Development of quantum hardware towards fault-tolerant quantum computing

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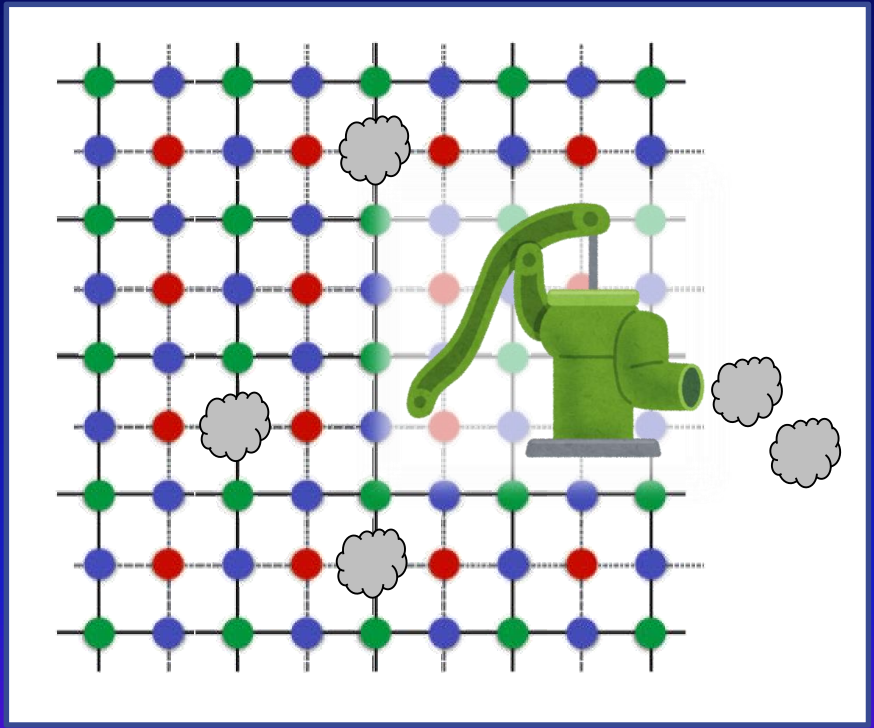
Center for Emergent Matter Science (CEMS), RIKEN

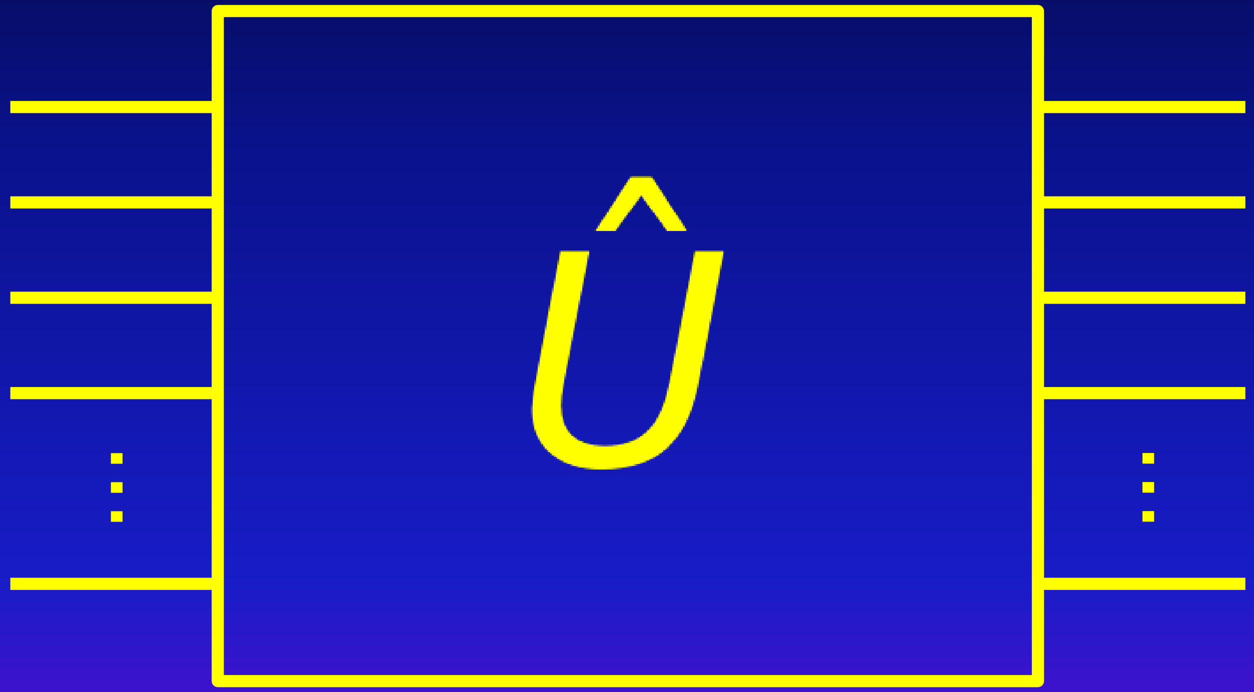
Fault-tolerant quantum computer

="Perpetual" quantum machines



Fault-tolerant quantum computer

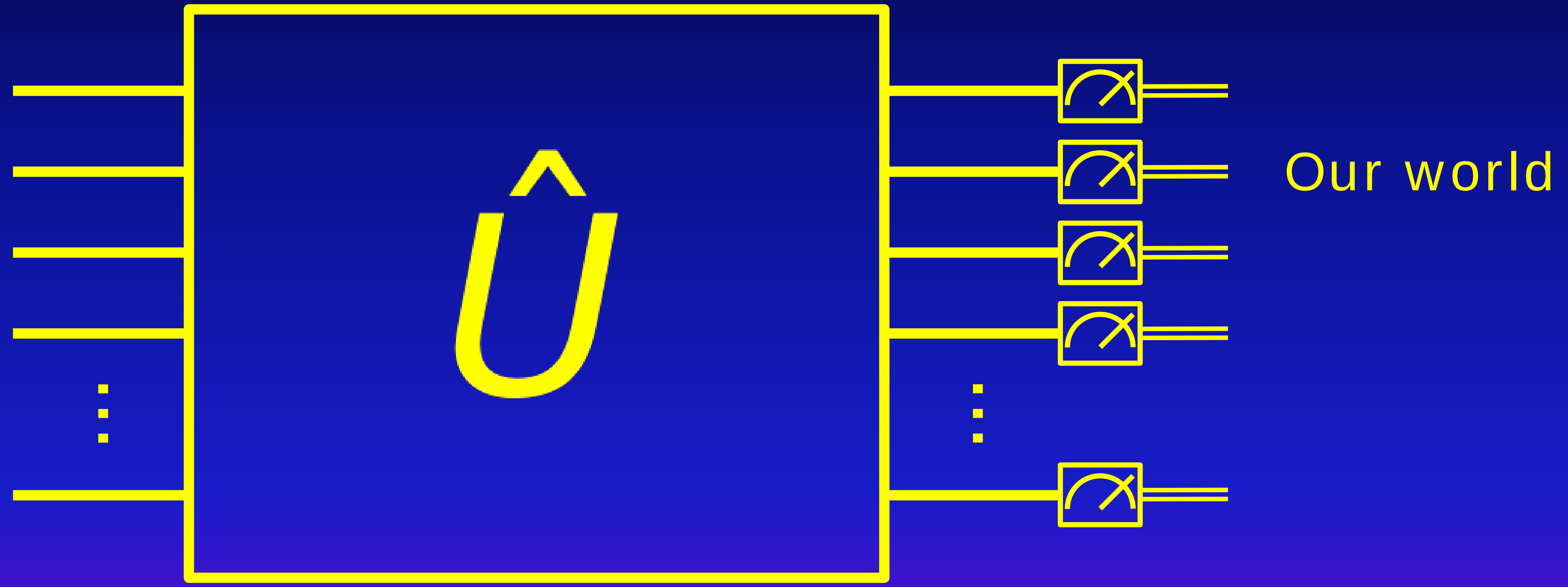
=”Perpetual” quantum machines



Many world !!!

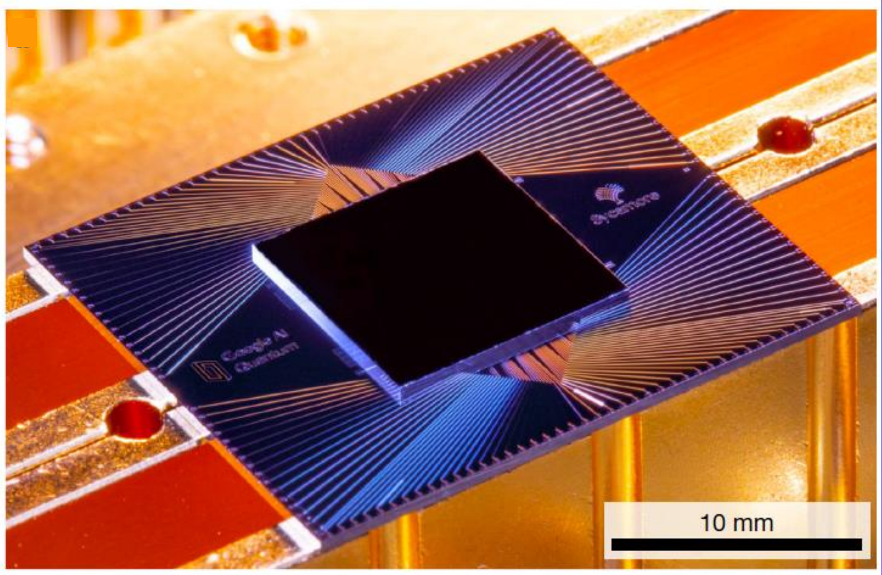
$O(2^N)$

Fault-tolerant quantum computer
=”Perpetual” quantum machines



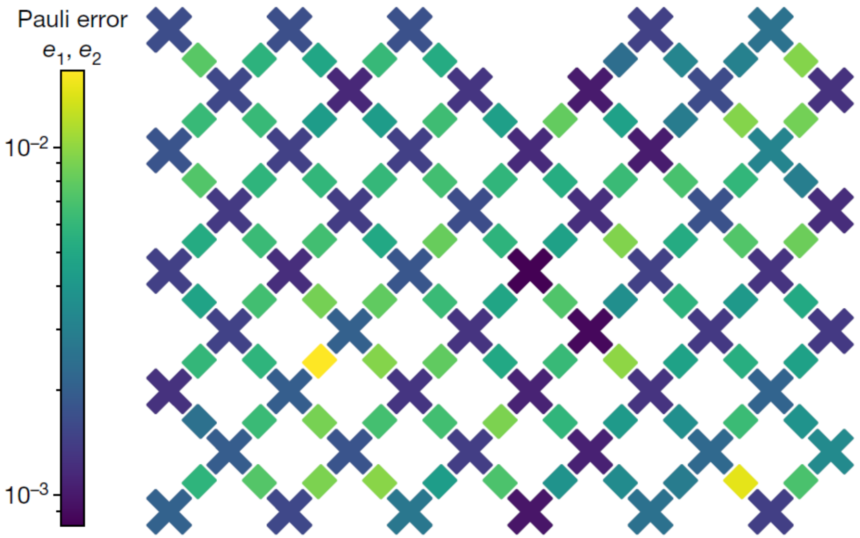
Quantum supremacy using a programmable superconducting processor

- Flip-chip bonding
- Frequency-tunable qubits
- Tunable-coupler architecture
    - Fast two-qubit gate ~ 12 ns
    - Small residual coupling



Google AI Quantum
Nature 574, 505 (2019)

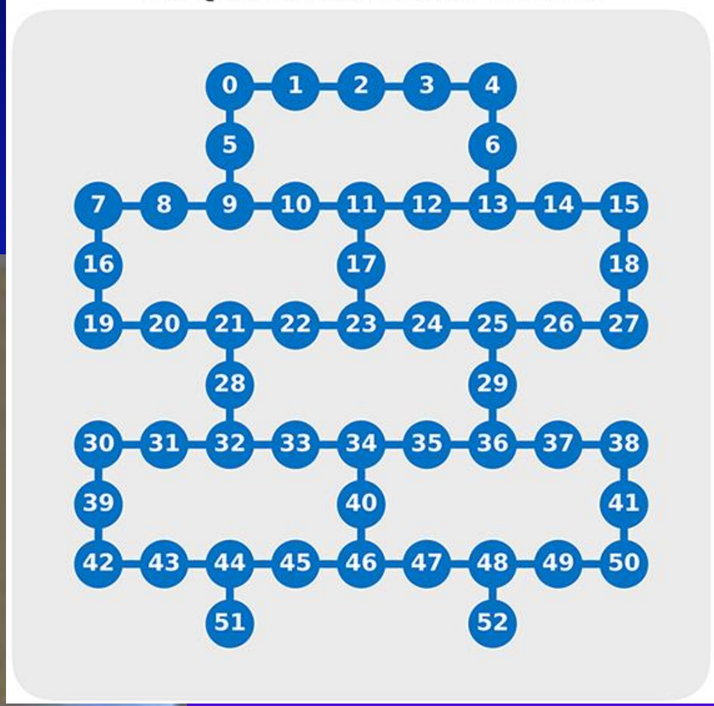
Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



$9 \times 6 - 1 = 53$ qubits

Fixed-frequency qubits

- Long coherence ~ 100 μs
- Cross-resonance gate ~ 150 ns
- 16-bit GHZ state generation
- 20-bit, 53-bit cloud service



53 Qubit Rochester Device

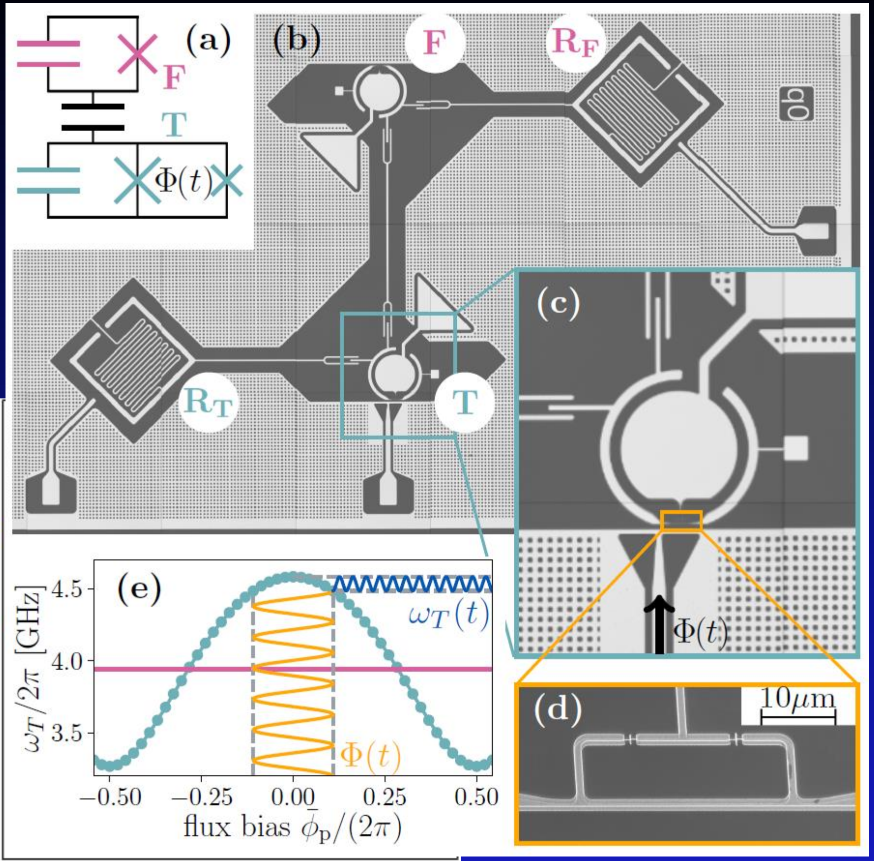
	IBM Q System One (In preparation for the IBM Q Network)
Relaxation (T1) in microseconds	73.9
mean	**132.9**
best	38.2
worst	
Dephasing (T2) in microseconds	69.1
mean	**100.8**
best	39.2
worst	
Two-qubit (CNOT) error rates x10-2	1.69
mean	**0.97**
best	2.85
worst	
Single-qubit error rates x10-3	0.41
mean	**0.19**
best	0.82
worst	

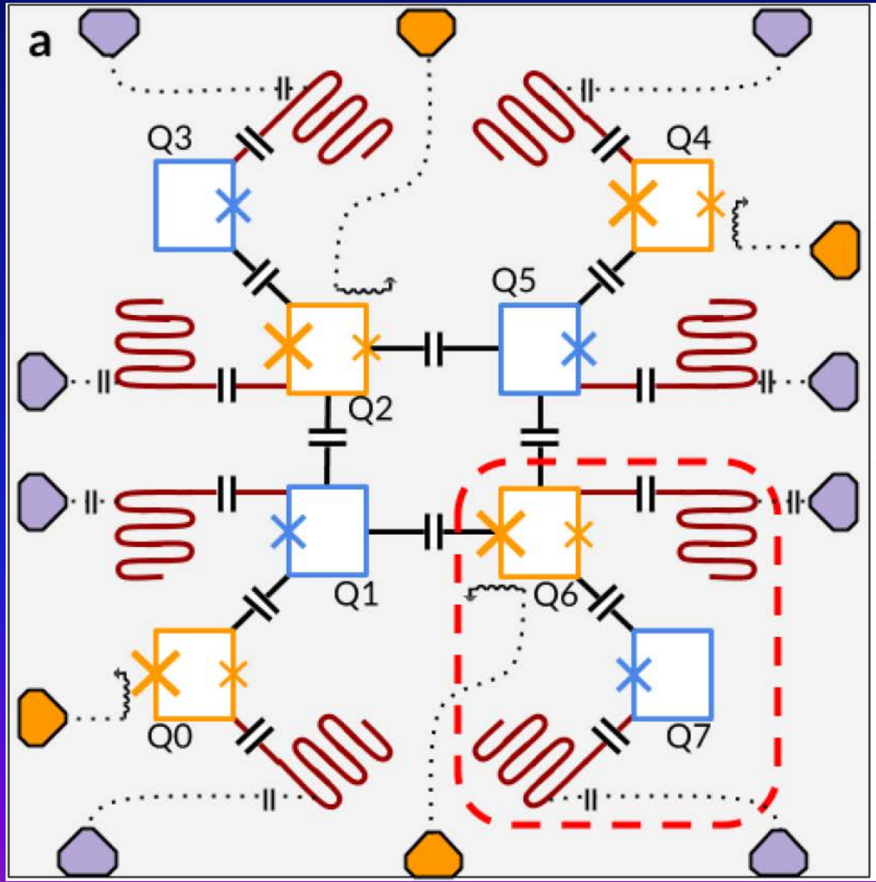
https://www.ibm.com/blogs/research/2017/11/the-future-is-quantum/?utm_source=twitter&utm_medium=social&utm_campaign=ibmq&utm_content=2050qubit

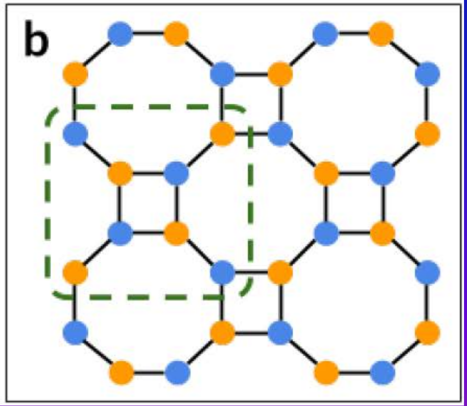
K.X. Wei et al. arXiv:1905.05720 (IBM)
https://www.ibm.com/blogs/research/2019/03/power-quantum-device/
https://www.ibm.com/blogs/research/2019/09/quantum-computation-center/

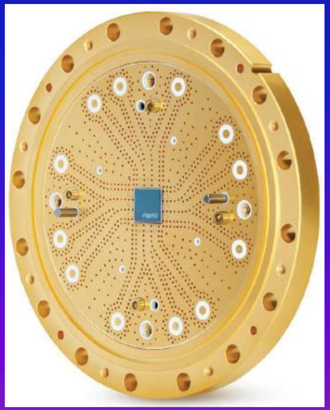
Parametric coupling

- Fixed- and tunable-freq qubits
- 16-bit cloud service



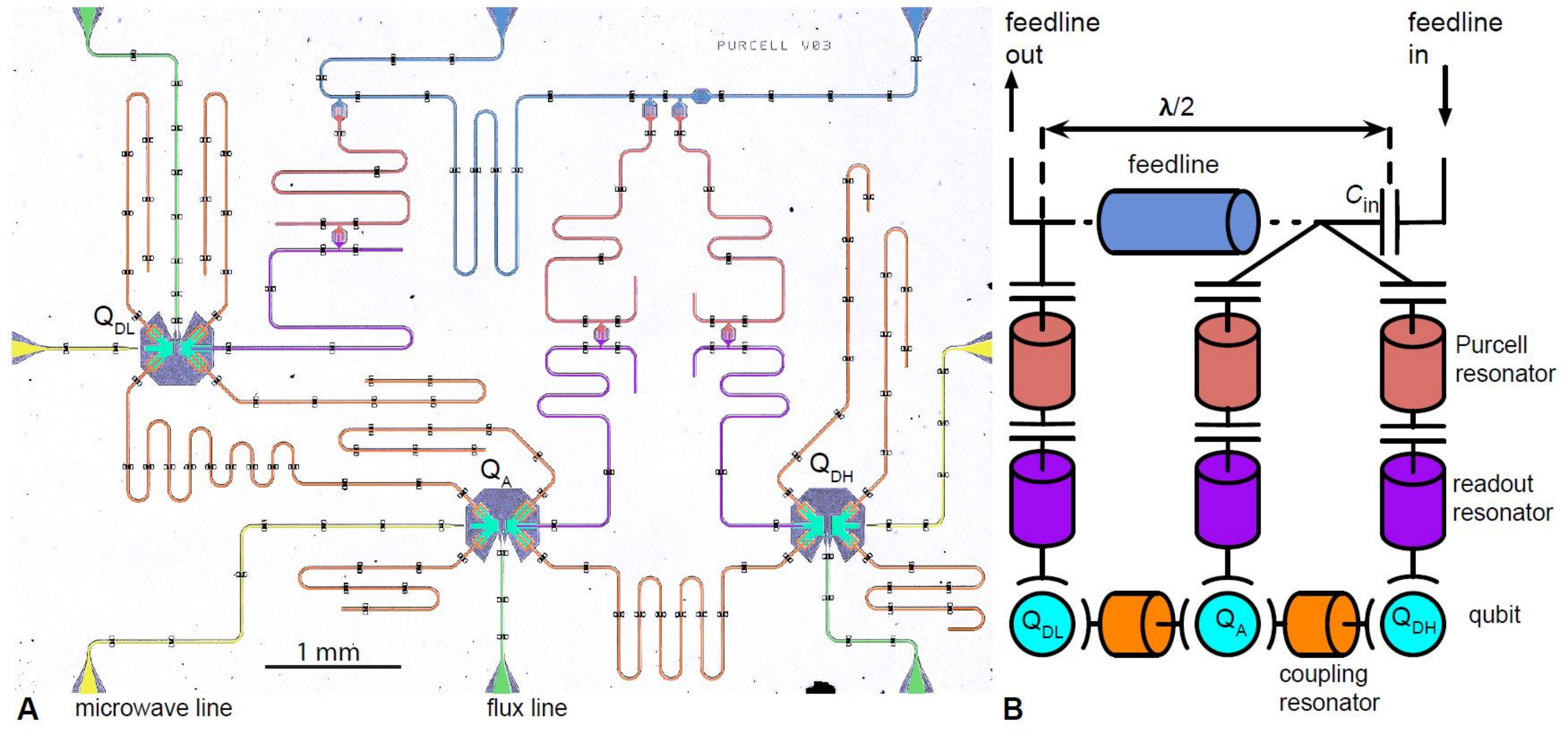




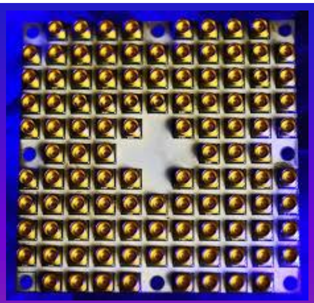


S. Caldwell et al. Phys. Rev. Appl. 10, 034050 (2018); S. Hong et al. arXiv:1901.08035 (Rigetti)

Resonator mediated coupling

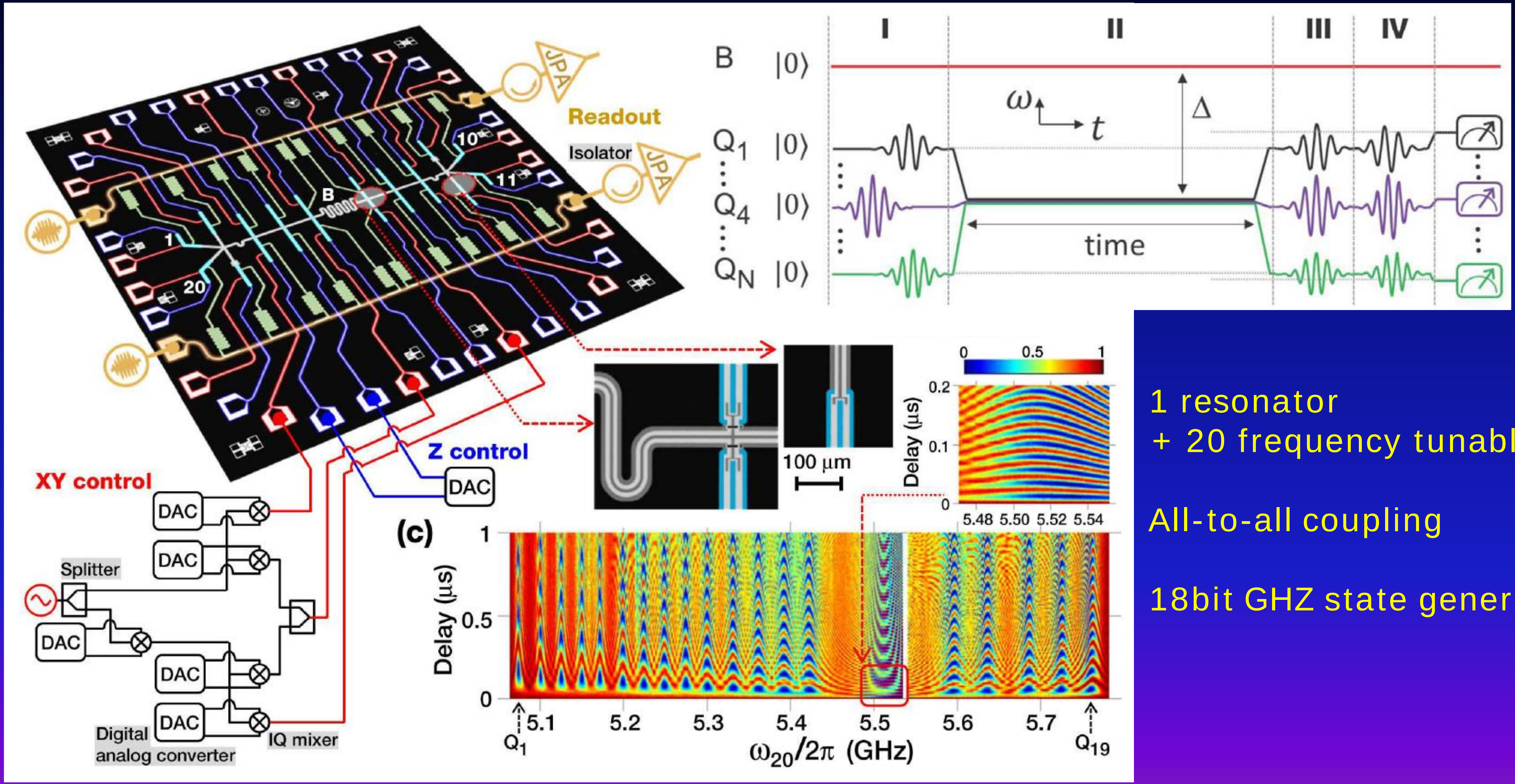


- Tunable qubits
- 49-bit chip under development



M. A. Rol et al. PRL 123, 120502 (2019); C. C. Bultink et al. arXiv:1905.12731 (Delft)

Quantum bus coupling



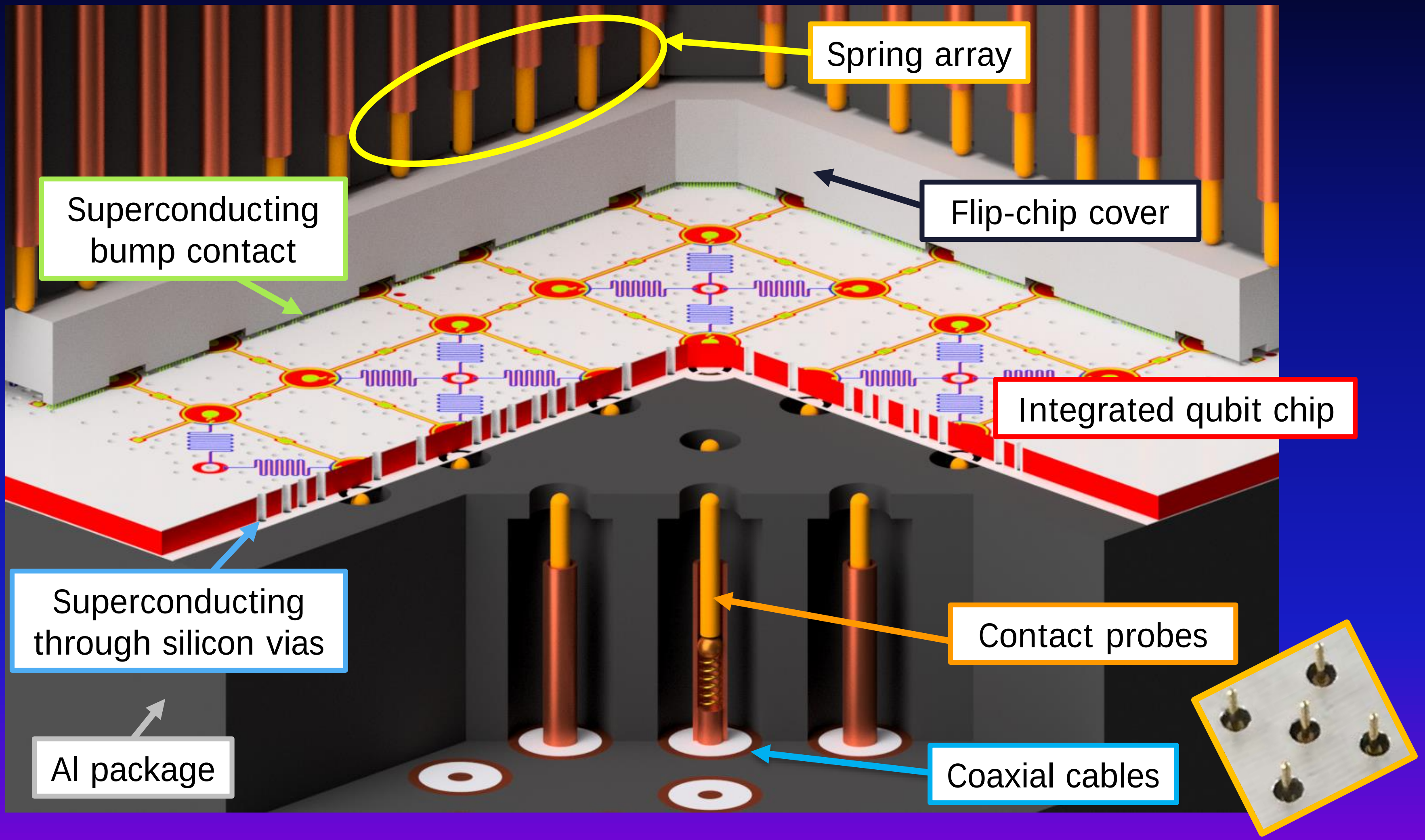
1 resonator
+ 20 frequency tunable qubits

All-to-all coupling

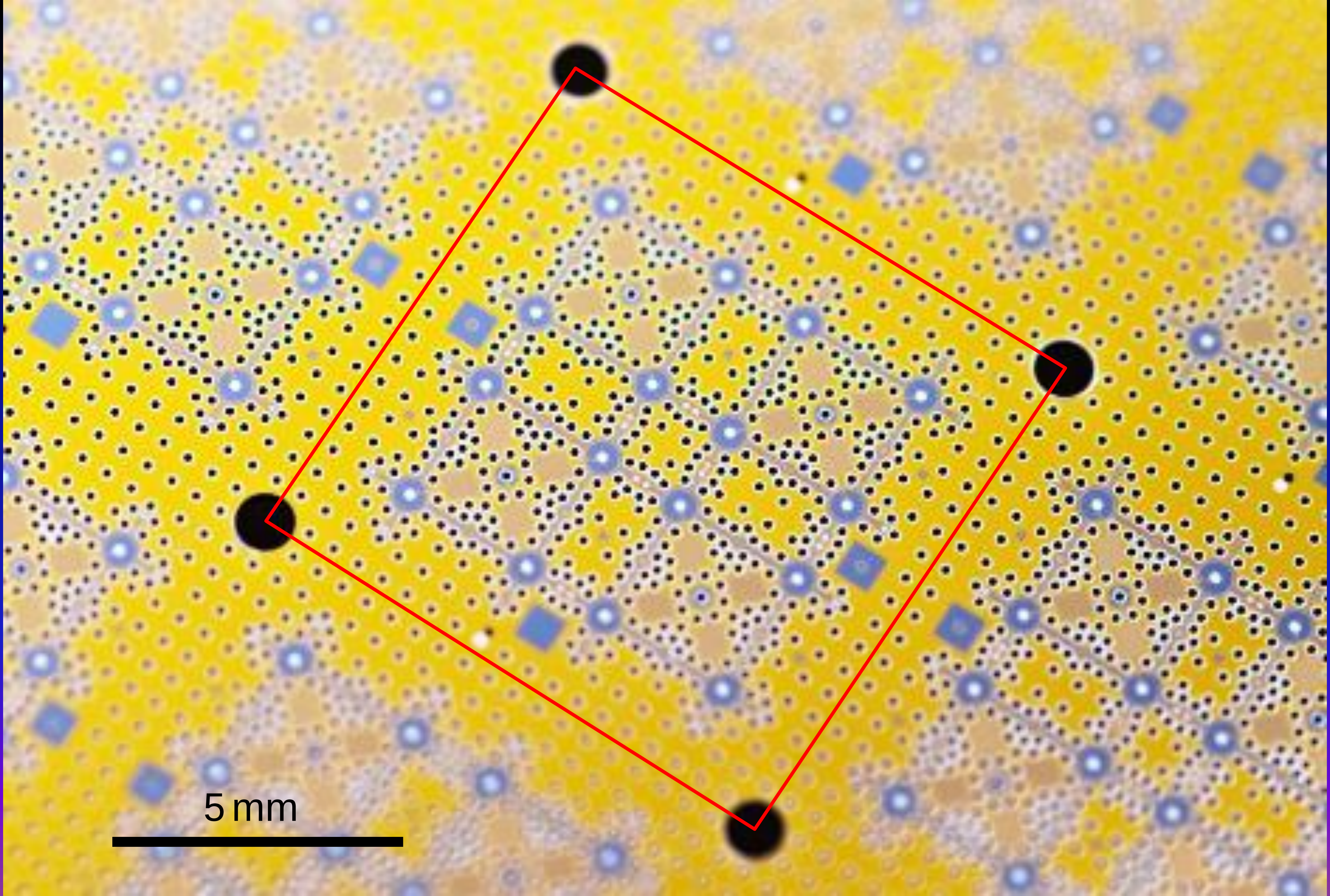
18bit GHZ state generation

C. Song et al. Science 365, 574 (2019) (Zhejiang)

2D integration with vertical access



Q-LEAP


5 mm

“Smart” brute force

Improved coherence
- materials
- fabrication

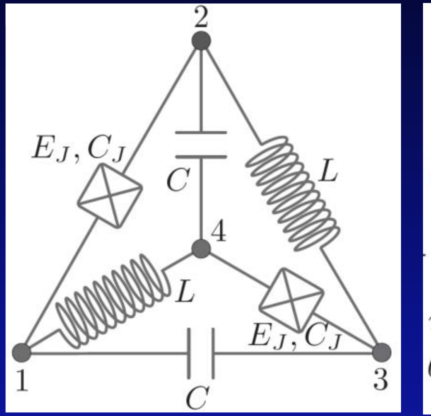
Fast gate/readout
- design
- architecture

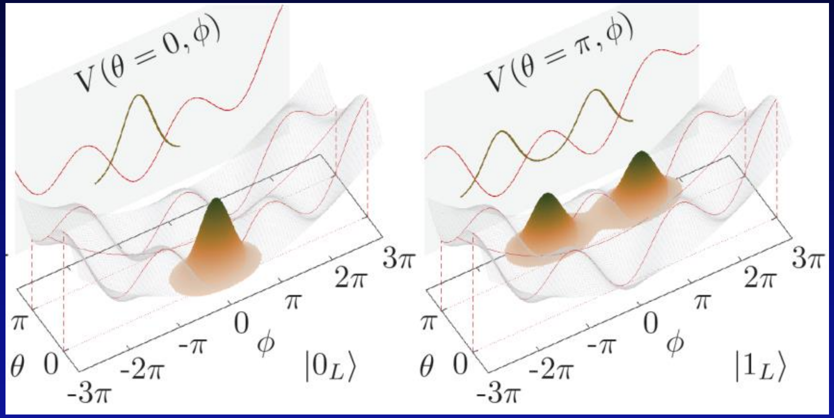
Better packaging/wiring
- filtering, shielding, thermalization
- high-density, miniaturized components

Peripheral technologies
- control electronics   low-latency, all-digital?
- SFQ/CryoCMOS
- cryogenics

New directions beyond brute force

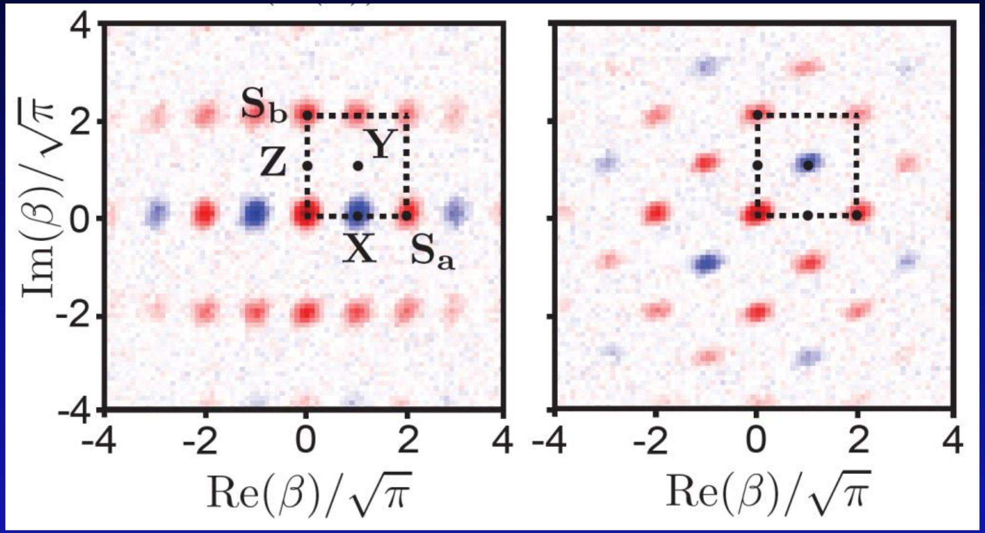
Robust qubits (0-π qubit, etc.)





arXiv:1910.07542 (Princeton)

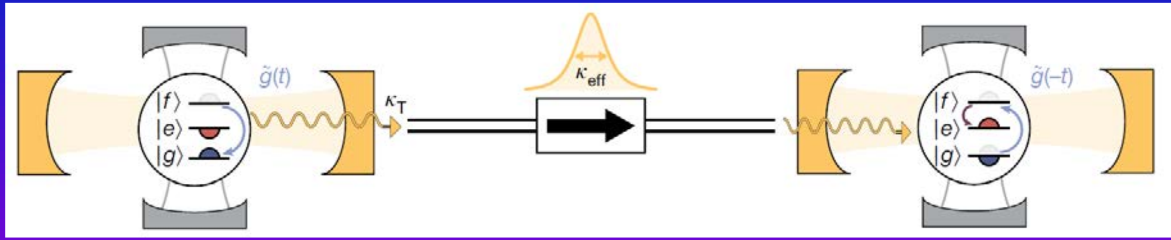
Bosonic codes (cat, binomial, GKP, etc.)



arXiv:1907.12487 (Yale)

Temporal-mode entanglement + Measurement-based quantum computing

Distributed quantum computing



Nature 558, 264 (2018) ETH Zurich

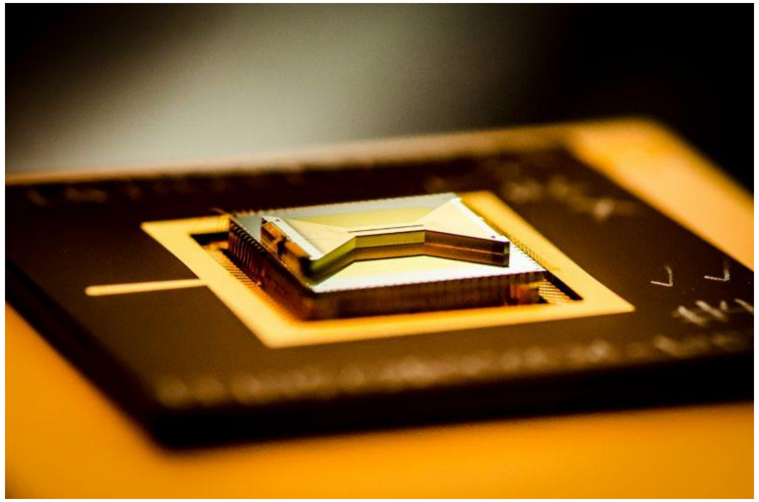
Current state-of-the-art of ion trap quantum computing

High-fidelity operations achieved in few-qubit systems

- **Single-qubit gate: 99.9999 %**
- **Two-qubit gate: 99.9 %**
- **SPAM: >99.9%**

PRL 113 220501(2014); PRL 117 060504(2016) Oxford

IONQ



Advantages of using trapped ions:

- **Long coherence times (~ 1 min)**
- **Identical qubits (cf. atomic clocks)**
- **Room temperature operation**
- **All-to-all qubit connection**

Disadvantages:

- **Slow gate speed**
- **Difficult to scale beyond >50 qubits**

IonQ quantum computer:

- Fully connected 11 ions
- >60 2-qubit gates w/ error < 1.0%
- Partnered w/ Microsoft Quantum Azure

Other leading institutions:

- NIST
- U. Innsbruck
- PTB
- U. Oxford
- U. Maryland
- ETH Zurich
- Honeywell
- Alpine Quantum Technologies

Prospects for ion trap quantum computing

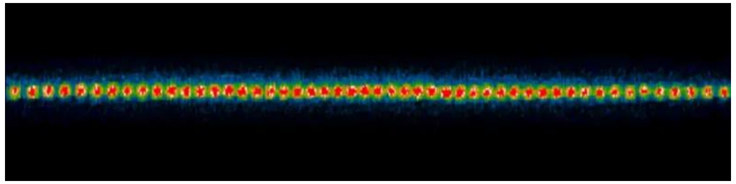
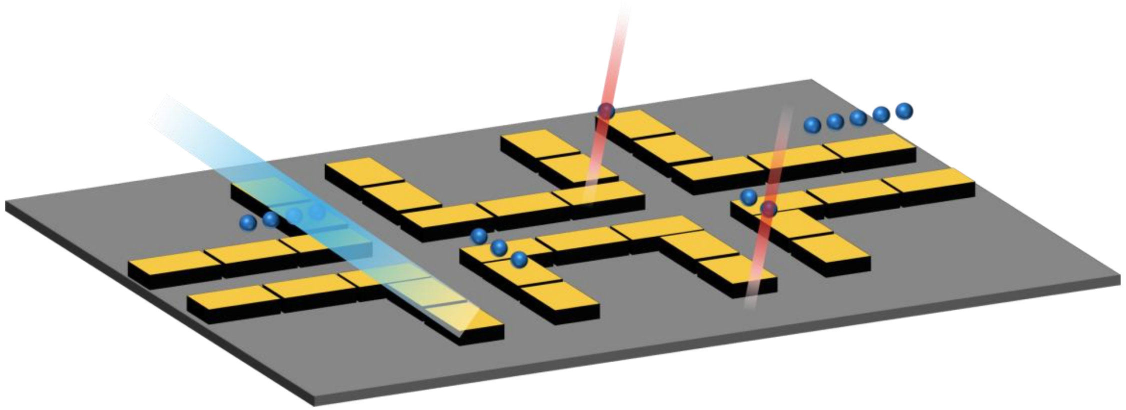


Photo by TIQI group, University of Maryland

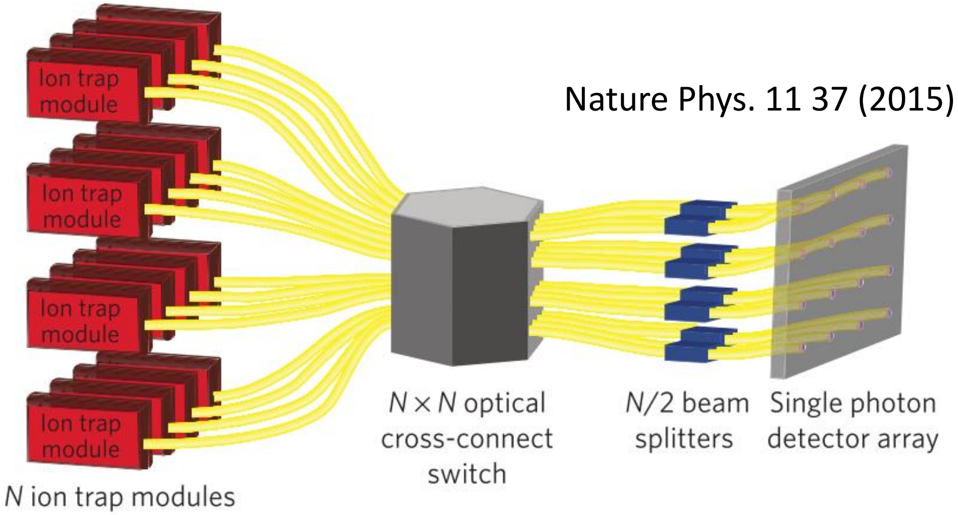
Increasing numbers of ions in a 1D chain increases difficulties of quantum operations due to motional mode crowding. → **Multi-trap architecture needed for >100 qubits.**

- **Quantum CCD**



- Separate trapping and interaction zones
- Ion shuttling on 2D electrode structure
- Microwave gate integration
- NIST, PTB, U.Sussex

- **Optical interconnect**

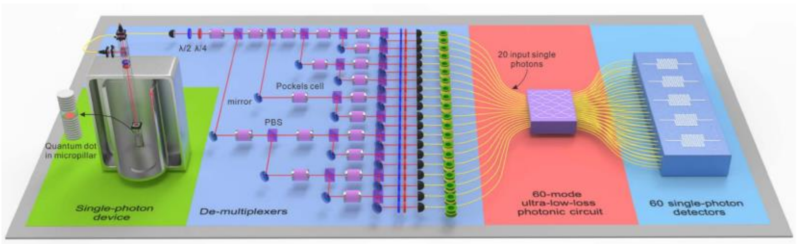


Nature Phys. 11 37 (2015)

- Trap modules connected via photons
- High modularity
- U.Maryland, U.Oxford, U.Osaka

Recent trends in photonic quantum computing

Boson sampling



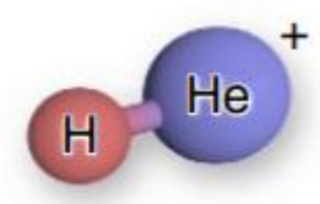
20 photons in 60 modes

arXiv:1910.09930

(Univ. of Science and Technology of China)

NISQ algorithms

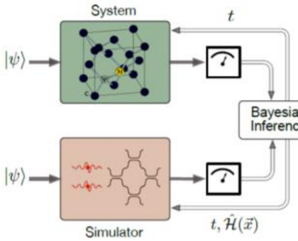
Variational quantum eigensolver



Nat. Commun. **5**, 4213 (2014)

(Univ. of Bristol)

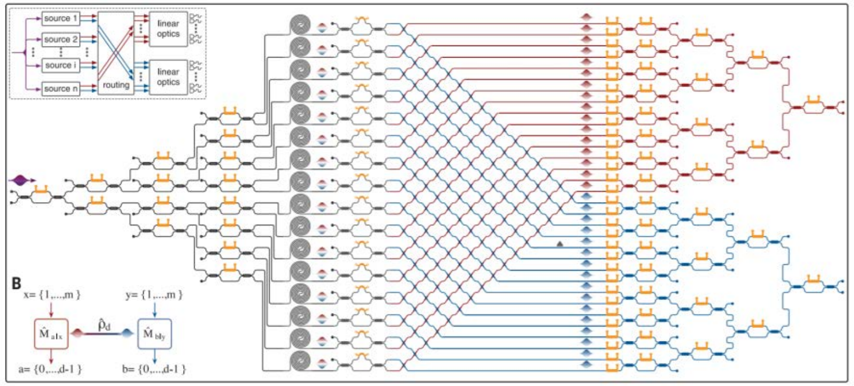
Quantum Hamiltonian learning



Nat. Phys. **13**, 551 (2017)

(Univ. of Bristol)

Integrated photonic chips



>550 components on a single chip

Science **360**, 285 (2018) (Univ. of Bristol)

PsiQ

Large-scale continuous-variable cluster states

5x5000

2D cluster states

Science **366**, 373 (2019) (Univ. of Tokyo)

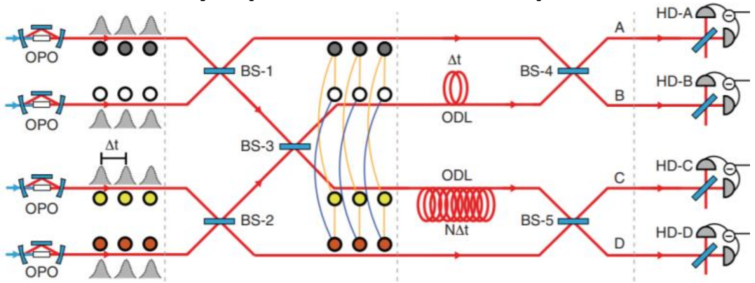
Science **366**, 369 (2019) (Technical Univ. of Denmark)

XANADU

Future prospects for large-scale fault-tolerant photonic QC

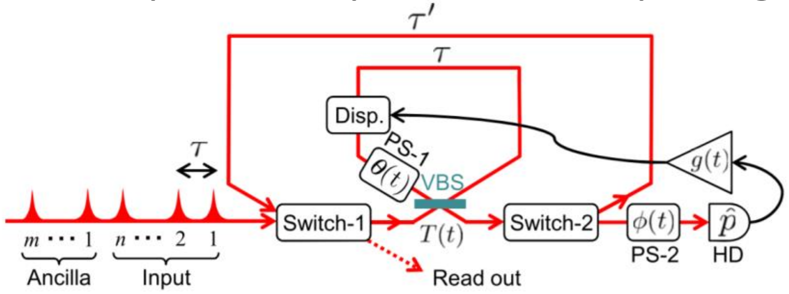
Architecture for scalable & universal quantum computing

Time-domain multiplexed one-way quantum computation



Science **366**, 373 (2019) (Univ. of Tokyo)

Loop-based quantum computing

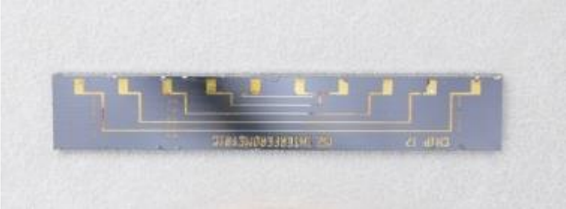


Phys. Rev. Lett. **119**, 120504 (2017) (Univ. of Tokyo)

High quality photonic circuits based on photonic chips & fibers

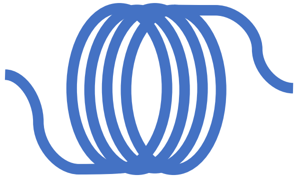
Free-space optical circuits

Photonic chip



Nat. Photon. **9**, 316 (2015) (Univ. of Tokyo)

Fiber delay line



Bosonic codes for fault-tolerant quantum computation

One optical pulse represents one logical qubit (cat/binomial/GKP code) => efficient!

Example: GKP code + continuous-variable quantum gates

$\Rightarrow$ Realistic threshold for fault-tolerant quantum computation (~10dB of squeezing)

Phys. Rev. X **8**, 021054 (2018) (Hokkaido Univ.)

Ou

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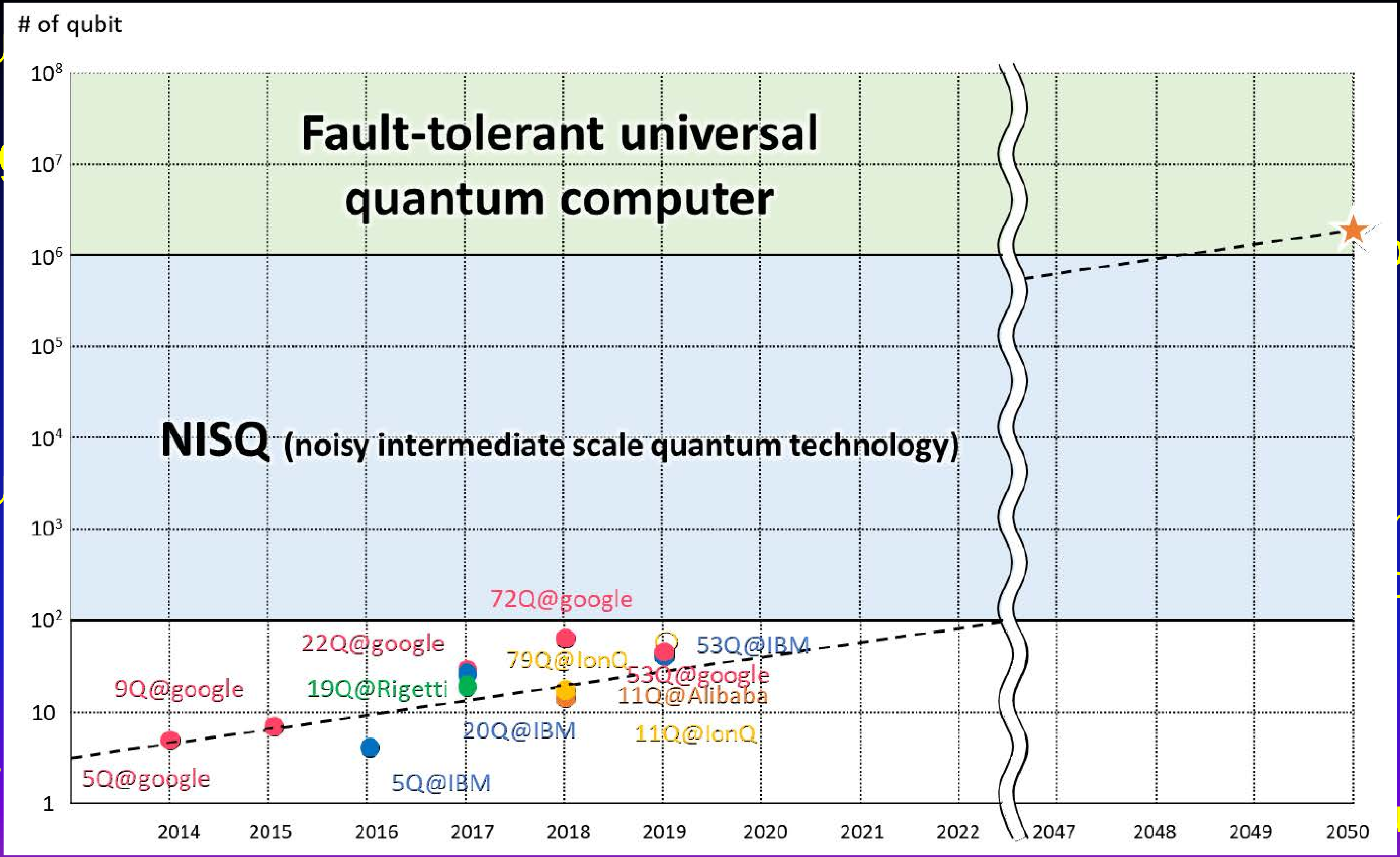

Qu

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Fa

up?

https://www.jst.go.jp/moonshot/sympo/sympo2019/wg6_e.html

Quantum computing research will inevitably (and hopefully) be as

- disruptive
- controversial
- provocative
- philosophical

as we have seen in the history of quantum mechanics

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM