PSI

Integrated photonics as enabler of scalable quantum technology

Cyber Alp Retreat 2025

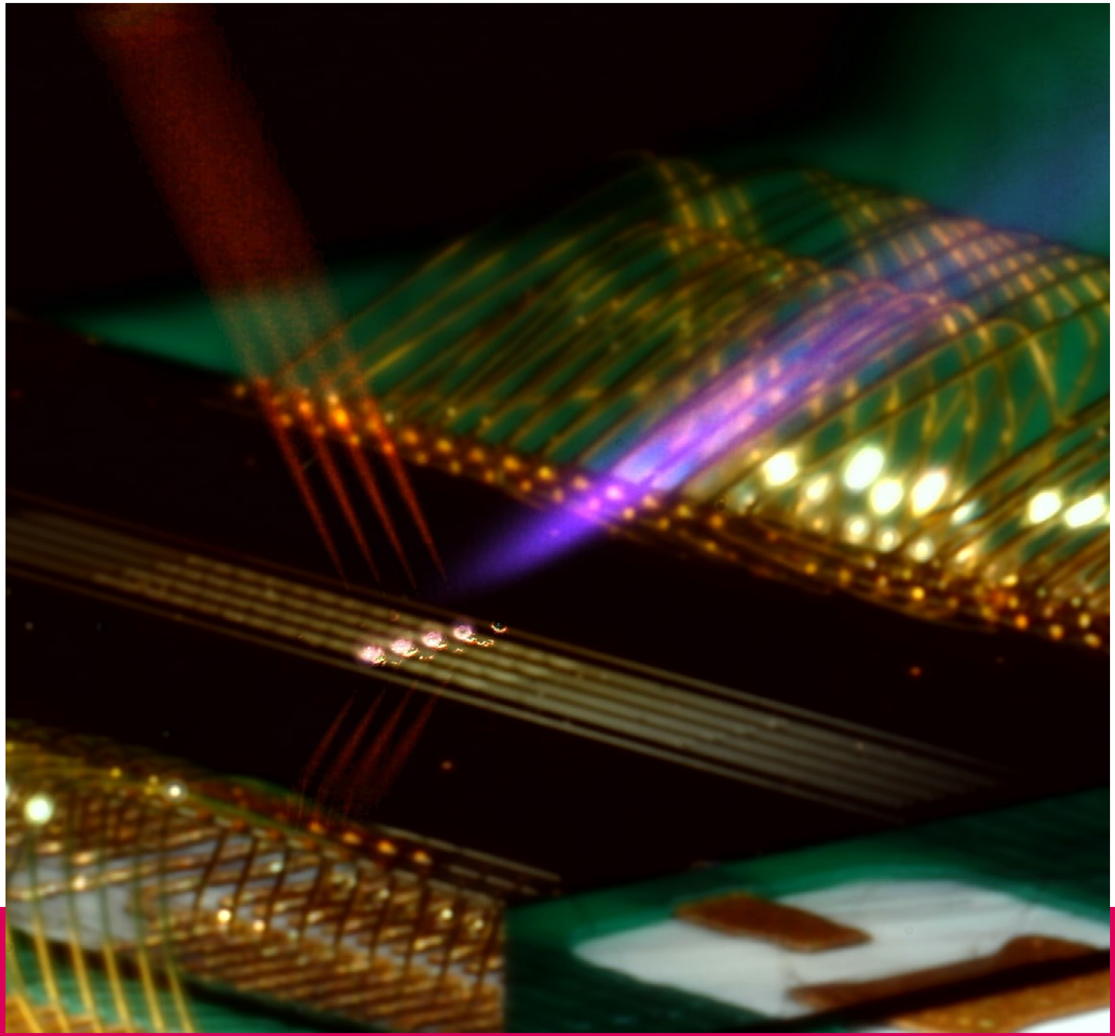

Photo: Noah Tajwar / Tereza Viskova

Sofia Cano Castro
Davos, 19.06.2025

Quantum Computing Hub

Trapped ion quantum computing at the Quantum Computing Hub

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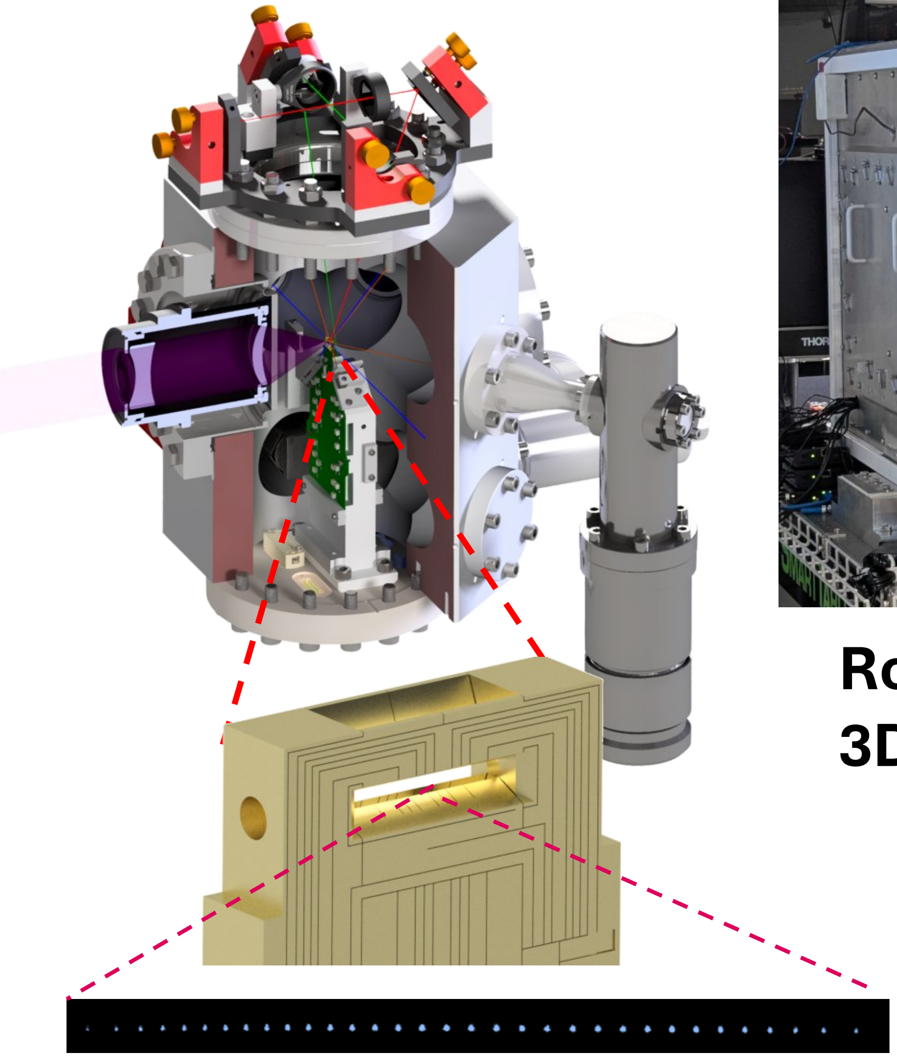
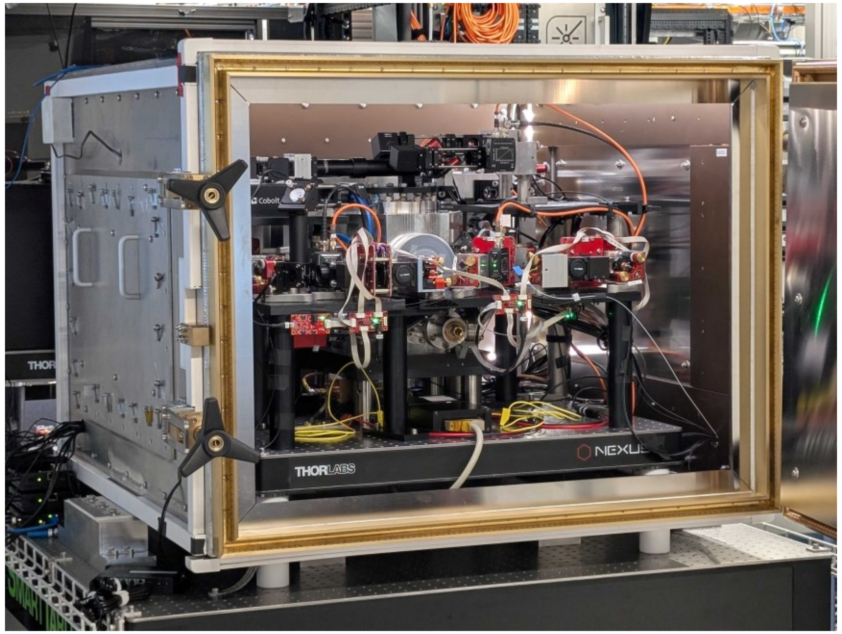
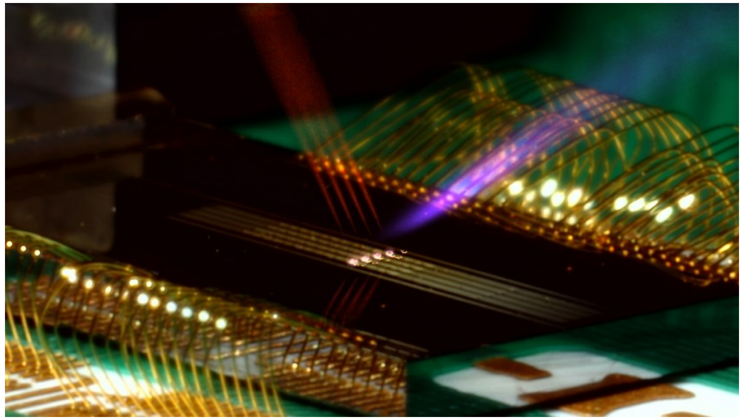


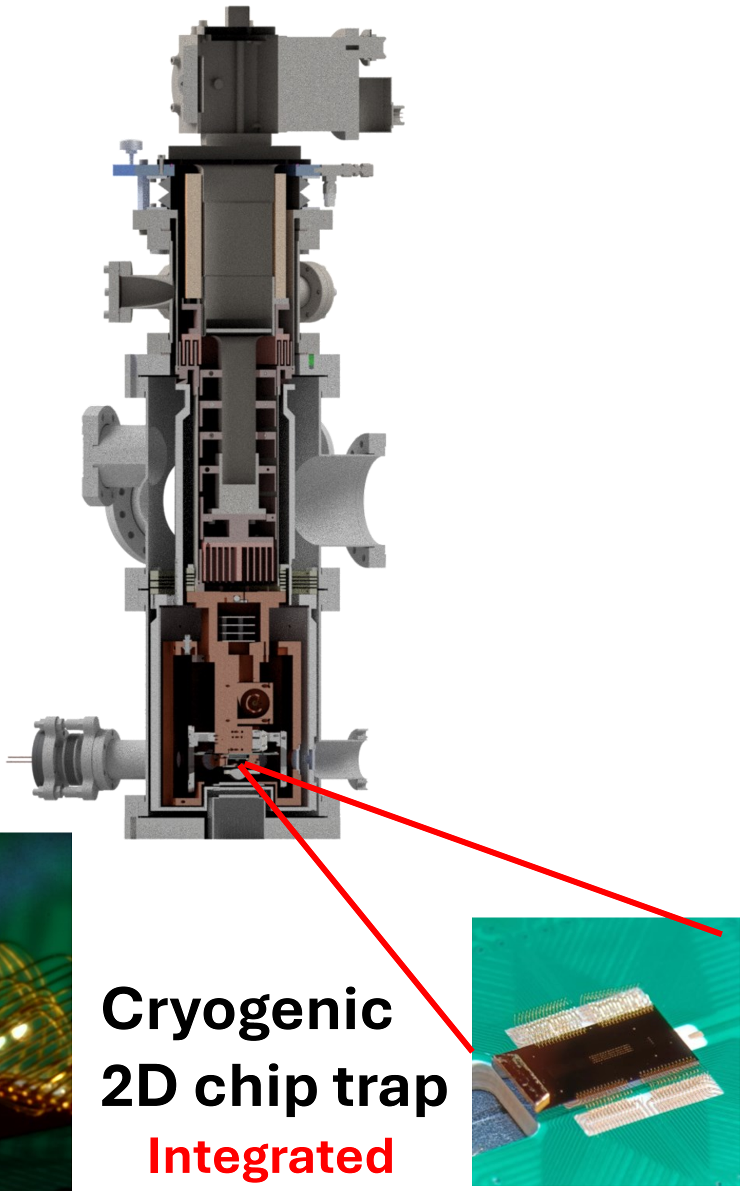
33 Ca^+ (supports up to 50 physical qubits)

Autonomous runs + remote operation



Room temperature
3D trap





Cryogenic
2D chip trap

Integrated
photonics

Outline

Quantum Computing

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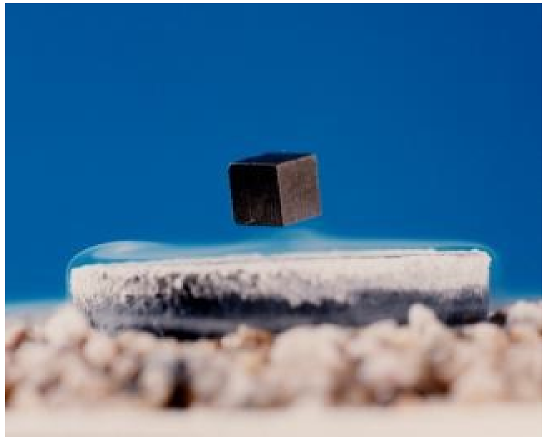
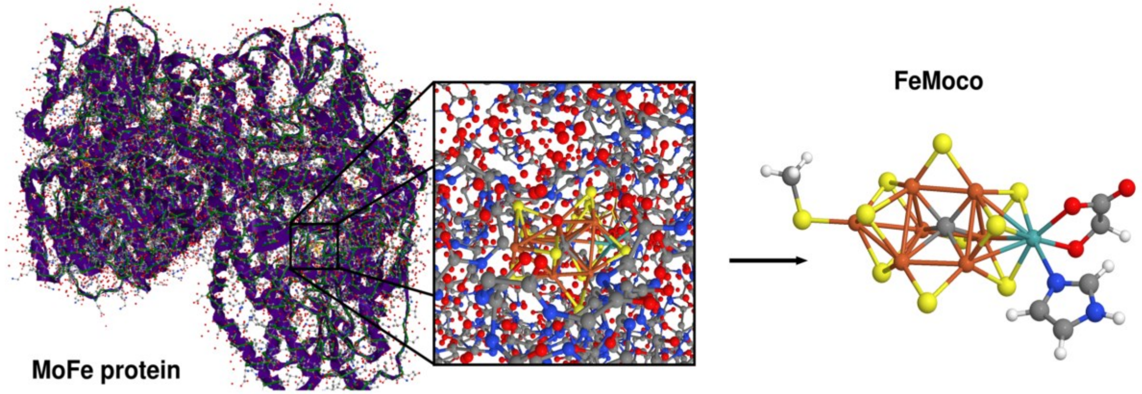
... to simulate nature at the quantum level

Richard Feynman
1982

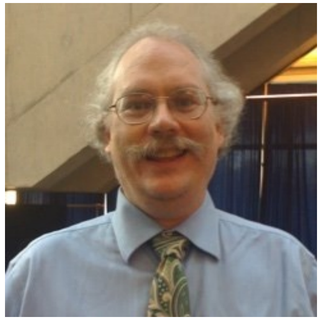


Superconductivity

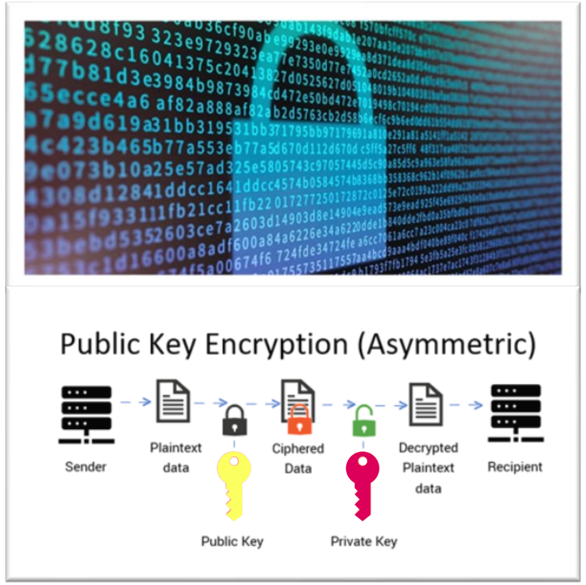


Nitrogen fixation

... as a general purpose computing "tool"

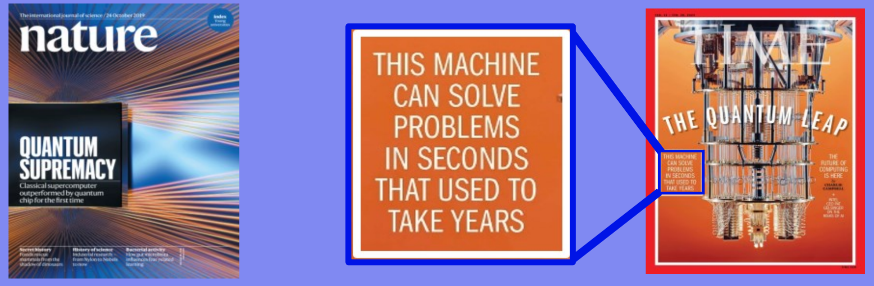


Peter Shor
1994



Prime factoring of large integers

Vying for quantum advantage



2019 → 2023

Hype

How to build a quantum computer for qu(antum) bits.

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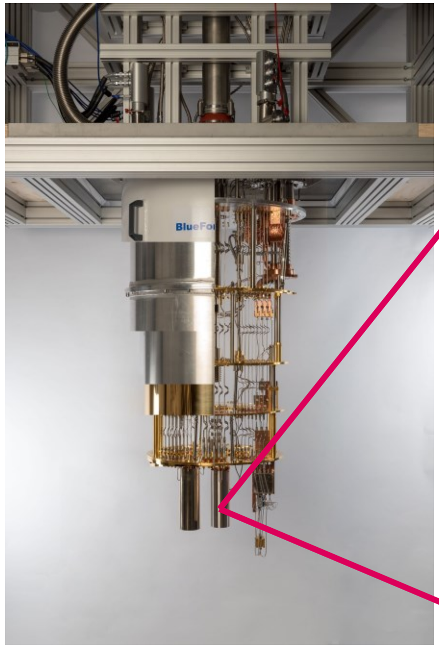
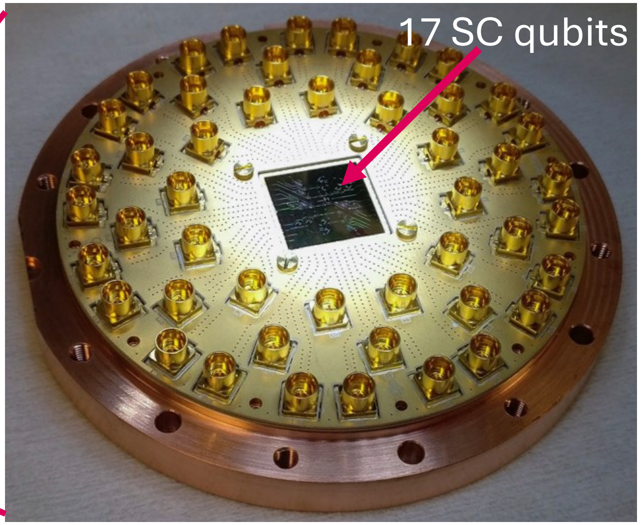
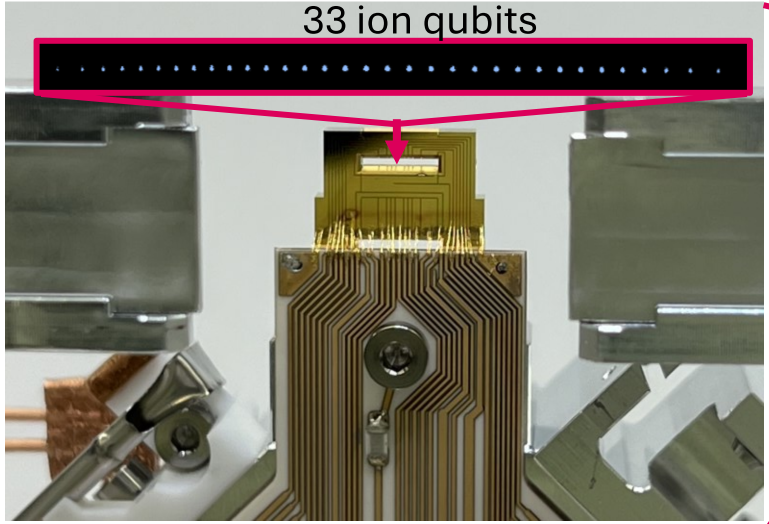
Made by humans

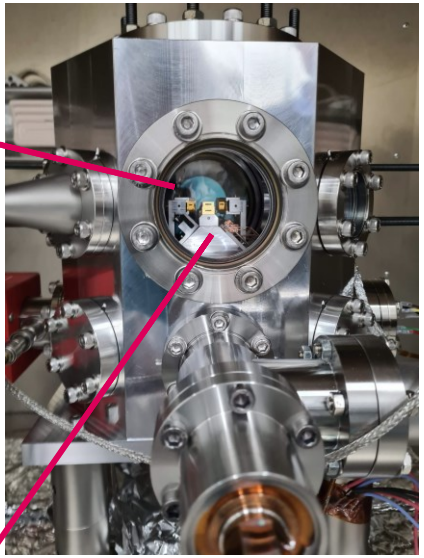




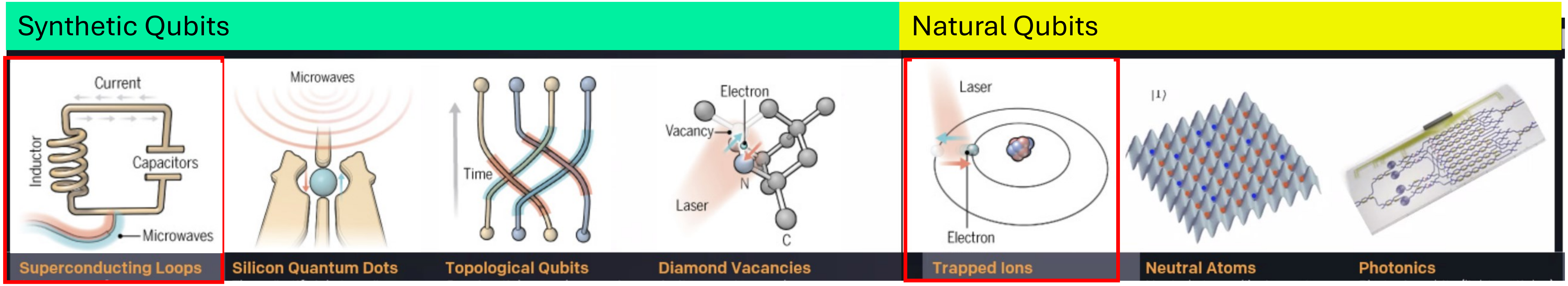
Superconducting circuits

Taken from nature





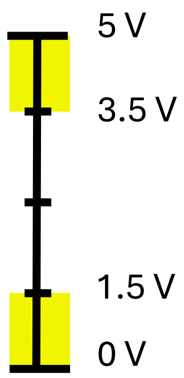
Trapped ions



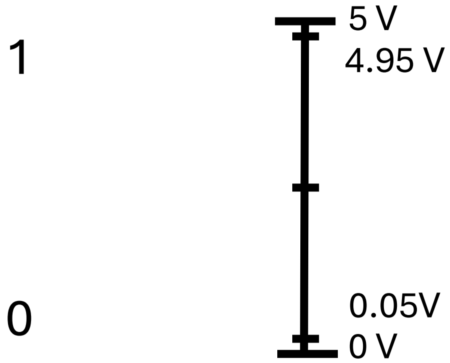
Modified from Science **354**, 1090 (2016)

Error corrected quantum computers

Boolean logic...

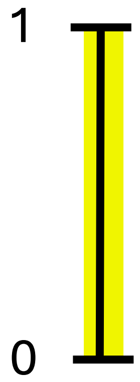


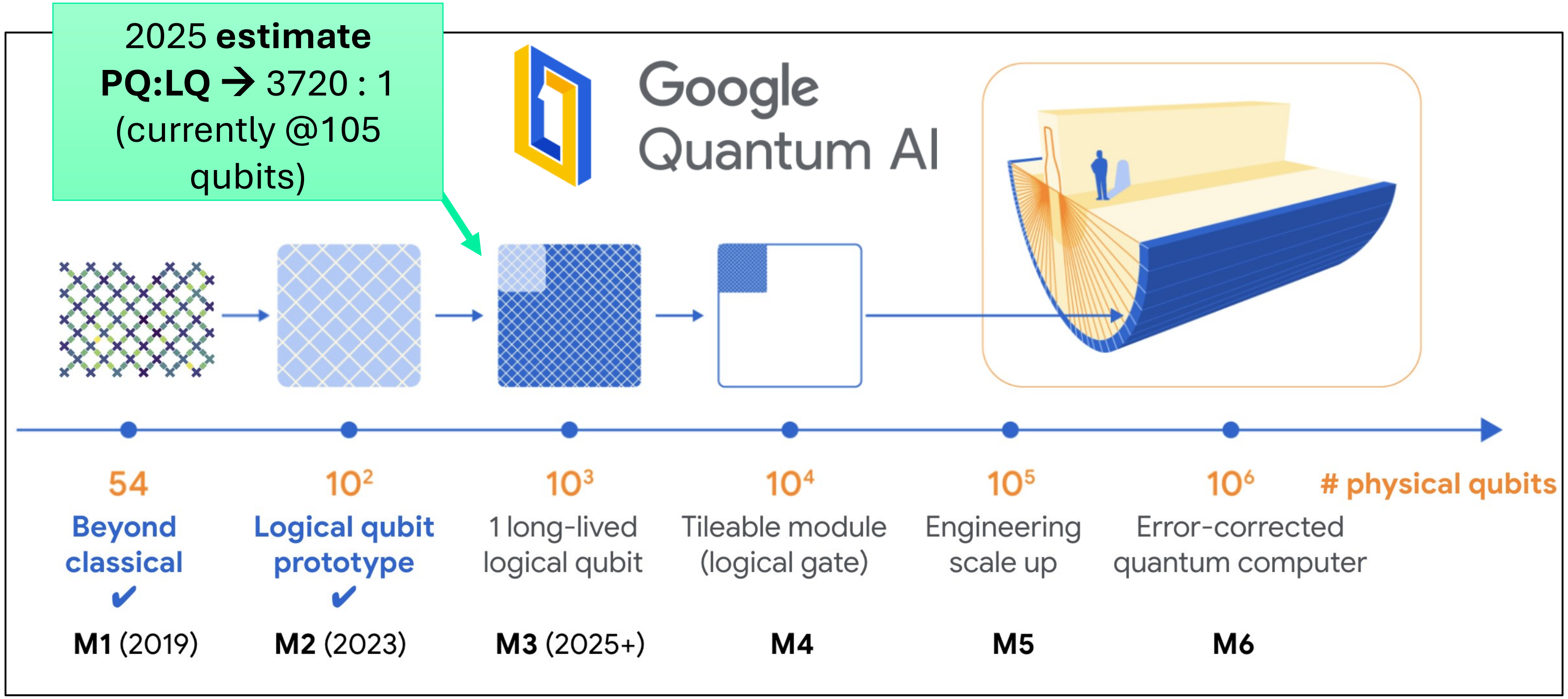
Acceptable CMOS gate input



Acceptable CMOS gate output

Quantum information...





Trapped ion quantum computer

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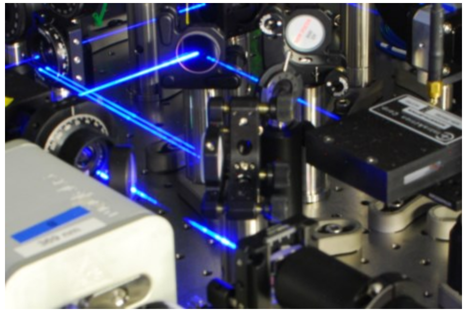
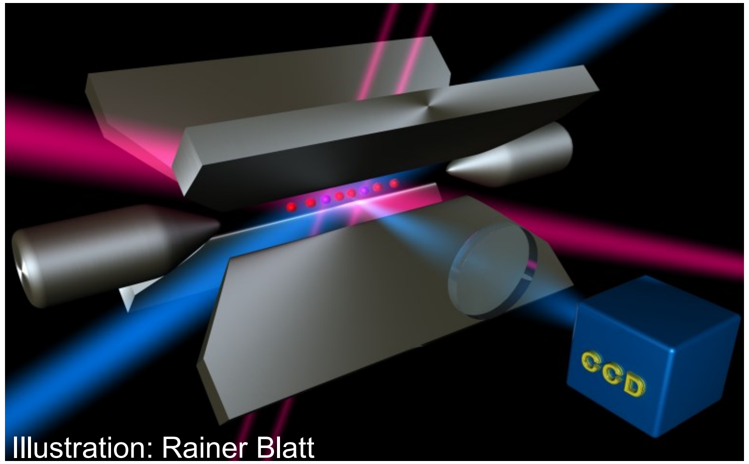
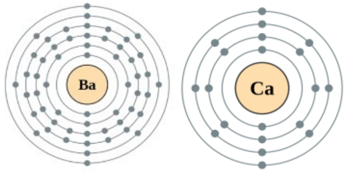
Encoding

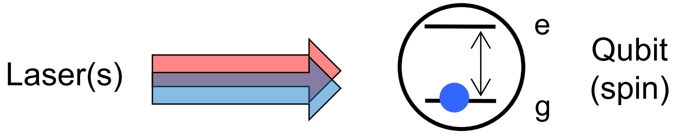
+ Laser(s)

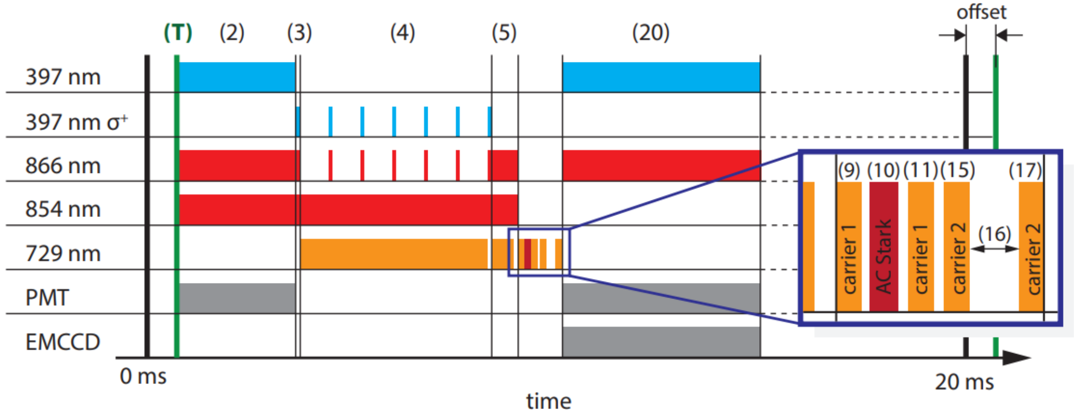


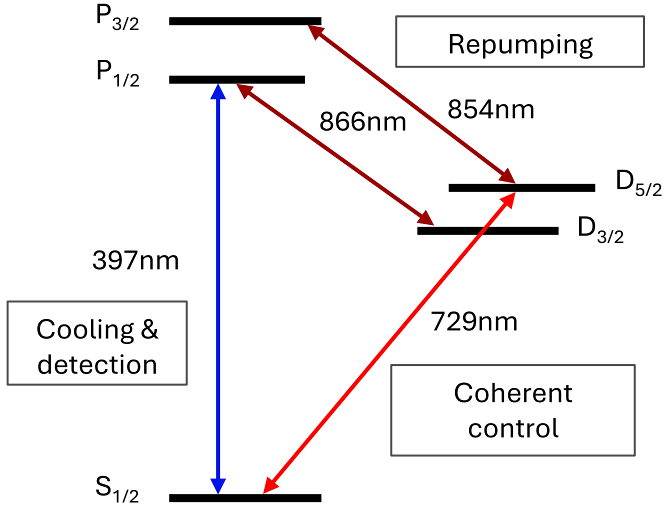
+ Ion trap



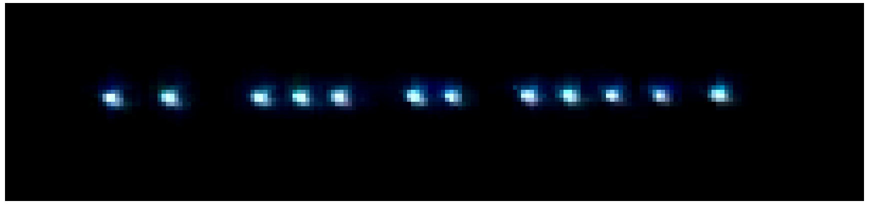








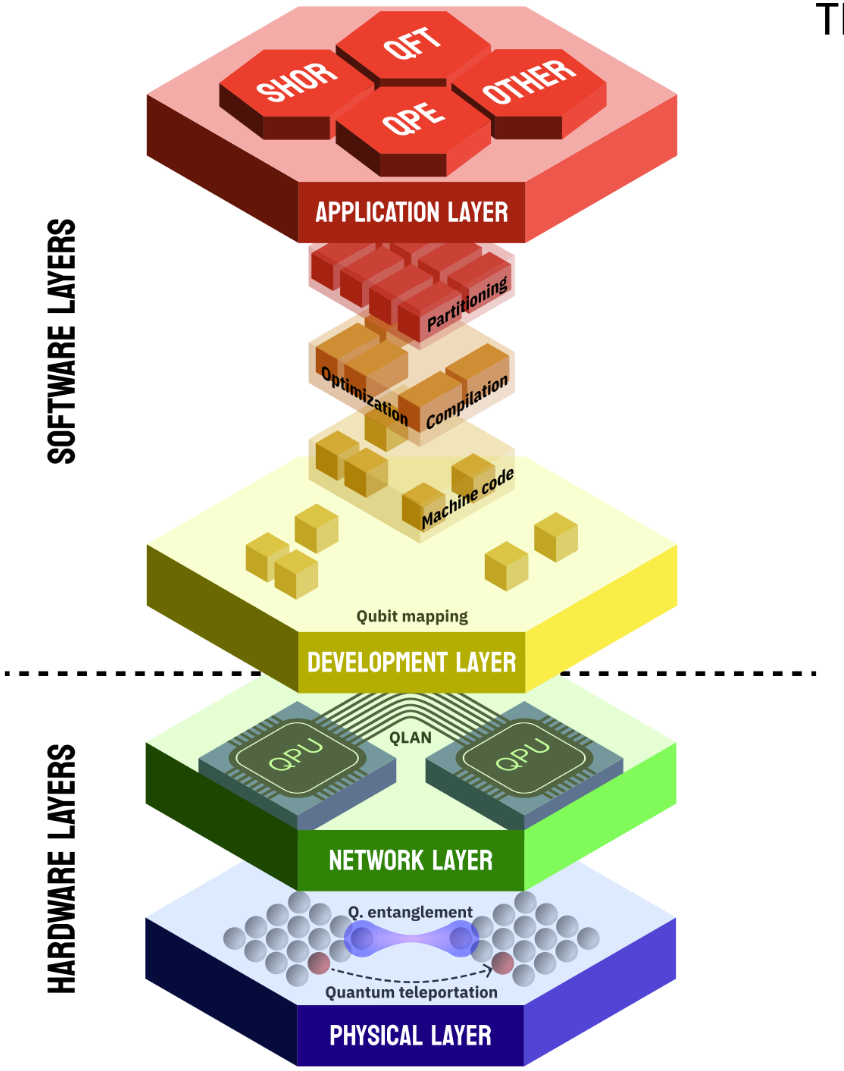
Result



Camera

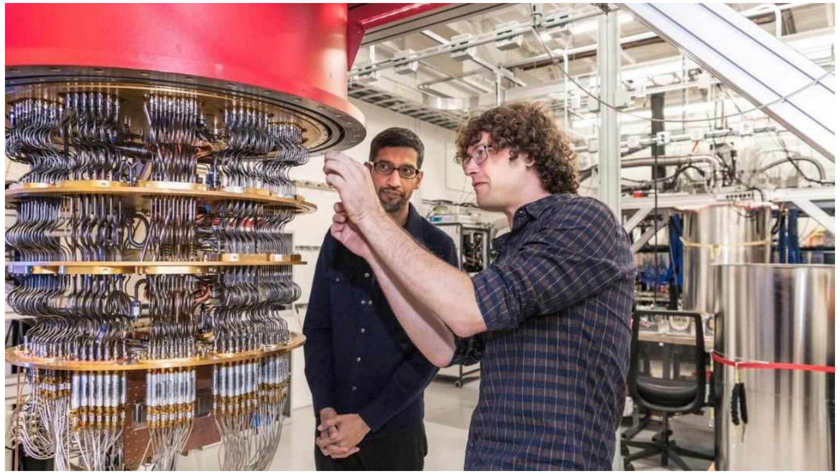
Integrated photonics

Motivation: key element for scaling quantum computers

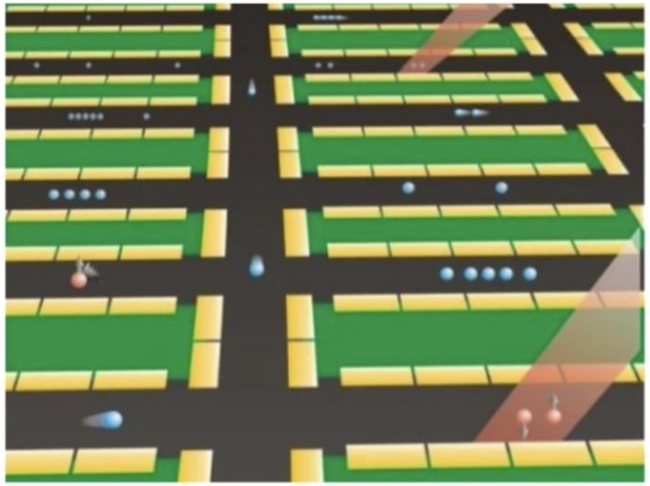


Barral et al. arXiv:2404.01265

The cabling for 56 superconducting qubits

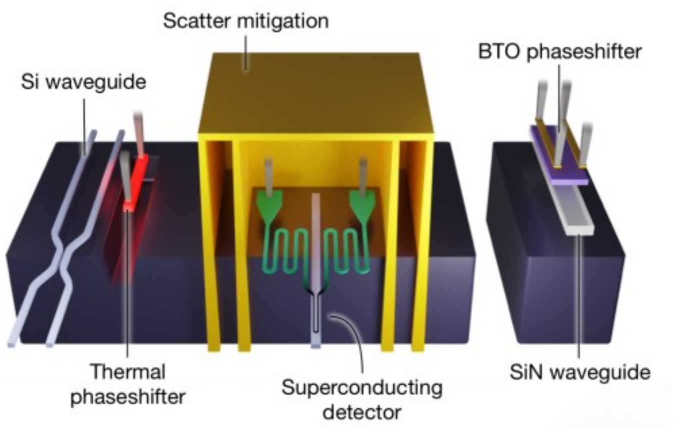


1000s of laser beams in an ion trap



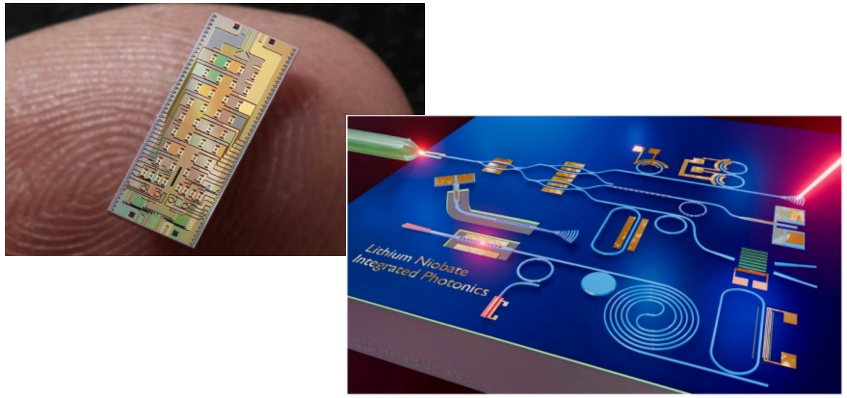
Kielpinski *et al*, Nature **417** 709 (2002).

Quantum photonic stack



PsiQuantum Team, https://arxiv.org/pdf/2404.17570

Miniaturized opto-electrical circuits



Two ways to scale up ions

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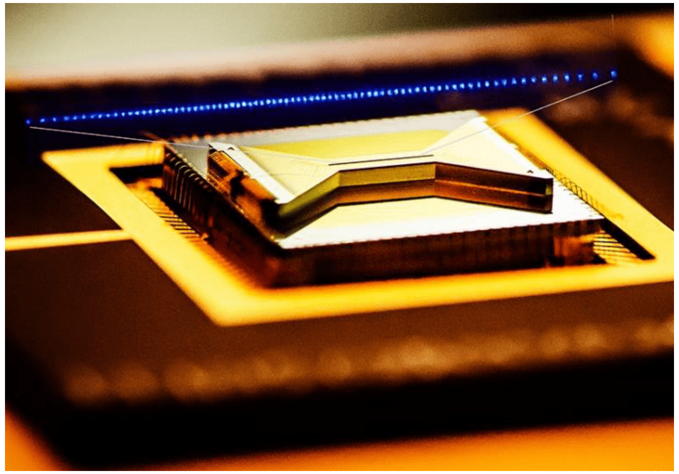
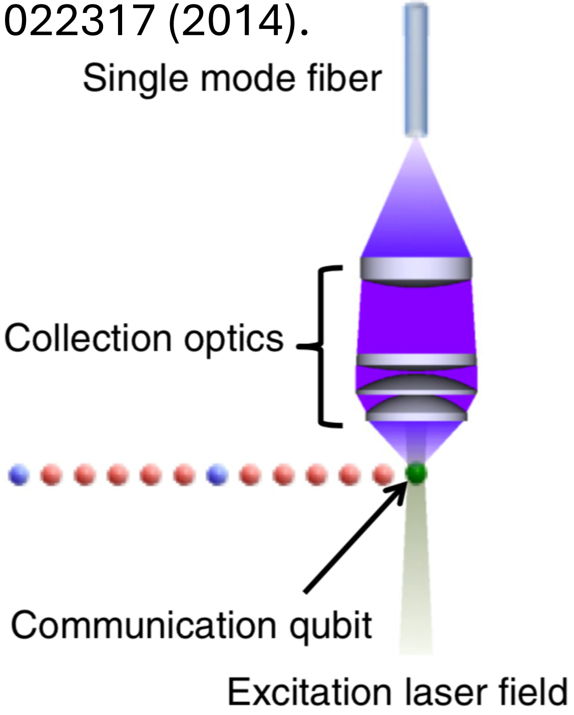
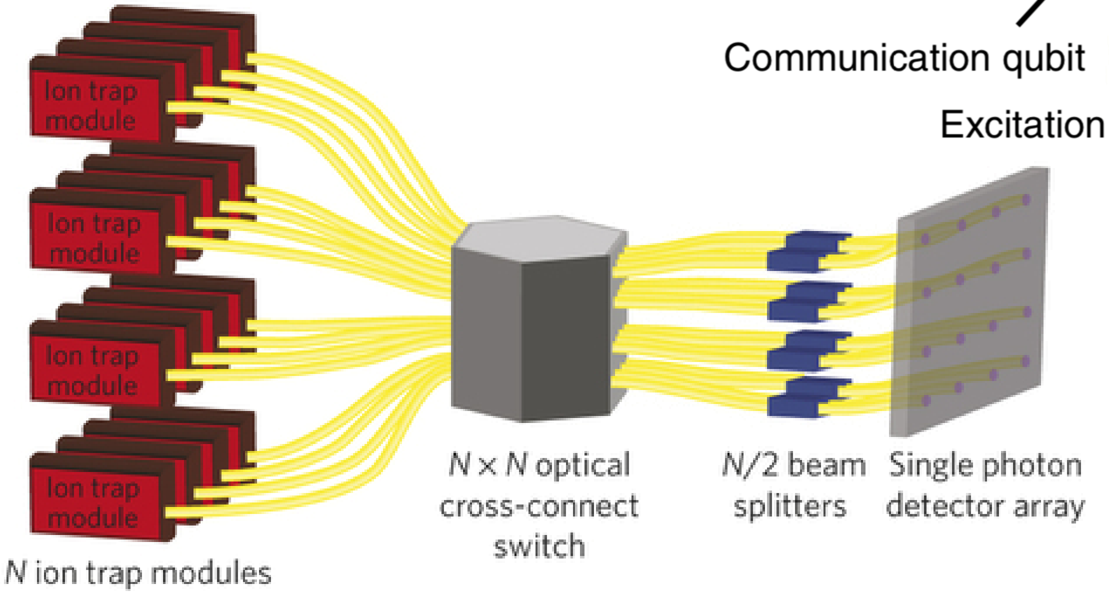
Photonic interconnects

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

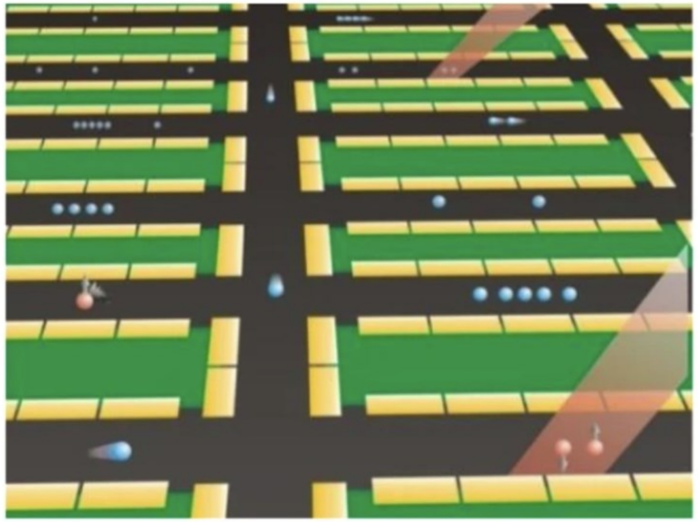


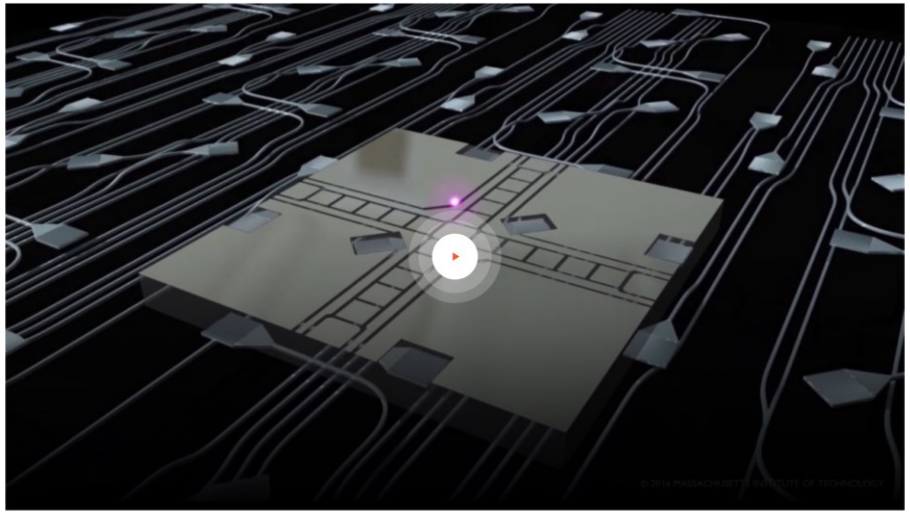




Q(uantum)CCD

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

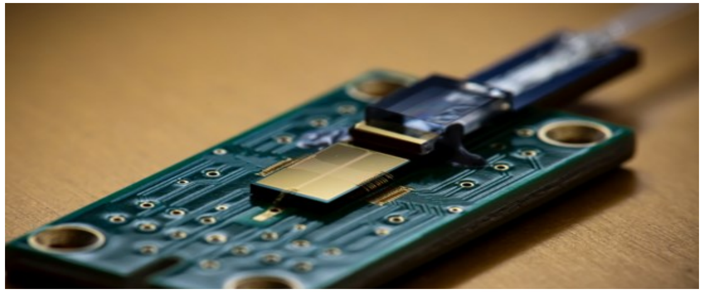


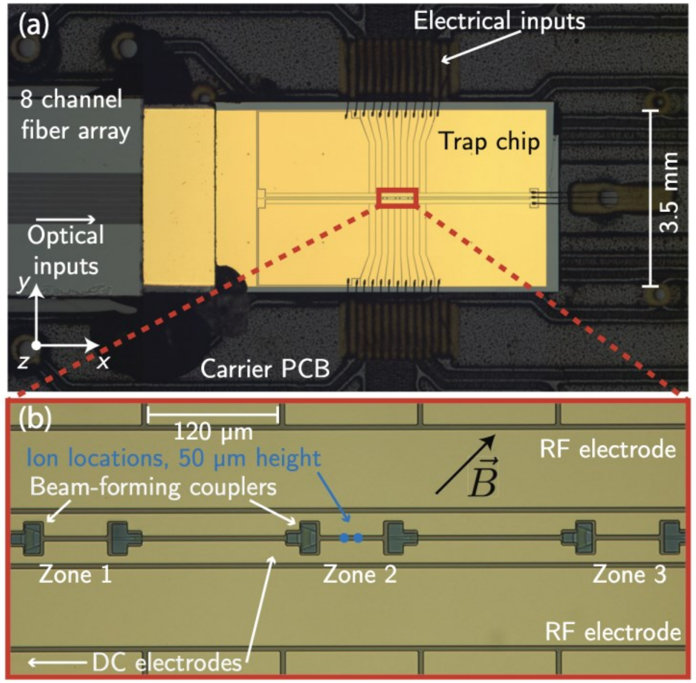


https://www.youtube.com/watch?v=UT3ev9OgkmY

MIT Lincoln Lab (2016)

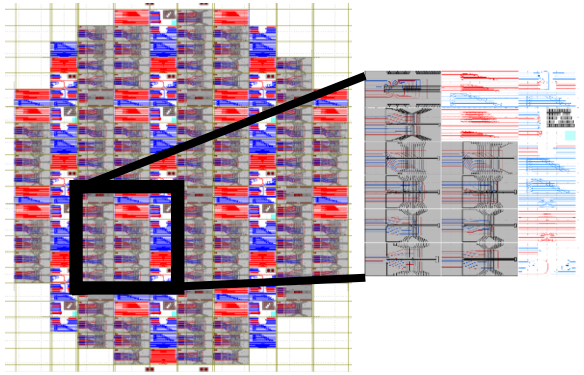
Status

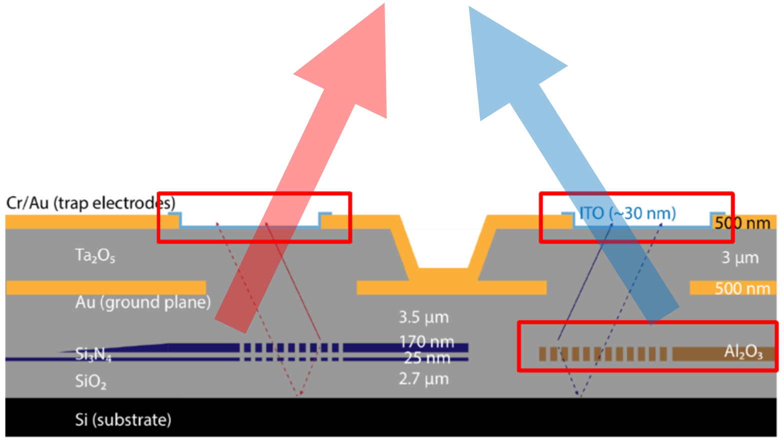


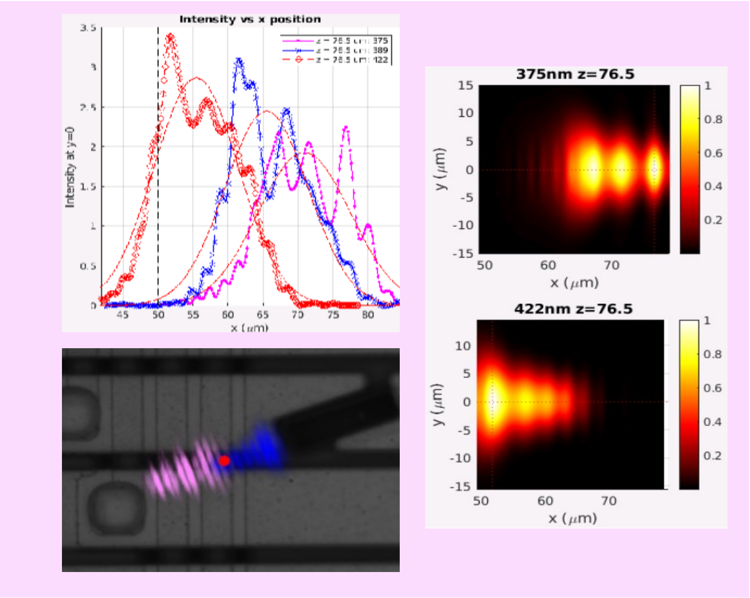


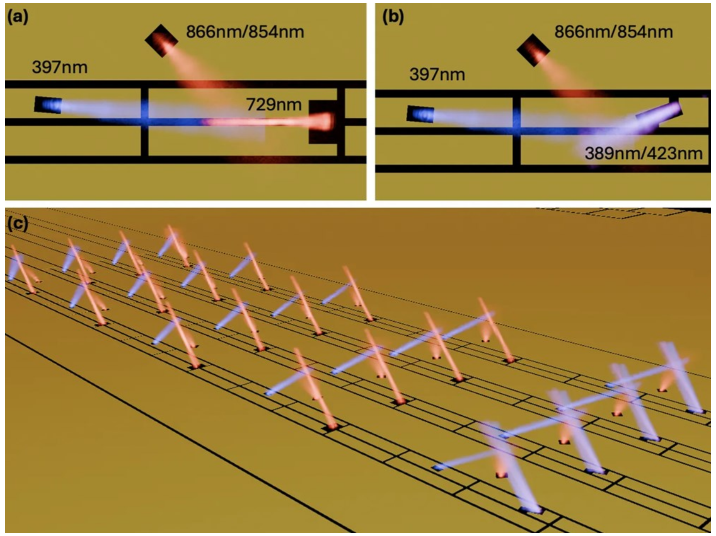
K. K. Mehta, C. Zhang, M. Malinowski, T.-L. Nguyen, M. Stadler, and J. P. Home, Nature **586**, 533-537 (2020).

ETH zürich
LIONIX INTERNATIONAL
LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY



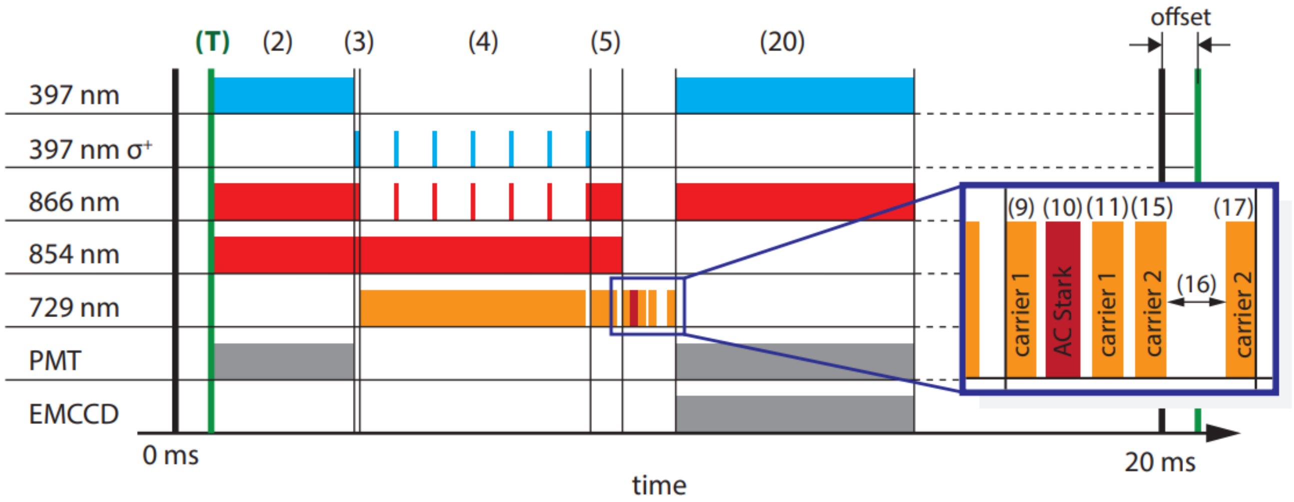


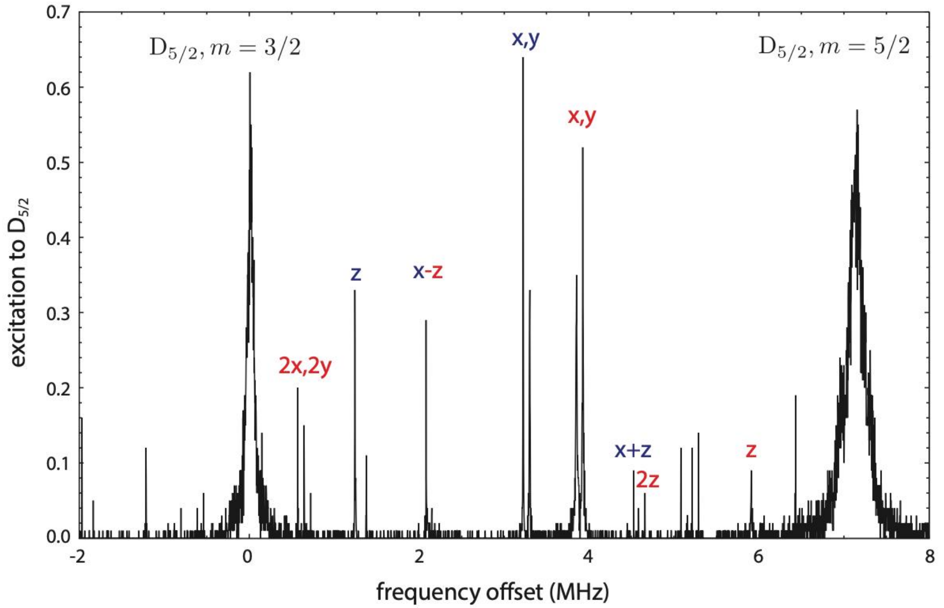




Active devices

Ion trap specifications

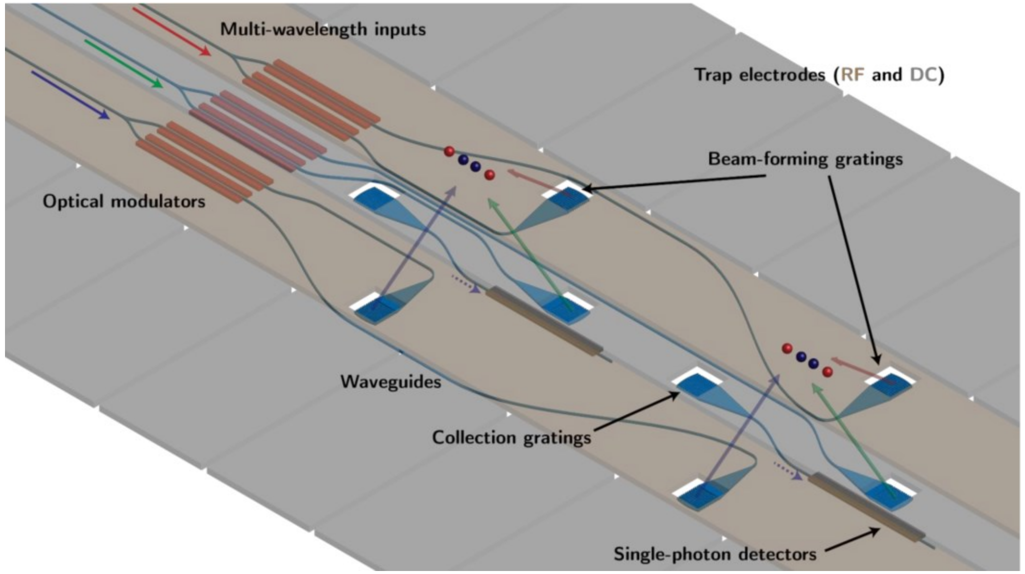




C. Hempel, Digital quantum simulation, Schrödinger cat state spectroscopy and setting up a linear ion trap, PhD thesis (2014)

Ca+

- Wavelength: 375 – 866 nm
- Power: 10 µW – 10 mW
- Target ER: >> 60 dB
- Bandwidth: 10 - 100 MHz*

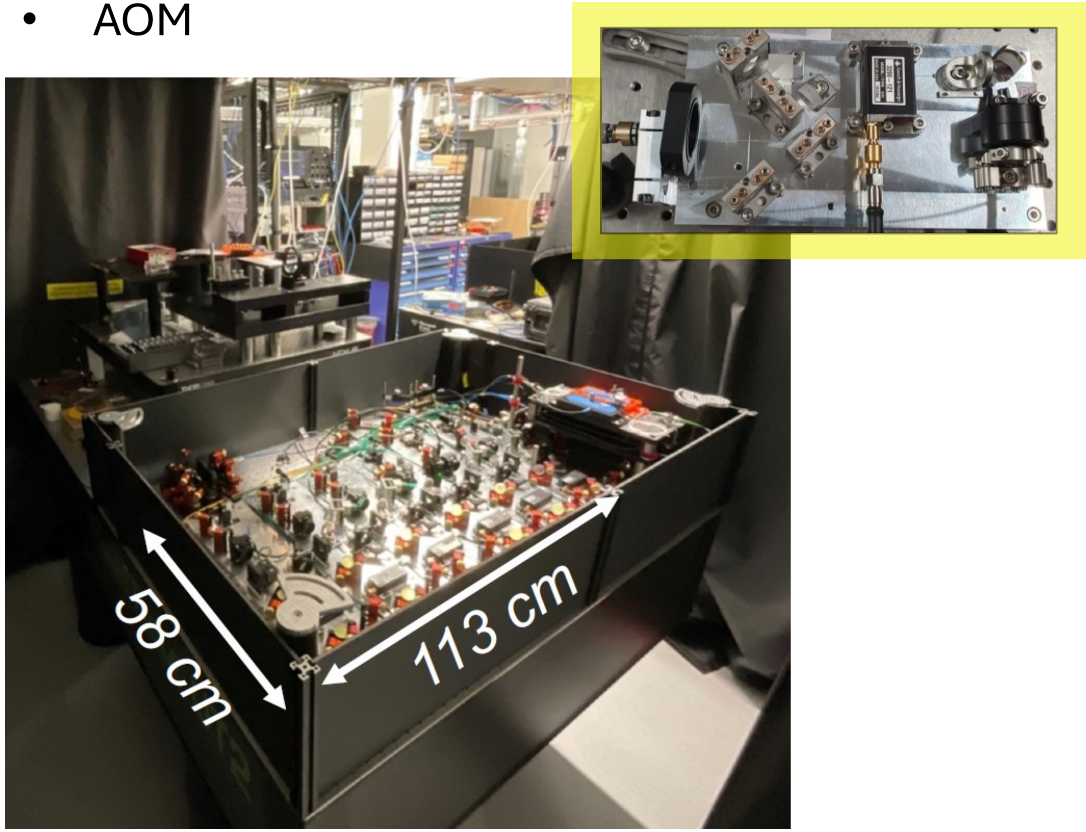


John Chiaverini and Karan K. Mehta in:
Moody, G. *et al.* 2022 Roadmap on integrated quantum photonics. *J Phys Photonics* **4**, 012501 (2022).

Active components

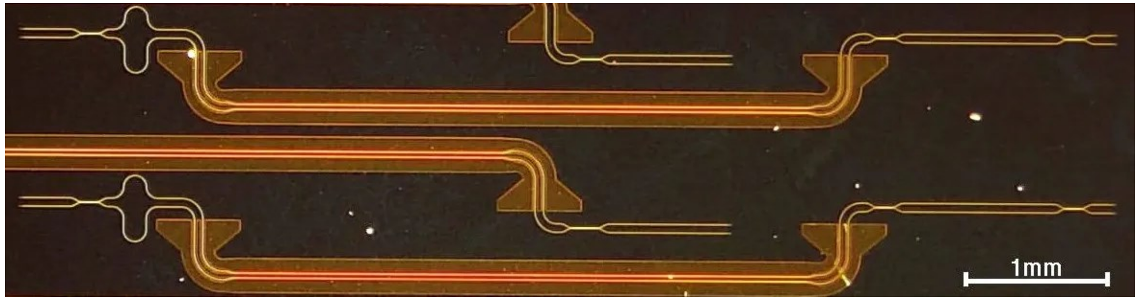
Signal control: Intensity, frequency and phase tuning.

- EOM
- AOM



- TFLN iEOM

CSEM



Optical Nanomaterials Group @ ETH Zürich (G. Finco, F. Kaufmann, J. Kellner, R. Grange)

Integrated optical modulators

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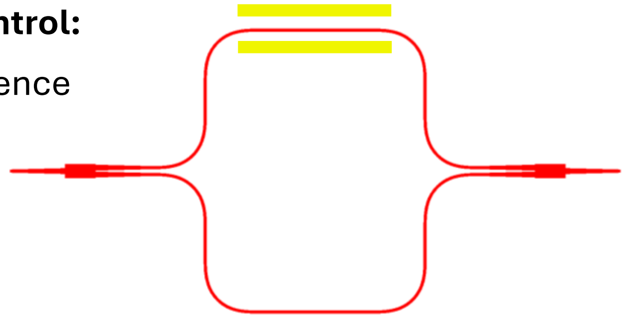
Optical phase shift:

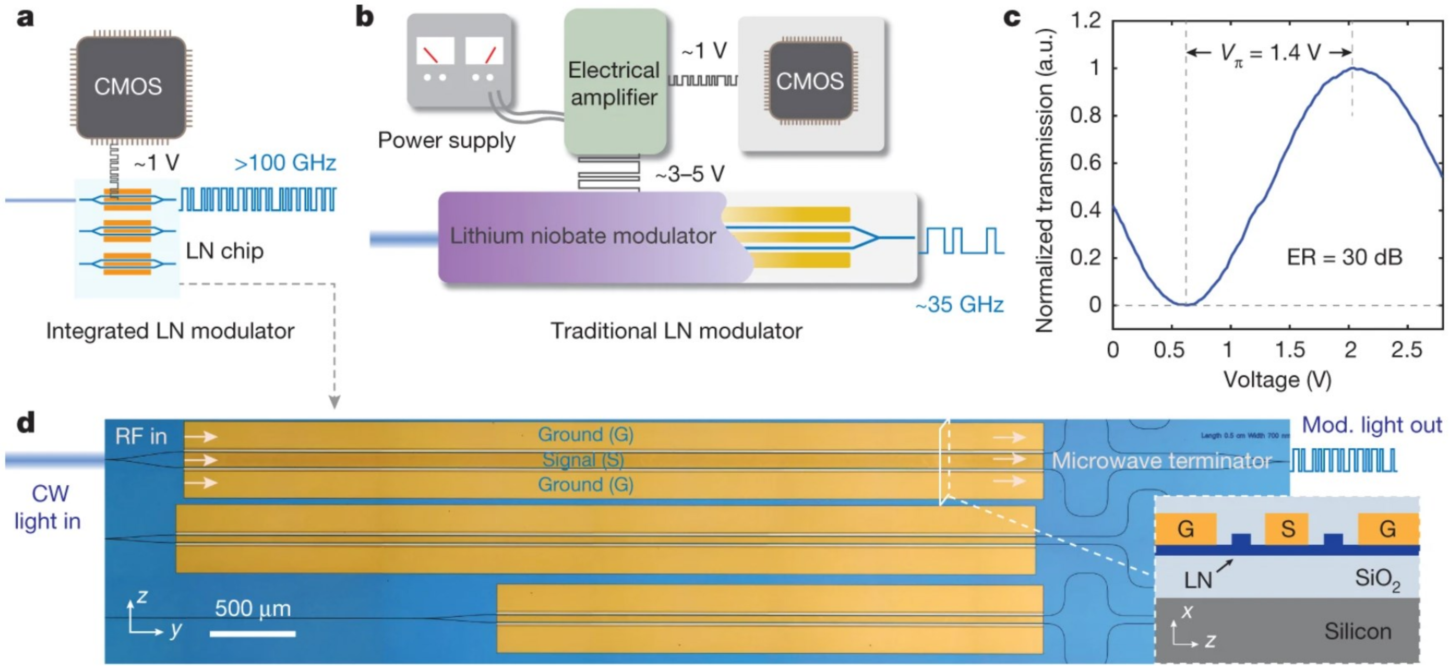
$$\Delta\Phi = (2\pi/\lambda_0)\Delta n_{\text{eff}} x$$

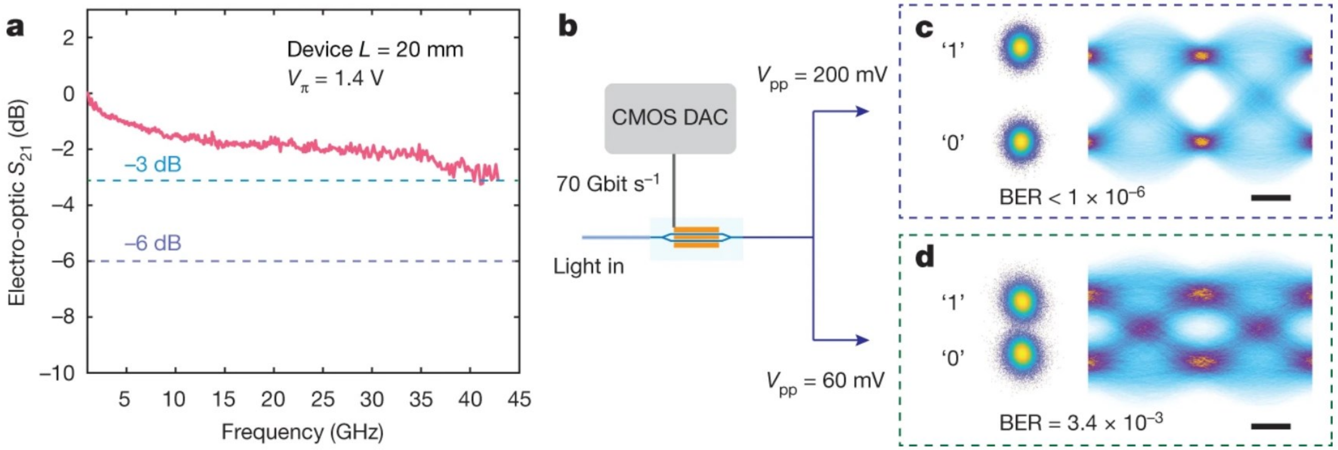
Electro-optic effect, i.e. refractive index changes due to material polarization under electric field

Intensity control:

Interference



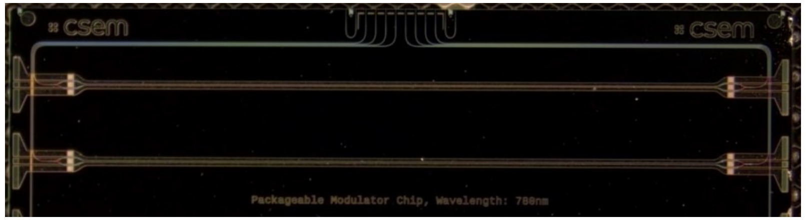


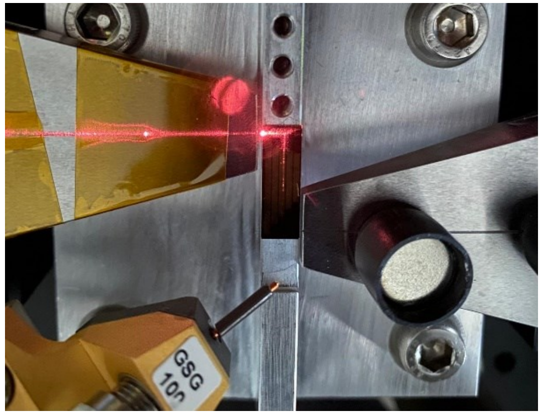


Wang, C.*et al.* Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages. *Nature* **562**, 101–104 (2018).https://doi.org/10.1038/s41586-018-0551-y

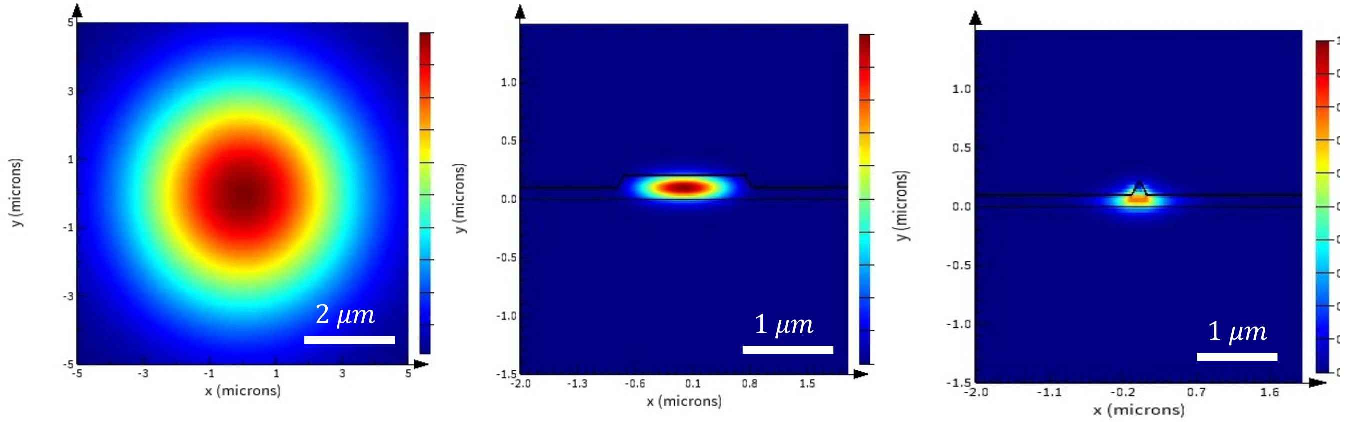
Observations

Challenge 1: Low loss interfacing



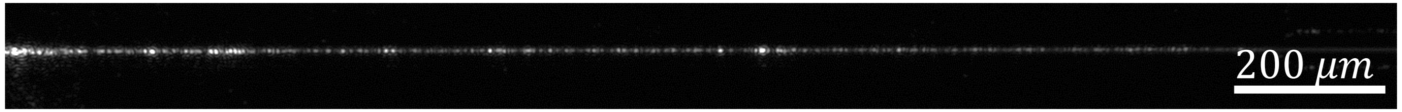


Issue: High index contrast and confined modes in thin film waveguides makes edge coupling not straight forward.

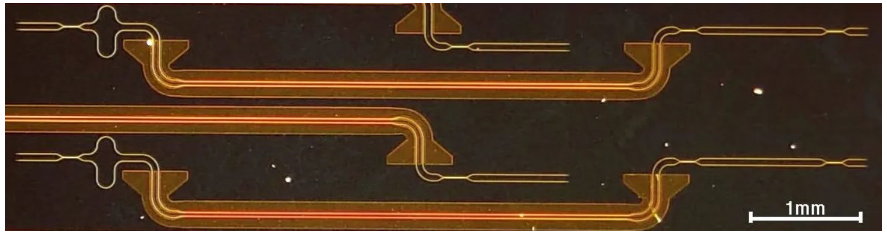


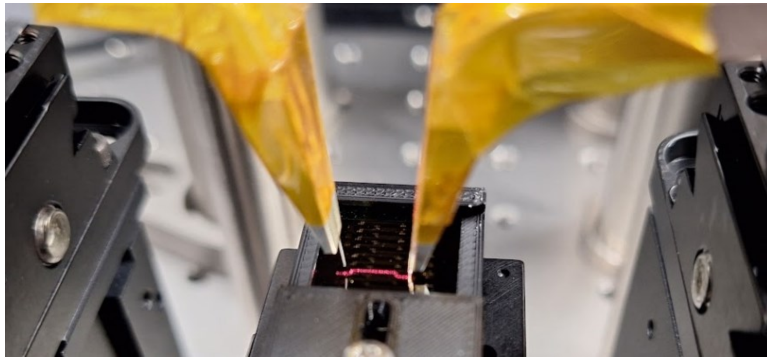
Scattering loss scales scale with the wavelength.

$$\alpha_{scattering} \propto \lambda^{-3}$$



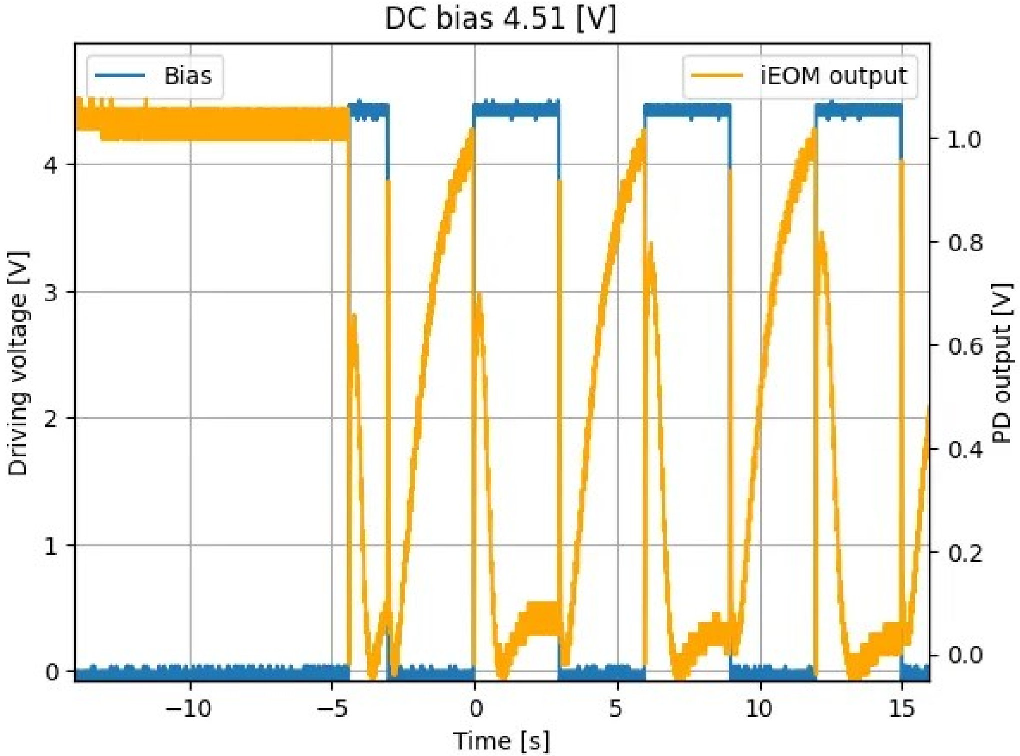
Challenge 2: Stability





$P_{in} = 12\ mW$
$V_\pi = 3.5\ V^*$

Issue: Observation of zero point drifts at lower frequencies (< 10 MHz).



- Trapped charges accumulating that may depend on fabrication, electrode distribution and temperature.

J. Holzgrafe et al, "Relaxation of the electro-optic response in thin-film lithium niobate modulators," Opt. Express 32, 3619-3631 (2024)

Opportunities

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- Integration with other platforms to exploit benefits from each (heterogenous integration), i.e. SiN for tapers/low loss routing.
- Test other active materials including lithium tantalate.
- Implement design mitigation strategies.
- Targeted development for visible/quantum technologies.
- Leverage expertise in packaging and fabrication in the Swiss ecosystem.

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Conclusions

- Passive photonic integration has been demostrated in the ion trap field and will enable scalable laser delivery in ion traps.
- Integrated active devices have not been yet explored to the same extend and will become very relevant for large scale implementations.
- Main challenges for the use of existing technologies include interfacing issues related to the working wavelengths and lack of stability at the required time scales.

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Thank you for your attention