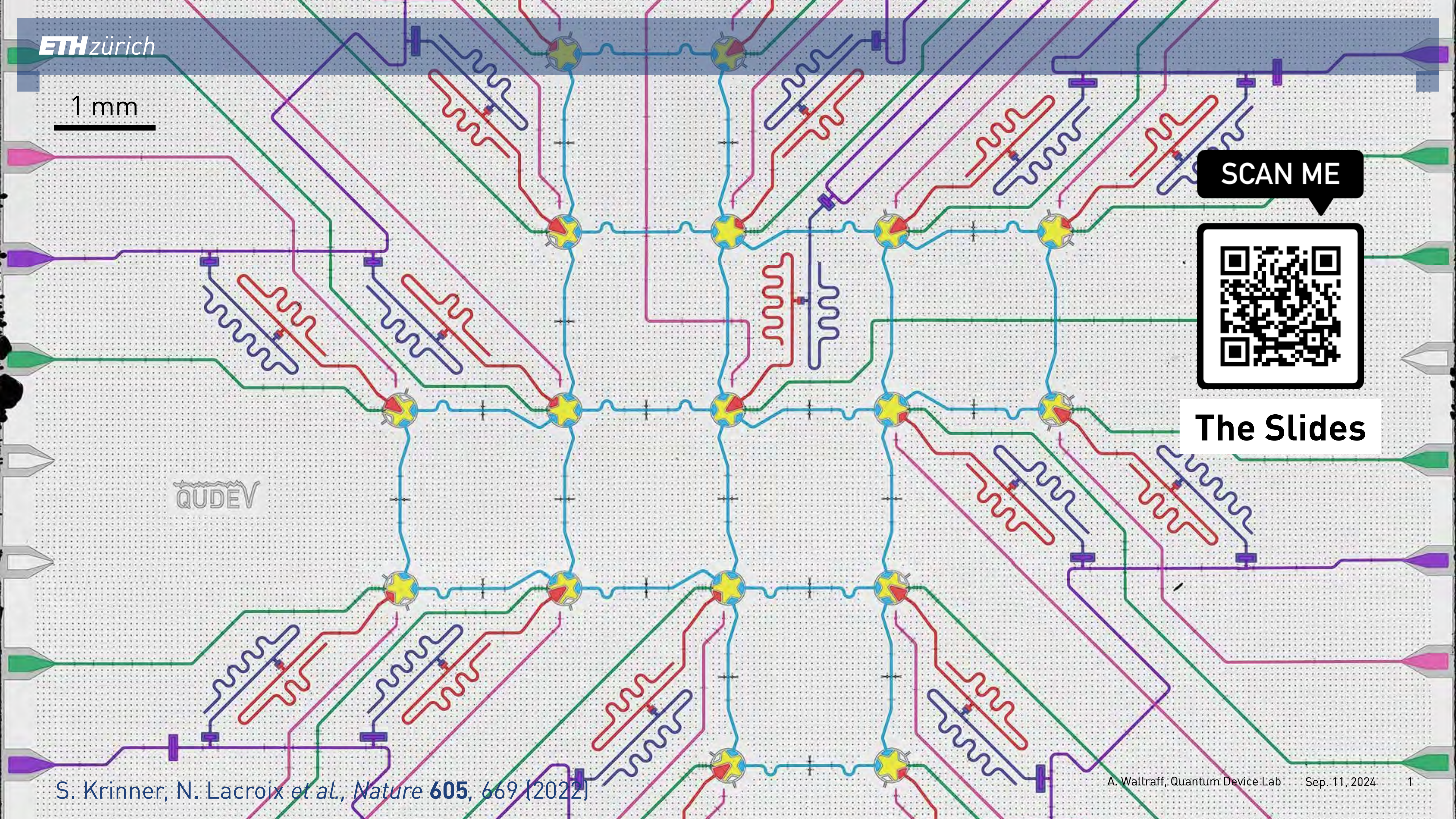
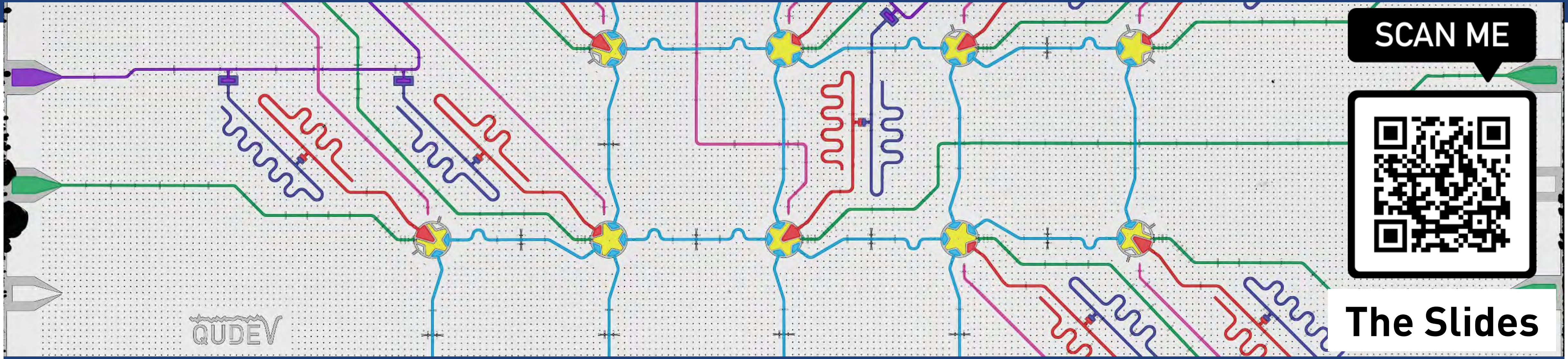


SCAN ME

The Slides

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



Quantum Science with Superconducting Circuits

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, S. Krinner, A. Kulikov, N. Lacroix, G. Norris, M. Pechal, K. Reuer, A. Rosario, C. Scarato, J. Schaer, Y. Song, F. Swiadek, F. Wagner, A. Wallraff *(ETH Zurich)*

Eng. & Tech. Team: A. Akin, M. Bahrani, A. Flasby, A. Fauquex, R. Keller, N. Kohli, R. Siegbert, M. Werner *(ETH Zurich)*

IARPA BE THE FUTURE

Schweizerischer Nationalfonds

Innovation project supported by

Schweizerische Eidgenossenschaft
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Past Group Members & Current Collaboration Partners

www.qudev.ethz.ch

Former group members now
Faculty/PostDoc/PhD/Industry

A. Abdumalikov (Gorba AG)
M. Allan (LMU Munich)
C. K. Andersen (TU Delft)
M. Baur (ABB)
J. Basset (U. Paris Sud)
S. Berger (AWK Group)
R. Bianchetti (ABB)
D. Bozyigit (Scandit)
R. D. Buijs (ASML)
M. Collodo (Zurich Instruments)
A. Copetudo (NU Singapore)
C. Eichler (FAU Erlangen)
A. Fedorov (UQ Brisbane)
Q. Ficheux (CNRS Grenoble)
S. Filipp (WMI & TU Munich)
J. Fink (IST Austria)
A. Fragner (Kappa)
T. Frey (Bosch)
M. Gabureac (Scrona)
S. Garcia (College de France)
S. Gasparinetti (Chalmers)
M. Goppl (Sensirion)
J. Govenius (VTT)
J. Heinsoo (IQM)
L. Huthmacher (Stellbrink & Prtnr)
D.-D. Jarausch (Leica)
K. Juliusson (IQM)
P. Kurpiers (Rohde & Schwarz)
J. Krause (U. Of Cologne)
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S. Lazar (Zurich Instruments)
P. Leek (Oxford)
S. M. Llima (BSC-CNS)
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P. Magnard (Alice and Bob)
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J. Mlynek (Siemens)
M. Mondal (IACS Kolkata)
M. Oppliger
J. O'Sullivan (CEA Saclay)
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G. Puebla (QZabre)
A. Remm (Atlantic Quantum)
A. Safavi-Naeini (Stanford)
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L. Steffen (AWK Group)
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I. Tsitsilin (TUM)
J. Ungerer (Harvard)
A. van Loo (RIKEN)
D. van Woerkom (Microsoft)
J. Waissman (HUJI)
T. Walter (deceased)
L. Wernli (Sensirion)
A. Wulff
S. Zeytinoğlu (Harvard)

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C. Abellan (Quside)
P. Bertet (CEA Saclay)
A. Blais (Sherbrooke)
J. Bylander (Chalmers)
H. J. Carmichael (Auckland)
A. Chin (Cambridge)
I. Cirac (MPQ)
K. Ensslin (ETH Zurich)
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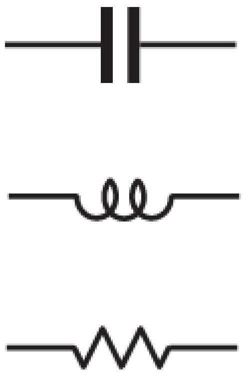
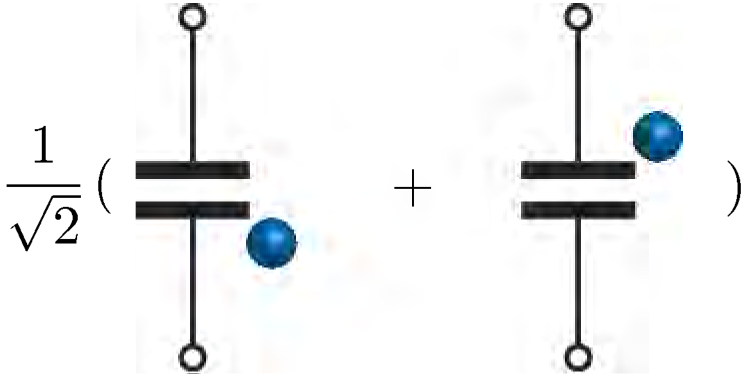
T. Ihn (ETH Zurich)
A. Imamoğlu (ETH Zurich)
F. Marquardt (MPL Erlangen)
F. Merkt (ETH Zurich)
A. Messmer (Zurich Instruments)
M. W. Mitchell (ICFO)
M. Müller (RWTH Aachen, FZJ)
M. A. Martin-Delgado (Madrid)
M. Poggio (Basel)
B. Royer (Sherbrooke)
N. Sangouard (CEA Saclay)
H. Tureci (Princeton)
W. Wegscheider (ETH Zurich)

Quantum Electronic Circuits

basic circuit elements:



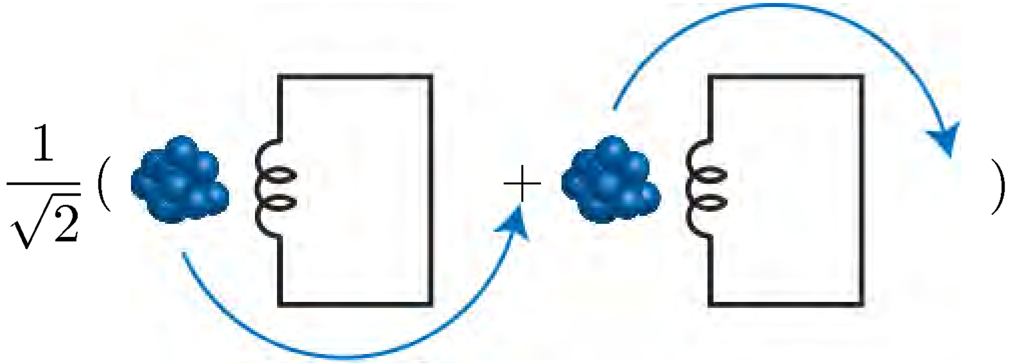
charge on a capacitor:



quantum superposition states of:

- charge Q
- flux ϕ

current or magnetic flux in an inductor:

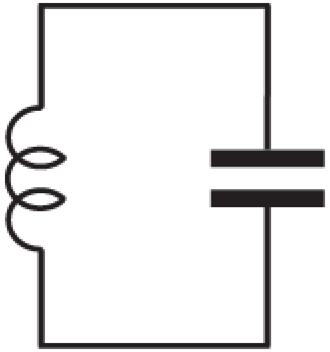


Q, ϕ are conjugate variables

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

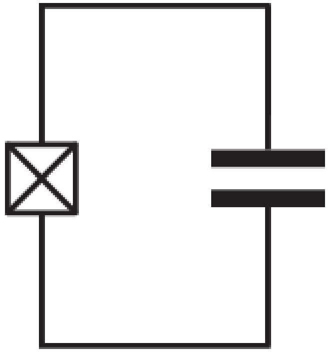
Linear and Nonlinear Superconducting Electronic Oscillators

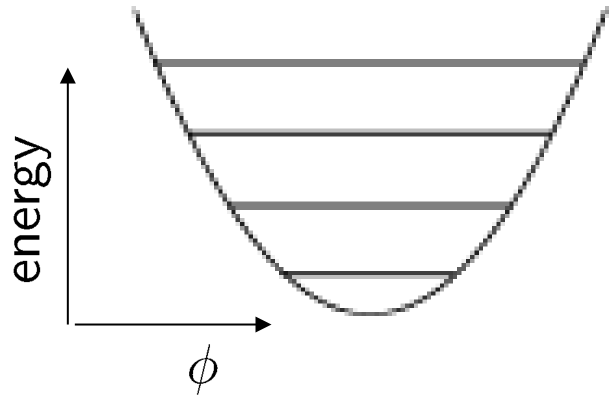
LC resonator:



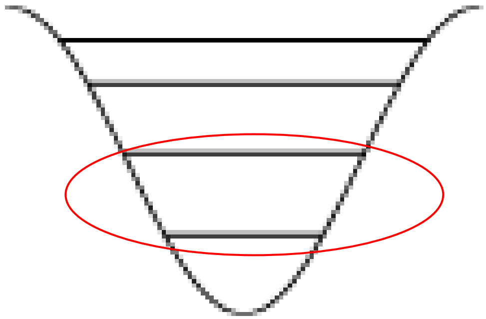
Josephson junction resonator:

Josephson junction = nonlinear inductor





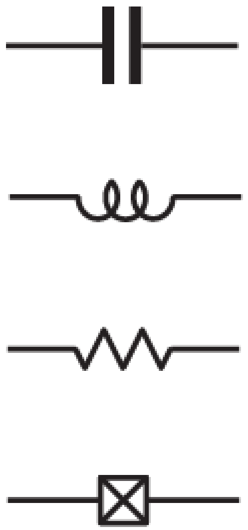
anharmonicity defines effective two-level system



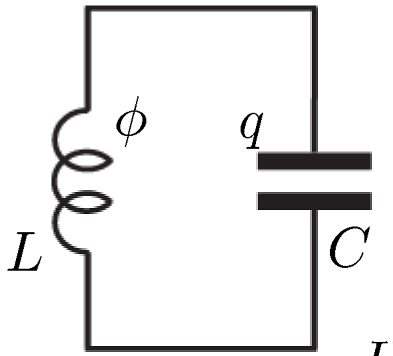
Circuit QED Review: A. Blais *et al.*, *Rev. Mod. Phys.* **93**, 025005 (2021)

Superconducting Circuits as Components for a Quantum Computer

constructing quantum electronic circuits from basic circuit elements:

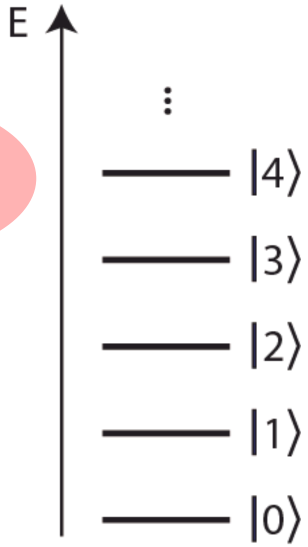


harmonic LC oscillator:

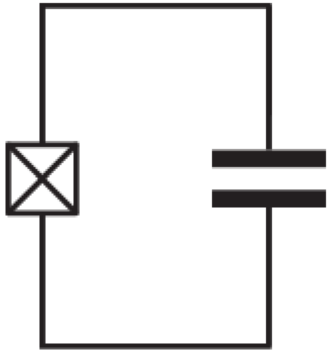


$$H = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2})$$

electronic photon

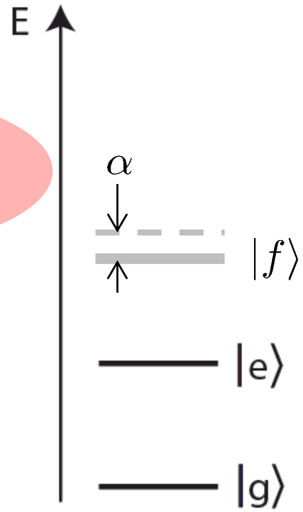


anharmonic oscillator:



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

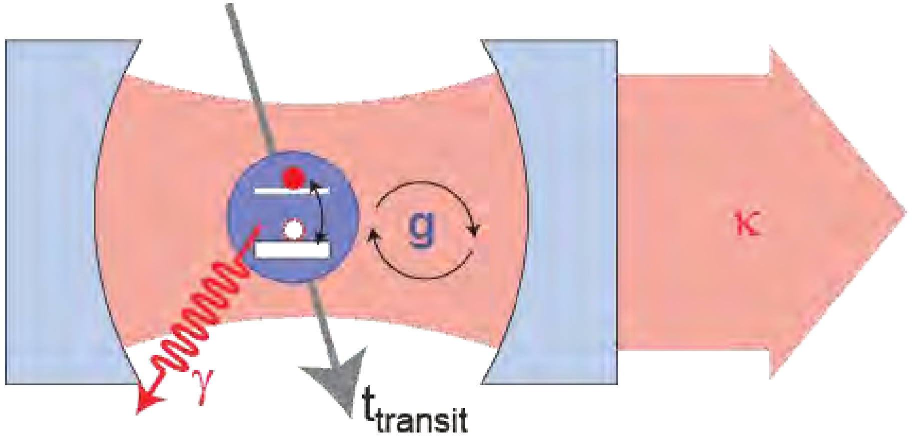
electronic artificial atom



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

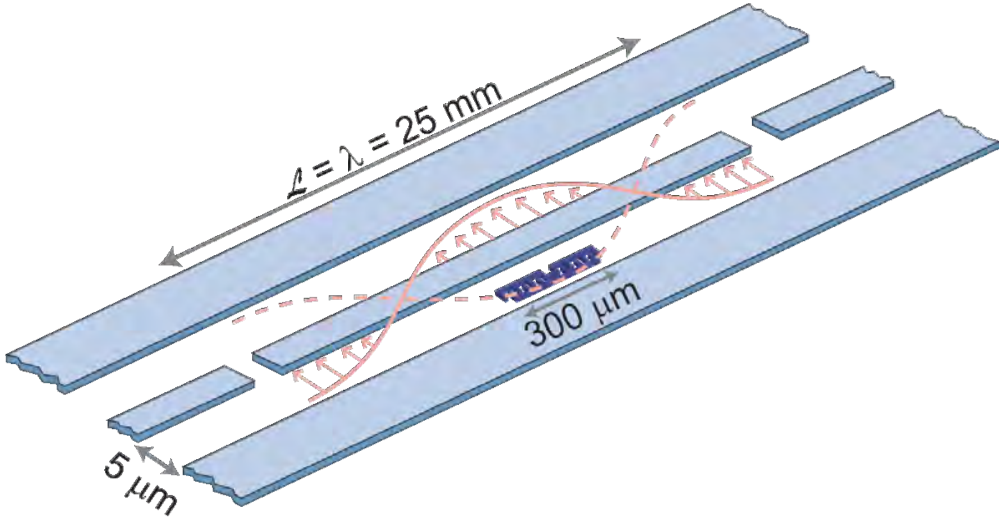
Circuit QED Review: A. Blais *et al.*, *Rev. Mod. Phys.* **93**, 025005 (2021)

Cavity Quantum Electrodynamics (QED) with Superconducting Circuits



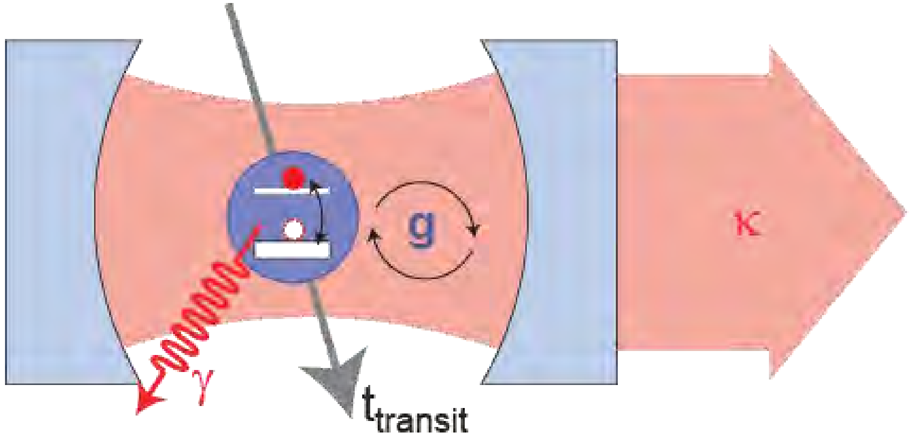
Controllable coherent interaction
of **single photons** with **individual two level systems** ...

With atoms:
J. M. Raimond *et al., Rev. Mod. Phys.* **73**, 565 (2001)
S. Haroche & J. Raimond, *OUP Oxford* (2006)
J. Ye., H. J. Kimble, H. Katori, *Science* **320**, 1734 (2008)



Circuit QED Review: A. Blais *et al.*, *Rev. Mod. Phys.* **93**, 025005 (2021)
Concept: A. Blais *et al.*, *PRA* **69**, 062320 (2004), Exp.: A. Wallraff et al., *Nature* **431**, 162 (2004)

Cavity Quantum Electrodynamics (QED) with Superconducting Circuits



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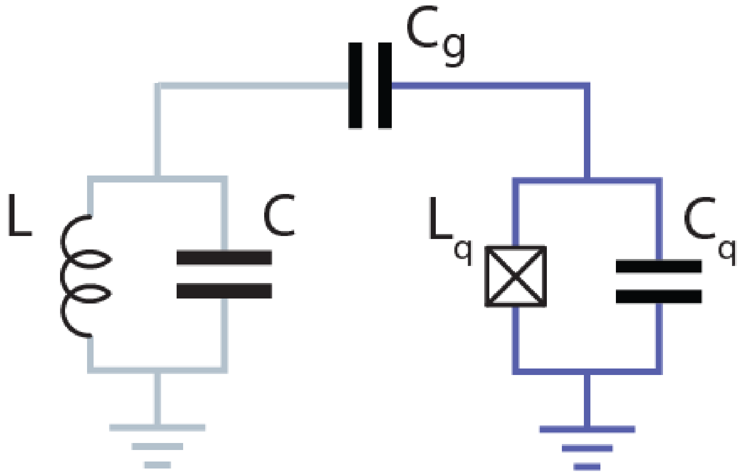
J. Ye., H. J. Kimble, H. Katori, *Science* **320**, 1734 (2008)

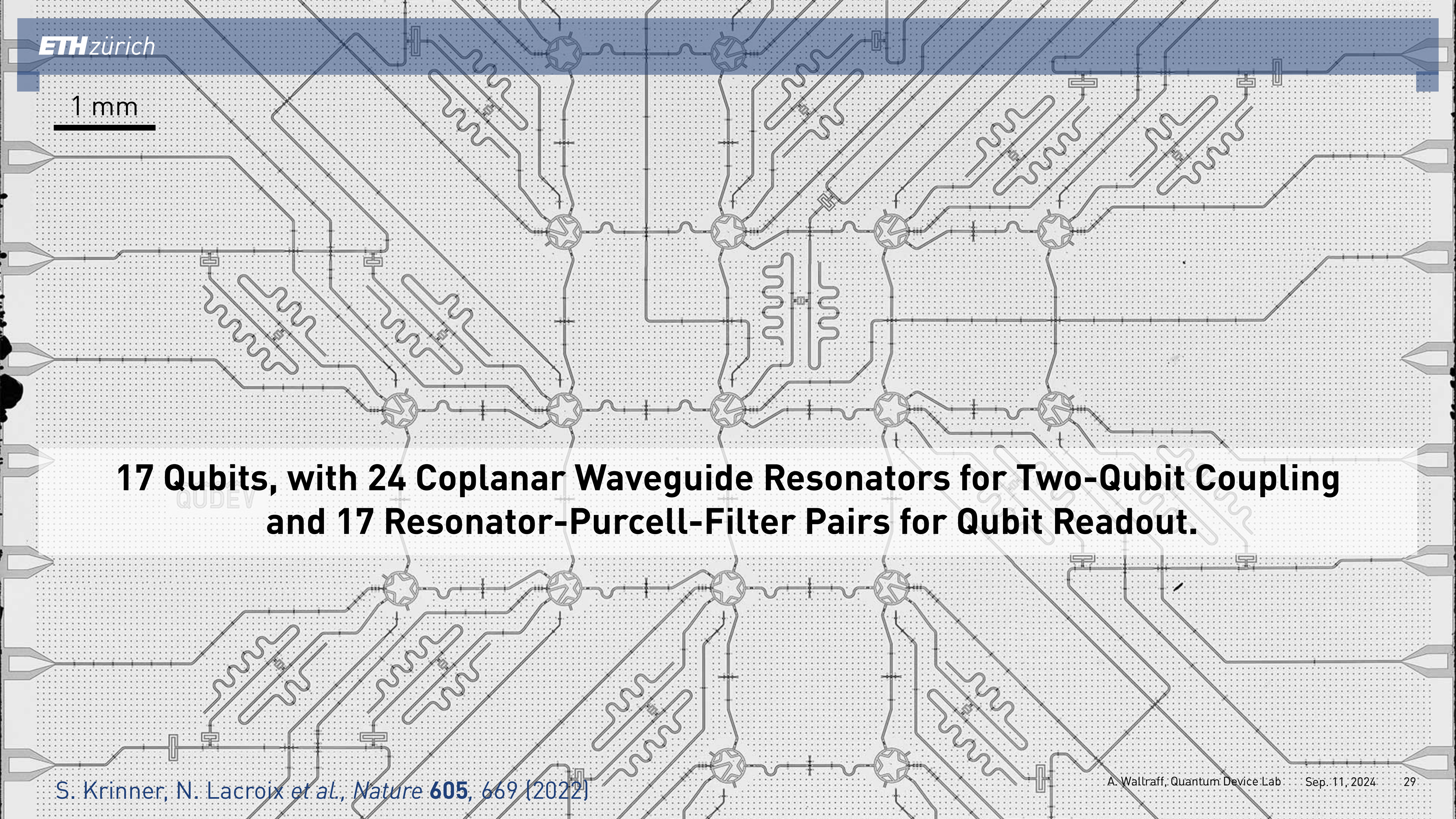
With superconducting circuits:



How is circuit QED useful for quantum information processing?

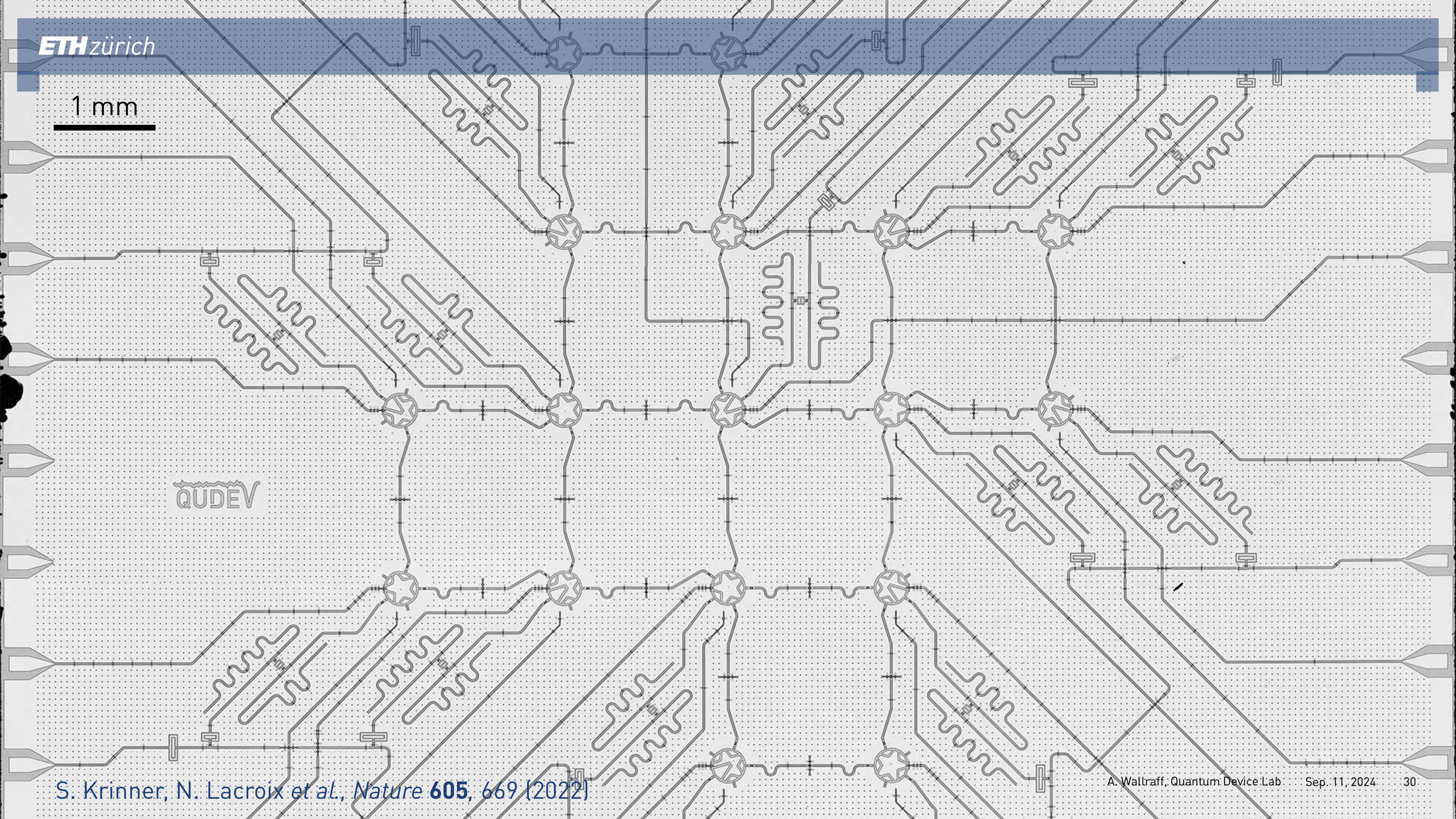
- Isolating qubits from their electromagnetic environment
- Maintaining addressability of qubits
- Reading out the state of qubits
- Coupling qubits to each other
- Converting stationary qubits to flying qubits

Circuit QED Review: A. Blais *et al., Rev. Mod. Phys.* **93**, 025005 (2021)
Concept: A. Blais *et al.*, *PRA* **69**, 062320 (2004), Exp.: A. Wallraff et al., *Nature* **431**, 162 (2004)



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

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



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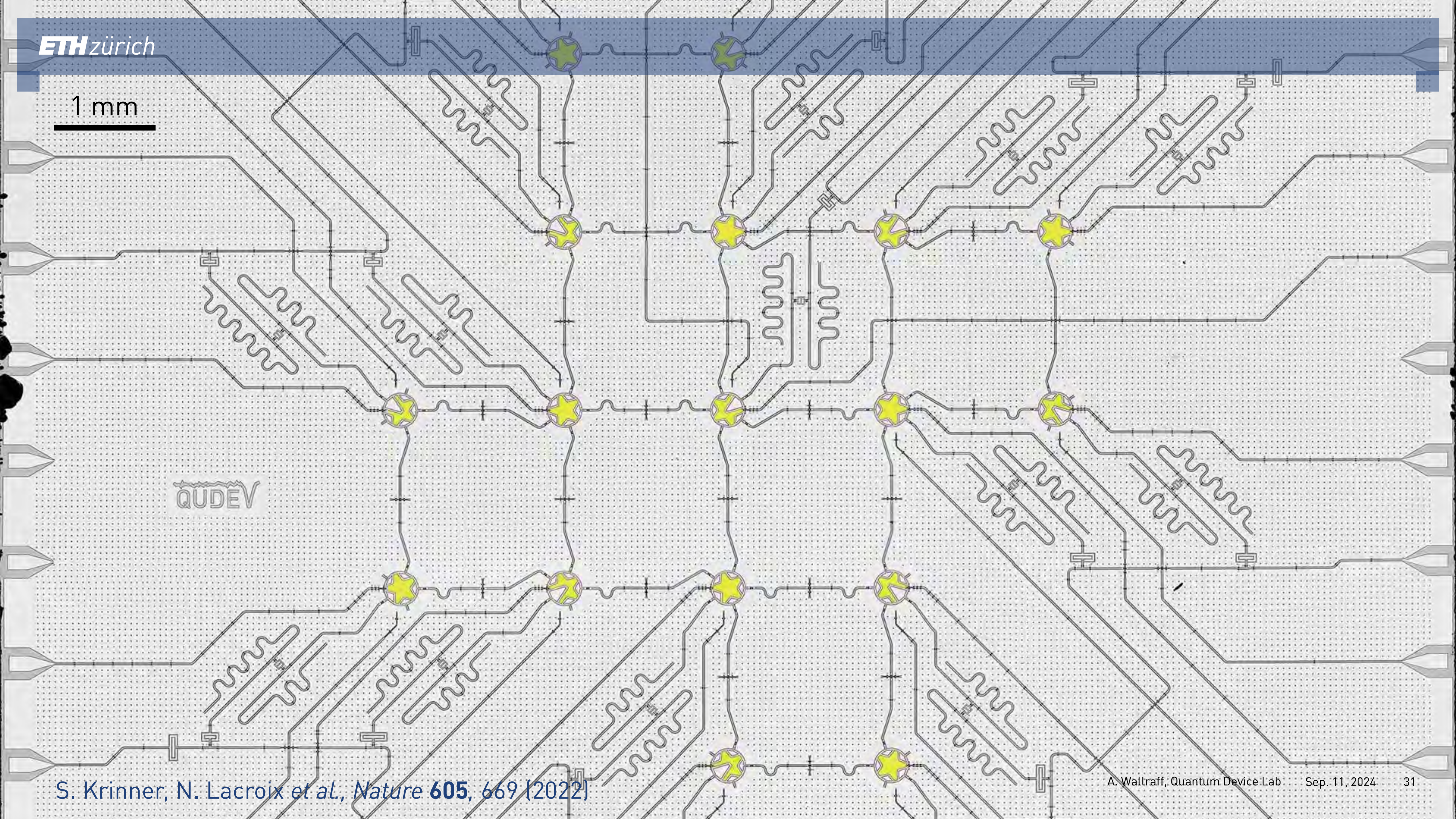

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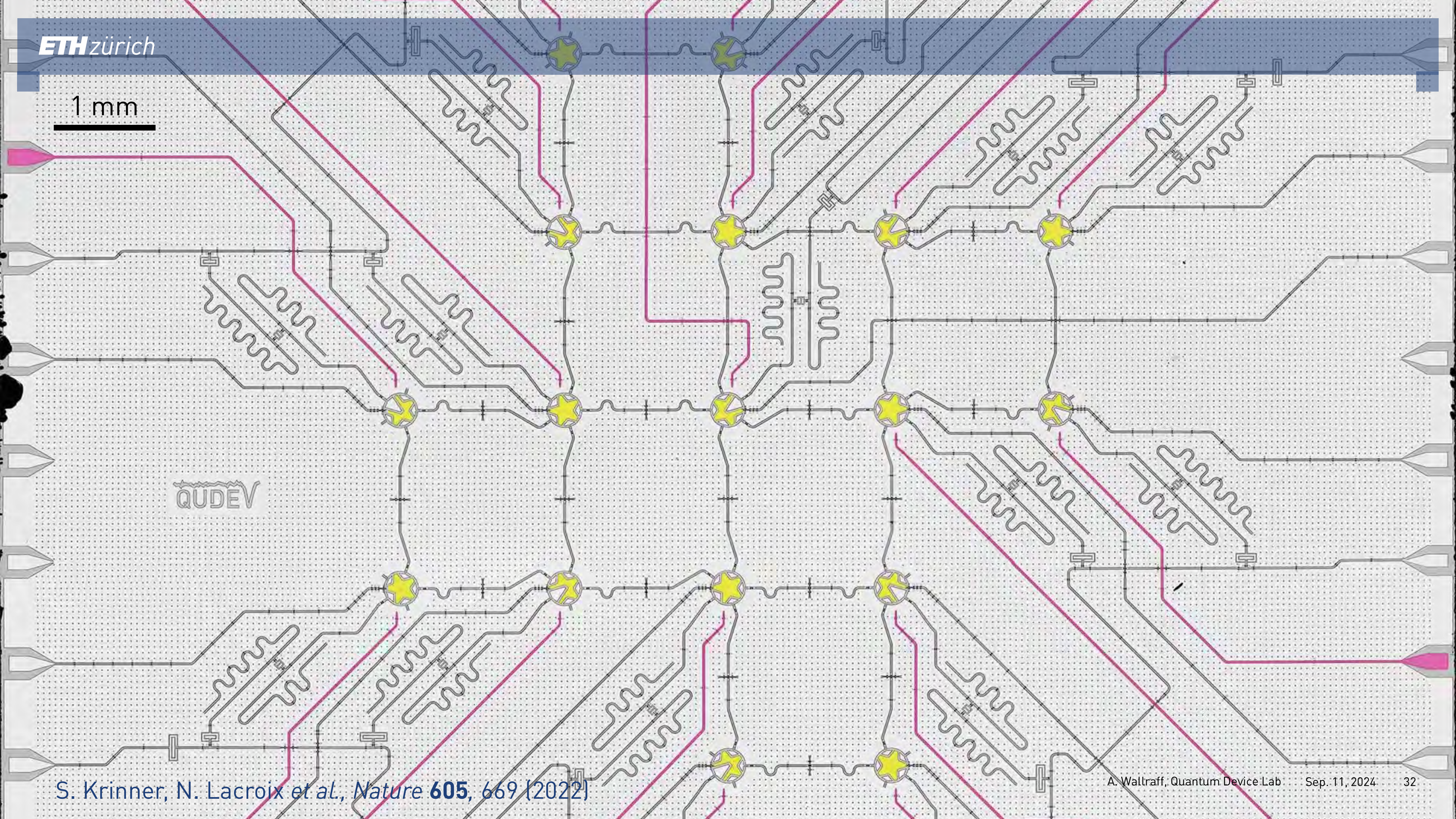
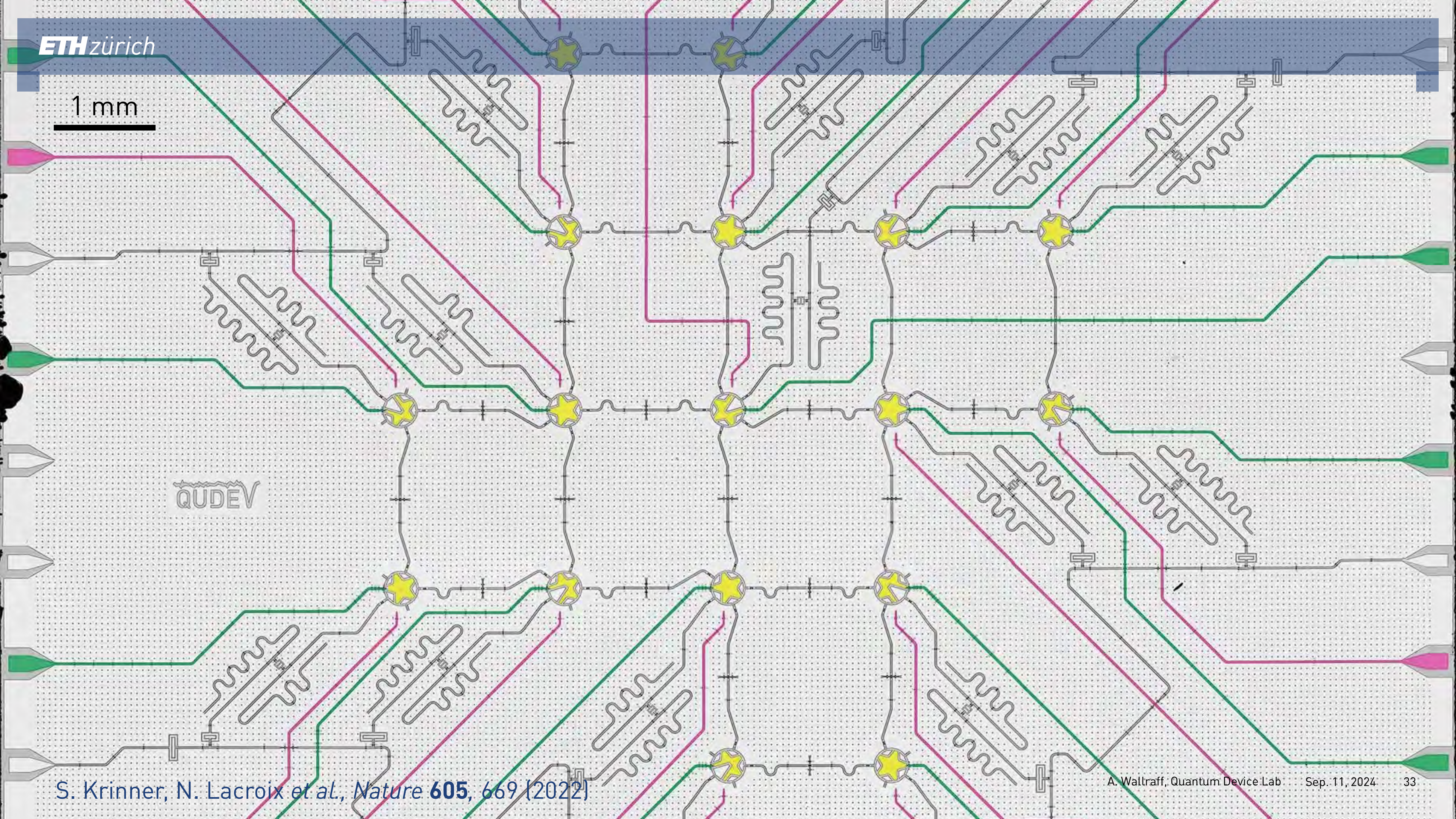
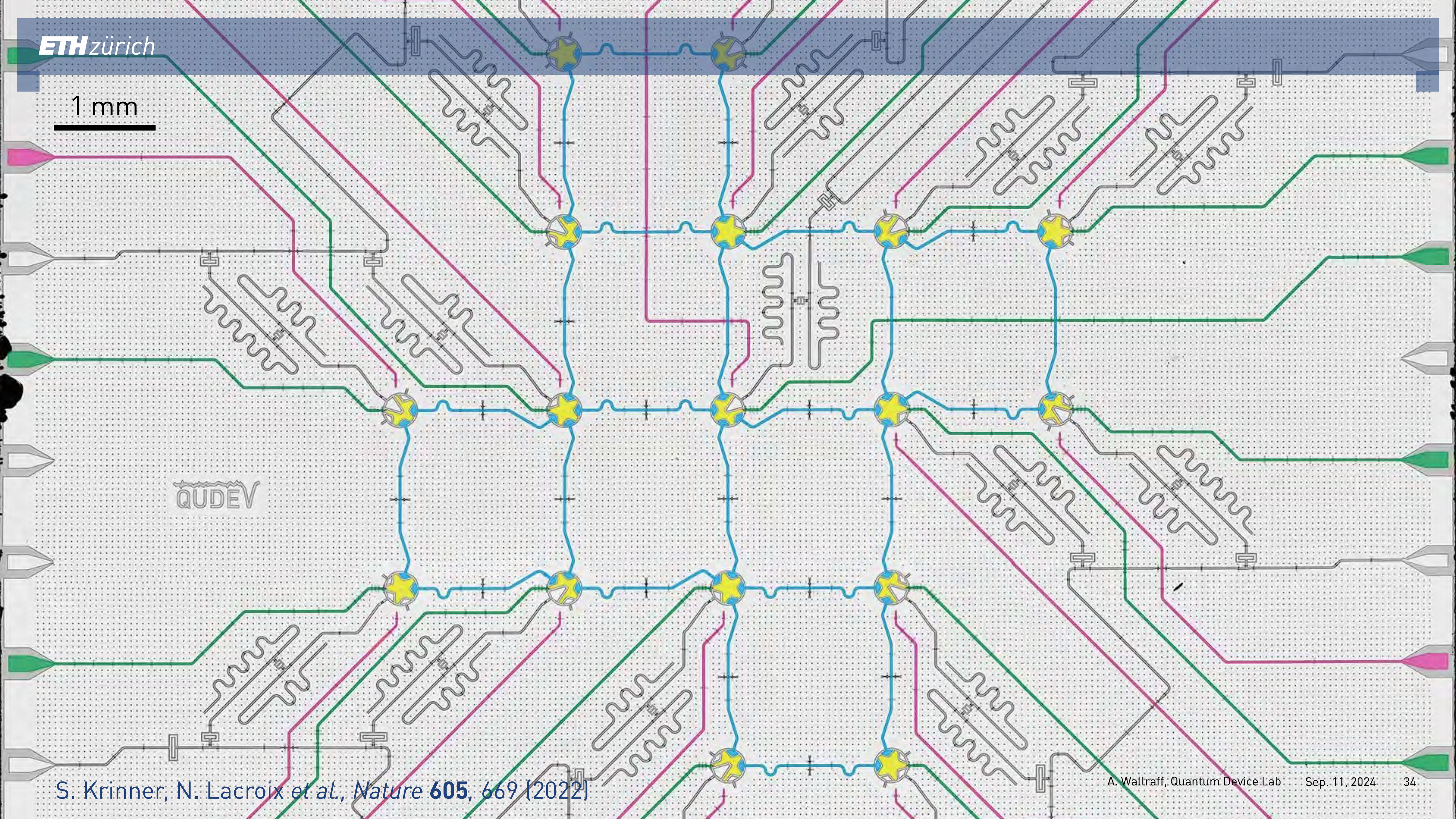


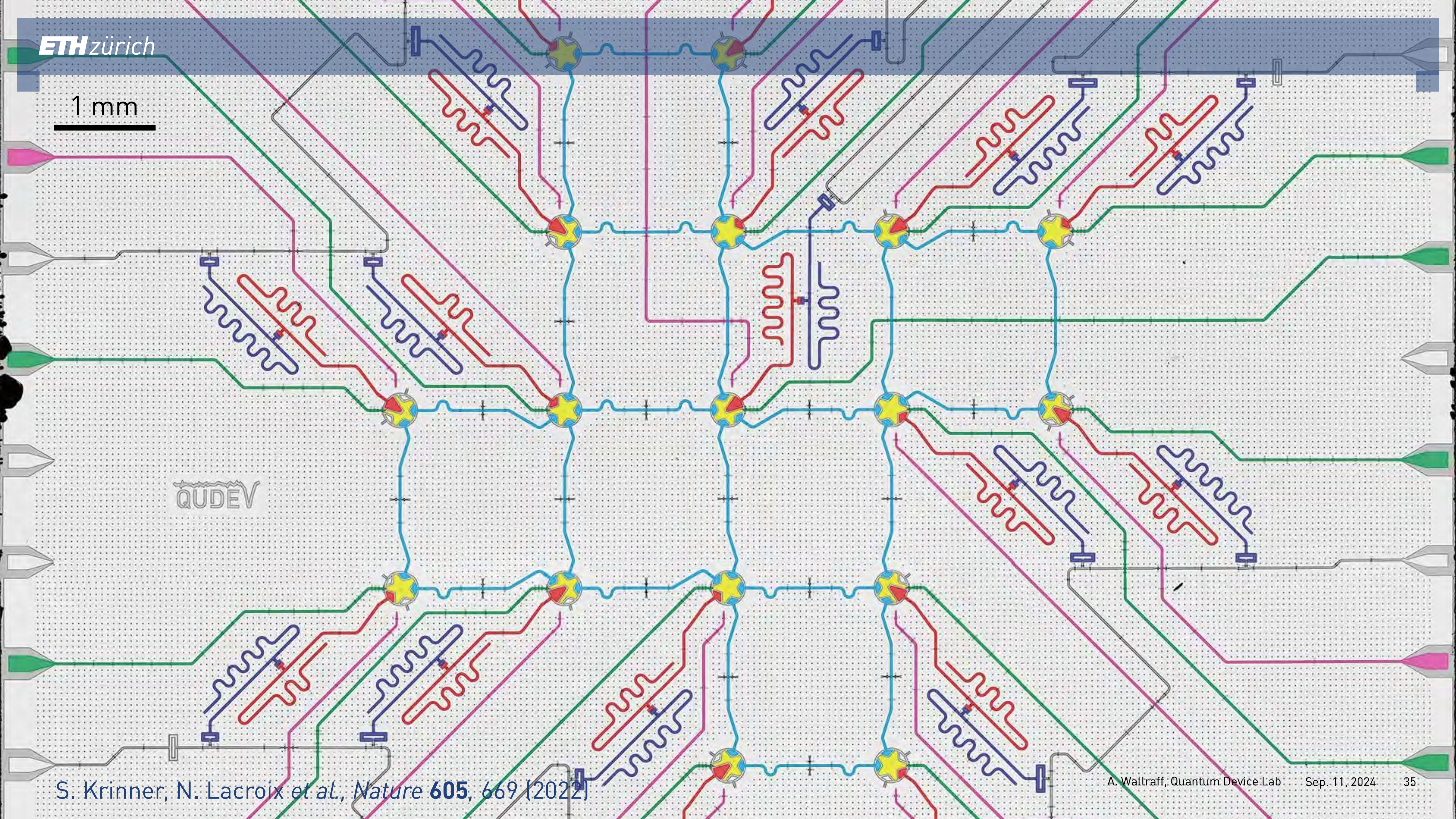
S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)



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

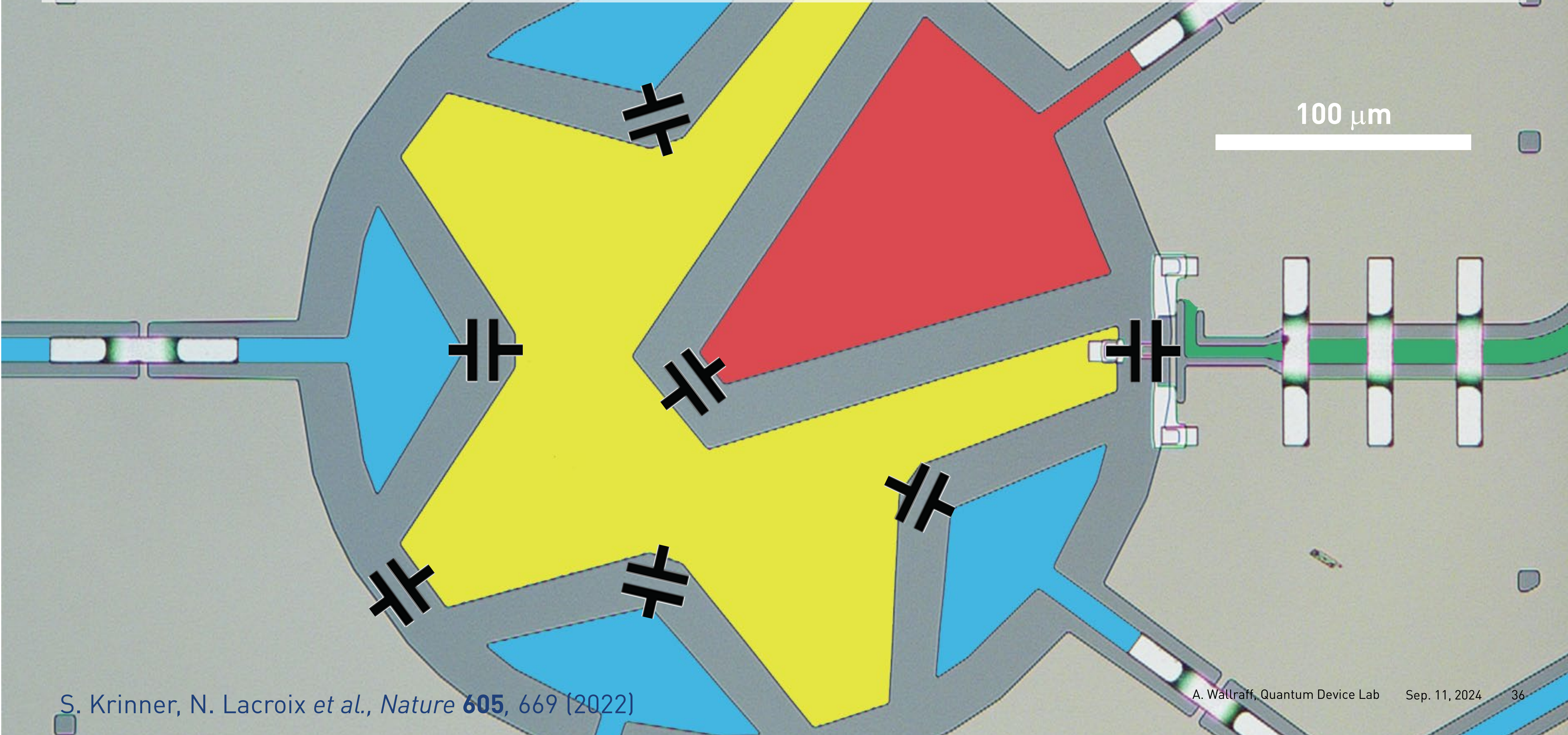


S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)



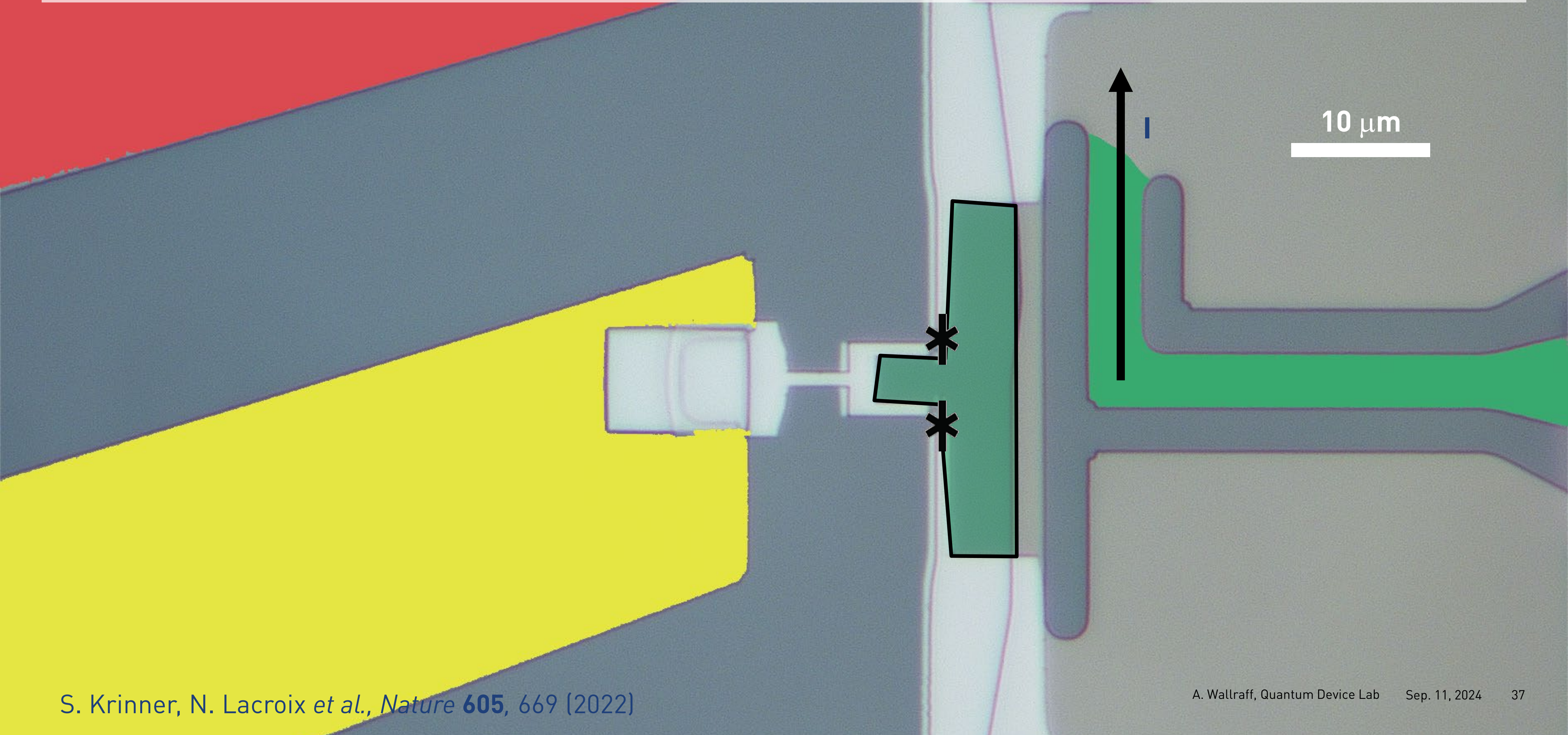
S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

A Superconducting Qubit – Transmon-Style

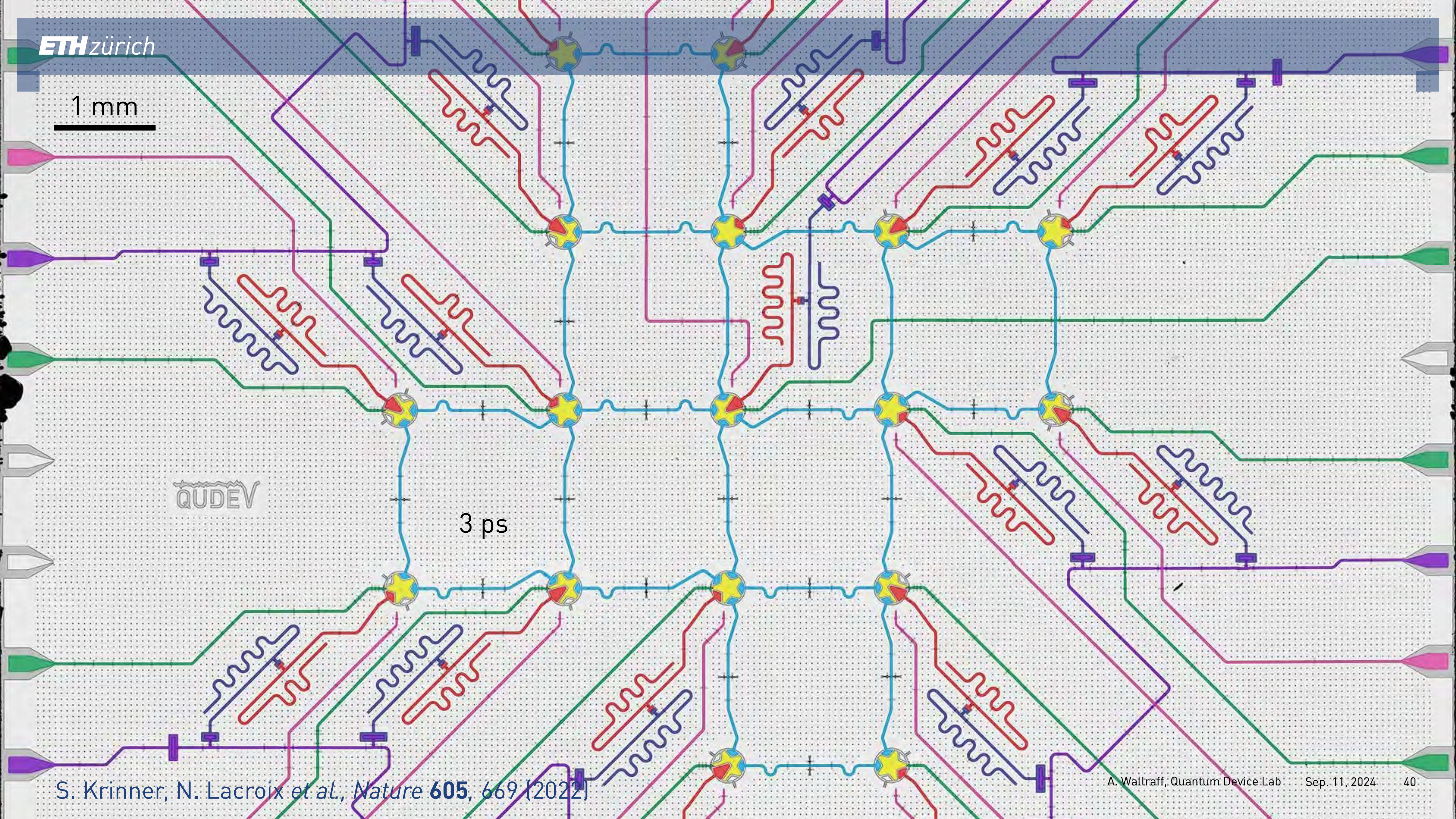


S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

Tunnel Junctions, SQUID, and Fluxline

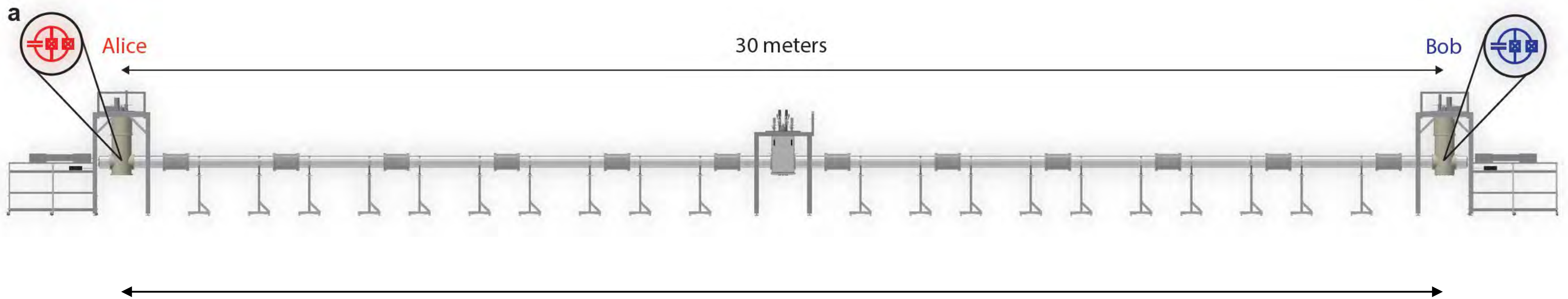


S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)



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

Entangle qubits over a distance 30-thousand times larger



100 ns
at the speed of light

S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

Bell Test Protocol

Alice and Bob …

1. … prepare a shared non-local entangled state $|\psi^{+}\rangle = \frac{|g,g\rangle + |e,e\rangle}{\sqrt{2}}$
2. … randomly select local measurement bases $a, b \in \{0,1\}$
3. … read out state of qubits with local outcome $x, y \in \{1, -1\}$

Repeat steps 1-3

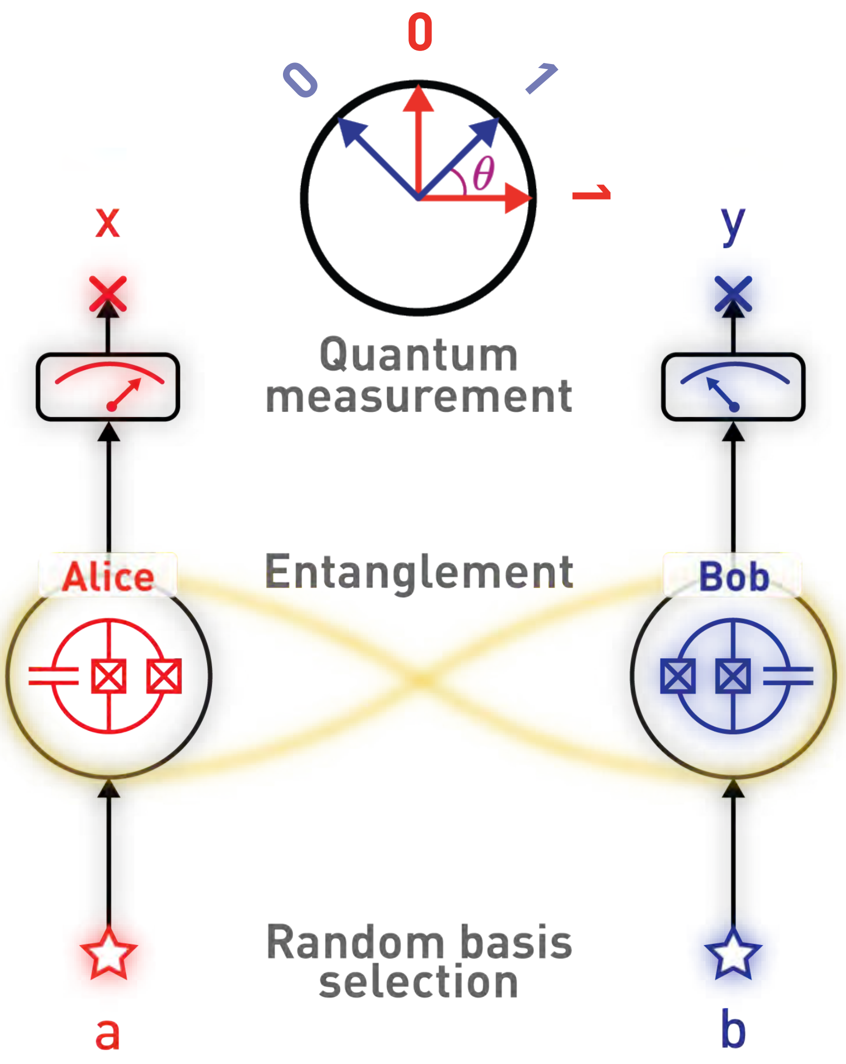
Calculate Clauser-Horne-Shimony-Holt S-value
J.F. Clauser et al., Phys. Rev. Lett., **23** 880-884, (1969)
from two qubit correlators xy with randomly selected basis a,b

$$\langle x \cdot y \rangle_{(\mathrm{a,b})}$$

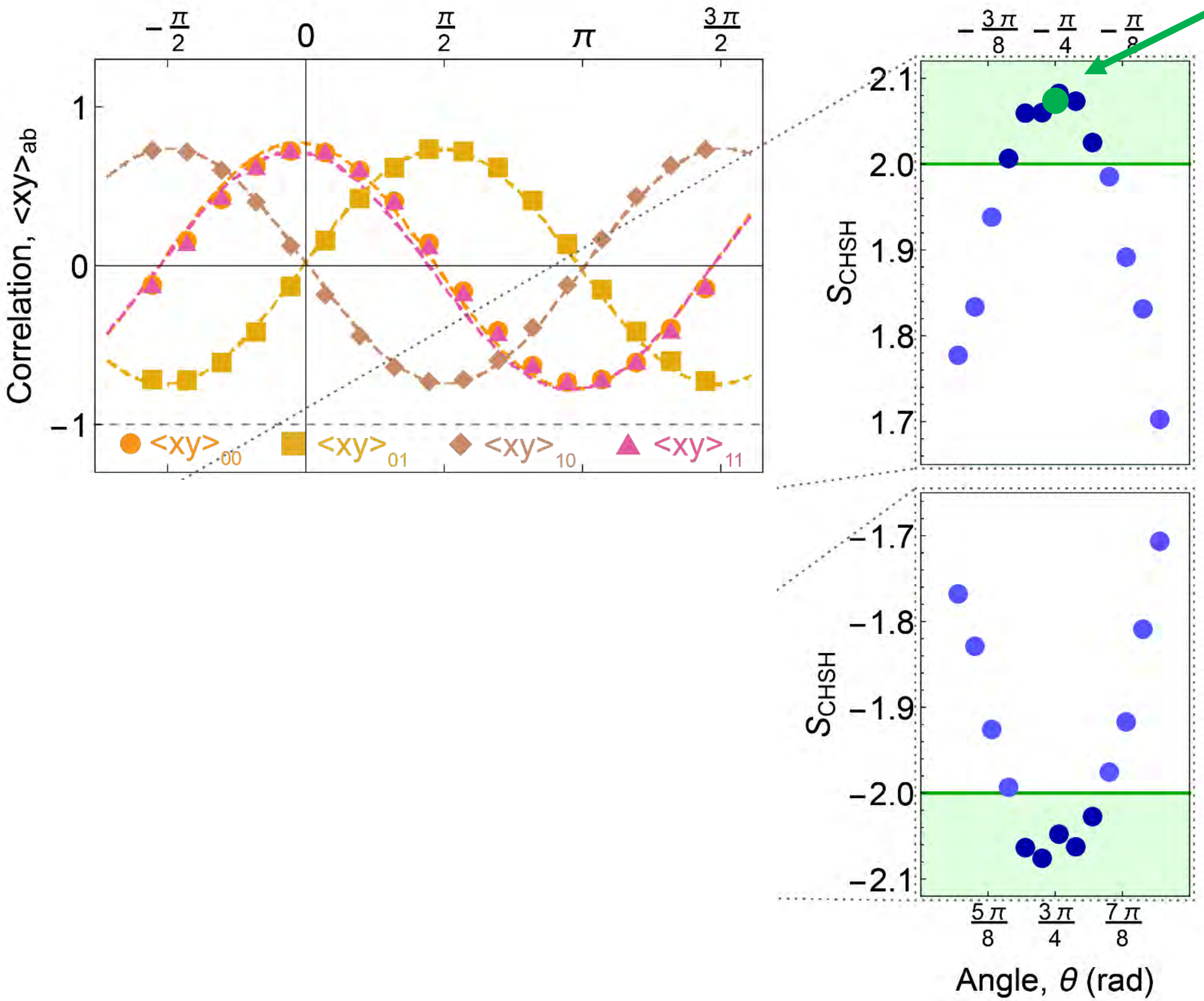
$$S_{\mathrm{CHSH}} = \langle x \cdot y \rangle_{(0,0)} - \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} + \langle x \cdot y \rangle_{(1,1)}$$

Expect Bell inequality violation for entangled quantum systems

$$S_{\mathrm{CHSH}} > 2$$



Experimental Results



S = 2.0747 +- 0.0033 **> 2**

- Extract correlations of measurement outcomes
- Calculate S_{CHSH}-value
  - Observe $S_{CHSH} > 2$
- Perform experiment at optimal angle
  - 2^{20} ($\sim 10^6$) repetitions
- Violates Bell inequality by
  - 22 σ
  - p-value of $p = 10^{-108}$

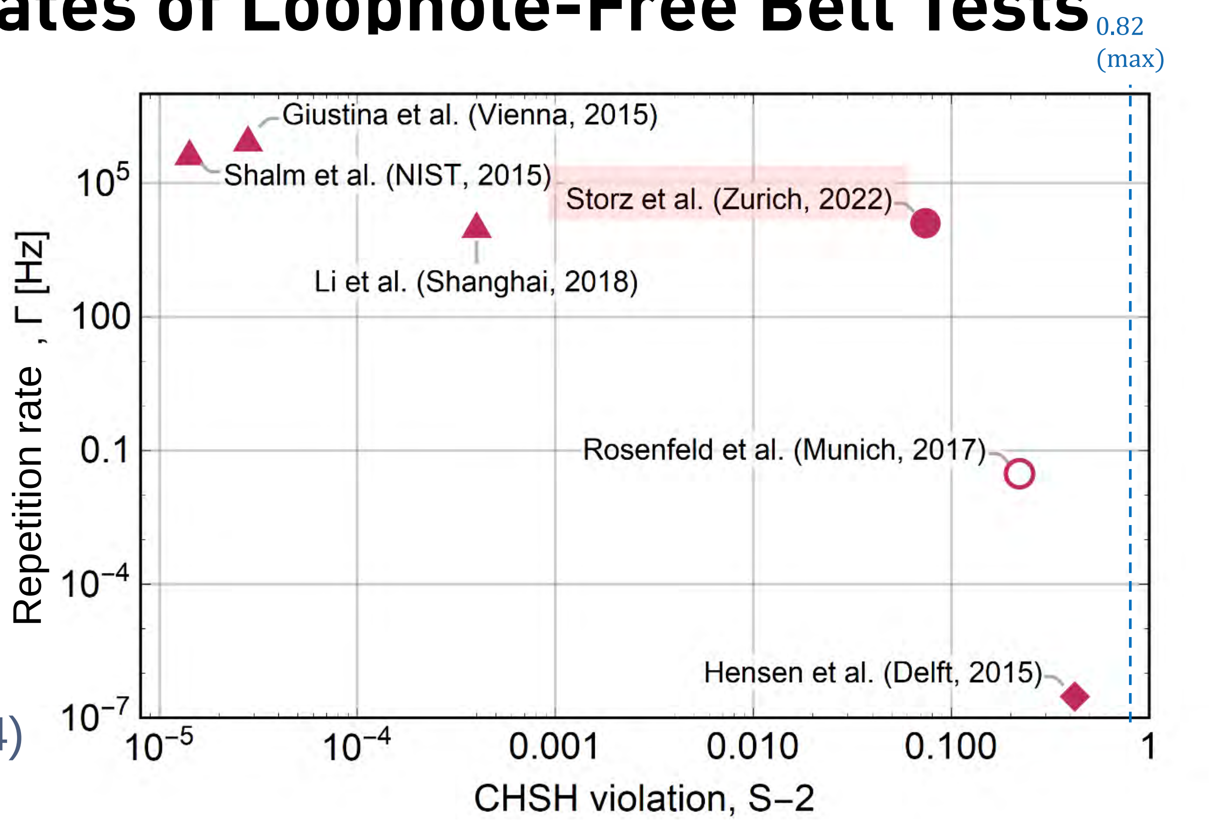
Superconducting circuits pass the most stringent tests of quantum physics.

S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

Bell Violation (S-2) and Repetition Rates of Loophole-Free Bell Tests

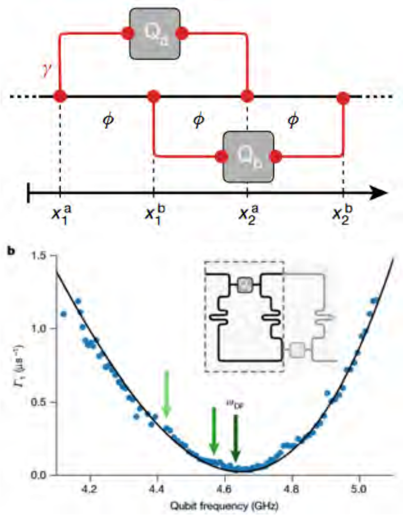
Comparison of **Bell tests** with
- **polarization-encoded photons** ▲
  High repetition rates, low S-value
- **NV-centers** ◆/ **neutral atoms** ○
  Low repetition rates, high S-value
- **superconducting circuits** ●
  Combination of high repetition rates *and* S-value

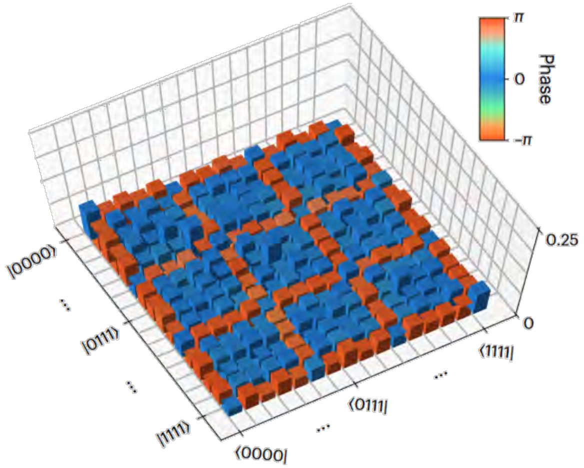
- **High rate** and **high violation** is interesting for implementation of device-independent QIP protocols
  - Quantum key distribution
    U. Vazirani and Thomas Vidick, *PRL* 113, 140501 (2014)
  - Randomness generation
    R. Colbeck, *PhD thesis*, University of Cambridge (2009)
  - Randomness expansion
    S. Pironio *et al.*, *Nature* **464**, 7291 (2010)
  - Randomness amplification
    R. Colbeck and R. Renner, *Nat. Phys.* ***8**, 450-454* (2012);
    M. Kessler and R. Arnon-Friedman, IEEE J. on Selected Areas in Information Theory, **1** no.2, 568-584 (2020)



S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

Recent Quantum Optics Experiments with Superconducting Circuits





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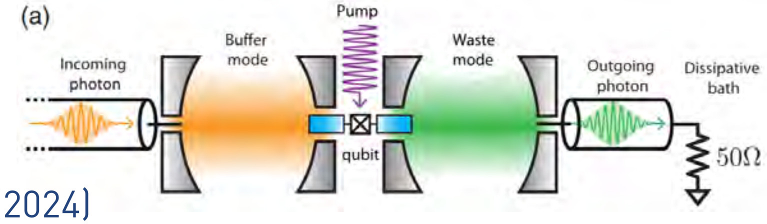
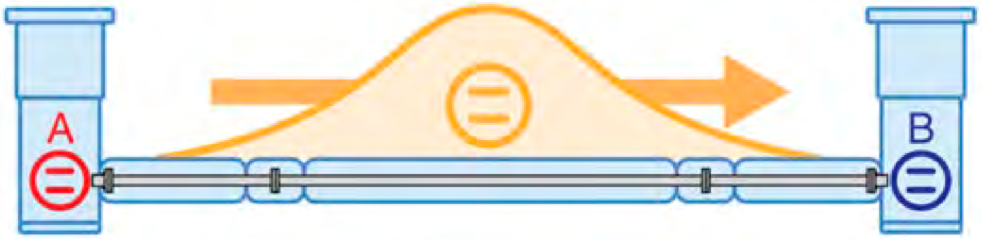
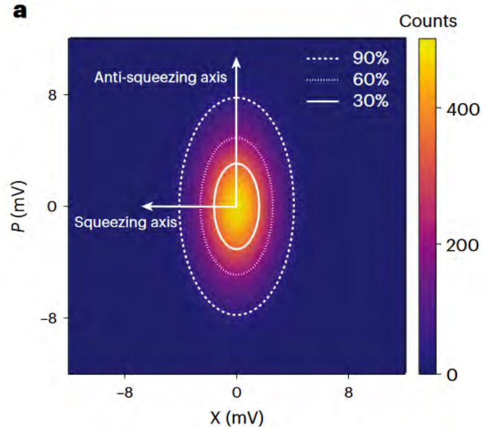
O'Sullivan et al., arXiv:2409.06623 (2024)
Ferreira et al. Nat Phys (2024)
Reuer et al. PRX **12**, 011008 (2022)
Besse et al. PRX **10**, 011046 (2020)

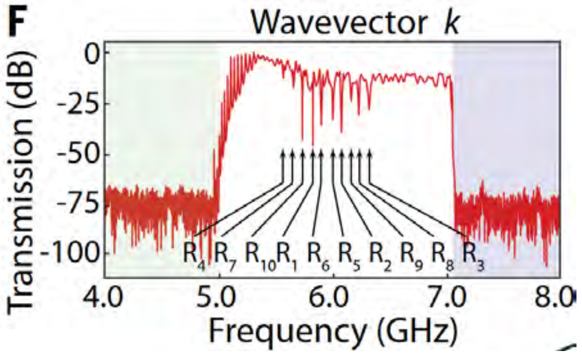


Single-Photon Detectors
Wang et al. Nature **619**, 276 (2023)
Lescanne et al. PRX **10**, 021038 (2020)
Lachance-Quirion et al. Science **367**, 425 (2020)
Besse et al. PRX **8**, 021003 (2018)

Giant Atoms
Joshi et al. PRX **13**, 021039 (2023)
Kannan et al. Nat Phys **19**, 394 (2022)
Kannan et al. Nature **583**, 775 (2020)







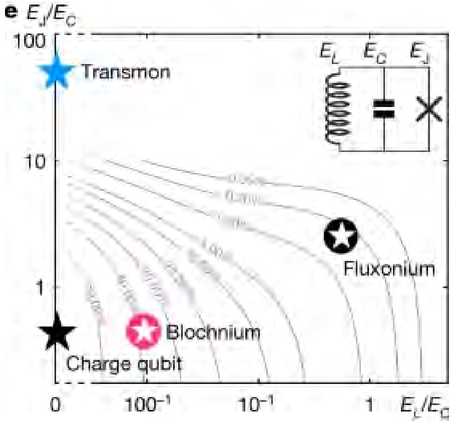
Waveguide QED
Zhang et al. Science **379**, 278 (2023)
Chakram et al. Nat Phys **18**, 879 (2022)
Fedorov et al. Sci Adv **7**, eabk0891 (2021)
Mirhosseini et al., Nature 569, 692 (2019)

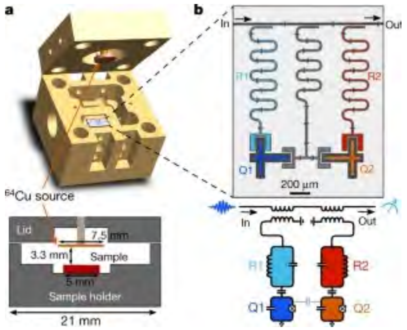
Quantum Communication
Storz et al. Nature **617**, 265 (2023)
Zhong et al. Nature **590**, 571 (2021)
Yan et al. PRL **128**, 080504 (2022)
Qiu et al. arXiv:2302.08756 (2023)

TWPAs & Squeezing
Qiu et al. Nat Phys **19**, 706 (2023)
Esposito et al. PRL **128**, 153603 (2022)

Superconducting Circuits for Quantum Information Processing

Novel Qubits
Pechenezhskiy et al., Nature 585, 368 (2020).





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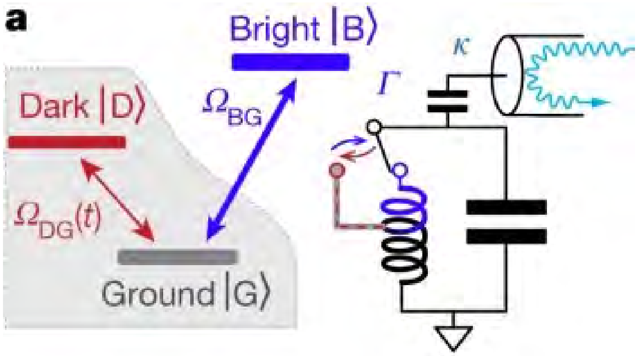
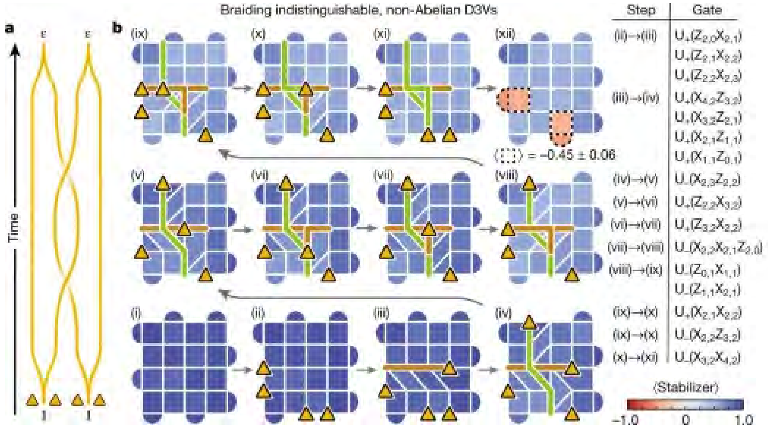
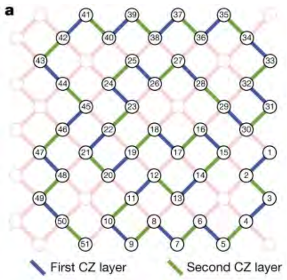
Vepsäläinen et al., Nature 584, 551 (2020).
Cardani et al., Nat Commun 12, 2733 (2021).

Fundamental Physics
Minev et al., Nature 570, 200 (2019).



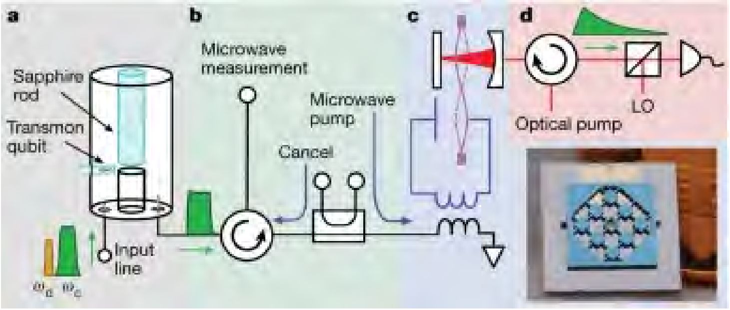
Topology, Braiding,
Google, Nature 618, 264–269 (2023).
Zhang et al., Nature 607, 468 (2022).
Kollár et al., Nature 571, 45–50 (2019).





Entanglement Generation
Cao et al. Nature 619, 738 (2023)

Quantum Advantage, Sampling, …
Kim et al., Nature 618, 500 (2023).
Layden et al., Nature 619, 282 (2023).
Arute et al., Nature 574, 505 (2019).



Control and Readout with Optics
Delaney et al., Nature 606, 489 (2022).
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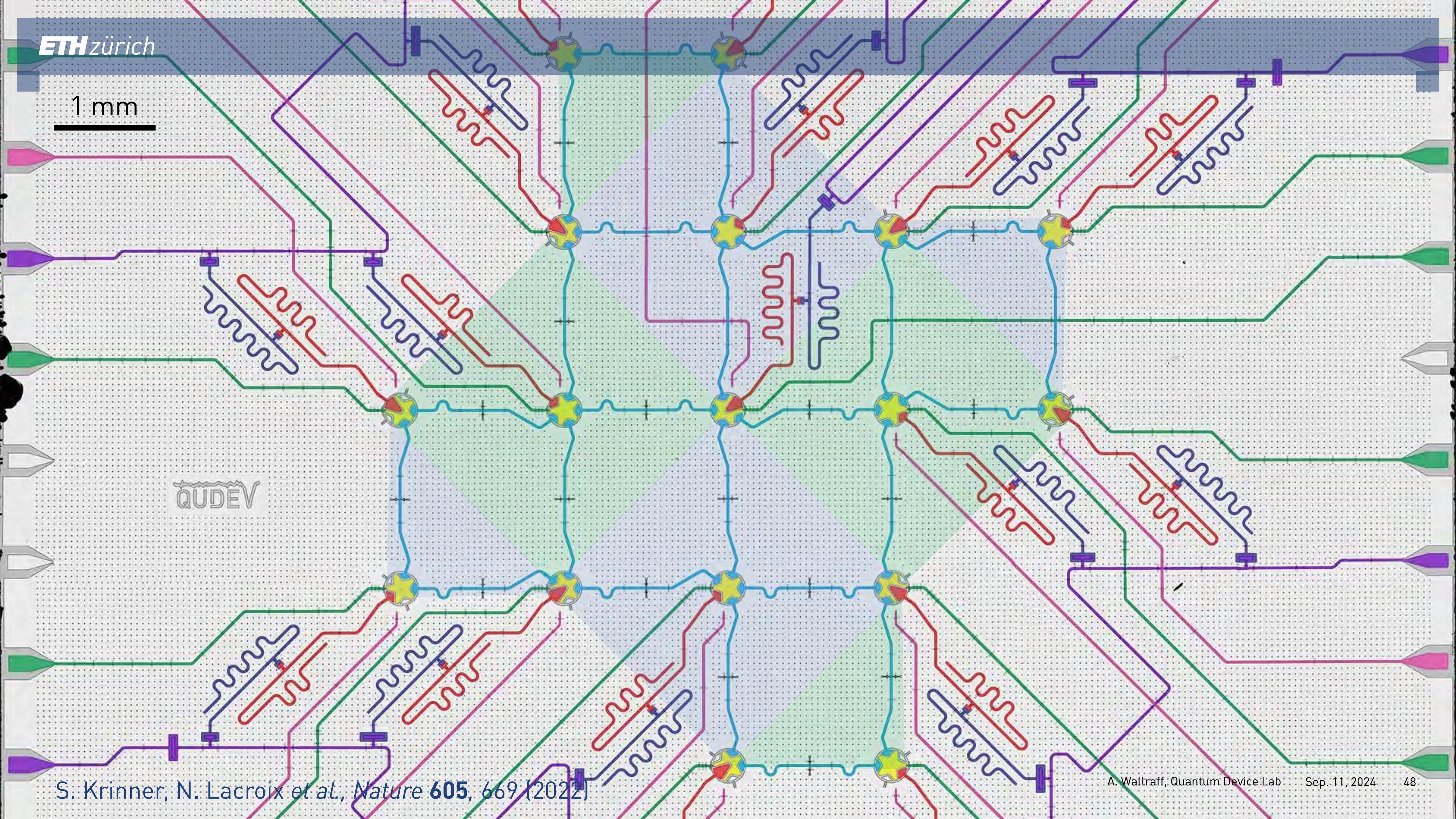
Mirhosseini et al., Nature 588, 599 (2020).

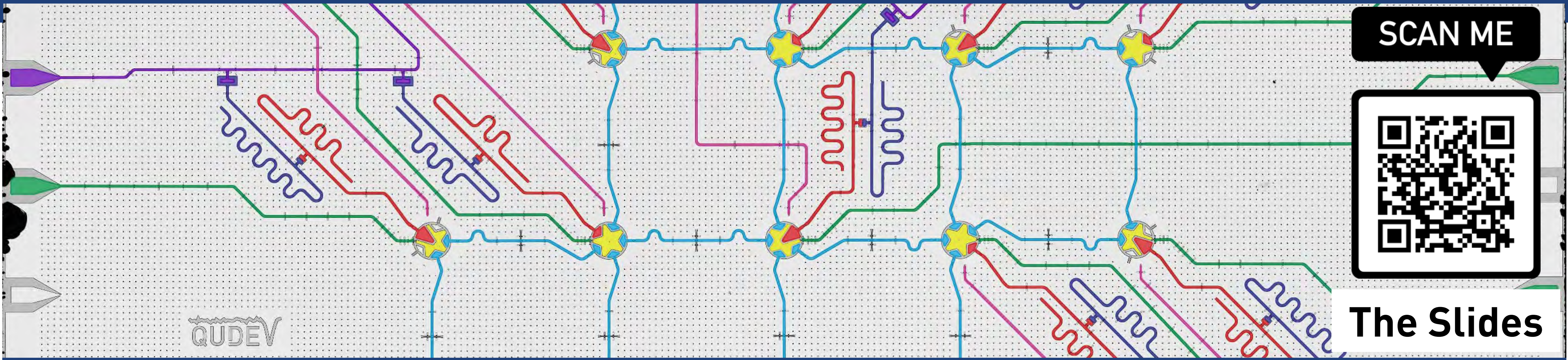
Machine Learning
Havlíček et al., Nature 567, 209 (2019).

Protocols: Teleportation
Google. Nature 622, 481 (2023).

Quantum Chemistry, Quantum Magnetism in VQE
Arute et al., Science 369, 1084 (2020).
Kandala et al., Nature 567, 491 (2019).
Kandala et al., Nature 549, 242-246 (2017).



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



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The Slides

Repeated Quantum Error Correction in a Distance-Three Surface Code Realized with Superconducting Circuits

Sci. Team: J.-C. Besse, D. Colao Zanuz, C. Hellings, J. Herrmann, S. Krinner, N. Lacroix, S. Lazar, G. Norris, A. Remm, K. Reuer, J. Schaer, S. Storz, F. Swiadek, C. Eichler, A. Wallraff *(ETH Zurich)*

A. Di Paolo, E. Genois, C. Leroux, A. Blais *(U. de Sherbrooke)*

M. Müller *(RWTH Aachen)*

Tech. Team: A. Akin, M. Bahrani, A. Flasby, A. Fauquex, T. Havy, N. Kohli, R. Schlatter *(ETH Zurich)*

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Schweizerischer Nationalfonds

Innovation project supported by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
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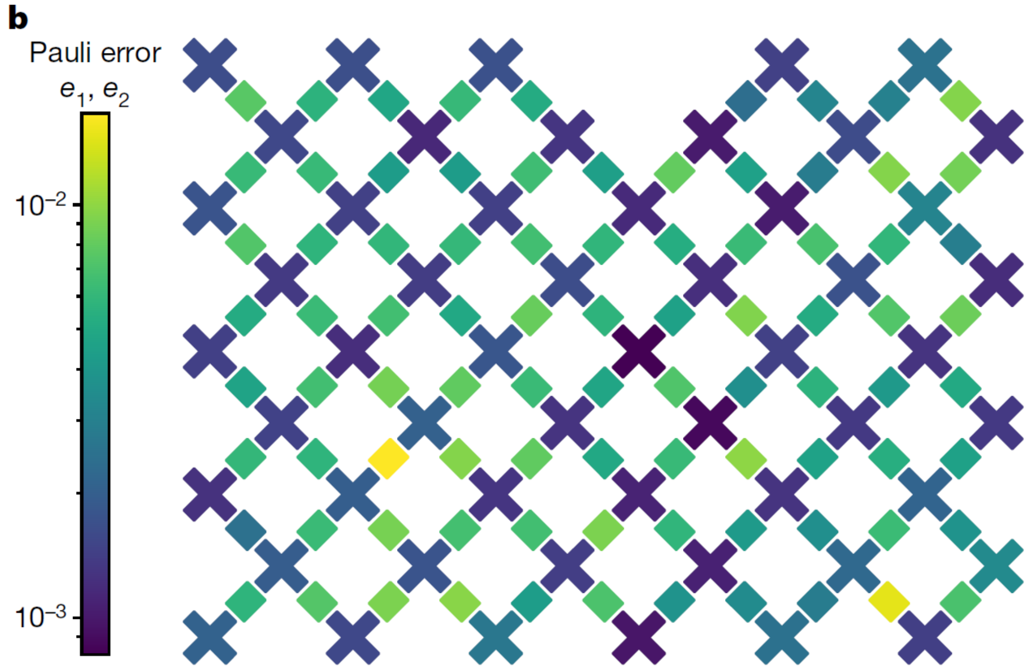
Two of the Major Goals in Quantum Information Processing ...

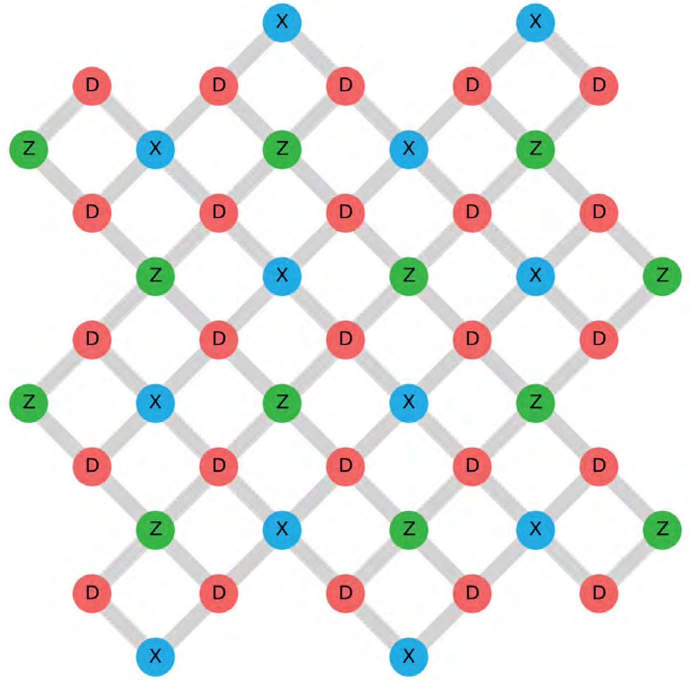
... with superconducting circuits

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

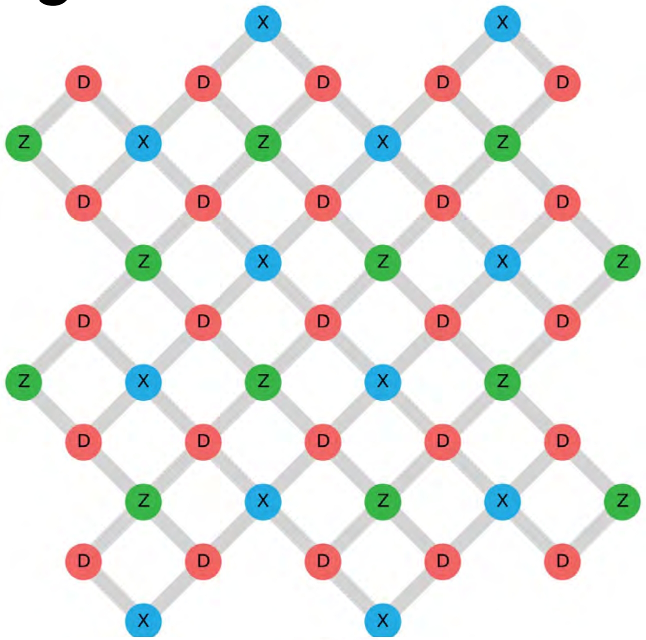


Fowler *et al.*, *Phys. Rev. A* **86**, 032324 (2012)

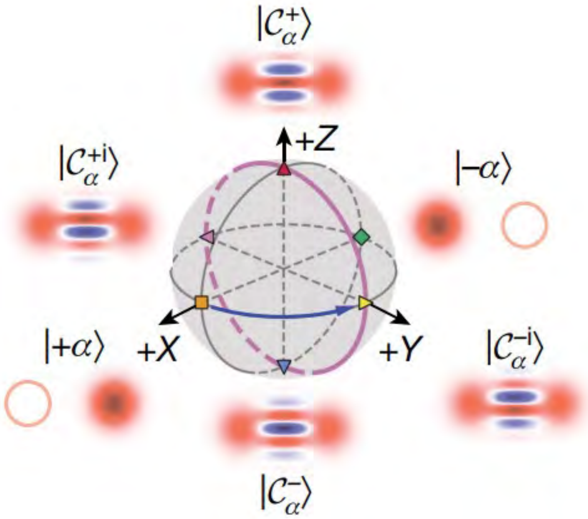
Quantum Error Correction with Superconducting Circuits

Approaches:

- Digital, qubit-based encodings: e.g. surface code, color code



- Continuous variable encodings in harmonic oscillator states: e.g. cat states, GKP states



picture from Grimm et al., *Nature* **584**, 205 (2020)

Preskill, *Quantum* **2**, 79 (2020)

Review: Terhal, *Rev. Mod. Phys*. **87**, 307 (2015)

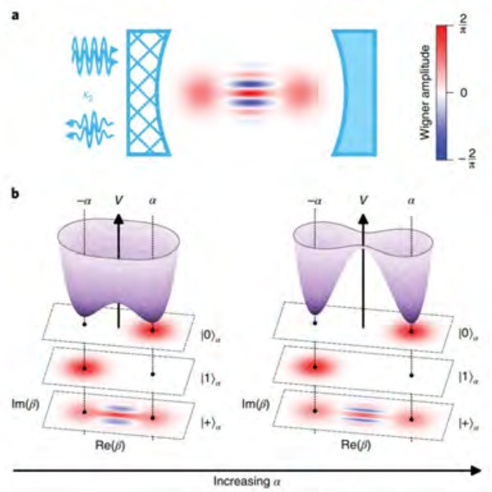
Bosonic Quantum Error Correction Experiments

Continuous QEC

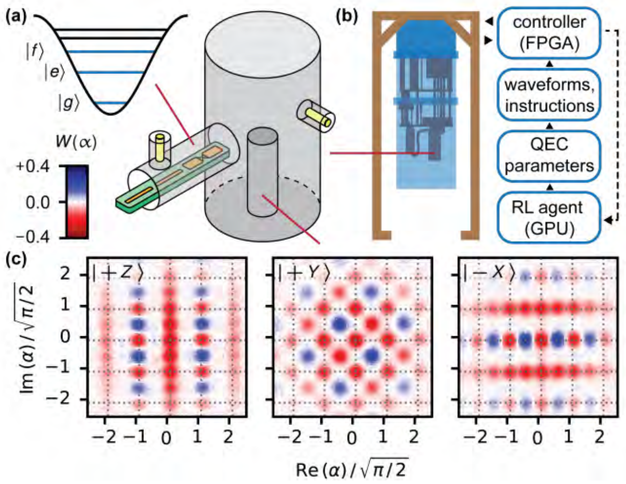
- Dissipative-cat codes
  Leghtas, et. al. Science 347, 853 (2015)
  Lescanne, et. al. Nature Physics 16, 509 (2020)
  Gertler et. al. Nature 590, 243 (2021)
- Kerr-cat codes
  Grimm, et. al. Nature 584, 205 (2020)

Discrete QEC

- Binomial bosonic codes
  Ni, Z. et al., Nature 616, 56 (2023).
  Hu et al., Nature Physics 15, 503 (2019).
- Cat-Codes
  Ofek et. al., Nature 536, 441 (2016)



Lescanne et. al. Nat. Phys. 16, 509 (2020)



Sivak et. al. arXiv:2211.09116 (2022)

GKP codes

- Trapped ions
  Flühmann et. al., Nature 566, 513 (2019)
  de Neeve et. al., Nature Physics 18, 296 (2022)
- Superconducting circuits
  Campagne-Ibarcq et. al., Nature 584, 368 (2020)
  Sivak et al., Nature 616, 50 (2023).

The Challenge of Quantum Error Correction

Detect and correct two types of errors:

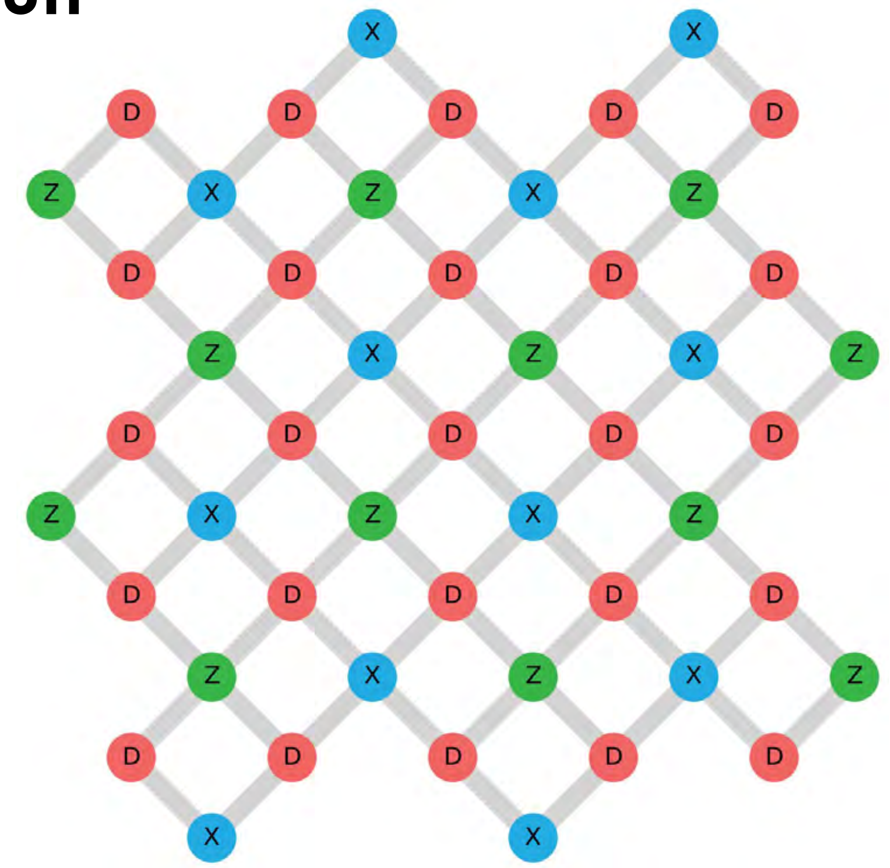
- Bit flips
- Phase flips

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

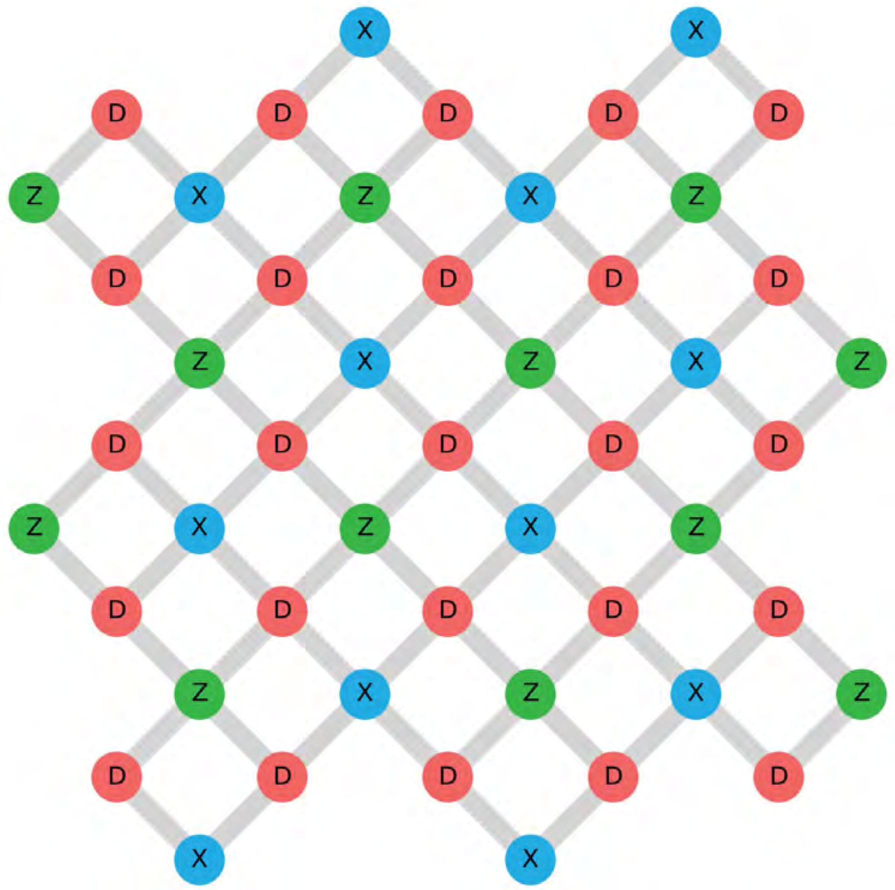
  ϵ_{phys}: Physical error rate per step

  ϵ_{th}: Threshold error rate

  d: Distance of the code

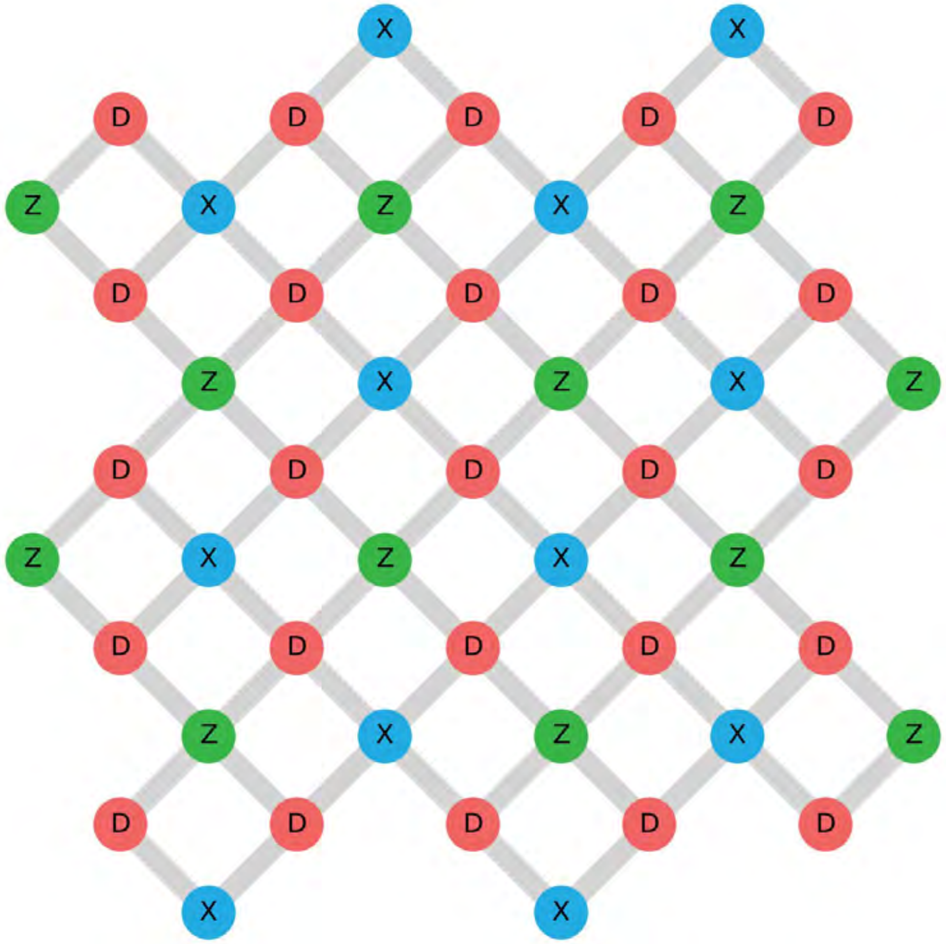
Two-dimensional architecture

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



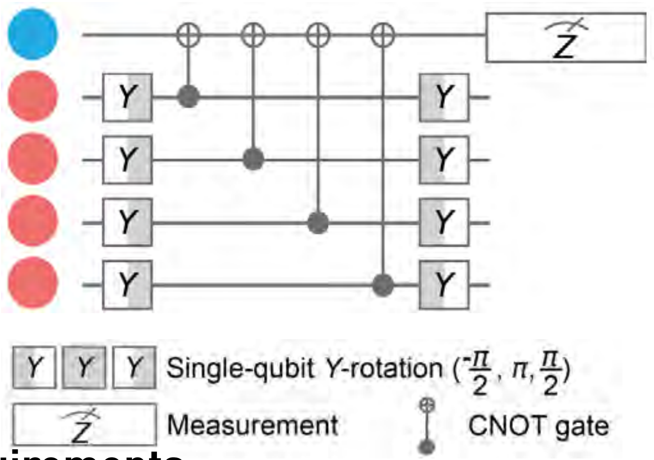
Kitaev, *Annals of Physics* **303**, 2 (2003),
Dennis et al., *Journ. of Math. Physics* **43**, 4452 (2002)
Raussendorff, Harrington, *Phys. Rev. Lett.* **98**, 190504 (2007)
Fowler *et al.*, *Phys. Rev. A* **86**, 032324 (2012)

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-Two Surface Code for Error Detection

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

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

- Logical eigenstates and their equal superpositions:

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

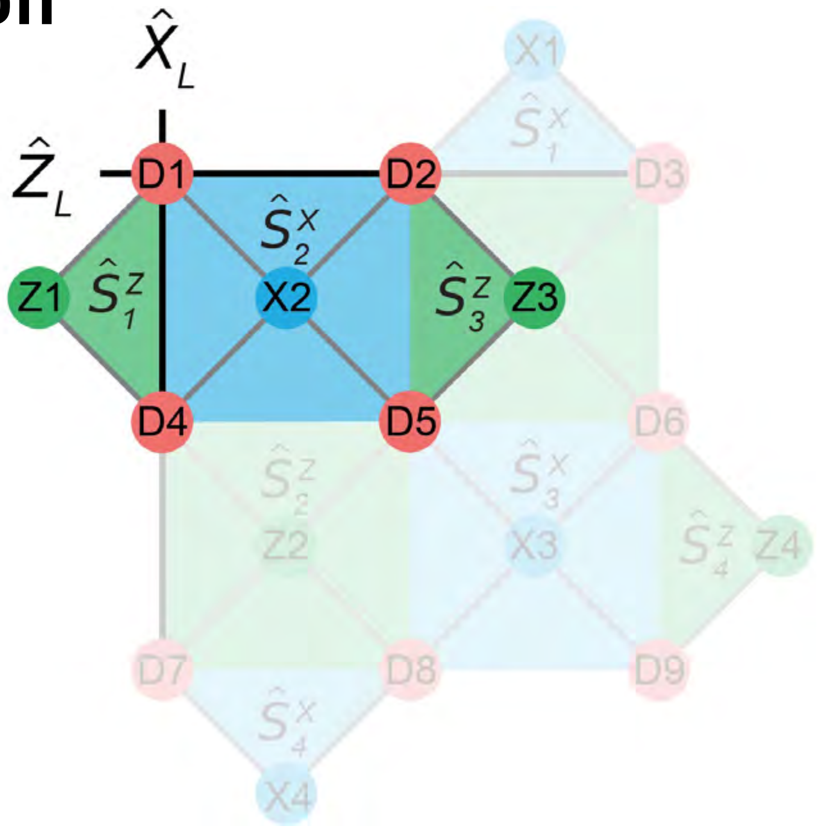
$$|1\rangle_L = \frac{1}{\sqrt{2}}(|0101\rangle + |1010\rangle)$$

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

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

- 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)

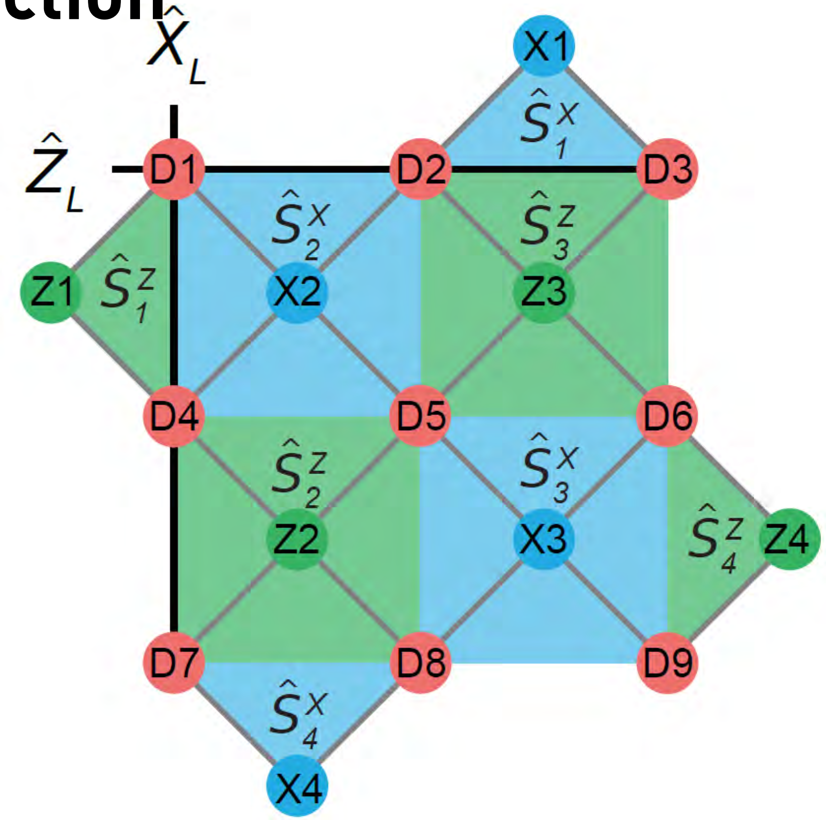
Distance-Three Surface Code for Error Correction

Two-dimensional square lattice of qubits

- $d^2 = 9$ Data qubits: encode single (logical) qubit
  - Logical operators: $\hat{Z}_L = \hat{Z}_1\hat{Z}_2\hat{Z}_3$ $\hat{X}_L = \hat{X}_1\hat{X}_4\hat{X}_7$
  - 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

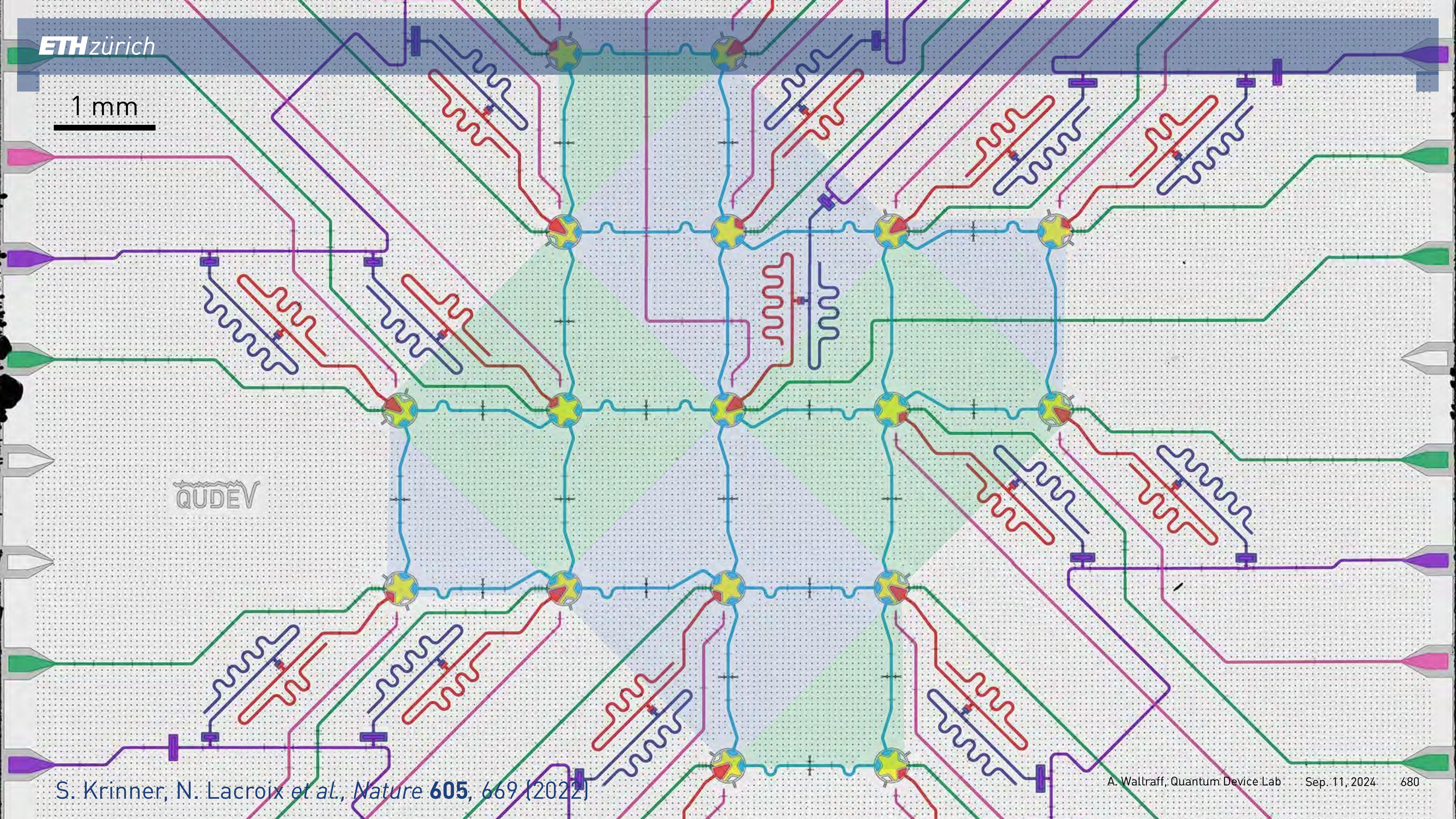


$\hat{S}^{Z1}$	$\hat{Z}_1\hat{Z}_4$
$\hat{S}^{Z2}$	$\hat{Z}_4\hat{Z}_5\hat{Z}_7\hat{Z}_8$
$\hat{S}^{Z3}$	$\hat{Z}_2\hat{Z}_3\hat{Z}_5\hat{Z}_6$
$\hat{S}^{Z4}$	$\hat{Z}_6\hat{Z}_9$

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

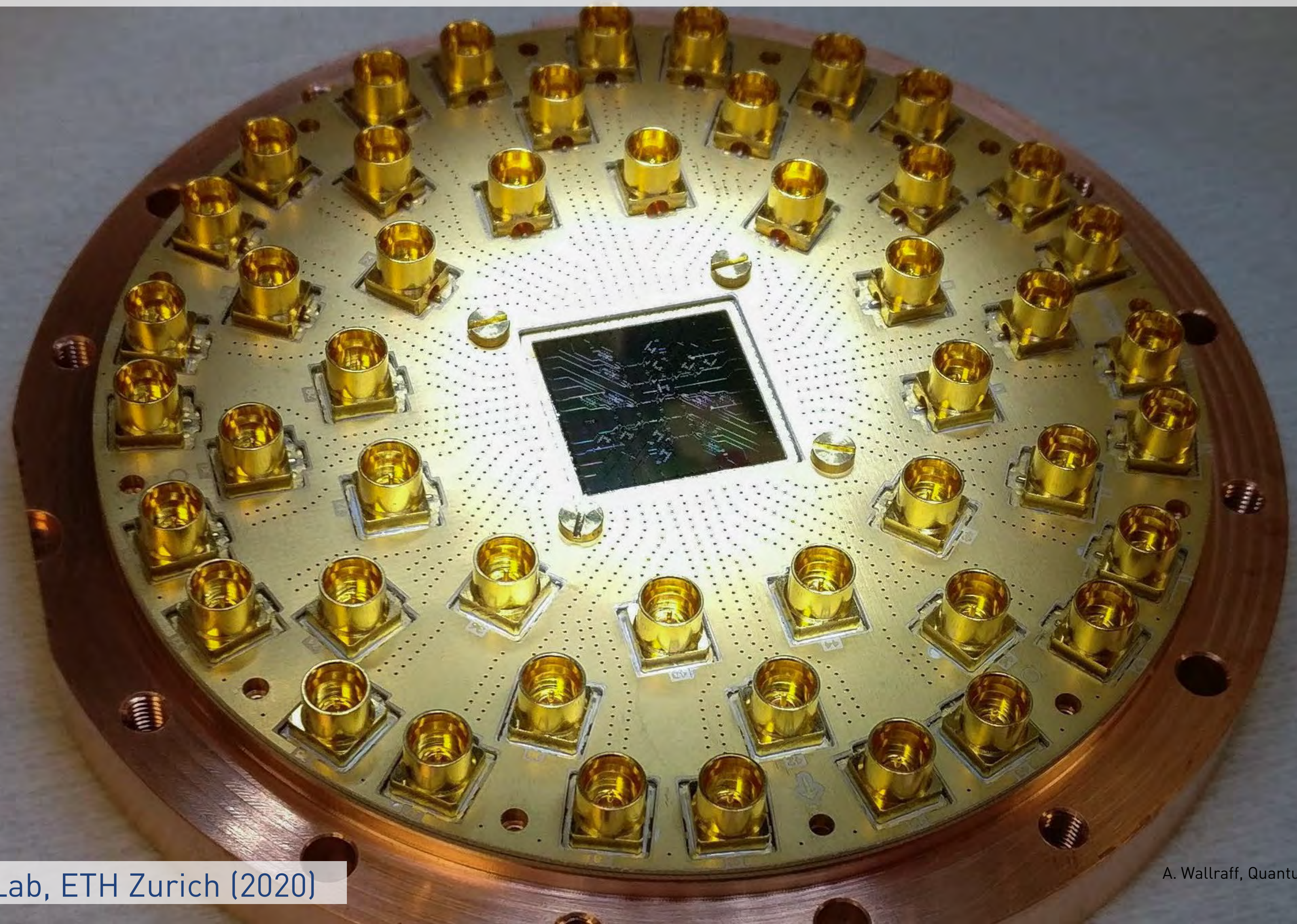
Bombin, Delgado, *Phys. Rev. A* **76**, 012305 (2007)

Tomita, Svore, *Phys. Rev. A* **90**, 062320 (2014)



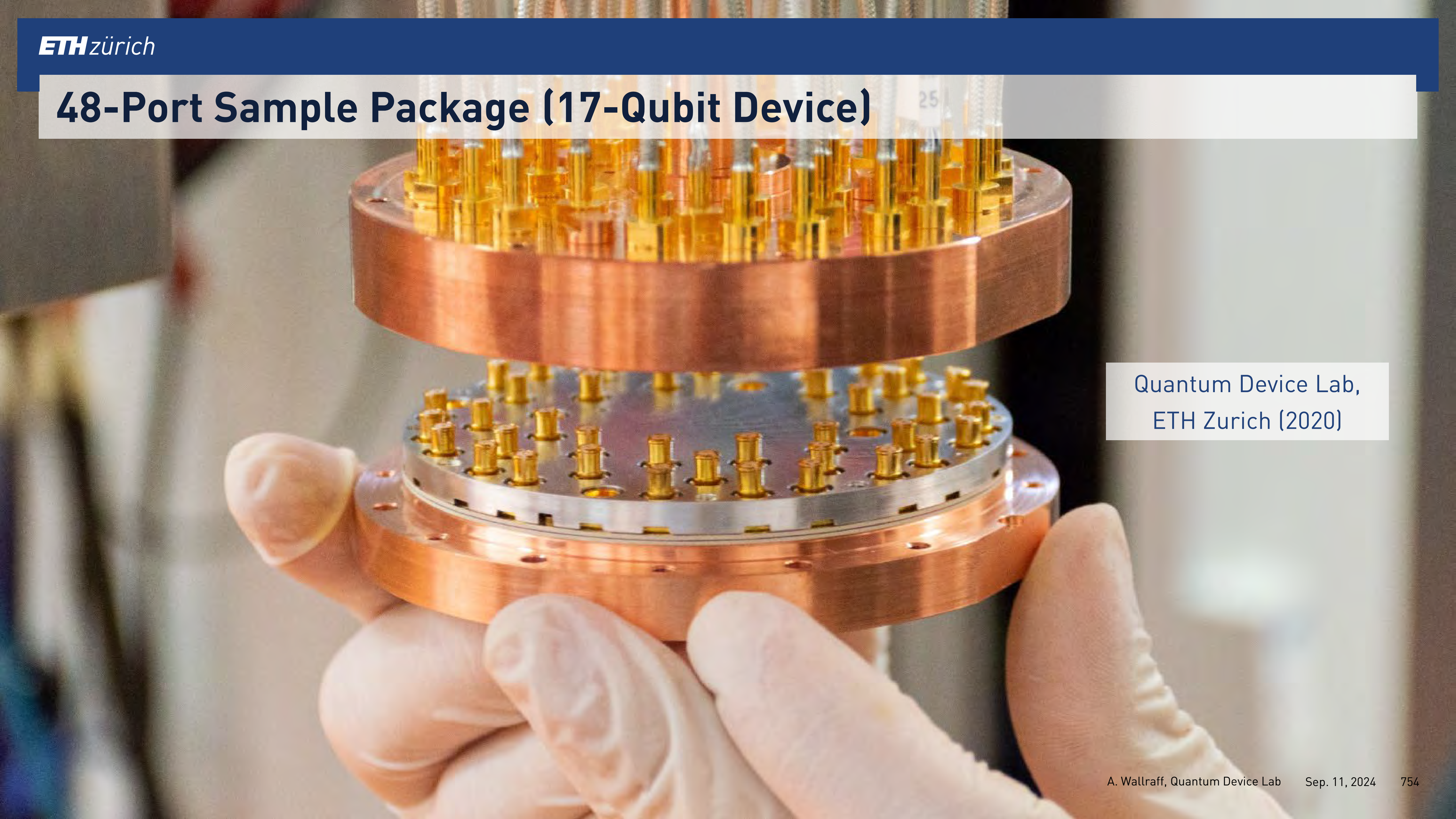
S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

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)

Quantum Device Lab, ETH Zurich (2022)

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)]

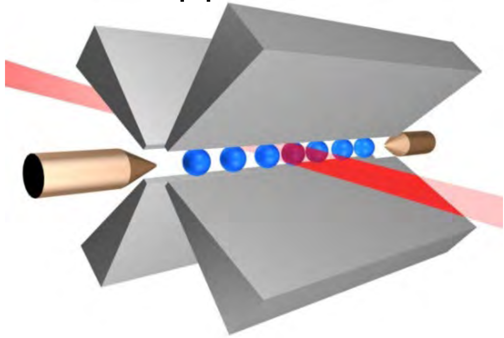
Quantum codes, single-cycle experiments:

- 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

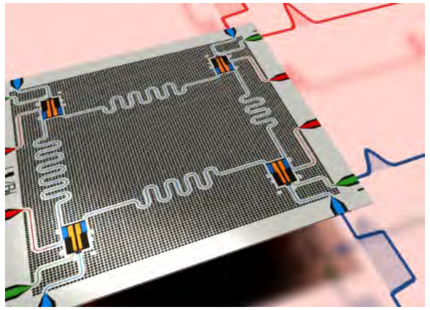
- Andersen et al., Nat. Phys. 16, 875 (2020)
- Chen et al., Nature 595, 7867 (2021)
- Marques et al., Nat. Phys. **18**, 80 (2022)

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)

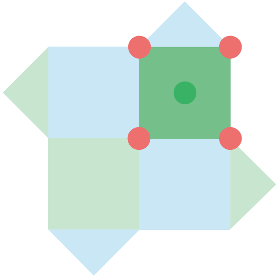
Repeated quantum error correction

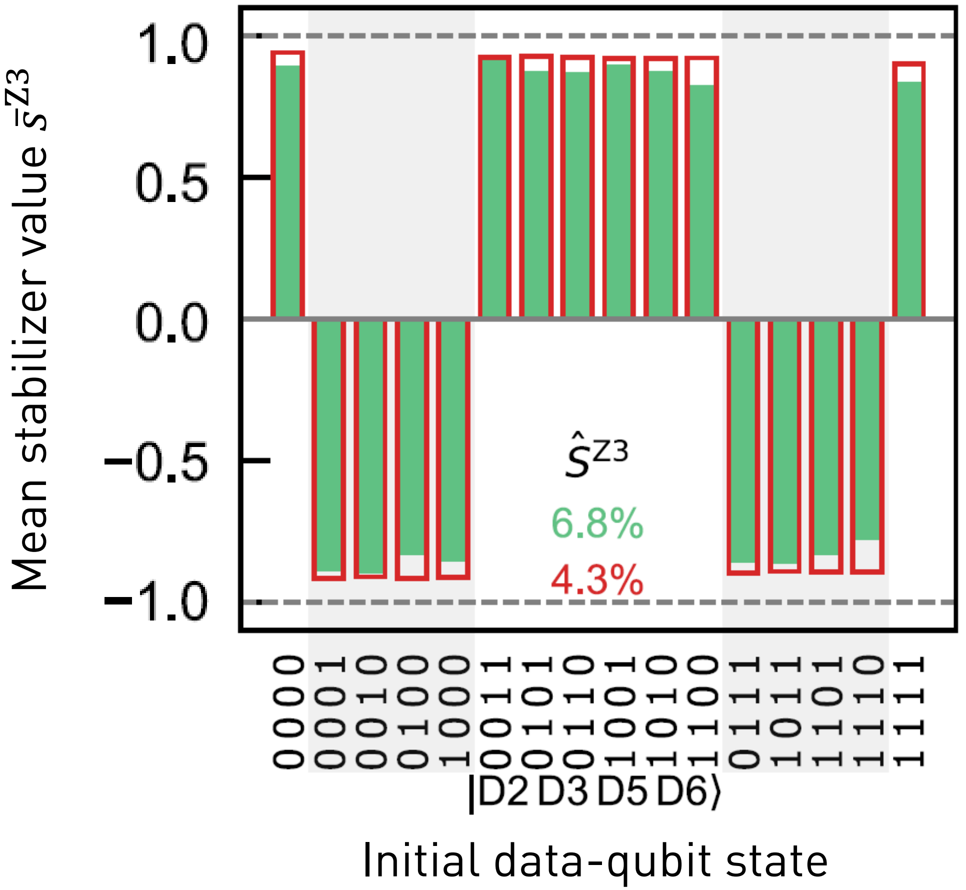
- Color code (trapped ions)
  Ryan-Anderson et al., PRX 11, 041058 (2021)
- Distance-3 surface code (s.c.)
  Krinner, Lacroix *et al.*, *Nature* **605**, 669 (2022)
  Zhao et al., *PRL* **129**, 030501 (2022)
- Distance-3 heavy-hexagon code (s.c.)
  Sundaresan et al., *Nat. Commun.* **14**, 2852 (2023)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

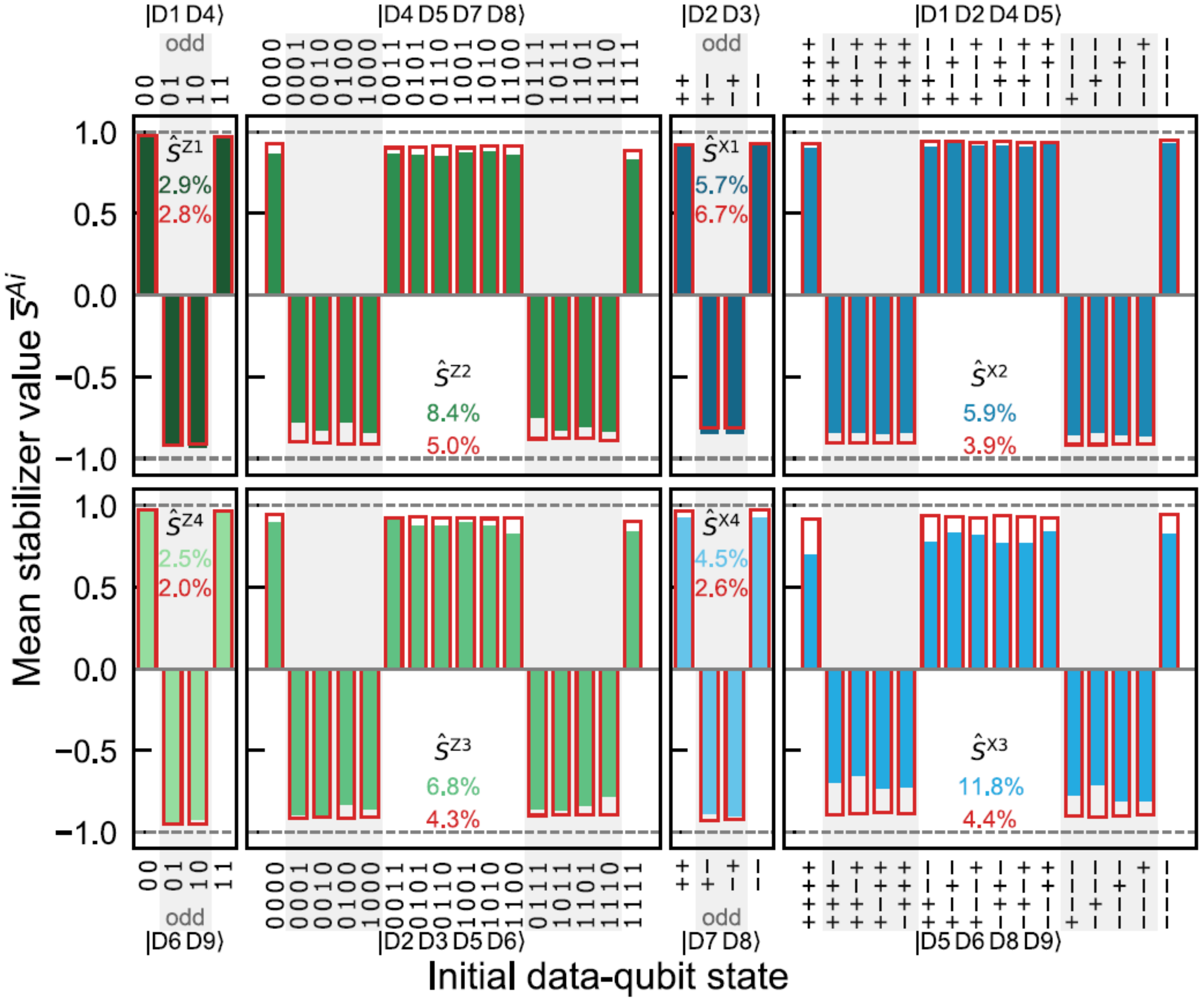
Individual characterization

- 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

Average parity error

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

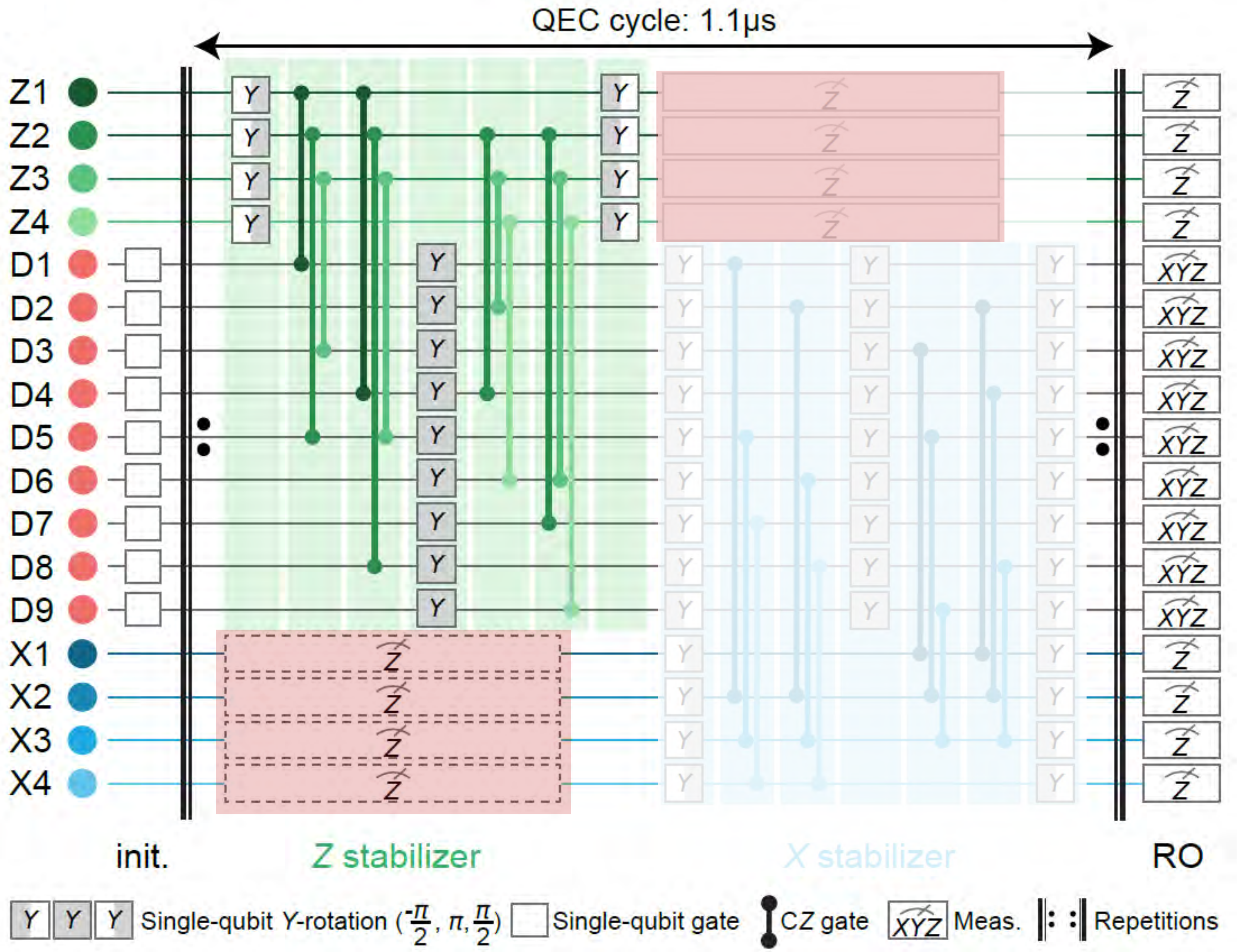
Qualitative agreement with master-equation simulations



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)

Logical Error Probability and Logical Error per Cycle

Logical error probability:

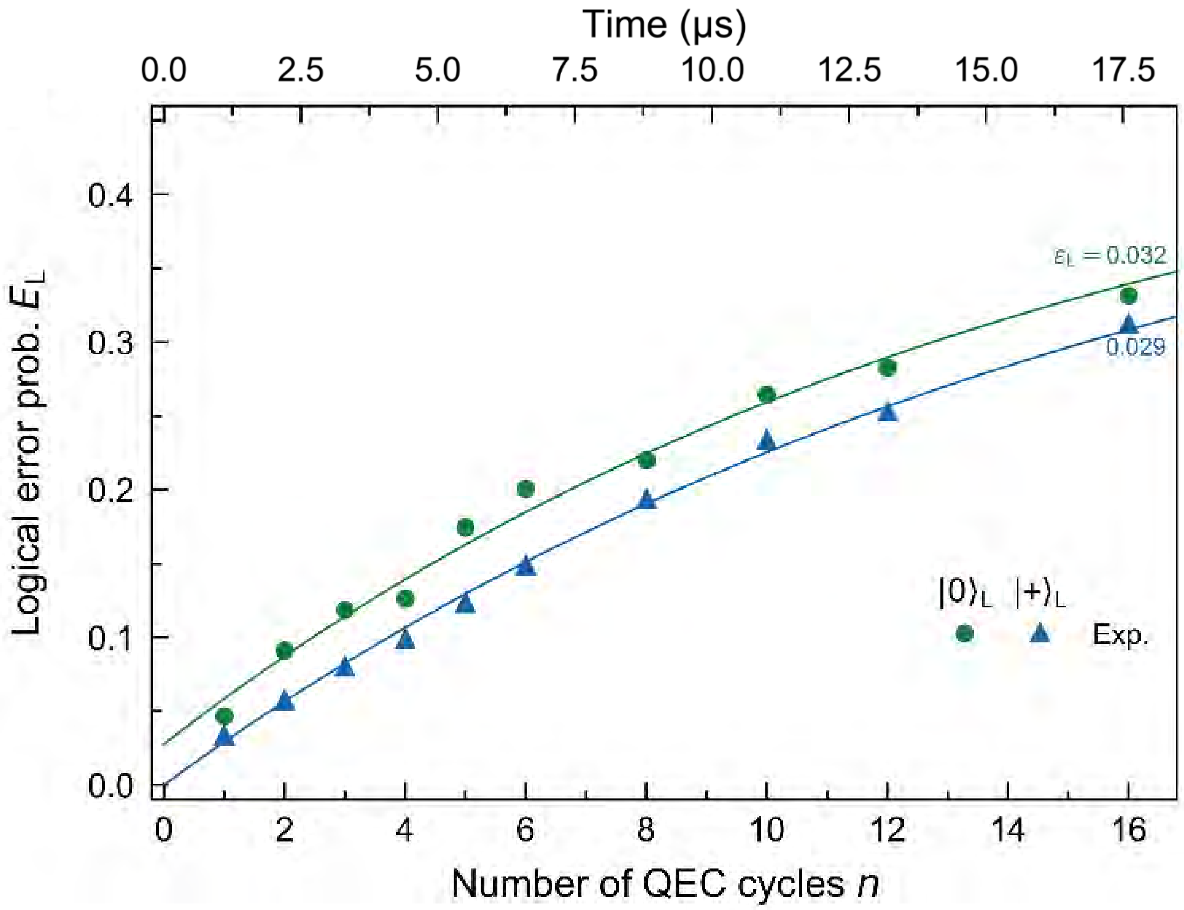
- $E_L = (1 - \langle \hat{Z}_L \rangle)/2$ for eigenstates of $\hat{Z}_L$
- $E_L = (1 - \langle \hat{X}_L \rangle)/2$ for eigenstates of $\hat{X}_L$

Logical error per cycle:

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

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

- $\epsilon_L \sim 0.03$

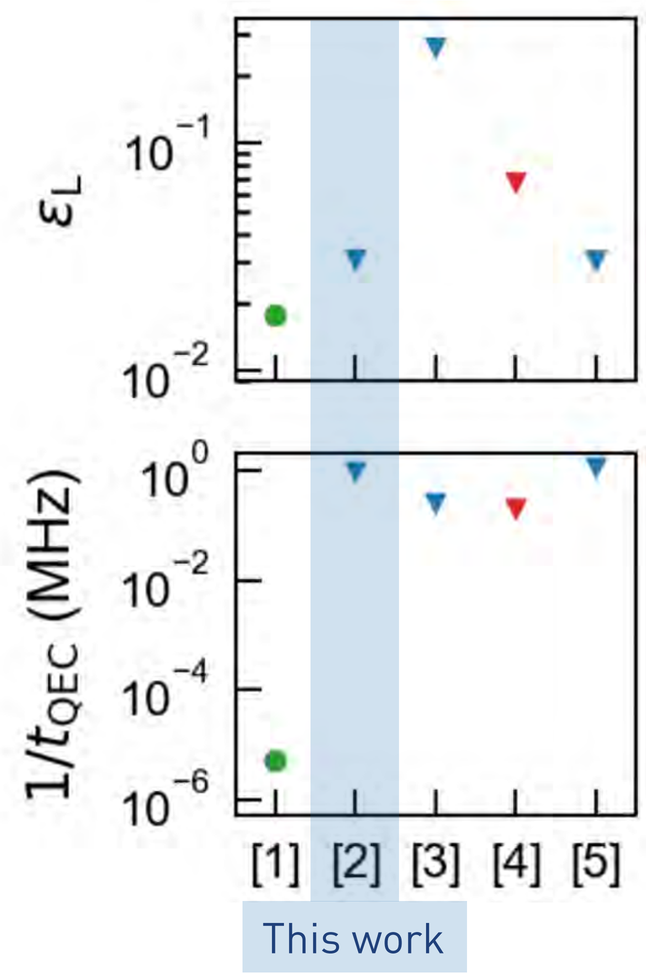


S. Krinner, N. Lacroix *et al.*, *Nature* **605**, 669 (2022)

Comparison of Repeated Distance-Three QEC Experiments

The competition:

- 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 AI, *Nature* **614**, 676 (2023)



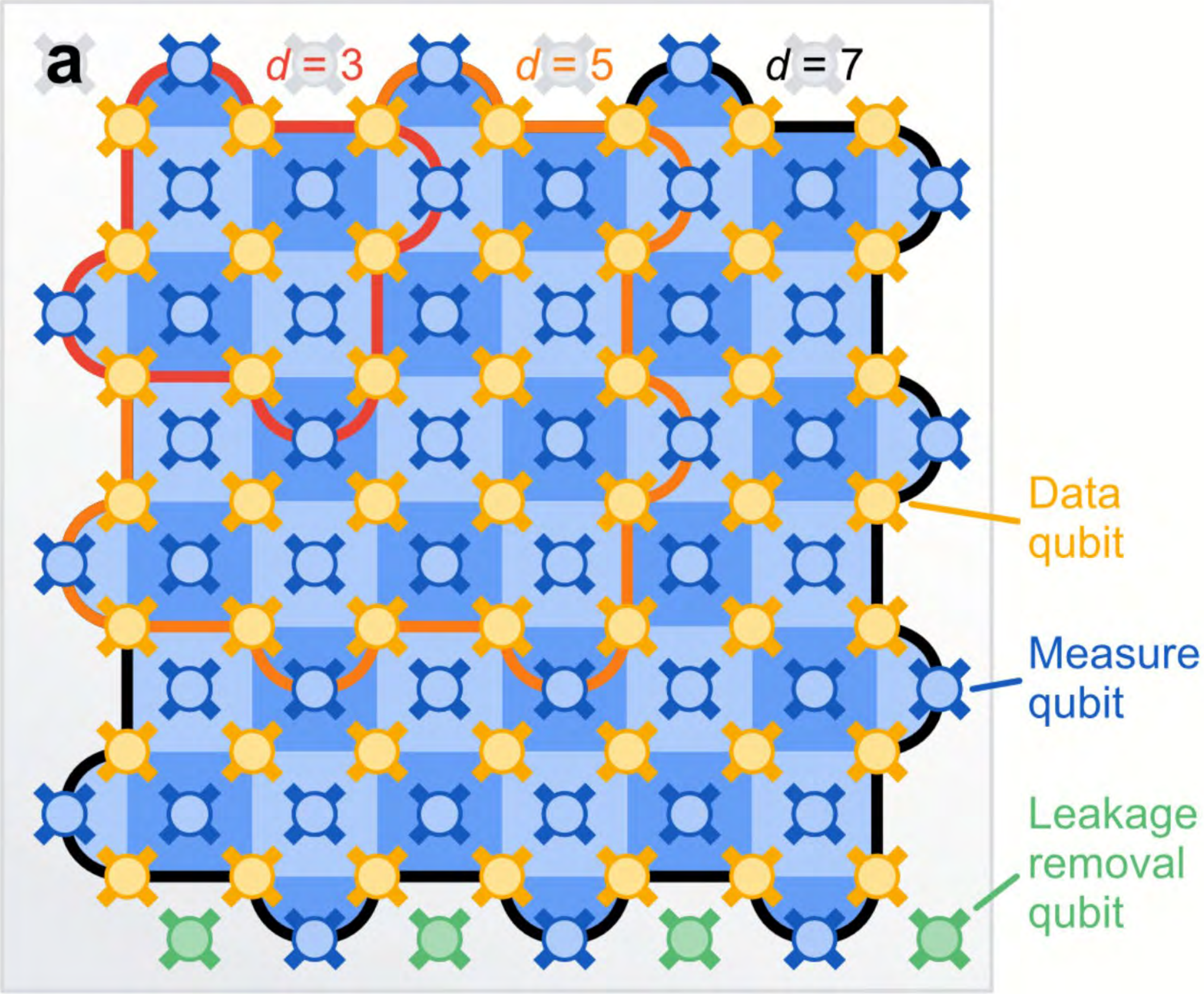
Implementations:

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

Performance criteria

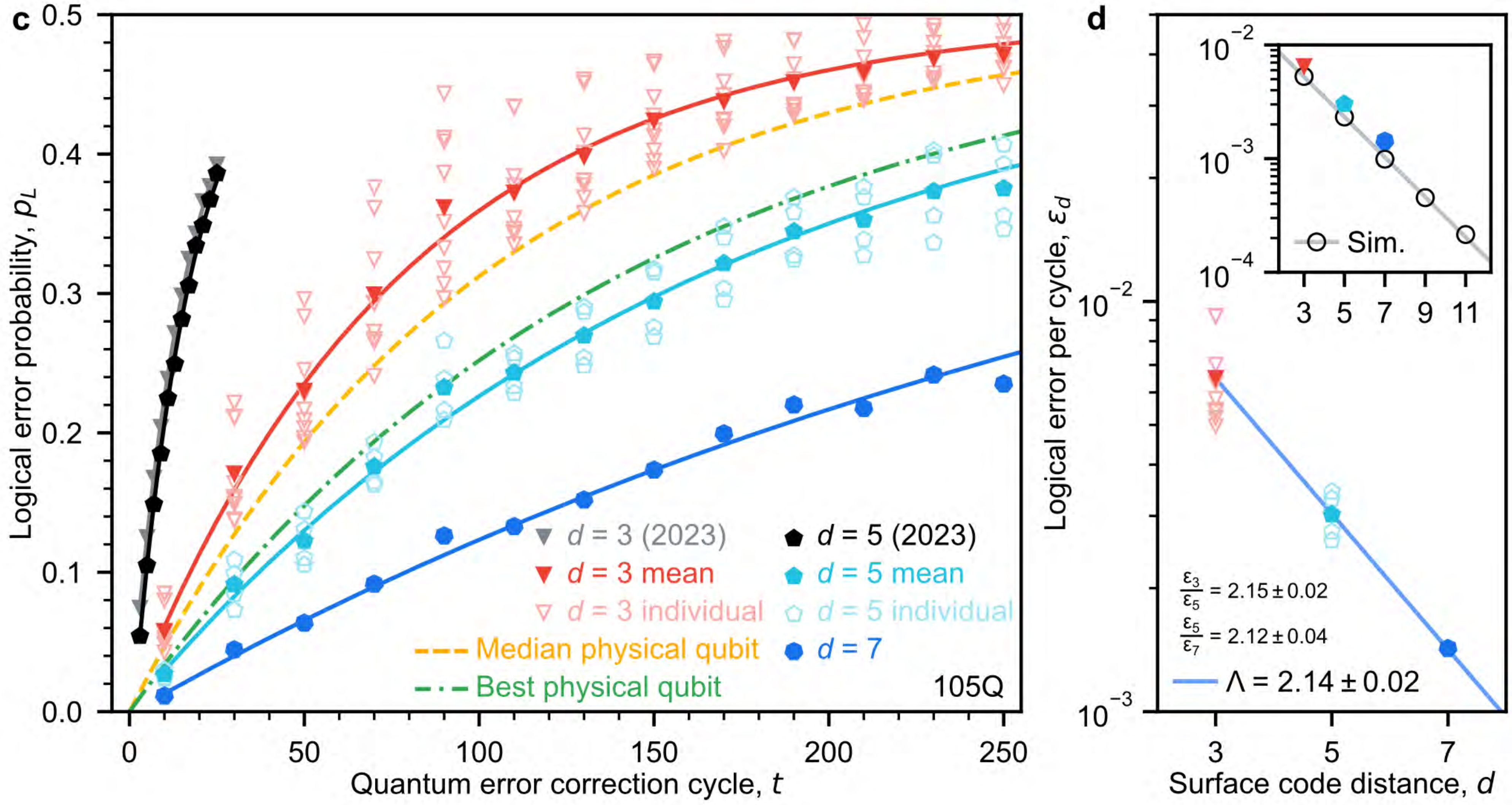
- Small logical error per cycle ε_L
  -> critical for fault tolerant quantum computing with high accuracy
- High QEC cycle rate $1/t_{QEC}$
  -> crucial for execution of deep quantum circuits on short time scales

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



Google Quantum AI and Collaborators, *arXiv:2408.13687v1* (2024)

Distance Scaling and Logical Error Suppression



Google Quantum AI and Collaborators, *arXiv:2408.13687v1* (2024)

Summary & Outlook

Here:

- Repeated quantum error correction in a distance-3 surface code
  - Fast QEC cycle of 1.1 μs
  - Low logical error per cycle $\epsilon_L \sim 0.03$
  - Leakage reduction units under development
  - Break-even within reach, potentially close to threshold

Up next:

- Logical operations on single logical qubit
- Gates between two logical qubits

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

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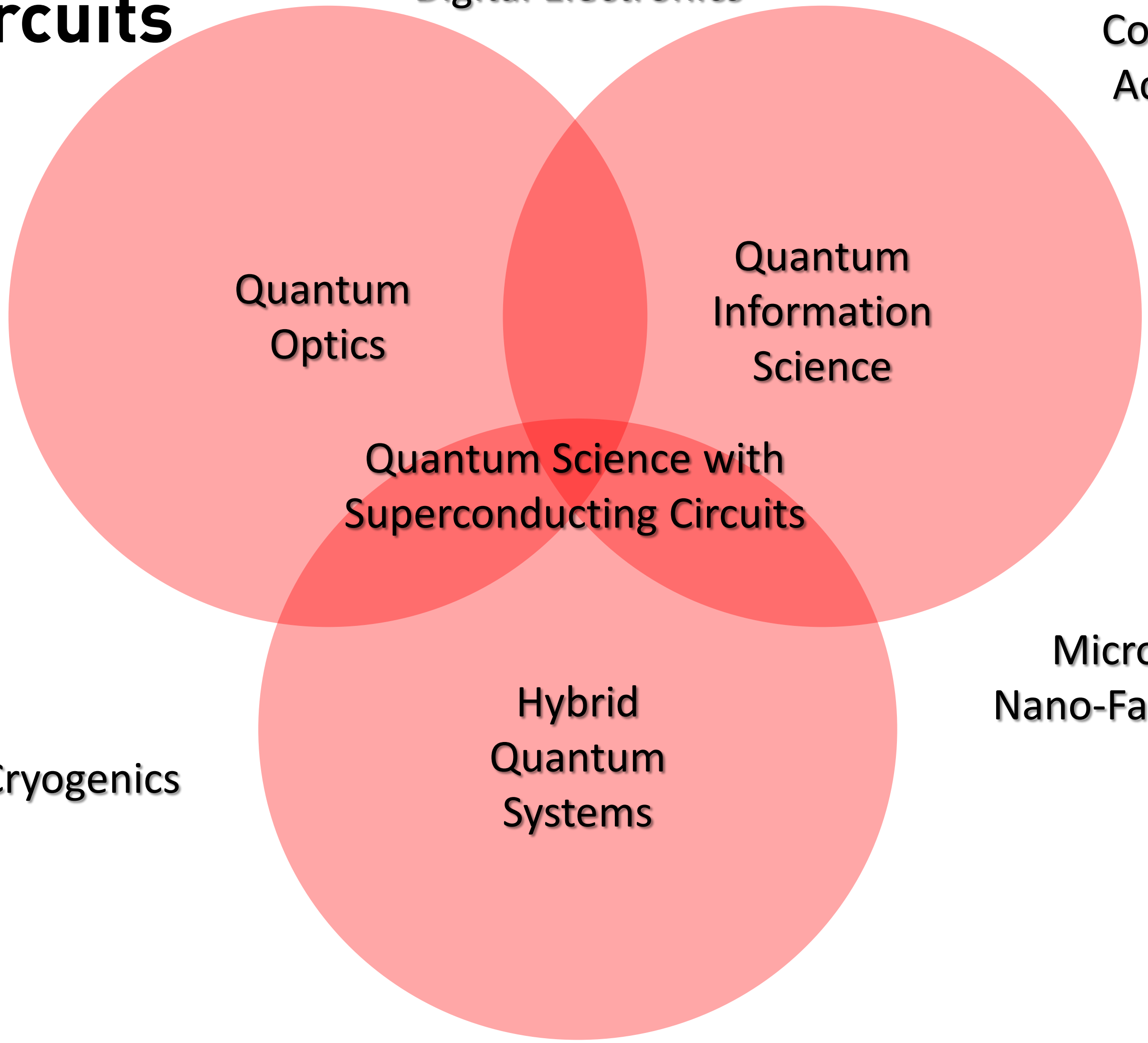
The Paper

Quantum Science with Superconducting Circuits



The Quantum Device Lab

with spring-term project students

Innovation project supported by

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