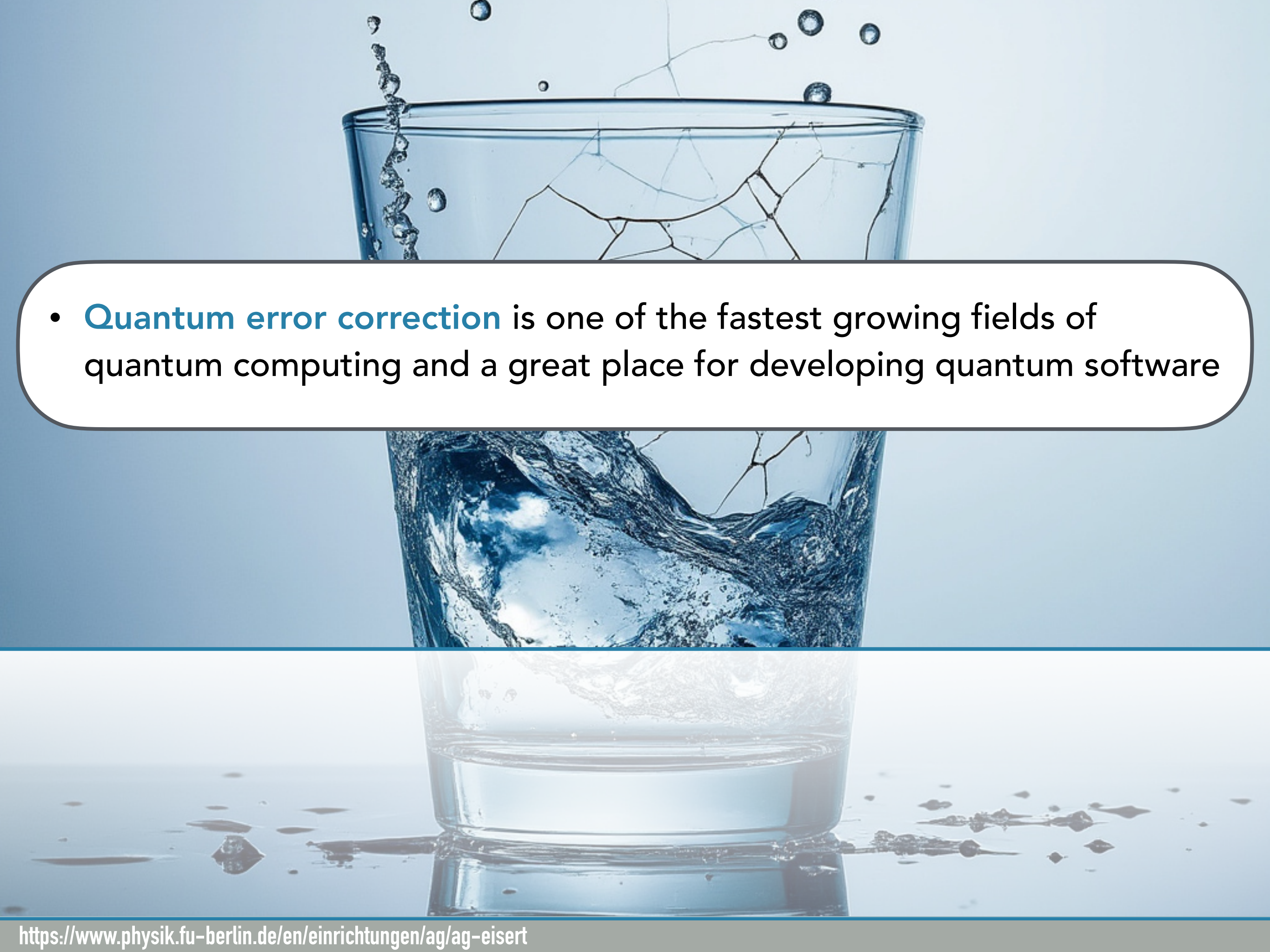


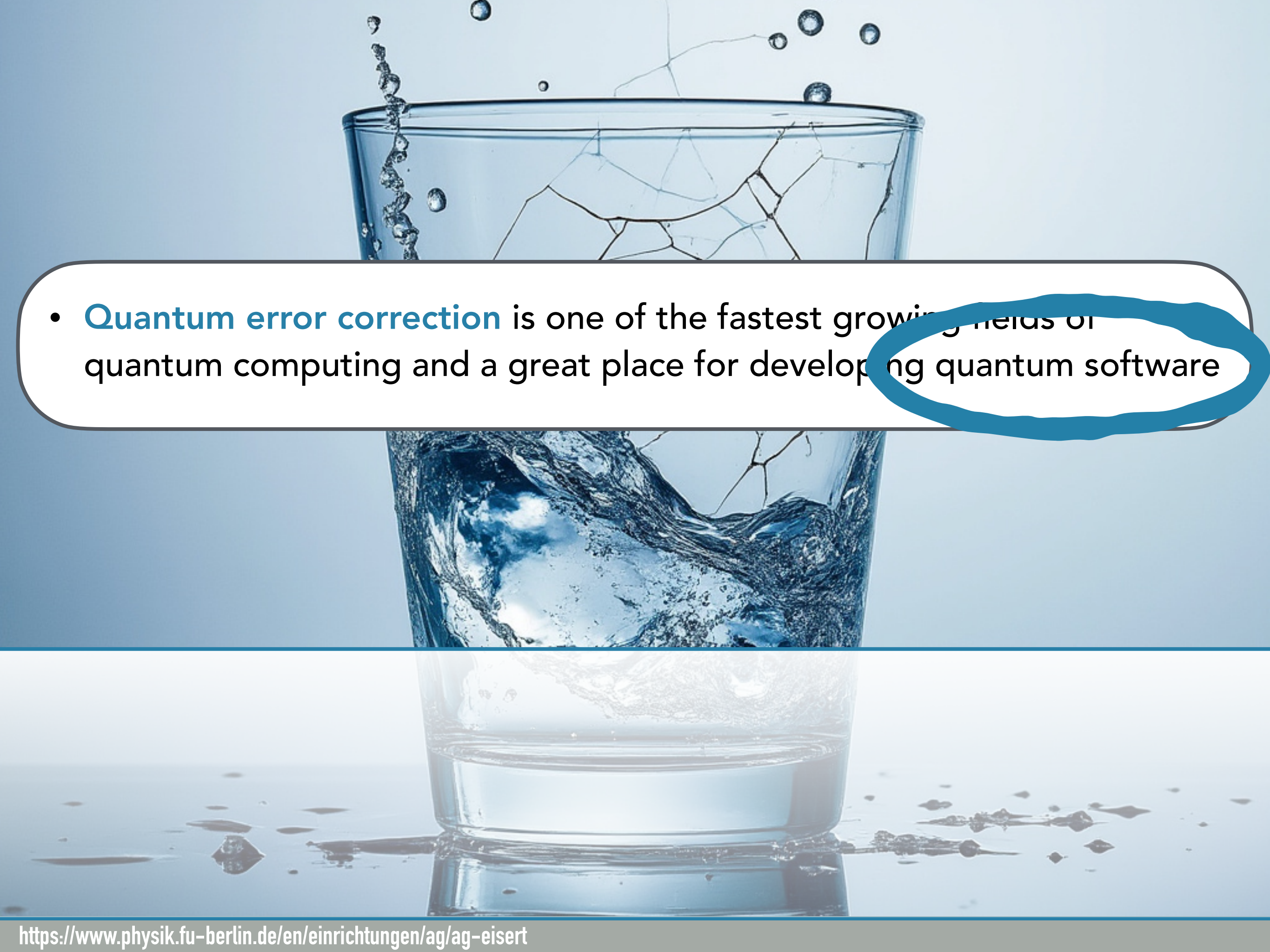


DECODING QUANTUM LOW DENSITY PARITY CHECK CODES AND OTHER PERSPECTIVES OF QUANTUM ERROR CORRECTION

JENS EISERT, FU BERLIN



- 
- A background image of a glass of water. The water surface is cracked, and there are several water droplets splashing out of the glass. The glass is partially filled with water, and the water level is visible. The background is a light blue gradient.
- **Quantum error correction** is one of the fastest growing fields of quantum computing and a great place for developing quantum software

- 
- A background image of a glass of water. The glass has a prominent crack running across its upper half. Water is splashing out of the top of the glass, with several droplets captured in mid-air. The water inside the glass is turbulent, with white foam and bubbles visible. The glass sits on a reflective surface, and the background is a light blue gradient.
- **Quantum error correction** is one of the fastest growing fields of quantum computing and a great place for developing quantum software



PART 1: A BRIEF HISTORY OF QUANTUM ERROR CORRECTION

- Quantum error correction is not a new idea



- Quantum error correction is not a new idea
- Classical redundancy

$$0 \mapsto 000, \quad 1 \mapsto 111$$



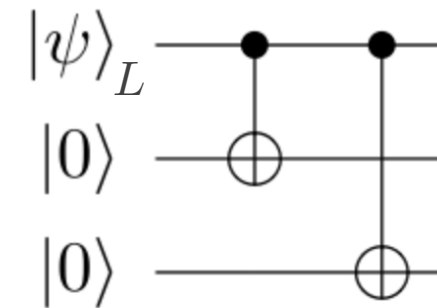
- **Quantum error correction** is not a new idea
- Classical **redundancy**

$$0 \mapsto 000, \quad 1 \mapsto 111$$

- **Peres repetition code**

Peres, Phys Rev A 32, 3266 (1985)

$$|0\rangle_L \mapsto |0, 0, 0\rangle, \quad |1\rangle_L \mapsto |1, 1, 1\rangle$$



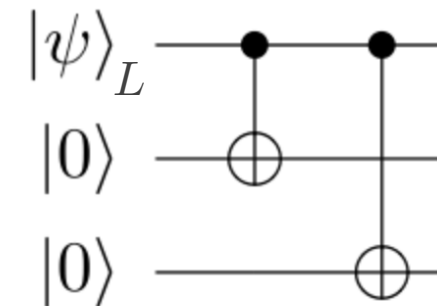
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- Encoding of $|\psi\rangle_L = \alpha|0\rangle_L + \beta|1\rangle_L$ gives, for single bit flips

$$\alpha|0, 0, 0\rangle + \beta|1, 1, 1\rangle \quad (\text{no error})$$

$$\alpha|1, 0, 0\rangle + \beta|0, 1, 1\rangle \quad (\text{error on 1st qubit})$$

$$\alpha|0, 1, 0\rangle + \beta|1, 0, 1\rangle \quad (\text{error on 2nd qubit})$$

$$\alpha|0, 0, 1\rangle + \beta|1, 1, 0\rangle \quad (\text{error on 3rd qubit})$$



- Are orthogonal, can be discriminated **without learning** logical info

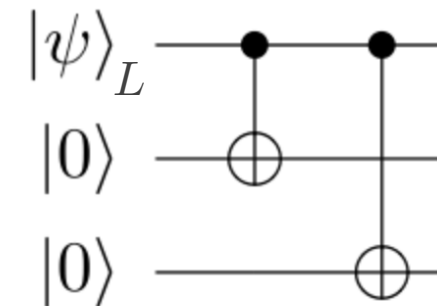
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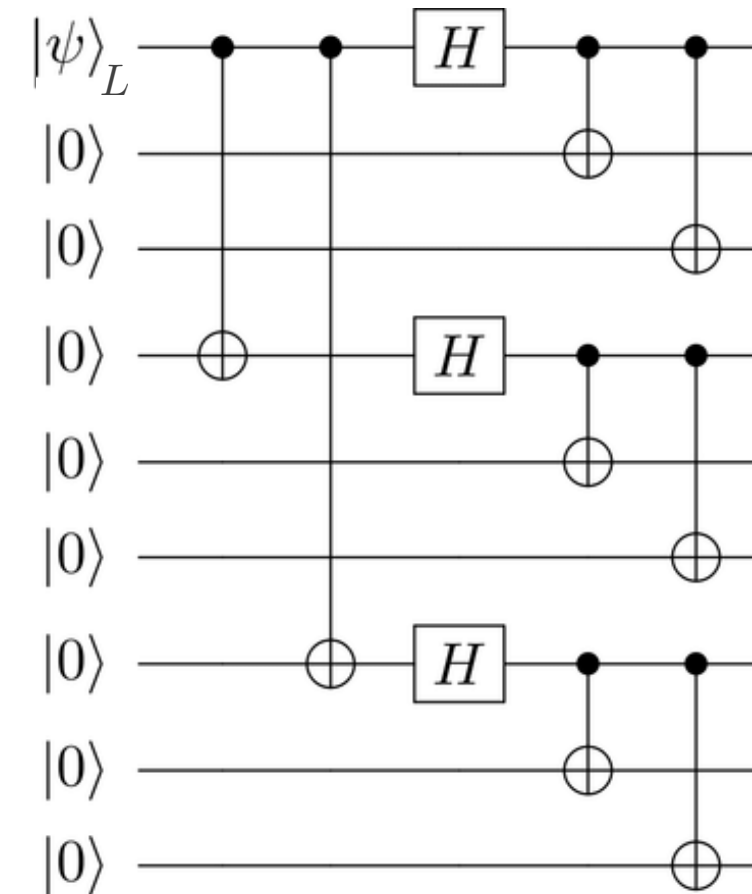
$$\alpha|0, 0, 1\rangle + \beta|1, 1, 0\rangle \quad (\text{error on 3rd qubit})$$



- **Syndrome extraction:** Measure $Z_1 Z_2$ and $Z_2 Z_3$

- Can be made **full error correcting code** by protecting against single Z and X - and hence **arbitrary** single-qubit errors: **Shor code**

Shor, Phys Rev A 52, R2493 (1995)



- Code words

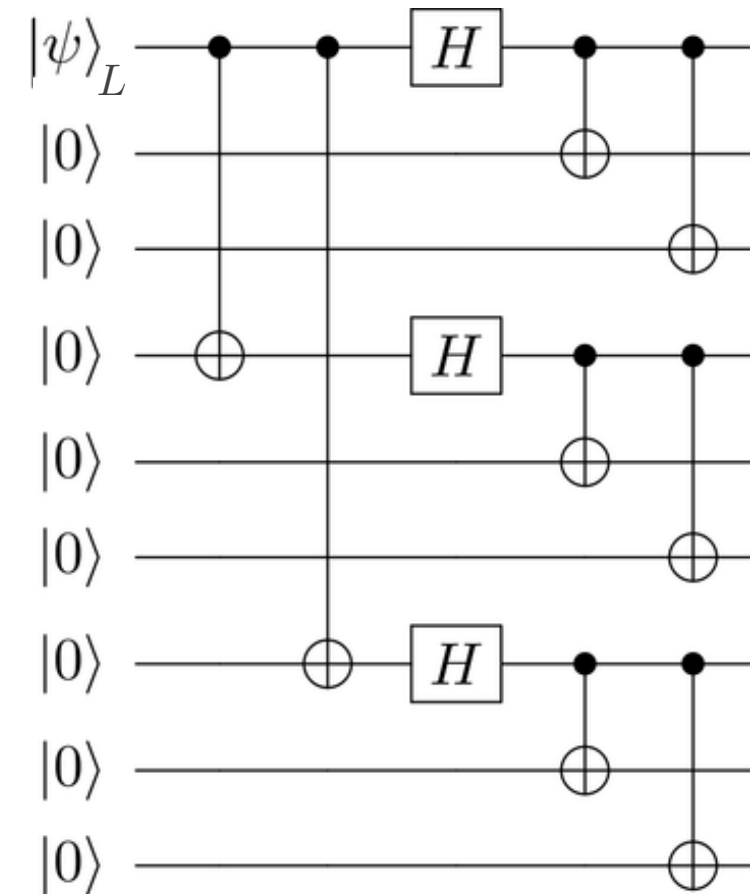
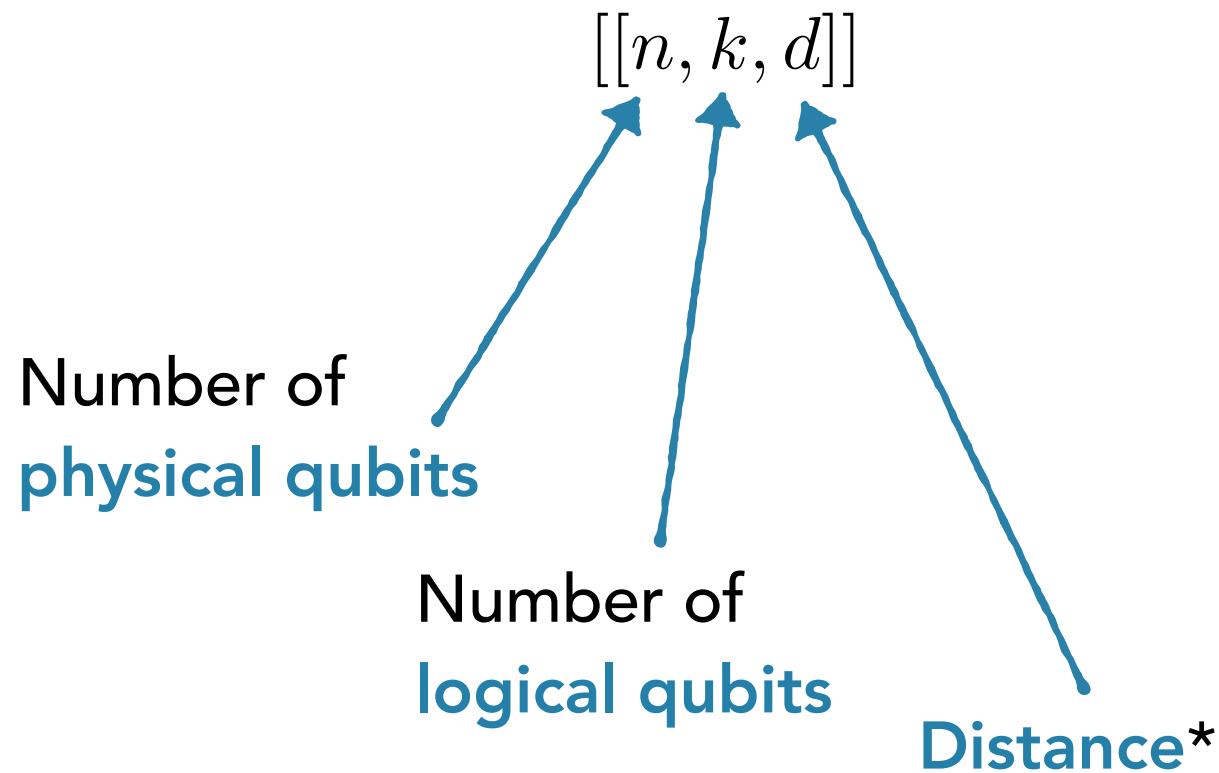
$$|0\rangle_L \mapsto \frac{1}{2\sqrt{2}}(|0, 0, 0\rangle + |1, 1, 1\rangle) \otimes (|0, 0, 0\rangle + |1, 1, 1\rangle) \otimes (|0, 0, 0\rangle + |1, 1, 1\rangle)$$

$$|1\rangle_L \mapsto \frac{1}{2\sqrt{2}}(|0, 0, 0\rangle - |1, 1, 1\rangle) \otimes (|0, 0, 0\rangle - |1, 1, 1\rangle) \otimes (|0, 0, 0\rangle - |1, 1, 1\rangle)$$

- Can be made **full error correcting code** by protecting against single Z and X - and hence **arbitrary** single-qubit errors: **Shor code**

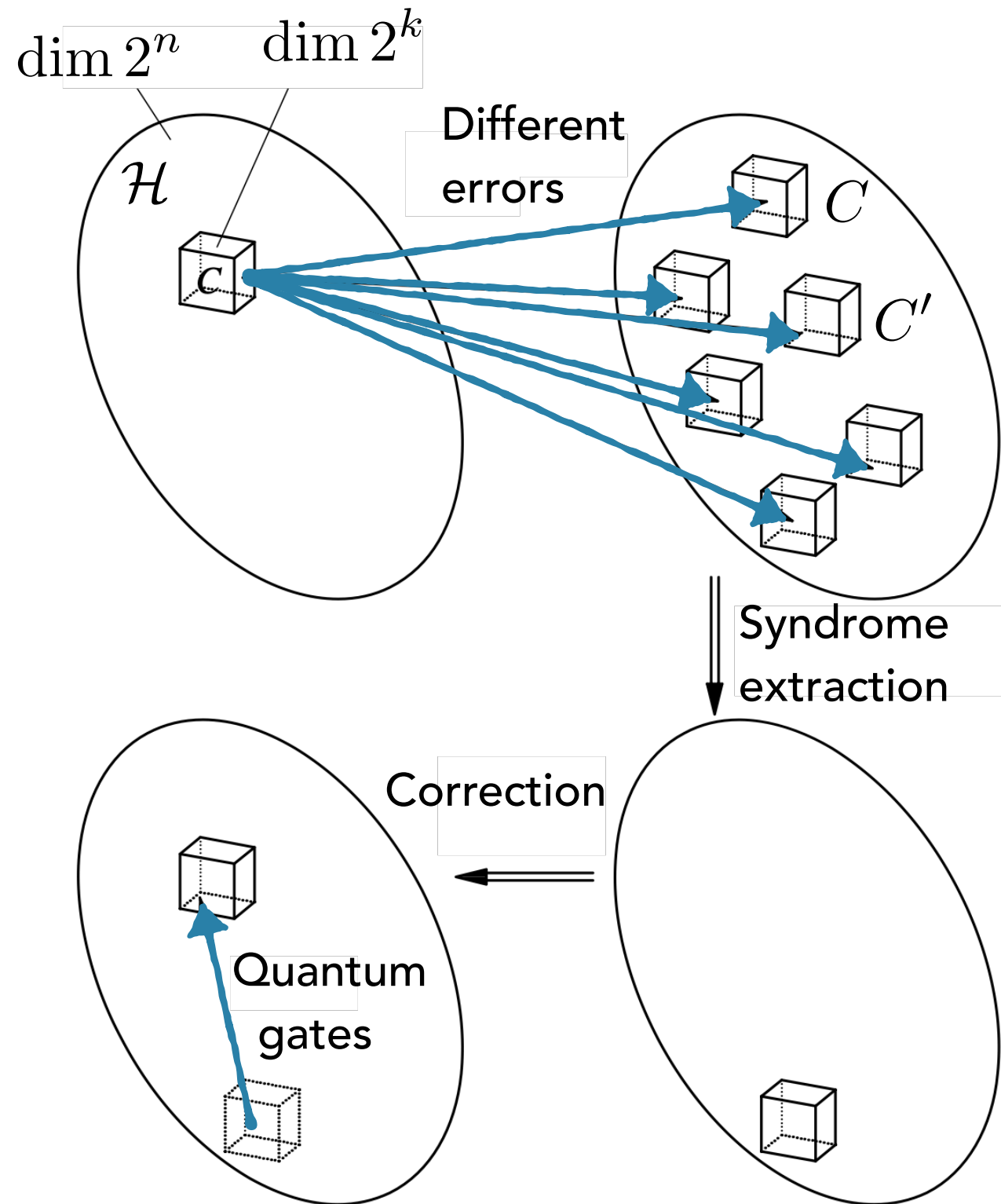
Shor, Phys Rev A 52, R2493 (1995)

- Protects **full qubit**: $[[9, 1, 3]]$ code



* Minimum weight of a Pauli operator to map one codeword into another)

- Idea of quantum error correction



- **First quantum error correcting codes**

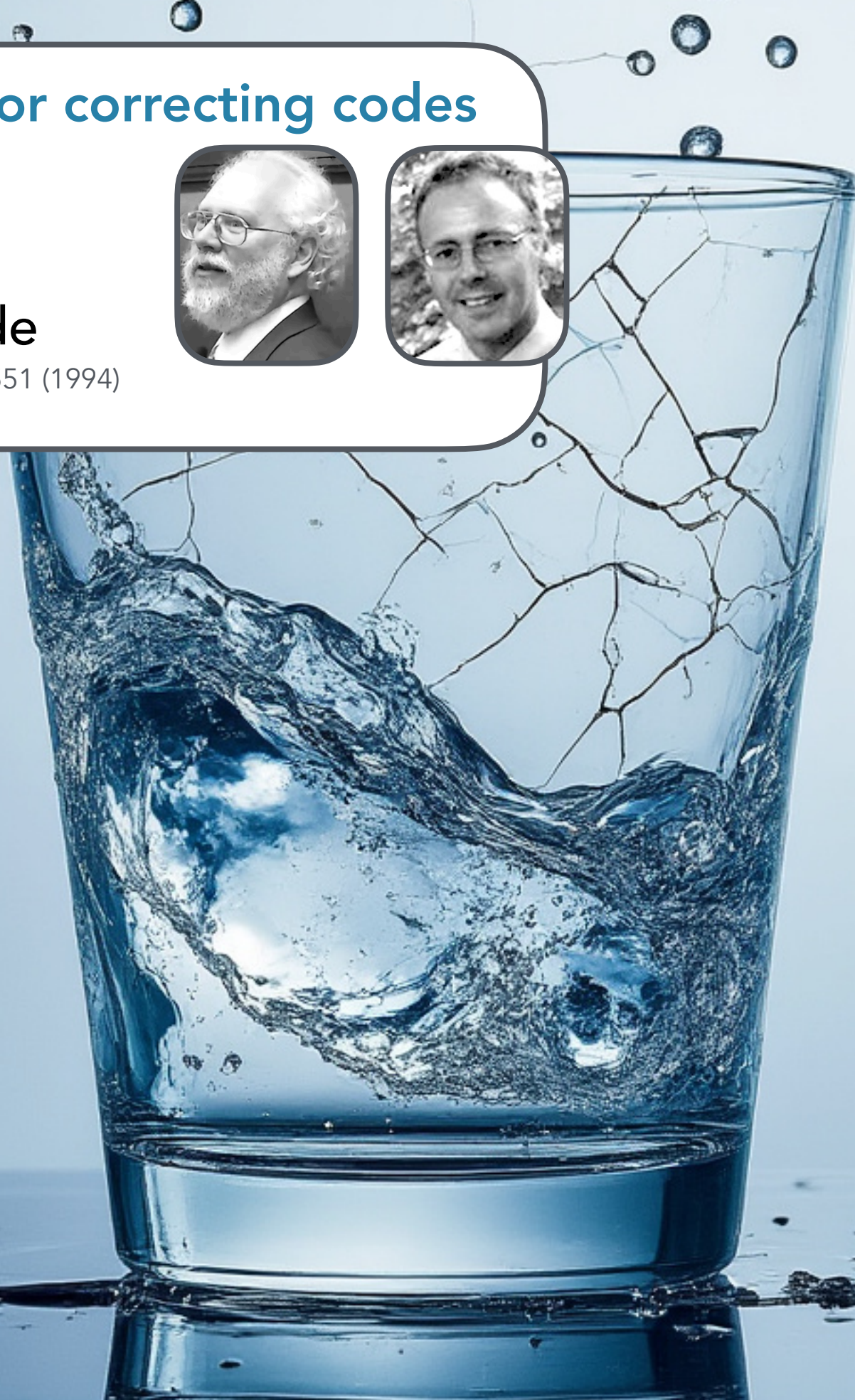
- **Shor $[[9, 1, 3]]$ code**

Shor, Phys Rev A 52, R2493 (1995)



- **Steane $[[7, 1, 3]]$ code**

Steane, Proc R Soc Lond A 452, 2551 (1994)



- Both (and actually most) are **qubit Pauli stabilizer codes**
- **Pauli matrices** $\mathbb{I}, X, Y, Z$ per qubit, n -qubit **Pauli group** $\mathcal{P}_n$
- Qubit stabilizer codes are defined by a **stabilizer group** $\mathcal{S}$, a group of commuting Paulis that does not contain the identity and is generated by $r = n - k$ independent* generators
 - Independent in that none of them is a product of any other two up to a phase

Gottesman, PhD thesis, quant-ph/9705052 (1997)

Calderbank, Rains, Shor, Sloane, IEEE Trans Inf Th 44, 1369 (1998)



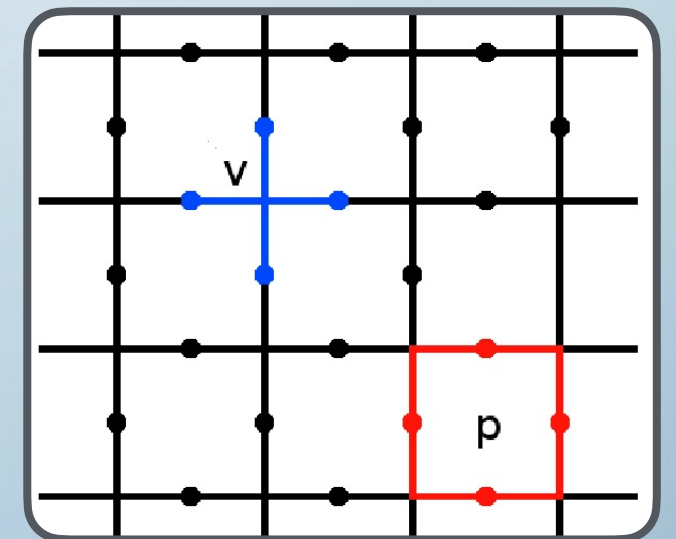
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- Qubit stabilizer codes are defined by a **stabilizer group** $\mathcal{S}$, a group of commuting Paulis that does not contain the identity and is generated by $r = n - k$ independent* generators
- **Knill-Laflamme conditions:** Define the **normalizer** $\mathcal{N}(\mathcal{S})$ of $\mathcal{S}$ to be the set of all Pauli operators that commute with all $S \in \mathcal{S}$.
A stabilizer code can correct a Pauli error set $\mathcal{E}$ if and only if

$$E^\dagger F \notin \mathcal{N}(\mathcal{S}) \quad \forall E, F \in \mathcal{E}$$

Knill, Laflamme, Phys Rev Lett 84, 2525 (2000)



- **Toric** (and **surface codes**): Most common **topological code**
- Defined on 2d lattice with qubits on edges



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- Defined on 2d lattice with qubits on edges
- Stabilizers are defined on the spins around each **vertex** v and **plaquette** p as

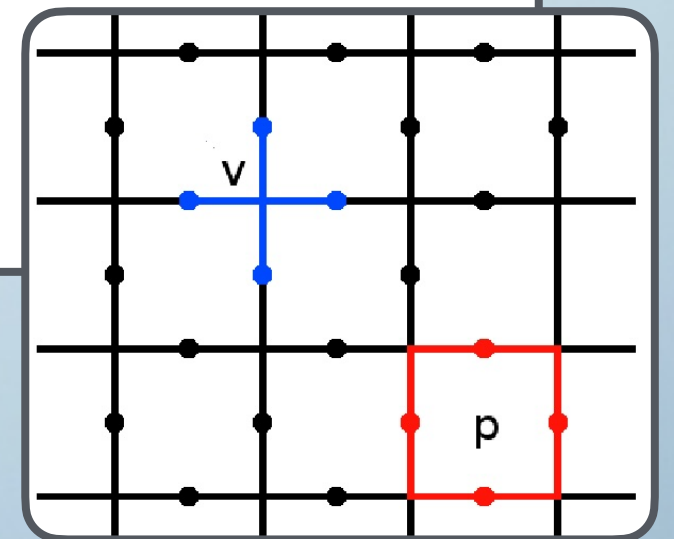
$$A_p = \prod_{i \in v} X_i, \quad B_p = \prod_{i \in p} Z_i$$

- Stabilizer code means that, for all state vectors $|\psi\rangle$ in code space,

$$A_v |\psi\rangle = |\psi\rangle, \quad \forall v, \quad B_p |\psi\rangle = |\psi\rangle, \quad \forall p$$

Kitaev, Proc 3rd Int Conf Quant Comm Meas (1997)

Kitaev, Ann Phys 321, 2 (2006)



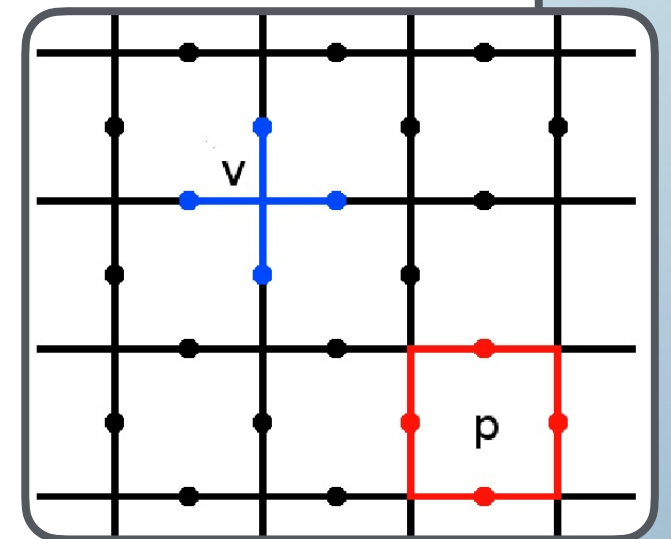
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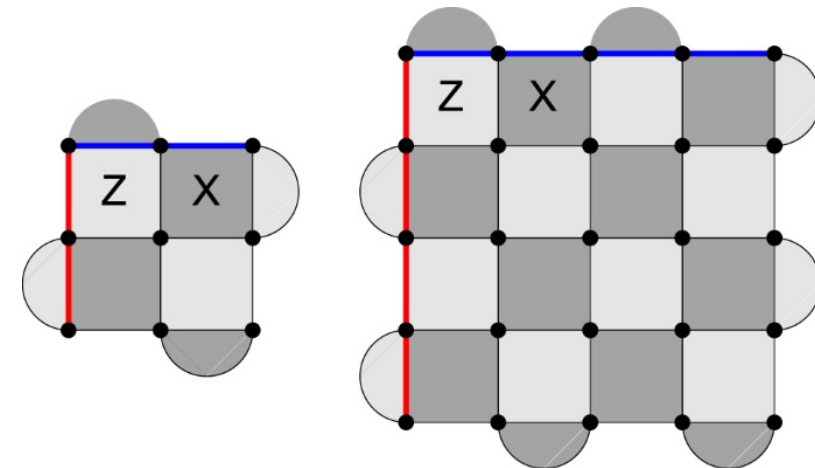
$$A_v |\psi\rangle = |\psi\rangle, \quad \forall v, \quad B_p |\psi\rangle = |\psi\rangle, \quad \forall p$$

- Logical dimension depends on topology of manifold and is 4-dim for torus, so that $k = 2$
- **Distance** $d = l$ for $l \times l$ lattice of $n = l^2$ qubits
- **GS** of local Hamiltonians, $\mathbb{Z}_2$ topological order, **quantum doubles**



- **Toric** (and **surface codes**): Most common **topological code**
- Surface codes are **planar variants**

Dennis, Kitaev, Landahl, Preskill, J Math Phys 43, 4452-4505 (2002)





- Then came (in Dan Gottesman's words) the “middle ages”



- But wonderful things were found: E.g., **quantum low density parity check (LDPC) codes**: Every qubit interacts with a finite number of
- other qubits (binary linear code with a sparse parity-check matrix)

Name	k	d	reference
2D hyperbolic codes	$\Theta(n)$	$\Theta(\log(n))$	Sec. III A
4D hyperbolic codes	$\Theta(n)$	$\Omega(\sqrt[10]{n})$	Sec. III A
Freedman–Meyer–Luo	2	$\Omega\left(\sqrt[4]{\log(n)}\sqrt{n}\right)$	Sec. III B
TP (good classical codes)	$\Theta(n)$	$\Theta(\sqrt{n})$	Sec. IV A
TP (Ramanujan complexes)	$\Theta(\sqrt{n})$	$\Omega(\text{polylog}(n)\sqrt{n})$	Sec. IV A
Fibre bundle codes	$\Theta(n^{3/5}/\text{polylog}(n))$	$\Omega(n^{3/5}/\text{polylog}(n))$	Sec. IV B
Lifted product codes	$\Theta(n^\alpha \log(n))$	$\Omega(n^{1-\alpha}/\log(n))$	Sec. IV C
Balanced product codes	$\Theta(n^{4/5})$	$\Omega(n^{3/5})$	Sec. IV D

Gottesman, Quant Inf Comp 14, 1338 (2013)

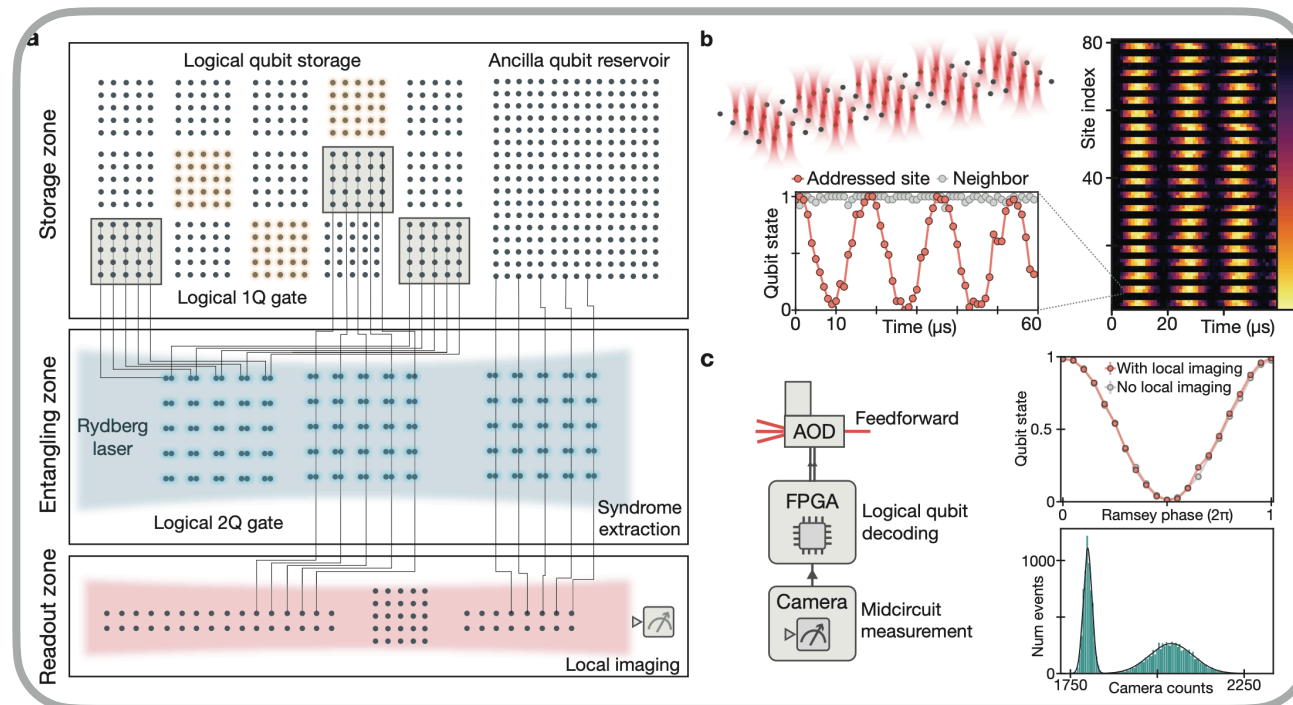
Breuckmann, Eberhardt, PRX Quantum 2, 040101 (2021)

- Now Renaissance: New ideas, experiments on QEC



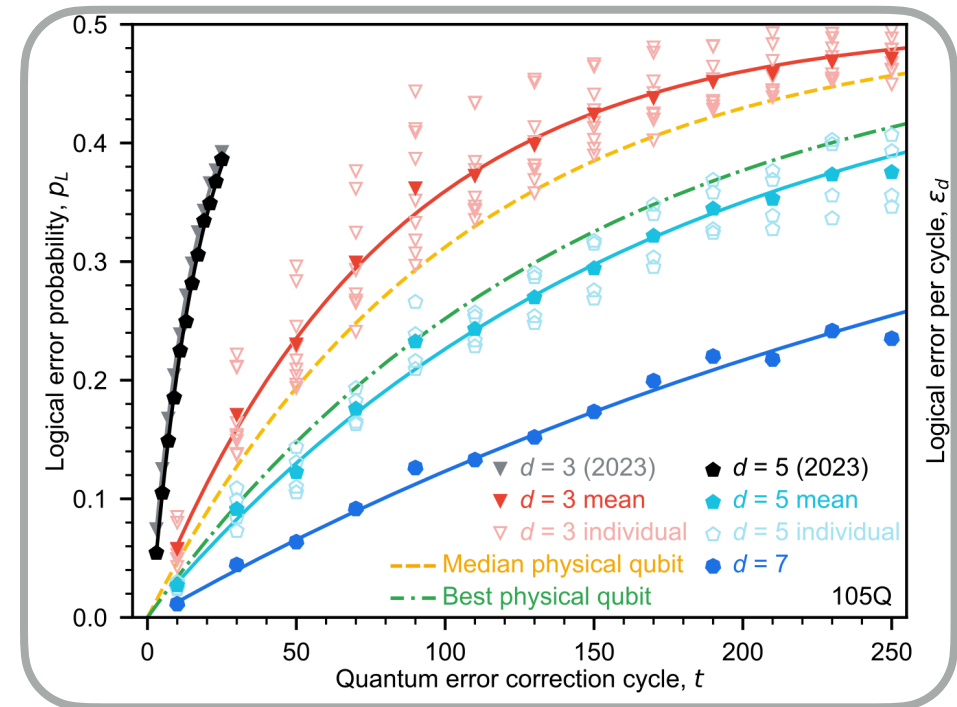
- Now **Renaissance**: New **ideas, experiments** on QEC

- Quantum processor based on 280 **reconfigurable atom arrays**



Bluvstein et al, Nature 626, 58 (2024)

- Surface codes** with Google's Willow chip and Mios rounds of decoding



Acharya et al, Nature 638, 920 (2025)

- Still, overheads are **insurmountably huge**, important **software problems**



PART 2: DECODING QUANTUM ERROR CORRECTING CODES



- **Binary linear code:** E.g., again

$$0 \mapsto 000 \quad 1 \mapsto 111$$

- **Parity check matrix:** Codewords are its null spaces, e.g.,

$$H = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix}$$

(generator matrix of dual code)

$$H \cdot c^T \bmod 2 = (00)^T$$

- Errors are detected by **syndromes**

$$H \cdot (001)^T \bmod 2 = (01)^T$$



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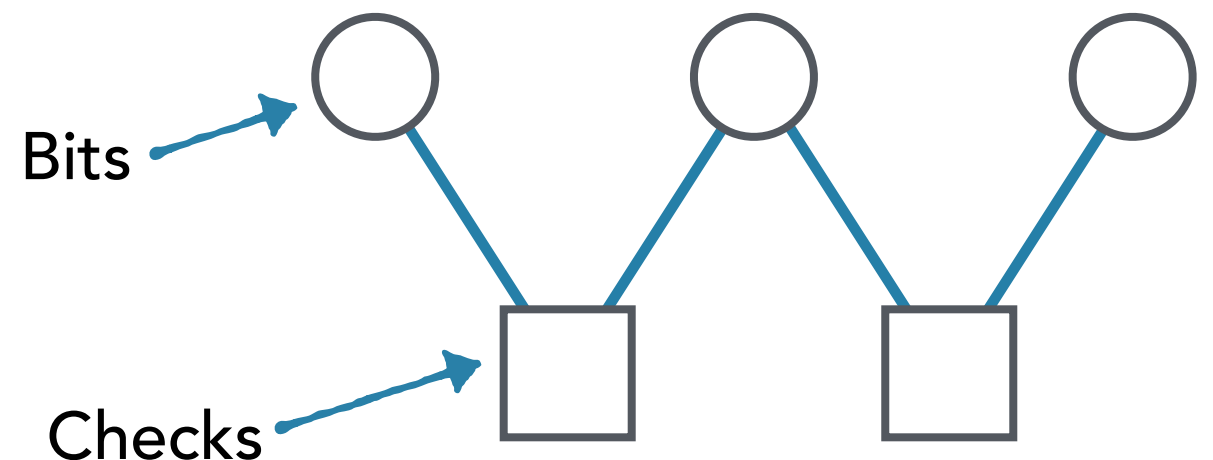
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- Errors are detected by **syndro**

$$H \cdot (001)^T \bmod 2 = (01)^T$$

- **Tanner graph:** Provides equivalent representation of parity check matrix





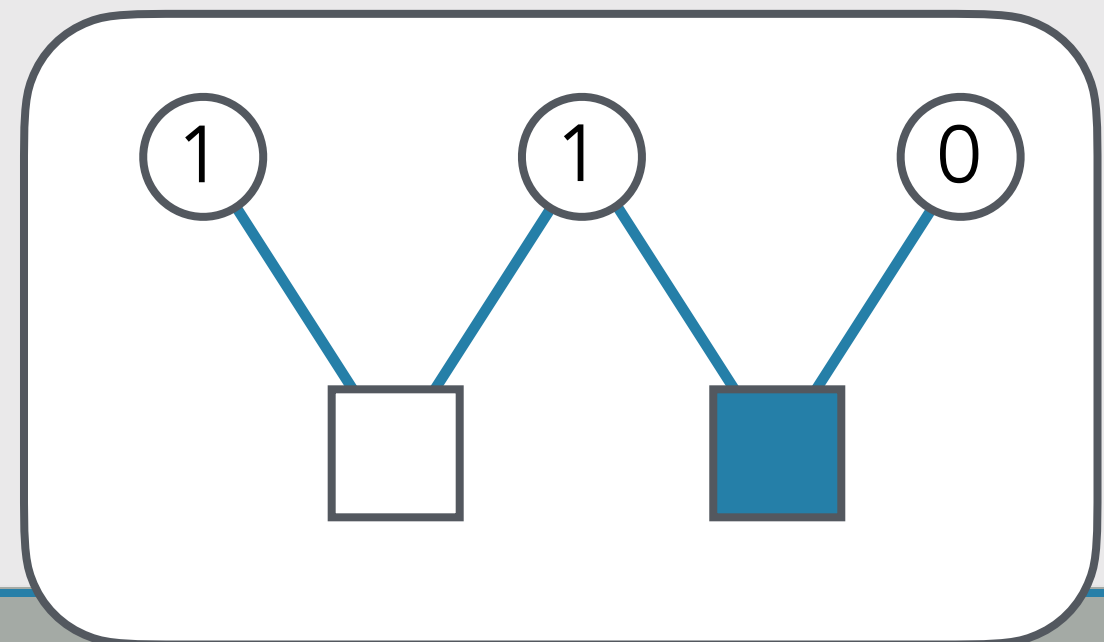
- **Syndrome equation**

$$s = H \cdot e \bmod 2$$

- **Decoding problem:** Find most likely value

$$e_{\text{ML}} = \operatorname{argmax}_e P(e|s)$$

- **Decoding:** Lookup, minimum weight perfect matching, belief propagation





- **Calderbank-Shor-Steane** (CSS) codes: Defined by two classical binary codes

- H_X : detects phase-flip errors (Z-errors)
- H_Z : detects bit-flip errors (X-errors)

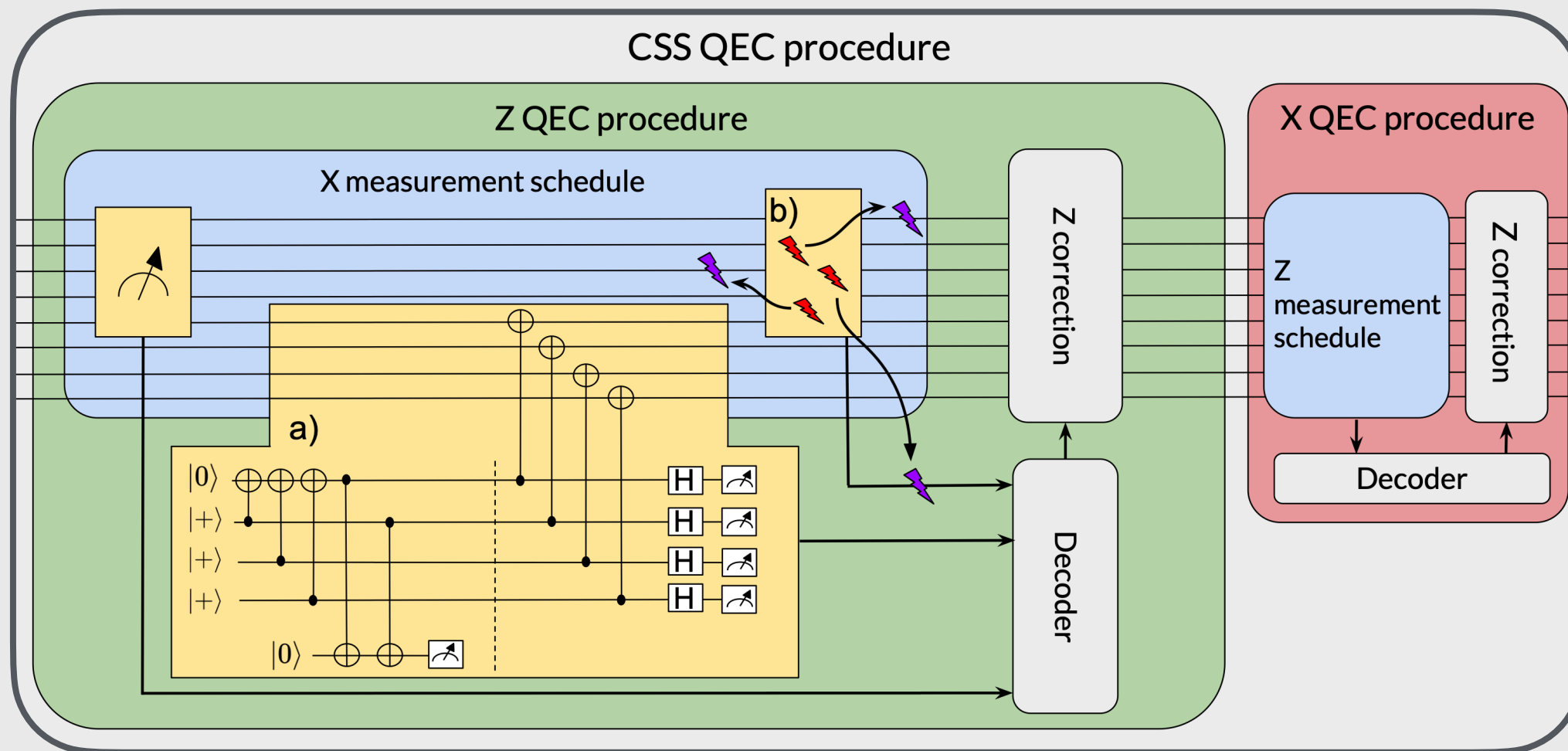


- **Example:** Steane $[[7, 1, 3]]$ code (aka $d = 3$ color code), both

$$H_X = X_Z = H = \begin{pmatrix} 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 1 \end{pmatrix}$$

- Is is **not** so easy

- **Errors propagate** in circuit implementation for **circuit level noise**



- **Errors propagation** rules

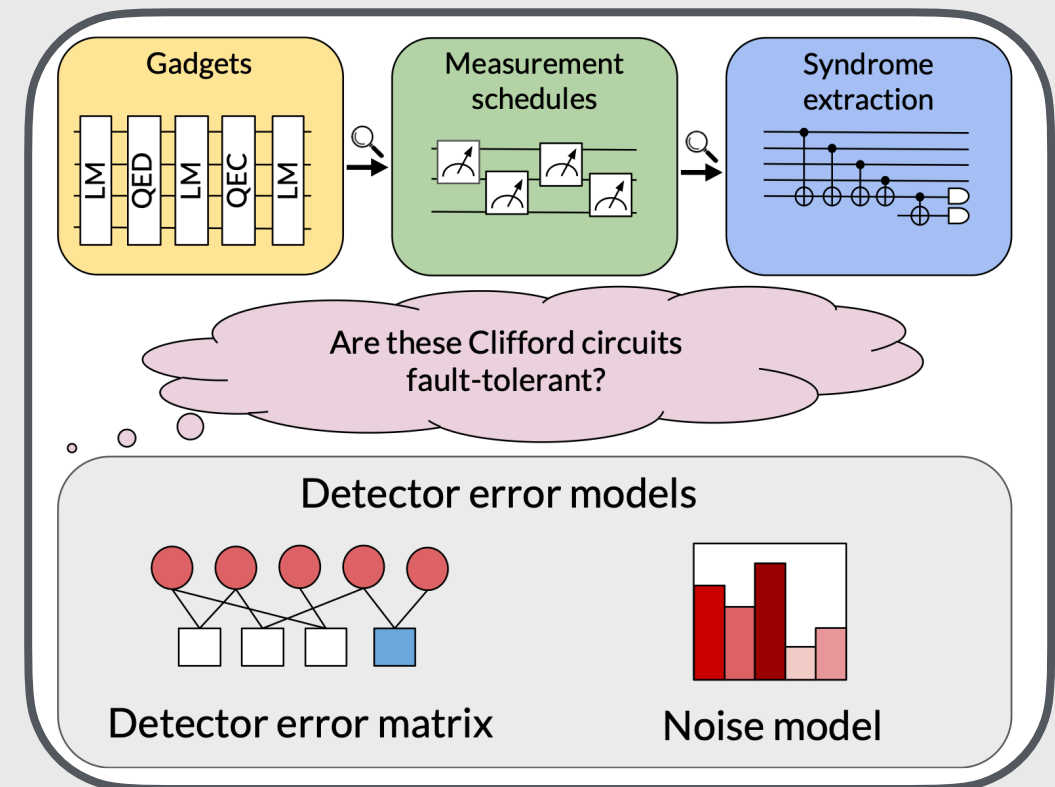


- Accounting for **circuit level** faults requires **detector error models**
- Detector matrix connects circuit faults to linear combinations of stabilizer measurements

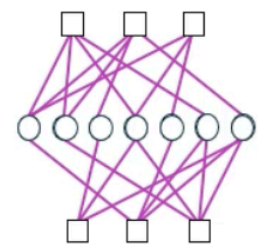
- Decoding problem**

$$s = D \cdot e^T$$

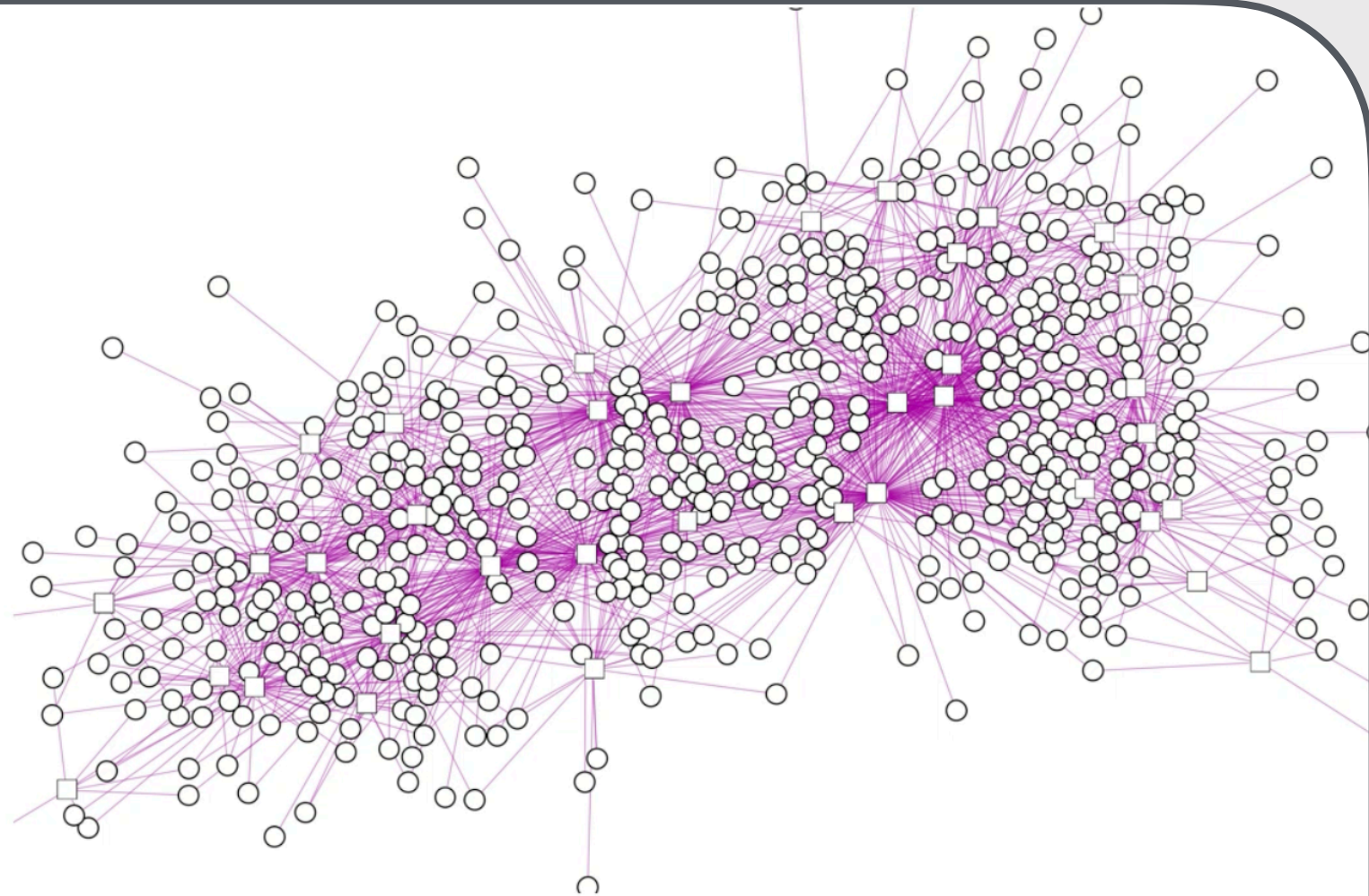
- s : code syndrome
 - D : binary detector matrix
 - e : error
- Detector matrix is binary linear code



- Accounting for **circuit level** faults requires **detector error models**



After Circuit-compilation



H : Code capacity parity check matrix for $d = 3$ Colour code.

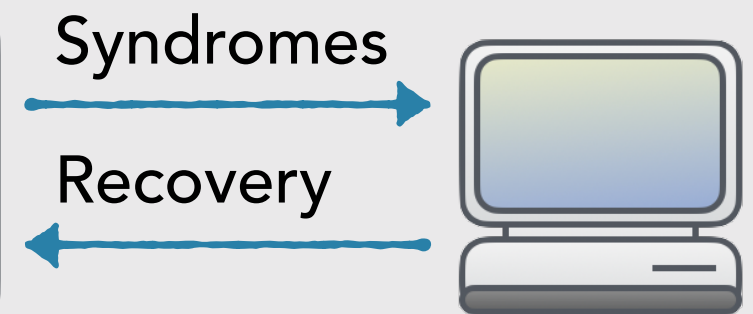
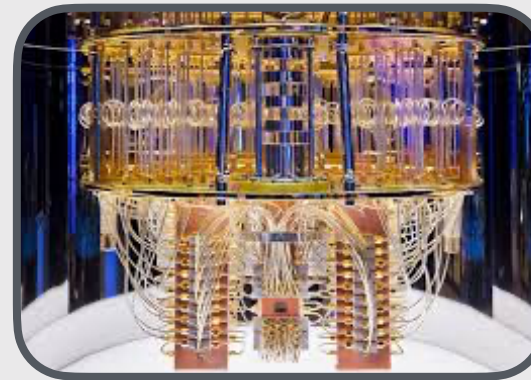
D : Circuit-level detector matrix for $d = 3$ Colour Code. Bell-flagged syndrome extraction circuit; 3 measurement rounds

Credit for picture: Joschka Roffe

REQUIREMENTS FOR DECODING

- Decoding comes with **three desiderata**: Decoding has to be...

- Fast**: Vast quantities of syndrome data, has to be faster than noise



- Versatile**: With logical operations, decoding graph is constantly **evolving**
- Accurate**: Decoder determines quality of QEC: **Balance** must be struck



PART 3: DECODING WITH BELIEF PROPAGATION AND ORDERED STATISTICS DECODING

BELIEF PROPAGATION DECODING

- For an error e and a parity check matrix H (sparse for qLDPC codes)

$$s = H \cdot e$$

- Decoding goal:** Find minimum weight estimate e_{MW} satisfying s

$$e_{MW} = \operatorname{argmax}_e P(e|s)$$

- For i.i.d. noise, becomes marginalization problem on each bit

$$P(e_i) = \sum_{\neg e_i} P(e_1, e_2, e_i = 1, e_3, \dots, e_n | s)$$



Exponentially
many terms

BELIEF PROPAGATION DECODING

- For an error e and a parity check matrix H (sparse for qLDPC codes)

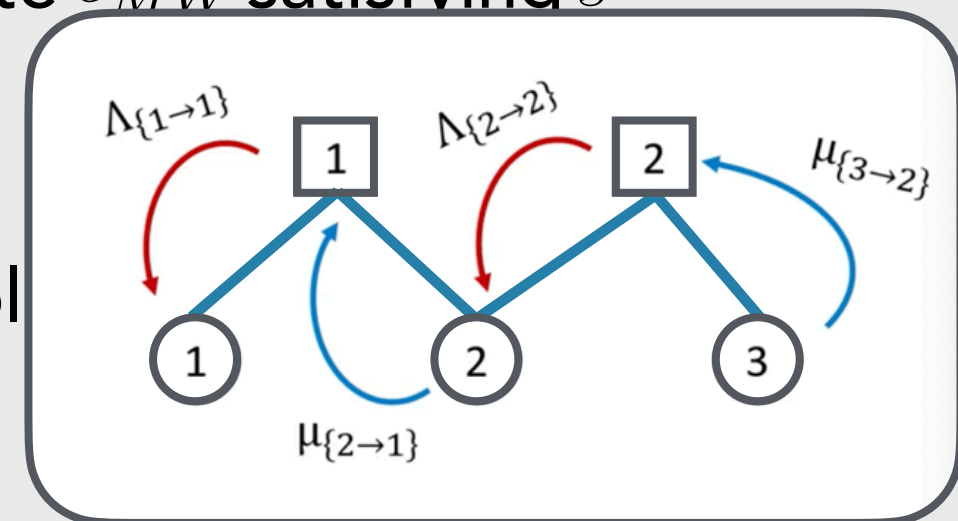
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$$\begin{aligned} P(e_i) &= \sum_{\neg e_i} P(e_1, e_2, e_i = 1, e_3, \dots, e_n | s) \\ &= \sum_{e_4} \sum_{e_5} \dots \sum_{e_n} f(e_4, \dots, e_n | s) \dots \sum_{e_2} f(e_s | s) \sum_{e_3} f(e_1, e_2, e_3 | s) \end{aligned}$$



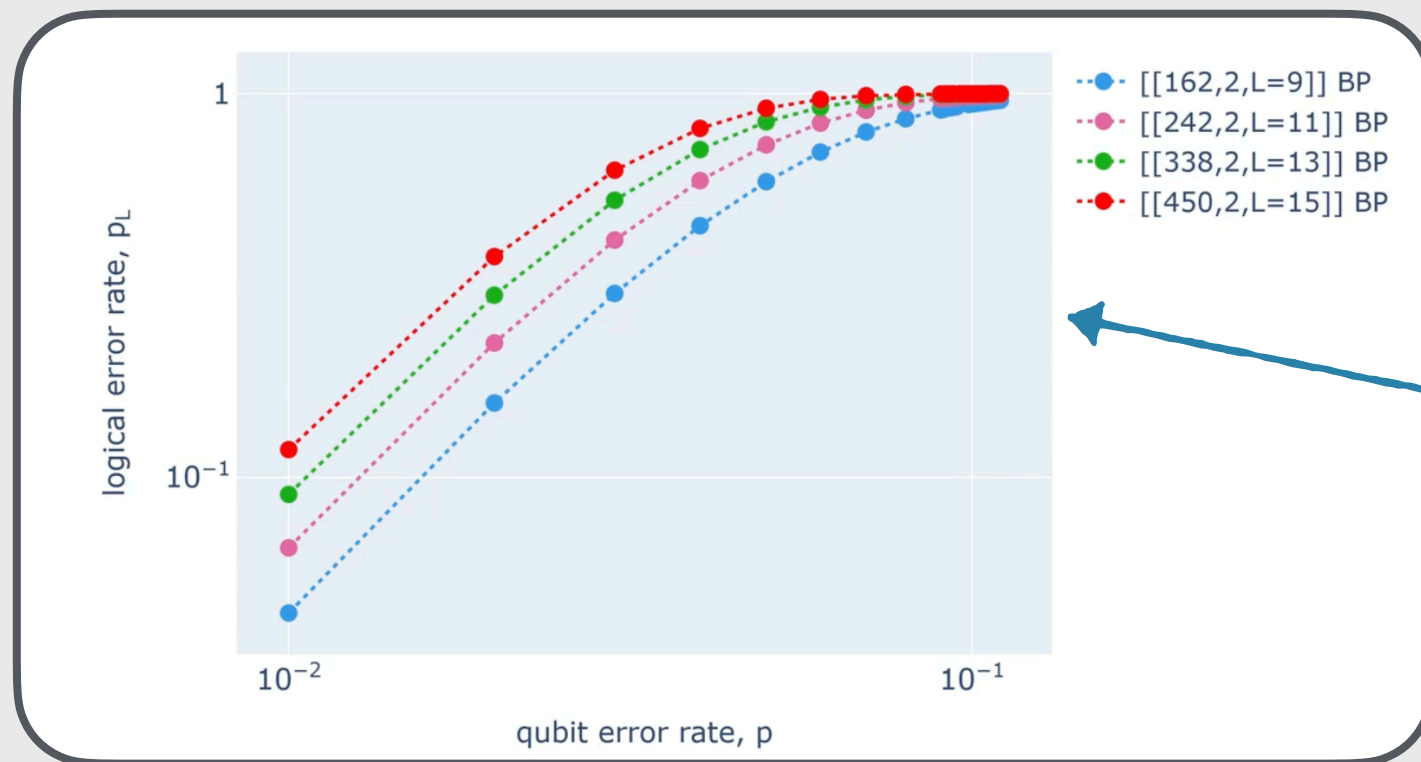
- Form of factorization determined via the the Tanner graph - precomputed sums are messages in an iterative message passing algorithm
- Approximate on graphs with cycles, but often good enough

BELIEF PROPAGATION DECODING

- Works **well** in practice for classical codes
 - **Fast** $O(n)$ 
 - **Versatile** 
 - **Accurate** 

BELIEF PROPAGATION DECODING

- Works **well** in practice for classical codes
 - **Fast** $O(n)$ ✓
 - **Versatile** ✓
 - **Accurate** ✓
- But has **no threshold** for the quantum toric code



Does not work for all error configurations: Many degenerate configurations

Tanner graph contains too many short loops, trapping sets

ORDERED STATISTICS DECODING AS A FIX

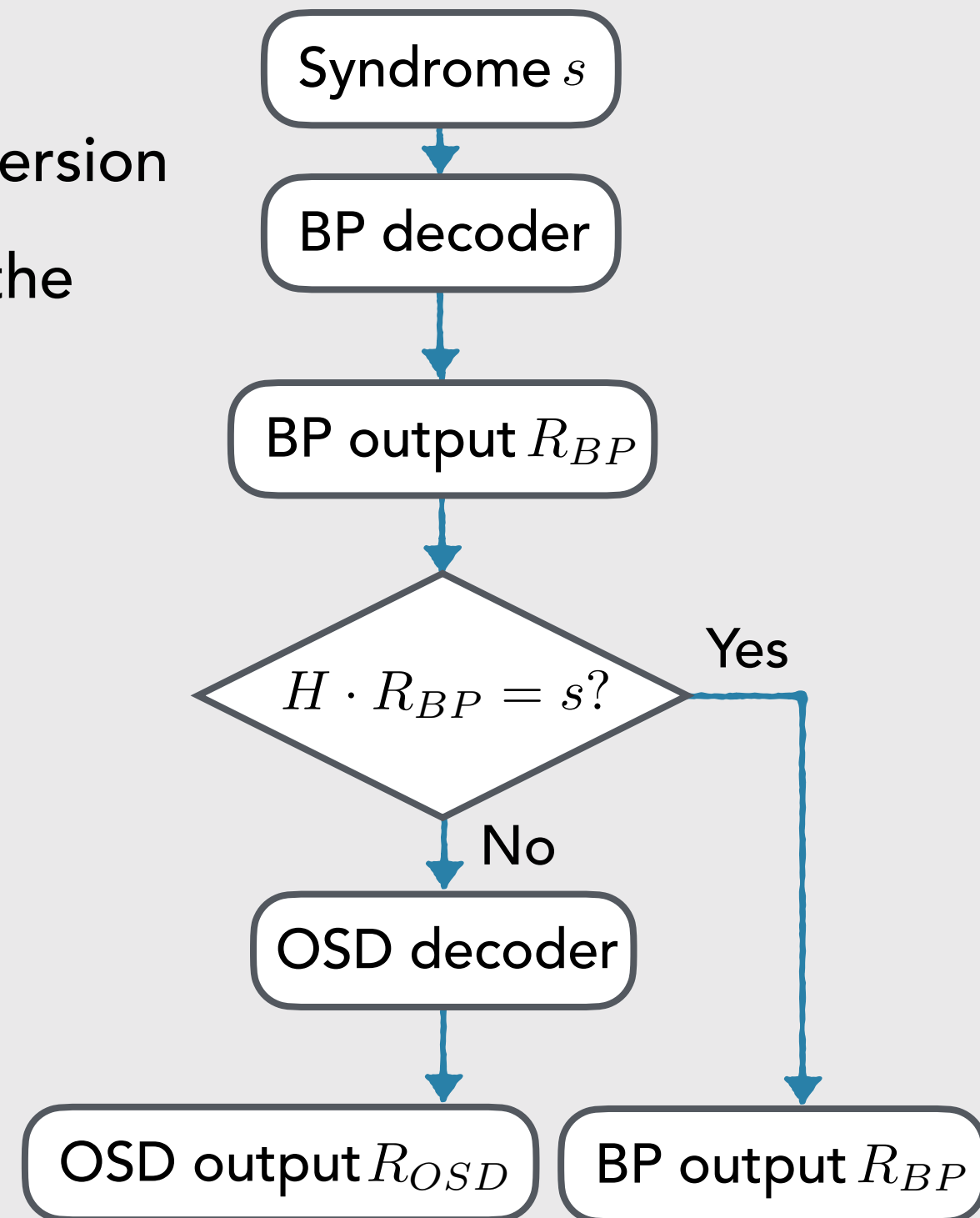
- Belief propagation postprocessing that **always** returns a solution satisfying the syndrome

- Enforces solution through matrix inversion
- Developed as method for reducing the error floor in classical LDPC codes

Fourrier, Lin, IEEE Trans Inf Th 44, 691 (1998)

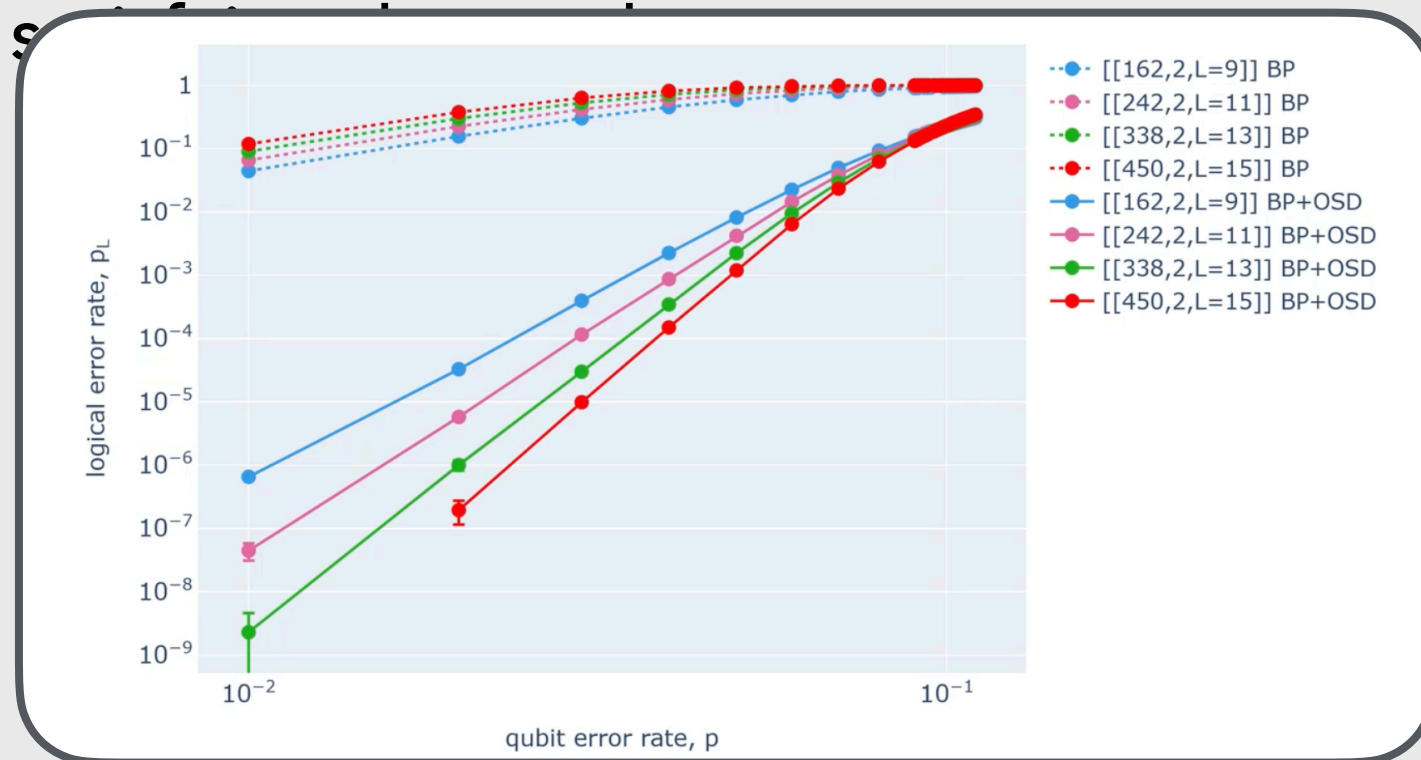
- Applied to the quantum setting

Pantaleev, Kalachev, Quantum 5, 585 (2021)

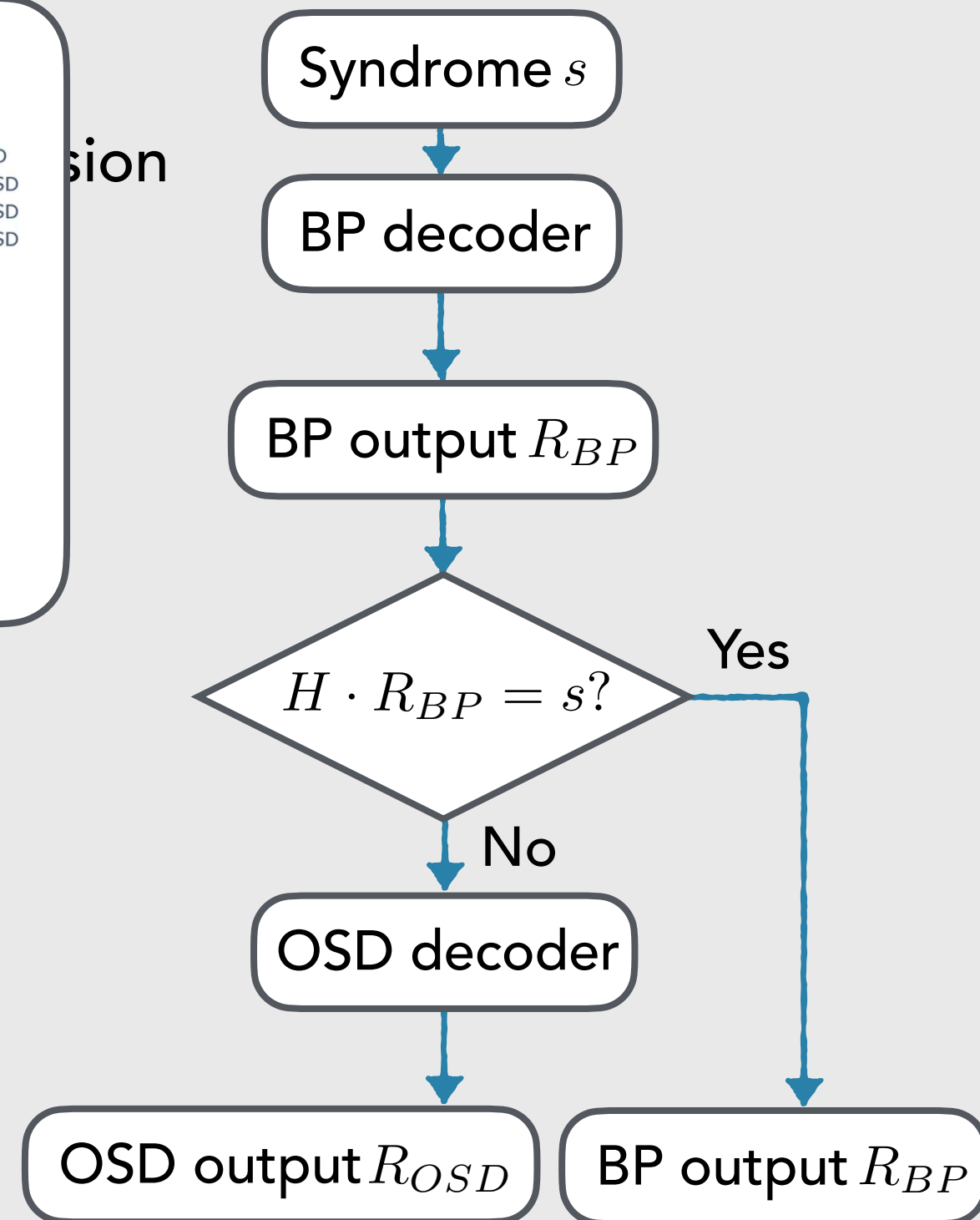


ORDERED STATISTICS DECODING AS A FIX

- Belief propagation postprocessing that **always** returns a solution



- Has a **threshold** for the toric code



ORDERED STATISTICS DECODING AS A FIX

- OSD requires Gaussian elimination, is with $O(n^3)$ too slow
 - Fast 
 - Versatile 
 - Accurate 

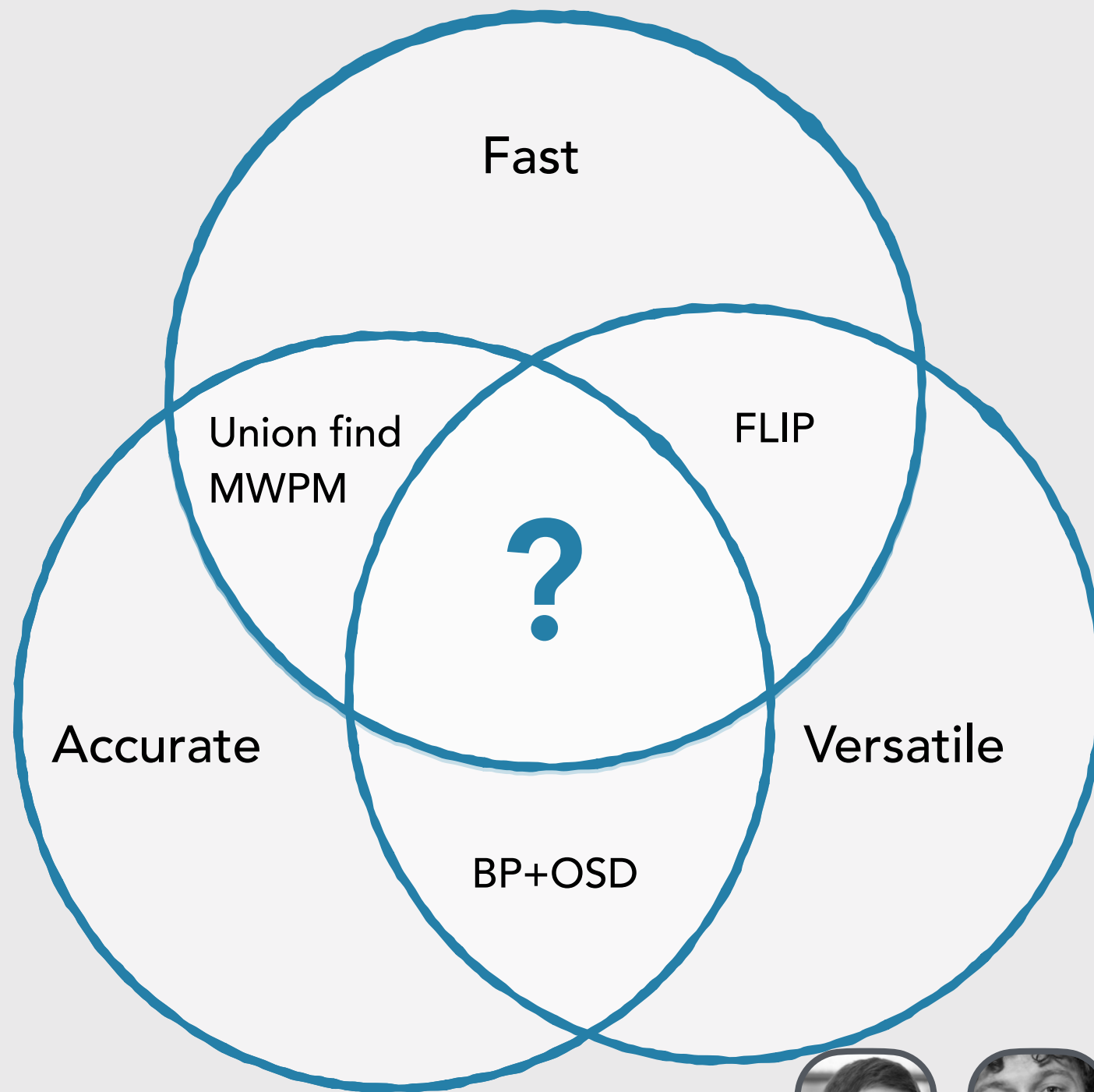
- Can we do fast decoding?



PART 4: DECODING QLDPC CODES WITH LOCALIZED STATISTICS DECODING

Nature Comm 16, 8214 (2025)

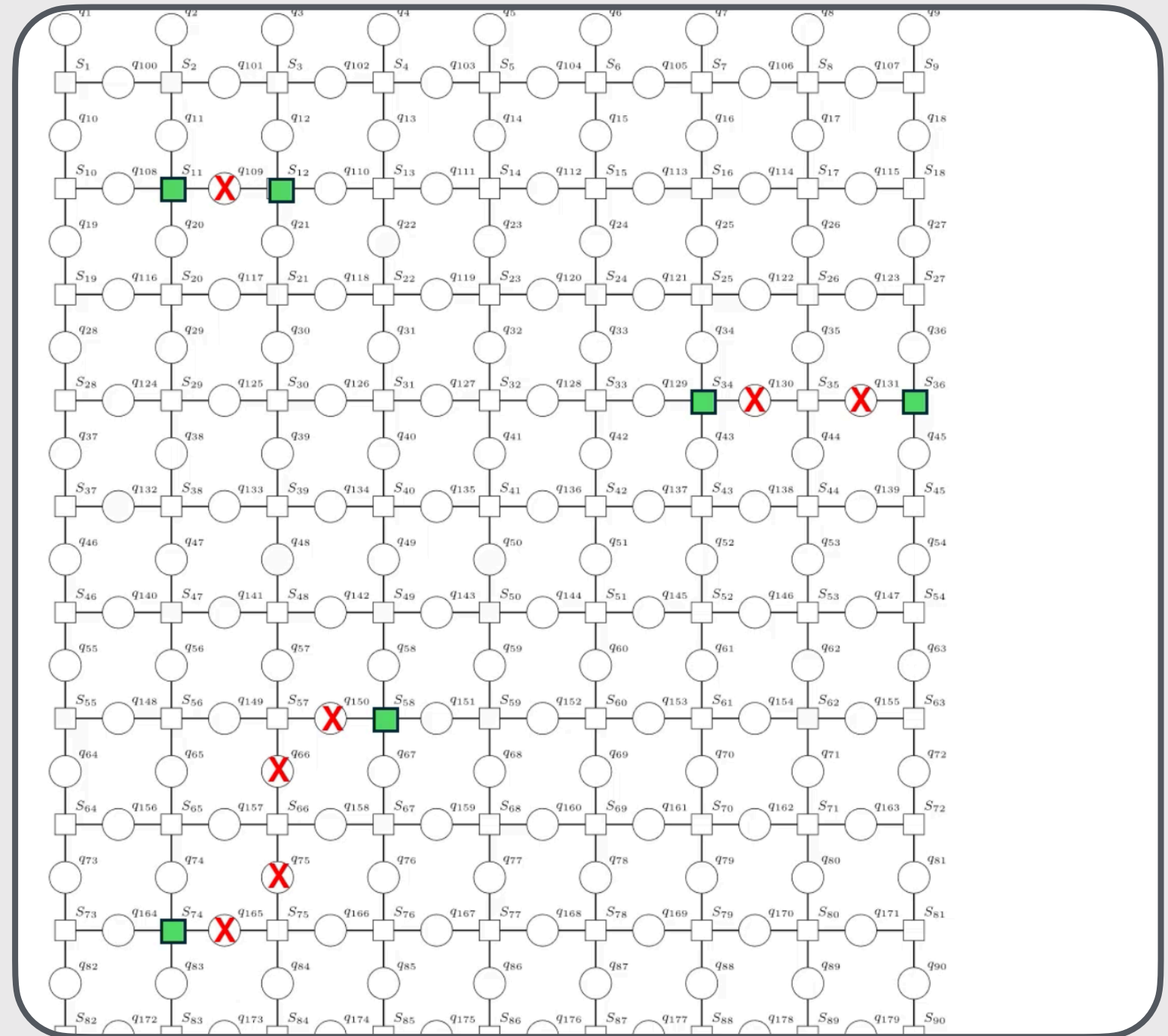
WISHLIST FOR FAST DECODERS



Hillmann, Berent, Quintavalle, Eisert, Wille, Roffe, Nature Comm 16, 8214 (2025)

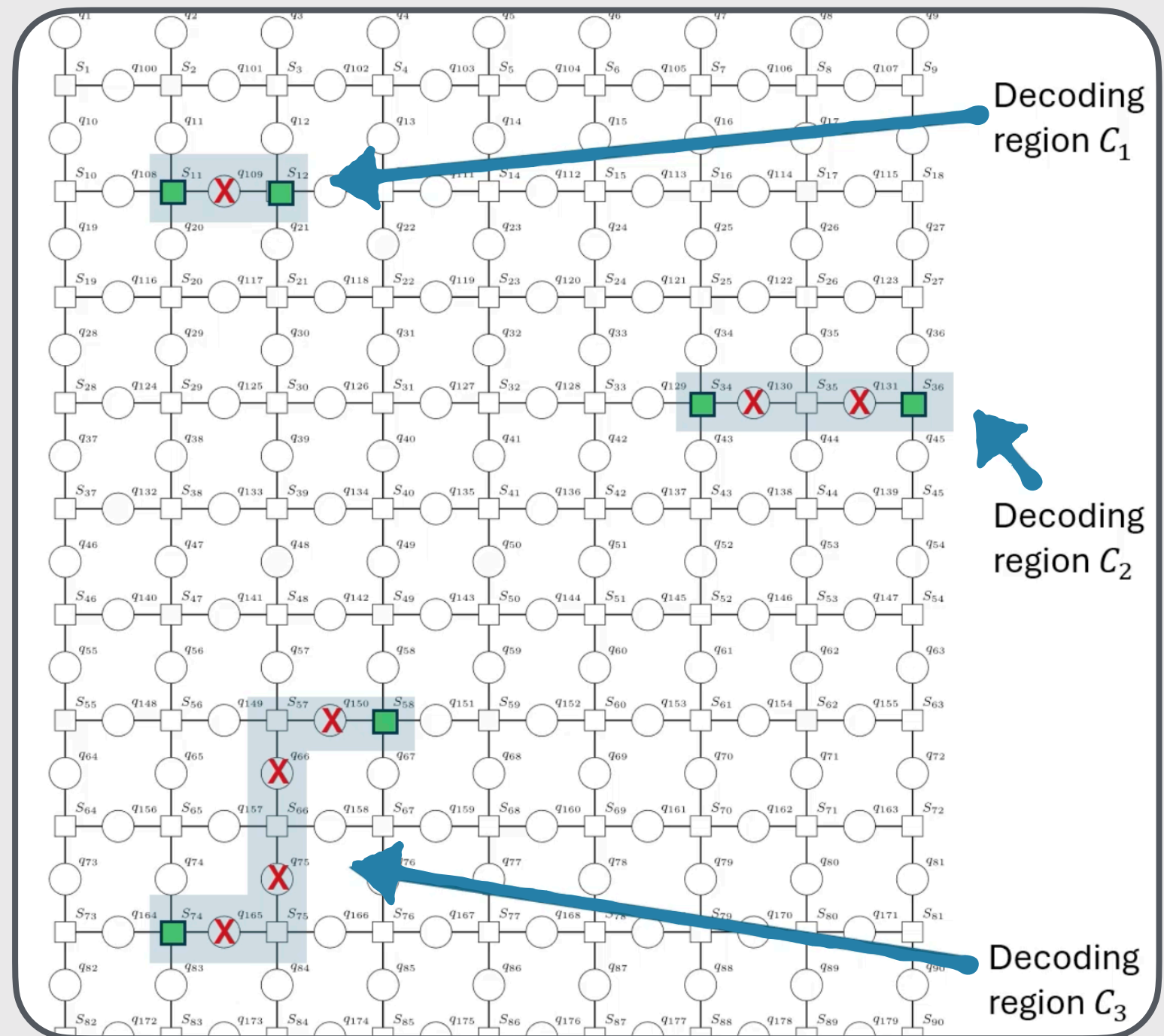
INTUITION: SPARSITY-AWARE MATRIX INVERSION

- QLDPC codes are **sparse**
- Sub-threshold: Errors span **independent regions** of decoding graph
- Matrix inversion **factorizes**
- Independent decoding regions decoded in **parallel**



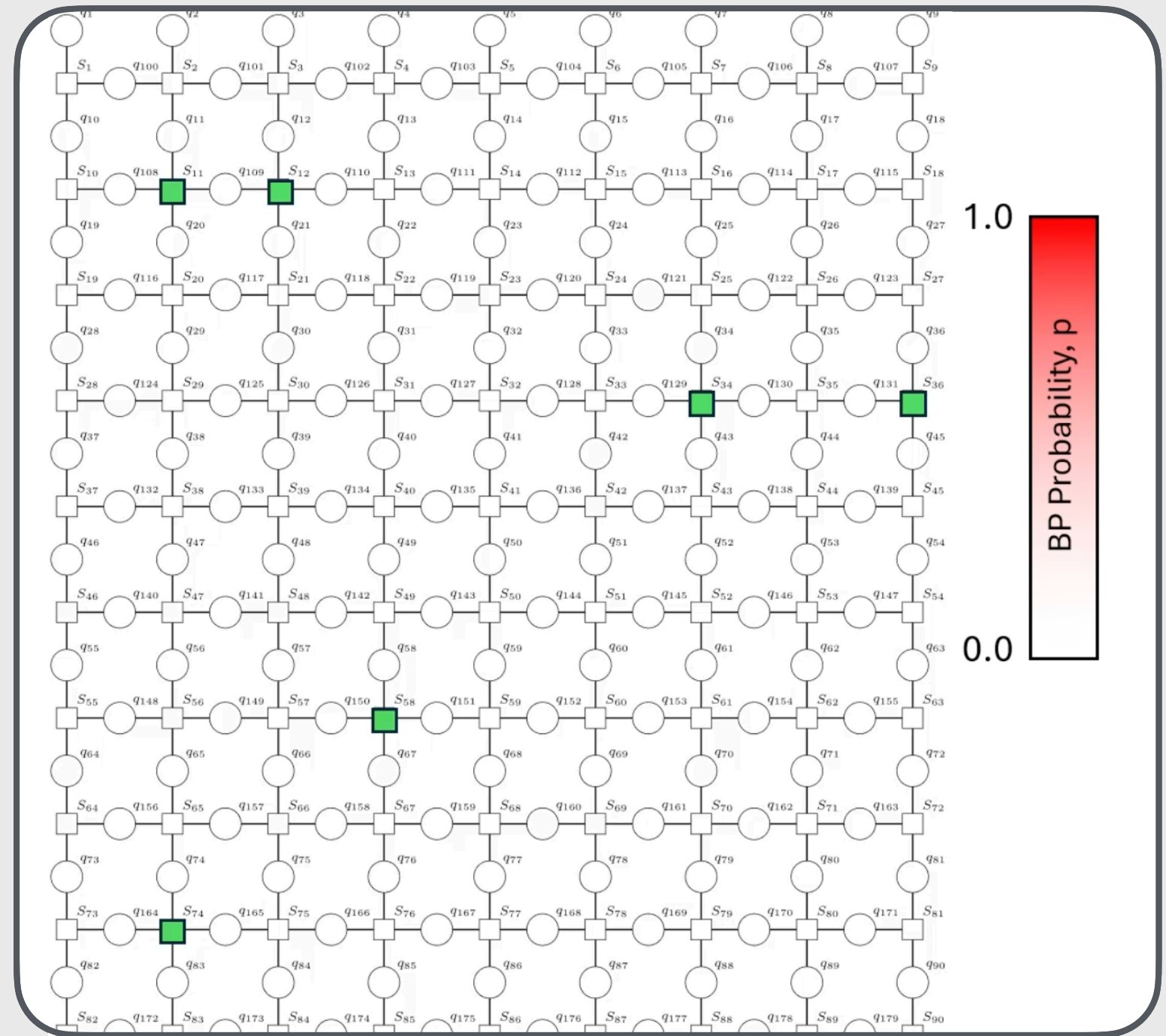
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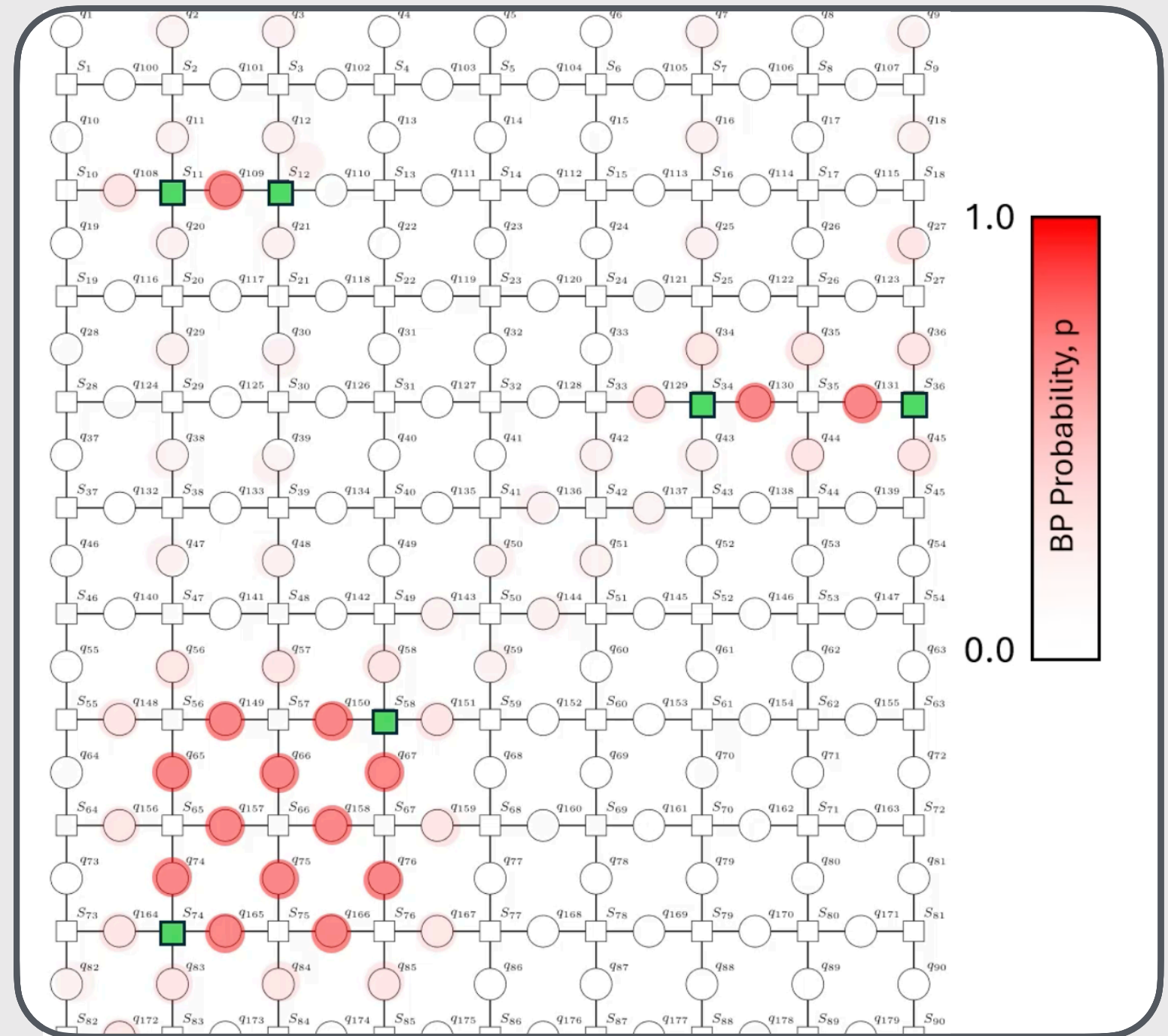
STEP 1: BELIEF PROPAGATION

- Run **belief propagation**, gives soft information



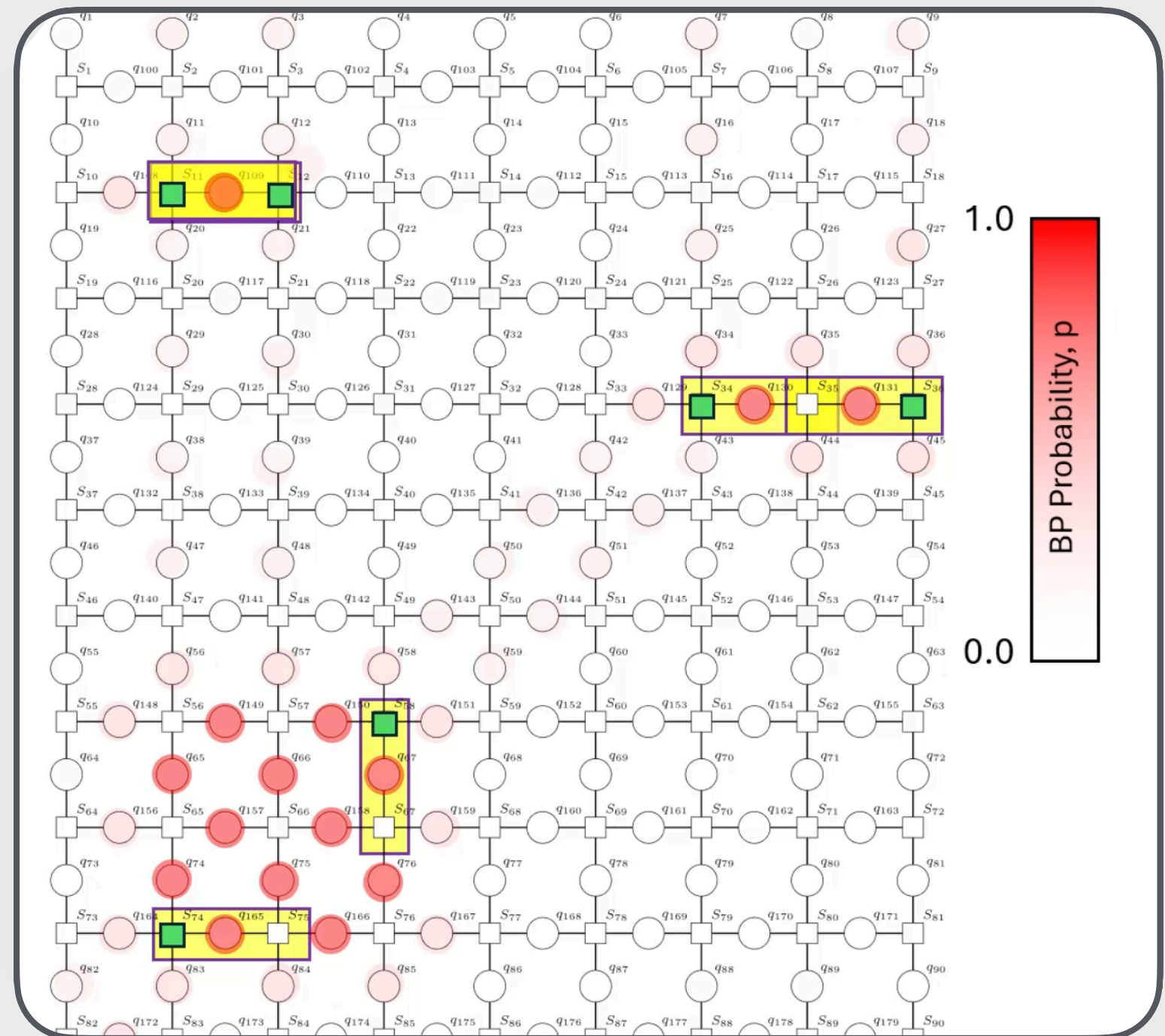
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STEP 2: CLUSTER GROWTH

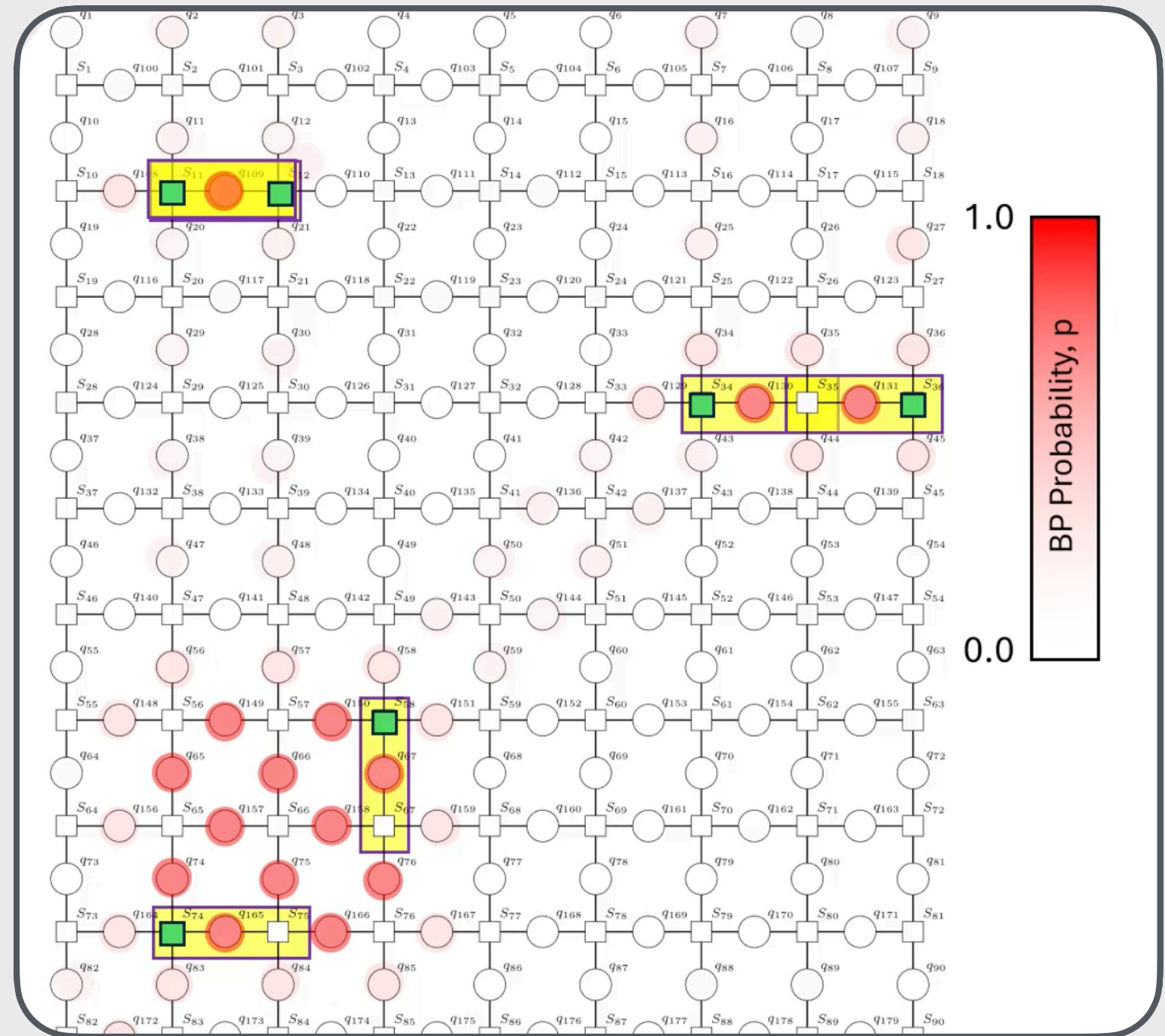
- Clusters grown in **parallel** from each activated syndrome node



Hillmann, Berent, Quintavalle, Eisert, Wille, Roffe, Nature Comm 16, 8214 (2025)

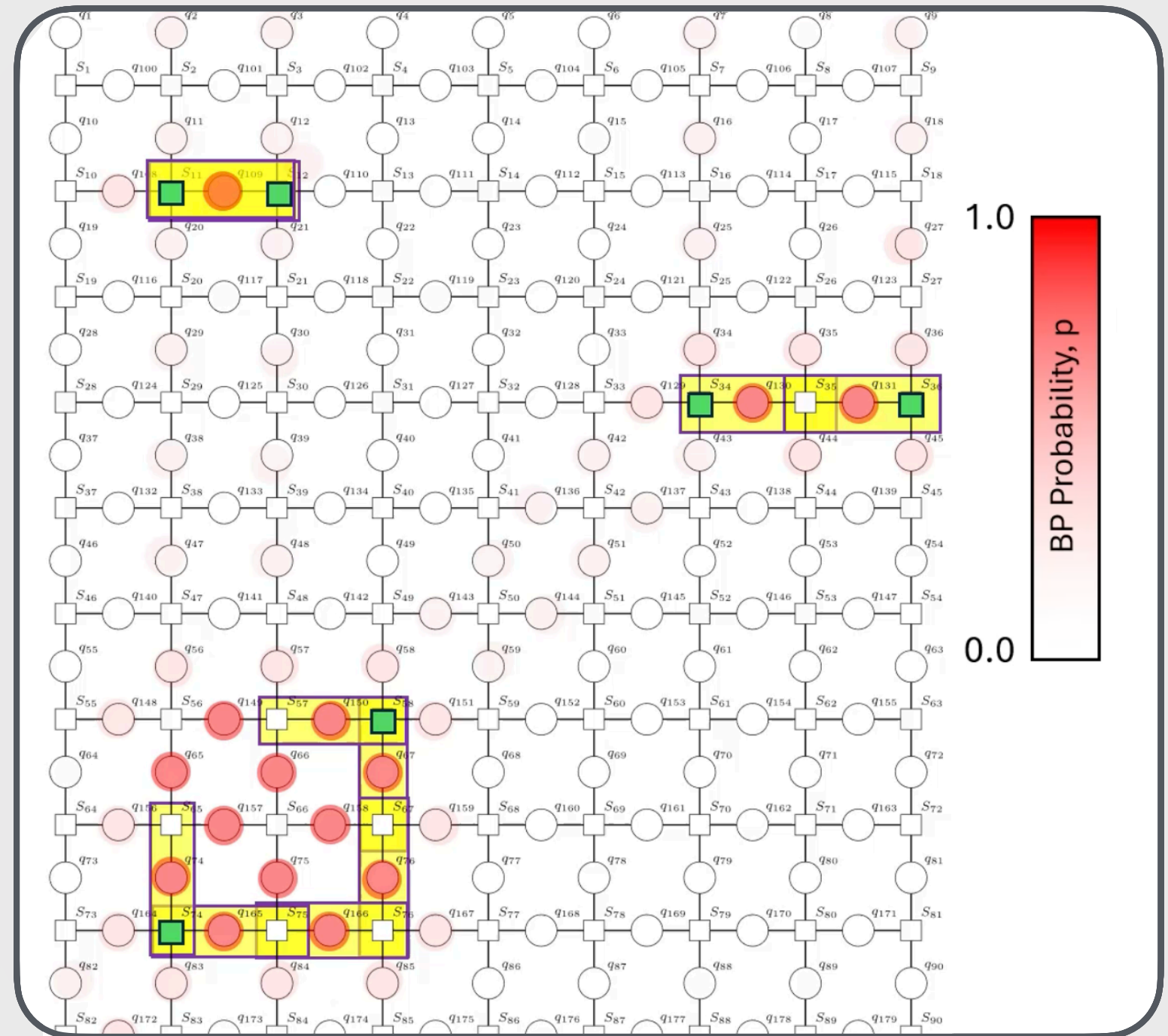
STEP 2: CLUSTER GROWTH

- **Grow** from each activated bit, expand one bit at a time
- Colliding clusters **merged**



STEP 2: CLUSTER GROWTH

- Cluster growth is **halted** when a cluster supports a solution to local decoding problem



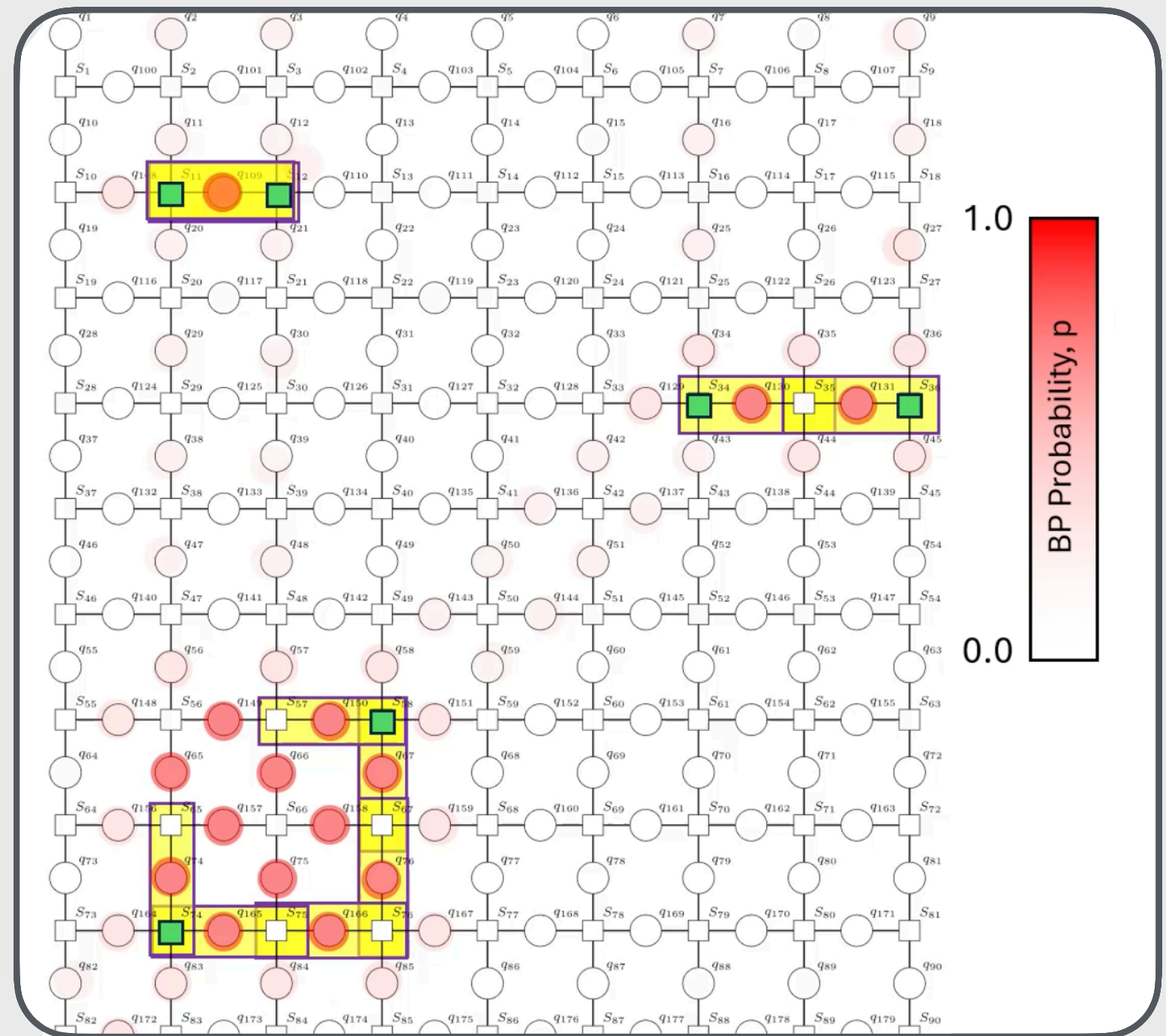
STEP 2: CLUSTER GROWTH

- A cluster is **valid** if it can be inverted to solve the local decoding problem

$$e_C = H_C^{-1} \cdot s_C$$

- A cluster is **valid** if

$$s_C \in \text{Image}(H_C)$$



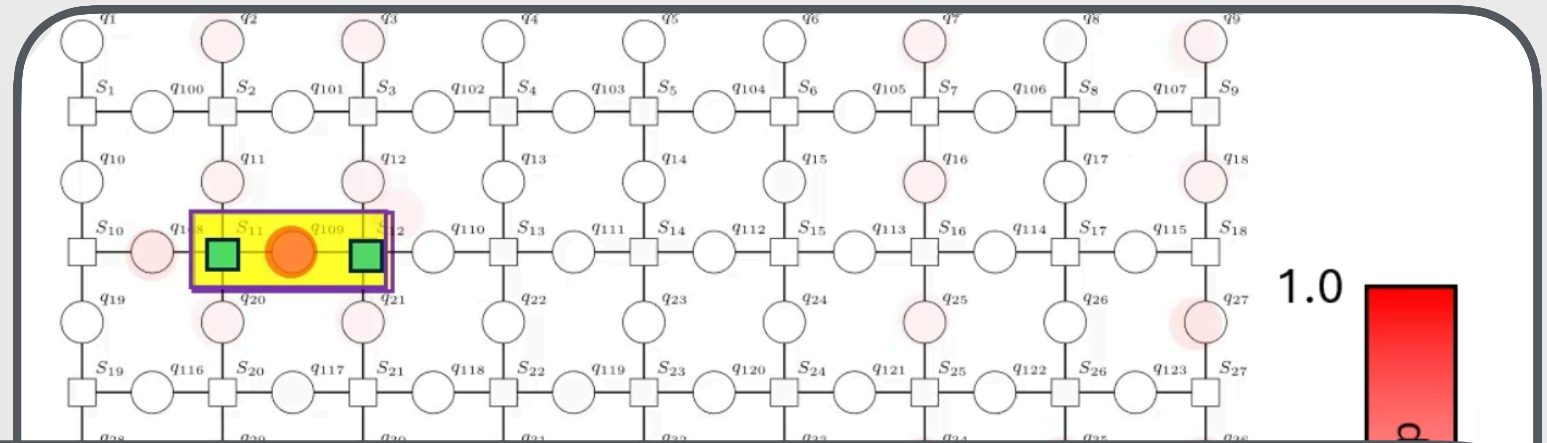
STEP 3: ON-THE-FLY ELIMINATION

- A cluster is **valid** if it can be inverted to solve the local decoding problem

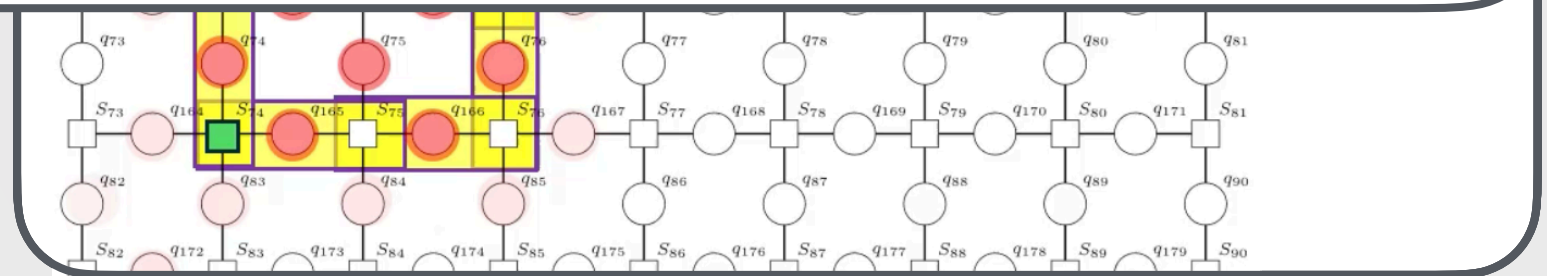
$$e_C = H_C^{-1} \cdot s_C$$

- A cluster is **valid** if

$$S_C \in \text{Image}(H_C)$$



- How do we efficiently **verify** the halting condition?
- Gaussian elimination in each step requires $O(\mu_C^4)$ steps in largest cluster size μ_C Delfosse, Londe, Beverland, arXiv:2103.08049 (2021)
- Here:** Introduce new algorithm, "on-the-fly elimination", dynamically eliminate clusters as they grow, in worst case $O(\mu_C^3)$



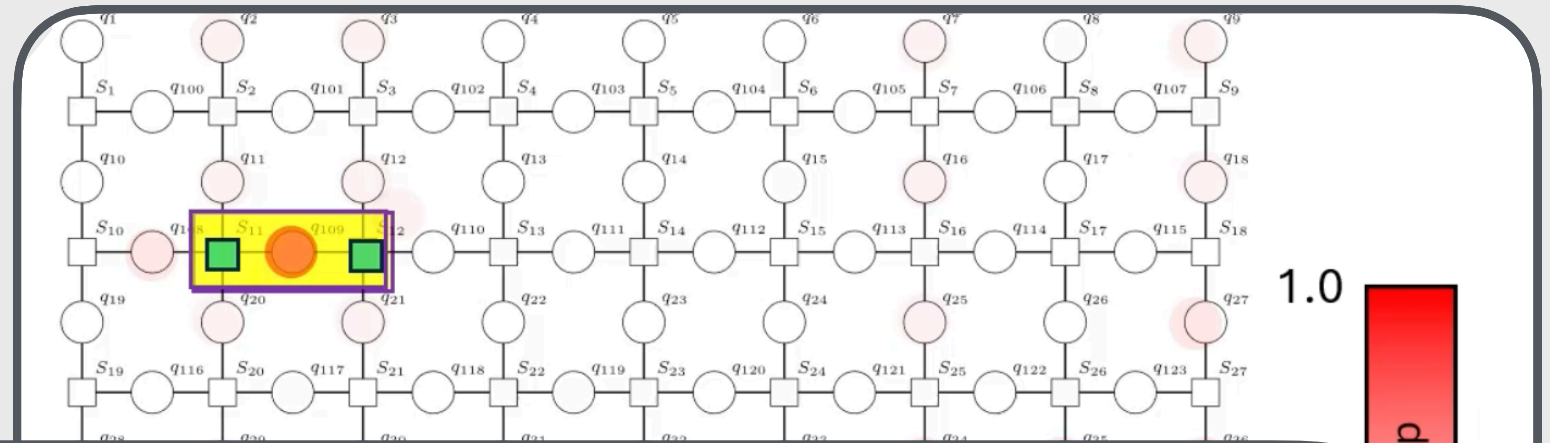
STEP 3: ON-THE-FLY ELIMINATION

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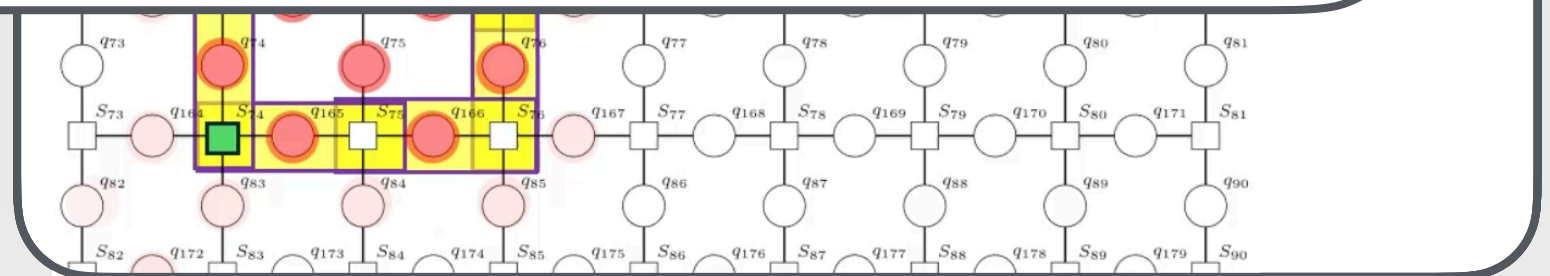
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$$S_C \in \text{Image}(H_C)$$



- Technically:** Solving linear systems over finite fields $\mathbb{F}_2$ with PLU decomposition $H_C = P_C L_C U_C$ - numerically stable, $O(n)$

$$\begin{array}{c}
 \boxed{H_C} \\
 \text{Permutation}
 \end{array}
 =
 \begin{array}{c}
 \boxed{P_C} \\
 \text{Permutation}
 \end{array}
 \times
 \begin{array}{c}
 \triangle L_C \\
 \text{Lower triangular}
 \end{array}
 \times
 \begin{array}{c}
 \triangle U_C \\
 \text{Upper triangular}
 \end{array}$$



GOOD PERFORMANCE OF LOCALIZED STATISTICS DECODING

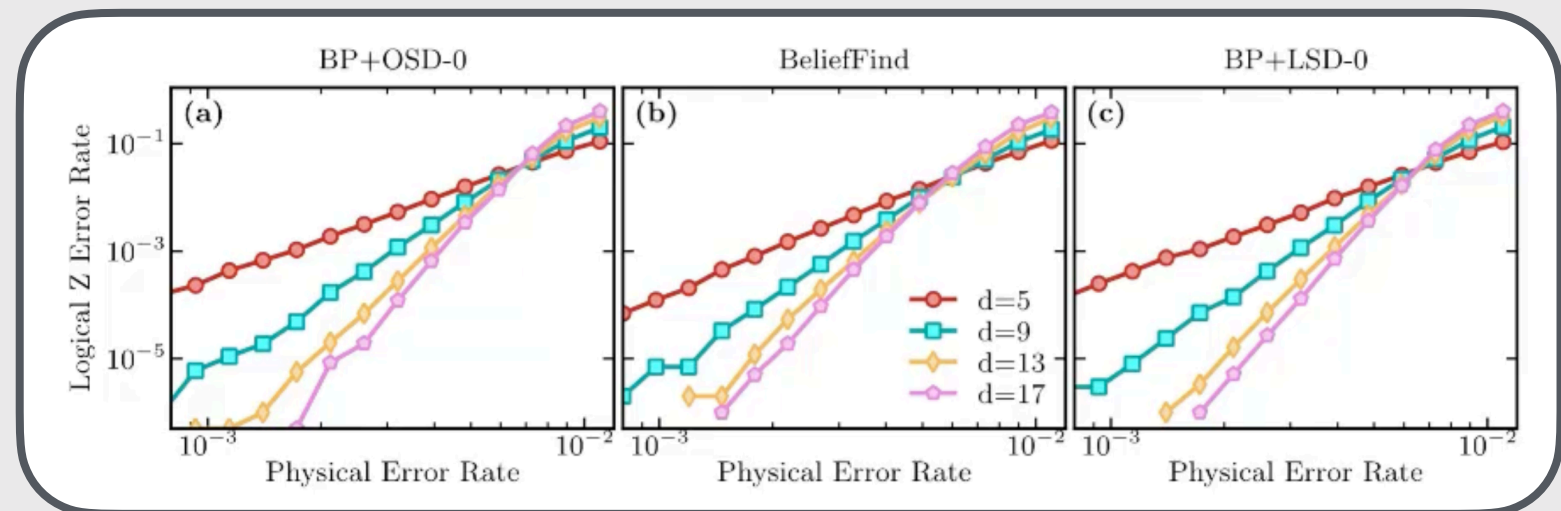
- Gives fast, versatile accurate decoder

- Fast ✓

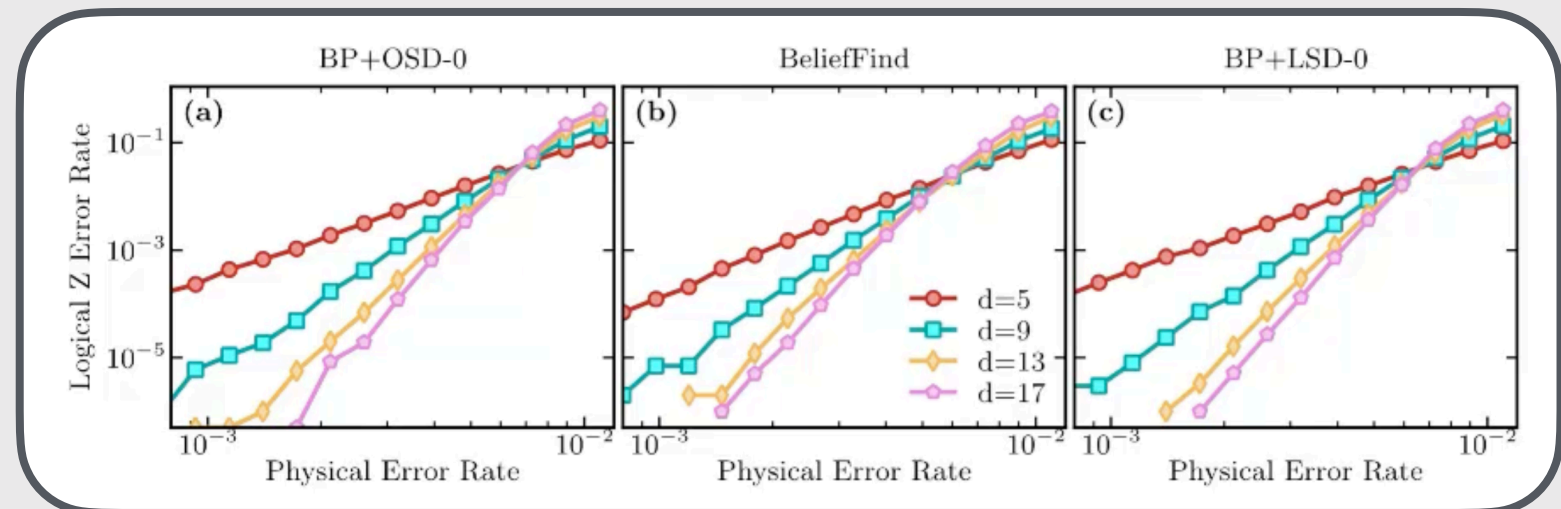
- Versatile ✓

- Accurate ✓

- **Rotated surface codes** with circuit level noise



- **Hypergraph products** and **bicycle bivariate codes**



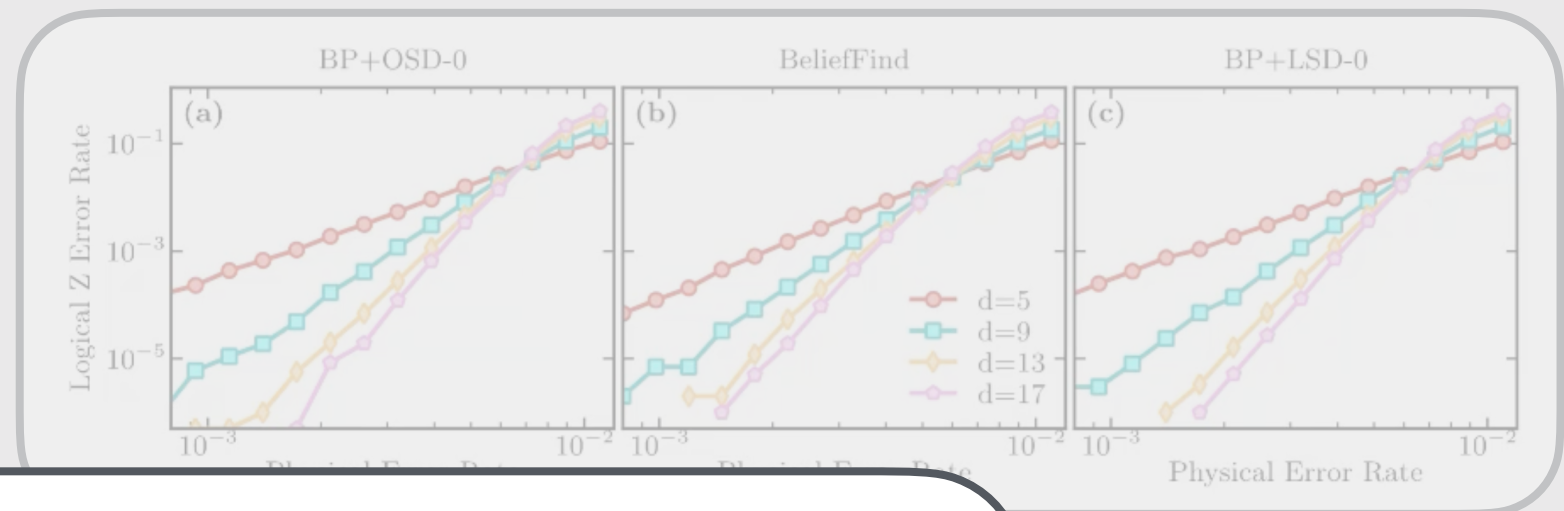
Compare Bravyi, Cross, Gambetta, Maslov, Rall, Yoder, Nature 627, 778 (2024)

Xu et al, Nature Phys 20, 1084 (2024)

Hillmann, Berent, Quintavalle, Eisert, Wille, Roffe, Nature Comm 16, 8214 (2025)

GOOD PERFORMANCE OF LOCALIZED STATISTICS DECODING

- Gives fast, versatile accurate decoder
 - Fast ✓
 - Versatile ✓
 - Accurate ✓
- Rotated surface codes with circuit level noise



- Performs very well, and showcases importance of quantum software

Connoisseur material,
e.g., on site percolation



Compare Bravyi, Cross, Gambetta, Maslov, Rall, Yoder, Nature 627, 778 (2024)
Xu et al, Nature Phys 20, 1084 (2024)

Hillmann, Berent, Quintavalle, Eisert, Wille, Roffe, Nature Comm 16, 8214 (2025)



OUTLOOK: PERSPECTIVES OF QEC

Nature Phys 20, 1648 (2024)

npj Quant Inf 10, 122 (2024)

Phys Rev Lett 133, 110601 (2024)

arXiv:2403.13927 (2024)

arXiv:2505.20261 (2025)

PRX Quantum 6, 010360 (2025)

PRX Quantum 5, 020349 (2024)

PRX Quantum 5, 010342 (2024)

Quantum 8, 1398 (2024)

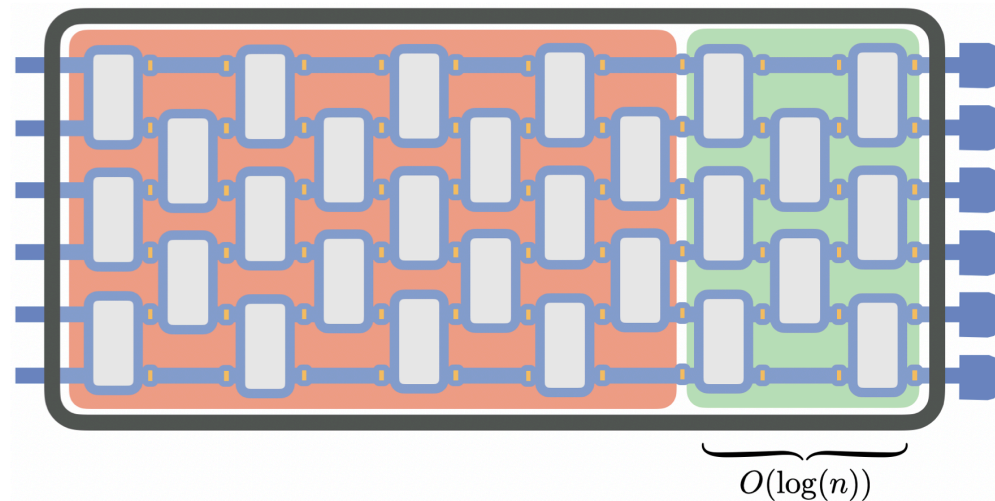
arXiv:2505.07658 (2025)

- **This talk:** Quantum error correction great playground for quantum software
- **Fast**, accurate and versatile decoder for qLDPC codes
- What else?



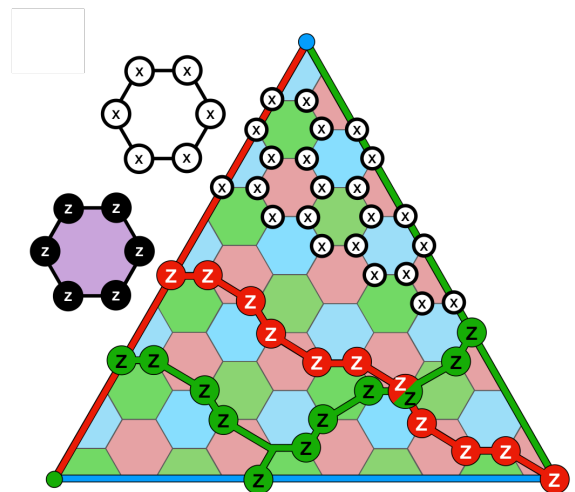
- Understanding **noise models** is important

- Comprehensive impact** of (possibly) non-unital noise and limits of mitigation



Quek, Stilck-Franca, Khatri, Meyer, Eisert, Nature Phys 20, 1648 (2024)
Mele, Angrisani, Ghosh, Khatri, Eisert, Stilck Frana, Quek,
arXiv:2403.13927, Nature Comm, in press (2025)

- Noise-tailored** variants of color QEC codes

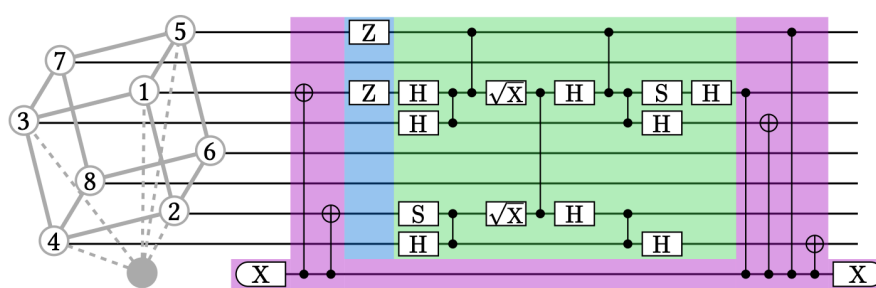


Tiurev, Pesah, Derks, Roffe, Eisert, Kesselring,
Reiner, Phys Rev Lett 133, 110601 (2024)

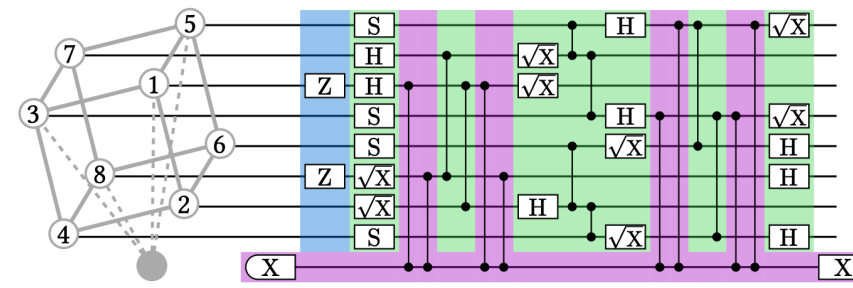
- Think of **hardware constraints: Locality**

- Hardware-tailored logical Clifford circuits for stabilizer codes**

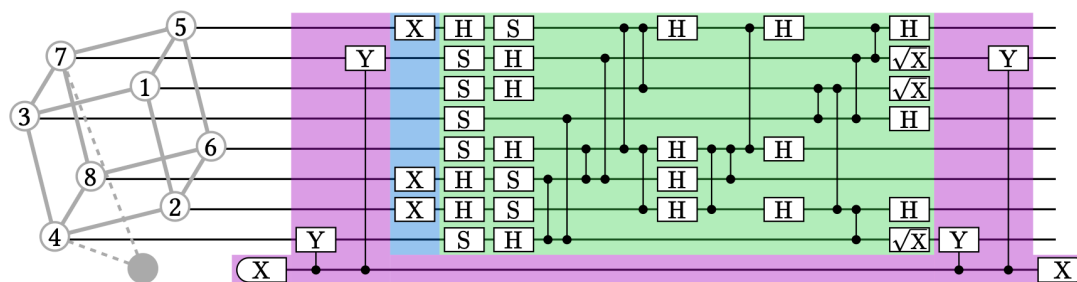
Framework for constructing hardware-tailored quantum circuits that implement any desired Clifford unitary on the logical level of any given stabilizer code



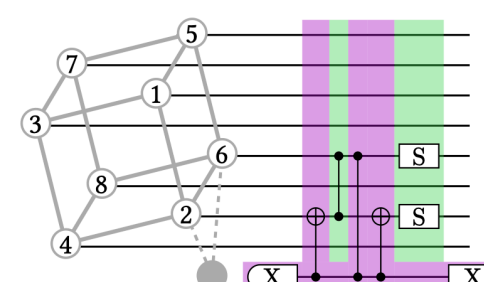
(a) Logical Hadamard gate, $\overline{H}_1$, on the first logical qubit.



(b) Logical Hadamard gates, $\overline{H}_{1,2}^{\otimes 2}$, on two logical qubits.



(c) Logical Hadamard gates, $\overline{H}_{1,2,3}^{\otimes 3}$, on all three logical qubits.



(d) Logical phase gate, $\overline{S}_1$, on the first logical qubit.

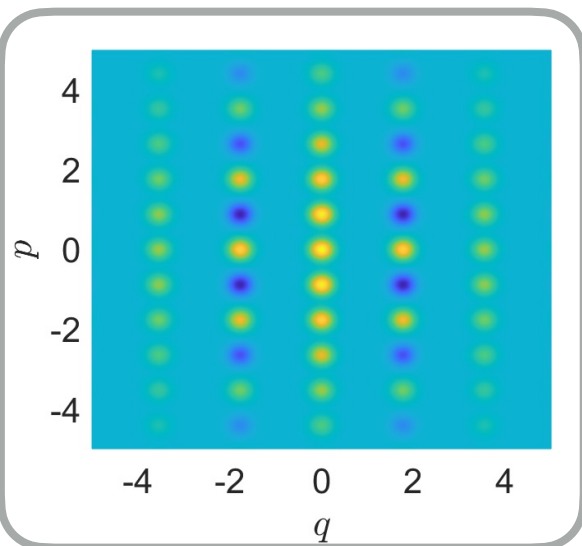
Kuehnke, Levi, Roffe, Eisert, Miller, arXiv:2505.20261 (2025)

Miller, Fischer, Levi, Kuehnke, Sokolov, Barkoutsos, Eisert, Tavernelli, npj Quant Inf 10, 122 (2024)

- **Continuous QEC** underrated



- **Good GKP codes** based on NTRU lattices and decoders



Conrad, Eisert, Seifert, Quantum 8, 1398 (2024)

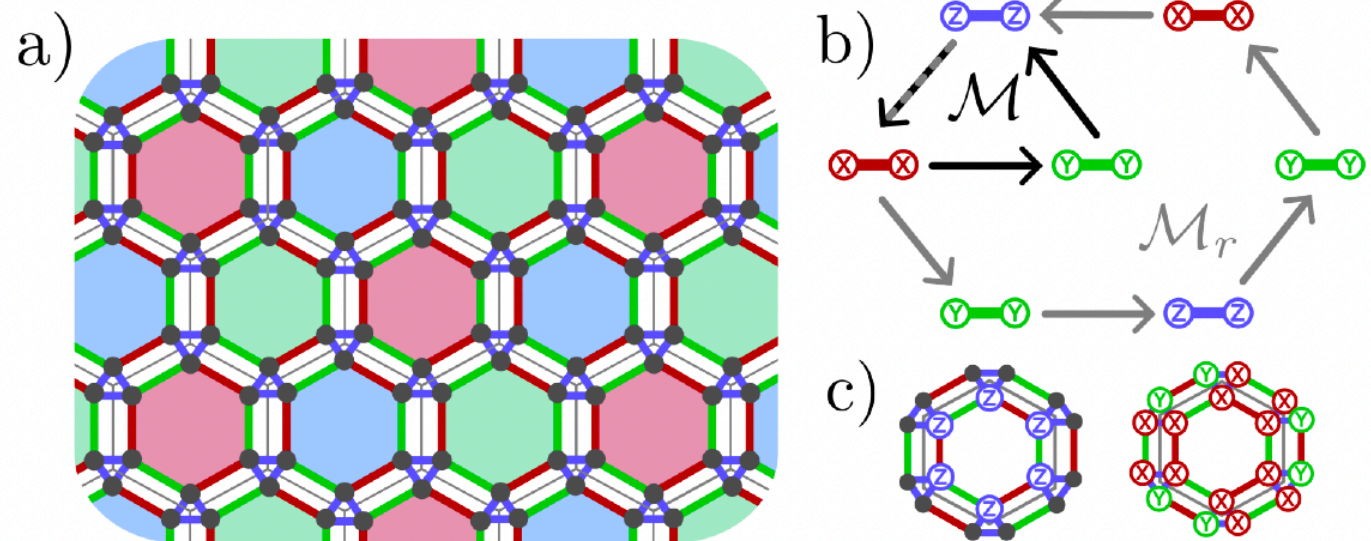
Berent, Hillmann, Eisert, Wille, Roffe, PRX Quantum 5, 020349 (2024)

- Simplify measurements

- Floquet codes

New Floquet codes derived from topological subsystem codes, XYZ ruby codes in color code phase with attractive thresholds - and new three colored calculus

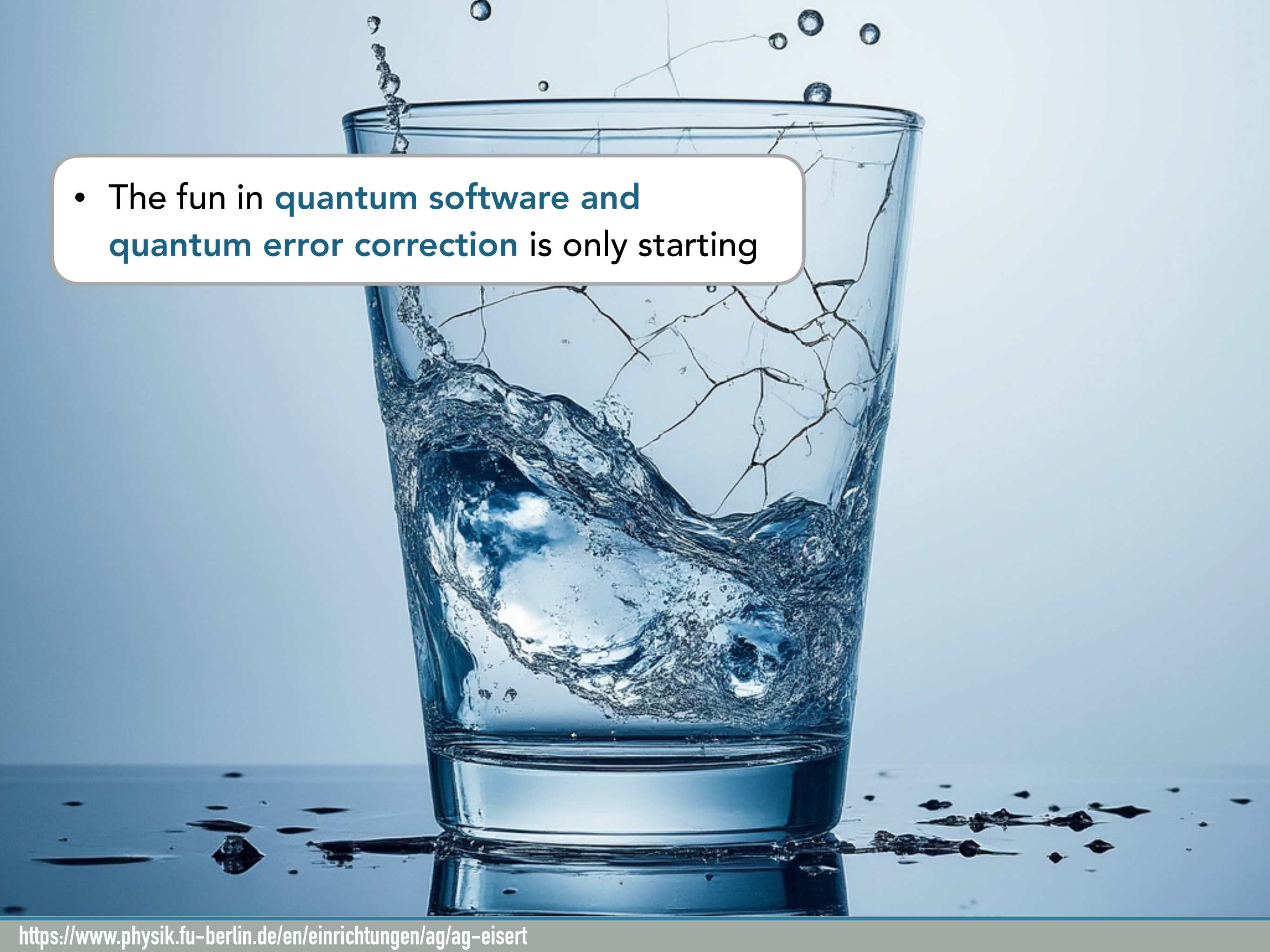
- Two qubit measurements only



de la Fuente, Townsend-Teague, Old, Rispler, Eisert, Mueller, PRX Quantum 6, 010360 (2025)

Derks, Townsend-Teague, Eisert, Kesselring, Higgott, Brown, arXiv:2505.07658 (2025)

Kesselring, Magdalena de la Fuente, Thomsen, Eisert, Bartlett, Brown, PRX Quantum 5, 010342 (2024)

- 
- A high-speed photograph of a glass of water with a large, dynamic splash. The water is splashing upwards and outwards, creating a complex, turbulent shape. The surface of the water is covered in a network of fine, dark cracks, resembling a spiderweb. Several water droplets are suspended in the air above the glass, and others are scattered on the surface below. The background is a solid, light blue color.
- The fun in **quantum software and quantum error correction** is only starting

- The fun in **quantum software and quantum error correction** is only starting

THANKS



Advanced
Grant



**POSTDOCS AND PHD
POSITIONS AVAILABLE**