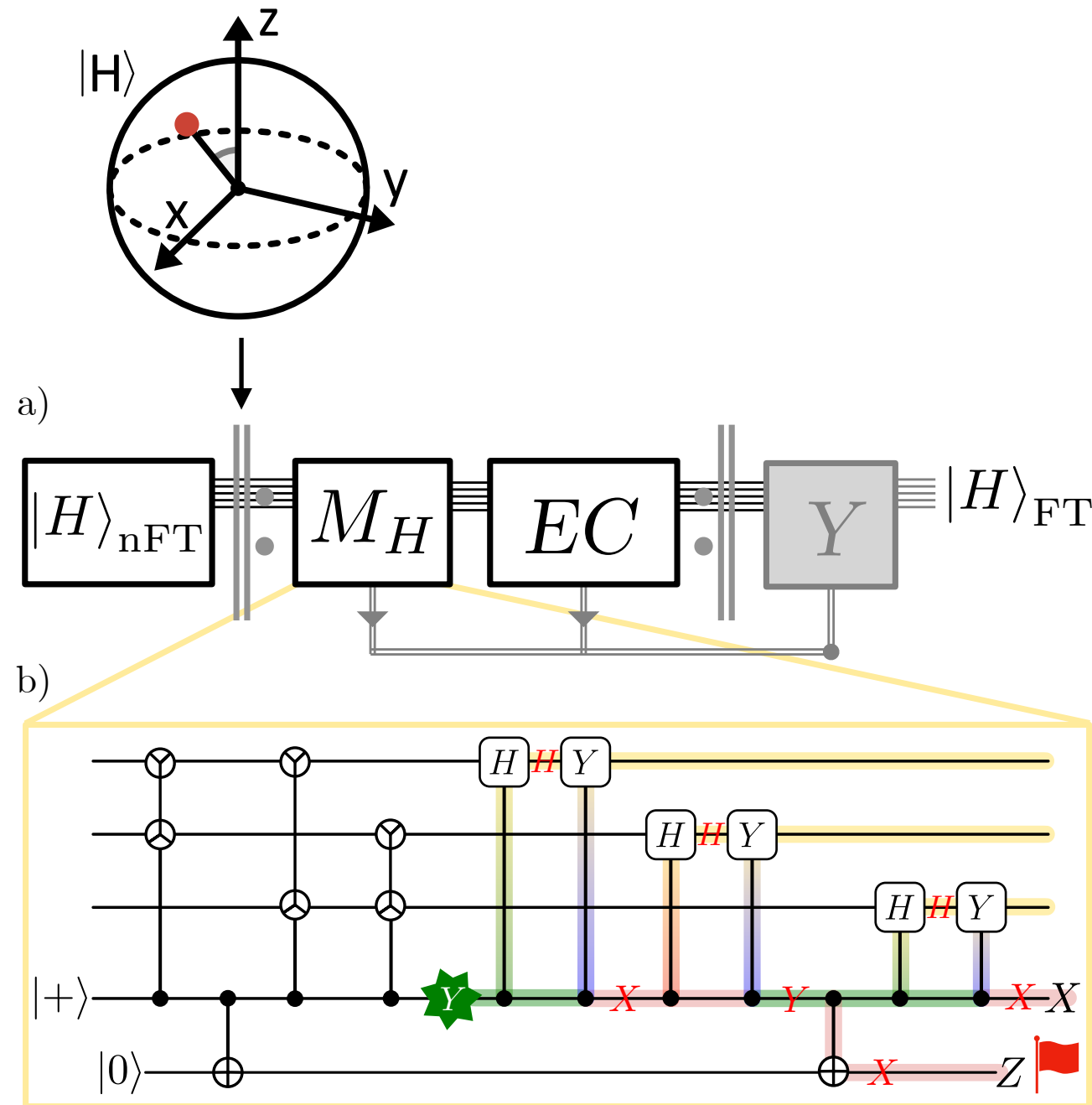
FT logical Clifford gates in lift-connected surface codes

- FT constructions for full Clifford group (S, H, CNOT), targeting arbitrary logical qubits in d=3 LCS codes
- Achieve FT by adding flag qubits to detect dangerous errors

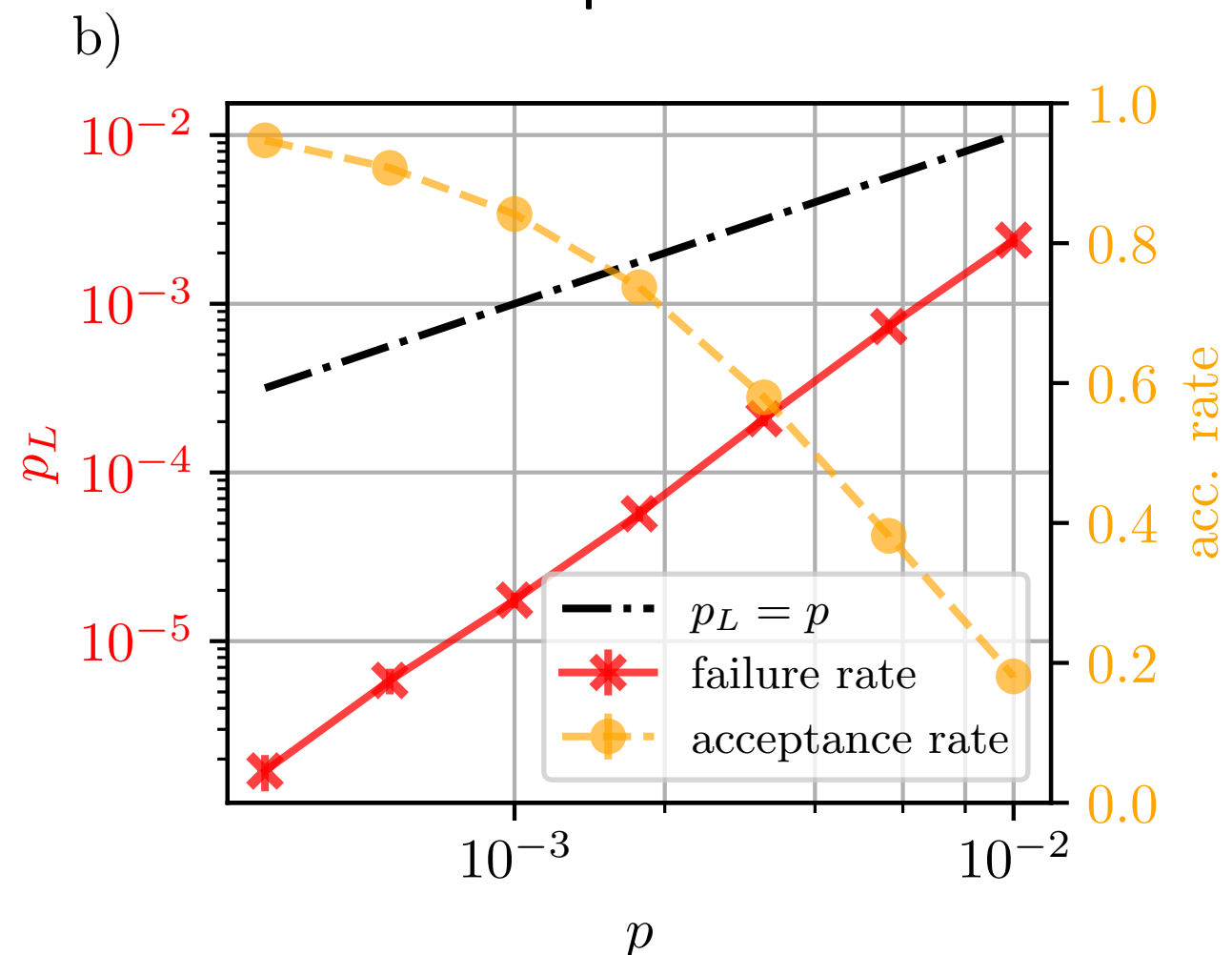


FT magic state preparation in lift-connected surface codes

- FT state preparation schemes for logical $|H\rangle$ magic state in $d=3$ LCS codes
- Idea: non-FT prep. $|H\rangle_L$ state, then verify it by FT measurement of H_L



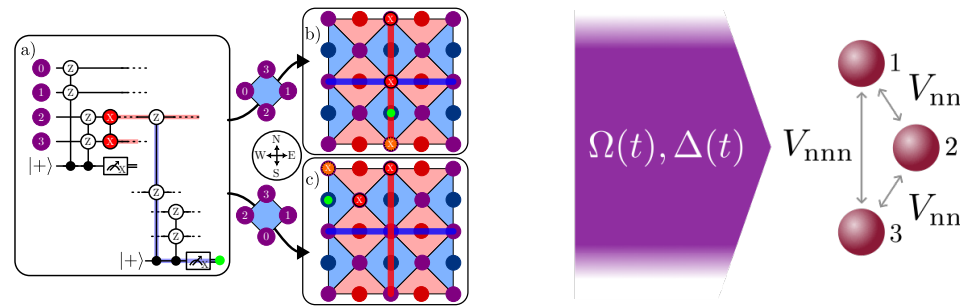
Repeat-until success scheme
with $> 10^{-2}$ pseudo-threshold



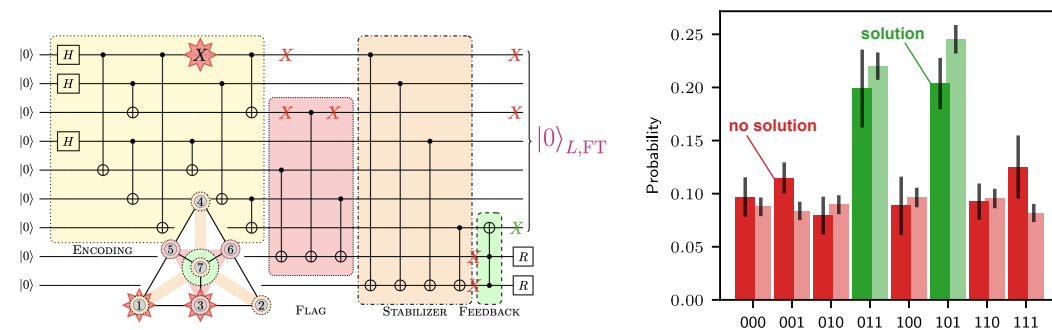
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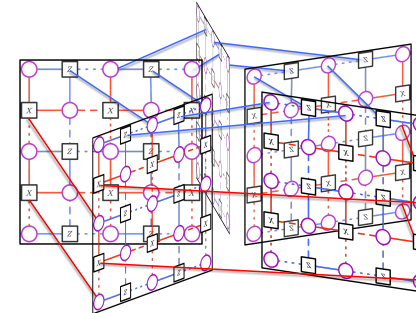
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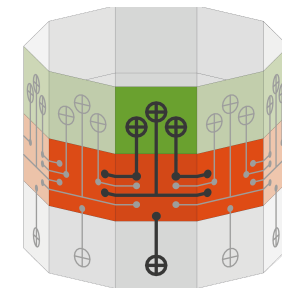
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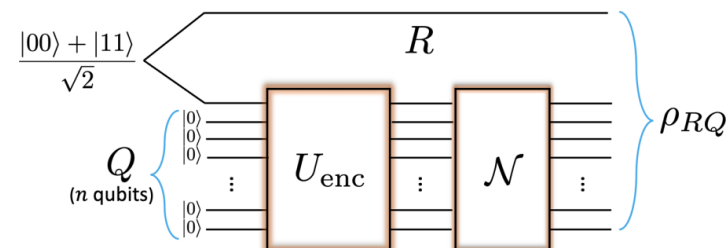
3 - Universal FT QC with **lift-connected surface codes**



4 - Classical and quantum **cellular automata for QEC**



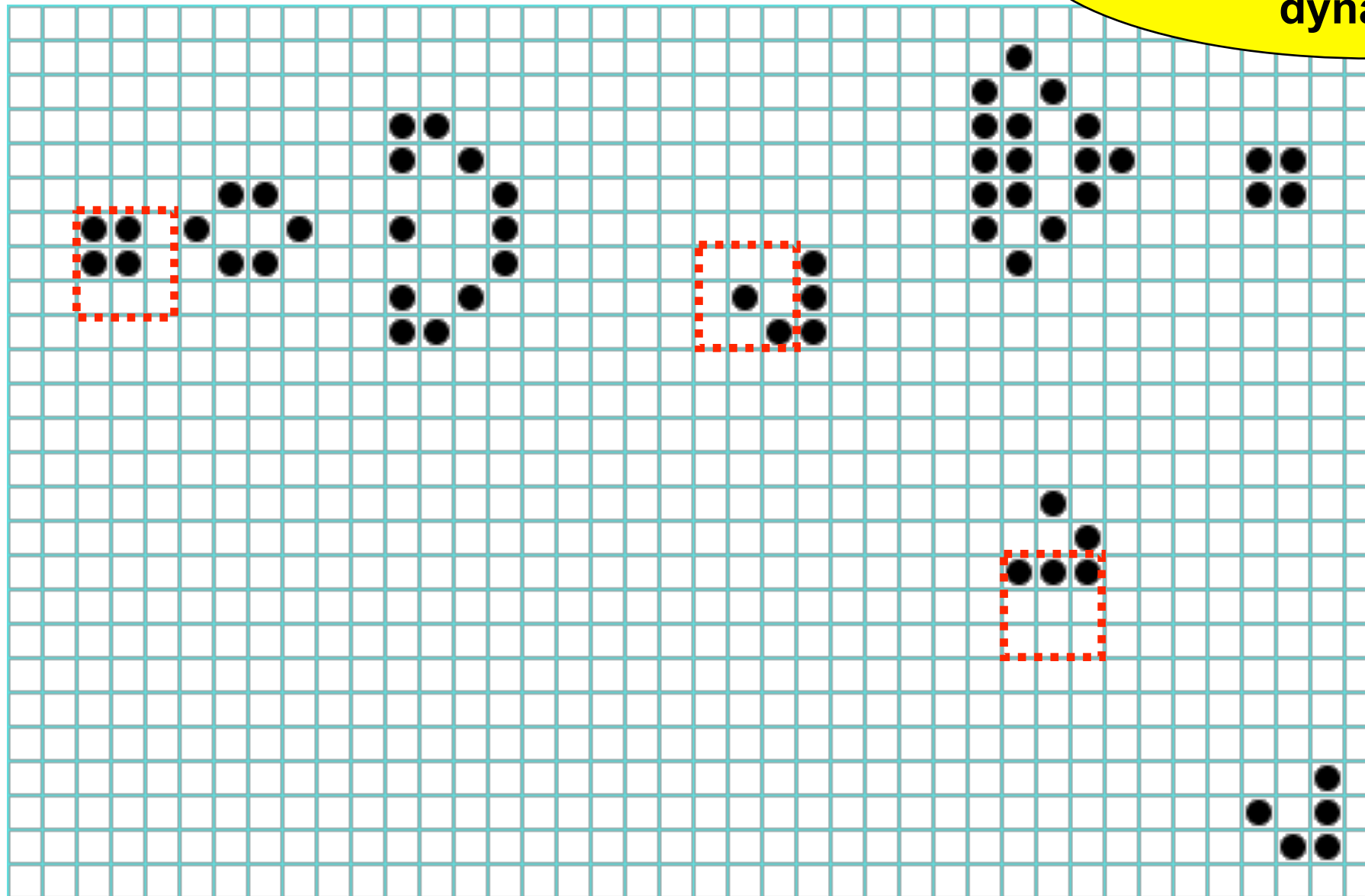
5 - Enhancing QEC thresholds by **Syndrome Resampling**



Classical cellular automata

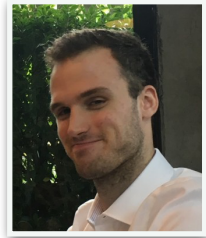
Convey's Game of Life (1970)

Simple local rules can give rise to complex emergent dynamics



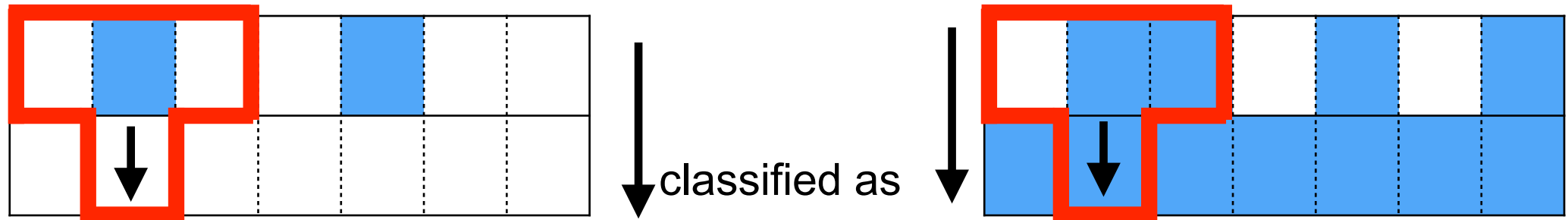
1. Live cell with < 2 live neighbors: dies (underpopulation)
2. Live cell with 2 or 3 live neighbors: stays alive
3. Live cell with > 3 live neighbors: dies (overpopulation)
4. Dead cell with exactly 3 live neighbors: becomes a live cell (reproduction).

Quantum Cellular Automata for Quantum Error Correction



T. Guedes, D. Winter

► Density classification problem



- **Fully-autonomous, measurement-free local quantum cellular automaton dynamics** to stabilise logical qubits?
- **Fundamental interest** - but also **practically relevant!**

$$|\psi\rangle_L = \alpha|0000000000\rangle + \beta|1111111111\rangle$$

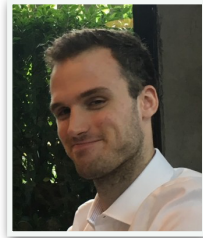
Errors
↓

$$|\psi\rangle_L = \alpha|0\textcolor{red}{1}00000\textcolor{red}{1}10\rangle + \beta|1\textcolor{red}{0}1111\textcolor{red}{0}01\rangle$$

Ideal Correction
↓

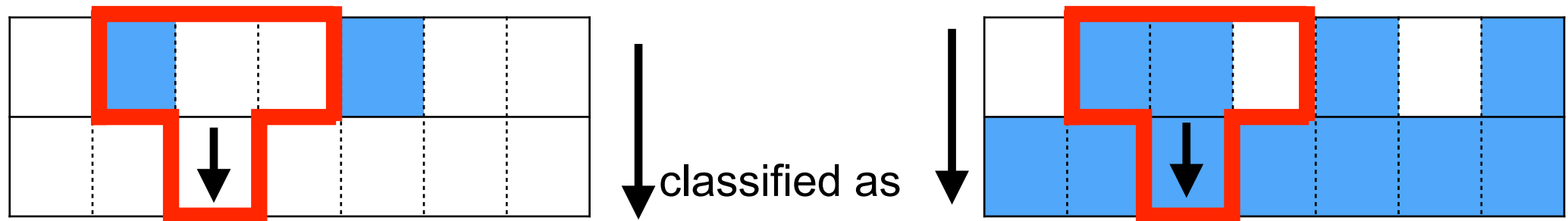
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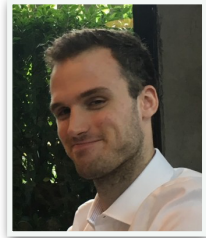
Errors

$$|\psi\rangle_L = \alpha|0100000110\rangle + \beta|101111001\rangle$$

Ideal Correction

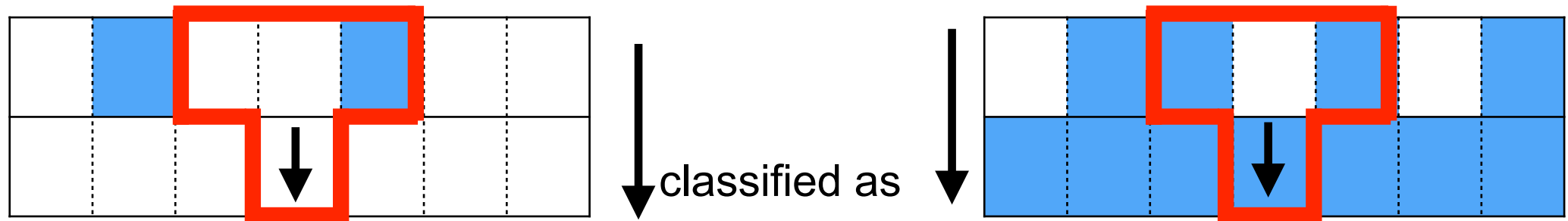
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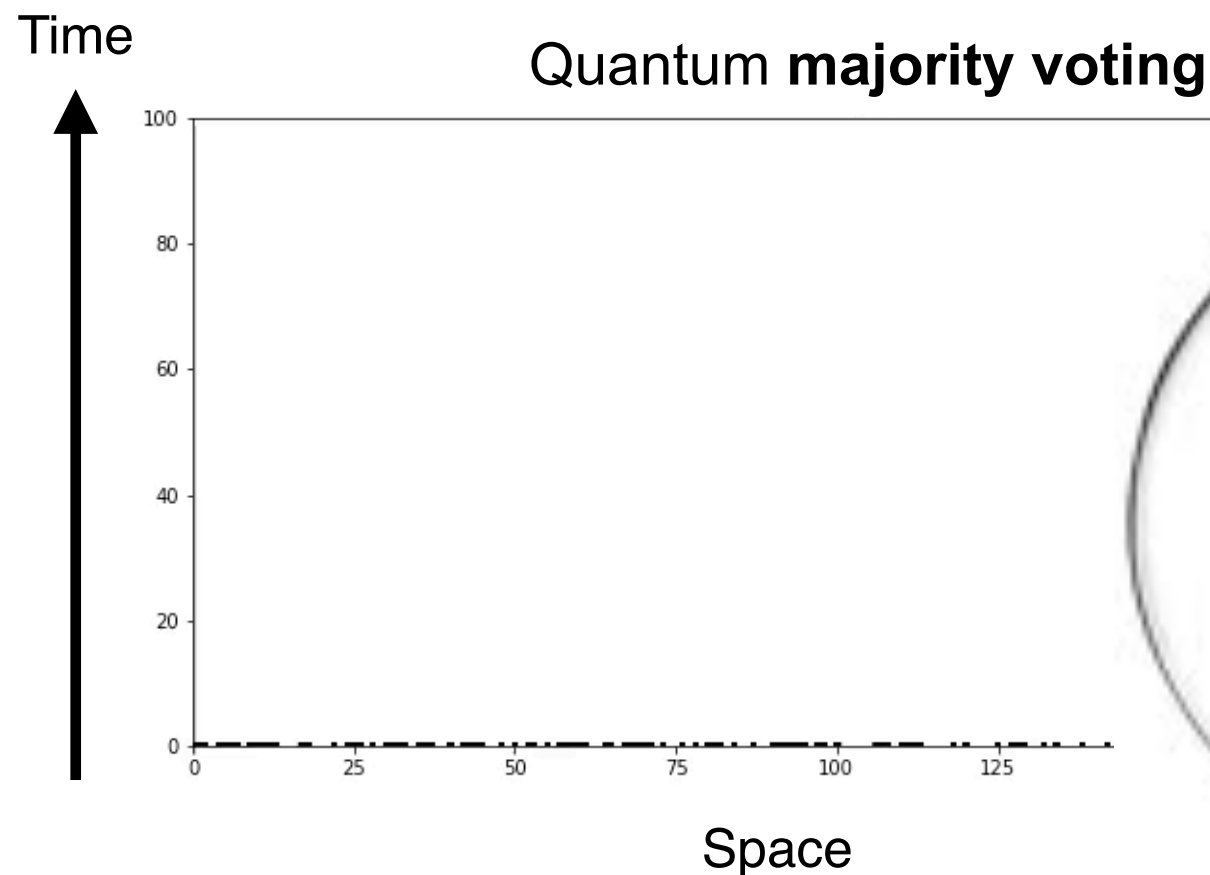
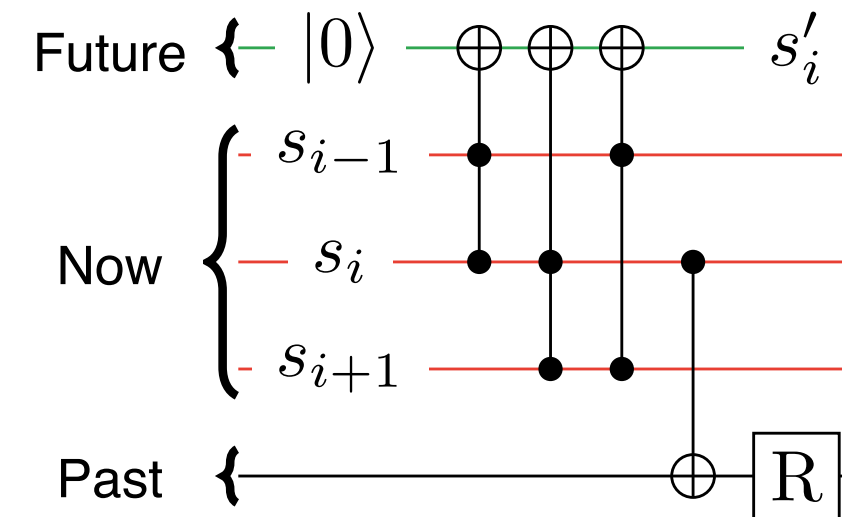
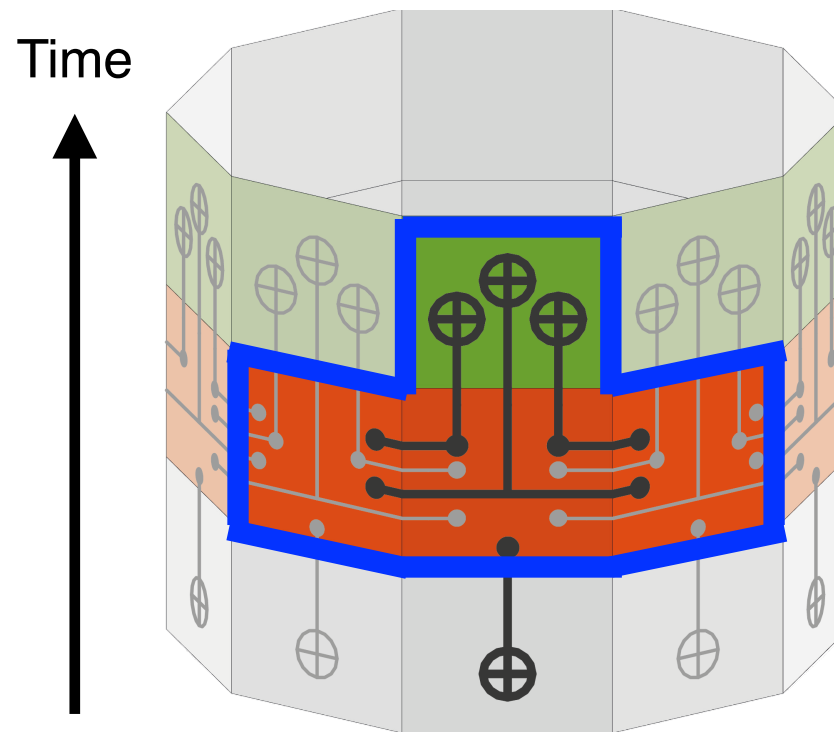
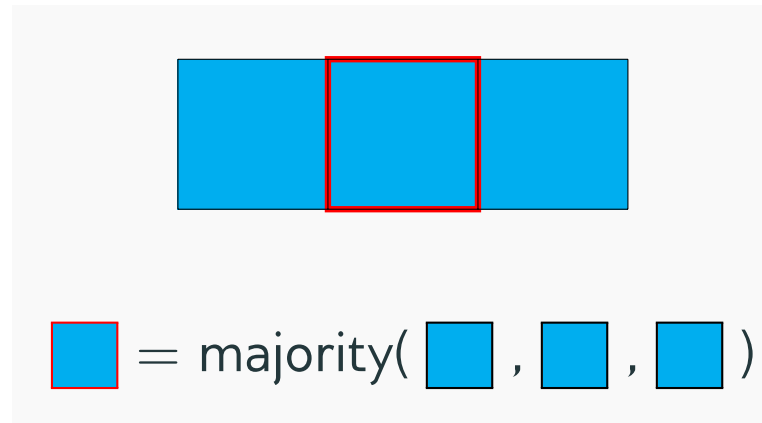
$$|\psi\rangle_L = \alpha|010000110\rangle + \beta|101111001\rangle$$

Ideal Correction
↓

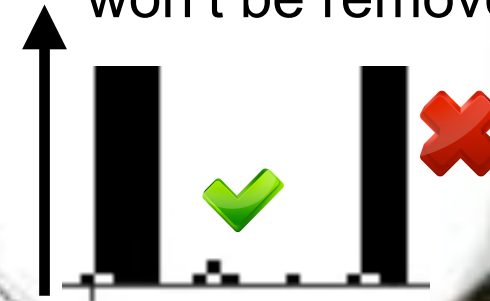
$$|\psi\rangle_L = \alpha|0000000000\rangle + \beta|1111111111\rangle$$

Quantum Cellular Automata for Quantum Error Correction

► First try: **majority voting rule**

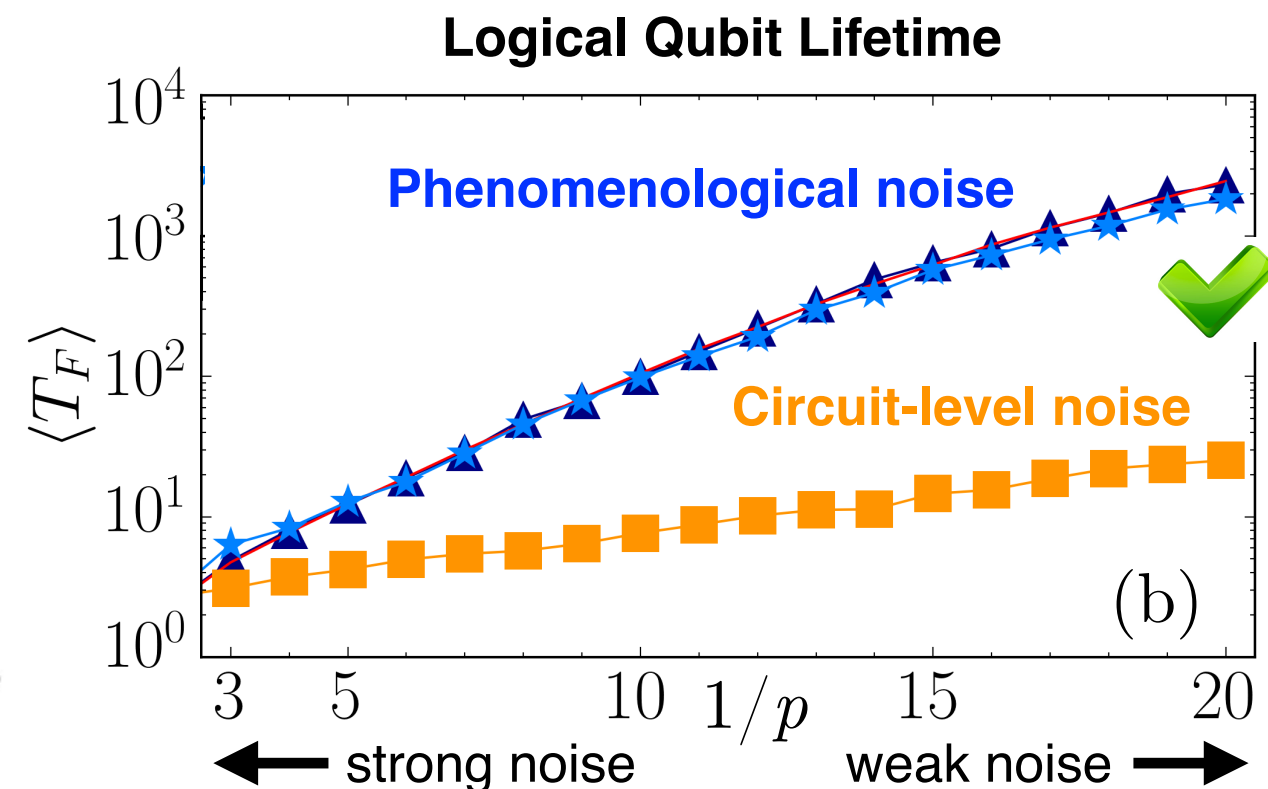
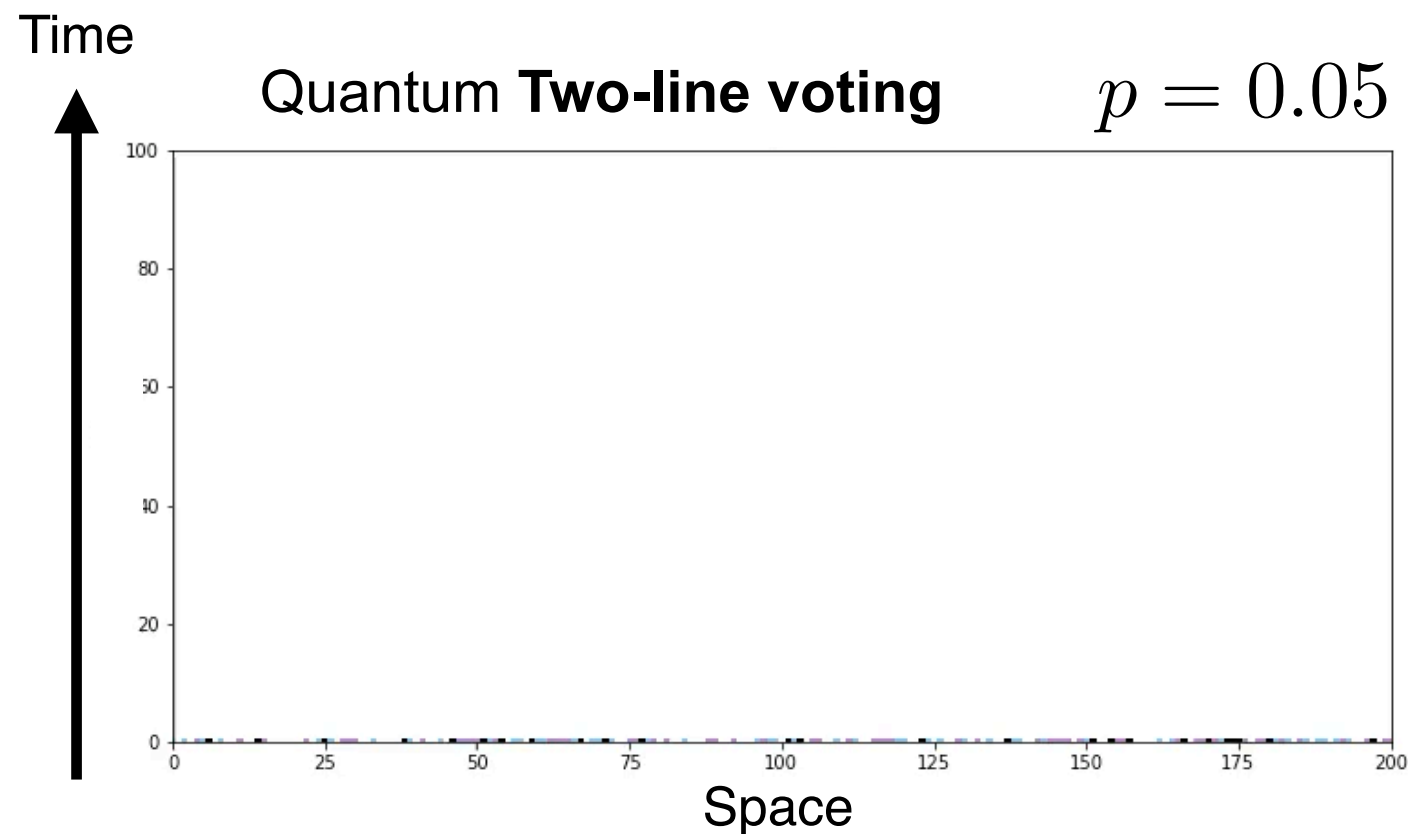
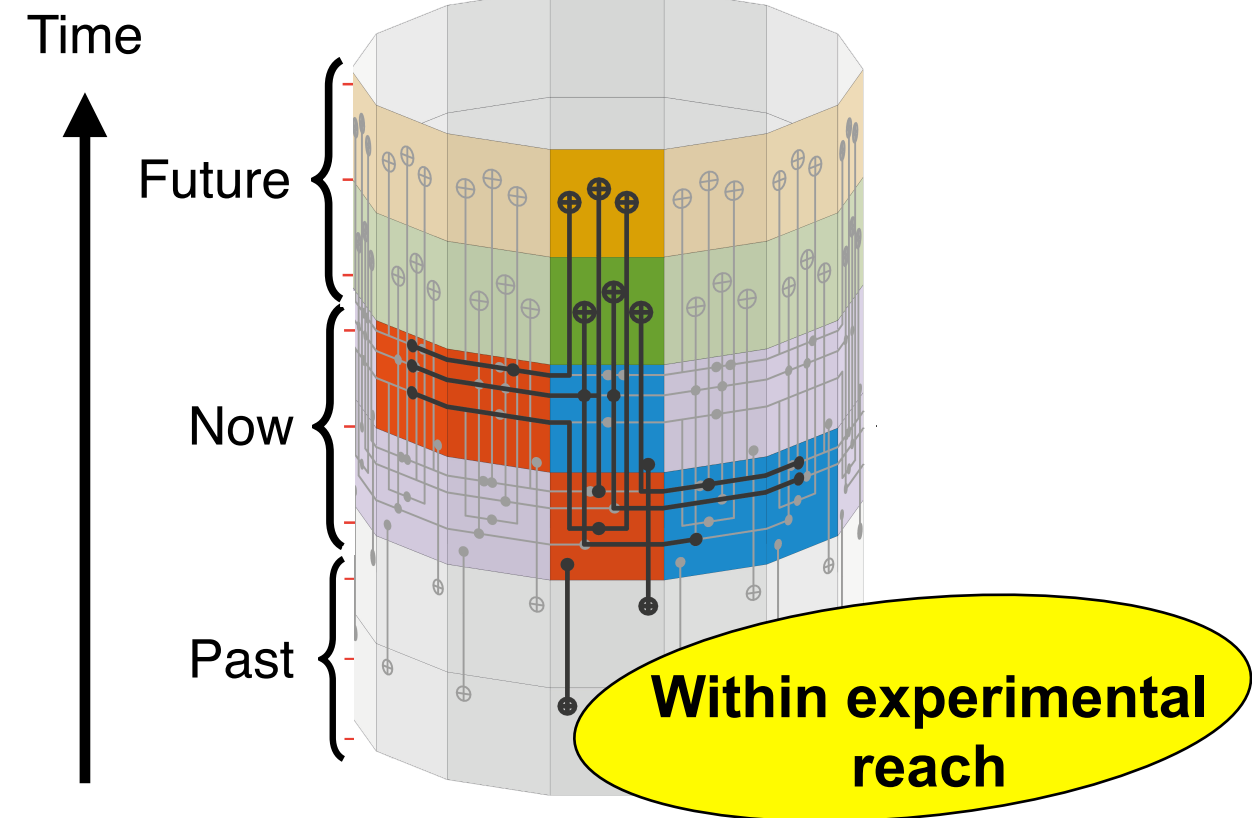
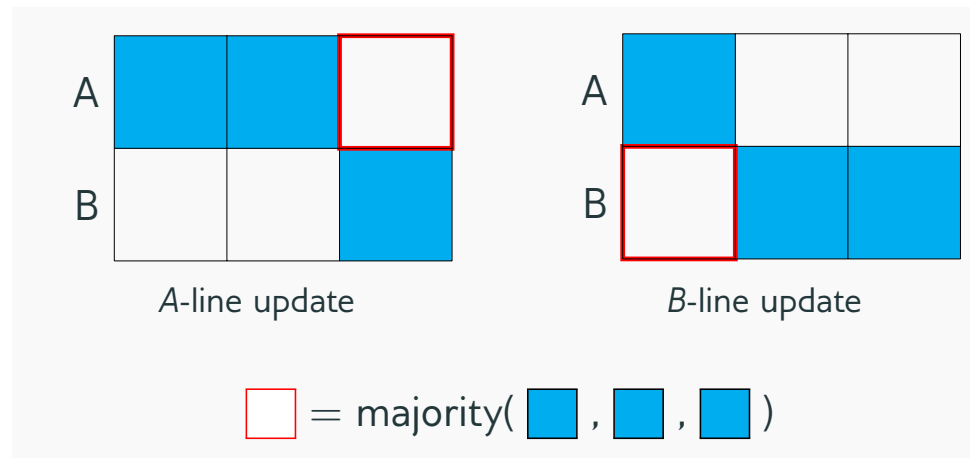


► Problem:
Islands are stable,
won't be removed



Quantum Cellular Automata for Quantum Error Correction

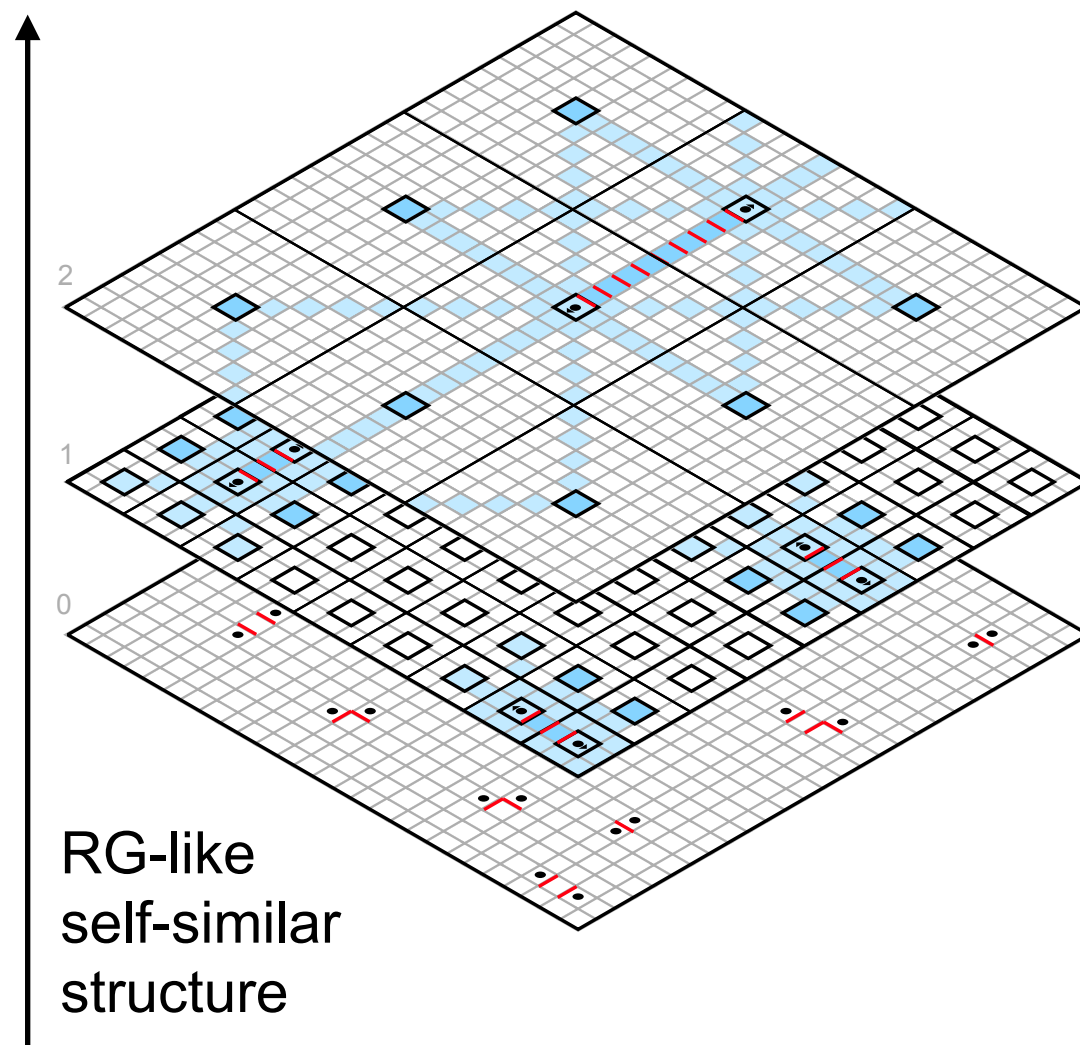
► Two-line voting quantum cellular automaton



Cellular Automata (CA) based Decoding

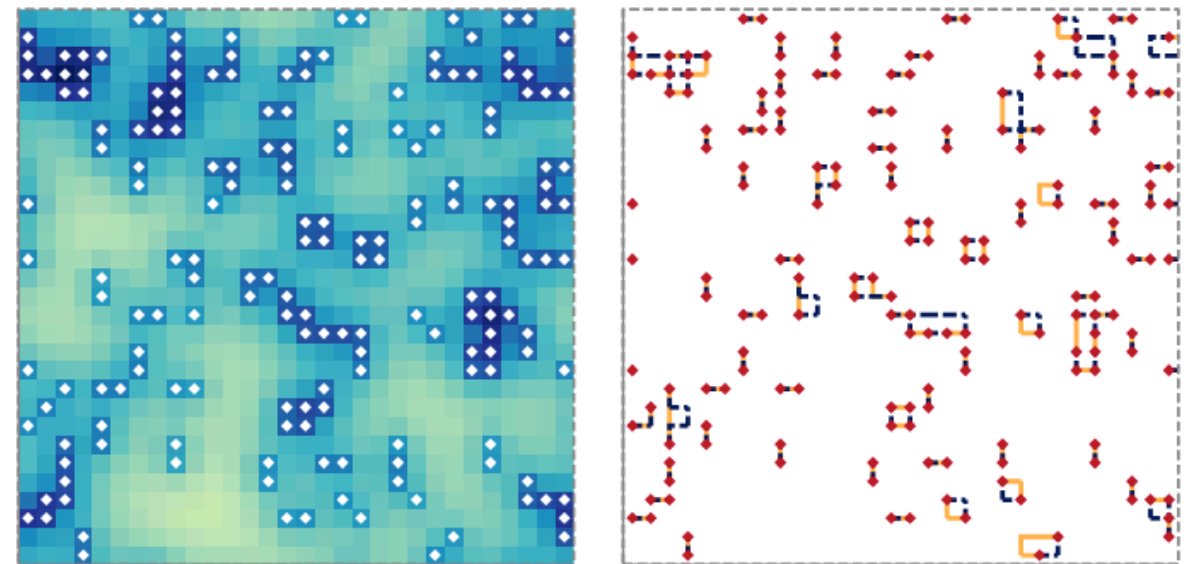
Hierarchical CA Decoder:

Recursive partitioning of the (toric code) lattice into colonies formed by $Q \times Q$ cells



Non-Hierarchical CA Decoder

(“Field-based” / “Signaling”)



Analysis of Quantum Error-Correcting Codes: Symplectic Lattice Codes and Toric Codes

J. W. Harrington, Ph.D. thesis, California Institute of Technology (2004)

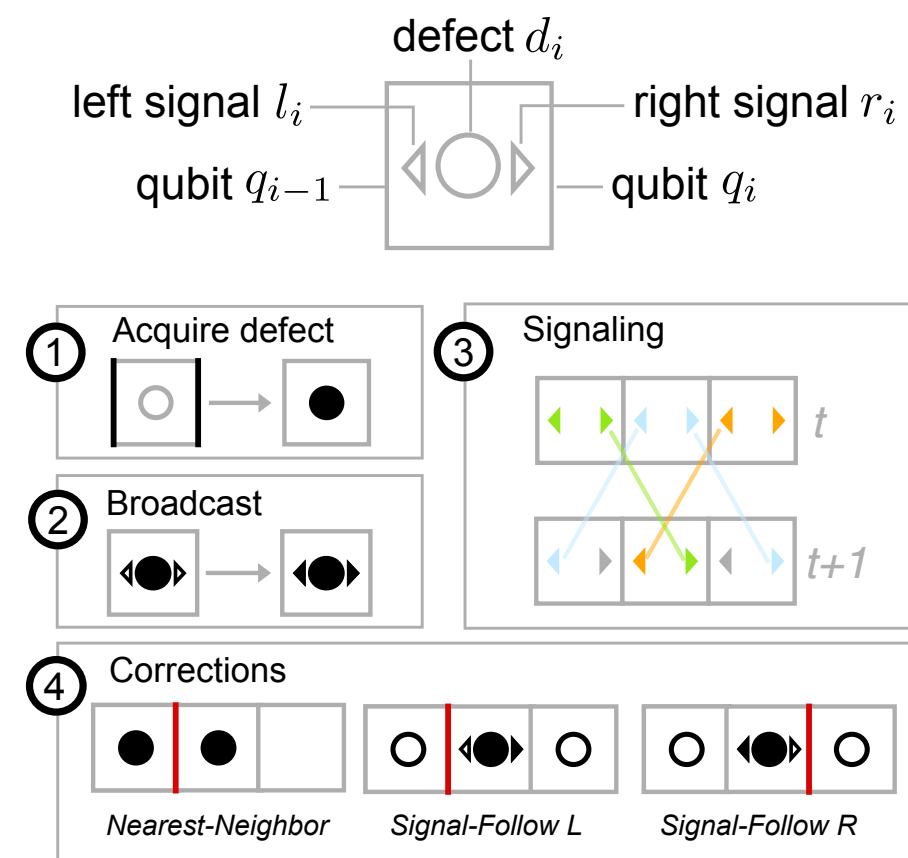
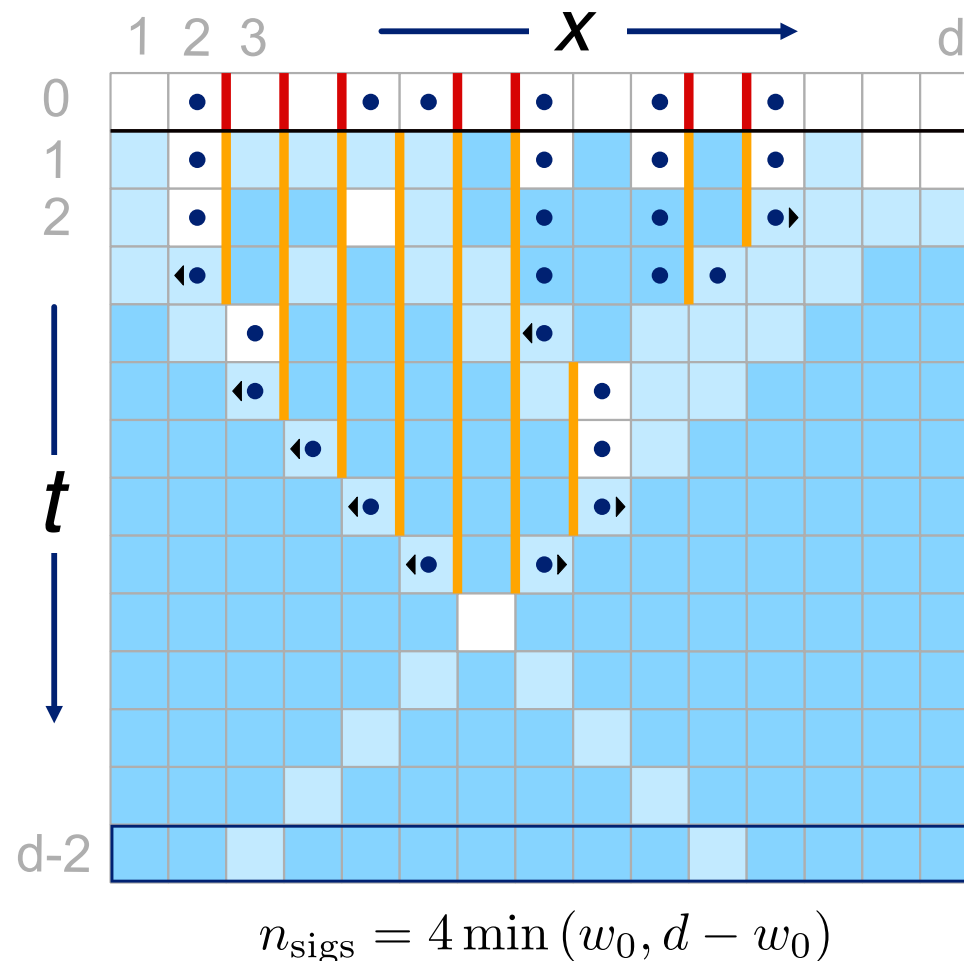
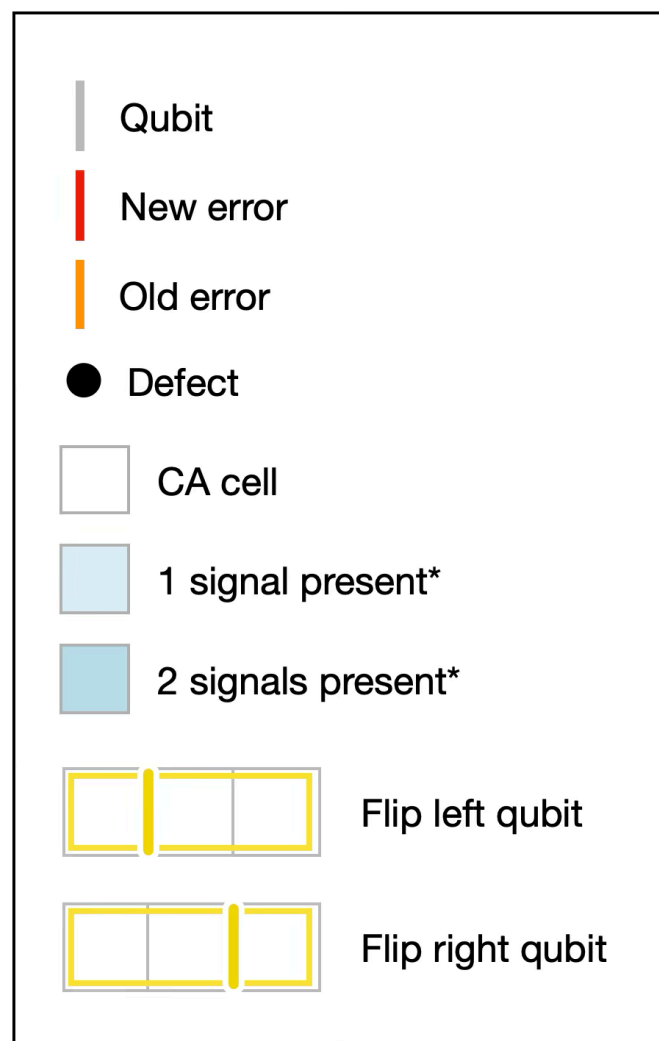
Local Decoders for the 2D and 4D Toric Code

N. Breuckmann et al., Quant. Inf. Comp. 17, 0181 (2017)

... and many more

SCALA 1D decoder

► SCALA (Signaling CA with Local Attraction)



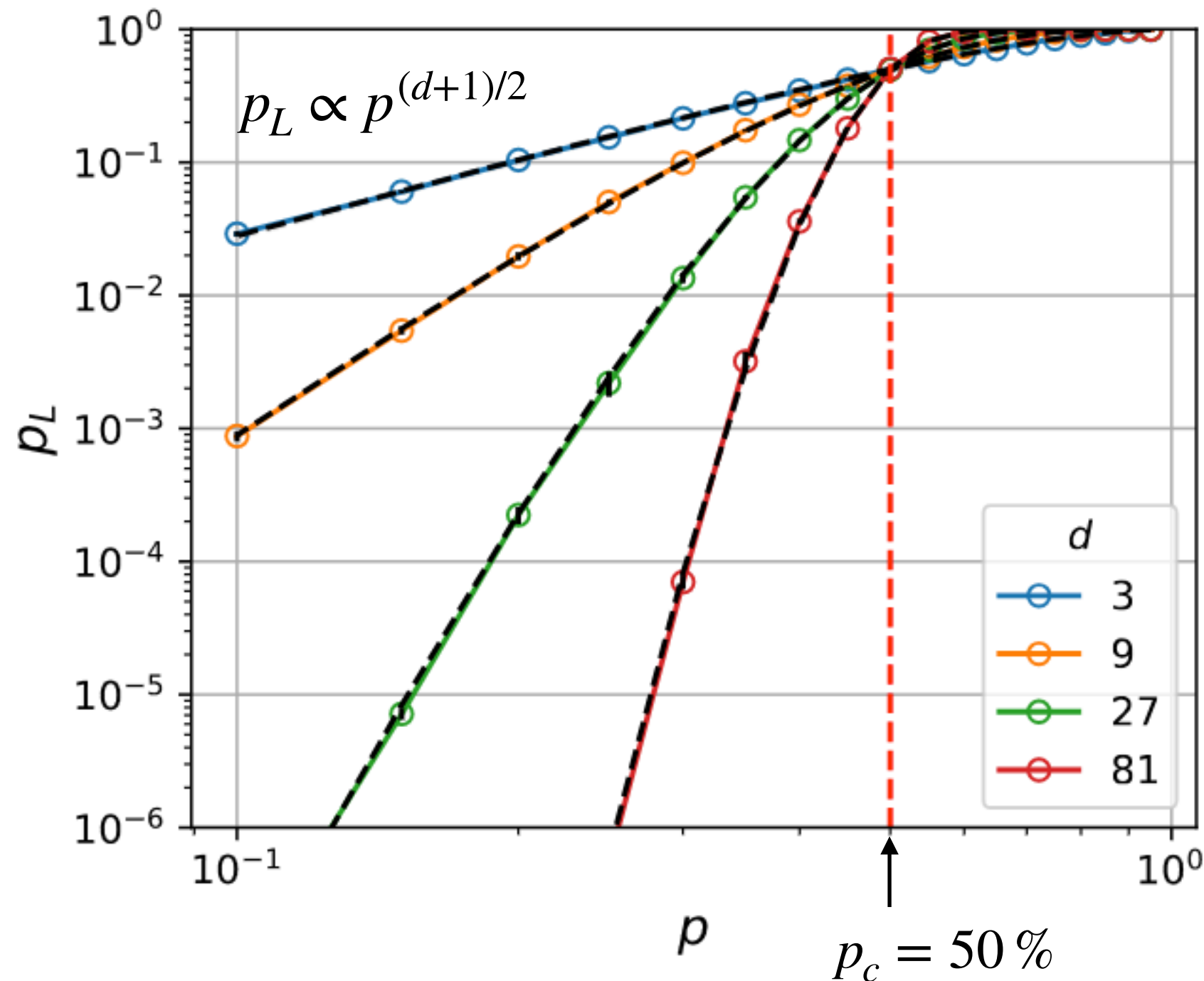
* Signal direction only shown when relevant

High-performance cellular automaton decoders for quantum repetition and toric code

D. Winter, T. L. M. Guedes, M. M., arXiv:2604.21866 (2026)

SCALA 1D decoder

- ▶ **SCALA** (Signaling **CA** with **L**ocal **A**ttraction)
- ▶ **Realises ML Decoding** for code capacity noise



For reference:
Global majority voting

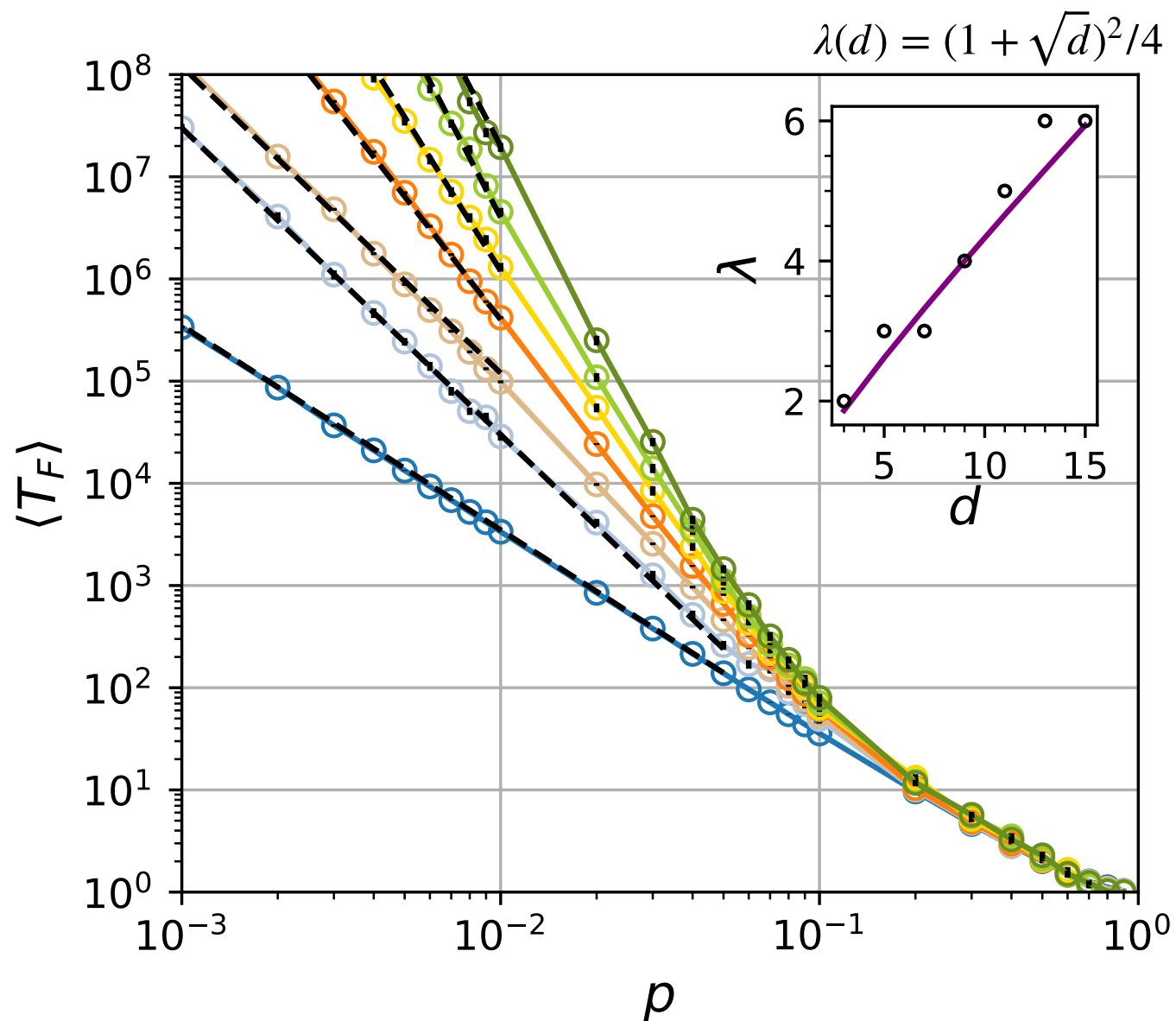
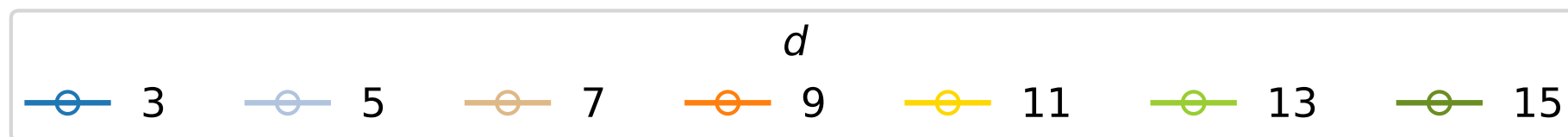
.....

SCALA 1D decoder

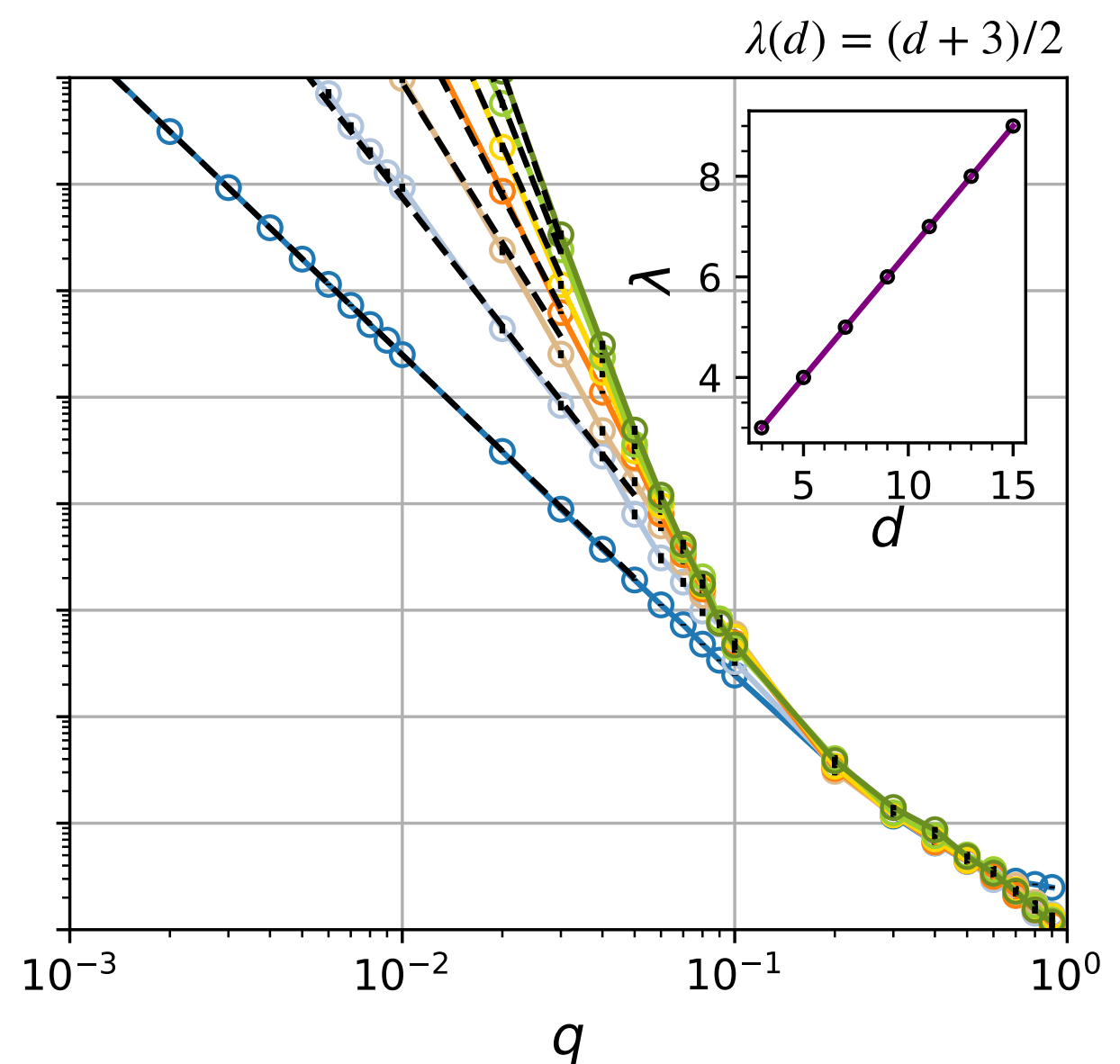
► **SCALA** (Signaling **CA** with **L**ocal **A**ttraction)

► **Phenomenological noise**

$$\text{Logical lifetime } \langle T_F \rangle \propto p^{-\lambda(d)}$$



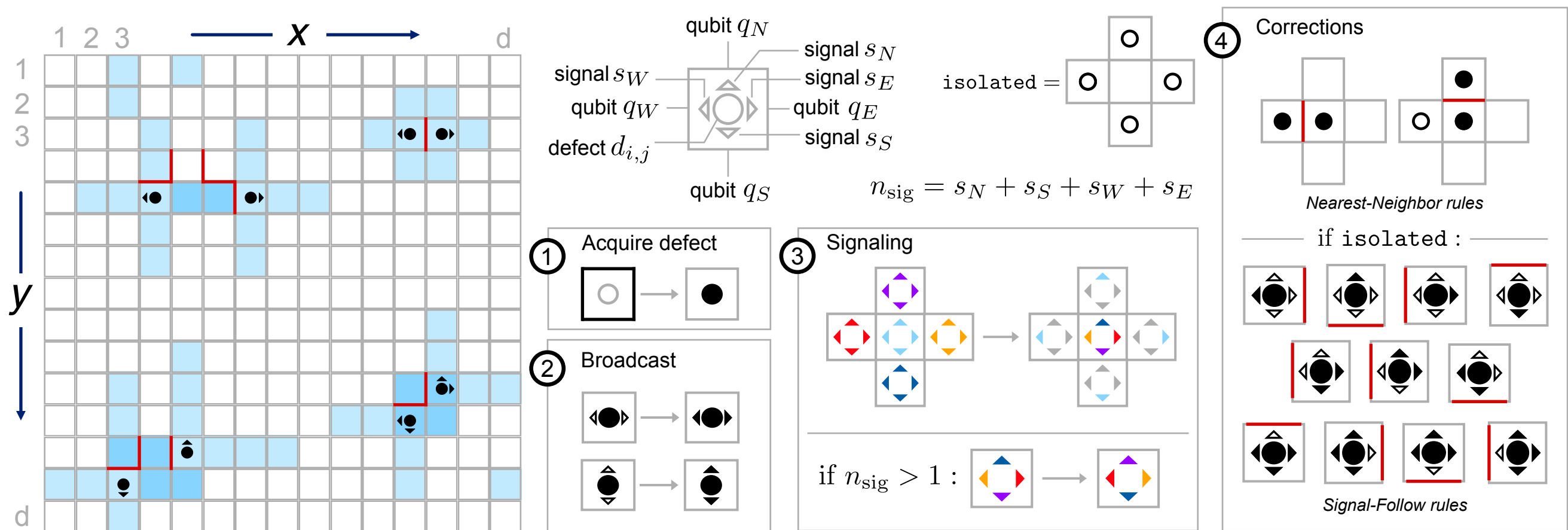
Only data qubit errors ($p \neq 0, q = 0$)



Only measurement errors ($q \neq 0, p = 0$)

SCALA 2D decoder

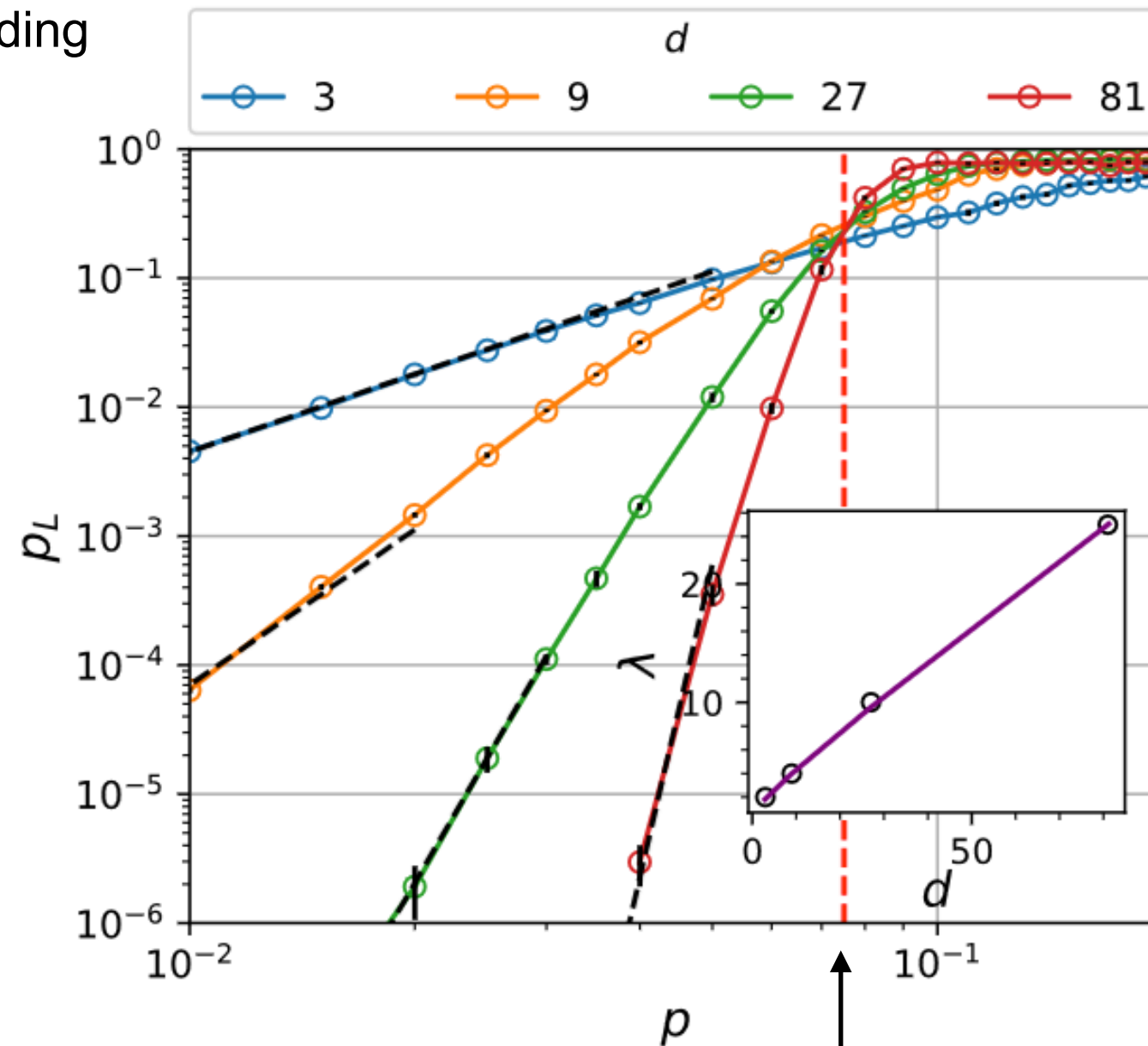
- **SCALA** (Signaling **CA** with **L**ocal **A**ttraction)
- **2D toric code** decoding
- 4 signal bits, slightly modified correction rules as compared to SCALA 1D



Performance of SCALA 2D

► **SCALA** (Signaling **CA** with **L**ocal **A**ttraction)

► **2D toric code** decoding



Competitive **code capacity** noise threshold of 7.5%
(as compared to 4.5 % for Harrington's decoder)

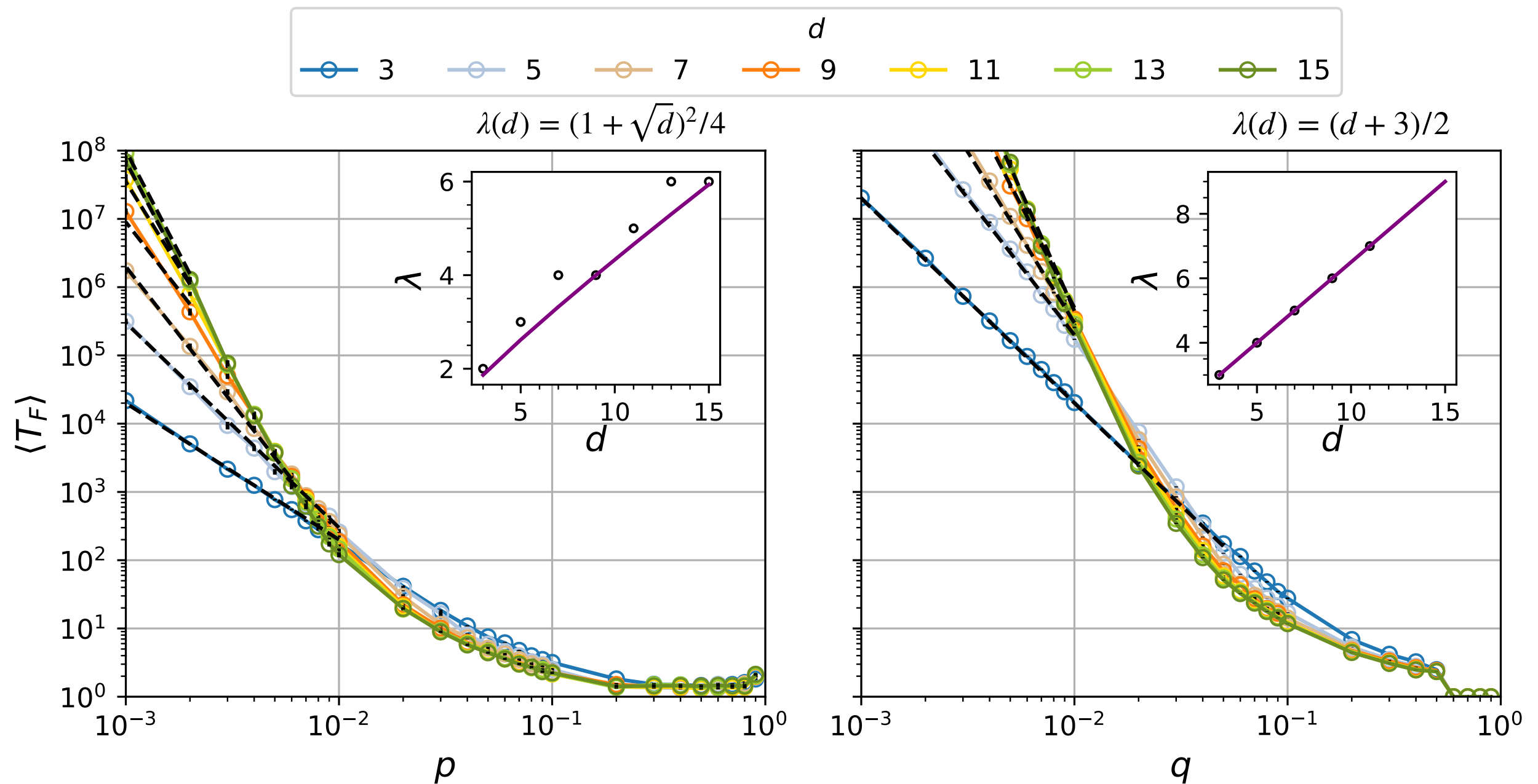
$$p_c = 7.5\%$$

Performance of SCALA 2D

► **SCALA** (Signaling **CA** with **L**ocal **A**ttraction)

► **Phenomenological noise**

$$\text{Logical lifetime } \langle T_F \rangle \propto p^{-\lambda(d)}$$



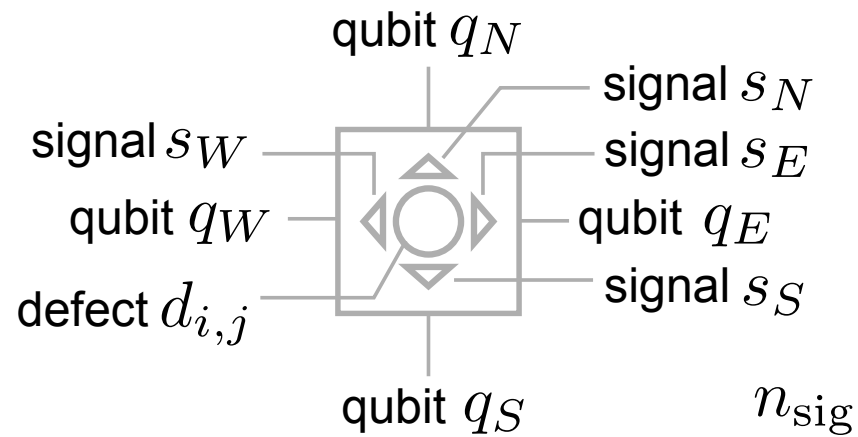
Only **data qubit errors** ($p \neq 0, q = 0$)

Only **measurement errors** ($q \neq 0, p = 0$)



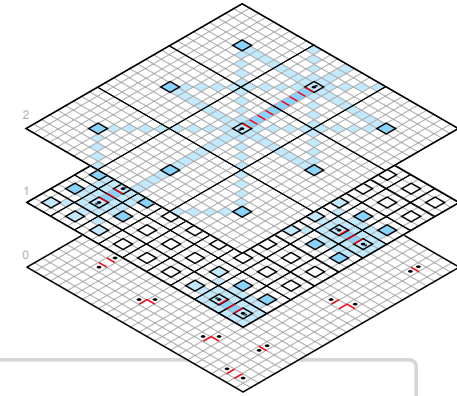
Strong robustness against measurement errors

Performance of SCALA 2D

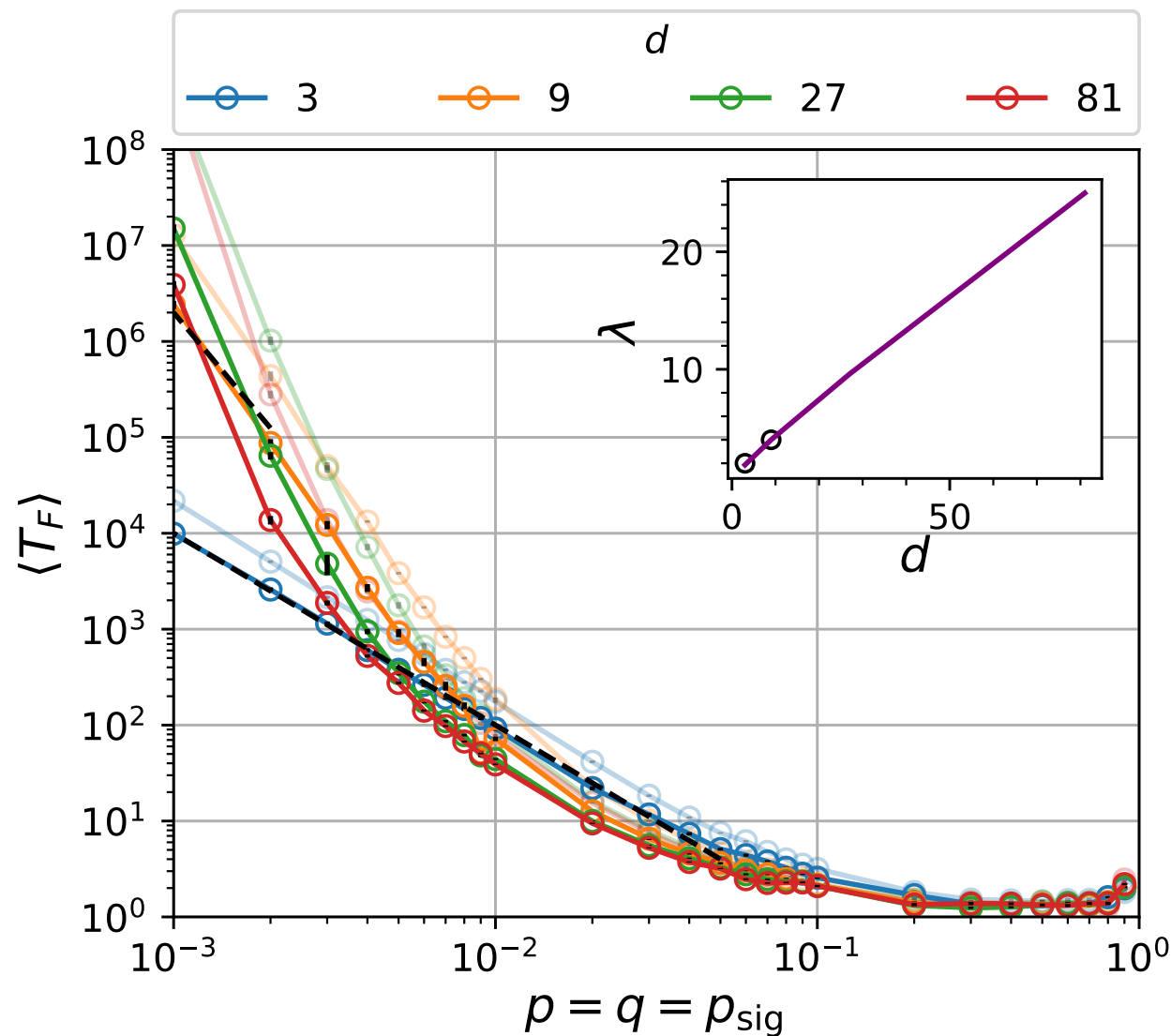


► **Phenom. noise + additionally signal noise**

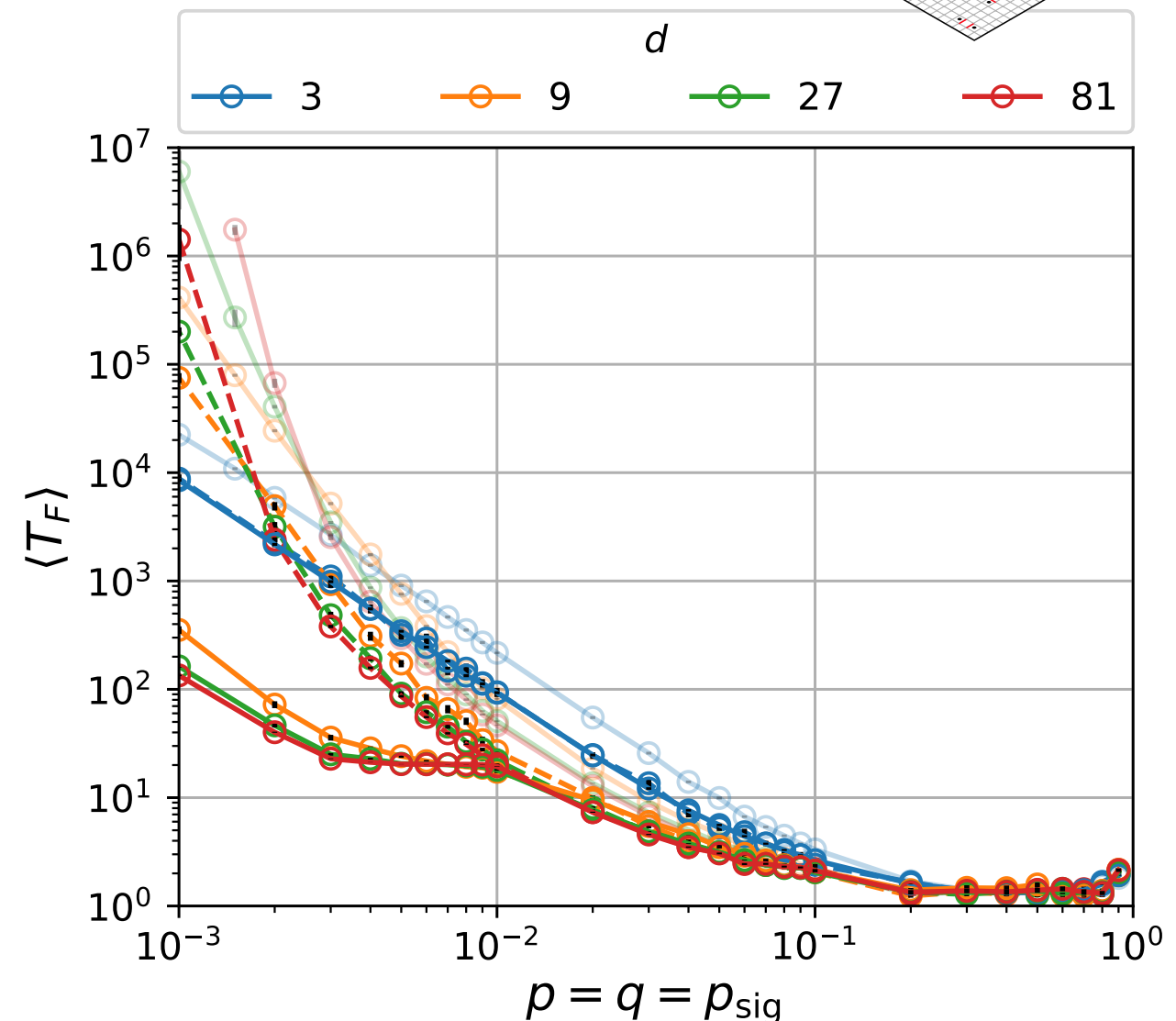
► **Signal noise can trigger wrong corrections**



SCALA 2D decoder



For comparison Harrington's decoder

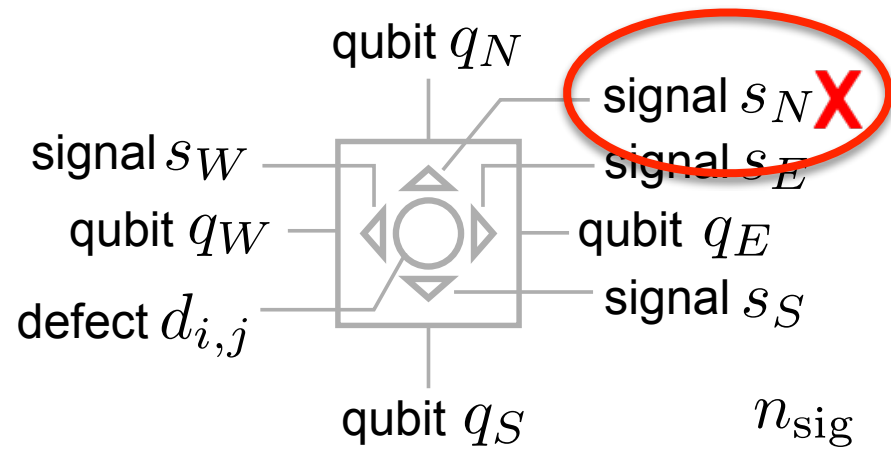


Strong robustness against signaling errors



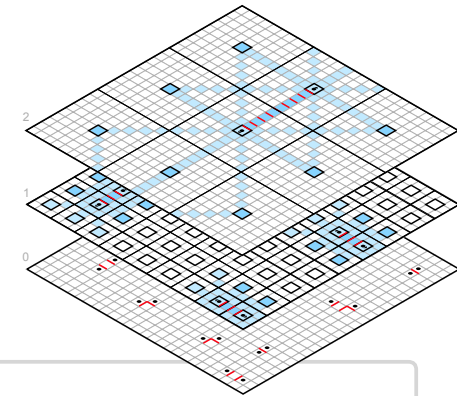
Breaks down for signaling noise

Performance of SCALA 2D

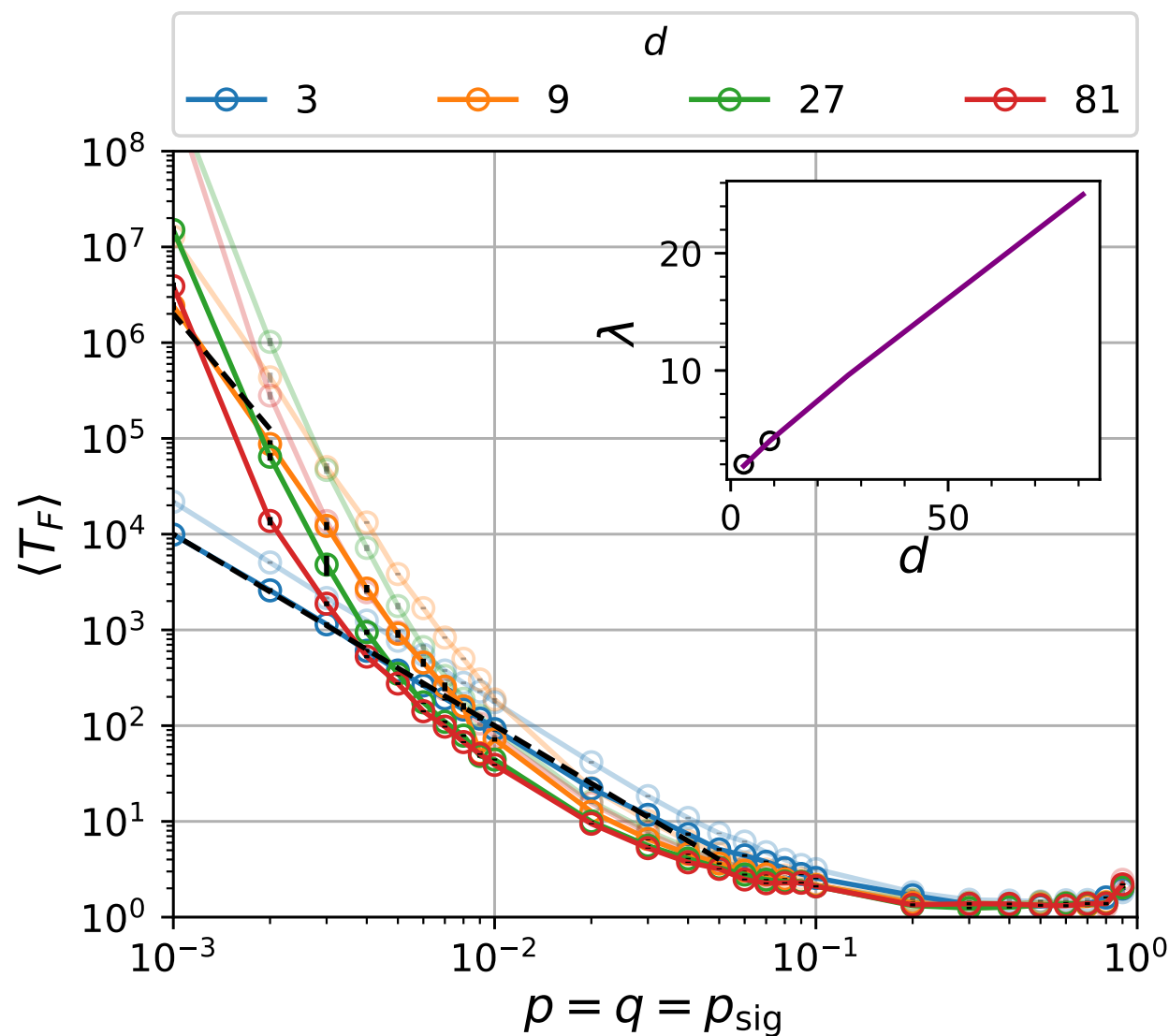


► **Phenom. noise + additionally signal noise**

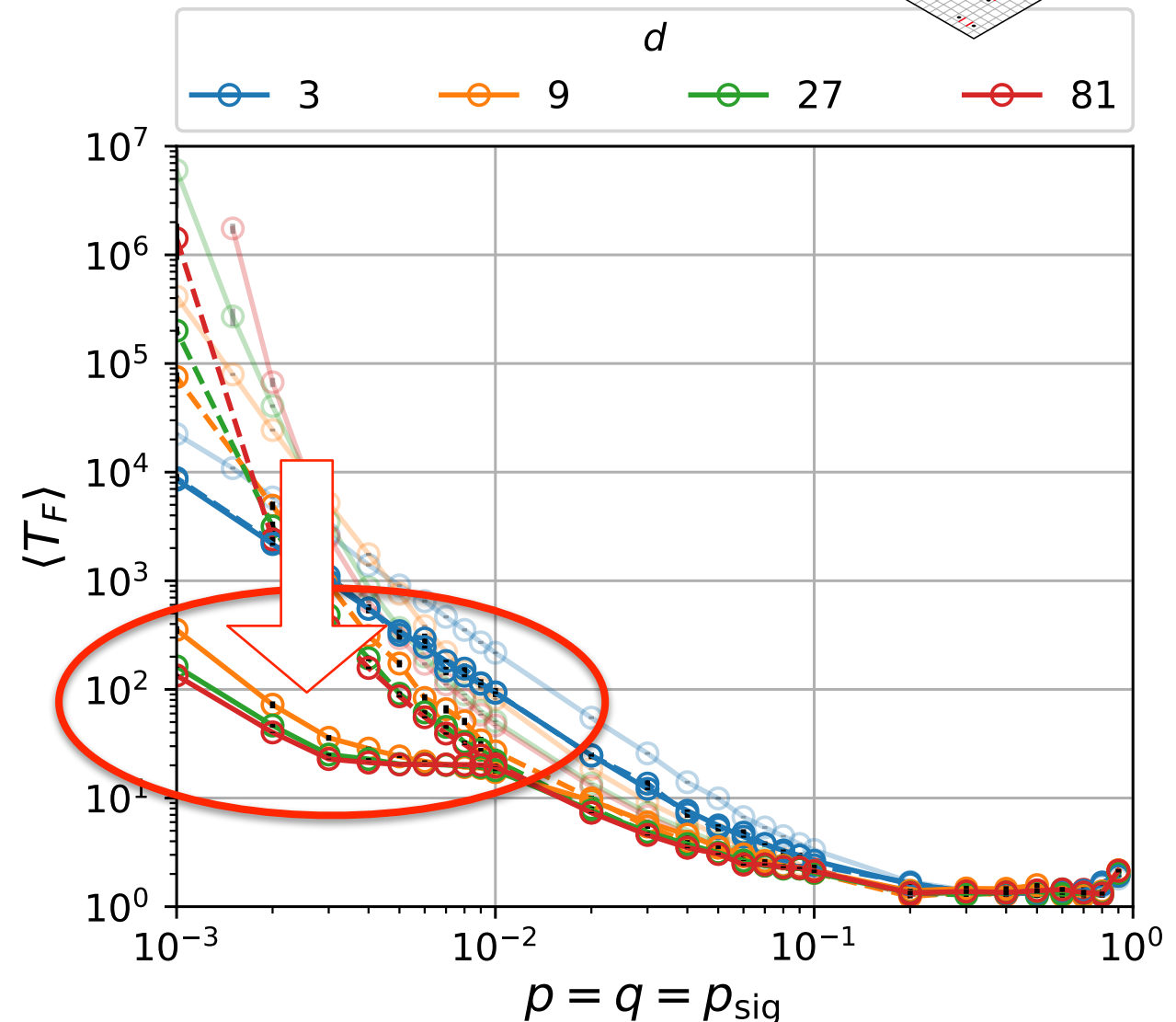
► **Signal noise can trigger wrong corrections**



SCALA 2D decoder



For comparison
Harrington's decoder



Strong robustness against signaling errors

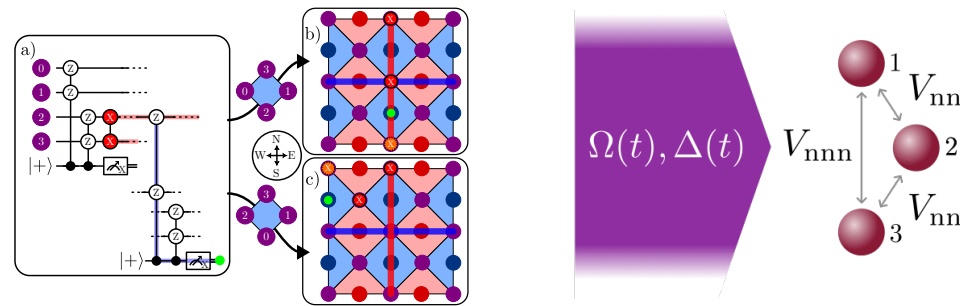


Breaks down for signaling noise

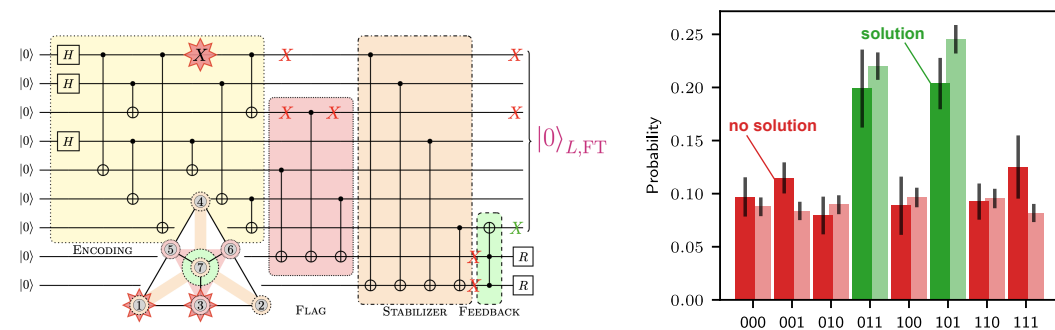
Performance of SCALA 2D

- ✓ Hierarchical CA decoders exhibit sublinear effective distance scaling $p_L \propto p^{\lambda(d)}$, $\lambda(d) \approx d^{0.631}$; **SCALA2D achieves linear scaling**, $\lambda(d) \geq d/4$.
- ✓ SCALA's **computational resources per cell are constant**.
In Harrington's CA, cell memory grows with d
- ✓ SCALA is **applicable to any lattice size**, hierarchical designs not
- ✓ SCALA shows **superior robustness against measurement noise**
- ✓ SCALA can **tolerate internal (signal) noise**
→ key requirement for **future quantum CA implementation**

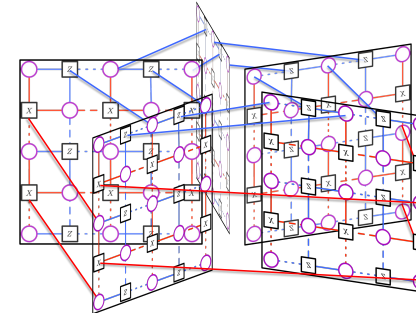
1 - FT QEC with optimized 3-qubit gates only



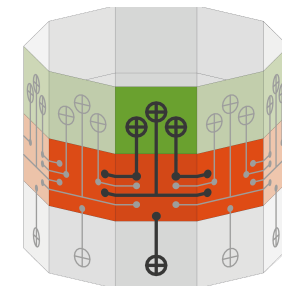
2 - FT **Measurement-free** QEC and universal computation



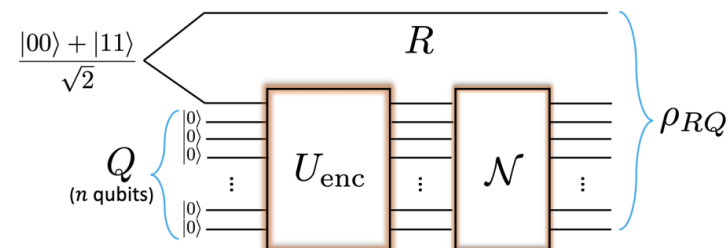
3 - Universal FT QC with **lift-connected surface codes**



4 - Classical and quantum **cellular automata for QEC**

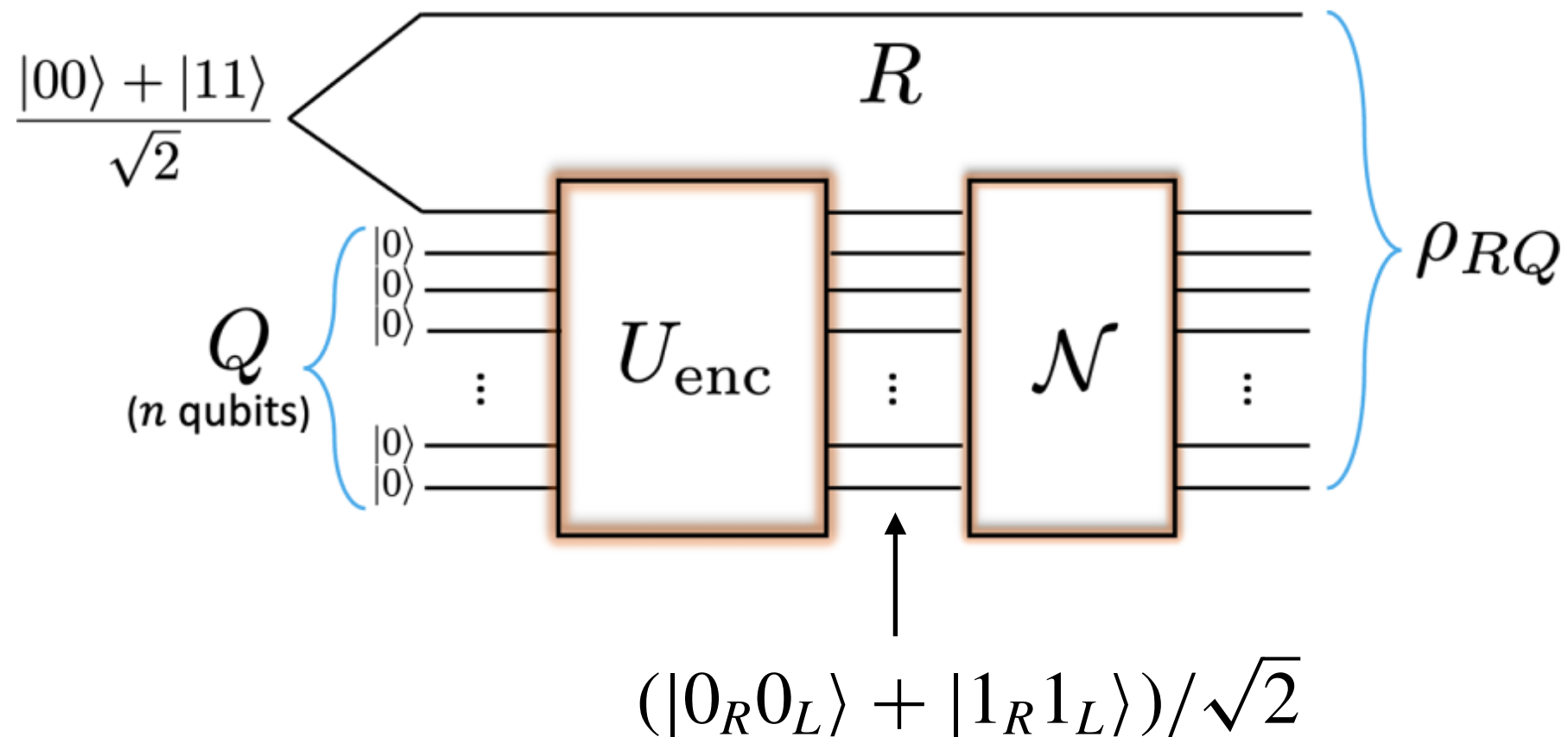


5 - Enhancing QEC thresholds by **Syndrome Resampling**



Syndrome resampling enhances QEC thresholds

- **Coherent information** signals correctability of a noisy logical qubit



$$I = S(\rho_Q) - S(\rho_{RQ})$$

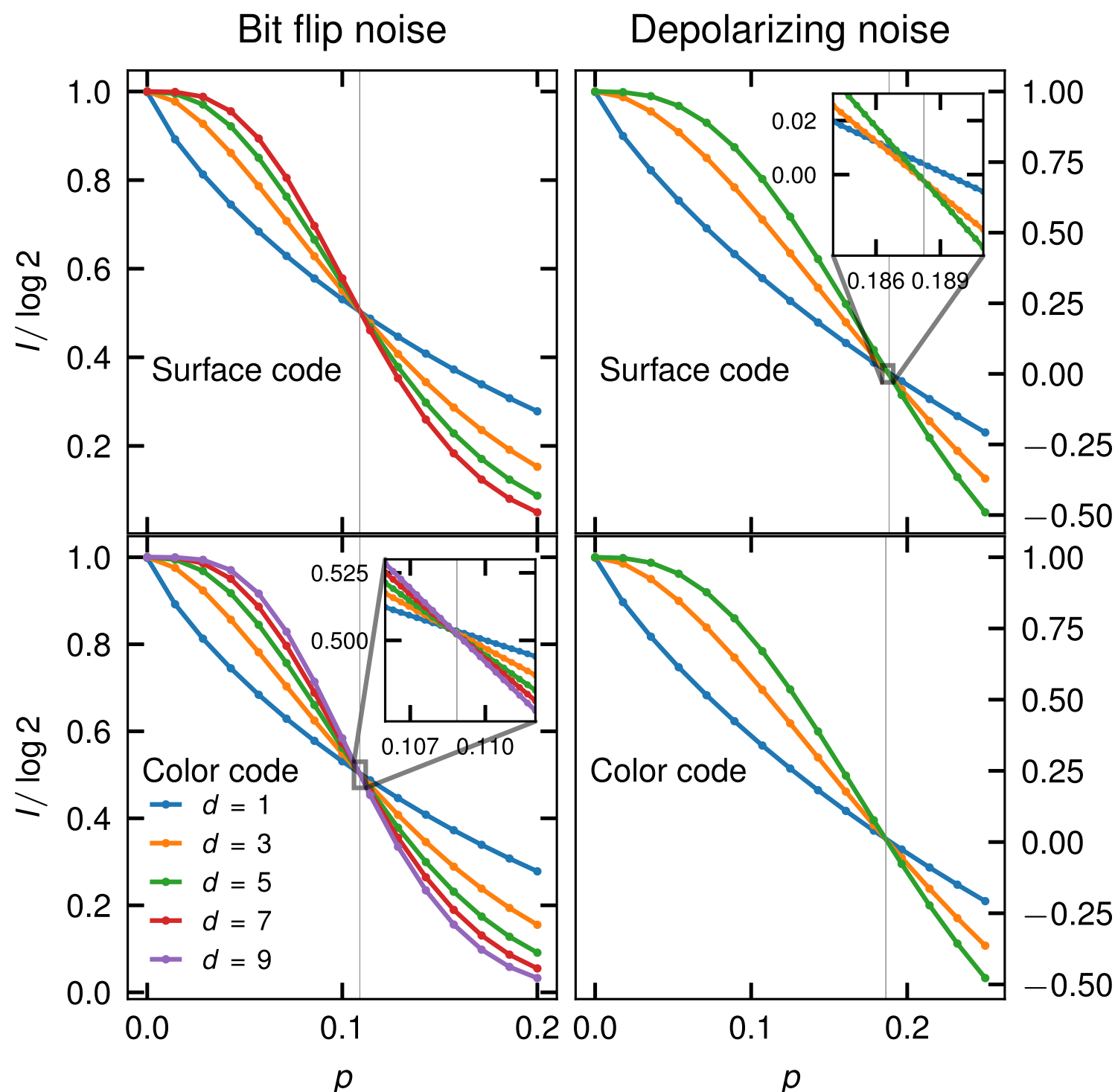
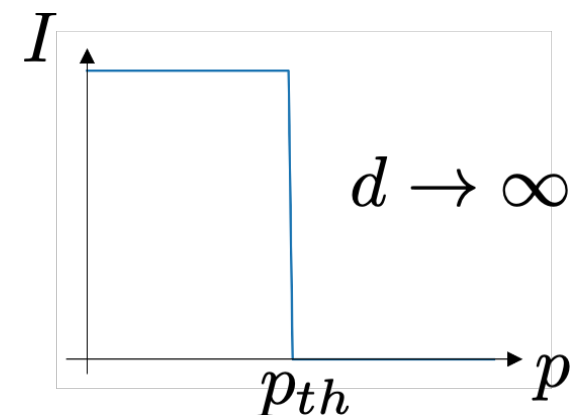
with $S(\rho) = -\text{Tr}(\rho \log \rho)$ as the von Neumann entropy

and $\rho_Q = \text{Tr}_R(\rho_{RQ})$ the reduced density matrix after tracing out the reference qubit

Syndrome resampling enhances QEC thresholds



Coherent information allows one to **practically** map out fundamental, i.e. optimal decoding QEC thresholds



	Bit-flip (CI)	Depol. (CI)	Bit flip p_{th}	Depol. p_{th}
Surface	0.1089(2)	0.1882(2)	0.1094(2) [24]	0.189(3) [30]
Color	0.1088(2)	0.1862(2)	0.10919(7) [49]	0.189(2) [30]



Very small finite size-effects



Less computationally demanding than spin-glass Monte-Carlo sims. of disordered stat-mech models

Accurate optimal quantum error correction thresholds from coherent information

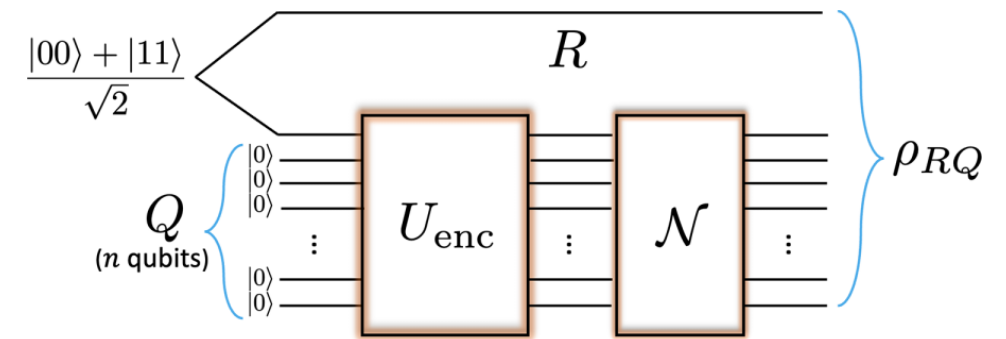
L. Colmenarez, Z.-M. Huang, S. Diehl, M. M., Physical Review Research 6, L042014 (2024)

Syndrome resampling enhances QEC thresholds

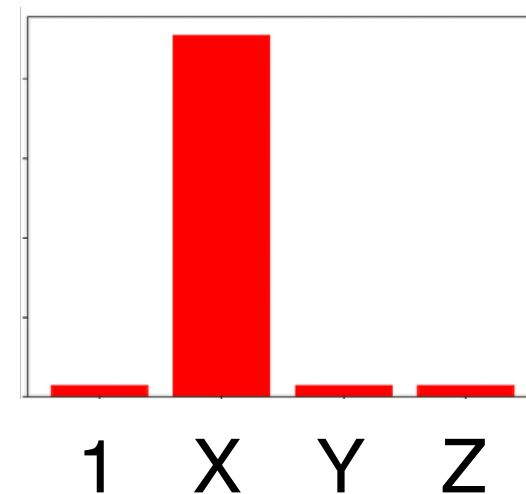
- Noisy reference & system density matrix

$$\rho_{RQ} = \sum_{s,l} P(l|s) P(s) |s, \Phi_l\rangle \langle s, \Phi_l|$$

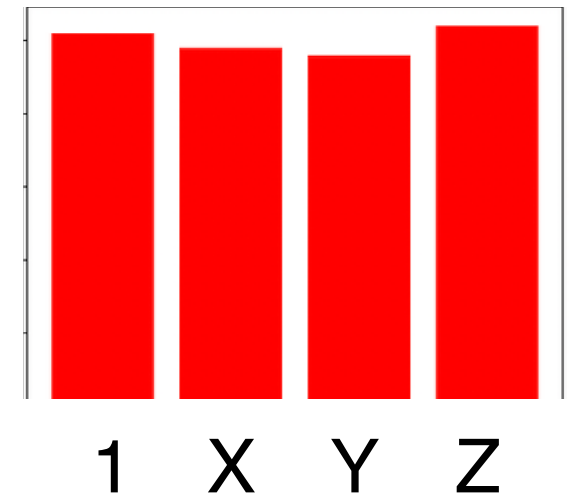
For a fixed syndrome



Likely **succeeds**



Likely **fails**



Idea: Syndromes that are likely to lead to a logical failure should be suppressed

Syndrome resampling enhances QEC thresholds

► Consider instead the **Renyi Coherent Information**

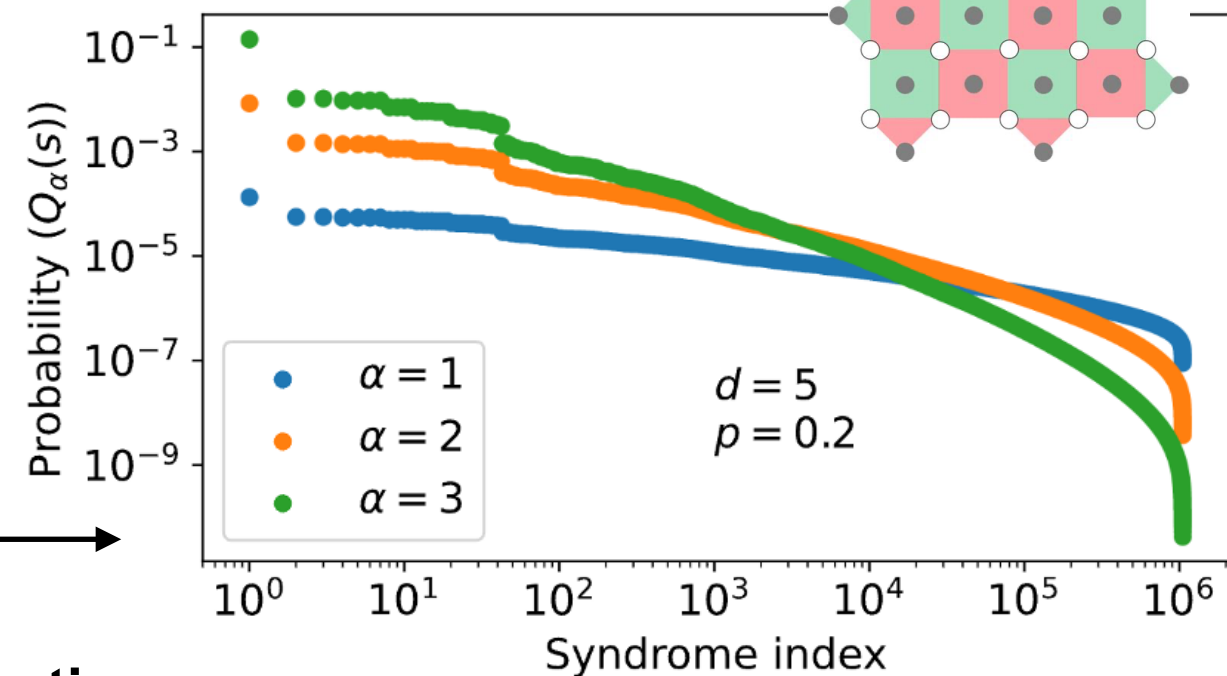
$$I^{(\alpha)} = S^{(\alpha)}(\rho_Q) - S^{(\alpha)}(\rho_{RQ})$$

$$S^{(\alpha)}(\rho) = \frac{1}{1-\alpha} \log[\text{Tr}(\rho^\alpha)] \quad \text{Renyi Entropy}$$

$$I^{(\alpha)} = \frac{1}{1-\alpha} \log \left[\sum_s Q_\alpha(s) \sum_l P^\alpha(l|s) \right]^{-1}$$

$$Q_\alpha(s) = \frac{P^\alpha(s)}{\sum_s P^\alpha(s)} \longrightarrow$$

Powers of the syndrome distribution



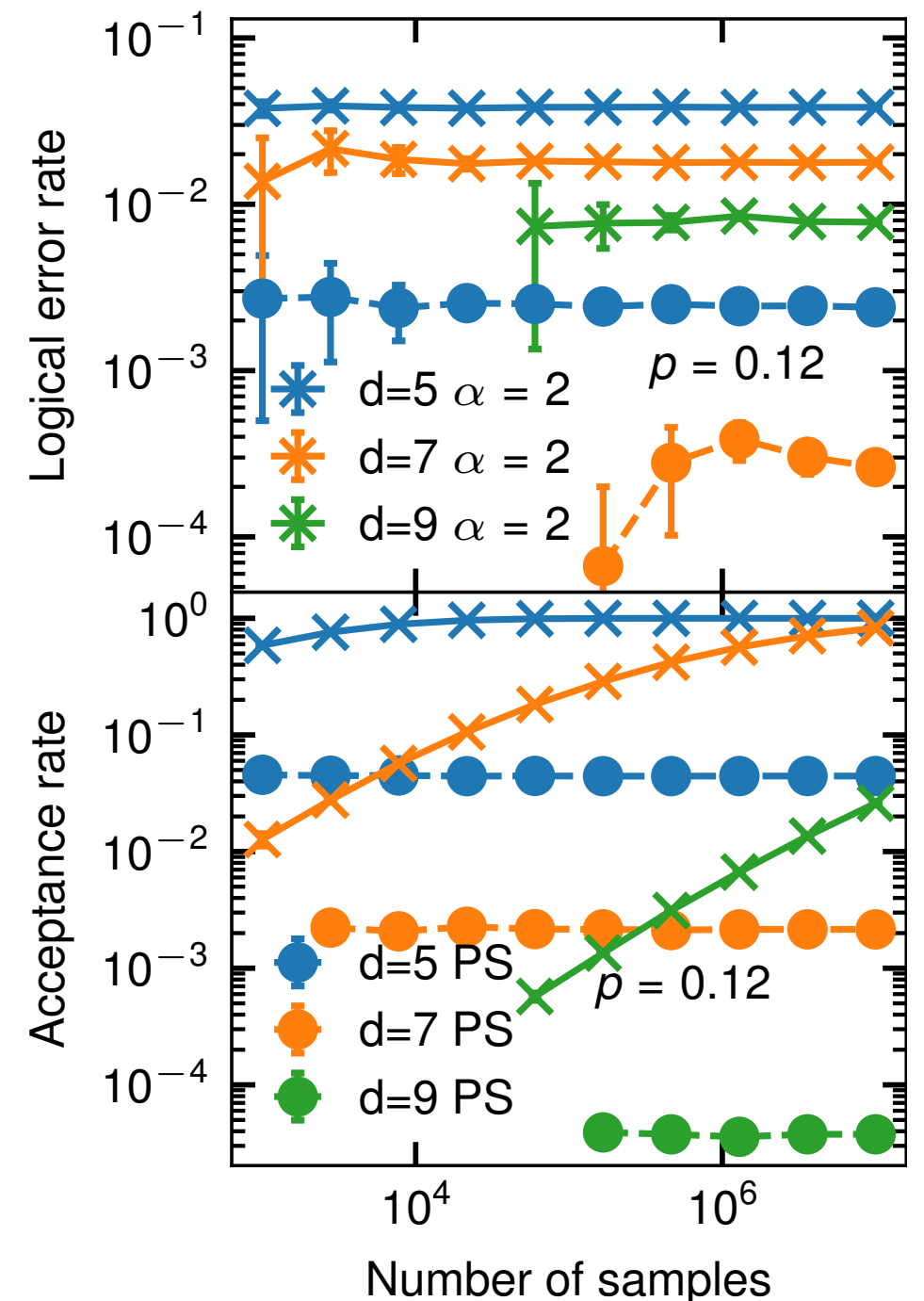
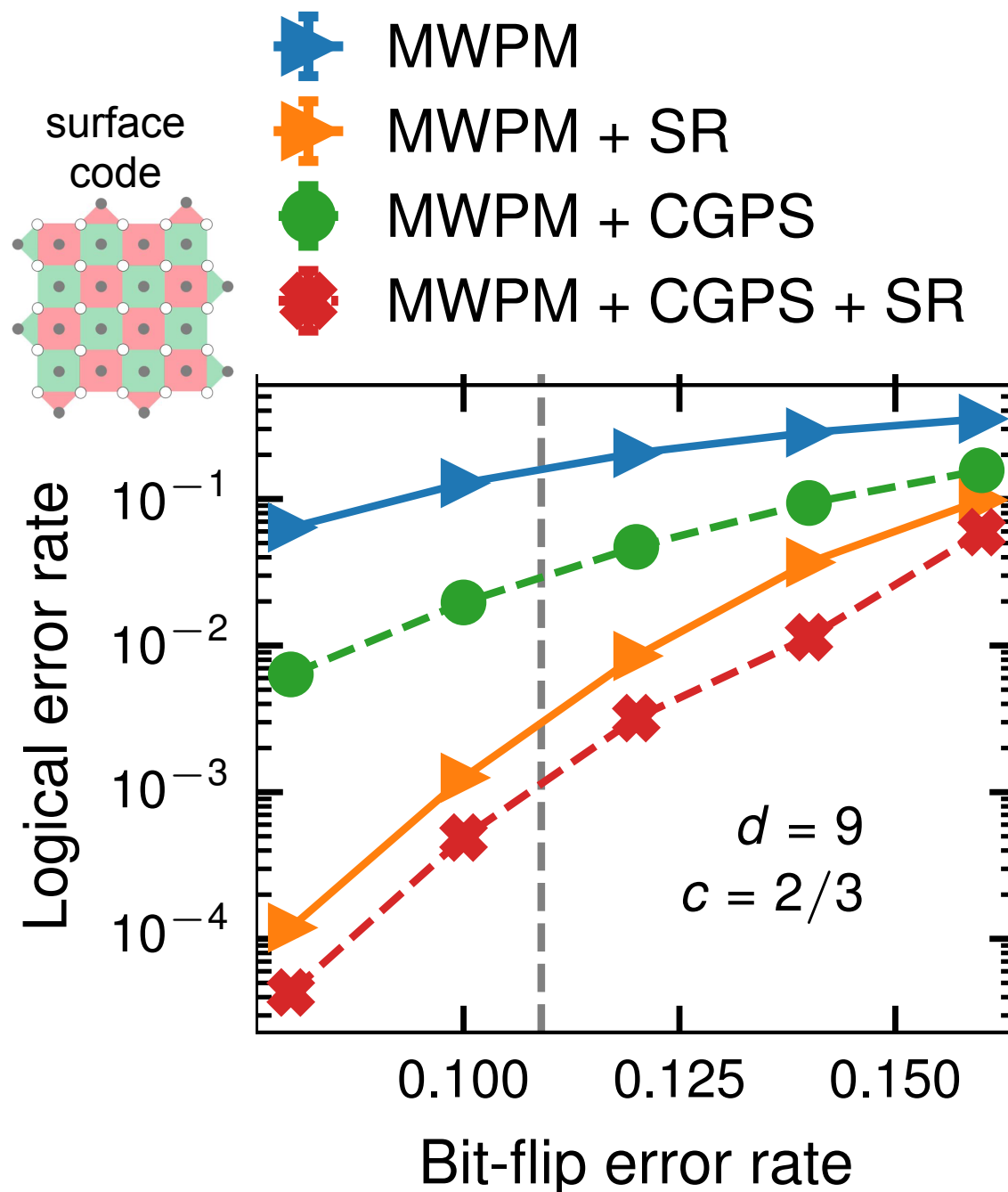
Idea: Syndromes that are likely to lead to a logical failure are suppressed

Syndrome resampling enhances quantum error correction thresholds

L. Colmenarez, A. Márton, M. M., arXiv:2605.06101 (2026)

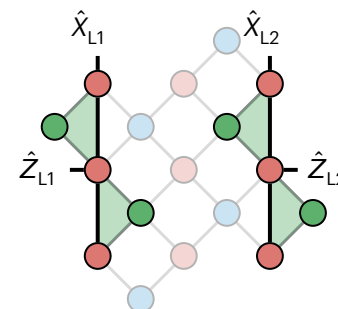
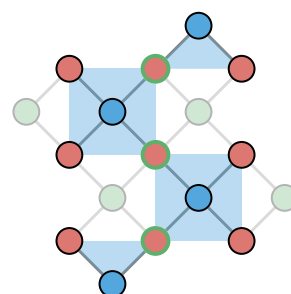
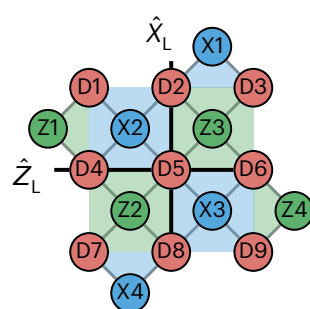
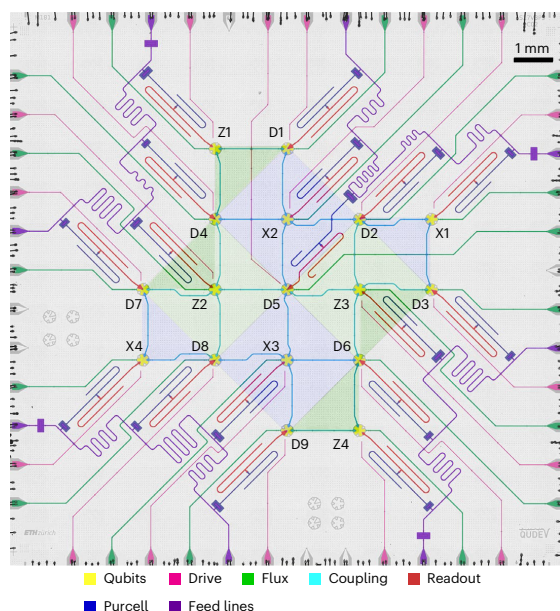
Syndrome resampling enhances QEC thresholds

- ▶ Syndrome resampling (SR) with $\alpha = 2$
- ▶ Can be combined with decoder confidence methods, such as Complementary Gap post-selection (CGPS) to further suppress logical errors
- ▶ Higher acceptance rate than for post-selection



Syndrome resampling enhancement ... in experiment

- Test the performance of Syndrome Resampling on a recent demonstration of lattice surgery

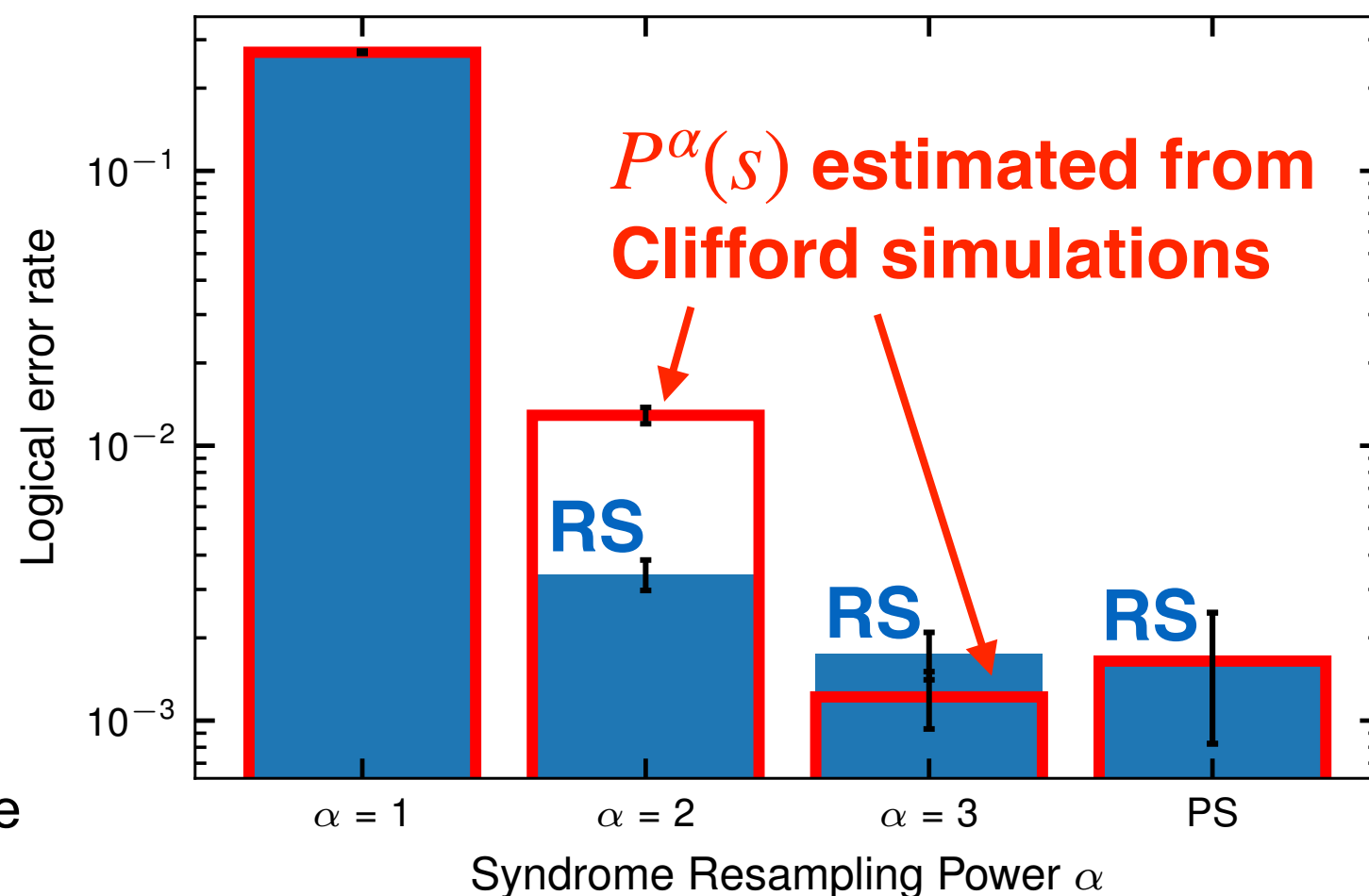


- Observed performance:

- $\alpha = 1$: standard case
- $\alpha = 2$: keep 42% and reweigh
- $\alpha = 3$: keep 37% and reweigh
- Post-selection: keeps 5%



2 orders of magnitude lower logical rate while keeping about 40% of data



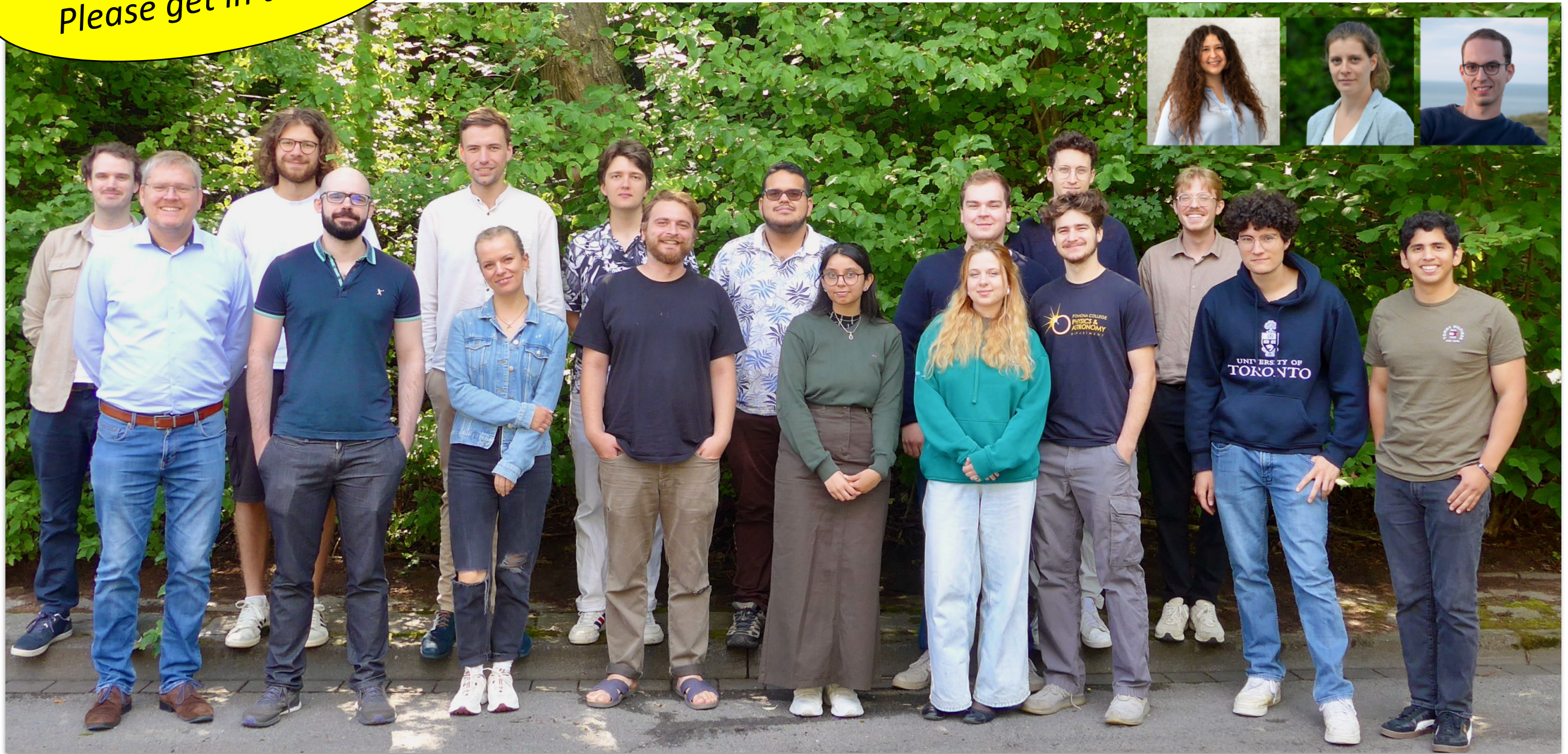
Syndrome resampling technique applied to experimental data from collaboration with ETH Zurich team

Realizing Lattice Surgery on Two Distance-Three Repetition Codes with Superconducting Qubitssholds

I. Besedin, ... M. M., A. Wallraff, Nature Physics 22, 189 (2026)

A big thank you to my group!

Open positions -
Please get in touch



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www.markus-mueller.website