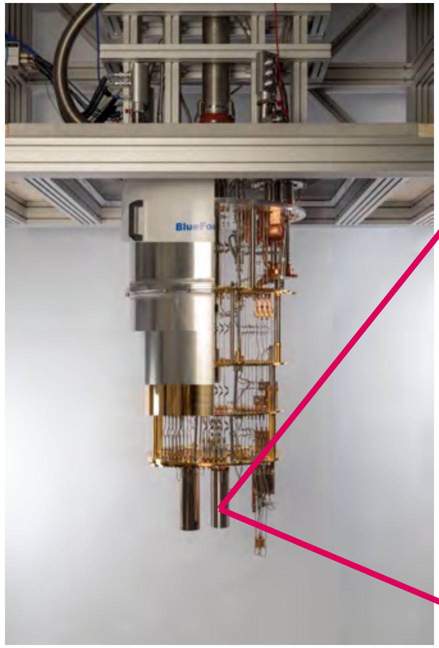
Integrated photonics requirements for a large scale trapped-ion quantum computer

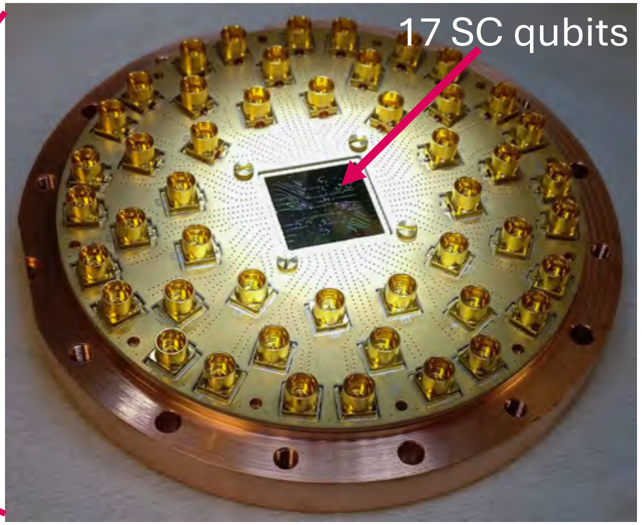
Cornelius Hempel :: Photonics4Quantum workshop :: 2025-05-08

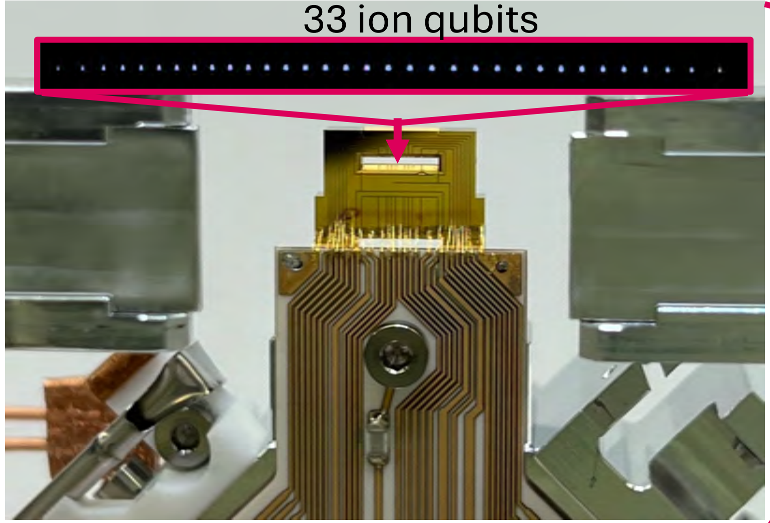
How to build a quantum computer from qu(antum)bits

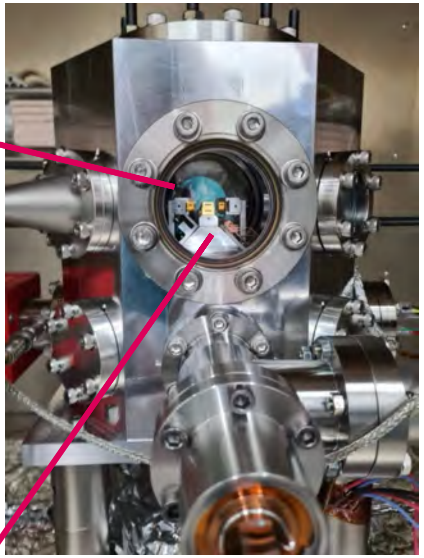
Made by humans

Taken from nature







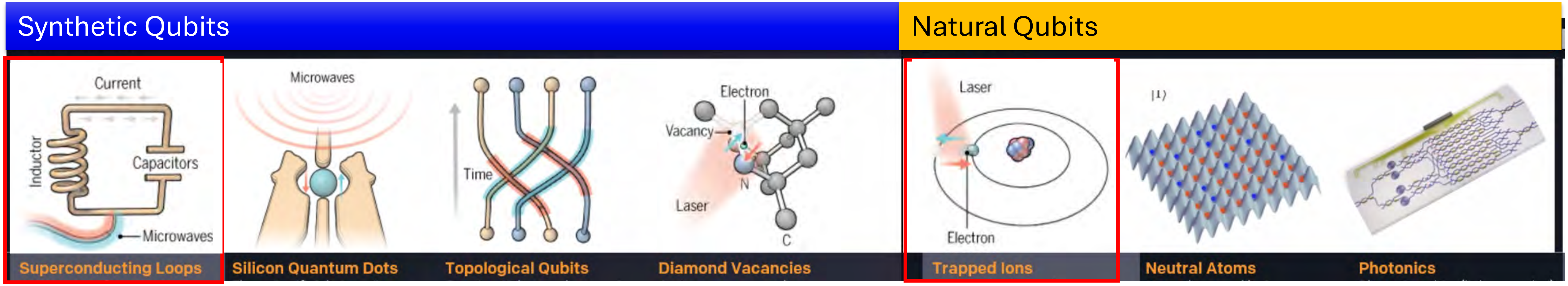


10 mK (-273.14 C)

Superconducting circuits

Trapped ions

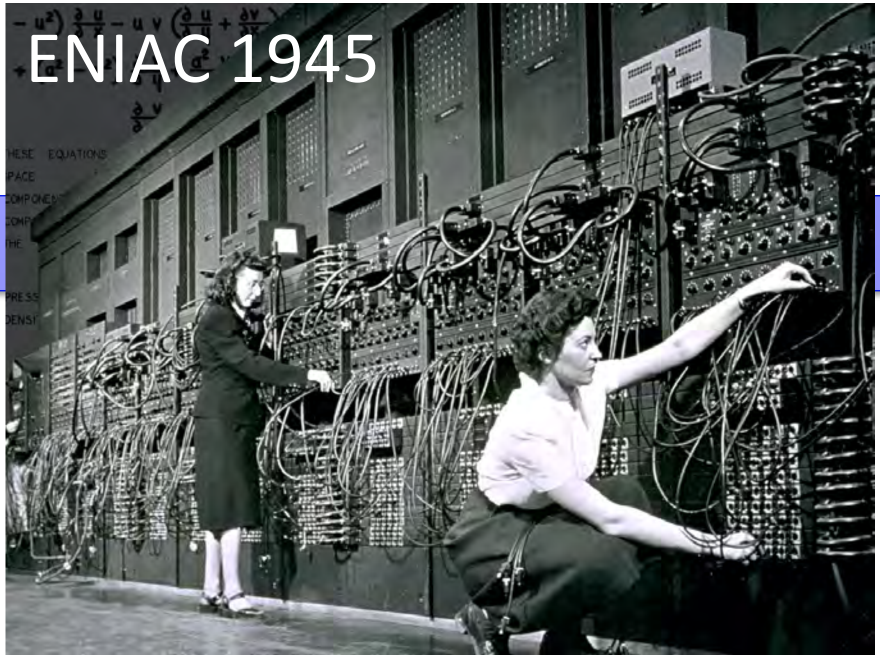
293 K, but
laser cooled to
0.5 mK (-273.1495 C)



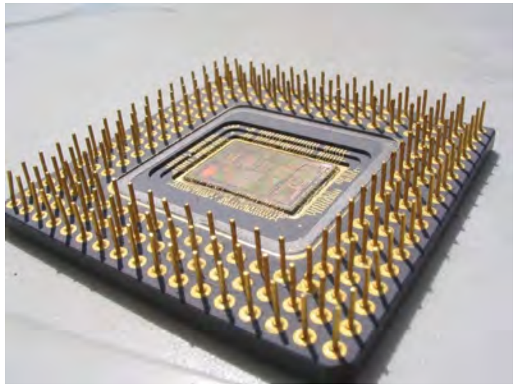
Modified from Science **354**, 1090 (2016)

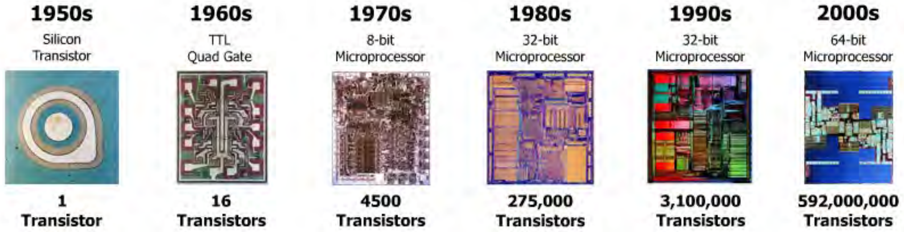
Classical computer timeline

PSI



today



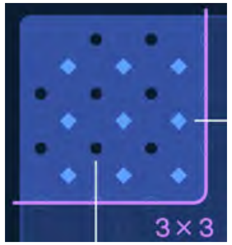


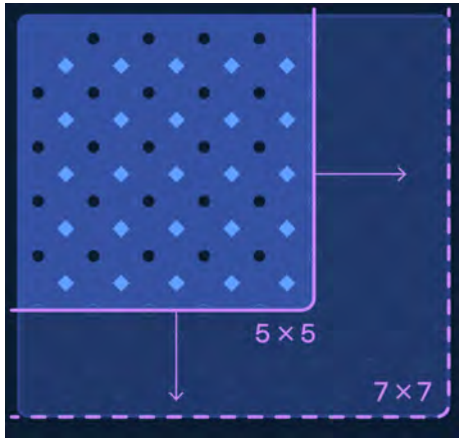
Quantum hardware is here in 2025

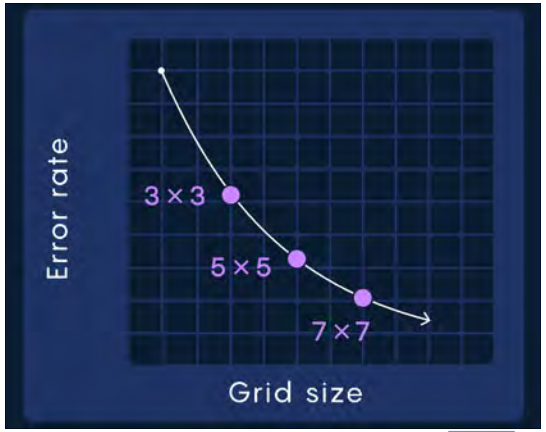
Today:
Noisy analog
quantum computers

"Tomorrow":
Error corrected, digital
quantum computers

Many physical qubits + algorithm = 1 logical qubit







Quantum
Error
Correction

2023/2024 experiments show it's working

Error corrected quantum computers will not be small

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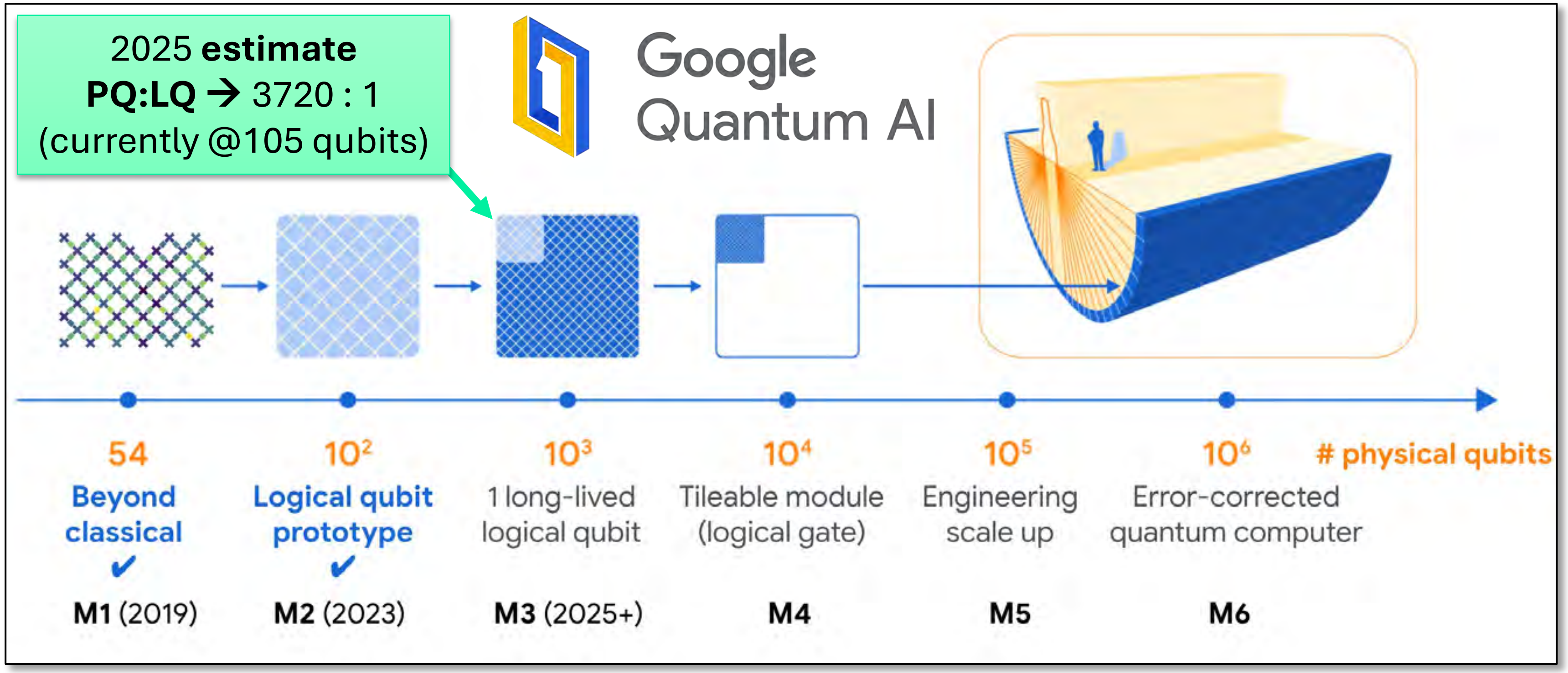
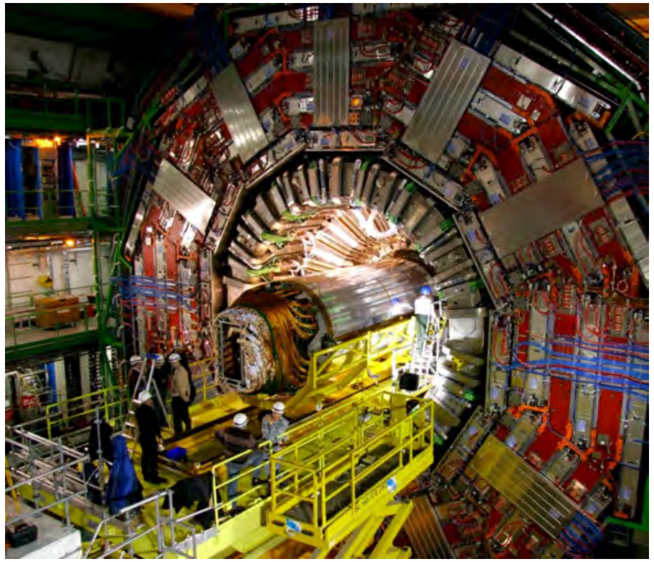
2025 estimate
PQ:LQ → 3720 : 1
(currently @105 qubits)



Towards high energy physics research: **255 authors** on a 2024 Google paper



CERN CMS PSI

- First error-corrected (logical) qubit prototypes made in 2021/2022 (academia!)

IARPA BE THE FUTURE LogiQ ETH zürich universität innsbruck

since November 2023

IARPA BE THE FUTURE ELQ

2 consortia
at ETHZ/PSI

https://www.psi.ch/en/news/psi-stories/two-projects-launched-to-connect-error-corrected-qubits

Trapped ion quantum processors in a nutshell

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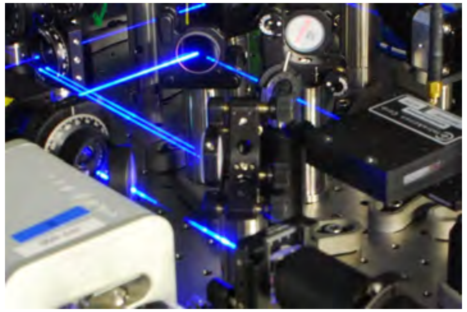
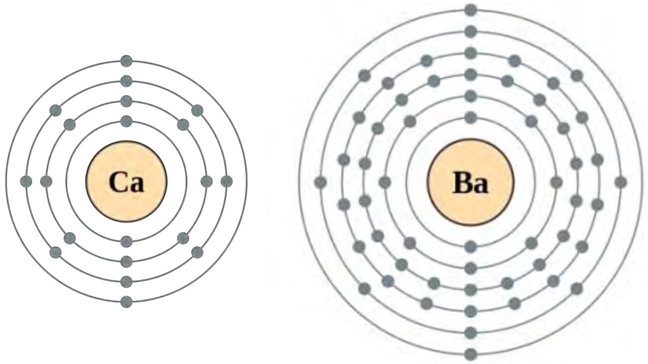
Encoding

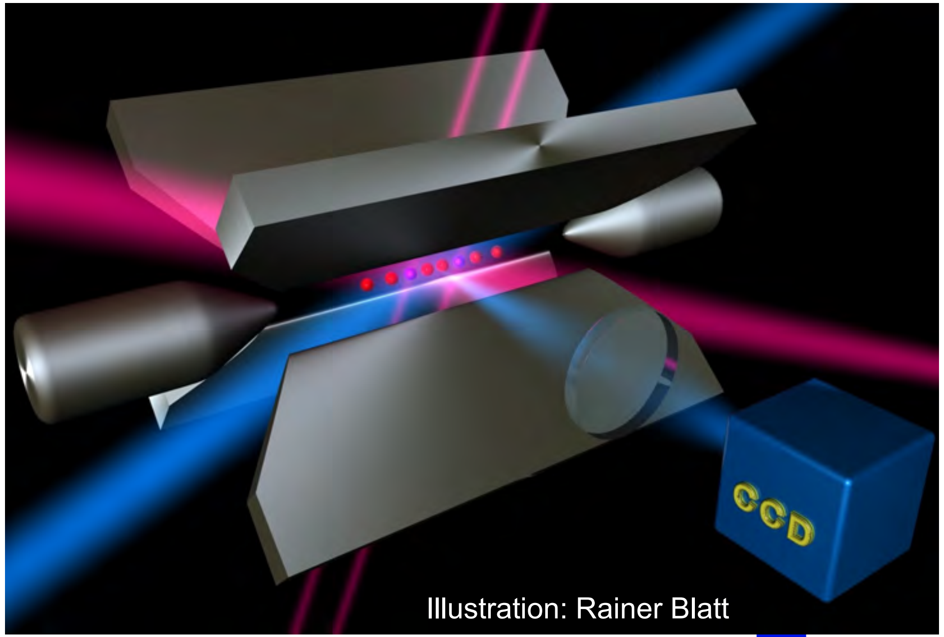
+ Laser(s)



+ Atoms (-> Ions)

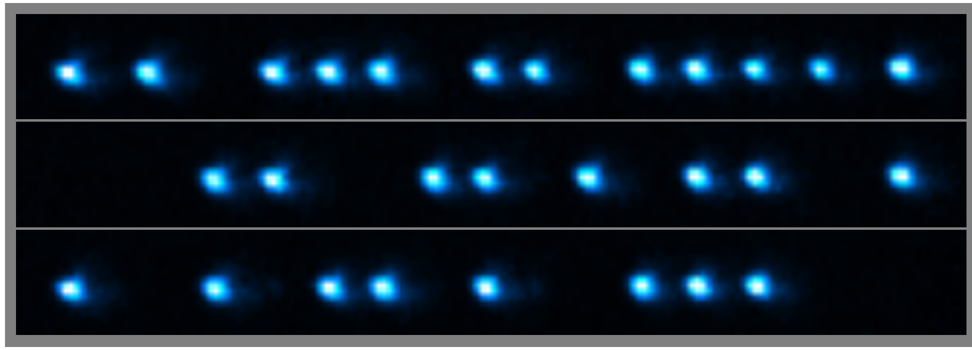


+ Ion trap



Camera

Single shot "samples"



a $|110111011011111\rangle$

b $|001100110101101\rangle$

c $|101011010011100\rangle$

Result

Two ways to scale up

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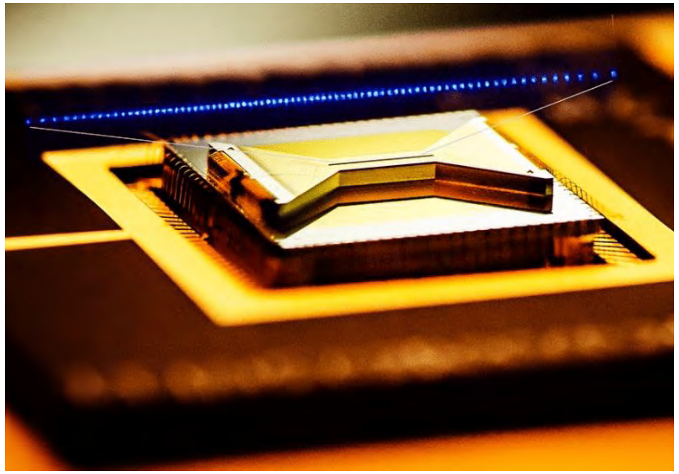
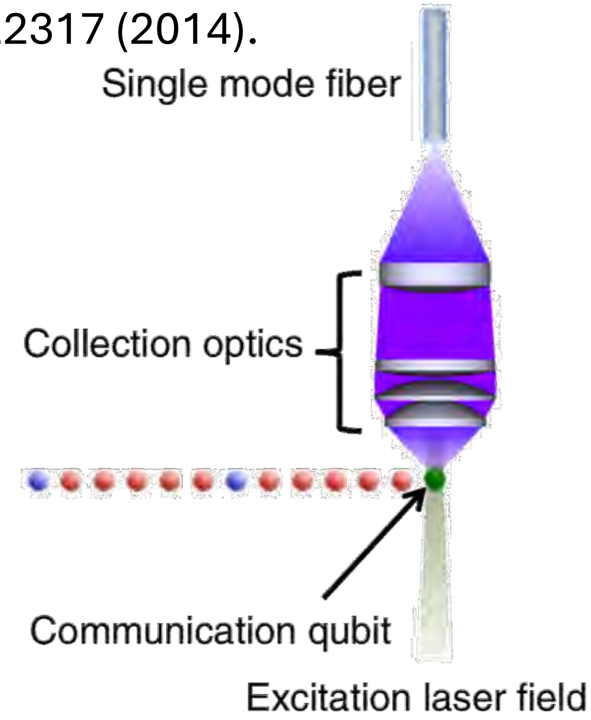
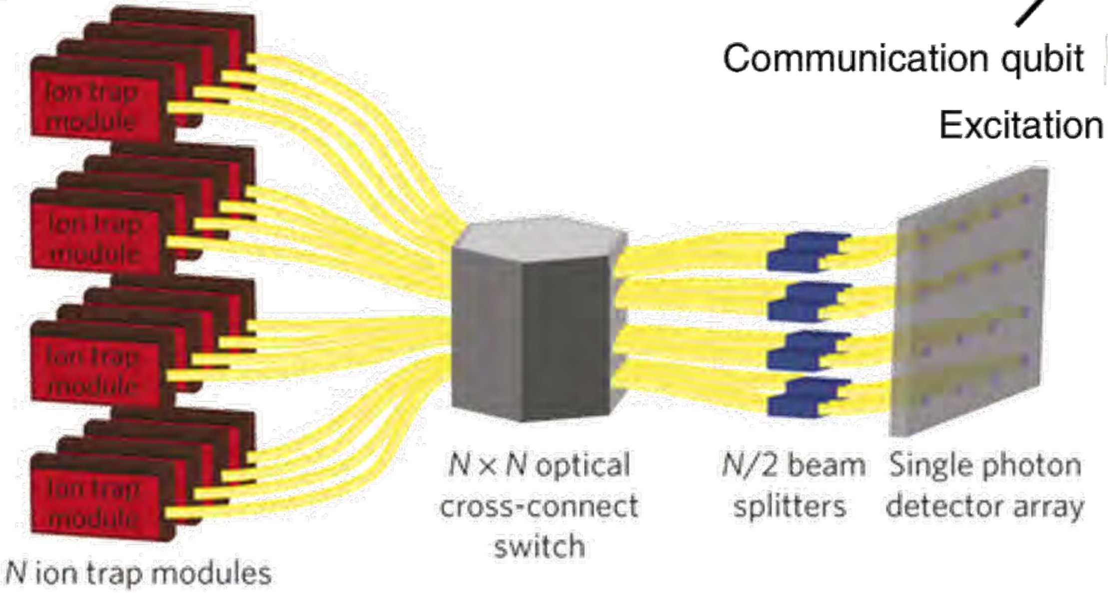
Photonic interconnects

Monroe *et al*. *Phys. Rev. A* **89,** 022317 (2014).

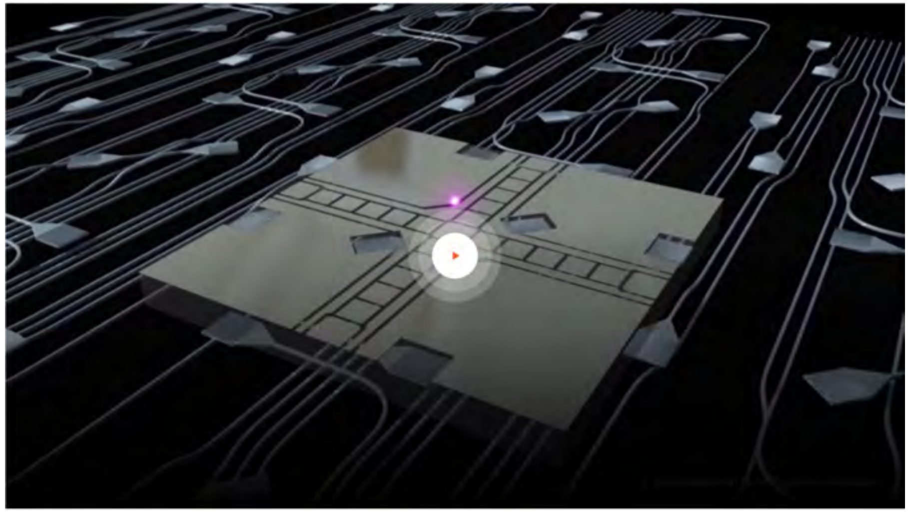






Q(uantum)CCD

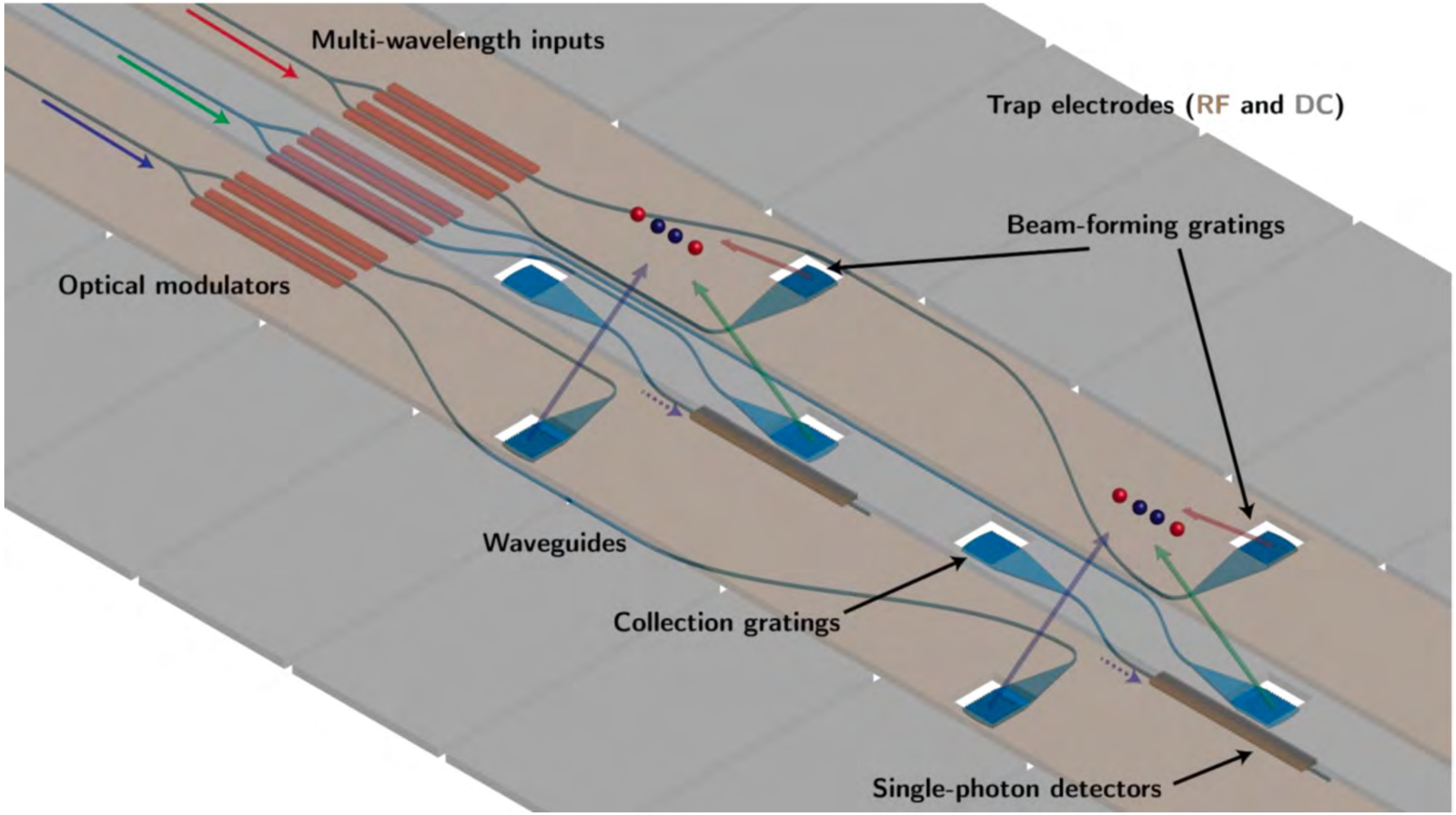
Kielpinski *et al*, Nature **417** 709 (2002).



MIT Lincoln Lab (2016)

https://www.youtube.com/watch?v=UT3ev9OgkmY

The holy grail of integration



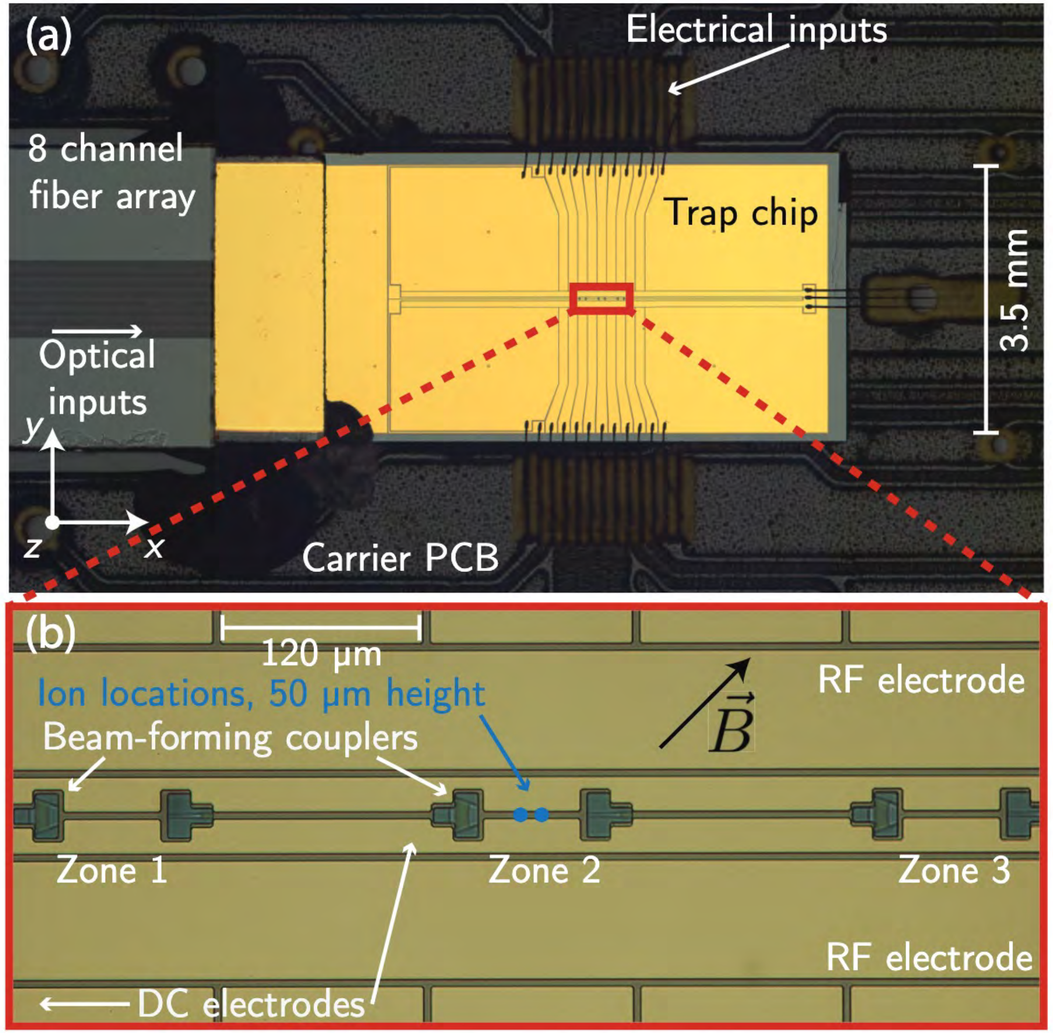
Chip integrated

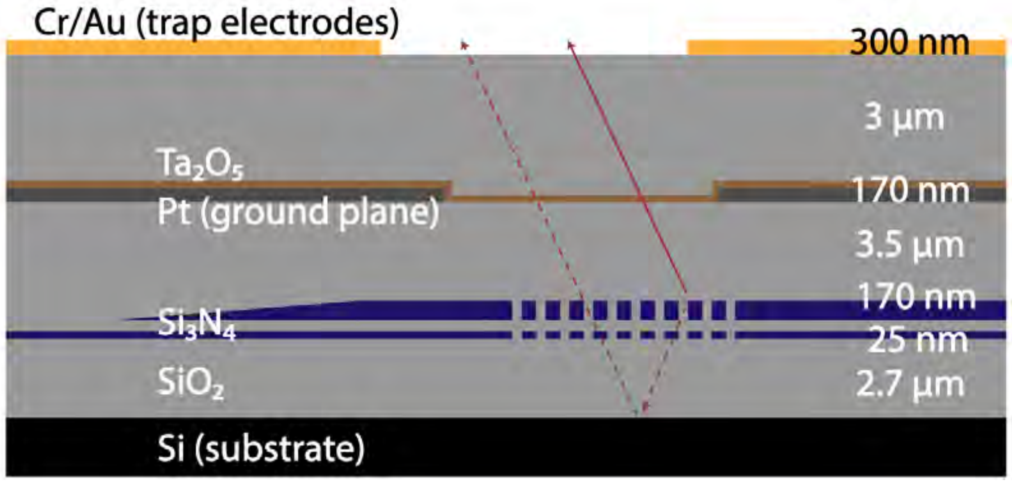
- multi-wavelength
  - waveguides
  - grating couplers
- light modulators
- photon detectors

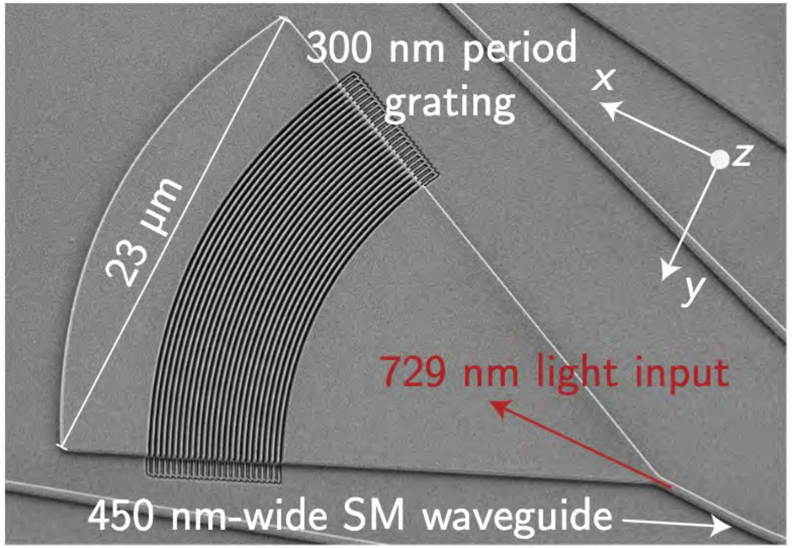
John Chiaverini and Karan K. Mehta in:
Moody, G. *et al.* 2022 Roadmap on integrated quantum photonics. *J Phys Photonics* **4**, 012501 (2022).

First demo of 2Q-gate operations with integrated photonics

ETH zürich







K. K. Mehta, C. Zhang, M. Malinowski, T.-L. Nguyen, M. Stadler, and J. P. Home, Nature **586**, 533-537 (2020).

Challenges: *transmissivity in near IR <u>and UV,</u> fabrication process (multi-layer, materials)*

Scaling up to 20 zones

Content removed as unpublished

What's hard about scaling this up?

6 zones → 384 zones

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Many DC connections (6 per zone → 2'304)

- Recent work from Quantinuum, Oxford Ionics on multiplexing, MIT-LL on trap-integrated DACs

arXiv:2403.00756 (2024) ; PRX Quantum **4**, 040313 (2023) ; PR Applied **11**, 024010 (2019)

Site-resolved readout

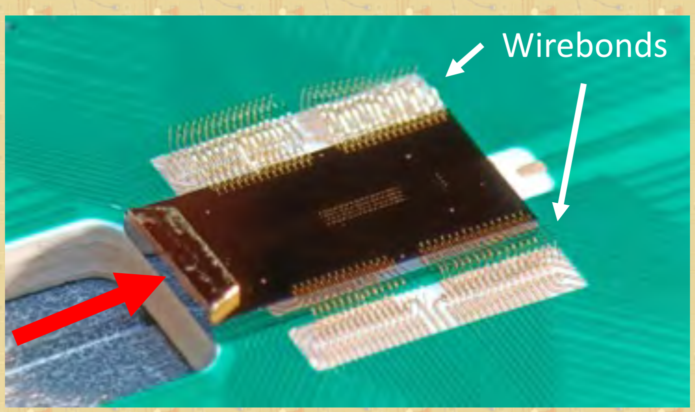
- Integrated detectors (see work from NIST, MIT-LL, Sandia)

APL **119**, 154002 (2021) ; PRL **126**, 010501 (2021) ; PRL **129**, 100502 (2022)

- <u>Lens arrays</u>

Many individually controlled laser beams (3 per zone → 1152 beams)

- wavelengths from 397 nm to 866 nm (or 493 nm to 1762 nm with Ba+)
- > 60 dB on-off extinction ratio
- Amplitude, frequency, phase control



Fiber V-groove array

Scalable readout

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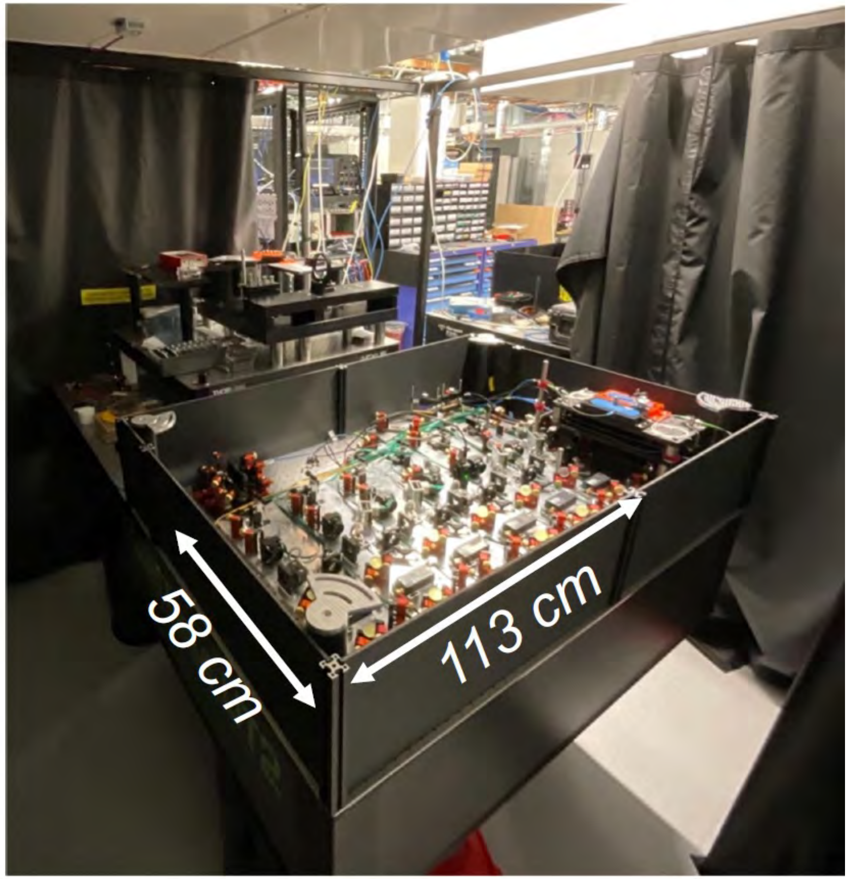
Shrinking the optical table...

1 input – 6 outputs



~10 channels / 3U in 19” rack

~16 channels in 25 mm^2

… to chip-integrated modulators

TFLN

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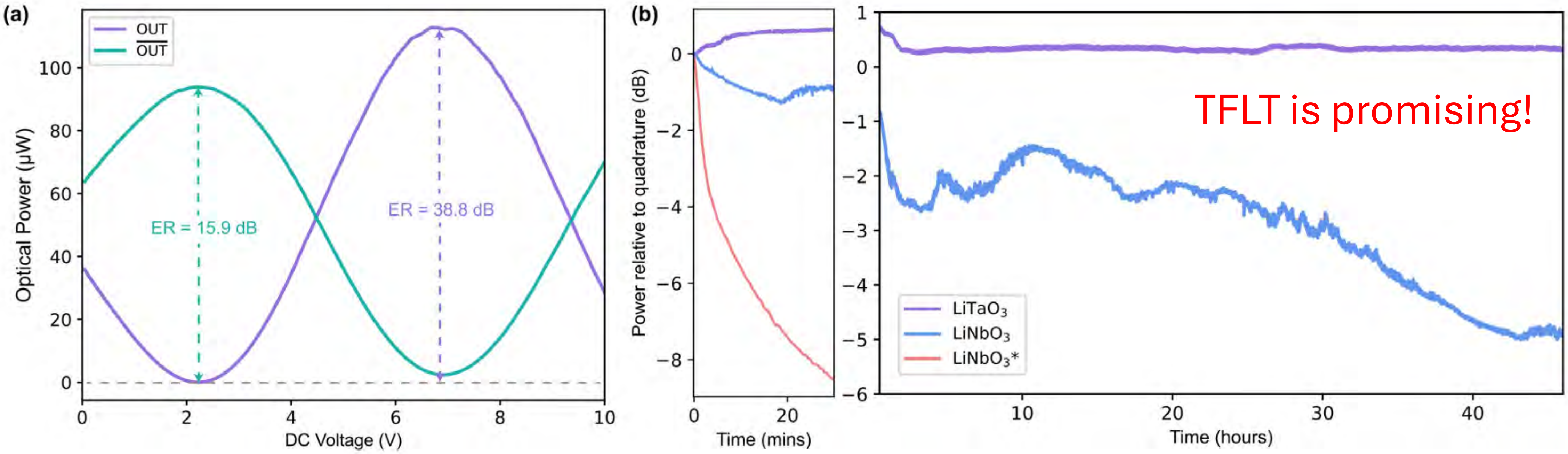
Targets:

- 60 dB ER
- **DC - 10 MHz** stability
- VIS and UV operation



TFLT is promising!

Powell et al. Opt. Express **32**, 44115-44122 (2024)

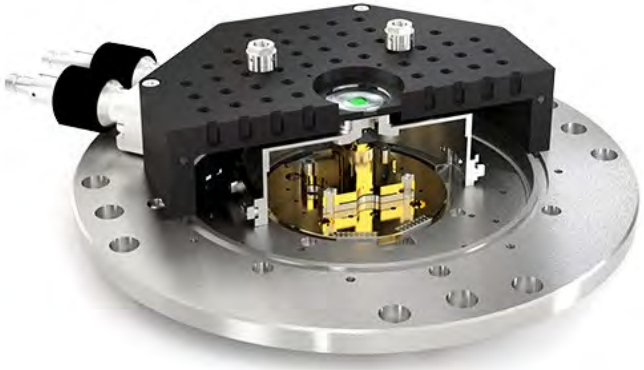
Cryogenic testbed for industry

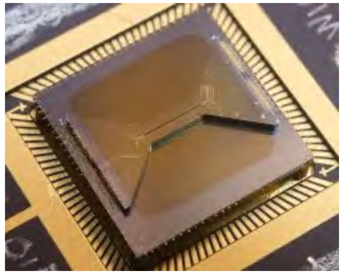
PSI

eureka
innovation beyond borders

eurostars™

2024 GLASTRAP





Sandia HOA2 on CPG10039

Rapid turn around testing (6.5 hrs cool-down)

- electronic circuits
- active and passive photonics
- complete ion traps using standardized socket

Advancing critical technologies for scaling at ETH Zürich – PSI Quantum Computing Hub

PSI

Ion traps

Design with academia (ETHZ, Cornell..)
Fabrication with industry (LioniX)

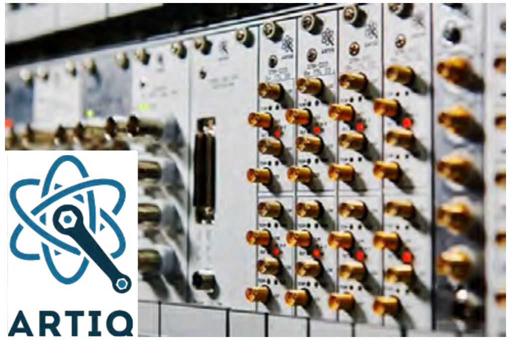
Lasers and photonics

Many partners in academia and industry

csem
pic Swiss Photonics Integration Center
XRnanotech
infineon
POLARITON
vario-optics ag

Electronics and control

Commercial and open hardware



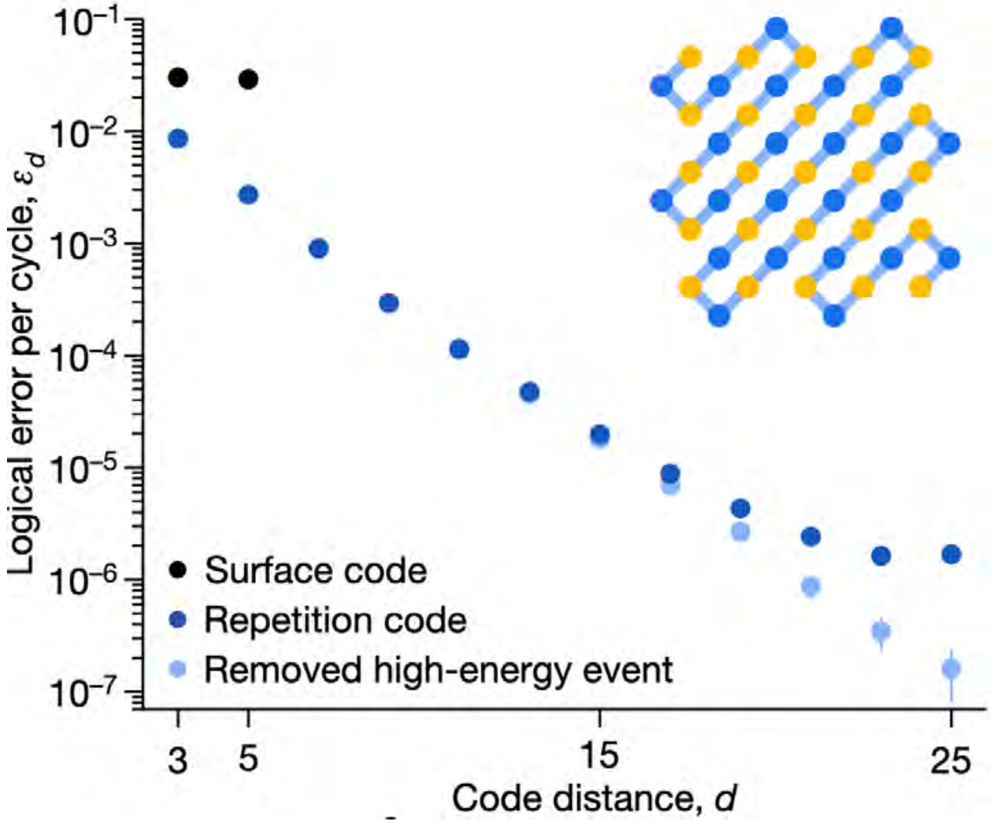
Zurich Instruments

Thank you!

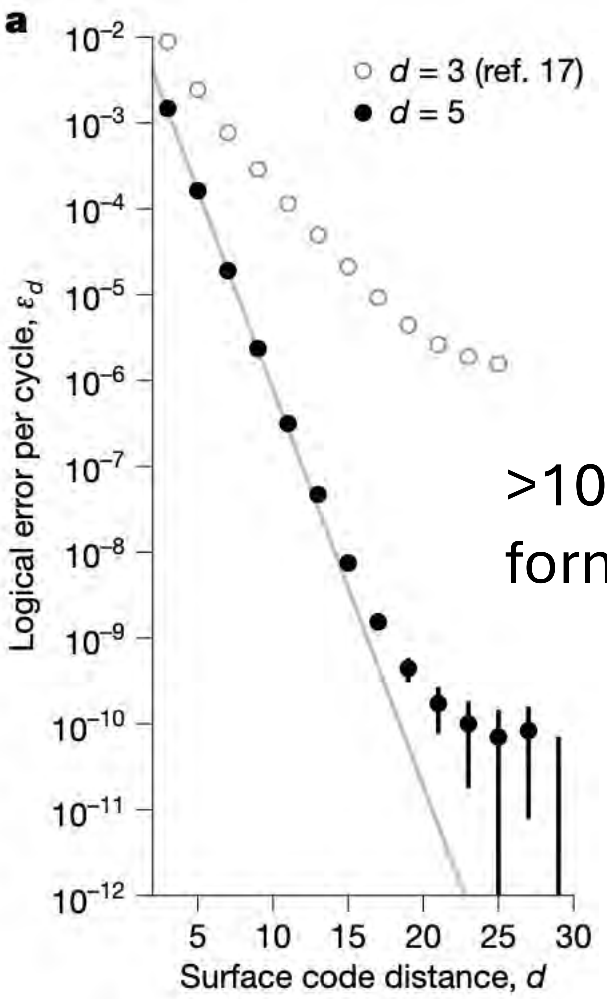
Cornelius Hempel :: Photonics4Quantum Wksp :: 2025-05-08

Quantum Error Correction … it works as expected!

PSI



Nature **614**, 676–681 (2023).



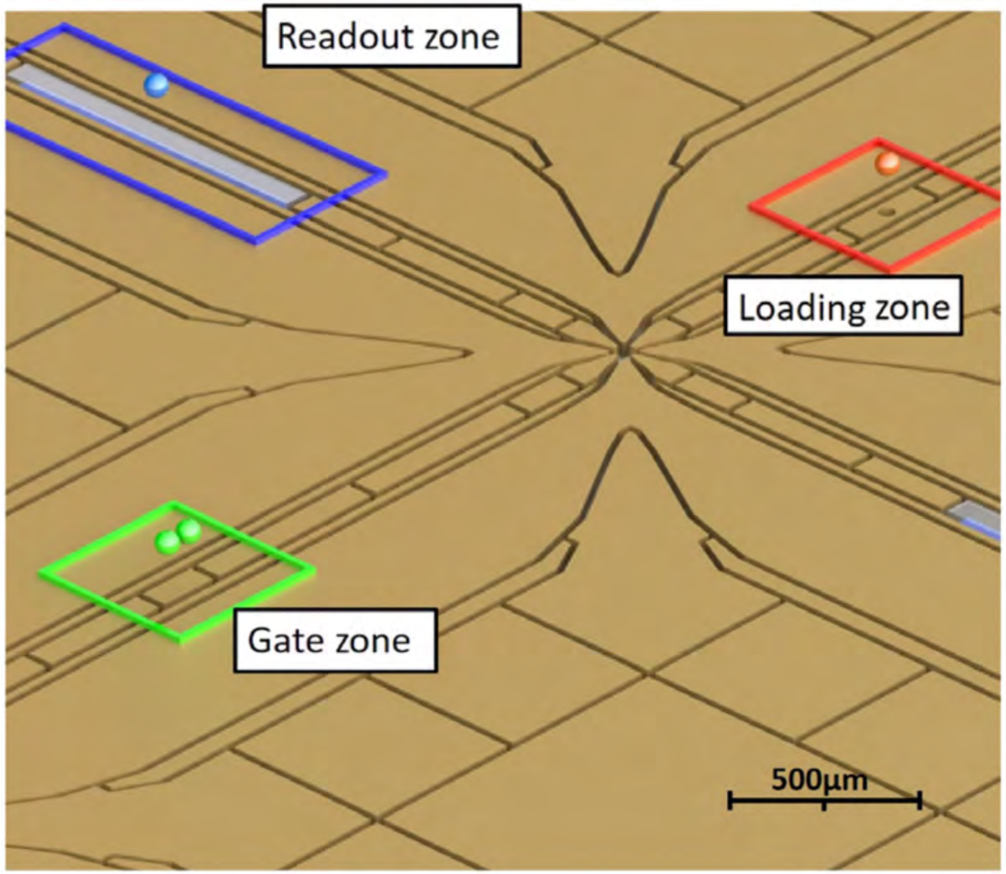
>100 physical qubits form 1 logical qubit

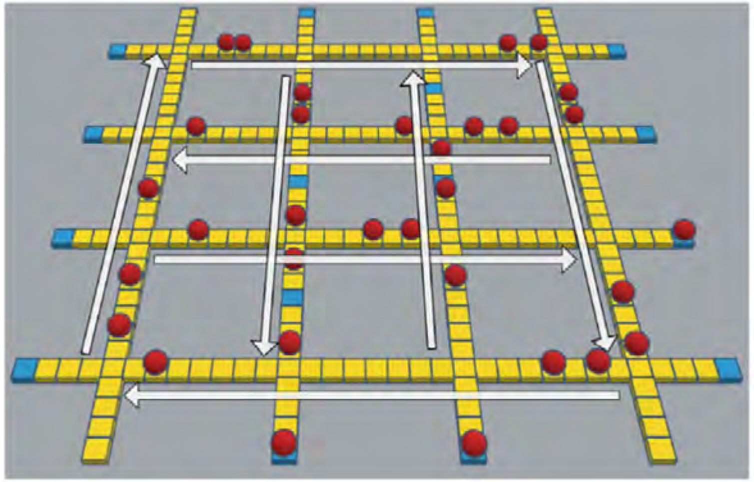
arXiv:2408.13687; (Nature 2025)

Quantum error correction is no longer a question of “if”, but rather a question of scale and which code to use.

What would these devices look like… at scale?

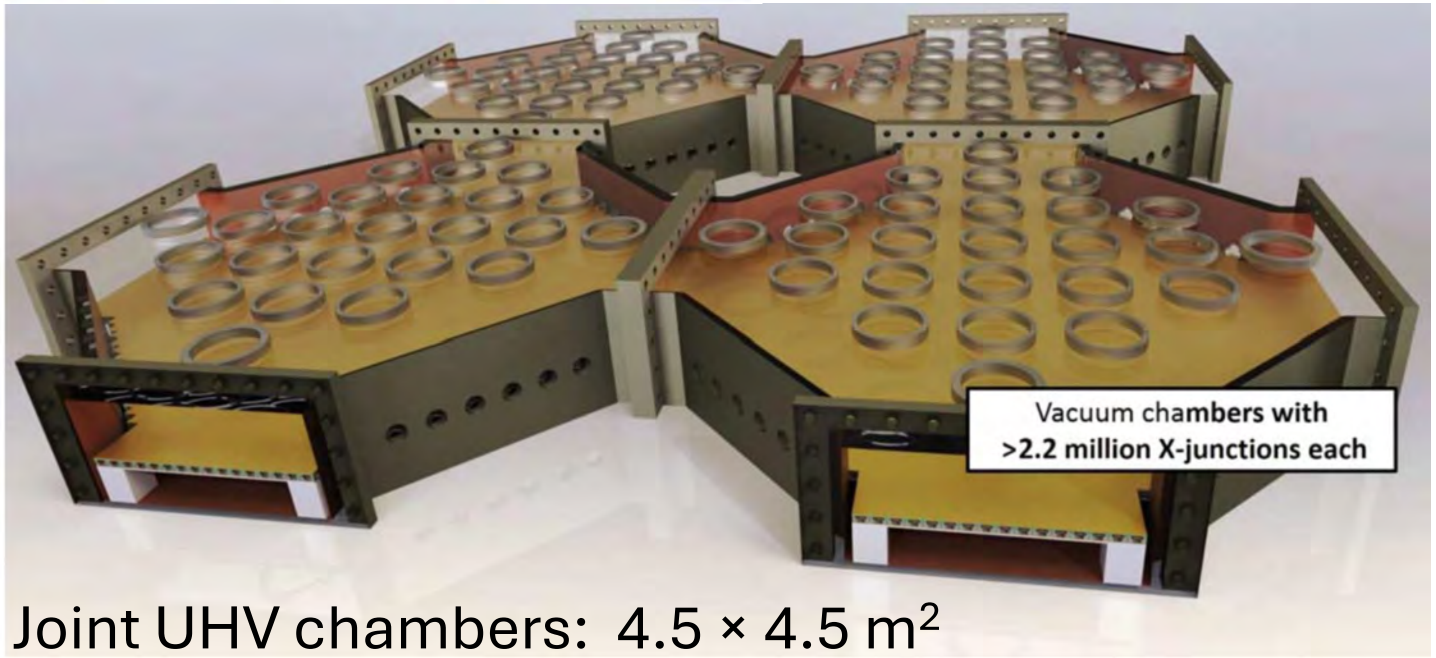
PSI





For Shor's algorithm:
<u>from</u> 2 Mio trapped ions
2048 bit RSA → 110 days

… *lowering errors < 0.01%*
<u>to</u> 500k trapped ions
2024 bit RSA → 10 days



Blueprint for a microwave trapped ion quantum computer
Lekitsch et al. Sci. Adv. 3 : e1601540 (2017)