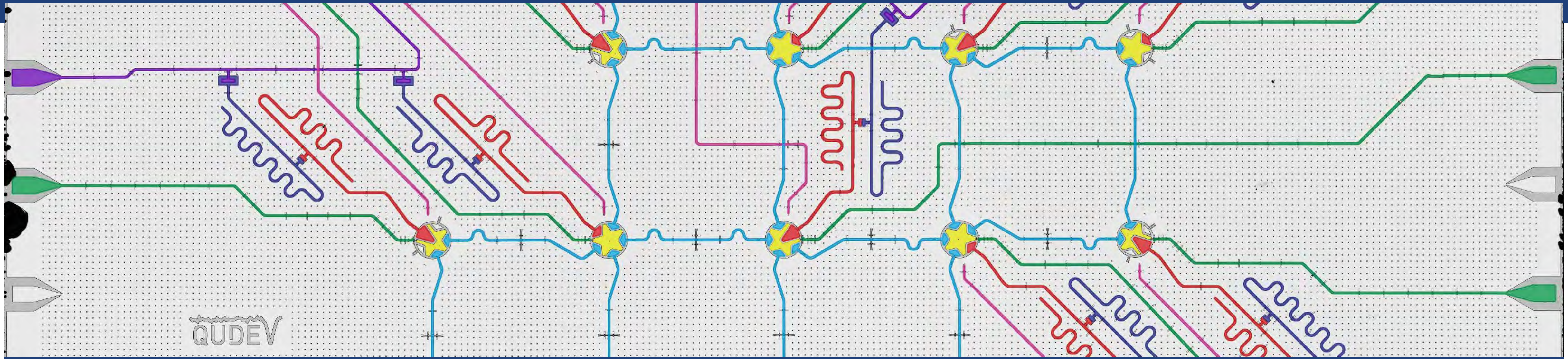
ETH zürich



Quantum Error Correction with Superconducting Circuits

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QSIT Quantum Science and Technology
National Centre of Competence in Research
FNSNF Swiss National Science Foundation
IARPA BE THE FUTURE
QuSurf

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www.qudev.ethz.ch

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J. Heinsoo (IQM)
L. Huthmacher (Cambridge)
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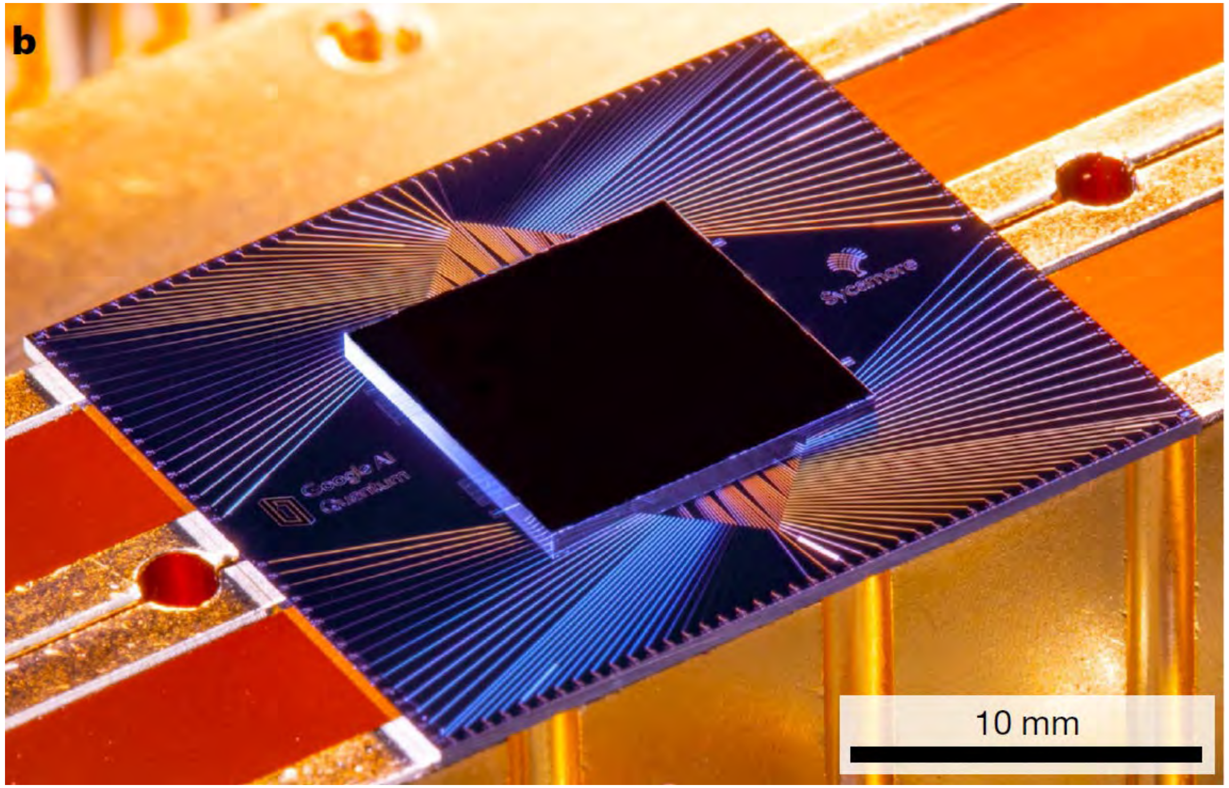
W. Wegscheider (ETH Zurich)

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich
FNSNF Swiss National Science Foundation
QSIT Quantum Science and Technology National Centre of Competence in Research
QED Circuit and Cavity Quantum Electrodynamics
erc
Seventh Framework Programme
SOLID
GEOMDISS
aqute
scaleQIT

Quantum Computational Advantage Experiment by Google

Main message

- Most complex quantum computing experiment with superconducting circuits to date (53 qubits)
- State-of-the-art gate fidelities.
- Milestone: Demonstrated advantage over conventional computers on one (not particularly useful) task



Challenges

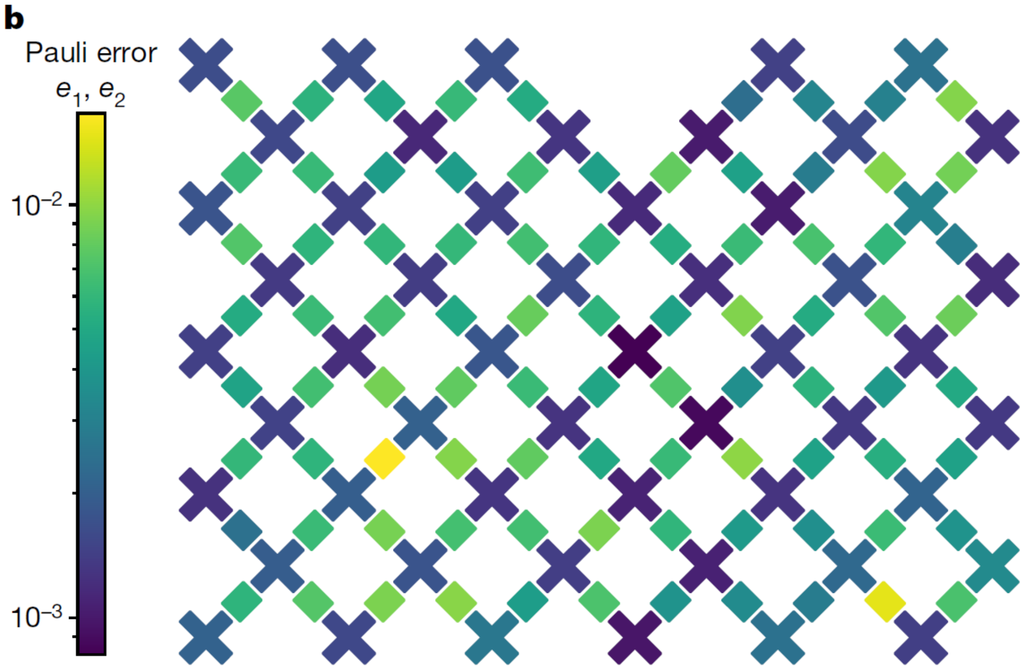
- Economically viable noisy intermediate scale quantum (NISQ) applications need more qubits
- Universal fault-tolerant quantum computation requires quantum error correction
- Major advances in technology are required

F. Arute, ..., J. M. Martinis *et al.*, *Nature* 574, 505 (2019)

Two of the Major Goals in Quantum Information Processing ...

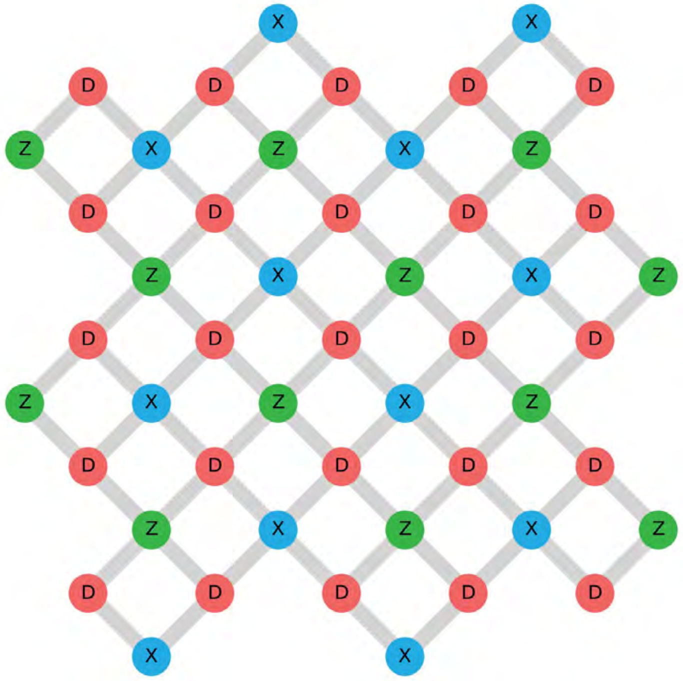
... with superconducting circuits

Noisy Intermediate Scale Quantum (NISQ) algorithms displaying a quantum advantage



F. Arute, ..., J. M. Martinis *et al.*, *Nature* **574**, 505 (2019)

Fault-tolerant, error-corrected, universal quantum information processor



Fowler *et al.*, *Phys. Rev. A* **86**, 032324 (2012)

The Challenge of Quantum Error Correction

Detect and correct two types of errors:

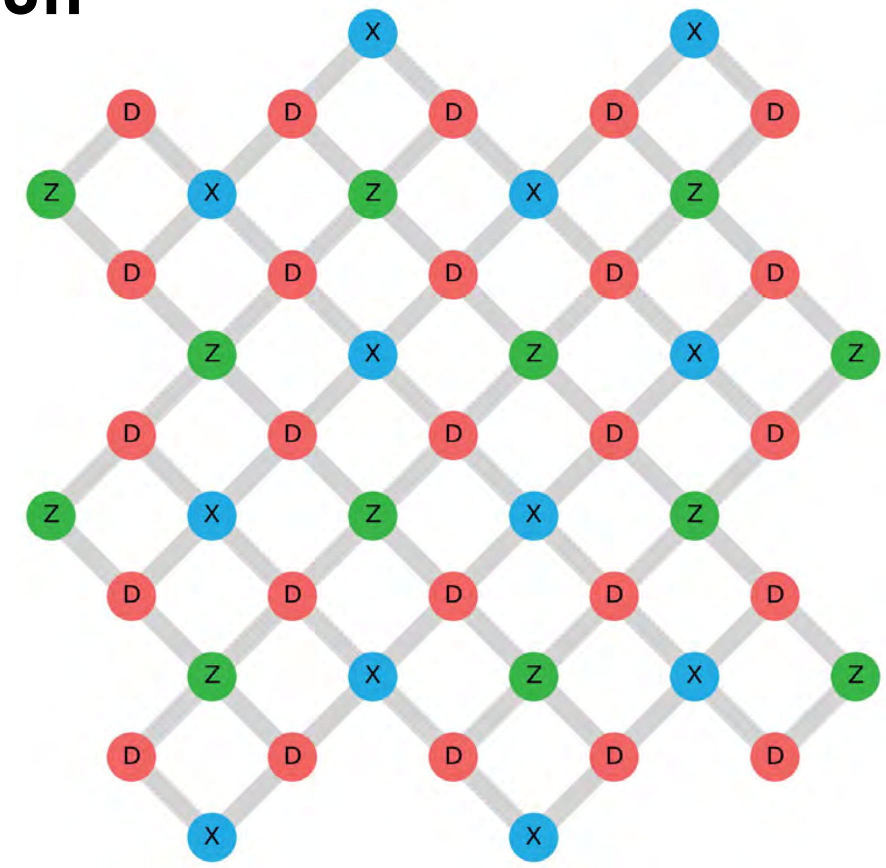
- Bit flips using Z-stabilizers
- Phase flips using X-stabilizers

Preserve stored quantum states while detecting and correcting errors:

- Measurements collapse quantum (superposition) states

Solution: Use encoding

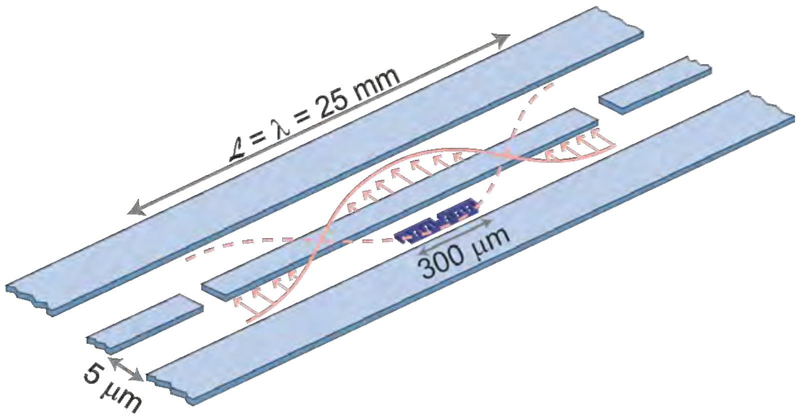
- Store **logical qubit** state $|\psi\rangle$ in a system of many **physical qubits**
- Make use of **symmetry properties (parity)** of logical qubit states
  - revealing errors …
  - … but not the encoded quantum state



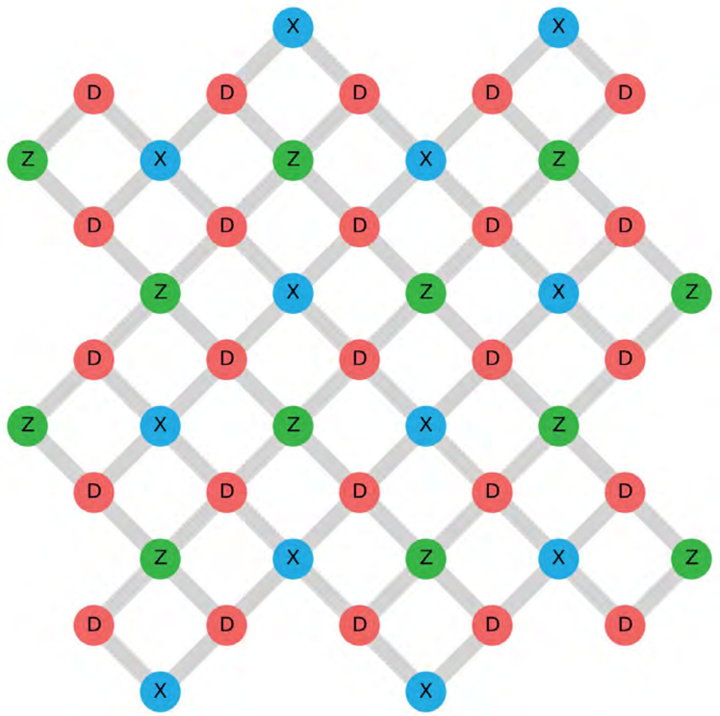
Kitaev, *Annals of Physics* **303**, 2 (2003),
Dennis et al., *Journ. of Math. Physics* **43**, 4452 (2002)
Raussendorff, Harrington, *Phys. Rev. Lett.* **98**, 190504 (2007)
Fowler *et al., Phys. Rev. A* **86**, 032324 (2012)

Content

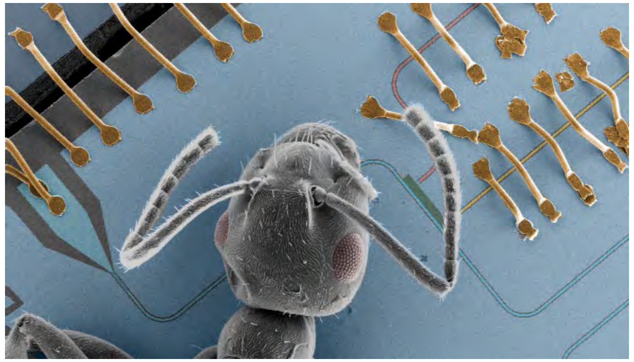
Mini-Introduction to Superconducting Qubits



Quantum Error Correction

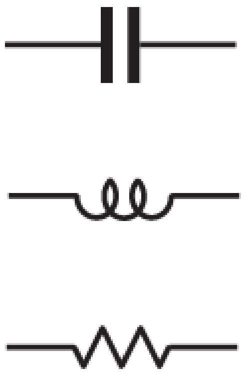


Future Challenges

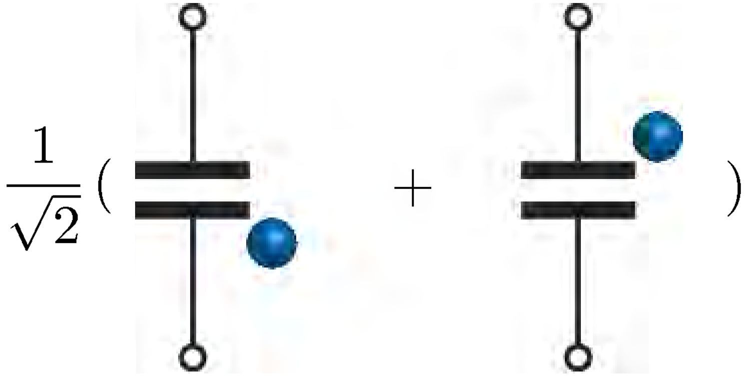


Quantum Electronic Circuits

basic circuit elements:



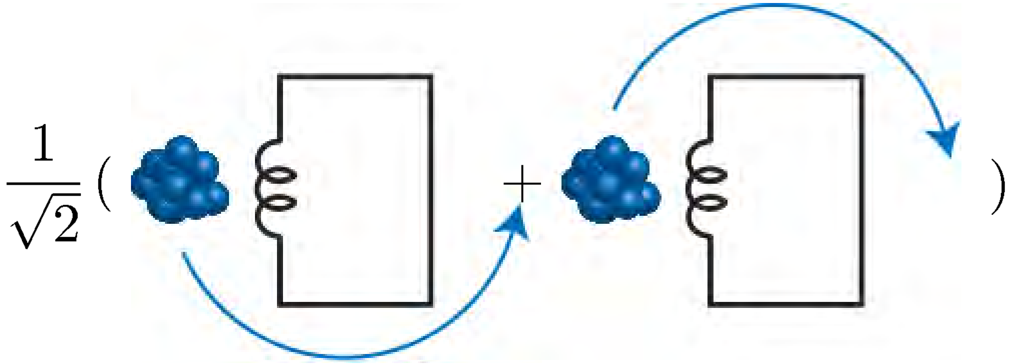
charge on a capacitor:



quantum superposition states of:

- charge Q
- flux ϕ

current or magnetic flux in an inductor:

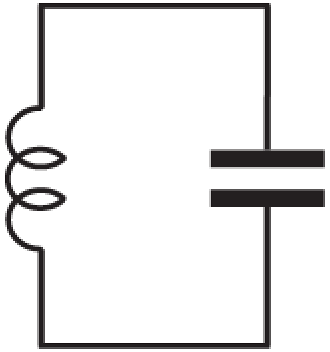


Q, ϕ are conjugate variables

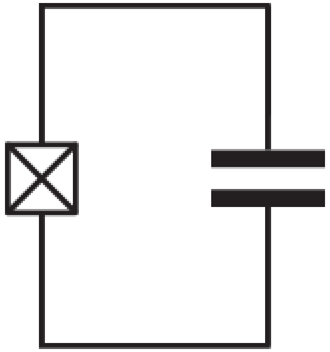
uncertainty relation $\Delta\phi\Delta Q > h$

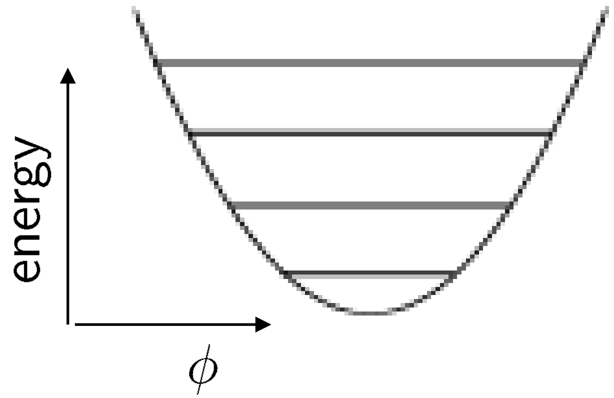
Linear vs. Nonlinear Superconducting Electronic Oscillators

LC resonator:

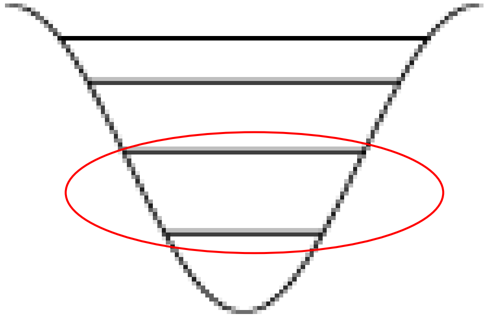


Josephson junction resonator:
Josephson junction = nonlinear inductor





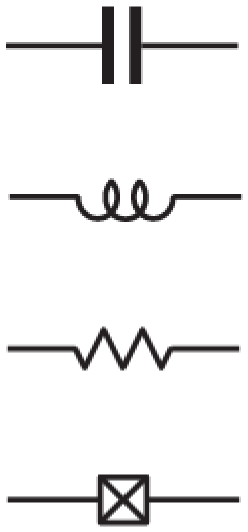
anharmonicity defines effective two-level system



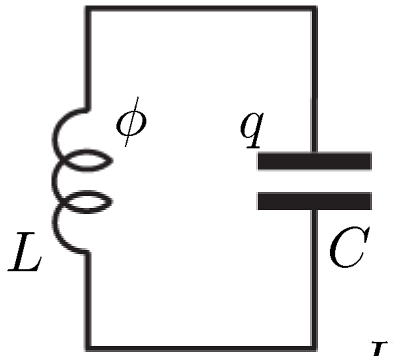
Circuit QED Review: A. Blais *et al.*, *Rev. Mod. Phys.* **93**, 025005 (2021)

Superconducting Circuits as Components for a Quantum Computer

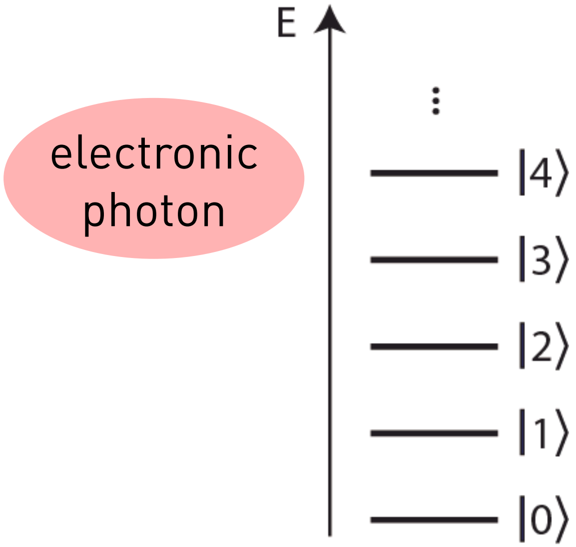
constructing quantum electronic circuits from basic circuit elements:



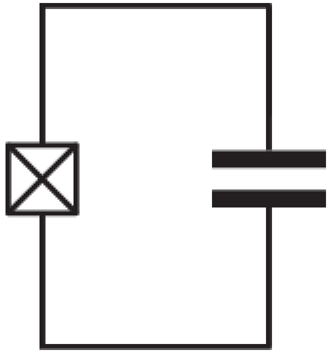
harmonic LC oscillator:



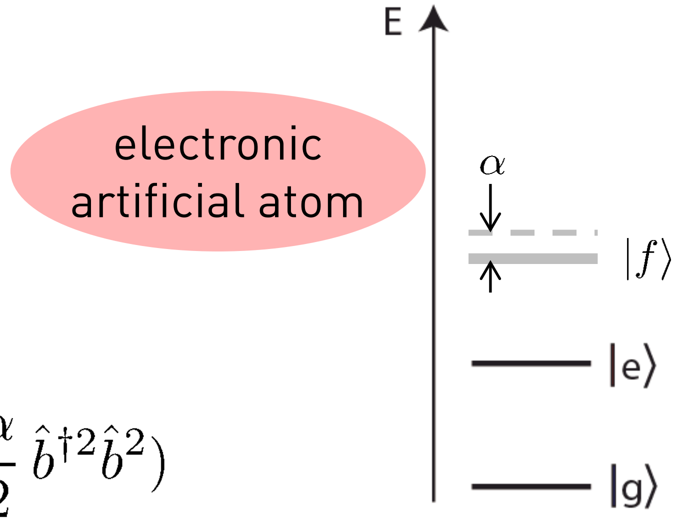
$$H = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2})$$



anharmonic oscillator:



$$H \approx \hbar(\omega_{ge}\,\hat{b}^\dagger\hat{b} - \frac{\alpha}{2}\,\hat{b}^{\dagger 2}\hat{b}^2)$$



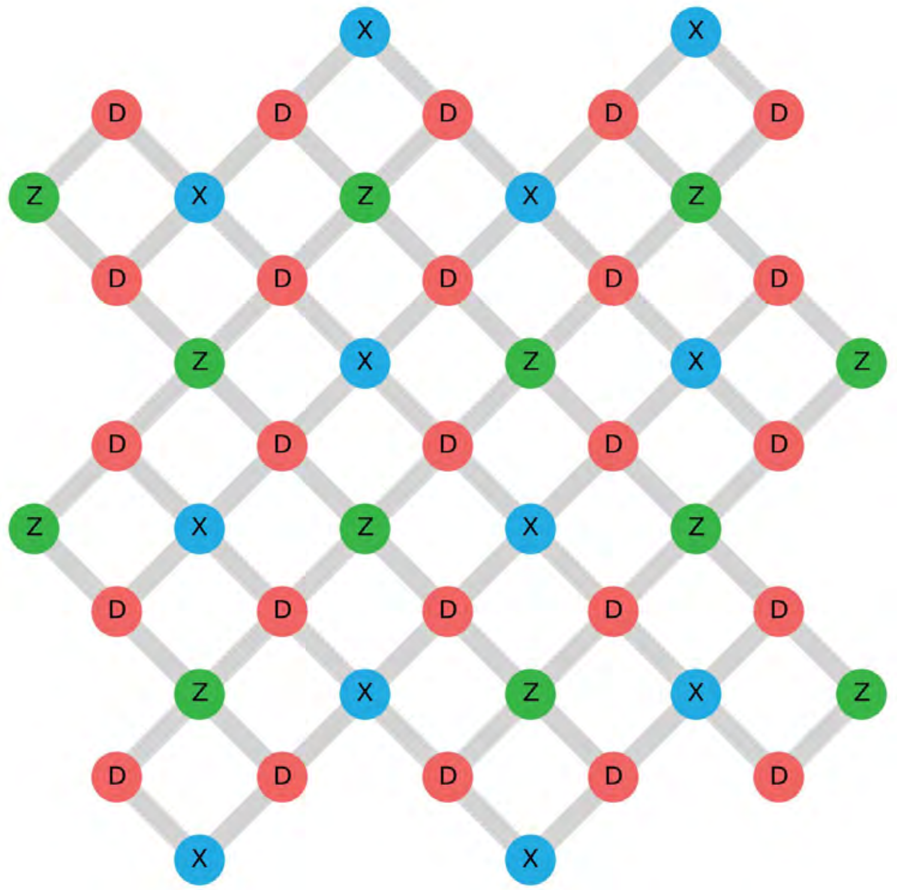
Josephson junction: a non-dissipative nonlinear element (inductor)

Circuit QED Review: A. Blais *et al.*, *Rev. Mod. Phys.* **93**, 025005 (2021)

Towards Fault-Tolerant Quantum Information Processing

Quantum error correction

- Encode quantum information in multiple physical data qubits
- Measure multi-qubit stabilizers (parity) using X- and Z-auxiliary qubits
- Correct errors based on parity (stabilizer) measurement outcomes



Fowler *et al., Phys. Rev. A* **86**, 032324 (2012)
Versluis *et al., Phys. Rev. Applied* **8**, 034021 (2017)

The Surface Code – Main Features

Two-dimensional architecture

- All operations realizable on a planar qubit lattice
- Topological code: only local operations needed for error correction process

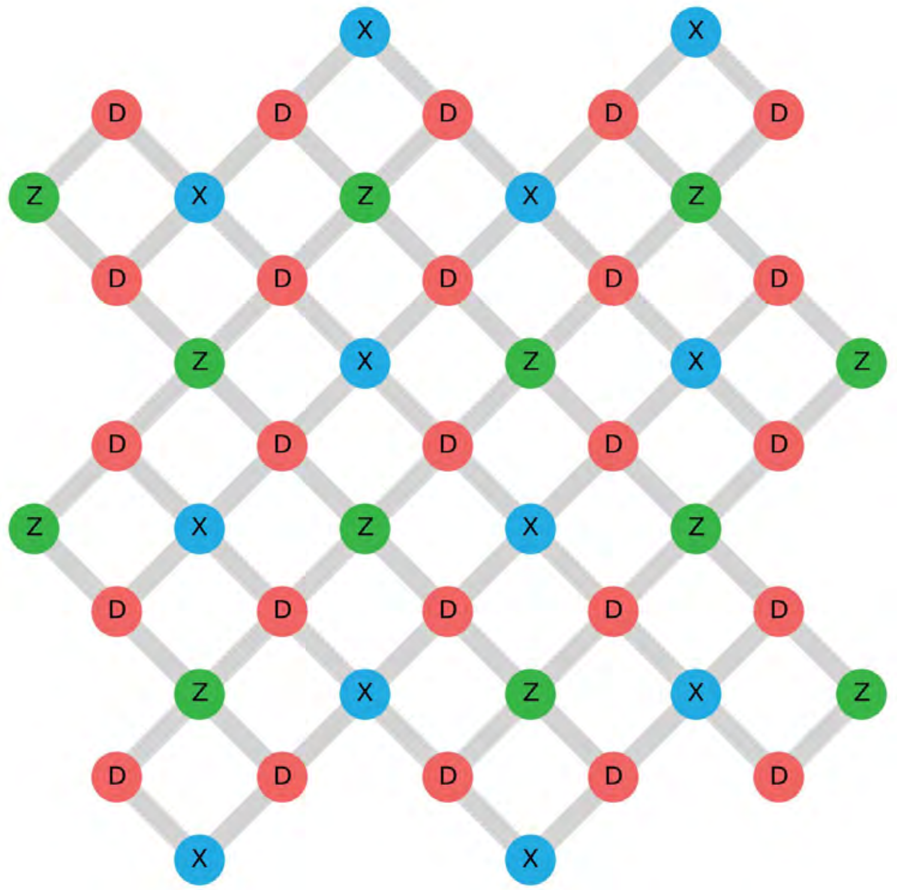
Large error threshold $\epsilon_{\mathrm{th}} \sim 1\ \%$

- Logical error rate $\epsilon_{\mathrm{L}} \propto \left(\epsilon_{\mathrm{phys}}/\epsilon_{\mathrm{th}}\right)^{(d+1)/2}$

  ϵ_{phys}: Physical error rate per step

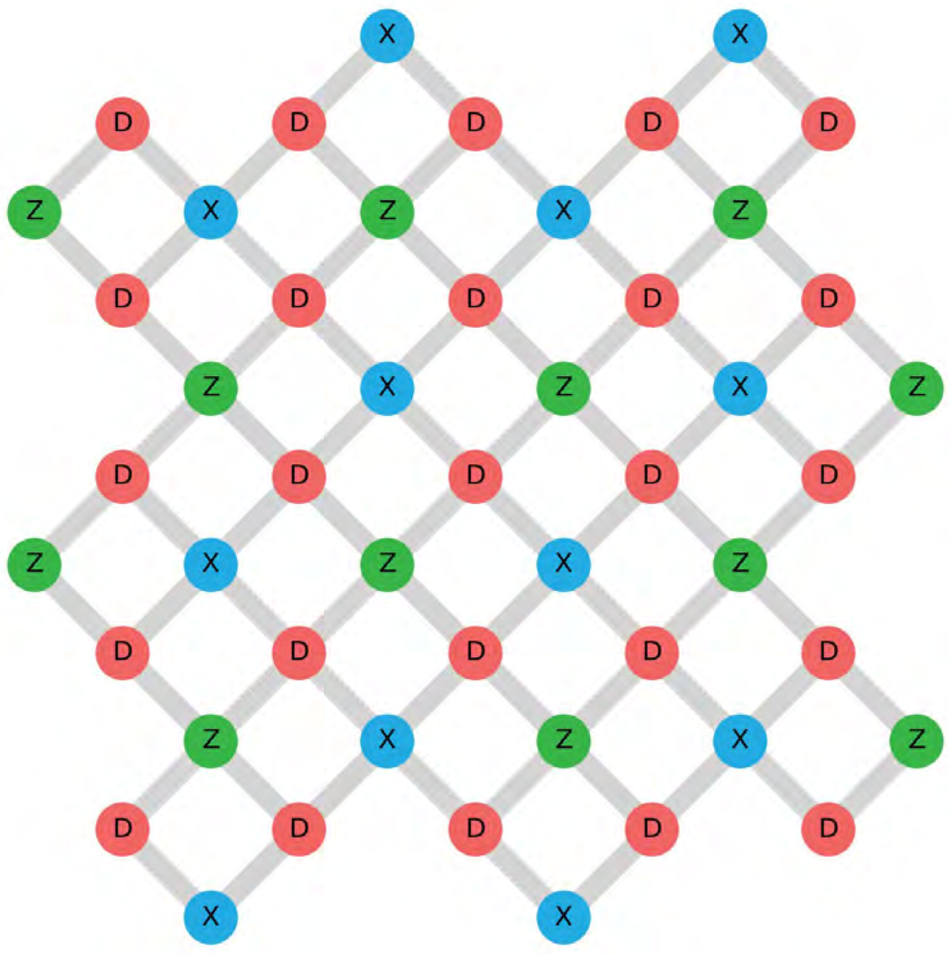
  ϵ_{th}: Threshold error rate

  d: Distance of the code

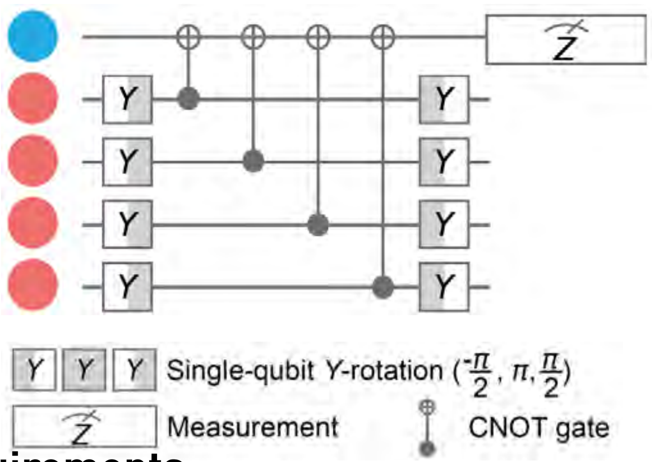


Kitaev, *Annals of Physics* **303**, 2 (2003),
Dennis et al., *Journ. of Math. Physics* **43**, 4452 (2002)
Raussendorff, Harrington, *Phys. Rev. Lett.* **98**, 190504 (2007)
Fowler *et al.*, *Phys. Rev. A* **86**, 032324 (2012)

Elements of the Surface Code



Features:
- Two-dimensional $(d \times d)$ grid of data qubits
- X-type and Z-type auxiliary qubits
- Auxiliary-qubit-assisted stabilizer measurement
  - $Z_1Z_2Z_3Z_4$ (or Z_1Z_2 at the edges)
  - $X_1X_2X_3X_4$ (or X_1X_2 at the edges)

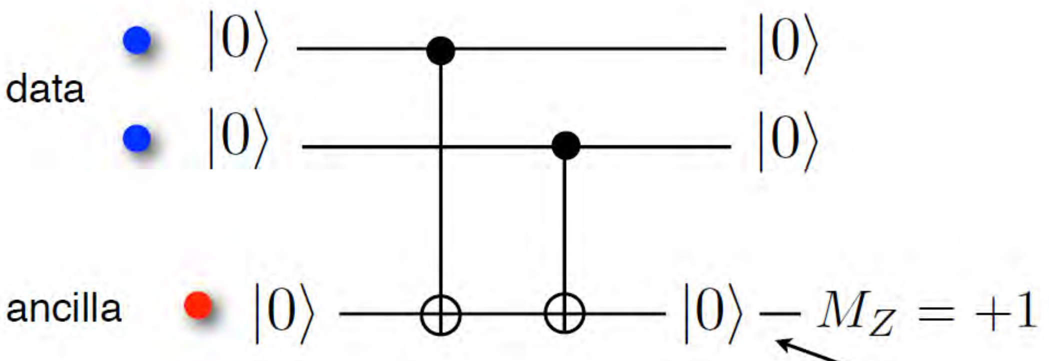


Requirements:
- High-fidelity entangling gates between data and ancilla qubits
- Fast high-fidelity measurements of the ancilla qubits
- Low readout crosstalk between ancilla and data qubits
- Ability to do repeated gates and mid-cycle measurements

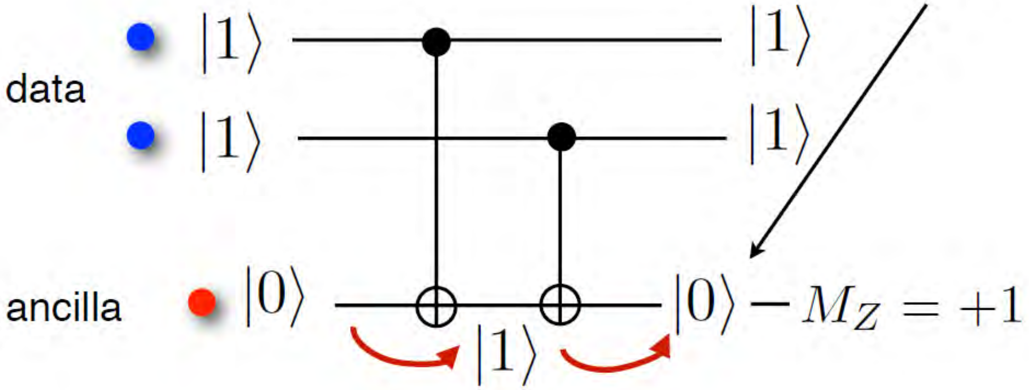
Fowler *et al., Phys. Rev. A* **86**, 032324 (2012)
Versluis *et al., Phys. Rev. Applied* **8**, 034021 (2017)

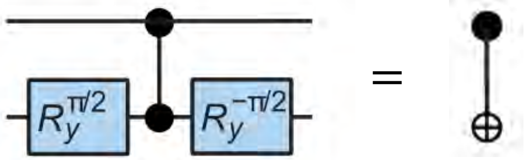
Parity Measurements

Goal: indirect (QND) measurement of two-qubit parity operator (stabiliser) $Z_1 Z_2$



ancilla ends in $|0\rangle$ if the **parity** of the data qubits is **even** (parallel orientation)





⇨ ancilla outcome

$$M_Z = +1$$

signals correlation

$$Z_1 Z_2 = +1$$

because

$$Z_1 Z_2 |00\rangle = +|00\rangle$$
$$Z_1 Z_2 |11\rangle = +|11\rangle$$

Markus Muller, RWTH Aachen

Error Detection in a Surface Code

- Distance-two code: detect 1 error, correct 0 errors
- Stabilizers for parity measurement:

$$\underbrace{\hat{X}_1\hat{X}_2\hat{X}_4\hat{X}_5,\qquad \hat{Z}_1\hat{Z}_4,\qquad \hat{Z}_2\hat{Z}_5}_{\text{Stabilizers commute, common eigenstates}}$$

- Logical eigenstates and their equal superpositions:

$$|0\rangle_L = \frac{1}{\sqrt{2}}(|0000\rangle + |1111\rangle)$$

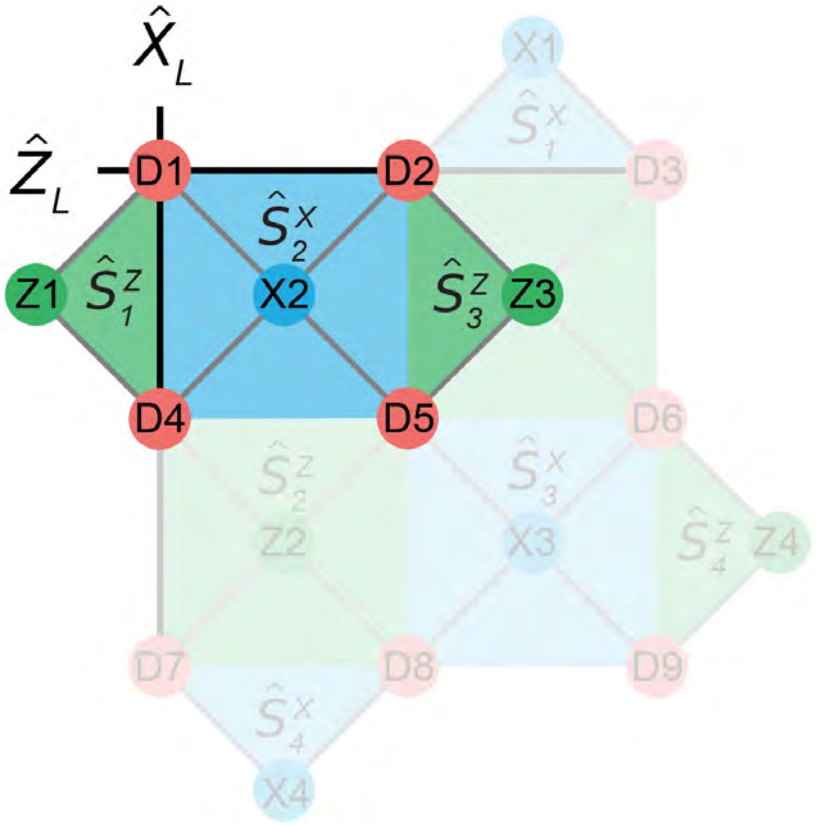
$$|1\rangle_L = \frac{1}{\sqrt{2}}(|0101\rangle + |1010\rangle)$$

$$|+\rangle_L = \frac{1}{2}(|0000\rangle + |1111\rangle + |0101\rangle + |1010\rangle)$$

$$|-\rangle_L = \frac{1}{2}(|0000\rangle + |1111\rangle - |0101\rangle - |1010\rangle)$$

- Logical operators:
  - $\hat{X}_L = \hat{X}_1\hat{X}_4$ or $\hat{X}_L = \hat{X}_2\hat{X}_5$
  - $\hat{Z}_L = \hat{Z}_1\hat{Z}_2$ or $\hat{Z}_L = \hat{Z}_4\hat{Z}_5$

  Anti-commute with each other and commute with stabilizers (as needed for logical operators in a stabilizer code)



Andersen et al., Nat. Phys. 16, 875 (2020)
Chen et al., Nature 595, 7867 (2021)
Marques et al., Nat. Phys. **18**, 80 (2022)

Distance-Three Surface Code in Brief

Four **Z** and four **X stabilizers** for parity measurement:

$\hat{S}^{Z1}$	$\hat{Z}_1\hat{Z}_4$
$\hat{S}^{Z2}$	$\hat{Z}_4\hat{Z}_5\hat{Z}_7\hat{Z}_8$
$\hat{S}^{Z3}$	$\hat{Z}_2\hat{Z}_3\hat{Z}_5\hat{Z}_6$
$\hat{S}^{Z4}$	$\hat{Z}_6\hat{Z}_9$

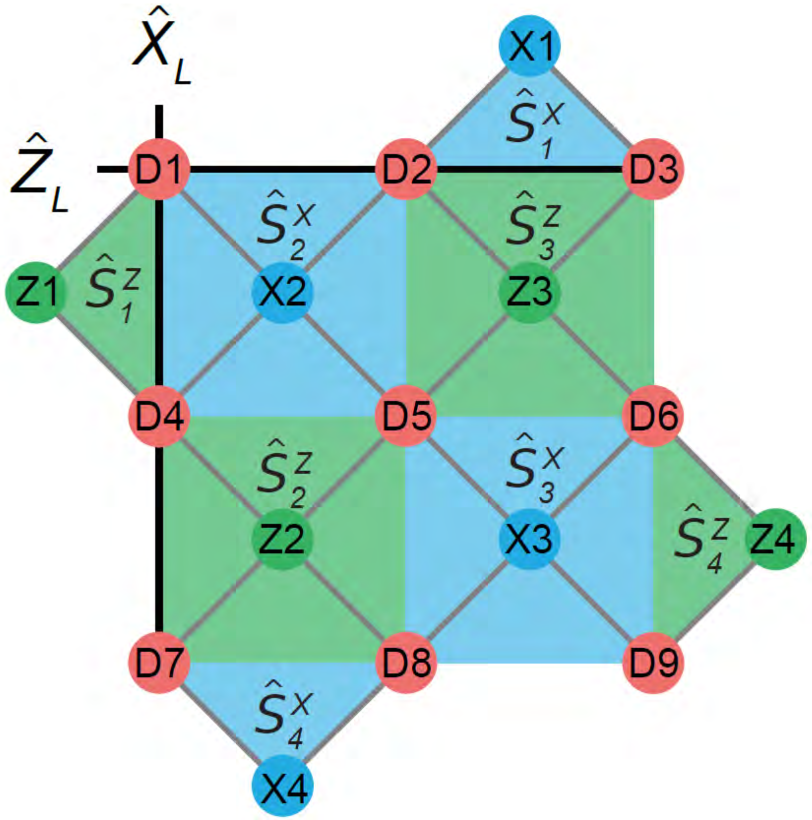
$\hat{S}^{X1}$	$\hat{X}_2\hat{X}_3$
$\hat{S}^{X2}$	$\hat{X}_1\hat{X}_2\hat{X}_4\hat{X}_5$
$\hat{S}^{X3}$	$\hat{X}_5\hat{X}_6\hat{X}_8\hat{X}_9$
$\hat{S}^{X4}$	$\hat{X}_7\hat{X}_8$

- Stabilizers and logical operators commute
- Example of $|0\rangle_L$ (16 basis states):

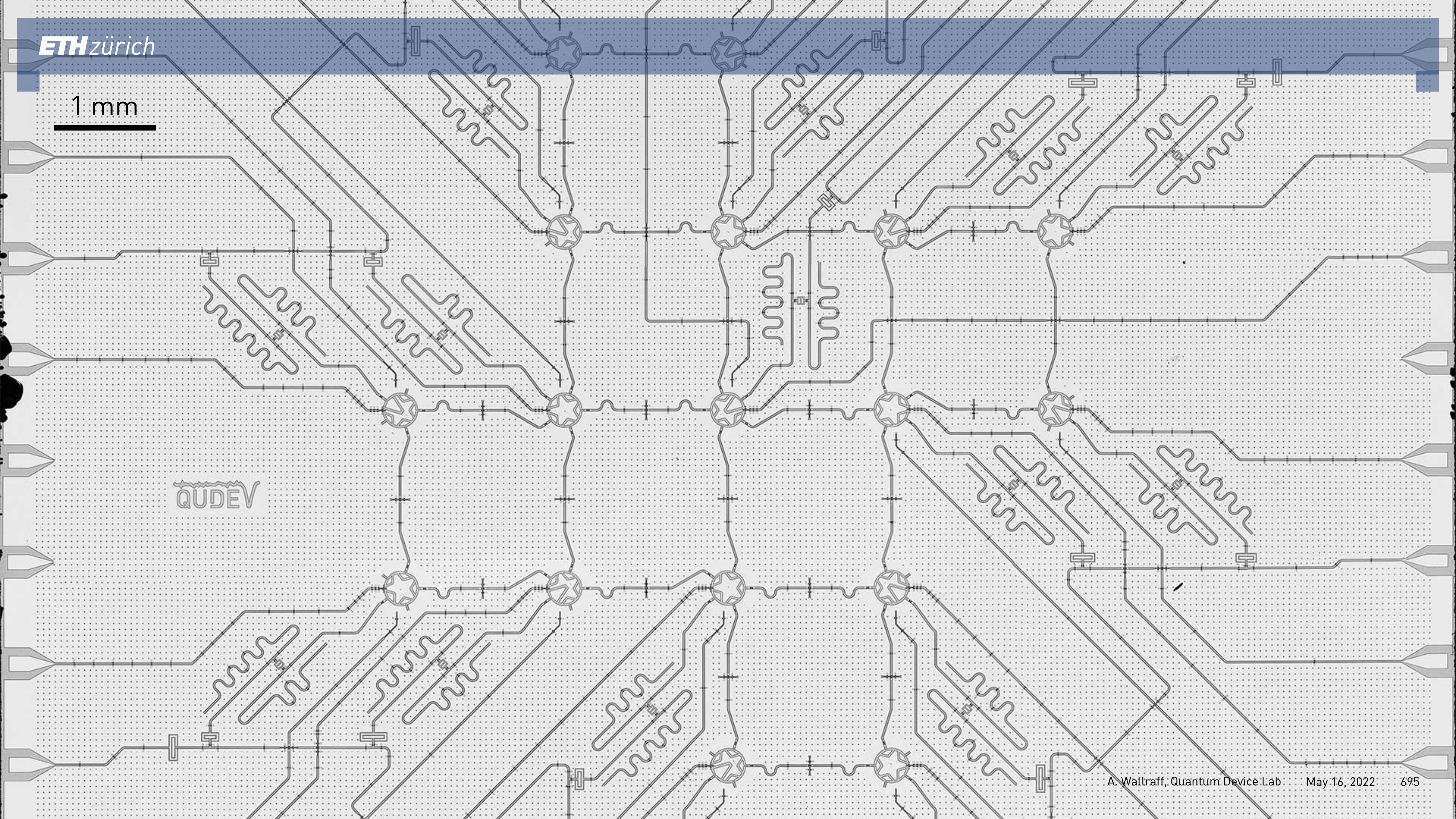
$$\tfrac{1}{4}\,(|000000000\rangle + |000000110\rangle + |000011011\rangle + |000011101\rangle$$
$$+|011000000\rangle + |011000110\rangle + |011011011\rangle + |011011101\rangle$$
$$+|101101011\rangle + |101101101\rangle + |101110000\rangle + |101110110\rangle$$
$$+|110101011\rangle + |110101101\rangle + |110110000\rangle + |110110110\rangle)$$

Logical operators:

$$\hat{Z}_L = \hat{Z}_1\hat{Z}_2\hat{Z}_3 \text{ or } \hat{Z}_4\hat{Z}_5\hat{Z}_6 \text{ or } \hat{Z}_7\hat{Z}_8\hat{Z}_9$$
$$\hat{X}_L = \hat{X}_1\hat{X}_4\hat{X}_7 \text{ or } \hat{X}_2\hat{X}_5\hat{X}_8 \text{ or } \hat{X}_3\hat{X}_6\hat{X}_9$$



Krinner, Lacroix et al., arXiv:2112.03708 (2021)
Zhao et al., arXiv:2112.13505 (2021)
Sundaresan et al., arXiv:2203.07205 (2022)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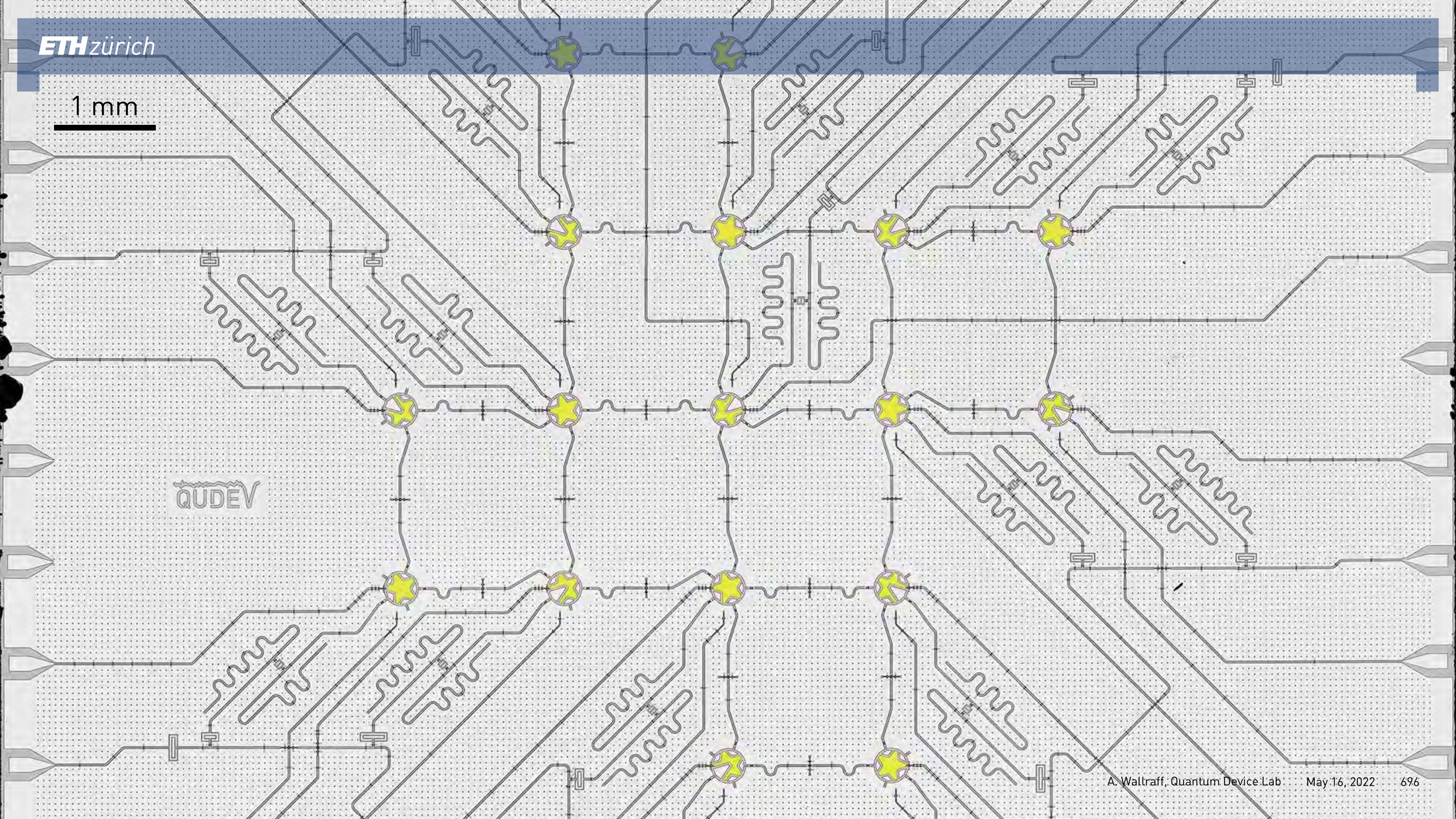
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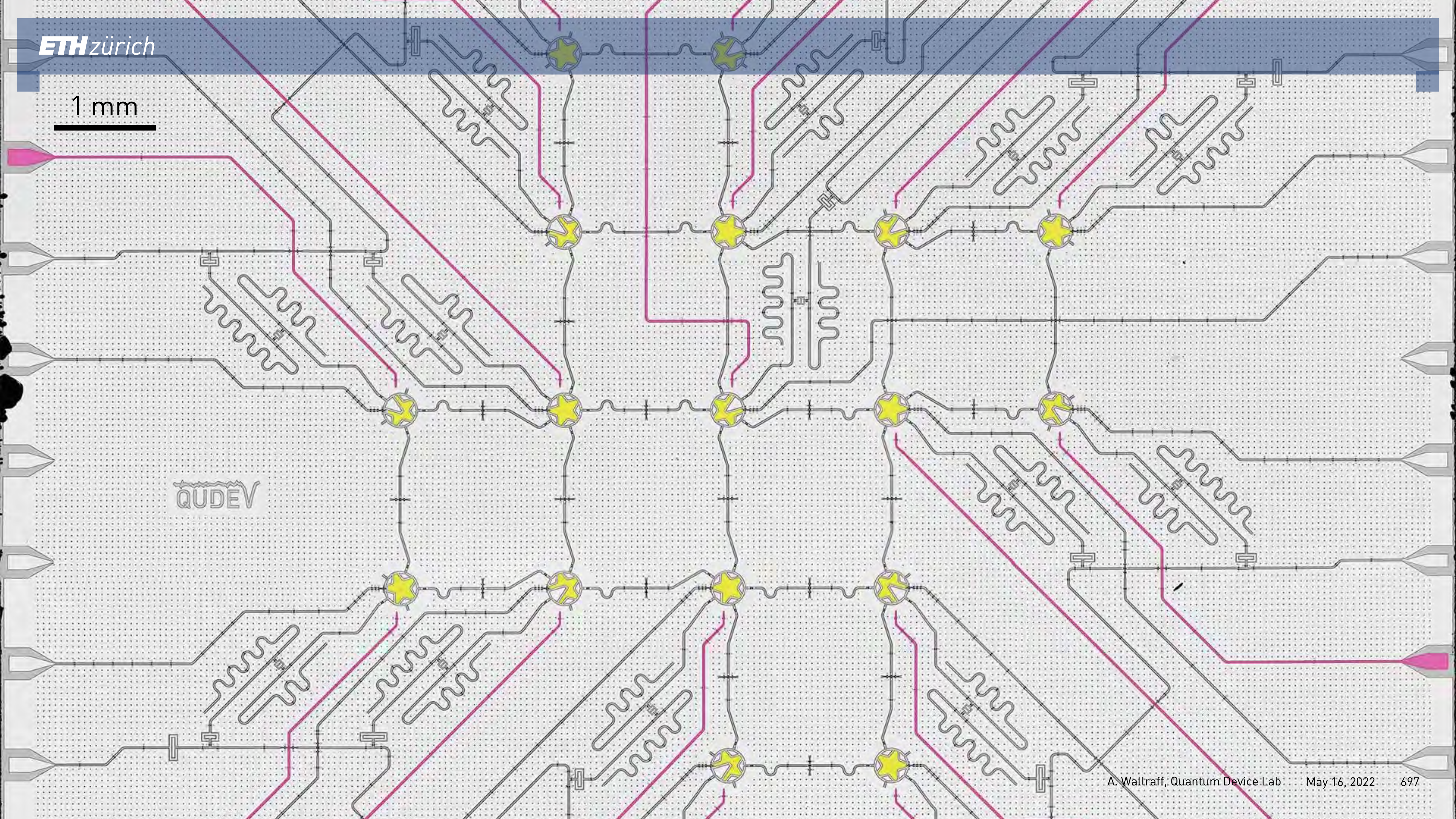
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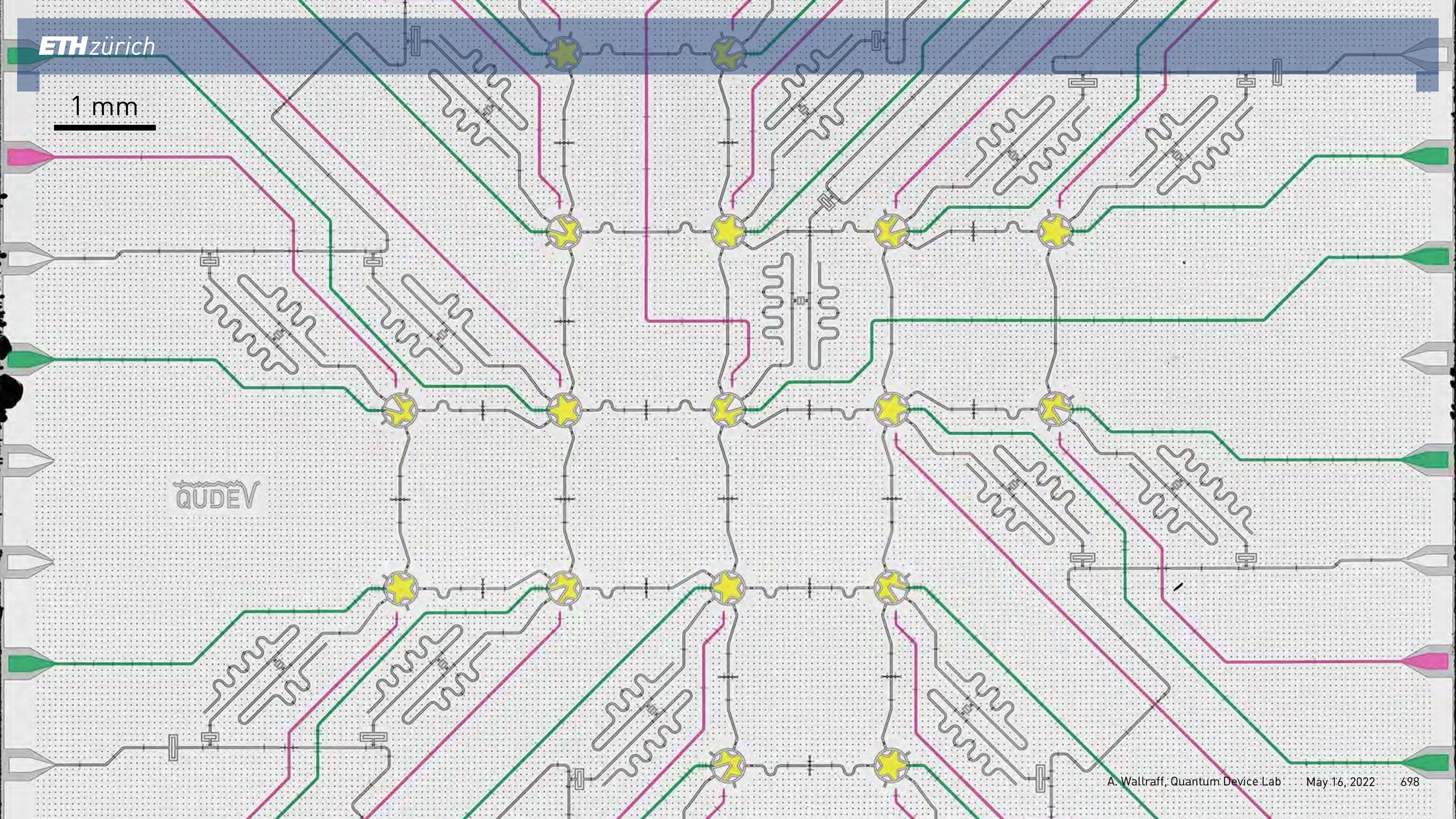
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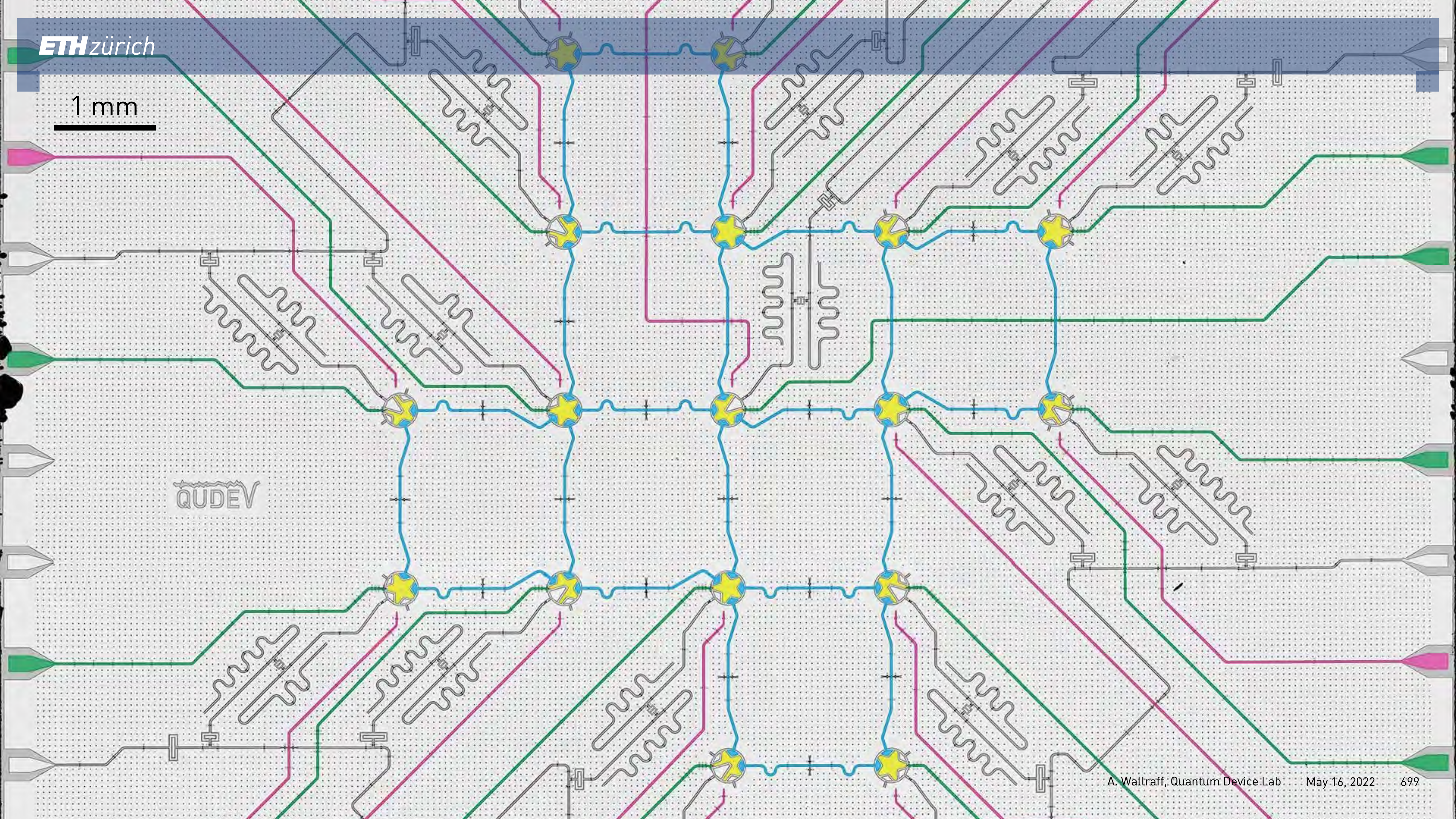
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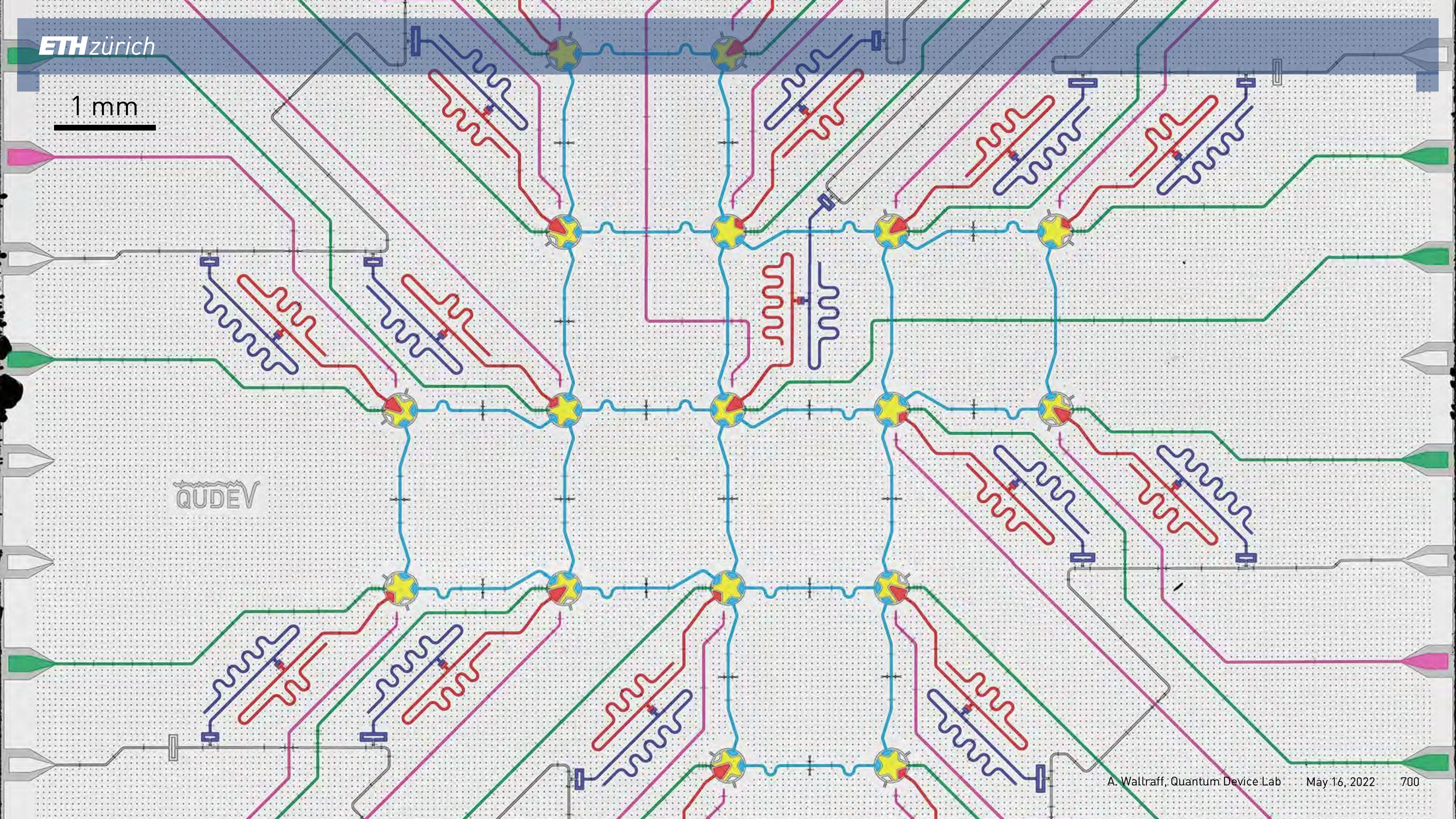
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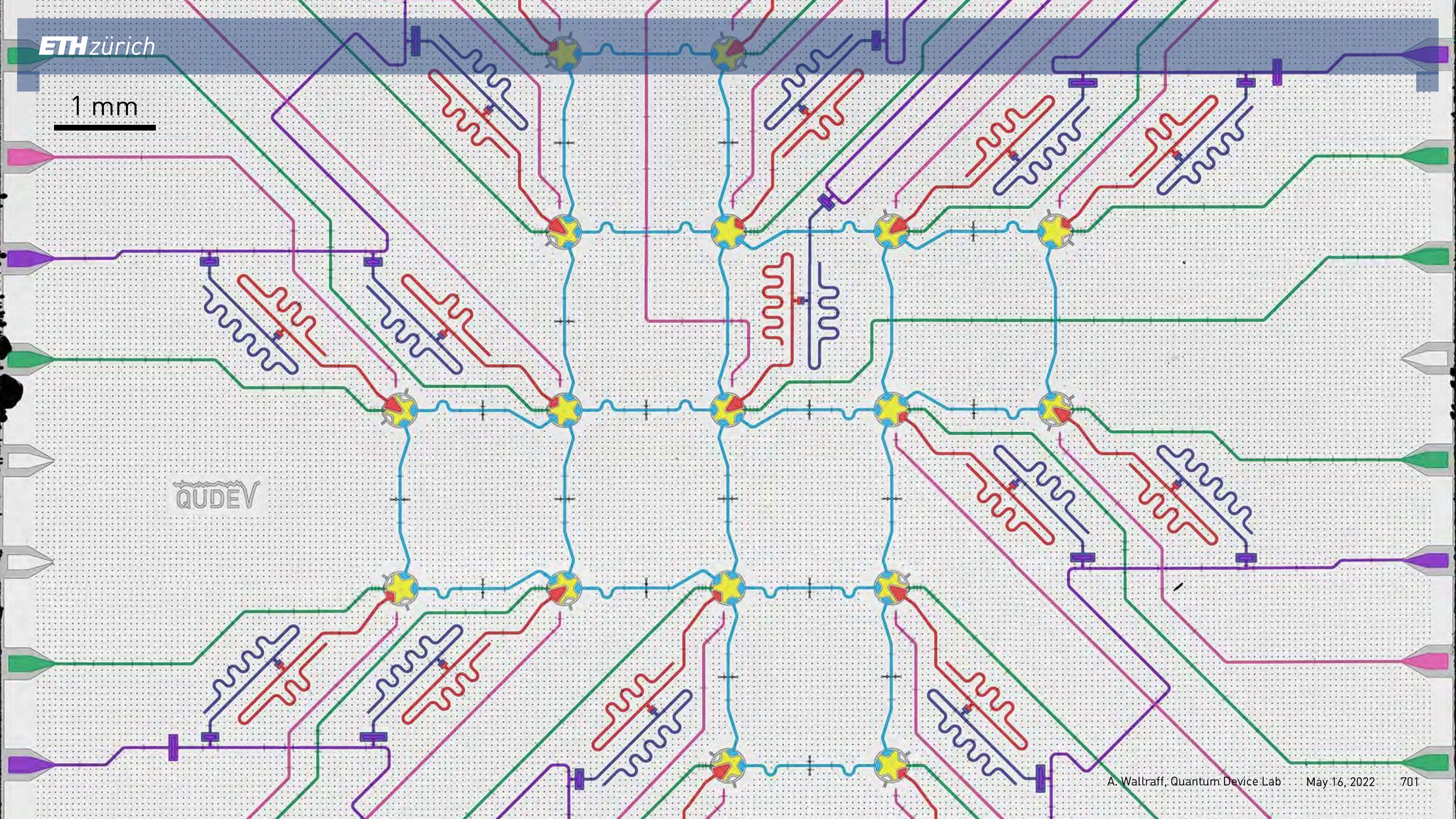
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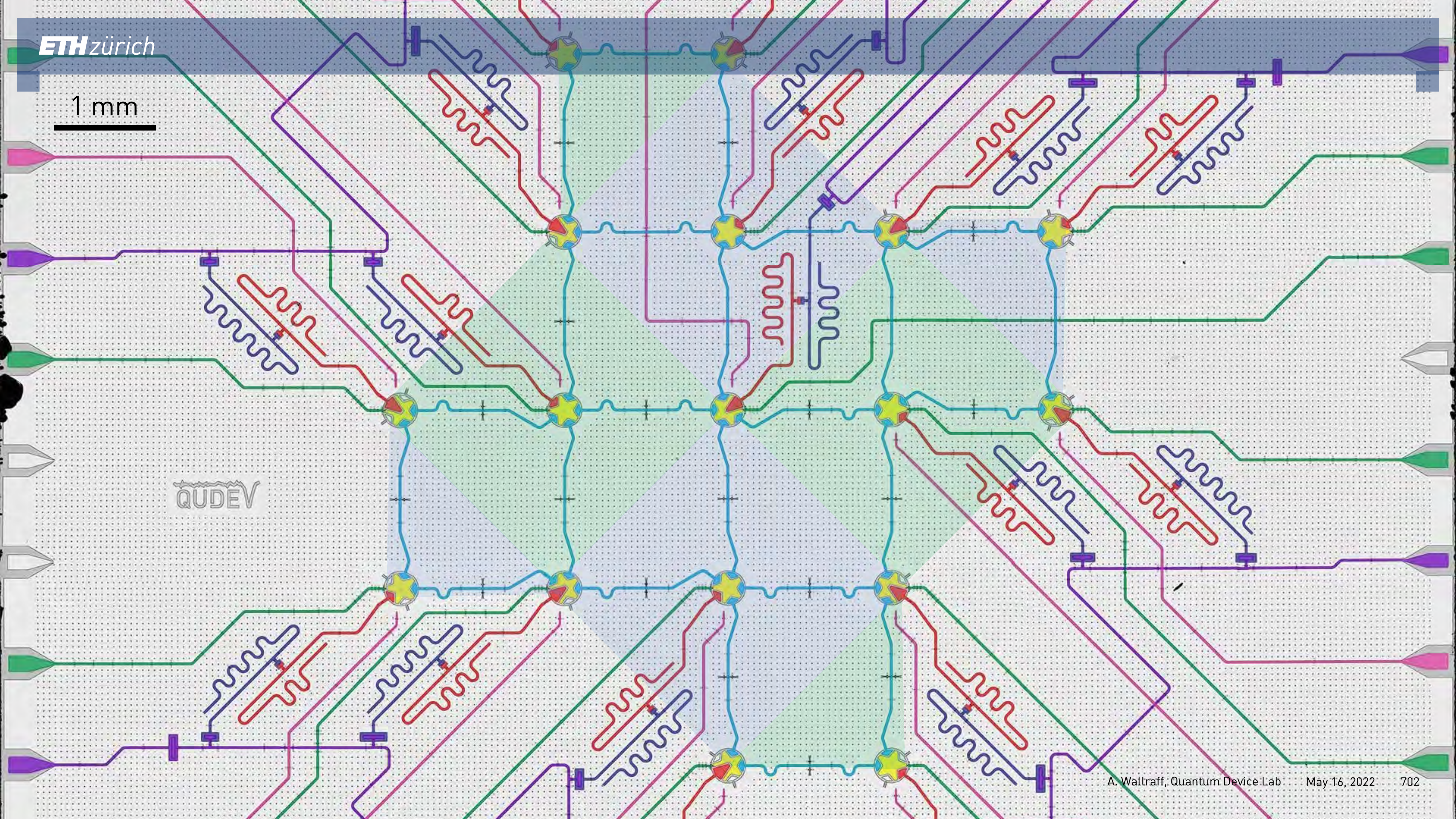
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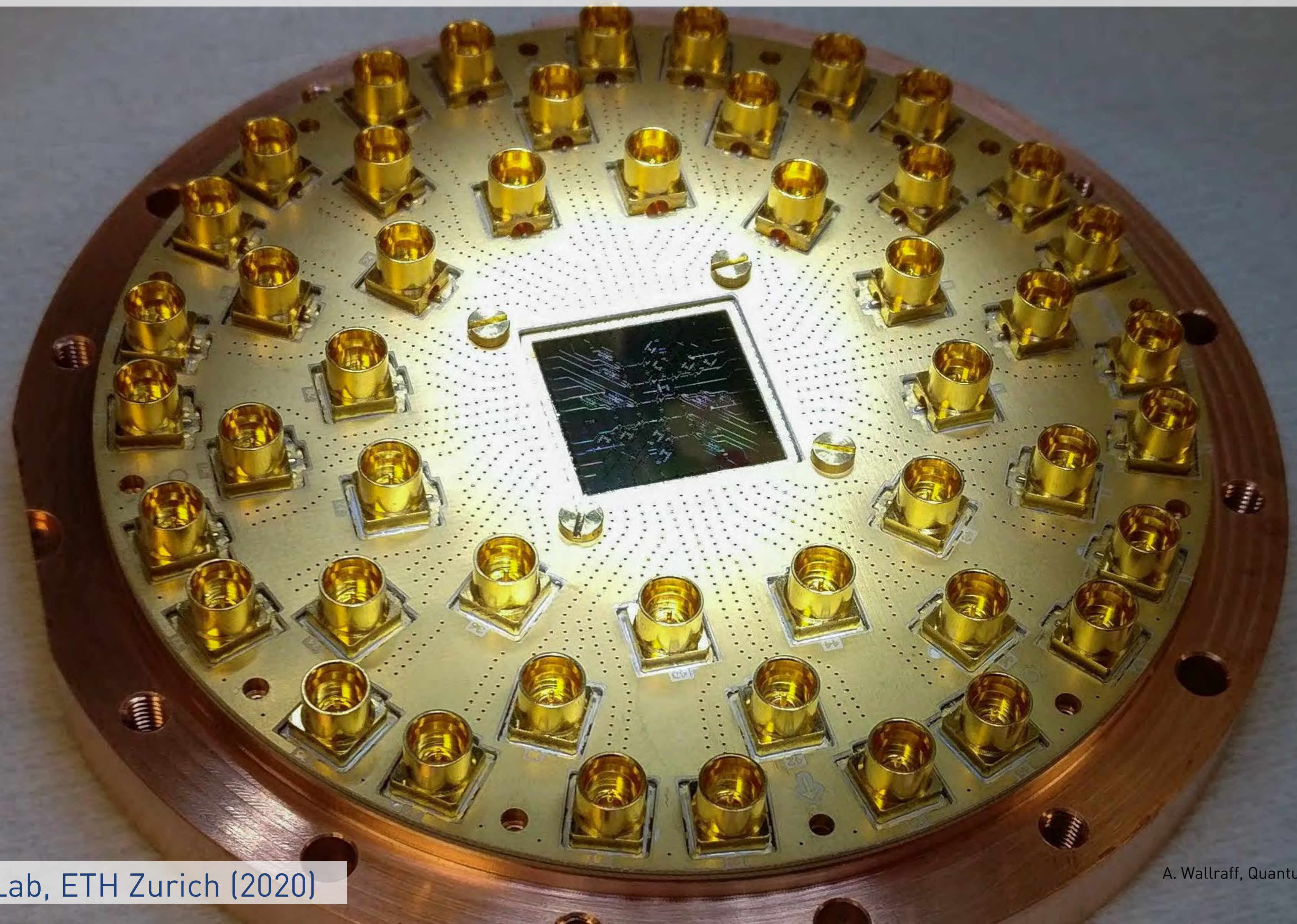
Distance-Three Surface-Code Device Mounted in Sample Holder



Quantum Device Lab, ETH Zurich (2020)

48-Port Sample Package (17-Qubit Device)

Quantum Device Lab,
ETH Zurich (2020)


QUDEV
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UHF QA
UHF QA
Zurich Instruments
PQSC
BlueFors CRYOGENICS


1 mm
PQSC
BLUE
FORS

Experimental Work toward Quantum Error Correction

Bit or phase-flip codes (only X or Z errors):

- NMR [Cory et al. Phys. Rev. Lett. 81, 2152 (1998)]
- Ions [Chiaverini et al. Nature 432, 602 (2004), Schindler et al. Science 322, 1059 (2011)]
- NV-Centers [Cramer et al. Nature Comm. 7, 11526 (2016)]
- Superconducting qubits [Riste et.al. Nature Comm. 6, 6983 (2015), Kelly et al. Nature 519, 66 (2015), Chen et al., Nat. 595, 7867 (2021)]

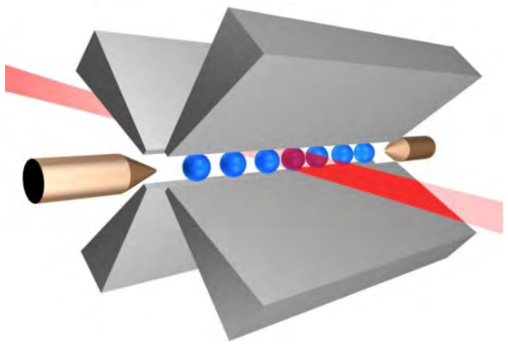
Quantum codes, single-cycle experiments:

- Five-qubit code [Knill et al., PRL 86, 5811 (2001), Abobeih et al., arXiv:2108.01646 (2021)]
- Bacon-Shor code [Egan et al., Nature 598, 281 (2021)]

Repeated error detection in the surface code

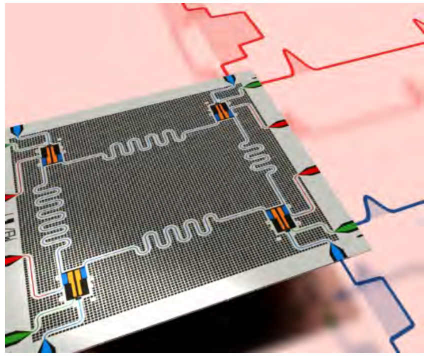
- Andersen et al., Nat. Phys. 16, 875 (2020)
- Chen et al., Nature 595, 7867 (2021)
- Marques et al., Nat. Phys. **18**, 80 (2022)

Trapped ions



e.g. Blatt & Roos, Nat. Phys. 8, 277 (2012)

Supercond. circuits



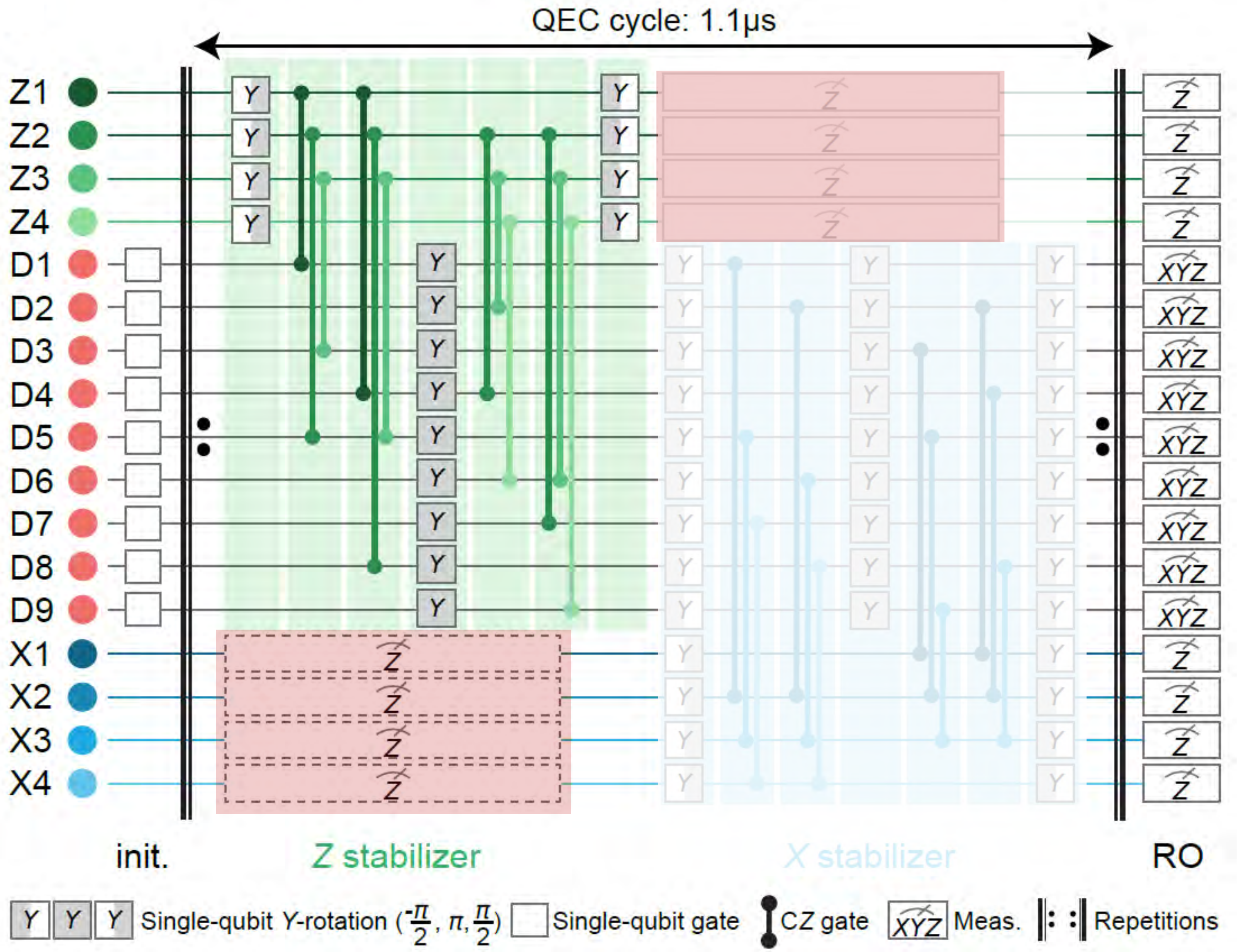
Picture: Y. Salathé
Review: e.g. Krantz et al., Appl. Phys. Rev. 6, 021318 (2019)

Repeated quantum error correction

- Color code (trapped ions) Ryan-Anderson et al., PRX 11, 041058 (2021)
- Distance-3 surface code (s.c.) Krinner, Lacroix et al., arXiv:2112.03708 (2021) Zhao et al., arXiv:2112.13505 (2021)
- Distance-3 heavy-hexagon code (s.c.) Sundaresan et al., arXiv:2203.07205 (2022)

The Surface Code Cycle

- All four $\hat{S}^{Zi}$ measured in parallel
- All four $\hat{S}^{Xi}$ measured in parallel
- Pipelining: Read out one stabilizer type while running gates of the other.
- For logical state preparation of $|0\rangle_L, |1\rangle_L$ and $|\pm\rangle_L = (|0\rangle_L \pm |1\rangle_L)/\sqrt{2}$ we execute a single cycle.
- For state preservation we repeat the cycle n times.
  - Cycle duration: 1.1 µs
  - Leakage detection and rejection executed in every cycle



Versluis et al., *PR Applied* **8**, 034021 (2017)

S. Krinner, N. Lacroix *et al., arXiv:2112.03708* (2021)

Logical Error Probability and Logical Error per Cycle

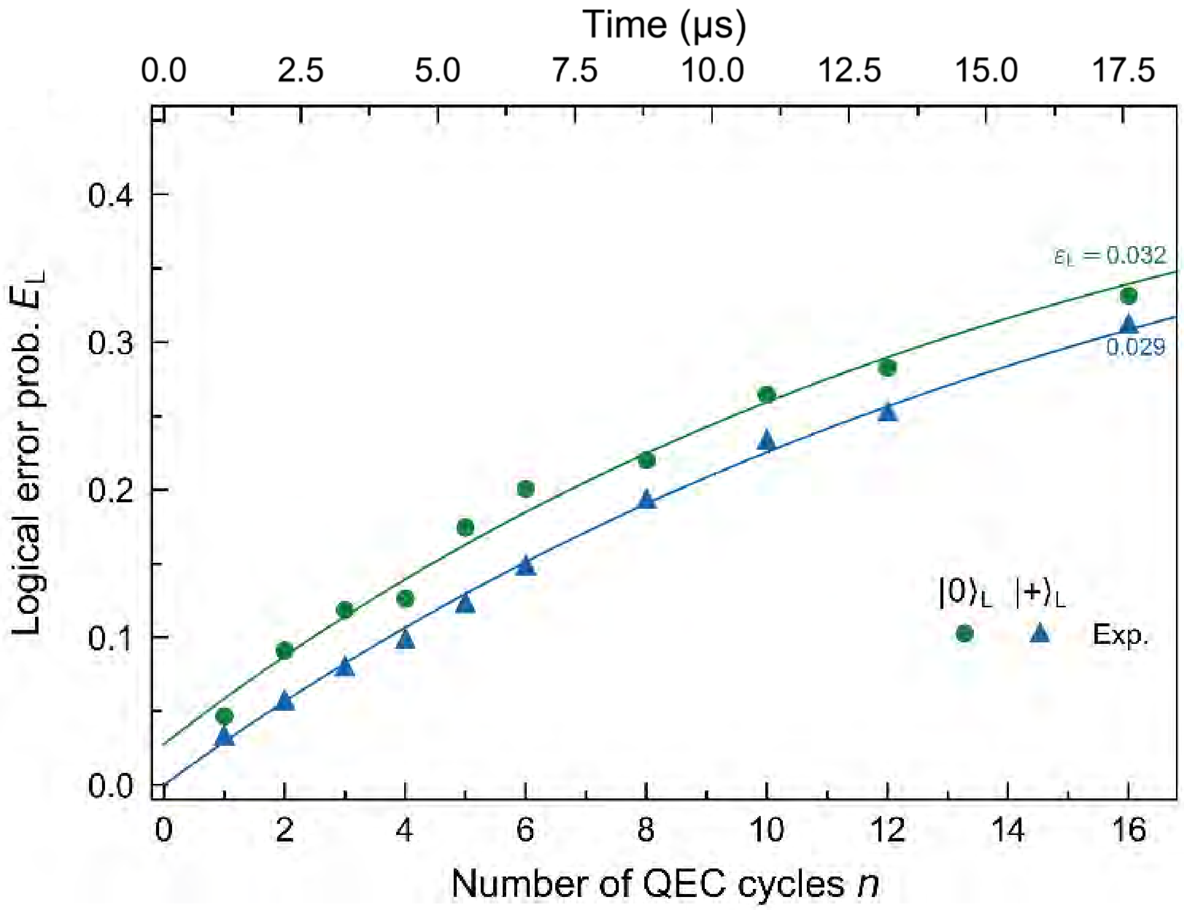
Logical error probability:

- $E_L = (1 - \langle \hat{Z}_L \rangle)/2$ for eigenstates of $\hat{Z}_L$
- $E_L = (1 - \langle \hat{X}_L \rangle)/2$ for eigenstates of $\hat{X}_L$

Logical error per cycle:

- Extracted from fit to $E_L(n)$ or from $T_{1/2,L}$:

  $\epsilon_L = \frac{1}{2}\left[1 - \exp(-t_c/T_{1/2,L})\right] \approx t_c/2T_{1/2,L}$
- $\epsilon_L \sim 0.03$

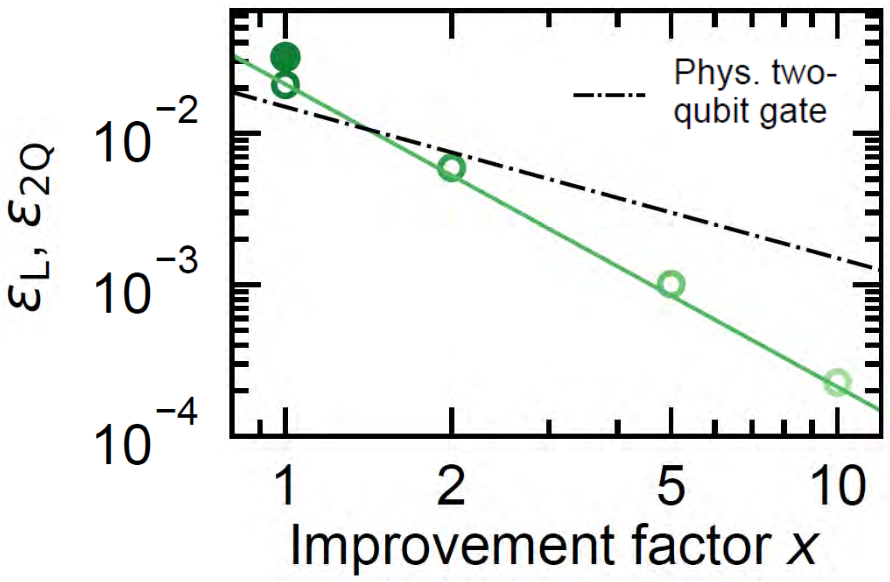


S. Krinner, N. Lacroix *et al., arXiv:2112.03708* (2021)

Performance Assessment and Projection

Two-qubit-gate break-even

- Compare $\epsilon_{\mathrm{L}} = 0.03$ to dominant physical error
  - Two-qubit gate error $\epsilon_{2\mathrm{Q}} = 0.015$
  - Logical two-qubit gate errori expected to be dominated by ϵ_{L}
- Used simulations to project performance with physical error rates reduced by factor x
  - $\epsilon_{\mathrm{L}} \propto 1/x^2$
  - Break-even within reach



Error threshold

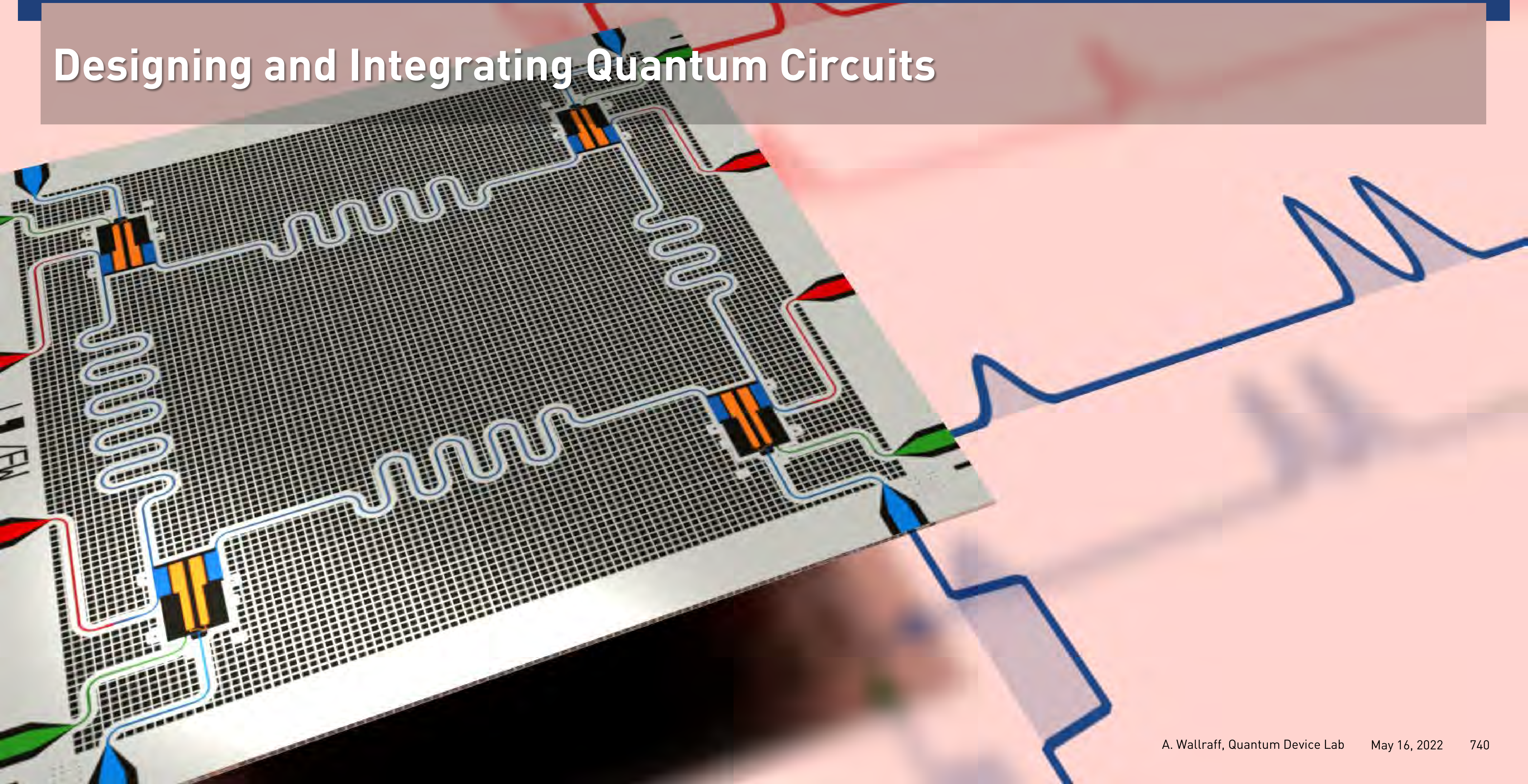
$\epsilon_{\mathrm{L}} \sim 0.03$ comparable to predicted logical error per cycle at error threshold

Fowler *et al.*, *Phys. Rev. A* **86**, 032324 (2012)

Stephens, *Phys. Rev. A* **89**, 022321 (2014).

S. Krinner, N. Lacroix *et al.*, *arXiv:2112.03708* (2021)

Designing and Integrating Quantum Circuits

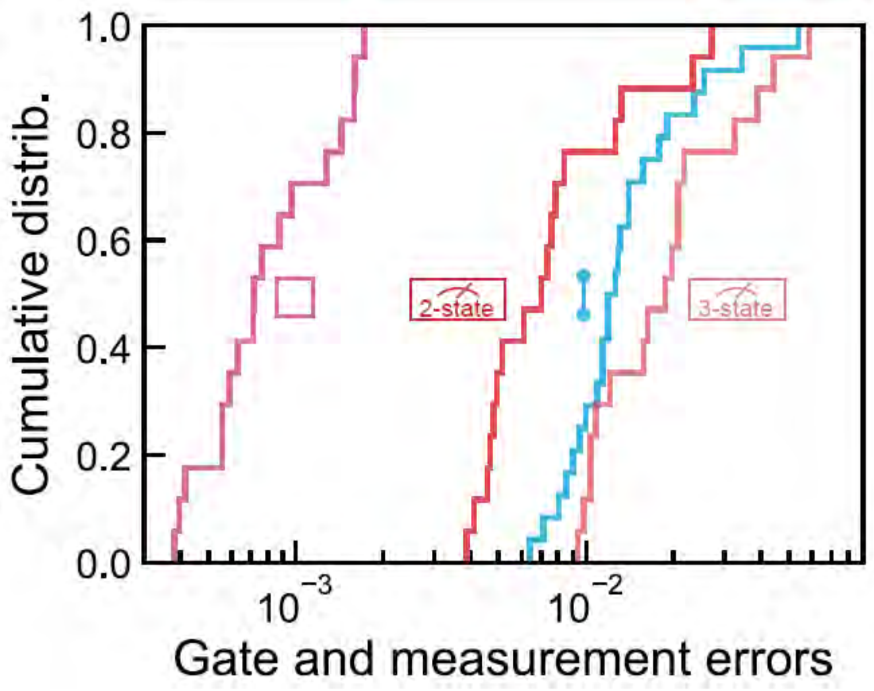


Selecting Materials

ETH zürich

Developing Processes

Device Performance



Averaged qubit coherence

- Energy relaxation time $T_1 \sim 33$ μs
- Ramsey decay time $T_2^* \sim 38$ μs

Single-qubit gates

- Mean gate error of 0.9(4) 10^{-3}
- Duration of 40 ns

Two-qubit gates

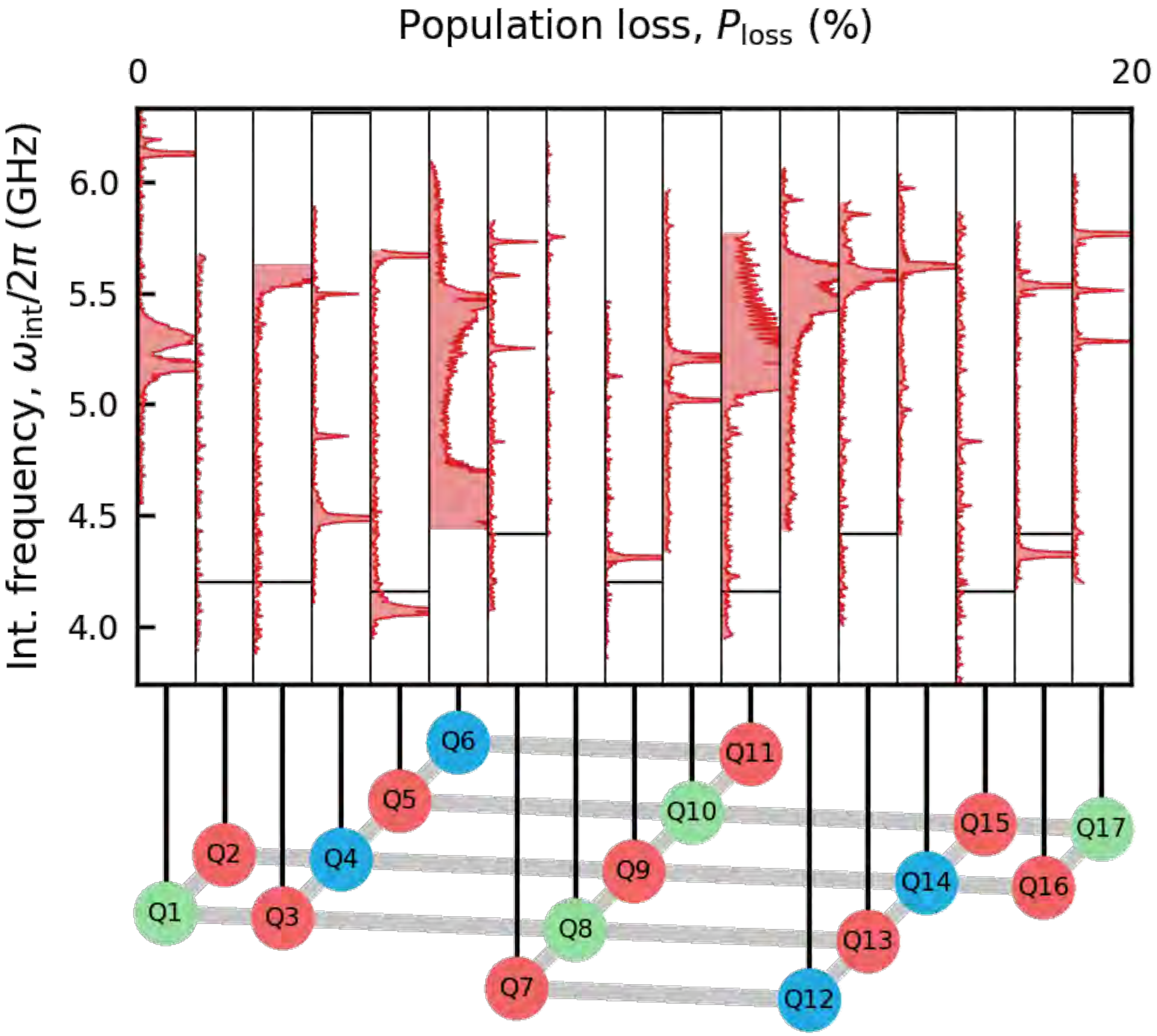
- Mean gate error of 15(10) 10^{-3}
- Mean duration of 98(7) ns (including buffers)

Readout:

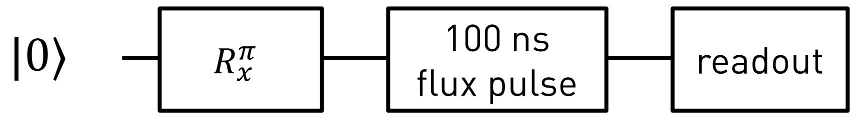
- Mean two-state assignment error: 9(7) 10^{-3} and three-state assignment error: 22(14) 10^{-3}
- Duration: 300 ns (aux.) to 400 ns (data)

S. Krinner, N. Lacroix *et al.*, *arXiv:2112.03708* (2021)

Microscopic Defect Modes



Experiment:



- Sweep amplitude of flux pulse

Results:

- Most qubits have high loss at discrete frequencies
- Linewidths of 10-s MHz
- No strong correlations between qubits

Current understanding

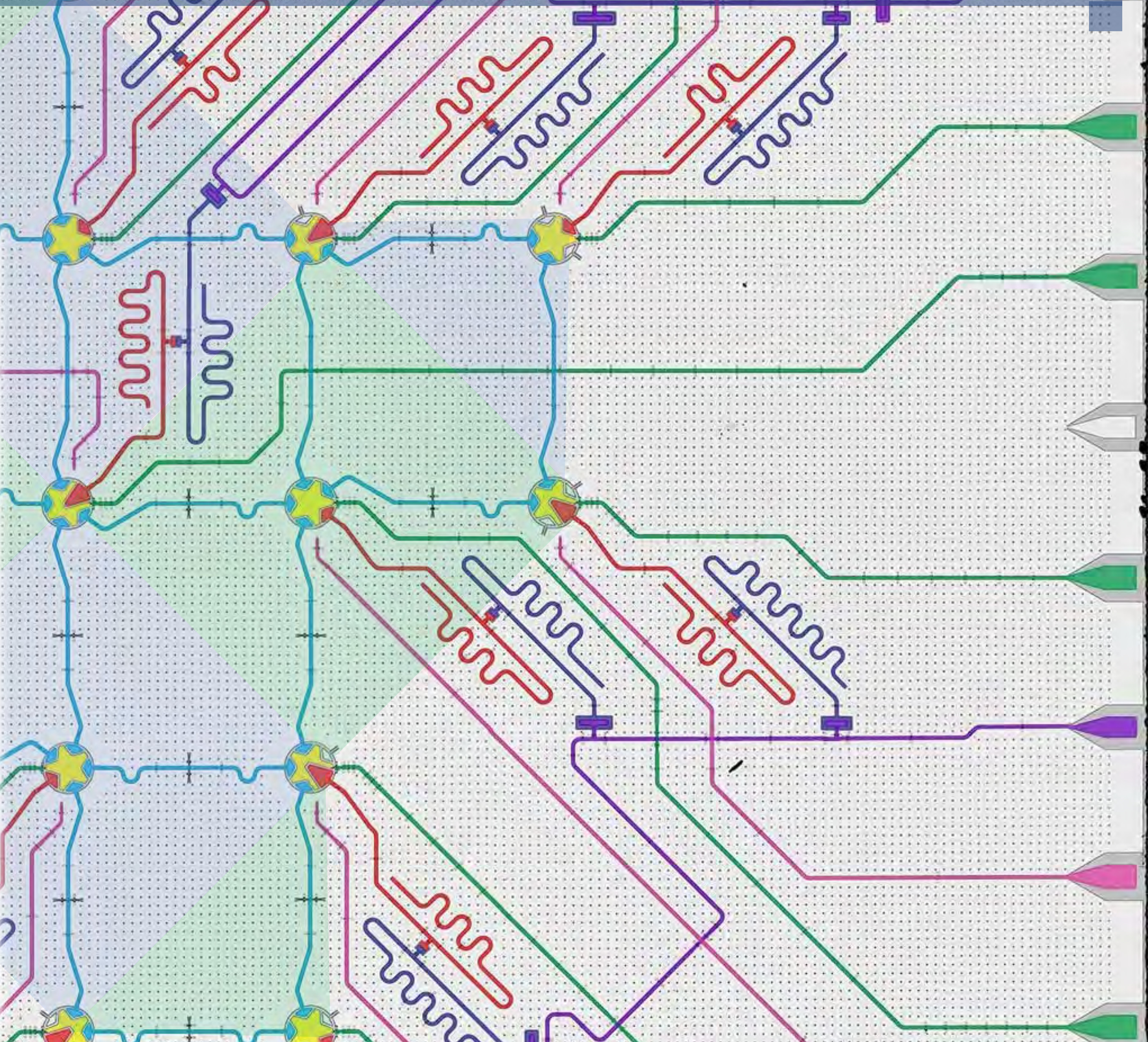
- Microscopic defects
  Bilmes et al., npj Qu. Inf. 8 , 1 (2022)
  Mueller et al., Rep. Prog. Phys 82, 124501 (2019)

Summary & Outlook

- Repeated quantum error correction in a distance-3 surface code
- Fast QEC cycle of 1.1 μs, circuits with up to >800 single qubit gates and ~400 two qubit gates
- Low logical error per cycle $\epsilon_L \sim 0.03$
- Break-even within reach, potentially close to threshold

- Feedback + reset operations
- Logical operations
- Noise injection, improved two-qubit gates, etc.

arXiv: 2112.03708 (2021)



The ETH Zurich Quantum Device Lab

incl. both spring and fall term project students

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

QSIT Quantum Science and Technology
National Centre of Competence in Research

FNSNF Swiss National Science Foundation

QuSurf

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