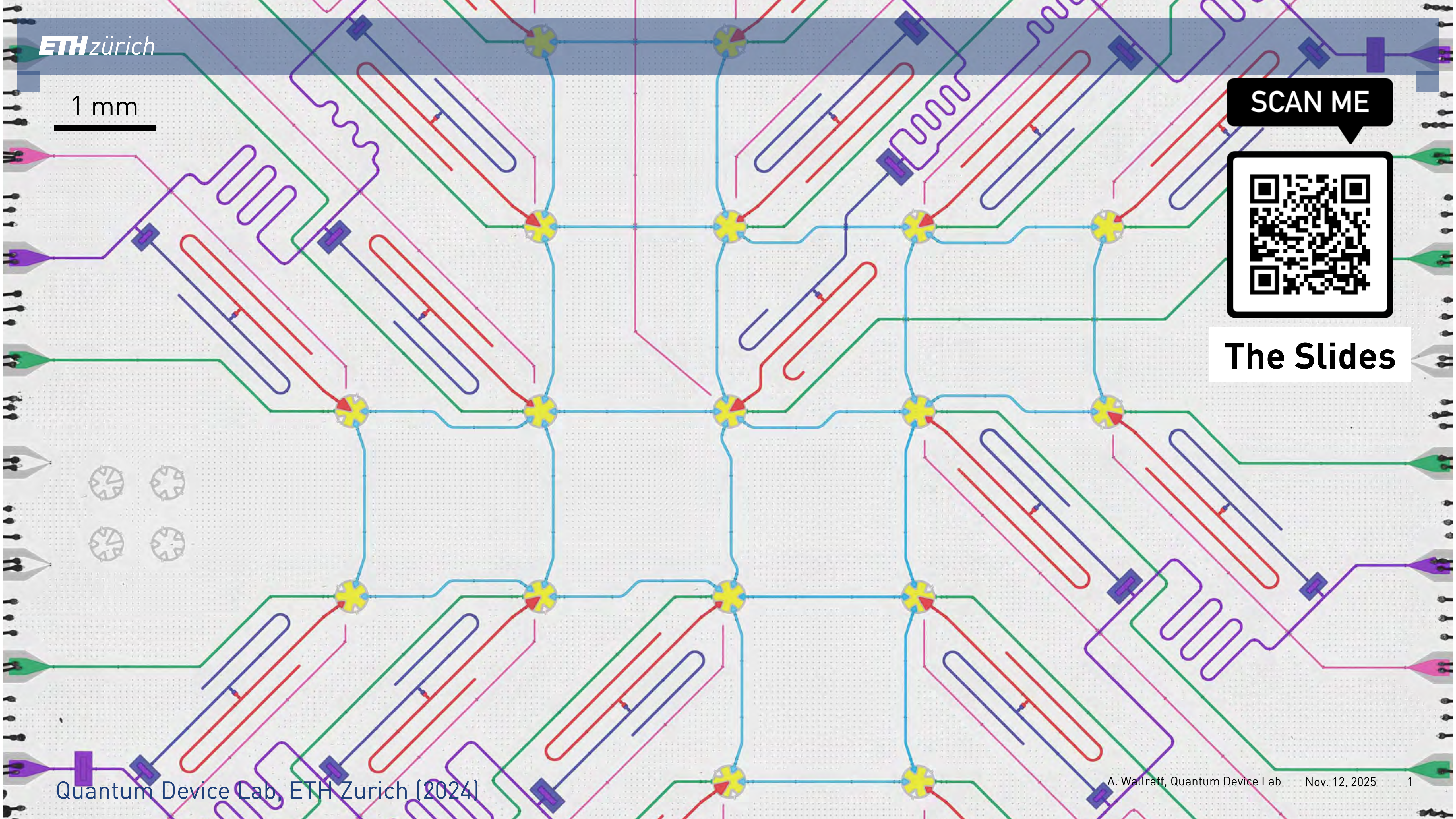
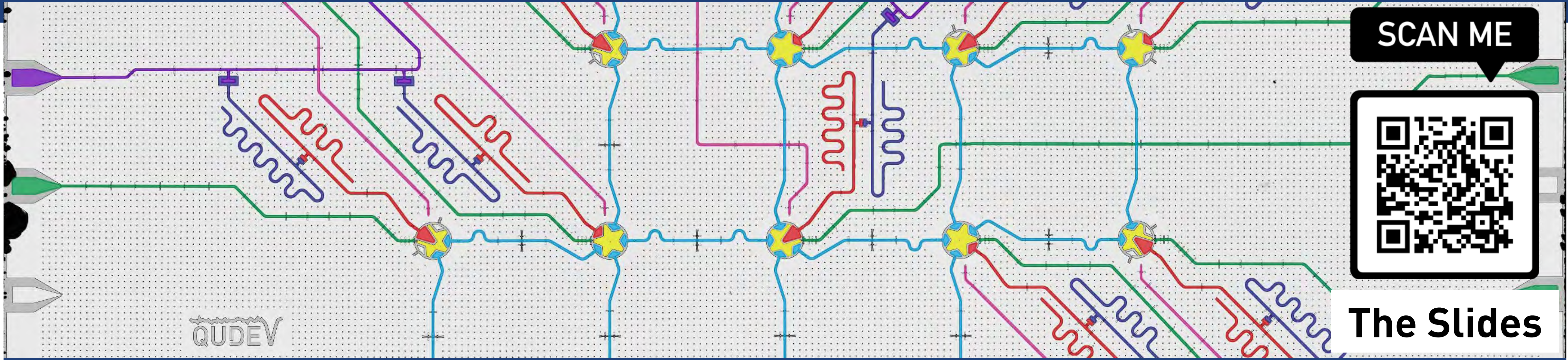
ETH zürich



Quantum Device Lab, ETH Zurich (2024)

SCAN ME

The Slides



Quantum Error Correction for Superconducting Quantum Information Processors

Sci. Team: E. Al-Tavil, L. Beltran, I. Besedin, J.-C. Besse, D. Colao Zanuz, Xi Dai, K. Dalton, J. Ekert, S. Frasca, A. Grigorev, D. Hagmann, C. Hellings, A. Hernandez-Anton, I. Hesner, L. Hofele, M. Kerschbaum, J. Knoll, A. Kulikov, N. Lacroix, M. Pechal, K. Reuer, A. Rosario, C. Scarato, J. Schaer, Y. Song, F. Swiadek, J. Trebst, F. Wagner, A. Wallraff *(ETH Zurich)*
L. Bödeker, L. Colmenarez, M. Müller *(RWTH Aachen)*
Eng. & Tech. Team: M. Bahrani, A. Flasby *(ETH Zurich)*

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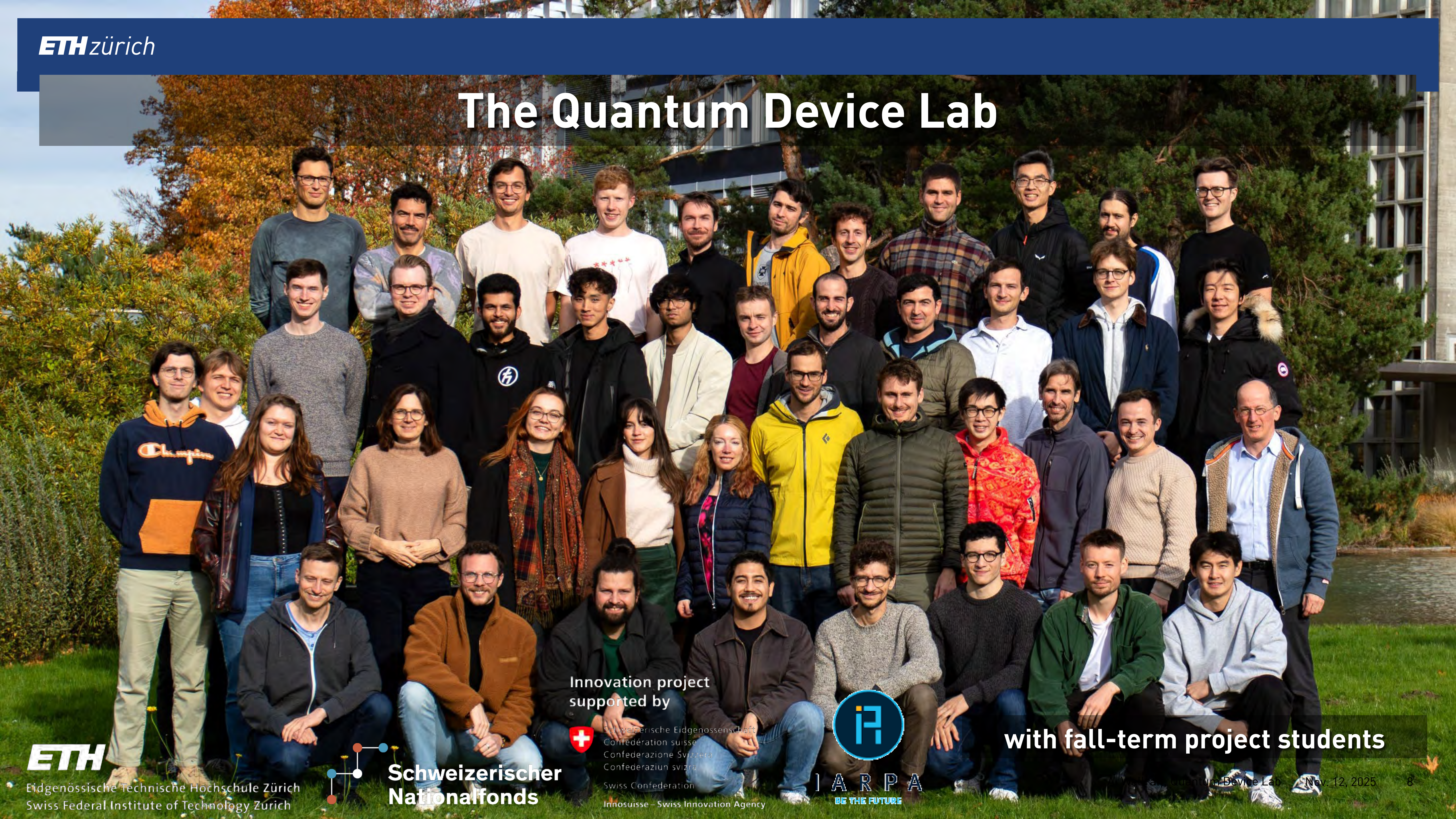
Schweizerischer Nationalfonds

Innovation project supported by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Innosuisse – Swiss Innovation Agency

The Quantum Device Lab



with fall-term project students

Innovation project supported by

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Confédération suisse
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Swiss Confederation

Innosuisse – Swiss Innovation Agency

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Schweizerischer Nationalfonds

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Past Group Members & Current Collaboration Partners

www.qudev.ethz.ch

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Faculty/PostDoc/PhD/Industry

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L. Huthmacher (Stellbrink & Prtnr)
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G. Puebla (QZabre)
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D. van Woerkom (Microsoft)
J. Waissman (HUJI)
T. Walter (deceased)
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A. Wulff
S. Zeytinoğlu (Harvard)

Collaborations (last 5 years) with groups of

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J. Bylander (Chalmers)
H. J. Carmichael (Auckland)
A. Chin (Cambridge)
I. Cirac (MPQ)
K. Ensslin (ETH Zurich)
M. Hartmann (FAU Erlangen)
T. Ihn (ETH Zurich)
A. Imamoğlu (ETH Zurich)
F. Marquardt (MPL Erlangen)
F. Merkt (ETH Zurich)
A. Messmer (Zurich Instruments)
M. W. Mitchell (ICFO)
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M. A. Martin-Delgado (Madrid)
M. Poggio (Basel)
B. Royer (Sherbrooke)
N. Sangouard (CEA Saclay)
H. Tureci (Princeton)
W. Wegscheider (ETH Zurich)

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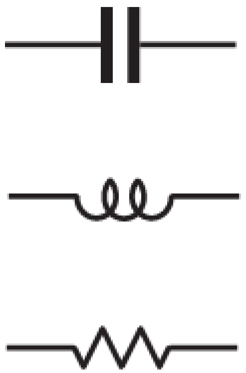
scaleQIT

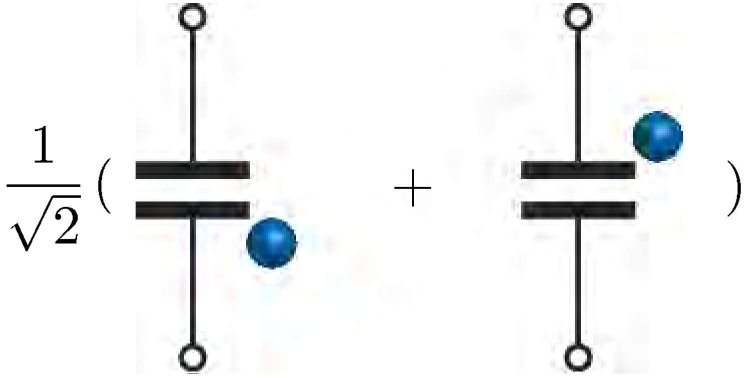
ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
FNSNF Swiss National Science Foundation
QSIT Quantum Science and Technology
National Centre of Competence in Research
QED Circuit and Cavity Quantum Electrodynamics
erc
Seventh Framework Programme
GEOMDISS

Quantum Physics with Electronic Circuits

basic circuit elements:



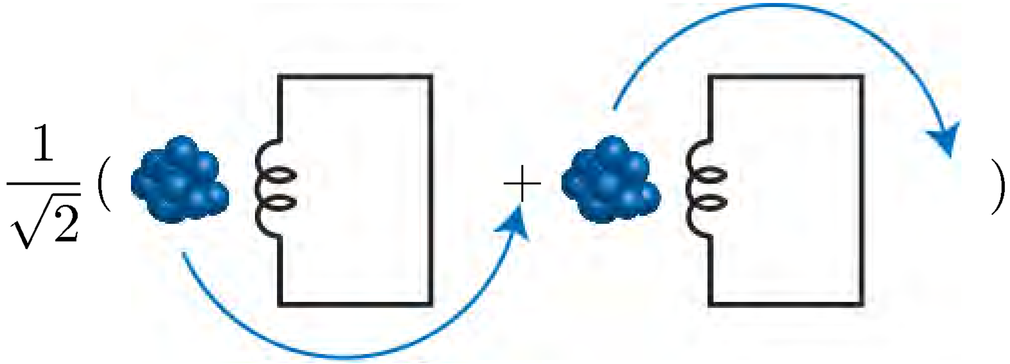
charge on a capacitor:



quantum superposition states of:

- charge Q
- flux ϕ

current or magnetic flux in an inductor:

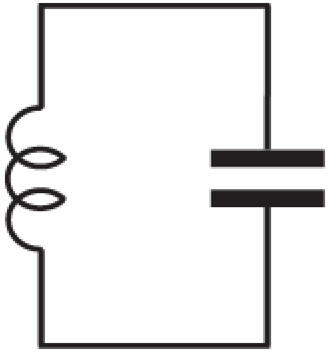


Q, ϕ are conjugate variables

commutation relation $\left[\hat{\phi}, \hat{Q}\right] = i\hbar$

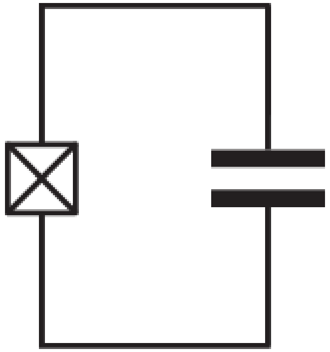
Linear and Nonlinear Superconducting Electronic Oscillators

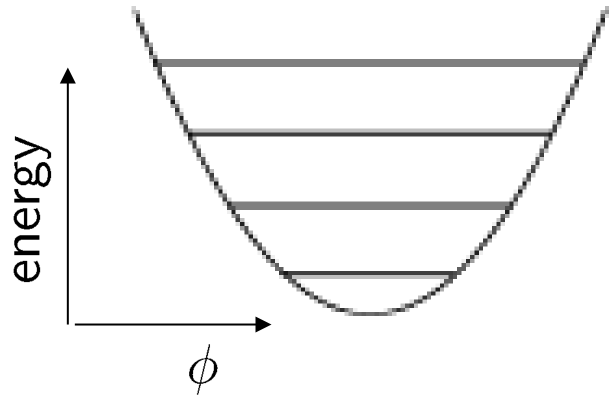
LC resonator:



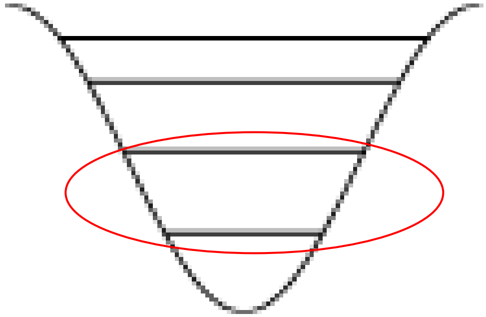
Josephson junction resonator:

Josephson junction = nonlinear inductor





anharmonicity defines effective two-level system



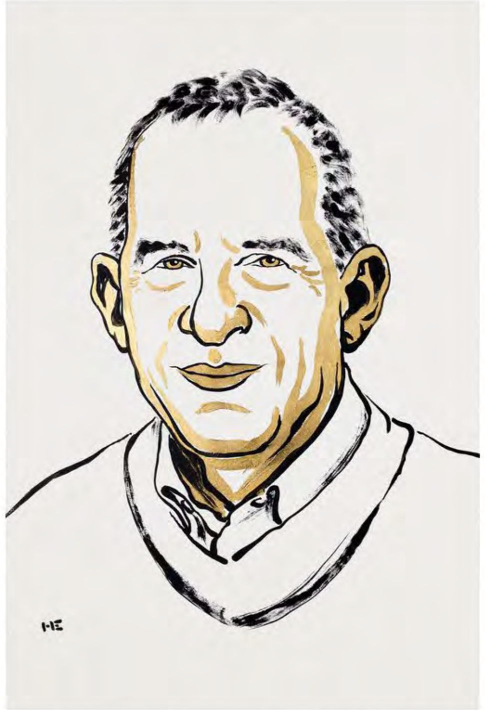
Circuit QED Review: A. Blais *et al.*, *Rev. Mod. Phys.* **93**, 025005 (2021)

Nobel Prize in Physics 2025: Macroscopic Quantum Tunneling and Energy Level Quantization in Electrical Circuits

Ill. Niklas Elmehed © Nobel Prize Outreach

John Clarke

Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach

Michel H. Devoret

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

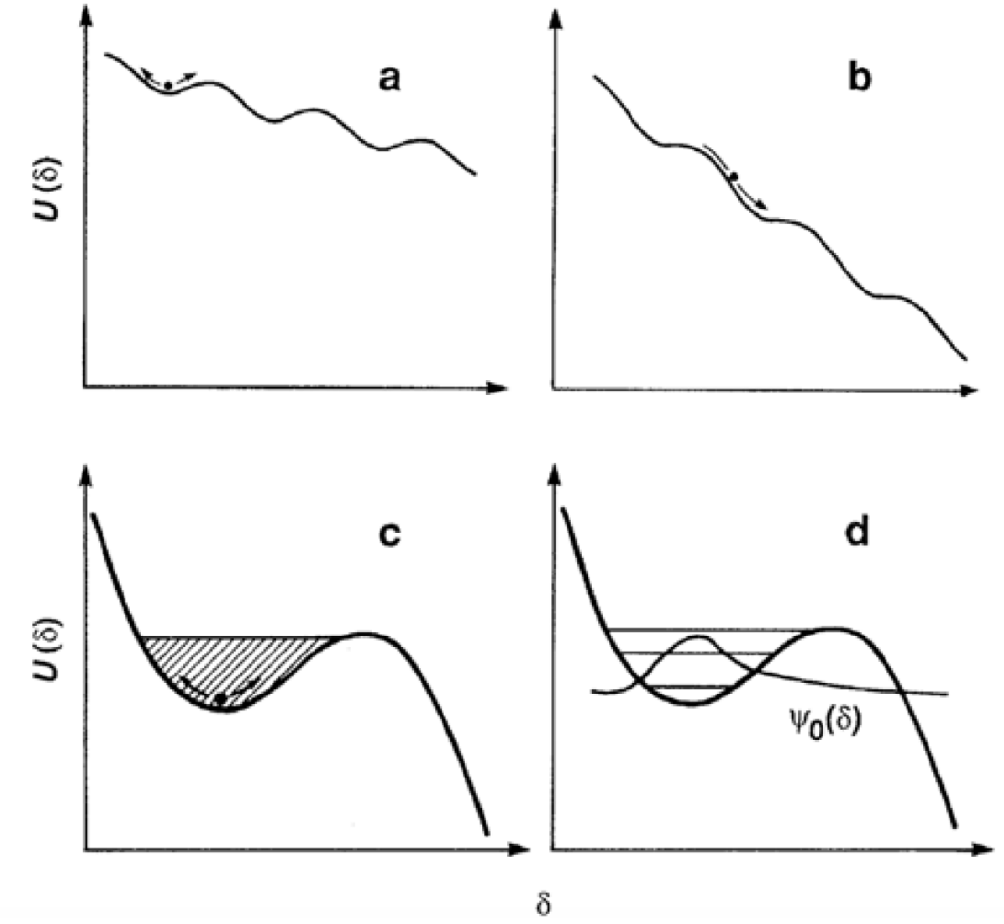
John M. Martinis

Prize share: 1/3

Physics 2025

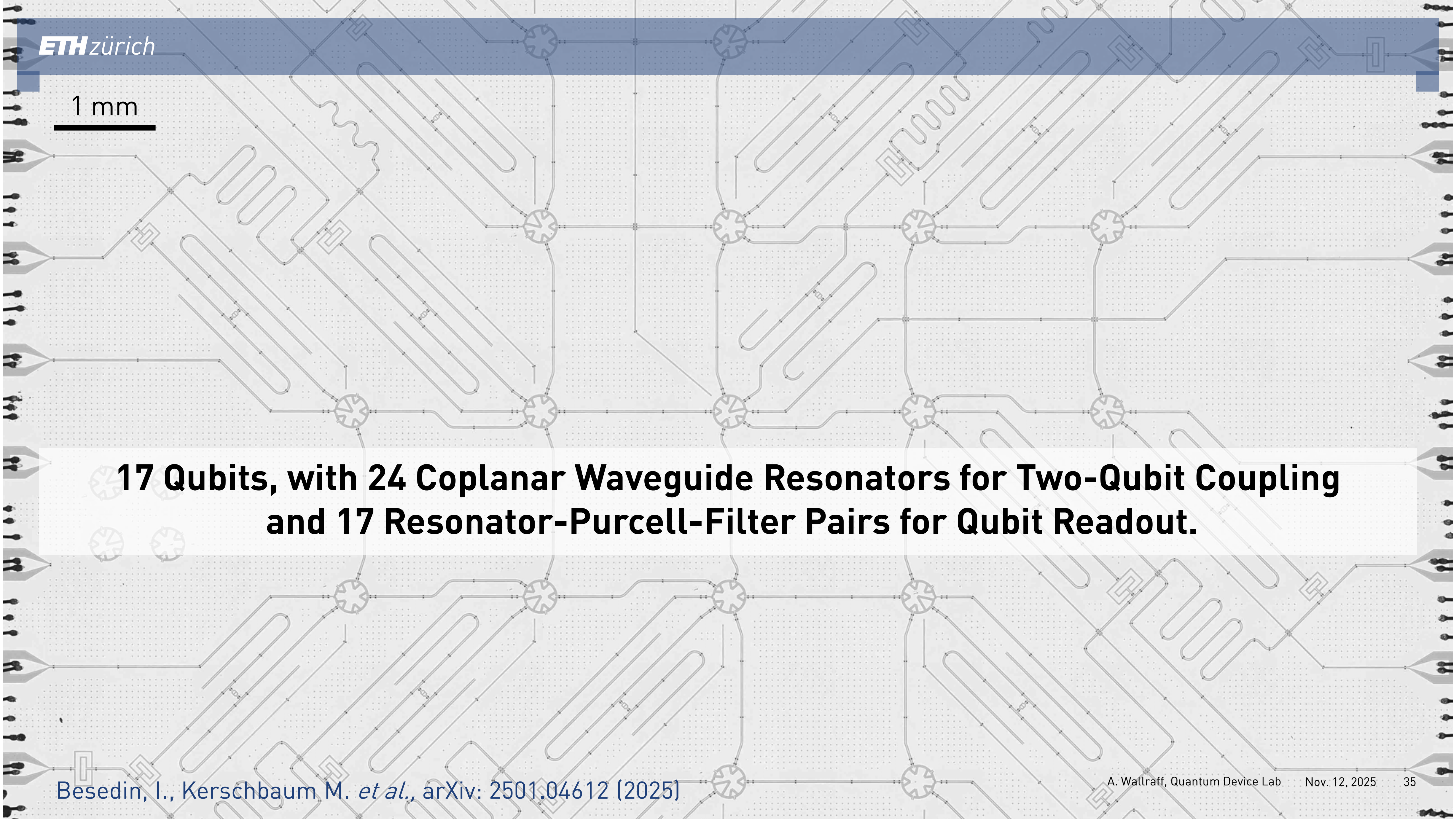
The Nobel Prize in Physics 2025 was awarded jointly to John Clarke, Michel H. Devoret and John M. Martinis "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

Thermal Activation and Quantum Tunneling in a Current-Biased Josephson Junction



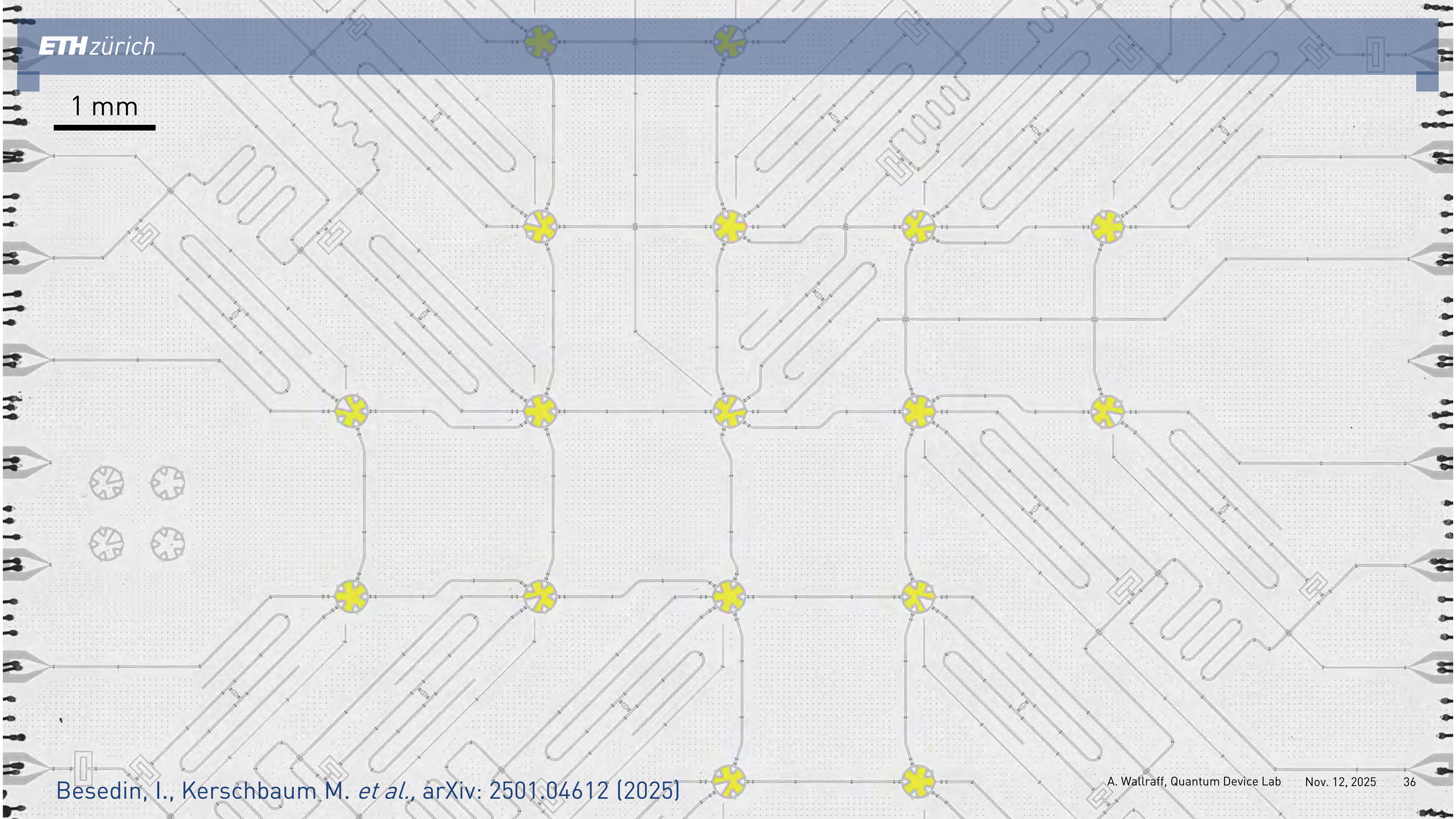
Tilted washboard potential

J. Clarke, J. Martinis, M. Devoret *et al.*, *Science* 239, 992 (1988).

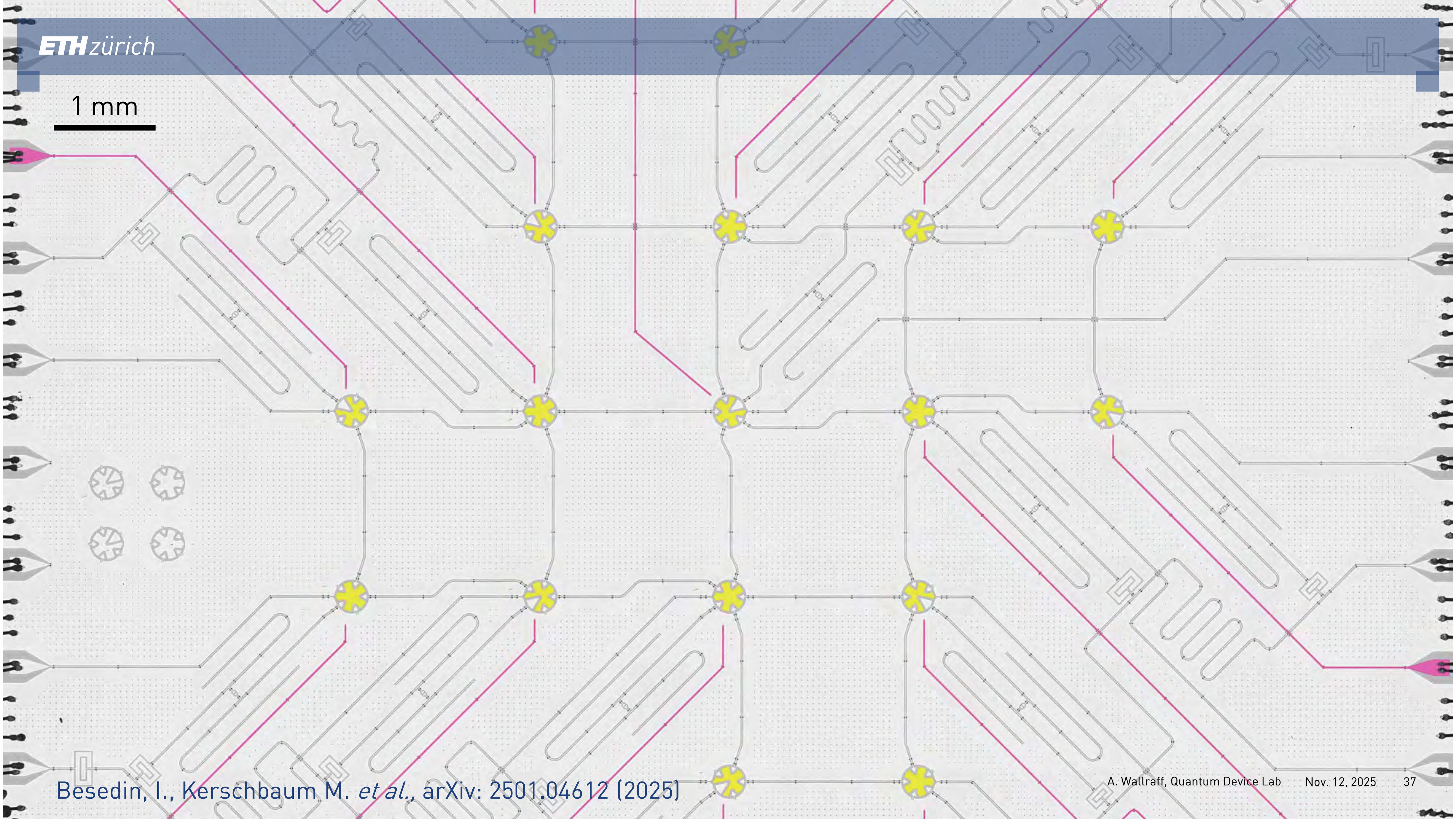


17 Qubits, with 24 Coplanar Waveguide Resonators for Two-Qubit Coupling and 17 Resonator-Purcell-Filter Pairs for Qubit Readout.

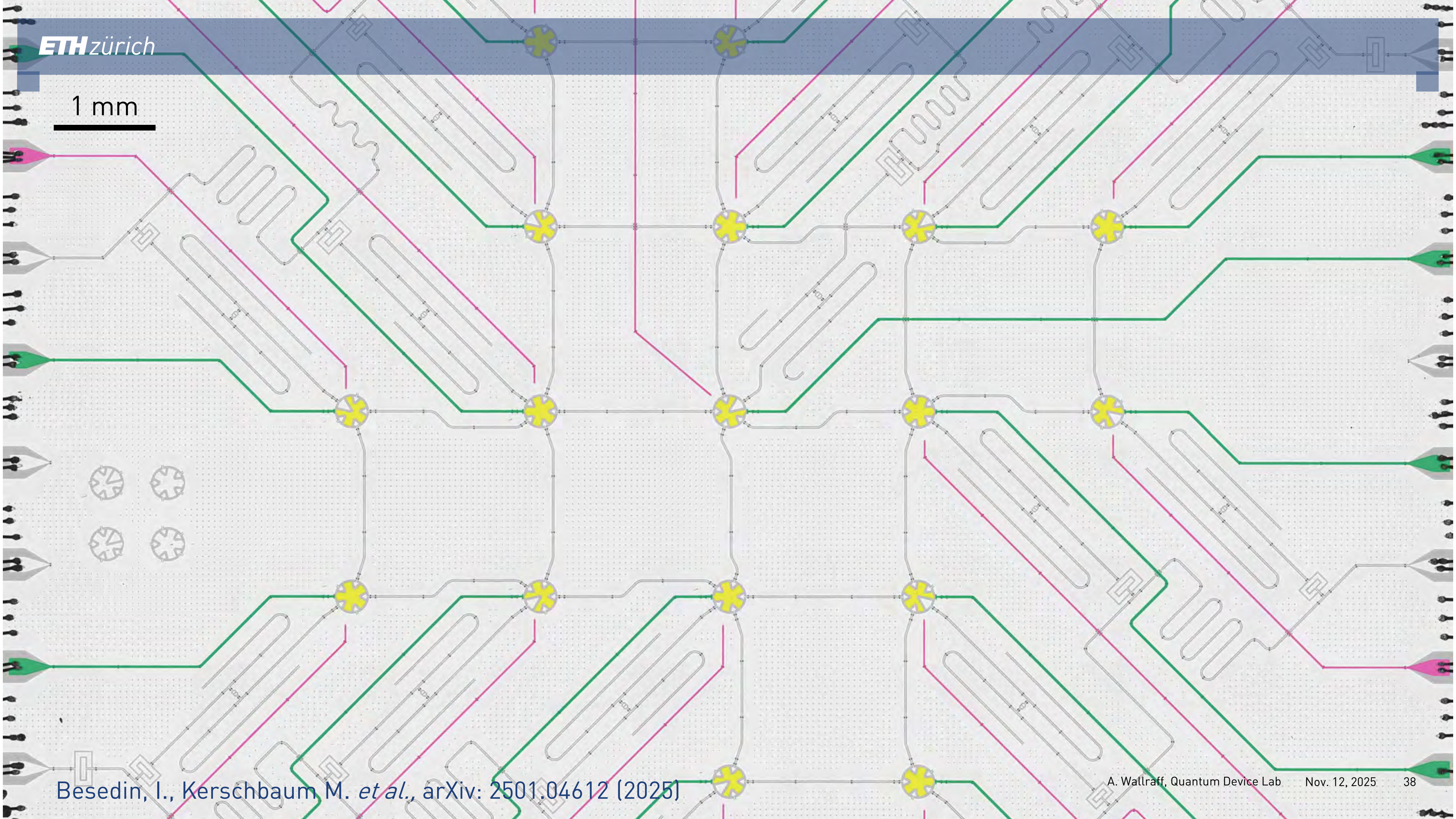
Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)



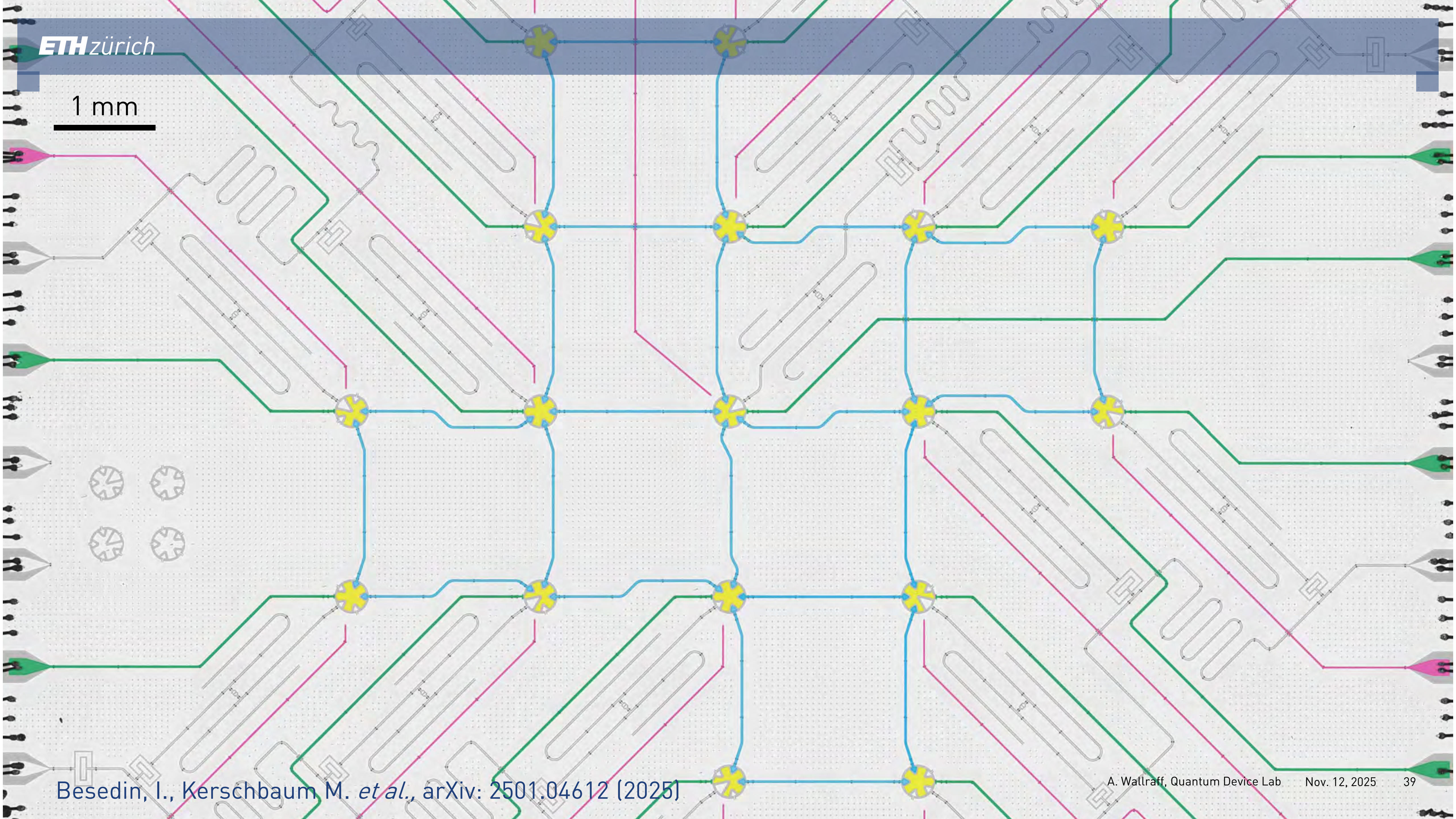
Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)



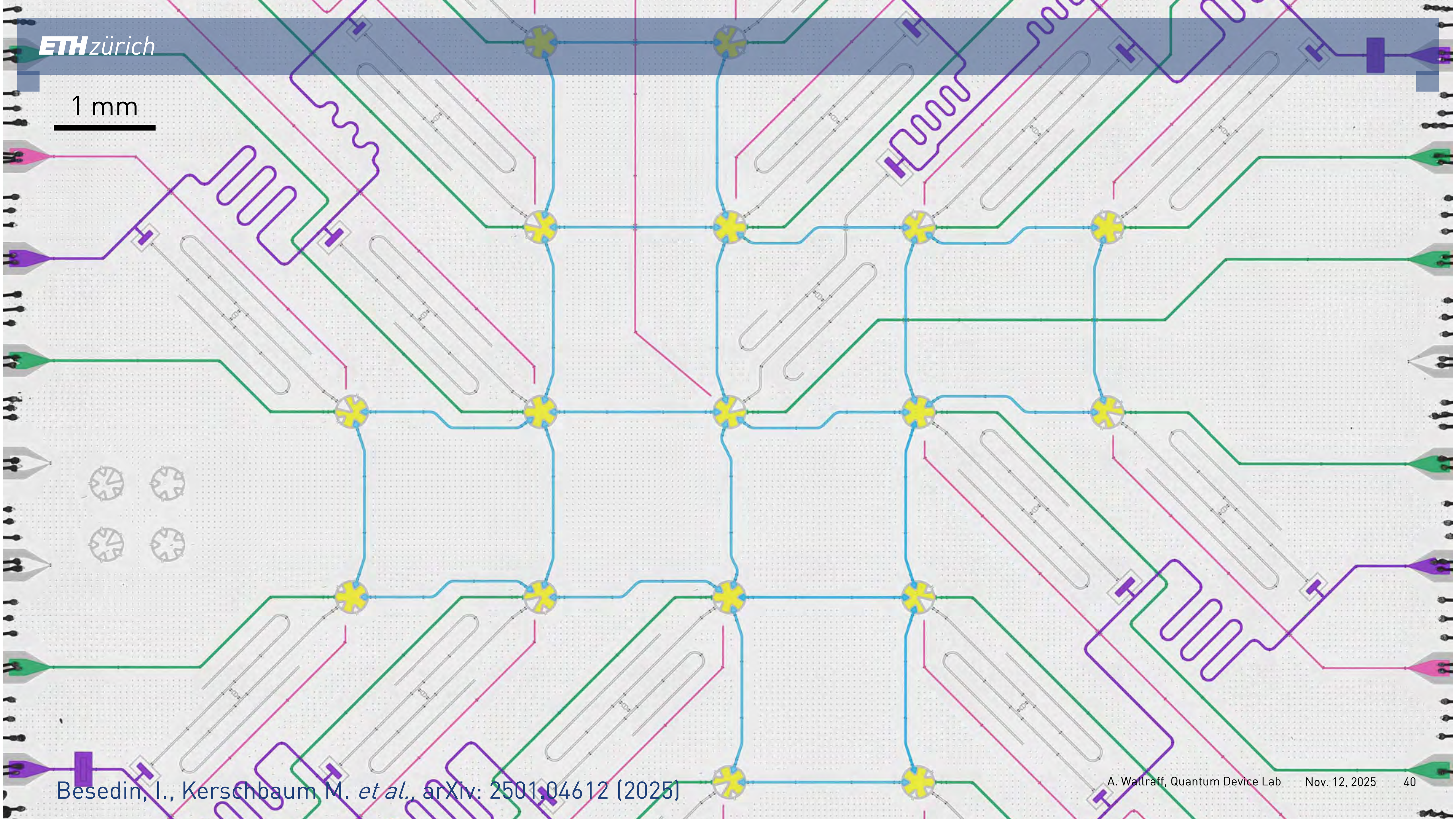
Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)



Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)

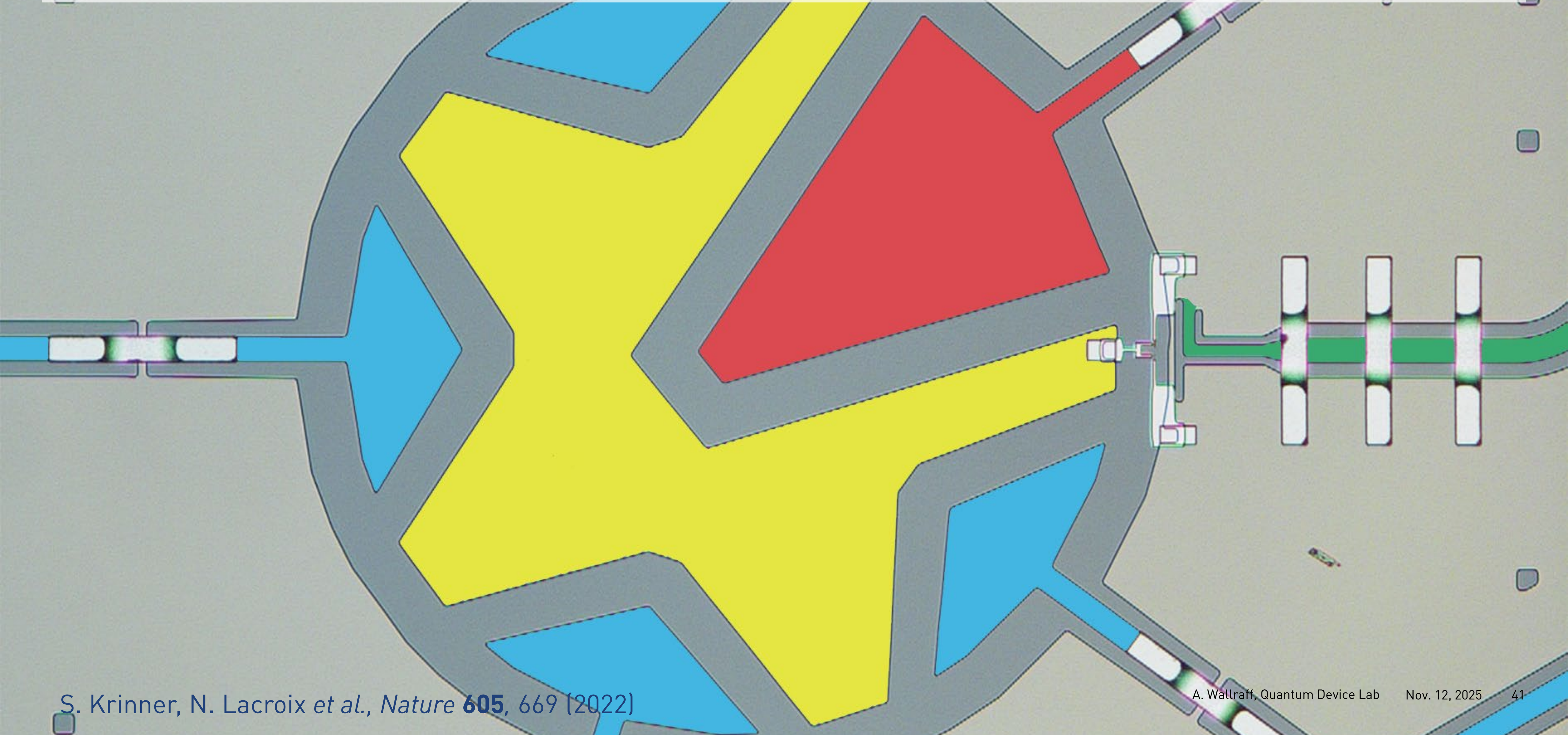


Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)



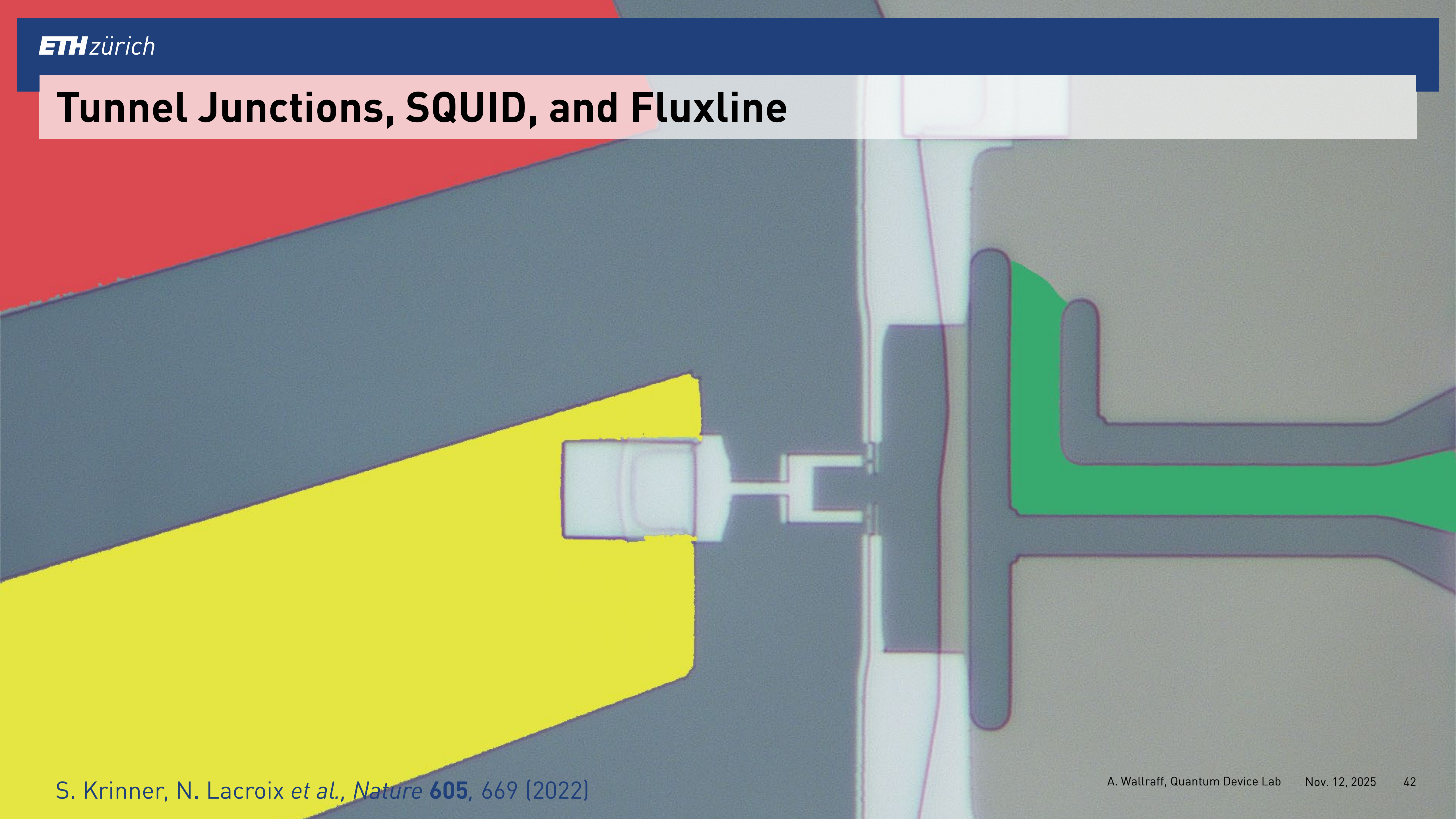
Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)

A Superconducting Qubit – Transmon-Style

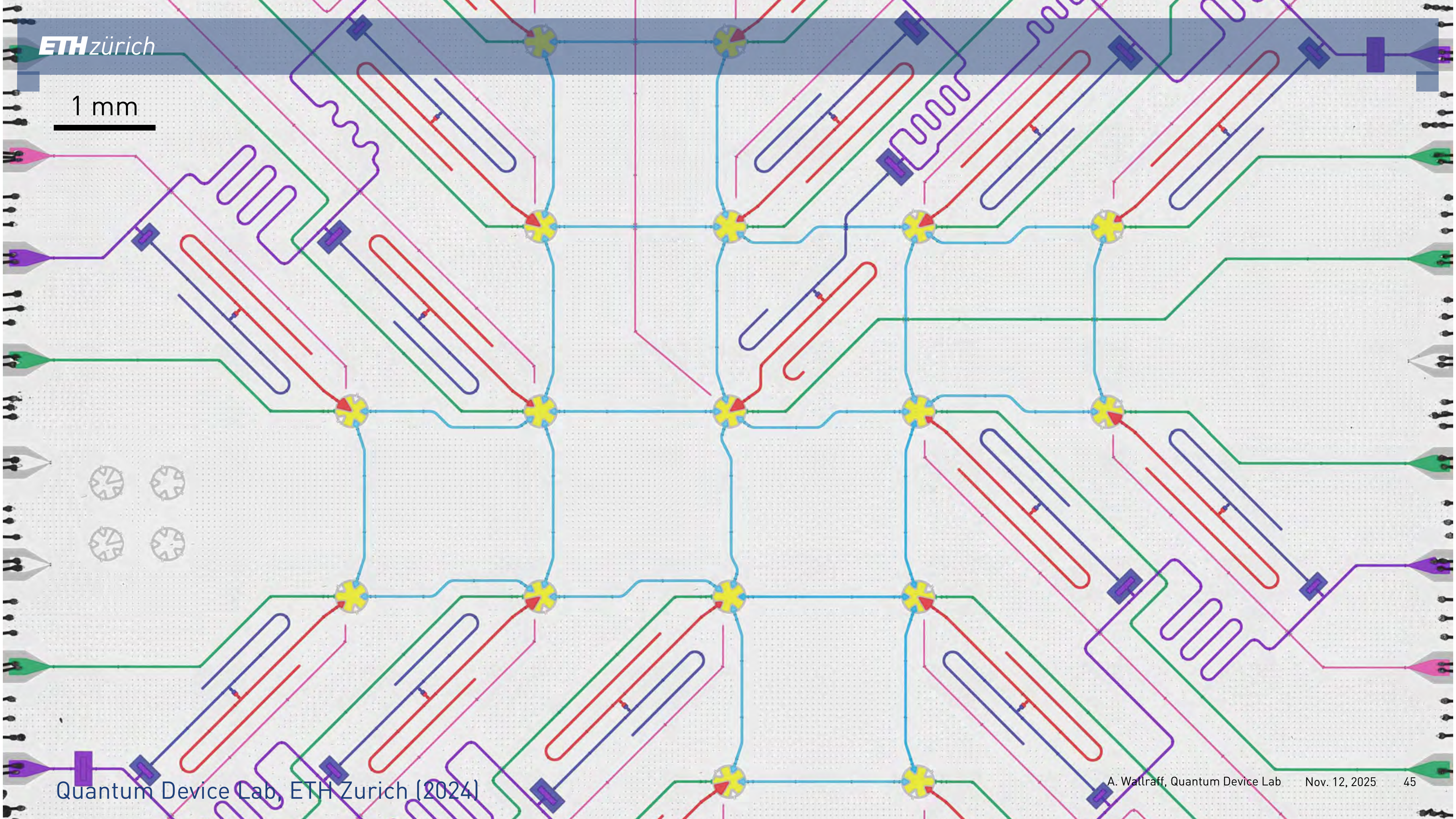


S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

Tunnel Junctions, SQUID, and Fluxline



S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

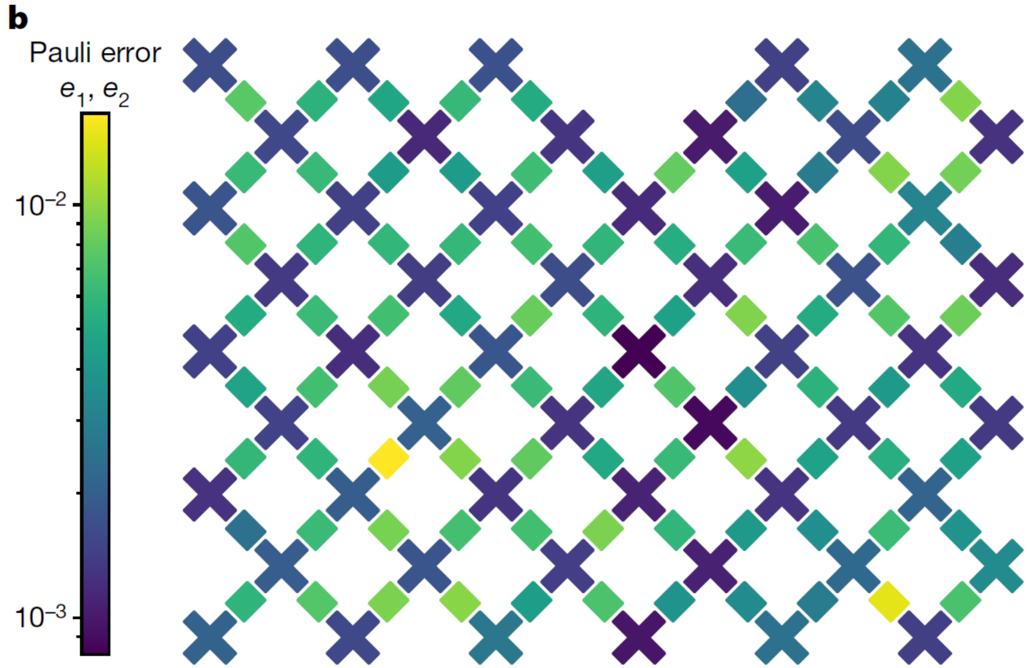


Quantum Device Lab, ETH Zurich (2024)

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

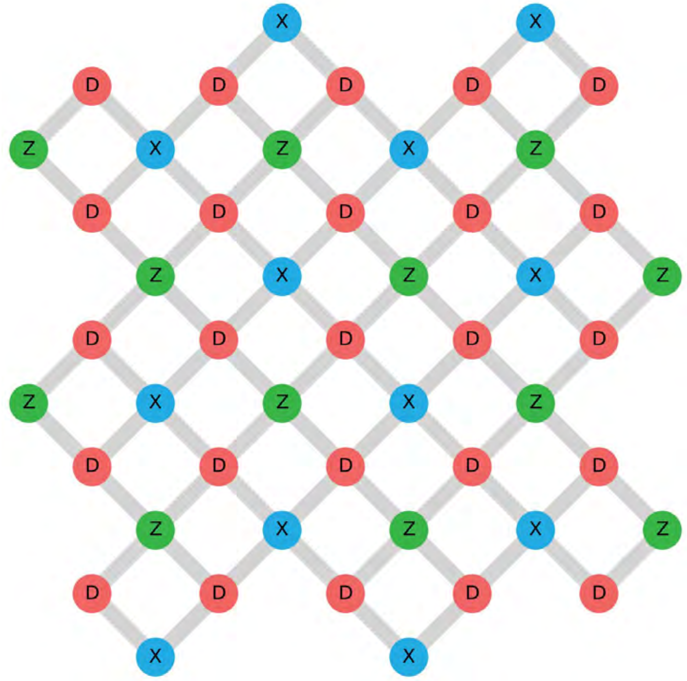
... with superconducting circuits

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:

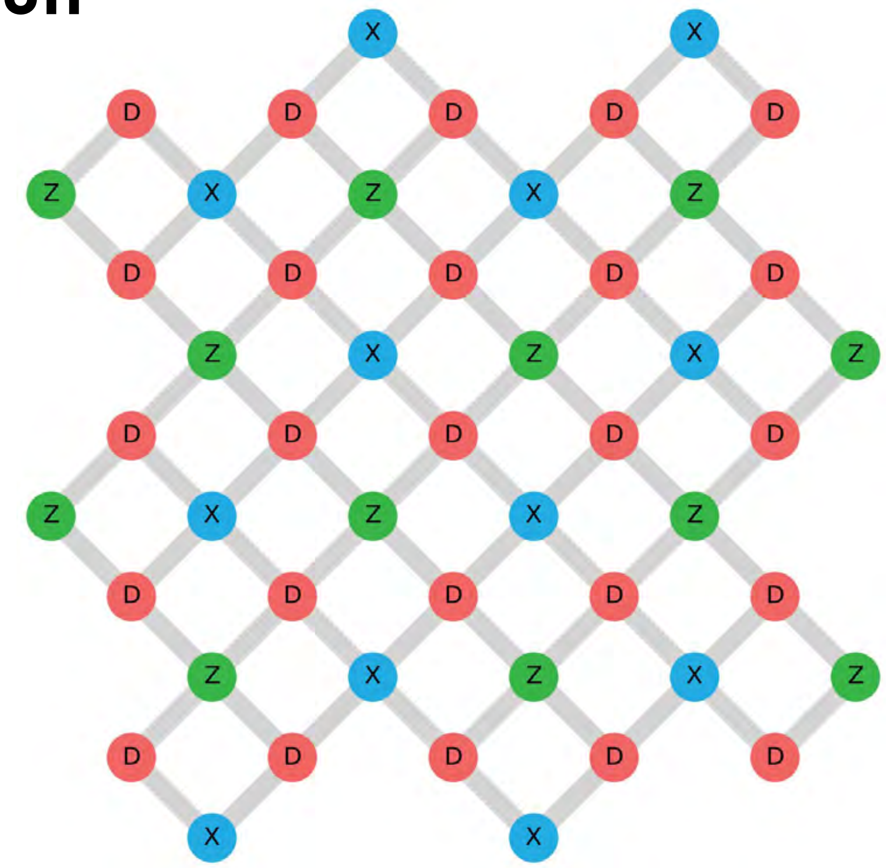
- Bit flips
- Phase flips

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)

The Surface Code – Main Features

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

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

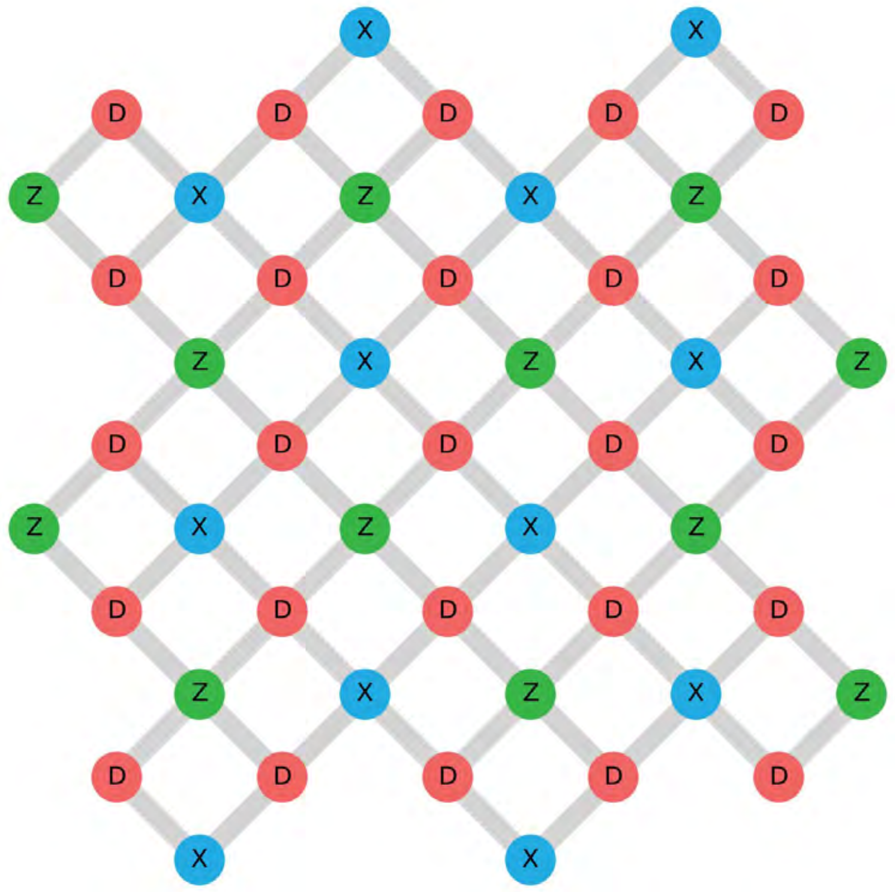
  ϵ_{phys}: Physical error rate per step

  ϵ_{th}: Threshold error rate

  d: Distance of the code

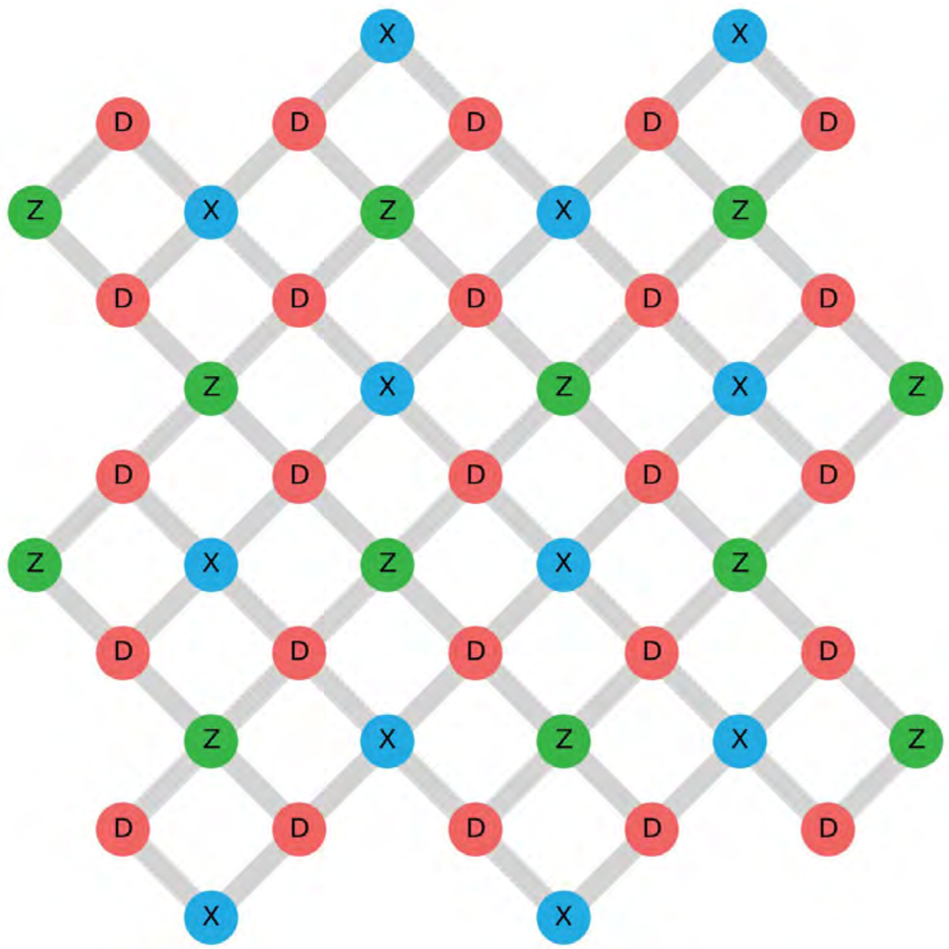
Two-dimensional architecture

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



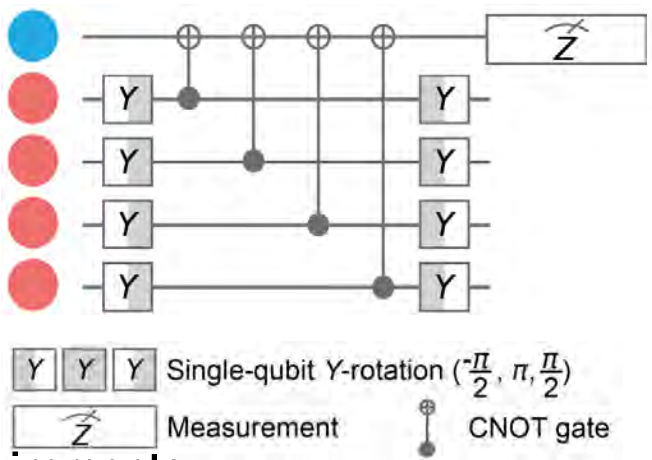
Kitaev, *Annals of Physics* **303**, 2 (2003),
Dennis et al., *Journ. of Math. Physics* **43**, 4452 (2002)
Raussendorff, Harrington, *Phys. Rev. Lett.* **98**, 190504 (2007)
Fowler *et al.*, *Phys. Rev. A* **86**, 032324 (2012)

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:

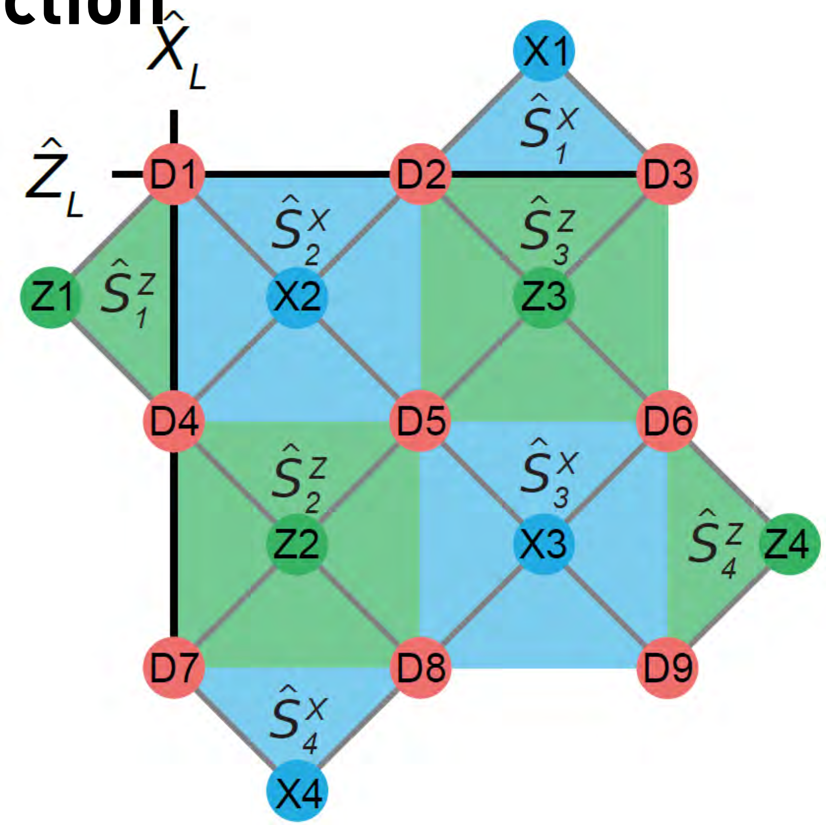
- High-fidelity entangling gates between data and ancilla qubits
- Fast high-fidelity measurements of the ancilla qubits
- Low readout crosstalk between ancilla and data qubits
- Ability to do repeated gates and mid-cycle measurements

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

Distance-Three Surface Code for Error Correction

Two-dimensional square lattice of qubits

- $d^2 = 9$ Data qubits: encode single (logical) qubit
  - Logical operators: $\hat{Z}_L = \hat{Z}_1\hat{Z}_2\hat{Z}_3 \quad \hat{X}_L = \hat{X}_1\hat{X}_4\hat{X}_7$
  - Distance d: min. number of Pauli operators in $\hat{Z}_L, \hat{X}_L$
  - Number of correctable errors: $\lfloor (d-1)/2 \rfloor = 1$
- $d^2 - 1 = 8$ Auxiliary qubits: for parity measurements



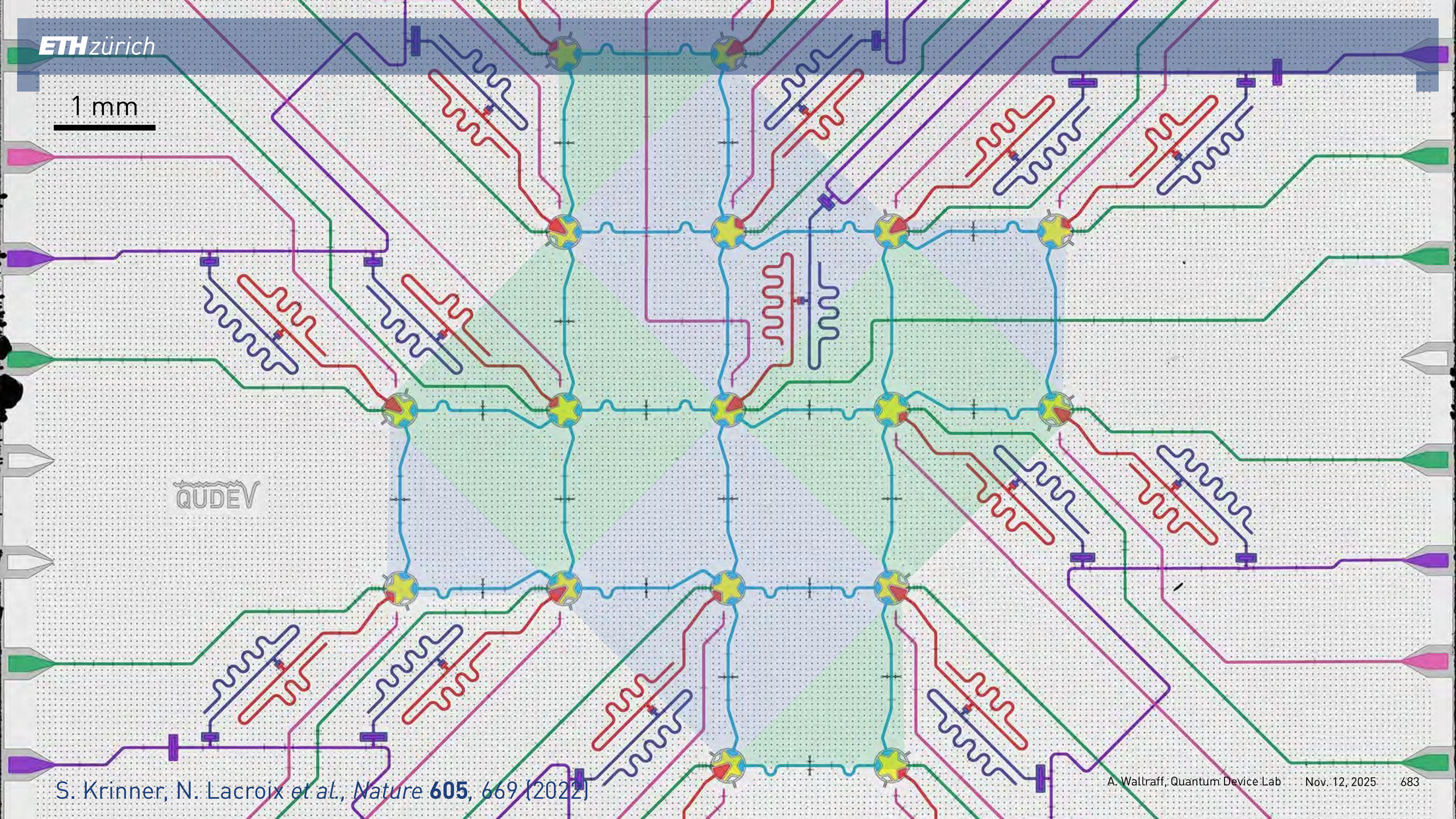
Parity/Stabilizer measurements

- Detect errors without collapsing data-qubit state (Stabilizer operators commute with $\hat{Z}_L, \hat{X}_L$)
- 4 Z-type Stabilizers $\hat{S}^{Zi}$ to detect bit-flip errors
- 4 X-type Stabilizers $\hat{S}^{Xi}$ to detect phase-flip errors

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

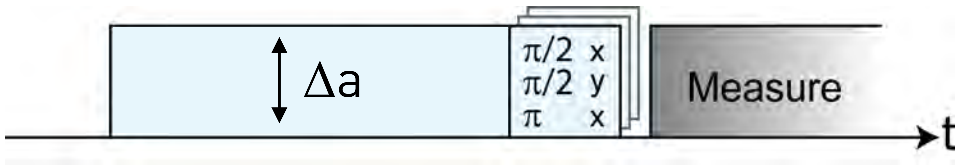
$\hat{S}^{X1}$	$\hat{X}_2\hat{X}_3$
$\hat{S}^{X2}$	$\hat{X}_1\hat{X}_2\hat{X}_4\hat{X}_5$
$\hat{S}^{X3}$	$\hat{X}_5\hat{X}_6\hat{X}_8\hat{X}_9$
$\hat{S}^{X4}$	$\hat{X}_7\hat{X}_8$

Bombin, Delgado, *Phys. Rev. A* **76**, 012305 (2007)
Tomita, Svore, *Phys. Rev. A* **90**, 062320 (2014)

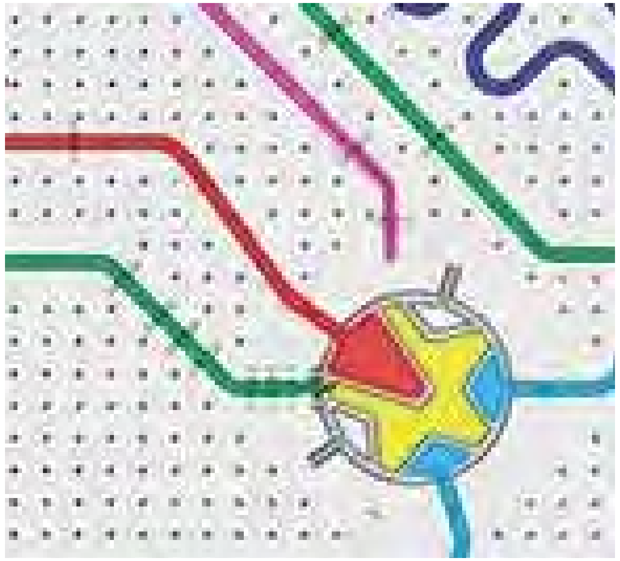


S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

Controlling Single Qubits (Y Rotation)

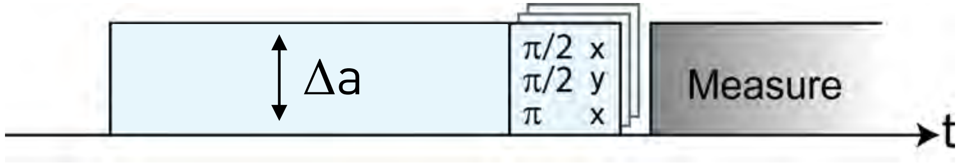


- apply microwave pulse
- followed by read-out pulse
- both with controlled length, amplitude and phase
- Characterize gates by randomized benchmarking
- F > 99 %



experimental density matrix and Pauli set:

Controlling Single Qubits (X Rotation)



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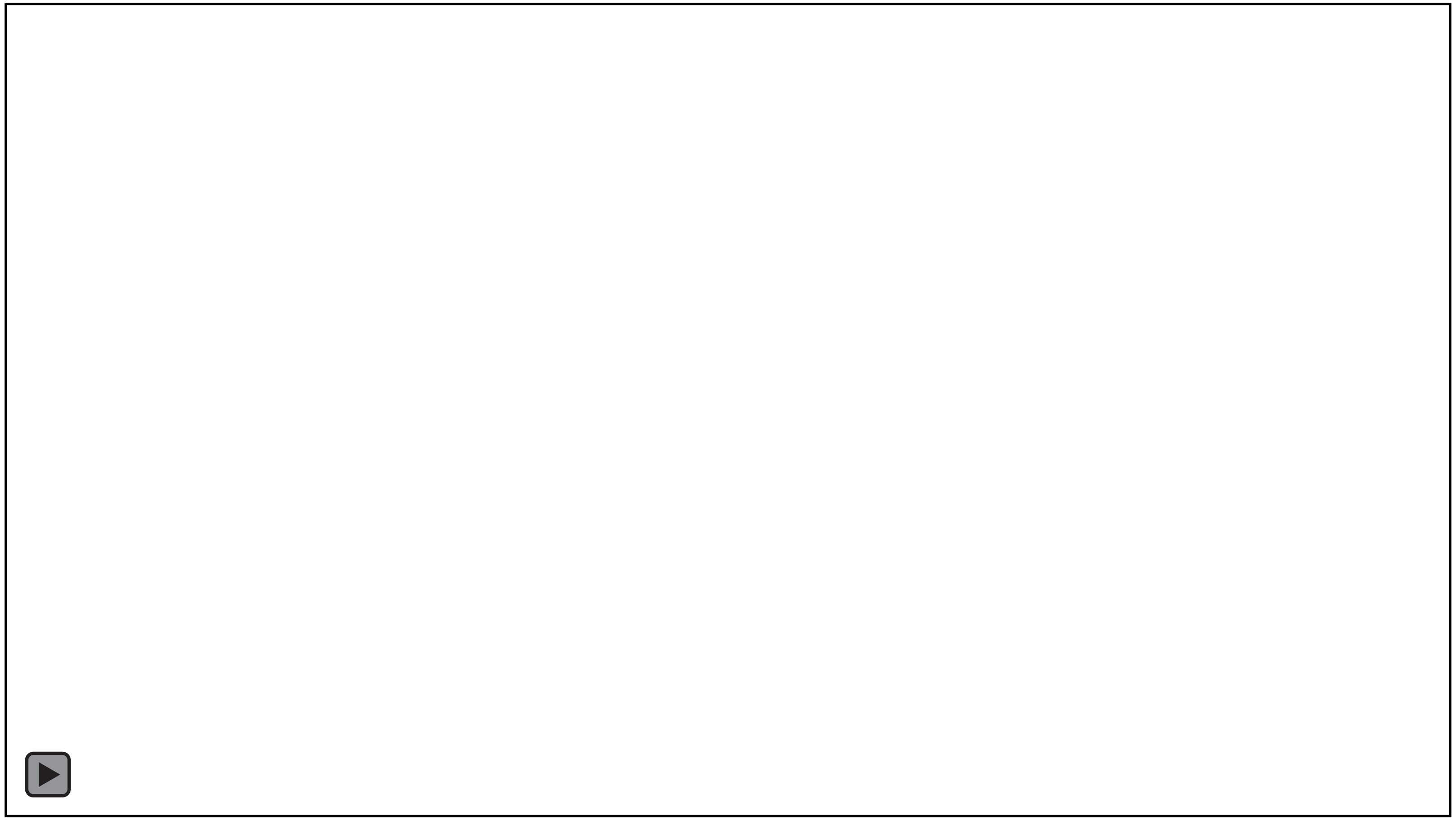
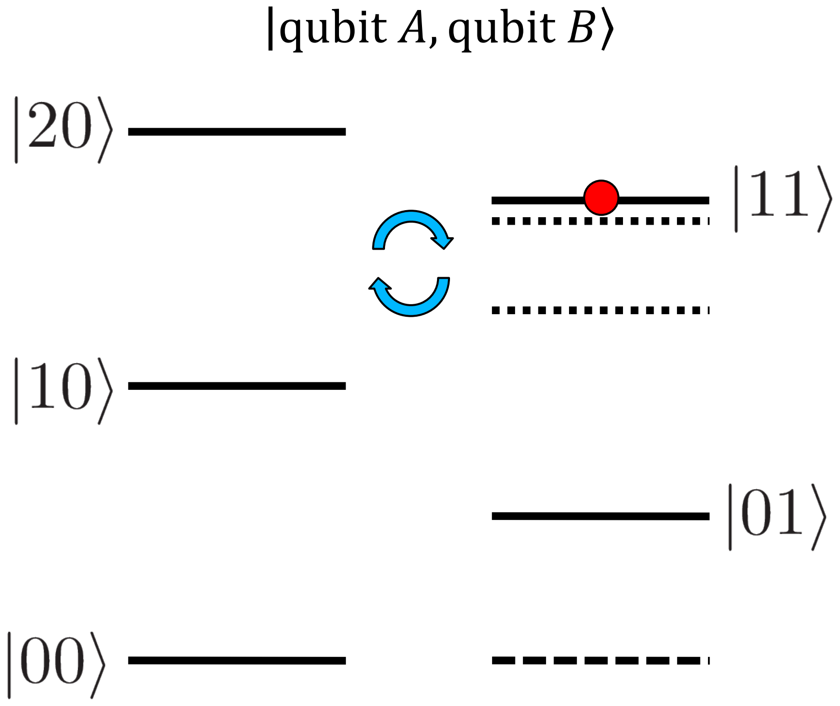
experimental density matrix and Pauli set:



Universal Two-Qubit Controlled Phase Gate

Make use of qubit states beyond 0, 1

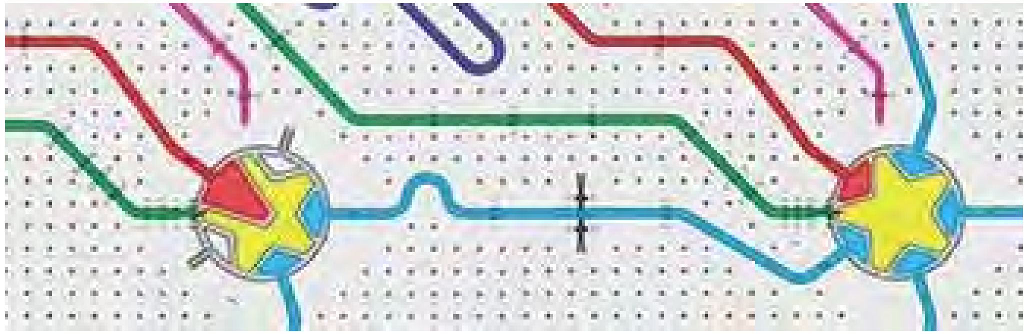


$$|11\rangle \longrightarrow i|20\rangle \longrightarrow -|11\rangle$$

Interaction mediated by virtual photon exchange through resonator

Full 2π rotation induces phase factor -1

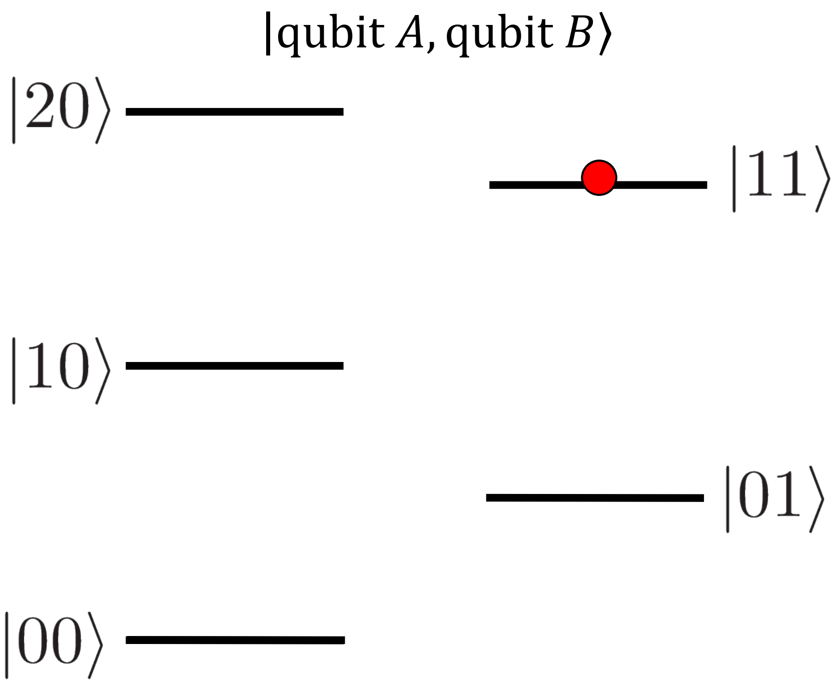
Tune levels into resonance using magnetic field



proposal: F. W. Strauch *et al., Phys. Rev. Lett.* **91**, 167005 (2003).
first implementation: L. DiCarlo *et al., Nature* **460**, 240 (2010).

Universal Two-Qubit Controlled Phase Gate

Make use of qubit states beyond 0, 1

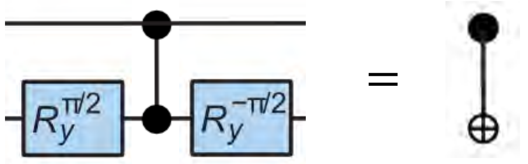


Qubits in states 01, 10 and 00 do not interact and thus acquire no phase shift

$$|11\rangle \longrightarrow i|20\rangle \longrightarrow -|11\rangle$$
$$|01\rangle \longrightarrow |01\rangle$$
$$|10\rangle \longrightarrow |10\rangle$$
$$|00\rangle \longrightarrow |00\rangle$$

C-Phase gate:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$



CNOT gate

Universal two-qubit gate.

Test performance with process tomography or randomized benchmarking.

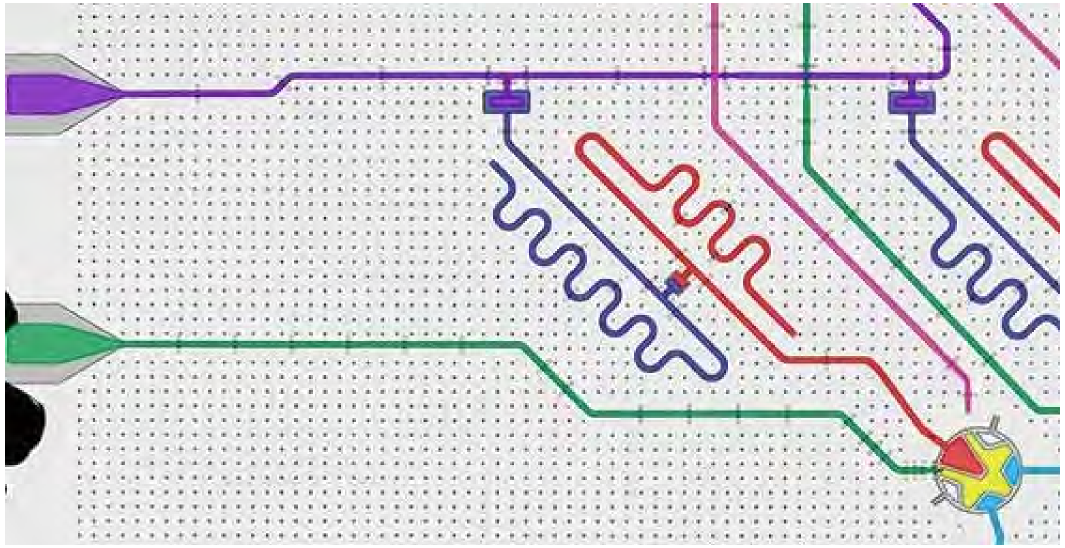
proposal: F. W. Strauch *et al., Phys. Rev. Lett.* **91**, 167005 (2003).

first implementation: L. DiCarlo *et al., Nature* **460**, 240 (2010).

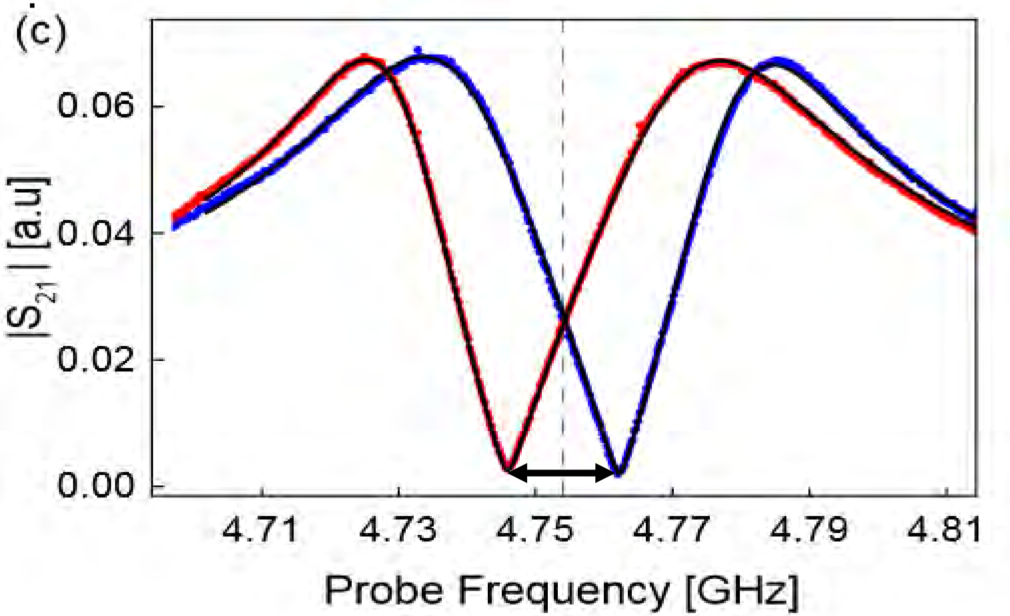
Qubit Readout

Circuit design

- λ/4 readout resonator & λ/4 Purcell filter



Transmission amplitude of readout circuit for qubit prepared in ground (g) or excited (e) state:



Performance

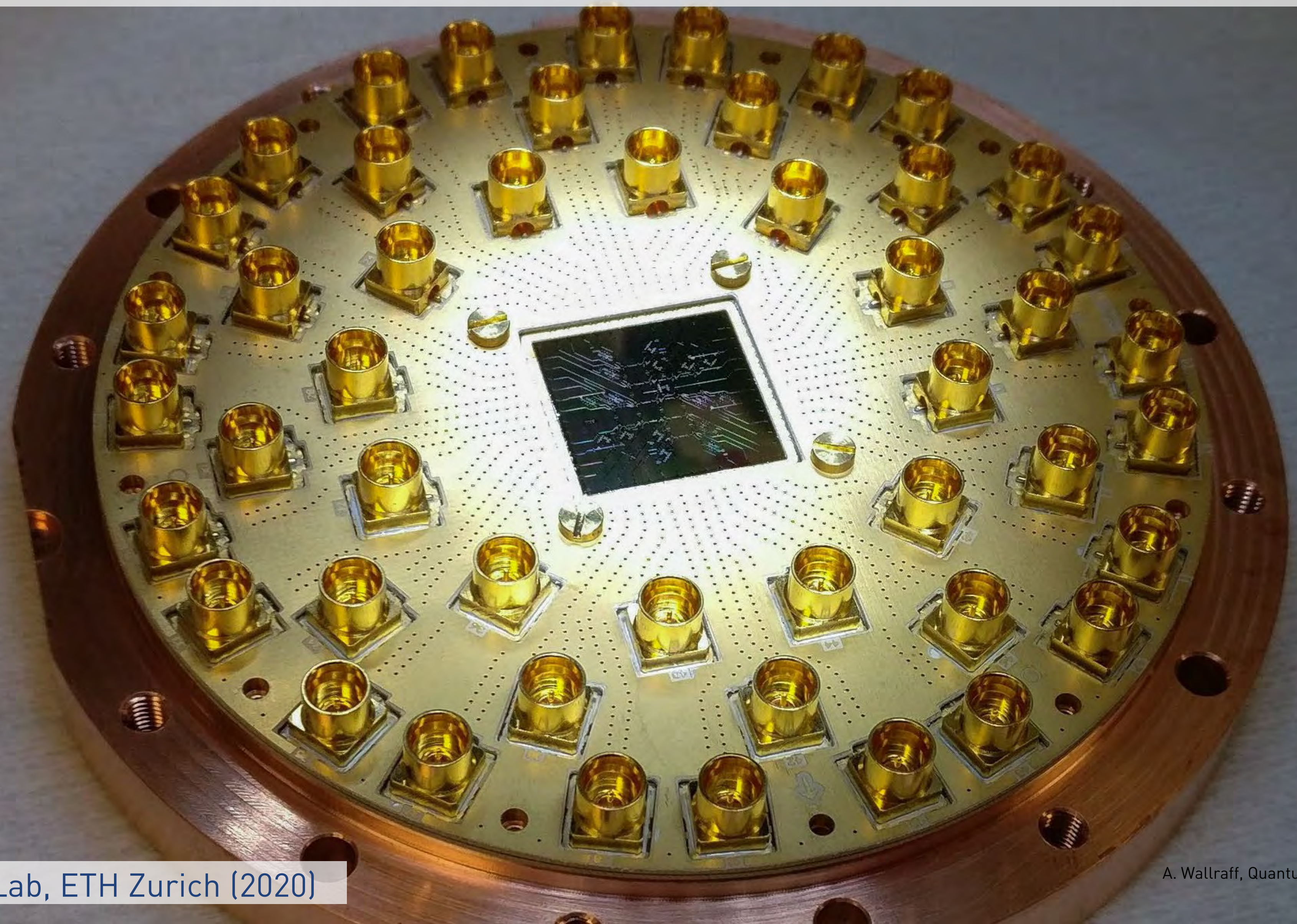
- F ~ 99.2 % at 88 ns integration time
- Optimized sample design
- Low-noise phase-sensitive JP-Amplifier

Features:

- large dispersive shift χ
- large resonator BW κ
- Purcell protection
- Low cross-talk when multiplexed

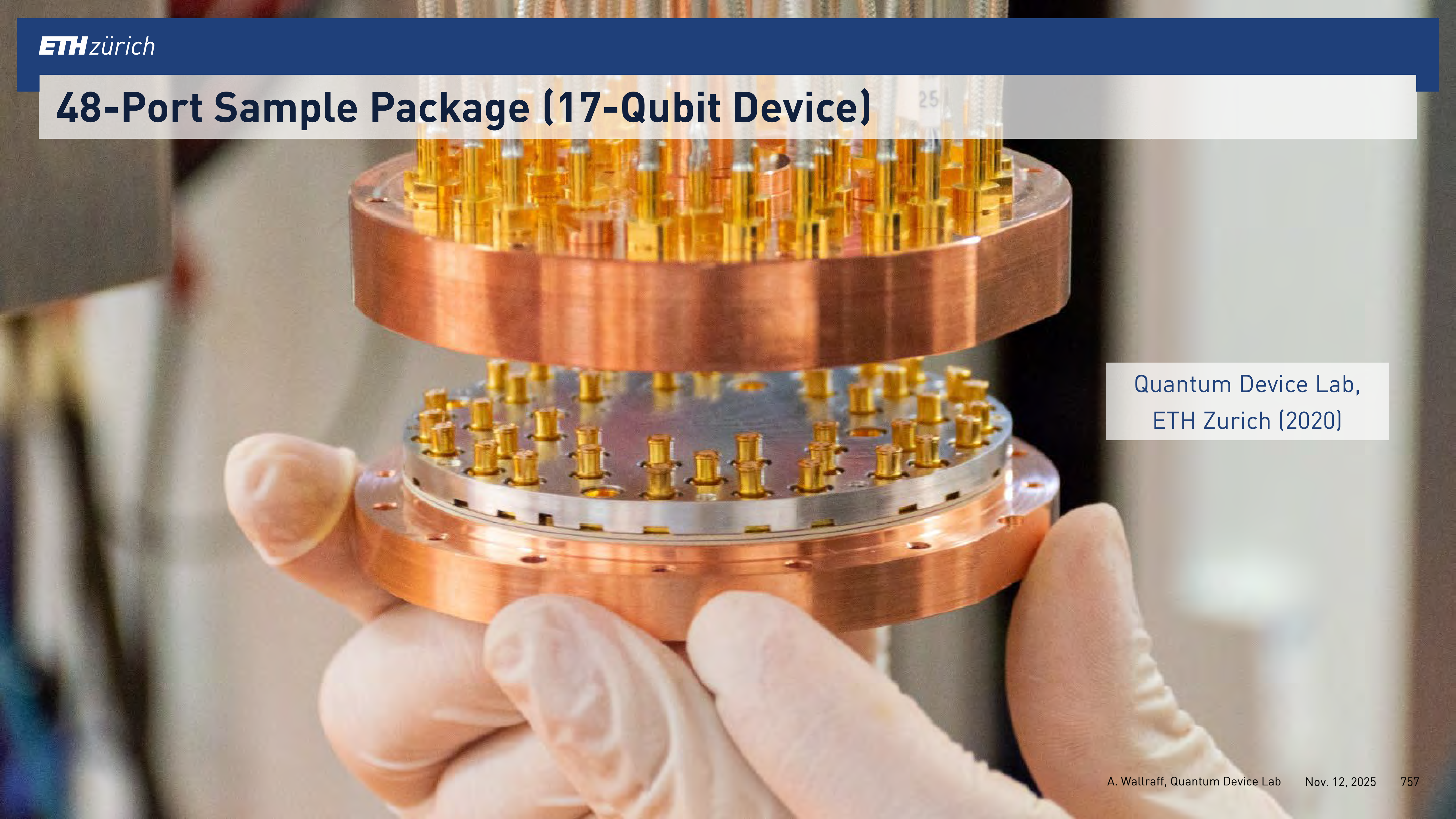
T. Walter, P. Kurpiers *et al., Phys. Rev. Applied* **7**, 054020 (2017)

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)

Quantum Device Lab, ETH Zurich (2021)


BLUE
FORS

Qubit-Encoded Quantum Error Correction Experiments

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., Nature 595, 7867 (2021)]

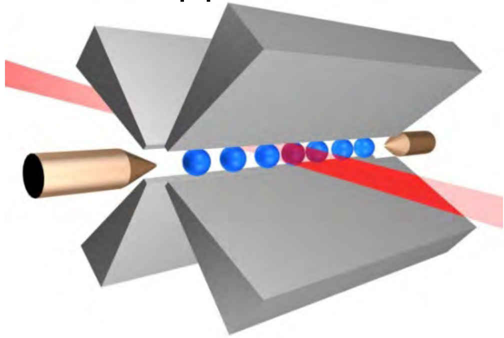
Quantum codes, single-cycle experiments:

- 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

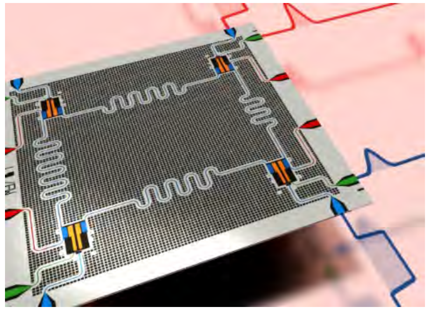
- Andersen et al., Nat. Phys. 16, 875 (2020)
- Chen et al., Nature 595, 7867 (2021)
- Marques et al., Nat. Phys. **18**, 80 (2022)

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)

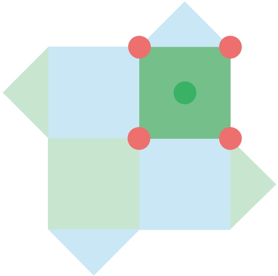
Repeated quantum error correction

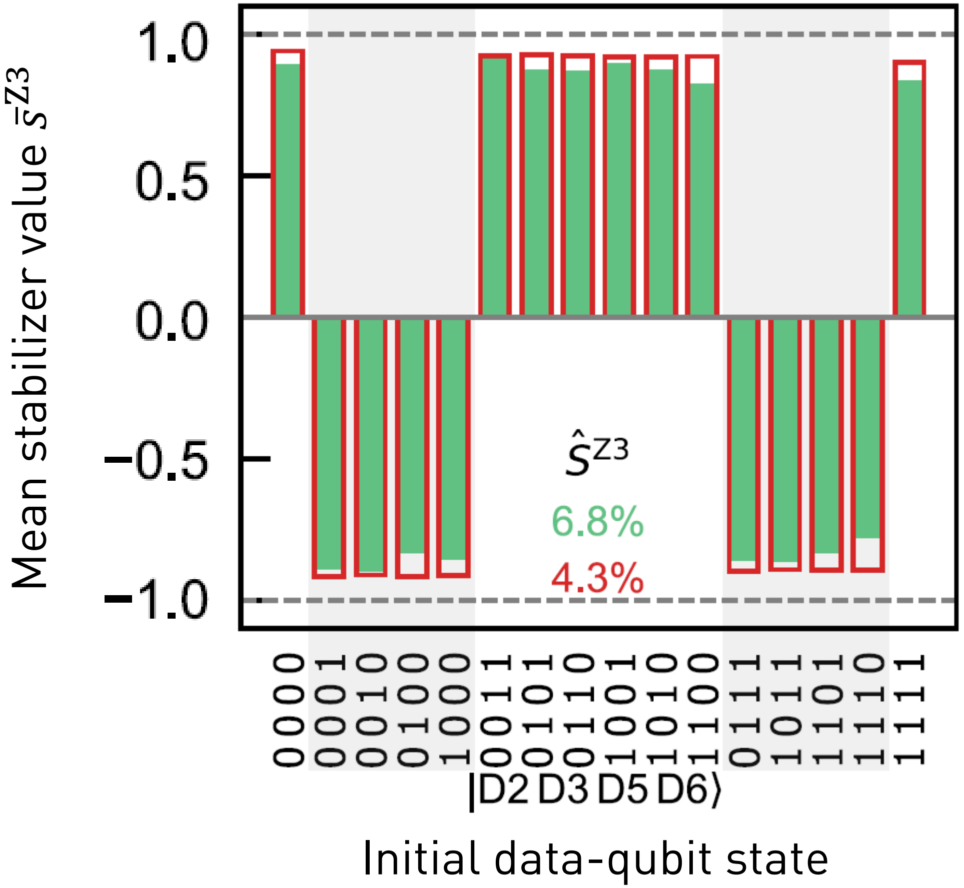
- Color code (trapped ions)
  Ryan-Anderson et al., PRX 11, 041058 (2021)
- Distance-3 surface code (s.c.)
  Krinner, Lacroix *et al.*, *Nature* **605**, 669 (2022)
  Zhao et al., *PRL* **129**, 030501 (2022)
- Distance-3 heavy-hexagon code (s.c.)
  Sundaresan et al., *Nat. Commun.* **14**, 2852 (2023)
- Distance-3 to 5 scaling of the surface code (s.c.)
  Google AI, *Nature* **614**, 676 (2023)

Stabilizer Characterization

Individual characterization

- Prepare data qubits of plaquette in all 4 (weight-2) or 16 (weight-4) basis states
- Stabilizer execution yields $s^{Ai} = \pm 1$
- Average over $\sim 4 \times 10^4$ measurements to obtain $\bar{s}^{Ai}$
- Measured and calculated error





S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

Stabilizer Characterization

Individual characterization

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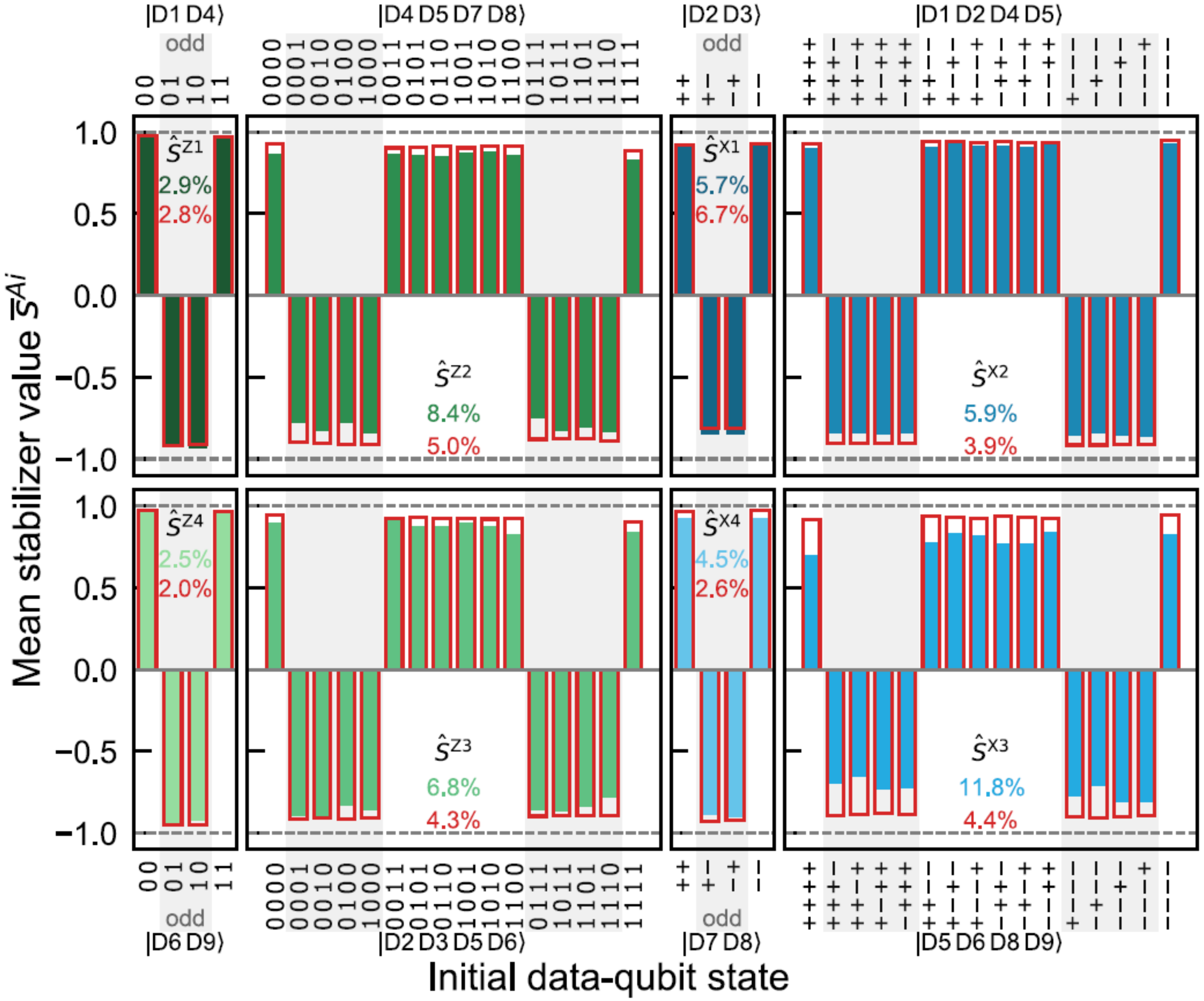
- Average over $\sim 4 \times 10^4$ measurements to obtain $\bar{s}^{Ai}$
- Measured and calculated error

Average parity error

- Weight-2 stabilizers: 3.9(1.3) %
- Weight-4 stabilizers: 8.2(2.2) %

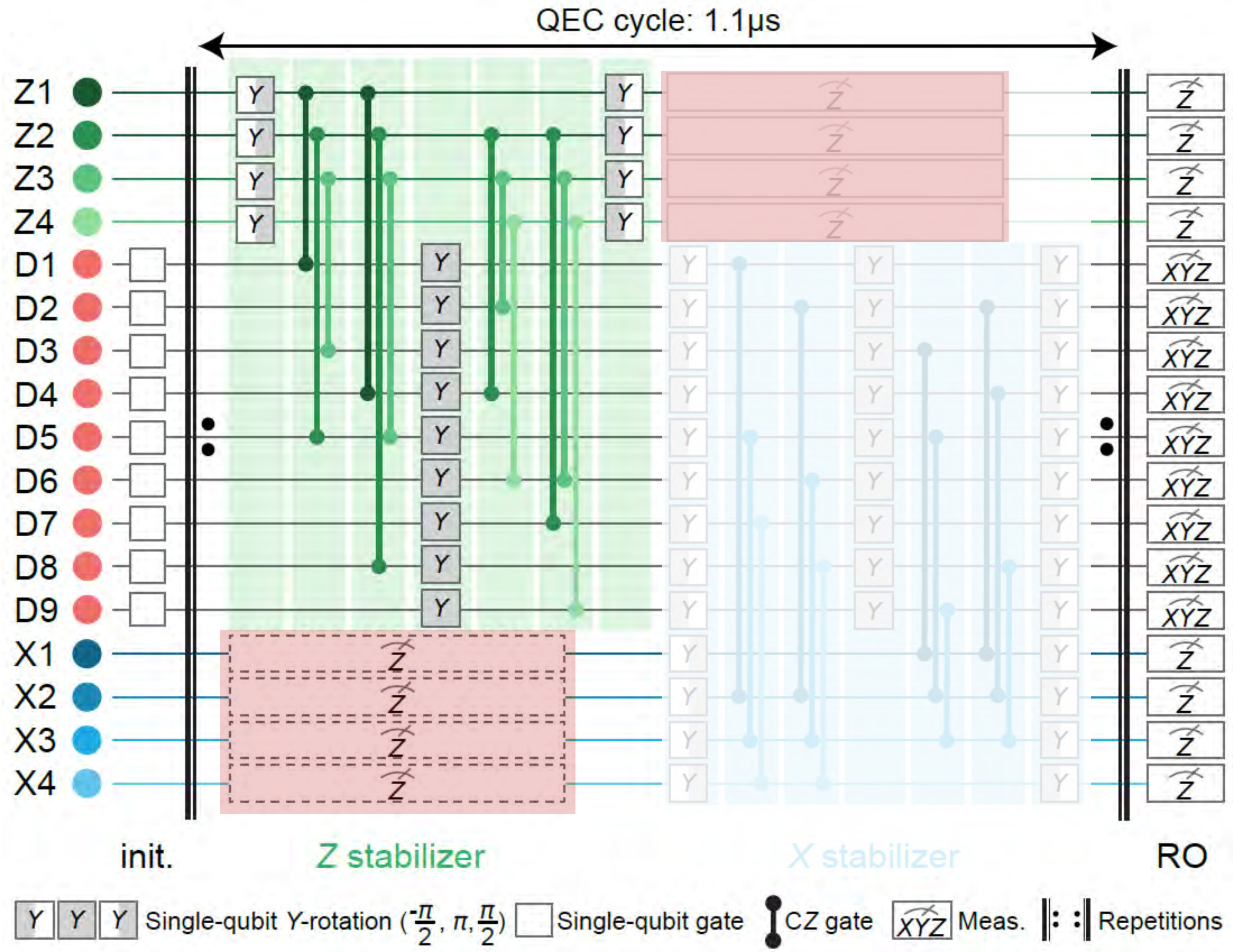
Qualitative agreement with master-equation simulations



S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (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.
- Logical state preparation: $|0\rangle_L, |1\rangle_L$ and $|\pm\rangle_L = (|0\rangle_L \pm |1\rangle_L)/\sqrt{2}$ in single cycle.
- State preservation over n cycles
  - Cycle duration: 1.1 μs
  - Leakage detection and rejection executed in every cycle
  - circuits with ~ 800 single-qubit gates and ~ 400 two-qubit gates



Versluis et al., *PR Applied* **8**, 034021 (2017)
S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

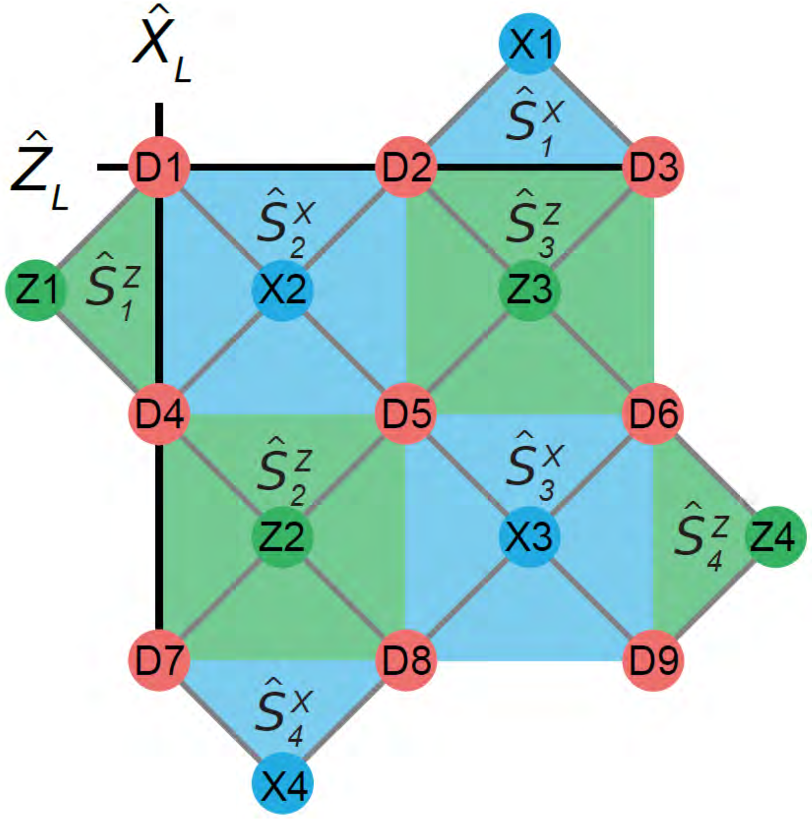
Repeated Quantum Error Correction

Measurement of Logical Z and Logical X Operators

- Initialization
  - $|0\rangle_L$: prepare data qubits in $|0\rangle^{\otimes 9}$
  - $|1\rangle_L$: prepare data qubits in $X_L|0\rangle^{\otimes 9}$
  - $|+\rangle_L$: prepare data qubits in $|+\rangle^{\otimes 9}$
  - $|-\rangle_L$: prepare data qubits in $Z_L|+\rangle^{\otimes 9}$
- Perform n QEC cyles
- Read out all data qubits in Z-basis (X-basis)

Analysis

- Determine logical operator $z_\mathrm{L} = z_1 z_2 z_3 = \pm 1$ ($x_\mathrm{L} = x_1 x_4 x_7 = \pm 1$) for each run with up to n repeated cycles
- Apply correction conditioned on decoded syndromes for each run
- Average over runs with n repeated cycles to compute $\bar{z}_\mathrm{L} = \langle \hat{Z}_\mathrm{L} \rangle$ ($\bar{x}_\mathrm{L} = \langle \hat{X}_\mathrm{L} \rangle$)

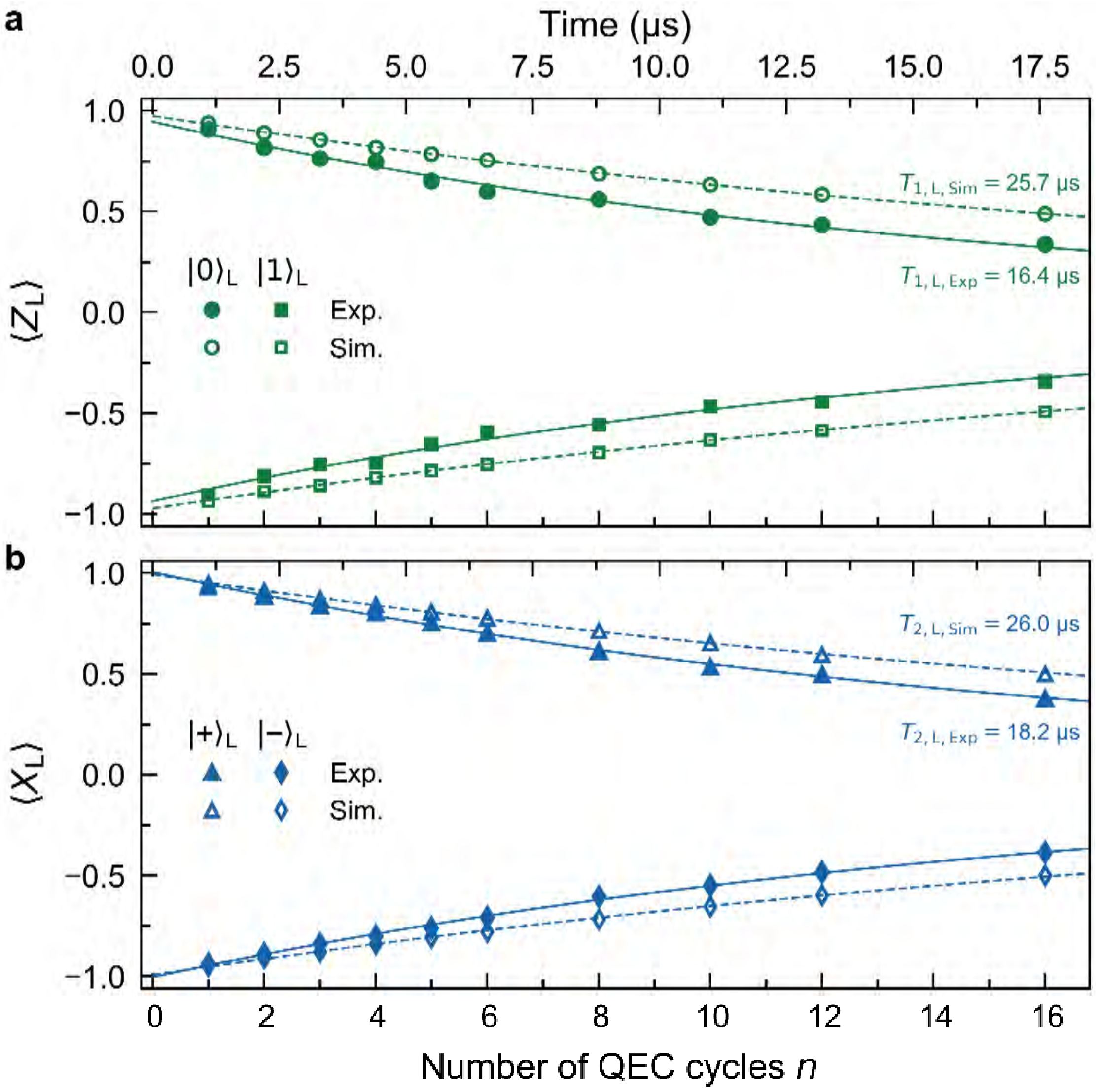


S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

Repeated Quantum Error Correction

Outcomes Logical Z and Logical X

- Exponential decay of logical expectation values
- Logical lifetime
  $T_{1,\mathrm{L}} = 16.4(8)\ \mu\mathrm{s} \gg t_c = 1.1\ \mu\mathrm{s}$
- Logical coherence time
  $T_{2,\mathrm{L}} = 18.2(5)\ \mu\mathrm{s} \gg t_c = 1.1\ \mu\mathrm{s}$
- Master equation simulation of logical lifetimes of $\sim$ 26 μs provide upper bound for achievable lifetimes with our device performance



S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

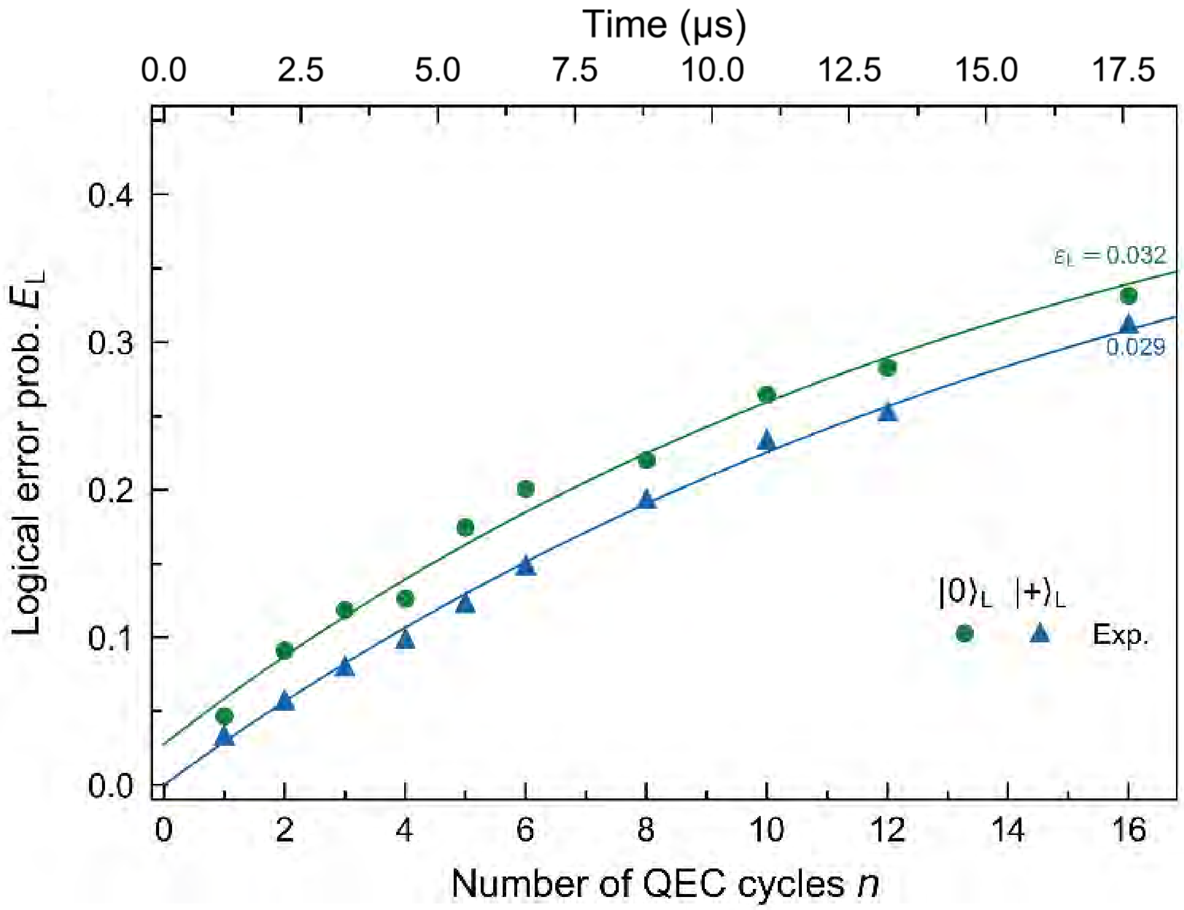
Logical Error Probability and Logical Error per Cycle

Logical error probability:

- $E_\mathrm{L} = (1 - \langle \hat{Z}_\mathrm{L} \rangle)/2$ for eigenstates of $\hat{Z}_\mathrm{L}$
- $E_\mathrm{L} = (1 - \langle \hat{X}_\mathrm{L} \rangle)/2$ for eigenstates of $\hat{X}_\mathrm{L}$

Logical error per cycle:

- Extracted from fit to $E_\mathrm{L}(n)$ or from $T_{1/2,\mathrm{L}}$:
  $\epsilon_\mathrm{L} = \frac{1}{2}\left[1 - \exp(-t_\mathrm{c}/T_{1/2,\mathrm{L}})\right] \approx t_\mathrm{c}/2T_{1/2,\mathrm{L}}$
- $\epsilon_\mathrm{L} \sim 0.03$



S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

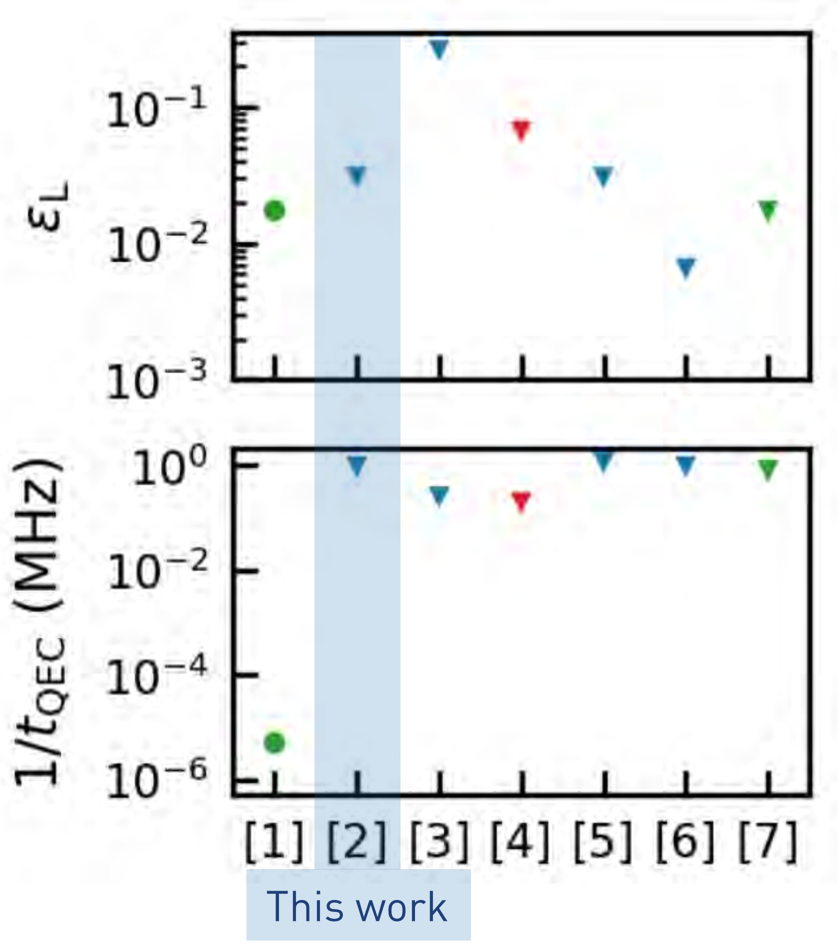
Repeated Quantum Error Correction with $d \geq 3$ Codes

Published work:

- Honeywell: [1] Ryan-Anderson *et al.*, *Phys. Rev. X* **11**, 041058 (2021)
  ETHZ: [2] Krinner, Lacroix *et al. Nature* **605**, 669 (2022)
  USTC: [3] Zhao et al., *PRL* **129**, 030501 (2022)
  IBM: [4] Sundaresan *et al., Nat. Commun.* **14**, *2852* (2023)
  Google: [5] Google Quantum AI, *Nature* **614**, 676 (2023)
  Google: [6] Google Quantum AI, *Nature* **638**, 920 (2025)
  Google: [7] Lacroix *et al., Nature* (2025)

Implementations:

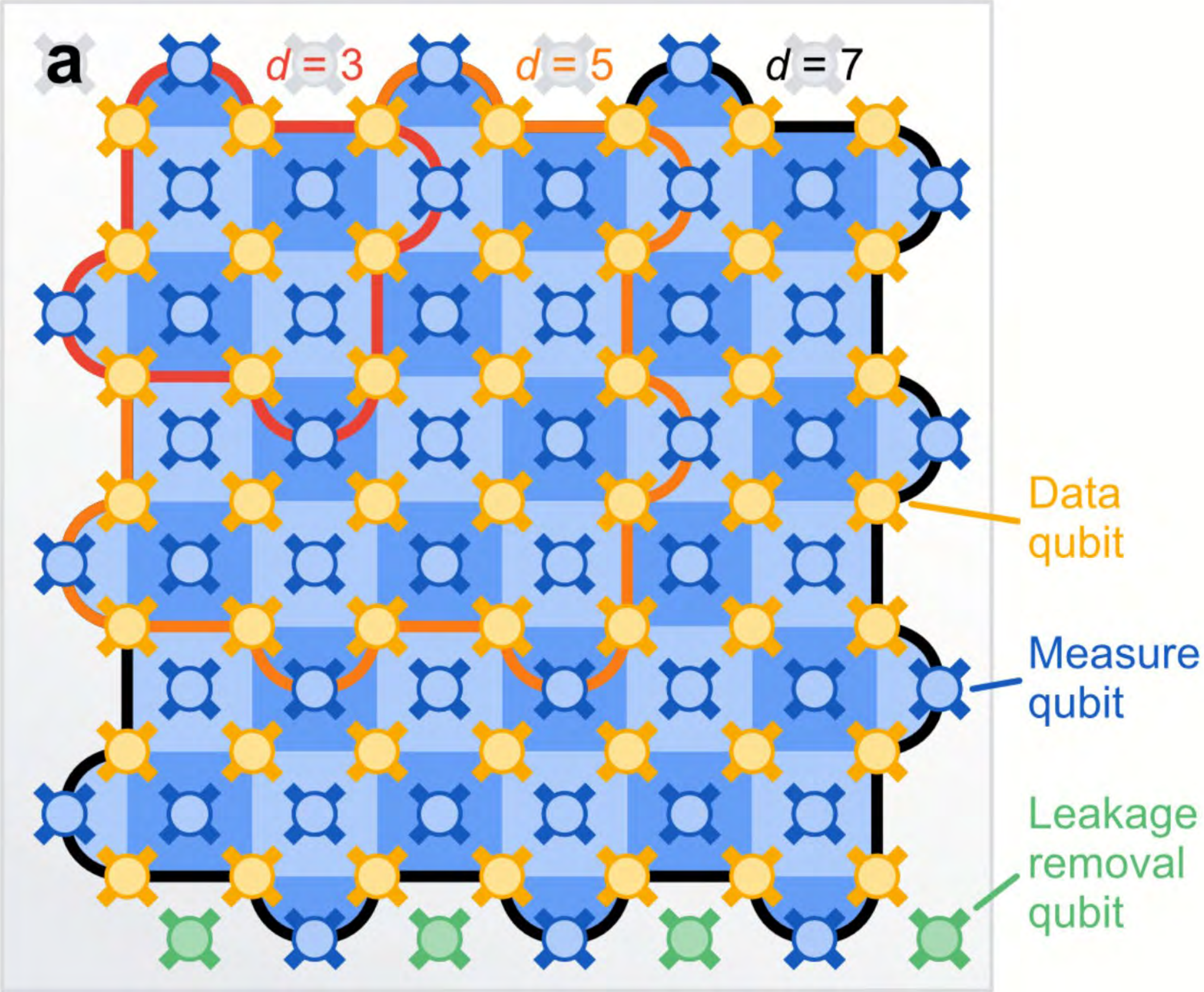
- superconducting-circuits (∇) and trapped-ions (O)
- Color code, surface code and heavy-hexagon code



Performance criteria

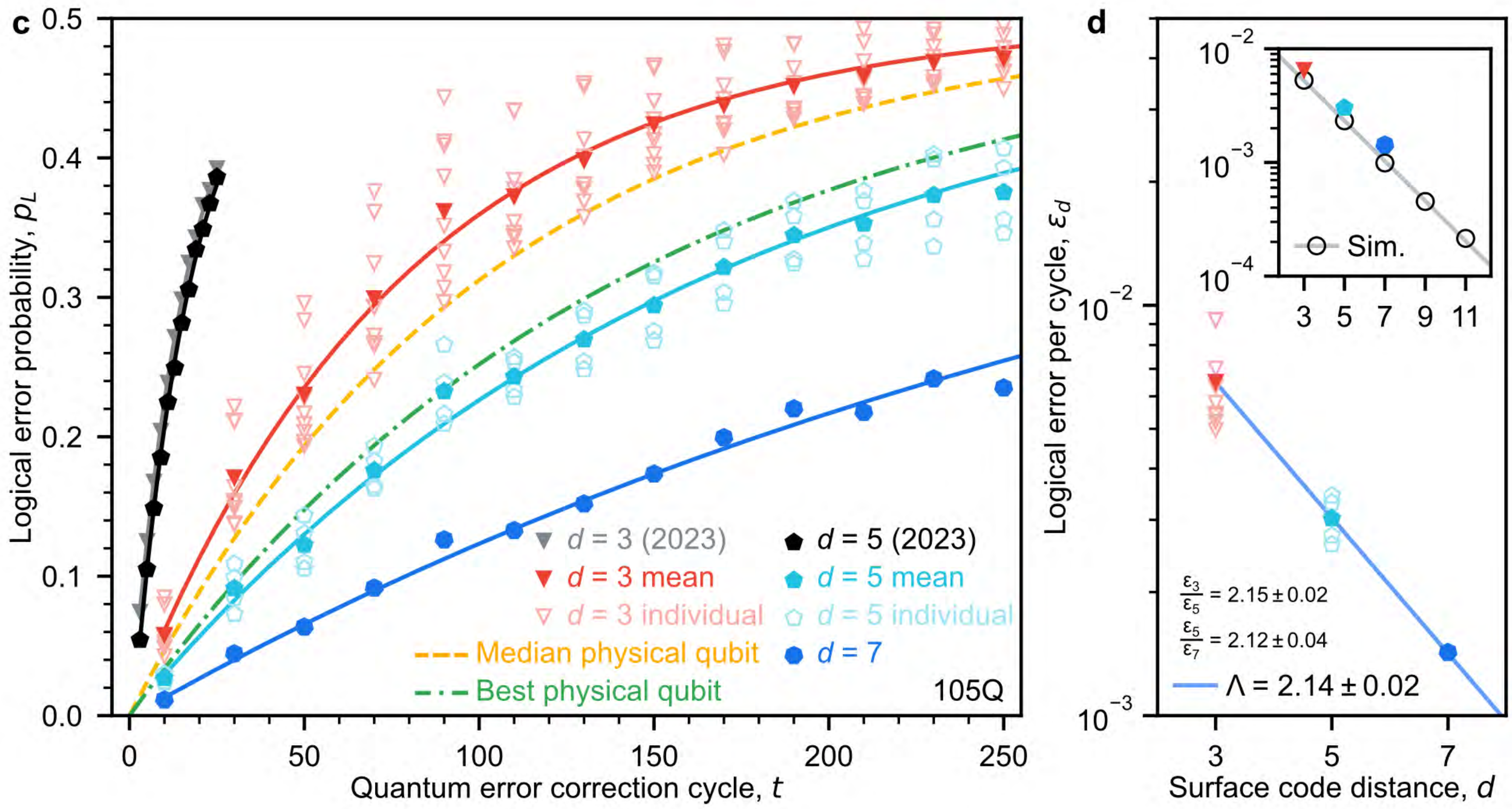
- Small logical error per cycle ε_L
- High QEC cycle rate $1/t_{QEC}$

Distance-Three, -Five and –Seven Surface Code Layout



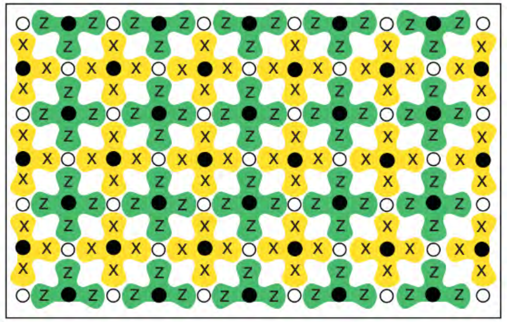
Google Quantum AI, *Nature* **638**, 920 (2025)

Distance Scaling and Logical Error Suppression



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

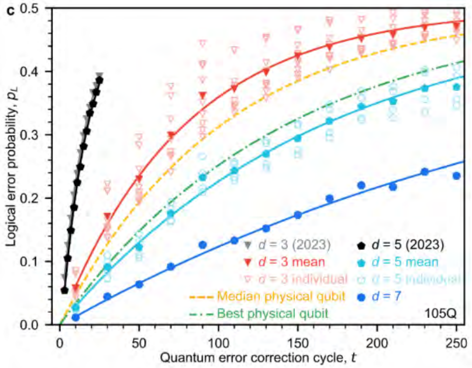
Surface Code and Lattice Surgery



- Surface code promising candidate for implementation of logical qubits in superconducting circuits

  Kitaev, A. Ann. Phys. 303 1 (2003)

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

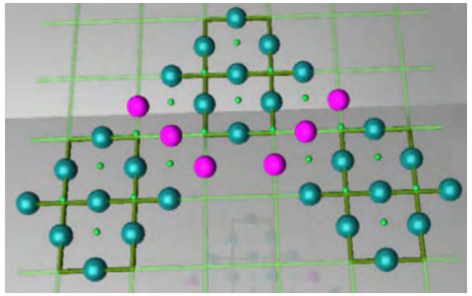


- Experimental realizations of logical state preservation near and beyond the threshold

  Krinner, S. et al. Nature 605, pages 669–674 (2022)

  Google Quantum AI, Nature 614, pages 676–681 (2023)

  Google Quantum AI and Collaborators, Nature (2024)



- Lattice surgery allows realization of non-transversal interactions between encoded qubits with low qubit-overhead

  Horsman, D. et al. New J. Phys. 14 123011 (2012)

Experimental Work on Logical Qubit Operations

Logical operations on **encoded qubits**:

- Fault-tolerant subset of Clifford group on [4,2,2] code (s.c.)
  Harper, R. et al. Phys. Rev. Lett. **122**, 080504 (2019)
- Transversal CNOT on two [7,1,3] color codes (ions)
  Postler, L. et al. Nature **605**, 675 (2022)

Non-fault-tolerant **arbitrary state preparation**

- d = 3 Bacon-Shor code (ions)
  Egan, L. et al. Nature **598**, 281 (2021)
- d = 3 surface code (s.c.)
  Ye, Y. et al. Phys. Rev. Lett. **131**, 210603 (2023)

Lattice surgery ...

- ... on a d = 2 surface code (ions)
  Erhard, A. et al. Nature **589**, 220 (2021)
- ... on interleaved d = 3 3CX and Bacon-Shor code (s.c.)
  Hetenyi, B. et al. PRX Quantum **5**, 040334 (2024)
- ... on a d = 3 color code (s.c.)
  Lacroix, N. et al., Nature (2025)

Independent logical qubits during idling (modularity):

- transversal implementation of various QEC codes (ryd.)
  Bluvstein, D. et al. Nature **626**, 58 (2024)
- state teleportation on three d = 3 color codes (ions)
  Ryan-Anderson, C. et al. Science **385**, 1327 (2024)

Here: Modular lattice surgery on surface code with partial decoding from repeated syndrome extraction on superconducting qubits

Transversal Gates vs. Lattice Surgery

All-to-all connectivity (ions, Rydberg atoms)

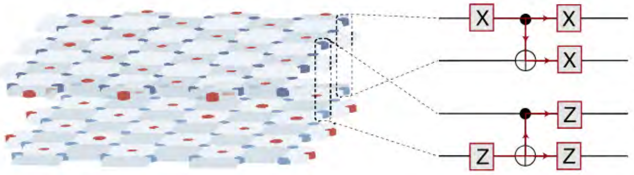
- Allows for transversal logical two-qubit gates

2D square lattice connectivity (s.c.)

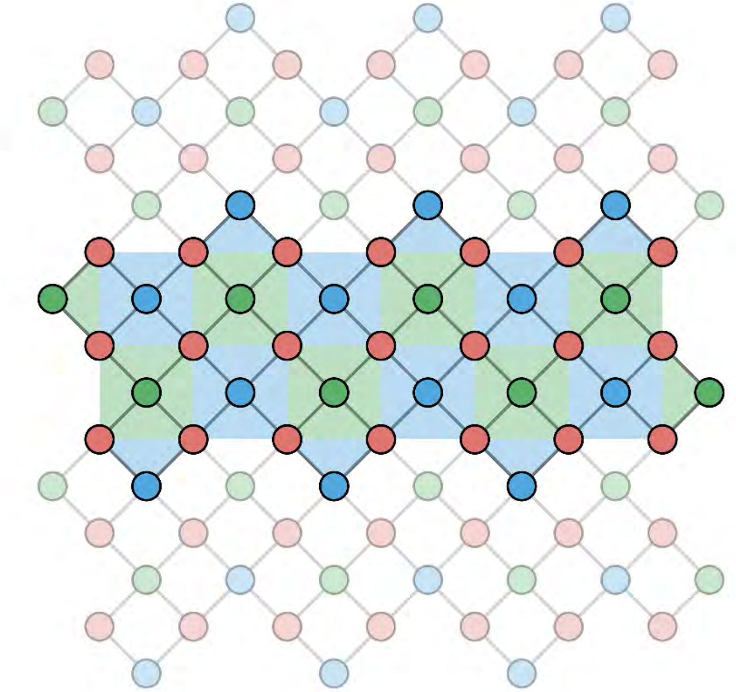
- Requires lattice surgery

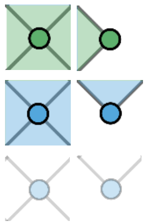
Lattice surgery operations:

- Merge
- Split
- Measurement of logical two-qubit observables $\hat{X}_{L1}\hat{X}_{L2}$ (or $\hat{Z}_{L1}\hat{Z}_{L2}$)



D. Bluvstein et al, Nature **626**, pages 58–65 (2024)





Z-type stabilizers

X-type stabilizers

Inactive aux qubits

Data qubit

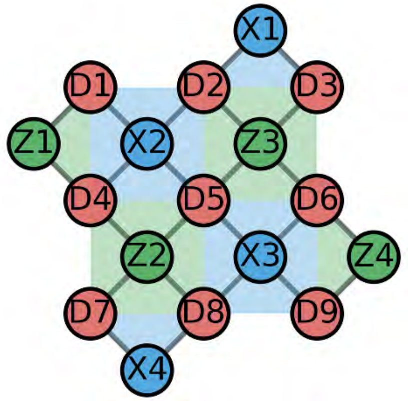
Data qubit (inactive)

Horsman, D. et al. New J. Phys. **14** 123011 (2012)

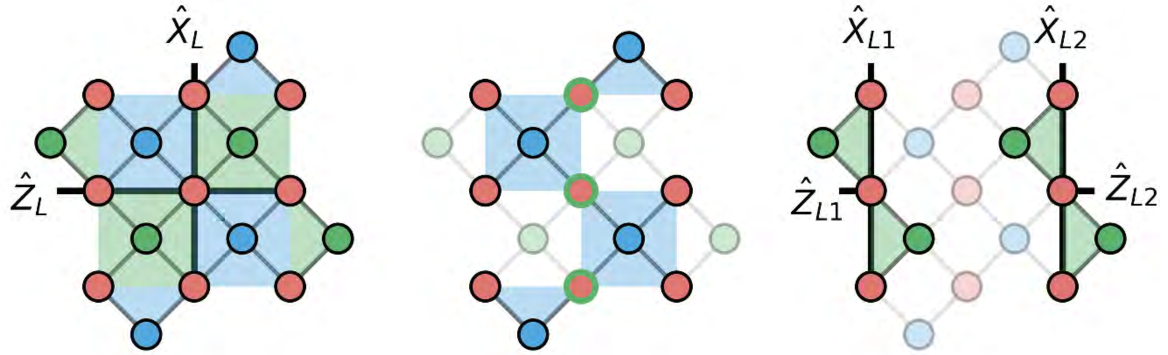
Austin G. Fowler, Craig Gidney arXiv:1808.06709 (2018)

Logical Operators of the Surface and the Repetition Codes

- Distance-three surface code qubit:
  - 3×3 patch on the data qubit lattice,
  - single bit-flip and phase-flip errors correctable
  - Logical operator definitions
- Lattice split operation transforms the d = 3 surface code into two d = 3 bit-flip codes:
  - Stop measuring X-type stabilizers
  - Readout of middle column of data qubits in Z-basis
- Two d = 3 bit-flip repetition codes:
  - Two 1×3 patches
  - Single bit-flip error correctable
  - Logical operator definitions



$$\hat{Z}_{L2} = \hat{Z}_{D6}$$
$$\hat{X}_{L2} = \hat{X}_{D3}\hat{X}_{D6}\hat{X}_{D9}$$
$$\hat{Y}_{L2} = \hat{X}_{D3}\hat{Y}_{D6}\hat{X}_{D9}$$



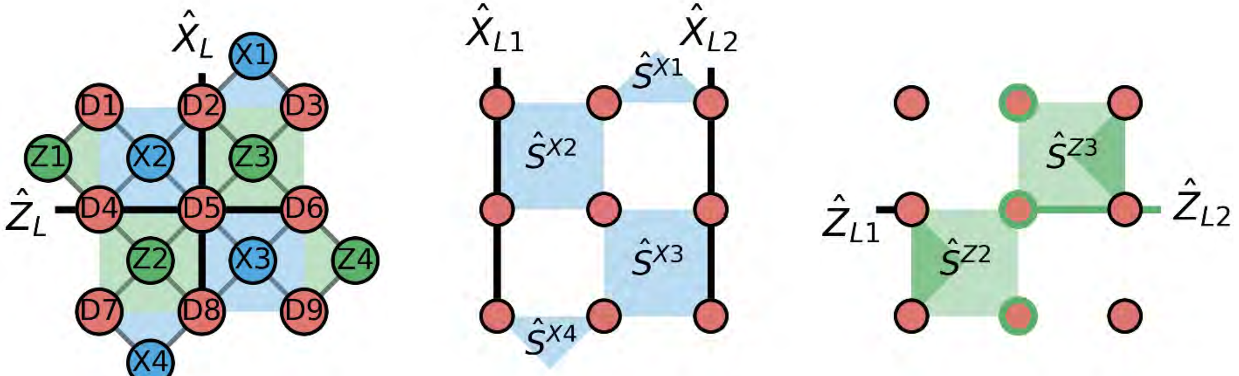
$$\hat{Z}_L = \hat{Z}_{D4}\hat{Z}_{D5}\hat{Z}_{D6}$$
$$\hat{X}_L = \hat{X}_{D2}\hat{X}_{D5}\hat{X}_{D8}$$
$$\hat{Y}_L = \hat{Z}_L\hat{X}_L = \hat{X}_{D2}\hat{Z}_{D4}\hat{Y}_{D5}\hat{Z}_{D6}\hat{X}_{D8}$$

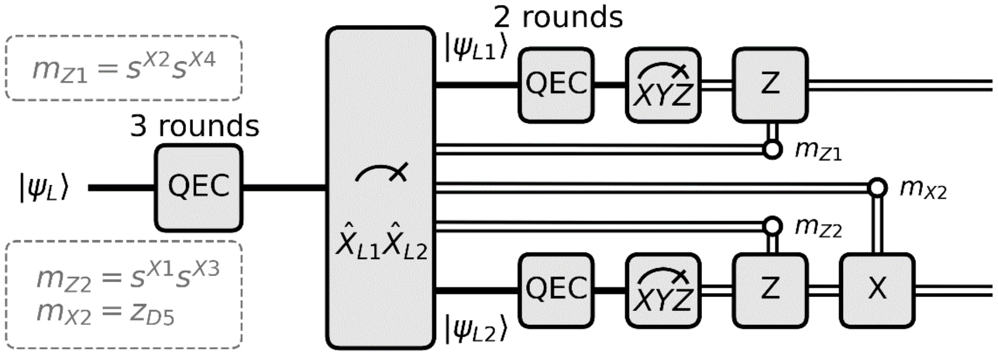
$$\hat{Z}_{L1} = \hat{Z}_{D4}$$
$$\hat{X}_{L1} = \hat{X}_{D1}\hat{X}_{D4}\hat{X}_{D7}$$
$$\hat{Y}_{L1} = \hat{X}_{D1}\hat{Y}_{D4}\hat{X}_{D7}$$

Besedin, I., Kerschbaum M. *et al.,* arXiv: 2501.04612 (2025)

Pauli Frame Update

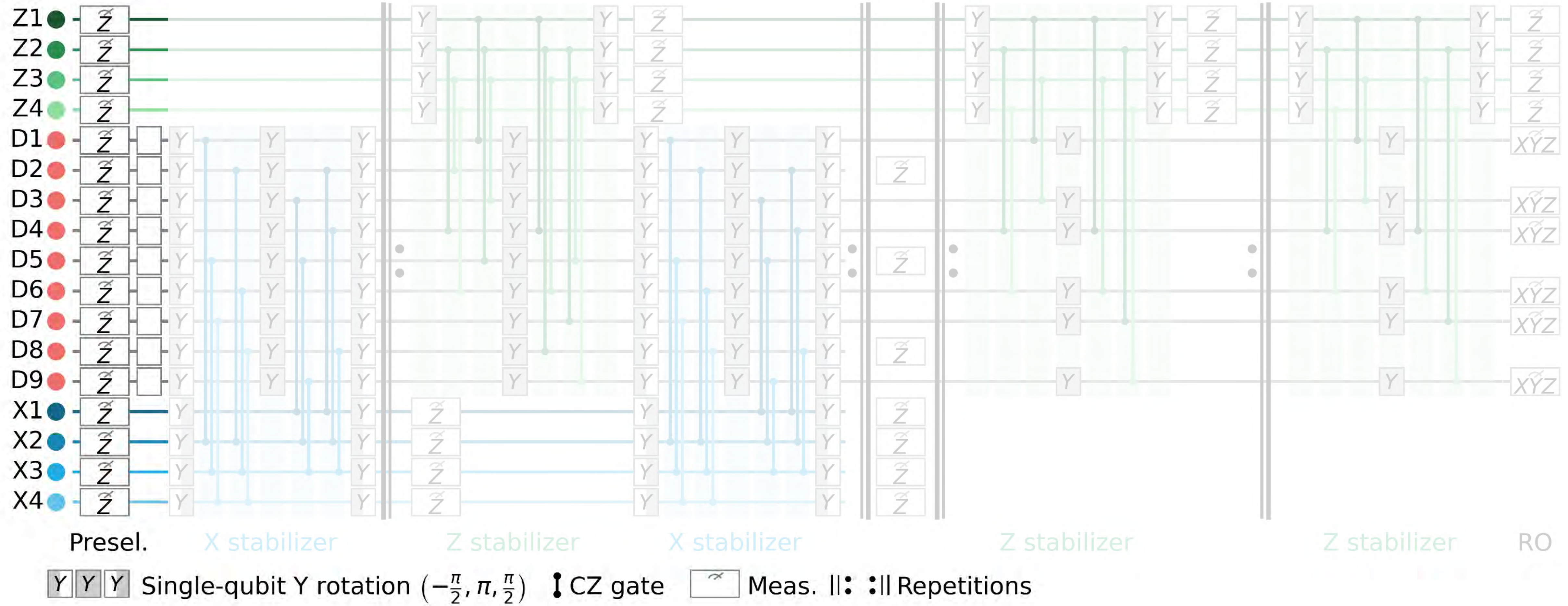
- Logical states after split depend on measurement outcomes
- Relation between repetition and surface code logical operators
  - Logical X-operators:
    $$\hat{X}_{L1} = \hat{X}_L \hat{S}^{X2} \hat{S}^{X4}$$
    $$\hat{X}_{L2} = \hat{X}_L \hat{S}^{X1} \hat{S}^{X3}$$
  - Logical Z-operators:
    $$\hat{Z}_L = \hat{Z}_{D4} \hat{Z}_{D5} \hat{Z}_{D6} = \hat{Z}_{L1} (\hat{Z}_{L2} \hat{Z}_{D5})$$
- Deterministic operation realized by feed-forward Pauli-Frame update:
  - $\hat{X}_L \to \hat{X}_{L1}, \hat{X}_{L2}$
  - $\hat{Z}_L \to \hat{Z}_{L1} \hat{Z}_{L2}$
  - performed in post-processing
- Weight-4 Z-type stabilizers become weight-2, value updated by data qubit readout outcome





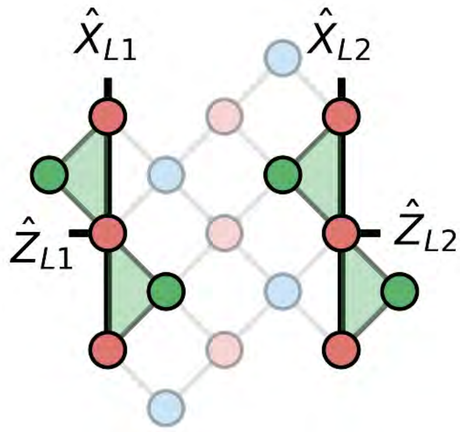
Besedin, I., Kerschbaum M. *et al.,* arXiv: 2501.04612 (2025)

Gate Sequence of Lattice-Split Operation



- Qubit initialization
- X-syndrome extraction to initialize d = 3 qubit
- Three rounds of syndrome extraction
- Lattice split
- Two rounds of syndrome extraction
- Logical observable readout

Logical Bell State Creation



- Prepare surface-code $|0\rangle_L$ and perform lattice split
- Fault-tolerant (d = 3) with respect to **bit-flip errors**
- Non-fault-tolerant (d = 1) with respect to **phase-flip errors**

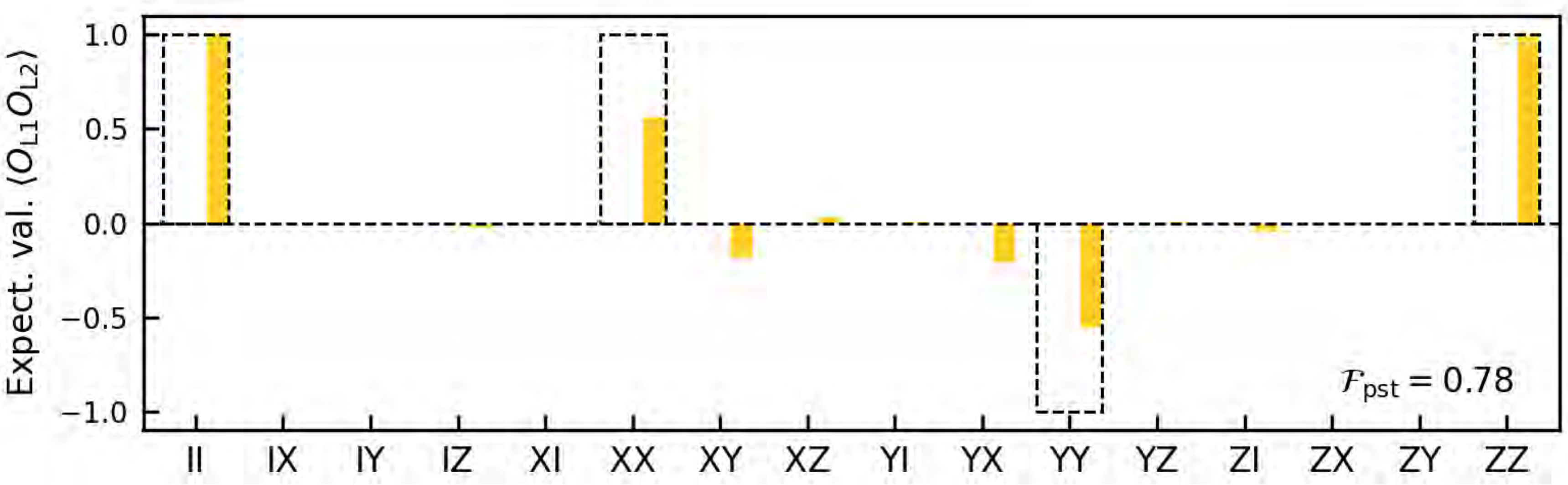
- Evaluate Logical Bell state after **Pauli-frame update**:
  - Ideally $X_{L1}X_{L2} = Z_{L1}Z_{L2} = 1$ and $Y_{L1}Y_{L2} = -1$
- ~70'000 shots per logical operator, reject leakage, and calculate **expectation values**

Besedin, I., Kerschbaum M. *et al.,* arXiv: 2501.04612 (2025)

Logical State Tomography

- Measure **all nine basis combinations of repetition code logical qubits** to perform **logical quantum state tomography**

- Use extracted syndromes to **post-select** on zero syndrome elements (no error)
  - $Z_{L1}Z_{L2}$ error <1%: **fault tolerant** with respect to **bit-flips**
  - Expectation value of $X_{L1}X_{L2}$ and $Y_{L1}Y_{L2}$ limited by repetition code



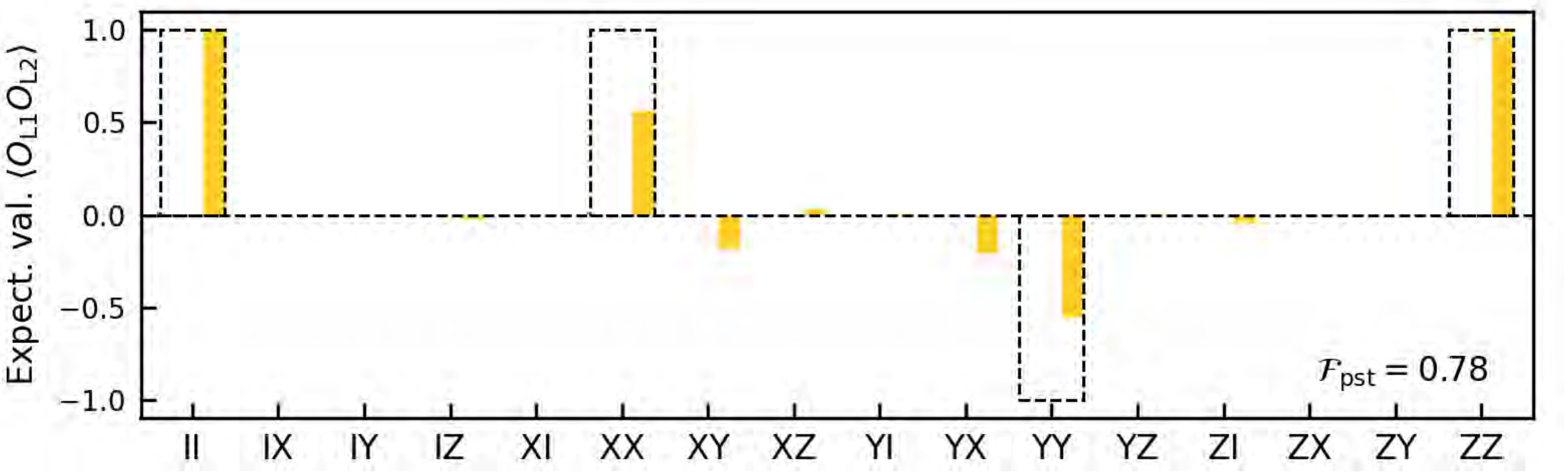
Besedin, I., Kerschbaum M. *et al.,* arXiv: 2501.04612 (2025)

Logical State Tomography

- Measure **all nine basis combinations of repetition code logical qubits** to perform **logical quantum state tomography**

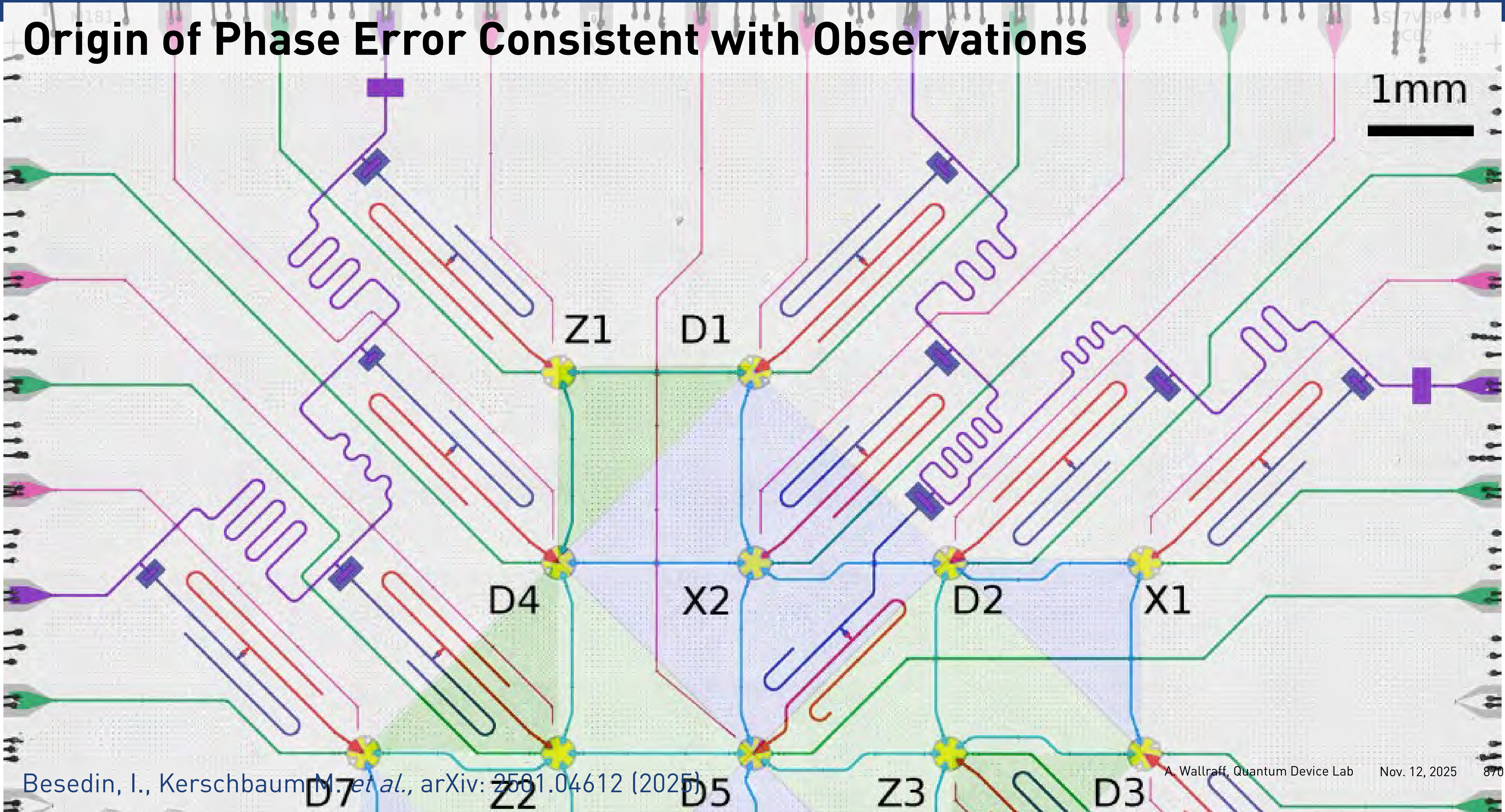
Note

- Non-zero $X_{L1}Y_{L2}$ and $Y_{L1}X_{L2}$ expectation values
- Consistent with a $0.11\,\pi$ phase error on the first logical qubit state



Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)

Origin of Phase Error Consistent with Observations

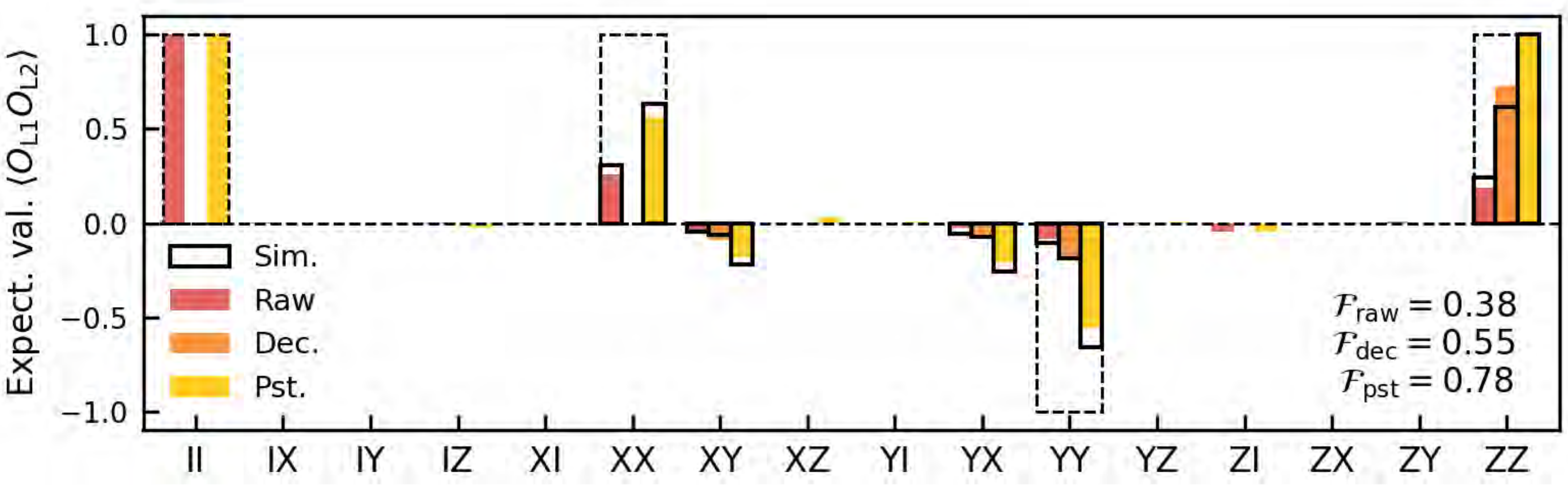


Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)

Logical State Tomography

- Measure **in all nine combinations of bases of logical qubits** to perform **logical quantum state tomography**

- Use **MWPM decoder**:
  - raw $Z_{L1}\ Z_{L2}$ = 0.19 is improved to 0.73
- Good agreement of data with Pauli error model **simulations** based on randomized benchmarking (RB) and coherence measurements (+ coherent error on D1)

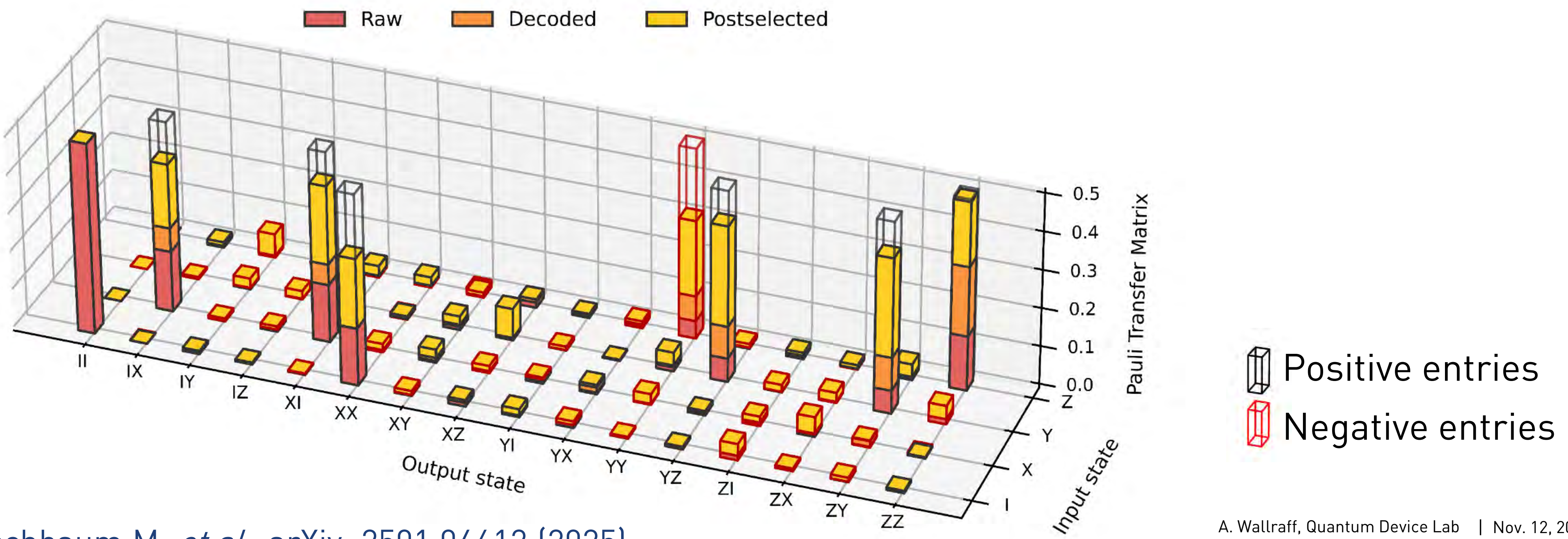


Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)

Logical Quantum Process Tomography

- Split acting on logical input states $|0\rangle_L, |1\rangle_L, |+\rangle_L, |-\rangle_L, |+i\rangle_L, |-i\rangle_L$ states
- Split operation maps Pauli operators to Pauli operators
- Note: single-qubit phase rotation of 0.11π on logical qubit 1 corrected for.

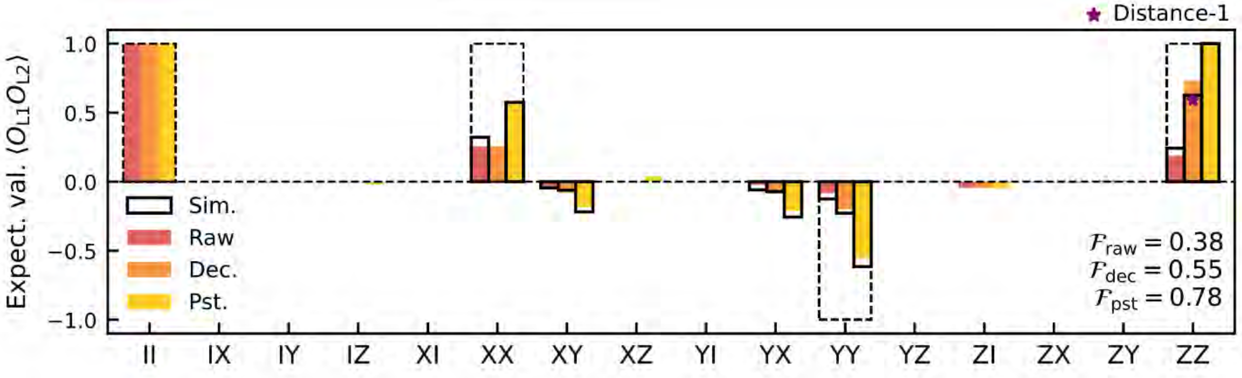
- Pauli transfer matrix (PTM) representation
  - ideal values $\pm 1/2$
- Process fidelity
  - raw: $\mathcal{F} = 0.310(12)$
  - decoded: $\mathcal{F} = 0.442(12)$
  - post-selected: $\mathcal{F} = 0.80(3)$

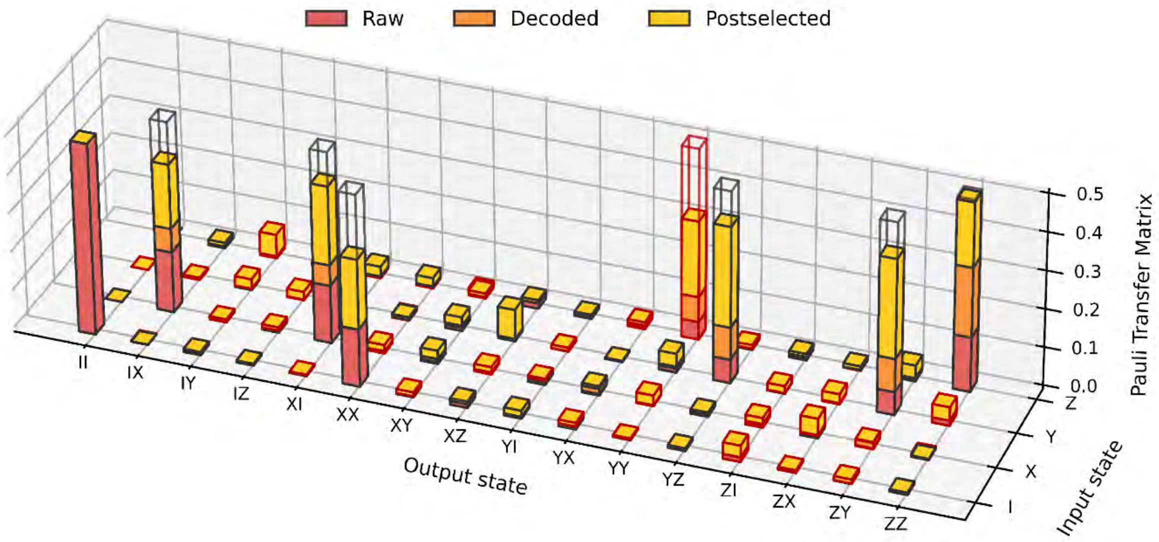


Besedin, I., Kerschbaum M. *et al.*, arXiv: 2501.04612 (2025)

Summary and Outlook

- Demonstrated **lattice surgery** on a distance-three surface code, **creating a logical Bell state** of two distance-three repetition codes
- **Increased decoded observable expectation value** compared to non-encoded variant
- Measured **logical Pauli-transfer matrix** for lattice split operation

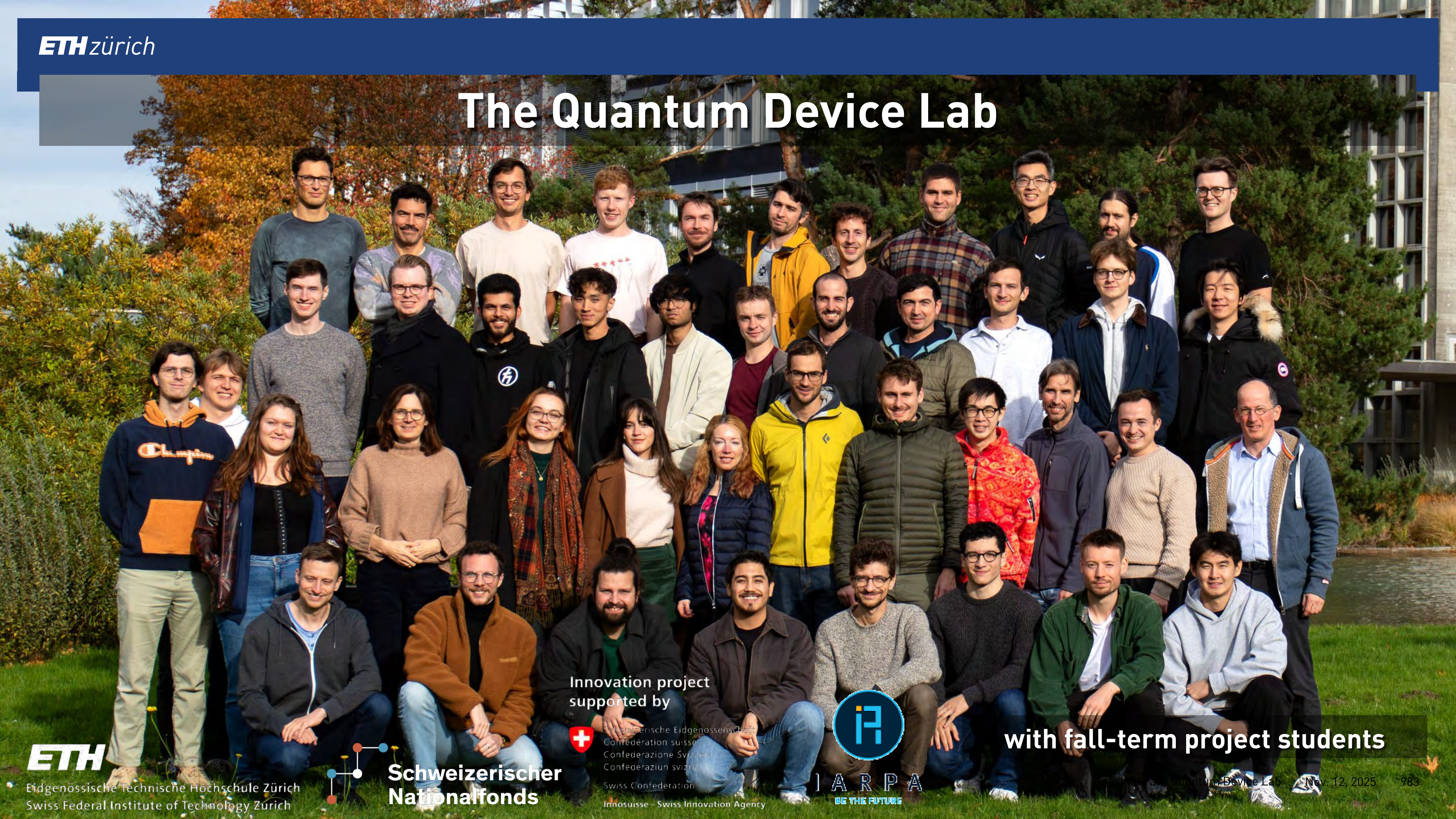




Outlook

- Deploy full scheme on two distance-three surface codes and integrate in **logical state teleportation protocol**

The Quantum Device Lab



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